The Search for the Supersymmetric Smuon

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1 Introduction

In this paper I discuss the search for supersymmetric smuons in a 500 GeV electron-positron accelerator. In particular, I will discuss methods for separating the supersymmetric signal from the Standard Model background and the cuts used to isolate the signal.

In order to save the reader (and the writer) from pointless repetition, this paper is meant to be an addendum to the work done by Goodman and Danielson [1], [2]. These papers contain much more detail than is included herein. With an emphasis on Point 2 slepton studies, they discuss standard model background modes and particle interactions, cross sections for Supersymmetric modes and background modes, methods for experimentally measuring sparticle masses, sparticle masses determined by theorists for each of the five parameter points, how changes in initial state electron polarization change cross sections, particularly for slepton events, theoretical motivations for Supersymmetry, programs used for data generation and analysis, and more.

1.1 The Method Used

- perform simulations at E_{cm} of 500 GeV, where we can expect to see $e^+e^- \to \widetilde{\mu}^-\widetilde{\mu}^+$, and analyze events with 80% right polarized incident electrons, because the cross section for the $\widetilde{\mu_R^{\pm}}$ is largest there (the search for $\widetilde{\mu}_L\widetilde{\mu}_L$ using an 80% left polarized beam at 750 GeV is discussed later)

- separate the Supersymmetric smuon signal from the Standard Model background and from other Supersymmetric production modes by applying cuts that reduce the background without changing the endpoints of the visible energy histogram of the smuon signal

- plot a histogram of the energy of the muons and antimuons that survived the cuts
- apply a fit function to the energy histogram of the $\mu^+\mu^-$
- using the endpoints of the fit (E_{max} and E_{min}), determine the masses of the $\tilde{\chi}_1^0$ and the $\tilde{\mu}_R$.[1]

2 Energy Histograms

Most of the histograms that follow depict the energy of visible muons and antimuons (in GeV) vs. the number of events. All histograms depict an integrated luminosity ($\mathcal{L}$) of 100 fb^{-1}, which is the simulated equivalent of two years of accelerator run-time. Our center of mass energy in all histograms is 500 GeV, and all events are generated with 80% right polarized incident electrons. "Pythia" refers to the following background processes, which are generated by the Pythia program: $\gamma + \gamma$, $\gamma^* or Z^0$, $\gamma + \gamma^* or Z^0$, $Z^0 + Z^0$. Two photon ($\gamma^*\gamma^*$) events only include lowest order processes.

Figure 1, top, shows a plot of the energy of muons and antimuons for the Standard Model background (blue), for all Supersymmetric events (green), and for Point 2 smuons (red).[2] Figure 1, bottom, shows the different types of events that contribute to our Standard Model Background. It is our goal to determine how to remove, using kinematical cuts, the Standard Model background and non-smuon Supersymmetric events while minimally affecting the Supersymmetric signal.

[1]Because the cross section for $\tilde{\mu}_L\tilde{\mu}_L$ is so small and the background is so large, the mass of the $\tilde{\mu}_L$ cannot be determined with reasonable accuracy using the $\mu^+\mu^-$ energy histograms in this study.

[2]In Figure 1 the signals for $\widetilde{\mu_R}\widetilde{\mu_R}$ and for $\widetilde{\mu_L}\widetilde{\mu_L}$ were combined to form the signal for total smuon production. The cross section of $\widetilde{\mu_L}\widetilde{\mu_R}$ is zero.

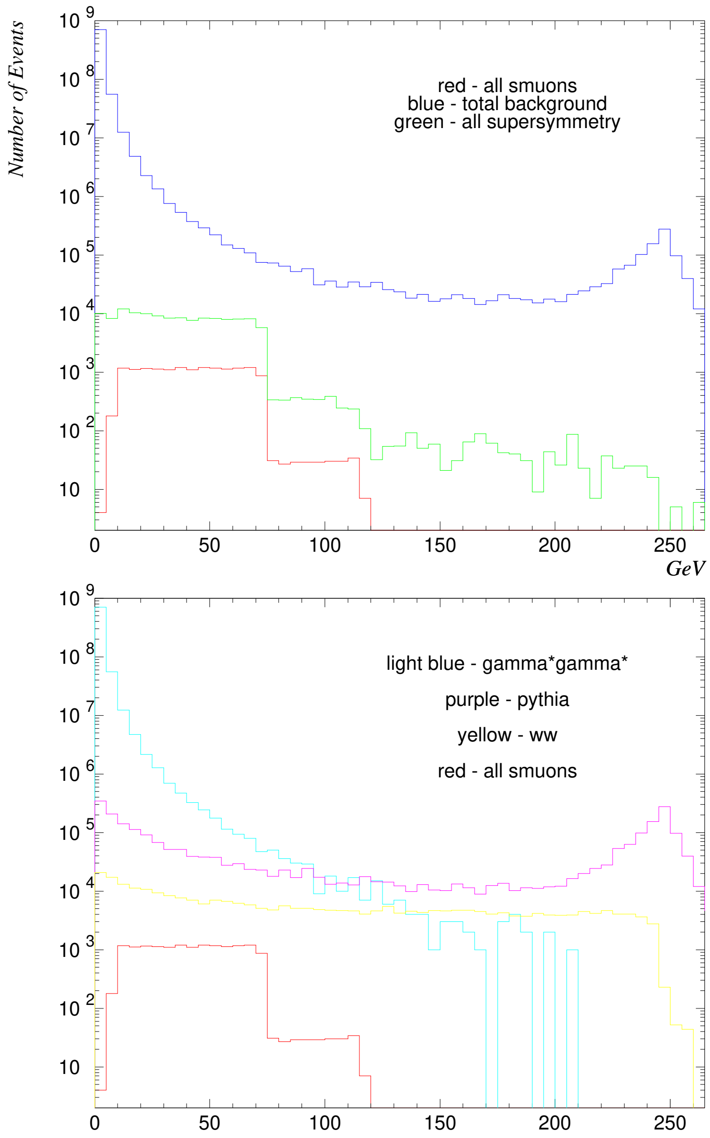
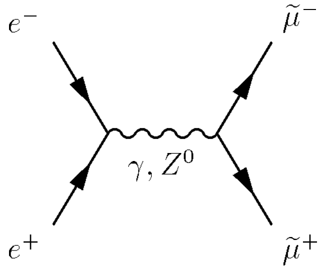


Figure 1: E_{μ^+,μ^-} before any cuts.

Smuons are produced in the following manner:[3]



Exactly Two Muons Figure 2 shows the muon energy histograms after limiting the events to those with exactly two visible particles: one muon and one antimuon. As can be seen from Figure 2, almost all of the remaining Supersymmetric events are smuon events, but the Supersymmetric signal is still indistinguishable from that of the background. In order to make a mass measurement, we need additional cuts to observe the leading and lagging edges of the muon energy histogram. At this point it is worth pointing out the edges of the smuon signal, which is now limited to events of the type shown in the previous Feynman diagram, with one visible muon and one visible antimuon. The edges that we are interested in are at about 8 GeV and about 75 GeV. From our study of the selectron events, we know these are the edges of the $\widetilde{\mu}_R\widetilde{\mu}_R$ signal. It is important that as we make cuts, we maintain the positions of these edges. The part of the histogram between about 70 GeV and 115 GeV is the $\widetilde{\mu}_L\widetilde{\mu}_L$ signal, which is impossible to see because the background is so big.

[3]This diagram is an s-channel process. Because smuon events only occur in s-channels, and never in t-channels, the cross section for smuons is much smaller than that of selectrons, which can occur via both t-channels and s-channels. Smuon events only occur via s-channel processes, so $\widetilde{\mu}_R\widetilde{\mu}_L$ events do not exist.

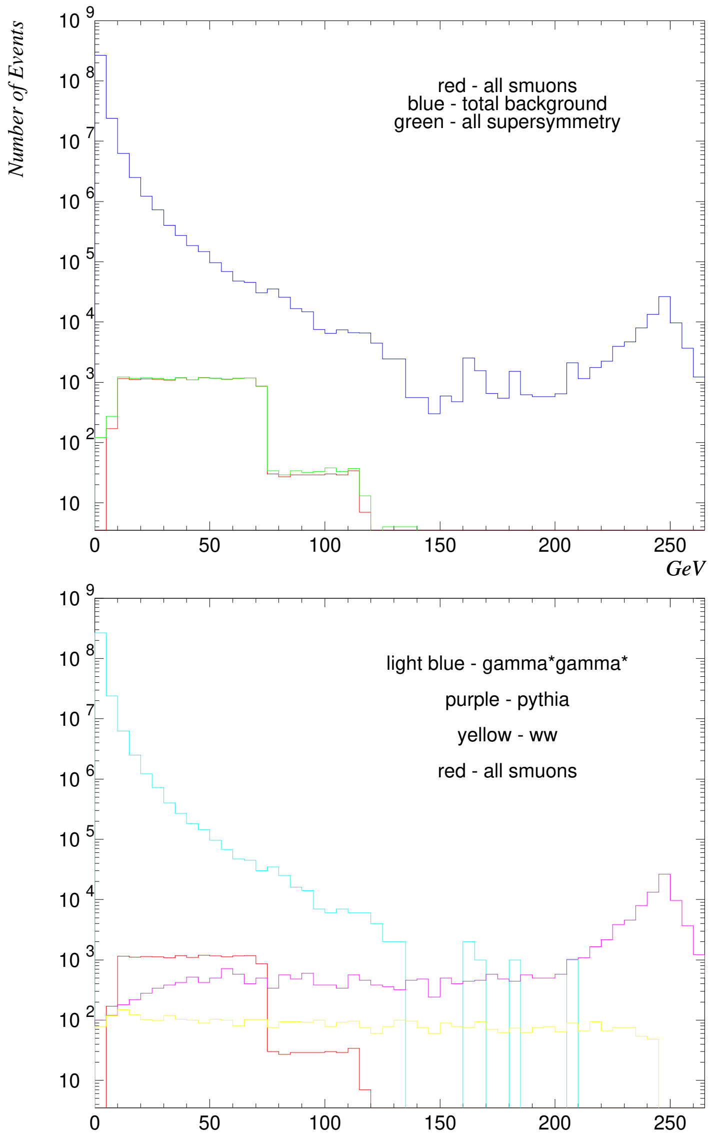


Figure 2: E_{μ^+,μ^-} after cut demanding exactly two muons.

Energy Distribution Figure 3 only includes events with visible energy in the forward direction less than 0.4 E_{cm}.

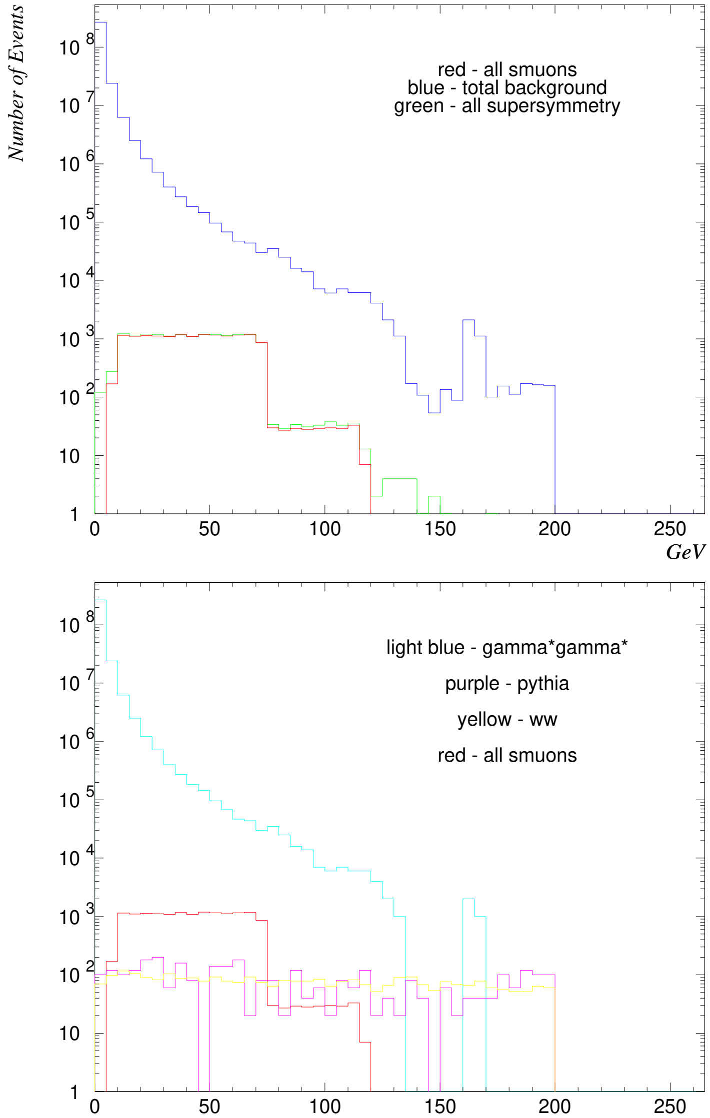


Figure 3: E_{μ^+,μ^-} after cut demanding forward energy less than 0.4 E_{cm}.

Angular Distribution of Visible Particles Figure 4 shows the angular distribution of visible particles in events that have exactly one muon and one antimuon.

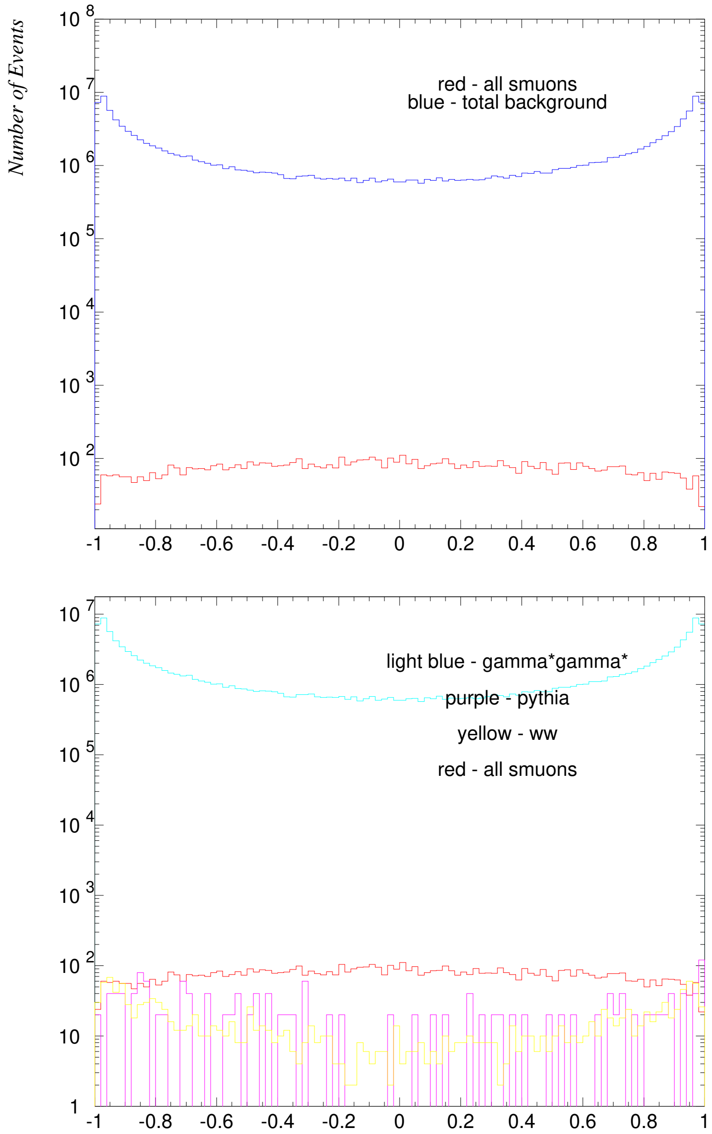


Figure 4: Cos(θ): Angular distribution of visible particles.

The next cut, Figure 5, limits the events to those that have less than 1 GeV visible energy between $.80 < |\cos(\theta)| < .995$.

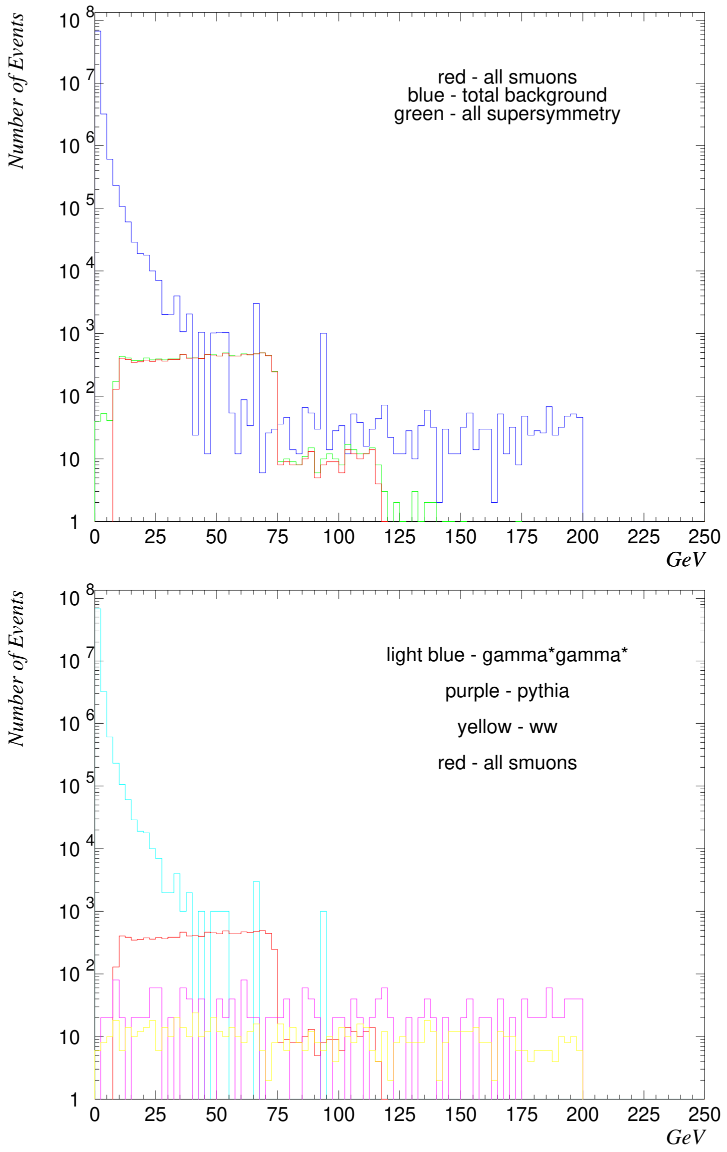


Figure 5: $E_{\mu^+\mu^-}$ after limiting events to those with less than 1 GeV visible energy between $.80 < |\cos(\theta)| < .995$.

Endpoints of the Signal Figure 6 shows the energy distributions of the Supersymmetric signals we are trying to see. This figure shows the energy of each of the muons and antimuons remaining in the *signal only* following the previous cuts:

- two visible particles, one muon and one antimuon
- forward energy $<$ 0.4 center of mass energy
- energy inside .80$<$ $|\cos(\theta)|$ $<$.995 $<$ 1 GeV.

The purpose of this figure is to show what the Supersymmetric signal looks like and where the edges are, *even though this is not information that can be had from the actual detector.* The endpoints of the signal have not been affected by the cuts we have made thus far. Take note of the position of the edges of the $\tilde{\mu}_R\tilde{\mu}_R$ events; these edges are what we use to calculate the masses of the right smuon and the neutralino.

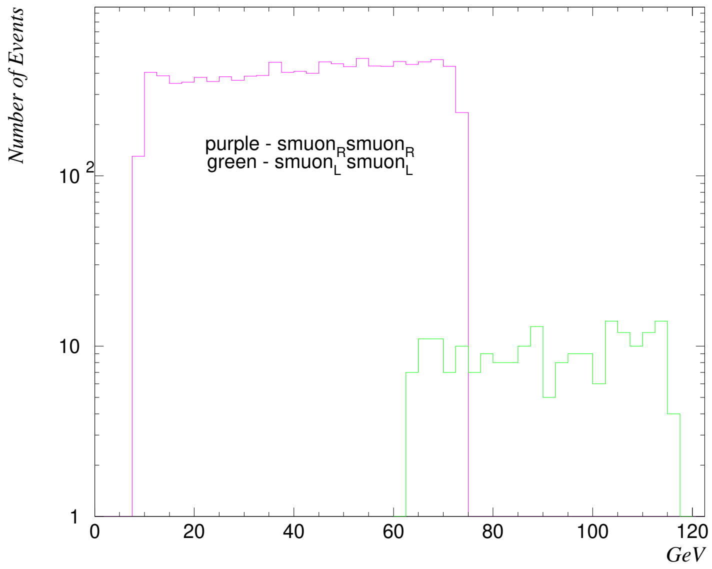


Figure 6: E$_{\mu^\pm}$ for Supersymmetric signal following cuts to remove background events.

Transverse Momentum We plot the transverse momentum of each event in Figure 7. It is possible to make a cut on transverse momentum if one is careful to maintain the edges of the Supersymmetric smuon signal.

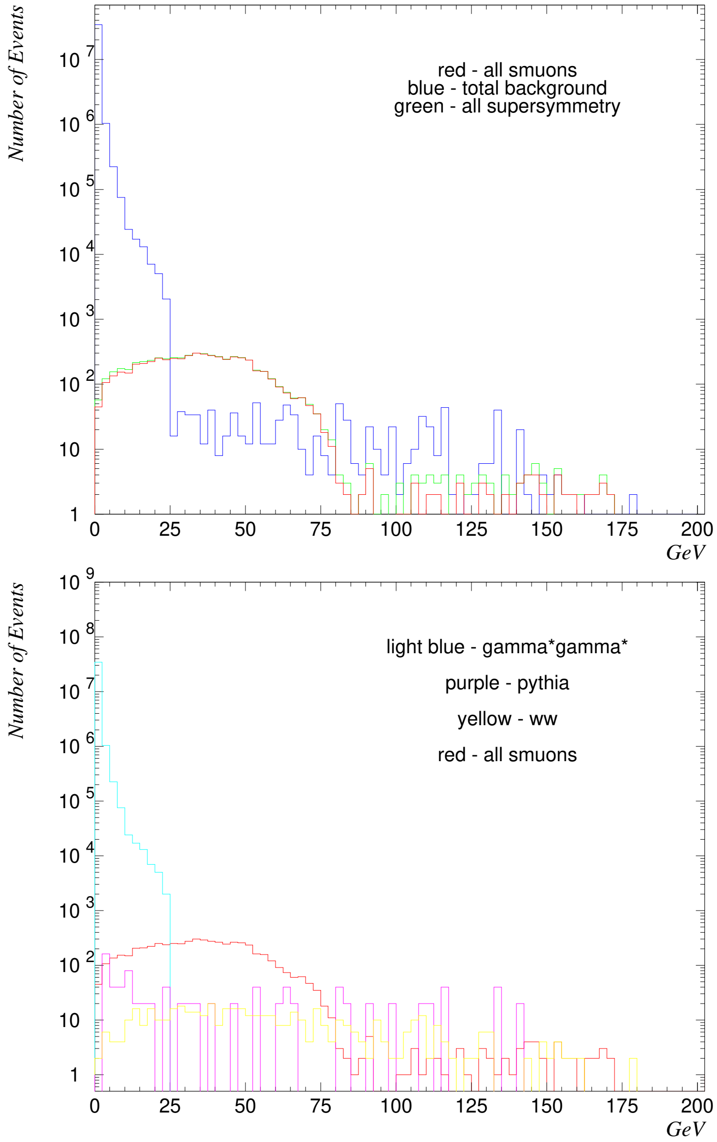


Figure 7: Transverse momentum.

We plot the energy of visible μ and $\bar{\mu}$ for varying transverse momentum cuts in Figure 8. Note how the leading and lagging edges of the $\tilde{\mu}_R\tilde{\mu}_R$ signal become observable as the transverse momentum cut is increased.

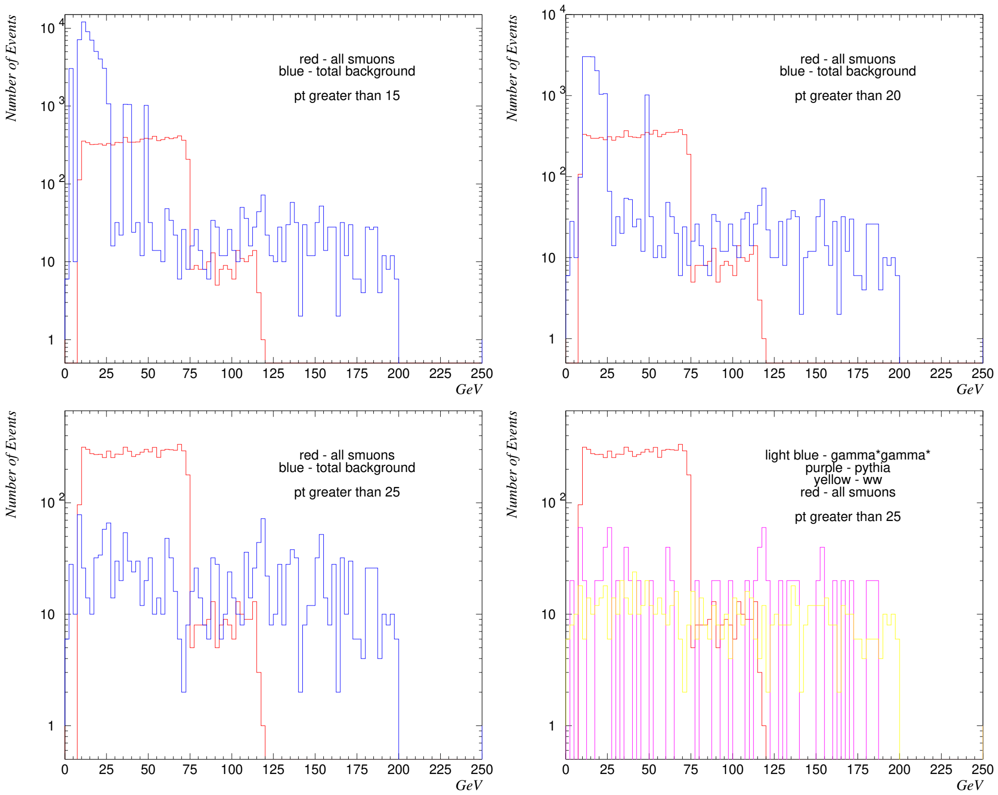


Figure 8: Energy of μ and $\bar{\mu}$ after removing events with varying transverse momenta.

Obviously, the best transverse momentum cut to use is the one in which we demand that transverse momentum is greater than 25 GeV. We lose all of the two photon background and maintain the edges of the $\tilde{\mu}_R\tilde{\mu}_R$ signal.

3 Mass Measurement

This set of cuts is the most effective way we found of reducing the background without changing the endpoints of the visible energy histogram for the signal. The edges of the Supersymmetric signal correspond to the minimum and maximum energies of the event, which are used to calculate the masses of the Supersymmetric particles. To summarize, the cuts we used are:

- two visible particles, one muon and one antimuon
- forward energy < 0.4 center of mass energy
- energy inside $.80 < |\cos(\theta)| < .995 < 1$ GeV
- transverse momentum > 25 GeV.

Muon Energies Following all of the cuts, we plot the energy of the muon and antimuon in each event. Figure 9 shows the $E_{\mu^{\pm}}$ for the the remaining signal plus the remaining Standard Model background.

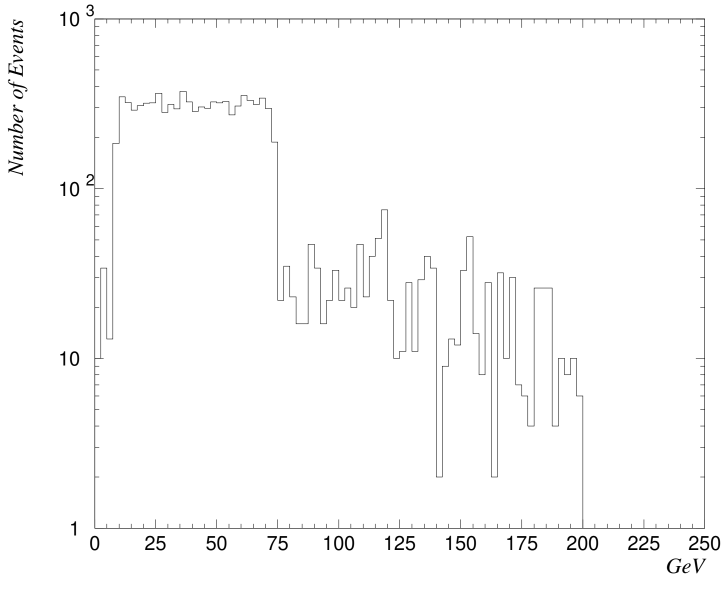


Figure 9: $E_{\mu^{\pm}}$ for Supersymmetric signal plus Standard Model background following cuts to reduce background.

We shall use the muons' minimum and maximum energies to determine the masses of the Supersymmetric particles.

We use the edges of the muon signal as the values of E_{min} and E_{max}. In Figure 9, the left endpoint is E_{min} (= 7.4 GeV), the right endpoint is E_{max} (= 74.7 GeV). We use these values in the following equations, where s is E^2_{cm}:[4]

$$m_{\tilde{\mu}_R} = \sqrt{s\left[\frac{E_{max}E_{min}}{(E_{max}+E_{min})^2}\right]}$$

$$m_{\tilde{\chi}^0_1} = \sqrt{s\left[\frac{E_{max}E_{min}}{(E_{max}+E_{min})^2}\right] - 2\sqrt{s}\frac{E_{max}E_{min}}{E_{max}+E_{min}}}$$

Table 1 shows the masses of the $\tilde{\chi}^0_1$ and the $\tilde{\mu}_R$.

Table 1: Masses of Supersymmetric particles (in GeV) calculated using end-point energies.

Particle	Known Mass	Measured Mass	Discrepancy
$\tilde{\chi}^0_1$	128.7	117.3	9%
$\tilde{\mu}_R$	157.1	143.2	9%

4 Ideas that don't help

Knowing that some cuts will not enhance the signal and reduce the background can be almost as valuable as knowing what cuts work. We now show plots of smuon signal events and Standard Model background events for variables that *may* have shown differences in the behavior of the signal and background, but didn't.

[4]We have neglected the mass of the $\mu^{\pm}$ because it is much smaller than the mass of the smuons and E_{cm}.

Angle Between Muons Figure 10 shows the angle between the muon and antimuon in each remaining event.

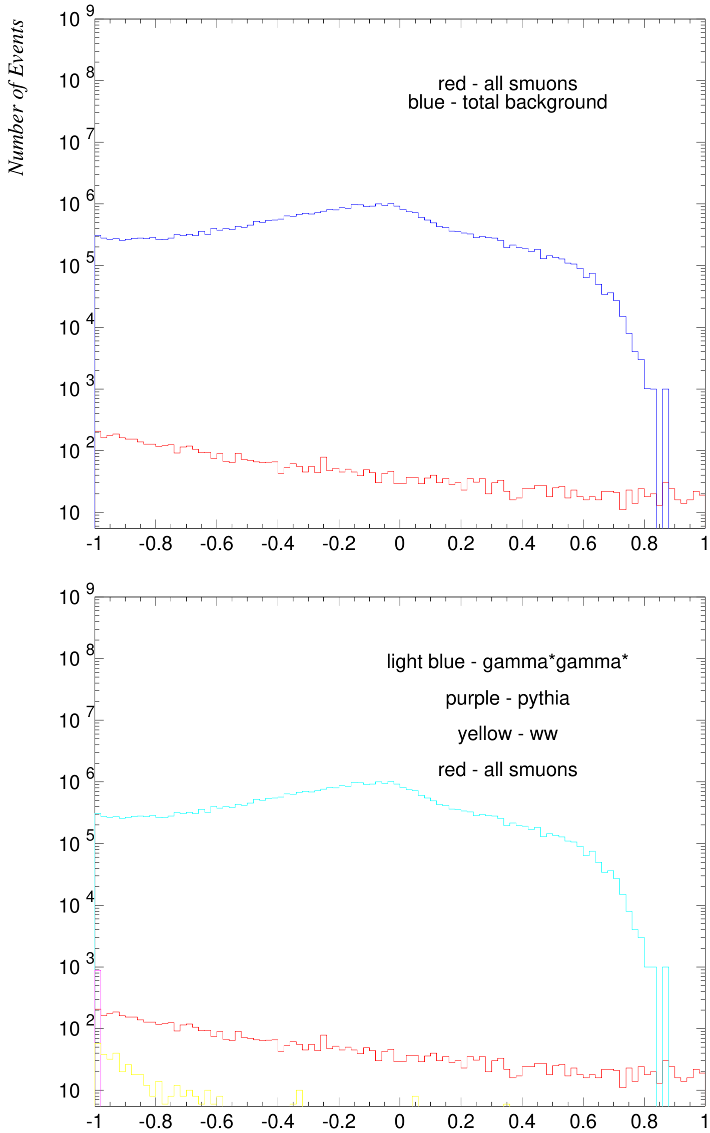


Figure 10: Cos(θ): Angle between muon and antimuon.

Acoplanarity It is sometimes useful to plot the acoplanarity of each event. The acoplanarity angle is the angle between the tracks projected onto a plane perpendicular to the beam plane. We plot the acoplanarity in Figure 11.

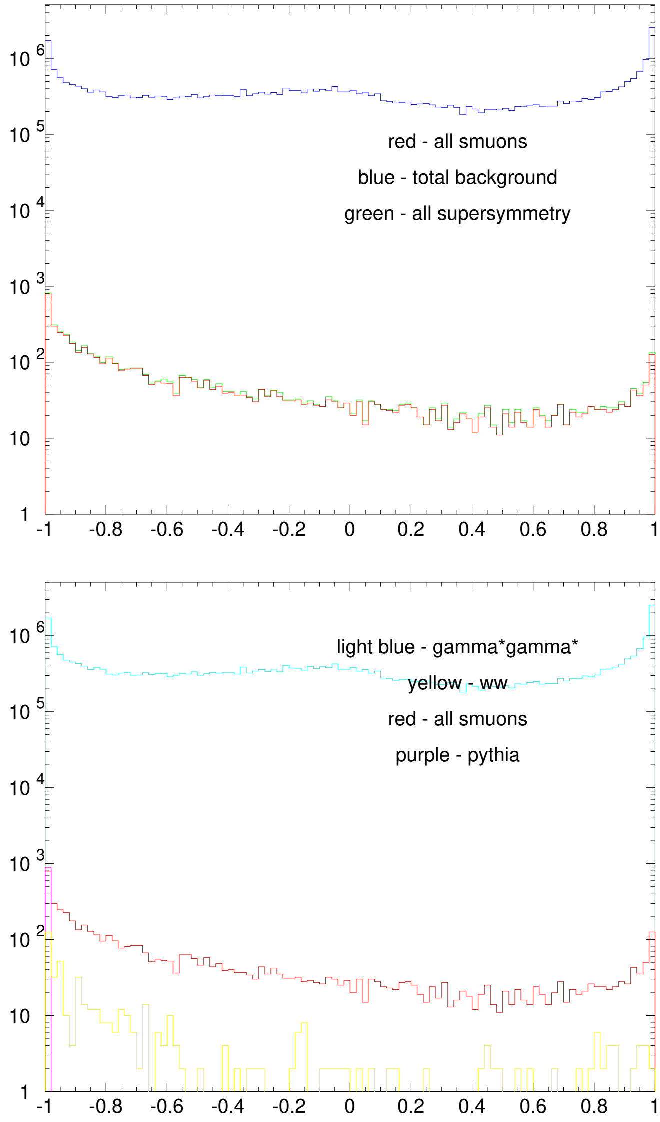
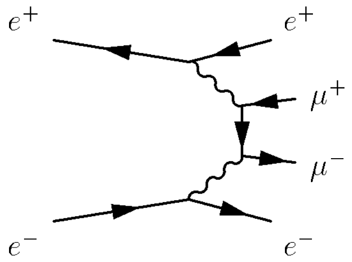


Figure 11: Acoplanarity: $\mathrm{Cos}(\Phi_{\mu+} - \Phi_{\mu-})$.

Angle of Beamhole Electron and Positron The two photon background is discussed extensively in *Point 2 Selectrons and the Standard Model Background* by Danielson and Goodman. Essentially, the problem is that the two initial state particles each emit a photon and continue to propagate down the beamhole, taking energy from the event in a manner similar to that of the smuon process. Since we have difficulty detecting particles in and around the beamhole, these events are hard to identify.

The Feynman diagram for the two photon process that presents the most difficulty for smuon studies is the following:



The muons in these events have very low energy, similiar to that of the muons produced in smuon decays. The electrons have very high energy, and tend to go down the beamhole (inside 100 mrad in our simulations). Figure 12 shows the angle of the beamhole electrons and positrons for two photon events.

Figure 13 shows the energy of the electrons and positrons inside varying angles for two photon events.

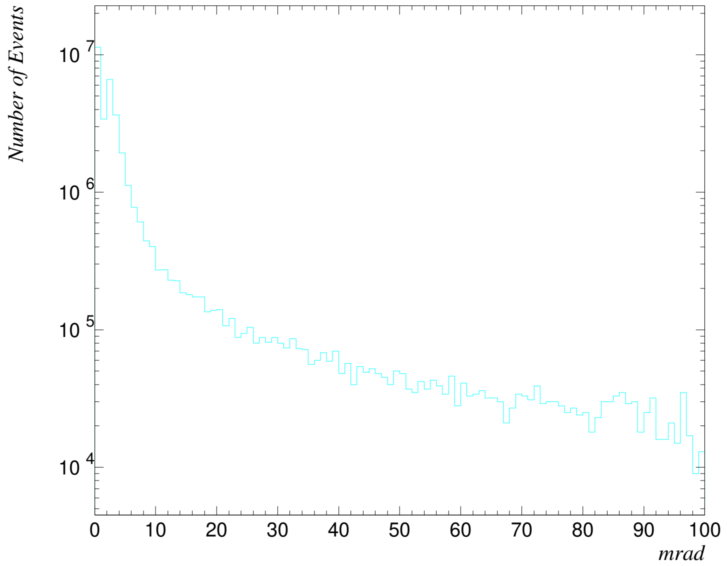


Figure 12: Angle of beamhole electron and positron in two photon events, shown in mrad.

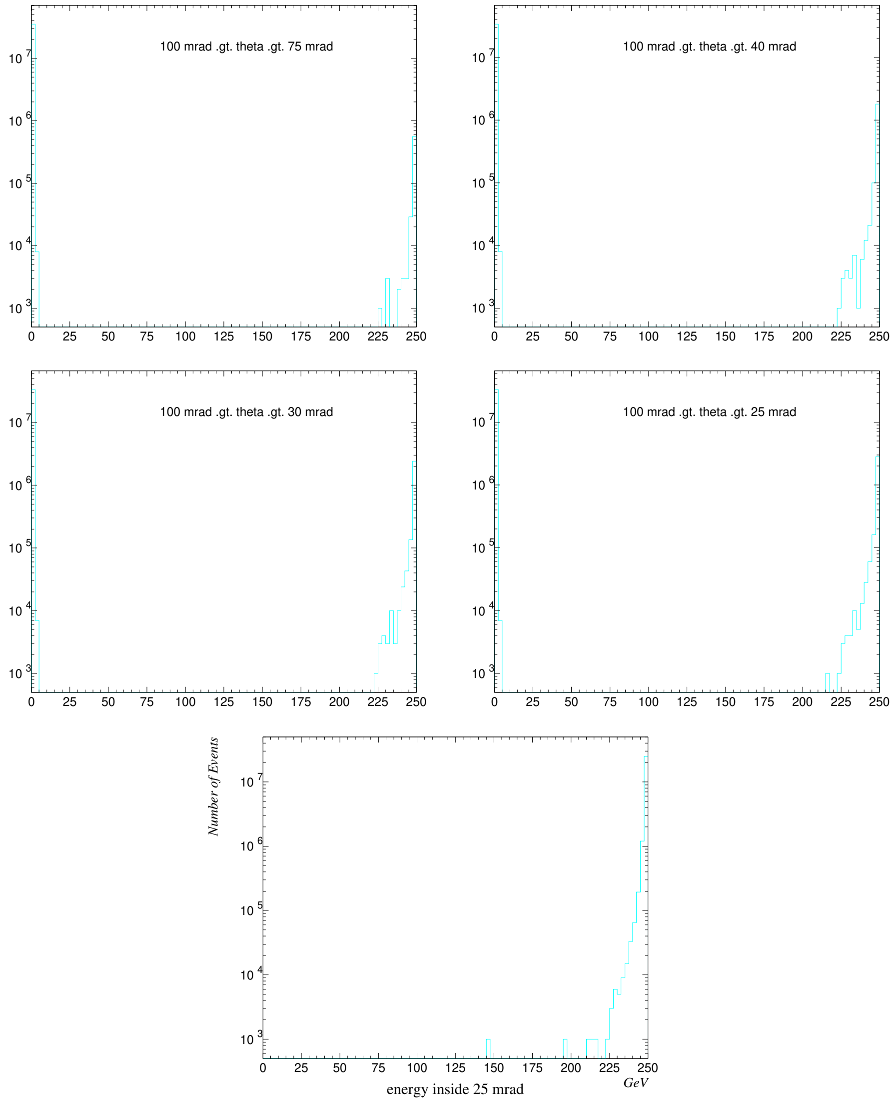


Figure 13: Energy of beamhole electrons and positrons for two photon events inside varying angles.

Figure 14 shows the energy of muons and antimuons after making cuts to remove electrons and positrons at different angles in the beamhole.

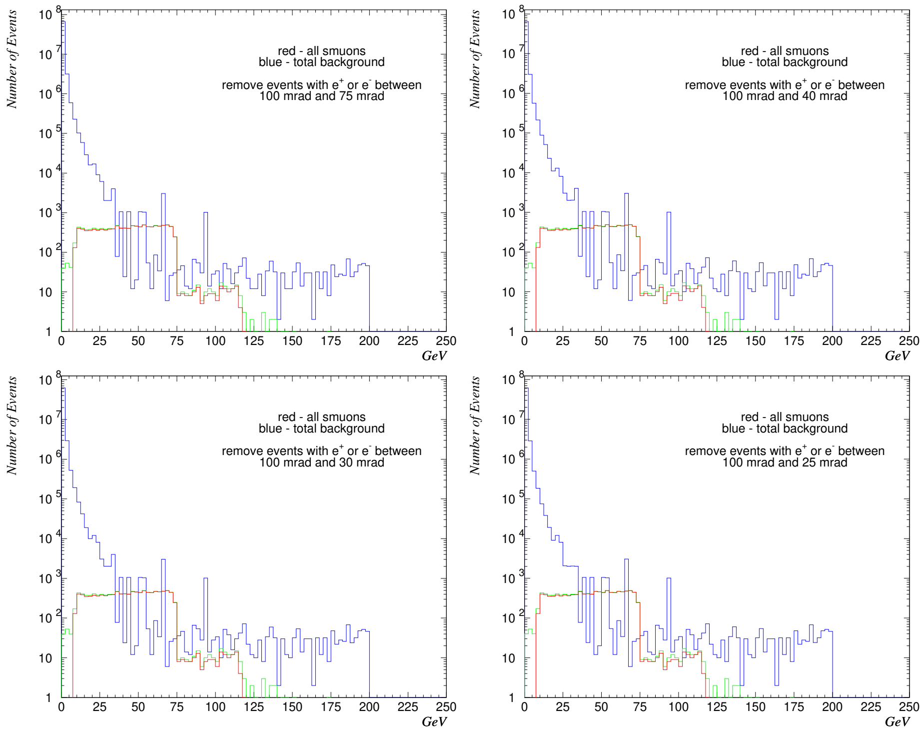


Figure 14: Energy of μ and $\bar{\mu}$ after removing events with electrons and positrons between various angles (in mrad) in the beamhole.

5 Conclusion

I have simulated an integrated luminosity of 100 fb^{-1} (which is equivalent to two years of data) and I have isolated the signal from Supersymmetric smuons using cuts that are reproduceable in a particle detector.

The masses obtained using simulations are within about 9% of the theoretically derived values.

The cut that demands transverse momentum be greater than 25 GeV removes all of the two photon background without changing the endpoints, but it does cut some Supersymmetric smuon events. This is acceptable for measuring particle masses, but it makes the measurement of the smuon cross sections impossible. Ideally, to measure masses *and* cross sections, we need to find a method to remove the background without removing as many signal events as we did when we demanded that transverse momentum is greater than 25 GeV.

The next step of this study is to measure the mass of the $\tilde{\mu}_L$ by running a study similar to this one at 750 GeV[5] where the cross section for $\tilde{\mu}_L\tilde{\mu}_L$ is largest.

References

[1] Goodman, E. "The Search for the Supersymmetric Selectron." COLO HEP 398. April, 1998, http://hep-www.colorado.edu/SUSY/.

[2] Danielson, D., Goodman, E. "Point 2 Selectrons and the Standard Model Background." September, 1998, http://hep-www.colorado.edu/SUSY/.

[5]see http://hep-www.Colorado.EDU/ duckwitz/slides/2p2r.html for a graph of how the cross section of $\tilde{\mu}_L\tilde{\mu}_L$ changes with energy.