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Opportunities and Challenges of Using Feynman Diagrams with Upper Secondary Students

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Abstract: Particle physics is an exciting subject for high school students, and there have been various approaches on how to introduce the topic in the classroom. Feynman diagrams (FDs) are an often-used form of representation in particle physics and could play an important role in such an introduction. However, their potential educational value has not yet been investigated. To this end, we interviewed four experts in the field of particle physics education on the opportunities and challenges Feynman diagrams could pose for high school students. We analyzed their answers using a thematic analysis framework, categorizing them into five themes. The results of these interviews show that there are two challenges (FDs elicit and perpetuate inadequate conceptions about particle physics, and FDs can only be treated superficially in school) and three opportunities (FDs can link particle physics and other physics topics in high school education, FDs offer an opportunity for different particle physics topics to be taught, and FDs offer a connection to current research). The results of this expert interview study lead to several suggestions on how to design learning environments that incorporate Feynman diagrams.

Keywords: particle physics; Feynman diagrams; secondary education; expert interviews; design-based research

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1. Introduction

Particle physics has been introduced in high school physics curricula in many countries. When teaching about particle physics, an often-used representation is that of so-called Feynman diagrams (FDs). However, while being of great use for particle physics, it is unclear whether using FDs in education benefits learners, since possible inadequate conceptions could be connected to them. The current study explores potential opportunities FDs can create for learning particle physics and the challenges that using these diagrams pose. To meet these aims, we interviewed experts in particle physics education.

1.1. Particle Physics in High School Education

The first calls to introduce particle physics in high school physics teaching date back to the 1980s [1], with one of the first conferences on the teaching of modern physics taking place at the European Organization for Nuclear Research (CERN) in 1984 [2]. Students might see particle physics as an exciting topic, which can serve as an example of the nature of physics as being tentative and constantly changing. Moreover, unknown phenomena and the newest scientific discoveries have been proven to be extremely interesting topics for adolescents [3]. Finding answers to the fundamental questions of nature can positively influence students' attitudes toward physics. The call for particle physics in high school education has since been replicated several times (e.g., [4–6]). Despite these calls, particle physics only rarely makes it into the curricula and subsequently into the teacher training courses at university. However, several suggestions have been made on how to incorporate particle physics into high school education (e.g., [7–10]). These suggestions vary greatly in the concepts they include and the approaches they take to introduce these concepts to high school students. They range from an overview of the "particle zoo" [10] to discussions of particle interactions, conservation laws, and symmetries [11,12] to coherent learning material for teaching the Standard Model of particle physics by connecting charges, particle interactions, and elementary particles [9].

Some approaches have been criticized as presenting the topic of particle physics in a superficial and oversimplified way [13,14]. Furthermore, presenting all the elementary particles in a merely enumerative manner might not be very motivating and might lead to rote learning of particle names instead of achieving a conceptual understanding of particle physics [15].

So far, few studies have been conducted to systematically investigate students' understanding of particle physics or the impact of specific interventions in the field [6,16,17].

1.2. Feynman Diagrams

A specific topic within particle physics is that of Feynman diagrams. The idea of FDs was first presented publicly by Richard Feynman at a conference in the spring of 1948 [18] and was subsequently published by Freeman Dyson and Feynman [19,20]. Since then, they have become a commonly used graphical tool in many areas of theoretical physics, but especially in quantum field theory and, thus, particle physics. In fact, they have been invented mainly as a tool for "bookkeeping" and visualization in the perturbation-theoretical calculation of processes in particle physics [18]. However, there is a debate about whether or not FDs are a form of representation of physical processes [21–23]. This debate dates to a disagreement between the inventor of the diagrams, Feynman, and the physicist who connected the diagram to a set of mathematical rules, Dyson. This disagreement is also known as the Feynman–Dyson split [18].

FDs are also part of many introductions to particle physics for high school students (e.g., [7–9]). However, Passon et al. [24] highlight various ideas associated with FDs that are present in educational material, which can be considered to be misleading. For example, any reading in which particles are assigned a trajectory in time and space is, according to the authors, physically nonsensical. Various physicists and physics educators have attempted to give educational introductions to FDs. For instance, Pascolini and Pietroni [25] introduced the diagrams as "accurate metaphors" and attempted to introduce the rules underlying Feynman diagrams to learners using a mechanical model. This approach was empirically investigated in a post-test one month after the intervention, where the learners performed satisfactorily. Hoekzema et al. [11,12] used a reduced form of FDs, which they call "reaction diagrams", to explain conservation laws and symmetries in particle physics. Their proposed teaching activity consists of two 50 min lessons embedded in a larger teaching project about nuclear reactions and elementary particles. The activity had been used for two years as part of a modern physics teaching project. In particular, the approach with the reduced form of the FDs was deemed more comprehensible than a previous text with conventional FDs.

Figure 1 shows a typical example of an FD. Explanations for this type of diagram differ in the extent to which it is explained 'literally'. "Literally" means, in this context, that the diagram is understood as a particle and an antiparticle traveling in straight lines toward each other, meeting and creating a photon, and, at some point, a new particle-antiparticle pair flying away from each other. While some parts of these explanations are compatible with the physical interpretation of the diagrams (for example, particles annihilate each other and new particles are created), others are rather inadequate conceptions (for example, particles do not have determined trajectories). In some texts, FDs are introduced as space–time diagrams [26], while in others, the individual fundamental vertices are explained and linked to mathematical terms in order to stress the inherent mathematical meaning of the diagrams [27]. Several authors try to avoid the problem of a too literal reading by emphasizing the fact that FDs contribute to a probability amplitude [7,28,29].

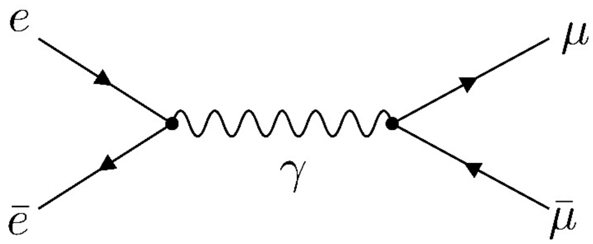

Figure 1. An example of a Feynman diagram of electron–positron (eē) annihilation. The diagram describes the transformation of an electron–positron pair into a muon–antimuon (μμ̄) pair. The interaction is mediated by a photon (γ) which is the interaction particle of the electromagnetic interaction. The direction of arrows determines whether it is a particle or an antiparticle.

A defining property of every FD is that charges are conserved throughout the diagram, meaning that the total amount of any charge (electromagnetic, weak, and strong charge) is the same on the left and on the right side of the diagram. In Figure 1, this can be straightforwardly checked for the electric charge, since the electron and the positron on the left have a total electric charge of zero, which is also true for the muon and the antimuon on the right side.

Different tools have been developed to teach the underlying principles of FDs, most notably the conservation of charges. For example, *FeynGame* is a software that can be used to draw FDs and check them for correctness [30]. Another example is the educational card game *Feynman-Rhombino*, which allows players to create FDs by applying the rules of charge conservation [31].

1.3. Context of the Present Study: Design-Based Research

As illustrated above, several proposals suggest how FDs can be used for educational purposes. However, to our knowledge, no empirical study has investigated the suitability and feasibility of FDs for use in the physics classroom. Therefore, the overarching aim of this research project is to iteratively develop a learning environment that introduces FDs to upper secondary students (16–18-year-olds) and to test the educational use of Feynman diagrams. To do so, we use the framework of design-based research (DBR) [32].

DBR has been used to create learning environments in various fields of modern physics, for example, for the topics of chaotic systems [33], general relativity [34], special relativity [35], and, in particular, particle physics [17].

The DBR framework, also known as design research, design experiments, or educational research design, has been widely used and has resulted in learning interventions that create improved outcomes or student attitudes among the students [36,37]. There are many different approaches to DBR, but a central element is the iterative design and testing of the material. DBR produces both new theories and teaching practices to impact learning [38]. In this way, DBR is a method designed to bridge the gap between research and practice.

A particularly interesting link can be created between DBR and the model of educational reconstruction [39]. In this model, the educational design is informed both by the content structure of the subject matter and by the perspectives of the learners. Analysis of the content structure leads to the formulation of key messages, whereas that of the learners' perspective identifies relevant prior knowledge and potential learning difficulties of the respective subject matter. These two perspectives influence each other in an iterative process. Therefore, the reconstruction of the subject matter does not necessarily follow the content structure of the subject matter. Both the analysis of the content structure and the learners' perspective can be informed by different sources such as experts, literature, and the students themselves.

1.4. Scope of the Study

Building on the existing work about how (not) to incorporate FDs in educational material about particle physics, the current study presents a systematic analysis of the challenges and learning opportunities that are connected to the teaching of FDs. This analysis is the basis for an educational reconstruction of FDs, which is currently undergoing iterative testing with high school students. The research question that guided this work was: What challenges and opportunities do FDs pose for high school students?

2. Materials and Methods

To answer the research question, explorative interviews were conducted with experts in the field of particle physics education [40]. The aim was to determine and summarize the experts' opinions on what purpose FDs could serve in upper secondary school education.

2.1. Selection of Experts

The experts were selected based on their expertise in conveying particle physics to high school students.

We selected three researchers from two German universities who are involved in education programs in particle physics aimed at high school students. Two of them are education researchers, and one is a particle physicist. All three experts have previously published on the educational use of FDs.

After conducting interviews with these three experts and discussing the results among the research team, a discussion point regarding the epistemological role of FDs was raised. Therefore, a science philosopher was interviewed as fourth expert. This expert had expertise in the philosophy of science and conceptual analysis of contemporary physics.

The present study is exploratory in that, for the first time, it gathers data for the challenges and opportunities of integrating important content of contemporary physics into high school physics teaching. While the sample size is small, the results provide evidence for considerable and informative variance on the one hand and increasing overlap between the answer sets on the other hand. This is well in line with the main purpose of the present study, namely an in-depth insight about potential challenges and opportunities to guide further development, and not an exhaustive treatment of the topic (see [41,42]).

2.2. Conducting the Interviews

The first author conducted the interviews in a semi-structured way, that is, the interviewer had an interview guideline with the core questions, but he could diverge from it depending on the answers the interviewees gave.

The interview guideline was constructed based on two guiding questions, which resulted from the research question stated above. These were:

- What challenges are connected to teaching FDs to high school students?
- What opportunities for physics education at the high school level are provided by FDs?

The interview guideline, which is published in the Supplementary Material, contained 12 questions, which were divided into three parts: In the first part, the interviewees described what FDs are. This part served as an entry point to the interview and was not connected to one of the guiding questions. The second part was concerned with possible learning obstacles the experts could imagine or had encountered. This included inadequate conceptions students might already have, or what prior knowledge is needed to read and draw FDs. The third part was connected to the second guiding question and focused on potential learning opportunities offered by FDs. In this part, it was asked, for example, how an appropriate instruction would look like and how students could benefit from learning about Feynman diagrams. In the end, the experts were asked how they would describe a particular Feynman diagram to a high school student.

Special emphasis was put on appropriateness for the target group. For example, concerning the question of what a Feynman diagram is, the experts were specifically asked to describe it for a 17-year-old high school student. Similarly, when asked about potential learning obstacles, the experts were asked about learning obstacles specific to high school students.

The guideline for the interview with the fourth expert was adapted to his expertise, which differed from the expertise of the other interviewees. Specifically, the original guideline was shortened, and the following three introductory segments were added to the interview guideline to better align the results of the fourth interview with the first three interviews: The first segment was intended to clarify the definition of terms such as "model" and "theory". The second segment touched upon the connection between models and reality, since one of the open discussion points concerned the epistemological meaning of FDs. In this part, the expert was asked, for example, to which extent models play a role in science and what role mathematical descriptions play for models. The third segment focused on the role of modern physics in schools, since the second open discussion point after the first three interviews led to the question of whether modern physics—or particle physics in particular—should be taught in high school. In this part, the expert was asked, for example, which aspects of the nature of science he sees as vital for a meaningful discussion of science in a high school classroom.

The interviews were conducted in German via a videoconferencing software and were subsequently transcribed verbatim by the interviewer. The interviews were scheduled to take one hour and lasted for 63, 81, 37, and 81 min. The third expert mentioned during the interview that he did not feel completely well, which led to shorter answers and a faster interview pace, resulting in a shorter interview length.

2.3. Coding Scheme

The interview transcripts were categorized according to the thematic analysis framework [43]. The coding scheme contained two dimensions based on the guiding questions, that is, opportunities and challenges of FDs. These dimensions subsequently served as the highest level of the category system.

The transcripts were scanned for segments referring to these dimensions. Only those segments that answered one of the two guiding questions were categorized. Segments were of different lengths, depending on how much context was given within one segment. The shortest segments consisted of one sentence and the longest of about ten sentences. The first author inductively categorized these segments with preliminary category descriptions. The segments were categorized at the least general level possible, based on their thematic similarities. After categorizing approximately 30% of the transcripts, the categorization was discussed with the co-authors and revised, that is, categories were added, renamed, or merged. Based on the revised categorization, the transcripts were categorized in full. The categories were then subsumed into common themes and subthemes. Some subthemes also had sub-subthemes. Since, depending on the number of segments in a theme, the division into themes and (sub-)subthemes is different, the lowest level is generically called categories in the further description. Further on, categories were dissolved, and the segments were categorized into other existing categories. Through this process, the number of categories was reduced. This categorization was subsequently reviewed while the categories were given instructive descriptions to be incorporated into a coding manual. This coding manual was then discussed with two German-speaking doctoral students in the field of physics education who were not previously involved in the research process. Based on this discussion, the manual was again adapted by redefining category descriptions and merging categories to further reduce their number.

2.4. Validating the Coding of the Data

The revised coding manual was eventually given to the two doctoral students who used this coding manual to code approximately 10% of the coded text segments. This coding manual had 37 categories categorized into five themes. Interrating yielded a Krippendorff's alpha [44] of 0.49. This interrating was subsequently discussed between the first author and the two interraters. Interrater reliability after the discussion was increased to an acceptable level of 0.87. During this interrater discussion, several remarks about the coding manual were made, which led to another revision of both the coding manual and the coding of categories. Disagreements in the coding were caused by giving too little context within segments, which is why some segments were extended to give more context. The final coding manual is shown in the Supplementary Material. It is divided into two dimensions (challenges and opportunities), of which the first dimension contains 12 categories divided into two themes and four subthemes. The second dimension contains 12 categories divided into three themes. A second round of interrating was conducted with a new set of segments and a new interrater who had not been involved in the process before. This interrating showed an initial Krippendorff's alpha of 0.37, and after another interrater discussion and a revised coding, the interrater reliability showed 100% agreement.

3. Results

In total, five themes emerged from the analysis of all four expert interviews, which in turn were assigned to the two dimensions "challenges" and "opportunities". Two themes concerned challenges and three themes concerned opportunities. Of the challenges, the most prominent theme was that FDs elicit and perpetuate inadequate conceptions, which is in line with prior work (see Section 1.2). The second theme was that FDs can only be discussed superficially when discussing them with high school students. In contrast, among the opportunities, the following three themes became apparent: (a) FDs offer the opportunity to discuss perspectives on science, (b) FDs offer a link between particle physics and other high school physics topics, and (c) FDs can be a hook for different particle physics topics, such as the conservation of charges in particle transformation processes.

These five themes are explained further in the following text using subthemes and example segments from the transcripts. The segments presented here are translated from the original. The experts are referred here to as E1, E2, E3, and E4 in the following. E1, E2, and E3 are the first three experts, while E4 is the science philosopher who was later interviewed.

3.1. Challenges

Table 1 shows the two themes and corresponding subthemes present within the dimension of challenges. The subthemes are also further divided into sub-subthemes. Moreover, not all the themes were mentioned by all the experts. Table 1, therefore, shows which of the four experts mentioned which sub-subtheme.

Table 1. Themes and subthemes of the dimension challenges. The order of the (sub-)subthemes within a (sub)theme is according to the frequency of mentions.

Theme	Subtheme	Sub-Subtheme	Mentioned by Experts (E1, E2, etc.)
Feynman diagrams (FDs) elicit and perpetuate inadequate conceptions	Types of inadequate conceptions connected to FDs	Particle processes are embedded in spacetime	E1, E2, E3, E4
		FDs show observable processes	E1, E2, E3, E4
		Particles are small balls	E1, E2, E3
		Focus on the concept of "building blocks" and neglect of the concept of "interaction"	E1, E2
	Potential sources of inadequate conceptions	Use of scientific language is a source of misconceptions	E1, E2, E3
		The axes of FDs are misleading	E2, E3
Particle physics can only be treated superficially	Limitations by educational setting	The time used for particle physics could be used otherwise	E1, E3
		Necessary prior knowledge is missing in school-level physics	E1, E3
		It is a challenge for teachers to teach modern physics	E1
	The disciplinary handling of FD is not taught in school	Calculations might be too difficult	E1, E2, E3, E4
		Drawing FDs is challenging	E2
		Some concepts are too difficult for school-level physics	E2

3.1.1. FDs Evoke and Perpetuate Inadequate Conceptions about Particle Physics

The experts discussed several inadequate conceptions, as well as possible sources of these conceptions, that are connected to FDs.

The conception that was mentioned most often as an inadequate conception connected to FDs was that they represent processes embedded in space–time. E1 pointed out that "this form of illustration in the sense of spatiotemporal embedding" should be avoided. However, E3 has "also noticed with teachers" that they "try to read off information from [the] geometry about the movement ... of the particles involved". E2 also clarifies that the interpretation of an FD as a space–time diagram is "only a crutch here" because it cannot "be a real space-time diagram at all", since there is "no concept of path in quantum mechanics". E4 describes it as a "graphic idealization of a process from which one thinks that it actually does not happen that way, but which seems to be the correct technique for bookkeeping".

Close to that idea, the experts said that it is a common misconception that FDs show observable processes. E2 explains that an FD is "not at all an image of a process in that sense" but "a quantum mechanical amplitude" and that "a process is not only described by one FD but by infinitely many". E3 emphasized that "an FD is not a literally readable description of an actually happening process". E1 went on to say that "a physical process, that must be something that I can observe in the world. The rock that falls. And FDs just do not play in this league". He also pointed out that FDs "ostensibly tell stories about what is happening" and expands on this point by emphasizing that quantum field theory, that is the theory underlying elementary particle physics, is "no less strange" than quantum mechanics and that the "form of clarity" suggested by FDs is "not [offered] by our modern theories".

Another inadequate conception closely connected to FDs is the conception of particles as being small balls which physically collide with each other. E2 explained in the context of Compton scattering that even university students still have the conception that "an electron- and a photon-ball meet each other and then there is an elastic collision, and then there is somehow energy- and momentum-transition and then the electron and the photon fly away from each other with a different momentum". E1 compared this to the transport conception of electric current which was "as wrong as only few things" but "still this naïve particle conception could be measured ... so strongly". He also made a point about interaction particles stating that "the idea that a particle mediates something through an exchange" is "pure use of a metaphor" in his eyes. He emphasized that "nothing is exchanged. It is not here before and there afterwards".

Not directly related to FDs, E1 mentioned the challenge that particle physics is often thought of as "searching the fundamental building blocks" while, in fact, "the part-whole relation of modern physics" would be in fact "superposition and mixing". E2 also mentioned this sub-subtheme but was more practical in the sense that he mentioned that he "is not a friend of first introducing all the particles because that only leads to learning them by heart". They shared the concern of conveying a reductionist image of particle physics as the theory of "the fundamental building blocks".

The experts discussed some sources of misconceptions stemming from the FDs. One important source for the origin of these misconceptions is the use of FDs in the everyday life of scientists and hence the use of scientific jargon which is closely related to their use. E1 described this circumstance as "the use of FDs is always embedded in a practice" and "talking about FDs ... is simply jargon". For students, however, "these diagrams ... are simply pure poison" because "there is the danger that school only conveys the jargon but not the practice of course". He stated that "experts talk like topsy-turvy about them" and would use "the most naïve metaphors such as 'comes in', 'comes out', 'get scattered'", but this would all be "embedded into practice which then clears the misconceptions". Besides these general considerations about scientific language, the experts mentioned several specific terms which might be a source of misconceptions, in particular, the term "virtual particle", which E2 calls "very misleading" because "it leads one to say they actually weren't there, as in virtual reality, and that's not the case". A term which was explicitly mentioned as a term used by experts by E2 and E3 but not suitable for students was the term "propagator".

Another source of misconceptions that was mentioned was the drawing of space- and time-axes in FDs. E2 explained that "in the region where the interactions take place, there is no linear order of time anymore . . . but only the initial and final state, where the two lines come in and where the two lines go out, there it can be imagined in good approximation as trajectories". He admitted that he was not sure whether "the axes should be omitted in the first place or only the *t*[time]-axis" and suggested to investigate *x*-*t*[space-time]-axes, whether they help or lead to even more misconceptions". E3, on the other hand, suggested that "one should not draw a space axis".

3.1.2. Feynman Diagrams Can Only Be Treated Superficially with High School Students

The second theme in the dimension of challenges concerned the treatment of FDs in in school physics classes. Two subthemes belong to this theme. The first subtheme is related to the framework conditions that might inhibit the appropriate treatment of FDs in the classroom. The second subtheme concerns the lack of practice when handling FDs.

One challenge that was pointed out by E1 was that the discussion of particle physics in school lessons takes time away from the discussion of other curricular topics, since particle physics is often not marked as a mandatory topic in high school physics. On the question of whether FDs or particle physics should be treated in school lessons, he explained that this was also connected with the question of what would be lost as a result. This time "should not be taken away from quantum mechanics, for example". E3 pointed out that "if the connection to theory and to quantum mechanics cannot be made due to lack of time and so forth, then it [the treatment of FDs] shouldn't be done".

E3 also pointed out that for an appropriate introduction of FDs in school lessons, a certain level of "prior knowledge is necessary in order not to be subject to a too literal reading of the diagrams", that is, "prior knowledge of quantum objects in general". E1 also raised the concern that the topic of particle physics might be taught "by teachers who never learned about that topic in their education", since particle physics is often not part of the mandatory courses for teacher training students.

The lack of practice is most prominent in calculations that are too difficult for school. E1 pointed out that particle physics in schools can only convey "an overview knowledge. Even more than in other fields of school physics, students will not learn any calculations, they won't solve any concrete problems". E2 described one experience with high school students when it was too difficult "to explain in one day" to draw a certain conclusion from a calculation. E4 points out that "one cannot hope that one can gain a complete understanding of these theories without diving deep into the mathematics".

E2 also mentioned the experience that "it seems to be more difficult for [university] students to draw FDs than to interpret presented FDs", but he admitted that "this was for reasons [he] doesn't understand".

Moreover, E2 mentioned two concepts which are explicitly too complicated for students, namely the transformation to the center-of-mass inertial system for arguing that certain decays are kinetically forbidden and the mixing via the Cabibbo–Kobayashi–Maskawa matrix.

3.2. Opportunities

Table 2 shows the three themes and their associated subthemes that were attributed to the dimension of 'opportunities'. In contrast to the first dimension, the subthemes are not further divided into sub-subthemes.

Table 2. Themes and subthemes for the dimension opportunities. The order of the subthemes within a theme is according to the frequency of overall mentions.

Theme	Subtheme	Mentioned by
FDs offer a link between particle physics and high school topics	FDs are suited to teach conservation laws	E1, E2, E3
	FDs link particle physics and quantum mechanics	E1, E2, E4
	FDs offer an insight into the use of structurally equivalent representations	E1, E2, E3
	FDs offer an analogy to resonance phenomena in classical oscillations	E2, E3
FDs offer an opportunity to teach different particle physics topics	Outer and inner lines/virtual particles	E1, E2, E3
	Introduction of interaction particles	E1, E2, E3
	Suggestions for educational uses of FDs	E1, E2, E3
	Particle types	E2, E3, E4
	Introduction of pair production and annihilation	E1
FDs offer a connection to current research	FDs help scientists to discuss particle processes	E1, E2, E3, E4
	Particle physics is a showcase for modern science	E1, E2, E3, E4
	Students can find FDs in popular scientific representations	E1, E3

3.2.1. FDs Offer a Link between Particle Physics and Other High School Physics Topics

The experts mentioned in the interviews that FDs are linked in many ways to concepts that occur in school lessons. Most prominently, the concept of charge conservation was judged to be very connectable. E2 described FDs as "a wonderful means to check for conservation laws" and even estimated that "charge conservation . . . could definitely be done with younger [than upper secondary] students". Furthermore, E1 uses conservation laws when he is asked to explain a specific FD.

Almost as often as the first subtheme, the experts mentioned that a link between quantum mechanics and particle physics could be established using FDs. E1 emphasized that in the teaching of elementary particle physics, "a certain unity of modern physics" should be presented and that "one should see where one can deepen what one has already learned in quantum mechanics, that this is regarded as [a] unity". E2 pointed out that "one should refer to the other world of quantum physics as early as possible". Moreover, E4 pointed out that "it is important to see that the Standard Model is a quantum theory, that the quantum effects which one has maybe discussed more generally are built into it". More specifically regarding FDs, E1 stated that he would "elucidate the meaning of an FD analogous to the single amplitudes in the double slit, . . . that there is one contribution of the wave function, which expresses that the electron goes through one slit". But this would not be a process "which occurs in nature. But the square of the sum of both of these parts corresponds to the observation". E2 summarized this by stating that "FDs don't describe the truth singularly but only the coherent sum describes the truth".

The experts also described the analogy of FDs offering an insight to structural equivalence in analogy to the teaching of electricity. E1 explained that FDs have structural similarities with drawings of electrical circuits. They both have in common that it is important to see "where something is only symbolically noted and how literally a symbolic depiction can be read . . . This kind of structural knowledge can be used . . . not to fall into the trap to think so vividly". The experts called this notion of invariance concerning different drawings 'topological equivalence'. E3 explained electrical circuits in this sense as "an example where one does not need to focus on the exact geometry in order to analyze what is depicted". E2 expanded on this thought by making the analogy that "the conservation law is the junction rule of currents for example. Current just doesn't get lost. . . . And these charge currents are also in the FDs". E1 also made another point connected to the teaching of electricity by stating that particle physics could already be introduced together with electricity "if we want to make the point in particle physics that actually there are no particles, then this could be the conclusion which already informs the teaching of electricity in lower secondary schools".

Another analogy that was highlighted by the experts was between the concept of virtual particles, which are "off mass-shell", and the concept of forced oscillations in mechanics. E2 explained this concept as: "in classical mechanics it is not special at all to have an oscillating system which can be excited with all frequencies and when it is excited with the eigenfrequency I get a high amplitude and it's just like that with virtual particles when I excite them with their eigenfrequency, then the process is very likely because I have a high amplitude". He also connected this concept to the nuclear fusion in the sun, which is happening so slowly because "there all the W-particles … are highly virtual". This concept might be "fascinating for high school students". E3 also mentioned this analogy and estimated that "it might work well for teachers", while for students it might be more difficult since "forced oscillations … do not play a role everywhere or only in selected courses".

3.2.2. FDs Offer an Opportunity for Different Particle Physics Topics to Be Taught

While the previous theme was about potential links between particle physics and other high school physics topics, the experts mentioned several aspects of particle physics that could be worthwhile to teach in high school physics. In all of these aspects, FDs play an important role.

One very prominent topic was the distinction between initial, intermediate, and final states. E1 stressed that "the initial state has a meaning, and the final state has a meaning. And when the diagrams do not differ in the initial and final state, then they aren't distinguishable in the measurement". Moreover, then one would be "interested in all possible intermediate processes which can connect them [the initial and final state] according to the rules". This distinction, in his view, has to be "brought home centrally". Further, E2 said that he would "clearly define particles in the initial state and particles in the final state". E3 further explained the distinction between outer lines and inner lines of FDs as for an inner line the "mass-energy-momentum relation … does not have to be fulfilled" while it has to be fulfilled for an outer line. He also made the connection that "virtual particles are inner lines in FDs". This concept, on the other hand, connects to the analogy of forced oscillations in mechanics mentioned in the previous theme. Connected to the topic of the inner lines is also the topic of "topological equivalence", which was already mentioned in connection with electrical circuits. E3 stressed this topic by explaining that "the temporal order of vertices is not fixed. One can shift vertices and transfer diagrams in other topologically equivalent diagrams, which are then the same diagrams".

Another promising opportunity mentioned is to introduce and further explain the notion of interaction particles (also known as exchange- or messenger-particles or force carriers). E1 even stated that he believes that "the only reason why one should talk about FDs is that one can introduce exchange particles or because exchange particles obtain their metaphorical meaning from this graphical symbolic language". E3 stated the contrasting view that "one needs the concept of exchange- or messenger-particles for that [FDs]" which, in turn, "only make sense … in this view of fundamental interactions". E2 expands this concept by stating that "when the concept of exchange- or messenger-particles is introduced, then one has to say that these exchange- or messenger-particles couple to charge, that is, they see—in quotation marks—only other objects which carry or own the charge of this interaction".

Two of the experts also mentioned a subtheme on how FDs are connected to different particle types. E2 stated that "it suffices to first only work with the electron, photon, up and down quark, … electron neutrino, … W and Z", that is, he only wants to introduce a selection of particles. E3 suggested that "messenger particles could be drawn differently from matter particles to emphasize the distinction". Another important point concerns the antiparticles, which in FDs are depicted with an arrow against the direction of time. E3 acknowledged the inadequate conception of a particle moving backward in time but also stressed that "in his experience, teachers accept [that it's just a symbolic convention]".

One other aspect raised by E1 was the introduction of pair production and particle annihilation, which would be "the main point of relativistic quantum field theory". He explains that "the type of question on which FDs could be an answer to" is about how a detector can detect many particles although only two particles interact with each other.

The experts also made several suggestions on how to introduce FDs in high school classrooms. For example, both E2 and E3 mentioned *Feynman-Rhombino*, a card game which was invented to practice the rules of creating FDs [31]. These rules were described by E2 as "chaining up [basic] vertices to build scattering processes, decay processes, annihilation- and creation processes". E2 also suggested that "in school, one can explain some basic calculation principles", and he described FDs as "a wonderful tool . . . that I can bring something from the right to the left side, from initial to final state" and by that one can make connections to reaction equations in chemistry or even mathematical equations.

3.2.3. FDs Offer the Opportunity to Discuss Insightful Perspectives on Science

The experts mentioned several aspects where FDs can offer perspectives on science in general and modern physics in particular.

E4 distinguished the roles of FDs "between a pedagogical role to convey the theory and a scientific role to work with the theory as a scientist". The latter was described by E2 from the point of view of a particle physicist. Specifically, for him, FDs are "[a] very clear representation, [a] very helpful, but also very impressively powerful representation". E4 raised the point that "FDs can serve to . . . also [show] the methodology of particle physics". According to him, physics classes in upper secondary schools should convey "the way of thinking, the methodology which lies behind [the theories and physics]" and "FDs [can be] an extremely good illustration [for this]".

Apart from the connection to the daily work, the experts also mentioned that FDs in particular, and particle physics in general, are showcases for modern science and modern physics. E2 emphasized that "physics has come so far that it has managed to predict what may happen, . . . what may not happen and even with what probability this or that will happen". This "predictive power" is something that "should definitely be emphasized at school". E4 also described this theory as "the most successful theory that humankind has ever come up with". E3 suggested that students can learn "something about the procedures of and mathematization in theoretical physics" using FDs. E1 suggested using FDs as an opportunity to "[convey] the big message of modern physics . . . We have theories which work perfectly in a functional sense, but actually we do not know what the objects refer to, at least they are not spatially and temporally embedded". He also raised another point on how particle physics might be useful for students, namely by highlighting "the science-sociological and nature of science aspect that science is a collaborative endeavor".

Another aspect related to the engagement with science is the critical examination of scientific representations, such as in textbooks or popular science texts. E3 explains that "of course, it should also be a learning goal" that "the students can classify popular science literature or sources . . . " E1 even notes that "the main benefit in the educational context" is that "one can point out widespread misunderstandings" and "send the students on a journey to find misleading or false representations in popular, but also subject-related representations". This could be "a contribution to an experience of autonomy".

4. Discussion

The results from the expert interviews show the potential, but also the difficulties, associated with the introduction of FDs in high school classrooms. The experts had different opinions on whether and how FDs should be used with high school students. Indeed, all experts presented both opportunities and challenges on this matter. Based on the results, four learning objectives for potential learning material with FDs were developed. These are presented and motivated here.

4.1. Learning Objectives

4.1.1. Charge Conservation

The first learning objective is: "Students will be able to use the concept of conservation of charge to determine whether a particle process is possible or not". The subtheme "FDs are a tool to teach about conservation laws" was the most often mentioned opportunity, and all three original experts mentioned it (the fourth expert did not mention this opportunity since the scope of that interview was to clarify discussion points connected to more advanced topics such as the connection to quantum physics). Since conservation laws are arguably one of the most important concepts in physics [45], this learning objective is well suited to also connect FDs to different physics topics such as mechanics or electricity. This connection has also been made by Hoekzema et al. [12], who used a modified version of FDs to teach about symmetries and conservation laws. Additionally, Pascolini and Pietroni [25] used FDs explicitly without their original meaning in the mathematical sense to teach concepts such as conservation laws. Furthermore, there have been different approaches to certain educational activities that help students to use conservation laws with FDs in a playful way [30,31].

We argue that conservation laws are the inevitable entry point to any learning unit dealing with FDs. If the deep connection between conservation laws and FDs is not understood, FDs cannot be used. This first learning objective therefore serves as a prerequisite to all of the following.

4.1.2. Interaction Particles

The second learning objective is: "Students will be able to explain the role of interaction particles and motivate their existence in the Standard Model of particle physics". The experts mentioned interaction particles as one of the most prominent subthemes of the opportunities that FDs can provide for the teaching of particle physics concepts. Lindenau and Kobel [15] argue that the concept of interaction particles is one of the core concepts in the Standard Model of particle physics. A common way to introduce interaction particles is through everyday analogies, such as people on a boat throwing balls and boomerangs at each other, but these tend to promote inadequate conceptions rather than explain physical concepts. We argue that FDs provide a motivation for the concept of interaction particles without going too much into the mathematical details of the Standard Model of particle physics on the one hand and avoiding simple heuristics on the other hand. A more sophisticated way is to connect interactions with fields using the concept of interaction particles [7,28,46]. While this is arguably an adequate way to think about interaction particles—or particles in general—it is also more abstract and thus more difficult to comprehend. However, the concept of interaction particles could be an opportunity to link this idea of how interactions are thought about in particle physics to the concept of the electromagnetic field, which might already be known from earlier school physics.

4.1.3. Superposition

The third learning objective should directly link particle physics to already known quantum physics concepts. It consists of two parts to make it more accessible and relevant to high school education. The first part is: "Students will be able to apply the superposition principle from quantum mechanics to particle processes". Here, students should realize that a process is not only represented by a single diagram, but that several diagrams always contribute to a process. This is in analogy to the double and multiple slit experiment, where several slits contribute equally to the interference pattern. Extending this principle, the second part of this learning objective is: "Students will recognize particle processes as a superposition of infinitely many contributions". Here, students learn that for any FD there can be another FD drawn that represents the same particle process.

Also in the literature, Passon et al. [29] mention the above mentioned analogy to the double slit experiment. Moreover, Allday [7] showcased how this principle is important for learning about the nature of interactions in particle physics. Passon et al. [29] made the connection to the concept of topological equivalence and pointed out structural similarities between FDs and electrical circuits.

This concept is closely connected to a common misunderstanding about FDs, that of representation. As stated above, the debate on whether FDs represent physical processes is almost as old as FDs themselves [21,22]. For certain processes, some diagrams are much more dominant in the calculation; therefore, in these cases, one diagram is a good approximation of what is happening. However, to distinguish between such processes where a single diagram might be a good approximation and processes where several diagrams are needed for a reasonable approximation, a good working knowledge of the corresponding mechanisms, the parameters, and the energies and momenta is needed. Therefore, for high school students, we argue that learning about the general principles might already be challenging enough. For advanced students who already know about the series expansion of a mathematical function, this learning objective could also be linked with an introduction to calculations, but in principle, the learning objective is achievable without addressing this mathematical concept.

4.1.4. Work of Particle Physicists

The experts emphasized that FDs can give an insight into how work is conducted in (theoretical) particle physics. To take advantage of this, the fourth learning objective is: "Students will be able to relate the method of FDs to the work of particle physicists". This learning objective accounts for the fact that a whole theme of opportunities was dedicated to the perspectives on science, and within that, a prominent subtheme was the helpfulness of FDs to scientists. Nevertheless, the helpfulness for scientists alone would not be an argument to use FDs in schools. Some prior knowledge is necessary to use the diagrams in a way scientists use them. We argue that, after achieving the first three learning objectives, students might have acquired enough knowledge to get a glimpse into why and how scientists use FDs. For instance, to achieve this learning objective, one can imagine presenting students with an example of a measurement that does not agree with a theoretical prediction. In this case, the students would have to realize that this could be due, among other things, to the fact that not enough FDs were considered. In this way, the use of FDs can be illustrated in practice.

However, even if all the learning goals were achieved, a full mathematical account would be too ambitious for high school students, as the underlying mathematics requires knowledge of quantum field theory. Nonetheless, as illustrated above, some of the basic underlying calculation principles might be suitable for advanced high school students.

Furthermore, even without going into the details of calculations, a simulation tool could help students understand why the calculation of different diagrams shapes the theoretical predictions for particle physics experiments.

This learning objective is particularly beneficial for learners from a nature of science perspective in the sense that students get to experience first-hand that science is theory-laden by exploring theoretical predictions and getting a glimpse of the tentativeness of science when open questions of modern physics can be examined by FDs (e.g., the high-precision measurement of the magnetic moment anomaly of the muon [47]).

4.2. Challenges to Address When Teaching with FDs

While all these learning objectives pose good opportunities for the learning of and with FDs, the inherent challenges that are connected also need to be addressed. These challenges might translate into domain-specific design principles when designing a learning environment that incorporates these learning objectives.

The most prominent theme mentioned within the challenges dimension was that FDs might evoke and perpetuate inadequate conceptions, most notably one of a space–time embedding of particle processes. One discussed source for this inadequate conception was that of the drawing of an FD as a space–time diagram. Among the experts, there was a tendency towards the opinion that while a time axis is useful to denote what is the initial and what is the final state, a space axis does not make any physical sense. Therefore, we argue that FDs should be clearly distinguished from space–time diagrams, or, at least, drawing a space axis should be avoided. Closely connected to this is the conception that particles are small balls that are physically colliding at the interaction points. Both conceptions might also be perpetuated by the depicting particles using lines with arrows. We therefore suggest exploring the possibility to omit the arrows when using FDs in educational contexts. The only function of the arrows in an FD is to distinguish particles from antiparticles. This distinction can be made differently, for example, by using colors or by writing the corresponding symbol. Conceptualizing antiparticles as particles that move backward in time might be a mathematically allowed description when also attributing a negative energy to antiparticles, but it does not represent the physical reality and might evoke misconceptions about the nature of antiparticles.

Another very prominent inadequate conception was that FDs show observable processes. Avoiding this conception is very challenging since part of the popularity of the diagrams is that they seem to "tell a story of what happens" (E1). We argue that pronouncing the third learning objective (particle processes are superpositions of FDs) addresses this inadequate conception.

The most prominent single subtheme in the expert interviews was the challenge that the use of scientific language is a source of inadequate conceptions. This issue might be addressed by a careful use of language in educational contexts [17,48], for example, when speaking of "decay" by clearly explaining that it is in fact a transformation of particles and speaking of "electrical charge" instead of just "charge" to emphasize the fact that there are different charges. However, more research is needed into which conceptions are connected to these different terms and in which way they are beneficial or hindering for learning.

Other challenges touch on the topic of too little time or missing prior knowledge for the meaningful use of FDs in high school physics classes. We propose to address this challenge by linking FDs to concepts that are already known, such as charges, conservation laws, and, for more advanced students, the superposition principle in quantum mechanics or even series expansion in mathematics. If the latter is not yet known by the students, calculations can be omitted in educational settings or substituted by simulation tools instead.

4.3. Outcomes and Limitations

The scope of the study was to explore possible challenges and opportunities of using FDs in high school education. In doing so, this study was the first one to explore the educational use of FDs empirically. Our goal was to interview experts whose opinions are representative of the field. For example, in the interviews we could find the above-mentioned "Feynman-Dyson split" [18,21] to some extent. While E1 stressed the purely mathematical nature of FDs and strongly opposed the notion of a too literal reading of the diagrams, E2 was very open to using the diagrams as a pictorial representation also in a qualitative sense, that is, without immediately referring to the mathematical expression that certain FDs represent. Nevertheless, we have only covered a narrow perspective on the topic, since all four experts came from the German-speaking region (the first three from Germany, the fourth from Switzerland). This might have led to a biased view. However, the small number of experts allowed an in-depth analysis in line with the explorative purpose of the current study. This study in its present form already gives valuable insight for the development of educational material. Moreover, it serves as a basis for future studies with a larger number of experts that can be envisaged to build upon our initial results by conducting a Delphi study [49] and gathering additional perspectives on the educational value of FDs.

4.4. Outlook

The learning objectives and design suggestions developed in this study are used to create learning material for introducing FDs to 14–18-year-olds within a massive open online course (MOOC) on particle physics. The development of this learning material follows the iterative design principles of the design-based research framework [32]. Specifically, design principles based on multimedia learning theories are developed for these learning materials and are combined with more domain-specific design principles resulting from this study. The developed learning material is tested in teaching experiments using eye-tracking data with high school students from the target group. The learning materials will be further developed based on the results of these teaching experiments.

5. Conclusions

The presented study systematically analyzed the risk and potential that lies in teaching about particle physics to high school students using FDs. We have found two general challenges and three major opportunities that are connected to this peculiar form of representation within particle physics. We argue that the opportunities we have found are calls for using FDs in teaching particle physics, even beyond their original function as mere calculation tools. Indeed, FDs can serve as a tool to connect particle physics to already known concepts, such as charges and conservation laws on the one hand and to other advanced topics such as quantum mechanics on the other hand. Since FDs are used by particle physicists every day, their educational use can offer high school students a window into the daily work of particle physicists. The challenges we have found can be addressed by domain-specific design principles for developing a learning environment for and with FDs.

We are confident that it is useful to introduce high school students to FDs, not least because FDs are part of popular representations of particle physics. As one of the experts who took part in this study stated, one can "send students on a journey to find misleading or wrong depictions in popular or even specialized media . . . that can be a contribution to an experience of autonomy". This could be a major strength of using this form of representation in physics classrooms.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/physics4040085/s1, Table S1: Coding Manual; Document S2: Interview guideline E1, E2, E3; Document S3: Interview guideline E4.

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Informed Consent Statement: The subjects gave their informed consent that their data will be used for research purposes.

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