Found Sci (2018) 23:705–717
https://doi.org/10.1007/s10699-018-9548-0

# A Proposal for a Coherent Ontology of Fundamental Entities

**Diego Romero-Maltrana**[1,2] · **Federico Benitez**[3,5] · **Cristian Soto**[4]

Published online: 14 February 2018


**Abstract** We argue that the distinction between *framework* and *interaction* theories should be taken carefully into consideration when dealing with the philosophical implications of fundamental theories in physics. In particular, conclusions concerning the nature of reality can only be consistently derived from assessing the ontological and epistemic purport of both types of theories. We put forward an epistemic form of realism regarding framework theories, such as Quantum Field Theory. The latter, indeed, informs us about the general properties of quantum fields, laying the groundwork for interaction theories. Yet, concerning interaction theories, we recommend a robust form of ontological realism regarding the entities whose existence is assumed by these theories. As an application, we refer to the case of the Standard Model, so long as it has proved to successfully inform us about the nature of various sorts of fundamental particles making up reality. In short, although we acknowledge that both framework and interaction theories partake in shaping our science-based view of reality, and that neither would do by itself the work we expect them to accomplish together, our proposal for a coherent ontology of fundamental entities advances a compromise between two forms of realism about theories in each case.

The authors acknowledge the financial support given by FONDECYT Grant Nos. 1150661 and 11160324.

✉ Diego Romero-Maltrana
diego.romero@pucv.cl

1 Instituto de Física, Pontificia Universidad Católica de Valparaíso, Avda. Universidad 330, Curauma, Valparaíso, Chile

2 Instituto de Filosofía y Ciencias de la Complejidad, Los Alerces 3024, Ñuñoa, Santiago, Chile

3 Institute of Physics, University of Bern, Sidlerstrasse 5, 3012 Bern, Switzerland

4 Universidad de Chile, Av. Capitán Ignacio Carrera Pinto 1025, Ñuñoa, Región Metropolitana, Chile

5 Present Address: Université de Lausanne, Faculté des lettres, Section de philosophie, Lausanne, Switzerland

**Keywords** Principle theory · Constructive Theory · Ontology · Quantum Field Theory · Particles

## 1 Introductory Remarks

In what follows, we advocate the view that current best scientific theories represent a privileged source of information when it comes to shaping our view of reality. The relevance of fundamental theories in physics to articulate a worldview is partly due to the fact that they provide us our finest approximation to the laws, relations, properties and entities that constitute the world; and partly because it is hard to argue against the intuition that theories about the fundamental structure and behaviour of, e.g., elementary particles and space–time are relevant starting points for the enterprise of understanding phenomena at different scales. Nevertheless, as shall come to be clear below, this should not prevent us from dealing with the issue that those same theories are generally surrounded by controversial interpretive difficulties. Accordingly, we acknowledge that one of the tasks of the philosophical examination of scientific endeavour is to make clear the epistemic and ontological implications of scientific theorizing, especially if we aim at articulating a coherent ontology from available theories, discerning the extent to which specific parcels of scientific theorizing do actually inform us about the ultimate nature of the world.

Recent debates in the philosophy of science (Bain 2000; Fraser 2008; Baker 2009; French 2014), among others, have addressed the ontological implications of Quantum Field Theory (hereafter QFT). The theoretical framework of QFT stands as the underlying structure for the Standard Model of Particle Physics (SM, for short). In turn, the SM has thus far become an extremely successful theory explaining the workings of three of the four known fundamental forces of nature. In this context, one of the issues raised by QFT has to do with the ontological status of particles (Haag 2012). It can be shown that localized particles do not have a proper place in an interacting QFT. That is, even if the notion of an electron is well defined at the level of a free field theory, it is impossible to rigorously express this notion in the full theory of Quantum Electrodynamics (hereafter, QED). This suggests key epistemic and ontological questions that concern not only the conceptual accuracy of the theory, but also the reality of the particles that furnish the world.

The following view has come to be widely accepted, namely, granted that it is the best fundamental theory known to us, QFT should be our main guiding principle when making ontological decisions. According to this interpretation, the concept of particle is to be relegated to a second place, amounting to only a useful analogy based on commonsense intuitions about medium-sized objects (French 2014). That is an example of the way may derive ontological consequences from fundamental theories (QFT in this case). In what follow, we provide reasons for a different strategy, especially since our main concern is related to the precise sense in which QFT can be considered a fundamental theory that neatly informs us about the ultimate constituents of the world. To be sure, we need not deny that QFT is fundamental in a relevant sense. However, we claim that its fundamental character has to be specified before extracting ontological conclusions from it.

Two issues are not usually acknowledged: first, QFT results from the combination of Quantum Mechanics (hereafter, QM) and Special Relativity (SR, for short), where none of these two theories can be considered ultimate as, for instance, QFT is taken to be. Indeed, these theories are only valid within specific ranges (scales) of energy, and QFT can thus only be expected to yield an effective description of a given range of both length and energy scales, which should be compared with the scales at which the particle concept appears to provide an adequate description of experimental outcomes. And second, while it is true that the QFT formalism lays the groundwork for SM, this does not account for the whole picture. In our view, we still need to introduce a clear distinction between the formal dimension of QFT, versus the SM as an instance of a very particular QFT that deals with the entities and properties that are detected by experimental devices.

Both issues are related to a single aspect of QFT, which it shares both with QM and SR (though not with SM), viz., it works as a framework for interaction theories. In what follows, we undertake the task task of thoroughly arguing for this claim. We shall refer to the distinction originally advanced by Einstein (1919) between two kinds of theories: namely, principle and constructive theories—or, as we prefer to say following Flores (1999), 'framework' and 'interaction' theories, respectively. In particular, according to Flores, the central feature of 'principle theories' is their 'framework' function in relation to other theories, whereas 'constructive theories' are intended to describe particular interactions. In turn, we argue that QFT is to be considered a framework theory that allows the construction of interaction theories such as QED or quantum chromodynamics (QCD for short). Lastly, we derive morals concerning ontological matters in view of the various ontological presuppositions underlying current fundamental physical theorizing.

## 2 Framework Theories Versus Interaction Theories

According to Einstein, theories can be classified into two categories, namely, those that provide generalizations of regularities with extensive empirical corroboration bearing the status of 'principles' (axioms, laws, and the like) from which further theories can be deductively developed in terms of standard top-down explanations; and those that are explicitly built on the basis of granting ontological status to entities that are thought to furnish the world, providing a causal, bottom-up explanation of phenomena (Flores 1999). The former are called principle (or framework) theories, whereas the latter, interaction (or constructive) theories.

The difference between principle and constructive theories can be pointed out by appealing (as Einstein himself did) to thermodynamics and statistical mechanics. Einstein acknowledged that the actual explanation of thermal phenomena emerges from the picture of colliding particles exchanging kinetic energy provided by the kinetic theory of gases (or KTG). KTG is a constructive theory insofar as it rests on the existence of particles capable of interacting.[1] However, he acknowledged that KTG achieves its position because it correctly delivers the expected results of thermodynamics, where the latter is a principle theory that applies to any physical process, regardless of the forces involved or the particularities of specific physical systems in each relevant case.[2] In particular, Einstein emphasizes this as follows:

[1] It should be stressed that in Boltzmann's time there was not direct evidence of the existence of atoms or of molecules. It was a very successful hypothesis that obtained experimental corroboration later on.

[2] Eddington nicely expresses a strong confidence in thermodynamics (Eddington 2012):

> ...If someone points out to you that your pet theory of the universe is in disagreement with Maxwells equations–then so much the worse for Maxwells equations. If it is found to be contradicted by observation–well, these experimentalists bungle things sometimes. But if your theory is found to be against the second law of thermodynamics I can give you no hope; there is nothing for it but to collapse in deepest humiliation.

> ...the advantages of the constructive theory are completeness, adaptability, and clearness, [whereas] those of the principle theory are logical perfection and security of the foundations (Einstein 1919).

Here is something to bear in mind. On one hand, Einstein thought that ultimate understanding can only be achieved from considering constructive theories. Yet, on the other, it is often the case that the attempt to find constructive theories is doomed to fail if no principle theories are available to frame, restrict, or guide the development of constructive theories (Howard 2015).

Flores (1999) observes that Einstein's distinction has a threefold dimension: ontological, epistemological and functional. In ontological terms, constructive theories postulate entities that furnish the world, whereas principle theories postulate general principles that govern a modal space of possible interactions among the entities that may furnish the world. Similarly, in epistemic terms, principle theories start from postulates that are granted the status of laws, axioms, and the like, whereas constructive theories are based on hypothetical constituents. Yet, in functional terms, the difference rests on the stability of postulates within principle theories, which guide the construction of possible constructive theories (Flores 1999).

Nevertheless, it could still be argued that the distinction at stake is not as clear-cut as we think, but rather a matter of degree. For instance, it could be argued that KTG—although it is a canonical example of a constructive theory based on the existence of hypothetical entities (atoms or molecules colliding elastically) upon which thermal phenomena unfold—can be reduced entirely to classical mechanics. All we would need for this is conservation of both energy and momentum through elastic collisions. Therefore, beyond the particle hypothesis, it does not exceed the physics encoded in Newton's laws. In a way, KTG could be a special case of mechanics, and it accordingly could be read as a principle theory rather than a constructive one.

Considering this, Flores proposes a shift in priority, making the functional role the one that should be addressed in distinguishing between theories that function as *framework* for other theories, and theories that instead address *interactions*:

> All principle theories are framework theories and vice versa; all constructive theories are interaction theories, but not vice versa. Thus, Einstein's distinction is a 'special case' of the distinction I have introduced (Flores 1999).

Flores selects the functional criterion over the ontological one to make clearer the distinction between theories. We take this to improve on clarity, without harming the ontological differences at stake between framework and interaction theories. It should be stressed that although we are interested in the ontological consequences of the distinction, it is relevant for our task to be able to clearly identify each theory as framework or interaction in order to explore ontological consequences.

Let us briefly exemplify the distinction with an example. Newtonian mechanics is a case of framework theory: there are three principles (Newton's three Laws) dictating a minimal regulation that any force must obey, independently of the nature of that force. The latter remark is crucial, since Newtonian mechanics does not inform us about the actual nature of specific physical systems instantiating the force. The expression $\mathbf{F} = m\mathbf{a}$ is not a definition of a particular force; it rather indicates how forces and accelerations are connected, and such a connection can potentially be satisfied by any forces of particular physical systems whatsoever. Because Newtonian mechanics does not reveal specific features of particular physical systems bearing the forces in question, $\mathbf{F}$ can be filled with a variety of interactions: gravitational forces, electromagnetic forces, Hooke's law, contact forces, tensions, and so forth. Note that different entities are involved in each case (charged particles in one case, masses attached to springs or pulleys in the other), and the forces behave quite differently (two of the alluded forces *decay with the square of* the distance, whereas the other is *proportional* to the distance). The point, however, is that anything amounting to an interaction at an appropriate scale can potentially satisfy Newton's laws.

It should be noted as well that every force in the aforementioned list is an example of an interaction theory intending to refer to physical systems that actually populate the world. Furthermore, these kinds of interaction theories are the ones that explain physical phenomena and refer to specific physical systems or to their particular properties providing the explanation mentioned by Einstein. In ontological terms, gravitational forces require the existence of a property of physical bodies, namely, their gravitational mass, which acts as the source of the gravitational field. Hence, being a realist about gravitation forces us to believe in the existence of gravitational mass as an actual property that is instantiated by some physical objects. The latter conclusion cannot be derived from Newton's laws only. The same applies to electromagnetism, where charges need to be postulated as a real property of some physical objects. Likewise, if the force at stake is tension, then we are compelled to be realists about ropes or surfaces capable of transmitting the force; to read Hooke's law at face value amounts to being a realist about the existence of specific properties of springs and so forth—where none of these cases is implied solely by Newton's law.

## 3 Two Forms of Realism

Interaction theories presuppose the existence of entities that interact. Those entities, it is claimed, are the ones that constitute the world. To believe in—i.e., to endorse a realist stance on—an interaction theory amounts to acknowledging the existence of such entities. Take again gravity or electromagnetism as examples: the acceptance of the former inclines us to be realists about objects with masses and about gravitational fields, whereas the later leads us to endorse realism about electric charges and electromagnetic fields. By contrast, framework theories entail a different interpretive stance, which we label modal realism, viz., to believe in a framework theory amounts to accepting the validity of mathematics-based structural relations that regulate potential physical processes that must necessarily take place—according to the framework theory—under specific conditions, regardless of the entities instantiating what the framework theory says (Flores 1999).

The distinction between framework and interaction theories proves to be important when dealing with the task of elaborating a coherent ontology. We declared our stance on the realism debate at the beginning of our paper, contending that current best scientific theories are to be the main source of information shaping our view of reality. This, however, calls for further elaboration. In view of the various fundamental theories currently accepted, the challenge is this: some form or another of realism is to be embraced if these theories (be it QFT or SM) are to guide our decisions concerning ontological matters.

In other words—and recurring to contemporary philosophical jargon in the realism debate—the distinction we hold can be expressed as follows. On the one hand, we endorse a form of epistemic realism about the modal structure mathematically described by framework theories, especially when it comes to the laws governing fundamental relations among physical systems. On the other, we endorse a robust form of realism regarding the entities belonging to interaction theories that intend to refer to entities in the world. We believe that such ontological commitment is granted by the scope of the theories in question.

Our proposal should not be interpreted as a promotion of constructive theories only, nor as inviting us to overlook framework theories. By contrast, the latter should be taken seriously when it comes to an informed understanding of the physical world. We warn, however, against straightforwardly adopting ontological commitment *to entities* within framework theories, because they do not generally require us to fully hold their existence. Here is an example: SR and QM are both framework theories that should be taken seriously if we aim at articulating a full picture of the world. Applied to these fine theories, our argument amounts to a warning against, for instance, space–time substantivalism in the case of SR, or ontic interpretations of the wave function in the case of QM. We are not claiming that space–time as a substance or the wave function as an entity are ruled out by our approach. We only contend that ontological commitments to such ontological presuppositions in framework theories are less coherent than endorsing commitment to the modal structure expressed by the mathematics of the same theories.

We are aware that this is all too schematic, and accordingly we shall return to this distinction below in Sects. 4 and 5. For the time being, it suffices to highlight that the distinction between framework and interaction theories, along with the forms of realism we advocate regarding QFT and the SM, contribute to refine our judgment about the extent to which fundamental theories are our best source of information about the building blocks of nature.

## 4 The Case of QFT

QFT can be viewed as the outcome of imposing the rules of SR—in particular, space–time locality and the structure of the Poincaré group—on the framework of QM. The mathematical notion of field is essential to maintain the locality properties of SR, even at the classical level (Weinberg 2005). At a purely formal level, one can see QFT as a *mathematical* consequence of QM and SR.[3]

QM emerges from a series of postulates about the law-like behaviour of systems and observable quantities in the world. We take this to indicate that QM is a framework theory. This appears to be evident in terms of the standard Copenhagen interpretation, as well as in the most formally complete version of the theory in algebraic QM. Likewise, this is true according to other interpretations, such as the Bohmian or the Everettian many-worlds approach. All of them start from roughly the same axioms and mathematical structures for the description of the evolution and measurements of quantum systems.[4]

The framework does not change—Hilbert spaces, the Born rule, the de Broglie principle, etc., but the ontology of the components may be radically different depending on the

[3] This view is generally agreed upon in the physics literature, and it is expressed as follows by Weinberg (2005):

> The reason that our field theories work so well is not that they are fundamental truths, but that any relativistic quantum theory will look as a field theory at sufficiently low energy.

[4] The de Broglie-Bohm interpretation appeals to extra elements apart from those present in the Copenhagen interpretation. Accordingly, it cannot be considered an interpretation of the theory. It rather stands as a version of the theory or as a different theory. Nevertheless, even in this case, both the mathematical and the empirical results are the same. This is also true for other versions—as opposed to interpretations—of QM.

status attributed to the wave-function.[5] Indeed, Clifton et al. (2003) contribute to demonstrate that QM is a theory of principles—or in Flores' characterization, a framework theory—, re-expressing QM in terms of information theory postulates. This equivalence is achieved using the algebraic version of QM as a basis, which, we think, is a top-down type of description of the behaviour of systems and observables. From this top-down approach, which is shared throughout different flavours of QM, it follows that this formalism should be considered a framework theory upon which interaction theories (e.g., theories of electronic, atomic, nuclear or molecular structures) can be constructed.

This was not clear over the development of QM, mainly since many of the initial results involved Schrödinger's constructive approach. Schrödinger explicitly created a wave function intended to provide a complete description of microscopic entities in terms of waves. Compare this with Heisenberg, who opens his 1925 paper as follows:

> The present paper seeks to establish a basis for theoretical QM founded exclusively upon relationships between quantities that in principle are observable (Weinberg 2005, p. 4).

Schrödinger himself famously showed the equivalence between Heisenberg's approach and his own. Therefore, there may not be enough room for a constructive theory after Born's successful interpretation of the wave function in terms of probabilities.

Once we firstly accept that QM is a framework theory; secondly, that the same structure is equally useful for molecules, atoms, electrons, nucleons, and so forth; and thirdly, that no particular information about the entities that are regulated by QM results directly from the theory; then it becomes clear that ontological consequences concerning the entities described by the theory must be carefully evaluated.

The case of SR, it seems to us, is clearer since the original distinction between types of theories used by Einstein was part of a broader effort to explain his theory of relativity (Einstein 1919). The usual construction of SR, which starts from the two principles of the invariance of physical laws and the constant velocity of the speed of light, bears the hallmarks of a framework theory. It introduces no assumption concerning the nature of entities or interactions. By contrast, general principles of universal scope are the starting point for a top-down construction that frames and restricts the modal space for any possible interaction theory.

Hence, given that QM and SR are both framework theories, and that QFT can be viewed as the outcome of imposing the rules of SR on the framework of QM, it is plausible to think that QFT belongs to the same class of theories. This is relevant if we are interested in drawing ontological consequences from QFT. As far as our argument goes, QFT provides a background structure for interaction theories (e.g., the SM), and it is only the entities involved in the latter that are to be taken as (tentatively) real. That is to say, QFT advances the regulative framework for the physical processes involving entities that are described by interaction theories. Again, the sole consideration of framework theories does not allow us to derive ontological consequences. By contrast, QFT delivers the theoretical set up that serves as a formalism that expresses, in a mathematically consistent way, possible constructive theories. As such, QFT deploys the theoretical background underlying the successes of the SM. In this sense, the SM computes and compares with experiments the

[5] See the large number of independent interpretations of the same formal theory as they appear summarized on the Stanford Encyclopedia of Philosophy (Laudisa and Rovelli 2013; Faye 2014; Vaidman 2016; Goldstein 2013; Griffiths 2014).

various properties of *interacting particles*, even though they cannot be granted a proper place in the QFT formalism.

Research in particle accelerators in this field looks into the particles of the SM, which are probed and referred to as real in at least two important senses. First, they are the entities that are accelerated and made to collide and generate empirical data; and secondly, the data obtained is assumed to provide relevant information about measurement results read off from detectors. In the end, this is what helps us determine the particles' *trajectories*, *speeds*, and various other magnitudes. Physicists employ a variety of methods when using field theory to produce predictions of these quantities. In general, such methods require strong assumptions and approximations—the complete separability of particles, i.e., that one can start with them far enough away so that the description in terms of free particles is valid, which is obviously false in theories with confinement such as QCD; or that an infinite (for all purposes) quantity of time elapses before and after a collision event.

The main lesson from Wilson's renormalization group (RG, for short) is that QFT "is, in most general terms, the study of renormalisation group flows" (Costello 2011). A property of generic RG flows, which is extremely relevant in this context, is the *decoupling* of high-energy modes (Collins 1984). This property implies that renormalizable field theories are not sensitive to the microscopic (or high-energy) structure of the physical world. In this—RG induced—view, the various theories included in QFT are only useful as effective theories, with a given range of validity in terms of the amount of energy *exchanged by the particles* in the processes under study.

When dealing with physics beyond the SM, one of the most fruitful avenues of research is the use of effective field theories (EFT) (Costello 2011). Broadly speaking, this runs as follows: a number of non-renormalizable extra-terms are added to the Lagrangian of the SM to model the most probable ('relevant' in the RG sense) corrections to the SM. In this case, the quantum fields work only as an effective description of what happens in the world, which is valid only up to a certain energy scale (generally higher than the energy currently accessible in experiments). This limited range of validity is clearly seen in the non-renormalizability of the effective theory in question. The main goal of the exercise is to evaluate in what way these new terms would affect the *cross sections of collisions and decaying rates of known particles*. In our view, the practice of EFT clearly addresses particles as entities whose reality is granted, which are understood by means of an effective description in terms of fields.

In brief, QFT should be understood as a framework theory that results from the combination of two framework theories, viz., QM and SR. Granted this, QFT is not be read as providing an ontology simpliciter; in particular, the notion of a quantum field is not to be reified just because QFT plays a fundamental role in the articulation of other theories in physics. By contrast, fundamental interaction theories, such as SM, properly inform us about the ultimate constituents of the world. We shall articulate this claim in the next section.

## 5 Reading the Ontology of the SM

Ontological conclusions concerning fundamental entities are better taken from interaction theories than from theories that stand on axiomatic principles playing the role of frameworks. From the viewpoint of fundamental physics, SM as an interaction theory is our best guide for what we currently know about the fundamental entities that make up the world. This tenet, we argue, can be used to outline a coherent ontological interpretation of SM.

This view aligns with the ideas of Wallace (2006, 2011) about the interpretation of QFT (see also Egg et al. 2017) for a detailed discussion of the relevance of this in the larger debate between epistemic and ontic structural realism). Wallace argues, as we do, that QFT is an effective theory approach that is valid at low energies only, in particular at energies much smaller than the Planck quantum gravity energy scale. This implies that the formalized algebraic version of QFT that is behind Haag's theorem cannot be a complete theory. The burden of proof is on this algebraic QFT approach rather than the conventional QFT that relates to experiments:

> ...if AQFT (more precisely, if this supposed interacting algebraic quantum field theory) does not admit quanta in at least some approximate sense, then so much the worse for it: the evidence for the electron is reasonably conclusive (Wallace 2011).

The best interpretation of what Wallace calls "conventional" QFT is the full interaction theory of the SM, i.e., the very particular instantiation of the QFT used by particle phenomenologists to explain experiments, and by particle theoreticians when trying to expand our knowledge of fundamental physics.

SM is based on a set of key ideas, namely QFT, gauge symmetry, and spontaneous symmetry breaking (SSB, via the Higgs mechanism), as well as a specific particle content stemming from observations (i.e., three generations of leptons instead of only one; six flavours of quarks; etc.). Gauge symmetries refer to symmetries in some internal space, associated with a given symmetry group ($SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$ in the standard model)[6]. The existence of symmetry in a theory gives us a further way of comparing the ontological merits of a theoretical construct.[7]

It has been argued that invariance under Lorentz transformations should be used as a criterion for reality (Lange 2001). The rationale behind this is that only those things that are the same for every observer should be considered as possessing an independent reality. Following the spirit underlying these ideas, it seems reasonable to consider as independently real only those entities that stand on their own, and whose existence has some physical consequence or another. If this criterion is adopted, only those entities that are invariant under contingent symmetries that leave the physics unchanged—as for example internal gauge symmetries—should be considered as candidates to be included in the fundamental layers of reality. The particles belonging to the SM fulfill this criterion—they are gauge invariant under the action of the SM symmetry group—, and hence they can be granted a core place in our assessment of scientific ontology.

This discussion leads us to suspect that the notion of a quantum field cannot be real in the sense that fundamental particles are real. Insofar as fields are generically gauge-dependent, a realist position about quantum fields will entail an unnecessary underdetermination of fundamental entities. Note that such underdetermination would be radical so long as it is a requisite for the correct functioning of the theory. This is trivially true for gauge fields such as photons, but it is also true for matter fields (Weinberg 1996; Peskin 1995). Any observable must be gauge-independent, but the fields themselves are not. By

[6] It is worth noting that these internal symmetries are reflected in the spectrum of the theory, and hence as multiplets of particles with the same—or nearly the same—mass, due to a theorem by Weyl (Weinberg 2005). This is indeed the way in which these symmetries were detected (and, more adequately, deduced) in the first place (Kragh 2002).

[7] The purported ontological merit of symmetries is frequently taken for granted. For a discussion of this matter and a proposal that recognizes the ontological priority of conserved quantities over symmetries, see (Romero-Maltrana 2015).

contrast, fundamental particles are routinely seen as gauge invariant, localized states, associated with the observables appearing in experimental devices.

In brief, an ontology of the SM is best understood in terms of *localized, gauge-independent* quantum field configurations, which are naturally associated with the (empirically useful) notion of particle. The SM is a very specific QFT, viz., an interaction theory telling that the ultimate entities in the world must have these properties—as far as we know.

This notion of particle can best be understood by referring to the Källén–Lehmann spectral representation for the propagator of an interacting QFT (Weinberg 1996; Peskin 1995). This expression allows us to see the non-perturbative full propagator of a field theory as an (infinite) sum of propagators of a free (interactionless) field theory. This sum is weighted in terms of a spectral density function, which can be rigorously defined, even in the context of formal algebraic QFT. For a free theory, the spectral density can be seen as a sum over Dirac delta functions of the free particle masses. In an interacting theory, the spectral density will in general be a real positive function of the 4-momentum modulus, with the peaks in this function interpreted as one or many particle states (including possible bound states).

The finite size of the peaks of the spectrum density are due to the unstable nature of most particles. The width of the peak is related in a well-defined way to the unstable particle lifetime. Accordingly, the following approach appears valid: to interpret the spectral density (which is in principle an experimentally measurable function) as describing the energies and lifetimes of particles. These particles are real in the sense here discussed, and they would be the (as far as we know) ultimate constituents of reality. The fact that our framework theories such as SR, QM, or QFT cannot yield a better description of their independent reality would be seen as a limitation of our framework theories and as a lack of a full grasp of the observed experimental results.

Considering SM, we think of reality in terms of particles (as experimentalists and phenomenologists routinely do). The fact that these particles can only be well-defined as 'in' and 'out' states does not deny the fact that particles are the entities suffering reactions inside accelerators. Fields are then effective, theoretical constructs addressing the interaction processes in which particles participate.

At this point, it could be argued that the Higgs mechanism poses a problem for our view. Indeed, the Higgs field, being a scalar, is allowed to have a vacuum expectation value (vev) via SSB. This vev is an entity different from a Higgs particle (it can be thought of as having an independent existence). As it is central to the SM, we can hardly deny its relevance. The acceptance of the vev may involve an implicit acceptance of the existence of the Higgs field as something fundamental. However, there are various indications that a scalar field should not be fundamental (Weinberg 1996), given that its existence leads to the famous hierarchy problem of the SM, due to the strong sensitivity of scalar fields to renormalization effects (and thus to physics at higher energies). Interestingly, the Higgs mechanism rests heavily on the vev, and the vev is gauge invariant although the Higgs field is not (Peskin 1995). This point may be taken as evidence for the existence of the field; yet, a more conservative view is possible. According to the latter, the vev is not necessarily a proof of the existence of the *Higgs field*. Rather, it is just an effective representation that correctly captures the real remnant of vacuum energy at the background associated to a scalar particle. Similar arguments can also be put forward for other physical effects of gauge fields, such as the Aharonov–Bohm effect (Vaidman 2012).

The incompleteness of the SM with respect to phenomena at higher energies (as expected by the hierarchy problem and the open issue of a quantization of gravity) imposes an understanding of this theory as being an EFT, which is only valid within the range of energies we can observe nowadays. If the day comes when theoretical ideas such as supersymmetry or grand unification schemes are neatly worked out and proven, the symmetry groups that are considered to be fundamental will change radically, as well as the nature of the fields themselves. Yet, in this scenario, fundamental particles known to us would be stable enough with respect to such a change. That is to say, if it is the case that the physicists' community demonstrates that a future complete string theory is in agreement with experiments and explains the dynamics of all four forces in a unified view, we would be dealing with fundamental objects—(super)strings—which are not described by QFT as we know it. Particles, however, would still be present in such a framework, having an existence as vibration modes of the purported fundamental strings. In brief, our point is none other than this: what will surely be preserved in a future theory, although perhaps modified, are the particle descriptions, whereas quantum fields will come to be seen as simply effective ways of describing particle interactions at low energies.

## 6 Concluding Remarks

In this work, we have explored the consequences of having two types of theories: those providing a general—usually axiomatic—framework, and those addressing observed interactions of entities in the world, namely, framework and interaction theories, respectively. Each group of theories has specific roles and informs us differently, although coherently, about the nature of reality. Granted that our scientific worldview is to be motivated by current best fundamental physical theories, we recommend embracing a realist stance on the ontological status of fundamental entities described by interaction theories such as the SM. By contrast, we propose a moderate form of epistemic realism about the modal structure governing the fields described in mathematical terms by framework theories such as QFT.

In other words, no thorough conclusions about the ontology of the fundamental nature of reality can be extracted from framework theories only. The epistemic success of QFT amounts to the fact that it provides us with our current best mathematical description of the modal space that frames the possibility for actual physical interactions to take place. We call it modal since it sets forth the conditions to be satisfied by actual physical processes. Similarly, the epistemic success of the SM consists in delivering our current best physico-mathematical description of the properties of various fundamental particles that are to be granted ontological rights. It is these fundamental particles that, as far as we know, furnish the world.

Throughout our argument, we have shown why the formal QFT should be considered a framework theory only. Reason for this is the fact that it emerges from the convergence of two framework theories, viz., SR and QM. This enables us to avoid the present-day enthronement of QFT by philosophies of physics, which broadly purports to reify the reality of fields in terms of relations without relata (Ladyman et al. 2007; Ladyman 1998). Such attempts face serious problems when RG flows are considered, insofar as RG discloses QFT's effective character (as manifested in the decoupling of high-energy modes). Furthermore, we emphasize that although QFT is routinely used in day-to-day research in high-energy physics as a general tool to calculate or predict empirical outcomes, observational data and experimental manipulations are achieved considering particles—and not fields—as the relevant interacting physical objects. This explains why the techniques of QFT are only employed once we introduce assumptions or approximations that are clearly wrong for field theories including interaction or confinement. Likewise, recall that the acceptance of fields as the fundamental objects of reality entails a spurious underdetermination of fundamental objects due to the gauge dependency of fields (as opposed to the invariance of physical observables under gauge transformations). We can avoid this arguing that we should not derive ontological claims about the fundamental nature of reality from QFT alone.

Our argument forces us to question the ultimate reality of fields as primordial building blocks of the world. Do we embrace an outright anti-realism about the fields described by QFT? No, we need not do that. We do not take the various quantum fields to be mere fictions or useful instrumental conventions. We need not commit ourselves to the claim that fields do not exist. Instead, we remain agnostic about their ontological status and still endorse a moderate form of epistemic realism that assumes that QFT describes fields in terms of the modal space that sets out the conditions to be satisfied by any interaction theory such as the SM.

Accordingly, we have argued that the interaction theory of the SM should be taken into consideration in regard to building a coherent ontology of fundamental entities in view of present-day physics. Such an ontology rests on the idea of particles. And the fact that particles cannot be consistently constructed as excitations of interacting quantum fields does not diminish their validity as the most fine-grained components of nature as we know it. By contrast, this inability of QFT to fully recover the microscopic notion of interacting particles should be seen as further evidence of the *effective* character of QFT, and the fact that QFT is an *incomplete* framework.

Certainly, when reading the ontology of the SM, we are aware that this theory is not final in any strong metaphysical sense. Rather, we are open to embracing the possibility that the notion of particle as a fundamental building block may be redefined or enriched in future investigation. Be that as it may, we fail to see how the notion of particle could possibly be entirely eradicated from our view of reality. Future theories may reveal currently unknown properties and interactions of present-day particles, or perhaps some underlying sub-structure; but the empirical success of the SM ensures that such properties and interactions must constitute a unity at low enough energies to be compatible with our current conception of fundamental entities.

## References

Bain, J. (2000). Against particle/field duality: Asymptotic particle states and interpolating fields in interacting qft (or: Who's afraid of haag's theorem?). *Erkenntnis*, *53*(3), 375–406.

Baker, D. J. (2009). Against field interpretations of quantum field theory. *The British Journal for the Philosophy of Science*, *60*(3), 585–609.

Clifton, R., Bub, J., & Halvorson, H. (2003). Characterizing quantum theory in terms of information-theoretic constraints. *Foundations of Physics*, *33*(11), 1561–1591.

Collins, J . C. (1984). *Renormalization: An introduction to renormalization, the renormalization group and the operator-product expansion*. Cambridge: Cambridge university press.

Costello, K. (2011). *Renormalization and effective field theory* (Vol. 170). Providence: American Mathematical Society.

Eddington, A. (2012). *The nature of the physical world: Gifford lectures (1927)*. Cambridge: Cambridge University Press.

Egg, M., Lam, V., & Oldofredi, A. (2017). Taking particle physics seriously: A critique of the algebraic approach to quantum field theory. *Foundations of Physics*, *47*, 453–466.

Einstein, A. (1919). Time, space, and gravitation. *Times (London)*, pp. 13–14.

Faye, J. (2014). Copenhagen interpretation of quantum mechanics. In E. N. Zalta (Ed.), *The Stanford Encyclopedia of Philosophy*. **(Fall 2014 edition)**. http://plato.stanford.edu/archives/fall2014/entries/qm-copenhagen/.

Flores, F. (1999). Einstein's theory of theories and types of theoretical explanation. *International Studies in the Philosophy of Science*, *13*(2), 123–134.

Fraser, D. (2008). The fate of particles in quantum field theories with interactions. *Studies in History and Philosophy of Science Part B: Studies in History and Philosophy of Modern Physics*, *39*(4), 841–859.

French, S. (2014). *The structure of the world: Metaphysics and representation*. Oxford: OUP.

Goldstein, S. (2013). Bohmian mechanics. In E. N. Zalta (Ed.), *The Stanford Encyclopedia of Philosophy*. **(Spring 2013 edition)**. http://plato.stanford.edu/archives/spr2013/entries/qm-bohm/.

Griffiths, R. B. (2014). The consistent histories approach to quantum mechanics. In E. N. Zalta (Ed.), *The Stanford Encyclopedia of Philosophy*. **(Fall 2014 edition)**. https://plato.stanford.edu/entries/qm-consistent-histories/.

Haag, R. (2012). *Local quantum physics: Fields, particles, algebras*. Berlin: Springer.

Howard, D. A. (2015). Einstein's philosophy of science. In E. N. Zalta (Ed.), *The Stanford Encyclopedia of Philosophy*. **(Winter 2015 edition)**

Kragh, H. (2002). *Quantum generations: A history of physics in the twentieth century*. Princeton: Princeton University Press.

Ladyman, J. (1998). What is structural realism? *Studies in History and Philosophy of Science*, *29*, 409–420.

Ladyman, J., Ross, D., Spurrett, D., & Collier, J. G. (2007). *Every thing must go: Metaphysics naturalized*. Oxford University Press on Demand.

Lange, M. (2001). The most famous equation. *The Journal of philosophy*, *98*(5), 219–238.

Laudisa, F., & Rovelli, C. (2013). Relational quantum mechanics. In E. N. Zalta (Ed.), *The Stanford Encyclopedia of Philosophy*. **(Summer 2013 edition)**. http://plato.stanford.edu/entries/qm-relational/.

Peskin, M. E. (1995). *An introduction to quantum field theory*. Westview Press.

Romero-Maltrana, D. (2015). Symmetries as by-products of conserved quantities. *Studies in History and Philosophy of Science Part B: Studies in History and Philosophy of Modern Physics*, *52*, 358–368.

Vaidman, L. (2012). Role of potentials in the Aharonov–Bohm effect. *Physical Review A*, *86*, 040101.

Vaidman, L. (2016). Many-worlds interpretation of quantum mechanics. In E. N. Zalta (Ed.), *The Stanford Encyclopedia of Philosophy*. **(Spring 2016 edition)**. http://plato.stanford.edu/archives/sum2002/entries/qm-manyworlds/.

Wallace, D. (2006). In defence of naiveté: The conceptual status of lagrangian quantum field theory. *Synthese*, *151*, 33.

Wallace, D. (2011). Taking particle physics seriously: A critique of the algebraic approach to quantum field theory. *Studies in History and Philosophy of Modern Physics*, *42*, 116.

Weinberg, S. (1996). *The quantum theory of fields* (Vol. 2). Cambridge, UK: Cambridge University Press.

Weinberg, S. (2005). *The quantum theory of fields* (Vol. 1). Cambridge, UK: Cambridge University Press.

**Diego Romero-Maltrana** obtained his Ph.D. in Physics in January 2011 at the Pontificia Universidad Católica de Chile with a study of the phenomenology of a Higgs triplet model containing a light fermiophobic Higgs-like boson. Hi was part of the e-\gamma trigger group of ATLAS at CERN from 2009 until 2011. Then he obtained an Mst. in Philosophy of Physics at Oxford University in 2013, and currently is an Associate Professor of Physics at the Instituto de Física, Pontificia Universidad Católica de Valparaíso.

**Federico Benitez** obtained his Ph.D. in Physics from the University of Paris 6 in 2013. His specialisation is the formal aspects of the use of renormalisation group methods in field theories. After obtaining his Ph.D. he performed postdoctoral research stays in the Max Planck Institute in Stuttgart, Germany, and in the Universities of Bern and Zurich in Switzerland. He is currently undertaking a second Ph.D. in the Philosophy of Physics under the advice of Prof. Michael Esfeld in the University of Lausanne.

**Cristian Soto** is assistant professor of philosophy at the Departamento de Filosofía, Universidad de Chile. He received his Ph.D. at the University of Melbourne, where he articulated a minimalist approach to the metaphysics of science, addressing such issues as the sources and boundaries of scientific ontology, the physico-mathematical structure of scientific laws, the epistemic reading of the indispensability argument in the philosophy of mathematics, and the role of models in scientific thinking. He is currently undertaken a Chilean governmental funded research grant (2016–2019) on the philosophy of scientific laws. As part of this investigation, he has visited the Department of Philosophy at the University of Miami, USA, and will hold a visiting fellowship appointment at the Centre for the Philosophy of Natural and Social Sciences, London School of Economics and Political Science, England, over April–June 2018.