PROCEEDINGS OF SCIENCE

Higgs measurements from CMS and ATLAS

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Since the discovery of the Higgs boson in 2012 by the ATLAS and CMS collaborations at the Large Hadron Collider (LHC), extensive programs have been carried out to further study its properties. Because the Higgs boson is predicted to interact with many particles in the Standard Model (SM), and there are many theories predicting its interaction with Beyond the SM (BSM) particles, the Higgs boson can potentially help answer many unanswered questions in particle physics. These proceedings will provide an overview of Higgs boson measurements from the ATLAS and CMS experiments using the Run 2 (2015-2018) and early Run 3 (2022) datasets, including measurements of its mass, width, spin, CP properties, production cross-sections, decay rates, and couplings to particles. So far, all ATLAS and CMS measurements are in agreement with each other, and with the SM.

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1. Introduction

In 2012, the ATLAS [1] and CMS [2] experiments at the CERN LHC announced the observation of the Higgs boson - a particle whose existence was predicted for decades, and was the final particle of the SM of particle physics to be experimentally observed. Since its discovery, the ATLAS and CMS experiments have carried out a substantial program of Higgs boson measurements in order to precisely measure its properties.

Through these measurements, an indirect search for physics beyond the standard model (BSM) is performed, as the existence of BSM may lead to interactions between the Higgs boson and other particles not predicted by the SM. Therefore, measurements of the Higgs boson's mass, decay width, spin, Charge Parity (CP) properties, production cross-section, decay rates, and couplings to other particles including itself act as a simultaneous validation of the SM, and search for BSM.

Various measurements of these properties have been performed by the ATLAS and CMS collaborations using the Run 2 (2015-2018) and early Run 3 (2022) datasets delivered by the CERN LHC. In particular, measurements taken by each experiment act as useful cross-checks of each other, and as the detectors are composed of different technologies, they avoid suffering from the same systematic uncertainties.

2. Theoretical motivation

While the SM is an extremely successful theory which agrees with the vast majority of observed phenomena, it is incomplete. There are several open points in particle physics which the SM does not provide an explanation for, including but not limited to: the matter-antimatter asymmetry of the universe, the Hierarchy problem, the mechanism by which neutrinos obtain mass, and the nature of dark matter. Because the Higgs boson plays a central role in the SM, and provides mass to most SM particles via their interactions with the Higgs field, it can be used as a possible way to probe for BSM.

The four main Higgs boson production modes from proton-proton collisions is shown in Figure 1. It is through these production modes that Higgs bosons are produced in abundance at the LHC, and can actively be studied at the ATLAS and CMS experiments.

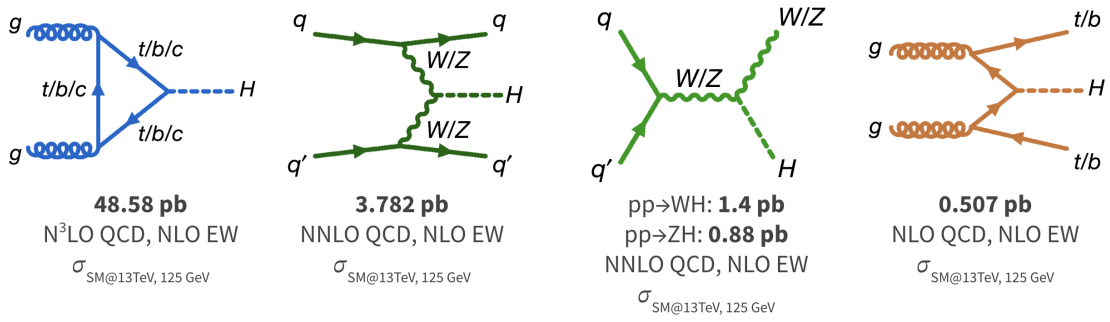

Figure 1: Main Higgs boson production modes. Diagrams from [3], cross-section values from [4].

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3. Experimental setups

Since 2010, the CERN LHC has been producing proton-proton collisions at center of mass energies of $\sqrt{s}$ = 7, 8, 13, and now 13.6 TeV, and additionally is capable of producing heavy ion collisions. The production modes shown in Figure 1 are accessible via proton-proton collisions, and are used to produce Higgs bosons which are studied by the ATLAS and CMS experiments.

Slices of the ATLAS and CMS experiments are shown in Figures 2a and 2b, respectively. ATLAS and CMS are both composed of several sub-detectors, meant to detect different types of particles. Both detectors use mainly silicon-based trackers to detect charged particles, liquid argon or lead tungstate crystal based electromagnetic (hadronic) calorimeters to measure the energy of electromagnetically (hadronically) interacting particles, and mainly gas-based muon chambers to detect muons. The information from all sub-detectors is combined in order to reconstruct the initial physics collision, and is used to detect the many different final states that the Higgs boson can decay into. Both detectors also make use of a two-tiered triggering system to choose which collisions to save for further analysis. It is important to note that the sensitivity to different Higgs boson final states is determined both by how often each final state occurs, and how precisely the detector is able to reconstruct its signature.

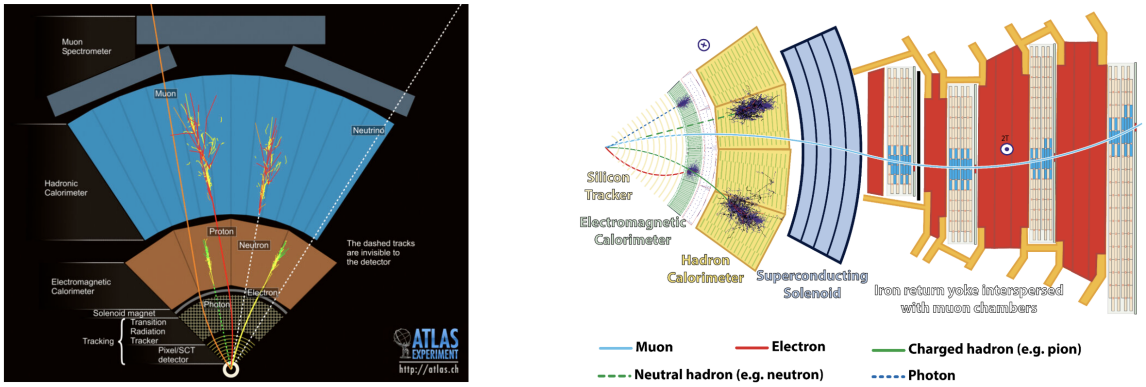

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Figure 2: Left: Slice of the ATLAS detector [5]. Right: Slice of the CMS detector [6].

4. Run 2

Using the Run 2 datasets provided by the LHC, corresponding to roughly 140 fb^{-1} of data with a 13 TeV center of mass energy, the ATLAS and CMS experiments have performed a variety of measurements of different Higgs boson properties.

In the SM, the Higgs boson width is predicted to be $\approx$ 4.1 MeV. This is extremely small compared to detector resolution, and is therefore too challenging to measure directly. However, it can be indirectly measured through a ratio of off-shell to on-shell Higgs boson yields. This was done by the ATLAS experiment using the H$\rightarrow$ZZ process, with cuts made on discriminating variables, and the use of neural networks to separate signal from background, where the output of the neural

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network targeting the gluon-gluon fusion production mode is shown in Figure 3a. This analysis resulted in a measured width of $4.5^{+3.0}_{-2.5}$ MeV, with a corresponding CMS result of $3.2^{+2.4}_{-1.7}$ MeV [8].

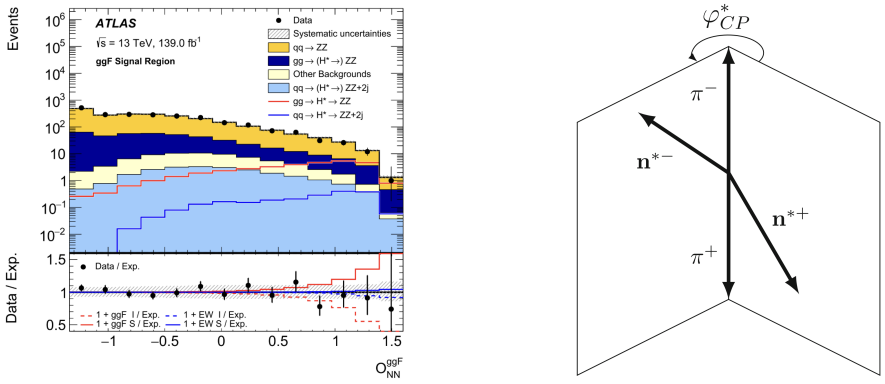

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Figure 3: Left: Distribution of a neural network based observable for the ZZ→4ℓ channel of the gluon-gluon fusion signal region [7]. Right: τ decay plane parameterized by ϕ^*_{CP} [9].

CP symmetry states that the laws of physics remain the same under inversion of charge and parity. In the SM, the Higgs boson is predicted to be CP-even, meaning CP symmetry is conserved. CP asymmetry would affect angular variables, which can be studied to search for CP violation in Higgs boson processes. An example of this is performed in a Run 2 ATLAS H→ $\tau\tau$ search, where a decay plane is defined between the τ decay products and shown in Figure 3b, and includes in its basis a CP-related observable ϕ^*_{CP}. This observable takes on different values for different CP-mixing scenarios with different likelihoods, illustrated in Figure 4a. This analysis leads to a disfavoring of the purely CP-odd hypothesis at a level of 3.4 σ, with the corresponding CMS analysis disfavoring the same scenario at a level of 3.0 σ [10].

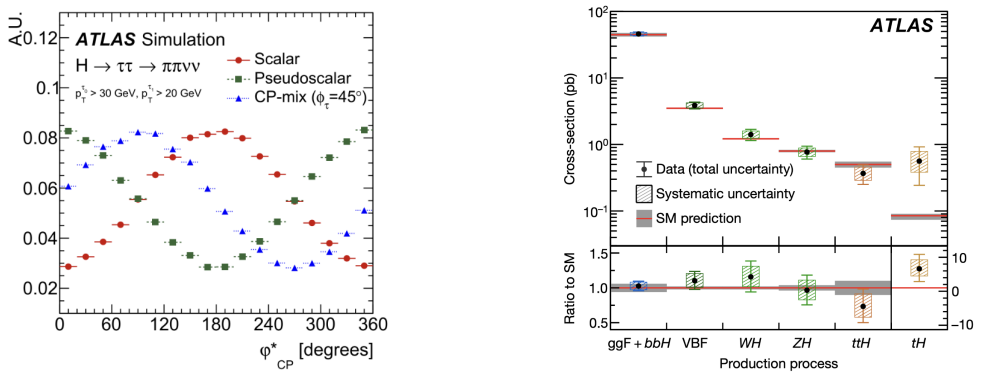

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Figure 4: Left: Likelihood of ϕ^*_{CP} observable values for different CP mixing scenarios [9]. Right: Run 2 production cross-section measurements from ATLAS [3].

Measurements of the different production modes of the Higgs boson are shown in Figure 4b. This makes use of a combination of the main Higgs boson decay channels, and yields results in

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agreement with the SM prediction, as there are no significant deviations. A recent measurement of the Higgs boson production cross-sections for the H→ $\tau\tau$ process has also been performed, and is shown in Figure 5a. The results are also in agreement with the SM.

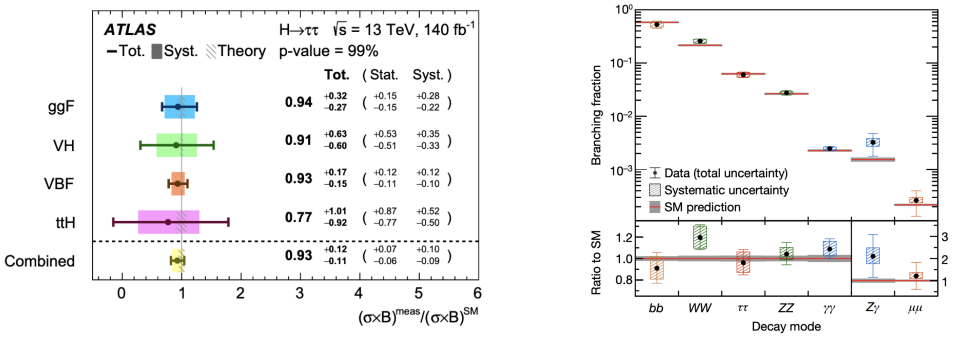

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Figure 5: Left: Run 2 ATLAS H→ $\tau\tau$ STXS analysis [11]. Branching ratio measurements from ATLAS [3].

A summary of branching ratio measurements from the Run 2 ATLAS datasets is shown in Figure 5b, for Higgs boson decay modes readily accessible at the LHC. These results are in agreement with the SM, and notably, recently evidence for relatively rare Higgs boson decays have been reported by ATLAS and CMS for the H→Zγ process [12], and by CMS for the H→ $\mu\mu$ process [13].

A summary of Higgs boson coupling values from the CMS experiment is shown in Figure 6a. All measurements agree with the SM, and couplings of the Higgs boson to vector bosons (fermions) are measured to ≈ 8% (10-20%) precision. A recent ATLAS measurement of the relative sign of the Higgs boson to W and Z bosons via the Vector Boson Fusion production mode is shown in Figure 6b, where the opposite-sign coupling hypothesis is ruled out at a significance of greater than 5σ.

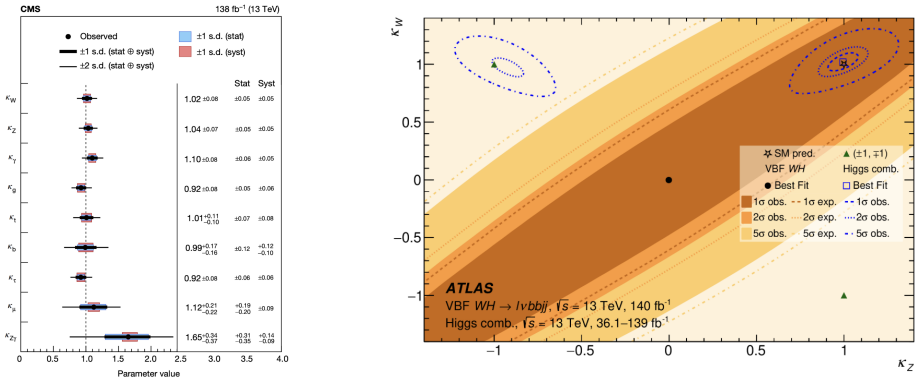

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Figure 6: Left: Run 2 CMS Higgs boson coupling measurements [14]. Right: Run 2 ATLAS W/Z relative coupling analysis result [15].

The magnitude of the Higgs boson's self-coupling is a parameter of major interest, as it has a direct impact on the shape of the Higgs boson's potential energy term in the SM lagrangian. It

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can be directly probed via Higgs boson pair production (HH): the simultaneous production of two Higgs bosons. At the LHC, HH production is about 1000 times less likely than single Higgs boson production, and therefore currently has a much less precise measurement compared to single Higgs boson measurements, and relies on the combination of many HH final states. The results from the full Run 2 HH combination from ATLAS is shown in Figure 7a, where a combined observed (expected) 95% CL upper limit of 2.9 (2.4) is set on HH signal strength.

In addition to the Higgs boson's self-coupling, HH can be used to probe additional couplings, such as the direct coupling of two vector bosons to two Higgs bosons. The Run 2 CMS result scanning this coupling is shown in Figure 7b. Thanks largely to the VBF HH to 4b final state, this result excludes the absence of the coupling of HH to two vector bosons with a significance of 6.6 σ.

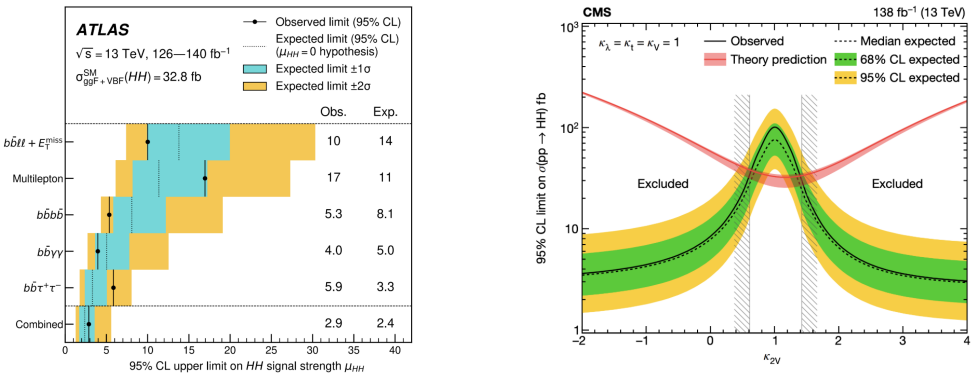

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Figure 7: Left: ATLAS Run 2 Higgs boson self-coupling result [16]. Right: CMS Run 2 κ_{2V} result [14].

5. Run 3 and beyond

In 2022, the LHC upgraded its proton proton collision center of mass energy from 13 to 13.6 TeV, coming with an increase in Higgs boson production cross-sections of about 10-15%. It is expected that the total Run 3 dataset, to be collected from 2022-2026, should be at roughly double the size of the Run 2 dataset, allowing for more precise results for all Higgs boson couplings. In order to check for consistency with Run 2 results, some early Run 3 analyses were performed by ATLAS and CMS in the most sensitive Higgs boson final states.

Early Run 3 results for the H→ZZ→ 4ℓ channel are shown in Figure 8a and 8b for ATLAS and CMS respectively, where both analyses make strategic kinematic selections following Run 2 analyses, and observe the 4-body mass peak around 125 GeV as expected. The measured fiducial cross-section for the ATLAS (CMS) analysis is 2.80±0.74 fb ($2.94^{+0.53}_{-0.49}$ (stat.)$^{+0.29}_{-0.22}$ (syst.) fb). These results are in agreement with each other, and the SM prediction.

Similarly, early Run 3 results for the H→ $\gamma\gamma$ channel are shown in Figure 9a and 9b for ATLAS and CMS respectively. In both cases, the di-photon mass is shown, with peaks observed at the Higgs boson's mass. The resulting fiducial cross-section measurement from ATLAS (CMS) is 76^{+14}_{-13} fb (78±11 (stat.)$^{+6}_{-5}$ (syst.) fb). These results are also in agreement with each other, and the SM prediction.

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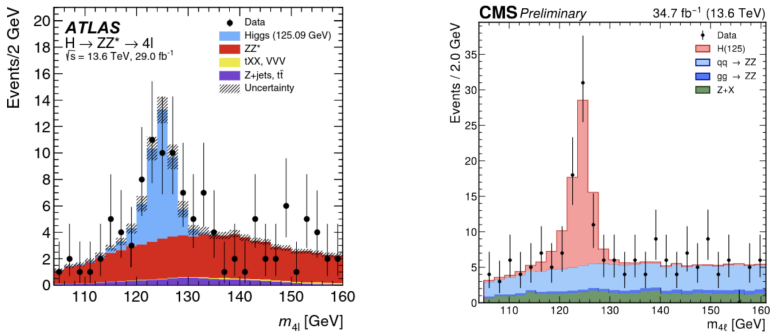

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Figure 8: Left: 4-lepton mass from the early ATLAS Run 3 analysis of H$\longrightarrow ZZ^* \rightarrow 4l$ [17]. Right: 4-lepton mass from the early CMS Run 3 analysis of H$\longrightarrow ZZ^* \rightarrow 4l$ [18].

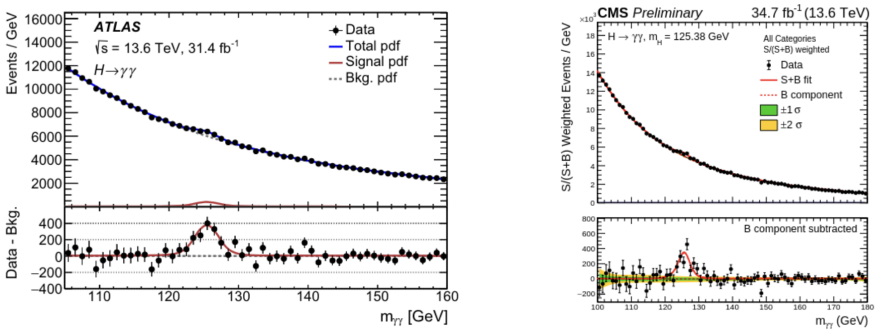

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Figure 9: Left: Di-photon mass from the early ATLAS Run 3 analysis of H$\longrightarrow \gamma\gamma$ [17]. Right: Di-photon mass from the early CMS Run 3 analysis of H$\longrightarrow \gamma\gamma$ [19].

As cross-section measurements have been taken at multiple center of mass energies from the LHC, they can be put together and are shown in Figure 10a. The expected trend predicted by the SM of an increase in cross-section is in agreement with ATLAS measurements.

At the conclusion of Run 3 of the LHC, the LHC will be upgraded to the High-Luminosity LHC (HL-LHC), expected to incease the size of the ATLAS and CMS datasets by a factor of about 10 compared to Run 2 plus Run 3. This is expected to lead to much more precise Higgs boson coupling measurements, projections of which are shown in Figure 10b. It is notable that for most final states, theoretical uncertainty is expected to become dominant, and that sub-2% precision is expected on the leading Higgs boson channels.

6. Conclusions

Since the discovery of the Higgs boson, a vast set of studies have been performed by the ATLAS and CMS experiments to provide a more complete description of the particle, and determine whether it is the SM Higgs boson. All measurements so far are consistent with the SM, but will continue

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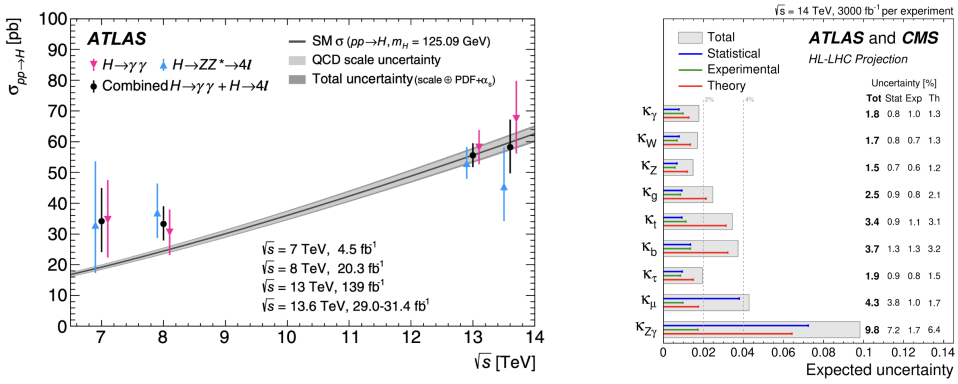

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Figure 10: Left: Higgs boson cross section result as a function of center-of-mass energy from the ATLAS experiment [17]. Right: HL-LHC projection of Higgs boson couplings to SM particles from the ATLAS and CMS experiments [20].

to gain statistical significance as the remainder of the Run 3 dataset is collected, and through the eventual collection of the HL-LHC dataset.

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