Higgs Boson to Diphoton Decay
Third Year Lab Report

Theo Broxton
Department of Physics and Astronomy, University of Manchester
(Dated: December 13, 2024)

An analysis of the Higgs boson to diphoton decay is presented using 10.064 fb^{-1} of proton-proton collision data at a centre-of-mass energy $\sqrt{s} = 13\,\text{TeV}$. The data set was recorded by the ATLAS experiment at the LHC and released publicly for educational purposes. The measured value of the cross section for the Higgs boson to diphoton decay channel is $84 \pm 35(\text{stat.}) \pm 19(\text{syst.}) \pm 1(\text{lumi.})\,\text{fb}$ which is in agreement with the most recent measurement from the ATLAS collaboration of $67 \pm 6\,\text{fb}$.

1. INTRODUCTION

The 20th century was certainly an exciting time for the field of physics, with developments from relativity to quantum mechanics. However, perhaps the most impressive theory to emerge was that of the Standard Model (SM). Often likened to the periodic table in chemistry, the SM describes the interaction of matter particles - quarks and leptons - with each other via the exchange of spin-1 gauge bosons [1]. In this paper though, we focus on the Higgs boson, a crucial element of the SM and a unique spin-0 boson.

1.1. *Higgs mechanism*

In the 1960s, Peter Higgs[1] proposed a mechanism to explain how particles acquire mass [2]. Goldstone's theorem states that a spinless, massless particle is created when a continuous symmetry is spontaneously broken (Goldstone bosons) [3]. A familiar example from condensed matter physics are magnons, which arise in magnets [4]. The gauge bosons 'eat' the degree of freedom from the Goldstone bosons and as a result obtain mass[2] [6].
The Higgs mechanism is crucial as it explains the masses of the W and Z bosons, which have been experimentally observed [7, 8]. The natural question for physicists is: how do we verify that this truly is the correct description of nature?

1.2. *Search for the Higgs*

Beyond endowing mass, Higgs also predicted that there should be a scalar particle produced from the Higgs mechanism - the Higgs boson. If the Higgs boson could be experimentally confirmed, then it would be further evidence for the success of the SM at describing our reality.
In 2008, the Large Hadron Collider (LHC) began operations and had been designed with Higgs discovery in mind [9]. As explained by Wyatt [10], some constraints on the mass of the Higgs had already been imposed by previous measurements at LEP and the Tevatron. Four years later, in 2012, a milestone paper detailing observation of the Higgs boson was published by the ATLAS collaboration [11].

[1] Although named after Higgs, multiple groups independently published slightly different theories around the same period.
[2] A more in-depth motivation for the Higgs mechanism is beyond the scope of this report; see Chapter 17 of Thomson for further details [5].

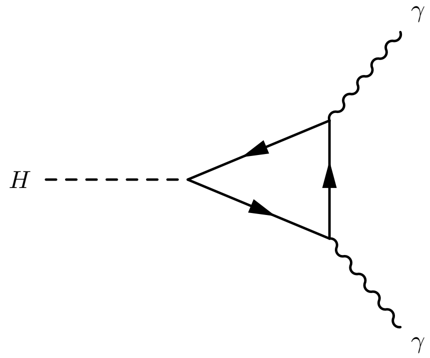

FIG. 1. Feynamn diagram for the Higgs to two photon decay produced using the LaTeXpackage `feynmp`. Figure adapted from Martin [14].

1.3. *Production and decay*

Having motivated the search for the Higgs boson as evidence for the Higgs mechanism and outlined its discovery, we now turn to how it is observed.
In this report we consider five main SM Higgs production modes: gluon-gluon fusion (ggF), vector-boson fusion (VBF), Higgs-strahlung (WH/ZH) and a top-quark pair ($t\bar{t}H$) [12]. The Higgs has a lifetime of $\mathcal{O}(10^{-22})$s, so it is identified via reconstruction from its decay products. The decay channel we explore here is $H \to \gamma\gamma$, shown in Figure 1. The Higgs must first decay to a virtual fermion (or W boson) loop since it does not couple directly to the massless photons. Although this has a low branching ratio of 0.227 % [13], the photons can be detected with high precision by ATLAS and the diphoton final state has a comparatively low background, making this a useful channel of study.

2. EVENT SELECTION

2.1. *Experimental setup*

The 13 TeV ATLAS Open Data set composed of data from the LHC run in 2016 was used. This was released to allow 'analysis of particle-physics data in educational environments' and has an integrated luminosity of 10.064 fb^{-1} [15]. In particular, the ATLAS data for diphoton final states and the Monte Carlo (MC) data for a SM diphoton Higgs decay were used. The analysis of this data was performed using the `ROOT` framework[3] as well as Python.

[3] See `https://root.cern/` for more information.

2.2. Selection cuts

Using the MC simulation of Higgs to diphoton decays, we were able to design selection cuts to apply to the ATLAS data such that extraneous background events were rejected. Whilst some information about 'ideal' distributions of events can be gleaned from the MC simulations, it is certainly not an exact science to select specific selection cuts by eye. To provide a more quantitative indicator of the success of our selection cuts, the statistical significance[4]

$$\sigma = \frac{S}{\sqrt{B}}\,, \tag{1}$$

where S are the signal events and B the background events, was calculated for each variation of selection cuts. The signal events were the MC simulations of true Higgs diphoton decays and the background events were taken to be the ATLAS events in their entirety. This approximation is valid since the number of background events in the ATLAS data is many orders of magnitude greater than signal events. The aim was then to maximise the statistical significance of our selection cuts.

The transverse momenta of the leading (sub-leading) photons were given lower bounds of 35(25) GeV, a cut which is also used in the literature [11]. This is due to the detector having better resolution at higher energies, reduced background from lower p_T QCD diphoton production and kinematic requirements that photons from a true Higgs decay must have some minimum p_T.

The ATLAS data set also includes the isolation variables ptcone (charged particles) and etcone (both charged and neutral particles). ATLAS works in a right-handed coordinate system and the radius of the cones is given as

$$\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}\,, \tag{2}$$

where η is the psuedorapidity[5] and ϕ is the usual azimuthal angle [16]. Photons from a Higgs decay are often isolated and so can be distinguished from the photons from other processes occurring in pp collisions that are accompanied by jets of other particles using these cone variables. After trying ranges from 1 to 10 GeV, the final selection cuts chosen were ptcone $< 3\,\text{GeV}$ and etcone $< 5\,\text{GeV}$.

Overall, the selection cuts employed improved the statistical significance from 0.9σ to 2.8σ.

3. BACKGROUND MODELLING

3.1. Invariant mass

To reconstruct the Higgs from its decay products, one uses its invariant mass. Using special relativity and a conversion from the kinematic set (p_x, p_y, p_z) to (p_T, ϕ, η), we find

$$m_{\gamma\gamma} = \sqrt{2p_{T1}p_{T2}\left(\cosh(\Delta\eta) - \cos(\Delta\phi)\right)}\,. \tag{3}$$

[4] σ is quite an overworked symbol in particle-physics, so be careful to discern its use from context.

[5] Defined as $\eta = -\ln\tan\theta/2$.

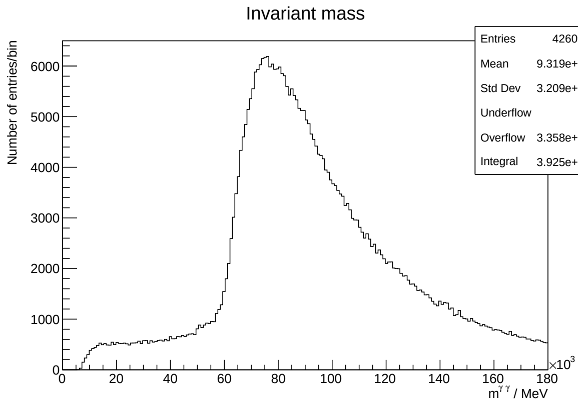

FIG. 2. Invariant mass distribution of diphoton ATLAS data set after final selection cuts have been applied.

In an ideal world, the selection cuts made would completely remove background events and we would be left with just signal Higgs events. Looking at the invariant mass, this should correspond to a 'Higgs peak', which is what the 2012 paper found [11]. What we actually found is shown in Figure 2. Instead of a clear peak at the mass of the Higgs, as seen in the corresponding MC plot, there is still a 'mountain' of background.

3.2. Modelling the background

In order to isolate the Higgs peak, we attempted to perform a fit of the background. To find the best fitting function, 15 different functional forms were tested. Of these, whenever a polynomial was present, degrees 1 through 9 of it were tested. Furthermore, the range of the fit (upper bound) was changed as well as the bin density. Similarly to the selection cuts, a quantitative measure of the reduced chi-squared χ^2_ν was employed to act as an indicator of the validity of the fit [17]. It was important to find a precise fit of the background in order to minimise the systematic uncertainty.

The best fit overall was found to be of the form $\exp\left(p_0x^2 + p_1x + p_2\right)$, where p_i are the fit parameters, which had $\chi^2_\nu = 1.06$ for 200 bins over the range 100-180 GeV.

4. CROSS SECTIONS

To calculate the cross section for $H \to \gamma\gamma$, we use the forumla

$$\sigma = \frac{N^{\text{sel.}} - N^{\text{back.}}}{\epsilon \int L\,\mathrm{d}t}\,, \tag{4}$$

where ϵ is the efficiency found as the ratio of events that pass selection cuts and the integrated luminosity is given for the data set as $10.064\ \text{fb}^{-1} \pm 1.7\%$. To find the numerator, which is the number of signal events, we employ two methods: background subtraction and signal scaling.

4.1. Background subtraction

We subtracted the optimal fitting function from the ATLAS invariant mass plot to produce a residual plot. Then by calculating the integral in the region 120-130 GeV an estimate of the number of signal events is obtained. The resulting cross section was found to

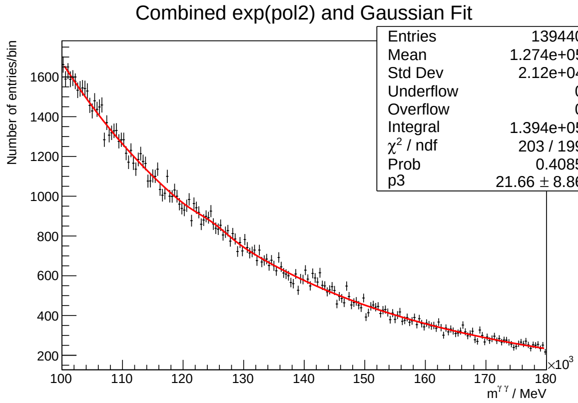

FIG. 3. Combined background fit of the form $\exp(p_0x^2 + p_1x + p_2)$ and Gaussian signal fit on the ATLAS invariant mass data.

be (88 ± 39) fb, where the uncertainty is the statistical uncertainty taken from the data and propagated through the calculations.

4.2. Signal scaling

The favoured method for this experiment was scaling a signal fit. Using the MC invariant mass histogram, a Gaussian fit of the Higgs peak was made. The parameters of this were then fixed, apart from the amplitude, and the Gaussian peak was fitted to the entire ATLAS data combined with the existing background fit, shown in Figure 3. By comparing the Gaussian amplitude of the MC fit to the combined ATLAS fit, we obtained a linear scale factor. This was then used to scale the integral from 120-130 GeV of the MC invariant mass histogram to the number of ATLAS signal events. The cross section was found to be (85 ± 34) fb.

4.3. Estimating systematic uncertainty

To estimate the systematic uncertainty, we reran the cross section analysis using the signal scaling method with different changes: the fit function used to model the background, the number of bins, the range and the selection cuts imposed on ptcone and etcone. To check that ptcone and etcone contributed to the systematic uncertainty, the resulting cross section values were plotted as a function of various upper bound cuts. A non-trivial relationship was found, so their cross section contributions were included in analysis of the systematic uncertainty.

Firstly a colour coded histogram was plotted to show the contribution of different changes to the cross section and then a combined cross section histogram was plotted and Gaussian fitted. To estimate the systematic uncertainty, an average of the standard deviation, FWHM, half-range and rms was taken, giving 19 fb.

5. RESULTS

Taking the mean of the Gaussian that fitted the various cross sections as the cross section value, we found the cross section to be $84 \pm 35(\text{stat.}) \pm 19(\text{syst.}) \pm 1(\text{lumi.})$ fb. This result agrees with the most recent experimental value of the cross section, 67 ± 6 fb, as well as theoretical value based on the SM, 64 ± 4 fb [18]. This is important as any discrepancy would indicate physics beyond the SM that is not being considered.

6. CONCLUSION

The aim of this experiment was to study the $H \to \gamma\gamma$ decay mode using data analysis. We have optimised selection cuts, modelled background events, calculated cross sections for this process and accounted for both statistical and systematic uncertainties. Furthermore, agreement has been achieved with the current literature for both experimental and theoretical results. Better results could be achieved by using a larger data set of higher integrated luminosity, as well as employing machine learning techniques in the analysis.

[1] M. K. Gaillard, P. D. Grannis, and F. J. Sciulli, Reviews of Modern Physics **71**, S96 (1999).

[2] The 1964 PRL symmetry breaking papers F. Englert and R. Brout, Physical Review Letters **13**, 321 (1964); P. W. Higgs, Physical Review Letters **13**, 508 (1964); G. S. Guralnik, C. R. Hagen, and T. W. B. Kibble, Physical Review Letters **13**, 585 (1964).

[3] J. Goldstone, A. Salam, and S. Weinberg, Physical Review **127**, 965 (1962).

[4] S. Blundell and S. Blundell, *Magnetism in Condensed Matter*, Oxford Master Series in Physics (Oxford University Press, Oxford, New York, 2001).

[5] M. Thomson, The higgs boson, in *Modern particle physics* (Cambridge University Press, New York, 2013) pp. 460–498.

[6] R. Wolf, *The Higgs Boson Discovery at the Large Hadron Collider*, Springer Tracts in Modern Physics, Vol. 264 (Springer International Publishing, Cham, 2015).

[7] F. Abe, M. G. Albrow, D. Amidei, *et al.*, Physical Review D **52**, 4784 (1995).

[8] The Working Group on LEP Energy and The LEP Collaborations ALEPH, DELPHI, L3 and OPAL, Physics Letters B **307**, 187 (1993).

[9] G. Aad *et al.* (ATLAS collaboration), Journal of Instrumentation **3** (08), S08003.

[10] T. Wyatt, Nature **448**, 274 (2007).

[11] G. Aad *et al.* (ATLAS collaboration), Physics Letters B **716**, 1 (2012), the original Higgs boson discovery paper.

[12] M. Spira, A. Djouadi, D. Graudenz, and R. M. Zerwas, Nuclear Physics B **453**, 17 (1995).

[13] D. de Florian, C. Grojean, Maltoni, *et al.*, *Handbook of LHC Higgs Cross Sections: 4. Deciphering the Nature of the Higgs Sector*, Tech. Rep. (CERN, Geneva, 2017) series: CERN Yellow Reports: Monographs.

[14] B. R. Martin, *Particle physics*, 4th ed., The Manchester Physics series (John Wiley & Sons, Chichester, West Sussex, United Kingdom, 2017).

[15] The ATLAS collaboration, Review of the 13 TeV ATLAS Open Data release (2020), ATLAS PUB Note.

[16] M. Aaboud *et al.* (ATLAS collaboration), Physical Review D **98**, 052005 (2018).

[17] P. E. Greenwood and M. S. Nikulin, *A guide to chi-squared testing*, Vol. 280 (John Wiley & Sons, 1996).

[18] G. Aad *et al.* (ATLAS collaboration), Journal of High Energy Physics **2022**, 27 (2022).