MARGINALISATION OF THE PHENOMENA AND THE LIMITS OF SCIENTIFIC KNOWLEDGE IN HIGH ENERGY PHYSICS

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It is argued that the evolution of fundamental microphysics throughout the twentieth century is characterised by two interrelated developments. On the one hand, the experimental signatures which confirm theoretical statements are moving towards the fringes of the phenomenal world and, at the same time, leave increasingly wide spaces for entirely theoretical reasoning with little or no empirical interference. On the other hand, assessments of limitations to scientific underdetermination gain importance within the theoretical process.

1: Introduction

The general conceptual framework of contemporary particle physics was created in the late 1960s and early 1970s. Experimentally as well as theoretically, particle physics from that time onwards looked quite differently from earlier fundamental micro-physics. Theoretically, new concepts like gauge symmetries shifted the focus of scientific reasoning and induced a genuinely theory driven theory dynamics. Experimentally, the huge size of experiments required for testing the new theories turned experimental particle physics into a global enterprise focussed on very few gigantic experiments run for many years by several hundreds or thousands of physicists.

The first non-physicists to pick up on those substantial changes in the field were historians of science ([Pickering 1984], [Gallison 1987], [Gallison 1997]) who were struck primarily by the new sociological complexity of experiment and the complex interrelation between the experimental and the theoretical process. Since the beginning of the 21st century, philosophers of physics started addressing crucial concepts of contemporary particle physics, in particular the concept of gauge symmetry. (see e.g. [Brading & Castellani 2003]).

The present paper aims at understanding the wider range of philosophical implications related to the shift of particle physics in the 1960s and 1970s. The investigation will focus on two important and interrelated aspects of that development. First, it will address the changing relation between the theories, their characteristic experimental signatures and the everyday world. This development will be termed the "marginalisation of the phenomena" and shall be discussed in Section 3. Those considerations will then lead up to an analysis of the interrelations between the dynamics of particle physics and the question of scientific underdetermination, i.e. the underdetermination of scientific theory building by the available empirical data. The latter question has already been addressed in slightly different contexts in [Dawid 2006] and [Dawid 2008]. Sections 4 to 6 of the present work can be seen as a continuation of the line of investigation begun in those works. Scientific underdetermination will turn out to be related to the marginalisation of the phenomena in a complex way. In order to make that point, it will be helpful to embed the developments of particle physics in the wider context of the evolution of fundamental microphysics in earlier periods of physics. To set the stage, the paper starts in Section 2 with a brief survey of the historical roots and the main developments in particle physics.

2: A Sketch of the History of Fundamental Microphysics

The idea of unobservable micro-objects was first developed for abstract philosophical reasons in ancient Greece and in India. Modern scientific reasoning took up those ideas very early on and tried to fit them more closely to observation. In the following, I will present the scientific history of micro-objects by distinguishing five distinct stages. The first three stages constitute the prehistory of modern particle physics and shall be sketched very briefly. Still, considering those early stages will prove important for putting the later developments into perspective. Stage four constitutes a transitional period to stage five, the contemporary situation in particle physics.

Stage 1, 18th and 19th Century: Scientific Macro-Physical Evidence for Micro-Objects: From the 18th century onwards, atoms and molecules were deployed with increasing success for providing scientific explanations of specific aspects of macrophysical phenomenology. Already in the late 17th century, Newton used a corpuscular theory of light to explain optical phenomena. In 1740, Daniel Bernoulli was the first to aim at explaining the macrophysical laws of thermodynamics in terms of molecules moving in empty space. Early in the 19th century, John Dalton used the concepts of the atom and the molecule to explain the small integers which appeared in characteristic mass ratios when different compounds were formed out of the same chemical elements. While all these ideas were refined throughout the 19th century, conclusive empirical evidence for any of the asserted micro-objects remained elusive. In fact, it was still considered an open question whether the posits of micro-objects should be taken seriously as ontological and scientific posits or rather be understood as toy concepts which could play a heuristic role in the absence of a fully developed mathematical theory but would inhibit scientific progress if mistaken for constitutive elements of mature scientific theories. Physicists like Pierre Duhem [Duhem 1906] and Ernst Mach [Mach 1896] as well as chemists like Wilhelm Ostwald [Ostwald 1895] adhered to the latter position until the early years of the 20th century.

Stage 2, first Quarter of the 20th Century: Empirical Confirmation of Micro-Objects: In the first decades of the 20th century, the status of microphysical objects changed substantially. While a full analysis of the reasons for this development would lie beyond the scope of the present article, some crucial points shall be mentioned. The significant technical improvement of precision measurements at the time clearly plays a crucial role in the process and had a number of important implications. First, the web of distinct but interrelated phenomena which could be observed and interpreted coherently based on the posit of atoms, molecules or electrons became much more dense. In the case of Avogadro's number, one particular quantitative characteristic of micro-physics could be determined coherently by following various different paths of theoretical reasoning and experimental testing. Furthermore, experiments like Rutherford's alpha-scattering (1909) could be interpreted as utilising individual micro-objects for testing specific properties of other micro-objects. Thus, transcending the previous phase of scientific reasoning where a micro-object's empirical relevance lay solely in its accumulative observable effects, the new experimental means used micro-objects as extensions of empirical devices capable of testing properties of other micro-objects.[1] Moreover, new techniques were increasingly capable of producing empirical phenomena which could be taken to be caused in their entirety by individual micro-objects. Examples were the changes of direction in Brownian motion (first observed already in 1827 but explained satisfactorily only in 1905), the ticks of a Geiger counter (1908) or the traces in a cloud chamber (1911). Finally, atomist science showed a level of predictive success that could not be matched by non-atomist scientific strategies. All these developments jointly led to the emergence of a well-established micro-phenomenology that could be extracted in a cogent way from the empirical data. It became possible to identify nature's elementary building blocks one by one and to construct complex and detailed schemes of the relations and interactions between those elements. At the same time, it became increasingly implausible to assume that equally powerful theories about the whole range of collected phenomena could be constructed without relying on the posit of micro-physical objects. As a consequence, the fertility of introducing posits of micro-objects as pivotal elements of scientific theories became universally acknowledged.[2]

Stage 3, 1926-1947: Naïve Ontology Abandoned: Precise experimental results in micro-physics soon made clear, however, that the newly identified micro-objects did not behave according to the well established laws of macro-physics. The attempts to account for this fact led to the conception of quantum mechanics, which introduced profoundly counter-intuitive conceptions of micro-physical dynamics.[3] The reconciliation of

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[1] The importance of this step was pointed out by Hacking [Hacking 1983] who uses what he calls the manipulation of micro-objects as the basis for his entity realism.

[2] The question of the philosophical status of those objects, of course, lingers on until today.

[3] The development of counter-intuitive physics had, of course, already started in the context of space and time with special and general relativity.

quantum mechanics with special relativity in quantum field theory and the development of a workable theory of quantum electrodynamics in the following years and decades only strengthened this message. Based on these theories, it was possible to acquire a clear understanding of how micro-physics could be mathematically defined and deployed for precise predictions of empirical phenomena. The involved micro-objects, however, could not any more be understood in terms of the set of intuitions that fitted observable objects.

Stage 4, 1947-1971: Theoretically Uncontrolled Experimental Particle Proliferation: From 1947 onwards,[4] scattering experiments at high energies provided evidence for increasing numbers of particle types which did not constitute building blocks of observable matter. These particles existed only for minimal time periods after a high energy scattering event before decaying back into the classical particles. Some of the new particles lived long enough for leaving particle traces (if charged) or conspicuous gaps (if electrically neutral) in detectors, others were so short-lived that their existence could only be inferred from unusually high scattering cross sections at specific energy levels. More than sixty unstable particle types had been found by the mid 1960s. What started as ontologically interesting additions to the elementary set of particles became inflationary and thus seemed to lack deeper ontological significance. This impression was enhanced by the lack of theoretical means for putting the particles into a coherent system. Using the slightly derogative term ‘particle zoo’, many theoretical physicists expressed their dissatisfaction with a situation where theory seemed to have lost its structuring power and could not do much more than keep account of the ongoing experimental spectacle.

In experimental particle physics, the fact that each new energy level promised new experimental discoveries led to a continuous increase of the size of the experimental apparatus. The length of the accelerator tube in the largest existing accelerator rose from 24 cm in 1931 to 5m in 1942, 72m in 1953 and 600m in 1959. The experimental testing of fundamental micro-physics turned from a small enterprise carried out by an individual researcher to a gigantic effort of a large community of collaborating scientists and technicians.

In theoretical physics, the seemingly uncontrollable proliferation of particle types and the serious conceptual obstacles to a coherent field theoretical description of the strong interaction[5] led to an ‘empirical turn’ in particle physics in the early 1960s. S-matrix theory and the bootstrap model (see e.g. [Chew & Frautschi 1961]) represented a distinctly instrumentalist strategy for understanding particle scattering. The approach dropped the idea that there existed a small number of elementary particles. Without specifying the ‘ontological details’ of the scattering process itself, it focussed on the ‘external’ calculation of observed scattering processes based on its initial and final states and some general physical principles.

Stage 5, Since 1971: Dominance of Theory: The 1960s mark the beginning of two interrelated developments which substantially changed the course of particle physics in the 1970s and put an end to the instrumentalist research programme of S-matrix theory and bootstrapping. The introduction of quarks as a new level of elementary particles was

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[4] The first discoveries of heavy hadrons in that year triggered the flood-wave of new particles. The first heavy lepton, the muon, was already discovered in 1936.

[5] one of the three nuclear interactions, see also below.

followed by the emergence of gauge symmetries as the core concept for describing nuclear interactions. These conceptual shifts defined the foundation of theoretical particle physics until today.

In 1964, Gell-Mann introduced the Quark model as a means of bringing the many known types of particles into a coherent system [Gell-Mann]. Since no isolated quarks had been observed – and arguably also due to the prevalent empiricist mood –, Gell-Mann initially did not suggest taking quarks to be genuine fundamental particles but understood them in terms of a mere mathematical conceptualisation for characterising symmetries among the various types of hadronic particles. Only after 1969, when a characteristic feature of hadronic high energy scattering data[6] was interpreted by Feynman in terms of individual components of nucleons (called partons by Feynman) which behaved like free particles at small distances [Feynman 1969], quarks/partons were widely acknowledged as the physical elementary constituents of all hadronic particles.

The unitary Lie-groups which provided the mathematical framework for the symmetries stated by the quark model also played a pivotal role in the second development. The point of departure for this development was an old problem in quantum field theory. In the 1930s, it had been understood that the field theoretical calculation of particle scattering processes led to infinite terms which, roughly speaking, corresponded to the possibility that two particles can come infinitely close to each other. Feynman [Feynman 1950] and Schwinger [Schwinger 1951] then developed the renormalisation technique which provided coherent calculations of electromagnetic interaction processes at the quantum level (thereby creating the research field of quantum electro dynamics, in short QED) by cancelling off the divergences in a physically meaningful way. It remained unclear, however, how to apply the renormalisation technique to the other known microphysical forces, as there were strong and weak interactions. Already in the 1950s, it was suspected that the renormalisability of QED crucially depended on its character as a gauge theory: the fact that the electromagnetic interaction was carried by a Vector Boson made the QED Lagrangian invariant under local U(1) transformations, i.e. the Lagrangian showed a local U(1) symmetry. This property secured the renormalisability of the theory. Yang and Mills [Yang & Mills 1954] suggested that the strong interaction might be based on the exchange of a set of Vector Bosons which showed a generalization of QED's local U(1) symmetry, namely a local permutation symmetry between the types of elementary particles bound together by the interaction.[7] In analogy with the U(1) case, this non-abelian gauge symmetry should then enforce renormalisability just like the local U(1) symmetry had done in the case of QED. The idea was used for developing a unified picture of electromagnetic and weak (i.e. electroweak) interactions by Glashow [Glashow 1961] and Salam [Salam 1964] and for describing the strong interaction based on the quark picture [Han & Nambu 1965]. The mechanism of spontaneous symmetry breaking [Nambu & Jona-Lasinio 1961], [Goldstone 1961], [Higgs 1964] provided a solution to the problem how to produce realistic particle masses in the context of non-abelian gauge theories. In 1967, Weinberg [Weinberg 1967] integrated all these ideas in a coherent way in what is today called the standard model of particle physics and thus provided a fully adequate conception of the electroweak interaction. 't Hooft's actual proof of the renormalizability of non-abelian

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[6] the so called Bjorken-Scaling

[7] Yang and Mills at that time still took the nucleons to be elementary particles.

gauge theory ['t Hooft 1971], ['t Hooft & Veltman 1972] finally established the standard model as the most promising candidate for a viable description of electroweak interactions. When Politzer, Gross, and Wilczek [Politzer 1973], [Gross & Wiczek 1973] demonstrated the asymptotic freedom of non-abelian gauge theory (i.e. the property that elementary particles at small distances behave like free particles under unbroken non-abelian gauge interactions), gauge theory became a convincing candidate for the description of strong interaction as well.

At that time, the standard model of electroweak and strong interactions appeared convincing because it was the only available candidate for solving a large range of puzzles in high energy physics in a coherent way. Above all, it offered a solution to the crucial technical problem of renormalisability of strong and weak interactions. Furthermore, it explained the phenomenon of asymptotic freedom of the quarks under strong interaction, it allowed for different masses of matter particle types and provided a viable system of quark bound states that could explain the particle zoo.

The standard model also made substantial empirical predictions. Beyond predicting further hadronic particles which were now understood in terms of quark boundstates, it also predicted a number of new elementary particles. It predicted the existence of W and Z Bosons which are responsible for electroweak interactions; the existence of Gluons which are responsible for the strong interaction; the existence of new quark an lepton types for symmetry reasons and in order to account for the observed CP-violation [Kobayashi & Maskawa 1973]; and finally the existence of a Higgs Boson responsible for spontaneous symmetry breaking. All those particles were understood to be testable in collider experiments of sufficient size but none of them had been discovered before 1974. Trust in the standard model at the time was thus based solely on arguments of theoretical consistency and coherence and on the belief that a theory that provided so many convincing explanations at once was unlikely to be wrong.

In order to confirm the standard model's predictions, a further increase of size and power of experimental devices was necessary. The Stanford Linear Accellerator of 1966 had a length of 3 km. The Large Electron Positron Collider finished at CERN in1989 measured 27 km in circumfence. In the following two decades, the new colliders led to the experimental discovery of most of the elementary particles predicted by the standard model. Charm quark and tauon were found in 1974; the bottom quark in 1977; gluons in 1979; The W-Boson 1983; the Z-Boson 1984; the Top quark in 1994. Only the Higgs Boson has eluded detection so far. Its detection is one main goal of the ongoing experiments at CERN's Large Hadron Collider (LHC).

The year 1974, which boosted the trust in the standard model due to the discovery of the fourth quark, also witnessed a number of significant conceptual innovations which went beyond the standard model. Each of those ideas laid the foundation for a multifaceted and influential theory in its own right. The development and analysis of those theories continues until today.

Georgi and Glashow proposed the first Grand Unified Theory (GUT) which derived the observed microphysical interaction structure from one simple gauge group [Georgi & Glashow 1974]. GUTs look attractive due to the aesthetic appeal of integrating all known particles and nuclear interactions into one simple structural framework. The measurements of the strengths of the three nuclear interactions seem coherent with the predictions of GUTs,[8] which may be interpreted as indirect empirical indication for the viability of grand unification..

Wess and Zumino were the first to write down the Lagrangian of a particle physics model that showed the property of spacetime supersymmetry [Wess & Zumino 1974]. Supersymmetry joins the internal symmetry groups which are important in gauge field theory with the Poincare group of space-time translations and Lorentz-boosts. Supersymmetry at low energies (i.e. supersymmetry that is spontaneously broken at an energy scale close to the scale where electroweak scale), is considered a promising idea for two reasons: First, it leads to a more precise unification of the gauge couplings and therefore would fit together with grand unification. Second, it offers a satisfactory technical explanation as to how the huge scale differences of the order 10^{13} (respectively 10^{16}) between the electroweak scale and the GUT scale (respectively the Planck scale) can arise. If supersymmetry was indeed viable at low energy scales, this would imply the existence of a large set of new particles which could be discovered with the experimental means presently available. The search for supersymmetry is the second major goal of the current experiments at the Large Hadron Collider (after the search for the Higgs particle). The physical relevance of supersymmetry in general (irrespectively of the question whether it is a low energy phenomenon) is supported by a third argument. Supersymmetry can be formulated as a local symmetry (a gauge symmetry) just like inner symmetries [Freedman, Ferrara & van Neuvenhuizen 1976]. It turns out that local supersymmetry in a natural way includes gravitation. Supergravity, as the resulting theory is called, is considered attractive as a promising step towards a fully unified understanding of all fundamental interactions.

Moving one step further towards a full unification of gravitation and particle physics, Scherk and Schwarz [Scherk & Schwarz 1974] proposed string theory, a unified theory of all interactions that is based on extended objects rather than point-like elementary particles. String theory is closely related to supergravity which can be understood as the former's low energy limit. String theory is considered the only plausible candidate for full unification of all fundamental interactions and has led to an enormous amount of new structural developments.

In the beginning 1980s, Alan Guth [Guth 1981] and Andrei Linde [Linde 1982] proposed the idea of cosmic inflation to account for the homogeneity of the microwave background of the universe. Inflation today is considered the only plausible account of the dynamics of the universe. It has grown into a highly active and dynamical field in recent years and shows interesting interrelations with quantum field theory and string theory.

While all of these conceptions have been extensively studied and developed during the following decades, none of them has found any direct empirical confirmation up to now. Neither has their creation been motivated by any empirical incompatibilities of the available empirical data with the standard model of particle physics. The latter correctly reproduces all data collected up to now.[9] The importance and influence of model building beyond the standard model in contemporary particle physics is entirely

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[8] The three nuclear couplings (whose values depend on the energy scale at which they are considered) roughly converge towards one common value at a certain energy scale (the so called GUT scale).

[9] Neutrino masses are not predicted by the standard model but can be integrated without substantial conceptual changes.

based on theoretical considerations about consistency, theory unification and increased explanatory power.[10]

We do not want to address the question at this point whether the current status quo of theory driven particle physics can be understood as a mere continuation of the trend of theory empowerment that is characteristic of stage five of the evolution of fundamental microphysics or whether it should rather be taken as a genuinely new phase - a ‘stage six’ - that relies on theoretical reasoning in a way that is qualitatively different from what was happening at earlier stages. Leaving this question aside, the following section will assess the philosophical significance of the overall physical development throughout all the evolutionary stages presented above.

3: The Marginalisation of the Phenomena

The evolution sketched in the previous section shows conflicting tendencies. In several respects, later steps seem to imply taking back or weakening philosophical conclusions which may have seemed justified based on earlier developments. A well known example is the case of a realist understanding of micro-physical objects which seemed to be supported by the micro-physical experiments at the beginning of the 20th century only to be drawn into question once again with the advent of modern quantum mechanics. However, a tendency I want to call the marginalisation of the phenomena can be observed coherently through all stages of microphysical evolution: the experimental signatures which confirm theoretical statements in fundamental micro-physics are moving towards the fringes of the phenomenal world and, at the same time, leave increasingly wide spaces for entirely theoretical reasoning with little or no empirical interference. This, to be sure, does not imply that empirical testing loses its crucial importance for scientific inquiry in high energy physics. The process is more subtle than that. It can be identified in a number of related but distinct contexts which shall be presented individually in the following.

i: Marginalisation of the micro-physical phenomena in an observational context:
The phenomena to be explained by topical microphysics move from the centre of the observational realm towards remote and barely accessible areas of experimental testing. In the early phases of the evolution of micro-physics (at stage one of the scheme applied above), micro-objects were introduced for explaining phenomenal laws like the laws of thermodynamics or basic features of chemistry. The phenomena guided by these laws, like e.g. air pressure or combustion, could be experienced in nature everyday.

At stage two, physicists started designing experiments which were capable of testing specific aspects of the microphysical theories and often produced subtle and minute phenomenological output, the observation of which required considerable

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[10] In cosmology, the situation is slightly different. The homogeneity of the microwave background that motivated the conception of cosmic inflation may be taken as a phenomenon that directly contradicts older cosmological models.

technological support. The tested theories as a whole, however, still had very substantial consequences which could be observed by everyone. The first decades of the 20th century saw microphysical theories being deployed in technical developments which changed and shaped everyone's life. From the utilization of X-rays to the building of nuclear bombs and power plants, from the development of television to the use of neutron physics in modern medical treatments, technological progress was and still is based on the fundamental theoretical concepts developed in the first half of the 20th century.

At stage four the detachment of a theory's experimental consequences from everyday life entered a new level. Due to the short life-span of newly discovered particles, neither the particles nor the structure they disclosed had any implications for the observable world which went beyond the precision experiments where they were found. The theories tested in these experiments have not acquired technological relevance until today and there are no indications that this could change in the foreseeable future. The signatures found in those experiments were limited to a few unusual lines on a set of pictures extracted from a particle detector. The specific structure of these lines remained entirely irrelevant if judged solely in the context of observable phenomena. They derived their significance solely from their theoretical interpretation.

At stage 5, the quest for consistent unified theories of physical forces led to theories which predicted conceptual unifications whose characteristic length scales lay many orders of magnitude below the scales accessible at the time and thus added substantially to the motivation for increasing the experimental energy levels. Today, it requires the multi-billion-euro construction of a many kilometres long particle collider and the sustained work of thousands of experimentalists to test physics at new energy scales. A large share of the experimental signatures of contemporary particle theories are, if at all, only accessible to one or two experiments in the world. The characteristic experimental signatures of advanced particle theories like grand unified theories or string theory lie entirely beyond the reach of any experiment imaginable today.

ii: Marginalisation of the phenomena in research motivation:

The motivation for developing fundamental theories of micro-physics cannot any more be based on explaining the theories' characteristic observable phenomena. This point is directly related to point one. As long as the phenomena to be explained by microphysics were of genuine significance irrespectively of the theories developed to explain them, science could be taken to be motivated mainly by its observable implications. It was plausible to claim that the primary relevance of microphysics lay in its potential to create, control and understand observable phenomena rather than in its posit of some weirdly behaving unobservable objects.

From stage four onwards, however, the relevance of experimental signatures in particle physics was based entirely on their capability to confirm or refute scientific theories.[11] A crucial part of an experiment's analysis today is related to the assessment whether the empirical data support a new fundamental theory or can be explained in terms of other physical effects. That analysis eventually decides whether or not the data are of any interest. The observable phenomena thus turn from the primary subject of

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[11] Obviously, empirical evidence has always been valued as a basis for the evaluation and development of scientific theories. In a more traditional scientific setting, however, the empiricist could explain the significance of the resulting theoretical developments once again by referring to the visible phenomena.

scientific curiosity into a means for developing and confirming theories whose genuine significance cannot be understood in terms of the phenomena themselves. In this new scientific environment, a convincing motivation for theory construction arguably has to be based on some quality that gives relevance to the theory itself and goes beyond the mere characterisation of the minimalist phenomenological surface.

iii: Marginalisation of the phenomena in connecting theory to experiment:

An increasingly complex theoretical machinery is required for connecting empirical signatures to specific theoretical claims. The patterns of particle traces observed on pictures extracted from particle detectors stand in a rather complex relation to the particles they are taken to confirm. A good examples for the complexities involved are the empirical identifications of those particles which have too short a lifespan for leaving a trace on a picture themselves. The occurrence of such particles can only be inferred indirectly from the analysis of the vertices on the pictures extracted from the collider experiment. Vertices are 'points' in those pictures where different particle traces meet. They are taken to represent locations where particles decay into other particles in the detector. The application of well established theories of particle physics can lead to the conclusion that the repeated occurrence of certain kinds of vertices on the collected pictures can only be understood based on the assumption that the corresponding particle decays have happened via the creation of specific intermediate particles whose life time was too short for leaving any visible traces themselves. The observation of a statistically significant number of vertices of the given kind is then interpreted as empirical confirmation of the specific particle in question. Obviously, inferences of the described sort require a lot of fairly stable theoretical knowledge about particle physics. The more complex the theories and the corresponding experiments get, the longer becomes the 'theoretical distance' from the empirical signature to the confirmation of a theoretical statement.

iv: Marginalisation of the phenomena in concept formation:

The example of the observed object loses its power over scientific conceptualising. Stage one of the evolution of micro-physics took micro-physical objects to be small copies of the objects of the everyday world. By and large, they were supposed to share all of the latters' physical properties. In the late 19th century, doubts grew whether it was possible to reconcile this naïve conceptual approach with the observed phenomenology. The lack of precision measurements of micro-physical objects did not allow to develop any specific and empirically successful alternative concepts, however. The discovery of specific inconsistencies of a classical understanding of the atom as it emerged based on the experiments of the early 20th century finally led to quantum mechanics and the abandonment of the classical paradigm. This step followed the similar development in the understanding of space and time which had taken place a little earlier and had led to the counter-intuitive conceptions of special and general relativity. Quantum mechanics' abandonment of the classical scientific understanding that an object must have a precise location and momentum and must move according to deterministic laws was followed by other infringements on intuition. Quantum field theory gave up on the assumption that, at each point in time, there must exist a precise number of objects. The standard model of particle physics abandoned the understanding of mass as a primitive characteristic of objects and explained it in terms of a specific interaction structure. Concepts of quantum gravity may eventually imply giving up the concepts of fundamental space and time. All these developments are based on mathematical reasoning aiming at providing a theoretical structure that is internally consistent and fits the empirical data. While the observed phenomena started out in a double function as empirical testing criterion and raw model for the posit of micro-objects, today the second function has all but dissolved.

v: Marginalisation of the phenomena in theory dynamics:
In contemporary particle physics, theory has replaced experiment as the primary driving force of scientific progress. In earlier microphysics, experiments typically guided the evolution of scientific theories by providing new discoveries which demanded new theoretical explanations. The structure of atoms and nuclei, the existence of a large number of new particles, the different types of nuclear interactions or phenomena like CP-violation were first discovered by experiment and described theoretically later on. Only step five of the evolution of fundamental micro-physics altered this balance between theory and experiment. During the last four decades, particle physicists have become accustomed to a scientific environment where theory building is guided mainly by the theoretical insufficiencies of the existing theories. New theoretical schemes are not introduced due to empirical refutations of their predecessors but rather in order to solve consistency problems of existing theories[12] or to explain theoretical features of existing theories that look unnatural in the old framework.[13] The resulting new theories predict new empirical phenomena which are then sought to be tested experimentally. The prediction and later discovery of the standard model particles followed this pattern; the experimental discoveries of the Higgs-boson and supersymmetry are current experimental goals, which would fall into the same category. Experiment thus is largely (though not entirely, to be sure) reduced to the role of a testing device for already existing particle theories.[14] In addition, the time lag between theoretical posits and their empirical testing is steadily increasing. While experiments in the 1970s were mostly testing theoretical predictions which had been made just a few years ago, the current experiments at CERN's Large Hadron Collider search for particles whose existence has been proposed in the 1960s (in the case of the Higgs Boson) or around 1980 (in the case of the supersymmetric particle spectrum).

vi: The trust in theoretical conceptions is increasingly based on theoretical considerations. In this case, it would not be justified to speak of a marginalisation of the phenomena. Empirical testing of theoretical claims remains the crucial final goal in contemporary particle physics just like in other scientific fields. After all, large sums are

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[12] Examples are the particle physics standard model or string theory. The standard model achieved the renormalizability of strong and weak interactions; String Theory is an attempt to solve the problem of infinities which arise when gravity is unified with point-like particle physics.

[13] Examples are grand unified theories and low-energy supersymmetry. Grand unified theories aim at explaining the fact that the three microphysical coupling constants have (approximately) the same value at a certain energy scale; low-energy supersymmetry offers an explanation for the huge scale difference between the electroweak scale and the GUT respectively Planck scale.

[14] This should only be taken as a tendency. Not all testable properties are predicted univocally by particle theory. The test of proton decay would be one example where experiment still sets the pace and theory follows.

invested in the construction of particle colliders in order to keep particle theory empirically testable. However, even in that context the balance between theory and experiment is shifting. The fact that the standard model has been constructed based on theoretical considerations and proved capable of determining the course of experimental progress for decades, predicting the discovery of W and Z bosons, new quark types and lepton generations without ever going wrong[15] increased the trust in pure theorising. During recent decades the feeling grew that a theory, even if experimentally totally unsupported, may be taken to be just too good to be wrong. Theoreticians started to be quite confident about their theoretical predictions just because they seemed theoretically unavoidable. No-one had the slightest doubts about the existence of the top quark during the years of experimental search for it. Few theoreticians doubt today that some kind of Higgs particle does exist, even though it has so far eluded experimental detection. In those cases, the predictions in question are understood to be based on a theory whose other aspects have been empirically confirmed. But even the physicists' trust in genuinely new and empirically unconfirmed theories is increasing. Many theoreticians would bet that supersymmetry will some day be found in collider experiments just because the concept is explanatorily too powerful to be 'neglected' by nature. The rise of theoretical theory assessment is most conspicuous in string physics, which has to rely on it due the lack of concrete perspectives for empirical testing.

At first glance, the marginalisation of the phenomena appears to constitute a coherent and continuous albeit potentially problematic development: the quest for new micro-physics leads ever deeper into the micro-structure of the world, which requires ever more remote and expensive methods of empirical testing and enforces theoretical schemes that differ increasingly from the concepts we apply when structuring the visible world; this evolution at some stage runs into problems as the creation of experimental tests cannot keep up the pace with the theoretical developments and theoretical reasoning starts floating freely without sufficient empirical guidance.

The evolution of microphysics conceals a second story line, however, which is less conspicuous but makes the entire process much more interesting at a philosophical level. Some of the described theoretical aspects of the marginalisation of the phenomena are not explicable without taking account of a process that in some sense balances the development described in the previous paragraph. Though feeling less and less direct connection to the empirical phenomena, theory building shows a surprising directedness and lack of arbitrariness. The reasons for this phenomenon shall be discussed in the following section. As it will turn out, they are related to the marginalisation of the phenomena in a complex way.

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[15] The phrase 'without ever going wrong' refers to those predictions of the standard model which were understood to be essential to the survival of the gauge theoretical programme. The Standard Model cannot be fully derived from first theoretical principles and does not determine all physical parameters. Therefore, there naturally existed alternatives to the Standard Model with different symmetry groups or other distinctive features which had to be tested experimentally to be excluded. However, physicists were well able to distinguish these hypothetical constructions which might or might not have been corroborated by experiment from the theoretically unique predictions which 'had to be true' to keep the overall theoretical structure consistent.

4: Limitations to Scientific Underdetermination

It has been argued elsewhere[16] that the question of trust in theoretical theory confirmation, addressed in point vi of Section 3, is intricately linked to the question of limitations to scientific underdetermination. The classical scientific paradigm rests on the assumption that scientific theory building is not uniquely determined by the available empirical data. Rather, a given experimental status quo is expected to be consistent with many scientific structures which, in turn, may imply many different sets of empirical predictions. This assumption, which shall be called the assumption of scientific underdetermination, implies that purely theoretical reasoning can not constitute a reliable way of finding out whether or not a theory that provides a set of empirical predictions should be taken to be scientifically viable. Thus, the assumption of scientific underdetermination establishes the crucial role of empirical testing in the scientific process.

Scientific underdetermination cannot be taken to be entirely unconstrained, however. If it were, that is if all imaginable regularity patterns of empirical data could be fitted by some satisfactory scientific theory, no correct predictions of new phenomena could be expected to occur. One would rather be led towards understanding the specific predictions offered by the presently available theory as one accidental 'pick' among an infinite number of theoretically viable options. In this light, it would not seem reasonable to take those predictions seriously. It is a fact, however, that successful predictions of new phenomena do happen frequently in advanced science. Based on what has been said above, this fact must be understood as an indication of considerable limitations to scientific underdetermination: advanced scientific fields seem to reveal a tendency of limiting the number of coherent scientific theories which could be constructed in accordance with the available empirical data (and with some generally valid scientific preconceptions adopted by the scientists). In the following, scientific underdetermination shall be examined in the context of empirically testable high energy physics. It shall be argued that a full understanding of that scientific field indeed requires an understanding of the ways limitations to scientific underdetermination enter the scientific analysis.

Let us first go back once again to the early stages of the evolution of microphysics. Atoms, molecules and electrons were predicted for a long period of time without any strategy for direct empirical testing. Atomism's capacity of offering explanations for a number of different empirical phenomena nevertheless led many scientists to have considerable trust in the concept's validity. The posit of the atom thus can be taken as one strong example of a prediction whose viability was believed for theoretical reasons.[17] Following the argumentation of the previous paragraph, it may be concluded that an implicit assessment of limitations to scientific underdetermination must have been the basis for that belief.

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[16] Dawid 2006

[17] Maxwell struggled to define a specific status for those 'unproven' but still trustworthy theoretical conceptions. (see [Achinstein, unpublished])

The step from the contested status of atomism to the consensual understanding that experiment can conclusively confirm the posit of atoms or electrons makes the situation even more interesting. As discussed in Section 2, a number of developments contributed to this shift, which are all related to the improvement of experimental technology. It is important to understand, however, that the experimental developments on their own could not possibly deliver a conclusive argument for atomism. The increase of the number of independent empirical phenomena that could be understood coherently in an atomistic framework, to give one example, is generally understood to provide a crucial argument for atomism. The argument only works, however, once it is implicitly taken to be highly unlikely that any satisfactory scientific scheme exists which can account for all observed phenomena in an equally coherent way without endorsing the atomist posits. In other words, the argument works only if based on implicit assumptions of limitations to scientific underdetermination. In a similar way, the case of Brownian motion shows that even experimental data that ended up constituting evidence for the motion of single molecules could work only once the observers had found reasons for being confident that an interpretation along these lines works better than any other interpretation imaginable.

The shift from viewing atomism as a speculative idea or a mere auxiliary construction to acknowledging it as an empirically well confirmed scientific claim thus must be understood in terms of a shift of the assessment of limitations to scientific underdetermination. Until the first years of the 20th century, many important physicists and chemists held the opinion that scientific underdetermination stood against accepting atomism at face value. Later, in an experimentally more advanced environment, scientists came to the conclusion that a satisfactory non-atomist interpretation of the available data was highly unlikely to exist. This change promoted the available empirical data from giving indications in favour of atomism to constituting outright empirical confirmation of the existence of atoms.

Note that the assessment of limitations to scientific underdetermination in the given case does not just serve as a basis for justifying a certain amount of trust in a scientific speculation, it actually constitutes a crucial element of accepting empirical data as scientific confirmation for a theory. We will encounter this important point once again in the next section

At this point, it is important to have a closer look at the nature of the scientific preconceptions which stood behind considerations of limitations to underdetermination in the case of atomism. Those considerations crucially involved a predilection for a classical or intuitive understanding of the unobservable objects of microphysics. The viability of the posit of atoms was not inferred from the claim that no other coherent mathematical scheme could possibly account for the observed regularities. Rather, it was established by a kind of ‘no miracles’ argument with respect to naïve realism: if a theory based on a classical ontology of the micro-physical realm (which does not necessarily have to be atomist, it could as well be based e.g. on classical continuum mechanics) could account for the given empirical phenomena and, beyond that, provided a substantial number of successful predictions, it was reasonable to assume that this ontology was real; otherwise the fact that it worked so well would have been a miracle. This argument crucially relied on an implicit assumption of limitations to underdetermination regarding those theories which were based on a classical physical ontology. The applicability of some classical ontology was first posited as part of the basic set of scientific preconceptions that offered the framework for scientific theory building. The predictive success of science relying on that posit was then taken to indicate that only a small subclass of all imaginable empirical phenomena can be modelled based on such classical theories. The observation that all (or most, for that matter) empirical phenomena with some accuracy fell into that subclass then vindicated the basic scientific preconceptions and justified inferring the viability of the classical scientific theory that fits the phenomena.

Duhem rejected atomism because he did not believe that any limitations to underdetermination of scientific theory building were enforced by assuming a classical ontology. He believed that atomism just like several other ontological preconceptions could be made compatible with any imaginable phenomenology. Thus he concluded that atomism did not constitute a meaningful scientific posit at all. The strengthening of the experimental case for atoms in the first decade of the 20th century eroded the plausibility of Duhem's understanding and established the classical atomists' stance. The confirmation of specific predictions of atomism arguably indicated that limitations to scientific underdetermination were indeed at work at some level, contrary to Duhem's assumption. At the same time, however, the limits of classical atomism began to show. The refutation of a naïve classical understanding of microphysical ontology demonstrated that the classical paradigm in fact was no viable part of the framework of scientific preconceptions for micro-physics, which once more refuted Duhem's idea of an unlimited flexibility of the classical atomistic paradigm. Classical atomism turned out to be applicable to a limited subclass of possible phenomenologies only – and the phenomena actually observed did not fall into that subclass.

Naïve classical ontology had turned out to work as a guideline towards microphysics but failed to play the role of a viable preconception for micro-physical theory building. As discussed in Section 2, the abandonment of elements of the classical notion of a physical object did not end with the advent of quantum physics but continues until today. If successful predictions of novel phenomena are directly linked to limitations to scientific underdetermination, however, that development constitutes a potential threat to the predictive power of microphysics. Since the demise of naïve ontology removes the corresponding constraints on theory building, all mathematically coherent ways of structuring the observed phenomena must henceforth be taken to be potentially physically viable. The resulting widened spectrum of all mathematically coherent structures, however, might well be assumed to be sufficiently large for allowing the reproduction of all imaginable sets of future empirical data. As long as there are no a priori reasons for taking any of those structures to be more likely than any other, such a scenario would lack a plausible perspective of successful predictions.

The general trend of the marginalisation of the phenomena in microphysics contains a second aspect that may be expected to weaken limitations to underdetermination and therefore to work against predictive power. It was pointed out in Section 3 that an increasing amount of theoretical reasoning is required in contemporary particle physics for connecting the empirical data to the scientific object it is supposed to confirm. This increasing conceptual complexity a priori may be expected to enhance the chances of finding alternative theoretical interpretations which construe the connection between empirical data and theoretical implications in a different way. Such alternatives, in turn, may imply different empirical predictions with respect to novel phenomena and therefore can endanger predictive power.

For some period in the history of particle physics, during phase four of the chronology presented in Section 2, the predictive power of theoretical reasoning indeed seemed to undergo a crisis. From the 1970s onwards, however, particle physics theory building has turned out to be capable of predicting new phenomena correctly despite the stated threats from the marginalisation of the phenomena. Arguably, the predictive power of scientific theories with respect to novel phenomena as well as the accuracy of quantitative predictions is greater in contemporary particle physics than at any other time in the history of science.

At the present stage, the continuous trend of the marginalisation of the phenomena thus shows two seemingly conflicting tendencies. On the one hand, the increasing distance between empirical signatures and theoretical claims (point iii in Section 3) as well as the decreasing influence of naïve ontological intuition on theory building (point iv) potentially pose threats to predictive power. On the other hand, the leading role of theorizing in the dynamics of particle physics (point v) and the increasing trust in theoretical theory assessment (point vi) are, at least in part, consequences of an actual enhancement of predictive power. These two potentially contradictory tendencies can be squared only by assuming that assessments of limitations to scientific underdetermination play an increasing role in particle physics.

After the demise of naïve ontology, limitations to scientific underdetermination must be enforced by abstract principles of scientific reasoning which stay clear of positing intuitive ideas about the nature of physical objects. Some general philosophical ideas on the nature of general scientific preconceptions which may be at work under these circumstances have been discussed in [Dawid 2008] and shall not be carried any further in the present article. Instead, I want to address a problem that lies closer to scientific practice. It is striking that theoretical theory assessment is still widely considered an auxiliary enterprise with highly limited relevance for theory confirmation. Particle physicists, like other physicists, would largely adhere to the position that empirical confirmation carries the full weight of theory confirmation and, in that regard, cannot be significantly supplemented, let alone replaced, by theoretical assessments of limitations to scientific underdetermination. Given that understanding, however, the question arises what exactly the role of theoretical assessments of scientific underdetermination could be. In the following, this problem shall be addressed by looking at the way assessments of limitations to scientific underdetermination appear in a specific example of contemporary particle physics, the search for the Higgs boson.

5: The Prediction of and the Search for the Higgs Particle

The standard model of particle physics predicts an electrically uncharged massive spin zero particle that couples to fermions and W- and Z-bosons.[18] This so called Higgs

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[18] Supersymmetric extensions of the standard model predict several Higgs particles, some of them electrically charged.

particle has not been found in past experiments and will be searched for at the LHC at CERN during the upcoming years. As it turns out, the question of scientific underdetermination arises distinctively in two different contexts: in the context of predicting the Higgs particle as well as in the context of confirming it.

Let us first look at theory confirmation. The question of the unique attribution of empirical signatures to a specific theoretical claim is of crucial importance for the interpretation of high energy experiments. Theoretical arguments suggest that Higgs particles should be produced in significant numbers when protons and anti-protons are smashed together at the energies available at the LHC. Due to its high mass, the Higgs particle is expected to decay too fast for leaving a visible trace or gap[19] on decay pictures taken in detectors. Thus the particle has to be identified on those pictures by looking at vertices. As it was described in Section 3, the theoretical understanding of particle physics can lead towards interpreting certain decay patterns in terms of a particle decay via specific kinds of particles within specific vertices visible on the pictures. The collection of a statistically significant number of clearly identified candidates for the occurrence of a Higgs particle would be considered an empirical confirmation of the Higgs particle.

Confronted with a set of experimental signatures which count as candidates for Higgs particles, it is crucial to understand whether all potential explanations of the set of signatures in question which do NOT rely on the existence of a Higgs particle can be confidently excluded. A number of potential alternative explanations have to be checked. Higgs-like signatures can be caused by atypical exponents of other particle decays or by intruders from outside the detector like cosmic radiation, there could be all sorts of technical errors related to the involved experimental devices, there also may be systematic errors in the analysis of the data; and, finally, the signatures could also be produced by an entirely new physical phenomenon that is not accounted for by the existing particle theories at all. Assessing all possible sources of error is a crucial and fully acknowledged part of experimental particle physics. It relies on strategies for looking at those alternatives which can be checked as well as on attributing a low probability to the possibility that any other theoretical explanation which has not been thought of applies. The process thus provides a conspicuous example for a situation where the assessment of limitations to underdetermination directly enters the scientific process.

One aspect of this assessment is of particular interest for our discussion. As it was mentioned above, before accepting a set of signatures as confirmation for the Higgs particle, one has to be confident that the signatures are unlikely to be explicable by some entirely new physical phenomenon for which no theoretical ideas exist so far. Naturally, the possibility of such a new phenomenon can never be excluded analytically. The only basis for discarding it relies on a meta-inductive argument. Given that there have not been all that many entirely new types of phenomena in the past, it would seem like a cosmic coincidence if such a new phenomenon independently produced exactly those signatures which are taken to confirm the theory in question (in our case the particle

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[19] The standard model Higgs particle, being electronically neutral, could only produce a gap on a decay picture, between the point where it is produced and the point where it decays. Supersymmetric models predict charged Higgs particles, however, which could in principle, if it weren't for their short life time, leave a trace.

physics standard model that predicts the Higgs particle). There still remains the possibility, of course, that a new and genuinely distinct theory explains the same new experimental signatures as the theory to be tested due to some deep structural connection between the two theories. Here, the theorist can do no more than stress that she does not see any indications for such a scenario. The step towards accepting some signature as confirmation of the Higgs particle therefore relies crucially on an inference from a statement on the scientist's intellectual horizon (namely that the scientist cannot think of any realistic alternative scenario that would lead to the empirical data taken as confirmation of the Higgs particle) to a probability statement about the world (namely that most likely there ARE no other conditions in the world which can create that empirical data).

The principle addressed above is closely reminiscent of what was discussed in Section 3 with respect to the process of the acceptance of empirical data as valid confirmation for atoms or electrons: the notion of the empirical confirmation of unobservable objects must rely on an assessment of limitations to underdetermination regarding alternative theoretical interpretations of the data. In the case of high energy physics, the marginalisation of the phenomena makes the point more conspicuous, however. The relation between observable experimental signatures and their theoretical interpretation is particularly complex in particle physics and the theories which provide those interpretations are abstract and mathematically demanding. The process of assessing the univocal character of the theoretical interpretation of experimental data therefore has turned into a highly complicated scientific sub-discipline of its own.[20]

Let us now move on to the second context where limitations to scientific underdetermination play a significant role: the theoretical prediction of the Higgs particle and the assessment of that prediction's plausibility before it has been empirically vindicated. The path of reasoning that leads to the prediction of the Higgs particle

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[20] At this point, it may be of interest to address conclusions drawn by some historians and sociologists of science from the situation characterised in the previous paragraphs. The high degree of theory laden-ness of experimental particle physics has led some observers with social constructivist inclinations (see e.g. [Pickering 1984]) to suspect that high energy physics might be a particularly good example for the automatism of self-confirmation they take to be characteristic of science in general. Their suspicion is not entirely unreasonable. A theoretical scheme of the complexity of the relation between particle data and particle theory indeed may be expected to open up many options for alternative interpretations. Moreover, particle theories do enter into the interpretation of the particle data collected to test those very theories, which means that the overall structure of reasoning shows elements of circularity. Social constructivists thus are right in pointing out that the theoretical conclusions within this complex and somewhat self-referential web of arguments would lack objective quality if made without a trustworthy assessment of the degree of scientific underdetermination that must be attributed to the theoretical interpretations of the data in question. What they miss, however, is the fact that particle physicists, as emphasised above, do carry out such assessments and that these assessments tend to be vindicated by later scientific developments. Throughout the twentieth century, past interpretations of experimental signatures in terms of new particles have consistently turned out to be stable as long as they are discussed at the given description's characteristic distance scale. This fact provides the foundation for the scientists' trust in new instances of experimental confirmation. The significance of that meta-inductive argument becomes clearer when contrasting it with the scientists' conclusions regarding a slightly different question. Posits placed at some distance scale frequently had to be replaced by a more complex structure at smaller distance scales. Consequently, scientists do not take the confirmation of some new 'elementary particle' as confirmation of its elementary character.

involves a number of separate steps. First, there is the physicists' understanding that the description of relativistic phenomena in micro-physics requires quantum field theory. Within quantum field theory, a fully consistent calculation of scattering processes is understood to require the theory's renormalisability. Renormalisable interaction theories, in turn, are understood to require a gauge symmetric structure. A gauge symmetric structure is understood to be compatible with massive interaction particles and a spectrum of different fermion masses only if the gauge symmetry is spontaneously broken. Coherent spontaneous symmetry breaking, finally, requires the existence of a Higgs boson.

The question arises, as to what extent it was or is justified to believe in the prediction of the Higgs particle based on the given sequence of theoretical arguments. The line of argument sketched above may be doubted on two grounds: first, the possibility may be considered that no consistent physical description of the phenomena in question exists at all; second, it may be suspected that physicists have overlooked theoretically viable alternatives which would break one of the stated inferences. The first worry, though by no means inherently absurd, goes counter to today's deeply entrenched convictions about the range of scientific reasoning. The second one, to the contrary, is a standard worry within the boundaries of general scientific reasoning. When the Higgs particle was first predicted, the first steps of the line of argument given above seemed particularly uncertain. The possibility seemed realistic that the whole framework of quantum field theory was inadequate for offering a fully coherent description of the nuclear forces;[21] and even if accepting the framework of quantum field theory at the given energy scale, the deployment of gauge symmetries could be questioned by suspecting that another equally viable solution to the problem of renormalisability had simply been overlooked. These two worries prevented excessive trust in the standard model before it had been tested empirically. Both worries seem largely defeated today, since experiments have provided ample confirmation for the validity of gauge field theory at the electroweak scale. The second part of the line of reasoning sketched above, the steps from the assumption of the validity of gauge field theory to the prediction of the Higgs particle seems to be rather solid. On the basis of gauge field theory, the observed mass spectrum of elementary particles enforces the spontaneous breaking of electroweak gauge symmetry based on straightforward mathematical reasoning. The final step towards the Higgs field is also well understood and there seems to be no way to avoid it.[22] Physicists today therefore believe quite strongly in the existence of the Higgs particle despite the lack of empirical evidence. Nevertheless, purely theoretical reasoning cannot remove all doubts. It can not be excluded that the overall scheme of gauge field theory and the standard model, though having been confirmed in so many cases in the past, must be replaced by a completely different theory in order to describe the generation of masses correctly. Particle physicists have two arguments why they consider that scenario

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[21] It should be noted that an argument of this type in fact does apply once one takes the additional step to look for a joint description of microscopic forces and gravity. Gauge theory is not able to provide such a joint description, which leads the way towards string theory. The success of the Standard Model thus obviously cannot be taken to suggest that the old frameworks will work for ever. It merely exemplifies that theoretically satisfactory solutions within the old frameworks, if they exist, do not exist 'in vain'.

[22] Physicists do have different opinions on the question whether the Higgs is an elementary or a composite particle and whether one or several Higgs particles should be expected. The basic principle that at least one scalar particle must exist in order to make gauge field theory work, however, remains fairly uncontested.

unlikely. First, it would be unclear why the standard model has been so successful in experiments at the electroweak scale in the past if it turns out to be the wrong theory at that energy scale after all. Second, there are no indications at hand how an alternative theory could look like.

In the end, the question boils down to an assessment of the limitations to underdetermination: how plausible does it seem that an alternative theory is capable of reproducing all the data that have been taken as confirmation of the standard model without enforcing the existence of a Higgs field? Particle physicists largely share the understanding that this scenario seems rather unlikely, but that the final word has to be spoken by experiment.

6: The Limits of Scientific Reasoning

We have now identified assessments of scientific underdetermination in two different contexts of analysis. Scientists take them to carry fundamentally different epistemic weight.

The first context, analysing sources of error in the interpretation of empirical data, is considered an integral part of the acquisition of scientific knowledge. The assessment of scientific underdetermination plays a crucial and scientifically fully respectable role in the process that leads towards the recognition of experimental signatures as empirical confirmation of a scientific hypothesis, for example the existence of a certain kind of particle or the viability of some abstract scientific principle like spontaneously broken gauge symmetry.

The second context, judging a theory's likelihood of being scientifically viable in the absence of empirical confirmation of its characteristic predictions, has a very different epistemic status in science. Assessments of this kind are acknowledged to be helpful in providing some understanding of a theory's chances for scientific success. Most scientists, as well as philosophers of science, would deny, however, that these assessments themselves constitute actual scientific knowledge about nature.

The reasons for the marked distinction between the two types of judgement are clear. Science is considered an empirical enterprise that is expected to confirm each new hypothesis on empirical grounds. Only empirical confirmation turns a hypothesis into scientific knowledge. The first kind of reasoning contributes to completing the step towards empirical confirmation and therefore generates scientific knowledge. The second kind of reasoning does not meet that crucial condition. Calling its conclusions scientific knowledge thus would blur the boundaries between scientific reasoning and other types of intellectual activity, which to erect has been the grand accomplishment of the scientific revolution.

The traditional view has difficulties to survive closer scrutiny, however. The previous section raises doubts as to how much fundamental epistemological significance can be attributed to the distinction between theories whose characteristic predictions have been empirically confirmed and those which do not meet that condition: can this distinction be the basis for denying the status of scientific knowledge to the latter while granting it to the former kind of theory?

First, it is important to emphasise that scientific theories whose characteristic predictions have not yet been empirically confirmed nevertheless rest on empirical data. Either they account for known empirical data that had remained unaccounted for before or they solve a theoretical problem that has arisen in previous theories about the known empirical phenomena. The difference between an empirically confirmed and an empirically unconfirmed theoretical claim lies in the path of reasoning that leads from the empirical data to holding the claim in question. The empirically confirmed claim can be accepted based solely on the coherent interpretation of the known empirical data. To the contrary, trusting an empirically unconfirmed scientific claim must rely on a more complex line of reasoning. The theory implying the claim is considered a candidate for a viable theory about nature because it provides a theoretical solution to a scientific problem that arises based on the available empirical data. Trust in that claim on that basis rests on the belief that no scientifically satisfactory solution to the given problem exists that does not imply the claim in question. In other words, trust must be based on an assessment of limitations to scientific underdetermination.

It is clear that this assessment represents an additional risk for a false belief in scientific claims. But denying the status of scientific knowledge about nature to all empirically unconfirmed scientific claims must be based on the assertion that assessments of limitations to scientific underdetermination are incapable in principle of providing a basis for scientific knowledge about nature. As the example of the Higgs particle has shown, however, assessments of limitations to scientific underdetermination of the very same kind used for arguing in favour of empirically unconfirmed theories enter the analysis of the empirical data itself. In both cases, there is the threat of potential new theoretical schemes which might offer interpretations/solutions for the given experimental signatures/theoretical problems which have not been thought of so far. And both kinds of reasoning crucially rely on offering theoretical reasons for confidently taking the existence of such alternatives to be unlikely. The notion that the application of theoretical assessments of scientific underdetermination as it is applied to assessing empirically unconfirmed theories per se blocks scientific knowledge about the world therefore would amount to denying the status of scientific knowledge to all statements of modern high energy physics.

In order to avoid the latter conclusion, it seems necessary to change the understanding of the role of assessments of limitations to scientific underdetermination in fundamental physics. It should be acknowledged that those assessments have turned into an important part of scientific reasoning that contributes decisively to the confirmation of scientific statements and thereby is constitutive for the acquisition of scientific knowledge. If that is the case, however, there is no conceptual reason for denying the status of scientific knowledge to theoretical claims whose characteristic empirical predictions have not been empirically tested but which are considered very likely based on assessments of limitations to scientific underdetermination.

A position along these lines does not deny the important difference between theoretical reasoning and empirical testing. It neither denies that empirical testing must be the ultimate goal of natural science nor that empirical confirmation substantially enhances the trustworthiness of an individual scientific theory. It does deny, however, that there is a clear-cut distinction between viable scientific knowledge that is always based on empirical confirmation and empirically unconfirmed speculation that is rendered tentative and unstable due to the fact that it has to rely on reasoning open to the threat of scientific underdetermination. Rather, empirically confirmed and empirically unconfirmed theory building should be placed on a continuum with respect to their trustworthiness. Empirically confirmed theories are very high up on that continuous scale under today's circumstances. It is not always true, however, that claims based on purely theoretical reasoning are at the bottom end of the scale. Though present day physics does not offer good examples for a scenario of that kind, it could happen in principle that certain statements argued for convincingly on entirely theoretical grounds may some day be considered more trustworthy than others that are taken to have empirical confirmation, but in a theoretically unclear context.

7: Conclusion

Step by step, the sections of this work have developed a connection between the specifics of experimentation in contemporary particle physics and the significance of the question of scientific underdetermination. The argument started out with the observation that the enormous experimental efforts necessary for collecting new data in particle physics today can be understood as part of a more general tendency that characterises fundamental micro-physics since the beginning of the 20th century: the role of theoretical reasoning is being strengthened by transferring to the theoretical regime elements of the scientific process that were initially understood to be placed in the empirical realm. This 'marginalisation of the phenomena' contains an intrinsic tension, however, between those of its aspects which have the potential to threaten the predictive power of scientific theories on the one hand and those aspects which are grounded in the actual increase of particle physics' predictive power on the other. The attempt to dissolve that tension generated the suggestion that the assessment of limitations to scientific underdetermination plays an increasing role in particle physics. The discussion of two specific examples from micro-physics, the process that led to the consensual adoption of atomism at the beginning of the 20th century and the case of Higgs physics today, finally led up to the conclusion that a coherent understanding of what is happening in those cases in fact requires acknowledging the assessment of limitations to scientific underdetermination as a genuine and important element of the scientific process. An understanding emerged, according to which the assessment of limitations to scientific underdetermination constitutes an important element of scientific reasoning that could already be invoked when needed at earlier stages of science but assumed a more central and integrated position in the scientific process in course of the developments of fundamental micro-physics during the 20th century.

The emerging new perspective is of particular importance with respect to those empirically unconfirmed theories which, as stated at the end of stage five in Section 2, play a defining role in particle physics reasoning today. It seems barely possible to account for the present influence of theories like supersymmetry, string theory or cosmic inflation as long as one adheres to the traditional understanding of scientific theory assessment. It has been argued in [Dawid 2006] for the case of string theory that trust in that theory is based on a particularly strong reliance on assessments of limitations to scientific underdetermination. String theory, supersymmetry or cosmic inflation differ from the theory of spontaneous symmetry breaking that leads up to the prediction of the Higgs particle in not constituting an integral part of a theoretical scheme whose other parts have already found empirical confirmation. Obviously, this difference makes theoretical reasoning for the theories' validity once again a more risky enterprise. The argumentative principle, however, that stands behind the assessment of limitations to scientific underdetermination deployed in those cases is the same as in the case of the Higgs particle. The conspicuously high status of some empirically unconfirmed theories that characterises today's high energy physics thus may be understood in terms of a new but continuously emerging phase of the ascend of theoretical theory assessment. Recognising the deep entrenchment of theoretical theory assessment in empirically confirmed micro-physics makes its scientific respectability appear in a more natural light also in the more advanced cases.

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