Chapter 21

Future Direction Beyond the Standard Theory

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With the Higgs discovery, the full Standard Model (SM) has been experimentally established, and most of its sectors accurately tested. Nevertheless, the SM deeply relies in the presence of the Higgs, a spin-zero field, whose mass term is not expected, on theoretical grounds, to be much smaller than the Planck scale. This problem of naturalness demands a modification of the SM around the weak scale, making the exploration of the TeV-energy regime a top experimental priority. In this chapter we briefly review the most well-motivated scenarios beyond the SM that can accommodate a light Higgs, mainly centering in two ideas: Supersymmetry and compositeness.

1. Motivations to go Beyond

How wonderful that we have met with a paradox;
now we have some hope of making progress.
Niels Bohr

The most important discoveries in physics have come out in physical regimes in which the existent theory had failed to give sensitive predictions, leading, in most of the cases, to a change of paradigm. Sometimes it was foreseen which new theory had to replace the old paradigm, and dedicated experimental searches were put forward. This has been the case for particle physics in recent times, as for example, in the search for the top-quark and Higgs. Nevertheless, sometimes we do not even realize that our current theory has a flaw, not making sense in certain energy regimes, as it happened with classical physics in the subatomic domain. In these circumstances experiments have led the new-physics searches, with the theory, in this case quantum mechanics, coming behind.

The Higgs discovery was led by a "no-lose theorem" for new physics:[1] Theories of massive vectors, as the W and Z bosons, did not make sense if no extra degrees of

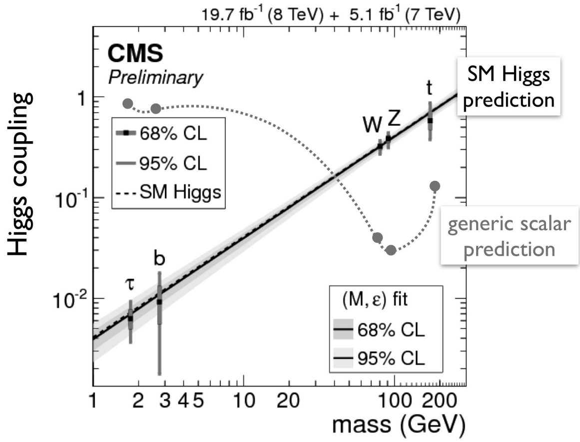

Fig. 1. Fit of the couplings of the newly discovered state at the LHC to the SM particles as a function of their masses.[3] The predictions from the SM Higgs are given by a straight black line. A generic scalar would have couplings to the SM particles laying in any point of this plane, as in the example shown with a dashed line. The experimental data clearly favors a SM Higgs.

freedom were added, since they were becoming strongly-coupled at energies above $\approx 4\pi m_W/g$. Therefore either new particles or new strong-dynamics were guaranteed to be discovered at the LHC below or around TeV energies. One possibility to make theories of massive vector bosons consistent was the Brout–Englert–Higgs (BEH) mechanism,[2] that predicted a new particle below the TeV, the Higgs, whose couplings were fully determined. At the LHC Run 1, a new state with these properties was indeed observed,[3,4] as shown in Fig. 1, giving the first experimental confirmation of the BEH-mechanism and a full validation of the Standard Model (SM) of elementary particles.[5] We can be proud of this outstanding achievement. For the first time we are confident to have a theory for the fundamental interactions of the universe that allows to make sensible predictions for physics all the way to very small scales. Indeed, being the Higgs mass $m_h \simeq 125$ GeV, the SM is a consistent effective field theory valid up to energies of order the Planck-mass $M_P = \sqrt{1/G_N} \sim 10^{19}$ GeV.[6] At these energies, of course, quantum gravitational effects are expected to be large, entering a new unpredictable strong-coupling regime, that asks again for a new paradigm. Either string theory or something else awaits there to be discovered.

The Planck-mass scale is however too large to be fully explored with present facilities. We can only hope to detect "echoes" arising from physics at those energies. For example, neutrino Majorana masses can be expected to arise from Planckian physics, incarnated in dimension-five operators suppressed by the heavy scale.[7] This can lead to a rate of neutrinoless double-beta decays observable within near future experiments.[8] Also processes mediated by Planckian states could lead to proton decay rates relatively close to present sensitivities. Dark Matter could also be a remnant of this very high-energy new physics, for example, as a very weakly interacting particle, such as the axion.[9] If this is the case, we will face a big challenge to detect DM beyond its gravitational presence already observed. Though very limited, it is clear that these types of searches must have a high priority in any experimental physics agenda.

With this in mind, TeV colliders seem hopeless to make any important discovery. The SM is a perfectly consistent theory at the TeV, giving us precise predictions. Nevertheless, we encounter, for the first time, a different motivation to expect new physics to show up at the TeV regime. We have reasons to believe that the BEH-mechanism cannot be the full story. It is true that a virtue of the BEH-mechanism for electroweak symmetry breaking (EWSB) is its simplicity. But, as it is well-known from daily life, simplicity is in conflict with stability.[a] The fact that the Higgs is a scalar, a spin-zero state, makes it difficult to keep it light ($m_h \ll M_P$), as Kenneth Wilson denounced long time ago:[10] "*Scalar particles are the only kind of free particles whose mass term does not break either an internal or a gauge symmetry.*"

The seed of the problem can be easily understood just by looking at the propagating degrees of freedom (DOF) of a massless and massive state of spin zero, as compared with those of a state of spin equal to 1/2, 1, or higher. A massless vector boson, like the photon, has two polarizations (2 DOF), while a massive vector has 3 polarizations. The simple formula $2 \neq 3$ guarantees that a massless vector can never get a mass by continuous variations of parameters (or quantum fluctuations); only a discrete change in the theory, increasing its DOF, can make vector massive. Similarly for fermions, we have that a charged massless fermion has 2 DOF, while a massive one has the double (the left- and right-handed chiral states), and therefore, for the same reason, massless fermions are safe from getting masses under small fluctuations.[b] Now, massless scalars have the same DOF as massive scalars: 1 DOF for neutral ones. Even if we start with a massless scalar at tree-level, it is not guaranteed that quantum corrections will not give it a mass. Natural expectations for this mass is then just dictated by dimensional analysis and approximate symmetries of the theory. In the SM, for example, in the presence of a large threshold scale M_P in which gravitational interactions are large and new physics must be present, the Higgs mass is expected to be

$$m_h^2 = aM_P^2, \tag{1}$$

where a is a number close to one, as no accidental symmetries in the SM dictate additional suppressions (at most a loop suppression, $\sim g^2/16\pi^2$, due to its unavoidable quantum nature). Therefore, the empirical evidence $m_h \ll M_P$ appears to be, for quantum field theorists, very unnatural.

[a] We learn this at the very early stages of our lives when at the kindergarten we become knowledgable with *The Three Little Pigs* fable.

[b] If a fermion has no charge, it can get a Majorana-type mass without increasing the DOF. For this reason, to keep naturally massless fermions, we must take the extra assumption that the fermion has some type of charge.

2. New Paradigms Awaiting at the TeV

Idealized models have a useful role to play,
as ways to clarify your thinking.
Paul Krugman

Theorists contemplate mainly two possible explanations for the above described Higgs-mass oddity. One is to consider that the SM is upgraded at TeV energies to incorporate an extra symmetry which could relate the Higgs, a scalar, to a fermion, whose mass can be protected. This is the case of supersymmetry. An alternative option is to assume that the Higgs is not really an elementary particle but a composite state made of elementary fermions, as pions in QCD. In this case, we must postulate a new strong-sector at the TeV from whose dynamics must emerge a Higgs-like state.

Recently, a third possibility has started to be seriously considered in the physics community. This relies in the quite controversial possibility that our universe is only one among a vast number of other universes in which the laws of physics can be different. If so, we can *naturally* expect that in most of the universes the Higgs mass is close to the Planck scale, with only few in which $m_h \ll M_P$. Nevertheless, it is in these few universes where the laws of physics can lead to observers.[11] The fact that we live in a special universe would be similar to the fact that we live in a special planet, the Earth, different from most of the planets. Where else could we live? This idea goes by the name of the "Multiverse", and has recently found a solid theoretical framework: Eternal inflation and the huge landscape of string theory vacua. The Multiverse approach is often criticized of being non-scientific, as if it could be used to explain anything. Nevertheless, this is far from being true. Scientifically speaking, this approach is in very similar footing as Darwin's Theory of Evolution: Though it cannot predict what species can arise on Earth, it affords a mechanism to explain their varieties and sophistications. And more importantly, it can be experimentally dismissed! Finding human's fossils in the Cambrian epoch would be enough to throw Darwin's theory away. We could also dismiss the Multiverse solution to the hierarchy problem if another scalar is discovered at the LHC. It can be argued that $m_h \ll M_P$ is crucial to have the chemistry of our universe,[12] but why on earth another unnaturally light scalar would be needed for? This would definitely point towards an alternative solution to the hierarchy problem. A special motivation for the Multiverse paradigm is that it is the only one that properly addresses the smallness of the cosmological constant. As Weinberg pointed out long ago,[13] a cosmological constant close to its present value could be anthropically selected in the landscape. We will not further discuss the Multiverse idea. It is clear that this will receive an important boost if no new physics is discovered at the LHC.

It is interesting to point out that all scenarios for new-physics discussed above predicted a Higgs with a mass around the observed one. For instance, in a minimal supersymmetric version of the SM, what is called the MSSM, the lightest-Higgs mass was predicted to be in the range[14]

$$m_h \lesssim 135 \text{ GeV}, \tag{2}$$

while in minimal versions of composite Higgs (MCHM) the predictions[15] were

$$115 \text{ GeV} \lesssim m_h \lesssim 185 \text{ GeV}. \tag{3}$$

Finally, to have the SM valid all the way up to Planck energies,[6] as could be natural in a Multiverse, the Higgs mass had to lie within

$$110 \text{ GeV} \lesssim m_h \lesssim 170 \text{ GeV}. \tag{4}$$

Finding the Higgs at around 125 GeV did not discriminate among these three possibilities. In the MSSM, it can be accommodated close to the upper limit, having the important implication though that the supersymmetry-breaking scale must be beyond the TeV.[16] On the contrary, in the MCHM a 125 GeV Higgs can be accommodated close to the lower limit, implying that color fermionic resonances must be below the TeV,[15,17] at the reach then of the LHC.

Supersymmetry

Supersymmetry allows to relate the properties of scalars with those of fermions such that the stability of the fermion masses can guarantee the stability of the scalar masses. The most economical realization would be to impose supersymmetry to relate the Higgs to any of the SM left-handed lepton, either the tau, muon or electron. Interestingly, this is doable since all these fields have the same quantum numbers under the SM. This possibility was proposed long ago,[18] but only recently realistic models have been explored.[19] The major difficulty comes however from the up-quark masses that can only be generated if supersymmetry is broken, requiring then extra dynamics at the TeV.

On the other hand, if we demand that all fermion masses must arise from supersymmetry-preserving terms, the minimal supersymmetric version of the SM is the MSSM. This requires to double the full spectrum of the SM, a new fermion for each SM boson and vice versa, implying a new layer of particles, the superpartners, to show up at TeV energies. We should not dismay with this doubling of the spectrum. We already came across before when Dirac predicted an anti-particle for each existing particle in the venue of relativistic quantum theories, a story with a successful ending. One of the most interesting prediction of the MSSM is the physical Higgs mass, that can be fully calculated as a function of the mass spectrum of the theory. For this reason, learning at the LHC the Higgs-mass value was the most relevant piece of information for the MSSM. In particular, a 125 GeV Higgs leads to the requirement that the breaking of supersymmetry in the stops, the partners of the top in the MSSM, must be large, above the TeV scale. This obviates many direct searches for superpartners at the LHC! Furthermore, this implies, based on naturalness, that the MSSM starts to be disfavored by the experimental data, and one must look for non-minimal versions such as the NMSSM in which an extra singlet field is added. This is one of the main lessons from the LHC Run 1. We stop here as further discussions on supersymmetry can be found in Chapter 20 of this book.

Compositeness

Probably the easiest solution to the Higgs-mass problem is to renounce of elementary scalars. This was one of the main motivation for Technicolor models[20] where a mechanism for EWSB similar to QCD was postulated at the TeV. In QCD the breaking of the electroweak symmetry comes from the condensate of quarks due to the strong-interacting gluons at GeV energies. This phenomena is close related to superconductivity in which the Cooper pair plays the role of the quark condensate. Following the same idea, Technicolor models consist of gauge theories strongly coupled at the TeV in which a condensate of Techni-fermions leads to EWSB. Nevertheless, Technicolor models do not predict a light Higgs-like state. In fact, in Technicolor models we expect many heavy resonances with different spins, but all with masses around the TeV and none of them with couplings to SM states necessarily proportional to their mass, as LHC data suggests (see Fig. 1). For this reason these type of models are at present dismissed.

A different, but close related possibility, is to look for theories at the TeV whose strong dynamics does not break the electroweak symmetry but instead deliver a composite BEH-mechanism.[21] At first glance, this might seem a tough demand. But this is in fact not the case, if we wisely make use of the so-called Goldstone theorem, a theorem inspired by the work of Nambu,[22] conjectured by Goldstone,[23] and proven by Goldstone, Salam and Weinberg.[24] This theorem states that whenever a spontaneous breaking of global symmetry occurs, massless bosons must appear. These are called Goldstone bosons. For example, if the global-symmetry breaking pattern of a quantum field theory is $SU(3) \to SU(2)_L \times U(1)_Y$, the Goldstone theorem tells us that a massless scalar field, transforming as a $SU(2)$-doublet with $Y = 1$, must be contained in the theory. This is a beautiful result! If we postulate to have at the TeV a new strong-sector with this breaking pattern, we are guaranteed to have a composite scalar with the right quantum numbers to be identified with the Higgs. Nevertheless, this simple incarnation does not fully work by many reasons, as it predicts, for instance, large deviations from the relation $m_W^2 \simeq m_Z^2 \cos^2\theta_W$ due to the absence of a custodial symmetry in the TeV strong-sector. The minimal realistic version of a composite Higgs model was given in Ref. 25 based on a TeV strong-sector with the global-symmetry breaking pattern

$$SO(5) \to SO(4) \simeq SU(2)_L \times SU(2)_R, \tag{5}$$

with the SM $U(1)_Y$ embedded in $SU(2)_R$. The Higgs appears as a Goldstone boson and the "custodial" $SO(4)$ symmetry preserves the relation $m_W^2 \simeq m_Z^2 \cos^2\theta_W$. There is an additional requirement to make the model realistic. SM fermions and gauge bosons must couple to the Higgs to get masses, that implies that they must have direct couplings to the TeV strong-sector. These couplings however break explicitly the global $SO(5)$ symmetry, making the Higgs a "Pseudo" Goldstone boson (PGB), as Weinberg pointed out long ago.[26] What this means is that the Higgs is not massless anymore, as a Higgs potential is generated by one-loop quantum corrections involving SM particles. The main contribution comes from the top-quark loop due to its large Yukawa coupling, which forces the Higgs to get a vacuum expectation value and trigger EWSB. This one-loop contribution can also allow to naturally accommodate a Higgs mass of 125 GeV.[15,17,c]

It is therefore clear that the top-quark is one of the main players in composite Higgs models. Had the top-quark been lighter, the SM gauge-boson one-loop contributions would have dominated the Higgs potential, and no EWSB would have occurred. Since the top-quark must have sizable linear couplings to the TeV strong sector, in order to get its large mass, the top can be used as a portal to this sector. Measuring then the properties of the top-quark can be as important as those of the Higgs.

The above are the generic features of the composite PGB Higgs idea. Nevertheless, one could wonder about which concrete underlying theory at the TeV could implement these properties, i.e., which are the UV degrees of freedom of the new TeV sector, such as quarks and gluons are to QCD hadrons and mesons. This quite ambitious question is however very difficult to address, mainly due to our limitation to deal with strong dynamics. We must recall that it took us many years, and plenty of experimental data, to discover that the underlying theory behind protons, neutrons and pions was QCD. One can find a theoretical handle in the work of Seiberg,[28] that conjectured some dualities between strongly-coupled gauge theories and weakly-coupled ones that are much easier to treat. Using these dualities, it was found in[29] different UV completed models of composite Higgs. It is also recently receiving some interest UV completed composite-Higgs models with enough (though not all) ingredients to be explored in the lattice.[30]

Alternatively, one can use the AdS/CFT correspondence[31] as a playground for these ideas. Composite Higgs models can be easily realized as weakly-coupled five-dimensional (5D) models in Anti-de Sitter (AdS),[32] in which the Higgs corresponds to the fifth-component of the 5D gauge bosons.[25] The Higgs mass is protected by 5D gauge invariance and can only get a nonzero value from non-local one-loop effects.[33] The AdS/CFT correspondence allows to built composite Higgs models where the mass spectrum of resonances, corresponding to the Kaluza–Klein modes, can be determined.[25]

[c] Variations on the composite PGB Higgs idea have also been put forward under the name of Little Higgs models.[27] In these models however the SM gauge and fermion sector is extended in order to guarantee that Higgs-mass corrections involving the new strong-sector arise at the two-loop level instead of one-loop, allowing for a better insensitivity of the electroweak scale to the new strong dynamics.

On the other hand, interestingly, many predictions of composite Higgs models do not require at all the full knowledge of the strong TeV theory, but only the symmetry breaking pattern. For instance, many Higgs properties can be model-independently derived in an equivalent way as pions in QCD can be very well described at low-energies by the Chiral Lagrangian. Following this approach, it was shown in Ref. 34 which Higgs couplings are expected to deviate from the SM predictions if the Higgs is composite. We will come back on this issue later on.

Up to now we have been independently discussing the two main ideas beyond the SM, supersymmetry and composite Higgs. Nevertheless nature could well be using, in a non-trivial way, a blend of these two ideas to deliver naturally a light Higgs. We must be aware that the territory of supersymmetric and strongly-coupled theories is still uncharted, so nature could surprise us with some unexpected new-physics. For example, if the strong-sector at the TeV is also supersymmetric, a light Higgs of 125 GeV could emerge due to supersymmetry, instead of its Goldstone nature.[35] The main crucial difference here with respect to the MSSM is that, beyond the Higgs, the rest of the SM would not need to be supersymmetric, implying that only the Higgs would have a supersymmetric partner, the Higgsino. An alternative option is to consider models in which the EWSB is triggered by a Technicolor sector coupled to the MSSM. These models can accommodate a 125 GeV Higgs without the need of very heavy stops, apart from also solving other difficulties of the MSSM such as the μ-problem.[36] More drastically, following the suggestion of Ref. 37, it could also be that string theory comes in at the TeV, as can occur if we allow gravity to propagate in large extra dimensions (LED). The lightness of the Higgs is not a big problem anymore, as quantum gravity does not appear in this case at the huge scale M_P but at energies around the corner, $\sim$ TeV. This is a dream scenario for experimental physics, as we could in the next decades address most of the fundamental questions of particle physics. The LED scenarios however still lack for an explanation of why $m_h \ll$ TeV; of course, a much milder requirement, but important to understand which new physics we could discover first (new string excitations, black holes, gravitons, ...).

3. Looking for Experimental Evidences of TeV New Physics

The great tragedy of science,
the slaying of a beautiful hypothesis by an ugly fact.
Thomas Huxley

If indeed new physics is lurking around TeV energies, this could show up either indirectly, by slightly modifying the SM predictions for physical processes, or in a direct way, as new states at colliders. In the first case, we must advocate for searches in the intensity frontier, while for the second it is clear that it is more convenient to explore the energy frontier. Though both approaches can provide relevant information on physics beyond the SM (BSM), it is clear that the search for indirect deviations is more limited as their interpretations are often unclear (for example, the anomalous rate of precession of the perihelion Mercury's orbit was first recognized in 1859, but it was not till 1915 with Einstein's General Relativity that its origin was determined). Therefore to fully determine which new theory will replace the SM, the exploration at the energy frontier will be really essential.

Let us start by understanding which indirect searches are the most interesting ones. For this purpose it is convenient to make use of Effective Quantum Field Theories (EQFT), as these give us a model-independent parametrization of all the indirect BSM effects. Assuming that the characteristic scale of new physics, Λ, is heavier than the electroweak scale, the SM EQFT is obtained as an expansion in SM fields and derivatives over Λ:

$$\mathcal{L}_{\rm EQFT} = \mathcal{L}_4 + \mathcal{L}_6 + \cdots , \tag{6}$$

where $\mathcal{L}_4$ is made of dimension-four operators and defines what we call the SM Lagrangian,[5] while $\mathcal{L}_6$, that contains dimension-six operators,[38] gives the leading indirect BSM effects.[d] In principle, one can expect that flavor and CP-violating processes are the most sensitive to $\mathcal{L}_6$, as they are suppressed in the SM by the smallness of the fermion masses of the first families.[39] — see also Chapter 17 in this book. Nevertheless, a similar suppression as in the SM is expected in certain BSM. For example, in supersymmetric theories where supersymmetry-breaking is mediated from a "hidden sector" to the SM by gauge interactions, the so-called gauge mediated supersymmetry breaking models (GMSB),[40] all squark masses are family-universal up to small corrections involving the SM fermion masses. Hence their effects to flavor observables are as suppressed as in the SM. Similar scenarios can be found in composite Higgs models. It is therefore not fully guaranteed that flavor and CP-violating effects are the most relevant ones.

Assuming family-universality, a full classification of the physical effects arising from $\mathcal{L}_6$ was provided in Ref. 41. These can be encoded in 59 *primary couplings* between SM fields (for one family) that can be chosen to be:

- 11 Higgs couplings.
- 7 Z-couplings to fermions.
- 1 W-coupling to right-handed fermions.
- 7 triple-gauge couplings.
- 8 fermion dipole-moments.
- 25 four-fermion interactions.

A first complete global fit to all these BSM effects was given in Ref. 42 (except for the four-fermion interactions), showing which sectors of the SM were very well-tested and which require more experimental examination.

[d] We are assuming lepton and baryon number conservation.

Among the 59 primaries, the most interesting ones are the Higgs couplings, as the Higgs is the most sensitive SM particle to BSM corrections. For this reason, as we will show below, today determination of the Higgs couplings, even if not very accurate, can place important bounds on new physics. From the EQFT analysis, one can deduce[43] that among the Higgs couplings, the most relevant ones are the primary couplings,[41] that for the case of CP-conservation correspond to

$$\begin{aligned}\mathcal{L}_h^{\rm primary} &= g^h_{VV}\, h \left[W^{+\,\mu}W^-_\mu + \frac{1}{2\cos^2\theta_W} Z^\mu Z_\mu\right] \\ &\quad + \frac{1}{6}\, g_{3h}\, h^3 + g^h_{ff}(h\bar f_L f_R + \text{h.c.}) \\ &\quad + \kappa_{GG}\,\frac{h}{2v} G^{A\,\mu\nu}G^A_{\mu\nu} + \kappa_{\gamma\gamma}\,\frac{h}{2v}A^{\mu\nu}A_{\mu\nu} + \kappa_{Z\gamma}\frac{h}{v}A^{\mu\nu}Z_{\mu\nu}, \end{aligned} \tag{7}$$

where $G^{A\,\mu\nu}$, $A_{\mu\nu}$, $Z_{\mu\nu}$ are the field-strengths of the gluon, photon and Z. Equation (7) gives the set of SM Higgs couplings whose effects from $\mathcal{L}_6$ are independent from effects to other SM observables.[43] On the contrary, the rest of the Higgs couplings can be always written as a function of other SM couplings, as explicitly shown in Ref. 44. At the LHC one can combine the different Higgs-production mechanisms and branching ratios to determine six of the primary Higgs couplings: g^h_{ff} $(f = t, b, \tau)$, g^h_{VV}, κ_{GG} and $\kappa_{\gamma\gamma}$.[e] The CMS and ATLAS fit of these six primary Higgs couplings can be found in Refs. 3 and 4, and for a combination of the ATLAS and CMS data see, for example, Ref. 45. Though the primary coupling $\kappa_{Z\gamma}$ has not yet been determined, one can use the experimental bound[46] $BR(h \to Z\gamma)/BR(h \to Z\gamma)_{\rm SM} \lesssim 10$ to derive the constraint[42] $-0.01 \lesssim \kappa_{Z\gamma} \lesssim 0.02$. The fact that in the SM $h \to Z\gamma$ arises at the one-loop level, and therefore has a small branching fraction, $BR(h \to Z\gamma) \sim 0.15\%$, makes this decay channel very sensitive to new physics; it probably provides the last chance to find large BSM effects in SM Higgs couplings. Among the remaining primary Higgs couplings to be measured we also have g_{3h}. Its determination however will be very difficult, since it requires to search for double-Higgs production $pp \to hh$ that has small rates.[47] Also Higgs couplings to light fermions g^h_{ff} (beyond the 3rd family) are going to be difficult to measure, since we expect these couplings to be proportional to m_f/m_W, giving then very small branching ratios. For example, for the case of the muon, that is probably the most accessible, we have in the SM $BR(h \to \mu\mu) \sim 0.02\%$. Therefore high luminosities will be needed to measure these Higgs couplings at the LHC Run 2.

The experimental fit of the Higgs primary couplings shows a good agreement with the SM predictions,[3,4] with no signal of new physics. This leads to important implications for BSM. In the MSSM, for example, the Higgs couplings to

[e]We note that g^h_{tt} and g^h_{VV} also affect $BR(h \to \gamma\gamma/Z\gamma)$ and $\sigma(GG \to h)$ at the one-loop level.[34]

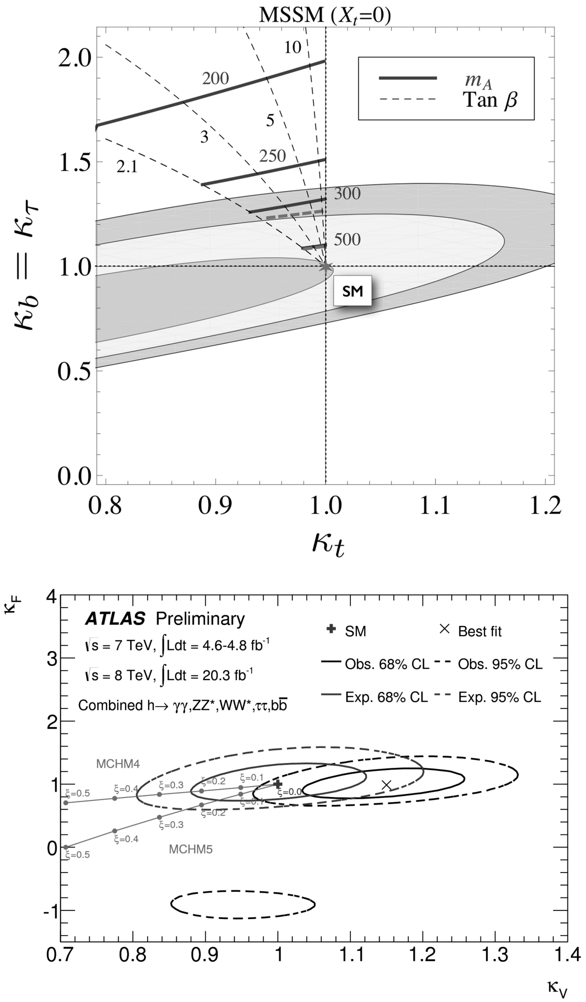

Fig. 2. Two-dimensional fit of Higgs couplings and predictions from the MSSM (top plot),[49] and composite Higgs models MCHM4 and MCHM5 (bottom plot).[50] Other Higgs couplings are put to their SM value. We follow the notation $\kappa_V \equiv g^h_{VV}/g^{h\,\mathrm{SM}}_{VV}$ and $\kappa_F \equiv g^h_{ff}/g^{h\,\mathrm{SM}}_{ff}$.

fermions receive sizable tree-level corrections due to the extra heavy Higgs.[f] The main effects[48,49] are then expected to be for g^h_{tt} and $g^h_{bb,\tau\tau}$, with a pattern of deviations with respect to the SM shown in Fig. 2 (top plot). The absence of deviations leads then to a lower-bound on the heavy Higgs mass of approximately $m_A \gtrsim 400$ GeV.[50] Similarly, in strongly-interacting BSM in which the Higgs is composite,

[f] Also g^h_{VV} and g_{3h} are modified at tree-level by the heavy Higgs exchange. Nevertheless, the corrections to g^h_{VV} are suppressed by extra powers of the heavy Higgs mass, while g_{3h} is, as we mentioned above, very difficult to be measured in the near future.

effects on the Higgs coupling to fermions and $V = W/Z$ can be enhanced by a strong-coupling factor g_ρ^2/g^2,[34] that can be as large as $g_\rho^2/g^2 \sim 16\pi^2$ with respect to effects in other SM sectors. The pattern of deviations is shown in Fig. 2 (bottom plot) for several MCHM and as a function of $\xi = (v/f)^2$ where f is the Higgs decay-constant, related to the composite scale by $\Lambda = g_\rho f$. Bounds on the scale of compositeness Λ coming from LHC Higgs physics are starting to to be as competitive as those from LEP, even that we have produced much less Higgs at the LHC than Z at LEP.[50]

The most compelling way to discover new physics is, without doubt, by direct detection of new particles. Both, supersymmetry and composite Higgs models, predict a bunch of new states lurking around the TeV. Specialized searches are on the way by LHC experimentalists and a large number of different analysis have been already pursued. If we had to prioritize few of them, we would select the hunting for color particles, specially those dedicated searches for the partners of the top, either in supersymmetric or composite Higgs models. The reason for this priority is the following. If TeV new-physics must explain the lightness of the Higgs versus M_P, the loop corrections to the Higgs mass must be "tamed" by the new particles. The most relevant one is the top-quark loop, since it has the largest coupling to the Higgs. This loop contribution is controlled by the top-quark partners, that generate a Higgs mass of order the electroweak scale if these new states are around 500 GeV. For larger masses, the parameters of the model must be tuned to keep the Higgs light. Therefore, based on naturalness arguments, the top partners are expected to be below the TeV. Furthermore, being color particles, we are guaranteed to have sizable production cross-section at the LHC to be easily discovered. In the case of supersymmetric models, the top partners correspond to scalars with the quantum numbers of the top and bottom, the so-called stops and sbottoms. They are supposed to mostly decay into tops and bottoms, and into the lightest supersymmetric particle that in most natural scenarios is the Higgsino, or the Gravitino for the case of GMSB models. For composite Higgs models, the top partners are color fermionic resonances with electric charges $Q = 5/3, 2/3, -1/3$,[15] and a phenomenology described in detail in Ref. 51. This is depicted in Fig. 3 where it is shown the mass spectrum of a natural supersymmetric and composite Higgs model. Present limits on top partners from the LHC Run 1 are around $500-800\,\text{GeV}$,[52] scratching at present the most natural region of the parameter space of the MSSM and MCHM. Nevertheless, it will not be until the LHC Run 2 where the naturalness of these BSM will be really at stake.

Clues for cosmological conundrums

Could TeV physics be behind other fundamental questions in particle physics and cosmology, such as the origin of Dark Matter (DM), the abundance of matter over anti-matter in our universe (Baryogenesis), the origin of inflation or neutrino masses? Though not necessary the case, as the mandatory new-physics at the Planck

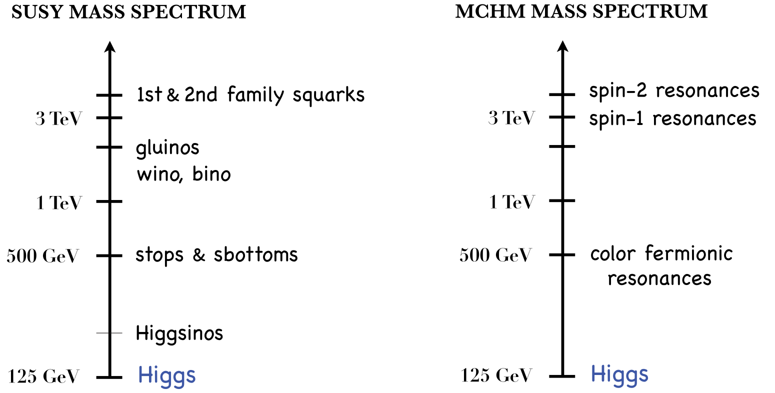

Fig. 3. Natural expectations for the mass spectrum in supersymmetric models (left) and composite Higgs models (right).

scale could be the true responsible for these phenomena, it is well possible that some of these questions are addressed by TeV physics, opening an exciting possibility of resolving these mysteries in well controlled experiments, such as TeV colliders. The most likely of the above important questions to be addressed by TeV new-physics is the DM origin. This hope arises from the so-called "WIMP miracle": A stable particle with mass of order the electroweak scale and $O(1)$ renormalizable-interactions is in the ballpark of the needed relic abundance for a DM candidate. In the MSSM, as well as in the MCHM, we find many DM candidates.[53] For instance, the lightest superpartner, if neutral, as the neutralinos (superpartners of the Z, photon or Higgs), can be a good candidate for DM in certain "well-tempered" region of the parameter space.[54] Similarly, DM can arise in composite Higgs models as an extra Goldstone boson,[55] or as the "baryons" of the TeV strong-sector which can be stable, as ordinary baryons in QCD, by an accidental symmetry.[56] Detecting these types of DM candidates is possible, but not guaranteed, as they could be too heavy, around few TeV, to have impact in present detectors. "Blind" searches at the LHC, i.e., model-independently looking for missing energy (from the undetected DM) plus a jet/vector-boson, can also be performed to scan over a large variety of models. A lot of effort has been put behind these searches that, with a little bit of luck, could give us significant rewards.

Baryogenesis is another interesting phenomena that could have its origin at the TeV. The universe, as it cools down, undergoes a phase transition from a symmetric vacuum to an EWSB one, at a critical temperature of $T_c \sim m_h$. If this transition is strongly first-order and bubbles of EWSB phase are produced as the universe gets cooler, there is the possibility to create the needed baryons that populate our universe. Of course, we still need that new physics at the TeV afford baryon number violating processes, apart from CP violation.[57] Unfortunately, if the electroweak phase transition is driven only by the SM Higgs, the transition is close to second-order and baryons cannot be produced. Different possibilities could change this behavior. If extra scalars, such as an extra singlet,[58] coexist with the SM Higgs, the electroweak phase transition could be of first-order. Therefore detecting this singlet at the LHC, though not an easy task,[59] can be of fundamental importance. Another possibility is to have Baryogengesis, not at the electroweak phase transition, but at a $T_c \sim$ TeV phase-transition arising from a new strong-sector at the TeV. As commented, this strong-sector must be there if the Higgs is composite, or even in the MSSM if supersymmetry is broken at low-energies. This option is quite interesting, but again will be difficult to be fully explored at the LHC, probably needing a more energetic collider.

4. Epilogue

Doubt is not a pleasant condition,
but certainty is absurd.
Voltaire

We are facing a new era in particle physics in which discoveries at the energy frontier are not anymore fully guaranteed. The times of "no-lose theorems" for discovery are gone for experimental physics at TeV energies and we have the risk of not finding any new physics at the LHC. In fact, the most radical change of the present paradigm, the Multiverse idea, gives the dramatic possibility to find nothing new at TeV colliders. We encompassed this situation before: For example, the Michelson–Morley experiment gave an unexpected null result. But in spite of the frustration of knowing that experimentally we could not learn anything about the properties of the medium in which electromagnetic waves were propagating, we were able to contemplate the birth of a new paradigm, Einstein's theory of relativity. We therefore should not fear as we always learn things from well-motivated experiments.

On the other hand, a different type of motivation is coming forth in the search for new physics at TeV energies: The unnaturalness of the SM. Understanding the smallness of the electroweak scale versus the Planck scale can require new physics to be present at the TeV. This gives us confidence to believe that the LHC has high chances to discover new physics. We have well-defined proposals and a loaded agenda for LHC searches. And, of course, we must be opened to whatever surprises nature can bring us beyond our expectations. As Thomas Henry Huxley once advised us, we must "*be prepared to give up every preconceived notion, follow humbly wherever and to whatever abysses nature leads, or you shall learn nothing.*"

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