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Theoretical implications of LHC results

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ABSTRACT

We present a concise outlook of particle physics after the first LHC results at 7–8 TeV. The discovery of the Higgs boson at 126 GeV will remain as one of the major physics discoveries of our time. But also the surprising absence of any signals of new physics, if confirmed in the continuation of the LHC experiments, is going to drastically change our vision of the field. At present the indication is that nature does not too much care about our notion of naturalness. Still the argument for naturalness is a solid one and we are facing a puzzling situation. We review the established facts so far and present a tentative assessment of the open problems.

1. Introduction

The first phase of the LHC experiments with the runs at 7 and 8 TeV was concluded in December 2012. The accelerator is now shut down till 2015 for the replacement of the magnet connections needed to allow the energy increase up to 13 and 14 TeV. The main results so far can be summarised as follows. A great triumph was the discovery [1,2] (announced at CERN on July 4th, 2012) of a $\sim$126 GeV particle that, in all its properties, appears just as the Higgs boson of the Standard Model (SM). With the Higgs discovery the main missing block for the experimental validation of the SM is now in place. The Higgs discovery is the last milestone in the long history (some 130 years) of the development of a field theory of fundamental interactions (apart from quantum gravity), starting with the Maxwell equations of classical electrodynamics, going through the great revolutions of Relativity and Quantum Mechanics, then the formulation of Quantum Electro Dynamics (QED) and the gradual build up of the gauge part of the Standard Model and finally completed with the tentative description of the Electro-Weak (EW) symmetry breaking sector of the SM in terms of a simple formulation of the Englert–Brout– Higgs mechanism [3]. An additional LHC result of great importance is that a large new territory has been explored and no new physics was found. If one considers that there has been a big step in going from the Tevatron at 2 TeV up to the LHC at 8 TeV (a factor of 4) and that only another factor of 1.75 remains to go up to 14 TeV, the negative result of all searches for new physics is particularly depressing but certainly brings a very important input to our field which implies a big change in perspective. In fact, while new physics can still appear at any moment, clearly it is now less unconceivable that no new physics will show up at the LHC. As well known, in addition to the negative searches for new particles, the constraints on new physics from flavour phenomenology are extremely demanding: when adding higher dimension effective operators to the SM, the flavour constraints generically lead to powers of very large suppression scales Λ in the denominators of the corresponding coefficients. In fact in the SM there are very powerful protections against flavour changing neutral currents and CP violation effects, in particular through the smallness of quark mixing angles. In this respect the SM is very special and, as a consequence, if there is new physics, it must be highly nongeneric in order to satisfy the present constraints. Only by imposing that the new physics shares the SM set of protections one can reduce the scale Λ down to o(1) TeV as, for example, in minimal flavour violation models [4]. One expected new physics at the EW scale based on a "natural" solution of the hierarchy problem [5]. The absence of new physics signals so far casts doubts on the relevance of our concept of naturalness. In the following we will elaborate on this naturalness crisis. Meanwhile we summarise the experimental information about the $\sim$126 GeV Higgs particle.

2. Measured properties of the 126 GeV particle

The Higgs particle has been observed by ATLAS and CMS in five channels $\gamma\gamma$, ZZ^*, WW^*, $b\bar{b}$ and $\tau^+\tau^-$. Also including the Tevatron experiments, especially important for the $b\bar{b}$ channel, the combined evidence is by now totally convincing. The ATLAS (CMS) combined values for the mass are $m_H = 125.5 \pm 0.6$ ($m_H = 125.7 \pm 0.4$). In order to be sure that this is the SM Higgs boson one must confirm

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that the spin-parity-charge conjugation is $J^{PC}=0^{++}$ and that the couplings are as predicted by the theory. Also it is essential to search for possible additional Higgs states as, for example, predicted in SUSY. We do not expect surprises on the J^{PC} assignment because, if different, then all the Lagrangian vertices would be changed and the profile of the SM Higgs particle would be completely altered. The existence of the $H\to\gamma\gamma$ mode proves that spin cannot be 1 and must be either 0 or 2, in the assumption of an s-wave decay. The $b\overline{b}$ and $\tau^+\tau^-$ modes are compatible with both possibilities. With large enough statistics the spin-parity can be determined from the distributions of $H\to ZZ^*\to$ 4 leptons, or $WW^*\to$ 4 leptons [6]. Information can also be obtained from the HZ invariant mass distributions in the associated production [7]. The existing data already appear to strongly favour a $J^P=0^+$ state against $0^-, 1^{+/-}, 2^+$.

The tree level couplings of the Higgs are in proportion to masses and, as a consequence, are very hierarchical. The loop effective vertices to $\gamma\gamma$, $Z\gamma$ and to gg, g being the gluon, are also completely specified in the SM, where no heavier than the top quark states exist that could contribute in the loop. As a consequence the SM Higgs couplings are predicted to exhibit a very special and very pronounced pattern [see, for example, Fig. 3 (right panel) of ref. [10]] which would be extremely difficult to fake by a random particle (only a dilaton, particle coupled to the trace of the energy-momentum tensor, could come close to simulate a Higgs particle, although in general there would be a universal rescaling of the couplings). The hierarchy of couplings is reflected in the branching ratios and the rates of production channels [8]. The combined signal strengths (that, modulo acceptance and selection cuts deformations, correspond to $\mu=\sigma Br/(\sigma Br)_{SM}$) are obtained as $\mu=0.8\pm0.14$ by CMS and $\mu=1.30\pm0.20$ by ATLAS. Taken together these numbers make a triumph for the SM! Within the present (July '13) limited accuracy the measured Higgs couplings are in reasonable agreement (at about a 20% accuracy) with the sharp predictions of the SM. Great interest was excited by a hint of an enhanced Higgs signal in $\gamma\gamma$ but, if we put the ATLAS and CMS data together, the evidence appears now to have evaporated. All included, if the CERN particle it is not the SM Higgs it must be a very close relative! Still it would be really astonishing if the H couplings would exactly be those of the minimal SM, meaning that no new physics distortions reach an appreciable contribution level. Thus, it becomes a firm priority to establish a roadmap for measuring the H couplings as precisely as possible. The planning of new machines beyond the LHC has already started. Meanwhile the strategies for analysing the already available and the forthcoming data in terms of suitable effective Lagrangians have been formulated (see, for example, Ref. [9] and references therein). A simplest test is to introduce a universal factor multiplying all $H\overline{\psi}\psi$ couplings to fermions, denoted by c, and another factor a multiplying the HWW and HZZ vertices. Both a and c are 1 in the SM limit. For example, in the Minimal Supersymmetric SM (MSSM), at the tree level, $a=\sin(\beta-\alpha)$, for fermions the u- and d-type quark couplings are different: $c_u=\cos\alpha/\sin\beta$ and $c_d=-\sin\alpha/\cos\beta$. The α angle is related to the A, Z masses and to β by $\tan 2\alpha=\tan 2\beta(m_A^2-m_Z^2)/(m_A^2+m_Z^2)$. If c_u is enhanced, c_d is suppressed. In the limit of large m_A $a=\sin(\beta-\alpha)\to 1$. Radiative corrections are in many cases necessary for a realistic description. All existing data on production times branching ratios are compared with the a- and c-distorted formulae to obtain the best fit values of these parameters (see [10–12] and references therein). At present this fit is performed routinely by the experimental Collaborations. But theorists have no retain to abusively combine the data from both experiments and the result is well in agreement with the SM as shown, for example, in Fig. 4 (left panel) of Ref. [10] or in Fig. 3 (left panel) of Ref. [12]. In conclusion it really appears that the Higgs sector of the minimal SM, with good approximation, is realised in nature.

3. The impact of the Higgs discovery

A particle that, within the present accuracy, perfectly fits with the profile of the minimal SM Higgs has been observed at the LHC. Thus, what was considered just as a toy model, a temporary addendum to the gauge part of the SM, presumably to be replaced by a more complex reality and likely to be accompanied by new physics, has now been experimentally established as the actual realisation of the EW symmetry breaking (at least to a very good approximation). If its role in the EW symmetry breaking will be confirmed it would be the only known example in physics of a fundamental, weakly coupled, scalar particle with vacuum expectation value (VEV). We know many composite types of Higgs-like particles, like the Cooper pairs of superconductivity or the quark condensates that break the chiral symmetry of massless QCD, but the LHC Higgs is the only possibly elementary one. This is a death blow not only to Higgsless models, to straightforward technicolor models and other unsophisticated strongly interacting Higgs sector models but actually a threat to all models with no fast enough decoupling (in that if new physics comes in a model with decoupling the absence of new particles at the LHC helps in explaining why large corrections to the H couplings are not observed).

The mass of the Higgs is in good agreement with the predictions from the EW precision tests analysed in the SM [13]. The possibility of a "conspiracy" (the Higgs is heavy but it falsely appears as light because of confusing new physics effects) has been discarded: the EW precision tests of the SM tell the truth and in fact, consistently, no "conspirators", namely no new particles, have been seen around.

4. Our concept of naturalness is challenged

The simplicity of the Higgs is surprising but even more so is the absence of accompanying new physics: this brings the issue of the relevance of our concept of naturalness at the forefront. As well known, in the SM the Higgs provides a solution to the occurrence of unitarity violations that, in the absence of a suitable remedy, occur in some amplitudes involving longitudinal gauge bosons as in V_LV_L scattering, with $V=W,Z$ [14]. To avoid these violations one needed either one or more Higgs particles or some new states (e.g. new vector bosons). Something had to happen at the few TeV scale!

While this was based on a theorem, once there is a Higgs particle, the threat of unitarity violations is tamed, and the necessity of new physics on the basis of naturalness has not the same status in the sense that it is not a theorem. Still the argument for naturalness is a solid conceptual demand that can be (once more!) summarised as follows. Nobody can believe that the SM is the definitive, complete theory but, rather, we all believe it is only an effective low energy theory. The dominant terms at low energy correspond to the SM renormalisable Lagrangian but additional nonrenormalisable terms should be added which are suppressed by powers (modulo logs) of the large scale Λ where physics beyond the SM becomes relevant (for simplicity we write down only one such scale of new physics, but there could be different levels). The complete Lagrangian takes the general form:

$$\mathcal{L}=o(\Lambda^4)+o(\Lambda^2)\mathcal{L}_2+o(\Lambda)\mathcal{L}_3+o(1)\mathcal{L}_4+o\left(\frac{1}{\Lambda}\right)\mathcal{L}_5+o\left(\frac{1}{\Lambda^2}\right)\mathcal{L}_6+\cdots \tag{1}$$

Here $\mathcal{L}_D$ are Lagrangian vertices of operator dimension D. In particular $\mathcal{L}_2=\Phi^\dagger\Phi$ is a scalar mass term, $\mathcal{L}_3=\overline{\Psi}\Psi$ is a fermion mass term, $\mathcal{L}_4$ describes all dimension-4 gauge and Higgs interactions, $\mathcal{L}_5$ is the Weinberg operator [15] for neutrino masses