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The Underdetermination of Metaphysics by Physics (An Open Problem With a Case Study)

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The aim of this paper is to discuss the problem of the underdetermination of metaphysics by physics. It is, in fact, possible to show that different metaphysical options are available to interpret the same physical theory. However, physics cannot help to decide which is the most correct one. In particular, in this paper I will focus on the case study of quantum field theory (and its algebraic formulation). I will show that there are at least two metaphysical theories that can be considered as legitimate interpretations of the theory. Yet, no choice can be made between them by only physical means, and we need to appeal to non-empirical criteria. I will show why such criteria

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are not eventually compelling from a naturalistic perspective. I will conclude the paper with a proposal of a pragmatic solution to this open problem.

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1. Introduction (or, why it is an open problem)

The contemporary debate on the underdetermination of scientific theories can be traced back to the historian and philosopher of science Pierre Duhem. In his *The Aim and Structure of Physical Theory*, Duhem discusses several cases of underdetermination in the context of different physical theories, and claims that this would be a serious problem with respect to the confirmation of scientific theories. This analysis led to the Duhem-Quine Thesis, according to which an individual theoretical proposition cannot confirm or falsify a scientific theory – that is, we always need to consider (ideally) the whole set of theoretic propositions that compose the theory (or a set of propositions that belong to other relevant scientific theories). The main reason for this claim is that individual theoretical propositions are underdetermined by empirical evidence. In other terms, an individual theoretical proposition can be compatible with different sets of empirical data. That is, empirical evidence would not suffice to uniquely determine which theoretical propositions are confirmed or not. As said, Duhem shows several examples of such an underdetermination and concludes that the only possible solution is to consider a series of theoretical propositions *holistically*, that is, theoretical propositions can be confirmed or falsified only with respect to a set of other scientific propositions that are part of the same theory or of other theories, which are relevant in the case of the proposition that we want to confirm or falsify.

Moreover, the underdetermination of scientific theories by empirical data has been also used as an argument in favor of the anti-realism about scientific theories. For, if the theoretical propositions might be not uniquely determined and confirmed by our evidence, we cannot be sure of what set of propositions describes correctly a series of phenomena, and hence we cannot be sure of

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which scientific theory is the correct theory for that series of phenomena either.[1]

Such a debate has also produced some of the most interesting philosophical proposals of the last century. For instance, on the one hand, we can mention structural realism, which was originally proposed by Worrall (1989) in order to define a new form of scientific realism, which would allegedly be immune from the problems of the precedent forms of scientific realism, and that is still discussed both in the context of the debate on scientific realism and on the ontology of scientific theories. On the other hand, the refusal of scientific realism led to a defense of instrumentalism and empiricism. One of the most interesting and discussed anti-realist proposals is Van Fraassen's constructive empiricism, which, in a sense, is strictly connected with the metaphysical theory that I will discuss in this paper. Van Fraassen (1980), in fact, claims that one has to be agnostic on theoretical terms about non-observables entities, and furthermore one has to be agnostic also on the metaphysical claims about scientific theories. In other terms, the fundamental aim of science is only to provide an explanation of our observations and experimental results.[2] I will come back to these issues in the final part of this paper.

Now, since these proposals have all received a great attention in the literature, in this paper I want to focus on another specific form of underdermination, which emerges in the context of the metaphysics of science. In particular, I will focus on the naturalistic metaphysics and on the problem of the underdetermination of metaphysics by physics.

Naturalistic metaphysics aims to provide an explanation of the metaphysical structure of the world based on our best scientific theories, and, in particular, on our best physical theories. This approach considers the relation between metaphysics and science as a fundamental element of our inquiry. On the one hand, in fact, one can argue that metaphysics should have its own methodological autonomy and, then, define and develop its own methods and concepts. On the other hand, however, it should be *tested* – though indirectly – with respect to its applicability to our scientific theories – that is, physical theories. For instance, French and McKenzie (2015) define metaphysics as a *toolbox*, which provides an analysis and the definition of all

[1] The literature on the problem of the underdetermination of scientific theories by empirical data is vast, and to discuss it is beyond the scope of this paper. The interested reader can see Stanford (2009) for a nice reconstruction of the historical origin of this problem and of its implications for the contemporary debate.

[2] Again, the interested reader can see respectively Ladyman (2023) for structural realism and Monton and Mohler (2021) for constructive empiricism.

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the concepts that we need (and actually use) to interpret our scientific theories and their experimental results. Moreover, Morganti (2013) defends an *experimental metaphysics*, which is a metaphysics that should be always tested with respect to the structure of our scientific theories. In particular, the fundamental idea is to analyze the relation between the empirical predictions of our scientific theories and the interpretations that we have provided for those theories. If a metaphysical interpretation of a theory does not allow to explain a set of empirical predictions, then that metaphysical interpretation should be discarded.[3] For instance, one of the most interesting debates about the metaphysical interpretation of quantum mechanics concerns the individuality or the non-individuality of quantum particles. We have in fact different metaphysical theories for the notion of individuality and we should show which one is compatible with the specific part of the formalism of quantum mechanics that describes the particles, and which one is not. In other terms, we should carefully study the structure of the theory and the properties that we can ascribe to (and measure for) quantum particles, and then sort out all the metaphysical notions of individuality that cannot account for what we know about quantum particles. Now, the *Received View* is that quantum particles cannot be genuinely considered as individuals, even though the debate is not yet settled and leaves room for a form of metaphysical underdetermination between the two positions, namely the interpretation of the theory in terms of individual particles and the interpretation in terms of non-individual particles.[4]

Now, if we adopt a naturalistic approach to metaphysics, we need to consider those scientific and physical theories that aim to describe the world at the most fundamental level. For, if our naturalistic metaphysics aims to provide an explanation of the fundamental structure of our reality, we need to take into account those theories that give us a scientific explanation of that level.[5] I think that the physical theory that better respects this requirement is

[3] This is only a brief and schematic presentation of Morganti (2013)'s proposal. See, in particular, the second chapter of Morganti (2013) for a complete discussion of this proposal.

[4] The discussion of this debate is beyond the aim of this paper. The interested reader can see French and Krause (2006) for a good introduction to this debate. See also Arroyo, Arenhart and Krause (2023) for a recent analysis of the implications of this debate for what concerns the more general problem of metaphysical underdetermination.

[5] Even though it is possible to claim that a scientific theory can explain our world by itself, I think that it is important to spell out which are the metaphysical assumptions that are implicitly assumed by that theory. For instance, suppose that we accept the standard formulation of quantum mechanics and its ontology in terms of particles. The theory itself does not suffice to decide which is the nature of those particles, that is, if they are individuals or not. On the one hand, standard quantum mechanics gives us a *physical explanation* of our

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Quantum Field Theory (QFT). QFT allows to explain the behavior of matter and radiation taking into account both the quantum physics and the special theory of relativity. QFT is at the basis of our Standard Model of elementary particles, and hence it is the background theory of our best explanation of the structure of matter and its interactions. However, it is not easy to provide a metaphysical interpretation of such a theory. On the one hand, there is a long discussed problem with respect to the ontology of the theory: is it a theory about particles, or fields, or events?[6] On the other hand, from a broader metaphysical perspective, there is a problem of underdetermination: different metaphysical theories are actually compatible with the structure of the theory. Since the first problem has received a great attention in the literature, I think that it would be interesting to focus on the latter, which is not yet properly discussed.

In this paper, I will specifically consider the algebraic formulation of QFT, namely the Algebraic Quantum Field Theory (AQFT). I will not enter here in the debate about the preferability of either the standard Lagrangian formulation of QFT or AQFT (see, for instance, Wallace (2006) and Fraser (2008)). I think, however, that AQFT can be properly understood as an algebraic reformulation of QFT, rather than a different theory, which will eventually be empirical equivalent. On the one hand, it is true that AQFT has not yet produced complete and rigorous models of interacting QFTs in four dimensions, as one needs in order to reproduce the results of quantum electrodynamics, quantum chromodynamics and local gauge theories in general. It is also true that there is not yet a complete and rigorous algebraic model for the Standard Model of elementary particles. However, on the other hand, several interesting algebraic models have been formulated in the context of Constructive QFT. Such models reproduce the structure of the standard Lagrangian formulation of the theory and of the interaction dynamics. There are some nice results also for what specifically concerns four-dimensional models that actually seem to satisfy both the standard axioms of AQFT and the mathematical structure of the Lagrangian formulation of QFT, and of the renormalization procedure as well. In particular, it is possible to provide four-dimensional models for a perturbative QFT, which are renormalizable and can account for the scattering dynamics.[7]

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world in terms of particles and their dynamics. On the other hand, we still need a *metaphysical explanation* that gives us a clear definition of, say, what a particle is, if it is an individual or not, and so on.

[6] See, for instance, Bain (2000), Baker (2009), Kuhlmann, Lyre and Wayne (2002), Kuhlmann (2020) and Rossanese (2013) and (2016).

[7] The aim of Constructive QFT is to provide algebraic models in the context of AQFT,

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Now, the problem with these algebraic models is that they contain some arbitrary parameters that have not yet been explained in terms of algebraic principles, as the axiomatic reconstruction of the theory would require. However, even though some of these models can be then considered as essentially instrumentalist computation techniques, I think that the same can be claimed also about the standard Lagrangian formalism of QFT, where we use renormalization techniques to rescale certain non-physical parameters. There is still work to be done, but I think that we are going in the right direction.

Moreover, AQFT has a clearer hierarchical structure and this in turn allows a clearer metaphysical analysis. I think then that we can consider AQFT as the correct formal background in order to discuss about metaphysical underdetermination.

There are, in fact, several metaphysical proposals on the table, but I think that it is possible to consider two fundamental alternatives in the literature. On the one hand, we have to consider a *monist metaphysics*; while, on the other hand, we must take into account the so-called (*quantum*) *holistic metaphysics*. Of course, there are several possible different approaches to these two main alternatives, as we shall see. In any case, the choice of the correct metaphysical option is underdetermined[8] and, therefore, I think that this case study can represent a good example of an open problem with respect to the relation between metaphysics and physics.

2. The Monist Scenario

A *monist metaphysics* for quantum theories has been suggested, for instance, by Schaffer (2010) who contends that the "cosmos is a one vast entangled system" (Schaffer, 2010: 52). First of all, it is important to notice that *monism* considers the universe as a unique ontological entity. As we will see,

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which can account for the relevant physical dynamics represented by the standard Lagrangian formulation of QFT and its effective theories. Summers (2016) provides an interesting explanation of all these models and compares the results of each of them. In particular, Summers discusses the modular localization for particle models, non-trivial S-matrices models within the Haag Ruelle scattering theories and perturbative AQFTs. See Fredenhagen and Rejzner (2015) for a more specific account of perturbative theories and Buchholz and Dybalski (2023) for a recent discussion of the new results of these approaches. See also Fraser and Rejzner (2023) for an interesting philosophical analysis.

[8] As said, in this paper I will focus only on the metaphysical underdetermination of the theory. For other forms of underdetermination in AQFT and in scientific and physical theories, see respectively Kuhlmann (2020) and Stanford (2009).

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however, it is possible to define at least two different forms of monism. On the one hand, there is *existence monism*, which is the view according to which there exists one and only one actual concrete object, that is, there is only the universe. On the other hand, there is *priority monism*, which holds that only one concrete object (the universe) is fundamental. However, the universe has *parts* that exist as "fragments" of the whole. According to *priority monism* the whole is therefore *ontologically prior* to its parts. As we will see, these two different forms of monism can be compatible with the formalism of AQFT, and can be legitimately considered as metaphysical interpretations of the theory. I will also show how these two forms of underdetermination can be compared with respect to a theory of physical composition proposed by Healey (2014).[9]

As said, Schaffer proposed his monist interpretation with respect to the entangled structure of the universe. It is interesting to note that the problem of the entanglement has been considered in quite the same terms also by Lam (2013), who in fact starts from this sort of considerations in order to justify his structuralist interpretation of AQFT.[10] The entanglement structure of AQFT is grounded in the algebraic structure of the theory. In AQFT the main objects of study are the algebras of observables rather than the observables themselves. The fundamental idea of AQFT is that the physical content of a system described by AQFT is not encoded in an individual algebra of observables, but rather in the mapping $O \rightarrow A(O)$ from regions O of

[9] Healey's theory of physical composition is particularly interesting for two reasons. On the one hand, it provides a theory of composition that is, in a sense, *pragmatic* and context-dependent. This means that the definition of a certain physical composition can be tested only when a certain physical context is specified, and hence depends on the actual compatibility with the empirical content of the theory – then, for this reason, it is compatible with the naturalistic metaphysics that is the main philosophical thesis discussed in this paper. On the other hand, it provides a general framework that is compatible with both the existence and priority monism, and thus provides a common background framework to make a comparison between these two forms of monism.

[10] A structuralist interpretation of a physical theory considers the mathematical/physical structures of the theory as the fundamental ontology. In other terms, The standard basic idea of a structuralist interpretation of a physical theory is that *structures* occupy the most fundamental ontological level of the theory. See, for instance, Rossanese (2016). However, as pointed out, by Morganti (2011), there is an important question that adherents to this strategy ought to answer: that is, what does it mean for an object and its properties to be, say, reduced to an invariant and for a symmetry (or an algebra) to be primitive? We can in fact define two categories: (i) the category of *abstract* and *formal structures* and (ii) the category of *concrete things*, i.e. *physical objects*. Some authors contend that there is no need to explain how the "physical" can be extracted by the "formal" (see, for example, Ladyman and Ross, 2007). However, even though this position is problematic, it cannot be discussed here – in any case, it must be noticed that some arguments can be provided in favor of it.

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Minkowski space-time to algebras of local observables *A(O)*, the so-called net of algebras. Such a mapping determines which observables are localized and then take value in the space-time region *O*. Another important notion here is that of a quasi-local algebra that includes global limits of the local observables as, for example, the total charge observable. The elements of an algebra represent, roughly speaking, the physical operations that can be performed in a certain space-time region which is associated with that algebra. Given that only finite regions of space-time are considered, we have to work with local observables and hence with their related local algebras of observables. The latter assumption is justified in order to implement the principle of locality: that is, measurements in a given spatial region must not depend on any measurements taken in a different spatial region. However, in AQFT quantum field systems are *unavoidably* and *intrinsically* open to entanglement.[11] On the one hand, we have the Reeh-Schlieder theorem that shows that the vacuum is entangled across many space-like separated regions. This means that it is (almost) impossible to isolate a system described by fields from outside effects. Moreover, the local algebras considered in AQFT are *type-III algebras*, and this kind of algebras *does not contain any projection operator*, and allows for no decomposition into well separate sub-systems. This means that there are many regions of space-time within which no local operations can be performed that will *disentangle* that region's state from that of its space like complement.[12] Since the *fundamental entanglement* and *non-separability* of quantum field systems is exemplified by the type-III structure of the algebra, Lam claims that we have to take the *local algebras* as the *primitive* and *fundamental* structure of AQFT.[13] Every other structure emerges from the general algebraic structure. For instance, one can argue that the topological, differential and metrical space-time structures can be derived from the *primitive algebras*.[14]

Now, a (Schafferean) argument in favor of a monist understanding of AQFT may thus be proposed as follows:

[11] For an introduction to different possible definitions of entanglement and their philosophical implications, see Earman (2015).

[12] See Halvorson and Mueger (2007) for a complete and rigorous analysis of the structure of the algebra of AQFT and the Reeh-Schlieder theorem. See also Ruetsche (2012).

[13] See Wilson (2021) for an interesting analysis of the notions of *primitiveness*, *foundamentality* and *emergence* in metaphysics.

[14] See, for instance, Dieks (2001: 237-238).

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1) In a pluralist view of our physical world, there should be a *Democritean account* for entanglement relations;[15]
2) Such an account should be spelled out in terms of particles (or fields) *plus* entanglement relations;
3) In AQFT, there are no particles (and no fields);[16]
4) Thus, we would have only entanglement relations;
5) But, such entanglement relations are spread over all the universe;
6) Hence, entangled systems are fundamental wholes;
7) Since the cosmos is an entangled system, then the cosmos is a fundamental whole.[17]

If one accepts the monistic viewpoint, it is then possible to account for *emergent properties* of the whole as *interactions* take place. In connection to this, two key notions are those of a *regional property* and of *regional instantiations*. On the one hand, we can define *regionalized properties*: the universe described by AQFT might be heterogeneous for it has a certain *charge relation to here* and *another charge relation to there*. On the other hand, we can define the notion of a *regionalized instantiation.* According to this account, the universe described by AQFT might be heterogeneous for *it instantiates-here a certain charge* and *instantiates-there another charge.*[18] In the context of AQFT, then, one may claim that the *emergence* of *regional properties* (or of *regional instantiations*) occurs whenever there is an interaction over the vacuum sector, through the action of an (unobservable) field or, in a sense, through a measurement.

[15] According to a *Democritean account* of the physical world, there is a plurality of entities that are the ontologically fundamental *building blocks* of the physical world itself.

[16] See again Kuhlmann (2020).

[17] French (2010: 105) seems to suggest something along the same lines: "A 'global' bounding of the relevant polyadic properties will yield the blob as structure of the world, with a 'local' bounding of the relevant properties giving us the putative 'objects'." Here the *blob* is what Schaffer calls cosmos. Horgan and Potrc (2000: 253) defend a similar position: "Our own world, in all its glorious complexity and spatio-temporal variation, does not have any real parts. Indeed, this is a conceptually coherent ontological framework for physics, especially if one focuses on broadly field-theoretic formulations of physical theories." In fact, French explicitly acknowledges that he takes his cue from the work of Horgan and Potrc.

[18] Schaffer (2010) discusses this point in terms of the problem of the *qualitative heterogeneity* of the whole. Our universe in fact exemplifies remarkable qualitative heterogeneity both spatially and temporally. Schaffer suggests then to consider also the notion of *distributional property* and take it as metaphysically fundamental. For example, being polka-dotted, or being hot at one end and cold at the other are examples of distributional properties. For a closer look at this issue and for the notion of distributional property see also, e.g., Parsons (2004) and McDaniel (2009).

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Schaffer's monism in fact does not eliminate the possibility for the fundamental whole to have *proper parts*: the fundamental whole should be only considered as *ontologically prior* to its parts. On the contrary, French (2010) seems to deny such a possibility, as he insists on an *eliminativist account* according to which there are no proper parts of the whole: parts can be considered only as *conceptual constructions*, rather than real physical aspects of our world.

In any case, to take a stance on these matters, I think that it is useful to look a bit more closely at the notion of composition that is in play in the context of AQFT. Healey (2014) provides an interesting analysis of the notion of composition in the context of different physical theories. He proposes a *pragmatic view*, according to which composition is *context-dependent*. The idea is then to answer, e.g., "the sunlight is composed of photons" when we have to deal with photo-detectors experiments and "the sunlight is composed of electromagnetic fields" when we have to deal with continuous process. Healey writes that "What constitutes composition is negotiable, and not settled prior and independently of any considerations advanced in the process of answering it." (Healey, 2014: 53) Healey then claims that "a system mat have more than one incompatible partition into constituents parts." (Healey, 2014: 61). A *physical composition relation* must prove its worth in the "empirical arena", by facilitating novel predictions or powerful explanations of experimental and/or observational findings.[19]

I agree with this *deflationary view* of composition in physics, but also think that more details can, and should, be added in the present case. In the context of AQFT, we could, for instance, consider spatio-temporal *regions* as the proper parts of the fundamental whole, that is, of the universe. Spatio-temporal regions and the relevant local algebras of observables associated to those regions are in fact the basic elements of the theory (as stressed, for example, also by Lam (2013)). However, given the Reeh-Schlieder theorem and the type-III structure of the local algebras of observables,[20] that is, given the *fundamental non-separability* of quantum field system, all these spatio-

[19] This position is in a certain sense similar to that of Varzi (2011) who defends the idea that the *boundaries* of common material bodies involves some degree of *arbitrariness*. Varzi claims that in the majority of the cases we ascribe *de dicto* boundaries to things and such *de dicto* boundaries make things to exist, that is, such boundaries are *fiat* boundaries. He then states that under a closer look all the boundaries are *de dicto* boundaries and therefore there are no genuine *de re* boundaries. In a sense, then, one can claim that every kind of ontological separation is arbitrary.

[20] See Halvorson and Mueger (2007) and Lam (2013) for a detailed discussion of the importance of the type III-structure of the local algebras of observables for what concerns the formal structure of AQFT and its ontological and metaphysical interpretation.

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temporal regions are *intrinsically related* (that is, *intrinsically entangled*) and therefore the whole universe could be considered as *ontologically prior* to its parts and thus *ontologically fundamental*. This would be an argument in favor of Schaffer's form of monism, namely *priority monism*.

Recently, Ismael and Schaffer (2016) have proposed a more detailed account of this monist metaphysics for quantum theories. In particular, they try to explain *quantum non-separability* with the notion of *common ground*, that is, a *common metaphysical ground* (that is, *cause*), which stands for a more unified underlying reality. In quantum theories, *non-separability* seems to show that the "coordinated randomness" of entangled systems corresponds to a failure of (standard) *mereological supervenience.* This means that the whole system has an intrinsic state that fails to supervene on the intrinsic states of its *proper parts plus their spatial relations.* They write that "there is an interpretative pressure to regard the separated components of entangled systems as grounded in the whole integrated entangled system, and thus to regard quantum mechanics as a theory that portrays entangled wholes as more fundamental than their parts." (Ismael and Schaffer, 2016: 20)

However, it is also possible to insist that Healey's *pragmatic approach* described above is only a reflection of our conceptualization of the physical world, without any necessary connection to the physical reality. This would lead to the conclusion that spatio-temporal regions are not proper parts of the fundamental whole. The only existent stuff is the whole, and we intend "parts" only as an artifact of our way to talk of the whole. Of course, this second alternative would rather support French's form of monism, *existence monism*.

In any case, I think that AQFT alone does not allow to make a clear decision between these two forms of monism, since both are compatible with the formalism and depend only on a different use of the notion of composition.[21]

[21] The underdetermination between *priority monism* and *existence monism* is not the only underdetermination that occurs in the metaphysics of AQFT. There are other metaphysics that can be compatible with the formalism of quantum theories and AQFT in particular. On the on hand, for example, there is Wallace and Timpson (2010)'s *spacetime state realism*, which is an ontology where the whole universe is divided into sub-systems, and density operators are assigned to the whole system and to each subsystem. However, this proposal faces a problem: entanglement relations does not allow to recover the density operator for the whole system from the density operators for any partial sub-systems. This means that it is necessary to assign a density operator also to the whole universe, which makes it redundant to assign any density operators to any sub-systems, given that the latter are mathematically derivable from the density operator of the whole universe. But, of course, if

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3. The Holistic Scenario

Teller (1986) and more recently Morganti (2009) and Calosi (2014) point out that it is possible to define a notion of *quantum holism*, where the fundamental metaphysics might include *particles*, their *intrinsic properties*, and *spatio-temporal relations*, but also *entanglement relations.* Such a proposal does not posit a fundamental whole, but rather a *new fundamental relation among fundamental parts*. More generally, several authors claim that a monist metaphysics does not necessarily follow from the considerations made so far. Indeed, several philosophers have recently attempted to defend a form of *Humeanism* in the quantum domain – whereby, in spite of entanglement, reality can nevertheless be conceived in terms of a *mosaic of local matters of fact*. This metaphysical option too seems to be compatible with the formalism of AQFT. Bhogal and Perry (2015), for example, define a *Two-State Humeanism*, where entanglement phenomena depend on the *whole mosaic*. The complete physical state of any region *O* is determined (supervenes on) the intrinsic physical states (and relations between) *O*'s sub-regions. They then define the notion of *L-state* as a state that is grounded *holistically* by the *entire mosaic.* This framework is conceived as the *best way* to systematize the world (in the same sense as the Humean conception of laws). That is, it is the best balance between *simplicity* and *informativeness.* This proposal seems to be implementable in the case of AQFT quite easily, where the entire mosaic is given by the vacuum sector (which represents the whole universe), and the sub-regions are the different – but intrinsically entangled – spatio-temporal regions. Another interesting interpretation is proposed by Morganti and Calosi (2016), who claim that the c*omposition process* is active and productive, in the sense that at a certain moment of time *composition* has taken place. *Composition* counts then as the *cause* of the existence of the (emergent) properties of entangled systems. They write that "when composition occurs it is just mereological composition, and yet the properties of the whole can have some degree of non-trivial variation, for they are at least partly dependent on which physical interactions are responsible for the composition in question to occur." (Morganti and Calosi, 2016: 1183) Morganti and Calosi claim then that entangled systems *emerge* from the interaction between different physical systems, leading to the emergence of some new properties that are specific of the entanglement relations. While distancing itself from Humeanism, this account of *quantum composition* does

we assign a *fundamental density operator* only to the whole universe, we would have a metaphysics that is equivalent to that proposed by Ismael and Schaffer.

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not eliminate the notion of part, nor does it posit the whole as ontologically prior or fundamental. In this context, the quantum world can be considered as a *net of relations plus the individual quantum systems which are related by entanglement.*

Recently, Morganti (2018) and Calosi and Morganti (2021) developed their proposal into a more general metaphysical theory, which they call *metaphysical coherentism*. The authors claim that their metaphysics is not *vertical* – whose inquiry is characterized by the search for the fundamental level of the reality –, but rather *horizontal*: what is important here is in fact the definition and the description of the *structure of mutual dependence among the physical objects.* The main idea is to consider *entities, which are mutually related into a structure*. That is, there is a series of *mutual dependence relations among objects*: physical objects and the relations they enter to are, ontologically speaking, *on a par*. Physical objects and the structural relations among them are then mutually defined by the *dependence chain* given by the structure itself. However, it is important to notice that this proposal does not necessarily need to posit the existence of a whole (which should be prior to its parts), and then it must be kept apart from other holistic metaphysics, such as Ismael and Schaffer's, which has been discussed above. In any case, Calosi and Morganti's framework too can be accommodated to the case of AQFT. As mentioned above, we can suppose that the individual quantum systems are the spatio-temporal regions with the relative associated algebra of observables, which are *intrinsically related* by the entanglement relations that were created by certain interactions that took place at a certain time of the evolution of the universe. In particular, it is interesting to note that Calosi and Morganti (2021) apply their metaphysical theory to the interpretation of quantum entanglement. The upshot of their analysis is to consider quantum entanglement as the result of quantum interactions among quantum objects (such as quantum particles), which determined (anti-)symmetric ontological dependence relations.[22] Fair enough, this goes exactly on the same lines of what we are proposing throughout this paper. All the spatio-temporal regions are then *relationally connected*, but without any necessary need to posit the priority of the whole, nor the reducibility of individual systems to relations.

A final interesting metaphysical proposal that seems to be relevant here has been discussed by Dasgupta (2009), who claims that the world is a *purely qualitative mosaic*. Dasgupta defines what he calls *algebraic generalism:* various qualities are stitched together by certain *algebraic operators* (such as,

[22] See Calosi and Morganti (2021) for the details of their proposal.

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e.g., a *conjunction operator*, a *negation operator* and a *permutation operator),* and individual facts *plurally* hold in virtue of the *World Fact,* that is, derivative individual facts flow from the whole (i.e., the *World Fact*) as a group, not one-by-one. This proposal is therefore a form of *holism*. *Algebraic generalism* in fact entails that *individualistic facts* supervene on *general facts* and all *fundamental facts* are *general.* The structure of the world is therefore *fundamentally general.* It is also possible to have a composition of higher order predicates, that is, a *cropping of complex properties* into *states of affairs.* In this way, properties are *stitched together* to construct states of affairs and the fundamental facts of the world thus concern which of these states obtain. The algebraic *generalism* constructs a complex state of affairs that characterizes the situation as a whole, and the fundamental fact will be that that the state of affairs obtain. Again, then, we have another interesting metaphysical framework that appears to be compatible with the formalism and the physical content of AQFT.

4. Conclusion (or, how this would remain an open problem)

As I tried to show, AQFT is compatible with several different metaphysical proposals and the physical theory alone does not allow to decide among them. In a sense, then, all the metaphysical theories that we have discussed in this paper have passed the test. In other words, each metaphysical theory can account for the structure of AQFT and its description of the world. However, we should have the possibility to evaluate our metaphysical options and eventually pick up the correct one. AQFT by itself offers no insights on such a choice, that is, it is not possible to choose among different metaphysical theories only on a *physical ground.* This would entail that we need to adopt *non-empirical criteria* – such as *simplicity,* for example – in order to defend the preferability of a metaphysical theory over the others.

Such criteria are often discussed in the literature on naturalistic metaphysics (see again, for instance, Morganti (2013)), but I think that appealing to them, in a sense, weakens the “naturalistic” aspect. For such criteria would not have a direct link to the empirical content of the scientific theories that we are trying to interpret, and, moreover, do not have any role in the empirical (indirect) testability of our metaphysical theories. It is true that such non-empirical criteria have an important role also in the choice between different empirically equivalent (or empirically underdetermined) physical theories. However, I would consider such theories as falling under a form of underdetermination that is in fact similar to the metaphysical

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underdetermination that I am discussing in this paper. In other words, if empirical considerations do not allow to choose between two theories, the choice will be always, in a certain sense, *arbitrary*. This does not mean that non-empirical criteria are not scientific criteria and do not play an important scientific role. Yet, I think that it is important to notice that such criteria are, in a sense, dependent on *epistemological* or *metaphysical stances*, rather than *physical*. In other terms, such criteria can and should be used in order to choose between scientific theories or metaphysical theories, but introduce a form of arbitrariness that cannot be completely eliminated.[23] In a sense, then, naturalistic metaphysics is more metaphysical than it seems.

I think that if we want to have a really naturalistic metaphysics without involving non-empirical criteria of selection, we should consider the possibility of not having a final answer on what is the best metaphysics – and AQFT is a good example of such a case.[24]

As a general methodological claim, then, I would suggest a *pragmatic approach* to this kind of problems. On the one hand, I think that metaphysics is important to define and develop concepts and notions that we can use in our interpretations of scientific theories, as French and McKenzie (2015) have suggested. On the other hand, however, I think that it is only possible to test if a metaphysical option needs to be discarded, once it is applied to a scientific theory. In other terms, if a metaphysical theory does not allow to account for a series of empirical predictions of a certain scientific theory, then, it should not be considered as a legitimate interpretation of that theory. In this sense, I think that naturalistic metaphysics can be really useful in sorting out all the metaphysical theories that do not pass the test of the "empirical arena". However, the problems emerge in the positive direction. That is, even though we can rule out certain metaphysical theories, it is not possible to select the correct one. As we have seen, it is possible to have several metaphysical theories that are all compatible with a scientific theory, as in the case of

[23] See, for instance, also Ivanova (2010) for an interesting analysis of the notion of *good sense*, which Duhem himself proposed to give a rational criterion of selection for scientific theories that would "solve" the problem of the underdermination of scientific theories by data. Such a notion is not completely different from what I'm proposing here. In particular, I think that it goes in the same direction of my proposal for a *pragmatic attitude* with respect to the metaphysical underdermination of physical theories and of AQFT in particular. See also McKenzie (2020) for an interesting comparison between *a priori* metaphysics and naturalistic metaphysics, which shows that also naturalistic metaphysics might face some of the problems that are usually considered in the context of *a priori* metaphysics.

[24] I do not intend here to dismiss the whole project of naturalistic metaphysics, but I want to stress that such form of metaphysics cannot help to solve the open problem of the underdetermination of metaphysics by physics, at least in the case study of AQFT.

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AQFT. Of course, this is just one case study, but nonetheless I think that it teaches us an important lesson.

Naturalistic metaphysics can be extremely helpful in providing us a series of criteria of empirical testability for metaphysical theories. However, it cannot eliminate a certain degree of arbitrariness in the choice of the correct metaphysical interpretation of scientific theories. We can adopt a monist metaphysics or a holistic metaphysics and both are compatible with the formalism and empirical content of AQFT. We can decide which one is the best for us, but at the end of the day such a choice will depend on criteria that have nothing to do with the physical content of the theory. As such, I would suggest to consider the metaphysical underdetermination as a genuine and open problem for physical theories, which have not been solved yet. At this point, however, I think that we have two alternatives. On the one hand, we can renounce to do metaphysics of science. On the other hand, as said, we can adopt a *pragmatic stance* and claim that all we can do is to test our metaphysical theories in the light of the empirical content of our physical theories. Some metaphysical theories will not pass the test, but the choice between the "winning" ones will still depend on reasons that are not completely physical (or empirical). As such, we can and should use these non-empirical criteria, but I do not think that they will solve the problem of the underdetermination, for they introduce a degree of arbitrariness that cannot be eliminated.[25]

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