

# Concluding remarks (on the Higgs boson)

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I want to focus here on the lessons that we have learned from preliminary LHC results on Higgs searches. I will concentrate mostly on the Higgs boson, rather than on new physics, not only because the mechanism of electroweak (EW) symmetry breaking is one of the priorities in the LHC program, but also because we have new data on the Higgs and it is exciting to think about where they lead us to.

The phenomenon of EW symmetry breaking had already been established before the LHC. After LEP we had ample evidence for gauge structure in interactions (including triple gauge bosons couplings  $\gamma WW$  and  $ZWW$ ) and for the existence of longitudinal components of  $W$  and  $Z$ . Combining this information with knowledge of gauge boson masses, we conclude that propagating particles do not share the full symmetry of interactions, and thus that the EW symmetry is spontaneously broken. This means that every known phenomenon in particle physics (at least before December 13, 2011) can be described by the Lagrangian

$$L = -\frac{1}{4}\text{Tr}F_{\mu\nu}F^{\mu\nu} + i\bar{f}\gamma^\mu D_\mu f + \frac{v^2}{4}\text{Tr}D_\mu\Sigma^\dagger D^\mu\Sigma - \frac{v}{\sqrt{2}}\bar{f}_L\Sigma\lambda_f f_R + \text{h.c.} \quad (1)$$

$$\Sigma \equiv \exp\left(\frac{iT^a\pi^a}{v}\right), \quad (2)$$

where  $\pi^a$  are the longitudinal polarizations of  $W$  and  $Z$ , and  $v = 246$  GeV. The first two terms in eq. (1) describe the kinetic terms and gauge interactions of the SM particles. The last two terms contain the effect of the longitudinal polarizations and the mass terms that arise when gauge symmetry is realized non-linearly.

Although the Lagrangian in eq. (1) was fully satisfying from the experimental point of view, even before Dec 13 every theorist knew that it could not be the full story. Scattering amplitudes of longitudinal gauge bosons grow like  $(E/4\pi v)^2$ , signaling loss of perturbative unitarity, and thus the onset of new phenomena, at  $E \approx 4\pi v = 3$  TeV. The goal of the LHC is to discover what is the new phenomenon. It is well known that the simplest option is given by a single real scalar field  $h$ , which forms a complete  $SU_2$  doublet together with  $\pi^a$ . So 3/4 of the Higgs have already been found and the LHC must find the missing 1/4. However, there is no strong motivation, other than simplicity, for choosing a single  $h$  and nature may have good reasons to make different choices. In this respect, hunting for the Higgs is not just looking for the last missing

piece of the SM, but it means exploring an unknown territory and identifying the nature of the new force responsible for EW breaking, which I will call the *fifth force*.

When we examine the SM, we note that almost all of its open problems originate from Higgs interactions. The flavor problem comes from Yukawa couplings, the hierarchy problem from the Higgs bilinear, the stability problem from the Higgs quartic coupling (and one can add the cosmological constant problem from a constant term in the scalar potential). The crux of these puzzles is that the fifth force is not a gauge force. Therefore, it lacks the properties of uniqueness, robustness against deformations, and predictivity, which are characteristic of gauge theory.

In order to discuss what we have learned from Higgs searches, I will identify two fundamental questions. The first question is: *What is the fifth force?* We want to know if it is weak or strong; if it is a gauge force or associated with a fundamental scalar. The answer to this question will come from measurements of Higgs couplings. These measurements will play the role that precision EW data played at the time of LEP. An important difference is that, in the case of Higgs couplings, deviations from the SM expectation could be large (not necessarily of one-loop size) and thus show up even at an early stage. Actually, the more natural the Higgs boson is, the more its properties must deviate from the SM. This is because a natural theory must give large corrections to the Higgs two-point function (to cure the hierarchy problem). These large corrections must also modify the Higgs production rate at the LHC and some of its decay channels, as can be easily seen by inserting two gluons (or two photons) in the Feynman diagram of the Higgs two-point function. This expectation is fully confirmed in all the examples of natural theories known to us. So measuring the Higgs couplings is the way to probe the fifth force and may be the first way for new physics to show up.

The second question is: *Is the Higgs natural?* This is not an idle question. Its importance goes beyond EW symmetry breaking and its answer will influence the strategy for future directions in particle physics. Naturalness is a concept fully linked to the use of effective field theories (EFT). EFT is the tool that we use to implement an intuitive notion: separation of scales. In simple words, separation of scales means that we don't need to know the motion of every atom inside the moon to compute its orbit. Or we don't need to know about quarks to describe physics at the atomic scale. We build a stack of EFT, one on top of the other, just like a matryoshka doll with one layer inside the other. Each EFT is appropriate to describe a certain energy regime, but it is connected to the next in the sense that free parameters in one layer can be computed in the next layer. One of the most remarkable results of modern physics has been the discovery that at each layer we find simpler physical laws, larger symmetry, unification of concepts that seemed unrelated in the previous layer. It is amazing that nature works this way, but it is just an empirical fact. We can use the criterion of naturalness in EFT to infer the energy at which the validity of one layer ends and a new layer must set in. Whenever a next layer exists, this procedure gives

a reasonable answer, as shown by various examples (electron self-energy, pion mass difference, neutral kaon mass difference). When applied to the Higgs boson mass, this criterion gives a maximum scale for new physics at about 500 GeV.

Since we have not yet found any new physics at the LHC, one may wonder what is the fate of naturalness. The issue is not yet settled. It is quite possible that new physics is just around the corner. After all, the LHC has entered the territory of naturalness, but the exploration is far from complete. The alternative is that the idea of naturalness does not apply to the Higgs because there is a failure of the EFT approach. After all, dark energy could already be taken as evidence for failure of EFT, since the naturalness of the cosmological constant suggests new physics around  $10^{-3}$  eV. Holography, gauge-gravity duality, and the AdS-CFT correspondence show that some theories are much richer than what a single Lagrangian can capture. The best we can do to describe the physical content is to resort to two different Lagrangians, two dual versions. Maybe this is an indication that our theoretical tools are failing, that an EFT Lagrangian is not able to catch all the underlying physics. There could be connections between small and large scales. A numerological curiosity is that, if we combine the largest possible scale (the Hubble length  $H^{-1} = 10^{26}$  m) with the smallest (the Planck length  $M_P^{-1} = 10^{-35}$  m), we can reproduce the scale of the cosmological constant ( $\Lambda_{CC} = \sqrt{H M_P} = 5 \times 10^{-3}$  eV) and the weak scale ( $\Lambda_{EW} = \sqrt{\Lambda_{CC} M_P} = 5$  TeV). If behind this numerical curiosity there is some theoretical IR/UV connection, we will never be able to catch it with an EFT.

Another approach which would invalidate naturalness is the idea of the multiverse. Out of the process of eternal inflation, a multitude of universes are created, each with its own values of the fundamental constants and its own physical laws. Anthropic arguments then select the kind of universe in which we live in or, in other words, the physical laws that govern nature. It may sound like a crazy idea to some (bordering on science fiction), but at present the multiverse yields the most convincing explanation of the cosmological constant. A lesson from the multiverse is that some of the questions that we thought to be fundamental may actually be just the result of environmental conditions, and carry no more significance than the shape of continents or the emergence of a particular animal species in Darwinian evolution.

So physics has reached a branching path and the LHC will tell us which way we have to follow. One path follows the road that guided us towards the extraordinary successes of particle physics in the last 100 years or so: a new layer, new symmetry, more unification that bring us closer to a single governing principle of nature. The other path is marked by the failure of naturalness, the collapse of the picture of a multi-layered matryoshka doll hiding a single final truth. We have only vague ideas of where this path leads to, and maybe the multiverse is the most concrete construction along this path. It is clear that establishing the fate of Higgs naturalness has far-reaching consequences for particle physics, well beyond the problem of EW breaking.

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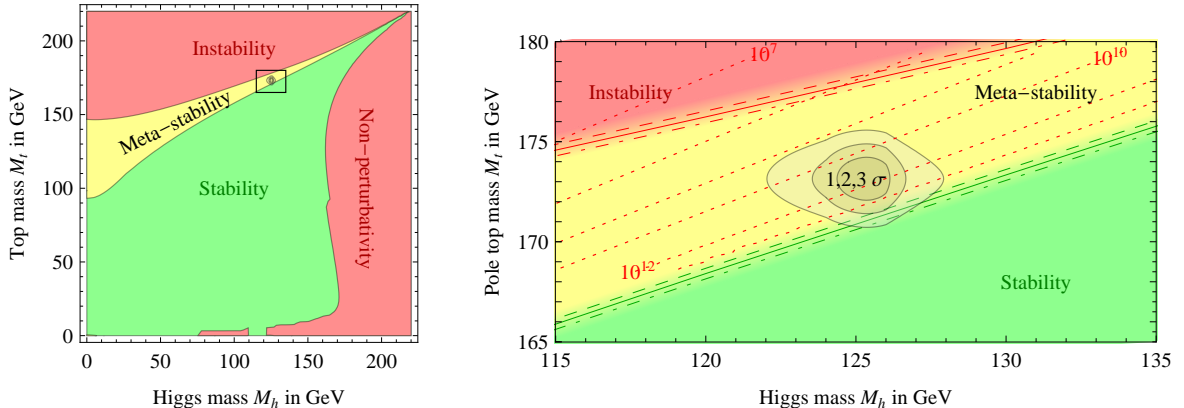


Figure 1: Regions of absolute stability, meta-stability and instability of the SM vacuum in the  $M_t$ - $M_h$  plane. The frame on the right zooms in the region of the preferred experimental range of  $M_h$  and  $M_t$  (the gray areas denote the allowed region at 1, 2, and  $3\sigma$ ). The three boundaries lines correspond to  $\alpha_s(M_Z) = 0.1184 \pm 0.0007$ , and the grading of the colors indicates the size of the theoretical error. The dotted contour-lines show the instability scale  $\Lambda$  in GeV assuming  $\alpha_s(M_Z) = 0.1184$ .

familiar to particle physicists and promises new discoveries on the road towards final unification. The other path may mean finding the Higgs and nothing else at the LHC. It will force us to abandon naturalness and EFT, and look for new paradigms in a holistic vision, where nature should be seen as a whole and cannot always be reduced to its smaller components. But physics is a natural science and we want to find answers with the experimental method. While along the first path there are new phenomena to be studied and the goals are clear, how will we be able to make progress if the second path turns out to be true? This is a difficult question and I don't have an answer. However, I want to show that measuring the Higgs mass may give us some indirect hints.

For the sake of argument, let me assume that the SM with a single Higgs fully describes physics up to a very large energy scale. I will also take seriously the LHC indication for a Higgs mass around 125–126 GeV. In this case, as shown in fig. 1, we learn that our universe lives in a very critical condition, at the verge of a cosmic catastrophe. It is a remarkable coincidence that we happen to live just at the boundary between two phases: the ordinary Higgs phase and a region where the Higgs field slides to very large values. The condition for absolute stability is

$$M_h [\text{GeV}] > 129.4 + 1.4 \left( \frac{M_t [\text{GeV}] - 173.1}{0.7} \right) - 0.5 \left( \frac{\alpha_s(M_Z) - 0.1184}{0.0007} \right) \pm 1.0_{\text{th}} .$$

Precise experimental information on the Higgs and top mass is needed to ascertain the ultimate fate of the universe and whether we live a stable vacuum or not. The Higgs mass can be measured very precisely at the LHC. Then the top mass will become the largest source of uncertainty and every GeV in  $M_t$  counts as a shift of 2 GeV in the Higgs mass. A reduction in the error on the top mass may become the best telescope to peek into the future of our universe.

Also the hierarchy problem can be interpreted as a sign of near criticality between two phases. The coefficient  $m^2$  of the Higgs bilinear in the scalar potential is the order parameter that describes the transition between the symmetric phase ( $m^2 > 0$ ) and the broken phase ( $m^2 < 0$ ). In principle,  $m^2$  could take any value between  $-M_P^2$  and  $+M_P^2$ , but quantum corrections push  $m^2$  away from zero towards one of the two end points of the allowed range. The hierarchy problem is the observation that in our universe the value of  $m^2$  is approximately zero or, in other words, sits near the boundary between the symmetric and broken phases. Therefore, if the LHC result is confirmed, we must conclude that both  $m^2$  and  $\lambda$ , the two parameters of the Higgs potential, happen to be near critical lines that separate the EW phase from a different (and inhospitable) phase of the SM. Is criticality just a capricious numerical coincidence or is it telling us something deep?

The occurrence of criticality could be the consequence of symmetry. For instance, supersymmetry implies  $m^2 = 0$ . If supersymmetry is marginally broken,  $m^2$  would remain near zero, solving the hierarchy problem. But if no new physics is discovered at the LHC, we should turn away from symmetry and look elsewhere for an explanation of the near-criticality. It is known that statistical systems often approach critical behaviors as a consequence of some internal dynamics or are attracted to the critical point by the phenomenon of self-organized criticality. As long as no new physics is discovered, the lack of evidence for a symmetry explanation of the hierarchy problem will stimulate the search for alternative solutions. The observation that both parameters in the Higgs potential are quasi-critical may be viewed as evidence for an underlying statistical system that approaches criticality. The multiverse is the most natural candidate to play the role of the underlying statistical system for SM parameters. If this vision is correct, it will lead to a new interpretation of our status in the multiverse: our universe is not a special element of the multiverse where the parameters have the peculiarity of allowing for life, but rather our universe is one of the most common products of the multiverse because it lies near an attractor critical point. In other words, the parameter distribution in the multiverse, instead of being flat or described by simple power laws (as usually assumed) could be highly peaked around critical lines because of some internal dynamics. Rather than being selected by anthropic reasons, our universe is simply a very generic specimen in the multitude of the multiverse. If you complained that string theory was making no predictions about our universe, do not rejoice in this. Now the situation may become even worse: the multiverse is making predictions, but about other universes.

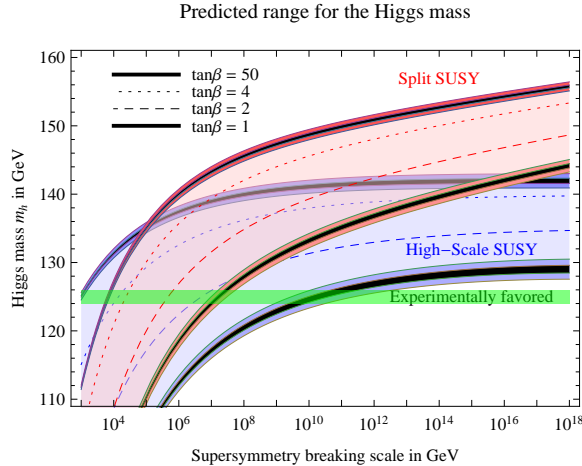


Figure 2: NNLO prediction for the Higgs mass  $M_h$  in High-Scale Supersymmetry (blue, lower) and Split Supersymmetry (red, upper) for  $\tan\beta = \{1, 2, 4, 50\}$ . The thickness of the lower boundary at  $\tan\beta = 1$  and of the upper boundary at  $\tan\beta = 50$  shows the uncertainty due to the present  $1\sigma$  error on  $\alpha_s$  (black band) and on the top mass (larger colored band).

What does a Higgs mass of 125-126 GeV tell us about natural theories? A Higgs mass smaller than 120 GeV would have been perfect for natural supersymmetry, while a mass larger than 130 GeV would have excluded the simplest scenarios. If the Higgs mass is really 125 GeV, right in the middle, then it looks like nature wants to tease theoretical physicists. In supersymmetry, a Higgs mass of 125 GeV can be reached, but only for extreme values of the parameters, especially those of the stop. Therefore certain natural setups, where parameters are correlated, are in bad shape (for instance gauge mediation), but the idea of low-energy supersymmetry is not killed. As shown in fig. 2, a Higgs mass of 125 GeV rules out the idea of Split Supersymmetry with a high scale, say larger than  $10^8$  GeV. However, it fits very well with Split Supersymmetry with a low scale. Actually the simplest model of Split Supersymmetry, based on anomaly mediation, predicts a hierarchy between scalars and fermions of a one-loop factor and thus looks like a very satisfactory solution.

The indication for a Higgs mass in the range 125–126 GeV is the most exciting result from the LHC so far. It has important consequences for supersymmetry and other theories beyond the SM, but the most puzzling (and surprising) message that we obtained from preliminary LHC data on the Higgs is the apparent near-criticality of the parameters entering the SM Higgs potential.