Search for a heavy boson in $WW\gamma\gamma$ channel at the Large Hadron Collider in pp at $\sqrt{s} = 13$ TeV and integrated luminosity of 36.5 fb$^{-1}$ with the ATLAS detector

A Fadol$^1$, B Mellado and X Ruan
School of Physics, University of the Witwatersrand, Johannesburg 2050, South Africa
E-mail: $^1$abdualazem.fadol.moohammed@cern.ch

Abstract. In this study, a search for heavy boson $H$, decaying into the Standard Model Higgs $h$, and scalar boson $S$ using 36.5 fb$^{-1}$ of proton-proton collision data recorded at $\sqrt{s} = 13$ TeV by the ATLAS detector at the Large Hadron Collider is presented in this note. The investigation is carried out with $h$ decaying into two photons and the semileptonic decays of two $W$'s from $S$. The analysis procedures are described and the sensitivity of the analysis is presented.

1. Introduction

The discovery of the Standard Model (SM) Higgs boson, $h$, in 2012, has been announced by the ATLAS and CMS Refs. [1, 2]; in which its spin, CP and charge have been extensively studied [3]. This opened a wide range of research area to investigate whether the discovered Higgs boson is unique in its nature or just one of the spectrum of the SM Higgs. Many theories have been introduced in so-called Beyond the Standard Model of particle physics (BSM), such as the 2HDM [4]. These theories are an extension for the SM, where additional massive Higgs bosons appear. The SM shows the possibility of the self-couplings of the SM Higgs boson. But to observe this production in Run I was impossible as reported in Ref. [5]. This is because of the large background and small signal at low luminosity approximately 20 fb$^{-1}$. However, physics BSM can significantly enhance the signal yield. For instance, in Ref. [6] a heavy neutral boson has been hypothesized. This heavy boson decays to a pair of scalar bosons, $SS$, or to SM Higgs and a scalar boson, $S$, ($gg \rightarrow H \rightarrow SS, Sh$) as shown in Figure 1 of the resonance case. In this search, the semi-leptonic $WW^{*}\gamma\gamma$ final state, i.e. with two photons from $h$, two jets and one charged lepton together with missing energy from $S$ is considered. Hence, the $W$'s bosons decay semileptonically and hadronically as in $gg \rightarrow H \rightarrow hS \rightarrow WW^{*}\gamma\gamma \rightarrow l\nu jj\gamma\gamma$. The work is organized as follows, the description of the data and the Monte Carlo (MC) samples is given in Section 2. The background
modeling and the spurious signal computation is discussed in Section 4. In Section 5, the signal parameterization is studied. In Section 6 we give preliminary statistical result of the fit on the Asimov data, where the background only hypothesis is used. A conclusion is drawn in Section 7.

2. Data and Monte Carlo samples

The data will be used is the data recorded by ATLAS detector in 2016 at $\sqrt{s} = 13$ TeV with luminosity of $36.5 \text{ fb}^{-1}$. The Monte Carlo samples used to simulate the signal samples are generated by the MadGraph5_aMC@NLO [7]. The resonance mass considered here is between 260-500 GeV, where we assumed that the resonance has small decay width. The background on the SM Higgs is estimated with the following production mechanism: $ggh$, VBF, Wh, Zh and tth, these samples have been generated with Pythia8 and Powheg by A14 NNPDF2.3LO tunes at center-of-mass energy of 13 TeV. The production cross-section for each sample are 48.52 pb, 3.779 pb, 1.369 pb, 0.8824 pb and 0.5065 pb respectively. Also, events with final states of $l\nu jj\gamma\gamma$ have been simulated with Madgraph5 and Pythia8 for events come from $pp \rightarrow l\nu jj\gamma\gamma$ and $pp \rightarrow jj\gamma\gamma$.

3. Analysis procedures

The events selections for the two photons are the same as described in Ref. [8]. In addition to the two photons selections, we introduce the following selection:

- The number of jets to be at least two central jets which are required to have $p_T^{\text{jets}} > 25$ GeV and $|\eta| < 2.5$.
- An event will be rejected if any b-tagged jet is found. The b-tagger is MV2c10 with a b-tagging efficiency of 70%.
- The number of leptons in the final state should be at least one lepton and it could be either a muon or an electron.
- The tight mass window is defined by $(125.09 - 2 \times 1.7) \leq m_{\gamma\gamma} \leq (125.09 + 2 \times 1.7)$. The selection efficiencies for the signal samples as a function of the mass of H are shown in Table 1. Where the selection efficiency at the mass, $m_{\gamma\gamma}$, cut is between 35.2-41.5%.
### Table 1. The cut efficiency for the signal samples.

| Cuts                | All Events | Duplicate | GRL | Pass Trigger | Detector Quality | has PV | 2 Loose Photons | Trig Match | Tight ID | Isolation | Rel. Pt cuts | $105 < m_{\gamma\gamma} < 160$ | At least 2 central jets | B-veto | At least 1 lepton | Tight mass window |
|---------------------|------------|------------|-----|--------------|------------------|--------|----------------|------------|----------|-----------|--------------|--------------------------|------------------------|---------|----------------------|---------------------|
| Samples S and h     | 100.0%     | 100.0%     | 100.0% | 100.0%       | 100.0%           | 100.0% | 100.0%         | 58.7%      | 49.1%    | 44.3%     | 40.8%        | 39.9%                    | 31.1%                  | 29.1%   | 5.9%                 | 5.10%               |
| Resonance Mass      |            |            |      |              |                  |        |                |            |          |           |              |                          |                        |         |                      |                     |
| 260 GeV             | 100.0%     | 100.0%     | 100.0% | 100.0%       | 100.0%           | 100.0% | 56.2%          | 55.9%      | 45.8%    | 38.4%     | 35.8%        | 35.2%                    | 19.8%                  | 18.8%   | 3.5%                 | 2.94%               |
| 300 GeV             | 100.0%     | 100.0%     | 100.0% | 100.0%       | 100.0%           | 100.0% | 55.7%          | 55.5%      | 45.3%    | 38.8%     | 35.1%        | 34.5%                    | 22.3%                  | 21.1%   | 3.9%                 | 3.36%               |
| 400 GeV             | 100.0%     | 100.0%     | 100.0% | 100.0%       | 100.0%           | 100.0% | 57.2%          | 56.9%      | 47.2%    | 42.3%     | 38.4%        | 37.6%                    | 28.2%                  | 26.5%   | 5.4%                 | 4.63%               |
| 500 GeV             | 100.0%     | 100.0%     | 100.0% | 100.0%       | 100.0%           | 100.0% | 59.7%          | 59.4%      | 50.0%    | 45.6%     | 42.4%        | 41.5%                    | 33.2%                  | 31.0%   | 6.3%                 | 5.52%               |

After additional cuts, the selection efficiencies for the signal is between 2.94-5.52% for the resonance mass from 260 GeV to 500 GeV. Also the selection efficiencies for the SM Higgs background is listed in Table 2. In this table, most of the contribution comes from the tth, and this is due to the top quark, which decays to jets and leptons.

### Table 2. The selection efficiency for the background samples.

| Cuts                | ggH | VBF | WH | ZH | tH |
|---------------------|-----|-----|----|----|----|
| All Events          | 100.0% | 100.0% | 100.0% | 100.0% | 100.0% |
| Duplicate           | 100.0% | 100.0% | 100.0% | 100.0% | 100.0% |
| GRL                 | 100.0% | 100.0% | 100.0% | 100.0% | 100.0% |
| Pass Trigger        | 61.6% | 63.3% | 58.4% | 57.9% | 74.6% |
| Detector Quality    | 61.6% | 63.3% | 58.4% | 57.9% | 74.6% |
| has PV              | 61.6% | 63.3% | 58.4% | 57.9% | 74.6% |
| 2 Loose Photons     | 52.6% | 54.0% | 47.0% | 47.7% | 61.2% |
| Trig Match          | 52.5% | 53.9% | 46.9% | 47.6% | 60.8% |
| Tight ID            | 45.9% | 46.9% | 40.5% | 41.1% | 50.8% |
| Isolation           | 41.1% | 42.4% | 35.8% | 36.3% | 42.0% |
| Rel. Pt cuts        | 38.2% | 38.5% | 32.8% | 33.2% | 38.4% |
| $105 < m_{\gamma\gamma} < 160$ | 38.0% | 38.1% | 32.4% | 32.8% | 37.7% |
| At least 2 central jets | 5.84% | 10.74% | 15.81% | 16.80% | 37.08% |
| B-veto              | 5.57% | 10.18% | 15.06% | 13.75% | 6.70% |
| At least 1 lepton   | 0.00390% | 0.01108% | 0.57536% | 0.38938% | 2.06% |
| Tight mass window   | 0.00363% | 0.01005% | 0.52710% | 0.3594% | 1.92% |

4. Spurious signal

The method of the spurious signal is to help us decide which probability density function (PDF) will be suitable for our study. In addition, It allows us to estimate the signal systematics due to the mis-modeling of the background.
Table 3. Spurious signal computation and the selection result of the PDF for the background.

| Function    | \( S \) | \( \text{Max}(S/\Delta S) \) | Result | Selection |
|-------------|---------|-------------------------------|--------|-----------|
| Exponential | -0.50   | -13.2%                        | Pass   | Selected  |
| Dijet       | 0.23    | 6.0 %                         | Pass   | -         |
| ExpPoly2    | -0.03   | -0.7 %                        | Pass   | -         |
| Bern3       | -0.03   | -0.6 %                        | Pass   | -         |

In order to perform the spurious signal study we have to prepare an input as a histogram that stored in a ROOT file. The spurious signal here will be computed only on the range of the Higgs signal. The model uses for the fitting is \( S + B \), which has the composite PDF form:

\[
N_S \times PDF_S + N_B \times PDF_B,
\]

Where \( N_S \), \( PDF_S \), \( N_B \) and \( PDF_B \) are number of signal, PDF of the signal, number of background and PDF of the background, respectively. The PDF of the signal is already stored in the workspace and the PDF of the background is to be determine by this study. The selection of the background PDF is as follows:

- A fit of \( (S + B) \) will be implemented first on the input MC for background, so that we can get the number of the signal, \( N_S \), for all the selected background PDF’s.
- The maximum fitted signal will be recorded.
- Hence, we apply selection as to whether to accept or reject a certain PDF. This achieved by the maximum signal over the error to be less than 20%, \( \text{Max}(S/\Delta S) < 20\% \).
- The PDF is chosen if it passed the condition above. However, if all the selected function are passed the selection criteria, then the PDF with less parameters will be selected by the tool.
- In the configuration file the integrated luminosity of the input dataset has to be consistent with the luminosity of the computed yield.
- The lower and upper end of the window to maximize over to compute the spurious signal is (Higgs mass \( \pm 8 \)) GeV.
- First and second order Exponential, Bernstein and Dijet are the PDF to be tested.
- The scan range has been set to be within the range of (115-135) GeV.
- The scan is performed by taking 0.5 as interval between the scan points.
The result of the PDF selection depending upon the criteria discussed above for the background is shown in Table 3.

5. Signal parametrization

We used the double-sided Crystal Ball to model the shape of the signal and to get the parameters of the best fit.

\[
\begin{align*}
\text{Events/1 GeV} & = 125.04 \\
\int & = 13 \text{ TeV}: s \\
1\text{Lep} & = 125.04 \\
\mu_{\text{CB}} & = 1.59 \\
\sigma_{\text{CB}} & = 1.51 \\
\alpha_{\text{CBLO}} & = 1.72 \\
\alpha_{\text{CBH}} & = 7.64 \\
\eta_{\text{CBLO}} & = 7.27 \\
\eta_{\text{CBH}} & = 7.27 \\
\text{Yield} & = 3.57 \\
\end{align*}
\]

Figure 3. Events pass the selections defined in the signal region.

The single signal and multiple signal fit is performed around the Higgs mass signal, \(m_H = 125\) GeV, for the one lepton category, as shown in Figure 3.

6. Statistical results

An Asimov test is performed to test the expected significance as shown in Figure 4, where we found that the expected significance to be 1.43 \(\sigma\). The Asimov data is generated as "Background + 1 \times SM Higgs + a Heavy Boson Signal".
Figure 4. A \((S + B)\) fit for the Asimov data. The Higgs yield is 3.65 and the BSM yield is 3.64\(\pm\)4.93.

7. Conclusion

This search shows preliminary study for the presence of a heavy boson, \(H\), in \(WW\gamma\gamma\) channel. Because the data still blinded we use the Asimov data. The analysis is based on the data that is collected at the ATLAS detector at 13 TeV and luminosity of 36.5 \(fb^{-1}\). This is to improve the analysis and test the expected significance, which is found to be 1.43\(\sigma\) with exclusion limit of 3.02 \(pb\).

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