SM Higgs Boson Measurements at CMS

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Summary. — Measurements of the Higgs boson performed by the CMS experiment at the LHC are presented. A selection of preliminary results based on proton-proton collisions data collected at a center of mass energy $\sqrt{s} = 13$ TeV and corresponding to an integrated luminosity of 12.9 fb^{-1} is reported.

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1. – Introduction

After the discovery of the Higgs boson by the ATLAS and CMS collaborations [1][2], a wide range on production and decay channels has been studied using the Run 1 data set at $\sqrt{s} = 7$ and 8 TeV to characterize the new observed particle. Measurements of its couplings and properties are found to be consistent with the Standard Model (SM) expectations, the mass is measured with 0.2% precision and only a small excess in the $\mathrm{t\bar{t}H}$ channel has been observed [3].

Preliminary results at $\sqrt{s}$= 13 TeV are presented here, based on the analysis of proton-proton collisions data collected by the CMS experiment [4] in 2016 and corresponding to and integrated luminosity of 12.9 fb^{-1}.

2. – H→ZZ→4l

Higgs boson decays to four leptons are selected from events with two pairs of opposite-sign, same-flavor well reconstructed and isolated leptons (electrons or muons). This channel is characterized by a fully reconstructed mass peak with large signal over background (Fig. 1 (left)). The analysis strategy is based on the definition of exclusive categories, with selections on kinematic discriminants defined using matrix element methods (MEM) and on the number of (b-)jets and additional leptons. The main backgrounds are from $qq \rightarrow$ZZ* and $gg \rightarrow$ZZ* processes and from fake leptons from Z+jets, Z+$\mathrm{b\bar{b}}$, $\mathrm{t\bar{t}}$ processes.

The significance observed with the 12.9 fb^{-1} data set is 6.2σ, where 6.5σ are expected. The best-fit signal strength $\mu = \sigma/\sigma_{SM}$ at the Run 1 measured mass $\mathrm{m_H} = 125.09$ GeV is $\mu = 0.99^{+0.33}_{-0.26}$. The signal strength measured per production mechanism, the fiducial

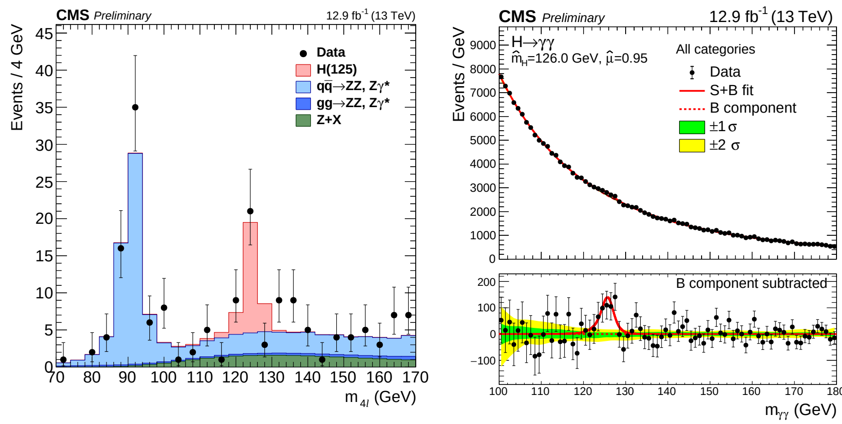

Fig. 1. – Four lepoton invariant mass distribution in the H→ZZ channel [5] (left) and di-photon invariant mass in the H→ $\gamma\gamma$ channel [6] (right).

cross section (Fig. 2 (left)) and differential cross section measurements as a function of the Higgs boson transverse momentum (Fig. 2 (right)) and number of jets in the events are compatible with the SM expectations [5].

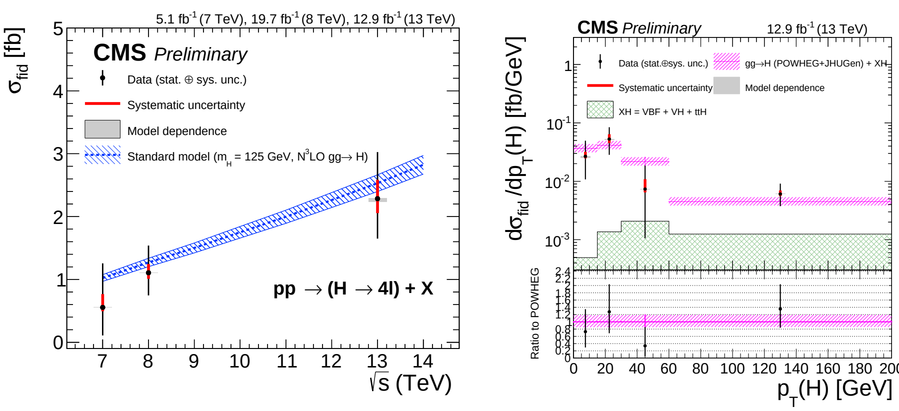

Fig. 2. – Measurements of the fiducial cross section as a function of the center of mass energy (left) and differential cross section as a function of the Higgs boson p_T (right) in the H→ZZ→ $4l$ decay channel [5].

3. – H→ $\gamma\gamma$

Despite its small branching ratio ($\sim 0.23\%$ for $m_H = 125$ GeV), the H→ $\gamma\gamma$ decay channel is characterized by a clean experimental signature, with two high transverse momentum isolated photons, which allow high precision for mass reconstruction.

To achieve the maximum sensitivity, events are classified in exclusive categories exploiting their different mass resolution and signal-over-background ratio. The event information, including the kinematics, photon quality and mass resolution, is combined in a multivariate classifier, which is built in such a way to be mass independent and to have high values for events with good di-photon mass resolution and high probability of being signal rather than background. Additional categorization is performed to select events with jets and leptons targeting specific Higgs production modes (namely VBF and $t\bar{t}H$ associated production).

A clear signal is observed in the di-photon channel (Fig. 1 (right)), with a significance of 6.1σ. The best-fit signal strength is $\mu = 0.95\ ^{+0.21}_{-0.18}$ (Fig. 3 (left)) and the best-fit value of the fiducial cross section is found to be $\sigma^{fid} = 69^{+18}_{-22}$ fb, where the SM theoretical prediction is 73.8 ± 3.8 fb (Fig. 3 (right)). All the measurements are consistent with the expectations from a SM Higgs boson [6].

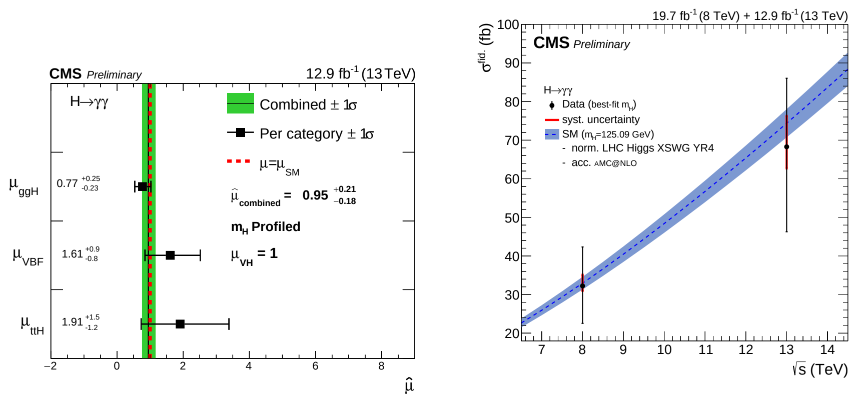

Fig. 3. – Signal strength per production mechanism (left) and fiducial cross section as a function of the center of mass energy (right) measured in the $H\rightarrow\gamma\gamma$ decay channel [6].

4. – $t\bar{t}H$ searches

4·1. *$t\bar{t}H$ multileptons.* – The search for $t\bar{t}H$ in multileptons targets a signature with H decays to $W^+W^-/ZZ/\tau^+\tau^-$ final states accompanied by additional products from $t\bar{t}$ decays. Events with multiple leptons and jets are selected and further categorization is performed based on the lepton flavour and charge, number of b-jets and hadronic τ decays. The main irreducible backgrounds are represented by $t\bar{t}V$ and di-bosons, while reducible backgrounds by non-prompt leptons from $t\bar{t}$ events. Boosted decision trees (BDT) are trained to separate the $t\bar{t}H$ signal from the generic $t\bar{t}$ background and from the irreducible $t\bar{t}V$ background, exploiting topological and kinematic variables, such as jet mutiplicity, lepton/jet angular sepration, missing transverse energy, leptons p_T. A signal is observed with 3.2σ significance (where 1.7σ is expected) from the combined analysis of the 2015 (2.3 fb^{-1}) and 2016 (12.9 fb^{-1}) data sets, with a best-fit signal strength $\mu = 2.0\ ^{+0.8}_{-0.7}$ (Fig. 4) [7].

4·2. *$t\bar{t}H(H\rightarrow bb)$.* – The $t\bar{t}H$ search through $H\rightarrow b\bar{b}$ decays exploits the large branching fraction of the Higgs to $b\bar{b}$ pairs (58%), but on the other hand is affected by large backgrounds. Two channels are considered for this search: the lepton+jets channel, with

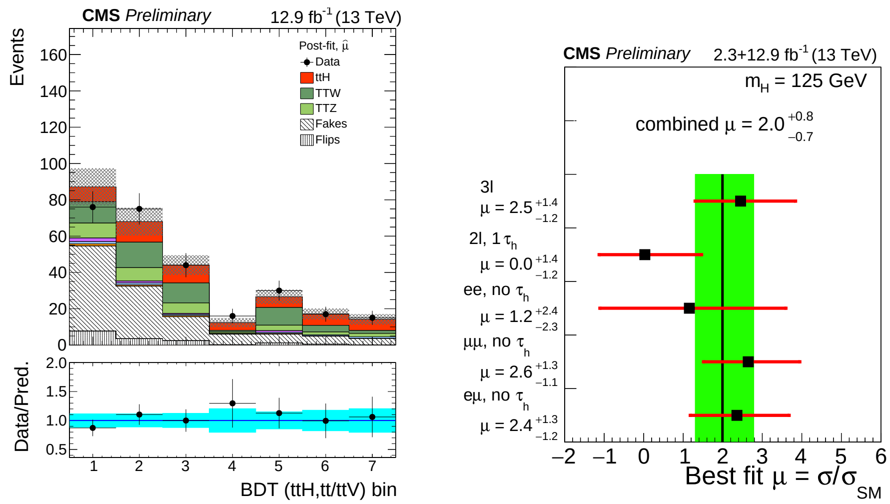

Fig. 4. – Example of BDT classifier output in the bins used for signal extraction in $\mathrm{t\bar{t}H}$ multilepton searches, for the same-sign dilepton channel (left); combined and per category best-fit signal strength for the combined 2015+2016 analysis (right) [7].

one lepton and at least four jets, and the dilepton channel, with two opposite sign leptons and at least two jets. Further classification is based on the number of jets and b-jets in the event. Sub-categories are finally defined based on multivariate and MEM discriminants. The MEM discriminant is optimized to separate the signal from the irreducible $\mathrm{t\bar{t}b\bar{b}}$ background. A combined fit of multivariate discriminant distributions in all categories results in an observed (expected) upper limit of $\sigma/\sigma_{SM} < 1.5$ (1.7) at the 95% confidence level (Fig. 5) [8].

4$\dot{}$3. *$t\bar{t}H$(H→ $\gamma\gamma$).* – The search for $\mathrm{t\bar{t}H}$ production with H→ $\gamma\gamma$ decays follows the analysis strategy of the H→ $\gamma\gamma$ analysis described in Sec. **3**. Events are then categorized depending on the decay of the $\mathrm{t\bar{t}}$ pair in two categories: a leptonic category, with two photons, at least one lepton (electron or muon) and three jets and a hadronic category, with two photons, at least five jets and no leptons. In each category, at least one of the jets must be b-tagged. Fig. 6 shows the di-photon invariant mass distribution in the two categories. The best-fit signal strength for $\mathrm{t\bar{t}H}$ production in the di-photon decay channel is $\mu = 1.91\,^{+1.5}_{-1.2}$ [6].

5. – Projections

The results obtained from the analysis of 13 TeV data are extrapolated to larger data sets of 300 $\mathrm{fb}^{-1}$and 3000 fb^{-1}, considering an upgraded CMS detector for the HL-LHC. Extrapolations are studied under different scenarios for the systematic uncertainties assumed in the measurements, which are either kept constant with the intergrated luminosity or scaled down (theoretical uncertainties by a factor 2 and experimental ones by the square root of the integrated luminosity until they reach a defined lower limit based on estimates of the achievable accuracy with the upgraded detector) [9]. A significant improvement with respect to the current measurements is expected in the precision on

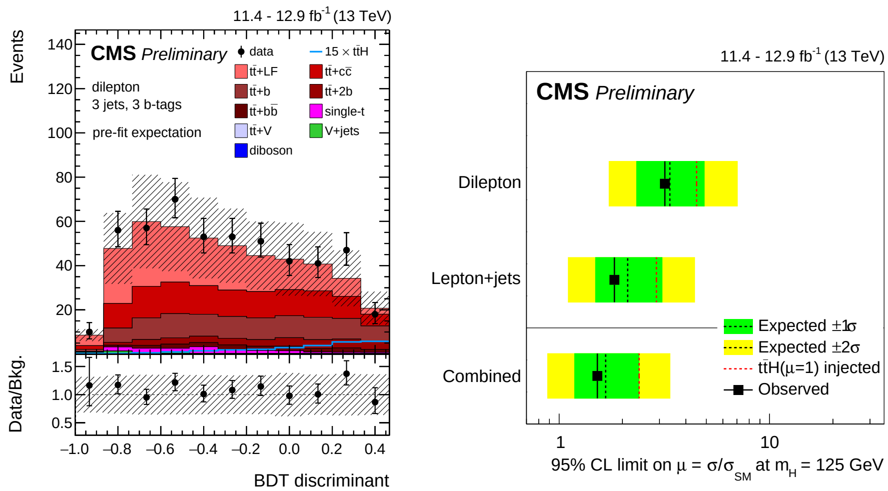

Fig. 5. – Example of BDT classifier output used for signal extraction, for the dilepton category with 3 jets and 3 b-jets (left) and upper limit of σ/σ_{SM} in the $t\bar{t}H(H\rightarrow b\bar{b})$ search channel (right) [8].

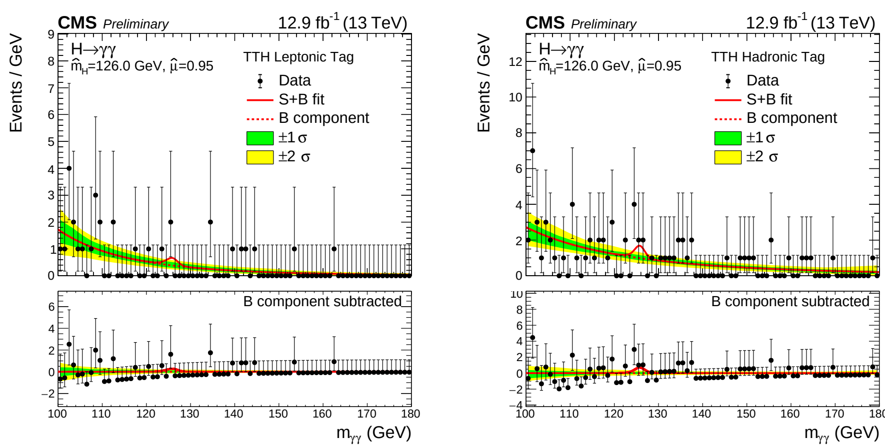

Fig. 6. – Di-photon invariant mass distribution in the $t\bar{t}H$ leptonic and hadronic categories [6].

the couplings, fiducial and differential cross sections, as shown in Fig. 7 and Fig. 8.

6. – Conclusions and outlook

A selection of preliminary Higgs boson measurements performed at CMS using 12.9 fb^{-1} of 13 TeV pp collisions data have been presented. The sensitivity reached with this data set is already close to the Run 1 one and measurements are found to be largely compatible with SM expectations. All the measurements are being updated analysing the entire 2016 data set (about 36 fb^{-1}) and substantial improvements are foreseen. LHC

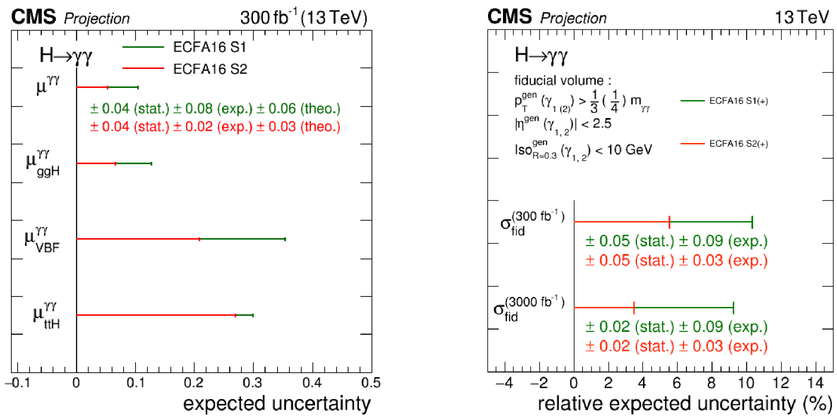

Fig. 7. – Projections of the precision on the signal strengths and fiducial cross section in the H→ $\gamma\gamma$ channel [9].

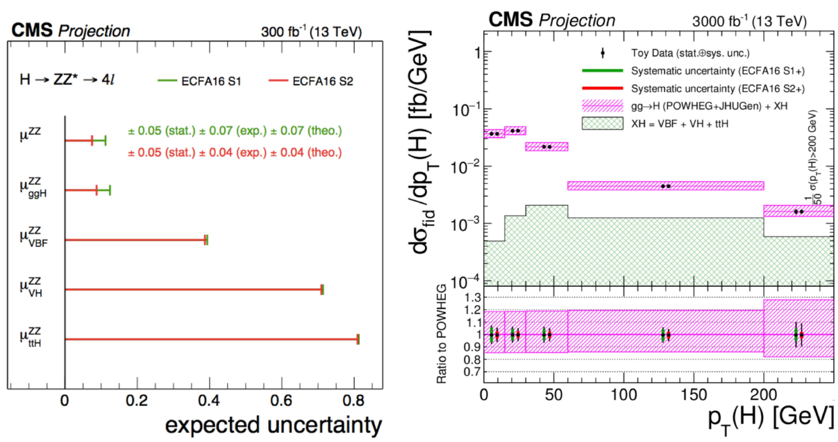

Fig. 8. – Projections of the precision on the signal strengths and fiducial cross section in the H→ZZ→4leptons channel [9].

is expected to deliver more than 100 fb^{-1}by the end of Run 2, allowing a further increase on the precision of the Higgs properties measurements.

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