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Higgs couplings and properties with the ATLAS detector at the LHC

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A review of the latest results on the main properties of the Higgs boson using the decay channels $H \to \gamma\gamma$, $H \to WW^* \to l\nu l\nu$, $H \to ZZ^* \to 4l$, $H \to b\bar{b}$ and $H \to \tau\tau$ with the ATLAS experiment at the CERN Large Hadron Collider at center-of-mass energies of $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV is presented. The analyzed dataset, collected in 2011 at center-of-mass energy of $\sqrt{s} = 7$ TeV and in 2012 at $\sqrt{s} = 8$ TeV, corresponds to an integrated luminosity of approximately 25 fb^{-1} of pp collisions. The combined mass measurements using the decays channels $H \to ZZ^* \to 4l$ and $H \to \gamma\gamma$, gives a mass value of $m_H = 125.5 \pm 0.2(\text{stat})^{+0.5}_{-0.6}(\text{sys})$. The results on the Higgs boson spin and quantum numbers obtained using all the three bosonic decay channels provide evidence for the spin-0 nature of the Higgs boson, with positive parity being strongly preferred. Evidence for Higgs decaying to fermions is found at 3.7σ level combining the newly available channels $H \to b\bar{b}$ and $H \to \tau\tau$. The combination of the Higgs decays channel results in a signal strength of $\mu = 1.30 \pm 0.12(\text{stat})^{+0.14}_{-0.11}(\text{sys})$ at a Higgs boson mass of 125.5 GeV. The measurements of the production and decay mode specific signal strengths and the Higgs boson coupling determinations in various benchmark models show good agreement with the Standard Model Higgs boson hypothesis.

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1. Introduction

In the Standard Model (SM) of particle physics, the Englert-Brout-Higgs [1–3] mechanism of electroweak symmetry breaking gives mass to all massive elementary particles and predicts the existence of a new scalar particle, the Higgs boson. In the summer of 2012, the ATLAS and CMS Collaborations at the CERN Large Hadron Collider (LHC) discovered a Higgs boson candidate with a mass of approximately $m_H = 125$ GeV [4, 5]. The detailed studies of the couplings and properties of this new particle and comparison with the expectations for the SM Higgs boson are currently performed by the ATLAS Collaboration. Since the publication on the diboson channels [6] , $H\rightarrow\gamma\gamma$, $H\rightarrow WW^*\rightarrow l\nu l\nu$, $H\rightarrow ZZ^*\rightarrow 4l$, the ATLAS Collaboration has made available important results on fermionic channels, namely $H\rightarrow b\bar{b}$ [7] and $H\rightarrow\tau\tau$ [8] which allow the update of the measurements of the coupling properties of the Higgs boson.

2. Higgs Mass measurements

The mass of the newly discovered boson can be measured precisely in the high mass resolution channels $H\rightarrow\gamma\gamma$ and $H\rightarrow ZZ^*\rightarrow 4l$. The combined results presented in this note assume that all measurements are compatible with a single resonance hypothesis. For the diphoton decay channel a mass of $m_H^{\gamma\gamma} = 126.8 \pm 0.2(\text{stat}) \pm 0.7(\text{sys})$ GeV is found whereas in the ZZ^* channel a mass value of $m_H^{4l} = 124.3^{+0.6}_{-0.5}(\text{stat})^{+0.5}_{-0.6}(\text{sys})$ GeV has been measured [6]. The combination of the two channel's mass measurements is based on the profile likelihood ratio $\Lambda(m_H)$ with the signal strengths treated as nuisance parameters while the ratios of the cross sections of the different production modes are fixed to the SM values. The combination gives a Higgs mass of $m_H = 125.5 \pm 0.2(\text{stat})^{+0.5}_{-0.6}(\text{sys})$ GeV.
To quantify the consistency between the two measured Higgs mass values, a likelihood function is considered for the mass difference $\Delta m_H = m_H^{\gamma\gamma} - m_H^{4l}$, with the averaged mass profiled in the fit. The estimated mass difference is $\Delta\hat{m}_H = \hat{m}_H^{\gamma\gamma} - \hat{m}_H^{4l} = 2.3^{+0.6}_{-0.7}(\text{stat}) \pm 0.6(\text{sys})$ GeV, giving a compatibility of 1.5% (2.4σ) with the single resonance hypothesis of $\Delta m_H = 0$.

3. Spin-parity measurement

In the SM, the Higgs boson is a spin-0 and CP-even particle ($J^P = 0^+$). This SM hypothesis is compared to several alternative hypotheses with $J^P = 0^-, 1^+, 1^-, 2^+$. For a complete discussion of the ATLAS spin-CP Higgs boson measurement see [9]. The spin-1 hypothesis is strongly disfavoured because of the observation of the $H\rightarrow\gamma\gamma$ decay. For spin-2 models, a graviton-inspired tensor with minimal couplings to SM particles model, denoted 2^+_m, is considered. A likelihood function that depends on the spin-parity assumption of the signal is constructed as a product of conditional probabilities over binned distributions of the discriminant observables in each of the channel considered, $H\rightarrow\gamma\gamma$, $H\rightarrow WW^*\rightarrow l\nu l\nu$, $H\rightarrow ZZ^*\rightarrow 4l$. To improve the sensitivity to different spin-parity hypotheses, several final states are combined. The numbers of signal events in each channel and for each tested hypothesis are treated as an independent nuisance parameters in the likelihood as the couplings to SM particles for the alternative hypothesis are not known a priori. The test statistic q used to distinguish between the two signal spin-parity hypotheses is based on a ratio of likelihoods: the maximum likelihood estimator evaluated under the SM hypothesis over the one evaluated under the tested spin-parity hypothesis. The exclusion of the alternative hypothesis in favour of the SM $J^P = 0^+$ hypothesis is evaluated in terms of the corresponding confidence level defined as: $CL_s(J^P_{alt}) = \frac{p_0(J^P_{alt})}{1-p_0(0^+)}$, where a very small value of $p_0(J^P_{alt})$ is interpreted as the hypothesis being in disagreement with SM hypothesis. In order to distinguish between pairs of spin-parity states, the spin-parity sensitive variables, are combined using a multivariate discriminant based on a boosted decision tree (BDT) for the ZZ^* and WW^* channels, whereas for the $\gamma\gamma$ channel the discriminate variable is used without any combination. The distributions are then used in binned likelihood fits to test the data for compatibility with the presence of particle with alternative spin-parity hypothesis in the data.

The $J^P = 0^-$ hypothesis is rejected at 97.8% CL by using the $H \to ZZ^* \to 4l$ decay alone. The $J^P = 1^-, 1^+$ hypotheses are rejected with a CL of at least 99.7 % by combining the $H \to ZZ^* \to 4l$ and $H \to WW^* \to l\nu l\nu$ channels. Finally, the $J^P = 2^+_m$ model is rejected at more than 99.9 % CL by combining all three bosonic channels.

4. Signal strength and couplings measurements

The measured yields from the Higgs boson decay channels have been analyzed in terms of signal strength for the different production and decay modes. Hypothesis testing and confidence intervals are based on the $\Lambda(\alpha)$ profile likelihood ratio test statistic where α represents one or more parameter of interest such as the Higgs boson signal strength μ, normalized to the SM expectation ($\mu = 1$ correspond to the SM Higgs boson hypothesis, $\mu = 0$ to the background-only hypothesis). The combination of the two fermion channels $H \to b\bar{b}$ and $H \to \tau\tau$ yields: $\mu^{bb,\tau\tau} = 1.09 \pm 0.24(\text{stat})^{+0.27}_{-0.21}(\text{sys})$, corresponding to 3.7σ evidence for the direct decay of the Higgs boson into fermions. The global signal strength combining all five channels is: $\mu = 1.30 \pm 0.12(\text{stat})^{+0.14}_{-0.11}(\text{sys})$. The results of the signal strengths measured in the five final states are given in figure 1.

The various Higgs analysis have been categorized in order to be sensitive to the various Higgs production mechanics: gluon-gluon fusion (ggF), the main production mechanism , vector boson fusion (VBF), associated (VH) production processes and $t\bar{t}$-fusion (ttH). Thus, the data are fitted separating the VBF and VH production processes, which involve the Higgs boson coupling to vector bosons, from the ggF and ttH, which involve the Higgs boson coupling to fermions to gain direct information on the relative contributions of the different production mechanisms. A model independent test of the theory can be done by taking the ratio of the two signal strength $\mu_{VBF+VH}/\mu_{ggF+ttH}$ for the individual final states and their combination.
The results is: $\mu_{VBF+VH}/\mu_{ggF+ttH} = 1.4^{+0.5}_{-0.4}(\text{stat})^{+0.4}_{-0.2}(\text{sys})$. To test the sensitivity to VBF alone, the data are fitted with the ratio $\mu_{VBF}/\mu_{ggF+ttH}$ treating independently and profiling the other parameter $\mu_{VH}/\mu_{ggF+ttH}$. The fit result is $\mu_{VBF}/\mu_{ggF+ttH} = 1.4^{+0.5}_{-0.4}(\text{stat})^{+0.4}_{-0.3}(\text{sys})$ which provides an evidence at the 4.1σ level that a fraction of Higgs boson production occurs through VBF. For a consistent treatment of Higgs boson couplings in production and decay modes some assumption are done. The signal originates from a single narrow resonance of mass and the width of the assumed Higgs boson near $m_H = 125.5$ GeV is neglected and only modifications of couplings strengths, i.e. of absolute values of couplings, are taken into account. In this way for all Higgs channels the prod-

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uct $\sigma \times BR(i \to H \to f)$ can be decomposed as: $\sigma \times BR(i \to H \to f) = \frac{\sigma_i \cdot \Gamma_f}{\Gamma_H}$ where Γ_H is the total width of the Higgs. The coupling scale factors κ_j are defined in such a way that the cross section σ_j and the partial decay width Γ_j associated with the SM particle j scale with the factor κ_j^2 when compared to the corresponding SM prediction: $\kappa_i^2 = \frac{\sigma_i}{\sigma_j^{SM}}, \kappa_f^2 = \frac{\Gamma_j}{\Gamma_j^{SM}}$. In a first benchmark model, the fit parameters are the coupling scale factors to all fermions κ_f ($\kappa_f = \kappa_t = \kappa_b = \kappa_\tau = \kappa_g$) and to all vector bosons κ_V ($\kappa_V = \kappa_W = \kappa_Z$) assuming only SM particles in the loop induced process $H \to \gamma\gamma$ and $gg \to H$. The best-fit values and uncertainties (experimental and theoretical), when the other parameter is profiled, are: $\kappa_V = 1.15 \pm 0.08$ and $\kappa_f = 0.99^{+0.17}_{-0.15}$. The two-dimensional compatibility of the SM hypothesis with the best-fit point is 10%. The fit can be repeated without assumption on the total Higgs width. In this case only ratios of coupling scale factors can be measured. The free parameters are: $\lambda_{FV} = \frac{\kappa_f}{\kappa_V}, \kappa_{VV} = \kappa_V \cdot \kappa_V / \kappa_H$ where κ_{VV} is an overall scale that includes the total width and applies to all rates. The best-fit values, when profiling the other parameter, are: $\lambda_{FV} = 0.86^{+0.14}_{-0.12}$ and $\kappa_{VV} = 1.28^{+0.16}_{-0.15}$. With the two fermionic Higgs decay channels it is possible to probe the relations between up- and down- type quarks. First, the ratio λ_{du} between down- and up-type fermions is probed, while vector boson couplings are taken unified (κ_V). The free parameters are: $\lambda_{du} = \kappa_d / \kappa_u$, $\lambda_{Vu} = \kappa_V / \kappa_u$ and $\kappa_{uu} = \kappa_u \cdot \kappa_u / \kappa_H$. Around the SM-like minimum at 1: $\lambda_{du} = 0.95^{+0.20}_{-0.18}$, $\lambda_{Vu} = 1.21^{+0.24}_{-0.26}$ and $\kappa_{uu} = 0.86^{+0.41}_{-0.21}$. This fit provides a 3.6σ level evidence of the coupling of the Higgs boson to down-type fermions.

The ratio λ_{lq} between leptons, denoted by l, and quarks, denoted by q has also been probed. In this case the free parameters are $\lambda_{lq} = \kappa_l / \kappa_q$, $\lambda_{Vq} = \kappa_V / \kappa_q$ and $\kappa_{qq} = \kappa_q \cdot \kappa_q / \kappa_H$. Around the SM$-$like minimum at 1, the ratio is $\lambda_{lq} = 1.22^{+0.28}_{-0.24}$, $\lambda_{Vq} = 1.27^{+0.23}_{-0.20}$ and $\kappa_{qq} = 0.82^{+0.23}_{-0.19}$. A vanishing Higgs coupling to leptons is excluded at the 4.0σ level. The three-dimensional compatibility of the SM hypothesis with the best-fit point is 15%. In a more general way, the couplings scale factors to $\kappa_W, \kappa_Z, \kappa_t, \kappa_b, \kappa_\tau$ are treated independently, while assuming only SM particles in the $gg \to H$, $H \to \gamma\gamma$ and Γ_H. The corresponding fitted values of the relative couplings can be seen in figure 1. Other results as well as more details on the couplings measurements can be found in [10]. All the measured values of the coupling scale factors and their ratios are used to constraint beyond the SM (BSM) models, see [11]. We can probe generic BSM contributions from new particles in loops or in new final states if we introduce effective scale factors κ_γ (for $H \to \gamma\gamma$) and κ_g (for $gg \to H$) as free parameters. With the assumption of no sizeable extra contributions to the total Higgs width caused by non-SM particles, we found: $\kappa_g = 1.08^{+0.15}_{-0.13}$ and $\kappa_\gamma = 1.19^{+0.15}_{-0.12}$. By constraining some of the factors to be equal to their SM values, it is possible to probe for new non-SM decay modes with a branching ratio $BR_{i.,u.}$ that might yield invisible or undetected final states. The free parameters in this case are κ_g, κ_γ and $BR_{i.,u.}$. The fit result is: $BR_{i.,u.} = -0.16^{+0.29}_{-0.30}$. With the physical constraint of $BR_{i.,u.} > 0$ the 95% CL upper limit is $BR_{i.,u.} < 0.41$. See [11] for more results.

5. Conclusion

A review of the latest results on the main properties of the Higgs boson has been presented. The combined Higgs mass is $m_H^{\gamma\gamma,4l} = 125.5 \pm 0.2(\text{stat})^{+0.5}_{-0.6}(\text{sys})$ GeV. The data provide evidence for the spin-0 nature of the Higgs boson, with positive parity being strongly preferred. The combination of the 5 Higgs decay channels considered in this analysis results in a signal strength value of $\mu = 1.30 \pm 0.12(\text{stat})^{+0.14}_{-0.11}(\text{sys})$. Evidence for Higgs decaying to fermions is found at the 3.7σ [10]

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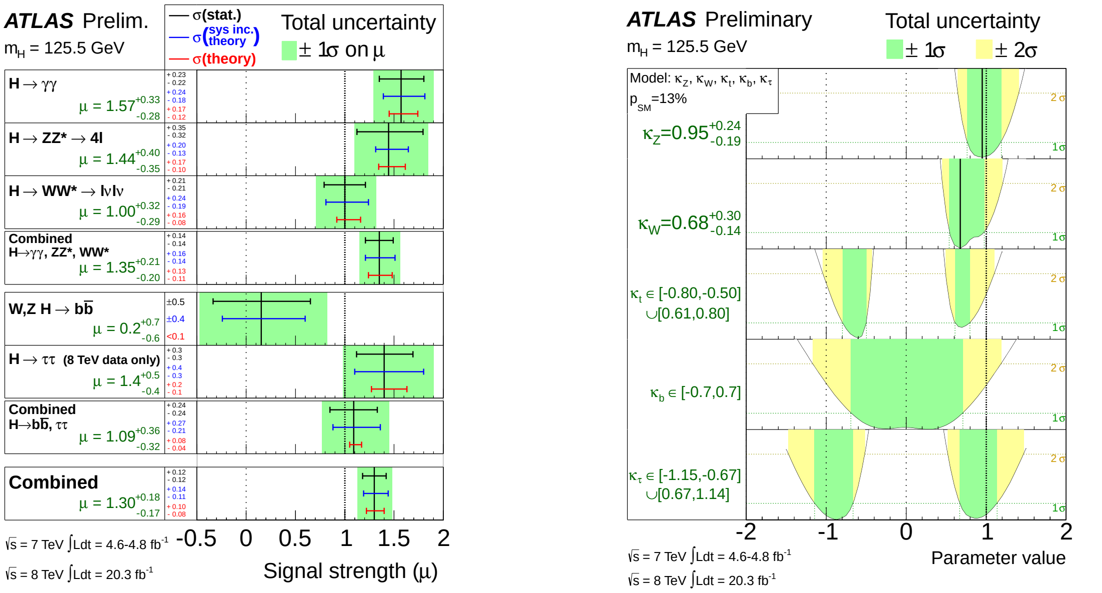

Figure 1: Left plot: The measured signal strengths, normalised to the SM expectations, for the individual final states and various combinations. The best-fit values are shown by the solid vertical lines. The total $\pm 1\sigma$ uncertainties are indicated by green shaded bands, with the individual contributions from the statistical uncertainty (top), the total (experimental and theoretical) systematic uncertainty (middle), and the theory uncertainty (bottom). Right plot: Summary of the coupling scale factor measurements assuming only SM particles. The best-fit values are represented by the solid vertical lines, with the total $\pm 1\sigma$ and $\pm\sigma$ uncertainties. The n-dimensional compatibility of the SM hypothesis with the best-fit point is given by p_{SM}.

level using the newly available channels $H \to b\bar{b}$ and $H \to \tau\tau$. The measurements of the production and decay mode specific signal strengths and the Higgs boson coupling determinations in various benchmark models show good agreement with the Standard Model Higgs boson hypothesis within the present uncertainties.

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