PROCEEDINGS OF SCIENCE

Searching for New Phenomena

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I briefly review few topics in searches for new phenomena. In particular, I show that no new physics beyond the SM can arise if its origin is the electroweak scale. Therefore, it is only possible to have new phenomena accessible at the LHC if this arises from a new fundamental scale. We focus in composite Higgs scenarios that give a possible link between this new physics scale and the electroweak scale, providing a motivation for LHC searches

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1. Introduction

There has been an impressive number of searches for new phenomena at LHC, giving us plenty of negative results [1]. In spite of it, null results can also allow us to make progress when they arise from well-motivated experiments. 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 should therefore not fear to obtain negative results at the LHC, as they could be pointing towards a new understanding in particle physics.

The first important thing we have learned from null results is that there are no more particles, than those of the SM, whose masses arise from the electroweak scale, i.e., the Higgs vacuum expectation value (VEV). This implies that we are now fully confident in the SM, and any new physics must come from a new fundamental scale beyond the electroweak one. This new scale do not have to be a priori related with the electroweak scale, implying that there is no guarantee to find this new phenomena at the LHC. It is only in certain cases in which both scales can be related, providing an important motivation for searching for this new physics at the LHC. An example is found in supersymmetric models in which the Higgs mass arises from a supersymmetry breaking scale, together with the masses of the supersymmetric partners. This implies that not only the Higgs had to be found around or below the TeV, but also the rest of supersymmetric particles. A second example is provided in composite Higgs models. In this case the new fundamental scale is the dynamical scale of a new strong sector (the equivalent of $\Lambda_{\rm QCD}$ in $SU(3)_c$ QCD), from which the Higgs arises as a pseudo-Goldstone boson (as pions arise in QCD). We will show in the following which are the most important searches for this second possibility.

2. New physics from the electroweak scale?

Let us start assuming that at TeV energies, those explore at the LHC, the only fundamental scale is the electroweak scale, or equivalently, the Higgs VEV, $v \simeq 246$ GeV (we do not pursue for the moment to understand its origin, so we just assume that it is tuned to its experimental value). If so, we still could ask ourselves whether there can be any new physics beyond the SM that we could access at the LHC. In principle, we could have new particles whose masses could arise from their couplings to the Higgs, after this gets a VEV. Nevertheless, as we will briefly show below, we have experimentally excluded this possibility, thanks to the interplay between direct and indirect searches.

Let us first consider the case of extra fermions. As they must be coupled to the Higgs to get masses, we are forced to consider only $SU(2)_L$ doublets L_L together with a singlet E_R such that

$$y_E H \bar{L}_L E_R + h.c.\,, \tag{2.1}$$

generates the mass $m_E = y_E v$. We leave for the moment free their hypercharge

$$Y \equiv Y_{E_R} = Y_{L_L} - 1/2\,. \tag{2.2}$$

To avoid anomalies in the SM gauge sector, we are forced to add more fermions than L_L, E_R. There are many possibilities. The simplest one is to add an extra pair L'_L, E'_R transforming as the conjugates of L_L, E_R. We also impose the parity

$$L_L, E_R \to -L_L, -E_R\,, \tag{2.3}$$

in order to forbid vector-like masses such as $M_L \bar{L}^c_L L'_L + M_E \bar{E}^c_R E'_R$ that would otherwise introduce a new scale (this will be discussed later). Now, direct searches at past and present colliders tell us that these new charged states cannot be very light, implying $y_E \gtrsim 1$. The precise allowed values for y_E, that mainly depend on how these states would decay to the SM, are not required, as indirect bounds on these type of new physics is at present cleanly ruled out by precision determination of the Higgs couplings. Indeed, the contribution from (L_L, E_R, L'_L, E'_R) at the one-loop level to the Higgs coupling to photons is given by

$$\frac{\Gamma(h\to\gamma\gamma)}{\Gamma(h\to\gamma\gamma)_{\rm SM}} \simeq \left|1+\frac{16/3(Y^2+1/4)}{1.7-8.3}\right|^2\,, \tag{2.4}$$

where we have assumed $y_E \gtrsim 1$ that makes the contribution independent of y_E. In Eq. (2.4) the denominator of the second-term corresponds to the SM contribution to $h\to\gamma\gamma$: this is 1.7 from the top loop and -8.3 from the W. The fact that they come with different sign makes $h\to\gamma\gamma$ smaller than expected in the SM, and therefore more sensitive to new physics. Eq. (2.4) minimizes for the case $Y=0$, that gives

$$\frac{\Gamma(h\to\gamma\gamma)}{\Gamma(h\to\gamma\gamma)_{\rm SM}} \simeq 0.6\,, \tag{2.5}$$

that is in clear contradiction with the limits on Higgs couplings obtained from the LHC, as can be appreciated in Figure 1. Therefore this minimal possibility is excluded by the experimental data. More complicated possibilities, such as adding more fermions with different SM quantum numbers, will only make things worse. This shows the importance of precision measurements to indirectly exclude new physics. Of special interest is the Higgs particle, and for this reason a Higgs factory could be a very useful machine to probe new physics at the TeV.

Let us now consider the case of extra bosons. Having extra scalars, H', at the electroweak is a difficult task. Scalar masses can arise independently from the electroweak scale as the term $M^2_{H'}|H'|^2$ cannot be forbidden by any symmetry in the SM. Therefore we must first understand why these terms would not be there, giving to the scalars masses beyond the electroweak scale. A possible way to have $M^2_{H'}$ related to the Higgs mass is by imposing a symmetry relating H' to the Higgs. This can be achieved by imposing the Z_2-symmetry $H' \leftrightarrow H$. This symmetry must be extended to the rest of interactions, and this requires adding a "SM mirror" related to the SM by the Z_2-parity. In this case, however, it can be shown that the "Higgs mirror" H' gets a very heavy VEV, making the full "SM mirror" heavy and not accessible at the LHC [2].

Finally, extra vector bosons are not possible as they would need extra Goldstones to get masses, implying that we will have to add extra scalars with different VEVs from the Higgs.

Therefore, we conclude that there cannot be anything else beyond the SM particles that get masses from the electroweak scale.

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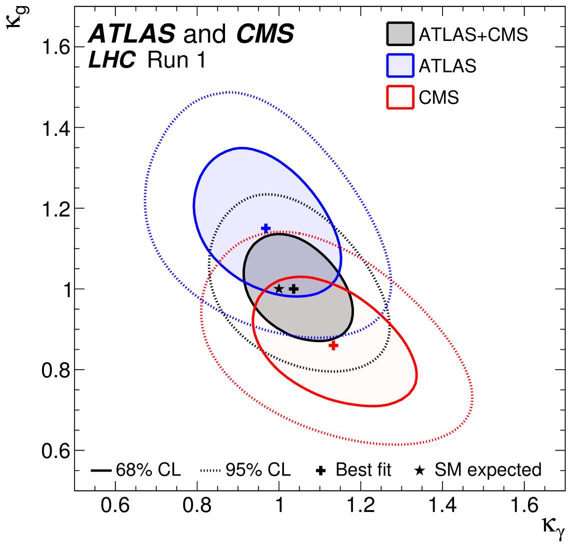

Figure 1: Bounds on the Higgs coupling to gluons and photons normalized to the SM value.

3. Strong dynamics at the TeV

The above statement leads to the consequence that any new physics beyond the SM must carry its own mass scale. For example, extra vector-like fermions, as the one proposed above, are only allowed if they have their own mass, independent of the electroweak scale:

$$M_L \bar{L}_L^c L'_L + M_E \bar{E}_R^c E'_R \,. \tag{3.1}$$

Nevertheless, these new masses do not have a priori any relation with the electroweak scale, and therefore could be very large, as large as M_P. This leads to a lack of motivation to search for them at the LHC.

A possible (the only one?) motivation can arise if we assume that the electroweak scale is derived from a more fundamental scale of new physics that lies around the TeV. We have few examples in which this can happen. For example, if the SM is embedded in a supersymmetric theory at the TeV, the Higgs mass can arise as a consequence of the breaking of supersymmetry at the TeV. An alternative, is to assume that the Higgs is a composite state arising from some strong dynamics at the TeV. Here we will show the main implications at the LHC of this second possibility.

The minimal realistic version of a composite Higgs model (MCHM) was given in [3] based on a TeV strong-sector with the global-symmetry breaking pattern

$$SO(5) \to SO(4) \simeq SU(2)_L \times SU(2)_R \,, \tag{3.2}$$

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 [4]. 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 [5, 6].[1]

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.

One can use the AdS/CFT correspondence [8] 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) [9], in which the Higgs corresponds to the fifth-component of the 5D gauge bosons [3]. The Higgs mass is protected by 5D gauge invariance and can only get a nonzero value from non-local one-loop effects [10]. 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 [3]. This is roughly depicted in Fig. 2.

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 [11] which Higgs couplings are expected to deviate from the SM predictions if the Higgs is composite.

The most compelling way to discover new dynamics at the TeV is, without doubt, by direct detection of new resonances which are predicted to be lurking around the TeV, as depicted in Fig. 2. Specialized searches are on the way by LHC experimentalists and a large number of different analysis have been already pursued, with negative results. 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. Being these color particles, we are guaranteed to have sizable production cross-section at the LHC to be easily discovered. In composite Higgs models the top partners are color fermionic resonances with electric charges $Q = 5/3, 2/3, -1/3$ [5], and a phenomenology described in detail in [12]. Limits on top partners from the LHC Run 1 were around $500-800$ GeV [13], scratching only the most natural region of the parameter space of the MCHM. Nevertheless, it has not been till the 13 TeV LHC Run 2 where the naturalness of these BSM scenarios has been really at stake. Present searches seems to see nothing, putting limit around the TeV. In particular, the bound on the cleanest signal of a top-partner, the search for an excess of same-sign dilepton, leads to a bound on the electric-charge $5/3$ resonance of $m_{X_{5/3}} > 960$ GeV, as shown in Figure 3. Things do not look then as expected. Could we missing something?

Another important search in composite Higgs models is that for spin-one resonances. They

[1] Variations on the composite PGB Higgs idea have also been put forward under the name of Little Higgs models [7]. 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.

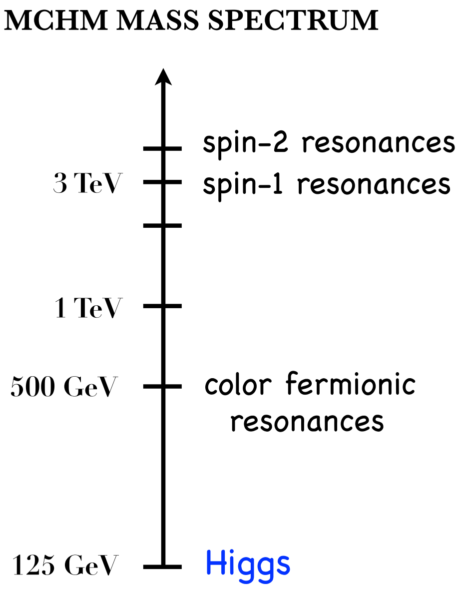

Figure 2: Natural expectations for the mass spectrum in composite Higgs models.

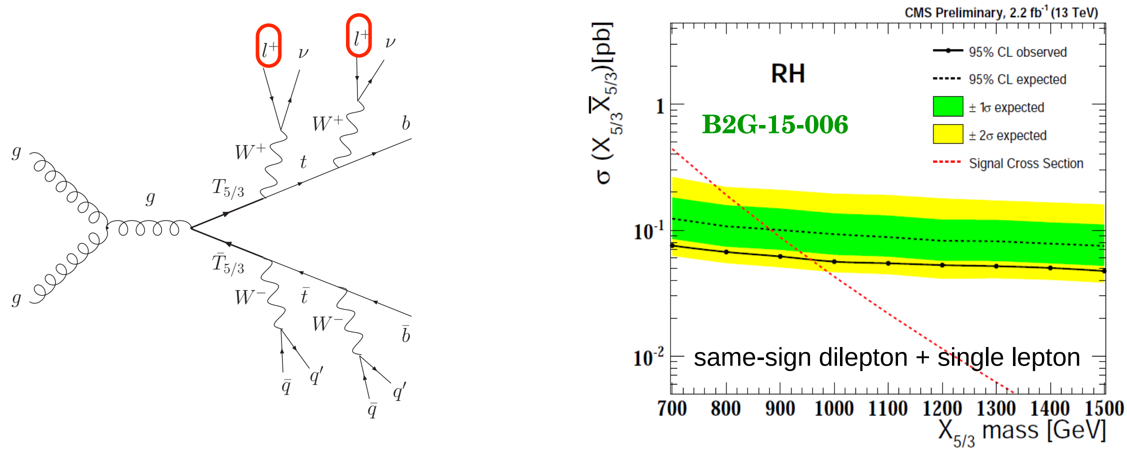

Figure 3: Same-sign dilepton searches for a spin-1/2 color resonance with electric charge $5/3$ [15].

are expected to have masses around few TeV – see Figure 2. These states transform in the adjoint representation of the $SU(2)_L \times SU(2)_R$ global-symmetry of Eq. (3.2). For the $SU(2)_L$-triplet the main decay channel is into the longitudinal components of the W and Z (the SM Goldstones, that as the Higgs, arise also from the strong sector), while the main production mechanism is through quarks as shown in Figure 4. This production cross-section is however quite small. This is because the coupling of these resonances to the SM fermions is suppressed by $\sim g/g_*$, where g_* is the coupling in the strong sector. At the 7-8 TeV LHC data we had an excess of events in the VV ($V = W,Z$) invariant-mass at around 2 TeV, seen mainly in the hadronic decays of the V. Unfortunately, this excess has not been confirmed by the 13 TeV Run –see Figure 5. We can then just put bounds on the mass of these resonances, that turn out to be today around 2-3 TeV. We just started to explore the interesting regions for these type of searches.

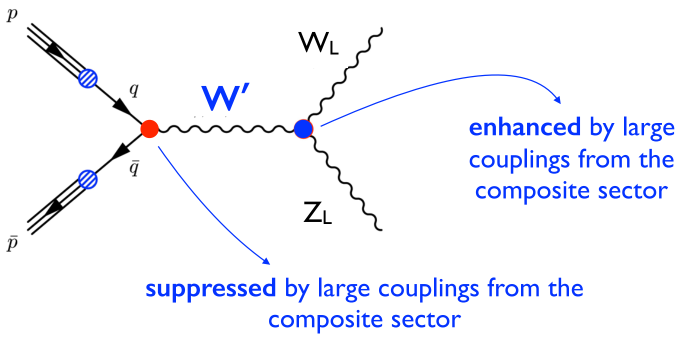

Figure 4: Main production mechanism and decay of a spin-one resonance from a strong sector at the LHC.

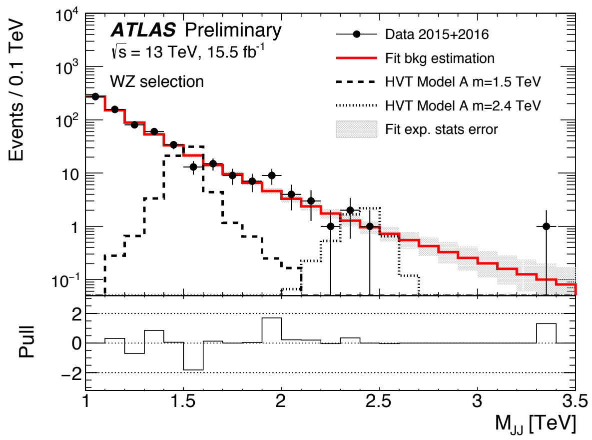

Figure 5: Searches for a spin-one $SU(2)_L$-triplet resonance decaying into WZ as a peak in the JJ invariant mass [14].

4. 750 GeV Post-Mortem

At the time of the LHCP16 conference, there was still hope to have soon the first evidences for new TeV physics, after the 2015 LHC data gave us more than 3 sigmas evidences for a new resonance at 750 GeV. Today, we know that these evidences have not been confirmed in the 2016 LHC Run 2, so we are back to the desperate situation that no new physics seems to show up at TeV energies. The SM is in excellent shape, even at energies around the TeV!

5. Conclusions

The long-awaited 13 TeV LHC Run 2 has finally started, having as its main motivation to learn on the origin of the SM electroweak scale. The first physics at 13 TeV seems however to only reinforce the SM, giving us only negative results in searches for new phenomena. Our hopes in the 750 GeV anomaly at the Run 1 are now gone. Furthermore, the absence of new color particles, necessary to stabilize the electroweak scale, is becoming more and more problematic. This is the so-called "missing top-partner problem" that only further searches will tell us how serious it is.

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