Solving the LHC Inverse Problem at ILC: Close Mass Chargino Analyses And More

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Carola and Tom are also talking about this project here.

Outline

Outline

LHC Inverse Problem

The original inspiration for our ILC study was to see whether the ILC could be used to solve the “LHC Inverse Problem.” Thus I’ll begin with a quick review of the LHC inverse problem.

MSSM Parameters

MSSM has many (124) parameters.

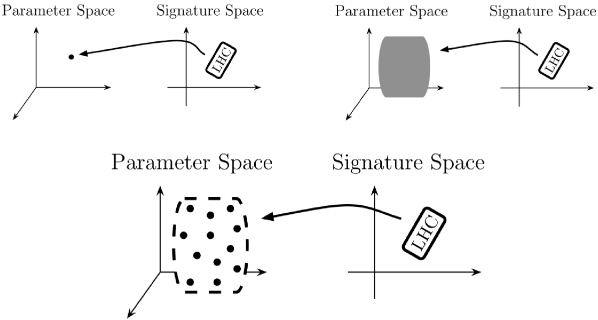
For many collider applications we only need to consider a smaller set of MSSM Lagrangian parameters:

- Weak scale gaugino masses
- Weak scale sfermion masses
- μ term
- $\tan\beta$
- Trilinear couplings $(A_{t,b,\tau})$

This is still a large number of parameters.

Inverse Problems

There are different possibilities for the inverse mapping. (Here we are looking at to where the actual LHC signature, a point in possible LHC signature space, maps.)



The LHC Inverse Problem in Practice

Arkani-Hamed, Kane, Thaler, and Wang (hep-ph/0512190) addressed the question of whether the MSSM has an inverse problem at the LHC.

- Generated 43,026 random points in an MSSM parameter space: “models”
- Generating 10 fb^{-1} of Monte Carlo SUSY signal at LHC
- Piped signal through PGS (fast detector simulation) and made histograms for hadron collider observables (signature)
- Compared each pair of model signatures using a statistical test, to determine whether the signatures are distinguishable.
- **Note**: they did not include standard model backgrounds

Parameter Choices

To generate each model, they selected each of the following parameters from the ranges shown below using uniform priors.

- Masses were kept below 1 TeV (keeps LHC cross sections high, naturalness)
- Colored sparticles tend to be heavier (theoretical preference, memory limitations)

Parameter	Min.	Max.
M_1, M_2, μ	100 GeV	1 TeV
$m_{l1,2}$, $m_{e1,2}$, m_{l3}, m_{e3}	100 GeV	1 TeV
M_3	600 GeV	1 TeV
$m_{q1,2}$, $m_{u1,2}$, $m_{d1,2}$	600 GeV	1 TeV
m_{q3}, m_{u3}, m_{d3}	600 GeV	1 TeV
$\tan\beta$	2	50
M_A	800 GeV	800 GeV
A_τ	0	0
A_b, A_t	850 GeV	850 GeV

Their Results

- They found that out of their 43,026 models there were 283 pairs of models whose signatures were indistinguishable (degenerate).
- These 283 pairs involved 383 models. Obviously some models were in more than one pair.
- This may seem like a small number. However for one to find this many degeneracies for the number of models generated suggests that each model would be degenerate with $\mathcal{O}(10-100)$ other points in parameter space.

Outline

Our Mission

- Consider the 383 models found to be in degeneracies at LHC
- Simulate these models at ILC (details follow)
- Compare ILC signatures of models in pairs at LHC. If statistically different, we have solved the LHC inverse problem.

Figure: Mission accomplished? Paper should be out within a week.

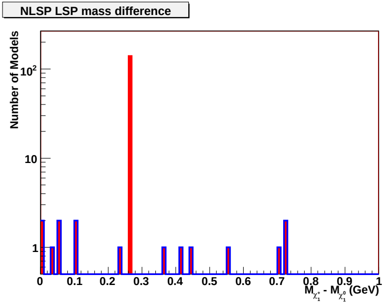
What We Did

- Simulated SUSY signals for each of 383 models in LHC degeneracies.
  - 250 fb^{-1} for each of 80% left and 80% right electron beam polarizations
  - Design energy: $\sqrt{s} = 500$ GeV
  - Used design specific beam spectrum
  - Positron polarization and $\sqrt{s} = 1$ TeV: Work in Progress!
- Obtained 2 SM background samples which were generated by Tim Barklow using WHIZARD/ O'Mega and used the same design specific beam spectrum as the signal
  - Used full tree level matrix elements
  - For all $2 \to 2$, $2 \to 4$, and $2 \to 6$ SM processes
  - From ee, $e\gamma$ and $\gamma\gamma$ initial states
  - This includes over 1000 processes
- Generated ~ 25 histograms of ILC observables for our signal and backgrounds using the SiD detector simulation package org.lcsim

What We Did

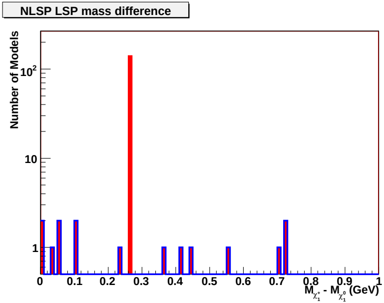
- Used a log likelihood test to compare (signal + background A) to background B for each model, to see if that model's SUSY signature was "visible"
  - Note: We did this for each histogram, so we know whether each produced sparticle is visible for each model.
- Used a χ^2 test to compare (model 1 signal + background A) to (model 2 signal + background B) for each LHC pair, to see if (for each histogram) the models yield distinguishable signatures.

Spectrum Problem: Our Reduced Set of Models



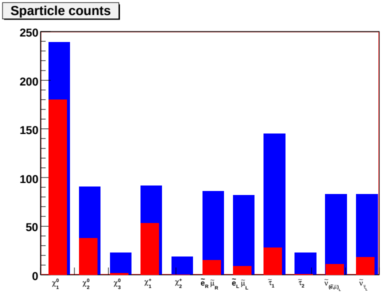
Many of the 383 models we were dealing with had $\Delta m = m_{\tilde{\chi}_1^+} - m_{\tilde{\chi}_1^0} = 0.269958$ when using the not-for-publication-use PYTHIA spectrum calculator. This is because if the lightest chargino mass turns out to be lighter than the lightest neutralino mass, its mass is artificially set to $2m_\pi$ greater than the lightest neutralino mass.

Spectrum Problem: Our Reduced Set of Models



We had to use the PYTHIA spectrum calculator, because that is what was used for the LHC analysis; so we discarded 141 models with this unphysical feature. This left us with 242 models.

The Models We Studied



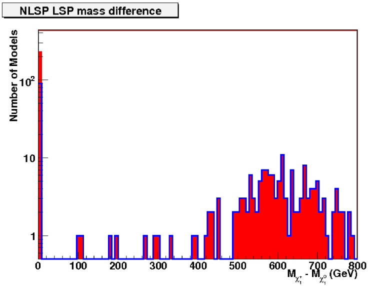
- Of our 242 models, 181 have sparticles accessible at 500 GeV.
- 85 have charged sparticles accessible at 500 GeV.
  - These models have a total of 140 accessible charged sparticles.
- At 1 TeV, all but 1 of the 242 models have accessible sparticles; many more charged sparticles are also accessible at this energy.

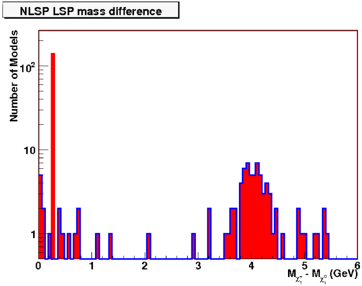
Outline

Outline

Chargino Masses and Δm

- 53 models have accessible charginos.
- In general lightest chargino mass is only a few GeV higher than the lightest neutralino mass ($\Delta m = m_{\chi_1^+} - m_{\chi_1^0}$).





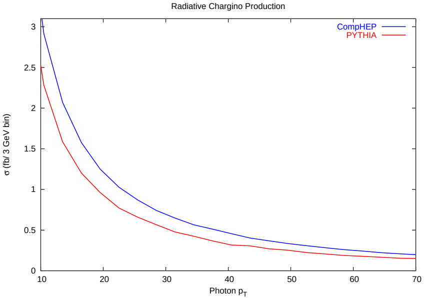
Chargino Analyses

We performed many different analyses: each of which was optimized for a different chargino signature. Naturally, different signatures are significant for different chargino masses and chargino-LSP mass differences. Our analyses were:

- $\Delta m \lesssim m_\pi$: Stable charged particle search (TGR Thursday)
- $m_\pi \lesssim \Delta m \lesssim 1\text{GeV}$: Radiative chargino search
- $\Delta m \gtrsim 1$ GeV: (CFB yesterday)
  - 4 jet + missing energy
  - 2 jet, muon + missing energy
  - 2 muons + missing energy

Why We Used CompHEP for Charginos

We found that the default treatment of final state radiation in PYTHIA could underestimate the cross section by $40-50\%$ at specially chosen points in parameter space and up to $\sim 25\%$ for some of our models.



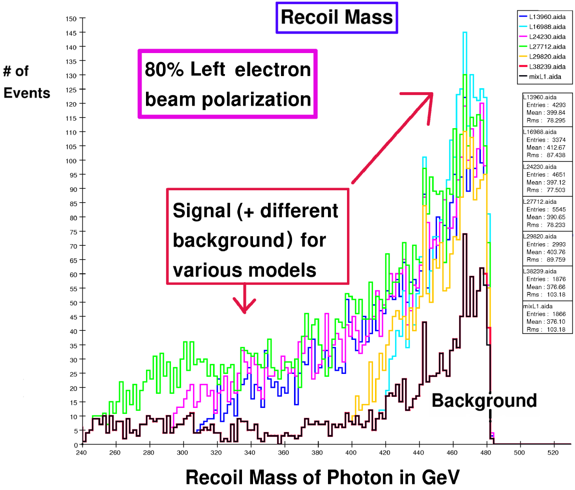
PYTHIA and CompHEP cross sections for chargino production with associated photon for a particular model with $m_{\tilde{\chi}^+} = 124.02$ GeV.

Radiative Chargino Search: Cuts

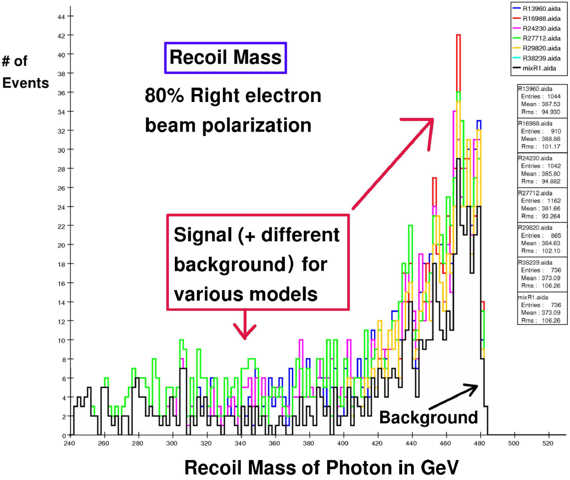
Following OPAL, as well as Gunion and Mrenna (2001), our cuts are

1. Exactly one photon with $p_T > 0.035\sqrt{s}$ and no other charged tracks within 25 degrees
2. No identified (i.e. above 142 mrad) electrons or muons in the event
3. $1 <$ number of charged tracks < 11
4. $E_{\text{vis, other particles}} - E_\gamma < 0.35\sqrt{s}$
5. We demand $\frac{p_{T,vis}}{E_{T,vis}} > 0.4$ and $\frac{p_{T,vis}}{p_{tot}} > 0.2$.
6. We require that $M_{recoil} = \sqrt{s}\sqrt{\left(1 - 2E_\gamma/\sqrt{s}\right)} > 160$ GeV

Radiative Chargino Search: Results



Radiative Chargino Search: Results

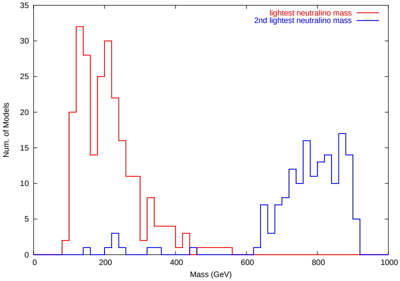


Radiative Chargino Search: Results

- We see signal in 14 models.
- We can see the signal using only our left handed polarization data in all of these models.
- We can see the signal using only our right handed polarization data in 9 of these models.

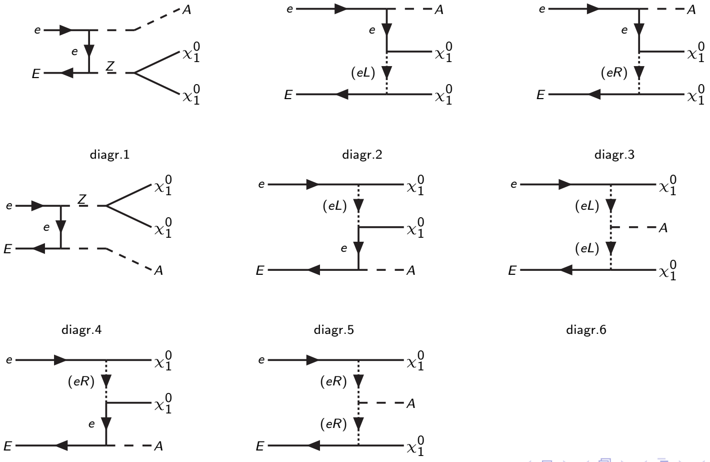
Outline

Neutralino Masses



- 180 models have an LSP neutralino which can be pair produced when $\sqrt{s} = 500$ GeV.
- For 91 of these models, this is the only accessible sparticle at 500 GeV.

Why We Used CompHEP Again



Radiative Neutralinos: Background and Cuts

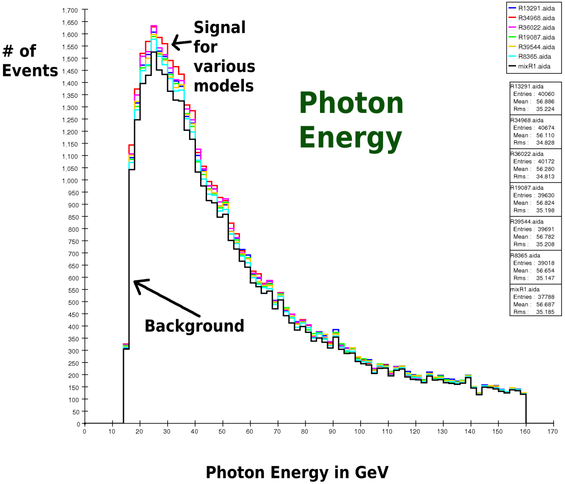
The main backgrounds are

1. $\nu\bar{\nu}$ production with associated photon
2. $\tilde{\nu}\tilde{\nu}^*$ production with associated photon

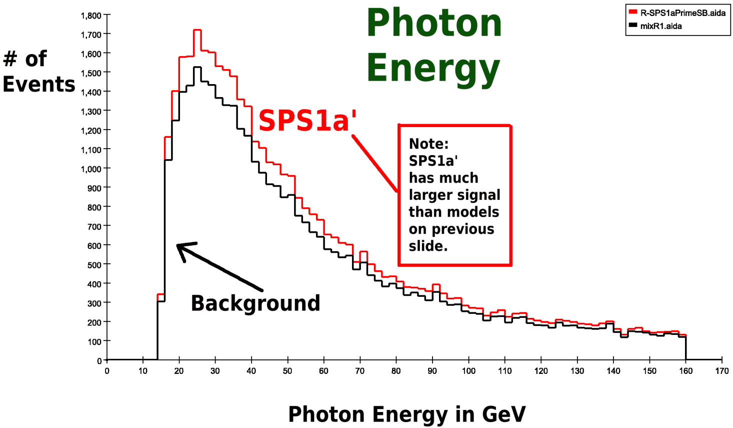
We use the following cuts (adapted from the TESLA TDR Photon + nothing excess search)

1. one photon and nothing else visible in the event
2. $E_T^\gamma = E^\gamma \sin\theta^\gamma > 0.03\sqrt{s}$
   Here, θ^γ is the angle of the photon with the beam axis (electron)
3. $\cos\theta^\gamma < 0.9$
4. $E^\gamma < 0.5\sqrt{s} - 90$ GeV
   This is to remove the Z-pole radiative return.

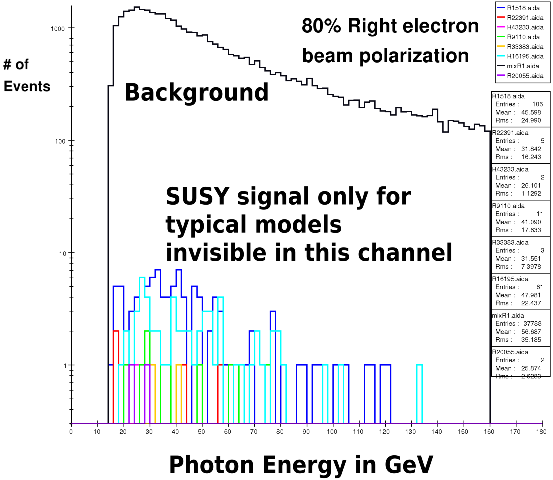
Radiative Neutralino Results



Radiative Neutralino Results



Radiative Neutralino Results



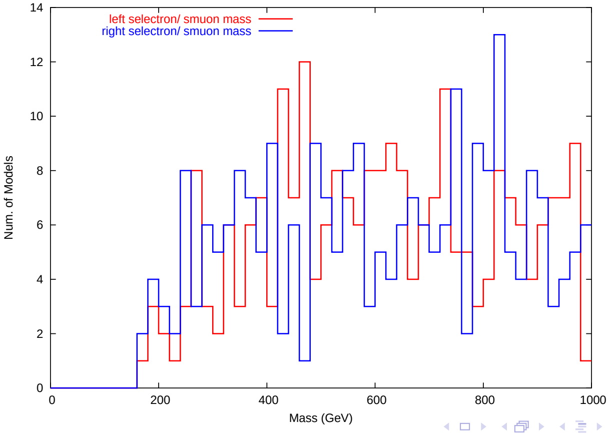
Radiative Neutralino Results

- Out of the 180 models with an accessible neutralino, we see the neutralino in this channel in 17 cases.
- Out of the 96 models with no charged sparticles visible, we can see the neutralino in 4/96 cases.

Outline

Selectron and Smuon Masses

Selectrons and smuons are exactly degenerate.



Slepton Production Backgrounds

In a generic slepton search, we look for leptons plus missing energy. Thus the major SM backgrounds are

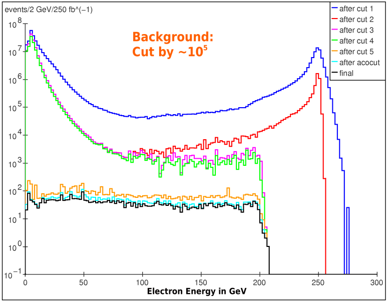
- W pair production with each W decaying leptonically
- Z pair production with one Z decaying to charged leptons the other to neutrinos
- Processes with γ in initial state ($\gamma\gamma -> l^+ l^-$ or processes where an initial electron or photon is kicked into the detector)

Selectron Cuts

Following Goodman.

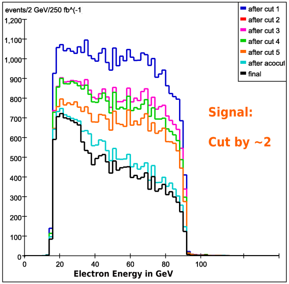
1. Exactly two leptons, identified as an electron and a positron, in the event and no other charged particles.
2. $E_{vis} < 1$ GeV for $|\cos\theta| \geq 0.9$
3. $E_{vis} < 0.4\sqrt{s}$ in the forward hemisphere.
4. $\cos\theta > -0.96$ for the reconstructed electron-positron pair.
5. We demand that the visible transverse momentum $> 0.04\sqrt{s}$.
6. Acoplanarity angle $\Delta\phi^{e^+e^-} > 40$ degrees
7. $M_{e^+,e^-} < M_Z - 5$ GeV or $M_{e^+,e^-} > M_Z + 5$ GeV.

Selectron Cuts

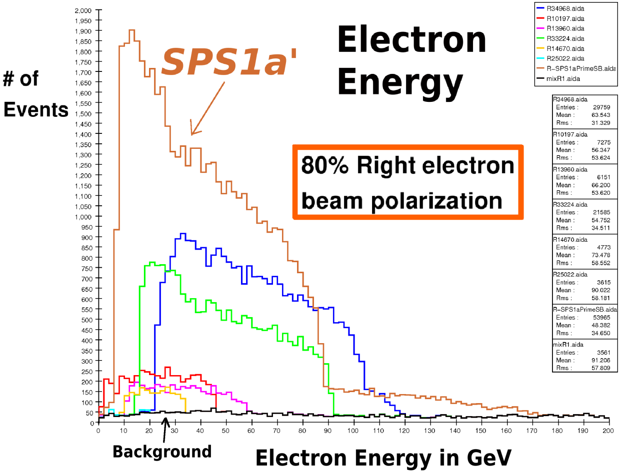


Electron Energy

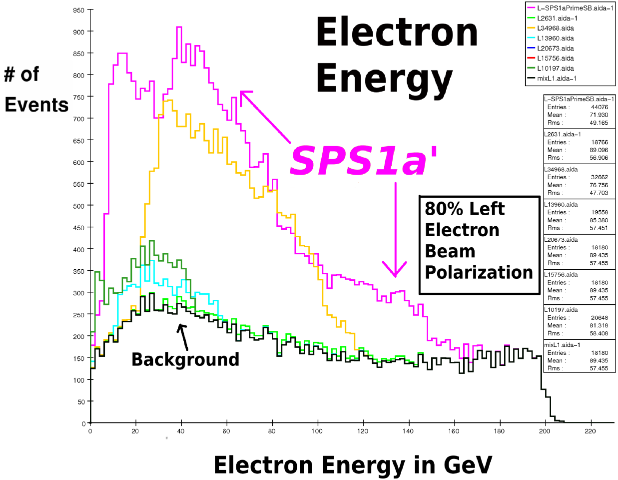
Selectron Analysis



Selectron Results



Selectron Results



Selectron Results

- Out of 22 models with selectrons accessible, we can see the selectrons in 18 cases.
- In all these cases, selectrons can be seen using our right handed polarization data set only.
- In 15/18 cases, selectrons can be seen using our left handed polarized data only.
- In the 4 cases where we cannot see selectrons, $m_{\tilde{e}} > 241$ GeV.
- Some models with no accessible selectrons, but which have a chargino or 2^{nd} lightest neutralino accessible show up in this analysis.

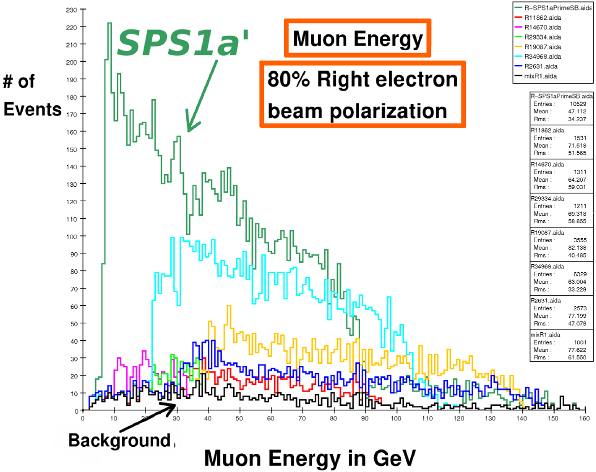
Outline

Smuon Cuts

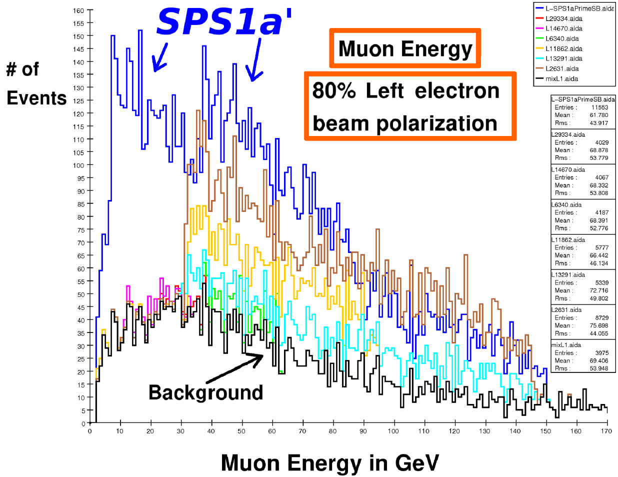
Following Martyn and Bambade et al.

1. No electromagnetic energy (or clusters) $> 0.01\sqrt{s}$ in $|\cos\theta| > 0.995$
2. Two muons weighted by their charge within the polar angle $-0.9 < Q_\mu \cos\theta_\mu < 0.75$ and no other visible particles
   This removes a substantial part of the W-pair-background.
3. Acoplanarity angle $\Delta\phi^{\mu\mu} > 40$ degrees.
   This reduces both the W-pair and $\gamma\gamma$-backgrounds.
4. $|\cos\theta_{p_{missing}}| < 0.9$
5. muon energy $E_\mu > 0.004\sqrt{s}$
6. transverse momentum of dimuon system, or equivalently, visible transverse momentum (since there is only the muon pair visible), $p_{T\,\text{vis}} = p_T^{\mu\mu} > 0.04\sqrt{s}$
   This remove a significant portion of the remaining $\gamma\gamma$- and $e^\pm\gamma$ backgrounds.

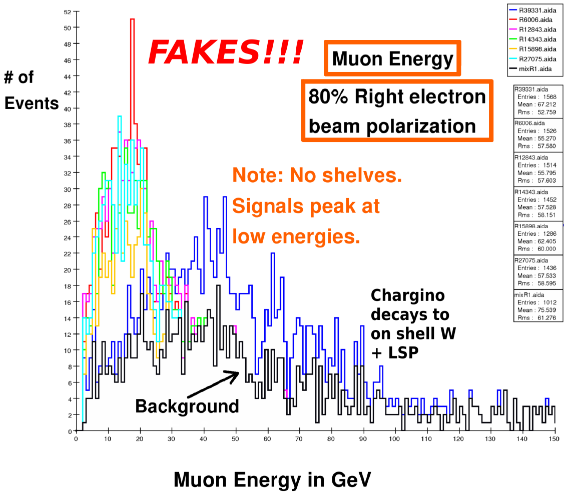
Smuon Results



Smuon Results



Smuon Results



Smuon Conclusions

1. Out of 22 models with smuons accessible, we can see the smuons in 19 cases (versus 18 for selectrons).
2. In all 19 of these cases, smuons can be seen using only our right handed polarization data set.
3. In 17/22 cases, smuons can be seen using the left handed polarization data only.
4. In the 3 cases where we cannot see smuons, $m_{\tilde{\mu}} > 241$ GeV.
5. Some models with no accessible smuons, but which have a chargino or 2^{nd} lightest neutralino accessible show up in this analysis.

Outline

Solving LHC Inverse Problem: Model Visibility

- Due to a PYTHIA feature, we only had 242 total models.
- Of these models (181 of which have sparticles accessible at 500 GeV), 82 are visible in our analyses.
- Of the 85 models with charged particles accessible, 78 are visible.

Solving the LHC Inverse Problem: Breaking Degeneracies

- Among these 242 models there are 162 pairs of models degenerate at LHC in which at least one of the models has at least one sparticle accessible at 500 GeV.
- Of these 162 pairs, 90 involve two models with only neutral sparticles accessible at 500 GeV. We are unable to resolve any of these degeneracies.
- Of the 72 pairs in which at least 1 model has an accessible charged sparticle at 500 GeV, 55 may be distinguished at ILC.
- These numbers may get slightly better.

General Conclusions

- If the parameter choices here are realistic, will want $\sqrt{s} > 500$ GeV.
- Most models don't look like SPS1a'. Relatively few light sparticles, small Δm and small cross sections make analysis difficult.
- SUSY can be the background to SUSY.