Higgs Boson at the LHC

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Abstract

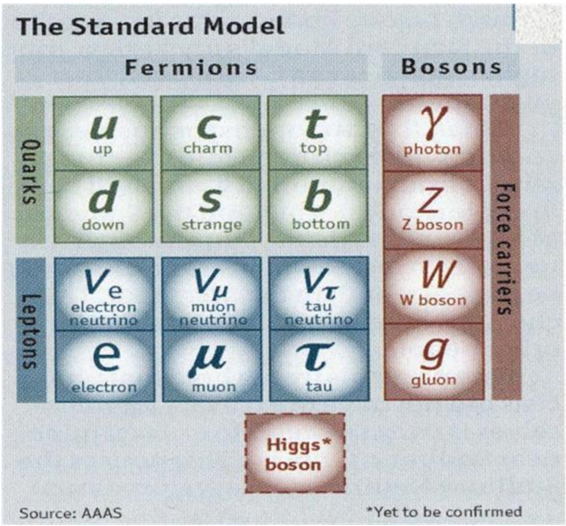
The Higgs boson, considered as the final particle of standard model (SM) of particle physics, has not been confirmed experimentally yet. It is an important particle because it is responsible for the Higgs mechanism by which all particles acquire mass. It has some unique properties which give a special status to it in the table of elementary particles of the SM. In this article, we discuss the recent results about the Higgs at the LHC briefly.

Keywords: Higgs boson, standard model, spontaneous breaking of gauge symmetries, LHC.

1. Introduction

The standard model (SM) [1, 2] of particle physics unifies three fundamental forces: electromagnetic, strong and weak force. These forces (electromagnetic, weak and strong force) are mediated by the gauge bosons: the photon (γ); the W^+, W^- and Z boson; and the gluons respectively. There are 6 types of quarks and 6 types of leptons in the SM. Quarks are called up (u), down (d), charm (c), strange (s), top (t) and bottom (b). Leptons are called electron (e^-), electron-neutrino (ν_e), muon (μ^-), muon-neutrino (ν_μ), tau (τ^-) and tau-neutrino (ν_τ). Fig.1 shows the particle content of the standard model. All the particles except the Higgs boson have been discovered. The final particle of the SM, the Higgs boson (H), has not been confirmed experimentally yet. It is theoretically predicted by Englert, Brout, Higgs, Guralinik, Hagens and Kibble [3–6]. It is very important because it is responsible for the mechanism (Higgs mechanism [3,4]) by which all particles acquire mass. The Higgs mechanism allows the generation of particle masses preserving the gauge symmetry of electroweak interactions.

The standard model suggests that just after the big bang all particles were massless. As time passed on, the universe cooled and temperature fell below a critical value, an invisible field called the 'Higgs field' filled all space [7]. The particle associated with the Higgs field is called the Higgs boson. Although the Higgs field is not directly measurable, accelerators can excite this field and can detect the Higgs boson. So far, experiments using the world's most powerful accelerators have not observed any Higgs bosons, but indirect experimental evidence suggests that it is possible in future. Since the Higgs field is a scalar field, the Higgs boson has no spin, and hence no intrinsic angular momentum. The Higgs boson is also its own antiparticle and is CP-even. One of the important properties of this field is that the Higgs field is exactly the same everywhere whereas the magnetic or gravitational fields vary from place to place. When particles are moving in a uniform Higgs field, they change their velocities i.e. they accelerate. The Higgs field exerts a certain amount of resistance or drag; this is the origin of inertial mass.



Source: AAAS *Yet to be confirmed

Fig. 1: Particles of the Standard Model

In the SM, the Higgs field consists of two neutral and two charged component fields. Both of the charged components and one of the neutral fields are Goldstone bosons, which act as the longitudinal third-polarization components of the massive W^+, W^- and Z bosons. The quantum of remaining neutral components corresponds to the massive Higgs boson. In the SM, there is only a single Higgs particle. But supersymmetric extensions of the SM predict the existence of different Higgs particles. The minimal supersymmetric extension of the SM (MSSM) predicts the smallest number (five) of Higgs boson [8–10]: two CP-even neutral Higgs boson *h* and *H*, a CP-odd neutral Higgs boson *A*, and two charged Higgs particles $H^\pm$. The lightest neutral Higgs particle h has the same properties as the standard Higgs boson but by virtue of supersymmetry, its mass is below 140 GeV.

Supersymmetry [11–15] is a hypothetical symmetry between fermions and bosons. Unlike traditional symmetries, supersymmetry does not treat bosons and fermions as two different classes of particles. The supersymmetry operation converts bosons into fermions and vice versa. For each particle, it predicts the existence of a superpartner (hence, doubles the SM particle spectrum) which should have the same properties [10] but with a spin different by a unit ½ and also a different mass as supersymmetry must be broken in nature. But super particles are not detected experimentally so far and are expected at the LHC [16] in the coming years. Some particles and their superpartners are shown in Table 1.

Table 1: Some Particles and their Superpartners

Particle	**Spin**	**Superpartner**	**Spin**
Electron	½	Selectron	0
Muon	½	Smuon	0
Tau	½	Stau	0
Neutrino	½	Sneutrino	0
Quark	½	Squark	0
Graviton	2	Gravitino	3/2
Photon	1	Photino	½
Gluon	1	Gluino	½
$W^\pm$	1	$Wino^\pm$	½

Z^0	1	Zino	½
Higgs	0	Higgsino	½

. 2. Properties of the Higgs Boson

The Higgs boson has some unique properties [10] which give a special status to it in the table of elementary particles of the SM:

(i) Matter particles have spin ½, gauge particles have spin 1 but Higgs boson has spin zero. At present there are no known elementary scalar bosons in nature, although many composite spin-0 particles are known. Since it has integer spin, it is a boson but it does not mediate gauge interactions.

(ii) The Higgs particle interacts with or couples to elementary particles proportionally to their masses: the more massive is the particle, the stronger is its interaction with the Higgs boson [17].

(iii) It does not couple to the neutrinos, which are considered as massless particles.

(iv)The Higgs boson does not couple directly to photons and gluons (in case of gluons, a direct coupling is also absent because the Higgs boson does not carry color quantum numbers). However, couplings can be induced in an indirect way through quantum fluctuations.

(v) According to Heisenberg's uncertainty principle, the Higgs boson can emit pairs of very heavy particles (for example, top quarks) and immediately absorb them, but these virtual particles can, in the meantime, emit photons or gluons. Higgs-photon-photon and Higgs-gluon-gluon couplings are then generated. However, they are expected to be rather small, as they imply intermediate interactions of the virtual particles to photons and gluons, which have a small intensity.

(vi) The Higgs boson has self-interactions. The magnitude of triple and quartic self-interactions is proportional to the Higgs boson mass (in fact, Higgs mass squared) [18].

3. Higgs Boson from Theoretical Calculations, at the LEP and Tevatron

The existence of Higgs boson is related to the spontaneous breaking of electroweak symmetry and to the generation of elementary particle masses. The Higgs boson is highly unstable and once produced, decays very quickly to either a fermion-antifermion pair or a pair of bosons. By energy conservation, the Higgs mass m_H , must be at least twice that of the particle in the pair to which it decays. The mass of the SM Higgs boson is given by $m_H = \sqrt{2\lambda}$ v, while the vacuum expectation value of the Higgs field v = 246 GeV is fixed by the Fermi coupling but the quartic Higgs self-coupling λ is not pre-determined; hence, the Higgs mass is not predicted. Constraints, at the theoretical as well as experimental level, restrict the value of Higgs mass quite strongly. Mahbubani [19] gives limits on the Higgs mass as 110 GeV $\leq m_H \leq$ 250 GeV in arbitrary extension of split supersymmetry. We [20] have predicted the mass of Higgs boson as $m_H \approx$ 120 GeV in a flavor-independent potential model. Recently [21], in compactified string/M theories it is predicted that there will be a single SM Higgs boson with a mass in the range 105 GeV ≤ m_H ≤ 129 GeV depending on $\tan\beta$ (the ratio of the Higgs vacuum expectation values in the MSSM). For $\tan\beta > 7$, the prediction is 122 GeV ≤ m_H ≤ 129 GeV.

The four LEP collaborations, ALEPH, DELPHI, L3 and OPAL were searching for the neutral Higgs boson in the SM. At LEP, the SM Higgs boson would be produced mainly in association with the Z boson through Higgs-strahlung process $e^+e^- \to H\,Z$. The lower bound on the mass of the SM Higgs boson obtained from LEP data [22] is 114.4 GeV at 95% CL. The SM Higgs boson is also searched at the Fermilab Tevatraon $p\bar{p}$ collider. The two experiments, CDF and DO, exclude two regions: 100 GeV $< m_H <$ 106 GeV and 147 GeV $< m_H <$ 179 GeV at 95% CL [23]. There is an excess of data events with respect to the background estimation in the mass range 115 GeV $< m_H <$ 135 GeV.

4. Higgs Boson at the LHC

The Large Hadron Collider (LHC), the world's largest and highest energy particle accelerator, at CERN is expected to measure the mass of Higgs boson accurately. Since 2010, it is in operation, in the first phase with an energy of 7 TeV, to be extended later to 14 TeV. There are six detectors constructed at the LHC: A Toridal LHC Apparatus (ATLAS), Compact Muon Solenoid (CMS), A Large Ion Collider Experiment (ALICE), Large Hadron Collider beauty Experiment (LHCb), Large Hadron Collider forward Experiment (LHCf), Total Cross section, Elastic Scattering and Diffraction Dissociation at the LHC (TOTEM). Two of them the ATLAS and CMS, are large and general purpose particle detectors. The last two LHCf and TOTEM are very much smaller and are for very specialized research. The two large detectors (ATLAS and CMS) at the LHC are searching for the Higgs boson. They have optimized for the Higgs boson search in a mass range from the LEP limit of 114.4 GeV up to $\approx$700 GeV. At the LHC, the SM Higgs boson production is dominated by gluon-gluon fusion ($gg \to H$) followed by the vector boson fusion (VBF) and associated production with a vector boson (VH), each of which contributes less than 10% of the total production cross section.

On 13th December, 2011 ATLAS and CMS reported their data collected by each experiment about the status of Higgs boson in a special seminar at CERN [24]. The main result is that the mass of SM Higgs boson, if it exists, is constrained to the range 115–131 GeV (ATLAS) and 115–127 GeV (CMS) at 95% CL (confidence level) with possible hints of evidence within a few GeV of 125 GeV [25]. Prof. Guido Tonelli, spokesman for CMS experiment, says "We have not collected enough evidence for a discovery. There is an excess of events compatible with the hypothesis that it could be a Higgs" [26]. Prof. Fabiola Gianotti, spokesman for ATLAS experiment, says "It could well be something intriguing, but it could be a background fluctuation". More data will be needed to establish the existence of the Higgs boson with confidence.

In February, 2012 the ATLAS and CMS collaborations have got the evidence for the Higgs signal in the mass range 124 –126 GeV [27–29]. Recently [30], in May, 2012 the CMS collaboration have searched the SM Higgs boson using approximately 5 fb^{-1} of 7 TeV pp collisions data at the LHC. Combining the results of different searches they exclude a SM Higgs boson with mass between 127.5 and 600 GeV at 95% CL. They find the most significant result for the SM Higgs boson with mass of about 125 GeV with a local significance of 2.8σ. Similarly, in May, 2012 the ATLAS collaboration [31] have also searched the SM Higgs boson using approximately 4.9 fb^{-1} of 7 TeV pp collisions data at the LHC. A Higgs boson with a mass ranges from 110.0 GeV to 117.5 GeV, 118.4 GeV to 122.7 GeV, and 128.6 GeV to 529.3 GeV is excluded at 95% CL. They find the most significant result around the Higgs boson mass of 126 GeV with a local significance of 2.5σ. The LHC will continue to collect the data regarding the Higgs boson till the end of 2012. The LHCb experiment is also planning to measure the Higgs boson mass. We expect that these experiments will tell us whether the Higgs boson exists or not.

5. Conclusions

The standard model of particle physics describes the strong and electroweak interactions of fermions (spin– ½), gauge bosons (spin–1) and a final vital ingredient – the spin–0 Higgs boson. The Higgs boson is a hypothetical elementary particle which would give the mechanism by which particles acquire mass. It has not been confirmed experimentally yet. If the Higgs boson exists, it is an integral and pervasive component of the material world. Its mass is not specified in the SM. Its mass is constraints as 114 GeV $\leq m_H \leq$ 1.4 TeV [32,33]. We [20] have predicted the mass of Higgs boson as $m_H \approx$ 120 GeV in a flavor-independent potential model. Recently [21], in compactified string/M theories it is predicted that there will be a single SM Higgs boson with a mass in the range 105 GeV $\leq m_H \leq$ 129 GeV depending on $\tan\beta$ (the ratio of the Higgs vacuum expectation values in the MSSM). For $\tan\beta > 7$, the prediction is 122 GeV $\leq m_H \leq$ 129 GeV. From the recent results of the CMS and ATLAS detectors [30,31] the most significant result for the SM Higgs boson mass is about 125 GeV and 126 GeV respectively. A Higgs particle with mass of $\approx$125 GeV would be a triumph for the SM [34]. Recently, by combining electroweak precision data with the results of Higgs boson searches at LEP 2, the Tevatron and the LHC, Erler [35] determine the mass of Higgs boson to m_H = 124.5 ± 0.8 GeV at the 68% CL. In finite unified theories (FUTs) [36], the mass of Higgs boson is predicted in the range 121–126 GeV. From the above discussion it is clear that the mass of the SM Higgs boson predicted in the string theory, at the LHC, the result obtained by Erler and in FUTs are nearly in the same range. The LHC will continue to collect the data regarding the Higgs boson till the end of 2012. The LHCb experiment is also planning to measure the Higgs boson mass. We expect that these experiments will tell us whether the Higgs boson exists or not. If the discovery of the Higgs boson will be confirmed, two new directions of physics will open up [37]: (i) the detailed investigation of the Higgs will be done to conform to the SM paradigm or to show deviations due to new physics. (ii) there will be investigations for the new physics which complements the Higgs boson, whether supersymmetry or extra dimensions or new strongly-interacting particles or…? Although the Higgs boson belongs to the SM of particle physics its study is a very challenging and fascinating topic which interplays between different branches of physics like particle physics, condensed matter physics and cosmology [38–40].

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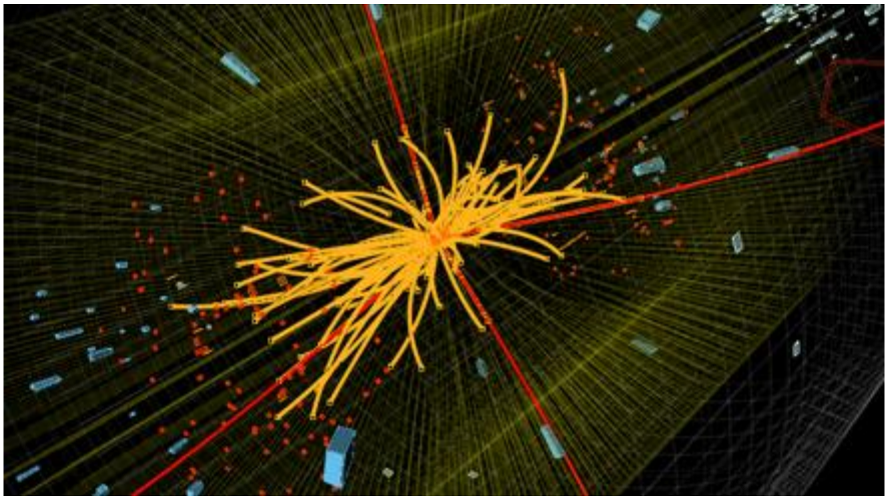
NEWS FLASH

HIGGS WITHIN REACH

The ATLAS and CMS experiments at CERN today (July 4 2012, on the eve of the 36th International Conference on High Energy Physics Conference at Melbourne, Australia) presented their latest results in the search for the long-sought Higgs boson. Both experiments see strong indications for the presence of a new particle, which could be the Higgs boson, in the mass region around 126 (GeV).

Both ATLAS and CMS gave the level of significance of the result as $5\ \sigma$ sigma level, qualifying to be a discovery.



A Higgs Candidate

A proton-proton collision event in the CMS experiment producing two high-energy photons (red towers). This is what we would expect to see from the decay of a Higgs boson but it is also consistent with background Standard Model

Editorial insert