Higgs results and other highlights from CMS

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Abstract. Latest results on Higgs physics at center of mass energy of 13 TeV in Run-II from CMS experiment are presented. The highlights of other physics results at 13 TeV are also briefly reviewed.

1 Introduction

On 4th July 2012, the Compact Muon Solenoid (CMS) and ATLAS experiments at the Large Hadron Collider (LHC) have reported the discovery of a new boson \cite{1–3} with a mass near 125 GeV. In the standard model, the Higgs boson is a spin zero particle and couples directly to the W and Z bosons, and indirectly to photons.

Since then, significant signals have been reported in channels where the boson decays to $\gamma\gamma$, $WW$ or $ZZ$ boson pairs \cite{4–6} and many precise measurements of the properties have been performed: the latest mass measurements, the signal strength and the coupling with other boson. All these measurements are compatible with a standard model (SM) Higgs boson. Overall, these results directly demonstrate that the new particle is intimately related to the mechanism of spontaneous electroweak symmetry breaking and thus it has been identified as a Higgs boson.

At the LHC, the Higgs boson can be produced in several ways, mainly by gluon-gluon fusion (ggH), also by Vector Boson Fusion (VBF), in association with a W/Z boson (VH), or in association with a top quark pair (ttH). It mostly decays into a pair of b-quarks (57%), in a pair of two $\tau$ leptons (6.3%), and more rare into a pair of muons (0.02%).

In this document, a brief introduction of CMS detectos is given in section 2, further the latest measurement on Higgs boson at a center of mass energy of 13 TeV, collected by CMS in 2015, are reviewed in section 3. The major decay mode described are $\tau\tau$, $\gamma\gamma$, $ZZ$, $ttH$. The exotica measurement is given in section 4. Further, the highlights of other physics results on SM, top physics and SUSY at 13 TeV will be given in section 5, section 6 and section 7. Finally, the summary is given in section 8.

2 CMS

The CMS is one of the two general-purpose detectors located at the LHC. It is 21.6 m long and has a diameter of 14.6 m with a total weight of 12500 t. Its name originates from the world’s largest superconducting solenoid, which sits in the center of the detector, with an inner diameter of 6 m, length of 12.5 m, and magnetic field of 3.8 T, cooled by liquid helium to -269°C. The overall layout of CMS can be seen in Fig. 1.
The bore of the magnet coil is large enough to accommodate the inner tracker and the calorimetry inside. The tracking volume is given by a cylinder of 5.8-m length and 2.6-m diameter. In order to deal with high track multiplicities, CMS employs 10 layers of silicon microstrip detectors, which provide the required granularity and precision. The electromagnetic calorimeter (ECAL) uses lead tungstate (PbWO4) crystals with coverage in pseudorapidity up to $|\eta| < 3.0$. The ECAL is surrounded by a brass/scintillator sampling hadron calorimeter (HCAL) with coverage up to $|\eta| < 3.0$. The scintillation light is converted by wavelength-shifting (WLS) fibres embedded in the scintillator tiles and channeled to photodetectors via clear fibers. The details of CMS detector can be found in [7].

![Compact Muon Solenoid (CMS) detector](image)

Figure 1. Compact Muon Solenoid (CMS) detector [7].

## 3 Higgs boson measurement

In this section, Higgs results in different decay mode of $\gamma\gamma$, ZZ, WW, ttH at a center of mass energy of 13 TeV are presented.

### 3.1 $H \rightarrow \tau\tau$

Among the Higgs decay to a di-lepton pair, the $\tau\tau$ is the one with the largest BR, because of the large event rate expected in the SM compared to the other leptonic decay modes. MSSM is the simplest extension of SM, include an extended Higgs sector and favored by many theoretical arguments. The Higgs sector of the MSSM consists of two Higgs doublets, one of which couples to up-type fermions and the other to down-type fermions. This results in five physical Higgs particles: two charged Higgs bosons, two neutral scalar Higgs bosons and one neutral pseudoscalar. This search is performed on a dataset corresponding to an integrated luminosity of 2.3 $fb^{-1}$ of pp collision data at a centre-of-mass energy of 13 TeV, collected by CMS in 2015 [10].

Four final states of the tau pair are considered: $e\mu$, $e\tau_h$, $\mu\tau_h$ and $\tau\tau$. The analysis strategy is close to the Run-I, though the physics objects, selection and analysis tools are re-optimized. The dominant production mode is gluon fusion ($ggf$) and b-associated production (bbf). The trigger situation was challenging in Run-II compared to Run-I. Fig. 2 show the efficiency of L1 and HLT as a function of offline $\tau p_T$ for data and simulation [8]. The analysis strategy is close to the Run-I, though the
physics objects, selection and analysis tools are re-optimized. For example, improved multivariate analysis (MVA) based discriminant using the information of combine isolation and lifetime [9]. Fig. 3 shows the performance improvement of MVA over cut-based for probability of mis-identification as a function of $\tau_h$ identification efficiency. Also, improved tau reconstruction and identification using the information of new strip reconstruction algorithm was introduced, where ECAL energy leakage of $\tau_h$ decay was accounted [9].

![Figure 2](image1.png)

**Figure 2.** L1 efficiency as a function of offline $\tau p_T$ (left), HLT efficiency as a function of offline $\tau p_T$ (right) [8].

![Figure 3](image2.png)

**Figure 3.** Probability of mis-identification vs $\tau_h$ identification efficiency for cut based and for MVA based selection [9].

A binned maximum likelihood fit is performed simultaneously to the transverse mass distributions in the b-tag and no b-tag categories and all four channels Fig. 4. As no significant excess of data over
the background predictions is found, we set 95% CL upper limits on cross-section times branching fraction for the two dominant production modes, ggf and bbf. Fig. 5 shows these limits as a function of \( m_\phi \). These results are shown for different values of the Higgs boson mass \( m_\phi \). Finally, Fig. 6 shows the model dependent limits for two different benchmark models, the \( m_{h^{\text{mod}}} \) and hMSSM scenarios.

**Figure 4.** Post–fit plot of the transverse mass distribution in the no b–tag category (left) and the b–tag category of the \( e\tau_h \) channel (right) [10].

**Figure 5.** Expected and observed limits on cross-section times branching fraction for the gluon fusion process (left) and the b–associated production process (right), resulting from the combination of all four channels [10].

### 3.2 \( H \rightarrow \gamma\gamma \)

This channel is one of the most important channel involved in the discovery and first measurement of the Higgs boson properties, despite the small branching ratio predicted by SM because \( H \rightarrow \gamma\gamma \)
Figure 6. Model dependent exclusion limits in the $m_A - \tan \beta$ plane, combining all channels, for the $m_{h^{mod+}}$ (left) and hMSSM (right) scenarios [10].

decay channel provides a clean final state with an invariant mass peak that can be reconstructed with great precision. The results shown here correspond to the data collected by CMS in 2016 so far, corresponding to 12.9 $fb^{-1}$ of integrated luminosity of pp collisions [11]. Multivariate discriminants are used for estimation of background events. The dominant background for this analysis consists of the irreducible prompt diphoton production, and the reducible backgrounds from $\gamma + \text{jet}$ and QCD multijet, where the jets are misidentified as isolated photons.

A parametrised model of the Higgs boson mass shape continuously varying between 120 and 130 GeV is obtained from simulation. This includes all the necessary tuning to the simulation as well as all the corrections for the relevant efficiencies measured in data. The chosen approach is to describe the signal model with an analytic function, whose parameters are determined by fitting the simulated events in each category and for each of the simulated Higgs boson mass points. The data and the signal plus background model fit for each category used in this analysis are shown in Fig. 7. The 1 standard deviation (green) and 2 standard deviation (yellow) uncertainty bands shown for the background component of the fit include the uncertainty in the fitted parameters.

The expected significance obtained after fitting is show in Fig. 8 (left) along with the observed significance. The local expected significance for the observation of a standard model Higgs boson at $m_H = 125.09$ GeV, i.e. the $m_H$ resulting from CMS and ATLAS combination of measurements performed during Run-1, is 6.2 $\sigma$, where $\sigma$ represents one standard deviation. The observed significance at $m_H = 125.09$ GeV is 5.6 $\sigma$, and the maximum significance of 6.1 $\sigma$ is observed at $m_H = 126.0$ GeV. Further, the likelihood scan of the signal strength performed using profiling all other nuisances can be found in Fig. 8 (right).

3.3 $H \to ZZ$

These studies are performed using 12.9 $fb^{-1}$ of pp collision data collected with the CMS experiment at the LHC in 2016 [12]. The $H \to ZZ \to 4l(l = e, \mu)$ has a large signal-to-background ratio due to the complete reconstruction of the final state decay products and excellent lepton momentum resolution and is one of the most important channels for studies of the Higgs boson’s properties.
Figure 7. Data points (black) and signal plus background model fits for all categories are summed weighted by their sensitivity [11].

Figure 8. The expected significance obtained after fitting and observed significance (left). The likelihood scan of the signal strength performed using profiling all other nuisances (right) [11].

This analysis primarily relies on electrons and muons, and the very low branching fraction of the $H \rightarrow ZZ \rightarrow 4l$ decay makes it especially important to maintain a very high lepton reconstruction and selection efficiency. In addition, the analysis makes use of jets for forming event categories and in the measurement of the fiducial cross sections for different jet multiplicities. Distribution of the four-lepton reconstructed invariant mass $m_{4l}$ in the low-mass range is shown in Fig. 9. The 125 GeV Higgs boson signal and the ZZ backgrounds are normalized to the SM expectation, the Z+X background to the estimation from data. No events are observed with $m_{4l} > 850$ GeV. The significance of the local fluctuation with respect to the SM background only expectation as a function of $m_H$ is shown
in Fig. 10 (left). The minimum of the local p-value is reached at 124.3 GeV and corresponds to a local significance of $6.4 \sigma$, while $6.3 \sigma$ are expected for the SM Higgs boson. At $m_H = 125.09$ GeV, which corresponds to the Run 1 LHC combined measurement of the Higgs boson mass, the observed significance is $6.2 \sigma$, for an expectation of $6.5 \sigma$. Further, Fig. 10 shows the observed values of the signal strength $\mu$ for the six event categories, compared to the combined $\mu$ shown as a vertical line.

**Figure 9.** Distribution of the four-lepton reconstructed invariant mass $m_{4l}$ in the low-mass range [12].

**Figure 10.** Significance of the local fluctuation with respect to the SM expectation as a function of the Higgs boson mass (left). Observed values of the signal strength $\mu$ for the six event categories (right) [12].
Figure 11. Possible Feynman diagrams for ttH production at pp colliders, where the Higgs boson decays to WW, ZZ, and $\tau\tau$ (from left to right). Subsequent W, Z, and t decays are shown representing examples of final states with four leptons, three leptons, and two same-sign leptons, respectively [13].

Figure 12. Flavor of the selected leptons for same-sign dilepton channel (left). Best fit signal strength for the combined 2015+2016 analysis, in the dilepton and trilepton channels (right) [13].

3.4 ttH measurement

The currently ongoing second LHC run at an increased center-of-mass energy of 13 TeV is now making an even larger sample of Higgs boson events available for analysis. One channel becoming newly accessible is the associated production of top quarks and Higgs bosons, in particular the production of a pair of top quarks with a Higgs (ttH). As the mass of the Higgs boson is far too small to allow a decay to a pair of top quarks, the ttH interaction vertex can only be studied in its production. These results report the search for ttH production in final states with multiple leptons, targeting Higgs decays into pairs of W or Z bosons or $\tau$ leptons with subsequent leptonic decays, and additional leptons from top quark decays. The first data of the 2016 run of the LHC is used, corresponding to an integrated luminosity of 12.9 $fb^{-1}$ at a center-of-mass energy of 13 TeV, where the expected production cross section of ttH is increased by a factor of about 4, compared to 8 TeV [13].

At the analysis level, events are selected to reflect the final state signature of the signal process: two opposite sign W bosons and two b quark jets from the top quark decays in addition to the Higgs
decay products. In case of a $H \to WW$ decay we therefore expect four W bosons (two pairs of opposite sign) and two b quarks in the final state. For the same-sign dilepton channels (2LSS) the signature comprises the two charged leptons (and their partner neutrinos), two hadronically decaying W bosons leading to four light quark jets, and the two b quark jets. In the three and four lepton channels (3L), one or both of the two remaining W bosons will yield another pair of charged lepton and neutrino, reducing the number of light quark jets in the events (see Fig. 11). The signal and background event yields extracted in the simultaneous fit to the two classifier outputs are compared with the expectations for the spectrum of backgrounds and for a signal with a SM Higgs boson of 125 GeV.

The distribution of the flavor of the selected leptons for same-sign dilepton channel is shown in Fig. 12 (left). The best fit signal strength on the combined categories amounts to $2.3^{+0.9}_{-0.8}$ times the standard model expectation, corresponding to an observed limit of $\sigma < 3.9\times\sigma_{SM}$ at 95% CL. The limit expected under a background-only hypothesis is $1.4^{+0.7}_{-0.4}$. When combining this result with the smaller 2015 dataset at the same center of mass energy, the best-fit signal strength is reduced to $2.0^{+0.7}_{-0.4} (syst.)$. Fig. 12 (right) shows the best fit signal strength for the combined 2015+2016 analysis, in the dilepton and trilepton channels.

Figure 13. Observed diphoton invariant mass $m_{\gamma\gamma}$ spectra, when both photons are in the ECAL barrel detector, for 2.7 $fb^{-1}$ data at 13 TeV. The results of a likelihood fit to the background-only hypothesis are also shown. The lower panels show the difference between the data and fit, divided by the statistical uncertainty in the data points [15].

4 Exotica

This section report on a search for resonant production of high mass photon pairs. Based on the first data collected in 2015, the ATLAS [14] and CMS [15] collaborations published the first results on searches for diphoton resonances at center of mass energy of 13 TeV, which correspond to an
integrated luminosity of about 3 \( fb^{-1} \) for each experiment. Both analyses reported the observation of a modest deviation from the background-only expectation, compatible with the production of a resonance with a mass of around 750 GeV, as shown in the \( m_{\gamma\gamma} \) distribution in Fig. 13, for the event category when both photons are in the electromagnetic calorimeter (ECAL) barrel detector [15]. The results of a likelihood fit to the background-only hypothesis are also shown. A modest excess of events compatible with a narrow resonance with a mass of about 750 GeV can be observed. The local significance of the excess is approximately 3.4 standard deviations. The significance is reduced to 1.6 standard deviations once the effect of searching under multiple signal hypotheses is considered.

Further, the same search for the spin-0 resonance was carried out using data correspond to an integrated luminosity of 12.9 \( fb^{-1} \) of pp collisions collected by the CMS experiment in 2016 at center of mass energy of 13 TeV [16]. It is aimed at spin-0 and spin-2 resonances of mass between 0.5 and 4.5 TeV and width, relative to the mass, up to \( 5.6 \times 10^{-2} \). The results obtained with the 2016 data set are combined statistically with those obtained in 2012 and 2015, corresponding to integrated luminosities of 19.7 and 3.3 \( fb^{-1} \) of data recorded at 8 and 13 TeV, respectively. The diphoton mass spectrum above 500 GeV is examined for evidence of the production of high-mass spin-0 and spin-2 resonances. Fig. 14 shows the observed invariant mass spectra \( m_{\gamma\gamma} \) for selected events in the category when both photons are in ECAL barrel detector (left), and the category when one photon in the ECAL barrel detector and the other in an ECAL endcap detector (right). The solid lines and the shaded bands show the results of likelihood fits to the data together with the associated 1 and 2 standard deviation uncertainty bands. The ratio of the difference between the data and the fit to the statistical uncertainty in the data is given in the lower plots. No significant excess is observed above the predictions of the standard model.

![Figure 14](image.png)

Figure 14. The observed invariant mass spectra \( m_{\gamma\gamma} \) for selected events in the (left) EBEB and (right) EBEE categories for 12.9 \( fb^{-1} \) data at 13 TeV. The solid lines and the shaded bands show the results of likelihood fits to the data together with the associated 1 and 2 standard deviation uncertainty bands [16].
5 SMP results

The production of W and Z bosons is one of the most prominent examples of hard scattering processes at hadron colliders. Theoretical predictions are available at next-to-next-to-leading order (NNLO) in perturbative quantum chromodynamics (QCD). Here, we report on the inclusive measurement at center of mass of 13 TeV, corresponding to an integrated luminosity of up to $43 \pm 2 \text{pb}^{-1}$, performed in the electron and muon decay channels, with the CMS detector [17]. Fig. 15 (left) show the ratio of the experimental results and the theoretical predictions. The experimental precision is already comparable with theoretical uncertainties. The uncertainty on the preliminary luminosity calibration dominates the comparison.

Further, differential cross section measurements of the Z boson production in association with jets are presented, using 13 TeV proton-proton collisions data recorded by the CMS detector at the LHC, corresponding to an integrated luminosity of $2.5 \text{fb}^{-1}$ [18]. The cross sections are presented as a function of jet multiplicity, the jet transverse momenta, and the jet rapidity for different jet multiplicities. The measured $Z + \text{ jets}$ cross sections are shown in Fig. 15 (right) in comparison with the prediction of MG5 AMC@NLO. Fig. 15 (right) shows the measured cross section as a function of the jets inclusive and exclusive multiplicity. Good agreement between reconstructed data and simulation is observed up to four jets.

![Figure 15. Summary of fiducial inclusive W$^+$, W$^-$, W, and Z production cross sections times branching fractions, W to Z and W$^+$ to W$^-$ ratios, and their theoretical predictions (left) [17]. Measured cross section as a function of the jets inclusive (right) [18].](image)

6 Top physics

A measurement of the tt production cross section at center of mass energy of 13 TeV is presented using $2.3 \text{fb}^{-1}$ of proton-proton collision data acquired by the CMS detector [19]. Final states including one isolated charged lepton (electron or muon) and at least one jet are selected and categorized according to the multiplicity of jets.

In analysis, events with 1, 2, 3 or at least 4 jets are considered as exclusive categories. We expect the low (high) multiplicity categories to be dominated by W+jets processes (tt) events. An improved
separation of the signal is achieved by counting the number of b-tagged jets in each category, as at least two b-jets are expected from $t \rightarrow Wb$ decays. Therefore, we further subdivide the four jet multiplicity categories according to the number of reconstructed b-tagged jets, considering events with 1, at least 2, or no b-tags, for a total of 11 independent categories. The comparison of the selected number of events for signal and expected backgrounds in each category is shown in Fig. 16, where a fair agreement between data and the expectations within the statistical uncertainties only is observed.

![Figure 16](image)

**Figure 16.** Event yields for data and expected signal and backgrounds for each of the 11 independent categories [19].

From a likelihood fit to the invariant mass of the isolated lepton and a jet identified as stemming from the fragmentation and hadronization of b quark, the cross section is measured to be $\sigma(tt) = 834.6 \pm 2.5(stat) \pm 22.8(syst) \pm 22.5(lumi) \text{pb}$ in agreement with the standard model prediction. Using the expected dependency of the cross section $m_t = 172.3^{+2.3}_{-2.3} \text{GeV}$.

Further, a measurement of the inclusive cross section of single top-quark production in the t channel has been performed at 13 TeV corresponding to 2.3 $\text{fb}^{-1}$ [20]. Fig. 17 shows the single top quark t channel cross section at various center of mass energies.

**7 SUSY Search**

This section present the results on search for new physics using events with multileptons in the final state at the CMS detector on a sample of proton-proton collisions collected in 2016 at a center-of-mass energy of 13 TeV at the LHC corresponding to an integrated luminosity of 12.9 $\text{fb}^{-1}$ [21]. The results of this analysis is interpreted in the context of supersymmetric (SUSY) models that feature gluino pair production with mass spectra that produce final state leptons through the decays of vector bosons. The results of the limit setting procedure are shown in Fig. 18 (left) for the T1tttt model. For the latter model the WW and ZZ final states have been filtered out and the gluino-gluino cross section has been scaled down accordingly. For both exclusion plots the gluino pair-production cross section is calculated at NLO-NLL (next-to-leading-logarithm) accuracy and assumes that other SUSY particles are decoupled (i.e. very massive). No significant deviation from the expected standard model background has been observed. In the absence of any observed excesses in the data, the result has been interpreted using a simplified gluino-pair production model that features cascade decays producing
four top quarks in the final state. In this model, we exclude gluinos with a mass of up to 1250 GeV in the case of a massless LSP. The maximum excluded LSP mass is 750 GeV for gluino masses up to 1150 GeV.

Further, the results on the on searches for the direct electroweak production of supersymmetric charginos and neutralinos are presented in signatures with two light leptons of the same charge and with three or more leptons including up to two hadronically decaying taus [22]. These results probe charginos and neutralinos with masses up to 400-1000 GeV depending on the assumed model parameters corresponding to an integrated luminosity of 12.9 fb^{-1}. No significant deviation from the standard model expectations is observed. The results are used to set limits on the various simplified
models with a chargino-neutralino pair production which is the electroweak SUSY process with the largest cross section. The results for of the interpretation in the “flavor-democratic” scenario is shown in Fig. 18 (right).

8 Summary

Latest results at center of mass energy of 13 TeV from CMS experiment are presented.

References

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