PROCEEDINGS OF SCIENCE

Measurements of Higgs boson properties with the ATLAS detector

Luca Franco on behalf of the ATLAS Collaboration

Nikhef - National Institute for subatomic physics,
Science Park 105, 1098 XG Amsterdam, the Netherlands
High energy physics department, Radboud University,
Heyendaalseweg 135, 6525 AJ Nijmegen, the Netherlands

E-mail: luca.franco@cern.ch

The most recent measurements of the properties of the Higgs boson, including its mass, total width, and *CP* quantum number, performed by the ATLAS experiment at the Large Hadron Collider (LHC), are reported. The measurements are performed in various Higgs boson production and decay modes, as well as their combinations. Observation of deviations between these measurements and Standard Model (SM) predictions would be a sign of possible new phenomena beyond the SM.

The 43rd International Symposium on Physics in Collision (PIC2024)
22–25 October 2024
Athens, Greece

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PoS(PIC2024)014

1. Introduction

The Higgs boson has a central role in the Standard Model (SM) of particle physics. Its existence was predicted by the theory for the first time more than 60 years ago and only about 10 years ago it was observed by the ATLAS [1] and CMS experiments at the Large Hadron Collider (LHC) [2, 3]. Since then, physicists have been wondering if the observed particle is really the SM Higgs boson or maybe an indirect sign of new physics. The mass m_H, the width Γ_H, and the *CP* properties of the Higgs boson interactions can all give hints to a new type of physics, which goes beyond the SM (BSM).

The value of m_H is not predicted by the SM and therefore is one of its free parameters. Once measured in our experiments, also the strength of the interaction with other SM particles is known. Furthermore, by measuring m_H, one can infer whether the universe is in a stable, minimum-energy state of the Higgs field potential, or in a metastable one, from which it might transition to the ground state in the future.

Since the Higgs boson is an unstable particle, it lives only a fraction of a second before it decays. Measuring a value of the total decay width Γ_H deviating from the SM prediction could be potentially explained by the presence of new unobserved particles. These can either be new decay final states that are invisible to our detector or can modify the interaction between the Higgs boson and other SM particles at loop level.

The Higgs boson in the SM is a scalar particle with spin 0 and is even under *CP* transformations. However, couplings which are a mixture of *CP*-even and *CP*-odd states have not been ruled out yet and can represent a source of *CP*-violation in the Higgs sector. Such violations could contribute to explaining the matter-antimatter asymmetry of the universe.

The following sections contain the most recent results on the measurements of the Higgs boson properties obtained by the ATLAS collaboration. The results are based on an integrated luminosity of 140 fb^{-1} of proton-proton collision data at a center-of-mass energy of 13 TeV recorded by the ATLAS detector during the second run of the LHC and, in some cases, in combination with the dataset from LHC Run 1.

2. Meaurements of the Higgs boson mass

The analysis of diphoton decay events ($H \to \gamma\gamma$) is optimal for measuring the Higgs boson mass, thanks to the excellent invariant mass ($m_{\gamma\gamma}$) resolution (about 1 GeV) that ATLAS has achieved in this channel. In Ref. [4], selected diphoton events are split into 14 categories according to the properties of the photon candidates, minimizing the total uncertainty on m_H. In each category, the resonant $H \to \gamma\gamma$ signal and the non-resonant QCD background are modeled using analytic functions, appearing as a narrow peak over a smoothly falling continuum in the $m_{\gamma\gamma}$ spectrum. After a simultaneous fit to the data distributions in the 14 categories, the value of m_H is extracted from the position of the peak. Nuisance parameters related to the photon energy scale systematic

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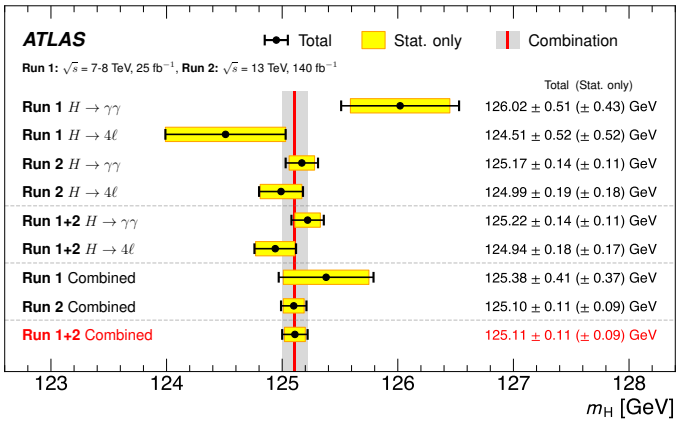

Figure 1: Summary of m_H measurements from the individual $H \to \gamma\gamma$ and $H \to 4l$ channels and their combination [6].

uncertainties may also affect the position of the peak, potentially making the measurement less precise. Thanks to a new method for the calibration of the photon energy, the impact of these systematics has been reduced by a factor of 4, with respect to the last m_H measurement performed in the same channel.

This new calibration was recently released by ATLAS and it is based on full Run 2 data [5]. This includes a better understanding of the liquid argon calorimeter readout response, an enhanced inter-layer energy calibration, and an improved description of the lateral development of the electromagnetic showers. Using a well-known physics process, the Z boson decay into an electron-positron pair, the data-MC simulation calibration scale factors are derived. A novel approach was introduced, called energy linearity, for which the scale factors depend on the energy of the particle. This way, calibration uncertainties were further constrained and we got a more precise calibration model, with a 0.2% precision on the energy scale of photons coming from the Higgs boson.

The results of the $H \to \gamma\gamma$ analysis are shown in Figure 1, together with those obtained by the other channel with the best resolution, namely the Higgs boson to four leptons ($H \to 4\ell$). The plot is a summary of all the ATLAS measurements in these channels, in Run 1 and Run 2, and their combinations [6]. The most complete result yields a value of m_H 125.11 ± 0.11 GeV, with an uncertainty at the level of one per mill. This unprecedented level of precision couldn't be possible without the commitment of our collaboration to a deep understanding of the detector and the calibration of its response.

3. Constraints on the Higgs boson total width

The SM expected value of Γ_H is 4.07 MeV, which is three orders of magnitude smaller than the resolution that we can achieve in our detector, which is about 1 GeV in our best channels, like $H \to 4\ell$. For this reason, a direct measurement fitting the lineshape of the Breit-Wigner is not really an option at the LHC. On the other hand, an indirect approach can be used for this purpose,

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which exploits the production of an off-shell Higgs boson. Off-shell production becomes accessible at large energy scales, i.e. far from the on-shell resonant peak at approximately 125 GeV, due to the opening up of vector-boson interactions and top-quark loops that lead to enhanced production. The production cross section in the off-shell region doesn't depend on the width, while the production cross section in the on-shell region does. Thanks to this feature, Γ_H can be extracted from the ratio of observed Higgs boson events, as shown in Eq. 1.

$$\sigma^{\text{on-shell}}_{gg\to H\to ZZ} \sim \frac{g^2_{\text{ggF}} g^2_{\text{HZZ}}}{m_H \Gamma_H};\ \sigma^{\text{off-shell}}_{gg\to H\to ZZ} \sim \frac{g^2_{\text{ggF}} g^2_{\text{HZZ}}}{m^2_{ZZ}} \implies \frac{\sigma^{\text{off-shell}}}{\sigma^{\text{on-shell}}} \propto \Gamma_H \tag{1}$$

This procedure relies on the assumption that the Higgs boson couplings have the same strength in the on-shell and in the off-shell regions. The process where an off-shell Higgs boson is produced and then decays to a pair of on-shell Z bosons has the same initial and final state as the non-resonant production of two on-shell Z bosons. This generates quantum interference between these processes, that has destructive effects on the cross section. In practice the signal of off-shell Higgs boson production manifests itself as a deficit in the invariant mass distribution of the final state [7].

The ATLAS $H \to ZZ$ off-shell analysis [8] is performed in two channels: in the 4 lepton channel, the output distribution of a neural network which enhances the signal is fitted. In the other channel, targeting the final state with two leptons and two neutrinos, the transverse mass of the ZZ system is the fit observable. After combination with the $H \to ZZ$ on-shell analysis, a measurement of the Higgs boson decay width can be done. The observed value is $4.5^{+3.3}_{-2.5}$ MeV and is mainly limited by statistics and the systematic uncertainty of theoretical modeling. An upper limit of 10.5 MeV on the value of Γ_H has also been set at 95% confidence level.

The Higgs boson total width was constrained by ATLAS using an alternative approach as well, which consists of an interpretation in terms of Γ_H of the recent measurements of Higgs boson production in association with a top-quark pair ($t\bar{t}H$) and the production of four top quarks ($t\bar{t}t\bar{t}$) [9]. As shown in Figure 2, $t\bar{t}t\bar{t}$ involves contributions from off-shell Higgs boson-mediated processes and can be used in combination with $t\bar{t}H$ where the Higgs boson is produced on-shell instead. This method also relies on the assumption that Htt couplings are the same in the off-shell and on-shell cases. However, this assumption is more robust with respect to the case involving effective Hgg couplings, which could contain BSM colored particles entering the Hgg loop and impacting the interaction differently in the off-shell and on-shell cases. The analysis constrained simultaneously the value of the Htt coupling strength (κ_t) and the Higgs boson total width, resulting in an upper limit on Γ_H of 160 MeV at 95% confidence level. The precision of this result is not very competitive with respect to similar studies, however, it can be considered complementary as it explores different model assumptions and contributes to our understanding of the Higgs boson width. In fact, it is for the first time that Γ_H was constrained using processes involving the top-quark Yukawa coupling.

4. Meaurements of the Higgs boson *CP* properties

ATLAS investigated possible *CP*-violations in the Higgs boson interaction with vector bosons (HVV). As shown in Eq. 2, a *CP*-odd component in the Higgs boson coupling to electroweak

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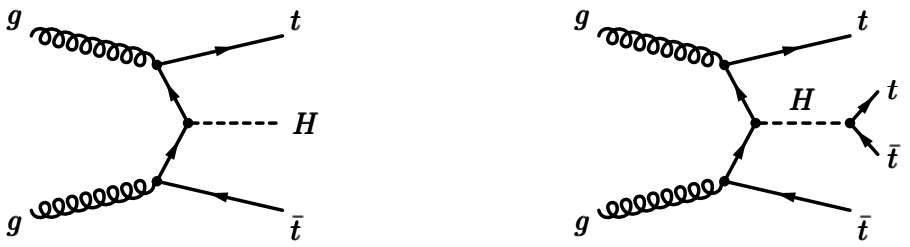

(a) (b)

Figure 2: Example leading-order Feynman diagrams for the (a) $t\bar{t}H$ and (b) Higgs-mediated $t\bar{t}t\bar{t}$ processes.

bosons can be described by adding dimension-6 operators $O_i^{(6)}$ to the SM Lagrangian $\mathcal{L}_{\text{SM}}$, using an effective field theory (EFT) approach:

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i}{\Lambda^2} O_i^{(6)} \ , \tag{2}$$

where the c_i are the corresponding dimensionless real coupling constants, the Wilson coefficients and Λ is the energy cutoff scale of the EFT.

The ATLAS $H \to ZZ \to 4\ell$ analysis used the method of the Optimal Observable [10] to test the *CP* invariance of the HVV coupling where both production level and decay level optimal observables were used. The aim of the analysis was to put constraints on the values of those Wilson coefficients responsible for a possible *CP* violation.

Ref. [11] contains an interpretation of the differential cross-section measurements in the channel where the Higgs boson decays into a pair of τ-leptons ($H \to \tau\tau$) using the SM EFT approach. The *CP*-odd operators that affect the HVV coupling are studied through the vector boson fusion (VBF) production mode. VBF jets are selected requiring high invariant mass and large pseudorapidity separation between them. The distribution of the angular distance between the two, versus the transverse momentum of the Higgs boson, is used to gain sensitivity to *CP*-odd Wilson coefficients like the $c_{H\tilde{W}}$, for which the tightest constraint to date was obtained. A summary of the results for *CP*-odd EFT coefficients is given in Figure 3.

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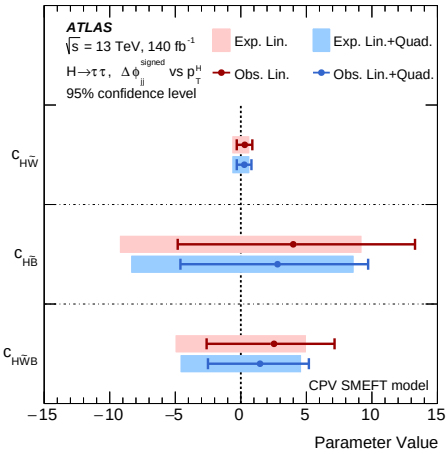

Figure 3: The 95% expected and observed confidence intervals for each of the three Wilson coefficients associated with the EFT *CP*-odd operators considered in the $H \to \tau\tau$ VBF analysis [11].

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