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Higgs Boson Measurements at the HL-LHC with CMS

Pallabi Das*
on behalf of the CMS Collaboration
Tata Institute of Fundamental Research, Mumbai-400005, India
E-mail: pallabi.das@cern.ch

The measurements of the properties of the Higgs boson at the LHC experiments have entered the precision era, however, some channels are still dominated by statistical uncertainties. A larger data sample is required to ensure whether the observed resonance completely agrees with the Standard Model (SM) predictions, or belongs to a new physics scenario. At the high luminosity LHC (HL-LHC) phase of data-taking $\sim$3000 fb^{-1} of integrated luminosity will be collected over the span of ten years. Detector degradation is also expected due to large rates of particle interactions and necessary upgrades are being carried out to maintain or improve the present performance. Current measurements are expected to improve with access to rare production and decay modes of the Higgs boson. It will thus be possible to derive additional constraints on new physics scenarios. This presentation discusses the foreseen development in Higgs boson precision physics.

European Physical Society Conference on High Energy Physics - EPS-HEP2019 -
10-17 July, 2019
Ghent, Belgium

*Speaker.

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1. Introduction

The discovery of the Higgs boson [1, 2, 3] by the ATLAS [4] and CMS [5] experiments completes the particle spectrum as predicted by the SM. However, in order to ascertain that the observed resonance is indeed the SM particle, its properties need to be measured accurately. In this context the couplings of the Higgs boson with other particles provide an excellent test of the theory. Given the observed Higgs boson mass [6], the predicted couplings to fermions and vector bosons are compared with the data using various production and decay modes.

With proton-proton collision data collected till Run 2, the Higgs to vector boson couplings are largely constrained to SM values. Among Higgs to fermion couplings, $H \to b\bar{b}$ [7] and $H \to \tau\tau$ [8] have been observed in the CMS experiment. One of the significant highlights of the LHC Run 2 is the observation of Higgs boson production with a top quark pair [9], providing direct access to the top-Higgs Yukawa coupling. Apart from these third generation particles, $H \to \mu\mu$, $H \to c\bar{c}$ decays are being probed, albeit with limited sensitivity. The Higgs boson self coupling is still out of reach with currently accumulated data. It therefore indicates the need of larger integrated luminosity (L) for complete characterization of the Higgs boson. The HL-LHC scheduled to run from 2026 to 2036 will collect about 3000 fb^{-1} data, providing the required sensitivity to rare processes, SM or beyond.

The high luminosity run will also result in a large number of pileup collisions, 140–200 per event, and severe detector damage. Upgrade operations (Phase II) have already started to prepare the detectors for the harsh data-taking conditions. Possible improvements are envisioned in acceptance and efficiency measurements. To determine the physics potential of HL-LHC, simple projection studies have been carried out with the improved detector conditions and uncertainties.

2. Projection scenarios

The projections are based on results or analysis strategies carried out using collision data collected in 2016. Two values of L have been considered: 300 fb^{-1} (up to Run 3) and 3000 fb^{-1} (end of HL-LHC). Evolution of statistical and systematic uncertainties follow the recommendations of CERN Yellow Report 2018 [10]:

1. **Run 2 systematic uncertainties (S1) :** Event yields are scaled with L, systematic uncertainties remain unchanged with respect to Run 2 analysis values.
2. **YR18 systematic uncertainties (S2) :** In addition to scaling of event yields, improved systematic uncertainties are considered. Theoretical uncertainties such as interaction energy scale, parton density functions etc. are reduced by a factor 1/2. Other experimental uncertainties are reduced as $1/\sqrt{L}$ until a predefined lowest threshold is reached.

In both scenarios, effects of statistical fluctuations have been neglected. For most evaluation of uncertainties, existing Run 2 analysis results have been used which assumes unchanged detector condition and pileup effects. In few cases simulations have been produced using Phase II detector conditions and analysis strategies have been re-evaluated. The upgraded detector conditions are simulated using the DELPHES package [11] which reliably implements larger pileup scenarios while being fast. The following results have been carried out using either of the above mentioned methods [12, 13, 14].

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3. Signal strength measurements

The sensitivity to a particular production process or decay mode of the Higgs boson is determined using the signal strength parameters (μ) which scale the cross sections and branching fractions (BR) with respect to the SM, defined as:

$$\mu_{\mathrm{i}}^{\mathrm{f}} = \mu_{\mathrm{i}} \times \mu^{\mathrm{f}} = \frac{\sigma_{\mathrm{i}}}{\sigma_{\mathrm{i}}^{\mathrm{SM}}} \times \frac{\mathrm{BR_f}}{\mathrm{BR_f^{SM}}}. \tag{3.1}$$

Figure 1 shows the expected uncertainty in measuring $\mu = 1.0$ corresponding to S1, S2 scenarios and statistical uncertainties alone at the HL-LHC. The precision reaches up to 3–10%, a significant improvement as compared to the Run 2 measurement of 10–50% [15]. The uncertainties are expected to be dominated by theoretical systematics.

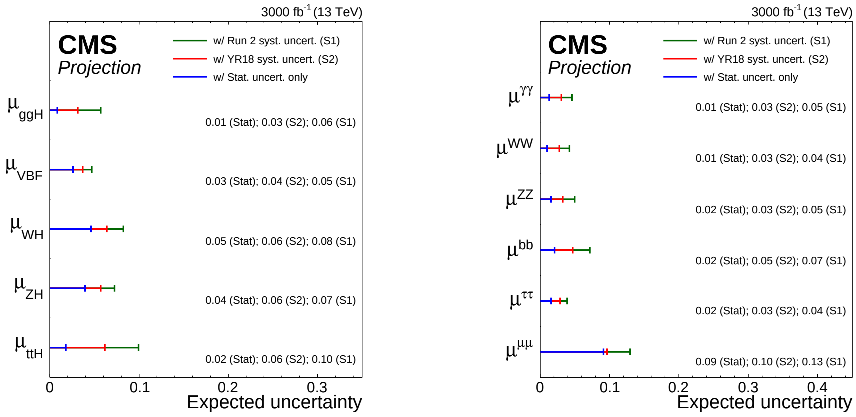

Figure 1: Uncertainties at 3000 fb^{-1} in measuring the signal strengths μ_{i} (left) and μ^{f} (right) corresponding to cross section and BR modification respectively [12].

4. Measurement of coupling strength modifiers

In order to de-couple measurements due to different productions and decay modes, coupling strength modifiers (κ) are used as an alternate to signal strength parameters. The κ are defined as scale factors of the Higgs boson couplings to other particles with respect to the SM:

$$\kappa_{\mathrm{i}}^2 = \frac{\sigma_{\mathrm{i}}}{\sigma_{\mathrm{i}}^{\mathrm{SM}}}, \qquad \kappa_{\mathrm{i}}^2 = \frac{\Gamma_{\mathrm{i}}}{\Gamma_{\mathrm{i}}^{\mathrm{SM}}}. \tag{4.1}$$

In this framework, a single narrow resonance is assumed (zero-width approximation), such that $\mu_{\mathrm{i}}^{\mathrm{f}} = (\kappa_{\mathrm{i}}^2.\kappa_{\mathrm{f}}^2)/\kappa_{\mathrm{H}}^2$ where κ_{H} denotes the deviation of the Higgs boson width (Γ_{H}) from the SM value.

The ratios of the coupling modifiers provide measurements independent of the assumption on Γ_{H}, in addition to cancelling out common uncertainties. Considering the reference coupling modifier $\kappa_{\mathrm{gZ}} = (\kappa_{\mathrm{g}}.\kappa_{\mathrm{Z}})/\kappa_{\mathrm{H}}$, the ratios $\lambda_{\mathrm{ij}} = \kappa_{\mathrm{i}}/\kappa_{\mathrm{j}}$ are measured.

Figure 2 shows the expected uncertainties in measuring κ_{i} and λ_{ij} values for different couplings of the Higgs boson at 3000 fb^{-1}. For both measurements, uncertainties at Run 2 range between values 10–100% [15], whereas at HL-LHC they are expected to be constrained within 2–5%.

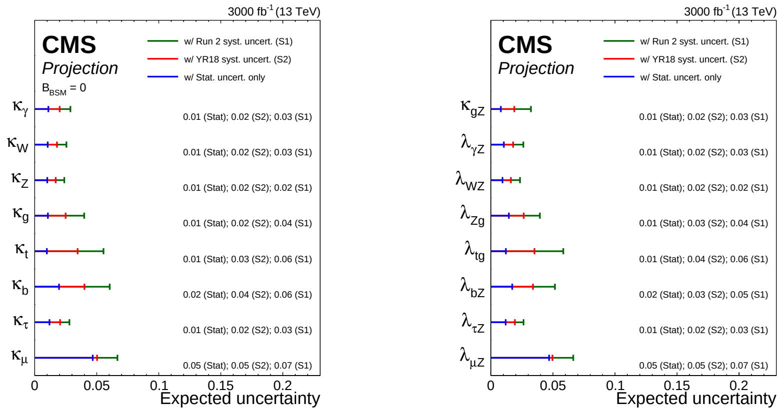

Figure 2: Uncertainties at 3000 fb^{-1} in measuring the coupling strength modifiers κ_i (left) and their ratios λ_{ij} (right) [12].

5. Measurements of $t\bar{t}H$ and VH processes

The $H \to b\bar{b}$ decay is observed in Run 2 in VH production mode [7]. In addition the $t\bar{t}H$ production process is observed in Higgs decaying to pairs of W bosons, Z bosons, photons, τ leptons and bottom quark jets [9]. A projection study of the VH production process using 2016 data shows improved signal strength measurement with better understanding of interaction energy scale uncertainties of signal and background processes. The $t\bar{t}H$, $H \to b\bar{b}$ process is yet to be observed. It is expected that the sensitivity of this analysis will improve with better knowledge of background estimation from control region. The evolution of group of uncertainties in the VH and $t\bar{t}H$ analyses is shown in Fig. 3.

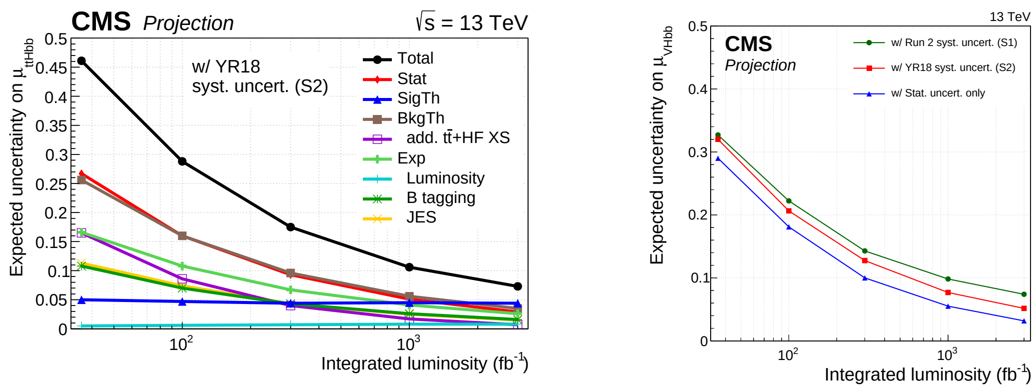

Figure 3: Variation of uncertainties as a function of integrated luminosities in measuring the signal strength $\mu = 1.0$ for the production processes $t\bar{t}H$ in S2 (left) and VH in S1 and S2 scenarios (right) with $H \to b\bar{b}$ [12].

6. Sensitivity to single top associated production of the Higgs boson

The Higgs boson produced in association with a single top quark (tH) is sensitive to the relative sign of the top-Higgs and W-Higgs couplings due to an interference effect of leading order diagrams. However, the SM production rate is very small to be probed with currently accumulated luminosity. The beyond SM scenarios where the top-Yukawa coupling modifier κ_t deviates from the SM value of 1.0, can be constrained using this process as the cross section can be significantly modified. With HL-LHC data the measurement uncertainty of the SM-like tH signal strength is expected to improve by a factor eight with respect to present analysis where observed (expected) signal strength is 25 (12) times the SM prediction [16]. The κ_t values will be more constrained around the SM prediction with $L = 3000$ fb^{-1}. Figure 4 shows the variation of the expected uncertainty on tH only signal strength and the negative log-likelihood scan of κ_t.

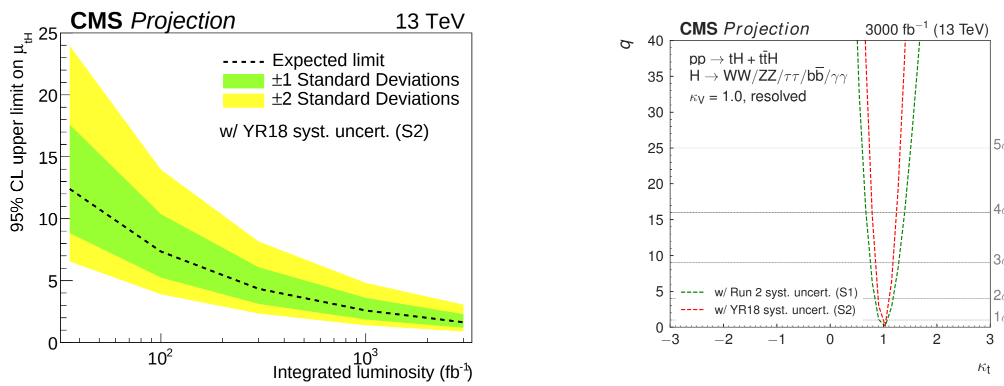

Figure 4: Variation of uncertainties as a function of integrated luminosities in measuring the signal strength $\mu = 1.0$ for the tH production process in scenario S2 (left) and negative log-likelihood scan of κ_t parameter with 3000 fb^{-1} data for both S1 and S2 (right) [12].

7. Differential distributions of Higgs boson transverse momentum

Instead of cross section measurements of different processes, kinematic variables may prove to be more sensitive to beyond SM physics. For example, the Higgs boson p_T distribution is modified by new physics effects at higher values, which is only accessible with large statistics. It is therefore suggestive to study the differential p_T distributions at the HL-LHC.

One such study carried out using 2016 data is projected to 3000 fb^{-1} to determine the sensitivity to deviations of the Higgs boson couplings from the SM predicted values. The combination of differential cross sections from the inclusive production of $\mathrm{H} \to \gamma\gamma$, $\mathrm{H} \to \mathrm{ZZ}$ and $\mathrm{H} \to \mathrm{b\bar{b}}$ is examined to study the p_T distribution of the Higgs boson. The current results are statistics dominated with large uncertainties [17], which is shown to improve by at least a factor of 10 with HL-LHC luminosity. Additional 25% improvement is expected with the systematic uncertainties envisioned in S2 scenario. A new study with Phase II simulated sample using DELPHES explores the possibility to disentangle the Higgs boson self-coupling with that of the anomalous top-Higgs coupling using the Higgs boson p_T spectrum in the $\mathrm{t\bar{t}H}$ and tH production modes while the Higgs boson decays to photon pair. The uncertainties on the differential cross section measurement in this analysis is expected to be within 20–40% at the HL-LHC. Figure 5 shows the Higgs boson p_T distributions for both the projected analysis and DELPHES simulated samples.

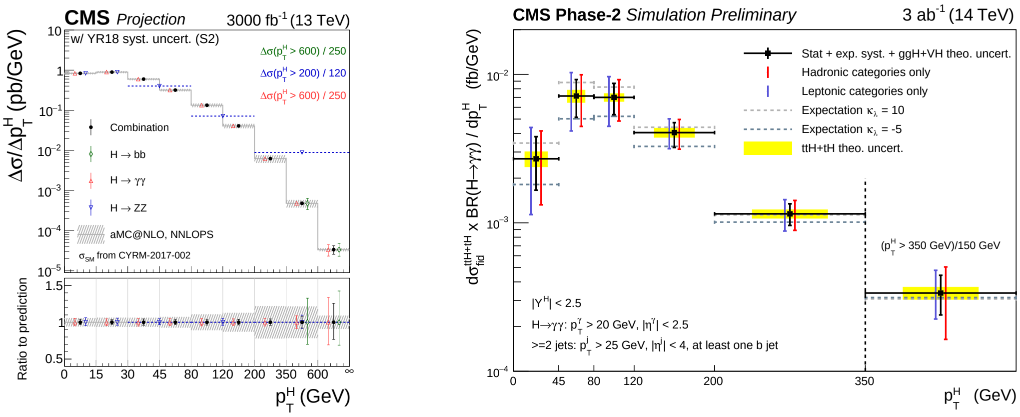

Figure 5: Differential distributions of Higgs boson p_T projected using Run 2 simulated samples (left) [12] and Phase II simulation (right) [13].

8. Measurement of the Higgs boson width

The physical width Γ_{H} of the Higgs boson resonance is much smaller than the current experimental resolution, thus it can only be constrained. Using Run 2 data, the off-shell and on-shell decays of $\mathrm{H} \to \mathrm{ZZ} \to 4\ell$ have been utilized to limit the Γ_{H} values in the positive ranges for the first time [18]. This result is extrapolated to 3000 fb^{-1}, and with S2 uncertainties Γ_{H} is expected to be constrained within a much smaller range between (2, 6) at 95% confidence level (CL). The off-shell production mode is also sensitive to anomalous Higgs to vector boson couplings. Considering the Higgs boson contains a CP-odd component, the corresponding phase (ϕ_3) is excluded outside the ranges (-0.0076, 0.0050) at 95% CL using Run 2 data [18]. At the HL-LHC, the allowed ranges are expected to be much more stringent, within (-0.00016, 0.00016) at 95% CL. The above results are shown in Fig. 6 which consider both projection scenarios. Limited improvement is observed between S1 and S2, due to the statistical uncertainty dominating even with HL-LHC statistics.

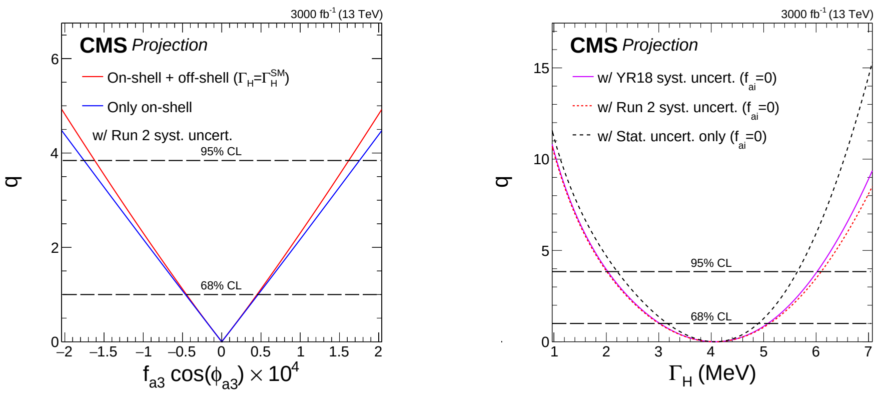

Figure 6: Negative log-likelihood scans of the anomalous phase of the Higgs to vector boson couplings (left) and the Higgs boson width (right) obtained from $\mathrm{H} \to \mathrm{ZZ} \to 4\ell$ decays [12].

9. Search for Higgs boson to invisible decays

Within the SM theory, the Higgs boson to invisible decay fraction is very low: $H \to ZZ \to 4\nu$ is about 0.01 %. If there exists Higgs boson decay modes to massive invisible particles or dark matter, a study of this final state will reveal information on the dark matter couplings. For rare Higgs boson decays the vector boson fusion (VBF) production process adds sensitivity to the measurement with the presence of high rapidity jets in the final state. With Run 2 data, a study of the invisible decays has been carried out in the VBF production which yields an upper limit of 33% on the branching ratio at 95% CL, dominated by statistical uncertainty [19]. The sensitivity is examined using Phase II simulated sample at 3000 fb^{-1}, the 95% CL upper limit reduces to 3.8% assuming SM decays of the Higgs boson. Figure 7 shows the expected upper limit on the Higgs boson to invisible decays, with variable minimum threshold on the missing transverse energy in the final state.

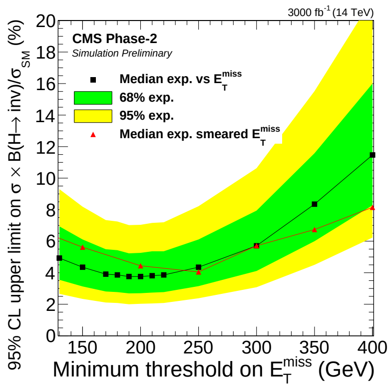

Figure 7: 95% CL expected upper limits on Higgs boson to invisible decays as a function of minimum threshold on missing transverse energy in the final state [14].

10. Conclusions

Precise measurements of the Higgs boson properties will immensely gain from the large dataset to be collected by HL-LHC. Rare production and decay modes will be explored and new physics scenarios will be tested. Studies show that a better handle of the theoretical and experimental uncertainties will improve the analysis sensitivities. In practice, the actual measurements with the HL-LHC data are likely to surpass the simple projections presented with more sophisticated analysis techniques and detector developments.

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.* **B716** (2012) 1–29, arXiv:1207.7214 [hep-ex].

[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.* **B716** (2012) 30–61, arXiv:1207.7235 [hep-ex].

[3] **CMS** Collaboration, S. Chatrchyan *et al.*, "Observation of a New Boson with Mass Near 125 GeV in pp Collisions at $\sqrt{s} = 7$ and 8 TeV," *JHEP* **06** (2013) 081, arXiv:1303.4571 [hep-ex].

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

[5] **CMS** Collaboration, S. Chatrchyan *et al.*, "The CMS Experiment at the CERN LHC," *JINST* **3** (2008) S08004.

[6] **ATLAS, CMS** Collaboration, G. Aad *et al.*, "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, arXiv:1503.07589 [hep-ex].

[7] **CMS** Collaboration, A. M. Sirunyan *et al.*, "Observation of Higgs boson decay to bottom quarks," *Phys. Rev. Lett.* **121** no.~12, (2018) 121801, arXiv:1808.08242 [hep-ex].

[8] **CMS** Collaboration, A. M. Sirunyan *et al.*, "Observation of the Higgs boson decay to a pair of τ leptons with the CMS detector," *Phys. Lett.* **B779** (2018) 283–316, arXiv:1708.00373 [hep-ex].

[9] **CMS** Collaboration, A. M. Sirunyan *et al.*, "Observation of $t\bar{t}$H production," *Phys. Rev. Lett.* **120** no.~23, (2018) 231801, arXiv:1804.02610 [hep-ex].

[10] **Physics of the HL-LHC Working Group** Collaboration, M. Cepeda *et al.*, "Higgs Physics at the HL-LHC and HE-LHC," arXiv:1902.00134 [hep-ph].

[11] **DELPHES3** Collaboration, de Favereau, J. and Delaere, C. and Demin, P. and Giammanco, A. and Lemaître, V. and Mertens, A. and Selvaggi, M., "DELPHES 3, A modular framework for fast simulation of a generic collider experiment", *JHEP* **02** (2014) 057, arXiv:1307.6346 [hep-ph].

[12] **CMS** Collaboration, "Sensitivity projections for Higgs boson properties measurements at the HL-LHC," CMS-PAS-FTR-18-011 (2018).

[13] **CMS** Collaboration, "Constraints on the Higgs boson self-coupling from ttH+tH, H to gamma gamma differential measurements at the HL-LHC," CMS-PAS-FTR-18-020 (2018).

[14] **CMS** Collaboration, "Search for VBF Higgs to invisible at the HL-LHC," CMS-PAS-FTR-18-016 (2018).

[15] **CMS** Collaboration, A. M. Sirunyan *et al.*, "Combined measurements of Higgs boson couplings in proton-proton collisions at $\sqrt{s} = 13$ TeV," *Eur. Phys. J.* **C79** no.~5, (2019) 421, arXiv:1809.10733 [hep-ex].

[16] **CMS** Collaboration, A. M. Sirunyan *et al.*, "Search for associated production of a Higgs boson and a single top quark in proton-proton collisions at $\sqrt{s} = 13$ TeV," *Phys. Rev.* **D99** no.~9, (2019) 092005, arXiv:1811.09696 [hep-ex].

[17] **CMS** Collaboration, A. M. Sirunyan *et al.*, "Measurement and interpretation of differential cross sections for Higgs boson production at $\sqrt{s} = 13$ TeV," *Phys. Lett.* **B792** (2019) 369–396, arXiv:1812.06504 [hep-ex].

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[18] **CMS** Collaboration, A. M. Sirunyan *et al.*, "Measurements of the Higgs boson width and anomalous HVV couplings from on-shell and off-shell production in the four-lepton final state," *Phys. Rev.* **D99** no.~11, (2019) 112003, arXiv:1901.00174 [hep-ex].

[19] **CMS** Collaboration, A. M. Sirunyan *et al.*, "Search for invisible decays of a Higgs boson produced through vector boson fusion in proton-proton collisions at $\sqrt{s} = 13$ TeV," *Phys. Lett.* **B793** (2019) 520–551, arXiv:1809.05937 [hep-ex].