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 to that for gluon fusion including associated production of top quark pairs: $\mu_{\mathrm{VBF+VH}}/\mu_{\mathrm{ggF+ttH}} = 1.4^{+0.4}_{-0.3}(\text{stat.})^{+0.6}_{-0.4}(\text{syst.})$ which is 3.3 Gaussian standard deviations from zero.

1 Introduction

The discovery of a new boson in the ATLAS Detector was announced in July 2012 based on 5.2 fb^{-1} of proton proton collision data collected at 7 TeV centre-of-mass and 5.1 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 7×10^{33} cm^{-2}s^{-1} created an experimental challenge with an average of 21 interactions per beam crossing. The analysis described in this proceedings focusses 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 proceeds via gluon fusion which produce the Higgs via a quark loop, or W or Z fusion to a Higgs boson, as well as in production of a Higgs in association with a vector boson or a top quark. The Standard Model Higgs with a mass of 125 GeV decays predominantly to b quark anti-quark 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 μm $\times 400\mu$m and six million strip channels (80 μm $\times$12cm) and giving a spatial tracking resolution of 15μm. A highly granular liquid argon electromagnetic calorimeter with cells pointing to the interaction region is robust to pileup and has good isolation to supress jets faking photons,

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a feature exploited in the Higgs decay to two photons as well for identifying and measuring electrons in the ZZ and WW decay modes.

2 Higgs Discovery modes

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

2.1 $H \to \gamma\gamma$ channel

The search for $H \to \gamma\gamma$ 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 contributions 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 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 limit 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 in association with a vector boson. The vector boson fusion mode has a signficance of $2.0\sigma_G$.

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

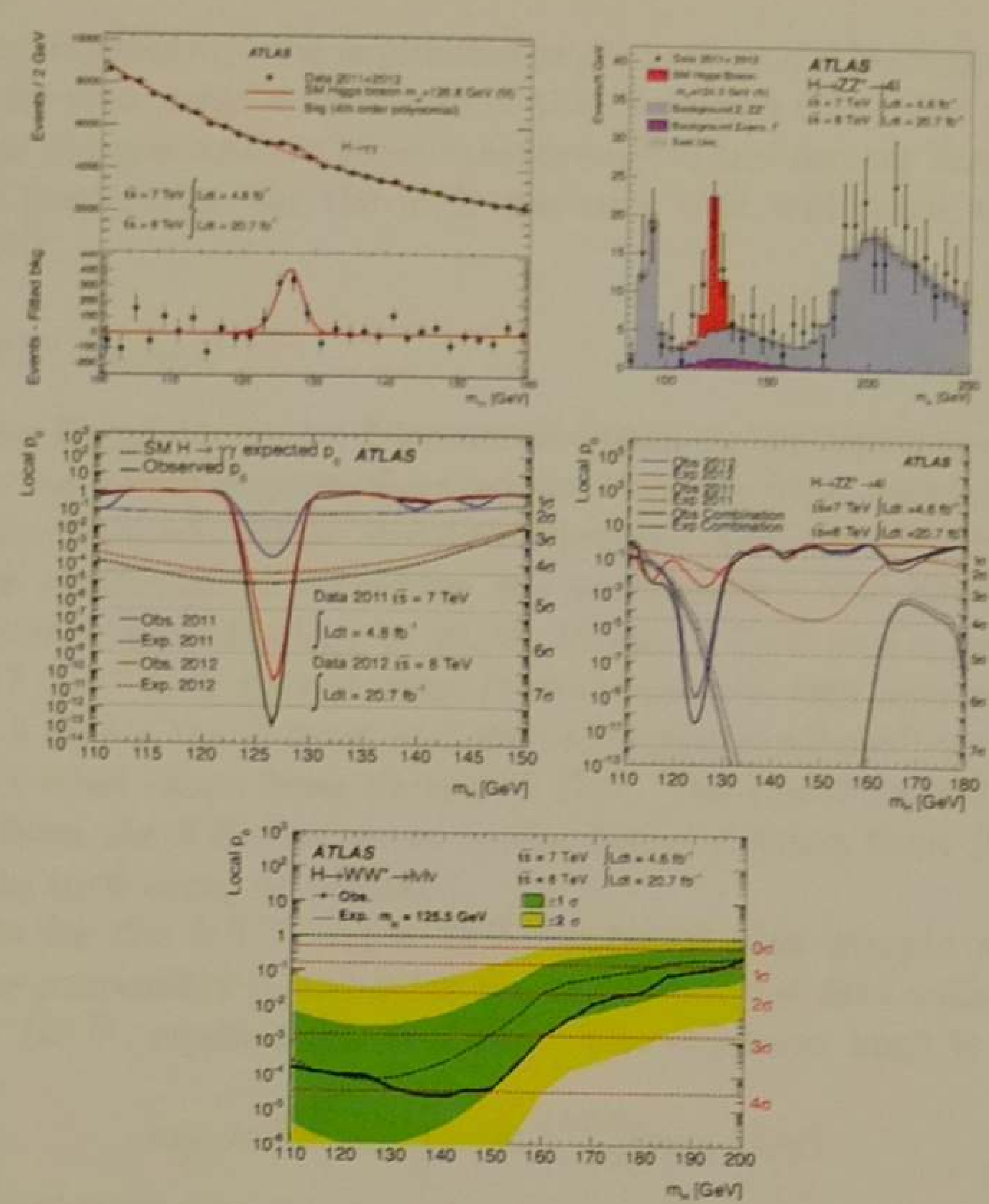

Figure 1: The $m_{\gamma\gamma}$ spectrum for the $H \to \gamma\gamma$ search and the $m_{4\ell}$ $H \to ZZ$ search as well the probabiilties for the backgrounds to fluctuate to a $H \to \gamma\gamma$, $H \to ZZ$ or $H \to WW$ [2].

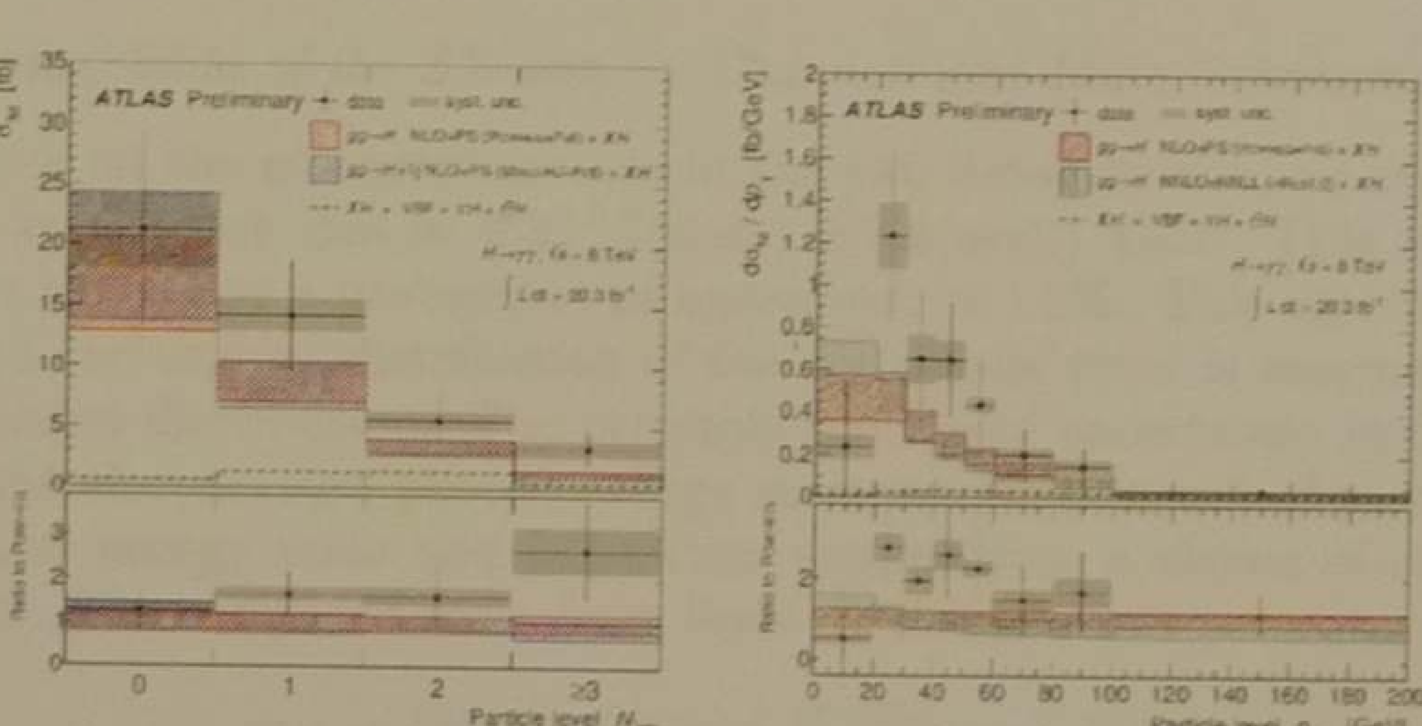

Figure 2: The jet multiplicity and Higgs transverse momentum differential distributions [4].

jet transverse momentum, the azimuthal angle betwen the leading and subleading jet and the transverse momentum of the combined Higgs 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 $H \to ZZ^*$ channel

The search for Higgs decays to Z bosons focusses 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 pseudorapidity cut $|\eta| < 2.47$ GeV. One pair of same flavour opposite sign leptons is required to be within 8 GeVof 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 in turn decay to leptons.

The results for the full 7 and 8 TeV combined data sample are shown in Figure 1. The probability p_0 value for the consistency of data with background only is 2.7×10^{-11}, equiavalent to $6.6\sigma_G$. The expected limit 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 $\Delta m = 2.3^{+0.6}_{-0.7}(\text{stat.}) \pm 0.6(\text{syst.})$ 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 principle 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 $H \to WW^*$ channel

The search for $H \to W^+W^-$ begins with a selection of events with two high transverse momenta leptons, 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 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 Figure 1 [2]. The probability p_0 value for the consistency of data with background only is 8×10^{-5}, equiavalent to a $3.8\sigma_G$ probability. The expected limit is $3.7\sigma_G$. The signal strength is

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

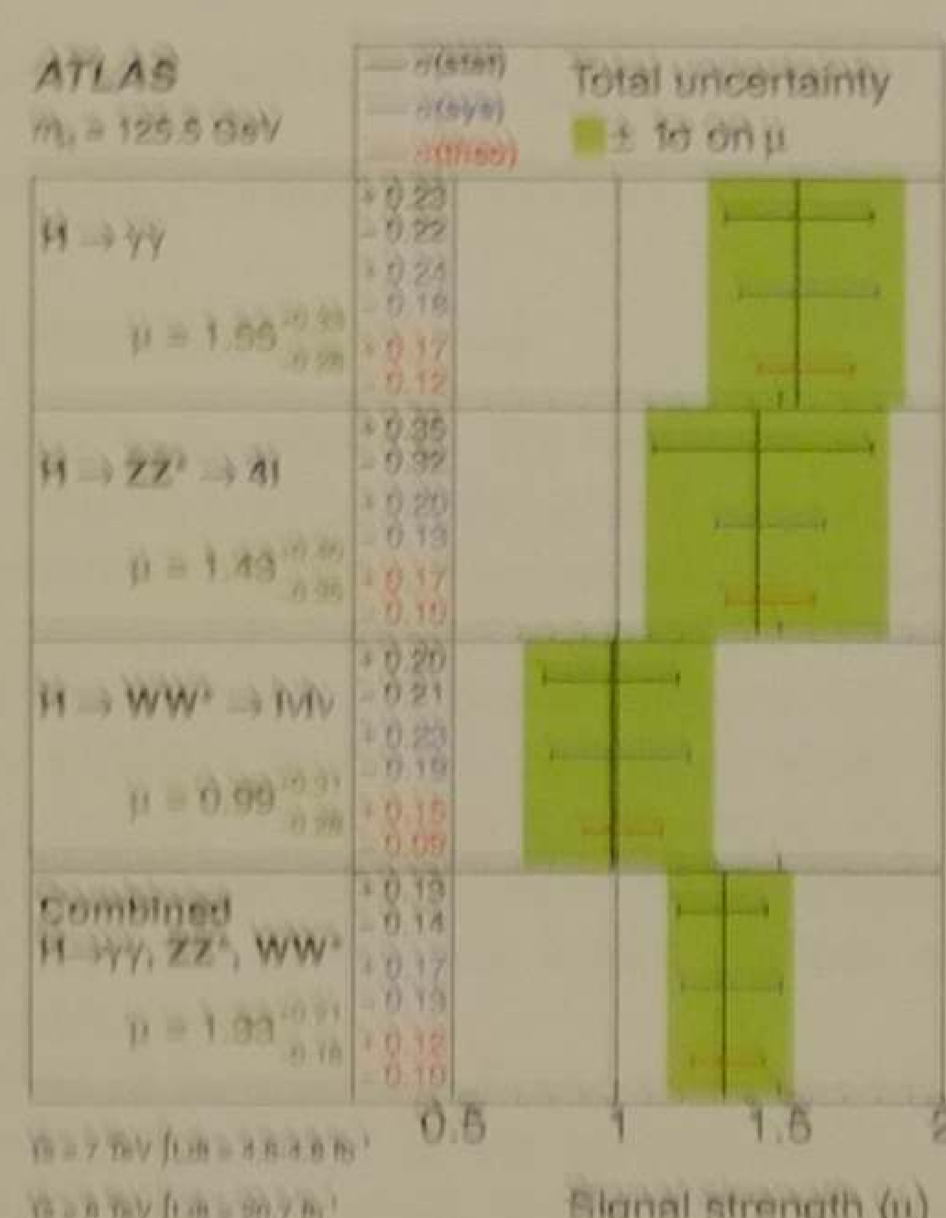

Figure 3: Signal strengths in the $H \to \gamma\gamma$, $H \to ZZ$ and $H \to WW$ decay modes and in the combination of these modes show consistency with the SM [2].

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 prouduction 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 mass is specified all the Standard Model couplings are determined [5]. 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 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 couples. For example in the production of Higgs 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 coupling to gluons, κ_g is defined as a function of the tree level couplings and the Higgs 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 $H \to \gamma\gamma$ 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 $\lambda_{WZ} = 1$.

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, 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 [6], [7]. 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 [8]. 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 analyzing the decay kinematics of the $H \to ZZ^* \to 4\ell$ 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 $H \to ZZ^*$ and $H \to WW^*$ 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 $H \to \gamma\gamma$ 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 behaviour of the exclusion as a function of the production fraction of quark antiquark relative to gluon fusion, this result does not depend on the fraction.

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 measurment 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 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 accomodated within the statistical power of the current sample and hence discovered if they exist in the larger statistical power of the anticipated sample.

Acknowledgments

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