PROCEEDINGS OF SCIENCE

Higgs Measurements

K. Tackmann[a,b,*] **on behalf of the ATLAS and CMS Collaborations**

[a] *Deutsches Elektronen-Synchrotron DESY,*
Notkestr. 85, Hamburg, Germany

[b] *Universität Hamburg,*
Luruper Chaussee 149, Hamburg, Germany

E-mail: kerstin.tackmann@desy.de

These proceedings report on recent analyses of the Higgs sector by the ATLAS and CMS experiments at the Large Hadron Collider. Most analyses are based on the dataset taken during the LHC Run2, corresponding to an integrated luminosity of close to 140 fb^{-1} per experiment. The analyses presented range from measurements of the main production and decay processes, over studies of non-Standard Model couplings and searches for not-yet-observed decay channels to searches for di-Higgs production. All results are consistent with the predictions of the Standard Model.

**** The European Physical Society Conference on High Energy Physics (EPS-HEP2021), ****
**** 26-30 July 2021 ****
**** Online conference, jointly organized by Universität Hamburg and the research center DESY ****

[*] Speaker

PoS(EPS-HEP2021)032

1. Introduction

The Standard Model of particle physics (SM) makes clear predictions about the properties of the Higgs boson, e.g. the couplings of the Higgs boson to the other SM particles are directly related to these particles' masses. At the Large Hadron Collider (LHC), there are four main production processes for the Higgs boson, gluon fusion, which accounts for about 88% of Higgs boson production, vector boson fusion, production in association with a vector boson, and production in association with a $t\bar{t}$ pair. The latter three have distinct experimental signatures, which can be used to distinguish the different processes.

With the data collected during the LHC Run1 and Run2 by the ATLAS [1] and CMS [2] experiments, all main production processes and decay channels, including decays to two bosons and to third-generation fermions, have been observed, and the large Run2 dataset is used to make more differential measurements, exploring also more extreme regions of phase space. Another emphasis are searches for decays to second-generation fermions and rare Higgs boson decays as well as searches for di-Higgs production, sensitive to the Higgs self-coupling.

2. Measurements in the main decay channels

The Higgs boson mass is measured in the two channels with high experimental resolution for the final state particles, $H \to ZZ^* \to 4\ell$ and $H \to \gamma\gamma$. These measurements rely on precise calibration of the final state particles' energy. The most recent measurements reach a precision of 0.11% [3] and 0.2% [4], respectively, still limited by statistical uncertainties. This precision is not a limiting factor for other Higgs measurements, nor for constraints on supersymmetric models.

The cross section measurements in the main decay channels can be split into categories. The first category consists of measurements that aim to separate different production processes, either to measure them separately or to improve the sensitivity to quantities inclusive in production process. Most of these measurements are based on simplified template cross sections (STXS) [5, 6], which define specific kinematic regions per production process to be measured. The second category consists of measurements inclusive in the production process and usually performed within a fiducial volume defined by the final state particles' kinematics, designed to be more model-independent and to provide more granular kinematic information.

Recent measurements in the first category have been obtained in the $H \to ZZ^* \to 4\ell$ [7] and the $H \to \gamma\gamma$ [8] decay channels by CMS, in the $H \to WW^*$ [10, 11] decay channel by both ATLAS and CMS and in the $H \to \tau\tau$ [15] decay channel by ATLAS (see Fig. 1 for results in the $H \to \gamma\gamma$ and $H \to \tau\tau$ decay channels). The differential measurements in the $H \to ZZ^* \to 4\ell$ are still limited by statistical uncertainties, while systematic uncertainties can be important for the measurements in the $H \to WW^*$ and the $H \to \tau\tau$ decay channels. In the $H \to WW^*$ measurements of gluon fusion and vector boson fusion production, the important uncertainties tend to be of theoretical nature and are related to the signal and background modeling. In the $H \to \tau\tau$ measurements, the largest uncertainties are those on the signal modeling. In addition to several bins for the more abundant production processes, the $H \to \gamma\gamma$ measurement includes five bins in Higgs transverse momentum for production in association with a $t\bar{t}$ pair. It includes a bin sensitive to tH production and sets a limit at 14 times the SM prediction for the tH production cross section at 95% CL (8 times the

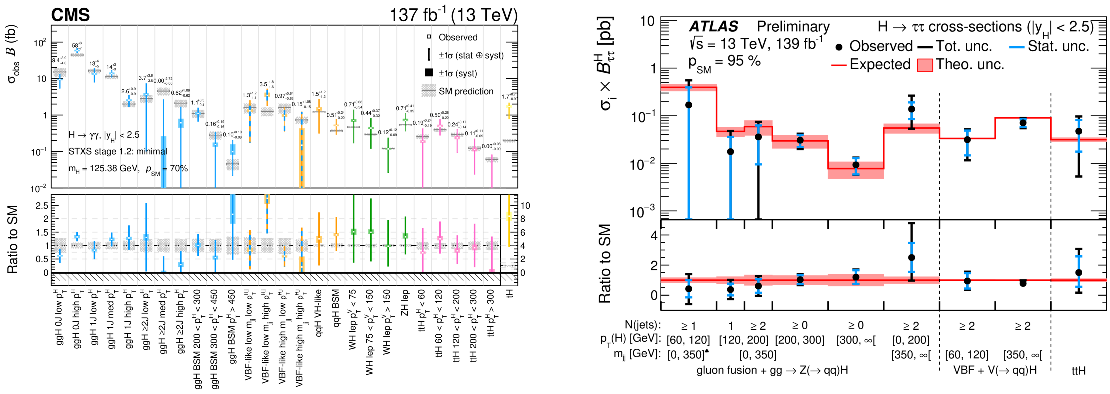

Figure 1: [Left] Measurements of cross sections in various kinematic regions for gluon fusion, vector boson fusion, production in association with a vector boson, production in association with $t\bar{t}$ and production in association with a top quark in the $H \to \gamma\gamma$ decay channel, compared to SM predictions [8]. [Right] Measurements of cross sections in various kinematic regions for gluon fusion, vector boson fusion and production in association with a vector boson, and production in association with all-hadronic $t\bar{t}$ in the $H \to \tau\tau$ decay channel, compared to SM predictions [15].

SM expected), while a similar analysis by ATLAS sets a limit at 8 times the SM prediction [9]. The $H \to WW^*$ measurement of associated production in association with a vector boson by CMS uses final states with two, three, or four leptons and reaches a significance for VH production of $4.7\,\sigma$ ($2.8\,\sigma$ expected). The $H \to \tau\tau$ analysis employs a new strategy to validate the modeling of the dominant $Z \to \tau\tau$ backgrounds using $Z \to \ell\ell$ events selected from data and to these applies simulation-based corrections to the kinematics (the lepton four vectors) and the efficiencies to mimic the $Z \to \tau\tau$ background. The measurement reaches a significance of $3.9\,\sigma$ ($4.6\,\sigma$ expected) for gluon fusion and $5.3\,\sigma$ ($6.2\,\sigma$ expected) for vector boson fusion and measures an inclusive cross section of $2.90^{+0.21}_{-0.21}\,(\mathrm{stat})^{+0.37}_{-0.32}\,(\mathrm{syst})$ pb for Higgs rapidities $|y_H| < 2.5$, in good agreement with the SM prediction of 3.14 ± 0.8 pb. The statistical and systematic uncertainties have both been improved by a factor of 2-2.5 compared to the previous analysis [16]. The most precise measurements are obtained from statistical combinations of measurements in various decay channels, and a recent combination has been performed by ATLAS [13]. The results of this statistical combination are also interpreted in terms of couplings scaling factors κ, reaching a typical precision of 6-15% for the different κ, and in Effective Field Theories, setting constraints on non-SM couplings [14].

Recent measurements in the second category have been obtained in the $H \to ZZ^* \to 4\ell$ [7] (see Fig. 2 left) and $H \to \tau\tau$ [12] decay channels, both by CMS. The former analysis measures a fiducial cross section of $2.84^{+023}_{-0.22}\,(\mathrm{stat})^{+026}_{-0.21}\,(\mathrm{syst})$ fb, in good agreement with the SM prediction of 2.84 ± 0.15 fb. In $H \to \tau\tau$ decay channel, this is the first measurements performed in a fiducial volume defined by the kinematics of the visible τ decay products. It also measures a fiducial cross section of 426 ± 102 fb, in good agreement with the SM prediction of 408 ± 27 fb. A recent measurement in the $H \to b\bar{b}$ decay channel by ATLAS focuses on the high-transverse momentum region, using $H \to b\bar{b}$ candidates reconstructed as a single large-R jet [17]. The analysis is sensitive to all Higgs production processes and sets a limit on the fiducial cross section for transverse momenta

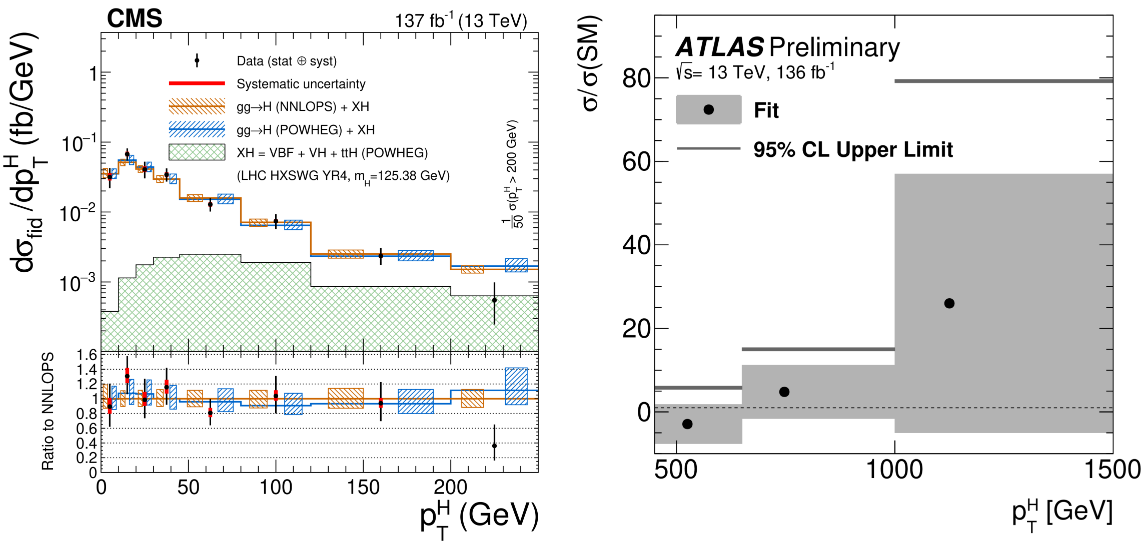

Figure 2: [Left] Measurement of the Higgs transverse momentum distribution measured in the $H \to ZZ^* \to 4\ell$ decay channel, compared to two SM predictions [7]. [Right] Best fit value and 95%CL upper limit on the cross section for $pp \to H \to b\bar{b}$ in various ranges of Higgs transverse momentum normalized to the SM prediction [17].

larger than 1 TeV of 10.3 fb at 95% CL (see Fig. 2 right).

3. Searches for decays into second-generation fermions and rare decay channels

In the SM, the Yukawa interactions are the only interactions that distinguish between the three fermion generations. For this reason, searches for Higgs boson decays to second-generation fermions are of particular interest to probe the validity of the SM. Recently, first evidence was found for Higgs boson decays to two muons, with a significance of 3.0 σ (2.5 σ expected) by CMS [18] (see Fig. 3 left), further supported by an observed (expected) significance of 2.0 σ (1.7 σ) seen by ATLAS [19]. The search for Higgs boson decays to a $c\bar{c}$ pair is challenging because of large and diverse backgrounds, which are controlled and estimated by performing the analysis in several exclusive event categories. A recent analysis by ATLAS obtains a limit on $pp \to H \to c\bar{c}$ of 25 times the SM prediction at 95% CL (31^{+12}_{-8} expected) [20]. This allowed to set the first direct limit on the charm coupling scaling factor $|\kappa_c|$ at 8.5 at 95% CL (12.4 expected).

The Higgs boson decay into $\ell\ell\gamma$ is predicted to be rare. The first evidence for this decay in the low-$m_{\ell\ell}$ region ($m_{\ell\ell}$ <30 GeV), which is dominated by $H \to \gamma^*\gamma$ has recently been found by ATLAS with a significance of 3.2 σ (2.1 σ expected) [21], while the significance for the $m_{\ell\ell} \approx m_Z$, which is dominated by $H \to Z\gamma$ has been found by ATLAS to be 2.2 σ (1.2 σ expected) [22]. The analysis of the very low $m_{\ell\ell}$ region requires dedicated trigger and identification strategies for the electron pairs as their showers overlap in the electromagnetic calorimeter. Their performance is validated with photons that convert in the detector material at low detector radii.

PoS(EPS-HEP2021)032

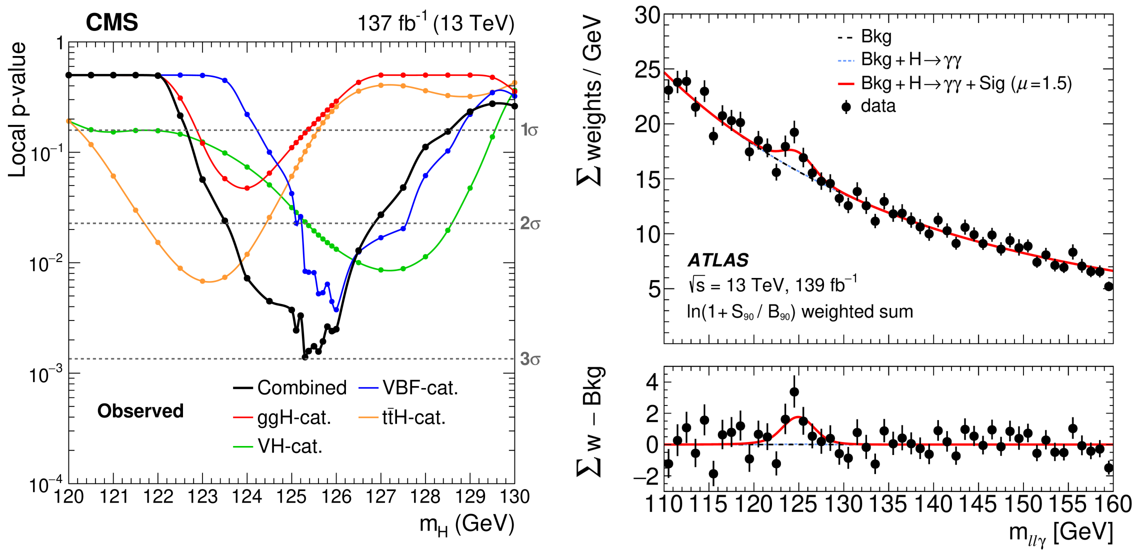

Figure 3: [Left] Local p-value for the background-only hypothesis for various experimental categories and their statistical combination in the search for $H \to \mu\mu$ decays [18]. [Right] Invariant mass of the $\ell\ell\gamma$ system and result of the signal+background fit in the search for $H \to \ell\ell\gamma$ decays with low dilepton invariant mass ($m_{\ell\ell}$ <30 GeV) [21].

4. Studies of *CP* and anomalous couplings

If the tensor structure of the interaction of the Higgs boson to SM particles is different than predicted by the SM, the kinematics of Higgs production and decay could be modified. A recent analysis by CMS uses all main Higgs production processes, as well as production in association with a single top quark and production in association with a $b\bar{b}$ pair and the $H \to ZZ^* \to 4\ell$ decay to study these effects [23]. The results are interpreted in a framework of anomalous couplings as well as an effective field theory, including also CP-odd couplings and operators. Two dedicated analyses are used to study effects in Higgs couplings to vector bosons and Higgs couplings to top quarks and gluons. The latter analysis is also combined with a recent analysis in $H \to \gamma\gamma$ decays using associated production in association with a $t\bar{t}$ pair [24]. No indications for non-SM couplings or tensor structures has been found (see Fig. 4 left).

5. Searches for invisible Higgs decays

Higgs boson decays to invisible final states are predicted to be very rare by the SM (taking place through $H \to ZZ^* \to 4\nu$), but could be significant in theories beyond the SM, e.g. if the Higgs couples to dark matter. A recent search by ATLAS uses Higgs boson production in association with a Z boson, reconstructed in its decay to two light leptons, with subsequent decay of the Higgs boson into invisible final states, resulting in large missing transverse momentum in the detector, sets a limit on the branching ratio of Higgs decaying to invisible final states at 18% at 95% CL (18% expected) [25]. This is not very far from the limit at 13% (13% expected) set previously by an

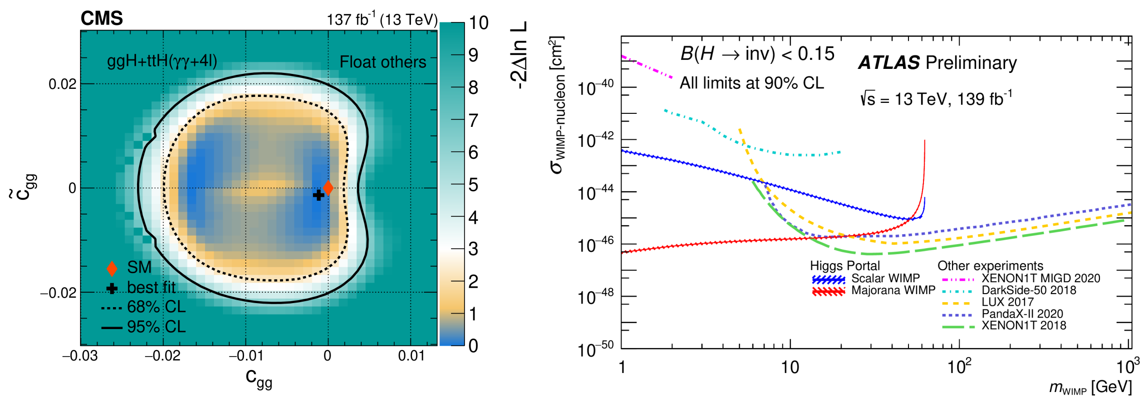

Figure 4: [Left] Constraints on CP-even and CP-odd Higgs couplings to gluons, while the respective couplings to top quarks are freely floating, based on Higgs production in gluon fusion and associated production with a $t\bar{t}$ pair and Higgs decays to four leptons and to two photons [23]. [Right] Constraints on the WIMP-nucleon interaction cross section for scalar and Majorana WIMPS from the search for Higgs decays to invisible final states, compared to direct dark matter detection experiments [25].

analysis using the vector-boson fusion topology [26] and the limit of 11% (11% expected) that had been obtained from a statistical combination of analyses based on the Run1 dataset and a partial set of analyses based on the full Run2 dataset, including [26], by ATLAS [27]. The result obtained by [25] has been interpreted as a limit on the WIMP-nucleon interaction cross section in Higgs portal models and compared to direct dark matter detection efficiencies, which have complementary sensitivity (see Fig. 4 right).

6. Searches for di-Higgs production and constraints on the Higgs self-coupling

Di-Higgs production is predicted to be very rare in the SM, with a cross section more than three orders of magnitude smaller than single Higgs production. One reason for this suppression is destructive interference between the dominant gluon fusion-like processes scaling with the Higgs–top coupling and with the Higgs self-coupling. The latter provides information about the potential of the Higgs field.

A recent analysis by CMS in the $HH \to 4b$ decay channel, the decay channel with the largest branching fraction, considers gluon fusion and vector boson fusion di-Higgs production and is hence sensitive to both the Higgs self-coupling and the $VVHH$ coupling [28]. A challenge in this analysis is to control and estimate the large backgrounds from multijet and $t\bar{t}$ production. Their estimation relies on control regions selected from data. It sets limits at 3.6 (7.3 expected) times the SM prediction for the $pp \to H \to 4b$ process, where a global scaling of all contributions to the signal is considered. It also sets limits at -2.3< κ_λ <9.4 (-5.0< κ_λ <12.0 expected) for the self-coupling scaling factor κ_λ and -0.1< κ_{2V} <2.2 (-0.4< κ_{2V} <2.5 expected) for the $VVHH$ coupling scaling factor κ_{2V} (all limits at 95% CL).

A second recent analysis by CMS in the same decay channel considers vector boson fusion production and uses final states where the Higgs decay products are boosted and reconstructed from large-R jets [29]. It employs graph convolutional neural networks for the identification of

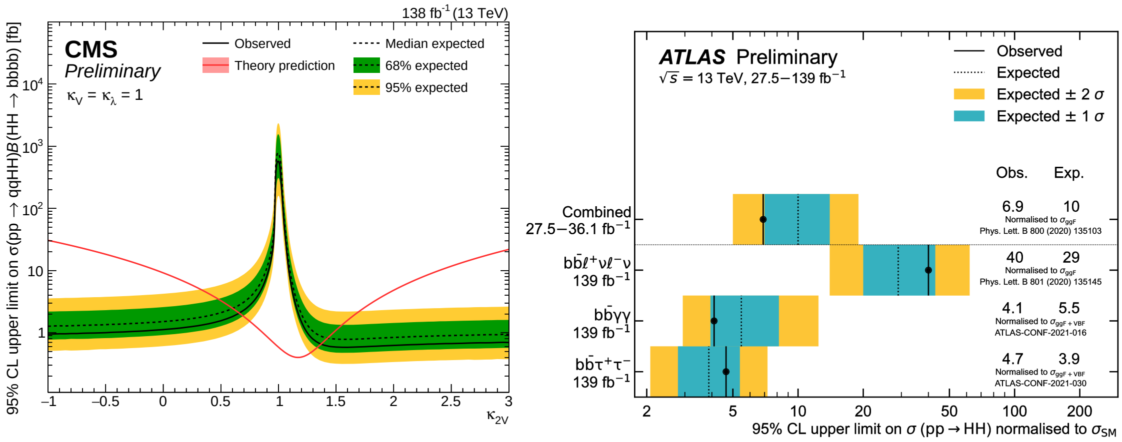

Figure 5: [Left] Upper limit on the $pp \to qqHH$ cross section times the $HH \to 4b$ branching ratio as a function of κ_{2V} from the analysis considering vector boson fusion production and boosted Higgs decays [29]. [Right] Summary of upper limits on the $pp \to HH$ cross section from analyses of the 139 fb^{-1} dataset compared to the statistical combination of analyses based on up to 36 fb^{-1} [32].

$H \to b\bar{b}$ decays and for the mass regression to improve the resolution of the Higgs candidate's mass. The data are found to agree with the background-only hypothesis and the analysis sets a limit at 0.6< κ_{2V} <1.4 (0.6< κ_{2V} <1.4 expected) at 95% CL and finds that κ_{2V} =0 is excluded at more than 95% CL for κ_V >0.5 and all other κ=1 (see Fig. 5 left).

A recent analysis by ATLAS in the very rare, but cleaner $b\bar{b}\gamma\gamma$ final state considers gluon fusion and vector boson fusion di-Higgs production [30]. It sets limits at 4.1 (5.5 expected) times the SM prediction for the $pp \to H \to b\bar{b}\gamma\gamma$ process, -1.5< κ_λ <6.7 (-2.4< κ_λ <7.7 expected), the best limit on the self-coupling to-date (each at 95% CL). Analyses of the $b\bar{b}\gamma\gamma$ and $b\bar{b}\tau\tau$ final states are more sensitive to κ_λ than analyses of the $4b$ final state due to their better acceptance in the low m_{HH} region.

The $b\bar{b}\tau\tau$ final state has a sizeable branching fraction and at the same time not too large but numerous backgrounds, consisting of $t\bar{t}$, V+jets, diboson, multijet and single Higgs events as well as misreconstructed hadronic τ decays. A recent analysis by ATLAS in this decay channel sets a limit at 4.7 (3.9 expected) times the SM prediction for the $pp \to H \to b\bar{b}\tau\tau$ process [31]. The limits from this analysis and the analysis in the $b\bar{b}\gamma\gamma$ final state are already better than the previous statistical combination of analyses based on up to 36 fb^{-1} [32] (see Fig. 5 right).

7. Conclusions

All recent analyses studying the Higgs sector at the ATLAS and CMS experiments at the LHC make use of the full dataset recorded during the LHC Run2. With the large Run2 dataset, the measurements of the main production processes and decay channels are becoming more precise and the size of the dataset is exploited by making more differential measurements and by studying more extreme regions of phase space. In addition, the searches for second-generation fermions and other rare decays are starting to be sensitive and first evidence has been obtained for the $H \to \mu\mu$

and $H \to \ell\ell\gamma$ decays. The new searches for di-Higgs production are obtaining cross section limits of the order of a few times the SM prediction.

References

[1] ATLAS Collaboration, *The ATLAS Experiment at the CERN Large Hadron Collider*, JINST 3 (2008) S08003.

[2] CMS Collaboration, *The CMS experiment at the CERN LHC*, JINST 3 (2008) S08004.

[3] CMS Collaboration, *A measurement of the Higgs boson mass in the diphoton decay channel*, Phys. Lett. B805 (2020) [arXiv:2002.06398 [hep-ex]].

[4] 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, https://cds.cern.ch/record/2714883.

[5] J. R. Andersen et al, *Les Houches 2015: Physics at TeV Colliders Standard Model Working Group Report*, [arXiv:1605.04692 [hep-ph]].

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

[7] CMS Collaboration, *Measurements of production cross sections of the Higgs boson in the four-lepton final state in proton-proton collisions at $\sqrt{s}$=13 TeV*, Eur. Phys. J. C 81 (2021) [arXiv:2103.04956 [hep-ex]].

[8] CMS Collaboration, *Measurements of Higgs boson production cross sections and couplings in the diphoton decay channel at $\sqrt{s}$=13 TeV*, JHEP 07 (2021) [arXiv:2103.06956 [hep-ex]]

[9] 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*, ATLAS-CONF-2020-026, https://cds.cern.ch/record/2725727.

[10] ATLAS Collaboration, *Measurements of gluon fusion and vector-boson-fusion production of the Higgs boson in $H \to WW^* \to e\nu\mu\nu$ decays using pp collisions at $\sqrt{s}$=13 TeV with the ATLAS detector*, ATLAS-CONF-2021-014, https://cds.cern.ch/record/2759651.

[11] CMS Collaboration, *Measurement of Higgs boson production in association with a W or Z boson in the $H \to WW$ decay channel*, CMS-PAS-HIG-19-017, https://cds.cern.ch/record/2758367.

[12] CMS Collaboration, *Measurement of the inclusive and differential Higgs boson production cross sections in the decay mode to a pair of τ leptons in pp collisions at $\sqrt{s}$=13 TeV*, Submitted to Phys. Rev. Lett. [arXiv:2107.11486 [hep-ex]].

[13] 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*, ATLAS-CONF-2020-027, https://cds.cern.ch/record/2725733.

PoS(EPS-HEP2021)032

[14] ATLAS Collaboration, *Interpretations of the combined measurement of Higgs boson production and decay*, ATLAS-CONF-2020-053, `https://cds.cern.ch/record/2743067`.

[15] ATLAS Collaboration, *Measurements of Higgs boson production cross-sections in the $H \to \tau^+\tau^-$ decay channel in pp collisions at $\sqrt{s}$=13 TeV with the ATLAS detector*, ATLAS-CONF-2021-044, `https://cds.cern.ch/record/2779179`.

[16] ATLAS Collaboration, *Cross-section measurements of the Higgs boson decaying into a pair of tau-leptons in proton-proton collisions at $\sqrt{s}$=13 TeV with the ATLAS detector*, Phys. Rev. D99 (2019) [`arXiv:1811.08856 [hep-ex]`]

[17] ATLAS Collaboration, *Study of Higgs-boson production with large transverse momentum using the $H \to b\bar{b}$ decay with the ATLAS detector*, ATLAS-CONF-2021-010, `https://cds.cern.ch/record/2759284`.

[18] CMS Collaboration, *Evidence for Higgs boson decay to a pair of muons*, JHEP 01 (2021) [`arXiv:2009.04363 [hep-ex]`].

[19] ATLAS Collaboration, *A search for the dimuon decay of the Standard Model Higgs boson with the ATLAS detector*, Phys. Lett. B812 (2021) [`arXiv:2007.07830 [hep-ex]`].

[20] ATLAS Collaboration, *Direct constraint on the Higgs-charm coupling from a search for Higgs boson decays to charm quarks with the ATLAS detector*, ATLAS-CONF-2021-021, `https://cds.cern.ch/record/2771724`.

[21] ATLAS Collaboration, *Evidence for Higgs boson decays to a low-mass dilepton system and a photon in pp collisions at $\sqrt{s}$=13 TeV with the ATLAS detector*, Phys. Lett. B819 (2021) [`arXiv:2103.10322 [hep-ex]`].

[22] ATLAS Collaboration, *A search for the $Z\gamma$ decay mode of the Higgs boson in pp collisions at $\sqrt{s}$=13 TeV with the ATLAS detector*, Phys. Lett. B809 (2020) [`arXiv:2005.05382 [hep-ex]`].

[23] CMS Collaboration, *Constraints on anomalous Higgs boson couplings to vector bosons and fermions in its production and decay using the four-lepton final state*, Accepted by Phys. Rev. D [`arXiv:2104.12152 [hep-ex]`].

[24] CMS Collaboration, *Measurements of $t\bar{t}H$ 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) [`arXiv:2003.10866 [hep-ex]`].

[25] ATLAS Collaboration, *Search for associated production of a Z boson with an invisibly decaying Higgs boson or dark matter candidates at $\sqrt{s}$=13 TeV with the ATLAS detector*, ATLAS-CONF-2021-029, `https://cds.cern.ch/record/2777235`.

[26] ATLAS Collaboration, *Search for invisible Higgs boson decays with vector boson fusion signatures with the ATLAS detector using an integrated luminosity of 139 fb^{-1}*, ATLAS-CONF-2020-008, `https://cds.cern.ch/record/2715447`.

[27] ATLAS Collaboration, *Combination of searches for invisible Higgs boson decays with the ATLAS experiment*, ATLAS-CONF-2020-052, `https://cds.cern.ch/record/2743055`.

[28] CMS Collaboration, *Search for Higgs boson pair production in the four b quark final state*, CMS-PAS-HIG-20-005, `https://cds.cern.ch/record/2771912`.

[29] CMS Collaboration, *Search for Higgs boson pair production via vector boson fusion with highly Lorentz-boosted Higgs bosons in the four b quark final state at* $\sqrt{s}$*=13 TeV*, CMS-PAS-B2G-21-001, `https://cds.cern.ch/record/2776802`.

[30] ATLAS Collaboration, *Search for Higgs boson pair production in the final state with two bottom quarks and two photons in* pp *collisions at* $\sqrt{s}$*=13 TeV with the ATLAS detector*, ATLAS-CONF-2021-016, `https://cds.cern.ch/record/2759683`.

[31] ATLAS Collaboration, *Search for resonant and non-resonant Higgs boson pair production in the* $b\bar{b}\tau^+\tau^-$ *decay channel using 13 TeV* pp *collision data from the ATLAS detector*, ATLAS-CONF-2021-030, `https://cds.cern.ch/record/2777236`.

[32] ATLAS Collaboration, *Summary of non-resonant and resonant Higgs boson pair searches from the ATLAS experiment*, ATL-PHYS-PUB-2021-031, `http://cdsweb.cern.ch/record/2777013`.