MEASUREMENT OF THE HIGGS SIMPLIFIED TEMPLATE CROSS SECTIONS USING $H \to \gamma\gamma$ DECAYS WITH THE ATLAS EXPERIMENT* **

Luca Franco

on behalf of the ATLAS Collaboration

Université Savoie Mont Blanc, CNRS
Laboratoire d'Annecy de Physique des Particules — IN2P3
74000 Annecy, France

(Received March 26, 2021; accepted May 4, 2021)

The measurement of Higgs Simplified Template Cross Sections (STXS) in the $H \to \gamma\gamma$ decay channel by the ATLAS experiment at the LHC is presented. The analysis relies on categorizing events with a machine learning approach according to their topology. In addition, strategies for the interpretation of the results in terms of an Effective Field Theory are discussed.

DOI:10.5506/APhysPolB.52.923

1. Introduction

The Higgs boson was discovered by the ATLAS and CMS experiments in 2012 [1, 2] at the Large Hadron Collider (LHC) at CERN. All measurements to date confirm that the properties of the new particle are compatible with those predicted for the Higgs boson by the Standard Model (SM) within experimental and theoretical uncertainties. Further investigation of the Higgs boson properties is crucial to understand if the particle discovered at the LHC is really the one predicted by the SM or if it is the first indirect evidence of new physics beyond the Standard Model (BSM).

Despite a small branching ratio of about 0.227% [3], the diphoton decay channel ($H \to \gamma\gamma$) allows very precise measurements of Higgs boson properties, thanks to the excellent performance of photon reconstruction

* Presented at XXVII Cracow Epiphany Conference on *Future of Particle Physics*, Cracow, Poland, January 7–10, 2021.

and identification of the ATLAS detector [4]. The signal signature in this final state is a narrow resonance with a width consistent with detector resolution rising above a smooth background in the diphoton invariant mass ($m_{\gamma\gamma}$) distribution, as shown in figure 1. Results use a data set of proton–proton collisions at a center-of-mass energy of $\sqrt{s} = 13$ TeV collected by the ATLAS experiment during the Run 2 period of LHC from 2015 to 2018, corresponding to an integrated luminosity of 139 fb^{-1} [5].

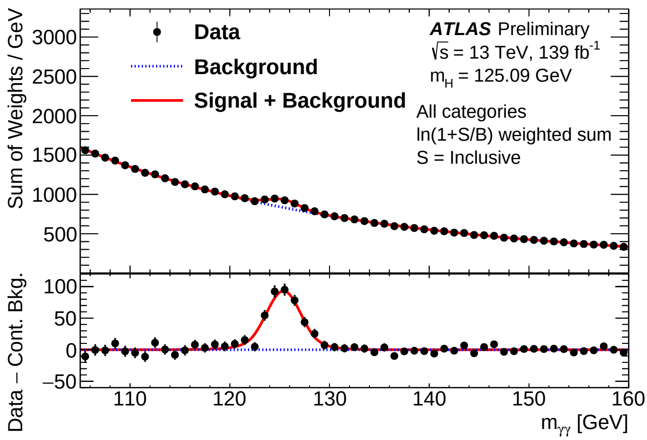

Fig. 1. Inclusive diphoton invariant mass ($m_{\gamma\gamma}$) distribution of events from all analysis categories. The data events (dots) in each category are weighted by $\ln(1 + \frac{S}{B})$, where S and B are the expected signal and background yields in this category within the smallest $m_{\gamma\gamma}$ window containing 90% of the signal events. The fitted signal plus background probability density functions (PDFs) from all categories are also weighted and summed, shown as the solid line [5].

The analysis is optimized to measure production cross sections in the Simplified Template Cross Section (STXS) framework [6], in which the Higgs production cross sections are considered in exclusive regions that are defined by kinematic selections on the most sensitive observables of the particles in the final state of the event and are specific to the different production modes: gluon–gluon fusion (ggF), vector-boson fusion (VBF), and associated production with a vector boson (VH where $V = W$ or Z) or a top-quark pair ($t\bar{t}H$). A measurement of the total Higgs boson production cross section having rapidity $|y_H| < 2.5$ is presented as well.

Finally, the combined STXS results in three Higgs decay channels are interpreted through the Effective Field Theory (EFT) framework [7].

2. Event selection and categorization

Reconstructed events are selected from the collision data set requiring the presence of two photons in the final state, having kinematic properties compatible with the hypothesis of being decay products of the Higgs boson. The background in the selected diphoton sample consists of continuum $\gamma\gamma$ production, γj and jj production, where one or more jets in the event are mis-identified as photons.

The selected events undergo a process of classification into mutually exclusive categories, which aims to optimize the sensitivity to the STXS signals and the SM background rejection. The categorization process is composed of two steps. First, a multi-class boosted decision tree (BDT) is trained to simultaneously separate signal events from different STXS regions using Monte Carlo (MC) simulation samples of the Higgs boson events. Then, using a binary BDT classifier, the events are further split in order to reduce the continuum background component in each class. The whole procedure results in the definition of 88 categories in total. The inputs to all the BDTs are variables describing the kinematic and identification properties of the reconstructed particles in the final state, such as the kinematics of the diphoton system, the number of reconstructed jets, b-jets, electrons, muons and top quarks, and the kinematics of systems composed by multiple physics objects.

3. Signal and background models

The $m_{\gamma\gamma}$ distribution in each category is described by an extended probability density function (PDF) in which the signal and background shapes are analytic functions. The likelihood function of the analysis is constructed by a simultaneous fit of the $m_{\gamma\gamma}$ distributions to their PDFs in the event categories.

The signal is modelled using a Double Sided Crystall Ball (DSCB) function, which has a Gaussian core and power-law tails.

The modelling of the continuum background consists of two main steps: firstly, a background $m_{\gamma\gamma}$ template is constructed from a combination of the $\gamma\gamma$, γj and jj processes weighted according to their fractions determined from control regions in data (ggH, VBF); or using simulated processes alone (VH, $t\bar{t}H$).

Secondly, for each category the template is used to choose an analytic function that optimally represents the background shape. The background-only template is fitted using a signal + background PDF and the amount of extracted signal S_{spur} estimates the bias associated to the choice of a given background function.

4. STXS measurements in $H \to \gamma\gamma$

The total production cross section of the Higgs (in the fiducial region $|y_H| < 2.5$) is measured to be 127 ± 10 fb, in good agreement with the SM prediction of 115 ± 5 fb. Cross sections for the ggF+bbH, VBF, WH, ZH and $t\bar{t}H + tH$ production are reported in figure 2. The compatibility between the measurement and the SM prediction corresponds to a p-value of 3%, corresponding to a 1.9σ deviation from the SM. The difference is mainly due to a larger than expected yield for the WH process, and a smaller than expected yield for the ZH process. The correlation coefficient between these two measurements is -41%. Cross sections in 27 regions of Higgs boson production phase space defined in the STXS framework are also reported in figure 3. The relative uncertainties on the measurements range from 20% to more than 100%. No significant deviations from the SM expectation are observed and the compatibility between the measurements and the SM predictions corresponds to a p-value of 60%. An upper limit of eight times the SM prediction is set for the tH process, which represents the most stringent experimental constraint on tH production to date.

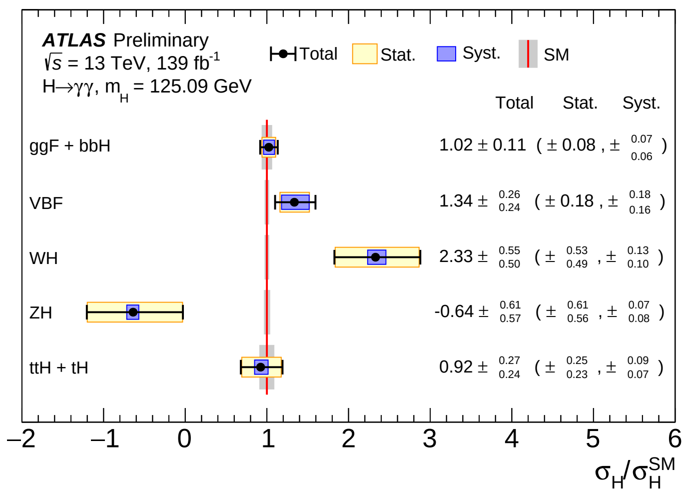

Fig. 2. Cross sections times branching fraction for ggF+bbH, VBF, VH and $t\bar{t}H + tH$ production, normalized to their SM predictions, as reported in Ref. [5].

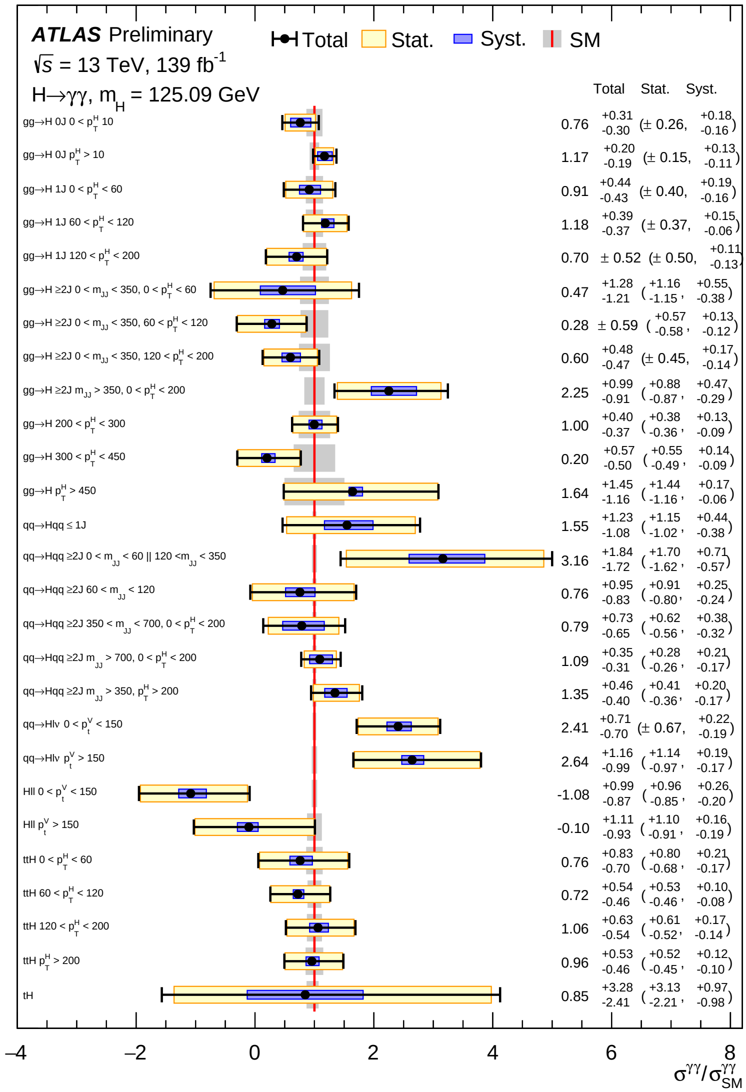

Fig. 3. Best-fit values and uncertainties for the STXS in each measurement region, normalized to the SM predictions for the various parameters, as reported in Ref. [5].

5. EFT interpretation of the STXS combination

The STXS results can be interpreted through the EFT framework. The SM EFT expands the SM Lagrangian by adding new terms which correspond to BSM operators

$$\mathcal{L}_{\mathrm{EFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_i \bar{c}_i^{(6)} \mathcal{O}_i^{(6)} \,. \tag{1}$$

The coefficients associated with the operators, also called *Wilson coefficients*, can be measured by reparametrising the STXS in terms of the c_i to which the dataset has maximum sensitivity. Experimental results obtained in terms of the EFT parameters can be interpreted as constraints on masses and couplings of new particles predicted by BSM models.

A measurement of a selection of combinations of Wilson coefficients, using both the linear and quadratic SMEFT, has been reported in Ref. [7] using a combination of Higgs STXS measurements based on the $H \to \gamma\gamma$, $H \to ZZ^* \to 4l$ (where $l = e$ or μ) and $H \to b\bar{b}$ (VH only) channels [8]. All the values of the measured EFT parameters are compatible with the SM prediction of 0.

REFERENCES

[1] ATLAS Collaboration (G. Aad *et al.*), «Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC», *Phys. Lett. B* **716**, 1 (2012).

[2] CMS Collaboration (S. Chatrchyan *et al.*), «Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC», *Phys. Lett. B* **716**, 30 (2012).

[3] LHC Higgs Cross Section Working Group, D. de Florian *et al.* (Eds.) «Vol. 2(2017) Handbook of LHC Higgs Cross Sections: 4. Deciphering the Nature of the Higgs Sector», *CERN Yellow Reports: Monographs*, CERN, Geneva 2017, arXiv:1610.07922 [hep-ph].

[4] ATLAS Collaboration (G. Aad *et al.*), «The ATLAS Experiment at the CERN Large Hadron Collider», *JINST* **3**, S08003 (2008).

[5] ATLAS Collaboration, «Measurement of the properties of Higgs boson production at $\sqrt{s} = 13$ TeV in the $H \to \gamma\gamma$ channel using 139 fb^{-1} of pp collision data with the ATLAS experiment», Technical report ATLAS-CONF-2020-026, Geneva, CERN, 2020, http://cds.cern.ch/record/2725727

[6] S. Amoroso *et al.*, «Les Houches 2019: Physics at TeV Colliders: Standard Model Working Group Report», arXiv:2003.01700 [hep-ph].

[7] ATLAS Collaboration, «Interpretations of the combined measurement of Higgs boson production and decay», Technical report ATLAS-CONF-2020-053, Geneva, CERN, 2020, http://cds.cern.ch/record/2743067

[8] ATLAS Collaboration, «A combination of measurements of Higgs boson production and decay using up to 139 fb^{-1} of proton–proton collision data at $\sqrt{s} = 13$ TeV collected with the ATLAS experiment», Technical report ATLAS-CONF-2020-027, Geneva, CERN, 2020, https://cds.cern.ch/record/2725733