PROCEEDINGS OF SCIENCE

Combined measurements of Higgs couplings, cross-sections and interpretation at the ATLAS experiment

Changqiao Li[a,*] **on behalf of the ATLAS collaboration**

[a] *Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), Boltzmannstr. 8, 85748 Garching, Germany*

E-mail: changqia@mpp.mpg.de

Simplified template cross-sections provide a detailed description of the properties of Higgs boson production at the LHC. These properties are most precisely determined in the combination of the measurements performed in the different Higgs boson decay channels. This article presents these combined measurements, as well as their interpretations in the context of specific scenarios of physics beyond the Standard Model, as well as in generic extensions within the framework of the Standard Model Effective Field Theory. A combination of measurements of the branching fractions of Higgs boson decays into invisible particles is also presented, and interpreted as constraints on the cross-section of WIMP dark matter interactions with nucleons. Through the combination between the analyses from ATLAS and CMS experiments, the evidence of the Higgs decay into a Z boson and a photon is established.

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In 2012, a new particle with properties consistent with that of the Higgs boson predicted by the Standard Model (SM) was discovered. The results of more investigations have confirmed the SM-like nature of the Higgs boson. In this article, recent results of combined measurements as well as their interpretation within beyond the Standard Model (BSM) predictions, and searches for $H \rightarrow$ invisible decay and $H \rightarrow Z\gamma$ decay are reported.

During the Run2 data-taking period, 2015-2018, an integrated luminosity of 139 inverse fb^{-1}of proton-proton collisions at 13 TeV data is collected, which brings 30 times more Higgs bosons than at the time of its discovery.

Up to now, at the LHC all main production modes are observed: gluon-gluon fusion (ggF), vector boson fusion (VBF), associate production of a Higgs with a W boson (WH), associate production of a Higgs with a Z boson (ZH) and associated production of a Higgs with a pair of top quarks (ttH). Also most of the decay channels (bb, WW, $\tau\tau$, ZZ, $\gamma\gamma$) are discovered. Combining the analyses targeting different production or decay modes allows for detailed checks of the SM prediction as, for instance, in Ref [1], via the measurement within Simplified Template Cross Section (STXS). The term STXS denotes a framework for Higgs cross-section measurements that targets well-defined kinematic regions split by production mode. The splitting scheme is designed to maximize the sensitivity to isolate BSM effects, while reducing theory dependences. It is a very powerful framework for a detailed check of the SM prediction.

The Higgs boson production cross-section in each kinematic region is measured and compared

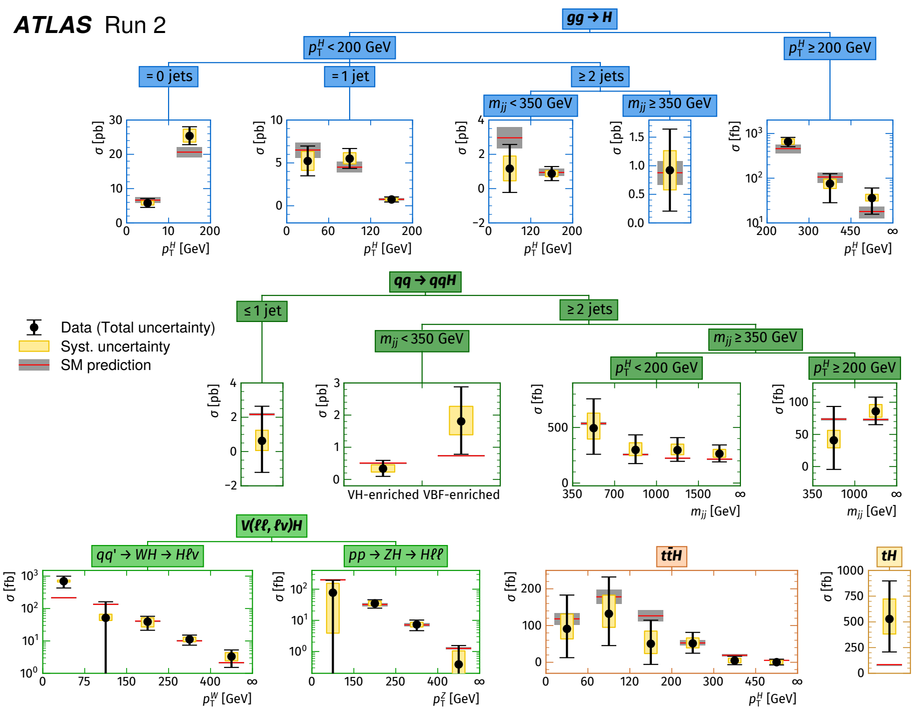

Figure 1: Observed and predicted Higgs boson production cross-sections in different kinematic regions from Ref [1]. The vertical bar on each point denotes the 68% confidence interval. Kinematic regions are defined separately for each production process, based on the jet multiplicity, the transverse momentum of the Higgs (p_T^H) and vector bosons (p_T^W and p_T^Z) and the two-jet invariant mass (m_{jj}).

with its prediction within the SM while the branching fractions ($\mathcal{B}$) and kinematic properties of the Higgs boson decay are assumed to those predicted by the SM. The measurement is performed simultaneously with 36 kinematic regions as presented in Fig 1. The results are consistent with the SM predictions. While the p-value for the compatibility of the combined measurement and the SM prediction is 94%. This measurement can be used for BSM model interpretations.

For instance, the interpretation based on an Effective Field Theory framework of the SM (SMEFT) is presented as in Ref [2]. In the SMEFT, the effects of BSM at energy scales Λ can be parameterised at low energies, E $\ll$ Λ, in which the SM Lagrangian is expanded with higher-dimensional operators preserving the SM gauge symmetries.

The "Warsaw" [3] basis forms a complete set of all d = 6 operators allowed by the SM gauge symmetries. This basis is widely used in various fields of particle physics and also used here.

In this article, the STXS measurement is used to set constraints on the d = 6 Wilson coefficients of these operators, corresponding to limits on BSM physics at a fixed scale Λ, here Λ =1 TeV. The cross-sections and branching ratios are parameterized with Wilson coefficient effects either in a linear model (only accounting for interference contributions between the SM and d=6 operators) or in a linear+quadratic model (the pure BSM terms accounted).

For total, 49 operators are considered, but the analysis is only sensitive to 19 combinations of these operators. Therefore, results for these combinations are reported, as shown in Fig 2 for the linear+quadratic case. The expected and observed results are in good agreement. The observed uncertainty is noticeably smaller than the expected uncertainty. This discrepancy is related to the multiple minima in the likelihood function caused by the quadratic parameter terms in the cross-section.

Within the SM, the only invisible decay of the Higgs boson is $H \to ZZ^* \to 4\nu$ with $\mathcal{B}$ around 0.1%. In several theoretical models, the 125 GeV Higgs boson acts as a portal between a dark sector and the SM sector. The Higgs boson therefore could decay into a pair of dark matter (DM) particles. The DM particles would not interact with the material of the detector. Thus it would make contributions to the invisible decay of the Higgs boson. The direct search for invisible decays of the Higgs boson thus is a way to probe DM production.

A combination of the searches for the $H \to$ invisible decay targeting VBF, $Z + H$, $t\bar{t}H$, VBF + photon and H+jet topologies, all of which use the full Run 2 data, is performed. [4] The upper limits for $\mathcal{B}_{H\to\text{inv}}$ at 95% CL are set for the combined Run 2 data. The observed limit is 0.113, while the expected one is 0.080. The combination brings a 22% relative improvement on sensitivity with respect to the most sensitive single analysis, the one targeting the VBF final state. A further Run 1+2 combination improves the observed and expected upper limits on $\mathcal{B}_{H\to\text{inv}}$ to 0.107 and 0.077, respectively, as shown in Fig 3.

To compare with the limits at 90% CL on the spin-independent scattering cross-section of a weakly interacting massive particle (WIMP) and a nucleon ($\sigma_{\text{WIMP-Nucleon}}$) from direct dark matter experiments, the limits are correspondingly. The observed limit of $\mathcal{B}_{H\to\text{inv}} < 0.093$ at 90% CL is translated into the limit on $\sigma_{\text{WIMP-Nucleon}}$ assuming the Higgs portal model, where Higgs decays into a pair of WIMP particles are possible, using an EFT framework. This translation assumes that the WIMP particle is either a scalar, a Majorana fermion, or a vector-like state as shown in Fig 4.

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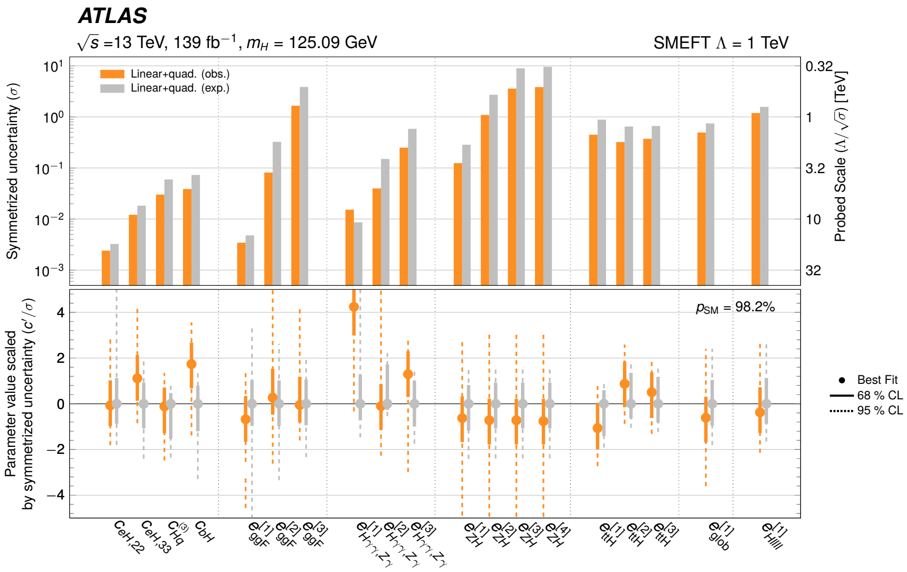


Figure 2: Comparison of the observed parameters of the rotated basis $\vec{c}'$ with the SMEFT linearised model (blue) and the model including quadratic terms (orange), where all other coefficients and nuisance parameters are profiled from Ref [2]. The top panel shows the symmetrised 68% CL uncertainty σ of each parameter measurement (left vertical axis) and the corresponding energy scale $\Lambda/\sqrt{\sigma}$ that is probed (right vertical axis). The bottom panel shows the measured parameter value and 68% (solid) and 95% (dashed) CL intervals, divided by the symmetrised uncertainty shown in the top panel.

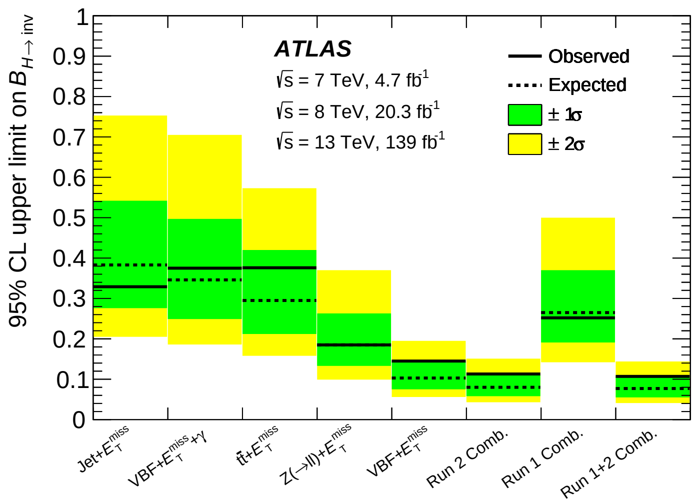


Figure 3: The observed and expected upper limits on $\mathcal{B}_{H\to\text{inv}}$ at 95% CL for the Run 2 analyses targeting various final states and their combination namely, the Run 1 and the full Run 1+2 combinations from Ref [4]. The 1σ and 2σ contours of the expected limit distributions are also shown.

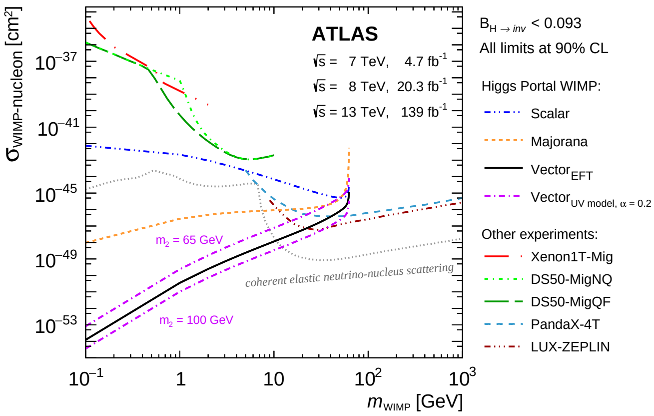


Figure 4: Upper limit at the 90% CL on $\sigma_{\text{WIMP-Nucleon}}$ as a function of the WIMP mass for direct detection experiments and the interpretation of the $H \to$ invisible combination result in the context of Higgs portal models considering various WIMP hypotheses from Ref [4]. For the vector case, results from UV-complete models are shown (pink curves) for two representative values for the mass of the predicted Dark Higgs particle (m_2) and a mixing angle α=0.2. Direct detection results are taken from Refs. [5–8]. The neutrino floor for coherent elastic neutrino-nucleus scattering (dotted gray line) is taken from Refs. [9, 10], which assume that germanium is the target over the whole WIMP mass range. The regions above the limit contours are excluded in the range shown in the plot.

In the SM prediction, the branching ratio of the Zγ decay of the Higgs boson is predicted to be $\mathcal{B}_{H\to Z\gamma} = (1.54 \pm 0.09) \times 10^{-3}$ for m_H at 125.09 GeV. Different predictions are obtained in some BSM models: for instance, the additional colourless charged scalars, leptons or vector bosons in some BSM models can make contributions via loop corrections, resulting in a different $\mathcal{B}_{H\to Z\gamma}$.

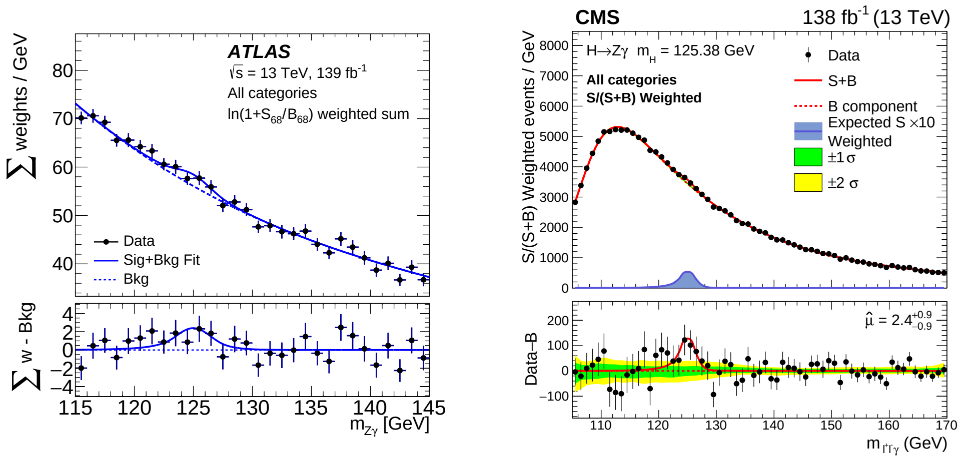
Searches for this decay mode are performed by the ATLAS [11] and CMS [12] experiments with full Run 2 data, using final states where the Z boson decays into a lepton pair (only electron and muon pairs are considered). This final state can be reconstructed completely with good invariant mass resolution and can be efficiently triggered. The best-fit value for the signal normalised to its SM prediction (μ) is obtained, shown in Table 1, from fits to the $m_{Z\gamma}$ distribution with analytic signal and background functions as shown in Fig 5. The statistical uncertainty is dominant.

The two analyses are combined [13]. The likelihood of the combined measurement is obtained as the product of those from the ATLAS and CMS experiments. Some changes, for instance to the QCD scale and branching fraction uncertainties, are made to achieve the consistency. These changes have either minor or negligible impacts. Although the two analyses have different assumed values of the m_H, namely 125.09 GeV by ATLAS and 125.38 GeV by CMS.

The negative profile log-likelihood ratio as a function of μ is shown in Fig 6. The best fitted values of μ together with observed and expected significances from the ATLAS and CMS analyses and their combination are summarized in Table 1. The observed significance of 3.4 σ is obtained from the combination, thus evidence for $H \to Z\gamma$ decay is established.

Experiments	μ	Obs. Sig. (σ)	Exp. Sig. (σ)
ATLAS	$2.0^{+1.0}_{-0.9}$	2.2	1.2
CMS	2.4 ± 0.9	2.7	1.2
Combination	2.2 ± 0.7	3.4	1.6

Table 1: Results on $H \to Z\gamma$ decays the by ATLAS, CMS experiments, and their combination



(a) ATLAS Higgs decays into Zγ from Ref [11]

(b) CMS Higgs decays into Zγ from Ref [12]

Figure 5: Weighted $Z\gamma$ invariant mass ($m_{Z\gamma}$) distribution from data and simultaneous signal-plus-background fits to each category for the ATLAS (a) and CMS (b) experiments respectively.

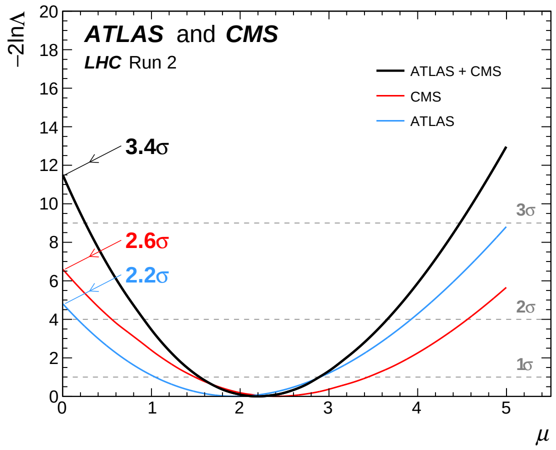


Figure 6: The negative profile log-likelihood test statistic, where Λ represents the likelihood ratio, as a function of the signal strength μ derived from the ATLAS data (blue line), the CMS data (red line), and the combined result (black line) from Ref [13]. The different Higgs boson masses assumed by the ATLAS and CMS experiments have a negligible impact on the results.

References

[1] The ATLAS collaboration, *A detailed map of Higgs boson interactions by the ATLAS experiment ten years after the discovery*, *Nature* **607** (2022) 52–59 [2207.00092].

[2] The ATLAS collaboration, "Interpretations of the ATLAS measurements of Higgs boson production and decay rates and differential cross-sections in pp collisions at $\sqrt{s} = 13$ TeV." ATLAS-CONF-2023-052.

[3] B. Grzadkowski, M. Iskrzyński, M. Misiak and J. Rosiek, *Dimension-six terms in the standard model lagrangian*, *JHEP* **10** (2010) 085 [1008.4884].

[4] The ATLAS collaboration, *Combination of searches for invisible decays of the Higgs boson using 139 fb $^{-1}$ of proton-proton collision data at $\sqrt{s} = 13$ TeV collected with the ATLAS experiment*, *Physics Letters B* **842** (2023) 137963 [2301.10731].

[5] DarkSide collaboration, *Search for Dark-Matter–Nucleon Interactions via Migdal Effect with DarkSide-50*, *Phys. Rev. Lett.* **130** (2023) 101001 [1802.06994].

[6] Y. Meng, Z. Wang, Y. Tao, A. Abdukerim, Z. Bo, W. Chen et al., *Dark Matter Search Results from the PandaX-4T Commissioning Run*, *Phys. Rev. Lett.* **127** (2021) 261802 [2107.13438].

[7] LUX-ZEPLIN collaboration, *First Dark Matter Search Results from the LUX-ZEPLIN (LZ) Experiment*, *Phys. Rev. Lett.* **131** (2023) 041002 [2207.03764].

[8] XENON collaboration, *Search for Light Dark Matter Interactions Enhanced by the Migdal Effect or Bremsstrahlung in XENON1T*, *Phys. Rev. Lett.* **123** (2019) 241803 [1907.12771].

[9] J. Billard, E. Figueroa-Feliciano and L. Strigari, *Implication of neutrino backgrounds on the reach of next generation dark matter direct detection experiments*, *Physical Review D* **89** (2014) 023524 [1307.5458].

[10] F. Ruppin, J. Billard, E. Figueroa-Feliciano and L. Strigari, *Complementarity of dark matter detectors in light of the neutrino background*, *Physical Review D* **90** (2014) 083510 [1408.3581].

[11] The 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*, *Physics Letters B* **809** (2020) 135754 [2005.05382].

[12] The CMS collaboration, *Search for Higgs boson decays to a Z boson and a photon in proton-proton collisions at $\sqrt{s} = 13$ TeV*, *Journal of High Energy Physics* **05** (2023) 233 [2204.12945].

[13] ATLAS and CMS collaboration, *Evidence for the Higgs Boson Decay to a Z Boson and a Photon at the LHC*, *Phys. Rev. Lett.* **132** (2024) 021803 [2309.03501].