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Nuclear and Particle Physics Proceedings 273–275 (2016) 11–20

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Physics of the Brout–Englert–Higgs boson: Theory

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Abstract

With the discovery of the Higgs boson a new era started with direct experimental information on the physics behind the breaking of the electroweak 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. The Higgs (inclusive and differential) production and decay rates offer a new way to probe this frontier.

Keywords:
Electroweak symmetry breaking, Higgs, Beyond the Standard Model

1. Introduction

The Standard Model (SM) is a triumph of the combination of the two pillars of twentieth-century physics, namely quantum mechanics and special relativity. Particles are defined as representations of the Poincaré group. Mathematically, these representations are labelled by two quantities: the spin that is quantized and takes only discrete values, and the mass, which a priori is a continuous parameter. However, the transformation laws for the various elementary particles under the gauge symmetries associated to the fundamental interactions force the masses of these particles to vanish. This would be in flagrant contradiction with the experimental measurements.

The Brout–Englert–Higgs mechanism (BEH) [1, 2, 3, 4] provides the solution to this mass conundrum. The discovery of a Higgs boson in July 2012 and the experimental confirmation of the BEH mechanism by the ATLAS and CMS collaborations [5, 6] has been a historical step in our understanding of nature: the masses of the elementary particles are not fundamental parameters defined at very high energy but rather emergent quantities appearing at low energy as a result of the particular structure of the vacuum.

This breakthrough discovery at the LHC surely stands out among the results of the first running period. For the first time a scalar particle has been found that assumes a vital role in the Standard Model and couples to all massive particles. In fact the Higgs particle dominates the structure of the vacuum.

2. The HEP landscape after the Higgs discovery

During its first run, the LHC certainly fulfilled its commitments: The machine and its detectors were mostly designed to find the Higgs boson and "[they] got it!" according to the words of R. Heuer, director general of CERN, on 4 July 2012. It was an important step in the understanding of the mechanism of electroweak symmetry breaking. But the journey is not over.

One can ask how the Higgs discovery reshaped the High Energy Physics (HEP) landscape. As it was emphasized in a recent conference by M. Mangano [7], the days of theoretically guaranteed discoveries imposed on us by some no-lose theorems are over: indeed, with the addition of a light Higgs boson with a mass around 125 GeV, the Standard Model is theoretically consistent and can be extrapolated up to very high energy, maybe as high as $10^{14\div16}$ GeV or even the Planck scale. But

http://dx.doi.org/10.1016/j.nuclphysbps.2015.09.003

at the same time, the big questions of our field, or the ones that we have considered so far as the big questions, remain wildly open: the hierarchy problem, the origin of flavor, the issue of the neutrino masses and mixings, the question of the identity of Dark Matter, the source of dynamical preponderance of matter over antimatter during the cosmological evolution of our Universe... are left unanswered. In the next decades, future progress in HEP is in the hands of experimentalists whose discoveries will reveal the way Nature has solved these big questions, forcing the theorists to renounce/review/question deeply rooted bias/prejudice. The Higgs discovery sets a large part of the agenda for the theoretical and experimental HEP programs over the next couple of decades.

3. Open questions about the Higgs

Run 1 accumulated striking evidence that the Higgs field is the cause of the screening of the weak interaction at long distances. Indeed, the observation and measurement of the $H \to ZZ^\star \to 4\ell$ channel indicate that the Higgs field develops a vacuum expectation value (vev) that is not invariant under the $SU(2)_L \times U(1)_Y$ gauge symmetry of the SM. Furthermore, this vev seems to be the common source of the Z-boson mass and the coupling between the Higgs boson and the Z boson.

However, this evidence only addresses the question of *how* the symmetry of the weak interaction is broken. It does not address the question of *why* the symmetry is broken or why the Higgs field acquires an expectation value. The situation is simply summarized in the following tautology

Why is electroweak symmetry broken?
Because the Higgs potential is unstable at the origin.
Why is the Higgs potential unstable at the origin?
Because otherwise EW symmetry would not be broken.

The discovery of a Higgs boson allowed first glimpses into a new sector of the microscopic world. Now comes the time of the detailed exploration of this new Higgs sector. And some key questions about the Higgs boson emerge:

1. Is it the SM Higgs?
2. Is it an elementary or a composite particle?
3. Is it unique and solitary? Or are there additional states populating the Higgs sector?
4. Is it eternal or only temporarily living in a metastable vacuum?
5. Is its mass natural following the criteria of Dirac, Wilson or 't Hoft?
6. Is it the first superparticle ever observed?
7. Is it really responsible for the masses of all the elementary particles?
8. Is it mainly produced by top quarks or by new heavy vector-like particles?
9. Is it a portal to a hidden world forming the dark matter component of the Universe?
10. Is it at the origin of the matter-antimatter asymmetry?
11. Has it driven the primordial inflationary expansion of the Universe?

The answers to these questions will have profound implications on our understanding of the fundamental laws of physics. Establishing that the Higgs boson is weakly coupled, elementary and solitary, would surely be as shocking as unexpected, but it may well indicate the existence of a multiverse ruled by anthropic selection rules. 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. The pattern of these deviations will carry indirect information about the nature of the completion of the SM at higher energies. In supersymmetric models, and more generally in models with an extended electroweak symmetry breaking sector, the largest deviations will be observed in the couplings to leptons and to the down-type quarks, as well as in the decay amplitudes to photons and gluons. In models of strong interactions, in which the Higgs boson is a bound state, the effects of compositeness uniformly suppress all the Higgs couplings while the self-interactions of the particles inside the Higgs sector, namely the Higgs particle and the longitudinal components of the W and Z bosons, will increase with the transferred energy. Moreover, the measurements of the Higgs couplings will also reveal the symmetry properties of the new state. For instance, it can be established whether the new scalar is indeed "a Higgs" fitting into a SU(2) doublet together with the degrees of freedom associated with the longitudinal W and Z and not some exotic impostor, like for instance a pseudo-dilaton. If the Higgs is found to have an internal structure, a detailed study of the Higgs couplings can also establish whether it is just an ordinary composite, like a σ particle, or whether it is a pseudo-Nambu–Goldstone boson endowed with additional symmetry properties, like the π's of QCD.

4. What is the SM Higgs the name of?

4.1. The SM Higgs boson as a UV regulator

The SM Higgs boson ensures the proper decoupling of the longitudinal polarizations of the massive EW