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Highlights of the LHC run 1 / Résultats marquants de la première période d'exploitation du GCH

Implications of the Higgs boson discovery

Les implications de la découverte du boson de Higgs

José R. Espinosa [a], Christophe Grojean [a,b,*]

[a] *ICREA at IFAE, Universitat Autònoma de Barcelona, 08193 Bellaterra, Spain*
[b] *DESY, Notkestraße 85, 22607 Hamburg, Germany*

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ABSTRACT

With the discovery of the Higgs boson by the LHC in 2012, a new era started in which we have direct experimental information on the physics behind the breaking of the electroweak (EW) symmetry. This breaking plays a fundamental role in our understanding of particle physics and sits at the high-energy frontier beyond which we expect new physics that supersedes the Standard Model (SM). In this review we summarize what we have learned so far from LHC data in this respect. In the absence of new particles having been discovered, we discuss how the scrutiny of the properties of the Higgs boson (in search for deviations from SM expectations) is crucial as it can point the way for physics beyond the SM. We also emphasize how the value of the Higgs mass could have far-reaching implications for the stability of the EW vacuum if there is no new physics up to extremely large energies.

RÉSUMÉ

La découverte du boson de Higgs par les expériences du GCH en 2012 a ouvert une nouvelle ère, avec un accès expérimental direct à la dynamique responsable de la brisure de la symétrie électrofaible. Cette brisure de symétrie joue un rôle fondamental dans notre compréhension de la physique des particules et se situe à la limite des nos connaissances dans un domaine d'énergie au-delà duquel le modèle standard de la physique des particules devrait montrer ses limites. Dans cet article, nous résumons ce que les données du LHC nous ont d'ores et déjà appris. En l'absence de découverte de nouvelles particules, nous expliquons en quoi une étude méticuleuse des propriétés du boson de Higgs, et en particulier la recherche de déviations par rapport aux prédictions standards, est primordiale, puisqu'elle peut en effet indiquer comment dépasser ce modèle standard. Nous discutons aussi les implications de la valeur de la masse du boson de Higgs sur la stabilité du vide électrofaible dans l'hypothèse où le modèle standard reste valide jusqu'à des énergies extrêmement élevées.
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* Corresponding author at: DESY, Notkestraße 85, 22607 Hamburg, Germany.
E-mail addresses: Jose.Espinosa@cern.ch (J.R. Espinosa), Christophe.Grojean@cern.ch (C. Grojean).

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1. Introduction

"With great power comes great responsibility" says a good book [1] and a bad movie [2]. And logically "with great discoveries should come great measurements". The discovery of the Higgs boson [3] is definitively one of the greatest achievements in the recent history of fundamental sciences. The emerging understanding of the nature of this new particle is confirmed by various measurements of its properties, all consistent with the Brout–Englert–Higgs mechanism [4] and other properties of the Standard Model (SM).

The observation of the Higgs boson makes the questions about the dynamics at the origin of electroweak symmetry breaking more pressing. The most relevant and urgent issue now facing us concerns the structure of the newly discovered Higgs scalar. Are there additional states accompanying it? Is it elementary or composite? Could this really be the first elementary scalar observed in Nature, or could it just be a bound state arising from some novel strong dynamics, like a π or η in QCD? The answer to these questions will have profound implications on our picture of fundamental physics through its bearing on the hierarchy problem. Establishing, to the best of our experimental capability, that the Higgs boson is elementary, weakly coupled and solitary, would surely be shocking, but it may well start a revolution in the basic concepts of quantum mechanics and space-time. If instead deviations from the SM emerge in the dynamics of the Higgs, we will have to use them as a diagnostic tool of the underlying dynamics. A crucial part of this program is the identification of the smoking guns of compositeness in Higgs dynamics. Moreover, along this basic question there are more specific ones we can ask, related to the symmetry properties of the new state. For instance, it is essential to establish whether the new scalar is indeed "a Higgs" fitting into a SU(2) doublet and not some exotic impostor, like for instance a pseudo-dilaton. Although there is really no strong theoretical motivation for such an alternative, and so far the data disfavor it, it remains a logical possibility that can be tested and possibly ruled out. A perhaps more interesting question is whether the Higgs particle is just an ordinary composite, like a σ, or whether it is a pseudo-Nambu–Goldstone boson, like the π. The answer to this question will give us important clues on the high-energy/ultra-violet (UV) completion of the electroweak breaking dynamics.

Identifying the expected deviations in the Higgs couplings should be one priority for the next runs of the LHC and might call in addition for a dedicated program at future colliders.

In the absence of any hint of physics beyond the Standard Model (BSM), a blind extrapolation of the Standard Model to high energies reveals an intriguing possibility: that the electroweak vacuum might be unstable, albeit with an extremely large lifetime against vacuum decay. This results from the rather peculiar region of parameter space in which we might be living (under the rather strong assumption about the absence of new physics), very close to the boundary between stability and instability. The meaning and possible implications of such coincidence are far from clear.

2. Beyond the standard model implications

2.1. Naturalness as a guide to BSM physics

With the addition of the Higgs boson, the SM is now theoretically consistent at the perturbative level a priori up to very high scale, possibly the Planck scale of quantum gravity, see Section 3. With the discovery of the Higgs boson by the ATLAS and CMS experiments [3], the picture would be perfect were it not for the fact that the quantum corrections to the Higgs potential reveal a dramatic sensitivity to the details of the physics at very high energy, as if Newton would have realized that the exact value of the top quark mass plays a crucial role in the motion of the Moon around the Earth. This property goes against our intuition that physical phenomena at different scales decouple from each other. Concretely, the one-loop corrections to M_{h}, the mass parameter in the Higgs potential, are depicted in Fig. 1 and amount to

$$\delta M_{\mathrm{h}}^2 = \left(\frac{1}{4}(9g^2+3g'^2) - 12y_{\mathrm{t}}^2 + 6\lambda\right)\frac{\Lambda^2}{32\pi^2} = \left(M_Z^2 + 2M_W^2 - 4M_{\mathrm{t}}^2 + M_H^2\right)\frac{3G_{\mathrm{F}}\Lambda^2}{16\sqrt{2}} \quad (1)$$

where Λ stands for the typical mass scale of any new threshold associated with new particles or new dynamics beyond the Standard Model, and g and g' are the $\mathrm{SU}(2)_L$ and $\mathrm{U}(1)_Y$ gauge couplings, y_{t} is the top Yukawa coupling and λ is the Higgs self-coupling, all these parameters being related to the masses of SM particles and the Fermi constant, G_{F}. As an example, for a 10 TeV SM cutoff, the gauge, top and Higgs contributions to the Higgs mass squared corrections are respectively of the order of $(600\ \mathrm{GeV})^2$, $-(1.5\ \mathrm{TeV})^2$ and $(800\ \mathrm{GeV})^2$, all quite far from what the Higgs mass should be. The SM particles give unnaturally large corrections to the Higgs mass: they destabilize the Higgs vacuum expectation value (vev) and tend to push it towards the UV cutoff of the SM. Some precise adjustment (fine-tuning) between the bare mass and the loop correction is needed to maintain the vev of the Higgs around the weak scale: given two large numbers, their sum/difference will naturally be of the same order unless these numbers are almost equal up to several significant digits. This is the so called hierarchy problem [5–7]. It is a generic technical problem in any theory involving elementary light scalar fields.

It is often argued that the quadratic divergences in the Higgs mass corrections have no meaning since they can be set to 0 in dimensional regularization. Hence the belief that there is no hierarchy problem. This is actually true in the SM (at least when gravity is ignored) which involves a single scale. The hierarchy problem exists only when multiple scales are present. The hierarchy problem can be seen when dealing with the renormalized running Higgs mass, see Ref. [8] for a