PROCEEDINGS OF SCIENCE

Higgs boson fiducial and differential measurements at CMS

Lorenzo Viliani[a,*] **on behalf of the CMS Collaboration**

[a] *INFN, Firenze (IT),*
Via G. Sansone 1, Sesto Fiorentino (FI), 50019, Italy

E-mail: lorenzo.viliani@cern.ch

Recent measurements from the CMS Collaboration on Higgs boson fiducial and differential cross sections are presented. Results from $\mathrm{W^+W^-}$, ZZ, $\gamma\gamma$ and $\mathrm{b\bar{b}}$ Higgs boson decay channels are briefly discussed, corresponding to data samples with an integrated luminosity varying from 35.9 $\mathrm{fb^{-1}}$ to 137.1 $\mathrm{fb^{-1}}$, collected by the CMS detector at the LHC in pp collisions at $\sqrt{s}$ = 13 TeV.

40th International Conference on High Energy physics - ICHEP2020
July 28 - August 6, 2020
Prague, Czech Republic (virtual meeting)

*Speaker

PoS(ICHEP2020)088

1. Introduction

After the discovery of the Higgs boson in 2012, one of the main priorities of the ATLAS and CMS Collaborations has become the precision measurement of the new particle properties. The data sample collected by the experiments during the CERN LHC Run 1, allowed the measurement of the new particle spin, parity, and couplings with the SM particles, which are found to be consistent with the SM predictions within uncertainties.

Thanks to the increase of integrated luminosity, the LHC Run 2 opened new frontiers to study the details of Higgs boson physics and represented a change of paradigm, from seeking the Higgs boson to performing precision measurements of its properties. In fact, most of the inclusive Higgs boson cross section measurements reported so far already start to be limited by the systematical component of the uncertainty, with sizable contributions from experimental and theoretical sources.

The way forward is to move from inclusive to fiducial differential cross section measurements, which can exploit the full potential of the available integrated luminosity to probe interesting and previously unreachable regions of the phase space. The key aspects of these measurements are that the cross section is reported in bins of the observable of interest (differential) and is extrapolated to a restricted portion of the phase space (fiducial), define to match as closely as possible the experimental event selection to reduce the model dependence introduced in case the extrapolation is done to the full phase space.

An example of an interesting observable is the Higgs boson transverse momentum ($p_{\mathrm{T}}^{\mathrm{H}}$), which is known to be sensitive to possible deviations from the SM of the Higgs boson Yukawa couplings, as well as to the presence of new physics at large energy scales.

A complementary approach to fiducial and differential measurements is represented by the Simplified Template Cross Section (STXS) framework [1]. This approach consists in the measurement of cross sections in pre-defined bins of phase space, established with the goal of minimizing the model dependence of the measurement, maximizing the experimental sensitivity, and isolating possible beyond the SM effects. No fiducial region is involved in the STXS bin definition, allowing to combine measurements of different channels at the expense of larger extrapolation uncertainties.

In this document we review the recent fiducial differential Higgs boson cross section measurements using data collected by the CMS experiment [2] during the Run 2 of the LHC in pp collisions at $\sqrt{s} = 13$ TeV. In particular we report a selection of results obtained from the Higgs boson decays to $\mathrm{W^+W^-}$ [3] and ZZ [4], both using an integrated luminosity of 137.1 $\mathrm{fb^{-1}}$, and to $\gamma\gamma$ [5], which makes use of an integrated luminosity of 35.9 $\mathrm{fb^{-1}}$. In addition, we also report results obtained from a combination of $\mathrm{H} \to \mathrm{ZZ}$, $\mathrm{H} \to \gamma\gamma$ and $\mathrm{H} \to \mathrm{b\bar{b}}$ decay channels [6] exploiting an integrated luminosity of 35.9 $\mathrm{fb^{-1}}$.

2. Measurements in $\mathrm{H} \to \mathrm{W^+W^-} \to \mathrm{e}^{\pm}\mu^{\mp}\nu\bar{\nu}$

The measurements in this channel are performed selecting $\mathrm{e}^{\pm}\mu^{\mp}\nu\bar{\nu}$ final states, corresponding to the leptonic decay of both W bosons and considering only pairs of charged leptons with different flavor. This final state is characterized by a large branching fraction and a good signal sensitivity, despite the rather large background, making the $\mathrm{H} \to \mathrm{W^+W^-}$ channel competitive with $\mathrm{H} \to \mathrm{ZZ}$ and $\mathrm{H} \to \gamma\gamma$.

The main background processes in this final state are W^+W^-, top quark, and nonprompt lepton production, although other minor backgrounds are also taken into account. The presence of neutrinos prevents the full reconstruction of the Higgs boson mass, and other variables are used in the fit procedure to discriminate between signal and background contributions, namely the invariant mass of the two charged leptons (m^{ll}) and the transverse mass (m_T^H) constructed from the dilepton transverse momentum and the missing transverse momentum ($\vec{p}_T^{\,miss}$).

The analysis focuses on the measurement of the Higgs boson differential production cross section as a function of the number of associated jets (N_{jet}) and p_T^H, where the latter is reconstructed as the magnitude of the vectorial sum of the transverse momenta of the two lepton candidates and $\vec{p}_T^{\,miss}$.

Events passing the preselection are split into reconstruction-level bins of the p_T^H and N_{jet} observables. In each bin, a two-dimensional template maximum likelihood fit is performed using the m^{ll} and m_T^H distributions. The likelihood function is defined such that the unfolding to particle level bins of p_T^H and N_{jet} is performed together with the fit procedure. The observables at particle level are defined in a fiducial phase space that mimics the event preselection at reconstruction level. For the p_T^H measurement, a regularization factor is also included as a penalty term in the likelihood function, to mitigate large non physical fluctuations due to the poor resolution of p_T^H. For the N_{jet} measurement no regularization term is implemented.

The fiducial differential production cross sections are shown in Fig. 1. The integrated fiducial cross section is measured to be 86.5 ± 9.5 fb, in good agreement with the SM expectation of 82.5 ± 4.2 fb within uncertainties.

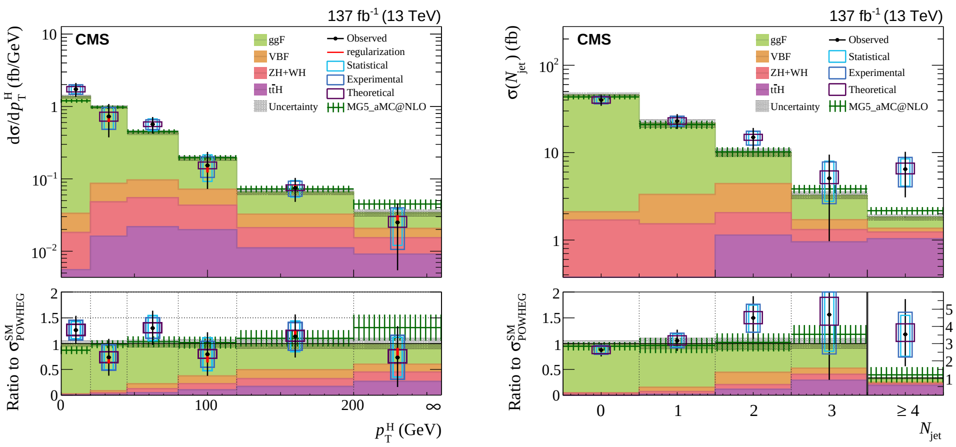

Figure 1: Observed fiducial cross sections as a function of p_T^H (left) and N_{jet} (right) measured in the $H \to W^+W^- \to e^\pm\mu^\mp\nu\bar{\nu}$ decay channel [3], overlaid with the predictions of different theoretical models.

3. Measurements in $H \to ZZ \to 4\ell$

Despite the small branching fraction of the $H \to ZZ \to 4\ell$ ($\ell = e, \mu$) decay channel, the decay products in the final state can be fully reconstructed with high precision, leading to a large signal–

to–background ratio. The major background contributions arise from gluon and quark induced ZZ production, as well as from Z + jets processes with jets misidentified as charged leptons.

The signal extraction strategy consists in a simultaneous maximum likelihood fit of the m_{4l} distribution in the 4e, 4μ and 2e2μ final states. Similarly to what is described in Sec. 2, the fit is performed in reconstruction level bins of the observables of interest and the unfolding to particle level fiducial distributions is embedded in the fit procedure. In this case no regularization is considered for all the measured observables.

The analysis focuses on the measurement of the differential production cross sections in bins of $p_{\mathrm{T}}^{\mathrm{H}}$, N_{jet}, Higgs boson rapidity and transverse momentum of the leading jet. The particle level fiducial phase space is defined to closely match the reconstruction level event selection.

The fiducial differential production cross sections as a function of $p_{\mathrm{T}}^{\mathrm{H}}$ and N_{jet} are shown in Fig. 2, the other distributions can be found in Ref. [4]. The measured differential cross sections are found to be in good agreement with the SM expectation within uncertainties. Similarly the inclusive fiducial cross section, which is measured to be $2.73^{+0.30}_{-0.29}$ fb, is in very good agreement with the SM value of 2.76 ± 0.14 fb.

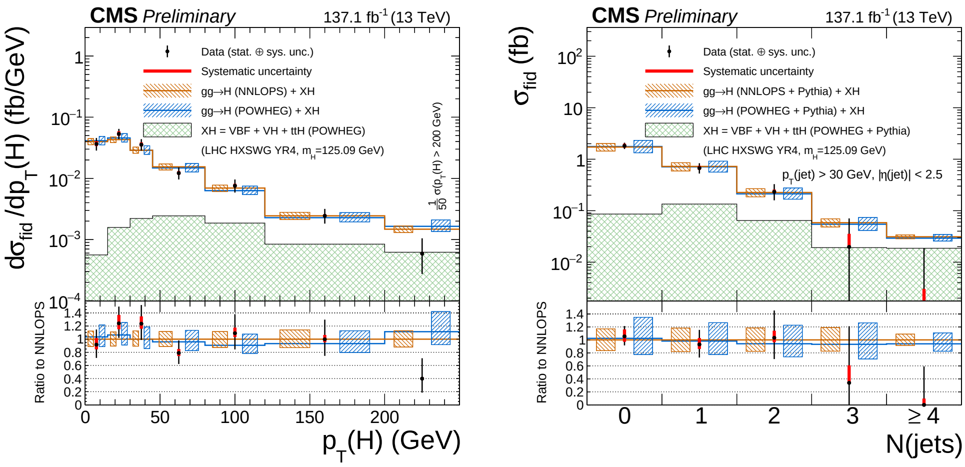

Figure 2: Observed fiducial cross sections as a function of $p_{\mathrm{T}}^{\mathrm{H}}$ (left) and N_{jet} (right) measured in the H $\rightarrow$ ZZ $\rightarrow 4\ell$ decay channel [4], overlaid with the predictions of different theoretical models.

4. Measurements in H $\rightarrow \gamma\gamma$

Thanks to the high precision in the reconstruction of the diphoton invariant mass, the H $\rightarrow \gamma\gamma$ decay channel has a very clean signature and allows for the precision measurement of a large variety of differential observables. The main background contributions in this channel arise from diphoton, γ + jets and dijet production.

Events containing two photons passing minimum identification and kinematic requirements are sorted into three categories according to their estimated relative mass resolution. In each of these categories, events are further categorized in bins of the observables to be measured. The diphoton invariant mass spectrum is fitted simultaneously in each category through a maximum likelihood procedure that embeds the unfolding to particle level without any regularization factor.

The fiducial phase space is defined at particle level based on photon kinematic and isolation variables, as well as variables describing the topology of the events. Differential production cross sections are measured as functions of many observables that describe the properties of the Higgs boson, and the kinematic properties of the jets, leptons and $p_{\mathrm{T}}^{\mathrm{miss}}$ that are produced along with the diphoton pairs. In addition to single-differential measurements, a double-differential cross section measurement of $p_{\mathrm{T}}^{\mathrm{H}}$ and N_{jet} is also performed in this decay channel.

The fiducial differential production cross sections as a function of $p_{\mathrm{T}}^{\mathrm{H}}$ and N_{jet} are shown in Fig. 3, and all the results can be found in Ref. [5]. The inclusive cross section in the fiducial region is measured to be 84 ± 13 fb, in agreement with the SM expectation of 73 ± 4 fb.

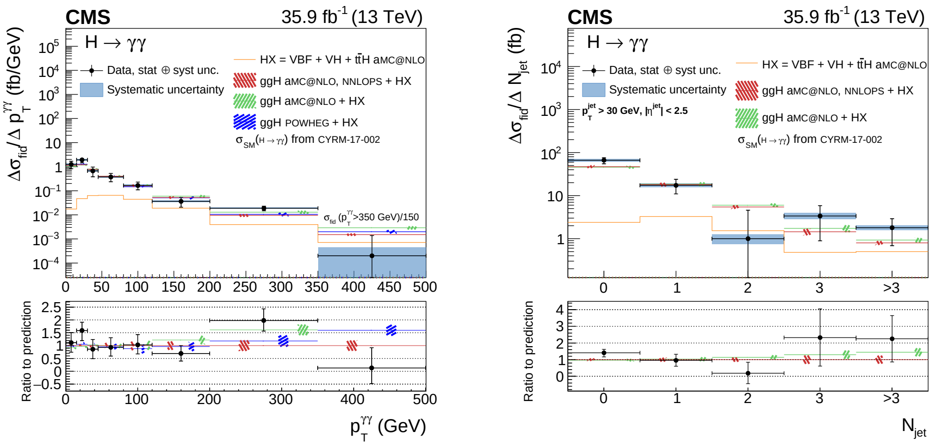

Figure 3: Observed fiducial cross sections as a function of $p_{\mathrm{T}}^{\mathrm{H}}$ (left) and N_{jet} (right) measured in the $\mathrm{H} \to \gamma\gamma$ decay channel [5], overlaid with the predictions of different theoretical models.

5. Combination of $\mathrm{H} \to \mathrm{ZZ} \to 4\ell$, $\mathrm{H} \to \gamma\gamma$ and $\mathrm{H} \to \mathrm{b\bar{b}}$

A combination of the differential cross section measurements in the $\mathrm{H} \to \mathrm{ZZ} \to 4\ell$ and $\mathrm{H} \to \gamma\gamma$ decay channels is also performed after extrapolating the measurements in the single channels to the full phase space, using data corresponding to an integrated luminosity of 35.9 fb^{-1}. For the measurement in bins of $p_{\mathrm{T}}^{\mathrm{H}}$ the $\mathrm{H} \to \mathrm{b\bar{b}}$ decay channel is also included, improving the measurement precision in the tail of the distribution. The combined differential $p_{\mathrm{T}}^{\mathrm{H}}$ spectrum is shown in Fig. 4. Overall no significant deviation from the SM expectation is observed. Notably, this result is also used to set constraints on the Higgs boson couplings to quarks, as explained in detail in Ref. [6].

6. Summary

The data recorded by the CMS experiment during the LHC Run 2 were exploited to provide measurements of the Higgs boson production with an unprecedented level of precision. Differential and fiducial cross section measurements were performed in several decay channels as functions of observables related to the properties of the Higgs boson production and of particles produced in

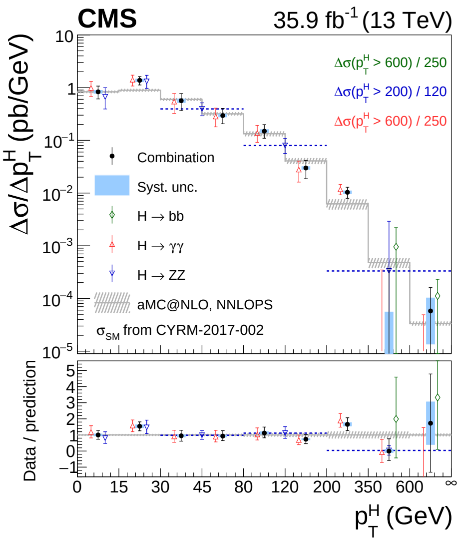

Figure 4: Observed fiducial cross sections as a function of p_T^H measured in a combination of the $H \to ZZ \to 4\ell$, $H \to \gamma\gamma$ and $H \to b\bar{b}$ decay channels [6], overlaid with the SM prediction.

association with it. Measurements reported so far do not show significant deviations from the SM expectation.

References

[1] Berger N. et al., "Simplified Template Cross Sections - Stage 1.1", (2019), https://arxiv.org/abs/1906.02754

[2] CMS Collaboration, "The CMS experiment at the CERN LHC", *JINST* **3** (2008) S08004 (2008), doi:10.1088/1748-0221/3/08/S08004

[3] CMS Collaboration, "Measurement of the inclusive and differential Higgs boson production cross sections in the leptonic WW decay mode at $\sqrt{s}$ = 13 TeV", *Submitted to JHEP* (2020), https://arxiv.org/abs/2007.01984

[4] CMS Collaboration, "Measurements of properties of the Higgs boson in the four-lepton final state in proton-proton collisions at $\sqrt{s}$ = 13 TeV", *CMS-PAS-HIG-19-001* (2019), http://cds.cern.ch/record/2668684

[5] CMS Collaboration, "Measurement of inclusive and differential Higgs boson production cross sections in the diphoton decay channel in proton-proton collisions at $\sqrt{s}$ = 13 TeV", *JHEP* **01** (2019) 183, doi:10.1007/JHEP01(2019)183

[6] CMS Collaboration, "Measurement and interpretation of differential cross sections for Higgs boson production at $\sqrt{s}$ = 13 TeV", *Phys. Lett. B* **792** (2019) 369, doi:10.1016/j.physletb.2019.03.059