PROCEEDINGS OF SCIENCE

What we learned about the Higgs boson

Luca Fiorini[a,1,2,*]

[a] *Instituto de Física Corpuscular (IFIC) and Departamento de Física Atómica, Molecular y Nuclear, University of Valencia and CSIC, Catedràtic José Beltrán 2, Paterna, Spain*

E-mail: Luca.Fiorini@cern.ch

The discovery of a Higgs boson with a mass of about 125 GeV by the ATLAS and CMS collaborations at the LHC has given access to a new fundamental sector of the Standard Model. The existence of this new particle provides the opportunity to measure its properties, such as the Higgs boson spin and mass, the coupling of the Higgs boson to gauge bosons and to fermions. The precise measurement of the Higgs boson mass is considered crucial to understand the stability of the Standard Model vacuum and the possible link between the physics at the electro-weak scale and the Planck scale. Experiments can shred light on the Yukawa coupling of the Higgs boson to fermions, which is a new kind of fundamental interaction. Run 2 of the LHC was completed in 2018 and provided about 140 fb^{-1} of data. These proceedings discuss the state of the art of the 125 GeV Higgs boson measurements and their implications for the understanding of the Higgs sector.

The Eighth Annual Conference on Large Hadron Collider Physics-LHCP2020
25-30 May, 2020
online

[1] on behalf of the ATLAS and CMS collaborations.

[2] The author acknowledges the support from project RTI2018-094270-B-I00, Spanish Ministry of Innovation and Research and ERDF.

[*] Speaker

PoS(LHCP2020)159

1. Introduction

A Higgs boson with a mass of about 125 GeV was discovered by the ATLAS [1] and CMS [2] collaborations in 2012 [3, 4]. Several properties of this particle, such as its coupling strengths to bosons and fermions, its mass, spin and charge-parity (CP) quantum numbers, were studied in proton-proton collisions at an energy in the centre of mass $\sqrt{s}$ = 7 and 8 TeV, delivered by the Large Hadron Collider (LHC) in 2011 and 2012 and referred to as 'Run 1' [5, 6]. These results established the observation of the gluon-gluon fusion (ggF) and vector bosons fusion (VBF) productions modes, as well as the decay of the Higgs boson into bosons ($H \rightarrow \gamma\gamma$, $H \rightarrow WW^*$ and $H \rightarrow ZZ^*$) and into τ-pairs ($H \rightarrow \tau\tau$). The latter is also the first observation of the Yukawa coupling of the Higgs boson, a new kind of interaction. Using data collected during Run 2 of the LHC (2015-2018), it was possible to observe the production of the Higgs boson in association with a Z-boson (ZH) [9] and top-antitop pair (ttH) [7, 8]. The decay of the Higgs boson into a pair of b-quarks ($H \rightarrow b\bar{b}$) has been observed as well [9, 10].

In these proceedings, the latest measurements of the Higgs boson properties with Run 2 data are presented. When applicable, the results are interpreted in terms of Standard Model (SM) or beyond the SM (BSM) parameters.

2. Cross-section measurements

ATLAS and CMS collaborations have performed measurements of the total cross-section of the Higgs boson production modes, as well as fiducial and differential measurements with the purpose of measuring particle interactions in the most model-independent way.

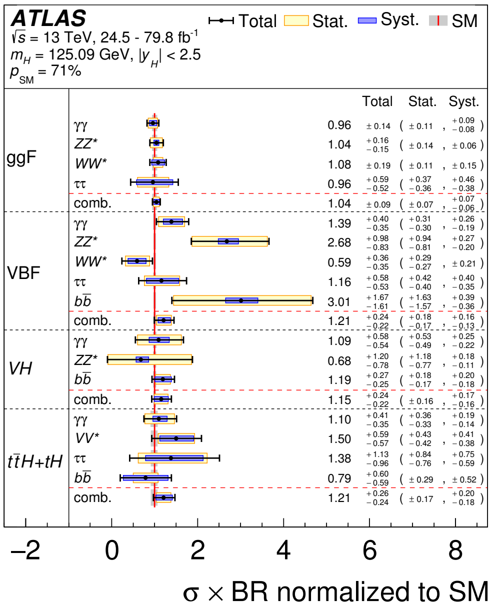
Total cross-section measurements have been performed for the five main production modes in the $H \rightarrow \gamma\gamma$, $H \rightarrow WW^*$, $H \rightarrow ZZ^*$, $H \rightarrow \tau\tau$ and $H \rightarrow b\bar{b}$ final states. Results show a high compatibility between the measurements and the SM predictions, as shown in Figure 1.

In the Simplified Template Cross-Section framework (STXS) [13–15], cross-sections are measured within exclusive fiducial phase spaces mimicking the experimental selection to avoid large extrapolation uncertainties to the full phase space. Results from the experiments are generally unfolded to be independent from resolution and efficiency effects. Migration effects are considered and corrected for. The measurements are also interpreted in a model-independent way in terms of modifications to the tensor structure of Higgs boson couplings using an effective field theory (EFT) approach. Example of STXS measurements and EFT interpretation of cross-section measurements are given in Figure 2.

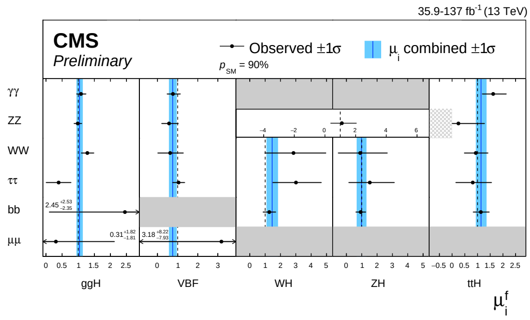
Similarly, unfolding techniques can be used in the measurement of differential cross-section of the Higgs boson production. Thanks to its large branching fraction, the $H \rightarrow b\bar{b}$ channel is particularly sensitive to the measurement of highly boosted Higgs boson production. Figure 3 shows STXS measurements [19] and differential cross-section measurements of highly boosted Higgs boson decaying into a $b\bar{b}$ pair [22].

3. CP structure of the Hff coupling

ATLAS and CMS measured with Run 1 data the spin and parity properties of the Higgs boson in interactions with gauge bosons, establishing a value of $J^P = 0^+$ with a high confidence level.



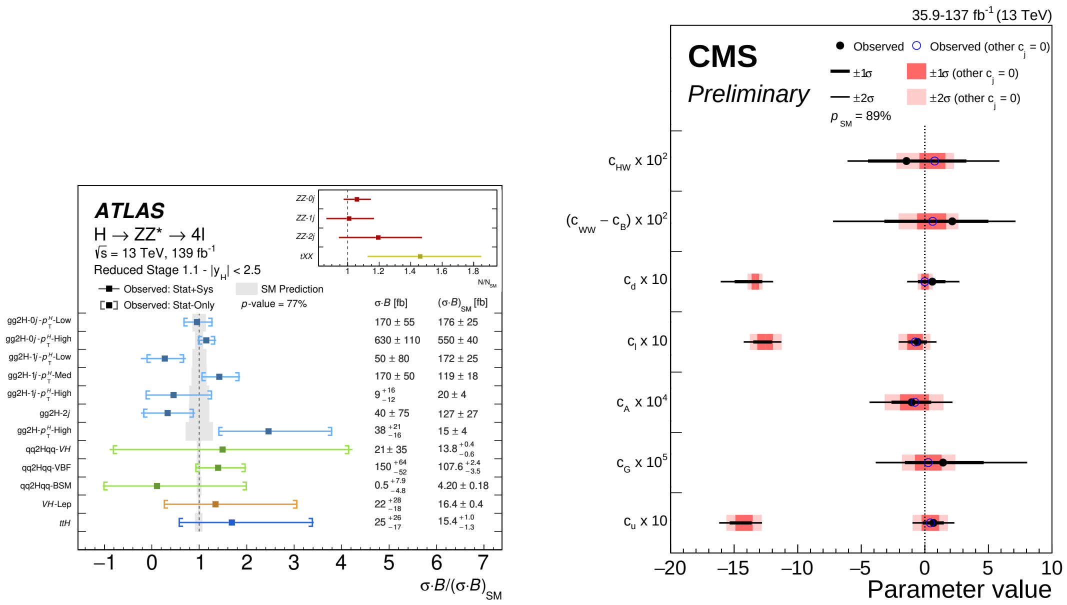
(a)



(b)

Figure 1: (a) The ATLAS measurement of the cross-section times branching fraction for the main Higgs boson production modes in each relevant decay mode is performed normalized to their SM predictions. The values are obtained from a simultaneous fit to all channels. Combined results for each production mode are also shown, assuming SM values for the branching fractions into each decay mode. The black error bars, blue boxes and yellow boxes show the total, systematic, and statistical uncertainties in the measurements, respectively. The gray bands show the theory uncertainties in the predictions [11]. (b) The CMS measurement of the signal strength modifiers for the production times decay mode, μ_i^f , is performed for a specific production and decay channel $i \to H \to f$, the signal strength for the production, μ_i, and for the decay, μ^f , are defined as $\mu_i = \frac{\sigma_i}{(\sigma_i)_{SM}}$ and $\mu_f = \frac{\mathcal{B}^f}{(\mathcal{B}^f)_{SM}}$. The black points and horizontal error bars show the best-fit values and 1 σ confidence intervals, respectively. The arrows indicate cases where the confidence intervals exceed the scale of the horizontal axis. The gray filled boxes indicate signal strength modifiers which are not included in the model, while the gray hatched box indicates the region for which the sum of signal and background becomes negative [12].

With Run 2 data, the two collaborations have started to study the CP properties of the Yukawa interaction between the Higgs boson and fermions. Measurements of the CP structure of the top-quark interaction with the Higgs boson are shown in Figure 4. ATLAS excludes a pure CP-odd coupling with a confidence level of 3.9 σ, observes the ttH process with a significance of 5.2 σ and set an upper limit of 12 times the SM expectation on the tH production process at 95% confidence level [23]. CMS excludes a pure CP-odd coupling with a confidence level of 3.2 σ and observes the ttH process with a significance of 6.6 σ [24].

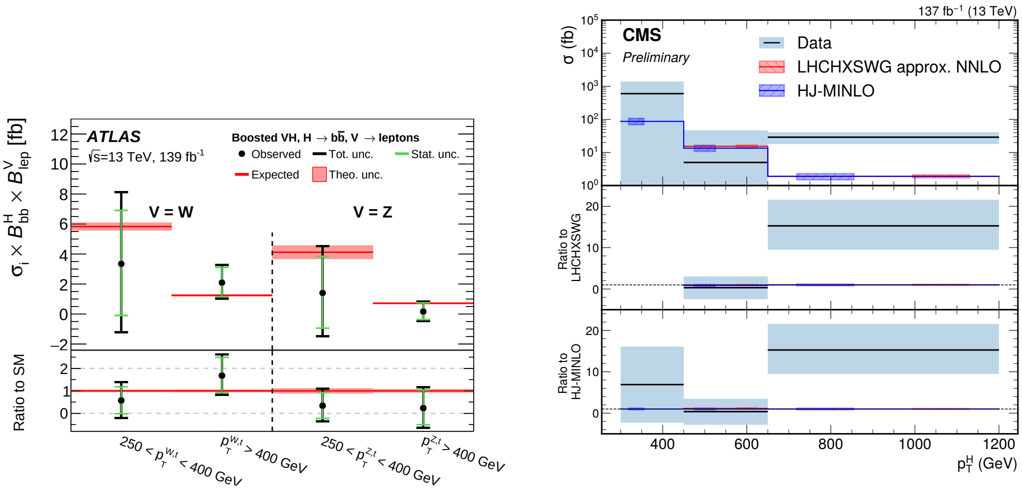


(a) (b)

Figure 2: (a) ATLAS observed and expected values of the cross-sections $\sigma \cdot \mathcal{B}$ normalised by the SM expectation for the STXS reduced stage-1.1 production bins [15]. The fitted normalisation factors for the ZZ and tXX backgrounds are shown in the inserts. Different colours indicate different Higgs boson production modes (or background sources) [16]. (b) Summary of the CMS results for the HEL[17, 18] parameter scans. The best fit values when profiling (fixing) the other parameters are shown by the solid black (hollow blue) points. The $\pm 1\sigma$ and $\pm 2\sigma$ confidence intervals are represented by the thick and thin black lines respectively for the profiled scenario, and the red and pink bands respectively for the fixed scenario [12].

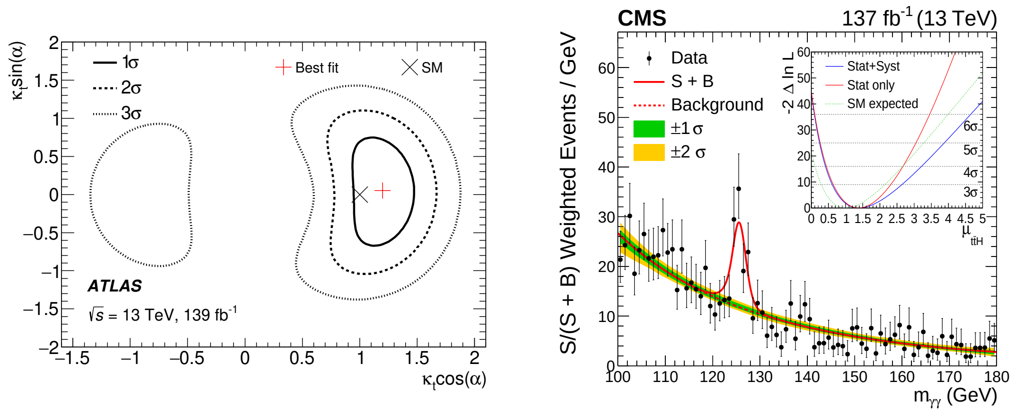
4. Mass measurements

The mass of the Higgs boson is one of the fundamental parameters of SM and it is crucial to understand the stability of the electro-weak vacuum. The $H \to \gamma\gamma$ and $H \to ZZ^*(\to 4\ell)$ decay modes are characterised by a small branching fraction, but provide clean final state topologies in which the invariant mass of the final state objects can be reconstructed with high precision. Figure 5 shows the results of the Higgs mass measurement by ATLAS and CMS with Run 2 data. ATLAS mass value measurement in the four leptons final state is $m_H = 124.92 \pm 0.19(\text{stat.})^{+0.09}_{-0.06}(\text{syst.})$ GeV [25]. CMS measures in the $H \to \gamma\gamma$ final state a mass value of $m_H = 125.78 \pm 0.26$ GeV [26]. This result, when combined with previous CMS results using Run 1 data and the measurement in the four leptons final state using Run 2 data provides a mass value measurement of $m_H = 125.38 \pm 0.14$ GeV.



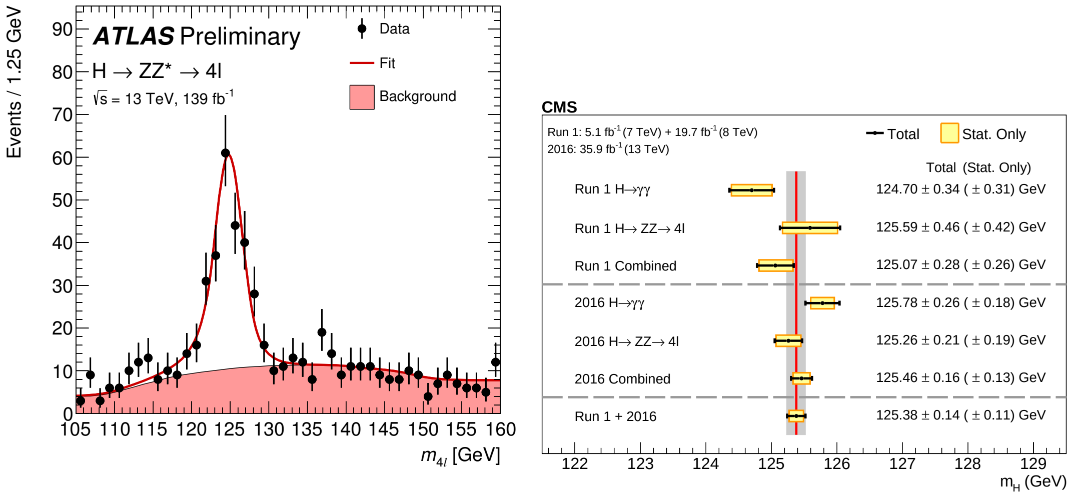
(a) (b)

Figure 3: (a) ATLAS measurement of the VH reduced stage-1.2 STXS [15] times the $H \to b\bar{b}$ and $V \to$ leptons branching fractions [19]. (b) CMS measurement of the differential fiducial cross-section as a function of Higgs boson p_T, compared to the predictions of Ref. [20], is shown in red, and HJ-MINLO [21], is shown in blue. In the bottom two panels, the dotted line corresponds to a ratio of one. The relative uncertainties in the predictions of Ref. [20] and HJ-MINLO are approximately 10% and 20%, respectively [22].



(a) (b)

Figure 4: (a) ATLAS results of the two-dimensional likelihood contours for $\kappa_t cos(\alpha)$ and $\kappa_t sin(\alpha)$ with ggF and $\mathcal{B}(H \to \gamma\gamma)$ constrained by the Higgs boson coupling combination. The α angle represents the CP-mixing angle [23]. (b) Invariant mass distribution obtained by CMS for the selected events (black points) weighted by S/(S+B), where S (B) is the numbers of expected signal (background) events in a $\pm 1\sigma_\mathrm{eff}$ mass window centered on m_H. The σ_eff is defined as the smallest interval containing 68.3% of the $m_{\gamma\gamma}$ distribution. The inner panel shows the likelihood scan for $\mu_{t\bar{t}H}$ with m_H profiled [24].



(a) (b)

Figure 5: The $m_{4\ell}$ data distribution obtained by ATLAS from all analysis categories combined (black points), is shown along with the fit result when accounting for the per-event resolution (red line). The background component of the fit result is shown separately in solid red [25]. (b) CMS summary of the measured Higgs boson mass in the $H \to \gamma\gamma$ and $H \to ZZ^*(\to 4\ell)$ decay channels, and their combination. The statistical (wider, yellow-shaded bands), and total (black error bars) uncertainties are indicated. The (red) vertical line and corresponding (grey) shaded column indicate the central value and the total uncertainty of the Run 1 + 2016 combined measurement, respectively [26].

5. Conclusions

Outstanding performance of the LHC collider and of the ATLAS and CMS experiments allowed to perform measurements of the Higgs boson properties with impressive precision. Precise cross-section measurements with Run 2 data are compared to SM predictions with STXS and EFT methodologies. Differential cross-section measurements with Run 2 data are used to measure particle interactions. Yukawa interaction and its CP structure have been probed by the ATLAS and CMS experiments. So far no significant deviation from the SM has been observed. The Higgs boson mass value has been measured with Run 2 achieving an accuracy already a factor two better than the LHC Run 1 combination and the measurement is still limited by statistical uncertainties. More refined analyses and measurements with more statistics will allow to probe the SM predictions with high accuracy and constrain a wider range of new physics operators, especially in the high-transverse momentum regions.

References

[1] ATLAS Collaboration, *The ATLAS Experiment at the CERN Large Hadron Collider*, JINST **3** (2008), S08003, doi:10.1088/1748-0221/3/08/S08003

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

[3] ATLAS Collaboration,*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** (2012), 1-29, doi:10.1016/j.physletb.2012.08.020, [arXiv:1207.7214 [hep-ex]].

[4] CMS Collaboration, *Observation of a New Boson at a Mass of 125 GeV with the CMS Experiment at the LHC*, Phys. Lett. B **716** (2012), 30-61, doi:10.1016/j.physletb.2012.08.021, [arXiv:1207.7235 [hep-ex]].

[5] ATLAS and CMS Collaborations, *Combined Measurement of the Higgs Boson Mass in pp Collisions at $\sqrt{s}$ = 7 and 8 TeV with the ATLAS and CMS Experiments*, Phys. Rev. Lett. **114** (2015), 191803, doi:10.1103/PhysRevLett.114.191803, [arxiv:1503.07589[hep-ex]].

[6] ATLAS and CMS Collaborations, *Measurements of the Higgs boson production and decay rates and constraints on its couplings from a combined ATLAS and CMS analysis of the LHC pp collision data at $\sqrt{s}$ = 7 and 8 TeV*, JHEP **08** (2016), 045, doi:10.1007/JHEP08(2016)045, [arXiv:1606.02266 [hep-ex]].

[7] ATLAS Collaboration, *Observation of Higgs boson production in association with a top quark pair at the LHC with the ATLAS detector*, Phys. Lett. B **784** (2018), 173-191, doi:10.1016/j.physletb.2018.07.035, [arXiv:1806.00425 [hep-ex]].

[8] CMS Collaboration, *Observation of $t\bar{t}H$ production*, Phys. Rev. Lett. **120** (2018) no.23, 231801, doi:10.1103/PhysRevLett.120.231801, [arXiv:1804.02610 [hep-ex]].

[9] ATLAS Collaboration, *Observation of $H \to b\bar{b}$ decays and VH production with the ATLAS detector*, Phys. Lett. B **786** (2018), 59-86, doi:10.1016/j.physletb.2018.09.013, [arXiv:1808.08238 [hep-ex]].

[10] CMS Collaboration, *Observation of Higgs boson decay to bottom quarks*, Phys. Rev. Lett. **121** (2018) no.12, 121801, doi:10.1103/PhysRevLett.121.121801, [arXiv:1808.08242 [hep-ex]].

[11] ATLAS Collaboration, *Combined measurements of Higgs boson production and decay using up to 80 fb^{-1} of proton-proton collision data at $\sqrt{s}$ = 13 TeV collected with the ATLAS experiment*, Phys. Rev. D **101** (2020) no.1, 012002, doi:10.1103/PhysRevD.101.012002, [arXiv:1909.02845 [hep-ex]].

[12] CMS Collaboration, *Combined Higgs boson production and decay measurements with up to 137 fb^{-1} of proton-proton collision data at $\sqrt{s}$ = 13 TeV*, CMS-PAS-HIG-19-005.

[13] J. Bendavid et al., *Les Houches 2017: Physics at TeV Colliders Standard Model Working Group Report*, 2018, arXiv: 1803.07977 [hep-ph].

[14] LHC Higgs Cross Section Working Group, D. de Florian et al., *Handbook of LHC Higgs Cross Sections: 4. Deciphering the nature of the Higgs sector*, CERN-2017-002-M (CERN, Geneva, 2016), arXiv: 1610.07922 [hep-ph].

[15] N. Berger et al., *Simplified Template Cross Sections - Stage 1.1, (2019)*, arXiv: 1906.02754 [hep-ph].

[16] ATLAS Collaboration, *Higgs boson production cross-section measurements and their EFT interpretation in the 4ℓ decay channel at $\sqrt{s}$ = 13 TeV with the ATLAS detector*, Eur. Phys. J. C **80** (2020) 10, 957, doi:10.1140/epjc/s10052-020-8227-9, [arXiv:2004.03447 [hep-ex]].

[17] R. Contino, M. Ghezzi, C. Grojean, M. Muhlleitner and M. Spira, *Effective Lagrangian for a light Higgs-like scalar*, JHEP **07** (2013), 035, doi:10.1007/JHEP07(2013)035, [arXiv:1303.3876 [hep-ph]].

[18] A. Alloul, B. Fuks and V. Sanz, *Phenomenology of the Higgs Effective Lagrangian via FEYNRULES*, JHEP **04** (2014), 110, doi:10.1007/JHEP04(2014)110, [arXiv:1310.5150 [hep-ph]].

[19] ATLAS Collaboration, *Measurement of the associated production of a Higgs boson decaying into b-quarks with a vector boson at high transverse momentum in pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector*, arXiv:2008.02508 [hep-ex].

[20] LHC Higgs Cross SectionWorking Group, *Recommended predictions for the boosted-Higgs cross section*, technical report, 2019.

[21] K. Hamilton, P. Nason, C. Oleari and G. Zanderighi, *Merging H/W/Z + 0 and 1 jet at NLO with no merging scale: a path to parton shower + NNLO matching*, JHEP **05** (2013), 082, doi:10.1007/JHEP05(2013)082, [arXiv:1212.4504 [hep-ph]].

[22] CMS Collaboration, *Inclusive search for a highly boosted Higgs boson decaying to a bottom quark-antiquark pair at* $\sqrt{s} = 13$ TeV *with* 137 fb^{-1}, CMS-PAS-HIG-19-003.

[23] ATLAS Collaboration, *CP Properties of Higgs Boson Interactions with Top Quarks in the* $t\bar{t}H$ *and* tH *Processes Using* $H \to \gamma\gamma$ *with the ATLAS Detector*, Phys. Rev. Lett. **125** (2020) no.6, 061802, doi:10.1103/PhysRevLett.125.061802, [arXiv:2004.04545 [hep-ex]].

[24] CMS Collaboration, *Measurements of* $\mathrm{t\bar{t}}H$ *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) no.6, 061801, doi:10.1103/PhysRevLett.125.061801, [arXiv:2003.10866 [hep-ex]].

[25] ATLAS Collaboration, *Measurement of the Higgs boson mass in the* $H \to ZZ^* \to 4\ell$ *decay channel with* $\sqrt{s} = 13$ *TeV* pp *collisions using the ATLAS detector at the LHC*, ATLAS-CONF-2020-005.

[26] CMS Collaboration, *A measurement of the Higgs boson mass in the diphoton decay channel*, Phys. Lett. B **805** (2020), 135425, doi:10.1016/j.physletb.2020.135425, [arXiv:2002.06398 [hep-ex]].