HIGGS BOSON PHYSICS AT ATLAS

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Abstract. The discovery of a new boson with the ATLAS detector at the LHC proton-proton collider is confirmed using the full data set collected at centre-of-mass energies of 7 and 8 TeV. The spin and parity properties of the boson are consistent with that of a scalar particle with positive parity. Comparison of the $J^P = 0^+$ hypothesis to alternatives $J^P = 0^-, 1^+, 1^-, 2^+$ result in exclusion of these other choices at 97.8%, 99.97%, 99.7%, and 99.3% CL. The Higgs boson mass is $m_H = 125.5 \pm 0.2(\text{stat.})_{-0.5}^{+0.5}(\text{syst.})$ GeV. Evidence for production of the Higgs boson by vector boson fusion is obtained in a model-independent approach by comparing the signal strengths μ of vector boson fusion and production associated with a vector boson to that for gluon fusion including associated production of top quark pairs: $\mu_{\text{VBF+VH}}/\mu_{\text{ggF+ttH}} = 1.4_{-0.3}^{+0.4}(\text{stat.})_{-0.4}^{+0.6}(\text{syst.})$ which is 3.3 Gaussian standard deviations from zero.

1 Introduction

The discovery of a new boson with the ATLAS Detector was announced in July 2012 based on 4.8 fb^{-1} of proton proton collision data collected at 7 TeV centre-of-mass and $5.8\text{-}5.9 \text{ fb}^{-1}$ collected at 8 TeV [1]. Since that time the analysis has been improved and includes the full 20.8 fb^{-1} sample of data collected at 8 TeV [2]. This was facilitated by the excellent LHC performance where peak luminosities of $7 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$ created an experimental challenge with an average of 21 interactions per beam crossing. The analysis described in this proceedings focuses on reconfirming the result and determining if the boson has properties consistent with that of the Standard Model (SM) Higgs boson.

The production of the SM Higgs boson proceeds via gluon fusion which produce the Higgs boson via a quark loop, or W or Z fusion to a Higgs boson, as well as in production of a Higgs boson in association with a vector boson or a top quark. The Standard Model Higgs boson with a mass of 125 GeV decays predominantly to b quark-antiquark pairs but in this analysis the channels examined are the WW , ZZ and $\gamma\gamma$ decays having branching ratios of 22.3%, 2.8% and 0.24% respectively.

The ATLAS experiment is described in detail elsewhere [3]. Here only a brief outline of the most important features is given. Starting from the beam collision point, the detector consists of high resolution silicon detectors including 100 million pixel channels ($50 \mu\text{m} \times 400 \mu\text{m}$) and six million strip channels ($80 \mu\text{m} \times 12\text{cm}$) and giving a spatial tracking resolution of $15 \mu\text{m}$. A highly granular liquid argon electromagnetic calorimeter with cells pointing to the interaction region is robust to pileup and has good isolation to suppress jets faking photons, a feature exploited in the Higgs boson decay to two photons as well for

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identifying and measuring electrons in the ZZ and WW decay modes.

2 Higgs boson Discovery modes

The Higgs boson analysis of the discovery modes of decay to two photons or to two vector bosons is updated in the following sections.

2.1 $H \rightarrow \gamma\gamma$ channel

The search for $H \rightarrow \gamma\gamma$ requires two isolated photons with transverse momenta $p_T > 40, 30$ GeV. The invariant mass $m_{\gamma\gamma}$ of the two photons is reconstructed. Monte Carlo simulation shows that the resolution is approximately 1.7 GeV for $m_H = 120$ GeV and that it is insensitive to the number of beam crossings. The signal-to-background ratio is 3%. There is a smooth irreducible prompt diphoton background contributing $75^{+3}_{-4}\%$ of the background events and a large reducible background contribution from γ -jet (22%) and jet-jet (3%) where the jets are identified as photons.

The results for the full 7 and 8 TeV combined data sample are shown in Figure 1 (upper and middle left) and establish the discovery of the new particle in the $\gamma\gamma$ channel alone. The probability p_0 value for the consistency of data with background only is 10^{-13} , equivalent to a $7.4\sigma_G$, where σ_G is the probability associated with a Gaussian. The expected p_0 is $4.3\sigma_G$. The mass is

$$m_H = 126.8 \pm 0.2(\text{stat.}) \pm 0.7(\text{syst.}) \text{ GeV}.$$

The signal strength μ defined as the observed cross section times branching ratio σ relative the Standard Model prediction σ_{SM} is

$$\mu \equiv \sigma/\sigma_{SM} = 1.55 \pm 0.23(\text{stat.}) \pm 0.15(\text{syst.}) \pm 0.15(\text{theor.}),$$

consistent with SM expectations.

The diphoton events have been divided into subsamples to distinguish the various production modes for the Higgs boson. One discriminant that is used is the transverse momentum of the diphoton system taken relative to the difference in the photon transverse momenta. This is larger for the vector boson fusion process than for the other processes and is applied to events with no jets. Events with two jets having a high transverse invariant mass also distinguish vector boson fusion production. Events with one jet are used to enhance the production of the Higgs boson in association with a vector boson. The vector boson fusion mode has an observed significance of $2.0\sigma_G$.

Differential distributions for the diphoton mode are shown for the jet multiplicity and the transverse momentum of the Higgs boson candidates in Figure 2. Additional measurements have been done including the rapidity, the leading

Figure 1: The $m_{\gamma\gamma}$ spectrum for the $H \rightarrow \gamma\gamma$ search and the $H \rightarrow ZZ \rightarrow m_{4\ell}$ spectrum for the $H \rightarrow ZZ$ search as well the p_0 values as a function of the test mass for $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ$ or $H \rightarrow WW$ [2].

jet transverse momentum, the azimuthal angle between the leading and sub-leading jet and the transverse momentum of the combined Higgs boson and dijet system. There is some disagreement in these measurements and further theoretical work is needed in preparation for the high statistics that will come with the next run of the LHC.

2.2 $H \rightarrow ZZ^*$ channel

The search for Higgs boson decays to Z bosons focuses on the leptonic decays of the Z . Therefore the search requires four isolated leptons from which the invariant mass $m_{4\ell}$ is computed. Only isolated electrons and muons are considered. The cuts are optimised to maximise the acceptance. The electrons have a transverse momentum cut of $p_T > 20, 15, 10$ and 7 GeV and a pseudo-rapidity cut $|\eta| < 2.47$ GeV. One pair of same flavour opposite sign leptons is

Figure 2: The measured unfolded jet multiplicity (left) and Higgs boson transverse momentum differential distributions (right) and their comparison to theory. [4].

required to be within 8 GeV of the Z mass and the other pair is off-shell and required to be in a broad mass range from 12 to 115 GeV. The signal rate is low but the background from the ZZ continuum is also low and arises from Z decays to b -quarks that hadronise and in turn decay to leptons.

The results for the full 7 and 8 TeV combined data sample are shown in Figure 1 (upper and middle right). The probability p_0 value for the consistency of data with background only is 2.7×10^{-11} , equivalent to $6.6\sigma_G$. The expected p_0 is $4.4\sigma_G$. The mass is

$$m_H = 124.3^{+0.6}_{-0.5}(\text{stat.})^{+0.5}_{-0.3}(\text{syst.}) \text{ GeV}$$

and has a signal strength

$$\mu = 1.43 \pm 0.33(\text{stat.}) \pm 0.17(\text{syst.}) \pm 0.14(\text{theor.}).$$

2.3 Compatibility of the ZZ and $\gamma\gamma$ Channels and Mass Determination

The results on the measured masses in the two decay modes, $\gamma\gamma$ and ZZ are different by a value $\Delta m = 2.3^{+0.6}_{-0.7}(\text{stat.}) \pm 0.6(\text{syst.}) \text{ GeV}$. This is a $2.4\sigma_G$ deviation which has a probability of agreement of 1.5%. This agreement rises to 8% if a rectangular distribution of the systematic error is assumed instead of a Gaussian distribution. The main sources of uncertainty in the difference in the electron and photon energy scale are the amount of material, the pre-sampler energy scale and differences arising from a choice of calibration procedure. The combined mass from these two channels is

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

2.4 $H \rightarrow WW^*$ channel

The search for $H \rightarrow W^+W^-$ begins with a selection of events with two high transverse momenta leptons with opposite charge, ee , $e\mu$ or $\mu\mu$, which are separated by less than 2 radians in the transverse plane and hence distinguishable from Drell-Yan production of leptons. The spin-0 Higgs boson correlates the spins of the leptons leading to a small azimuthal separation $\Delta\phi_{ll}$ of the charged leptons, a larger missing transverse energy from the neutrinos and influences the dilepton invariant mass. The analysis is divided into different jet multiplicities since the backgrounds vary with the number of jets. The dominant backgrounds for 0 and 1 jets are Drell-Yan and WW whereas events with two or more jets are dominated by top quark production. Control regions are used to obtain these background rates from data.

The results for the full 7 and 8 TeV combined data sample are shown in the lower plot of Figure 1 [2]. The probability p_0 value for the consistency of data with background only is 8×10^{-5} , equivalent to a $3.8\sigma_G$ probability. The expected p_0 is $3.7\sigma_G$. The signal strength is

$$\mu = 0.99 \pm 0.21(\text{stat.}) \pm 0.12(\text{syst.}) \pm 0.19(\text{theor.}).$$

Figure 3: Signal strengths in the $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ$ and $H \rightarrow WW$ decay modes and in the combination of these modes show consistency with the SM [2].

3 Production Properties and Quantum Numbers of the New Particle

In this section the question of the consistency of the quantum numbers of the new particle with those expected for the Higgs boson is addressed. The production rates, spin and parity are analysed.

3.1 Signal Strength and VBF Production

The results from all three decay modes shown in Figure 3 are combined and are consistent in signal strength to that of a Standard Model Higgs boson:

$$\mu = 1.33 \pm 0.14(\text{stat.}) \pm 0.15(\text{syst.}).$$

The combined samples are also divided into production associated with top as well as gluon fusion (ttH and ggF) and vector boson associated production as well as vector boson fusion production modes (VH + VBF). A model-independent result is obtained by calculating the ratio of the signal strengths in these modes:

$$\mu_{\text{VBF+VH}}/\mu_{\text{ggF+ttH}} = 1.4^{+0.4}_{-0.3}(\text{stat.})^{+0.6}_{-0.4}(\text{syst.}).$$

which is $3.3\sigma_G$ from zero, providing evidence for vector boson fusion production.

3.2 Couplings to Fermions and Bosons

Once the Higgs boson mass is specified all the Standard Model couplings are determined [2]. In order to explore possible new physics that arises in altered couplings, it is assumed that the tensor structure of the Standard Model is unchanged: the Higgs boson is a CP-even scalar and there are no new particles. The couplings are scaled by a factor κ_i where i indicates the particle to which the Higgs boson couples. For example in the production of Higgs boson associated with a W boson, $k_W^2 \equiv \sigma_{WH}/(\sigma_{WH})^{SM}$ whereas for the decay $k_W^2 \equiv \Gamma_{WH}/(\Gamma_{WH})^{SM}$. In the case of a loop, such as that required for the Higgs boson coupling to gluons, κ_g is defined as a function of the tree level couplings and the Higgs boson mass: $\kappa_g^2 \equiv \kappa_g^2(\kappa_b, \kappa_t, \kappa_c, \kappa_W, m_H)$. For the comparison of fermion and boson couplings and because of limited statistics, it is assumed that there is one vector coupling $\kappa_V \equiv \kappa_Z = \kappa_W$ and one fermion coupling $\kappa_F \equiv \kappa_t = \kappa_b = \kappa_\tau$. The sensitivity to the relative sign between κ_F and κ_V arises in the interference term in the $H \rightarrow \gamma\gamma$ mode. The data are consistent with the SM expectation showing a consistency of 12% in the two dimensional fit to the vector and fermion couplings. The 68% confidence intervals are $0.76 \leq \kappa_f \leq 1.18$ and $1.05 \leq \kappa_V \leq 1.22$.

To compare the ratio of the W and Z boson couplings, the single factor for κ_F is still assumed but the value of $\lambda_{WZ} \equiv \kappa_W/\kappa_Z = 0.82 \pm 0.15$ consistent with the requirement from custodial symmetry that is $\lambda_{WZ} = 1$.

A test for new particles in the production and decay loops can be done under the assumption that all nominal couplings to Standard Model particles have $\kappa_i = 1$ and there is no contribution due to new particles to the Higgs boson width. Scale factors κ_g and κ_γ are introduced. A fit to the data shows a consistency with the Standard Model with a probability of 14% with $\kappa_g = 1.04 \pm 0.14$ and $\kappa_\gamma = 1.20 \pm 0.15$.

3.3 Spin and Parity

For the Standard Model Higgs boson, the spin and parity quantum numbers are $J^P = 0^+$. In order to test this other hypotheses are proposed: $J^P = 0^-, 1^+, 1^-, 2^+$. The Spin-1 hypothesis is disfavoured by the Landau-Yang theorem [5], [6]. For the Spin-2 hypothesis there are many parameters in a general theory. For this test a graviton-like tensor is considered, equivalent to a Kaluza-Klein graviton [7]. Production via gluon fusion and quark annihilation are both possible. There are higher order corrections that lead to a large uncertainty in the production fraction attributed to quark-antiquark annihilation and hence the results are quoted as a function of this fraction.

The comparison of $J^P = 0^-$ to $J^P = 0^+$ is done by analysing the decay kinematics of the $H \rightarrow ZZ^* \rightarrow 4\ell$ decays. Variables sensitive to the difference in parity are the masses of the two Z particles, the production angle in the centre-of-mass, and the four decay angles specifying the orientation of the decay planes of each Z with respect to the beam and the center of mass decay angle of each lepton in the Z decay plane relative to the direction of the Z . A multivariate analysis using a Boosted Decision Tree (BDT) is performed and a likelihood fit to the output of the BDT excludes the $J^P = 0^-$ hypothesis with 97.8% CL compared to the $J^P = 0^+$ hypothesis.

The comparison of $J^P = 1^{+/-}$ to $J^P = 0^+$ hypothesis is done in the $H \rightarrow ZZ^*$ and $H \rightarrow WW^*$ decay modes. For the W decays it is necessary to repeat the full analysis since the angular distribution of the leptons is altered by the spin. The exclusion probability for the Z decay mode alone is 94% and that for the W decay mode is 98.3%. Combining these, the $J^P = 1^{+/-}$ hypothesis is excluded relative to the $J^P = 0^+$ hypothesis at a confidence level of 99.7%.

The comparison of $J^P = 2^+$ to $J^P = 0^+$ hypothesis is done using the decay angle of the photons on the $H \rightarrow \gamma\gamma$ mode and is excluded at 99.3% CL. Combining the WW , ZZ and $\gamma\gamma$ results in an exclusion of the $J^P = 2^+$ mode with greater than 99.9% CL. Due to the complimentary sensitivity of the confidence level in $H \rightarrow \gamma\gamma$ compared to $H \rightarrow WW^*$ as a function of the production fraction of quark-antiquark relative to gluon fusion, the combined result does not depend on this fraction [8].

4 Conclusions

A milestone discovery in particle physics was made in July, 2012. The signals have been confirmed beyond doubt with additional data and the discovery phase has been transformed into a measurement phase. The ATLAS data are consistent with the expectations of the Standard Model Higgs boson in production rates and coupling strengths, evidence for vector boson fusion production and evidence that the particle has spin and parity quantum numbers $J^P = 0^+$. The mass of the Higgs boson is

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

Nonetheless statistics are limited and the era of measurement of the differential distributions has only begun; therefore, exciting times still lie ahead since deviations or even more Higgs bosons can be accommodated within the statistical power of the current sample and hence discovered if they exist in the larger statistical power of the anticipated sample.

Acknowledgments

The author would like to thank the organisers of the conference for their hospitality and the intellectually stimulating atmosphere.

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