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Review

What Does the Curriculum Say? Review of the Particle Physics Content in 27 High-School Physics Curricula

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Abstract: This international curricular review provides a structured overview of the particle physics content in 27 state, national, and international high-school physics curricula. The review was based on a coding manual that included 60 concepts that were identified as relevant for high-school particle physics education. Two types of curricula were reviewed, namely curricula with a dedicated particle physics chapter and curricula without a dedicated particle physics chapter. The results of the curricular review show that particle physics concepts are explicitly or implicitly present in all reviewed curricula. However, the number of particle physics concepts that are featured in a curriculum varies greatly across the reviewed curricula. We identified core particle physics concepts that can be found in most curricula. Here, elementary particles, fundamental interactions, and charges were identified as explicit particle physics concepts that are featured in more than half of the reviewed curricula either as content or context. Indeed, theoretical particle physics concepts are more prominent in high-school physics curricula than experimental particle physics concepts. Overall, this international curricular review provides the basis for future curricular development with respect to particle physics and suggests an increased inclusion of experimental particle physics concepts in high-school physics curricula.

Keywords: curricular review; particle physics; high-school education

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1. Introduction

Spectacular phenomena and ground-breaking discoveries in particle physics often shake the media. One of the main keywords in particle physics research is CERN, the European Organization for Nuclear Research, as the largest particle physics research institution in the world. While CERN is mostly famous for its state-of-the-art particle physics research, one of its main missions is also education. Thus, CERN offers various educational programmes for research professionals, high-school students, and high-school teachers from around the world. However, offering programmes for an international selection of high-school students and teachers can be challenging, especially as the curricula of different countries can differ significantly. Therefore, a broader overview of the particle physics content in high-school curricula is needed to better support future educational programmes for high-school students and teachers.

Why should one include particle physics? First, phenomena in particle physics are spectacular. From high-energy particle collisions in detectors weighing several thousand tonnes, particle accelerators deep underground spanning across borders, to matter-antimatter annihilation, particle physics often attracts the attention of the media—and students. Indeed, students have been shown to be interested in spectacular phenomena of physics [1]. Second, particle physics is not limited to spectacular phenomena in big research laboratories. Various particle physics applications are present in everyday lives (e.g., medical imaging or radiation therapy). As such, particle physics shows a recent image of physics, which can help students to increase their knowledge of the nature of science made over the past few decades [2–7]. For example, one prominent call for including particle physics in more curricula comes directly from the latest European Strategy for Particle Physics Update, the cornerstone of the decision-making process in Europe for the long-term future of the field of particle physics, which states that: "The particle physics community should work with educators and relevant authorities to explore the adoption of basic knowledge of elementary particles and their interactions in the regular school curriculum." [8] (p. 13).

Since the first calls, several high-school physics curricula have already introduced particle physics. However, changes to curricula are slow [9,10] and most curricula still lag behind.

There are no research-based guidelines on how to introduce particle physics in high-school education. Therefore, an overview of practices in other educational systems can be beneficial. Indeed, curricular reviews are common practice in curriculum development (see, e.g., [11,12]). However, current reviews of particle physics content in high-school curricula are either limited to one educational system [6] or do not explicitly target particle physics [13]. Additionally, all efforts mostly focus on explicit particle physics in the curricula. Nevertheless, particle physics can be connected to other curricular topics as well. For example, when explaining the acceleration of particles in a particle accelerator, one can highlight aspects of mechanics, electromagnetism, quantum physics, and special relativity [14]. As such, neither a generalized overview of particle physics in high-school physics curricula nor high-school education in general can be inferred from the reviewed studies. Therefore, we designed a study to address this research gap by investigating the following questions:

1. Which concepts related to particle physics are the most common in national and international high-school physics curricula *with* a dedicated particle physics chapter?
2. Which concepts related to particle physics are the most common in national and international high-school physics curricula *without* a dedicated particle physics chapter?
3. What are the differences and similarities between particle physics contents in curricula with and without a dedicated particle physics chapter?

Overall, this study aims to give a clear overview of the particle physics content in various national and international curricula by taking stock of which particle physics concepts appear in the reviewed curricula.

2. State of the Research

This study reviewed particle physics content in high-school curricula. The following Sections focus on clarifying the necessary definitions and reviewing the current state of the research.

2.1. The Definition of a Curriculum

The term curriculum does not have a consensual definition in educational literature. The differences in the definition often stem from the various roles and characteristics that define curricula [15,16]. Generally, curriculum theorists distinguish three categories of curricula based on their role: formal, intended, and enacted curriculum [16–18]. This study focused on formal curricula. Formal curricula describe a set of guidelines for what should be taught in school and are designed and outlined by stakeholders of the respective educational system.

However, formal curricula can differ greatly depending on the educational system and the purpose of the curriculum in the respective system. Some curricula provide general guidelines with main key concepts (e.g., the Austrian curriculum), while others provide a detailed syllabus (e.g., the International Baccalaureate (IB) curriculum). Thus, curricula can be difficult to compare directly. An additional problem in curricular review is the language obstacle. Indeed, high-school curricula are typically written in the respective language of the instruction (e.g., the Slovenian curriculum is written in Slovenian). Furthermore, research suggests that curricula are subject to different interpretations [16].

Specifically, teachers interpret the formal curriculum within the scope of their teaching practices, which can lead to differences between the formal curriculum and the enacted curriculum. The possible differences in interpretation must be considered when designing a curriculum review.

2.2. Particle Physics in High-School Education

Particle physics is often perceived as a difficult topic in physics, associated with complex mathematics and difficult concepts. This perception can make the introduction of particle physics in high schools sound daunting and challenging. However, studies have shown that students can understand basic concepts of particle physics. For example, a study by Gourlay looked at high-school students' understanding of particle physics after they had explicit particle physics lessons [19]. The study showed that students could learn about quarks, leptons, particle systems, and annihilation. However, the students' knowledge was mostly declarative, which might reflect the curricular structure and content. For example, students knew that "electron is a type of lepton". Yet, they also mistakenly remembered matter as "made of particles and antiparticles" [19] (p. 6).

Similarly, Tuzón and Solbes reviewed the knowledge of Spanish high-school students that had no explicit lessons on particle physics before the study [5]. They had also shown some understanding of basic particle physics concepts. For example, half of the students knew that new particles can be observed from collisions. However, their overall particle physics knowledge was unstructured and incomplete. Indeed, without an explicit focus on particle physics, students only learn about particle physics implicitly and in fragments. Here, a structured introduction to particle physics can help students organize and expand their existing particle physics knowledge in a more meaningful way.

An introduction of particle physics as an explicit learning unit has not yet been empirically explored in the literature. Still, a few different approaches can be found. First, particle physics can be introduced through the perspective of particle interactions [20–22]. Here, particle interactions serve as a context for introducing the different charges, fundamental interactions, and elementary particles, which build the basis of the Standard Model of particle physics. Overall, this approach focuses on introducing mostly theoretical particle physics concepts.

Second, the challenge of teaching particle physics can be approached from the perspective of quantum mechanics [23,24]. This learning unit builds upon electromagnetism, quantum field theory, and quantum electrodynamics. However, students do not necessarily have experience with quantum field theory and quantum electrodynamics. While this approach does touch upon the reasons behind particles' existence, which is not the case in other approaches, its implementation might be too advanced and time-consuming to be included in high-school education. Furthermore, only theoretical particle physics concepts and some history of particle physics are included in this example.

Last, one suggestion features experimental particle physics concepts explicitly. Here, Polen proposes a broader chapter, including all concepts mentioned above with the addition of particle accelerators and detectors [25]. However, this suggestion is less detailed and provides less insight into the lesson structure. Thus, which concepts should be included and how they should connect within the lesson is unclear.

Likewise, suggestions for introducing individual particle physics concepts also focus more on theoretical particle physics than experimental particle physics. For example, several authors suggest using the Standard Model of particle physics as a possible window into the world of particle physics [22,26,27]. However, the Standard Model is a complex mathematical description of particle physics that goes beyond the level of high-school physics education. This level of complexity can lead to a naïve and reductionistic approach to introducing the Standard Model of particle physics [28,29]. Therefore, the complex mathematics of the Standard Model of particle physics is probably best avoided in the classroom. Here, for example, Lindenau and Kobel suggested a simplified introduction to the Standard Model of particle physics. Indeed, they focus on the three pillars of the

Standard Model of particle physics: elementary particles, fundamental interactions, and charges [22]. Furthermore, they connect these three concepts to other curricular topics to allow for better integration of particle physics.

Several other publications also explored the introduction of the three main concepts of the Standard Model of particle physics, i.e., elementary particles, fundamental interactions, and charges. Here, various innovative techniques have been suggested to enhance the introduction of elementary particles, for example, through hands-on activities and art [27,30–34]. For instance, McGinness et al. developed an activity using 3D-printed models of elementary particles, which students can use to learn about the different characteristics of elementary particles [31]. However, many of the published suggestions aim at introducing elementary particles and their properties in a declarative way, similar to the introduction of the periodic system of elements [20,22]. While students can memorize these concepts [19], it is questionable whether such rote learning contributes to the understanding of particle physics. One example that ties learning about elementary particles closer to understanding particle physics and how it is conducted are particle physics masterclasses. Here, students explore real data from particle colliders to identify which particles were created in a collision [35]. This approach is also one of the few that connect theoretical particle physics concepts, such as elementary particles and fundamental interactions, to experimental particle physics processes.

Several suggestions in the literature also explore the introduction of charges and fundamental interactions. Here, charges are typically mentioned as properties of elementary particles. In the example above, the 3D-printed elementary particle models by McGinness included information on particles' charges [31]. Likewise, the particle dance by Nikolopoulos and Pardalaki helped students embody elementary particles and particle interactions [27]. Moreover, the study by Wiener et al. that strongly focused on the representation of fundamental charges contextualized the concept of charges with elementary particles [36].

Overall, a big part of the reviewed suggestions on how to introduce particle physics in high-school education focused on theoretical particle physics concepts. Only a few suggestions for inclusions of experimental particle physics can also be found in the literature. Here, particle physics concepts are generally used as context for other curricular topics. For example, Barradas-Solas et al. suggested introducing particle detectors in the context of radiation [37]. Similarly, Cid-Vidal and Cid connected the acceleration of lead ions for particle collisions to electromagnetism [38]. Another extensive suggestion for contextualizing particle physics comes from Wiener et al. [14]. They suggested introducing particle physics concepts also in the contexts of mechanics, electromagnetism, thermodynamics, optics, radiation, quantum physics, and the theory of relativity. Indeed, experimental particle physics offers many links to other curricular topics. However, only a few mentioned publications on experimental particle physics explicitly included connections to theoretical particle physics concepts. For example, the above-mentioned suggestion by Wiener et al. connects charges and fundamental interactions to the Large Hadron Collider (LHC) at CERN, the largest particle accelerator in the world [14]. Additionally, Barradas-Solas [37] and Kvita et al. [39] use the context of particle detectors to introduce various elementary particles. Still, in most examples, experimental particle physics and theoretical particle physics concepts are presented as two separate entities with scarce connections.

Based on this literature review and the identified research gap, we conducted a curriculum review that is described in the following Sections.

3. Methods

This curriculum review consists of three steps. First, a coding manual was developed to guide the curriculum review. Second, the selected curricula were reviewed by experts. Last, the reviews were compared and analysed by the researchers. Each step is presented in more detail in the following Sections.

3.1. Coding Manual

The coding manual was developed following the dualistic method of deductive and inductive code creation [40,41]. First, the deductive part of the coding manual stemmed from previous research [11,42], including an expert concept mapping study with 13 experts in particle physics and physics education research [43]. Overall, the included concepts were not limited only to explicit particle physics, especially as curricula without a particle chapter were also included in the design. Indeed, concepts from other curricular topics were added to the review. These curricular topics were identified by the experts in the development phase of the coding manual as relevant for particle physics education, and they are also mentioned in various suggestions in the literature for particle physics introduction in high schools. For example, electromagnetism, special relativity, quantum physics, thermodynamics, radiation, and mechanics are some of the topics that were suggested by Wiener et al. as possible contexts for introducing particle physics concepts [14]. Second, the concepts that emerged from previous studies were used as the basis for an initial thematic analysis of a selected sample of curricula. Several additional concepts were added to the coding manual based on the patterns that emerged during this initial thematic analysis. For example, the initial analysis led to the addition of the concepts history of quantum physics and history of particle physics to the coding manual.

After the initial thematic analysis, the coding manual was re-tested on five curricula by at least two independent reviewers per curriculum. In addition to reviewing, the reviewers noted any ambiguities, problems, and suggestions they might encounter during their review. Next, the reviewers discussed their reviews with the first author. This discussion led to several modifications to the coding manual. For example, the concept electromagnetic waves was added to the coding manual due to its presence in several curricula and strong connection to particle accelerators. Additionally, the coding agreement increased from 60% to 100% after the review discussion.

Last, two physics education researchers and a particle physicist verified the updated coding manual. In the verification phase, some codes were combined based on their similarities. Indeed, various types of real-life applications (medical, technical) were merged into a bigger concept of real-life applications. Likewise, the concepts of Brout-Englert-Higgs field and Higgs boson were joined under the concept of Brout-Englert-Higgs mechanism. Additionally, the concept of Newtonian gravity was added to the category of other curricular topics. This addition ensured the separation between the concepts of Newtonian gravity and gravitational interaction. Furthermore, the concept of Einsteinian gravity was added to ensure that all mentions of gravity in the context of general relativity theory were coded separately from the concept of gravitational interaction in the context of particle physics. Likewise, the topic of particle transformations was split into three separate concepts: particle transformations, alpha radiation, and beta radiation. Here, the concepts of alpha radiation and beta radiation only included codes that appeared in the context of the topic of radiation. The concept of particle transformation only denoted processes of particle transformation in the explicit context of particle physics. Similarly, the concept of Feynman diagrams only included the explicit mention of Feynman diagrams as tools in particle physics. Furthermore, any indirectly hinted concepts (e.g., the concept of particle transformations is closely related to Feynman diagrams) were not to be coded unless explicitly mentioned elsewhere in the curriculum.

The final coding manual includes 60 codes that are either directly or indirectly related to particle physics. The codes are hierarchically organized into three levels. First, each code describes a specific concept, e.g., the concept of quarks. Second, the concepts are combined into topics, e.g., the concepts of quarks and leptons are in the topic of elementary particles. Overall, 25 topics were defined. Last, the topics are joined into three categories: explicit particle physics, other curricular topics, and history and nature of science. Within the category of explicit particle physics, some topics were additionally identified as theoretical or experimental particle physics topics based on their inherent nature. For example, the topic of elementary particles includes inherently theoretical particle physics concepts, while the topic of particle accelerators covers inherently experimental particle physics concepts. This distinction does not reflect the actual context in which the concepts appear in the curricula (e.g., the concept of leptons in an experimental context is still a theoretical particle physics concept).

Within the coding manual, each code is described by a short definition and a possible example from a curriculum, as shown in Table 1. Furthermore, exclusion criteria were added to codes that could be understood differently from what was intended (see the example of the concept of interaction particles in Table 1).

Table 1. Two examples of codes in the coding manual. Both examples fall into the category of explicit particle physics. The complete coding manual with all 60 codes can be found in the Supplementary Materials.

Topic	Code	Description	Exclusion	Example
Interaction particles	Interaction particles	The curriculum mentions bosons or at least one of the following: photons (as interaction particles), W bosons, Z bosons, gluons, gauge bosons.	To code the Higgs boson, please use the code "Brout-Englert-Higgs mechanism".	"The Standard Model explains three of the four (strong, weak and electromagnetic forces) in terms of an exchange of force-carrying particles called gauge bosons."
Elementary particles	Quarks	The 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.).		"Compare and contrast the up quark, the down quark, the electron and the electron neutrino, and their antiparticles, in terms of charge and energy (mass-energy)."

3.2. Reviewing the Curricula

The selection of the curricula was initially influenced by the fact that the study was conducted at CERN. Therefore, the initial selection of curricula was made by focusing on several CERN's member and associate member states. The list of all CERN's member and associate member states can be found on CERN's website [44]. The selection of countries was later expanded to include a more representative sample. Specifically, curricula from various other countries, such as Australia, Brazil, Russia, South Africa, and the United States of America, were added to the selection. Furthermore, the IB curriculum was included in the review due to its international character and relevance.

Several of the selected countries have more than one high-school physics curriculum. In that case, a curriculum with the most advanced physics curriculum was chosen for the review. This selection was made as particle physics is more likely to be included in more advanced curricula. Additionally, the curricula were chosen in a way that would reflect high-school students' expected knowledge at the end of their high-school education (i.e., age 18–19). With this selection, the study aimed to cover all relevant years of high-school education in a respective educational system. Overall, 27 curricula were selected, including 6 state curricula, 20 national curricula, and 1 international curriculum.

As mentioned above, the review and the comparison of different national and international curricula presented several obstacles. Thus, special attention was given to the selection of suitable reviewers. The curricula were reviewed by experts, namely teachers with experience in the relevant curriculum, sufficient particle physics knowledge and knowledge of the respective language. Two independent experts reviewed each curriculum following the coding manual to increase the reliability of the coding. In addition, each curriculum was examined by the first author, some with the help of online translators. Additional peer validation was conducted by the second author.

All discrepancies between the reviews of the experts and the researcher were addressed either by the first author directly or through discussion with the respective experts. For example, if one expert missed coding “the beginning and evolution of the Universe” as the concept of Big Bang, the first author would assign the respective code. Another example would be that “describe elementary particles” was coded as the concept of Standard Model of particle physics by one expert and not the other. Here, the first author discussed the discrepancy with the experts to find a consensus. In this example, the concept of Standard Model of particle physics was agreed not to be coded for that curriculum.

3.3. Analysis

The curricula were split into two types for analysis: curricula with a dedicated particle physics chapter and curricula without a dedicated particle physics chapter. Here, a chapter is defined as a section in the curriculum with an explicit focus on particle physics and a telling header, e.g., “Particle physics” or “The Standard Model of particle physics”. Several curricula included the particle physics focus in a broader “Modern physics” chapter. These curricula were also counted as curricula with a dedicated particle physics chapter. Curricula without an explicit focus on particle physics or with no chapter were counted as curricula without a dedicated particle physics chapter.

The next step in the analysis was determining which concepts and topics are the most common in each type of curricula. As mentioned above, the review included 60 concepts that were grouped into 25 topics. Furthermore, the topics were grouped into three categories, namely the categories of explicit particle physics, other curricular topics, and history and nature of science. The number of curricula in which a specific concept would be featured was determined as follows: for each curriculum in which a concept was identified one or more times, the count increased by one. For example, if the concept of magnetic field was identified twice in the Slovenian curriculum, the count only increased by one. The topics were counted slightly differently. Here, a topic is counted as having appeared in a curriculum if at least one concept from the topic was identified in the curriculum. For example, the topic of charges contains concepts of electric charge, weak charge, and strong charge. Thus, the topic of charges was counted to appear in a curriculum if at least one of the three concepts was coded in the curriculum (e.g., the concept of electric charge). If a concept is featured multiple times in one curriculum or various concepts within the topic were identified in one curriculum, the count was still only increased by one.

Based on the count in the previous step, the concepts and topics that were found in more than half of the curricula were identified. Identifying the most featured concepts and topics allowed for a better comparison between the particle physics content in curricula with a dedicated particle physics chapter and curricula without a dedicated particle physics chapter. The results of this analysis are presented in Section 4.

4. Results

4.1. Curriculum Types

This curricular review reviewed 27 state, national and international high-school physics curricula. First, the structure of the curricula was inspected to define chapters and identify whether they include a dedicated particle physics chapter.

The 12 curricula with a dedicated particle physics chapter were the curricula of the IB [45], Austria [46], Australia—Queensland [47], Croatia [48], Germany—Brandenburg [49], Israel [50], Russia [51], Switzerland—Nidwalden [52], Serbia [53], South Africa [54], Spain [55], and the United Kingdom—A levels [56]. In most of these curricula, particle physics was included as a dedicated chapter towards the end of the curriculum. Thus, students would typically explicitly learn particle physics at the end of their high-school education, typically between ages 17 and 19.

The 15 curricula without a dedicated particle physics chapter were curricula of Brazil—São Paolo [57], Canada—Manitoba [58], Germany—Baden-Württemberg [59], Germany—Saxony [60], France [61], Ghana [62], Greece [63], Italy [64], Lebanon [65], Netherlands [66], Poland [67], Slovakia [68], Slovenia [69], Sweden [70] and the United States of America—Next Generation Science Standards (NGSS) [71]. In both types of curricula, all chapters included in the curriculum were reviewed for explicit and implicit particle physics concepts.

4.2. Results of the Analysis

The curricula were reviewed based on the coding manual with 60 hierarchically organized concepts, as described above. The concepts were organized into 25 topics that were grouped into three categories, namely the categories of explicit particle physics, other curricular topics, and history and nature of science. After reviewers identified the presence of individual concepts, the number of times individual concepts appeared in different curricula was counted. Special focus was given to determining which concepts appear in more than half of the curricula.

The curricula were grouped and compared based on whether they contained a dedicated particle physics chapter. First, the curricula with a dedicated particle physics chapter were analysed. Here, 35 out of 60 concepts were found in more than half of the curricula with a dedicated particle physics chapter. Furthermore, 19 out of 25 topics were identified in more than half of said curricula. Second, the curricula without a dedicated particle physics chapter were analysed. Overall, 27 out of 60 concepts were identified in more than half of the curricula. Furthermore, 14 out of 25 topics appear in over half of the curricula without a dedicated particle physics chapter. The overall overlap between the curricula with and without a dedicated particle physics chapter is 80%. More details are presented in the paragraphs below.

4.2.1. Explicit Particle Physics

The results for the category of explicit particle physics are shown in Table 2 and Figure 1. Additionally, these results are summarized in the following paragraphs.

The review of the curricula with a dedicated particle physics chapter showed that the following nine explicit particle physics topics were identified in more than half of said curricula: topics of cosmology, the Standard Model of particle physics, fundamental interactions, charges, elementary particles, interaction particles, antimatter research, open questions in particle physics, and particle accelerators. All but two of these topics are from theoretical particle physics. All topics from the category of explicit particle physics were identified in at least one curriculum. Likewise, ten concepts were found in more than half of the reviewed curricula with a dedicated particle physics chapter: the concepts of Standard Model of particle physics, electromagnetic interaction, strong interaction, weak interaction, quarks, leptons, interaction particles, antimatter research, general particle accelerators, and open questions in particle physics. The following three concepts were not found in any reviewed curricula: the concepts of weak charge, strong charge, and modern particle detectors.

The review of the curricula without a dedicated particle physics chapter showed that four topics in the category of explicit particle physics were identified in more than half of the curricula, namely the topics of cosmology, fundamental interactions, charges, and elementary particles. Likewise, four concepts were found in more than half of the curricula, namely the concepts of Big Bang, electromagnetic interaction, electric charge, and leptons. Here, the review showed that the topic of cosmology and the concept of Big Bang typically appeared in parts of curricula that focused on astronomy. On the other hand, concepts within the topics of fundamental interactions, charges, and elementary particles were mostly featured in the topic of electromagnetism. They were represented by the concepts of electromagnetic interaction, electric charge, and an electron as an example of the concept of leptons, respectively.

Overall, the overlap of concepts appearing in curricula with and without a dedicated particle physics chapter is 32%. Each type of curricula includes concepts that the other type does not. The explicit particle physics concepts that appear in both types of curricula are the concepts of electromagnetic interaction, electric charge, and leptons. More than half of the curricula with a dedicated particle physics chapter also feature the concepts of the Standard Model of particle physics, strong interaction, weak interaction, quarks, interaction particles, antimatter research, general particle accelerators, and open questions in particle physics. Additionally, the following topics were identified only in more than half of the curricula with a dedicated particle physics chapter: the topics of the Standard Model of particle physics, interaction particles, particle accelerators, antimatter research, and open questions in particle physics.

Table 2. Overview of the concepts and topics within the category of explicit particle physics and their count across the curricula with and without a dedicated particle physics chapter. Topics in the first column are marked with T as theoretical and E as experimental.

		12 Curricula *with* a Dedicated Particle Physics Chapter		**15 Curricula *without* a Dedicated Particle Physics Chapter**	
Topic	**Concept**	**Count (Topic)**	**Count (Concept)**	**Count (Topic)**	**Count (Concept)**
1 ^{T} Cosmology	Big Bang	7 *	6	9 *	9 *
	Inflation		5		4
	Expansion		5		5
2 ^{T} Standard Model	Standard Model	8 *	8 *	3	3
3 ^{T} Fundamental interactions	Electromagnetic interaction	9 *	8 *	9 *	9 *
	Strong interaction		9 *		3
	Weak interaction		8 *		2
	Gravitational interaction		5		0
4 ^{T} Charges	Electric charge	11 *	11 *	11 *	11 *
	Strong charge		0		0
	Weak charge		0		0
5 ^{T} Elementary particles	Quarks	10 *	9 *	11 *	4
	Leptons		10 *		10 *
6 ^{T} Interaction particles	Interaction particles	8	8 *	7	7
7 ^{T} Brout-Englert-Higgs mechanism	Brout-Englert-Higgs mechanism	3	3	0	0
8 ^{T} Particle transformations	Particle transformations	6	6	4	4
9 ^{T} Feynman diagrams	Feynman diagrams	3	3	0	0
10 ^{T} Antimatter research	Antimatter research	7 *	7 *	4	4
11 ^{E} Particle accelerators	Linear accelerators	8 *	1	4	3
	Circular accelerators		5		3
	General particle accelerators		7 *		2
12 ^{E} Particle detectors	Historical detectors	4	1	2	1
	Modern detectors		0		0
	General particle detectors		3		1
13 ^{E} Data storage and data analysis	Data storage and data analysis	2	2	3	3
14 Advances in particle physics	Experimental results	7 *	3	1	1
	Open questions		7 *		0
15 Real-life applications of particle physics	Real-life applications of particle physics	6	6	5	5

* Concepts and topics that were identified in more than six curricula with a dedicated particle physics chapter or in more than eight curricula without a dedicated particle physics chapter. ^{T} Topics that were categorized as theoretical particle physics topics. ^{E} Topics that were categorized as experimental particle physics topics.

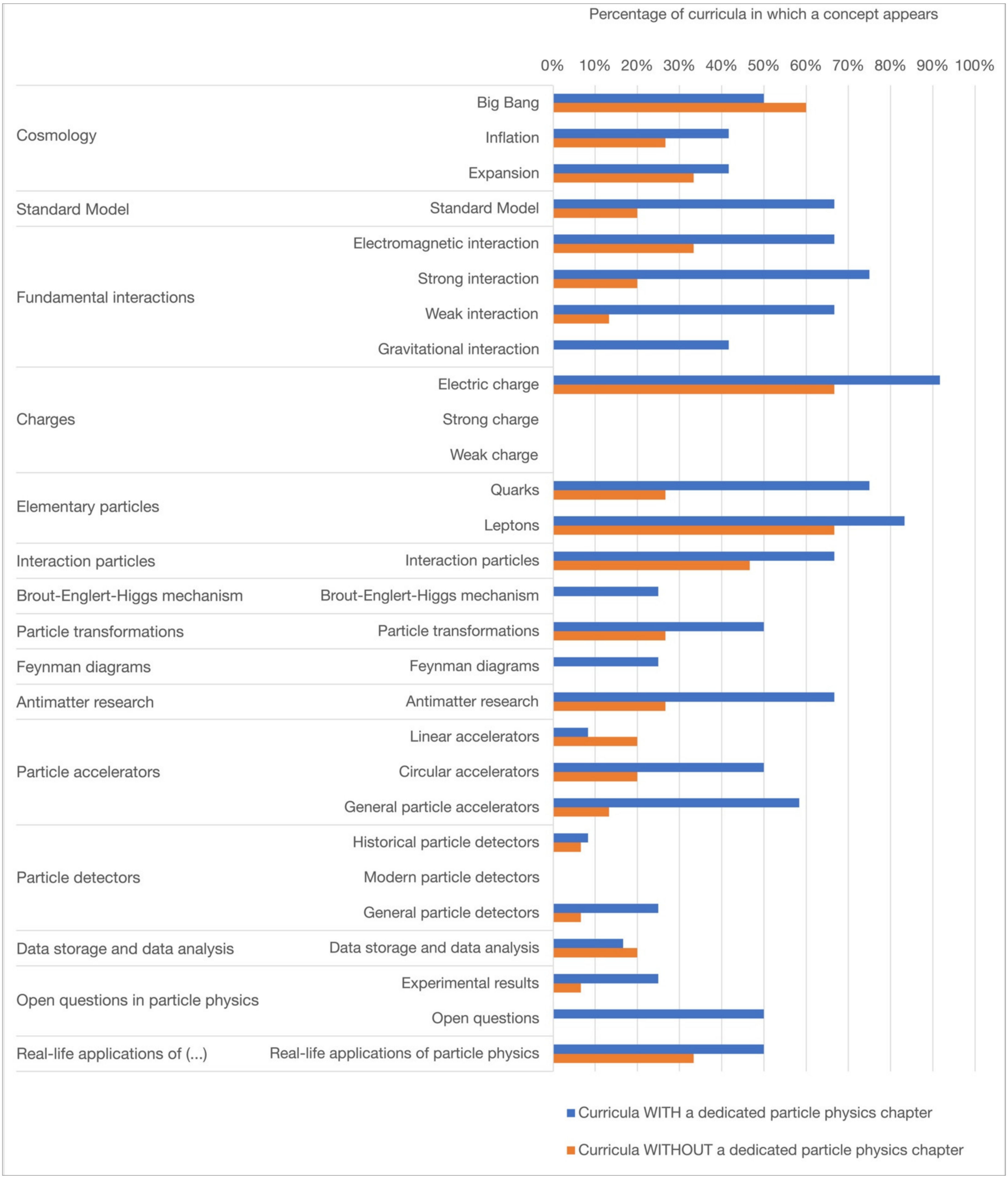

Figure 1. Graphic overview of the concepts within the category of explicit particle physics and the percentage of curricula in which they are featured. The bars in blue represent curricula with a dedicated particle physics chapter. The bars in orange represent curricula without a dedicated particle physics chapter. The figure corresponds to Table 2.

4.2.2. Other Curricular Topics

The results for the category of other curricular topics are shown in Table 3 and Figure 2. Additionally, these results are summarized in this Section.

The review of the curricula with a dedicated particle physics chapter showed that all topics from the category of other curricular topics are featured in all reviewed curricula. Similarly, 22 out of 29 concepts from the category of other curricular topics were identified in more than half of the curricula with a dedicated particle physics chapter. Only a few concepts were not found in more than half of the curricula, namely the concepts of Einsteinian gravity, conservation of angular momentum, conservation of charges, ionization, superconductivity, cosmic radiation, and quantum effects.

Table 3. Overview of concepts and topics within the category of other curricular topics and their count across the curricula with and without a dedicated particle physics chapter.

		12 Curricula *with* a Dedicated Particle Physics Chapter		**15 Curricula *without* a Dedicated Particle Physics Chapter**	
Topic	**Concept**	**Count (Topic)**	**Count (Concept)**	**Count (Topic)**	**Count (Concept)**
Mechanics	Linear motion	12 *	11 *	15 *	15 *
	Circular motion		11 *		15 *
Gravity	Newtonian gravity	12 *	12*	15 *	15 *
	Einsteinian gravity		5		2
Conservation Laws (of)	Energy	12 *	12 *	15 *	15 *
	Linear momentum		11 *		13 *
	Angular momentum		4		7
	Charges		6		4
Thermodynamics	Particle model	12 *	11 *	14 *	14 *
	Phase transitions		7 *		*
	Vacuum		7 *		4
Electromagnetism	Electric fields	12 *	12 *	15 *	14 *
	Magnetic fields		12 *		1 *
	Magnetic force		11 *		12 *
	Ionisation		5		10 *
	Electromagnetic waves		12 *		13 *
	Superconductivity		5		2
Radiation	Cosmic radiation	12 *	4	14*	3
	Alpha radiation		10 *		12 *
	Beta radiation		10 *		12 *
	Gamma radiation		10 *		12 *
	Radiation (general)		12 *		14 *
Special relativity	Relativistic motion	12 *	11 *	11 *	7
	$E = mc^2$		11 *		11 *
Quantum physics	Quantum effects	12 *	2	15 *	4
	Probability in quantum physics		11 *		11 *
	Atomic models		12 *		14*
	Atomic energy levels		11 *		11 *
	Quantum mechanics		10 *		9 *

* Concepts and topics that were identified in more than six curricula with a dedicated particle physics chapter or in more than eight curricula without a dedicated particle physics chapter.

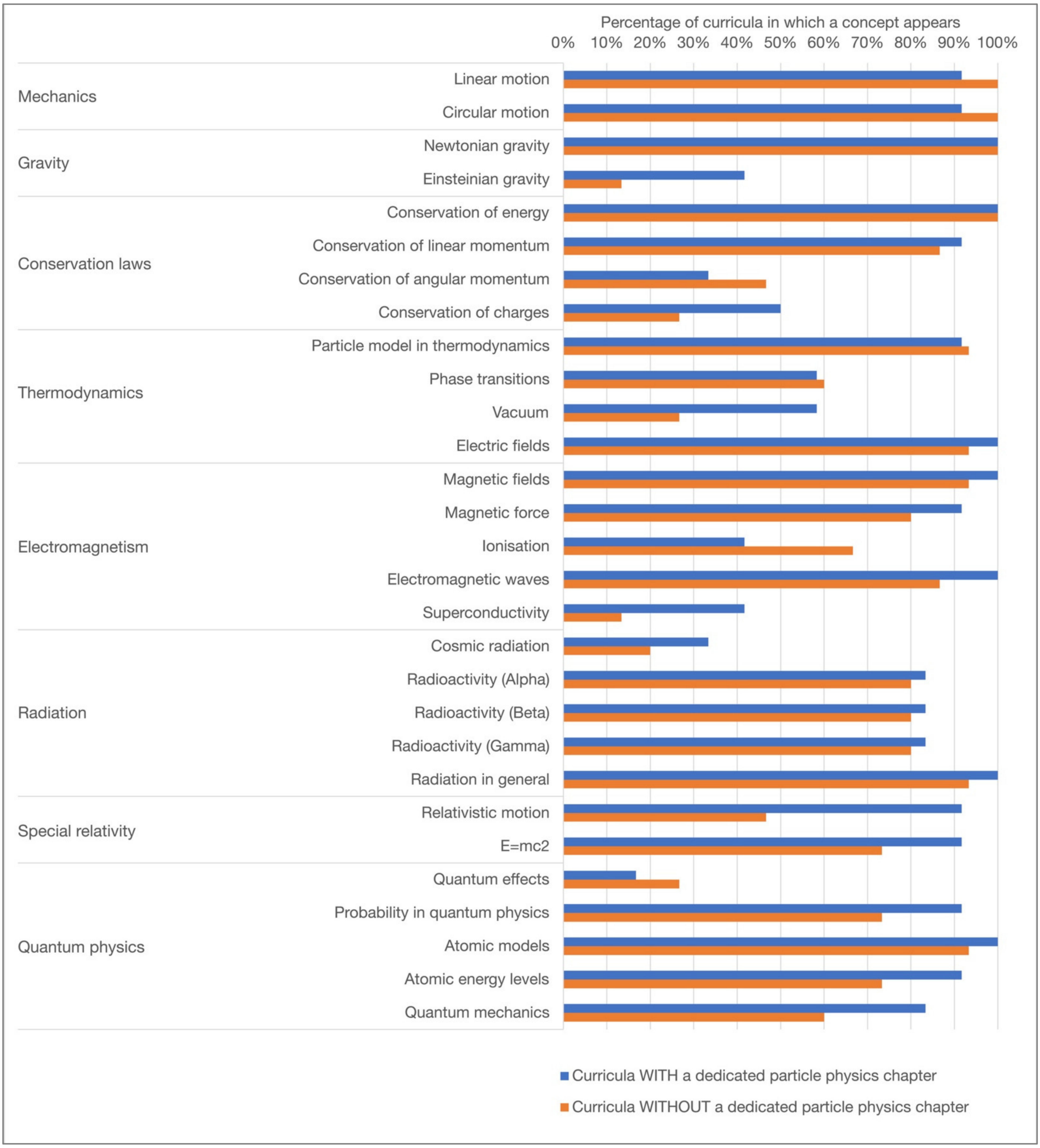

Figure 2. Graphic overview of the concepts within the category of other curricular topics and the percentage of curricula in which they are featured. The bars in blue represent curricula with a dedicated particle physics chapter. The bars in orange represent curricula without a dedicated particle physics chapter. The figure corresponds to Table 3.

Likewise, all topics from the category of other curricular topics are featured in more than half of the curricula without a dedicated particle physics chapter. Only the topics of thermodynamics, radiation, and special relativity were not identified in all curricula. Similarly, 21 out of 29 concepts from the category of other curricular topics were identified in more than half of the curricula without a dedicated particle physics chapter. Last, nine concepts were not found in more than half of the curricula, namely the concepts of Einsteinian gravity, conservation of angular momentum, conservation of charge, vacuum, superconductivity, cosmic radiation, relativistic motion, and quantum effects.

A 90% overlap was identified between the two types of curricula. Concepts that were identified in more than half of the curricula with a dedicated particle physics chapter and not in the other type are the concepts of vacuum and relativistic motion. Conversely, curricula without a dedicated particle physics chapter also feature the concept of ionization, which is typically introduced in the context of radiation.

4.2.3. History and Nature of Science

The results for the category of history and nature of science are shown in Table 4 and Figure 3. The category of history and nature of science has a complete overlap (100%) between the two types of curricula. Out of the three concepts in the category of history and nature of science, two were featured in more than half of the curricula: the concepts of history of quantum physics and the nature of science. Here, the concept of nature of science was typically present only implicitly. Most curricula listed aspects of the nature of science as general goals of physics as a subject. However, most curricula explicitly mentioned the topic of history of science within the content part of the curricula (either as content or context).

Table 4. Overview of concepts and topics within the category of history and nature of science and their count across the curricula with and without a dedicated particle physics chapter.

		12 Curricula *with* a Dedicated Particle Physics Chapter		**15 Curricula *without* a Dedicated Particle Physics Chapter**	
Topic	**Concept**	**Count (Topic)**	**Count (Concept)**	**Count (Topic)**	**Count (Concept)**
History of science	History of quantum physics	10 *	10 *	10 *	10 *
	History of particle physics		3		2
Nature of science	Nature of science	10 *	10 *	13 *	13 *

* Concepts and topics that were identified in more than six curricula with a dedicated particle physics chapter or in more than eight curricula without a dedicated particle physics chapter.

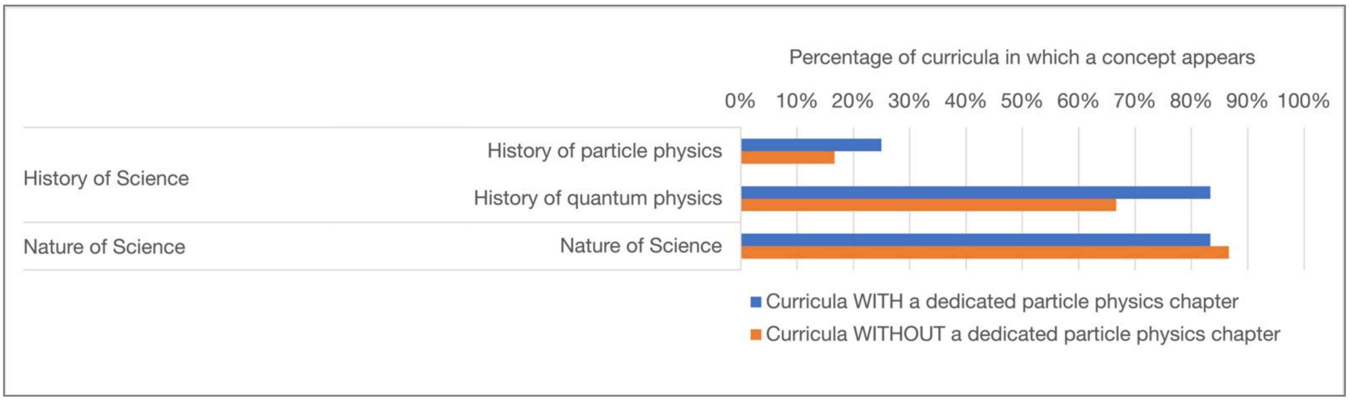

Figure 3. Graphic overview of the concepts within the category of history and nature of science and the percentage of curricula in which they are featured. The bars in blue represent curricula with a dedicated particle physics chapter. The bars in orange represent curricula without a dedicated particle physics chapter. The figure corresponds to Table 4.

5. Discussion

This curricular review investigated the particle physics content in 27 state, national, and international high-school physics curricula. Two types of curricula were reviewed: namely curricula with a dedicated particle physics chapter and curricula without a dedicated particle physics chapter. The analysis resulted in an overview of particle physics topics and concepts that are featured in more than half of the curricula with or without a dedicated particle physics chapter.

The reviewed curricula have many similarities. First, both types of curricula have a stronger focus on theoretical than experimental particle physics. Indeed, only curricula with a dedicated particle physics chapter feature experimental particle physics concepts. This result corresponds to what was found in the literature. Indeed, most suggestions for the introduction of particle physics focused more on theoretical than experimental particle physics concepts, e.g., [20–24]. Furthermore, the concepts that were most prominently mentioned in the literature are also present in more than half of the reviewed curricula, namely the topics of fundamental interactions, elementary particles, and charges. The results of this curricular review show that curricula with a dedicated particle physics chapter come somewhat close to Polen's suggested learning unit [25]. They suggested a learning unit that would include understanding particle accelerators and particle detectors as one of the goals. Indeed, most reviewed curricula also mention particle accelerators, at least as context for electromagnetism or circular motion. However, the topic of particle detectors is not present in a great majority of the curricula, regardless of how much the curriculum focuses on particle physics. Moreover, none of the curricula mentioned the concept of modern particle detectors. In the literature, particle detectors are generally introduced as a context for other curricular topics, for example, the topic of radiation—if at all [37]. Here, not including particle detectors appears to be a lost opportunity for more active learning and better representations. Indeed, introducing particle detectors in the classroom can help students better visualize an otherwise very abstract chapter [72].

The lack of including experimental aspects is not limited to particle physics. While experiments play a central role in physics education, their importance and value are often not introduced well enough in the physics education literature [73,74]. Specifically, Park et al. noted that physics is mostly presented in curricula and textbooks as "hardened facts with its making process erased" [75] (p. 1078). Thus, students often struggle to understand the role of experiments in science [75,76]. For example, most students think that confirming previously known results is the main goal of doing experiments [75]. Explicitly including aspects of modern experimental physics in curricula could help change this conception.

Second, three explicit particle physics concepts were not identified in any curriculum: the concepts of strong charge, weak charge, and modern particle detectors. Indeed, while electric charge has been identified as one of the most common concepts, the concepts of strong charge and weak charge are not mentioned in any curricula. However, the concept of electric charge was commonly mentioned in the context of electromagnetism, where it was typically referred to only as merely "charge". This nomenclature is not surprising, as no other charge appeared in the curriculum. Using "charge" to denote only electric charge also means that the concept of conservation of charge only constitutes the conservation of electric charge. However, the concepts of strong interaction and weak interaction are both mentioned in several curricula. Their description is generally limited to their role in nuclear reactions. Indeed, other studies have found that teachers often mention the concepts of strong interaction and weak interaction as decontextualized and in passing [5,77]. While the introduction of the strong interaction and weak interaction can include a short discussion about the nature of these fundamental interactions (e.g., range and relative strength), it typically avoids the associated charges. For example, the international baccalaureate (IB) curriculum, one of the most comprehensive curricula in this curricular review, prominently includes strong interaction and weak interaction [45]. However, while it describes the electromagnetic charge and the baryon numbers of elementary particles and interaction particles, the IB curriculum does not introduce strong charge or weak charge. Omitting the topic of charges from curricula means omitting the information about the role of charges in weak interaction and strong interaction. It can be argued that charges, especially strong charge and weak charge, can be a complex topic in particle physics. At higher levels of education, the topic of charges is often introduced through complex mathematics and difficult equations. However, as Wiener et al. [36] argued, the notion of charge can be introduced to learners as young as 12 years old without much complex mathematics. Furthermore, introducing at least the concepts of strong charge and weak charge can aid later studies by expanding the concept of charge to fields beyond electromagnetism.

Last, most curricula include the topic of history and nature of science, albeit most of them only implicitly. For example, the Austrian curriculum provides several aspects of nature of science at the beginning of the curriculum to highlight what teachers should convey throughout their teaching. However, the nature of science aspects are later not present in the content part of the Austrian curriculum. Indeed, the concept of nature of science is rarely found within the content part of curricula. Likewise, most textbooks only implicitly include the nature of science [78,79]. Yet, research shows that the nature of science is most effectively taught explicitly [80]. Therefore, finding appropriate context to support the teaching of the nature of science as content is crucial for teachers. Previous studies have suggested that contemporary topics can be used as the basis for teaching the nature of science [74,81]. Thus, as a contemporary field of physics, particle physics can help contextualize various aspects of the nature of science [82,83]. Here, the introduction of the concept of nature of science again calls for more experimental particle physics to be included in high-school education. Indeed, through learning about modern particle physics methods, students experience particle physics as "science-in-the-making". Through it, students can understand the principles of modern scientific explorations, from the importance of theoretical prediction to inference and social aspects of science. The role of theoretical predictions in designing future experiments and the tentativeness of science can further be highlighted through the discussion about open questions in particle physics. Indeed, open questions in particle physics can trigger conversations about science beyond what is typically perceived as facts. Likewise, by learning about real-life applications of particle physics, students can discover the value of modern science and its impact on life and society. As such, particle physics, similarly to other contemporary fields of science, presents itself as an excellent context for teaching the nature of science.

5.1. Strengths and Limitations

This international curricular review provides an overview of particle physics contents in 27 high-school state, national and international physics curricula. The curricula were screened using a coding manual that contained 60 concepts in particle physics and related topics. The coding manual was developed through an extensive literature review and the expert knowledge of multiple particle physicists and physics education researchers. Additionally, the manual was extensively pre-tested to ensure clarity. In its final form, the coding manual provides a clear and concise overview of particle physics concepts that experts perceive as the most relevant for high-school education. As such, the coding manual is a powerful tool both for evaluating particle physics content in curricula and possible further curricular development.

The curricular review was conducted by teachers with vast experience in the relevant curriculum, sufficient particle physics knowledge and knowledge of the respective language. These qualifications make them experts in their respective curricula, improving the quality of the review. Additionally, all curricula were reviewed by at least two experts in addition to being reviewed by the authors as well. The multitude of reviewers and the discussions to reach a consensus improved the overall reliability of the reviews.

However, the review of the curricula in this study was limited to science-oriented high-school physics curricula (when applicable) with no differentiation between elective and compulsory concepts. Such a selection of the curricula was purposeful to include the physics curricula with the maximum particle physics content in each country to determine the "ideal" scenario within physics curricula. However, this selection excludes curricula with less physics and curricula of other high-school subjects (e.g., astronomy and chemistry). This limitation can be addressed by broadening the scope of future studies to review curricula of other school types (e.g., technical high schools) and other school subjects.

Additionally, this curricular review focused on identifying which particle physics concepts are prominently featured in international curricula. As such, the review did not explore how particle physics concepts are introduced or how they are connected to other topics. Likewise, the levels of competence that students are expected to achieve in the context of particle physics were not analysed. The main reason for this decision is the stylistic differences between the curricula. Indeed, while some curricula are written as an extensive syllabus (e.g., the IB curriculum), others describe the required course content in open terms (e.g., the Austrian curriculum). However, the focus of this study was only to give an overview of which particle physics concepts are explicitly included in the curriculum. Therefore, the contextualization of particle physics and the level of competency students achieve on the topic should be a subject of a subsequent study.

Similarly, this curricular review focused on formal curricula provided by the governing bodies of the respective educational systems. Teachers, especially experienced teachers with deeper content knowledge in particle physics, can choose to include more concepts and more examples that are not mentioned in the formal curriculum. Likewise, how particle physics is introduced in textbooks can significantly change how particle physics is taught in classrooms. Indeed, textbooks are often used as a primary source of instruction [74]. As such, the results of this curricular review only show the baselines set by physics curricula. Further investigations into classroom practice and textbooks are needed to identify how teachers' instructional practices correspond to the official curriculum and how many elective topics are presented in the classroom. Furthermore, such investigations could provide a better overview of how particle physics context enters teachers' instructional practices.

5.2. Implications

The results of this first international curricular review of the particle physics content in high-school curricula show that particle physics is present in all high-school physics curricula, albeit not always explicitly. Regardless, particle physics is typically introduced with a strong focus on theoretical particle physics. Indeed, very little attention is given to experimental particle physics in high-school physics curricula. Based on these results, we can draw several implications for teaching, future curricular development, and future research, as presented below.

First, the coding manual developed for this curricular review is a powerful tool for identifying important concepts in particle physics education. The coding manual was based on the literature and further developed by experts in particle physics and physics education. Therefore, the manual itself can be used as a guide for teachers when implementing particle physics in their teaching practice.

Second, the curricular review uncovered many aspects for improving the curricula in general. The most striking is the lack of experimental particle physics concepts. Here, studies have shown that students often struggle with understanding the role of experiments in science [76,77]. Therefore, including more modern experimental physics in physics curricula can help students understand not only the importance but also the role of experiments in modern physics. Furthermore, several suggestions in the literature showed that experimental particle physics concepts could be a suitable context for other curricular topics, e.g., [14,37,38]. As such, connecting different parts of the curriculum to new concepts can help students to learn more meaningfully [84]. Additionally, giving a modern experimental example from an interesting topic in an otherwise classical topic can increase students' interest in other parts of physics as well. Indeed, especially real-life applications of experimental technologies in physics in fields such as medicine, food safety, and art (among others) can appeal to students on a personal level.

Likewise, particle physics can be a powerful context for learning about the nature of science. The results of this study show that the knowledge of the nature of science is often included as one of the overarching goals of physics education. Although the nature of science has been shown to be best taught explicitly [80], most curricula do not include it in the content part of the curricular document. Thus, a modern context such as particle physics can be used to introduce the nature of science more explicitly. However, further studies are needed to investigate how best to showcase the nature of science in the context of particle physics.

Last, the methodology in this curricular review relied greatly on expert practitioners, namely teachers with experience with their respective curricula. As such, the researchers were able to explore various curricula in different languages with little chance of mistranslation. Additionally, including several reviewers per curriculum reduced the possibility of misinterpretations of the curriculum and increased the reliability of the review. As such, the curriculum review was more streamlined, with less back-and-forth between the reviewers and the researchers. Therefore, this method is very suitable for future curriculum reviews.

To conclude, particle physics concepts are included in all curricula either explicitly or implicitly. Therefore, particle physics can provide students with an excellent example of science-in-action. However, particle physics is not the only modern physics topic that can fulfil that role. Indeed, quantum physics, nanotechnology, and soft condensed matter are only some examples of topics that can have a similar role in the curriculum. They are all examples of science-in-action, can be used as context for the explicit teaching of the Nature of Science, and are closely connected to various other parts of the curriculum. Furthermore, these topics might come even closer to students' everyday lives as they have or explicitly strive for more direct applications, e.g., nanotechnology for surface coatings or quantum computers. While there are several very prominent examples of particle physics applications in real-life situations (e.g., hadron therapy, positron emission tomography (PET), safety scanners), particle physics introduces a discussion on the value of purely basic science. Indeed, particle physics research is not explicitly aiming to result in a practical application, e.g., an equivalent of a quantum computer. The aim of particle physics remains to address the most fundamental questions of human nature: what are we made of, where do we come from, and where are we going. Therefore, the introduction of particle physics in high-school education provides a unique opportunity to discuss the importance of basic sciences in modern society.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/physics4040082/s1, Table S1: Coding Manual; Table S2: Overview of the particle physics topics and concepts in high-school curricula with and without a dedicated particle physics chapter.

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References

1. Sjøberg, S.; Schreiner, C. Results and perspectives from the ROSE project: Attitudinal aspects of young people and science in a comparative perspective. In *Science Education Research and Practice in Europe*; Jorde, D., Dillon, J., Eds.; Brill: Leiden, The Netherlands, 2012; pp. 203–236. Available online: https://brill.com/view/book/edcoll/9789460919008/BP000010.xml (accessed on 27 September 2022).
2. Gil, D.; Solbes, J. The introduction of modern physics: Overcoming a deformed vision of science. *Int. J. Sci. Educ.* **1993**, *15*, 255–260. [CrossRef]
3. Chatterjee, L. Introducing particle physics through story. *Phys. Educ.* **2002**, *37*, 260–262. [CrossRef]
4. Kobel, M. High school students' exposure to modern particle physics. *Europhys. News* **2003**, *34*, 108–110. [CrossRef]
5. Tuzón, P.; Solbes, J. Particle physics in high school: A diagnose Study. *PLoS ONE* **2016**, *11*, e0156526. [CrossRef] [PubMed]
6. Hanley, P. Teaching particle physics. *Phys. Educ.* **2000**, *35*, 332–338. [CrossRef]
7. Aubrecht, G.J. Report on the conference on the teaching of modern physics. *Phys. Teach.* **1986**, *24*, 540–547. [CrossRef]
8. The European Strategy Group. *Deliberation Document on the 2020 Update of the European Strategy for Particle Physics*; Report CERN-ESU-014; CERN: Geneva, Switzerland, 2020. [CrossRef]
9. Young, M. What is a curriculum and whatcan it do? *Curric. J.* **2014**, *25*, 7–13. [CrossRef]
10. Fullan, M.G. Coordinating top-down and bottom-up strategies for educational reform. In *Systemic Reform. Perspectives on Personalizing Education*; Report No. OR 94-3308; Anson, R.J., Ed.; U.S. Department of Education, Office of Educational Research and Improvement: Washington, DC, USA, 1994; pp. 7–23. Available online: https://eric.ed.gov/?id=ED376557 (accessed on 27 September 2022).
11. Stadermann, H.K.E.; van den Berg, E.; Goedhart, M.J. Analysis of secondary school quantum physics curricula of 15 different countries: Different perspectives on a challenging topic. *Phys. Rev. Phys. Educ. Res.* **2019**, *15*, 010130. [CrossRef]
12. Lobato, T.; Greca, I.M. Análise da inserção de conteúdos de teoria quântica nos currículos de física do ensino médio. *Ciência Educ.* **2005**, *11*, 119–132. [CrossRef]
13. Mullis, I.V.S.; Martin, M.O.; Foy, P.; Hooper, M. *TIMSS Advanced 2015 International Results in Advanced Mathematics and Physics*; TIMSS & PIRLS International Study Center, Boston College: Chestnut Hill, MA, USA, 2016; Available online: http://timssandpirls.bc.edu/timss2015/international-results/advanced/ (accessed on 27 September 2022).
14. Wiener, G.J.; Woithe, J.; Brown, A.; Jende, K. Introducing the LHC in the classroom: An overview of education resources available. *Phys. Educ.* **2016**, *51*, 035001. [CrossRef]
15. Van den Akker, J. Curriculum perspectives: An introduction. In *Curriculum Landscapes and Trends*; Akker, J., Kuiper, W., Hameyer, U., Eds.; Springer Science+Business Meadia: Dordrecht, The Netherlands, 2003; pp. 1–10. [CrossRef]
16. Remillard, J.T. Examining key concepts in research on teachers' use of mathematics curricula. *Rev. Educ. Res.* **2005**, *75*, 211–246. [CrossRef]
17. Gehrke, N.J.; Knapp, M.S.; Sirotnik, K.A. Chapter 2: In search of the school curriculum. *Rev. Res. Educ.* **1992**, *18*, 51–110. [CrossRef]
18. Nawaz, H.; Akbar, R.A. Exploration of Gaps between intended and enacted physics curriculum: Teachers' professional development perspective. *Bull. Educ. Res.* **2019**, *41*, 1–10.
19. Gourlay, H. Learning about A level physics students' understandings of particle physics using concept mapping. *Phys. Educ.* **2017**, *52*, 014001. [CrossRef]
20. van den Berg, E.; Hoekzema, D. Teaching conservation laws, symmetries and elementary particles with fast feedback. *Phys. Educ.* **2006**, *41*, 47–56. [CrossRef]
21. Hoekzema, D.; Schooten, G.; van den Berg, E.; Lijnse, P. Conservation laws, symmetries, and elementary particles. *Phys. Teach.* **2005**, *43*, 266–271. [CrossRef]
22. Lindenau, P.; Kobel, M. Introducing an innovative approach of teaching the Standard Model of particle physics at high school. *J. Phys. Conf. Ser.* **2019**, *1287*, 012045. [CrossRef]
23. Hobson, A. Teaching elementary particle physics. Part I. *Phys. Teach.* **2011**, *49*, 12–15. [CrossRef]
24. Hobson, A. Teaching elementary particle physics. Part II. *Phys. Teach.* **2011**, *49*, 136–138. [CrossRef]
25. Polen, C. Particle physics: An essential and engaging part of the high school physics program. *Phys. Teach.* **2019**, *57*, 320–322. [CrossRef]
26. Woithe, J.; Wiener, G.J.; van der Veken, F.F. Let's have a coffee with the Standard Model of particle physics! *Phys. Educ.* **2017**, *52*, 034001. [CrossRef]
27. Nikolopoulos, K.; Pardalaki, M. Particle dance: Particle physics in the dance studio. *Phys. Educ.* **2020**, *55*, 025018. [CrossRef]
28. Michelini, M. Innovation of curriculum and frontiers of fundamental physics in secondary school: Research-based proposals. In *Fundamental Physics and Physics Education Research*; Sidharth, B.G., Murillo, J.C., Michelini, M., Perea, C., Eds.; Springer International Publishing: Cham, Switzerland, 2021; pp. 101–116. [CrossRef]
29. Passon, O.; Zügge, T.; Grebe-Ellis, J. Pitfalls in the teaching of elementary particle physics. *Phys. Educ.* **2019**, *54*, 015014. [CrossRef]
30. Alexopoulos, A.; Pavlidou, M.; Cherouvis, S. "Playing with Protons": A training course for primary school teachers at CERN. *Phys. Educ.* **2019**, *54*, 015013. [CrossRef]
31. McGinness, L.; Dührkoop, S.; Woithe, J.; Jansky, A. 3D printable quark puzzle: A model to build your own particle systems. *Phys. Teach.* **2019**, *57*, 526–528. [CrossRef]

32. MacDonald, T.; Bean, A. Quarked!—Adventures in particle physics education. *Phys. Teach.* **2009**, *47*, 38–41. [CrossRef]
33. Pavlidou, M.; Lazzeroni, C. Particle physics for primary schools—Enthusing future physicists. *Phys. Educ.* **2016**, *51*, 054003. [CrossRef]
34. Johansson, K.E.; Kobel, M.; Hillebrandt, D.; Engeln, K.; Euler, M. European particle physics masterclasses make students into scientists for a day. *Phys. Educ.* **2007**, *42*, 636. [CrossRef]
35. Cecire, K.; Bardeen, M.; McCauley, T. The CMS masterclass and particle physics outreach. *EPJ Web Conf.* **2014**, *71*, 00027. [CrossRef]
36. Wiener, G.J.; Schmeling, S.M.; Hopf, M. An alternative proposal for the graphical representation of anticolor charge. *Phys. Teach.* **2017**, *55*, 472–474. [CrossRef]
37. Barradas-Solas, F. Giving new life to old equipment. *Phys. Educ.* **2007**, *42*, 9–11. [CrossRef]
38. Cid-Vidal, X.; Cid, R. Lead ions and Coulomb's law at the LHC (CERN). *Phys. Educ.* **2018**, *53*, 024002. [CrossRef]
39. Kvita, J.; Čermáková, B.; Matulová, N.; Poštulka, J.; Staník, D. Particle camera MX-10 in physics education. *Phys. Educ.* **2019**, *54*, 025011. [CrossRef]
40. Fereday, J.; Muir-Cochrane, E. Demonstrating rigor using thematic analysis: A hybrid approach of inductive and deductive coding and theme development. *Int. J. Qualit. Meth.* **2006**, *5*, 80–92. [CrossRef]
41. Roberts, K.; Dowell, A.; Nie, J.-B. Attempting rigour and replicability in thematic analysis of qualitative research data; a case study of codebook development. *BMC Med. Res. Methodol.* **2019**, *19*, 66. [CrossRef] [PubMed]
42. Pavlin, J.; Stefanel, A.; Lindenau, P.; Kobel, M.; Kranjc Horvat, A.; Wiener, J.; Schmeling, S.; Borowski, A.; Sokołowska, D.; Čepič, M. Introduction of contemporary physics to pre-university education. In *Teaching-Learning Contemporary Physics. From Research to Practice*; Jarosievitz, B., Sükösd, C., Eds.; Springer International Publishing: Cham, Switzerland, 2021; pp. 71–90. [CrossRef]
43. CERN. Our Member States. Available online: https://home.cern/about/who-we-are/our-governance/member-states (accessed on 27 September 2022).
44. Kranjc Horvat, A. Particle Physics in High-School Education: What Should Students and Teachers Learn? Ph.D. Thesis, University of Potsdam, Potsdam, Germany, 2022.
45. International Baccalaureate Organization. Diploma Programme Physics Guide: First Assessment 2016. Available online: http://www.holyheart.ca/wp-content/uploads/2016/10/IB-Physics-Guide-2016.pdf (accessed on 27 September 2022).
46. Austrian Federal Ministry of Education, Science. Gesamte Rechtsvorschrift für Lehrpläne—Allgemeinbildende Höhere Schulen, Gymnasium Physik. 2018. Available online: https://www.ris.bka.gv.at/GeltendeFassung.wxe?Abfrage=Bundesnormen&Gesetzesnummer=10008568 (accessed on 27 September 2022). (In German)
47. Queensland Curriculum and Assessment Authority. Physics Geeneral Senior Syllabus 2019: Syllabus v1.3. Available online: https://www.qcaa.qld.edu.au/senior/senior-subjects/sciences/physics/syllabus (accessed on 27 September 2022).
48. Narodne Novine; Ministarstvo Znanosti i Obrazovanja. *Kurikulum Nastavnog Predmeta Fizika za Osnovne Škole i Gimnazije. Odluka, NN 10/2019-210.*. Available online: https://narodne-novine.nn.hr/clanci/sluzbeni/2019_01_10_210.html (accessed on 27 September 2022). (In Croatian)
49. *Rahmenlehrplan für den Unterricht in der Gymnasialen Oberstufe im Land Brandenburg. Physik*; Ministerium für Bildung, Jugend und Sport des Landes Brandenburg: Berlin–Brandenburg, Germany, 2018. Available online: https://bildungsserver.berlin-brandenburg.de/fileadmin/bbb/unterricht/rahmenlehrplaene/gymnasiale_oberstufe/curricula/2018/RLP_GOST_Physik_BB_2018.pdf (accessed on 27 September 2022). (In German)
50. Ministry of Education. Physics Curriculum for Upper Division. Available online: https://edu.gov.il/special/Curriculum/High-School/physics/Pages/Syllabus.aspx (accessed on 27 September 2022). (In Hebrew)
51. *Federal Component of the State Standard of General Education*; Ministry of Education of the Russian Federation: Moscow, Russia, 2016. Available online: https://mosmetod.ru/files/dokumenty/Primernaya-osnovnaya-obrazovatelnaya-programma-srednego-obshhego-obrazovaniya.pdf (accessed on 27 September 2022). (In Russian)
52. *Lehr-und Stoffplan*; Amt für Berufsbildung und Mittelschule, Kanton Nidwalden: Stans, Switzerland, 2020. Available online: https://www.kollegistans.ch/wp-content/uploads/LPSP-Kollegium-030522.pdf (accessed on 27 September 2022).
53. *Requirements for Curriculum and Program for Gift Students in Mathematics High School*; Ministry of Education, Science and Technological Development of Republic of Serbia: Belgrade, Serbia, 2016. Available online: https://www.mpn.gov.rs/wp-content/uploads/2018/02/%D0%9F%D1%80%D0%B0%D0%B2%D0%B8%D0%BB%D0%BD%D0%B8%D0%BA-%D0%BE-%D0%BD%D0%B0%D1%81%D1%82%D0%B0%D0%B2%D0%BD%D0%BE%D0%BC-%D0%BF%D0%BB%D0%B0%D0%BD%D1%83-%D0%B8-%D0%BF%D1%80%D0%BE%D0%B3%D1%80%D0%B0%D0%BC%D1%83-%D0%B7%D0%B0-%D0%BE%D0%B1%D0%B4%D0%B0%D1%80%D0%B5%D0%BD%D0%B5-%D1%83%D1%87%D0%B5%D0%BD%D0%B8%D0%BA%D0%B5-%D1%83-%D0%9C%D0%B0%D1%82%D0%B5%D0%BC%D0%B0%D1%82%D0%B8%D1%87%D0%BA%D0%BE%D1%98-%D0%B3%D0%B8%D0%BC%D0%BD%D0%B0%D0%B7%D0%B8%D1%98%D0%B8.pdf (accessed on 27 September 2022). (In Serbian)
54. Independent Examinations Board. *Advanced Programme Physics*; Independent Examinations Board: Gauteng, South Africa, 2019.
55. Ministerio de Educacion, Cultura y Deporte. I. Disposiciones Generales. *Bolet. Ofic. Estado* **2015**, *3/1*, 169–546. Available online: https://www.boe.es/boe/dias/2015/01/03/pdfs/BOE-A-2015-37.pdf (accessed on 27 September 2022). (In Spanish).
56. *AS and A-Level Physics*; AQA Education: Manchester, UK, 2017; Available online: https://filestore.aqa.org.uk/resources/physics/specifications/AQA-7407-7408-SP-2015.PDF (accessed on 27 September 2022).

57. *Currículo Paulista*; Governo do Estado de São Paolo, Secretaria da Educação: São Paolo, Brazil, 2021. Available online: https://efape.educacao.sp.gov.br/curriculopaulista/wpcontent/uploads/2021/01/TEMPLATE-Divis%C3%A3o-Habilidades-por-Ci%C3%AAncias-da-Natureza-e-suas-Tecnologias-1o-S%C3%A9rie-EM.pdf (accessed on 27 September 2022). (In Portuguese)
58. *Senior 3 Physics. A Foundation for Implementation*; Manitoba Departement of Education and Youth: Winnipeg, MB, Canada, 2003. Available online: https://www.edu.gov.mb.ca/k12/cur/science/found/physics30s/full_doc.pdf (accessed on 27 September 2022).
59. *Bildungsplan des Gymnasiums. Physik*; Ministerium für Kultus, Jugend und Sport Baden-Württemberg: Stuttgart, Germany, 2016. Available online: http://www.bildungsplaene-bw.de/site/bildungsplan/get/documents/lsbw/export-pdf/depot-pdf/ALLG/BP2016BW_ALLG_GYM_PH.pdf (accessed on 27 September 2022). (In German)
60. *Lehrplan Oberschule. Physik*; Sächsisches Staatsministeriums für Kultus: Dresden, Germany, 2019. Available online: http://lpdb.schule-sachsen.de/lpdb/web/downloads/54_lp_os_physik_2019.pdf?v2 (accessed on 27 September 2022). (In German)
61. Groupe Réussite. Programme de Physique-Chimie en Terminale. 2019. Available online: https://groupe-reussite.fr/ressources/programme-terminale-s-physique-chimie/ (accessed on 27 September 2022). (In French).
62. Ministry of Education. *Teaching Syllabus for Physics (Senior High School 1–3)*; Ministry of Education Science and Sports: Accra, Ghana, 2010. Available online: https://unesdoc.unesco.org/ark:/48223/pf0000221448.locale=en (accessed on 27 September 2022).
63. Ministry of Education and Religious Affairs; Institute of Educational Policy. Material and Instructions for the Teaching of Physical Sciences (Physics, Chemistry, Biology) in Grades A, B and C of the General High School. 2020. Available online: http://iep.edu.gr/el/graf-b-yliko/geniko-lykeio (accessed on 27 September 2022). (In Greek)
64. Ministero Dell'istruzione, Dell'università e della Ricerca. Indicazioni Nazionali Riguardanti Gli Obiettivi Specifici Di Apprendimento Concernenti Le Attività e Gli Insegnamenti Compresi Nei Piani Degli Studi Previsti per i Percorsi Liceali. 2010. Available online: https://www.gazzettaufficiale.it/gunewsletter/dettaglio.jsp?service=1&datagu=2010-12-14&task=dettaglio&numgu=291&redaz=010G0232&tmstp=1292405356450 (accessed on 27 September 2022). (In Italian)
65. Center of Educational Research and Development. *Curriculum Decree & General Target*; Center for Educational Research and Development: Beirut, Lebanon, 1997.
66. *Syllabus Centraal Examen 2021*; College voor Toetsen en Examens: Utrecht, The Netherlands, 2019; Available online: https://www.examenblad.nl/examenstof/syllabus-2021-natuurkunde-vwo/2021/f=/natuurkunde_3_versie_vwo_2021_av.pdf (accessed on 27 September 2022). (In Dutch)
67. Ministerstwo Edukacji Narodowej. Fizyka. Liceum/Technikum. 2018. Available online: https://podstawaprogramowa.pl/Liceum-technikum/Fizyka (accessed on 27 September 2022). (In Polish)
68. Štátny Inštitút Odborného Vzdelávania. Fyzika. 2019. Available online: https://siov.sk/wp-content/uploads/2019/06/B10_VO_ČaP_FY_CH_BI.pdf (accessed on 27 September 2022). (In Slovak)
69. *Curriculum: High School Physics*; Ministry of Science, Education and Sports of Republic of Slovenia: Ljubljana, Slovenia, 2015. Available online: http://eportal.mss.edus.si/msswww/programi2017/programi/media/pdf/un_gimnazija/2015/UN-FIZIKA-gimn-12.pdf (accessed on 27 September 2022). (In Slovenian)
70. Swedish National Agency for Education. Fysik. 2020. Available online: 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 (accessed on 27 September 2022). (In Swedish)
71. National Academy of Sciences. Next Generation Science Standards. Available online: https://www.nextgenscience.org (accessed on 27 September 2022).
72. Keller, O.; Schmeling, S.; Müller, A.; Benoit, M. IPadPix—A novel educational tool to visualise radioactivity measured by a hybrid pixel detector. *J. Instrum.* **2016**, *11*, C11032. [CrossRef]
73. Koponen, I.T.; Mäntylä, T. Generative role of experiments in physics and in teaching physics: A suggestion for epistemological reconstruction. *Sci. Educ.* **2006**, *15*, 31–54. [CrossRef]
74. Park, W.; Yang, S.; Song, J. When modern physics meets nature of science: The representation of nature of science in general relativity in new Korean physics textbooks. *Sci. Educ.* **2019**, *28*, 1055–1083. [CrossRef]
75. Angell, C.; Henriksen, E.K.; Isnes, A. physics: Frightful, but fun. Pupils' and teachers' views of physics and physics teaching. *Sci. Educ.* **2004**, *88*, 683–706. [CrossRef]
76. Wilcox, B.R.; Lewandowski, H.J. Students' views about the nature of experimental physics. *Phys. Rev. Phys. Educ. Res.* **2017**, *13*, 020110. [CrossRef]
77. Sirola, C. May the forces be with you! *Phys. Teach.* **2018**, *56*, 118–119. [CrossRef]
78. Campanile, M.F.; Lederman, N.G.; Kampourakis, K. Mendelian genetics as a platform for teaching about nature of science and scientific inquiry: The value of textbooks. *Sci. Educ.* **2015**, *24*, 205–225. [CrossRef]
79. McDonald, C.V. 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*; McDonald, C.V., Abd-El-Khalick, F., Eds.; Routledge: New York, NY, USA, 2017; pp. 98–117.
80. Lederman, N.G. Nature of science: Past, present, and future. In *Handbook of Research on Science Education*; Abell, S.K., Lederman, N.G., Eds.; Routledge: New York, NY, USA, 2007; pp. 845–894.

81. Stadermann, H.K.E.; Goedhart, M.J. 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. *Phys. Rev. Phys. Educ. Res.* **2021**, *17*, 20132. [CrossRef]
82. Woithe, J.; Boselli, M.; Chatzidaki, P.; Dahlkemper, M.N.; Duggan, R.; Durey, G.; Herff, N.; Kranjc Horvat, A.; Molaro, D.; Scheerer, G.W.; et al. Higgs in a box: Investigating the nature of a scientific discovery. *arXiv* **2022**, arXiv:2206.06107. [CrossRef]
83. Kranjc Horvat, A.; Boselli, M.; Chatzidaki, P.; Dahlkemper, M.N.; Duggan, R.; Durey, G.; Herff, N.; Molaro, D.; Scheerer, G.W.; Schmeling, S.; et al. The Mystery Box Challenge: Exploring the Nature of Science. *Sci. Sch.* **2022**, *59*. Available online: https://www.scienceinschool.org/article/2022/mystery-box-challenge/ (accessed on 27 September 2022).
84. Ausubel, D.P. *The Acquisition and Retention of Knowledge: A Cognitive View*; Springer Media: Dordrecht, The Netherlands, 2000. [CrossRef]