

The teaching of physics and the practice of science: bridging them with the philosophy of scientific models in the case of particle physics

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Abstract

Globally, public policy formulators, science education researchers, teachers and students sustain the teaching of topics from Modern and Contemporary Physics in basic school. Among those topics, the potential insertion of Particle Physics in secondary school is investigated. In this context, already present in publications from over two decades, are critical propositions to the “Laundry List”, which consists in a teaching that is reduced to presenting the numerous elementary particles, much criticized for promoting a “received view” of the Standard Model. In the present work, converging with this criticisms, we propose an engagement based curriculum that seeks to teach the content of science and about science. The argumentation about science is connected to investigations developed by the Nature of Science area. Afterward, we identify the Feynman Diagrams as models in the understanding of the pragmatic conception of the Philosophy of Science. Finally, we analyse some pedagogical proposals involving the Feynman Diagrams that have overcome the “Laundry List” approach and compare them to our proposal.

Keywords: Particle Physics Teaching, Feynman Diagrams, Models, Curriculum, Nature of Science.

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Introduction

Proposals related to the teaching of Particle Physics have been discussed for some years, both for undergraduate physics and for high schools (PIETROCOLA, 2010; PASSON, ZÜGGE; GREBE-ELLIS, 2018). As it is a topic of Modern and Contemporary Physics, in many countries (such as Brazil) its teaching in schools is associated with curriculum innovation, which implies a series of difficulties. Pietrocola and Gurgel (2017) suggest that the obstacles encountered in their teaching are both of the didactic-epistemological type (related to the difficulties of knowledge itself, such as phenomenology, formalization, conceptual structure and ontology), and of the didactic-pedagogical type (related to the difficulties in teaching this knowledge, associated with the preconceptions of participants in the school environment).

In the face of these difficulties, even in scenarios where Particle Physics (PP) is taught, some authors identify recurrent problems in the approaches. In Germany, Passon, Zügge and Grebe-Ellis (2018) carried out a systematic bibliographic survey of the European and Anglophone PP teaching literature, including content defenses, teaching proposals and curricula, criticizing the so-called “received view” of PP. This is how PP is characterized according to this conception: starting from the Standard Model and presenting quarks and leptons as “fundamental blocks” of the material world; interactions are characterized as exchanges of particles; the visualization of interactions is valued, for the realization of which, at times, he appropriates the Feynman Diagrams (FD). In the US, Hobson (2011) criticizes this approach and names it “Laundry List”. In Brazil, Ostermann (2020) pointed out that one of his concerns is to understand aspects related to Quantum Mechanics relevant to PP because, in the absence of discussion on physical principles of this discipline, in high school, the theme of Elementary Particles can fall into a classification exercise and memorization of a subatomic zoo, and even suggested that the Particle Physics teaching area should dialogue more with the curricular research of science education.

A large part of these concerns mentioned above assume that **knowledge** - or more specifically, **disciplinary knowledge** - is of fundamental importance for teaching-learning proposals. Going further, the objective is not (or, in our view, it should not be) that this knowledge replaces traditional knowledge exercising the same function it commonly performs: memorization to succeed in the exam. If it



were, the “Laundry List” approach would not necessarily be a problem, it is still a good source of closed problems for these assessments.

To try to deal with these problems, this work, of a theoretical nature, has the following objectives:

- Advocate for a Particle Physics Teaching in a *curriculum based on engagement*.
- Identify Feynman Diagrams as models of Particle Physics from the pragmatic approach of the Philosophy of Science, for the teaching *of* and *about* Particle Physics.
- From this perspective, we discuss proposals that have already abandoned the “Laundry List” approach.

In the remainder of this section we will justify why, given the problems mentioned above, we want to achieve the first two objectives.

First, it is important to briefly discuss the assumption that we should be concerned with the scientific knowledge to be taught, especially if we take into account Sonia Salem’s (2012) thesis, which points to a movement where specific knowledge becomes implicit or absent in the second half of the 2000s in research in the area of teaching physics in Brazil (SALEM, 2012, p. 287). As the motivations for teaching models in Science Education (SE) sometimes start from the objective of teaching *about* science, this approach *a priori* does not presuppose major commitments to the knowledge of science. This greater commitment to knowledge *about* science at the expense of knowledge *about* science appears explicitly in works in the survey by Coll, France and Taylor (2005, p. 191-192), and implicitly in proposals that aim to teach about science through knowledge atypical in the science canon, such as Adúriz-Bravo’s (2014) proposal to use narratives.

In our view, the identification and privilege of explaining the scientific models of PP during its teaching should not make the specific knowledge of this discipline secondary. On the contrary, this movement is about valuing this knowledge, explaining its epistemological dimension. Gilbert (2004) points out that the use of models is a way to guarantee a more authentic SE. We agree with this statement, since genuine science learning is achieved by learning the concepts *of* science and *about* science - and although models are not *enough*, they are *necessary* for that purpose.

Almost 30 years ago, Terrazzan (1992), in a brief text, presented how Modern and Contemporary Physics (MCP) should gain more space in teaching at the expense of classical physics, weaving arguments that keep premises similar to ours, namely: how knowledge of MCP can provide students with an updated understanding of the world (and consequent improvement in citizen participation) and also update the way of teaching, a necessity. These premises are also similar to the justifications that appear in the survey by Ostermann and Moreira (2000), among others such as: attracting young people to a scientific career, protection against pseudosciences, updated understanding of scientific practice, taking advantage of students' enthusiasm when learning knowledge of MCP and increase your understanding of the world in terms of technology. In the approach that we will propose, some of these premises will not be the focus, as our approach does not open up as much space as justifications for the teaching of PP, for those who defend the attraction to the scientific career or the enthusiasm of students. Not that they have no value at all - they do, from a pedagogical point of view.

We understand that PP knowledge is immersed within a discipline, understanding that disciplinary knowledge is historically developed, whose field of action has epistemological, ontological and axiological commitments (PIETROCOLA, 2019, p. 42). In Curriculum Theory, Young (2010) presents what he calls "curriculum based on engagement", as opposed to the traditional concept that would be "curriculum based on compliance", although both start from knowledge to elaborate the curriculum. We agree with the author that the curriculum corresponds to the knowledge that must be available to all students, not as facts to be memorized, but explicit its epistemological dimension. In this sense, the curriculum has its own purpose: the intellectual development of students, which is based on concepts and not on content or skills. Because concepts are always about something, they imply some content and not others. (YOUNG, 2010, p. 25). These concepts are developed within communities of researchers (YOUNG, 2010, p. 25), in our case, within the discipline of Physics. These concepts allow for reliable generalizations and are related to each other (YOUNG, 2010, p. 26). Sometimes, these concepts have a referent outside the school, as in our case (although it is not a referent of the student's life): the FD can be used to analyze the primary cosmic ray that interacts with particles in the atmosphere. Young (2010) cites other examples, such as electrons and atoms. These concepts allow the student to treat the world as an "object of knowledge" and not



as a “place of experience” (YOUNG, 2011, p. 25), enabling a greater understanding of the world, based on “powerful knowledge” (YOUNG, 2010, p. 29). In this work, the central concept is the FD, which is related to the concept of particle interaction, symmetry and conservation. The FD is the most popular manifestation of the concept of interaction, considering scientific practice.

Once the commitment to knowledge is established, pedagogical and institutional actions can eventually contribute to the resolution of social problems, although the problem that the school must be burdened with facing is educational inequality. It is not, for example, the school’s task to end hunger, although school meals play an important role, especially in poorer regions. This also establishes a clear commitment for the scientific education research community who agree with these assumptions and seek to carry out interventions: the knowledge to be taught plays an important role (although, we emphasize, it is not the only concern). This contributes to the reduction of educational inequality at the national level (especially in works with public schools) and also at the international level (especially for developing countries).

Given the complexity of PP knowledge (manifested, for example, by the *didactical-epistemological obstacles* mentioned), in order for its teaching in the classroom to become viable, it is necessary to carry out the *transposition* of this knowledge. From the perspective of the work, the challenge is to approximate as much as possible the scientific models to be taught to the episteme of the scientific models of the scientific community.

Despite this, the diversity of meta-scientific disciplines indicates that making the epistemological dimension explicit is a challenge. More specifically, this problem lies in answering: *what* of the epistemological dimension of the FD do we want to explain to engage students in this way of taking the world as an object of knowledge? We can find answers to this question through the large area of research in Science Education named **Nature of Science** (NoS). In different literatures it is possible to find the statement that the definition of what is NoS is not consensual. Moura (2014, p. 37) in his survey suggests the following answer (although he recognizes that it is limited): “studying the nature of Science means understanding how man builds scientific knowledge in each context and at each time, based on their philosophical, ideological and methodological conceptions”.

Research carried out in NoS, being a longstanding research area, spreads out in different purposes, such as: **Why teach**, **What to teach**, **How to teach** and **Instruments** to assess the NdC conceptions of students and teachers. Lederman (2007) did a great job of reviewing the different researches in the area so far.

In a dimension of **Why teach**, Lederman (2007), in his assessment of the area, points out that NoS is an important component for Scientific Literacy. Driver et al. (1996) establishes five lines of argument (Economic, Utilitarian, Democratic, Cultural and Moral). Different arguments from these lines of argument and different authors suggest that learning NoS would be associated with improved citizenship. In this context, Hodson (2018) seeks to deepen the discussion about which citizenship we are talking about, defending a curriculum that forms a radical scientific citizen (HODSON, 2018, p. 46).

As the discussion established here was based on knowledge of science, and not knowledge about science, we will not delve into the discussion about **Why teach NoS** in Science Education. We would just like to point out that, in agreement with Pereira and Gurgel (2020), it is a challenge of our time to avoid “naive positivism” and, at the same time, to avoid epistemic relativism. In this sense, the explanation of the epistemological dimension taking scientific knowledge from the approach of models in a pragmatic perspective is our bet. On the other hand, as the NoS, in a way, will be present in our proposal, it is natural that some NoS objectives are fulfilled - except those objectives that have a well-specified final result, as in the case of Hodson (2018).

In the dimension of **What to Teach**, converging with Irzik and Nola (2011, p. 593), we conceive that the separation of Scientific Inquiry (SI) from NoS, as proposed by Lederman (2007; 2018), is merely artificial, since the elements that make up the investigation are themselves elements of the NoS and the SI is an important part of understanding the epistemological characteristics suggested by the authors of the “Consensual View”, who describe these characteristics of science organized into items (*tenets*), through a few lines (KIMBALL, 1967) or a paragraph (LEDERMAN, 2007). In this sense, we see models as an important part of NoS teaching, something that is not really new in the literature in this area (IRZIK; NOLA, 2011; DUSCHL; GRANDY, 2013; SANTOS; MAIA; JUSTI, 2020; MARTINS, 2015).



Ariza, Lorenzano and Adúriz-Bravo (2016) point out that advances in the Philosophy of Science have been excluded from didactic proposals, although a portion of researchers adhere to the model approach - more specifically, the semantic approach. In this work, the authors present four approaches to the semantic family: Ronald Giere, Bas Van Fraassen, Frederick Suppe and meta-theoretical structuralism. They also point out that there is an exaggerated simplification of the idea of models (among other meta-theoretical ideas) in the appropriations of the SE area and, therefore, they seek to present the main points of the semantic approaches, so that there is a more convergent appropriation of these meta-theoretical ideas with their use in meta-scientific disciplines. We agree with this diagnosis, but in this work we start not from the semantic approach, but from the pragmatic one, whose distinctions will be clarified in the next section.

In short, we defend a curriculum based on engagement, which implies making the epistemological dimension of the concepts explicit, while these concepts play a central role. One way to explain the epistemological dimension is using the concept of models - more specifically, taking the FDs as models. This is a movement contrary to the “Laundry List”. Models play a prominent role in NoS, especially when we consider the investigation and nature of the knowledge produced.

On the other hand, the most secure knowledge is located within disciplines. In this way, the most secure knowledge *about* science is located within the meta-scientific disciplines. Therefore, to find a better characterization of models, we must turn to the Philosophy of Science. What in this characterization will be useful for the classroom is a second move to be made? We chose the pragmatic approach of models because we believe that it better explains the problems of the received view of Particle Physics teaching, that is, the low correlation between the role of FD in the classroom and in scientific practice.

Scientific Models and Feynman Diagrams

Despite some spark of interest in its early days from greats like Ernest Nagel and Norman Campbell, the professional philosophy of science turned to the role of models in scientific inquiry as recently as the second half of the 20th century. This movement was associated with a paradigm shift on the conception of scientific theory, from the syntactic (which composed the so-called Received Vision of the

Philosophy of Science) to the semantic¹ (VAN FRAASSEN, 1991, p. 1-17). While in the first they are understood as a set of axioms from which true deductions are syntactically drawn using the methods of logic, in the second they are understood as semantic models of some predefined logical structure. In this second conception, the meaning attributed to the theory's terms and predicates are as essential to assess the validity of its conclusions as the logic syntax in which a theory is written.

However, the adoption of the term “model” of logic ends up causing, ironically, a semantic confusion with the traditional use of the term “model” by scientists, the latter referring to a set of objects that serve as auxiliary tools in an investigation, in which is usually involved some abstraction or idealization, together with experiments and theories, but without being reduced to either. The philosopher of science Luís Henrique de Araújo Dutra studied in his book *Pragmática de Modelos* the role of these objects in science, emphasizing the autonomy of this meaning of model in relation to that which somehow dominates the philosophy of contemporary science, the semantic, distinguishing the former by the epithet “scientific”².

Scientific models would then be classified as *nomic*, the way Nagel and Campbell understood them, when they encode some nomological statement. This law, expressed in a complete or approximate way in some *model system*, is then abstracted from the contingent characteristics of the model system and used in further investigations, carried out in systems now called *modeled*, as a first approximation of their behavior, as a test of the theory, such as a simulation, etc. An example from Physics for this type of model is Ohm's Law, which linearly relates the electric current with a potential difference in a circuit, essentially the same as Poiseuille's Law, which linearly relates the volume of fluid that passes through a certain cross section given a pressure difference (DUTRA, 2013, p. 93-94). There is no absolute sense in which a system is model or modeled. In the case cited, therefore, there is no essential difference between saying that the electrical circuit is modeled by a pipe or that a pipe is modeled by an electrical circuit³.

A type of scientific model close to the nomic one, but broader, is the mathematical one. We understand this type of modeling as the one behind a good part of the natural sciences - in particular Physics - and some human sciences, in which certain characteristics and relationships of the concrete world correspond to certain mathematical entities and relationships which they can, making use of its intrinsic properties, inform previously unsuspected properties, relationships and behaviors of



the concrete world. In this type of relationship between model and modeled, there is a certain asymmetry, with the properties of the model system being a much more important source of information about the modeled system than the model system.

The importance of this type of asymmetries was highlighted by the philosopher Mary Hesse, giving the ideal gas as an example of a model (DUTRA, 2013, p. 51-52). In this model, we compare the particles of a gas to billiard balls. We do this by assuming that these two classes of objects have a series of properties in common, which we summarize here as those that characterize a Newtonian material point, which allow this approximation. Hesse will call this the model's *positive analogy*. There are a number of other features that we do not know if they are common to both systems, it is the *neutral* aspect of the analogy, and it is in this field that the model can provide knowledge about the model, through experimental testing and simulation. There is also the *negative analogy*, the senses in which systems are dissimilar. It is in the delimitation of these analogies that the asymmetry between the two systems is found, of an epistemological nature, as there is, in scientific *practice*, a clear sense in which one system is a model and the other is modeled: it is when you know more about a system than on the other. It is precisely by making use of a better known, model system, and its positive analogies with a lesser known, modeled system, that the modeling activity is undertaken, in order to test the field of possibilities of neutral analogies.

This approach of identifying and understanding the nature of elements of science, in this case scientific models, based on their uses and their dynamics in scientific practice is called *pragmatics* in the philosophy of science and it is this approach that interests us in this work.

We will now mention two important pragmatic understandings of the scientific model. The first is Nancy Cartwright's concept of the *nomological machine* (DUTRA, 2013, p 130-159; CARTWRIGHT, 1999, p. 49-75). Nomological machines would be concrete systems designed in such a way that they exhibit behavior directly expressed by a scientific law⁴, without the confusion of cross-effects and multiple causes of most more realistic systems. A nomological machine *project* would be the abstract system corresponding to the nomological machine, which is a scientific model. An example of Applied Physics of a nomological machine is the *laser*, whose design of a corresponding nomological machine would be, among many possible ones, the simplified three-level model present in many textbooks (EISBERG; RESNICK,

1985, p. 397; CARTWRIGHT, 1983, p. 148). For Cartwright, scientific practice would be centered around these systems, which, expressly designed to fit the concepts and laws of theory, would be used to test them, develop applications, plan experiments, compute simulations and, most importantly, enable knowledge about systems that, in principle, would not be reached by theory.

Dutra (2013) argues that, precisely because nomological machines have these characteristics, they would be as models as their projects, even if they are concrete models, in this case. This connects the conception of the nomological machine with the second understanding that we would like to highlight, that of models as mediators between theory, experiment and the concrete world, elaborated by philosophers Margaret Morrison and Mary Morgan (MaM).

Central to this conception is that scientific models are autonomous entities in relation to the concrete domain (which one wants to study) and to that of theory. This autonomy grants to models, as they are, fundamentally, additional tools to theories in the repertoire of science, their capacity to represent the phenomena of the concrete world, transcending the limitations of theories. The notion of representation considered by the authors escapes the intuitive notion of physical (in the case of concrete models) or isomorphic (in the case of abstract models) “similarity” with the concrete world, being closer to an *epistemic* sense: the representation offered by the model it consists of what can be learned about the aspect of the world shaped by it. Thus, the models would be *representatives* of the modeled systems.

As representation, in this conception, in an epistemic sense, it is in the analysis of the construction and application stage of the model that the knowledge achieved with it is understood, instead of an *in vacuo* analysis, which would be characteristic of the semantic conception of representation.

A characteristic example of the authors’ model conception is the Prandtl water tunnel, used to understand the nature of the interaction of a fluid with a solid object (MORRISON; MORGAN, 1999, p. 26-27). This model allowed Prandtl to visually identify two regions of fluid flow over an object disposed in the tunnel. The use of this concrete model taught Prandtl a knowledge which he then took as the basis for an abstract, mathematical modelling.

It is observed that the water tunnel functions as a representative of more realistic situations of fluid-solid interaction as it leads to valid knowledge about the modeled situation. This knowledge was obtained because experimental, theoretical



and external elements were used to build the model, and because their construction and manipulation informed the use of theory in dealing with the problem. Similar examples can be found in the manufacture of lenses, in the study of nuclear stability and in laser experiments (MORRISON; MORGAN, 1999, p. 23-25).

Next, we will briefly introduce Feynman diagrams, highlighting the elements that will help explain them as models in the sense of MaM.

The diagrams were first introduced in Physics at the Pocono meeting in 1948, in the context of the “infinite problem” of Quantum Electrodynamics (QED), consisting essentially of divergences that appeared in the calculation of the change in electron energy in a process of scattering (ie, perturbative) between two electrons. Complicated *renormalization* processes, in which divergences are ingeniously assimilated into the calculation by changing the mass and energy values of interacting electrons, were developed by Julian Schwinger and Sin-Itiro Tomonaga⁵, but were little disseminated beyond interacting groups direct with its authors, even Pocono.

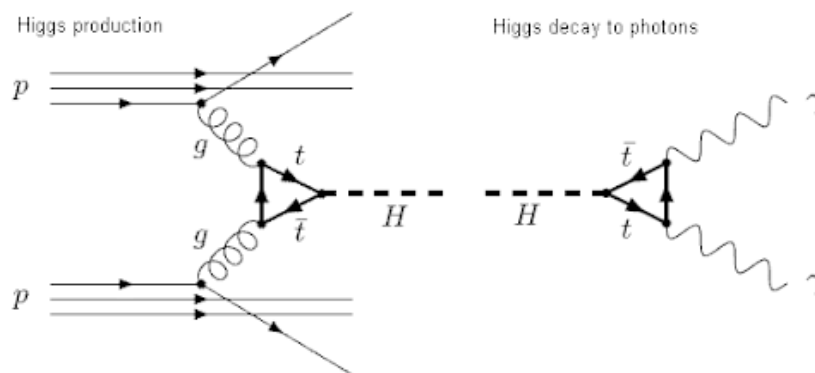
At this meeting, Feynman introduced with the first diagram, of an electron-electron scattering, an ingenious iconographic way of “taking note” of all elements of the scattering matrix (S-Matrix) with an important contribution to the calculation of the energies involved using the renormalization procedure. After the meeting, it was studied, developed and disseminated by Freeman Dyson, and the method of calculation of perturbations using Feynman diagrams spread beyond the limits of QED and even Particle Physics, being used in other quantum field theories, such as Meson Theory, Quantum Chromodynamics, and in other disciplines, such as Condensed Matter Physics. This success was partly attributed to the diagrams being related to a certain tradition of iconographic representation in Physics that dates back to the introduction of Minkowski spacetime diagrams, decades earlier, and to the similarity with trajectories in cloud chambers (KAISER, 2005).

Despite being essentially an instrument for calculating the S-Matrix, and only the inner product of the series has physical meaning⁶, Feynman Diagrams (FD) since their introduction are appropriate as an iconic representation of the processes they represent in the language of a essentially non-iconic physical theory, Quantum Mechanics (QM), in which we should not speak fundamentally about particle trajectories. In the next session, we will, with Passon, Zügge and Grebe-Ellis (2018), present examples of how this conception of FDs permeates the uses of this resource in the teaching of PP. For now, we will present Stöltzner’s (2017) reading of FDs as mediators (MaM).

The first characteristic of a model as a mediator served by the FD is its *autonomy*, as the reference in the previous paragraphs to its use in theories and disciplines quite different for which it was conceived (QED). The FD also serve as *representatives* in the sense of MaM: in an electron-electron scattering, for example, the corresponding FD can be taken as a representative of the entire infinite series contained in the S-Matrix⁷, as well as each “branch” (each drawn line of the diagram) can be taken as representing a term different from the perturbative calculus.

We can also draw a FD with only the branches that we consider most important in a certain process and take it as representative of the entire process, as is the case of the Higgs boson production guide given by gluon fusion (Figure 1), which helps to explain the obtainment of the particle, as well as to guide the experimental search for it. This procedure, then, involves a reordering of the series aiming at an explanatory and predictive objective, and so it is modeling in the sense of MaM⁸.

Figure 1: The Feynman diagram representing the Higgs boson production guide.



Available in: <<http://lppp.lancs.ac.uk/higgs/en-GB/higgs.html?LPPPSession=1567036800030>>

In a similar context, but now in the domain of spectroscopy, we can only draw the FD branches (or tabulate the perturbative calculation orders) corresponding to the terms counted in light of the accuracy of the measurement performed, for example, the Lamb Deviation of the spectral lines of Hydrogen. This example illustrates the role of simulation and design of experiments that models, from a MaM perspective, would promote.

In this brief exposition, we see how the FDs, due to their flexibility and usefulness for the most diverse objectives of scientific practice, fit, in the understanding of the

pragmatic aspect of the philosophy of science, as scientific models. In the next section, we assess how FDs are usually transposed into educational practice and how they appear in academic research in PP teaching, highlighting the senses in which our proposal, based on the educational and philosophical perspectives outlined in the article, departs from those.

Feynman Diagrams in Science Teaching Literature and Pedagogical Practice

Passon, Zügge and Grebe-Ellis (2018) surveyed the presence of PP in school curricula, generally occupying almost entirely the module reserved for Modern and Contemporary Physics, and in the science teaching literature. They realized that the alternative approaches to PP advocated by authors in the field of education who are opposed to the “Laundry List” include several conceptual and interpretive misconceptions, the two main ones being: the choice of an ontological interpretation of a quantum field theory (QFT) without “precautionary warning”, and the representational nature of Feynman Diagrams.

The most widespread ontological interpretation of QFT, that is, the most common answer to the question of which entities this theory refers to and describes, follows the “received view” in admitting that they are “elementary particles”, thus being a “corpuscular” interpretation (ALLDAY, 1997; FARMELO, 1992; JOHANSSON; WATKINS, 2013)⁹. One of the problems with this approach is that it fails to explain the impossibility of locating these entities and their interactions in terms of the theory (assigning position eigenfunctions/eigenstates).

Authors who defend a “wave” interpretation of the QFT (DANIEL, 2006; HOBSON, 2005; 2013) attribute reality to one or more of a kind of “universal” field filling the Universe, capable of being “excited”, and whose “excitations” would play an important role in the interactions measured in the experiments and in the theoretical description of these interactions. The main problem surrounding this approach follows from the theoretical element of a QFT that assumes the role of “field” of a classical theory, being QM operators, entities that have interdependent existence of the vector state/wavefunction. Thus, answering “the field” to the question “which entity does QFT refer to?” requires a second question: “which entity does the field apply to?”.

FDs, in turn, usually appear when the temptation to use traditional (classical) physics teaching tools, such as visualizations and mental images, outweighs the authors' caution, in particular because there is another temptation in physics teaching: to avoid mathematics (WOITHE; WIENER; VAN DER VEKEN, 2017). There are authors who reproduce the most naive view of FDs, that they are visual representations of spatiotemporal events, or that they represent physical processes occurring "in reality" (JONES, 2002; KONTOKOSTAS; KALKANIS, 2013)¹⁰, but there are also authors who, in an attempt to reconcile the didactic use of FDs with the minimum of technical discussion of their nature, confuse interpretations, in addition to making conceptual errors, and reach wrong conclusions (ALLDAY, 1997; ORGANTINI, 2011).

Allday (1997) seeks to discuss the "nature of force in particle physics". The author fills the discussion with his experiences in teacher education and with students, exemplifying these concepts mainly through analogies. Among the analogies, when discussing attraction and repulsion, the author compares the various terms of the series represented in the branches of a FD to the various simultaneous motions that a material point can develop in Mechanics. This interpretation of the FD, however, in addition to going against the author's mostly corpuscular interpretation (similar to what the waveform interpretation of the QM would say about a double slit experiment), is conceptually wrong, because it ignores that the inner product of the series is taken (the processes have to "interfere" with each other, as in QM).

Além disso, Allday (1997) apresenta majoritariamente características gerais dos FD, e pouco diz sobre os usos desses dispositivos na prática científica. Organtini (2011) usa o argumento do sucesso preditivo para defender a realidade dos processos descritos pelos FD. Esse argumento, entretanto, só tem valor no contexto do debate, interno à disciplina de Filosofia da Ciência, acerca da realidade de entidades inobserváveis em teorias, o que não é o caso dos FD.

Dunne (2001, p. 368) points out: "The purpose of this article is an attempt to persuade the teaching community to become aware of the rules for constructing diagrams and adopt a consistent approach to the representation of particle reactions". The author's argumentative construction suggests that the FDs would be representations of the interactions between particles, also pointing out that: "Description of the interactions in words or equations makes the subject seem very complicated and difficult to follow. The use of Feynman diagrams makes it much easier to categorize and visualize what is going on" (p. 370).



As for the meanings of representation, the author takes care to point out that the vertices do not represent the space-time trajectories of the particles. The article is full of different FDs, serving as examples for the author to explain the rules for its construction. At the end of the article, the author clarifies that this is a movement to show the FD more as a “formal tool” rather than an “informal illustration”. In the light of our discussion, this work values the FD more in terms of “skill” (learn correctly the rules for preparing the FD). The author provides little clarification on what is being represented in the FD, and in some excerpts (such as the one mentioned above), his article can lead to a conceptual misunderstanding. Taking the notion of representative that we are appropriating, from the pragmatics of models, the FD is representative of the entire infinite series contained in the S-Matrix. In terms of scientific practice, FDs are closely linked to mathematization: closer to a system of equations than to a free-body diagram.

Although we take the sense of representation in a less restricted way, with a sense close to natural language, the use of the visual representation proposed from the FD can be explored as a pedagogical resource, but without ignoring its epistemic representation (as a *representative*, in the sense of MaM). Otherwise, the concept suffers great mischaracterization.

The use of visual representation as a pedagogical resource appears more intensely in Pascolini and Pietroni (2002). The authors, seeking to avoid the conceptual problems that arise when images of the macroscopic world are imposed on the microscopic world, state that: “Instead, we decided to explore those images that are generated by the mathematics of quantum field theory, that is Feynman diagrams, which we thought could play the role of accurate metaphors” (p. 325).

With this, the authors suggest that students can learn several concepts, such as: “[...] as the relation between matter and antimatter, the indistinguishability of identical particles, the existence of virtual particles and their role as mediators of interactions, and so on” (PASCOLINI; PIETRONI, 2002, p. 325).

Thus, the FD concept ends up being a means to study other concepts. They report an activity taught to students, which consists in the construction of mechanical models of the FD, using materials such as cans and rods (PASCOLINI; PIETRONI, 2002, p. 326). Given the mechanical restrictions, it is not possible to “assemble” a FD that violates conservation laws. Although, in principle, this raises doubts whether the students are actually understanding these other concepts (such as

conservation) or whether they are actually just doing manual work - the latter being an interpretation that is corroborated by the authors' own report, in which students tried by different means to build a FD that was impossible and only a few noticed that it was impossible -, the authors indicate that the use of this activity improved students' performance when dealing with issues involving the FD without this mechanical system, especially for issues involving FD that were impossible.

It is not clear what is effectively discussed with students about Feynman Diagrams, although the authors mention that they carry out an introduction to the phenomena described by QED (PASCOLINI; PIETRONI, 2002, p. 327). Again, the use of imagery and mechanical resources as pedagogical instruments is not, *a priori*, configured as a problem, but they become as their limitations are not explained. On the other hand, taking the FDs as models, they have a specific purpose in scientific investigation - which, for the most part, is not what the authors are proposing. This is an aspect that could be explained in the proposal, but it was not, because the authors do not see this concept in that way.

Two other interesting works, which are correlated, are Hoekzema et al. (2005) and Van der Berg and Hoekzema (2006). In the first work, Hoekzema et al. (2005) presents a part of the MCP teaching project - more specifically the text for students on transformation, reaction equation, conservation laws and symmetry. The laws of conservation and symmetry, which are the focus of Van der Berg and Hoekzema (2006), are taught using *reaction diagrams* (an expression used in the text for students) or *simplified Feynman diagrams* (VAN DER BERG; HOEKZEMA, p. 48, 2006). According to Hoekzema et al. (2005, p. 266), the preference for using simplified Feynman diagrams (which are used only to describe and predict reactions, without inferring the probability of reactions or examining more deeply the nature of interactions) was due to previous experience with the FD, which was not successful.

The authors point out that the *reaction diagrams* were well received by the teachers, being much more 'understandable', and the authors suspect that the teachers find it so easy that they 'go fast', with few exercises (HOEKZEMA, 2005, p. 271). In the student text, reaction diagrams appear as a way of 'visualizing reactions', where the main focus is on how conservation laws are manifested and enable operations to be carried out. This relationship with knowledge is more explicit in the article by Van der Berg and Hoekzema (2006). In this article, the authors report the use of a fast feedback method, which consists of a teaching method in



which the teacher gives a series of short tasks to be performed individually, but collectively (VAN DER BERG; HOEKZEMA, 2006, p. 49). Contrasting this project with our work, different points can be discussed. First, that the relationship that the authors weave with the FD is analogous to that of Pascolini and Pietroni (2002): the FD are a means to understand some other concept. As we have already said, taking the FD as models, what should be highlighted changes. A second point, although the papers are teaching concepts, the teaching of concepts is more based on a 'curriculum based on compliance' than an 'curriculum based on engagement'. This is because the epistemological basis of these concepts is not made explicit. The relationship established with the concepts is operational (which is not, *a priori*, a problem), but only operational.

Third, using *reaction diagrams* instead of FD is an artificial separation. It has the good intention of making didactic practice simpler and at the same time not explicitly talking about FD, as FD is another concept that will be studied at the university. In addition to being debatable whether the class will effectively pursue a scientific career, using *reaction diagrams*, there remains a conceptual gap in the FD that will be filled by the spontaneous conceptions of the students themselves.

Conclusion

We see how, although many authors in the field of Science Education agree that PP teaching is seriously flawed given the dissemination of the "received view" of the Standard Model and the "Laundry List", there is no consensus on how to transpose these contents. Amidst this dissent, there are even proposals that include conceptual mistakes, like most of those that appropriate the FD, since they lend themselves, in an interpretation that ignores their use in scientific practice, to be taken as resources pedagogical aspects that adapt to deeply ingrained characteristics of the broader school culture, and of the specific teaching of physics, mostly classical physics (GURGEL; PIETROCOLA, 2017): the emphasis on images, intuitions and little mathematization, or a mathematization that reduces to a mere "formulism", a famous term coined by Zanetti (1989).

We conclude that if PP is to figure in the basic school curriculum, this knowledge needs to suffer as little distortion as possible, and therefore, it is necessary that teachers are trained with a transposed version of this knowledge that better reflects

the practices that it structures, and the episteme that, in turn, structures it. In other words, knowledge of MCP will only enter primary school if teacher training promotes autonomy in relation to this knowledge, and we bet that this autonomy will only be achieved through teaching that converges with scientific practice. This aspect is crucial for teachers' sense of identity as members of a profession (YOUNG, 2010, p. 27).

In our outline of a pedagogical proposal for the teaching of PP, we therefore delve into the specific epistemological characteristics of this discipline and its practice and do not consider open problems of interpretation of the theories involved as solved. Through this dive, we were able to identify elements of this knowledge that allow us to simultaneously value the nature of PP knowledge and the characteristic knowledge of the discipline, converging with our theoretical and axiological affiliations of Curriculum Theory and Scientific Education. As a result, we do not present ready-made formulas or a finished proposal, but we open the way so that future proposals following these guidelines do not run into old problems. We like to think that, rather than engaging with the “normal” problems of PP teaching, we are proposing a new perspective from which these problems are understood differently, and in which, therefore, new types of solutions are possible, opening a horizon yet to be scrutinized.

O ensino de Física e a prática da ciência: aproximando-os com filosofia de modelos científicos no caso da física de partículas

Resumo

Mundialmente, formuladores de políticas públicas, pesquisadores em educação científica, professores e alunos defendem o ensino de tópicos da Física Moderna e Contemporânea na educação básica. Dentre esses tópicos, investiga-se a potencial introdução da Física de Partículas no ensino médio. Dentre as justificativas encontradas há, em grande parte, uma valorização do conhecimento científico. Neste contexto, há quase duas décadas, surgiram diferentes propostas críticas com relação às abordagens do tipo “Lista de Compras”, que consiste em um ensino que se reduz a apresentar inúmeras partículas elementares. Recentemente, surgiram críticas a essas propostas, por considerá-las insuficientemente críticas do que se convencionou chamar a “concepção herdada” do Modelo Padrão. Neste trabalho, de natureza teórica, concordamos com essas críticas e propomos uma nova perspectiva para analisar essa questão, tomando como foco de análise um conceito específico: os Diagramas de Feynman. Para a construção da nossa



argumentação, propomos um currículo baseado em engajamento, que busca ensinar a ciência e sobre a ciência. A argumentação sobre a ciência é vinculada às pesquisas desenvolvidas na área de Natureza da Ciência. Posteriormente, identificamos os Diagramas de Feynman como modelos a partir da concepção pragmática da Filosofia da Ciência. Por fim, a partir dessa argumentação, analisamos algumas propostas de ensino que já superaram a “Lista de Compras” vinculadas aos Diagramas de Feynman, e as comparamos a nossa proposta.

Palavra-chave: Ensino de Física de Partículas, Diagramas de Feynman, Modelo, Currículo, Natureza da Ciência

Notas

- ¹ In this brief history, we are restricting ourselves to the philosophy of science with an analytical tradition, centered on Anglophone countries, and derived from the works of Bertrand Russell, the first Wittgenstein and, later, David Lewis, in the beginning of the 20th century. Hence the centrality of this logical-linguistic reading of science.
- ² We appropriated more of the epistemological discussions in the book, leaving somewhat aside the meta-physical discussion about the existential status of models. Although, as we shall see, it can contribute to the discussion about the existence of entities dealt with in Particle Physics, which is relevant for its teaching, we avoided it in the present work, leaving it for the future.
- ³ The analysis is therefore intended to be valid whatever the scientist's perspective. Thus, it is useful both for a Physics student who learns Fluid Mechanics after Electromagnetism and for a student of the History of Physics, for whom the sense of model and modeled will be reversed.
- ⁴ In Cartwright's (1999) preference, we would say the *capacities* of the natural world (and equally of the social and economic in the human sciences), a notion that evokes the Aristotelian *powers*.
- ⁵ For historical details of the introduction of renormalization methods in Quantum Electrodynamics, see Schweber, 1994.
- ⁶ It is a situation analogous to a double-slit experiment. Although the measurable results can be explained using wave interference (the numerous elements of the perturbative calculation in scattering), the measurable results are given by the internal product of the superposition (of the series). Another analogy, this one due to the philosopher of physics Michael Redhead (1988), is with Fourier's analysis of the note emitted by a violin. Would it make sense to talk about the existence of the countless harmonics that make up the note?
- ⁷ Even if, in abstract, we take a FD composed of infinite branches that represent, in “maximum isomorphism”, the S-Matrix, its convergence is not always well defined. Thus, this object would still have an idealization character and an investigative pragmatic role, according to the general characterization we made of the scientific model.
- ⁸ Mathematically, reordering the terms of a series, separating it into different subseries, is only justified if it absolutely converges. If this is not proven in the case considered, we can consider the application of the procedure yet another level of modeling.
- ⁹ It is common, in the aforementioned literature, for authors to make passing references to the existence of a field and the relationship of particles with the field, but without delving into the discussion and always giving preference to the term “particle”.
- ¹⁰ Taking a teaching in historical progression of Classical Physics, QM and QFT, this approach would already promote a “devolution” of the teaching of Physics, by the teaching of QFT, to a stage prior to one of the educational goals of teaching QM: in MCP, we don't describe the motions of material points in space-time.

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