IL NUOVO CIMENTO Vol. 37 C, N. 1 Gennaio-Febbraio 2014
DOI 10.1393/ncc/i2014-11698-1

Colloquia: IFAE 2013

Measurements of the Higgs boson properties at the ATLAS experiment

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ricevuto l'1 Ottobre 2013

Summary. — The ATLAS and CMS Collaborations observed a new resonance decaying in two photons, in four leptons via Z-boson pair production, and in two W-bosons decaying leptonically. With the total amount of LHC run-1 data, amounting to about $25\,\text{fb}^{-1}$ collected at $\sqrt{s} = 7\,\text{TeV}$ and $8\,\text{TeV}$, it is now possible to probe the fundamental properties of this particle: mass, spin, couplings, showing that it is compatible with a Standard Model Higgs boson. This document contains a review of the most recent results from the ATLAS Collaboration.

PACS `14.80.Bn` – Standard-model Higgs bosons.

1. – Introduction

The Standard Model (SM) of particle physics describes all fundamental interactions by means of gauge symmetries, where a local symmetry group $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$ generates vector-boson-mediated interactions. The masses of vector bosons and fermions are introduced through a spontaneous symmetry breaking of the vacuum state —the "Higgs mechanism"— in which a scalar field acquires non-vanishing vacuum expectation value v [1]. In this model, all particles interacting with the scalar field acquire mass dynamically. Moreover, an observable particle H is predicted, with null charge, spin zero, even parity and unknown mass m_H, interacting with all massive particles through couplings $g_V = 2m_V^2/v$ for vector bosons $V = W, Z$ and $g_F = m_F/v$ for fermions F.

During the search of the SM Higgs boson, both the ATLAS and CMS Collaborations have reported evidence of a new resonance H [2], that can decay in two photons, two Z-bosons, or two $W^{\pm}$-bosons. If this resonance were indeed the SM Higgs boson, it would have two typical "fingerprints": a spin-parity state $J^P = 0^+$ and couplings related to the masses, as described. Moreover, through the $H \to \gamma\gamma$ and $H \to ZZ^* \to 4\ell$ decays its mass can be measured with high accuracy, thus providing the last missing parameter of the SM. All the observable properties of the Higgs boson (production cross-sections, decay width, branching ratios) would then be calculable.

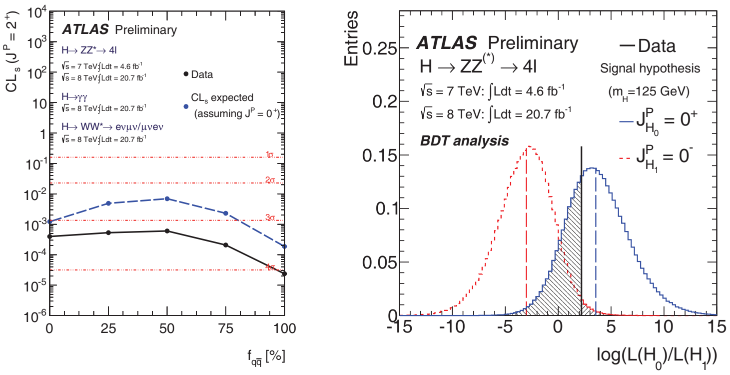

Fig. 1. – Left: expected (blue dashed line) and observed (black solid line) probability that observed data come from a $J^P = 2^+$ state, as a function of the fraction $f_{q\bar{q}}$ (see text) [10]. Right: distributions of the likelihood ratio for the $J^P = 0^+$ and $J^P = 0^-$ hypotheses, expected for $J^P = 0^+$ (blue/solid line distribution) and 0^- (red/dashed line distribution) signals. The observed value is indicated by the vertical solid line and the expected medians by the dashed lines. The coloured areas are used to compute the confidence levels for the rejection of each hypothesis [9].

This document reports the most recent measurements of the properties of the new resonance, obtained by the ATLAS Collaboration.

2. – Mass measurement

The mass measurement is performed combining the $\gamma\gamma$ and $ZZ^* \to 4\ell$ decay channels [3]. The two channels individually give $m_H^{\gamma\gamma} = 126.8 \pm 0.2(stat) \pm 0.7(syst)$ GeV and $m_H^{4\ell} = 124.3^{+0.6}_{-0.5}(stat)^{+0.5}_{-0.3}(syst)$ GeV, respectively. The main source of systematic uncertainty in the $\gamma\gamma$ channel is the photon energy scale. This relies on several assumptions (electron energy scale from $Z \to e^+e^-$ decays, $e \to \gamma$ extrapolation and knowledge of the material budget in front of the calorimeter, intercalibration of the calorimeters' layers), which overall bring a relative uncertainty of $\sim 0.55\%$ on the $\gamma\gamma$ invariant mass. In the 4ℓ channel, the measurement is dominated by the 4μ decays. The muon energy scale is calibrated using Υ, $Z \to \mu^+\mu^-$ decays, and its extrapolation carries a systematic uncertainty of $\sim 0.2\%$ on the 4μ invariant mass. The combined measurement is

$$m_H = 125.5 \pm 0.2(stat)^{+0.5}_{-0.6}(syst)\,\text{GeV}. \tag{1}$$

3. – Spin and parity measurements

The observed decay channels imply integer spin. The $\gamma\gamma$ decay, in particular, forbids the spin-1 state (Landau-Yang theorem [4]), however as a cross-check this state is anyway investigated in the ZZ^* decays. Exploiting the angular distributions of the decay products, and the di-lepton invariant masses in the ZZ^*, WW^* decays, the spin-parity hypothesis $J^P = 0^+$ characteristic of a Higgs boson is compared with alternative hypotheses $J^P_{\text{alt}} = 0^-, 2^+, 1^\pm$.

For the $J^P = 2^+$ hypothesis, a graviton-inspired tensor with minimal couplings to SM particles has been adopted [5]. This state can be produced via gluon-gluon fusion or

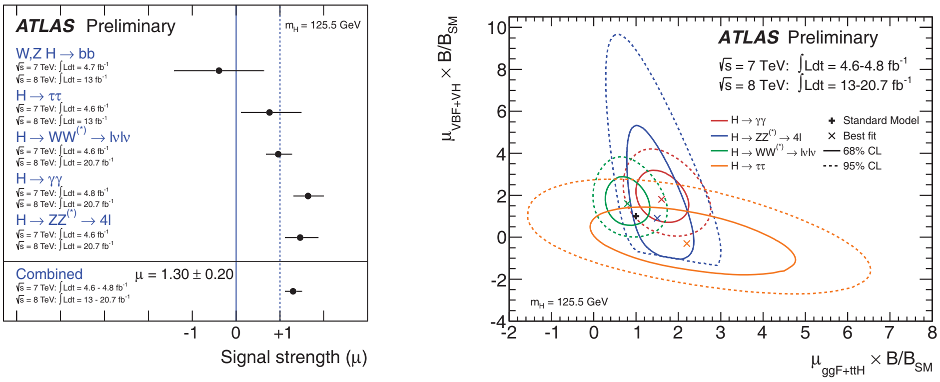

Fig. 2. – Left: signal strength, by decay channels and combined [11]. Right: signal strength by decay channels, for ggF+$t\bar{t}H$ (horizontal axis) and for VBF+VH (vertical axis) [11].

quark-antiquark annihilation, the proportion of the two mechanisms being unknown. For this reason, several admixtures of the two processes are tested, by scanning the fraction of $q\bar{q}$-annihilation $f_{q\bar{q}}$ from 0% to 100% in steps of 25%. All $\gamma\gamma$, $WW^* \to e\nu\mu\nu$ and $ZZ^* \to 4\ell$ decays are exploited. In the $\gamma\gamma$ channel [6], the photon production angle in the Collins-Soper centre-of-mass frame [7] is used. In the WW^* [8] and ZZ^* [9] channels, several kinematic variables are combined in a multi-variate estimator. For each decay channel individually, and for each value of $f_{q\bar{q}}$, data always favour the 0^+ hypothesis. With a statistical combination of all the channels [10], the 2^+ state can be excluded at a confidence level (CL) higher than 99.9%, as displayed in fig. 1 (left).

The $ZZ^* \to 4\ell$ decays are also sensitive to 0^- and $1^\pm$ states. The 0^- state is excluded at 98% CL, as displayed in fig. 1 (right). The states 1^+ and 1^- are excluded at 99.8% CL and 94% CL, respectively.

4. – Couplings measurements

At LHC, the Higgs boson can be produced through four processes [1]: the dominant is the gluon fusion (ggF), mediated by a top-quark loop; the second is the vector-boson fusion (VBF) where the valence quarks of the colliding protons radiate weak bosons that collide to form a Higgs boson. Associated production (VH, with V being Z or W) may also occur, in processes $V^* \to VH$. Finally, two gluons may split to $t\bar{t}$ pairs, where a t and a $\bar{t}$ collide producing the Higgs boson ($t\bar{t}H$). These production mechanisms can be identified from the different final states: two energetic forward/backward jets for the VBF, leptons or missing transverse momentum or two close-by jets for VH, and $t\bar{t}$ identification for $t\bar{t}H$.

A first test of SM predictions is performed by measuring the "signal strength" $\mu = \sigma^{\text{obs}}/\sigma^{\text{SM}}$, *i.e.* the ratio between the observed signal yield and that expected for a SM Higgs boson. This can be done for all sought decay channels $\gamma\gamma$, ZZ^*, WW^*, $b\bar{b}$, $\tau^+\tau^-$ individually, and for their combination [11]. The results are displayed in fig. 2 (left). The individual signal strenghts are compatible among each other at a level of 13%. The combined signal strength is

$$\mu = 1.30 \pm 0.13(stat) \pm 0.14(syst) \tag{2}$$

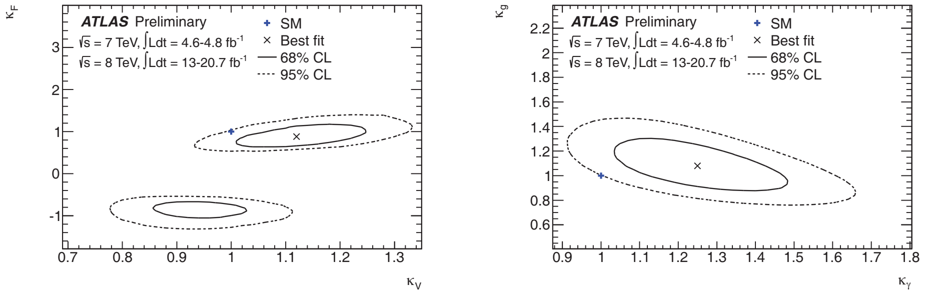

Fig. 3. – Left: confidence regions for coupling scale factors for fermions (κ_F) and for vector bosons (κ_V). All other effective couplings (κ_g, κ_γ) are expressed in terms of them [11]. Right: confidence regions for effective coupling scale factors for gluons (κ_g) and for photons (κ_γ). All other couplings are assumed as fixed by SM [11].

compatible with SM at 9% level.

To probe the couplings to fermions and vector bosons separately, two signal strengths are introduced, one involving ttH coupling (ggF+$t\bar{t}H$) and one involving WWH and ZZH couplings (VBF and VH). The results are shown in fig. 2 (right).

A deeper investigation implies probing all couplings individually. Assuming a tree-level process $ii \to H \to ff$, and introducing coupling scale factors $\kappa = g^{\mathrm{obs}}/g^{\mathrm{SM}}$ [11], the observed yields can be expressed in terms of the SM expectation through the relation

$$[\sigma(ii \to H) \times BR(H \to ff)]^{\mathrm{obs}} = [\sigma(ii \to H) \times BR(H \to ff)]^{\mathrm{SM}} \times \frac{\kappa_i^2 \kappa_f^2}{\kappa_H^2}\,. \tag{3}$$

Due to the large number of κ-parameters, some assumptions are needed. The first is the universality of couplings scale factors for fermions ($\kappa_t, \kappa_b, \kappa_\tau = \kappa_F$) and vector bosons ($\kappa_W, \kappa_Z = \kappa_V$) separately. Then, the ggH interaction is assumed to be modelled by a top loop as in SM, therefore $\kappa_g = \kappa_F$. Similarly, the $H\gamma\gamma$ interaction is also assumed to be mediated by W and top loops, therefore $\kappa_\gamma^2 = (1.26 \cdot \kappa_V - 0.26 \cdot \kappa_F)^2$ at the measured value of m_H. With these assumptions, the confidence region obtained for κ_F, κ_V is displayed in fig. 3 (left). Equation (3) leaves the sign of κ's arbitrary: κ_V is chosen positive by convention, while sentitivity to the sign of κ_F comes from the parametrization of κ_γ. The confidence region is two-fold, but $\kappa_F > 0$ is preferred by the fit. The compatibility with SM is at a level of 8%. If $\kappa_\gamma, \kappa_Z, \kappa_W$ are treated as independent parameters, their ratios result:

$$\frac{\kappa_W}{\kappa_Z} = 0.80 \pm 0.15, \qquad \frac{\kappa_\gamma}{\kappa_Z} = 1.10 \pm 0.18. \tag{4}$$

Since the ggH and $H\gamma\gamma$ interactions are entirely loop-mediated, probing directly κ_g, κ_γ could provide sensitivity to the existence of new particles beyond the SM that could enter these loops. Therefore, all κ-parameters are set to 1 except κ_g, κ_γ that are left free: the result is shown in fig. 3 (right). The compatibility with SM is at a level of 5%.

5. – Conclusions

The new resonance discovered by ATLAS and CMS Collaborations has been studied in detail to see whether it is compatible to the Standard Model Higgs boson. Its mass is $m_H = 125.5 \pm 0.2(stat)^{+0.5}_{-0.6}(syst)\,\mathrm{GeV}$. Its spin-parity state is compatible with that of a Higgs boson: $J^P = 0^+$. An alternative hypothesis $J^P = 2^+$ is excluded with a confidence level higher than 99.9%. The 0^- state is excluded at 98% CL, while 1^+ and 1^- states are excluded at 99.8% CL and 94% CL, respectively.

None of the couplings measurements shows significant deviations from the Standard Model expectations. This conveys confidence that the new particle is indeed involved in symmetry breaking and mass generation. However, the statistical and systematic uncertainties are still sizable ($\sim$ 20% in the best cases), therefore it is not possible at present to conclude whether this particle is the Standard Model Higgs boson.

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