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Higgs boson mass, width, CP and anomalous couplings measurements at CMS

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The CMS experiment at the Large Hadron Collider (LHC) has recorded about 140 fb^{-1} of proton-proton collision data at $\sqrt{s}$ = 13 TeV during Run 2 data taking period. Such an enormous amount of collision data provide good oppotunities for Higgs boson properties measurements. In this talk, measurements of Higgs boson mass, width, CP and anomalous couplings conducted by the CMS experiment are presented. No significant deviation from the Standard Model prediction is observed.

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1. Introduction

In the Standard Model (SM) of particle physics, the Brout-Englert-Higgs (BEH) mechanism is responsible to explain the origin of mass. It introduces a complex scalar field, whose quantum manifestation is known as the SM Higgs boson. In 2012, both ATLAS [1] and CMS [2] experiments at the LHC discovered a new particle with mass around 125 GeV which is consistent with the SM Higgs boson. After the discovery of the Higgs boson, a lot of analyses have been conducted by both ATLAS and CMS experiments to understand its nature.

During 2015-2018 (a.k.a. Run 2 data taking period), the LHC has successfully delivered proton-proton collision data with center-of-mass energy at 13 TeV. The CMS experiment has recorded about 140 fb^{-1} of data which are good for physics analyses. With such big amount of collision data, the CMS experiment has done many measurements about the Higgs boson properties.

In this contribution, several analyses performed by the CMS experiment based on Run 2 data about Higgs boson properties measurements are presented, including mass, width, CP and anomalous couplings.

2. Higgs boson mass

The Higgs boson mass (m_H) is not predicted in the SM. Precise measurement of m_H in experiment is crucial, given the fact that many other properties of the SM Higgs boson, such as its production cross section and decay widths, can be predicted if m_H is known. Besides, m_H is related to the values of the masses of the W boson and top quark in the SM. The measurements of the Higgs boson, W boson, and top quark masses can be directly used to test the consistency of the SM prediction and experimental results.

The best decay channels to be used to measure m_H are $H \to \gamma\gamma$ and $H \to ZZ \to 4l$, because only these two channels could reconstruct the Higgs boson mass peak with very good resolution. The CMS collaboration has published a measurement of m_H by combining these two channels together using combined 2016 and Run 1 data sets[3], which gives $m_H = 125.38 \pm 0.14$ GeV as shown in Fig 1.

Prospects studies for Higgs boson mass measurements in HL-LHC with expected luminosity of 3000 fb^{-1} were also performed by projecting Run 2 data analyses and taking into account several changes, such as higher pile-up, increased detector granularity etc. For $H \to ZZ \to 4l$ channel, the best fit mass of the Higgs boson is expected to be $m_H = 125.38 \pm 0.022(stat) \pm 0.20(syst)$ GeV[4]. As for $H \to \gamma\gamma$ channel, the corresponding result is $m_H = 125.38 \pm 0.02(stat) \pm 0.07(syst)$ GeV[5].

3. Higgs boson width

The natural width of the Higgs boson (Γ_H) in the SM is predicted to be around 4.1 MeV. The typical mass resolution after event reconstruction is 1-2 GeV in either $H \to \gamma\gamma$ or $H \to ZZ \to 4l$ channel due to the detector response, therefore it is impossible to measure the Higgs boson width directly from the mass peak of the on-shell events at the LHC. The off-shell production method [6] could constrain/measure Γ_H in a much more precise way. In this method, the on-shell and off-shell

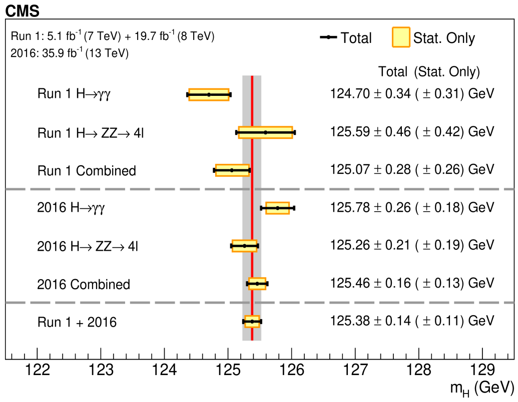

Figure 1: Summary of the measured Higgs boson mass in $H \to \gamma\gamma$ and $H \to ZZ \to 4l$ channels separately and for the combination [3].

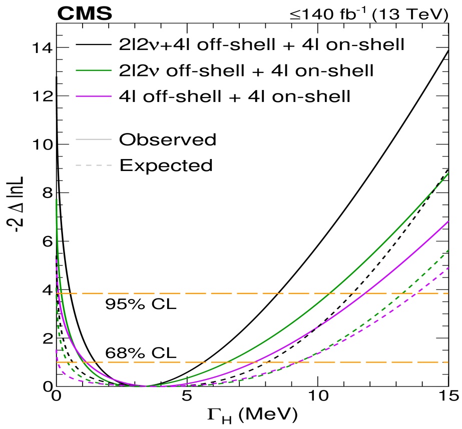

Figure 2: The observed (solid) and expected (dashed) likelihood scans over Γ_H [7].

Higgs boson signal yields are related by $\sigma^{on-shell} \propto \mu^{on-shell}$ and $\sigma^{off\text{-}shell} \propto \mu^{on-shell} \times \Gamma_H/\Gamma_H^{SM}$, where $\mu^{on-shell}$ is defined as the on-shell signal strength, i.e the ratio of the observed number of Higgs boson events relative to the SM expectation. Usually, the invariant mass of final state particles in the range of $105 < m < 140$ GeV is considered as on-shell region, while $m > 220$ GeV is considered as off-shell region. The on-shell and off-shell signal strengths should be measured separately, and their ratio is then proportional to the Higgs boson width. Using this method, the CMS experiment has firstly observed the evidence of the Higgs boson off-shell production by combining $ZZ \to 4l$ and $ZZ \to 2l2\nu$ channels together based on Run 2 data [7]. The width of the Higgs boson is measured to be $\Gamma_H = 3.2^{+2.4}_{-1.7}$ MeV, as shown in Fig 2.

4. Higgs boson CP and anomalous couplings

The SM Higgs boson is even under charge-parity (CP) inversion. A lot of studies have excluded pure pseudoscalar (CP-odd) interactions of the Higgs boson with electroweak bosons (i.e the W and Z bosons). There are still strong theoretical motivations to search for CP-violating effects in couplings of the Higgs boson and fermions, because a renormalisable CP-violating Higgs-to-fermion couplings may occur at tree level, while it is suppressed by $1/\Lambda^2$ in the Higgs-to-boson couplings (where Λ is the scale of the physics beyond the SM in an effective theory).

The Lagrangian for the τ Yukawa coupling can be parameterised as $\mathcal{L}_Y = -\frac{m_\tau}{\upsilon} H(\kappa_\tau \bar{\tau}\tau + \tilde{\kappa}_\tau \bar{\tau} i\gamma_5 \tau)$, where m_τ is the mass of the τ lepton, υ is the vacuum expectation value of the Higgs field (i.e 246 GeV), the coupling strength modifiers κ_τ and $\tilde{\kappa}_\tau$ represent the CP-even and CP-odd contributions respectively, τ denotes the Dirac spinor of the τ lepton fields. The effective mixing angle $\alpha^{H\tau\tau}$ for the H$\tau\tau$ coupling is defined as the ratio of the coupling modifiers: $\tan(\alpha^{H\tau\tau}) = \frac{\tilde{\kappa}_\tau}{\kappa_\tau}$. An analysis based on full Run 2 data was done to measure the effective mixing angle $\alpha^{H\tau\tau}$ in $H \to \tau\tau$ channel in CMS [8]. The data disfavour the pure CP-odd scenario at 3.0σ. The observed (expected) value of $\alpha^{H\tau\tau}$ is found to be $-1 \pm 19°$ ($0 \pm 21°$) at the 68.3% CL as shown in Fig 3.

Similarly, the $t\bar{t}H$ Lagrangian can be parameterized as $\mathcal{L}_{t\bar{t}H} = \frac{m_t}{\upsilon}\overline{\psi}_t(\kappa_t + i\gamma_5\tilde{\kappa}_t)\psi_t H$, where $\overline{\psi}_t$ and ψ_t are Dirac spinors, κ_t and $\tilde{\kappa}_t$ denote the CP-even and CP-odd top-Higgs Yukawa coupling

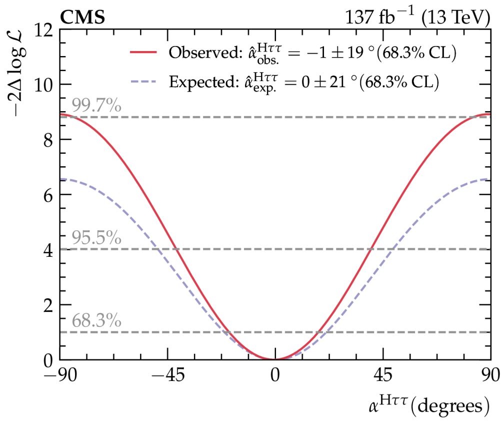

Figure 3: The observed (red solid) and expected (blue dashed) likelihood scans over the effective mixing angle $\alpha^{H\tau\tau}$ in $H \to \tau\tau$ channel [8].

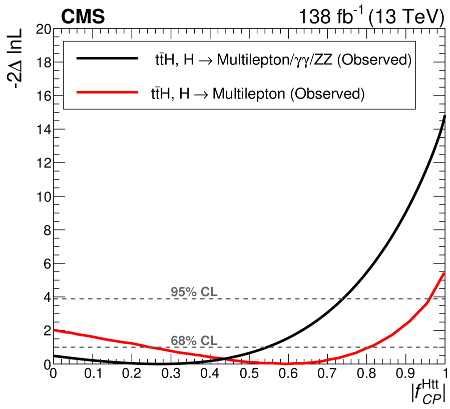

Figure 4: The observed likelihood scans over $|f^{Htt}_{CP}|$ for the CP violation search in ttH and tH production [9].

modifiers respectively. The parameter $|f^{Htt}_{CP}| = \frac{|\tilde{\kappa}_t^2|}{|\tilde{\kappa}_t|^2+|\kappa_t|^2}$ is introduced to parameterize the possible fractional CP-odd contribution. A study targeting $t\bar{t}H$ and tH productions, where the Higgs boson decays via WW or $\tau\tau$ and the top quarks decay via $t \to Wb$ with at least two leptons in the final states is performed [9]. The results are combined with $H \to \gamma\gamma$ [10] and $H \to ZZ$ [11] decay modes. As seen in Fig 4, $|f^{Htt}_{CP}|$ is determined to be 0.28 with an interval of $|f^{Htt}_{CP}| < 0.55$ at 68% CL.

The current results for spin-parity measurements of Higgs boson strongly favor $J^{PC} = 0^{++}$. However, anomalous couplings of the Higgs boson with electroweak bosons (HVV) or gluons (Hgg) are still allowed due to the limited precision of current studies. The scattering amplitude between the Higgs boson and two spin-1 gauge bosons VV, including WW, ZZ, $Z\gamma$, $\gamma\gamma$ and gg, can be expressed as $\mathcal{A}(HVV) \sim [a_1^{VV} + \frac{\kappa_1^{VV} p_1^2 + \kappa_2^{VV} p_2^2}{(\Lambda_1^{VV})^2}] m_{V1}^2 \epsilon_{V1}^* \epsilon_{V2}^* + a_2^{VV} f_{\mu\nu}^{*(1)} f^{*(2)\mu\nu} + a_3^{VV} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2)\mu\nu}$. Here p_i, ϵ_{Vi} and m_{V1} are the four-momentum, polarization vector, and pole mass of the gauge boson, $f^{(i)\mu\nu}$ and $\tilde{f}^{(i)}_{\mu\nu}$ are the gauge boson's field strength tensor and the dual field strength tensor. The coupling coefficients a_i^{VV} represent the anomalous couplings. As most uncertainties cancel in the effective cross section ratios $f_{ai} = \frac{|a_i|^2\sigma_i}{\Sigma_j |a_j|^2 \sigma_j}$, where $a_j = a_2, a_3, 1/\Lambda_1^2$, constraints are set on f_{ai} instead of a_i^{VV}. Several analyses based on Run 2 data are performed in CMS [10–12] to probe the anomalous couplings in such formalism. Constraints have also been set on the CP-violating effects in the ggH production in terms of the effective cross section ratio f_{a3}^{ggH}. The combination of $H \to \tau\tau$, $H \to 4l$ and $H \to \gamma\gamma$ channels excludes the pure CP-odd scenario of the Higgs couplings to gluons with a significance of 2.4 standard deviations.

5. Conclusion

With about 140 fb^{-1} of certified proton-proton collision data at $\sqrt{s} = 13$ TeV, the CMS experiment has conducted measurements of many properties of the Higgs boson to understand its nature, such as its mass, width, CP and anomalous couplings. The results of those measurements show that the properties of the Higgs boson are consistent with the SM predictions.

References

[1] ATLAS Collaboration, *Oberservation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC*, *Phys.Lett.B **716**(2012)1-29*

[2] CMS Collaboration, *Oberservation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC*, *Phys.Lett.B **716**(2012)30-61*

[3] CMS Collaboration, *A measurement of the Higgs boson mass in the diphoton decay channel*, *Phys.Lett.B **805**(2020)135425*

[4] CMS Collaboration, *Projection of the Higgs boson mass and on-shell width measurements in $H \to ZZ \to 4l$ decay channel at the HL-LHC*, *CMS-PAS-FTR-21-007*

[5] CMS Collaboration, *A projection of the precision of the Higgs boson mass measurement in the diphoton decay channel at the High Luminosity LHC*, *CMS-PAS-FTR-21-008*

[6] Fabrizio Caola and Kirill Melnikov, *Constraining the Higgs boson width with ZZ production at the LHC*, *Phys. Rev. D **88**(2013)054024*

[7] CMS Collaboration, *Measurement of the Higgs boson width and evidence of its off-shell contributions to ZZ production*, *Nature Physics **18**(2022)1329-1334*

[8] CMS Collaboration, *Analysis of the CP structure of the Yukawa coupling between the Higgs boson and τ leptons in proton-proton collisions at $\sqrt{s} = 13$ TeV* , *JHEP **06**(2022)012*

[9] CMS Collaboration, *Search for CP violation in ttH and tH production in multilepton channels in proton-proton collisions at $\sqrt{s}$= 13 TeV*, *JHEP **07**(2023)092*

[10] CMS Collaboration, *Measurements of $t\bar{t}H$ production and the CP structure of the Yukawa Interaction between the Higgs boson and top quark in the diphoton decay channel*, *Phys.Rev.Lett **125**(2020)061801*

[11] CMS Collaboration, *Constraints on anomalous Higgs boson couplings to vector bosons and fermions in its production and decay using the four-lepton final state*, *Phys.Rev.D **104**(2021)052004*

[12] CMS Collaboration, *Constraints on anomalous Higgs boson couplings to vector bosons and fermions from the production of Higgs bosons using the $\tau\tau$ final state*, *Phys.Rev.D **108**(2023)032013*