Scientific Realism and High Energy Physics

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The paper discusses major implications of high energy physics for the scientific realism debate. The first part analyses the ways in which aspects of the empirically well-confirmed standard model of particle physics are relevant for a reassessment of entity realism, ontological realism and structural realism. The second part looks at the implications of more far-reaching concepts like string theory. While those theories have not found empirical confirmation, if they turned out viable, their implications for the realism debate would be more substantial than those of the standard model.

1: Introduction

The present article discusses the implications of high energy physics for the scientific realism debate. The analysis covers developments in fundamental microphysics roughly from the 1950s onwards. In order to specify those characteristics of high energy physics that set it apart from earlier microphysics, let us have a brief look at the state of microphysics around 1950. Conceptually, microphysics at the time was based on quantum field theory, the special relativistic extension of quantum mechanics. The technique of renormalization was turning quantum field theory into a workable method of calculating scattering amplitudes at high energies. The particle spectrum had just started to transcend the set of stable particles that made up macro-physical material objects.

Two fundamental developments characterize the evolution of high energy physics from that time onwards. Experimentally, the search for new unstable types of particles in experiments that produced highly energetic collisions of electrons or protons turned out to be the most dynamical generator of new developments in microphysics. The production of new particles in collider experiments is based on a basic property of special relativity: rest mass is understood as a form of energy, which provides a conceptual basis for turning kinetic energy into mass energy. Collision energy on that basis can be used for producing new particles. The higher the collision energy, the more massive the particles produced in the collision can be. Quantum mechanics then adds a second important ingredient: the stochastic nature of quantum mechanics implies that any process that is allowed based on the relevant conservation laws happens with a given probability. Therefore, generating a certain collision energy is sufficient for creating all particles that can be generated from the initial state according to the relevant conservation laws. The build-up of increasingly powerful particle colliders thus allowed for the discovery of a series of new physical particles that did not exist under everyday circumstances because i) their generation required higher kinetic energy than what was available under standard conditions on earth and ii) once generated, they quickly decayed back into the stable constituents of matter.

The theoretical shift of perspective that complimented the described experimental shift happened a little later, from the 1960s onwards. The wealth of new particles at first seemed confusing and conceptually arbitrary. In the 1960s, a new perspective emerged that related the spectrum of particles directly to fundamental structural characteristics of microphysics. Nuclear interactions were now understood as implications of a specific form of symmetry: local gauge symmetry. Local gauge symmetries can be understood as a reparametrization invariance of a physical theory. One can define an internal space of particle degrees of freedom by attributing an additional characteristic property, let us call it color, with n possible values, to each fermionic particle of a given type. At first, no physical implication is being attached to the property of having a certain color. The theory then is called locally gauge invariant under unitary rotations in the n-dimensional color-space if it is possible to define the "color-directions" in internal color-space anew at each point in spacetime without changing the theory's physical implications. As it turns out, most quantum field theories that could be constructed in principle aren't locally gauge invariant. The only way to achieve gauge invariance is to introduce vector bosons that couple to the fermions in a specific way and in effect play the role of interaction particles (called gauge-Bosons). We thus have the peculiar situation that the requirement of turning a symmetry under the variation of a physically empty property into a local gauge symmetry enforces the introduction of a physically very relevant characteristic of the theory, namely a specific form of interaction that is based on particle exchange.[1]

Gauge symmetries assumed a crucial role in high energy physics for a technical reason. Straightforward calculations of cross sections in quantum field theory lead to infinite values. Those infinities can be treated in a controlled way that allows for extracting predictions if the theory is renormalizable.[2] It turns out that the only renormalizable interacting theories that include fermions are gauge theories. Gauge symmetry thus plays a pivotal role for making high energy physics predictive. As it turns out, gauge symmetry in some cases is spontaneously broken, which means that the gauge symmetry transforms between physically distinguishable particle types. (This is the case for the gauge group of weak interaction and for all possible gauge symmetry structures that reach beyond the standard model.)

The precise role of the property of renormalizability in high energy physics became clearer in the early 1970s within the framework of renormalization group methods (Wilson 1974) and was fully understood in Polchinski (1984). Gauge invariance has also been the first topic in high energy physics that was addressed in greater depth by philosophers of science (Teller 2000, Healey 2001, 2007, Earman 2002). Since the present article focuses on the question of scientific realism, we have to leave those discussions aside.

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[1] In the simplest 'abelian' case, the gauge transformation is a mere U(1) phase transformations (that is, n=1). The standard model of particle physics does contain a U(1) gauge symmetry that roughly corresponds to the photon.

[2] Non-renormalizable theories are only predictive far below the characteristic energy scale of the non-renormalizable sectors.

Gauge field theory in conjunction with the discovery that nucleons had constituents (the quarks) that were bound together by a specific gauge interaction called the strong force, generated an entirely different view on high energy physics. Theory became far more predictive than before. The gauge structure to a large degree enforced both the particle content and the interaction structure of the world. The vast spectrum of seemingly arbitrary elementary objects was replaced by a tightly knit theory-based system of elementary particles and interactions that came to be known as the standard model of particle physics. Based on a set of empirical data that specified the general structure of the standard model, a wide range of predictions could be extracted from the theory and was then, step by step, confirmed in collider experiments. Gauge theory inverted the hierarchy between theory and experiment. While up to the early 1970s, theory was busy finding conceptual answers to the phenomena and empirical anomalies discovered by experiment, no serious anomaly has been produced up to this point that contradicted the standard model.[3] From the early 1970s onwards, experiment thus followed theory, aiming at testing theory's predictions.

Theorizing from the mid-1970s onwards was characterized by attempts to develop theories beyond the standard model for other reasons than empirical anomalies. One reason was to find a coherent theory of gravity and nuclear forces. This was deemed necessary for developing a coherent understanding of the very early phases of the universe. The theory physicists came up with was string theory. Another reason was to explain conspicuous coincidences of measured parameter values. This led to grand unified theories and, in a different context, to cosmic inflation. Another theory, supersymmetry, turned out to be contained in string theory and to be related to grand unification. It also offered promises for explaining a number of other conspicuous aspects of high energy physics. These theories, despite remaining empirically unconfirmed or, in the case of inflationary cosmology, inconclusively confirmed, to a high degree determine today's perspective on cosmology and the fundamental characteristics of matter.

2: A First Take on the General Relevance of HEP for Scientific Realism

In a number of ways, high energy physics has further eroded what had survived of the intuitive notion of an ontological object that was badly damaged already by quantum physics and quantum field theory. To begin with, many unstable particles generated in collider experiments can never be identified individually but only be attributed to an individual scattering event measured in a detector with an (often fairly small) probability. At a more conceptual level, mass loses its status as a fundamental property of objects and is understood in terms of the way fields couple to the vacuum; Hadrons (such as protons and neutrons) consist of constituents (the quarks) that cannot be isolated; and the characteristics of hadrons are to a large degree determined by field theoretical effects that

[3] The only discovery so far that, strictly speaking, transcends the original standard model is the neutrino mass. Neutrino masses, however, always seemed natural in a standard model context and were only left out because they had not been found in experiment. Experimentalists at CERN hope to find significant deviations from the Standard Model at the very time I am writing this text, however.

cannot be expressed in terms of the dynamics of their real constituents. (For a philosophical discussion of the last points, see Falkenburg (2007). Falkenburg argues that only a mereological understanding of the term 'particle' survives in a particle physics context.) Finally, developments in quantum gravity suggest the dissolution of space-time structure at the most fundamental levels of description.

All those points seem to disfavor a realist view on high energy physics. But other developments in high energy physics may actually be taken to support scientific realism. The standard model of particle physics is a prime example of novel predictive success and therefore strengthens the basis for no-miracles kinds of reasoning. On a more pragmatic note, high energy physics today is a field without any perspectives of technical utilization. Experimental data extracted from collider experiments in high energy physics have no relevance beyond their role in testing theories. If research in high energy physics was not about finding the truth about the world in some sense, little reason remained for being interested in its results.

High energy physics thus is an interesting and multifaceted context for discussing scientific realism. While philosophical discussions of the implications of high energy physics for the realism debate are still scarce, there are more of them than could reasonably be discussed in a survey of this kind. In the following, I will therefore focus on a few important contexts.

3: High Energy Physics Versus Entity Realism

Let us first have a look at a form of realism that may expected to be at variance with high energy physics. Entity realism (Hacking 1983, Cartwright 1983) offers an approach towards scientific realism that avoids the subtleties of theoretical physics and aims at grounding realism in the intuitive understanding of experimental procedures. More specifically, Ian Hackings experimental realism relies on the observation that physicists treat specific objects as tools for probing other aspects of physics. This utilization of physical objects, Hacking argues, presupposes the existence of those objects and therefore justifies realism with respect to those objects.

Hacking makes clear that his argument for realism does not justify realism about all empirically well confirmed existence claims in microphysics. It is one thing to achieve empirical confirmation and another thing to use the corresponding objects as tools for probing new physics. It is an interesting question, however, whether any empirically confirmed physical object could in principle find a realist interpretation pace experimental realism once the right experimental setup has been developed, or whether general conceptual arguments enforce limits to the reach of Hacking's approach.

The suspicion that fundamental limits of that kind may exist can be related to one of the core criticisms of experimental realism. It has been argued (see e.g. Psillos 1999) that no clear-cut distinction between the experimentalist perspective and the corresponding theory can be made. Any experimentalist causal story about the use of physical objects as tools must be based on theoretical knowledge in order to specify how this tool can be deployed. It is plausible to expect that the use of theory in specifying the object within the experimental story increases with the conceptual complexity of the theory to be tested. High energy physics in this light appears as a prime candidate for a research context where Hacking's ideas make no sense anymore because the theory's empirical implications can't be formulated in terms of an intuitive experimental story.

A first confrontation of Hacking's entity realism with high energy physics was carried out by Hones (1991), who discusses meson and baryon spectroscopy in the late 1960s. Hones comes to the conclusion that, while the use of π-mesons in resonance physics can be viewed as a nice example of the use of a particle as a tool, Hacking's approach only provides a very rough view on what is going on in the experiment.

Massimi (2004) looks at the testing of the quark hypothesis in the 1970s and comes to a more critical conclusion. Massimi chooses a peculiar point of departure. Quarks are probed by other particles like electrons, but they are not themselves used as instruments in Hacking's sense. Massimi assumes that the described situation may be sufficient for a weakened version of entity realism that relies on being probed rather than on being used as an instrument. This idea may seem like a far stretch, given that it destroys Hacking's key idea that manipulation of objects provides a significantly stronger basis for realism than mere testing of the object's properties. Still, let us accept Massimi's softened criterion for entity realism and look at her argument.

Massimi observes that probing the constituents of nucleons in the 1970s had one important goal: deciding whether the quark model, which assumed effects of gluon exchange based on a gauge field theoretical understanding of strong interaction, or the parton model, which assumed freely moving constituents inside the nucleon, were empirically adequate. Eventually, the probing of the constituents of nucleons showed that the quark model was viable and the parton model was empirically inadequate. Massimi now points out that making this distinction was only possible by taking into account the theoretical characteristics of gauge field theory and the theory behind the experimental signatures collected. Already the specification of the property of experimental signatures that indicates the absence of interaction between constituents of the nucleon, the so called 'Bjorken scaling', is a theoretically difficult concept that can't be viewed in terms of a simple and straightforwardly intuitive experimental story. Matching violations of Bjorken scaling with predictions of gauge field theory then requires the full body of gauge theory. A simple experimental story cannot describe what is going on in the experiment. As Massimi puts it, "at a lower = experimental realist level (i.e., experiments plus phenomenological laws) partons and quarks are empirically equivalent. At a higher = scientific realist level (i.e., experiments plus QCD theory), partons and quarks are no longer empirically equivalent." Therefore, only the latter level allows us to understand what the experiments that probe the constituents of nucleons are all about. In other words, even based on the weakened notion of experimental realism Massimi is ready to accept, experimental realism is incapable of providing a basis for a realist understanding of quarks.

4: Group Structural Realism

Contrary to experimental realism, structural realism focuses on the specifics of physical theory and is advertised by its exponents to account for the decay of intuitive notions of ontology in fundamental physics. In recent years, a number of structural realists have put emphasis on the role of internal continuous symmetries and on gauge symmetries in high energy physics in particular. The idea that group structure is the most adequate place to anchor structural realism about fundamental physical theories has been named 'group structural realism by Brian Roberts (2011).

In the following, I will focus on internal gauge symmetries, where the case for a structural realist understanding arguably is most plausible. As described in Section 1, particle spectra and interaction structures in high energy physics are determined by the requirements of gauge invariance. Interactions are based on gauge boson exchange between those matter (spin 1/2) particles that form representations of the corresponding gauge symmetry group.

The crucial role of gauge symmetry lends support to a structural understanding of the theory's core tenets in a fairly straightforward way. While classical theories and quantum mechanics are based on the specification of the fundamental building blocks of the world, be they particles or fields, to which properties are attributed that determine their dynamics, theory construction in the case of gauge field theory may be taken to start at a structural level with the specification of the theory's gauge structure. The particle content then is given by a representation of the gauge group and can be extracted in a second step[4]. Particle ontology from that point of view looks secondary to structure. Two authors, Holger Lyre (2004) and Aharon Kantorovich (2003, 2009), have tried to make that idea more specific.

Lyre (2004) gives three reasons for a primacy of structure.

1: Viewed in terms of representations of gauge symmetries, particles are no individual objects in the sense of observable, identifiable entities that correspond to specific points in internal symmetry space. Objects are only defined, as Lyre puts it, "as members of equivalence classes under symmetry transformations". This suggests, according to Lyre, that objects are strictly secondary to the symmetry structure within which they are embedded.

2: The nature of ontological commitments in quantum field theory is underdetermined. Ontology may be based on field strengths, on potentials, or even on holonomies[5] (closed curves characterising the connection of a manifold). The symmetry statement, however, is unaffected by that choice and therefore seems to allow a unique expression of ontic commitment. (Lyre makes the additional point that, if the holonomy interpretation eventually turned out to be preferable, this would also support a structural perspective on realism because the nonlocal character of holonomies is at variance with an interpretation in terms of localized fundamental objects).

3: Lyre thinks that, in high energy physics, statements on symmetry structure have proved more stable than claims about ontological objects. This, of course, would play squarely into Worrall's classic argument that choosing the structural level for realist claims avoids the pitfalls of the pessimistic meta-induction.

Lyre argues that all three arguments favor gauge symmetry as the natural candidate for a structurally realist commitment.

Kantorovich chooses a substantially different perspective on the issue. His starting point is the mindset behind the ontological realist's focus on objects. This focus, in Kantorovich's view, is rooted in the following line of reasoning: while it is doubtful at best whether relations can be specified in a meaningful way without relata, physics can be fully understood in terms of actual micro-objects, the properties of which determine their dynamics; therefore, it seems plausible to attribute the ontological primacy to objects.

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[4] In the standard model, elementary particles are all attributed to the fundamental representations of the simple gauge groups and therefore seem to be implied immediately by the group choice. In grand unified theories, however, this is not the case, which in a sense emancipates the choice of the particle spectrum from the choice of the gauge group. This may be seen as a first worry about group structural realism.

[5] see Healey (2007)

This understanding, Kantorovich points out, is not applicable any more in the context of quantum field theory. One core implication of quantum field theory is the generation of new types of particles from radiation or kinetic energy. The particles that can be generated are determined by the corresponding theory's gauge structure and the representations that are physically realized. As described in Section 1, the possible outcomes of a particle collision in a high energy physics collider experiment are not fully determined by the incoming particles but depend on the internal symmetry structure and the conservation laws that characterize 'the world'. Those characteristics of 'the world' are not attributable to any objects existing at the initial stage of the collision process. Gauge structure is not a characteristic of existing objects but a feature 'globally' attributable to the world. Even if not a single particle of a given type existed a given point in time, the gauge structure would still imply that its creation was possible. In this sense, Kantorovich claims, structure is primary and ontological objects are secondary.

Let me point at an interesting general aspect of group structural realism. Scientific realism amounts to the claim that mature scientific theories are typically approximately true. In ontological realism, this claim is usually connected to the notion that scientific objects refer to something in the external world. Since ontological objects are not available as natural referents in structural realism, the question arises whether and if so in which way it makes sense to keep up the definition of scientific realism in terms of reference to something in the external world at all. The question may be phrased in terms of the distinction between placing realist commitments at a type or at a token level. In ontological realism, reference to the external world is understood at a token level: the term electron refers if it can be related to tokens of electrons in the external world. Structural realism, both in its epistemic and its ontic form, deemphasizes the token level of analysis compared to the type level.

It is a striking feature of group structural realism about high energy physics that its realist commitment is very difficult to express at a token level at all. The internal gauge symmetry structure is attributed to the Lagrangian of a given theory. It cannot be expressed as a property or characteristic of an individual object or phenomenon in the external world. One does not find tokens of gauge symmetry in this world. This aspect of the role of gauge symmetry in high energy physics is implicit in Lyre's analysis. For Kantorovich, the pre-eminence of structural features that are expressible only at the type level is the central reason for endorsing a structuralist position.

Group structural realism has been criticized on two accounts. It has been pointed out (McKenzie 2013, see also Nounou 2015) that mathematical group structure in itself does not amount to any physical claim. The parameters characterizing particles that sit in the representations of a gauge group need to be interpreted physically, that is in terms of their role in the dynamics of individual objects in order to acquire physical meaning. Only based on those specifications, which correspond to specifying a particle in terms of its position in a specific representation of the (spontaneously broken) symmetry group, can gauge field theory play the role of a physical theory that has the rich spectrum of empirical implications we know. In this light, the primacy of group structure, though plausible in terms of important mathematical features of the theory, looks less natural once one starts viewing the theory in terms of its physical import. (One might add that a theory's empirical import plays a crucial role in the no miracles argument, a main argument in favor of scientific realism.)

Kantorovich's position is less affected by this line of criticism. His main argument, stating that the theory describes more than actual objects, plays out once the physics behind the group structure has been fully taken into account.

A different line of criticism has been put forward in Roberts (2011). Roberts points out that it is highly non-trivial to specify what is meant by real structure in the context of group structural realism. The problem is that symmetry groups themselves can be characterized in terms of their symmetry structure. Technically this is done based on what is called the automorphism group of a given symmetry group. Repeating the step from a group to its automorphism group can lead to an infinite tower of meta-structural characterizations. The group structural realist thus faces the task of specifying which level(s) of structural description she wants to understand realistically, and for what reason. This, in Roberts' view makes the enterprise of specifying real structure uncomfortably arbitrary. Roberts adds that the argument from higher stability of structure (Lyre's third argument) might actually exert pressure towards shifting the realist understanding to higher level structures, since different groups can have the same automorphism group, which renders the latter potentially more stable under theory change than the former.

There is also a more general problem with Lyre's third argument. Lyre argues that symmetry statements are less prone to being superseded at future stages of theory building than other claims that are more closely bound to a given ontology. The problem is that Lyre's claim is itself bound to a given state of high energy physics theory building and therefore looks dangerously ahistoric. It is difficult to predict whether or not the fundamental role that has been attributed to gauge symmetry during the last half a century will be the final verdict in high energy physics. In fact, Joseph Polchinski has speculated in (2015) that gauge symmetry might in the end turn out to be an effective phenomenon that does not exist at the most fundamental level.

To conclude, whether or not full-fledged ontic structural realism follows from high energy physics remains contentious. Lyre and Kantorovich do deserve credit, however, for having highlighted a number of aspects of high energy physics that significantly reduce the role of ontological objects.

3: Realism and Non-Empirical Confirmation

The previous section was focused on analyzing the standard model of high energy physics, which is an empirically well confirmed theory. However, high energy physics today is characterized by a particularly important role of theories that have not found empirical confirmation. In fact, no fundamental theory in high energy physics that has been developed since 1974 has found empirical confirmation up to this point. Despite the lack of empirical confirmation, theories like grand unified theories, supersymmetry, supergravity and string theory have played a pre-eminent role in the field for many years. In this light, if one wants to discuss philosophical implications of recent concepts in the field, one needs to discuss empirically unconfirmed theories.

But does it make sense to take those theories seriously with regard to their implications for the scientific realism debate? Interestingly, important empirically unconfirmed theories are quite strongly believed to be viable by their exponents despite the lack of empirical confirmation. The degree of trust many physicists have in their theories is at variance with the canonical understanding of theory assessment and confirmation. It was argued in Dawid (2013) that, for a number of reasons, it seems advisable to modify that canonical understanding in a way that accounts for the actual status of today's empirically unconfirmed theories in the eyes of their exponents. Others (see e.g. Ellis and Silk 2014) have spoken out against taking empirically unconfirmed theories overly seriously.

Even if one does not endorse an extension of the concept of theory confirmation along the lines suggested in (Dawid 2013), it arguably makes sense to take well accepted but empirically unconfirmed theories seriously from a realist perspective. According to the canonical understanding of scientific theory confirmation, confirmation must be based on empirical data predicted by the theory in question. Arguing for epistemic scientific realism, however, requires going beyond this set of empirical evidence. It relies on the understanding that there is something in the record of doing science that suggests a specific relation between (some of) our scientific theories and truth. Arguing for realism with respect to a scientific theory therefore crucially relies on the understanding that considerations reaching out beyond empirical confirmation do have epistemic value. But that very understanding also constitutes the basis for the trust physicists have in empirically unconfirmed theories. Scientific realism thus naturally opens up to the question as to how it is affected by theories that are empirically unconfirmed but well trusted by considerable parts of the physics community.

4: String Dualities

Among the empirically unconfirmed theories that have been developed in high energy physics during the last four decades, string theory is the most influential one. It aims at providing a unified description of all fundamental interactions based on the basic idea that elementary objects are not point-like but extended in one dimension. The length of those strings is assumed to be far too small for being observable by current experimental methods.

Two characteristics of string theory arguably constitute high energy physics' most substantial novel contributions to the realism debate. The first of those characteristics is the abundance of duality relations in the theory. In order to understand the point, we need to say a few words about the basics of string theory. String theory contains no free parameters. This means that the theory does not allow for parameter values that can be chosen freely at a fundamental level. However, according to the best current understanding, the theory does have a very large number of ground states that correspond to specific parameter values that characterize the actual form of the string theoretical structure on which the world we observe is based. Parameters of that kind are, for example, the string coupling or the radii of string theory's compact dimensions. (Superstring theory, the kind of string theory that describes bosons and fermions, must have 10 spacetime dimensions to be consistent. 6 of them are assumed to be compact, that is they run back into themselves like a cylinder surface with a very small radius.) Which of those groundstates is actually selected is a matter of the dynamics of the system. Since string theory is a quantum theory, the choice of its groundstate is driven by quantum statistics.

At a fundamental level, it was initially believed that one could construct 5 different types of superstring theory. In the mid-1990s, it turned out that those 5 types of string theory were in fact only different descriptions of the same theory that were related to each other by so called duality relations. A duality connects two seemingly very different theories that, though being constructed based on different kinds of elementary objects, describe identical observable phenomena. In the case of the 5 seemingly different types of string theory, these theories are based on different internal symmetry structures and different spacetime structures. They also involve higher dimensional objects (so-called D-branes) of different dimensions. If two theories are dual, one theory with a specific parameter value (corresponding to a specific groundstate of the fundamental theory) is empirically fully equivalent to the dual theory with the inverted parameter value. Parameter values can for example be the string coupling constant (in the case of S-duality) or radii of compact dimensions measured in unities of the string length (in the case of T-duality). S- and T-duality connect all five types of string theory plus an additional 11-dimensional theory called M-theory. This means that, via a series of duality transformations, one can get from any type of string theory to any other.

The inversion of parameter values from one theory to its dual implies that there will often be one 'natural' formulation while the dual one will be less handy. For example, if one theory contains a compact dimension much larger than the string length, this dimension behaves in the way we expect a spatial dimension to behave. The extra-dimension of the dual theory, being much smaller than the string length, is in some sense too small for having the known characteristics of an extended dimension in which particles propagate. This means that it makes sense to discuss the first theory if we want to make contact with the dynamics of our observed world.

It may also happen, however, that the parameter values of the theory and its dual are both close to one, which means that no theory looks more natural than the other.

In 1998 it was understood by Maldacena (1998) that duality relations even reach out beyond string theory proper. String theory with a specific spacetime structure (asymptotic anti de Sitter Space) is conjectured to be empirically equivalent to a specific form of gauge field theory (a conformal field theory) that is based on point-like objects and does not contain a gravitational interaction.

Duality relations create serious problems for the ontological realist. Ontological realism is based on the understanding that there exists a set of real objects the world consists of. As has been discussed in a number of papers (Dawid 2007 and 2013, Rickles 2011, Matsubara 2013), this seems irreconcilable with the phenomenon of string dualities. A theory that contains duality relations which connect substantially different ontologies cannot be committed to one real set of ontological objects.

A metaphysical realist might hope to declare one of the dual ontologies the real one, even in the absence of an empirical way of identifying the true ontology. But this move is incompatible with the character of string physics for a number of reasons. First and foremost, string theory cannot be fully understood, let alone calculated, within the framework of one of the dual theories. The entire web of dual theories is needed in order to understand the theory's overall structure. And the theory's overall structure, in turn, is necessary for understanding the dynamics that leads towards the selection of a specific string theory groundstate. Focusing on just one type of string theory as the real one thus makes no conceptual sense.

Second, as has been pointed out e.g. in (Polchinski 2015), the limits in which one theory is more 'natural' than its dual correspond to classical limits: close to those limits, quantum effects are small. Those parts of parameter space where none of the dual theories is preferred correspond to physical situations that are dominated by quantum effects. The implication of this understanding is the following. The adequacy of a specific ontology must be understood as a property of a specific classical limit of the theory rather than of the theory itself. The existence of several types of string theory that are related to each other by duality relations demonstrates that string theory has several classical limits. Away from the classical limits of the theory, there is no way of making sense of any ontological formulation of the theory. It may well be the case that the actual string theory ground-state that corresponds to the world we live in is close to one of the classical limits. The full theory, however, and thereby the dynamics that has led to the selection of that groundstate, cannot be understood just by discussing the corresponding limit. Therefore, ontological scientific realism is no adequate basis for characterizing string theory at a fundamental level. If string theory is viable, ontological scientific realism as a fundamental perspective on physics is dead.

How structural realism fares in the face of string and string/gauge dualities is a more complicated question. String dualities imply that there is no fundamental structure that can be attributed to a given spacetime region. Dualities connect very different fundamental structures that can be used to characterize the situation; and spacetime structure itself changes from a theory to its dual. In this light, structural realism only seems compatible with string dualities if understood in a way that is fully decoupled from the notion of embedding structure in spacetime. It must allow for taking the overall structure of string physics, including the body of gauge theoretical structures that is connected to string theory by gauge/gravity dualities, as the true structure without referring to any spacetime background.

The strong role of dualities in string physics also has a more general implication for the realism debate. We observe two novel characteristics of theory building. First, in order to acquire a full understanding of the theory, it seems necessary to consider the entire web of dual formulations. Second, full empirical equivalence turns into an issue that is mostly discussed in terms of duality relations. In conjunction, those two observations imply that empirical equivalence is mostly viewed as an inner-theoretical issue rather than an issue of comparing different theories. On this basis, string physics de-emphasizes the distinction between truth and empirical adequacy. If understanding a theory means understanding how the empirically equivalent approaches that can be developed are related to each other, the truth of a theory refers to the entire spectrum of such empirically equivalent approaches. It wouldn't make sense to interpret empirical confirmation of string theory – if it occurred - as indicating that one of the empirically equivalent formulations is true. If one wants to call string theory true, one has to assert the truth of the entire web of dual formulations.

5: Final Theory Claims

Vague forms of final theory claims appeared in physics at various stages. Throughout most of the 18th and 19th century Newtonian physics was, except for the issue of its most convenient formulation, taken to be the last word on the physical phenomena described on its basis. In the late 19th century, a number of physicists thought that the fundamental pillars of physics had been provided by Newton and Maxwell's theory of electromagnetism. The advent of quantum mechanics and general relativity changed all this. It was understood that even the most successful theories could eventually turn out deeply inadequate at a fundamental level. Moreover, the understanding emerged that the conceptual incompatibility between the two grand physical frameworks of quantum physics and general relativity most likely would have to be overcome by further deep conceptual changes. The example of the supersession of even the most cherished classical theories by the conceptually very different successor theories quantum mechanics and general relativity seemed to suggest a perspective of infinite theory succession that played an important role in establishing antirealist perspectives among many philosophers of science once the scientific realism debate took center stage in the philosophy of science in the 1970s and 1980s.

String Theory is considered a promising candidate for a theory that unifies nuclear interactions and gravity. Therefore, it is a universal theory of all interactions, which makes it a candidate for a final theory. In this sense, it reconnects to the question of finality as it was raised in the 19th century. But in two respects string theory provides a qualitatively much stronger final theory claim than its classical forbears ever could. First, string theory cannot be combined in a consistent way with additional theories that describe additional phenomena. It is not possible to treat it in the way Newtonian mechanics was treated when electromagnetic phenomena were described independently but without generating any incoherence with the former. If a phenomenon that is not covered by string theory were discovered at energy scales below the string scale, the entire theory would have to be discarded. Second, and even more significantly, string theory introduces a minimal length scale based on its duality structure. It turns out that every formulation of string theory that introduces length scales below the string length can also be expressed in terms of the inverse length scale (in units of the string length). Therefore, once the entire phenomenology of string theory down to the string length has been specified, all has been said about the system. (see e.g. Witten 1996). On that basis, string theory suggests that no new physics should occur at all that goes beyond string theory. These two implications of string theory for the first time in the history of physics generate an explicit final theory claim based on a theory's structure: if string theory is viable, nothing can be added to it and no new physics can arise beyond its own characteristic scale.

The status of these claims has been analyzed in Dawid (2013,2013a). Theory-based final theory claims, if naively understood, seem to be begging the question. In effect, they amount to the claim that the theory is final if all its implications are true. But whether or not all implications of the theory are true is exactly what is at issue when a final theory claim is raised. So what can be the significance of string theory's final theory claim? Dawid (2013, 2013a) argues that a theory-based final theory claim can be relevant in connection with other strategies that aim at understanding the possible alternatives to a given theory. Since those other strategies also play an important role in assessing the current status of string theory, it is argued that string theory's final theory claim is a substantial, though not a conclusive statement.

A substantial final theory claim obviously is of high significance for the scientific realism debate. Note that the way the final theory claim is argued for in string physics only asserts the full empirical adequacy of the theory. It does not explicitly address the question of truth. However, we have argued in the previous section that string dualities suggest a conflation of the question of empirical equivalence and the question of truth. On that basis, string theory's final theory claim can be understood in terms of the theory's absolute truth. It must be emphasized, though, that string theory has not found a complete formulation yet. It rather resembles a number of statements that are deduced from a set of fundamental posits. The final theory claim should be read as the claim that there is a way to turn that set of statements into a complete theory based on consistency arguments. The resulting theory, whatever it is, is conjectured to be a true description of the world.

In this sense, string theory in conjunction with its final theory claim implies a realist interpretation. However, due to the conflation of truth and empirical adequacy and the lack of any ontological interpretation of the theory's claims, the emerging kind of realism remains fairly weak. On what grounds does it deserve to be called realism at all? Dawid

(2013, Chapter 7) proposes a formulation of scientific realism that characterizes the status of string theory (if confirmed) in conjunction with a final theory claim. This position, presented under the name of consistent structure realism, identifies as the substance of the realist conjecture in the given context the claim that there is a level of description of empirical phenomena that lies below mere bookkeeping of empirical data and that reduces the number of possible alternatives, based on a given set of empirical data, to one. The realist commitment then amounts to the understanding that, due to the lack of possible alternatives, empirical data will always agree with that "true" theory of the world.

6: Conclusion

If we try to distill a common message from the lines of reasoning presented in this paper, it may be the following. High energy physics continues and intensifies the development already discernible in quantum physics and general relativity towards a decay of the intuitive foundations of ontological realism and related concepts like entity realism. Developments in high energy physics can only be grasped from a theoretical point of view, which renders entity realism inadequate for dealing with it. They are based on abstract mathematical concepts that become increasingly difficult to frame in terms of a realist ontology of objects. Some crucial concepts seem to have no convincing interpretation at a token level at all.

The character of contemporary high energy physics in conjunction with the general mindset behind a realist view on science strongly suggest to treat those approaches in high energy physics that strongly influence the physical world view despite the lack of empirical confirmation as a serious source of arguments in the realism debate. If one follows that strategy, arguments against ontological realism become even more cogent. Sting dualities look like the final nail in the coffin of ontological realism. On the other hand, final theory claims do suggest a weak form of scientific realism that focuses on the issues of truth and the lack of scientific alternatives without adhering to traditional views about ontological objects or an external world.

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