Breaking Degeneracies in the MSSM: Inverting the LHC with the ILC

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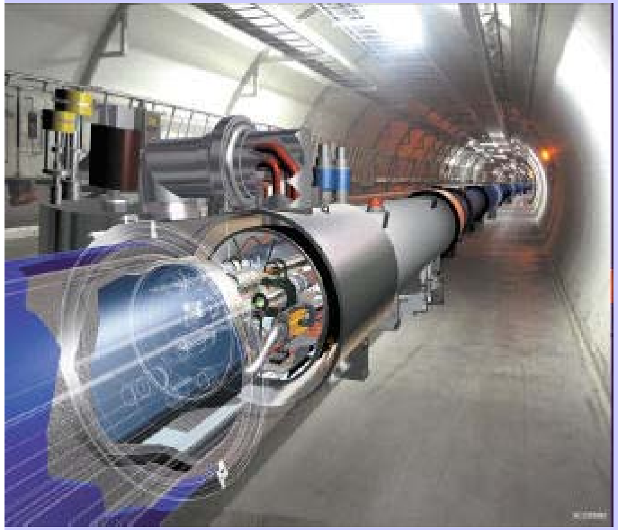
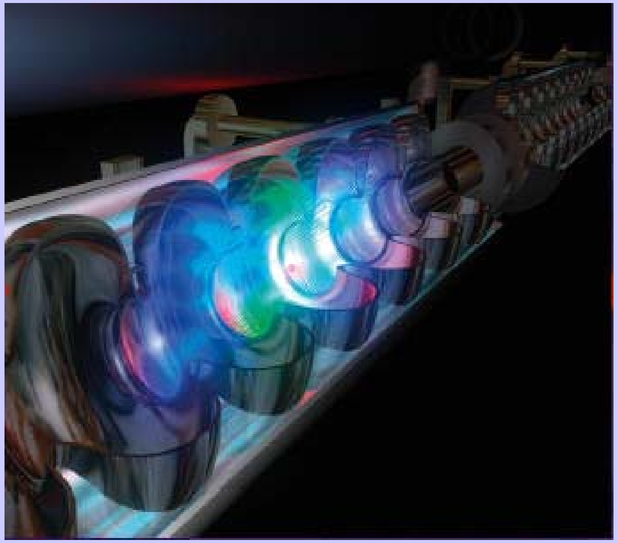
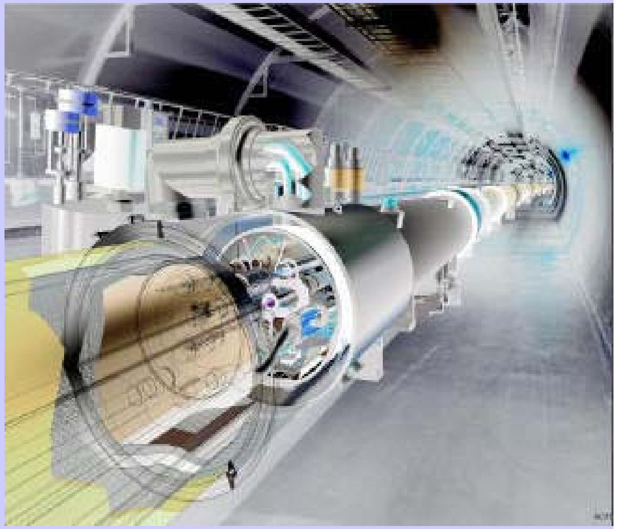
arXiv:0706.xxxx

LHC Inverse Problem

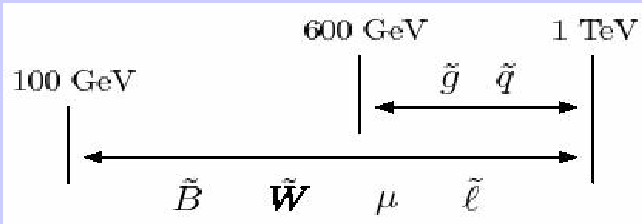
Generate blind SUSY data and map it back to parameters in the fundamental Lagrangian

- Generated 43,026 models within MSSM for 10 fb^{-1} @ LHC (Pythia 6.324)
- 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:



$2 < \tan\beta < 50$

kept 1st two scalar generations degenerate

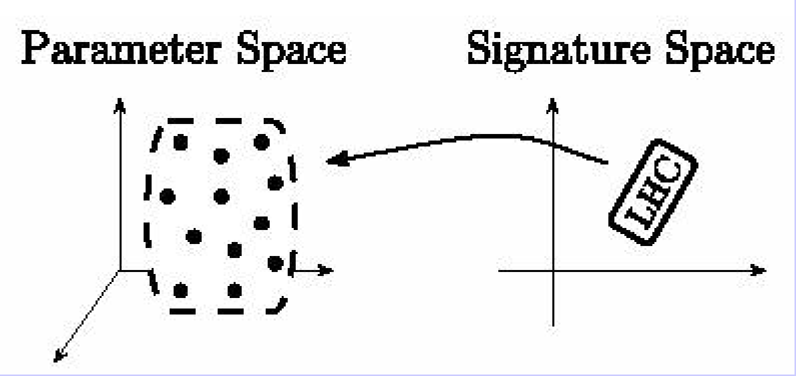
- Used ~1808 LHC MSSM Observables
  - Rate counting, kinematic distributions
- NO SM Background!

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

LHC Inverse Problem: Results

- Main result: 283 pairs of models (383 distinct models*) were found indistinguishable!
  - Recall the birthday problem
  - A signature maps back into a number of small islands in parameter space

* 242 models are physical

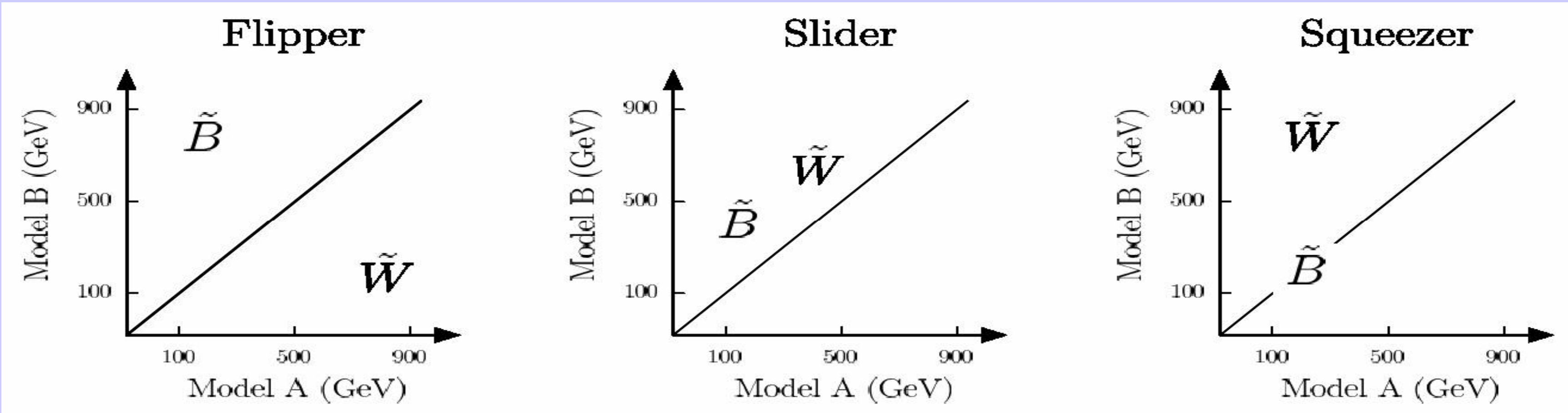


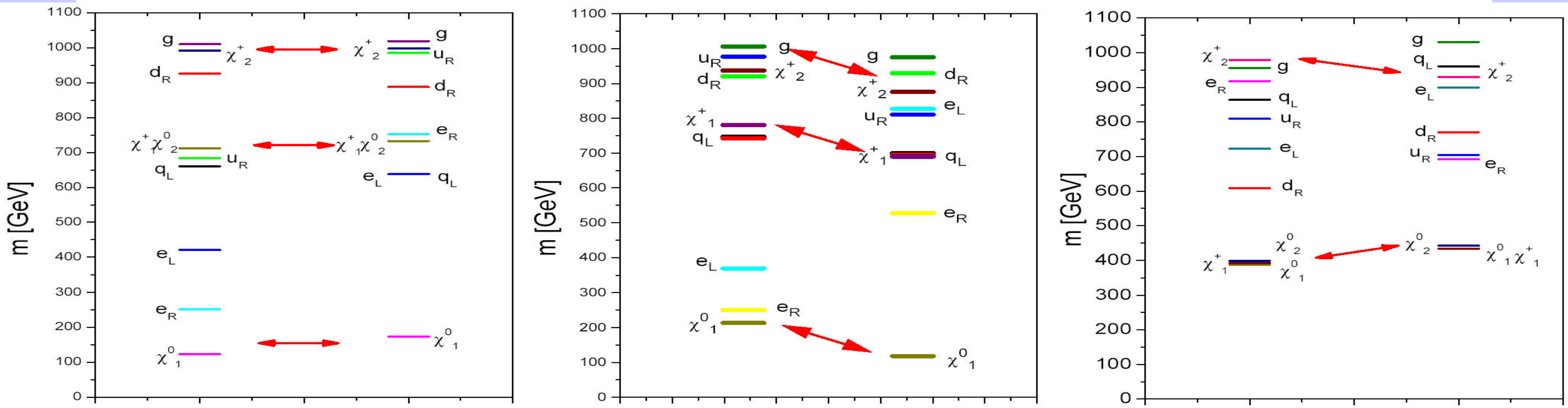
- Begs the question:
  Can the ILC resolve these degeneracies?
  - We will quantify this

Characteristics of Degenerate Models

LHC: measure mass differences in cascade decays

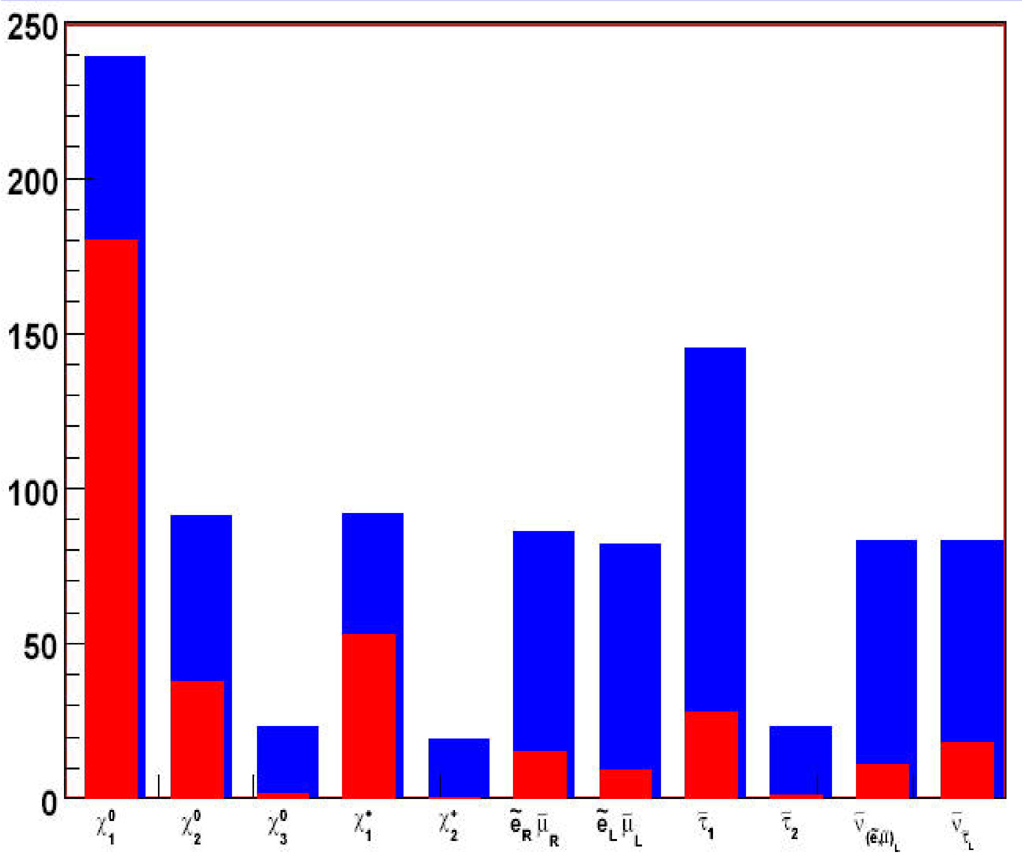
- Flippers: Fixed mass eigenvalues, but flipped mixing components
- Sliders: Same mass differences, but different absolute masses
- Squeezers: Small mass differences





Sparticle Counts

Kinematically accessible sparticles
@ 500 GeV, 1 TeV



At 500 GeV:

- 20 models with selectrons & smuons.
- 28 models with staus
- 53 models with charginos
- 99 models have only χ_1^0

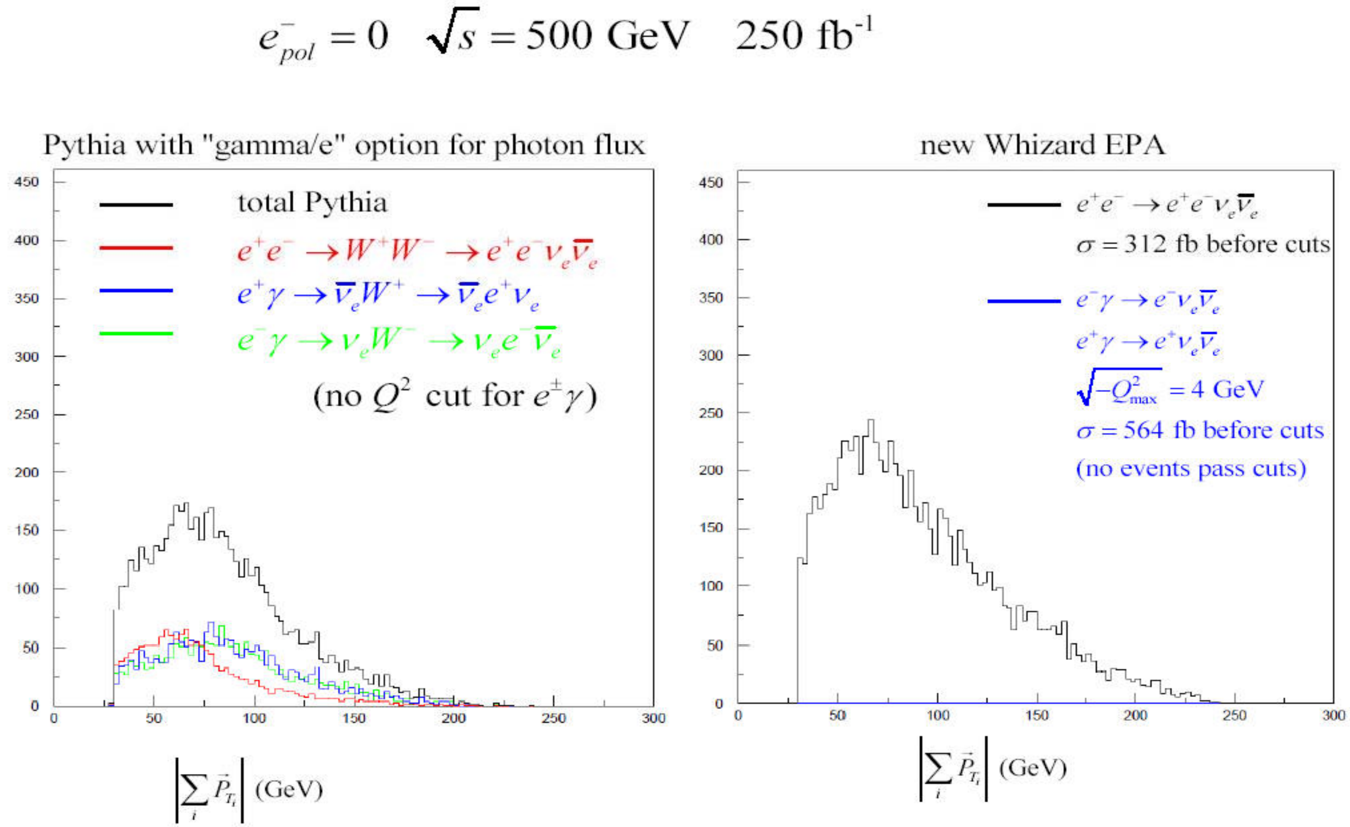
Only 1 model inaccessible at 1 TeV

Our Analysis

- We start with their degenerate pairs (242 distinct models)
  - 1st ILC SUSY study with 100's of models chosen at random
- Simulate signal events with Pythia 6.324 & CompHEP, include ISR, beamstrahlung (generated via WHIZARD/GuineaPig), beam energy spread
- Add SM background (1016 processes), produced by Tim Barklow via Whizard – stored @ SLAC, size on disk = 1.7 Tb
- Pipe through fast detector simulation: SiD detector concept, Java-based simulation, org.lcsim
  - 1st user analysis using SiD lcsim
- Analyze 500 fb^{-1} "data" @ 500 GeV with 80% P_{e-} and appropriate cuts. Several iterations necessary to find best cuts!
- We have stimulated much debugging of the various software

Analysis: Background

- Generated by Tim Barklow with WHIZARD
  - all SM e^+e^-, $e\gamma$, $\gamma\gamma \to$ 2f, 4f, and 6f processes calculated with full matrix elements from MadGraph and CompHEP
  - After cuts, gives larger background, with higher p_T tail, compared to Pythia!



Backgrounds to selectron analysis

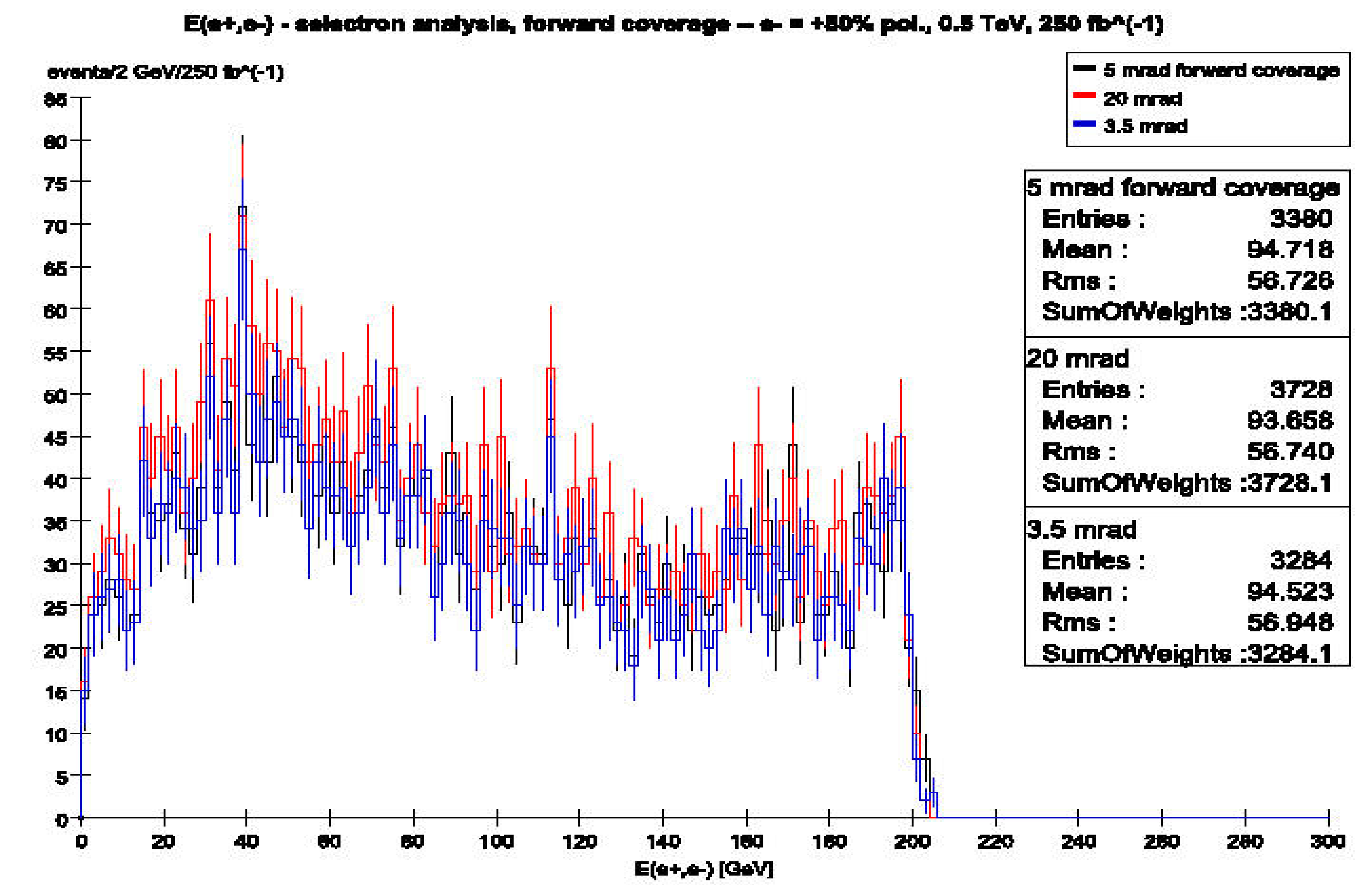
T. Barklow

Analysis: Detector Simulation

- Use SiD Snowmass05 design
  - 2 mrad crossing angle (checked that 20 mrad has negligible difference in analyses)
  - Particle tracking and ID only down to 150 mrad
  - Below 150 mrad, charged particles appear as neutral energy cluster. Coverage is tunable: we take $\theta > 5$ mrad
  - Low angle particles assigned γ or K^0 ID: causes problems in particle energy determination
  - Highly energetic μ's at low angles are not reconstructed: causes problems for stau analysis
  - Default jet finding algorithm is JADE with $y_{cut} = 0.005$. This is too low! Numerous soft gluons counted as jets: we take $y_{cut} = 0.05$

Importance of Forward Coverage

Selectron Analysis



20 mrad $\xrightarrow{-9\%}$ 5 mrad $\xrightarrow{-3\%}$ 3.5 mrad

Analysis: Signal @ $\sqrt{s}$ = 500 GeV

We simulate 10 channels:

- $\text{Selectron}_{L,R}$
- $\text{Smuon}_{L,R}$
- Stau_1
- Lightest Chargino, $\chi_1^{\pm}$, χ_1^0 mass splitting > 1 GeV
  - 4 channels: off- & on-shell W's decay to 4-jet, jj +μ final states
- Lightest Chargino, $\chi_1^{\pm}$, χ_1^0 mass splitting < 1 GeV
  - tag on high-Energy radiative γ, 2 final states
- Radiative Neutralino production: $\chi_1^0\chi_1^0 + \gamma$

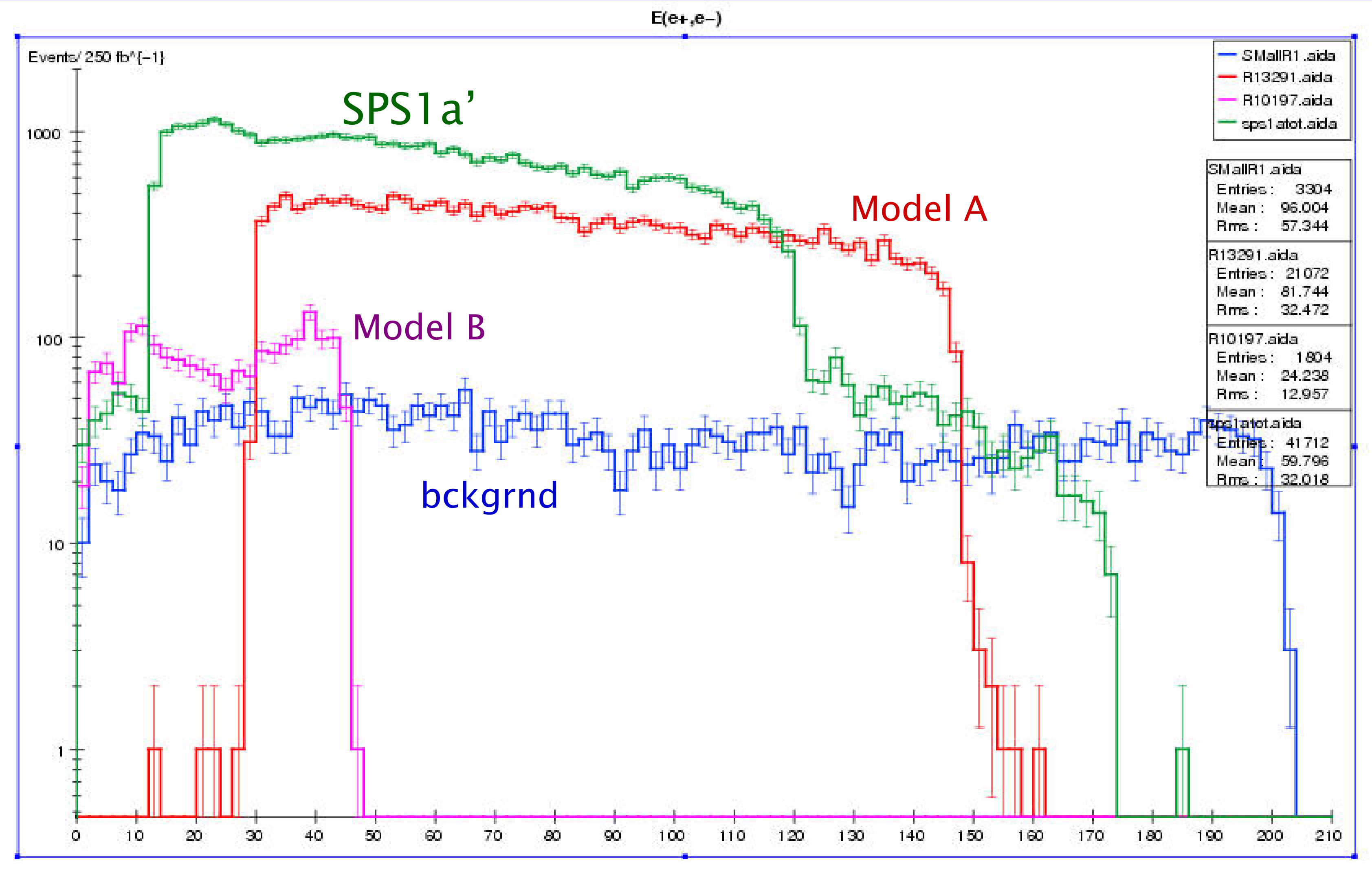
Analysis: Cuts

Cuts adapted and expanded from:

- U. Nauenberg, *et al.*, Colorado SUSY group, http://hep-www.colorado.edu/SUSY/susynlc.html
- H. U. Martyn, arXiv:hep-ph/0408226
- P. Bambade, M. Berggren, F. Richard and Z. Zhang, arXiv:hep-ph/0406010
- G. Abbiendi *et al.* [OPAL Collaboration], Eur. Phys. J. C 35, 1 (2004) [arXiv:hep-ex/0401026]
- C. H. Chen, M. Drees and J. F. Gunion, Phys. Rev. Lett. 76, 2002 (1996) [arXiv:hep-ph/9512230]; J. F. Gunion and S. Mrenna, Phys. Rev. D 64, 075002 (2001) [arXiv:hep-ph/0103167]
- H. K. Dreiner, O. Kittel and U. Langenfeld, arXiv:hep-ph/0703009

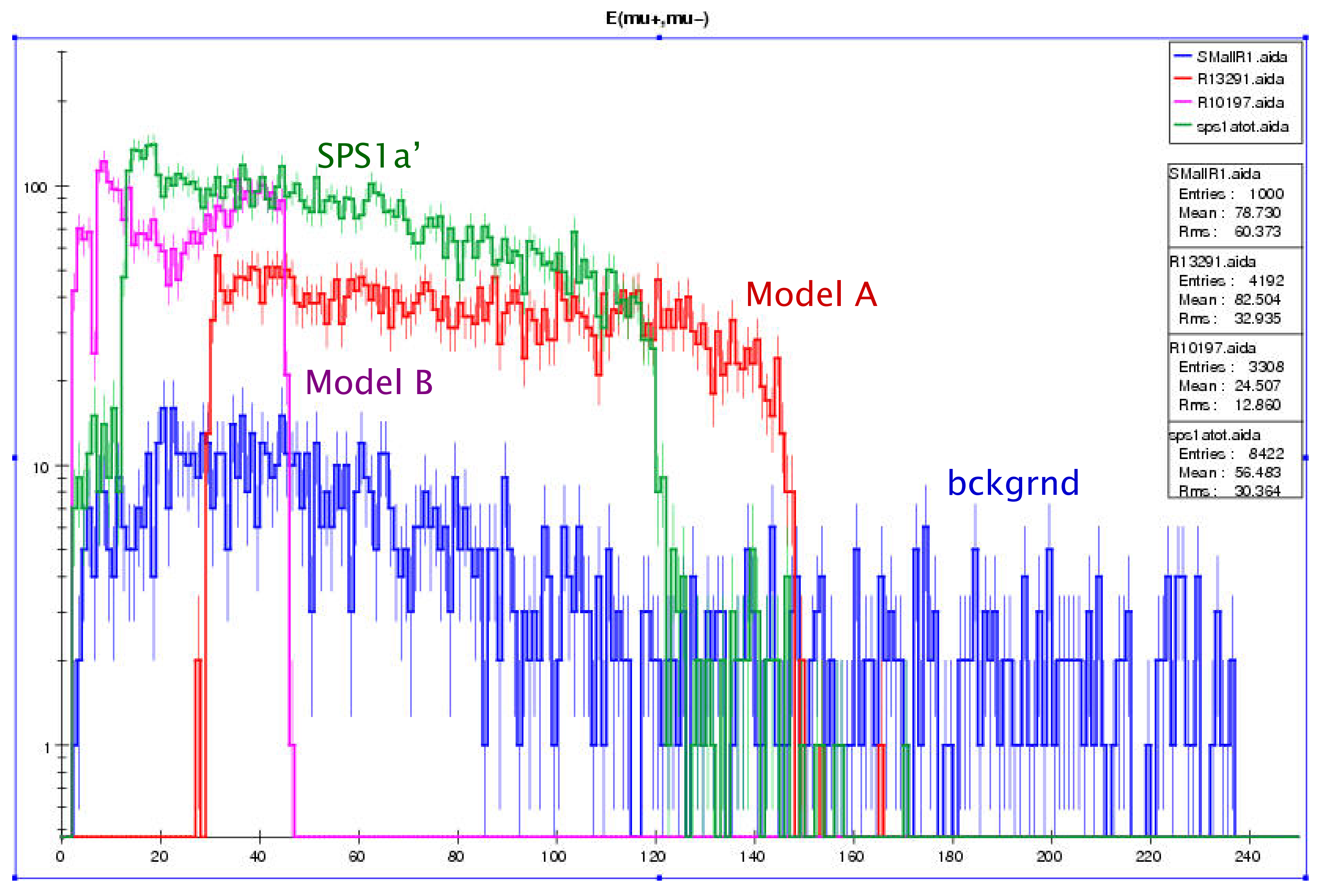
Results: Selectrons

$$e^- e^+ \rightarrow \tilde{e}^- \tilde{e}^+ \rightarrow e^- \chi_1^0 + e^+ \chi_1^0$$



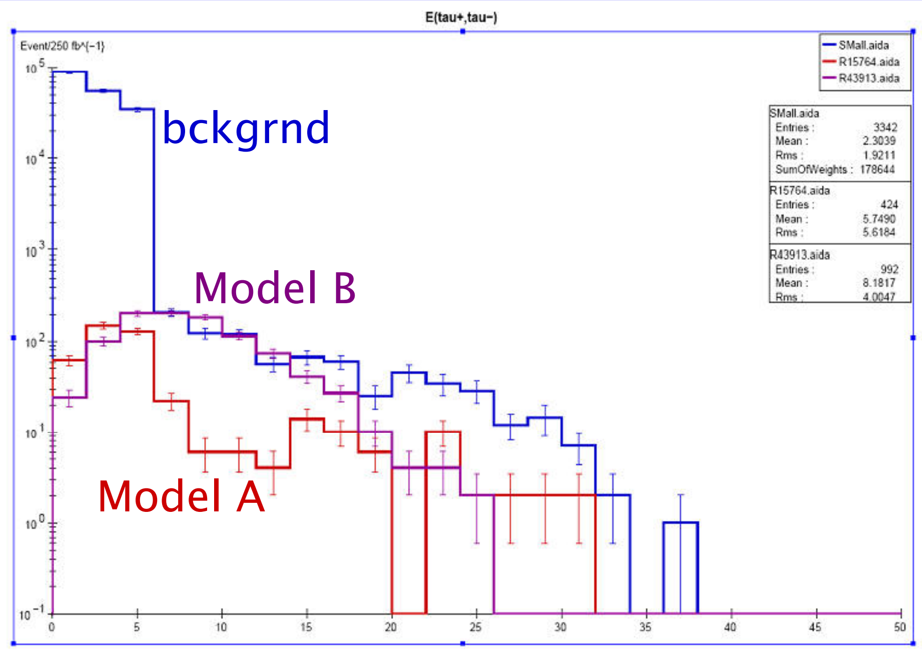
Results: Smuons

$$e^+e^- \rightarrow \tilde{\mu}^+\tilde{\mu}^- \rightarrow \mu^+\chi_1{}^0 + \mu^-\chi_1{}^0$$



Results: Staus

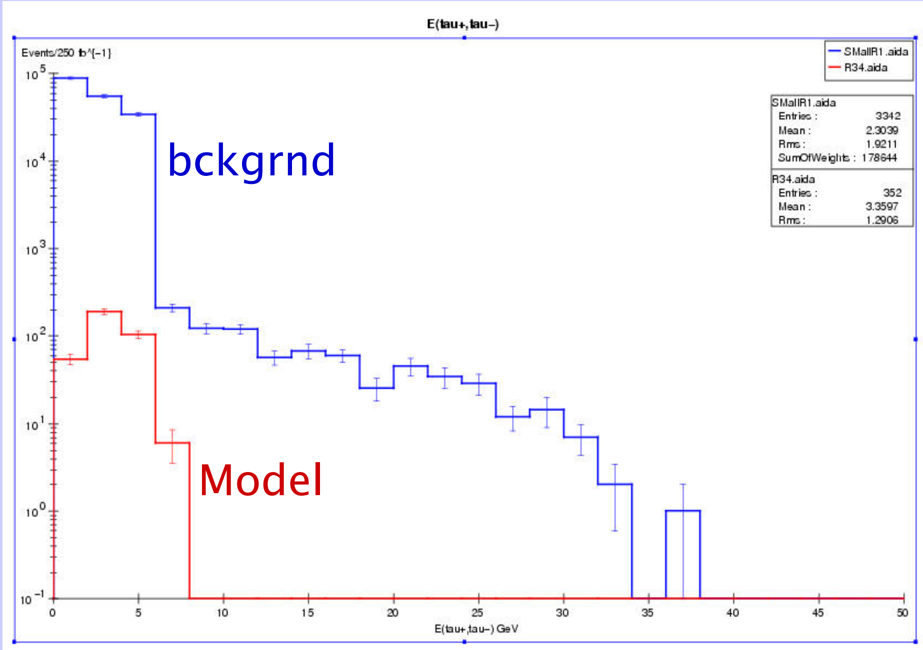
$e^+e^- \rightarrow \tilde{\tau}^+\tilde{\tau}^- \rightarrow \tau^+\chi_1{}^0 + \tau^-\chi_1{}^0$



Well separated stau & LSP

1. ID τ's:
   - 1- & 3-prong hadronic dks
   - 1 hadronic, 1 leptonic dks
   - 1 e, 1 μ dks
2. Apply cuts

Close mass stau & LSP
is a problem….



Case Study: $\gamma\gamma \rightarrow \mu\mu$ Background to Stau Production

Typical event:

- e^- : nearly full energy (244 GeV) goes down the beampipe with $p_T = 0$, not reconstructed for obvious reasons
- e^+ : kicked out with decent p_T and is reconstructed
  4-momentum (E=51.665, -7.6473, -3.2886, -50.990)
- μ^- : is reconstructed and gives a cluster
  (E = 5.9698, -4.7366, 0.11118, 3.6319)
- μ^+ : very energetic, doesn't show up in the reconstructed particle list at all, leaves no cluster, and no track,
  (E =198.03,12.384, 3.1775, -197.62) -- it's at ~65 mrad

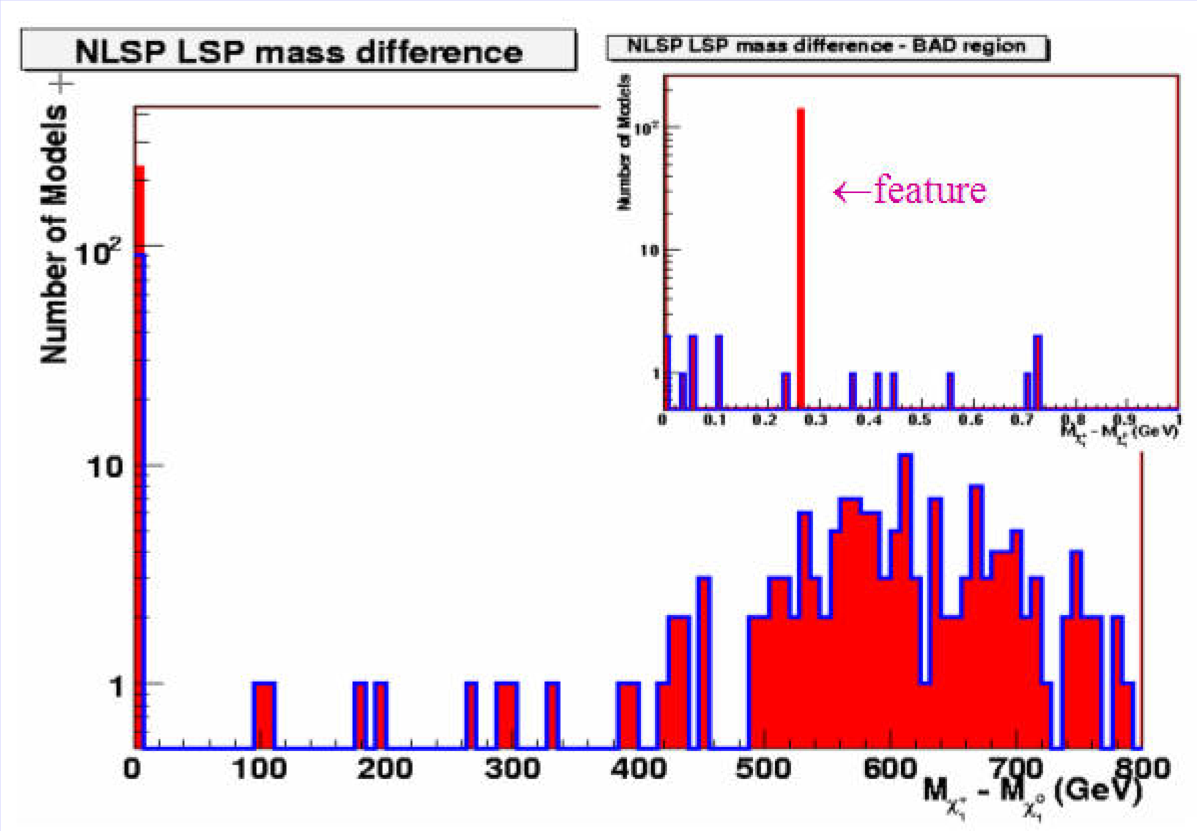
We are checking what happens if we remove the $e\mu$ signal from the two τ decays

Chargino Decays

$\Delta m = m_{\chi_1^\pm} - m_{\chi_1^0}$ is a critical parameter in $\chi_1^\pm$ analyses

Mass separation with LSP determines $\chi_1^\pm$ decay modes

We perform analyses for 6 decay channels



If the chargino mass is less than that of the LSP then PYTHIA resets the chargino mass to be that of the LSP $+2m_\pi$

A warning statement now appears in Pythia 6.410.

Chargino Analyses: Non-Close Mass Case

$$\Delta m_{\tilde\chi} \equiv m_{\tilde\chi^\pm} - m_{\tilde\chi_1^0} > 1 \text{ GeV}.$$

1. Muon decay channel:

$$\chi_1^\pm \rightarrow \tilde\mu^\pm \nu, \mu^\pm \tilde\nu \rightarrow \mu E^{miss}$$

$\chi_1^\pm \rightarrow W(*)\ \chi_1^0 \ \rightarrow \mu + \chi_1^0$

resulting in

$$\chi_1^+ \chi_1^- \rightarrow 2j + \mu^\pm + E^{miss}$$

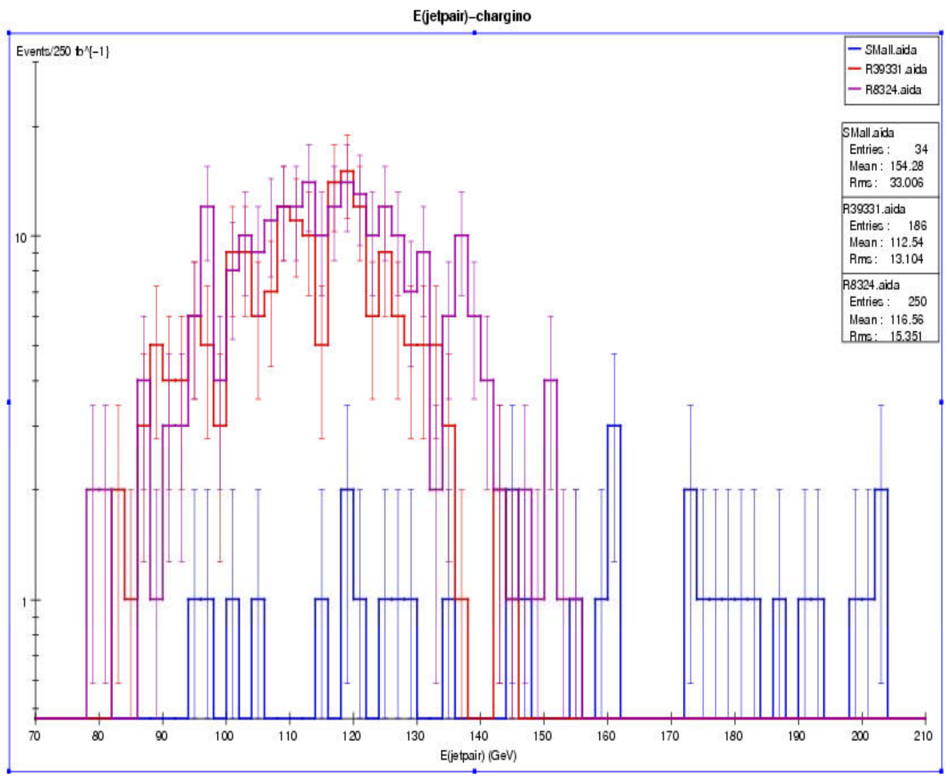
2. Four-jet final state

$$\tilde\chi_1^+ \tilde\chi_1^- \rightarrow W^+ W^- \tilde\chi_1^0 \tilde\chi_1^0,$$
$$W^\pm \rightarrow q\bar q.$$

Depending on the mass splitting the W can be virtual but in the latter case the W mass will not be reconstructed in dijets

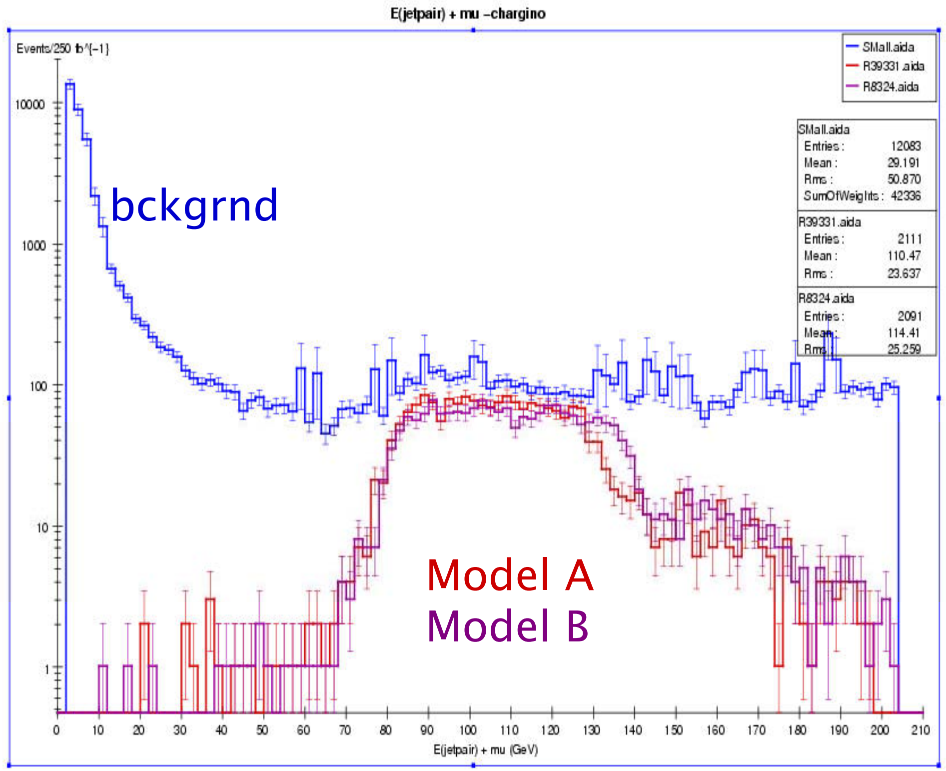
Distinct analysis to cover cases with both real and virtual W's

Results: Chargino, on-shell W's



4-jet + missing

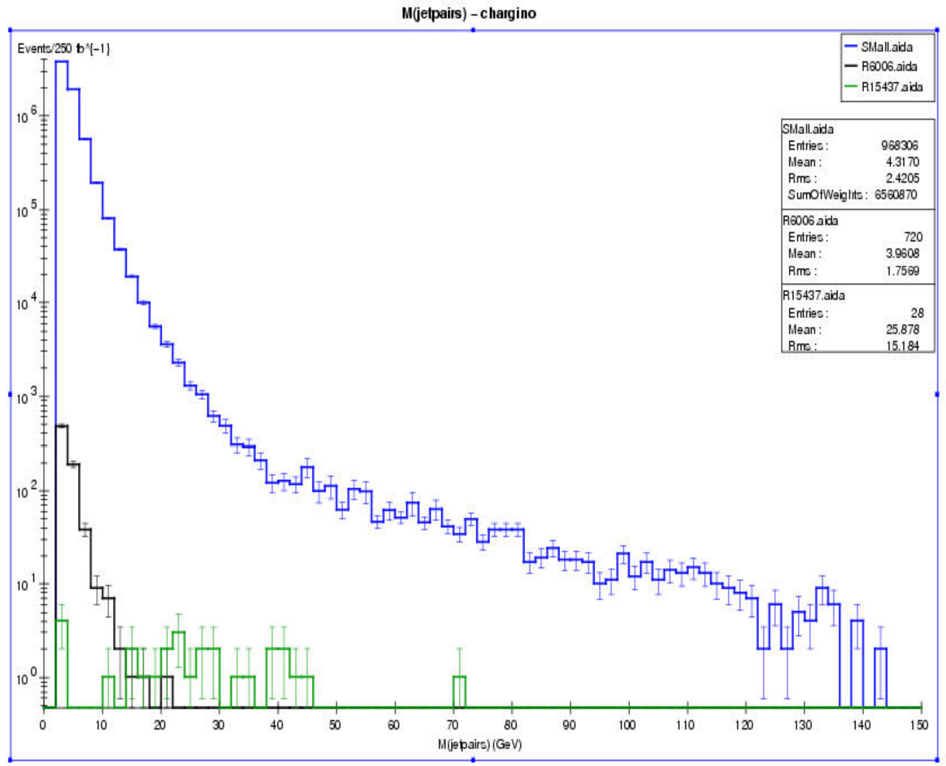
2-jet + μ + missing



Good separation of signal
& bckgrnd, but difficult
to separate models

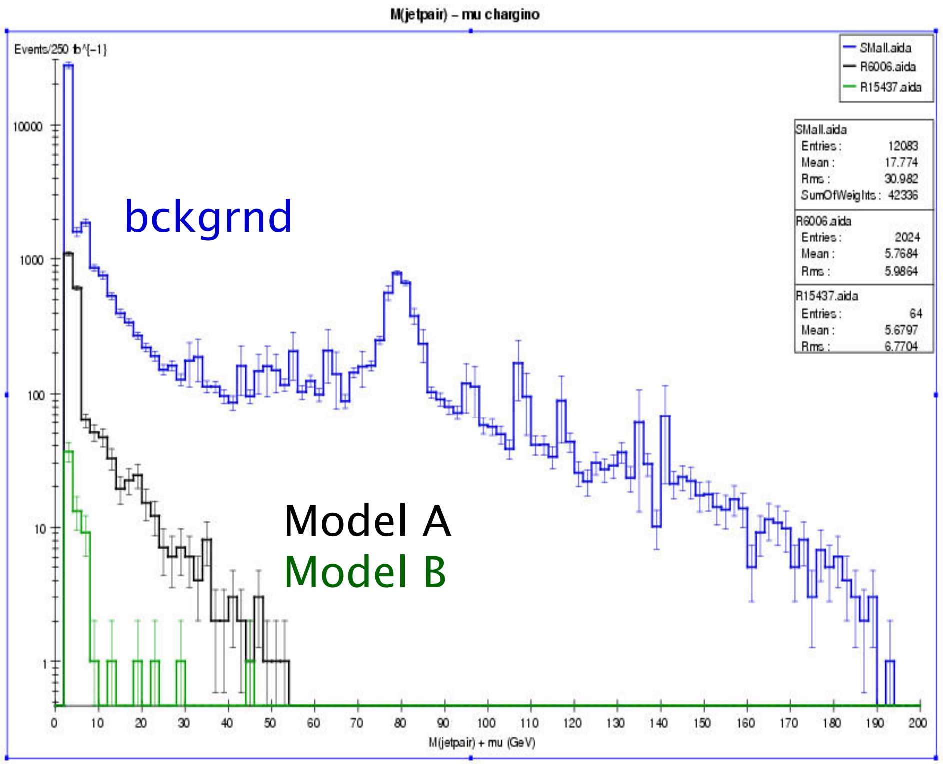
Results: Chargino, off-shell W's

4-jet + missing



This case is problematic…

2-jet + μ + missing

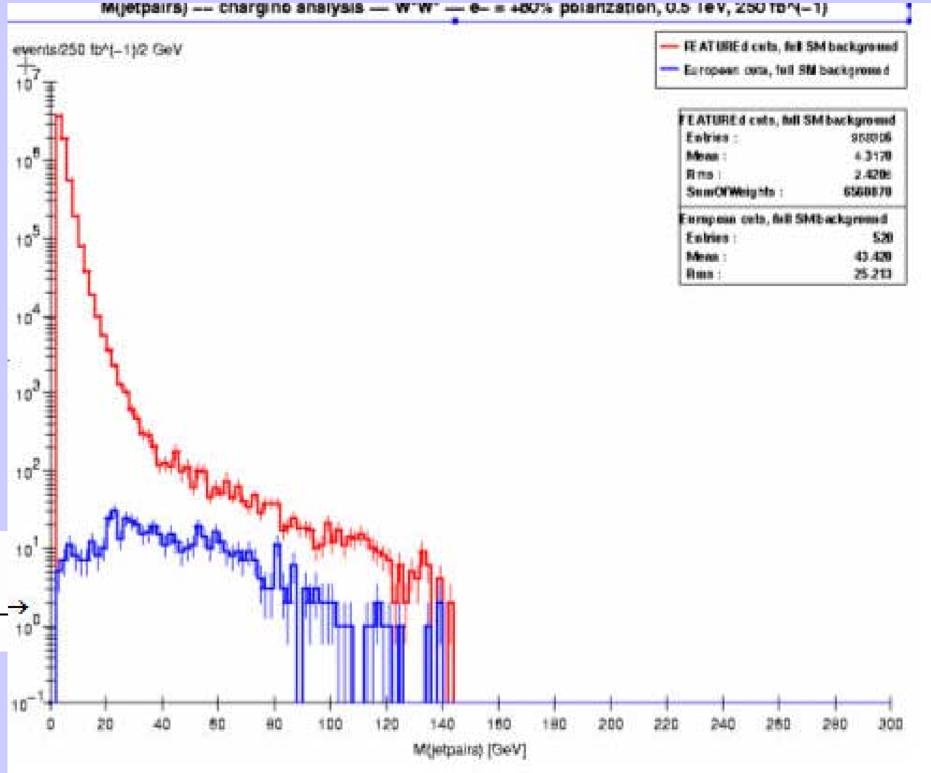


Results: Chargino, off-shell W's

Adopt cuts from OPAL close-mass chargino analysis: hep-ex/0401026

Lesson: One has to be careful in adopting cuts used to analyze specific points, to the case of an arbitrary MSSM model point. For example, while this cut drastically reduces the low mass background it *completely* removes the signal as well in our models

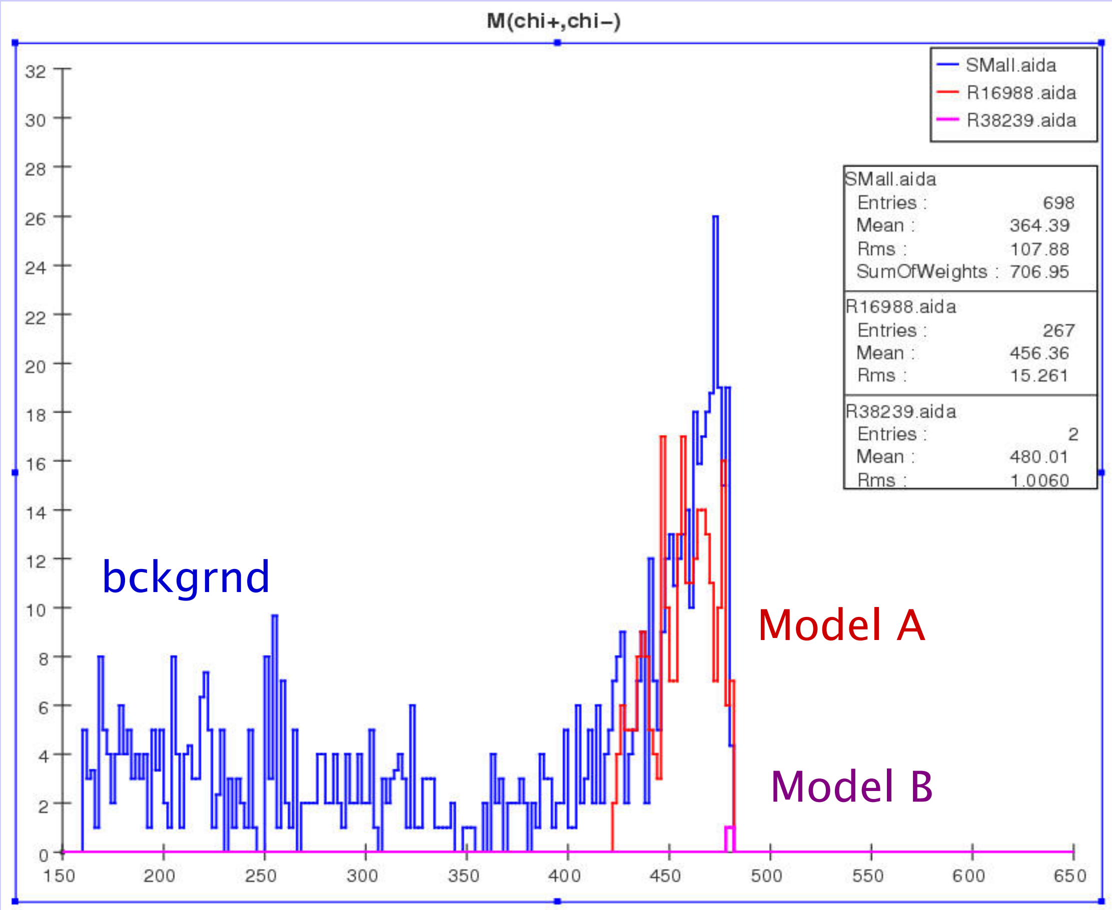
Includes an extra cut, $p_T^{vis} \geq 30$ GeV →



Chargino Analyses: Close Mass Case

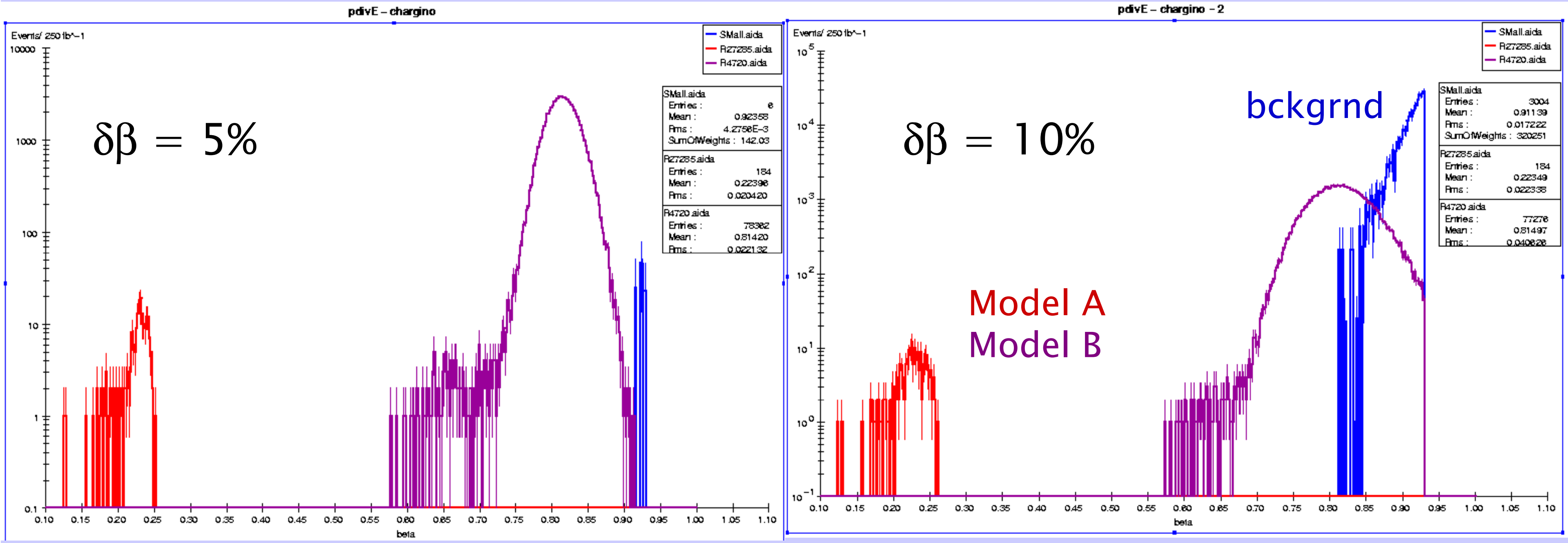
1. $m_\pi \leq \Delta M\chi < 1$ GeV: Use $e^+e^- \rightarrow \chi_1^+\chi_1^- + \gamma$

   Tag on high P_T photon! Use CompHEP to generate hard matrix element



Chargino Analyses: Close Mass Case

2. $\Delta M\chi < m_\pi$: Chargino decays into electron, neutrino, & LSP after traversing many meters – nearly back-to-back, stable, massive tracks $\Rightarrow$ stable particle search



These two models are clearly different for either velocity resolution

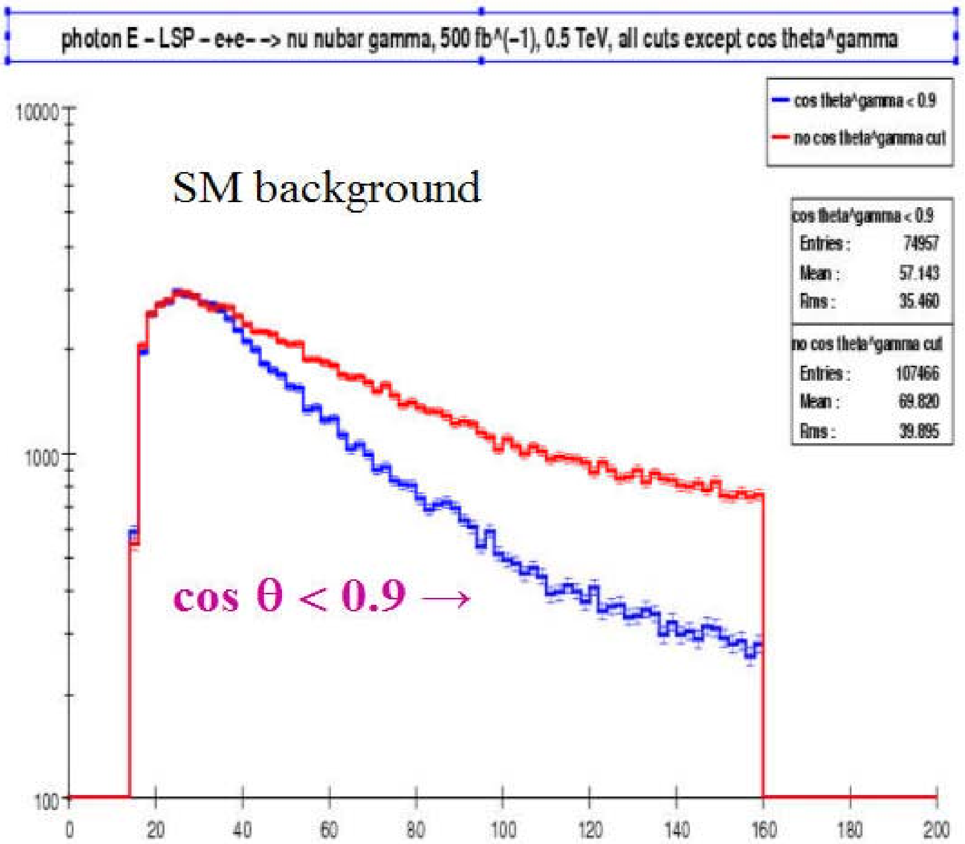
Results: Radiative Neutralino Production

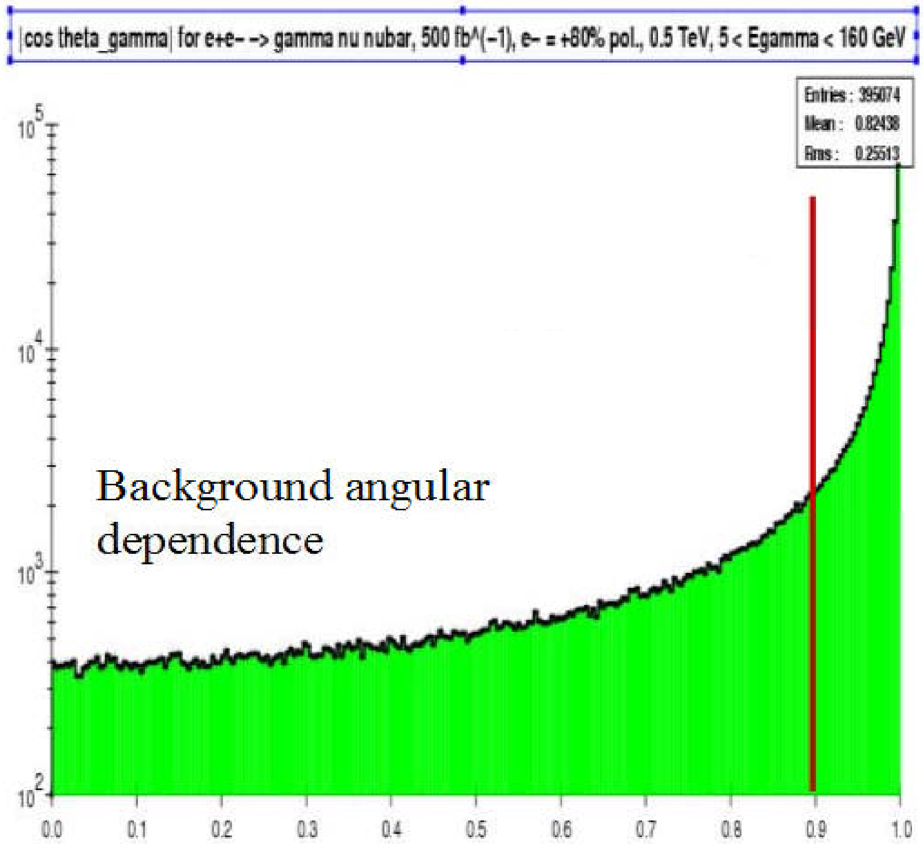
$$e^+e^- \rightarrow \chi_1^0\chi_1^0 + \gamma$$

Background:

$$e^+e^- \rightarrow \nu\bar{\nu}\gamma$$

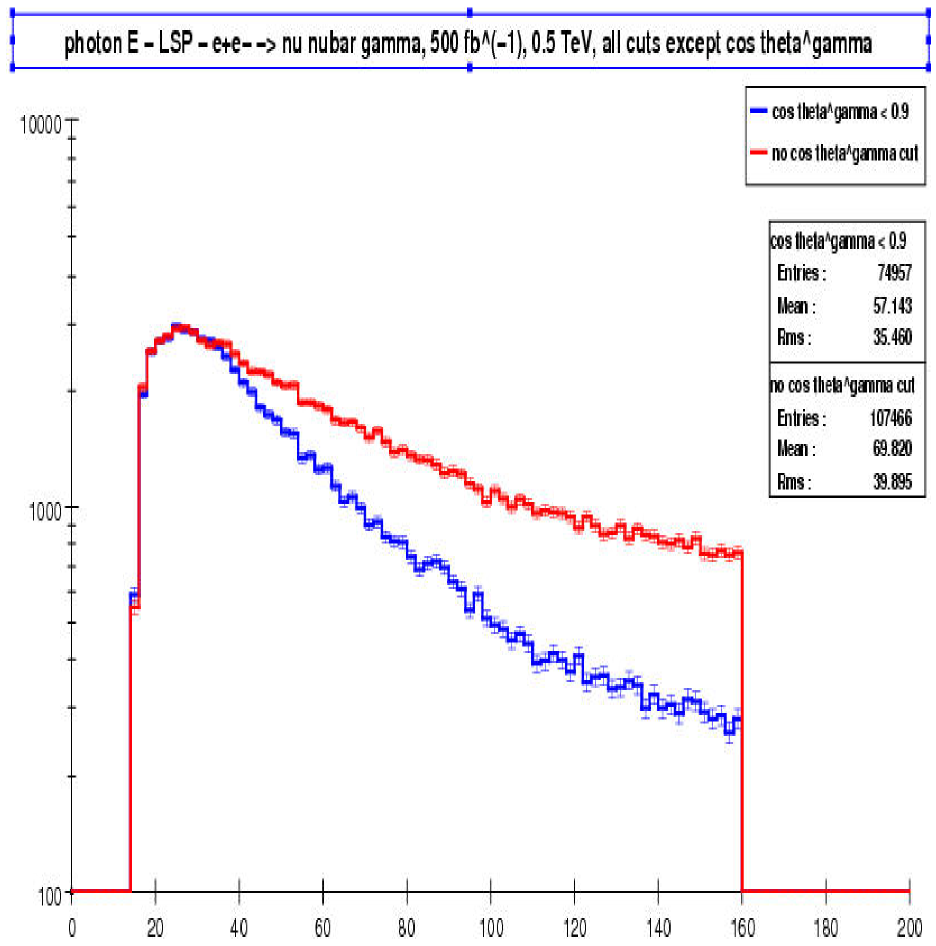
The γ is strongly peaked forward in the SM background but this is also true in many of the signal models depending on the MSSM spectrum details.



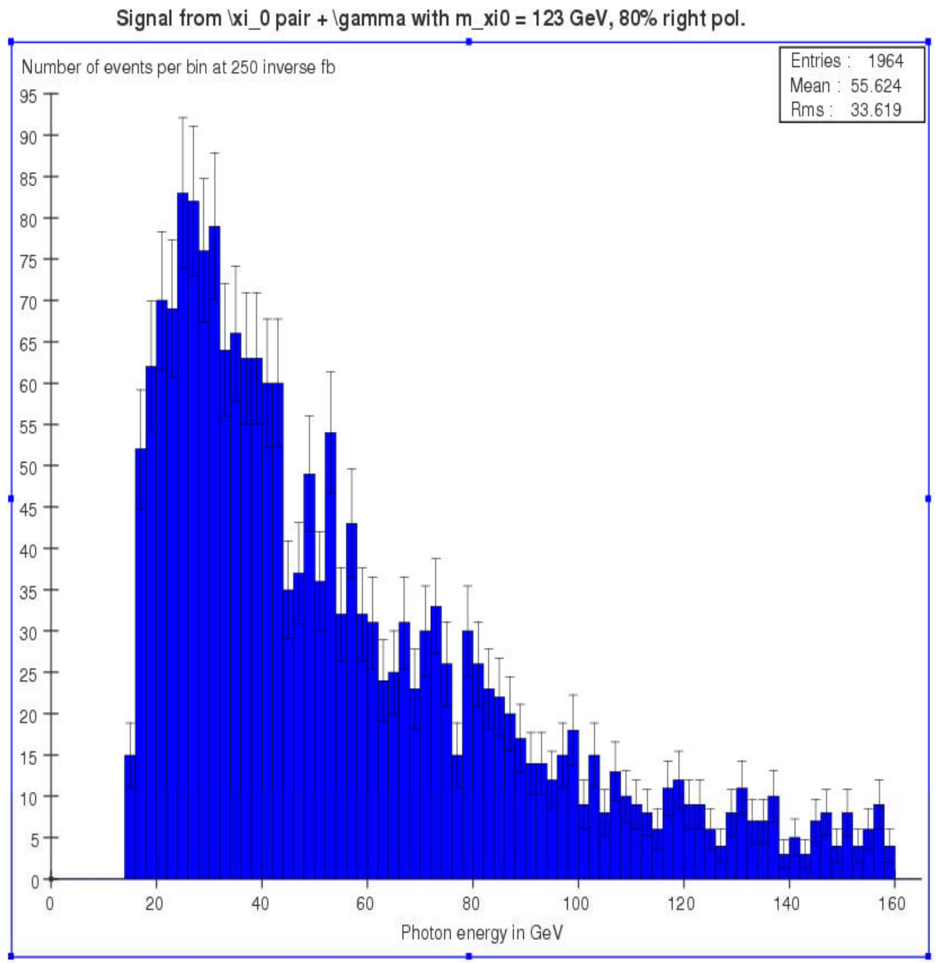


Typically, S/B ~ 1/20 in our models

Background



Model 8365



Model Comparisons

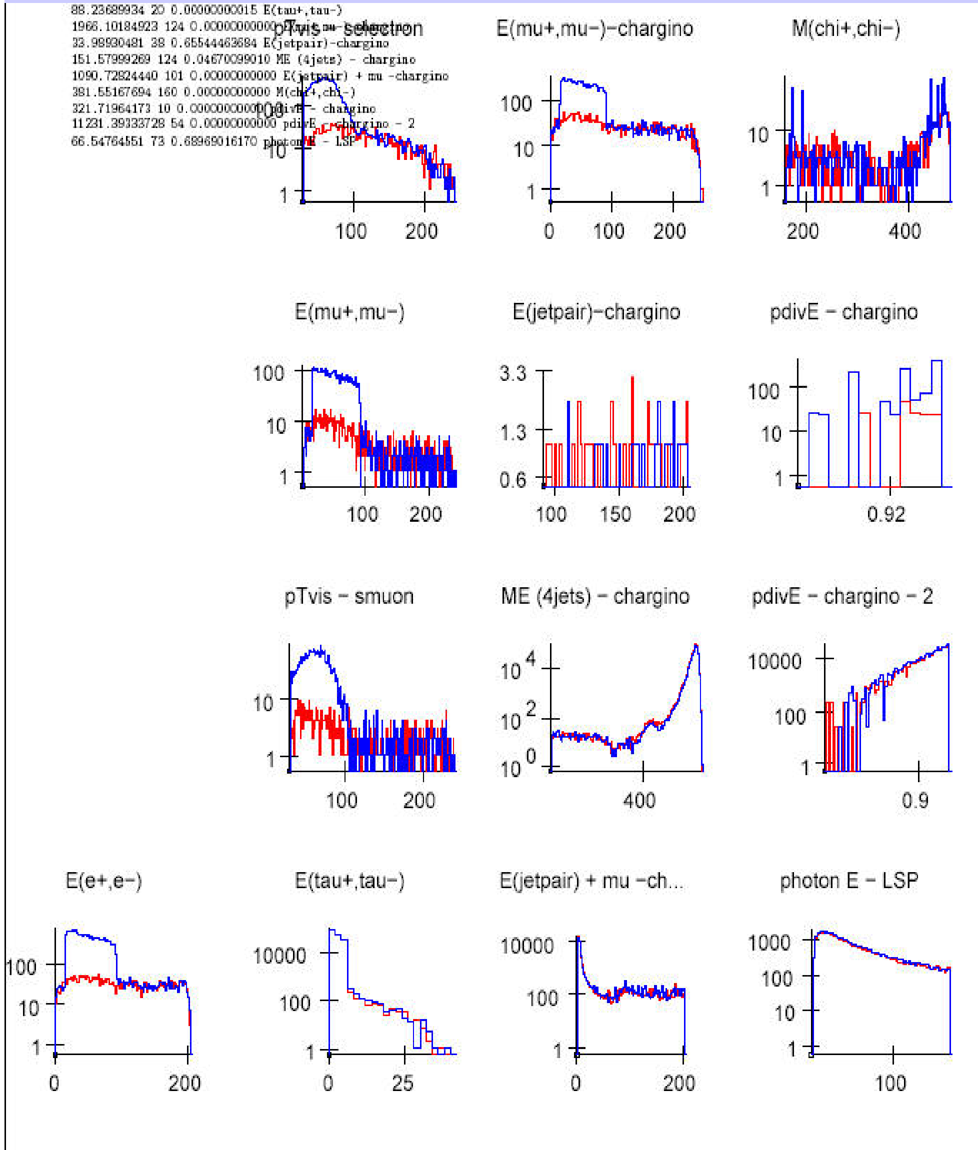


Figure 3: Right 1125 (red) 33224 (blue)

- We combine the results for each analysis for Models A and B with those obtained from two different full background samples, B1 & B2
- For each $e_{L,R}$ beam we perform a statistical comparison of the various distributions for (A+B1) vs (B+B2)
- We then ask if the 2 models are distinguishable at a given level of significance , e.g, 5σ
- We are just starting to make these comparisons…

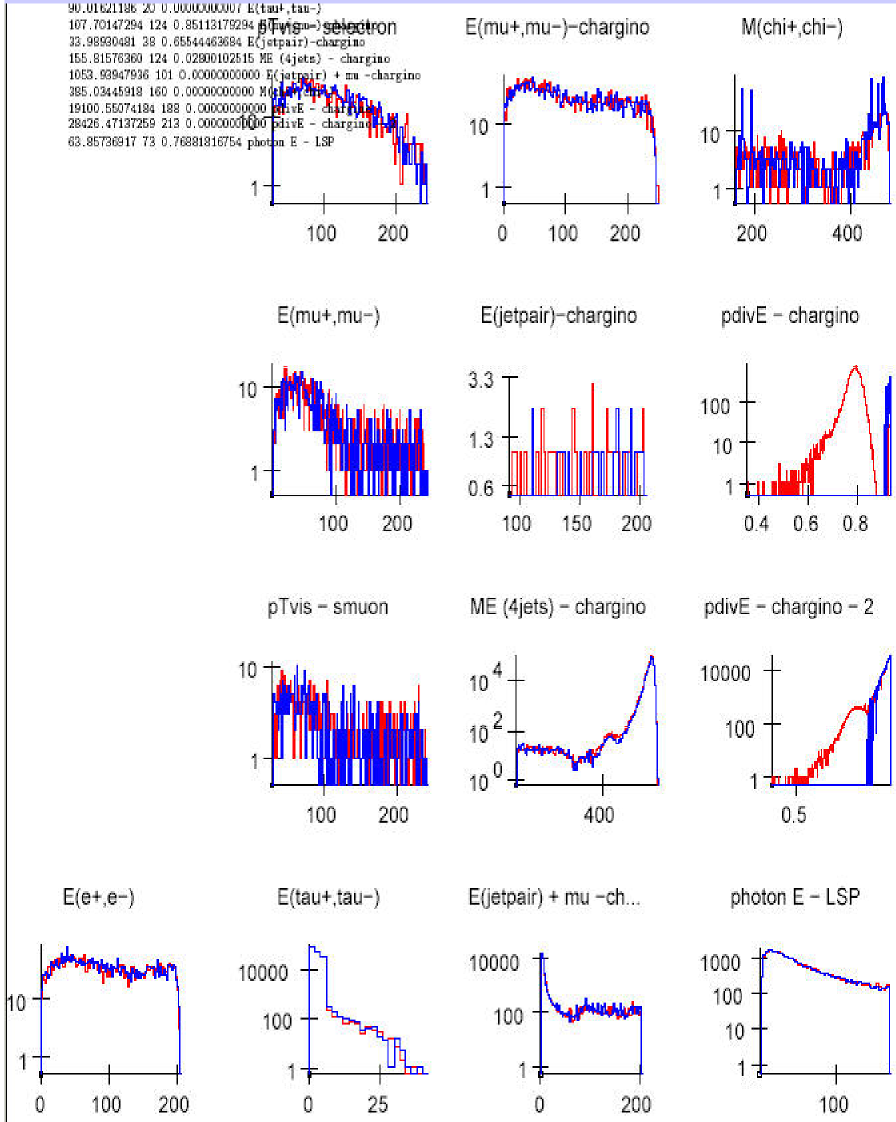


Figure 1: Right 207 (red) 3848 (blue)

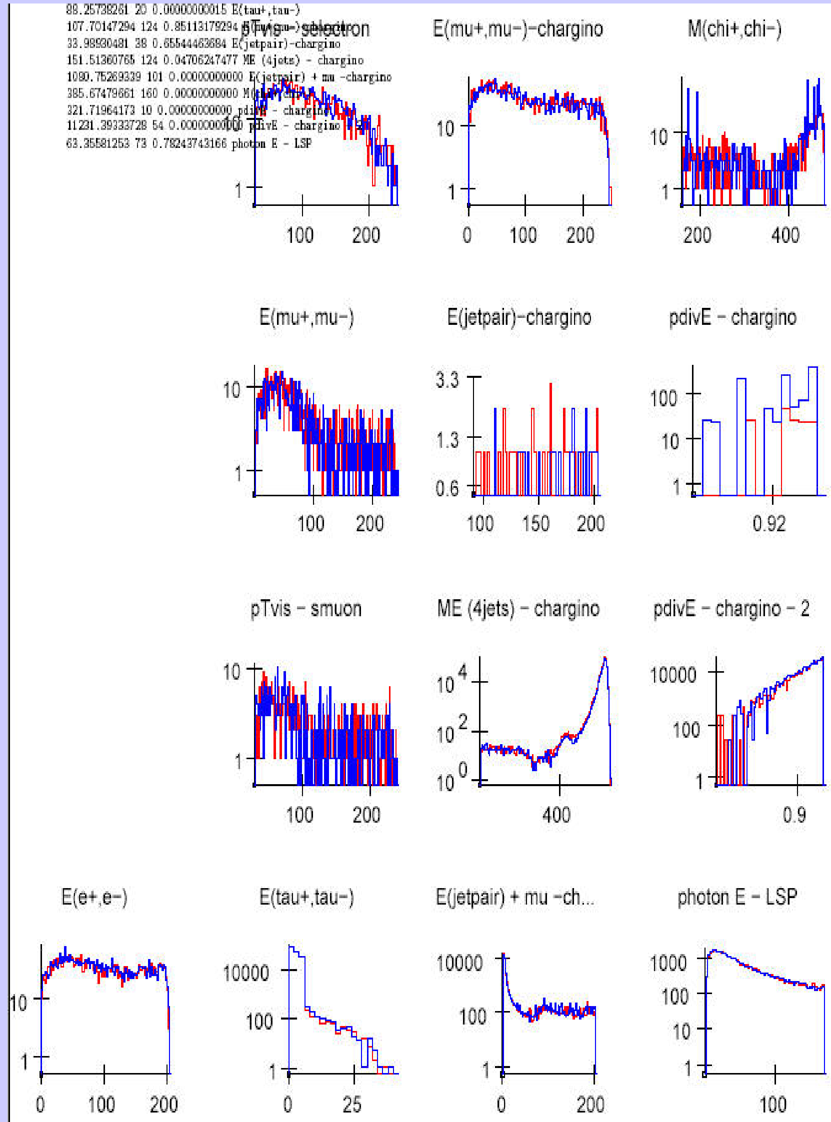


Figure 9: Right 1861 (red) 20055 (blue)

Summary & Outlook

1. 1st ILC analysis of 100's of random SUSY models
   (smaller rates than SPS1a)
2. $\sqrt{s}$ = 500 GeV is not enough for this sample of models
3. Some cuts designed for specific models (SPS1a) kill random SUSY signal
4. SM Background from WHIZARD with full matrix element is larger than that from Pythia
5. Forward detector coverage is critical
6. Some difficult cases:
   - close stau – LSP mass
   - $\chi_1^{\pm} \rightarrow W^{*}\chi_1^0 \rightarrow jj\ \chi_1^0$
7. Model comparisons just beginning, but there are some cases where it will be difficult to distinguish models
8. Next task is to study 1 TeV case and posi-pol