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

The Higgs boson discovery and measurements

La découverte du boson de Higgs et les mesures

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ABSTRACT

The discovery of the Higgs boson at a mass around 125 GeV by the ATLAS and CMS experiments at the LHC collider in 2012 establishes a new landscape in high-energy physics. The analysis of the full data sample collected with pp collisions at centre-of-mass energies of 7 and 8 TeV has allowed for considerable progress since the discovery. A review of the latest results is presented.

RÉSUMÉ

La découverte du boson de Higgs à une masse proche de 125 GeV par les expériences ATLAS et CMS auprès du collisionneur LHC en 2012 a redéfini le paysage de la physique des hautes énergies. L'analyse de l'ensemble complet des données collectées en collisions pp à des énergies dans le centre de masse de 7 et 8 TeV a permis des progrès considérables depuis la découverte. Une revue des derniers résultats est présentée.

1. Introduction: the standard model and the Higgs boson

The standard model (SM) of particle physics has provided a remarkably accurate description of numerous results from accelerator- and non-accelerator-based experiments over the past four decades. Yet, the question of how the W and Z gauge bosons acquire mass remained an opened question. This question could have jeopardised the validity of the theory at higher energies or, equivalently, at smaller distance scales. Understanding the origin of the electroweak symmetry breaking (EWSB), how the W and Z bosons acquire mass whilst the photon remains massless, has been set as one of the most important objectives of the Large Hadron collider (LHC) physics program at the birth of the project more than twenty years ago. The SM remained an unchallenged [1] but incomplete theory for the interactions of particles until the Large Hadron Collider

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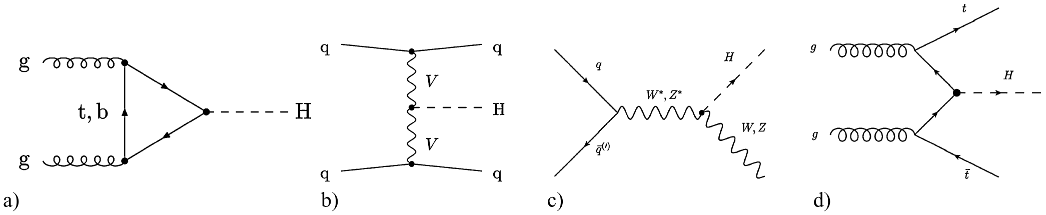

Fig. 1. Examples of leading order Feynman diagrams contribution to the production of the SM Higgs boson in hadronic collisions; (a) gluon–gluon fusion gg → H through b- and t-quark fermion loops; (b) vector boson fusion WWH or ZZH; (c) Higgs-strahlung WH or ZH; (d) associated production of a Higgs boson and a $t\bar{t}$ pair.

(LHC) finally provided its first high-energy proton–proton collisions at 7 TeV in 2010. The discovery of a Higgs boson at a mass of about 125 GeV by the ATLAS [2] and CMS [3,4] experiments in 2012 has now considerably changed the landscape.

The SM comprises matter fields, the quarks and leptons as the building blocks of matter, and describes their interactions through the exchange of force carriers: the photon for electromagnetic interactions, the W and Z gauge bosons for weak interactions, and the gluons for strong interactions. The electromagnetic and weak interactions are partially unified in the Glashow–Weinberg–Salam electroweak theory [5–7]. The gauge bosons are a direct consequence of the underlying gauge symmetries. It is sufficient to postulate the invariance under $SU(2) \times U(1)$ gauge symmetry in the electroweak sector to see emerging as a necessity the existence of the photon, for the electromagnetic interaction, and the W and Z bosons, for the weak interactions. The gauge symmetries are the essential pillars of the theory and thus must be preserved. This is only possible if the gauge bosons remain massless in the fundamental theory. Besides the question of the origin of the mass of vector bosons, the very existence of these massive bosons was threatening the theory at the TeV scale. In contrast to quantum electrodynamics, where a renormalisable theory is obtained by injecting the masses and charges measured at a given scale, no such trick is possible for the weak interaction while preserving the gauge symmetries. The massive vector bosons lead to violation of unitarity for calculations at the TeV scale, unless something else is added. The SM with the gauge bosons and matter fields is incomplete. An additional structure is needed.

Since the advent of the electroweak theory, the Brout–Englert–Higgs mechanism [8–13] had been adopted as a solution to both the EWSB and the unitarisation of the theory. In this mechanism, the introduction of a complex scalar doublet field with self-interactions allows for a spontaneous EWSB. This leads to the generation of the W and Z masses (the weak boson acquire longitudinal degrees of freedom), and to the prediction of the existence of one physical Higgs boson (H). The left- and right-handed chiralities of the fundamental fermions become coupled by the interaction with the scalar field, such that the fermions acquire mass when propagating in the physical vacuum. The mass m_{H} of the Higgs boson in the SM is not predicted by the theory, but general considerations [14–17] on the finite self-coupling of the Higgs field, the stability of the vacuum, and unitarisation bounds suggest that it should be smaller than about 1 TeV. The existence of a scalar boson is sufficient to allow for an exact unitarisation of the theory. But saving the theory has a cost: the arbitrariness of m_{H} (and of the self-couplings) and the fact that the Higgs boson is not a gauge boson. Thus, the mass m_{H} is not protected by any symmetry of the theory. The mass is sensitive to any new scale beyond the SM which could contribute in quantum loop corrections. The theory would have to be fine-tuned to maintain m_{H} at the weak scale.

With these considerations in mind, the scene is set to describe the search, the discovery, and the measurements of the Higgs boson at the LHC. This review is organised as follows. We first briefly remind about the relevant phenomenology aspects in Section 2. We then recollect in Section 3 the adventure of the search for the Higgs boson at the LEP e^+e^- collider, the Tevatron $p\bar{p}$ collider, and the LHC pp collider including the data collected at $\sqrt{s} = 7$ TeV in 2011. The additional data collected at the LHC at $\sqrt{s} = 8$ TeV led, in July 2012, to the discovery of the new boson via di-boson channels, as reminded in Section 3. We then turn in Section 4 to the measurements and properties of the Higgs boson using all available LHC data from 2011 and 2012, corresponding to about 5 fb^{-1} of integrated luminosity at $\sqrt{s} = 7$ TeV, and 20 fb^{-1} at $\sqrt{s} = 8$ TeV. We first discuss the high-resolution channels and the measurement of the Higgs boson mass, then present constraints on the resonance width, tests and constraints on the spin–parity state, comparisons of the signal rates with SM expectation in various production and decay modes, and finally the coupling constraints and compatibility with SM expectation. We conclude in Section 5 with some elements of prospects for the future data taking at the LHC.

2. Phenomenology at the LHC

2.1. Production and decay modes

In pp collisions, the Higgs boson (H) is produced dominantly by a gluon fusion (ggH) process involving a virtual top (or bottom) quark loop. The other main production modes are the vector boson fusion (VBF), the “Higgstrahlung” (VH with V = W or Z), and the associated production ($t\bar{t}$H). The production modes are illustrated in Fig. 1.

The total production cross sections for a SM Higgs [18] boson at the LHC are shown as a function of m_{H} in Fig. 2 (left). A huge effort to provide the theoretical cross-section calculations at next-to-next-to-leading order (NNLO) level has been made over the past years, and this effort continues with increased interest.