Techniques for Measuring the Masses of the Chargino and Sneutrino at NLC

James S. Barron

June 21, 2002

Acknowledgments

I thank my adviser Dr. Uriel Nauenberg for all of his patience, guidance, and understanding. I also thank Mihai Dima for helping me to understand analysis techniques. And I thank all the other people in my group who have helped me along the way.

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1 Introduction

The current theory of particle physics is the Standard Model. It describes the interactions between all the particles we have observed. These particles are in two groups. There are the matter particles which make up all the stuff around us. Then there are the force mediating particles. They are responsible for all the forces. The Standard Model describes how these particles interact with each other. Experiment has verified the predictions of the Standard Model to 0.1% or better. In spite of its great success, there are still some problems and many unanswered questions.

One problematic aspect of the Standard Model is that all calculations for particle masses and interactions diverge. Most of these infinities can be eliminated via a process called renormalization. The finite answers that result agree with experiment to fairly high precision. One would like a theory that has no divergences, but such a theory is a long way off. Renormalization works for every particle except scalars. The only scalar in the Standard Model is the Higgs boson. It is important because all particles aquire their mass by interacting with it. When one tries to calculate the mass of the Higgs, renormalization does not work very well. For the other particles, the calculations diverge logarithmically, but the Higgs calculation diverges quadratically. This quadratic divergence means that the renormalized mass could end up being as high as the Plank scale. Guaranteeing that the mass of the Higgs be at the level of hundereds of GeV requires fine tuning up to 15 decimal places or more. Such a precise and arbitrary level of fine tuning seems far to artificial and is called the fine tuning problem. To make matters even more interesting, the Higgs has never been directly seen in experiment. The high energy physics community hopes that its discovery will happen within a decade.

Several extensions to the Standard Model have been proposed for fixing the Higgs problem as well as several other problems that will be discussed in section 3. The most popular class of such extensions invoke what is called supersymmetry. This is a spin symmetry that will also be discussed further in section 3. These theories effectively double the number of particles because it states that each Standard Model particle should have a supersymmetric partner. None of these particles have been seen. It is thought that these particles have not been seen because they are too massive to be produced in current particle colliders. New colliders need to be built in order to investigate this possibility. The Large Hadron Collider (LHC) is currently under construction at CERN in Switzerland. It will collide protons and antiprotons at very high energies that hopefully will produce at least the lightest of these particles.

Many physicists think that the Large Hadron Collider will not be enough [1]. Protons are great for reaching very high energies, but it is argued that it is difficult to make measurements because the interactions produce a very large number of particles. If one wanted to make precision measurements, a cleaner environment is needed. An electron positron collider would be cleaner, but it is more difficult to reach high energies with electrons. When charged particles are accelerated, they radiate energy. This produces an inefficiency. With protons, this radiation is manageable. So one can build a circular collider without insurmountable difficulty. The inefficiencies associated with electrons are much greater. At the energies we need, circular colliders are impossible. To keep radiation down, one needs a huge ring to minimize curvature. Instead, linear colliders are being proposed, which are more difficult to build. But the cleaner environment makes it worth while.

Three linear colliders have been proposed. Japan is working on the Japanese Linear Collider (JLC). Germany is proposing the Tera Electronvolt Superconducting Linear Accelerator (TESLA). And the United States wants to build the Next Linear Collider (NLC). Only one of these three will be built. There is not enough funding for all. Whichever project wins will be the world experiment, and the other two groups will then devote their energies to that project. It will be a world effort with several countries sharing cost, construction, and running. I am working with the NLC group to help figure out the best analysis techniques.

2 The Standard Model

In order to adequately understand supersymmetry, one needs to first talk about the Standard Model. The Standard Model is the current, experimentally verified theory for describing particle interactions. There are two kinds of particles in nature, matter particles and force-carrying particles. Each particle has an intrinsic amount of angular momentum called spin. Spin, like many things, is quantized. Thus each particle has a quantum spin number that describes all the possible spin states. This spin number can only be in integer and half integer units. Matter particles have half integer spin numbers and are called fermions. The force-carrying particles have integer spin numbers and are called bosons. These particles are shown in table 1.

The fermions come in two varieties, each with three generations. The first variety of fermion is called the lepton. An example of this is the electron (e) and its neutrino (ν_e). Then there is the muon (μ) and tau (τ) with their neutrinos. They are just like the first pair except the muon and tau are more massive and are not stable. The next variety is the quark. They make up neutrons, protons, and other particles. The first generation consists of the up (u) and down (d), which compose nuclear matter. Then there are two other generations quite similar to the first. There are the charm (c) and strange (s) as well as the top (t) and bottom (b). Each generation is progressively more massive and less stable. Each generation decays to particles in the previous generation until you reach the first generation particles.

Bosons are responsible for the forces. The Standard Model has three forces, the electromagnetic, weak, and strong forces. Gravity is not included because we do not know how to quantize it. Photons (γ) mediate the electromagnetic force, the $W^{\pm}$ and Z^0 mediate the weak force, and gluons (g) mediate the strong force. Thus we have all the known particles.

There is one more particle in the Standard Model called the Higgs (h_0). It is the only Standard Model particle that has not yet been seen directly in experiments. The concept of the Higgs particle was invented to fix a major problem with the Standard Model. Unless all the particles are massless, the mathematics diverges unmanageably. The Higgs particle fixes this by supplying a mechanism for acquiring mass. In the Standard Model, particles do not have an intrinsic mass but get their mass by interacting with the Higgs particle. In this way, particles can have mass without the theory breaking down. But as mentioned in the introduction, the Higgs calculations diverge quadratically causing the fine tuning problem.

3 SuperSymmetry

Supersymmetry states that for every boson there is a fermion counter part and vice versa. Thus the electron has the superpartner called the selectron, and the photon has the counterpart called the photino. All the particles are shown in table 2. This theory was initially studied because of its theoretical elegance. Further studies revealed that it has several nice properties that may lead to answers to many problems.

The first observation is that in the Standard Model, the electromagnetic

Fermions		Bosons
Leptons	Quarks	$W^{\pm}$, Z^0
$e^{\pm}$, ν_e	u, d	γ
$\mu^{\pm}$, ν_μ	c, s	g
$\tau^{\pm}$, ν_τ	t, b	h^0

Table 1: The Standard Model particles

and weak forces have been replaced by electroweak theory. In this theory there are only two fields called the U(1) and SU(2), named after the symmetries they exhibit. The photon and the Z^0 are mixtures of the U(1) and SU(2) fields while the $W^{\pm}$ is pure SU(2). So the electromagnetic and weak forces are actually just two aspects of one thing. The strong force is SU(3). Each of these three fields have coupling constants that describe the strength of their interactions. The coupling constants are not actually constant. They vary with the energies involved in the interaction. What happens is that any particle has many virtual particles comming in and out of existence around it. Particles then interact by exchanging these virtual particles. But a particle can also interact with the virtual cloud itself thus polarizing it. Space itself then become a polarized medium that effects the amount of effective charge sensed by nearby particles. For electromagnetic charge, this polarization screens the charge making it appear weaker at ”large” distances. This is because virtual particles of opposite charge congregate around it. At high energies, particles can probe deeper into this cloud and see more of the charge. For the strong force, the opposite happens. Particles of the same color charge stay near the particle. Hence the more energy involved in the interaction of particles, the deeper they probe into the virtual cloud and the strength of the interaction changes. If there are supersymmetric particles with masses within the range of 100 to 1000 GeV, then these coupling constants converge at very high energies. This suggests that there is a unification of the forces at these high energies, that they are just aspects of one unifying principle similar to the unification in electroweak theory. This unification does not happen in the Standard Model.

Next there is the cosmological question about the energy content of the universe. Astronomical measurements have shown how much of the energy density of the universe is due to matter, but we do not observe enough matter to account for this fraction. It is believed that there is some kind of "dark matter" that we cannot see. Supersymmetric Models could provide an explanation to dark matter since some varieties predict the existence of heavy particles that only interact via the weak force and are stable. The variety we assume here is such a theory. It comes from what is called R-parity conservation, which is explained in section 3. Since it only interacts weakly, no current instrumentation can see them.

It also provides a solution to the problem with the Higgs. The Higgs mass calculations diverge because of how it interacts with all the other particles. If there are superpartners, then their interactions can partially cancel the contributions from the Standard Model particles to render a finite mass. Actually, supersymmetry introduces several Higgs particles. There are two neutral and a charged version of the particle.

Below is a table of all the supersymmetric particles with their Standard Model partners on the left. The chargino ($\widetilde{\chi}_1^{\pm}$) and muon sneutrino ($\widetilde{\nu_\mu}$) are highlighted in red. These are the particles that I am studying in this thesis. The chargino is actually a mixture of the superpartners of the charged bosons (W's and charged Higgs). In this study I am only interested in the lightest of these mixtures.

Supersymmetry has a lot of room for variation. Since there is not much data to restrict possible models, there are virtually an infinite number of possibilities. In this paper we assume a minimal supergravity inspired version of supersymmetry. A very important consequence of the theory comes from the fact that proton decay has not been observed. Several experiments have been done to see if protons decay. The experimental results show that if protons do decay, they have half lives that are several times the age of the universe. So here we assume that protons do not decay. This puts a constraint on the theory. This constraint is codified as conservation of R-parity. In R-parity, each Standard Model particle has parity 1 and supersymmetric particles have parity -1. In any interaction, the product of parities for particles going into the interaction must equal the product of parities for those leaving the interaction. This means that supersymmetric particles must decay into an odd number of supersymmetric particles, thus at least one. The logical result is that the lightest one must be stable because of energy conservation. There are several candidates for this particle, but here we assume it to be the neutralino ($\widetilde{\chi}_1^0$). The neutralino only interacts via the weak force, thus it would be a source of dark matter. Note that in other theories the lightest supersymmetric particle is something else such as the sneutrino.

Even this is not enough to nail things down. The theory has several parameters that can be adjusted over a large phase space [2]. These parameters are the universal scalar mass m_0, the universal gaugino mass $m_{1/2}$, the supersymmetric Higgsino mass parameter μ, and $tan\beta$, the ratio of the vacuum expectation values of the two neutral Higgs scalars. The first two parameterize the masses of the sleptons while the other two parameterize the masses of the neutralinos and charginos. Since we do not know which set of parameter values, if any, are correct, several representative points have been picked for research. It is thought that most qualitative possibilities would be reflected in these points. There was a meeting at the Snowmass resort in Colorado in 1996 and one in 2001 (which I attended) where selection of these points was discussed and decided upon [3]. The ones for 1996 are shown in table 3 along with the masses of the particles at those points. I am working with the parameters in point 2 from the 1996 meeting.

Nonsupersymmetric		Supersymmetric
$e^{\pm}\ \nu_e$		$\widetilde{e}_L^{\pm},\ \widetilde{e}_R^{\pm}\ \widetilde{\nu}_e$
$\mu^{\pm}\ \nu_\mu$		$\widetilde{\mu}_L^{\pm},\ \widetilde{\mu}_R^{\pm}\ \widetilde{\nu}_\mu$
$\tau^{\pm}\ \nu_\tau$		$\widetilde{\tau}_L^{\pm},\widetilde{\tau}_R^{\pm}\ \widetilde{\nu}_\tau$
$u,\ d$	$\Leftrightarrow$	$\widetilde{u},\ \widetilde{d}$
$c,\ s$		$\widetilde{c},\ \widetilde{s}$
$t,\ b$		$\widetilde{t},\ \widetilde{b}$
g		$\widetilde{g}$
$W^{\pm},\ H^{\pm}$		$\widetilde{\chi}_1^{\pm}\ ,\ \widetilde{\chi}_2^{\pm}$
$\gamma,\ Z^0,\ h^0,\ H^0$		$\widetilde{\chi}_1^0\ ,\ \widetilde{\chi}_2^0,\ \widetilde{\chi}_3^0,\ \widetilde{\chi}_4^0$

Table 2: The Supersymmetric Model: Particles in blue are nonsupersymmetric particles introduced by supersymmetry. Those in red are the particles I am measuring.

4 The NLC

None of these supersymmetric particles (sparticles) have been seen so far. It is thought that this is because the particles are too massive to produce in current colliders. What is needed are colliders that accelerate to higher energies. These higher energies can then produce heavier particles. The Next Linear Collider is a proposed machine that would do just this [4]. A layout is given in figure 1. It would collide a beam of electrons with a beam of positrons at very high energies. Hopefully this will produce new particles for physicists to study. Our hope is that these new particles will be the supersymmetric ones. The machine has not been approved yet. Much research is being done and proposals will soon be presented to several governments for its construction. My project is to simulate the detector and use the simulated data to figure out how one would reconstruct particle masses.

	Point 1	Point 2	Point 3	Point 4	Point 5
m_0	400	100	200	–	300
$m_{1/2}$	200	300	100	–	150
A_0	0	0	0	–	-600
$\tan\beta$	2	2	2	10	2
μ	-502	-528	-256	-100	427
$\widetilde{\chi}_1^0$	86	129	45	77	57
$\widetilde{\chi}_2^0$	176	258	97	115	111
$\widetilde{\chi}_3^0$	505	531	276	146	428
$\widetilde{\chi}_4^0$	514	538	278	292	449
$\widetilde{\chi}_1^\pm$	176	258	97	96	109
$\widetilde{\chi}_2^\pm$	513	537	276	292	446
h^0	79	83	68	126	92
H^0	739	649	377	201	597
A^0	733	643	369	200	593
$H^\pm$	738	648	377	214	598
$\widetilde{\nu}$	421	230	207	1000	315
$\widetilde{\ell}_R^\pm$	409	157	207	1000	307
$\widetilde{\ell}_L^\pm$	426	238	216	1000	321
$\widetilde{t}_1$	394	507	249	924	176
$\widetilde{t}_2$	524	621	310	1096	463
$\widetilde{b}_1$	501	596	264	1000	370
$\widetilde{b}_2$	579	622	302	1000	443
$\widetilde{q}_R$	580	626	301	1000	442
$\widetilde{q}_L$	593	653	306	1000	456
$\widetilde{g}$	531	731	285	900	406

Table 3: The supersymmetry points from Snowmass 1996. Here the parameters and particle masses are given in GeV. My work assumes point 2.

The collider sends the two beams down pipes where they intersect and interact. Around the interaction point would be the detector, which is made of several components, each being a module that measures the origin, momentum, and kinetic energy of particles produced by the collisions. This is illustrated in figure 2. The closest layer is the vertex detector (light blue), which figures out where in space particles decay. After this is the tracker (rust color) which reconstructs the trajectories of particles, their momenta, and charge. There is a magnet (green) to bend the tracks of charged particles so we can measure their momentum and charge. Then there are a few layers of calorimeters which reconstruct how much kinetic energy each particle has (dark blue, maize, and red). I am only looking at the tracking data for reasons that will be elaborated later.

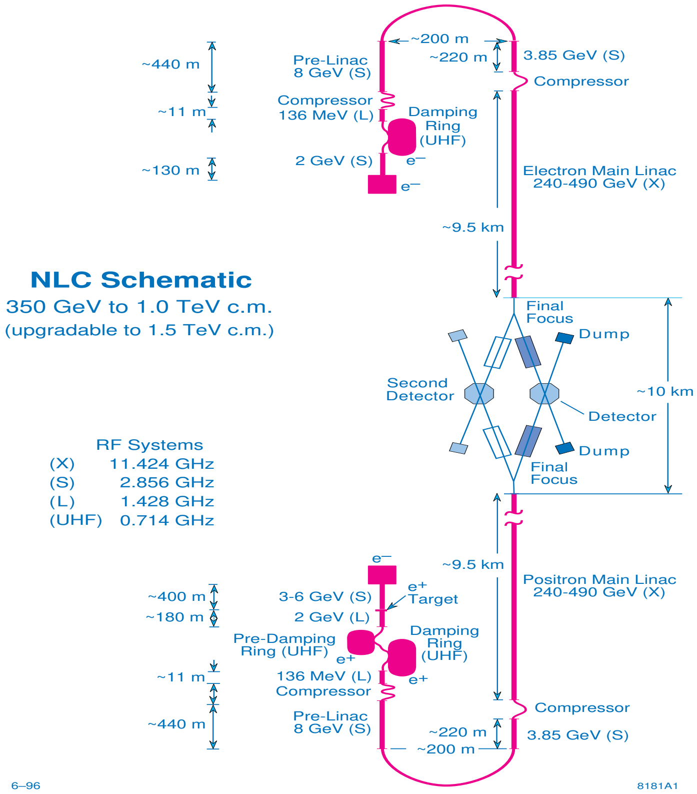

Figure 1: The NLC

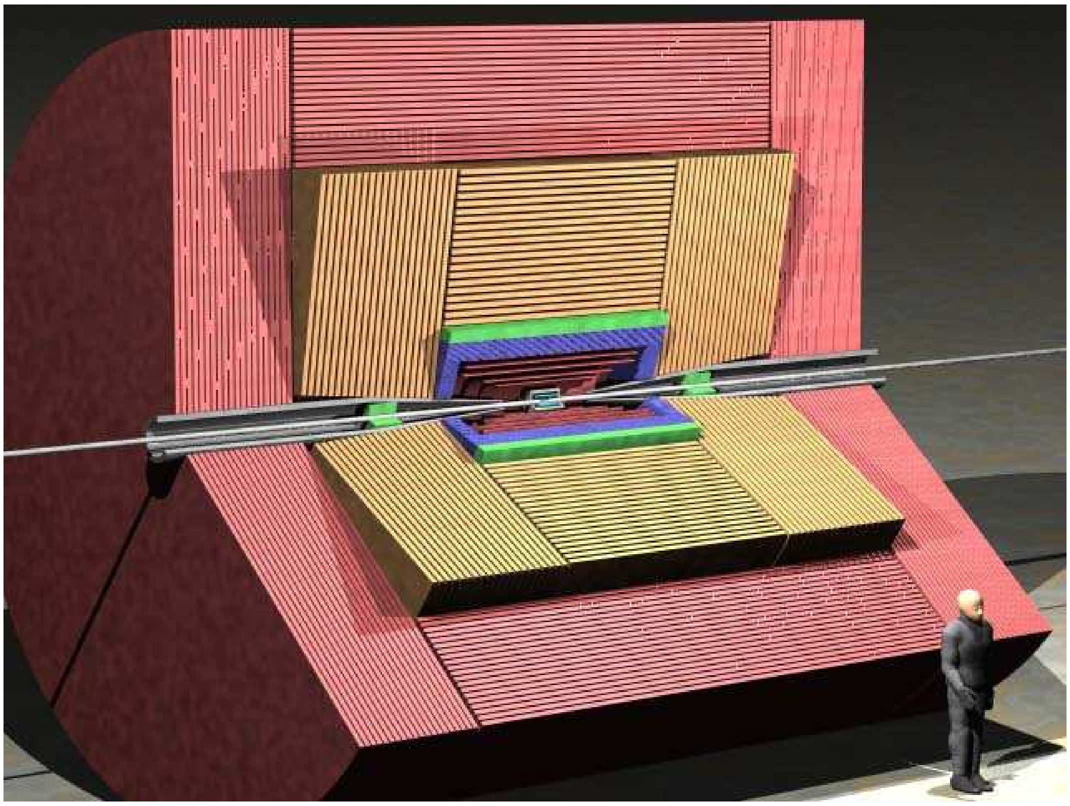

Figure 2: The detectors

mode	fraction
$\widetilde{\nu}_\ell l$	65.8%
$\widetilde{\ell}_L \nu_l$	21.4%
$\widetilde{\tau}_2 \nu_t$	10.5%
$\widetilde{\chi}_1^0 W^\pm$	1.7%

Table 4: Decay modes of the $\widetilde{\chi}_1^\pm$.

5 My Project

I work for Dr. Uriel Nauenberg at the University of Colorado at Boulder. We do high energy particle physics simulations for the NLC. Our focus is to determine the best methods for measuring supersymmetric parameters if supersymmetry is found at a linear collider or the Large Hadron Collider. My project is to figure out the masses of two supersymmetric particles, the lightest chargino and the sneutrino, using the output of our simulated detector.

5.1 The Event

My specific project is to study the reaction where electrons and positrons annihilate and produce a chargino-antichargino pair. There are two varieties of chargino, and I am looking at the lighter version. A light chargino can decay into several different particles. The various decay modes and their branching ratios (probabilities of occurring) are shown in table 4. I am analyzing those events where both charginos decay into a muon and muon sneutrino. At this supersymmetry point, the sneutrino only decays into a neutralino and neutrino, both of which only interact weakly. Thus they are never seen. All one sees is a pair of muons with a lot of missing energy that was taken away by the sneutrino. The event is diagrammed in figure 3.

The reason I picked muons is because they are rather easy to identify. Muons generally pass through all of the detectors, leaving an energy trail as it goes. All the other charged particles stop before exiting the detectors. Since I know the mass of a muon and can find out its momentum from the tracker, I do not need to use calorimeters at all, which is nice for me because our algorithms for analyzing calorimeter data are not working very well at the moment.

I can use the energy distribution of the muons to find the masses of the chargino and sneutrino. From relativity it turns out that the muons can range between a minimum and a maximum energy which are determined by the masses of the two particles. If one can measure these limits, one can calculate the masses using the equations derived in appendix A. The kinematics of the event guarantees that the distribution of energies between these limits should be homogeneous. Hence it is just as likely to be at one energy as any other. So if one plots a histogram of the number of particles versus their energy, the plot looks like a box. My job is to try to observe and measure at what muon energies the edges of the box are located.

This chargino event is not the only one that can produce a pair of muons. There are several others, both supersymmetric and from the Standard Model. These events are called background. They can obscure the box and prevent measurements of the edges. So one must eliminate as much of the background as possible so as to make the most accurate measurement of the box edges.

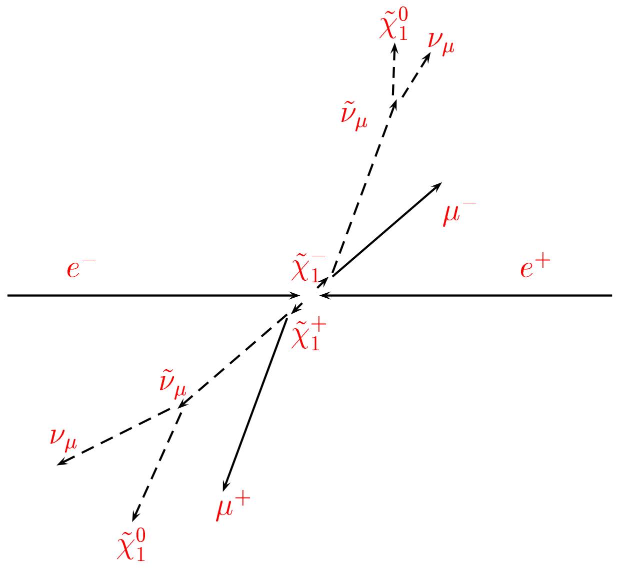

Figure 3: Chargino Event. Particles with dashed lines are not seen by the detectors.

5.2 The Simulation

The simulation is essentially a three stage process. The first stage was generating a year's worth of events using the program Isajet [5], which is a program that generates particle interactions with the statistics predicted by your version of supersymmetry. I also used HERWIG [6] to generate the muons from scattering (two photon events). The next step is to put these events into a detector simulation to see what output would be produced. I used GEANT 3 developed by CERN [7] and NLCProc developed here at CU [8]. The final stage is to analyze the data to reconstruct what happened. I used Java Analysis Studio developed at SLAC [9] as well as ROOT developed at CERN [10]. These programs do track and cluster reconstructions as well as general analysis. I used these to find out the muon energy distributions, make cuts, and find the edges to the box. Since there is a lot of data to generate for many types of events, signal and background, I developed shell scripts that manage the data production, breaking the tasks up into smaller jobs that our computers can manage.

5.3 The Data

The data is shown in figure 4 with all the background. The major source of background is what is called the two photon background. This is where an electron and positron can scatter, producing a pair of muons [11]. The electrons continue down the beam pipe and are not seen while the muons enter the detectors. We call it the two photon background because it is caused by two virtual photons interacting to produce a pair of real muons. There is a detector that lies in the beam pipe to detect these deflected electrons. Since the beam would destroy anything in its path, there must be a hole in the center of this detector, so those deflected electrons that pass through the hole will not be detected. These detectors would be about 150cm away from the interaction point. I have assumed the hole has a 3cm radius. This means that any electrons traveling at an angle smaller than 20 mrad will escape detection. This detector can veto about 99% of these events, but some still remain. This turns out to be about 12 million. The full signal is in figure 4 and includes the 12 million two photon events. The two photon background completely obscures everything else because the rest adds up to a mere 9000 events including other background.

Here is a breakdown of everything else. In figure 5 is the plot of the

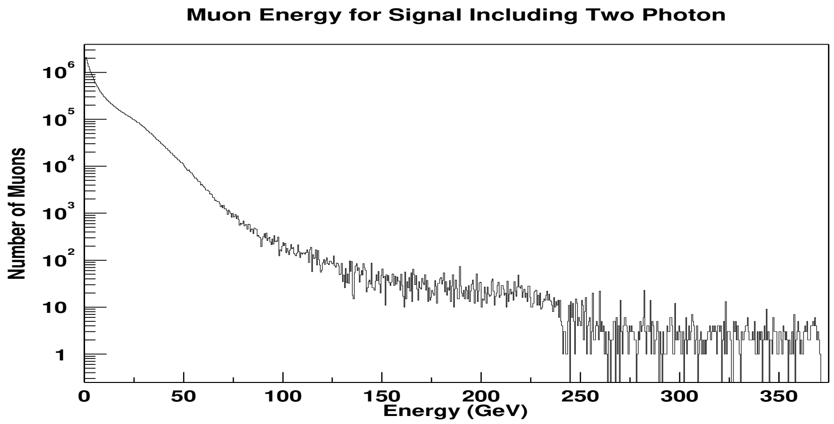

Figure 4: The data

pure signal (what we want), and figures 6 to 10 show each source of background other than two photon. WW events are the only other significant Standard Model background. This is where the annihilation of the electron and positron produces two W particles. Each can then decay into a muon and muon neutrino. As one can see in figure 6, the WW events cover a wide range of energies all the way up to about 375 GeV.

The others come from supersymmetric channels. We have the direct production of smuons, which decay into muons. This is shown in figure 7. There are actually two kinds of smuons. It turns out that supersymmetric particles must have the same number of degrees of freedom as their Standard Model counterparts. Electrons have spin number $\frac{1}{2}$ and can be oriented in the direction of motion or away. This is called right and left handed polarization. Smuons have spin zero, thus they cannot have polarization states. Instead, there are two versions with different masses. This accounts for that degree of freedom. Because of these two different masses, there are two boxes, one for each kind of smuon. We could also have charginos that decay into smuons. This is in figure 8. At this point, charginos can only decay into the "left handed" smuon. Thus you only see one box.

Charginos can decay to taus which can go to muons. This is shown in figure 9. Since this is a tertiary decay (chargino to tau to muon), it is not a box. Instead the distribution is exponential. It is true that the chargino to smuon to muon decay mentioned in the previous paragraph is also a tertiary

mode	fraction
$\tilde{\nu}_\mu \mu$	22%
$\tilde{\mu}\nu_\mu \to \tilde{\chi}_1^0 \mu \nu_\mu$	11%
$\tilde{\chi}_1^0 W \to \tilde{\chi}_1^0 \mu \nu_\mu$	0.18%

Table 5: Decay modes of the $\tilde{\chi}_1^{\pm}$ that produce μ's. The one in red is my event.

decay, but that gave you a box because the first decay involved a smuon and neutrino. The neutrino takes away almost no energy or momentum, so the box shape is largely preserved. Tau decays, on the other hand, are more complicated, and this dynamics produces the exponential distributions instead.

Finally, one can produce two neutralinos. One is the lightest, called the $\tilde{\chi}_1^0$, and does not decay. It is never seen because it only interacts via the weak force. The other is the second lightest, or $\tilde{\chi}_2^0$. It can decay into a smuon and a muon or a tau which could eventually decay into muons. The box at the lower end of figure 10 is from the secondary decay. The rest is from the tertiary decays.

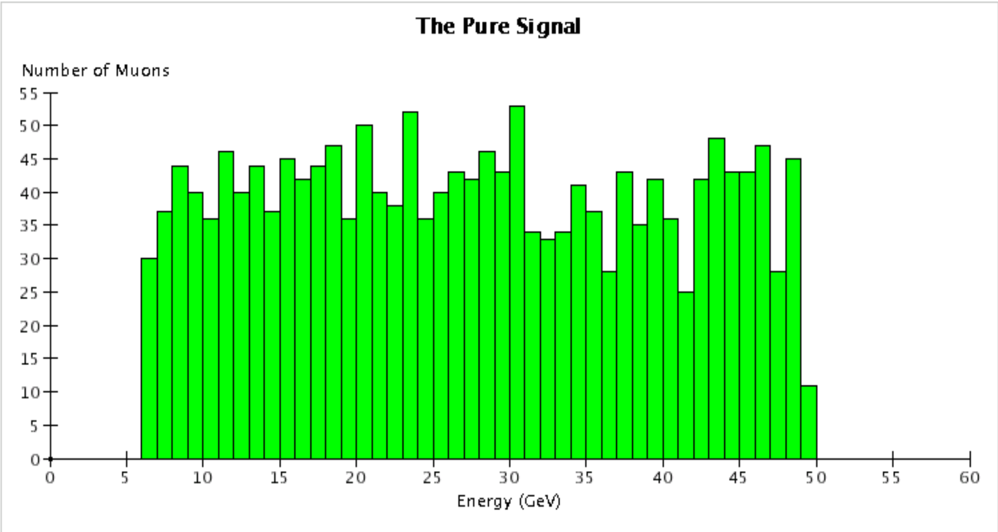

Figure 5: The pure signal

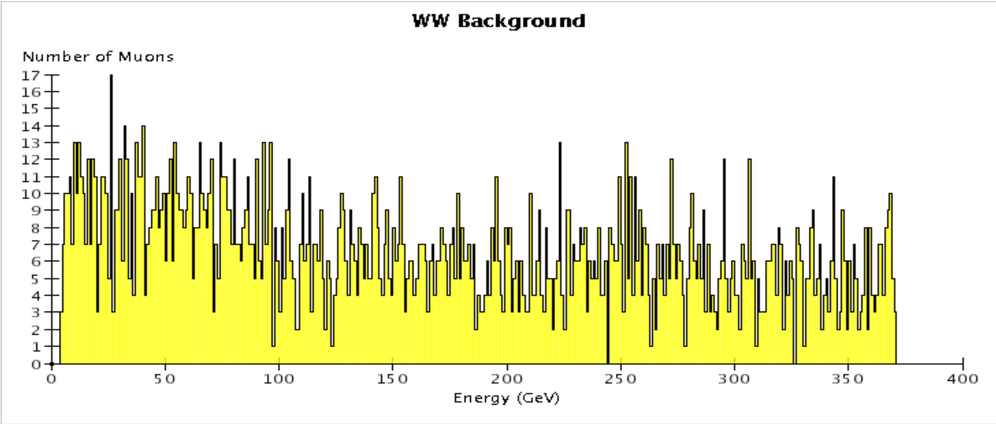

Figure 6: The W^+W^- background

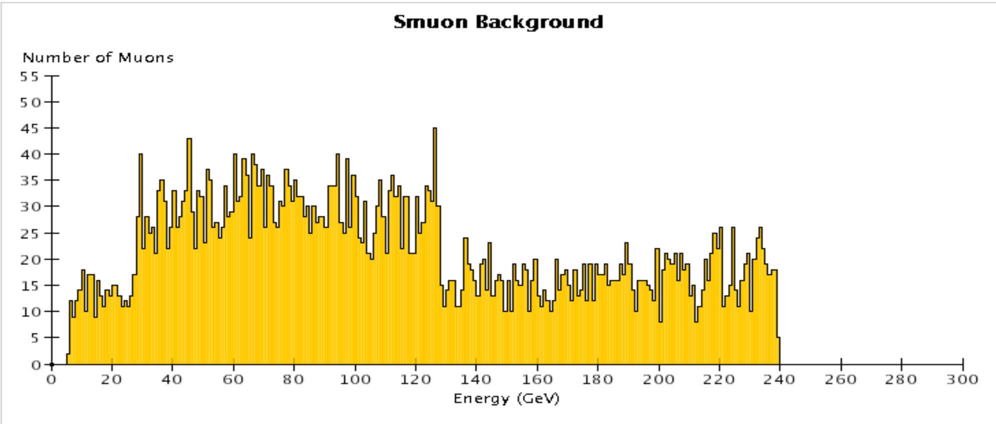

Figure 7: The $\widetilde{\mu}$ background

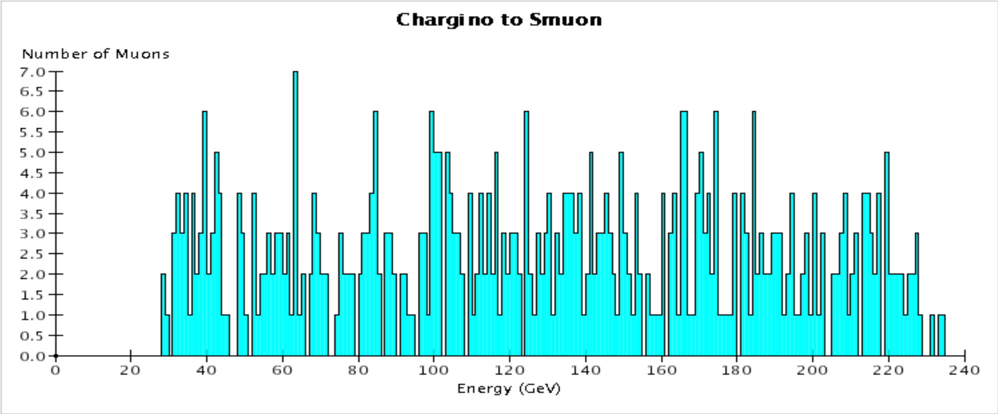

Figure 8: $\widetilde{\chi}_1^{\pm}$ to $\widetilde{\mu}$ background

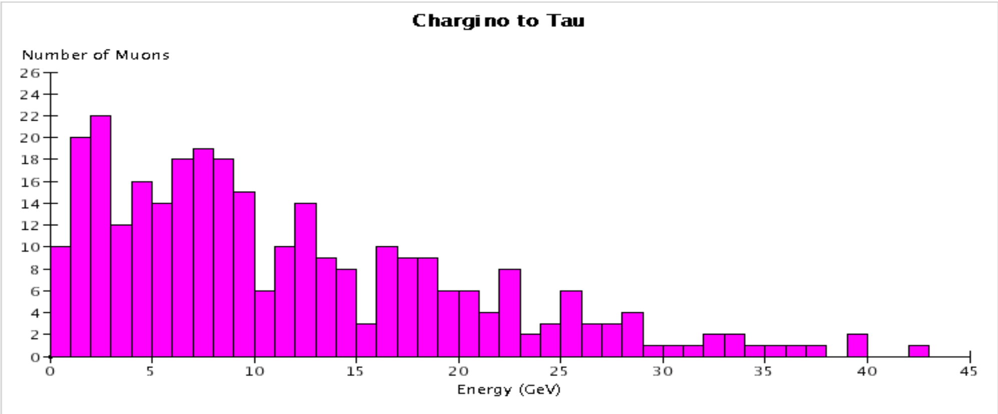

Figure 9: $\widetilde{\chi}_1^{\pm}$ to τ background

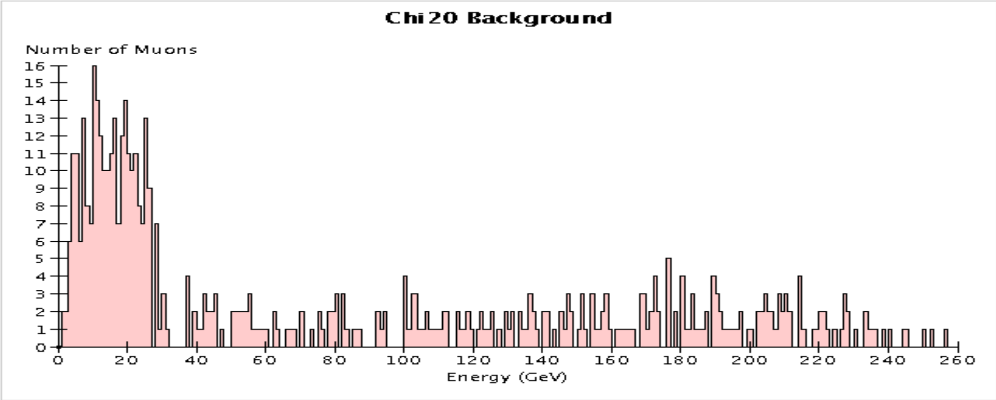

Figure 10: $\widetilde{\chi}_2^0$ background

5.4 Getting Rid of the Two Photon Background

The two photon background is the main background to worry about. Figure 11 shows a plot of everything without the two photon background. The box is clearly seen on the left side of the plot. So the other backgrounds are nothing compared to the two photon events. We are going to try to cut out the two photon background and in the process reveal this structure.

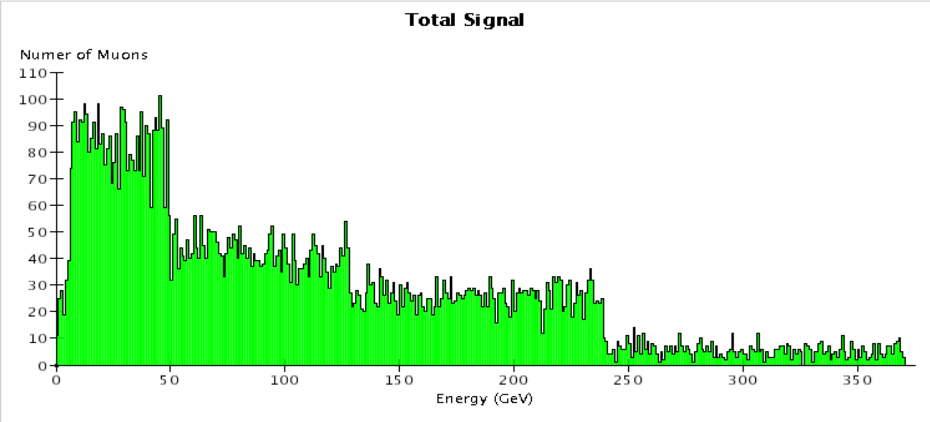

Figure 11: The data without two photon

I use a cut based on transverse momentum to get rid of the two photon background. If one could see all the particles and add up their momenta, then there would be no component transverse to the beam direction by conservation of momentum. Since supersymmetric events have momentum carried off by an invisible neutralino, there is some nonzero transverse momentum. There is also transverse momentum in two photon processes because of the electrons that do not enter the detector, but the distributions of transverse momentum are different. So one can try to use this difference for a cut. One can look at the transverse momentum of one muon versus the other.

Figure 12 shows the transverse momentum distribution for the two photon background when you have a 3cm radius hole in the beam pipe detector. Figure 13 shows the distribution for everything else. Notice that in figure 12, all the events are below 14 GeV/c. This is to be expected since the electrons would need low transverse momentum to pass through the holes in our detectors. But in figure 13, everything else is mostly above 14 GeV/c. So I cut out every event with transverse momentum less than 14 GeV/c.

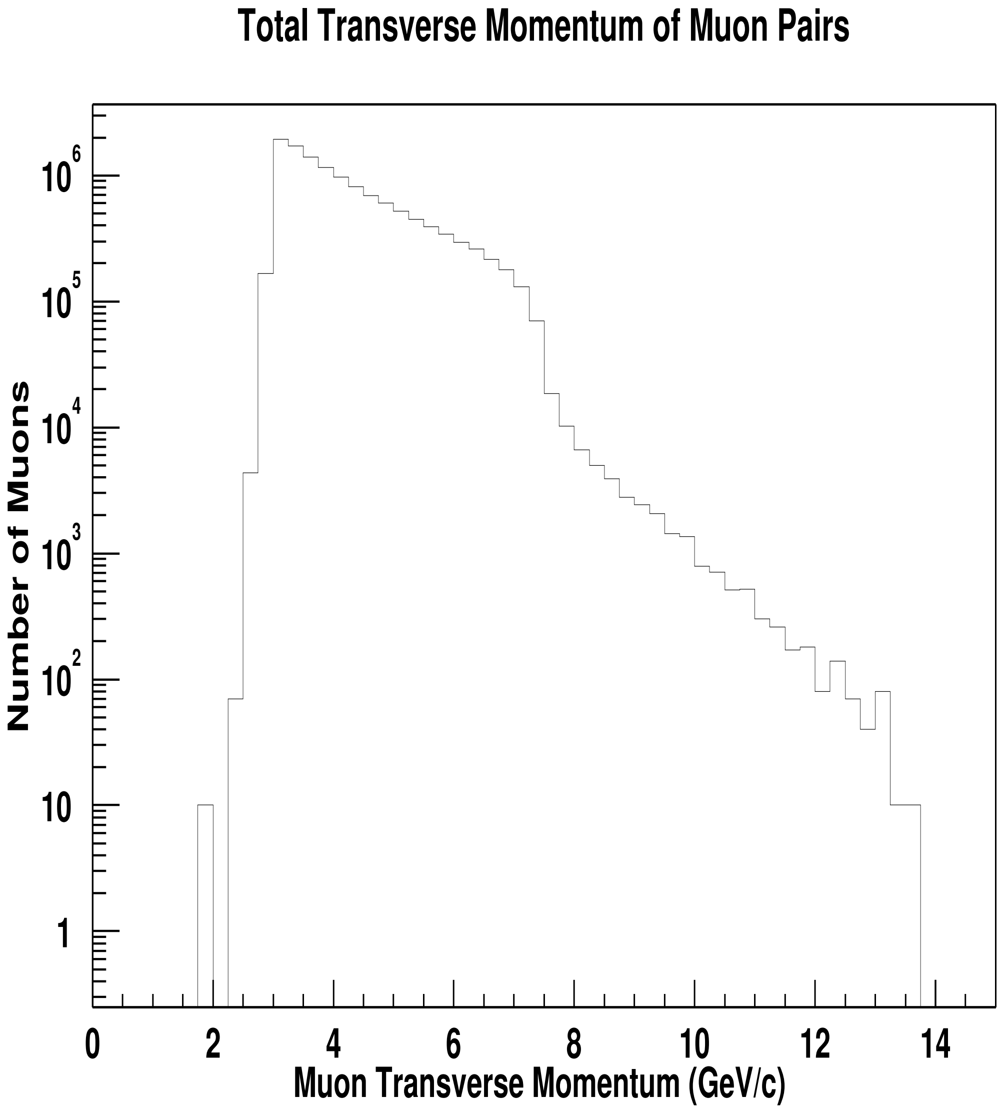

Figure 12: Transverse momentum of muon pairs for two photon background

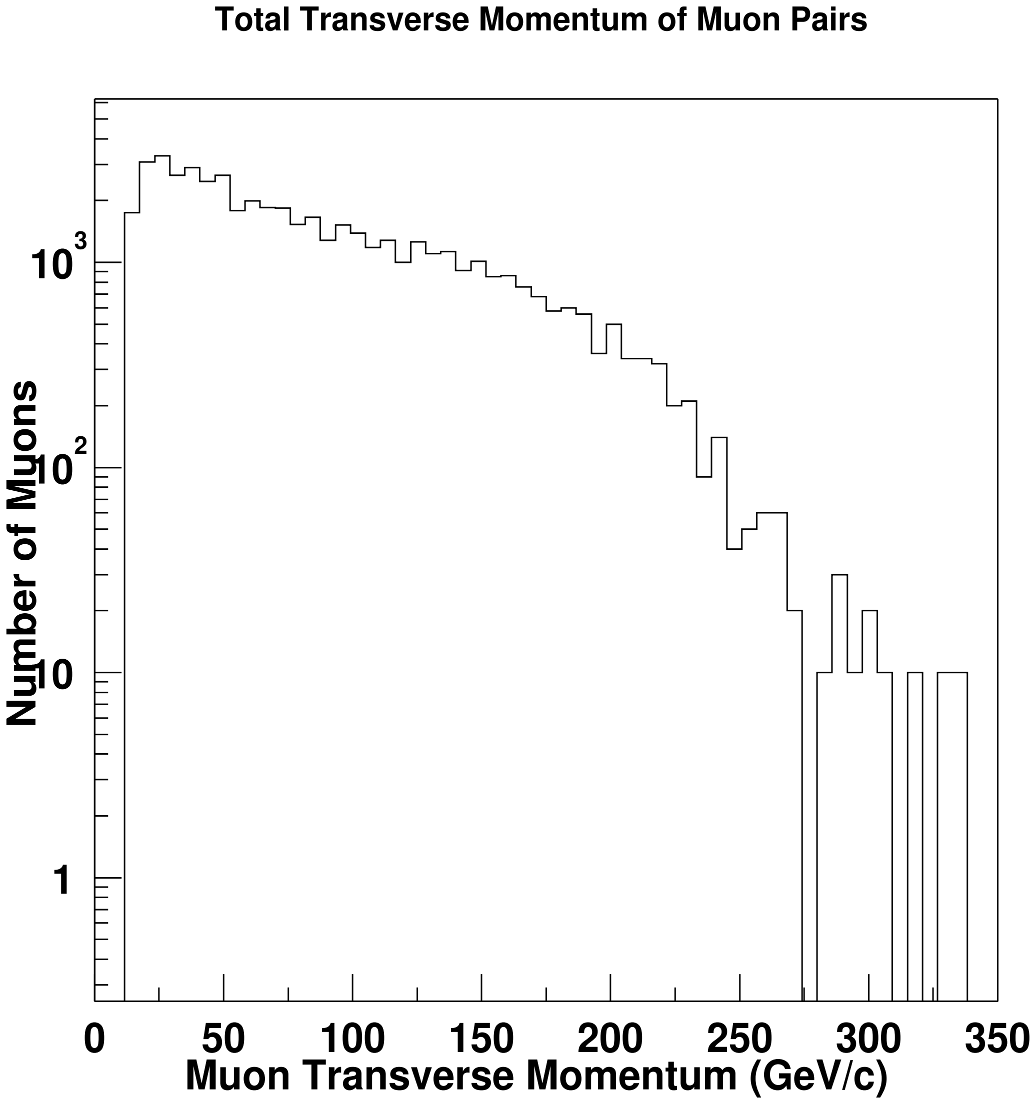

Figure 13: Transverse momentum of muon pairs for the rest of the signal

Obviously it cuts out all of the two photon background, but all the other backgrounds remain pretty much the same. About 17% of the signal is removed, but the box edges are still intact (figure 14).

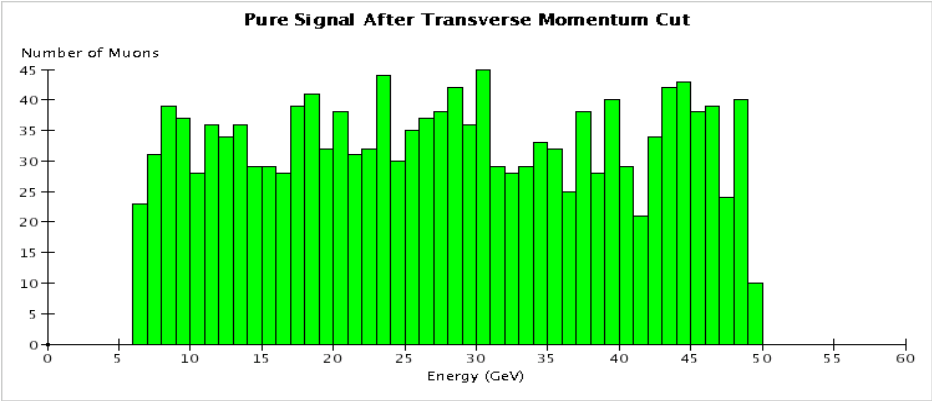

Figure 14: The pure signal after the transverse momentum cut

5.5 Measuring the Edge

In figure 15 is the total signal after the transverse momentum cut. Notice that it looks a lot like figure 11. That is because the other backgrounds are almost unaffected by the cut. The box has a dip in the middle because of the transverse momentum cut. It mainly removes signal in the center of the box, leaving the edges intact. In order to measure the edges of the box, I fit arctangents to each side (figures 16 and 17). From the edges one gets masses of 237.2 GeV/c^2 $\pm$ 2.8 and 218.9 $\pm$ 2.5 GeV/c^2 for the chargino and sneutrino. The actual masses are 238.7 and 220.3 GeV/c^2. This is only about 0.64% discrepancy.

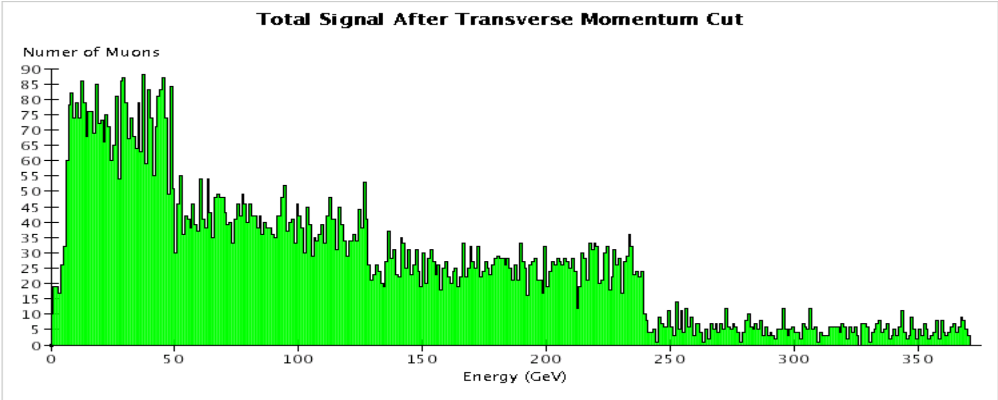

Figure 15: The data after cut

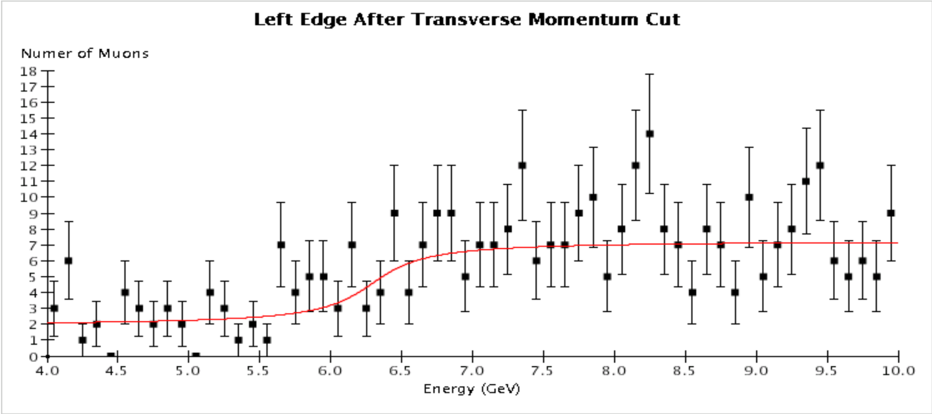

Figure 16: Left side fit after transverse cut with 1.5cm hole. $E_{\mu min} = 6.26 \pm 0.19 GeV$

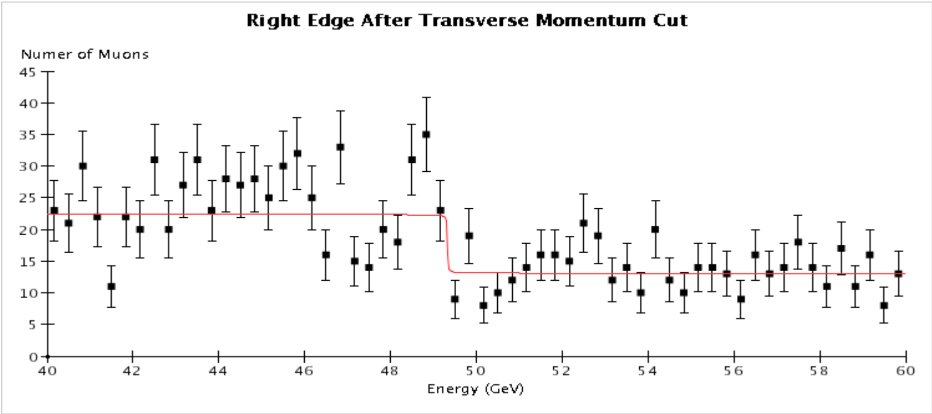

Figure 17: Right side fit after transverse cut with 1.5cm hole. $E_{\mu max} = 49.31 \pm 0.23 GeV$

5.6 The Two Dimensional Cut

To make better measurements, I want to get rid of more background. In figure 18 I plot the energy of one muon versus another. In the corner one can see a dense box. This is where all the pure signal is located. There is plenty of signal where both muons are in the box, but relatively few background events will also have both muons inside the box. By cutting out all events with one lepton outside of the box using the previously determined edges, one can eliminate not only all the leptons outside of the box, but many that are in the box as well. Since the previously established edges are outside of the actual box, this will not eliminate signal where both muons come from chargino events. Since much of the background that happens to be in the box is eliminated, the hope is that the one can resolve the edges better. Notice that the corner is missing. This is due to the transverse momentum cut. Also a small amount of the diagonal is missing because one can have two high energy particles that are roughly back to back so that the total momentum is under 14 GeV/c. What happens to the remaining background after this two dimensional cut is shown in figures 19 through 23.

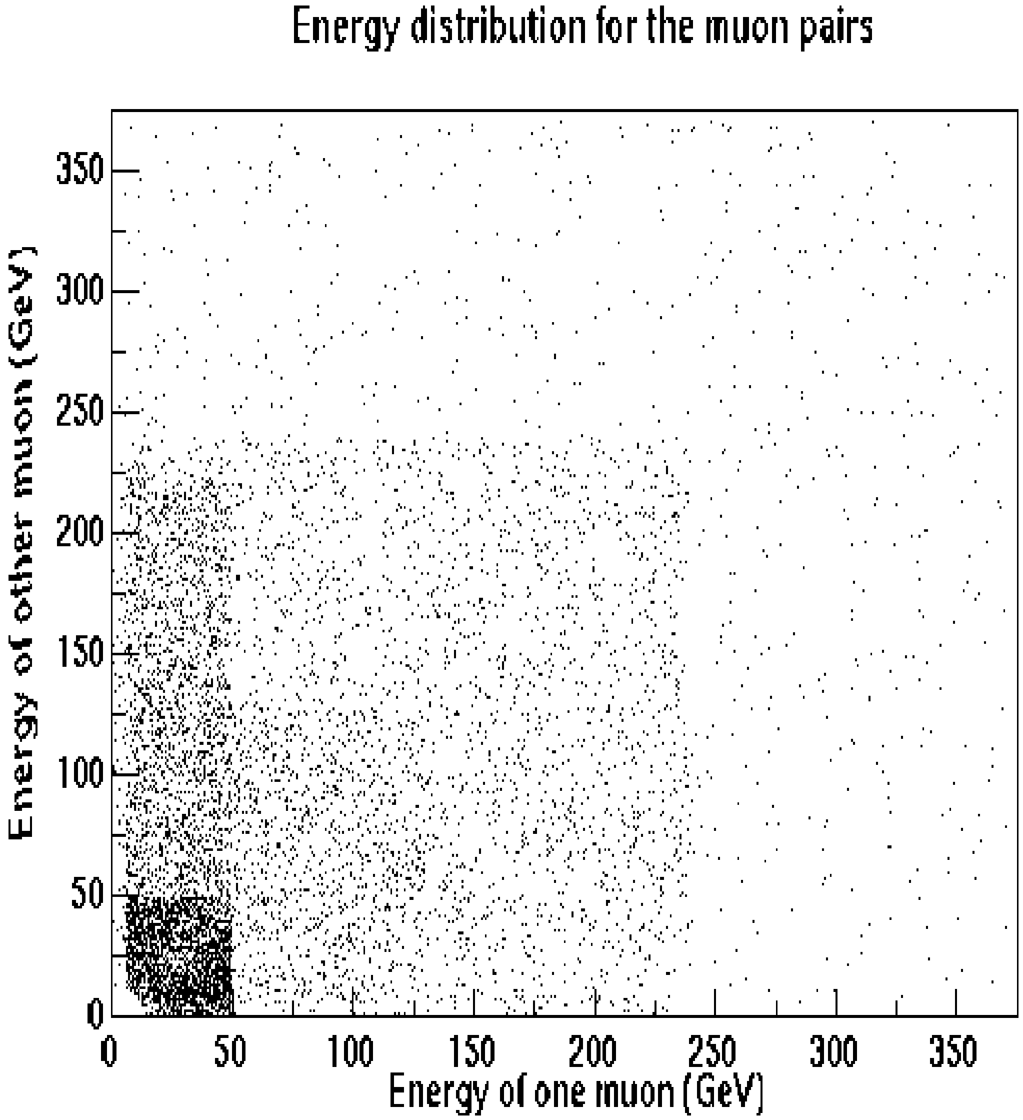

Figure 18: Energy of one muon versus the other for the whole spectrum

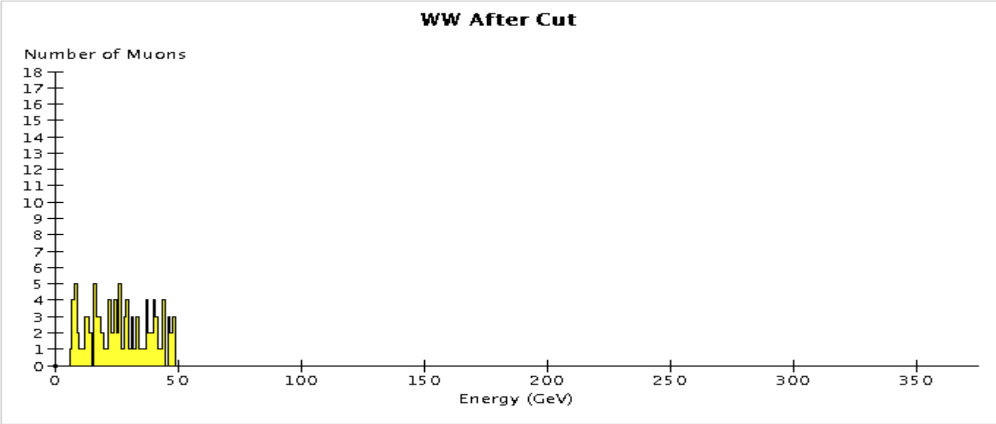

Figure 19: The W^+W^- background after angle cut

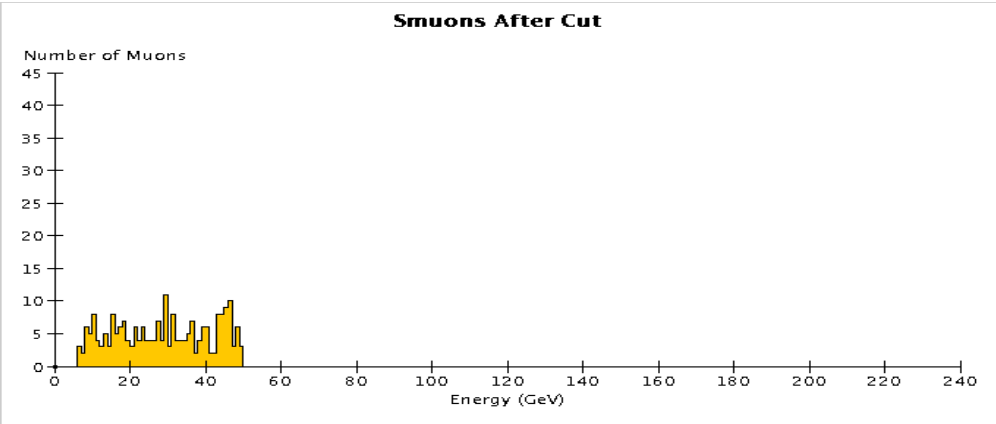

Figure 20: The $\widetilde{\mu}$ background after angle cut

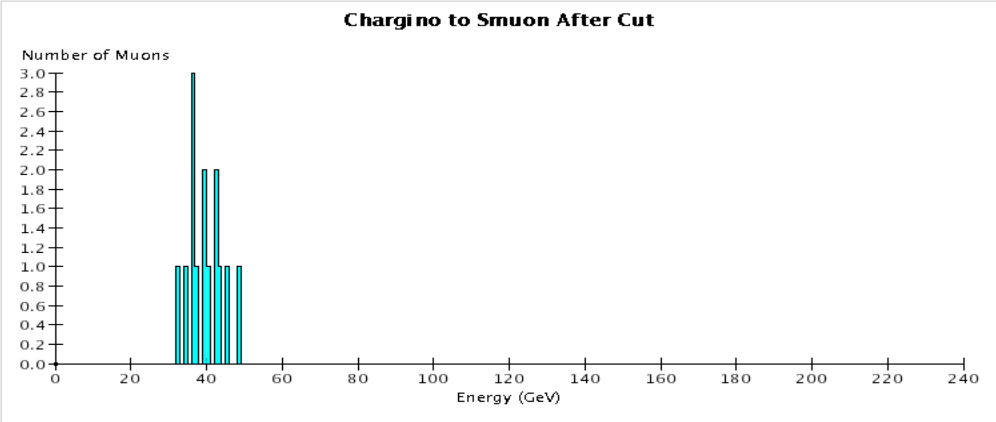

Figure 21: $\widetilde{\chi}_1^{\pm}$ to $\widetilde{\mu}$ background after two dimensional cut

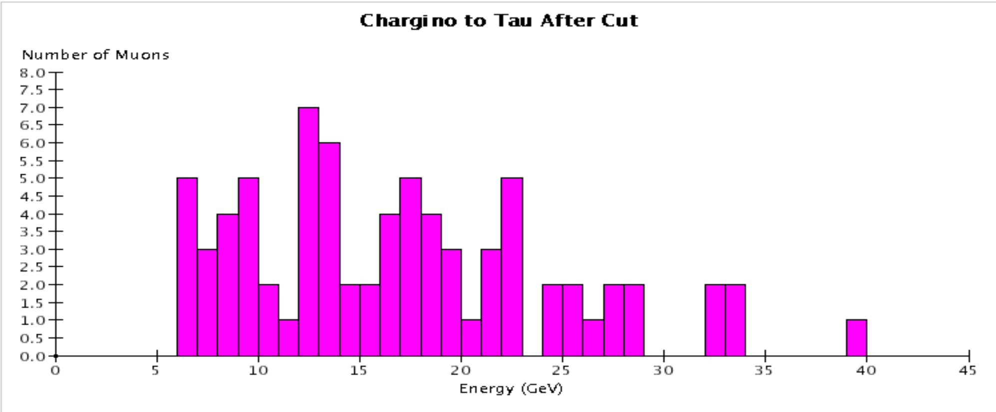

Figure 22: $\widetilde{\chi}_1^{\pm}$ to τ background after two dimensional cut

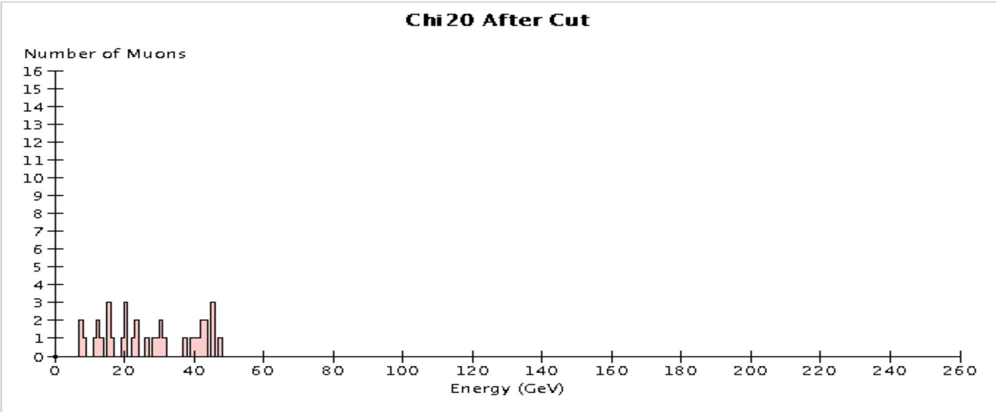

Figure 23: $\widetilde{\chi}_2^0$ background after two dimensional cut

The resulting box is shown in figure 24. I refit the edges as shown in figures 25 and 26, and from these edges I measure masses of 238.6 ± 1.3 and 220.1 ± 1.2 GeV/c^2, a discrepancy of about 0.06%.

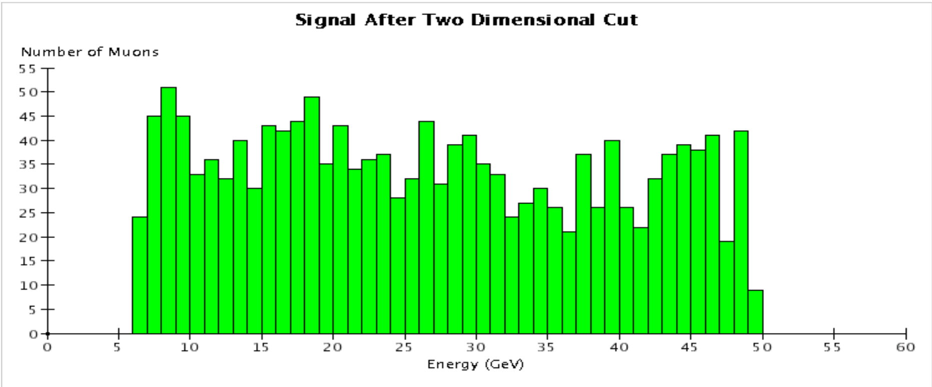

Figure 24: The total signal after the two dimensional cut

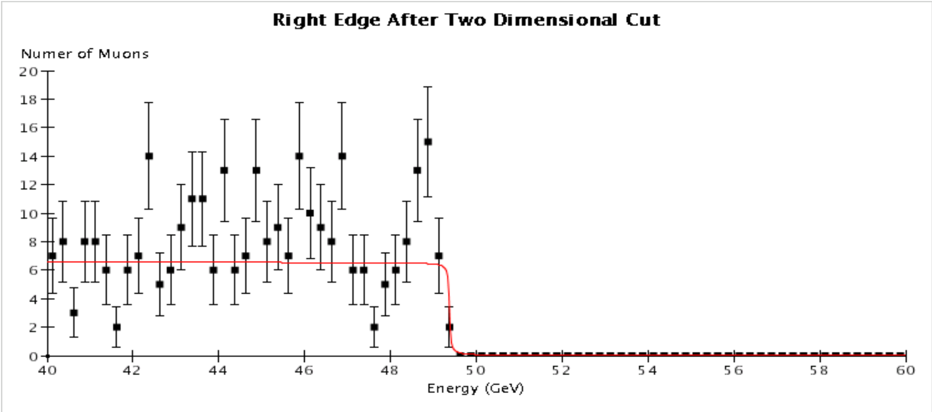

Figure 25: Right edge after cosine cut. The edge is 49.36 ± 0.02 GeV

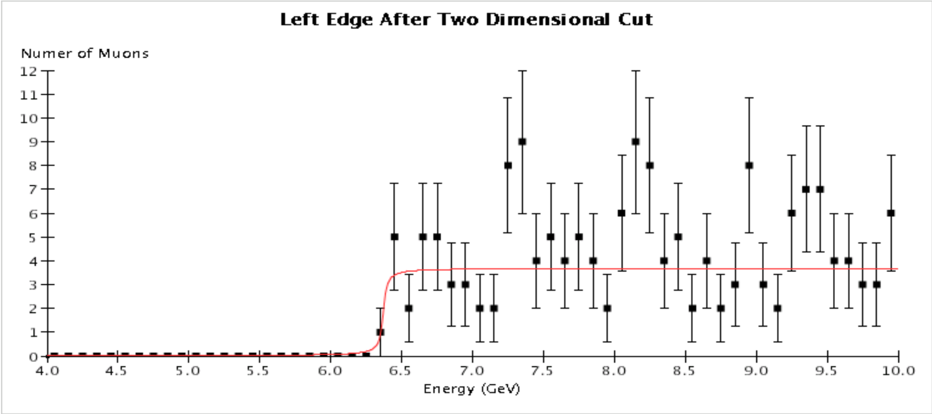

Figure 26: Left edge after cosine cut. The edge is 6.37 ± 0.09 GeV

6 Conclusion

The background from the two photon process is the major problem. The others are tiny in comparison. A detector within the beam pipe to detect the low angle electrons must be implemented in order to reduce this background. But this will not be enough because millions of events will still have both the electron and positron pass through the hole undetected. A cut based on the transverse momenta of the muons can eliminate most of the two photon background while preserving the box shape of the signal. But the cut also leaves a lot of the other background intact. A two dimensional energy cut can eliminate much of the other background and make the edge determination much better. With these two cuts, an accurate mass determination can be made. But this requires a detector within the beam pipe 150 cm away from the interaction point with a hole around 3 cm in radius leading to a 20mrad angle limit.

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A Derivation of Box Edges

Here I go into the detailed derivation of why the muons can only have energies within a range determined by the masses of the chargino and sneutrino (see [12]). Here we will do our derivation using the rest frame of the chargino. The energy of the muon in the lab frame is related to the rest frame of the chargino via the equation

$$E_\mu^{lab} = \gamma(E_\mu^{lab} + \beta P_\mu^{cm} cos\theta).$$

where E is energy, P is momentum,

$$\gamma = \frac{1}{\sqrt{1 - \frac{v_{\tilde{\chi}_1^\pm}{}^2}{c^2}}}, \text{ and } \beta = \frac{v_{\tilde{\chi}_1^\pm}}{c}.$$

Here we use units where $c = 1$. Since the muon has such a small mass and is very relativistic, its momentum is almost equal to the energy. So we get

$$E_\mu^{lab} = \gamma(1 + \beta cos\theta)E_\mu^{cm}.$$

Since θ ranges from -1 to 1, you get

$$E_\mu^{min} = \gamma(1 - \beta)E_\mu^{cm} \text{ and } E_\mu^{max} = \gamma(1 - \beta)E_\mu^{cm}.$$

So we need to know γ, β, and E_μ^{cm} in terms of the chargino and sneutrino parameters in the center of mass. Well, relativity tells us that

$$\gamma = \frac{E_{\tilde{\chi}_1^\pm}^{lab}}{M_{\tilde{\chi}_1^\pm}} \text{ and } \beta = \frac{P_{\tilde{\chi}_1^\pm}^{lab}}{E_{\tilde{\chi}_1^\pm}^{lab}}.$$

Since each chargino takes half of the energy,

$$E_{\tilde{\chi}_1^\pm}^{lab} = \frac{E_{cm}}{2}.$$

Also we know that

$$P_{\tilde{\chi}_1^\pm}^{lab\,2} = E_{\tilde{\chi}_1^\pm}^{lab\,2} - M_{\tilde{\chi}_1^\pm}^2.$$

So you have

$$\gamma = \frac{E_{cm}}{2M_{\widetilde{\chi}_1^\pm}} \text{ and } \beta = \sqrt{1 - \frac{4M_{\widetilde{\chi}_1^\pm}^2}{E_{cm}^2}}.$$

Now we derive E_μ^{cm}. Obviously,

$$E_{\widetilde{\chi}_1^\pm}^{cm} = M_{\widetilde{\chi}_1^\pm}.$$

Also, we know that

$$E_{\widetilde{\chi}_1^\pm}^{cm} = E_\mu^{cm} + E_{\widetilde{\nu}_\mu}^{cm}.$$

So

$$E_{\widetilde{\nu}_\mu}^{cm} = M_{\widetilde{\chi}_1^\pm} - E_\mu^{cm},$$

or

$$E_{\widetilde{\nu}_\mu}^{cm2} = {M_{\widetilde{\chi}_1^\pm}}^2 - 2E_\mu^{cm} M_{\widetilde{\chi}_1^\pm} + E_\mu^{cm2}.$$

This yields

$$P_{\widetilde{\nu}_\mu}^{cm2} + {M_{\widetilde{\nu}_\mu}}^2 = {M_{\widetilde{\chi}_1^\pm}}^2 - 2E_\mu^{cm} M_{\widetilde{\chi}_1^\pm} + P_\mu^{cm2} + M_\mu^2.$$

Since $P_{\widetilde{\nu}_\mu}^{cm2} = P_\mu^{cm2}$ and neglecting M_μ^2, you get

$${M_{\widetilde{\nu}_\mu}}^2 = {M_{\widetilde{\chi}_1^\pm}}^2 - 2E_\mu^{cm} M_{\widetilde{\chi}_1^\pm}.$$

Thus one has

$$E_\mu^{cm} = \frac{M_{\widetilde{\chi}_1^\pm}^2 - M_{\widetilde{\nu}_\mu}^2}{2M_{\widetilde{\chi}_1^\pm}} = \frac{M_{\widetilde{\chi}_1^\pm}}{2}\left(1 - \frac{{M_{\widetilde{\nu}_\mu}}^2}{M_{\widetilde{\chi}_1^\pm}^2}\right).$$

One can plug these into the equations for E_μ^{min} and E_μ^{max} to get

$$E_\mu^{min} = \frac{E_{cm}}{4}\left(1 - \sqrt{1 - \frac{4{M_{\widetilde{\chi}_1^\pm}}^2}{E_{cm}^2}}\right)\left(1 - \frac{{M_{\widetilde{\nu}_\mu}}^2}{{M_{\widetilde{\chi}_1^\pm}}^2}\right)$$

$$E_\mu^{max} = \frac{E_{cm}}{4}\left(1 + \sqrt{1 - \frac{4{M_{\widetilde{\chi}_1^\pm}}^2}{E_{cm}^2}}\right)\left(1 - \frac{{M_{\widetilde{\nu}_\mu}}^2}{M_{\widetilde{\chi}_1^\pm}^2}\right).$$

So now we are almost have what we want. We want to be able to express the masses of the chargino and sneutrino in terms of the extreme muon energies. We have two equations, so lets go to it. Eliminating the sneurtino mass can be simply done by dividing the last two equations. Afterwards, do some tedious math and one gets

$$M_{\widetilde{\chi}_1^{\pm}}{}^2 = E_{cm}^2 \tfrac{E_\mu^{min} E_\mu^{max}}{(E_\mu^{min} + E_\mu^{max})^2}.$$

Doing some equally nasty algebra yields the mass of the sneutrino to be

$$M_{\widetilde{\nu}_\mu}{}^2 = M_{\widetilde{\chi}_1^{\pm}}{}^2 - 2E_{cm} \tfrac{E_\mu^{min} E_\mu^{max}}{(E_\mu^{min} + E_\mu^{max})}.$$