Institut für Physik und Astronomie
Lehrstuhl Didaktik der Physik

Particle Physics in High-School Education: What Should Students and Teachers Learn?

Anja Kranjc Horvat

Dissertation zur Erlangung des akademischen Grades
"doctor rerum naturalium"
(Dr. rer. nat.)
in der Wissenschaftsdisziplin "Didaktik der Physik"

eingereicht an der Mathematisch-Naturwissenschaftlichen Fakultät

Institut für Physik und Astronomie

der Universität Potsdam

27 June 2021

Betreuer:	Prof. Dr. Andreas Borowski
Gutachter:	Prof. Dr. Andreas Borowski, Universität Potsdam Prof. Dr. Wouter van Joolingen, Universiteit Utrecht Prof. Dr. Amitabh Banerji, Universität Potsdam

https://doi.org/10.25932/publishup-56026
https://nbn-resolving.org/urn:nbn:de:kobv:517-opus4-560260

Ich versichere, dass ich diese Arbeit selbständig verfasst und keine anderen als die angegebenen Quellen und Hilfsmittel benutzt, sowie die Zitate kenntlich gemacht habe.

ABSTRACT

Elementary particle physics is a contemporary topic in science that is slowly being integrated into high-school education. These new implementations are challenging teachers' professional knowledge worldwide. Therefore, physics education research is faced with two important questions, namely, how can particle physics be integrated in high-school physics curricula and how best to support teachers in enhancing their professional knowledge on particle physics. This doctoral research project set up to provide better guidelines for answering these two questions by conducting three studies on high-school particle physics education.

First, an expert concept mapping study was conducted to elicit experts' expectations on what high-school students should learn about particle physics. Overall, 13 experts in particle physics, computing, and physics education participated in 9 concept mapping rounds. The broad knowledge base of the experts ensured that the final expert concept map covers all major particle physics aspects. Specifically, the final expert concept map includes 180 concepts and examples, connected with 266 links and crosslinks. Among them are also several links to students' prior knowledge in topics such as mechanics and thermodynamics. The high interconnectedness of the concepts shows possible opportunities for including particle physics as a context for other curricular topics. As such, the resulting expert concept map is showcased as a well-suited tool for teachers to scaffold their instructional practice.

Second, a review of 27 high-school physics curricula was conducted. The review uncovered which concepts related to particle physics can be identified in most curricula. Each curriculum was reviewed by two reviewers that followed a codebook with 60 concepts related to particle physics. The analysis showed that most curricula mention *cosmology*, *elementary particles*, and *charges*, all of which are considered theoretical particle physics concepts. None of the experimental particle physics concepts appeared in more than half of the reviewed curricula. Additional analysis was done on two curricular subsets, namely curricula with and curricula without an explicit particle physics chapter. Curricula with an explicit particle physics chapter mention several additional explicit particle physics concepts, namely the *Standard Model of particle physics*, *fundamental interactions*, *antimatter research*, and *particle accelerators*. The latter is an example of experimental particle physics concepts. Additionally, the analysis revealed that, overall, most curricula include *Nature of Science* and *history of physics*, albeit both are typically used as context or as a tool for teaching, respectively.

Third, a Delphi study was conducted to investigate stakeholders' expectations regarding what teachers should learn in particle physics professional development programmes. Over 100 stakeholders from 41 countries represented four stakeholder groups, namely physics education researchers, research scientists, government representatives, and high-school teachers. The study resulted in a ranked list of the 13 most important topics to be included in particle physics professional development programmes. The highest-ranked topics are *cosmology*, the *Standard Model*, and *real-life applications of particle physics*. All stakeholder groups agreed on the overall ranking of the topics. While the highest-ranked topics are again more theoretical,

stakeholders also expect teachers to learn about experimental particle physics topics, which are ranked as medium importance topics.

The three studies addressed two research aims of this doctoral project. The first research aim was to explore to what extent particle physics is featured in high-school physics curricula. The comparison of the outcomes of the curricular review and the expert concept map showed that curricula cover significantly less than what experts expect high-school students to learn about particle physics. For example, most curricula do not include concepts that could be classified as experimental particle physics. However, the strong connections between the different concept show that experimental particle physics can be used as context for theoretical particle physics concepts, Nature of Science, and other curricular topics. In doing so, particle physics can be introduced in classrooms even though it is not (yet) explicitly mentioned in the respective curriculum.

The second research aim was to identify which aspects of content knowledge teachers are expected to learn about particle physics. The comparison of the Delphi study results to the outcomes of the curricular review and the expert concept map showed that stakeholders generally expect teachers to enhance their school knowledge as defined by the curricula. Furthermore, teachers are also expected to enhance their deeper school knowledge by learning how to connect concepts from their school knowledge to other concepts in particle physics and beyond. As such, professional development programmes that focus on enhancing teachers' school knowledge and deeper school knowledge best support teachers in building relevant context in their instruction.

Overall, this doctoral research project reviewed the current state of high-school particle physics education and provided guidelines for future enhancements of the particle physics content in high-school student and teacher education. The outcomes of the project support further implementations of particle physics in high-school education both as explicit content and as context for other curricular topics. Furthermore, the mixed-methods approach and the outcomes of this research project lead to several implications for professional development programmes and science education research, that are discussed in the final chapters of this dissertation.

ZUSAMMENFASSUNG

Elementarteilchenphysik ist ein aktuelles naturwissenschaftliches Thema, das langsam in den Oberstufenunterricht integriert wird. Diese neuen Umsetzungen stellen das Professionswissen der Lehrpersonen weltweit infrage. Die Fachdidaktik sieht sich daher mit zwei wichtigen Fragen beschäftigt: Wie kann die Teilchenphysik in die Oberstufenlehrpläne integriert werden und wie können Lehrpersonen am besten dabei unterstützt werden, ihr Professionswissen über Teilchenphysik zu erweitern? Im Rahmen dieses Promotionsprojekts wurden drei Studien zum Unterricht von Teilchenphysik in der Oberstufe durchgeführt, um bessere Leitlinien für die Beantwortung dieser beiden Fragen zu erarbeiten.

Zunächst wurde eine Concept-Mapping-Studie durchgeführt, um die Erwartungen von ExpertInnen darüber zu ermitteln, was SchülerInnen der Oberstufe über Teilchenphysik lernen sollten. Insgesamt nahmen 13 ExpertInnen aus den Bereichen Teilchenphysik, Informatik und Physikdidaktik an 9 Concept-Mapping-Runden teil. Die breite Wissensbasis der Experten stellte sicher, dass die endgültige Expert Concept Map alle wichtigen Aspekte der Teilchenphysik umspannt. Die endgültige Expert Concept Map enthält 180 Konzepte und Beispiele, die mit 266 Verbindungen und Querverweisen verknüpft sind. Darunter befinden sich auch mehrere Bezüge zum Vorwissen der SchülerInnen in Themen wie Mechanik und Thermodynamik. Die starke Vernetzung der Konzepte zeigt, dass es möglich ist, die Teilchenphysik als Kontext für andere Lehrplanthemen zu nutzen. Die so entstandene Expert Concept Map wird als geeignetes Instrument für Lehrpersonen zur Unterstützung ihrer Unterrichtspraxis vorgestellt.

Zweitens wurde ein Vergleich von 27 Physiklehrplänen für die Oberstufe durchgeführt. Dabei wurde festgestellt, welche Konzepte mit Bezug zur Teilchenphysik in den meisten Lehrplänen zu finden sind. Jeder Lehrplan wurde von zwei Gutachtern mittels einer Kodieranleitung mit 60 Konzepten zur Teilchenphysik analysiert. Die Lehrplananalyse ergab, dass in den meisten Lehrplänen *Kosmologie*, *Elementarteilchen* und *Ladungen* erwähnt werden, die alle als theoretische Konzepte der Teilchenphysik gelten. Keines der Konzepte der experimentellen Teilchenphysik kam in mehr als der Hälfte der untersuchten Lehrpläne vor. Eine zusätzliche Analyse wurde für zwei Untergruppen von Lehrplänen durchgeführt, nämlich Lehrpläne mit und Lehrpläne ohne ein explizites Teilchenphysik-Kapitel. In Lehrplänen mit einem expliziten Teilchenphysik-Kapitel werden mehrere zusätzliche Teilchenphysik-Konzepte erwähnt, nämlich das *Standardmodell der Teilchenphysik*, *fundamentale Wechselwirkungen*, *Antimaterieforschung* und *Teilchenbeschleuniger*. Letzteres ist ein Beispiel für Konzepte der experimentellen Teilchenphysik. Darüber hinaus ergab die Analyse, dass die meisten Lehrpläne Aspekte der *Nature of Science* und der *Geschichte der Physik* enthalten, obwohl beide typischerweise als Kontext bzw. als Hilfsmittel für den Unterricht verwendet werden.

Drittens wurde eine Delphi-Studie durchgeführt, um die Erwartungen von Stakeholder in Bezug darauf zu untersuchen, was Lehrpersonen in Weiterbildungsprogrammen zur Teilchenphysik lernen sollten. Über 100 Stakeholder aus 41 Ländern vertraten vier

Stakeholder-Gruppen, nämlich FachdidaktikerInnen, FachwissenschaftlerInnen, RegierungsvertreterInnen und Lehrpersonen. Das Ergebnis der Studie ist eine Rangliste der 13 wichtigsten Themen, die in Fortbildungsprogrammen für Teilchenphysik behandelt werden sollten. Die am höchsten bewerteten Themen waren *Kosmologie*, das *Standardmodell der Teilchenphysik* und *Anwendungen der Teilchenphysik*. Alle Stakeholder-Gruppen waren sich über die Gesamtwertung der Themen einig. Während die am höchsten bewerteten Themen wiederum eher theoretischer Natur waren, erwarten die Stakeholder auch, dass Lehrpersonen etwas über experimentelle Teilchenphysik Themen lernen, die mit mittlerer Bedeutung eingestuft wurden.

Mit den drei Studien wurden zwei Forschungsziele dieses Promotionsprojekts verfolgt. Das erste Forschungsziel bestand darin, zu untersuchen, inwiefern die Teilchenphysik in den Physiklehrplänen für die Oberstufe behandelt wird. Der Vergleich der Ergebnisse der Lehrplananalyse und der Expert Concept Map zeigte, dass die Lehrpläne deutlich weniger abdecken als das, was ExpertInnen von OberstufenschülerInnen über Teilchenphysik erwarten. Beispielsweise enthalten die meisten Lehrpläne keine Konzepte, die der experimentellen Teilchenphysik zugeordnet werden können. Die vielfältigen Verbindungen zwischen den verschiedenen Konzepten zeigen jedoch, dass die experimentelle Teilchenphysik als Kontext für Konzepte der theoretischen Teilchenphysik, Nature of Science und andere Lehrplanthemen verwendet werden kann. Auf diese Weise kann die Teilchenphysik im Unterricht eingeführt werden, selbst wenn diese (noch) nicht explizit im jeweiligen Lehrplan erwähnt wird.

Das zweite Forschungsziel bestand darin, herauszufinden, welche Aspekte des Fachwissens Lehrpersonen über Teilchenphysik vermittelt werden sollen. Der Vergleich der Ergebnisse der Delphi-Studie mit den Resultaten der Lehrplananalyse und der Expert Concept Map zeigte, dass die Stakeholder im Allgemeinen erwarten, dass Lehrpersonen ihr Schulwissen im Sinne der Lehrpläne erweitern. Darüber hinaus wird von den Lehrpersonen erwartet, dass sie ihr Schulwissen vertiefen, indem sie lernen, wie sie Konzepte aus ihrem Schulwissen mit anderen Konzepten der Teilchenphysik verbinden können. Fortbildungsprogramme, die den Schwerpunkt auf die Verbesserung des Schulwissens und des vertieften Schulwissens der Lehrpersonen legen, unterstützen somit bestmöglich die Lehrpersonen beim Aufbau relevanter Zusammenhänge für ihren Unterricht.

Insgesamt wurde im Rahmen dieses Promotionsprojekts der aktuelle Stand des Teilchenphysikunterrichts in der Oberstufe untersucht und es wurden Leitlinien für die künftige Aufwertung teilchenphysikalischer Inhalte in der Ausbildung von Jugendlichen und Lehrpersonen erarbeitet. Die Ergebnisse des Projekts unterstützen die aktuelle Einführung der Teilchenphysik im Oberstufenunterricht sowohl als expliziten Inhalt als auch als Kontext für andere Lehrplanthemen. Darüber hinaus ergeben sich aus der Methodik und den Ergebnissen dieses Forschungsprojekts mehrere Implikationen für Weiterbildungsprogramme und für die Physikdidaktik, die in den letzten Kapiteln dieser Dissertation diskutiert werden.

TABLE OF CONTENTS

TABLE OF FIGURES

LIST OF TABLES

1 INTRODUCTION

My first encounter with particle physics was in the last year of high school when I picked up some books on cosmology and string theory. The books opened my eyes to a bunch of new questions: What is dark matter? Why did antimatter disappear? What happened just after Big Bang? What are particles? Those were not topics I ever encountered in the classroom. At that time, high-school physics was typically presented to us as “done,” making it a dull and old-fashioned subject that only few found interesting. While I enjoyed understanding the processes around us, it never appeared to me that this is something I – or anyone else for that matter – could consider as a career option. Only when I learned there were still things to explore did I become interested.

My experience was not a lonely one. Students are generally interested in unknown phenomena such as cosmology or particle physics, as shown by the ROSE study (Sjøberg & Schreiner, 2012). Still, many students of my generation left high school without learning about open questions or even just a glimpse into modern physics – and many still do. Modern physics generally receives little attention from curriculum policies and educational research (Park et al., 2019). For example, Slovenian high-school physics curriculum barely touches upon modern physics topics. Furthermore, particle physics is not necessarily a part of pre-service education for physics teachers in Slovenia. Therefore, it is challenging for them to include particle physics in their classroom even outside of the curricular requirements.

Luckily, teachers’ education does not end when they start teaching. Quite the opposite, in many countries, including Slovenia, teachers are actively encouraged to participate in professional development (OECD, 2019). In response to the need for professional development, various organisations and research institutions organise professional development for in-service teachers. Indeed, professional development is central to all curricular changes (Borko, 2004; Corcoran, 1995; Garet et al., 2001; OECD, 2019). One of the, if not the largest and most successful professional development programmes in particle physics is organised at the European Organization for Nuclear Research, CERN. Indeed, CERN has been managing professional development programmes in particle physics, namely CERN’s teacher programmes, for over 23 years. These programmes, aimed at in-service high-school teachers, started as an extension to CERN’s summer student programme. Over the years, the programmes developed and became more professionalised. Now, teachers can participate in one of the two types of teacher programmes, namely national or international teacher programmes. First, CERN’s national teacher programmes run in the national language of the teachers (e.g., Serbian, Slovenian, German) and last between three to five days. Second, CERN’s international teacher programmes are held in English and welcome teachers from around the world for two weeks. Overall, 35-40 programmes per year take place, each welcoming up to 48 teachers. They contain a mixture of lectures by experts in modern science and technology related to CERN, visits to on-site research facilities, hands-on workshops, sessions for questions and answers, and social events. Together, CERN welcomes around a thousand teachers worldwide each year that is not stained by a pandemic.

I have been a part of the team managing these programmes for the last three and a half years. I got to meet the teachers, I got to talk to them about their struggles and their victories, and I got to be inspired by them every single day - just like I was inspired by particle physics books I found all those years ago in high school. Every day, I could see what participating in these programmes and visiting CERN's facilities means to them personally and professionally. And I asked myself:

What do teachers achieve in these programmes, and how can I help them achieve more?

Answering these questions was my main motivation for my doctoral research project. Starting from the beginning, the project's original aim was to evaluate CERN's teacher programmes in three steps. First, I planned to conduct a Delphi study with CERN's teacher programmes stakeholders to identify what they think teachers should learn during their time at CERN. Second, I wanted to ask experts in particle physics and physics education which concepts related to particle physics they find important for teachers and students to learn. Last, I wished to evaluate what teachers learned through a pre/post concept mapping study. Teachers would be asked to create a concept map on particle physics before and after the programme. Comparing the two concept maps would show s which topics they learned about the most.

The first study was successfully conducted in 2019, with the second one following suit in 2020. However, the third part did not go as planned. Like many other plans around the world, my plans shifted in early 2020. The global pandemic reflected strongly on CERN's teacher programmes. With the health and travel restriction, teachers could not travel to CERN anymore. The programmes got cancelled one after the other and were eventually replaced by tailor-made online events. While this meant that the evaluation of CERN's teacher programmes was no longer possible, not all was lost. I took this challenge as an opportunity to investigate the current state of particle physics in high-school curricula by conducting a large-scale international curricular review. Overall, 27 curricula from all continents were included in this study. Some were in English, others in Serbian, Greek, or even French. Each of them was slightly different and each had slightly different ways of introducing various particle physics concepts to high-school education. Therefore, this extensive curricular review offered me an insight into how physics is taught in high-school classrooms around the world. Furthermore, the review better connected the previous two studies as a meaningful whole. This connection resulted in better suggestions for future particle physics implementations in high-school education and particle physics professional development programmes.

Hence, this doctoral research project still managed to reach a part of its original goal – to help teachers. Through the three studies, I uncovered various ways in which particle physics can be introduced in high-school physics classrooms either as content or context for other curricular topics. Hopefully, this will encourage even more teachers to embrace the magnificent and exciting world of particle physics education.

2 THEORETICAL BACKGROUND

2.1 Particle Physics in the Classroom

Some of the first records of including particle physics in pre-university learning units come from Utrecht University in 1980 (PLON, 1981, as cited in Swinbank, 1992). Not long after, the inclusion of particle physics in more curricula was discussed at the first conference on teaching modern physics in high schools (Aubrecht, 1986). Similar calls for particle physics inclusion were often repeated throughout the years (e.g., Chatterjee, 2002; Hanley, 2000; Kobel, 2003; Tuzón & Solbes, 2016). Now, several high-school physics curricula include particle physics (Gourlay, 2017; Mullis et al., 2016). Furthermore, a relatively large number of studies on including individual particle physics concepts in high-school education have been published. In the following two sections, a short overview of some of the most important publications in the field of high-school particle physics education is given.

2.1.1 Students' Understanding of Particle Physics

This literature review identified two studies that investigated students' understanding of particle physics directly. First, Tuzón and Solbes (2016) investigated Spanish second-to-last-year high-school students' understanding of particle physics. The study revealed that students had some knowledge about particle physics, although particle physics was not an explicit chapter in their curriculum. However, their knowledge was incomplete and lacked structure. For example, students were generally confused about the difference between the fundamental interactions (e.g., electromagnetic interaction) and the derived forces (e.g., friction).

Overall, students expressed interest in including particle physics in the curriculum in various ways. Here, Tuzón and Solbes (2016) suggested including particle physics in the curriculum implicitly by connecting it to other curricular topics rather than as an explicit chapter. Many suggestions on connecting particle physics to other parts of the curricula were given also in other publications (e.g., Barradas-Solas, 2007; Cid-Vidal & Cid, 2018; Wiener et al., 2016). On the other hand, few connections were made to the social context (e.g., latest scientific results), although students expressed high interest in connecting particle physics to everyday life. The outcomes of the Tuzón and Solbes (2016) study showed that knowledge of particle physics needs to connect to students' social context and other curricular topics. Similarly, the concepts' interconnectedness is central to the constructivist theory by Ausubel (2000). Nevertheless, there are no studies on how different concepts within particle physics are expected to connect in a structured network.

Second, Gourlay (2017) investigated particle physics knowledge of year-12 high-school students from the United Kingdom. These students have already had explicit lessons on particle physics, and their knowledge of the topic has been summatively assessed. In the study, students' knowledge was explored with concept maps. Concept maps are graphic organisers that represent organised knowledge in a hierarchical network (Novak, 1985; Novak & Cañas, 2008). As such, concept maps help uncover cognitive structures on a specific topic, for example, particle physics. Gourlay (2017) analysed students' particle physics concept maps and searched for the most common patterns of correct and incorrect conceptions. The analysis showed that students most often correctly connected quarks, leptons, particle systems, and annihilation.

Interestingly, most incorrect conceptions were also connected to leptons and particle systems. In all cases, connections were very superficial; for example, "up is a type of quark." Very few of the connections, either correct or incorrect, featured a process (e.g., "when a particle and its antiparticle meet, they annihilate each other") or a property (e.g., "hadrons are subject to the strong nuclear force") (Gourlay, 2017, p.4). Following Tuzón and Solbes (2016), the students' knowledge strongly reflects textbooks and the curriculum. Thus, it can be assumed that textbooks and the curriculum are superficial as well. This assumption reflects the notion by Hobson (2011a), Michelini (2021), and Passon et al. (2018), who noted that particle physics is often oversimplified. However, if curricula and textbooks are oversimplified, how can the cycle of superficial teaching and learning particle physics be broken?

2.1.2 Particle Physics Concepts in High-School Education

In the last two decades, many studies have been published on introducing particle physics to high-school students. However, only a few have published suggestions for particle physics as an independent part of the curriculum. First, Berg and Hoekzema (2006) and Hoekzema et al. (2005) formed a particle physics chapter around the discussion about particle interactions, conservation laws, and symmetries. Similarly, Lindenau and Kobel (2019) also focused their suggestion on particle interactions. Here, the particle interactions acted as a context for introducing charges, fundamental interactions, and elementary particles. In their study, the authors connected charges, fundamental interactions, and elementary particles into a triangle where each concept lead to the other two. Together, they build the basis of the Standard Model of particle physics. Conversely, Hobson (2011a, 2011b) approached the challenge of teaching particle physics in high schools from the perspective of quantum mechanics. Starting from quantum field theory and quantum electrodynamics, they introduced the concept of elementary particles, fundamental interactions, interaction particles, and annihilation. All five approaches presented in this paragraph build a strong case for introducing theoretical foundations of particle physics.

Experimental particle physics and, especially, particle physics research laboratories were merely mentioned in the literature presented above, acting more as an example than as content itself. On the other hand, Polen (2019) proposed a broader chapter, including all concepts mentioned above with the addition of particle accelerators and detectors. However, their proposal was less detailed and provided less insight into the lesson structure. Thus, it is unclear which concepts should be included and how they should connect within the lesson. Furthermore, no connections to students' prior knowledge were made.

Connections between particle physics and other curricular topics are widely discussed in Wiener et al. (2016). Here, the Large Hadron Collider (LHC), the largest particle collider in the world, was proposed as context for various other curricular topics, e.g., electromagnetism and quantum mechanics. Additionally, various real-life applications of accelerator technology were introduced. The focus of this proposal was different from most previous suggestions in the literature where theoretical particle physics was in the centre. Indeed, most previous publications focused on a narrow field within particle physics and tried building a lesson around this narrow field or connecting it to other curricular topics. In the following paragraphs, the individual concepts appearing in the literature are presented.

Several publications suggested that the Standard Model of particle physics is one of the possible windows into the world of particle physics (e.g., Andrews & Nikolopoulos, 2018; Lindenau & Kobel, 2019; Polen, 2019; Woithe et al., 2017). By describing fundamental interactions between the elementary particles, the theory of the Standard Model of particle physics frames theoretical particle physics. However, the mathematical description of these interactions between particles is complex (Woithe et al., 2017), too complex for high-school level of mathematics. This complexity can lead to a naïve and reductionistic approach of introducing the Standard Model (Michelini, 2021; Passon, 2020). Thus, Lindenau and Kobel (2019) suggested the Standard Model to be simplified to three concepts – elementary particles, fundamental interactions, and charges – as mentioned above. These three concepts were explored further by various other authors individually or in pairs.

First, various innovative techniques have been suggested to enhance the learning of the elementary particles, for example, hands-on experiments (e.g., Alexopoulos et al., 2019; Johansson et al., 2007; MacDonald & Bean, 2009; McGinness et al., 2019) and art (e.g., Alexopoulos et al., 2019; Andrews & Nikolopoulos, 2018; MacDonald & Bean, 2009; Nikolopoulos & Pardalaki, 2020; Pavlidou & Lazzeroni, 2016). However, elementary particles and their properties were often presented in an oversimplified manner in the classroom, similar to the periodic system of elements (Berg & Hoekzema, 2006; Lindenau & Kobel, 2019). While students could memorise these concepts (Gourlay, 2017), it is questionable whether such rote learning contributes to the understanding of particle physics.

Second, basic properties and connections of fundamental interactions to charges and elementary particles were often explored in the literature (Cecire et al., 2014; Lindenau & Kobel, 2019; Nikolopoulos & Pardalaki, 2020; Wiener et al., 2017a; Woithe et al., 2017). Here, Woithe et al. (2017) stated that “a charge is a property of an elementary particle that defines the fundamental interaction by which it is influenced” (p. 1). Some authors also introduced interaction particles that mediate fundamental interactions (Cecire et al., 2014; Hobson, 2011a; Johansson et al., 2007; Nikolopoulos & Pardalaki, 2020). However, interaction particles were more often mentioned in the literature without referencing fundamental interactions and their role in them. For example, photons were usually mentioned in the context of optics or quantum mechanics (e.g., Olsen, 2002) and not so often in the context of particle physics.

Third, charges were typically discussed in connection to elementary particles (Cecire et al., 2014; Lindenau & Kobel, 2019; Wiener et al., 2017a, 2017b; Woithe et al., 2017) and fundamental interactions (Lindenau & Kobel, 2019). Very few suggestions in the literature focused on charges explicitly. Here, Wiener et al. (2017a, 2017b) discussed the representations of colour charges, and Lindenau & Kobel (2019) included charges as one of the three central concepts of their approach. Strong connections of charges to other concepts in the literature show that while introducing charges is challenging in a stand-alone activity, they play a significant role in connecting other concepts in particle physics in a meaningful network.

Overall, a big part of the reviewed literature on high-school particle physics content included theoretical particle physics. Still, some suggestions for including experimental particle physics can be found in the literature as well. However, they are generally used as context for other curricular topics. For example, many authors suggested connecting modern-day particle physics equipment, especially particle accelerators, to electromagnetism, optics, and the theory of relativity (e.g., Cid-Vidal et al., 2021; Cid-Vidal & Cid, 2011, 2018; Wiener et al., 2016). Similarly, Barradas-Solas (2007) and Kvita et al. (2019) suggested introducing particle detectors through the framework of radiation. However, not all mentioned publications on experimental particle physics included connections to theoretical particle physics concepts. Here, Wiener et al. (2016) introduced fundamental interactions and charges in the context of the LHC. Barradas-Solas (2007) talked about leptons in the context of historical particle detectors. Likewise, Kvita et al. (2019) used the context of a modern particle detector to mention elementary particles. Indeed, experimental particle physics and theoretical particle physics were generally presented as two separate entities with scarce connections.

Finally, several suggestions on introducing open questions in particle physics were made in the literature. Andrews and Nikolopoulos (2018) and Woithe and Kersting (2021) suggested including dark matter in the physics courses. Similarly, several studies recommended adding questions regarding the Big Bang, inflation, and expansion (Alexopoulos et al., 2019; Kobel, 2003; Ma & Zhang, 2016; Xu et al., 2018). Open questions represent an important aspect of the Nature of Science (NOS), namely the “tentative Nature of Science” (Schwartz et al., 2004; Schwartz & Lederman, 2008, 2002). Here, NOS can be defined as the “values and underlying assumptions that are intrinsic to scientific knowledge, including the influences and limitations that result from science as a human endeavour” (Schwartz et al., 2004, p.611). Lederman et al. (2013) suggested that NOS should be integrated into the instruction of the content itself. Thus, introducing open questions in particle physics, integrating experimental physics, and framing the topic into students’ social context can help enhance their scientific literacy (Lederman et al., 2013; Schwartz et al., 2004; Schwartz & Lederman, 2008, 2002). However, introducing both particle physics concepts and the NOS requires teachers to have a sufficient level of professional knowledge.

2.2 Teachers' Professional Knowledge

Teachers' professional knowledge is a key factor for instructional quality and as such the essential mediating factor in student performance (Abell, 2007; Carter & Darling-Hammond, 2016; H. E. Fischer et al., 2012; Kulgemeyer & Riese, 2018; Martin et al., 2012; Sadler et al., 2013). For successful teaching, teachers need to know more than just the content they are intended to teach (Mahler et al., 2017). High-quality teaching requires teachers to be able to justify the content and the selected pedagogical techniques from the perspective of student learning (Gess-Newsome et al., 2019). Thus, three dimensions within teachers' professional knowledge have been defined in various studies: content knowledge, pedagogical knowledge, and pedagogical content knowledge (e.g., Abell, 2007; Chan & Hume, 2019; Kulgemeyer & Riese, 2018; Park & Oliver, 2008). First, content knowledge (CK) represents the syntactic and substantive knowledge of the subject matter selected for teaching. As CK is one of the focal points of this thesis, it is described in more detail in subsequent sections. Second, pedagogical knowledge (PK) describes general knowledge of learners and learning situations (Grossman, 1990). PK encompasses the knowledge of learning theories, instructional principles, and managing heterogeneous groups (e.g., Guerriero, 2017; Richardson, 1996). Last, pedagogical content knowledge (PCK) is defined as the knowledge on teaching a particular content (e.g., Abell, 2007; Chan & Hume, 2019; Cochran & Jones, 1998; Kulgemeyer & Riese, 2018; Park & Oliver, 2008; Shulman, 1986, 1987). Additionally, Schwartz & Lederman (2002) extend professional knowledge by adding another category, namely the Nature of Science knowledge (NOSk). While NOSk is sometimes included in the CK dimension (e.g., Chan & Hume, 2019), it can be argued that the Nature of Science extends beyond the CK on a respective topic (e.g., physics). Indeed, teachers' CK was shown not to be significantly related to teachers' conceptions of the Nature of Science (Lederman, 2013) despite an overlap between the two dimensions, as seen in Schwartz & Lederman (2002).

All four dimensions of professional knowledge are distinct yet interconnected. For example, both CK and PCK play an important role in improving teachers' explanation skills. PCK takes the role of a mediator between CK and the explanation (Abell, 2007; Baumert et al., 2010; Kulgemeyer & Riese, 2018). In return, science teachers' CK feeds into their PCK (Şen et al., 2018), specifically knowledge of what students understand in science and knowledge of instructional strategies. Indeed, both CK and PK are foundations for the development of PCK (Sorge et al., 2019). Similarly, a strong NOSk is the foundation for the NOS aspect of PCK (Schwartz & Lederman, 2002). The interplay between the dimensions of professional knowledge makes teacher education a complex and dynamic process. Therefore, most studies focus on a smaller subset of professional knowledge dimensions. As the second part of my doctoral research project focused mostly on CK, this dimension is discussed in more detail below.

2.2.1 Content Knowledge for Teaching

As mentioned above, teachers' CK has been defined as knowledge of the subject matter selected for teaching and its organising structures (Abell, 2007; Chan & Hume, 2019). As such, CK includes the knowledge of facts, concepts, and procedures in the discipline (Lucero et al., 2017). In science education, CK includes "understanding of science subject matter", "research experience within the discipline", "knowledge of science in general", and "an understanding of the Nature of Science" (Wenning et al., 2011, p. 4).

Various studies have found that better CK reflects positively on teachers' effectiveness. Fleer (2009) reported that the lack of sufficient CK is often seen as the main reason teachers are ineffective. Indeed, teachers teaching the content area in which they claimed greater expertise knew how to present the key concepts better, make better real-world connections and integrate a wider range of knowledge (Gess-Newsome & Lederman, 1993; Sanders et al., 1993). Here, Şen et al. (2018) argued that teachers with higher levels of CK tend to ask more higher-level questions, e.g., connections between concepts. Similarly, Sanders et al. (1993) found that teachers with greater CK also better realise that their CK needs to be transformed for their students.

Furthermore, Ball et al. (2001) found that an adequate CK is necessary for teachers implementing curricular updates successfully. This is one of the reasons to focus on CK when considering new additions to the curriculum, such as particle physics. Indeed, Covay Minor et al. (2016) and Şen et al. (2018) found that teachers with weaker CK tend to stick stronger to their existing curriculum and away from further changes. However, strong CK may still not be sufficient for introducing new topics (Chan & Yung, 2018) or new instructional methods (Wilkins, 2008) to the curriculum.

Similarly, the relationship between teachers' CK and students' performance has also been widely researched. However, the studies led to somewhat conflicting results. For example, several studies found a positive influence of teachers' CK on student achievement (Diamond et al., 2014; Hill et al., 2005; Metzler & Woessmann, 2012). Indeed, Diamond et al. (2014) found teachers' CK to be the largest teacher-level predictor of student achievement. On the other hand, the results of the COACTIV study show that teachers' CK has a very limited predictive power of student success (Baumert et al., 2010). Likewise, the PULS study showed no correlation between teachers' CK and student improvement (Ohle et al., 2011). Cauet et al. (2015) found that teachers' CK cannot explain students' knowledge variations. However, they did notice that teachers with a higher level of CK were created more challenging learning opportunities for their students. Here, Cauet et al. (2015) suggest that their test might not be able to differentiate between teachers' CK necessary for effective physics teaching and the more complex CK that might not be useful in the classroom.

2.2.2 Dimensions of Content Knowledge

Studies have shown that teachers' CK exceeds the required students' knowledge (Grossman, 1990; Shulman, 1986, 1987; Tchoshanov, 2011; Wenning et al., 2011). Thus, teachers need to participate in subject-specific education that exceeds school knowledge. Dreher et al. (2016) further noticed that school subjects differs greatly from academic subjects. The disparity between required teachers' and students' knowledge called for a deeper insight into the subscales of CK. Three dimensions have been identified, namely (1) school knowledge (SK), (2) university knowledge (UK), and (3) deeper school knowledge (DSK). First, SK reflects the expected knowledge that good students achieve, typically defined by the curriculum and school textbooks. Second, UK is defined by the university curriculum, generally including more complex calculations and in-depth research (Enkrott et al., 2017; Kulgemeyer et al., 2020; Kulgemeyer & Riese, 2018). Last, DSK describes a deeper understanding of school knowledge (e.g., knowledge of different procedures and solutions) (Kulgemeyer et al., 2020; Riese, 2009; Riese et al., 2015). DSK models five skills, namely to (1) apply different ways of solving a task, (2) plan the solution of a task from a theoretical point of view, (3) recognise boundary conditions, (4) adapt tasks for the target group, and (5) recognise connections, similarities and differences between physical phenomena (Riese, 2009; Riese et al., 2015).

The studies on the effects of different aspects of CK on teacher quality and student achievement show contradictory results. For example, Lee and Mamerow (2019) showed that students who were taught by teachers with a higher level of UK (e.g., a major in the subject they teach) are more likely to perform better and enrol in college. Likewise, teachers with academic training in the subject outperform teachers without such training (Betts et al., 2003, Goldhaber & Brewer, 2000, Greenwald et al., 1996). However, several other studies had different conclusions. They found that having a stronger UK reflects only marginally or not at all on both student achievement and teacher quality (Clotfelter et al., 2007; Hanushek et al., 2005; Harris & Sass, 2011; Ladd & Sorensen, 2015; Rivkin et al., 2005; Wu, 2011).

However, most studies on the effect of CK on teacher quality and student achievement did not evaluate all three CK aspects simultaneously. This was later done by Kulgemeyer and Riese (2018). They found that SK and DSK correlate strongly with the explaining performance. Meanwhile, UK does not seem to reflect on the quality of teachers' explanations. This difference could be explained by the studies by Arzi and White (2008) and Wheeldon et al. (2012). They found that 15 years after finishing the pre-service education, SK predominates over UK in teaching. Indeed, teachers' major sources of knowledge shift from university textbooks and scientific journals to the school curriculum itself. With higher reliance on the curriculum, teachers can become less malleable and less likely "to encourage student questions that can trigger both student and teacher learning" (Arzi & White, 2008, p. 26). Unwillingness to encourage student questions could mean that teachers are less sure about their CK, as those questions go beyond the scope of the curriculum. Not knowing the answer to student questions shows teachers the limitation of their CK. These limits are harder to reach when teachers source their CK from other sources as well. Indeed, a higher number of science courses in pre-service education and thus higher UK reflects positively on self-reported CK (Diamond et al., 2014).

Regardless of the partition of CK, what constitutes “content” is not well defined (Ball et al., 2008), neither at the general subject-matter level nor the more specific topic levels. Thus, to increase CK, further research in the content definition and different types of content knowledge is needed before further developing professional development programmes (PDPs) on respective topics. In particle physics, the first step in determining the content was done by Oettle (2021). They investigated which content areas teachers are expected to know for teaching particle physics. The content areas were defined through a Delphi study with particle physics experts and physics teachers. Ten content areas were identified, as shown in Table 1. However, no research has been done to determine how this knowledge reflects the curricula, on which of these topics teachers are expected to enhance their knowledge, and which aspects of CK these content areas represent.

2.2.3 Professional Development Programmes

Professional development is one of the key factors in successful curricular reforms (Borko, 2004; Corcoran, 1995; Garet et al., 2001; OECD, 2019). Indeed, teachers’ professional knowledge needs to match the content of the curricula to implement any changes successfully. In many countries, teachers’ participation in professional development is a prerequisite for either maintaining employment, promotion, or salary increases (OECD, 2019). Therefore, it is hardly surprising that, on average, 94% of primary, secondary, and high-school teachers reported having participated in at least one form of teacher training in 2018 (OECD, 2019).

One kind of professional development opportunity for enhancing teachers’ instructional skills, professional knowledge, and other teacher characteristics are professional development programmes (PDPs) (Banilower et al., 2007; Borko, 2004; Fischer et al., 2018; Greene et al., 2013; Hewson, 2007; Luft & Hewson, 2014; OECD, 2019; Pena-Lopez, 2009; Schneider, 2019). Such programmes usually act as shorter structured interventions organised by various institutions. In the field of particle physics, several such programmes can be found around the world (e.g., CERN, Ligo, Netzwerk Teilchenwelt, Perimeter, Quarknet). In this doctoral research project, the focus is shifted towards CERN and CERN’s teacher programmes, which were shortly described in Chapter 1.

Table 1. Content areas within teachers’ CK on particle physics.

Content areas (by Oettle)	
The Standard Model	The structure of matter
Particles in high-energy physics	Symmetries and conservation laws
Fundamental interactions	Cosmology
Brout-Englert-Higgs mechanism	Special theory of relativity, quantum mechanics, and quantum field theory in respect to particle physics and quantum field theory
School experiments	
Open questions in particle physics	

Note. Adapted from Oettle (2021).

As mentioned in the Introduction, the initial goal of this doctoral research project was to evaluate CERN's teacher programmes. The research project started with a Delphi study investigating stakeholders' expectations regarding PDPs in large particle physics research institutions, such as CERN. A part of the outcomes is represented in Chapter 6. However, the Delphi study investigated several other aspects of PDPs as well: learning goals of PDPs on particle physics and in general, activities to be included in particle physics PDPs, expected follow-up activities, and expected resources for teachers. The results of these aspects from the Delphi study are shown in Appendix A. Furthermore, the results of the Delphi study on learning goals of PDPs on particle physics were already published in the Journal of Science Teacher Education in 2021 (Kranjc Horvat et al., 2021). These results are also relevant for the studies in this doctoral thesis. Therefore, a short overview of the results is presented below, while the methodology is better described in Chapter 5.

As mentioned, a part of the Delphi study investigated the stakeholders' expectations regarding the learning goals of PDPs at large particle physics research institutions. The stakeholders who participated in the study were particle physics researchers, country representatives, physics education researchers, and teachers. Overall, the Delphi study included three rounds. First, an open-ended questionnaire elicited the free ideas of the stakeholders. Second, stakeholders rated the themes from the first round based on their perceived importance of particle physics professional development programmes. Third, the stakeholders ranked the themes from most to least important to increase the differentiation between the topics. This resulted in a list of the most important learning goals for professional development programmes in large particle physics research institutions, presented in Table 2.

Table 2. Most important learning goals for professional development programmes in large particle physics research institutions. Learning goals are classified based on their respective dimensions of professional knowledge. Additionally, they are grouped based on how the stakeholders ranked them.

Learning goal	**Importance level**
PCK: Enhance knowledge of curriculum	High
CK: Enhance knowledge of concepts and models	High
CK: Learn about connections between different fields of science	Medium
PK: Enhance general knowledge of learners and learning situations	Medium
PCK: Gain experience in new subject-specific instructional strategies	Medium
PCK: Learn about subject-specific instructional strategies	Medium
PK: Learn to address inequalities	Medium
CK: Enhance knowledge of solving equations	Low
PCK: Enhance knowledge of the use of multimedia in instruction	Low
PCK: Knowledge of assessments	Low

Note. Adapted from Kranjc Horvat et al. (2021).

The two most important learning goals, as perceived by stakeholders, were "enhance knowledge of curriculum" as part of PCK and "enhance knowledge of concepts and models" as part of CK. Furthermore, most learning goals from this list fit under CK or PCK, with stakeholders strongly agreeing on their ranking. Therefore, it is important to further research which aspects of CK and PCK are important in such professional development programmes.

3 RESEARCH AIMS

Particle physics is a relatively new topic in many high-school physics curricula. Thus, the particle physics content of educational programmes is not yet well defined. Little is known about which concepts and topics high-school students and teachers are expected to achieve during their respective particle physics courses. With continuous calls for introducing particle physics to more high-school physics curricula (e.g., Chatterjee, 2002; Hanley, 2000; Kobel, 2003; Tuzón & Solbes, 2016), it is necessary to define what particle physics is supposed to include in high-school education. Thus, this doctoral research project focused on investigating the content that high-school students and teachers are expected to learn.

3.1 Research Aim 1: How Extensively do High-School Curricula cover particle Physics?

The introduction of particle physics in high schools has been criticized for being presented in a very oversimplified and superficial manner (Gourlay, 2017; Michelini, 2021). However, the extent of this has not yet been determined. Therefore, the first research aim of this doctoral research project was to **evaluate how extensively is particle physics covered by high-school physics curricula** and whether it indeed is oversimplified.

Two studies were conducted to address this research aim. First, an expert concept map was developed through an iterative study with 13 experts in particle physics and physics education. Concept mapping enabled experts to structure concepts they identified as the most relevant for high-school education into a hierarchic network. The expert concept map on particle physics showed how the concepts in particle physics connect with each other and concepts in other physics fields. The final concept map represents the expected students' knowledge structure after a particle physics course. The iterative design of the study enabled the experts to identify and add all relevant fields and concepts within particle physics. As such, the expert concept map provides a general overview of what particle physics in high-school physics education should entail.

Second, a curricular review was conducted with 27 state, national, and international high-school physics curricula. The curricula were reviewed by expert teachers and physics education researchers following a coding manual. The coding manual was a collection of particle physics-related concepts that were mostly based on the concept of the expert concept map. The objective of the curricular review was to identify concepts and topics that appear in most high-school physics curricula. Thus, the outcomes of the curricular review represent what high-school students are learning.

Last, the outcomes of the two studies were compared. The most mentioned concepts and topics were mapped onto the expert concept map to measure overlap. The bigger the overlap, the closer the curricula are to experts' expectations regarding what high-school students should learn about particle physics. A small overlap would mean that the experts expect high-school students to learn more about particle physics than what their curricula expect them to learn.

3.2 Research Aim 2: What should Teachers Learn about Particle Physics?

The expected high-school students' knowledge does not directly reflect on the expected high-school teachers' content knowledge. Indeed, teachers' content knowledge needs to extend beyond what they are expected to teach their students (Mahler et al., 2017). Teachers' content knowledge for teaching consists of three main aspects: school knowledge, deeper school knowledge, and university knowledge, as described in Chapter 2. Previous studies have not explored how different aspects of content knowledge were featured in professional development programmes. Therefore, the second research aim of this doctoral research project was to **identify which aspects of content knowledge are teachers expected to enhance during their participation in professional development programmes**.

All three studies included in this doctoral research project were compared to address the second research aim. First, a Delphi study was conducted to identify the most important content areas for particle physics professional development programmes. Over 100 stakeholders from four stakeholder groups participated in the three-round Delphi study. The outcomes of the Delphi study represent content knowledge that the stakeholders expect to be enhanced by teachers' participation in particle physics professional development programmes.

Second, the outcomes of the Delphi study were compared to the curricular review results. The most mentioned curriculum concepts define teachers' school knowledge, one of the aspects of content knowledge (Enkrott et al., 2017; Kulgemeyer et al., 2020; Kulgemeyer & Riese, 2018). The content areas from the Delphi study that correspond to concepts or topics from the curricular review are considered school knowledge.

Third, the outcomes of the Delphi study were compared to the expert concept map. Here, the connections of the explicit particle physics concept to other curricular concepts represent deeper school knowledge, as defined by Kulgemeyer et al. (2020).

All three studies of this doctoral research project are described, discussed, and put in a broader context in subsequent chapters. In **Chapter 4**, the methodology and the outcomes of the expert concept mapping study on the expected students' knowledge in particle physics are presented. Next, **Chapter 5** describes the methodology and the outcomes of the international curricular review of particle physics in high-school curricula. The third study, namely the Delphi study on what the stakeholders of CERN's teacher programmes expect high-school teachers to learn during their participation at the said programmes, is presented in **Chapter 6**. The three studies were pairwise compared, and the results of the comparisons are presented in **Chapter 7**. In **Chapter 8**, the comparisons are discussed in light of the two research aims. Finally, **Chapter 9** reviews the outcomes, strengths, limitations, and further implications of the three studies and the doctoral research project.

4 EXPECTED HIGH-SCHOOL STUDENTS' KNOWLEDGE: EXPERT CONCEPT MAP

Including particle physics in physics classrooms has been shown to appeal greatly to high-school students (Johansson et al., 2007; Polen, 2019; Tuzón & Solbes, 2016). However, curricula are often met with strict time constraints. These time constraints can come as the amount of time students spend on physics as a subject or the amount of time policymakers allocate to this specific issue. Therefore, particle physics is often introduced in a very superficial and oversimplified way, giving way to rote learning (Levin et al., 2008; Michelini, 2021). With the time and the content limitation, the following question presents itself: how can students still learn about particle physics in a meaningful way?

Meaningful learning is at the heart of Ausubel's (2000) theory of constructivism. Ausubel (2000) found that meaningful learning required three main conditions: (1) learners must possess prior knowledge, (2) learners must choose to learn in a meaningful way, and (3) conceptually clear language should be used with examples relatable to learners' prior knowledge. Therefore, particle physics education needs to satisfy all three conditions to allow for meaningful learning. First, particle physics is generally introduced only at the end of high school (Levin et al., 2008). Therefore, the students have prior knowledge which likely includes the entire classical physics curriculum (e.g., mechanics, thermodynamics). However, classical physics is not necessarily a predisposition for learning particle physics (Walwema et al., 2016; Wiener et al., 2017a). Second, particle physics appeals to students (Angell et al., 2004; Polen, 2019; Tuzón & Solbes, 2016). Thus, it is likely for students to choose to learn about it in a meaningful way. Third, the content of particle physics for high-school classrooms needs to be clearly defined and connected to students' prior knowledge, namely classical physics. Before the study presented in this chapter, the overall content of particle physics and relevant connections to prior knowledge were underdefined.

The implementation of meaningful learning can be helped using advanced organisers. These organisers help by explicitly linking what the learners already know and what they need to know to learn new material (Ausubel, 2000). Furthermore, advanced organisers can reduce learners' cognitive load and strengthen the knowledge of the relationships between concepts. Thus, the organisers are a great teaching resource (O'Donnell et al., 2002), improving students' and teachers' understanding of the topic. Indeed, Tchoshanov (2011) discovered that teachers with a better-connected knowledge framework are more conceptual in their teaching. In contrast, the teaching practices of teachers with fewer connections between concepts are more rule-based. Furthermore, in physics, organised and coherent structures reflect the typical knowledge framework (Nousiainen, 2013). Based on constructivist theory, Novak (1985) developed the framework of concept maps as educational tools.

4.1 State of the Research: Concept maps

Concept maps are graphic organisers that provide an external representation of the knowledge framework (Novak, 1985; Novak & Cañas, 2008; Torre et al., 2007). The main characteristics of a concept map are hierarchically organised key concepts connected with arrowed lines and linking words (Novak, 1985; Novak & Cañas, 2008; Ruiz-Primo & Shavelson, 1996), as shown in Figure 1. The connection "concept-linking words-concept" forms a proposition, which can be read as a meaningful statement (e.g., concept map-is-graphic organiser) (Kinchin et al., 2019; Novak & Cañas, 2008). The concepts are classified into hierarchy levels based on how many steps it takes from the central, most general concept to a given concept. Lower-tier concepts stem in one or more directions from the central concept. The different directions are called branches. Concepts in different branches can be further connected with cross-links. Cross-links tend to be more prominent when representing complex expert understanding (Hay et al., 2008; Novak, 1985; Novak & Cañas, 2008; Watson et al., 2016; Yin et al., 2005). Concept maps often also contain examples connected to concepts with an arrowed line and a linking word (Novak, 1985; Novak & Cañas, 2008; Ruiz-Primo & Shavelson, 1996).

The concept map structure thus provide a great representation of highly organised and coherent physics conceptual knowledge (Nousiainen, 2013). The organisation and coherence of conceptual physics knowledge reflect further in physics education, where students are required to learn about concepts and connections between the concepts (Sands et al., 2018). The overlap between concept maps and physics conceptual knowledge structures makes concept maps a good candidate for physics evaluation methods. Indeed, Cañas et al. (2005) stated that the "strength of concept maps lies in their ability to measure a particular person's knowledge about a given topic in a specific context" (p. 207). Various studies reviewed the possibilities of using concept maps as evaluation tools (Daley & Torre, 2010; Novak & Cañas, 2008; Ruiz-Primo, 2004; Ruiz-Primo & Shavelson, 1996; Shavelson, 1993; Yin et al., 2005). Here, one of the methods of evaluating concept maps is the qualitative comparison of a students' maps to an expert concept map (Ruiz-Primo & Shavelson, 1996). An expert concept map is a concept map created by one or more experts in the field of the respective focus question. Typically, an expert concept map shows a well-organised knowledge structure with strongly interconnected concepts (Ruiz-Primo, 2000). By comparing the overlap between the students' and the expert concept map, the level of students' expertise can be determined (Ruiz-Primo & Shavelson, 1996).

However, expert concept maps are not only useful in the context of evaluation. Expert concept maps can also be used to elicit and share expert knowledge (Coffey et al., 2002; Coffey & Hoffman, 2003) and as a knowledge visualisation tool (Cañas et al., 2005). As such, expert concept maps are useful teaching and learning resource, promoting meaningful learning by summarising the study topic and helping students organise their thinking (Cañas et al., 2003; Daley & Torre, 2010; Laight, 2004; Samarawickrema & O'Reilly, 2003).

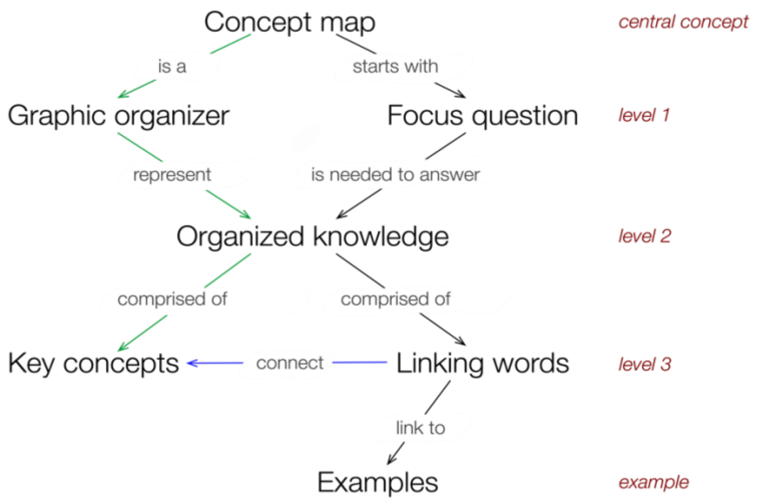


Figure 1. Graphic representation of a concept map. On the right-hand side, the different hierarchical levels are marked. The three green arrows depict one branch of the concept map. The blue arrow shows an example of a cross-link. Based on Novak & Cañas (2008).

4.2 Research Questions

The main idea of constructivism and concept maps is that new knowledge builds into prior knowledge (Ausubel, 2000). Here, prior knowledge is an established cumulatively acquired and hierarchical organised cognitive network. According to Ausubel (2000), new emergent meaningful information builds into the existing cognitive network by connecting to the concepts in the network. The incorporation of new knowledge into the existing cognitive network can be aided by advance organisers (Ausubel, 2000; Novak, 2010).

This study focused on building an advanced organiser on the topic of particle physics. An advance organiser could help both teachers and curriculum developers to introduce particle physics to students in a meaningful way. According to Ausubel (2000), the function of an advance organiser is to provide a scaffold of connections between existing ideas and new information. Experts' cognitive networks typically include more connections (Ruiz-Primo, 2000). Thus, their expertise is crucial for building a strongly connected network. Therefore, an expert concept mapping study was designed to answer the following research two questions:

RQ4.1: Which concepts do experts in particle physics and physics education expect high-school students to know about particle physics?
RQ4.2: How do the experts from (1) structure the concepts they find important for high-school education in a concept map?

Both research questions were answered through an iterative expert concept mapping study. The following chapters describe the methodology and the results in more detail.

4.3 Methodology

To answer the research questions, an iterative concept mapping study was designed to elicit the knowledge of several prominent researchers in the field of particle physics and physics education. The study followed six steps of expert knowledge elicitation by Coffey and Hoffman (2003) and McBride and Burgman (2012), namely the (1) development of a focus question, (2) expert selection, (3) training of the experts, (4) expert knowledge elicitation session, (5) verification, and (6) analysis. Steps 2-5 were repeated nine times. Overall, 13 experts participated in the study. Each step and the iterative process of the study are explained in more detail below.

4.3.1 Development of the Focus Question

Concept mapping always starts with a focus question that guides the concept mapping process. Here, the focus question was developed based on the above-stated research questions. Hence, the main focus was set on particle physics and high-school students' learning of particle physics. An additional focus on CERN was added to explore possible connections between high-school particle physics education and the world's largest particle physics laboratory. Thus, the focus question that guided all subsequent steps of the expert concept mapping was: "What would you like high-school students to know about particle physics and CERN?"

The four subsequent steps were conducted iteratively through nine rounds. Each round included the expert selection, training of the experts, expert knowledge elicitation, and verification (Coffey & Hoffman, 2003; McBride & Burgman, 2012). The most important features of the nine rounds are presented in Figure 2.

4.3.2 Expert Selection

The main qualifications of the experts were specified in the research questions. Namely, the required expertise was knowledge and experience in particle physics, physics education research, physics teaching, or CERN. Furthermore, all participating experts needed to have previously been involved in facilitating any educational programme for teachers or students at CERN. The experts for each round were identified based on the aim of the respective round. For example, Round 5 aimed to review and update the computing part of the expert concept map. Thus, a computer scientist with knowledge of particle physics and physics education was invited to participate in Round 5. Overall, thirteen experts participated in the study, five of whom were female. The main expertise of the experts in each round is shown in Figure 2.

4.3.3 Training of the Experts

The construction of a high-quality concept map requires the participants to be specifically trained for the task (Novak, 1986). In this study, the experts received the training directly before their respective expert knowledge elicitation round. The training included an explanation of the aim of the study, an overview of the concept mapping method with a simple unrelated example, and the round's structure. No hands-on training on concept mapping was given to the experts as the author facilitated all rounds of expert concept mapping.

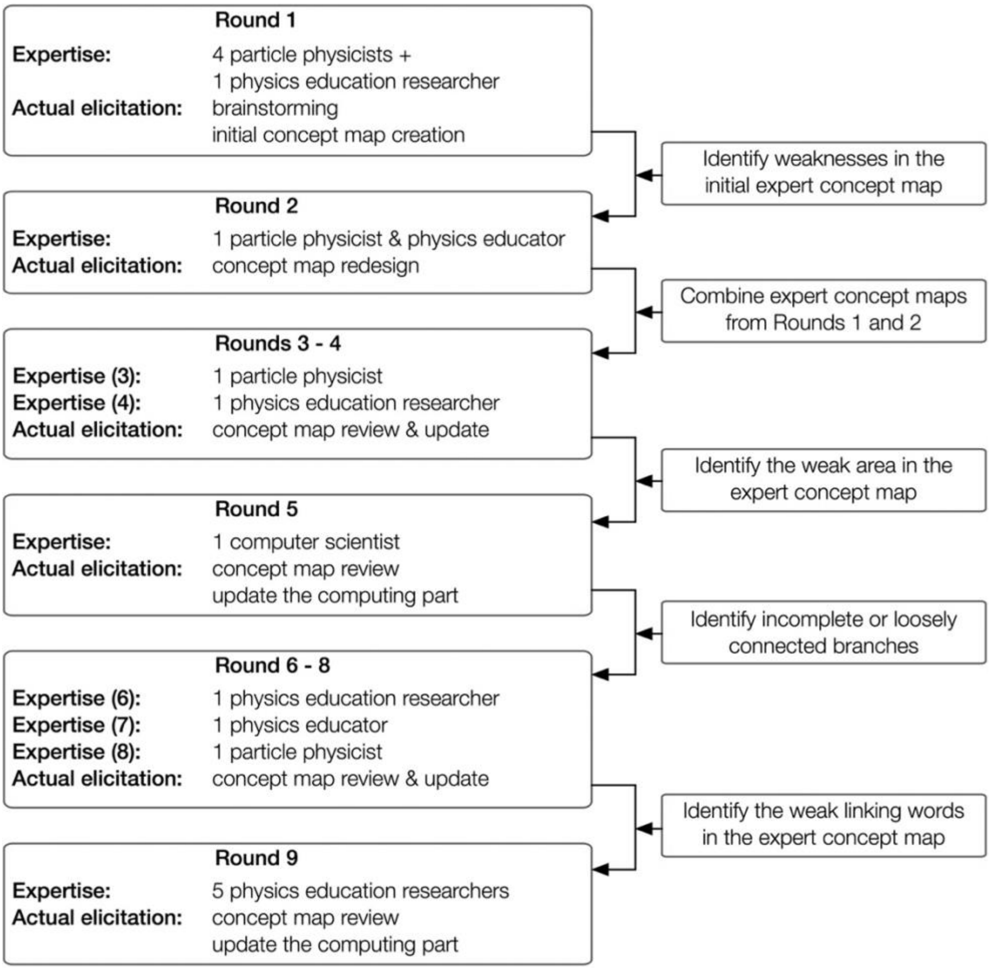


Figure 2. Overview of the nine rounds of the expert concept mapping study. The left column presents the nine rounds, the expertise of the experts, and a short overview of the elicitation process. The right column presents the validation specifics.

4.3.4 Expert Knowledge Elicitation Session

The expert knowledge elicitation sessions were designed as think-aloud concept-mapping sessions. Here, the experts were able to discuss the structure and possible updates of the expert concept map with the researcher and other participants, when applicable. Each round built on the expert concept map from the previous round (e.g., Round 4 was based on the expert concept map from Round 3). Thus, the aim and the structure of the individual rounds somewhat differed. Additionally, due to the pandemic, only the first two rounds were conducted live. In contrast, the rest were conducted online using an interactive concept mapping tool.

In all rounds, the experts were invited to think aloud and discuss the updates with the researcher during concept mapping. The experts' decisions for additions or updates to the expert concept map were discussed and later entered by the researcher to the expert concept map directly during the round. Additionally, all rounds were recorded to better understand the experts' reasonings for concepts, connections, and possible updates. The round specifics are further described in the following paragraphs.

Round 1

The first round was a focus group session with five experts. The group session included two theoretical particle physicists, two experimental particle physicists, and one physics education researcher. The elicitation was structured in three parts. First, the experts individually wrote the most important concepts related to particle physics and CERN on sticky notes. Second, they used these concepts to individually build concept maps answering the focus question, “What would you like high-school students to know about particle physics and CERN?” Last, after discussing the individual concepts and concept maps, experts collaboratively structured the suggested concepts in an expert concept map. The hierarchy of the concepts and the linking words between concepts were thoroughly discussed and agreed upon within the group before concluding the session. Still, many questions were left open after the session to be answered in the subsequent sessions. For example, should particle accelerators and particle detectors not be on the same hierarchical level, and how can we include charges as intrinsic properties of fundamental particles?

Round 2

The expert in the second expert knowledge elicitation session was an experimental particle physicist with extensive experience with high-school particle physics education. Due to the open questions from Round 1, the expert opted for a greater structural reconstruction of the expert concept map. Thus, the hierarchy of the map changed significantly. Still, many of the propositions remained the same. Several new propositions and concepts were added. In the end, the expert suggested that the author combines the expert concept maps from both rounds to ensure the completeness of the map better.

Rounds 3-4

Due to the large reconstruction in Round 2, two experts from Round 1 were invited to participate in individual rounds as well. Thus, one theoretical particle physicist and the physics education researcher from the group session in Round 1 participated in Round 3 and Round 4, respectively. In both rounds, the experts reviewed the expert concept map from the previous round and suggested further changes and additions. Additionally, the experts identified “computing facilities” as an under-represented area on the map. Thus, an expert in computing was invited to the next round to update the computing area of the map.

Round 5

As suggested by the experts in Round 4, the fifth round was conducted with a computer scientist with extensive experience in both particle physics and education. Again, the expert was invited to review and comment on the whole expert concept map from Round 4. However, the greatest part of this session was focused on updating, expanding, and better connecting the computing part of the map.

Round 6-8

The experts in Rounds 6-8 were a physics education researcher, a physics educator interested in particle physics, and a particle physicist, respectively. In these rounds, the experts further reviewed and updated the hierarchy, the cross-links, and the propositions. In all three rounds, five examples were added to the map. No other changes were made to the curricula, suggesting that the expert concept mapping study can be concluded.

Round 9

The last round aimed to review the wording of several linking words, for which the experts in previous rounds did not find agreeable wording. Thus, five physics education researchers with experience in particle physics education were invited to find consensus on the linking words. One of the experts in this session already participated in Round 1 and Round 4, while another participated in Round 6. During the session, the selected propositions were presented without linking words (e.g., *detection principle* - ____→ *electromagnetism*). The experts were then invited to propose suitable linking words using an online voting tool. The suggestions were then discussed and agreed upon within the group.

4.3.5 Verification

After each round, the latest version of the expert concept map was digitalised and prepared for review. The hierarchy and the propositions in the expert concept map were inspected for inconsistencies and ambiguities by the researchers and the respective expert (or experts). The subsequent round was structured based on the review, including the expert selection and the session aims. As the review after Round 9 left no open questions, no further sessions were required, and the expert concept mapping study was concluded.

4.3.6 Analysis

The final expert concept map was quantitatively and qualitatively analysed. First, the number of concepts, connections, cross-links, and examples was counted, and the highest hierarchy level was defined. Based on this, the complexity of the map was evaluated, as seen in various studies (Kinchin et al., 2000; Watson et al., 2016; Yin et al., 2005). Second, a hierarchical cluster analysis using Ward's algorithm was used to identify clustering within the map, as Kane and Trochim (2007) suggested. Here, clusters represent homogeneous subgroups within the expert concept map (Lopes & Gosling, 2021). Last, the map was qualitatively analysed to identify possible connections to the core high-school physics curricula.

4.4 Results

The expert concept mapping study concluded after nine rounds of expert knowledge elicitation. The final expert concept map connects 87 key concepts and 93 examples with 266 links, including 87 cross-links, as seen in Figure 3. The expert concept map has six levels of hierarchy and spreads into five main branches. Therefore, the traditional complexity score of the map is 993. Typically, scores in other concept mapping studies generally stayed under 100, even for high-achieving concept mappers (e.g., Erdimez et al., 2017; McClure et al., 1999). Thus, the score of this map shows a high level of complexity.

Ward's cluster analysis shows that the ideal number of clusters within this expert concept map is one. This result shows that the expert concept map is homogeneous without clusters of tightly related concepts that do not connect to the rest of the map. All areas within the map are strongly connected.

As there are no clusters to define smaller areas within the map, the short description of the map below describes the five branches that stem from the central concept *particle physics*. The branches are categorised by the highest-level concept in each branch, namely *CERN*, *engineering*, *experimental particle physics*, *theoretical particle physics*, and *human knowledge and curiosity*, as seen in Figure 3. These five concepts represent the broadest concepts in the expert concept map (Novak, 1985). *Theoretical particle physics* and *experimental particle physics* represent the two fields within particle physics. *Engineering* is an essential tool in particle physics, and *CERN* is one of the laboratories that provide the opportunities for all other three branches to work together. *Human knowledge and curiosity* drive all other four directions towards new enhancements.

The branches lead to various numbers of concepts directly (not counting cross-links). All branches are strongly connected. The branches *CERN* and *human knowledge and curiosity* lead to the lowest number of concepts. First, *human knowledge and curiosity* only lead to one lower-level concept, namely to *fundamental questions*. Second, the branch *CERN* only has two additional hierarchy levels. Conversely, branches of *engineering* and *experimental particle physics* contain many concepts that are strongly interconnected. Indeed, two of the three lower-level concepts that stem directly from *experimental particle physics* also stem directly from *engineering*. Thus, the two concepts are intrinsically connected through their hierarchy.

Similarly, *experimental particle physics* and *theoretical particle physics* are connected even more directly. Indeed, the two concepts connect in a circular matter through two additional concepts. *Experimental particle physics* thus leads to *observations* that disprove *theoretical particle physics*. In return, *theoretical particle physics* leads to *predictions* that inform *experimental particle physics*.

The expert concept map also connects to the core high-school physics curriculum. The concepts that connect particle physics to the core curriculum are *mechanics*, *conservation laws*, *thermodynamics*, *electromagnetism*, and *special relativity*, shown on the left side of the map, and *quantum mechanics* on the right side.

4.5 Summary and Discussions

The experts in this study developed an expert concept map that captures the most important concepts related to particle physics and CERN as perceived by various experts. Overall, thirteen experts in particle physics, physics education, and computing participated in nine rounds of the study. In each round, experts built on the expert concept map from previous rounds to answer the focus question "What would you like high-school students to know about particle physics and CERN?" The study concluded with a highly integrated map of 180 concepts and examples connected with 266 links and cross-links. In the following sections, the outcomes and the implications of the study are discussed. Finally, possible implications of the study on the field of physics education research are given. The role of the study within the whole research project is described in later chapters.

4.5.1 Most Important Concepts for Particle Physics Education

The first research question of this study asked: "Which concepts do experts in particle physics and physics education research expect high-school students to know about particle physics?" The experts in this study identified 87 key concepts as important for high-school education, with "particle physics" as the central concept, as seen in Figure 3. All concepts can be found in the expert concept map in Figure 3. The most relevant concepts and links are discussed in detail below.

Most concepts included in the expert concept map already appeared in the literature on what could be included in the classrooms, for example, the *Standard Model* [of particle physics] (e.g., Andrews & Nikolopoulos, 2018; Lindenau & Kobel, 2019; Polen, 2019; Woithe et al., 2017), and *elementary particles* (e.g., Berg & Hoekzema, 2006; Lindenau & Kobel, 2019). However, several different concepts were also added. For example, *personnel*, *computing facilities*, *engineering*, and several *open questions in particle physics* are among the concepts that have previously been scarcely recommended to be included in high-school education. Including these concepts in the expert concept map provides a better picture of particle physics. Here, introducing *computing facilities* and *engineering* as part of particle physics broaden students' views of particle physics. Indeed, *computing facilities* and *engineering* represent important parts of experimental particle physics research methodology. Next, including *personnel* provides students with a better understanding of science as a human endeavour, and cooperation and collaboration in the development of human knowledge, all aspects of Nature of Science (Osborne et al., 2003; Schwartz et al., 2004; Schwartz & Lederman, 2008, 2002) while providing them with some very different career options. Similarly, the *open questions in particle physics* reflect the tentative Nature of Science (Schwartz et al., 2004; Schwartz & Lederman, 2008, 2002). These concepts that only appeared in the expert concept map can help particle physics be better contextualised in high-school education. Furthermore, they expand particle physics towards other fields, such as computing, engineering, and even social sciences. Therefore, including these concepts in high-school education could help bring particle physics closer to students with lower interest in physics.

Several concepts in the expert concept map act as bridges between particle physics and classical physics topics, e.g., *mechanics*, *electromagnetism*, and *special relativity*. These concepts already appeared in the literature as examples of how particle physics can be introduced in a classroom as context (e.g., Cid-Vidal et al., 2021; Cid-Vidal & Cid, 2018; Wiener et al., 2016). Introducing bits and pieces of particle physics as a context in other chapters in the curricula follows Ausubel's (2000) definition of meaningful learning. Indeed, by introducing particle physics first as a context, the foundations for introducing it as content become stronger for students to build a more stable knowledge framework.

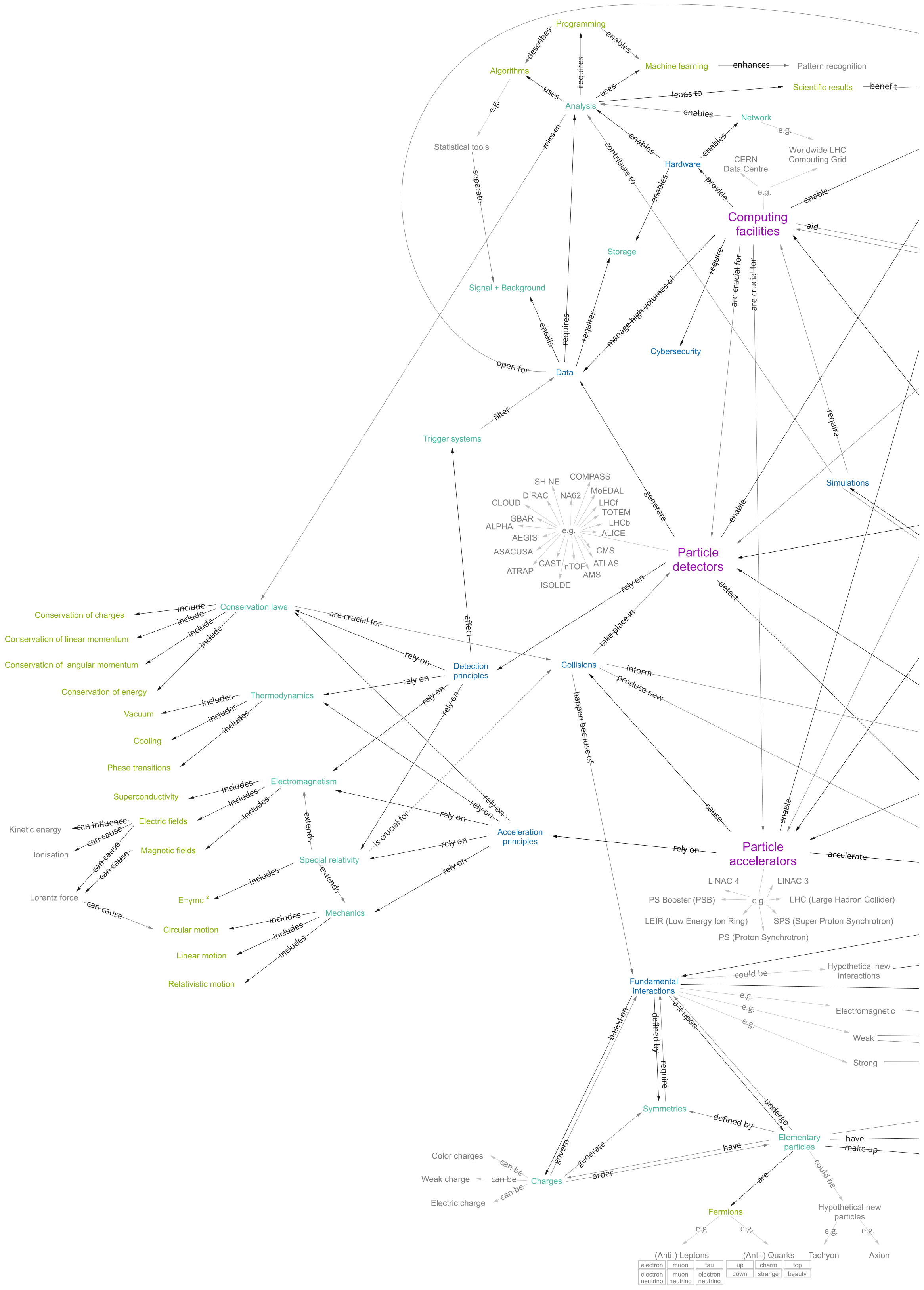
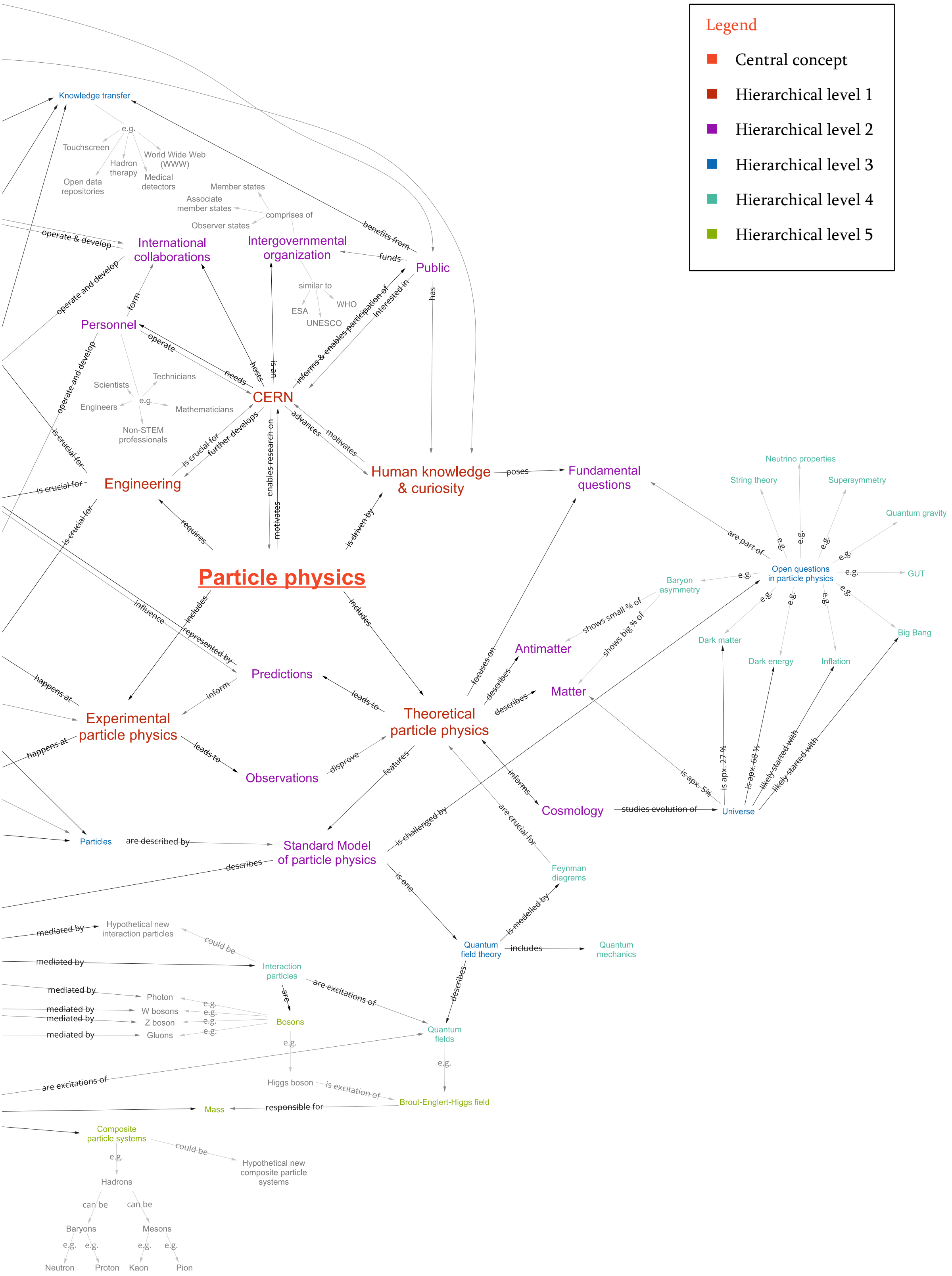


Figure 3. The expert concept map. This expert concept map on what high-school students should know about particle physics and CERN was created by 13 experts in particle physics, computer engineering, and physics education. The different colours in the expert concept map represent different hierarchical levels of concepts (e.g., dark red is level 1, purple is level 2, etc.). Examples are written in grey.


Legend
Central concept
Hierarchical level 1
Hierarchical level 2
Hierarchical level 3
Hierarchical level 4
Hierarchical level 5
Knowledge transfer
e.g.
Touchscreen
Hadron therapy
World Wide Web (WWW)
Open data repositories
Medical detectors
Member states
Associate member states
Observer states
comprises of
benefits from
operate & develop
International collaborations
Intergovernmental organization
funds
Public
operate and develop
form
similar to
ESA
WHO
UNESCO
informs & enables participation of
interested in
has
Personnel
operate
needs
hosts
is an
CERN
Technicians
Scientists
Engineers
Mathematicians
Non-STEM professionals
operate and develop
is crucial for
is crucial for
further develops
enables research on
advances
motivates
Human knowledge & curiosity
poses
Fundamental questions
is crucial for
Engineering
requires
motivates
is driven by
is crucial for
Particle physics
influence
includes
represented by
includes
Predictions
leads to
inform
happens at
Experimental particle physics
happens at
leads to
Observations
disprove
Theoretical particle physics
focuses on
describes
describes
Antimatter
Matter
shows small % of
shows big % of
Baryon asymmetry
Neutrino properties
String theory
Supersymmetry
Quantum gravity
are part of
Open questions in particle physics
GUT
Big Bang
Dark matter
Dark energy
Inflation
is apx. 5%
is apx. 27 %
is apx. 68 %
likely started with
likely started with
informs
Cosmology
studies evolution of
Universe
features
are crucial for
Feynman diagrams
is challenged by
Particles
are described by
Standard Model of particle physics
describes
is one
is modelled by
Quantum field theory
includes
Quantum mechanics
mediated by
Hypothetical new interaction particles
could be
mediated by
Interaction particles
are excitations of
are
describes
mediated by
Photon
mediated by
W bosons
mediated by
Z boson
mediated by
Gluons
Bosons
Quantum fields
are excitations of
Higgs boson
is excitation of
Brout-Englert-Higgs field
Mass
responsible for
Composite particle systems
could be
Hypothetical new composite particle systems
Hadrons
can be
can be
Baryons
Mesons
Neutron
Proton
Kaon
Pion

The expert concept map includes 93 examples. Most examples were the Standard Model particles (e.g., electron, up quark, photon) or specific particle accelerators and particle detectors (e.g., LHC, ATLAS, CMS). The examples within the *Standard Model* are general and would only change with new scientific discoveries. Conversely, all examples of *particle accelerators* and *particle detectors* are CERN-specific. The specificity is due to the focus question used in the expert concept mapping study, namely “What would you like high-school students to know about particle physics and CERN?” Indeed, including CERN in the focus question introduced a bias to the study. However, the examples mentioned above could be expanded with many other particle accelerators or detectors (e.g., Tevatron and CDF at Fermilab, HERA and HERMES at DESY). Indeed, *particle detectors* and *particle accelerators* generally work using the same scientific principles described in the expert concept map. As such, the CERN bias is not very strong. The only concepts that are specific to CERN are the *intergovernmental organisation* and the respective examples. Indeed, not all research laboratories are intergovernmental (e.g., SLAC, DESY). However, the research efforts remain international regardless of the laboratory. The collaborative Nature of Science is ever-present in particle physics research and, as such, would remain in the expert concept map regardless of the context of the map.

Overall, the expert concept map has a high level of detail. While this level of detail seems daunting at first, it stands to mention that not all concepts are expected to be taught in one learning unit. On the contrary, particle physics concepts can act as context in other topics, e.g., electromagnetism and quantum mechanics (Cid-Vidal et al., 2021; Cid-Vidal & Cid, 2018; Olsen, 2002; Wiener et al., 2016). Indeed, using particle physics as context should not be discarded. Studies have shown that well-chosen context can increase students’ interest more than pure content (Hoffmann et al., 1998; Sjøberg & Schreiner, 2012). Consequently, students’ achievement can also improve (M. M. Keller et al., 2017). Additionally, using particle physics as context can go beyond physics curricula. For example, calls have been made in the literature for including machine learning in high-school mathematics and computer technology curricula (Mariescu-Istodor & Jormanainen, 2019; Touretzky et al., 2019). Such connections between particle physics concepts and other subjects in curricula further expands and strengthens students’ knowledge frameworks. Consequently, the connections help improving both students’ knowledge of particle physics and other subjects.

4.5.2 Expert Concept Map Structure

The second research question of this study asked: “How do the experts in particle physics and physics education research structure the concepts they find important for high-school education in a concept map?” Through nine rounds of concept mapping, the experts connected the concepts with 266 links, including 87 cross-links. The links are homogeneously dispersed across the map, creating no smaller clusters. Therefore, the final expert concept map can be described as a highly integrated map with a hierarchical network structure (Kinchin et al., 2000; Yin et al., 2005). The large number of connections and links shows that it represents a true expert knowledge framework (Ruiz-Primo, 2000). The map has six levels of hierarchy and spreads into five branches. These five branches follow from the first-level concepts, namely *theoretical particle physics*, *experimental particle physics*, *engineering*, *CERN*, and *human knowledge and curiosity*. All branches are interconnected, as discussed below.

First, *CERN* and *human knowledge and curiosity* are connected with a circular connection. Here, a circular connection means that one arrow points from *CERN* to *human knowledge and curiosity* (*CERN* advances *human knowledge and curiosity*), while another arrow points in the opposite direction (*human knowledge and curiosity* motivate *CERN*). The two connecting propositions reflect different aspects of the Nature of Science. *CERN* shows the "cooperation and collaboration in the development of scientific knowledge." Meanwhile, *human knowledge and curiosity* represent "science and questioning" and "creativity" (Osborne et al., 2003, p. 713). As such, both represent the implicit presence of the Nature of Science.

Second, the circular connection between *experimental particle physics* and *theoretical particle physics* also represents the tentative Nature of Science (e.g., Schwartz & Lederman, 2008). Here, *experimental particle physics* leads to *observations* that disprove *theoretical particle physics*. In return, *theoretical particle physics* leads to *predictions* that inform *experimental particle physics*. Introducing this connection between *experimental particle physics* and *theoretical particle physics* can help improve students' understanding of the nature of experimental physics. The study by Wilcox and Lewandowski (2017) showed that students' ideas about the nature of experimental physics do not match with those of practising scientists. Therefore, explicitly showing the interconnection between experimental and theoretical physics in a contemporary context could help students to better integrate the nature of experimental physics into their cognitive networks.

Similarly, *CERN* and *engineering* are also connected with a circular connection. Here, *engineering* is crucial for *CERN*, which is why *CERN* further develops *engineering*. Indeed, as *CERN* is a particle physics laboratory, *engineering* is crucial for developing, maintaining, and updating the plethora of *particle detectors*, *particle accelerators*, *computing facilities*, etc. This strong connection to engineering is not specific to CERN or particle physics. Various scientific fields require engineers and engineering to keep the research going and progressing. Therefore, *engineering* can be implemented as context in various topics across different fields of science.

Surprisingly, the branches of *theoretical particle physics*, *experimental particle physics*, and *engineering* all lead to a similar number of concepts. Indeed, the area of *theoretical particle physics* is similar in size, the number of concepts, and the number of links as the *experimental particle physics* and *engineering* branches. However, the review of existing particle physics education literature in Chapter 3.1 showed a strong prevalence of *theoretical particle physics concepts*. Thus, existing publications reflect Michelini's (2021) finding that particle physics is taught in an superficial way. Indeed, as previous studies often skip the part of "science in the making," the remainder of concepts quickly becomes a list of elementary particles and a set of simplified equations. The learning can become more meaningful by including more concepts from *experimental particle physics* and *engineering*. Indeed, these concepts are generally more strongly connected to prior knowledge, as discussed in the following paragraph.

Concepts that are directly linked to other curricular topics (e.g., *mechanics*) are generally on the outer edges of the expert concept map and at the end of the hierarchy. These links to other curricular topics represent one of the basic criteria of meaningful learning – connections to learners' prior knowledge (Ausubel, 2000), although classical physics is not a pre-requisite for learning modern physics topics. Still, in most cases, particle physics is introduced at the end of high school (Levin et al., 2008). Therefore, students are expected to have the knowledge of other curricular topics to which this map links.

A great majority of concepts from other curricular topics are most closely linked to *acceleration* and *detection principles*. This close connection reflects connections found in the literature. For example, *electromagnetism* and *vacuum* are suggested to be explained in the context of particle accelerators (Cid-Vidal et al., 2021; Cid-Vidal & Cid, 2018; Wiener et al., 2016). The only connection to other curricular topics that is not directly connected to either *acceleration principles* or *detection principles* is *quantum mechanics*. Indeed, *quantum mechanics* stems from *quantum field theory*. As *Standard Model* is a *quantum field theory*, it is not surprising that *quantum mechanics* is closer to the *Standard Model* than experimental tools in particle physics.

The expert concept map meets another criterium of meaningful learning, namely conceptually clear language with relatable examples (Ausubel, 2000). Indeed, several iterations of the expert concept map that included various physics education experts ensured that the language was clear, concise, and understandable. Additionally, 93 examples and connections to everyday *technology* (e.g., *world wide web*) and other *real-life applications* (e.g., *hadron therapy*) provide the relevant examples for students learning to be meaningful.

Therefore, the final expert concept map can be used by teachers as advanced organisers that help them organise their lessons. Using this expert concept map in preparing their lessons allows teachers to organise their knowledge better and structure it in a meaningful hierarchical order. Furthermore, the expert concept map can also be directly used as a teaching and learning resource in the classroom, as seen in Baliga et al. (2021) and Romero et al. (2017). The highly organised knowledge network can further be expanded to represent elements of teachers' pedagogical content knowledge (PCK). As such, the utility of the expert concept map expands further to represent better the necessary professional knowledge needed for teachers to teach particle physics. More on what teachers need to learn on particle physics is described in Chapter 6.

However, no research tells us which of the concepts in the expert concept map appear in the curricula. Therefore, the study, presented in the following chapter, investigated various national and international curricula to identify the most common concepts around the world when teaching particle physics. Based on the curricular review, the expert concept map can be used to enhance the curricula further.

5 HIGH-SCHOOL PARTICLE PHYSICS: CURRICULAR REVIEW

School curricula are typically aimed at structuring the teaching and learning process to prepare the students for the future (Moore, 2015). Therefore, together with textbooks, curriculum materials are among the main teachers' resources for teaching and learning. Teachers, especially at the beginning of their career or teaching outside their subject area, rely greatly on the curriculum to provide some or even all content for teaching (Ball & Feiman-Nemser, 1988). Although teachers are expected to know more than what is in the curriculum (Mahler et al., 2017), the curriculum remains an important source of teacher knowledge. With every update to the curriculum, special attention should be given to synchronising teachers' knowledge with the content of the new curriculum. Indeed, professional development programmes, aimed at increasing teachers' professional knowledge, are at the heart of all educational reforms (Borko, 2004; Corcoran, 1995; Garet et al., 2001; OECD, 2019).

Changes to the curricula are generally slow, and new concepts require decades to be included (Fullan, 1994; Young, 2014). Most science curricula, especially in physics, thus still tend to focus mostly on scientific theories established before the 1900s (Siqueira, 2017). Although introducing particle physics to the high-school curriculum was suggested as early as 1984 during the first Conference on Teaching Modern Physics at CERN (Aubrecht, 1986), particle physics only started entering curricula in recent years. Still, by 2015, several curricula already included particle physics (Mullis et al., 2016). However, the extent to which modern curricula cover particle physics has not yet been documented.

The following chapter presents a short literature overview of curricular theory to define the terms relevant for this study. Next, the methodology of the curricular review is described, followed by an overview of the results. Last, the results are discussed, considering the study's three research questions.

5.1 State of the Research: Defining the Curricula

The word "curriculum" is defined in Merriam-Webster (n.d.) as "a set of courses constituting an area of specialisation". However, no consensual definition is given in the educational literature (Moore, 2015; Stadermann et al., 2019; Wiles, 2009; Young, 2014). The different definitions greatly reflect the characteristics and the various roles the curricula have taken (Remillard, 2005; van den Akker, 2004). The following paragraphs provide a short overview of the different curricular characteristics to better frame the final working definition for this thesis.

Curricular theory distinguishes three interlinked categories of the curricula based on their role. First, a "formal curriculum" is a set of student learning outcomes, teaching and learning activities, content, instructional materials, and evaluation guidelines designed and outlined by the respective educational system's stakeholders (Gehrke et al., 1992; Nawaz & Rafaqat, 2019; Remillard, 2005). Second, the "intended curriculum" builds upon the formal curriculum and represents the teachers' aims for students' learning and course structure (Gehrke et al., 1992; Remillard, 2005). Last, the "enacted curriculum" represents what takes place in a classroom (Gehrke et al., 1992; Remillard, 2005). Both the intended and the enacted curricula build upon the formal curriculum (Remillard, 2005), although the level of fidelity to the formal curriculum varies (van den Akker, 2004). However, it is worth mentioning that some studies also offer different hierarchies and definitions of the three categories. For example, van den Akker (2004) classifies "formal curriculum" as a subclass of the "intended curriculum".

Curriculum development can follow various frameworks (Elby & Yerdelen-Damar, 2020; Haagen-Schützenhöfer & Hopf, 2020; Irving et al., 2020; Kustusch et al., 2020; van den Akker, 2004). Generally, several stakeholders and participants within a single or a group of institutions develop a curriculum through a long cyclic process (Kustusch et al., 2020; van den Akker, 2004). Through the development process, the curriculum developers usually focus on addressing the following three components: the rationale, aims and objectives, and content (van den Akker, 2004). Typically, these components develop from the pre-set list of subjects and topics. However, lately, many have shifted towards aims-based curricula (Reiss & White, 2013, 2014). Thus, the curricular documents can be somewhat difficult to compare directly (Stadermann et al., 2019).

In this study, the term "curriculum" was used to describe the formal curriculum as a framework given by the respective system's policymakers that specifies what should be taught in the classroom (Gehrke et al., 1992; Remillard, 2005). The study focused on the content of the curricula, as written in the respective curricular documents. The term "curricular documents" was defined as the official documents describing the characteristics of the curricula provided by the governing bodies of the respective educational systems. The selected curricular documents are described in detail in the Methodology section and Appendix B.

5.2 Research Questions

The extent to which particle physics has been covered in various state curricula, national curricula, and international curricula is unknown. Thus, a curricular review was designed to find similarities between different implementations. The following research question guided this exploration:

RQ5.1: Which concepts related to particle physics are the most prominent in national and international high-school physics curricula?

However, not all curricula include particle physics (e.g., Slovenian). There, concepts related to particle physics could appear in a curriculum implicitly as context for other concepts (e.g., Wiener et al., 2016). Thus, the second research question of the curricular review was:

RQ5.2: What are the differences and similarities between the particle physics content in curricula with or without an explicit particle physics chapter?

Both research questions were answered through an international curricular review. The following chapters describe the methodology and results in more detail.

5.3 Methodology

Exploration of the research questions called for a review of several different state, national, and international curricular documents. However, curricular documents are typically written in the country’s native language. Therefore, the study required to include experts from the respective educational systems for individual curricular reviews. The selected experts were teachers with a native-level knowledge of the respective language, vast teaching experience with their respective curriculum, and sufficient knowledge of particle physics. A coding manual in English was developed to ensure a consistent review across the international curricula. The experts then used the coding manual to code their respective curricular documents. Last, the differences and similarities between the curricula were assessed to identify the common particle physics curriculum. Each step of the curricular review is further explained in the sections below.

5.3.1 Selection of the Coders

This curricular review aimed to provide an overview of concepts related to particle physics in various state, national, and international educational systems. Here, the selection of coders for the review is crucial for the validity of the study. Thus, the selected coders needed to have the following three characteristics: (1) professional experience with the respective educational system and its high-school physics curriculum, (2) sufficient knowledge of required particle physics concepts, and (3) sufficient English skills. To ensure all three requirements were satisfied, most coders were selected from the pool of CERN's teacher programmes alumni, described in the introduction of this thesis. All additional coders were also selected based on the three described characteristics. At least two coders per educational system were selected to allow for comparison and verification of the results.

5.3.2 Curricular Documents

There is no straightforward way to find in which educational systems is particle physics explicitly included in the curriculum. Furthermore, various concepts related to particle physics appear in other parts of the curriculum (e.g., electromagnetism). Thus, this study aimed to provide a general overview of which concepts appear in the curricula. In selecting curricular documents, specific focus was given to include curricula from CERN's member and associate member states. Additionally, several other relevant educational systems from other continents were included. The final criterium for selecting the educational system was the availability and the accessibility of suitable coders within the respective system. Finally, 27 educational systems were selected for analysis.

Within most educational systems various high-school physics curricula exist. The final choice of curricular documents that would represent a specific educational system was guided by discussions with coders as experts on their respective curricula. In general, curricular documents with the strongest physics focus were selected, as others often contain fewer physical concepts. By only including the curricula with a strong physics focus, this study provides the upper limit of how much particle physics a certain educational system can include. The selected curricular documents and their characteristics are presented in Appendix B.

Additionally, several characteristics of curricula were reviewed, most importantly the presence of a particle physics chapter. Here, a chapter was defined as a distinct group of related concepts with a specific title. For example, a particle physics chapter could combine concepts like electric charge, leptons, and bosons under the title "Particle physics". The presence of a particle physics chapter was used as one of the variables for the curricular analysis.

5.3.3 Codebook Development

The codebook represents a crucial part of this curricular review as it provides the basis for the thematic analysis of the curricula. Thus, the aim was to develop a codebook that is "as detailed as necessary and as short as possible" (Stadermann et al., 2019, p. 5). The codebook development followed a dualistic technique of deductive and inductive code creation and testing, as seen in Fereday and Muir-Cochrane (2006) and Roberts et al. (2019). First, the deductive component of the code creation involved the creation of a preliminary codebook based on concepts and topics from the concept mapping study, which is described in Chapter 6. Additionally, several codes were added from the study by Stadermann et al. (2019).

Second, the author used the preliminary codebook on the Slovenian, Croatian, UK (A-levels), and the International Baccalaureate (IB) high-school physics curriculum. Several new codes emerged from this curricular review inductively. Through this process, the codes were refined, labelled, and a more specific code description was developed. All codes, descriptions, exclusions, and examples were written in English to enable the international review. The codes were hierarchically structured, as shown in Table 3. Two particle physics researchers reviewed the codebook to ensure the independence and unambiguity of the codes. Additionally, coding instructions for coding the curricula were developed to aid the coding of independent coders.

Third, the updated codebook was pretested on the Austrian, Slovenian, and three German state curricula (Brandenburg, North-Rhine-Westfall, and Sachsen) by at least two coders per curriculum. The coders in this pretest were encouraged to note any ambiguities, problems, and suggestions they encountered through their coding. The initial inter-rater agreement for each curriculum was at least 60%, and the agreement grew to 100% after discussion. Based on the comments from the coders and the ambiguities that became apparent through the inter-rater analysis, the codebook was further refined. Two codes were added based on the suggestions of the coders, and one code was eliminated due to irrelevance.

Table 3. Hierarchical overview of the concepts included in the curricular review. The first columns in the left and right table represent categories, the second topics, and the third concepts. The abbreviations NOS and HOP stand for Nature of Science and history of physics, respectively.

	Topic	**Concept**
Other curricular topics	Mechanics	Linear motion
		Circular motion
	Gravity	Newtonian gravity
		Einsteinian gravity
	Conservation laws (of)	Energy
		Linear momentum
		Angular momentum
		Charges
	Thermodynamics	Particle model
		Phase transitions
		Vacuum
	Electromagnetism (EM)	Electric fields
		Magnetic fields
		Magnetic force
		Ionisation
		EM waves
		Superconductivity
	Radiation	Cosmic radiation
		Radioactivity (alpha)
		Radioactivity (beta)
		Radioactivity (gamma)
		Radiation (general)
	Special relativity	Relativistic motion
		$E=mc^2$
	Quantum physics	Quantum effects
		Probability in QP
		Atomic models
		Atomic energy levels
		Quantum mechanics
NOS	Nature of Science	Nature of Science

	Topic	**Concept**
Particle physics	Cosmology	Big Bang
		Inflation
		Expansion
	Standard Model	Standard Model
	Fundamental interactions	EM interaction
		Strong interaction
		Weak interaction
		Gravity in PP
	Charges	Electric charge
		Strong charge
		Weak charge
	Elementary particles	Quarks
		Leptons
	Interaction particles	Bosons
	Brout-Englert-Higgs mechanism	Brout-Englert-Higgs mechanism
	Particle transformations	Particle transformations
	Feynman diagrams	Feynman diagrams
	Antimatter research	Antimatter research
	Particle accelerators	Linear accelerator
		Circular accelerator
		Particle acc. (general)
	Particle detector	Historical detectors
		Modern detectors
		Particle det. (general)
	Data storage and data analysis	Data storage and data analysis
	Advances in particle physics	Experimental results
		Open questions
	Real-life applications	Real-life applications
HOP	History of quantum physics	History of quantum physics
	History of particle physics	History of particle physics

Additionally, eleven codes were combined into four broader codes to reduce the unnecessary level of details. The definitions of the codes were updated to include better criteria for inclusion. Where needed, exclusion criteria were added to the codebook to reduce ambiguity.

Last, two physics education researchers and a particle physicist reviewed the codebook and its codes for ambiguity and independence. The final codebook development concluded with 60 codes related to particle physics. Each codebook entry included a short key, the name of the concept, a description with inclusion criteria, exclusion criteria, and a curricular example.

The complete list of codes and the hierarchy is shown in Table 3. The complete codebook with the descriptions, exclusion criteria and curricular examples can be found in Appendix C. An example of a codebook entry is shown in Table 4.

5.3.4 Coding the Curricular Documents

The codebook and coding instructions were sent to the selected experienced teachers worldwide to code their respective curricula. The coders had one month time to code their respective curriculum. The coding of the two (or more) coders within each educational system were pairwise analysed to identify any possible discrepancies. Indeed, previous studies have shown that curriculum materials can be very differently interpreted by different practising teachers (Porter et al., 2015; Remillard, 2005). Additionally, the researchers reviewed all curricula with the help of an online translator. The ambiguous discrepancies between coders or between coders and the author were rediscussed to reach a consensus.

After reaching the consensus for each curriculum, the researchers determined the frequency of the concepts appearing in the curricula. Each concept was counted as having appeared in a curriculum if the said curriculum included at least one mention of the said concept. If the concept appears in the curriculum more than once, it still counts as one. For example, if *magnetic field* appears twice in the Slovenian curriculum, the count is increased by one. As described in the subsequent paragraphs, the frequency of the concepts appearing in the curricula was the basis for determining the common curricular concepts and common curricular topics.

Table 4. Example of code in the codebook. The full codebook can be found in Appendix C.

Key	Concept	Description	Exclusion	Example
SM5.1	Bosons	Curriculum mentions bosons or at least one of the following: photons, bosons, gluons, …	To code Higgs boson, use code "Brout-Englert-Higgs mechanism".	"The Standard Model explains exchange of force-carrying particles called gauge bosons."

5.3.5 Analysis of the Curricula

The analysis of the curricula was done in two steps. First, common curricular concepts (CCCs) and common curricular topics (CCTs) in particle physics were derived. Second, the curricula were grouped into two groups based on whether they contained an explicit particle physics chapter. The CCCs and CCTs in the two curricula groups were then compared to identify similarities and differences between the groups.

Determining the common curricular concepts (CCCs)

The common curricular concepts (CCCs) were defined as the concepts that appear in more than half of the curricula. Each curriculum that included at least one occurrence of the said concept counted as one. Similarly, the common curricular topics (CCTs) were assessed. Here, a topic counted as having "appeared in the curriculum" when at least one concept within the topic appeared in the respective curriculum. Following the example from Table 3, if the concepts *of electromagnetic* and *strong interaction* appeared in curriculum A, *fundamental interactions* was counted as having appeared in the said curriculum. In this example, the frequency count was increased by one.

Comparing the CCCs in curricula with and without particle physics chapter

First, the presence of a particle physics chapter within each curriculum was determined. The particle physics chapter was defined as a specific section in the curriculum with an increased focus on particle physics. Usually, such sections were defined with a telling title, e.g., *particle physics* or *Standard Model*. Several curricula included a specific focus on particle physics within the chapter *modern physics* or *quantum physics*. Here, these curricula were counted as having a focus on particle physics as well. The curricula were then grouped into those with an explicit particle physics focus (EPP) and those merely implicit particle physics connections (IPP). Second, the CCCs in particle physics were determined for EPP and IPP curricula. Again, the CCCs were defined as the most common concepts across the curricular group. The two groups were descriptively compared to identify potential differences and similarities.

Last, the researchers compared the prevalence of the topics in EPP and IPP, similar to the overall CCC analysis described in the previous chapter. The relative frequencies of the topics appearing in each curricular group were compared to determine any differences or trends.

5.4 Results

This curricular review included six state, twenty national, and one international curricular document. The curricular documents are described in more detail in Appendix B. The review was based on a codebook with 60 concepts related to particle physics. The concepts were clustered into 26 topics, which were further combined into four categories: particle physics, Nature of Science, history of science, and connections to other curricular topics. The hierarchy and the individual concepts are shown in Chapter 3.

At least two coders coded each curriculum. At least one was an expert teacher with experience with their coded curriculum. In the sections below, the comparison results between the coders and the comparison of all reviewed curricula are presented.

5.4.1 Comparing the Codings

The codings of two coders per curricula were compared among each other and to the researcher's analysis of the respective curriculum. The comparison was aimed at identifying possible discrepancies, as indicated in the methodology section. Overall, three types of discrepancies were identified, as shown in Table 5. First, the solvable discrepancies were solved by re-checking the code's definition, e.g., the coded text included a word from the definition. The researchers resolved these discrepancies. Second, the unsolvable discrepancies did not have an apparent solution as the coded text was too vague and could not be resolved by looking at the definition. These discrepancies were rediscussed with coders before resolving. Last, possible missing codes were discrepancies where the researchers' identified the said code in the curriculum, but neither of the coders did. These discrepancies were rediscussed with coders before resolving. On average, 2.2 (*SD* = 1.6) discrepancies per curriculum were rediscussed with coders before reaching an agreement.

Table 5. Examples of discrepancies that appear during the intercoder comparison. All examples were coded as "magnetic field."

Text example	Coders' codings	Discrepancy type	Action
Definition of the magnetic field.	**A**: Magnetic field **B**: Magnetic field	No discrepancy	Code "magnetic field" per code definition
Definition of the magnetic field.	**A**: Magnetic field **B**: Electric field	Solvable discrepancy	Code "magnetic field" per code definition
Definition of the magnetic field.	**A**: Magnetic field **B**: /	Solvable discrepancy	Code "magnetic field" per code definition
Describe properties of permanent magnets.	**A**: / **B**: Magnetic field	Unsolvable discrepancy	Rediscuss with coders
Describe properties of permanent magnets.	**A**: / **B**: /	Possible missing code	Rediscuss with coders

5.4.2 Determining the CCCs and CCTs

After the agreements were reached, the frequencies of the concepts within the curricula were calculated. The overview of the concepts appearing in the individual curricula is shown in Table 6. The curricula were then reviewed in three groups, namely curricula with an explicit particle physics chapter (*n* = 12), curricula without the said focus (*n* = 15), and curricula overall (*n* = 27), as mentioned in the methodology section.

The review of the curricula determined that all but one curriculum were structured into explicit chapters. Here, only the reviewed Italian curriculum was not structured into chapters. As such, it could not be categorised as a curriculum with an explicit particle physics chapter. A particle physics chapter was identified in nine of the reviewed curricula, as denoted in Table 6.

The chapter was often titled "Particle physics" or "Elementary particles". Only in Spain and South Africa, the chapter was titled "Physics of the 21st century" or "The structure of matter", respectively.

Furthermore, while the Croatian curriculum did not have chapters with titles, it did include thematic units. As such, particle physics principles were grouped in one thematic unit. Thus, Croatia was identified as a country with an explicit particle physics chapter. The common curriculum for curricula with and without a particle physics chapter is presented in the subsequent paragraphs.

The frequencies of concepts and topics appearing within each group of curricula are presented in Table 7. Based on these frequencies, the CCCs and CCTs were defined. The CCCs were the concepts that appeared in more than half of the reviewed curricula. Similarly, the CCTs were topics that appeared in more than half of the reviewed curricula. Both CCCs and CCTs are highlighted in Table 7.

Overall Curricula

Overall, 28 concepts (out of 60) appear in over half of the curricula (more than 13). These concepts are defined as the CCCs. Out of these, 22 concepts are from the category *connections to other curricular topics*, four concepts from the category *particle physics*, and one concept in both the categories *Nature of Science* and *history of physics*.

Similarly, 15 topics (out of 26) topics appear in over half of the curricula. These topics are defined as the CCTs. Here, all topics in the category *connections to other curricular topics* are CCTs. In the category *particle physics*, five topics are the CCTs and one topic in both the *Nature of Science* and the *history of physics*. More details on which topics are the overall CCCs and CCTs can be found in Table 7.

Curricula with an Explicit Particle Physics Chapter

Twelve reviewed EPP curricula have an explicit particle physics chapter, namely the International Baccalaureate (IB), Austria, Australia (Queensland), Croatia, Germany (Brandenburg), Israel, Russia, Switzerland (Nidwalden), Serbia, South Africa, Spain, and the United Kingdom (A-levels).

Overall, 35 concepts (out of 60) appear in over half of the curricula (over 6). These concepts are defined as the EPP CCCs. Out of these, 22 concepts are from the category *connections to other curricular topics*, six concepts from the category *particle physics*, and one concept in both the categories *Nature of Science* and *history of physics*.

Similarly, 19 topics (out of 26) topics appear in over half of the curricula. These topics are defined as the EPP CCTs. Here, all topics in the category *connections to other curricular topics* are CCTs. In the category *particle physics*, nine topics are the CCTs. One topic is a CCT in both the categories *Nature of Science* and *history of physics*. More details on which topics are the EPP CCCs and CCTs can be found in Table 7.

Table 6. Overview of the particle physics topics covered in the high-school curriculum documents. This part of the table shows connections to other curricular topics within curricula that also have an explicit particle physics chapter.

Category	**Topic**	**Concept**	**IB**	**AT**	**AU-QLD**	**HR**	**DE-BB**	**IL**	**RU**	**CH-NW**	**SR**	**SA**	**ES**	**UK**
Other curricular topics	Mechanics	Linear motion	■	■	■	■		■	■	■	■	■	■	■
		Circular motion	■	■	■	■	■	■	■	■	■		■	■
	Gravity	Newtonian gravity	■	■	■	■	■	■	■	■	■	■	■	■
		Einsteinian gravity	■	■			■				■	■		
	Conservation laws (of)	Energy	■	■	■	■	■	■	■	■	■	■	■	■
		Linear momentum	■	■	■	■	■	■	■	■	■	■		■
		Angular momentum	■	■						■	■			
		Charges	■		■	■			■			■		■
	Thermodynamics	Particle model	■	■	■	■	■	■	■	■	■	■		■
		Phase transitions	■		■	■			■	■	■	■		
		Vacuum	■		■				■		■	■	■	■
	Electromagnetism (EM)	Electric fields	■	■	■	■	■	■	■	■	■	■	■	■
		Magnetic fields	■	■	■	■	■	■	■	■	■	■	■	■
		Magnetic force	■		■	■	■	■	■	■	■	■	■	■
		Ionisation				■	■		■	■				■
		EM waves	■	■	■	■	■	■	■	■	■	■	■	■
		Superconductivity	■		■	■			■		■			
	Radiation	Cosmic radiation			■	■				■	■			
		Alpha R.	■		■	■	■	■	■		■	■	■	■
		Beta R.	■		■	■	■	■	■		■	■	■	■
		Gamma R.	■		■	■	■	■	■		■	■	■	■
		Radiation (general)	■	■	■	■	■	■	■	■	■	■	■	■
	Special relativity	Relativistic motion	■	■	■	■	■	■	■	■	■		■	■
		$E=mc^2$	■	■	■	■	■		■	■	■	■	■	■
	Quantum physics (QP)	Quantum effects	■				■							
		Probability in QP	■	■	■	■	■	■	■		■	■	■	■
		Atomic models	■	■	■	■	■	■	■	■	■	■	■	■
		Atomic energy levels	■	■	■	■	■	■	■		■	■	■	■
		Quantum mechanics	■	■	■		■	■	■	■	■		■	■

Table 6 (continued).

Category	**Topic**	**Concept**	**BR**	**CA-MB**	**DE-BW**	**FR**	**DE-SN**	**GH**	**GR**	**IT**	**LB**	**NL**	**PL**	**SK**	**SI**	**SE**	**US**
Other curricular topics	Mechanics	Linear motion	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
		Circular motion	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
	Gravity	Newtonian gravity	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
		Einsteinian gravity					■									■	
	Conservation laws (of)	Energy	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
		Linear momentum	■	■	■		■	■	■	■	■		■	■	■	■	■
		Angular momentum							■	■	■		■	■	■	■	
		Charges								■	■		■		■		
	Thermodynamics	Particle model	■	■		■	■	■	■	■	■	■	■	■	■	■	■
		Phase transitions	■			■	■	■	■		■		■		■	■	
		Vacuum						■			■				■		■
	Electromagnetism (EM)	Electric fields	■	■	■	■	■	■	■	■	■	■	■		■	■	■
		Magnetic fields	■	■	■		■	■	■	■	■	■	■	■	■	■	■
		Magnetic force		■	■		■	■	■	■	■	■	■	■	■		■
		Ionisation	■	■	■		■	■				■	■		■	■	■
		EM waves	■	■	■	■	■	■		■	■	■	■		■	■	■
		Superconductivity					■				■						
	Radiation	Cosmic radiation					■									■	■
		Alpha R.	■	■	■	■	■	■		■	■	■	■	■	■		
		Beta R.	■	■	■	■	■	■		■	■	■	■	■	■		
		Gamma R.	■	■	■	■	■	■		■	■	■	■	■	■		
		Radiation (general)	■	■	■	■	■	■		■	■	■	■	■	■	■	■
	Special relativity	Relativistic motion					■			■	■	■	■		■	■	
		$E=mc^2$	■			■	■	■		■	■	■	■	■	■	■	
	Quantum physics (QP)	Quantum effects			■		■					■				■	
		Probability in QP	■	■	■		■	■		■		■	■		■	■	■
		Atomic models	■	■	■	■	■	■	■		■	■	■	■	■	■	■
		Atomic energy levels				■	■	■	■	■	■		■	■	■	■	■
		Quantum mechanics			■	■	■	■		■	■	■			■	■	

Table 6 (continued).

Category	Topic	Concept	IB	AT	AU-QLD	HR	DE-BB	IL	RU	CH-NW	SR	SA	ES	UK
Particle physics	Cosmology	Big Bang	■	■	■	■							■	■
		Inflation		■		■			■				■	■
		Expansion	■		■	■						■		■
	Standard Model		■	■	■		■			■	■	■		■
	Fundamental interactions	EM interaction	■		■	■	■		■		■	■	■	
		Strong interaction	■		■	■	■	■	■		■	■	■	
		Weak interaction	■		■	■	■		■		■	■	■	
		Gravity in PP	■			■			■		■		■	
	Charges	Electric charge	■	■	■	■	■		■	■	■	■	■	■
		Strong charge												
		Weak charge												
	Elementary particles	Quarks	■		■	■		■	■		■	■	■	■
		Leptons	■		■	■	■ e	■	■		■	■	■	■
	Interaction particles	Bosons	■		■	■ p	■ p		■		■	■		■
	Brout-Englert-Higgs mechanism		■		■								■	
	Particle transformations		■		■						■	■	■	■
	Feynman diagrams		■		■						■			
	Antimatter research		■		■	■					■	■	■	■
	Particle accelerators	Linear accelerator										■		
		Circular accelerator	■		■	■						■	■	
		Particle acc. (general)	■		■	■	■		■		■	■		
	Particle detector	Historical detectors					■							
		Modern detectors												
		Particle detectors (general)	■					■			■			
	Data storage and data analysis		■										■	
	Advances in particle physics	Experimental results	■	■									■	
		Open questions	■	■	■	■			■			■	■	
	Real-life applications of particle physics		■	■	■		■		■				■	
Nature of Science			▨		▨		▨	▨	▨	▨	▨	▨	▨	▨
History of (physics)		Quantum physics	▒	▒	▒	▒	▒	▒	▒			▒	▒	▒
		Particle physics		▒	▒									

[e] The respective curriculum only mentions "electrons" specifically.

[p] The respective curriculum only mentions "photons" specifically.

Table 6 (continued).

Category	**Topic**	**Concept**	**BR**	**CA-MB**	**DE-BW**	**FR**	**DE-SN**	**GH**	**GR**	**IT**	**LB**	**NL**	**PL**	**SK**	**SI**	**SE**	**US**
Particle physics	Cosmology	Big Bang	■		■	■	■			■	■		■			■	■
		Inflation	■							■	■		■				
		Expansion				■				■	■		■				■
	Standard Model				■					■						■	
	Fundamental interactions	EM interaction	■			■	■	■			■		■		■	■	■
		Strong interaction	■								■					■	
		Weak interaction	■													■	
		Gravity in PP															
	Charges	Electric charge		■		■	■	■	■		■	■	■	■	■		■
		Strong charge															
		Weak charge															
	Elementary particles	Quarks	■		■						■					■	
		Leptons		■	■	e	■		e		e	e	e		e	e	
	Interaction particles	Bosons				p	p					p	p	p	p	■	
	Brout-Englert-Higgs mechanism																
	Particle transformations						■					■	■		■		
	Feynman diagrams																
	Antimatter research										■	■	■		■		
	Particle accelerators	Linear accelerator				■	■								■		
		Circular accelerator					■				■				■		
		Particle acc. (general)					■				■						
	Particle detector	Historical detectors					■										
		Modern detectors															
		Particle detectors (general)									■						
	Data storage and data analysis		■													■	■
	Advances in particle physics	Experimental results					■										
		Open questions															
	Real-life applications of particle physics			■				■				■				■	■
Nature of Science			▒	▒	▒	▒	▒	▒		▒		▒	▒	▒	▒	▒	▒
History of (physics)		Quantum physics	▓	▓	▓	▓	▓			▓	▓		▓	▓		▓	
		Particle physics	▓													▓	

Table 7. Overview of the common curricular concepts (CCCs) and common curricular topics (CCTs) over the entire set of the curricula or the individual curricular groups, namely the curricula with and without explicit particle physics thematic focus. The leftmost column shows the categories. Green numbers represent that the concept or topic sufficed the criteria to be a CCC or CCT, respectively.

			EPP curricula		**IPP curricula**		**Overall curricula**	
	Topic	**Concept**	**CCC**	**CCT**	**CCC**	**CCT**	**CCC**	**CCT**
Other curricular topics	Mechanics	Linear motion	11	12	15	15	26	27
		Circular motion	11		15		26	
	Gravity	Newtonian gravity	12	12	15	15	27	27
		Einsteinian gravity	5		2		7	
	Conservation laws (of)	Energy	12	12	15	15	27	27
		Linear momentum	11		13		24	
		Angular momentum	4		7		11	
		Charges	6		4		10	
	Thermodynamics	Particle model	11	12	14	14	25	26
		Phase transitions	7		9		16	
		Vacuum	7		4		11	
	Electromagnetism (EM)	Electric fields	12	12	14	15	26	27
		Magnetic fields	12		14		26	
		Magnetic force	11		12		23	
		Ionisation	5		10		15	
		EM waves	12		13		25	
		Superconductivity	5		2		7	
	Radiation	Cosmic radiation	4	12	3	14	7	26
		Alpha R.	10		12		22	
		Beta R.	10		12		22	
		Gamma R.	10		12		22	
		Radiation (general)	12		14		26	
	Special relativity	Relativistic motion	11	12	7	11	18	23
		$E=mc^2$	11		11		22	
	Quantum physics	Quantum effects	2	12	4	15	6	27
		Probability in QP	11		11		22	
		Atomic models	12		14		26	
		Atomic energy levels	11		11		22	
		Quantum mechanics	10		9		19	

Table 7 (continued).

			EPP curricula		**IPP curricula**		**Overall curricula**	
	Topic	**Concept**	**CCC**	**CCT**	**CCC**	**CCT**	**CCC**	**CCT**
Particle physics	Cosmology	Big Bang	6	8	9	9	15	16
		Inflation	5		4		8	
		Expansion	5		5		10	
	Standard Model		8	8	3	3	11	11
	Fundamental interactions	EM interaction	8	9	9	9	17	18
		Strong interaction	9		3		12	
		Weak interaction	8		2		10	
		Gravity in PP	5		0		5	
	Charges	Electric charge	11	11	11	11	22	22
		Strong charge	0		0		0	
		Weak charge	0		0		0	
	Elementary particles	Quarks	9	10	4	11	13	21
		Leptons	10		10		20	
	Interaction particles	Bosons	8	8	7	7	15	15
	Brout-Englert-Higgs mechanism		3	3	0	0	3	3
	Particle transformations		6	6	4	4	10	10
	Feynman diagrams		3	3	0	0	3	3
	Antimatter research		7	7	4	4	12	12
	Particle accelerators	Linear accelerator	1	8	3	4	4	12
		Circular accelerator	5		3		8	
		Particle acc. (general)	7		2		9	
	Particle detector	Historical detectors	1	4	1	2	2	6
		Modern detectors	0		0		0	
		Particle det. (general)	3		1		4	
	Data storage and data analysis		2	2	3	3	5	5
	Advances in particle physics	Experimental results	3	7	1	1	4	8
		Open questions	7		0		7	
	Real-life applications of particle physics		6	6	5	5	11	11
Nature of Science			10	10	13	13	23	23
History of (physics)		Quantum physics	10	10	10	10	20	20
		Particle physics	3		2		5	

Curricula without an Explicit Particle Physics Thematic Focus

Fifteen reviewed IPP curricula have no explicit particle physics thematic focus. These curricula are of Brazil, Canada (Manitoba), Germany (Baden-Württemberg and Saxony), France, Ghana, Greece, Italy, Lebanon, Netherlands, Poland, Slovakia, Slovenia, Sweden, and the USA (Next Generation Science Standards NGSS).

Overall, 26 concepts (out of 60) appear in over half of the IPP curricula (over 7). These concepts are defined as the IPP CCCs. Out of these, 21 concepts are from the category *connections to other curricular topics*, three concepts from the category *particle physics*, and one concept in both the categories *Nature of Science* and *history of physics*.

Similarly, 14 topics (out of 26) topics appear in over half of the curricula. These topics are defined as the IPP CCTs. Here, all topics in the category *connections to other curricular topics* are CCTs. In the category *particle physics*, four topics are the CCTs and one topic in both the categories *Nature of Science* and *history of physics*. More details on which topics are the IPP CCCs and CCTs can be found in Table 7.

There is a 71% overlap between the CCCs in the EPP and IPP curricula. The strongest overlap is in the categories *Nature of Science* and *history of physics* (100%), followed by *connections to other curricular topics* (91%), and lastly, *particle physics* (30%). Here, the 30% overlap means that 30% of CCCs are common between the two curricular groups.

5.5 Summary and Discussion

This study provides a structured overview of 60 concepts related to particle physics in 27 state, national, and international high-school physics curricula. The curricula were reviewed both overall and split into two distinct groups based on whether they have an explicit particle physics thematic focus. The curricular review identified concepts and topics that appear in most curricula. In the following paragraphs, these most common curricular concepts (CCCs) and topics (CCTs) are discussed and used to answer the three research questions.

5.5.1 Most Common Particle Physics Concepts in the Curricula

The first research question asked: Which concepts related to particle physics are the most prominent in national and international high-school physics curricula? The curricular review found that 28 (out of 60) concepts appeared in over half of the curricula. The concepts were grouped into 26 topics, 15 of which also appeared in most curricula. Lastly, the topics were grouped into four categories: the *connections to other thematic topics*, *particle physics*, *Nature of Science*, and *history of physics*. Concepts within all categories appeared in over half of the reviewed curricula.

Two concepts appeared in all reviewed curricula, namely *Newtonian gravity* and *conservation of energy*. Both concepts fall under the category *connections to other curricular topics*. Indeed, an overwhelming majority of concepts within the category *connection to other curricular topics* appeared in most curricula. However, this was expected, as the topics within this category generally represent the chapters in the so-called classical physics curriculum (e.g., mechanics, thermodynamics; Olsen, 2002). The concepts within the category *connections to other curricular topics* can be considered students' prior knowledge, especially when particle physics is taught at the end of high school. Indeed, they act as a base upon which modern physics topics can be built, as shown in the expert concept map in Chapter 4. Thus, their overarching presence across the curricula allows for more generalised suggestions for further curricular updates.

Beyond the *connections to other curricular topics*, six more concepts were mentioned in most curricula, namely the *leptons, bosons*, *electric charge*, *Big Bang, Nature of Science*, and *history of quantum physics.* First, finding *leptons* and *bosons* on this list paint a slightly biased picture. Based on the coding manual, any example of the respective concept was coded as a lepton or boson. Thus, all *electrons* have been coded as an example of *leptons*, and any mention of the *photon* was coded as an example of *bosons*. While it could be argued that this should not be coded as it does not explicitly mention leptons or bosons, including these examples is important for the study and the teaching. Indeed, these examples can provide an entry point for including particle physics even when they are not explicitly connected to particle physics (e.g., in the context of electromagnetism).

Many other particle physics concepts also enter curricula as context for other curricular topics. For example, *cosmology* is often mentioned in the context of astronomy or astrophysics, and *electric charge* in the context of electromagnetism. As such, explicit particle physics concepts can be intrinsically connected to other curricular topics. By highlighting the connections to other curricular topics and other particle physics concepts, curricula can further support students' meaningful learning (Ausubel, 2000). Indeed, the more connections a specific concept has, the more stable the concept is in the cognitive network. Therefore, using particle physics as context should be encouraged in high-school education.

Similarly, the *Nature of Science* rarely enters curricula as explicit content. Although research shows that the *Nature of Science* should be taught explicitly (Lederman, 2013), most curricula rather call for its implicit introduction. Typically, a list of the *Nature of Science* concepts is presented at the beginning of curricula to highlight what teachers should convey throughout their teaching. Very few examples of the *Nature of Science* can be found within the content part of curricula or expecting teachers to teach the *Nature of Science* explicitly. Likewise, most textbooks only implicitly include the *Nature of Science* (e.g., Campanile et al., 2015; McDonald, 2017). Finding good content to support the teaching of the *Nature of Science* as context is crucial for teachers. Here, several studies already suggested contemporary topics, such as quantum mechanics, to use as the basis for the *Nature of Science*. Hence, particle physics could also be used to convey this topic to students. However, the connection between the *Nature of Science* and particle physics surpasses the curricular review. Therefore, more on this connection is discussed in Chapter 8.

Last, the *history of quantum physics* was also present in most curricula. As opposed to the *Nature of Science*, the *history of physics* was always featured within the content part of the curricula. While it is not always clear if the content in the reviewed intended curricula matches the evaluated curricula (i.e., the content to be evaluated), teachers are expected to teach this content in school explicitly. This is interesting, as some studies have found the *history of science* to be merely a tool for teaching (Galili, 2008; Leone, 2014). However, the *history of quantum physics* often plays a more explicit role in teaching. Indeed, quantum physics concepts, such as *atomic models*, are often introduced using a historical approach (Harrison & Treagust, 2003). Interestingly, the *history of particle physics* very scarcely appeared in the curricula. Here, the historical facts focused more on discoveries of particles (e.g., muons) than on the development of a model. Therefore, such introduction of the historical aspect is not as important for meaningful learning of particle physics.

Three explicit particle physics concepts were not mentioned in any curricula. First, *strong charge* and *weak charge* are not mentioned in any of the curricula. However, *electric charge* has been identified as one of the most common concepts. Indeed, the *electric charge* was commonly mentioned in the context of electromagnetism, which is a part of the classical curriculum. Interestingly, it was typically referred to only as "charge," as no other charges appeared in the curriculum. Thus, the concept of *conservation of charge* again only holds for *electric charge*. This leaves very little space for introducing *weak charge* and *strong charge* in the curricula, as the word "charge" was already introduced to mean electric charge. As such, the term "charge" in *strong charge* and *weak charge* could be thought of as electric charge as well, making the *strong charge* and *weak charge* seem like types of electric charge. Meanwhile, the *strong interaction* and *weak interaction* are still mentioned in several curricula. However, their description is generally limited to their role in nuclear reactions. Indeed, other studies have found that *teachers often mention strong* and *weak interactions* as decontextualised and in passing (Sirola, 2018; Tuzón & Solbes, 2016). While introducing the *strong* and *weak interaction* can include short discussion about the nature of these interactions (e.g., range and relative strength), it typically avoids the charge. For example, the international baccalaureate (IB) curriculum, one of the most comprehensive curricula in this curricular review, prominently includes *weak* and *strong interactions*. However, while it describes the electromagnetic charge and the baryon numbers of the elementary particles and the interaction particles, the IB curriculum still does not introduce the *strong* and *weak charge*. Omitting *charges* from the curricula means omitting the information about charges for *weak* and *strong interaction.* Therefore, this finding directly supports Michelini's (2021) claim about superficial introductions of particle physics in classrooms.

Second, none of the curricula mentioned *modern particle detectors*. However, contrarily to the *strong* and *weak charge*, the lack of mentions of *modern particle detectors* is not that surprising. When at all, *particle detectors* generally appear in the literature as a context for other curricular topics, for example, radiation (Barradas-Solas, 2007). Nevertheless, with various possibilities of introducing some sort of particle detector in the classrooms, not including particle detectors seems like a lost opportunity for more active learning. Indeed, *particle detectors* are bridges between other curricular topics and *theoretical particle physics,* as seen in the expert concept map in Chapter 4. Furthermore, many newer particle detectors can be used as hands-on experiments in the classroom (e.g., Keller et al., 2016). Here, using particle detectors in the classroom can help students visualise what is otherwise a very abstract chapter. Therefore, *particle detectors* should enter at least teachers' enacted curricula to support more meaningful learning.

5.5.2 Curricula with an Explicit Focus on Particle Physics

The second research question asked: What are the differences and similarities between the particle physics content in curricula with or without an explicit particle physics chapter? Here, the two groups of curricula were first defined. Twelve curricula were identified to have an explicit particle physics thematic focus (EPP). Fifteen curricula only showed implicit connections to particle physics (IPP). In both groups, the most common curricular concepts (CCCs) were determined. The CCCs were the basis for the comparison of the two groups. The results show that while the two groups are very similar in some respects, there are some visible differences.

EPP curricula include more CCCs and CCTs in particle physics than the IPP curricula. This is not surprising, as EPP curricula focus more explicitly on particle physics. The majority of the CCCs and CCTs in particle physics remain in theoretical particle physics. Indeed, only one CCT in EPP curricula can be classified as an experimental particle physics concept, namely the *particle accelerators*. This concept was mainly included in the curricula as a context for electromagnetism. Again, including a concept in the curriculum as context can be very beneficial to students' learning if it is connected to other concepts in the curriculum. However, in the case of *particle accelerators*, this was not the case. *Particle accelerators* were not explicitly connected to any other particle physics concepts or the particle physics chapter itself. Indeed, *particle accelerators per se* very rarely explicitly appeared in the particle physics chapter. Therefore, theoretical particle physics concepts remain disconnected from the experimental particle physics concept. As such, learning about theoretical particle physics can quickly turn into rote learning of facts and numbers that describe particles and fundamental interactions without knowing their meaning in the context of physics, modern research, and everyday life. Therefore, it is up to teachers to better connect particle physics concepts to each other and beyond.

Interestingly, CCCs and CCTs within the category *other curricular topics* overlap significantly. Indeed, the two types of curricula differ only in three CCCs, namely the *relative motion* and *vacuum* that were only CCCs in EPP curricula, and *ionisation* that was only a CCC in IPP curricula. *Other curricular topics* can be considered as students' prior knowledge when learning about particle physics. Therefore, when discussing particle physics, all curricula lead to a similar level and breadth of students' prior knowledge. As such, most suggestions for including particle physics in classrooms can apply to most high-school physics curricula.

This curricular review provides an overview of what is being expected by educational systems in the context of particle physics in high school education around the world. However, only the most extensive physics curricula within each educational system were included (e.g., science-oriented high-school curricula). Furthermore, the intended curricula do not necessarily match the enacted curricula, i.e., what teachers finally bring into the classroom. Further studies should investigate what teachers include in their classrooms to better identify how particle physics is included, both as content and context.

The first two studies of this doctoral research project investigated what students are expected to learn. Together, the two studies give a good overview of how particle physics is presented in high-school education. A detailed comparison between the two studies is given in Chapter 7. However, nothing was said on how teachers could improve their knowledge on the topic. Thus, a third study was designed to identify what the stakeholders of CERN's professional development programme expect teachers to learn in a one-week programme at CERN. This study is presented in the next chapter.

6 CONTENT OF PARTICLE PHYSICS PROFESSIONAL DEVELOPMENT

The inclusions of new topics, such as particle physics, as well as other advancements in curricula quickly overgrow teachers' initial training (OECD, 2019). Thus, in-service teachers worldwide are driven to participate in different professional development opportunities to advance their skills and knowledge and prepare for new learning situations (Finlayson et al., 1998; Greene et al., 2013; Hewson, 2007; Pena-Lopez, 2009). In particle physics, various research organisations are running professional development programmes (PDPs). For instance, thousands of teachers worldwide already participated in CERN's teacher programmes on particle physics (Coldham, 2016). A similar situation can be seen in many other particle physics PDPs worldwide (e.g., Netzwerk Teilchenwelt, QuarkNet, EinsteinPlus). However, until recently, information on what teachers are expected to learn at particle physics PDPs was scarce.

6.1 State of the Research: Effective Professional Development Programmes

Secondary science teachers' content knowledge (CK) and its structure rarely advance only through classroom practice (Nixon et al., 2017). When changes in the curriculum exceed teachers' previous education, the best option is to enhance their CK through professional development further. Therefore, professional development programmes (PDPs) are one of the building blocks of successful systematic educational reforms (Borko, 2004; Corcoran, 1995; Garet et al., 2001; OECD, 2019), as mentioned in Chapter 2.

The main goal of a great number of PDPs is the enhancement of teachers' content knowledge (Borko, 2004; Desimone, 2009; Garet et al., 2001; Park Rogers et al., 2007; Smith & Gillespie, 2007). Teachers' participation in effective PDPs has been shown to improve their professional knowledge and skills (Banilower et al., 2007; Blömeke et al., 2016; Borko, 2004; Boyd et al., 2009; Desimone, 2009; Greene et al., 2013; Hewson, 2007; Luft & Hewson, 2014; OECD, 2019; Pena-Lopez, 2009; Tatto & Menter, 2019). The increase in teachers' professional knowledge and instructional quality further reflects on students' achievement. Indeed, Lee and Mamerow (2019) found that students with highly qualified teachers tend to have better achievements and better educational outcomes in science, technology, engineering, or mathematics (STEM). Thus, it is important to enable teachers to further develop their knowledge and skills throughout their profession. Here, participation in PDPs enhances teachers' CK (Diamond et al., 2014; Garet et al., 2001; Greene et al., 2013; Heller et al., 2012; Morewood et al., 2010), which can also reflect on students' achievement (Heller et al., 2012). Thus, professional development is an essential part of any curricular reform (Borko, 2004; Corcoran, 1995; Garet et al., 2001; OECD, 2019). Indeed, students' achievement is greater when their teachers continue with the older curricular standards than updated standards if they do not receive supporting professional development (Doppelt et al., 2009). However, not all professional development can be considered effective. Based on the study by Darling-Hammond et al. (2017), effective professional developments can be defined as “structured professional learning that results in changes in teacher practices” (Darling-Hammond et al., 2017, p. 2).

Effective professional development relies on several interdependent characteristics (Darling-Hammond et al., 2017). First, a strong CK focus is at the heart of most effective professional development (Darling-Hammond et al., 2017; Desimone, 2009; Doyle et al., 2020). Indeed, professional developments focusing on CK and pedagogical content knowledge (PCK) raise teachers’ confidence in teaching (Shallcross et al., 2002). Similarly, Garet et al. (2001) found that a strong focus on CK in professional development significantly improves teachers’ knowledge and instruction practice. Within the content focus, professional development should emphasise the use of models and modelling to make them more effective (Darling-Hammond et al., 2017).

Second, effective professional development should incorporate active learning experiences, such as using authentic artefacts and interactive activities. Indeed, active learning experiences allow teachers to encounter the resources they are expected to utilise in the classroom (Darling-Hammond et al., 2017; Desimone, 2009; Doyle et al., 2020; Trotter, 2006). Here, active learning promotes active engagement of educators as well as students and thus provides opportunities for highly contextualised learning (Darling-Hammond et al., 2017).

Third, Darling-Hammond et al. (2017) call for strong coaching and expert support throughout professional development. Indeed, experts and coaches can provide teachers with a stronger scaffold for effective implementations of new curricula, tools, and approaches (Gallagher et al., 2017; Penuel et al., 2011; Roth et al., 2011). Most effective professional development also shows strong overall coherence (Darling-Hammond et al., 2017; Desimone, 2009; Doyle et al., 2020). Coherence means that professional development is consistent with national and local education policies and connect to what teachers already know (Desimone, 2009; Qian et al., 2018).

Last, several studies emphasised the importance of the sustained duration of professional development (Banilower et al., 2007; Darling-Hammond et al., 2017; Guskey, 2000; Liu & Phelps, 2020; Smith & Gillespie, 2007). However, Banilower et al. (2007) found that the overall effects of length on the quality of professional development were small to moderate. Indeed, the content focus and the activities within professional development likely have a greater influence on the professional development effectiveness than its length (Lipowsky & Rzejak, 2015; Wiener et al., 2018). A well-defined content of professional development is thus of crucial importance.

As seen in several studies, focus of professional development on CK aligns strongly with teachers’ personal learning goals. Indeed, teachers identified enhancement of content knowledge as their personal aim through participation in professional development (Anderson & Mitchener, 1994; Louws et al., 2018; Owens et al., 2018; Park Rogers et al., 2007; Van Duzor, 2012). Here, a strong connection between teachers’ personal learning goals and the programmes' goals is crucial as it increases the likelihood of teachers becoming ambitious and successful while learning (Coburn, 2004; Penuel et al., 2007; Zepeda, 2013). Likewise, the policy approaches to professional development often, at least loosely, call for enhancement of teachers' CK through their participation in PDPs, as seen in Loeb et al. (2009). Furthermore, the same goal is shared by research scientists that facilitate the programmes (Drayton & Falk, 2006; Gentsch, 1999; Schuster & Carlsen, 2009; Taylor et al., 2008). Indeed, research scientists typically value the goal of enhancing teachers' CK more than enhancing their pedagogical knowledge (PK) or PCK (Gentsch, 1999). Similarly, the paper the author published on learning goals of PDPs confirms that all stakeholders agree on enhancing CK as one of the most important goals (Kranjc Horvat et al., 2021), as described in Chapter 3.

6.2 Research Questions

Enhancing teachers' CK was recognised as one of the PDPs' most important learning goals by various stakeholder groups in several studies (e.g., Gentsch, 1999; Kranjc Horvat et al., 2021; Schuster & Carlsen, 2009; Zepeda, 2013). However, in the context of high-school particle physics, little is known about what this content knowledge should entail. Therefore, the Delphi study, described in Chapter 3, included a section for determining the expected content of PDPs. The following research question guided the content knowledge part of the Delphi study:

> **RQ6.1**: Which particle physics content is perceived by the relevant stakeholders as the most important for teachers to learn about in professional development programmes (PDPs) in particle physics for in-service high-school science teachers?

However, different stakeholders could hold different perspectives on the characteristics of effective PDPs. The different perspectives can lead to disparities between theory and practice, expectations, and realisations (Park Rogers et al., 2007). For example, PDP developers sometimes fail to consider teachers and their learning goals in top-down PDP initiatives. Therefore, the teachers cannot implement changes in the expected way (Collinson et al., 2009). The study presented in this chapter thus explored the differences between various stakeholder groups. The following research question guided this exploration:

> **RQ6.2**: Which differences and similarities can be identified between the expectations of the different stakeholder groups regarding high-school teachers' particle physics content knowledge (CK)?

Both research questions were addressed in a Delphi study on experts' expectations regarding particle physics PDPs, described in Chapter 3. The part of the study that focused on the content of particle physics PDP is described in detail in the sections below.

6.3 Methodology

The exploration of research questions called for a robust research method for expert opinion elicitation. Thus, a conventional Delphi study was conducted. Delphi study is an iterative expert method, aiming to elicit ideas, judgements, and predictions of experts with relevant knowledge and experience (Osborne et al., 2003; Reeves & Jauch, 1987). Typically, a conventional Delphi study includes three rounds of questionnaires which alternate with structured feedback that allows the experts to deliberate on the common opinion (Clayton, 2006; Goldstein, 1975; Gupta & Clarke, 1996; Hasson et al., 2000; Hsu & Sandford, 2007; Linstone & Turoff, 1975; Rowe & Wright, 1999). The first round of the Delphi study is usually an open or semi-open questionnaire (Clayton, 2006; Enzer, 1975; Hasson et al., 2000; Linstone & Turoff, 1975; Osborne et al., 2001; Reeves & Jauch, 1987; Rowe & Wright, 1999). In subsequent questionnaires, the experts deliberate on themes that emerge from the first-round questionnaire and possible additional literature review (Hasson et al., 2000; Linstone & Turoff, 1975; Rowe & Wright, 1999). Between the rounds, the experts are provided with feedback from the latest round. The feedback includes the results of the analysis of the latest round and comments made by the experts in the respective round. The experts are encouraged to review the feedback and revise their judgement considering suggestions and comments of other experts (Brady, 2015; Clayton, 2006; Gupta & Clarke, 1996; Hsu & Sandford, 2007; Linstone & Turoff, 1975).

Experts' ideas and judgments are central to the Delphi study. Therefore, the quality and width of the Delphi study depend greatly on the expert selection (Baker et al., 2006; Powell, 2003; Rowe & Wright, 1999). Indeed, experts' required knowledge, experience, or political influence need to be well defined beforehand (Baker et al., 2006; Okoli & Pawlowski, 2004; Osborne et al., 2001). Here, a broader definition of expertise leads to more heterogeneous groups with a wider knowledge base and, thus, to greater interest and more unique ideas of stakeholders in the study (Baker et al., 2006; Okoli & Pawlowski, 2004; Powell, 2003; Rowe et al., 2011). However, heterogeneous groups bear the risk of stronger social influence of the individuals (Bolger & Wright, 2011). Hence, splitting the heterogeneous expert group into several homogeneous groups can ensure a fairer representation of views (Bolger & Wright, 2011; Jones, 1975; Osborne et al., 2003). While the reliability of a Delphi study improves with the increasing number of participating experts (Hasson et al., 2000), there is little to no increase in the number of generated ideas in homogeneous groups with over 30 experts (Delbecq et al., 1975). Thus, most studies include between 10 and 25 experts per homogeneous group (Clayton, 2006; Okoli & Pawlowski, 2004; Osborne et al., 2001, 2003). Including several homogeneous groups in a study leads to a great number of experts that are often unavailable for a long discussion at the same time. Fortunately, the iterative nature of the Delphi study design allows more experts to deliberate on the ideas and opinions of others while being geographically dispersed (Clayton, 2006; Enzer, 1975; Hasson et al., 2000; Osborne et al., 2003). Furthermore, the experts can remain anonymous (Hasson et al., 2000; McMillan et al., 2016; Osborne et al., 2003; Rowe & Wright, 1999), which further reduces the potential social influences of the individuals (Bolger & Wright, 2011).

Based on the recommendations from the extensive body of research on Delphi studies (e.g., Clayton, 2006; Linstone & Turoff, 1975; Osborne et al., 2003), this Delphi study followed the described three-round design with interspersed feedback. The expert selection and the design of each round are described in more detail in the sections below.

6.3.1 Participants

All experts in this study were stakeholders of CERN's teacher programmes. The stakeholders were invited to form four stakeholder groups: (a) physics education researchers, (b) government representatives of different countries with experience in particle physics policies (hereafter referred to as country representatives), (c) research scientists in the fields of natural science and informational technology, and (d) in-service high-school science teachers. All stakeholder groups and the respective qualifications of the stakeholders are described in Table 8.

The stakeholders within each group were chosen using a different technique due to the inherent differences between the groups. First, potential physics education researchers were identified using the snowballing nomination technique. Here, nominations by peers created a stronger personal connection to the study and, thus, helped ensure expert retention (Braun & Clarke, 2006; Gupta & Clarke, 1996; Rowe et al., 2011). The qualifications of each nominee were checked against predefined criteria (see Table 8). Second, country representatives were nominated based on their experience with and knowledge of the educational programmes and policies in their institutions and home countries, respectively. Third, all invited research scientists were identified as experts in natural sciences or engineering. Additionally, all were experienced PDP facilitators at CERN in their respective national languages. Last, in-service high-school science teachers from various countries were invited either shortly before or after participating in their respective national or international PDP at CERN. Overall, the stakeholders came from 33 countries. Here, country delegates came from 24 countries, research scientists from 19 countries, teachers from 12 countries, and physics education researchers from 9 countries.

Throughout the rounds, the number of stakeholders per stakeholder group always exceeded 10, as recommended in the literature (Clayton, 2006; Hasson et al., 2000; Okoli & Pawlowski, 2004; Osborne et al., 2001, 2003). Furthermore, all stakeholders that were invited to participate in the first round of the study were also invited to subsequent rounds, regardless of their participation in previous rounds. Thus, the number of stakeholders in some of the stakeholder groups increased between the rounds, as seen in Table 9.

6.3.2 Conduct of the Study

Conventional Delphi studies have an iterative design, where the outcomes of each round directly affect the methodology of the subsequent rounds. Thus, the study's methodology is best presented by including intermediate results between the rounds' descriptions. The final results and outcomes of the Delphi study are presented in Chapter 6.4.

As defined by the research questions, this study aimed to identify topics within particle physics that stakeholders perceive to be the most important for teachers to learn at a particle physics PDP. Thus, the first-round open-ended question was designed to elicit various stakeholders' ideas for possible topics. The question was pretested in two steps. First, semi-structured interviews were conducted with three members of the stakeholder groups. The interviews ensured that the question was unambiguous and not leading. Second, the updated question was pretested with five physics education researchers to ensure that it was appropriate for the international stakeholder groups. None of the stakeholders in the pretests took part in the first round of the study. Based on the outcomes of the pretests, the following first-round question was designed:

> What should in-service high-school science teachers learn about particle physics at PDPs at CERN or a similar particle physics research institution?

Round 1: Data collection and analysis

The first-round questionnaire was designed as an online questionnaire. The selected stakeholders were encouraged to provide their ideas and any additional comments within a one-month deadline for completion.

The first-round data were analysed using inductive thematic network analysis (Attride-Stirling, 2001; Brady, 2015; Kranjc Horvat et al., 2021; Linstone & Turoff, 1975). Most themes emerged inductively from the patterns identified in the first 15 responses, as recommended by Braun & Clarke (2006). As per Attride-Stirling (2001), the themes were organised into a hierarchical network, where they were clustered into categories. Each theme was described based on the patterns to increase the unambiguity of the themes.

The themes and the descriptions were validated with an inter-rater analysis. Here, 10% of the data was validated by an inter-rater. Initially, the inter-rater agreement was 80%. After the discussion, the agreement rose to 100%. All themes, their descriptions, and the respective examples were then combined into a feedback package for the stakeholders.

Table 8. The stakeholder groups and their respective qualifications.

Stakeholder group	Qualifications
Physics education researchers	Experience in the research of PDPs or modern physics education.
Country delegates	Extensive knowledge of education policies and programs in their respective home countries and institutions.
Research scientists	Researchers in natural sciences or informational technology; involved with the organisation of national PDPs.
Teachers	High-school science teachers; participated in the PDP at the particle physics laboratory in the past or applied to participate in the future.

Table 9. Number of stakeholders per stakeholder group in each round.

Stakeholder group	1st Round	2nd Round	3rd Round
Physics Education Researchers	28	31	32
Country Delegates	16	11	12
Research scientists	18	14	11
Teachers	19	45	43
Total	**81**	**101**	**98**

Round 1: Results

The thematic network analysis of 81 stakeholders' responses in Round 1 resulted in 8 categories with 17 themes. The categories, the themes, and respective examples are presented in Table 10.

The themes that were identified in the first round were used as the basis for the second-round questionnaire. There, the aim was to identify which of the themes were perceived by stakeholders as the most important for teachers to enhance through their participation in particle physics PDPs. Therefore, all stakeholders were asked to rate each theme on a Likert-type scale in the second round. The online questionnaire was pretested by nine physics education researchers and two high-school science teachers. None of the researchers or teachers in the pretest later participated in the second round of the Delphi study. The pretest showed that the questionnaire was unambiguous and understandable to international participants. The questionnaire was then sent to the stakeholders in an online form with a one-month deadline for completion.

Round 2: Data collection and analysis

In the second-round questionnaire, stakeholders rated the importance of each theme. The importance was rated on a 6-point Likert-type scale, ranging from 1 ("Very unimportant") to 6 ("Very important"). The scale was explained on the first page of the questionnaire, as seen in Clayton (2006). The even number of points for the Likert-type scale was selected to avoid a neutral option, as Harvey and Holmes (2012) and Turoff (1975) suggested.

The Likert-type responses were analysed descriptively, as suggested by Boone and Boone (2012). The central tendency was assessed using the median (Day, 1975; Hsu & Sandford, 2007; Ludlow, 1975; McMillan et al., 2016; Rowe & Wright, 1999). Additional frequency analysis showed the variance of the answers (Williams et al., 2004).

The frequency analysis was later used as the basis for ranking the themes based on their importance. Namely, the theme rated as at least "Rather important" by the most stakeholders were ranked the highest. The differences between adjacent themes within such ranking were assessed with the Mann-Whitney-Wilcoxon test to determine whether the difference between their respective ranks was statistically significant. Furthermore, the agreement on the rating of each theme between the stakeholder groups was assessed using the Kruskal-Wallis test.

Table 10. Overview of the 17 themes that emerged from the analysis of the first round of the Delphi study. The themes are grouped into eight categories, as shown in the first column. The last column presents respective examples from the data for each theme.

Category	Theme	Example
Particle physics	Particle physics (in general)	Teachers should hear about particle physics and technology at the highest professional level.
	Standard Model	Short lectures on (…) Standard Model and why to look beyond it.
	Elementary particles	Explain the basic properties of hadrons and leptons.
	Fundamental interactions	Allow acquiring the necessary knowledge (…) on elementary particles and how they interact.
Technology	Technology and engineering	New information about the technology used at LHC and detectors.
	Particle accelerators	Enhance teachers' knowledge on (…) accelerator principles.
	Particle detectors	Understand the principle and new methods of measurement [at CERN].
	Computing and data analysis	Learn about computing and software design.
Cosmology	Cosmology	Explaining the context and relevance of the research being done to understand the Universe better.
Antimatter research	Antimatter research	Visit antimatter factory as the next step after a lecture.
New results and open questions	Theoretical advances	Contact to modern physics and questions of the front of modern research
	Dark matter and dark energy	Teachers should learn about the mysteries of dark matter and dark energy.
	Experimental advances	Information about the last results in particle physics - theory and experiment.
Real-life applications	Real-life applications	Educate teachers about research done at CERN and explain spinoffs for society.
History and philosophy of science	Philosophy of science and societal impacts	To impose scientific thinking, we hold an evening discussion on the "philosophy of science".
	History of science	Historical development of physics research and physics knowledge.
Relativity theory	Relativity theory	A teacher should deepen his/her knowledge of modern physics with an emphasis on relativity.

In addition to rating the themes on the Likert-type scale, stakeholders were encouraged to provide comments to justify their ratings and suggest any changes to the themes. The stakeholders' justifications and suggestions increased the validity of the study as they reduced researchers' bias (Brady, 2015; Osborne et al., 2001). The comments were inductively thematically analysed to identify any patterns that called for further updates.

The results of the second-round questionnaire were combined and summarised in the feedback package for stakeholders. In addition to the representation of the ranking outcome, the results of statistical analysis and an overview of the comments were also provided. The differences between groups were shown; however, they were not discussed to avoid potential researchers' bias. Any changes to the list of themes were highlighted and explained to increase the transparency of the process. The feedback package was sent to the stakeholders together with the invitation for the third-round questionnaire.

Round 2: Results

The descriptive analysis of the second-round questionnaire showed a significant ceiling effect. The median of the theme *real-life applications* was 6 ("very important"), and all other medians were 5 ("rather important"), as seen in Table 11. Similarly, all themes were rated as at least "slightly important" by more than 83% of all stakeholders. Here, only *history of science*, *philosophy of science*, and *theoretical advances* were rated as at least "slightly important" by less than 90% of all stakeholders, as shown in Table 11 and Figure 4. These are also the only three themes that received the rating "very important" by less than 25% of all stakeholders.

The themes were ranked based on the percentage of stakeholders rating them as at least "slightly important". The Mann-Whitney-Wilcoxon test was used to assess the differences between the adjacent themes in the ranking. The only two pairs of adjacent themes with statistically significant differences between their respective ratings were the *Standard Model* and *antimatter research* (W=3750.5, p=.002), and the *experimental advances* and *technology and engineering* (W=5820, p=.03). Thus, only these two pairs can be statistically differentiated. The ratings of all other pairs of adjacent themes were not statistically different (p>.05).

The Kruskal-Wallis test on all themes showed that 12 out of 17 themes were ranked significantly differently (p<.05) by at least one stakeholder group. For example, physics education researchers rated *technology and engineering* as "slightly important". At the same time, all other stakeholder groups considered it "rather important." Only *cosmology*, *dark matter and dark energy*, *relativity theory*, *history of science*, and *philosophy of science* were similarly rated in all stakeholder groups. However, the results show a strong ceiling effect, and most ranked themes are statistically indistinguishable. As such, any conclusions overall or per group are unreliable. Therefore, the next round of the Delphi study needed to be designed in a way that would increase the validity of the results.

Thus, the third-round questionnaire included a ranking task and an hour-assignment task to better differentiate between the relative importance of the themes. However, the large number of themes in the third round could increase stakeholders' cognitive load (Rokeach, 1973; Smyth et al., 2018). Therefore, several themes were combined to reduce the overall number of themes. The themes were joined through think-aloud interviews with three particle physicists and a physics education researcher. This procedure ensured the merging validity and reduced the researchers' bias. Themes *particle physics (general)*, *Standard Model*, *elementary particles*, and *fundamental interactions* were combined into *Standard Model of particle physics*. The themes *dark matter and dark energy* and *cosmology* merged into *cosmology*.

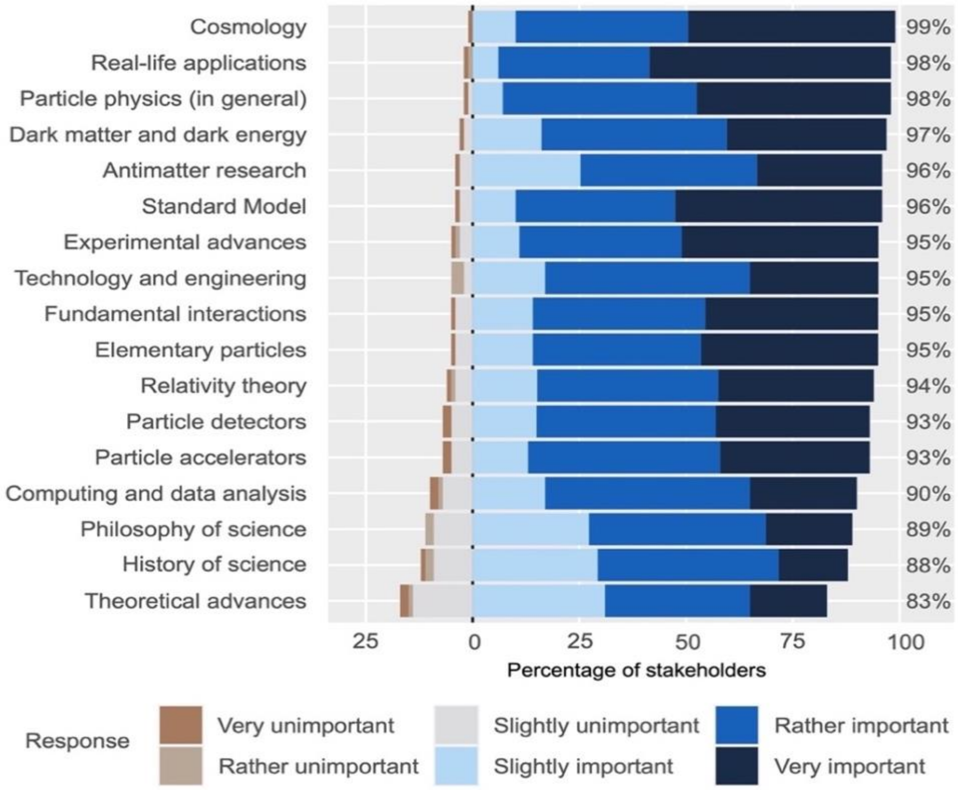


Figure 4. Frequency analysis of the second-round ratings. The Likert stacked bar chart represents the combined responses of all stakeholders. The themes are sorted by the percentage of stakeholders that rated the respective theme as important (blue), meaning either “slightly important”, “rather important”, or “very important”.

Altogether, 16 stakeholders added comments on the second-round questionnaire. Neither of them included suggestions for additional topics. The comments on individual themes were grouped and are presented as such in the paragraphs below.

First, stakeholders deliberated on *particle physics*, *different particles and their properties*, *particle interactions*, *the Standard Model*, *cosmology*, *antimatter research*, *the mysteries of dark matter and dark energy*, and *advances in theoretical physics*. Here, comments by two country representatives and a research scientist noted that all the topics in this grouping could indeed be considered one topic overall. Thus, most themes within this grouping were joined into one for the third round, namely the *Standard Model*. Furthermore, several stakeholders mentioned interest and motivation. For example, one teacher mentioned that introducing these topics in a classroom would “generate interest and excitement in the field.” Similarly, a country representative noted that “the beginning of the Universe would certainly be compelling for students as well as antimatter research and dark matter.” Furthermore, a teacher commented that “antimatter and dark anything have been very attractive nowadays.”

Table 11. Overview of the analysis of the second-round rating by all stakeholders. The second column presents the percentage of stakeholders that rated the respective theme as important, namely either “slightly important”, “rather important”, or “very important”. The third column presents only the percentage of the stakeholders that rated the respective theme as “very important”. The third column presents the median for each theme. Here, 5 stands for “rather important”, and 6 for “very important”. The last column presents the differences between the rating of different stakeholder groups that were assessed using the Kruskal-Wallis test.

Theme	**% Important**	**% Very important**	**Median**	**Kruskal-Wallis *p-value***
Cosmology	99	49	5	.107
Real-life applications	98	57	6	.006**
Particle physics (general)	98	46	5	.002**
Dark matter & dark energy	97	37	5	.130
Antimatter research	96	29	5	.009**
Standard Model	96	49	5	.002**
Experimental advances	95	46	5	.014*
Technology & engineering	95	30	5	.002**
Fundamental interactions	95	40	5	.015*
Elementary particles	95	41	5	.009**
Relativity theory	94	36	5	.080
Particle detectors	93	36	5	.030*
Particle accelerators	93	35	5	.007**
Computing & data analysis	90	25	5	.012*
Philosophy of science	89	20	5	.525
History of science	88	16	5	.152
Theoretical advances	83	18	5	.018*

*Statistical differences denoted as *p<.05; **p<0.01.*

Another cluster that appears is around the notion that these topics should “avoid being too theoretical” (physics education researcher). Here, a country representative noted that “all of these are important topics, but it is difficult for high-school teachers to learn all of them.” Similarly, another country representative mentioned that “advances in theory should probably cover the general aspects but look rather difficult to me to convey on an appropriate level.”

Second, several stakeholders commented on *particle accelerators*, *particle detectors*, *computing and data analysis*, and *technology and engineering*. Here, one physics education researcher emphasised that the PDPs should “avoid being too technical.” This notion was supported by a physics education researcher, who mentioned that “the specifics are not as important as the ‘big ideas.’" A country representative agreed:

> “I don't know how important the technical details are – [teachers] should be able to answer questions of their students with respect to the large concepts, but not in detail.”

Additionally, the research scientist agreed that it “depends on the level” of complexity of the theme. One teacher connected these experimental methods and the Nature of Science:

> “Far too often, students leave high school physics with the idea that physics research is basically finished. When we can tie concepts in high-school courses (such as

> electromagnetism) to particle accelerators and detectors, then we can open their eyes to the limits of what we know and where the frontiers of research are."

Similarly, a teacher commented that introducing *latest findings* in the classroom introduces students to "future prospects." The country representatives were split on this theme. While one believed that learning about *latest results* is "secondary," another country representative noted that:

> "At a place like CERN, the participating teachers are expecting to learn about the latest findings and newest results; anything less would constitute a disappointment for them."

One teacher agreed, mentioning particle physics PDPs are a great place "to learn what is new from those doing the research." However, three stakeholders emphasised that these topics might be difficult to understand. Indeed, one physics education researcher commented that an "assessment of necessary preliminary knowledge for understanding" is important. This would then allow the theme to be better "'translated' for teachers" (teacher) as to make them more "comfortable with latest findings and newest result" (teacher).

The *theory of relativity* sparked fewer comments overall. Here, one teacher and one country representative found it "important," and one teacher noted they "rarely have had an opportunity to be introduced to [theory of relativity]." However, a physics education researcher commented that teachers generally already know the basics and should thus rather "learn to apply the basic equations to particle accelerators and processes between particles."

The *real-life applications of particle physics* sparked more comments. Again, several stakeholders connected it to the Nature of Science. Here, a teacher commented that introducing *real-life applications* shows that "science is 'everywhere and everything,'" with another teacher adding that it helps to show that "research can help people." Another teacher complemented this by writing that this theme "helps students with the question 'where will I ever use this?'" Similarly, a physics education researcher noted that this theme answers the student's "why bother" questions. A country representative agreed with this notion, saying that "it could be appealing to students to know that science is not only up in the air but that it touches their everyday lives." On the other hand, one physics education researcher thought that "[teachers] can probably learn about this topic elsewhere."

Similarly, two physics education researchers commented that teachers could learn about *philosophy* and *history of science* "on their own" or "elsewhere" rather than at a particle physics PDP. One research scientist also noted that *history* and *philosophy of science* are "marginally important" at such programmes. Additionally, one physics education researcher wrote that if included, *history* and *philosophy of science* should be "made relevant" rather than just introduced with "a lot of talking." Here, another physics education researcher highlighted the importance of talking about the "the good and the bad of history" and not only "showing the upside." Two teachers remarked that learning about *history* and *philosophy of science* is "quite important" as "teachers are not always the best trained in these two areas." Furthermore, a country representative wrote that "when you ask physicists, it is often these aspects that attracted them to science."

Finally, two comments were made about the entire group of themes. First, a research scientist indicated that there is usually “no time to cover all the [themes]” in a short programme. Second, a physics education researcher emphasised that it is important that “not only lectures” are used to introduce these themes.

The results of the second round, the stakeholders’ comments, and the joining of the themes were presented to the stakeholders in the feedback package. The feedback package was sent to the stakeholders together with the invitation to the third round of the Delphi study.

Round 3: Data collection and analysis

In the third round of the Delphi study, the stakeholders re-evaluated their importance ratings from the previous round. Their re-evaluation was based on the ratings of all stakeholders and the rating of their respective stakeholder groups in Round 2. The stakeholders received the list of the themes presented in Table 12 in an online form. The themes were sorted according to their rating in the second round. Here, the joined themes assumed the position that was previously taken by the highest-ranked theme included in the new theme. For example, the *Standard Model of particle physics* was on the third place as the theme *Particle physics (in general)* was ranked third in the second round. Additionally, an item *Other* was added to the ranking task to allow for additional topics to be ranked. An option to specify the “Other” was added as well. The stakeholders ranked the themes from highest to lowest importance.

The analysis of the ranking task was done in several steps. First, the overall ranking and rankings per stakeholder group were constructed using medians and interquartile ranges of the themes. Next, differences between the ranks were assessed for significance using the Mann-Whitney-Wilcoxon test. Here, the differences between 33% of the adjacently ranked themes (e.g., themes in second and third place) were not significant ($p > .05$; see Table 13).

The themes were grouped into three groups based on the relative position of the respective theme’s median in relation to the questionnaire’s interquartile range to increase the differences in the ranking. Themes with medians in the first quartile were grouped into high importance themes. Themes with medians in the interquartile range were grouped as medium importance themes. Themes with medians in the fourth quartile were grouped as low importance themes, as seen in Figure 5. The differences between groups were assessed with the Mann-Whitney-Wilcoxon test.

The third-round analysis assessed the agreement between stakeholder groups per theme using the Kruskal-Wallis test. Any disagreements were further explored with the pairwise Wilcoxon test with Bonferroni adjustment. The overall agreement between stakeholder groups was assessed using Kendall’s W coefficient of concordance (Moslem et al., 2019).

Finally, the stakeholders were encouraged to provide additional justifications, comments, or additional ideas. The comments were thematically analysed to identify any new patterns. This questionnaire concluded the rounds of questionnaires of this Delphi study. Thus, the third-round results are the final results, as presented in the next section.

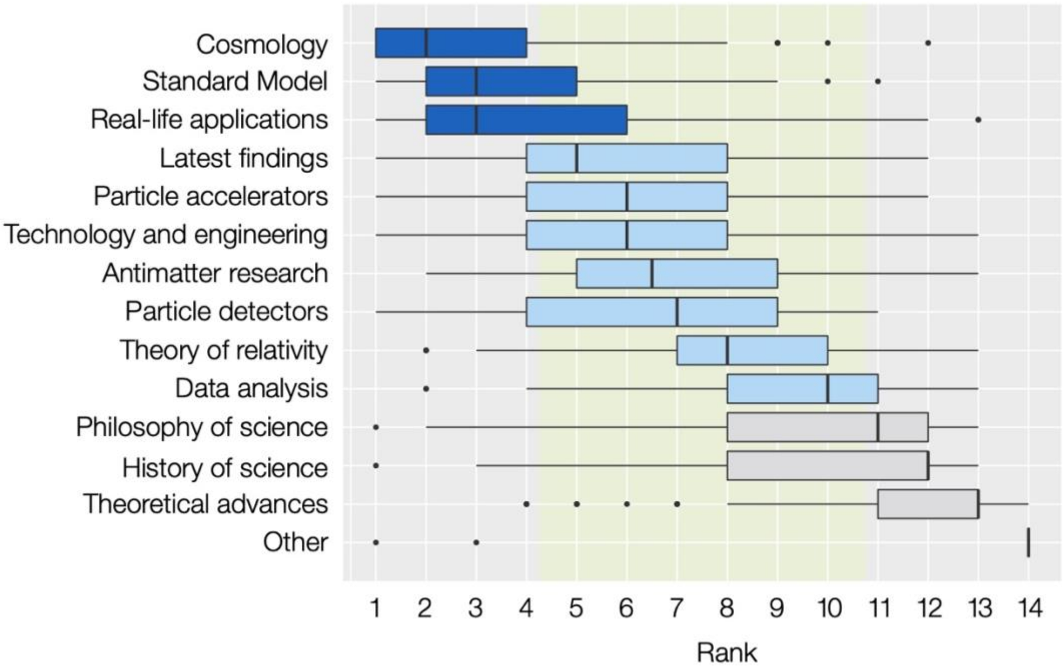


Figure 5. Boxplot of the overall rankings of 13 themes and 1 "other" option in the Delphi study. The yellow shaded area represents the interquartile range of all themes. This is used to differentiate between the high, medium, and low importance themes. Dark blue bars represent high importance themes, light blue bars represent medium importance themes, and grey bars represent low importance themes.

6.4 Results

Overall, 13 themes emerged from the three-round Delphi study on the most important topics in particle physics for high-school science teachers PDPs. The final themes and the results of the analysis are presented in Table 13. The stakeholders ranked the 13 themes and one additional item (*Other*) based on their perceived importance. The overall ranking was based on the medians and the interquartile ranges of the themes. Due to insignificant differences between a third of the themes, the themes were grouped into high, medium, and low importance, as shown in Figure 5. Ranking by individual stakeholder groups is shown in Appendix E. The Mann-Whitney-Wilcoxon test on the grouped themes showed significant differences between both high and medium, and medium and low importance groups ($W = 50860$, $p < .001$, and $W = 50860$, $p < .001$, respectively).

The themes ranked as "high importance" themes are *cosmology*, the *Standard Model of particle physics*, and *real-life applications of particle physics*. The themes ranked as "medium importance" themes are *experimental advances*, *technology in modern physics*, *particle accelerators*, *particle detectors*, *data analysis*, *antimatter research*, and *theory of relativity*. The themes ranked as "low importance" themes are *philosophy of science*, *history of science*, *theoretical advances*, and *other*.

Kendall's coefficient of concordance showed that the groups of stakeholders strongly agreed ($W = 0.87$) on the overall importance ranking of the themes. The analysis of agreement per theme with a Kruskal-Wallis test showed no statistically significant disagreements ($p > .05$) between stakeholder groups in 8 out of 14 themes, as shown in Table 12.

The themes for which the Kruskal-Wallis test showed significant disagreement were further analysed with a pairwise Wilcoxon test. First, research scientists ranked the *Standard Model of particle physics* significantly lower ($p = .010$) than physics education researchers. Research scientists ranked this topic as medium importance, while other stakeholder groups ranked it as high importance. Second, *country representatives ranked antimatter research significantly lower* than teachers ($p = .002$) and research scientists ($p = .03$). All stakeholder groups still ranked the topic within the medium importance group. Third, the country representatives ranked *computing and data analysis* significantly higher than in-service teachers ($p = .011$) and physics education researchers ($p = .012$). All stakeholder groups ranked the theme within the medium importance themes. Next, *history of science* was ranked significantly lower by research scientists than by physics education researchers ($p = .025$). Still, all stakeholder groups agreed that *history of science* should be ranked as a low importance theme. Last, the Kruskal-Wallis test showed significant disagreement for *real-life applications* ($p = .030$). However, the pairwise Wilcoxon test with Bonferroni adjustment found no significant pairwise disagreements ($p < .05$). In other words, no two stakeholder groups ranked *real-life applications* significantly differently. There could have been a difference between pairs of stakeholder groups (e.g., physics education researchers and teachers vs research scientists and country representatives). Nevertheless, this level of detail is not relevant for this study. Therefore, the difference was not further explored.

Additionally, stakeholders' comments were analysed. Two types of comments were recorded. First, the experts were invited to provide ideas for additional topics, denoted in the ranking task as *other*. Stakeholders suggested adding the following topics: (1) "research-based educational paths on the treated topics" by a physics education researcher, (2) "quantum physics" by another physics education researcher, (3) "gender and racial inequity of science" by a physics educations researcher, (4) "humanity of scientists and science, cooperative work, and internationality and peacebuilding aspect of scientific collaborations" by a research scientist, and (5) "ethics in science and technology" by a country representative.

Second, stakeholders added comments to explain their ranking. The first group of comments justified their ranking by how interesting the topics are for students. Here, a physics education researcher wrote that they ranked *cosmology* high as "space is one area where students tend to be more interested in than their teachers." In the second group of comments, stakeholders justified their ranking by how connected the topics are to curricula. For example, a physics education researcher mentioned that *cosmology* is connected to astronomy, which is "in the curricula of many countries." Similarly, another physics education researcher highlighted that "particle detection and acceleration can be explored as an application of electromagnetic forces, conservation laws etc." The third cluster comprised a comment that called for merging topics, namely "real-life applications and societal impacts of science." Last, five stakeholders highlighted that it was difficult to rank the topics. Indeed, one research scientist wrote that the topics were "almost impossible to rate; all of them must be included in the programmes." On the other hand, the physics education researcher called for "selecting maximum four topics for the concept appropriation by teachers."

Table 12. Statistical analysis of the third-round importance ranking task. The second column shows medians of each theme, where 1 means “most important” and 14 “least important”. The fourth column shows the significance of the disagreement between the stakeholder groups per respective theme. The last column shows significance ($p < .05$) of the differences between the adjacent themes in the ranking.

			Ranking	
Theme	**Median**	**Interquartile range**	**Kruskal-Wallis *(p-value)***	**Mann-Whitney-Wilcoxon (*p*)**
Cosmology	2	3	.439	
				.009**
Standard Model	3	3	.031*	
				.481
Real-life applications	3	4	.030*	
				.001**
Latest findings	5	4	.706	
				.206
Particle accelerators	6	4	.816	
				.868
Antimatter research	6	4	.003**	
				.030*
Technology&engineering	6.5	4	.274	
				.191
Particle detectors	7	5	.391	
				<.001**
Theory of relativity	8	3	.084	
				<.001**
Data analysis	10	3	.009**	
				.031*
Philosophy of science	11	4	.200	
				.017*
History of science	12	4	.046*	
				<.001**
Theoretical advances	13	2	.011*	
				<.001**
Other	14	0	.268	

*p < .05; **p < .01*

6.5 Summary and Discussion

The Delphi study on the stakeholders’ expectations regarding high-school teachers’ content knowledge (CK) in particle physics included four stakeholder groups: research scientists, physics education researchers, country representatives, and in-service high-school science teachers. The stakeholders provided their views on the topic through three rounds of questionnaires. The study results show strong agreement between the four stakeholder groups on which are the most important topics for particle physics professional development programmes (PDPs). In the following sections, the outcomes of the study are further discussed. Finally, some possible implications of the study on the field of physics education research are given. The role of the study within the whole research project is described in later chapters.

6.5.1 Most Important Topics in Particle Physics PDPs

The first research question asked: “Which particle physics content is perceived by the relevant stakeholders as the most important for teachers to learn about in PDPs in particle physics for in-service high-school science teachers?” Stakeholders identified 13 topics as important for high-school teachers to learn about in particle physics PDPs, as shown in Table 13. The three topics were ranked as most important to be included, namely *cosmology*, the *Standard Model of particle physics*, and *real-life applications*. In the following paragraphs, all topics from the Delphi study are discussed in light of previous research. A slightly stronger focus is given to the comparison to the study by Oettle (2021), as both studies investigated teachers' content knowledge in particle physics.

The biggest difference between this Delphi study and the study by Oettle (2021) is the overall focus of the topics. Here, the study by Oettle shows a stronger focus on theoretical particle physics, while this Delphi study also includes experimental particle physics. For example, as defined in this Delphi study, the *Standard Model of particle physics* is represented by four smaller topics in the Oettle study. Furthermore, Oettle included neither *particle accelerators*, *particle detectors*, nor *data analysis*, all of which are included in this Delphi study. This difference between the two studies reflects their individual biases. The Delphi study was conducted in the context of PDPs at CERN, the world’s largest particle physics research laboratory. Consequently, the results are somewhat biased towards experimental particle physics. Meanwhile, Oettle included mostly teachers and experts from universities. Here, the participants likely focused more strongly on the curricula. As the curricular review in Chapter 5 revealed that curricula generally focus more strongly on theoretical particle physics, so do the results of the Oettle study. However, the difference between the two studies does not mean that results of one study are more relevant than outcomes of the other. Rather, the outcomes of both studies need to be considered in their respective contexts. The same holds for all other PDPs. Each PDP needs to evaluate what their specific context can offer to teachers, what teachers need in their classrooms, and how to use those specifics to design authentic PDPs that are relevant to teachers.

While different in focus, the study by Oettle (2021) and this Delphi study agreed on two of the three highest-ranking topics, namely the *Standard Model of particle physics* and *cosmology*. However, *real-life applications of particle physics*, which were also ranked as a high importance topic in this study, did not appear in the Oettle study. Again, this difference likely comes down to the curricula. As seen in Chapter 5, concepts within the topics *Standard Model of particle physics* and *cosmology*, as defined in this study, were included in most reviewed curricula overall. Their high ranking in both studies is thus due to their strong connection to the curricula, as also mentioned by some of the stakeholders in this Delphi study. However, *real-life applications* were scarcely mentioned. Therefore, as the experts in the study by Oettle likely followed the curricula more and did not consider topics that do not appear in the curricula. In the following paragraphs, each of the three highest-ranked topics is discussed a bit more in detail.

First, *cosmology* was ranked as the most important topic. This result corroborates previous studies that argue that *cosmology* should be prominently featured in high-school physics curricula (e.g., Kragh, 2011; McLin & Cominsky, 2007). This suggestion seems to be enacted by the curricula. Indeed, the curricular review in Chapter 5 showed that cosmology is featured in most curricula regardless of their particle physics focus. Cosmology is likely featured in curricula so strongly due to its popularity with high school students (OECD, 2016; Sjøberg & Schreiner, 2012). Also, in this Delphi study, several stakeholders commented that *cosmology* is interesting to the students. Furthermore, several stakeholders noted that they ranked *cosmology* as a high importance topic due to its strong connection to another curricular topic, namely astronomy. Interestingly, the connection to astronomy was not explicitly included in the expert concept map in Chapter 4. However, the concept *Universe* is included in the map, which can act as an implicit connection to astronomy. Furthermore, *cosmology* is strongly connected to *theoretical particle physics* in the expert concept map. Therefore, it is not surprising that *cosmology* is also considered important for particle physics PDPs.

Second, the *Standard Model of particle physics* was ranked as one of the most important topics. The *Standard Model of particle physics* included teachers learning about fundamental interactions, charges, elementary particles, and interaction particles. The concept of the *Standard Model* has appeared in several studies with suggestions on how to introduce particle physics to students (e.g., Andrews & Nikolopoulos, 2018; Lindenau & Kobel, 2019; Polen, 2019; Woithe et al., 2017). The concepts within the *Standard Model of particle physics* are typically the ones included in explicit particle physics chapters in high-school physics curricula. Therefore, it is not surprising that this topic ranks high on the list. However, it is important to note that by itself, this topic is typically disconnected from all other topics. As such, students might find it difficult to build a complete understanding of particle physics and its role in science without better contextualisation. A stronger discussion on this requires connecting all three studies in this doctoral research project. Therefore, the disconnection and contextualisation are further discussed in Chapter 8.

Third, *real-life applications of particle physics* were also ranked as one of the most important topics for particle physics PDPs. Here, very few examples for introducing *real-life applications of particle physics* to high-school classrooms can be found in the literature (e.g., Schleicher et al., 2005; Strunk et al., 2018). Generally, *real-life applications of particle physics* are perceived more as context for introducing scientific ideas (e.g., Kobel, 2003). However, this does not reduce the value of teachers knowing about this topic. Indeed, connecting science to daily life has been recognised as an important feature of science teaching (Andrée, 2005) as students find connections to real-life situations useful (Irish & Kang, 2018). Especially in particle physics, including examples from everyday experience could help students and teachers to overcome the feeling of this intangible field of physics being too abstract. This has also been recognised by the stakeholders, as some noted that teaching about *real-life applications of particle physics* can help teachers answer the “why bother” and “where will I ever use this?” questions. Thus, this result calls for further research to allow for *real-life applications of particle physics* to enter real-life classrooms better.

Six topics in our Delphi study were grouped as medium importance topics, namely *particle accelerators*, *particle detectors*, *latest findings*, *technology in particle physics research*, *antimatter research*, and the *theory of relativity*. The great majority of these concepts can be considered as parts of experimental particle physics. This group of topics comes into contrast with *Standard Model of particle physics* and *cosmology* that are defined as more theoretical. Although the study had a strong CERN focus with several stakeholders being experts in experimental particle physics research, neither of the topics that aid learning about experimental particle physics is in the "high importance" group. Again, this ranking reflects the fact that stakeholders often perceived topics related to the curriculum as more important for teachers to enhance their knowledge about.

However, a strong connection to the curriculum does not always mean a higher importance ranking of the respective topics. Indeed, *philosophy* and *history of science* were both ranked as low importance topics, albeit both were mentioned in almost all curricula. Nevertheless, both *philosophy of science* and *history of science* enter the curricula either completely implicitly or as tools for teaching. Similarly, both take a more passive presence also in most previous studies. There, *history of science* is often considered more as context or a tool for teaching (Galili, 2008; Leone, 2014) rather than as explicit content. Likewise, *philosophy of science* is often included in the learning process merely implicitly rather than as an explicit concept (e.g., Abd-El-Khalick & Lederman, 2000; Duschl & Grandy, 2013). Neither of the topics was explicitly present in the expert concept map, shown in Chapter 4. Furthermore, two particle physics researchers and one research scientist in this Delphi study were sceptical in the comments regarding including the two topics in particle physics PDPs at all. Thus, including them as explicit content within PDPs can be perceived by stakeholders as out of place. Moreover, one physics education researcher voiced their concerns of *philosophy of science* and *history of science* not being made relevant to the teachers and just being introduced with "a lot of talking." Therefore, should particle physics PDPs include explicit content on *history of science* and *philosophy of science*, the PDP facilitators need to ensure that the content is made relevant to the teachers and their professional needs. At the same time, they need to provide them with all the necessary tools to convey the messages of *history* and *philosophy of science* to their students in a meaningful way.

Overall, the 13 topics that emerged from this Delphi study were very broadly defined. They act as anchors for future programme development but do not suffice for determining what teachers should learn. Future studies are needed to better define the syllabus for particle physics professional development programmes both at CERN and in other similar research institutions.

6.5.2 Differences and Similarities between the Different Groups of Stakeholders

The second research question was: Which differences and similarities can be identified between the expectations of the different stakeholder groups regarding high-school teachers' particle physics content knowledge (CK)? The differences and similarities between the different stakeholder groups on this topic have recently been assessed by a study by Oettle (2021). There, opinions of two stakeholder groups were compared, namely of high-school teachers and experts in particle physics, physics education, and outreach. The comparison of the two groups showed general agreement with some differences in four of the topics. Similarly, in this Delphi study, the opinions of four stakeholder groups were analysed, namely the research scientists, physics education researchers, country representatives, and teachers. In the analysis, special care was given to identifying the level of agreement between all groups together and pairwise. The results of this Delphi study show that all four participating stakeholder groups strongly agreed on the overall ranking of the 13 most important topics that teachers should learn in a particle physics PDP.

On closer inspection, no significant differences were found in 9 out of 13 topics even when the stakeholder groups were compared pairwise. Furthermore, only the *Standard Model of particle physics* would qualify as different levels of importance by a stakeholder group. Indeed, research scientists ranked the *Standard Model* as “medium importance,” while other stakeholders considered it to be a “high importance” topic. The lower-ranking by research scientists reflects the CERN-specific context of the study. Indeed, many research scientists in the Delphi study were experimental particle physicists working at CERN. Therefore, they prefer teachers at CERN to experience what they are less likely to experience in other PDPs, namely, to see and learn about experimental particle physics from people who work at CERN.

Indeed, the CERN context can be considered as a bias in this study. Three out of four groups of stakeholders were directly connected to CERN. First, as mentioned above, most research scientists worked at or in close connection to CERN. A great deal of them worked in experimental particle physics. Most research scientists were regularly involved in the facilitation of CERN’s teacher programmes. As such, research scientists were biased from the perspective of how CERN’s teacher programmes have been running so far. Many of them introduced teachers to particle accelerators, particle detectors, data analysis, and any other aspect of experimental particle physics with which they have personal experience. Furthermore, they are familiar with the types of activities that happen at CERN’s teacher programmes. Here, teachers' large source of interest are guided tours around several CERN’s facilities, e.g., detectors and accelerators. During those guided tours, teachers get to learn the working principles of different pieces of equipment. Therefore, research scientists expect teachers to learn more about the experimental research aspect than particle physics' theoretical aspect.

Similarly, the country representatives were representatives of CERN’s member and associate member states in CERN’s council. As such, they were familiar with the facilitation of teacher programmes and different types of activities teachers are offered during their time at CERN. Therefore, country representatives’ bias was similar to the bias of research scientists.

Last, teachers in this Delphi study either already participated or were selected to participate at a CERN’s PDP. Here, it is important to note that participating teachers were not only (going to be) affiliated with CERN but also highly motivated to learn about particle physics. Thus, they are not necessarily representative of the general teacher population. However, as the study aimed to discover the content of particle physics PDPs, it can be assumed that the content is aimed at motivated teachers such as the ones participating in the study.

Despite the close connection to CERN, both research scientists, country representatives, and teachers still agreed strongly with physics education researchers with little to no direct connections to CERN. Therefore, regardless of the CERN connections, the study can be generalised to PDPs at other particle physics research institutions. However, further studies are needed to determine how these topics need to be implemented into coherent and authentic PDPs.

This international Delphi study on particle physics topics in PDPs at large research institutions comprised over 100 experts from 42 countries. The participating stakeholders were diverse in expertise, backgrounds, nationalities, and home institutions. Their opinions provided a broader overview and a high heterogeneity of ideas. Through three rounds of questionnaires, the stakeholders showed high levels of agreement. Indeed, they agreed both on which topics should be included in particle physics PDPs and which topics are the most important to be included. Therefore, the results represent the complete hierarchy of the most important topics to be included in PDPs at particle physics laboratories.

7 PAIRWISE COMPARISONS

Overall, the three studies that were conducted within this doctoral project concluded with very promising results. These results, presented in Chapters 4-6, contributed greatly to the understanding of the expected particle physics content in high-school education. Specifically, their pairwise comparisons helped address the two research aims, stated in Chapter 3. The first research aim was to investigate how extensively do high-school physics curricula cover particle physics. Here, the answer can be found by comparing the outcomes of the first two studies, namely the expert concept mapping study and the curricular review. The second research aim was to explore what high-school teachers are expected to learn about particle physics. A deeper insight into this question is provided by comparing all three studies of this doctoral research project. In this chapter, the results of the pairwise comparison of the three studies are presented. The results are better discussed from the perspective of the research aims in Chapter 8.

7.1 Comparing the Expert Concept Map and the Curricular Review

The first aim of this doctoral research project was to determine how particle physics content of high-school physics curricula compares to experts' expectations on what high-school students should learn about particle physics. Here, the expectations of experts in particle physics and physics education on high-school students' knowledge of particle physics were investigated through the expert concept mapping study. The common particle physics content of high-school physics curricula was determined through a curricular review. In the curricular review, the frequency of individual concepts appearing in the reviewed curricula was determined. The concepts that appeared in more than half of the curricula are considered the study's main outcome.

Additionally, the curricula were grouped into two groups – explicit particle physics (EPP) curricula with an explicit particle physics chapter and implicit particle physics (IPP) curricula with no explicit particle physics chapter. The specifics of the two groups are explored as well. By comparing the two studies, the first research aim can be addressed.

The two studies were compared by mapping the results of the curricular review onto the expert concept map, as shown in Figure 6. Generally, the mapping was straightforward, as the concepts within the curricular review are based mostly on the expert concept map. Similarly, the grouping of the concepts into topics follows the hierarchy of the expert concept map. Thus, both topics and concepts in the curricular review generally match the concepts of the expert concept map (i.e., same name, same definition). Some concepts in the curricular review were added inductively based on the patterns in the curricula. Those concepts do not have a direct match in the curriculum. However, an indirect representation of such concepts can appear on the map as well. Overall, the differences and similarities between the two studies are described in the following paragraphs and discussed in Chapter 8.

Overall, 15 concepts and 11 topics appeared explicitly both in the expert concept map and in most high-school curricula. In other words, most curricula included 14% of concepts in the expert concept map. The strongest overlap was with the concepts from *other curricular topics*. These concepts accounted for 11 concepts and 6 topics from the overlap. The rest of the common curricular concepts and topics were closely connected to *theoretical particle physics*, e.g., *elementary particles* and *fundamental interactions*. Indeed, only curricula with an explicit particle physics chapter prominently featured an *experimental particle physics* concept *particle accelerators*.

The outcomes of each study included several concepts that were not included in the other study. First, most concepts in the expert concept map did not appear in most high-school curricula, as seen in Figure 6. The biggest part of the expert concept map with concepts that have not appeared in most curricula were concepts within *experimental particle physics* and *engineering*. This area included concepts such as *particle detectors*, *particle accelerators*, and *computing facilities*. Neither these three concepts nor the underlying concepts appeared in most curricula overall. The exception were curricula with an explicit particle physics chapter. Albeit most concepts mentioned above were still not included in most curricula with a particle physics chapter, the concept *particle accelerators* was mentioned in more than half of them.

Several concepts that stem primarily from *theoretical particle physics* in the expert concept map were also excluded from most curricula. For example, curricula generally did not include the *Standard Model of particle physics*, the *Brout-Englert-Higgs mechanism*, *Feynman diagrams*, and *quantum fields*. However, several of these concepts were included in curricula with an explicit particle physics chapter, e.g., the *Standard Model*, *electromagnetic*, *strong*, and *weak interaction*, *quarks*, and *antimatter research*. Neither of these concepts was prominent in curricula without an explicit particle physics chapter. On the other hand, one concept from the category *particle physics* of the curricular review appeared in more than half of the curricula without an explicit particle physics chapter and not in most curricula with an explicit particle physics chapter, namely the *Big Bang*.

While concepts from *other curricular topics* generally overlapped well between the two studies, several concepts from the expert concept map did not often appear in the reviewed curricula. These concepts are *cooling* within *thermodynamics*, *superconductivity* within *electromagnetism*, and *conservation of angular momentum* and *conservation of charge* within *conservation laws*. Very few differences between curricula with or without an explicit particle physics chapter were identified within *other curricular topics*. Here, curricula with an explicit particle physics chapter included the concept of *vacuum* and *relativistic motion*, both of which were not included in the curricula without an explicit particle physics chapter. On the other hand, *ionization* was not included in most curricula with an explicit particle physics focus.

Second, some concepts related to particle physics were identified in more than half of the reviewed curricula but were not included in the expert concept map. Neither of such concepts was from the category *particle physics*. Thus, none of the concepts that appeared only as a CCC or CCT in the curricular review and not in the expert concept map was an explicit particle physics concept. All such concepts were either part of the *Nature of Science*, *history of physics*, or *other curricular topics*.

Both the *Nature of Science* and *history of quantum physics* were mentioned in more than half reviewed curricula and not explicitly included in the expert concept map. However, the *Nature of Science* was implicitly present through several concepts in the expert concept map. The implicit mentions of the *Nature of Science* can be identified by using the definition of the Nature of Science. Following the definitions from the Osborne (2003) study, several concepts in the expert concept map can be considered as examples of the *Nature of Science*. Some examples of different aspects of the Nature of Science are presented in the next paragraph.

First, the "science and certainty" aspect was presented by the connection "*observations* disprove *theoretical particle physics*". Second, the "analysis and interpretation of data" was covered by *statistical tools*, *signal + background*, *data*, *analysis*, and *observations*. Next, "scientific method and critical testing" was again represented by *statistical tools* and *analysis*. Additionally, this aspect hid in concepts *predictions* and *observations*, and their connections to *theoretical* and *experimental particle physics*. "Science and questioning" entered the expert concept map already at the first hierarchical level with *human knowledge and curiosity*. Furthermore, this aspect was covered both by the many examples of *open questions in particle physics* and *hypothetical new elementary particles*, *hypothetical new interaction particles*, *hypothetical new composite particle systems*, and *hypothetical new fundamental interactions*. The concepts closely connected to *CERN* strongly represented the aspect of "cooperation and collaboration in the development of scientific knowledge." Some examples of these concepts are *personnel*, *international collaborations*, and *intergovernmental organization*, together with all their accompanying examples. "Science and technology" connected strongly with *engineering* in the expert concept map. However, "historical development of scientific knowledge," represented by a separate concept in the curricular review (i.e., *history of physics*), was not explicitly or implicitly featured in the expert concept map.

Several concepts and topics from *other curricular topics* appeared in more than half curricula and not in the expert concept map. First, the topic *gravity* and, more specifically, *Newtonian gravity* appeared in more than half of curricula overall. *Einsteinian gravity* was not prominent in none of the groups of curricula. Similarly, topic *radiation* was added, with *alpha*, *beta*, and *gamma radioactivity* and *radiation (in general)* appearing in most curricula. Within *thermodynamics*, the concept *particle model* was added and mentioned in more than half of the curricula. *Magnetic force* and *electromagnetic waves* were also prominent in curricula overall. At the same time, *ionization* appeared in most curricula without an explicit particle physics chapter. Last, while *quantum physics* was included in the expert concept map, it was expanded in the curricular review. The concepts *probability in quantum physics*, *atomic models*, *atomic energy levels*, and *quantum mechanics* appeared in more than half of curricula.

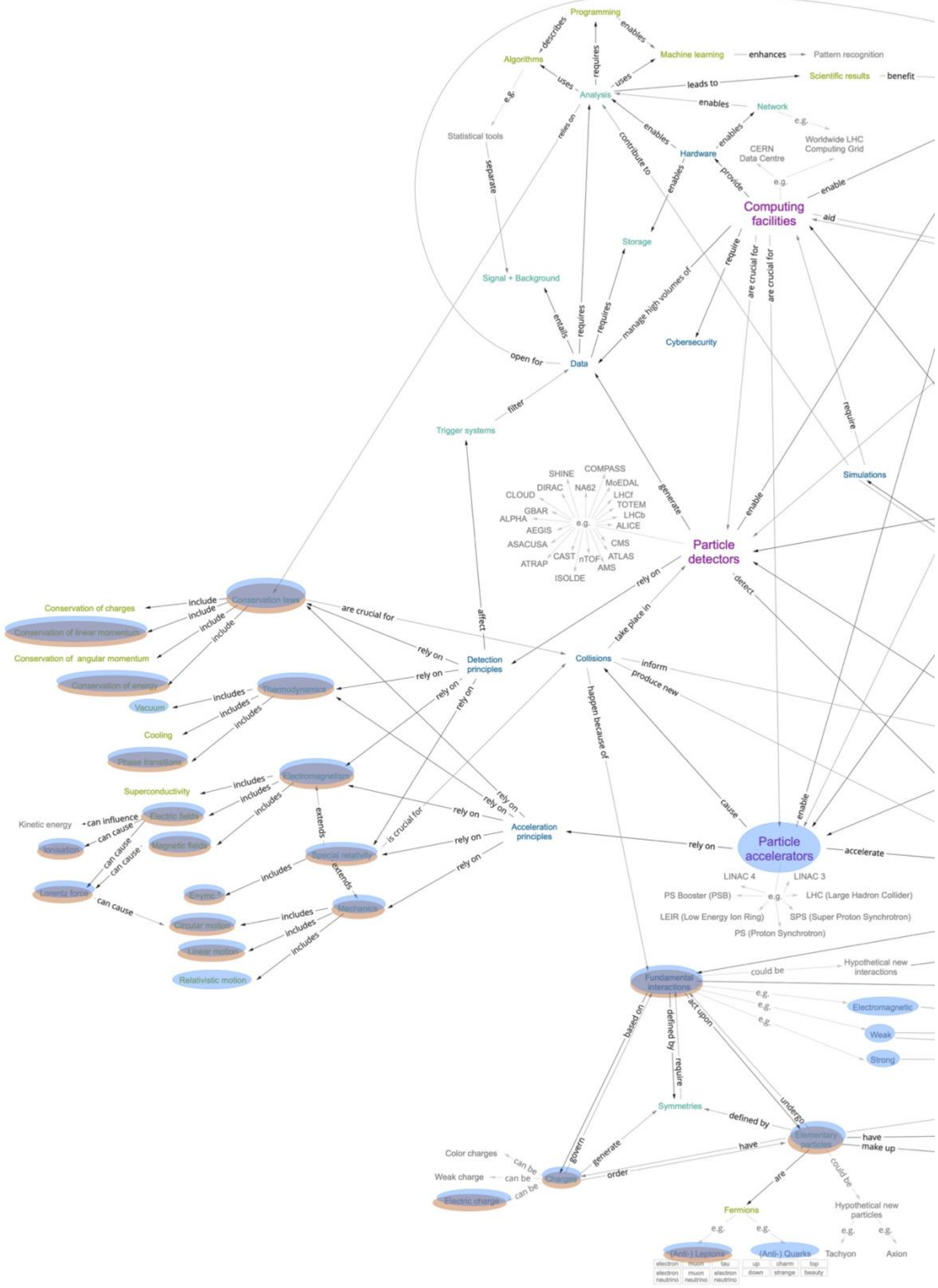


Figure 6. Comparison between the expert concept map and the outcomes of the curricular review. Concepts marked with yellow appear in most curricula without an explicit particle physics concept. Concepts marked with blue appear in most curricula with an explicit particle physics concept.

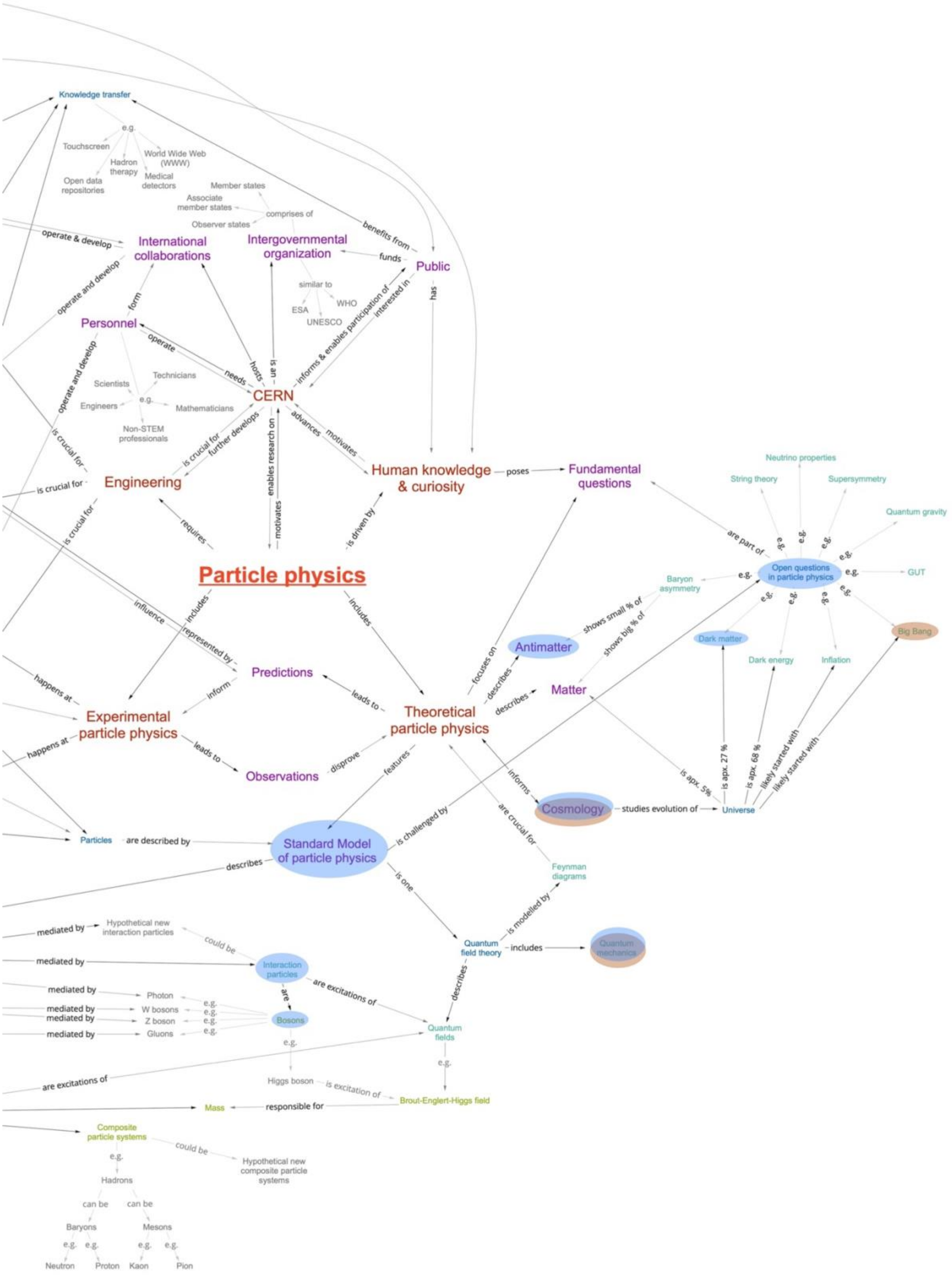


Figure 6 (continued).

7.2 Comparing the Curricular Review and the Delphi Study

The second aim of this doctoral research project was to use the outcomes of the three studies to identify which dimensions of content knowledge teachers are expected to enhance during their participation in a particle physics professional development programme. The dimensions of content knowledge that this research project investigates are school knowledge (SK), deeper school knowledge (DSK), and university knowledge (UK), as described in Chapter 2. Here, SK is typically defined by the curriculum (Enkrott et al., 2017; Kulgemeyer et al., 2020; Kulgemeyer & Riese, 2018). Therefore, SK was defined by comparing the outcomes of the Delphi study to the curricular review.

The outcomes of the Delphi study and the curricular review overlapped greatly. Indeed, several topics from the Delphi study had equivalents in the curricula. To sufficiently identify the overlaps, the definitions of the topics in the Delphi study, shown in Appendix D, needed to be considered. The following paragraphs describe the identification of similarities between the outcomes of the two studies. The similarities are structured based on the results of the Delphi study, grouping the topics by their perceived importance for particle physics professional development programmes.

First, the "high importance" topics from the Delphi study were *cosmology*, the *Standard Model*, and *real-life applications of particle physics*. *Cosmology* had a clear overlap with the curricular review. Indeed, *cosmology* as a topic appeared in most curricula overall regardless of whether they have an explicit particle physics chapter. On the other hand, the concept *Standard Model* was prominent only in curricula with an explicit particle physics chapter. However, the definition of the *Standard Model* in the Delphi study included elementary particles, fundamental interactions, and interactions particles. As these three concepts were included in most curricula overall, the two studies overlapped also within the concept *Standard Model*. On the other hand, the reviewed curricula scarcely mentioned *real-life applications of particle physics*.

Second, the "medium importance" topics from the Delphi study were *particle accelerators*, *particle detectors*, *technology and engineering*, *latest findings*, *antimatter research*, *data analysis*, and *theory of relativity*. Most curricula did not mention four of these topics, namely *particle detectors*, *technology and engineering*, *data analysis*, and the *latest findings*. Furthermore, these concepts were some of the least mentioned concepts in the curricula. Indeed, all appeared only in 4-7 curricula. *Particle accelerators* and *antimatter research* were also not present in more than half of curricula overall. However, these two concepts were both mentioned by most curricula with an explicit particle physics chapter. Only *theory of relativity*, specifically *special relativity*, was found in most of the curricula overall.

Last, the "low importance" topics in the Delphi study were *philosophy of science*, *history of science*, *theoretical advances*, and *other*. Curricula scarcely mentioned *theoretical advances*. Furthermore, all instances of *theoretical advances* appeared in the curricula with an explicit particle physics chapter. Still, this concept was not prominent in this subgroup of curricula as well. *History of science* appeared in most curricula as *history of quantum physics*.

Philosophy of science was not present in the curricula as such. However, the definition of *philosophy of science* in the Delphi study (see Appendix D) overlapped greatly with the definition of the *Nature of Science*. As such, *philosophy of science* was present in most reviewed curricula as well. An overwhelming majority of the stakeholders did not explicitly define any specific topics to stand in as *other*. Therefore, the overlap with the curricula was impossible to determine. However, some stakeholders suggested adding *quantum physics*, which was present in most curricula.

7.3 Comparing the Expert Concept Map and the Delphi Study

As the reader might recall, the second aim of this research project was to identify the different dimensions of content knowledge within the topics included in a particle physics professional development programme. The topics that are expected to be included in a particle physics professional development programme were defined through a Delphi study. In the previous section, the outcomes of the Delphi study were compared to the curricular review outcomes to identify the SK. In this section, the Delphi study results are compared to the expert concept map on particle physics. This expert concept map was created to identify what experts in particle physics and physics education expect high-school students to learn about particle physics. Furthermore, the map indicates the connections between different particle physics concepts and links to other curricular topics. Comparing the Delphi study and the expert concept map helps defining the deeper school knowledge (DSK).

Topics from the Delphi study were defined more broadly than individual concepts in the expert concept map. Therefore, several concepts from the expert concept map fell under the definition of topics of the Delphi study. By adhering to the definitions, the author defined the overlap of the two outcomes, as seen in Figure 7. In the paragraphs below, a short overview of the connections between topics and concepts is given.

First, *cosmology* was defined in the Delphi study as “learning about the beginning and development of the Universe.” In the expert concept map, this definition was reflected in *cosmology* and *Universe*, together with several examples of *open questions in particle physics*. These examples were the *Big Bang*, *inflation*, *dark matter* and *dark energy*, and *baryon asymmetry*. The concepts under *cosmology* connected directly to the Delphi topics *theoretical advances* and *antimatter research*.

Second, the topic *Standard Model* included learning about the Standard Model of particle physics, elementary particles and their properties, and fundamental interactions and their properties. Thus, this topic contained concepts like the *Standard Model*, *fundamental interactions*, *elementary particles*, *charges*, *symmetries*, *interaction particles*, *composite particle systems*, and the *Brout-Englert-Higgs field*. Consequently, all examples of these concepts were included in the identified overlap as well. The concepts that were included in the Delphi topic *Standard Model* connected directly to topics *particle accelerators*, *particle detectors*, and *theoretical advances*.

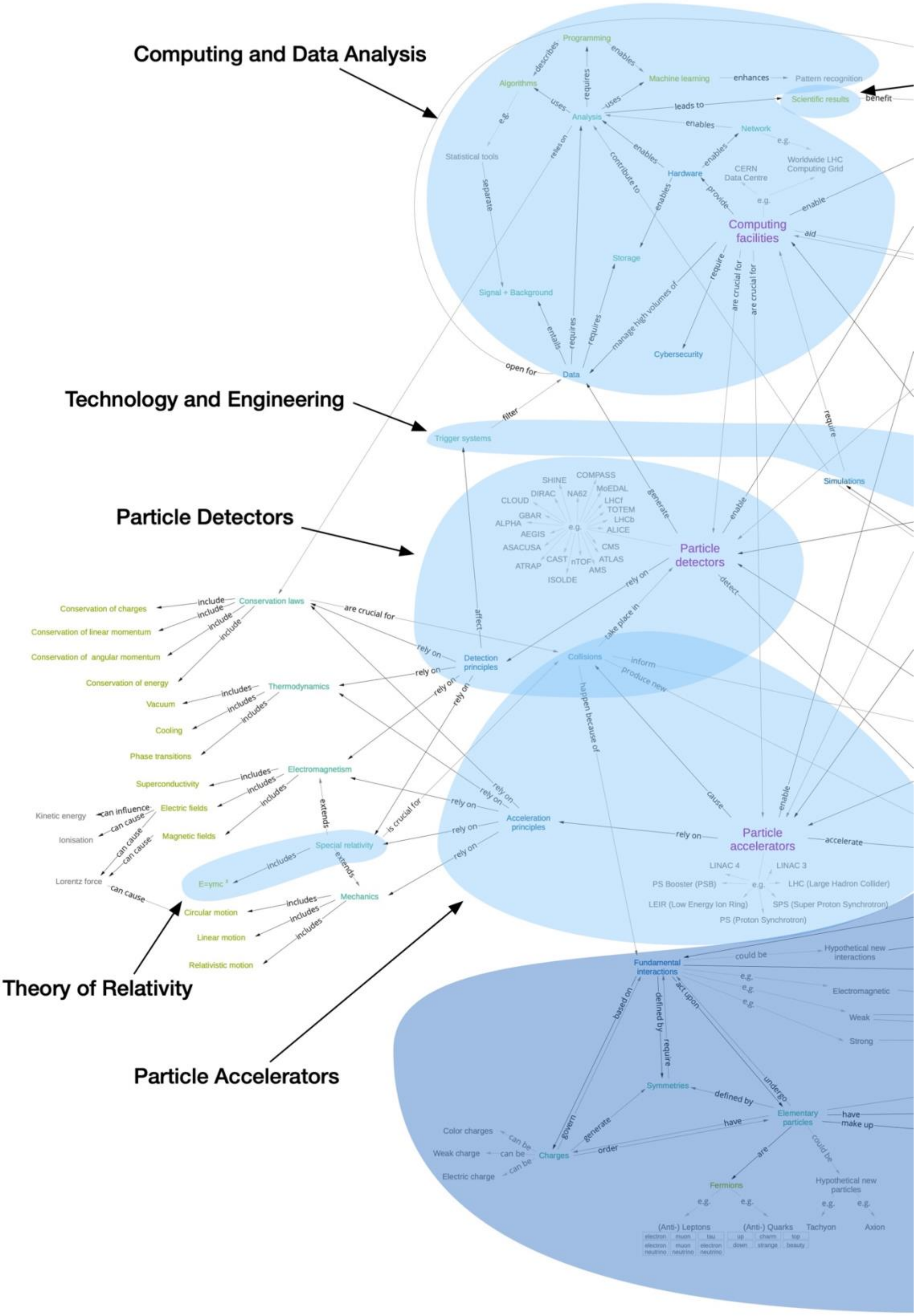


Figure 7. Comparison between the expert concept map and the Delphi study. The shaded areas represent different topics from the Delphi study. Dark blue areas represent high importance topics, light blue areas medium importance topics, and grey areas low importance topics.

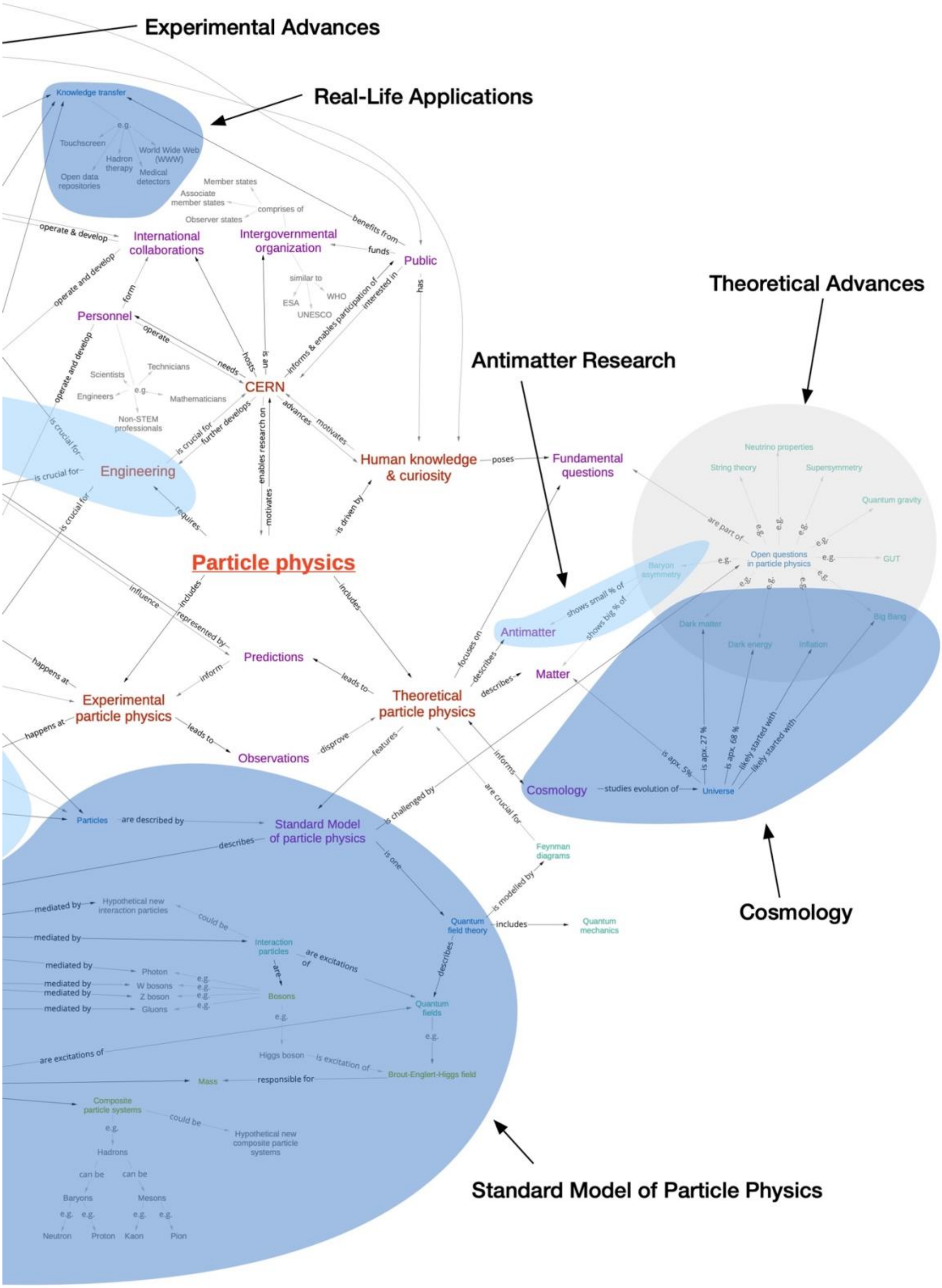


Figure 7 (continued).

Third, *real-life applications of particle physics* were represented in the expert concept map with the concept *knowledge transfer* and its examples. While only one concept was included in this topic, it was well connected to other topics. Indeed, the Delphi topics *particle accelerators*, *particle detectors*, and *computing and data analysis* all lead to *real-life particle physics applications.*

Next, *particle accelerators* included concepts *particle accelerators* and *acceleration principles* and various examples of particle accelerators at CERN. Similarly, *particle detectors* included *particle detectors*, *detection principles*, and examples of particle detectors at CERN. Both topics also included the concept of *collisions*. The two topics are thus strongly connected. Furthermore, both topics were well connected to Delphi topics *Standard Model*, *real-life particle physics applications*, *technology and engineering*, *computing and data analysis*, and the *theory of relativity*.

Technology and engineering were defined as learning about “technology and engineering that is being used in modern scientific research, e.g., material science, computing hardware.” As such, the following concepts in the expert concept map represented the topic *technology and engineering*: *engineering*, *hardware*, *vacuum*, *cooling*, *electric fields*, *magnetic fields*, and *superconductivity*. These concepts were not all directly connected. Rather, they appeared close to various other Delphi topics, like *particle detectors*, *particle accelerators*, and *computing and data analysis*.

Computing and data analysis included several concepts in the expert concept map: *computing facilities*, *network*, *trigger systems*, *data*, *analysis*, *storage*, *statistical tools*, *algorithms*, *programming*, *cybersecurity*, *machine learning*, and *pattern recognition*. These concepts were directly connected to Delphi topics *particle detectors*, *particle accelerators*, *technology and engineering*, *latest results*, and *real-life applications of particle physics*.

Next, *antimatter research* was represented by only three concepts: *antimatter*, *matter*, and *baryon asymmetry*. However, several examples of *antimatter* were also present under *elementary particles*, namely the *antiquarks* and *antileptons*. As such, *antimatter research* is strongly connected to the Delphi topics the *Standard Model of particle physics*, *theoretical advances*, and *cosmology*.

The *latest findings* were defined as the “newest results in experimental particle physics”. As such, they were found in the expert concept map as *scientific results* and *observations*. The two concepts were not directly connected. The only explicit connection to either of them was from the Delphi topic of *computing and data analysis*.

The *theory of relativity* was not considered an explicit particle physics topic. However, it was still considered important for high-school students and teachers to learn about in the context of particle physics. In the expert concept map, the *theory of relatvity* appeared as *special relativity*, *relativistic motion*, and $E = mc^2$. As such, the *theory of relativity* was directly connected to Delphi topics *particle accelerators* and *particle detectors*.

Next, *theoretical advances* were defined in the Delphi study as “advances in theoretical physics in describing the less-understood particle physics phenomena.” As such, *theoretical advances* appeared in the expert concept map as *open questions in particle physics* and the accompanying examples, e.g., *dark matter*, *dark energy*, *supersymmetry*, and *Grand Unifying Theory*. The *open questions* were strongly connected to the Delphi topics *Standard Model*, *antimatter research*, *cosmology*, and *philosophy of science*.

The Delphi study defined *philosophy of science* as “the process of scientific discovery, societal impacts, and collaboration and cooperation on the development of scientific knowledge.” As mentioned in the previous section, this definition strongly overlaps with the definition of the *Nature of Science* in the curricular review. Thus, the overlap of *philosophy of science* with the expert concept map was identical to the overlap of the map with the *Nature of Science*, described in Chapter 7.1. Therefore, the following concepts represented the *philosophy of science* in the expert concept map: *CERN*, *personnel*, *international collaborations*, *intergovernmental organization*, *public*, *predictions*, *observations*, *simulations*, *human knowledge and curiosity*, and *fundamental questions*. Additionally, all examples of these concepts were also included in *philosophy of science*. In the expert concept map, *philosophy of science* connected to the Delphi topics *particle detectors*, *particle accelerators*, *computing and data analysis*, *latest results*, *theoretical advances*, and *real-life particle physics applications*.

Last, *history of science* was defined as “historical developments of scientific knowledge and technology.” As such, this Delphi topic was not included in the expert concept map either explicitly or implicitly.

Overall, most concepts in the expert concept map were included in the Delphi study topics. Still, a few concepts were not included in any of the topics. First, the central concept *particle physics* and two first-level concepts, *experimental particle physics* and *theoretical particle physics*, were not included in any topics. Indeed, they were too broad to be assigned to any particular Delphi topic. Second, Delphi topics did not include the concepts that connect explicit particle physics concepts to other curricular topics, e.g., *mechanics* and *conservation laws*. These concepts were typically lower-level concepts that were well connected to the Delphi study topics.

8 DISCUSSION

In this doctoral research project, three studies were conducted and pairwise compared to address two research aims. In the previous chapter, the outcomes of the three studies were pairwise compared. In the following sections, these comparisons are discussed within the frame of the research aims and prior studies.

8.1 Research Aim 1: How Extensively do High-School Curricula Cover Particle Physics?

This doctoral research project's first aim was to explore how extensively high-school physics curricula cover particle physics. This research aim was addressed by comparing a representative selection of physics curricula to experts' expectations regarding what high-school students should learn about particle physics, as seen in Chapter 6.1. The comparison outcomes showed that experts expect high-school students to learn significantly more about particle physics than most curricula. Indeed, experts expect students' knowledge of particle physics to be broader than what is in high-school curricula. Furthermore, experts expect students' particle physics knowledge to be integrated as a context for their prior knowledge and real-life experiences.

Using particle physics as context for other curricular topics can increase students' interest in physics in general. The results of the Relevance of Science Education (ROSE) study showed that students are interested in spectacular things (Sjøberg & Schreiner, 2010). Certainly, many aspects of particle physics can be considered spectacular, for example, high energy collisions, enormous particle accelerators and detectors, and cosmic rays. Therefore, including particle physics as context for other topics can increase students' interest. Furthermore, several studies have shown that context has a bigger positive effect on students' interest than learning activity's content, task, or learning environment (Hoffmann et al., 1998; Sjøberg & Schreiner, 2012). Subsequently, increasing student interest can lead to higher achievement (M. M. Keller et al., 2017). Therefore, including particle physics as context for other topics can lead to students' higher understanding of both. Indeed, adding connections between concepts solidifies the role of both particle physics and other topics in students' conceptual networks (Ausubel, 2000).

In high-school curricula, explicit particle physics content mostly focused on fundamental interactions, elementary particles, interaction particles, charges, and cosmology. When compared to the expert concept map, these topics were generally disconnected from students' prior knowledge. As such, particle physics neither acts as a context for other topics nor is contextualised with prior knowledge. The disconnection between new concepts and students' prior knowledge can lead to rote learning (Ausubel, 2000). Indeed, modern physics topics such as particle physics have been criticised for encouraging rote learning (Michelini, 2021; Passon et al., 2018). Students could learn about particle physics more meaningfully if particle physics concepts were presented in relation to students' prior knowledge (Novak & Cañas, 2008). Therefore, bridging the gap between particle physics concepts in curricula and other curricular topics is necessary.

The expert concept map showed that prior knowledge can be connected to curricular particle physics concepts by introducing engineering and experimental particle physics concepts. For example, *thermodynamics* can be connected to *fundamental interactions* via *particle detectors* and the *Standard Model*. In the literature, experimental particle physics concepts were often used as context for other curricular topics. For example, Barradas-Solas (2007) and Kvita et al. (2019) connected particle detectors to radiation. Similarly, Wiener et al. (2016) linked particle accelerators to various topics such as energy, momentum, and oscillations. All three studies highlighted connections to theoretical particle physics as well. Likewise, even in curricula where experimental particle physics concepts appeared, they were usually introduced as context for *electromagnetism* or *mechanics*. Introducing experimental particle physics as context already helps students integrate some particle physics concepts into their cognitive network. For example, when *particle accelerators* are introduced as a context for *electromagnetism*, students connect new knowledge about *accelerators* to their existing knowledge of *electromagnetism* in their cognitive network. The concepts implemented in students' cognitive structure as context before can then act as anchors for the later introduction of the topic. As such, students can easier learn about the topic in a meaningful way by connecting new concepts to the previously learned anchors.

However, in most curricula, experimental particle physics or engineering concepts were neither included as content nor as context. This exclusion leaves a big gap between students' prior knowledge and the introduced theoretical particle physics concepts. Therefore, theoretical particle physics concepts are introduced in a stand-alone manner. As such, particle physics might appear as facts presenting *ready-made science*. Here, Park et al. (2019) note that physics in curricula and textbooks is mostly presented as “hardened facts with its making process erased” (p. 1078). Especially in modern science, this presentation could not be further from the truth. Modern science is constantly evolving, and new data continuously changes our understanding of the world around us. Therefore, including (modern) experimental methods and principles in teaching contemporary scientific topics could help students learn about *science-in-the-making* and, with it, the Nature of Science.

A deeper insight into the reviewed curricula showed one important distinction. Twelve curricula included an explicit particle physics chapter, and fifteen did not. Unsurprisingly, curricula with an explicit particle physics chapter introduced more particle physics concepts than curricula without such chapters. However, both types of curricula still generally focus on theoretical particle physics concepts. Both types cover *elementary particles*, *fundamental interactions*, *charges*, and *cosmology*. The presence of these concepts in most curricula without an explicit particle physics focus shows that particle physics can appear implicitly in curricula. There, particle physics is used as context for other curricular topics.

In addition to *elementary particles*, *fundamental interactions*, *charges*, and *cosmology,* curricula with an explicit particle physics chapter also cover the *Standard Model of particle physics*, *interaction particles*, *antimatter research*, and *particle accelerators*. Again, most concepts fall under theoretical particle physics. Only *particle accelerators* represented experimental particle physics. Still, concepts in the expert concept map were well connected. Therefore, even just one concept from experimental particle physics connected theoretical particle physics to most other curricular topics. For example, *particle accelerators* connected the *Standard Model* to *mechanics*, *special relativity*, *electromagnetism*, *thermodynamics*, and *conservation laws*. Adding more experimental particle physics and engineering concepts further strengthens this connection and makes learning more meaningful. However, in many curricula, *particle accelerators* were only mentioned as a context in electromagnetism. Indeed, *particle accelerators* were not mentioned together with other particle physics concepts. Therefore, teachers should ensure that *particle accelerators* also connect to other concepts in particle physics through their teaching. Students might not be able to form this connection themselves without explicitly specifying it, especially as *particle accelerators* are typically only used as context.

Curricula leaving out experimental physics leads to students’ weak understanding of the role of experiments in science (Angell et al., 2004). Furthermore, Wilcox and Lewandowski (2017) found that students' ideas about the nature of experimental physics are inconsistent with those of practising physics. For example, most students think that confirming previously known results is the main goal of doing experiments. Explicitly including aspects of experimental physics in curricula could help change this conception. Indeed, in the expert concept map, aspects of experimental particle physics are featured as prime examples of the Nature of Science, specifically the empirical bases, creativity, and observation and interference. Therefore, by bridging the gap between prior knowledge and curricular particle physics concepts students can also understand the Nature of Science better. However, further studies are required to define better the activities that best support student learning of experimental physics. Indeed, well-defined activities that are suited to be implemented directly in the classroom can appeal to a broader spectrum of teachers and increase the chances of the new context entering high-school classrooms more often.

Understanding the Nature of Science is considered at the core of scientific literacy (American Association for the Advancement of Science, 1994). Previous research shows that the Nature of Science is best taught explicitly (Lederman, 2013). However, most reviewed curricula only include the Nature of Science implicitly. For example, the Austrian high-school physics curriculum explicitly states understanding the Nature of Science as an overall goal. Still, it does not include the Nature of Science as explicit content to be taught. Similarly, studies have shown that most textbooks also only include the Nature of Science implicitly (e.g., Campanile et al., 2015; McDonald, 2017). Furthermore, teachers have been found to avoid teaching the Nature of Science due to gaps in their professional knowledge, perceived irrelevance for students' learning, or time restrictions by the curriculum (Abd-El-Khalick et al., 1998; Dunlop & Veneu, 2019; Galili & Hazan, 2001; Henke & Höttecke, 2015).

Therefore, teaching about the Nature of Science often remains implicit. Thanks to its rooting in fundamental research, contemporary physics presents itself as a good example for introducing the Nature of Science. Studies by Park et al. (2019) and Wong et al. (2009) showed that modern physics topics are well-suited for introducing scientific practices. Indeed, contemporary physics topics are prime examples of science in the making, which makes the Nature of Science more apparent. For instance, Stadermann and Goedhart (2021) and Stadermann et al. (2019) showed that many Nature of Science concepts are linked to the content of quantum physics in high-school curricula. Similarly, particle physics offers a great opportunity for introducing the Nature of Science in classrooms. The analysis of the expert concept map on particle physics in light of the results of the curricular review in Chapter 6.1 showed that the Nature of Science is deeply embedded in particle physics. Many of the concepts and links between concepts reflect various aspects of the Nature of Science.

One concept that appeared in most curricula but not in the expert concept map – neither implicitly nor explicitly – is *the history of science*. By some definitions, *the history of science* is a part of the Nature of Science (e.g., Osborne et al., 2003). Others say that *history of science* is a tool for teaching (Galili, 2008; Leone, 2014). Likely, it is a combination of both. Williams and Rudge (2019) found that using *the history of science* in teaching is a powerful strategy for teaching the Nature of Science. Still, the expert concept mapping study does not include any concepts related to the *history of science* in the expert concept map on particle physics. The lack of *history of science* in the expert concept map suggests that the experts do not consider this topic as part of the knowledge students should obtain to understand particle physics. Instead, the experts likely consider *the history of science* as a context for teaching rather than explicit content. Further research is needed to determine to which extent and which parts of *the history of science* are relevant and useful for supporting meaningful learning.

Overall, most curricula omit the opportunity to discuss the future of physics research. Indeed, only curricula with an explicit particle physics chapter touch upon dark matter as the only example of open questions. At the same time, open questions are prominently featured in the expert concept map. Indeed, the experts expect students to learn about various open questions in physics. This notion corroborates previous studies showing that learning about unsolved problems can provide meaningful learning opportunities (Bennett & Hogarth, 2009; Bungum et al., 2018; Levrini & Fantini, 2013). Furthermore, open questions in physics can be used as context for learning about the tentative Nature of Science. Albeit useful to students, open questions remain outside official curricula, and it is unlikely that teachers introduce them themselves. Indeed, teachers in Dunlop and Veneu (2019) study considered teaching "the facts" most important. Open questions are far from being facts – they are, as the name says, questions. Additionally, teachers frequently report that they already often run out of time for "facts." Therefore, curricula should be updated to include the concepts that are currently excluded.

The updates of state, national, and international curricula reflect on multiple generations of students in the respective region. Therefore, all updates need to be supported by research findings and enable teachers to introduce and students to learn new content in a meaningful way. Furthermore, any updates to the curricula should account for students' interests. Indeed, curricula that include interesting content and context better integrate new concepts in students' cognitive structures (Häussler & Hoffmann, 2000). However, curricula are limited by the allotted time, resources that the educational system and individual schools can work with, teacher professional knowledge, and students' prior knowledge. All these limitations make the design and update process of curricula a complex process. The complexity of this process results in curricula changing and updating very slowly. While the rigidity of the intended curricula enabled the curricular review in Chapter 5, it prevents intended curricula from quickly responding to new findings in science and science education. Furthermore, changes in the intended curricula do not always reflect in teaching (Boesen et al., 2014). Therefore, motivating teachers to introduce particle physics as either explicit content or context for other curricular topics might be the fastest way to introduce particle physics in the classroom.

Teacher motivation is only partially responsible for positive student outcomes (Keller et al., 2017). Teachers also need sufficient professional knowledge to enhance student achievement. This requirement circles back to teacher professional development as a crucial part of educational reforms (Borko, 2004; Corcoran, 1995; Garet et al., 2001; OECD, 2019). Indeed, teachers' professional knowledge is connected to the level of curricular enactment (Son & Kim, 2016). However, external limitations often limit teachers in adding new topics either as content or context to their enacted curriculum (Ertmer, 1999). Therefore, further studies are needed to explore if teachers' professional development influences the integration of new topics either as content or context. Furthermore, the support teachers need to contextualise the existing curriculum with more contemporary topics should be better determined. Defining the necessary support will enable more efficient professional development and teaching resources.

8.2 Research Aim 2: What Should Teachers Learn About Particle Physics?

This doctoral research project's second aim was to identify which aspects of content knowledge (CK) are teachers expected to enhance through their participation in particle physics PDPs. The Delphi study has explored the content areas relevant to particle physics professional development programmes described in Chapter 6. In Chapter 7, the Delphi study was compared to the outcomes of the curricular review and the expert concept map. These comparisons reveal that teachers are expected to learn about more than just the curricular topics. Furthermore, comparing the three studies helped address the second research aim and identify the different aspects of content knowledge. The two aspects described in the paragraphs below are school knowledge (SK) and deeper school knowledge (DSK). As described below, identifying which aspects stakeholders expect teachers to enhance most will help better tailor future particle physics professional development programmes.

Identification of the different aspects of CK requires clear definitions of the aspects. First, SK reflects the expected knowledge that good students achieve, typically defined by the curriculum and the school textbooks (Enkrott et al., 2017; Kulgemeyer et al., 2020; Kulgemeyer & Riese, 2018). Second, DSK describes the knowledge of handling tasks and models from different perspectives, knowing their limitations, and connecting SK concepts both among each other and to other physical concepts (Kulgemeyer et al., 2020; Riese, 2009; Riese et al., 2015). However, it becomes increasingly difficult to differentiate between the two aspects based on these definitions when focusing on a single content area. Here, concepts can be included in the curriculum and, at the same time, represent a connection between the topic and a different physical phenomenon. The same concepts thus constitute both SK and DSK.

One such example is the *theory of relativity*. This concept appears both in the outcomes of the Delphi study and the curricular review. As such, *the theory of relativity* can be considered to constitute SK. Nevertheless, the *theory of relativity* is not an explicit particle physics concept. In fact, in most curricula, *the theory of relativity* and particle physics are a part of different chapters. As such, *the theory of relativity* can be considered DSK within the particle physics context, although it is included in the curriculum.

Therefore, the definitions of SK and DSK were updated to reflect the specifics of this research project. First, SK in a specific content area was redefined as expected knowledge that good students achieve within the content area, typically defined by the curriculum and the school textbooks. For example, the *Standard Model of particle physics* is an explicit particle physics concept and thus constitutes particle physics SK. Second, DSK in a specific content area is represented by connections between explicit concepts within the content area (namely SK concepts) and other physical phenomena. For example, the *theory of relativity* is not an explicit particle physics concept. However, it connects to explicit particle physics concepts. Therefore, the *theory of relativity* is a DSK concept. However, DSK still also constitutes skilful problem solving and identification of model limitations (Kulgemeyer et al., 2020; Riese, 2009; Riese et al., 2015). The SK and DSK within the topics teachers are expected to learn through particle physics PDPs can be identified using the updated definitions.

The SK topics that teachers are expected to enhance were identified by comparing outcomes of the Delphi study and the curricular review. The outcome of this comparison shows that teachers' knowledge is expected to go beyond the curricula content. This finding supports previous claims that teachers' knowledge needs to go beyond SK (Grossman, 1990; Shulman, 1986, 1987; Tchoshanov, 2011; Wenning et al., 2011). Moreover, PDPs are expected to help teachers enhance their knowledge beyond the curricula as well. This knowledge can help teachers better contextualise curricular particle physics. Indeed, in the previous section, the need for building context in classrooms was discussed. For teachers to contextualise a content area, such as particle physics, their knowledge needs to reach beyond what students are expected to learn according to the respective curricula.

Several shared topics appeared in the Delphi study and most curricula, as shown in Chapter 6.2. These topics were the *Standard Model*, *cosmology*, the *theory of relativity*, *philosophy of science*, and *history of physics*. However, only the *Standard Model* and *cosmology* are explicit particle physics topics. As such, the two topics constitute SK by the updated definition when considering all reviewed curricula. Furthermore, the *Standard Model* and *cosmology* include all explicit particle physics concepts that have been identified in most curricula overall. In other words, teachers are expected to enhance their knowledge about all explicit particle physics concepts that appeared in most reviewed curricula – and more.

The *Standard Model* and *cosmology* ranked as high importance topics for inclusion in particle physics PDPs. The high importance of these two topics means that stakeholders put a stronger emphasis on the topics that students are expected to learn. Thus, particle physics PDPs are expected in the first place to enhance teachers' knowledge of the *Standard Model* and *cosmology* to a more expert level. However, this does not necessarily mean teachers need only to enhance their university knowledge (UK). Although UK is considered more complex and expert-like, in-service teachers shift to mostly using SK in their teaching in the first 15 years of practice (Arzi & White, 2008; Wheeldon et al., 2012). At that time, UK is not that important anymore. Therefore, enhancing their SK is more useful for experienced teachers as it is directly applicable to their teaching situations.

Two additional topics constituted SK when focusing on curricula with an explicit particle physics chapter, namely *antimatter research* and *particle accelerators*. A bigger number of topics considered as SK sheds light on an important point. In this project, the topics that teachers are expected to learn are classified as different aspects of teachers’ CK based on the outcomes of the curricular review. However, individual curricula could differ significantly from the average of all curricula. What constitutes SK in one educational system is not always considered SK in a different system. For example, *cosmology* is present in the Croatian curriculum, while the Serbian curriculum omits this topic completely. Therefore, *cosmology* constitutes Croatian teachers' SK but does not constitute Serbian teachers' SK. The SK topics, as defined in this chapter, are therefore not the same for all countries. These differences between curricula have direct consequences for PDPs, especially CERN's national teacher programmes. As described in Chapter 2, CERN's national teacher programmes are aimed at teachers from individual countries. Here, teachers from the same country participate in a particle physics PDP in their language and, ideally, focused on their needs. Typically, teachers’ needs are, at least partially, defined by their respective curricula. However, each state or national curriculum likely differs from what the results of the curricular review show. As such, teachers’ SK can differ significantly from SK described in this chapter. Therefore, CERN's national teacher programmes and their facilitators should use the results of this research project as a guideline for addressing the most important topics. Following the example above, Croatian teachers should learn about *cosmology* from the perspective of how and what students should learn about this topic. On the other hand, Serbian teachers might wish to enhance their knowledge on how *cosmology* can connect to other topics in a meaningful way.

History of science and *philosophy of science* were both mentioned in both the Delphi study and most curricula. However, they cannot necessarily be classified purely as SK or CK. According to the Schwartz and Lederman (2002) definition of teachers’ professional knowledge, both *philosophy* and *history of physics* are included in the knowledge of the Nature of Science (NOSk). By their definition, NOSk is an individual dimension of professional knowledge. While it is defined as separate from CK, the two dimensions overlap. Thus, *philosophy* and *history of science* extend into CK as well. Here, *history of science* connects explicitly to particle physics through historical overviews of particle physics discoveries. As such, *the history of science* is an SK component as defined in this project.

On the other hand, *philosophy of science* is not explicitly implemented in the curricula, as discussed in the previous chapter. Therefore, it cannot be considered an SK topic by the definition used in this project. Similarly, the expert concept map does not include *philosophy of science* explicitly. However, *philosophy of science* is reflected in several concepts and connections between them. As such, *philosophy of science* constitutes DSK.

As described above, deeper school knowledge (DSK) in a specific content area is represented by connections between explicit concepts within the content area and other physical phenomena. The DSK topics that teachers are expected to learn more about were identified by comparing outcomes of the Delphi study and the expert concept map on particle physics. There, DSK topics are those that are directly connected to the SK topics. As such, these topics provide a connection between curricular concepts and other physical phenomena. For example, concepts within the *Standard model* are directly connected to concepts within *particle detectors*, *particle accelerators*, and *theoretical advances*. As the last three topics are not in most curricula, they generally do not constitute SK. Hence, the comparison of the two studies shows that what stakeholders expect teachers to learn about particle physics overlaps greatly with what experts expect students to know, as shown in Chapter 6.3.

Most topics that teachers are expected to learn about are generally very well connected. Here, all but two topics are explicitly present in the expert concept map. One of the remaining two topics, namely *philosophy of science*, is present in the map implicitly. *History of science* is the only topic from the Delphi study that does not appear in the expert concept map. All other topics are connected to at least two topics directly – even the SK topics. This connectedness shows the importance of DSK and building a strong and well-interconnected knowledge framework. Furthermore, it shows that even the SK topics have a DSK component, allowing them to connect in a knowledge framework. Indeed, building a good content knowledge framework helps teachers understand the content area better and transform content knowledge into pedagogical content knowledge (Bruner & Lufburrow, 1963). By knowing the connections between different concepts and topics, teachers can better determine the most powerful analogies and the most useful context for the content to be taught. As such, teachers can balance between the intended curriculum and experts' expectations regarding what high-school students should know about particle physics.

All topics in the Delphi study outcomes were classified as either SK or DSK. In other words, there were no topics in the Delphi study that were either classified as UK or unclassifiable. The lack of purely UK topics is not surprising. Indeed, the learning goals part of the Delphi study already showed that stakeholders perceive teachers' UK to be of lesser importance (Kranjc Horvat et al., 2021). Even so, these outcomes do not mean that PDPs should steer away from enhancing teachers' UK completely. Classifying the topics into SK and DSK does not exclude the possibility that these topics include some concepts or explanations at the university level. Further studies are needed to identify the full syllabus for particle physics PDPs. At that level, this will allow further disambiguation between different aspects of CK.

Identifying different aspects of knowledge within teachers' expected CK will help further the development of PDPs, e.g., CERN's teacher programmes. The outcomes of this research project suggest that these programmes should focus strongly on enhancing both SK and DSK. First, the programmes need to address all topics included in the relevant content area of the curriculum to increase teachers' SK. For example, future CERN Slovenian teacher programmes should focus on the *Standard Model of particle physics*, *antimatter research*, and *particle accelerators*. These topics need to be re-introduced to teachers by including possible activities, problems, and classroom resources. These topics should also be used as an anchor for DSK topics. Indeed, DSK topics should be addressed as connections between students' prior knowledge and the main content. Focusing on their role as DSK topics will allow teachers to understand better their role as bridges in their and their students' knowledge. At the same time, these topics can be introduced as the context for the main content. For example, future CERN Croatian teacher programmes can benefit from showing teachers how to use examples from *real-life applications of particle physics* as the context for *particle accelerators*. The connection between everyday physics and fundamental research also gives way to a meaningful discussion of *philosophy of science*. As such, *philosophy of science* can be more explicitly addressed both in a PDP and, later, in classrooms. Knowing which aspects of teachers' CK a programme should focus on thus extends beyond the content discussed in this section.

The outcomes of this doctoral research project provide strong guidelines for further implementation of particle physics in high-school student and teacher education. However, these guidelines expand beyond the limitations of particle physics. The constant development of science in all fields leads to many contemporary topics that are not yet well integrated into curricula, for example, genetics, nanotechnology, and global warming. These topics are parts of everyday conversations as they enter the lives of millions of people through various media sources, fiction, and politics. As such, it is important that these topics are already introduced in high-school classrooms. By using the methods used in this doctoral research project, connections to the existing curricula can be more easily identified. Teachers can then use these connections as ways to introduce the topic as context. Introducing a new topic as an example for multiple other curricular topics slowly builds students' understanding of the topic. However, such introduction requires sufficient teachers' CK. Therefore, professional development programmes aiming to introduce teachers to new topics should show teachers what they need to teach about the topic and how this connects to other curricular topics. With this knowledge, teachers can best support students' meaningful learning about topics beyond the curriculum.

8.3 Strengths, Limitations, and Future Studies

Overall, this doctoral research project provides a springboard for further updates and implementations of particle physics into high-school student and teacher education. The findings of the project connect previous research on this topic into a strongly connected network. The project included three large international studies. The studies combined over 150 experts from more than 50 countries, including experts from all seven populated continents. The experts that participated in either of the three studies covered a wide range of expertise, including particle physics, physics education, and physics education research. Previous suggestions in the literature typically focused on introducing students and teachers to a smaller number of concepts within particle physics (e.g., Andrews & Nikolopoulos, 2018; Atkin, 2019; Barradas-Solas, 2007). This research project reviewed the current state of particle physics in high-school education and provided suggestions for expanding the particle physics content in classrooms. By looking at the high-school particle physics content from three very different angles, this research project provides a multi-faceted account of the most important concepts and topics in particle physics education. The comparison of the three studies shows that experts' expectations regarding students' and teachers' particle physics learning are very consistent. Furthermore, the results of the two studies repeat most of the ideas previously identified in other studies (e.g., Barradas-Solas, 2007; Lindenau & Kobel, 2019; Wiener et al., 2016). However, the high-school physics curricula, in general, remain far from the desired outcome. Combining the three studies better frames future developments to provide high-school students and teachers with a better overview of particle physics.

Finally, several potential limitations need to be considered. First, the curricular review included only a very limited selection of curricula. Indeed, only physics curricula of high schools preparing students for university studies were included in the study. Additionally, in countries like Serbia and Croatia, only the science-oriented curricula were reviewed. Such selection of the curricula was purposeful to include only the curricula with maximum particle physics content in each country. Likewise, no differentiation between obligatory and elective concepts was made to only account for the "ideal" scenario with the broadest particle physics scope. A better overview of how particle physics can be included in the curricula was provided by only focusing on these curricula. However, this limitation leaves way for future research on a broader selection of curricula, including curricula of other high-school types (e.g., technical high schools) and other school subjects (e.g., med). Furthermore, the curricular review only included information on the official curricula provided by the governing bodies of the respective educational systems. Research shows that the prescribed curricula do not necessarily directly reflect in the classroom (Ziebell & Clarke, 2018). Therefore, further investigation is needed to identify how teachers' instructional practices correspond to the official curriculum. Such investigation could also provide a better overview of the way different context enters teachers' instructional practices.

Second, only two aspects of teachers’ content knowledge were considered: school knowledge (SK) and deeper school knowledge (DSK). University knowledge (UK) was not explored in this doctoral research project. This is partially due to difficulties in identifying representative university curricula. Indeed, university curricula are typically set by individual professors and not by states, governments, or universities. Furthermore, particle physics can be introduced at the university level through several different courses. Therefore, multiple particle physics curricula can exist at each university. Moreover, not all teachers necessarily hold the same level of qualification, even from the same country. As such, an international review of university curricula to identify aspects of university knowledge would be very ambitious. However, a similar project on a national level would be easier to conduct, considering the obstacles in reviewing university curricula. Such a study on a smaller, national scale would provide a more specific view of the aspects, which would be less generalisable. Still, it would show a better insight into if and how much teachers are expected to enhance their UK through their participation in PDPs.

Next, topics that emerged from the Delphi study are broad compared to concepts included in the other two studies. Here, a more detailed syllabus would provide a better insight into how the different aspects of teachers' CK are integrated within each topic. Indeed, each topic could include hints of other aspects in addition to the one it was assigned in this study. For example, in this research project, the *Standard Model of particle physics* has been identified as SK. At the same time, this topic can also be described with very complex mathematical descriptions and concepts beyond high-school curricula. As such, a component of the topics *Standard Model of particle physics* can be considered UK. Therefore, future studies of different CK aspects within the syllabus would provide a better insight into the interplay of the aspects within each topic. Consequently, a better understanding of teachers' CK can be achieved.

Another limitation of the Delphi study is the lack of a clear definition of what "important" means. As the stakeholders ranked the topics based on how important they perceived them, they had their specific criteria for what makes a topic important. Several stakeholders already mentioned that they perceive topics connected to the curricula and CERN as more important in the comments. However, the two mentioned characteristics of more important topics cannot fully explain the ranking. Future research exploring stakeholders' personal constructs behind the word "important" in this context could offer a better insight into how specific topics are made important for teacher and student education.

All three studies in this research project focused strongly on the content of particle physics education. However, designing successful learning interventions requires more than structuring the content knowledge base. Both in high-school education and PDPs, the activities that support content learning carry significant importance in the learning process. Here, an initial study on activities in PDPs at CERN has already been conducted. Indeed, a part of the Delphi study investigated stakeholders' expectations regarding which activities should be included in CERN's teacher programmes. The final ranked list of the suggested activities can be found in Appendix A. These results can be generalised to some extent to high-school education. Indeed, research shows that activities in PDPs model the expected teachers' instructional practice (Guskey, 2003; Van Driel & Berry, 2012). As such, teachers would more likely use similar activities to convey the topics in the classroom as they experienced during their participation in PDPs. Still, further work is required to identify which activities fit best with the content in high schools. Specifically, future studies should continue investigating how particle physics can be a context for the Nature of Science and other curricular topics. Furthermore, future studies on particle physics as context should consider the connectedness of individual particle physics concepts to others. For example, suppose *particle detectors* are used as context for *ionisation*. In that case, researchers should consider how *particle detectors* connect to *particle accelerators*, the *Standard Model*, or *cosmology*. Such explicit connections can help teachers to support students' meaningful learning of particle physics.

Next, the expert concept map and the Delphi study were both conducted in the context of CERN. While the connection to CERN was more apparent in the expert concept map, the outcomes of the Delphi study have been affected by it as well. Indeed, comparing the outcomes of the Delphi study to the study by Oettle (2021), summarised in Chapter 2, shows a stronger affinity of the Delphi study towards experimental particle physics, albeit CERN was not an explicit topic in the Delphi study. Furthermore, several stakeholders were experts and facilitators from other research institutions (not CERN). Therefore, the topics and their importance ranking could also be implemented in PDPs at other institutions similar to CERN.

Last, due to the internationality of the three studies, all materials were administered and produced in English. In the expert concept mapping study, all selected experts had a very good working knowledge of English. Furthermore, the author followed the concept mapping process and ensured the language was understandable by asking clarification questions when needed. Additionally, the iterations allowed experts to rephrase any ambiguities. However, in the Delphi study and the curricular review, stakeholders and experts participated individually without strong direct contact with the author for immediate clarification. Therefore, the materials for both studies were pretested within an international group of researchers to reduce the language bias. Furthermore, an option "I do not understand the question" was added in the Delphi study. Adding this option allowed the author to automatically discard the responses from people without sufficient knowledge of English. However, none of the participants showed a lack of understanding of the question. In the curricular review, the possible language bias was reduced already by including two reviewers per country. Additionally, all reviewers were alumni of CERN's teacher programmes. Their knowledge of English was shown to be sufficient during their respective PDP. Therefore, the language bias in all three studies is likely of minor effect.

9 IMPLICATIONS AND CONCLUSIONS

This doctoral research project focused on defining and investigating what particle physics content are high-school students and teachers expected to learn. Three studies supported the investigation. Each of the studies investigated a different aspect of including particle physics into high-school education and followed a different methodology. The three studies were focused on particle physics. Nevertheless, implications for teaching, curricular developments, professional development programmes, and educational research can be extended to other contemporary scientific topics, as presented in the following sections.

9.1 Implications for Teaching Contemporary Science Topics

The first part of this research project focused on what high-school students need to learn about particle physics. The outcomes show that experts in particle physics and physics education expect students to learn far more than what is in curricula. Furthermore, what curricula expect high-school students to learn about particle physics is disconnected from their prior knowledge. This disconnection can hinder the process of meaningful learning (Ausubel, 2000). Therefore, teachers should aim to bridge that gap by introducing the missing concepts as context. For example, *particle detectors* and *detection principles* can be introduced as a context for *ionisation*. Indeed, *ionisation* is one of the main principles for particle detection. Therefore, by introducing, for example, a cloud chamber when discussing *ionisation*, students can learn about both *ionisation* and *particle detectors* simultaneously.

The expert concept map on particle physics, described in Chapter 4, can be helpful when searching an appropriate context. Indeed, expert concept maps are prime examples of advanced organisers (Novak, 2010). As such, these maps can be used to scaffold teaching practice. First, the hierarchical structure of the expert concept map leads teachers from broader concepts to more specific examples. Therefore, teachers can follow the branches of the expert concept map to introduce a specific concept in more detail. For example, *theoretical particle physics* first leads teachers to the *Standard Model of particle physics*. There, teachers can explain the *Standard Model of particle physics* by introducing concepts from a lower hierarchical level, such as *fundamental interactions*. Students would then be introduced to the different types of *interactions* and the respective *interaction particles following the hierarchy*. With this succession, students learn first about broader concepts and slowly go into more details.

Second, the interconnectedness of the concept map helps teachers to connect concepts from different branches. As such, teachers can more easily identify suitable contexts for different particle physics concepts, including those from other curricular topics. Following the previous example, teachers can use *particle collisions* to connect *fundamental interactions* with *particle accelerators* and *particle detectors*. As such, teachers can use experimental particle physics as context for introducing the *Standard Model* and *theoretical particle physics*.

Last, the graphical representation of the knowledge structure in an expert concept map helps identifying possible weak areas in teaching practices to guide further improvements. Here, weak areas are characterised by being either disconnected or very weakly connected to other concepts in the expert concept map. Indeed, the fewer connections there are to a concept or area in a map, the fewer the opportunities for meaningfully learning about it. For example, the concept map based on the curricular review would have a gap between theoretical particle physics concepts and other curricular topics. Finding this gap helps teachers to identify possible content or context to help them build better connections. With the help of the expert concept map created in my research project, identifying suitable content and context becomes easier. In summary, the expert concept maps can facilitate teachers' instruction planning and, consequently, students' meaningful learning of particle physics.

Similarly, the expert concept map can be used to evaluate students' understanding of particle physics. Several studies have already used concept maps as a method for evaluation (e.g., Anohina-Naumeca & Milasevicha, 2011; Erdimez et al., 2017; Yin et al., 2005). Here, students receive a task of creating a concept map on a certain topic. In this task, students need to design a concept map either with their own concepts or with concepts provided by the teacher. In both cases, students' concept maps are then compared to the expert concept map to see the overlap of the two. Based on this overlap, areas for improvement can be identified. Additionally, using concept mapping with students can give teachers an overview of possible preconceptions or misunderstandings. Future teaching interventions can then be planned accordingly.

9.2 Implications for Curricular Developments

The comparison between the results of the curricular review and the expert concept map revealed several gaps in high-school particle physics content. Indeed, the existing particle physics content is not well connected to other curricular topics. Such gaps impede students' meaningful learning, as new knowledge builds upon prior knowledge (Ausubel, 2000). While teachers can bridge gaps within their curricula, curricular limitations leave little space for additional topics. Furthermore, experienced teachers typically rely more on their school knowledge and, thus, their curricula (Arzi & White, 2008; Wheeldon et al., 2012). Therefore, bridging the conceptual gaps should at least partially already be done within curricula. The connections between different chapters in the curricula should be explicit either as content or as suggestions for possible context. For example, if the curricula included connections between particle physics concepts and other parts of the curricula, teachers would more likely include them in their instructional practice.

The hierarchical structure of the expert concept map can be very helpful in curricular development. In the expert concept map, the central concept at the highest hierarchical level is the broadest. With each subsequent level of the hierarchy, the concepts get narrower and more specific. Therefore, by selecting a hierarchical cut-off level, the curricula can include arbitrarily broad concepts. Depending on the type of curriculum, different levels of hierarchy can be included. For example, syllabus-like curricula likely include most or even all concepts in the expert concept map. Conversely, a more general curriculum stops at a higher level of hierarchy. For example, a general curriculum in particle physics might stop at the second level of hierarchy. Then, the curriculum would include concepts such as *particle accelerators*, *particle detectors*, the *Standard Model*, and *cosmology*. In this curricular example, teachers would have more freedom for building context. However, they would also have less explicit suggestions for connecting to students' prior knowledge. Therefore, a balance needs to be found between giving teachers enough suggestions for designing their courses and not saturating the curriculum with too many details. An example of such a curriculum would include the *Standard Model* with links to the *elementary particles-charges-fundamental interactions* triangle as an example of theoretical particle physics. In experimental physics, the curriculum could include *particle accelerators* with *acceleration principles*, *particle detectors* with *detection principles*, and *data analysis* linked to *signal + background*. It is then up to teachers to decide how deep into details they go. Perhaps they still wanted to focus on the list of *elementary particles* and skip over the detailed specifics of particle detectors. Other teachers might want to focus on the workings of the LHC and not require students to learn the whole list of *quarks*. In any case, the curriculum would have had specified the most important aspects of both theoretical and experimental particle physics, together with connections to students' prior knowledge.

The example of curriculum building above works well for including a topic explicitly in the curriculum. However, expert concept maps are useful also for identifying where a topic can be used as context and how it can be contextualised. For example, particle physics can serve as a context for *electromagnetism* even if it is not explicitly mentioned in the curriculum. This way, particle physics can get introduced in a bottom-up approach. Using particle physics as context can lead to a good representation of the topic with proper scaffolding. In addition, contextualising topics is important for increasing students' interest (Hoffmann et al., 1998; Sjøberg & Schreiner, 2012). Therefore, curricula should not only be formulated concisely but should also highlight possible contexts within each topic.

Last, this research project showed that particle physics is a prime example for contextualising the Nature of Science. Indeed, as particle physics is a contemporary field of physics, facets of the Nature of Science are present in many aspects of particle physics. Therefore, contextualising the Nature of Science with particle physics or vice versa should be one of the aims of future curricular developments. For example, the tentative aspect of the Nature of Science can be shown in the context of "*observations* disproving *theoretical particle physics*", as shown in the expert concept map. Identifying similar contexts across the curricula can help teachers introduce the Nature of Science more meaningfully to students, especially if it is not introduced explicitly.

9.3 Implications for Professional Development Programmes

Introducing a new topic to high-school education always requires sufficient teachers' professional knowledge. Therefore, professional development programmes (PDPs) are the backbones of all curricular updates. This research project investigated which aspects of knowledge teachers should enhance during their participation in a particle physics PDP. The outcomes of this project show that stakeholders of a PDP on particle physics at CERN expect teachers to mainly enhance their school knowledge (SK) and deeper school knowledge (DSK). Furthermore, stakeholders perceive SK topics as the most important topics in PDPs. These outcomes suggest that PDPs need to ensure their content is connected to the curricula.

One way for PDPs to achieve that is to include teachers in their evaluation. In this research project, teachers were invited to help with the curricular review. Through this task, teachers had the opportunity to reflect on the curriculum and their instructional practices from a particle physics perspective. Furthermore, through identifying different connections to particle physics in the curriculum themselves, teachers can get more motivated to implement the knowledge they acquired as content and context for various other curricular topics. As such, reviewing the curricula can continue teachers' respective professional development, both in particle physics and in other topics. Meanwhile, professional development facilitators and educational researchers can use their data to gather important information regarding the curricular content and the relevance of the respective PDP. If the mismatch between a curriculum and a PDP was too great, it would show a need to update the programme – or the curriculum. Therefore, a focused curricular review should be a part of the follow-up activities of all PDPs.

However, stakeholders expect teachers to learn more than what is in the curriculum. Indeed, teachers are expected to learn about several additional topics, such as *particle detectors* and *particle accelerators*. These topics help connect particle physics that is in the curriculum to students' prior knowledge. Learning about these connections is crucial for building context and supporting students' meaningful learning. Therefore, teachers' content knowledge within a specific chapter needs to be complete, even if it surpasses the curricular suggestions.

9.4 Implications for Science Education Research

Educational interventions typically require a multi-directional approach. Indeed, changes in curricula require high-school teachers to adapt their teaching, university professors to review their assumptions on prior knowledge, and professional development facilitators to support the changes with their programmes. Therefore, this research project looked at introducing particle physics in classrooms with three studies from the curricular perspective, the experts' perspective, and the stakeholders' perspective. All three studies in this doctoral research project used a different methodology. In the following paragraphs, lessons learned and suggestions for future researchers are described.

First, an iterative expert concept mapping study was conducted. As the name describes, expert concept mapping is an expert knowledge elicitation technique. Expert techniques rely greatly on the experts' expertise. Therefore, the identification of suitable experts is crucial. The expertise of the experts needs to be broad enough to cover the field sufficiently. Including a broad range of experts in expert concept mapping facilitates a better generation of ideas and reduces the risk of false consensus. For example, including educational experts in this research project ensured a better connection of concepts to students' prior knowledge. Furthermore, the experts should be selected based on the progress of the expert concept map development. In this expert concept mapping study, the expert in Round 4 identified a need for including a computer scientist to cover the computing area of the map better. Therefore, a computer scientist was included in the subsequent round. Indeed, a broad and dynamic expert selection should be at the centre of similar expert concept mapping studies.

The expert concept mapping study in this research project used an iterative approach, modelled by the studies by Coffey and Hoffman (2003) and McBride and Burgman (2012). The iterative approach allowed for better verification of the expert concept map. Each round included expert training, evaluation of the latest version of the expert concept map, think-aloud concept mapping, verification with the expert, and identification of criteria for the next expert. The rounds were repeated until no need for additional experts is identified. In this research project, the expert concept mapping study thus concluded after nine rounds. This process of expert analysis, updates, and verification enhances the validity of the expert concept map. Furthermore, it allows the researchers to understand the experts' reasoning behind each decision fully. Moreover, as the verification of the results is always done through discussions with the participating experts, the role of the researcher in the process is minimised. Therefore, this methodology for creating a concept map is ideal for researchers aiming to develop an expert concept map that represents the cumulative knowledge of a larger group of experts.

Seven rounds of the expert concept mapping study in this research project have been conducted during the pandemic. Therefore, they could not be conducted live. Rather, the experts met with the researcher in an online environment. The move to an online setting has enhanced the process significantly. The concept mapping was done using online interactive concept mapping tools that both the researcher and the expert could manipulate at the same time. The possibility of independent manipulation allowed both to have a better overview of the map as it was changing. Additionally, changing and updating a concept map is significantly simplified in an online tool, especially when the map becomes more ramified. Links and concepts in an online expert concept map are clear, easy to follow, and easy to move around. Furthermore, an online setting allows researchers also to reach experts that are not geographically close. Therefore, concept mapping online should be preferred for interactive concept mapping sessions, especially in a one-on-one setting.

Second, a review of 27 high-school physics curricula from around the world was conducted. Here, a representative sample of curricula was selected rather than focusing only on curricula that already include particle physics explicitly. By reviewing a representative sample, the analysis showed how particle physics enters the curricula explicitly and implicitly. Furthermore, it showed that particle physics is present in the curricula even when it does not include an explicit particle physics chapter. Indeed, other curricular topics either introduce particle physics as context or already contain particle physics concepts intrinsically. For example, electrons and electric charge are almost always mentioned in the chapter on electromagnetism. Therefore, reviewing a representative sample of all curricula helped identify particle physics' explicit and implicit presence.

Curricula are written in the language of teachers and students in the respective educational system. Furthermore, the overall curricular design differs greatly between different educational systems. Therefore, including teachers as experts on their respective curricula was an important methodological choice. With knowledge of the language and experience with their respective curriculum, teachers can be considered as prime experts for a curricular review and a variety of other similar studies (e.g., lesson studies, mentoring). Hence, including them in other studies could provide educational researchers with additional meaningful insight.

9.5 Final Conclusions

Particle physics represents merely a small bit of physics education. With the strict limitations provided by the curricula, particle physics might be easy to disregard. However, my research project showed that particle physics could provide a meaningful context for the entire physics curriculum. Indeed, it is a prime example of contemporary physics to be included in high school physics education and beyond.

There is still a lot to be done in the field of high-school particle physics education. However, the field is developing rapidly. A great number of studies on how to introduce different particle physics concepts in the classroom are emerging. This doctoral research project provides a framework that connects these concepts and studies in a meaningful way. As such, it leads the way for further, less informative implementations of particle physics in high-school physics curricula. Here, it does not matter whether particle physics or similar contemporary topics get integrated into the intended or enacted curricula as content or context. The only important thing is that all science is introduced in a meaningful way. Only then can we achieve a real understanding of the ever-changing world around us.

REFERENCES

Abd-El-Khalick, F., Bell, R. L., & Lederman, N. G. (1998). The Nature of Science and instructional practice: Making the unnatural natural. *Science Education*, *82*(4), 417–436. https://doi.org/10.1002/(SICI)1098-237X(199807)82:4<417::AID-SCE1>3.0.CO;2-E

Abd-El-Khalick, F., & Lederman, N. G. (2000). Improving science teachers' conceptions of Nature of Science: A critical review of the literature. *International Journal of Science Education*, *22*(7), 665–701. https://doi.org/10.1080/095006900050044044

Abell, S. K. (2007). Research on science teacher knowledge. In S. K. Abell & N. G. Lederman (Eds.), *Handbook of research on science education* (Vol. 1–v, pp. 1105–1149). Mahwah, NJ: Lawrence Erlbaum.

Alexopoulos, A., Pavlidou, M., & Cherouvis, S. (2019). 'Playing with Protons': A training course for primary school teachers at CERN. *Physics Education*, *54*(1), 015013. https://doi.org/10.1088/1361-6552/aae7a4

American Association for the Advancement of Science. (1994). *Benchmarks for science literacy*. Oxford University Press.

Anderson, R. D., & Mitchener, C. P. (1994). Research on science teacher education. In *Handbook of research on science teaching and learning* (pp. 3–44). Macmillan Publishing Company.

Andrée, M. (2005). Ways of Using 'Everyday Life' in the Science Classroom. In K. Boersma, M. Goedhart, O. de Jong, & H. Eijkelhof (Eds.), *Research and the Quality of Science Education* (pp. 107–116). Springer Netherlands. https://doi.org/10.1007/1-4020-3673-6_9

Andrews, I., & Nikolopoulos, K. (2018). Introducing particle physics concepts through visual art. *Physics Education*, *53*(5), 054001. https://doi.org/10.1088/1361-6552/aad276

Angell, C., Guttersrud, �ystein, Henriksen, E. K., & Isnes, A. (2004). Physics: Frightful, but fun. Pupils' and teachers' views of physics and physics teaching. *Science Education*, *88*(5), 683–706. https://doi.org/10.1002/sce.10141

Anohina-Naumeca, A., & Milasevicha, S. (2011). Studying possibilities to use several experts' maps in the concept map based knowledge assessment system. *Proceedings of the 12th International Conference on Computer Systems and Technologies - CompSysTech '11*, 534. https://doi.org/10.1145/2023607.2023696

Arzi, H. J., & White, R. T. (2008). Change in teachers' knowledge of subject matter: A 17-year longitudinal study. *Science Education*, *92*(2), 221–251. https://doi.org/10.1002/sce.20239

Atkin, K. (2019). Using small disc magnets to model particle interactions. *Physics Education*, *54*(3), 035013. https://doi.org/10.1088/1361-6552/ab1050

Attride-Stirling, J. (2001). Thematic networks: An analytic tool for qualitative research. *Qualitative Research*, *1*(3), 385–405. https://doi.org/10.1177/146879410100100307

Aubrecht, G. J. (1986). Report on the conference on the teaching of modern physics. *The Physics Teacher*, *24*(9), 540–547.

Ausubel, D. P. (2000). *The Acquisition and Retention of Knowledge: A Cognitive View*. Springer Netherlands. https://doi.org/10.1007/978-94-015-9454-7

Baker, J. A., Lovell, K., & Harris, N. (2006). How expert are the experts? An exploration of the concept of ‘expert’ within Delphi panel techniques. *Nurse Researcher*, *14*(1), 59–70. https://doi.org/10.7748/nr2006.10.14.1.59.c6010

Baliga, S., Walvekar, P., & Mahantshetti, G. (2021). Concept map as a teaching and learning tool for medical students. *Journal of Education and Health Promotion*, *10*(1), 35. https://doi.org/10.4103/jehp.jehp_146_20

Ball, D. L., & Feiman-Nemser, S. (1988). Using Textbooks and Teachers’ Guides: A Dilemma for Beginning Teachers and Teacher Educators. *Curriculum Inquiry*, *18*(4), 401–423. https://doi.org/10.1080/03626784.1988.11076050

Ball, D. L., Lubienski, S. T., & Mewborn, D. S. (2001). Research on teaching mathematics: The unsolved problem of teachers’ mathematical knowledge. *Handbook of Research on Teaching*, *4*, 433–456.

Ball, D. L., Thames, M. H., & Phelps, G. (2008). Content Knowledge for Teaching: What Makes It Special? *Journal of Teacher Education*, *59*(5), 389–407. https://doi.org/10.1177/0022487108324554

Banilower, E. R., Heck, D. J., & Weiss, I. R. (2007). Can professional development make the vision of the standards a reality? The impact of the national science foundation’s local systemic change through teacher enhancement initiative. *Journal of Research in Science Teaching*, *44*(3), 375–395. https://doi.org/10.1002/tea.20145

Barradas-Solas, F. (2007). Giving new life to old equipment. *Physics Education*, *42*(1), 9–11. https://doi.org/10.1088/0031-9120/42/1/F03

Baumert, J., Kunter, M., Blum, W., Brunner, M., Voss, T., Jordan, A., Klusmann, U., Krauss, S., Neubrand, M., & Tsai, Y.-M. (2010). Teachers’ Mathematical Knowledge, Cognitive Activation in the Classroom, and Student Progress. *American Educational Research Journal*, *47*(1), 133–180. https://doi.org/10.3102/0002831209345157

Bennett, J., & Hogarth, S. (2009). Would You Want to Talk to a Scientist at a Party? High school students’ attitudes to school science and to science. *International Journal of Science Education*, *31*(14), 1975–1998. https://doi.org/10.1080/09500690802425581

Berg, E. van den, & Hoekzema, D. (2006). Teaching conservation laws, symmetries and elementary particles with fast feedback. *Physics Education*, *41*(1), 47–56. https://doi.org/10.1088/0031-9120/41/1/004

Betts, J. R., Zau, A., & Rice, L. (2003). *Determinants of student achievement: New evidence from San Diego*. Public Policy Institute of California.

Blömeke, S., Olsen, R. V., & Suhl, U. (2016). Relation of Student Achievement to the Quality of Their Teachers and Instructional Quality. In T. Nilsen & J.-E. Gustafsson (Eds.), *Teacher Quality, Instructional Quality and Student Outcomes* (Vol. 2, pp. 21–50). Springer International Publishing. https://doi.org/10.1007/978-3-319-41252-8_2

Boesen, J., Helenius, O., Bergqvist, E., Bergqvist, T., Lithner, J., Palm, T., & Palmberg, B. (2014). Developing mathematical competence: From the intended to the enacted curriculum. *The Journal of Mathematical Behavior*, *33*, 72–87. https://doi.org/10.1016/j.jmathb.2013.10.001

Bolger, F. M. I., & Wright, G. (2011). Improving the Delphi process: Lessons from social psychological research. *Technological Forecasting and Social Change*, *78*(9), 1500–1513.

Boone, H. N., & Boone, D. A. (2012). Analyzing likert data. *Journal of Extension*, *50*(2), 1–5.

Borko, H. (2004). Professional Development and Teacher Learning: Mapping the Terrain. *Educational Researcher*, *33*(8), 3–15. https://doi.org/10.3102/0013189X033008003

Boyd, D. J., Grossman, P. L., Lankford, H., Loeb, S., & Wyckoff, J. (2009). Teacher Preparation and Student Achievement. *Educational Evaluation and Policy Analysis*, *31*(4), 416–440. https://doi.org/10.3102/0162373709353129

Brady, S. R. (2015). Utilising and adapting the Delphi method for use in qualitative research. *International Journal of Qualitative Methods*, *14*(5), 1–6. https://doi.org/10.1177/1609406915621381

Braun, V., & Clarke, V. (2006). Using thematic analysis in psychology. *Qualitative Research in Psychology*, *3*(2), 77–101.

Bruner, J. S., & Lufburrow, R. A. (1963). The Process of Education. *American Journal of Physics*, *31*(6), 468–469. https://doi.org/10.1119/1.1969598

Bungum, B., Bøe, M. V., & Henriksen, E. K. (2018). Quantum talk: How small-group discussions may enhance students' understanding in quantum physics. *Science Education*, *102*(4), 856–877. https://doi.org/10.1002/sce.21447

Campanile, M. F., Lederman, N. G., & Kampourakis, K. (2015). Mendelian Genetics as a Platform for Teaching About Nature of Science and Scientific Inquiry: The Value of Textbooks. *Science & Education*, *24*(1–2), 205–225. https://doi.org/10.1007/s11191-013-9607-4

Cañas, A. J., Carff, R., Hill, G., Carvalho, M., Arguedas, M., Eskridge, T. C., Lott, J., & Carvajal, R. (2005). Concept Maps: Integrating Knowledge and Information Visualization. In S.-O. Tergan & T. Keller (Eds.), *Knowledge and Information Visualization* (Vol. 3426, pp. 205–219). Springer Berlin Heidelberg. https://doi.org/10.1007/11510154_11

Cañas, A. J., Coffey, J. W., Carnot, M.-J., Feltovich, P., Hoffman, R. R., Feltovich, J., & Novak, J. D. (2003). A summary of literature pertaining to the use of concept mapping techniques and technologies for education and performance support. *Report to the Chief of Naval Education and Training*, 1–108.

Carter, P., & Darling-Hammond, L. (2016). Teaching diverse learners. In D. H. Gitomer & C. A. Bell (Eds.), *Handbook of research on teaching* (Fifth edition, pp. 593–638). American Educational Research Association.

Cauet, E., Liepertz, S., Borowski, A., & Fischer, H. E. (2015). Does it matter what we measure? Domain-specific professional knowledge of physics teachers. *Schweizerische Zeitschrift Für Bildungswissenschaften*, *37*(3), 462–479. https://doi.org/10.25656/01:12746

Cecire, K., Bardeen, M., & McCauley, T. (2014). The CMS masterclass and particle physics outreach. *EPJ Web of Conferences*, *71*, 00027. https://doi.org/10.1051/epjconf/20147100027

Chan, K. K. H., & Hume, A. (2019). Towards a Consensus Model: Literature Review of How Science Teachers' Pedagogical Content Knowledge Is Investigated in Empirical Studies. In A. Hume, R. Cooper, & A. Borowski (Eds.), *Repositioning Pedagogical Content Knowledge* *in Teachers' Knowledge for Teaching Science* (pp. 3–76). Springer Singapore. https://doi.org/10.1007/978-981-13-5898-2_1

Chan, K. K. H., & Yung, B. H. W. (2018). Developing Pedagogical Content Knowledge for Teaching a New Topic: More Than Teaching Experience and Subject Matter Knowledge. *Research in Science Education*, *48*(2), 233–265. https://doi.org/10.1007/s11165-016-9567-1

Chatterjee, L. (2002). Introducing particle physics through story. *Physics Education*, *37*(3), 260–262. https://doi.org/10.1088/0031-9120/37/3/405

Cid-Vidal, X., & Cid, R. (2011). LHC: The emptiest space in the solar system. *Physics Education*, *46*(1), 45–49. https://doi.org/10.1088/0031-9120/46/1/005

Cid-Vidal, X., & Cid, R. (2018). Lead ions and Coulomb's Law at the LHC (CERN). *Physics Education*, *53*(2), 024002. https://doi.org/10.1088/1361-6552/aa95d4

Cid-Vidal, X., Cid, R., & Cliff, H. V. (2021). Introducing the Future Circular Collider (FCC) into Secondary Classrooms. *The Physics Teacher*, *59*(3), 189–191. https://doi.org/10.1119/10.0003661

Clayton, M. J. (2006). Delphi: A technique to harness expert opinion for critical decision-making tasks in education. *Educational Psychology*, *17*(4), 373–386. https://doi.org/10.1080/0144341970170401

Clotfelter, C., Ladd, H., & Vigdor, J. (2007). *How and Why do Teacher Credentials Matter for Student Achievement?* (No. w12828; p. w12828). National Bureau of Economic Research. https://doi.org/10.3386/w12828

Coburn, C. E. (2004). Beyond decoupling: Rethinking the relationship between the institutional environment and the classroom. *Sociology of Education*, *77*(3), 211–244.

Cochran, K. F., & Jones, L. L. (1998). The subject matter knowledge of preservice science teachers. *International Handbook of Science Education*, *2*, 707–718.

Coffey, J. W., & Hoffman, R. R. (2003). Knowledge modeling for the preservation of institutional memory. *Journal of Knowledge Management*, *7*(3), 38–52. https://doi.org/10.1108/13673270310485613

Coffey, J. W., Hoffman, R. R., Cañas, A. J., & Ford, K. M. (2002). A concept map-based knowledge modeling approach to expert knowledge sharing. *Proceedings of IKS*, 212–217.

Coldham, K. (2016). *10,000th teacher visits CERN. Le CERN accueille son 10000ème enseignant*. https://cds.cern.ch/record/2196985

Corcoran, T. B. (1995). *Helping Teachers Teach Well: Transforming Professional Development. CPRE Policy Briefs.*

Covay Minor, E., Desimone, L., Caines Lee, J., & Hochberg, E. D. (2016). Insights on how to shape teacher learning policy: The role of teacher content knowledge in explaining differential effects of professional development. *Education Policy Analysis Archives*, *24*, 61. https://doi.org/10.14507/epaa.24.2365

Daley, B. J., & Torre, D. M. (2010). Concept maps in medical education: An analytical literature review. *Medical Education*, *44*(5), 440–448. https://doi.org/10.1111/j.1365-2923.2010.03628.x

Darling-Hammond, L., Hyler, M. E., & Gardner, M. (2017). Effective teacher professional development. *Learning Policy Institute*.

Day, L. H. (1975). Delphi Research in the Corporate Environment. In *The Delphi Method: Techniques and Applications* (pp. 162–188). Addison-Wesley Educational Publishers Inc.

Delbecq, A. L., Van de Ven, A. H., & Gustafson, D. H. (1975). *Group techniques for program planning: A guide to nominal group and delphi processes*. Scott, Foresman and Company.

Desimone, L. M. (2009). Improving Impact Studies of Teachers' Professional Development: Toward Better Conceptualizations and Measures. *Educational Researcher*, *38*(3), 181–199. https://doi.org/10.3102/0013189X08331140

Diamond, B. S., Maerten-Rivera, J., Rohrer, R. E., & Lee, O. (2014). Effectiveness of a curricular and professional development intervention at improving elementary teachers' science content knowledge and student achievement outcomes: Year 1 results: ELEMENTARY TEACHERS' SCIENCE CONTENT KNOWLEDGE. *Journal of Research in Science Teaching*, *51*(5), 635–658. https://doi.org/10.1002/tea.21148

Doppelt, Y., Schunn, C. D., Silk, E. M., Mehalik, M. M., Reynolds, B., & Ward, E. (2009). Evaluating the impact of a facilitated learning community approach to professional development on teacher practice and student achievement. *Research in Science & Technological Education*, *27*(3), 339–354. https://doi.org/10.1080/02635140903166026

Doyle, J., Sonnert, G., & Sadler, P. (2020). How professional development program features impact the knowledge of science teachers. *Professional Development in Education*, *46*(2), 195–210. https://doi.org/10.1080/19415257.2018.1561493

Drayton, B., & Falk, J. (2006). Dimensions that shape teacher–scientist collaborations for teacher enhancement. *Science Education*, *90*(4), 734–761. https://doi.org/10.1002/sce.20138

Dreher, A., Lindmeier, A., & Heinze, A. (2016). Conceptualizing professional content knowledge of secondary teachers taking into account the gap between academic and school mathematics. *Proceedings of the 40th Conference of the International Group for the Psychology of Mathematics Education*, *2*, 219–226.

Dunlop, L., & Veneu, F. (2019). Controversies in Science: To Teach or Not to Teach? *Science & Education*, *28*(6–7), 689–710. https://doi.org/10.1007/s11191-019-00048-y

Duschl, R. A., & Grandy, R. (2013). Two Views About Explicitly Teaching Nature of Science. *Science & Education*, *22*(9), 2109–2139. https://doi.org/10.1007/s11191-012-9539-4

Elby, A., & Yerdelen-Damar, S. (2020). Rethinking the relationship between instructors and physics education researchers. *Physical Review Physics Education Research*, *16*(2), 020151. https://doi.org/10.1103/PhysRevPhysEducRes.16.020151

Enkrott, P., Buschhüter, D., & Borowski, A. (2017). Modeling and Development of Professional Content Knowledge of Pre-Service Physics Teachers. *Qualitätsvoller Chemie- Und Physikunterricht-Normative Und Empirische Dimensionen. Gesellschaft Für Didaktik Der Chemie Und Physik, Jahrestagung in Regensburg.*

Enzer, S. (1975). Plastics and Competing Materials by 1985: A Delphi Forecasting Study. In *The Delphi Method: Techniques and Applications* (pp. 189–203). Addison-Wesley Educational Publishers Inc.

Erdimez, O., Tan, S., & Zimmerman, R. (2017). The Use of Concept Maps as a Tool to Measure Higher Level Thinking Skills in Elementary School Science Classes. *Journal for the Education of Gifted Young Scientists*, *5*(2), 1–20. https://doi.org/10.17478/JEGYS.2016221898

Ertmer, P. A. (1999). Addressing first- and second-order barriers to change: Strategies for technology integration. *Educational Technology Research and Development*, *47*(4), 47–61. https://doi.org/10.1007/BF02299597

Fereday, J., & Muir-Cochrane, E. (2006). Demonstrating Rigor Using Thematic Analysis: A Hybrid Approach of Inductive and Deductive Coding and Theme Development. *International Journal of Qualitative Methods*, *5*(1), 80–92. https://doi.org/10.1177/160940690600500107

Finlayson, H., Lock, R., Soares, A., & Tebbutt, M. (1998). Are We Producing Teaching Technicians or Science Educators? The consequences of differential demands on trainee science teachers. *Educational Review*, *50*(1), 45–54. https://doi.org/10.1080/0013191980500105

Fischer, C., Fishman, B., Dede, C., Eisenkraft, A., Frumin, K., Foster, B., Lawrenz, F., Levy, A. J., & McCoy, A. (2018). Investigating relationships between school context, teacher professional development, teaching practices, and student achievement in response to a nationwide science reform. *Teaching and Teacher Education*, *72*, 107–121. https://doi.org/10.1016/j.tate.2018.02.011

Fischer, H. E., Borowski, A., & Tepner, O. (2012). Professional knowledge of science teachers. In *Second international handbook of science education* (pp. 435–448). Springer.

Fleer, M. (2009). Supporting Scientific Conceptual Consciousness or Learning in 'a Roundabout Way' in Play-based Contexts. *International Journal of Science Education*, *31*(8), 1069–1089. https://doi.org/10.1080/09500690801953161

Fullan, M. G. (1994). Coordinating Top-Down and Bottom-Up Strategies for Educational Reform. In R. J. Anson (Ed.), *Systemic reform: Perspectives on personalizing education*. U.S. Dept. of Education, Office of Educational Research and Improvement : For sale by the U.S. G.P.O., Supt. of Docs.

Galili, I., & Hazan, A. (2001). Experts' views on using history and philosophy of science in the practice of physics instruction. *Science and Education*, *10*(4), 345–367. https://doi.org/10.1023/A:1011209131446

Gallagher, H. A., Arshan, N., & Woodworth, K. (2017). Impact of the National Writing Project's College-Ready Writers Program in High-Need Rural Districts. *Journal of Research on Educational Effectiveness*, *10*(3), 570–595. https://doi.org/10.1080/19345747.2017.1300361

Garet, M. S., Porter, A. C., Desimone, L. M., Birman, B. F., & Suk Yoon, K. (2001). What Makes Professional Development Effective? Results From a National Sample of Teachers. *American Education Research Journal*, *38*(4), 915–945. https://doi.org/10.3102/00028312038004915

Gehrke, N. J., Knapp, M. S., & Sirotnik, K. A. (1992). Chapter 2: In Search of the School Curriculum. *Review of Research in Education*, *18*(1), 51–110. https://doi.org/10.3102/0091732X018001051

Gentsch, K. L. H. (1999). Science education goals: Views from scientists and teachers. *Journal of Elementary Science Education*, *11*(1), 61–68. https://doi.org/10.1007/BF03173791

Gess-Newsome, J., & Lederman, N. G. (1993). Preservice biology teachers' knowledge structures as a function of professional teacher education: A year-long assessment. *Science Education*, *77*(1), 25–45. https://doi.org/10.1002/sce.3730770103

Gess-Newsome, J., Taylor, J. A., Carlson, J., Gardner, A. L., Wilson, C. D., & Stuhlsatz, M. A. M. (2019). Teacher pedagogical content knowledge, practice, and student achievement. *International Journal of Science Education*, *41*(7), 944–963. https://doi.org/10.1080/09500693.2016.1265158

Goldhaber, D. D., & Brewer, D. J. (2000). Does Teacher Certification Matter? High School Teacher Certification Status and Student Achievement. *Educational Evaluation and Policy Analysis*, *22*(2), 129–145. https://doi.org/10.3102/01623737022002129

Goldstein, N. H. (1975). A Delphi on the Future of the Steel and Ferroalloy Industries. In *The Delphi Method: Techniques and Applications* (pp. 204–220). Addison-Wesley Educational Publishers Inc.

Gourlay, H. (2017). Learning about A level physics students' understandings of particle physics using concept mapping. *Physics Education*, *52*(1), 014001. https://doi.org/10.1088/1361-6552/52/1/014001

Greene, B. A., Lubin, I. A., Slater, J. L., & Walden, S. E. (2013). Mapping Changes in Science Teachers' Content Knowledge: Concept Maps and Authentic Professional Development. *Journal of Science Education and Technology*, *22*(3), 287–299.

Greenwald, R., Hedges, L. V., & Laine, R. D. (1996). The Effect of School Resources on Student Achievement. *Review of Educational Research*, *66*(3), 361–396. https://doi.org/10.3102/00346543066003361

Grossman, P. L. (1990). *The making of a teacher: Teacher knowledge and teacher education*. Teachers College Press, Teachers College, Columbia University.

Guerriero, S. (Ed.). (2017). Teachers' pedagogical knowledge: What it is and how it functions. In OECD, *Pedagogical Knowledge and the Changing Nature of the Teaching Profession* (pp. 99–118). OECD. https://doi.org/10.1787/9789264270695-6-en

Gupta, U. G., & Clarke, R. E. (1996). Theory and applications of the Delphi technique: A bibliography (1975–1994). *Technological Forecasting and Social Change*, *53*(2), 185–211. https://doi.org/10.1016/s0040-1625(96)00094-7

Guskey, T. R. (2000). *Evaluating Professional Development*. Corwin Press, Inc.

Guskey, T. R. (2003). What Makes Professional Development Effective? *Phi Delta Kappan*, *84*(10), 748–750. https://doi.org/10.1177/003172170308401007

Haagen-Schützenhöfer, C., & Hopf, M. (2020). Design-based research as a model for systematic curriculum development: The example of a curriculum for introductory optics. *Physical Review Physics Education Research*, *16*(2), 020152. https://doi.org/10.1103/PhysRevPhysEducRes.16.020152

Hanley, P. (2000). Teaching particle physics. *Physics Education*, *35*(5), 332–338. https://doi.org/10.1088/0031-9120/35/5/303

Hanushek, E., Kain, J., O'Brien, D., & Rivkin, S. (2005). *The Market for Teacher Quality* (No. w11154; p. w11154). National Bureau of Economic Research. https://doi.org/10.3386/w11154

Harris, D. N., & Sass, T. R. (2011). Teacher training, teacher quality and student achievement. *Journal of Public Economics*, *95*(7–8), 798–812. https://doi.org/10.1016/j.jpubeco.2010.11.009

Harrison, A. G., & Treagust, D. F. (2003). The Particulate Nature of Matter: Challenges in Understanding the Submicroscopic World. In J. K. Gilbert, O. Jong, R. Justi, D. F. Treagust, & J. H. Driel (Eds.), *Chemical Education: Towards Research-based Practice* (Vol. 17, pp. 189–212). Kluwer Academic Publishers. https://doi.org/10.1007/0-306-47977-X_9

Harvey, N., & Holmes, C. A. (2012). Nominal group technique: An effective method for obtaining consensus. *International Journal of Nursing Practice*, *18*(2), 188–194. https://doi.org/10.1111/j.1440-172X.2012.02017.x

Hasson, F., Keeney, S., & McKenna, H. P. (2000). Research guidelines for the Delphi survey technique. *Journal of Advanced Nursing*, *32*(4), 1008–1015. https://doi.org/10.1046/j.1365-2648.2000.t01-1-01567.x

Häussler, P., & Hoffmann, L. (2000). A curricular frame for physics education: Development, comparison with students' interests, and impact on students' achievement and self-concept. *Science Education*, *84*(6), 689–705. https://doi.org/10.1002/1098-237X(200011)84:6<689::AID-SCE1>3.0.CO;2-L

Hay, D., Kinchin, I., & Lygo-Baker, S. (2008). Making learning visible: The role of concept mapping in higher education. *Studies in Higher Education*, *33*(3), 295–311. https://doi.org/10.1080/03075070802049251

Heller, J. I., Daehler, K. R., Wong, N., Shinohara, M., & Miratrix, L. W. (2012). Differential effects of three professional development models on teacher knowledge and student achievement in elementary science. *Journal of Research in Science Teaching*, *49*(3), 333–362. https://doi.org/10.1002/tea.21004

Henke, A., & Höttecke, D. (2015). Physics Teachers' Challenges in Using History and Philosophy of Science in Teaching. *Science & Education*, *24*(4), 349–385. https://doi.org/10.1007/s11191-014-9737-3

Hewson, P. W. (2007). Teacher Professional Development in Science. In *Handbook of Research on Science Education* (Vol. 1, pp. 1179–1203). Routledge.

Hill, H. C., Rowan, B., & Ball, D. L. (2005). Effects of Teachers' Mathematical Knowledge for Teaching on Student Achievement. *American Educational Research Journal*, *42*(2), 371–406. https://doi.org/10.3102/00028312042002371

Hobson, A. (2011a). Teaching Elementary Particle Physics: Part I 1. *The Physics Teacher*, *49*(1), 12–15. https://doi.org/10.1119/1.3527746

Hobson, A. (2011b). Teaching Elementary Particle Physics, Part II. *The Physics Teacher*, *49*(3), 136–138. https://doi.org/10.1119/1.3555495

Hoekzema, D., Schooten, G., van den Berg, E., & Lijnse, P. (2005). Conservation Laws, Symmetries, and Elementary Particles. *The Physics Teacher*, *43*(5), 266–271. https://doi.org/10.1119/1.1903808

Hoffmann, L., Häußler, P., & Lehrke, M. (1998). *Die IPN-Interessenstudie Physik*. IPN.

Hsu, C.-C., & Sandford, B. A. (2007). The Delphi Technique: Making Sense Of Consensus. *Practical Assessment, Research & Evaluation*, *12*(10), 1–8. https://doi.org/10.7275/pdz9-th90

Irish, T., & Kang, N.-H. (2018). Connecting Classroom Science with Everyday Life: Teachers' Attempts and Students' Insights. *International Journal of Science and Mathematics Education*, *16*(7), 1227–1245. https://doi.org/10.1007/s10763-017-9836-0

Irving, P. W., McPadden, D., & Caballero, M. D. (2020). Communities of practice as a curriculum design theory in an introductory physics class for engineers. *Physical Review Physics Education Research*, *16*(2), 020143. https://doi.org/10.1103/PhysRevPhysEducRes.16.020143

Johansson, K., Kobel, M., Hillebrandt, D., Engeln, K., & Euler, M. (2007). European particle physics masterclasses make students into scientists for a day. *Physics Education*, *42*(6), 636. https://doi.org/10.1088/0031-9120/42/6/012

Jones, C. G. (1975). A Delphi Evaluation of Agreement between Organisations. In *The Delphi Method: Techniques and Applications* (pp. 155–161). Addison-Wesley Educational Publishers Inc.

Kane, M., & Trochim, W. (2007). *Concept mapping for planning and evaluation*. Sage Publications.

Keller, M. M., Neumann, K., & Fischer, H. E. (2017). The impact of physics teachers' pedagogical content knowledge and motivation on students' achievement and interest. *Journal of Research in Science Teaching*, *54*(5), 586–614. https://doi.org/10.1002/tea.21378

Keller, O., Schmeling, S., Müller, A., & Benoit, M. (2016). iPadPix—A novel educational tool to visualise radioactivity measured by a hybrid pixel detector. *Journal of Instrumentation*, *11*(11), C11032–C11032. https://doi.org/10.1088/1748-0221/11/11/C11032

Kinchin, I. M., Hay, D. B., & Adams, A. (2000). How a qualitative approach to concept map analysis can be used to aid learning by illustrating patterns of conceptual development. *Educational Research*, *42*(1), 43–57. https://doi.org/10.1080/001318800363908

Kinchin, I. M., Möllits, A., & Reiska, P. (2019). Uncovering Types of Knowledge in Concept Maps. *Education Sciences*, *9*(2). https://doi.org/10.3390/educsci9020131

Kobel, M. (2003). High school students' exposure to modern particle physics. *Europhysics News*, *34*(3), 108–110. https://doi.org/10.1051/epn:2003307

Kragh, H. (2011). On Modern Cosmology and its Place in Science Education. *Science & Education*, *20*(3–4), 343–357. https://doi.org/10.1007/s11191-010-9271-x

Kranjc Horvat, A., Wiener, J., Schmeling, S., & Borowski, A. (2021). Learning Goals of Professional Development Programs at Science Research Institutions: A Delphi Study with Different Stakeholder Groups. *Journal of Science Teacher Education*, 1–23. https://doi.org/10.1080/1046560X.2021.1905330

Kulgemeyer, C., Borowski, A., Buschhüter, D., Enkrott, P., Kempin, M., Reinhold, P., Riese, J., Schecker, H., Schröder, J., & Vogelsang, C. (2020). Professional knowledge affects ACTION-RELATED skills: The development of PRESERVICE physics teachers' explaining skills during a field experience. *Journal of Research in Science Teaching*, *57*(10), 1554–1582. https://doi.org/10.1002/tea.21632

Kulgemeyer, C., & Riese, J. (2018). From professional knowledge to professional performance: The impact of CK and PCK on teaching quality in explaining situations. *Journal of Research in Science Teaching*, *55*(10), 1393–1418. https://doi.org/10.1002/tea.21457

Kustusch, M. B., Manogue, C., & Price, E. (2020). Design tactics in curriculum development: Examples from the Paradigms in Physics ring cycle. *Physical Review Physics Education Research*, *16*(2), 020145. https://doi.org/10.1103/PhysRevPhysEducRes.16.020145

Kvita, J., Čermáková, B., Matulová, N., Poštulka, J., & Staník, D. (2019). Particle camera MX-10 in physics education. *Physics Education*, *54*(2), 025011. https://doi.org/10.1088/1361-6552/aae9a0

Ladd, H. F., & Sorensen, L. C. (2015). Do Master's Degrees Matter? Advanced Degrees, Career Paths, and the Effectiveness of Teachers. Working Paper 136. *National Center for Analysis of Longitudinal Data in Education Research (CALDER)*.

Laight, D. W. (2004). Attitudes to concept maps as a teaching/learning activity in undergraduate health professional education: Influence of preferred learning style. *Medical Teacher*, *26*(3), 229–233. https://doi.org/10.1080/0142159042000192064

Lederman, N. G. (2013). Nature of science: Past, present, and future. In *Handbook of research on science education* (pp. 845–894). Routledge.

Lederman, N. G., Lederman, J. S., & Antink, A. (2013). Nature of science and scientific inquiry as contexts for the learning of science and achievement of scientific literacy. *International Journal of Education in Mathematics, Science and Technology*, *1*(3).

Lee, S. W., & Mamerow, G. (2019). Understanding the role cumulative exposure to highly qualified science teachers plays in students' educational pathways. *Journal of Research in Science Teaching*, *56*(10), 1362–1383. https://doi.org/10.1002/tea.21558

Levin, B., Connelly, G. A.-M., & Lundgren, U. P. (2008). Curriculum policy and the politics of what should be learned in schools. In *The SAGE Handbook of Curriculum and Instruction* (pp. 7–24). SAGE Publications Inc.; DiVA. https://doi.org/10.4135/9781412976572.n1

Levrini, O., & Fantini, P. (2013). Encountering Productive Forms of Complexity in Learning Modern Physics. *Science & Education*, *22*(8), 1895–1910. https://doi.org/10.1007/s11191-013-9587-4

Lindenau, P., & Kobel, M. (2019). Introducing an innovative approach of teaching the Standard Model of particle physics at high school. *Journal of Physics: Conference Series*, *1287*. https://doi.org/10.1088/1742-6596/1287/1/012045

Linstone, H. A., & Turoff, M. (1975). Introduction. In *The Delphi Method: Techniques and Applications* (pp. 3–14). Addison-Wesley Educational Publishers Inc.

Lipowsky, F., & Rzejak, D. (2015). *Key features of effective professional development programmes for teachers*.

Liu, S., & Phelps, G. (2020). Does Teacher Learning Last? Understanding How Much Teachers Retain Their Knowledge After Professional Development. *Journal of Teacher Education*, *71*(5), 537–550. https://doi.org/10.1177/0022487119886290

Loeb, S., Miller, L. C., & Strunk, K. O. (2009). The State Role in Teacher Professional Development and Education Throughout Teachers' Careers. *Education Finance and Policy*, *4*(2), 212–228. https://doi.org/10.1162/edfp.2009.4.2.212

Lopes, H. E. G., & Gosling, M. de S. (2021). Cluster Analysis in Practice: Dealing with Outliers in Managerial Research. *Revista de Administração Contemporânea*, *25*(1), e200081. https://doi.org/10.1590/1982-7849rac2021200081

Louws, M. L., Meirink, J. A., van Veen, K., & van Driel, J. H. (2018). Understanding teachers' professional learning goals from their current professional concerns. *Teachers and Teaching*, *24*(1), 63–80. https://doi.org/10.1080/13540602.2017.1383237

Lucero, M. M., Petrosino, A. J., & Delgado, C. (2017). Exploring the relationship between secondary science teachers' subject matter knowledge and knowledge of student conceptions while teaching evolution by natural selection: SCIENCE TEACHERS' SMK AND KOSC FOR NATURAL SELECTION. *Journal of Research in Science Teaching*, *54*(2), 219–246. https://doi.org/10.1002/tea.21344

Ludlow, J. (1975). Delphi Inquiries and Knowledge Utilization. In *The Delphi Method: Techniques and Applications* (pp. 97–118). Addison-Wesley Educational Publishers Inc.

Luft, J. A., & Hewson, P. W. (2014). Research on Professional Development Programs in Science. In *Handbook of Research on Science Education* (Vol. 2, pp. 97–118). Routledge.

Ma, Y.-Z., & Zhang, S.-N. (2016). Hubble expansion is not a velocity. *Physics Education*, *51*(6), 065011. https://doi.org/10.1088/0031-9120/51/6/065011

MacDonald, T., & Bean, A. (2009). Quarked! —Adventures in Particle Physics Education. *The Physics Teacher*, *47*(1), 38–41. https://doi.org/10.1119/1.3049879

Mahler, D., Großschedl, J., & Harms, U. (2017). Using doubly latent multilevel analysis to elucidate relationships between science teachers' professional knowledge and students' performance. *International Journal of Science Education*, *39*(2), 213–237. https://doi.org/10.1080/09500693.2016.1276641

Mariescu-Istodor, R., & Jormanainen, I. (2019). Machine Learning for High School Students. Proceedings of the 19th Koli Calling International Conference on Computing Education Research, 1–9. https://doi.org/10.1145/3364510.3364520

Martin, M. O., Mullis, I. V., Foy, P., & Stanco, G. M. (2012). *TIMSS 2011 International Results in Science.* ERIC.

McBride, M. F., & Burgman, M. A. (2012). What Is Expert Knowledge, How Is Such Knowledge Gathered, and How Do We Use It to Address Questions in Landscape Ecology? In A. H. Perera, C. A. Drew, & C. J. Johnson (Eds.), *Expert Knowledge and Its Application in Landscape Ecology* (pp. 11–38). Springer. https://doi.org/10.1007/978-1-4614-1034-8_2

McClure, J. R., Sonak, B., & Suen, H. K. (1999). Concept map assessment of classroom learning: Reliability, validity, and logistical practicality. *Journal of Research in Science Teaching*, *36*(4), 475–492. https://doi.org/10.1002/(SICI)1098-2736(199904)36:4<475::AID-TEA5>3.0.CO;2-O

McDonald, C. V. (2017). Exploring representations of Nature of Science in Australian junior secondary school science textbooks: A case study of genetics. In *Representations of Nature of Science in school science textbooks* (pp. 98–117). Routledge.

McGinness, L., Dührkoop, S., Woithe, J., & Jansky, A. (2019). 3D printable quark puzzle: A model to build your own particle systems. *The Physics Teacher*, *57*(8), 526–528.

McLin, K. M., & Cominsky, L. R. (2007). Teaching In-Service and Pre-Service Teachers Modern Cosmology, Part I: A Concept Inventory. *American Astronomical Society Meeting Abstracts*, *211*, 31.06.

McMillan, S. S., King, M., & Tully, M. P. (2016). How to use the nominal group and Delphi techniques. *International Journal of Clinical Pharmacy*, *38*(3), 655–662. https://doi.org/10.1007/s11096-016-0257-x

Merriam-Webster. (n.d.). Curriculum. In *Merriam-Webster.com dictionary*. Retrieved 12 August 2021, from https://www.merriam-webster.com/dictionary/curriculum

Metzler, J., & Woessmann, L. (2012). The impact of teacher subject knowledge on student achievement: Evidence from within-teacher within-student variation. *Journal of Development Economics*, *99*(2), 486–496. https://doi.org/10.1016/j.jdeveco.2012.06.002

Michelini, M. (2021). Innovation of Curriculum and Frontiers of Fundamental Physics in Secondary School: Research-Based Proposals. In B. G. Sidharth, J. C. Murillo, M. Michelini, & C. Perea (Eds.), *Fundamental Physics and Physics Education Research* (pp. 101–116). Springer International Publishing. https://doi.org/10.1007/978-3-030-52923-9_10

Moore, A. (2015). *Understanding the school curriculum: Theory, politics and principles*. Routledge.

Morewood, A. L., Ankrum, J. W., & Bean, R. M. (2010). *Teachers' perceptions of the influence of professional development on their knowledge of content, pedagogy, and curriculum*.

Moslem, S., Ghorbanzadeh, O., Blaschke, T., & Duleba, S. (2019). Analysing Stakeholder Consensus for a Sustainable Transport Development Decision by the Fuzzy AHP and Interval AHP. *Sustainability*, *11*(12), 3271. https://doi.org/10.3390/su11123271

Mullis, I. V. S., Martin, M. O., Foy, P., & Hooper, M. (2016). *TIMSS Advanced 2015 International Results in Advanced Mathematics and Physics*. Boston College, TIMSS & PIRLS International Study Center. http://timssandpirls.bc.edu/timss2015/international-results/advanced/

Nawaz, H., & Rafaqat, A. A. (2019). Exploration of Gaps between Intended and Enacted Physics Curriculum: Teachers' Professional Development Perspective. *Bulletin of Education and Research*, *41*(2), 1–10.

Nikolopoulos, K., & Pardalaki, M. (2020). Particle dance: Particle physics in the dance studio. *Physics Education*, *55*(2), 025018. https://doi.org/10.1088/1361-6552/ab6952

Nixon, R. S., Hill, K. M., & Luft, J. A. (2017). Secondary Science Teachers' Subject Matter Knowledge Development Across the First 5 Years. *Journal of Science Teacher Education*, *28*(7), 574–589. https://doi.org/10.1080/1046560X.2017.1388086

Nousiainen, M. (2013). Coherence of pre-service physics teachers' views of the relatedness of physics concepts. *Science & Education*, *22*(3), 505–525.

Novak, J. D. (1985). Concept mapping as an educational tool. *New Horizons for Learning's On The Beam*, *5*(2), 4–5.

Novak, J. D. (2010). *Learning, Creating, and Using Knowledge* (0 ed.). Routledge. https://doi.org/10.4324/9780203862001

Novak, J. D., & Cañas, A. J. (2008). *The Theory Underlying Concept Maps and How to Construct and Use Them* (p. 36) [Technical report]. Institute for Human and Machine Cognition. http://cmap.ihmc.us/Publications/ResearchPapers/TheoryUnderlyingConceptMaps.pdf

O'Donnell, A. M., Dansereau, D. F., & Hall, R. H. (2002). Knowledge Maps as Scaffolds for Cognitive Processing. *Educational Psychology Review*, *14*(1), 71–86. https://doi.org/10.1023/A:1013132527007

OECD. (2016). *PISA 2015 Results (Volume I): Excellence and Equity in Education*. OECD. https://doi.org/10.1787/9789264266490-en

OECD. (2019). *TALIS 2018 results (Volume 1): Teachers and School Leaders as Lifelong Learners*. Organisation for Economic Cooperation and Development (OECD).

Ohle, A., Fischer, H. E., & Kauertz, A. (2011). Der Einfluss des physikalischen Fachwissens von Primarstufenlehrkräften auf Unterrichtsgestaltung und Schülerleistung. *Zeitschrift Für Didaktik Der Naturwissenschaften*, *17*(2), 357–389.

Okoli, C., & Pawlowski, S. D. (2004). The Delphi method as a research tool: An example, design considerations and applications. *Information & Management*, *42*(1), 15–29. https://doi.org/10.1016/j.im.2003.11.002

Olsen, R. V. (2002). Introducing quantum mechanics in the upper secondary school: A study in Norway. *International Journal of Science Education*, *24*(6), 565–574. https://doi.org/10.1080/09500690110073982

Osborne, J., Collins, S., Ratcliffe, M., Millar, R., & Duschl, R. (2003). What "ideas-about-science" should be taught in school science? A Delphi study of the expert community. *Journal of Research in Science Teaching*, *40*(7), 692–720. https://doi.org/10.1002/tea.10105

Osborne, J., Ratcliffe, M., Collins, S., Millar, R., & Duschl, R. (2001). *What should we teach about science? A Delphi study*. Evidence-based Practice in Science Education (EPSE).

Owens, D. C., Sadler, T. D., Murakami, C. D., & Tsai, C.-L. (2018). Teachers' views on and preferences for meeting their professional development needs in STEM. *School Science and Mathematics*, *118*(8), 370–384. https://doi.org/10.1111/ssm.12306

Park Rogers, M. A., Abell, S., Lannin, J., Wang, C., Musikul, K., Barker, D., & Dinkman, S. (2007). Effective professional development in science and mathematics education: Teachers' and facilitators' views. *International Journal of Science and Mathematics Education*, *5*(3), 507–532.

Park, S., & Oliver, J. S. (2008). Revisiting the Conceptualisation of Pedagogical Content Knowledge (PCK): PCK as a Conceptual Tool to Understand Teachers as Professionals. *Research in Science Education*, *38*(3), 261–284. https://doi.org/10.1007/s11165-007-9049-6

Park, W., Yang, S., & Song, J. (2019). When Modern Physics Meets Nature of Science: The Representation of Nature of Science in General Relativity in New Korean Physics

Textbooks. *Science & Education*, *28*(9–10), 1055–1083. https://doi.org/10.1007/s11191-019-00075-9

Passon, O. (2020). Mystifizierung der Quantenmechanik und Trivialisierung der Teilchenphysik. In O. Passon, T. Zügge, & J. Grebe-Ellis (Eds.), *Kohärenz im Unterricht der Elementarteilchenphysik: Tagungsband des Symposiums zur Didaktik der Teilchenphysik, Wuppertal 2018* (pp. 79–90). Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-662-61607-9_5

Pavlidou, M., & Lazzeroni, C. (2016). Particle physics for primary schools—Enthusing future physicists. *Physics Education*, *51*(5), 054003. https://doi.org/10.1088/0031-9120/51/5/054003

Pena-Lopez, I. (2009). *Creating Effective Teaching and Learning Environments: First Results from TALIS*. Organisation for Economic Cooperation and Development (OECD).

Penuel, W. R., Fishman, B. J., Yamaguchi, R., & Gallagher, L. P. (2007). What makes professional development effective? Strategies that foster curriculum implementation. *American Education Research Journal*, *44*(4), 921–958.

Penuel, W. R., Gallagher, L. P., & Moorthy, S. (2011). Preparing Teachers to Design Sequences of Instruction in Earth Systems Science: A Comparison of Three Professional Development Programs. *American Educational Research Journal*, *48*(4), 996–1025. https://doi.org/10.3102/0002831211410864

Polen, C. (2019). Particle Physics: An Essential and Engaging Part of the High School Physics Program. *The Physics Teacher*, *57*(5), 320–322. https://doi.org/10.1119/1.5098922

Porter, R. E., Fusarelli, L. D., & Fusarelli, B. C. (2015). Implementing the Common Core: How Educators Interpret Curriculum Reform. *Educational Policy*, *29*(1), 111–139. https://doi.org/10.1177/0895904814559248

Powell, C. (2003). The Delphi technique: Myths and realities. *Journal of Advanced Nursing*, *41*(4), 376–382. https://doi.org/0.1046/j.1365-2648.2003.02537.x

Qian, Y., Hambrusch, S., Yadav, A., & Gretter, S. (2018). Who Needs What: Recommendations for Designing Effective Online Professional Development for Computer Science Teachers. *Journal of Research on Technology in Education*, *50*(2), 164–181. https://doi.org/10.1080/15391523.2018.1433565

Reeves, G., & Jauch, L. R. (1987). Curriculum development through Delphi. *Research in Higher Education*, *8*(2), 157–168.

Reiss, M. J., & White, J. (2013). *An aims-based curriculum: The significance of human flourishing for schools*. Institute of Education Press.

Reiss, M. J., & White, J. (2014). An aims-based curriculum illustrated by the teaching of science in schools. *The Curriculum Journal*, *25*(1), 76–89. https://doi.org/10.1080/09585176.2013.874953

Remillard, J. T. (2005). Examining Key Concepts in Research on Teachers' Use of Mathematics Curricula. *Review of Educational Research*, *75*(2), 211–246. https://doi.org/10.3102/00346543075002211

Richardson, V. (1996). The role of attitudes and beliefs in learning to teach. *Handbook of Research on Teacher Education*, *2*(102–119), 273–290.

Riese, J. (2009). *Professionelles Wissen und professionelle Handlungskompetenz von (angehenden) Physiklehrkräften*. Logos Verlag.

Riese, J., Kulgemeyer, C., Zander, S., Borowski, A., Fischer, H. E., Gramzow, Y., Reinhold, P., Schecker, H., & Tomczyszyn, E. (2015). Modellierung und Messung des Professionswissens in der Lehramtsausbildung Physik. In S. Blömeke & O. Zlatkin-Troitschanskaia (Eds.), *Kompetenzen von Studierenden: 61. Beiheft der Zeitschrift für Pädagogik* (pp. 55–79). Beltz.

Rivkin, S. G., Hanushek, E. A., & Kain, J. F. (2005). Teachers, Schools, and Academic Achievement. *Econometrica*, *73*(2), 417–458. https://doi.org/10.1111/j.1468-0262.2005.00584.x

Roberts, K., Dowell, A., & Nie, J.-B. (2019). Attempting rigour and replicability in thematic analysis of qualitative research data; a case study of codebook development. *BMC Medical Research Methodology*, *19*(1), 66. https://doi.org/10.1186/s12874-019-0707-y

Rokeach, M. (1973). *The nature of human values.* Free press.

Romero, C., Cazorla, M., & Buzón, O. (2017). Meaningful learning using concept maps as a learning strategy. *Journal of Technology and Science Education*, *7*(3), 313. https://doi.org/10.3926/jotse.276

Roth, K. J., Garnier, H. E., Chen, C., Lemmens, M., Schwille, K., & Wickler, N. I. Z. (2011). Videobased lesson analysis: Effective science PD for teacher and student learning. *Journal of Research in Science Teaching*, *48*(2), 117–148. https://doi.org/10.1002/tea.20408

Rowe, G., & Wright, G. (1999). The Delphi technique as a forecasting tool: Issues and analysis. *International Journal of Forecasting*, *15*(4), 353–375.

Rowe, G., Wright, G., & Bolger, F. M. I. (2011). Delphi: A reevaluation of research and theory. *Technological Forecasting and Social Change*, *39*(3), 235–251. https://doi.org/10.1016/0040-1625(91)90039-I

Ruiz-Primo, M. A. (2000). On the use of concept maps as an assessment tool in science: What we have learned so far. *REDIE. Revista Electrónica de Investigación Educativa*, *2*(1), 29–53.

Ruiz-Primo, M. A. (2004). *Examining concept maps as an assessment tool*. 555–562.

Ruiz-Primo, M. A., & Shavelson, R. J. (1996). Problems and issues in the use of concept maps in science assessment. *Journal of Research in Science Teaching*, *33*(6), 569–600.

Sadler, P. M., Sonnert, G., Coyle, H. P., Cook-Smith, N., & Miller, J. L. (2013). The Influence of Teachers' Knowledge on Student Learning in Middle School Physical Science Classrooms. *American Educational Research Journal*, *50*(5), 1020–1049. https://doi.org/10.3102/0002831213477680

Samarawickrema, G., & O'Reilly, J. (2003). Using concept maps to improve the quality of learning law at a distance. In *Quality education@ a distance* (pp. 161–168). Springer.

Sanders, L. R., Borko, H., & Lockard, J. D. (1993). Secondary science teachers' knowledge base when teaching science courses in and out of their area of certification. *Journal of Research in Science Teaching*, *30*(7), 723–736. https://doi.org/10.1002/tea.3660300710

Sands, D., Parker, M., Hedgeland, H., Jordan, S., & Galloway, R. (2018). Using concept inventories to measure understanding. *Higher Education Pedagogies*, *3*(1), 173–182. https://doi.org/10.1080/23752696.2018.1433546

Schleicher, S., Hunt, A., Brophy, S., Garay, C., Paschal, C., & Klein-Gardner, S. (2005). Teaching X Ray Imaging In The High School Physics Classroom: Safe, Inexpensive And Hands On Instruction. *2005 Annual Conference Proceedings*, 10.1239.1-10.1239.9. https://doi.org/10.18260/1-2--14159

Schneider, R. M. (2019). Illustrating and Developing Science Teachers' Pedagogical Content Knowledge Through Learning Study. In A. Hume, R. Cooper, & A. Borowski (Eds.), *Repositioning Pedagogical Content Knowledge in Teachers' Knowledge for Teaching Science* (pp. 167–186). Springer Singapore. https://doi.org/10.1007/978-981-13-5898-2_7

Schuster, D. A., & Carlsen, W. S. (2009). Scientists' teaching orientations in the context of teacher professional development. *Science Education*, *93*(4), 635–655.

Schwartz, R. S., & Lederman, N. (2008). What Scientists Say: Scientists' views of Nature of Science and relation to science context. *International Journal of Science Education*, *30*(6), 727–771. https://doi.org/10.1080/09500690701225801

Schwartz, R. S., & Lederman, N. G. (2002). 'It's the nature of the beast': The influence of knowledge and intentions on learning and teaching Nature of Science. *Journal of Research in Science Teaching*, *39*(3), 205–236. https://doi.org/10.1002/tea.10021

Schwartz, R. S., Lederman, N. G., & Crawford, B. A. (2004). Developing views of Nature of Science in an authentic context: An explicit approach to bridging the gap between Nature of Science and scientific inquiry. *Science Education*, *88*(4), 610–645. https://doi.org/10.1002/sce.10128

Şen, M., Öztekin, C., & Demirdöğen, B. (2018). Impact of Content Knowledge on Pedagogical Content Knowledge in the Context of Cell Division. *Journal of Science Teacher Education*, *29*(2), 102–127. https://doi.org/10.1080/1046560X.2018.1425819

Shallcross, T., Spink, E., Stephenson, P., & Warwick, P. (2002). How primary trainee teachers perceive the development of their own scientific knowledge: Links between confidence, content and competence? *International Journal of Science Education*, *24*(12), 1293–1312. https://doi.org/10.1080/09500690110110106

Shavelson, R. J. (1993). *On Concept Maps as Potential" Authentic" Assessments in Science. Indirect Approaches to Knowledge Representation of High School Science.*

Shulman, L. S. (1986). Those Who Understand: Knowledge Growth in Teaching. *Educational Researcher*, *15*(2), 4–14. https://doi.org/10.3102/0013189X015002004

Shulman, L. S. (1987). Knowledge and Teaching:Foundations of the New Reform. *Harvard Educational Review*, *57*(1), 1–23. https://doi.org/10.17763/haer.57.1.j463w79r56455411

Siqueira, M. (2017). Elementary Particle Physics for High Schools. In M. Pietrocola & I. Gurgel (Eds.), *Crossing the Border of the Traditional Science Curriculum: Innovative Teaching and Learning in Basic Science Education* (pp. 23–43). SensePublishers.

Sirola, C. (2018). May the forces be with you! *The Physics Teacher*, *56*(2), 118–119. https://doi.org/10.1119/1.5021444

Sjøberg, S., & Schreiner, C. (2010). *The ROSE project: An overview and key findings*. Oslo: University of Oslo. http://www.cemf.ca/%5C/PDFs/SjobergSchreinerOverview2010.pdf

Sjøberg, S., & Schreiner, C. (2012). *Results and Perspectives from the ROSE Project: Attitudinal aspects of young people and science in a comparative perspective* (pp. 203–236). Brill. https://brill.com/view/book/edcoll/9789460919008/BP000010.xml

Smith, C., & Gillespie, M. (2007). Research on professional development and teacher change: Implications for adult basic education. *Review of Adult Learning and Literacy*, *7*(7), 205–244.

Smyth, J. D., Olson, K., & Burke, A. (2018). Comparing survey ranking question formats in mail surveys. *International Journal of Market Research*, *60*(5), 502–516. https://doi.org/10.1177/1470785318767286

Son, J.-W., & Kim, O.-K. (2016). Curriculum enactment patterns and associated factors from teachers' perspectives. *Mathematics Education Research Journal*, *28*(4), 585–614. https://doi.org/10.1007/s13394-016-0181-3

Sorge, S., Stender, A., & Neumann, K. (2019). The Development of Science Teachers' Professional Competence. In A. Hume, R. Cooper, & A. Borowski (Eds.), *Repositioning Pedagogical Content Knowledge in Teachers' Knowledge for Teaching Science* (pp. 149–164). Springer Singapore. https://doi.org/10.1007/978-981-13-5898-2_1

Stadermann, H. K. E., & Goedhart, M. J. (2021). Why and how teachers use Nature of Science in teaching quantum physics: Research on the use of an ecological teaching intervention in upper secondary schools. *Physical Review Physics Education Research*, *17*(2), 020132. https://doi.org/10.1103/PhysRevPhysEducRes.17.020132

Stadermann, H. K. E., van den Berg, E., & Goedhart, M. J. (2019). Analysis of secondary school quantum physics curricula of 15 different countries: Different perspectives on a challenging topic. *Physical Review Physics Education Research*, *15*(1), 010130. https://doi.org/10.1103/PhysRevPhysEducRes.15.010130

Strunk, A., Gazdovich, J., Redouté, O., Reverte, J. M., Shelley, S., & Todorova, V. (2018). Model PET Scan Activity. *The Physics Teacher*, *56*(5), 278–280. https://doi.org/10.1119/1.5033868

Swinbank, E. (1992). Particle physics: A new course for schools and colleges. *Physics Education*, *27*(2), 87–91. https://doi.org/10.1088/0031-9120/27/2/006

Tatto, M., & Menter, I. (2019). The significance of teacher education. *Knowledge, Policy and Practice in Teacher Education: A Cross-National Study*, 9–20.

Taylor, A. R., Jones, M. G., Broadwell, B., & Oppewal, T. (2008). Creativity, inquiry, or accountability? Scientists' and teachers' perceptions of science education. *Science Education*, *92*(6), 1058–1075. https://doi.org/10.1002/sce.20272

Tchoshanov, M. A. (2011). Relationship between teacher knowledge of concepts and connections, teaching practice, and student achievement in middle grades mathematics. *Educational Studies in Mathematics*, *76*(2), 141–164. https://doi.org/10.1007/s10649-010-9269-y

Torre, D. M., Daley, B., Stark-Schweitzer, T., Siddartha, S., Petkova, J., & Ziebert, M. (2007). A qualitative evaluation of medical student learning with concept maps. *Medical Teacher*, *29*(9–10), 949–955. https://doi.org/10.1080/01421590701689506

Touretzky, D., Gardner-McCune, C., Martin, F., & Seehorn, D. (2019). Envisioning AI for K-12: What Should Every Child Know about AI? Proceedings of the AAAI Conference on Artificial Intelligence, 33, 9795–9799. https://doi.org/10.1609/aaai.v33i01.33019795

Trotter, Y. D. (2006). Adult learning theories: Impacting professional development programs. *Delta Kappa Gamma Bulletin*, *72*(2).

Turoff, M. (1975). The Policy Delphi. In *The Delphi Method: Techniques and Applications* (pp. 80–96). Addison-Wesley Educational Publishers Inc.

Tuzón, P., & Solbes, J. (2016). Particle Physics in High School: A Diagnose Study. *PLOS ONE*, *11*(6), e0156526. https://doi.org/10.1371/journal.pone.0156526

van den Akker, J. (2004). Curriculum Perspectives: An Introduction. In J. van den Akker, W. Kuiper, & U. Hameyer, *Curriculum Landscapes and Trends* (pp. 1–10). Springer Netherlands. https://doi.org/10.1007/978-94-017-1205-7_1

Van Driel, J. H., & Berry, A. (2012). Teacher Professional Development Focusing on Pedagogical Content Knowledge. *Educational Researcher*, *41*(1), 26–28. https://doi.org/10.3102/0013189X11431010

Van Duzor, A. G. (2012). Evidence that Teacher Interactions with Pedagogical Contexts Facilitate Chemistry-Content Learning in K-8 Professional Development. *Journal of Science Teacher Education*, *23*(5), 481–502.

Walwema, G. B., French, D. A., Verley, J. D., & Burrows, A. C. (2016). Is classical mechanics a prerequisite for learning physics of the 20th century? *Physics Education*, *51*(6), 065022. https://doi.org/10.1088/0031-9120/51/6/065022

Watson, M. K., Pelkey, J., Noyes, C. R., & Rodgers, M. O. (2016). Assessing Conceptual Knowledge Using Three Concept Map Scoring Methods: Assessing Conceptual Knowledge Using Concept Map Scoring. *Journal of Engineering Education*, *105*(1), 118–146. https://doi.org/10.1002/jee.20111

Wenning, C., Wester, K., Donaldson, N., Henning, S., Holbrook, T., Jabot, M., MacIsaac, D., Merrell, D., Riendeau, D., & Truedson, J. (2011). Professional knowledge standards for physics teacher educators: Recommendations from the CeMaST Commission on NIPTE. *Journal of Physics Teacher Education Online*, *6*(1), 1–7.

Wheeldon, R., Atkinson, R., Dawes, A., & Levinson, R. (2012). Do high school chemistry examinations inhibit deeper level understanding of dynamic reversible chemical reactions? *Research in Science & Technological Education*, *30*(2), 107–130. https://doi.org/10.1080/02635143.2012.692362

Wiener, G. J., Schmeling, S. M., & Hopf, M. (2017a). Introducing 12 year-olds to elementary particles. *Physics Education*, *52*(4), 044001. https://doi.org/10.1088/1361-6552/aa6cfe

Wiener, G. J., Schmeling, S. M., & Hopf, M. (2017b). An Alternative Proposal for the Graphical Representation of Anticolor Charge. *The Physics Teacher*, *55*(8), 472–474. https://doi.org/10.1119/1.5008340

Wiener, G. J., Schmeling, S. M., & Hopf, M. (2018). The technique of probing acceptance as a tool for teachers' professional development: A PCK study. *Journal of Research in Science Teaching*, *55*(6), 849–875. https://doi.org/10.1002/tea.21442

Wiener, G. J., Woithe, J., Brown, A., & Jende, K. (2016). Introducing the LHC in the classroom: An overview of education resources available. *Physics Education*, *51*(3), 035001. https://doi.org/10.1088/0031-9120/51/3/035001

Wilcox, B. R., & Lewandowski, H. J. (2017). Students' views about the nature of experimental physics. *Physical Review Physics Education Research*, *13*(2), 020110. https://doi.org/10.1103/PhysRevPhysEducRes.13.020110

Wiles, J. (2009). *Leading curriculum development*. Corwin Press.

Wilkins, J. L. M. (2008). The relationship among elementary teachers' content knowledge, attitudes, beliefs, and practices. *Journal of Mathematics Teacher Education*, *11*(2), 139–164. https://doi.org/10.1007/s10857-007-9068-2

Williams, D. L., Boone, R., & Kingsley, K. V. (2004). Teacher Beliefs About Educational Software: A Delphi Study. *Journal of Research on Technology in Education*, *36*(3), 213–229. https://doi.org/10.1080/15391523.2004.10782413

Woithe, J., & Kersting, M. (2021). Bend it like dark matter! *Physics Education*, *56*(3), 035011.

Woithe, J., Wiener, G. J., & Van der Veken, F. F. (2017). Let's have a coffee with the Standard Model of particle physics! *Physics Education*, *52*(3), 034001. https://doi.org/10.1088/1361-6552/aa5b25

Wong, S. L., Kwan, J., Hodson, D., & Yung, B. H. W. (2009). Turning Crisis into Opportunity: Nature of Science and Scientific Inquiry as Illustrated in the Scientific Research on Severe Acute Respiratory Syndrome. *Science & Education*, *18*(1), 95–118. https://doi.org/10.1007/s11191-007-9123-5

Wu, H. (2011). The mis-education of mathematics teachers. *Notices of the AMS*, *58*(3), 372–384.

Xu, B., Su, J., & Wang, W. (2018). An expanding balloon: A small universe. *Physics Education*, *53*(6), 065005. https://doi.org/10.1088/1361-6552/aad71f

Yin, Y., Vanides, J., Ruiz-Primo, M. A., Ayala, C. C., & Shavelson, R. J. (2005). Comparison of two concept-mapping techniques: Implications for scoring, interpretation, and use. *Journal of Research in Science Teaching*, *42*(2), 166–184. https://doi.org/10.1002/tea.20049

Young, M. (2014). What is a curriculum and what can it do? *The Curriculum Journal*, *25*(1), 7–13. https://doi.org/10.1080/09585176.2014.902526

Zepeda, S. J. (2013). *Professional Development: What Works.* Taylor and Francis.

Ziebell, N., & Clarke, D. (2018). Curriculum Alignment: Performance Types in the Intended, Enacted, and Assessed Curriculum in Primary Mathematics and Science Classrooms. *Studia Paedagogica*, *23*(2), 175. https://doi.org/10.5817/SP2018-2-10

LIST OF ABBREVIATIONS

CCC	Common curricular concepts
CCK	Common content knowledge
CCT	Common curricular topics
CERN	European Organization for Nuclear Research
CK	Content knowledge
DSK	Deeper school knowledge
EPP	Explicit particle physics
IB	International Baccalaureate
IPP	Implicit particle physics
LHC	Large Hadron Collider
PCK	Pedagogical content knowledge
PDP	Professional development programmes
PK	Pedagogical knowledge
SK	School knowledge
UK	University knowledge

APPENDICES

Appendix A: Other Outcomes of the Delphi Study

1. Activities

Importance level	Activity
High importance	Hands-on workshops
	Guided tours
Medium importance	Networking with other teachers
	Networking with scientists
	Lectures
	Question-and-answer sessions
	Demonstrations of experiments
	Work in groups
	Data analysis workshops
Low importance	Theory workshops
	Other

2. Resources for teachers to prepare for participation in a professional development programme

Importance level	Preparation resource
High importance	Illustrated textbooks
Medium importance	Educational websites in STEM
	Educational videos
	Online courses
	Animations
	Simulations
Low importance	Other

3. Classrooms resources for teachers to take back home

Importance level	Classroom resource
High importance	Illustrated textbooks
Medium importance	Animations and simulations
	Instructions and materials for experiments
	Educational videos
	Online courses
	Student worksheets
	Editable slideshow presentations
Low importance	Lesson plans
	Souvenirs
	Other

4. Follow-up activities

Importance level	Follow-up activity
High importance	Workshops in home countries
	Online platform for teachers of the same programme
Medium importance	Joint projects with other teachers
	Online platform for teachers of all programmes
	Real or virtual visits to CERN
	Video conferences with physicists and educational researchers
	Lesson studies
Low importance	Reflection on the programme
	Other

5. Impact of CERN's teacher programmes

a) Impact on **students**

Importance	**Impact**
High importance	Students become more motivated.
Medium importance	More students want to study science.
Low importance	Students are aware of the diversity in science.

b) Impact on **teachers**

Importance	**Impact**
High importance	Teachers become more motivated.
Medium importance	Teachers know and use new teaching methods.
	Teachers have a professional connection with other teachers.
	Teachers are aware of diversity in science.
Low importance	Teachers have a professional connection with scientists.

c) Impact on **curriculum**

Importance	**Impact**
High importance	Modern physics is included as context in existing curriculum.
Medium importance	Modern physics is included as part of enacted curriculum.
	Modern physics is included through extracurricular activities.
Low importance	Modern physics is included in the national curriculum.

d) Impact on **general public**

Importance	**Impact**
High importance	General public is more aware of the importance of research.
Medium importance	General public uses scientific thinking more often.
Low importance	General public is aware of diversity and opportunities in science.

Appendix B: Curricular Documents

Country code	Country	Curriculum type	Curriculum document
AT	Austria	Upper secondary school	Austrian Federal Ministry of Education, Science and Research. (2018). Gesamte Rechtsvorschrift für Lehrpläne—allgemeinbildende höhere Schulen, Gymnasium Physik. Retrieved from: https://www.ris .bka.gv.at/GeltendeFassung.wxe?Abfrage =Bundesnormen&Gesetzesnummer=10008568
AU-QL	Australia - Queensland	Senior secondary school	Queensland Curriculum and Assessment Authority (2019). Physics 2019 v1.2. Retrieved from: https://www.qcaa.qld.edu.au/senior/senior-subjects/sciences/physics/syllabus
BR	Brasil	High school	Area ciências da natureza. https://efape.educacao.sp.gov.br/curriculopaulista/wp-content/uploads/2021/01/TEMPLATE-Divisão-Habilidades-por-Ciências-da-Natureza-e-suas-Tecnologias-1º-Série-EM.pdf
CA-MB	Canada - Manitoba	Senior high school	Manitoba Departement of Education and Youth (2003). Senior 3 Physics. A Foundation for Implementation. Retrieved from: https://www.edu.gov.mb.ca/k12/cur/science/found/physics30s/full_doc.pdf
CH-NW	Switzerland - Nidwalden	Secondary school	Amt für Berufsbildung und Mittelschule (2020). Lehr- und Stoffplan. Retrieved from: https://www.kollegistans.ch/mittelschule/lehr-und-stoffplan-des-kollegiums-st-fidelis/
DE-BB	Germany - Brandenburg	Upper secondary school	Ministerium für Bildung, Jugend und Sport Land Brandenburg (2018). Rahmenlehrplan für den Unterricht in der gymnasialen Oberstufe im Land Brandenburg. Retrieved from: https://bildungsserver.berlin-brandenburg.de/fileadmin/bbb/unterricht/rahmenlehrplaene/gymnasiale_oberstufe/curricula/2018/RLP_GOST_Physik_BB_2018.pdf
DE-BW	Germany - Baden-Württemberg	Upper secondary school	Ministerium für Kultus, Jugend un Sport (2016). Physik. Retrieved from: http://www.bildungsplaene-bw.de/site/bildungsplan/get/documents/lsbw/export-pdf/depot-pdf/ALLG/BP2016BW_ALLG_GMSO_PH.pdf
DE-SN	Germany - Saxony	Upper secondary school	Staatsministeriums fur Kultus (2019). Lehrplan Oberschule. Physik. Retrieved from: http://lpdb.schule-sachsen.de/lpdb/web/downloads/54_lp_os_physik_2019.pdf?v2
ES	Spain	Baccalaureate	Ministerio de educacion, cultura y deporte (2015). Boletin oficial del estado. Retrieved from: https://www.boe.es/boe/dias/2015/01/03/pdfs/BOE-A-2015-37.pdf
FR	France	Upper secondary school	Ministère de l'éducation nationale, de la jeunesse et des sports (2019). Programme de physique-chimie de terminale générale. Retrieved from: https://cache.media.education.gouv.fr/file/SPE8_MENJ_25_7_2019/92/9/spe249_annexe_1158929.pdf

Country code	Country	Curriculum type	Curriculum document
GH	Ghana	Senior high school	Ministry of education (2010). Teaching syllabus for physics (senior high school 1-3). Retrieved from: https://mingycomputersgh.files.wordpress.com/2015/03/elective-physics-syallbus-14-10-10.pdf
GR	Greece	General high school	Ministry of Education and Religious Affairs. Institute of Educationa Policy (2020). Material and instructions for the teaching of Physical Sciences (Physics, Chemistry, Biology) in grades A, B and C of the General High School. Retrieved from: http://iep.edu.gr/el/graf-b-yliko/geniko-lykeio
HR	Croatia	General gymnasium	Ministarstvo znanosti i obrazovanja (2019). Kurikulum nastavnog predmeta fizika za osnovne škole i gimnazije. Retrieved from: https://narodne-novine.nn.hr/clanci/sluzbeni/2019_01_10_210.html
IL	Israel	Extended secondary school	Ministry of Education (2009). Retrieved from: https://edu.gov.il/special/Curriculum/High-School/physics/Pages/Syllabus.aspx
IT	Italy	Scientific secondary school (liceo scientifico)	Ministero dell'istruzione, dell'università e della ricerca (2010). Retrieved from: https://www.isnitti.edu.it/menu_didattica/nota_liceo.pdf
LB	Lebanon	Secondary school	Center of Educational Research and Development. (1997). Curriculum Decree & General Target. CRDP.
NL	Netherlands	Pre-university high school (VWO)	College voor Toetsen en Examens (2019). Syllabus centraal examen 2021. Retrieved from: https://www.examenblad.nl/examen/natuurkunde-vwo-2/2021
PL	Poland	Technical secondary school	Ministerstwo Edukacji Narodowej (2018). Fizyka. Liceum/technikum. Retrieved from: https://podstawaprogramowa.pl/Liceum-technikum/Fizyka
RU	Russia	Secondary school	Ministry of Education of the Russian Federation (2017). Federal component of the state standard of general education.
SA	South Africa	Advanced placement secondary school	Independent Examinations Board (2019). Advanced Programme Physics. Retrieved from: https://www.ieb.co.za/pages/resources
SE	Sweden	Gymnasium	Swedish National Agency for Education (2020). Fysik. Retrieved from: https://www.skolverket.se/undervisning/vuxenutbildningen/komvux-gymnasial/laroplan-for-vux-och-amnesplaner-for-komvux-gymnasial/amne?url=1530314731%2Fsyllabuscw%2Fjsp%2Fsubject.htm%3FsubjectCode%3DFYS%26tos%3Dvuxgy%26p%3Dp&sv.url=12.b173ee8160557dd0b8100d
SI	Slovenia	General gymnasium	Ministrstvo za šolstvo, znanost in šport (2017). Učni načrt. Splošna gimnazija. Fizika. 2. popravljena izdaja. Retrieved from: http://eportal.mss.edus.si/msswww/programi2017/programi/media/pdf/un_gimnazija/2015/UN-FIZIKA-gimn-12.pdf

Country code	Country	Curriculum type	Curriculum document
SK	Slovakia	Grammar school	Štátny inštitút odborného vzdelávania (2019). Fyzika. https://siov.sk/wp-content/uploads/2019/06/B10_VO_ČaP_FY_CH_BI.pdf
SR	Serbia	Mathematical and scientific gymnasium	Ministarstvo prosvete, nauke i tehnološkog razvoja (2018). Наставни план и програм за обдарене ученике у Математичкој гимназији. Retrieved from: https://www.mpn.gov.rs/wp-content/uploads/2018/02/Правилник-о-наставном-плану-и-програму-за-обдарене-ученике-у-Математичкој-гимназији.pdf
UK	United Kingdom	Secondary school (A levels)	AQA Education (2017). AS and A-level physics. Retrieved from https://filestore.aqa.org.uk/resources/physics/specifications/AQA-7407-7408-SP- 2015.PDF
US	United States	High schools (NGSS)	National Academy of Sciences (2013). Next Generation Science Standards. Retrieved from: https://www.nextgenscience.org
IB	International Baccalaureate	Higher level	International Baccalaureate Organization. (2014). Diploma programme physics guide: First assessment 2016. Cardiff, Wales: International Baccalaureate Organization (UK) Ltd. http://www.holyheart.ca/wp-content/uploads/2016/10/IB-Physics-Guide-2016.pdf

Appendix C: Codebook

Category	Topic	Concept	Guideline for using the code
Particle physics	Cosmology	Big Bang	Curriculum mentions Big Bang or the beginning of the Universe.
		Inflation	Curriculum mentions the inflation of the early Universe.
		Expansion	Curriculum mentions the continuous expansion of the Universe or the red shift.
	Standard Model		Curriculum explicitly mentions the Standard Model of particle physics.
	Fundamental interactions	EM interaction	Curriculum mentions at least one of the following: electromagnetic force or electromagnetic interaction (in the context of particle physics), electric charge (in the context of particle physics), photon (as an interaction particle for electromagnetic interaction).
		Strong interaction	Curriculum mentions at least one of the following: strong interaction, strong nuclear force, strong force (as a nomenclature for this particle interaction), colour force, gluons.
		Weak interaction	Curriculum mentions at least one of the following: weak interaction, weak nuclear force, weak force (as a nomenclature for this particle interaction), W & Z bosons.
		Gravity in PP	Curriculum mentions at least one of the following: gravity (in the context of particle physics), gravitational force (in the context of particle physics), gravitational interaction (in the context of particle physics), graviton.
	Charges	Electric charge	Curriculum mentions electric charge.
		Strong charge	Curriculum mentions strong charge or colour charge.
		Weak charge	Curriculum mentions weak charge.
	Elementary particles	Quarks	Curriculum mentions quarks or at least one of the following: up quark, down quark, strange quark, charm quark, top quark, bottom quark, anti-(up quark, down quark, etc.).
		Leptons	Curriculum mentions leptons or at least one of the following: electron, muon, tauon, neutrino, electron neutrino, muon neutrino, tauon neutrino, anti-(electron, muon, etc.).
	Interaction particles	Bosons	Curriculum mentions bosons or at least one of the following: photons (as interaction particles), W bosons, Z bosons, gluons, gauge bosons.
	Brout-Englert-Higgs mechanism		Curriculum mentions at least one of the following: Brout-Englert-Higgs mechanism, Higgs mechanism, Brout-Englert-Higgs field, Higgs field, interaction of particles with the Brout-Englert-Higgs field through which the particles can gain mass, Higgs boson or Higgs particle.

Category	Topic	Concept	Guideline for using the code
Particle physics (continued)	Particle transformations		Curriculum mentions at least one of the following: particle transformation, particle decay, beta decay, alpha decay, particle annihilation, pair production.
	Feynman diagrams		Curriculum mentions at least one of the following: Feynman diagrams, particle interaction diagrams, reaction diagrams (in the context of particle physics).
	Antimatter research		Curriculum mentions at least one of the following: antiparticles, antiquarks, anti-(up, down, …, muon, …), positron, annihilation, beta+ decay, positron emission, positron emission tomography, antimatter, the mystery of antimatter, anti-hydrogen, antimatter research, matter-antimatter asymmetry, baryon asymmetry, etc.
	Particle accelerators	Linear accelerator	Curriculum mentions at least one of the following: linear particle accelerator, linear accelerator, linac. Curriculum can also mention specific examples: SLAC, LINAC4 etc.
		Circular accelerator	Curriculum mentions at least one of the following: circular particle accelerator, synchrotron, particle collider. Curriculum can mention examples: LHC, SPS etc.
		Particle acc. (general)	Curriculum mentions particle accelerators without specifying the type of the particle accelerator.
	Particle detector	Historical detectors	Curriculum mentions at least one of the following: historical particle detectors, cloud chamber, bubble chamber, spark chamber, Geiger-Müller tube (or counter).
		Modern detectors	Curriculum mentions modern particle detectors. Curriculum can also mention specific examples: ATLAS, CMS, ALICE, CDF, ZEUS, AMS, Super-Kamiokande …
		Particle det. (general)	Curriculum mentions particle detectors without specifying the type or an example of the detector.
	Data storage and data analysis		Curriculum mentions at least one of the following in the context of modern (particle) physics: data, big data, data analysis, analysis, statistical methods, statistical tools, sigma, signal, measurements, background (in context of measurements in particle physics), data storage, big data, www, internet, cloud, data centre, magnetic strip tape.
	Advances in particle physics	Experimental results	Curriculum encourages teachers to keep up with the latest experimental results in particle physics.
		Open questions	Curriculum mentions at least one of the following: string theory, supersymmetry, dark matter, dark energy, grand unifying theory, limitations of the Standard Model, the limitations of the Big Bang theory, baryon asymmetry, matter-antimatter asymmetry, quantum gravity.
	Real-life applications of particle physics		Curriculum mentions at least one of the following in the context of particle physics: medical applications, medical accelerators, hadron therapy, proton therapy, positron emission tomography, radiation therapy, X-rays, WWW, touchscreens, modern technology, computer science, material science, cryogenics, security scans, solenoid magnets, superconductors, data processing devices.

Category	**Topic**	**Concept**	**Guideline for using the code**
Other curricular topics	Mechanics	Linear motion	Curriculum mentions linear motion, straight line motion or rectilinear motion.
		Circular motion	Curriculum mentions circular motion or angular motion.
	Gravity	Newtonian gravity	Curriculum mentions at least one of the following: gravity, gravitational force, gravitational interaction.
		Einsteinian gravity	Curriculum mentions at least one of the following: curvature of space-time, general relativity, general theory of relativity, gravitational lensing.
	Conservation laws (of)	Energy	Curriculum mentions conservation of energy, regardless of the type of energy that is being conserved.
		Linear momentum	Curriculum mentions conservation of momentum in the context of linear momentum.
		Angular momentum	Curriculum mentions conservation of angular momentum.
		Charges	Curriculum mentions conservation of charges.
	Thermodynamics	Particle model	Curriculum mentions at least one of the following: the particle model of matter (in the context of thermodynamics), the kinetic theory of gasses, particle model of ideal gas.
		Phase transitions	Curriculum mentions any of the phase transitions or phase transitions in general.
		Vacuum	Curriculum mentions vacuum. Do not code unless vacuum is explicitly mentioned in the curriculum.
	Electromagnetism (EM)	Electric fields	Curriculum mentions the homogeneous or non-homogeneous electric fields, or interaction between electric field and particles.
		Magnetic fields	Curriculum mentions the interaction between homogeneous or non-homogeneous magnetic field and particles.
		Magnetic force	Curriculum mentions the magnetic force or one of its synonyms, for example: Lorentz force, Fleming law, right-hand rule, left-hand rule, etc.
		Ionisation	Curriculum mentions ionisation.
		EM waves	Curriculum mentions electromagnetic waves.
		Superconductivity	Curriculum mentions superconductors, either as main content or an example.

Category	**Topic**	**Concept**	**Guideline for using the code**
	Radiation	Cosmic radiation	Curriculum mentions at least one of the following: the origins, the properties, the detection of cosmic rays, history of the detection of cosmic rays.
		Alpha radioactivity	Curriculum mentions at least one of the following: alpha radioactivity, alpha decay, alpha particle.
		Beta radioactivity	Curriculum mentions at least one of the following: beta radioactivity, beta decay, beta minus, beta plus, electron capture, beta ray.
		Gamma radioactivity	Curriculum mentions at least one of the following: gamma ray, gamma radioactivity, gamma decay.
		Radiation (general)	Curriculum mentions at least one of the following: ionising radiation, radioactive sources, radiation protection, background radiation, radioactive decay.
	Special relativity	Relativistic motion	Curriculum mentions relativistic motion or its effects, such as time dilation and contraction of space-time.
		$E=mc^2$	Curriculum mentions at least one of the following: $E=mc^2$, $E=\gamma mc^2$, $E=Sqrt(m^2c^4+p^2c^2)$, invariant mass, mass-energy equivalence.
	Quantum physics	Quantum effects	Curriculum mentions at least one of the following: (quantum) tunnelling, (quantum) entanglement, non-locality, the EPR experiment.
		Probability in QP	Curriculum mentions at least one of the following: uncertainty principle, Heisenberg’s principle, wave-particle duality, Schrödinger equation, wave nature of particles, the double-slit experiment, wave model of matter, electron diffraction, de Broglie wavelength.
		Atomic models	Curriculum mentions at least one of the following: atomic model, the atomic orbital model, electron cloud, atomic theory, Bohr atomic model.
		At. energy levels	Curriculum mentions at least one of the following: discrete energy levels in an atom, atomic energy levels, line spectrum.
		Qu. mechanics	Curriculum mentions at least one of the following: quantum physics, quantum mechanics, quantum theory.
Nature of science			Curriculum mentions at least one of the following: the function and limitations of models, the tentative and changing Nature of Science, the role of hypothesis and observations, various controversies in science, and the societal impacts of science.
History of (physics)		Quantum physics	Curriculum mentions the historical developments of quantum physics, for example: the atomic model, wave-matter duality etc.
		Particle physics	Curriculum mentions discoveries of quarks, bosons, leptons (apart from electron), Higgs bosons etc. and strong and weak interactions.

Appendix D: Definitions of Topics in the Delphi Study

Topic	Definition
Cosmology	The description of and research methods for beginning and the development of the Universe.
Standard Model	Description and explanation of the Standard Model of particle physics, including elementary particles, fundamental interactions, and interaction particles.
Real-life applications	Real-life applications of particle physics research (e.g., world wide web, touchscreens, medical applications).
Latest findings	Updates on newest findings in particle physics, e.g., Higgs boson, pentaquarks.
Particle accelerators	Particle accelerators and their working principles, e.g., acceleration, steering, beam dump.
Antimatter research	Description of antimatter and principles of antimatter research, e.g., particle decelerators, particle traps, antihydrogen.
Technology and engineering	Technology and engineering used for particle physics research, e.g., superconductors, material science, geoengineering.
Particle detectors	Particle detectors and their working principles, e.g., calorimeters, trackers, detector systems.
Theory of relativity	Einstein’s theory of special relativity.
Data analysis	Reasons, principles, and the statistical methods for data analysis
Philosophy of science	The process of scientific discovery, societal impacts, and collaboration and cooperation on the development of scientific knowledge.
History of science	The development of particle physics and particle physics research over time.
Theoretical advances	Advances in theoretical particle physics, e.g., dark matter, dark energy, supersymmetry, string theory.
Other	Other topics connected to particle physics.

Appendix E: Full Rankings of the Topics per Stakeholder Group

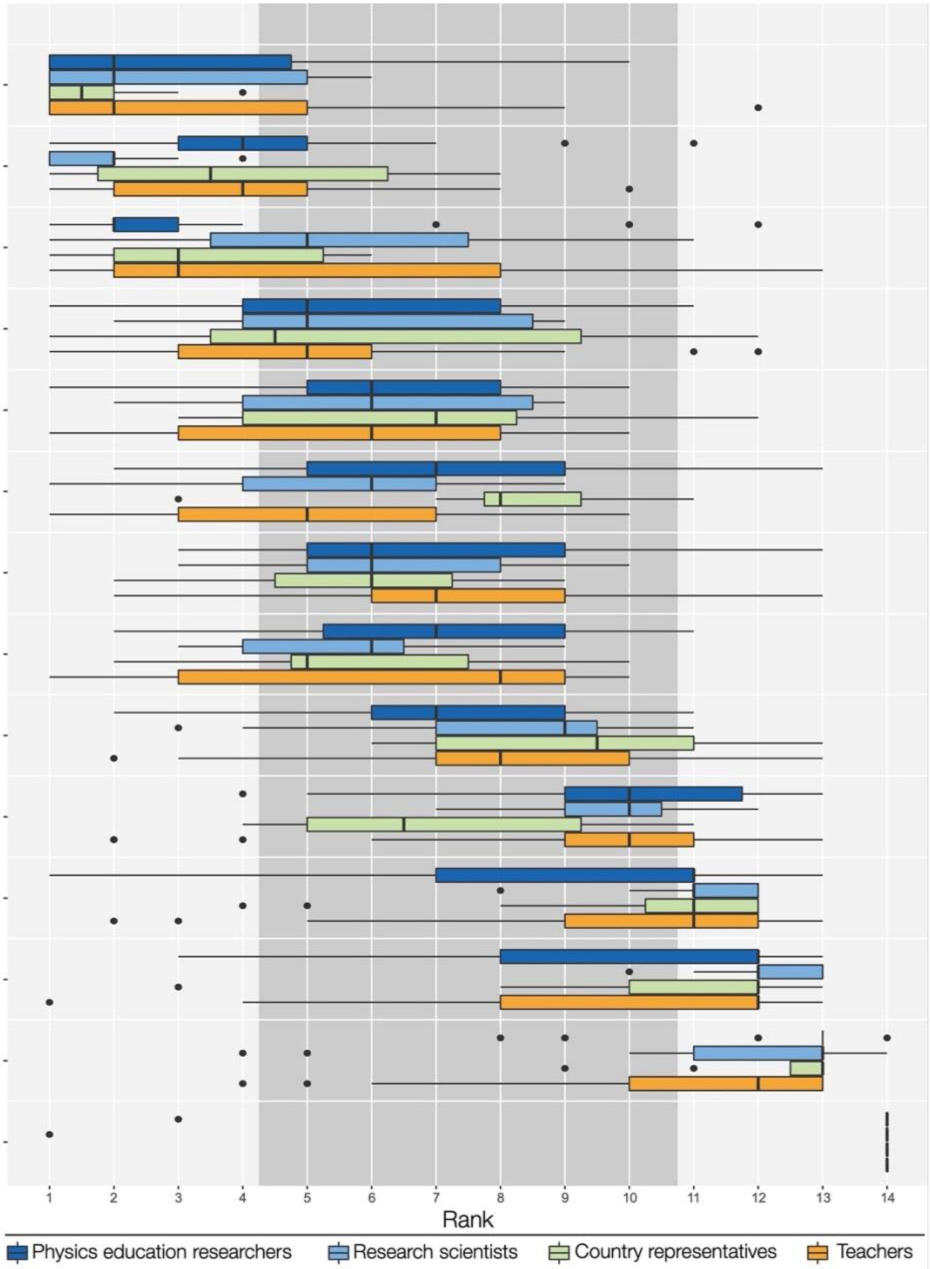


Figure 8. Topic rankings by stakeholder groups. The grey area represents the interquartile range of the entire set of topics. Ranks 1-4 represent high importance topics, 5-10 are medium importance topics, and 11-14 are low importance topics.

ACKNOWLEDGEMENTS

This is it: the final step, the final pages. The work in front of you makes me feel proud but also humbled and grateful - extremely grateful. It was a road filled with several obstacles and sharp turns but also amazing adventures and wonderful people. Each of them helped me grow and develop into a better researcher and, hopefully, a better person.

Above all, I wish to thank my incredible team of supervisors. First, I have greatly benefited from the generous support and expert guidance of my university supervisor, Prof Dr Andreas Borowski. His broad understanding of the field helped me advance my research, writing, and knowledge of the field immensely. His continuous encouragement helped me cross all obstacles, and for that, I will be forever grateful. Thank you, Andreas!

Next, I am deeply thankful to my CERN supervisors Dr Jeff Wiener and Dr Sascha Schmeling. Dr Jeff Wiener has masterfully “megavised” me from the first day. His constant encouragement, meticulous feedback, and strong example have helped me grow and develop as a researcher and a professional. I will be forever indebted to him for all last-minute meetings, lemon stands, and hilarious jokes that kept me smiling. Thank you, Jeff!

Likewise, Dr Sascha Schmeling has been greatly tolerant and supportive along my way. I am sincerely grateful to him for giving me the opportunity to join CERN for this amazing adventure. With his encouragement, I was able to pursue my passions within physics education research and beyond. I am looking forward to our future collaborations.

I also need to mention my two wonderful teams at CERN and Potsdam. Each of you has made my last three and a half years better and more exciting. It was a pleasure working alongside you. Specifically, I want to thank Julia for her continuous encouragement and sending me papers that made her think of me. I also want to thank Sarah A., Sarah Z., Patrick T., Patrick E., David, and Joost for their direct support and conversations about my three studies. Likewise, I will be eternally indebted to Alexandra, Daria, Merten, and Stavie, who kept my mind focused on what is most important in life.

I dedicate the last few sentences of my thesis to my friends and family. First, I want to thank Simon and Natalia for long conversations about everything and anything, countless board game nights, and a continuous supply of support and encouragement. I am happy and grateful to have you two as my friends.

Hvala mami Renati ter očetoma Zlatku in Slavkotu, za spodbujanje in podporo na vseh mojih podvigih. Hvala Alenki in Boštjanu, ki sta nama vedrila dneve z lepimi besedami in fotografijami z njunih popotovanj. In hvala vsem ostalim, ki ste bodrili tako naju v Franciji kot najine starše v Sloveniji.

Last, I want to thank Blaž for staying with me through thick and thin, supporting me in following my dreams and waking up super early every morning to walk Ohi. I promise I will let you sleep longer from now on (at least on most days).

Thank you! Vielen Dank! Merci beaucoup! Najlepša hvala!