

School of Physics and Astronomy



MPhys Project Top squark study at the CLIC

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Abstract

The top squark with a mass of 844GeV has been studied at the CLIC. The top squarks are pair produced at $\sqrt{s} = 3\text{TeV}$ in e^+e^- collisions. In the decay mode studied both top squarks decay into a top quark and the lightest neutralino ($\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$). The top squark mass was measured as $834\text{GeV} \pm 23\text{GeV}$ using a template fit in the fully hadronic final state with six jets.

Declaration

I declare that this project and report is my own work.

Signature:

Date:

Supervisor: Dr. Victoria Martin



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1 Introduction

The Large Hadron Collider (LHC) is the world's highest energy collider. From 2010 to 2012, the LHC collided protons at centre of mass energies, $\sqrt{s} = 7\text{-}8\text{TeV}$.

The LHC will begin its second run later this year, colliding protons at $\sqrt{s} = 13\text{TeV}$. Protons are not fundamental particles but made up of quarks and gluons bound together by the strong force. In a collision at the LHC, it is the quarks and gluons which interact. The momentum of these quarks and gluons which interact is not known before the collision takes place. This limits the precision that can be achieved at a proton collider.

There are proposals to build a collider which would collide electrons and positrons. Electrons and positrons are fundamental point like particles, this allows more precise measurements than can be obtained at the LHC. One of the collider proposals is known as the Compact Linear Collider (CLIC).

A key part of planning for a future collider is to study the physics that can be done at the new collider. Simulated physics studies demonstrate the potential the new collider could have and can also lead to the hardware in the new collider being optimised for physics purposes.

It is thought that more fundamental particles could exist than are already known. There are several reasons for this belief but the biggest experimental observation is the dark matter that exists in the Universe [1]. The Standard Model does not provide a fundamental particle that could be a good candidate for dark matter.

One of the theories that predicts new particles is known as Supersymmetry (SUSY). It predicts that every fundamental particle has a new particle as a partner that differs by half a unit of Spin. The partner to the top quark is known as the top squark, $\tilde{t}_1$. In this project the top squark is studied at the CLIC. The experiments at the LHC have searched extensively for the top squark but haven't found any evidence so far that would indicate that the particle exists [2]. One of the reasons for this could be that the mass of the top squark is too large for the current LHC to have access to. The top squark mass in this project is set to 844GeV to be compatible with the current LHC results.

In the SUSY model used the top squark decays into a top quark and the dark matter candidate, the neutralino $\tilde{\chi}_1^0$ the majority of the time. The neutralino escapes the detectors.

In most SUSY models, the particles in the Standard Model are produced more often than the SUSY particles in collisions. In this study, top quarks are produced approximately 36 times more often than their SUSY partner, the top squark. In both processes the detectors only detect the top quarks and their subsequent decay products. Hence discriminating between the times when Standard Model particles are produced and when the SUSY particles are produced is challenging and it could be another reason why the experiments at the LHC have not observed the top squark.

The objectives of this project are to reduce the large Standard Model background so the SUSY events can be observed. Once this is complete, the mass of the top squark can be measured. The centre of mass energy at CLIC in this project is $\sqrt{s} = 3\text{TeV}$.

2 CLIC

The LHC is a circular collider, high energy circular colliders are possible for protons but not for electrons. When a charged particle moves in a circular path it emits electromagnetic radiation known as synchrotron radiation. The energy loss for a particle due to synchrotron radiation is inversely proportional to the mass of that particle to the power of 4. The electron is approximately 2000 times lighter than the proton so the energy losses for a circular e^+e^- collider are much greater. A high energy e^+e^- collider must therefore be linear. The CLIC is currently the only option for a multi-TeV e^+e^- collider.

The CLIC is planned to be a staged construction, initially it is to start at $\sqrt{s} = 380\text{GeV}$. This energy stage will allow precision Higgs and top quark physics. The next energy stages are currently planned as $\sqrt{s} = 1.4\text{TeV}$ and $\sqrt{s} = 3\text{TeV}$ but could be adapted depending on the LHC results. These two energy stages would target rare Higgs decays and Beyond Standard Model (BSM) physics.

The electron and positron bunches at CLIC are very dense since the beams are small. A consequence of this is that the bunches have strong electromagnetic fields. The electrons and positrons in each bunch radiate photons due to the electromagnetic interaction with the opposite bunch. This phenomenon is known as beamstrahlung. These photons create e^+e^- pairs or $\gamma\gamma \rightarrow \text{hadrons}$ interactions. This effect gets larger as the centre of mass energy increases. The centre of mass energy for the initial e^+e^- hard scatter for CLIC operating at $\sqrt{s} = 3\text{TeV}$ is shown in Figure 1. 64% of the events have an energy greater than 2.7TeV.

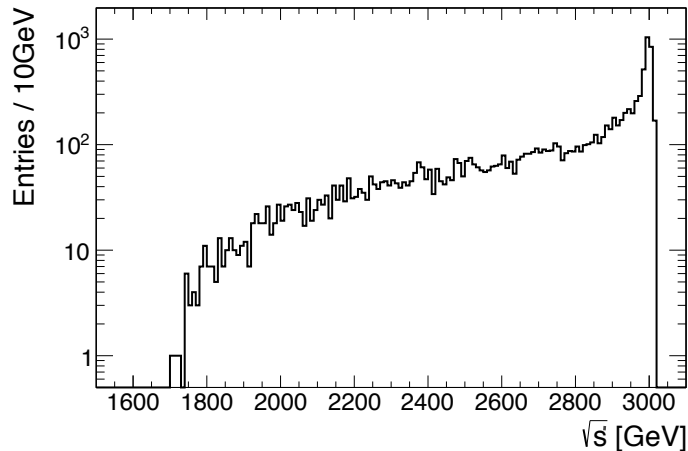


Figure 1: The centre of mass energy $\sqrt{s}$ in 10,000 $e^+e^- \rightarrow \tilde{t}_1\tilde{t}_1$ events. The y axis has a log scale.

The beam induced backgrounds discussed above are suppressed by timing cuts and cuts on the transverse momentum of the particles. There are three different levels of cuts available on the particles, loose, default and tight. This is detailed further in [3]. In this analysis, the tight cuts are used since the top squarks are studied at $\sqrt{s} = 3\text{TeV}$, an energy stage where beamstrahlung has a large effect.

The CLIC currently has two detector models. The CLIC_ILD detector as shown in Figure 2 was used in this study. The ILD detector has been developed for the International Linear Collider (ILC) and has been modified for the different experimental conditions at CLIC into the CLIC_ILD detector.

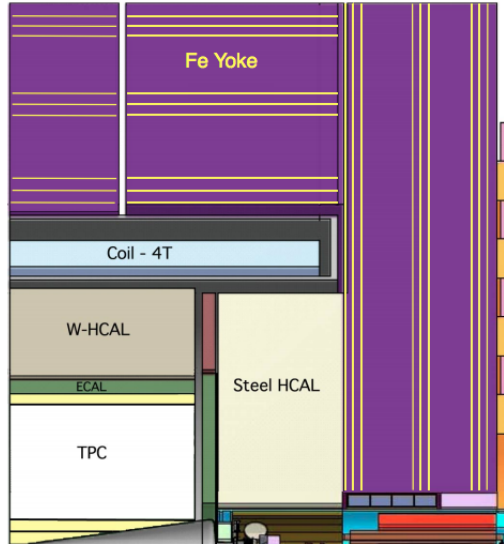


Figure 2: CLIC_ILD Detector [3]

The Time Projection Chamber (TPC) provides the charged particle track reconstruction in the CLIC_ILD detector. The TPC has an inner silicon tracker and a silicon envelope surrounding it. The silicon layers surrounding the TPC extend the coverage to small angles and are important in measuring the momentum of the charged particles precisely. The electronic calorimeter (ECAL) is a silicon-tungsten calorimeter which is followed by two hadronic calorimeters, one made out of tungsten (W-HCAL) and the other made out of steel (Steel HCAL). Both the ECAL and HCAL are surrounded by a superconducting solenoid (coil) which has an axial magnetic field of 4T. The iron yoke returns the magnetic flux, it is also instrumented with track sensitive chambers which increase muon identification [3].

Reconstructing the invariant mass of two jets precisely is very important at CLIC, as many physics channels depend on separating W and Z bosons that have decayed hadronically. In the CLIC_ILD detector model, the jet energy resolution is best when reconstructing charged particles in the TPC, photons in the ECAL and neutral hadrons in the ECAL and HCAL [4].

In this study an integrated luminosity of $2ab^{-1}$ has been assumed. This corresponds to running CLIC at $\sqrt{s} = 3\text{TeV}$ for 4 years. This assumption has been used in other benchmark studies [5] for CLIC.

3 Supersymmetry Phenomenology

3.1 Motivation for Supersymmetry

Supersymmetry (SUSY) is one of the most popular extensions of the Standard Model. Supersymmetry predicts that every Standard Model particle has a supersymmetric particle as a partner that differs by half a unit of Spin. Hence every fermion has a boson as a partner and every boson has a fermion as a partner. If SUSY was an exact symmetry then these fermion-boson pairs would have the same mass, since these particles do not exist in nature it implies that SUSY is a broken symmetry if it does indeed exist.

Supersymmetry is popular because it can solve some of the problems the Standard Model currently faces. The discovery of the Higgs boson [6] at the LHC by the ATLAS and CMS experiments in 2012 has brought more attention to the gauge hierarchy problem. SUSY presents a viable solution to this problem, assuming the masses of the SUSY particles are of the order 1TeV [7].

It is already known that the electromagnetic coupling constant increases with energy whilst the weak and strong coupling constants decrease. It is thought that at some energy scale the strength of the couplings could converge on a single value, however if only Standard Model particles are included it is found that this cannot occur. If SUSY particles are included then the evolution of the coupling constants change and they can be made to converge on a single value as shown in Figure 3. The point at which the couplings converge is known as the Grand Unified Theory (GUT) scale.

Most SUSY models have a stable weakly interacting particle, often referred to as the neutralino, $\tilde{\chi}_1^0$. This could potentially make up the dark matter that exists in the Universe.

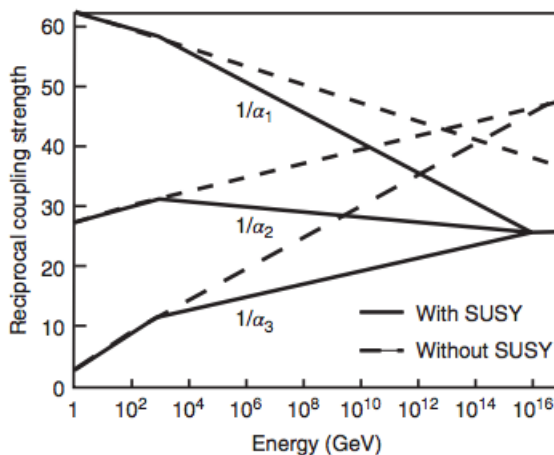


Figure 3: The reciprocal of the strength of the coupling constants as a function of energy. The change in the straight line at 1TeV shows SUSY breaking [7].

3.2 Constrained Supersymmetry

In the Standard Model there are 26 free parameters including the neutrino masses, there are several SUSY models which increase this number to over 100. One method of reducing the number of free parameters is to assume that there is some unification at the GUT scale. It is common to assume that all the spin 0 particles in SUSY have the same mass, m_0 and all the spin 1/2 particles in SUSY have the same mass, $m_{1/2}$ at the GUT scale.

3.3 Supersymmetric Particles

3.3.1 Sfermions

Every chiral fermion has a spin 0 scalar boson as its supersymmetric partner. These bosons are referred to as sfermions. The bosons do not carry chirality so for every fermion f there are two bosons $\tilde{f}_L$ and $\tilde{f}_R$. When the electroweak symmetry breaks, both $\tilde{f}_L$ and $\tilde{f}_R$ couple to the Higgs boson. The bosons mix to form the mass eigenstates f_1 and f_2 . The mixing is proportional to the mass of the fermion so it can be ignored for the first two generations of particles as well as all the neutrinos.

The mixing between $\tilde{f}_L$ and $\tilde{f}_R$ to form the mass eigenstates f_1 and f_2 is described by a 2×2 matrix of the form [8]

$$\tilde{m}^2(\tilde{t}) = \begin{pmatrix} M_1^2 & m_t a_t \\ m_t a_t & M_2^2 \end{pmatrix} \quad (1)$$

The diagonal terms M_1^2 and M_2^2 are proportional to the $m_0^2 + m_t^2$, where m_0 is the mass of the spin 0 SUSY bosons at the GUT scale and m_t is the mass of the top quark. The term a_t is proportional to other SUSY parameters which are unified at the GUT scale. The masses of $\tilde{t}_1$ and $\tilde{t}_2$ can be determined by finding the eigenvalues of the matrix $\tilde{m}^2(\tilde{t})$. The masses are:

$$m_{\tilde{t}_{1,2}}^2 = \frac{1}{2}(M_1^2 + M_2^2 \mp \sqrt{(M_1^2 - M_2^2)^2 + 4m_t^2 a_t^2}) \quad (2)$$

where the terms are the same as before. Since the mass of the top quark is 173 GeV, it is clear why there is a large mass splitting between $\tilde{t}_1$ and $\tilde{t}_2$. For this reason it is thought that the $\tilde{t}_1$ could be the lightest squark.

3.3.2 Gauginos

Every spin 1 particle has a spin 1/2 fermion as its supersymmetric partner. These fermions are referred to as gauginos. However only the gluino is a mass eigenstate. The table below shows all the Standard Model spin 1 bosons and their SUSY partners.

	Standard Model			Supersymmetry	
	Particle	Spin		Gauge Eigenstate	Spin
Gluon	g	1	Gluino	$\tilde{g}$	1/2
Photon	γ	1	Photino	$\tilde{\gamma}$	1/2
Z boson	Z	1	Zino	$\tilde{Z}$	1/2
W boson	$W^\pm$ W^0	1	Wino	$\tilde{W}^\pm$ $\tilde{W}^0$	1/2
B boson	B	1	Bino	$\tilde{B}$	1/2

In the Standard Model, the Higgs mechanism consists of two complex scalar fields in a single weak isospin doublet. A single Higgs doublet gives four degrees of freedom. Supersymmetry requires at least two Higgs doublets which gives eight degrees of freedom. Three of these degrees of freedom are absorbed to give masses to the $W^\pm$ and Z bosons as in the Standard Model. The remaining five degrees of freedom correspond to five physical Higgs bosons. There are two CP-even H^0 and h , two charged $H^\pm$ and one CP-odd A.

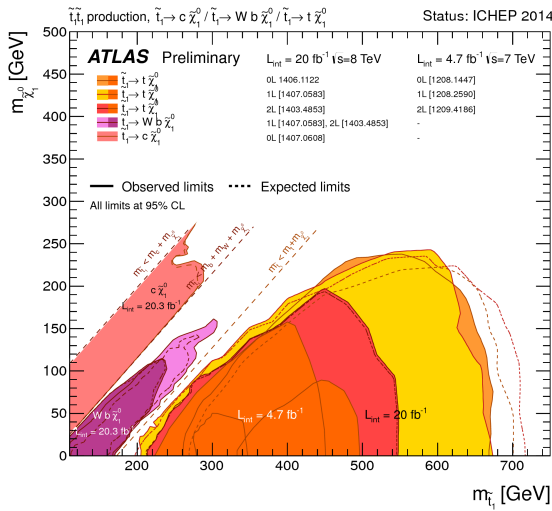
These extra Higgs bosons have SUSY partners, the higgsinos which are $\tilde{A}$, $\tilde{H}^\pm$, $\tilde{H}^0$ and $\tilde{h}$. These higgsinos, however are not mass eigenstates. They mix with the Winos and Binors to form neutralinos and charginos which are mass eigenstates [9].

When the electroweak symmetry breaks, the charged higgsinos $\tilde{H}^\pm$ and Winos mix to form the charginos $\chi_1^\pm, \chi_2^\pm$. The Bino $\tilde{B}$, neutral Wino $\tilde{W}^0$ and the CP even higgsinos $\tilde{H}^0$ and $\tilde{h}$ mix to form the neutralinos $\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0$ [7].

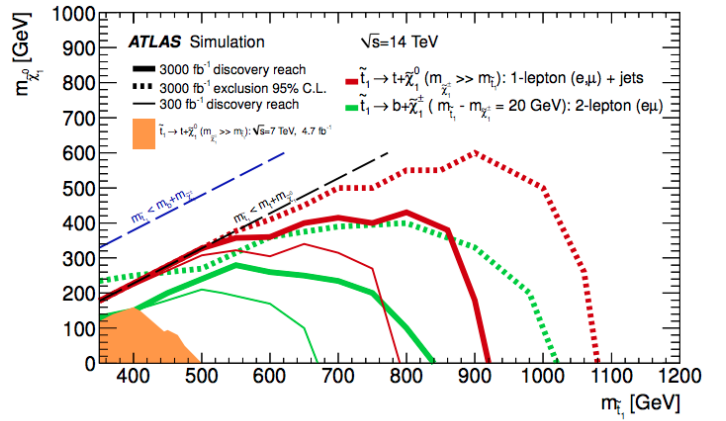
3.4 LHC Results and Experimental Signatures

One of the main focuses of BSM physics at the LHC is the search for SUSY particles. In most SUSY models it is predicted that the squarks will decay into their quark partner and the lightest neutralino $\tilde{\chi}_1^0$. If the top squark decays like $\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$, it could be easier to find than the first and second generation squarks because the top quark has a characteristic decay mode. The top quark has an extremely short lifetime (10^{-25} s) so it does not hadronise into a jet, instead it almost always decays into a bottom quark and a W boson due to the large V_{tb} element in the CKM matrix. The W boson can decay into quarks or it can decay leptonically. Hence there are several experimental signatures which help to reduce the Standard Model background in top squark searches. For example b-tagged jets, missing transverse momentum and isolated leptons.

Both the ATLAS and CMS collaborations have searched for the top squark at the LHC in a number of different decay modes. They have seen no evidence for the top squark so far. The current exclusion limits set by the ATLAS collaboration are shown in Figure 4 (a). The experiments will continue to search for the top squark in Run II and at the High Luminosity LHC (HL-LHC). The discovery reach at the HL-LHC is for a top squark mass of approximately ~ 1 TeV (see Figure 4 (b)) for the decay mode $\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$.



(a)



(b)

Figure 4: a) Summary of the ATLAS searches for top squark pair production at the LHC [2] b) The discovery reach (solid lines) and exclusion limits (dashed lines) for $\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$ (red) and $\tilde{t}_1 \rightarrow \chi_1^\pm b$ (green) at the the HL-LHC with the ATLAS detector [10]

3.5 CLIC Conceptual Design Report Model III

Three SUSY models were created for the CLIC Conceptual Design Reports. The model selected for this study was CLIC CDR Model III which is a variant on minimal supergravity (mSUGRA). In this model the mass of the top squark $\tilde{t}_1$ is 844 GeV so they are pair produced at $\sqrt{s} = 3\text{TeV}$. The cross section for top squark pair production is 1.65 fb [11]. This model was created before the discovery of the Higgs boson so the lightest neutral Higgs boson h has a mass of 117.8 GeV.

The three largest decay modes of the top squark in the model are:

- $\text{BR}(\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0) = 52.4\%$
- $\text{BR}(\tilde{t}_1 \rightarrow \chi_1^\pm b) = 34.1\%$
- $\text{BR}(\tilde{t}_1 \rightarrow t\tilde{\chi}_2^0) = 13.2\%$

The other branching ratios are less than 0.02%.

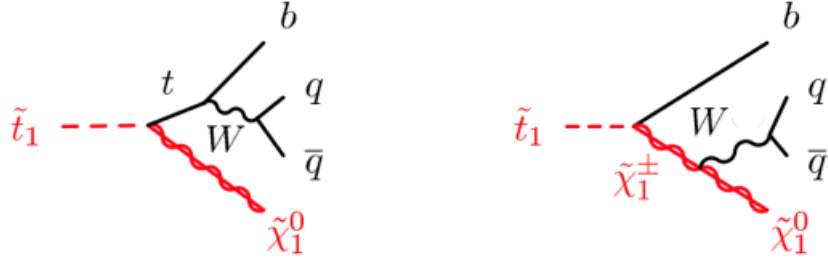


Figure 5: Feynman diagrams for the two largest decay modes of the top squark. [12]

The largest branching ratios of the other SUSY particles in the above decays are $\text{BR}(\chi_1^\pm \rightarrow W^\pm b) = 99.7\%$ and $\text{BR}(\tilde{\chi}_2^0 \rightarrow h\tilde{\chi}_1^0) = 94.6\%$.

The masses of the $\chi_1^\pm$, $\tilde{\chi}_2^0$, $\tilde{\chi}_1^0$ are 487 GeV, 487 GeV and 357 GeV respectively.

The main topologies of the pair produced top squarks are below. The branching pair fraction is shown in brackets beside the channel.

$$e^+e^- \rightarrow \tilde{t}_1\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0\chi_1^\pm b \rightarrow W^+W^-b\bar{b}\tilde{\chi}_1^0\tilde{\chi}_1^0 \quad (35.8\%) \quad (3)$$

$$e^+e^- \rightarrow \tilde{t}_1\tilde{t}_1 \rightarrow t\bar{t}\tilde{\chi}_1^0\tilde{\chi}_1^0 \rightarrow W^+W^-b\bar{b}\tilde{\chi}_1^0\tilde{\chi}_1^0 \quad (27.4\%) \quad (4)$$

$$e^+e^- \rightarrow \tilde{t}_1\tilde{t}_1 \rightarrow t\bar{t}\tilde{\chi}_1^0\tilde{\chi}_2^0 \rightarrow W^+W^-b\bar{b}h\tilde{\chi}_1^0\tilde{\chi}_1^0 \quad (13.7\%) \quad (5)$$

$$e^+e^- \rightarrow \tilde{t}_1\tilde{t}_1 \rightarrow \chi_1^+\chi_1^-\bar{b}b \rightarrow W^+W^-\bar{b}b\tilde{\chi}_1^0\tilde{\chi}_1^0 \quad (11.6\%) \quad (6)$$

$$e^+e^- \rightarrow \tilde{t}_1\tilde{t}_1 \rightarrow t\tilde{\chi}_2^0\chi_1^\pm b \rightarrow W^+W^-b\bar{b}h\tilde{\chi}_1^0\tilde{\chi}_1^0 \quad (9.0\%) \quad (7)$$

The decay modes are further characterised by the decays of the W boson and the Higgs boson. The branching ratios of the W boson are:

- $\text{BR}(W \rightarrow q\bar{q}) = 67.8\%$
- $\text{BR}(W \rightarrow l\nu_l) = 32.2\%$

where l indicates the the sum over all leptons.

In order to reconstruct the mass of the top squark, it is advantageous to reconstruct as many top quarks as possible (See Section 4.6). When a W decays leptonically it is not possible to fully reconstruct the top quark because of the two neutralinos in the final state.

The channel used to reconstruct the top squark mass is therefore Equation (4) with both W bosons decaying hadronically. The number of events expected, assuming an integrated luminosity of $2ab^{-1}$ is

$$N = 0.274 \times \text{BR}(W \rightarrow qq) \text{BR}(W \rightarrow qq) \sigma \int Ldt = 422 \quad (8)$$

where the factor of 0.274 comes from the branching pair fraction in Equation (4).

The background for this analysis is $e^+e^- \rightarrow t\bar{t}$. The cross section for this process is 59fb. There are 118,000 $e^+e^- \rightarrow t\bar{t}$ events for an integrated luminosity of $2ab^{-1}$.

3.6 Reconstructing SUSY particle masses

There is always a $\tilde{\chi}_1^0$ in the final state from a top squark decay. The $\tilde{\chi}_1^0$ escapes detection so it is not possible to obtain the top squark mass directly.

Indirect methods have to be used to obtain the mass of a squark. The method used in this project assumes the centre of mass energy $\sqrt{s}$ is known and that the centre of mass is at rest in the laboratory frame. Using momentum and energy conservation principles and assuming the squark decays like $\tilde{q} \rightarrow q\tilde{\chi}_1^0$ it is possible to calculate the mass of the squark as

$$m_{\tilde{q}} = \frac{\sqrt{s}}{2} \sqrt{1 - \frac{(E_{q_{max}} - E_{q_{min}})^2}{(E_{q_{max}} + E_{q_{min}})^2}} \quad (9)$$

where $E_{q_{max}}$ and $E_{q_{min}}$ are the maximum and minimum energies of the quark in the laboratory frame. The full derivation of the above is available at [13]. The mass of the $\tilde{\chi}_1^0$ can also be found using the end points of the energy spectrum of the top quark. It is not done in this analysis because it can be measured with much more precision in slepton decays. The $\tilde{\chi}_1^0$ can be measured with a statistical uncertainty of $\pm 3\text{GeV}$ at CLIC [5] in slepton decays.

4 Methods

4.1 Event simulation and reconstruction

All events were simulated using the PYTHIA program [14]. The luminosity spectrum at CLIC operating at $\sqrt{s} = 3\text{TeV}$ was taken into account during the event generation and the beam induced $\gamma\gamma \rightarrow \text{hadrons}$ interactions were overlaid each event. The particle interactions with the CLIC_ILD detector were simulated using the Geant4 program [15]. Each event was reconstructed using the Marlin [16] reconstruction package. Table 1 shows the Monte Carlo data samples that were used in this analysis.

Table 1: Available Monte Carlo data samples

$M(\tilde{t}_1)$	Process	σ (fb)	Events in $2ab^{-1}$	Events available
844GeV	$e^+e^- \rightarrow \tilde{t}_1\tilde{t}_1$	1.65	3300	50,000
894GeV	$e^+e^- \rightarrow \tilde{t}_1\tilde{t}_1$	1.4	2800	10,000
944GeV	$e^+e^- \rightarrow \tilde{t}_1\tilde{t}_1$	1.2	2400	10,000
1044GeV	$e^+e^- \rightarrow \tilde{t}_1\tilde{t}_1$	0.8	1600	10,000
794GeV	$e^+e^- \rightarrow \tilde{t}_1\tilde{t}_1$	1.9	3800	10,000
744GeV	$e^+e^- \rightarrow \tilde{t}_1\tilde{t}_1$	2.2	4400	10,000
644GeV	$e^+e^- \rightarrow \tilde{t}_1\tilde{t}_1$	2.8	5600	10,000
-	$e^+e^- \rightarrow t\bar{t}$	59.0	118000	500000

4.2 Finding Jets

There are three selections of particles available in each event (loose, default and tight) which correspond to different timing and momentum cuts. These cuts help suppress the beam induced backgrounds. The tight selection was used in this project. The particles are forced to reconstruct into exactly 6 jets using the longitudinally invariant k_t algorithm as implemented in FastJet [17]. The energy recombination scheme was used with $R=0.7$. The k_t algorithm computes the distance d_{ij} between each pair of particles in the event as

$$d_{ij} = \min(p_{t_i}^2 p_{t_j}^2) \frac{\Delta R_{ij}^2}{R^2} \quad (10)$$

where ΔR_{ij} is equal to $(y_i - y_j)^2 + (\phi_i - \phi_j)^2$ and p_{t_i} , y_i , ϕ_i are the transverse momentum, rapidity and azimuthal angle of particle i . The four momentum of the pair of particles with the smallest d_{ij} are added to form a single particle. The distances between all pairs are then computed again and the clustering continues until all d_{ij} are above some minimum value, d_{min} .

4.2.1 Flavour tagging

The particles within the jets found using the k_t algorithm were passed to the LCFIPlus package. The LCFIPlus package has algorithms which search for primary and secondary vertices in each event. Using this information, the jets are then clustered together. Each jet is assigned a b-tag and c-tag probability (See Figure 6).

300,000 $e^+e^- \rightarrow Z\nu_e\nu_e \rightarrow qq\nu_e\nu_e$ events are used to train boosted decision trees (BDTs). The BDTs are trained with the properties of the jets in these events, for example the distance between the first and second vertex within a jet. Figure 7 shows the fake rates as a function of b-jet efficiency. For a b-jet efficiency of 0.7, 10% of c-jets are retained.

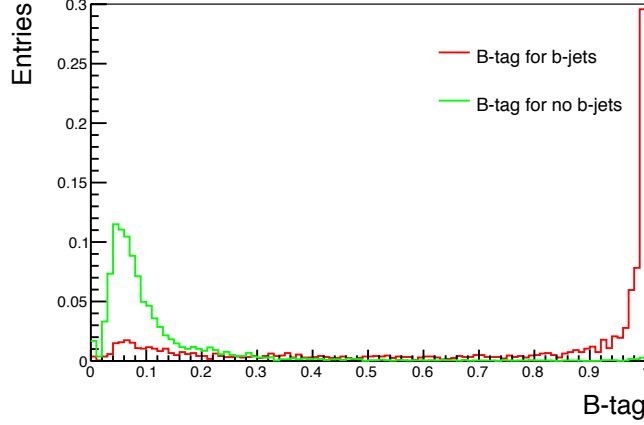


Figure 6

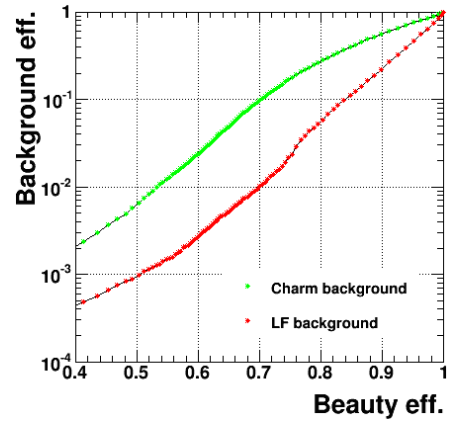


Figure 7

Figure 6: Monte Carlo information is used to plot the B-tag probability for b-jets and non b-jets in $\tilde{t}_1$ events. The histogram is normalised to unit area.

Figure 7: Light flavour (red) jets and c-jets (green) background efficiency as a function of b-jet efficiency.

4.3 Finding Leptons

The Isolated Lepton Processor in Marlin [16] was used to find electrons or muons which originate from W boson decays. The processor loops over all reconstructed particles in the event and searches for isolated leptons. The criteria for a lepton being isolated is detailed in this section.

4.3.1 Optimising Isolated Lepton Processor

The Isolated Lepton Processor has to be optimised for each analysis at CLIC. The variables the processor uses in its selection criteria were plotted for the reconstructed particle closest in space to the generator level lepton and all other reconstructed particles in the event. The closeness of two particles was measured by the quantity

$$\Delta R = \sqrt{(\theta_i - \theta_j)^2 + (\phi_i - \phi_j)^2} \quad (11)$$

where θ is the polar angle, ϕ is the azimuthal angle, and i and j label the particles.

Electrons, positrons and photons deposit most of their energy in the electronic calorimeter whilst hadrons deposit most of their energy in the hadronic calorimeter. The processor can use cuts on two different ratios that use calorimeter information. The first ratio R_1 is defined as

$$R_1 = \frac{E_{ECAL}}{E_{ECAL} + E_{HCAL}} \quad (12)$$

where E_{ECAL} is the energy deposited in the electronic calorimeter and E_{HCAL} is the energy deposited in the hadronic calorimeter. The second ratio R_2 is defined as

$$R_2 = \frac{E_{ECAL} + E_{HCAL}}{p} \quad (13)$$

where p is the magnitude of the momentum of the reconstructed particle. The cuts on R_1 and R_2 can be defined separately for electrons and muons.

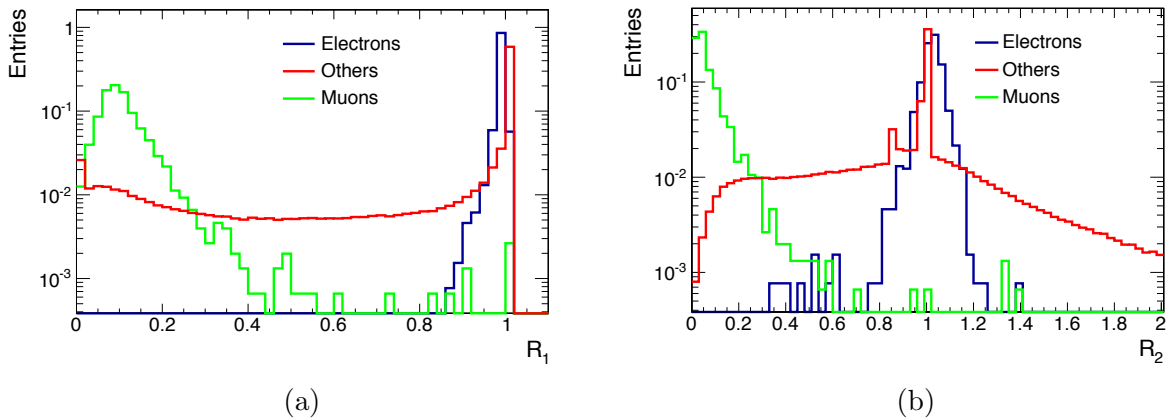


Figure 8: The ratios as defined in Equations (12) and (13) plotted for electrons, muons and other reconstructed particles in each event. The histograms are normalised to unit area with logarithmic y-axes.

Since $W^\pm$ bosons have short lifetimes, the leptons typically come from the primary vertex. In most of the events studied there are hadrons that contain a bottom quark. These hadrons have longer lifetimes so leptons which come from a B hadron decay are more likely to come from the secondary vertex. This information is therefore useful in finding leptons which come from a W boson only. The impact parameter of a track is the perpendicular distance between the track and the primary vertex at closest approach. The impact parameter can be decomposed into two separate components Z_0 and d_0 can be combined to give the full impact parameter:

$$R_0 = \sqrt{Z_0^2 + d_0^2} \quad (14)$$

The full impact parameter R_0 and the transverse component d_0 are shown in Figures 9 (a) and (b) for the matched lepton and all other particles in each event.

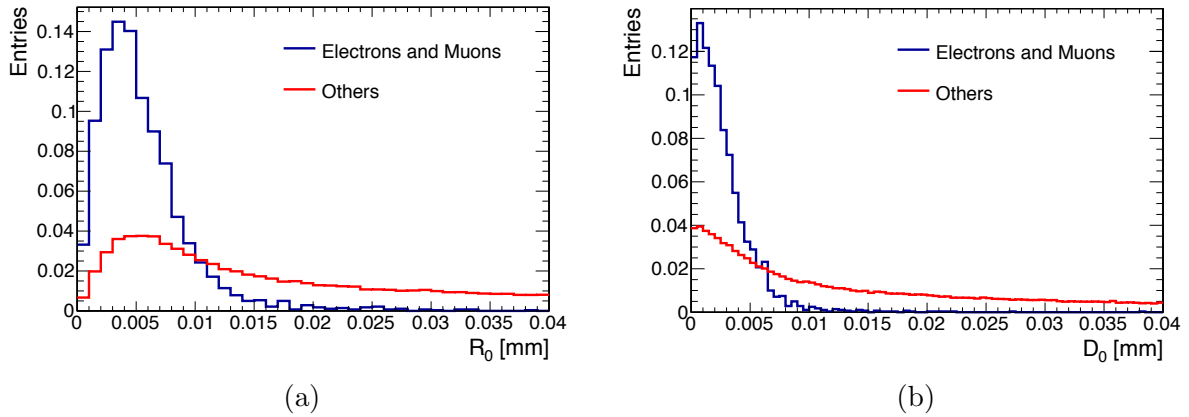


Figure 9: The full impact parameter R_0 (a) and the transverse component d_0 (b) plotted for electrons and muons (blue) and all other reconstructed particles in the event (red). Both histograms are normalised to unit area.

Figure 9 shows that the impact parameter of the lepton from the W decay is smaller than that of other particles on average as expected from the discussion above.

The lepton from the W decay should not have as many particles close to it on average in comparison to other particles in the event. An isolation requirement that is based on the energy of the particles in a cone around a selected particle was used. The cone energy E_{Cone} is defined as the sum of the energy of particles that are within an angle $\cos\theta$ of the selected particle. This angle can be varied. In this project $\cos\theta$ was set to 0.995.

The isolation requirement can be a cut on the maximum and minimum of the cone energy or it can be a polynomial cut in the 2D plane of track energy vs cone energy. The polynomial cut is defined as:

$$E_{Cone}^2 < AE_{Track}^2 + BE_{Track} + C \quad (15)$$

If this equation holds for the selected particle then it passes the isolation requirement. The polynomial cut was used in this analysis with $A = 0.2$, $B = 1$ and $C = 100$. The track energy against cone energy is shown for all matched leptons in Figure 10 (a) and

for matched leptons which pass the isolation requirement in Figure 10 (b). This is also done for all other particles in each event in Figures 10 (c) and 10(d).

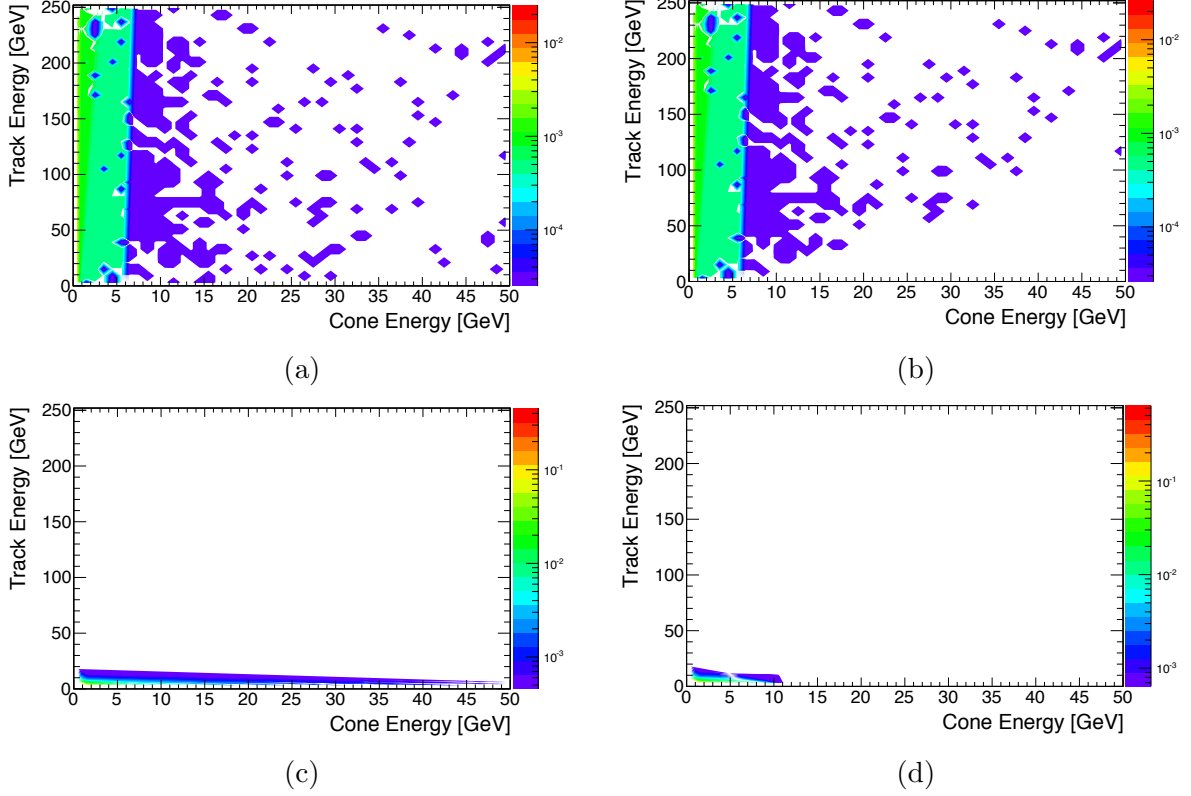


Figure 10: Track Energy against Cone Energy for the matched leptons and all other particles before and after the isolation requirement. The histograms are normalised to unit area and have a log scale in the z axis.

There was also a cut placed on the track energy, the lepton candidate was required to have $E_{Track} > 20\text{GeV}$. The parameters used in the Isolated Lepton Processor are summarised below:

Parameters	Electrons	Muons
Min/Max R_1	0.9/1.0	0/10.0
Min/Max R_2	0.7/1.4	0/0.3
Min/Max d_0 (mm)	0/0.05	0/0.05
Min/Max Z_0 (mm)	0/0.05	0/0.05
Min/Max R_0 (mm)	0/0.05	0/0.05
Minimum E_{Track}	20GeV	20GeV
A, B, C	0.2, 1, 100	0.2, 1, 100

Using these parameters, an isolated lepton was found in 88.6% semileptonic events and in 2.5% fully hadronic events. This based on 10,000 $e^+e^- \rightarrow \tilde{t}_1\tilde{t}_1$ events.

4.4 W boson and top quark reconstruction

The W boson and the top quark were reconstructed by choosing the jet pairings which minimise the χ^2 function

$$\chi^2 = \frac{(m_{j_1 j_2} - m_W)^2}{\sigma_W^2} + \frac{(m_{j_1 j_2 j_3} - m_t)^2}{\sigma_t^2} + \frac{(m_{j_4 j_5} - m_W)^2}{\sigma_W^2} + \frac{(m_{j_4 j_5 j_6} - m_t)^2}{\sigma_t^2} \quad (16)$$

where m_W and m_t are the masses of the W boson and top quark at generator level. The widths σ_W and σ_t were found by matching the position of the generator level particles to the jets in space using ΔR as defined in Equation (11). The invariant mass distributions found by doing this are shown in Figure 11. A Gaussian function is fitted to each mass distribution to obtain the widths.

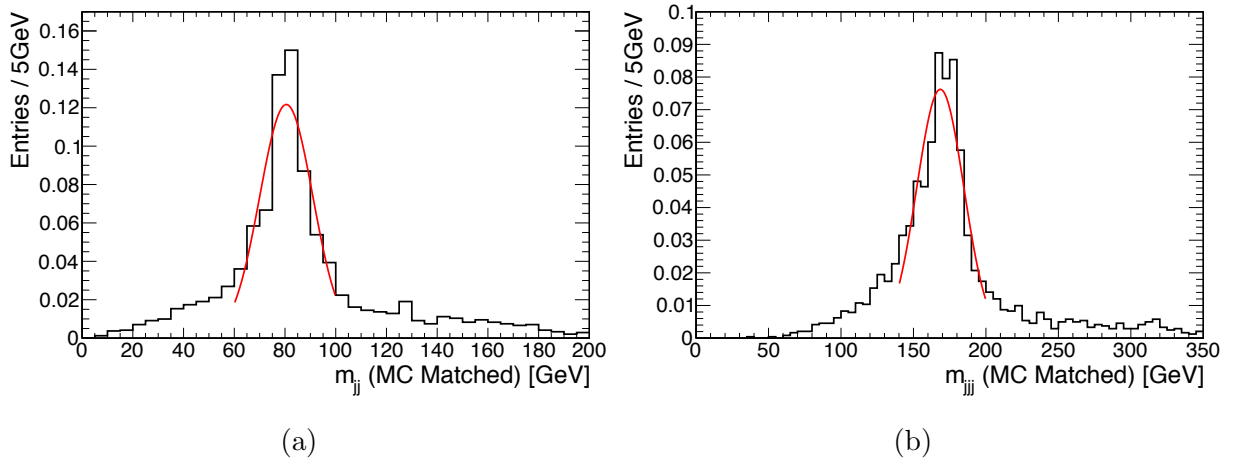


Figure 11: The invariant mass distributions of the W bosons and top quarks found by matching the jets to the generator level particles. Both histograms are normalised to unit area.

The width of the top quark σ_t was determined as 16.2GeV and the width of the W boson σ_W was determined as 10.5GeV.

4.5 Event Selection

The events considered as background in this study are $e^+e^- \rightarrow t\bar{t}$ and all top squark decays other than the channel being investigated.

The following preselection cuts are made on all events:

- No isolated leptons found using the Isolated Lepton Processor.
- $E_{visible} < 2\text{TeV}$ where $E_{visible}$ is defined as the sum of the energy of the jets.
- $E_{j_1j_2j_3} < 1.2\text{TeV}$ and $E_{j_4j_5j_6} < 1.2\text{TeV}$

98% of signal events and 26% of background events pass these cuts.

4.5.1 Boosted Decision Tree

Events were selected using a Boosted Decision Tree (BDT) as implemented in the Toolkit for Multivariate Data Analysis (TMVA) [18]. 10,000 $e^+e^- \rightarrow \tilde{t}_1\tilde{t}_1$ and 30,000 $e^+e^- \rightarrow t\bar{t}$ events were used in the training and testing of the BDT. The events were weighted in TMVA to correspond to an integrated luminosity of $2ab^{-1}$.

The following discriminating variables were used as input to the BDT:

- $E_{visible}$.
- P_T , defined as the total transverse momentum of the particles in the events.
- $\theta^{missing}$, defined as the polar angle of the missing momentum when the momentum of the jets are summed together.
- The invariant masses of the top candidates, $m_{j_1j_2j_3}$ and $m_{j_4j_5j_6}$. In many of the SUSY events, there are 6 jets but only one top quark.
- The invariant masses of the W candidates, $m_{j_1j_2}$ and $m_{j_4j_5}$.
- $\Delta\phi$ between the reconstructed top quarks. In $e^+e^- \rightarrow t\bar{t}$, the ϕ angle between the top quarks will be π . The ϕ angle between the top quarks in SUSY events will vary in each event.
- ΔR between both W candidates and b jets which make up the top candidates.
- Number of particles in the event.
- $\cos\theta_{j_1j_2j_3}$ and $\cos\theta_{j_4j_5j_6}$. The top quarks in $e^+e^- \rightarrow t\bar{t}$ are more boosted than the top quarks in SUSY events.
- Thrust, as defined in [19]
- Oblateness, as defined in [19]
- Acoplanarity, as defined in [19]
- The three highest b-tag and c-tag values

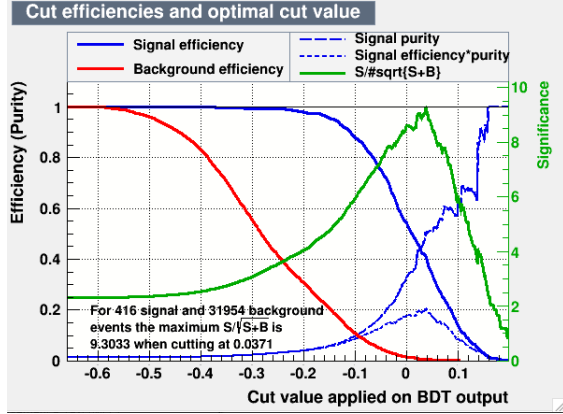
- The jet transition values $y_{34}, y_{45}, y_{56}, y_{67}, y_{78}$, the jet transition value y_{ij} is defined for jets i and $j = i + 1$ as

$$y_{ij} = \min(E_i^2, E_j^2) \frac{(1 - \cos\theta_{ij})}{s} \quad (17)$$

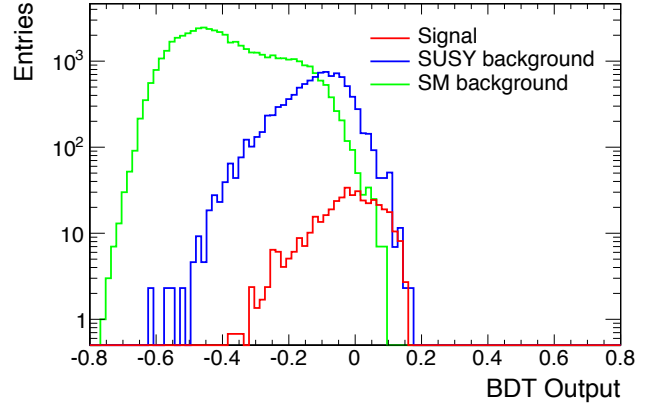
where E is the energy of the jet and $\theta_{ij} = \theta_i - \theta_j$, jets i and j are selected such that y_{ij} is the minimum value out of all jet pair permutations.

TMVA splits the data sample given to it in two samples. One sample is used to train the BDT probability classifier using the discriminating variables in order to create the weight files. TMVA then applies these weight files to the other data sample. The weight files are applied to each event and a probability is calculated to determine whether the event is signal like or background like. The probabilities calculated for events that have passed the preselection cut are shown in Figure 12 (b). The user is free to choose the probability value to cut on. In this analysis the cut value selected was the one which optimised the statistical significance $S/\sqrt{S+B}$ where S is the number of signal events and B is the number of the background events passing the BDT cut. The significance achieved was 9.3 as shown in Figure 12 (a).

The BDT was optimised to increase the significance. The BDT was used in the Adaboost mode with the number of trees reduced to 650. All other settings were the default settings in TMVA.



(a)



(b)

Figure 12: a) The fraction of signal events (blue) and background events (red) passing the BDT cut as a function of the BDT cut. The highest value of the significance (green) gives the value to cut on.

b) The BDT output for signal events (red), other top squark decays (blue) and SM events (green). The y-axis has a log scale.

TMVA lists the discriminating variables in order of how powerful they were in discriminating between signal and background. The four leading discriminating variables were P_T , θ^{missing} , $\cos\theta_{jjj}$ and $\Delta\phi$ between the reconstructed top quarks. These variables are shown in Figures 13 (a), (b), (c) and (d) respectively. The variables were plotted for the signal, fully hadronic final states of other top squark decays and $e^+e^- \rightarrow t\bar{t}$ (fully hadronic).

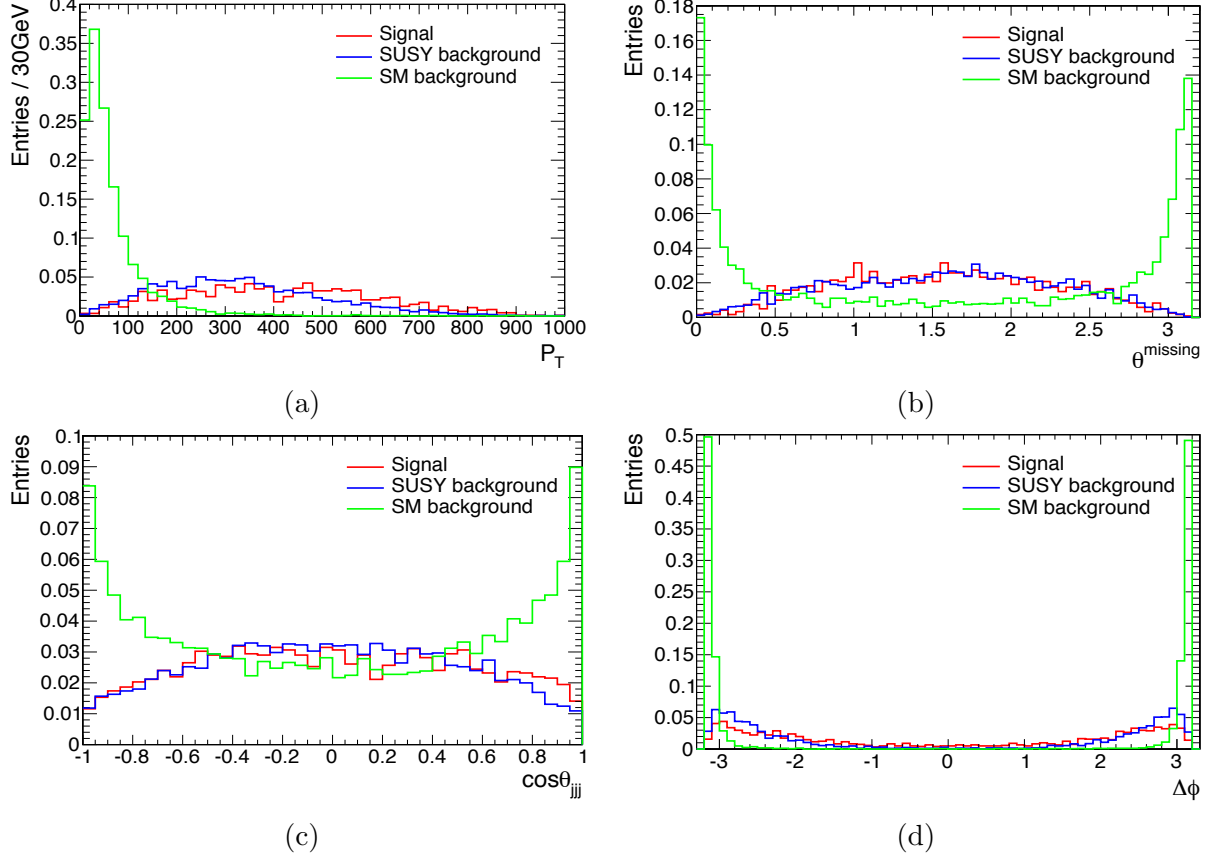


Figure 13: The transverse momentum P_T (a), the polar angle of the missing momentum vector (b), The cosine of the polar angle the top quarks make with the z-axis (c), $\Delta\phi$ between the top quarks (d) are shown for signal events (red), other fully hadronic top squark events (blue) and fully hadronic Standard Model events (green). All histograms are normalised to unit area.

4.6 Energy spectrum of the top quark

The energy spectrum of the top quark is shown in Figure 14 (a) for the signal events. If there was no beamstrahlung, the number of entries would be constant with respect to E_{jjj} . However as discussed previously the beamstrahlung lowers the centre of mass energy for a fraction of events so the energy spectrum is distorted. There are less statistics towards E_{max} and more statistics towards E_{min} .

The weight files from the BDT are applied to data samples which were not used to train the BDT. Figure 14 (b) shows the signal efficiency as a function of E_{jjj} where the signal efficiency is defined as the number of events passing the BDT cut divided by the total number of signal events.

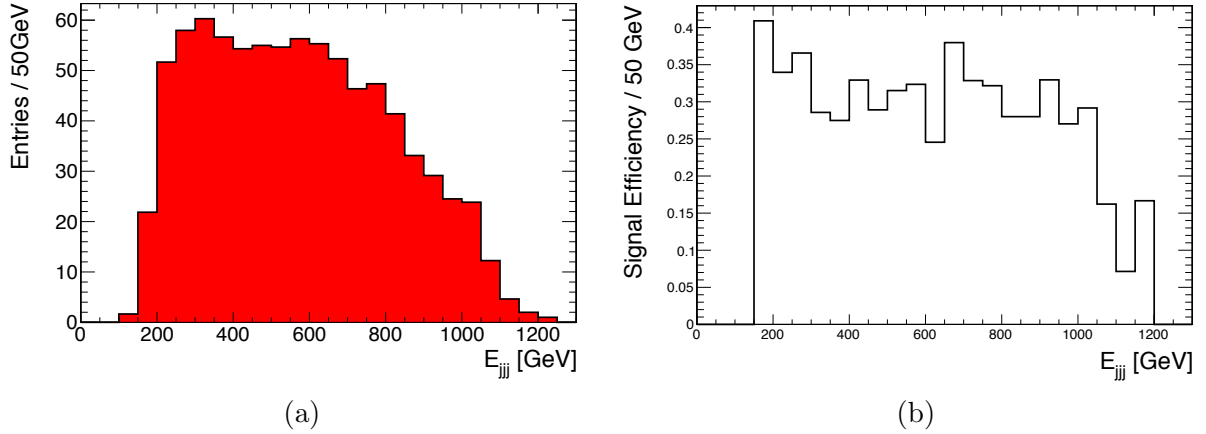
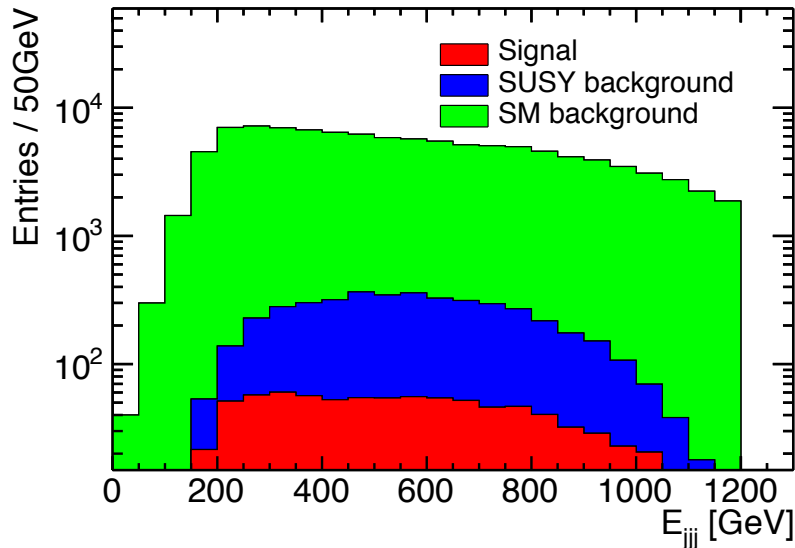
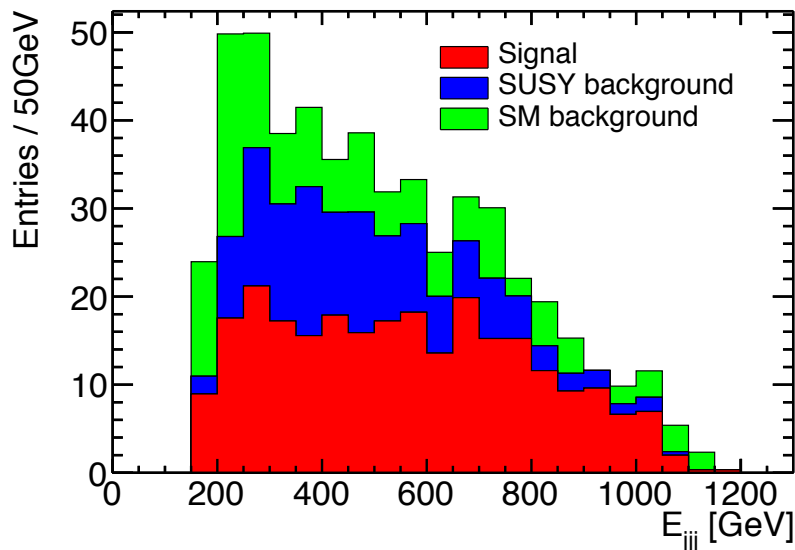


Figure 14: a) Energy spectrum of the reconstructed top quarks in all signal events.
b) Signal efficiency as a function of E_{jjj} .

The top quark energy spectrum for all events that pass the preselection cut and the BDT cut are shown in Figures 15 (a) and (b). 32% of signal events, 2% of SUSY background events and 0.05% of Standard Model events pass the BDT cut. Figure 15 shows significant improvement in the signal to background ratio due to the use of the BDT.



(a)



(b)

Figure 15: a) Energy spectrum of the reconstructed top quarks after the preselection cuts. The y axis has a log scale.

b) Energy spectrum of the reconstructed top quarks after the BDT cut

5 Results

5.1 Template Fitting

Any fit to the end points of the energy spectrum to determine the top squark mass would have to take the beamstrahlung effect discussed in Section 3 into account. A template fit is used instead. In the template fit, the top squark mass is varied with the masses of all other particles kept the same. The following templates were created:

Table 2: Templates created and their associated cross section

$M_{template}$	σ (fb)
$M(\tilde{t}_1) - 200\text{GeV}$	2.8
$M(\tilde{t}_1) - 100\text{GeV}$	2.2
$M(\tilde{t}_1) - 50\text{GeV}$	1.9
$M(\tilde{t}_1)$	1.65
$M(\tilde{t}_1) + 50\text{GeV}$	1.4
$M(\tilde{t}_1) + 100\text{GeV}$	1.2
$M(\tilde{t}_1) + 200\text{GeV}$	0.8

5.1.1 Method 1

In this method, a knowledge of the cross section for each template listed in Table 2 and the branching ratio of $\text{BR}(\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0)$ is assumed. The following quantity was calculated for each template:

$$\chi^2 = \sum_i \frac{(n_{data_i} - n_{template_i})^2}{\sigma_{data_i}^2 + \sigma_{template_i}^2} \quad (18)$$

where the sum is over the bins of the energy spectrum and n_{data_i} and $n_{template_i}$ are the number of entries in each bin for the data and template respectively. The signal events and the SUSY background events from each top squark mass are used when creating the templates. A second order polynomial was fitted to the data points of χ^2 and $M(\tilde{t}_1)$. The minimum of the polynomial was 834GeV. This is shown in Figure 16 (a).

A toy Monte Carlo method was used to find the statistical uncertainty. Each bin in the energy spectrum of the data was smeared with a Gaussian of width $\sqrt{n_{data_i}}$, the mass measurement was then repeated 5000 times. The distribution of the measured masses found using this method are shown in Figure 16 (b). A Gaussian is fitted to this distribution. The width of the fitted gaussian was 23GeV. The measured top squark mass is therefore $M(\tilde{t}_1) = 834 \pm 23\text{GeV}$.

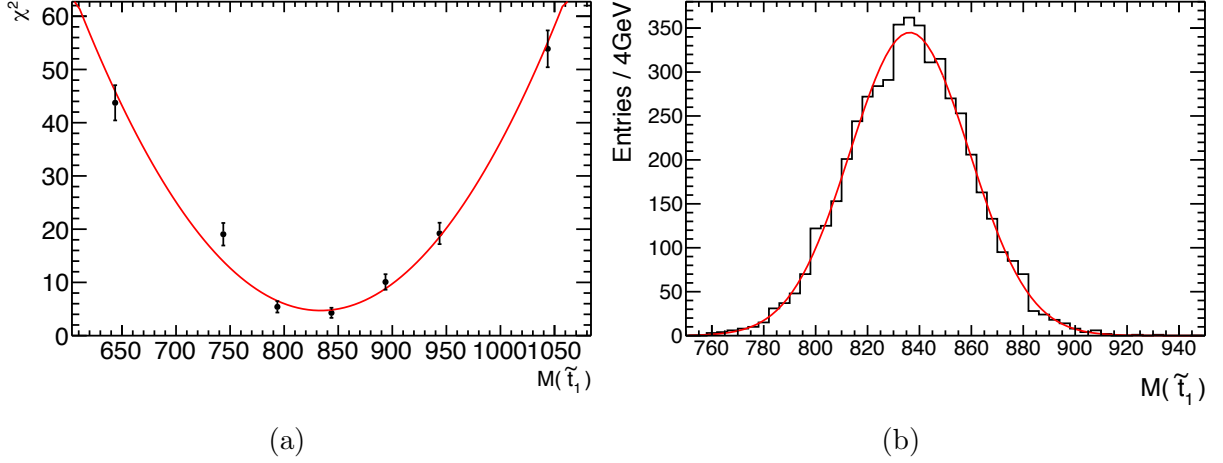


Figure 16: a) The values of χ^2 calculated using Equation (18) for each template. A quadratic is fitted to the data points.

b) Distribution of measured masses after smearing the data and repeating the measurement 5000 times.

5.1.2 Method 2

Another method that allowed the mass and the cross section for pair production to be measured was briefly investigated. In this method the templates are normalised as in the previous method and when calculating the χ^2 the normalisation of the templates is allowed to vary. The following quantity is calculated for each template

$$\chi_j^2 = \sum_i \frac{(n_{data_i} - c_j n_{template_i} - n_{background_i})^2}{\sigma_{data_i}^2 + \sigma_{template_i}^2} \quad (19)$$

where $n_{background_i}$ is the number of Standard Model events passing the BDT cut and c_j is allowed to vary in some interval therefore changing the normalisation. The minimum value of χ_j^2 is selected corresponding to some value c_j . The degree that c_j is allowed to vary impacts the measurement significantly. If knowledge of $\text{BR}(\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0)$ is assumed the cross section for pair production can be measured. Table 3 summaries the measurements:

Table 3: Variation of c_j and the measurements

c_j	Mass measurement	Cross section measurement
$0.8 \rightarrow 1.2$	$818 \pm 26\text{GeV}$	$1.9 \pm 0.1\text{fb}$
$0.5 \rightarrow 1.5$	$816 \pm 43\text{GeV}$	$1.9 \pm 0.2\text{fb}$
$0.2 \rightarrow 5.0$	$867 \pm 85\text{GeV}$	$1.7 \pm 0.5\text{fb}$

The value of c_j for the minimum χ_j^2 calculated for each template was checked. The minimum values of c_j were in the range 0.6 to 2.1. Hence only the results when c_j is varied in the interval $0.2 \rightarrow 5.0$ are valid.

Figure 17 (a) and (c) show the data points of χ_j^2 against the template cross sections and masses. Figure 17 (b) and (d) show the results of the toy Monte Carlo, this is for c_j varying in the interval $0.2 \rightarrow 5.0$.

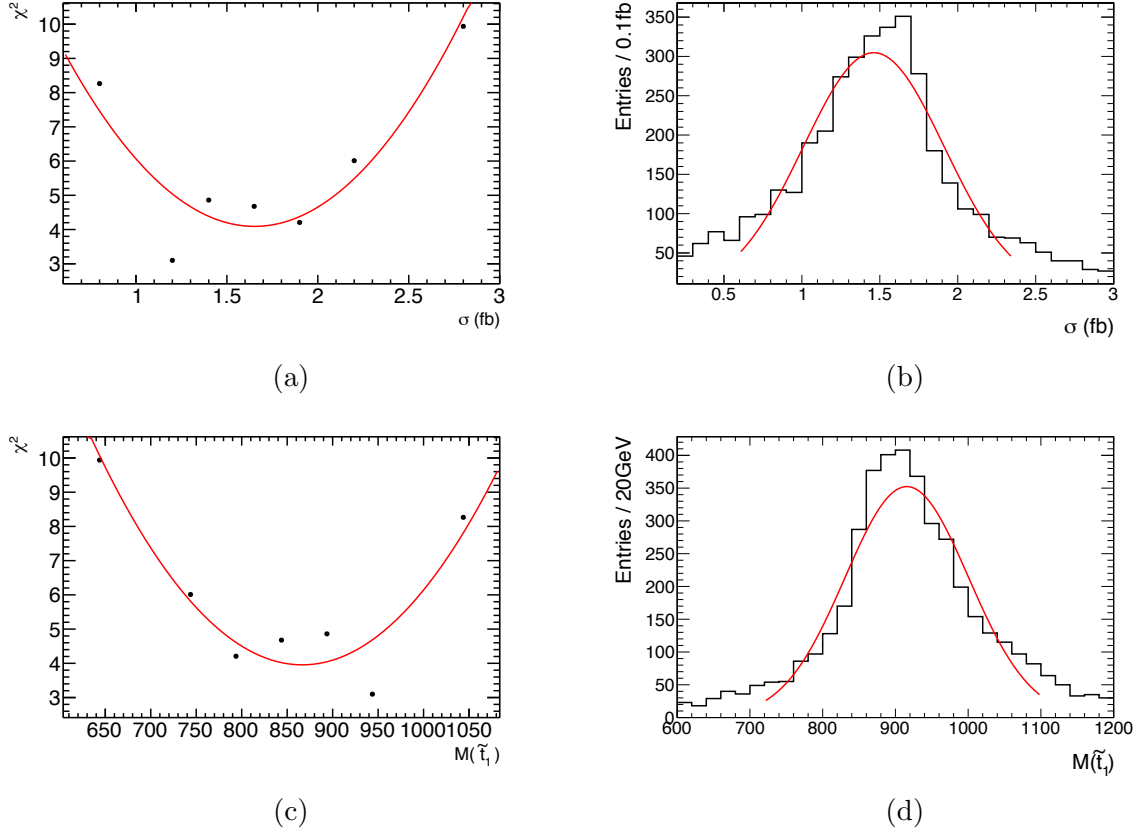


Figure 17

5.2 Systematic Uncertainty

The systematic uncertainties are likely to be negligible in comparison to the statistical uncertainty of 23GeV found in Method 1. Two sources of systematic uncertainty are discussed below.

5.2.1 Uncertainty on the lightest neutralino mass

The end points of the energy spectrum of the top quark are sensitive to the neutralino $\tilde{\chi}_1^0$ mass. The template fits in this project assume knowledge of the mass of $\tilde{\chi}_1^0$. This is acceptable because it can be measured with a precision of $\pm 3\text{GeV}$ in slepton decays [5].

5.2.2 Uncertainty due to event selection

The Boosted Decision Tree (BDT) was trained with a Monte Carlo sample with the top squark mass set to 844GeV. If the top squark does exist then the mass won't be known a priori. The BDT was therefore trained with one of the templates, $M(\tilde{t}_1)+50\text{GeV}$. The mass measurement using Method 1 was then repeated. The result obtained was $M(\tilde{t}_1) = 843 \pm 20\text{GeV}$.

If an excess of events were to be observed that are incompatible with the Standard Model, it is likely that many Monte Carlo data samples would be simulated in order to match the real data. It is likely these samples would be closer to $M(\tilde{t}_1)$ than 50GeV so this uncertainty is also negligible.

6 Discussion

6.1 Mass measurement

The top squark mass was measured as $834 \pm 23\text{GeV}$, a precision of 2.8% at a 3TeV CLIC. The top squark mass in the SUSY model was set to 844GeV so this measurement is in good agreement with the generator value.

There have been other benchmark studies for the CLIC which have measured SUSY particle masses with more precision. For example the chargino $\chi_1^\pm$ and the neutralino $\tilde{\chi}_1^0$ masses have been determined with statistical errors of 1.1% [20] and 1.0% [5] respectively.

The precision for the top squark mass is lower because the cross section for top squark pair production is 1.65fb in comparison to 10.6fb for chargino pair production. In the model studied for the chargino benchmark study, $BR(\chi_1^\pm \rightarrow W\tilde{\chi}_1^0)$ was also 100%. The largest decay mode of the top squark is $\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$, equal to 53.1%. If a ratio R is defined as

$$R = \frac{\sigma(e^+e^- \rightarrow \chi_1^\pm \chi_1^\pm)}{\sigma(e^+e^- \rightarrow \tilde{t}_1 \tilde{t}_1) BR(\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0) BR(\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0)} \quad (20)$$

then $R = 23$. Other benchmark studies have significantly more signal events so it is clear why the statistical uncertainty is larger in this study.

6.2 Mass and cross section measurement

Another method was briefly investigated which allowed the mass and the cross section to be measured simultaneously. In this method the mass was measured as $867 \pm 85\text{GeV}$ and the pair production cross section was measured as $1.7 \pm 0.5\text{fb}$. Both these values are in agreement with the generator values of 844GeV and 1.65fb respectively. Figures 17 (a) and (c) show the polynomial fits to χ_j^2 and the template masses and cross sections are very sensitive to the $\pm 200\text{GeV}$ template data points. More templates could potentially reduce the statistical uncertainties obtained using this method.

6.3 Further Work

The statistical uncertainty on the top squark mass could potentially be reduced by studying the other channels outlined in Section 4.5. The channel studied in this project was

$$e^+e^- \rightarrow \tilde{t}_1 \tilde{t}_1 \rightarrow t\bar{t}\tilde{\chi}_1^0\tilde{\chi}_1^0 \rightarrow W^+W^-b\bar{b}\tilde{\chi}_1^0\tilde{\chi}_1^0 \quad (27.4\%) \quad (21)$$

with both W bosons decaying hadronically. This channel could also be studied with a W boson decaying leptonically. However there are disadvantages of this channel. It is only possible to fully reconstruct one top quark in each event because of the two neutralinos and neutrino in the final state. The most powerful discriminating variable in the BDT was P_T , the sum of the transverse momentum of the particles in the event. This would not be as powerful in reducing the Standard Model background because there is missing P_T in the Standard Model semileptonic events as well. Assuming that 30% of the signal events would pass the BDT cut, the number of reconstructed top quarks in this channel would only be approximately 40.

Another channel that could be studied is

$$e^+e^- \rightarrow \tilde{t}_1 \tilde{t}_1 \rightarrow t \bar{t} \tilde{\chi}_1^0 \tilde{\chi}_2^0 \rightarrow W^+ W^- b \bar{b} h \tilde{\chi}_1^0 \tilde{\chi}_1^0 \quad (13.7\%) \quad (22)$$

in the fully hadronic final state. Although the branching fraction is approximately half that of the channel studied. It is likely that one would be able to reject the background more easily since there are extra discriminating variables. The combined branching ratio of $h \rightarrow b\bar{b}/c\bar{c}/gg$ is 74% so in many events there will be 8 jets. The extra discriminating variables that could be used as input to the BDT are $m_{j_7 j_8}$, extra b-tag and c-tag values and more jet transition values.

The mass and cross section measurements assume knowledge of $\text{BR}(\tilde{t}_1 \rightarrow t \tilde{\chi}_1^0)$ so measuring this quantity would be a priority if the top squark does exist. In the model used in this study it is likely to be challenging because $\text{BR}(\tilde{t}_1 \rightarrow \chi_1^\pm b)$ is equal to 34.1% and $\text{BR}(\chi_1^\pm \rightarrow W^\pm b) = 99.7\%$. Hence the only clear discriminating variable between $\tilde{t}_1 \rightarrow t \tilde{\chi}_1^0$ and $\tilde{t}_1 \rightarrow \chi_1^\pm b$ is the invariant mass of the 3 jets which will be equal to the mass of the top quark in the case of $\tilde{t}_1 \rightarrow t \tilde{\chi}_1^0$. This variable would be lost when the W decays leptonically also.

7 Conclusions

The top squark with a mass of 844GeV has been studied at CLIC at $\sqrt{s} = 3\text{TeV}$. This is an important benchmark study for CLIC because Supersymmetry (SUSY) is one of the leading theories for extending the Standard Model and the top squark is one of the new particles SUSY predicts. It has been demonstrated that a small SUSY signal can be seen over the large Standard Model background using a multivariable analysis approach and that the mass can be measured as $834 \pm 23\text{GeV}$ using a template fit in the fully hadronic final state with 6 jets. This measurement is in good agreement with the generator value.

8 Acknowledgements

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