Physical Metaphysics and Theorem-Proving Philosophy: the case of particles in relativistic quantum field theory.

[Draft]

On Physical Metaphysics

Far from being tempted to provide a definition of *Metaphysics*, one may understand the term as referring to *any account of what it is to be; what entities populate the world(s) or can populate it (them); what features these entities have or may have, if any; how do or can relate to, or connect with, one another.*

1.1 Pure Metaphysics. The analysis of the concept of existence and of the concept of property are traditionally recognized tasks of *pure* metaphysics[1].

> There is a science which investigates being as being and the attributes which belong to this in virtue of its own nature. Now this is not the same as any of the so-called special sciences; for none of these others deals generally with being as being.

Aristotle *Metaphysics* Γ*,* 1003a22-1003a25
(tr. J. Barnes)

In its pure sense, metaphysics does not refer to any particular domain of existence. Investigates into the nature of being in the most general sense: "being as being" without any further reference to any specific science, art or any other context of discourse. As Jacquette notes "it is indifferent to whether or not there are physical objects, or whether there are numbers and sets, or numbers but no sets, or sets but no numbers, or universals or propositions, or minds, or God. The questions of pure philosophical ontology, ultimately about the meaning of the concept of being, are much more rudimentary." (2002: 5)

To illustrate with an example, when a metaphysician, in the pure sense, discusses what it is for an object - let that object be an ashtray - to exist, they do not enquire into the existence of a compound of quarks and leptons, as the physicist does, or the existence of an object having economic value, in the way of the economist, or the existence of an object of artistic value, or the existence of a medium-sized object having a function with respect to smoking. Pure metaphysics does not consider what it means for a physical object in distinction to a mental one to exist, or of a concrete object in distinction to an abstract one. It forgets all these qualifications pertaining to specific contexts and examines general questions of the following sort: "what is it to be (exist)?", (the ashtray exists); "what is it to be (something)?", (to be an ashtray); "what is it to be (something accidentally)?", (to be a *red* ashtray); "what is it to be (actually)?", (actually an ashtray); "what is it to be (potentially)?", (potentially an ashtray).

To get an idea of an approach in pure metaphysics, take combinatorial ontology, a view based on logic, which, very roughly, deems an object to be a predication subject, properties to be predications of that subject and existence a maximally consistent property combination. Hence, not all objects exist; only those which have a maximally consistent property combination. In this way, one may explain why there is something rather than nothing in terms of maximal consistency. This is a

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[1] Jacquette uses the term *pure ontology* (2002:3). In this paper I consider the two terms, *metaphysics* and *ontology*, indistinguishable. Another traditionally recognized task of metaphysics, of 'wisdom' ('σοφία') according to Aristotle, is the knowledge of the first principles and causes, i.e. a philosophical analysis of causation and related concepts. (*Met. A.*982b1-15).

problem in pure metaphysics that has its roots in Parmenides' poem and has been solved by Leibniz in 1697 with reference to God's goodness and creative will. (see Jacquette, 2002:65,89)

1.2 Scientific Metaphysics. Scientific metaphysics on the other hand, deals with the metaphysics of specific fields of knowledge and discourse. It "builds on the conceptual analysis of what it means for something to exist in order to recommend a preferred existence domain, thereby committing itself to the existence of a particular choice of entities." (Jacquette 2002:4).

Jacquette suggests a distinction between scientific metaphysics (ontology, in particular) as a discipline and scientific metaphysics as domain of existence (no such distinction can apply to pure metaphysics):

"As a *discipline*, scientific ontology is a method of enquiry dedicated to identifying a system of categories for a preferred domain of existent entities. As [*an existence*] *domain*, applied scientific ontology is divided in its responsibilities to identify the ontology of specific areas of thought and discourse whose meaning requires the positing of a particular choice of entities." (Jacquette 2002:5).

Since the history of the sciences is rich in examples of theories that emerged and declined, which are not necessarily compatible with regard to their predictions, or commensurable in terms of their metaphysical edifice, while all of them were making a claim to truth in their specific domain, positing entities that were believed to exist for a certain period of time and then be lost forever in the dungeons of oblivion – one needs to distinguish between two kinds of existence domain in scientific metaphysics: the theoretical domain of existence and the extant.

The *theoretical domain of existence* can be understood as an answer to a series of questions: What kind of entities or structures would populate the world if a given scientific theory were true? What type of relations would these entities bear, or what kind of connections, causal or other, are compatible with the strictures of that theory?

The commitment to a preferred theoretical domain of existence does not require a commitment to the truth of a scientific theory. One is not committed to the belief that the theory that they interpret ontologically provides a true description of the actual world.

It commits us only to the idea of a literal interpretation of the scientific theory: the claims of the theory that they posit entities, relations and connection among them should be taken at face value, as having genuine reference. They are assertoric and their truth-makers are the elements of the theoretical domain of existence. Moreover, one is not allowed to consider the theory instrumentally, as just a tool for making successful predictions and the entities posited at the level of existence as a shortcut to phenomena. The commitment at this level is a commitment to *semantic realism*, a stance that is generally taken as a rather weak form of realism.

The theoretical domain of existence consists of the truth-makers of any metaphysical claims *stemming from* the scientific theory. In what follows, I will try to elucidate the idea of metaphysics "stemming from" a scientific theory in terms of Carnap's "explication", Psillos's notion of indispensable contribution of a hypothesis to the generation of a prediction and a tentative suggestion for metaphysical underdetermination. This part of the talk is work-in-progress.

The *Extant Domain of Existence* consists of all existing entities and their relations and connections in the actual world as described by a complete, true theoretical ontology (Jacquette:3). This domain suggests more than that a scientific theory should be considered true or that its claims are assertoric and should be taken at face value. It commits us to the existence of a *final theory*, of a final description of a specific domain, if not to a final theory of everything. The ontological baggage of such an ultimate theory is the extant domain.

Notice that the realist would not have any problem to believe that there is an ultimate account of the world, although a commitment to its existence is not sufficient for being a scientific realist.

1.3 Metaphysical Claims: Assertoric and A priori. To provide an account in metaphysics, it is required to formulate assertoric claims about existence and existents, i.e. claims that have a truth-value.

Metaphysical claims are not empirically testable: the claims themselves and their consequences cannot be either verified, confirmed or falsified in terms of any particular experiences. Metaphysical claims are *a priori*.

1.3.1 In the eve of 20th century, the Logical Positivists argued against the view that metaphysical claims are assertoric. They contended that metaphysical talk is non-sensical and metaphysical claims have no truth-value exactly because they are remote from experience, while meaning and truth is conveyed to a claim only if it is verifiable in terms of possible experience or it may lead to verifiable consequences.

1.3.2 On the other hand, Shimony (1984) and Redhead (1987), quite provocatively, used the term '*experimental metaphysics*' to refer to the philosophical implications of the experimental confirmation of the violation of Bell inequalities in quantum mechanics for our world view. In this way, they brought back together metaphysical claims and empirical evidence.

Let me delve a bit more into the matter. A Bell-type inequality (I) may be deduced from experimentally confirmed, and quantum mechanically justified, premises about statistical correlations of measurable physical quantities of pairs of particles emitted from a common source and being spatially remote (P_{exp}), along with metaphysical assumptions of relativistic inspiration such as the statistical independence of outcomes for measurements performed at distant objects or the validity of the principle of common cause (suitably interpreted) (P_{met})[2].

$$P_{\mathrm{exp}}, P_{\mathrm{met}} \vdash I$$

In numerous experiments, dating back to 1974 and still being developed (see, Rosenfeld *et al* 2017), with most significant that of Alain Aspect and his team (Aspect *et al.* 1982), the violation of a Bell type inequality and the quantum mechanical predictions for the two-particle system have become a well-confirmed empirical fact.

As a consequence, either P_{exp} or P_{met} are false. Since, the set of experimental premises P_{exp} are satisfied by the experimental setting, the so-called metaphysical premises are false. Hence, not only *contra* positivism, metaphysical claims are assertoric, but they are also falsifiable by experience in an analogous way, and with similar philosophical reservations, that scientific claims are deemed falsifiable.

Shall we, then, renounce the *a priori* character of metaphysical claims and accept the view that metaphysics touches on experience? In a sense, 'yes', since we have already accepted the prospect of applied scientific metaphysics; however, this sense involves a *partial* and *indirect* relation between metaphysics and experience.

Indirect, because metaphysical claims come into contact with the empirical realm through our best scientific theories. Science stands as a mediator between metaphysics and experience.

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[2] Actually one needs to refer to the principle of *common* common cause in order to derive a Bell-type inequality (Redei); but that need not to bother us here.

Partial, because metaphysical claims do not have a unique formulation in the context of a scientific theory; hence, they continually tend to evade being tested.

I will come back to this partial and indirect relation between metaphysical claims and experience after having analyzed the relation between scientific theories and metaphysical claims, in particular, after having discussed Carnap's notion of explication.

What I am not willing to accept is that metaphysical claims are empirically testable in the same way as scientific claims – and this is what experimental metaphysics seems to suggest.

1.4 On Explication. "The task of explication" says Carnap "consists in transforming a given more or less inexact concept into an exact one or, rather, in replacing the first by the second. We call the given concept (or the term used for it) the explicandum, and the exact concept proposed to take the place of the first (or the term proposed for it) the explicatum. The explicandum may belong to everyday language or to a previous stage in the development of scientific language. The explicatum must be given by explicit rules for its use, for example, by a definition which incorporates it into a well-constructed system of scientific either logicomathematical or empirical concepts." (Carnap 1950:3)

The problem explication does not have a unique solution. There may be different explicata of the same explicandum without any of them being the right one. As Carnap argues, "[s]ince the datum is inexact, the problem itself is not stated in exact terms; and yet we are asked to give an exact solution." (1950:4) The different solutions to the problem can be compared only in terms of one being more satisfactory than another. Thus, Carnap formulated four requirements for a satisfactory explicatum:

> "1. The explicatum is to be similar to the explicandum in such a way that, in most cases in which the explicandum has so far been used, the explicatum can be used; however, close similarity is not required, and considerable differences are permitted.
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> 2. The characterization of the explicatum, that is, the rules of its use (for instance, in the form of a definition), is to be given in an exact form, so as to introduce the explicatum into a well-connected system of scientific concepts.
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> 3. The explicatum is to be a fruitful concept, that is, useful for the formulation of many universal statements (empirical laws in the case of a nonlogical concept, logical theorems in the case of a logical concept).
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> 4. The explicatum should be as simple as possible; this means as simple as the more important requirements (1), (2), and (3) permit." (Carnap 1950:7)

Inexact metaphysical concepts explicated in the context of a scientific theory may give rise to a plurality of explicata and, in turn, to several different exact formulations of a single metaphysical claim. This guarantees that if one explicatum of a given concept is not properly incorporated in the body of a scientific theory, or yields claims that are dumped by experience, there are always other formal expressions in terms of which the metaphysical claim may be formulated. This provides the necessary leeway for one to contend that although a statement formulated in terms of a given explicatum corresponding to a metaphysical concept has been disconfirmed, it is not the metaphysical claim itself that has been tested and has been falsified. In this way I understand that metaphysical claims touch upon experience only partially.

1.3.1.1 To return to the logical positivist, they may have some leeway to answer back. In the case of the violation of Bell inequalities, they may distinguish between P_{met}, the mathematical relations used in the derivation of the inequalities I, from the metaphysical claim P_{met} purport to explicate; the former are testable whereas the latter is not. In addition, there may be different explications of one and the same metaphysical claim. To test one of these formulations, say P_{met}, does not entail the verification or the falsification of the metaphysical claim itself. In this sense, although the explication of a metaphysical claim is testable, the claim itself may be not and its non-assertoric character can be safeguarded.

1.5 On the Testability of Metaphysical claims. Next, I suggest an understanding of testing a metaphysical claim M explicated in the context of a scientific theory T. It rests on Psillos' notion of indispensable contribution of a hypothesis to the generation of a prediction (Psillos 1999:110; see also, Hawley 2006).

M is empirically testable if it indispensably contributes to the generation of a prediction ϕ in a scientific theory T.

Assume that M together with another set of hypotheses H and some auxiliary conditions A entail ϕ,

$$M, H, A \vdash \phi.$$

M indispensably contributes to the generation of ϕ if H, A alone cannot yield ϕ,

$$H, A \nvdash \phi,$$

and there is no other set of hypotheses H', which is consistent with H, A, and along with H, A entail ϕ.

$$H', H, A \nvdash ; H', H, A \vdash \phi.$$

The first condition connects the metaphysical hypothesis with an observation sentence, a prediction. If the latter is false, then the set of claims $\{M\} \cup H \cup A$ is inconsistent, while, if ϕ is true then the set of claims $\{M\} \cup H \cup A$ is inductively confirmed. The two other conditions are needed to distribute blame and praise to M for the failure or for the success of the test. The first of these shows that something more, an extra hypothesis other than H and A, is needed for the derivation of ϕ and the second condition shows that this extra ingredient cannot be anything other than M, given that any other set of hypotheses H' that would render $H' \cup H \cup A$ inconsistent has been excluded (since from inconsistent premises anything can be inferred).

Of course, as Psillos notes, it's not only the case of a derivation of ϕ from an inconsistent set of premises that ought to be excluded: "there are senses in which all theoretical assertions are eliminable, if, for instance we take the Craig-transform of a theory, or we 'cook up' a hypothesis $[H']$ by writing $[\phi]$ into it." To avoid such unwelcome, nongenuine potential replacements for M, one may impose some epistemic constraints: "…if, for instance, we require that the replacement be independently motivated, non ad hoc, potentially explanatory, etc…". In this case, Psillos tentatively claims that "it is not certain at all that a suitable replacement can always be found."(1999:110)

The notion of indispensable contribution of a hypothesis to the generation of a prediction can be couched also in model-theoretic terms, by means of three conditions:

A metaphysical claim M indispensably contributes to the generation of a prediction ϕ in a scientific theory T, if (1) there is a set of hypotheses H and some auxiliary conditions A such that every model of T that satisfies M, H, A, satisfies also ϕ; (2) there is at least one model of T that satisfies H, A and does not satisfy ϕ; (3) there is no other hypothesis H' such that there is at least one model of T that satisfies H', H, A, and in every such model, ϕ is also satisfied.

1.6 Metaphysical Underdetermination. Assume that two different collections metaphysical concepts, intending to capture two rival metaphysical views, have been explicated and incorporated into the system of empirical and logico-mathematical concepts of a scientific theory. Let M_1be the basic claims pertaining to the first metaphysical view as explicated in T and M_2be the basic claims pertaining to the second one. If there is no set of *distinguishability conditions* C and no proposition ϕ such that

$$M_1, T, C \nvdash \text{ and } M_2, T, C \nvdash$$

$$M_1, T, C \vdash \phi \text{ and } M_2, T, C \vdash \sim\phi,$$

one may say that M_1, M_2 are indistinguishable metaphysical views with respect to the scientific theory T. Two metaphysical views that are indistinguishable with respect to a scientific theory are said to be *underdetermined* by that theory.

Nevertheless, neither all propositions ϕ nor every set of distinguishability conditions C are adequate for the distinction between two rival metaphysical views M_1, M_2, since they may consist of physically unrealizable facts. Thus, one may justifiably stipulate, further, that the pair (C, ϕ) should consist of physically realizable facts.

Yet, the demarcation of physical possibility from impossibility is not something given once and for all. It depends on the theoretical and experimental development of science. What previously was considered impossible, tomorrow may become a physically realizable condition. As a result, the characterization of two rival metaphysical views M_1, M_2 as metaphysically underdetermined by a scientific theory T is never a definite one: the judgement regarding metaphysical underdetermination is itself underdetermined.

1.7 On the Possibility of Informing Metaphysics by Physics. If one believes that it is possible to test a metaphysical claim explicated in a scientific theory by examining the predictions for which it is indispensable, in the sense explained previously, they adhere to optimism about informing metaphysics by physics. Here is how Hawley (2006) and French (2017:51) describe this stance:

"(Optimism) There are actual cases in which the involvement of a metaphysical claim in an empirical successful scientific theory provides some reasons to think that the claim is true."

The notion of involvement denotes that the metaphysical claim is responsible for the empirical success of the theory and, for Hawley, can be explicated in terms of Psillos's idea of indispensability. Optimism can be further distinguished into two types, which lead to different strategies:

'Inductivist' Optimism: metaphysical claims can be strengthened inductively, as more and more empirically successful theories involve one and the same claim.

'Falsificationist' Optimism: metaphysical claims can be ruled out by science.

In both stances, scientific theories are adduced as evidence, confirming or falsifying, for the metaphysical claims. No-go theorems in philosophy of science, realize a falsification strategy. Moreover, as French points out "as apparently falsified [scientific] theories may regain life as either evidence or the theory itself are reinterpreted so the kind of rejection of metaphysics suggested here might be conditional on factors such as the formulation of the theory, its interpretation, the nature and formulation of the metaphysical posit, and so on…" (53).

Contrary to optimism one might be pessimist about the prospects of informing metaphysics by physics. Pessimism comes in two versions, a radical and a moderate one (Hawley 2006):

“(Radical Pessimism) The involvement of a metaphysical claim in an empirically successful scientific theory can never provide any reason to think that the claim is true.

“(Moderate Pessimism) There is a kind of involvement in theory which, were a metaphysical claim to achieve this involvement, would provide some reason to think the claim is true; but there are no metaphysical claims being involved in theory in this way.

So, optimism and moderate pessimism agree that there are justifying conditions on which a metaphysical claim is justifiable in terms of empirical evidence. They differ on whether these justifying conditions are satisfiable: the optimist says that they can be satisfied, and the claim can be justified, while the moderate pessimism believes that they are an unattainable ideal. On the contrary, radical pessimists believe that there are no such justifying conditions.

Particles in Relativistic Quantum Theories

2.1 A necessary clarification: in physics, one may find different accounts of particles on the basis of different considerations regarding the salient features and intuitions related to these entities. Here is an incomplete list of such features: (1) Discreteness - enumerability; (2) Invariance under symmetries of nature; (3) Primitive Thisness (Haecceity), the idea that expresses the strict or numerical identity of an object in contrast with qualitative identity defined in terms of state independent properties); (4) Building blocks of matter; (5) Localizability; (6) Possibility of interacting at a distance; (7) Massiveness (mass is a classification property of relativistic particles but there are massless particles); (8) Impenetrability; (9) Carriers of energy and momentum.

In what follows, I refer to two accounts of particles that focus (a) on invariance under natural symmetries and on the conception of particles as building blocks of matter; (b) on the conception of particles as localizable entities. I intend to discuss these conceptions in the context of relativistic quantum physics. In particular, I present three arguments, two of them having the form of no-go theorems and one resting on a celebrated theorem of axiomatic quantum field theory, which illustrate the problems regarding the localizable entities conception of particles in relativistic quantum physics.

2.2 Symmetries and Particles: Wigner's account

A symmetry of nature, is a collection of transformations that do not change the laws of nature, which has the mathematical structure of a group. These transformations maybe interpreted as connecting points of view of different observers and experimenters. For instance, experimental results obtained when the same experiment is performed in labs located at different places or in moving or rotating labs, or, features of a physical object recognized by observers who look at spatially reflected mirror images of that object.

In general, groups of transformations expressing symmetries of nature act on states and on determinable properties of the physical system. To demand invariance of the laws of physics under these transformations is to demand that the different observation viewpoints do not alter the physics of the system or the fundamental entities involved in its description. Hence, one may say that for something to belong to the ontology of a theory, it is a necessary condition to exhibit invariance under a group expressing symmetries of nature. (Kuhlmann:88)

Special Relativity Theory (STR) stipulates that laws of physics should be invariant under a particular group of transformation called *Poincaré group* of transformations. These are geometrical transformations in Minkowski spacetime in terms of which one may describe different kinds of motions in the physical spacetime of STR. If a theory conforms with STR, then to every transformation of the geometry of the system should correspond a transformation of the values of all physical magnitudes so that their relations as expressed by the laws of physics, before and after the application of the transformation, remain unaltered. To obtain the transformation of the values of all physical magnitudes in accordance with the geometric change, each element of the Poincaré group should be represented in the state space of the system i.e. in the set of all possible states of a physical system, and the structure formed by the representors should be also that of a group. A representation of the Poincaré group of transformations in the state space of the system, expresses how the state of the system would change if it were subject to those transformations: the representors of the elements of the Poincaré group act on the state of the system and transform it into the one that the system would have if translated from one place to another or if put to rotational motion about an axis in the physical space or if observed by a moving observer etc. I stress that these transformations should leave the physics of the system invariant, if the theory complies with STR.

In conventional quantum mechanics, the pure states of a system are represented by vectors (rays) in a Hilbert space $\mathcal{H}$ and the representation of a symmetry group is given in terms of unitary operators that act on the state vectors of the system. In particular, we demand that all observables of the system should have the same expectation values before and after the symmetry transformation occurs. Wigner proved that to this end unitary operators may be used to transform the state of the system. Hence, he suggested a representation of the Poincaré group of geometrical transformations by a group of unitary transformations of the Hilbert space.

$$\mathcal{P}_+^\uparrow \ni g = (a, \Lambda) \mapsto U(a, \Lambda) \in \mathcal{B}(\mathcal{H})$$

To every element g of the Poincaré group $\mathcal{P}_+^\uparrow$, consisting of a translation a and a Lorentz transformation Λ in space time, corresponds a unitary operator $U(a, \Lambda)$ which belongs in $\mathcal{B}(\mathcal{H})$, the algebra of bounded operators that act on the Hilbert space $\mathcal{H}$.

Wigner (1939) sought to define elementary particles by examining these representations of the Poincaré group in a Hilbert space.[3] In particular, he examined the irreducible representations of that group, since these are the basic building blocks out of which all other (reducible) representations can be built up, in a way analogous to how all matter is built up by elementary particles. Moreover, irreducible representations of the Poincaré group yield unitary transformations that *do not* leave any non-trivial subset of the Hilbert space invariant. Hence, a type of particle that corresponds to an irreducible representation of the Poincaré group has a stable state space with respect to that symmetry group. No novel structure corresponding to a reduced state space can be considered by any observer who is moving in spacetime.

Wigner classified the irreducible representations of the Poincaré group in terms of two relativistic invariants: the mass of the particle and the spin (or helicity) of the particle. The idea is that all states obtained by a Poincaré transformation will be characterized by the same mass and the same spin, which are invariant characteristics of the relativistic particle involved in that representation. Here is the classification in terms of the four-momentum and the mass of the particle:

(i) $p^\mu p_\mu = m^2 > 0,\ p^0 > 0$
(ii) $p^\mu p_\mu = m^2 > 0,\ p^0 < 0$
(iii) $p^\mu p_\mu = 0,\ p^0 > 0$
(iv) $p^\mu p_\mu = 0,\ p^0 < 0$
(v) $p^\mu = 0$
(vi) $p^\mu p_\mu < 0$

(i) describes particles with positive mass and energy while (iii) describes particles with no mass and positive energy (such as the photons); (v) describes the vacuum – no mass, hence, no particle and (vi) virtual particles (carriers of interaction). (iii) and (iv) describe unphysical cases of particles having negative energy. Analogously one may proceed with the classification of particles in terms of spin (or helicity) given that they have fixed (m, p^0).

[3] This is not accurate according to Falkenburg: "Wigner's original paper deals with a mathematical problem of group theory. Where the physical applications of this problem are mentioned, the paper deals with quantum mechanical states and fields rather than particles. The term 'particle' does not belong to its vocabulary. One might say that Wigner's definition of the particle concept is due rather to Wigner's followers than to himself." (2007:231)

According to Streater, the definition of a particle that Wigner proposed in terms of the irreducible representations of the Poincaré group is the following:

> "an elementary particle is an irreducible projective representation of the Poincaré group, $\mathcal{P}$, with mass ≥ 0 and energy ≥ 0, and spin $s \in \left\{0, \frac{1}{2}, 1, \ldots\right\}$. He did not merely say that a particle is well described by such a representation: this would leave the word particle still undefined. Thus, a particle is a pair $(\mathcal{H}, U_{[m,s]})$ where $\mathcal{H}$ is a Hilbert space, and U is a unitary continuous action of $\mathcal{P}$ on $\mathcal{H}$, obeying $U(a, \Lambda) + U(b, M) = \omega U(a + \Lambda b, \Lambda M)$, where $a, b \in \mathbb{R}^4$ are space-time vectors, and Λ, M are Lorentz matrices, and where $[m, s]$ are the mass and spin." (1988:144)

Two weaknesses may be pointed out with respect to Wigner's definition of a particle: a) it is limited to on-shell particles (to particles that satisfy the relativistic relation between the energy and the momentum); b) it does not define what an individual particle is.

To begin with, Wigner's classification of the irreducible representations cannot describe all types of particle in relativistic quantum field theory. As Buchholz notes, "There is ample evidence, both from the study of exactly soluble models and from more abstract arguments, that particles carrying an electric charge are inevitably accompanied by clouds of soft photons, and therefore cannot be described by eigenstates of the mass operator." (1986) Schroer (see, Haag 1996:280) coined the term *infraparticle* to refer to particles not associated to an exact value of mass. In his doctoral dissertation, Porrmann outlined Buchholz argument that traces the infraparticle problem back to Gauss' law (1999):

> "Due to Gauss' law, the charge of a physical state can be determined by measuring the electromagnetic field at asymptotic spacelike distances. These measurements do not interfere with those performed within bounded regions; therefore, being a c-number, the asymptotic field configuration is a superselection rule of the theory. Its dependence on the state of motion of the charged particle implies that there exists a multitude of superselection sectors and that the Lorentz symmetry is broken. Consequently, charged particles cannot be described according to Wigner's theory."

The electric charge of a particle can be determined by calculating the total electric flux through an arbitrarily large sphere around the particle. This calculation is performed in terms of an observable $\varphi_{\vec{n}}$ that expresses the electric flux through the spherical surface, in a given spatial direction $\vec{n}$, asymptotically ($R \to \infty$)[4]. Due to relativistic locality the measurement of the electric flux in any direction at infinite spatial distance from any bounded region cannot influence the values of local observables in any region. Hence, the observable $\varphi_{\vec{n}}$ commutes with the algebra of local observables. Put differently, for a given state of the system one may associate to each spatial direction, a c-number expressing the flux through the spherical surface, in that direction, asymptotically. i.e. $\vec{n} \mapsto \varphi_{\vec{n}}$. All vectors in the Hilbert space of a particle associated to a c-number function $\vec{n} \mapsto \varphi_{\vec{n}}$ form a superselection sector, a subspace of the Hilbert space that is stable under the action of the algebra generated by local observables. The only constraint imposed on this function is that integration over all directions should yield a multiple of the electric charge of the given particle, $\int d\omega \varphi_{\vec{n}}$. What is amazing is that one cannot associate a unique sector to a particle of a given charge! One may produce a continuum of sectors corresponding to different functions $\vec{n} \mapsto \varphi_{\vec{n}}$, by operating on any vector belonging to a superselection sector with representors of Lorentz transformations Λ. The physical justification of this fact can be traced back to the relativistic

[4] As Horuzhy notes, "the presence of massless bosons [soft-photons] reveals itself in the fact the asymptotic direction of the string S [of the flux of the charged field] is now an observable quantity." (Horuzhy 1990:156)

provision that the electric field of a charged particle has different directional distribution in space, for different particle motions; hence the asymptotic flow through a segment of the sphere in any direction will be different (Haag 1996:282). Notice that this multitude of superselection sectors in the c-number function $\vec{n} \mapsto \varphi_{\vec{n}}$ is additional to the superselection sector in the charge: "…each charge sector…splits into an uncountable set of φ-sectors corresponding to all localization directions of states with a given value of Q." (Horuzhy 1990:156). However, although Lorentz transformations map state vectors associated with a fixed value of charge to state vectors with the same value of charge, since charge is a Poincaré invariant, they do not map state vectors associated with a given c-number function $\vec{n} \mapsto \varphi_{\vec{n}}$ to states associated with the same function, Lorentz symmetry is broken. Thus, one cannot define, following Streater's account of Wigner particles, an elementary charged particle as a pair $(\mathcal{H}_{\varphi}, U_{[m,s]})$, where $\mathcal{H}_{\varphi}$ is the superselection sector associated with a fixed value of charge and a fixed asymptotic directional distribution of electric flux. As a consequence, Wigner's definition of particle does not constitute a viable strategy for infraparticles.

As to the second point of criticism, Kuhlmann (2010: 93) claimed that Wigner did not provide any definition of what a particle is but just a necessary condition for a typology of a particle ontology of relativistic quantum mechanics: if relativistic quantum mechanics were to be interpreted in terms of a particle ontology, the typology of this ontology should be given in terms of the classification of the irreducible representations of the Poincaré group.

Kuhlmann is right in claiming that in terms of invariant properties of particles under any group of transformations expressing symmetries of nature, only types of particles can be defined and not particle-tokens. Group-theoretic considerations do no suffice to define the particle as a particular, distinct from other similar ones (see also, Castellani, 1998: 184). Thus, if one wants to define what a particle is in relativistic quantum theory, there is a missing factor that would induce the required particularization:

$$Particle = An\ Irreducible\ Representation\ of\ a\ Symmetry\ Group + X$$

Can this missing X-factor be provided by the localizability property of a particle? Can the idea that an individual particle is characterized by being localized at a given place at a given time provide the sufficient condition that would lead us from a typology of particles in relativistic quantum theory to the particle-token?

2.3 Localizable Particles.

The conception of (quantum) particles as localizable entities draws on three main sources. The first is the layman's experience of medium-sized objects that occupy a fixed region of space at a given time.

The second source is related to classical physics idealizations of particles that occupy points in space, at a given time, or describing trajectories in physical space, or being represented by worldlines in spacetime. These idealizations are produced by shrinking down to zero volume extended three-dimensional objects performing translatory motions. These point particles may act on one another, at a distance, or interact by contact through collisions.

The third source for the localizable particles imagery is the language of the experiments in High Energy Physics that aim at testing fundamental physical theories, such as QFT. In experimental HEP, physicists' talk refers to entities, particles, that are localized in space and time. In terms, of geometrical properties of these objects they infer theoretical properties of these particles. The following passage from the CERN webpage is illustrative:

> Accelerators at CERN boost particles to high energies before they are made to collide inside detectors. The detectors gather clues about the particles – including their speed, mass and charge – from which physicists can work out a particle's identity. The process requires accelerators, powerful electromagnets, and layer upon layer of complex subdetectors.
>
> Particles produced in collisions normally travel in straight lines, but in the presence of a magnetic field their paths become curved. Electromagnets around particle detectors generate magnetic fields to exploit this effect. Physicists can calculate the momentum of a particle – a clue to its identity – from the curvature of its path: particles with high momentum travel in almost straight lines, whereas those with very low momentum move forward in tight spirals inside the detector.
>
> Modern particle detectors consist of layers of subdetectors, each designed to look for particular properties, or specific types of particle. Tracking devices reveal the path of a particle; calorimeters stop, absorb and measure a particle's energy; and particle-identification detectors use a range of techniques to pin down a particle's identity.

https://home.cern/about/how-detector-works

Assume now, that one accepts that particles are localizable entities, as classical physics intuitions and experimental talk in HEP seem to suggest, do these particles exist only at the level of phenomena or one may trace them deeper down in the fundamental ontology of the world in accordance with an atomistic conception of the world?

Relativistic (A)QFT literature suggests that although one may retain a phenomenology of localizable particles, a localizable particles' talk, in compliance with the language of the experiment, they cannot hold consistently a localizable particles' ontology. A phenomenology of localizable particles may be recovered from quantum fields, however, the assumption that localizable particles exist is incompatible with other desirable features of physical theories. Thus, contra Democritus, *by convention, and not in truth, are the atoms and void* in modern quantum theories.

In what follows, I present the main argument against a localizable particle ontology in AQFT, put forth by Redhead (1995), the restoration of a particle phenomenology as suggested by Halvorson and Clifton, and the exploration of the limits of this phenomenological account in terms of the Arageorgis-Stergiou proposition regarding a minimally statistically faithful particle detection experiment.

2.3.1 Redhead's Argument (1995). This argument is developed in the context of AQFT, an axiomatic theory of quantum fields formulated in terms of von Neumann (or C*) algebras associated with open bounded spacetime regions. The core idea of AQFT is that all information related to measurements of local observables which take place in any spatial region and have a fixed duration, is encoded in the algebraic structure of the corresponding algebras. The whole net of algebras satisfies the Haag-Araki axioms that provide physical significance to the mathematical structure. The models of the theory are structures of the following type

$$\langle \mathcal{H}, O \mapsto \mathcal{R}(O), (a, \Lambda) \mapsto U(a, \Lambda) \rangle,$$

where $\mathcal{H}$ is a complex Hilbert space, $O \mapsto \mathcal{R}(O)$ is a net associating a von Neumann algebra $\mathcal{R}(O)$ with every open bounded region of Minkowski spacetime, and $(a, \Lambda) \mapsto U(a, \Lambda)$ is a strongly unitary representation of the (proper orthochronous) Poincaré group in $\mathcal{H}$. Moreover, we assume that there exist a translationally invariant state, the vacuum state, represented by a vector, Ω.

The venerable Reeh-Schlieder theorem claims that for any open bounded region O one can approximate any vector in $\mathcal{H}$ by acting on the vacuum vector, Ω, with elements from the local algebra $\mathcal{R}(O)$; moreover, that no element of the local algebra $\mathcal{R}(O)$ can annihilate Ω.

Redhead argued that the question "Is the system in a state of N particles?" is not a local one. This means that one cannot make a detection experiment in a spacetime region O represented by a local projection operator $P_N \in \mathcal{R}(O)$, which would tell us whether there are N particles in O. For such a projection operator, $P_N\Omega = 0$, and, by the Reeh-Schlieder theorem, $P_N = 0$. Moreover, in case there are no particle $P_0\Omega = 1$ (by the definition of the vacuum state), and the complementary projection $(I - P_0)\Omega = 0$, thus, $P_0 = I$. Hence, there is no non-trivial projection operator that would represent a local particle detection experiment.

Along the same lines one may argue that in relativistic QFT, contrary to the non-relativistic case (the quantized Schrödinger field), one cannot introduce operators associated with the number of particles in any open bounded spacetime region. These arguments are usually taken to support that there are no localized particles in relativistic QFT.

"Furthermore, it can be shown independently of the full framework of AQFT, and without the RS Theorem, that a positive energy condition combined with microcausality rules out local number operators [Halvorson and Clifton, 2002]" (Halvorson-Mueger, 2006).

2.3.2 The Halvorson Clifton Idea (2002). They argued that particle talk, although strictly *fictional*, may have a legitimate role to play in describing empirical evidence from experimental HEP inasmuch as AQFT shows how the particle "illusion" can arise.

The Halvorson Clifton Idea is briefly this. What we take as the detection of a particle in an open bounded spacetime region O is the measurement of a *local* observable C' - a self-adjoint element of $\mathcal{R}(O)$- whose expectation value in the vacuum is nonzero but below the experimental error, say $\delta > 0$. Still, the measurement of the local observable can be approximated to the desired degree of accuracy, within experimental error, by an *almost local* observable C that *does annihilate* the vacuum, as a particle detection observable is expected to behave. This approximation is valid for all practical purposes.

Hence, although one may talk about particle detection, about the presence or the absence of a particle at a given spacetime region, in reality, no such measurement takes place. The only measurable observables are the local ones and they cannot be taken to represent the existence of particles.

2.3.3 How much local is almost local? To explore the extend of local behavior of almost local observables that represent particles, Arageorgis and Stergiou (2013), went beyond the simple *fictional* particle talk and examined the consequences of a *fictional* act of particle detection.

They showed that in the context of an AQFT satisfying Haag-Araki axioms, the following three propositions form an inconsistent set: (1) A minimally statistically faithful particle detection experiment involves a positive observable (of norm less than 1) whose measurement gives no response in the vacuum state but a positive response in at least one other state. (2) The minimally statistically faithful particle detection experiment is represented as a non-selective Lüders measurement of an almost local positive observable (of norm less than 1). (3) If a minimally statistically faithful particle detection experiment is performed there is one region O of Minkowski spacetime such that the expectation values of all observables in the local algebra $\mathcal{R}(O)$ remain unaltered regardless of the state the system is in.

The significance of this inconsistency rests on the presumed violation of relativistic causality by a minimally statistically faithful particle detection experiment. According to STR all regions of Minkowski spacetime that can be reached only by entities travelling at a velocity that exceeds the velocity of light in the vacuum, from a given region, are shielded from any causal influence produced in this region. This is the core idea of relativistic causality.

If one identified causal influence with the change in the state of the system that is produced by a non-selective measurement[5] of a local observable in a spacetime region, described by Lüders rule, one may stipulate, in accordance with relativistic causality, that the expectation values of local observables in spacelike separation from the region in which causal influence was produced, did not to change, as result of propagation of causal influence.

In AQFT this is true. In particular, the axiom of microcausality, the commutativity of the local algebras of two spacetime regions in spacelike separation, is equivalent to the requirement that the non-selective measurement of any local observable, obeying Lüders rule, from any of two regions does not change the expectation values of the observables in the other region.

Yet the fictional interaction which occurs in a minimally statistically faithful particle detection experiment and may be associated with a region O - being defined in terms of an almost local observable that approximates an local observable in O to any degree of accuracy - produces causal influence that pervades the entire spacetime, violating, thus, relativistic causality.

2.3.4 Valente's criticism (2015). The Arageorgis-Stergiou proposition was criticized on three different grounds.

Firstly, Valente claimed that relativistic causality is not violated in minimally faithful detection experiments, since "one cannot infer from Arageorgis and Stergiou's theorem that the attempt to localize a particle, even in the non-strict sense captured by Halvorson and Clifton's approximate localization scheme, violates microcausality."

It is correct that our argument does not entail a violation of microcausality, in the same way that the violation of Bell inequalities or the Reeh-Schlieder do not entail a violation of microcausality. Does that mean that they do not pose any challenge for relativistic causality? Other locality conditions are violated which express intuitions related to relativistic causality. Microcausality is a very important condition, an axiom of AQFT, but it's not the only condition that expresses relativistic causality.

Moreover, as I explained before, the condition we employ, at the level of local observables, is related to microcausality: if by a non-selective measurement of some local observable one could influence the expectation values of local observables at spacelike distance, microcausality would not hold. Of course, in our case we do not work with local observables, the fictional detection requires almost local observables, but still the intuition of a presumed violation of relativistic causality is alive.

Secondly, Valente claimed that the scope of the argument is restricted since it rests substantially on the formalization of particle detection experiments in terms of Lüders rule. "[T]here exist plenty of

[5] A non-selective measurement is an act of measurement of an observable in a collection of physical systems without selection of outcome, i.e. at the end of the measurement all physical systems that originally formed the collection are retained, keeping, thus, unchanged the size of the collection.

other operations of a different form … [f]or such maps … the proof of the theorem would not go through as it stands”.

Of course, there exist other maps for which the theorem does not hold. However, to take this objection seriously, Valente has the burden of arguing why these alternative maps provide a better formalization of a particle detection experiment than the Lüders rule. Such an argumentation has not been provided.

Thirdly, Valente argues that the change in the expectation value of a local observable produced by the act of measuring an almost local observable does not threaten relativistic causality because almost local observables are not localized, and the presumed act does not take place anywhere in spacetime.

We cannot agree more on this point. The association of a particle detection observable with a spacetime region is only indirect and, thus, not genuine. It rests on the stipulation that the almost local observable representing a particle detection is approximated (in norm) by a local observable arbitrarily close. Apart from that, by construction, almost local observables are constructed by smearing the translation of a local observable in the entire Minkowski spacetime. To lay emphasis on this point, Valente characterizes almost local observables as “global” ones.

Yet, the most illuminating point in this third part of Valente’s criticism is with regard to the role of the almost local observable used for the representation of a particle detection experiment: “The role of the fictional observable… is to assure that, even though … [a local observable] cannot annihilate the [vacuum] vector … for any [spacetime] region…, its expectation value computed in the vacuum is arbitrarily small.” Indeed, to say that an almost local observable represents a particle detection, according to Halvorson and Clifton, entails that the expectation value of a corresponding local observable is as small as one desires.

Summary

In this talk, I attempted to explore the prospects of Physical Metaphysics, or, put differently, of Metaphysics informed by Physics, as both a general research program and with respect to the discussion about particles in Relativistic Quantum Theory.

Firstly, I surveyed the distinction, put forth by Jacquette, between Pure and Scientific Metaphysics as areas of research and domains of existence. The former explores the meaning of existence *simpliciter*, whereas the latter with respect to some discipline or area of thought. While Pure Metaphysics is not committed to any specific metaphysical scheme or ontology, Scientific Metaphysics suggests such a metaphysical setting and is committed to some ontology in compliance with currently available scientific theories.

Secondly, I claimed that to provide a metaphysical picture of the world one needs to consider metaphysical claims to be assertoric. Moreover, contrary to traditional metaphysics, in scientific metaphysics the claims made are not *a priori.* However, they are only indirectly and partially testable: they are testable only through scientific theories and only if explicated in a scientific theory. The explication of a metaphysical claim is not unique; thus, in its generality, a metaphysical claim will always evade empirical testing.

Thirdly, I referred to an idea concerning the testability of metaphysical claims already explicated in the context of a scientific theory, as presented by Hawley (2006). This idea rests on Psillos' notion of indispensable contribution of a hypothesis to the generation of a prediction. Along the same lines I suggested a tentative explication of the notion of metaphysical underdetermination by a scientific theory. Cases of scientifically underdetermined metaphysical claims need to be examined so as to make this suggestion more robust.

In the last section of this first part of the talk, I surveyed different stances regarding physically informed metaphysics.

To provide a case study in physical metaphysics, I referred to the concept(s) of particle in Relativistic Quantum Theory.

The first conception of particles I examined relies on symmetries of nature. Particles are defined in terms properties' invariance under symmetry transformations. This idea is explicated in terms of representations of the symmetry group in the state space of the system. The distinction between elementary and complex particles is explained as well as the composition of matter by elementary constituents is couched in terms of the mathematical distinction between reducible and irreducible representations. The problem with this account is that defines particle types and not particle tokens.

Particles are also considered to be localizable entities. However, in the setting of relativistic (A)QFT, the most well-confirmed physical theory available, this idea does not get off the ground. A particle ontology is problematic due to the celebrated Reeh-Schlieder theorem. Nevertheless, one may talk about by particles as being localized entities, they may adhere to a localized particles' phenomenology.

To explore the limits of the suggested particle phenomenology I (along with Dr. A. Arageorgis) proved a proposition about a *fictional* act of particle detection. We have shown that such an act would stumble upon well-established causal intuitions that have their source in STR. Finally, I discussed some critical considerations raised against the interpretation of our proposition.

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