

The search for Physics Beyond the SM: Wins and Losses

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Abstract.

In this paper we review briefly the motivations for physics Beyond the Standard Model, which generate many possible signals that can be searched at the LHC. To get some perspective on the current affairs, we discuss some landmark success in the sub-fields of theoretical particle physics: formal QFT developments, Model Building and Phenomenology. By studying how these developments were done, we can learn some lessons about how to be cautious and optimistic at the same time, when looking at potential signals of new physics. We conclude by considering the case of the 750 GeV state and what we have learned from the theoretical activity that tried to reproduce this signal.

1. Introduction

The Standard Model (SM) of fundamental particles and interactions has been extremely successful to explain most data in the field. In particular, the discovery of a Higgs-like particle with $m_h = 125$ GeV at the LHC [1, 2], has tested the mechanism of electroweak symmetry breaking [3]. The agreement of the measured Higgs mass with the range predicted by electroweak precision tests [4], confirms the success of the SM. Similarly, the measurements of spin, parity, and couplings, seem also consistent with the expectations from the SM.

Despite this success, there are several arguments that lead us to expect that the SM could not be the final theory and that some form of new physics will come after the SM. Some scenarios for physics beyond the SM have been conjectured in order to address some of the SM open problems, such as hierarchy, flavor, unification, etc [5]. What is not known is the energy/mass scale (Λ) at which effects of such new physics could appear. It could be that $\Lambda = O(\text{TeV})$ and it is possible that such effects could be seen at LHC or near future colliders. Here we could include the supersymmetric extensions of the SM [6], but many more models could be included too.

However, the LHC has not detected, so far, any sign of new physics, but instead has provided bounds on the scale Λ . For instance, the LHC bounds on the mass of superpartners (gluinos and squarks) are entering into the Multi-TeV range. These results suggest that SUSY breaking involves a heavy mass scale, and put some questioning into the original motivation to solve the hierarchy/naturalness problem, as the resulting constraints are difficult to satisfy in the most constrained versions of the MSSM, namely for the cMSSM or minimal SUGRA. More recently, the possibility to have superpartners with masses beyond the reach of LHC, or large CPV phases, has been considered [7], and this has opened the discussion about the construction



of future accelerators. In particular, a recent interesting proposal for future collider machine working at 100 TeV has been discussed.

It could also happen that the scale of new physics Λ is near the GUT or Planck scales, and then its effects are far from conventional colliders, but still in such case the Intensity and Cosmology frontiers provide tools that may allow us to test such effects; for instance by looking at proton decay, neutrino oscillations or LFV interactions, it could be possible to probe very high energy scales. Test of the fundamental principles, such as Lorentz invariance and CPT symmetry have been considered too.

Recently CERN LHC found hints of a diphoton resonance with $\Lambda = 750$ GeV, with statistical level of 2.7σ - 2.9σ (after considering LEE). The data from 2015 [8, 9], could not allow to conclude whether the signal was just a fluctuation or a real effect of a possible major discovery. However weak the signal could had been, it attracted lots of attention from the theoretical community, with more than 500 new papers trying to explain such effect. The new 2016 results [10] did not bring what some of us were expecting or dreamed. Essentially the signal is now gone to the land of less than 2σ fluctuations.

As part of the activities of the Annual Meeting of the Mexican Division of Particles and fields, held in May 2016, in the city of Puebla, I acted as coordinator of a round table devoted to discuss the 750 resonance, together with my colleagues Azucena Bolaños, Isabel Pedraza and Saúl Ramos. Then, I was asked to write a short note in this topic, but given the speed of recent events, with a signal being present one semester and gone next one, I decided to write the coming section first, to look in perspective these events and the lessons we can learn for the future. In blogs of different ideology, we could find some harsh comments about the particle theory community. But really? Should the theorist be taken to the flames for their actions? Care and some knowledge on how the field has evolved and achieved some of its greatest success, could help to keep a cool mind. Furthermore, at some stages the known principles do not allow to discriminate among several models, and to make things worse, in some epochs the experiments find full agreement between theory (SM) and experiment. Thus, model building has some lottery side and it is nature who chooses the right one.

2. Theoretical Particle Physics

One could say that theoretical particle physics started with the discovery of the electron, proton and neutron. Then came beta decay and the neutrino, followed by the diversity of hadrons found in the 40-50's. The completion of QED was the first great theoretical construction, which allowed to calculate cross sections and magnetic moments of leptons from first principles, with techniques being developed to renormalize the infinities. The generalization to Yang-Mills theories with its non-abelian symmetries provided another turn of the screw. The discovery of SSB, DIS, Renormalization of gauge theories, the Electroweak model and QCD provided the next theoretical tools that shaped our current understanding of the fundamental constituents of matter and its interactions; namely, quarks and leptons interacting through vector gauge bosons, with masses arising from SSB.

How come that the HEP community was able to build such great intellectual machinery? Through lots and lots of success and failures, with efforts being aligned into three main avenues; namely,

2.1. Formal Development

Formal developments are perhaps the area that has the far reaching goals. The current theoretical framework is provided by Quantum Field Theory. When progress is made in this area, the results could have some influence even other areas of physics. Here we can list a few examples where success is obtained

- (a) SSB: After the works of Englert and Brout and P. Higgs, particle physics acquired a general method to provide masses to gauge vector bosons. From these techniques, it was a matter of time, experiments and model building, to find out the model that was chosen by nature to describe the fundamental interactions.
- (b) Renormalization of Gauge Theories: This is another example where the product of research provided a general method to build renormalizable gauge theories with massive vector bosons. Not only one model, but a whole class of models were at the disposal of model builders to describe the subatomic world.
- (c) Renormalization Group Methods: Here it was the genius of K. Wilson, who developed new methods to treat the evolution of parameters, which has such influence that it was used in statistical physics.

2.2. Model Building

In this area one tries to apply the ideas and methods obtained in formal developments, either to describe phenomena already observed or to predict new phenomena from the model. When some phenomenon is already observed, for example with β -decay and weak interactions, it could take a long time, but finally the correct model is found. This happened for the electroweak unified model, but also for the construction of quark model and QCD, which provide another of such examples.

This process has some lottery side, as sometimes many models could do the job. For instance, Weinberg proposed a model of leptons with gauge group $SU(2) \times U(1)$, that used SSB to generate the masses. However, the rules of the game and the lack of experimental data, allowed other possibilities, and so he proposed the $SU(3)_L \times U(1)_Y$ model too. But then the models are useful at least as generators of signals, which motivate the experimental searches.

In a few occasions, a model is created with the greatest goals, and here I included as examples, the GUT $SU(5)$ model of Georgi and Glashow, as well as the Pati-Salam model, with lepton number as the 4th color. But is nature that has the final word, and as beautiful as the model could look, the proton decay was not observed at the rates predicted by the model.

2.3. Phenomenology

Finally, we have a third area of research, phenomenology, which at some times it is seen as less glamorous, but it plays a crucial role as it allows to test the predictions of models of particle physics, as well as the validity of the principles that support them. Here we can include great work that requires gigantic calculations, programming and careful treatment of statistics. For example, the area of perturbative QCD provides the radiative corrections that are of vital importance, for instance to study Higgs production at hadron colliders. The detection of the Higgs particle at LHC is a great output of this area.

Very solid results could be obtained when one uses axiomatic properties of QFT to analyze some signal. In general, it requires a lot of ingenuity to extract the SM parameters from experimental data, ranging from masses of light quarks, CKM angles and phases, gauge couplings up to the Higgs mass and its couplings. I ask for an applause for the practitioners of such artcraft.

3. The 750 GeV resonance is gone

The 2015 results of the LHC run with c.m. energy of 13 TeV has shown surprising hints of a new resonance in the di-photon channel with invariant mass of 750 GeV, which clearly represents a signal of Physics beyond the SM. ATLAS [8] collected 3.2 fb^{-1} of data and reported a signal with significance of 3.6 (local), which becomes 2.3 (after LEE), while CMS [9] collected an integrated luminosity of 2.6 fb^{-1} and reported a significance 2.6 (local) that became 2.0 (after LEE).

For our contribution to this subject, we explored the possibility that the 750 GeV di-photon resonance, could be identified with a low-scale flavon field [11]. We worked within an SM extension of the IDMS-type that contains two Higgs doublets and one complex FN singlet; one of the doublets is of the inert type, and thus provides a viable DM candidate. Mixing of the doublet and singlet induces flavor violation in the Higgs sector, which predicts a branching ratio for LFV Higgs decay $h \rightarrow \tau\mu$ of order 10^{-5} , which could be searched at LHC too. We find that within this model it was possible to explain both the decay $h \rightarrow \mu\tau$, as well as the new 750 GeV resonance observed at LHC13 in the two-photon final state. We also studied the Higgs couplings, within a model of the IDMS-FN type, where fermion masses for each fermion type (up, down and leptons) are generated by one Higgs doublet each, while a fourth doublet is of inert-type and contains a dark matter candidate [12]. Constraints on these couplings, are derived from the Higgs search at LHC, and their implications for Higgs anomalies observed at LHC is also studied.

Another contribution that studied the properties of the 750 resonance is ref. [13], also made in Mexico, focused on the large width of the resonance. This is very difficult to accommodate within weakly interacting BSM theories, hinting a composite scenario. By means of forward sum-rules for $\gamma\gamma$ and gg scattering, the authors show that a spin-0 resonance with mass of the order of the TeV and a sizable partial width -of the order of a few GeV- must be accompanied by higher spin resonances with $JR \geq 2$ with similar properties, as expected in strongly coupled extensions of the Standard Model or, alternatively, in higher dimensional deconstructed duals. Furthermore, independently of whether the 750 GeV candidate is a scalar or a tensor, the large contribution to the forward sum-rules in the referred scenario implies the presence of states in the spectrum with $JR \geq 2$, being these high spin particles a manifestation of new extra-dimensions or composite states of a new strong sector.

However, the 2016 data delivered by LHC [10] indicates that essentially the signal was gone to the territory of less than 2σ fluctuations. The implications for our model is that flavons with generic couplings can not be as light as 750 GeV, unless we somehow fine-tune the parameters of the model. LHC and future colliders should keep looking for low-scale flavons, either a signal is found or we will keep increasing the bounds on the flavon mass. On the other hand, the conclusions of ref. [13], which used more general QFT methods, remain valid for hypothetical or real particles with large width.

4. Conclusions

In this paper we have reviewed the motivations for physics Beyond the Standard Model, which generate many possible signals that can be searched at the LHC. After the vanishing of the signal for the 750 GeV resonance in the 2016 LHC data, which was reported first by LHC in 2015, some pessimism has invaded the field. However, in order to get some perspective on the current affairs, we review briefly some of the landmark success in each of the subfields of theoretical particle physics, namely: formal QFT developments, Model Building and Phenomenology. I think that we can learn some lessons about to judge potential signals of new physics by looking at these issues from a historical perspective. In the first place, it is not easy that nature will deliver any surprises. What we know about particles respects QFT, and it is very likely that it will continue to do so for quite some time. Overall, we have learned something from the theoretical activity on this hypothetical signal. I do not think that it was a waste of time.

We ended this work by summarizing the contribution from the Mexican HEP community to the 750 GeV state. In our own work [11], we tried to interpret the signal as coming from Higgs-Flavon mixing, while the work of ref. [13] focused on the implications of the large width of the resonance.

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