NATURALNESS AFTER LHC RUN I

Andrea Romanino
SISSA/ISAS and INFN, I–34136 Trieste, Italy
ICTP, Strada Costiera 11, I–34151 Trieste, Italy

Abstract

Thanks to the discovery of the Higgs boson, the 8 TeV run of the LHC was a tremendous success. At the same time, the lack of signals of physics beyond the Standard Model was unexpected. Waiting for the first results of the 13 TeV run, as assessment of the implications of such a puzzling situation is appropriate. After a critical appraisal of the naturalness argument, we will discuss i) the status of models addressing the naturalness problem (supersymmetry and composite Higgs as prototypical examples) and ii) possible alternative models evading the naturalness argument.

1 The naturalness argument: a critical appraisal

The naturalness problem arises from the longing for a complete understanding of the electroweak (EW) scale. A first aspect of the problem is whether the description of the EW scale provided by the SM is correct. Data definitely support the SM parameterisation: the Higgs particle i) is a scalar with positive parity, ii) is neutral under color and charge, iii) it respects the custodial symmetry, and iii) it couples to the SM fermions and gauge bosons proportionally to their masses, within the present experimental accuracy. While there is still room for the Higgs couplings to deviate from the SM prediction, it is fair to say that possible departures are bound to be corrections to a leading order picture in agreement with the SM one.

The second aspect, more relevant for our purposes, is whether the SM description of the EW scale is complete. The SM parameterises the EW scale in terms of its only dimensionful parameter, the Higgs mass parameter μ^2, provided that the latter has a negative sign. On the other hand, a deeper understanding of the origin of that parameter, in the context of the standard reductionist paradigm of particle physics, should allow to compute that parameter in terms of more fundamental physics lying at a higher scale. A simple quantum field theory calculation then shows that the physical Higgs mass develops a quadratic dependence on the physical scale M associated to the high scale degrees of freedom (dofs), weighted by their coupling to the Higgs and a loop factor: $m_H^2 \sim -2\mu^2 + \lambda^2/(4\pi)^2 M^2$. If $M = 10^{15}\,\text{GeV}$ and $\lambda \sim 1$, for example, the second term in the RHS would be 24 orders of magnitude larger than m_H^2, requiring an extremely fine-tuned cancellation. Hence the expectation that some new physics should exist at a much lower scale taming the sensitivity of the Higgs mass to M. This is the celebrated naturalness argument.

The above formulation of the naturalness argument does not involve an arbitrary cutoff, nor quadratic divergences, and needless to say still holds in dimensional regularisation, where quadratic divergences are not seen. Also, it clarifies the assumptions on which it is based, and the corresponding way outs. The argument assumes the existence of high scale physical dofs coupled to the SM, and can be evaded if no such states exist. Or, the cancellation in the Higgs mass could take place, but not be accidental. On the other hand, if high scale coupled dofs do exist, and a cancellation can only be explained by an accident, the need to make the Higgs mass natural by getting rid of the M^2 dependence becomes compelling. This is the standard case, in which the "natural" scale m_{NP} of the new physics in charge of cancelling the M^2

dependence can be estimated by computing the top loop corrections to the Higgs mass in the presence of the new physics. Which typically gives $m_H^2 \sim -2\mu^2 + 12\lambda_t^2/(4\pi)^2 m_{\rm NP}^2$. In the absence of large cancellations, we expect $m_{\rm NP} \sim 0.5\,\text{TeV}$.

2 "Quasi-natural" new physics

Let us consider in greater detail the standard case in which the Higgs mass is protected by new dofs at a scale in turn subject to the naturalness constraint, and briefly discuss the two prototypical examples: supersymmetric models and composite Higgs models.

A few preliminary comments are in order. First of all, the scale $m_{\rm NP}$, although undoubtedly tied to the weak scale, is not precisely determined. According to the previous qualitative estimate, any value of $m_{\rm NP}$ is viable, as long as a cancellation of one part out of $\Delta \sim (m_{\rm NP}/(0.5\,\text{TeV}))^2$ is accepted, where Δ is called the fine-tuning parameter. The amount of fine-tuning one is willing to accept is of course subjective. For example, $\Delta \sim 10$ corresponds to $m_{\rm NP} \sim 1.5\,\text{TeV}$, while $\Delta \sim 100$ corresponds to $m_{\rm NP} \sim 5\,\text{TeV}$. Note that the reach in terms of fine-tuning grows quadratically with the reach in terms of $m_{\rm NP}$. A second comment is that the previous estimate of Δ is actually model dependent. A broad distinction arises, depending on the possible residual dependence on the superheavy scale M. "Natural" models are supposed to get rid of the quadratic dependence on M, but they may still have a residual logarithmic dependence on M ("soft" models), or they can completely decouple the Higgs mass from M ("supersoft" models). The above fine-tuning estimate is appropriate for supersoft models, such as composite Higgs. In soft models, on the other hand, Δ is enhanced by the (possibly large) logarithm $\log(M/m_{\rm NP})$. This is the case of supersymmetry, where the role of M is played by the scale at which supersymmetry breaking is mediated.

2.1 Supersymmetry

The $\log(M/m_{\rm NP})$ enhancement of Δ lowers the scale at which new physics, the stop mass in this case, is expected, as now $\Delta \sim (m_{\rm NP}/(0.5\,\text{TeV}/\log))^2$, where $\log = \log(M/m_{\rm NP})^2$. This in turn is the reason why the first expectations on the scale of supersymmetric particles, based on supergravity, were not far from the Z-boson mass scale. Indeed, in the case of supergravity, $M = M_{\rm Pl}$, giving $m_{\rm NP} \sim 0.5\,{\rm TeV}/\log \sim M_Z$ for $\Delta \sim 1$. As a consequence, minimal realisations of supergravity have been known to have a fine-tuning problem since LEP2 failed to discover supersymmetry [1]. A first message that the present lack of signal may be sending is then that supersymmetry is communicated at a relatively low scale M.

Another well known source of pressure on minimal supersymmetric models comes from the value of the Higgs mass. When nothing but the SM dofs and their supersymmetric partners are assumed to be part of the TeV-scale spectrum, multi-TeV stop masses or A-terms are needed in order to account for the fact that m_H^2 exceeds M_Z^2 by almost a factor of 2. On the other hand, the independently motivated, harmless introduction of a gauge singlet in the TeV spectrum (NMSSM) significantly helps from this point of view [2].

The naturalness status of supersymmetric models, and its model dependence, can be summarised in Fig. 1 [3], where two different set-up are considered. On the left panel, a minimal supergravity model with $M = M_{\rm Pl}$ is considered, while the right panel refers to a model with $M = 100\,{\rm TeV}$ and a gauge singlet relaxing the bounds on the Higgs mass. The fine-tuning isolines are shown in the stop-gluino mass plane, where representative values of run I and expected future bounds are also shown. The minimal supergravity case is not very promising from the point of view of future searches: a large part of the experimentally accessible parameter space is excluded by the indirect Higgs mass bound on stop masses (a conservative one, corresponding to large stop mixing) and the remaining one is significantly fine-tuned. On the other hand, the low M set up, while as simple and motivated as the minimal supergravity one, is in better shape, with the parameter space opened up by the possibility to account for the Higgs mass through the tree level contribution of the singlet, and significantly lower values of the fine-tuning.

2.2 Composite Higgs

From the point of view of naturalness, composite Higgs models do not suffer from large $\log(M/m_{\rm NP})$ enhancements of the sensitivity to $m_{\rm NP}$, as they are supersoft. In the expression $\Delta \sim (m_{\rm NP}/(0.5\,{\rm TeV}))^2$, $m_{\rm NP}$ can be interpreted as the mass of the first stop resonances. The composite Higgs arises as the pseudo-Goldstone boson of new strong interactions characterised by a compositeness

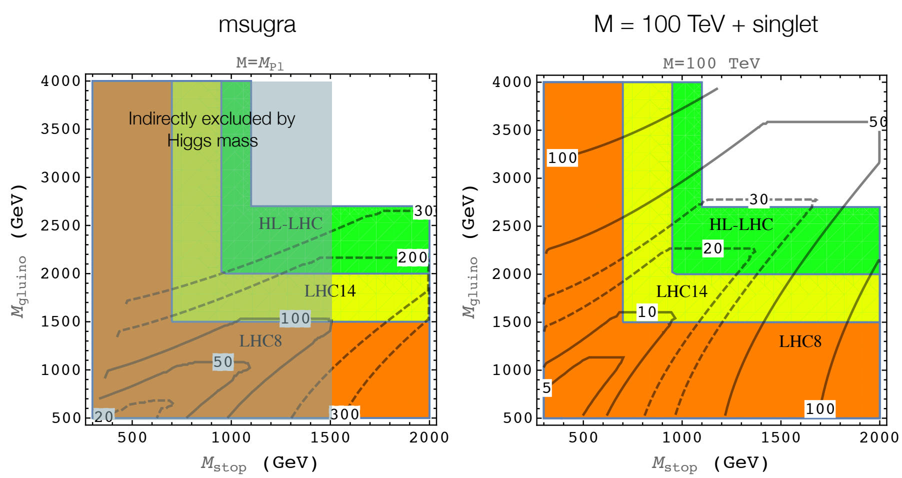

Figure 1: *Representative present and future bounds on stop and gluino masses and naturalness status of two types of supersymmetric models: minimal supergravity (left) and a NMSSM model with low-scale mediation of supersymmetry breaking (right)* [3].

scale $\Lambda \gtrsim 3\,\text{TeV}$, with the bound due to electroweak precision tests. If the scale of the stop resonances is near Λ, as expected, the fine-tuning still turns out to be of the order of a few percent. On the other hand, the value Higgs mass (largish and forcing large stop masses in minimal supersymmetric models) turns out to be smallish and forcing small top resonance masses in minimal composite Higgs models. Lighter top resonances then naively correspond to a smaller fine-tuning, but their lightness may actually itself represent a source of fine-tuning.

Fig. 2 [4, 3] corresponds to a simple model where the Higgs arises as the pseudo-Goldstone boson of the spontaneous breaking to SO(4) of an approximate global SO(5) symmetry. Present bounds and future prospects for the detection of the lightest top resonance, here assumed to be a hypercharge 7/6 doublet X, are shown. Both single and double production are considered, with the latter relatively model independent and the former depending on the model-dependent dimensionless parameter c_R on the vertical axis in the Figure. The naive estimate of the fine-tuning parameter is also shown and correspond

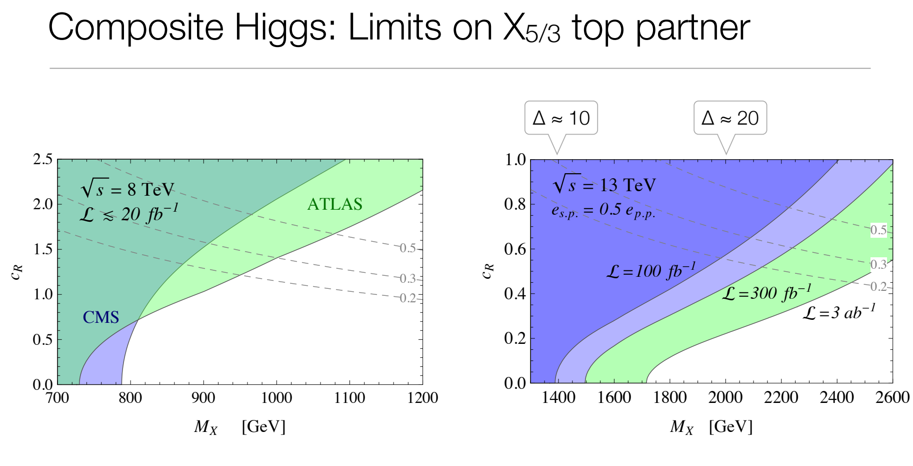

Figure 2: *Present and future bounds on the lightest stop resonances in a representative composite Higgs model. A naive, possibly underestimated, estimate of the fine-tuning parameter is shown* [4, 3].

3 Alternatives

Evading the naturalness argument is possible but not painless.

As discussed, the argument is based on the assumption that superheavy dofs exist with a non-negligible coupling to the SM dofs. An easy way out is then offered by the possibility that this is not the case. Of course, there are many reasons to believe that new dofs exist, at the Planck, GUT, lepton number breaking scales, for example. But it turns out that it is actually possible to account for the experimental shortcomings of the SM (neutrino masses, dark matter, baryon asymmetry) with new dofs, light or weakly coupled enough not to represent a problem for naturalness [5]. At the price of course of giving up two of the most compelling ideas about physics beyond the electroweak scale: i) the understanding of the smallness of neutrino masses in terms of a breaking of lepton number at very high scales and ii) the understanding of the peculiar pattern of SM fermion gauge quantum numbers in terms of a unified description of gauge interactions. Above all, a viable understanding of gravity not involving Planck scale dofs is not known so far (for an interesting attempt see [6]).

If high scale dofs exist, and an unnatural contribution to the Higgs mass does arise at those scales, the fine-tuned cancellation needed to reproduce the much smaller Higgs mass can in principle be accounted for by a dynamical mechanism or by anthropic selection [7].

The first example of an alternative solution of the Higgs mass puzzle was obtained using anthropic considerations [8]. Such a solution is compatible with an unified description of gauge interactions at superheavy scales and with a high scale origin of neutrino masses; it can be realised in a calculable supersymmetric context that can be extrapolated up to the Planck scale and is non-trivially consistent with gauge coupling unification and WIMP dark matter; it predicts a Higgs mass significantly above the M_Z bound even in minimal models. On the other hand, it is based on highly non-trivial assumptions, such as the existence of the huge landscape of vacua of string theory, and of a cosmology populating that landscape. And of course, it requires giving up a reductionist understanding of the EW scale.

A perhaps more satisfying way to account for a fine-tuned cancellation, would be through a dynamical mechanism forcing that cancellation. An example, though in another domain, is the almost complete cancellation of the $\theta_{\rm QCD}$ parameter of the QCD lagrangian in the minimum of the axion potential. Recently, a possible mechanism based on a cosmological relaxation of the EW scale has been proposed [9]. Interestingly enough, such a proposal makes again use, in its simplest realisation, of an axion. The role of the axion ϕ is twofold. First, it slowly scans a broad range of scales during its cosmological evolution, and is initially larger than the scale of the radiative corrections to the Higgs mass $\lambda^2/(4\pi)^2 M^2$. Through a coupling to the Higgs, this allows the Higgs mass to scan a correspondingly broad range of values, starting from large, positive values in the first part of the evolution, down to negative values (much) later on. The second role is to be itself, an axion, thus developing an oscillating potential $\sim \lambda\Lambda^3 |H| \cos(\phi/f)$ when the Higgs mass turns negative, the EW symmetry is broken, and the SM fermions get a mass through the Higgs vev $|H|$. The new contribution to the axion potential then adds to the terms responsible for the slow roll and generates local minima separated by the oscillation period. If certain conditions are satisfied, the axion might relax in one of those minima, where the Higgs mass, which had just turned negative, is still much smaller than the $\mathcal{O}\left(\lambda^2/(4\pi) M^2\right)$ corrections to it. An apparently accidental large cancellation in the Higgs mass has been forced. The value $m_H^2 \approx 0$ is special in this case not because of a symmetry, but because it corresponds to a phase transition. It is early to judge anything but the cuteness of the mechanism. It is fair to say, though, that realising the simplest axion scenario requires a low cut-off; extreme values of the parameters, such as a (technically natural) axion-Higgs coupling of order of 10^{-30}, or an extremely long cosmological evolution, corresponding to $\mathcal{O}\left(10^{30}\right)$ e-foldings; and it spoils the axion solution of the CP problem. Variations on the theme have just begun to be studied, addressing some of those issues [10]. Conceptual issues, related to the tunnelling to larger, negative values of the Higgs mass, might also need to be addressed.

4 Final remark

The new LHC run at higher energy will hopefully very soon wipe out the above considerations with the discovery of new physics around the TeV scale, as widely expected since decades. Even in that case, though, once the excitement for the discovery and its interpretation in terms of dofs and interactions will settle, the understanding in a grander context will still require, I believe, an understanding of the question: why not earlier?

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