PROCEEDINGS OF SCIENCE

Measurement of the Higgs Boson Mass

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Measurements of the Higgs boson mass in Higgs boson decays to two photons or four leptons, as well as their combination, based on pp collision data collected at 13 TeV by the ATLAS Collaboration are presented.

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1. Introduction

The mass of the Higgs boson is a free parameter of the Standard Model (SM) and, as such, an important ingredient in SM predictions of Higgs boson physics. As an increasing quantity of LHC data makes precision measurements of Higgs boson properties possible, precise measurements of the Higgs boson mass become more and more important. Previously, data taken during the LHC Run-1 by both the ATLAS and CMS experiments was used to obtain a value of $125.09 \pm 0.21(\text{stat}) \pm 0.11(\text{syst})$ GeV for the mass [1]. Recently, the ATLAS experiment re-measured the Higgs boson mass using 36 fb^{-1} of data taken at $\sqrt{s} = 13$ TeV in 2015 and 2016 [2], using the $H \to ZZ^* \to 4\ell$ and $H \to \gamma\gamma$ decay channels: a brief overview of this measurement in both channels is presented below.

2. Measuring Particle Momenta

The ATLAS detector is a multi-purpose particle detector with excellent detection and reconstruction capabilities [3]. These capabilities are essential to precisely measure the Higgs boson mass, as the achievable precision will be constrained by the precision with which the decay products – muons, electrons, and photons in the cases of the two decay channels used – can be measured. Furthermore, the signal model to be fit to the data is built from simulations, making it very important that the simulation accurately model the response of the detector.

Muon tracks are reconstructed separately in the Muon Spectrometer (MS) and Inner Detector (ID), and then a combined fit including all hits and energy lost in the calorimeter is performed [4]. The muon resolution and p_T scale, up to a p_T of 300 GeV, are measured in $Z \to \mu\mu$ and $J/\psi \to \mu\mu$ decays. Simulated momenta are corrected and smeared to match the data, using factors obtained by fitting to data. The resulting uncertainties on the p_T scale, largely from the energy loss in the calorimeter, detector material and radial distortions, and fluctuations in the magnetic field, are quite small, less than 0.05% (0.2%) in the barrel (endcaps). The resolution is measured to a precision of 2% (10%) in the barrel (endcaps). Uncertainties increase at lower and higher values of p_T. Additionally, a correction is applied to account for misalignments in the ID that produce charge-asymmetric effects on the measured p_T: this improves the $Z \to \mu\mu$ resolution by 1-5%.

The momenta of electrons and photons are measured similarly [5]. Reconstruction of both particles starts with clusters in the electromagnetic calorimeter, to which a track (electrons), a conversion vertex (converted photons), or nothing (unconverted photons) can be matched: different calibration corrections are derived for each. The data are corrected to ensure that the calorimeter response matches that in simulation, and then a calibration is applied based on an MVA, trained on simulated samples, that corrects for energy loss in front of the calorimeter, punch-through, shower leakage, and cluster response variation. The data are further corrected to account for geometrical variations in the calorimeter before the scale and resolution are measured in $Z \to ee$ decays. Finally, the data energy scale is corrected to match simulation, while the simulated resolution is corrected to match the data. For particles with $p_\mathrm{T} < 300$ GeV, the uncertainty on the scale is less than 0.1% (0.5%) for electrons (photons), increasing at lower and higher p_T values: it stems largely from the relative calibration of the calorimeter layers, the material, the energy response linearity, and shower shape differences between electrons and photons.

3. Mass Measurement in the $H \to ZZ^* \to 4\ell$ Channel

The requirement of four leptons in the final state greatly suppresses backgrounds, allowing leptons that pass loose requirements on quality and isolation to be accepted, and the p_{T} range to be extended down to 7 GeV for electrons and 5 GeV for muons. A constraint on the four-lepton vertex provides further background rejection. The remaining backgrounds consist of non-resonant SM ZZ^* production – the dominant background, estimated from simulation – and reducible backgrounds mainly from Z+jets and $t\bar{t}$ events, which are estimated using data-driven methods. FSR photons are identified and included in the mass calculation. The mass is measured using the per-event response method, which takes into account the variations in the response of each event, important for small data sets where fluctuations in the response cannot be expected to even out. The method models the response of each lepton (binned by $|\eta|$ and E) as the sum of three Gaussians by performing a fit to the simulated lepton response $\frac{E_{reco}-E_{truth}}{E_{reco}}$. The four-lepton response is obtained by convolving the responses of the leptons together: the resulting $81(=3^4)$ Gaussians can be reduced to four without losing significant information. The four-lepton response is then convolved with the Higgs boson lineshape, a Breit-Wigner (BW) function, to obtain the event probability distribution function (PDF), and the overall PDF is the convolution of all event PDFs. The method is validated on $Z \to 4\ell$ events. A template method, in which the signal PDF is obtained by interpolating smoothed distributions from simulations at different Higgs boson mass values, is used as a cross-check: the uncertainties obtained from the per-event response method are about 3% smaller.

The mass resolution is improved by about 15% by kinematically constraining the mass of the leading lepton pair using a BW with mean m_Z. Dividing the data by final state (4μ, $2\mu 2e$, $2e2\mu$, or 4e), and then into four bins obtained from a BDT trained to separate gluon-gluon fusion production (the main signal) from ZZ^* (the main background), gives an 8% improvement thanks to increased significance. The background is modeled by smoothing the m_{4l} distribution obtained from simulated samples. The final result is obtained from a simultaneous fit over all the categories.

4. Mass Measurement in the $H \to \gamma\gamma$ Channel

$H \to \gamma\gamma$ events are obtained by imposing strict requirements on the quality and isolation of the photons. The diphoton vertex is chosen from the vertices in the event using a neural network trained on simulated data. Events are then sorted into 31 exclusive categories based on the properties of the photons and of the other objects in the event. The backgrounds arise largely from non-resonant SM diphoton production, as well as events in which at least one jet fakes a photon. They are parameterized with a functional form depending on the category: the form is chosen to ensure a small fitted signal yield when fitting to background-only simulated samples. The signal in each category is modeled as a double-sided Crystal Ball function, with parameters that are linear functions of m_H. The dependence of the parameters on m_H is obtained from a simultaneous fit to samples simulated at different m_H values. The cross-section for each production mode and the branching ratio are also parameterized as a function of the Higgs boson mass. The result is obtained from a simultaneous fit over all categories, and cross-checked by allowing the mass value to float in different, detector-defined categories, and calculating the global p-value between the masses obtained in these categories and that obtained from the simultaneous fit.

5. Results and Conclusion

An overview of all ATLAS measurements of the Higgs boson mass can be found in Figure 1. In the 4ℓ channel, the Run-2 uncertainty of 0.37 GeV is compatible with the expected uncertainty of 0.35 GeV. The muon momentum scale and electron energy scale are the dominant systematic uncertainties, though the measurement in this channel is still statistics-limited. By contrast, the result in the $\gamma\gamma$ channel is dominated by systematic uncertainties from the photon energy scale. In both channels, a combination with the Run-1 result is performed, providing a slight increase in precision. Systematics are correlated where possible (though the dominant piece of the photon energy scale systematic uncertainty, that associated to electromagnetic calorimeter cell non-linearity, cannot be correlated as it was calculated by different methods), but the signal strength is not correlated. Finally, the results in the two channels are combined, with electron and photon calibration systematics correlated between them but the signal strength left free. The final result of $m_H = 124.97 \pm 0.24$ GeV is compatible with the Run-1 combined CMS+ATLAS result and represents a precision of 0.2% on this important SM parameter.

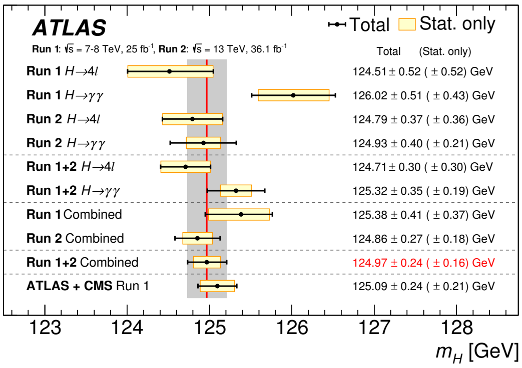

Figure 1: Higgs boson mass as measured in various datasets and channels by the ATLAS Collaboration compared with the combined ATLAS+CMS result from Run-1 [2].

References

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