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# Understanding Particle Interactions with Feynman Diagrams

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Feynman diagrams are used to calculate scattering amplitudes in quantum field theory, where they simplify the derivation of individual terms in the corresponding perturbation series. Considered mathematical tools with an approximative character, the received view in the philosophy of physics denies that individual diagrams can represent physical processes. A different story, however, can be observed in physics practice. From education to high-profile research publications, Feynman diagrams are used in connection with particle phenomena without any reference to perturbative calculations. In the first part of the paper, I argue that this illuminates an additional use of Feynman diagrams that is not calculatory but representational. It is not a possible translation into mathematical terms that prompts this practice but rather the epistemic insights into the target phenomenon that the diagrams provide. Based on this practical use, I intend to push back against the received view. In the second part of the paper, I conceptualize the representative use of Feynman diagrams as models that provide modal understanding of their associated target phenomena. The set of Feynman diagrams corresponding to an interaction is taken as a possibility space whose dependency relations can be analysed, allowing an agent to grasp possible target behaviour, leading to understanding. In clearly separating the diagrams from perturbative calculations for their use as a model, the concerns that hinder a representative reading can be resolved.

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## 1. Introduction

Calculating amplitudes for particle scattering, perturbation theory is typically applied to approximate results that cannot be obtained analytically. Feynman diagrams can be used to derive individual terms in such a perturbation series, greatly simplifying the calculation. They are thus first and foremost a calculational device to derive individual terms in a perturbation series, where each diagram corresponds to one contribution to the scattering amplitude. The received view in the philosophy of physics consequently denies that Feynman diagrams represent physical processes, concluding also that a realist interpretation of virtual particles is impossible (Redhead [1988]; Weingard [1988]; Brown [2018]; Passon [2018]).

However, taking a closer look at physics practice, the received view appears to be make a hasty judgement. A representative dimension is visible: the diagrams' use is taught independently of the calculation of scattering amplitudes and their publication as figures appears detached from the derivation of perturbation terms. Physicists refer to Feynman diagrams when discussing particle processes, connecting individual diagrams to interaction mechanisms and decay channels without any calculations, ignoring their origins as calculation tools. I claim that this use of Feynman diagrams presents a distinct case from that which philosophers rightfully worry about. The problem that philosophers highlight stems from the diagrams' intricate connection to the perturbative series, which in principle requires large sets of diagrams for one individual process and does not allow a realist interpretation of internal lines. Physicists, when using Feynman diagrams in a detached manner, are, however, not concerned with calculating perturbative terms. Using the diagrams in the context of particle phenomena, they do not refer to their function as calculational tools. Rather, they hope the diagrams convey something else, something that cannot be attained otherwise.

In this article, I intend to push back against the received view by arguing that the representative use of Feynman diagrams can be accounted for in a fruitful manner if it is clearly separated from the calculatory use. In doing so, I conceptualize Feynman diagrams as an independent modelling practice. Here, a small number of diagrams serve as a representative model of the associated particle interaction. Importantly, this model perspective allows autonomy from perturbative calculations, as well as the interpretation of Feynman diagrams as idealizations, of which virtual particles are crucial and productive elements. As representative models, the diagrams can provide modal understanding of particle processes by allowing agents to analyse possible target behaviour. It is precisely the explicit depiction of virtual particles and the consequences of this style of notation that, I conclude, allow the Feynman diagram model to provide understanding without falling prey to the interpretive issues highlighted by philosophers.

This article is structured as follows: After a short introduction to Feynman diagrams in section 2.1, which those familiar with the subject matter are invited to skip, section 2.2 provides an overview of the use of Feynman diagrams in physics practice as well as of their perception in the philosophy of physics. This prompts a conceptualization of the diagrams as independent models in section 2.3. The details of the representative relation between a Feynman diagram model and its particle phenomenon target are discussed in section 3. Section 4 elaborates how the diagrams provide understanding of particle processes and section 5 concludes with discussing an example.

## 2. The Representative Use of Feynman Diagrams

This section provides an introduction to Feynman diagrams and their construction, followed by a discussion of their use in physics practice and their reception in the philosophy of physics. This prompts a conceptualization of the diagrams as constituting an independent model of particle processes.

### 2.1. Feynman diagrams: A primer

Feynman diagrams are used to facilitate the calculation of scattering terms in quantum field theory. They allow a diagrammatic construction of individual terms in a perturbative series that approximates the amplitude of a particle scattering or other kind of interaction. To calculate a scattering amplitude, we need to consider all possible transitions between the final state $|\Psi_f\rangle$ at $t = \infty$ and the initial state $|\Psi_i\rangle$ at $t = -\infty$ via the scattering matrix $S$ in which all the required information for the scattering is stored, and which maps the incoming states $i$ to the outgoing states $f$:

$$S_{fi} = \langle \Psi_f | S | \Psi_i \rangle , \tag{1}$$

where $\Psi_f$ and $\Psi_i$ evolve according to the free Hamiltonian, $H_0$. The operator $S_{fi}$ cannot be computed analytically, as interaction terms introduce non-linear equations of motion. Instead, perturbation theory needs to be used, where the Hamiltonian $H$, describing the interaction as a whole, is split into a free part $H_0$ and an interaction part $H_I$: $H = H_0 + H_I$. Here, $H_I$ describes a particle interaction in the interaction picture with an interaction potential $H_I = gV$ and coupling constant $g$. The $S$-matrix itself is defined as

$$S = T \left\{ \exp \left( -i \int_{-\infty}^{\infty} d^4 x H_I \right) \right\} , \tag{2}$$

with $T$ the time-ordering operator. We can then approximate $S_{fi}$ by replacing $S$ with its power series to obtain the following sum that increases in order of $g$:

$$S_{fi} = \sum_{n=0}^{\infty} \frac{(-ig)^n}{n!} \lim_{t_2 \to \infty} \lim_{t_1 \to -\infty} \langle \Psi_f \mid \int_{t_1}^{t_2} d\tau_1 \cdots \int_{t_1}^{t_2} d\tau_n T \left\{ V(\tau_1) \ldots V(\tau_n) \right\} \mid \Psi_i \rangle , \tag{3}$$

where $T\left\{V(t_1)\ldots V(t_n)\right\}$ is the time ordering of the potentials $V$ at times $t_i$.[1] All entries in

[1] While the series $S_{fi}$ in equation 3 contains an infinite sum, after employing renormalization techniques, we

this sum need to be calculated individually. For evaluating each $\langle \Psi_f | T\{V(\tau_1)\ldots V(\tau_n)\} | \Psi_i \rangle$, it helps to use the Feynman propagator $D_F(x_i, y_j) = D_{ij}$, which is a way to express the time-ordered product of two fields for the non-interacting (vacuum) ground state $|0\rangle$ (see Peskin and Schroeder [1995], pp. 90f.; Schwartz [2014], p. 81):

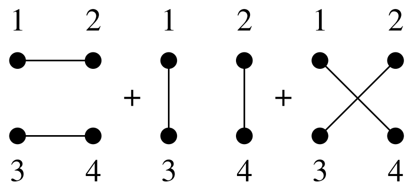
$$\langle 0 \mid T\{\phi_0(x_1)\phi_0(x_2)\} \mid 0\rangle = \lim_{\varepsilon \searrow 0} \int \frac{d^4k}{(2\pi)^4} \frac{i}{k^2 - m^2 + i\varepsilon} e^{ik(x_1 - x_2)} = D_{12}. \tag{4}$$

While for two fields there is only one propagator, $D_{12}$, for more than two fields, $\phi(x_i)$, we need to take into account all possible contractions between all fields. For example, for four non-interacting fields $\phi_i$ at four spacetime points $x_i$, ordered in time from left to right, we get all possible contractions of the four fields as a sum[2]:

$$\langle 0 | T\{\phi_1\phi_2\phi_3\phi_4\} | 0\rangle = D_{12}D_{34} + D_{13}D_{24} + D_{14}D_{23}. \tag{5}$$

This expression can be represented as a sum of three diagrams, where each propagator $D_{ij}$ is represented by a line connecting the points $x_i$ and $x_j$ (Peskin and Schroeder [1995], pp. 90f; Schwartz [2014], p. 81):

$$\langle 0 | T\{\phi_1\phi_2\phi_3\phi_4\} | 0\rangle = D_{12}D_{34} + D_{13}D_{24} + D_{14}D_{23}$$

= 

. (6)

This diagrammatic representation of the propagators provides the basis for the theory of Feynman diagrams.

Instead of drawing diagrams based on propagators as done in equation 6, Feynman proposed to first construct possible diagrams for some interaction and then translate them into mathematical expressions (see, for example, Feynman [1949]). This technique proved much simpler than the converse, and has since become a standard method for deriving scattering terms. Given some particle interaction, we construct a diagram according to this scheme, also called the rules of generation:

(1) Draw lines (called external lines) for each incoming and outgoing particle.

obtain a potentially asymptotic sum that typically diverges. In practice, the series needs to be truncated, leaving a large but finite number of terms. See (Dyson [1952]; Fraser [2020]; Cangiotti et al. [2025]).

[2] Wick's theorem is used to find all contractions (Peskin and Schroeder [1995], pp. 88–90; Schwartz [2014], p. 102).

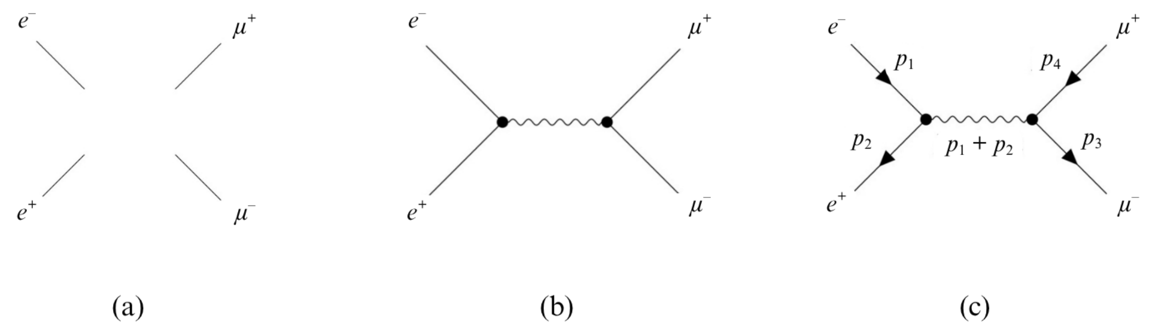



**Figure 1.** Construction of the second order Feynman diagram of $e^-e^+ \to \mu^-\mu^+$: (a) step 1; (b) step 2; (c) steps 3–5.

(2) Leave one end of each external line free and attach the other to a vertex at which exactly three lines meet. Include extra internal lines to do this. In this way, draw all possible diagrams that are topologically inequivalent, using the given number of internal vertices.

(3) On each incoming external line, draw an arrow pointing towards the vertex. On each outgoing external line, draw an arrow pointing away from the vertex. Reverse the direction of the arrows for anti-particles. The arrows on each continuous fermion line have to point in the same direction.

(4) Assign each external line the four-momentum $p$ of the corresponding particle.

(5) For an internal line, think of the four-momenta as flowing along the arrows, and conserve four-momentum at each vertex.

Then, with the help of a set of accompanying rules called the Feynman rules, which can be seen in table 1, the diagram can be translated into a mathematical expression (Peskin and Schroeder [1995], p. 95; Schwartz [2014], p. 225).[3] This procedure is repeated for as many of the possible diagrams as needed, where the highest order to be included depends on a variety of pragmatic and epistemic considerations. The resulting factors, contributions to the approximative series, are then summed.

As an example, we consider the pair annihilation of an electron–positron pair and subsequent pair creation of a muon–anti-muon pair: $e^-e^+ \to \mu^-\mu^+$. The first contributing order is the

[3] Matters of renormalization and details of the integration, while certainly crucial for Feynman diagrams in their quantum field theory and perturbation theory use, will not be of relevant for the model to be developed, and will thus not be addressed in this article. Thorough discussions of the topic can be found in most quantum field theory textbooks.

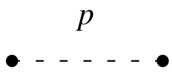
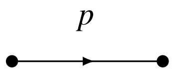
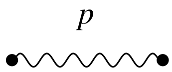
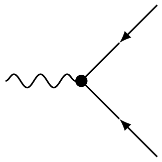
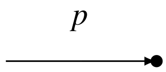
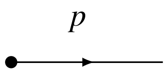
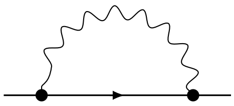
| **Diagrammatical Expression** | **Mathematical Expression** | **Particle Expression** |
|---|---|---|
|  | $\frac{1}{p^2-m^2+i\varepsilon}$ | Virtual scalar |
|  | $\frac{i(\not{p}+m)}{p^2-m^2+i\varepsilon}$ | Virtual fermion |
|  | $\frac{-ig_{\mu\nu}}{p^2+i\varepsilon}$ | Virtual photon |
|  | $-i\varepsilon$ | Interaction vertex |
|  | $u(p)$ | External fermion (momentum flow towards vertex) |
|  | $\overline{u}(p)$ | External fermion (momentum flow away from vertex) |
|  | $\int \frac{d^4p}{(2\pi^4)}$ | Closed loop |

**Table 1.** Translation rules between elements of Feynman diagrams, mathematical terms and 'particle speech' in the case of quantum electrodynamics.

second, $(-ig)^2$, with two vertices, as odd orders result in asymmetries in the integrands and vanish. Following the rules of generation already specified, we obtain, as the only second-order diagram, that seen in figure 1. As the interaction is electromagnetic, $g$ is the elementary charge $e$ and the interaction is mediated by a virtual photon, represented by the squiggly line.

With the help of the Feynman rules seen in table 1, we can then translate the diagram in figure 1c into a mathematical expression $i\mathscr{M}$ for the leading-order contribution to $S_{fi}$ for $e^-e^+ \to \mu^-\mu^+$ (Schwartz [2014], p. 227; Peskin and Schroeder [1995], p. 125):

$$-i\mathscr{M} = \underbrace{(-ie)^2}_{\text{two vertices}} \ \underbrace{\overline{v}(p_2)}_{\text{incoming } e^+} \ \gamma^\mu \ \underbrace{u(p_1)}_{\text{incoming } e^-} \ \underbrace{\frac{-ig_{\mu\nu}}{(p_1+p_2)^2}}_{\text{internal photon line}} \ \underbrace{\overline{u}(p_3)}_{\text{outgoing } \mu^-} \ \gamma^\nu \ \underbrace{v(p_4)}_{\text{outgoing } \mu^+} \ .$$

With the same method, we can also construct diagrams and derive mathematical terms of higher order.

### 2.2. Feynman diagrams in theory and practice

After this introduction to Feynman diagrams, it should have become apparent that their original use is that of a calculation tool, where the diagrammatic method serves as a way to derive terms needed for the calculation of the scattering amplitude of a given interaction. Although the different lines might look as if they depict different types of particles and the internal lines seem to show that what is sometimes called a 'virtual photon mediating the electromagnetic force', a basic principle of quantum theory, the position–momentum uncertainty relation, makes a literal reading of the diagrams' lines as particle trajectories impossible. In addition to the depiction of detectable particles in a trajectory-like manner, the diagrams feature virtual particles, internal lines, as mediators of the force. Virtual particles are unlocalizable and do not obey the relativistic energy–momentum relation. Their existence is thus contested, and a literal reading of the diagrams is often considered to ascribe them more reality than appropriate.[4] Finally, equation 3 reminds us that due to the approximative nature of perturbation theory, not one but a sum of diagrams needs to be considered for any one process. Taking all of this into account, the majority of philosophers of physics conclude that a literal reading of Feynman diagrams is not possible, and that an individual diagram cannot represent anything beyond a mathematical term.[5]

Against this reading, I argue in this article that a representative use of Feynman diagrams is possible if it is combined with a detachment from perturbative calculations as well as a non-literal reading of the diagrams in which they are taken to be models of particle processes. As I will show in section 3, the literature on scientific modelling and representation commonly allows a non-literal interpretation of the model in relation to its target. I will now illustrate that such a use is prevalent in physics practice.[6]

In high energy physics, published articles often feature one or a small number of Feynman diagrams called upon in the text when the particle phenomenon of interest—for example, a

[4] For more on the nature of virtual entities in physics and beyond, see, for example, (Martinez [2024]; Broeks et al. [2024]; Cangiotti et al. [2025]).

[5] I will not provide a detailed discussion of the debate on how to read Feynman diagrams here but refer to the literature. For more on the received view, see (Redhead [1988]; Weingard [1988]; Brown [1996]; Passon [2018]). For counter-arguments, see (Harré [1988]; Bacelar Valente [2011]; Jaeger [2019]).

[6] In this paper, I take 'physics practice' to refer to the use of Feynman diagrams in written sources of education and research in experimental and theoretical physics, such as in publications, textbooks or lectures. It aims to consider Feynman diagrams independent of their theoretical or historical origins or their depiction by philosophy of physics, but rather their applied everyday use by practitioners of the field (such as when discussing their objects of research, presenting their reasoning or results to members of their community or teaching students). A complete systematic analysis of the practical use of Feynman diagrams, however, is beyond the scope of this article. Other authors that have considered the use of Feynman diagrams in physics practice, with varying conclusions, include (Harré [1988]; Falkenburg [2007]; Passon [2018]; Stöltzner [2018]). For historical considerations, see (Kaiser [2005]; Wüthrich [2010]).

decay channel—is introduced. This creates a direct association between the diagram(s) and the phenomenon. Usually, there are one or a few leading-order diagrams depicted, and no reference is made to the fact that, coming from a calculatory perspective, a summation of diagrams is to be considered. The diagrams are brought into close connection with the phenomenon to be discussed, where they are used to familiarize the readers with the interaction discussed and visualize the mechanisms involved. In contrast, the particles do not explicitly use the diagrams to derive mathematical terms.

One example of the representative use of Feynman diagrams is given in a publication by the ATLAS Collaboration at CERN on experimental results obtained in a search for a heavy Higgs boson decaying into a $Z$ boson and another Higgs via different decay channels. In the paper's introduction, the authors present the particle processes they are interested in as follows:

> The search [for $A \to ZH$ decays] considers $Z \to ll$, where $l = e, \mu$, to take advantage of the clean leptonic final state. The $H$ boson is studied in the $H \to bb$ and $H \to WW$ decay channels [. . . ] This search considers both the gluon–gluon fusion [see fig. 2a] and $b$-associated production mechanisms [see fig. 2b] for the $A \to ZH \to bb$ channel. The $b$-associated production mode of the $A \to ZH \to WW$ channel is theoretically allowed, but [. . . ] only the gluon–gluon fusion production mode [see fig. 2c] is considered here. (Atlas Collaboration [2021], p. 2)

The figures referenced in this quote (see fig. 2) are what the authors call 'example lowest-order Feynman diagrams' (Atlas Collaboration [2021], p. 2) for the decay channel in the figure's caption, implying that these diagrams do not distinctly or unambiguously depict the process. Certain other diagrams could take the place of those printed. At the same time, they are referenced in the quotation when a production mechanism, that is, an entire particle process, is referred to. The diagrams thus appear to be connected to the entire process; the reader can easily come to the conclusion that figure 2c corresponds to the $A \to ZH \to llWW$ channel as a whole process, and not just to a specific order of mathematical contribution to that decay. Furthermore, the diagrams are shown as a figure—rather than in an equation—and are referred to in the text when the decay channels that were studied are introduced. They are not referenced at any later point in the discussion, and do not help any calculations. This suggests a direct connection between the diagrams and the phenomenon studied, a particle process. Such a direct connection is observed not only for individual Feynman diagrams, but includes also small groups of diagrams. Both figures 2a and 2b appear to be connected to the $A \to ZH \to bb$ process. In this case, too, no connection to calculations or orders is made, but rather to the particle process itself.[7]

[7] Further example publications with similar use of Feynman diagrams include (Cirigliano et al. [2012]; CMS Collaboration [2013], [2014]; Bahl et al. [2021]; Borgulat et al. [2024]).

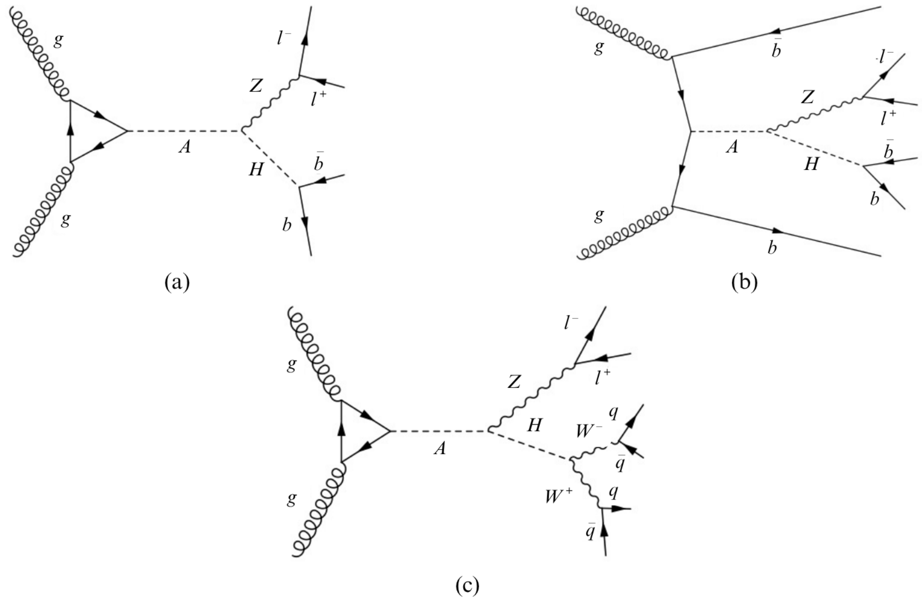



**Figure 2.** 'Example of lowest-order Feynman diagrams for (a) gluon–gluon fusion production of $A$ bosons decaying into $ZH \to llbb$, (b) $b$-associated production of $A$ bosons decaying into $ZH \to llbb$, and (c) gluon–gluon fusion production of $A$ boson decaying into $ZH \to llWW$' (Atlas Collaboration [2021], p. 2). Image credit: Reproduced from (Atlas Collaboration [2021]), under the Creative Commons CC-BY 4.0 licence, available at <creativecommons.org/licenses/by/4.0/deed.en>.

A practice of using Feynman diagrams independently of their calculatory formalism can also be observed in physics education. As an example, I consider Aitchison and Hey's ([2013]) widely used textbook, which introduces Feynman diagrams in an earlier chapter than the Feynman rules, thus presenting the diagrams independently of the mathematical formalism. The first figure in the entire textbook is a solitary Feynman diagram. Explaining the corresponding Feynman rules, however, is postponed until chapter 6 where, as the authors note, 'we shall see how diagrams which we have begun to draw in a merely descriptive way become true "Feynman diagrams", each diagram representing by a precise mathematical correspondence a specific expression for a quantum amplitude' (Aitchison and Hey [2013], p. 20). In addition, the textbook presents the first diagrams in reference to interaction mechanisms. For example, it includes a diagram that pictures as a 'typical one-photon exchange scattering process' the second-order Feynman diagram for the $e^+e^- \to \mu^+\mu^-$ process ([2013], p. 21, fig. 1.3). This creates, again, a direct connection between a Feynman diagram removed from its mathematical context, on the one hand, and a whole particle process, on the other hand. Standard textbooks by Griffiths ([2004]) and Schwartz ([2014]) show similar strategies in acquainting students with particle physics. Cvitanovic ([1983]) even chooses explicitly to introduce quantum field theory starting with Feynman diagrams, rather than with mathematical expressions. This provides further

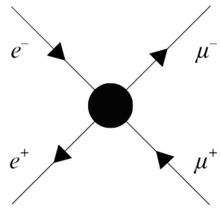



**Figure 3.** A diagram of a $e^-e^+ \to \mu^-\mu^+$ interaction, with the interaction represented by a black circle.

support for the observed detachment of Feynman diagrams from the mathematical formalism in physics education.

Overall, this analysis of physics practice illuminates a representative dimension that appears to be present in addition to the well-known use of Feynman diagrams as mathematical tools. Practicing physicists and teachers not only use Feynman diagrams for the derivation of perturbation terms but also in connection to particle phenomena, exploiting their straightforward and intuitive visualization of complicated particle processes. This observed use is independent of any calculations, diagrams are not related to perturbation terms or series. Instead, they are connected to particle processes as a whole. The diagrams are not used as mere illustrations, easily omittable from an article, and not only as a tool for learning about the phenomenon. Their algorithmic construction and reference to particles combines aspects of both. Therefore, I conclude that they are representations, or rather representative models of particle phenomena.[8] The goal of this representative practice is not the same as the goal of using Feynman diagrams as tools for calculations. It embodies an additional application of the diagrams that is centred around their reflection of key features of a process, such as the particles involved, which allows an intuitive access to the particle processes. Rather than to calculate transition probabilities, a representative use of Feynman diagrams aims to aid the grasping of on associated phenomenon. In addition, I claim that this appears to be a benefit that is particular to using Feynman diagrams in such a representative way, as opposed to other vehicles of representation. Physicists pursue this representative strategy despite their being aware of the conceptual difficulties associated with a more literal reading of the diagrams. The remainder of this article will expound why

[8] In this section, I take representing, standing for, and similar notions to refer to the relation between a target and another object that stands in for it. This notion does not require the depiction or mapping of specific target elements but refers only to the surrogative relation. Furthermore, I take representation—at least in this context—to not be ontologically committing. Section 3 will take a closer look at the topic.

exactly Feynman diagrams, including their virtual particles, are more telling representations than a diagram where the interaction is black-boxed (as seen in figure 3). In the next section, I will explain that the best way to capture this benefit is by conceptualizing virtual particles as productive elements of an idealized model.

### 2.3. Feynman diagrams as representative models of particle phenomena

In the previous section, I concluded that the best way to capture the representational use of Feynman diagrams is to conceptualize them as models of particle processes. I propose an approach that reflects physics practice as observed in section 2.2 and considers the diagrams independently, detached from the calculatory methods. This entails that the diagrams, including the lines and vertices, the rules of generation, the dictionary to 'particle speech', applicable higher-order principles such as the conservation laws, as well as further background assumptions such as the validity of the standard model of particle physics, are considered as standalone. This allows us to avoid interpretive issues such as the addition of many diagrams or the unsettled status of virtual particles, which are associated with Feynman diagrams in their original framework.

Detaching the diagrams from the calculatory framework leaves us with a model in which the diagrams are constructed in an algorithmic fashion via the rules of generation seen in section 2.1, starting with the incoming and outgoing particles of the phenomenon and considering additionally the rules of conservation of, for example, energy, momentum, or lepton number as known in quantum field theory. While this removes the diagrams from the context and constraints of the perturbation series and its associated calculations, it does not remove them from the wider scientific background in which they are situated, such as the standard model of particle physics.[9] That way, the model contains everything that is needed to entail a target phenomenon, which is a specific particle process with clearly identifiable incoming and outgoing particles, such as $e^-e^+ \to \mu^-\mu^+$. Connected processes, such as a further decay of the involved muon, will not be considered as the same but as a different target phenomenon of a different modelling endeavour. Models that include only the core factors needed to give rise to a phenomenon, so-called difference-makers, are often referred to as minimal models (Weisberg [2007]; Reutlinger [2016]).

The construction of Feynman diagrams is not the only aspect the model should capture; it

[9] While we separate Feynman diagrams from the framework of calculating perturbative terms, in which they figure prominently, we do not detach them from perturbation theory altogether. After all, only with perturbation theory do we get the construction of several diagrams for on particle process. It is the calculation of scattering amplitudes and the perturbative series that become irrelevant in the model use of the diagrams.

should also include the subsequent use of the diagrams in relation to a particle process. Here, the construction and comparison of different diagrams for the same process becomes important. It is often the case that not only one but a small number of leading-order diagrams are depicted. Alternatively, the diagrammatic scheme easily allows the construction of alternative diagrams for the considered target. For any one particle process, we consider individual Feynman diagrams to be model objects. The set of all diagrams for one process, together with the higher-order principles and rules of generation, constitute the representative model.[10] Such a set of diagrams allows us to ask 'what-if-things-had-been-different' questions (or w-questions) regarding the process under consideration—such as 'what if this process consisted of more virtual particles?' or 'what happens if I cross these two external lines?'—with whose help the target phenomenon can be explored.[11] These two aspects—an explorative component based on constructing different diagrams and the denotation of key target features such as the incoming and outgoing lines as well as conservation laws—allows us to draw the conclusion that the model has not only minimal but also explorative features as characterized in the literature. Explorative models, according to Massimi ([2019]), are models that are proposed not primarily to learn something about an existing target, but to serve as starting points for an open-ended exploration of a wider scientific area (see also Gelfert [2016], chap. 4). This modelling practice allows scientists to explore possible (causal) mechanisms behind a given phenomenon via a hypothetical target acting as a proxy, and also to imagine non-veridical scenarios about a given target.

The disconnection of the diagrams from the perturbation series allows a new perspective on the interpretive issues of Feynman diagrams. As model objects, Feynman diagrams can be considered to be idealizations of a particle process, thus altogether constituting an idealized model. They are idealizations of their target because they do not depict the actual process. In picking explicit depictions of the process via chosen sets of virtual particles, each diagram individually as well as the model itself idealize the target. Virtual particles cannot be removed in a process of de-idealization—as required by, for example, McMullin ([1985]) to allow conclusions about the target—without completely giving up the premises on which the model rests.[12] Indeed, if

[10] Not all diagrams in a model need to be considered, and it is, in principle, possible that a model consists of only one explicitly considered model object.

[11] These questions are often taken to explore counterfactual dependencies (Woodward [2003]). In this case, the term counterfactual is avoided, as this analysis is not concerned with facts, and does not want to make ontological commitments. Instead, I refer to the analogous analysis as an analysis of possibilities or subjunctives that proceeds via w-questions. The purpose and use of w-questions will be explained in section 4.

[12] There are different types of idealizations that can be distinguished, depending on how they distort and how they are obtained from the target (Hughes [1997]). Some use a more liberal notion of idealization that does not focus on how the idealization is derived from the target but that rather on its epistemic function (Potochnik [2020]). Idealizations that cannot be de-idealized are also called uncontrolled or uncontrollable idealizations; see (Sklar

the model were to be de-idealized, it would be transformed into the black box diagram seen in figure 3, a diagram that does not appear to provide the same epistemic insights as Feynman diagrams do. Virtual particles are thus crucial elements of the idealization. Generally, idealizations in models are taken to point to irrelevancies in their targets, features that are not relevant to the task at hand and can be idealized away (McMullin [1985], p. 272; Strevens [2008], p. 70). In recent years, however, philosophers have emphasized that there are many cases where we should not require a complete match between model and target, as idealizations—or distortions more generally—contribute crucially to achieving specific modelling aims (Elgin [2017]; Potochnik [2017]; Rice [2019]). Feynman diagrams, despite being idealizations of the associated particle process, allow an analysis of the target process with the help of w-questions, which provides some epistemic insight into the phenomenon of interest. This makes virtual particles not only crucial but also productive elements of the idealization.[13]

The detached model can be seen as an alternative to the models-as-mediators approach that has been endorsed by several authors as a characterization of Feynman diagrams (Wüthrich [2012]; Stöltzner [2018]; Forgione [2024]); for the original approach, see Morrison and Morgan [1999]).[14] In the models-as-mediators approach, the authors consider Feynman diagrams to be models that mediate between the perturbative series and some particle phenomenon, representing both at once. As a consequence, we need to maintain two readings of individual diagrams simultaneously: On the one hand, the diagram is read as a direct representation of a particle process. On the other hand, the diagram is read as only one specific term of a perturbative series that, only as a whole, corresponds to that process.[15]

While this simultaneity is not necessarily contradictory, maintaining two interpretations at the same time is possibly problematic. Depending on the target of the model's mediation—from particle phenomenon to perturbation theory or back—a different reading is needed, all while staying within one model framework. Furthermore, the models-as-mediators approach does not allow the observed use of Feynman diagrams as independent models, detached from perturbative calculations. Rather than representing particle phenomena with Feynman diagrams, a perturbation series is connected to a phenomenon, with Feynman diagrams merely as the

[2000]; Antoniou and Thébault [2025]) and references therein. For the distinction between idealization and approximation, see (Norton [2012]; Fraser [2020]).

[13] For an alternative characterization of Feynman diagrams as idealizations, where virtual particles are approximations, see (Bacelar Valente [2011]; Cangiotti et al. [2025]). I thank an anonymous reviewer for making me aware of the distinction between approximative and idealizing approaches.

[14] Brown ([2018]), Dorato and Rossanese ([2018]), and Wüthrich ([2018]) also discuss how to potentially treat Feynman diagrams as models but do not provide a complete characterization.

[15] Non-model approaches to Feynman diagrams that argue for a literal yet representative reading of the diagrams (Harré [1988]; Bacelar Valente [2011]; Jaeger [2019]; Cangiotti et al. [2025]) run into the same problem.

mediating tool.

Yet, this is a problem that can be avoided by separating the two strands of Feynman diagram use. Having detached the representational aspect, the model approach I defend in this article permits a reading of individual Feynman diagrams as directly representative of a particle phenomenon without the need to combine it with its role in a perturbative calculation. This not only allows a more fruitful characterization of the representational use and its epistemic benefits as observed in physics practice, but also avoids the danger of contradictions.

## 3. How Does the Feynman Diagram Model Represent?

Having reinterpreted Feynman diagrams as models, it is now possible to look more closely at the details of their relationship to a particle phenomenon target. The two systems stand in a representative relationship with one another, which allows conclusions to be drawn about the target from the model. This surrogative reasoning, where the model is used as a substitute for the target system, needs to be justified somehow. The literature on scientific representation contains different approaches to the criteria a legitimate representation needs to fulfil. In this section, I will show how Feynman diagrams, on a detached model approach, can represent a particle phenomenon target, and see when this representation is successful.

### 3.1. Representation with Feynman diagrams: Conditions and considerations

A plenitude of approaches are available in the literature on how to characterize the relationship that allows agents to use a model to learn about its represented target. While some focus on the user and their intentions for creating a representative link (Giere [2009]), others try to systematize the representative relationship by stipulating which element of a model represents which element in the target (Contessa [2007]). Still others propose to disregard representation altogether and conceptualize models as epistemic tools instead (Knuuttila [2011]). In this subsection, I will explore how well different accounts of representation fit the specific requirements that the Feynman diagram model poses.

An important feature of this model is the use of virtual particles, productive elements of the idealization. These particles appear to be a crucial part of why Feynman diagrams are used in a representative manner, as seen in physics practice. I thus take them to contribute explicitly to the modelling aim. Therefore, they should also be considered in the representative strategy to be chosen. Nonetheless, idealizations are often considered to indicate target irrelevancies, and thus many accounts of representation focus only on non-idealized features of a model. This is the case for structuralist accounts, where a structural mapping between model and target elements allows inferences to be made from the model to the target (Contessa [2007]; Bokulich

[2011]). For Feynman diagrams, this would mean that there is no possible contribution from virtual particles, as they cannot themselves be matched effectively to target features. While a very coarse-grained structure might possibly permit a matching of 'virtual particle' in the model to 'interaction' in the target, this does not allow anything new to be obtained with the model that could not also be achieved by the simpler black box model. A structuralist approach therefore does not appear to be suitable for the specifics of the Feynman diagram model.

This prompts a follow-up question: how, exactly, should we read Feynman diagrams? If we do not want to read an individual Feynman diagram as prescribing things like 'the interaction is mediated by one virtual photon' based on 'one internal photon line in the Feynman diagram', then we cannot read a Feynman diagram literally. This problem is closely connected to that of the accuracy of a representation. Accuracy is usually understood as the target actually possessing those features that the model imputes on it.[16] For Feynman diagrams, no conclusions about actual target behaviour can be imputed onto the model—we cannot conclude any of those. Hence, accuracy needs to be defined in a more minimal sense. I require instead that the Feynman diagram model does not lead us to conclude any falsehoods about the target. This is guaranteed by it containing the rules of generation and higher-order principles of the interaction, which ensures that no 'wrong' Feynman diagrams are admitted to the model.

As most models are not completely truthful representations of their targets—they distort them by idealizing or simplifying—accuracy needs to be distinguished from truthfulness (Elgin [2017]). Frigg and Nguyen ([2021]) have argued that any representation can be truthful if we can interpret it in such a way that it does not state any falsehoods about its target. Maintaining truthfulness, or veritism, often implies employing a non-literal reading of the model. This is also what I contend is the most suitable interpretation for the Feynman diagram case; we do not interpret the diagrams as literal depictions of particles in time and space but employ a more sophisticated reading in which we take an individual diagram to display possible behaviour of the target. 'Possible' is meant here in the sense that the specific mechanism shown by a single diagram is one that is possible given the accuracy criteria. As we have no way to experimentally verify whether this is, in fact, how the interaction transpires, no Feynman diagram ever depicts actual target behaviour.[17]

One way to escape problems with the reading and matching of distorting models to real-life targets proposed in the literature is by arguing that models are alike to fictions, entities that we can ascribe properties and truth values to, but which we do not expect to be real. A

[16] While some authors call inaccurate representation misrepresentation, others argue that essentially no models are completely accurate, and accuracy and representation should rather be considered as being fulfiled independently. In this article, I will follow the latter strategy.

[17] These possibilities are not to be confused with the possibilities inherent to quantum theory.

model then functions as 'a prop in a game of make-believe' (Toon [2012], p. 62). Meynell ([2018]), among others, has argued that Feynman diagrams are models of this kind. However, this conception leads her to the conclusion that Feynman diagrams are representations but not representations of anything (Meynell [2008], p. 48; [2018], p. 461; see also Forgione [2024], p. 13). On the fiction account, we cannot conclude that Feynman diagrams are representations of particle processes, as we are merely engaged in imaginative play. It does not tell us how to draw inferences about the real-life target from the model imaginings. I hence conclude that a fiction account is not suitable if we want to learn about real-world phenomena with Feynman diagrams.

Finally, as a last consideration, representation per se should not be an arbitrary stipulation. This means that if I claim that *A* represents *B*, it should imply that there is some kind of connection between these two entities beyond my statement. In other words, a scientific representation should be genuinely useful. This use of a representation is often stated as allowing surrogative inferences. However, as should have become clear by now, no factual conclusions about actual target behaviour can be drawn on the basis of a Feynman diagram. In addition, the model should capture the diagrams' use in all areas of physics practice, including teaching, where they are used by students with little background knowledge. The question in need of answering is thus: In virtue of what do Feynman diagrams represent particle phenomena?

### 3.2. A functional approach centred around understanding

The question of the virtue of representation has also been asked by Suárez ([2004]) to motivate his inferential account of representation. With this approach, he wants to emphasize that the most important aspect of a scientific representation is not how a model represents, but rather why it does (Suárez [2004], [2024]). He concludes that a model represents because of the inferences that can be drawn with its help: '*A* represents *B* only if (i) the representational force of *A* points towards *B* and (ii) *A* allows competent and informed agents to draw specific inferences regarding *B*' (Suárez [2004], p. 773). This account is considered to be in the tradition of other inference-based accounts of representation, most importantly the DDI (denotation, demonstration, and interpretation) approach given by Hughes ([1997]).[18] Suárez ([2004]) takes the representational force to be analogous to denotation, where it protects against misrepresentation or mistargeting, but can also accommodate fictional targets that cannot be denoted in the true sense of the word. That the representational force points from a Feynman diagram model to a particle phenomenon is ensured by it being a minimal model of the target, containing the

[18] Another example of which is DEKI: denotation, exemplification, keying-up, and imputation (see, for example, Frigg and Nguyen [2022]).

same external interacting particles and higher-order principles.

While other accounts of representation specify criteria for accuracy explicitly, Suárez argues that it is the model itself that has to ensure it can function as a suitable representation. The accuracy criterion is thus set independently for each case. The model, or source, has to have the capacity 'to lead a competent and informed user to a consideration of the target' (Suárez [2004], p. 768). In the Feynman diagram case, this means that the model includes all rules of generation and higher-order principles that are needed to allow, for example, a model user, a scientist, or a student to draw true inferences regarding the corresponding particle phenomenon. Whether a model user is competent and informed depends on the context in which the model is used and the inferences that are to be drawn. In the Feynman diagram case, I take the level of competence to be variable with the context. A student who encounters a Feynman diagram for the first time can be considered competent in their specific context, where the inferences to be made might be different from the case where the agent is a researcher with twenty years of experience in high energy physics.[19] As long as some kind of inference can be made that is true, representation is successful. Importantly, this account of representation does not require any (structural) similarities between the model and target nor a literal reading of a model's elements. Instead, it allows the contribution of idealizations to the modelling aim as long as they permit the informed agent to draw inferences about the target.

Although we now know that the question of the virtue of representation can drive an account of representation suitable for the detached Feynman diagram model, the precise nature of this virtue has so far remained unclear; I 'need to set the intended representational uses' for the model (Suárez [2004], p. 774). Considering the Feynman diagram case, the most fitting choice of this representational use of Feynman diagrams, the one that reflects physics practice and takes into account the specific properties of the representative Feynman diagram model as discussed in section 3.1, is that the model provides understanding of the target. The second condition for representation, that $A$ must allow an informative inference regarding $B$, does not include any further requirements regarding the nature of these inferences. This account is thus especially suitable for models where the modelling aim is not necessarily a derivation of true target facts (Suárez [2004], pp. 9, 258). Section 4 will provide justification for why understanding is the best outcome of the inferences that can be made, what kind of understanding is attainable, and how this captures the representative use of Feynman diagrams in a range of

[19] In principle, the idea of context-dependence can also be applied to further research traditions in which Feynman diagrams are used differently. In addition to the calculatory use, Feynman diagrams might also be used for model building in research, not only for teaching purposes. A detailed analysis of these practices is, however, beyond the scope of this article.

settings.[20]

## 4. Understanding Particle Phenomena with the Feynman Diagram Model

In the previous section, I concluded that a minimal approach to scientific representation that focuses on the inferences that can be made is the most suitable for Feynman diagrams, and that these inferences allow an understanding of the associated particle interaction. In section 4.1, I argue that this understanding is of modal nature and explain how the Feynman diagram model can provide it. In section 4.2, I provide more support for the claim that understanding is the most suitable epistemic modelling aim in this case by contrasting it with an explanation of the particle process.

### 4.1. Feynman diagrams provide modal understanding

Scientific understanding is closely related to scientific explanations. Yet, while an explanation can be shared between two agents, understanding is the subjective and cognitive achievement of having grasped something, for example, that explanation.[21] Some accounts of understanding presuppose an explanation and thus often also some theory that describes a phenomenon (Strevens [2008]; Khalifa [2017]). However, there are also approaches where understanding is independent of or prior to explanation, as argued in, for example, (Lipton [2008]; Elgin [2017]; Regt [2017]; Verreault-Julien [2019]). I will consider primarily such understanding-first approaches.

According to Massimi ([2009], p. 874), the aim of an explorative modelling pursuit such as the one discussed in this article is to 'ultimately deliver important modal knowledge about what is causally possible concerning a phenomenon under study'. The idea of modal or subjunctive reasoning has prompted the development of a modal account of scientific understanding (Le Bihan [2016]; Rice [2016], [2025]; Nguyen [2021]). According to Rice ([2025], p. 58): 'An agent or community has scientific understanding of a phenomenon if and only if they grasp what would occur in some possible situation(s) that enables them to correctly answer a range of what-if-things-had-been-different questions about the real-world phenomenon'. Understanding is thus provided by grasping behaviours that could possibly make a target phenomenon occur,

[20] Applying this inferential account of representation to Feynman diagrams with the inferences leading to an understanding of the target is quite similar to a proposal recently made by Forgione ([2024], pp. 12–14), who argues that Feynman diagrams represent particle phenomena in a weak, ontologically non-committing way. I extend this idea in section 4 by explicitly illustrating a way this understanding is obtained, and why it is understanding of an actual particle process.

[21] I understand grasping as making sense of a subject matter, knowing how to interpret a body of information or being able to recognize instances of that property (Strevens [2024]; Elgin [2017]).

and how these different possibilities relate to one another. On the modal account, understanding is provided by what is called a counterfactual or subjunctive analysis. While the phenomenon investigated itself remains stable (Fletcher [2020]), w-questions enable the model user to learn about what would happen in possible systems that differ from each other but all give rise to the phenomenon. This deepens the understanding. For example, investigating the consequences of varying the value of the gravitational constant $G$ can deepen a student's understanding of planetary motions despite their knowledge of $G$'s empirically determined value.

The implicit idea of a space of possibilities whose analysis can provide modal understanding is made explicit by Le Bihan ([2016], p. 112), who argues that modal understanding is obtained 'if and only if one knows how to navigate some of the possibility space associated with the phenomena'. The possibility space (or P-space) is defined as including all possible structures that can possibly give rise to the phenomenon of interest, as well as information on how these structures relate to each other. By asking and correctly answering w-questions, the elements of the P-space can be related to one another. With those questions, the model user moves around the different branches or members of the possibility space, which is spanned out by the different alternatives and their relations. Depending on how well we are able to navigate this space, we have a more or less deep understanding of the phenomenon studied.

Importantly, modal facts are true beliefs about possible target behaviour without it having to be actualized. The members of the possibility space are to be understood not in a metaphysical sense of possible worlds, but as potential target behaviour that is possible given the constrains of the model. No ontological commitment has to follow from this subjunctive reasoning. Nonetheless, an analysis of the possibility space of a given target can be considered to provide understanding of that target. Grasping different possible behaviours, their connections to one another and the underlying mechanisms for their admittance deepens the understanding of a phenomenon in a way that can only be achieved with the help of a model.[22]

This seems to fit the modelling of particle processes with Feynman diagrams very well for two main reasons: First, it reflects the construction of several diagrams within one modelling pursuit, such as diagrams of different orders. Second, modal understanding is obtained by exploring a space of possibilities. It is not required that any of those possibilities will actually be instantiated in the target. As we cannot know that any of the Feynman diagrams are literally truthful depictions of the decay, Feynman diagrams are instead interpreted as representing possible ways for an interaction to transpire. This fits well with an account of understanding that

[22] This approach is different to fictional accounts, which do not aim to prescribe anything about the target but remain in a sphere of imagination. On the modal account, understanding is provided by true statements about the target; these, however, are statements not about actual but merely possible behaviour.

only requires the knowledge of possibilities.

I thus consider the Feynman diagram model as providing understanding of particle phenomena in the following way: Exactly all diagrams of one target phenomenon, model objects of one Feynman diagram model, are in the target's possibility space, but not any others.[23] This is ensured by the higher-order principles and rules of generation of the model, which prohibits the admission of 'wrong' diagrams, ones unrelated to the interaction. In practice, the P-space does not have to be spanned out in its entirety, as not all possible diagrams have to be instantiated to obtain understanding. The different diagrams in the possibility space depend on one another in that they share more or less similar features. It is possible to navigate the space with the help of w-questions. The w-questions that can be asked are limited by what the model's accuracy conditions allow. What is stipulated by our background knowledge cannot be changed, such as fundamental principles of quantum field theory or assumptions of the standard model. This ensures the stability of the phenomenon under investigation. By looking at one member of the space and asking what if $X$ were different, we can hop to a different member of the space. Not only does finding a fitting diagram provide some understanding, but the path to it from a given starting point generates insights into the dependencies between different members of the P-space, and thus into the rules of generation and higher-order principles. In this way, we obtain insights into possible target behaviour, such as possible mediating forces, allowing us to better grasp the phenomenon as a whole. Section 5 will provide more tangible examples of an analysis of the possibility space.

The ability to navigate the space of possibilities can come in different degrees, as each uniquely equipped agent provides an individual context to the representation. A more capable agent is able to navigate more of the possibility space, but the criterion for representation is fulfiled if an agent has the ability to obtain any understanding whatsoever. In a first step, the agent grasps one possibility of how the particle phenomenon is possibly entailed by the set of incoming and outgoing particles, higher-order principles, and involved virtual particles. This is understanding provided by grasping a possible target behaviour. A great advance comes with the consideration and grasping of different diagrams in the P-space and their relation to one another. Constructing different diagrams and asking more w-questions allows the agent to grasp how the members of the possibility space are dependent on and related to one another. This lets the agent grasp the possible target behaviour to a higher degree than that provided by an individual diagram because it gives a better sense of the possibilities and of the target behaviour

[23] This does not mean that the model equals the possibility space. The Feynman diagram model contains also the higher-order principles, rules of generation and appropriate background knowledge. Still, there is a close connection: the model spans open the P-space which consists of the model objects, the individual diagrams.

in itself. On this level, the modal character of the understanding that Feynman diagrams can provide is made explicit.

The different degrees to which the possibility space allows grasping can account for the different degrees of understanding that can be obtained by different agents. A first-year university student might gain some understanding by grasping the dependencies in a lowest-order diagram but will not be able to grasp the relation of that diagram to more complex ones. Nonetheless, they can successfully navigate the possibility space to some degree. Therefore, the student has gained an understanding of the process. A graduate student, having more background knowledge, will be able to grasp the dependencies between a larger set of diagrams. They will be able to ask more, and more advanced, w-questions, and are thus better at navigating the possibility space. The more diagrams are constructed and considered, the more w-questions can be asked, spanning a larger subset of the possibility space. Being able to navigate a larger portion of the possibility space, and grasping its relations, gives a deeper understanding than a smaller subset of the space would.

### 4.2. Why (modal) understanding?

The production of knowledge is usually considered a main aim of science and the search for explanations, which are to be true and objective, is a main route to achieve it. Understanding, however, is a more subjective and cognitive affair. This prompts the question of whether we should aim for an explanation of some particle phenomenon with a Feynman diagram model, either instead of or in addition to understanding.

I argued that as we cannot know if any of the Feynman diagrams is a true description of the target mechanism, and we cannot explain how the interaction takes place any better than without a diagram, we do not look at actual but at possible target behaviour with Feynman diagrams. Nozick ([1981]) maintains that for explanations, we should consider actualities; but for understanding, a sense of associated possibilities is of greater interest. In the actualities lie the key reason why understanding appears more fitting for Feynman diagram models than explanation. Explanations are generally considered to be subject to a veridicality condition. This means that an explanation should be based on true explanans. This is the case both for prominent early accounts such as the deductive-nomological model (Hempel and Oppenheim [1948]), as well as more recent approaches, such as Woodward's ([2003]) counterfactual approach. As an explanation should be objective, transferable, and truly (and not falsely or arbitrarily) explanatory, a veridicality condition for explanations cannot be avoided. However, as Reutlinger et al. ([2018]) note, such a veridicality condition cannot be fulfiled by all (or even most) models. They thus propose that some models instead provide how-possibly explanations that only refer to possible explanatory factors that are not necessarily actualized in the target (Reutlinger et al. [2018], p. 1085). They cannot, however, provide actual knowledge of its mechanisms as for this, the model description needs to be truthful. They are 'heuristically useful in constructing a space of possible mechanisms, but they are not adequate explanations' (Craver [2006], p. 361). Hence, not all models are constructed to provide target explanations.

Staying in the spheres of explanation, models like the Feynman diagram model that cannot facilitate any conclusion about actual target behaviour will not be able to provide true explanations. They are limited to the exploration of possible mechanisms without any way to turn them into actual explanations of an actual target. With understanding, however, these possibilities can be turned into something more. Knowledge of possible target behaviour can be used to obtain true understanding of the target itself. As modal facts are not false, the fact that they are statements about possibilities does not hinder us in connecting them to the target for the purpose of understanding, contrary to the case of explanation. Thus, in instances where explanations of actual target behaviour are out of reach, modelling for understanding turns out to be more fruitful, especially if the understanding is of modal nature.

The modal account, I argue, can capture the observed physics practice especially well. It takes into account that for an interaction, usually a small number of diagrams is depicted and a diagram is introduced as 'exemplary', indicating that the consideration of alternatives is advised. The model comes with a straightforward translation between a small set of easily readable graphical elements and 'particle speech' to be associated with the target interaction. Internal lines allow insights into the possible force of the interaction. This concise set of rules and elements permits a direct connection between the model and the phenomenon without the need for the perturbative series with its mathematical terms to be involved. Whether we can obtain understanding is thus directly connected to how well the model can visualize the related phenomenon and its space of possible behaviour.[24] The modal approach to understanding particle phenomena with Feynman diagrams captures the way Feynman diagrams are used in current physics practice. It provides a different perspective to Meynell's ([2018]) and Forgione's ([2024]) more historical discussion of Feynman's personal notion of the diagrams as understanding-providing vehicles. It also advances approaches that notice an epistemic component to Feynman diagram use but do not provide a philosophical framework for it (Harré [1988]; Bacelar Valente [2011]; Wüthrich [2012]; Passon [2018]).

Finally, the modal approach provides an answer to the question of why Feynman diagrams are preferable over the black box diagram (fig. 3). The explicit depiction of internal lines is crucial to obtaining modal understanding, as the possibility space is span open only with the

[24] On visualization and understanding, see also (Regt [2014]).

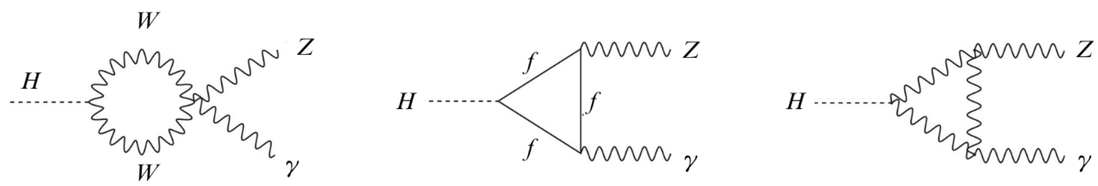



**Figure 4.** Diagrams contributing to $\Gamma_{Z\gamma}$. Image credit: CMS Collaboration ([2013], p. 587). Reproduced under the Creative Commons CC 3.0 licence, available at <creativecommons.org/licenses/by/3.0/deed.en>.

consideration of different virtual particles. A direct grasping of possibility dependency relations present, their relation to the higher-order principles, as well as the analysis of alternatives would not be possible with black box diagrams that offer only one singular representation of an interaction. Feynman diagrams thus provide a unique strategy for understanding particle phenomena.

## 5. Example: The $H \to Z\gamma$ Decay

Using an example, in this section I will show how the framework presented in this paper—complete with modelling, representing and understanding—can capture the representative use of Feynman diagrams observed in physics practice. Figure 4 depicts Feynman diagrams of a Higgs boson decaying into a $Z$ boson and a photon, as published in a paper by the CMS collaboration at CERN. The authors introduced the diagrams as the 'contributing diagrams to $\Gamma_{Z\gamma}$ [which] are shown in [figure 4]' (CMS Collaboration [2013], p. 587).

Following the account presented in this article, these diagrams, taken together, are considered as a model of a particle phenomenon, in this case the $H \to Z\gamma$ decay process. As a model, the diagrams are disconnected from their origins as mathematical tools for a perturbative calculation, while retaining the established rules of generation, higher-order principles and scientific background. This direct connection between the diagrams and the phenomenon has several advantages. First of all, there is no need to be concerned with the realism problem virtual particles pose. Instead, internal lines are interpreted as crucial and productive features of the idealized model. The virtual particles are crucial elements of the idealization in that they explicitly represent the interaction with a chosen set of internal lines, a distortion of the actual process where this choice cannot be made, and productive because they are necessary for the model's epistemic success. The diagrams of figure 4 and the target phenomenon all share the same stable large-scale behaviour that generates the $H \to Z\gamma$ decay but vary in their details. All Feynman diagrams seen in figure 4 are model objects of one model, as they are diagrams of the same particle process. This gives the model an explorative aspect. The alternative model objects present different possible mechanisms to obtain the same target phenomenon.

In order to capture the representative use of Feynman diagrams, a suitable account of representation is needed. It should take into account that the model use has to be fruitful: the model user learns something from the modelling and that this learning is in large part due to an idealization the explicit depiction of an interaction with virtual particles. This is captured by an inferential account of representation, where I take the inferences to allow target understanding. The accuracy of the representation is ensured by the model itself, as it contains the necessary higher-order principles and rules of generations to ensure that only those Feynman diagrams are admitted to the model that are 'true' diagrams of the target and provide understanding of it. To successfully establish representation, the modelling agent needs to be competent and informed. In the Feynman diagram case, the level of competence is considered to be variable with the context, allowing different agents to establish representation as long as they are competent enough to obtain an understanding.

The Feynman diagram model provides modal understanding of particle processes by allowing the agent to grasp how to navigate the possibility space associated with the target, span open by the corresponding Feynman diagrams. In the $H \to Z\gamma$ decay, this means that the P-space of possible target behaviour is span open by the diagrams in figure 4, as well as other admissible diagrams for this decay that can be constructed explicitly or implicitly. Understanding of the phenomenon is obtained if we are able to navigate the P-space and its members with the help of answering w-questions. This analysis of the space of possibilities can be more or less involved and mirrors the different depths of understanding attainable with Feynman diagrams. For example, a student might ask if this interaction could possibly be mediated with different internal particles. In navigating through the P-space, they will find that the answer to their question is that it could possibly be mediated by fermions, $W$ bosons and photons. A physicist with a different background knowledge than the student could also ask whether the interaction could possibly involve further particle types, or a number of internal particles larger than three. Navigating through more and more involved diagrams will answer these w-questions, providing an even deeper understanding. In both cases, insights into how the particle process could transpire are obtained, including possibly involved particles and possible mediating forces. This grasping of possible behaviour provides understanding of the target, without the need for the behaviour to be actualized.

## 6. Conclusion

In this paper, I claim that the representative dimension observed in the practical use of Feynman diagrams should be considered as independent of the calculatory use. Separating Feynman diagrams from the original mathematical framework allows—I argue, contra the received view—their treatment as representative models that provide an agent with modal understanding of the corresponding target phenomenon. Modal understanding not only successfully draws on the productive use of virtual particles as crucial contributors to a fruitful use of the Feynman diagram model, it also honours the fact that the model cannot provide conclusions about any actual target behaviour but provides understanding nonetheless. This understanding is not attainable with the black box diagram in figure 3. The approach to Feynman diagrams presented here allows us to account for modern physics practice, where the diagrams are used as representations of particle processes in areas from undergraduate teaching to research publications. Separating the representative from the computational use of Feynman diagrams clarifies some of the questions in the philosophical debate and connects the historical perspective to today's practical use.

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