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Higgs boson mass and width measurement at CMS

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The characterisation of the Higgs boson relies on the determination of its properties, including its mass, which is a free parameter in the SM, and its width. Here we review the latest measurements of the Higgs boson mass and width in the four-lepton final state at a center-of-mass-energy of 13 TeV with the CMS detector. The most precise measurement of the Higgs boson mass in a single channel $m_H = 125.04 \pm 0.12$ GeV is derived using the full CMS Run 2 data set corresponding to a total luminosity of 138 fb^{-1}. The resulting on-shell mass measurement leads to an upper limit on the Higgs boson width of $\Gamma_H < 60$ MeV at 68 % confidence level. By combining the on-shell and the off-shell measurements in the four-lepton final state, the value of the Higgs boson width of $\Gamma_H = 2.9^{+2.3}_{-1.7}$ MeV is obtained.

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1. Introduction

The discovery of a particle [1–3] compatible with the Higgs boson of the Standard Model (SM) with a mass around 125 GeV was jointly announced by the ATLAS and CMS [4] Collaborations in 2012. This observation has been followed by a decade-long investigation of the properties of the Higgs boson during the different LHC run periods at a center-of-mass energy $\sqrt{s}$ = 7, 8, 13 and 13.6 TeV. The mass of the Higgs boson is a fundamental, free parameter of the SM whose value must be determined experimentally with high precision as it determines all its other properties, in particular the phenomenology of its production and decay modes. For instance, the coupling of the vector bosons to the Higgs boson depend on m_H and are predicted precisely by the SM. Therefore, an accurate measurement of the Higgs boson mass, jointly with the determination of the Higgs boson production cross section and decays constitutes a self-consistency test of the SM. In addition, a precise measurement of the Higgs boson mass is crucial to determine the fate of the electroweak vacuum stability [5]. The Higgs boson width is precisely predicted for a given value of m_H. A narrow width of Γ_H = 4.1MeV is predicted in the SM, due to the tiny couplings of the Higgs boson to the observed SM particles. The potential presence of not yet discovered BSM particles, foreseen for instance in Higgs portal models, could enhance the value of Γ_H. In this work, we review the most recent measurement [6] of the Higgs boson mass and direct constraint on the width in the $H \to ZZ^* \to 4l$ channel with the full CMS LHC Run 2 data corresponding to an integrated luminosity of 138fb^{-1} at $\sqrt{s}$ = 13 TeV. In addition, the indirect constraint on the Higgs boson width with the off-shell method in the $H \to ZZ^* \to 4l$ channel will also be discussed.

2. The Higgs boson mass measurement

A precision measurement on the Higgs boson mass can be performed at the LHC in the bosonic channels $H \to ZZ^* \to 4l$ and $H \to \gamma\gamma$ owing to their excellent mass resolution and fully reconstructible final state. An accuracy of better than 2 per-mille in the mass measurement was achieved during the LHC Run 1 [7] by combining data from the measurements with the CMS and ATLAS detectors. In addition, the CMS Collaboration performed an on-shell and mass measurement in the $H \to ZZ^* \to 4l$ channel using the CMS 2016 data set with a total luminosity of 35.9fb^{-1} [8] at 13 TeV. In this analysis, the signal extraction fit was obtained using three observables for the statistical modelling: the invariant mass m_{4l} of the four-lepton system, the kinematic discriminant D^{kin}_{bkg}, defined using the Matrix Element (MELA) approach from the ratio of probabilities of the signal $P_{H\to 4l}$ and background $P_{q\bar{q}\to 4l}$ processes:

$$D^{kin}_{bkg} = \frac{P_{H\to 4l}}{P_{H\to 4l}, + P_{q\bar{q}\to 4l}}, \quad (1)$$

needed to distinguish the kinematics of the Higgs decay products from the dominant QCD background ($q\bar{q}$ annihilation), and the per-event mass resolution uncertainty δ_{4l}. The latter is derived by combining the momentum uncertainty in the reconstruction of each final state lepton. In the case of muons, the full covariance matrix is computed from the track fit procedure, while for electrons, the momentum uncertainty is extrapolated by combining the information of the ECAL and Tracker.

Several improvements are introduced in the strategy of the CMS analysis with the full LHC Run 2 data set, collected from 2016 to 2018[6] with respect to the result with the 2016 data set [8]. In the

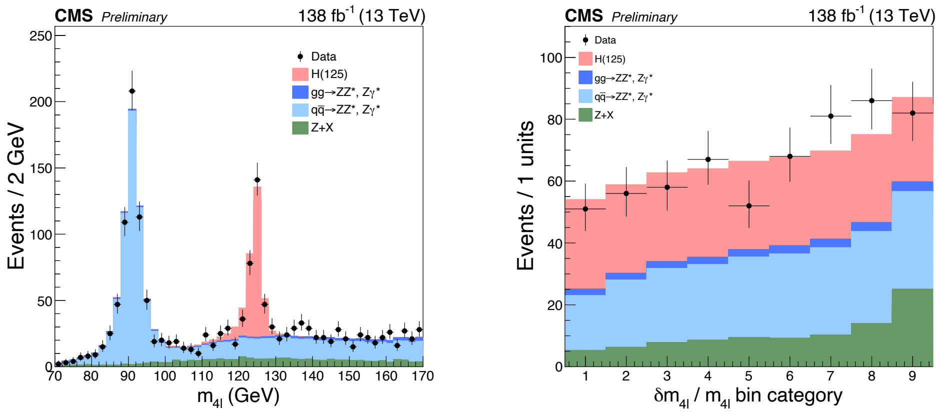

Figure 1: Invariant mass distribution for the four-lepton system for all final states (left) and in each category of mass resolution uncertainty δ_{m4l} with equivalent signal yield [6].

mass and on-shell width measurement, a vertex-beamspot constraint is applied to adjust the muon kinematic parameters such that all four lepton tracks must arise from a common vertex compatible with the beamspot. Electrons are not modified since their momentum is mostly determined from ECAL energy deposit measurements rather than track curvature, hence applying a constraint would have a negligible effect. Depending on the flavour of the final state, the beamspot constraint further improves the mass resolution by 3-8%. The events are categorized into 9 bins with comparable signal yield to isolate events with better mass resolution to improve the Z-lineshape, as illustrated in Figure 1. In addition, a kinematic fit performed using a mass constraint on the intermediate on-shell Z resonance is enforced to improve the mass resolution. The Z_1 candidate, whose mass is closest to the nominal Z-peak value, is selected to be the on-shell boson, while the other Z-boson candidate has a broader mass peak whose width exceeds the detector resolution. The lepton daughters p_T stemming from the Z_1 candidate are re-evaluated under the constraint that the reconstructed Z boson must follow the true Z-lineshape.

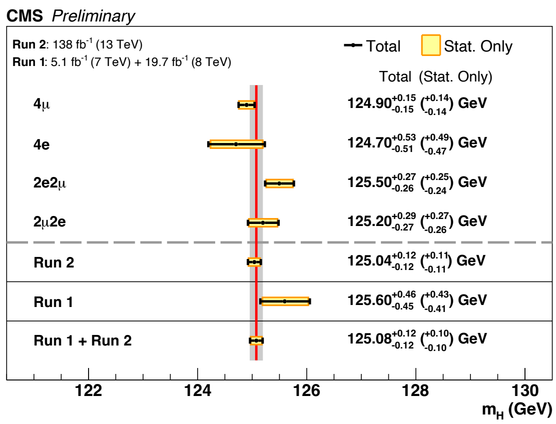

Figure 2: Summary of the Higgs boson mass measurement in the four-lepton channel using CMS data collected during LHC Run 1 and Run 2, and their combination, respectively [6].

The resulting measured mass value is $m_H = 125.04 \pm 0.12[0.11(\text{stat}) \pm 0.05(\text{syst})]$ GeV [6], which is the most precise measurement of the Higgs boson mass from a single channel at the LHC. The inclusion of the Z_1 mass kinematic refit plus the beamspot constraint improves the mass measurement by 15%, while using as observables the kinematic MELA discriminant and the per-event mass resolution contribute respectively 4% and 10%. This measurement is statistically limited and the dominant systematic uncertainties arise from the lepton energy scale, with an impact on the uncertainty of 30(40 MeV) for muons(electrons), respectively. The results are further combined with the Run 1 CMS data at $\sqrt{s} = 7$, 8 TeV yielding a measurement of $m_H = 125.08 \pm 0.12[0.10(\text{stat}) \pm 0.05(\text{syst})]$ [6] leading to an overall improvement driven by the higher statistical precision. Figure 2 presents a summary of the Higgs boson mass measurements with CMS data in the $4l$ channel for all the final states considered.

3. The Higgs boson on-shell and off-shell width measurement

In the on-shell measurement, the Higgs boson width can be directly constrained by analysing the reconstructed lineshape in the $H \to ZZ^{(*)}$ channel. The experimental mass resolution is of the order of 1-2 GeV, which is much larger than the expected width of SM Higgs boson. The main challenges of this measurement are the modelling of resolution uncertainties and of the interference between the signal and the continuum background. The resulting direct upper bound derived using the CMS Run 2 data set [6] on the width is $\Gamma_H < 330$ MeV at 95 % confidence level, which is approximately $80 \times \Gamma_{SM}$.

An indirect constraint on the value of Γ_H can be obtained by constraining simultaneously the on-shell and the off-shell couplings in bosonic channels as illustrated in [6]. In this off-shell method, the signal strength for the on-shell ($\mu_{\text{on-shell}}$) and off-shell ($\mu_{\text{off-shell}}$) production can be parameterized as a function of the coupling modifiers κ_g and κ_V in the main process $gg \to H \to ZZ^{(*)}$. An indirect constraint on the Higgs boson width can be obtained by taking the ratio of the off-shell to the on-shell yield, i.e.:

$$\Gamma_H/\Gamma_{SM} = \frac{\mu_{\text{off-shell}}}{\mu_{\text{on-shell}}}, \tag{2}$$

assuming the absence of BSM contributions, the theoretical knowledge of the coupling ratio between the on-shell and the off-shell couplings, and the dominance of the top quark loop in the ggF production. In the off-shell region, defined with the requirement $m_{4l} > 340$ GeV, the continuum background from the $gg \to ZZ$ process interferes destructively with the electroweak $H \to ZZ$ production. Events are categorised in three categories targeting each production mode, i.e. VBF, VH and ggH, using a set of dedicated kinematic discriminants to parameterize the signal strength modifier $\mu_{F,\text{off-shell}}$ of the Higgs coupling to fermions via the top loop (ggF) and $\mu_{V,\text{off-shell}}$ to vector bosons (electroweak) in the combined likelihood fit. The measured value of the Higgs boson width using the ratio of the off-shell to the on-shell production rates is observed to be $\Gamma_H = 2.9^{+2.3}_{-1.7}$ MeV. Figure 3 shows the projection of the profile likelihood on the Higgs boson width with the combination of the on-shell and off-shell production as well as the combined two-dimensional likelihood scan in the off-shell signal strength modifiers μ_F and μ_V.

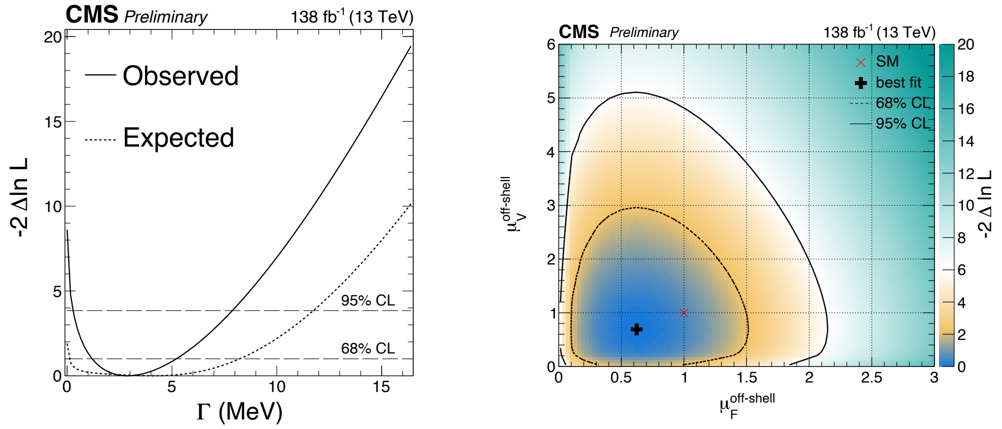

Figure 3: Profile likelihood projection on the Higgs boson width with the off-shell method (left) and two-dimensional likelihood scan on the off-shell signal strength modifiers μ_F and μ_V (right) [6].

4. Summary

The measurements of the Higgs boson mass and width by the CMS Collaboration in the four-lepton channel have been reviewed. The most accurate measurement of the Higgs boson mass in a single channel was obtained with the LHC Run 2 data, with a precision at the per-mille level, owing to the reduction in lepton momentum scale systematic uncertainties, the improvement in the analysis strategy and the increased statistical precision. The observed constraint on the Higgs boson width from the on-shell production in the four-lepton channel was found to be $\Gamma_H < 60$ MeV at 68% confidence level. The most accurate width measurement is extrapolated by comparing the on-shell and the off-shell production rates, leading to a value of $\Gamma_H = 2.9^{+2.3}_{-1.7}$ MeV, which is compatible with the SM expectation of 4.1 MeV.

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