

STUDIES OF THE SM HIGGS BOSON AND SEARCHES FOR BSM HIGGS BOSONS WITH THE ATLAS DETECTOR *

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The ATLAS Collaboration has searched for the Standard Model Higgs boson in the first LHC Run 2 data using 3.2 fb^{-1} at 13 TeV. Results are presented in terms of central values and limits on the total cross section in the four-lepton and $\gamma\gamma$ channels. Several “Beyond Standard Model” theories predict the existence of additional heavy Higgs particles or di-Higgs resonances. Searches are conducted using the $\gamma\gamma$, ZZ , WW and fermionic decay channels, and cover a large range of masses for the hypothetical resonances.

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1. Introduction

The ATLAS detector at the LHC is a multi-purpose particle detector with excellent detection and reconstruction capabilities [1], designed to make precision measurements of known particles and conduct searches for new particles. In particular, there is strong interest in measuring as precisely as possible the parameters of the Higgs boson and searching for a heavy Higgs boson as predicted by a number of theories. This document describes the current status of Higgs boson measurements and gives an overview of the first searches for heavy Higgs bosons using data from the LHC Run 2.

2. Recap of Run 1 Higgs results

During the LHC Run 1, the ATLAS and CMS collaborations discovered a new particle with a mass of approximately 125 GeV [2,3]. All subsequent measurements are compatible with the particle being the Standard Model (SM) Higgs boson. An overview of these measurements is given below.

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The signal strength μ is defined as the ratio of an experimental observation (of cross sections, branching ratios, *etc.*) to the SM prediction. For the Higgs boson [4], one can only measure the combination of the cross section and branching ratio, so the signal strength values for cross sections are extracted by assuming the branching ratio predicted by the SM, and *vice versa*. All measurements of production mechanisms and decay channels are entirely consistent with the SM predictions. The Higgs boson couplings can also be measured directly. One approach is to use a model that treats each coupling independently, assuming only that there are no new particles in loops or decays (as there is no evidence of such particles). A simultaneous fit to the data is used to extract the couplings, characterized by the scales κ_f or κ_V for fermions and vector bosons, respectively. Deviations from unity in these scales represent deviations from the SM predictions: however, the measured couplings show no significant difference from the SM expectation.

The Higgs boson mass [5] is measured in the $\gamma\gamma$ and four-lepton (4ℓ) channels, as these can be fully reconstructed. For the $\gamma\gamma$ channel, the background parameterization is obtained by fitting the invariant mass $m_{\gamma\gamma}$ spectrum in a signal-free control region and the signal is modeled as the sum of a Crystal Ball and a wide Gaussian. For the 4ℓ channel, the reducible background from Z +jets and $t\bar{t}$ is estimated by extrapolating to the signal region from an orthogonal control region, while the irreducible background from SM ZZ production is obtained from Monte Carlo simulations. The current ATLAS–CMS combined value for the Higgs boson mass is $M_H = 125.09 \pm 0.21(\text{stat.}) \pm 0.11(\text{syst.})$ GeV.

A direct measurement of the Higgs boson width is not feasible because the detector resolution of ~ 1 GeV is far larger than the SM prediction of 4.1 MeV. An indirect measurement can be made by exploiting the width-independence of off-shell Higgs boson production for $H \rightarrow VV$ decays [6]. Under certain strong assumptions (on the off-shell couplings and the size of the interference between the $gg \rightarrow VV$ and $gg \rightarrow H^* \rightarrow VV$ processes), the ratio of the off-shell and on-shell Higgs boson signal strength yields a measurement of the width. Using these assumptions, an upper limit of 22 MeV for the Higgs boson width is obtained.

To probe the spin and CP of the new particle, an effective field theory (EFT) approach is used, considering three scenarios: spin 2, 0^- or BSM 0^+ , and a mixture of 0^- and 0^+ states [7] (spin 1 is excluded due to the observation of $H \rightarrow \gamma\gamma$ decays). Each scenario is defined by using the Higgs boson characterization model: values of the couplings are probed via the kinematic properties of $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ^* \rightarrow 4\ell$, and $H \rightarrow WW^* \rightarrow e\nu\mu\nu$ decays. Each spin–parity hypothesis is evaluated using distributions of a test statistic q , the ratio of the profiled SM likelihood to the profiled likelihood for the tested hypothesis, obtained from Monte Carlo pseudo-experiments: all non-

SM hypotheses are excluded at $> 99\%$ confidence. The tensor structure of the HVV interaction is also probed: confidence intervals on the parameters are derived using a test statistic equal to minus twice the log of the profiled likelihood. All results are consistent with the SM within uncertainties.

3. Run 2 results

In 2015 the ATLAS experiment took its first data at $\sqrt{s} = 13$ TeV, an integrated luminosity of 3.2 fb^{-1} useful for physics. This higher center-of-mass energy allows ATLAS to probe higher masses for possible new particles and to make precision measurements with less data than for Run 1. Higgs-boson results and BSM Higgs boson searches are described below.

3.1. The SM Higgs boson in Run 2

Due to the limited size of the dataset, significant improvements on the Run 1 measurement are not yet possible. Figure 1 [8] shows the Higgs boson cross-section measurement at each value of $\sqrt{s}$: uncertainties on the 13 TeV measurements are still large. A 3.4σ significant measurement (assuming SM yields) was expected but the observation was only 1.4σ . Given the relatively small amount of data and the correspondingly large statistical uncertainty, compatibility with the SM is maintained at the 1.3σ level.

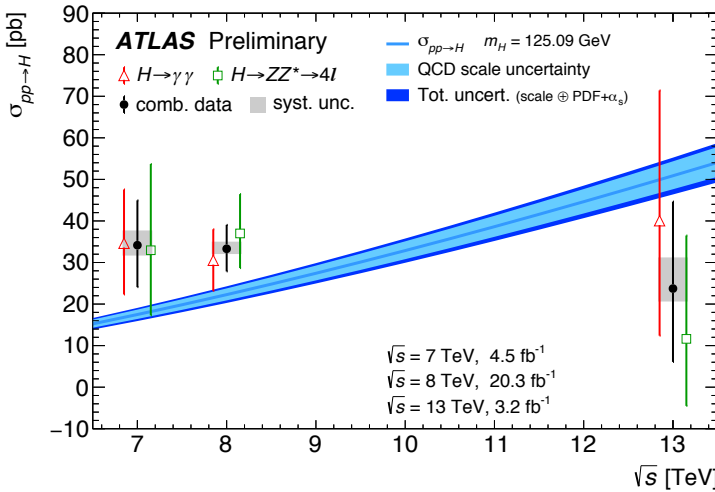


Fig. 1. ATLAS Higgs boson cross-section measurements *vs.* $\sqrt{s}$ from Ref. [8].

3.2. Searches for heavy Higgs bosons

Despite the relatively small amount of data taken in 2015, it does allow for searches for heavy Higgs bosons to take place at higher masses than were possible in Run 1. Such searches are motivated by the presence of a heavy Higgs boson in many of the theories, such as the electroweak singlet model [9] or the two-Higgs doublet model [10], that attempt to resolve issues such as the hierarchy problem or the origin of dark matter. Below, a number of searches in various channels for high-mass Higgs bosons are described.

Searches can be performed by simply extending a low-mass Higgs boson analysis to higher masses, as in the case of the 4ℓ channel in the 200 GeV–1 TeV range [11]. In this mass range, SM ZZ^* production, taken from Monte Carlo simulation, is by far the dominant background with small contributions from Z +jets, $t\bar{t}$, and VVV . The data match the background predictions quite well.

Other analyses attempt to exploit features of the decay of heavy particles. In particular, should a heavy Higgs boson decay to two bosons, both will be significantly boosted, meaning that hadronic decays of such bosons will not be resolved. The resulting large jets can be reconstructed using the anti- k_t algorithm and then trimmed [12] to remove contributions from underlying event and pileup. Based on the mass and distribution of energy within the jet, the original boson mass can be recovered: multiple searches based on this method have been carried out. One such search is for a heavy Higgs boson decaying to ZZ , with one Z boson reconstructed as a large jet and the other decaying to e^+e^- or $\mu^+\mu^-$, or $\nu\bar{\nu}$ [13, 14]. As the neutrino momenta cannot be reconstructed, that search uses a transverse mass as its observable: for the leptonic Z decay, the observable is the mass of the dilepton–jet system. A similar search can be carried out in WW final states where one W boson decays hadronically into a large jet and one decays leptonically [15]. The search uses the observable $m_{l\nu J}$ as the neutrino momentum can be estimated by requiring that the mass of the l – ν system be the mass of the W . Finally, this method can be used to search for the decay of a high-mass CP-odd boson $A \rightarrow HZ$ [16]. In this case, it is the hadronic decay of the Higgs boson that is reconstructed as a large jet, while the Z boson is required to decay to e^+e^- or $\mu^+\mu^-$. As the Higgs boson is likely to decay to a pair of b quarks, b -tagging is used to enhance the sensitivity of the measurement. For all of these searches, V +jets and $t\bar{t}$ are the dominant backgrounds. In all cases, the data match the background predictions.

Other searches have a more direct theoretical motivation. For large $\tan\beta$ values, the MSSM favors $H \rightarrow \tau\tau$ decay, hence there is a strong interest in this channel. Searches have been performed for the cases in which at least one τ decays hadronically [17]. As direct reconstruction of the di- τ mass is not possible due to the neutrinos in the final state, a total transverse mass

is used. The dominant backgrounds are misidentified jets, $Z \rightarrow \tau\tau$, and top quark production. Once again, the background predictions match the data, and no evidence is found to support the hMSSM scenario, among others.

The currently most interesting search is for heavy $H \rightarrow \gamma\gamma$ [18]. Photons are identified using tight criteria, and photon energies are measured to better than 2%. Photon trajectories are obtained from the longitudinal segmentation of the calorimeter: based on these trajectories, a neural network finds their vertex of origin to within 0.3 mm over 80% of the time. Isolation requirements are used to remove jet backgrounds, yielding a final diphoton purity of over 90%, with a signal efficiency between 25 and 45%. Signal and background yields are then determined by fitting analytical descriptions to the measured $m_{\gamma\gamma}$ spectrum. The result is shown in Fig. 2: an excess at 750 GeV, with a local and global significances of 3.6σ and 2.0σ respectively, is visible. A maximum global significance of 2.3σ is obtained for a width of 45 GeV.

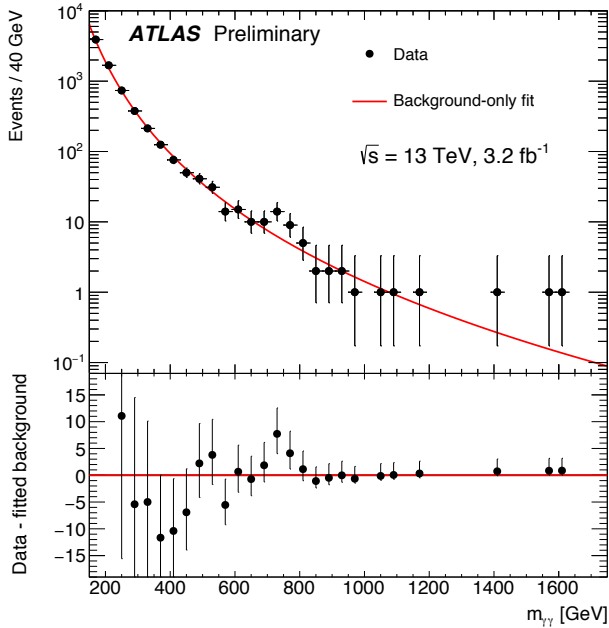


Fig. 2. Observed $m_{\gamma\gamma}$ spectrum at $\sqrt{s} = 13$ TeV in Ref. [18].

4. Summary and outlook

Over the past few years, significant progress has been made on characterizing the Higgs boson. Its mass has been precisely measured and its spin, CP, and couplings have been shown to be in good agreement with the SM

predictions. Although no high-mass Higgs boson has been found yet, the 750 GeV excess in the $\gamma\gamma$ channel is intriguing, and the higher Run 2 $\sqrt{s}$ is already allowing us to set limits more stringent than those obtained in Run 1. By August, the 13 TeV data is expected to have roughly the same statistical power as the full Run 1 dataset, and the end of the year expectation of $\sim 25 \text{ fb}^{-1}$ will double it. This new data should enable more powerful searches and bring interesting new results.

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