

# THE LHC INVERSE PROBLEM AND THE ILC

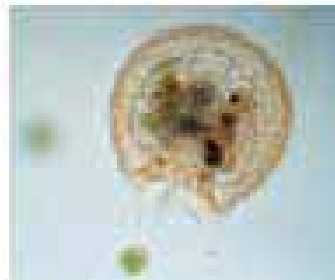
...a SUSY study

C.F. Berger, J. Gainer, J.L Hewett, B. Lillie and TGR

- If new physics is discovered at the LHC, can we uniquely determine what it is? Does a specific signature map back into a unique model with a fixed set of parameters? Many kinds of new physics can produce similar signatures...
- Even within a very specific context, e.g., the MSSM, can we uniquely determine the values of, e.g., the weak scale Lagrangian parameters from LHC data alone?
- This is the LHC Inverse Problem, i.e., instead of going from the model parameters and determining the experimental signatures, as theorists usually do, here (finally!) we want to do the reverse!
- A first past study of this kind has been performed not long ago (Arkani-Hamed et al.) for the MSSM with a number of simplifying assumptions...it was found that the answer to the above question is, obviously, 'No'.....

# is it an amoeba or is it Sharon Stone?

decoding the compositions of primary constituents



From  
Maria Spiropulu  
@SUSY07..

- Just like decoding DNA we have to decode the signals we will observe. And we do expect more similarities than differences, so fast discrimination will require smart and simple measurements.



# LHC Inverse Problem

- Generate blind SUSY data and map it back to parameters in the fundamental Lagrangian
- Generated *many* models within MSSM for  $10 \text{ fb}^{-1}$  @ LHC (Pythia 6.324). Here a ‘model’ = a particular parameter space point...
- For 15 parameters:

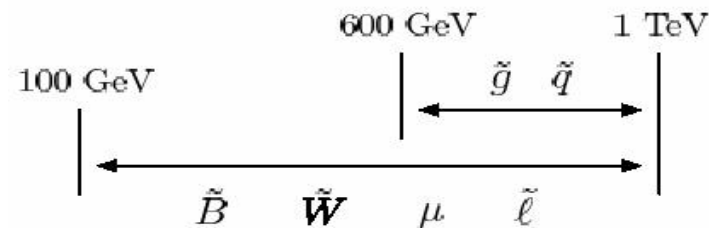
Inos :  $M_1, M_2, M_3, \mu$

Squarks :  $m_{\tilde{Q}_{1,2}}, m_{\tilde{U}_{1,2}}, m_{\tilde{D}_{1,2}}, m_{\tilde{Q}_3}, m_{\tilde{t}_R}, m_{\tilde{b}_R} + \tan \beta$

Sleptons :  $m_{\tilde{L}_{1,2}}, m_{\tilde{E}_{1,2}}, m_{\tilde{L}_3}, m_{\tilde{\tau}_R}$

w/ flat priors...

Within the constraints:



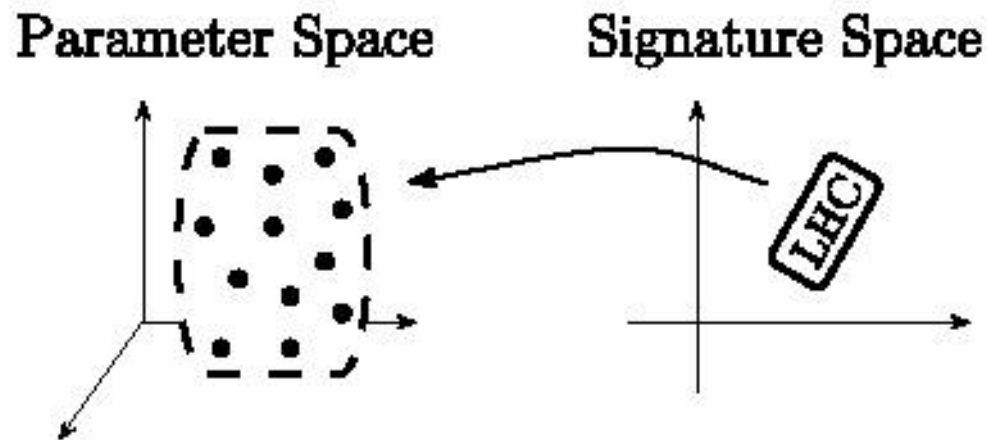
$$2 < \tan \beta < 50$$

...and keeping the 1<sup>st</sup> two scalar generations degenerate

- Used ~1800 LHC MSSM ‘Observables’
  - Rate counting, kinematic distributions,...
- NO SM Backgrounds! (so the REAL world is far worse!)

# LHC Inverse Problem: Results

- Main result: 283 pairs of models (383 distinct models\*) were found to be 'indistinguishable', i.e., had the same 'signature'...many more than suggested by a statistical analysis...termed 'degeneracy'.
  - A 'signature' maps back into a number of small islands in parameter space



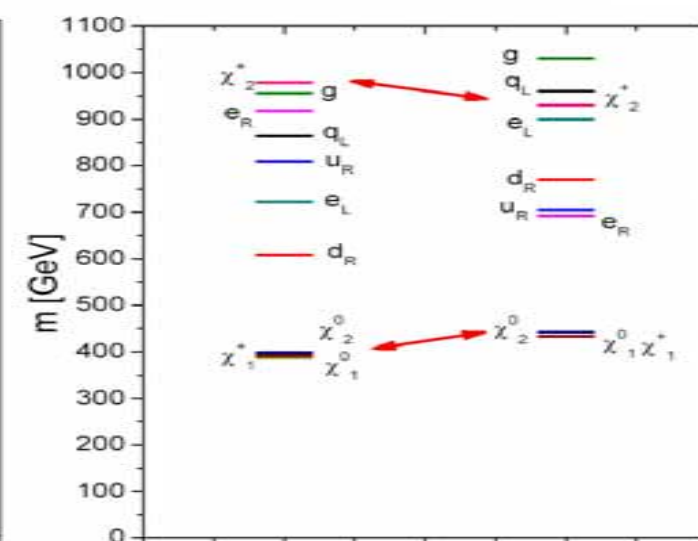
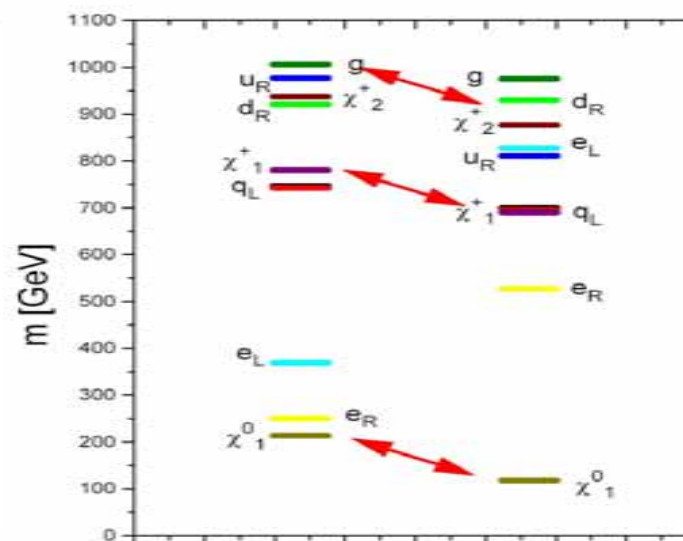
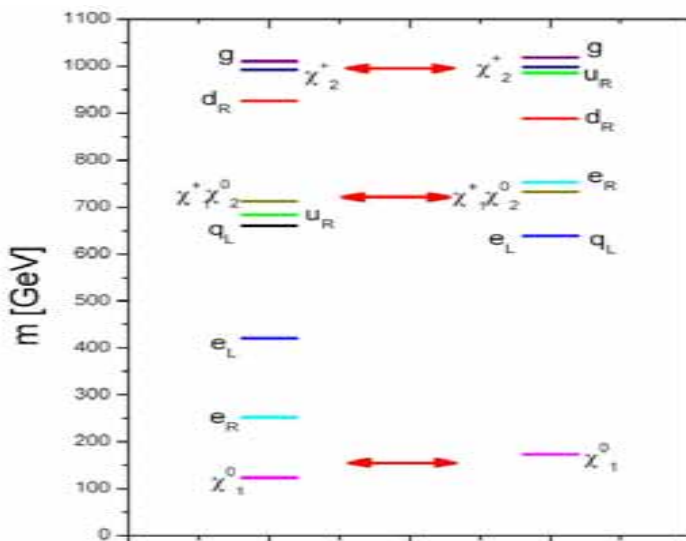
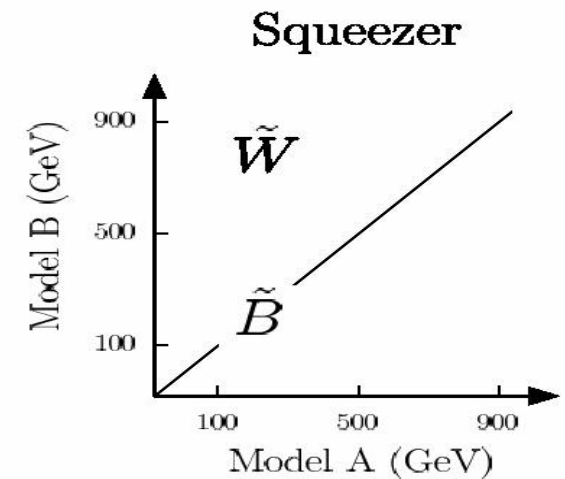
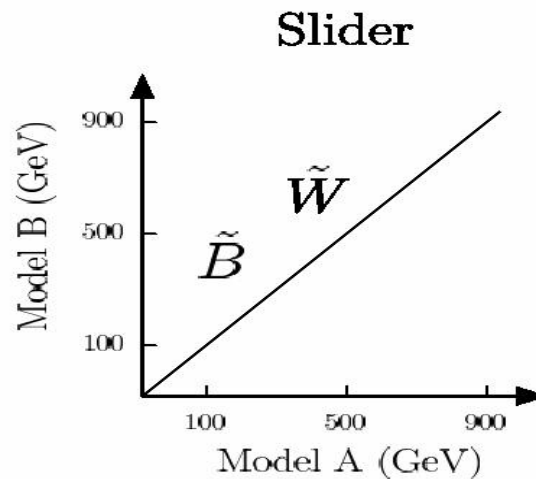
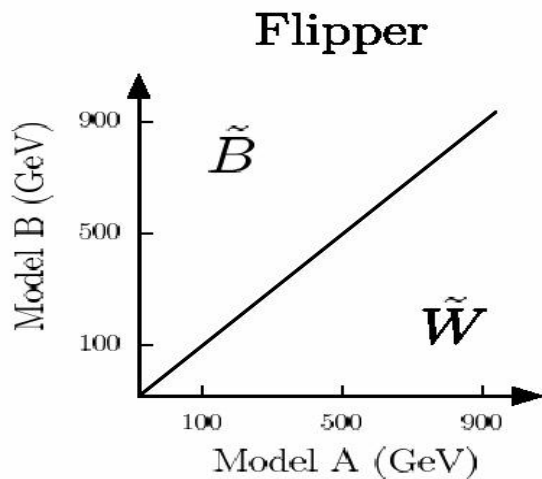
\* as we will see  
only 242 models  
are physical

This begs the question: Can the ILC resolve these degeneracies? We will address this issue below..  
How do these degeneracies arise?

# Characteristics of Degenerate Models

LHC: measures mass differences in cascade decays quite well...

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



# LHC<sup>-1</sup> = ILC ?? PROJECT

- ♣ The original purpose of this project was to examine whether or not ~200 pairs of MSSM SUSY models which produced `identical' signals at the LHC can be distinguished at ILC.
- ◆ Though we are still attacking this question this project has morphed into something far larger...we are performing a general study of the signals and backgrounds for hundreds of `random' MSSM models at the ILC which provides a unique opportunity to examine, e.g., signatures, cuts, detector and simulation properties & our basic assumptions/prejudices about SUSY analyses at the ILC.
- ♠ We've had many surprises and have learned many lessons...

☺ People find it difficult to resist your  
persuasive manner. ☺  
23 21 22 28 32 5

c/o the Kirin Chinese-Japanese restaurant

## Our Analysis\*

- We start with their 283 degenerate pairs (383 distinct models) ...provided to us by Nima & friends
- Simulate signal events with Pythia & CompHEP, and feed in appropriate beamspectrum generated via Whizard/GuineaPig (at 500 GeV)
- Add SM background (1066 different processes), produced by Tim Barklow – stored @ SLAC
- Pipe through detector simulation: Java-based SiD simulation, org.lcsim
- Analyze 500 fb<sup>-1</sup> “data” with 80% P<sub>e-</sub> and appropriate cuts.  
Several iterations necessary to find best cuts!  
→ Do analyses....Models visible? → Compare models

\* This is a lot of software for theorists to learn: long lead time!

Table 12:

Process Class	Initial state	Final state
44(a)	$e^- e^+$	$\nu_e \bar{\nu}_e u \bar{u} \mu^- \mu^+$
	$e^- e^+$	$\nu_e \bar{\nu}_e u \bar{u} \tau^- \tau^+$
	$e^- e^+$	$\nu_\mu \bar{\nu}_\mu u \bar{u} e^- e^+$
	$e^- e^+$	$\nu_\mu \bar{\nu}_\mu u \bar{u} \tau^- \tau^+$
	$e^- e^+$	$\nu_\tau \bar{\nu}_\tau u \bar{u} e^- e^+$
	$e^- e^+$	$\nu_\tau \bar{\nu}_\tau u \bar{u} \mu^- \mu^+$
	$e^- e^+$	$u \bar{u} \nu_e e^+ e^- \bar{\nu}_e$
	$e^- e^+$	$u \bar{u} \nu_e e^+ \mu^- \bar{\nu}_\mu$
	$e^- e^+$	$u \bar{u} \nu_e e^+ \tau^- \bar{\nu}_\tau$
	$e^- e^+$	$u \bar{u} \nu_\mu \mu^+ e^- \bar{\nu}_e$
	$e^- e^+$	$u \bar{u} \nu_\mu \mu^+ \mu^- \bar{\nu}_\mu$
	$e^- e^+$	$u \bar{u} \nu_\mu \mu^+ \tau^- \bar{\nu}_\tau$
	$e^- e^+$	$u \bar{u} \nu_\tau \tau^+ e^- \bar{\nu}_e$
	$e^- e^+$	$u \bar{u} \nu_\tau \tau^+ \mu^- \bar{\nu}_\mu$
	$e^- e^+$	$u \bar{u} \nu_\tau \tau^+ \tau^- \bar{\nu}_\tau$
	$e^- e^+$	$\nu_e \bar{\nu}_e \mu^- \mu^+ d \bar{d}$
	$e^- e^+$	$\nu_e \bar{\nu}_e \tau^- \tau^+ d \bar{d}$
	$e^- e^+$	$\nu_\mu \bar{\nu}_\mu e^- e^+ d \bar{d}$
	$e^- e^+$	$\nu_\mu \bar{\nu}_\mu \tau^- \tau^+ d \bar{d}$
	$e^- e^+$	$\nu_\tau \bar{\nu}_\tau e^- e^+ d \bar{d}$
	$e^- e^+$	$\nu_\tau \bar{\nu}_\tau \mu^- \mu^+ d \bar{d}$
	$e^- e^+$	$d \bar{d} \nu_e e^+ e^- \bar{\nu}_e$
	$e^- e^+$	$d \bar{d} \nu_e e^+ \mu^- \bar{\nu}_\mu$
	$e^- e^+$	$d \bar{d} \nu_e e^+ \tau^- \bar{\nu}_\tau$
	$e^- e^+$	$d \bar{d} \nu_\mu \mu^+ e^- \bar{\nu}_e$
	$e^- e^+$	$d \bar{d} \nu_\mu \mu^+ \mu^- \bar{\nu}_\mu$
	$e^- e^+$	$d \bar{d} \nu_\mu \mu^+ \tau^- \bar{\nu}_\tau$
	$e^- e^+$	$d \bar{d} \nu_\tau \tau^+ e^- \bar{\nu}_e$
	$e^- e^+$	$d \bar{d} \nu_\tau \tau^+ \mu^- \bar{\nu}_\mu$
	$e^- e^+$	$d \bar{d} \nu_\tau \tau^+ \tau^- \bar{\nu}_\tau$
	$e^- e^+$	$\nu_e \bar{\nu}_e \mu^- \mu^+ s \bar{s}$
	$e^- e^+$	$\nu_e \bar{\nu}_e \tau^- \tau^+ s \bar{s}$
	$e^- e^+$	$\nu_\mu \bar{\nu}_\mu e^- e^+ s \bar{s}$
	$e^- e^+$	$\nu_\mu \bar{\nu}_\mu \tau^- \tau^+ s \bar{s}$
	$e^- e^+$	$\nu_\tau \bar{\nu}_\tau e^- e^+ s \bar{s}$
	$e^- e^+$	$\nu_\tau \bar{\nu}_\tau \mu^- \mu^+ s \bar{s}$
	$e^- e^+$	$s \bar{s} \nu_e e^+ e^- \bar{\nu}_e$
	$e^- e^+$	$s \bar{s} \nu_e e^+ \mu^- \bar{\nu}_\mu$
	$e^- e^+$	$s \bar{s} \nu_e e^+ \tau^- \bar{\nu}_\tau$
	$e^- e^+$	$s \bar{s} \nu_\mu \mu^+ e^- \bar{\nu}_e$
	$e^- e^+$	$s \bar{s} \nu_\mu \mu^+ \mu^- \bar{\nu}_\mu$
	$e^- e^+$	$s \bar{s} \nu_\mu \mu^+ \tau^- \bar{\nu}_\tau$

All  $ee, \gamma e, \gamma\gamma \rightarrow 2, 4, 6$  processes w/ full matrix elements included, e.g.,

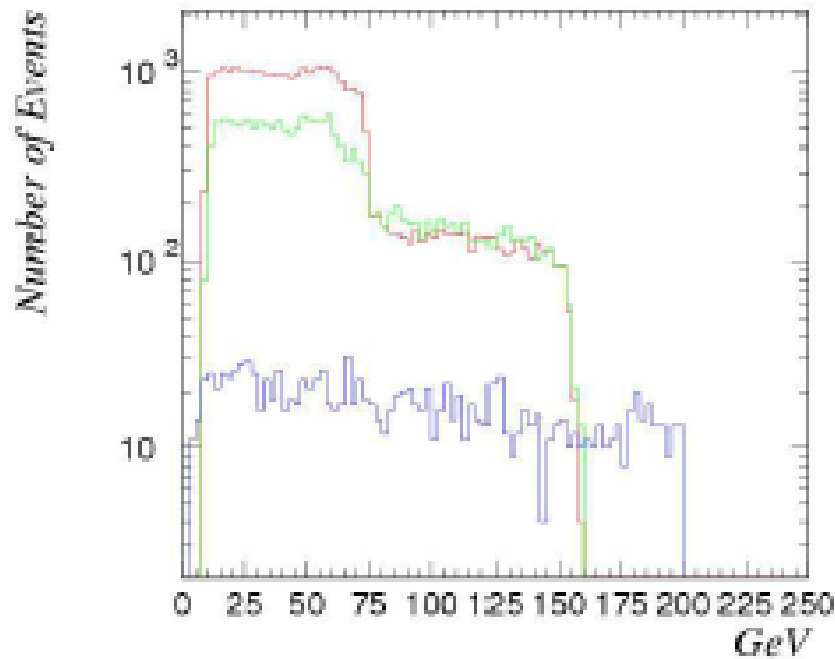
Table 13:

Process Class	Initial state	Final state
44(b)	$e^- e^+$	$s \bar{s} \nu_\tau \tau^+ e^- \bar{\nu}_e$
	$e^- e^+$	$s \bar{s} \nu_\tau \tau^+ \mu^- \bar{\nu}_\mu$
	$e^- e^+$	$s \bar{s} \nu_\tau \tau^+ \tau^- \bar{\nu}_\tau$
	$e^- e^+$	$\nu_e \bar{\nu}_e c \bar{c} \mu^- \mu^+$
	$e^- e^+$	$\nu_e \bar{\nu}_e c \bar{c} \tau^- \tau^+$
	$e^- e^+$	$\nu_\mu \bar{\nu}_\mu c \bar{c} e^- e^+$
	$e^- e^+$	$\nu_\mu \bar{\nu}_\mu c \bar{c} \tau^- \tau^+$
	$e^- e^+$	$\nu_\tau \bar{\nu}_\tau c \bar{c} e^- e^+$
	$e^- e^+$	$\nu_\tau \bar{\nu}_\tau c \bar{c} \mu^- \mu^+$
	$e^- e^+$	$c \bar{c} \nu_e e^+ e^- \bar{\nu}_e$
	$e^- e^+$	$c \bar{c} \nu_e e^+ \mu^- \bar{\nu}_\mu$
	$e^- e^+$	$c \bar{c} \nu_e e^+ \tau^- \bar{\nu}_\tau$
	$e^- e^+$	$c \bar{c} \nu_\mu \mu^+ e^- \bar{\nu}_e$
	$e^- e^+$	$c \bar{c} \nu_\mu \mu^+ \mu^- \bar{\nu}_\mu$
	$e^- e^+$	$c \bar{c} \nu_\mu \mu^+ \tau^- \bar{\nu}_\tau$
	$e^- e^+$	$c \bar{c} \nu_\tau \tau^+ e^- \bar{\nu}_e$
	$e^- e^+$	$c \bar{c} \nu_\tau \tau^+ \mu^- \bar{\nu}_\mu$
	$e^- e^+$	$c \bar{c} \nu_\tau \tau^+ \tau^- \bar{\nu}_\tau$
45	$e^- e^+$	$b \bar{b} u \bar{d} s \bar{c}$
	$e^- e^+$	$b \bar{b} c \bar{s} d \bar{u}$
46	$e^- e^+$	$b \bar{b} u \bar{d} d \bar{u}$
	$e^- e^+$	$b \bar{b} c \bar{s} s \bar{c}$
47	$e^- e^+$	$b \bar{b} u \bar{d} e^- \bar{\nu}_e$
	$e^- e^+$	$b \bar{b} u \bar{d} \mu^- \bar{\nu}_\mu$
	$e^- e^+$	$b \bar{b} u \bar{d} \tau^- \bar{\nu}_\tau$
	$e^- e^+$	$b \bar{b} c \bar{s} e^- \bar{\nu}_e$
	$e^- e^+$	$b \bar{b} c \bar{s} \mu^- \bar{\nu}_\mu$
	$e^- e^+$	$b \bar{b} c \bar{s} \tau^- \bar{\nu}_\tau$
	$e^- e^+$	$b \bar{b} \nu_e e^+ d \bar{u}$
	$e^- e^+$	$b \bar{b} \nu_e e^+ s \bar{c}$
	$e^- e^+$	$b \bar{b} \nu_\mu \mu^+ d \bar{u}$
	$e^- e^+$	$b \bar{b} \nu_\mu \mu^+ s \bar{c}$
	$e^- e^+$	$b \bar{b} \nu_\tau \tau^+ d \bar{u}$
	$e^- e^+$	$b \bar{b} \nu_\tau \tau^+ s \bar{c}$

## The present analysis is the first ILC study with

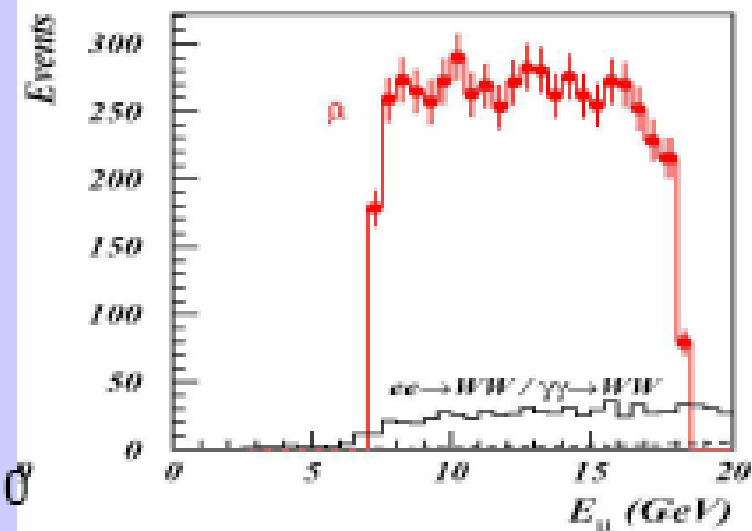
- 100's of `randomly' chosen MSSM SUSY models ...  
NOT SPS1a !!
- Complete SM backgrounds calculated with full matrix elements
- Full ISR/beam spectrum including finite energy spread & beam crossing angle
- SiD detector simulation
- Over 20 simultaneous analyses using multiple observables

# Previous ILC SUSY Studies

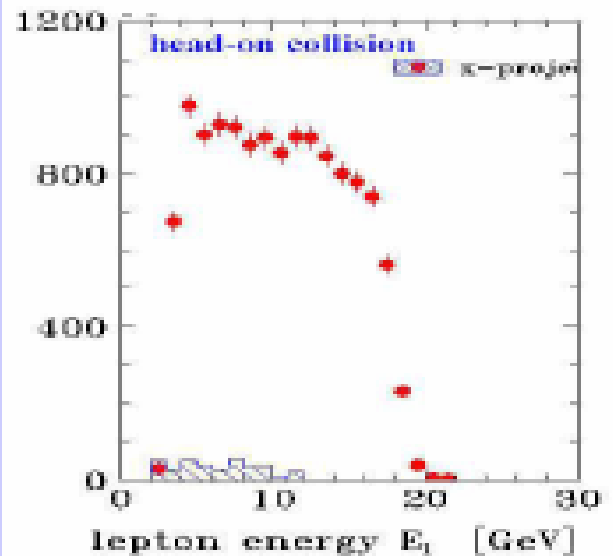


Colorado Group  
Goodman et al

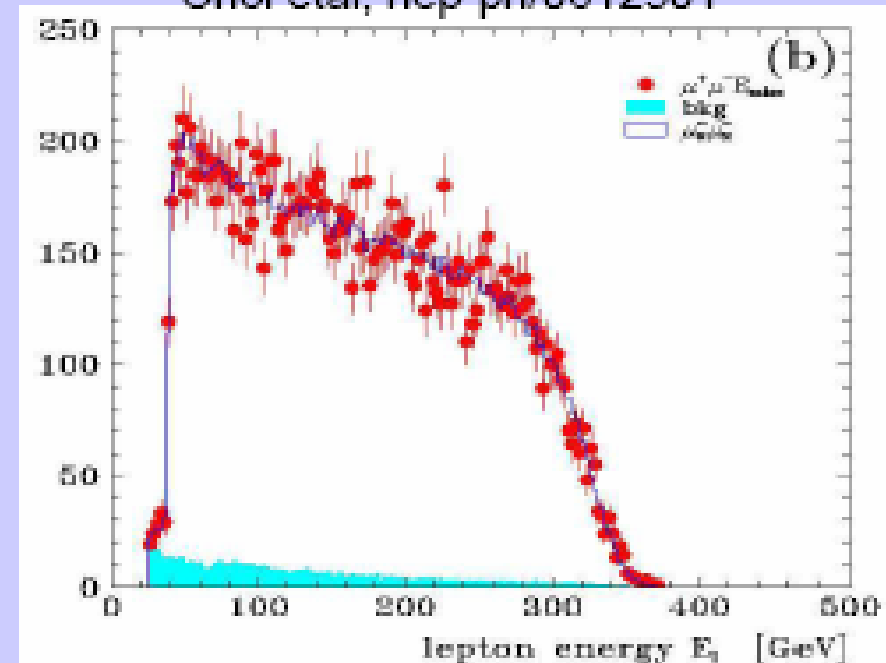
Bambade et al  
hep-ph/0406010



Choi et al, hep-ph/0612301



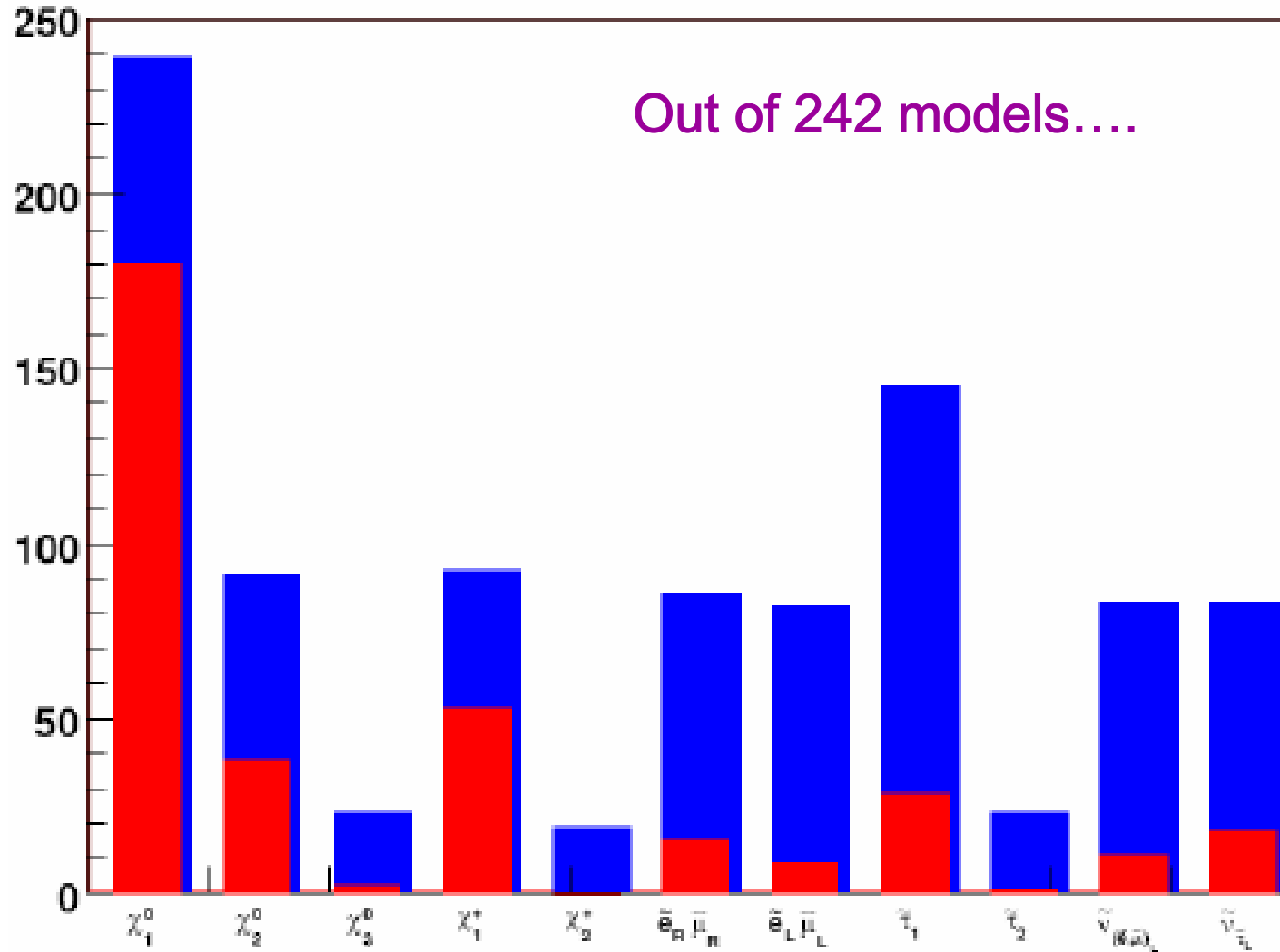
Martyn  
hep-ph/0408226



From these examples, one would believe that the ILC environment is so clean that observing and identifying SUSY particles should be a rather straightforward task for just about any point in MSSM parameter space...this was certainly my belief before I began this project...

...as we will see, this isn't the picture that we will arrive at in some of these models once we go to some arbitrary point in MSSM parameter space, include the full matrix element backgrounds and when the SiD detector simulation is employed....

# What Particles are Kinematically Accessible at the ILC ???



Accessible at **500 GeV**, **1 TeV** c.m. energy

Let's look at some numbers...

# Kinematic accessibility does not equal observability of models

500 GeV      1 TeV  
Visible

selectrons or smuons	22	17	116
staus	27	8	125
All slepton types	7	3?	55
$\chi^+_1$	53	42?	78
$\chi^+_1$ + smuons	2	2?	12
$\chi^+_1$ + staus	8	7?	12
$\chi^+_1 \chi^-_2$	0	0	16
$\chi^0_1 \chi^0_1$ <i>only</i>	99	0	1
$\chi^0_1 \chi^0_2$	46	2?	178
nothing	59	0	1

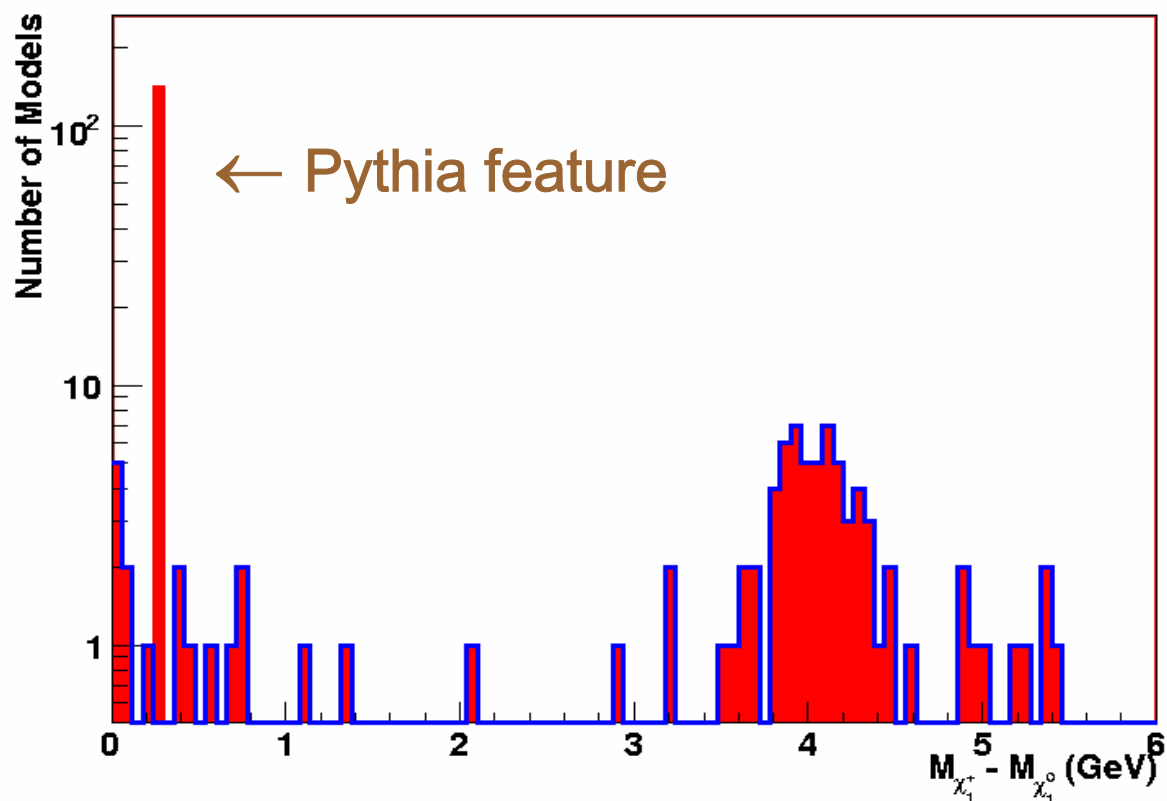
Out of 242 models, at 500 GeV, 59+99=158/242 = 65% have NO signal observable...the percentage is actually higher (~75% !) after some further investigation as we will see. But this fraction is much smaller at 1 TeV .

→ 'visible' here is the number of models where a signal is observable over background

This may be very strong argument for 1 TeV as soon as possible...

# BEWARE OF BLIND USE OF PYTHIA, PART I:

NLSP LSP mass difference



Chargino – LSP Mass Difference

In PYTHIA6.324 or earlier, if the  $\chi_1^+$  is calculated to be lighter than the LSP, then the code automatically, and without ANY warning, resets the  $\chi_1^+$  mass to that of the LSP+  $2m_\pi$ . This happens in 141/383 original model (unphysical) cases !!

This reduces our sample:  
383→242 models

This issue has now been dealt with in the latest version of

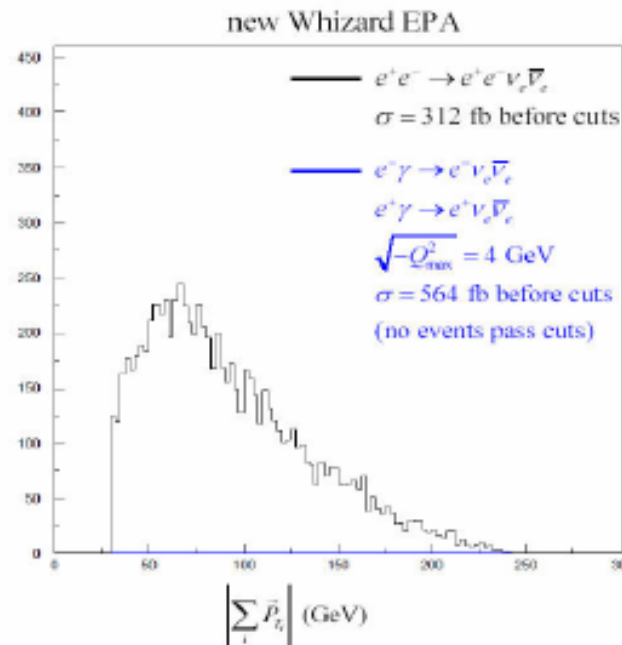
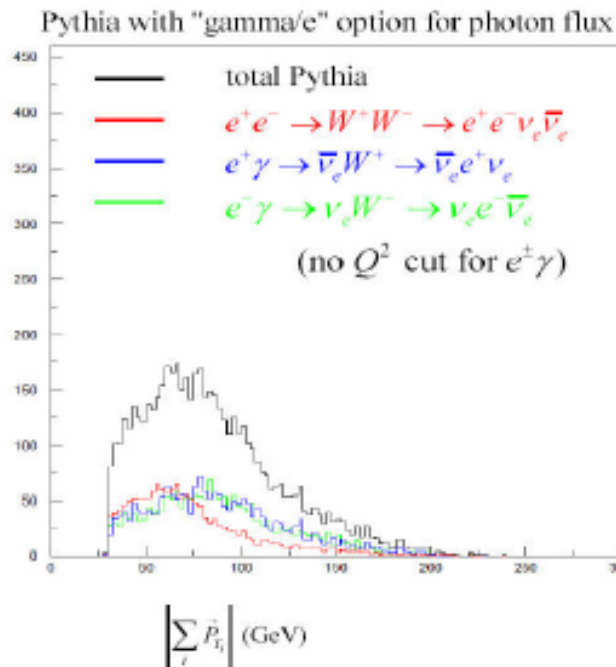
PYTHIA (thanks to Steve & Peter)

# BEWARE OF BLIND USE OF PYTHIA , PART II : PYTHIA UNDERESTIMATES BACKGROUNDS

- Using full matrix elements makes a difference
  - Here we compare standard model background to our selectron analysis as calculated in PYTHIA and WHIZARD/O'mega
  - Cross section after cuts with WHIZARD is 30% higher
  - Tail is higher
  - Difference arises from using explicit matrix element for  $ee \rightarrow ee\nu\nu$  instead of decaying on-shell resonances

$$e_{pol}^- = 0 \quad \sqrt{s} = 500 \text{ GeV} \quad 250 \text{ fb}^{-1}$$

No surprise to LHC'ers....

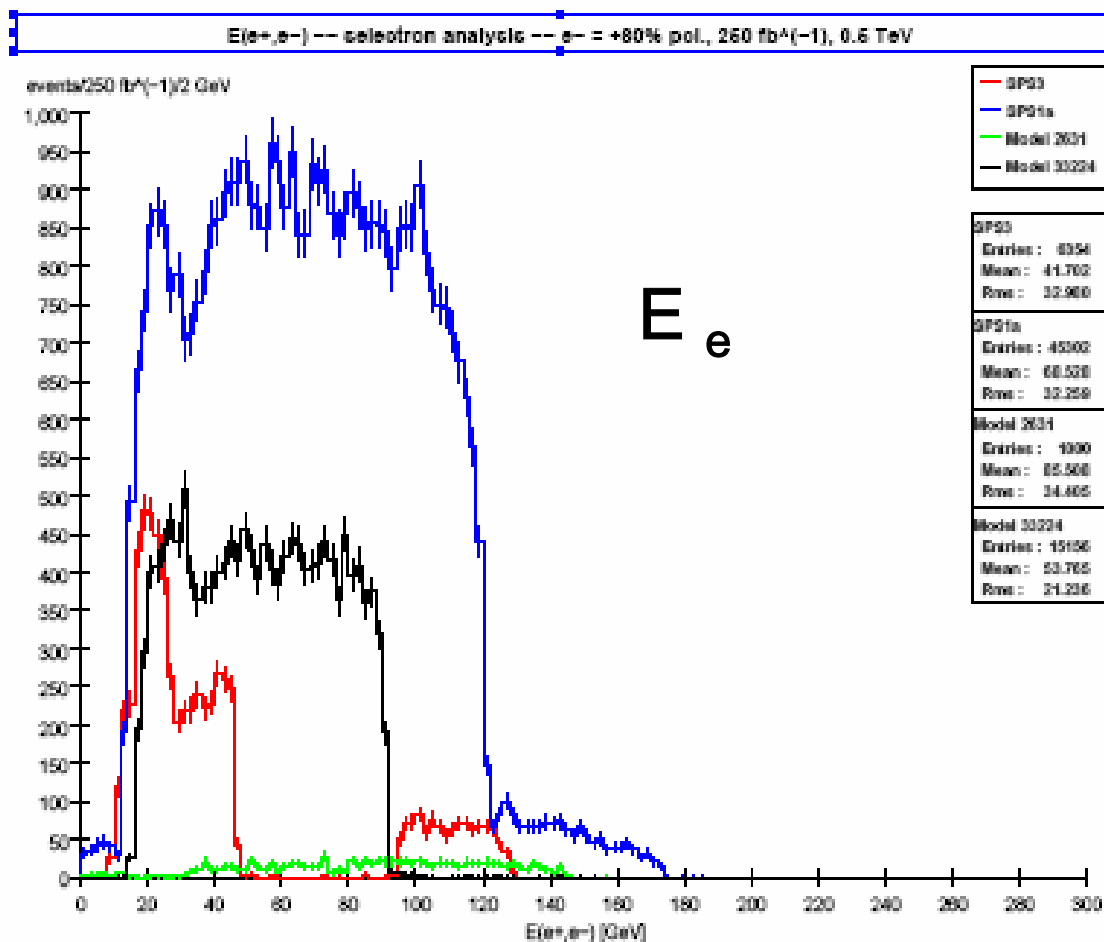


Thanks to Tim Barklow

→ using full backgrounds is important !

# SPS1a is SPECIAL .. Part I :

Looking at 100s of random MSSM models, we find that most have smaller rates than the **SPS** points commonly studied

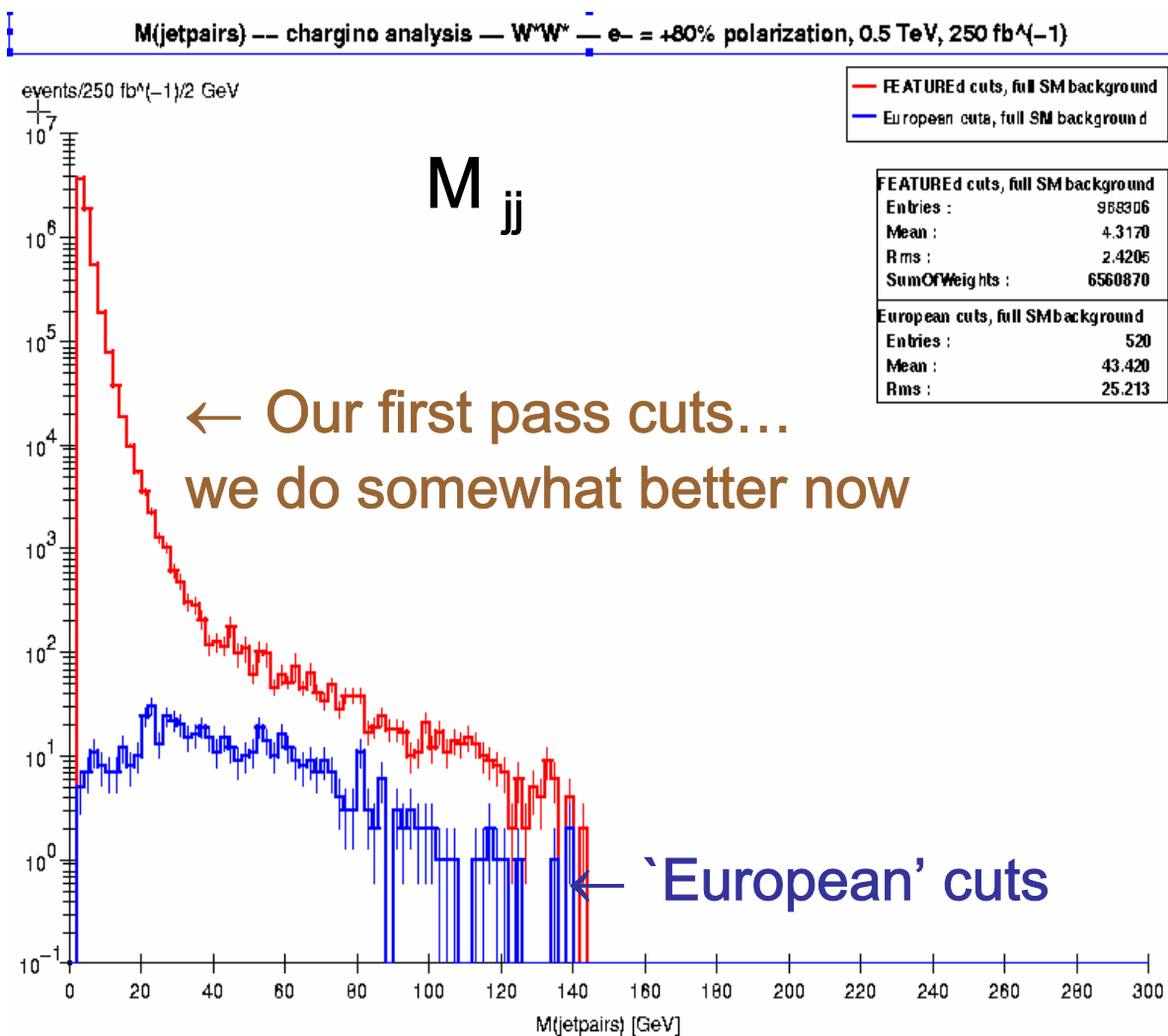


It will be much more difficult to see SUSY particles in general than in the well-studied specialized points...in some cases signal rates are over 50x smaller than in the SPS1a scenario...

But we can still see them sometimes...

# SPS1a is SPECIAL .. Part II :

The `standard' cuts are not particularly useful.



We cannot use the cuts that have been developed at ILC historically for the SPS1a point....while they do help reduce backgrounds we find that for some analyses they kill all the signals from our models !

We thus needed to develop and employ our own universal cuts that generally lead to larger SM backgrounds to SUSY...

# ANALYSES :

To cover all the possibilities many simultaneous analyses are required:

(i) Selectron/smuon/stau pairs  $\rightarrow$  SM analogues + missing E

(ii) Radiative neutralino (LSP) pairs using tagging  $\gamma$ 's

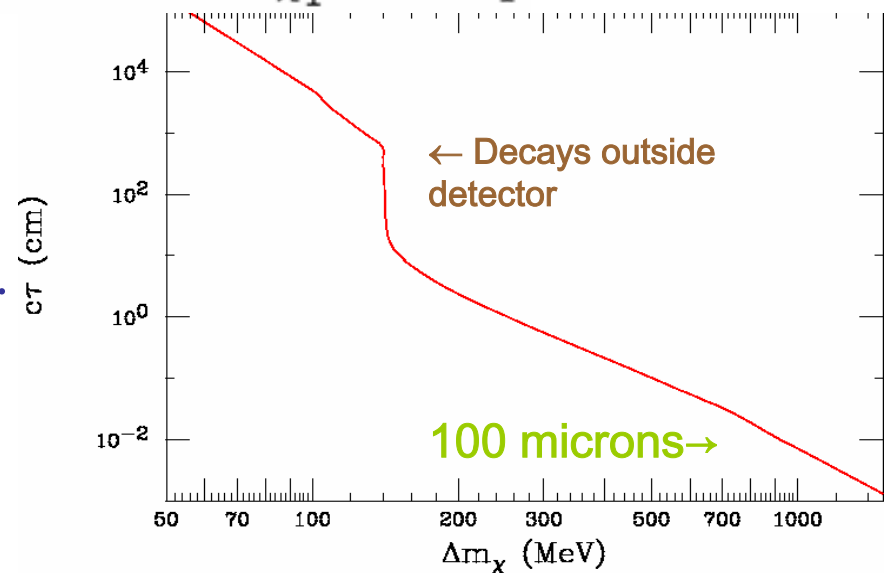
(iii)  $\chi_2^0 \chi_1^0 \rightarrow$  missing E + Z/H (jj /l+l-)

(iv) Sneutrino pairs  $\rightarrow$  (4jets+ lepton pair/6jets) + missing E , +.....

(v)  $\chi_1^+ \chi_1^-$  : analyses will depend on the

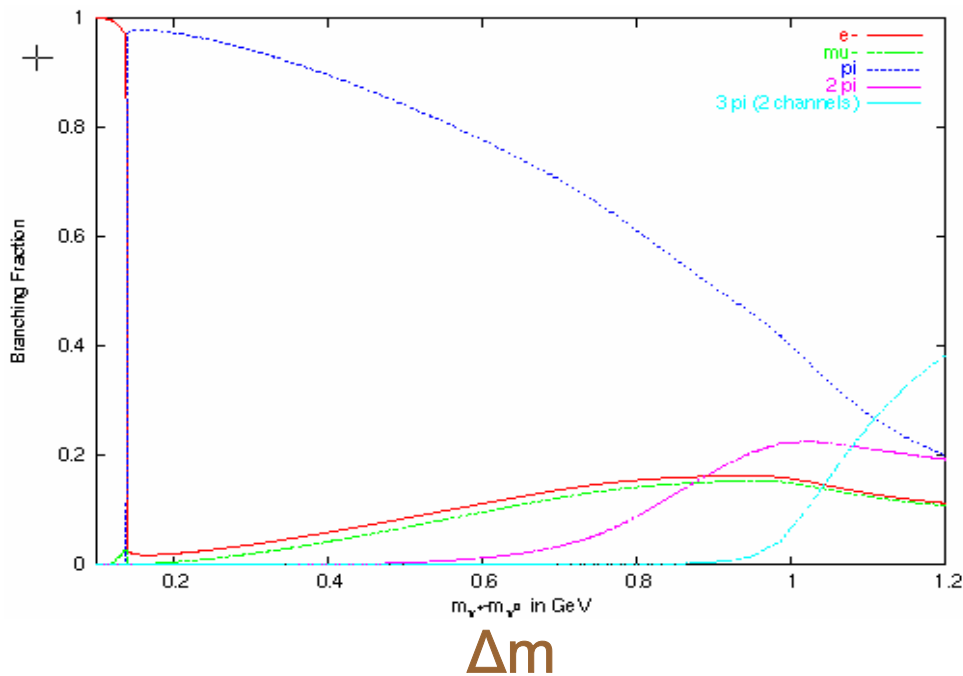
Critical parameter for charginos:  $\Delta m = m_{\chi_1^\pm} - m_{\chi_1^0}$

(a)  $\rightarrow$  if  $\Delta m < m_\pi$  we need to do a stable charged particle search ..

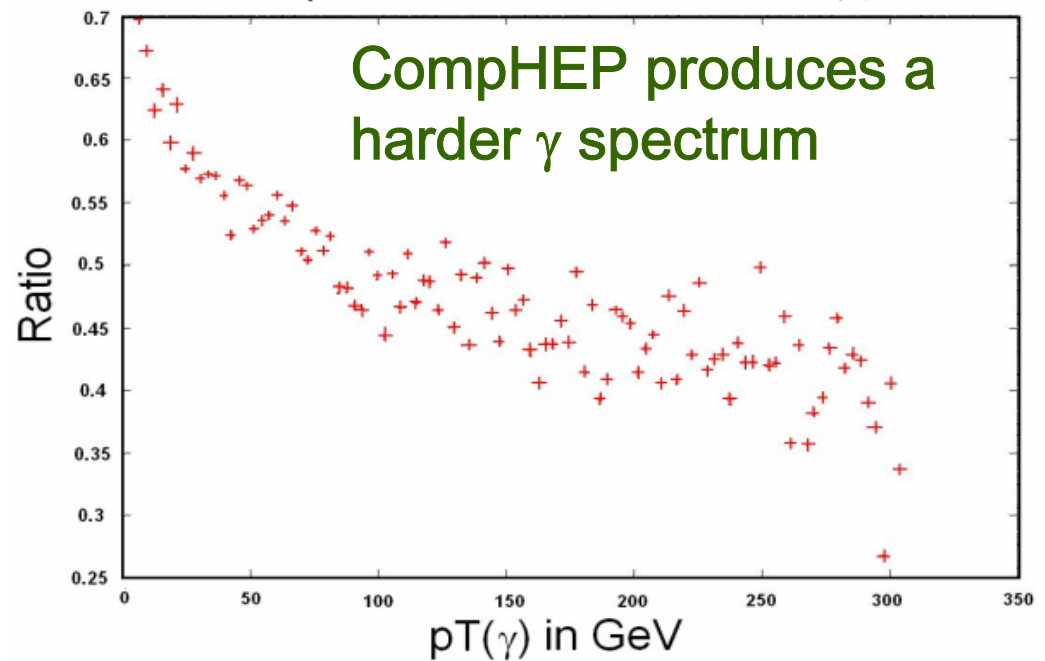


## Analyses Continued :

(b) When  $m_\pi < \Delta m < \sim 1$  GeV the chargino decays to soft hadrons which we tag by a hard photon. A full matrix element calculation is important here...



PYTHIA  $\sigma$  / CompHEP  $\sigma$  for associated hard  $\gamma$  production



(c) For larger  $\Delta m$ , we look for chargino decays through real or virtual W's or through smuons which lead to  $(4j/jj + \mu/\mu\mu) +$  missing E final states. There are multiple sub-analyses here depending on the specific final state and W virtuality.

Now for some results.....

# Sample Analysis Cuts : Selectrons

As already mentioned above, we study the channel

$$\bar{e}^+ \bar{e}^- \rightarrow e^+ e^- \tilde{\chi}_1^0 \tilde{\chi}_1^0, \quad (4.2)$$

that is, the signature is an electron pair plus missing energy. We demand:

1. Exactly two leptons, identified as an electron and a positron, in the event.  
This cuts out SM background where for example both  $Z$ s decay leptonically.
2.  $E_{\text{vis}} < 1 \text{ GeV}$  for  $|\cos \theta| \geq 0.9$   
This is to cut down the main SM backgrounds from  $W$ s and beam-/bremsstrahlung that produce leptons predominantly along the beam axis.
3.  $E_{\text{vis}} < 0.4\sqrt{s}$  in the forward hemisphere.  
The forward hemisphere is defined as the hemisphere around the thrust axis that has more visible energy. (In this case we only have 2 visible particles, so this amounts to taking the highest energy of one of the particles.)  
The SUSY signal has missing energy in both hemispheres, whereas SM  $e^+e^-$  production via  $Z$ -pairs has missing energy only in one of the hemispheres, because the other  $Z$  decays into neutrinos in the other hemisphere.
4.  $\cos \theta > -0.96$  for the reconstructed electron-positron pair.  
Since SUSY has a lot of missing  $E_T$ , the SUSY-produced pair will not be back-to-back, in contrast to the SM background events.
5. We demand that the visible transverse momentum, or equivalently, the transverse momentum of the electron-positron pair,  $p_{T,\text{vis}} = p_T^{e^+e^-} > 0.04\sqrt{s}$ .  
This cut is to reduce the  $\gamma\gamma$  and  $e^\pm\gamma$  background which has mostly low  $p_T$ .
6. Acoplanarity angle  $\Delta\phi^{e^+e^-} > 40$  degrees  
In our case, since we demand two electron candidates, the acoplanarity angle is equivalent to  $\pi$  minus the angle between the electron  $p_{T,e}$ ,  $\Delta\phi^{e^+e^-} = \pi - \theta_T$ ,

Minimal quality cuts applied

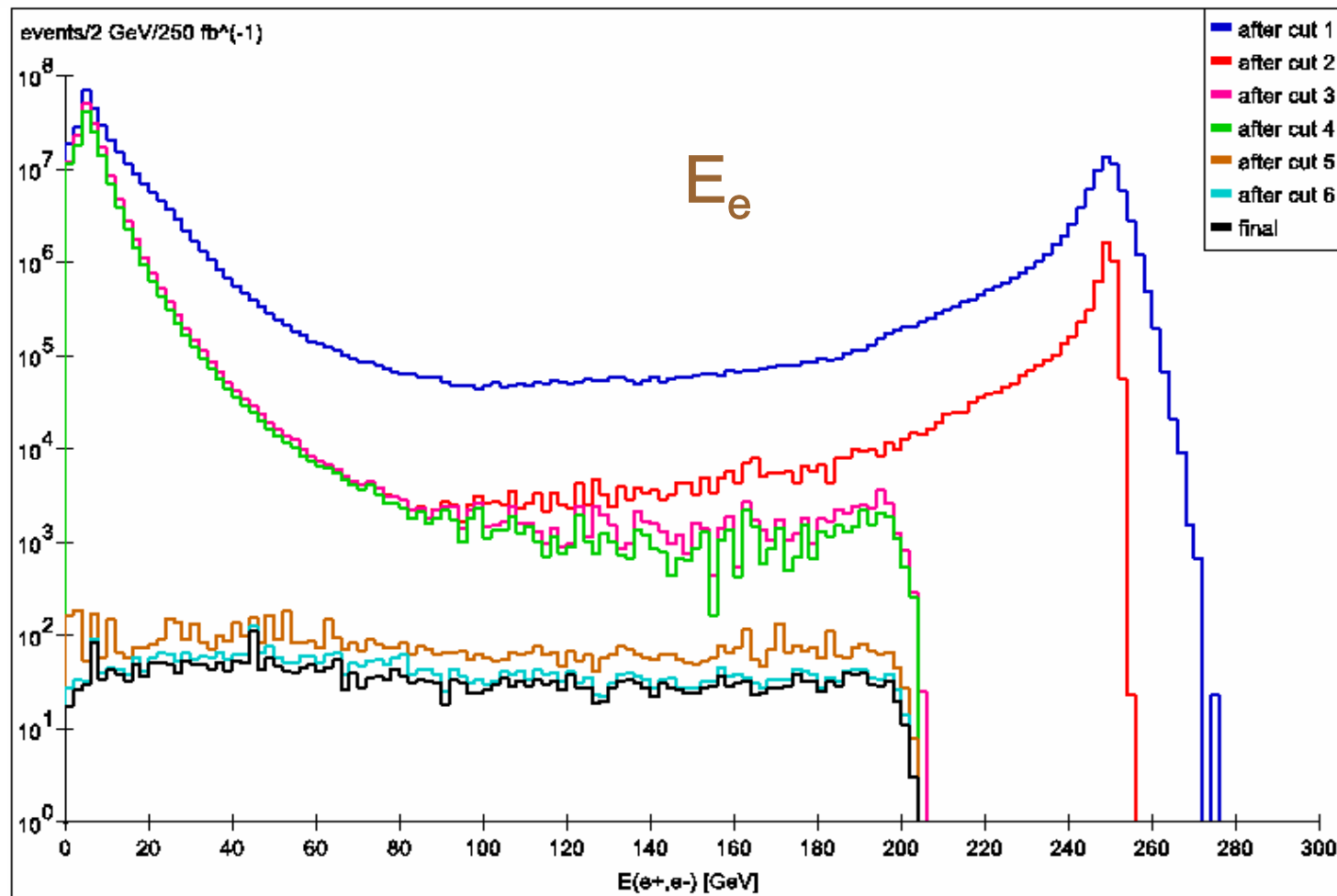
# Sample Analysis Cuts : Selectrons (cont.)

which translates the above requirement to a restriction of the transverse angle  $\cos\theta_T > 0.94$ .

This cuts out a lot of  $W$ -pair and  $\gamma\gamma$ -background which tends to be more back-to-back.

7.  $M_{e^+e^-} < M_Z - 5 \text{ GeV}$  or  $M_{e^+e^-} > M_Z + 5 \text{ GeV}$ .

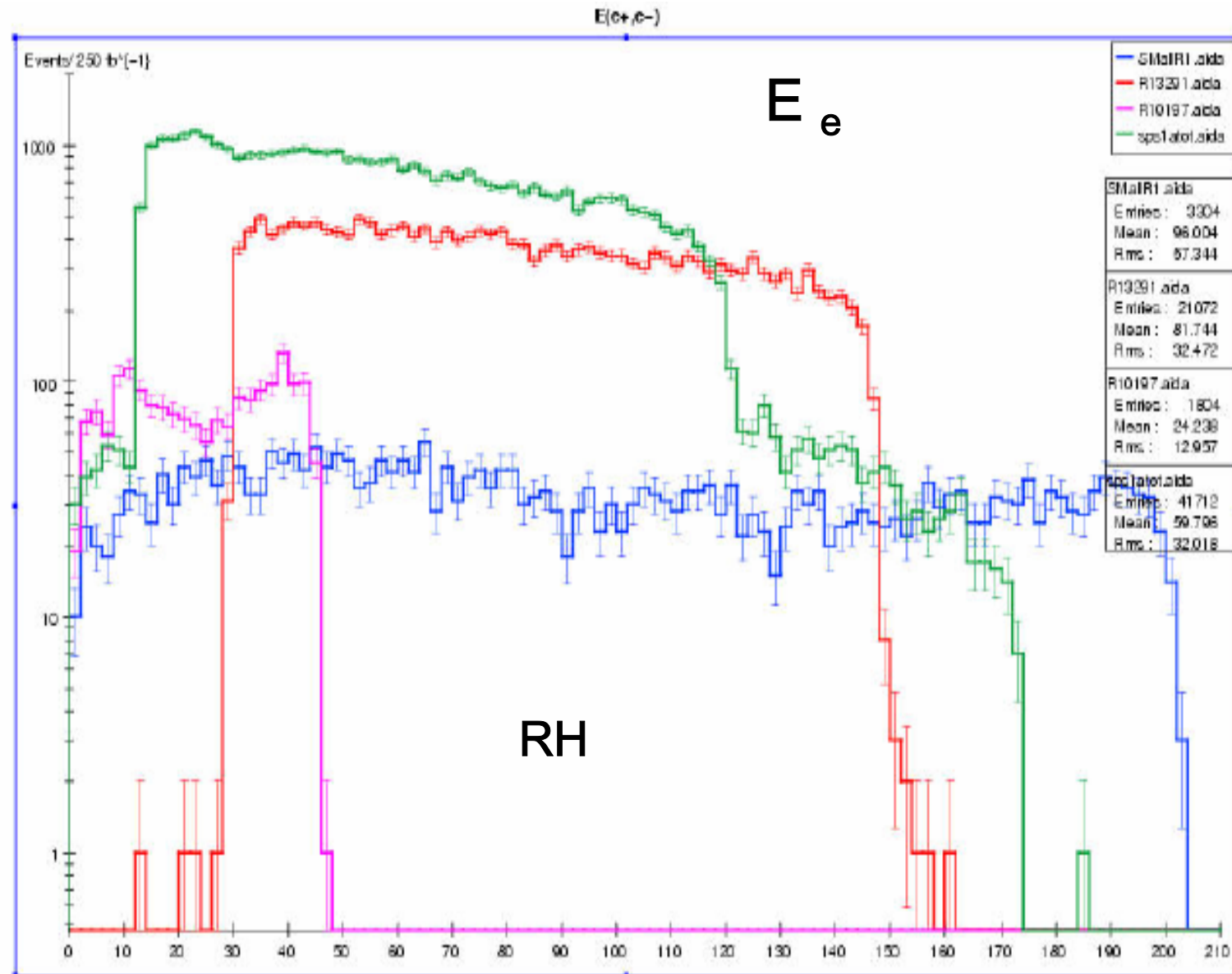
This is to cut out events from  $Z$ s, that is,  $e^+e^- \rightarrow ZZ \rightarrow e^+e^- \nu\bar{\nu}$ .



# Selectron Example: Good S/B here...

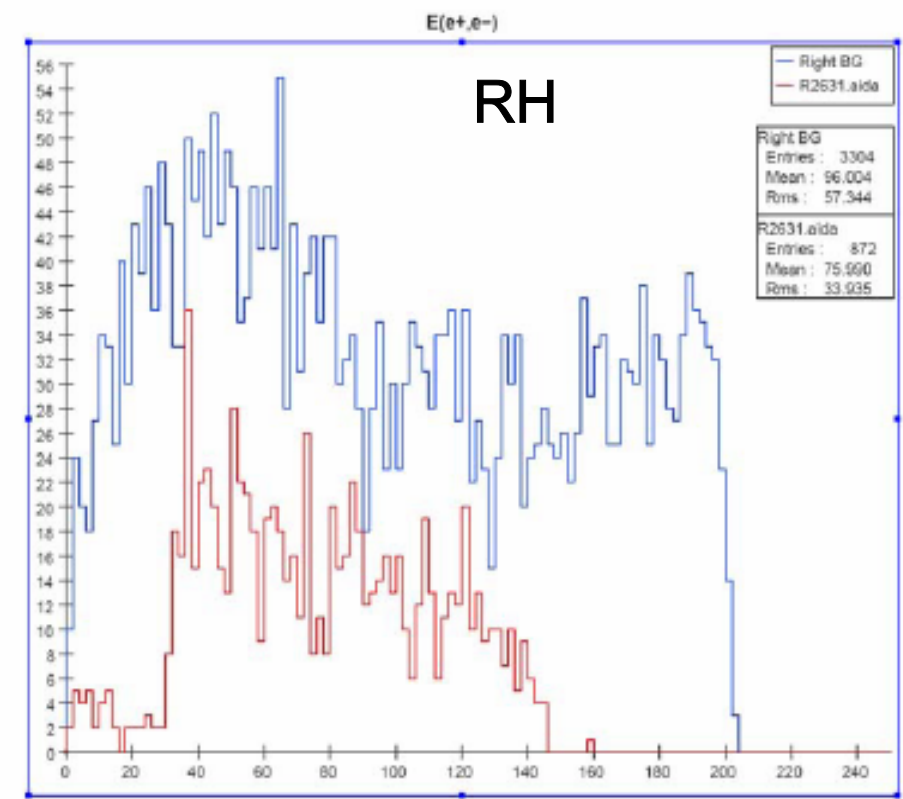
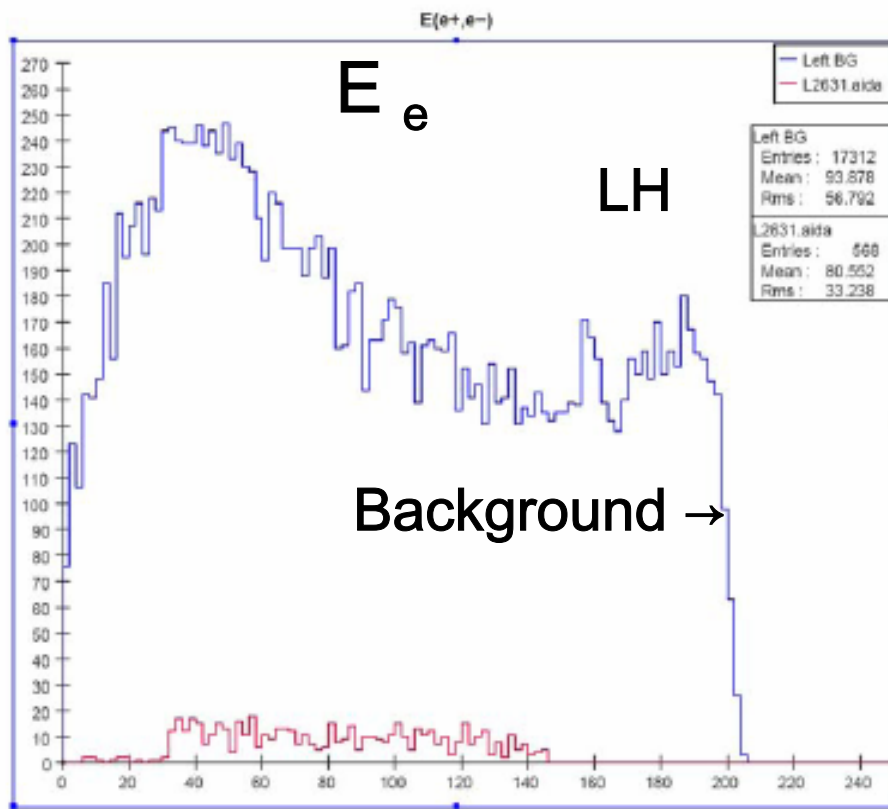
(note log scale)

- Model 13291:
  - Smuon Masses
    - L: 968.63 GeV
    - R: 187.02 GeV
  - LSP Mass: 101.16 GeV
- Model 10197:
  - Selectron Masses
    - L: 794.92 GeV
    - R: 170.88 GeV
  - LSP Mass: 151.93 GeV
- SPS1A:
  - Selectron Masses
    - L: 202.14 GeV
    - R: 142.97 GeV
  - LSP Mass: 96.05 GeV



However, sometimes the signal is buried and things are not as good:

Note the scale difference in RH vs LH



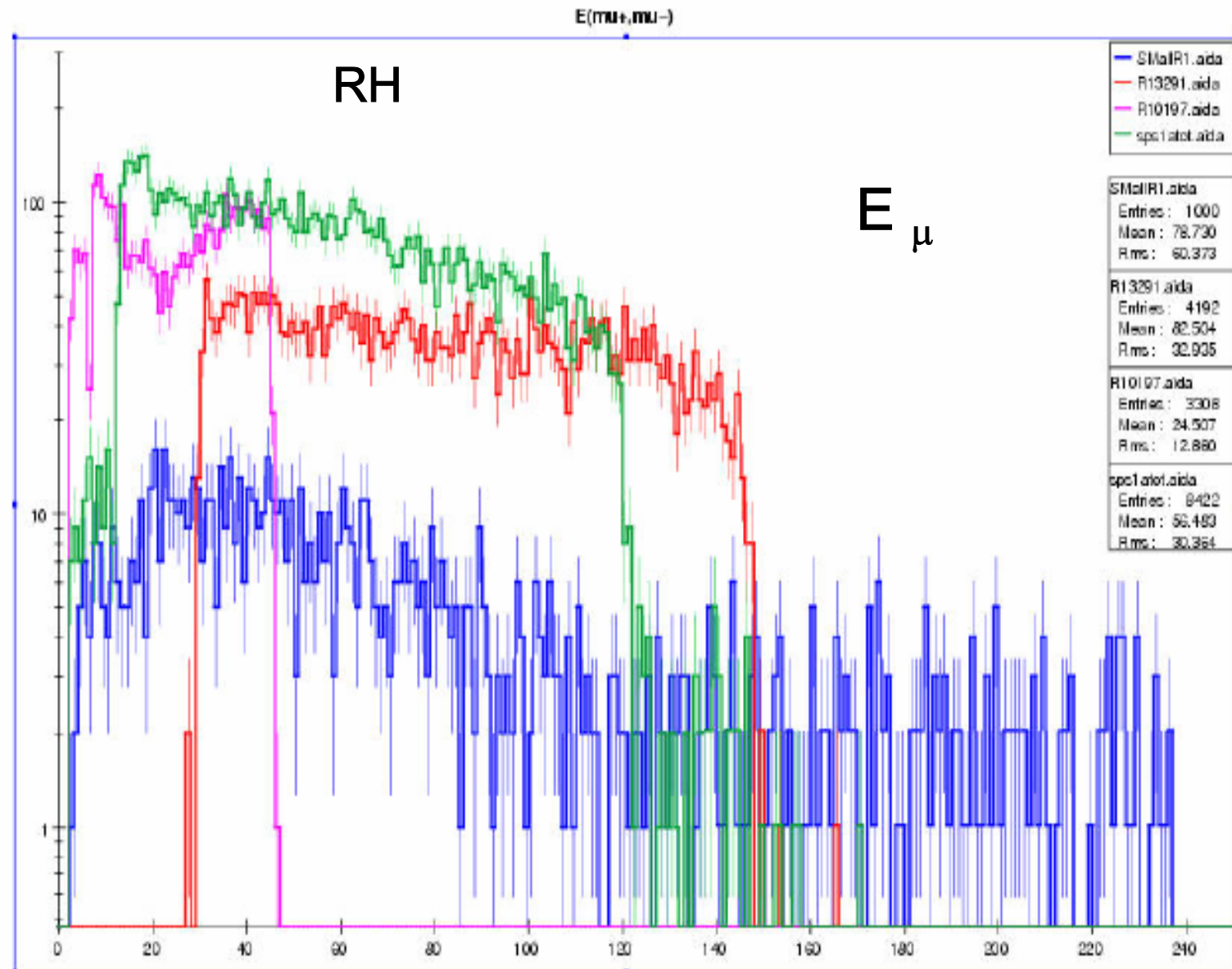
- Selectron signal from model 2631 is totally invisible for left-handed polarization, marginally visible for right-handed polarization

RH almost always gives best S/B...

# Smuon Example: Good S/B here

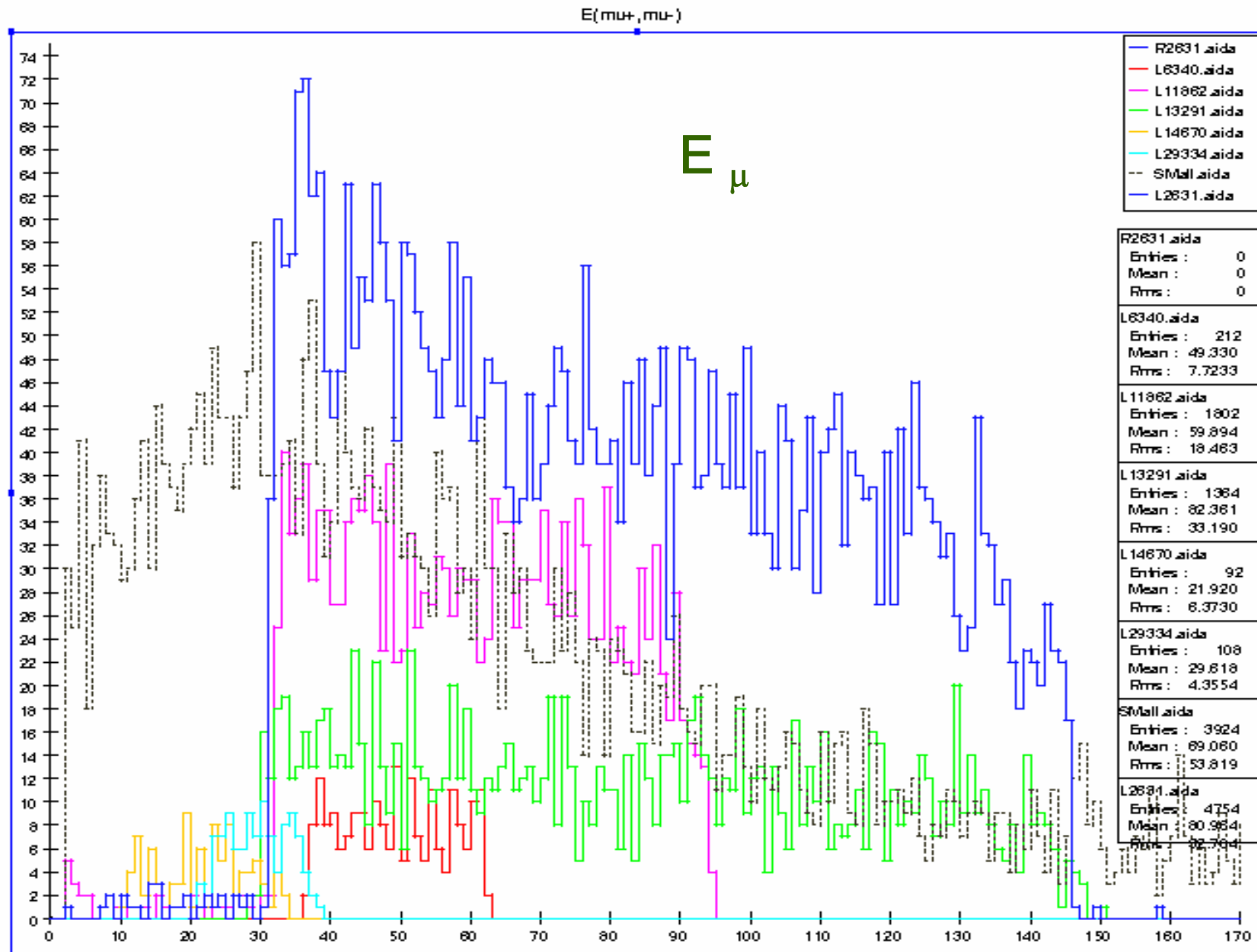
Generally very clean !

- Model 13291:
  - Smuon Masses
    - L: 968.63 GeV
    - R: 187.02 GeV
  - LSP Mass: 101.16 GeV
- Model 10197:
  - Smuon Masses
    - L: 794.92 GeV
    - R: 170.88 GeV
  - LSP Mass: 151.93 GeV
- SPS1A:
  - L: 202.14 GeV
  - R: 142.97 GeV
  - LSP Mass: 96.05 GeV



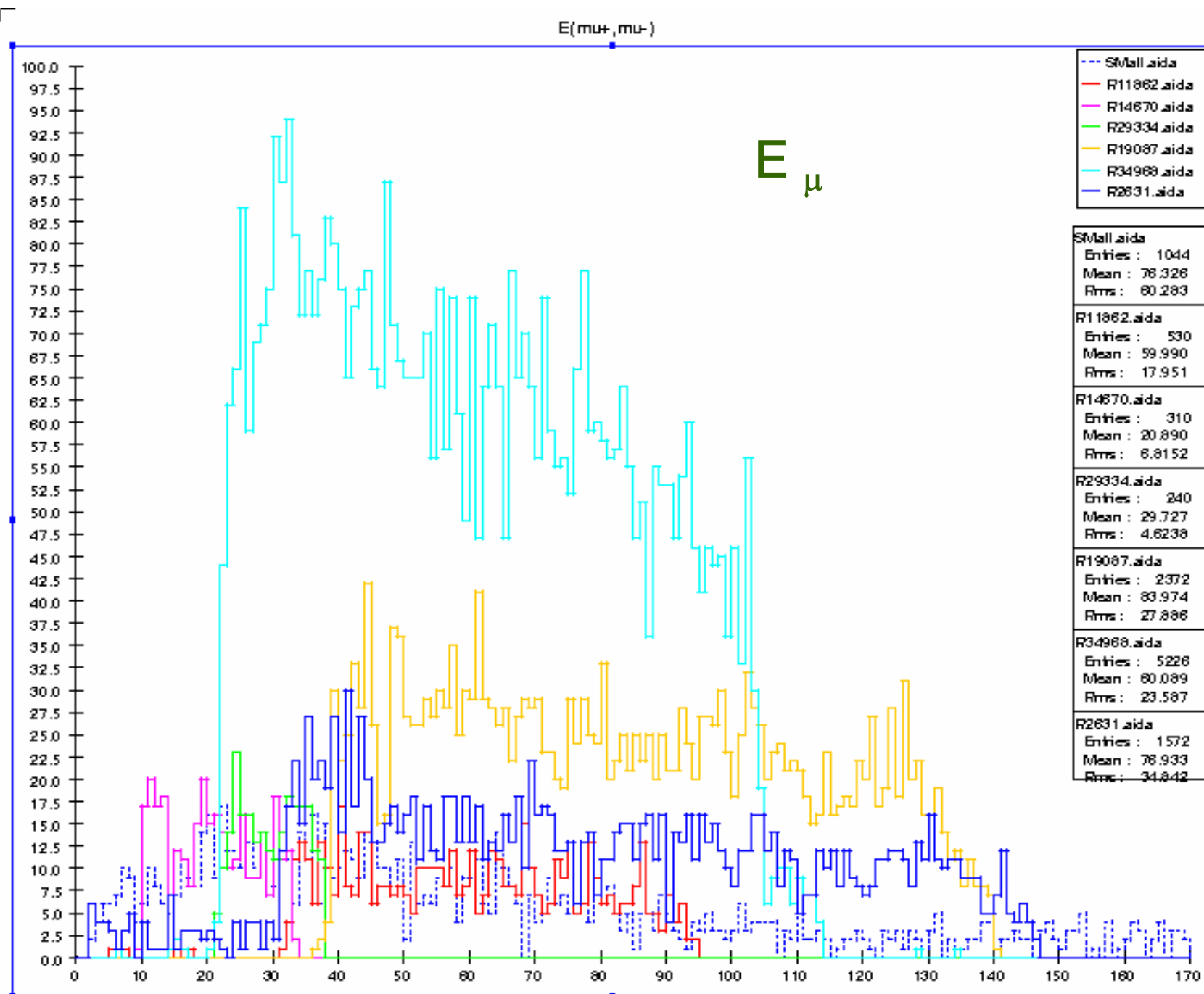
However... some models are more difficult to see...

LH Polarization



Note the event rates on these plots.....

RH Polarization



More smuons? Here are 6 models passing the smuon search criteria that are NOT smuons but feed-down from other SUSY particles...note the different spectrum structure.

$E(\mu^+, \mu^-)$

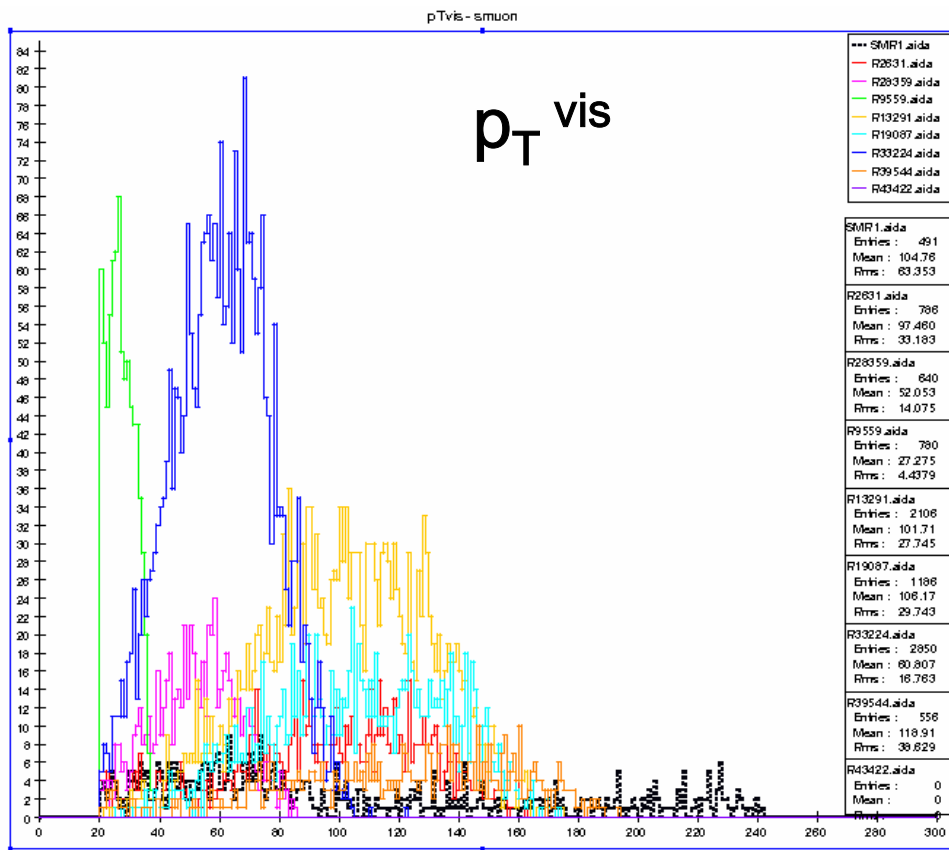
$E_\mu$

- mixR1.aida
- R8006.aida
- R12843.aida
- R14343.aida
- R15898.aida
- R27075.aida
- R39331.aida

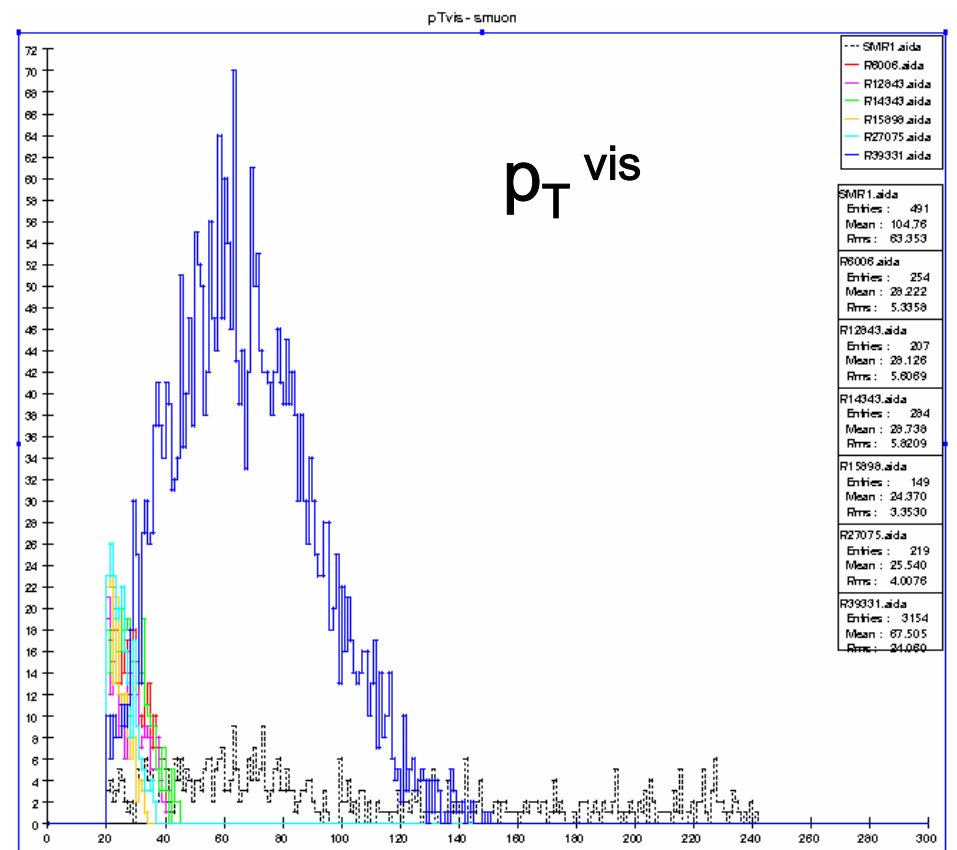
mixR1.aida	Entries : 960	Mean : 74.572	Rms : 58.887
R8006.aida	Entries : 508	Mean : 15.716	Rms : 7.5239
R12843.aida	Entries : 414	Mean : 16.254	Rms : 8.2713
R14343.aida	Entries : 968	Mean : 16.301	Rms : 7.8241
R15898.aida	Entries : 298	Mean : 13.308	Rms : 5.8917
R27075.aida	Entries : 438	Mean : 14.252	Rms : 6.7334
R39331.aida	Entries : 6308	Mean : 51.141	Rms : 23.298

## RH Polarization

This is a rather common feature.. here we have mostly charginos.. notice the shape difference with the previous plot..



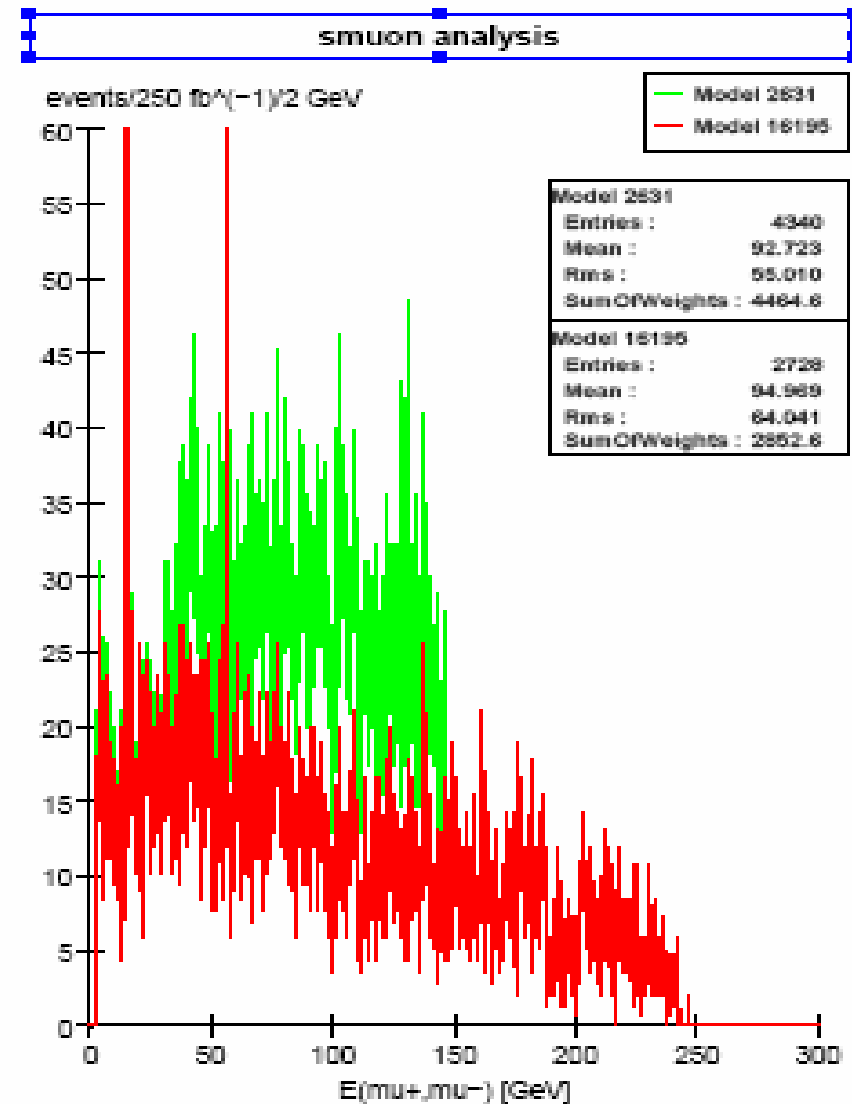
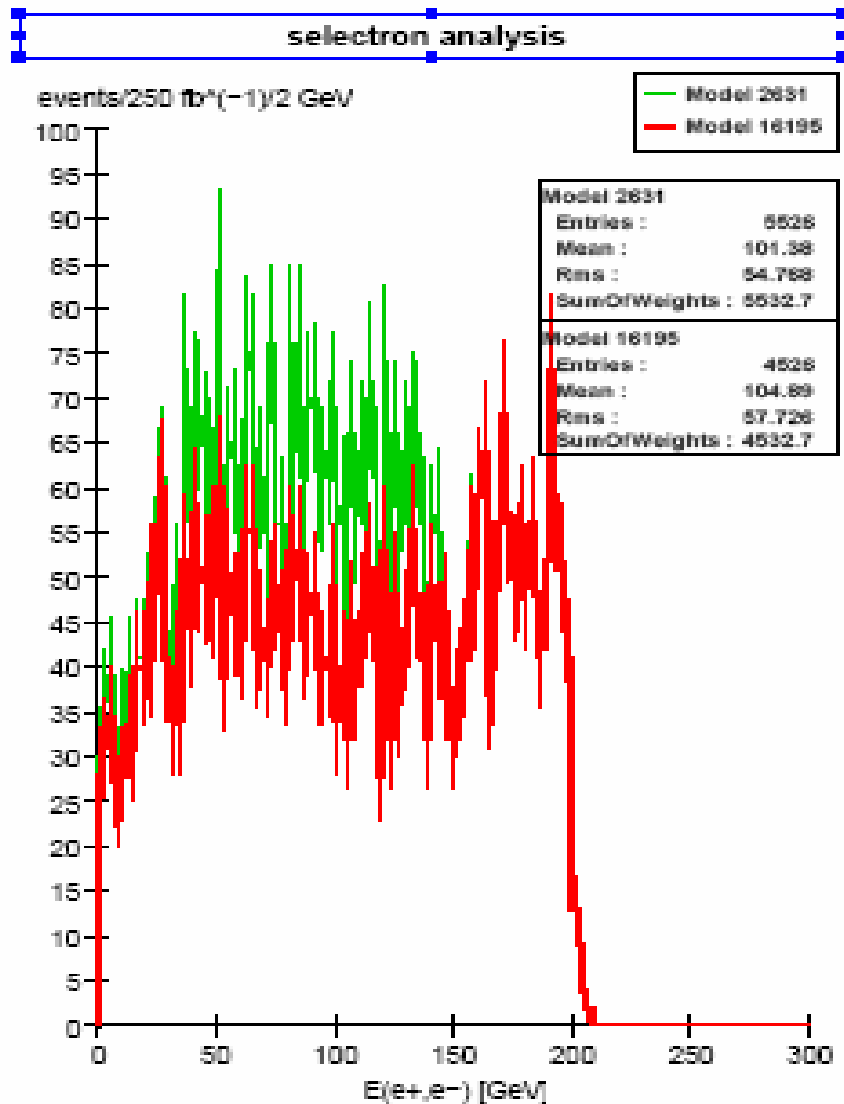
smuons



inos

$\mu$ 's from smuons are *usually* relatively high  $p_T$  since they arise from a two body decay (unless the smuon is not far in mass from the LSP) whereas those from decaying inos are *generally* from multibody modes and are far softer (unless on-shell W's are produced).

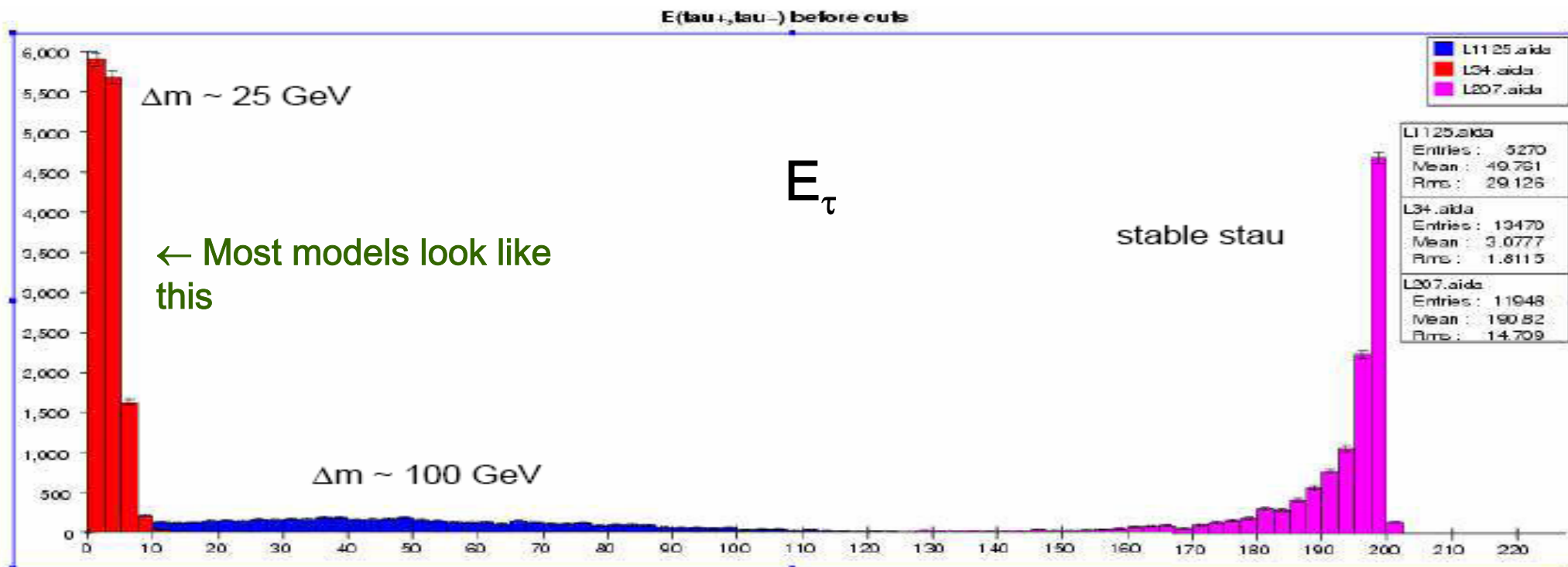
For some slepton cases it is RELATIVELY easy to distinguish models...



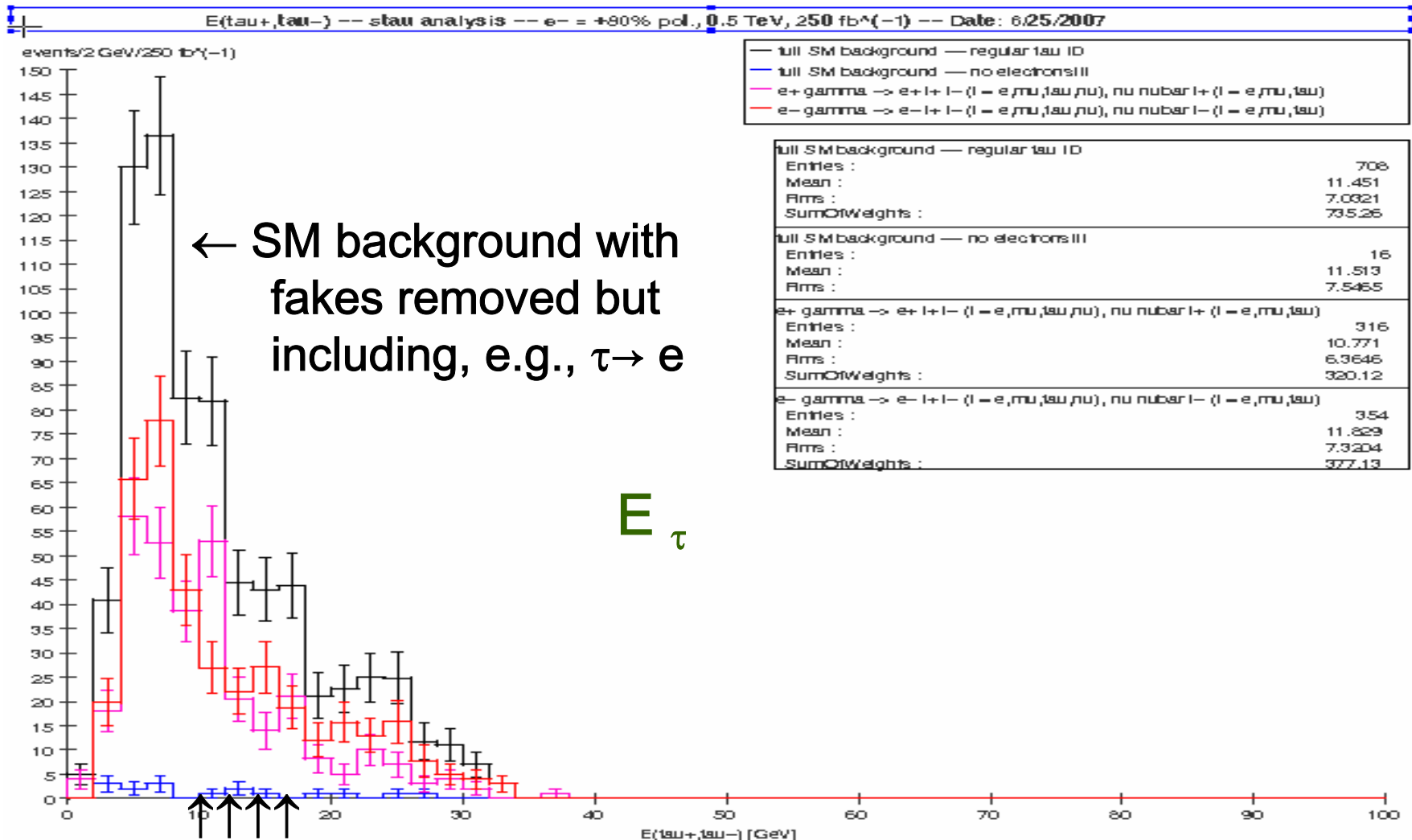
## Staus are generally somewhat harder :

For large  $\Delta m$ , rates are low while for smaller values the signal is all piled up at low jet energies..which is where the backgrounds are...

Also in some cases the stau is the lightest MSSM state and is 'stable'.



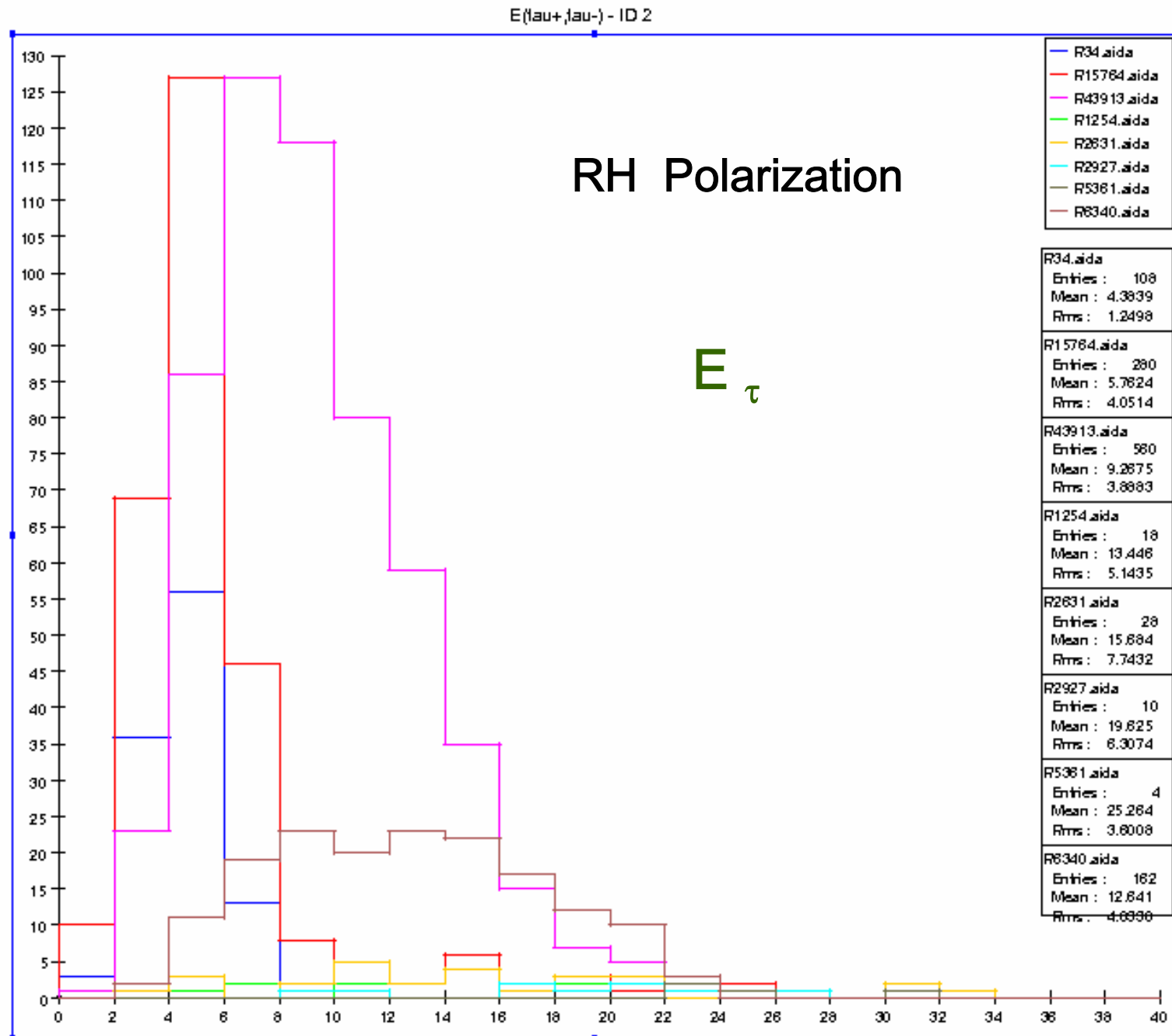
# Stau backgrounds are quite reasonable once one finds suitable tau ID cuts and removes leptons faking jets...



SM background (after removing events with electrons) !

However, not too many models yield a large enough signal...

↑



## ♠ Sneutrino pairs are kinematically accessible in 11/242 models

For the first two generations we have :

- (i) sneutrino  $\rightarrow \nu + \text{LSP}$  is invisible, but generally dominates X
- (ii) sneutrino  $\rightarrow W + \text{slepton} \rightarrow jj + \text{lepton} + \text{LSP}$  : not allowed on-shell X
- (iii) sneutrino  $\rightarrow \chi_1^+ + \text{lepton} \rightarrow jj + \text{lepton} + \text{LSP}$  : allowed in only one model and the resulting jets are rather soft..... X
- (iv) sneutrino  $\rightarrow \nu + \chi_2^0 \rightarrow jj + \text{missing E}$  : allowed only in one model and the jets are again too soft... X

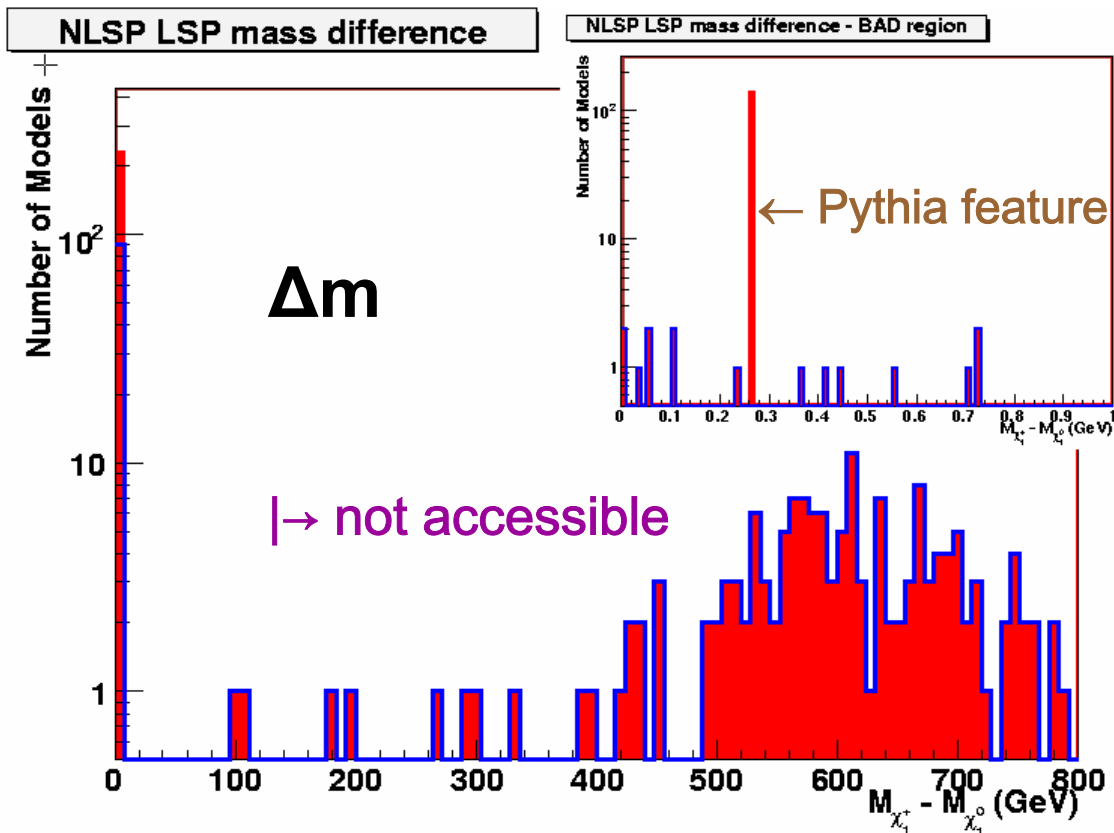
♣  $\rightarrow$  sneutrinos are not observable at 500 GeV in any model.....

...and tagging the sneutrino final state with a  $\gamma$  doesn't work either.

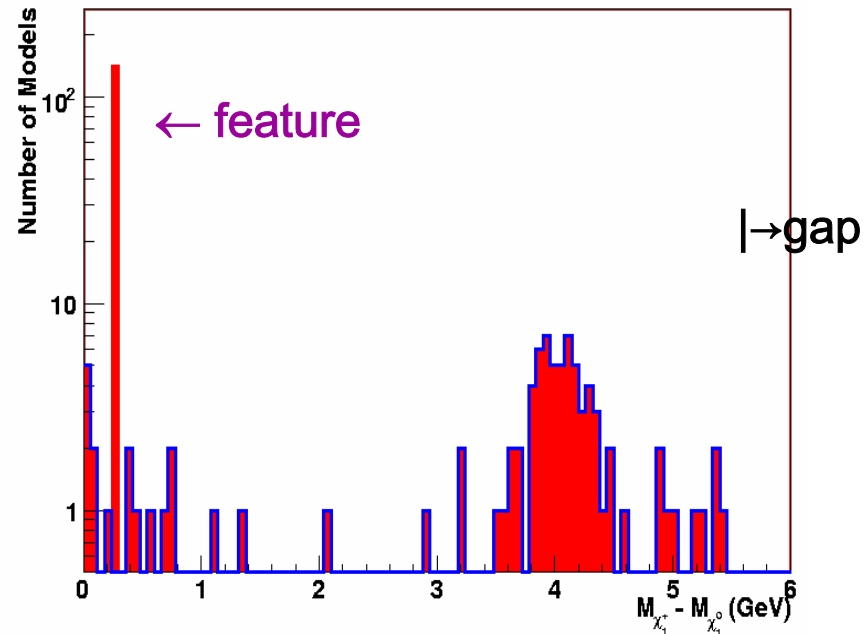
# Chargino Analyses:

Difficult spectrum

$\Delta m$  is mostly either very small (leading to difficult signatures) or too large (not kinematically accessible).



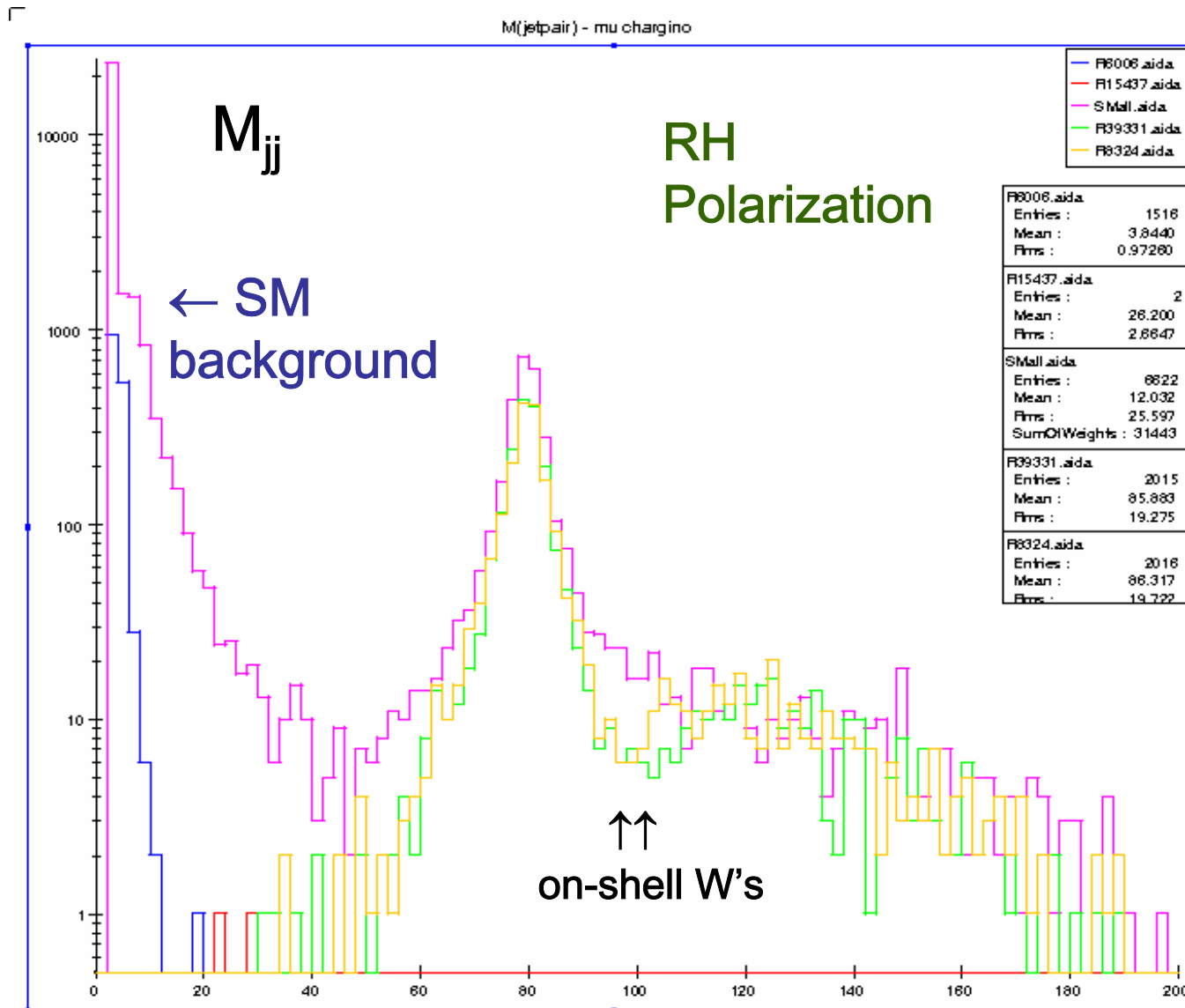
NLSP LSP mass difference



$\Delta m$  clusters in the few GeV mass region which has a lot of serious  $\gamma\gamma/\gamma e$ -induced backgrounds

# Charginos-- 2 jet+ muon+missing E Analysis : Dijet Mass

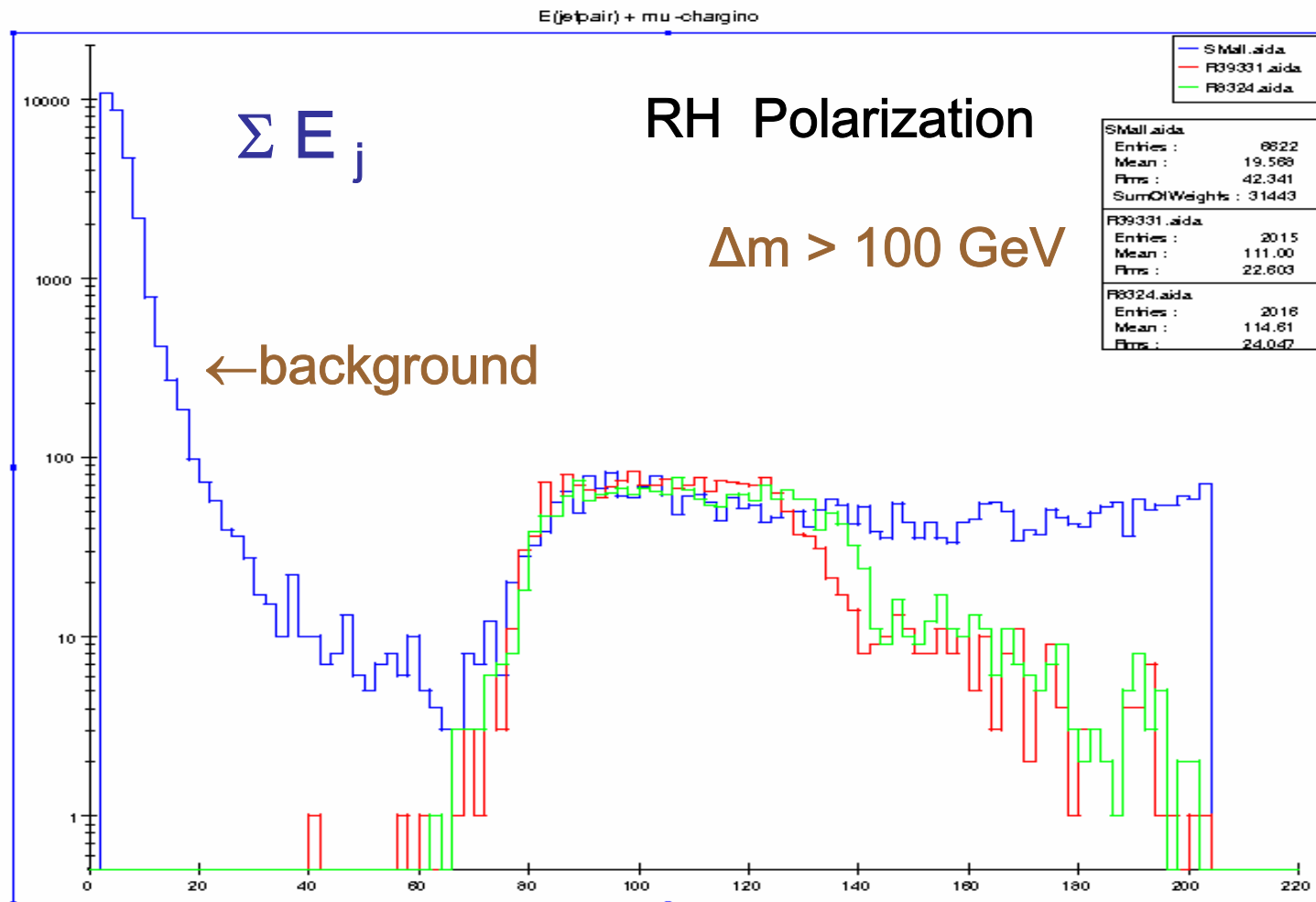
Some of the final state particles are much too soft in many of these models...



...except when  $\Delta m > M_W$

# Charginos--2 jet+ muon+missing E Analysis : Jet Pair Energy

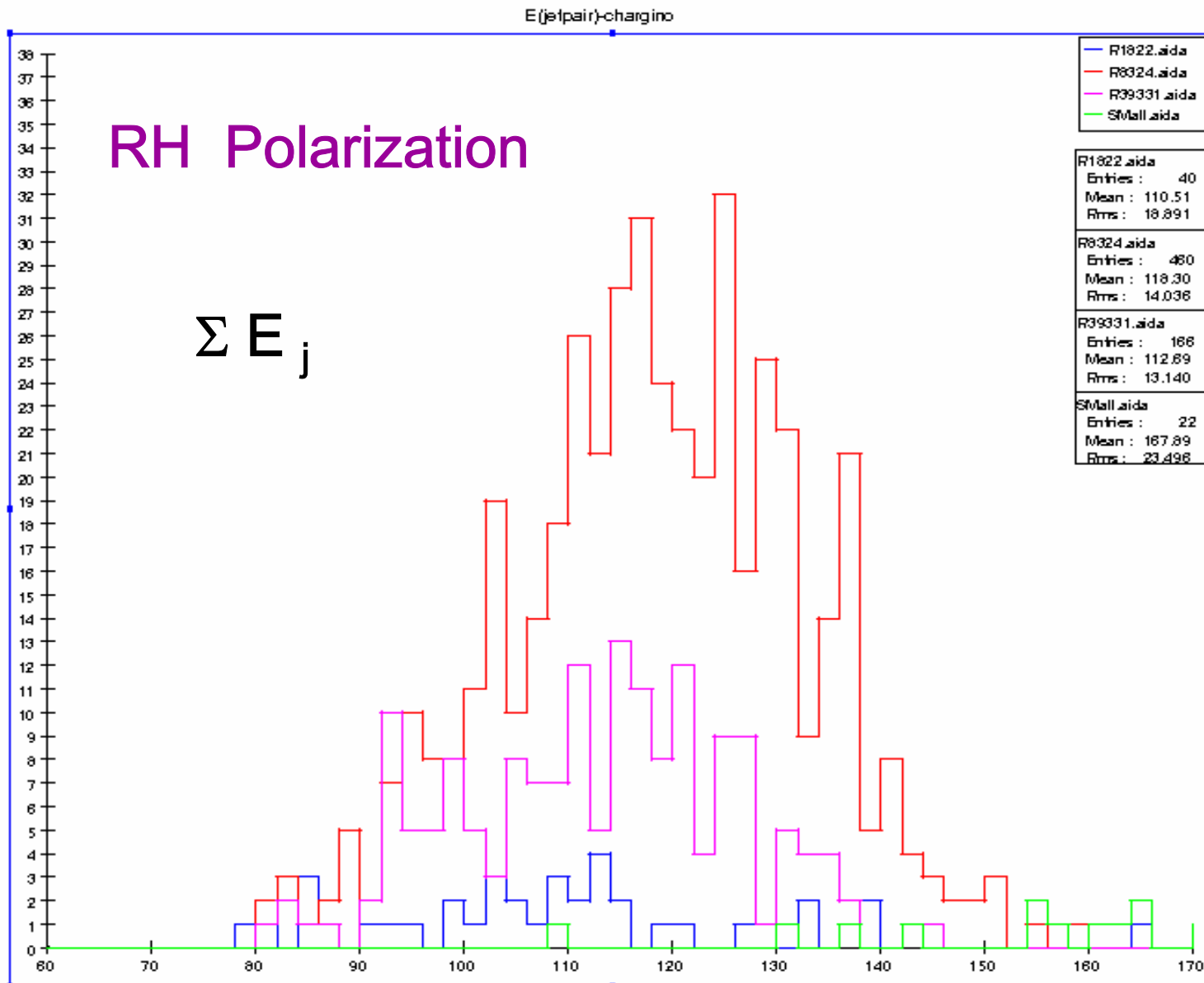
Signals are visible for on-shell W's as  $\Delta m$  is now large....



These models are rare...

# Chargino--4j + missing E analysis : Jet Pair Energy

Again, OK for the on-shell cases..

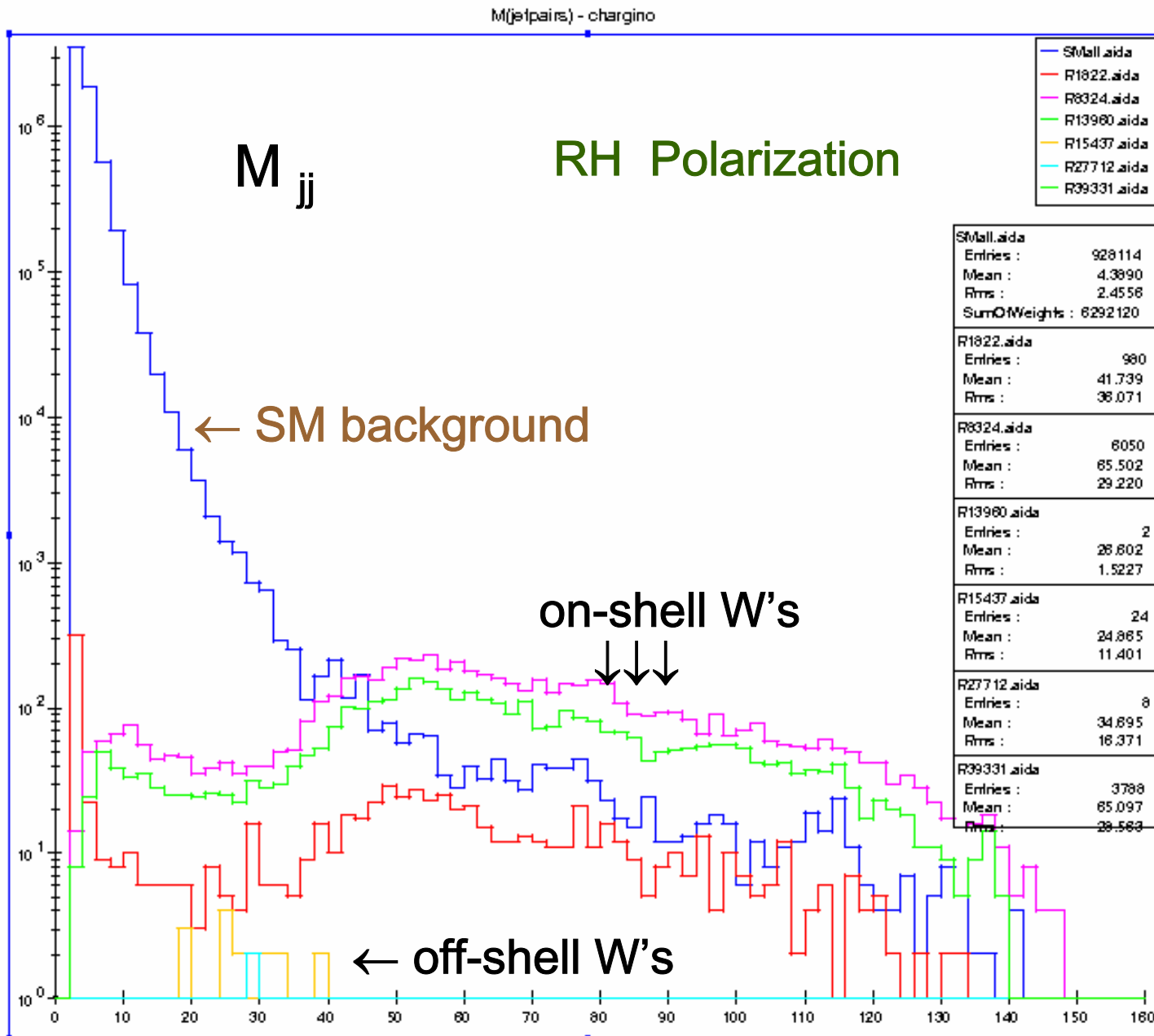


Model 39331  
 $\Delta m = 103.85$  GeV

Model 8324  
 $\Delta m = 108.23$  GeV

Model 1822  
 $\Delta m = 0.133$  GeV !!  
 $2\chi_2^0 \rightarrow 4j + \text{Missing}$

# Chargino--4j + missing E analysis (off-shell): Jet Pair Mass

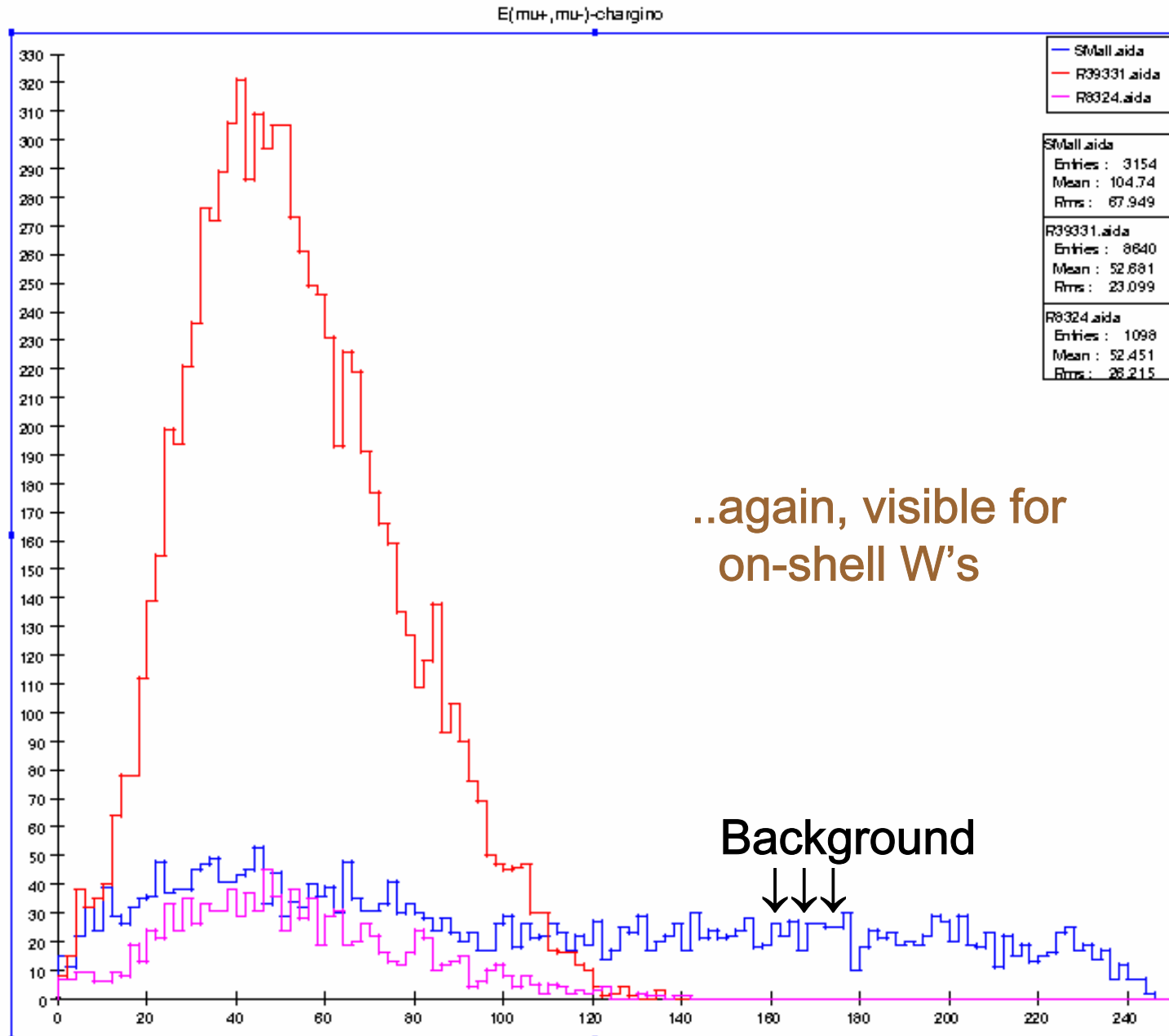


Again very difficult when off-shell W's are produced ....

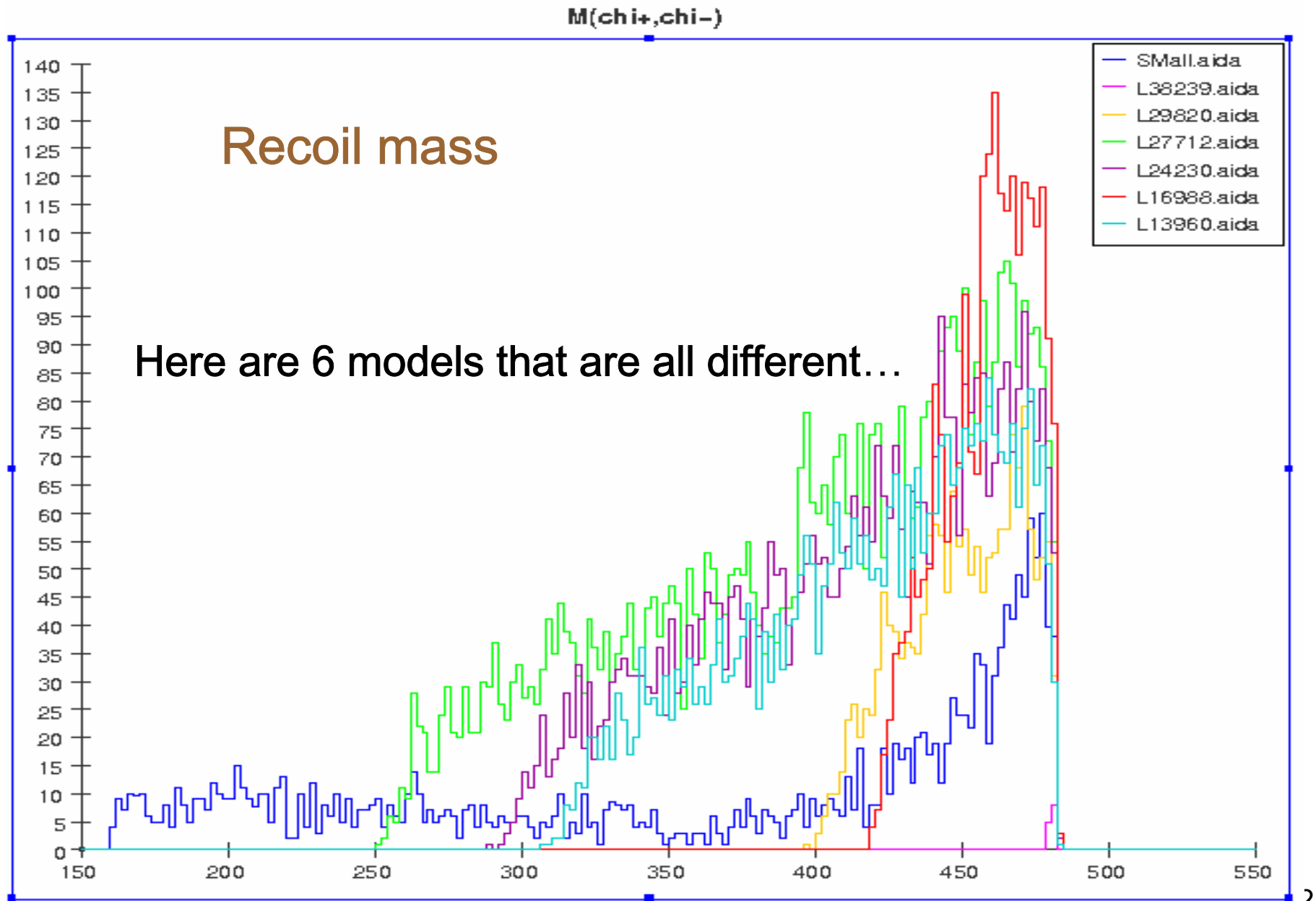
Model 1822 again,  $2\chi_2^0$  production

# Chargino-- $2\mu$ + missing E analysis : Muon Energy Analysis

┌



# Small $\Delta m \sim 1$ GeV, Charginos: soft hadrons + photon tag



# Long-lived Chargino Analysis

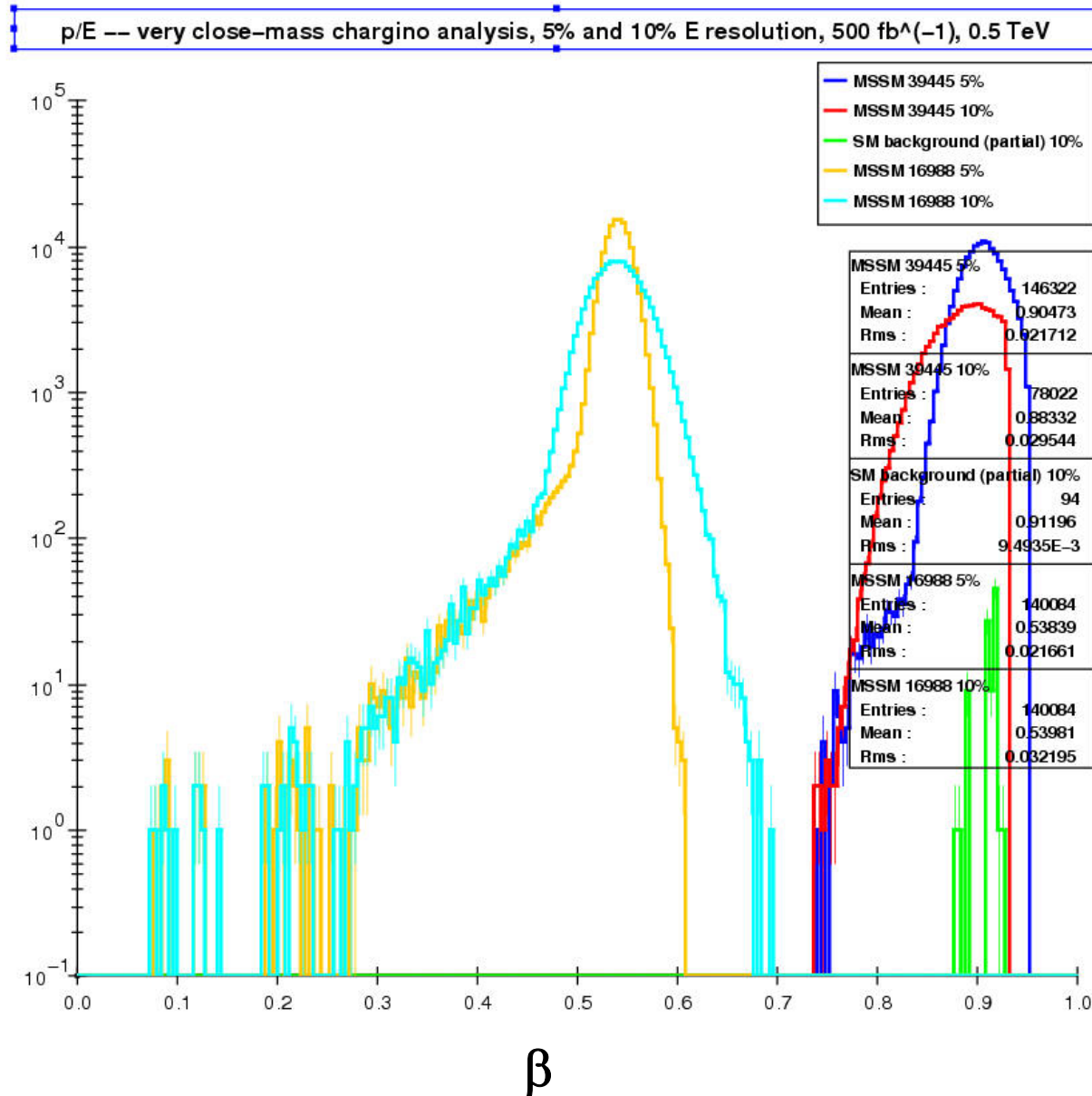
A surprisingly large number of our models have these particles

1. 2 massive, charged tracks only
2. no tracks within  $< 100$  mrad
3.  $\frac{p}{E} < 0.93$  for both (since they were not seen at LEP II)
4.  $\sum_{i=1}^2 E_i > 0.75\sqrt{s}$

These last two cuts kill any potential muon background. There should not be any background left (aside from detector fakes).

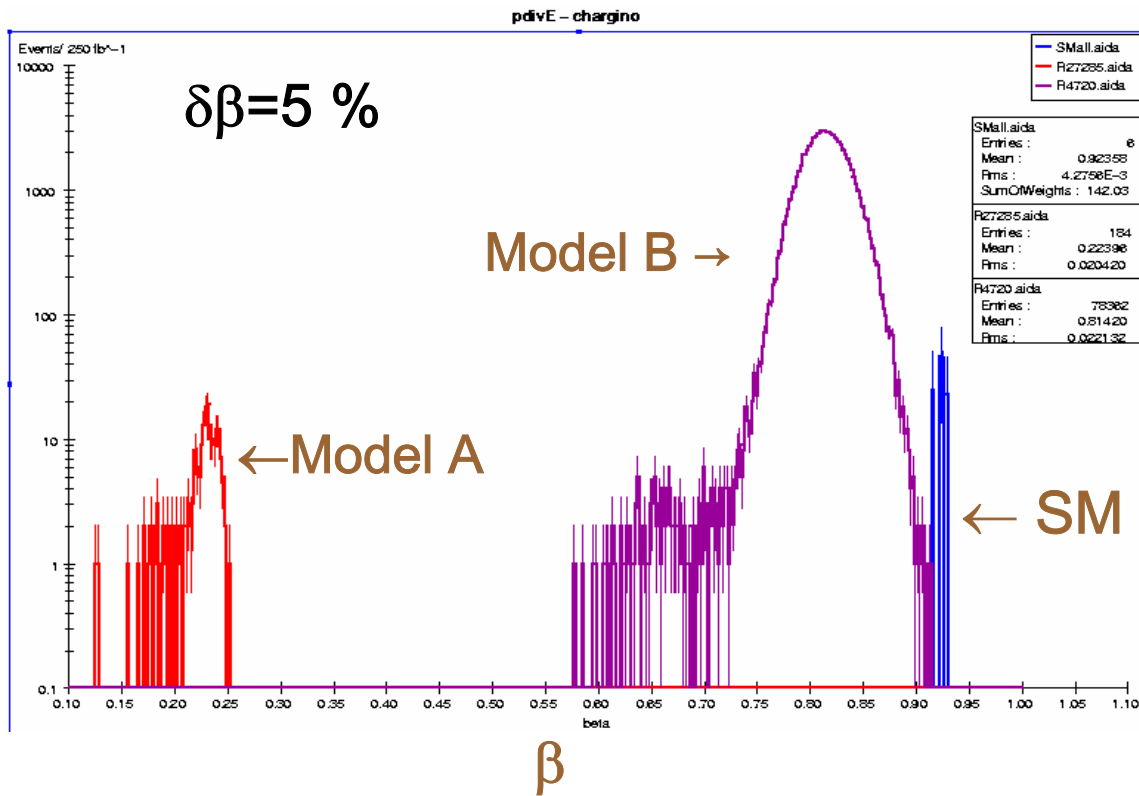
$\beta=p/E$  :  $p$  is determined by track curvature in the  $B$  field while  $E$  is determined by some other method (TOF or  $dE/dx$  not yet in vanilla lcsim)...we assume a resolution of  $\delta\beta=5(10)$  % in our analysis consistent with ILC detector models. (thanks to B. Schumm)

# Background & Signal for Close Mass Case #2

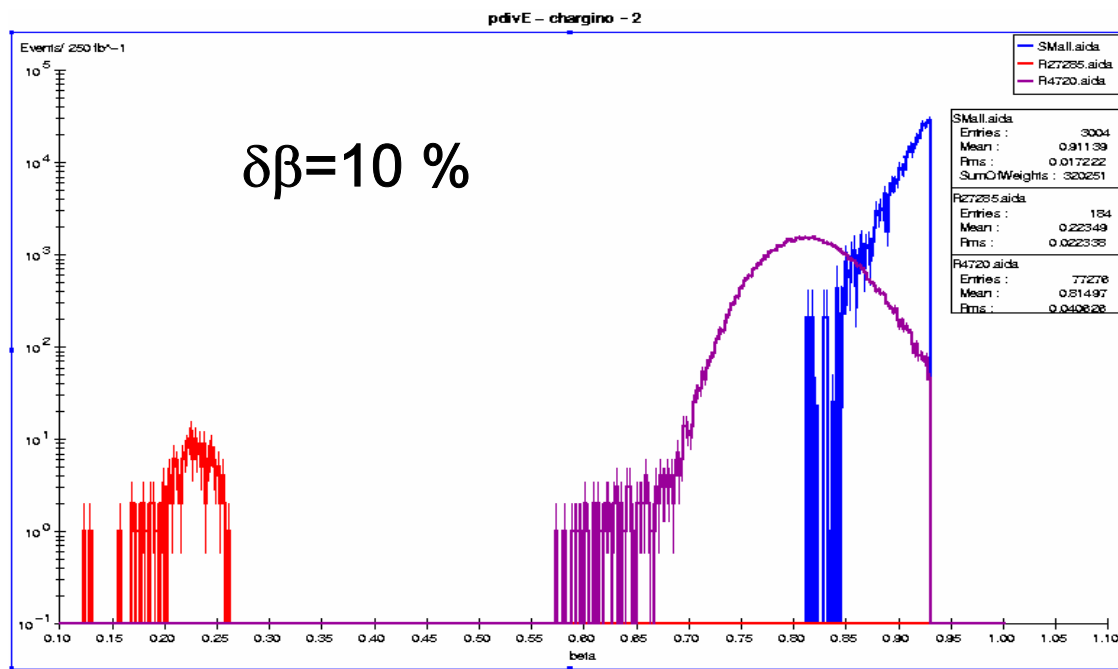


Looks pretty good!

Stable chargino  
Analysis

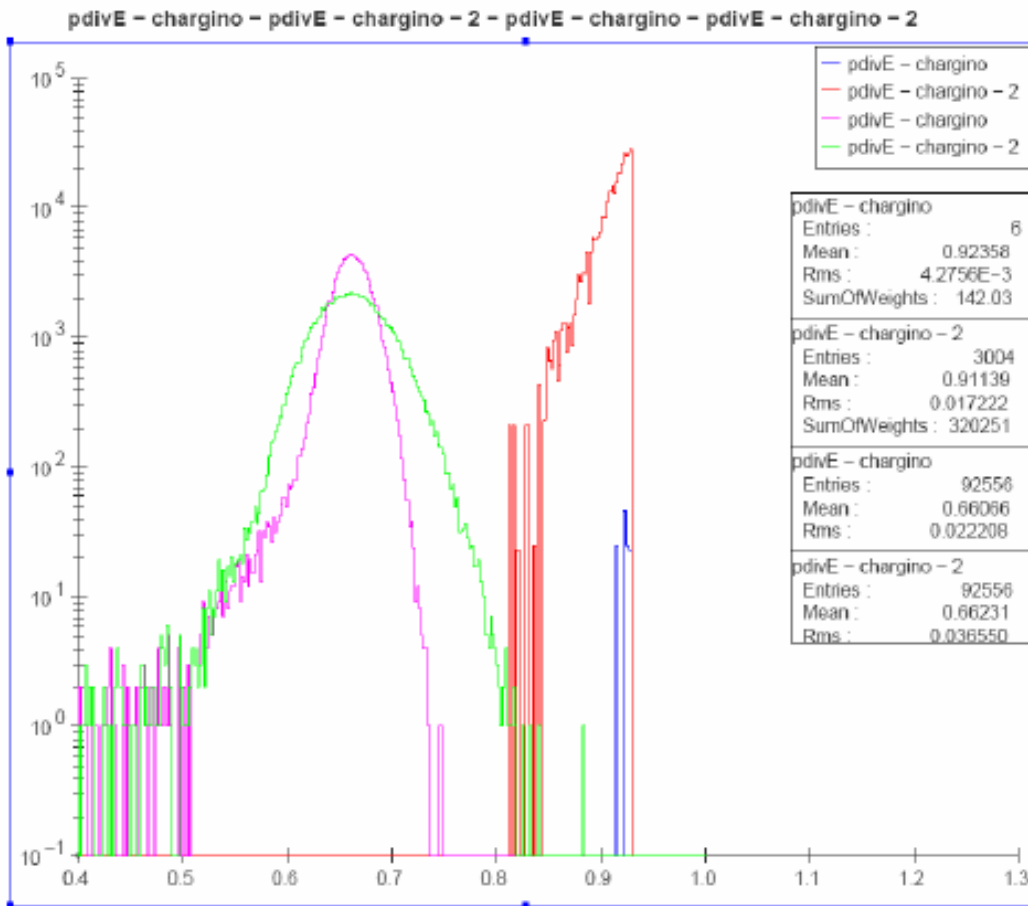


## Stable Particle Searches



These two models are clearly different for either velocity resolution choice.

# Long-lived Chargino Analysis (cont)



Signals and background for 80% right-handed electron polarization.

- **Model 39445:**  
Chargino Mass: 104.92 GeV  
 $\Delta m = 1.78$  MeV
- Easy discovery, measurement of chargino mass for either energy spread

**Some analyses are easy...**

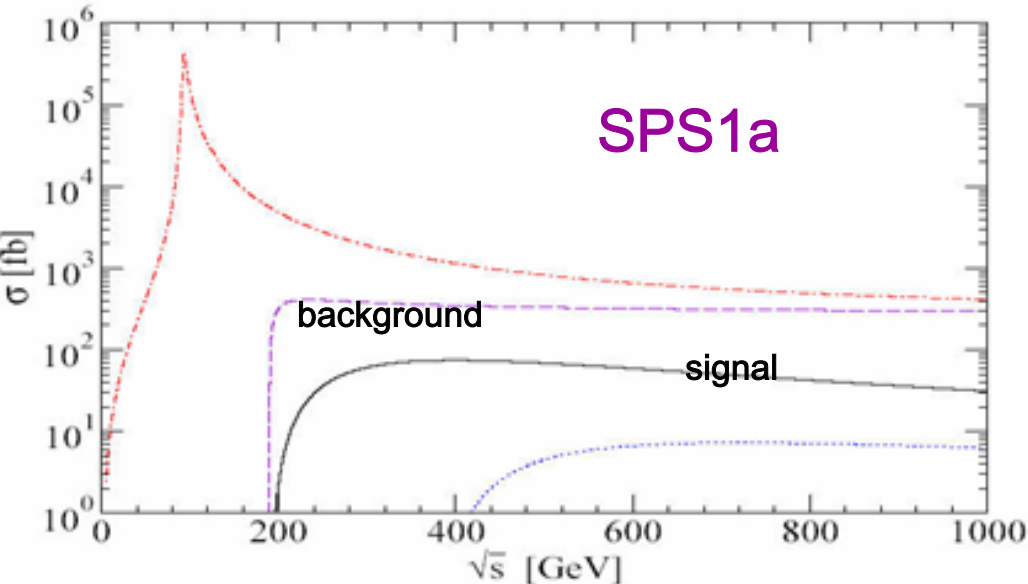
# Radiative Neutralino Production

$e^+e^- \rightarrow \chi_1^0\chi_1^0$  is *invisible* so we employ the  $\gamma$ -tag again  $e^+e^- \rightarrow \chi_1^0\chi_1^0 + \gamma$  which we calculate using CompHEP.....

## ANALYSIS CUTS AT 500 GeV

:

1. One  $\gamma$  and nothing else visible in the event
2.  $E_T^\gamma = E^\gamma \sin\theta^\gamma > 0.03 \sqrt{s}$ ,  $\theta^\gamma$  is  $\gamma$  angle w/ beam axis
3.  $\sin\theta^\gamma > 0.1$
4.  $E^\gamma < 160.0$  GeV (removes radiative return to the Z)
5. Use CompHEP to generate hard matrix element



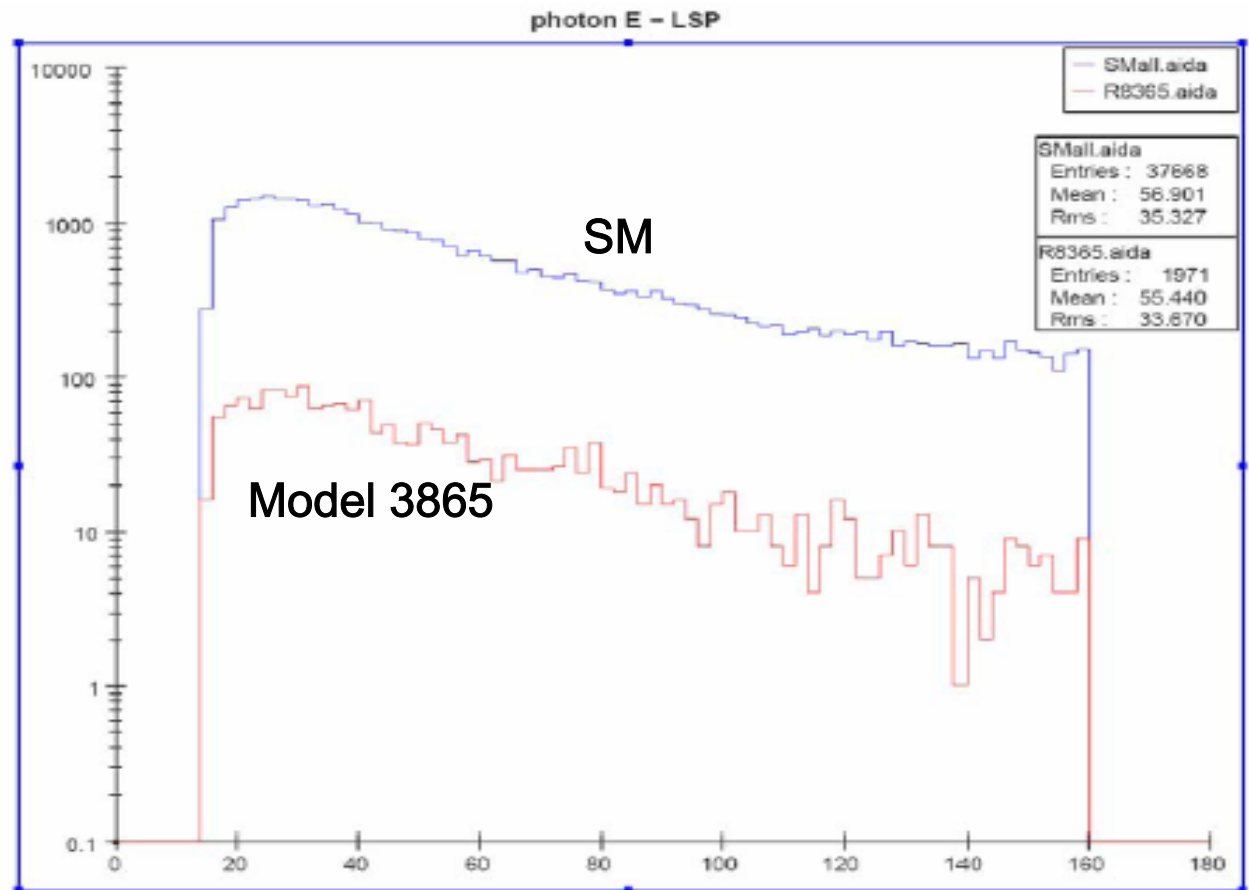
The signal is `big' for SPS1a but this is *not so* over the model space that we explore... SM backgrounds from  $e^+e^- \rightarrow \nu\nu\gamma(\gamma)$  are also very large and difficult to kill with standardized cuts

# Radiative Neutralino Production

This is a situation where positron polarization would be helpful with killing the backgrounds and increasing the signal....

This is the neutralino-only model with the largest signal cross section....

The background here is about 20x larger than the signal so these models look hopeless!!



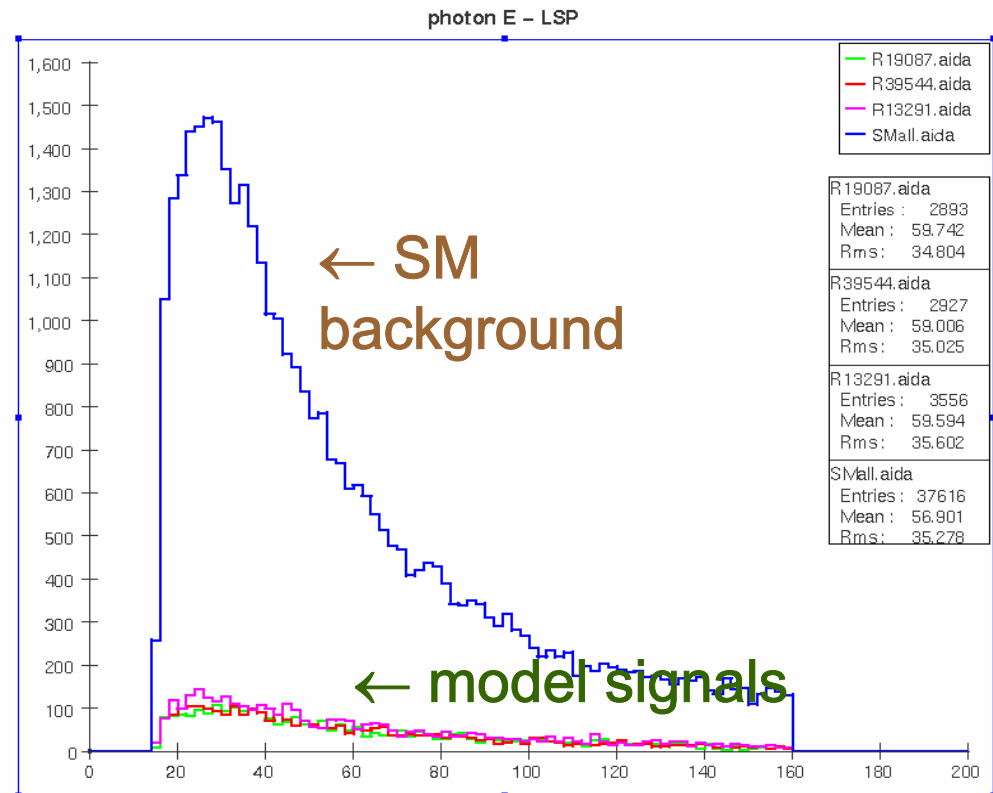
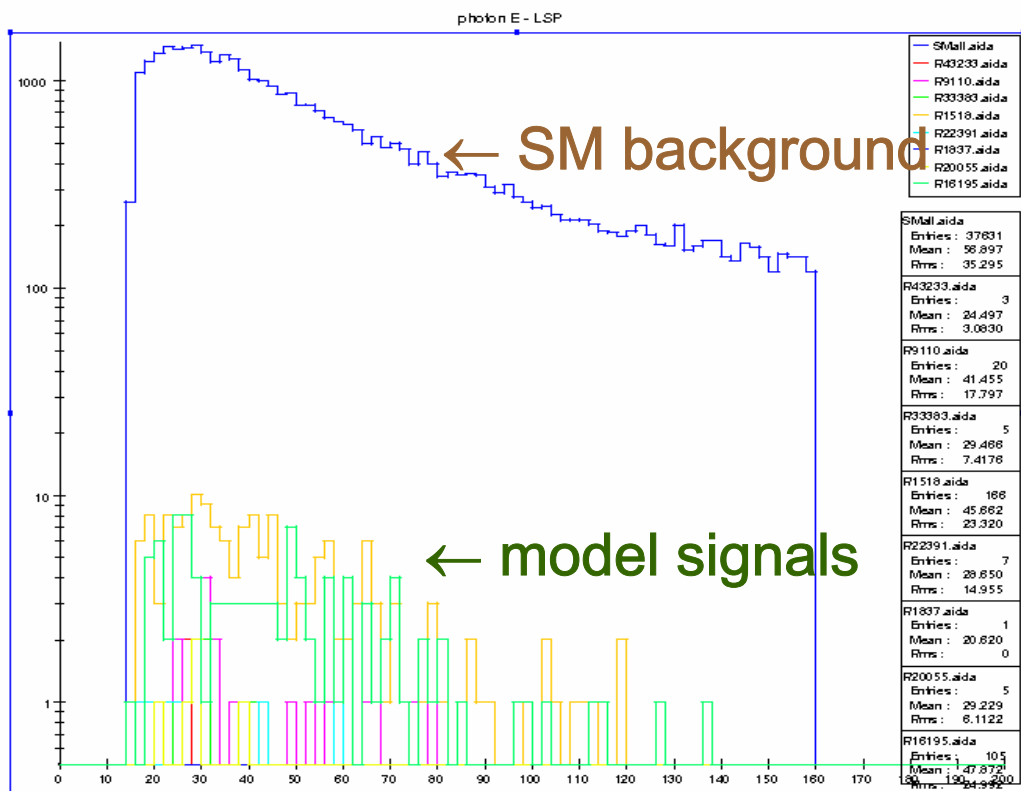
Signal and background for 80% right-handed electron polarization.

....the situation is much worse in all other model cases...

It is clear from this analysis that the LSP-pair final state remains invisible due to the very large SM backgrounds unless we do something different.

$E_\gamma$

RH Polarization



The largest contribution to the  $e^+e^- \rightarrow \nu\nu\gamma$  background is from graphs with a W-exchange coupling to a LH  $e^-$ , but this shows a strong polarization dependence,  $\sigma^B(e^-_L) \sim 50 \sigma^B(e^-_R)$ ....

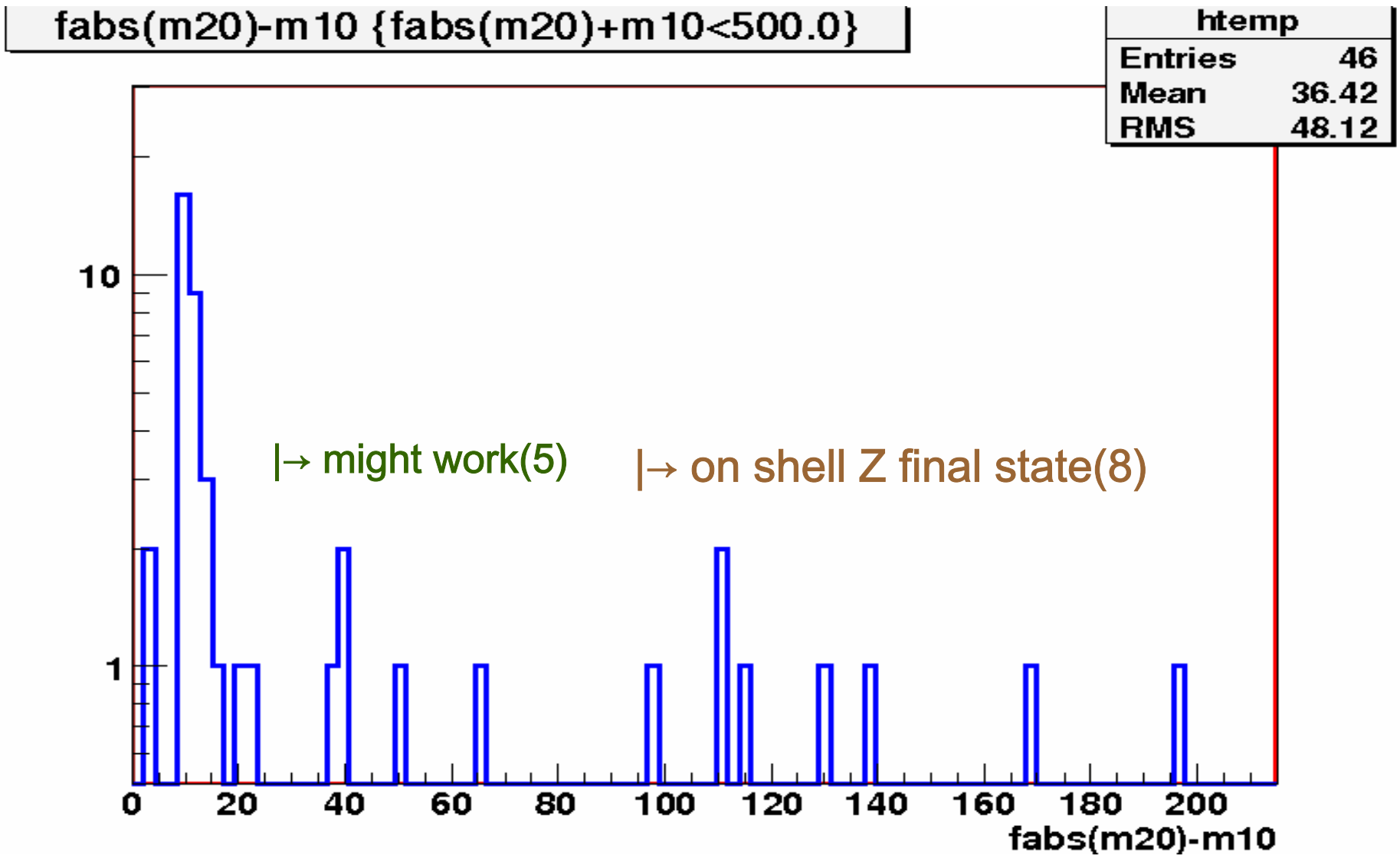
The best way to remove this background is with RH beam polarization and having both beams polarized is even *better*. For the signal, the models mostly cluster with either (i)  $\sigma^S_L \sim \sigma^S_R$  or (ii)  $\sigma^S_R \gg \sigma^S_L$ . This provides another good reason to have positron polarization. (hep-ph/0507011)

What does beam polarization ( $P_+ = 0.8$  +?) do compared to unpolarized beams?

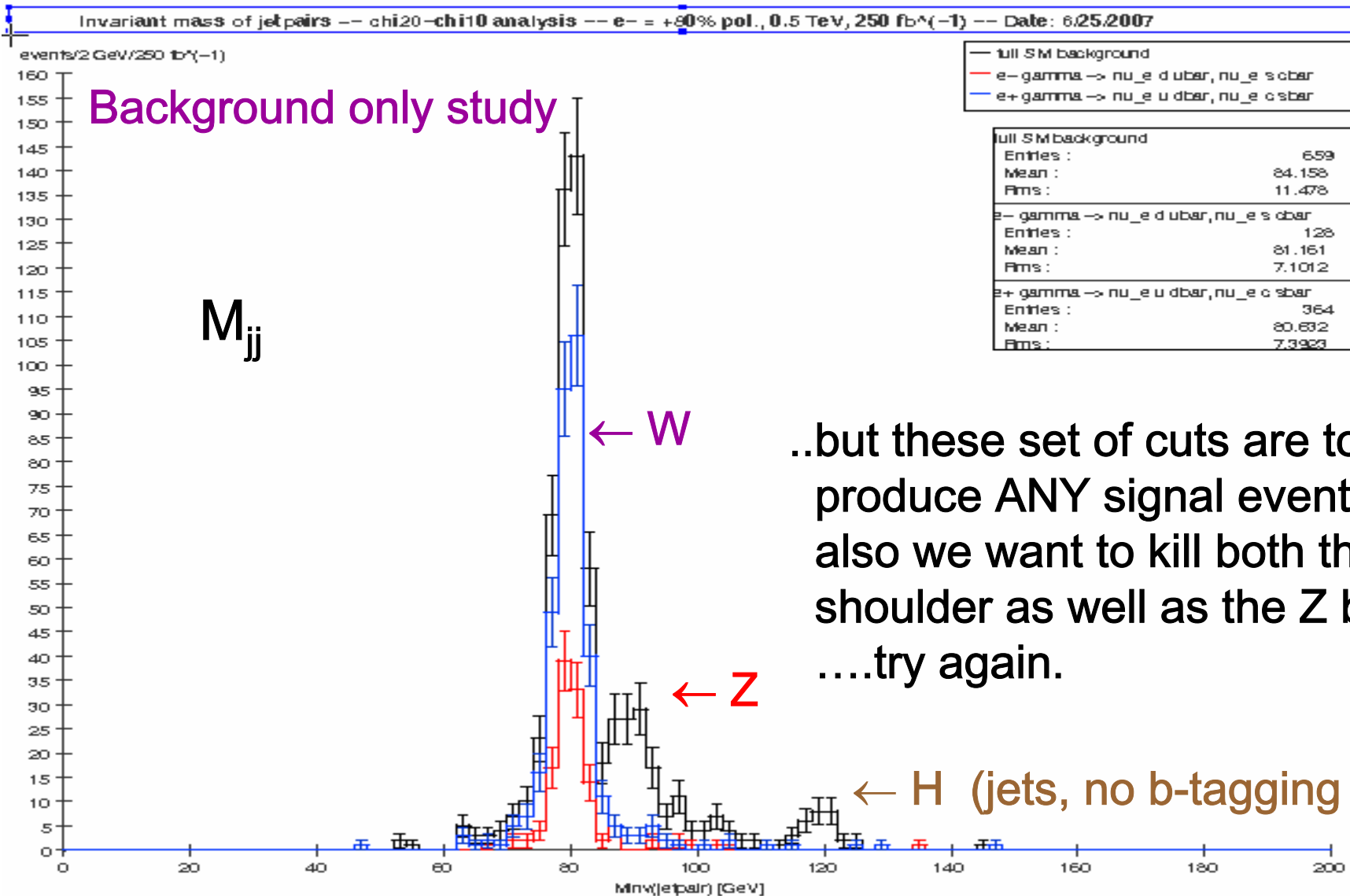
$P_+$	$S_i$	$S_{ii}$	B	$S_i/B$	$S_{ii}/B$
0.0	1	1.8	0.2	5.0	8.0
0.30	1.24	2.34	0.14	8.9	16.7
0.45	1.36	2.61	0.11	12.4	23.7
0.60	1.48	2.88	0.08	18.5	36.0

# $\chi_2^0 \chi_1^0$ Analysis :

most models accessible at 500 GeV have a smallish mass splitting and will be tough...



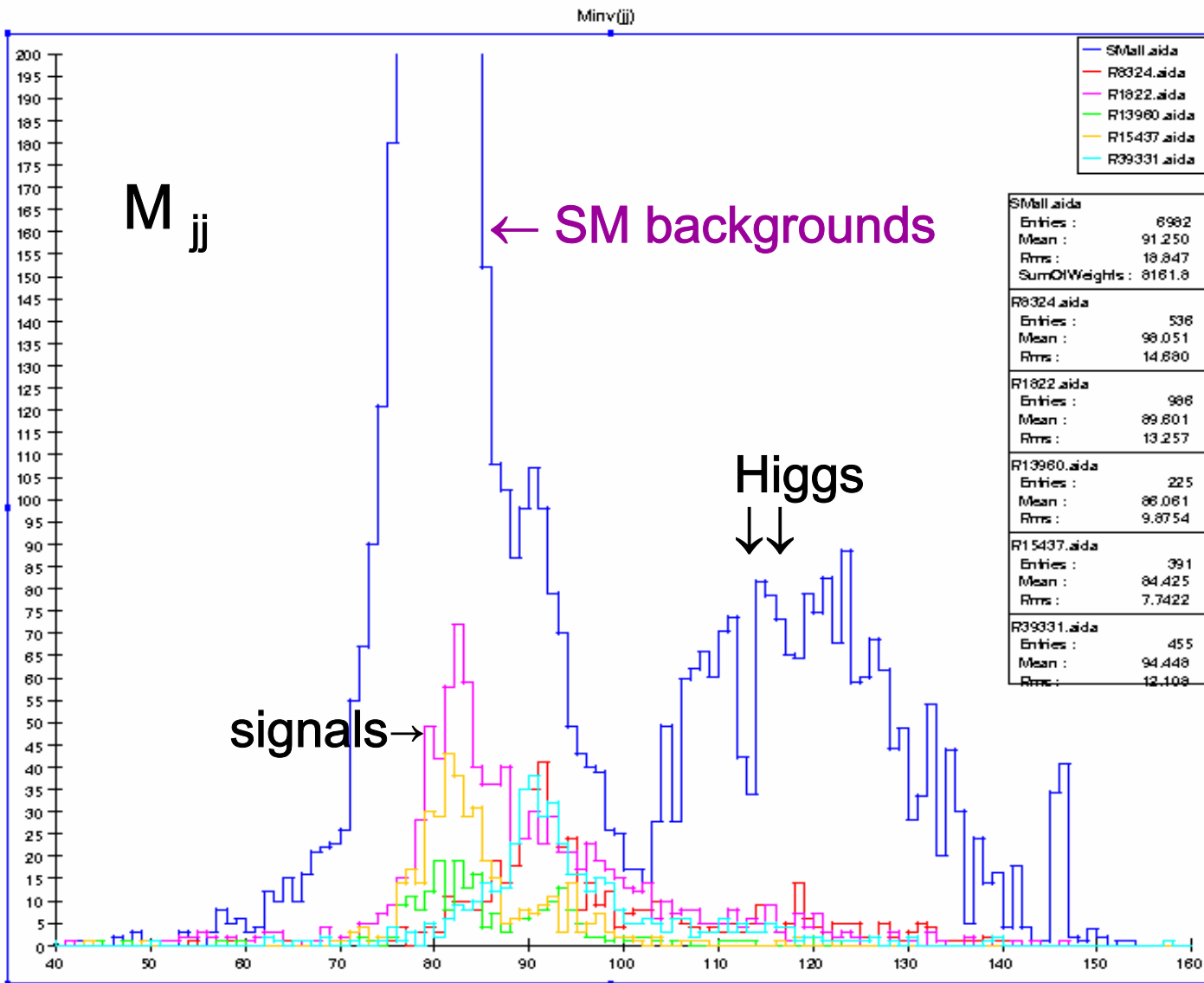
# $\chi_2^0 \chi_1^0 \rightarrow jj + \text{Missing E}$ Analysis : Backgrounds are serious



..but these set of cuts are too tight to produce ANY signal events and also we want to kill both the W shoulder as well as the Z background ....try again.

Changing cuts we now have the `best' S/B ratio ...

SM Z almost removed...



RH Polarization

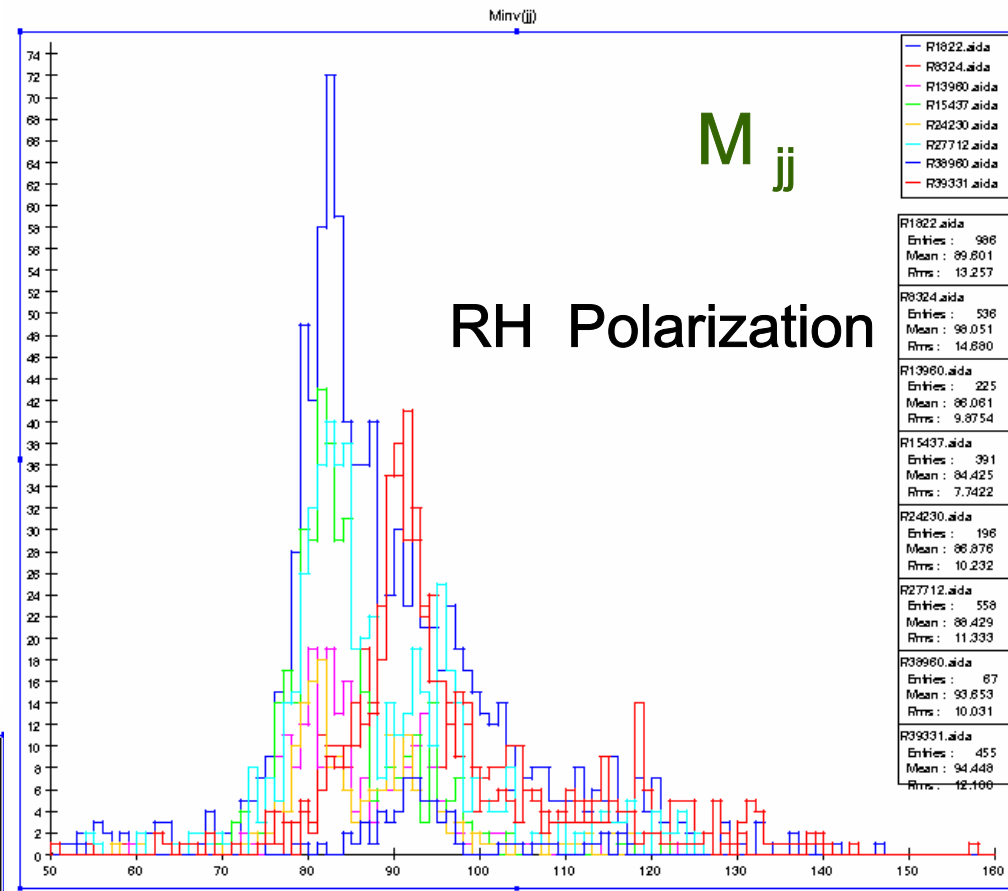
The Higgs(120) is now a serious background

Still all the signals are reasonably small yet some may be visible

Let's look at the signal only rates.....

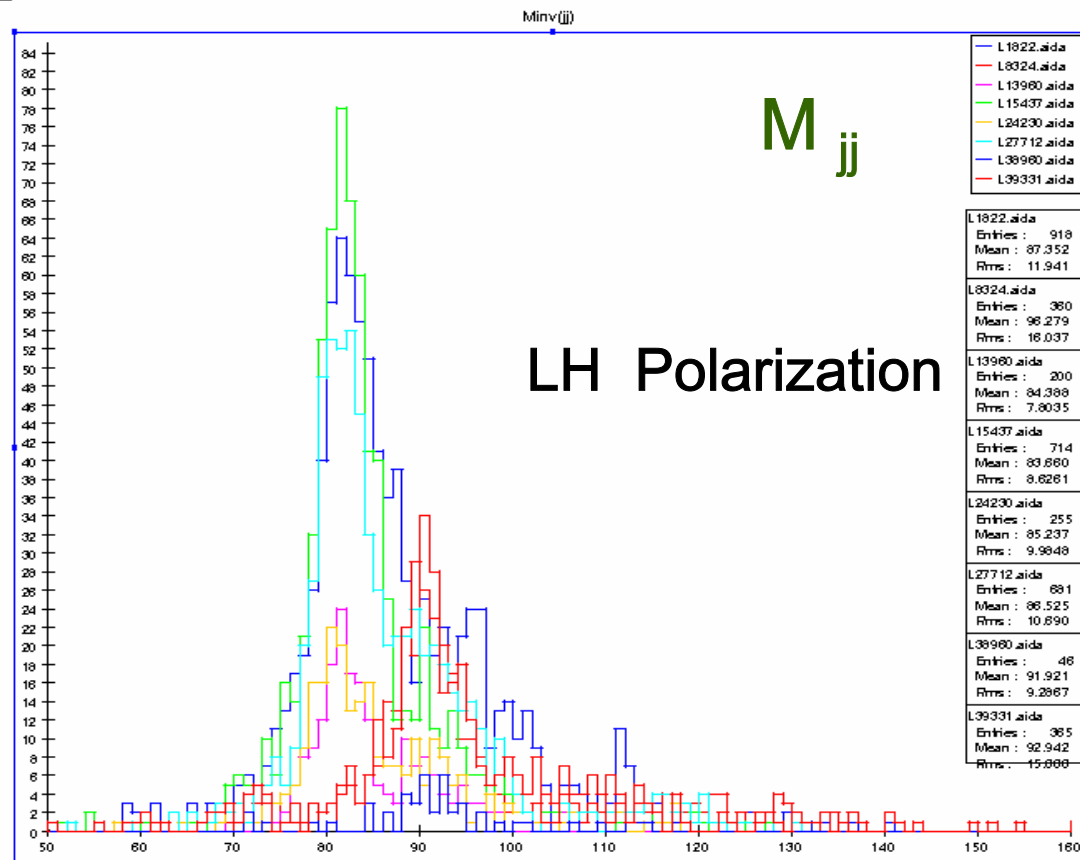
We see that the signals for either polarization are quite small but might still be visible...

Contrary to claims, this is not an easy channel for our models.



Note the feed-down from other SUSY particle decays...

A detailed study of cuts does help somewhat with S/B in this case...



As we have seen several times...

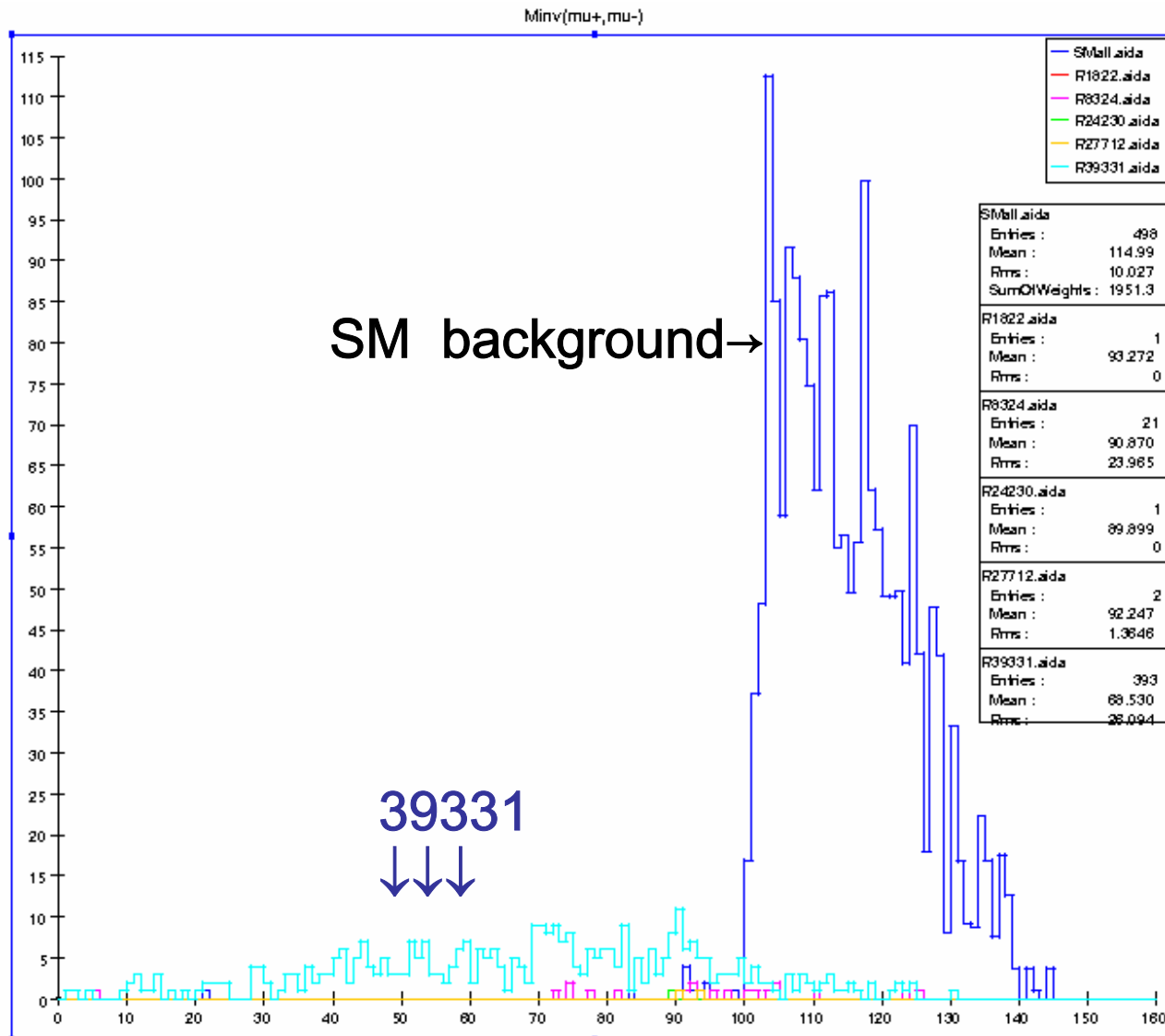
## “SUSY IS A BACKGROUND FOR SUSY”

Just because you are looking for smuons or selectrons or neutralinos doesn't mean what you find is the state you are actually looking for... though it *is* SUSY.

E.g., more models may pass our 'staus search' criteria than there are models with kinematically accessible staus... BUT the models with *real* staus can be somewhat tricky to find. This is true for other analyses as well and we are performing a detailed study of this result....

# $\chi_2^0 \chi_1^0 \rightarrow \mu\mu + \text{Missing E Analysis}$

The signal rate is very low...unfortunately



Here we see muons being produced by chargino pairs in model 39331.

# Analysis Procedure

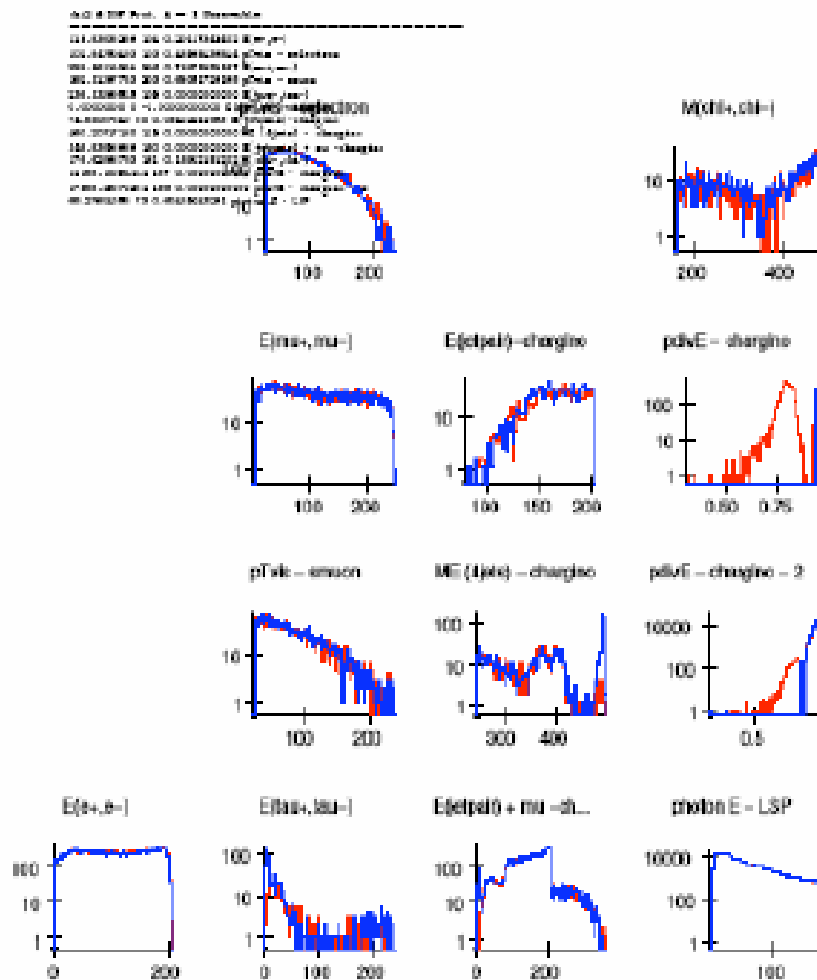


Figure 1: Left 207 (red) 3848 (blue)

- We combine the results for each analysis of Model A and Model B with those obtained from two different full background samples, B1 & B2
- For each e- polarization 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,  $5\sigma$
- We're just starting to do these comparisons

# Important Check :

It is important to compare, e.g., two SM background samples to make sure the analysis procedures are correct....and no additional features are present.

This is a comparison of two 250 fb<sup>-1</sup> background samples for both beam polarizations, (almost) analysis by analysis...

Looks good!

Left:

chi2	# DOF	Prob. A == B	Observable
92.08963136	104	0.79187612496	E(e+,e-)
112.85905539	107	0.33039599401	pTvis - selectron
221.32529743	239	0.78772902665	E(mu+,mu-)
216.61517012	211	0.38081413495	pTvis - smuon
30.65695446	23	0.13145653865	E(tau+,tau-)
118.23462747	126	0.67629670097	E(mu+,mu-)-chargino
56.06415979	55	0.43473420163	E(jetpair)-chargino
111.56081988	124	0.78090391966	ME (4jets) - chargino
105.44583049	101	0.36126053896	E(jetpair) + mu -chargino
120.51035301	162	0.99378619662	M(chi+,chi-)
4.44011455	9	0.88013599486	pdivE - chargino
37.29750322	53	0.94972506149	pdivE - chargino - 2
80.44910112	73	0.25737977593	photon E - LSP

Right:

chi2	# DOF	Prob. A == B	Observable
106.01645797	102	0.37291350805	E(e+,e-)
101.79927418	106	0.59733261853	pTvis - selectron
238.79176004	235	0.41890903853	E(mu+,mu-)
197.65332465	206	0.64948719567	pTvis - smuon
17.12542085	20	0.64481520022	E(tau+,tau-)
125.74878243	124	0.43926622034	E(mu+,mu-)-chargino
40.64708387	38	0.35457482707	E(jetpair)-chargino
114.07390660	124	0.72751661161	ME (4jets) - chargino
82.40425867	101	0.91163764135	E(jetpair) + mu -chargino
164.27493113	160	0.39201277758	M(chi+,chi-)
11.31168432	10	0.33375612034	pdivE - chargino
57.08471565	54	0.36119612586	pdivE - chargino - 2
78.34174502	73	0.31326295224	photon E - LSP

BTW: it takes us ~3 weeks to generate a full background sample with a fixed set of cuts since the background files are so large (~ 1.7TB)...this drastically reduces the number of tests we can perform with full samples... ~300 GHz-yrs

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Here's an example of an old analysis where you see the differences in both the sleptons and the charginos

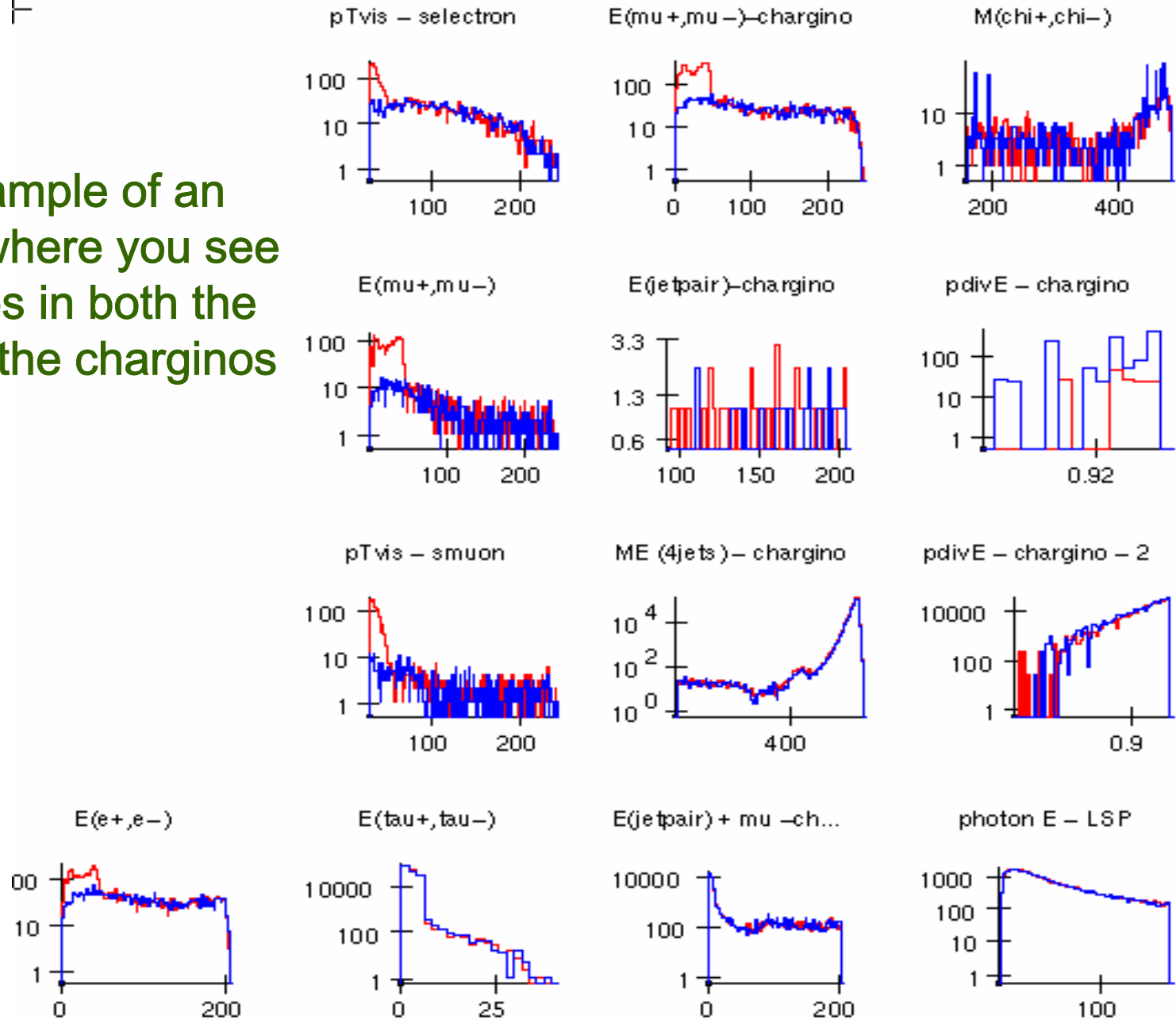


Figure 111: Right 10197<sup>111</sup> (red) 13274 (blue)

...and here is another case also showing significant differences...

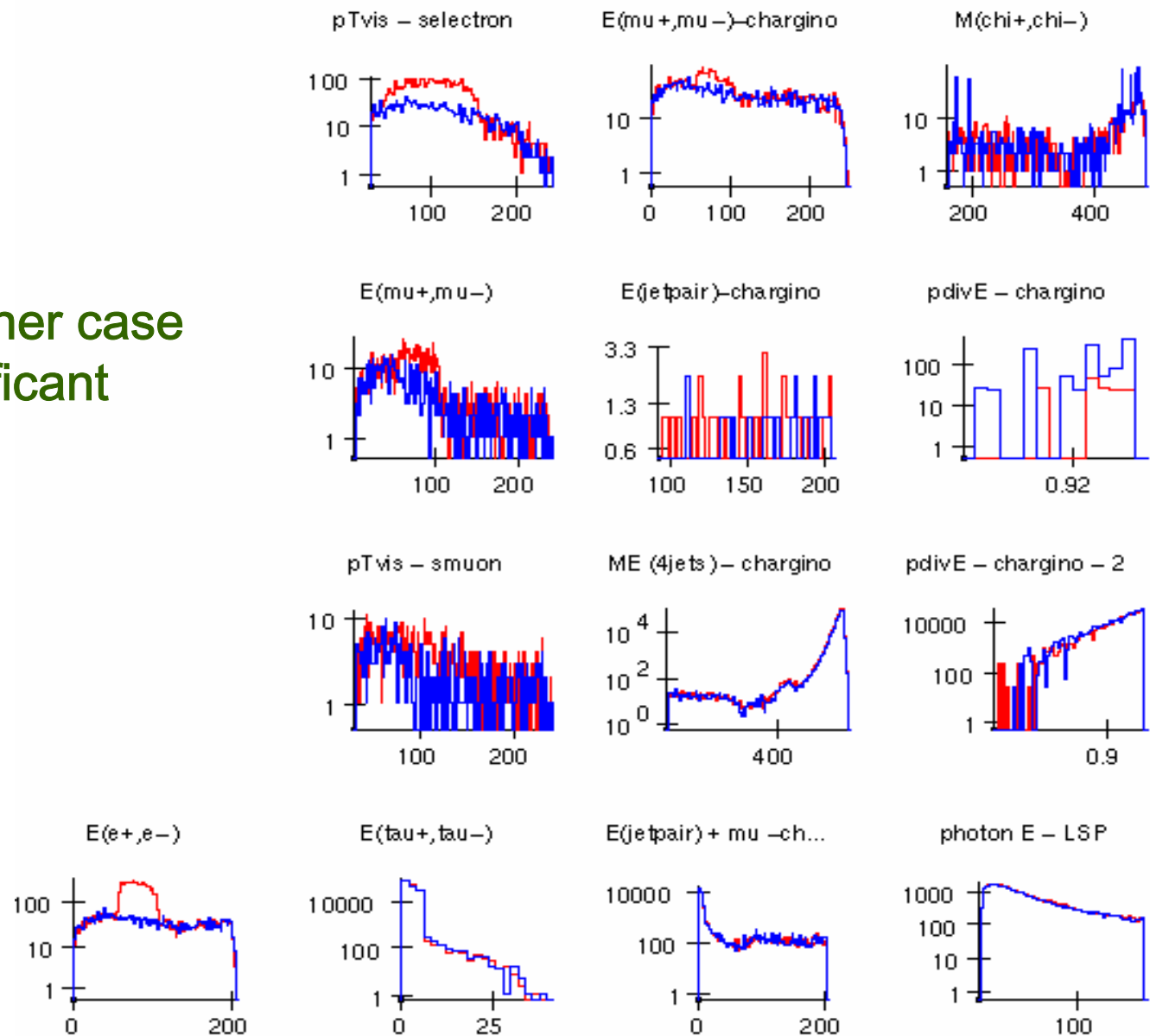


Figure 213: Right 27913<sup>213</sup> (red) 43006 (blue)



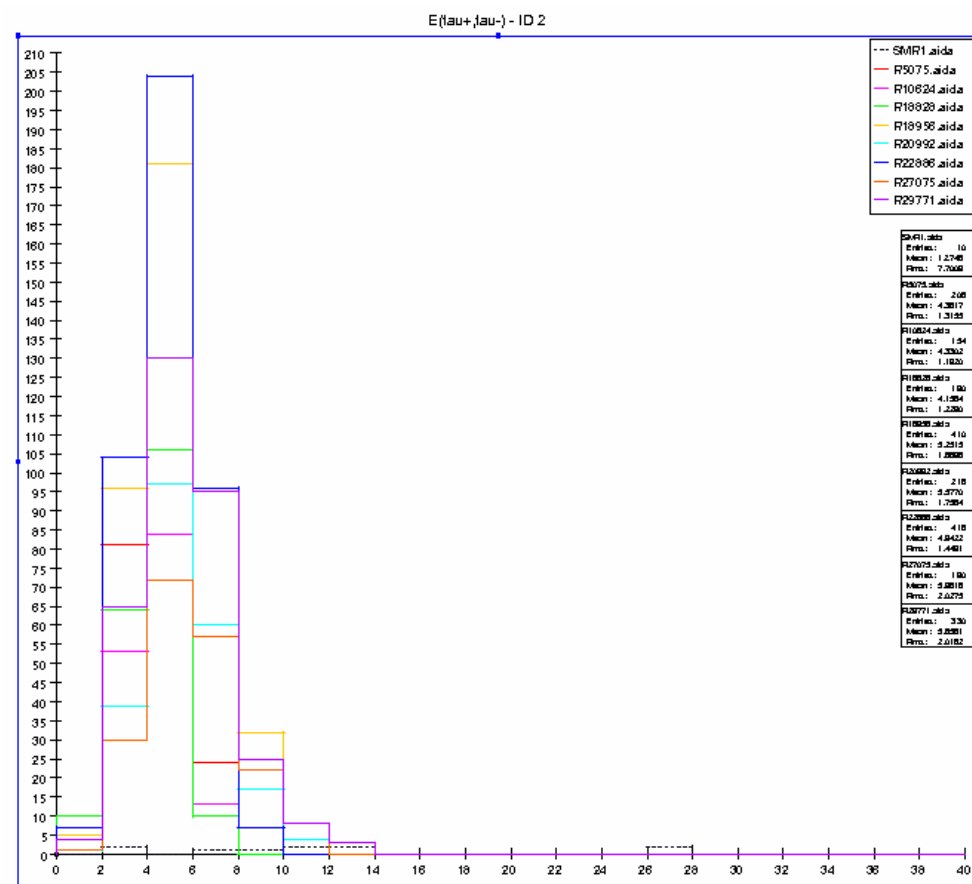
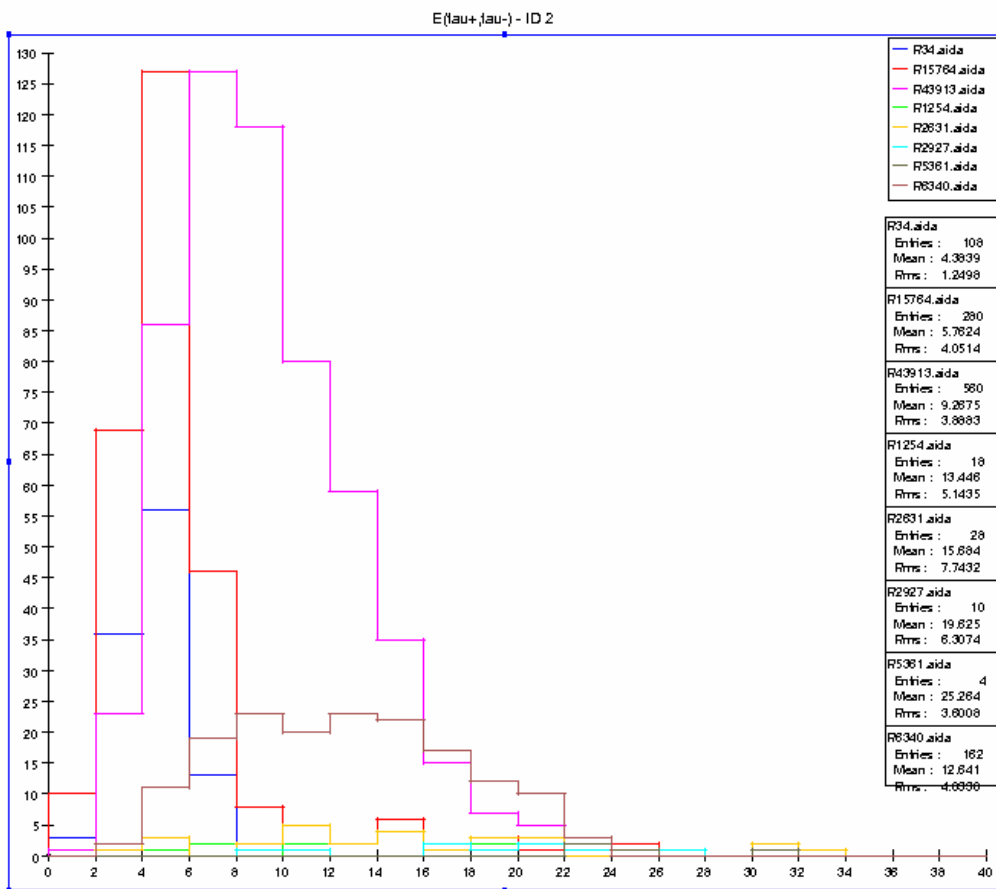
# SUMMARY

This project has been a learning experience....and full of many surprises. The first round of our analysis is now reaching its completion (so that we can finally get a paper out!) but there are many extensions to the present work we wish to pursue...

- (i) Study the 1 TeV case and the influence of positron polarization on both signals and backgrounds (+more channels to look at). Do threshold scans of some kind, include vertex detector analyses...
- (ii) Explore using CompHEP to generate SUSY signal events for all analysis channels which allows for interference.
- (iii) Study variations in the detector properties, in particular, the effect of introducing low-angle tracking below  $\sim 140$  mr.
- (iv) Begin a completely new analysis with a more realistic set of models which includes other constraints from, e.g., the Tevatron, LEP, WMAP,  $g-2$ ,  $b \rightarrow s\gamma$ , dark matter searches, etc.

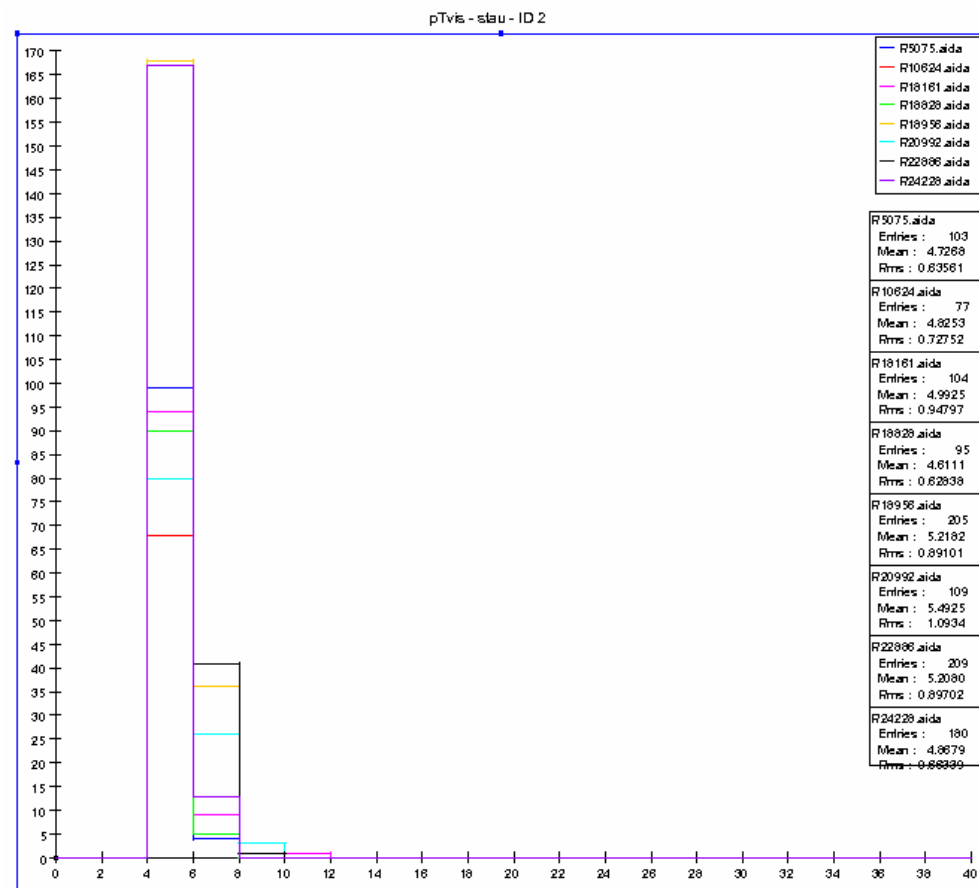
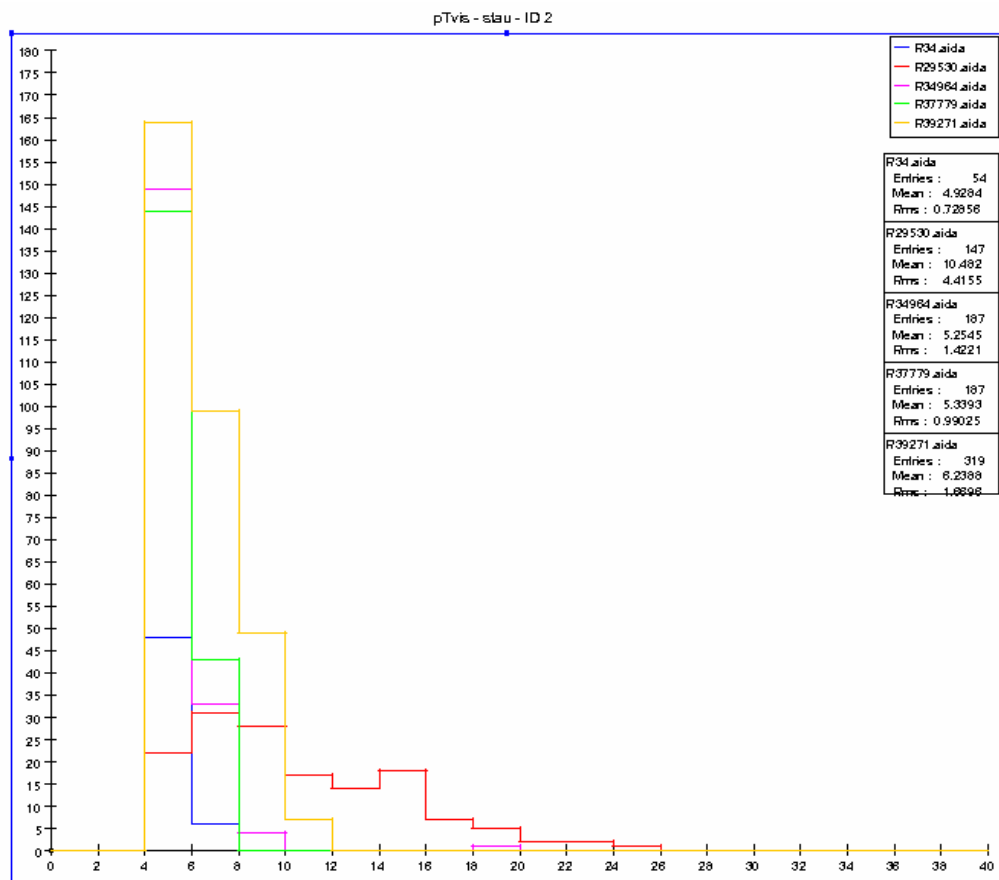
# BACKUP SLIDES

These are plots of the (signal only) reconstructed tau energy from the stau search analysis...



On the left is *REAL* staus & on the right from inos...

Similarly, these are plots (signal only) of the reconstructed tau  $p_T$  from the stau search analysis...



On the left is REAL staus while on the right are inos...

