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Philosophy of Quantum Field Theory: an introduction with interviews and comments

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Abstract

In this thesis, I address quantum theories and specifically quantum field theories in their interpretive aspects, with the aim of capturing some of the most controversial and challenging issues, also in relation to possible future developments of physics. To do so, I rely on and review some of the discussions carried on in philosophy of physics, highlighting methodologies and goals. This makes the thesis an introduction to these discussions. Based on these arguments, I built and conducted 7 face-to-face interviews with physics professors and an online survey (which received 88 responses from master's and PhD students and postdoctoral researchers in physics), with the aim of understanding how physicists make sense of concepts related to quantum theories and to find out what they can add to the discussion. Of the data collected, I report a qualitative analysis through three constructed themes.

Contents

Introduction

This thesis stems from my need to recast and enrich the concepts I have studied in recent years. By enrolling in Theoretical physics curriculum, I had the opportunity to engage with incredibly articulate and brilliant, as well as creative, reasoning and constructions. My path was not linear in terms of content, as I needed to explore approaches to different problems. Like all the students in my course, I encountered quantum field theory, its formulations and formal complexity. To sum up, I learned that QFT is a framework theory which has allowed to unify the non gravitational interactions in a way that is consistent with special relativity, through its best-know concrete theory: the Standard Model of particle physics. In addition, it is one of the frameworks employed in condensed matter physics. It convinced most physicists that the Universe can be thought of as consisting of quantum fields (at least below a certain energy scale), each associated with a particle. Clearly, the relationship between them is not unambiguously established and, as we shall see, one of the greatest interpretative challenges is to understand their structure. Moreover, beyond its formal complexity, QFT inherits the interpretative difficulties of quantum mechanics. I think it is fair to say that quantum theories and their implications are so difficult to swallow and interiorise, that they generate a great fascination in the students' minds. My fascination, mixed with a great deal of misunderstanding, doubt and frustration, led me to approach the philosophy of physics. My need for reformulation was related to QFT specifically, however as I was reading in a disorderly fashion through the sources that were recommended to me, I realised that it was not enough to just reflect on the contents of the theory, but I needed to do some preliminary thinking on what it means to know, what a physical theory is, what it means to interpret it, how physical theories relate to reality. Without exploring questions of this kind, the conceptual analysis of QFT was incomprehensible to me. Another thing I needed to understand was how the theory stands in relation to other physical theories. After having more or less understood what kind of analyses can be conducted on them, and specifically on QFT, from what perspectives and with what aims, I decided to engage with physicists to discuss and understand how they make sense of quantum and quantum field theory-related concepts. Again, the discussion expanded to epistemological conceptions, in the understanding of physical theories and interpretations. What I got was a mixture of more formal and professional views and more personal and informal approaches. This was accomplished by conducting 8 face-to-face interviews with physics professors (of which only 7 are presented in the analysis due to a loss of data that occurred for technical reasons) and through the administration of an online survey that received 88 responses, mainly from master's students, doctoral students, and postdocs. The interviews were designed in a semi-structured manner in order to capture the perspectives that are more personal and more related to each professor's academic background (as the research fields in which they work are different from each other, both in the theoretical and experimental fields). The online questionnaire, on the other hand, consists of open and closed questions mixed together. The analysis I propose is almost purely qualitative, an analysis that can possibly become quantitative by expanding the survey. All the excerpts I report are anonymous. Therefore, this thesis ultimately succeeds in doing two things. Firstly, it can provide a brief introduction to the philosophical discussions related to the quantum world, mainly QFT and to get an insight into how to place them epistemologically by emphasizing what are the premises from which a philosophical inquiry starts. Often simplifying, this work can still help to spread a somewhat more conceptual and discursive approach. In addition, it is operationally useful because it provides tools for understanding some of the discussions that emerged in the interviews and in the online survey. This is the function of Chapter 1 and Chapter 2. And secondly, the thesis tells a story from the data collected with respect to physicists' personal conceptualizations and narratives of quantum-related issues. This is the goal of Chapter 3. As the collected data are very rich, what I report is a very concise overview of the responses and a more personal section constructed through a portion of the data that allowed me to build three themes, as part of the qualitative thematic analysis.

Chapter 1

Setting the framework: from physical theories, interpretations and reality to QFT

The purpose of this Chapter is to reflect on physical theories and the meaning and nature of interpretations. Furthermore, I will discuss the different postures that can be adopted regarding the relationship between physical theories and reality, as classified in philosophy of physics. To set up the discussion, I will briefly refer to the interpretations of QM and then I will provide an introduction to QFT and its status with regard to what we know of the physical world. Instead, specific conceptual issues will be explored in the next Chapter. This framework will be useful to understand and analyse the answers I got from the physicists I interviewed. Clearly, it is not meant to be exhaustive, considering that the perspectives mentioned answer very broad questions and may use philosophical language not necessarily shared and adopted by physicists.

1.1 What is a physical theory?

To begin with, let us ask what a physical theory is or can be. Clearly, it is not a straightforward or conclusive process since it requires interdisciplinary considerations, and can vary according to the evolution of physics. However, I will sketch a simple and posture-free representation with respect to what can be known and to what extent, following Teller in [30]. The author describes theories as collections of models, going beyond an old narrative that considers them as consisting of general laws from which all applications can be strictly deduced. According to him, a model can be simply thought of as an abstract object, constructed to describe certain aspects of a system, meaning those properties that are considered interesting from a physical point of view. Teller points out that, even in the modelled aspects, we do not expect a total correspondence between the model and the physical system. The connection between them is more a matter of similarity than of correspondence, a similarity limited to some aspects and to a certain extent. It is sufficient for him to mention the case of the harmonic oscillator, a model widely used in both classical and quantum physics, which, for instance, can correspond to the real pendulum only in the case where small displacements are considered, and when uninteresting properties are neglected. To use his words:

> “This view makes sense of the practice of science. Laws are not eternal truths. [...] Instead, they are like basic dress pattern, to be tailored to suit the idiosyncrasies of the different customers. Properly tailored laws work together to form a model. Theories, in turn, are collections of models that have been loosely grouped both according to phenomena to be modelled and according to common technical tools used in building the models.”

Teller then proceeds to note that, with this conception of theories in mind, their boundaries are blurred. A new theory can be seen as an improvement of another when it models better a set of phenomena. This is the case, for instance, for both special relativity and QM, since they have provided better descriptions of some phenomena that were already modelled by classical mechanics. Indeed, each new theory has been able to better model certain aspects and has done so with different techniques. Therefore:

> ”We should expect no neat linear succession if the point of theories is to provide models similar to the things modelled in a variety of ways”.

Concerning relations between theories, Wallace in [33] draws a similar conclusion. However, before explaining that, let us make a distinction between framework theories and concrete theories, a differentiation commonly employed among physicists and philosophers. In particular, Wallace considers classical mechanics, QM and QFT as framework theories (where the latter can be considered a sub-framework of QM) [35]. Concrete theories (also called instances), which are those actually tested, are constructed from these framework theories, which serve as the abstract mathematical background. By testing concrete theories, it is possible to draw conclusions related to the framework. QFT is probably the most widely used framework in contemporary theoretical physics, and SM represents its most powerful concrete theory. When Wallace talks about relations between theories [33], he means relations between specific, concrete ones. He contrasts the common view according to which physical theories can be represented by a tower. This tower should be composed of theories in which each one approximates ”the theory below it in the appropriate limit”. At the bottom of the tower there should be the SM (underlined by a future theory of quantum gravity), followed by QED, then quantum theory of photons and non relativistic atoms, non relativistic quantum mechanics, and finally classical particle mechanics and classical fluid mechanics. Wallace considers this picture as misleading, since he rejects the idea of a clear hierarchy of theories because the same system can be described by different models at various levels of detail. Additionally, the tower view gives the impression that, when we describe a given phenomenon, all elements are simultaneously described by the same theory. Instead, as he states, the practice of "modelling is local". His proposal is the following:

> "So a better picture is more like a patchwork than a tower: for any given system there are various levels of description at which various theories are applicable. And since the notion of 'system' is itself theory-laden, there is no theory-free starting language with which we can describe this picture."

Even though he does not acknowledge a well-defined hierarchy, local relations between theories can be illustrated as follows:

> "if theory X describes a system at some level of description, and theory Y describes that same system at a more detailed level, then the description from theory X can in some sense be derived from that of theory Y. And if several systems S_1 through S_n can be described separately by theory X at higher level, and collectively by theory Y at lower level, we can derive from theory Y both the applicability of X to the systems separately and the validity, at that level, of the decomposition into subsystems. Ultimately we might hope to find a sufficiently finegrained level of description at which the whole Universe can be jointly regarded as a single system, and the applicabilities of all the higher-level theories derived directly or indirectly from it."

This means that the description provided by one theory can be derived from another, in a certain limit of validity. Indeed, studying the limits within which one theory tends to another is physically interesting and commonly accomplished. As the author notices, Nature may not be so unified. Various counter-arguments can be brought, studying particular cases and also adopting an epistemological position in which theories are considered incommensurable as they are generated from different historical contexts [19]. Nevertheless, as Wallace replies, the tendency towards unification in physics on the theory-builders' side is there and there are cases where definite relationships between theories are obtained.

1.2 What does it mean to interpret a (quantum) theory?

Interpreting the quantum world is a controversial business. This is an intellectual challenge that has been going on for a century and remains open despite the fact that physics has built new, much more advanced quantum-related subframeworks. Obviously, although it may be considered unnecessary, having guidelines for interpreting a theory can be very helpful. Additionally, as Teller notes in [30], when a scientist constructs a theory, it is difficult for it to emerge totally uninterpreted, as well as it provides guidance on how to be tested. He concludes that interpreters:

> "[elaborate] in any way that clarifies, sharpens, or extends the similarity relation between a model [...] and the things described by the theory".

The author identifies two main interpretative issues in quantum theories: the superposition and the measurement problem. To put it very briefly, without adopting any of the interpretations currently in play and explicitly opposing the hidden-variable ones, Teller considers the superimposed properties as follows:

> "If the property Q is the superposition of properties P_1 and P_2, then Q is a property in its own right, but it also includes a propensity to yield as a measurement result the superimposed properties P_1 or P_2, when the right "measurement" activating conditions are in place, with the probabilities given by the probability amplitudes."

Although this conception is clear, there is still the measurement problem for which he admits to not prefer any of the proposed explanations, considering them all unsatisfactory. According to Wallace [33], interpreting theories means to provide an interpretative recipe that allows to understand each concrete theory, consistently with the inter-theoretic relations. He asserts that for classical mechanics we have this kind of recipe, meaning that we consider the phase space as the space of possible states and the dynamical history $x(t)$ represents the physical features at a given time. Based on the distinction between framework theories and concrete ones, he states that the search for an ontology (a usual interpreters' commitment) makes sense only when one considers a particular theory. He illustrates the interpretative challenges raised by QM in a very simple way in [34]. They are the measurement problem, the interpretation of the quantum state, the entanglement and the non-locality implied by the violation of Bell's inequality. His conclusion is that only the Everett interpretation for quantum theories has this form, which we will explore briefly in 1.4. Switching to QFT specifically, which are the interpretative issues that need to be addressed? Teller's work is about building "a larger interpretative framework for quantum field theory [whose] usefulness for thinking about more specific issues will be its most severe test." Indeed, as we will see, his work raised an interesting debate, which can be explored further in [18]. The conceptual issues raised by him concern the evolution of the concept of particle, its relation with the field, the different ways of achieving the particle-like and field-theoretic formulations of the theory, and the meaning and approaches to renormalization. Using his words:

> "Appreciating the theory involves grasping the new forms of the two elements [particles and fields] and seeing clearly how they fit together."

Clearly, he warns us that depending on one's position with respect to physical theories and interpretations of quantum probability, his discussions and proposals must be reconsidered and, if necessary, adapted. In [18] an ontological analysis is conducted. According to Kuhlmann, Lyre and Wayne, the aim of this inquiry is:

> "to get a coherent picture of the most general structures of the world [...]. One wants to know which kinds of things there are and how everything is related, whether and how some things are composed of parts and whether there are fundamental entities out of which everything else is composed. [...] The ontologist of QFT is then concerned specifically with the story that QFT tells about the world- provided that QFT is a true theory."

To achieve this, the authors propose an active collaboration between pure philosophers, philosophers of physics and physicists. Their wish is that philosophical tools may be useful for heuristics, since QFT is not complete due to incompatibility with the theory of gravity. While physicists are concerned with figuring out what the properties of a certain system are, its dynamics and what it is composed of, philosophers are concerned with establishing what a property is, how to distinguish an entity from its properties, and to explore the relationships between the parts and the whole. If you wish, you can find discussions of this type in [7]. Without going into details, the authors identify three disciplines through which the ontologists must equip themselves. They are QFT itself, analytical ontology (considering the great significance given to empirical science and logic), and philosophy of science. Following Quine's stance:

> "it is essential for ontology (as a philosophical discipline) to look for the "ontological commitments" of the "best science available"."

As they soon notice, it is difficult to establish which is the "best science available" related to QFT, considering that there are at least three possible formulations, meaning Path Integrals, Canonical Quantization procedure and Algebraic QFT, that will be addressed briefly in the next Chapter. Obviously, "ontological commitments" are directly connected to the formulation. Very shortly, each one has its own ontological commitments, and they are different from each other. The first formulation is strictly related to paths, while in Canonical Quantization the central concept seems to be the field, which does not really appear in AQFT. As Carroll notes in [5], the dispute over which formulation to choose can be outlined in terms of "heuristic" QFT and axiomatic QFT. He summarises the discussion as follows:

> "Heuristic QFT [...] is what the vast majority of working field theorists actually do — putting aside delicate questions of whether series converge and integrals are well defined, and instead leaping forward and attempting to match predictions to the data. Philosophers like things to be well-defined, so it's not surprising that many of them are sympathetic to the axiomatic QFT program, tangible results be damned."

Clearly, the debate is open and the choice is a subjective matter.

1.3 Physical theories and reality

About the picture outlined in section 1.1, Teller writes that ”this view of theories [is intended] to be neutral on the issue of realism”. And this is the case if we refer to theories as collections of models and to interpretations as clarifying reflections. The patchwork picture can be neutral too, as well as the requirement of an interpretative recipe[1]. The same cannot be said for the ontological investigation just mentioned. However, it must be noticed that the picture just drawn is in sharp contrast with the Kuhnian-historicist view of physical theories, which are considered incommensurable [19]. Since this view rejects the idea of cumulative progress of scientific knowledge, the practice of comparing theories in common application ranges is somewhat depleted of its meaning, since they are products of different contexts and communities. Hence, time has come to briefly illustrate the never-ending dispute between realism and antirealism. The key point to elaborate on is: what is the relationship between physical theories and reality? Are we interested in this question? Van Frassen in [32] puts the subject in these terms:

> ”A current view, not altogether uncontroversial but still generally accepted, is that theories account for the phenomena (which means, the observable processes and structures) by postulating other processes and structures not directly accessible to observation; and that a system of any sort is described by a theory in terms of its possible states. This is a view about the structure of theories shared by many philosophers who nevertheless disagree on the issues concerning a theory's relation to the world and its users. [...] One relation a theory may have to the world is that of being true, of giving a true account of the facts. It may at first seem trivial to assert that science aims to find true theories. But coupled with the preceding view of what theories are like, the triviality disappears. Together they imply that science aims to find a true description of unobservable processes that explain the observable ones, and also of what are possible states of affairs, not just of what is actual.”

Let's pretend to be realists. Finding an ultimate definition is complicated, so I will try to give some general indications. In [8], Chakravartty writes that:

> “[realism can be seen as] an epistemically positive attitude toward the outputs of scientific investigation, regarding both observable and unobservable aspects of the world”.

The latter mean those that cannot be experienced directly, while they can be detected using instruments. Another way the author puts it is:

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[1] However, Wallace defines himself a structural realist.

> “Our best scientific theories give true or approximately true descriptions of observable and unobservable aspects of a mind-independent world.”

Van Frassen in [32] prefers the following definition:

> ”Science aims to give us, in its theories, a literally true story of what the world is like; and acceptance of a scientific theory involves the belief that it is true.”

To be more specific, there are several ways to make the connection between theories and reality. One can consider the unobservable manipulable entities implied by the theory to be real (entity realism), or the aspects of the theories necessary to justify their empirical success (explanationism), or even the recurring mathematical structures of the unobservable realm (structural realism). Redhead in [22] criticizes entity realism using the following argument:

> “The main reason for [his structural realist position] is that there is significantly greater continuity in structural aspects than there is in ontology, and one of the principal arguments against realism is the abrupt about-turns in ontological commitment even in the development of classical physics. Of course, the structural aspects also change, but there is a more obvious sense in which one structure grows out of another in a natural development or generalization, so that a cumulative model of scientific progress is much easier to maintain.”

This position is shared by Wallace [34]. A typical claim in favour of realism is the ’Miracle Argument’. It states that, without assuming that theories describe reality to some degree, the empirical success of some of them would be ascribed to a miraculous process. Another supportive argument cited in [34] comes from the insight that the observational content of theory cannot be separated from its purely theoretical content, as measuring instruments themselves are constructed and understood on the basis of physical theories. According to realists, accepting the observational part implies accepting the whole theory. However, the realist posture encounters many challenges due to the possible ’Underdetermination of theories’. The key point is that it exists the possibility to have a number of theories or interpretations that experience the same empirical success. That’s why a realist commitment is about defining an unambiguous interpretation of the theories which, as already mentioned, in the quantum world and even more so in QFT, is challenging. Let’s switch to antirealism. It may take various forms as noted in [8]:

> ”The term “antirealism” (or “anti-realism”) encompasses any position that is opposed to realism along one or more of the dimensions [...]: the metaphysical commitment to the existence of a mind-independent reality; the semantic

> commitment to interpret theories literally or at face value; and the epistemological commitment to regard theories as furnishing knowledge of both observables and unobservables. As a result, and as one might expect, there are many different ways to be an antirealist, and many different positions qualify as antirealism."

As Chakravartty notices, a popular criticism to the metaphysical commitment is related to the belief that our experience of the world cannot be mind-independent, even assuming that its existence may be so. The second commitment is about literally interpreting the theories, that is explicitly contrasted by the instrumentalist posture, for which theories are mere tools used to make predictions. The third is related to the belief that scientific investigation can provide knowledge of the world, and clearly it is opposed by various forms of scepticism and empiricism. Let us briefly try to deal with these objections. Following Redhead in [22]:

> "[instrumentalism sees] theories in physics as mathematical 'black boxes' linking empirical input with empirical output."

Adopting this position implies considering metaphysical questions as pointless. However, this is not the only alternative to realism. Indeed, Van Frassen in [32] formalised a kind of empiricism called constructive empiricism, that can be introduced as follows:

> "Science aims to give us theories which are empirically adequate; and acceptance of a theory involves as belief only that it is empirically adequate. [...] a theory is empirically adequate exactly if what it says about the observable things and events in this world, is true - exactly if it "saves the phenomena"."

Simplifying, he adopts a form of realism towards the realm of the observable and agnosticism towards the unobservable. Another popular form of antirealism is the historicist and social constructivist reading. This posture is adopted when one wants to locate a particular theory in the historical period in which it was constructed, regarding science on a par with other cultural movements. Thus, the focus of this reading is not so much to establish the truth of certain theoretical claims, but to analyse the social composition of the scientific community, how scientific conceptual revolutions are linked to culture, to analyse the psychology of individuals and groups in the scientific community, and to investigate how economic arrangements are connected with research traditions. Clearly, in this framework, it is possible to stand in specific viewpoints. I will just mention Pickering's work. The author in [21], while presenting the history of High Energy Physics, specifically considering the transition from old physics to new physics (where quarks and gauge theories were established), severely attacks what he calls the scientist's account. He contrasts the idea that theories are compelled by experimental facts, arguing that scientific judgments are always present. He sees members of scientific communities as agents and world-builders of the new physics, rather than mere observers. Using his words:

> “Judgements [are related to] whether particular observation reports should be accepted as facts or rejected, and to whether particular theories should be regarded as acceptable candidate explanations of a given range of observations. I noted that the scientist’s account factored such judgments out of consideration by adopting a stance of retrospective realism. Having decided upon how the natural world really is, those data which supported this image were granted the status of natural facts, and the theories which constituted the chosen world-view were presented as intrinsically plausible.”

According to the author, these scientific judgments present a social coherence, based on the shared resources. Throughout the history of HEP, he found research traditions in which experimental facts and theories were in a symbiotic relationship of mutual support. So, decisions had to sustain these research traditions. This very short sketch clearly frames the conflict with the realist view of theories.

1.4 Interpretations of Quantum Mechanics

Let us briefly discuss the interpretations of QM at play, and do so for two reasons. The first is that, since QFT is an evolution of the standard non-relativistic QM, it inherits its interpretation problems. The second reason is that I discussed them with physicists and to understand the answers it makes sense to cite them. Furthermore, we will see how postures towards reality can manifest themselves in the construction of interpretations. However, this section is not intended to be exhaustive, but only to provide insights into the various interpretations, as the main purpose of this work is to focus on QFT. As I mentioned in 1.2, one interpretative challenge of QM is connected to the quantum state. It is ideally possible to interpret a quantum superimposed state in two ways, of which you can find a detailed description in [34]. According to the indefinite description approach, the system is in a state with indefinite, delocalised, but known properties. On the other hand, according to probability description, the system is in a state that is definite, localised, but its properties are unknown. The key point is that if we consider both the interference and the outcome of a measurement, we see that it is possible to adopt the indefinite description for the former and the probability description for the latter. And the two processes, as well as the two interpretations, are apparently incompatible. An instrumentalist would solve this puzzle as follows, quoting Wallace’s words in [34]:

> ”[...] hold on to the idea that the quantum state is understood in terms of the probabilities of various measurement outcomes, but abandon the idea that those measurement outcomes are reports on the preexisting properties that the system has. [...] Questions about what the system is doing when we don’t measure it [...] are set aside [...] as meaningless.”

This approach began to develop since 1920 and Bohr and Heinsenberg "were to varying degrees sympathetic". Wallace replies with the objection already illustrated, i.e. it is not possible to cleanly or unambiguously separate the observational part of theories from the purely theoretical side, a premise on which instrumentalism is based. Other interpretative possibilities consist in modifying the theory, trying to "justify" why we do not see the superposition or adding new postulates. Paul Dirac, for instance, proposed to add the wave function collapse postulate, for which when a measurement is performed the previously superimposed state collapses into a definite one. As Wallace notes, despite "this way of presenting quantum mechanics is still found in introductory textbooks [...] its basic problem is that it treats 'measurement' as a primitive, unanalysed notion." Others (as Ghirardi-Rimini-Weber) proposed a dynamical collapse, by introducing physical mechanisms for it to occur, even before measurement. Another possibility that has been pursued is adding hidden-variables, which, if known, would give reason for the non-superposition of states when a measurement is performed. A famous one is Bohmian mechanics. The problem with these two interpretations, according to Wallace, is that "[...] neither class of theories- nor any other approach that relies on modifying quantum theory- has succeeded in reproducing quantum theory's predictions outside a relatively narrow range of applications." I will avoid going further into the discussion and move on to briefly illustrate the Everett interpretation. The key point stands on avoiding to change the theory and taking seriously the unitary evolution of quantum systems. This implies the denial of the wave function collapse. In this framework, both the state of the system and that of the observer are treated as quantum. Through measurement, which is an interaction like any other, they become entangled. Then they evolve in a superimposed joint state. Wallace in [34] asserts that:

> "[...] if we take quantum mechanics literally and realistically, the world we live in is one of the innumerably greater plurality- an emergent multiverse- all existing in parallel with one another, each one constantly branching from the others."

Although its implication is something striking, this strategy is "the most conservative [...] a branching reality is a consequence of the quantum formalism itself, not some additional postulate layered on top of it." In [33], he specifies that his choice is the version of the Everett interpretation based on decoherence, which is the process that explains the mechanism by which the classical world emerges. The interpretations just cited (Everett and modify-the-theory strategies) are realist readings of QM. Clearly, there exist others, i.e. non-realist ones, which Wallace refers to as non-representational [33], since the key point is that "the quantum state does not play a representational role". Among these, he mentions the various Copenhagen interpretations, whose position with respect to realism/instrumentalism dispute is still discussed, as noted in [12] regarding Bohr's philosophy. However, in this context it is sufficient to know that when one talks about Copenhagen interpretations, one refers to Bohr's Correspondence rule (the use of classical concepts that are extended to the quantum world), to Complementarity (as an experimental and epistemological position) and to the Born rule (his interpretation of the wave function as related to the probability amplitude). Other non-representational interpretative strategies that Wallace cites are QBism and Healey's quantum pragmatism, that I will not explain here [16]. Clearly, there are other possibilities, such as Relational QM, simply explained in [24].

1.5 QFT: Why and What it is

I have already outlined that QFT is a framework theory. Mainly, it led to the development of the Standard Model of particle physics, and it is used in Condensed Matter Physics to describe extended bodies. QFT in flat space-time is a Poincaré-invariant quantum theory. Physicists describe it as emerged from the need to address a marriage between QM and special relativity, as Zee in [40] refers to it[2]. And this occurred because QFT has allowed to describe processes in which the particle number is not conserved, as SR (through energy-mass equivalence) and QM (through uncertainty principle) require. Moreover, it treats space and time on the same footing (as labels rather than dynamical variables), and it has solved the asymmetry between the description of the photon (already treated as a field) and all the other particles. Additionally, the particle indistinguishability comes naturally from the theory, while in QM it had to be added by hand. Often, one refers to QFT as the second quantization; however, this is misleading, because it is not the wavefunction to have been quantised. Weinberg in [38] suggests banning this expression from physics. Introducing QFT is not a straightforward process, both because of its formal and conceptual complexity and because, as already said in previous sections, at least two paths can be followed. Historically, Canonical Quantization procedure was built first and then Path Integrals were constructed. These two procedures are equivalent and complementary, meaning that there are results clearer in the former and others more intuitive in the latter. On the other hand, Algebraic QFT is an attempt to formulate it in a mathematically rigorous way. Let's elaborate more on the necessity of QFT and its status. Srednicki in [29] makes a very clear reconstruction of the attempts to build a quantum theory for relativistic particles. Without going into detail, what we are interested in is the following reasoning. What Srednicki illustrates is that while trying to use Schrödinger equation

$$i\hbar\frac{\partial}{\partial t}\left|\psi,t\right\rangle = H\left|\psi,t\right\rangle \tag{1.1}$$

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[2] However, as noted in [17], there exists a relativistic version of QM (with several problems) and a non-relativistic version of QFT.

for the time evolution of a relativistic particle, many difficulties were encountered. First of all, using the relativistic Hamiltonian we obtain the following equation

$$i\hbar\frac{\partial}{\partial t}\psi(\mathbf{x},t) = +\sqrt{-\hbar^2c^2\nabla^2 + m^2c^4}\psi(\mathbf{x},t). \tag{1.2}$$

It does not seem relativistic because it is asymmetrical with respect to space and time and, expanding the square root in powers of ∇^2, it is not local in space. Moreover, it can be seen that with this Hamiltonian, causality is violated, since the probability for a particle to travel outside the light cone is non-zero. Then, to make it relativistic, one can try to square the differential operators in each side. You will obtain the Klein Gordon equation

$$-\hbar^2\frac{\partial^2}{\partial t^2}\psi(\mathbf{x},t) = (-\hbar^2c^2\nabla^2 + m^2c^4)\psi(\mathbf{x},t), \tag{1.3}$$

which, interpreted as an equation for the wave function of a relativistic particle is consistent with relativity, whereas it is inconsistent with quantum mechanics, since it can be seen that probability is not conserved. The problem lies in the fact that it is a second-order equation, unlike Schrödinger's. Dirac tryed to solve this trouble for spin-one-half relativistic particles, by writing an equation of this form

$$i\hbar\frac{\partial}{\partial t}\psi_a(x) = (-i\hbar c(\alpha^j)_{ab}\partial_j + mc^2(\beta)_{ab})\psi_b(x), \tag{1.4}$$

where $a = 1, 2$ is the label for the spin. To obtain the correct energy-momentum relationship, the matrices α^j and β must have certain properties. Without going into detail, it turns out that they must be 4×4 matrices. Therefore, there's the problem to interpret the two extra spin states. Furthermore, acting on momentum eigenstates, the Hamiltonian becomes $H = c\alpha \cdot \mathbf{p} + mc^2\beta$, whose trace is zero. This implies that there are states with negative energies, i.e. there is no ground state. Dirac proposed the existence of a Dirac sea of electrons, meaning a set of negative energy states already occupied. Exciting one of them would leave a hole with positive charge and energy. This explanation hinted at the possibility of the existence of antiparticles. The key point that Srednicki outlines is that trying to write a theory for a single relativistic particle leads to a theory that requires an infinite number of particles. And there is another issue that cannot be ignored. Let us recall the axioms of QM.

> The state of the system is represented by a vector in Hilbert space.
> Observables are represented by hermitian operators.
> The measurement of an observable yields one of its eigenvalues as the result.

There is a subtlety we are not considering with regard to the axiom on observables. Time is not an observable in QM, while position is so. Srednicki points out that

> "[...] it is not surprising that we are having trouble incorporating a symmetry [Lorentz group] that mixes them up. So, what are we to do? In principle, the problem could be an intractable one: it might be *impossible* to combine quantum mechanics and relativity. [...] This however, turns out not to be the case. We can solve our problem."

One solution is QFT itself, in which, as we have just said, space and time are labels on operators, the quantum fields. Another viable option is to promote time to an operator, a procedure that is implemented in the framework of worldlines. Srednicki reminds us that "one of the advantages of considering different formalism is that they may suggest different directions for generalizations". String theory, indeed, is a generalization of this procedure. Fortunately, "any relativistic quantum physics that can be treated in one formalism can also be treated in the other". Weinberg developed his own way of introducing the theory. In [38] he asserts that:

> "In the course of teaching quantum field theory, I developed a rationale for it, which very briefly is that it is the only way of satisfying the principles of Lorentz invariance plus quantum mechanics plus one other principle. [. . .] The other principle that has to be added is the cluster decomposition principle, which requires that distant experiments give uncorrelated results."

In this way, fields, particles, and antiparticles are direct consequences of these assumptions, and the same is true for locality and causality. He states that a formalism cannot be taught without being motivated, since the purpose of physics is not only to describe the world. Therefore, it must explain why the world is made the way it is, by embracing a form of realism, I would add. However, he realizes the impossibility of establishing such a strong necessity relation between the assumptions and QFT, because string theory can represent a counterexample to that. He solves the question as follows:

> "[...] although you can not argue that relativity plus quantum mechanics plus cluster decomposition necessarily leads only to quantum field theory, it is very likely that any quantum theory that at sufficiently low energy and large distances looks Lorentz invariant and satisfies cluster decomposition principle will also at sufficiently low energy *looks* like a quantum field theory. [...] This leads us to the idea of effective field theories."

His key point here is that QFT (and its concrete theories) should not be seen as final or fundamental, whereas it should be thought of as a low-energy approximation to a deeper theory. You can find discussions of this kind in [36]. Many physicists, as Weinberg himself, believe that string theory could be the suitable and the correct candidate for this role. However, beyond any underlying theory, the issue of effective field theories comes from the renormalization process. When QFT was developed, it was soon realised that it encountered problems with infinities. This occurred because it was considered valid for any energy scale or length scale. Through the renormalisation process, it has been possible to write quantum field theories whose couplings depend on the energy scale. As explained in [17]:

> "The basic idea of this new story about renormalization is that the influences of higher energy processes are localizable in a few structural properties which can be captured by an adjustment of parameters."

1.6 Effective field theories and the Final Theory

This modern view of QFT and its concrete theories as EFT has led to reconsider the notion of fundamentality and may affect the development of physical theories themselves and their interpretations. As Wallace notices in [35]:

> "[...] philosophy of physics proceeds by taking a theory like classical or quantum particle mechanics, or classical general relativity, and studying it under the fiction that it is fundamental. [...] It is a remarkable irony that the Standard Model at one and the same time is the nearest we have ever come to a Theory of Everything, and is uninterpretable even in fiction as an exact description of the world. It is further irony that the theory itself tells us that it is compatible with an indefinitely large range of ways in which the deeper-level physics might be specified."

His conclusion is that:

> "Quantum field theory is a reminder to philosophers that physics, like other sciences, is hardly ever in the business of formulating theories that purport to describe the world on all scales. They who wish to learn ontology from our best science, in the era of effective field theories, have two choices: recognise that deep and interesting metaphysical questions come up at all length scales in physics and are not confined to the 'fundamental', or remain silent and wait, and hope, for a truly fundamental theory in the physics that is to come."

Let us say one further thing. The presence of effective theories does not in itself presuppose the existence of a final theory underlying them. It is somewhat a philosophical position to claim that a theory of everything can be constructed. Indeed, in [3], you can find some discussions in this regard. For some physicists and philosophers, the idea of a final theory appears more mentally exciting. According to Redhead [22]:

> "[...] the regulative ideal of an ultimate theory of everything remains a powerful aesthetic ingredient motivating the exercise of the greatest intellectual ingenuity in the pursuit of what may admittedly, in itself, be an illusory goal. But that after all is the proper function of regulative ideas."

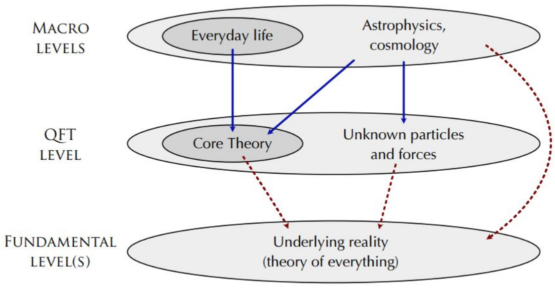
Instead, for some others as Cao [4]:

> "The vision of effective field theories is not meant to take a purely phenomenological approach. Rather, it is fully compatible with a pluralist view of fundamentality".

And pursuing the construction of a final theory:

> "closes our eyes to any new physics, any future development, except for some not so exciting applications".

Figure 1.1: Levels of reality



To understand the status of QFT in relation to what we know of the physical world, I report the Figure 1.1 provided by Carroll in [6]. Without addressing the subject of his discussion- that concerns the fact that, according to him, it is reasonable to think that the Laws of Physics Underlying Everyday Life are completely known- I find the picture indeed clarifying. As the author explains the picture, levels of reality are arranged vertically. The QFT level consists in the Core Theory of the SM, the gravitational interaction in the weak field limit and other possible unknown particles and forces. Below, other possible levels are set, which we may or may not consider fundamental, while above the physics of Everyday life and Astrophysics and Cosmology lie. The blue arrows represent the known relations, while the dashed ones are "plausible but unknown". His claim is that it is reasonable to think that there are not relations between the physics of Everyday life and unknown physics, which does not concern our discussion. However, beyond the lines and his specific claim, what we are interesting in is the fact that this kind of reasoning comes from the effective nature of QFT.

Chapter 2

Focus on QFT

As noted in [17], towards the end of the 1980s, philosophical reflection previously focused on QM turned its attention to QFT, on the grounds of the great empirical success of the SM. The enormous predictive power and experimental agreement alone is enough to build a philosophical reflection on the framework, plus there is the hope that a discussion on quantum fields will bring new insight into the problems associated with standard QM. We will connect to the previous Chapter by elaborating on some discussions already mentioned and then explore some more. As already said, one of the interpretative challenges that QFT sets in front of us is that of the relationship between particles and fields. The discussion can be approached from different perspectives and starting from different premises. Clearly, it has to do with formulations, postures in regard to theories and experimental observations, and depends on the type of analysis one wants to carry out. We will have the opportunity to note the similarities and differences with which physicists and philosophers ask questions, what they consider crucial and the line of reasoning that emerges. We will need to briefly introduce the formal construction so that the conceptual reflection can be connected to the theory. As mentioned earlier, from a physical point of view different formulations provide several perspectives which are often intertwined. They are also beneficial in the direction of building new physics and tackling new problems, whereas from the philosophical and especially ontological point of view (for those epistemological currents for which it makes sense to ask questions of this kind), it is problematic. And this is so, because a criterion must be established through which to choose a formulation and draw the desired ontological conclusions from that, which can vary greatly between different formalisms. This is precisely the case with QFT. I have already said that a division can be made between heuristic or prediction oriented and axiomatic QFT, where the former refers to Canonical quantization and Path integrals strategies and the latter to AQFT. I will mainly refer to heuristic QFT, while the idea of AQFT and the discussions involved will only be mentioned. We will discuss particles, paths to build the framework, interactions, renormalisation and open problems.

2.1 Canonical Quantization and Particle Interpretation

Let us start with Canonical quantization. It acts on classical fields and on their conjugate momenta promoting them to operator-valued functions of the space-time[1]. For the sake of simplicity, we will only deal with the real scalar field. This section is derived from Tong's lecture notes [31]. Before going into detail, let's review the quantum version of the simple harmonic oscillator. Its quantum Hamiltonian is:

$$H = \frac{1}{2}p^2 + \frac{1}{2}\omega^2 q^2, \tag{2.1}$$

where $[q, p] = i$. One can define annihilation a and creation $a^\dagger$ operators as:

$$a = \sqrt{\frac{\omega}{2}}q + \frac{i}{\sqrt{2\omega}}p \qquad a^\dagger = \sqrt{\frac{\omega}{2}}q - \frac{i}{\sqrt{2w}}p, \tag{2.2}$$

and obtain:

$$[a, a^\dagger] = 1 \qquad H = \omega(a^\dagger a + \frac{1}{2}). \tag{2.3}$$

It's straightforward to show that:

$$[H, a^\dagger] = \omega a^\dagger \qquad [H, a] = -\omega a. \tag{2.4}$$

The creation and annihilation operators allow you to shift between energy eigenstates. To put it better, they create or destroy quanta. Indeed, if $|E\rangle$ is an eigenstate of the Hamiltonian such that $H|E\rangle = E|E\rangle$, then:

$$Ha^\dagger |E\rangle = (E + \omega)a^\dagger |E\rangle \qquad Ha|E\rangle = (E - \omega)a|E\rangle. \tag{2.5}$$

The ground state $|0\rangle$ is defined as $a|0\rangle = 0$, and the excited states look like $|n\rangle = (a^\dagger)^n |0\rangle$, ignoring normalization. Now, let's consider a real scalar field $\varphi(x)$ in classical field theory and its conjugate momentum, $\pi(x)$. The corresponding free Lagrangian density is:

$$\mathcal{L} = \frac{1}{2}\eta^{\mu\nu}\partial_\mu\varphi(x)\partial_\nu\varphi(x) - \frac{1}{2}m^2\varphi^2, \tag{2.6}$$

where $\eta^{\mu\nu} = \eta_{\mu\nu} = diag(1, -1, -1, -1)$ is Minkowski metric. It can be obtained by taking the continuum limit of the Lagrangian of N coupled harmonic oscillators. This means that we can think of this scalar field as composed of an infinite number of harmonic oscillators, one for each point of the space-time. To have a clue, you can look up [40]. However, Zee tells us the treatment from harmonic oscillators is carried out for

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[1] Actually, they are operator-valued distributions.

pedagogical reasons, while "nobody believes that the fields observed in Nature, such as the meson field or the photon field, are actually constructed of point masses tied together with springs. The modern view [...] is that we start with the desidered symmetry, say Lorentz invariance if we want to do particle physics, decide on the fields we want by specifying how they transform under the symmetry [...] and then write down the action involving no more than two time derivatives". Having said this, let us move on. The Euler-Lagrange equation will be:

$$(\partial^\mu \partial_\mu + m^2)\varphi(x) = 0, \tag{2.7}$$

that is known as Klein-Gordon equation, already mentioned in the previous Chapter[2]. One can define the conjugate momentum as follows, as in classical mechanics, in order to switch to the Hamiltonian formalism:

$$\pi(x) = \frac{\partial \mathcal{L}}{\partial \dot{\varphi}}. \tag{2.8}$$

To quantize this field, we need to quantize each harmonic oscillator, labelled by $\mathbf{p}$. The general solution in Heisenberg picture is the following:

$$\varphi(x) = \int \frac{d^3p}{(2\pi)^3\sqrt{2\omega_{\mathbf{p}}}}[a(\mathbf{p})e^{-ipx} + a(\mathbf{p})^\dagger e^{ipx}], \tag{2.9}$$

with $\omega^2 = \mathbf{p}^2 + m^2$ and $px = \omega t - \mathbf{p}\cdot\mathbf{x}$. Therefore, $\varphi(x)$, as well as $\pi(x)$, is an operator-valued distribution of the space-time, expressed in terms of creation and annihilation operators. Additionally, let's stress that $\mathbf{x}$ and t are just labels, unlike quantum mechanics in which position is an observable. This symmetry allows to get a glimpse of Poincaré invariance. We impose the following equal-time commutation relations, as in quantum mechanics:

$$\begin{aligned}
&[\varphi(\mathbf{x},t), \varphi(\mathbf{x}',t)] = 0\\
&[\pi(\mathbf{x},t), \pi(\mathbf{x}',t)] = 0\\
&[\varphi(\mathbf{x},t), \pi(\mathbf{x}',t)] = i\delta^{(3)}(\mathbf{x}-\mathbf{x}').
\end{aligned} \tag{2.10}$$

From these, one can obtain the corresponding relations between $a(\mathbf{p})$ and $a(\mathbf{p})^\dagger$:

$$\begin{aligned}
&[a(\mathbf{p}), a(\mathbf{p}')] = 0\\
&[a(\mathbf{p})^\dagger, a(\mathbf{p}')^\dagger] = 0\\
&[a(\mathbf{p}), a(\mathbf{p}')^\dagger] = (2\pi)^3\delta^{(3)}(\mathbf{p}-\mathbf{p}').
\end{aligned} \tag{2.11}$$

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[2] The difference between the two equations, apart from the relativistic notation, is that the metric is considered with different signatures.

Through a Legendre transformation, you can obtain the corresponding Hamiltonian density:

$$H = \int \frac{d^3p}{(2\pi)^3} \omega_{\mathbf{p}} (a(\mathbf{p})^\dagger a(\mathbf{p}) + \frac{1}{2}(2\pi)^3 \delta^{(3)}(0)). \tag{2.12}$$

As for the simple harmonic oscillator, vacuum is defined as $a(\mathbf{p}) |0\rangle = 0 \ \forall \mathbf{p}$. Its energy is infinite:

$$H |0\rangle = (\int d^3p \frac{1}{2} \omega_{\mathbf{p}} \delta^{(3)}(0)) |0\rangle = \infty |0\rangle . \tag{2.13}$$

The theory already presents two divergences, which give two different troubles. The first is known as *infra-red divergence* and it is due to the fact that we are considering a space that is infinitely large. Although, if you compute the energy density, you can solve the problem. The other one is known as *ultra-violet divergence* and is due to the fact that we are integrating over all possible $\mathbf{p}$, so we are assuming that the theory is valid for all energies or length scales. Therefore, we impose a cut-off, below which we consider the theory to be valid[3]. An equivalent way to obtain this result is by considering the normal ordering $: H :$ which implies placing $a(\mathbf{p})$ on the right. The Hamiltonian density will be:

$$: H := \int \frac{d^3p}{(2\pi)^3} \omega_{\mathbf{p}} a(\mathbf{p})^\dagger a(\mathbf{p}). \tag{2.14}$$

So far, we have quantized a scalar field. Instead, to quantize a spinor field (Dirac theory), one must choose anticommutators rather than commutators. This is a general result, called Spin-Statistics theorem. It states that for integer spin particles (bosons), you need to use commutators to quantize, while for half-integer spin particles (fermions), you must use anticommutators in order to obtain a non-trivial Lagrangian density. The use of commutators or anticommutators automatically gives the correct statistics for bosons and fermions, namely Bose-Einstein and Fermi-Dirac. See [29]. Therefore, Pauli's principle can be naturally recovered. As I mentioned before, this scalar quantum field (as all the others in flat space-time) has a global symmetry represented by the Poincaré group, a symmetry of space-time. It is a group of 10 parameters, which gives 10 conserved currents (and 10 corresponding conserved quantities), due to Noether's theorem. Translational invariance gives the conservation of the total energy and the total four-momentum of the field, while the rotation invariance gives the conservation of the total angular momentum.

2.1.1 Particles

Time has come to focus on the particle interpretation. As for the simple harmonic oscillator, we have:

$$[H, a(\mathbf{p})^\dagger] = \omega(\mathbf{p}) a(\mathbf{p})^\dagger \qquad [H, a(\mathbf{p})] = -\omega(\mathbf{p}) a(\mathbf{p}). \tag{2.15}$$

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[3] As mentioned in the previous Chapter, it is from imposition of the cut-off that effective field theories arise.

Therefore, we can construct energy eigenvalues $|\mathbf{p}\rangle = a(\mathbf{p})^\dagger |0\rangle$ such that:

$$H |\mathbf{p}\rangle = \omega(\mathbf{p}) |\mathbf{p}\rangle \qquad \omega(\mathbf{p})^2 = \mathbf{p}^2 + m^2, \tag{2.16}$$

that is the relativistic dispersion relation or energy momentum relation. Thus, we interpret it as a 1-particle state, with 3-momentum $\mathbf{p}$ and mass m. This particle is not localised in space, it is, in a sense, a global concept. As I alluded to earlier, the field operator, as well as the creation and annhilation operators, is an operator-valued distribution, i.e. it is not well defined since it does not produce normalizable states. However, from those operators one can construct wavepackets, such as $|\varphi\rangle = \int \frac{d^3p}{(2\pi)^3} e^{-i\mathbf{p}\cdot\mathbf{x}} e^{\frac{-\mathbf{p}^2}{2m^2}} |\mathbf{p}\rangle$, that are partially localised in both position and momentum space. As I said before, the invariance under spatial translations gives a conserved charge that, after quantization, becomes an operator with this form, in normal ordering:

$$\mathbf{P} = \int \frac{d^3p}{(2\pi)^3} \mathbf{p}(a(\mathbf{p})^\dagger a(\mathbf{p})) \qquad \mathbf{P} |\mathbf{p}\rangle = \mathbf{p} |\mathbf{p}\rangle . \tag{2.17}$$

The invariance under rotations gives the conservation of the total angular momentum, that is interpreted as the spin. If you apply it to $|\mathbf{p} = 0\rangle$, it gives zero, meaning that the scalar field is spinless. By acting n times on the vacuum state with the creation operator, you can create a multiparticle state like this $|\mathbf{p}_1, ..., \mathbf{p}_n\rangle = a(\mathbf{p}_1)^\dagger ... a(\mathbf{p}_n)^\dagger |0\rangle$. Since the creation operators commute, this state is symmetric under the exchange of any two particles. Hence, the particles are bosons, as we expected. These states create the Fock space, that is a generalization of the Hilbert space which encodes the possibility of having a number of particles that can vary. It is possible to define the total number operator, that counts these particles as:

$$N = \int \frac{d^3p}{(2\pi)^3} a(\mathbf{p})^\dagger a(\mathbf{p}) \qquad N = |\mathbf{p}_1, ..., \mathbf{p}_n\rangle = n |\mathbf{p}_1, ..., \mathbf{p}_n\rangle . \tag{2.18}$$

In free theories the number of particles is conserved because $[N, H] = 0$, whereas this is not true for interacting theories. However, we have developed the adequate formalism to be able to include this possibility, that is the Fock space. Its formal definition is:

$$\mathcal{F} = \mathcal{H}_1 \oplus \mathcal{H}_2 \oplus ... \oplus \mathcal{H}_n \oplus ... \tag{2.19}$$

where $\mathcal{H}_n = \mathcal{H}_1 \otimes ... \otimes \mathcal{H}_1$, n times and represents the Hilbert space where each of these n bosons can have any momentum. For now, we are considering a real scalar field whose excitations do not interact. Before adding self-interactions, let us pause for a moment to reflect.

2.2 What is meant by a particle?

The particle notion has transformed radically throughout the history of physics. To make a long story short, it has gone from being considered a point mass to becoming a quantum field excitation, as we have seen in 2.1.1. Although its nature and properties depend on the physical theory considered, we use this notion to communicate both between physicists and with the non-expert audience. As I have already said, Teller in [30] does an interpretative work which is part of a very interesting and involving debate. Before going into the subject, I would like to explain what this type of reasoning is for. In the previous Chapter, greatly simplifying, I said that physicists are in the business of describing physical systems and their properties, whereas philosophers are interested in understanding what makes an object such, in distinguishing it from its properties and similar. I find this a reasonable 'division' of tasks, although clearly it is less clear-cut than this. Since, in the previous section, we have briefly explored the formal construction in a simple but paradigmatic case, time has come to understand in what terms the philosophical reasoning on QFT is developed. Philosophers attempt to apply notions and categories that are typical of reasoning about the world we experience (which we can improperly call classical), to quantum objects, in order to see if it can work and if so how to adapt, reconstruct notions. This means that the task is to understand how the objects of QFT look like in relation to different possible objects of experience. With regard to quantum particles, there is much debate with respect to what it means that they are not individuals (as they are indistinguishable) and how to define them in the quantum framework. For an interesting and detailed discussion on this, see [7]. Another ongoing debate is whether to consider particles or fields as the basic ontology. We will try to understand the arguments in favour of one or the other.

2.2.1 Particles VS Quanta

One of the notions debated in regard to quantum particles is that of "primitive thisness". Simplifying much, it is that "something" which provides identity to an object, independently of its properties. Teller defines this notion as a pretheoretical conception that we have in mind in some sense. The question that arises is: does it make sense to think that quantum particles are equipped with that? A different matter is to consider a quantum particle as a bearer of properties, that certainly is. His claim is that "quantal facts give good reasons for rejecting any aspect of quantum entities which might be thought to do the job of primitive thisness". This view is derived from Bose-Einstein and Fermi-Dirac statistics and it is known for decades. For instance, in 1950 Schrödinger in [26] asserted that:

> "the elementary particle is not an individual; it cannot be identified, it lacks "sameness." The fact is known to every physicist, but is rarely given any

> prominence in surveys readable by nonspecialists. [...] The implication, far from obvious, is that the unsuspected epithet "this" is not quite properly applicable to, say, an electron, except with caution, in a restricted sense, and sometimes not at all."

I would like to stress here the fact that this lack of 'thisness' of quantum particles has led Teller to identify two formalisms (to construct a state consisting of two or more quantum particles) and to prefer one of them, since, in his view, it is more in line with this new notion of particle. The first one is the Labeled Tensor Product Hilbert Space Formalism (LTPHSF). Very briefly, when one considers a system composed of two particles, it is possible to build the joint space of states as a tensor product of two Hilbert spaces (each associated to one quantum), $\mathcal{H}(1) \otimes \mathcal{H}(2)$, where the two labels indicate the particle considered and, in principle, could do the job for primitive thisness. Therefore, if a and b are two eigenvalues of a certain observable O, "primitive thisness permits us to interpret $|a(1)\rangle\,|b(2)\rangle$ in $\mathcal{H}(1) \otimes \mathcal{H}(2)$ as representing a state in which particle labeled '1' has eigenvalue a for O and a particle labeled '2' has eigenvalue b for O". With this interpretation in mind and in the case in which the observable has only two associated eigenvalues, it would be possible to build states as:

$$\begin{gathered} |a(1)\rangle\,|a(2)\rangle \\ |b(1)\rangle\,|b(2)\rangle \\ |a(1)\rangle\,|b(2)\rangle \\ |b(1)\rangle\,|a(2)\rangle \end{gathered} \tag{2.20}$$

These states give rise to the Maxwell-Boltzmann statistic, which works for classical particles. However, the experiments show different statistics for quantum particles. This is because actually $|b(1)\rangle\,|a(2)\rangle$ and $|a(1)\rangle\,|b(2)\rangle$ are indistinguishable and therefore they have to be counted only once. Thus, according to Teller, LTPHSF carries a surplus formal structure, either of uninterpreted labels (giving up primitive thisness) or allowing states to be constructed that do not occur, without providing an explanation. This reasoning leads him to make a distinction between old-fashioned particles (or just particles), which are objects that "can be counted, ordered, and exchanged" and therefore they could be endowed with primitive thisness, and quanta. The latter are those that "can merely be aggregated" and "given an "amount" of quanta, there is no intelligibility to reordering or reassigning them while keeping fixed the property combinations that occur". What they retain of the notion of a particle is discreteness and localizability to a certain extent. So his proposal is, on one hand, to use a new name when referring to quantum particles and, on the other hand, to prefer the Fock space formalism to the LTPHSF. Teller notes that, often, physicists propose the following strategy: "for n Bosons start with the LTPHSF for n Bosons, and then restrict attention to the subspace of symmetric states. (Analogous remarks go for Fermions and the antisymmetric subspace)." He concludes by saying that this procedure is similar to leaving labels uninterpreted and therefore does not believe it is a solution.

Fock space formalism

Let us now return to the Fock space for a moment, following Teller. Let us consider an Hilbert space for one quantum $\mathcal{H}_1$, whose basis is given by a set of discrete eigenstates of $|a_1\rangle, |a_2\rangle, |a_3\rangle, ...$ of an observable A. The basis $|a_i\rangle$ can be written also as $|0, ..., 1, 0, ...\rangle$, where 1 is in the i-th position. One can interpret it as one quantum with the i-th eigenvalue a_i. The general case will be $|n_1, n_2, ..., n_i, ..., n_k\rangle_A$. If we introduce a collection of number operators N_i^A, we will have $N_i^A |n_1, n_2, ..., n_i, ..., n_k\rangle_A = n_i |n_1, n_2, ..., n_i, ..., n_k\rangle_A$, where all the n_i are called occupation numbers. The vacuum state is defined as $|0\rangle = |0, ..., 0\rangle$ and it is the state without quanta. Therefore, a Fock space is a space spanned by the vectors $|n_1, n_2, ..., n_i, ..., n_k\rangle_A$. As said before, it can be also built as:

$$\mathcal{F} = \mathcal{H}_0 \oplus \mathcal{H}_1 \oplus \mathcal{H}_2 \oplus ... \oplus \mathcal{H}_n \oplus ... \tag{2.21}$$

where $\mathcal{H}_n = \mathcal{H}_1 \otimes ... \otimes \mathcal{H}_1$, n times. No labels appear in this formalism, so it is easier to dispense with primitive thisness. In addition, according to Teller, this formalism allows superimposed states to be interpreted more naturally. This is because it "provides for [...] superpositions of states with different numbers ("amounts") of aggregated quanta". And within this formalism, "an indefinite-number state [can be viewed as] the presence of a property that does not involve any already occurring particles but does involve the propensity for one or another definite number of particles, corresponding to the superposition". Clearly, both bosons and fermions can be described with this formalism. If for bosons the occupation numbers can be any, for fermions one must impose $n_i = 0, 1$ for each i. Teller admits that for fermions this notion of quanta is more troubling. The objection he raises is: "given the intuitive picture that I have suggested, one expects that quanta of one kind can be aggregated without limit. Why, for Fermions, is there a limit of one to a kind? I have no answer to suggest".

Field- and non-field-theoretic descriptions

As already guessed from the previous sections, it is possible to construct the entire Fock space from the vacuum state by making the creation operators act on it. According to Teller, this construction from quanta represents one of the two ways to construct QFT, where the other would be the one set out in section 2.1, starting from the classical field, which he calls field-theoretic. Referring to the fact that historically the 'second quantisation' procedure was developed first, he says that "many have tended to see the subject matter as intrinsically "field-theoretic". In particular, inasmuch as the subject is seen as that of a "quantized field", many tend to think of the quanta as "quantized field excitations". The existence of a non-field theoretic alternative [...] shows that a field-theoretic perspective provides only one way of thinking about the subject.” Let us examine some of the objections that can be raised.

2.2.2 Objections

One objection I would like to make is that I find the discussion about the primitive thisness far removed from today’s physicists’ thinking. Decades after the formalisation of quantum statistics, I think that physicists (at least those who have been dealing with the theory for a while), have no problem with the question of indistinguishability, nor with the fact that particles cannot be considered individuals. In some sense Teller agrees with me, as he states that ”I know that some, perhaps many, readers will have found my talk about primitive thisness abstruse, even silly, supposing themselves never to have been caught up in such woolly-headed metaphysics.” However he notes that there are interpreters who find quantum statistics astonishing. And what he thinks is that, despite they may have internalised the fact that quantum theories don’t allow exact and individuating space-time trajectories, yet by seeing the labels they may be reminded of primitive thisness and thus remain incredulous. I think this may apply to the lay public or even to students approaching quantum theories for the first time. Going forward, one of the objections to the choice of Fock space over LTPHSF is reported by Teller himself. It can be argued that there is a degree of arbitrariness in imposing the commutation or anticommutation relations when constructing the Fock space. This requirement makes it possible to obtain the correct statistics for bosons and fermions, and avoid getting the non-physical joint Hilbert space, i.e. that which contains neither symmetrical nor antisymmetrical states. He replies to his objection by arguing that, despite both formalisms make assumptions without justifying them, LTPHSF is worse because it presents the surplus formal structure. Another objection comes this time from Fleming, a particle physicist [18]. His point is that surplus formal structures are not necessarily something to be discarded and run away from. He mentions gauge fields that could ”qualify as excess formal structure” since they are not all ”directly susceptible of physical interpretation”. And another thing the physicist notes is that, without the alternative of the Fock space, Teller would not be so fierce against LTPHSF. He adds that when speaking of an indefinite number of quanta, the comparison must be made between Fock space and the direct sum of Hilbert space, not the product of Hilbert spaces describing a quantum, which is how we defined Fock space, by the way.

2.3 Fields and Quanta

Let us continue our reflection with regard to the relationship between the concepts of field and particle. The discussion with respect to which, between particle and field to consider the basic ontology, is articulated in various forms. One argument in support of particle ontology is the fact that it is their traces that are actually observed, while arguments in favour of field ontology concern both the construction of QFT from classical field theories and the fact that when considering interacting field theories, QFT in curved space-time and certain phenomena such as the Unruh effect, the notion of particle is not clearly defined. We will explore some of the arguments in favour of both duality and field priority.

2.3.1 Operator-valued field

Let us talk about the quantum field, understood as an operator-valued field. When dealing with this, Teller asserts that, in his opinion, the expression is misleading, since it leads one to think of operators assigned to each space-time point as being values of properties of space-time. To better explain his position, he makes a distinction between determinables and values. The former is "a collection of properties such that anything that can have one of the properties in the collection must have exactly one of the properties", while the latter are "its individual properties [...] represented by mathematical entities such as real numbers and vectors". These notions apply to the classical context and, as it is often the case, he tries to understand what the quantum analogues are. For instance, considering classical fields, one of the determinables could be the collection of all possible field configurations and a specific configuration the corresponding value. In the quantum context, he considers eigenvalues or expectation values as values, and operators as determinables. His point is that one could "think of the association of operators with space-time points as analogous to a classical field configuration", especially in the Heisenberg picture, in which the operator evolves over time. However, "a temporally evolving operator does not represent an evolving value; it represents the pattern of evolution of all values of the quantity in question". Therefore, "the assignment of these "field operators" to the space-time points does not look at all like a classical field configuration", because, as already mentioned, operators are closer to determinables than to values. This implies that the field configurations are given by the expectation values.

2.3.2 Particle-field duality

In Teller's reading of QFT, quanta and fields are in a duality or complementarity relationship, such as wave-particle duality. According to him, this complementarity manifests itself in the non-commutativity between the number operator and operators containing the field. And he gives three very interesting examples. The first is that of coherent states, in which the minimum of uncertainty about the phase requires a maximum of uncertainty about the number of quanta. The second concerns vacuum expectation values for operators consisting of field products. In this case, the number of quanta is known (it is zero), while VEVs have undefined values. Therefore, "$|0\rangle$ is the vacuum, a state in which there are no actually occurring entities. But it is also a state in which there are propensities for values of quantities, such as $\varphi(\mathbf{x}, t)$ and $\varphi(\mathbf{x}, t)^2$, which do not commute with N", the number operator. Finally, he refers to the Rindler quanta. Very briefly and avoiding formal construction, what happens is that the vacuum of an inertial observer may not coincide with the vacuum of a uniformly accelerated observer. Thus, even though an inertial observer does not detect quanta, the accelerated one could. This is called Unruh effect. In line with the equivalence principle, this is also true when considering curved space-times. Teller states that "this fact has caused consternation in the interpretative literature", since, in his opinion, many interpreters keep the primitive thisness. And so "some [...] conclude that the whole particle concept has to be junked and retreat to instrumentalism in the style of Bohr". He clearly resolves this with the notion of quanta, of which there are several types, as Minkowski and Rindler ones. Thus, "a state in which one kind of quantum actually occurs is a state in which there are only propensities for complementary kinds of quanta". In summary, it can be said that this duality implies a mixed ontology.

2.3.3 Objections

Still Fleming in [18] opposes both Teller's view about the operator-valued field, and the view according to which one should not look at QFT as firstly a field theory. He reminds us that operator-valued fields "also determine the eigenvectors that are associated with the eigenvalues and these eigenvectors do change from space-time point to space-time point. So if the determinable is taken as the set of all possible eigenvector associations with a fixed set of eigenvalues then the operator assigned to a space-time point is equivalent to assigning a value of the determinable to that space-time point. To that extent the analogy with a classical field holds." Therefore, he also opposes the identification between values and expectation values since the latter "severely underdetermine the quantum state and its relation to the operator field." In order not to underdetermine one should consider "the expectation values of all possible products of the operator fields with each factor evaluated at arbitrarily chosen space-time points." And this does not reflect the not entirely field-oriented character of the theory, but rather a greater richness of QFT compared to classical field theory. I report in full his position on quantum particles, fields and their relationship.

> "Quantum particles are not classical particles but they are closer to classical particles than to classical fields by virtue of being localizable and, if stable, satisfying an energy-momentum relationship parameterized by a definite rest mass. Quantum fields are not classical fields but they are closer to classical fields than to classical particles by virtue of being distributed over all of space-time and not having a rest mass. Quantum fields and quantum particles are more closely related than classical fields and classical particles. A physical state for a set of interacting quantum fields can be described, at least tem-

> porally asymptotically and perturbatively, as a system of types of quantum particles of temporally variable and indefinite number and other properties. A sensible reason for calling such a system a quantum field system rather than a quantum particle system is that the quantum particles are so much more ephemeral as Teller notes [...]. They come and go like the wind and may not be present in definite numbers at all. The quantum fields, on the other hand, are identified at the outset and remain fixed in type and number throughout. It is they that persist!"

In [18] they can be found other discussions on Teller's book and Teller's response to Fleming as well, which I will avoid reporting.

2.4 Particles and Interactions

Wallace in [35] asserts that for the non-interacting field theories the "reinterpretation of a continuum theory as a multi-particle theory is exact, and indeed serves as an alternative construction of a quantum field theory", as we have already understood from previous discussions, and this allows us to speak of duality. However, as Wallace notes "this talk of duality only really applies in "the (ultimately physically uninteresting) case of theories without interactions." And he goes on with the discussion introducing the notion of 'emergence'.

> "If a small interaction term is introduced to the free Hamiltonian, we expect that the particle analysis of the theory remains approximately valid. The interaction term can then be naturally interpreted as introducing transitions between excited modes of the harmonic oscillators, which under the particle interpretation can be understood as scattering effects between particles, and its effects can be studied by means of perturbation theory. But this analysis will only ever be approximate: as the interaction strength increases, the particle description of the theory becomes less and less valid, and eventually will need to be abandoned altogether as a useful description of the theory. For this reason we would (in my view) do better here to speak of 'emergence' of particles from the continuum theory, rather than of duality. From this perspective, 'particles' are certain excitations of the ground state of the continuum which, to a varyingly good degree of accuracy, approximately instantiate the physics of an interacting-particle theory."

This also has to do with renormalisation, as we will see in the next sections. If you are interested in learning more about why particle ontology cannot be used in interacting theories in a further philosophical reflection, you can consult [13].

2.4.1 The Interaction picture

To add interactions, let us consider small perturbations of the free theory, following Tong in [31]. The Lagrangian density will be:

$$\mathcal{L} = \frac{1}{2}\partial_\mu\varphi\partial^\mu\varphi - \frac{1}{2}m^2\varphi^2 - \sum_{n\geq 3}\frac{\lambda_n}{n!}\varphi^n, \tag{2.22}$$

where λ_n are the coupling constants. To define them as small, a dimensional analysis is required. Implicitly, we have already chosen the natural units $\hbar = c = 1$ and if a physical quantity A has dimension $(mass)^d$, we write $[A] = d$. It is easy to see that $[\lambda_n] = 4 - n$ in 4 dimensions. We can classify the couplings as *relevant* when the mass dimension is positive, *irrelevant* when it is negative and *marginal* when it is zero. In our case, $[\lambda_3] = 1$ is relevant and the dimensionless parameter will be $\frac{\lambda_3}{E}$, where E is the energy scale of the process. Therefore, $\frac{\lambda_3\varphi^3}{3!}$ is a small perturbation at high energies, i.e. for $E \gg \lambda_3$, while it is large at low energies $E \ll \lambda_3$. They are called relevant because they are so at low energies. To ensure that they are small it is enough to take $\lambda_3 \ll m$, since $E > m$. Instead, the marginal will be $[\lambda_4] = 0$, which is small for $\lambda_4 \ll 1$. Lastly, $[\lambda_n] < 0$ for $n \geq 5$ are the irrelevant ones. The dimensionless parameter is $(\lambda_n E^{n-4})$, that is small at low energies and large at high energies. This kind of couplings are associated with non-renormalizable quantum field theories, that are theories incomplete at some energy scale. However, non-renormalisable theories are not to be discarded; they play a role and are used to make predictions. Wallace in [35] gives two examples, the four-fermion theory (direct interaction between neutrinos) and quantum gravity. Both are theories with only non-renormalisable interactions. This explains why interactions are very weak compared to the Compton wavelenght of the weak force mediators (for the four-fermion theory) and compared to the Planck length (for gravity). Tong explains that QFT is simple because at low energies it is sufficient to consider only marginal and relevant couplings (so in our case just two), as the irrelevant ones are precisely such at low energies, which are those that can be tested. This reasoning gives us a hint for understanding EFT. Indeed, let us consider a very high energy scale such as the Planck scale and call it Λ. We could write our dimensionful coupling constants in terms of dimensionless couplings g_n as $\lambda_n = \frac{g_n}{\Lambda^{n-4}}$, since $[\Lambda] = 1$. g_n will be the exact coupling constants at high energies, that are determined by a high energy theory that we do not know about. However they are expected to be of order 1. Thus, for experiments at low energies $E \ll \Lambda$, the interaction terms for $n \gg 5$ will be suppressed by powers of $(\frac{E}{\Lambda})^{n-4}$. For instance, for the energies explored at LHC we have $\frac{E}{M_{pl}} \sim 10^{-16}$. This means that "if we only have access to low-energy experiments (which we do!), it's going to be very difficult to figure out the high energy theory (which it is!), because its effects are highly diluted excepts for the relevant and marginal interactions." Without going into detail, when considering interacting fields as small perturbations of the free theory, one must use the interaction picture, which is a hybrid of Schrödinger and Heisenberg. The Hamiltonian will be $H = H_0 + H_{int}$, where H_0 gives the free solution that can be exactly solved, while H_{int} should be the small corrections. Dyson's formula allows us to evaluate the time evolution of the state, as in QM. Then, it is possible to evaluate the probability amplitudes for scattering processes, through the S-matrix. Assuming then that the initial and final states are eigenstates of the free theory, the S-matrix is used to evaluate the probability amplitudes for the scattering processes. Alternatively, in a simpler way, Feynman diagrams are used to write down the various terms of the perturbative expansion, following some simple rules, which I will avoid repeating here. An equivalent way to introduce interactions is to start with Path integrals, that I will explain very briefly.

2.4.2 Path Integrals

Following Zee in [40], the Path integral formalism can be introduced in the framework of standard QM because "it offers a convenient way of going from quantum mechanics to quantum field theory". Zee tells us a story that he defines "apocryphal as many physics stories are". Figure 2.1 and 2.2 are taken from [40]. In a QM class, the professor was explaining the double-slit experiment. As you can see in Figure 2.1, there is a particle emitted from a source S and two holes A_1 and A_2. It is emitted at time $t = 0$ and detected by O at time $t = T$. The amplitude for detection is given by the superposition principle, i.e. it is the sum of the amplitude for the particle to propagate through A_1 and then go to O and the same for A_2. "Suddenly, a very bright student, let us call him Feynman, asked: Professor, what if we drill a third hole in the screen?" The professor replied, "Clearly, the amplitude [...] is now given by the sum of three amplitudes. [...] But Feynman persisted, "What if we know add another screen [in Figure 2.2] with some holes drilled in it?"". The answer was still the same. "Feynman continued to pester [...] "What if I put in a screen and drill an infinite number of holes in it so that the screen is no longer there?"". I find this introduction brilliant in its simplicity. The result of this reasoning is that to calculate the probability amplitude you need to sum over all the possible paths.

Figure 2.1: Double-slit experiment

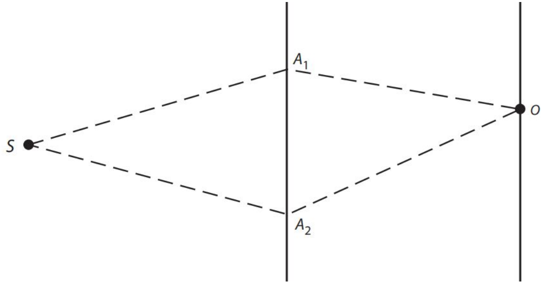
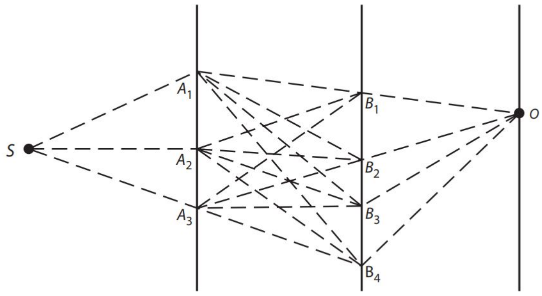


Figure 2.2: Adding new screens and holes.



Zee points out that another possible reasoning for writing the Path Integrals is the Dirac derivation, proposed before Feynman's reasoning on screens and holes, starting from the probability amplitude for a particle to propagate from a point q_i to a point q_f in time T. It is given by $\langle q_f| e^{-iHT} |q_i\rangle$, where H is the Hamiltonian. If we divide the time T into segments $\delta t = T/N$, it becomes $\langle q_f| e^{-iH\delta t} ... e^{-iH\delta t} |q_i\rangle$ and inserting the operator $1 = \int dq \, |q\rangle \langle q|$ between all factors, since $|q\rangle$ forms a complete set of states, we obtain the following probability amplitude (avoiding the complete mathematical derivation):

$$\langle q_f| e^{-iHT} |q_i\rangle = \int Dq e^{i \int_0^T dt L(\dot{q},q)}, \tag{2.23}$$

where L is the Lagrangian. For QFT, using the idea of infinite harmonic oscillators (making the continuum limit and quantising the field, as already mentioned), we obtain:

$$Z = \langle 0|0\rangle = \int D\varphi e^{i \int d^d x \mathcal{L}}, \tag{2.24}$$

where $\mathcal{L}$ is the Lagrangian density and so $\int d^d x \mathcal{L}$ is the action. To consider the interactions, it is sufficient to write the corresponding terms in $\mathcal{L}$. Zee points out that a (0+1)-dimensional quantum field theory is simply QM. It should be noted that it is possible to add a source term $J(x)\varphi(x)$ that "corresponds precisely to sources (and sinks) for particles". As before, considering the perturbative expansion each term can be associated with Feynman diagrams.

Feynman diagrams

I would like to briefly mention a discussion on Feynman diagrams. What happened in the late 1940s with regard to the formulation of QED is very reminiscent of the discussion between Schrödinger wave mechanics and Heinsenberg matrix mechanics. In fact, while Schwinger and Tomonaga had proposed a mathematically rigorous formulation of the QED, Feynman came up with his diagrams, which have turned out to be a very powerful tool to make calculations in QFT. They can fit into an interesting discussion of visualizability, as a direct (but not the only) road to the intelligibility of a theory. In [10], it is asserted (reporting a reasoning due to Kaiser) that "the appeal of visualization was a key factor in the enormous success of Feynman's method". Feynman himself stated that for him visualisation was a fundamental element of his learning. However, the key point that Kaiser outlines is that it is not only the visualizability that has made diagrams widespread, but perhaps the fact that they seem to depict what is actually happening, i.e. "their similarity to “real” pictures of “real” particle trajectories (such as bubble-chamber photographs)".

2.5 Renormalization

Let us briefly return to the discussion of parameters and renormalisation, following Wallace who provides a heuristic explanation in [35]. We have said that in the interaction picture the Hamiltonian will be $H = H_0 + H_{int}$. Introducing a cutoff Λ, each Hamiltonian will be finite. Let us limit ourselves to considering only the self-interacting term $\frac{\lambda_4}{4!}\varphi^4$. Let us consider the perturbative series associated with this term. The tree-order level (the term proportional to λ_4) will be well-defined, however, the term proportional to λ_4^2 will already yield large values (but not infinite thanks to the cutoff). This casts doubt on the validity of the perturbative procedure. Clearly, the higher perturbative orders are considered, the worse it is. As we have already mentioned, however, the theory is renormalisable since the coupling constant is marginal. In practice, it is possible to absorb these very large terms in the parameters, i.e. mass and coupling constant, defining new parameters m^{ren} and λ_4^{ren}. Wallace puts it in these terms:

> "This might seem a block to the applicability of the theory: to make calculations we need to know $(m^2)^{ren}$ and λ_4^{ren}, and we can only calculate them from m^2 and λ_4 via detailed knowledge of the cutoff mechanism and scale. And indeed this would be a block if we were presented with the theory by giving the original parameters m^2 and λ_4 (the so-called “bare parameters”) as a gift from God. But in fact, we determine the parameters through experiment — and what the experiment gives us is the renormalised parameters, not the bare parameters. The latter are related to the measured parameters through a cutoff-dependent expression, but we don't in any case need them for calculations."

Following this line of reasoning, Wallace points out that particles themselves are a scale-dependent concept. Referring to the QED and so to electrons, he reminds us that "the definitions of the creation operators, and of the free-field ground state, depend on the parameters of the theory". These parameters are the mass and the coupling constant λ between electrons and photons, which descreases as the length scale increases. "So the one-particle Hilbert space constructed to analyse QED at high energies is a different Hilbert space from the one constructed at low energies. This ought to drive home the point that electrons cannot be thought of as fundamental building blocks of nature; they are simply a useful, but scale-relative, emergent feature of the underlying theory. But recall that this theory, too, should not be thought of as fundamental, given the tacit presence of the cutoff".

2.5.1 What is meant by an elementary particle?

Sticking with the line of reasoning that particles are an emergent and scale-dependent concept, I cite this very instructive and simple article by Weinberg [37]. There, he admits to getting nervous at the idea of a stranger asking him what an elementary particle is. His point is the following:

> "Let me declare first of all that there is no difficulty in saying what is meant by a particle. A particle is simply a physical system that has no continuous degrees of freedom except for its total momentum. For instance, we can give a complete description of an electron by specifying its momentum, as well as its spin around any given axis, a quantity that in quantum mechanics is discrete rather than continuous. On the other hand, a system consisting of a free electron and a free proton is not a particle, because to describe it one has to specify the momenta of both the electron and the proton— not just their sum. But a bound state of an electron and a proton, such as a hydrogen atom in its state of lowest energy, is a particle. Everyone would agree that a hydrogen atom is not an elementary particle, but it is not always so easy to make this distinction, or even to say what it means."

He briefly tells us the history of particle physics. He reminds us that in the early decades of the 1900s, there seemed to be no debate on the subject. In fact, it was believed that there were only two elementary particles, the proton and the electron. Later, with the discovery of neutrons, nuclear forces and even muons, pions and neutrinos, the debate took hold. The particle physics community, considering all particles detected by bubble chambers and accelerators, began to wonder how to determine whether or not a particle is composite, since in some cases the binding energies would have to be very high. "How could one tell which of these particles is elementary and which composite? As soon as this question was asked, it was clear that the old answer- that particles are elementary if you can't knock anything out of them- was inadequate." The issue was so tricky that Heisenberg stated in 1975, as Weinberg reports:

> "A proton, for example, could be made up of neutron and pion, or Lambda-hyperon and kaon, or out of two nucleons and an antinucleon; it would be simplest of all to say that a proton just consists of continuous matter, and all

> these statements are equally correct or equally false. The difference between elementary and composite particles has thus basically disappeared. And that is no doubt the most important experimental discovery of the last fifty years."

According to Weinberg, QFT by replacing fields to particles as basic ingredients, solved the problem. The elementary ones, whatever their characteristics, are those that appear in the Lagrangian. According to the SM, they are quarks, leptons and gauge fields. However, since the SM is an effective field theory, we don't have a final answer without a final theory of force and matter, according to him. His conclusion is that: "There is a lesson in all this. The task of physics is not to answer a set of fixed questions about Nature, such as deciding which particles are elementary. We do not know in advance what are the right questions to ask, and we often do not find out until we are close to an answer." So, despite the initial embarrassment that Weinberg might have felt towards a curious stranger, he provides an answer that is, however, less straightforward than perhaps a person in a casual conversation might want to hear. About the relation between particles and fields and the path followed to illustrate the theory in [36], the physicist asserts: "I start with particles in this book, not because they are more fundamental, but because what we know about particles is more certain, more directly derivable from the principles of quantum mechanics and relativity. If it turned out that some physical system could not be described by a quantum field theory, it would be a sensation; if it turned out that the system did not obey the rules of quantum mechanics and relativity, it would be a cataclysm." To understand in what sense QFT solves the problem, let us follow Wallace in [35]. He say that "if we ask, independent of their origin as excitations of a field, what quantum states deserve the name "particles", we can argue — following Wigner (1939) — that they should correspond to irreducible representations of the Poincaré group." This means that they can be classified through group theoretical considerations. In particular, they are totally characterised by mass and spin, which can be integer and semi-integer, as we know. If the particle has a positive mass and has a spin s, $2s + 1$ internal degrees of freedom are associated with it. On the other hand, if the mass is zero, as for photons, it has only two internal degrees of freedom. Born in [1], an article from 1953, conceptualises what has just been said with the notion of invariant. Responding to the same question he states that "we find that these words [such as photon or electron] signify definite invariants which can be unambiguously constructed by combining a number of observations. [...] The final result of complementary experiments is a set of invariants, characteristic of the entity. The main invariants are called charge, mass (or rather: rest-mass), spin, etc.; and in every instance, when we are able to determine these quantities, we decide we have to do with a definite particle." He too refers to them as non individuals. However, Born goes beyond this, claiming that these invariants are what comes closest to defining reality, strongly opposing what he sees as subjective epistemologies, as epistemological solipsism whereby there is no reality independent of our perception. However, he realises that quantum theory requires the formulation of a clearer unifying philosophy "expressible in ordinary language, to bridge this gulf between 'reality' as thought of in practice and in theory." With respect to invariants he states that "this power of the mind to neglect the differences of sense impressions and to be aware only of their invariant features seems to me the most impressive fact of our mental structure." Thus he sees the notion of invariant as a connection to reality not only with respect to physics but in all aspects of the world.

2.6 Symmetries

The invariants are closely linked to symmetries and symmetry groups. Gross in [14] asserts that symmetries "summarize the regularities of the laws that are independent of the specific dynamics. Thus invariance principles provide a structure and coherence to the laws of nature just as the laws of nature provide a structure and coherence to the set of events. Indeed, it is hard to imagine that much progress could have been made in deducing the laws of nature without the existence of certain symmetries. The ability to repeat experiments at different places and at different times is based on the invariance of the laws of nature under space-time translations. [...] Today we realize that symmetry principles are even more powerful—they dictate the form of the laws of nature". He points out that the conceptual revolution that made symmetries dictate laws and not vice versa, owes its origin to Einstein's thought and theory and, subsequently, to QM. There are various kinds of symmetries, but the quickest way to classify them is to distinguish between local and global symmetries. In the case of Minkowski space-time QFT, it has a global symmetry that is Poincaré space-time symmetry, as already mentioned, internal symmetries (field transformations) and local gauge symmetries. The latter (related to the possibility of redefining the field locally without yielding any empirical difference) were difficult to interpret at first. However, they made it possible to construct the Standard Model. Indeed, "as Yang has stated: Symmetry dictates interaction". The first example of this was general relativity. According to Gross "the secret of nature is symmetry, but much of the texture of the world is due to mechanisms of symmetry breaking", which occurs in the case of approximate symmetries (and approximate conservation laws) and symmetries (of laws) broken by solutions, i.e. the spontaneous symmetry breaking. Modern physical theories have revealed that the symmetries that have the greatest physical relevance are local. "Indeed today we believe that global symmetries are unnatural. They smell of action at a distance. We now suspect that all fundamental symmetries are local gauge symmetries. Global symmetries are either all broken (such as parity, time reversal invariance, and charge symmetry) or approximate (such as isotopic spin invariance) or they are the remnants of spontaneously broken local symmetries. Thus, Poincaré invariance can be regarded as the residual symmetry of the Minkowski vacuum under changes of the coordinates." Gross goes on wondering why Nature is so symmetric. And here it is clear that the questions physicists ask themselves are often not limited to description, although they always preserve a clear reference to physical theories. He identifies two possible reactions, linked to different and conflicting attitudes. The first is related to condensed matter physics in which symmetries emerge dynamically, looking from further away, i.e. at greater distances. He calls this view "Garbage in—Beauty out". The opposite view states that symmetries are present at the 'fundamental' level, i.e. scales of higher energies and shorter distances, and that at lower energies they are broken. Clearly, advocating this position, he calls it "Beauty in—Garbage out". Therefore "if this is the case then it provides us with an important tool for the exploration of nature. When searching for new and more fundamental laws of nature we should search for new symmetries." Understandably Gross cites the theory of supersymmetry and string theory.

2.7 Problems of the theory

It is common to hear that one of the problems with QFT (or rather SM) is that it fails to include the gravitational interaction. Another problem is related to the fact that SM does not account for its parameters (such as the coupling "constants"), which are evaluated experimentally. About the parameters, Wallace in [35] mentions the fine-tuning of the Higgs mass and the cosmological constant. The key point is that one would expect values for the renormalised Higgs mass and the cosmological constant to be much higher than those that are measured experimentally. He explain that this is not a contradiction, as one can choose values for bare mass and bare cosmological constant that are capable of returning the values actually measured. Yet this "seems to involve rather unattractive fine-tuning of the theory's parameters". About quantum gravity, that seems to be the playground where QM and GR manifest their incompatibility, he notices that "this is not the perspective of most quantum field theorists: to them, the metric field is at least pertubatively perfectly well-behaved- albeit non-renormalisable- and can be handled in the effective-field theory framework". Therefore, quantum gravity should be that theory that appears at the Planck length, where the effective description breaks down. The issue, however is that, as already mentioned, "the great insensitivity of an effective field theory to the physical details of its high-energy cutoff [...] makes it very hard to gain evidence about the details of that theory". The hope is that experimental insights will come from early-universe cosmology and black holes. Another problem with QFT is that it lacks mathematical rigour. As already mentioned, the Algebraic QFT is intended to be a consistent reformulation. I will try to give an idea of what it is about, very briefly.

2.7.1 Algebraic QFT

Kulhmann in [17] explains that since the 1950s, a research program called axiomatic QFT has emerged for three reasons. They are the need for operationalism, meaning the requirement that "the core elements of an empirical theory should be observable quantities, which can be measured by means of certain physical operations." The other reasons, as said, are linked to mathematical rigour and to the problem of dealing with the inequivalent Hilbert space representations for systems with an infinite number of degrees of freedom, as it is the case with QFT. To understand what the inequivalent representations mean, see Wightman in [39]. These attempts include Wightman's field axiomatics from the early 1950s and Algebraic QFT, constructed by Haag and co-workers in 1960s. Without going into detail, it focuses on the algebra of operators that correspond to observables and it is based on a strict notion of locality. In this framework, many theorems have been proven, which in turn have given rise to an intense debate. One of these is Malament's no-go theorem which, under four assumptions about a relativistic quantum theory of a fixed number of particles, proves that it is impossible to find a particle in a finite region, implying the impossibility of a particle ontology. However, the debate is still open. If interested, you can find details in [18]. As already mentioned, many physicists resist this reformulation, as it is not QFT used in research, except by mathematically oriented physicists, and anyway applications and predictions are not its main purpose. In addition, it fails to capture the richness of heuristic QFT.

2.7.2 QFT and space-time

To end the discussion, I would like to briefly mention a speech by Rovelli, that you can find in [23]. There, the physicist wonders whether QFT can represent a fundamental framework, not in the reductionist sense, but as "a fundamental description of the structure of the physical world". The question is whether it is compatible with what we know so far, as was Newtonian mechanics (in its Lagrangian and Hamiltonian formulations) until the late 1800s, in particular with what we know about space-time. Answering this question is possible, according to Rovelli, even without a substitute theory, a bit like what happened to Newtonian mechanics at the beginning of the 20th century with special relativity, which established the impossibility of action at distance. This happened even before the formulation of GR, thus in the absence of a (classical) field theory for the gravitational interaction. Therefore, the comparison must be made between QFT and the space-time described by GR. At this point, Rovelli distinguishes between two meanings for QFT. The first, that he calls general QFT, indicates a quantum theory with an infinite number of variables, characterised by an infinite-dimensional algebra of observables. The second meaning includes the particular theories, such as the SM, and the axiomatic formulations, which we discussed briefly in the previous section. He calls it conventional QFT. This distinction allows him to conclude that the latter is incompatible with GR, while the general QFT is not. Where does this incompatibility lie? To understand, it is necessary to discuss the notion of localizability in GR. According to Rovelli, a more common perspective on GR emphasises simply that space-time is better described in terms of four-dimensional curved geometry, which is dynamical, i.e. affected by the presence of matter by means of Einstein's equations. In his view, however, the true novelty of the theory lies in its relational core, which also corresponds to Einstein's vision. The relational feature does not only apply to space (something already implemented in philosophy), but also to time. And he candidly says that, although for some philosophies, the relational character of space is something accepted and now trivial, physics was born with Newton and his notion of absolute space. In addition, he reminds us that physics before GR identified two entities, space-time (through a fixed metric which was not governed by dynamical equations) and matter (subject to dynamical equations and in motion in space-time). What he wants to tell us is that the conventional QFT is built on the pre-general-relativistic conception of space-time, that is associated to the notion of reference-system. The localization, in the pre-general-relativistic perspective, occurs in terms of coordinates $\mathbf{x}$ and t which "express the contiguity of given dynamical objects with reference-system objects, which are dynamically independent from the dynamical objects, and are labeled in terms of physical distances and time intervals". He says that conventional QFT is based on this structure, since "the quantum observables are local- that is, they are characterized by their space-time location [which] is determined with respect to 'space-time', considered as an absolute entity *à la* Newton, or, equivalently but more precisely, with respect to a set of physical objects, which are considered, for the purpose of the measurement, as physically non-interacting with the system, namely with the quantum field (within the relevant measurement's accuracy)". The point is that in GR, since it is not possible to define reference systems independent of the dynamics of the system being studied, considering that everything gravitates, the distinction between space-time and matter loses its meaning. The fact that there are no non-dynamical objects translates mathematically into the invariance of the Einstein equations with respect to active diffeomorphisms. This gives rise to the following point: "If space-time points cannot be determined by using physical objects *external* to the dynamical system we are considering, what are the physical points?" Einstein himself struggled to accept this property of his theory. This reasoning is called the 'hole argument'. Rovelli says that "it is well-known by whoever has applied general relativity to concrete experimental contexts that the theory's quantities that one must compare with experiments are the quantities that are fully *independent* from $\mathbf{x}$ and t". Thus, there is no physical meaning of $\mathbf{x}$ and t. Let's repeat it: "objects do not move with respect to space-time, nor with respect to anything external: they move in relation to one another." Embedded in the matter/space-time dichotomy, from Faraday and Maxwell to the SM, we deal with matter in terms of fields. As we know, GR has made the identification between the gravitation field and the metric. Therefore, the distinction between matter and space-time doesn't make sense anymore, since "metric/gravitational field has acquired most, if not all, the attributes that have characterized matter (as opposed to space-time) from Descartes to Feynman: it satisfies differential equations; it carries energy and momentum; in Leibnizian terms: it can act and also be acted upon, and so on." According to Rovelli, "it is perhaps more appriopriate to reserve the expression *space-time* for the differential manifold, and to use the expression *matter* for everything which is dynamical [...], namely all the fields *including the gravitational field.* [...] This is not to say that the gravitational field is *exactly* the same object as any other field. The very fact that it *admits* an interpretation in geometrical terms witnesses to its peculiarity [that] can be understood as a result of the peculiar way it couples with the other fields." This last sentence refers to the fact that it interacts with everything. Therefore, how can a QFT be compatible with GR? According to the physicist, it could be so if it is built as diffeomorphism invariant. In this theory, observables cannot be labeled using space-time regions and it should be defined on a differential manifold. Having said that, he explains that there are active research programs in this regard. Those he mentions are topological QFT, Euclidean quantum gravity, non-perturbative string theory, loop quantum gravity and others. He then refers to the intellectual challenges such a theory presents us with. One of these is the absence of time, which can be interpreted as a phenomenological concept, not an absolute one. He believes it can be addressed, however he admits that "the radical step that quantum gravity seems to ask us to take, i.e., learning how to think of the world in completely non-temporal terms, is definitely the hardest". To conclude, what Rovelli says and that I fully agree with is that "if a new synthesis is to be reached, I believe that philosophical thinking will be, once more, one of its ingredients. Owing to the conceptual vastness of the problematic involved, the generality and accuracy of philosophical thinking, and its capacity to clarify conceptual premises, are probably necessary to help physics out of a situation in which we have learned so much about the world, but we no longer know what matter, time, space and causality are. As a physicist involved in this effort, I wish the philosophers who are interested in the scientific description of the world would not confine themselves to commenting and polishing the present fragmentary physical theories, but would take the risk of trying to look *ahead*".

Chapter 3

Interacting with physicists: interviews and online survey

After having an overview of some of the discussions that are carried on by physicists and philosophers of physics with respect to the quantum world and QFT, this chapter was born out of a desire to engage directly with physicists. The process occurred in two ways. I conducted 8 face-to-face interviews[1] (some in-person, some by video call) to professors of physics dealing with different fields and an online survey that received 88 responses. This reached mainly master's students, PhD students and postdoctoral researchers in physics. What was reported in the previous chapters in addition to my formal background were the source material that guided me in constructing the interviews and the online questionnaire. In the following sections it can be seen that, as far as the latter is concerned, there is some continuity with the subjects covered in the previous chapters in the questions and response options, and this also applies to some of the questions I asked during the interviews. Clearly, in actually approaching the physicists what emerged follows perspectives that are also very different from those carried out in the previous chapters. And this probably also stems from the fact that physicists have a different language, other goals and approaches with respect to philosophers. The analysis I report here is almost predominantly qualitative. It is inspired by the thematic analysis formalised by Braun and Clarke in [2] and continuously expanded and enriched by them and co-workers. A simple introduction can be found in [9]. Another source I used to understand how to deal with the qualitative data I collected is [20]. The qualitative data I am referring to, besides the interviews, are the various open-ended questions of which the questionnaire is composed. That said, this work can certainly be extended quantitatively, following a rationale for which a form of methodological eclecticism based on both quantitative and qualitative methodologies can be fruitful and constructive, beyond rigid positions on either side. You can find an interesting discussion

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[1] The analysis presented here, however, is based on only 7 of these.

of this in [15], in which it is explained how in the field of education and social sciences the division between qualitative and quantitative is actually not so clear-cut. For this reason, when I refer to thematic analysis, which is very briefly based on the construction of themes from the qualitative data available, I use it as a method and not as a position taken in opposition to quantitative analysis. Therefore, what I intend to do here is to tell about some perspectives found in the data, that can add interesting insights to the debate. Indeed, I will follow the attitude according to which qualitative analysis is about telling "one story among many that could be told about the data" [9]. Thus, they could be partial and subjective, however "any good analysis needs to be plausible, coherent and grounded in the data", which is why I will report quoted extracts. In qualitative analysis one usually specifies the ontological and epistemological assumptions underlying the analysis presented. Braun and Clarke describe these positions as continua, in which there are no sharp opposing sides but in which it is possible to place oneself flexibly. The continua the researchers refer to are 3 in which the extremes can be summed up as bottom-up and top-down. Specifically bottom-up involves primarily inductive, experiential, and critical realist methodologies, while top-down is identified with a deductive, critical, and constructionist approach. Without going into details, I specify that my analysis is bottom-up, which in concrete terms means that the categories and themes constructed derive from an orientation to the data in which they are primarily the ones speaking, in which philosophical discussions influence my analysis as less as possible (although they did affect the construction of the questions). In addition, more space is given to the meanings and visions of the participants which are considered located truths, without focusing on how and why those realities were constructed and without questioning them. Clearly, this is not a clear-cut position because my disciplinary background comes into play, as well as the categories constructed in the philosophy of physics and the discussions carried on that I am aware of and which I addressed in previous chapters, as I mentioned. That said, this chapter is organized as follows. First, I explain according to what criteria and how both the interviews and the online questionnaire were constructed and the methods I used to approach the data, i.e. the process of coding. Then I report on the more "quantitative" responses from the questionnaire and a very brief introduction to the interviews, just to get an idea of the things we talked about. Next, I will explain what themes I constructed as a result of a personal and reflected analysis, with the aim of telling a story based on my perspective and those coming from the interviews. As already stated then, I hope that in future, the work can also be conducted through quantitative criteria where possible and sensible.

3.1 Design and methods

Let us begin by explaining how both the interviews and the online questionnaire were constructed. The reason they were built is simple: to understand how physicists make sense of some concepts and notions that are much debated in philosophy of physics and in epistemology in general, and to see what they can add to the discussion. We can distinguish the arguments into two categories. The first is more general (but clearly can latch onto a specific theory and vary depending on it) and concerns physical theories, their interpretation and when and how it makes sense to do so, what is the relationship with reality and the role of history and philosophy of physics. The second category includes questions related specifically to QM and QFT (interpretations of QM, particles and fields, QFT problems and future developments of quantum-related areas). This is the same logic with which the previous two chapters are constructed, serving somewhat as a guide to the research. Thus, it moves from more general questions and then focuses on QFT. Clearly the two mediums are different, which is why what I just said declined differently. Let's explore this more specifically.

3.1.1 Interviews

The style of interviews can be described as semi-structured and means that "in this approach, the researcher has prepared an interview guide before the interview, but does not rigidly adhere to it, either in terms of the precise wording of questions, or the order in which questions are asked" [9]. The reason I chose this approach lies in the fact that I agree with the point of view whereby "question wording and order are contextual, and responsive to the participant's developing account". Therefore, the questions were clearly open-ended and broad because the purpose was to bring out the interviewee's perspective. In addition, contextual questions arising from the discussion and others to clarify concepts that emerged were added to the questions already prepared and previously sent out. Besides, considering that the professors I interviewed have different backgrounds, the questions constructed before were slightly different in order to fit the person. The skeleton, however, was the same for everyone. I wrote to 12 physics professors from different areas. Of these, 8 agreed to participate. As mentioned, I sent out the questions in advance to have a guideline and give an idea of the interview, and asked for and got consent from all of them to record and transcribe it. The analysis I report here, however, is based on 7 interviews because during a video call interview the program I was using did not store the recording. I really cared about having a certain gender balance (as much as possible in a field numerically dominated by men), however the 3 female professors I wrote to did not respond. For this reason, the interviewees are all male. I hope that in future work I can do better on this point. I have chosen not to report the full interviews, but only extracts that I find most meaningful in relation to the constructed themes. All the interviews were conducted during July and August 2022. The following is a list of interviewees whom I will quote anonymously, in which I report their areas of research.

- Interviewee 1 (theoretical physics): "quantum field theory and classical and quantum gravity, classical and quantum cosmology, and also occasionally a little bit of fundamental quantum mechanical problems".

- Interviewee 2 (theoretical physics): "string theory and of trying to link string theory to the universe that we see in four dimensions [...]. I try both to reproduce all the known physics at the level of both particle physics and cosmology and astrophysics, but also to try to find some new physics in an attempt to test or find ideas, so that we can test the theory experimentally".

- Interviewee 3 (experimental particle physics): "I worked from the beginning on the experiments at CERN, where I still work, and I have always been involved in elementary particle physics and, within that, I then carved out my own areas of interest which I would thus generally qualify as phenomenological". He stated, however, that since he considers "physics to be enormously interesting" he "always cultivated it even a little bit outside of my research area, and always jumped at opportunities to teach".

- Interviewee 4 (experimental high-energy physics): "a member of the ATLAS collaboration at CERN [and] of LHC", focusing on neutrino physics, accelerator physics, SM physics, "all the way to research that goes beyond the SM, the so-called exotic physics, [so] anything that can be predicted by models that try to extend SM beyond the scales that we have been used to [...]. I have always done data analysis a bit in between phenomenology and data analysis".

- Interviewee 5 (nuclear and subnuclear experimental physics) : a member of "the ATLAS experiment at CERN, which had among its purposes to search for the Higgs boson, and with my group I participated in the final phase of the experiment and the data taking", still admitting to having done "a little bit of everything, particle physics, instrumental physics, applied physics, here and there depending on what was interesting".

- Interviewee 6 (theoretical physics): "quantum gravity".

- Interviewee 7 (theoretical particle physics and history and philosophy of modern physics): "foundations of QFT [...], on whether or to what extent renormalized quantum field theory is a consistent theory [...], taking the existence of quantum field theory as a set of theoretical practice, that is something that people do and have been doing for a while [...] as a given historical fact. And to safely compare that with more naive ideas that we have about what theories are and what physics is, how it's practiced, its relations to the world and try to see how through historical analysis we can get a better understanding of what this thing we call quantum field theory is".

3.1.2 Online survey

The online survey was constructed with the goal of reaching more people and giving students a voice as well. As a tool it can get more people to participate with less time (a face-to-face interview can take up to 2 hours), however, the drawback is that the data produced may be less rich when considering individual responses. That said, it is composed of open and closed questions mixed together. Purely qualitative questionnaires usually do not include closed questions, since the open-ended ones allows respondents to express themselves more freely and idiosyncratically. However, again with a mixed approach that can be in case extended quantitatively, there are also closed questions and answers involving scales from 1 to 5. Apart from the latter, however, closed questions always contain the options ’None of the above’ and ’Don’t know’ to avoid forcing respondents into one of the predetermined options. In addition, these questions also contain the ’Other’ option, which allows the respondent to express themselves in their own words. Only a certain number of questions were mandatory in the questionnaire so that everyone could send me their answer even without replying to more technical questions such as ”In your opinion, which are the main problems of QFT?”. Making an overview of the answers I will indicate this from case to case. Surveys focused on foundational issues related to QM have already been given and analyzed. Very interesting are the cases of [27] [28] [25]. They employed the same questionnaire consisting of several closed questions which was submitted to experts in both the fields of physics and mathematics and philosophy. Since they were all closed questions, their purpose was to identify patterns in the responses by defining correlations of various kinds among them. As mentioned above, in my case it is more difficult to make correlations as there are several open questions. Surely in the future it could be rephrased as closed questions and use their same approach. I made the survey through Google Forms and sent it to fellow students in the physics department of Bologna, only after submitting it to my colleagues from various master’s curricula to test its comprehensibility. Respondents’ personal information is shown in Figure 3.1 and 3.2.

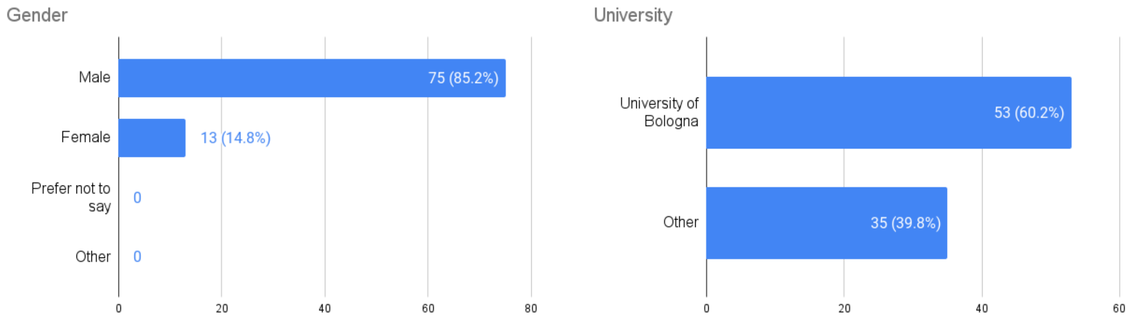


Figure 3.1: Gender and University

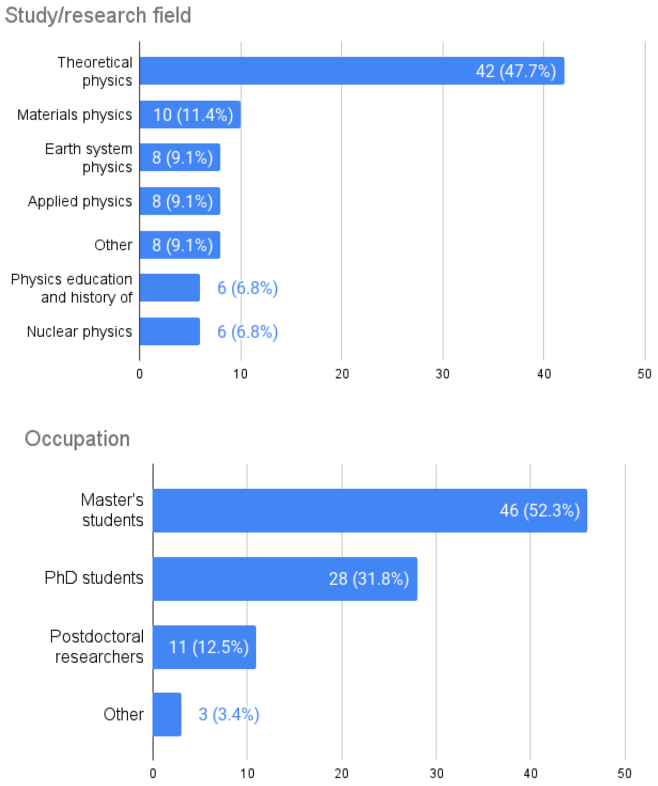


Figure 3.2: Study/research field and Occupation

3.1.3 Coding

After explaining the rationale behind the construction of the questionnaire and interviews, the objectives and relevant information about the respondents, let us talk about coding. In thematic analysis, it represents one of six given steps. Without going into detail, it involves two first steps, one of familiarization with the data (in which one also reflects on the disciplinary content that the interviewer/researcher themselves put in) and a coding phase. Next, there are stages in which initial themes are constructed, which are then revisited and redefined and finally given a name. Lastly, finalization of the report comes. Coding is defined as ”the simple operation of identifying segments of meaning in your data and labeling them with a code” [20], that means words or sentences that are able to capture the meaning of that portion of data. The procedure allows to acquire deep insights into data, make them accessible and retrievable, structuring them, ensuring transparency and validity and give a voice to one’s participant. I made use of descriptive coding consisting of several cycles, which applies to both interview transcripts and open-ended survey questions. In the first coding step, I read each answer and attributed a few words (or few sentences in the case of the interviews) to describe the meaning of the replies. Then, in subsequent coding cycles, I identified repeating keywords and in some cases created categories.

3.2 Overview

At this stage, let us begin with a descriptive and very short overview of the responses received, both through the questionnaire and through the interviews, so that we can then move on to a more structured narrative of the themes.

3.2.1 Interviews

The skeleton of the interviews can be broadly summarized in two moments, as already mentioned. The first concerns the interviewees' relationship with history and philosophy of physics, definition of physical theory, the role of mathematics and empirical inquiry and the role of interpretation, theory-reality relationship and the role of historical context. The second part refers to the quantum world, interpretations of quantum aspects, the notion of particle and its relation to the field, problems of QFT and its concrete theories (both theoretical and experimental), and possible future developments. All interviews were very rich and participatory. I thank the professors who expressed so much willingness, openness to dialogue and deep insights. I asked them so many questions and in some cases they themselves turned some of them back to me. With all interviewees, personal and professional views emerged. Almost all expressed interest in history and philosophy of physics and reported formal or informal situations of contact and collaboration in which multidisciplinary approaches and many different points of view were favored. In addition, most of them presented me with their own reading of QM, either through their choice of a specific interpretation (Copenhagen, Everett and Dynamical collapse theories were mentioned), or through a reformulation or specific version (such as Dirac's). Finally, most of them with respect to the ontological debate related to the relationship between field and particle said they lean toward the field (for some not without problems, as we shall see).

- With interviewee 1, deep insights came to light with respect to the role of mathematics and quantum gravity.
- With interviewee 2, the talk focused mainly on the role of string theory in reconsidering fundamental entities, space-time and gravity and its relationship to QFT and to the conception of physical theory.
- With interviewee 3, the discussion was very interdisciplinary, with varied references to both modern and ancient physics, and it emerged at various points how physics and physicists proceed in theory development and experimental practice.

- With interviewee 4, the discussion was very much focused on the crisis of current theoretical and experimental physics and all the possible ways forward, as well as the interviewee's personal and more speculative views.
- With interviewee 5, the discussion centered much on the quantum aspects of the microscopic and obstacles in the experimental field.
- With interviewee 6, a well-defined conception of physical theory emerged that serves as a framework to set up the role of interpretations and questions and future developments.
- With interviewee 7, the discussion focused on the interpretation and contextualization work that he and his research group do on quantum physics and QFT. I was impressed by the methodological framework used in questioning with respect to how to interpret theories and in general in approaching discussions of a more philosophical nature, in which the formal aspect of physics and history are intertwined. It happened almost throughout the course of the interview that he changed form to my questions revealing to me an extremely fruitful methodology.

3.2.2 Online survey

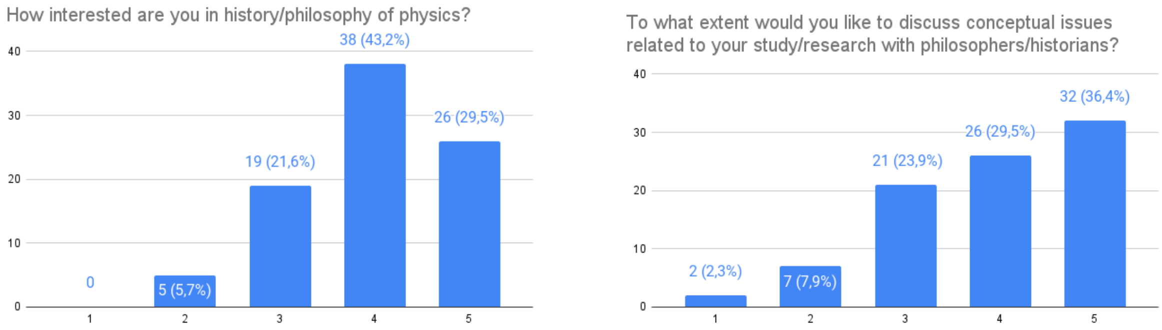
The online survey is divided into three sections: physical theories, particles, and quantum world. Let us briefly look at the responses obtained.

Physical theories

This part consists of 6 mandatory closed questions. The answer to 5 of these is set on a scale from 1 to 5, while the remaining one is a closed question. Let us consider the first question in Figure 3.3. However "quantitative," I interpret this scale as:

- 1 means not at all interested;
- 2 means slightly interested;
- 3 means neutral;
- 4 means very interested;
- 5 means extremely interested.

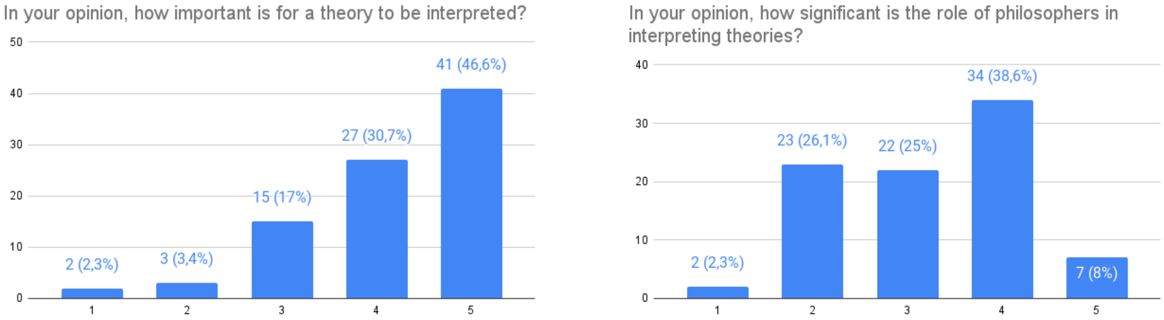
A readjustment of this also applies to all the questions of this kind. In Figure 3.3, you can see that beyond the specific percentages for each question, it can be seen that in both cases more than a majority of respondents said they are very (or extremely) interested in the two disciplines and wanted to find themselves in opportunities for discussion



How interested are you in history/philosophy of physics?

To what extent would you like to discuss conceptual issues related to your study/research with philosophers/historians?

Figure 3.3: History and philosophy of physics



In your opinion, how important is for a theory to be interpreted?

In your opinion, how significant is the role of philosophers in interpreting theories?

Figure 3.4: Interpretations

with philosophers and historians of physics. In Figure 3.4, you can see that more than 77% of respondents consider very or extremely important to interpret physical theories, however, the percentage with respect to how very or extremely significant the contribution of philosophers might be drops to just under 47%. Then, based on the discussion that occurred in Chapter 1, which very briefly outlines the categorizations proposed by philosophers with respect to the theory-reality relationship, I constructed the closed question you find in Figure 3.5. The answers I provided refer to the positions that can be defined as realist, instrumentalist, agnostic and constructive empiricist. 77 out of 88 people responded using an option already provided, while the rest of them preferred to express themselves in their own words. We can see that the most chosen options are the two most often contrasted (even in literature), namely the instrumentalist and realist positions. The 'Other' option gives us more nuances, some of which will be explored later. The section ends with the question in Figure 3.6. It can be seen that most of the respondents (more than 80%) considered the historical context very or extremely relevant to the development of a theory, its interpretation and the interest

Figure 3.5: Attitudes towards theories

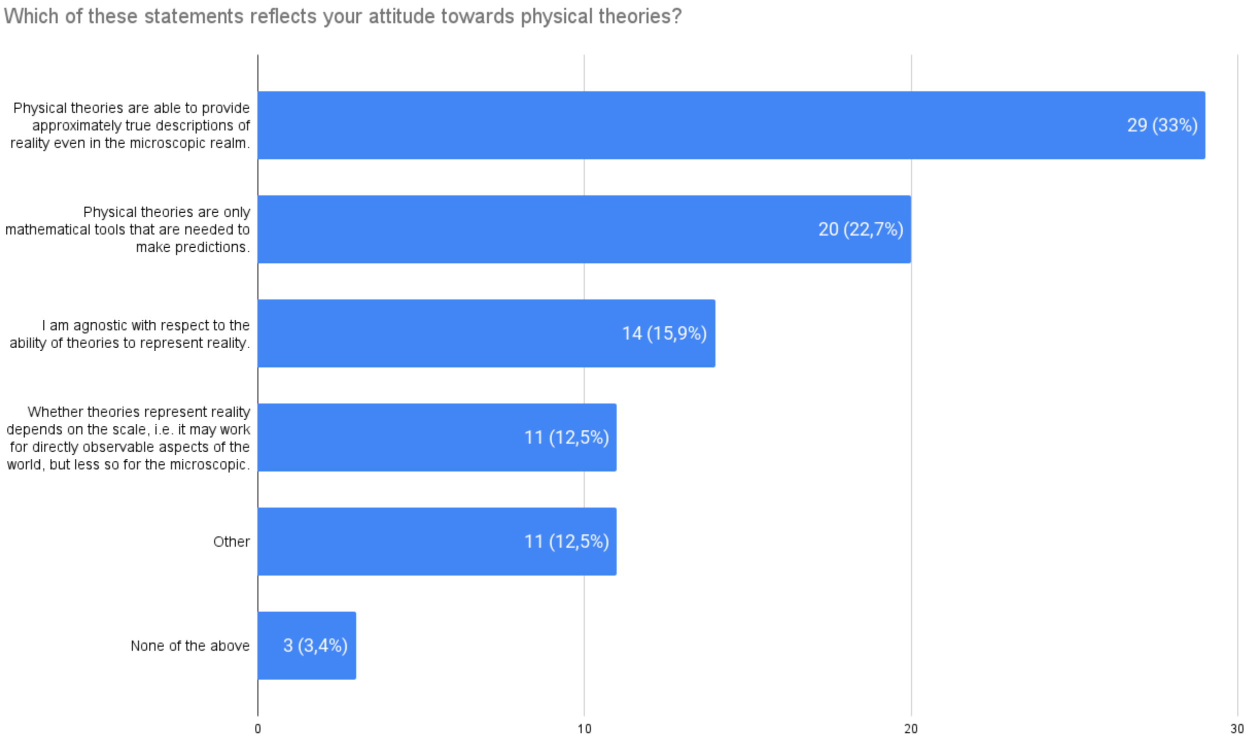
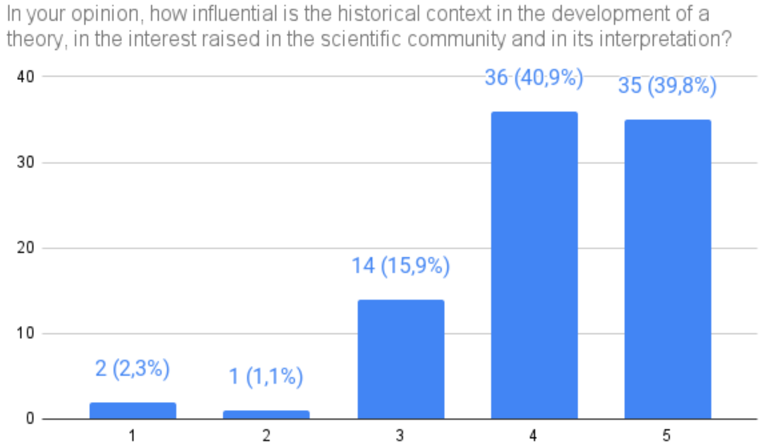


Figure 3.6: Historical context



raised. It is complicated to compare this answer with the one given above, as this belief can be considered and made more or less consistent with instrumentalist, realist positions and so on depending on the discourse constructed. Probably, in this case an open-ended question could have provided more insight into how the two answers do or do not fit together. This can definitely be kept in mind for future work.

Particles

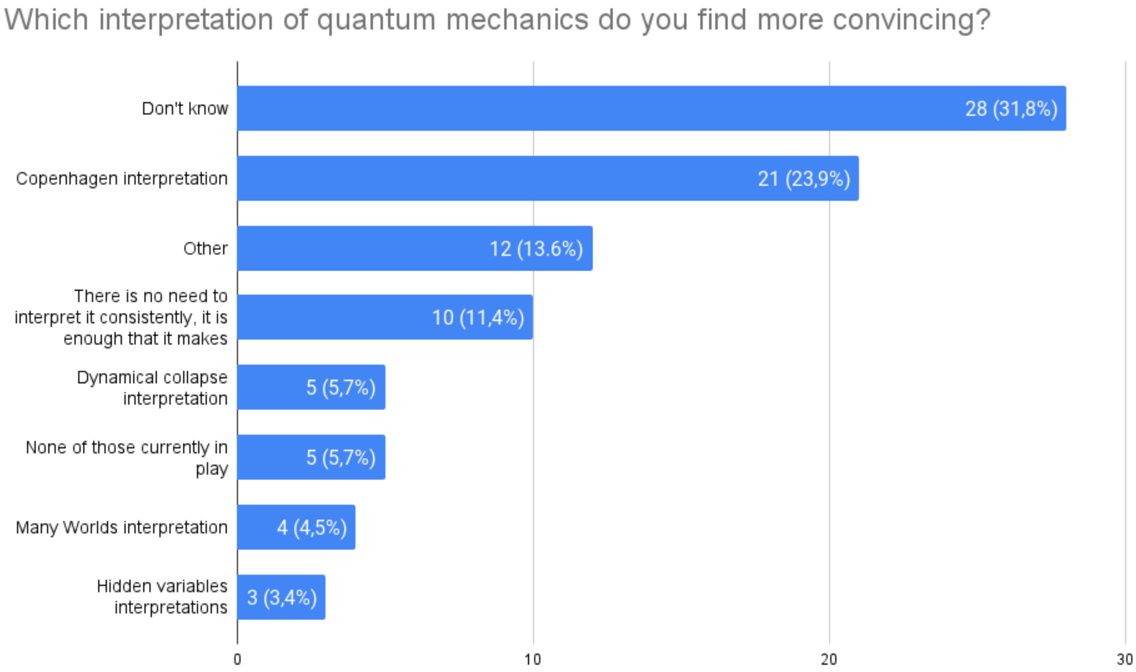
The second part of the online survey consists of the direct mandatory question: 'how would you define a particle?' The question is introduced by the following sentence: "I will ask you how you think about the particle. Just remember, any answer, more or less formal, is fine." I wrote this because I wanted to prevent people from being inhibited in responding by thinking that I was looking for a formal answer. By the way, my interest is mainly in how physicists get an idea of the particle, even in an informal and perhaps classical way. For this reason, the question is asked before the section in which explicit reference to the quantum world is made. The partially overlapping categories are as follows: QFT and QM with explicit reference, dependence on theory and scale, focus on features and focus on relational aspects. In this context, I chose not to report numbers (i.e., how many of the definitions provided I put in a given category). The only indicative fact I would like to report is the following: more than half of the responses did not explicitly refer to QFT. Of these, however, less than half made use of quantum concepts such as wavefunction or refer to standard quantum theory. People who mentioned QFT referred to particles either as excitations, quantum field fluctuations or as reducible (in the case of composite particles) or irreducible (in the case of elementary particles) representations of the Poincaré group. Some although referring to QFT, pointed to a broader discourse arguing the fact that the notion is theory-and-scale dependent. However, this latter can still be considered a category of its own which intersects somewhat with QFT and QM explicitly referred. On the other hand, those who did not refer to QFT in these terms but to the standard QM regard the particle as a wavefunction or wavepacket. Then, let's move on to the other two categories. The first (more conspicuous) consists of definitions that focused on the characteristics of particles such as the fact to be the smallest thing we understand, fundamentality, localizability, and being what constitutes matter. In addition, in this category there are the answers that focused on considering particles as bearers of precise and defining properties (such as mass and charge). The last category (into which fewer responses fell) is composed of replies that focused more on the relational aspect, on particles being something whose features we observe, on interactions with other systems, the environment and measuring apparatuses. Although there was no explicit reference to quantum theories here (in the sense that the more formal concepts expressed earlier such as field, excitation, wavefunction were not used), I believe that many had quantum theories in mind when they used words such as matter, fundamental, and even interaction. I should add that there were many answers in which the categories just proposed overlap, because respondents often used more than one definition to better clarify their definition. Besides, there were responses that greatly problematized the issue. Finally, I would like to add that only one response made explicit reference to the indistinguishability of particles (although, using a quantum framework it is implied). Below are some relevant examples, each by category.

- Explicit reference to QM and QFT: "A particle is the excitation of a quantum field. Their characteristics are determined by the properties of the underlying field, especially its symmetries and its interactions with other fields."
- Theory-and-scale dependence: "A particle is an object of unknowable nature that is used in the description(s) of phenomena (like behaviours of condensed matter traced to the interactions among these so-called particles); depending on the field/scale of study, it takes on a different interpretation, which is a way for us to have a mental representation of it."
- Focus on its features: "the smallest object of the universe that we understand", "A point-like object defined by its fundamental properties, e.g. mass and charge".
- Focus on its relational dimension: "An object that it is not observable but that has a set of observables that can be measured to detect it and differentiate from other objects", "a way to call a discrete signal on a detector".

Quantum world

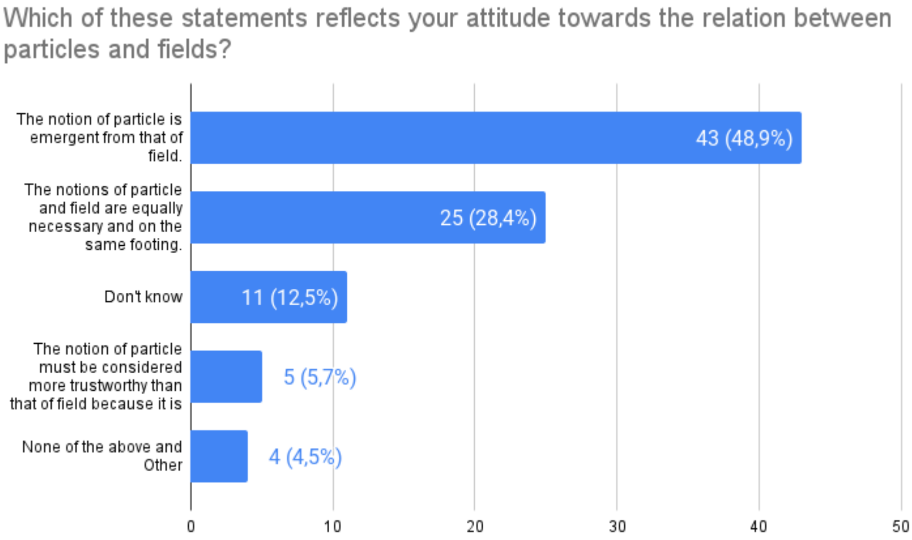
The last section consists of 6 questions, some open some closed and none of these was mandatory. The first question is open and asks: "What do you think are the most revolutionary concepts related to the quantum world?". It is preparatory to the next one that is related to the famous QM Interpretations. People responded by citing various issues, especially the most famous ones related to standard QM. Among them, the most cited were entanglement, Heisenberg's uncertainty principle, the intrinsically probabilistic nature of quantum theories, the superposition of states and the wave-particle duality. Few people referred to QFT and its specific interpretive challenges, citing antiparticles, renormalization group and and the path integral formalism connected to effective theories. The next question as mentioned is related to QM interpretations. In Figure 3.7, you can find the default answers including the 'Other' option. 76 people selected one of my proposed options. Out of these (as was perhaps to be expected) the answer 'Don't know' prevailed, followed by the Copenhagen interpretation (which is the one usually included in textbooks). Immediately after that the option "There is no need to interpret it consistently, it is enough that it makes prediction" was selected, which can be associated with a certain thread called 'shut up and calculate'. However, the number of people who selected this option is smaller than the number of people who selected the instrumentalist option in the question about posture toward physical theories (10 people here, 20 people there 3.5). In the 'Other' option, some added other interpretations such

Figure 3.7: QM interpretations



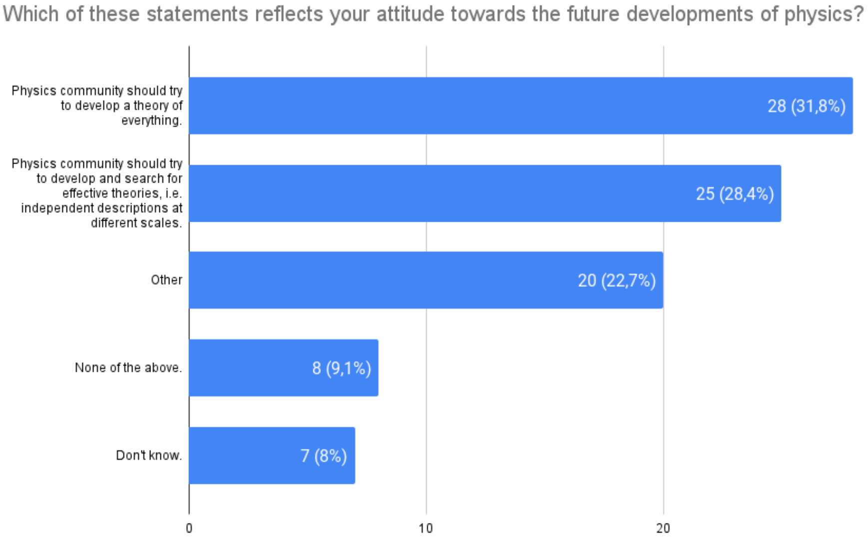
as the relational one, others problematized the issue of underdetermination due to the fact that if they do not make different predictions it is difficult to choose. One person referred to the simplicity criterion and another said that the debates about interpretations are nothing more than ”desperate attempts to find classical interpretations of what is going on.” Another respondent raised an additional function that interpretation can have, i.e. as an individual reading asserting that ”if someone can think more clearly using one interpretation instead of another then so be it”. Regarding QFT, I have constructed two questions. The first closed-ended one is about the relationship between field and particle. In Figure 3.8 it can be seen that the most chosen option is the one for which the particle is an emergent concept, right after comes the option that considers them on the same footing. Next comes the ’Don’t know’ option, followed by 5 responses that the particle being something measured is more reliable, and finally the ’None of the above’ and ’Other’ options. Only two people expressed themselves in their own words. Instead, the second question is open-ended and reads: ’In your opinion, which are the main problems of QFT?’ Many people answered ’Don’t know’ or something like ’I am not an expert’. There were 47 actual responses. The most frequently cited problem was related to the fact that QFT does not include gravity. Right after there was the problem of renormalization and nonrenormalizable theories. Some responses then, distinguished between possible framework problems (mainly mathematical in nature) and Standard Model theoretical problems. Another relevant issue that emerged is related to experimental practice. The last two questions are related to the future development of physics.

Figure 3.8: Particles and fields



The first closed with predefined answers is as follows: ”Which of these statements reflects your attitude towards the future developments of physics?". In Figure 3.9, it can be seen that the two opposing alternatives have similar response rates. In the 'Other' option 8 people explicitly said that both paths should be pursued. Some responded that physics should be useful and others that it is too presumptuous to believe that a theory of everything can be developed. Others wrote that a revolution in some sense is needed, that is, to find a new framework. The last question is again open-ended and reads: 'In your opinion, which quantum-related research programs are the most promising?' Removing the 'I don't know' responses left 42 actual responses. The most cited fields of research has included quantum computing and quantum information theory. Next came condensed matter and quantum gravity. Others answered quite specific things with respect to SM and quantum gravity theories, and some mentioned strings.

Figure 3.9: Future development of physics



3.3 Storytelling by means of themes

From the replies to the online survey, it can be seen that many people responded by choosing predefined options, which might suggest that the categorizations constructed in the literature are shared to a large extent by physicists and are certainly a useful tool for placing what is being studied and researched in a larger picture (though these are still closed questions that therefore by their nature flatten the debate). In addition to open questions, we have seen that there were also a variety of responses expressed in their own words using the 'Other' option through which respondents provided many nuances that suggest that, as useful as categorizations are and an excellent tool for approaching the various issues, they clearly fail to capture the complexity of the reasoning. This became extremely clear during the interviews. Another thing I noticed is that clearly philosophers and physicists have different approaches and goals, which are not necessarily irreconcilable; indeed, they may appear to be complementary. The data collected from both the online survey and the interviews are extremely rich and multifaceted. For this reason, I will not be able to integrate them all, both in quantity and variety. However, what I can do is narrate some of the ones I found most relevant and integrated through the construction of 3 themes: *how to make rigid requirements and schemes more flexible*, *the multi-functions of QFT*, and *the representational role of mathematics in quantum and non quantum theories*. Before we begin, I would like to clarify what is meant by themes. In [2] a theme is defined as something that "captures something important about the data in relation to the research question, and represents some level of *patterned* response or meaning within the data set". In [9] it is explained that "a theme has a central organising concept, but will contain lots of different ideas or aspects related to the central organising concept (each of those might be a code)". So a theme is something that is built from similar codes integrated together into a larger idea with an evocative name.

3.3.1 How to make rigid requirements and schemes more flexible

Let us begin to explore this first theme. It includes answers to questions of different content. It has three dimensions through which to understand its meaning.

First dimension

The first dimension relates to a rigidity of positions with which physics is approached. In particular, I refer to the theory-reality relation and to the meaning of interpretation, discussed in previous chapters. Both during the interviews and in the questionnaire, I always brought up this discussion. What I noticed was that some respondents reacted by changing the form of the question or default answers by showing greater complexity and the coexistence of more multifaceted and less rigid instances. Let's look at some meaningful examples from interviews, of which I report the crucial parts.

Interviewee 7, theoretical physics and history and philosophy of modern physics.

Interviewee 7 referred to the realism anti-realism debate as a not-so-clear dichotomy by arguing that since knowledge construction is a process, it is difficult to stop at a certain point and ask which abstract entity is real and which is not. Similarly, he outlined that the process of interpretation should be a complex two-way activity in which theory itself has to provide its own interpretive categories. The following is the excerpt from the interview.

Interviewer: "Do you adopt a position as a research group with respect to the realism and anti-realism debate or do you not deal with it, and resolve it with personal perspectives?"

Interviewee 7: "Realism anti-realism is really a very specific debate about the existence of abstract entities in scientific theories. And there I don't really see a clear dichotomy [...]. As far as I can see, there are many different kinds of standards one could apply when saying I want to be realist about this aspect of the theory or whatever [...]. I don't see this as in any way black or white [...]. I think in general there's the feeling that we're finding out something about the world when we are doing science but since it's a process, it's very hard to nail down at any point in time what exactly we can be sure of [...]. That seems kind of a nonsensical thing to do because it privileges one point in time [...]. It might become relevant what kind of [scientists'] personal convictions were about the reality of certain abstract entities, not of abstract entities in general."

Interviewer: "How important is for you to interpret theories and it is necessary to interpret them all or only those considered fundamental, whatever it means?"

Interviewee 7: "I guess if you use interpret not as a technical philosophical term, but in its common language use, then of course you have to interpret theories. You need to be able to think about what you're doing otherwise, if it's not interpreted in any way, it's just mathematical space. [...] Now, of course, interpret can mean a far more formalistic process of treating a theory according to the methodology of the philosophy of science and it makes sense, right? To do this kind of interpretation that you have to do anyway on some sort of intuitive or practical level, to do that in a more systematical manner, I think this is a sensible thing. And that applies to any kind of theory, but one can't expect to have a preconceived notion of a theory and then use that notion to interpret it. The interpretation process always has to be one of feedback where what you're doing in interpreting the theory also tells you something about the tools and categories you should be using for interpretation [...]. There is too much emphasis on, like in philosophy of science, on finding universal analytical categories that will allow you to in principle interpret any theory rather than actually engaging with a certain theory in detail and working out what it means."

Interviewee 6, theoretical physics.

Similarly, interviewee 6 starting with his own definition of physical theory, which I report, expressed how because of too rigid positions on how reality should be, difficulties in interpretation can arise, with reference to the quantum world and how little it can be intuitive. According to him, theory is made to answer some specific questions and is always subject to error, as is true of measurements. Hence, he concluded by saying that it is legitimate to get an idea of what reality should be like, but without being overconfident and entangled in it.

Interviewer: "How would you define a physical theory?"

Interviewee 6: "It is the result of an information-loss compression algorithm. [...] From measurements you extract regularities typically described using mathematical formulas [...]. It keeps [information] according to some criterion that our brains like or that some of our brains like. [It is] a formulation that should capture the fundamental aspects of those data. What it means in essence is [that] it helps us answer questions that we are interested in. Everything that we are not interested in is thrown out [...]. Formulas that we have never describe exactly any event and there is the error, the important thing is that the formula has something that falls inside [it]. If it stops falling inside the error we throw away the theory or we refine it, so actually these formulas that we call theories, they describe something in that sense. They help us answer some questions, but not others. And they're fine as long as they fall back into errors."

Interviewer: "How does the final result of the algorithm relate to reality in your opinion? That is, does it make sense to ask this question, or is it enough that, precisely, the input experimental data are related to the output experimental data?"

Interviewee 6: "[...] if we could answer that question I wouldn't need to play this game [developing theories], I would know reality for what it is [...]. It is also not clear how to define what reality is beyond experimental data. [...] it is also quite dangerous from a scientific point of view to give too much weight to this kind of reasoning. I give an example, in classical prequantum physics the observer was the image and likeness of God, therefore, could intervene in the world and made measurements ideally with arbitrary precision, without disturbing anything. Then, at some point one wakes up in the morning and discovers the uncertainty principle which is not true, we are part of the world [...]. Theory is about measurements, inevitably so. The link between theory and reality goes through the procedure of measurements, it is behind a veil. One can form the idea one wants, just don't believe too much in any one."

Interviewer: "Which interpretation of QM, if you are interested, do you feel most akin to?"

Interviewee 6: "[the ingredients] that characterize quantum physics are unintuitive. This has then led to all various disquisitions, complications, interpretive difficulties. They come into play the moment one tries to discuss the reality that lies beyond the measurement process, if one just considers a quantum theory as the theory that describes the results of measurements, in my opinion there is no problem. All the interpretive problems between discussions emerge the moment I start to think, but there is a reality, regardless of what I measure etc. etc., there a world opens up. But it's a world that goes beyond that. Theory itself by definition, theory is about measurements, precisely [...]. The fact that it is non-intuitive means nothing. This is a limitation of us not of the theories."

Answers that belong to this theme can also be derived from the questionnaire. Let's look at some examples.

Figure 3.5, attitudes towards theories.
When asked in the questionnaire about attitudes toward physical theories many respondents added different nuances to their answers, again revealing that positions and categories are more diverse, less strict and even overlapping. For instance, expanding the instrumentalist option someone wrote:
"I would answer "Physical theories are only mathematical tools that are needed to make predictions", but that "only" seems too much restrictive to me. They are MOSTLY mathematical tools, but they come with a physical picture of reality that is crucial to help us developing an intuition, therefore guiding our description of the world. It doesn't matter if this picture describes the true reality (or our way of perceiving it), as long as it works to guide our understanding".
And another one, showing a coexistence between underdetermination and 'realism' in some sense wrote:
"If a theory can predict the behavior of certain objects it is a true description of reality. If there are more then 2 theories that do that, both are true unless one is shown to be incorrect",

Figure 3.7, Interpretations.
A respondent said that the debates about interpretations are nothing more than "desperate attempts to find classical interpretations of what is going on." Another respondent raised an additional function that interpretation can have, i.e. as an individual reading asserting that "if someone can think more clearly using one interpretation instead of another then so be it".

Second dimension

The second dimension of the theme concerns the definition of particle. Again, this can be read as tension between seeking more rigorous definitions and more flexible approaches to it. On the one hand, there is an emerging acceptance that it is a notion dependent on the theory and scale being considered (and this is evidenced by the fact that the data allowed me to build a category on it). However, there are also those who problematized this. Let's look at some examples.

Interviewee 7, theoretical physics and history and philosophy of modern physics.

Interviewee 7, in a sense, rephrased the question, stating that the definition must be lived pragmatically with respect to the reason and context in which it is needed. However, he admitted that it can be problematic to use the same word.

Interviewer: "How would you define a particle?"

Interviewee 7 : "[...] I'm not a big fan of a priori definitions. Certainly, people mean different things when they talk about particles and they legitimately do [since different things] can't fit under one universal definition. Certainly, that can be problematic, right? Because people think they are talking about the same thing when they are not. I think in some cases you can make more or less definite different statements about what you want to mean by particle here. [...] it's a pragmatic question of what you want that definition for."

I found several answers in the online survey that can be interpreted in light of this theme. To cite a significant example, a master's degree student expressed with a very fitting example, how particle attribution can be ambiguous, which could be understood as too much flexibility.

Online survey: a reply from a master's student to "How would you define a particle?"

"It depends. Sometimes by particles we refer to elementary particles, which I know [...] to be the quanta of energy of the vibrational normal modes of the several fermionic and bosonic fields classified by the standard model [...]. More "qualitatively" we physicist (or at least me) tend to think of them as the smallest unit known at that historical moment of some physical entity which can exist in vacuum. I added "which can exist in vacuum" because in condensed matter physics we also have quasi-particles like phonons or even the electrons for how we treat them, but let's focus more on phonons for example: nobody thinks of them as existing "as much as" the particles of the standard model but they are still quanta of energy of the vibrational modes of the ions in a crystalline lattice (treating the displacement from the equilibrium position harmonically) and can be treated in many ways as particles (with Feynman diagrams and creation and annihilation operators and so on). But sometimes we call particles even entities like hadrons, which we know think of as not elementary, but composite, or even atoms or molecules. I guess that here we can still consider them to be the smallest part of a certain scientific (also chemical) category that has certain properties (ex. Atoms for a substance made of a single element or molecules for a compound substance) thus that can be attributed that identity. But then, given that certain properties of a system emerge from a collection of these chemical units (a crystal doesn't behave as a single atom of the crystal isolated) why in a polycristal we don't consider the monocrystalline grains that compose it as particles? They are the smallest units of that system which maintain the properties of the system (still not all of the because mechanically for example they are definitely different on the macro scale). But maybe there's something that I'm not seeing which constitutes a difference between this case and the one of atoms. So honestly the more I think about it, the more I find the definition not so rigorous after all. I also wanted to cite the not so scientific, but maybe epistemologically relevant, fact that I am convinced that many of us still can't (even if they don't necessarily let this inexact image infiltrate their professional physical reasonings) avoid visualizing intuitively a particle as a small spherical-ish thing with exact position and momentum (or, even less correct but more intuitive, velocity). And that is why we find so difficult the wave-particle duality and Heisenberg's infamous uncertainty".

Interviewee 3, experimental particle physics.

Interviewee 3 also seemed to problematize the notion of particle, pulling in the notion of field as well. In particular, he was referring to how physicists do not define entities well, change the form of the question without actually answering it. At various points in the interview he stated how it is 'forbidden' to talk about substance.

Interviewer: "How do you think about the particle even given your experience at CERN?"

Interviewee 3: "There is a pragmatism there that is extreme [...] the particle is an object that manifests itself in its detectors that leaves visible traces which you can measure. [...] on the theoretical side we know that particles are sub-product of the field, so they are not the fundamental object, which is the field and that, moreover, we do not see, we only see when it changes energy and we do not even know how it does. We describe it mathematically, so there is the operator that has certain properties, however what we believe that object there describes, what physical entity and how this physical entity is made, no one knows. So, as far as I'm concerned, not only do particle physicists not know what a particle is, but neither do theoretical physicists, in the sense that they changed the form of the question. You might say 'what is a particle?', and they might tell you 'it is the quantum of energy of a field'. Well, then you afterwards might ask 'what is the field? What substance makes it up?' And there they also stop."

Interviewer 3 in line with what has just been reported, at other points in the interview referred to how physicists throughout history have lost the previously widespread sacred dimension of doing science, citing Ptolemy and the Almagest among others. This led him to assert that today's physicists "seem to be jokers who play very clever and very difficult games but there is hardly ever in them the feeling of privilege because you get to take a different look at reality." And because of that it would be hard to ask questions with respect to the substance of the field. Thus, he stated that while philosophers are "crucial in reminding physicists of the fundamental points of discourse and that there are questions that cannot be evaded", this attitude of holding back "obscure and ill-defined notions" is "healthy" in a sense because it allows it to move forward. So the not reaching the essence could be "the fate of physics [...]. Physics, indeed, is successful precisely because it has abandoned the problem of essences, however it is present in our minds as a constant woodworm".

Interviewee 5, nuclear and subnuclear experimental physics.

In the definition of particle, another aspect that emerged is related to the possible coexistence of professional approaches and "instinctive", more informal and imagination-driven approaches. Interviewee 5, for example, answered me as follows.

Interviewer: "How do you think of the particle?"

Interviewee 5: "If I have to tell you instinctively how I think of it, I think of it wrongly, as a ball. I got used to thinking of it that way. Then, afterwards when you think about it, you understand that it can't be thought of as a ball, however in the end when you imagine a collision of particles, you imagine two balls colliding, breaking and transforming. Although, I understand that it is not the right interpretation to think of it, however by now I got used to think it this way. Then, it is interesting also to think of it as a string that vibrates, that moves by the modes of vibration, like in string theory. However, if I have to tell you instinctively I imagine it as a little ball and already I struggle already about thinking of it as a wave."

Third dimension

The third dimension of the theme concerns future developments. Here I am referring to theoretical and experimental obstacles. Many referred to the difficulty of today's experimental physics in providing experimental input to test the theories we have or to construct new ones. I would like to introduce this with the words of interviewee 4 who stated that "physics is questioning nature, ask the right questions and be able to answer. Who is asking the questions are the experimentalists, who is understanding the answer, let's put it this way, are the theorists. So there the mouth and ears of the same person, but right now we don't know how to either ask questions or listen to the answers [...] we are no longer able to communicate so it's fundamental that there is really an overall paradigm shift". Let's start with the experimental obstacles, which can be interpreted as a rigidity in experimental practice and again to a wish for flexibility and open-mindedness, which is what interviewee 4 raised by imagining a use of artificial intelligence.

Interviewee 4, experimental high-energy physics.

Interviewer: "What are the problems of QFT and SM from the experimental side? Are they just technological in nature?"

Interviewee 4: "No, I think that if there was right now an omniscient being, a superintelligence might already be able with what we have, to construct the right question and get the right answer. That means, we already have it and now the problem is that we don't get it, so in that sense an artificial intelligence might be helpful [...] to look for the unexpected, look for deviations in an unconventional way. So saying 'maybe, I'm a human being and so I'm too biased'."

Interviewee 3, experimental particle physics.

I posed a similar question to interviewee 3 who outlined various experimental problems and one in particular was related to over-attachment to technique in experimental practice. In this case, the paradigm shift refers to a return to a more structured dimension of the experiment, as was done in the past.

Interviewer: "What are the problems of QFT and SM related to the experimental practice? Are they just technological in nature?

Interviewee 3: "There are stricter laws that limit the ability to do experiments than there are laws that can limit theory building. That is limited by our ability to imagine, it then clearly has to be a consistent theory that meets certain rules etc., however apart from those there are no limits. In the case of experiments, the limits are first of all technology [...], then there is the economic fact, since it must be something that is within reasonable funding. And then, there must be something that is less and less true, that is to say an experimental logic of investigation. Once it was decisive, experiments always hid inside a clever idea to be able to get the info you wanted, now it is less and less true. You tend to do experiments that can do anything, they are not based on an idea but, let's say so, on a technique pushed to the extreme of each of its components [...] so inside the big experiment there is not really an idea of physics from the point of view of the logic of measurement You make an apparatus that can do everything, all the particles all the energies, then something interesting will turn up".

Let us turn to theoretical obstacles with respect to future developments in physics beyond the SM. Here various discussions related to space-time, mathematical consistency and the alleged incompatibility between quantum field theory and gravitational interaction are intertwined. The rigidity I refer to and have encountered is, on the one hand this alleged incompatibility, and on the other of constraints that might be related to cultural legacy. Let us discuss the alleged inconsistency with general relativity. Again, it can be seen that the issue of the link between the two theories is more complex and flexible, in the sense of dependent on interpretation. Interviewer 6, interviewer 2, and interviewer 1 pointed out to me how this is possible.

Interviewee 2, theoretical physics.

Interviewer: "How important is it to interpret a theory? Does it apply to all theories, even 'non-fundamental' ones, or is it enough for them to agree with experiments, with observations?"

Interviewee 2: "On this point here I have a fairly pragmatic approach [...] because then the important thing is to reproduce the experimental data [...], that the theory correctly represents the physical world at the level of predictions. However, interpretation is important, in my opinion, in trying to go beyond that theory there [...]. I can give an example, I don't know, relativity comes to my mind, okay? One can say 'I interpret gravitational interaction geometrically, so actually between two bodies, between two sources of energy, there is no force. These curve space-time and then these here move freely in space time'. One can see it that way, someone else can say 'no, I see it simply as an interaction, I don't see any curvature of space time, I don't see any geometric interpretation'. And those who have this approach say 'because I don't see the other forces geometrically in this sense, so seeing gravity like this can help me to unify it with the others'".

Interviewer: "Why does the covariant derivative appear in general relativity and in interacting gauge theories, that have a somewhat contradictory notion of space time?"

Interviewee 2: "One can also see [gravity] as an interaction with exchange of gravitons. [...] in the case of gravity [the symmetry] is Poincaré's global symmetry which one makes local and they become the diffeomorphisms and the derivative becomes the covariant derivative. When one has a theory, let's take elettromagnetism, there is the global symmetry U(1) and one makes it local and it becomes a gauge symmetry U(1), and even there the derivative becomes covariant derivative because U(1) comes to put a correction to the ordinary derivative that depends on the gauge field. In a similar way, you can say the gauge field for gravity is the graviton is the non-Minkowskian metric and even there you see it the same way.”

Interviewee 6, theoretical physics.

Interviewee 6 told me that using the word incompatibility might not be appropriate, since we are who define theories and again he referred to the non-geometric interpretation. Admitting that the geometric interpretation of gravity is richer mathematically, the interviewee raised a major problem with quantum gravity, namely its non-linearity.

Interviewer: ”What is the relationship between the theory of gravity and quantum field theories? Can we speak of incompatibility, even conceptual incompatibility?”

Interviewee 6: ”So first of all, reality, whatever it is, is one. Gravity is not incompatible with other forces, otherwise we would not even be here talking about it. [...] General relativity is not built on the same kind of mathematics or mathematical vision that is used in field theories, but the motivation is simple, the geometric interpretation of gravity is a consequence of the equivalence principle. And gravity is the only force that satisfies the equivalence principle [...]. That is why you can make a geometric description from gravity, that is, you could also make a geometric description of the other forces, it would be like introducing a different metric for each type of particle, at which point it becomes unnecessarily complicated. But the geometric interpretation of general relativity is not the only possible interpretation and a priori it is not necessarily the best. So, I only see this incompatibility if one insists on using very rigid concepts on either side. Rigidity is never a quality.”

Interviewer: ”I do not know if this is true, however, I have the impression that in any case the geometric interpretation allows more to be done than treating the gravitational field in the weak field approximation.”

Interviewee 6: ”Then certainly geometric theory is richer of mathematical solutions. If I think that spacetime has a certain fixed topological structure I throw away a lot of solutions that instead exist in the theory. However, a priori we can’t be the ones to determine what is the right way to proceed and, if you throw away stuff, it’s true, you have to figure out if and how you can recover these things. In the context of a field theory then, there is involved the fact, actually the biggest complication when one goes on quantum physics and gravity, that is the fact that gravity is a theory that even classically is nonlinear. Einstein’s field equations are nonlinear, as opposed to elettromagnetism, for example, which is the only other long-range force that we know. And the truth is that we also don’t have particularly well-established tools to study quantum physics of nonlinear systems, and I am also quite optimistic in that. I often feel that we don’t have a clue how to do it.”

Interviewee 3, experimental particle physics.

Interviewee 3, regarding space-time, expressed a very interesting reasoning regarding our need to consider it fundamental in thinking and developing physical theories. The topic came up immediately after the discussion we had about fields, which are uncharacterized from the point of view of substance, as illustrated above. At that point I raised to him the question of the gravitational field and how much more complicated it is to interpret, referring again to the alleged incompatibility with QFT. What he pointed out to me was that, according to him, the big conceptual challenge might be to write a theory without space-time.

Interviewer: "I was reading the fact that since quantum field theory in both the case of flat and curved space-time treats it as a background in which position and time become labels, in a way, rehabilitates the Newtonian conception of space-time as something absolute, as substance, and it is strange that it does so after the construction of general relativity, in which instead it is dynamic."

Interviewee 3: "Yes, it's dynamic, be careful though [...]. For Newton it was an untouchable space for Einstein, it's not so rigid anymore, however it always remains as a substrate of reference and there there's something very fundamental behind. It's our mind that thinks that way but in a dramatic way [...]. For us, the temptation to think of space and time as containers of everything, something in which we put all things is irresistible, is the way we read reality. [...] so the idea of container space is so ingrained in us that will we be able to do physics without these assumptions? It's a good question, I don't know. Sometimes, I wonder about it, I would like to figure out how you can deal with a problem like that, I don't even know if anyone has tried to build a physical theory that expressly gives up the concept of space and time. It will probably have other variables [...], I imagine something where space and time pop up later as a by-product of these variables that come even earlier. However, that needs imagination, because here it is a matter of getting out of a mental habit that imprisons us, here this is another aspect of physics that I am very interested in and I see, at least as far as I am concerned, how little imagination there is and we have, indeed I have, in getting out of those patterns of reasoning that we have learned, how hard we struggle tremendously. However this is another of the interesting aspects of physics."

Interviewer: "But then there is also to be said that you also have to collide a little bit with reality, that means with the fact that there are traditions so you are inclined to do something that you have already done and then anyway there is to be said that some things are funded, others are not."

Interviewee 3: "Certainly, here it would be interesting for a historian, for example, to say if there are cultures that have developed a different way of thinking than this, because I realize that sometimes it sounds like a cliché but there is a period in our history which is that period that is in the first centuries which coincides with Greek and Alexandrian history, that really shaped our thinking with a force and a power that we still don't come out of it today. In my opinion, the foundations of our way of thinking were been put there and since that is a historical moment and in other cases that moment may not have been there, it is interesting. I would like to understand if somewhere in the world, some civilization doesn't see space and time as something central, that thinks with different concepts in mind and has a different view of reality, because there is no doubt that a choice was made, a definite choice, there were some thinkers who made decisions for all of us."

Another nuance of how flexible attitudes toward physics development are made is evident in many of the 'Other' option responses received to the online survey question shown in **Figure 3.9**, which outlines the dichotomy between the search for effective theories theories and for a final theory. In this case, several responses highlighted the belief that both paths can be pursued simultaneously.

3.3.2 The multi-functions of QFT

The second theme constructed is called the multi-functions of QFT. It concerns the varied reconsiderations that the theoretical framework allows for, beyond the predictions that his concrete theories make.

Interviewee 6, theoretical physics.

QFT clearly can be related to the foundational issues of QM. Interviewee 6 outlined this, while problematizing the relationship between the community of QM foundations and the QFT community. His criticism is about the fact that they don't talk to each other and that they use different languages to talk about the same things. Using his words:

Interviewee 6: "For example, when people talk about quantum fundamentals they think of the two-slit experiment and so on, while people who do quantum field theory calculate cross sections as if they were two completely separate things. Now, the passage of particles through a slit is a diffusion process. Eventually, the particle passes through the slit and not through the wall, why? It bumps into it, a cross section, and the problem is that it would be extremely complicated to describe those experiments that are usually treated in quantum mechanics using the whole quantum field theory, because it would have to take into account the wall inside which the slits are actually a collection of molecules and so on. The idea of measurement would be impossible as well, the two communities have very different ideas of measurement, right? Measurement for those who do quantum mechanics is the collapse of the wave function, these things a little bit abstract invented at the time because one didn't know far better. Those who do quantum field theory calculate cross sections and they give them to Monte Carlo and they find the accelerator data. They are not different worlds, it is the same world we are studying. Wave function collapse, what it means is that I interact with the system in a certain way and make a measurement, in the end it is a diffusion process. The simplest and most instructive example is Heisenberg's microscope from which Heisenberg himself later used to motivate the uncertainty principle. It's a collision process, it's not a different stuff."

Interviewee 7, theoretical physics and history and philosophy of modern physics.

With interviewee 7 too, I discussed the relationship between QM and QFT. Unlike interviewee 6, he emphasized how differences in theoretical and experimental practices make the two framework theories empirically different.

Interviewee 7: "The perspective of my research group is that that question is less trivial than it's often made out to be. There's kind of a traditional point of view, that says that quantum field theory is just a model that fits within the framework of quantum mechanics. That's clearly, empirically not true in practice, right? I mean you can see that these are separate subject matters that of course share certain conceptual similarities, but there certainly is a distinct field of research and theoretical practice called quantum field theory and the relation is primarily problematic because of the ill-defined mathematical structures of quantum field theory. You can do certain limiting relations [...] but the question is, from what sort of foundation are you taking the limiting relations? And, I mean, there clearly are qualitative differences related to, in particular, the infinite number of degrees of freedom that you have in quantum field theories [...]. I don't think that's a question that has been fully resolved, whether the transition from quantum mechanics on field theory is just one of clever formalism, or of whether this requires certain of the novel approaches that have been adopted on a pragmatic basis."

Then he further elaborated on the consistency of QFT later, since he is researching on it. He explained to me that mathematical consistency of QFT is closely related to the empirical consistency and he pointed out that it is the same issue as quantum gravity.

Interviewee 6: "They're both about finding a quantum field theory or whether it can exist a quantum field theory that can in principle be reconciled with a continuous space time". [The key point is] to answer the question whether there exists a quantum field theory that is in principle valid up to arbitrarily high energy or arbitrarily short distances".

Interviewee 2, theoretical physics.

With interviewee 2, who is involved in string theory, two roles that QFT plays emerged. One is in the particle-field, string-field analogy. This means that the string field and the string are in the same relationship as the field and the particle, as if the string field theory were a second quantization. In both cases, however, the respondent considers the field fundamental and string and particle the emergent entities. The other role that QFT plays is in the discovery of the holographic principle. In his words:

Interviewee 2: "At present, string theory is a theory that seems that it can't be wrong because quantum field theory is not wrong and because we have discovered dualities between string theory and quantum field theory. Basically, we have certain theories versions [...] that, if seen from a certain point of view they are string theories, if seen from another point of view they are quantum field theories. So, since the field theory is true, string theory must be true. It's easy to explain. It's called holography. [...] We have string theories in 10 dimensions, then there are solutions that are not realistic, because one assumes that 5 dimensions are small and 5 are large. We know that 4 are the large ones, however one mathematically can construct these solutions. So 5 are big and they are anti de Sitter spaces and there lives a string theory, then on the boundary, that is 4 dimensional, there lives a quantum field theory. And there is a duality in the sense that one can compute two point functions, three point amplitudes, these things here. One can compute them with string theory or with quantum field theory, that is on the boundary and the results are the same. So, there is a whole dictionary of duality, that means certain operators in field theory, the normal operators that you have, are mapped to states in string theory with certain masses and so, from that point of view, the theory must be true. Then, whether it really describes our world I don't know, this has to be seen because we have found these dualities for non-physical solutions."

3.3.3 The representational role of mathematics in quantum and non-quantum theories

The relationship between physics and mathematics is very complex, and often their development proceeds simultaneously and with mutual influences. The arguments that can be made from this theme, i.e. the representational role of mathematics in quantum and non-quantum theories, are many. Here, I will limit myself to reporting some of the aspects touched upon in the interviews. Let's start.

Interviewee 2, theoretical physics.

Interviewee 2, while defining himself as a pragmatist, referred to a dual nature of mathematics: being a human product and simultaneously the language of nature. This consideration, allowed him to arrive at the following conclusion:

Interviewee 2: "The impressive thing is that something that we have invented actually finds correspondence in nature, in the sense that it really seems, at least from my point of view, to be there an objective reality. It is there regardless of our brains and our constructions, with laws that we try to discover and that are written in mathematical language. And the fact that we all agree as scientists [...] is as if there is something objective there, that is, we all agree because it is not a thing of my mind."

Interviewee 3, experimental particle physics.

Interviewee 3 represents a critical voice with respect to the representative and even communicative capacity of maths. In defining a physical theory he referred to its conceptual content beyond the experiment considering this its "true richness". Thus, the experiment is necessary to decide whether to hold the theory, but the theory does not end with it. And clearly mathematics came into play. This is how he understands their relationship:

Interviewee 3: "I strongly believe that the role of mathematics is simply to be a very economical, very synthetic and therefore very powerful language to express physical concepts. I believe that the substance of a physical theory can be expressed even without mathematics, of that I am very convinced, and therefore that mathematics is simply a language but what the theory has to say could also be said in words [...]. Mathematical language does not carry physical concepts in it, they are inside the theory and its creator puts them in it [...]. This means that mathematics does not carry physics in any way."

Later in the interview he calls it "a dress" into which conceptual content must be added, citing examples from the history of physics such as the Dirac or Lorentz case. In line with this view of mathematics as a tool, he said to prefer Rimini-Ghirardi-Weber's theories of Dynamical Collapse, since they address the problem of the wavefunction collapse, referring to the double-slit experiment in which he participated in person. In addition, he outlined how this overconfidence in mathematics, as well as the belief that nature will make us see more in an unlimited way are the result of a "cultural attitude."

Interviewee 1, theoretical physics.

The two perspectives I am about to report are very different from the one just told. When asked specifically with respect to the power of mathematics to represent reality, Interviewee 1 paraphrased DeWitt stating that "the mathematical formalism of quantum theories is capable of interpreting itself" [11]. He went on to say that physical theories succeed in representing reality even in its microscopic aspects, consistently with the fact that there is "much of the truth" in mathematics. In line with this, the interviewer told me that among the various interpretations of QM he favors the Many Worlds interpretation.

Interviewee 4, experimental high energy physics.

Interviewee 4 used mathematics to express some very interesting personal and "mystical" views. At various points in the interview, two levels became apparent. A more professional level, which includes the conception of physical theory and the experimental nature of the discipline (despite not being reduced to experiments, but coupled with interpretations) that has to regulate another level, the more speculative and mystical one, precisely. Let us see. The process of developing a physical theory follows these steps:

Interviewee 4: "I observe a phenomenon I want to interpret, [it is] fundamental that there is an interpretation underlying this phenomenon, [so] I build a physical theory, therefore postulates that for me are irreducible and from these postulates I go on to predict a series of phenomena. [These predictions] must clearly include what I have just observed [...] but it is necessary that this theory is also able to predict phenomena that I have not yet observed and this allows me to falsify or confirm it".

He said that experimental data is something that drives theory building, but then later it is crucial to discuss interpretations, in a professional way, clearly. Added to this, there is a more speculative attitude, which, however, must then be governed by observations. About maths he claimed:

Interviewee 4: "From a purely mystical point of view [I am] more attached to the idea of mathematics existing apart from us".

In this more speculative dimension falls a personal vision related to space-time:

Interviewee 4: "I think the deeper problem of knowledge is to fight the concept of infinity as both great and infinitesimal, so I don't believe in either the infinite or the continuous. I have always espoused this somewhat naive image and I would love it if someone would tell us that all reality is actually discrete, that space-time itself is discrete, and all we do is observe emergent things. The quantum field itself, however, surely hides an insecurity. Surely the problem of renormalizability of theories arises from this, that is we have the problem of continuum so, when we then send the scale to infinity or to zero quantities explode, so we created these techniques to renormalize, discretize and then send the size of the lattice to zero. I would very much like this lattice to be real, so I imagine space-time as mathematical points connected by a kind of springs at an extremely small Planck scale and our quantum fields are nothing but macroscopic manifestations of these objects. But again, I don't study fundamentals of field theory, so I don't know how realistic this could be. I have always liked since I was a student to imagine ultimate reality in this way, as something finite and discrete and not continuous and infinite, this is the idea I have in my mind of physical reality."

This representational potential of mathematics also emerges in the preference of the QM interpretation, namely the Many worlds interpretation. However, even in this case he specified to me that we need to think about how to test it, citing some attempts in this regard.

Interviewee 7, theoretical physics and history and philosophy of physics.

With respect to the theme, with interviewee 7 the discussion focused on how QM has forced us to reconsider the representative role of mathematics as more complex. This came up in talking about his research group's reading of QM, regarding interpretations. He stated that it is mainly about the tension between Heisenberg's vision and Schrödinger's one. The crucial interpretive problem they identify is related to the fact that the theory appears hybrid in the sense that "on the one hand, we're holding onto notions which go back to Newtonian mechanics of states evolving in time according to partial differential equations, but on the other hand we can't fully view it that way because of the absence of being able to say something clear about a state evolving in time and in between measurements". And this is "witnessed by its double creation, one is like an entirely new theory that just deals with spectroscopy [Heisenberg's matrix mechanics] and does not deal with states evolving in time at all, and on the other hand, Schrodinger's attempts." He stated that this tension is relevant since it "has never really left the field, [it seems that] in quantum field theory things move along more Heisenberg direction because the actual differential equations that govern time evolution of states don't actually appear in the way we do quantum field theory. But I think it's never been fully resolved whether we should think about the world and about physical theories an entirely new way that might be closer to Heisenberg's original vision, or if called that, is just being pragmatic about calculating scattering amplitudes and really at the bottom we have something like a short equation which still has states evolving in time in a well defined Hilbert space and so". And it is in this tension that the complexity of the representative role of mathematics emerges.

3.3.4 Comments

Let us briefly reflect on the themes. They allow us to see how categories and positions can be more messy and complex. The first theme illustrates to us how a tendency toward flexibility and a need for more rigidity or rigor may coexist. These broad concepts have different meanings depending on the context. Rigor and rigidity can mean overly rigid positions but also something desirable that allows knowledge to fall into place and answer essential questions. Flexibility, on the other hand, can be understood as open-mindedness that allows one to break out of traditional and restrictive research patterns, but it can also take on the meaning of obscurity that needs clearer and better defined reworkings. The other theme is related to the richness of QFT in its ability to serve so many conceptual purposes. The last one elaborates on the role of mathematics from a representational point of view and shows us some contrasting and nuanced views. Let me conclude by saying that the physicists who participated, both professors and fellow students, Ph.D. students and postdocs, provided me with very interesting insights that are partly akin, partly complementary to what is being debated within the philosophy of physics. The fact that the goals and paths of reasoning followed may be far apart can be a great asset for people like me who need to make sense of more or less specific concepts related to the very large portion of human knowledge that is physics and to situate it in relation to other forms of knowledge.

Conclusion

In this thesis, I approached the interpretive issues related to quantum theories and QFT in particular. The aim was to grasp some of the most debated and challenging topics, presenting some discussions raised in philosophy of physics. During the process, I also interviewed some physics professors and constructed an online survey, to understand how physicists make sense of concepts related to quantum theory and quantum field theory, and to see what they could add to the discussions. The interactions with physicists, as well as the re-elaboration of some of the sources related to philosophy of quantum theories, were really interesting and enriching. Let's review for a moment what I worked out specifically. In Chapter 1 I was concerned with providing an introduction to the philosophical debates related to QM and QFT. In particular, the chapter gave representations formalized by philosophers of physics with respect to what a physical theory is and what it means to interpret it. It then briefly introduced categorizations related to postures toward theories, formalized in the literature. Then, it introduced interpretive debates related to QM by linking them to the attitude towards the theory-reality relation. Finally, QFT was introduced, discussing briefly what kind of conceptual analysis were conducted and some of the more interesting debates related to it. In Chapter 2 I presented a focus on QFT, elaborating more in depth on its peculiar interpretive challenges and presenting formal paradigmatic examples to connect to the theory in concrete. It could neither be complete nor satisfactory from a formal point of view, given the complexity and richness of the framework. However, it did allow for a peek. There, apart from briefly presenting the different formulations, I narrated some of the discussions regarding the notion of particle and its relation to the field. Two different ontologies emerged. The first supports ontological duality of field and particle, while the second supports a field ontology. Arguments in favor of both positions were highlighted. The discussion then moved briefly to renormalization and its consequences. Finally, some problems with QFT, understood both as a framework and through the Standard Model, were raised. Chapter 3, on the other hand, was concerned with reporting the data collected through the interviews and online survey and defining the reasons for the sought interactions and the methods used. After providing an overview, I presented a qualitative thematic analysis through 3 themes, based on some data taken from both channels. The philosophical discussions reported in the first two chapters, and my personal disciplinary background, guided me in constructing the questions. The thematic analysis presented, was guided primarily by the data collected, with an approach that can be described as bottom-up. The constructed themes allowed me to tell a story related to the data, with the intention of highlighting the personal perspectives of the interviewees. It was very interesting to note how personal visions are intertwined with professional ones. As mentioned before, the research and analysis can be made quantitative in the future by expanding the survey. In conclusion, I would like to thank all the people who participated, providing rich and interesting insights.

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