Does the ILC Solve the LHC Inverse Problem?

C. Berger, J. Gainer, J. Hewett, B. Lillie, T. Rizzo

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- Paying homage to Hinchliffe's theorem:

General SUSY Studies at the ILC

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Does the ILC Solve the LHC Inverse Problem?

- Paying homage to Hinchliffe's theorem:

General SUSY Studies at the ILC

- Hinchliffe's theorem can't be avoided:

Wanted: Background Reduction

C. Berger, J. Gainer, J. Hewett, B. Lillie, T. Rizzo

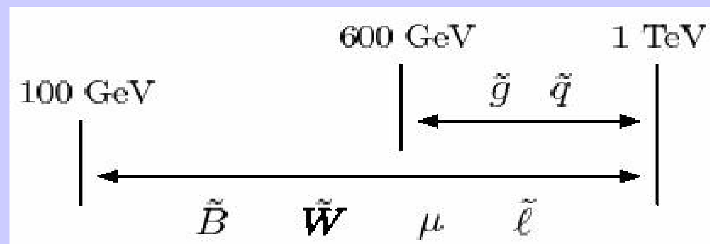
LHC Inverse Problem

- Generate blind SUSY data and map it back to parameters
  - Generated 43,026 models within MSSM for 10 fb^{-1} @ LHC
  - For 15 parameters:

Inos :	$M_1,\ M_2,\ M_3,\ \mu$
Squarks :	$m_{\tilde{Q}_{1,2}},\ m_{\tilde{U}_{1,2}},\ m_{\tilde{D}_{1,2}},\ m_{\tilde{Q}_3},\ m_{\tilde{t}_R},\ m_{\tilde{b}_R}$
Sleptons :	$m_{\tilde{L}_{1,2}},\ m_{\tilde{E}_{1,2}},\ m_{\tilde{L}_3},\ m_{\tilde{\tau}_R}$

+ tan β

Within the constraints:



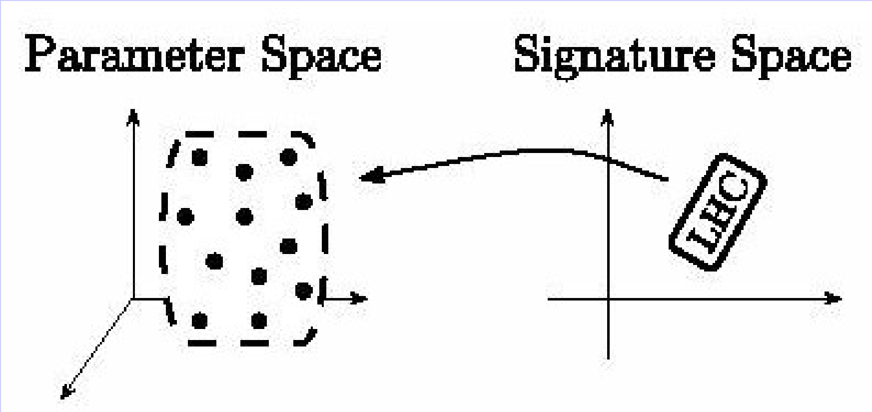
  - Used ~1808 LHC MSSM Observables – NO Background!

- Question: Can the models be uniquely determined from the LHC data?

Arkani- Hamed, Kane, Thaler, Wang,
hep- ph/0512190

LHC Inverse Problem

- Main result: 320 pairs of models were indistinguishable!
  - A signature maps back into a number of small islands in parameter space



Begs the question: Can the ILC resolve these degeneracies?

Our Analysis

- We start with their ~320 degenerate pairs (383 distinct models)
- Simulate signal events with Pythia, and feed in appropriate beamspectrum generatied via Whizard/GuineaPig
- Add SM background (1016 different processes), produced by Tim
- Pipe through detector simulation: Java-based SiD simulation, org.lcsim
- Analyze 500 fb^{-1} "data" with 80% P_{e-} and appropriate cuts. Several iterations necessary to find best cuts!

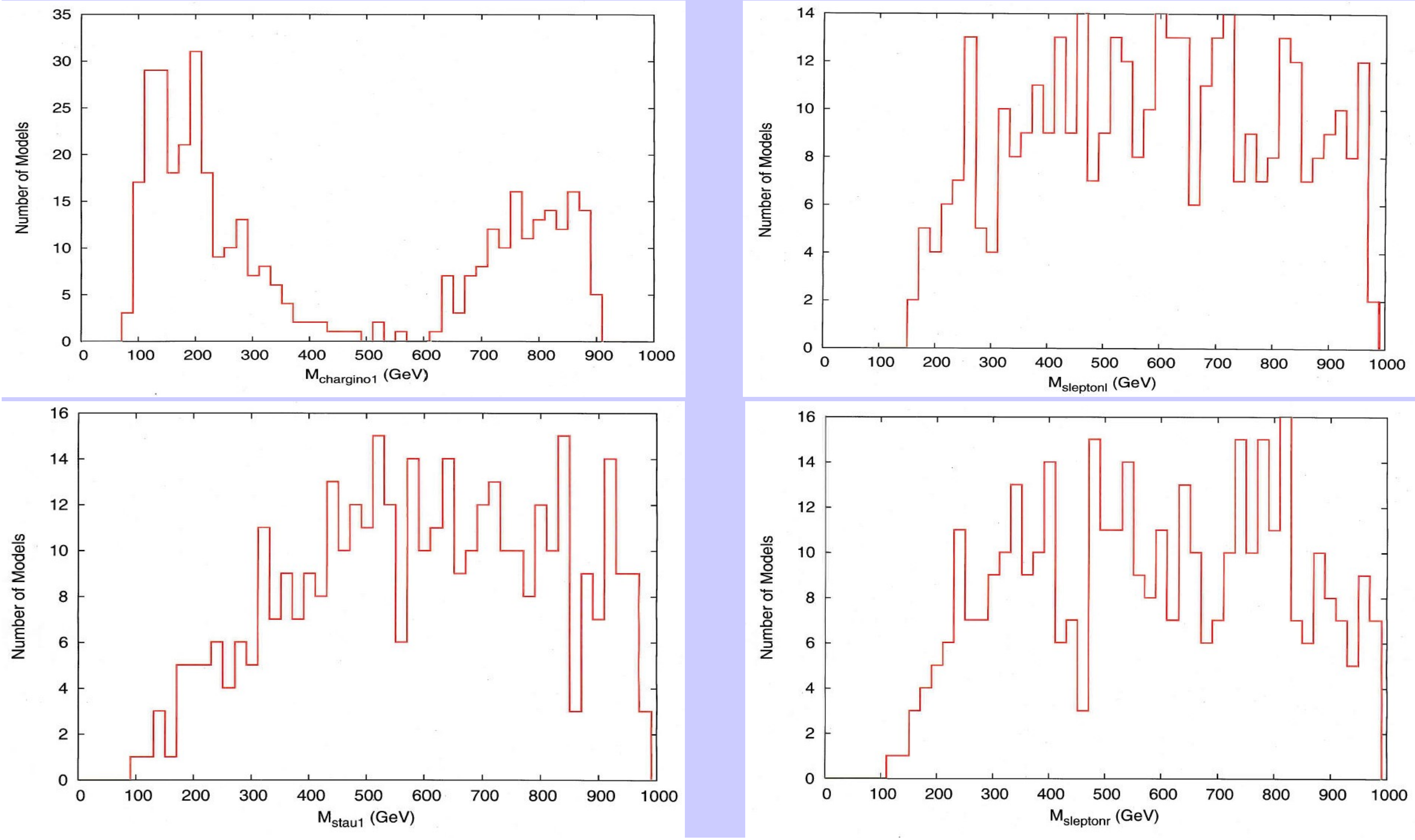
Our Analysis II

We are simulating:

- Left- and Right-handed selectrons
- Left- and Right-handed smuons
- $Stau_{1,2}$
- Lightest Chargino, $\chi^{\pm}$, χ^{0} mass splitting > 1 GeV
- Lightest Chargino, $\chi^{\pm}$, χ^{0} mass splitting < 1 GeV

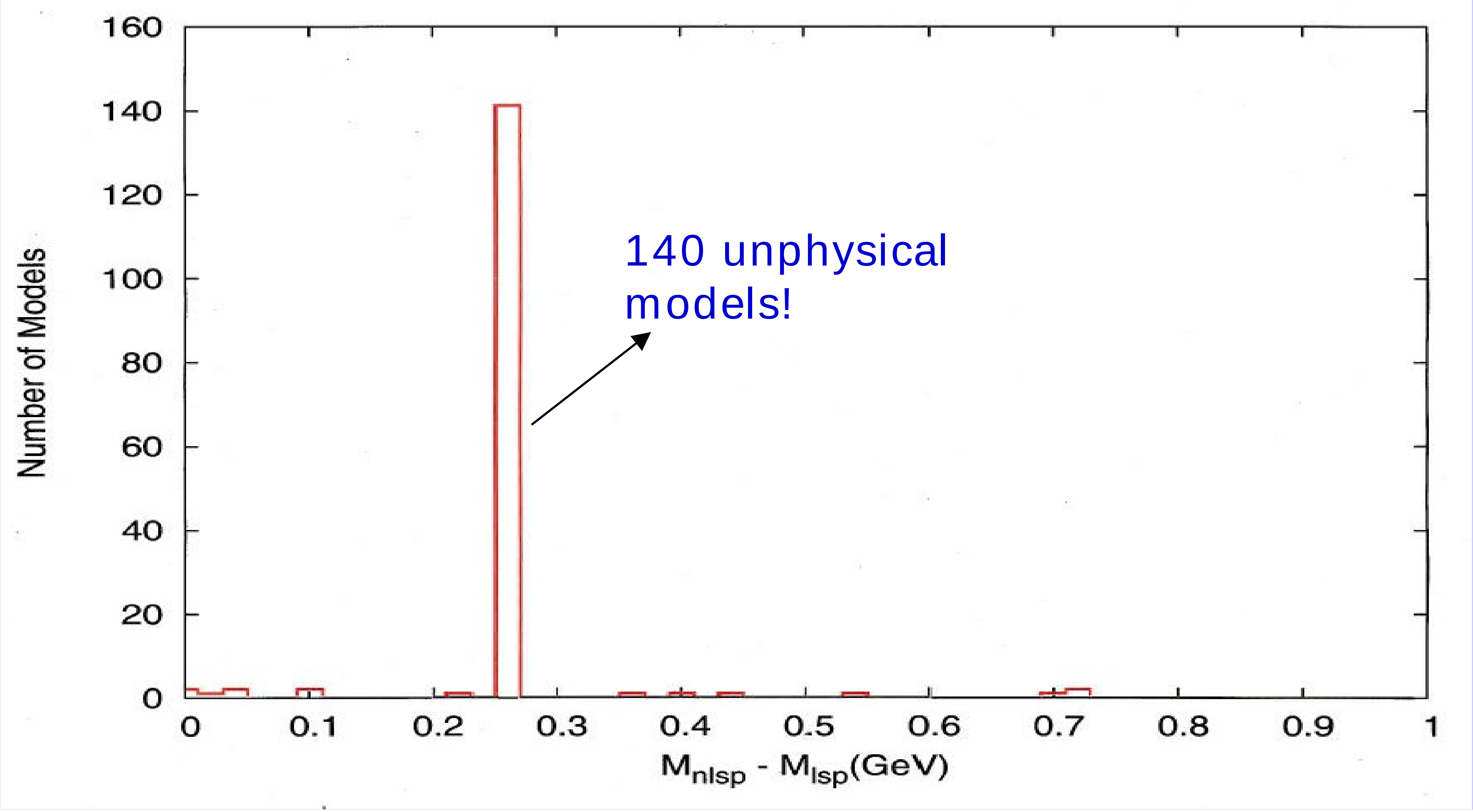
SUSY Spectrum of 383 models

Only 3 models without sparticles @0.5-1.0 TeV

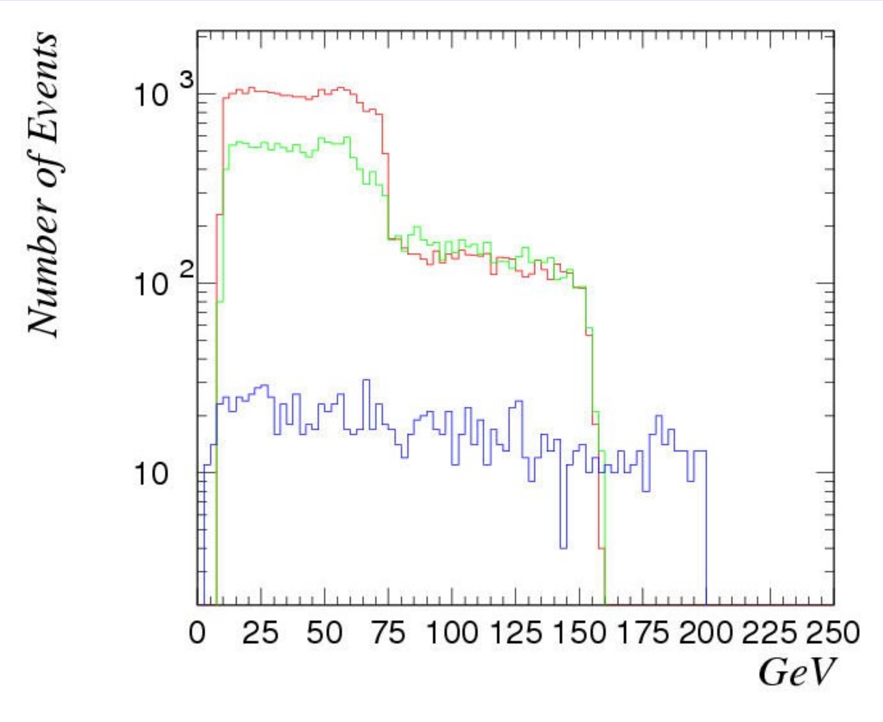


Close Mass Charginos

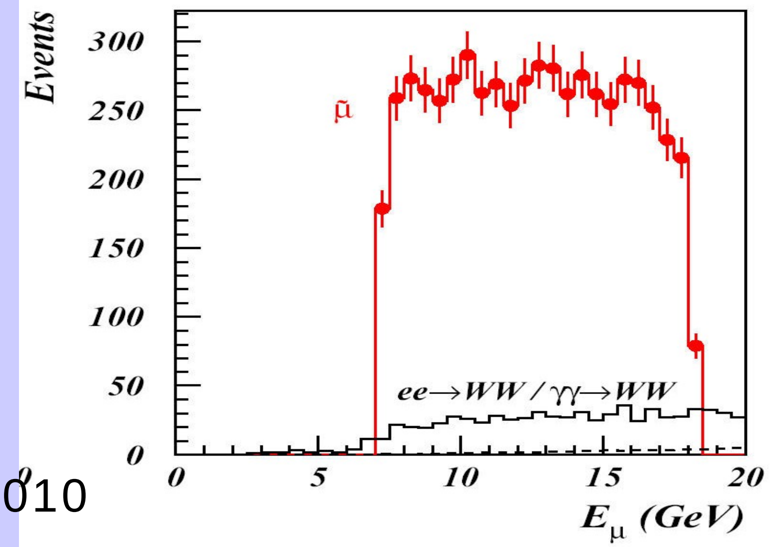
- Discovered Pythia FEATURE: If $M_{chargino} < M_{LSP}$ after RGE then Pythia sets $M_{chargino} = m_{2\pi} + M_{LSP}$



Previous ILC SUSY Studies

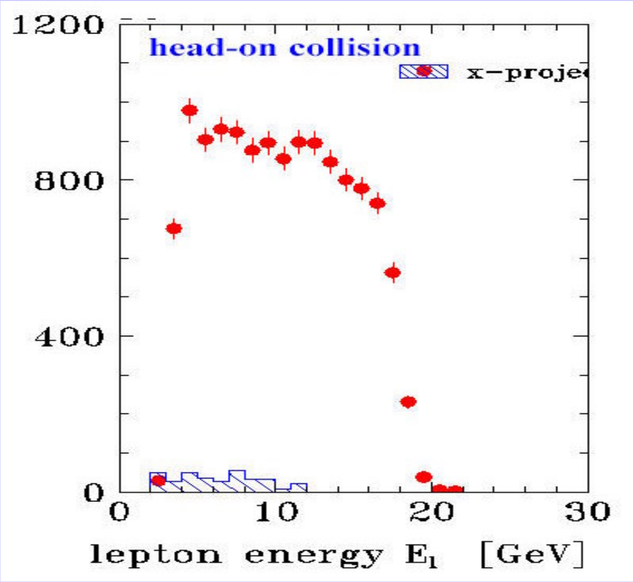


Colorado Group
Goodman etal

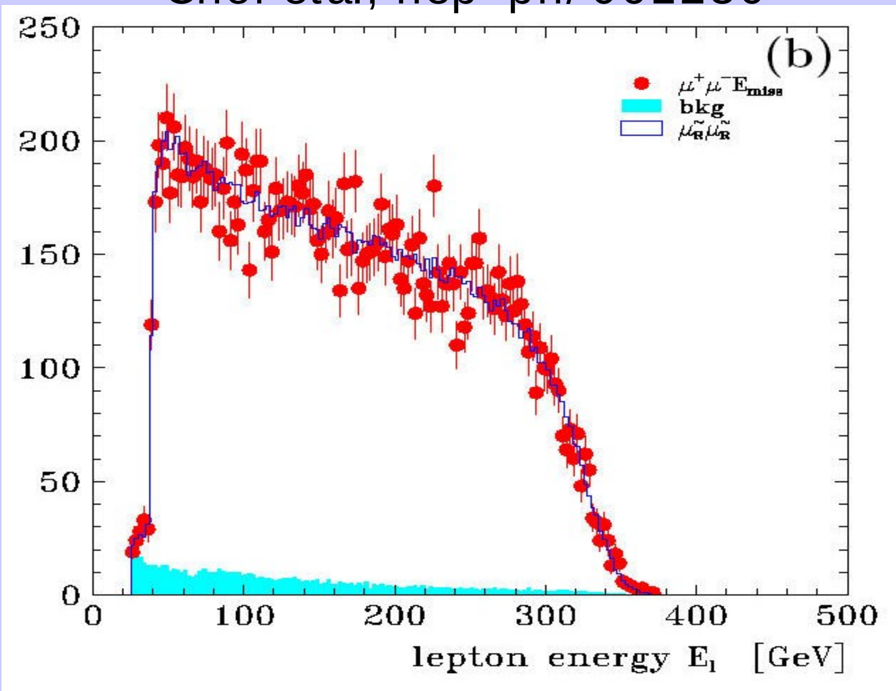


Bambade etal
hep-ph/0406010

Choi etal, hep-ph/061230`



Martyn
hep-ph/0408226



Present study is the first ILC SUSY study with

- 100’s of SUSY models chosen at random
- Full SM background included

Selectron Analysis Timeline: Mid-November

1. Exactly 2 leptons, identified as $e^{+,-}$ in the event.

   Cuts SM bckgrnd with ZZ $\rightarrow$ leptons

2. $E_{vis} < 1$ GeV between $0.9 \leq |\cos\theta| \leq 0.995$

   Cuts forward-peaked WW bckgrnd

3. $E_{vis} < 0.4\sqrt{s}$ in the forward hemisphere

   Forward hemisphere is defined around thrust axis. SUSY (SM) has missing E_T in both (one) hemisphere

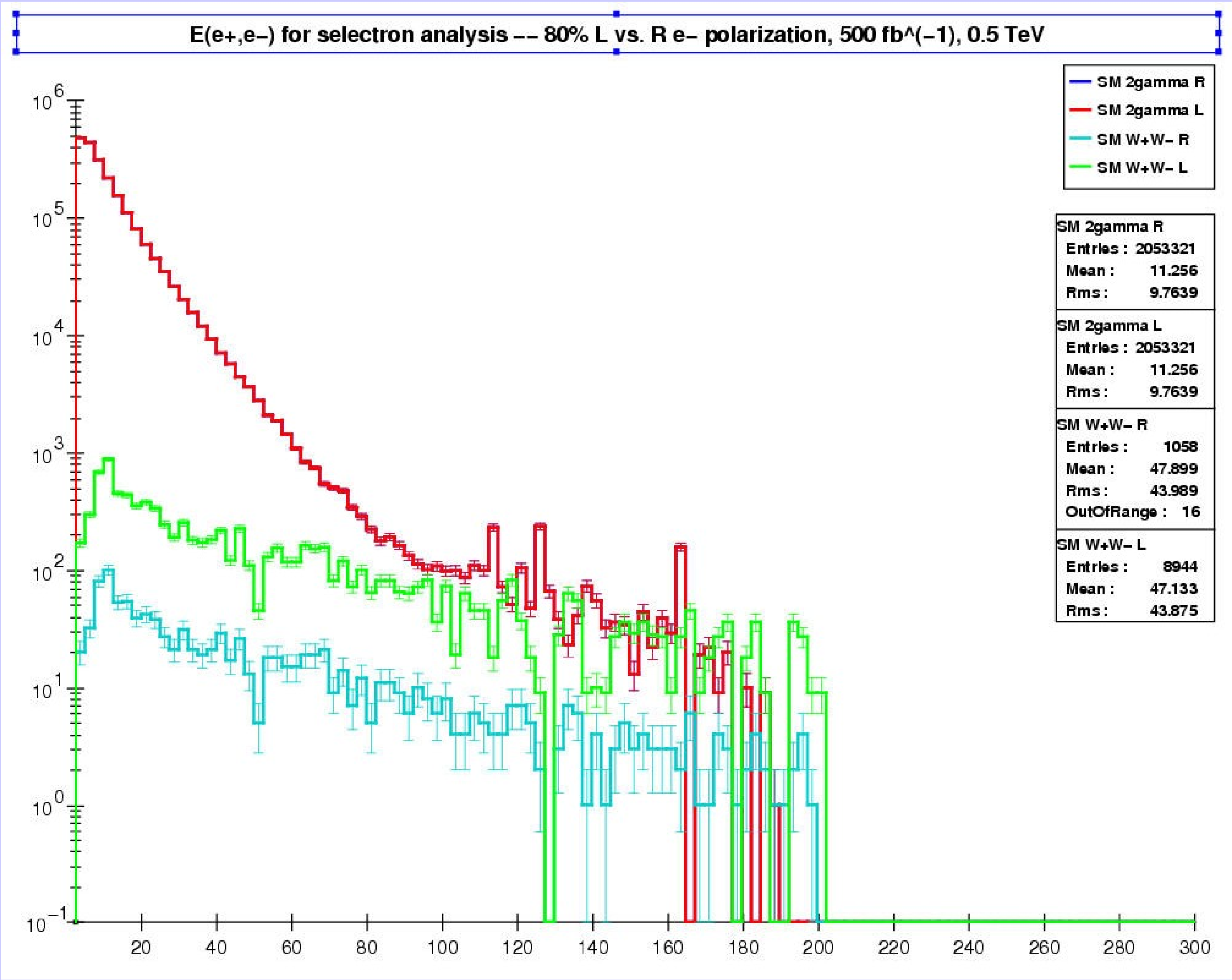
4. Min ($E_{particle\ 1}$, $E_{particle\ 2}$) $< 0.486\sqrt{s}$ IF both particles in $0.99995 \leq |\cos\theta| \leq 1$

   Eliminates ISR where emitting $e^{+,-}$ goes down beampipe

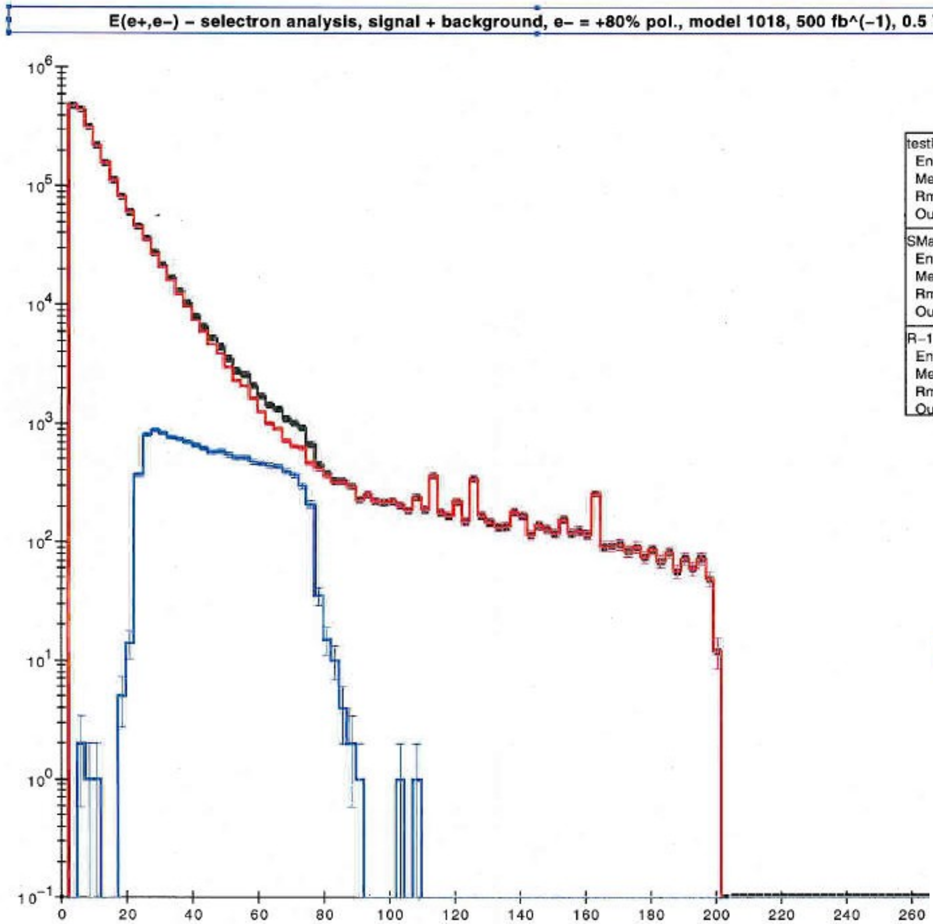
5. $\cos\theta_{open} > -0.96$ for the reconstructed $e^{+,-}$ pair

   SUSY pair not back-to-back due to missing E_T

Background Summary: mid-November

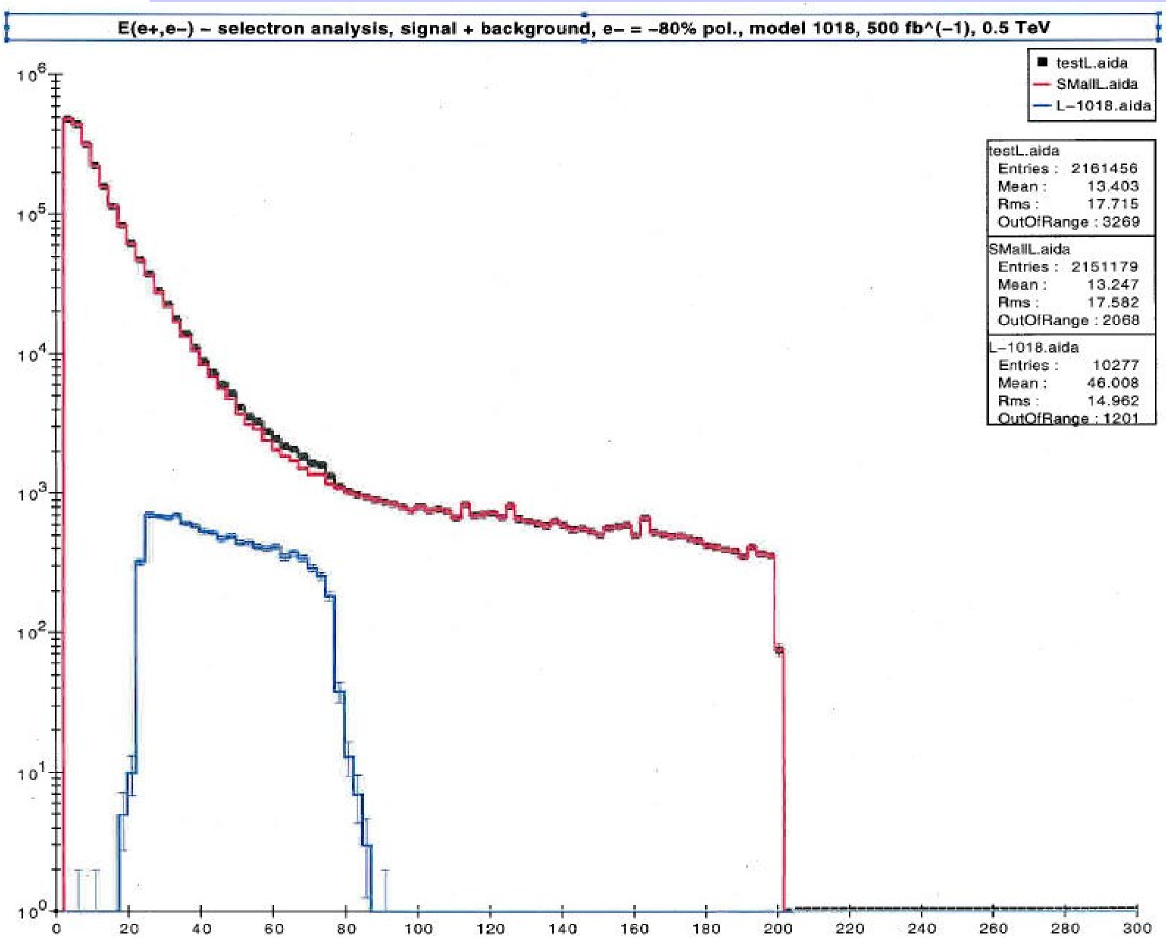


Signal vs Background mid-November Model 1018



Right-handed

Left-handed



Selectron Analysis Timeline: Mid-December

Cuts 1-5 as above

6. $E_{vis} < 0.2\sqrt{s}$ for $|\cos\theta| > 0.995$ (100 mrad)

   Eliminates ISR where emitting $e^{+,-}$ goes down beampipe, but not lumi monitor

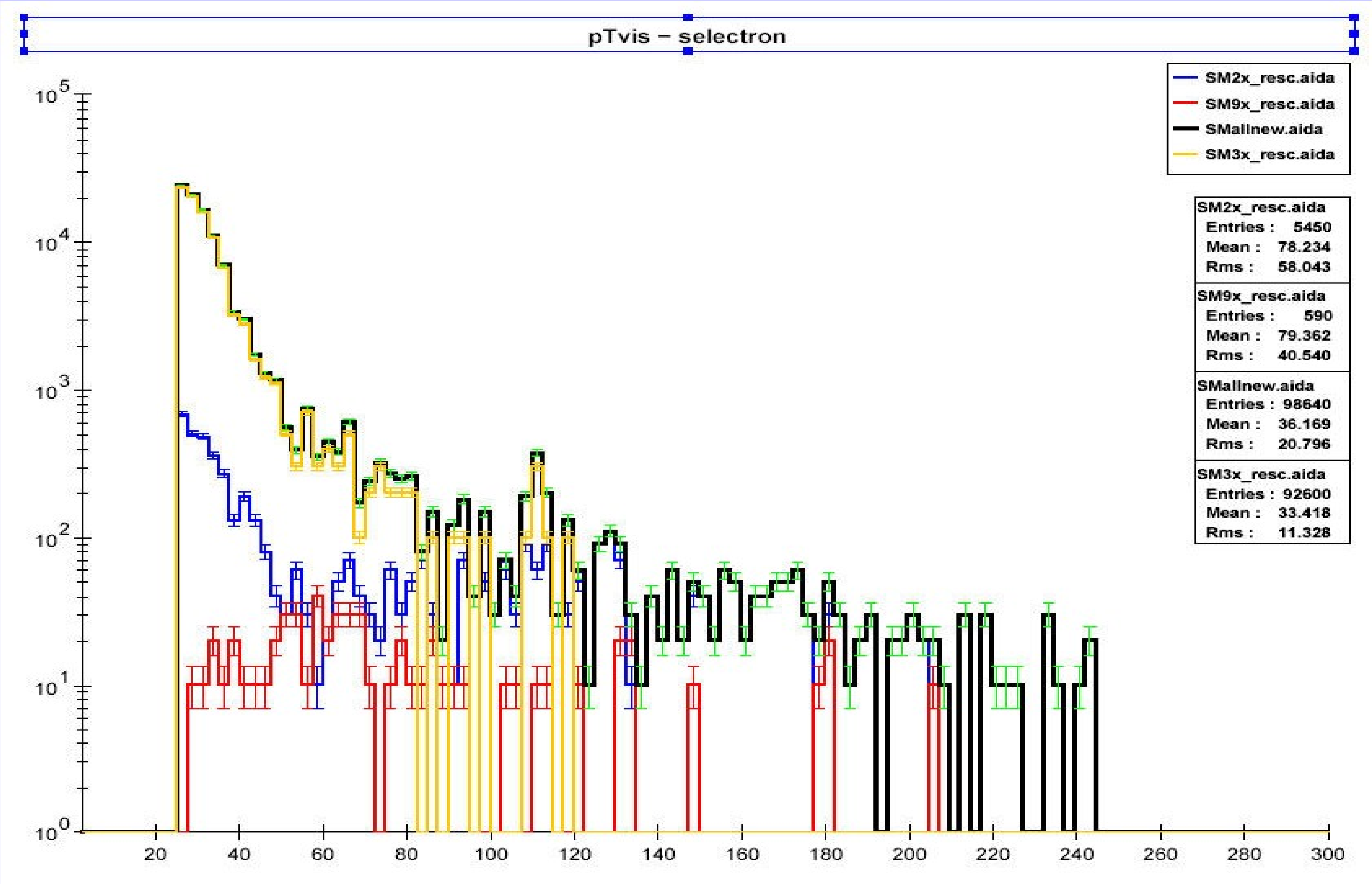
7. $p_{T,vis} > 0.05\sqrt{s}$

   Reduces $\gamma\gamma$ background

8. $M_Z - 5$ GeV $< M_{e+e-} < M_Z + 5$ GeV

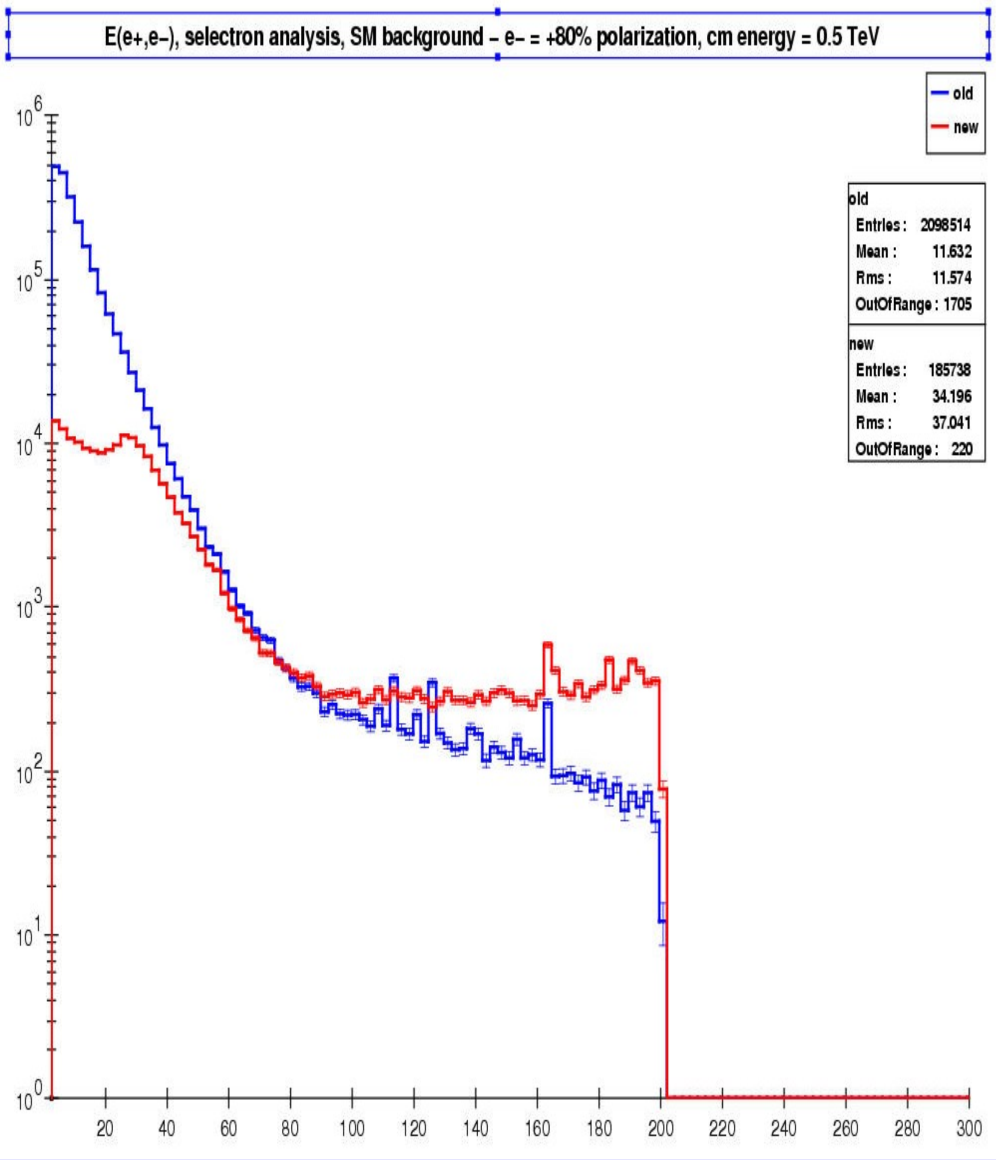
   Reduces ZZ background

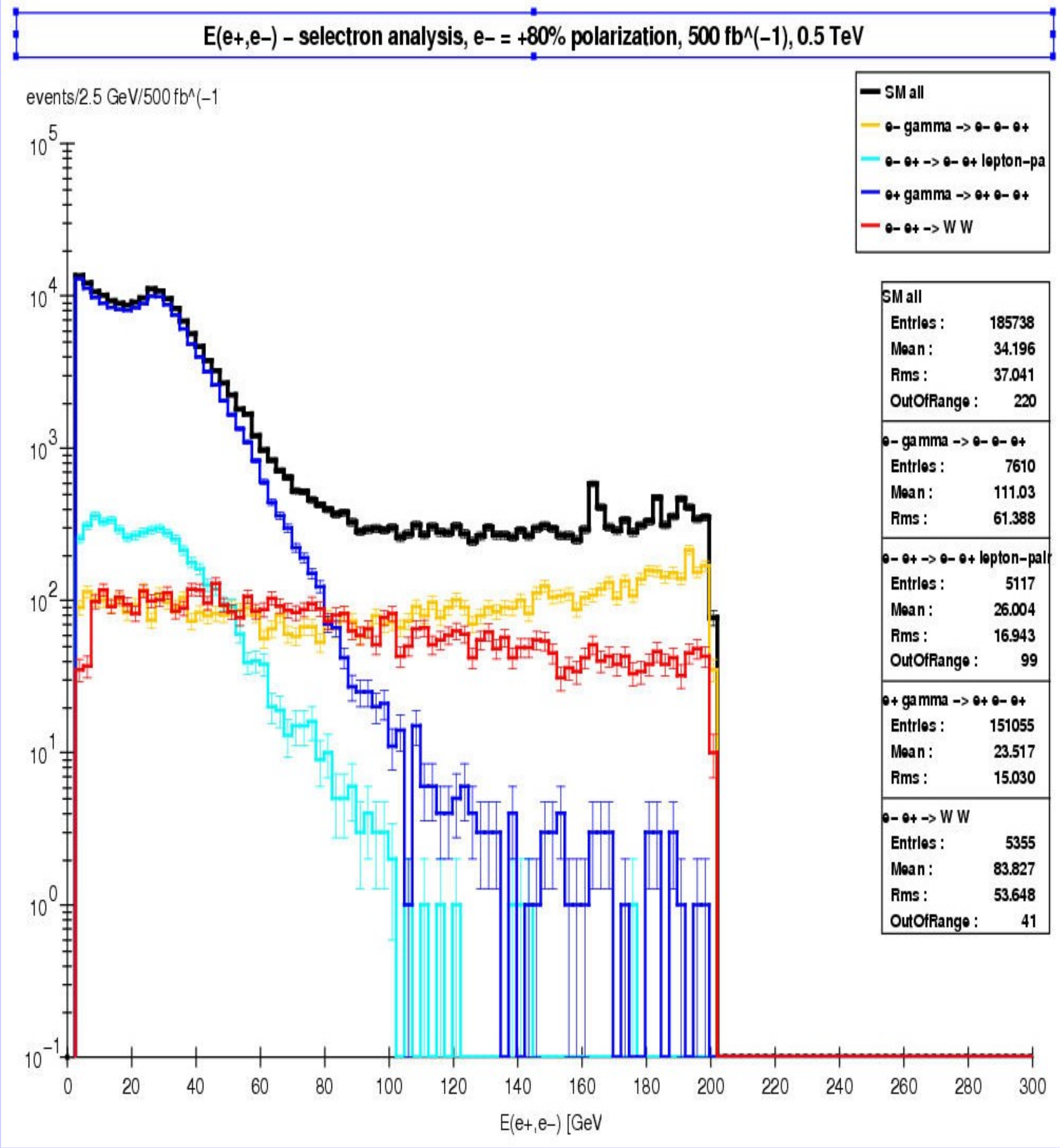
Background Summary: mid-December



Background Summary II: mid-December

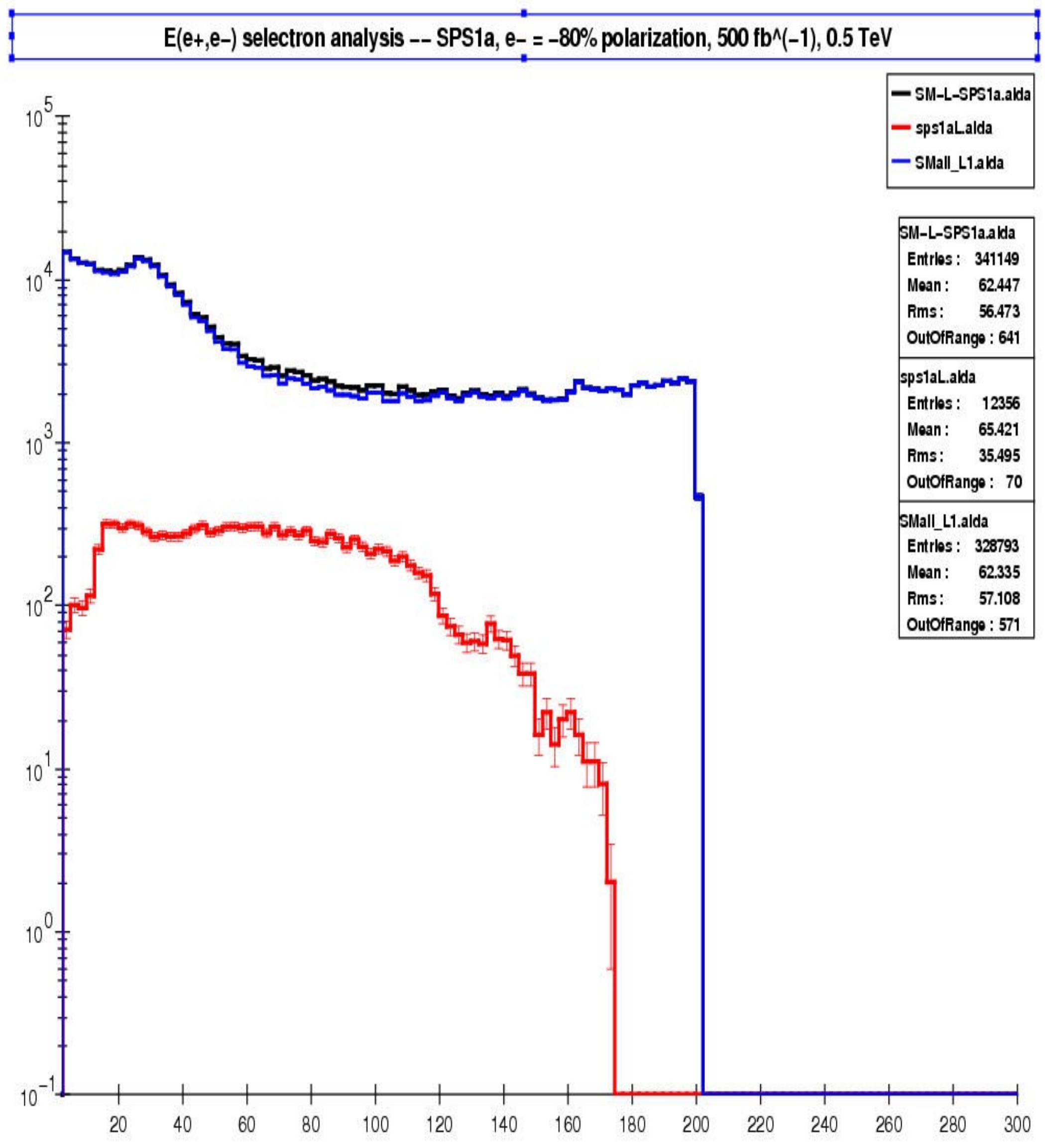
Right-handed



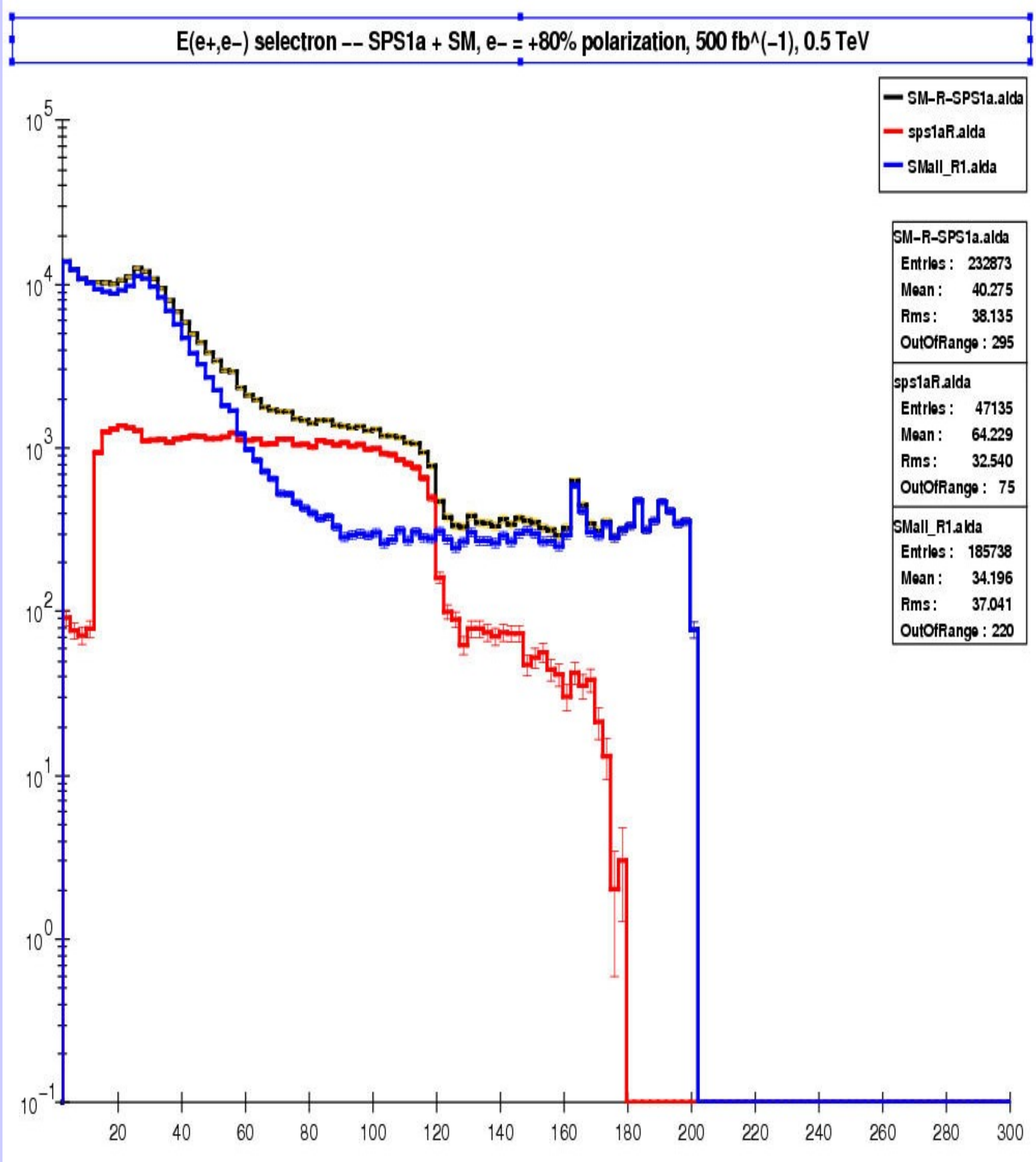


SPS1a Signal & Background: mid-December

Left-handed



Right-handed



Selectron Analysis Timeline: Mid-January

Cuts 1-5 as above

6. $E_{vis} < 0.2\sqrt{s}$ for $|\cos\theta| > 0.995$ (100 mrad)

   Eliminates ISR where emitting $e^{+,-}$ goes down beampipe, but not lumi monitor

7. $p_{T,vis} > 0.06\sqrt{s}$

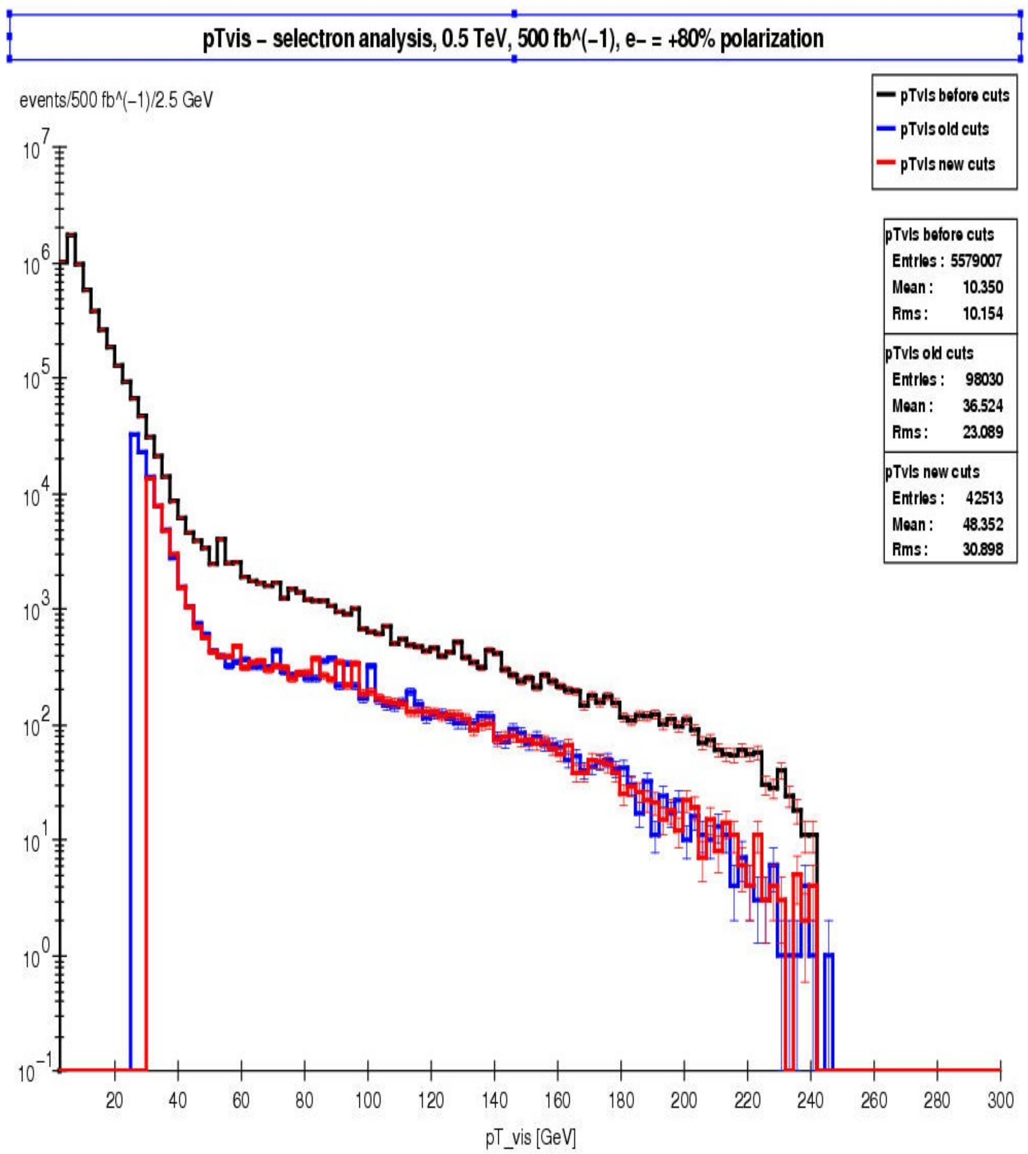
   Reduces $\gamma\gamma$ background

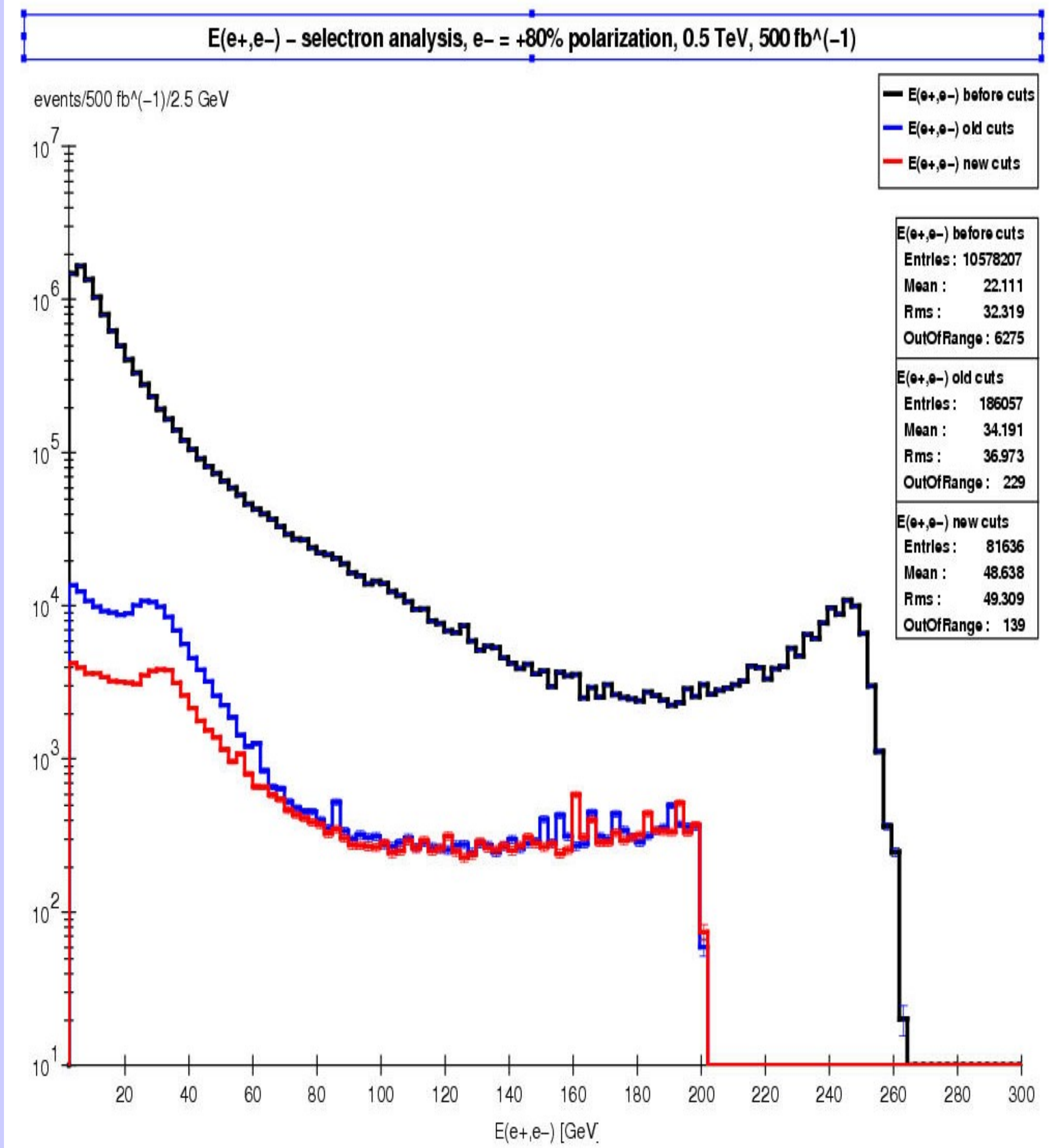
8. $M_Z - 5$ GeV $< M_{e+e-} < M_Z + 5$ GeV

   Reduces ZZ background

Background Summary: mid-January

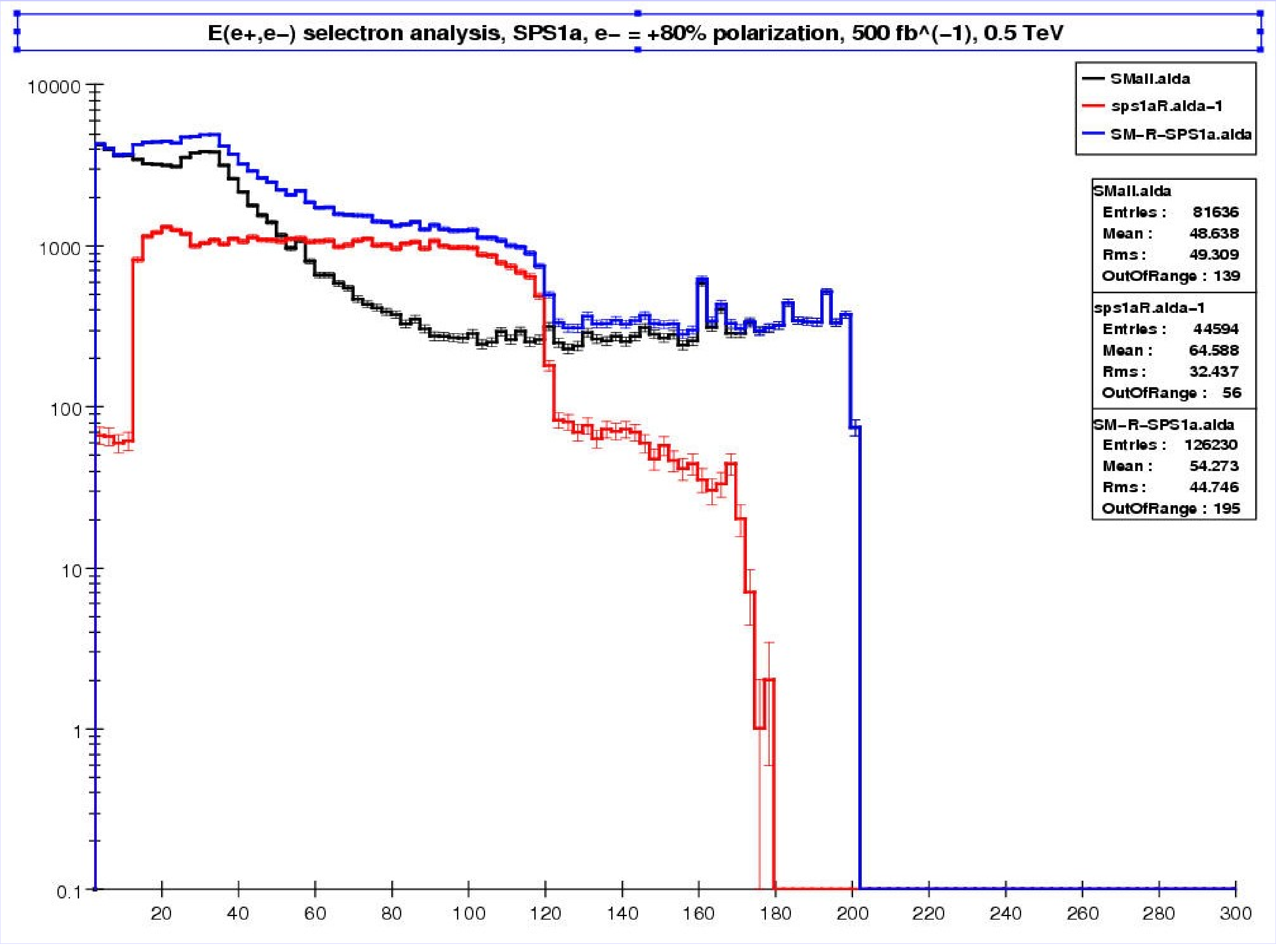
Right-handed



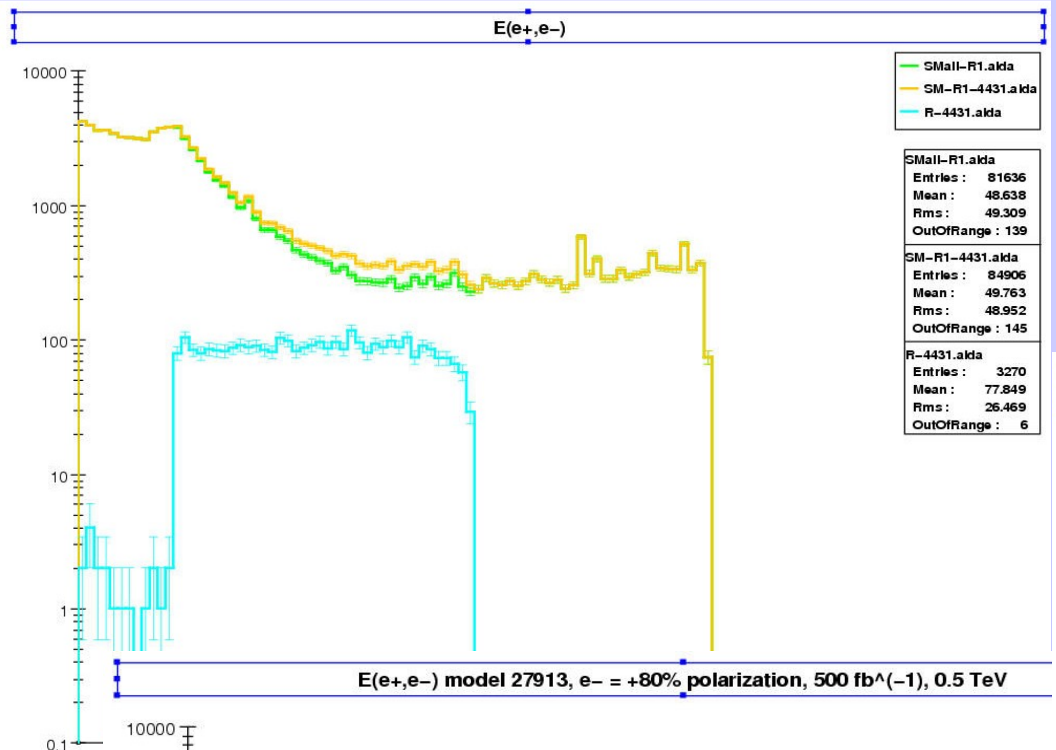


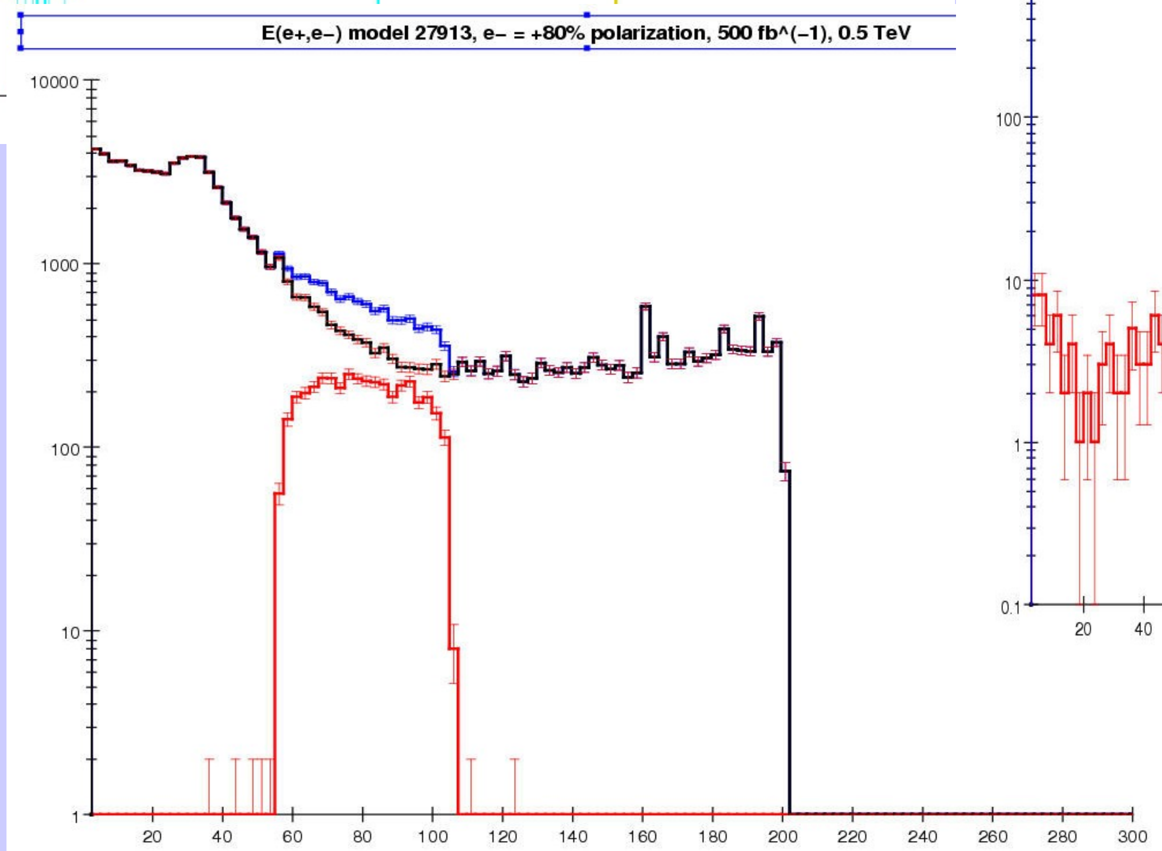
Signal vs Background SPS1a: mid-January

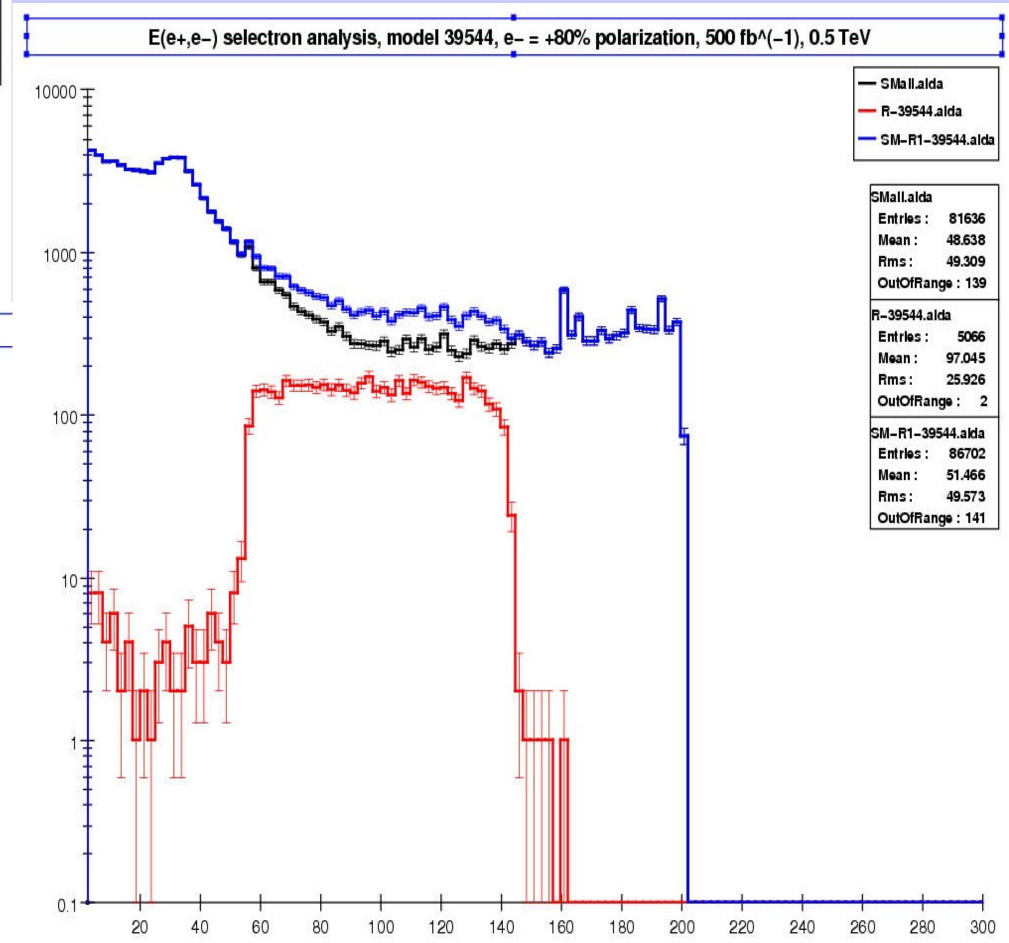
Right-handed



Signal vs background, Harvard models: mid-January

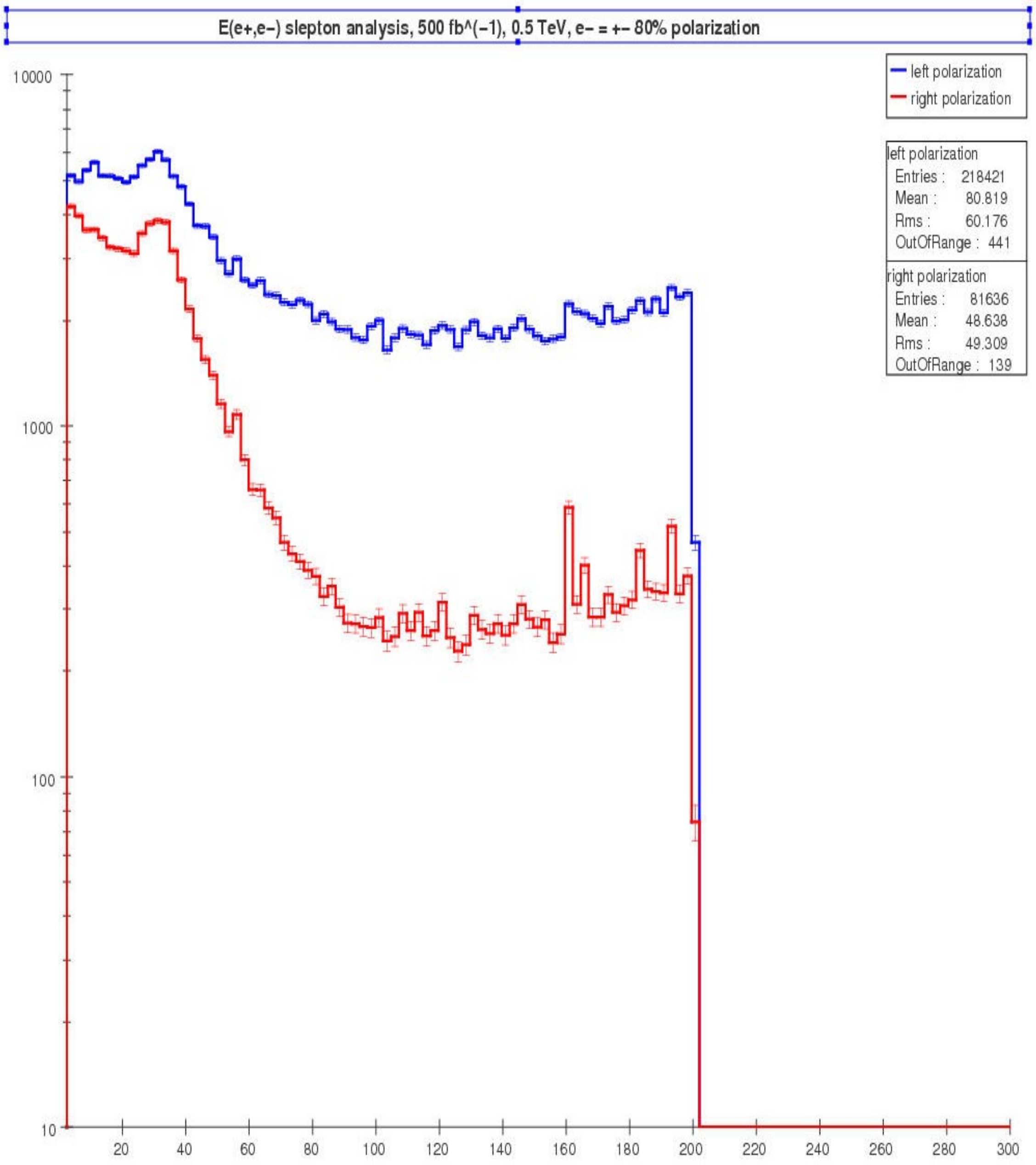


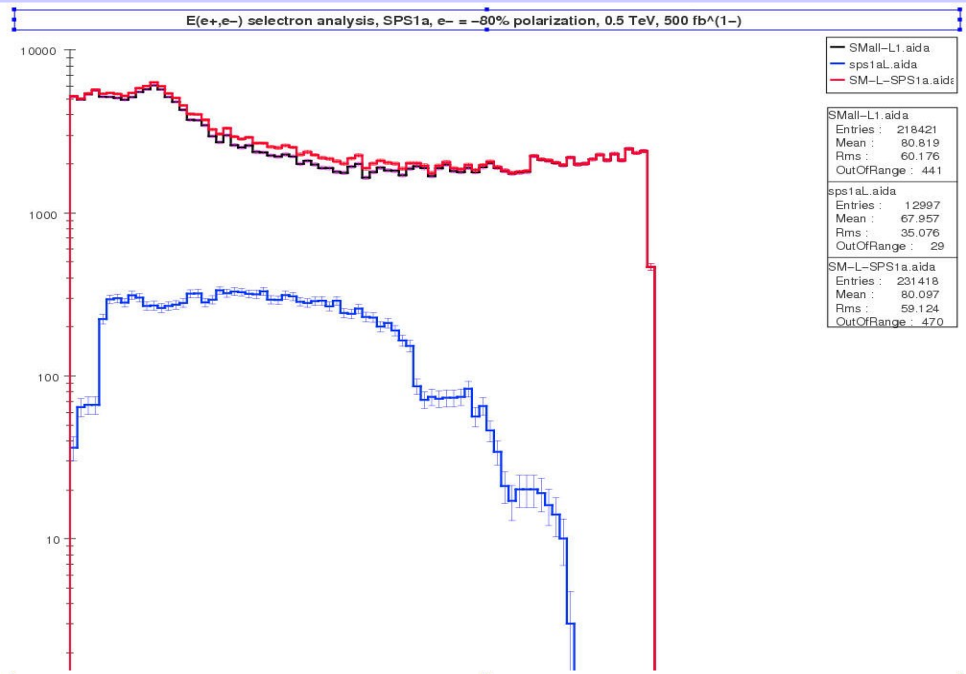


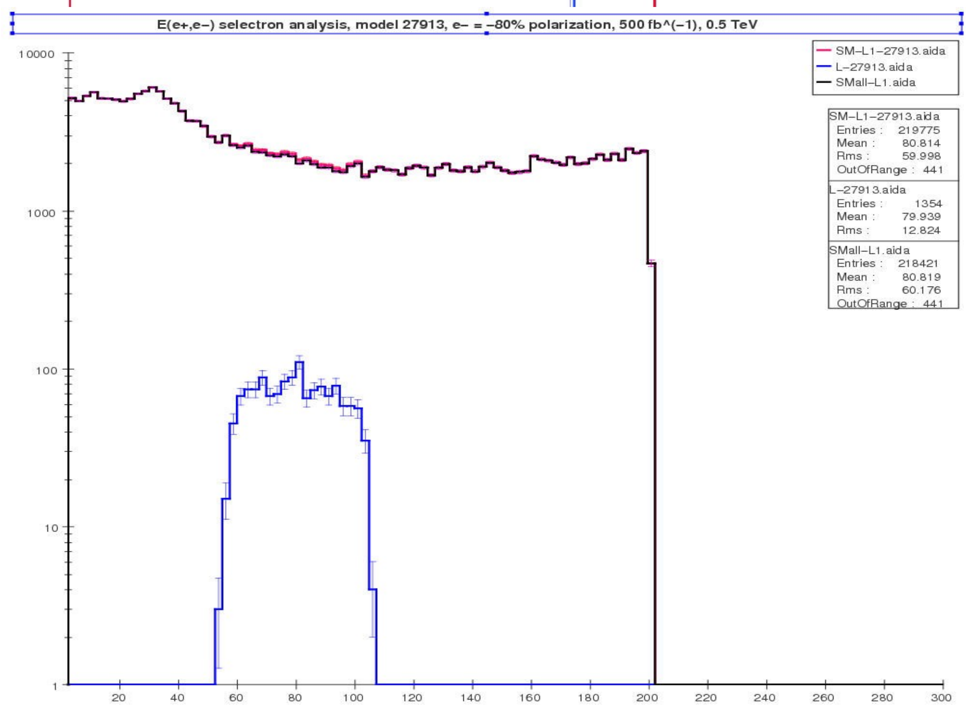


Right-handed

Left-handed samples: end-January







Smuon Analysis I

1. Exactly 2 leptons, identified as $\mu^{+,-}$ in the event.
   Cuts SM bckgrnd with ZZ $\rightarrow$ leptons
2. E_{vis} < 1 GeV between $0.9 \leq |\cos\theta| \leq 0.995$
   Cuts forward-peaked WW bckgrnd
3. $E_{vis} < 0.4\sqrt{s}$ in the forward hemisphere
   Forward hemisphere is defined around thrust axis. SUSY (SM) has missing E_T in both (one) hemisphere
4. $E_{vis} < 0.2\sqrt{s}$ for $|\cos\theta| > 0.995$ (100 mrad)
   Eliminates ISR where emitting e+,- goes down beampipe, but not lumi monitor
5. $p_{T,vis} > 0.06\sqrt{s}$
   Reduces $\gamma\gamma$ background
6. $M_Z - 5$ GeV < $M_{\mu+\mu-}$ < $M_Z + 5$ GeV
   Reduces ZZ background

Smuon Analysis II

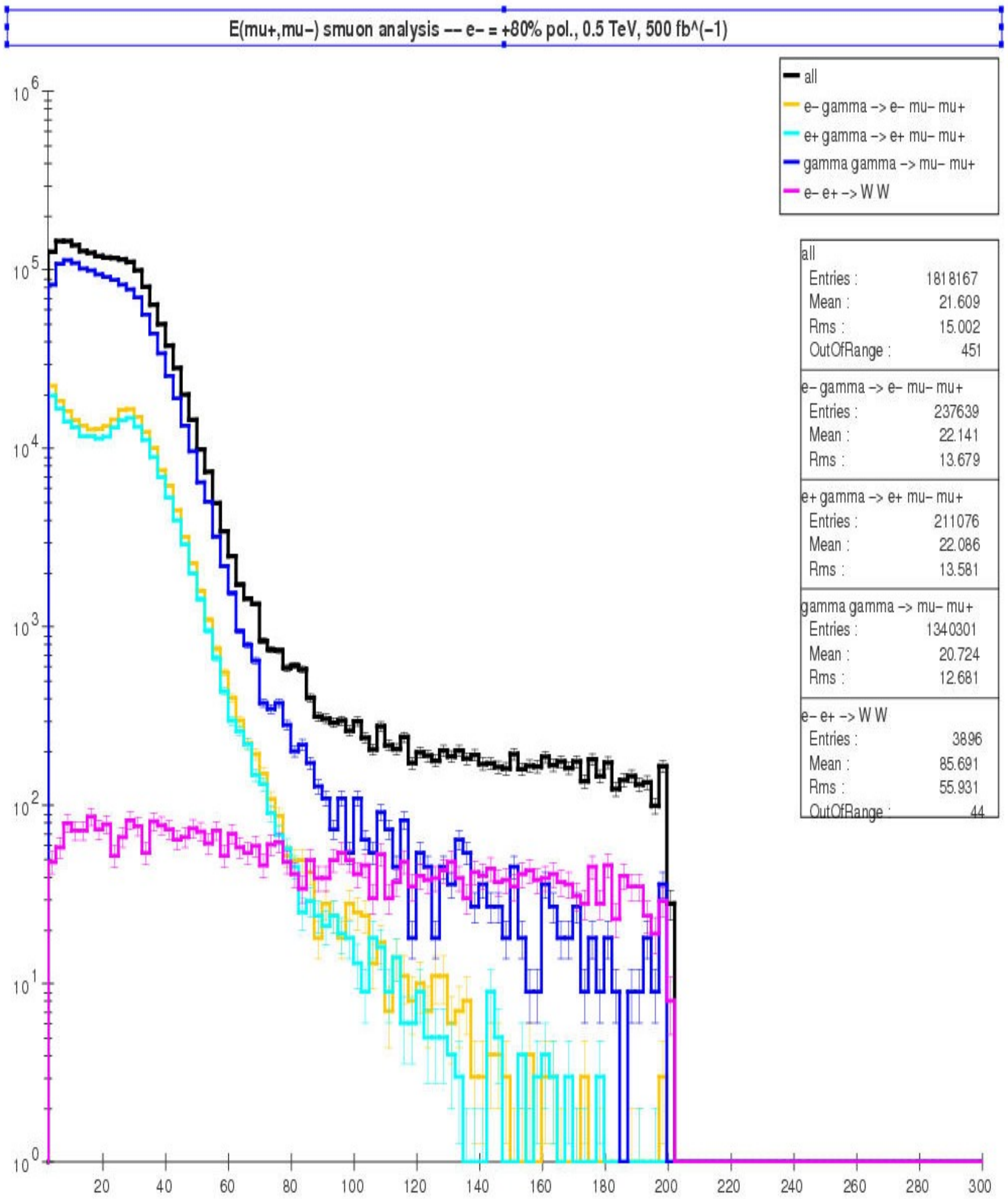
1. No electromagnetic energy > $0.01\sqrt{s}$ in $|\cos\theta| > 0.995$
2. 2 muons weighted by charge within polar angle $-0.9 < Q_\mu \cos\theta_\mu < 0.75$

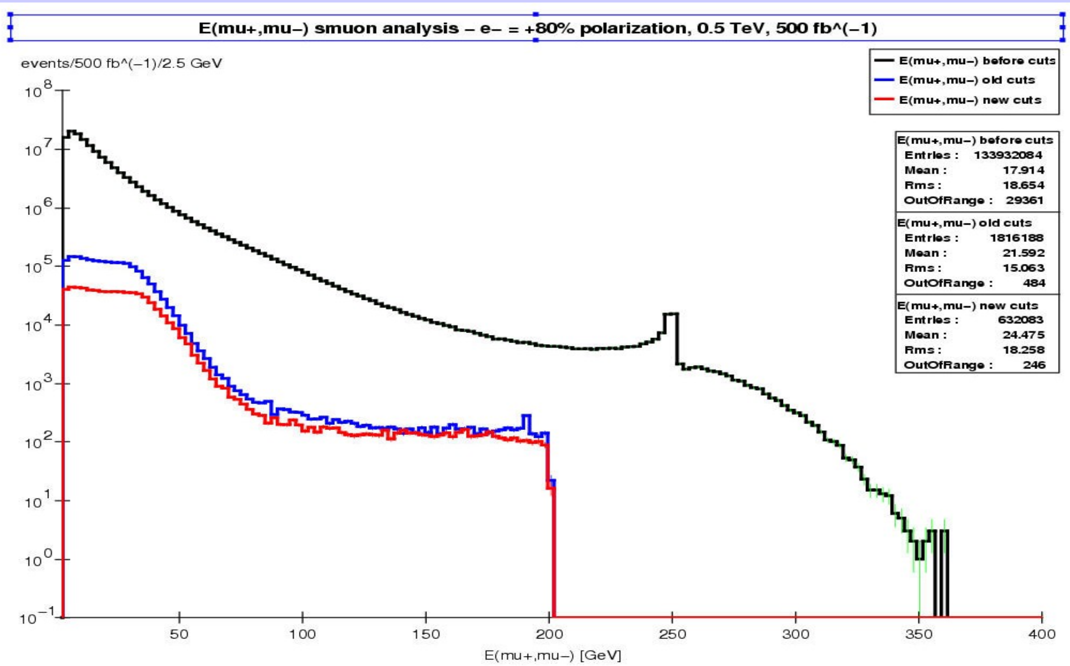
   Cuts WW background
3. Acoplanarity angle $\Delta\phi^{\mu\mu} < 160$ degrees (= angle between muon p_T, $\cos\theta_T > -0.94$)

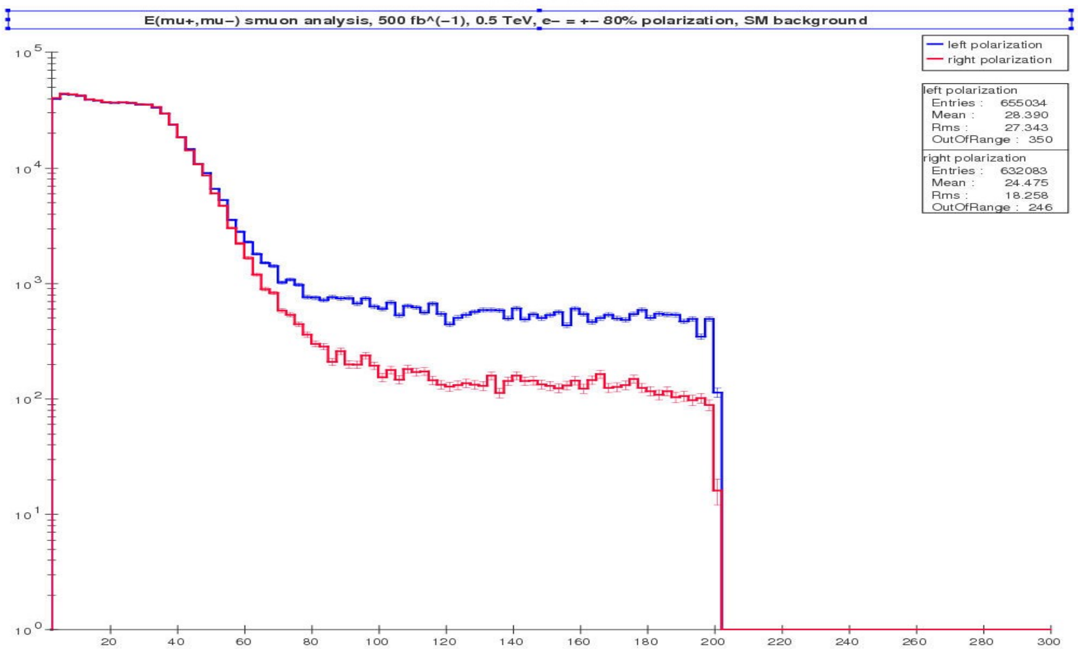
   Cuts WW and $\gamma\gamma$ background (similar to selectron cut)
4. $|\cos\theta_{pmissing}| < 0.9$
5. $E_\mu > 0.004\sqrt{s}$
6. $p_T^{\mu\mu} > 0.05\sqrt{s}$

   Cuts $\gamma\gamma$ and $e\gamma$ background

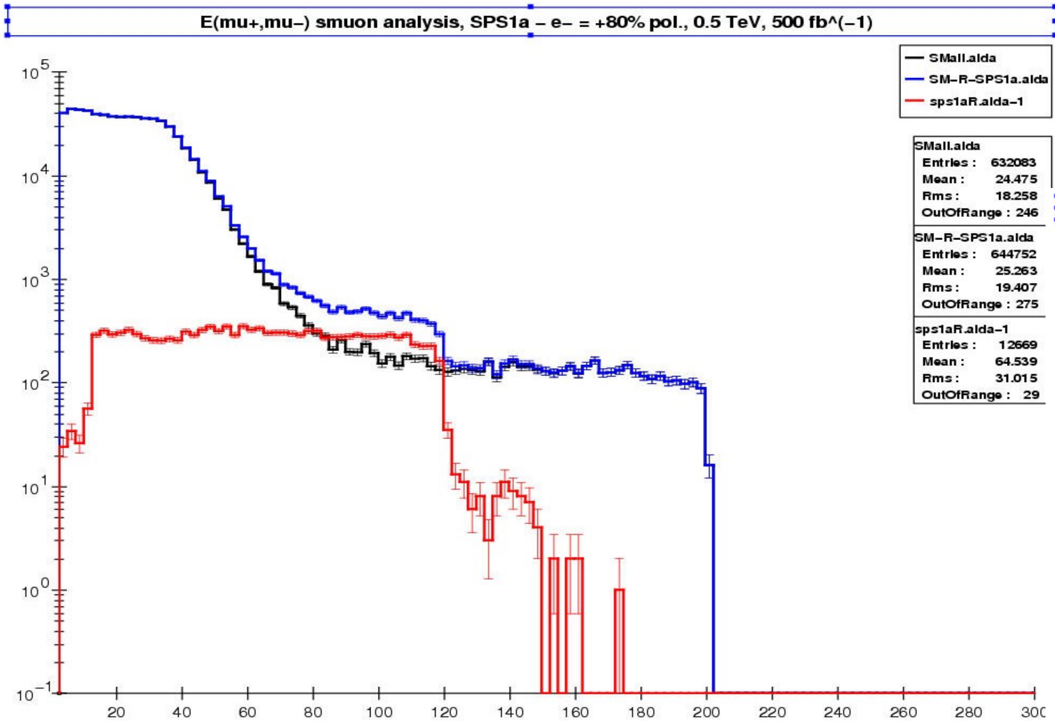
Smuon Background Summary

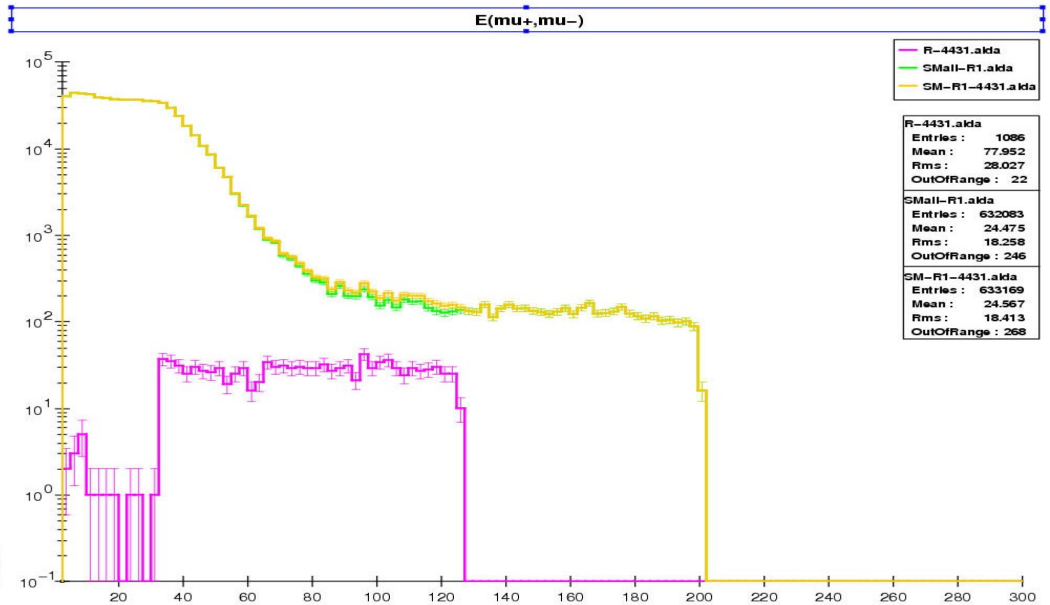


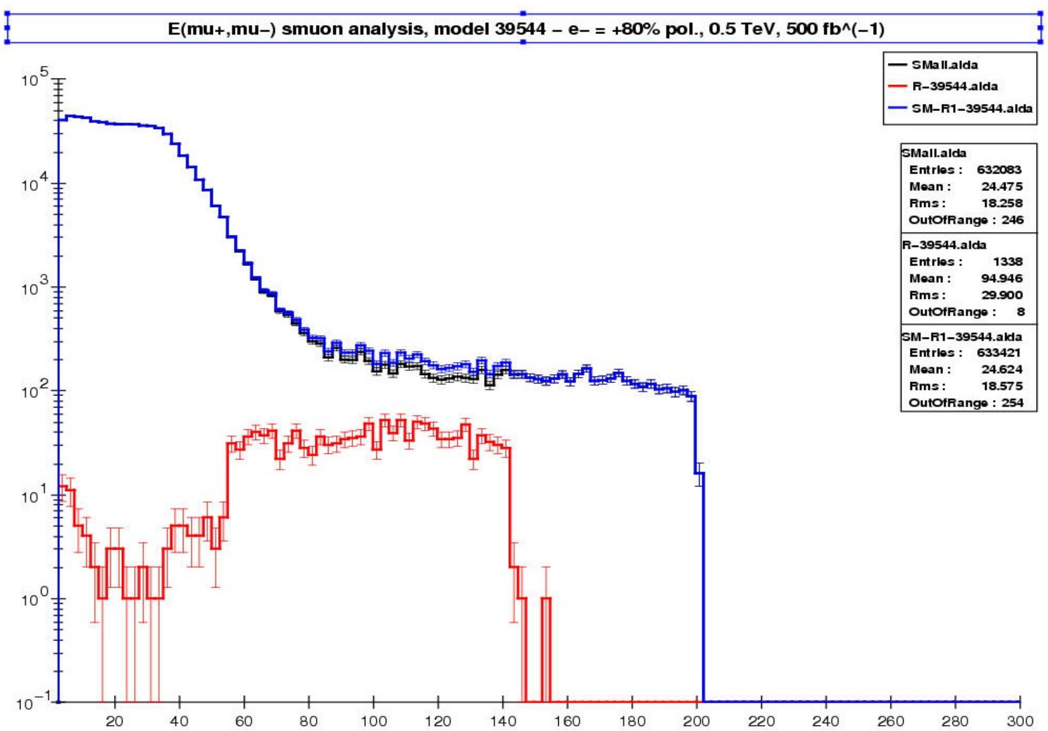


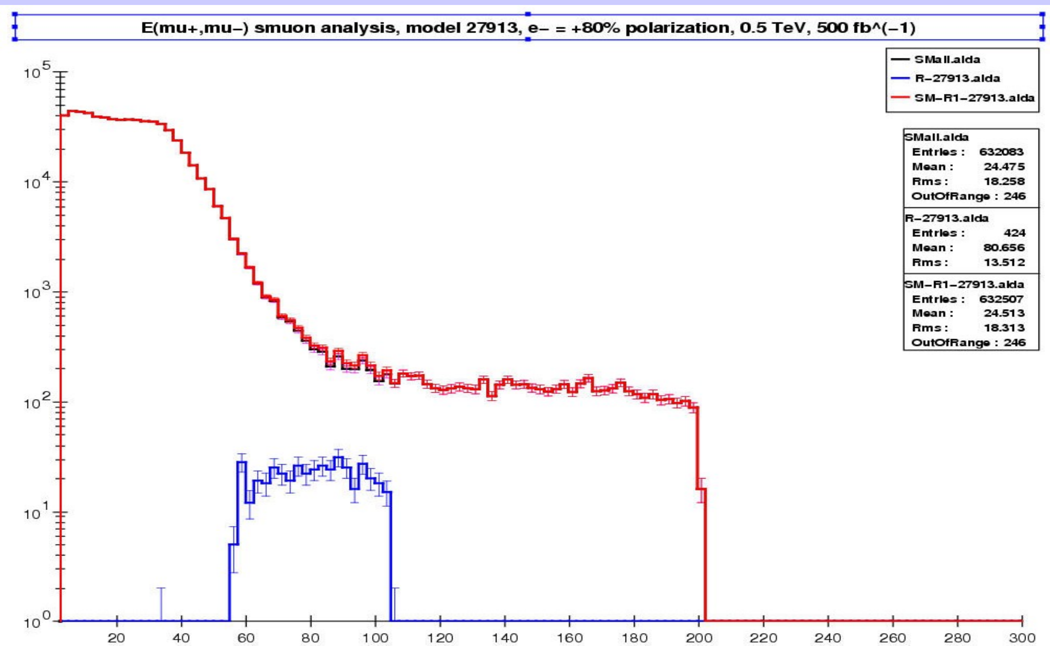


Smuon Signal versus Background









Stau Analysis I

5.1 Tau ID

We focus on the hadronic decays of taus into pions, $\tau \to \pi\nu_\tau$; $\tau \to \rho\nu_\tau \to \pi^\pm\pi^0\nu_\tau$; $\tau \to 3\pi\nu_\tau$, the latter being a 3-prong jet. In the hadronic decay channel, taus are just identified as jets with a charged multiplicity of 1 or 3, and with invariant mass less than some maximum value. The tau selection cuts are as follows [10]:

1. 2 jets with charged multiplicity of 1 (ρ or π or 3π-decay with $2\pi^0$s) or 3 (3 charged pions)
2. invariant mass of tau-jet < 2 GeV
3. If the jet is 3-prong (charged multiplicity of 3), then none of the charged particles should be an electron or muon
4. If the jets are 1-prong, then we reject events where both jets are same-flavor leptons, that is, with an electron-positron- or a muon-pair, but we keep jets for example with an electron and a muon, or an electron and a pion, whereby a pion is defined as a charged tracked that is not IDd as an electron or a muon.
   This means that we allow one of the taus to decay leptonically, but the other one has to decay hadronically.

So, for practical purposes, the difference between the muon analysis and the tau analysis is that we compute the cuts below with the jets instead of the reconstructed particles, if the event passes the above tau ID preselection.

Stau Analysis II

5.2 Selection Cuts

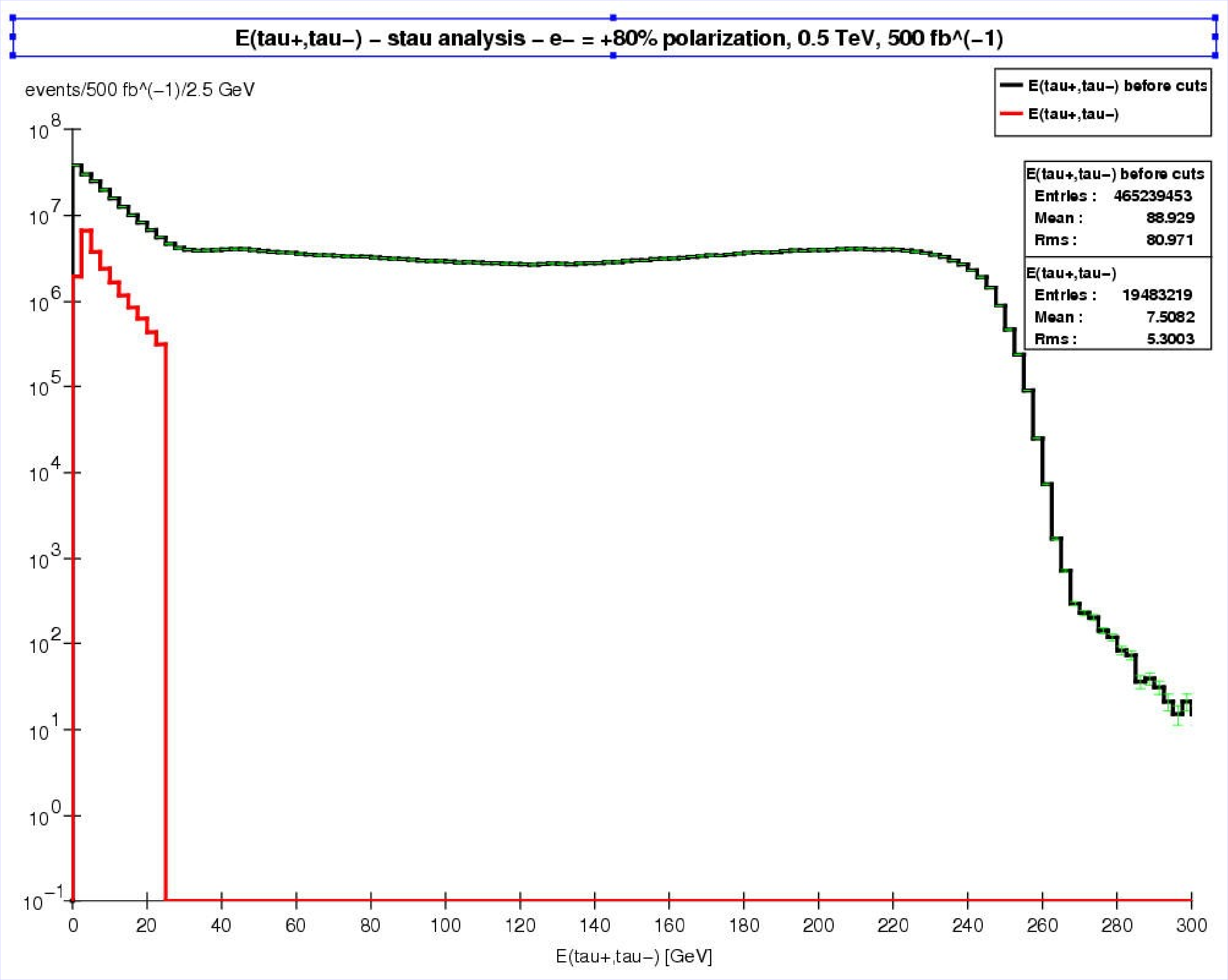
We implement the cuts proposed by Martyn [10]:

1. No electromagnetic energy $> 0.01\sqrt{s}$ in $|\cos\theta| > 0.995$
2. Two tau candidates as identified above, weighted by their charge within the polar angle $-0.75 < Q_\tau \cos\theta_\tau < 0.75$
   This cuts out a lot of W-pair-background.
3. tau energy $0.004\sqrt{s} < E_\tau < 0.05\sqrt{s}$
4. Acoplanarity angle $\Delta\phi^{\tau\tau} < 160$ degrees (= equivalent to the angle between the tau p_Ts, $\cos\theta_T > -0.94$).
   This cuts out a lot of W-pair and $\gamma\gamma$-background.
5. $|\cos\theta_{p_{missing}}| < 0.8$
6. transverse momentum of ditau system $0.006\sqrt{s} < p_T^{\tau\tau} < 0.05\sqrt{s}$
   This cuts out a lot of the $\gamma\gamma$-background.
7. Combined cut on $\sum p^\tau_{\perp,\vec{T}}$ and $\Delta\phi^{\tau\tau}$
   This is necessary because cuts 5 and 7 are not as efficient in cutting out the $\gamma\gamma$ background as in the smuon analysis above.
   Here, $\sum p^\tau_{\perp,\vec{T}}$ is the sum of the tau momenta projected onto the transverse thrust axis $\vec{T}_\perp$ (whereby the transverse thrust axis is just given by the xy-components of the thrust axis). Also, there is no analytical expression for the 2D cut plotted in fig. 3 of [10], so we approximate the curve by

$$\sum p^\tau_{\perp,\vec{T}} > 0.00125\sqrt{s}\,(1 + 5\,\sin\Delta\phi^{\tau\tau}) = 0.00125\sqrt{s}\left(1 + 5\,\sqrt{1-\cos^2\theta_T^{\tau\tau}}\right). \qquad (14)$$

   whereby we scaled the curve appropriately from $\sqrt{s} = 400$ GeV to a general c.m. energy, and reexpressed the acoplanarity in terms of the angle between the tau jet p_Ts as explained above.

Stau Backgrounds (Awaiting Signal)



Chargino Analysis

4.1 $m_\pi \leq \Delta m_{\tilde{\chi}} < 1$ GeV

We tag on a high-p_T photon, produced by our signal either off the initial state electron-positron pair, or radiated off on of the charginos. We demand, following [2, 4]:

1. Exactly one photon with $p_T > 0.035\sqrt{s}$ and no other charged tracks within 25 degrees
   This isolation cut removes a lot of the two-γ background
2. $1 <$ number of charged tracks < 11
   This removes high-multiplicity events.
3. $E_{\text{vis, other particles}} - E_\gamma < 0.35\sqrt{s}$
   Another preselection cut to remove a lot of the two-γ background
4. ratio of total visible transverse momentum to transverse energy $\frac{p_{T\,\text{vis}}}{E_{T\,\text{vis,particles}}} > 0.4$
   and
   ratio of total transverse momentum to total momentum $\frac{p_{T\,\text{vis}}}{p_{tot\,\text{vis,particles}}} > 0.2$
   This removes most of the hadronic two-γ processes and two-fermion processes.
5. $M_{\text{recoil}} = \sqrt{s}\sqrt{(1 - 2E_\gamma/\sqrt{s})} > 160$ GeV
   This is the recoil mass of the tagged photon, which should be at least twice the chargino mass. The limit of 160 GeV comes from EWP exclusion measurements.

We then histogram

$$M_{\text{recoil}} = \sqrt{s}\sqrt{\left(1 - 2E_\gamma/\sqrt{s}\right)}\,. \qquad (12)$$

Chargino Analysis

4.2 $\Delta m_{\tilde{\chi}} < m_{\pi}$

As mentioned above, in this case the chargino decays into an electron, a neutrino, and an LSP. The electron and positron pair produce two nearly back-to-back stable, massive tracks that pass through the entire detector. We demand:

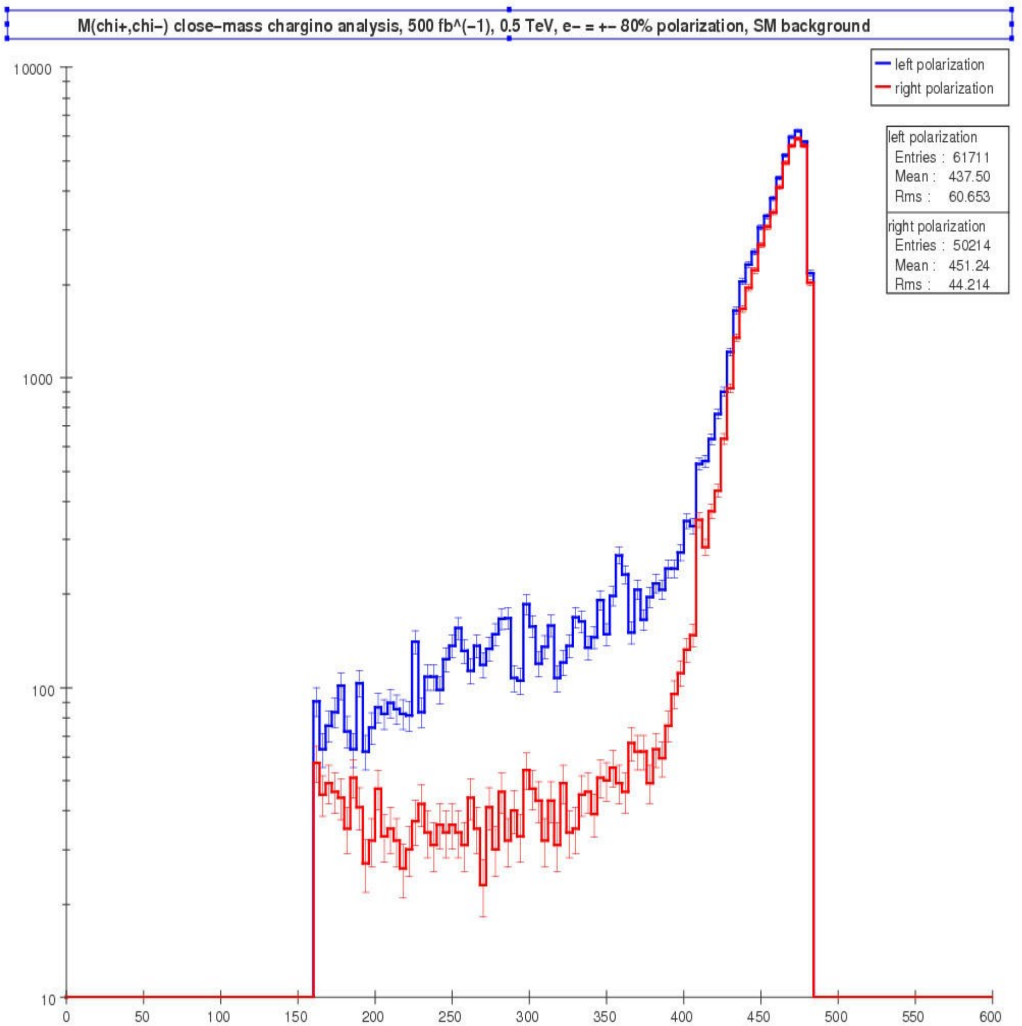
1. 2 massive, charged tracks only
2. $\frac{p}{E} < 0.95$ for both
   This kills any potential muon background. There should not be any background left (aside from detector fakes).

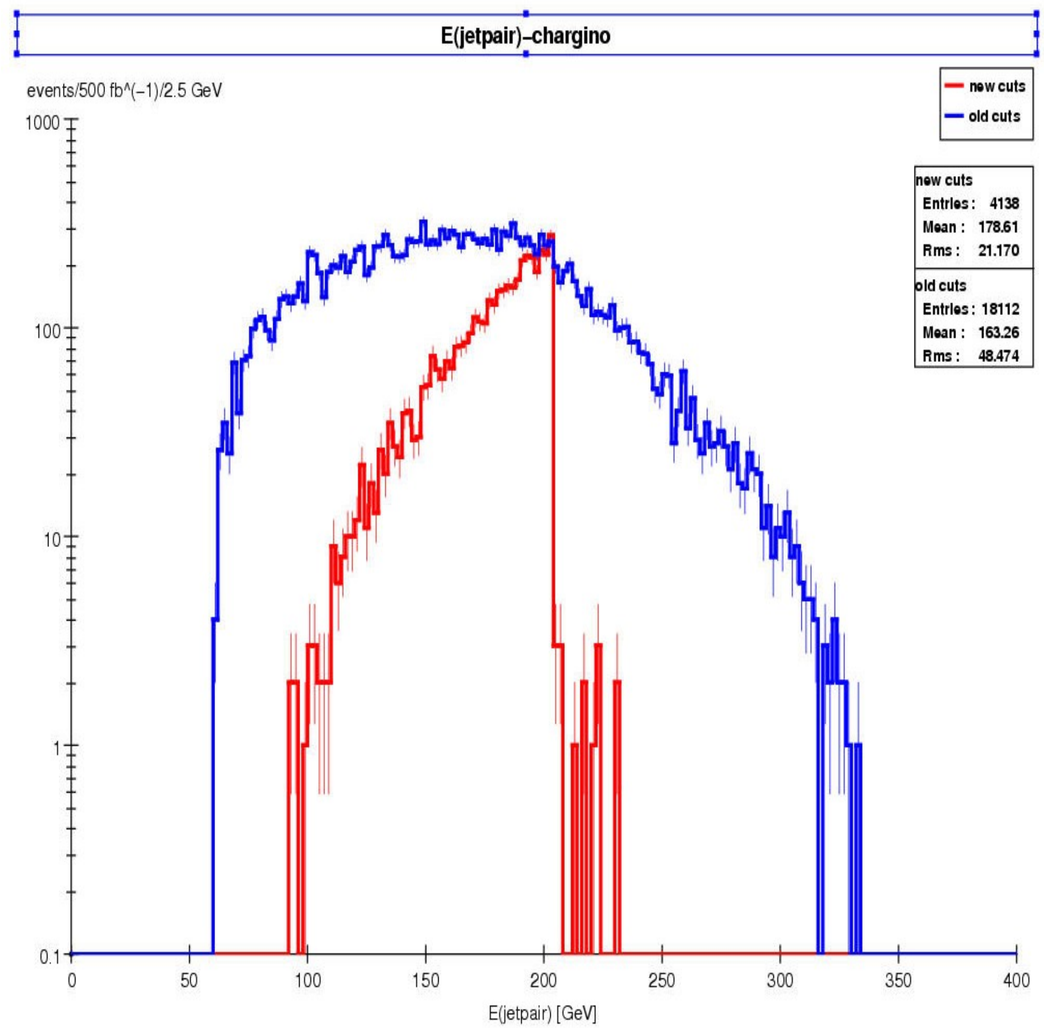
We then histogram $\frac{p}{E}$ for both tracks.

Chargino Backgrounds (Awaiting Signal)

Close mass

Separated Mass





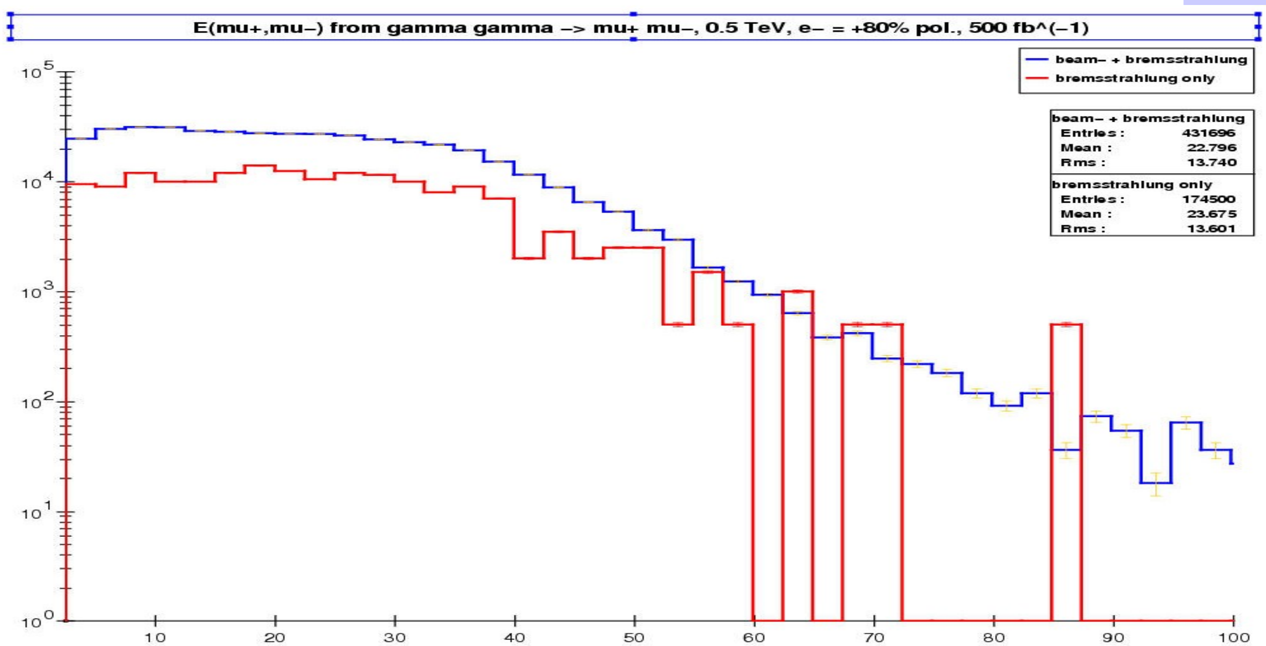
One Last Thing (selectron analysis):

"cards", which have the following relevant switches (along with a ton of other stuff which I didn't mess around with, aside from polarization and cm energy), which are by default

```
 bremsstr_eminus =  1.0
 bremsstr_eplus  =  1.0
 beamstr_eminus =  1.0
 beamstr_eplus  =  1.0
```

So, I turned off (i.e. = 0.0) bremsstr or beamstr. And at 1fb^(-1) got 0 events that pass the cuts for
bremsstr = 0.0
beamstr = 1.0
Maybe a few would sneak through the cuts for the full 500 fb^(-1).
However, there are muon pairs in the event, they just don't pass the cuts.

and 354 events at 1 fb^(-1) that pass the cuts for
bremsstr = 1.0
beamstr = 0.0
Makes roughly 1.8 10^5 events at 500 fb^(-1). Which is in the plot
Emumu_nobeam_Jan28



Your suggestions are most welcome!