ATLAS prospects in Early Data of $h_1 \rightarrow a_1 a_1$ in the Next to Minimal Supersymmetric Model

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Abstract

The decay of the NMSSM light higgs boson, $h_1 \rightarrow a_1 a_1$ is studied using MonteCarlo simulated data. Cuts are found to reduce the background signal to zero, with a final efficiency of $\approx 0.25\%$. A QCD background is also analysed, and cuts made limiting transverse energy in a region of Δr around a detected muon is sufficient in reducing the background QCD to a factor of 10 below the signal.

1 Background Theory

The Large Hadron Collidor (LHC), located at CERN, is primed for collisions, and will soon begin to investigate matter at the highest energies and smallest length scales ever acheived in the lab. As one of the two general detectors on the LHC, the ATLAS experiment is ready to probe this high energy frontier. Of particular interest, ATLAS will be searching for the elusive Higgs boson, a particle responsible for giving mass. In addition, ATLAS will be looking for physics beyond the standard model.In particular, this paper focuses on one such model, the next to minimal supersymmetric model (NMSSM).

2 Beyond the Standard Model

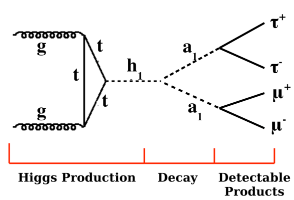

Figure 1: The decay scheme of the NMSSM higgs, h_1.

The standard model provides a theory which explains the fundamental particles and forces. To date, this model has been in incredible agreement with experimental evidence. However there exist several conspicuous theoretical problems, which have yet to be explained.
The NMSSM provides solutions to these problems, while remaining in agreement with experiments[1]. The NMSSM has a more complicated Higgs sector than the standard model, one which includes 7 Higgs Particles (3 CP even Higgs: h_1,h_2,h_3; 2 CP odd Higgs: a_1,a_2; and 2 charged Higgs:h^+,h^-). This report is an analysis of the decay $h_1 \rightarrow a_1 a_1$. Figure 1 shows the decay scheme which is analysed. The h_1 is produced via gluon fusion, decays into two a_1 particles, which subsequently decay into 2 muons, and 2 taus respectively. The two muons are detected directly in the detector, while the taus can decay in one of three ways:

- **Fully Leptonically** Both taus will undergo the decay : $\tau \rightarrow l\, \nu_l\, \bar{\nu}_l$ The leptons can be directly detected, while the neutrinos are reconstructed as missing transverse energy.

- **Semi Leptonically**One tau will undergo the decay: $\tau \rightarrow l\, \nu_l\, \bar{\nu}_l$, while the other decays into hadrons, to be detected as a jet.

- **Fully Hadronically**Both taus will decay into hadrons, and two jets will be detected in the detector.

The analysis in this paper will be restricted to the fully leptonic and semi leptonic cases only.

3 Analysis

The goal of this analysis is to take in simulated data received by the detector to efficiently eliminate the background in order to reconstruct the mass of the h_1 particle. This analysis was performed with full detector simulation. The signal simulation was created by H.K.Lou, with the parameters outlined in table 1.

Table 1: Simulation and Decay Parameters

BR($a1 \rightarrow \tau^+\tau^-$)	0.8
BR($a1 \rightarrow \mu^+\mu^-$)	0.005
$\int \mathrm{d}tL$	200pb^{-1}
Cross Section (σ)	51.3 pb

The background used is the TopMix sample written by Richard Hawking. The aim of the TopMix sample is to create one file which included a mix of background events. [1]

3.1 Cut on Muon Multipilicity

The first cut used in the elimintation of the background is a cut on the muon multiplicity. In any decay there are a minimum of 2 muons in this decay process, coming from the decay $a_1 \rightarrow \mu^+\mu^-$. If each tau were, as well, to decay into a muon and the corresponding neutrino antineutrino pair the event would have the maximum number of muons (4). The conservation of charge in these decays places constraints on the allowed charges of the muons implying that the cut made is to require 2, 3, or 4 muons whose charges satisfy the conservation of charge in each event selected.

3.2 Cut on Lepton and Tau Jet Multiplicity

The second cut determines the exact decay of the each Tau. The possible decays are outlined below:
$\tau^+ \rightarrow e^+\,\nu_e\,\bar{\nu_e}$
$\tau^+ \rightarrow \mu^+\,\nu_\mu\,\bar{\nu_\mu}$
$\tau^+ \rightarrow jet$

and similarly for the negativly charged tau.

This cut ensures that the event has the lepton and tau jet multiplicities, with the proper charge, which agree with the above decays.

[1] For more information on the Topmix sample, including the events included see: https://twiki.cern.ch/twiki/bin/view/AtlasProtected/TopMixingExercise

3.3 Overlap Removal

At this point there exists an opportunity for error as there is the chance that the event reconstruction has identified one particle in ‘overlap’. For example, if some EM energy leaked into the hadronic calorimeter an electron would be reconstructed as both an electron and as a jet. This overlap can be the source of throwing away legitimate events, or keeping illegitimate events. To account for this problem, we calculate the delta-r value for each identified jet. This value is then compared next to the delta-r of each lepton in the event. If the difference in these values is under a certain lower bound, it is concluded that the event reconstrucation created an ‘overlap’ and the jet information is then ignored. In this analysis the lower bound is set to be 0.1.

3.4 Reconstruction of the a_1 and h_1 mass

Once we have selected events which satisfy the lepton and jet requirements for the pertinant decays, as well as taken into account the problem of overlap, we can reconstruct the invariant mass of the a_1. The Lorentz vectors of each decay product are constructed, and then added together to give that of the a_1. The mod of this vector will give this mass. There is the case where there is more than one way to possibly combine the leptons to obtain the a1. For example, consider the case where each tau will decay by : $\tau \rightarrow \mu\, \nu_\mu\, \bar{\nu_\mu}$. In this case the event reconstruction just shows that there are 2 positivly charged muons, and 2 negatively charged muons. All possible combinations of the muons are considered, and the combination which yields the lower invariant mass is considered to have originated from the decay of the a_1 into two τ particles.

A final cut is performed after the reconstruction of the a_1 masses. Kinematically the a_1 mass is required to be greater than that of two tau particles. As well there exists an upper bound on the mass, taken to be 10 GeV.

In a similar way, the Lorentz Vectors of the two a_1 particles are added, and then the modulus is taken to obtain the invariant mass of the h_1.

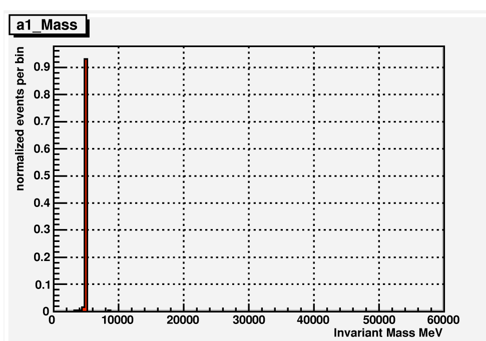

Figure 2: The reconstructed mass of the a_1 from the decay $a_1 \rightarrow \mu^+\mu^-$,after all cuts.

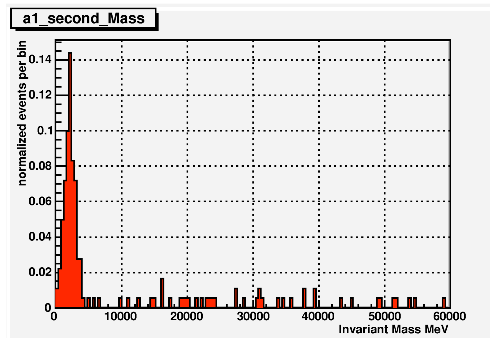

Figure 3: The reconstructed mass of the a_1 from the decay $a_1 \to \tau^+\tau^-$,after all cuts.

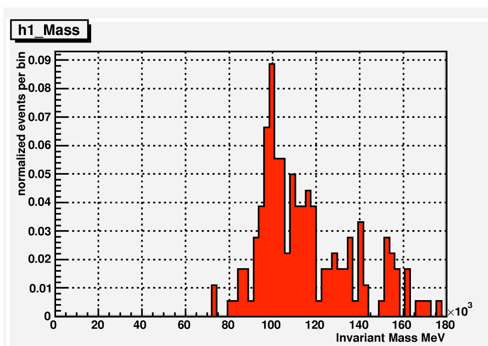

Figure 4: The reconstructed mass of the h1, after all cuts.

The reconstructed masses are shown in figures 2,3, and4.

3.5 High Mass Reconstruction of the a_1

We can see in figure 3 that there exist several events from which the a_1 mass, reconstructed from the Lorentz vectors of the two taus, is significantly higher than the expected value of 5 GeV. Isolating these events, we found that they were coming exclusivly from events where one tau was decaying hadronically. To understand the source of this discrepancy, the data from these reconstructions was compared to the corresponding truth data. Figure 5 shows the absolute

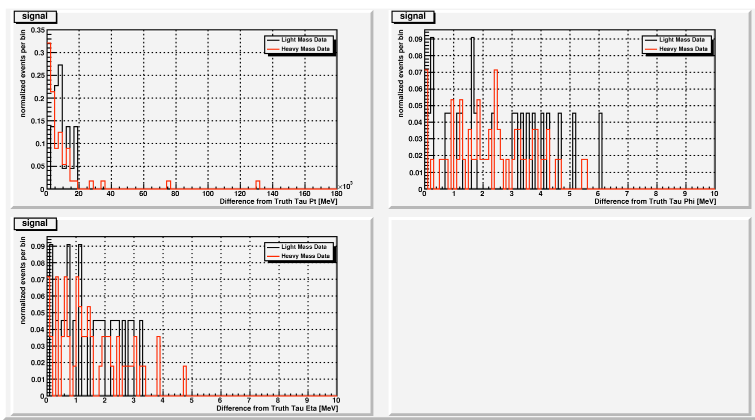

Figure 5: Absolute Difference between Collection Tree data and the corresponding data from Truth Tree. Only hadronic taus are included in this plot. The line in red corresponds to events which reconstructed a heavy ($>$ 10GeV) a_1 mass, while the line in black corresponds to an event which reconstructed a light ($<$ 10GeV) a_1 mass.

difference between the reconstructed data and the truth data. The line in red shows events for which the reconstructed a_1 mass was greater than 10 GeV. The black line is the same data, but for the events where the mass was less than 10 GeV. The two lines allows us to compare this erroneous data from that which gave the expected results. From the varying nature of both sets of data we can conclude that the reconstruction is arbitrary in nature; our ability to accurately reconstruct the invariant mass of the a_1 is therefore limited by the ability to correctly reconstruct the tau jet data. In the plot of transverse momentum (figure 5, top left), there are events which have significantly greater difference in the high mass (red line) case. However, there is also a peak at the low difference bin, which suggests these fluctuations may be only statistical, and have no significance.

As a reference point, the muons from the leptonic decay scheme were also studied.and it was found that all reconstructions of the pt, phi and eta were very close to that given in the truth data, as it would be expected.

After this analysis, a high mass cut on the $2\tau a_1$ was decided to be invoked at 10 GeV. This cut eliminates the high mass events mentioned in figure 3.

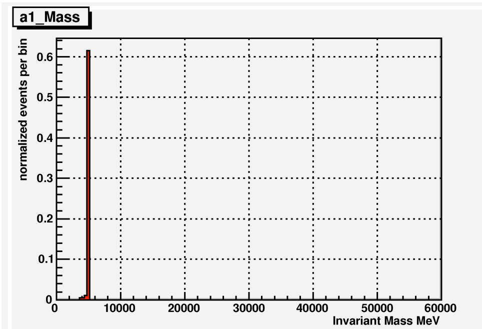

Figure 6: The reconstructed mass of the a_1 from the decay $a_1 \to \mu^+\mu^-$, including the final cut on a_1 mass.

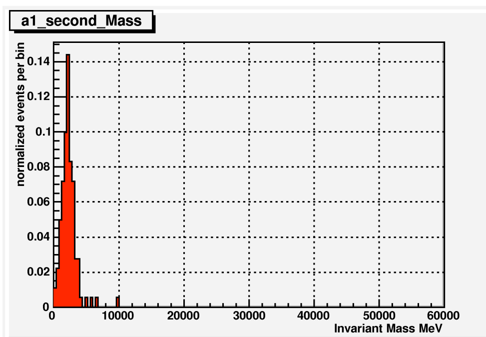

Figure 7: The reconstructed mass of the a_1 from the decay $a_1 \to \tau^+\tau^-$,including the final cut on a_1 mass.

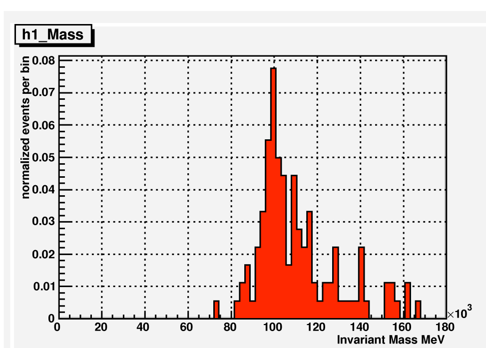

Figure 8: The reconstructed mass of the h1, including the final cut on a_1 mass.

Theoretically this is justified by the requirement that the mass of the a_1 in this analysis must remain under the mass of two B particles. The invariant mass of the a1 particles, as well as the h1, after this cuts has been made can be seen in figures 6, 7, 8.

3.6 Efficiency

Table 2: Cut Efficiencies

	Cut Made	Events Left	Efficiency (%)
Signal	No Cut	14824	100
	Muon Multiplicity	9108	61.44
	Lepton Multiplicity	199	1.34
	A_1 Mass	115	0.76
	Trigger 2mu10	37	0.25
	Cut Made	Events Left	Efficiency (%)
Background	No Cut	1315954	100
	Muon Multiplicity	148720	11.30
	Lepton Multiplicity	77	0.006
	A_1 Mass	0	0

The total efficiencies of these cuts, as well as for the final trigger used, has been summarized in table 2

3.7 QCD Background

Up to this point in the analysis the background sample (topmix) has been free of QCD events. This section focuses on these QCD events, and how to efficiently reduce them from the background. In this analysis we looked at two things: one, the overlap of muon and jets, and two, the amount of energy deposited in the detector within a certain delta-r of a detected muon. Due to the nature of the signal, we expect the signal muons to be isolated, therefore giving no overlap of jet and muon, as well as minimal energy deposited within some radius of the muon.

As we can see in figure 9, the overlap jet does not give a very efficient cut. We see clearly that the majority of QCD events which have the 2 muons which characterize our signal are not overlapping a jet. However, looking at figure 10 we can see that these cuts provide a much more efficient way at reducing the background. For example, in the bottom right corner, we see that a cut of very low mu_et40 (or energy within a Δ r of 0.4) would leave the background an order of magnitude below the signal.

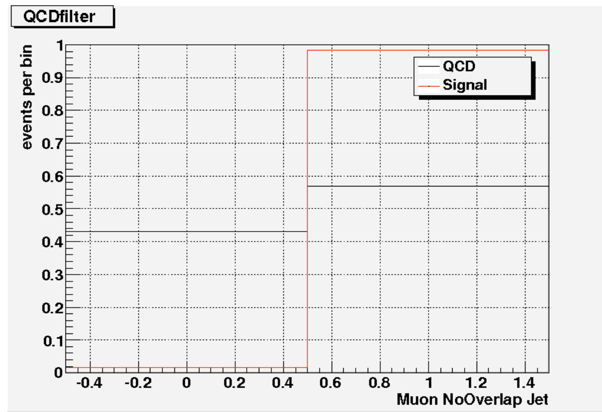

Figure 9: The 'nooverlap' of jets with muons in both the signal(red) and the QCD background events (black). A value of 1 indicates that the muon and jet are *not* overlaping, while a value of 0 indicates the muon and jet *are* overlapped. Only QCD events with two oppositely charged muons, with a reconstructed mass between 3.4 and 10 GeV are plotted. **Note: Both signal and background have been normalized to integrate to one**

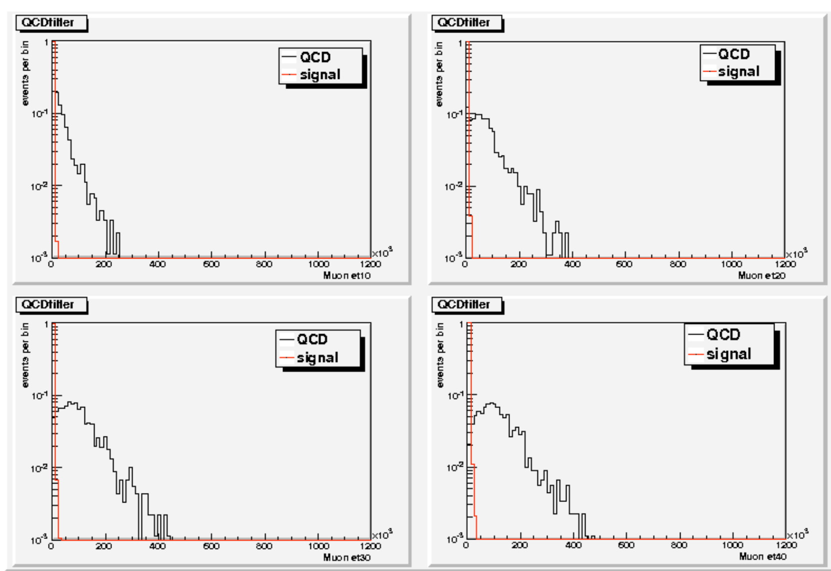

Figure 10: A plot of transverse energy deposited in the detector within a given radius of delta-r. The top left indicates a radius of 0.1 in Δr, top right 0.2, bottom left, 0.3 and bottom right 0.4. Only QCD events with two oppositely charged muons, with a reconstructed mass between 3.4 and 10 GeV are plotted.**Note: Both signal and background have been normalized to integrate to one**

4 Conclusions

We can conclude that straightforward cuts will reduce the background signal to zero. Although it is difficult to simulate the amount of QCD necessary to accuratly predict a real event, we have found that using the energy deposition in the calorimeter within a given value of Δr we can significantly reduce this background. With data from the LHC immenint this analysis provides a basic framework we can use to either confirm or refute the NMSSM.

References

[1] J.F. Gunion *A light CP-odd Higgs Boson and the mon anolmalous magnetic moment*