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On the eve of the LHC: conceptual questions in high-energy physics

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Abstract

The LHC is an opportunity to make a change. By thinking, and speaking publicly, about fundamental concepts that underlie physical theory, the physicist may both accrue public interest in his work and contribute to the analysis of the foundations of modern physics.

We start by several remarks on the scientific and societal context of today's theoretical physics. Major classes of models for physics to be explored at the LHC are then reviewed. This leads us to propose an LHC timeline and a list of potential effects on theoretical physics and the society.

We then explore three conceptual questions connected with the LHC physics. These are placed in the context of debates both in high-energy physics and in the philosophy of physics. Symmetry is the first issue: we critically review the argument for its a priori and instrumental functions in physical theory and study its connection with naturalness. If perceived as a dynamical process in analogy with non-unitary measurement in quantum mechanics, spontaneous symmetry breaking is found to emphasize the role of randomness against physical law. Contrary to this cosmological view, the strictly non-dynamical role of spontaneous symmetry breaking within quantum field theory provides one of the strongest arguments in favour of the instrumental approach to symmetry. Second, we study the concept of effective field theory and its philosophical significance. Analogy with S-matrix suggests that one should treat effective theory both as a pragmatic and a provisional tool. Finally, we question the meaning of fine tuning. Legitimate fine-tuning arguments are interpreted non-ontologically. These are contrasted with unsound use of fine tuning, e.g., for comparing different models. Counterfactual reasoning referring to the anthropic principle is shown to be problematic both conceptually and in the light of quantum theory.

Contents

1 What use for conceptual questions?

1.1 Look back and look forward

Several times in history new, unintuitive physics invalidated previously existing commonplace views and revolutionized our understanding of the world. New concepts appeared, which were consequently hailed as the centerpiece of a conceptual foundation of physics. With regard to the launch in 2008 of the Large Hadron Collider (LHC) at CERN, few share the obstinate ambition to start a similarly radical physical revolution. This event may however become the tipping point of a new conceptual revolution. Indeed, models have been developed in significant depth beyond the theories of the Standard Model (SM), but we still miss a decisive input that would pick as correct one of the new ideas that underlie these models. Which will be the one to triumph? This question leads to two further questions about the future of theoretical physics: first, we stand in the need of a forward-looking analysis of concepts which may soon make their way to the center of the debate; second, the whole field may benefit from a systematic study of argumentation methods that have been used to promote theories beyond the Standard Model.

The LHC will probe the scale of symmetry breaking of the electroweak (EW) interaction. As of today, this is the last element of the Standard Model left without unambiguous support from experiment. We do not know whether the Higgs mechanism will turn out to be what the Standard Model takes it to be: a relatively unambitious but efficient way to remove the problem of Goldstone bosons and to give a quantitatively sound account of the electroweak symmetry breaking. It may be revealed that the SM Higgs mechanism is but a veil of new physics (NP) beyond the Standard Model: either supersymmetry or extra strong force or perhaps theories with extra dimensions.

Theorists have developed a great number of models. They were followed by phenomenologists and experimentalists, who have thought about experimental scenarios for corroborating these models in the signature content of the LHC data. The job has taken at least 25 years of hard work of a big community;

what has emerged at the end still sustains a lively discussion. On the eve of the launch of the LHC, it is now time both for physicists and for the philosophers of physics to look back at these 25 years, and to look forward at the future LHC physics, wondering whether new models will put forward novel ideas capable of entering the pantheon of fundamental physical knowledge.

1.2 Speak out but choose what you say

The launch of LHC will be an immediate scoop covered by mass media. However, it may or may not have a long-term, lasting effect on physics and on society. Whether it will have an effect on physics will depend on physical discoveries that remain to be made and on the existing landscape of competing models, to be discussed below. Whether it will have an effect on society, aside from purely scientific causes, will be influenced by the behaviour of all interested parties, foremostly communicating scientists and educators. Being the first major accelerator built for fundamental physics since 1980s, the LHC provides a unique opportunity for raising public awareness of the set of concepts and ideas which underlie the scientific worldview. Above all, in societal terms, LHC is an opportunity to renew the enthusiasm for *understanding the world*, after decades of its gradual fading and of growing fatigue for all things complex, like science or mathematics.

The LHC is an opportunity to make a change. Whether such a change will occur in the public attitude toward physics depends on how physicists will speak about the LHC and what they will say. The best way to oppose the decline of public interest for high energy physics is to think critically about our current choice of both rhetoric and content in outreach activities. A new, different choice could boost a move from communication focused on the mathematical content or projected results of advanced physical theories, to the language and rhetoric that would emphasize the key conceptual ideas and fundamental principles which are at stake. When a physicist tells the public a popular story about one or another mathematical model, or about concerns of a closed community whose interests are not shared by the larger group, the public is no less estranged that when it hears an oracle in a temple. The physicist casually tends to adopt the attitude of lecturing: “You don’t understand this, I’ll explain you that...” What follows is an attempt to give a glimpse of the theory that has a complex mathematical formulation, and one often hears phrases like “This is not really true, but for now I’ll take it to be so-and-so, because I can’t explain without the full mathematics what is *really* going on.” There is nothing bad in lecturing on subjects such as advanced physical theories. Popularization of science is a fascinating occupation. The problem lies elsewhere: the physicist typically believes that a lecture will suffice to illuminate and calm the audience and create a feeling of awe for his work. He all too often ignores that it can also create estrangement, alienation, and a feeling of futility.

The path to regained interest of the public lies through the creation of a sense of inclusion and familiarity, so that the public could identify themselves with the physics community and sympathize with it in its concerns. Popular science is not enough a tool to achieve this. An alternative way of telling the story is now pressing: instead of alienating the public with words which it does not understand, start with a comprehensible notion like symmetry or chance, and then lead the public gradually to the deeper analysis of the role and meaning of this notion in science. One can only be successful in telling this story if one has first thought deeply himself about the conceptual questions in physics and has sorted out and structured his knowledge accordingly.

Most physicists are unready to venture into what they commonly call ‘philosophy’: not the familiar solid ground of mainstream research, where a scientifically valid ‘yes’ or ‘no’ can always be given, but a shaky and risky field of not-just-science, i.e., of thinking *about* science. The working physicist rarely makes an effort to comprehend and convey deep conceptual issues that come before any mathematical development in the theory he’s working on. Members of the theoretical physics community, including some of the most lucid, sometimes claim that they all work like one person, in unison, and there can be no disagreement between them about well-known physics. This is true, or almost, as far as the mathematical content of physical theory is concerned. It is not true with respect to the meaning of mathematical models or the significance of the underlying concepts. That the claim about thinking in unison is made so often indicates that the theoretical physics community does not fully appreciate the importance and the role of what is dubbed 'philosophy' — of asking questions about meaning. Such questions were outmoded at the time when theoretical physics became a technology-oriented endeavour in close connection with nuclear engineering. This is true no more; the time has changed. The LHC physics is not technoscience developed for industrial application or competitive economic benefit; rather it is an issue of fundamental curiosity. Hence it is no more possible to wave the questions of meaning aside as non-practical. They belong inherently with the curiosity that keeps the LHC physics going.

For example, let the physicist ask what it means to take symmetry for a fundamental building block of our understanding of the world. How does renormalization group change our view of scales, of reality, and of how we theorize? What new understanding of mathematical entities such as the infinity or the perturbation series does it bring along? Ask these questions before students and welcome controversy and absence, better impossibility, of *the* right answer. Explain that taking sides with respect to such questions is not a cheap business or pure rhetoric: one has to master a great deal of scientific theory before his argument becomes sound and defendable in view of its harsh critique by opponents. Show the path leading from a simple "I think" or "I believe" to the complex physical knowledge that one must possess, and the full set of choices to which this particular belief commits.

Do not say that physics has been separated from philosophy. The latter has evolved with the former. Every particular field of knowledge, and physics is no exception, presupposes the most general principles without which it would not be knowledge. The philosophy of physics is a study of this foundational and systematic core: fundamental notions formulated in a non-technical way still underlie any development in physical theory. For Schlick [89] as well as for Friedman [38], "all great scientists think every problem with which they are concerned up to the end, and the end of every problem lies in philosophy."

Explain to the student that it is not possible nowadays to play with words as if there were no price to pay for this game, in terms of consistency of what is being said. Tell him that science underwrites much of what is sound in philosophy. Start your first lecture with the words of ordinary language, like symmetry or probability, and continue all the way down to the last lecture, where complex mathematics, which is necessary to distinguish a serious theory using these ordinary terms from a language game, will become familiar.

The job of theoretical physicist is not to write equations. It belongs with reaching to the essence of things, as quantum gravity pioneer Matvei Bronstein said at the beginning of 1930s. Theoretical physicist receives training in *understanding what is essential*, and so formulated, this training is highly attractive for the young. Later in his career, theoretical physicist may change jobs and become, for instance, a biologist or a financier. Nonetheless, he will be uniquely qualified for this new life because he will have learned to seek the deepest level of meaning of all things.

The LHC is an opportunity to explain to the society and to young students what it is to be a particle physicist. Teach students about concepts and ideas first; learning complex mathematics will follow. Speak to them not in the incomprehensible technical language, but make sure they will learn a method and a way of thinking. To keep them interested, tell them a story about symmetry, or the vacuum, or the infinity, or the role of the observer, or the meaning of probabilistic reasoning.

1.3 Structure of this article

In Section 2 we describe the SM Higgs mechanism and its problems. Alternative models beyond the SM are presented in Section 3. A timeline for their searches at the LHC is proposed in Section 4 along with a hypothetical timeline for impacts of these searches on the physics community.

Three conceptual problems, among others, will be influenced by the LHC results: the role of symmetry (Section 5), the use of effective theories (Section 6), and the value of probabilistic reasoning (Section 7). Symmetry is both an apriori justification of physical theories and a tool for their construction. It is the cornerstone of a worldview dating back from the early 1920s, which has proved very successful for the 20th-century physics. In 1970s the fundamental notion of symmetry was complemented by another key concept, the effective theory approach. Both of these may have attained their limit. Physics of the 21st century may be driven by new ideas like, for instance, duality relations or the holographic principle. Perturbation theory used for building our current models may cease to play the central role. A radically minded observer would claim that we may witness an overwhelming victory of models with strong forces, where perturbative methods are inapplicable. Be it true or not, even a conservative ought to acknowledge that the long-serving physics toolkit was extended to include new instruments.

The third conceptual question concerns probabilistic reasoning. It stems from a sheer observation that doing cutting-edge physics is a difficult task and it often remains beyond the reach of experimental verification. From the problems of the Standard Model we know that we shall eventually find new physics. It is also clear that in order to correspond to the available experimental data, simple proposals for this new physics, not overladen with extra structure, must be fine-tuned. Models that may be tuned not as highly are complicated and less beautiful. In the absence of conclusive experimental data, some are tempted to use reasoning based on the degree of fine tuning as argument pro or contra particular theories. This surprising inference, as well as the reference to the anthropic principle, raises the question of value and meaning of probabilistic reasoning in theoretical physics.

Further conceptual questions could be asked, i.e., about the meaning and the role of anomalies or concerning the fine distinction between the concept of theory and that of model. These are left beyond the scope of present work.

2 Meaning of the Higgs mechanism

The observed weak interaction is not locally gauge invariant. Its unification with electromagnetic interaction must take this fact into account. This is achieved by proposing a mechanism within the unification model, which puts the two interactions back on unequal grounds. By offering one such mechanism the Standard Model describes the electroweak symmetry breaking quantitatively, but does not explain it [83, p. 8]. This mechanism, theorized in 1964 independently by several different groups and named after Peter Higgs, can be summarized as follows: a massless spin-one particle has two polarization states; a massive one has three. The physical degree of freedom of the would-be Goldstone boson from EW symmetry breaking is absorbed by the massless gauge boson in order to allow it to increase the number of its polarization states from two to three and to become massive. Massive gauge bosons will then account for the absence of gauge symmetry in the observed weak interaction.*

This description was quickly recognized to be not very compelling [45, p. 12], precisely due to its lack of explanatory power. Many physicists did not find important the conceptual problems of the Higgs mechanism simply because they took it for no more than a convenient, but temporary, solution of the problem of electroweak symmetry breaking. For example, Jean Iliopoulos said at the 1979 Einstein Symposium: "Several people believe, and I share this view, that the Higgs scheme is a convenient parametrization of our ignorance concerning the dynamics of spontaneous symmetry breaking, and elementary scalar particles do not exist" [59]. On a similar note, in an article written at the end of 1970, Wilson had clearly stated his doubt: "It is interesting to note that there are no weakly coupled scalar particles in nature; scalar particles are the only kind of free particles whose mass term does not break either an internal or a gauge symmetry. . . . Mass or symmetry-breaking terms must be 'protected' from

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*Ten years after the original proposal, the Higgs mechanism was interpreted as a solution to the problem of maintaining unitarity of the weak interaction at high energies [69, 68]. This view originated in the S-matrix approach, where unitarity is a condition imposed on S matrix (see Section 6.3). Thirty years later the same line of thought produced higgsless models of electroweak interactions which restore unitarity through extra dimensions [27].

large corrections at large momenta due to various interactions (electromagnetic, weak, or strong). . . . This requirement means that weak interactions cannot be mediated by scalar particles" [108].

Things have seemingly changed since. The discovery of W and Z bosons and further experiments providing EW data have confirmed the Standard Model with a very good precision, including quantum corrections. The result was a change in the majority of physicists' view on the scalar Higgs boson. By 2004, for example, Wilson has been completely assured: "A claim that scalar elementary particles were unlikely to occur in elementary particle physics at currently measurable energies . . . makes no sense" [109]. We have today more confidence in the Standard Model; and we have learned that changing it could only come with a great cost in adjusting the theory's parameters, thanks to the exceedingly large number of experimental tests with which they have to conform. Still, two paths remain open for that who wishes to express uneasiness about the SM Higgs mechanism.

The first path has to do with the lack of comprehension of the spontaneous symmetry breaking (SSB). As Morrison notes [74], the Standard Model rests on crucial assumptions about the nature of the vacuum, and yet these assumptions are, in a very significant sense, not subject to direct empirical confirmation. For Morrison, application of the SSB mechanism in the SM is a question about the reality status of the $SU(2)_L \times U(1)_Y$ symmetry, i.e., an issue of physical ontology. For Healey [55], it is an issue of providing a sound mathematical foundation of the SSB mechanism, which would resolve the problem of comprehending SSB in a rigorous language. Discovery of the Higgs boson would allegedly provide more assurance that these two challenges could be met.

The second path is due to a problem of different nature with the SM Higgs mechanism: experimental rather than methodological. Certainly the Higgs mechanism is the most economical solution for breaking the electroweak symmetry. Moreover, the global fit of the electroweak precision data is consistent with the Standard Model, giving some indications for the presence of a light Higgs. These indications, however, are troublesome in the details: different ways of calculating the Higgs mass m_H, based on different confirmed experimental data, lead to incompatible predictions. The fit of the observables most sensitive to m_H has a probability of less than 2%. Giudice provides a compelling demonstration of the arising tension [46]:

> The preferred value of the Higgs mass is $m_H = 76^{+33}_{-24}$ GeV, with a 95% CL upper limit $m_H < 144$ GeV, raised to $m_H < 182$ GeV once the direct lower limit $m_H > 114$ GeV is included [51]. There are however some reasons of concern for the SM picture with a light Higgs.
>
> First of all, the decrease in the value of the top-quark mass measured at the Tevatron has worsened the SM fit. In particular, the value of the top mass extracted from EW data (excluding the direct Tevatron measurements) is $m_t = 178.9^{+11.7}_{-8.6}$ GeV, while the latest CDF/D0 result is $m_t = 170.9 \pm 1.8$ GeV [24][*].
>
> Of more direct impact on the light Higgs hypothesis is the observation that the two most precise measurements of $\sin^2\theta_W$ do not agree very well, differing by more than 3σ. The $b\bar{b}$ forward-backward asymmetry $A^{0,l}_{fb}$ measured at LEP gives a large value of $\sin^2\theta_W$, which leads to the prediction of a relatively heavy Higgs with $m_H = 420^{+420}_{-190}$ GeV. On the other hand, the lepton left-right asymmetry A_l measured at SLD (in agreement with the leptonic asymmetries measured at LEP) gives a low value of $\sin^2\theta_W$, corresponding to $m_H = 31^{+33}_{-19}$ GeV, in conflict with the lower limit $m_H > 114$ GeV from direct LEP searches [9]. Moreover, the world average of the W mass, $m_W = 80.392 \pm 0.029$ GeV, is larger than the value extracted from a SM fit, again requiring m_H to be smaller than what is allowed by the LEP Higgs searches.

The situation is summarized on Figure 1, where the predicted values of physical Higgs mass from different observables are shown. While $A^{0,l}_{fb}$ prefers a

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[*] This is the 2007 result. The 2008 one is $m_t = 172.6 \pm 0.8(\text{stat}) \pm 1.1(\text{syst})$ GeV [37].

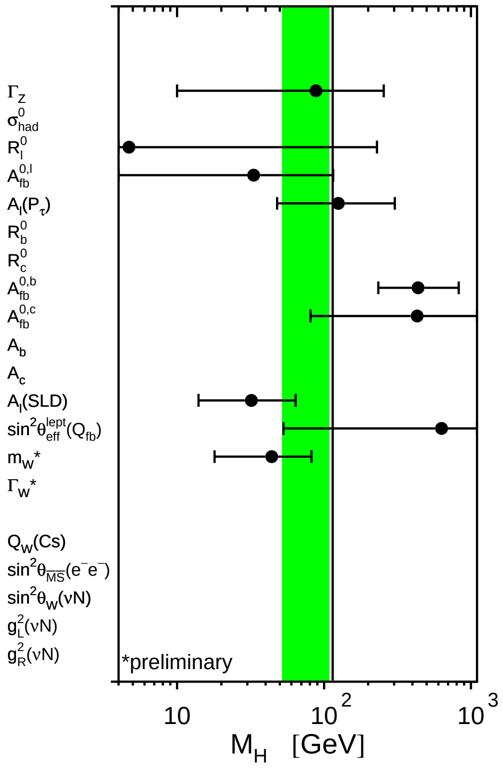

Figure 1: Values of the Higgs mass extracted from different EW observables. The vertical line is the direct LEP lower limit of 114 GeV. The average is shown as a green band [51].

relatively heavy Higgs, A_l and m_W require a very light Higgs already excluded by LEP. Only when we average over all (partially inconsistent!) data, as Giudice emphasizes, do we obtain the prediction for a relatively light Higgs and the usual upper bound $m_H < 182$ GeV. He then continues, "Although there is little doubt that the SM gives a satisfactory description of the EW data, this inconsistency of predictions makes the argument in favor of SM with a light Higgs less compelling." What is the meaning of the probabilistic argument based on a 2% fit? In what sense exactly does it make the SM Higgs less compelling?

3 Some theories beyond the Standard Model

3.1 Big and little hierarchy problems

This section is adapted from Rattazzi's account of what he calls the 'LEP paradox' [83]. We deliberately quote it at length, with only one modification: Rattazzi's discussion of fine tuning, scattered in the original all over the text, is brought together in one final paragraph.

The Standard Model suffers from the 'big' hierarchy problem: in the Lagrangian, the Higgs mass parameter m_H^2, which is related to the physical mass by $m_h^2 = -2m_H^2$, is affected by incalculable cut-off dependent quantum corrections. Whichever new theory replaces the Standard Model above some scale $\Lambda_{\rm NP}$, it is reasonable to expect, barring unwarranted cancelations, the Higgs mass parameter to be at least of the same size as (or bigger than) the SM contribution computed with a cut-off scale $\Lambda_{\rm NP}$. This way of estimating the size of the Higgs mass is made reasonable by many explicit examples that solve the hierarchy problem, and also by the analogy with the electromagnetic contribution to $m_{\pi^+}^2 - m_{\pi^0}^2$. The leading quantum correction is then expected to come from the top sector and is estimated to be

$$\delta m_H^2 \sim -\frac{3\lambda_t^2}{8\pi^2}\Lambda_{\rm NP}^2\,. \tag{1}$$

This contribution is compatible with the allowed range of m_h^2 only if the cut-off is rather low

$$\Lambda_{\rm NP} < 600 \times (\frac{m_h}{200\,{\rm GeV}})\,{\rm GeV}\,. \tag{2}$$

Now, if the energy range of the SM validity is as low as 500 GeV – 1 TeV, why did previous experiments not detect any deviation from the SM predictions? Even though the center of mass energy of these experiments was significantly lower than 1 TeV, still their precision was high enough to make them sensitive to virtual effects associated with a much higher scale.

Effects from new physics at a scale $\Lambda_{\rm NP}$ can in general be parametrized by adding to the SM renormalizable Lagrangian the whole tower of higher dimensional local operators, with coefficients suppressed by the suitable powers of

$\Lambda_{\rm NP}$:

$$\mathcal{L}_{eff}^{\rm NP} = \frac{1}{\Lambda_{NP}^2}\left\{c_1(\bar{e}\gamma_\mu e)^2 + c_2 W_{\mu\nu}^I B^{\mu\nu} H^\dagger \tau_I H + \ldots\right\} . \quad (3)$$

At leading order it is also sufficient to consider only the operators of lowest dimension, $d = 6$. The lower bound on $\Lambda_{\rm NP}$ for each individual operator $\mathcal{O}_i$, neglecting the effects of all the others and normalizing $|c_i| = 1$, ranges between 2 and 10 TeV. Turning several coefficients on at the same time does not qualitatively change the result, unless parameters are tuned. The interpretation of these results is that if New Physics affects electroweak observables at tree level, for which case $c_i \sim O(1)$, the generic lower bound on the new threshold is a few TeV. The tension between this lower bound and eq. (2) defines what is known as the little hierarchy problem.

The little hierarchy problem is apparently mild. But its behaviour with respect to fine tuning is problematic. If we allow fine tuning of order ϵ then the bound in eq. (2) is relaxed by a factor $1/\sqrt{\epsilon}$. The needed value of ϵ grows quadratically with $\Lambda_{\rm NP}$, so that for $\Lambda_{\rm NP} = 6$ TeV we need to tune to 1 part in a hundred in order to have $m_H = 200$ GeV.

3.2 Supersymmetry

Among known solutions to the big hierarchy problem supersymmetry at first appears to be the most satisfactory. This is mainly because it also leads to the unification of coupling constants and provides dark matter candidates. The main problem of supersymmetry is that neither the Higgs nor any supersymmetric particles have been observed at LEP, while the most studied realization of supersymmetry, MSSM, having a minimal field content, predicts the mass of the lightest CP-even Higgs particle below 140 GeV [52, p. 55]. Comparing with the LEP lower bound of 114 GeV, an official report concludes that MSSM has the "'fine tuning' and 'little hierarchy' problems" [52, p. 57].

How much of a problem is the fine tuning will be discussed below. There are different ways of quantifying its degree in MSSM. One way is to do a standard calculation which leads to the result that MSSM is fine tuned at 1 to 5% [83,

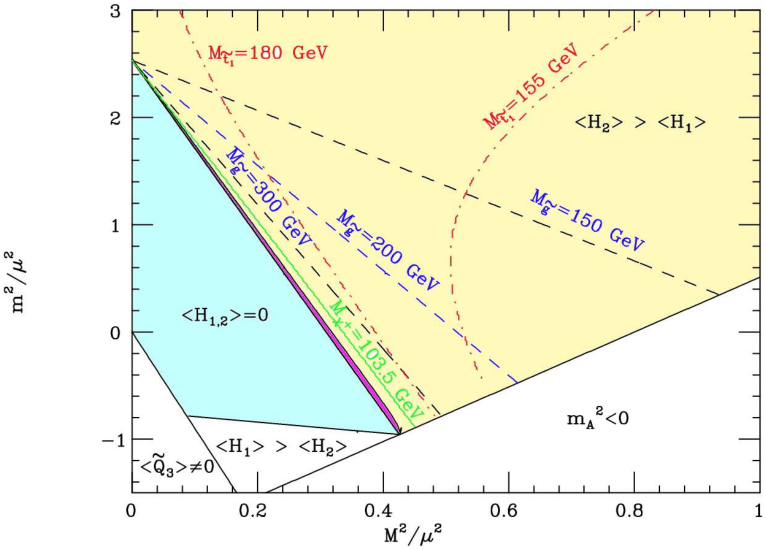

Figure 2: Phase diagram of a minimal supersymmetric model with universal scalar mass m, unified gaugino mass M and Higgsino mass μ at the GUT scale [47].

p. 4]. Another way is illustrated in Figure 2. It shows the phase diagram of a typical supersymmetric model. In a large fraction of parameter space (the yellow area) we find a phase with symmetry breaking $SU_2 \times U_1 \to U_1$, showing that the radiative EW symmetry breaking phenomenon is a rather typical feature of low-energy supersymmetry. However, in most of this region, the supersymmetric particles have masses not far from M_Z; they have been excluded by experimental searches. Only a thin sliver of parameter space survives (the purple area), a measure of the amount of tuning that supersymmetric theories must have in order to pass the experimental tests. The surviving region has the characteristic of lying very close to the critical line that separates the phases with broken and unbroken EW symmetry. Either minimal supersymmetry is not the right solution or, if and when it is eventually discovered at the LHC, we will have to understand why it lies in a 'near-critical' condition with respect to EW symmetry breaking. And this discovery, if minimal supersymmetry is correct, cannot be missed: we now have a no-lose theorem for the MSSM, which stipulates that the MSSM lightest Higgs boson cannot be present in nature and yet beyond the observational capacity of the LHC [53].

Another family of supersymmetric models, NMSSM, has lately become popular due to the expectations that MSSM may fail experimentally. The simplest member of the NMSSM family (further called, as the whole family, NMSSM) is a model which differs from MSSM by the introduction of just one neutral singlet superfield. For NMSSM, there is only a partial no-lose theorem [35]. Indeed, by its very design NMSSM is constructed so as to avoid the MSSM limitations on the Higgs particle, and it is therefore natural to expect that the NMSSM Higgs may escape observation at the LHC. At the tree level the NMSSM Higgs sector has seven parameters, while the one of MSSM has four. Thus, NMSSM has more freedom for fitting its parameters to the EW precision data: it is fine tuned at about 10%, one order of magnitude above the MSSM [83, p. 4].

If supersymmetry is discovered, a difficult task for the experiments will be to disentangle the various supersymmetric models and identify the pattern of soft terms [46]. Not only can this problem be experimentally challenging [52, Section 3.3], but it can also be theoretically intricate due to the possible involvement of a hidden sector in the running of TeV-scale SUSY terms to the Planck scale. Identification of soft terms contributes to answering a more general question of how supersymmetry is broken. Candidate SUSY breaking mechanisms abound, covering a large spectrum of models from metastable vacua and the involvement of gravity to several kinds of dynamical symmetry breaking [60], and their phenomenology remains to be explored and confronted with experiment.

3.3 Little Higgs models

There exist various interesting models beyond the SM in which the Higgs is a composite particle. In the last ten years appeared a new class of such models called Little Higgs (LH) models. The idea is to overcome the little hierarchy problem and make m_H much smaller with respect to Λ_{NP} than suggested in eq. (1) by turning the Higgs into a pseudo-Goldstone boson. Consequently, treating the Higgs as a pseudo-Golstone boson is prototypical of this class. The Higgs mass is here protected by multiple approximate symmetries and it can be generated only after collective symmetry breaking at two or more loops. The distinctive feature at the LHC will be the production of new states of the W, Z, t.

Inspiration for the pseudo-Goldstone idea comes from low energy hadron physics, where pions represent the Goldstone bosons associated with the spontaneous breakdown of chiral symmetry group $SU(2)_L \times SU(2)_R$ down to diagonal isospin group $SU(2)_I$. Quark masses m_q and the electromagnetic interaction α_{EM} explicitly break chiral symmetry by a small amount, giving rise to small pion masses. In particular, $m^2_{\pi^+}$ receives an electromagnetic correction of order

$$m^2_{\pi^+} \sim \frac{\alpha_{EM}}{4\pi}\Lambda^2_{QCD} \ll \Lambda^2_{QCD}. \tag{4}$$

In analogy with this process, we could think of an extension of the Standard Model where the Higgs particle is a composite Goldstone boson associated to some new strong dynamics at a scale $\Lambda_{\mathrm{Strong}}$.

General scheme of symmetry breaking in the Little Higgs models is given on

Figure 3. Its concrete realizations depend on whether G and F are chosen to be a simple or a product group. For a product group, a typical representative is the Littlest Higgs model [6], where $G/H = SU(5)/SO(5)$ and $F = [SU(2) \times U(1)]^2$. Example of a simple group little Higgs is $G/H = [SU(3)/SU(2)]^2$, $F = SU(3)[\times U(1)]$ [63].

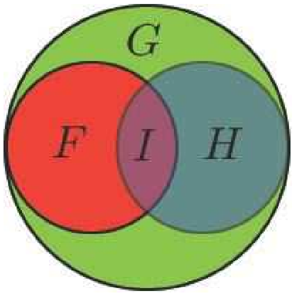

Figure 3: A global symmetry group of the Little Higgs models G is spontaneously broken down to a subgroup H by the Goldstone mechanism. Only a subgroup F of G is gauged, and therefore the SM electroweak gauge symmetry is identified with $I = F \cap H$ [25].

By replacing $\alpha_{EM} \to \alpha_t$ and $\Lambda_{QCD} \to \Lambda_{\rm Strong}$ in eq. (4), we generically expect, in analogy with QCD, $m_H^2 \sim \frac{\alpha_t}{4\pi}\Lambda^2_{\rm Strong}$. Since in this case $\Lambda_{\rm NP} \sim \Lambda_{\rm Strong}$, this is the same order as the very big leading quantum correction to m_H. Therefore, the Little Higgs construction must avoid the appearance of the lowest order contribution to m_H^2.

Consider indeed the expression for the mass of a Higgs pseudo-Goldstone boson, to all orders in the coupling constants

$$m_H^2 = \left(c_i \frac{\alpha_i}{4\pi} + c_{ij} \frac{\alpha_i \alpha_j}{(4\pi)^2} + \dots \right) \Lambda^2_{\rm Strong} \, .$$

We can think of couplings α_i as external sources that transform non-trivially under the Goldstone symmetry, thus breaking it, very much like an external electric field breaks the rotational invariance of atomic levels. As in atomic physics, the coefficients c_i, c_{ij}, … are controlled by the symmetry selection rules. We can then in principle think of a clever choice of symmetry group and couplings such that the Goldstone symmetry is partially restored when any single coupling α_i vanishes. In that situation only the combined effect of at least two distinct couplings α_i and α_j can destroy the Goldstone nature of the Higgs thus contributing a mass to it. The symmetry is said to be collectively broken, $c_i = 0$ and

$$m_H^2 \sim (\frac{\alpha}{4\pi})^2 \Lambda_{\rm Strong}^2 \,. \tag{5}$$

From this equation we then expect $\Lambda_{\rm Strong} \sim 10\,\rm TeV$, which seems to be what is needed to avoid the little hierarchy problem.

In the Little Higgs models there are two sources of operator contributions to the Lagrangian of effective theory. The first source is associated to the yet unknown physics at the cut-off $\Lambda_{\rm Strong}$, at which the Higgs is composite. It necessarily gives rise to operators involving just the Higgs boson, where vector bosons appear only through covariant derivatives. For $\Lambda_{\rm Strong} \sim 10\,\rm TeV$, these effects are not in contradiction with the data. The situation would however be bad if light fermions too were composite at $\Lambda_{\rm Strong}$, but, fortunately, fermion compositeness is not a necessary ingredient of LH models. The second source of effects is mainly associated with the intermediate vector bosons $W_H^{\pm}$, Z^H, ... with mass $\sim 1\,\rm TeV$. It leads to fine tuning LH models, and the calculated amount of fine tuning for normally weak gauge couplings — below 10% — is comparable with the amount of fine tuning in supersymmetry.

3.4 Models with extra dimensions

Until recently, Newtonian gravity has been tested only down to distances of the order of centimeter. This left open the possibility that its behaviour could be different below 1 mm. New experiments have put more severe constraints on a possible departure from Newtonian gravity, but due to an enormous difficulty to measure the gravitational force at short distances, these constraints are currently too mild to be conclusive (Figure 4).

Thus, extra spatial dimensions could accommodate gravitational interactions beyond reach of currently available data. Moreover, this could be done in such a way that that the resulting picture contribute to the solution of the big

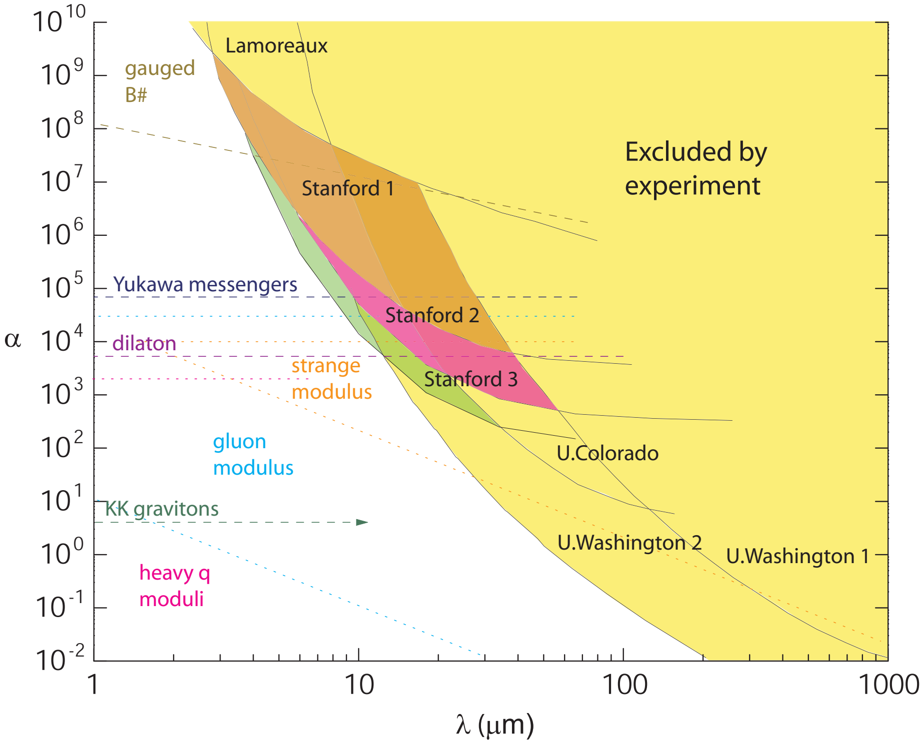

Figure 4: Limits on the correction to Newtonian potential parametrized as Yukawa force of strength α relative to gravity and of range λ. Also shown are various theoretical predictions that would modify Newtonian gravity [42].

hierarchy problem. No new fundamental scale of 10^{19} GeV would be needed, and the hierarchy between electroweak and Planck scales would be explained away thanks to effects of gravity in extra dimensions. Two principal scenarios realizing this idea are the ADD model with large extra dimensions [5] and the class of Randall-Sundrum models with warped extra dimensions [82]. A third class of models includes so called TeV^{-1} and universal extra dimensions, which avoid addressing the big hierarchy problem.

The idea to relate physics of extra dimensions with observable phenomena has first appeared in the context of string theory. Later on, it was realized that stringy braneworld scenarios could be brought to the TeV scale without the use of strings and developed into full-fledged models independently of one's preferred theory of quantum gravity.

Because extra spatial dimensions do not lead to modifications of gravity at observable scales, they must be compactified. Upon compactification, the full gauge group G_{extra} breaks down to G_{weak}, and the remaining extra dimensional polarizations (if any) A_5^α, A_6^α, $\ldots$ are massless at tree level. Like in the Little Higgs models, one can imagine that $G_{\text{extra}}/G_{\text{weak}}$ contains a Higgs doublet at EW scale. The extra dimensional symmetry then forbids large local contributions to the Higgs mass, implying that all remaining contributions to m_H^2 must be associated to non-local, hence finite, quantum corrections [46].

In the large extra dimensions model, the SM fields (except for singlets like right-handed neutrinos) are confined to the 3-dimensional brane while gravity propagates in all $3 + n$ spatial dimensions. The n extra dimensions are compactified, and, depending on $n = 2 \ldots 7$, their characteristic radius may vary from 1 mm to 10^{-15} m, hence the name 'large'. In fact, 'largeness' is not explained and is a mere artifact necessary for removing the hierarchy problem. The Planck-weak hierarchy is replaced by a new hierarchy problem, whereby the gap between the scales of gravity and electroweak forces, though now much smaller, still needs explication.

In this model, gravity is strong at the TeV scale and produces a continuous tower of Kaluza-Klein states. Its signatures in collider experiments include direct graviton production and virtual graviton exchange in scattering processes. LEP and Tevatron data together with constraints from cosmology have succeeded in excluding the case $n = 2$ as a solution to the hierarchy problem [67, 12]. However other options in the ADD construction remain open.

The TeV^{-1} extra dimensions model lowers the GUT scale by changing the running of the coupling constants. Gauge bosons are in the bulk, and gravity is not at all a part of this picture. Current limits set the lower limit of 6 TeV^{-1} on the characteristic radius of extra dimensions. The KK tower of the model contains equally distanced excitations, which resembles the phenomenology of yet another model called universal extra dimensions. In the latter, branes are not present at all and all SM field propagate in the bulk.

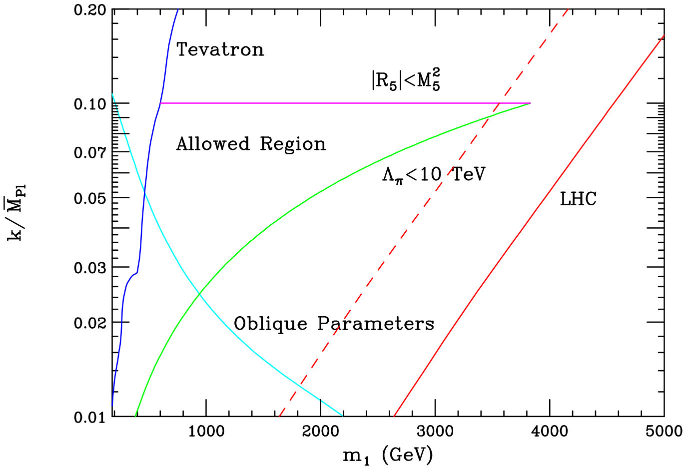

Figure 5: Summary of experimental and theoretical constraints on the Randall-Sundrum model for the case where the Standard Model fields are constrained to the TeV-brane. Sensitivity of the Tevatron and of the LHC to graviton resonances in the Drell-Yan channel is represented respectively by the blue curve and red dashed and solid lines, corresponding to 10 and 100 fb^{-1} of the LHC integrated luminosity. Thus, the full parameter space can be completely explored at the LHC, which will either discover or exclude the simple RS model [56, 28].

Arguably most daring and conceptually innovating idea of extra dimensions is based on the AdS/CFT correspondence [70]. It is a manifestation of the fundamental concept of holography, born within string theory and imported in model building and phenomenology. Holography suggests that there exists a deep relation between 5-d and 4-d theories. As in quantum mechanics, where particles and waves are two different aspects of the same physical reality, concepts of spatial dimension and force may turn out to be nothing more than dual descriptions of the same phenomenon. In the Randall–Sundrum (RS) model [82], interval $y = [0, R_c]$ in the fifth dimension is warped by the metric

$$ds^2 = e^{-2ky} dx_\mu dx^\mu + dy^2. \tag{6}$$

Geometrically, this is a slice of anti-de-Sitter space AdS_5 with two branes (called the TeV and the Planck branes) sitting at the boundaries of the slice, each of which has the Minkowski metric. The picture of a TeV brane and a Planck brane separated along the fifth coordinate can be replaced by the usual 4-d renormalization group flow between infrared (TeV) and ultraviolet (Planck) scales. In this sense, there is also a correspondence between position in the fifth dimension and energy, which is typical of a gravitational field.

Length k^{-1} in eq. (6) characterizes the distance beyond which curvature effects are important. Warp factor e^{-2ky} describes therefore the red shift in the energy of any process taking place at y relative to the same process taking place at $y = 0$. As Rattazzi notes, this is conceptually analogous to the relative red shift of light emitted in a given atomic transition by atoms sitting at different heights in the gravitational field of the Earth [83]. However, unlike on Earth, in the RS metric the curvature of space-time is large; the red shift is then huge and can explain the big hierarchy problem between electroweak and Planck scales.

The peculiarity of the ADD and RS models is that phenomenological predictions at the TeV scale are combined with a solution of the big hierarchy problem. In this sense both can be considered serious competitors of supersymmetry. In the RS case, extra dimensions are small and can be stabilized at $kR_c \simeq 11 - 12$ [56]. Still, as in supersymmetry, the estimate of the amount of fine tuning for the simple RS model due to electroweak constraints is at the level of 10%, which is analogous to LH models [26]. The collider signature and the allowed parameter space of the simple RS model (Figure 5) are such that the LHC will either confirm or completely exclude it. However, extensions of the RS model, with fermions allowed to reside in the bulk, are more complex, less fine tuned, and not so easily detectable experimentally.

4 The LHC physical and societal timeline

The main advantage of the LHC is that its event rate will be much higher than at previous accelerators thanks to the center-of-mass energy of 14 TeV. In many important channels, numbers of events produced per year will be 3 to 4 orders of magnitude larger than at the Tevatron. However, it would be precocious to claim that "the LHC will immediately enter new territory as it turns on" or that "major discoveries could very well follow during the first year of operation" [44]. Historical precedents are ambivalent and suggest a more moderate rhetoric: if the discovery of W and Z bosons followed in the first month of collider operation, ten years later it took the Tevatron much longer to start exploring truly new territory [43].

The main problem of the LHC is that although signal rates will be larger than at the Tevatron, in many cases signal-to-background ratios are expected to be worse. For example, at 14 TeV the cross-section for background hadron jets in searches of the Higgs boson at 150 GeV is five orders of magnitude larger than the signal cross-section. Thus, the enormous QCD background completely overwhelms the signal. To be able to detect the light Higgs on such a background, one has to spend considerable time on mastering the structure of the background; and then to look for significantly less probable Higgs decay channels than the dominant mode of hadron jet production $H \to b\bar{b}$. The leading detectable mode is a rare decay of the Higgs into a photon pair $H \to \gamma\gamma$ [52, p. 87]. Presence of the dominant decay into hadron jets may however suppress the branching ratio of the photon mode by a factor of the order of 10 to several hundred, depending on the coupling of the Higgs boson to new particles. It is sometimes stated that this "raises serious questions as to the capability of the LHC to discover the light Higgs boson" [52, p. 91]. To summarize, both the overly optimistic and the overly pessimistic exaggerations of the Higgs detection will probably prove not to be true. It is clear that a gradual increase in luminosity and more statistics will be necessary before the LHC can start reaching definitive conclusions.

Correct identification of the underlying new physics will not be easy too. A percent level accuracy appears to be mandatory in order to have a suitable sensitivity to discriminate between different models [52, p. 61]. For example, universal extra dimensions, where all SM fields are in the bulk, can be mistaken for the production of supersymmetric states [52, p. 63]. Similarly, distinguishing between different Little Higgs models may require many years of data collection at the LHC.

Slowness may become the keyword, and not necessarily an unwelcome one. If the discoveries don't pop up quickly, a meticulous, slow analysis of the collected data will have more credibility than the promises of "the most glorious and fruitful" epoch in the history of CERN [44].

Because of the little hierarchy problem, one expects that if there is SUSY at the TeV scale, then masses of squarks and gluinos should not exceed 3 TeV. The LHC may quickly discover SUSY at 1 TeV thanks to spectacular signatures of the decays of sparticles in the form of missing energy due to undetectable LSPs. However, it will take up to 8 to 10 years and a big increase in luminosity to say if there is SUSY at 3 TeV. During all these years, while SUSY will not be exactly falsified, the possible negative results will be dealt with by changing the parameters of the theory, as it happened in the past with LEP2 searches. At the same time, the failure to discover TeV-scale SUSY during the first year of the LHC may result, sociologically, in a growing dissatisfaction of the physics community with the idea of low-energy SUSY. We hypothesize that if by the end of 2010 no Higgs particle below 140 GeV is found and no evidence for TeV-scale SUSY is produced, the sociological effect may be such that new concepts, like extra dimensions, will become the main focal point of the physics community. Already today solutions of the hierarchy problem alternative to SUSY have shown a clear gain in popularity [18, p. 6]. It may happen so that, without waiting for the full test of SUSY up to 3 TeV, theoretical physics will become more interested in the notions of duality and the holographic principle and will terminate its 30-year-long romance with supersymmetry. The latter will only survive at high energies as a necessary ingredient of string theory. But in two or three years its low-energy version as well as the general fascination with supersymmetry may be both gone.

We adopt here with additions and modifications a timeline for the LHC operation proposed recently by Seiden [90]:

- 2009: Supersymmetry if squarks and gluinos have masses around 1 TeV.

- 2009-2010: Higgs boson if its mass is around 180 GeV. A heavy Higgs mainly decays into W pairs. The discovery may be quick and only require integrated luminosity of 5-10 fb^{-1} thanks to the essentially background-free four-lepton channel $H \to 4l$ [43]. If the Higgs has mass in this range, it may however be discovered by the Tevatron before the LHC.

- 2009: Extra dimensions if gravity scale is around 1 TeV. This will result in a copious production of mini black holes with a spectacular signature*, because evaporation of black holes through the Hawking radiation produces unique ratios of photons and charged leptons compared to quarks [77, 66]. However, making the distinction between different models with extra dimensions will be neither easy nor quick.

- 2009-2011: Z' if its mass is around 1 TeV. Evidence of a new $U(1)$ gauge boson Z' with couplings identical to the Standard model levels could be made with as little as 100 pb^{-1} of integrated luminosity [84], placing it as early as 2009. However, the necessity to measure Z' couplings and to distinguish it from other candidate particles will delay confirmation, with a 3σ result possible at 10 fb^{-1} of integrated luminosity; a 5σ result with 30 fb^{-1} [79].

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*Recently doubts have been expressed as for how profuse the production of black holes may be, if any at all [73].

- 2010: Simple Randall-Sundrum model will be found or excluded. Warped extra dimensions have a special signature consisting in resonance production of spin-2 gravitons. This makes the RS1 model easily detectable at the LHC at already 10 fb^{-1} of integrated luminosity.

- 2010-2011: Higgs boson if its mass is around 120 GeV. Rarity of the Higgs decay into photon pairs will require more and better statistics than needed for a heavy Higgs. Thus, the light Higgs will require more than 10 fb^{-1} of integrated luminosity, which may take up to 3 years of the LHC operation [44]. Input from both ATLAS and CMS and contribution of observations from other minor channels will be crucial for distilling a convincing signal of the light Higgs.

- 2012: Extra dimensions of space if the energy scale is 9 TeV.

The first upgrade of the LHC will take place in 2012 or 2013, leading to a 2 to 3 times increase in luminosity. Decisions with regard to the future of the machine will hugely depend on the discoveries that the LHC will have made by then. It may for example happen that the planned second upgrade (10 times increase in luminosity) will never become reality or be delayed due to political or financial reasons. Therefore the following long-term estimates are extremely speculative and only reflect our current knowledge of physics. More accurate estimates for the LHC functioning after the first upgrade will become possible by 2012.

- 2013: Compositeness if quarks are actually composite particles instead of being fundamental and that their composite nature reveals itself on an energy scale of 40 TeV.

- 2017: Supersymmetry if the appropriate energy scale is 3 TeV.

- 2019: Z' if a new strong force comes into play at 6 TeV. Although Z' decaying into e^+e^- is one of the easiest objects to discover at the LHC already during the first year of operation [43], careful analyses are required to distinguish various Z' from possible manifestations of new physics which can have a somewhat similar phenomenology, but a completely different physical origin [52, p. 62]. For example, signatures similar to composite Higgs models could be observed in decays of the lightest Kaluza-Klein excitations in models with large extra dimensions.

- 2019: Extended Randall-Sundrum models with fermions in the bulk. In such models dominant decay channels of gravitons in the simple RS model are suppressed [2]. One then needs significantly more precision, including the measurement of spin 2 of the graviton, which will require an integrated luminosity of at least 100 fb^{-1}.

5 Symmetry

5.1 Role of symmetry

The 20th century was a "century of symmetry" [71]. At its beginning, Einstein elevated the principle of invariance to the status of fundamental postulate. A decade later, Weyl introduced gauge symmetry in an ingenious move consisting of bringing down to the local level a notion of symmetry previously only thought of globally, as one symmetry for all space. Weyl was the first to write the action of a symmetry transformation at individual spacetime points and to allow this action to depend on the point in question. He was also the first to treat symmetry groups as relevant to the construction of physical theory. His use of group theory and of the notion of local gauge invariance have paved the way to the century of symmetry.

The method of local gauge symmetry was put to practical use by a generation of young physicists developing quantum theory in 1920s and 1930s. Fock, Schrödinger, Dirac and others have made lasting contributions. Today Weyl stands together with Eugene Wigner as founding fathers of the modern view of physics of which symmetry is the cornerstone. Summarized in Weyl's and Wigner's seminal books [104, 106], this view emphasizes two chief aspects of symmetry (other aspects have also been discussed in the literature [15]).

First, symmetries have a normative role: they are a priori constraints on physical theories. We do not derive symmetries from dynamical laws, as did Poincaré; on the contrary, we postulate symmetries and use them to derive dynamical laws. Symmetry participates in the dynamics and acquires its own constitutive power: e.g., symmetry which remains after symmetry breaking in the process of cosmological evolution is dynamically constituted. This new power of symmetry required conceptualization. Living at the time when every major physicist had a serious interest in philosophy, Weyl argued for a revision of Kantian epistemology which would make room for his claim that "all a priori statements in physics have their origin in symmetry". Thus, for Weyl, not only symmetry is a priori, but all physical a priori stems from symmetry principles. The latter, as a consequence, take the place of Kantian transcendental categorical basis of science. Wigner, although much less explicitly philosophical than Weyl, defended a similar view of symmetries when he said that "symmetries are laws, which the laws of nature have to observe" [107]. Symmetries, for Wigner, are therefore 'laws of the laws,' which is equivalent to Weyl's assertion that their normative role can be described as transcendental a priori.

Second, symmetry plays a heuristic role for the construction of modern physical theories. Gauge theory has been progressing since its introduction by Weyl in 1918 and has attained the level of an indispensable, if not taken for granted, element of model building in theoretical physics. Other symmetries, like an early Heisenberg's 'discovery' of permutation symmetry in 1926, or the CPT symmetry, shape the form of theories in which they are postulated. Thus, pragmatically speaking, symmetry principles "dictate the very existence" [103] of all the known forces of nature. This heuristic role, allowing for the construction of dynamical laws via established formalisms, gives to symmetry an instrumental status. By putting together the transcendental a priori role of symmetry and its heuristic value, one arrives at a transcendental-instrumental view on symmetry proposed by Ryckman [87].

It is interesting to note that the point of view according to which symmetry is "the secret of nature" [50] is not unanimous. With respect to global symmetries, the opinion that they are "unnatural" is not infrequent [93]. However very few oppose the role of local symmetries as a postulate describing invariance of physical phenomena under an abstract, theoretical transformation. Still such opponents exist; they would like to see symmetry emerge as a property of a fixed point or an asymptotic solution of the underlying equation which in itself would have no symmetry [39, 40, 36]. The debate between the two points of view resorts to subjective arguments about what is more beautiful, but it also makes the point that the reductionist program associated with the postulation of symmetries and the consequent derivation of laws has proved more efficient than the opposite idea of starting with 'nothing' and getting 'something' [49]. The future will show whether an advanced physical theory is possible that would not be based on symmetry principles.

5.2 Symmetry breaking

Looking for symmetric solutions to symmetric problems simplifies the construction of the solution, but there are situations in which the symmetric solutions are not, in Iliopoulos's words, "the most interesting ones" [59]. If a symmetry available in the model is not present in the physical solution of the model's equations, then it must be 'broken', i.e., the theory must contain a descriptive account of why the symmetry in question does not exist in the exact sense. There are two types of mechanisms for symmetry breaking: explicit and spontaneous symmetry breaking. Both of them emphasize the heuristic role of symmetry in model building. Indeed, when at the end of the construction symmetry is broken so that it is completely unobservable, using this very symmetry as an a priori postulate may simply be empirically inadequate. While not seen by Weyl [104, pp. 125-126], this argument about empirical inadequacy of a priori constraints has played a role in the establishment of Friedman's idea of relativized a priori [38] and particularly in the discussion initiated by van Fraassen [98]. To save the symmetry method of model building, one has to provide an explanatory account of the divergence between empirical reality and the postulates needed for model construction. Thus, breaking the symmetry while preserving its benefits is indeed “the main challenge in model building” [83, p. 8].

In the group-theoretic treatment of symmetry, symmetry breaking amounts to saying that the system is invariant under the action of a subgroup rather than the full group corresponding to unbroken symmetry. Symmetry breaking can therefore be described in mathematical terms through a relation between transformation groups. This fact provides a natural language for the description of physical models as possessing such-or-such full symmetry group, broken down to one or another of its subgroups.

Explicit symmetry breaking occurs in virtue of terms in the Lagrangian of the system that are not invariant under the considered symmetry group. The origin of such terms can vary: they could either be introduced manifestly, for instance in the case of parity violation; or appear as anomalies on the path from classical to quantum field theory, like violation of chirality; or even appear in regularization schemes as side effects of the introduction of a cut-off. For example, collective symmetry breaking is a new concept in symmetry breaking methods, introduced in the Little Higgs models. It requires two interactions to explicitly break all symmetries that protect the Higgs mass. At the one-loop level symmetry breaking does not occur and is only triggered by the second order terms (see Section 3.3).

Spontaneous symmetry breaking (SSB) corresponds to situations where symmetry is not broken explicitly, but the solution of the equations is however not symmetric. In gauge theory, the choice of the solution is typically the choice of a particular ground state of the theory, which is not invariant under the symmetry transformation. The original symmetry, although broken, is still ‘hidden’, meaning that we cannot predict which non-symmetric ground state will be chosen. Thus, this choice is not a dynamical process in the sense of unitary time evolution. Viewed strictly from within quantum field theory, SSB is a not a process at all: ‘breaking’ only occurs in the theorist’s mind when he writes, first, a QFT Lagrangian with exact symmetry and then another, different QFT Lagrangian, where this symmetry is broken. The two lagrangians aren’t connected by physics. They do not correspond to the descriptions of some system either at earlier and later times or as synchronic or diachronic cause and effect, as Curie's principle would require [11, 62].* Strictly within QFT, SSB and time evolution are unrelated. Thus, SSB becomes here but a mere tool for model building, providing a strong case in favour of the instrumental approach to symmetry in quantum field theory.

To take a typical example, the full symmetry in a model containing left and right fermions corresponds to group $\mathrm{SU}(2)_{\mathrm{L}} \times \mathrm{SU}(2)_{\mathrm{R}}$. Right-handed fermions are not a part of the observed reality and must be excluded from the Standard Model. Spontaneous symmetry breaking then consists in giving a non-zero vacuum expectation value (vev) to the Higgs doublet that exists in this general model; it leads to reducing the full symmetry group down to the diagonal subgroup $\mathrm{SU}(2)_{\mathrm{V}}$ called custodial symmetry. The choice of a particular vev for the Higgs boson cannot be predicted theoretically and must be deduced from experimental data. Once determined, the vev appears explicitly in the Lagrangian of the new QFT with broken symmetry.

A philosophical question about symmetry breaking is why we search for a way to obtain a symmetric, rather than asymmetric, laws and why we assign the observed asymmetry to solutions, not directly to laws [32]. As Kosso puts it, "Why not just give up on the idea of gauge symmetry for the weak interaction, given the evidence that it is not gauge invariant? Is there good reason for the commitment to the gauge principle... even if that symmetry is hidden in all circumstances?" [64]† Another way to ask the same question would be to wonder at a paradoxically sounding but precise phrase by David Gross: "The *search* for new symmetries of nature is based on the possibility of finding mechanisms, such as spontaneous symmetry breaking or confinement, that *hide* the new

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[*] Numerous discussions of symmetry in physics focus on Curie's principle and argue sometimes that spontaneous symmetry breaking provides an argument against it [16]. In our view, strictly quantum field theoretic SSB is irrelevant for the analysis of Curie's principle. Similarly, claims that SSB represents a "failure of determinism" [31] cannot be grounded in the pure quantum field theory but require an additional speculative cosmological model.

[†] With respect to the weak interaction the answer is that we need gauge invariance in order to obtain a renormalizable theory. The question still holds in the general sense: why, conceptually, do we need to use quantum field theoretic models, like Yang-Mills with its divergences and the necessity of gauge symmetry to avoid them, rather than using a theory which would not postulate a symmetry only to break it at the next stage of model building?

symmetry" [50, our emphasis].

Castellani following Earman provides a useful insight by connecting this question with Curie's assertion that the absence of certain elements of symmetry, or dissymmetry, is what creates the phenomenon [31, 23]. The normative a priori role of symmetry as 'law of the laws' places it in the transcendental background, making symmetry the condition of possibility of lawfulness in physics. No law is possible other than determined by, and derived from, a symmetry.

This transcendental argument, which sets up the condition of possibility of lawfulness, needs explication. Physical law is what applies to many individual experimental cases, of which it provides a uniform, and unified, treatment. There cannot be a law without the existence, by postulation, of common features among these diverse experimental situations. If there had been no common trait between them, no method nor language for making the comparison between disparate occurrences, then indeed no unification of these occurrences would be possible. Symmetry is the tool that we employ to name these common traits and to manipulate them within a theory, whereby we establish connections between them under symmetry transformations. Thus, symmetry becomes unavoidable if one is willing to unify physical theories.

It is for those who represent physics as a series of theoretical unifications that the symmetry group obtains the transcendental meaning given to it by Weyl. Now, it is individual phenomena that are governed by the law established with the help of a priori symmetry. We have postulated the existence of common traits between them. As in the case with a priori constraints, this postulate may not always be empirically adequate. If we are interested in a single given phenomenon, or an individual solution of the equations of a physical model, there is no reason why this particular occurrence would be completely described by the features that had previously been identified as common to a class of phenomena. It may well be that the complete description require the use of unique properties, which do not transform under the symmetry group or even aren't subject to physical law. Therefore, in the description of a unique phenomenon we must be ready to encounter unique descriptive elements alongside lawful properties stemming from the considerations of symmetry.

Complete description of a particular phenomenon may be unpredictable. One usual example is the measurement problem in quantum mechanics. The value observed in a given measurement is random although the quantum system evolves on the lawful background of unitary dynamics. Predictions of the theory are probabilistic and do not completely determine the result of any one given measurement.

From the cosmological point of view where it is treated as a dynamical process, spontaneous symmetry breaking in the EW sector is another example of unlawful feature of the particular Universe in which we live, although this Universe is described by the physical law based on symmetry. The earlier state with the full a priori symmetry is physically lawful, and to generate a unique case we must resort to chance. Thus, from the point of view of cosmological evolution, the Higgs vev is what it is in nature very much like the result of one particular measurement in quantum mechanics is what it is; the theory does not predict it. To summarize, dynamically perceived spontaneous symmetry breaking is a manifestation of the unlawful uniqueness of a particular solution. We frame it to the largest possible extent in a rigorous mathematical setting, which describes the symmetry breaking mechanism and leaves us with one bare unpredictable number that only the experimental data will supply. Healey's sincere predicament before the failure to find a satisfactory dynamical explanation of the Higgs mechanism is but an indication that the purpose of this mechanism is to provide a description of the unlawful randomness [55, p. 174].

5.3 Naturalness and symmetry

Arguments from naturalness have dominated QFT research in a very significant way in the last 25 years. The first historic notion of naturalness in particle physics, formulated by Gerard 't Hooft, connects it with symmetry:

> The naturalness criterion states that one such [dimensionless and measured in units of the cut-off] parameter is allowed to be much

> smaller than unity only if setting it to zero increases the symmetry of the theory. If this does not happen, the theory is unnatural. [96]

The connection with symmetry could have allegedly provided a philosophical background for naturalness, based on the transcendental justification of symmetry; this did not happen. The notion has evolved, and its current meaning is rarely justified differently than by saying that naturalness is a "question of aesthetics" [29] or "the sense of 'aesthetic beauty' is a powerful guiding principle for physicists" [45]. For sure, arguments from beauty such as they appear when one speaks of naturalness in natural science may turn out to be either extraordinarily fruitful or completely misleading. Polkinghorne, for example, discusses at length the power of beauty in mathematics [81]. However, what he calls "rational beauty" and applies to physics rather than mathematics can only be admired post factum, i.e., when we have established a sound scientific account in agreement with nature. For the universe is not just beautiful; one can also discern in it 'futility' [101] or inefficiency [30]. Thus, using beauty as a guidance rule, prior to verification of the theory against experimental data, is logically unsound and heuristically doubtful. It can at best be warranted by arguments from design.

The first modern meaning of naturalness is a reformulation of the hierarchy problem. This arises from the fact that masses of scalar particles are not protected against quantum corrections, and keeping a hierarchical separation between the scale of EW symmetry breaking and the Planck scale requires the existence of some mechanism that would *naturally* explain such a hierarchy. Although the difference in hierarchies is a dimensionless parameter much smaller than unity ($\frac{10^3\mathrm{GeV}}{10^{19}\mathrm{GeV}} = 10^{-16}$), setting it to zero is out of question because gravity exists even if it is weak (one exception from this argument are models with large extra dimensions, where the scale of gravity is different from 10^{19} GeV). With all its known problems, the Standard Model does not become more symmetric in the hypothetical case where gravity is infinitely weaker than weak interactions. Thus, 't Hooft's criterion does not apply, and the notion of naturalness as the hierarchy problem indeed differs from the one he defined. This new meaning of naturalness leads to the use of fine-tuning arguments and will be further discussed in Section 7.

For Giudice [45, p. 9-10, 20], the second ingredient of the naturalness criterion is the use of effective field theories. He claims that "if the experiments at the LHC find no new phenomena linked to the TeV scale, the naturalness criterion would fail and the explanation of the hierarchy between electroweak and gravitational scales would be beyond the reach of effective field theories. But if new particles at the TeV scale are indeed discovered, it will be a triumph for our understanding of physics in terms of symmetries and effective field theories." Effective field theories and their role will be discussed in Section 6.

Thus, the word 'naturalness' is used in several non-equivalent situations and can have different meanings depending on the authors. One example is however commonly agreed as a test for the naturalness criterion. Split supersymmetry is a high-energy SUSY scenario, which abandons naturalness for the use of an anthropic argument requiring that at low-energy the theory allow the existence of complex chemistry (atoms other than hydrogen). It is also required that the lightest supersymmetric particle, a neutralino, provide the dark matter of the universe. In split supersymmetry squarks and sleptons are made heavy, maintaining the predictions of gauge-coupling unification, but discarding a too light Higgs, fast proton decay and the flavour problem [46]. This scenario is argued to have a detectable experimental signature, in particular through its CP-violating mechanism. If found at the LHC, split supersymmetry will provide tangible experimental evidence against use of the aesthetically motivated naturalness criterion in physics.

6 Effective field theory

6.1 EFT approach

The notion of renormalizability in the context of quantum field theory (QFT) and its early representatives like quantum electrodynamics (QED) was developed by Bethe, Schwinger, Tomonaga, Feynman, and Dyson. The latter introduced crucial power-counting techniques for the analysis of operator relevance. Since his 1949 work and up to 1970s renormalizability had been thought of as a necessary condition for a quantum field theory to make sense. Wilson's work on the renormalization group has paved the way to a change of attitude toward renormalizability. This was mainly due to a change of attitude toward the reality of the renormalization cut-off. In the older understanding, the cut-off scale was a residue of abstract mathematics introduced with the only goal of avoiding infinities in summation series. The new appreciation of non-renormalizable theories came with the understanding that the cut-off could be taken as physical and corresponding to the limit of applicability of a given theory. Thus the domain of applicability of QFTs has become clearly limited by a number denoting an energy scale. QFTs started to be seen as effective field theories (EFTs) valid up to some frontier rather than fundamental theories of nature. Wilson's work and Weinberg's reintroduction of EFTs as useful theories with 'phenomenological Lagrangians' [99, 100, 102] boosted this new view on EFTs.

Much of the historic development of EFTs focused on the top-down approach, where the fundamental physical theory is known but is inapplicable for practical purposes. These may be due to complexity of the high-energy theory or, as in the case of EFT in condensed matter physics, "Even when one knows the theory at a microscopic level (i.e., the fundamental theory), there is often a good reason to deliberately move away to an effective theory" [91]. A typical example from particle physics is the chiral perturbation theory, which gives a low-energy approximation of quantum chromodynamics (QCD) in the light quark sector (for a review see [80]). But the top-down approach has a longer history: one of its first examples involves the Euler-Heisenberg calculation in the 1930s of photon-photon scattering at small energies within the framework of Dirac's quantum field theory.

The LHC physics uses a different EFT approach, sometimes called 'bottom-up'. Its popularity reflects a change in the way in which EFTs are now conceived. Today physicists tend to think of *all* physical theories, including the Standard

Model, as EFTs with respect to new physics at higher energies.

A typical model-building scenario, following Wilson, starts with Lagrangian of an effective field theory (EFT) valid up to scale Λ. This Lagrangian can be generally written as a sum over local operator products:

$$\mathcal{L} = \sum_{n=0}^{\infty} \frac{\lambda_n}{\Lambda^n} \mathcal{O}_n. \tag{7}$$

Coefficients λ_n are coupling constants. They encode information on the physics at scales higher than Λ and can be fixed experimentally or through a calculation by the renormalization group if the underlying high-energy theory is known. The only constraints on the form of operator product terms $\mathcal{O}_n$ come from symmetries of the theory.

The main value of Lagrangian (7) for the LHC physics is that one can use it to study low-energy effects of new physics beyond the SM without having to specify what this new physics actually is. Tree level of the power series in $\frac{1}{\Lambda}$ is obtained by the usual Standard Model calculation. Effects of new physics appear in loop corrections and influence the value of coupling constants λ_n. Thus, after the concept of symmetry, that of EFT is the second most important instrument for the construction of new models to be tested at the LHC. A disadvantage is that it does not allow us to establish correlations of new physics effects at low and high energies. The number of correlations among different low-energy observables is also very limited, unless some restrictive assumptions about the structure of the EFT are employed [61, p. 2].

For example, consider a ‘top-down’ electroweak EFT that reproduces the SM for the light degrees of freedom (light quarks, leptons and gauge bosons) as long as energies involved are small compared with the Higgs mass [80]. This EFT is Higgless in the sense that it cuts off the Higgs sector by choice of Λ. The lowest order effective Lagrangian fixes the masses of Z and W bosons at tree level and does not carry information on the underlying symmetry breaking $SU(2)_L \times U(1)_Y \to U(1)_{\mathrm{QED}}$. At the next order the most general effective chiral

Lagrangian with only gauge bosons and Goldstone fields,

$$\mathcal{L}_{\mathrm{EW}}^{(4)} = \sum_{i=0}^{14} a_i \mathcal{O}_i, \tag{8}$$

contains 15 independent operators. This complexity is essential as it stems from the requirement that we use the most general form of the Lagrangian compatible with symmetry principles. Gell-Mann has even formulated this rule as a "totalitarian principle" which states that everything which is not forbidden is compulsory [13]. Weinberg insists that absence of any assumption of simplicity about the Lagrangian is what makes EFT so efficient [103, p. 246]. For Lagrangian (8), constraints from symmetry include invariance with respect to CP and $SU(2)_L \times U(1)_Y$. Also, three of the fifteen operators vanish as a consequence of the equations of motion under the assumption of light fermions. With the remaining terms, one finds various effects such as the usual electroweak oblique corrections (6 operators involved at the bilinear, 4 at the trilinear and 5 at the quartic levels), corrections to rare B and K decays, the CP-violating parameter, etc. Thus, the approximation of a very large Higgs mass in the SM gives an EFT which possesses predictive power, providing a simpler than the complete SM way to make calculations.

6.2 Philosophy of EFT

Three philosophical ideas quickly come to mind with respect to EFT. These have been discussed since a somewhat controversial early study by Cao and Schweber [19, 20] and form today the core of the philosophical debate. Cao and Schweber argued that EFT commits one to ontological pluralism, antireductionism and antifoundationalism.

Ontological pluralism is a form of realism which stipulates the view of reality as a tower of quasi-autonomous layers, each of which can be described by a physical theory without reference to the underlying layer. Not only this realist point of view can be criticized [85, 54], but the layer autonomy is in itself doubtful. While the latter is admitted for all practical purposes in model building, physics shows that there is no obvious decoupling of the layers unless we are in possession of a high-energy renormalizable theory. A theorem by Appelquist and Carazzone states that in a renormalizable high-energy theory with exact gauge symmetry, a low-energy EFT can be given without reference to massive particles at the price of rewriting the Lagrangian with renormalized coupling constants [4]. However, decoupling of the levels does not necessarily arise in theories with spontaneously broken symmetry, where mass generation through the mechanism of symmetry breaking is associated with interaction terms. Because of this, and with the acceptance of non-renormalizability as unpathological feature of QFTs, strict decoupling has become less important. It was replaced by a milder form of the decoupling thesis suitable for use of the EFT method in the description of new physics effects at energies of the order of 1 TeV. Thus, in the LHC physics, decoupling of the levels is not warranted by theory; it is only grounded in the empirical fact that the SM predictions correspond very well to the experimental data, and with respect to them any corrections coming from new physics must remain minor. Hence, it is hypothesized that the NP layer decouples from the electroweak scale. Mildness of this empirical decoupling thesis leaves open a possibility of its breakdown, i.e., of a tension between the levels leading to problems with formulation of the effective theory. One such tension is exactly reflected in the little hierarchy problem.

If the claim of ontological pluralism made by Cao and Schweber appears too far-fetched, their antireductionism argument has produced a lively debate (see [57, 22]). As Shankar puts it, “Often the opponents of EFT or even its practitioners feel they are somehow compromising” [91]. One thus finds physicists who argue for a reductionist perspective on EFT; for instance, Giudice writes unabashedly, “Effective field theories are a powerful realization of the reductionist approach” [45]. Others, e.g., Georgi, are more cautious and antireductionist. What emerges, although not without disagreement, is that EFT enables the argument that fundamentality of theories is a provisional, almost uninteresting attribute. The tower of EFTs effectively leads to the renunciation of the search for a complete description of new physics. This renunciation is neither hic et nunc nor circumstantial. It is a methodological anti-foundationalist stance opening a way to do high-energy physics without having to search for a unified theory.

Eventually the fundamental theory will have to surface. If it does not, then we'll be left with a tower of EFTs. This tower will not inherit all the methodological advantages that an individual EFT, useful in calculations, has over a yet-to-be-found fundamental theory. The tower will become complicated as significantly more higher-dimensional operators will appear at higher orders in Λ. To respond to the continuing demand of accounting for new minor details, EFTs will have to be supplied with additional parameters. As a result, for Hartmann, "the predictive power [of the EFT tower] will go down just as the predictive power of the Ptolemaic system went down when more epicycles were added" [54, p. 296]. Perhaps even more vividly than Ptolemaic epicycles, doubts about the significance of theories based on postulated principles, viz. symmetry principles or the decoupling, have been expressed by Einstein.

After his paper describing the photoelectric effect in terms of light quanta, Einstein's belief in the fundamental character and the exact validity of Maxwell's electrodynamics was destabilized. As he wrote in his 1949 *Autobiographical Notes*,

> Reflections of this type [on the dual wave-particle nature of radiation] made it clear to me as long ago as shortly after 1900, i.e., shortly after Plancks trailblazing work, that neither mechanics nor electrodynamics could (except in limiting cases) claim exact validity. By and by I despaired of the possibility of discovering the true laws by means of constructive efforts based on known facts. [33, p. 51, 53]

Einstein's desperation has led him to propose special relativity. The price to be paid was a retreat to the principle theory approach, described by Einstein in 1919 as the opposite of 'constructive efforts'. Already since 1908 Einstein had expressed his concern with principle theories, based on postulated principles, as being in some respect 'less fundamental' than constructive theories based on "known facts". This was mainly due to Einstein's urgent feeling of a necessity to provide a theory that would describe rods and clocks, viz., the measurement apparatus of special relativity, on equal grounds with other physical systems. Current debate on principle theories has been focused on this question [17, 48], overlooking the following different aspect of Einstein's 1905 situation.

Einstein's hope was to construct a new theory based on known facts. Facts however proved to be insufficient: "It was if the ground had been pulled out from under one, with no firm foundation to be seen anywhere, upon which one could have built" [33, p. 45]. So Einstein resorted to what seemed to him a less fundamental, lighter foundation for theoretical physics. On the example of thermodynamics, he elevated the relativity principle to the status of universal postulate and derived the theory of special relativity. Similarly, with the LHC physics we are in a situation when known facts are as yet insufficient for the construction of a new theory. We have then chosen a less fundamental EFT approach based on general principles rather than known facts.

Unlike Einstein, whose special relativity has enjoyed a long life, new facts that will soon be available may terminate our doubts and lay the missing empirical basis on which a new physical theory will be chosen. Still, according to the EFT view, although the new theory will describe all known facts, we should take it as a limited effective solution with respect to unknown physics at yet higher energies. At the same time, the status of our current 'bottom-up' EFTs, which we use in absence of the more fundamental theory, will be downshifted after its advent. Their use will be severely limited and they will stay as monuments to the physicists' perseverence. There will be no tower of EFTs: new EFTs may be used for physics at yet higher energies, but older EFTs will lie as ruined stones torn down from the tower. Furthermore, if one day we discover a unique full theory that wouldn't use QFT methods, then our idea of bottom-up EFT may be altogether wrong.

6.3 Pragmatic view of EFT

The most appealing modification of the ontological pluralism thesis was proposed by Hartmann. Based on a discussion of Georgi's writings, he argues that a viable solution to the troubles of ontological pluralism would be to regard EFT as purely pragmatic, without seeing in it a commitment either to reductionism or to anti-reductionism. When Georgi writes,

> In addition to being a great convenience, effective field theory allows us to ask all the really scientific questions that we want to ask without committing ourselves to a picture of what happens at arbitrarily high energy, [41]

he means by “all the really scientific questions” that EFT is a pragmatic approach to the unknown new physics which is focused only on its effects observable as corrections to the SM predictions for the experiments at our current technological reach. The pragmatic strategy would then consist in focusing on these corrections as having the primary importance. All other content of new physics is neglected and other ‘really scientific questions’ that one may have with regard to new physics are not taken into account. This evokes a parallel, emphasized by Weinberg, between EFT and the theory of S-matrix. Indeed, the S-matrix approach only asked ‘practical’ questions about the yet unknown theory of strong interactions, formulated in the language of physical observables, and methodically avoided the need to have a full theory. In the LHC physics the unknown is not the theory of strong and weak interactions but new physics beyond the SM. With little prospect for distinguishing in the near future between the different alternatives for this new physics, EFT allows us to develop a consciously and purposefully model-independent approach, where all that matters about the new unknown physics are its observable effects.

This is not the full story though. The analogy with the S-matrix suggests that there exists an aspect in the EFT approach to new physics at the LHC that has a counterpart in the S-matrix case but has none in other, ‘top-down’ uses of EFT like the chiral perturbation theory. In 1950s it has not been clear whether QFT with its gauge symmetry method was an appropriate framework for building a theory of strong interactions*. The hope of S-matrix, writes Weinberg,

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*A very telling example of this is a 1954 (same year as the work by Yang and Mills) discussion involving, among others, Oppenheimer, Gell-Mann, Fermi, Wick, and Dyson, in "was that, by using principles of unitarity, analyticity, Lorentz invariance and other symmetries, it would be possible to calculate the S-matrix, and you would never have to think about a quantum field..." [103, p. 248]. This is in complete analogy with the situation with EFT, whereby the terms in the Lagrangian must be written in the most general form compatible with symmetry principles. Just as S-matrix allows one not to "think about a quantum field", EFT relieves one from the need to worry about physical content of the high-energy theory.

While Weinberg says that "the S-matrix philosophy is not far from the modern philosophy of effective field theories", he adds with respect to the former that "more important than any philosophical hang-ups was the fact that quantum field theory didn't seem to be going anywhere in accounting for the strong and weak interactions". So S-matrix was not only an attempt to formulate theories exclusively in terms of observable quantities. It was equally a reaction to the situation in which no one knew what language to use, and in which direction to look, for theories of strong and weak interactions. Much like today we have no idea whether supersymmetry, or extra dimensions, or something else, will turn out to be the right solution for new physics, physicists in the early 1960s did not agree on the language needed for formulating what had for them been new physics. In the absence of any agreed-upon idea for new physics at the LHC, we resort to the language that does not require one to have such an idea. Both for us and for physicists working on the S-matrix, new physics may turn out something completely new and wild. Our path to tackling this unknown is EFT. In both cases, quantum field theory and its method based on symmetries is but one alternative framework; for the theories of weak and strong interactions this alternative has proven correct. Today we continue to use it in SUSY models; but there is no guarantee that QFT will again prove to be the correct language.

One upshot of the analogy between S-matrix and EFT is that today, when the S-matrix theory of strong interactions has been superseded by QCD, we know where it has gone wrong: its emphasis on analyticity as fundamental

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which Goldberger challenged the applicability of QFT methods to nuclear interactions and nobody in the audience spoke clearly to the contrary [76]. This example was still remembered in the 1970s as a typical case of the early doubts about the future of QFT [3].

principle was misguided, because no one could ever state the detailed analyticity properties of general S-matrix elements. Perhaps something like this is happening today with EFT and the model-independent analysis of new physics. Some of the symmetries that we postulate and impose on the Lagrangian in eq. (7) may turn out to be blinding us rather than leading to a result which will ultimately emerge as the correct one.

7 Chance and the establishment of physical theory

7.1 Probabilistic reasoning

Human beings engage in probabilistic reasoning more or less constantly, whether knowingly or not. We sometimes reason probabilistically in ways that suit our purposes very well and at other times we do rather poorly in this regard [75]. This constant engagement in probabilistic reasoning is due to the fact that in the face of growing complexity of today's world we often look for a simple heuristic that short-cuts unwanted complications in the decision making process. Probabilistic reasoning is the main such heuristic thanks to its rigorous mathematical methods. To calculate probabilities is reassuring. Whether one takes such calculation as reflecting objective frequencies of event occurrence or mere subjective degrees of belief, the sheer act of making the calculation and the reliance upon it have become a common tool for the justification of action in many areas of human endeavour. Furthermore, over and beyond its heuristic use, probabilistic reasoning has to some extent acquired the power of explanation. We form scientifically informed subjective probabilities about a future unique event, such as the climate change; we then consider action that could reduce or enlarge these probabilities as if they could explain why the future event will have occurred. Not only do we refer to probabilistic reasoning to justify our own action, but we do so in cases where human beings have no causal role to play. Nature herself is represented as a subject making her choice between different options, each with a probabilistic weight attached.

Probabilistic reasoning has started its journey into the general public's mind from its place in the scientific analysis of complex systems, e.g., in statistical physics. Rigorous accounts of individual processes or mechanisms forming a complex system and contributing to its large-scale, emergent behaviour require exceedingly large memory and exceedingly large computing power. Faced with these problems, 19^{th}-century physics was the first discipline to give scientific validity to mathematical methods of probability. Social scientists, such as economists and sociologists, have been quick to follow.

The inherent impossibility of unquestionable causal determinism in social science obviously weakens the claims of social scientists for rigor and, consequently, their status as true scientists. This lack of causality was compensated for, and successfully, by the mass propagation of probabilistic 'explanations'. These were applied in all areas with a decision-making subject facing uncertainty. In such contexts, typically, some information would be available to the subject before his decision is made, and further information could flow in. The Bayes theory provided a useful and legitimate tool for calculating and justifying optimal choice. This legitimate use of probabilistic reasoning was extended to situations where one is concerned with unique events, i.e., situations where no subject has at any time had the power to enact a different future. The choice would be then justified and dubbed 'correct' based on the same probabilistic reasoning, although alternative scenarios now become merely fictitious games of imagination. Psychologically, the public perceive today as scientific and, therefore, sound *any* explanation based on probabilities. To persuade the layman, one frequently gives an argument containing percentages which are easy to compare, while wilfully preserving the mystery around the origin of these numbers.

Historically the only clear-cut case of a marked departure from the deterministic paradigm of causal explanation in physics was the theory of measurement in quantum mechanics. The wave function describes only a distribution of probabilities for a quantum measurement and cannot predict the exact result to be obtained in a given act of measurement. Taken outside the statistical series of repeated measurements, a given observation yields a random result. Lawlike generalizations, as described by the laws of quantum theory, are only possible with respect to repeated identical measurements.

The concept of spontaneous symmetry breaking, applied in cosmology, marked a new departure from the deterministic paradigm in theoretical physics. Similarly to the situation with quantum measurement, the choice of a particular symmetry-breaking ground state among many in the history of the Universe was a matter of chance. It cannot be implemented by the unitary dynamics of the theory [88, 58]. Spontaneous symmetry breaking being a useful and successful tool in constructing models, physicists often do not fully appreciate the fact that it poses conceptual problems of interpretation [86, 55, 32].

The cases of quantum measurement and spontaneous symmetry breaking represent two situations where randomness is an integral part of the best scientific explanation we can produce. Science however has not been shielded from the tendency to use probabilistic reasoning far from its primary domain of application. Thus, probabilistic reasoning has made its way to ‘explaining away’ more scientific conundrums. In the case of several problems in cosmology and in particle physics, while doubt was growing that science may ever solve them by causal explanation, an argument based on probabilistic reasoning is often accepted as a sufficient and satisfactory answer. The question belongs with the methodology and the philosophy of science, whether the new method of explanation is sound. In the LHC physics it makes its appearance in the use of the fine tuning argument.

7.2 Fine tuning

The Higgs mechanism of the Standard Model is based on an improbable fit of electroweak data, with less than 2% overlap between EW precision tests, and sometimes a direct contradiction. Alternative models do not fare much better. The supersymmetric models agree with the EW data only if their free parameters are tuned at the level of few percent [45, p. 15]. The amount of fine tuning in the Little Higgs models is similar. As it is schematically shown on Figure 6, there is no simple model without any tuning remaining in the valid model space. Still, notwithstanding such ‘improbability’, physicists do not hurry to reject the Higgs mechanism as a working solution for the EW symmetry breaking. Why? The issue is with the meaning of ‘improbable’ in the fine-tuning argument.

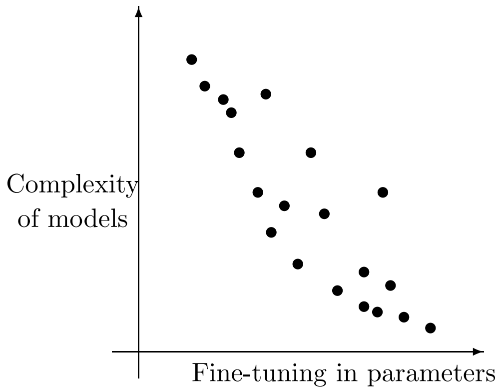

Figure 6: Schematic graph of fine tuning versus model complexity in the space of models beyond SM [25].

To say that a highly fine-tuned model is improbable is an argument from probabilistic reasoning. It has the merit of having the form of a perfectly normal pattern of scientific argument [92]. Thus, its conclusion is likely to be taken for true without a second thought. Instigation to further reflection is then needed to avoid a flaw in argumentation.

A usual philosophical justification of the fine-tuning argument is given via distributing probabilities over many ontologically interpreted worlds. This justification inserts the fine-tuning argument in a larger class of anthropic arguments based on the many-worlds reasoning. Among all possible worlds, those containing highly fine-tuned models are probabilistically rare. Compared to the full number of worlds, their proportion is tiny, and reflects the amount of fine tuning in the model. Therefore, if ‘we’ evaluate ‘our’ chances to be in such a world, the resulting estimate will be low. Depending on the concrete variety of the anthropic argument, the pronoun ‘we’ here alternatively refers either to intelligent beings, or worlds with carbon-based life, or worlds with complex chemical elements, etc. In this ontological reasoning, everything happens as if there were a choice-making subject called Nature or God who would blindly decide to put us in a world of her choice. Thrown so unto one world of many, our task being to predict where we shall end up, we cannot do better than use probabilities.

The ontological scenario seems totally fictitious, but it is the one shared intuitively by many physicists [21]. Particle physicists start by arguing that the contradictions in the EW precision data render the SM Higgs mechanism less compelling. They represent these contradictions as a numerical percentage supposedly denoting a probability for the SM to be true. Going beyond SM, they argue that a large amount of fine tuning in any physical model makes it also less compelling. They refer to naturalness and argue that their argument has a rigorous meaning given by the rejection as fine-tuned of any model where the bare value of a physical constant and quantum corrections result in a measured value that differs from them by many orders of magnitude. It is at this point that the argument is not obvious. The two parts of it: with respect to SM and with respect to models beyond SM, are not completely analogous.

In the first case, it is legitimate to claim that the observed experimental inconsistencies may question the validity of the theory. This is precisely because we have certainty with regard to the existing data (including error in real measurements of real physical constants).

In the second case, the same argument based on the same data is used to imply a little more. At the level of logic of the argument, what is at play is not a mere calculation of a degree of rarity on the background of many possible worlds. Fine tuning becomes a tool for comparing models and forming preferences with respect to one or another of them:

> Some existing models. . . are not elevated to the position of supersymmetric standard models by the community. That may be because they involve fine-tunings. . . [14]
>
> The focus point region of mSUGRA model is *especially compelling*

> in that heavy scalar masses can co-exist with low fine-tuning… [8, our emphasis]
>
> We …find *preferable* ratios which reduce the degree of fine tuning. [1, our emphasis]
>
> …the fine-tuning *price* of LEP… [10, our emphasis]

The physicist using the fine-tuning argument with regard to theories beyond SM makes a bet on his future state of knowledge. We do not know what the correct theory will be. There will however be one and only one such true theory. We believe that the LHC will help us to decide which of the existing alternatives is true, and we therefore believe that at some point in the future, hopefully soon enough, we shall know what the correct theory is. In this situation of uncertainty with respect to our future state of knowledge, we cannot fare better than put bets, in the form of subjective probabilities, with respect to this unknown unique state of knowledge. Such subjective probabilities are scientifically informed, meaning that they agree with the best of our scientific knowledge expressed as percentage of fine tuning of different models. They are however subjective in the sense of referring to a unique future state of knowledge whose uncertainty, from today's point of view, only allows one trial after which the correct answer will be unveiled once and for all. Thus, the fine-tuning argument is a way to calculate numeric values of the bets that we place on the future state of knowledge.

Like in the general case of probabilistic reasoning, the role of fine-tuning argument is often extended to providing an explanation as for why the future state of knowledge will have come about in its unique future form. This use of the fine-tuning argument is a psychological aberration and should be clearly identified as non-scientific. Thus, the fine-tuning argument is not a problem in and by itself; its true role is however limited. For example, Rattazzi asks if we should "really worry" about fine tuning [83, p. 5]. He then argues that perhaps not, but "we should keep in mind that once we are willing to accept some tuning, the motivation for New Physics at the LHC becomes weaker". This "motivation" is clearly connected not with explaining away new physics, but with betting on the future unique state of knowledge: when numeric value of probability becomes smaller, our bet is less likely to win. If we agree that betting could not help to explain away new physics, we are left free to imagine that 'improbable' scenarios may be realized, including those in which sparticles are out of reach at the LHC or the SM Higgs mechanism itself avoids contradictions in the EW data.

Psychologically, it is very difficult to resist the temptation and refuse to make a guess at the future state of knowledge. Donoghue's suggestion that we simply "live with the existence of fine tuning" promises a hard way of life [29]. Its difficulty though is not completely unfamiliar as we already live in a world with many fine tunings, for example:

- The apparent angular size of the Moon is the same as the angular size of the Sun within 2.5%.
- The recount of the US presidential election results in Florida in 2000 had the official result of 2913321 Republican vs. 2913144 Democratic votes, with the ratio equal to 1.000061, i.e., fine-tuned to one with the precision of 0.006%.
- The ratio of 987654321 to 123456789 is equal to 8.000000073, i.e., eight with the precision of 9.1×10^{-9}. In this case, unlike in the previous two which are mere coincidences, there is a 'hidden' principle in number theory which is responsible for the large amount of fine tuning. [65]

Once we accept to place bets, it is difficult to imagine that on the day when the future state of knowledge will have come about, our own Gedankenspiel will not be judged retrospectively as having had a causal effect on, and therefore the power of explanation of, that particular state. In this future situation, thanks to the LHC experimental data, the correct physical theory beyond SM that we shall have discovered will be not merely possible, but necessary. The fine-tuning argument as it is used today to compare different models will have lost all interest.

7.3 Counterfactual reasoning

It is essential to understand the precise structure of the fine-tuning argument. To say that a fine-tuned model is improbable, hence it must be rejected, assumes that one can give a meaning to ‘improbable’. Calculations of the degree of improbability lead to numbers expressed as a certain percentage. Such calculations of probability can only be sound if there were behind the fine-tuning argument a normalizable probability distribution of the fine-tuned property in some ensemble $\mathcal{H}$. Whether such a distribution can be defined is open to debate. Normalizability is one problem: the difficulty lies with the fact that most attempts to rigorously define the ‘parameter space’ lead to its non-normalizability. In this case, ratios between regions of the space cannot be established [72]. Rigorous definition of ensemble $\mathcal{H}$ another problem. For example, when Athron and Miller discuss the measures of fine tuning in SUSY models, they claim that “our fundamental notion of fine tuning [is] a measure of how atypical a scenario is” [7]. One wonders what meaning could ‘atypical’ have in absence of a well-defined ensemble on which a probability distribution could be defined. To introduce probability, all parameter values must be treated as potentially realizable. This in turn involves postulating a distribution of parameter values over many worlds, each of which has a definite set of these values. Thus, the mere need to define $\mathcal{H}$ pushes in the direction of the many-worlds ontology.

The fine-tuning argument shares with a larger class of anthropic arguments a twofold logical nature: these arguments can either be formulated in purely indicative terms or by using counterfactuals. The first kind of formulations, using only indicative terms, are typically employed by opponents of the anthropic principle [94]. They mean to dissolve the apparent explanatory power of the argument by rewording it in terms of facts and of the laws of inference in classic Boolean logic. Devoid of the counterfactual, the anthropic argument indeed becomes trivial.

The second kind of logic involving explicit counterfactuals is more common. Anthropic arguments take the form of statements like ‘If parameters were different then intelligent life would not have existed"; or 'If parameters were different then complex chemistry would not have existed'; or 'If parameters were different then carbon-based life would not be possible'. What is most often discussed in the literature with respect to such statements is whether they can be taken as arguments having the power to explain physics. What is often overlooked is the more general but no less fundamental problem of validity and applicability of the counterfactual logical structure.

Counterfactuals in physics have been discussed at least since the Einstein, Podolsky and Rosen paper about quantum mechanics in 1935 [34]. The key point in the EPR argument is in the wording: "If... we had chosen another quantity... we should have obtained...". The Kochen-Specker theorem and Specker's discussion of counterfactuals in 1960 placing them in the context of medieval scholastic philosophy were the starting point of a heated debate on the use of counterfactuals in quantum mechanics (for recent reviews see [97, 95]). Peres formulated perhaps clearest statements about the post-Bell-theorem status of counterfactuals:

> The discussion involves a comparison of the results of experiments which were actually performed, with those of hypothetical experiments which could have been performed but were not. It is shown that it is *impossible to imagine* the latter results in a way compatible with (a) the results of the actually performed experiments, (b) long-range separability of results of individual measurements, and (c) quantum mechanics. ...
>
> There are two possible attitudes in the face of these results. One is to say that it is illegitimate to speculate about unperformed experiments. In brief "Thou shalt not think." Physics is then free from many epistemological difficulties.... Alternatively, for those who cannot refrain from thinking, we can abandon the assumption that the results of measurements by A are independent of what is being done by B. ...Bell's theorem tells us that such a separation is impossible

> for individual experiments, although it still holds for averages. [78]

The debate in quantum mechanics shows that the applicability of Boolean logic to statements about physical observables should not taken for granted in any branch of physics, especially those based on quantum mechanics. Quantum field theory is one. Simply, its focus has stayed with technical feats for so long that conceptual issues about measurement, inherited from quantum mechanics, have been neglected. The tendency has prevailed to assign values to unobserved parameters in unrealized experimental settings (when we measure physics of the Universe, it effectively becomes an experimental setting). For example, the counterfactual in the fine-tuning argument bears on physical parameters in worlds impossible to observe. Admittedly, this does not lead to a direct contradiction with quantum mechanical theorems, for quantum mechanics deals with normalized probability spaces and Hermitian observables. It nonetheless remains true that the logic of anthropic arguments runs counter to the trend warranted by the lessons from quantum mechanics. Speculation about unperformed experiments is illegitimate not only in the case of unrealized measurements of Hermitian operators, but in a more general sense: it is unsound to extend to unperformed experiments in unrealized worlds the Boolean logical structure allowing us to say that physical constants in those worlds have definite values.

This line of critique resonates with Bohr's answer to Professor Høffding when the latter asked him and Heisenberg during a discussion at the University of Copenhagen: "Where can the electron be said to be in its travel from the point of entry to the point of detection?" Bohr replied: "To be? What does it mean *to be*?" [105, p. 18-19] The fine-tuning argument as well as general anthropic arguments employ counterfactuals that contain the verb 'to be' in the conditional. What it means that a world which is referred to in this conditional, *had been*, *was* or *is*, would have been unclear for Bohr. He was greatly concerned with the meaning of utterances, famously claiming that "physics is what we can say about physics" [105, p. 16]. In the case of fine tuning this claim may be understood as supporting the view according to which statements of the fine-tuning argument express no more than bets on the unknown future unique state of knowledge.

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