2HDM $pp \to A \to Zh, Z \to ll, \to> b\bar{b}$ Sensitvity Study ATLAS 2015

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1 Introduction

The 2 Higgs Doublet Model (2HDM) is an extension of the Standard Model originally created as a solution for strong CP violation. It predicts the existence of not one but five higgs particles: $h(h1), H(h2), A(h3), H\pm$. The model proposes that the Higgs field is composed of two doublets $H1$ and $H2$ which couple to different fermions to give them mass. This study aims to determine the sensitivty of the ATLAS detector at the LHC in 2015 to discovery of the pseudoscalar heavy higgs A in a variety of parameter spaces. Pseudoscalar means that the particle has spin 0, but under parity transformation its wave function changes sign.

1.1 Signal & Background Processes

For this study a specific decay process for A was chosen:

$$pp \to A \to Zh, Z \to l+l-, h \to b\bar{b}$$

In this process two protons collide to create A through either gluon fusion or quark annhilation. A then decays to a Z and h boson, with the Z decaying to either $e+e-$ or $mu+mu-$ and h decaying to a bottom(b)-quark and anti b($\bar{b}$)-quark in the form of jets. Since single quarks have color charge, due to color confinement, they do not exist in nature on their own. Therefore as a quark accelerates it hadronizes and releases other particles such as gluons, so we observe these quarks as streams of particles which can be 'tagged' by the detector as being started by a certain flavor of quark. These streams of particls are called jets. The signal process is described in the below Feynman diagram for the gluon fusion and electron decay specific process.

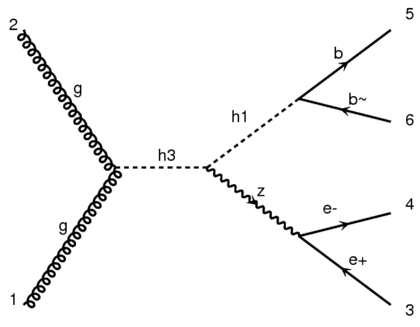


diagram 1 QCD=0, QED=4

It is important to note that what the detector will pick up from this process are the leptons and b-jets. The background processes will be processes that produce these same ouput. This means that it is impossible to tell the processes apart simply from the particles that are detected. The first possible background process is

$$pp \to Zb\bar{b}, Z \to l + l-$$

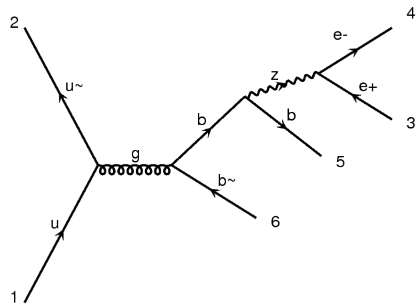


diagram 1 QCD=2, QED=2

It is clear that in this background process there is no pseudoscalar A particle ever produced, but the same final output, two leptons and two b-jets, is produced and will be visible to the detector. The second background process is similar but has other light-quark jets (j), consisting of up, down, charm, and strange quarks, substituted for the b-jets. These jets can be mistagged by the detector as b-jets at a rate of 10% for charm(c)-jets and 0.67% for the other lighter jets.

1.2 Parameter Space Investigated

The 2HDM model contains a large number of free parameters, but this study investigated changes in the mass of A (mA), $\tan\beta$, $\cos\beta - \alpha$ for the Type II 2HDM. Values investigated include

$$mA = 0.3TeV, 0.5TeV, 1TeV, 2TeV, and 3TeV$$

$$\tan\beta = v_1/v_2 = 1, 10$$

$$\cos\beta - \alpha = -0.4, 0, 0.4$$

where v_1 and v_2 represent the vacuum expectation value (vev) of the neutral components of the two Higgs doublets $H1$ and $H2$ respectively. $\cos\beta - \alpha$ does not directly represent such a physical quality, but α is the angle of rotation that diagonalizes the mass-squared matrix for the scalar higgses. It should also be noted that for $\cos\beta - \alpha = \pm 0.4$, the sign did not change the outcome of the study and the two points will therefore be considered together. Then in the Type II 2HDM, $H2$ couples to up-type fermions, while $H1$ couples to down-type fermions and leptons, giving them mass.

2 Sample Production

Data samples were produced for each of these decay process using MadGraph5 v1.5.14 to simulate the collision and decays, Pythia 2.2.0 to simulate parton showering, and Delphes 3.0.12 to simulate the ATLAS detector response. For each parameter space investigated 50k signal events were generated by modifying the mass of A and the decay width of A according to the 2HDM model. For the background events, samples were generated with controlled particle transverse momentum (PT). In the signal process, the output leptons and jets tend to have high PT, while the PT of the same particles in the background processes tends to be much lower. In order to have better statistics at high PT for the background processes, 50k events were generated for particle PT varying each from 0-100GeV, 100-200GeV, ... 2900-3000GeV, the highest mass of A. These samples were all normalized by production cross-section and added together to have the correct background distribution but with much better statistics at high PT. For the signal and background the cross-sections of production (xsec) are listed below. For the signal the xsec includes the branching ratio (probability of decay) of $A \rightarrow Zh$.

mA(GeV)	tan(b)	cos(b-a)	width_A (GeV)	xsec*Br
300	1	0.4	4.898E-01	2.893E+01
300	1	0	2.605E-02	2.893E+01
300	1	-0.4	4.898E-01	2.893E+01
300	10	0.4	1.068E+00	1.245E-01
300	10	0	6.045E-01	1.245E-01
300	10	-0.4	1.068E+00	1.245E-01
500	1	0.4	2.766E+01	1.447E+00
500	1	0	2.288E+01	1.447E+00
500	1	-0.4	1.447E+00	1.725E+00
500	10	0.4	5.938E+00	1.027E-01
500	10	0	1.159E+00	1.027E-01
500	10	-0.4	5.938E+00	1.027E-01
1000	1	0.4	9.751E+01	7.335E-02
1000	1	0	4.873E+01	7.335E-02
1000	1	-0.4	9.751E+01	7.335E-02
1000	10	0.4	5.096E+01	2.336E-03
1000	10	0	2.172E+00	2.336E-03
1000	10	-0.4	5.096E+01	2.336E-03
2000	1	0.4	5.030E+02	2.519E-03
2000	1	0	9.051E+01	2.519E-03
2000	1	-0.4	5.030E+02	2.519E-03
2000	10	0.4	4.165E+02	1.767E-05
2000	10	0	3.988E+00	1.767E-05
2000	10	-0.4	4.165E+02	1.767E-05
3000	1	0.4	1.535E+03	2.983E-05
3000	1	0	1.286E+02	2.983E-05
3000	1	-0.4	1.535E+03	2.983E-05
3000	10	0.4	1.412E+03	5.133E-07
3000	10	0	5.695E+00	5.133E-07
3000	10	-0.4	1.412E+03	5.133E-07

The cross-section for the background processes was in total 348.45pb for both b-jet and light-jet background processes. It should be noted that this is much greater than that of the signal.

Some other important sample production parameters include setting minimum distance between leptons and jets (deltaR) to be 0. This was done because when the particles are decaying from other highly boosted particles (Z and h), the leptons and jets will be close together. Similarly for the detector, a maximum cut was applied for this deltaR at 0.5. Also, since this study was performed for ATLAS 2015, the total beam energy of the protons at the LHC was set to 13TeV.

3 Sensitivity

A sensitivity study seeks to answer whether or not one will be able to see a certain process above the background by comparing their yields.

$$Yield = Luminosity * Cross\text{-}section * Acceptance * Efficiency$$

Yield is a unitless quantity that describes how much of a given process we will be able to see. Luminosity is how much data has been collected in the units of inverse femtobarns (fb^{-1}). After 2015 it is estimated that there will $5fb^{-1}$ of data from ATLAS with the LHC running at $\sqrt{s} = 13$TeV.

$$Luminosity = 5fb^{-1}$$

The cross-section (xsec) as discussed depends on whether or not we are looking at our signal or background process and for the signal depends on which parameter space is being investigated. The acceptance and efficiency describe what fraction of the produced events will be fully detected by the detector, ATLAS, and will pass through analysis cuts. The end goal of the sensitivity study is significance and tells us whether or not the signal will be visible and is given in terms of σ.

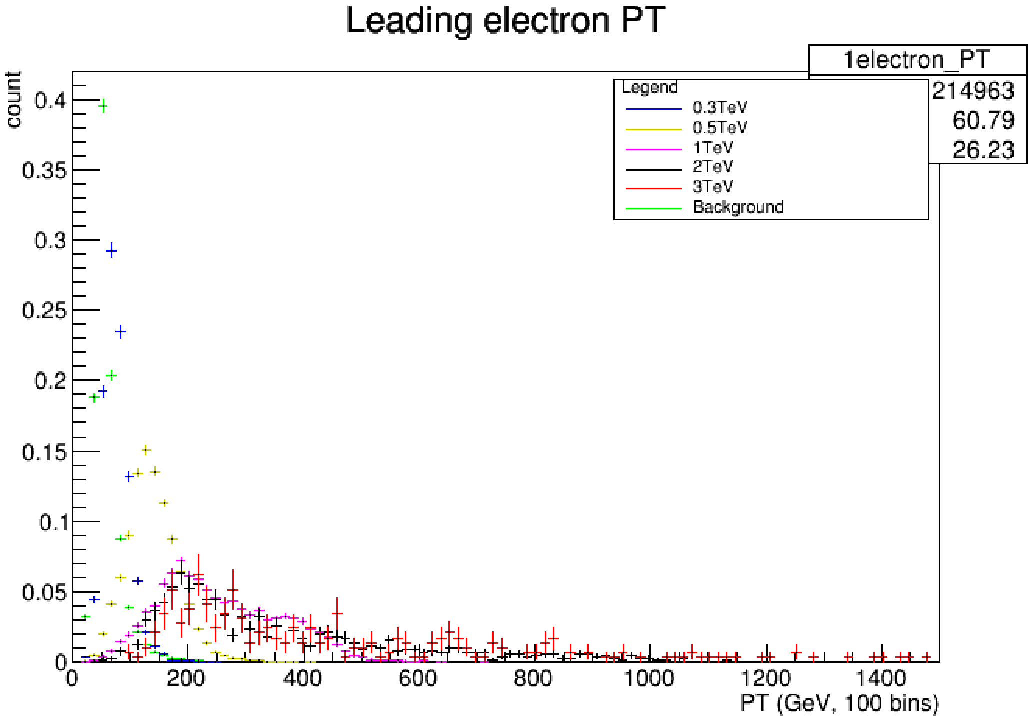
$$Significance = \frac{SignalYield}{\sqrt{BackgroundYield}}$$

Since the background is roughly a Poisson distribution the square root of its yield is equal to its uncertainty which determines how confident we can be that there is a visible signal. If a certain parameter space gives a signficance of less than 2 that means that it will not be visible at ATLAS 2015. However if there is a significance of greater than 2 it will be visible at ATLAS 2015. Therefore, if the signal does show up it is legitimate, and if it does not, this parameter space can be ruled out.

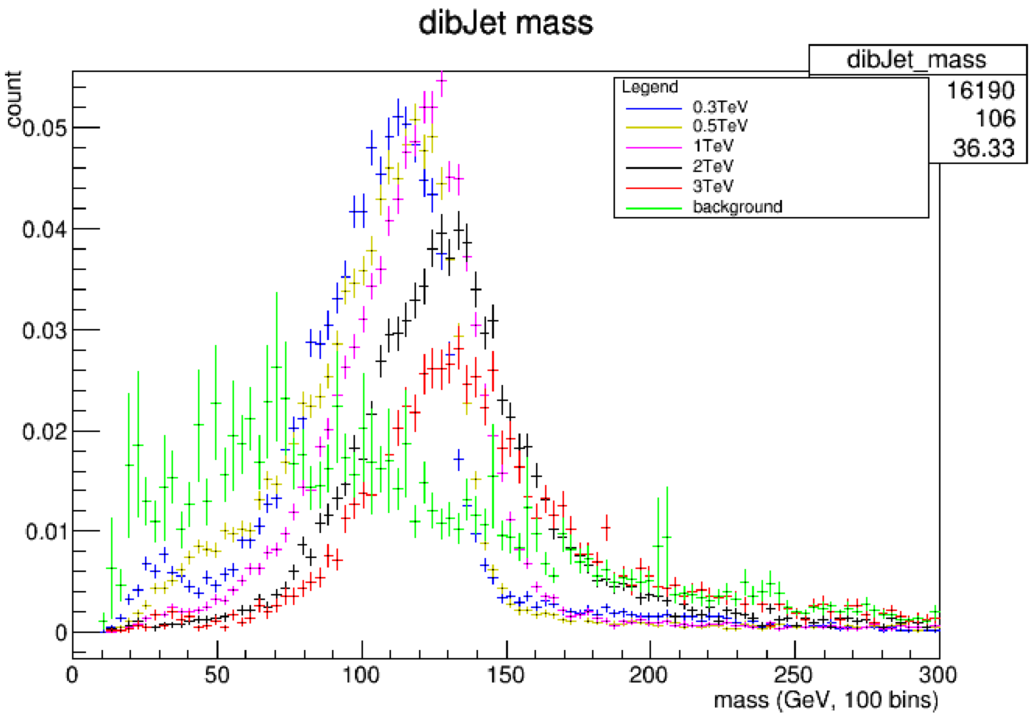
3.1 Kinematics

In order to differentiate between the signal and background processes the kinematics of the output particles can be analyzed then be used to filter out the background by making cuts. The cuts to be made turned out to be minimum PT cuts on leptons and b-jets, a minimum and maximum cut on reconstructed $b\bar{b}$ mass, and a minimum and maximum cut on reconstructed $llb\bar{b}$ mass. Using conservation of momentum and energy the mass of the particle from which other particles have decayed can be reconstructed. So for instance in both our signal and background processes there should be a peak in the reconstructed dilepton mass at about 90GeV, the mass of the Z from which the leptons decayed. The kinematics are described by the plots below. The plots are for the parameter space where $\tan\beta = 10$ and $\cos\beta - \alpha = 0$. This parameter space was chosen because the width of A was minimized for the larger masses here, making the necessary cuts most obvious.

The mass of A is labeled in the legend. The histogram below describes the PT of the electron with the highest PT for the various masses of A and for the background. The plots presented below are normalized so that the area under all curves is the same (1). This allows us to see the of the graphs and compare even for when there is very little yield.



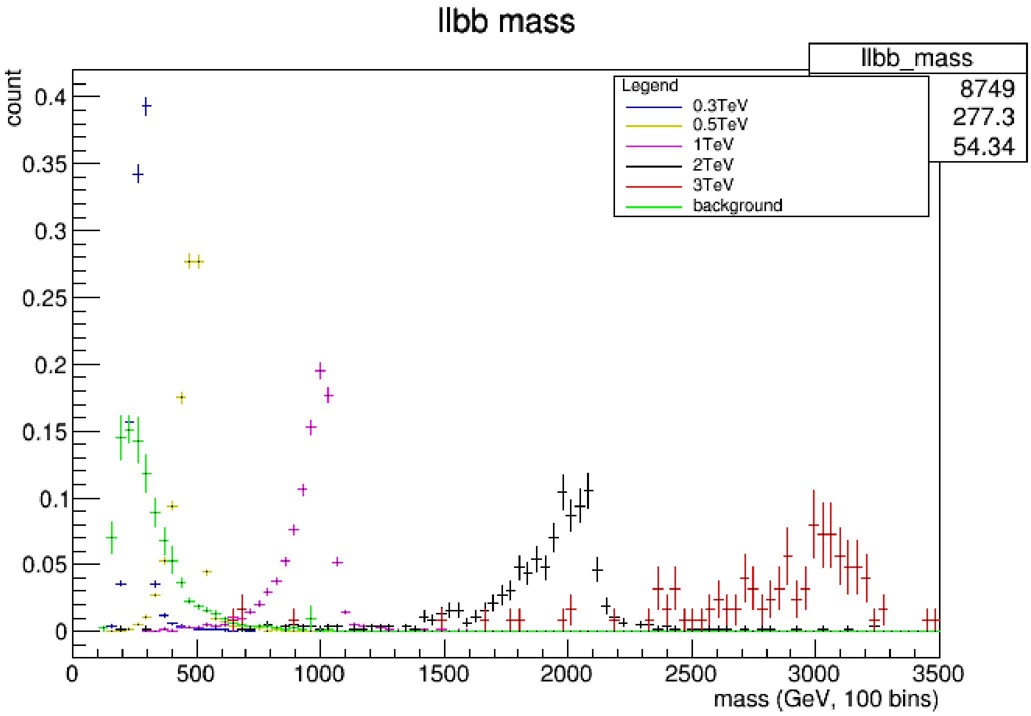
It is obvious that the PT of the electrons in the signal is higher than for the background, leading us to choose to make a minimum PT cut at 30GeV. The next cut was for reconstructed $b\bar{b}$ mass.



Here there is clearly a different distribution for the background (green) than for the signal. There is a much sharper peak for the signal right around 125GeV (the mass of the SM higgs from which the b-jets decayed). Cuts can be made around this feature to reduce background while maintaining signal yield. For instance for the lower mass range the cuts made were

$$50GeV < b\bar{b} < 150GeV$$

Only choosing final events for which this is true will remove more of the signal than the background. The other cut that was made was for the llbbar reconstructed mass.

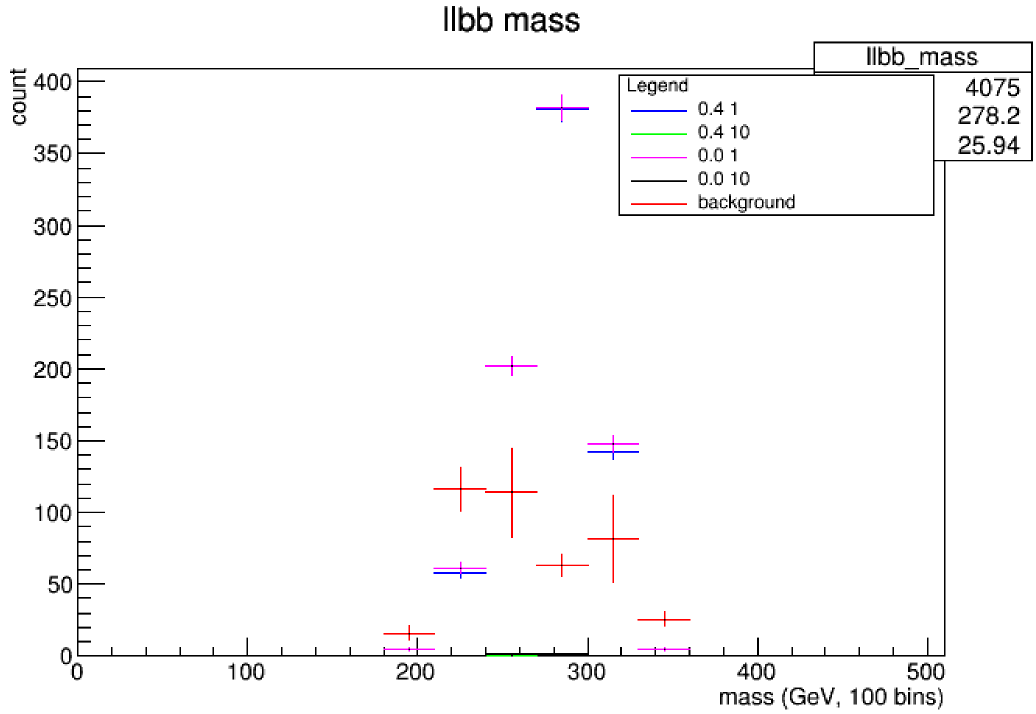


One can easily observe the different peaks in the signal corresponding to the mass of A. Different cuts can be made for these varying masses. The summary of all of the cuts is presented below.

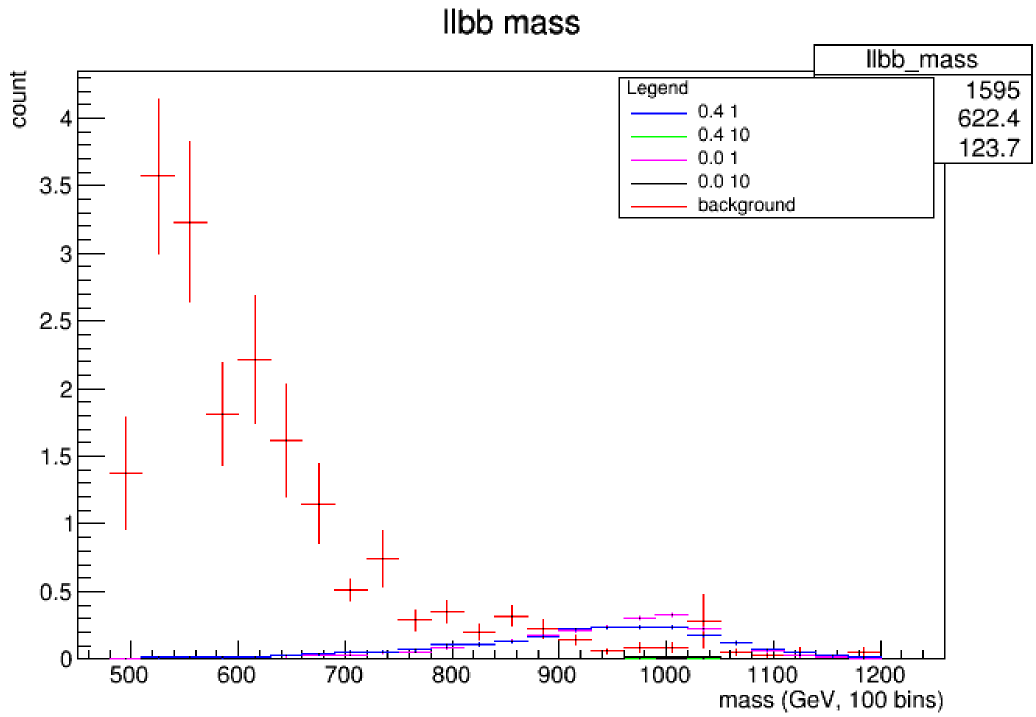
mA (TeV)	min PT(GeV)	min bb~(GeV)	max bb~(GeV)	min llbb(GeV)	max llbb(GeV)
0.3	30	50	150	200	350
0.5	30	50	150	200	700
1	30	50	150	500	1200
2	30	50	200	1000	2500
3	30	50	200	2000	3500

3.2 Yields and Significance

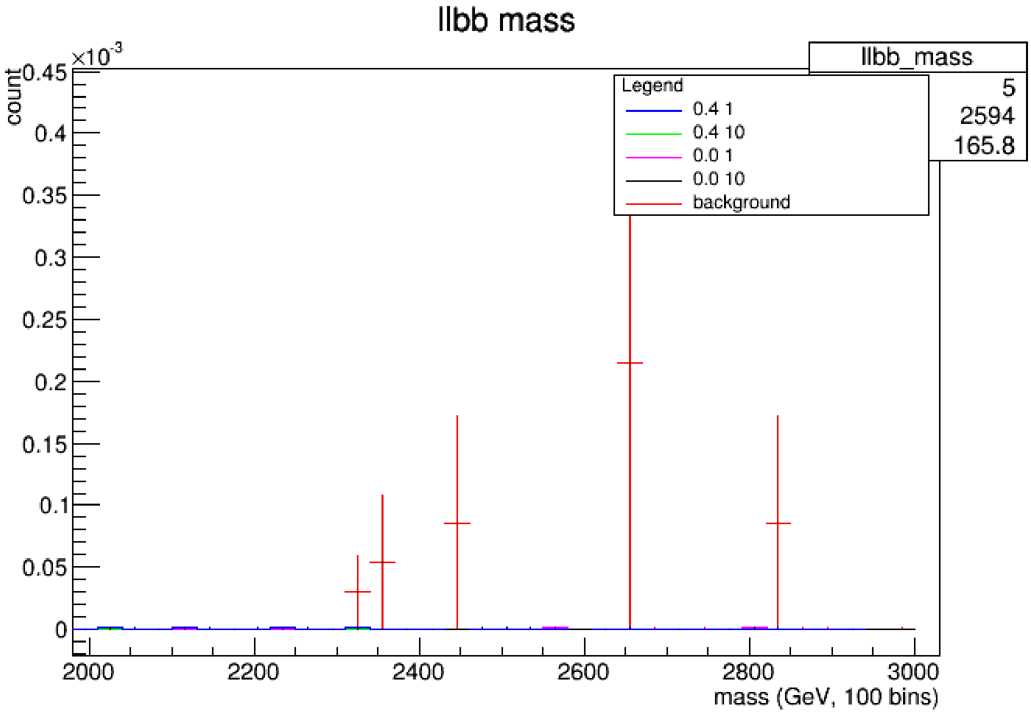
After all of the cuts were made, the following plots demonstrate the difference between the signal and background yield for when mA = 0.3TeV, 0.5TeV, 1TeV.



When mA = 0.3TeV and $\tan\beta = 1$, the signal is clearly way above the background and should be discoverable. However when $\tan\beta = 10$, the signal is much lower than the background and should not be discovered. The results are the exact same for mA = 0.5TeV. Below presents the results for mA=1TeV.



Here there is a large background yield due to the low minimum $llb\bar{b}$ cut. This was necessary however because of the large decay width of A in this region of parameter space. For no parameter space with mA = 1TeV will the signal be visible above the background. Then for mA = 3TeV.



Here the background is simply way above the signal because of the extremely small cross-section for the signal at such high masses. The case is the same for when mA = 2TeV.

The final significances are presented below

mA300	xSec*BrA_Zh (	Yield	A*E(%)	Signficance
0.4-1	2.89E+01	792.33	8.15	3.89E+01
0.0-1	2.89E+01	802.247	8.252	3.93E+01
0.4-10	1.24E-01	3.49956	8.366	1.72E-01
0.0-10	1.24E-01	3.48282	8.326	1.71E-01
mA500				
0.4-1	1.45E+00	77.6602	15.972	5.40E+00
0.0-1	1.45E+00	79.0313	16.254	5.49E+00
0.4-10	1.03E-01	5.73272	16.614	3.98E-01
0.0-10	1.03E-01	5.69614	16.508	3.96E-01
mA1000				
0.4-1	7.33E-02	2.15247	8.734	5.02E-01
0.0-1	7.33E-02	2.22937	9.046	5.19E-01
0.4-10	2.34E-03	0.0694536	8.85	1.62E-02
0.0-10	2.34E-03	0.0692337	8.822	1.61E-02
mA2000				
0.4-1	2.52E-03	9.48E-003	1.12	1.66E-02
0.0-1	2.52E-03	8.48E-003	1.002	1.49E-02
0.4-10	1.77E-05	6.52E-005	1.098	1.14E-04
0.0-10	1.77E-05	5.33E-005	0.898	9.34E-05
mA3000				
0.4-1	2.98E-05	1.80E-005	0.18	8.32E-04
0.0-1	2.98E-05	1.78E-005	0.178	8.23E-04
0.4-10	5.13E-07	2.73E-007	0.158	1.26E-05
0.0-10	5.13E-07	2.83E-007	0.164	1.30E-05

It is clear from the chart that the only parameter spaces where the pseudoscalar A particle will be visible is for when its mass is less than 0.5TeV and when $\tan\beta \approx 1$. Other than that the signal will be too small to see at ATLAS 2015.