Search for resonances decaying to photon pairs in 3.2 fb$^{-1}$ of pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector.

Robert Graham Reed
School of Physics, University of the Witwatersrand, Johannesburg 2050, South Africa
E-mail: robert.reed@cern.ch

Abstract. This proceedings summarises the search for resonances decaying into two photons with a mass greater than 200 GeV. Models, which have scalars, such as the extended Higgs sector are used to optimise the analysis. The results presented are for a dataset containing 3.2 fb$^{-1}$ of pp collisions at $\sqrt{s} = 13$ TeV using the ATLAS detector. The data is consistent with the expected background with the most significant deviation appearing in the 750 GeV region with a global significance of 2$\sigma$. A detailed description of the analysis will be presented.

1. Introduction

The ATLAS and CMS collaborations first announced the observation of a new scalar boson [1,2] in 2012 marking the discovery of the Higgs boson, the final piece to the Standard Model. The next logical step is the search for physics beyond the Standard Model (BSM). The diphoton channel offers a clean signal, offering excellent mass resolution, and has a well understood background. The LHC is, for the first time, providing means to probe higher energies than ever before. In models with an extended Higgs sector [3–5] new scalars with masses different to the Standard Model (SM) Higgs may be observed. This proceedings describes the analysis that has been optimised for masses larger than 200 GeV [6]. The study involves selecting two photons using tight identification to minimise the background that are not from SM diphoton production. Any Higgs-like resonance will appear as a localised excess above the smooth background.

2. The ATLAS detector

The ATLAS detector [7] is one of two main general purpose detector at the LHC. The detector is cylindrical in shape and has a forward-backward symmetry with a near 4$\pi$ coverage in solid angle. ATLAS uses a right-handed coordinate system with the origin at the nominal interaction point and the z-axis along the beam pipe with the x-axis pointing towards the centre of the LHC ring. The detector consists of multiple concentric sub detectors. Starting from the inner detector (ID) we have the inner tracker and silicon microstrip detector located inside the transition radiation tracker which provide tracking in the pseudorapidity range $|\eta| < 2.5$, electromagnetic (EM) calorimeter and lead liquid-argon sampling device is divided into one barrel ($|\eta| < 1.45$) and two end cap regions ($1.375 < |\eta| < 3.2$), the hadron calorimeter is divided into a barrel ($|\eta| < 0.8$) and extended barrel ($0.8 < |\eta| < 1.7$) both of which consist of steel and plastic scintillators.
Each sub detector is designed to identify different particles, their energies and trajectories which when combined together can provide a detailed account of an entire event collision.

3. Data and triggering
The data was recorded by ATLAS during the 2015 data taking period with a centre-of-mass energy of $\sqrt{s} = 13$ TeV with bunch spacing of 25 ns. The average interactions per bunch crossing was about 13 with a peak instantaneous luminosity of $\mathcal{L} = 5.2 \times 10^{33} \text{ cm}^{-2} \text{s}^{-1}$. A diphoton trigger with transverse energy ($E_T$) thresholds of 35 GeV and 25 GeV, for $E_T$ ordered photons, was used. Clusters of energy in the EM calorimeter are reconstructed and required to satisfy a loose criteria to what is expected for EM showers initiated by photons. The efficiency for the signal trigger is close to 99% for events that pass the full selection. Events are only considered if they were recorded during stable beam conditions where the trigger system, tracking devices and calorimeters are all operational. The total integrated luminosity was recorded to be 3.2 fb$^{-1}$.

4. Monte Carlo simulation
Simulated events are used to profile the diphoton signal shape and to estimate the background by parametrising its shape. The simulation can provide selection inefficiencies as well as detector resolution effects which can be used to correct the results from the data. The signal is simulated as a gluon fusion (ggF) process resulting in a SM Higgs-like boson produced under the same conditions as those expected for data. A single dataset is simulated for various mass hypothesis in the range [200, 2000] GeV. A narrow width approximation (NWA) of 4 MeV is used for the simulated boson which correspond to a 125 GeV SM Higgs boson. The interference between the signal and background is assumed to be tiny and is neglected. Resonances with a large natural width also need to be considered so a large width approximation (LWA) is also studied. To obtain the mass distribution for the large natural width the theoretical line shape is convoluted with a resolution function. The resolution function takes into account the detector resolution effects which can be used to correct the results from the data. The signal trigger is close to 99% for events that pass the full selection. Events are only considered if they were recorded during stable beam conditions where the trigger system, tracking devices and calorimeters are all operational. The total integrated luminosity was recorded to be 3.2 fb$^{-1}$.

5. Object and Event selections
Photon reconstruction begins with EM cells that have a transverse energy exceeding 2.5 GeV. The cells are matched to tracks in the ID and extrapolated to the calorimeter. If no tracks are found then the cluster is marked as an unconverted photon, one track is an electron candidate.
and two tracks is a converted photon under the hypothesis of $\gamma \rightarrow e^+e^-$. The efficiency to correctly reconstruct photons from the clusters and tracks is 97% with the other 3% incorrectly reconstructed only as electron candidates. Dedicated energy calibrations, for both converted and unconverted photons, are used which account for lateral and longitudinal leakage and other upstream energy losses [9]. Photons are required to satisfy an identification criteria which is based on the shower shape in the EM calorimeter and the energy leakage in to the hadronic calorimeter. The efficiency of the tight identification for unconverted (converted) photons asymptotically reaches 95% (98%) for $E_T > 200$ GeV. In order to reduce the backgrounds from jets an isolation requirement is used on photon candidates. This makes use of the isolation transverse energy ($E_{isoT}$) which is the sum of transverse energies of the positive-energy topological clusters within a cone of size $\Delta R = 0.4$, where $\Delta R \equiv \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2}$. An additional requirement on the track isolation transverse momentum ($p_{isoT}$) which is the sum of the $p_T$ of tracks from the primary vertex in a cone of $\Delta R = 0.2$. The pileup dependence of the track isolation transverse momentum is reduced by selecting tracks consistent with the originating diphoton production vertex. Two selected photons passing the object definitions are required to satisfy $E_{isoT}^{\gamma_1}/m_{\gamma\gamma}>0.4$ and $E_{isoT}^{\gamma_2}/m_{\gamma\gamma}>0.3$. The isolation transverse energy requirement is $E_{isoT} < 0.22 \times E_T + 2.45$ GeV and track isolation transverse momentum must satisfy $p_{isoT} < 0.05 \times E_T$.

6. Statistical analysis
6.1. Introduction
The yields for the signal and background events are obtained by performing an unbinned maximum likelihood fit on the diphoton invariant mass distribution for each mass hypothesis for both the LWA and NWA. The entire mass spectrum is used for every mass hypothesis tested. The asymptotic approximation [10] is used to calculate the background-only local $p$-value ($p_0$). A global significance is computed with the look-elsewhere-effect (LEE) taken into account based on the number of positive crossing of the $2 \sigma$ significance levels in the region $m_X \in [200, 2000]$ GeV. The expected and observed 95% CL exclusion limits are computed using the asymptotic approximation described in Ref [10].

6.2. Background model
The background is modelled using a data driven approach to estimate the continuous background contribution. It is modelled using a smooth function of the form of an exponential. The simplest functional form containing the least degrees of freedom is used and has the form:

$$f_0(x; b, a_0) = (1 - x^{1/3})^b x^{a_0}$$

where $a_0$ and $b$ are allowed to be free floating and $x = \frac{m_{\gamma\gamma}}{\sqrt{s}}$.

6.3. Signal model
The signal is parametrised using a DSCB (See Equation 1) that has been characterised using fully simulated ggF samples for both NWA and LWA for various mass hypotheses. Each parameter of the DSCB is fitted with a polynomial as a function of the mass hypothesis allowing a continuous description of the signal shape for all mass hypothesis values.

6.4. Systematics
Systematic uncertainties are treated as nuisance parameters that are introduced into the likelihood functions in the background-only and signal-plus-background fits. There are a large number of systematic sources such as object uncertainties (photon energy resolution), theoretical sources (production cross sections) and fitting errors (Signal shape and background shape).
### Source Uncertainty

| Source                  | Uncertainty                                      |
|-------------------------|--------------------------------------------------|
| **Background modeling** | ••                                               |
| Spurious signal         | $2 - 10^{-3}$ events, mass-dependent             |
| Background fit          | $\leq 50\% - 20\%$ of the total signal yield uncertainty, mass- and signal-dependent |
| **Signal modeling**     | ••                                               |
| Photon energy resolution| $^{+0.55-1.10\%}_{-0.20-0.40\%}$, mass-dependent |
| **Signal yield**        | ••                                               |
| Luminosity              | $\pm 5\%$                                        |
| Trigger                 | $\pm 0.63\%$                                     |
| $C_X$ factors           | ••                                               |
| Photon identification   | $\pm (3-2)\%$, mass-dependent                    |
| Photon isolation        | $\pm (4.1-1)\%$, mass-dependent                  |
| Production process      | $\pm 3.1\%$                                      |

Table 1: Summary of the systematic uncertainties in the signal-plus-background likelihood fit when considering the NWA signal model. The ◦ symbol indicates categories of uncertainties that affect the local $p$-value for the background-only hypothesis, while the • symbol denotes uncertainties that impact the limit on $\sigma_{\text{fiducial}} \times \text{BR} (X \rightarrow \gamma\gamma)$.

Table 1 shows a summary of the uncertainty contributions when considering the NWA signal model.

### 7. Results

The background only likelihood fit to the observed data from ATLAS is shown in Figure 1. Figure 2 a) shows the ATLAS results for the local $p$-value for the background-only fit for the NWA and Figure 2 b) shows the corresponding 95% CL for the NWA. The largest deviation is observed at about 750 GeV with a local significance of 3.6$\sigma$ which is reduced to 2.0$\sigma$ when the LEE affect is taken into account. CMS performed a similar study in Run I and II [11] and measured a combined $p$-value which has the largest deviation at 750 GeV with a significance of 3.0 $\sigma$ which is reduced to 1.7 $\sigma$ after taking into account the LEE.

### 8. Discussion and Conclusions

A search for scalar resonances in the diphoton channel was performed by ATLAS with the 2015 dataset consisting of 3.2 fb$^{-1}$ of $pp$ collisions. The largest deviation from the background-only hypothesis occurs in the 750 GeV region with a global significance around 2$\sigma$. The limits exceed those set in Run I. The excess at 750 GeV was also observed by the CMS Collaboration Final clarification on this excess is expected to happen with more data taken during the 2016 physics period.

### References

[1] The ATLAS Collaboration 2012 *Physics Letters B* **716** 1–29 URL http://www.sciencedirect.com/science/article/pii/S037026931200857X
[2] The CMS Collaboration 2012 *Physics Letters, Section B: Nuclear, Elementary Particle and High-Energy Physics* **716** 30–61
[3] Veltman M J G and Yndurain F J 1989 *NPB* **325** 1
Figure 1: The invariant mass distribution for ATLAS with the background-only fit overlaid.

Figure 2: ATLAS results for a) $p$-value for the background-only hypothesis $p_0$ as a function of the mass $m_X$ of a probed NWA resonance signal and b) Expected and observed upper limits on $\sigma_{\text{fiducial}} \times \text{BR}(X \rightarrow \gamma\gamma)$ expressed at 95% CL, as a function of the assumed value of the narrow-width scalar resonance mass.

[4] Binoth T and van der Bij J J 1997 *ZfPC* 75 17–25
[5] Schabinger R and Wells J D 2005 *PRD* 72 093007
[6] ATLAS Collaboration 2015 Search for resonances decaying to photon pairs in 3.2 fb$^{-1}$ of $pp$ collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector Tech. Rep. ATLAS-COM-CONF-2015-096 CERN Geneva URL https://cds.cern.ch/record/2111338
[7] ATLAS Collaboration 2008 *JINST* 3 S08003
[8] CMS Collaboration (CMS) 2015 *PLB* 750 494–519
[9] ATLAS Collaboration 2014 *Eur. Phys. J. C74* 3071
[10] Cowan G, Cranmer K, Gross E and Vitells O 2011 *EPJC* 71 1554
[11] 2015 Search for new physics in high mass diphoton events in proton-proton collisions at $\sqrt{s} = 13$ TeV Tech. Rep. CMS-PAS-EXO-15-004 CERN Geneva URL https://cds.cern.ch/record/2114808