Looking for SUSY Dark Matter with ATLAS:

The Story of a Lonely Lepton

Nadia Davidson

THE UNIVERSITY OF
MELBOURNE

School of Physics
The University of Melbourne

Supervisor: Dr Elisabetta Barberio

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Statement of Contributions

Chapter 2 is an original overview of the theory on supersymmetry, its connection with cosmology and the ATLAS detector with sources cited.

Chapter 3 is a description of the methodology by the author with software specifics taken from the cited sources.

Chapter 4 and 5 are an original data analysis done by the author.

Chapter 6 was a review of a cited paper.

Abstract

While cold dark matter makes up a significant proportion of the mass of the Universe, its constituents are unknown. Candidates for dark matter include particles described by extensions to the Standard Model such as supersymmetry. The ATLAS experiment at the Large Hadron Collider (LHC), to commence in 2007, may allow the creation and observation of such particles via a signature of missing energy. In this project I looked at a decay channel specific to these particles in the SUGRA supersymmetric model. Specifically, the decay of a chargino into a neutralino and leptons, $\tilde{\chi}^{\pm} \rightarrow \tilde{\chi}^{0} l\nu$, in a region of supersymmetry parameters favoured by cosmology when considering the lightest supersymmetric particle (the neutralino) as being a constituent of the cold dark matter in the Universe. The above decay was simulated with the Monte Carlo generator, HERWIG and the detector with the ALTFAST package. Appropriate selection cuts were then determined to separate the decay signatures from Standard Model and supersymmetric background. This decay was examined to study the possibility of determining the masses of $\tilde{\chi}^{\pm}$ and $\tilde{\chi}^{0}$ at the LHC using the ATLAS detector. It was found that the masses of the $\tilde{\chi}^{\pm}$ and $\tilde{\chi}^{0}$ could be constrained with a model-dependent kinematical variable, while no model-independent variable could be found.

Contents

Chapter 1

Introduction

Latest results from Astrophysics show that the Universe comprises of 73 % Dark Energy, 23% Cold Dark Matter and only 4% regular Standard Model matter which we understand[1]. While Dark Energy is not understood, for Cold Dark Matter at least, high energy particle physics may soon provide some answers. The ATLAS experiment (see section 2.3) at the Large Hadron Collider (LHC) begins taking data in 2007. The LHC will provide centre of mass energies of 14 TeV and will allow us to recreate conditions closer to the Big Bang. It may allow the creation of Cold Dark Matter in the laboratory.

There are no particles in the Standard Model which can explain Cold Dark Matter. Neutrinos are the only exclusively weakly interacting particles, but their masses are orders of magnitude too small to explain the abundance of Cold Dark Matter in the Universe. Therefore, a class of particles only explained by new physics is required, eg weakly interacting massive particles (WIMPs).

There are many extensions of the Standard Model which allow for such particles. One popular extension is supersymmetry. There are several supersymmetric models distinguishable by the way the symmetry breaking occurs. In the model in which gravity is the mediator of symmetry breaking, minimal supergravity (mSUGRA) the lightest superpartner (LSP) is stable and a WIMP. This provides a motivation to study mSUGRA signals at LHC looking specifically at SUGRA parameters where Cold Dark Matter consists primarily of the LSP. A description of SUGRA and its parameters are described in more detail in section 2.1.

ATLAS, as a discovery experiment, is designed to look for the Higgs particle and new physics beyond the standard model such as supersymmetry. It has been shown by simulation work that ATLAS can not only discover SUSY but also pin down the parameters of the model. It is important to cover as much parameter space and as many topological scenarios as possible. Often the parameters studied are motivated by evidence from other experiments or areas of physics. One of the parameter sets chosen by the LHC Committee allows the LSP to account for Cold Dark Matter. This parameter set is called point 5.

The goal of my project was to examine signals for SUGRA at point 5 for the following decay.

$$pp \to \tilde{g}\tilde{g} \to ... \to \tilde{\chi}_1^{\pm} \to W(\to l\nu_l)\tilde{\chi}_1^0$$

The supersymmetric particles in this decay, denoted by tildes, are described further in section 2.1. This decay was chosen because its large branching ratio at point 5 means signal could be seen in less time compared to other decays. It has not yet been studied because of its difficulty. The signature of this decay is a large amount of missing energy and a lepton. As can be seen in section 5 it is hard to reconstruct the kinematics of a decay from only this much information. From the signal we would like to try and pin down some parameters of the underlying theory. For this decay this involved finding ways to constrain the $\tilde{\chi}_1^{\pm}$ and $\tilde{\chi}_1^0$ masses which depend on the SUGRA parameters. It was found that this could be done by measuring the mean transverse momentum of the lepton, which depends linearly on the $\tilde{\chi}_1^{\pm}$ and $\tilde{\chi}_1^0$ mass difference.

Chapter 2

Background

2.1 Supersymmetry

The Standard Model of particle physics is the currently accepted theory which describes all known fundamental particles and their interactions. Particles can be broken up into two groups: fermions with half integer spin and bosons with integer spin. The fermions make up regular matter while the bosons are force carriers.

Supersymmetry is an extension to the standard model in which a symmetry between fermions and bosons exist. For each standard model fermion there is a superpartner boson, generally given the same name with an "s" prefix, and for each boson a fermion given the same name with an "ino" suffix.

The Standard Model belongs to the gauge group $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$. The $SU(3)_C$ gauge invariance of the Standard Model Lagrangian describes the strong force and $SU(2)_L \otimes U(1)_Y$ electroweak. $SU(2)$ gauge invariance is broken by the fermion mass terms as well as those of the electroweak bosons. Hence we need to introduce a mechanism to break the symmetry. The mechanism in the Standard Model is spontaneous symmetry breaking via Higgs potential. Associated with this is the Higgs boson.

However the Higgs coupling suffers from a quadratic divergence. One of the major motivations for the existence of supersymmetry is that it would solve this problem. New loop contributions to the Higgs mass squared would cancel out the quadratic divergences due to couplings with standard model particles. Another motivation is the unification of the forces at the GUT scale. If supersymmetric particles have masses low enough it is possible for the three coupling constants from QCD, electromagnetism and the weak force to meet at energies of around $10^{15} GeV$. Additionally, supersymmetry is the basis for some quantum gravity theories, such as superstring, which unify gravity with the other three forces.

A Standard Model particle and its superpartner form what is called a supermultiplet. The phenomenology of the supersymmetric particles is born out of the fact that within each supermultiplet the number of fermionic degrees of freedom must match the number of bosonic degrees of freedom. This regular Standard Model fermions with two helicity state degrees of freedom can exist in a supermultiplet with a complex scalar field (also two degrees of freedom). As right handed and left handed fermions interact differently with electroweak, they cannot belong to the same supermultiplet and so there are two independent scalar supersymmetric particles associated with each handedness. The spin 1 gauge bosons from the Standard Model form supermultiplets with spin $\frac{1}{2}$ fermions (both of which have two helicity states and hence two degrees of freedom). Finally the Higgs scalar boson requires two spin $\frac{1}{2}$ higgsino doublets with opposite hypercharge. This is required in order to preserve the anomaly-free nature of the standard model. The higgs doublets associated with each higgsino are called H_u and H_d as they are responsible for giving mass to the up-type and down-type quarks respectively. The regular neutral higgs corresponds to a superposition of the neutral components of each. [2] [3]

The simplest possible set of multiplets is called the minimal supersymmetric extension of the standard model (MSSM) and a table of the described constituent particles is given in tables 2.1 and 2.2.

Names		spin 0	spin 1/2	$SU(3)_C, SU(2)_L, U(1)_Y$
squarks, quarks ($\times 3$)	Q	$(\tilde{u}_L\ \tilde{d}_L)$	$(u_L\ d_L)$	(3,2,$\frac{1}{6}$)
	$\bar{u}$	$\tilde{u}^*_R$	$u^\dagger_R$	($\bar{3}$,2,$-\frac{2}{3}$)
	$\bar{d}$	$\tilde{d}^*_R$	$d^\dagger_R$	($\bar{3}$,2,$\frac{1}{3}$)
sleptons, leptons ($X3$)	L	$(\tilde{\nu}\ \tilde{e}_L)$	$(\nu\ e_L)$	(1,2,$-\frac{1}{2}$)
	$\bar{e}$	$\tilde{e}^*_R$	$e^\dagger_R$	(1,1,1)
Higgs, higgsinos	H_u	$(H^+_u\ H^0_u)$	$(\tilde{H}^+_u\ \tilde{H}^0_u)$	(1,2,$+\frac{1}{2}$)
	H_d	$(H^0_d\ H^-_d)$	$(\tilde{H}^0_d\ \tilde{H}^-_d)$	(1,2,$-\frac{1}{2}$)

Table 2.1: Spin 0 and $\frac{1}{2}$ supermultiplets. Source: [2]

Names	spin 1/2	spin 1	$SU(3)_C, SU(2)_L, U(1)_Y$
gluino, gluon	$\tilde{g}$	g	(8,1,0)
winos, W bosons	$\tilde{W}^\pm\ \tilde{W}^0$	$W^\pm\ W^0$	(1,3,0)
bino, B boson	$\tilde{B}^0$	B^0	(1,1,0)

Table 2.2: Spin $\frac{1}{2}$ and 1 supermultiplets. Source: [2]

This symmetry, if it is to be consistent with nature, must be broken because we do not see particles which have identical quantum numbers but differ in spin by $\frac{1}{2}$. The masses of the superpartners must be much larger than their Standard Model counterparts because there is, as yet, no experimental evidence for their existence. The symmetry could be broken spontaneously as in electroweak and this would require a massless Goldstone fermion. This particle can be removed if we require the symmetry to be local. One of the SUSY models where symmetry breaking is achieved in this way is supergravity (SUGRA). Here the graviton's superpartner, the gravitino, gains mass by absorbing the Goldstone fermion. In this model the symmetry breaking occurs in a hidden sector (a sector of particles which are non-interacting with respect to the Standard Model). The symmetry breaking is then communicated to the supersymmetric particles via gravity [3].

In the minimal supergravity model (mSUGRA) the number of parameters are reduced by assuming unification of particular masses and coupling constants at the GUT scale. The spin 0 and spin $\frac{1}{2}$ supersymmetric particles have a common mass, m_0 and $m_{\frac{1}{2}}$ respectively. The trilinear couplings (the coupling between the higgs and two spin $\frac{1}{2}$ supersymmetric particles) have the common value at A_0. There are two additional parameters, $tan\beta$, which is the ratio between the H_u and H_d vacuum expectation values, and $sgn(\mu)$ which is the sign of the higgsino mass term in the supersymmetric Lagrangian. From these parameters, the low-energy masses can be found by solving the Renormalisation Group Equations.

In MSSM the mass and electroweak eigenstates for the gauginos and higgsinos do not need to be the same as particles with the same quantum numbers can mix. The mass eigenstates formed from the mixing of the charged spin $\frac{1}{2}$ supersymmetric particles ($\tilde{W}^\pm$ and $\tilde{H}^\pm$) are called charginos $\tilde{\chi}^\pm_i$, where $i = 1, 2$ with 1 being the lightest of the two. The neutral counterparts to these are called the neutralinos $\tilde{\chi}^0_i$, where $i = 1, 2, 3, 4$. These mass eigenstates are formed from the superposition of the neutral spin $\frac{1}{2}$ $\tilde{W}^0, \tilde{B}, \tilde{H}_u$ and $\tilde{H}_d$ particles. In the mSUGRA model, these masses just like the other superpartner masses are determined by the 5 free parameters. At point 5 these are:

$$m_0 = 100GeV, m_{\frac{1}{2}} = 300GeV, A_0 = 300GeV, tan\beta = 2.1, \mu > 0$$

This gives the neutralino and chargino masses of 232GeV and 122GeV respectively. The goal of this project was to see how the masses of the chargino and neutralino around these values effected the signal from my decay channel for ATLAS. Just as the neutralino and chargino masses can be deduced from the SUGRA parameters the reverse is true, we can use the masses to put constraints on the parameters of the model. If SUSY exists, this is how ATLAS may determine the free parameters of the model.

2.2 The Cosmological Connection

The bulk of the cold dark matter in the Universe should be made up of weakly interacting particles much like neutrinos, but with a much larger mass. They should be heavy, and electrically and colour neutral. In the parameter space of SUGRA studied the lightest neutralino has these properties. (Indeed this is why the parameters of point 5 was chosen by the LHC Committee [4][5]). In R parity conversing SUSY models, such as SUGRA, the neutralino is stable and produced in abundance in supersymmetric interactions. R parity is defined by $R = (-1)^{3(B-L)+2S}$ where B, L and S represent baryon number, lepton number and spin respectively. As Standard Model particles have odd R parity, and their superpartners even, it means that supersymmetric particles must be produced in pairs. Each of these sparticles decays into a series of lighter sparticles ending with the LSP [3].

Inflationary models of the universe along with astronomical data can be used to put limits on the rates of neutralino production and annihilation. At a certain point in the expansion of the early Universe the density of neutralinos could have become low enough to cease annihilation leaving relic Cold Dark Matter. From cosmology, constraints can be placed on the SUGRA parameters which control the rates of neutralino annihilation in the early universe. An example of this is shown in figure 2.1. The source of the figure is [6] and shows contours of the total energy density of the Universe Ωh^2 as a function of the SUGRA parameters m_0 and $m_{\frac{1}{2}}$. Note that the other parameters are fixed at $tan\beta = 2$, $A_0 = 0$ and $\mu > 0$ so this figures is the relevant one for point 5. The value of A_0 for point 5 is 300GeV rather than 0, but this only effects the relic density by a small amount according to the literature. From [6] any region for which $\Omega h^2 > 0.025$ (to explain galactic rotation curves) and $\Omega h^2 < 1$ (to give the required age of the universe) is of interest. Results from the Cosmic Background Explorer (COBE) put Ωh^2 between 0.15 and 0.4. This region is indicated in the figure by the dotted lines. A predominantly Cold Dark Matter Universe would have Ωh^2 between 0.25 and 0.75. The benchmark point 5 lies within both these regions.

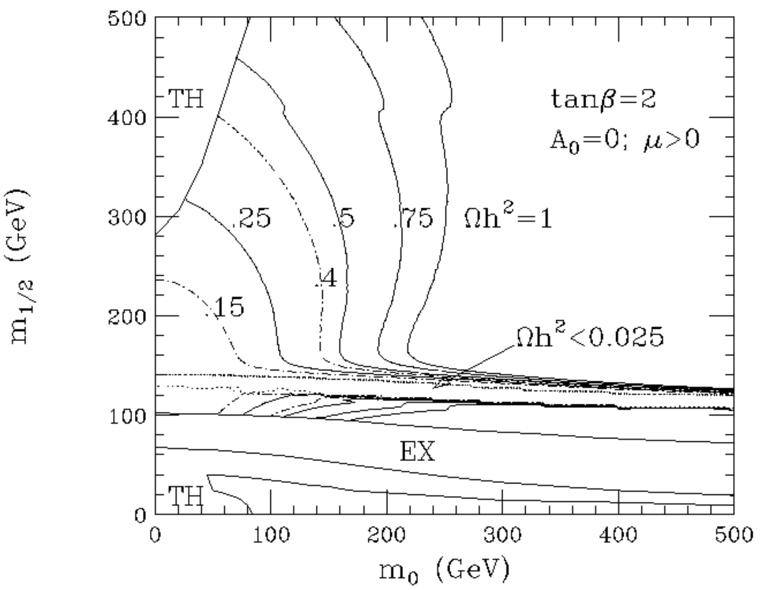


Figure 2.1: Contours of constant Ωh^2 in the $m_0, m_{\frac{1}{2}}$ plane. Regions labelled by TH and EX are excluded by theory and experimental considerations. Source: [6]

Note that more recently, the WMAP satellite experiment combined with other experiments have made the constraint of $\Omega = 1.02 \pm 0.02$ (a flat universe) and $h = 0.72 \pm 0.05$ giving $\Omega h^2 \approx 0.53$ [1]. According to [7] this and the measurement of $0.095 < \Omega_{CDM} h^2 < 0.129$ now yield the benchmark point 5 less consistent with relic densities.

2.3 The ATLAS Experiment

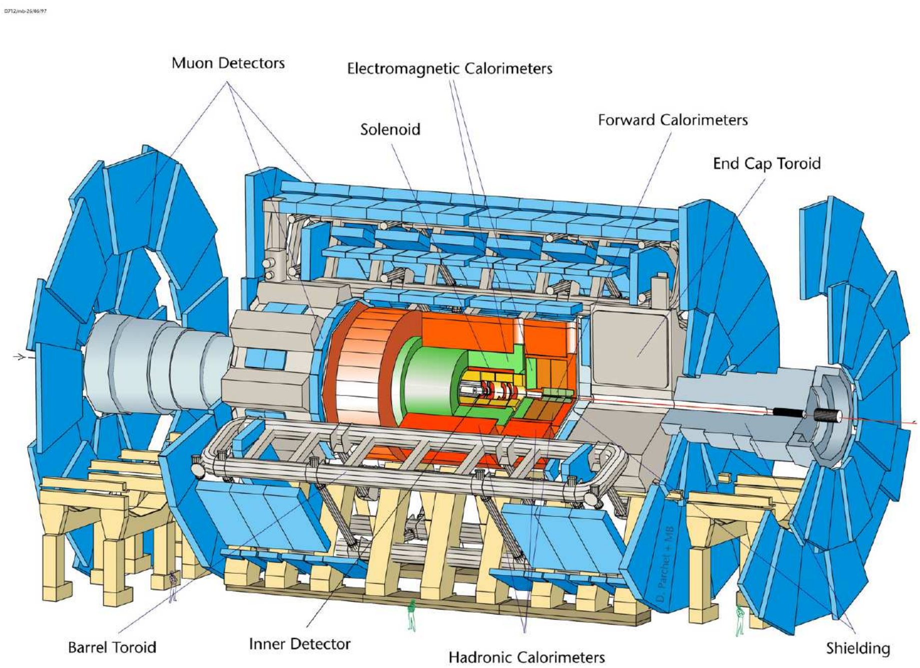


Figure 2.2: The ATLAS detector

As mentioned, the ATLAS detector at the Large Hadron Collider (LHC) is due to start collecting data in 2007. The LHC is a 27km circumference proton-proton collider which will provide centre of mass energies of 14 TeV and a luminosity of $10^{33}cm^{-2}s^{-1}$ initially up to $10^{34}cm^{-2}s^{-1}$ after 3 years of operation [8]. Four experiments will be constructed on the LHC, one of which is ATLAS.

Pictured in figure 2.2, the ATLAS detector consists of the major components: an Inner Tracker, Calorimeters and Muon Spectrometer. All of these components are vital for reconstructing the lepton energy and momentum from my decay channel.

The Inner Tracker is responsible for tracking the momentum and position of charged particles with the use of a 2T magnetic field. It consists of a Transition Radiation Tracker (TRT), Semi-Conductor Tracker (SCT) and Pixel Detector (PD).

The electromagnetic calorimeter is responsible for measuring the energy of any particles which interact electromagnetically. This is where the energy of any electron emerging from my decay channel is absorbed.

The hadronic calorimeter measures the energies of the strongly interacting particles. In ATLAS this has a large η range which is particularly important to the accuracy of the E_T^{miss} measurement [9]. This value is the sum of transverse energies of all particles escaping the detector. This is a vital measurement as both the neutralino and chargino have no interaction with the detector.

Finally, because the lepton produced in my decay may be a muon, the muon spectrometer should be described. Momentum measurements are made by tracking the deflection of muons in a magnetic field much like the inner tracker. Few particles apart from muons will pass through the calorimeters and be detected by the muon spectrometer.

Chapter 3

Data Generation Method

As this project is a preliminary study before ATLAS and the LHC begin taking real data, simulations were made of both the physical interactions at LHC and the detector for analysis.

The general method used to acquire and analyse data of this type is to:

1. Simulate events, with and without the required decay channel.
2. Simulate the detectors response to those events.
3. Look for combinations of the detectors output variables such as particle type, energy etc. in order to find trends that are unique to the required decay channel.
4. Put limits on these variable values to separate background from signal, known as "selection cuts".
5. Finally, look at particular variables using the cut data to ascertain something about the decay, for example the masses of the particles involved.

The final three points are discussed in chapters 4 and 5, in particular the results for some variables are presented and the efficiency of selection cuts given.

A description of the simulation chain and software used is given here.

The major steps in producing SUGRA data for analysis are:

1. A decay table must first be produced which takes the model parameters and produces a list of supersymmetric particles masses, lifetimes and decay branching ratios.
2. A Monte-Carlo event generator then simulates events where a pair of supersymmetric particles are produced. It then uses the decay table to simulate follow-on decays.
3. The result of event generation is then processed by a detector simulator. The output of this is parallel to what you would expect to see in the detector after reconstruction.

Figure 3.1 shows the process described to acquire data for analysis. The boxed steps represent the software packages used with the unboxed text being the input/output at each stage in the process. More detail about each component is given in the subsections that follow.

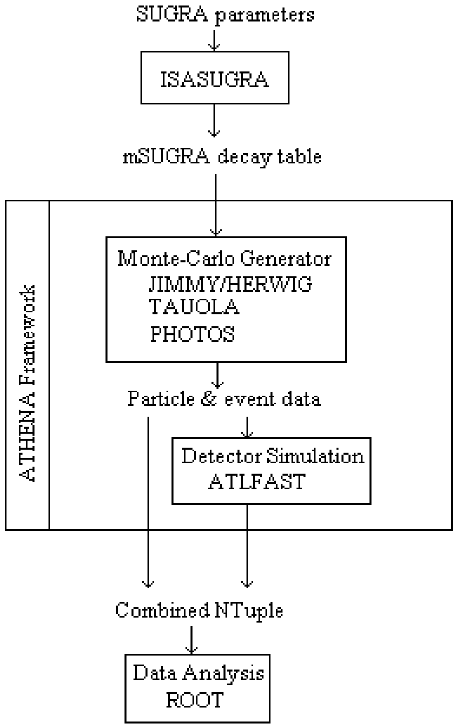


Figure 3.1: Process used to generate SUGRA event data

3.1 Event Generation and Detector Simulation Framework - Athena

A series of software packages were used in order to acquire data used for analysis. All of these were run on the Athena framework, which is a framework created specifically for software related to the ATLAS experiment [10]. It provides a common interface and data store. The Athena Startup Kit (ASK) was used as an interface to the Athena framework [11]. The command line is a python interpreter, so all simulations used a python file ('jobOption' file) to control the running of the software.

3.2 Decay Table Creation - ISASUGRA

ISASUGRA is a package which takes as input the independent parameters of the mSUGRA model ($m_{1/2}$, m_0, A_0, $tan\beta$ and $sgn(\mu)$) and calculates supersymmetric particle masses. This is done by solving the Renormalisation Group Equations numerically through Runge-Kutta integration [12]. It creates a table of particle lifetimes, decay modes and branching ratios which can be used by a Monte-Carlo event generator. The format for the input decay table for JIMMY is different to that produced by ISASUGRA, so an additional package, ISAWIG is used for conversion.

In this project I created a decay table for point 5 using this process. Additional decay tables were also produced by altering the $m_{1/2}$ parameter in order to change the mass of the supersymmetric particles. Another approach used to change the masses, involved altering the masses in the decay table directly.

3.3 Monte-Carlo Event Generators - HERWIG/JIMMY

There are several Mote-Carlo Event Generators available that are capable of simulating supersymmetric events. The difference between these is the way in which QCD is modelled in the initial hadron-hadron collision. Some generators used in previous studies include ISAJET, SPYTHIA and HERWIG. For my project HERWIG (Hadron Emission Reactions With Interfering Gluons) Version 6.505 [13] was used for this purpose along with an add-on package JIMMY Version 4.0. JIMMY uses a model of parton-parton interactions beyond perturbative quantum chromodynamics to simulate the underlying proton-proton event [14]. HERWIG was used because examples of its use, including jobOption file parameters were easily available (at [15]). Due to time constraints on the project it was not possible to confirm that all event generators gave similar results. A difference in results, for example, may be a slight change in the boost of the final particles. This is due to the handling of QCD in the initial pp interaction differently by generators. Looking at this is something that could be done as further work.

Additionally Monte-Carlo programs which handle τ decay (TAUOLA) and radiative corrections (PHOTOS) were used on the event data created by JIMMY.

The Standard Model background was generated using PYTHIA (for W and Z events) and MC@NLO (for $t\bar{t}$ event). A description of this background is given in section 4.1. This data was not produced by myself, but by people undertaking data analysis of SUSY channels with similar competing standard model background.

It is also worth noting that in this step of the software chain some pre-detector simulation data, as produced by the Monte-Carlo generator, was recorded directly into the output file (a combined ntuple). This included all momentum and energy information about the particles involved in my decay as well as any neutralino information from background events. This not only tagged those events which contained my decay channel (the signal) from the background, but allowed a more detailed study of the kinematics of the events than the post-detector data allowed. The Athena algorithm responsible for storing this data was called 'CBNT_Truth'. For here after this data will therefore be referred to as the 'truth' or 'particle level' data.

3.4 Detector Simulation - ATLFAST

The ATLAS detector was simulated using ATLFAST [16]. It is an alternative to full detector simulation and event reconstruction. It works by parameterising the resolution of ATLAS and smearing the output of the event generator accordingly. ATLFAST is appropriate for feasibility studies such as this as it runs much faster than the full ATLAS simulation and reconstruction. The results of this were stored into a combined ntuple file for analysis.

3.5 Analysis - ROOT

All data analysis was done with the aid of ROOT, a tool design for high energy particle physics [17]. Through the use of a C++ interpreter it allows the user to accessing data, creating histograms etc. from the ntuple file.

Chapter 4

Selection Cuts and Background

The data generated from the process described in chapter 3 was then analysed to separate the signal from background and investigate the signals dependence on the chargino and neutralino masses. The first of these is described here where it can be seen that the majority of background came from purely standard model events. Due to the characteristics of Standard Model processes verses supersymmetric ones, selection cuts significantly reduced this background. Cuts of this sort are required in order to be certain we are looking at new physics such as SUSY. Reduction of SUSY background events, however, required examination of a larger variety of variables but was still effective as can be seen in 4.2.

4.1 Standard Model Background

The decay channel was characterised by a lepton and a very large amount of missing energy (as the neutrino and neutralino escape detection). Because of this, you would expect that the competing Standard Model background must involve production of high energy leptons and neutrinos. The processes that satisfy this are given below.

- W decay: $W \to l\nu_l$. If the lepton is a τ we have a further decay $\tau \to l\nu_l\nu_\tau$.
- Z decay: $Z \to \nu\nu$ as well as $Z \to \tau\tau$ where τ decays as before.
- $t\bar{t}$ decay: t decays as $t \to bl\nu_l$.

Simulation data of 500,000 events for each process type were obtained. The samples contained some initial cuts to require a lepton, large missing energy and hard jets. Table 4.1 shows the cross-sections of each events. The cross-section for SUSY at point 5 is $\sigma \approx 19pb$, so the scale factor shows the proportion of these SM background processes to all SUSY processes.

Two primary selection cuts were required to bring the level of Standard Model events below the signal. These were cuts on the amount of transverse missing energy, E_{Tmiss}, and the invariant mass of the

SM process	σ(pb)	Events per year	Scale Factor for Sample
W	300	$3 \cdot 10^6$	15
Z	200	$2 \cdot 10^6$	10
$t\bar{t}$	750	$7.5 \cdot 10^6$	37.5

Table 4.1: Standard Model background with cross-section of generated sample. Number of event per year are for a luminosity of $10^4pb^{-1}year^{-1}$

missing energy and lepton, m_{Tlmiss}. The distribution of each variable for the signal, W and $t\bar{t}$ can be found in appendix A. Although these variables are somewhat correlated, a constraint on both is required to kill the majority of SM background.

A cut on E_{Tmiss} would be expected because at least $2 \times m_{\tilde{\chi}_1^0}$ escapes detection for any R-parity conserving SUGRA process. This is because all supersymmetric particles are produced in pairs and eventually decay into a $\tilde{\chi}_1^0$. Additionally, the input energy required to produce the original pair of supersymmetric particles is large due to their mass so it would be expected that some of this energy would be passed onto the $\tilde{\chi}_1^0$ as kinetic energy. The E_{Tmiss} of the signal was therefore distributed towards higher values. It was found that a requirement of $E_{Tmiss} > 600GeV$ on top of cuts used to reduce the SUSY background left the $t\bar{t}$ background minimal. This was a rather brutal cut when we consider that it reduced the signal by approximately one quarter. However, it becomes a requirement if we consider that the cross-section of the $t\bar{t}$ background is around 40 times as large as that of our signal. You may expect to reduce $t\bar{t}$ events by making cuts on the number of b jets produced, but this turned out to be far less effective than the E_{Tmiss} requirement.

The other cut which dramatically reduced the SM background was to require that the transverse invariant mass of the lepton and missing energy, m_{Tlmiss}, be greater than 300GeV. Where the transverse invariant mass is given by: $m_{Tlmiss}^2 = (E_{Tl} + E_{Tmiss})^2 - (\vec{p}_{Tl} + \vec{p}_{Tmiss})^2$. If a neutrino is the only invisible particle produced in an event and we choose the lepton from the same decay, our variable is just the transverse mass of the W, $m_{Tlmiss} = m_{TW} < m_W$. i.e. the invariant mass for neutrinos produced from Ws has an upper bound of $m_W \approx 80GeV$. A requirement of $m_{Tlmiss} > 80GeV$ would therefore rule out a large number of events from the W background. An even higher upper limit of $m_{Tlmiss} > 300GeV$ also cuts out many multiple neutrino events. The beauty of this cut was that after the requirement on E_{Tmiss} very little signal gave $m_{Tlmiss} < 300GeV$.

The Z background turned out to be negligible with no events surviving less stringent constraints on E_{Tmiss} and m_{Tmissl}.

The efficiency of the cuts described here can be found in table 4.5.

4.2 SUSY Background

The background from SUSY events was more difficult to separate from the signal because the missing energies are comparable to those of my decay channel. However the magnitude of the background was of a similar order to that of the signal, so highly efficient cuts were not needed. In fact the branching fraction for my decay channel was high, with about 10% of all SUSY Monte-Carlo data being signal. Note that this is after an initial cut on low momentum leptons so the actual fraction would be even higher. This can be seen in the dominant branching fractions at point 5:

The relevant dominant pp processes are given in table 4.2.

Process	**Branching Ratio**
$pp \to \tilde{g}\tilde{g}$	10%
$pp \to \tilde{q}_L\tilde{q}_L$	8%
$pp \to \tilde{q}_L\tilde{q}_R$	12%
$pp \to \tilde{q}_L\tilde{g}$	21%
$pp \to \tilde{q}_R\tilde{g}$	21%
$pp \to \tilde{t}_1\tilde{t}_1$	4%
$pp \to \tilde{\chi}_2^0\tilde{\chi}_1^\pm$	2%
$pp \to \tilde{\chi}_1^\pm\tilde{\chi}_1^\pm$	1%

Table 4.2: Branching Ratios of pp into SUSY particles at point 5. Source: [4]

Although the ratio directly into a $\tilde{\chi}_1^\pm$ is low, the other supersymmetric particles have a high decay rate into the $\tilde{\chi}_1^{\pm}$ as seen in table 4.3.

Decay	Branching Ratio
$\tilde{g} \rightarrow \tilde{q}q$	65%
$\tilde{g} \rightarrow \tilde{t}_1 t$	15%
$\tilde{q}_L \rightarrow \tilde{\chi}_1^+ q'$	65%
$\tilde{t}_1 \rightarrow \tilde{\chi}_1^+ b$	21%

Table 4.3: Branching Ratios of SUSY particle decays. Only the decays relevant to $\tilde{\chi}_1^{\pm}$ production are shown. Source [4]

We then have 98% of $\tilde{\chi}_1^{\pm}$ particles decaying via $\tilde{\chi}_1^{\pm} \rightarrow \tilde{\chi}_1^0 W$.

After the initial low momentum lepton cut, the signal was more than half the background, however we would still like to see the SUSY background reduced. The following selection cuts were found to achieve this.

1. A lepton with $P_T > 20$ GeV.
   This was an initial cut to ensure high energy leptons.

2. Number of leptons > 2 or $= 1$.
   2 lepton events were disallowed because it was found that the background was much larger than the signal. This was possibly due to the competing decay of $\tilde{\chi}_2^0 \rightarrow \tilde{l}_R(\rightarrow \tilde{\chi}_1^0 l)l$ which also has a large branching fraction at point 5 and is well studied in [4].

3. Lepton must be isolated.
   We expected this because the lepton comes from a double two body decay, neither of which produced any other visible particles.

4. Transverse angle between lepton and missing energy $< 90^o$.
   The missing energy was in general in the same direction as the chargino so this selection cut required that the lepton was in the forward direction of the chargino (and W).

5. $2 <$ number of jets < 9.
   The average number of jets was lower for my decay as compared to SUSY background. However it was higher on average than the number of W and Z Standard Model background jets. This cut reaches a balance between these two.

The efficiency for each of these cuts is given in table 4.4.

4.3 Cut Efficiency

The following tables show the efficiency of cuts with respect to eliminating SUSY and Standard Model background. It also shows the reduction in signal from each cut.

Cut	1	2	3	4	5
Signal (events per 300,000 SUSY events)	27,060	21,180	18,210	13,020	9,750
SUSY background (events per 300,000 SUSY events)	48,180	27,600	13,560	7,890	4,950
Signal/Signal + Background	36%	43%	57%	62%	66%

Table 4.4: SUSY background and signal cut efficiencies showing the number of surviving events

Cut	**After SUSY cuts**	$E_{miss} > 600GeV$	$m_{Tlmiss} > 350GeV$
Signal: (events per 300,000 SUSY events)	9,750	2,370	2,310
SUSY background: (event per 300,000 events)	4,950	900	870
$t\bar{t}$ background: (events per 50,000 $t\bar{t}$ events) (events per 300,000 SUSY events)	6,500 1,462,500	1 225	1 225
W background (events per 500,000 W events) (events per 300,000 SUSY events)	134,000 3,350,000	30 750	5 125
Z remaining/Z before (events per 500,000 events) (events per 300,000 SUSY events)	123,000 2,000,000	0 0	0 0
Signal/Total background+Signal	$\approx 0\%$	56%	65%

Table 4.5: Total background cut efficiency

After all cuts the resulting sample will comprised of about 65% signal. However, this means a large reduction in the number of possible events per year. The cross-section of SUSY events passing is reduced to 0.2pb (from 19pb). The ATLAS experiment is believe to have an integrated luminosity of $10^4 pb^{-1}$ for its first year, and $3 \cdot 10^5 pb^{-1}$ after 10 years [8]. The corresponding number of event passing cuts would then be $\approx$ 2,000 initially, up to 60,000. This is enough for a reasonable analysis provided there is a suitable variable to study. Such a variable is the topic of our next chapter.

Chapter 5

Analysis of Variables Sensitive to Supersymmetric Masses

If SUSY exists we would like to obtain a better understanding of its symmetry breaking mechanism and parameters. One way of achieving this is by determining the masses of the superpartner particles. The goal of analysing Monte-Carlo data is therefore to try and find kinematic variables which are sensitive to the masses of these particles. To some extent all the kinematics we see from a particular decay depend on the masses of the particles involved. However the dependence on other properties of the decay, for example initial momentum of the mother particle, often make the mass information inextractable. Ideally we would like to be able to find a kinematic variable which only depends on the masses of the particles and not other unknowns. The other properties involved may be hard to predict analytically, especially for events from a pp collider where the particles are produced with a large variable boost. In the case of SUSY, the other properties may also be highly dependent on the model and parameters used.

Invariant masses depend only on the mass of the parent particle and the energy and momentum of the produced particles. The complication with R-parity conserving SUGRA is that the resulting decay always ends in a neutralino. The neutralino escapes detection so only missing energy is observed. Because there are two neutralinos and only transverse information is known about their sum, the invariant mass becomes more complicated. In the study of other SUGRA decay channels the missing energy was excluded as there was more than one visible particle and a variable related to the transverse invariant mass was used. The upper and lower bounds, kinematical end points, were functions only of the involved particles masses. Therefore an appropriate variable existed to study. For my decay channel this was not possible as only one visible particle was produced, the lepton.

In this chapter I will show that due to the complexity of my decay channel, the invariant mass can not be used to put constraints on the chargino and neutralino masses (see 5.1). However, the transverse momentum of the lepton, p_{Tl}, proved to be sensitive to those masses. This variable is not model independent, ie. it depends on properties of the intermediate decays which change with the SUGRA parameters. I therefore examined the dependence of p_{Tl} in two ways. Firstly, when the neutralino and chargino masses were changed 'by-hand' ignoring any other mass or branching fraction. This left the intermediate decays unchanged. Secondly by changing the fundamental SUGRA parameters and using the recalculated masses and branching fractions which did change the intermediate decays. (see 5.2).

5.1 Invariant Mass of the Lepton and Missing Energy

Finding kinematical endpoints for my decay was highly complicated by the fact that there were not just two invisible particles (neutralinos), but a third (the neutrino). This meant the missing transverse momentum and energy was a sum of three unknowns. Additionally, because only one visible particle was produced, the missing momentum had to be used in the invariant mass. This variable proved to be inviable for putting limitations on the supersymmetric particle masses. The figures that follow show the progressive loss of information beginning at the truth level data and ending with the detector smeared invariant mass. Only the final figure would be producible from detector data. Each figure is for 27,000 signal events (before selection cuts).

Figure 5.1 shows the invariant mass for the chargino, given by:

$$m^2_{\tilde{\chi}^\pm_1} = (E_l + E_\nu + E_{\tilde{\chi}^0_1})^2 - (\vec{p}_l + \vec{p}_\nu + \vec{p}_{\tilde{\chi}^0_1})^2$$

It clearly peaks at $m_{\tilde{\chi}^\pm_1} = 212.485GeV$ as expected for the mass of the $\tilde{\chi}^\pm_1$ produced by ISASUGRA. When only the transverse momentum and energy were used the resulting distribution had a clear edge at $m_{\tilde{\chi}^\pm_1}$ as shown in figure 5.2. Both these figures demonstrate how mass information can be obtained independent of details earlier in the event.

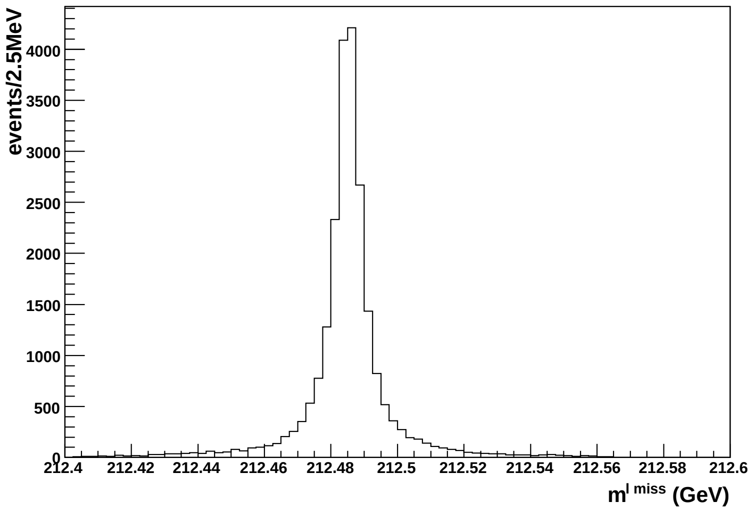


Figure 5.1: Truth level invariant mass of lepton, neutrino and neutralino.

Figure 5.3 shows the result of the second neutralinos inclusion which spoils the edge seen previously. The background, scaled to the same number of events, is also shown for comparison. Clearly there is an offset between the background and the signal which could be of interest to study. However, this offset is not a function of just particles masses. ie. it is model dependent, and as it turns out the lepton p_T is more sensitive to the supersymmetric masses than the transverse invariant mass. This is not surprising considering the invariant mass depends on the lepton p_T.

Analytically the distribution is hard to study because of the second neutralino. The invariant transverse mass with this extra neutralino denoted by $'$ is:

$$m^2_{lmiss} = (E_l + E_\nu + E_{\tilde{\chi}^0_1} + E'_{\tilde{\chi}^0_1})^2 - (\vec{p}_l + \vec{p}_\nu + \vec{p}_{\tilde{\chi}^0_1} + \vec{p}'_{\tilde{\chi}^0_1})^2$$

Where the $_T$ has been left off, but assume that all components are transverse.

This can be rewritten as:

$$m^2_{lmiss} = m^2_{\tilde{\chi}^\pm_1} + m^2_{\tilde{\chi}^0_1} + 2E'_{\tilde{\chi}^0_1}E_{\tilde{\chi}^\pm_1} - 2\vec{p}'_{\tilde{\chi}^0_1} \cdot \vec{p}_{\tilde{\chi}^\pm_1}$$

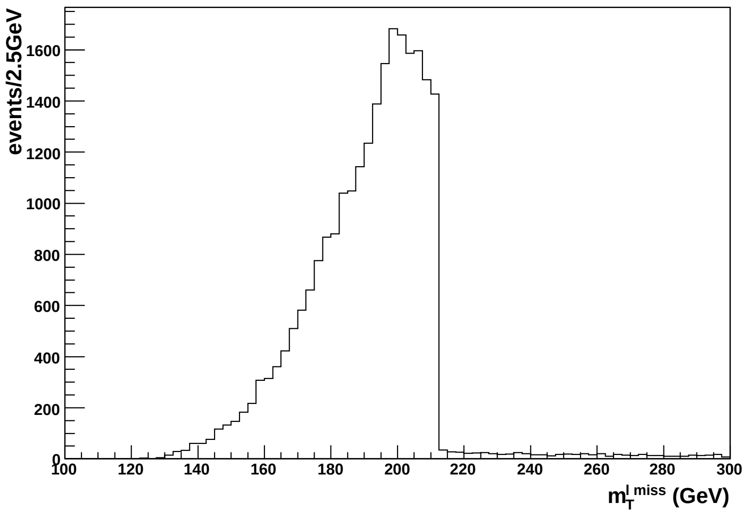


Figure 5.2: Truth level invariant mass of lepton, neutrino and neutralino. Transverse components only used.

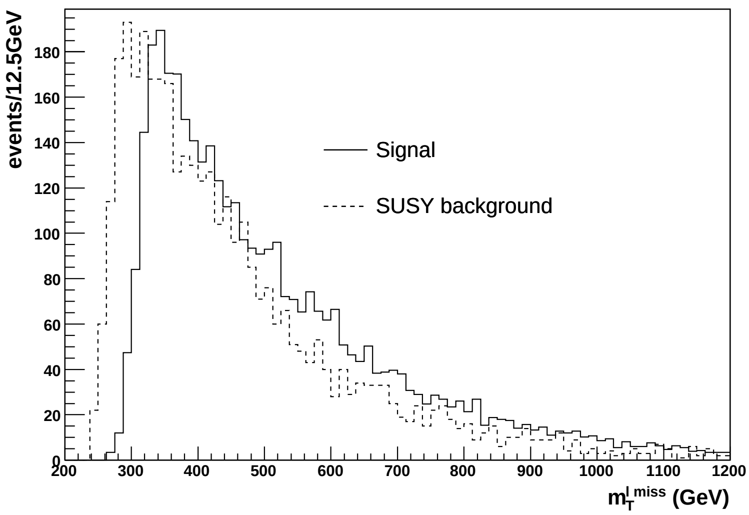


Figure 5.3: Transverse invariant mass of the lepton and all invisibles. Before detector smearing.

However there is no correlation between the $\tilde{\chi}_1^{0\prime}$ momentum and energy and those of the $\tilde{\chi}_1^{\pm}$ even at the truth data level. We could try to reduce the total number of unknowns in the invariant mass if we remember that the lepton and neutrino were produced by an on-shell W.

$$m_W^2 = 2|\vec{p_l}||\vec{p_\nu}|(1 - cos\theta)$$

Where θ is the angle between $\vec{p_l}$ and $\vec{p_\nu}$. The most we can hope to gain from this is to eliminate one of the two unknown: θ and $|\vec{p_\nu}|$. This does little to improve the situation as we still do not have enough information to study. Therefore an analytic approach to finding a reasonable variable seems difficult. When we also consider the accuracy of the detector for missing energy it seems as though the use of

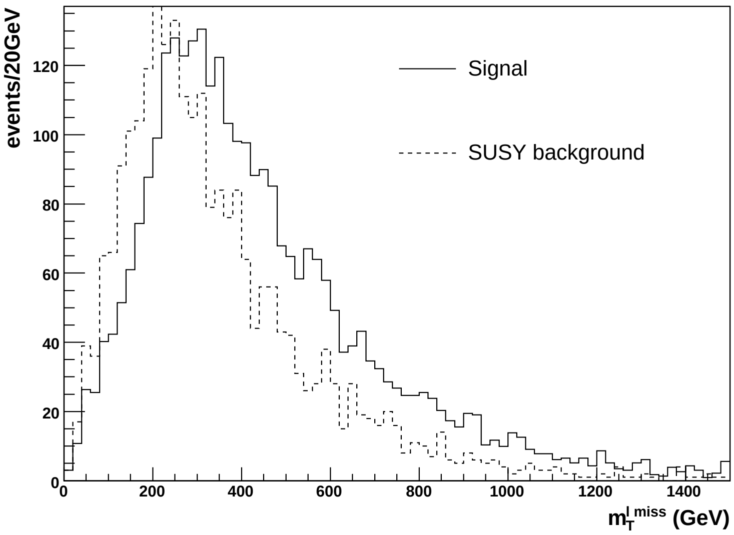


Figure 5.4: Transverse invariant mass of the lepton and all invisibles. After detector smearing.

this (apart from selection cuts to eliminate Standard Model background) limited. However, there does appears to be a method involving a complicated kinematical variable based on the invariant transverse mass. This variable gives model independent edges to study. More discussion of this can be found in chapter 6 on further work.

Finding a model independent variable sensitive to the neutralino and chargino masses in non-trivial so I will go on show how a model-dependent variable can be used. If we try to avoid using the missing energy the most obvious variables are those of the lepton and the simplest of these are its transverse momentum.

5.2 Lepton Transverse Momentum

When the chargino decays at rest into a neutralino and W:

$$\tilde{\chi}_1^{\pm} \rightarrow W\tilde{\chi}_1^0$$

The energy provided to the W is given by:

$$E_w = \frac{1}{2m_{\tilde{\chi}_1^{\pm}}}(m_{\tilde{\chi}_1^{\pm}}^2 - m_{\tilde{\chi}_1^0}^2 + m_W^2) \quad (5.1)$$

In the rest frame of the $\tilde{\chi}_1^{\pm}$ therefore, there is a clear relationship between E_W and both $m_{\tilde{\chi}_1^{\pm}}$ and $m_{\tilde{\chi}_1^0}$. It would be reasonable to expect that in the boosted laboratory frame the transverse momentum is also effected by both these masses. We can look at the Lorentz transformation into the laboratory frame:

$$p = \gamma p' \cos\theta + v\gamma E' \quad (5.2)$$

Where $'$ indicates the value in the rest frame of $\tilde{\chi}_1^{\pm}$ and θ is the angle between $\vec{p}'$ and the boost direction.

From 5.1, increasing the mass difference $m_{\tilde{\chi}_1^{\pm}} - m_{\tilde{\chi}_1^0}$ leads to an increase in both p' and E'. This in turn leads to an increase in the boosted momentum p.

This can now be taken one step further and applied to the lepton. In the rest frame of the W we have another two body decay:

$$W \rightarrow l\nu$$

As the lepton and neutrino masses are insignificant, momentum and energy conservation require that each daughter particle gets equal energy. Hence, each has approximately 40GeV in momentum. In equation 5.2, p' and E' clearly do not change with p_W, but v and γ do. Therefore we would expect that a change in $m_{\tilde{\chi}_1^{\pm}}$ or $m_{\tilde{\chi}_1^0}$ should on average influence the value of p for the lepton.

Because of this an examination of the W and lepton p_T was done to determine their sensitivity to $m_{\tilde{\chi}_1^{\pm}}$ and $m_{\tilde{\chi}_1^0}$ as these masses were varied.

Changing the masses was done in two different ways. One method explored was to change $m_{\tilde{\chi}_1^0}$ directly in the decay table read by the Monte-Carlo generator. This seemed somewhat forced because there was an implicit assumption that the mass spectrum remained consistent with SUGRA and the cross-sections and branching fractions were unchanged. As a comparison I later changed the entire mass spectrum by altering the underlying model parameters and looked at the effect.

5.2.1 Variation of $m_{\tilde{\chi}_1^0}$

For the method of directly changing the supersymmetric masses in the decay table, we would like to leave the momentum distribution of the $\tilde{\chi}_1^{\pm}$ unchanged. This is so that we can study the sole effect of the mass difference $m_{\tilde{\chi}_1^{\pm}} - m_{\tilde{\chi}_1^0}$. For this reason $m_{\tilde{\chi}_1^0}$ was chosen to be varied instead of $m_{\tilde{\chi}_1^{\pm}}$. If SUGRA is found at LHC, the value of $m_{\tilde{\chi}_1^0}$ is likely to be tightly constrained early on, so a study varying $m_{\tilde{\chi}_1^{\pm}}$ instead would be valuable if time had permitted.

Initially the transverse W momentum for a number of different $m_{\tilde{\chi}_1^0}$ values was explored. As no detector level data was known about the W, this was done with the truth information. Plotted in figure 5.5 we can see that the mass difference $m_{\tilde{\chi}_1^{\pm}} - m_{\tilde{\chi}_1^0}$ does indeed change the distribution of transverse momentum. As the manner in which the mass difference was changed left the transverse $\tilde{\chi}_1^{\pm}$ momentum distribution unchanged, the shift in the W p_T must be directly related to $m_{\tilde{\chi}_1^0}$.

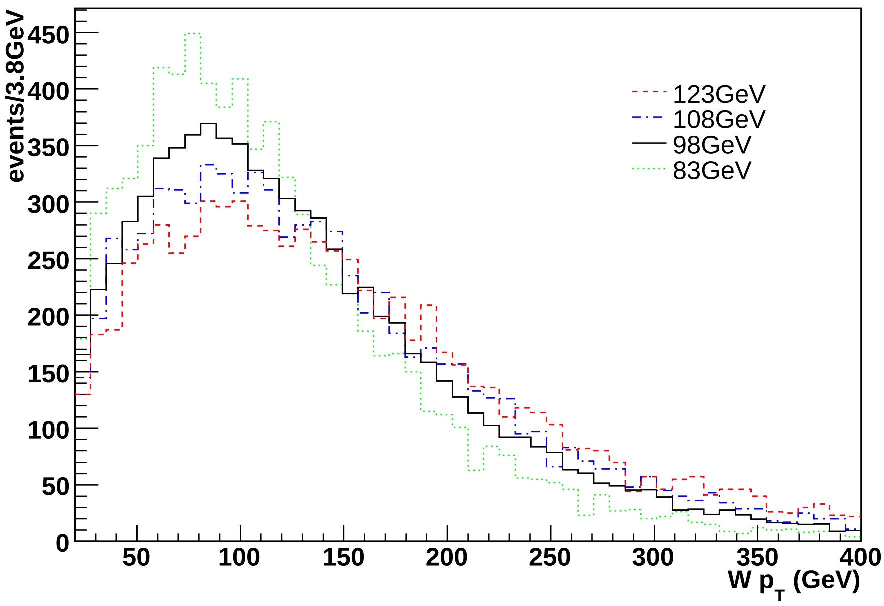


Figure 5.5: Distribution of W p_T for several values of $m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0}$. 8,000 preselection events were used.

It is interesting to plot the average value of the W's transverse momentum. This shows clearly the dependence on the neutralino mass, and therefore the mass difference (see figure 5.6). The error plotted here is due to the limited number of event used to find the mean. The relationship, at least for the small mass changes looked at, appears to be linear with a gradient of ≈ 1, meaning the W is particularly sensitive to the $m_{\tilde{\chi}_1^0}$.

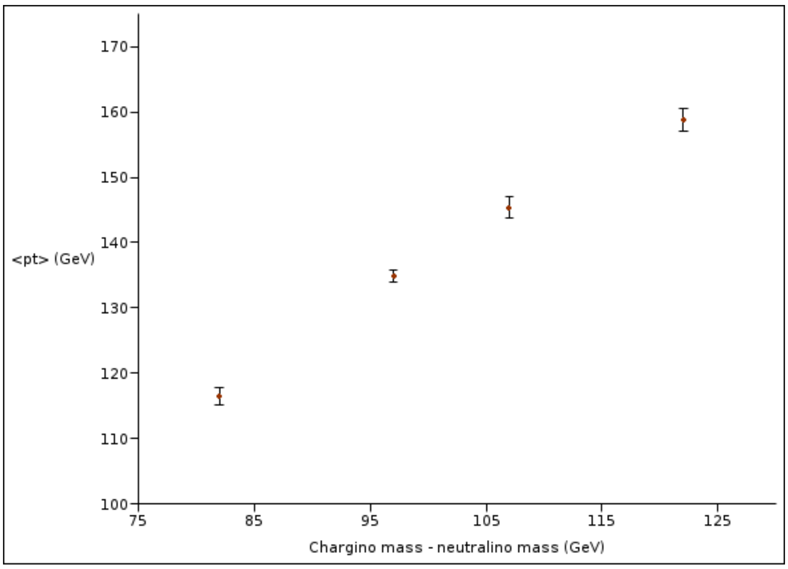


Figure 5.6: Dependence of W average transverse momentum of neutralino-chargino mass difference

The idea of a shift is momentum was then explored with the leptons p_T. This can be seen in figure 5.7.

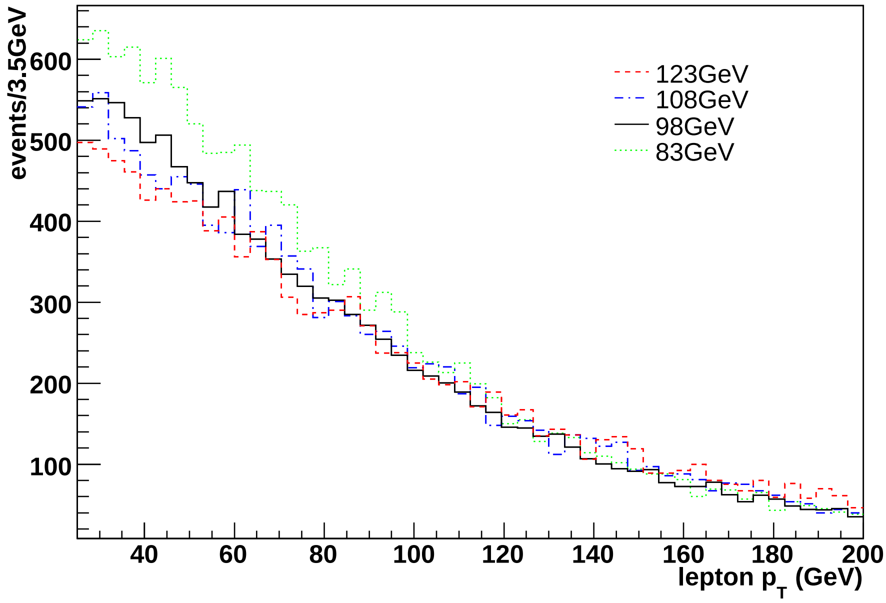


Figure 5.7: Distribution of lepton transverse momentum with changing neutralino-chargino mass difference

Again plotting the mean lepton p_T (for approximately 8,000 events with no cuts applied) we see that the relationship appears linear, this time with a gradient of 0.5, so that the lepton p_T is half as sensitive to the mass change as the W p_T. This is certainly large enough for a measurement of the signal lepton p_T at point 5 to give constraints on $m_{\tilde{\chi}^0}$. The background is also plotted for comparison and remains constant with the mass to within statistical errors as expected. However, as this was an uncut pure signal sample, an analysis of cut signal + background was also required.

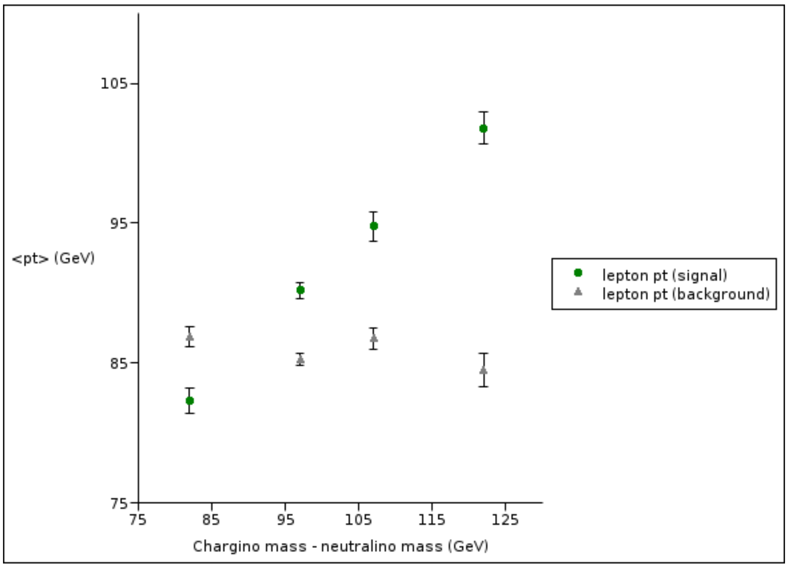


Figure 5.8: Dependence of lepton average transverse momentum on neutralino-chargino mass difference

After applying cuts and combining background and signal p_T is not as sensitive to mass changes. This is shown in figure 5.9. The sample sizes for these points are low which makes the error large and could somewhat account for the degradation in the linearity. For the fully cut samples about 800 events were used which corresponds to the number of ATLAS event is approximately half of the first year. The other possibility for the degradation is that the cuts are biasing the lepton p_T. At the very least they must cause an over-all translation towards higher p_T because of the excessive cuts on E_{miss} and m_{Tlmiss}. This is seen in the results in comparison to those of figure 5.8. The second set of values in figure 5.9 shows the effect of removing the final two cuts on SUSY background. This would be a reasonable thing to do as these do not dramatically remove the background. We would expect that this both increases the number of events as well as decreasing the biasing the cuts may cause. This is reflected in the results. To make a better judgement on the effectiveness of measuring masses this way a larger sample size of events would be required. Then the full feasibility of measuring the chargino and neutralino masses this way could be determined.

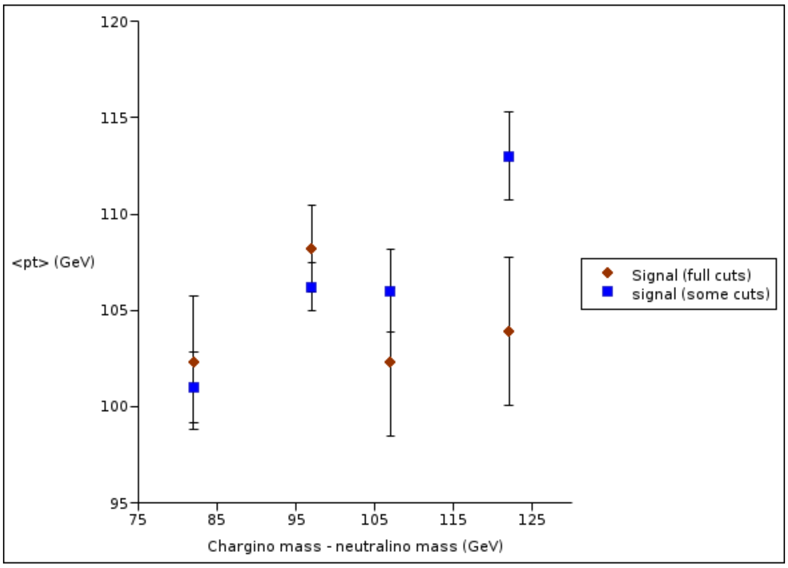


Figure 5.9: Dependence of lepton average transverse momentum on neutralino-chargino mass difference

5.2.2 Variation of mSUGRA Parameters

In the previous section we made an assumption that a small change in neutralino mass would leave all process cross-sections unchanged. By changing instead the mSUGRA parameters that determine the mass, we can avoid making this assumption and also cover a larger section of parameter space. The trade off is that our mass measuring variable turns out to be more sensitive to overall traits of the parameterisation, such as cross-section and average boost, rather than to the individual mass differences. Many variables are sensitive to overall traits of a particular parameterisation and as feasibility studies have already been carried out on 'inclusive' signatures, we would probably not gain anything new by examining p_T.

The mass spectrum was changed my altering the mSUGRA parameter $m_{\frac{1}{2}}$ for four different values as seen in table 5.1.

$m_{\frac{1}{2}}(GeV)$	$m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0}(GeV)$	$\approx \sigma(pb)$	**Signal events passing cuts**	**SUSY background events passing cuts**
250	77	46	3,159	12,110
300	96	19	4,509	8,030
350	116	9.2	3,493	5,638
400	136	4.6	1,717	13,130

Table 5.1: $m_{\frac{1}{2}}$ parameters examined for a sample of 50,000 SUSY events

It is interesting to note here that for $m_{\frac{1}{2}} = 400$ the proportion of signal to background events is reduced dramatically, so what would be seen in the detector would look basically like background. For $m_{\frac{1}{2}} = 250$ the neutralino-chargino mass difference is less than the mass of the W so only a three body decay occurs. The p_T distribution for this also happens to behaves like background, so perhaps the distribution of the lepton p_T can allow us to put upper and lower bounds on the mass difference after all. Figure 5.10 shows the distribution of just the signal before any cuts. The histograms are rescaled according to cross-sections which explains the loss in amplitude as the masses increase. The dominant feature to notice is the exponentially decaying curve of the three-body decay compared with the smeared peak of the others.

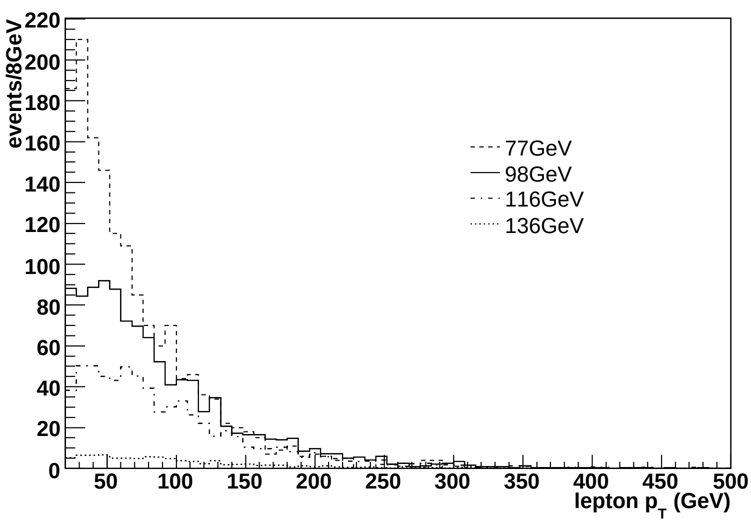


Figure 5.10: Distribution of lepton transverse momentum with changing SUGRA parameters

When the mean p_T is plotted we find a similar linear relationship to that in the previous section. However this is also seen in the background which suggest as overall boost to all particles as the variable $m_{\frac{1}{2}}$ increases. The fact that the signal lepton is more sensitive to the masses (with its higher gradient) suggests that there may still be a dominant effect from the mass difference rather than just the over-all boost. It is also interesting to note the position of the point for the three-body decay which lies slightly below what would be expected for a two body decay.

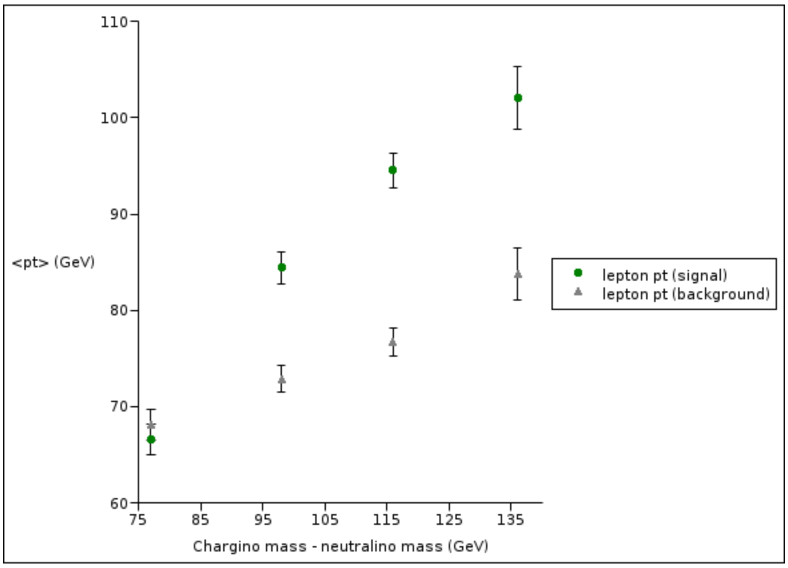


Figure 5.11: Dependence of lepton average transverse momentum on changing SUGRA parameters.

As it turns out the higher gradient of the signal lepton is caused by a large boost to the chargino as shown in figure 5.12. The effect on the W (also plotted) is then clearly dominated by the chargino boost rather than the chargino-neutralino mass difference.

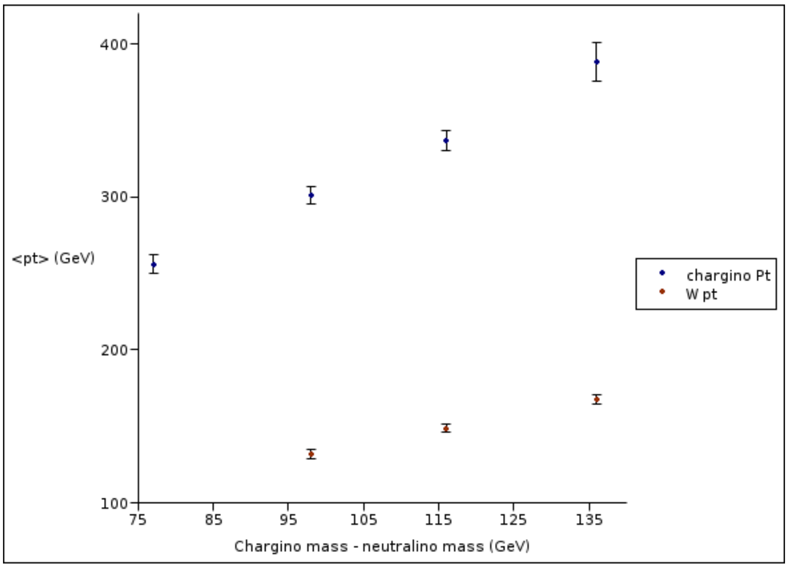


Figure 5.12: Dependence of chargino and W average transverse momentum on changing SUGRA parameters.

Chapter 6

Further Work

If time permitted a study of the transverse mass like variable presented in [18] may allow a model-independent reconstruction of supersymmetric particle masses. This variable, called m_{TX} was designed especially for R-parity conserving events at the LHC where there are several factors which make conventional analysis impossible, the primary one being the existence of multiple invisible particles.

The trouble with the missing momentum is that we do not know how it is divided amongst the invisible particles. m_{TX} parameterises away our ignorance of the division by introducing dummy variables ($\vec{q}^{(n)}$) for each invisible particles. These are then constrained by

$$\sum \vec{q}_T^{(n)} = \vec{p}_T^{missing}$$

The catch is that we need the second invisible to have been produced by a similar process as the first. By this I mean that the mother and invisible daughter supersymmetric particles need to be the same, but the visible particles do not need to be. For example $\tilde{\chi}_1^{\pm} \to \tilde{\chi}_1^0 l\nu$ and $\tilde{\chi}_1^{\pm} \to \tilde{\chi}_1^0 \pi^{\pm}$ are allowed. This would clearly lower the number of events seen per year for analysis.

As an example, in a decay involving two invisible particles (X=2), the variable m_{T2} is given by:

$$m_{T2} = min[max\{m_T^2(\vec{p}_T^{(1)}, \vec{q}_T^{(1)}), m_T^2(\vec{p}_T^{(2)}, \vec{q}_T^{(2)})\}]$$

Here $m_T^2(\vec{p}_T^{(a)}, \vec{p}_T^{(b)}) = m_{(a)}^2 + m_{\tilde{\chi}_1^0}^2 + 2(E_T^{(a)} E_T^{(b)} - \vec{p}_T^{(a)} \cdot \vec{p}_T^{(b)})$

This variable turns out to be bounded by the masses of those particles involved in the decay because $m_{visible} + m_{invisible} \leq m_{T2} \leq m_{motherparticle}$. So the end points of this variable can be used to find masses.

In the case of my decay channel, the above can be generalised for four invisible particles (two neutralinos and two neutrinos). An example of this particular decay is given in [18] for the Anomaly Mediated Symmetry Breaking (AMSB) SUSY model. For this example the mass spectrum of particles is different, but the topology is similar so it is highly relevant. The example given is a three body decay rather than a double set of two body decays. However this should simplify the problem because there is an extra set of constraints on the electron and neutrino on both sides.

Therefore, it would be interesting to explore the technique used in [18] to determine the feasibility of its use in my particular decay and parameterisation of mSUGRA.

Chapter 7

Conclusion

The ATLAS detector is less than two years away from collecting its first set of data. This will allow us to further test models of particle physics which are currently excepted, look for signs of theories which have not been seen or even give us hints to new theories which have not yet be devised. In preparation for this, we would like to understand the signs that indicate new physics and map out what these signals will tell us about the underlying model.

In this project I studied one specific decay channel within the mSUGRA model, $\tilde{\chi}_1^{\pm} \rightarrow \tilde{\chi}_1^0 l\nu$ where the l and ν decay via a W. The parameterisation of the model ($m_0 = 100GeV, m_{\frac{1}{2}} = 300GeV, A_0 = 300GeV, tan\beta = 2.1, \mu > 0$) was initially chosen as it allowed the Lightest Supersymmetric Particle (LSP) to be a prime candidate for Cold Dark Matter. In this project the LSP is a $\tilde{\chi}_1^0$. Appropriate selection cuts were found which reduced both the Standard Model background and background events from other SUSY processes to approximately half the signal while still giving a cross-section of 0.2pb. (or 20,000 events per year at full luminosity).

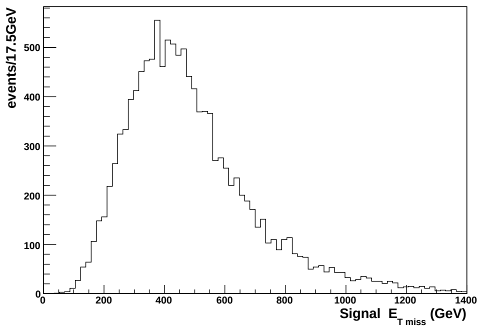
An analysis was then done to see how well the $m_{\tilde{\chi}_1^{\pm}}$ and $m_{\tilde{\chi}_1^0}$ parameters could be determined from the signal. No model-independent variable could be found due to the complexity of the missing momentum of invisibles within the event. However, I found that the kinematic variables of the lepton alone were sensitive to the mass difference between the neutralino and chargino. The lepton transverse momentum, p_T was studied and at low mass differences a linear relationship between the mass of the $m_{\tilde{\chi}_1^0}$ and mean lepton p_T was seen.

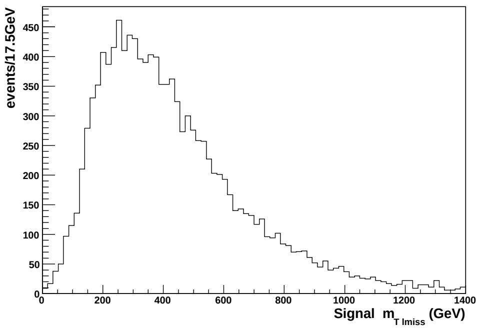
Finally, literature was found which suggested the use of a model independent variable sensitive to masses for difficult decay channels such as this one. The job of extracting model parameter information from a decay where all we observe is a single lepton and a “whole lot of nothing” is not easy, but to some degree doable.

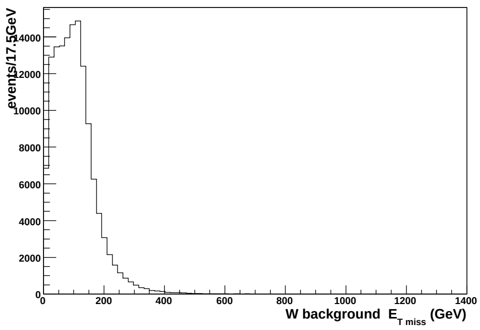
Appendix A

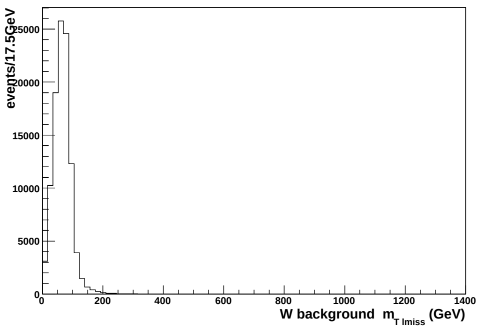
Standard Model Background Cuts

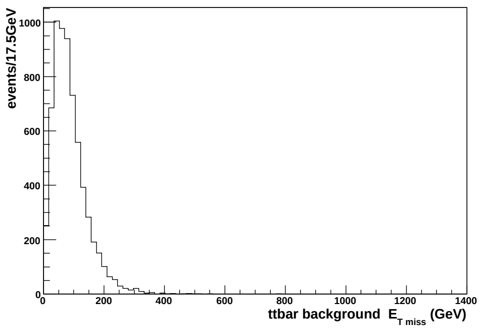
Only events with $E_{Tmiss} > 600GeV$ and $m_{Tlmiss} > 300GeV$ were kept. Below is the distribution of signal and and standard model background for each variable (same scale used for all).

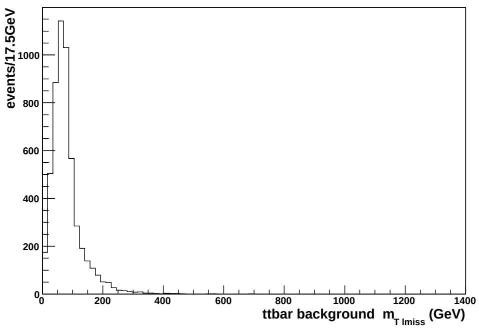












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Sally and the Dres for chats

Simon for being as mad as this year has been and to Joris for putting up with him

all the characters in the physics build for keeping me amused.

all my friend outside physics for distracting me when I needed it.

Angelina for looking after me. I saw what honours did to you and I did it anyway :) Also to James. Sorry about the birthday incident.

Mum, Dad, Cherie. I'll be visiting you soon.

Friday nights, for keeping me sane, but not sober.

Sunday mornings, for being themselves.

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