The search for Dark Matter in association with the Higgs boson with the di-photon decay

C. O. Kureba, X. Ruan and B. Mellado

University of Witwatersrand,
1 Jan Smuts Avenue Braamfontein 2000,
Johannesburg, South Africa

E-mail: cokureba@gmail.com

Abstract. The ATLAS and CMS experiments at the Large Hadron Collider discovered a Higgs boson like particle in 2012. The differential and fiducial cross sections of the Higgs boson are measured using $20.3\,\mathrm{fb}^{-1}$ 2012 data taken at $\sqrt{s}=8\,\mathrm{TeV}$ after the discovery by ATLAS. The measurement is focusing on the Higgs boson kinematics and jet activity, including the Higgs boson transverse momentum, rapidity and the Higgs boson+jet production mode. The Higgs boson candidates are extracted by fitting the two-photon invariant mass spectrum. The observed kinematic distribution of the Higgs boson is translated to particle level to reduce the detector efficiency and resolution, using bin-by-bin unfolding method. A distortion of the Higgs boson transverse momentum is found in comparison with the state-of-the-art predictions. One of the explanations is the Higgs boson production in association with invisible particles, such as the dark matter. The observation indicates that the missing particle has intermediate energy and same order of production cross-section as the Standard Model gluon-gluon fusion to the Higgs boson process. The search for dark matter in association with the Higgs boson will be performed in the 2015 data taking in the Higgs boson decaying into two-photon channel. The study will focus on the Higgs boson production associated with intermediate missing transverse energy. The knowledge and understanding of the missing transverse energy reconstruction is critical.

Keywords: ATLAS; Higgs boson; Diphoton; Differential; Fiducial; Dark matter

1. Introduction

The Standard Model (SM) Higgs boson-like particle was observed in 2012 by ATLAS and CMS [1] [2]. After the discovery, the Higgs boson differential cross section and fiducial cross section were measured [3].

The ATLAS detector [4] is one of the general purpose detectors at the LHC. Its four sub-detectors: the inner detector, the electromagnetic calorimeter, the hadronic calorimeter and the muon spectrometer provide the precise track and energy measurements. Electrons, muons, photons and jets are reconstructed in the detector. The measurements of the Higgs boson production cross section and mass were performed by combining the $20.3\,\mathrm{fb}^{-1}$ $\sqrt{s}=8\,\mathrm{TeV}$ data taken in 2012 and $4.5\,\mathrm{fb}^{-1}$ $\sqrt{s}=7\,\mathrm{TeV}$ data taken from 2011. The differential and fiducial cross section measurements were derived only using 2012 data to avoid large statistical fluctuation. The photon energy was re-calibrated in 2013 including implementing the multivariate analysis (MVA) method to improve the identification performance. The unfolding technique was implemented to extract the Higgs boson distribution from data to the particle level. The results are compared with several Monte Carlo (MC) predictions using higher order QCD calculations.

In the measured result, a small excess in the Higgs boson transverse momentum (p_T) spectrum were observed. This excess provided evidence for the Higgs boson production associated with missing particle. A dark matter particle, which is not observable via electromagnetic spectrum, is one of the possible candidate. Figure 1 shows one of the possible explanation of the distortion of Higgs boson p_T spectrum. The search based on the 2011 and 2012 run I result will be performed in 2015 $\sqrt{s} = 13$ TeV run II new data.

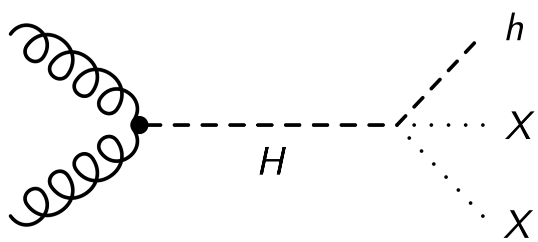

Figure 1. The Feynman diagram of a kind of the Higgs boson production in association with the dark matter particles. The SM Higgs boson is h and the dark matter candidates are Xs. The h and Xs are coupled with a heavy mediator H, which is produced by gluon-gluon fusion process. This model provides moderate missing transverse energy.

2. The Event Selection

In the Higgs boson decaying into the diphoton channel, events are required to have at least two photons. The events must pass the trigger criteria that the transverse energy (E_T) should be larger than 35 GeV and 25 GeV for the leading (highest E_T) and sub-leading photons, respectively. The photons are restricted to be within the fiducial calorimeter region of $|\eta| < 2.37$ [1] and to exclude the transition region between the barrel and the endcap calorimeters, $1.37 < |\eta| < 1.56$. The relative p_T: $p_T/m_{\gamma\gamma}$ of the leading and subleading photon should be larger than 0.35 and 0.25, respectively, in which the $m_{\gamma\gamma}$ is the invariant mass of the two photons. The photons are well identified and isolated. The jets are required to have $E_T > 25$ GeV for $|\eta| < 2.4$ and $E_T > 30$ GeV for $2.4 < |\eta| < 4.5$.

3. The Extraction of the Higgs Boson

To extract the Higgs boson in the continuous background, the signal plus background fit was performed on the diphoton invariant mass spectrum. The signal shape was modelled by fitting the MC signal shape using Crystal-ball+Gaussian function. The signal MC consists of gluon-gluon fusion (ggF), vector boson fusion (VBF), the Higgs boson produced in association with W boson (WH), Z boson (ZH) and top quarks ($t\bar{t}$H). The ggF and VBF are produced using Powheg [5] generator and showered by Pythia [6], the WH, ZH and $t\bar{t}$H are produced and showered using Pythia. The signal shape and predicted event yields are parameterised as a function of the Higgs boson mass.

The background shape are fitted using exponential, polynomial, Bernstein polynomial and power law functions. The final function type used on a particular background shape is decided

[1] η is the pseudorapidity, defined as $\eta = -\ln[\tan(\theta/2)]$, θ is the angle between the particle momentum and the beam axis.

 ISBN: 978-0-620-70714-5

by minimising the spurious signal, which is obtained by fitting the high statistics background MC with signal plus background model. The typical diphoton mass spectrums in jet bins are shown in the Fig. 2.

All of the systematic uncertainties are considered in the analysis. The photon energy scale, photon energy resolution, the photon selection and identification efficiencies are considered. In the jet categories, the jet energy scale and resolution are dominant. All of the photon, jet and lepton uncertainties are propagated to the missing transverse energy calculation. The theoretical uncertainties like the energy scale, PDF are taken into account as well.

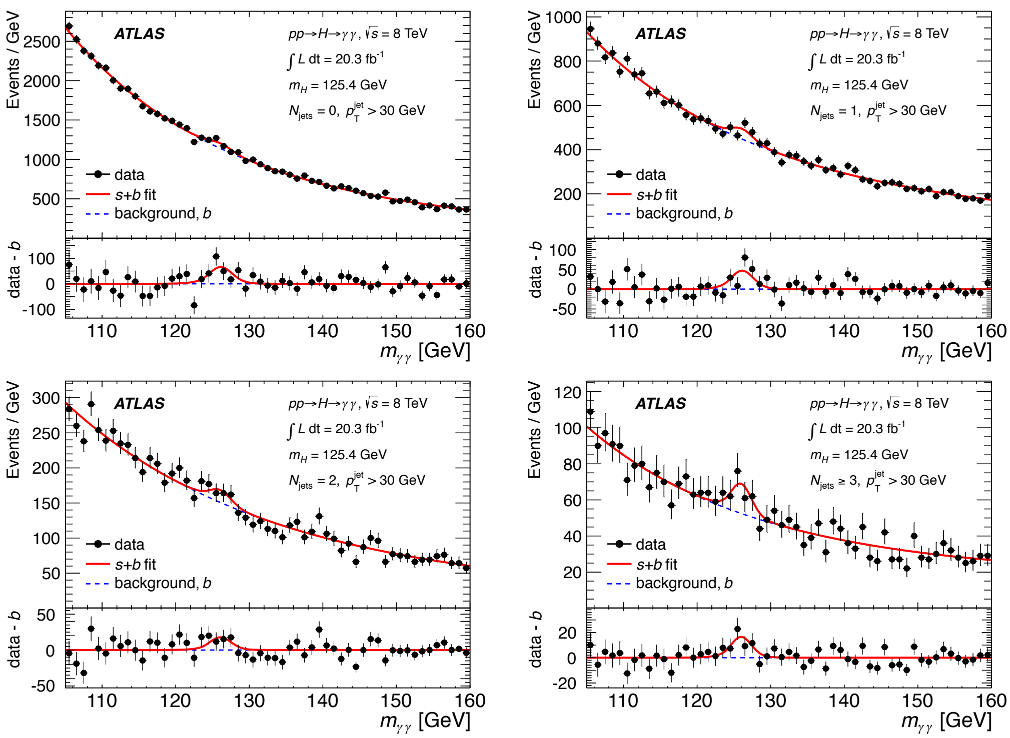

Figure 2. The diphoton invariant mass spectrum for four bins of jet multiplicity as described in the legend. The curves show the results of the single simultaneous fit to data for all multiplicity bins, where the Higgs boson mass is fixed to be $m_H = 125.4\,\mathrm{GeV}$. The red line is the combined signal and background probability distribution functions, and the dashed line shows the background-only probability distribution function. The difference of the two curves is the extracted signal yield. The bottom inset displays the residuals of the data with respect to the fitted background component. [3]

4. The Differential and Fiducial Cross Sections

The Higgs boson event yields were measured in each bin of the differential distribution. The distributions include the jet activity, the Higgs boson kinematics, VBF sensitive variables and spin-CP variable. The variables are listed as below:

- The Higgs boson kinematics: $p^T_{\gamma\gamma}$, $|y_{\gamma\gamma}|$,
- Jet activity: Jet multiplicity N_{jets}, $p_T^{j_1}$, $|y_{j_1}|$, $p_T^{j_2}$, the scalar sum of jet transverse momenta, H_T.

- Spin-CP sensitive variables: $\Delta\phi_{jj}$, $|cos\theta^{\star}|$
- VBF-sensitive variables: $|\Delta\phi_{\gamma\gamma,jj}|$, $|\Delta y_{jj}|$

The jet multiplicity distribution is shown in the right column of Fig. 3. The signal yields were corrected for the effects of detector inefficiency and resolution. The correction were made using the bin-by-bin unfolding correction factors derived from MC samples. The results were compared with multiple theoretical predictions describing the Higgs boson+jets activities. The HRes 2.2 [7] [8] calculation was used to provide the inclusive kinematics of the diphoton system via gluon fusion. HRes is accurate to NNLO+NNLL in QCD. The BLPTW (soft-collinear effective theory, NNLO+NNLL 0-jet + NLO+NLL 1-jet cross sections), JetVHeto and MINLO [9] [10] [11] provided predictions for events associated with jets. A small distortion in the Higgs boson p_T distribution was observed by comparing the MC and the data, as shown in Fig. 3. One of the possible reason is that the Higgs boson was produced in association with the dark matter particles, which can cause the relatively higher missing transverse energy and the Higgs boson transverse momentum.

The fiducial cross section was also measured in the fiducial range $p_{T\gamma,leading(subleading)}/m_{\gamma\gamma} > 0.35(0.25)$ and $105\,\text{GeV} < m_{\gamma\gamma} < 160\,\text{GeV}$:

$$43.2 \pm 9.4(stat)^{+3.2}_{-2.9}(syst) \pm 1.2(lumi)\,\text{fb}$$

The results are shown in Fig. 4.

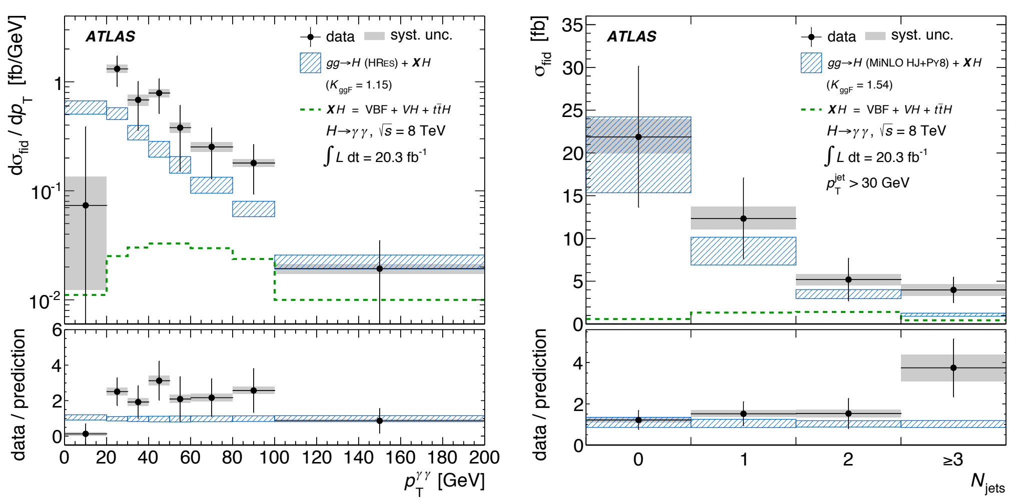

Figure 3. Left: the differential cross section of p_T^H measured in two photon final state. Right: the jet multiplicity distribution. The jets p_T threshold is 30 GeV [3]. The Hres calculation is normalised to the LHC-XS prediction using a K-factor K_{ggF}.

5. The Search for Dark Matter

The Higgs boson produced in association with dark matter candidates can explain the distortion in the diphoton p_T spectrum. Figure 1 shows a way of dark matter production, an mediator couples with two dark matter candidate and the Higgs boson. By setting up the mediator mass at 300 GeV and dark matter mass around 60 GeV, this process provides a moderate missing transverse energy (MET). The excess could be observed in both the Higgs boson p_T region and intermediate MET region. A data driven search is proposed to find the new physics. The search will be performed in two photon and MET phase space. Several categories will be used to catch

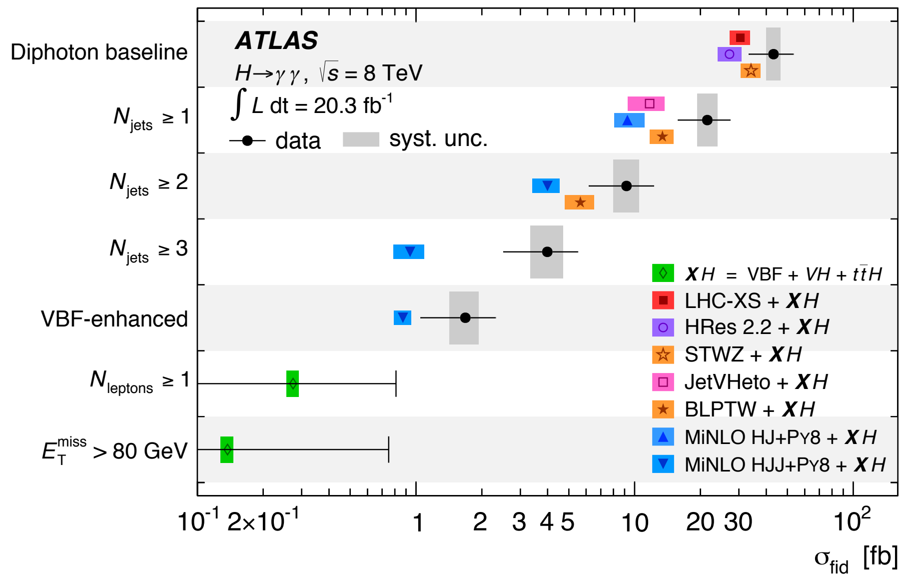

Figure 4. The measured cross sections and cross-section limits for $pp \rightarrow H$ in the seven fiducial regions. The intervals on the vertical axis each represent one of these fiducial regions. The data are shown as filled (black) circles. The error bar on each measured cross section represents the total uncertainty in the measurement, with the systematic uncertainty shown as dark grey rectangles. The error bar on each cross-section limit is shown at the 95% confidence level. The width of each theoretical prediction represents the total uncertainty in that prediction. All regions include the SM prediction arising from VBF, V H and ttH, which are collectively labelled as XH [3].

up the diphoton plus high, intermediate and low MET final states. The search will optimise the categories using 2011+2012 data and MC to find the best selection criteria through which the data has the largest excess with respect to the SM Higgs boson. The selection criteria will be applied in 2015 $\sqrt{s} = 13$ TeV, with the consideration on the changes brought from the higher centre mass energy and higher pile up contamination. Meanwhile, the MET performance of the SM Higgs boson, background and data is critical for the search. A track based MET definition will be used in 2011+2012 and 2015 data to suppress the dependence of pile up. If the excess does exist, it should be observed in other channels as well, such as ZZ to 4 leptons channel. However the diphoton selection is the most sensitive analysis in the early data.

6. Conclusions

The differential and fiducial cross section were measured after the recalibration of photon energy in ATLAS in 2014. The small excess from the Higgs boson p_T distribution could indicate a dark matter candidate produced in association with the Higgs boson. The data driven search for new physics on 2015 $\sqrt{s} = 13$ TeV data using 2011+2012 results will be performed.

References

[1] ATLAS Collaboration, Phys.Lett. B716 (2012) 1, arXiv:1207.7214[hep-ex]
[2] CMS Collaboration, Phys.Lett. B716 (2012) 30, arXiv:1207.7235 [hep-ex]
[3] ATLAS Collaboration, JHEP 1409 (2014) 112, arXiv:1407.4222 [hep-ex]
[4] ATLAS Collaboration, The ATLAS experiment at the CERN large hadron collider, J.Instrum., 3 (2008)

[5] S. Alioli, P. Nason, C. Oleari, and E. Re, JHEP 0904 (2009) 002, arXiv:0812.0578 [hep-ph]
[6] Sjostrand, Torbjrn et al. Comput.Phys.Commun. 191 (2015) 159-177 arXiv:1410.3012 [hep-ph]
[7] D. de Florian, G. Ferrera, M. Grazzini, and D. Tommasini, JHEP 06 (2012) 132, [arXiv:1203.6321].
[8] M. Grazzini and H. Sargsyan, JHEP 09 (2013) 129, [arXiv:1306.4581].
[9] R. Boughezal, X. Liu, F. Petriello, F. J. Tackmann, and J. R. Walsh, Phys. Rev. D89 (2014) 074044, [arXiv:1312.4535].
[10] A. Banfi, P. F. Monni, G. P. Salam, and G. Zanderighi, Phys. Rev. Lett. 109 (2012) 202001,[arXiv:1206.4998]
[11] K. Hamilton, P. Nason, and G. Zanderighi, JHEP 10 (2012) 155, [arXiv:1206.3572].