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SM Higgs properties

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Abstract

This note presents the latest measurements of the Higgs boson properties with the ATLAS and CMS detector using Run I LHC data. The mass, width, spin-CP properties, and differential cross sections are examined. The measurements are compatible with the standard model predictions for a Higgs boson with mass of 125 GeV.

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Properties of the standard model Higgs boson

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1 Introduction

The Higgs boson (H) is the particle predicted to exist as a consequence of the spontaneous symmetry breaking mechanism acting in the electroweak sector of the standard model (SM). This mechanism introduces a complex scalar field, which gives masses to W and Z bosons. The scalar field gives also mass to the fundamental fermions through a Yukawa interaction. In 2012, the ATLAS [1] and CMS [2] collaborations announced the observation [3, 4] of a new boson with a mass of about 125 GeV, with properties consistent with expectations for the SM Higgs boson.

This note will review the latest measurements of its properties: mass, width, spin-CP properties, and differential cross sections. The main decay channels used for these measurements are $H \to \gamma\gamma$ and $H \to ZZ^* \to 4l$ $(l = e, \mu)$, thanks to their excellent mass resolution. Despite its poorer resolution the $H \to WW^* \to 2l2\nu$ channel is also used for width and spin measurement. In the SM once the mass of the Higgs boson is fixed, all the other parameters are determined, providing consistent predictions for Higgs boson related observables. Deviations potentially found in the properties of the Higgs boson would point to new physics at a higher mass scale. Such anomalous couplings can be parametrized with model-independent effective lagrangians describing the impact of new physics on low energy observables.

2 Higgs boson mass and width

The mass of the Higgs boson is not predicted in the SM, but prior to the Higgs boson discovery, theoretical constraints on the Higgs boson mass (triviality, unitarity) and electroweak precision tests were favouring low mass Higgs boson. The Higgs boson mass was measured by the ATLAS and CMS Collaborations [5] using Run I LHC data, approximately 5 fb^{-1} of integrated luminosity at $\sqrt{s} = 7$ TeV and 20 fb^{-1} at $\sqrt{s} = 8$ TeV.

The $H \to \gamma\gamma$ and $H \to ZZ^* \to 4l$ $(l = e, \mu)$ channels are analyzed because they provide an uncertainty in the mass of less than 1% thanks to the excellent precision of the electromagnetic calorimeters (ECAL) and muon spectrometers. The $H \to \gamma\gamma$ analysis in CMS is based on boosted decision trees (BDT) for categorizing the events while ATLAS categorization is based on sequential criteria. In each category the signal is extracted by fitting the diphoton mass with a model for signal and background. In $H \to 4l$ multi-dimensional likelihood involving BDT or matrix element method are used.

The mass and its uncertainty as measured from both channels in each experiment, and their combination, is presented on fig. 1. The tension between ATLAS and CMS results in the $H \to \gamma\gamma$ channel is 2.1σ, and 1.3σ in the $H \to 4l$ channel. Combining the four measurements, a mass $m_H = 125.09 \pm 0.24$ GeV is obtained. The main sources of systematic uncertainties are the nonlinearity of the energy response in the ECAL and the amount of material in front of the ECAL, with and impact of resp. 50 MeV and 40 MeV on the combined mass. Other source of uncertainties are the ECAL longitudinal response, lateral shower shape, and muon momentum scale and resolution.

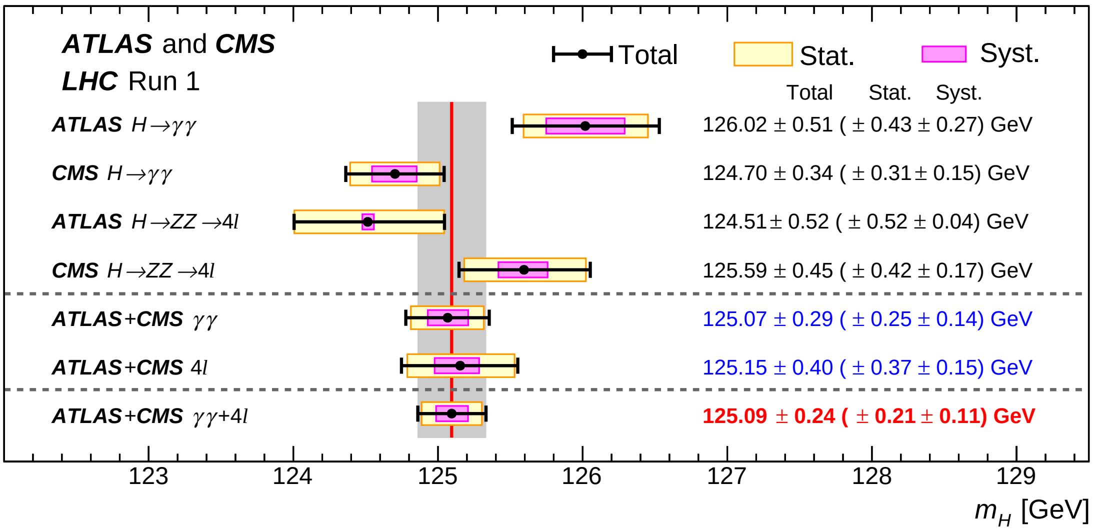

Figure 1: Combined mass of the Higgs boson in ATLAS and CMS [5].

For a Higgs boson with a mass close to 125 GeV, the width is predicted to be $\Gamma_H \approx 4$ MeV in the SM, three orders of magnitude below the reach of direct measurements with particle detectors at the LHC. CMS measures an upper limit of the Higgs boson width of 1.5 GeV at 95% CL [6]. Indirect measurements using interferometry were suggested to circumvent this difficulty (see for instance [7]), relying on the idea that in most beyond-SM scenarios, the ratio of the off-shell and on-shell cross sections is proportional to the width:

$$\sigma^{on-shell}_{gg\to H\to ZZ^*} \approx \frac{g^2_{ggH} g^2_{HZZ}}{m_H \Gamma_H} \qquad \sigma^{off-shell}_{gg\to H\to ZZ^*} \approx \frac{g^2_{ggH} g^2_{HZZ}}{(2m_Z)^2}, \tag{1}$$

where g_{ggH} is the Higgs boson coupling to the gluons, g_{HZZ} its coupling to Z bosons. Fig. 2 shows an upper limit at 95% CL of $\Gamma_H < 22$ MeV [8] set by CMS with the $H \to ZZ^*$ channel and a very similar result are obtained at ATLAS [9] with $H \to ZZ^*$ and $H \to WW^*$. Since the ratio of on-shell and off-shell cross sections depends strongly on the interference between

$gg \to H \to ZZ^*$ and $gg \to ZZ^*$, ATLAS presents its result as a function of the ratio of these two processes. The limit can vary within a factor 5-7.5.

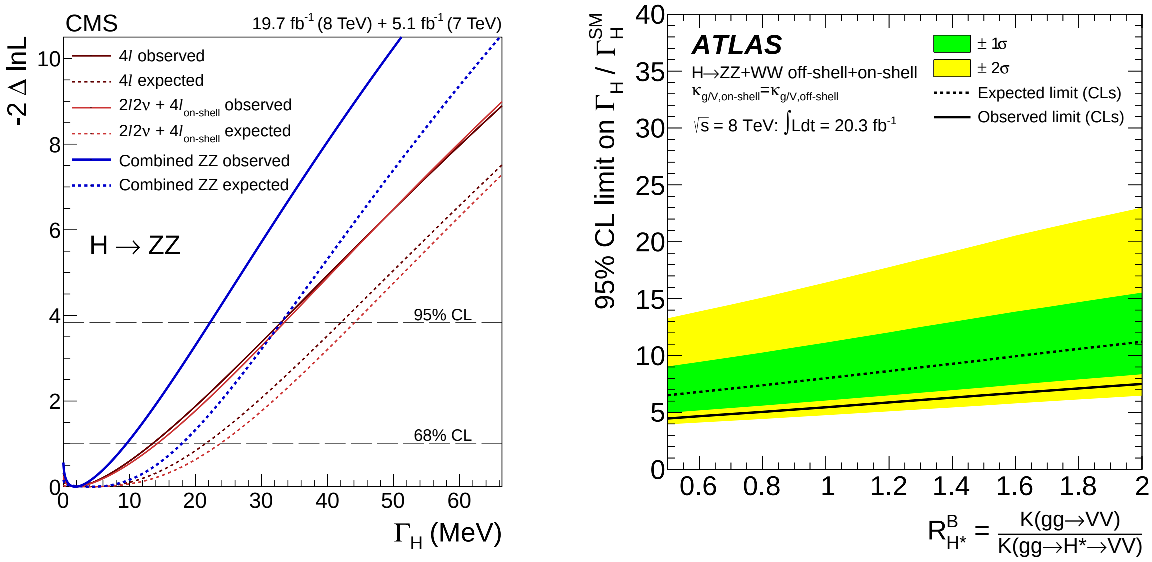

Figure 2: (left) Likelihood as a function of Γ_H at CMS [8], (right) Exclusion limit at 95% CL on the ratio of Γ_H to its value in the SM at ATLAS [9].

A lower limit on the width can be inferred from life-time measurement [10] using Higgs boson time of flight, requiring four leptons consistent with a displaced vertex. Although interesting, this method provides a limit $\Gamma_H > 3.5 \times 10^{-9}$ MeV, orders of magnitude below the value predicted in the SM.

3 Higgs boson spin and CP properties

In the SM the Higgs boson is a scalar particle, i.e. with $J^{CP} = 0^+$. Since the Higgs boson decay was observed in the $H \to \gamma\gamma$ channel and assuming the resonance observed in the other channels is the same, the spin 1 hypothesis is excluded by the Landau-Yang theorem. Measuring the full tensor structure is not yet possible with the available amount of integrated luminosity, though it is possible to test some reasonable benchmark models for alternative J^{CP} hypotheses.

Kinematic analyses are performed at ATLAS [11] and CMS [12] using the angles of the decay particles and variables correlated with them, Collins-Soper $cos(\theta^*)$ in $H \to \gamma\gamma$, matrix element method and boosted decision tree in $H \to ZZ^*$ and BDT in $H \to WW^* \to e\nu\mu\nu$. Processes initiated via gluon fusion and $q\bar{q}$ annihilation are tested. Minimal model for $J^{CP} = 2^+$ hypothesis (graviton-like 2^+_m) is disfavoured by data. In general, the SM hypothesis is preferred over all benchmark models that were tested, including anomalous couplings in the spin 0 and spin 2 tensor structure, as shown in Fig. 3. The exclusion of

0^- and 2^+ hypotheses is also confirmed by the combination of results from CDF and D0 collaborations at Tevatron, using associated production of $H \to b\bar{b}$ with a vector boson [13]. At CMS, Spin 1 hypotheses tested with $H \to ZZ^*$ and $H \to WW^* \to e\nu\mu\nu$ are also disfavoured. Mixtures of 0^+ and 0^- states were tested, resulting in an exclusion at 95% CL for proportions of 0^- state greater than 43%. More anomalous couplings impacting the spin and the kinematics of the Higgs boson were also measured, in agreement with the SM hypothesis within uncertainties of the measurement.

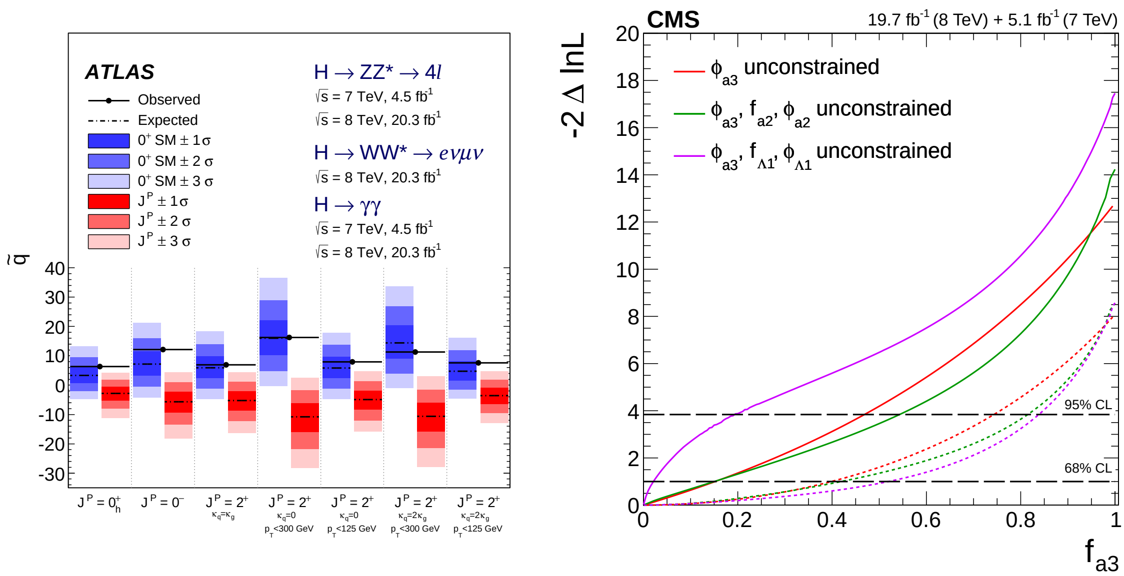

Figure 3: (left) Likelihood values for several spin 0 and spin 2 hypotheses [11], (right) Likelihood as a function of proportions of 0^+ and 0^- state [12].

4 Differential cross sections for the Higgs boson production

With 20 fb^{-1} at $\sqrt{s} = 8$ TeV, one step beyond measuring the signal strength for Higgs boson production was achieved. The fiducial and differential cross sections for Higgs boson production were measured for several observables, in the $H \to \gamma\gamma$ channel [14, 15] which profits from relatively high signal efficiency with an expected signal yield greater than 300 events by experiment, and $H \to 4l$ channels [16, 17] where there is a very good signal over background ratio of approximately 1.

The measurements are performed within a fiducial volume at generator level designed to match closely to the reconstructed selection, in order to minimize the model dependence on the measurement. Simple definitions for the fiducial volume are used. For the $H \to \gamma\gamma$ channel, two isolated photons must have $p_T/m_{\gamma\gamma} > 0.33(0.35), 0.25$ within $|\eta| < 2.5$ (2.37) in CMS (ATLAS), where p_T is the transverse momentum of the photon and $m_{\gamma\gamma}$ the diphoton mass. ATLAS measures as well the fiducial cross sections for diphotons associated with jets. In the case of $H \to 4l$ channel the fiducial region is defined as four leptons following the same p_T and η requirements as at reconstructed level. ATLAS also combines the $H \to \gamma\gamma$ and $H \to 4l$ measurements [18] by extrapolating to the full phase space. Fiducial cross sections measured at ATLAS are slightly above but compatible with the SM predictions. In CMS measurement data and SM predictions are compatible.

The signal extraction is performed simultaneously in all bins of a given observable. Methods independent from the kinematics are used to not bias the signal extraction. Detector effects are corrected from the measured yields: ATLAS uses bin-by-bin unfolding, and CMS folds the response matrix into the likelihood to measure directly the corrected yields.

The transverse momentum of the Higgs boson is sensitive to new physics contribution in the gluon fusion loop. The Higgs boson p_T is presented in Fig. 4. Although compatible with the SM within theoretical and experimental uncertainties, ATLAS measurements shows a harder spectrum than CMS. Many other observables are measured: the Higgs boson rapidity, angular distributions of the Higgs boson decay, number of jets associated with the Higgs boson production, properties of the leading jet. In the case of the $H \to \gamma\gamma$ channel where the event yield is higher, observables with two associated jets are also measured. In particular the distributions in the dijet mass and azimuthal angle between the two jets are measured. These observables are used in the reference analysis to enhance the contribution of Higgs production via vector boson fusion and are highly sensitive to the anomalous coupling of the Higgs boson to the gauge bosons. The dijet mass measured is presented in Fig. 5 and shows good agreement with the SM predictions.

Differential distributions can also be used to set limits on the anomalous couplings of the Higgs boson. ATLAS presented such an analysis [19], combining information from the Higgs boson transverse momentum, number of jets, dijet mass, azimuthal angle between jets and transverse momentum of the leading jet through a likelihood, taking into account the correlations. The interpretation is made with an effective lagrangian framework, probing the Higgs boson coupling to gluons, photons and vector bosons, either CP-conserving or CP-violating. In case of new physics, the most impacted distributions are the dijet mass and azimuthal angle between the two jets. No evidence for anomalous couplings was found.

5 Summary

The mass of the Higgs boson was measured at ATLAS and CMS using LHC Run I data, and is known with a precision of 0.2%: $m_H = 125.09 \pm 0.24$ GeV. An upper limit on the width of the Higgs boson of 22 MeV at 95% CL was set (about 5 times the SM prediction). Data are favouring the 0^+ hypothesis over all other benchmarks for spin-CP hypotheses that were tested. Differential distributions measured with $H \to \gamma\gamma$ and $H \to ZZ^* \to 4l$ are in agreement with SM predictions, although data do not allow yet to favour one of the MC predictions. First measurements of the anomalous couplings of the Higgs boson are becoming available. No significant deviation from the SM predictions is observed. LHC Run II started in 2015 and will allow to probe further the Higgs boson properties.

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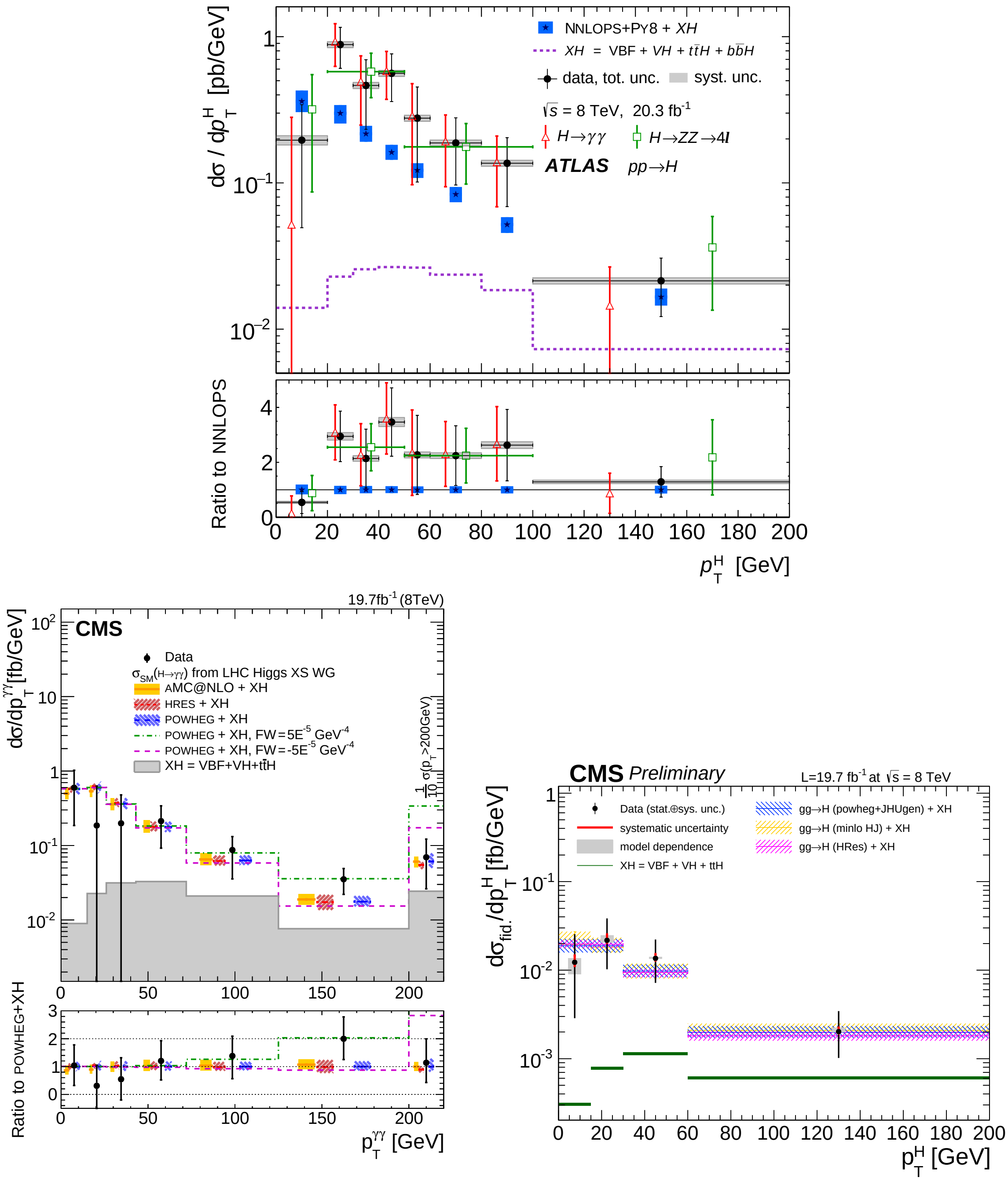

Figure 4: Differential cross section in the transverse momentum of the Higgs boson in (top) $H \to \gamma\gamma$ and $H \to 4l$ ATLAS combination [18] (bottom left) $H \to \gamma\gamma$ at CMS [15], (bottom right) $H \to 4l$ at CMS [17].

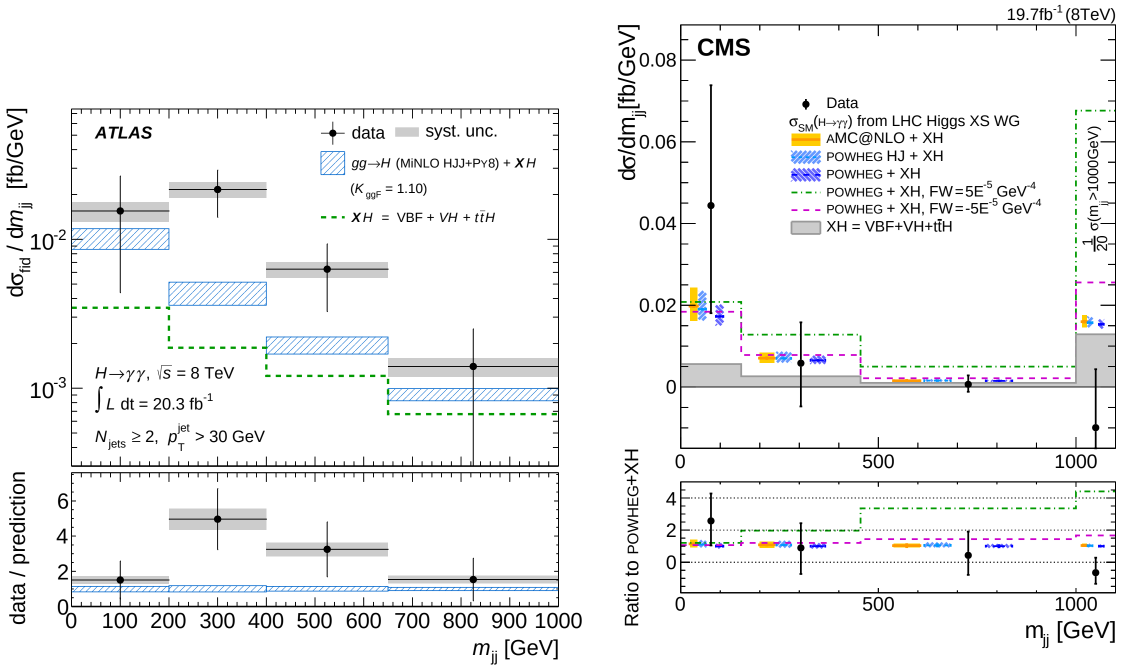

Figure 5: Differential cross section in the dijet mass with $H \to \gamma\gamma$ events at (left) ATLAS [14], (right) CMS [15].