The LHC Inverse Problem, Supersymmetry and the ILC

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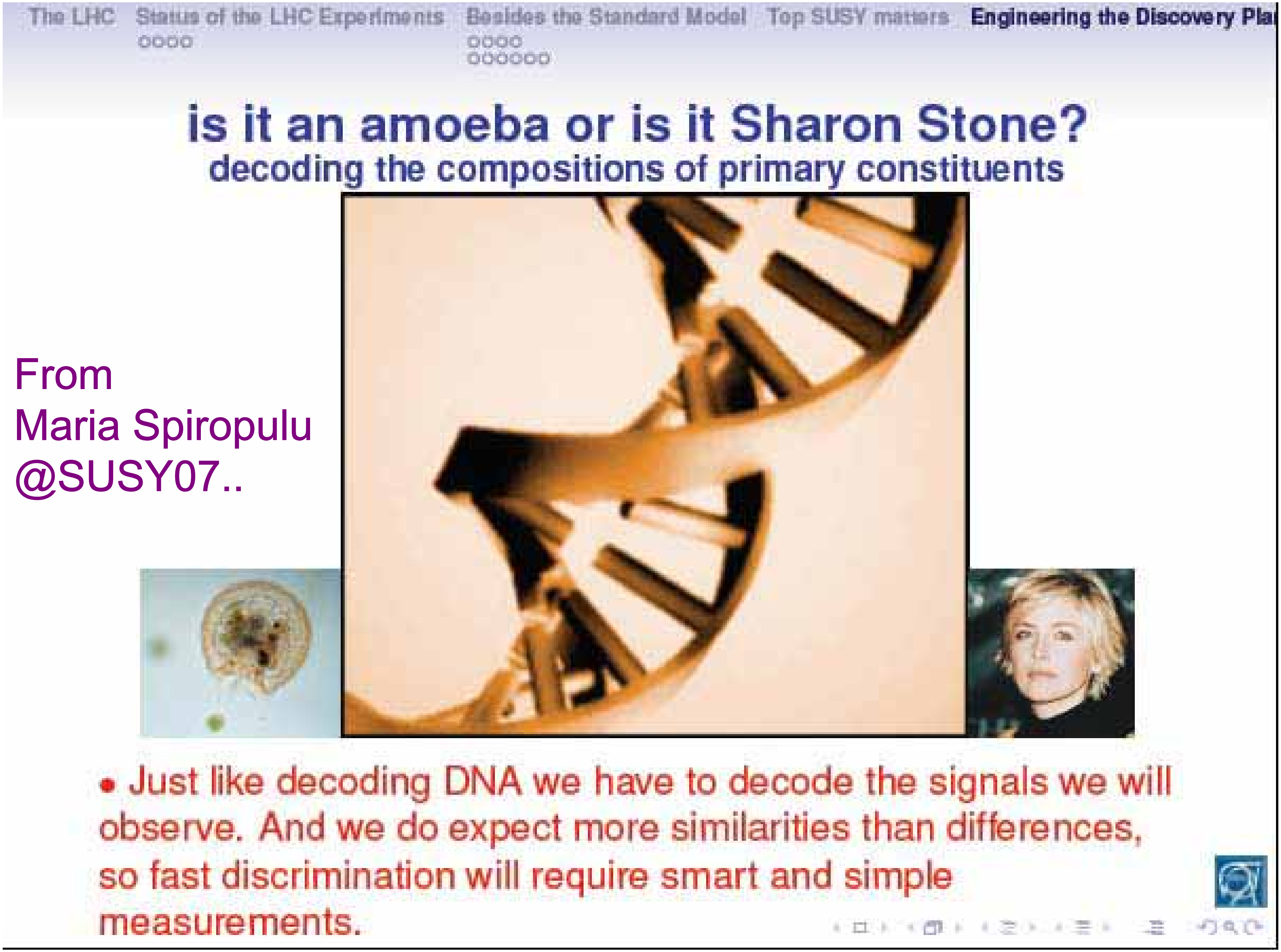
The LHC Inverse Problem

If new physics is discovered at the LHC, can we determine what it is? Does a specific experimental 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 Minimal Supersymmetric Standard Model (the MSSM), can one uniquely determine the values of, e.g., the weak scale Lagrangian parameters from LHC data alone?

This is the LHC Inverse Problem: instead of going from the model parameters and determining the experimental signatures, as theorists usually do, here we want to do the reverse…and the mapping is NOT unique!



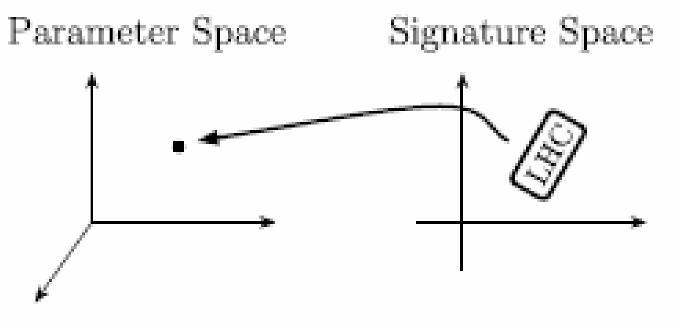
is it an amoeba or is it Sharon Stone?

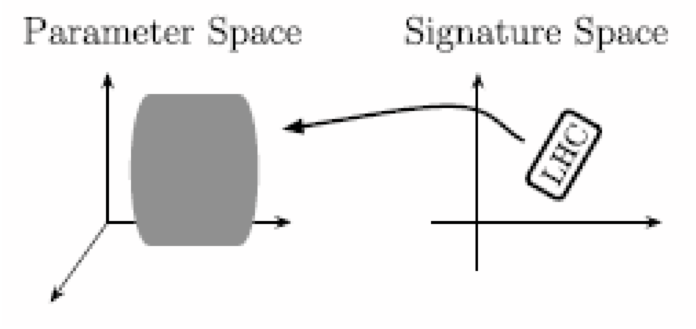
decoding the compositions of primary constituents

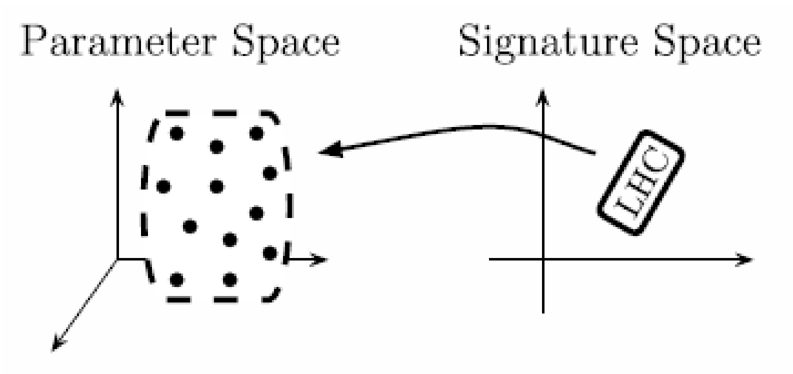
From
Maria Spiropulu
@SUSY07..

- 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.

The Inverse Mapping of data → theory can have many possible outcomes….







Much of the time a specific set of data maps back into many distinct islands/points in the model parameter space… → model degeneracy

What happens for the case of the MSSM??

Arkani-Hamed etal., hep-ph/0512190

LHC Inverse Problem

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

- Generated *many* models within MSSM for 10 fb^{-1} @ LHC (Pythia 6.324). Here a `model' = a particular parameter space point…
- For 15 parameters:

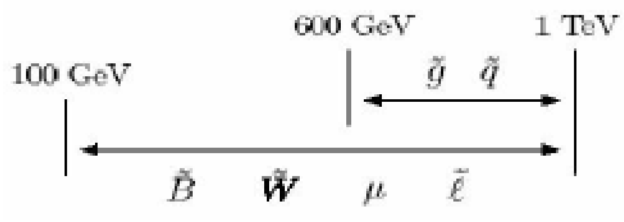
Inos : $M_1,\ M_2,\ M_3,\ \mu$

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 β

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 1st two scalar generations degenerate

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

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

Essentials of MSSM Parameters…

$$\begin{pmatrix} M_2 & M_W\sqrt{2}\sin\beta \\ M_W\sqrt{2}\cos\beta & \mu \end{pmatrix}$$

Wino + charged Higgsino → $\chi^{+}_{1,2}$

bino + neutral wino and Higgsinos → $\chi^{0}_{1,2,3,4}$

$$\begin{pmatrix} M_1 & 0 & -M_Z s_W\cos\beta & M_Z s_W\sin\beta \\ 0 & M_2 & M_Z c_W\cos\beta & -M_Z c_W\sin\beta \\ -M_Z s_W\cos\beta & M_Z c_W\cos\beta & 0 & -\mu \\ M_Z s_W\sin\beta & -M_Z c_W\sin\beta & -\mu & 0 \end{pmatrix}$$

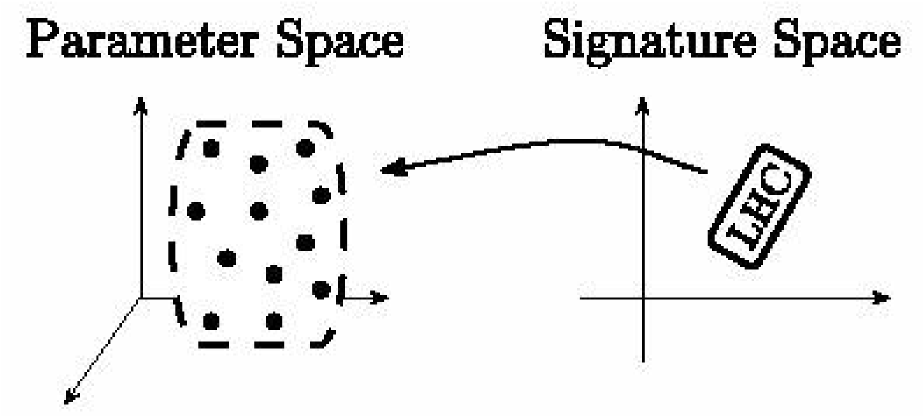
$$M^2_{\tilde f} = \begin{pmatrix} M^2_{LL} & m_f X_f^* \\ m_f X_f & M^2_{RR} \end{pmatrix},$$

$$\begin{aligned} M^2_{LL} &= m_f^2 + m^2_{L,\tilde f} + M_Z^2\cos 2\beta\,(I_3^f - Q^f s_W^2), \\ M^2_{RR} &= m_f^2 + m^2_{R,\tilde f} + M_Z^2\cos 2\beta\; Q^f s_W^2\,, \\ X_f &= A_f - \mu^*\{\cot\beta, \tan\beta\} \end{aligned}$$

left- and right-sfermions → sfermions$_{1,2}$ ….mostly relevant for stops, sbottoms and staus.

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 ILC500 resolve these degeneracies?   We will address this issue below..

How do these degeneracies arise?

A Few Comments on AKTW Model Generation

- There are certainly other ways one could have chosen to generate this set of models: parameter ranges, prior `tilts’, etc...

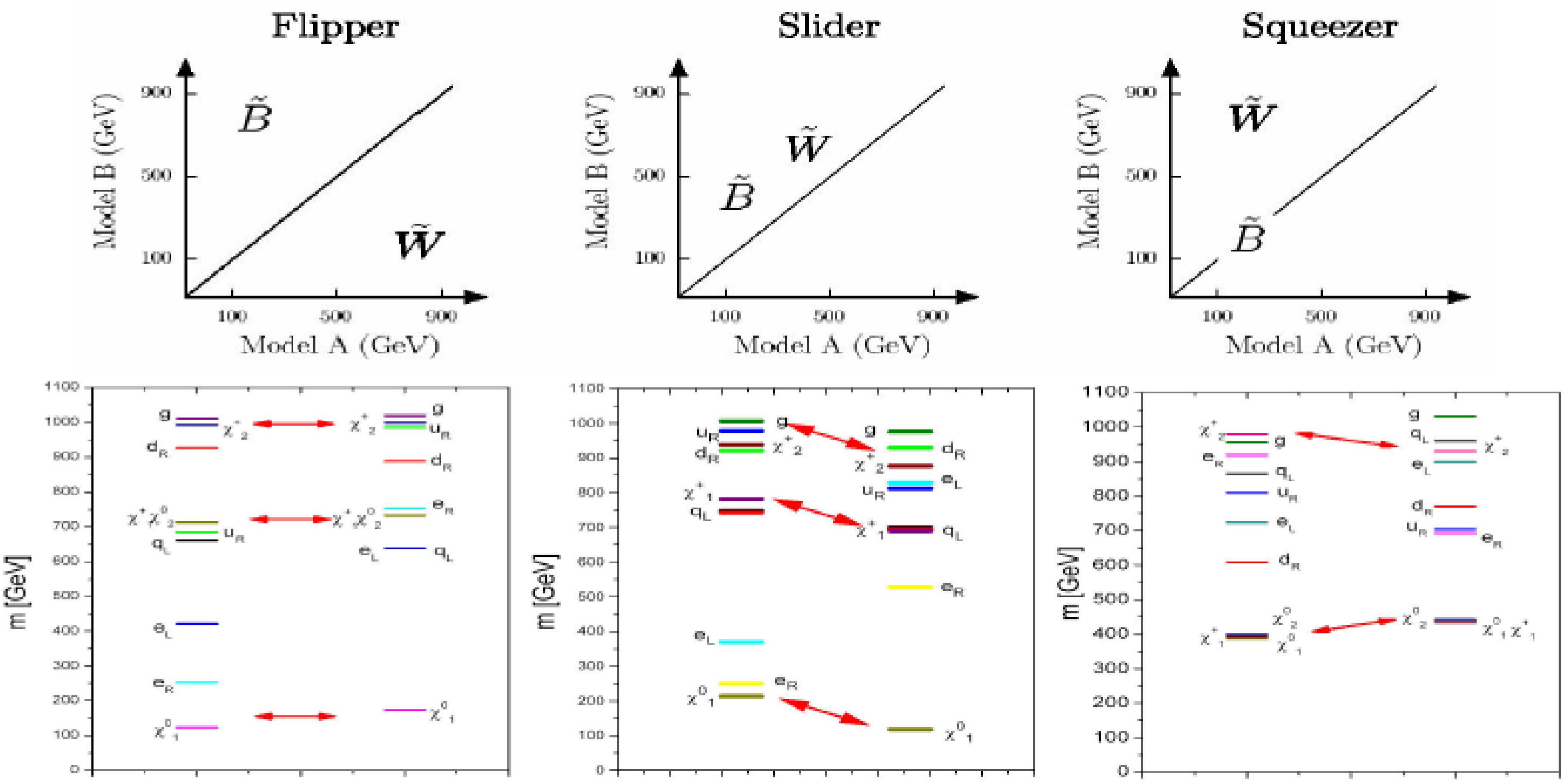
- These models satisfy the LEPII constraints as well as the Tevatron naïve squark and gluino bounds but not, e.g., WMAP, g-2, b → $s\gamma$, direct dark matter searches, Higgs search constraints, etc…

- But to address our questions within this context we have to follow their lead for now…

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^{-1} = ILC ?? PROJECT

The original purpose of this project was to examine whether or not ~280 pairs of MSSM SUSY models which produced `identical' signals at the LHC could be distinguished at ILC. But before that we have to ask how *visible* SUSY is at ILC.

Though we did attack these questions, this project morphed into something far larger…we performed 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 and prejudices about SUSY analyses at the ILC.

We've had a few surprises and have learned many lessons…

How :

- Pick one of the models provided by Nima & friends. Simulate SUSY signal events with PYTHIA and CompHEP feeding in Whizard/GuineaPig generated beam spectrum

- Add the SM backgrounds: all 2 -> 2, 4 & 6 ($e^+ e^-$, γe & $\gamma\gamma$) full matrix element processes (1016) produced by Tim Barklow

- Pipe this all through java-based SiD fast detect simulation org.lcsim

- Assume E_{cm}=500 GeV, L=500 fb^{-1} with P_{e-} =80% and analyze after appropriate generalized, i.e., *model-independent* cuts are applied.. this is highly non-trivial requiring many iterations

→→ ADD lots (and lots) of time…

All ee,γe,γγ → 2,4,6 processes w/ full matrix elements included, e.g.,

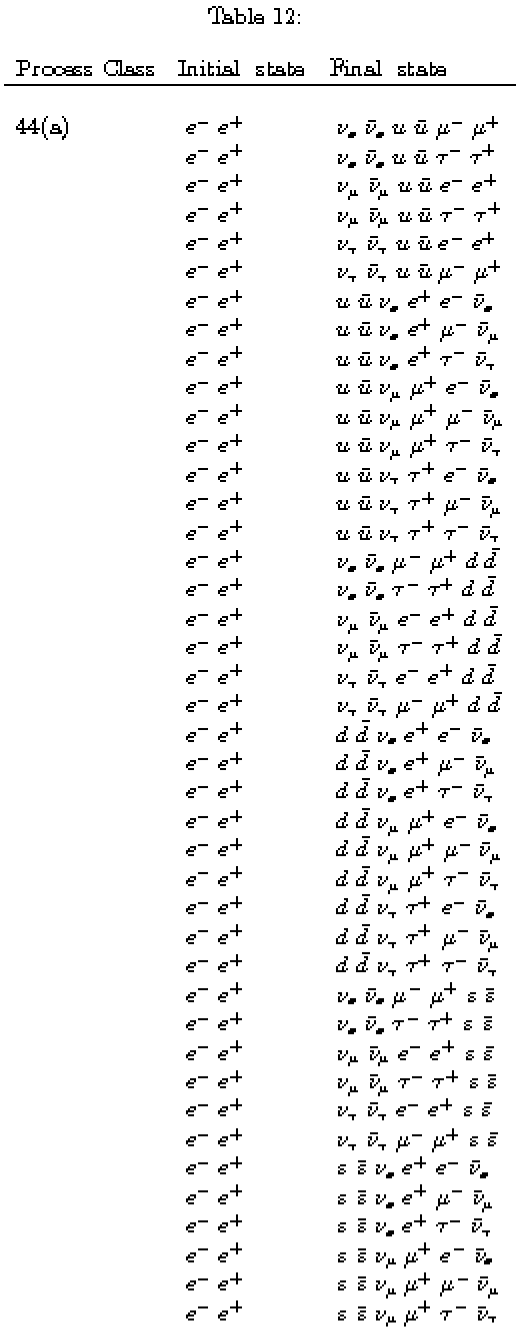


Table 12:

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

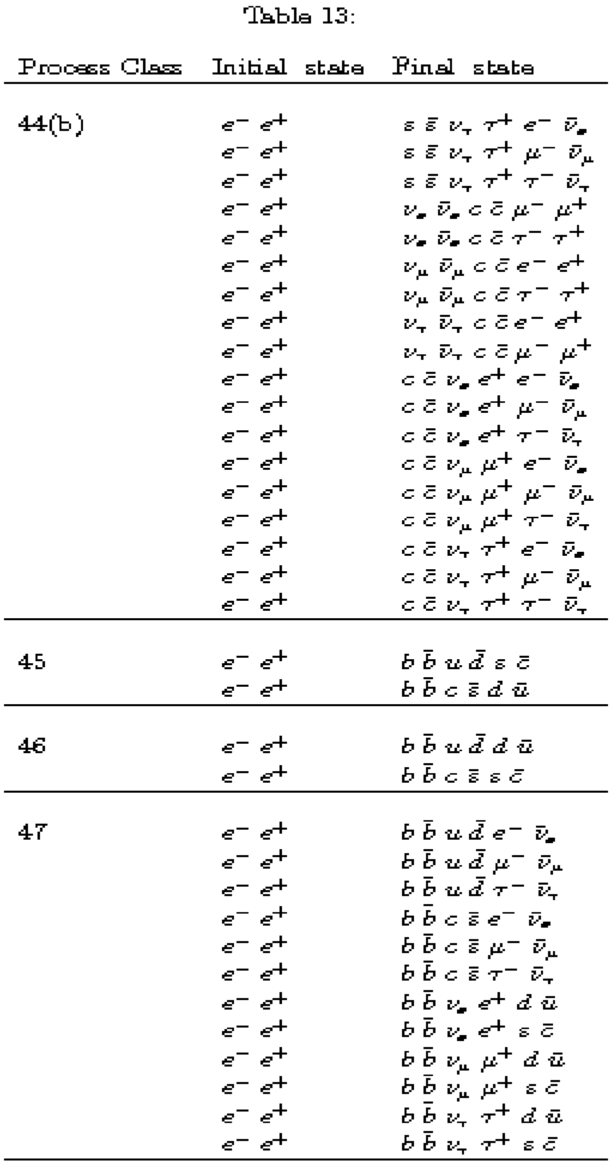
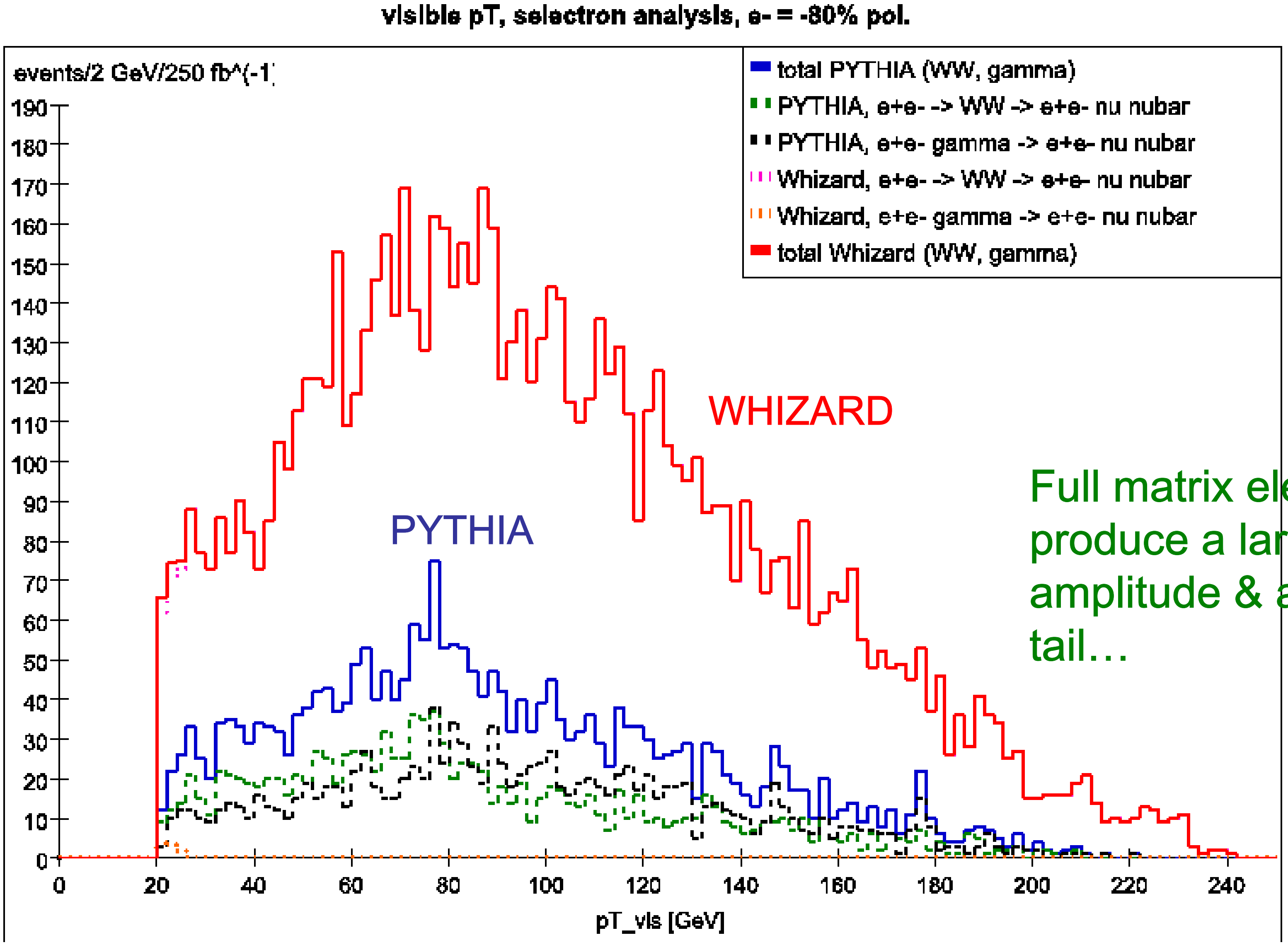


Table 13:

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 use of full matrix elements for the SM background is important: PYTHIA underestimates backgrounds

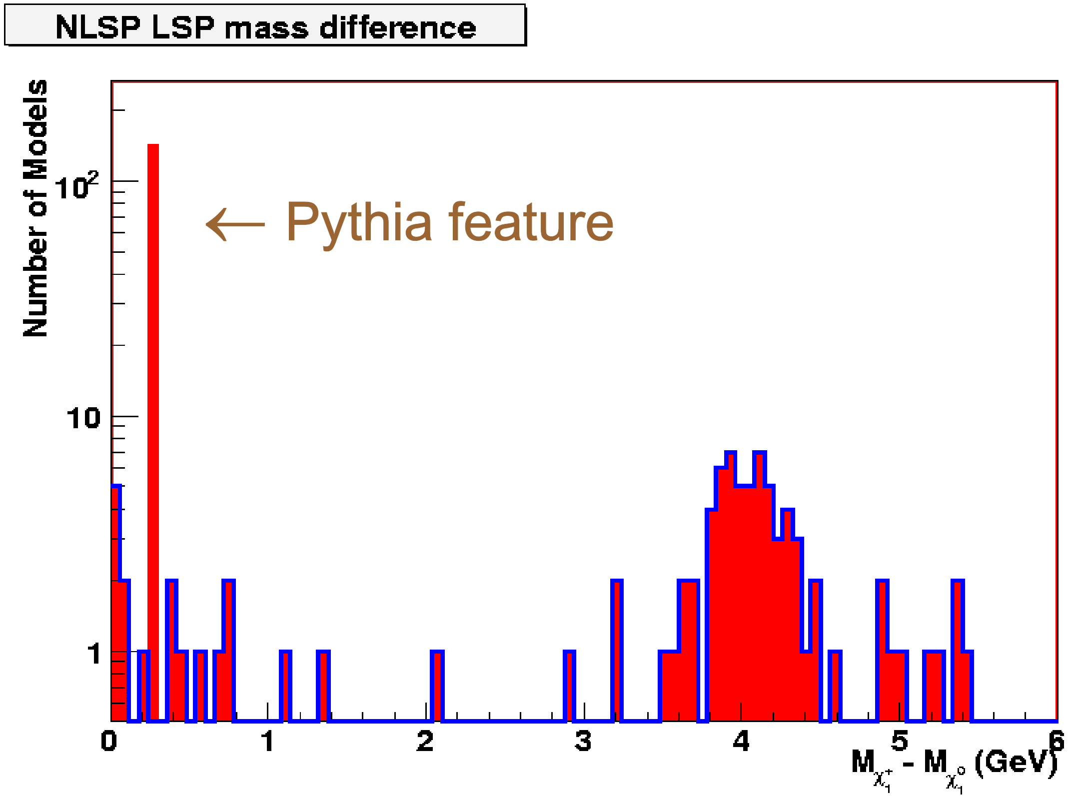


Full matrix elements produce a larger amplitude & a longer tail…

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 fast detector simulation
- Over 20 simultaneous analyses using multiple observables

BEWARE OF BLIND USE OF PYTHIA, PART II:



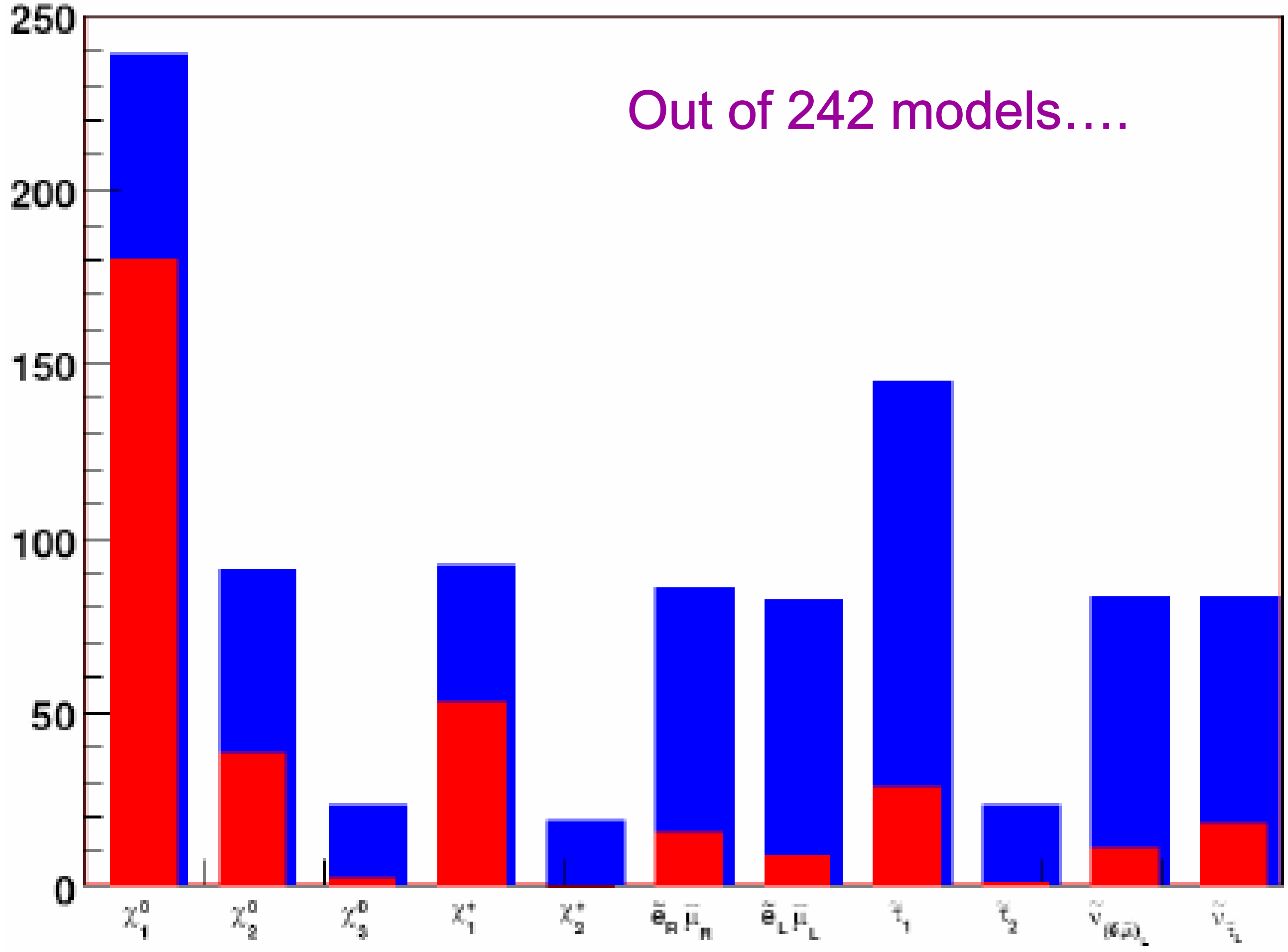
Chargino – LSP Mass Difference

In PYTHIA6.324 or earlier, if the χ_1^+ is calculated to be lighter than the LSP, then the code automatically resets the χ_1^+ mass to that of the LSP+ $2m_\pi$. This happens in 141/383 of the original model (unphysical) cases !!

This reduces our sample:
383 → 242 models
283 → 161 pairs

This issue has now been dealt with in the latest version of PYTHIA (thanks to Steve & Peter)

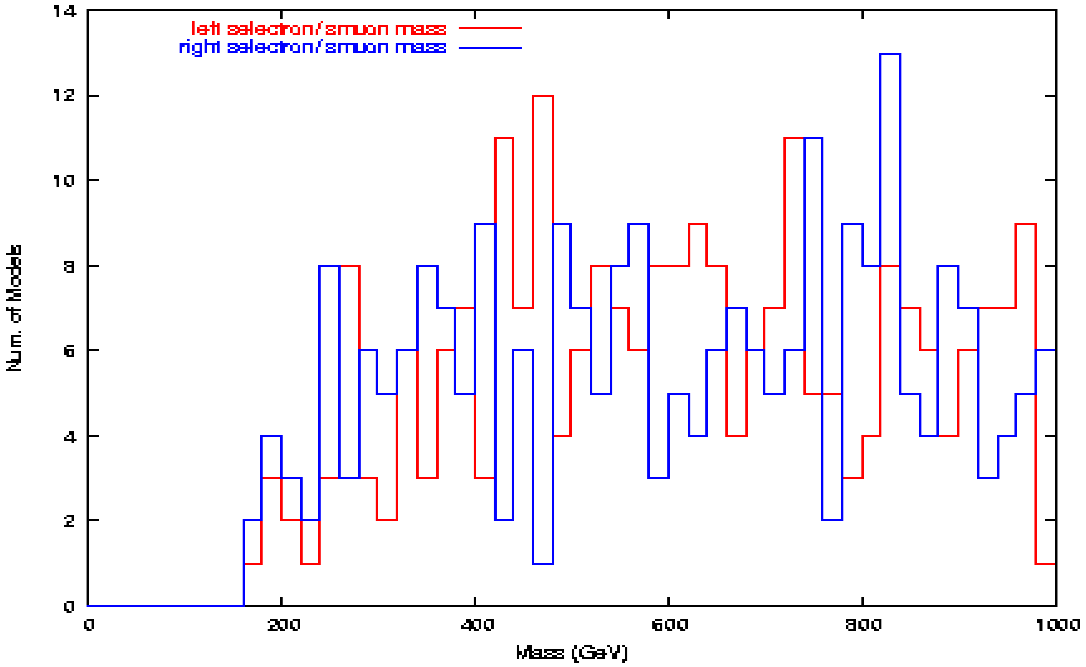
What Particles are Kinematically Accessible at the ILC ???

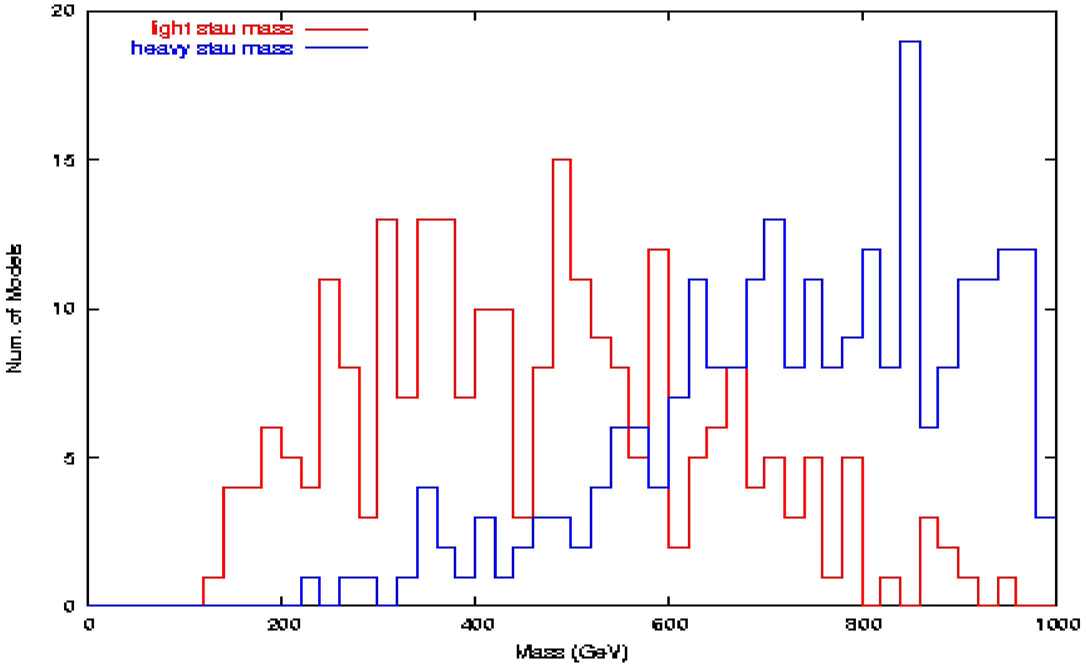


Out of 242 models….

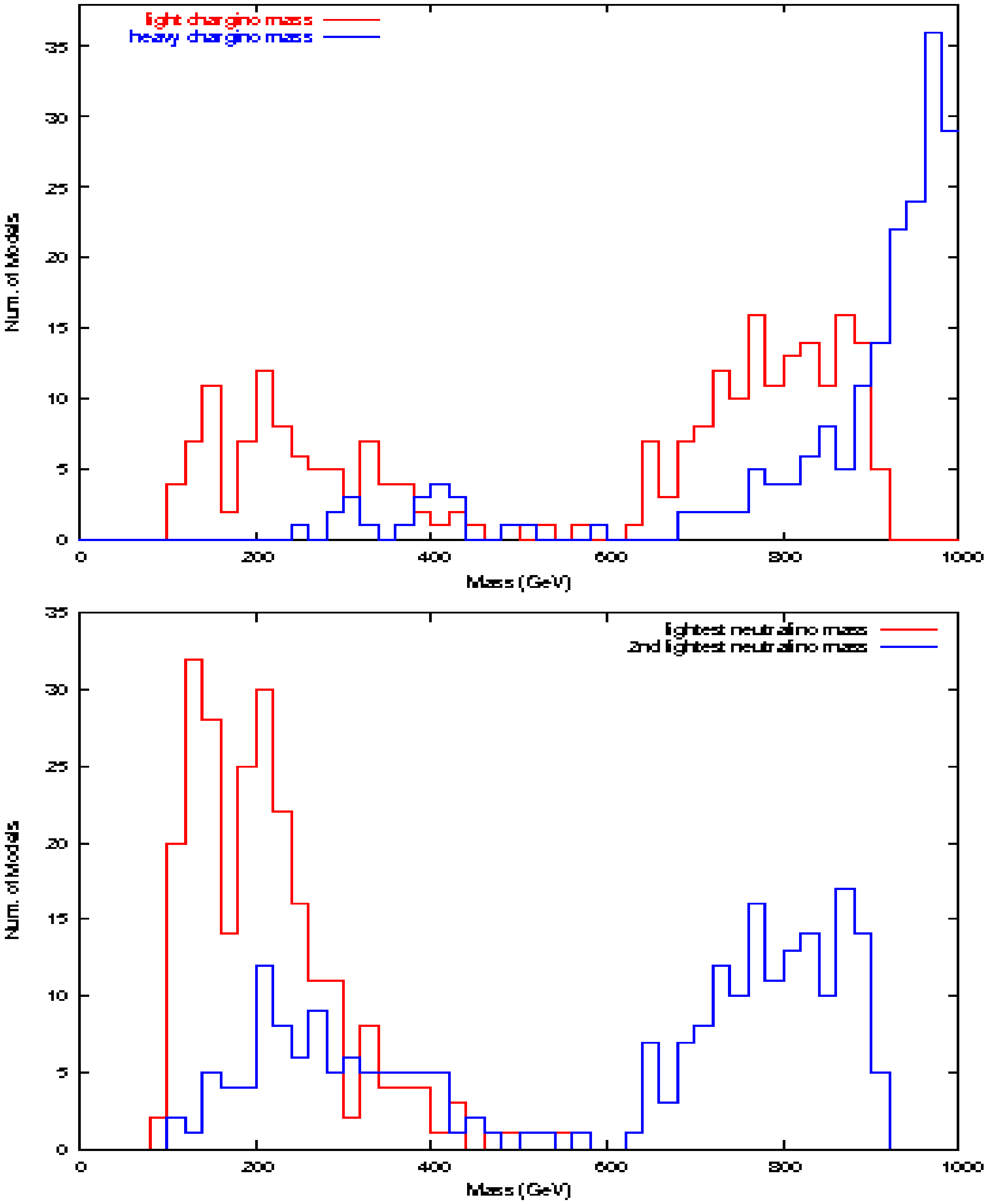
Accessible at 500 GeV, 1 TeV c.m. energy

Let’s look at some numbers…



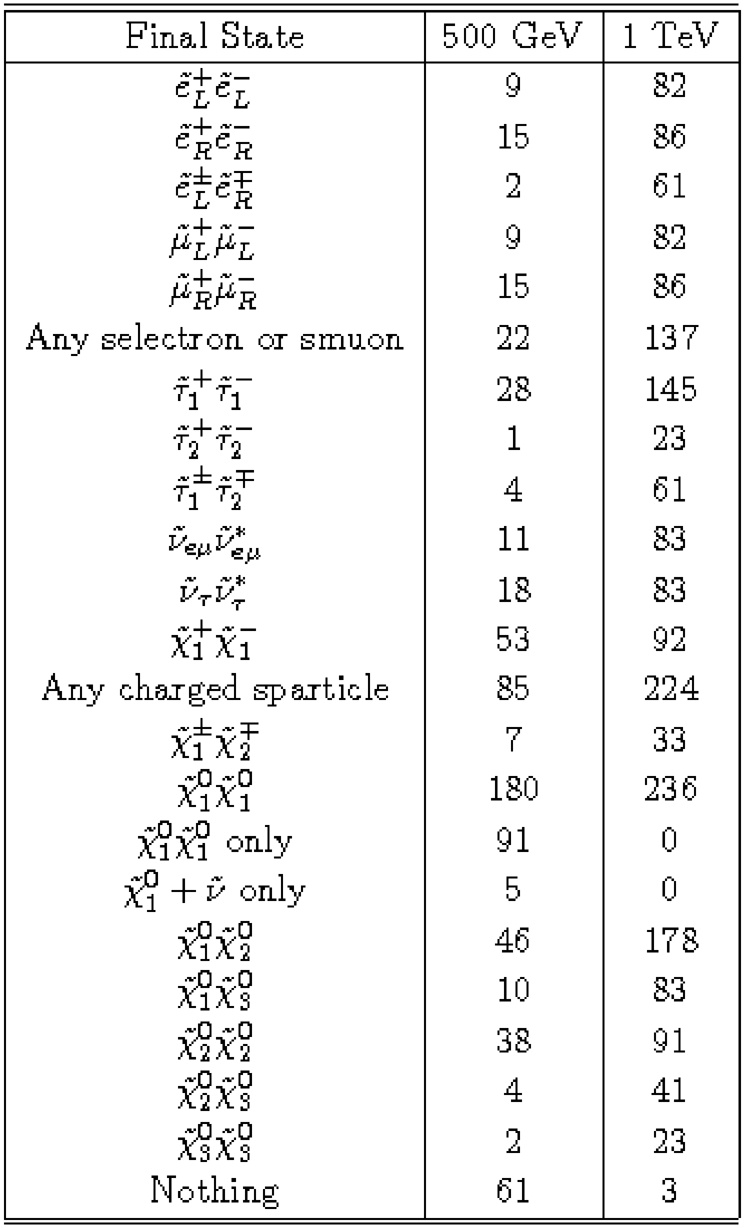


Particle mass spectrum for selectrons, smuons and staus



Particle mass spectrum for charginos and neutralinos

Kinematic Accessibility ≠ Observability



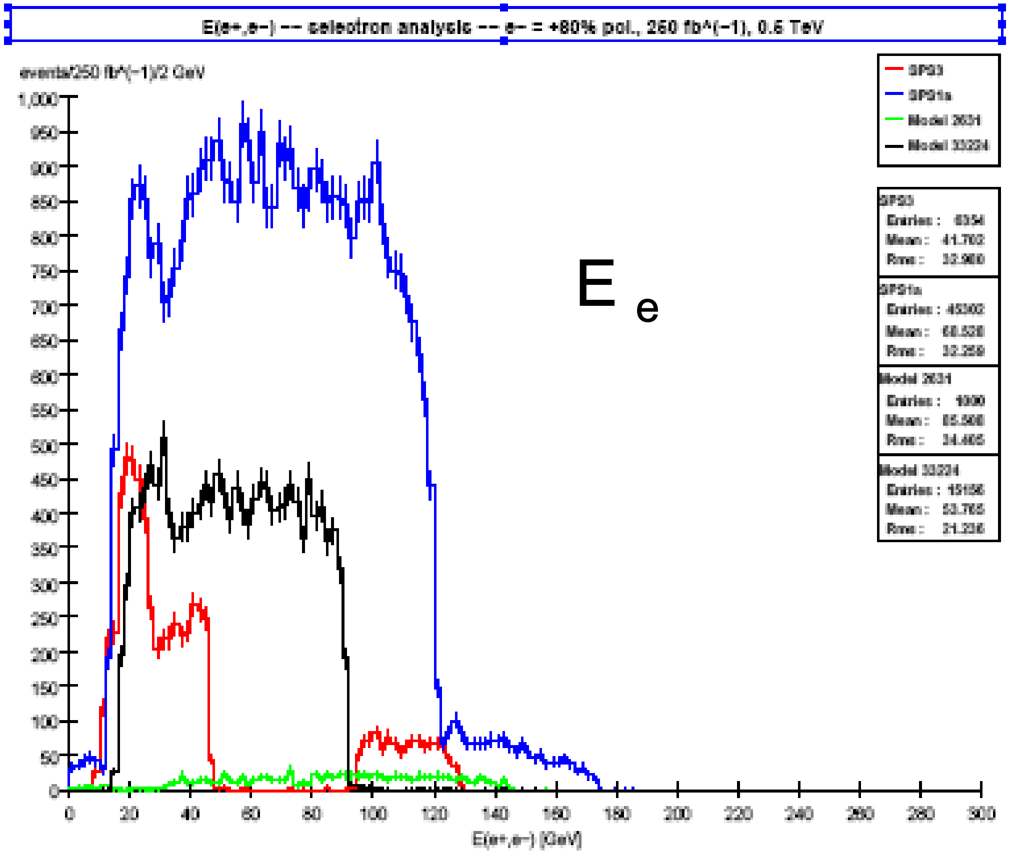
Final State	500 GeV	1 TeV
$\tilde{e}_L^+\tilde{e}_L^-$	9	82
$\tilde{e}_R^+\tilde{e}_R^-$	15	86
$\tilde{e}_L^\pm\tilde{e}_R^\mp$	2	61
$\tilde{\mu}_L^+\tilde{\mu}_L^-$	9	82
$\tilde{\mu}_R^+\tilde{\mu}_R^-$	15	86
Any selectron or smuon	22	137
$\tilde{\tau}_1^+\tilde{\tau}_1^-$	28	145
$\tilde{\tau}_2^+\tilde{\tau}_2^-$	1	23
$\tilde{\tau}_1^\pm\tilde{\tau}_2^\mp$	4	61
$\tilde{\nu}_{e\mu}\tilde{\nu}_{e\mu}^*$	11	83
$\tilde{\nu}_\tau\tilde{\nu}_\tau^*$	18	83
$\tilde{\chi}_1^+\tilde{\chi}_1^-$	53	92
Any charged sparticle	85	224
$\tilde{\chi}_1^\pm\tilde{\chi}_2^\mp$	7	33
$\tilde{\chi}_1^0\tilde{\chi}_1^0$	180	236
$\tilde{\chi}_1^0\tilde{\chi}_1^0$ only	91	0
$\tilde{\chi}_1^0 + \tilde{\nu}$ only	5	0
$\tilde{\chi}_1^0\tilde{\chi}_2^0$	46	178
$\tilde{\chi}_1^0\tilde{\chi}_3^0$	10	83
$\tilde{\chi}_2^0\tilde{\chi}_2^0$	38	91
$\tilde{\chi}_2^0\tilde{\chi}_3^0$	4	41
$\tilde{\chi}_3^0\tilde{\chi}_3^0$	2	23
Nothing	61	3

Out of 242 models at 500 GeV, 61+91+5=157/242 ~ 65% have no obvious observable signal at the ILC…the percentage will actually be a bit higher after some further investigation as discussed later. But this fraction is *much* smaller at 1 TeV…

This is a strong argument for 1 TeV as soon as possible!

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

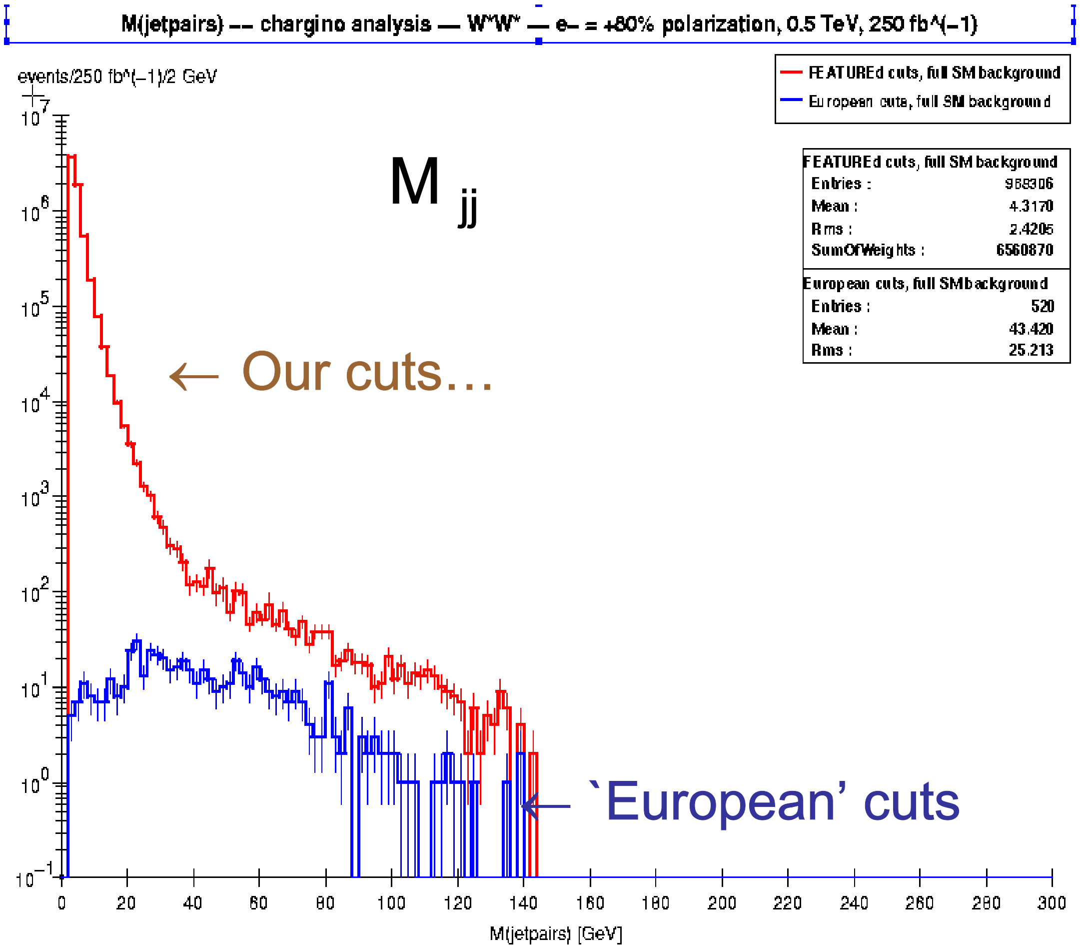


It will be much more difficult to see SUSY particles in general than in the well-studied specialized points…in some cases signal rates are over 50x smaller than in the SPS1a scenario as we'll see..

But we can still see them most of the time…

SPS1a is SPECIAL .. Part II :

The `standard' cuts are not particularly useful.



M_{jj}

← Our cuts…

← `European' cuts

European analyses assume VERY aggressive detector designs, especially at low angles .

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 → SM analogues + missing E

(ii) Radiative neutralino (LSP) pairs using tagging γ's

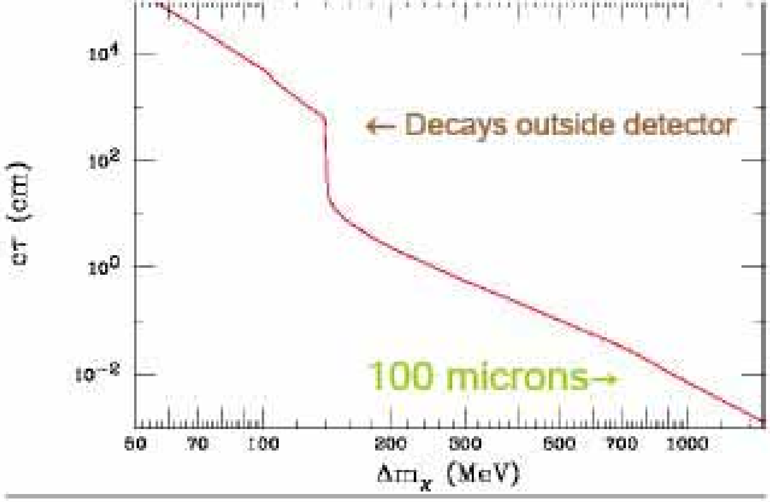
(iii) $\chi_2^0 \chi_1^0$ → missing E + Z/H (jj /l^+l^-)

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

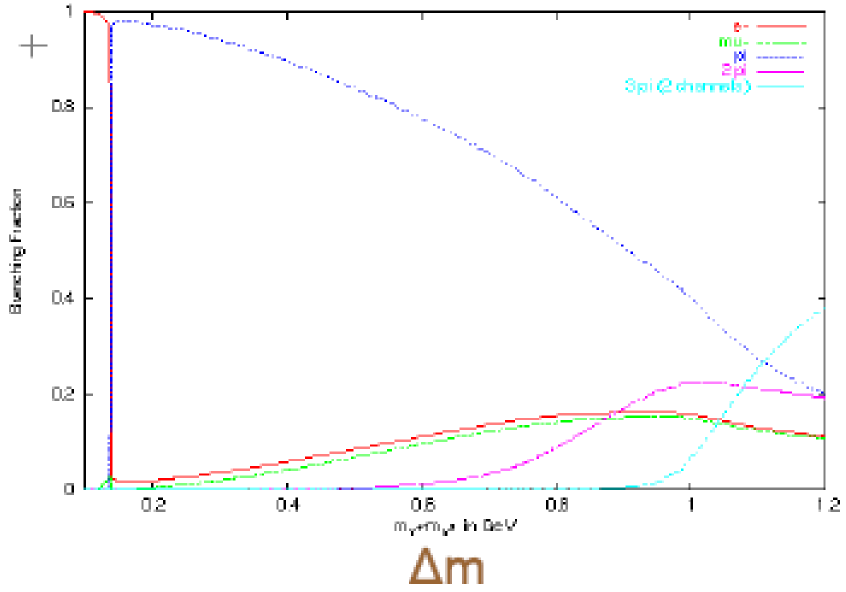


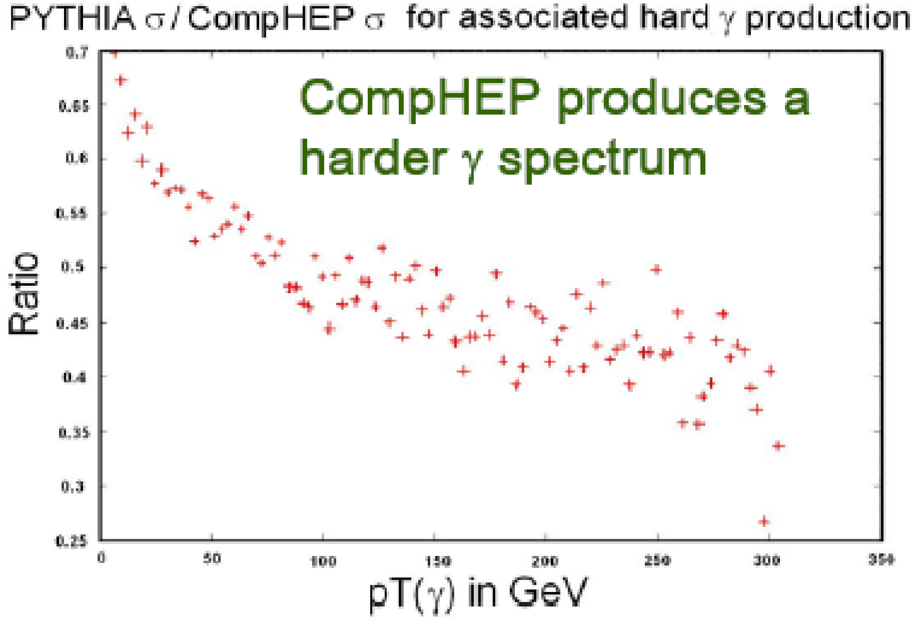
← Decays outside detector

100 microns→

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...



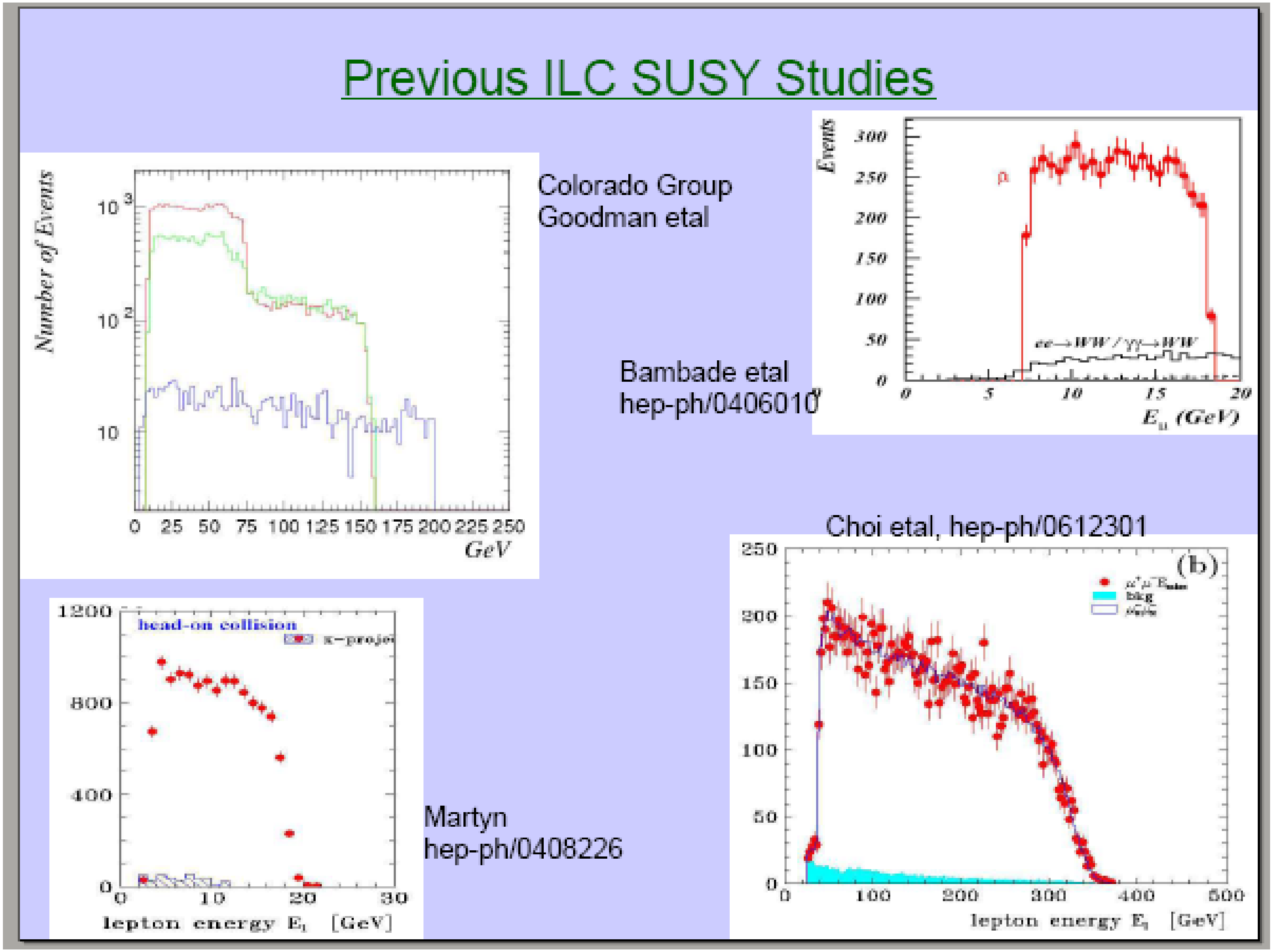

PYTHIA σ / CompHEP σ for associated hard γ production

CompHEP produces a harder γ spectrum

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

Now for some results.....

Is it REALLY this easy ??? Yes (sort of) with SPS1a..



Previous ILC SUSY Studies

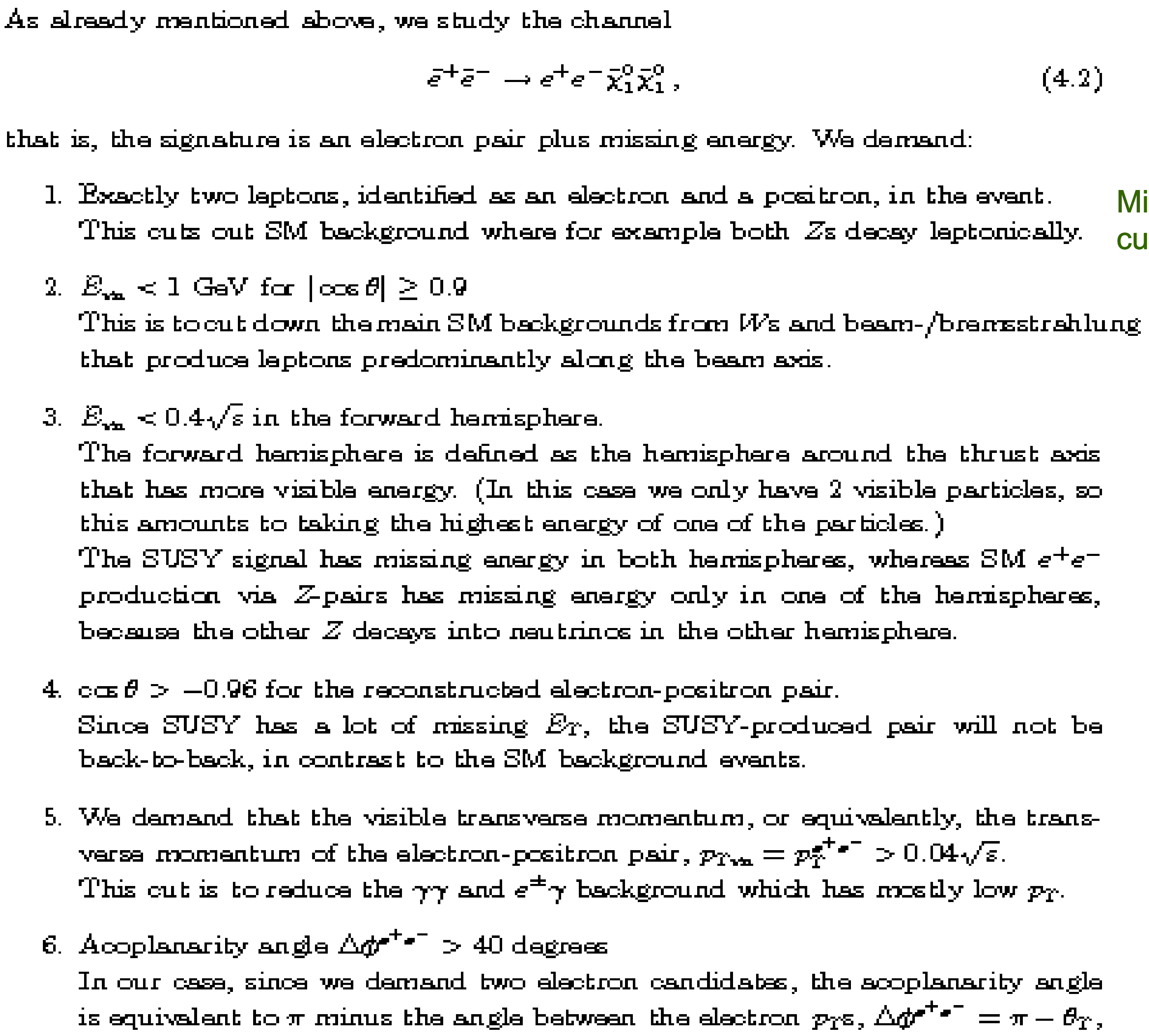
Colorado Group
Goodman etal

Bambade etal
hep-ph/0406010

Choi etal, hep-ph/0612301

Martyn
hep-ph/0408226

Sample Analysis Cuts : Selectrons



As already mentioned above, we study the channel

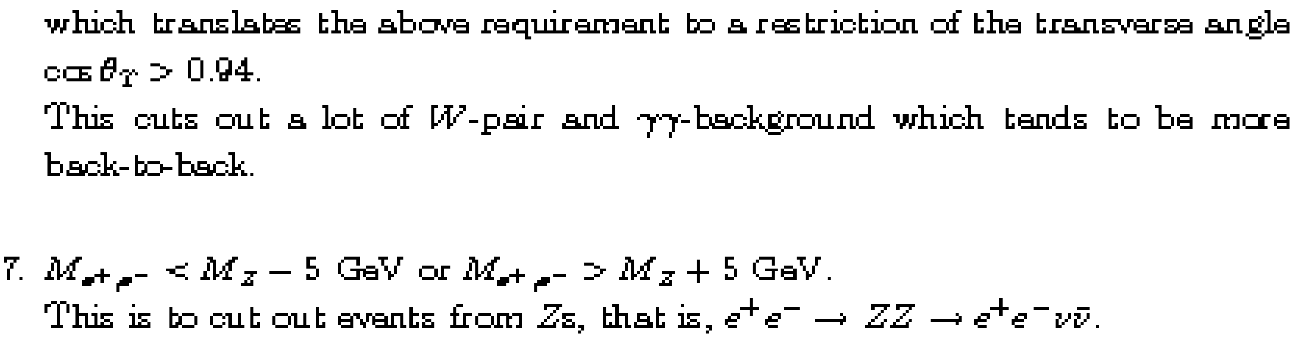
$$\tilde e^+\tilde e^- \to e^+e^-\tilde\chi_1^0\tilde\chi_1^0\,, \qquad (4.2)$$

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 Zs decay leptonically.
2. $E_{vis} < 1$ GeV for $|\cos\theta| \geq 0.9$ This is to cut down the main SM backgrounds from Ws and beam-/bremsstrahlung that produce leptons predominantly along the beam axis.
3. $E_{vis} < 0.4\sqrt{s}$ 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, $p_{T vis} = p_T^{e^+e^-} > 0.04\sqrt{s}$. 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 π minus the angle between the electron p_Ts, $\Delta\phi^{e^+e^-} = \pi - \theta_T$,

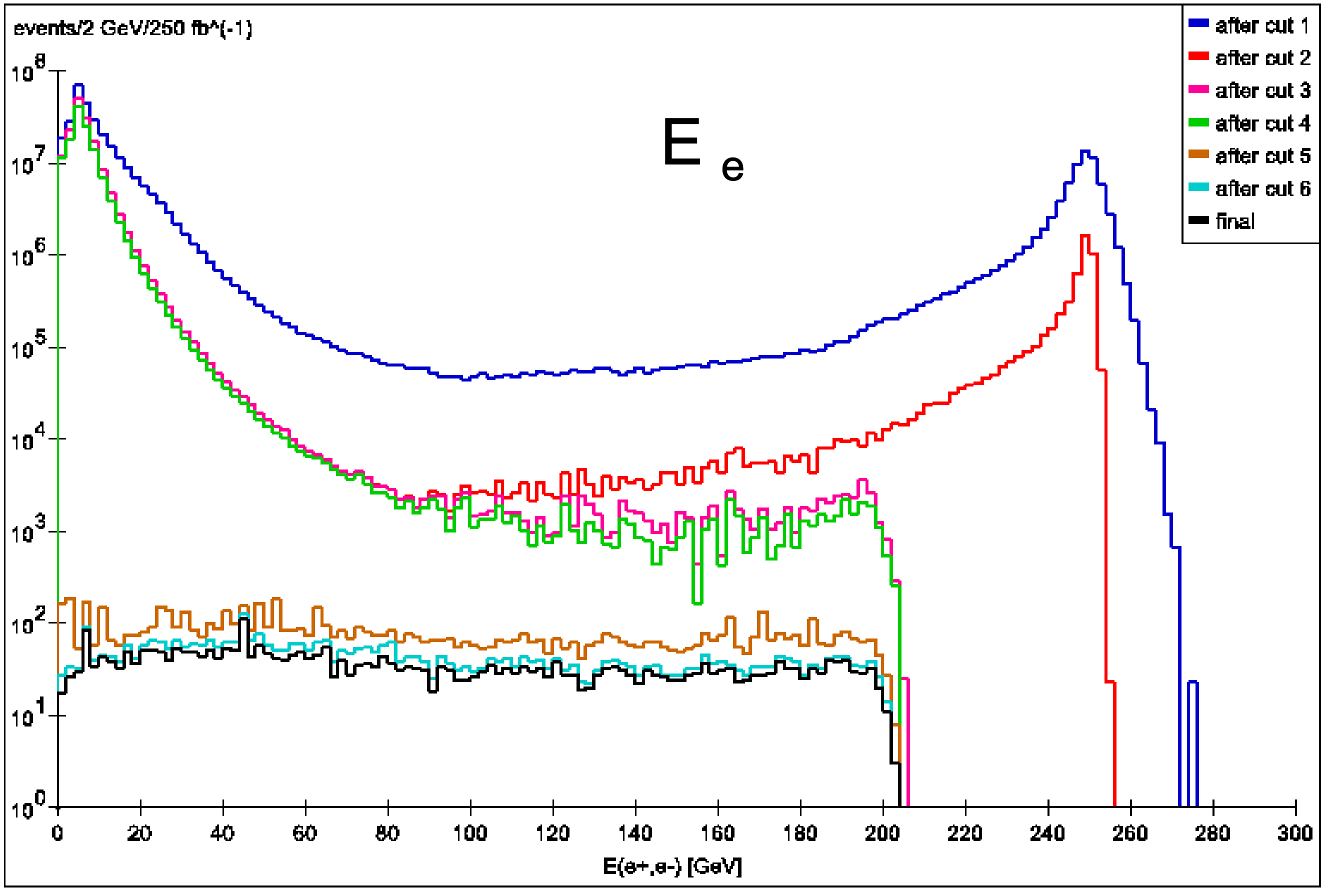
Minimal quality cuts applied

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.

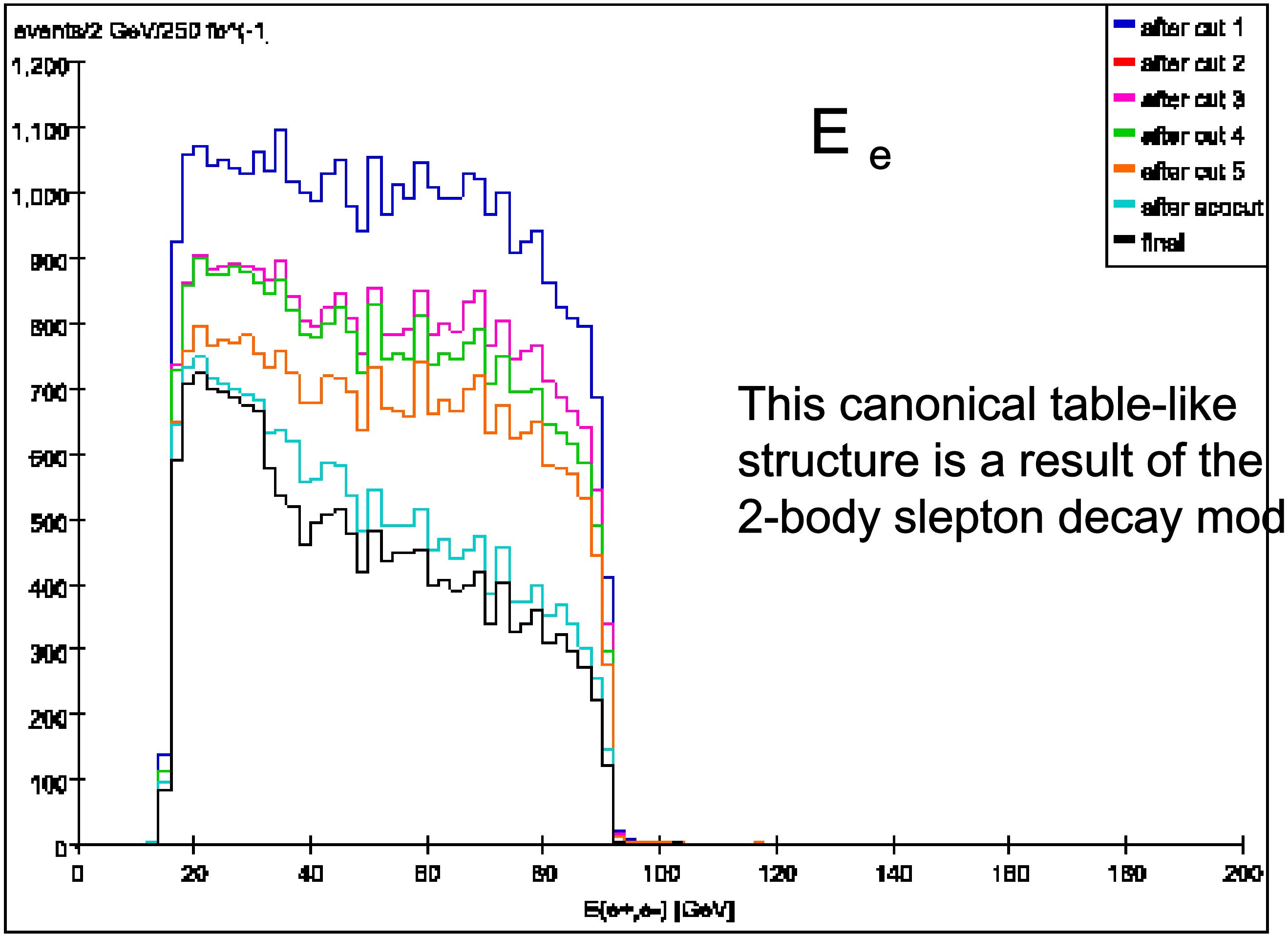
7. $M_{e^+e^-} < M_Z - 5$ GeV or $M_{e^+e^-} > M_Z + 5$ GeV.
This is to cut out events from Zs, that is, $e^+e^- \to ZZ \to e^+e^-\nu\bar{\nu}$.



These cuts are very effective at reducing enormous SM backgrounds by several orders of magnitude…

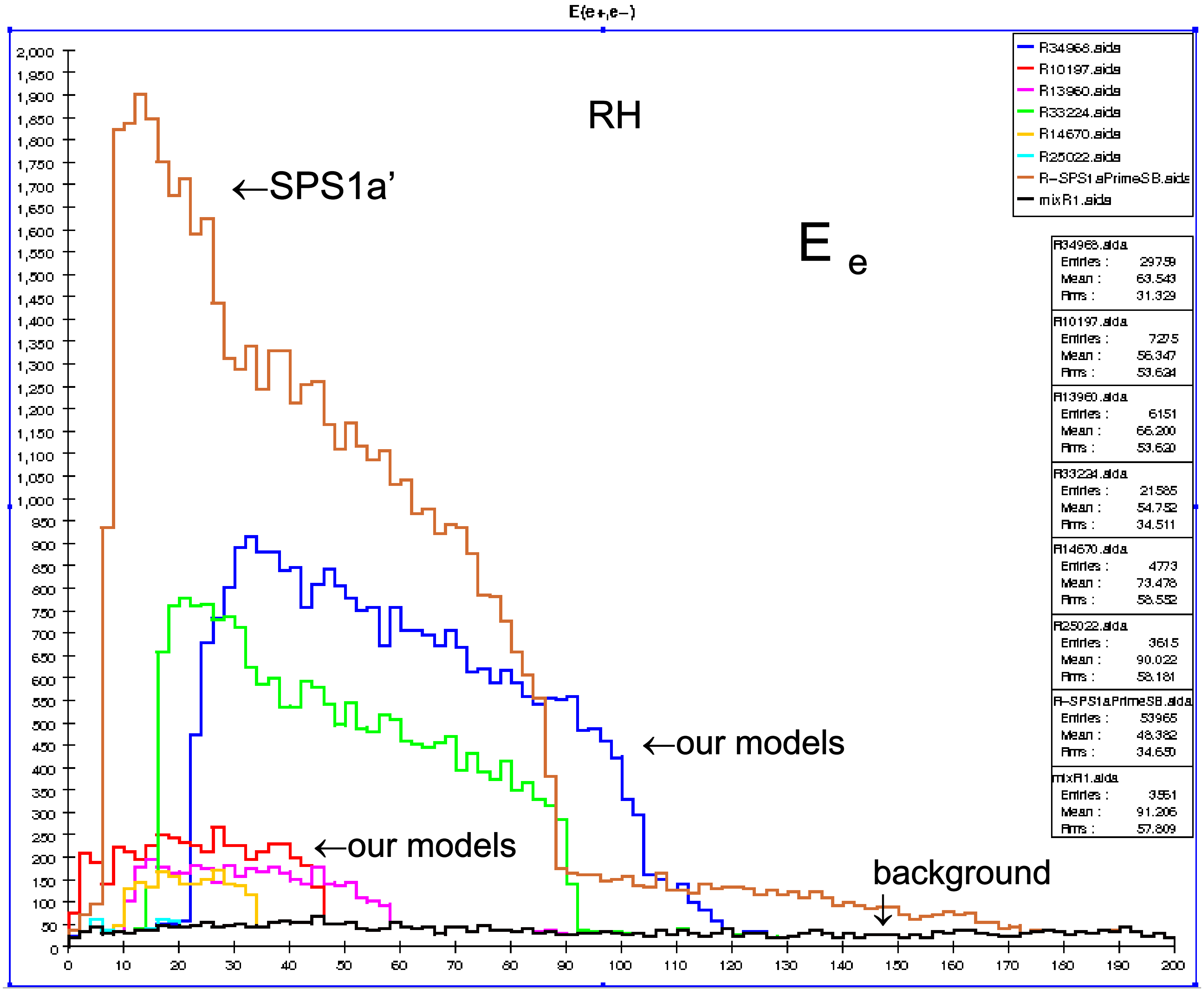
Sample Analysis Cuts : Selectrons (cont.)

..but the signal is only reduced by a factor of 2!!!



This canonical table-like structure is a result of the 2-body slepton decay mode

Now for some analyses…



RH

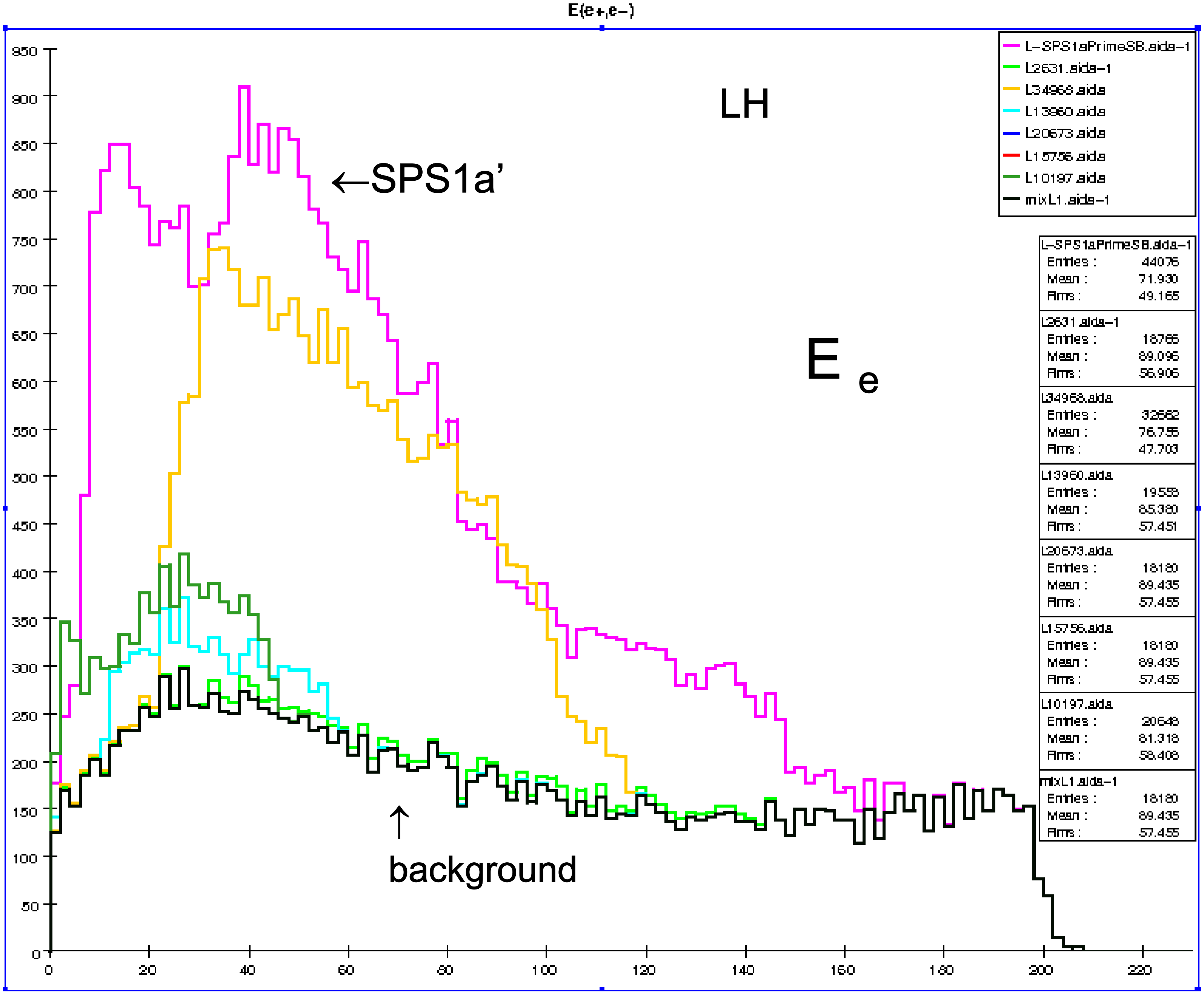
E_e

←SPS1a'

←our models

←our models

background
↓



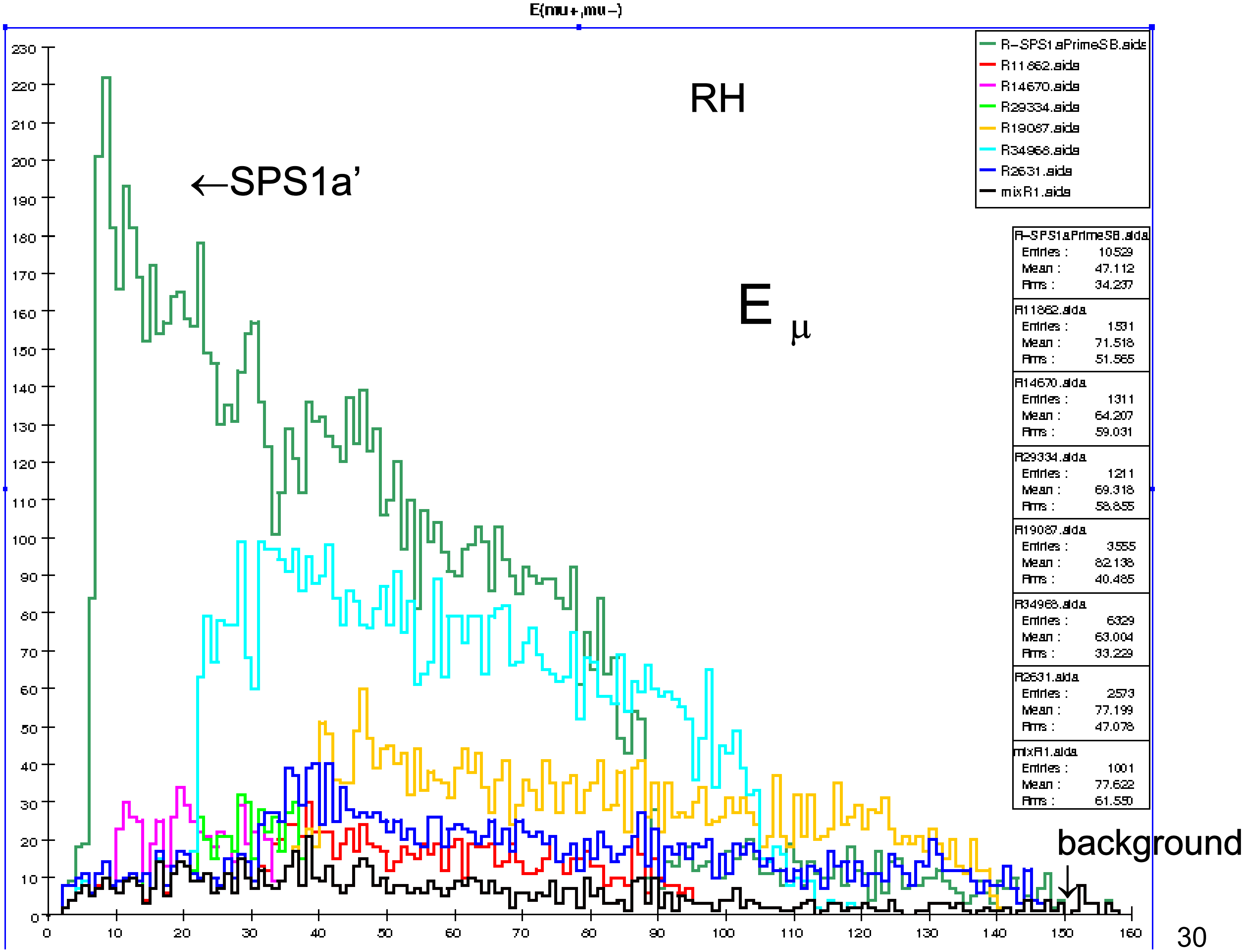
LH

E_e

←SPS1a’

↑

background

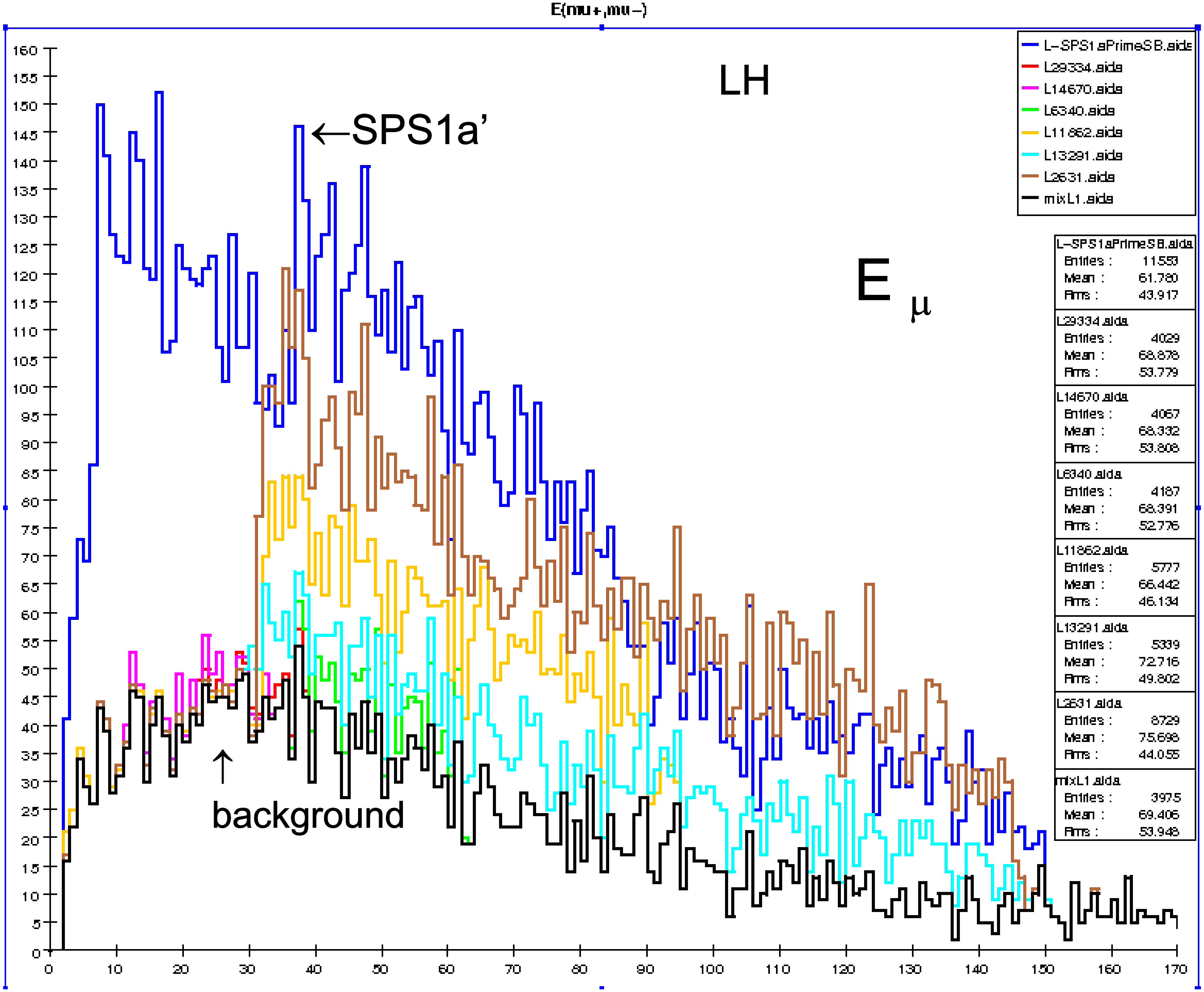


RH

←SPS1a’

E $_{\mu}$

background
↓

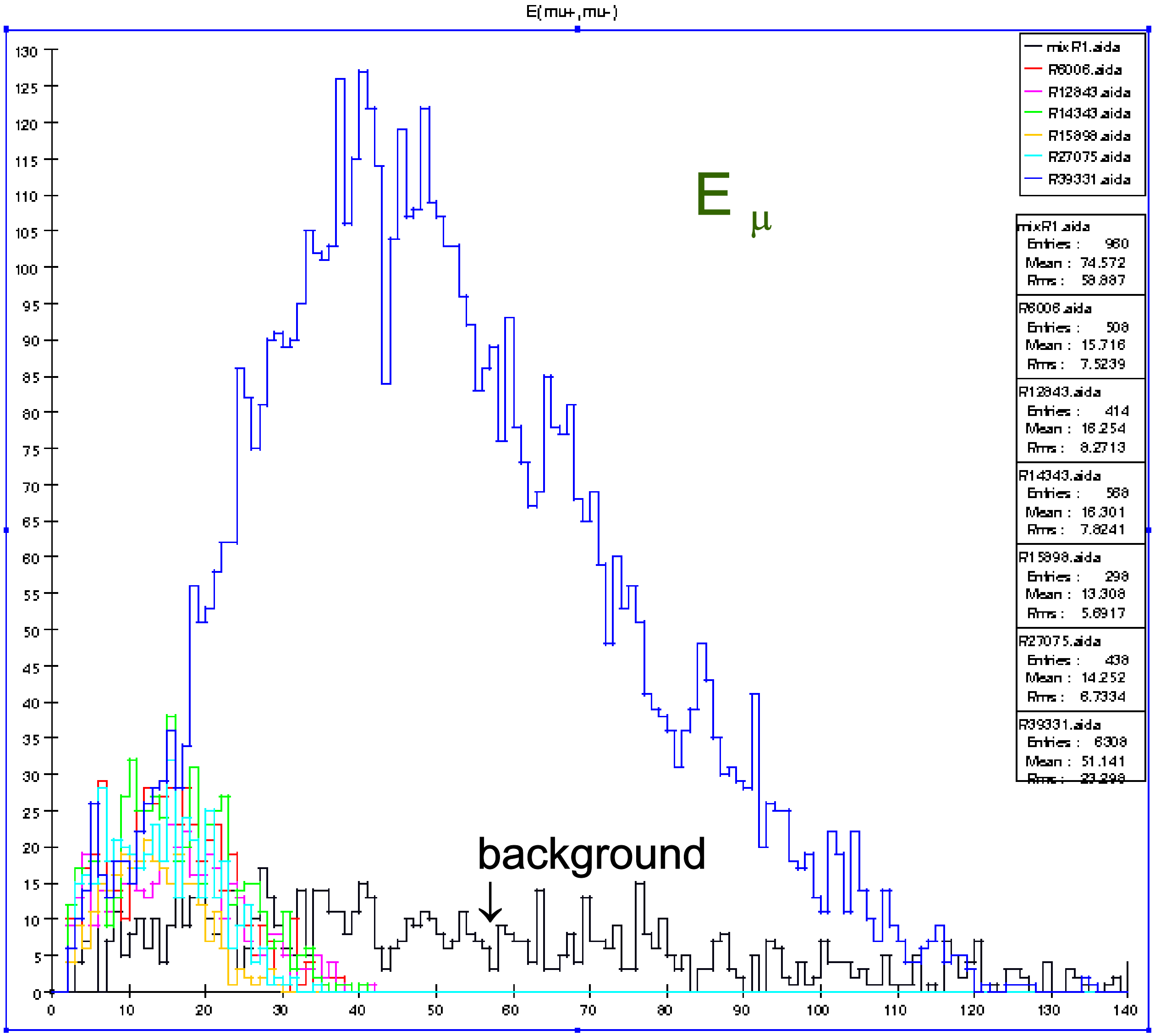

E(mu+,mu-)
LH
E_μ
←SPS1a'
↑
background
L-SPS1aPrimeSB.aida
L29334.aida
L14670.aida
L6340.aida
L11862.aida
L13291.aida
L2631.aida
mixL1.aida
L-SPS1aPrimeSB.aida Entries : 11553 Mean : 61.780 Rms : 43.917
L29334.aida Entries : 4029 Mean : 68.878 Rms : 53.779
L14670.aida Entries : 4067 Mean : 68.332 Rms : 53.808
L6340.aida Entries : 4187 Mean : 68.391 Rms : 52.776
L11862.aida Entries : 5777 Mean : 66.442 Rms : 46.134
L13291.aida Entries : 5339 Mean : 72.716 Rms : 49.802
L2631.aida Entries : 8729 Mean : 75.698 Rms : 44.055
mixL1.aida Entries : 3975 Mean : 69.406 Rms : 53.948
0 5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85 90 95 100 105 110 115 120 125 130 135 140 145 150 155 160
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170

Some Immediate Lessons:

- SPS1a’ produces rates significantly larger than all our models
- The variation in rates is by up to a factor of ~50! Clearly models with smaller rates will be challenging…
- The ratio of signals and backgrounds is very polarization dependent… usually one polarization choice is far better than another but the particular choice depends on the final state. For sleptons, RH polarization is the best choice to kill large WW backgrounds.

And now for another lesson: SUSY is a background for SUSY…

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.



RH Polarization

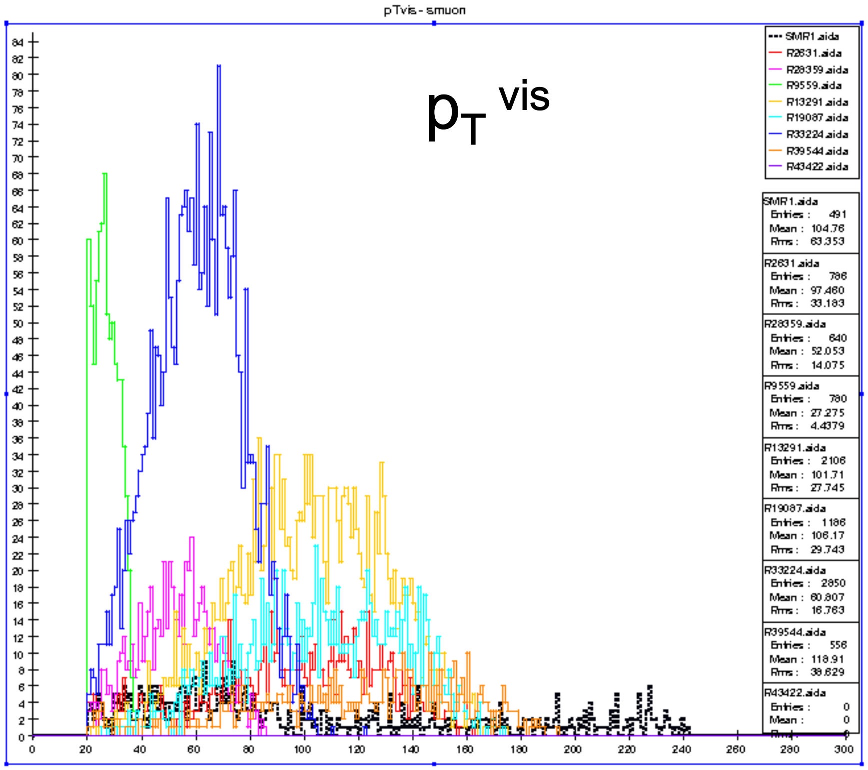
This is a rather common feature.. here we have mostly charginos.. notice the shape difference with the previous plot..

Sometimes both real signals and fakes appear together

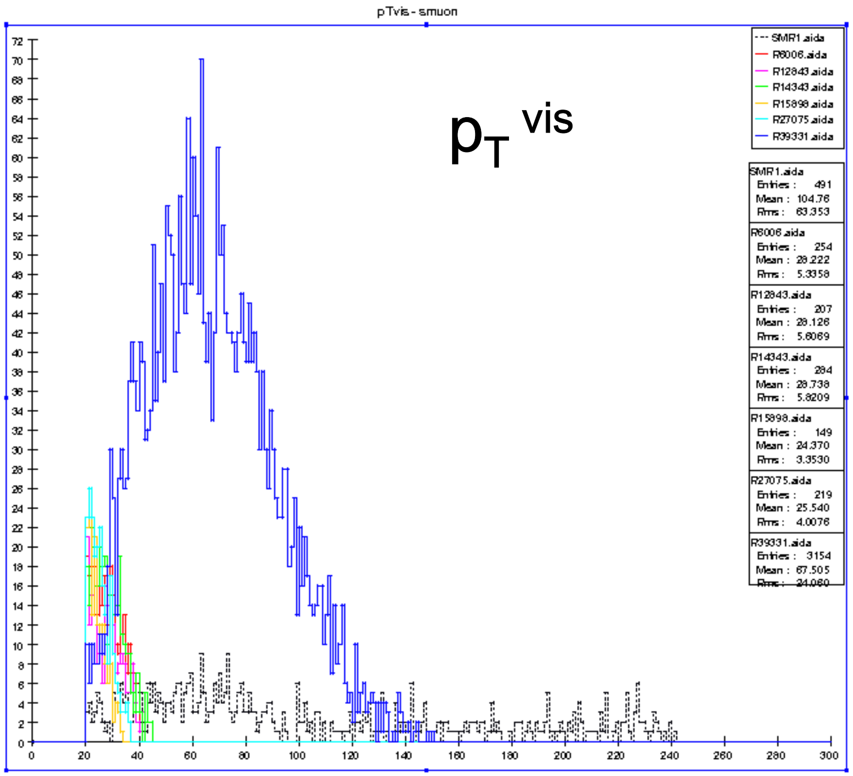
Just because you are looking for smuons or selectrons or neutralinos doesn’t mean what you find is the state you are actually looking for… though a signal is clearly observed above the background and it *is* SUSY.

This happens in almost every analysis we’ve done; the trick is to be able to ascertain the true source of the signal…

Much of the time this can be done by looking at several other kinematic distributions which depend on the particular choice of final state, e.g.,



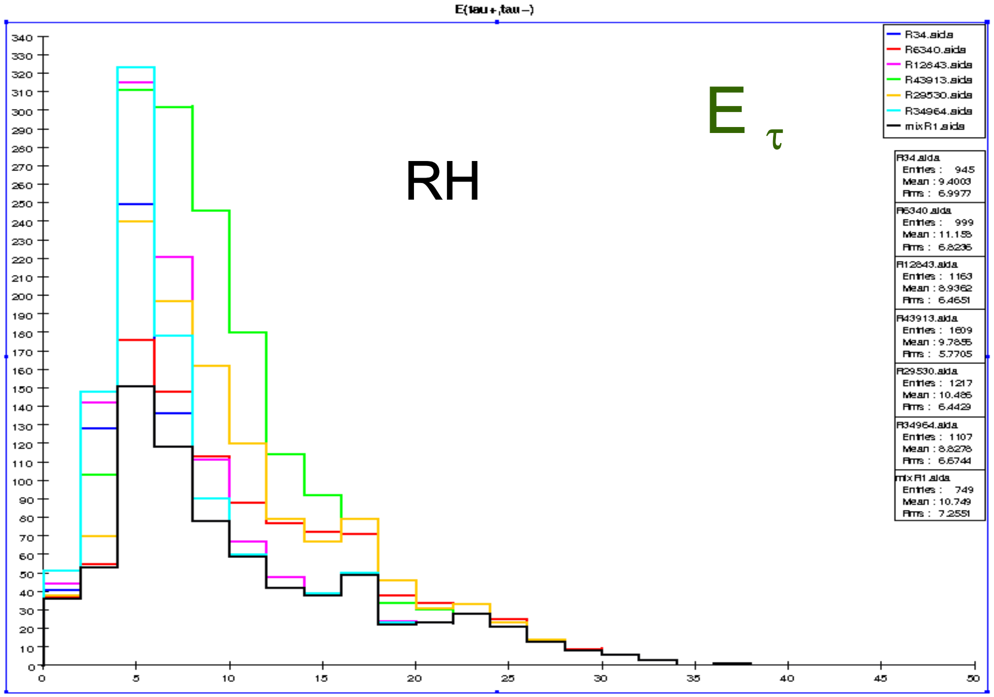
smuons

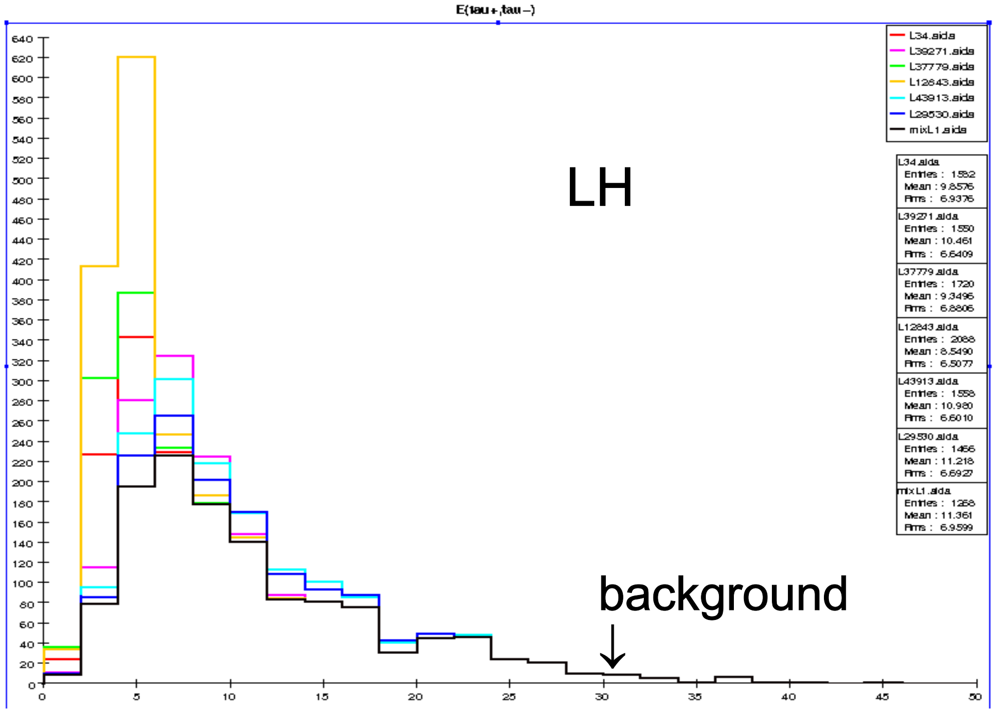


inos

For our set of models, μ'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 arising from decaying inos are *generally* from multibody modes and are far softer (unless on-shell W's are produced).

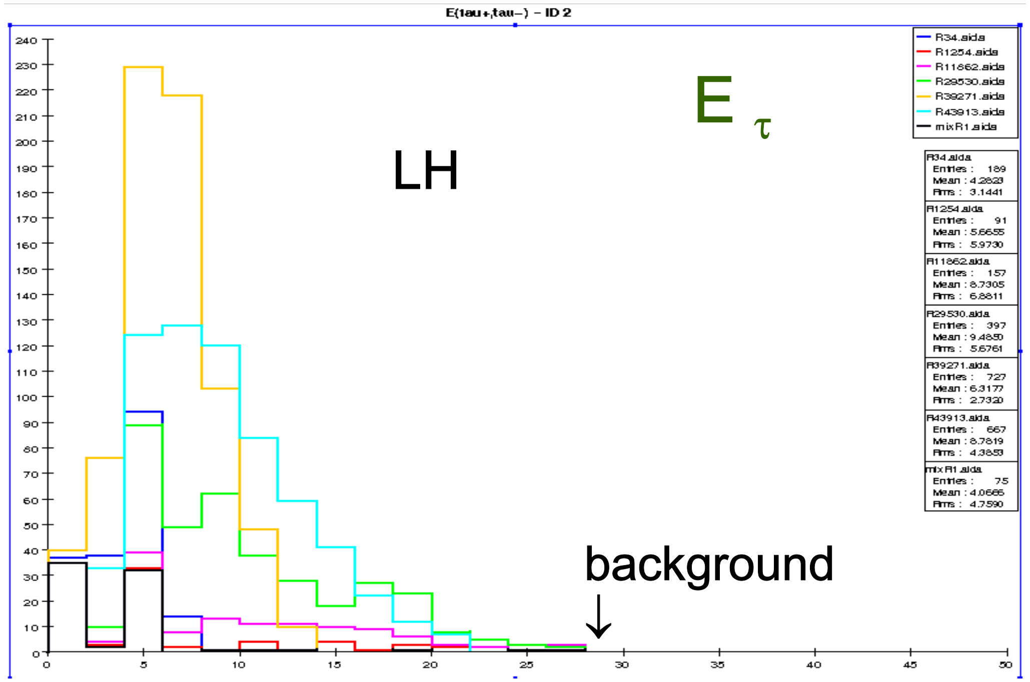
STAUS

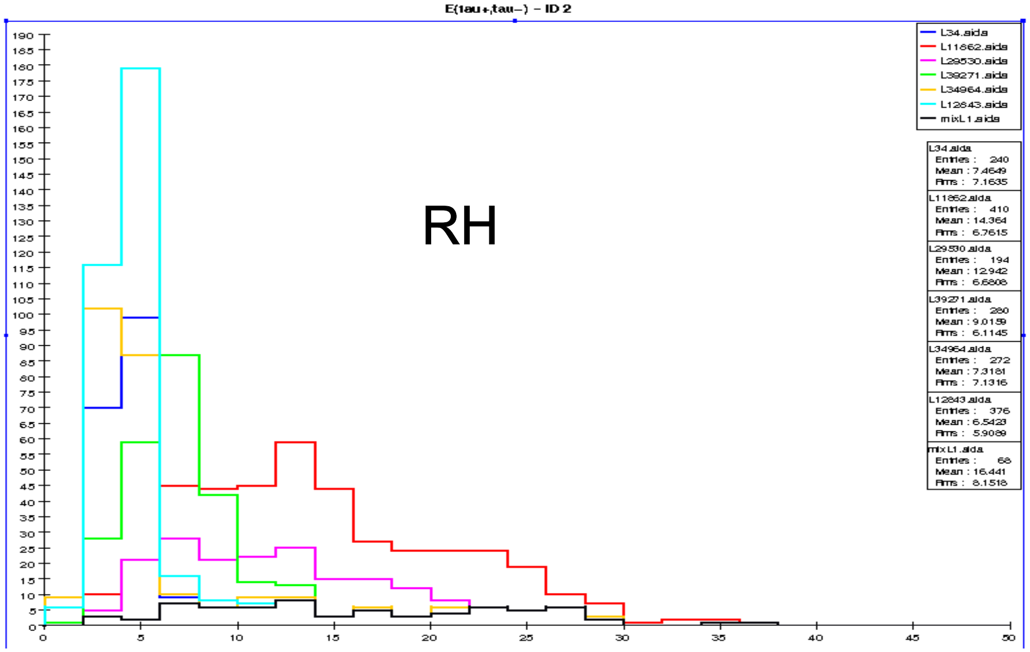




Staus are somewhat harder to see due to both the efficiency of tau identification and the large beam backgrounds due to the lack of low angle muon ID. These can be reduced by *not* including the electron mode in the tau decays…

Furthermore, jet energies are fairly low…





The backgrounds are now indeed tiny..

..Of course this doesn't solve all our problems as now the number of fake models is a bit increased.

As in the smuon case we can devise ways to help differentiate the source of the SUSY signal..

♠ Sneutrino pairs are kinematically accessible in 11/242 models

For the first two generations we have :

(*i*) sneutrino → ν + LSP is invisible, but generally dominates X

(*ii*) sneutrino → W + slepton → jj + lepton + LSP : not allowed on-shell X

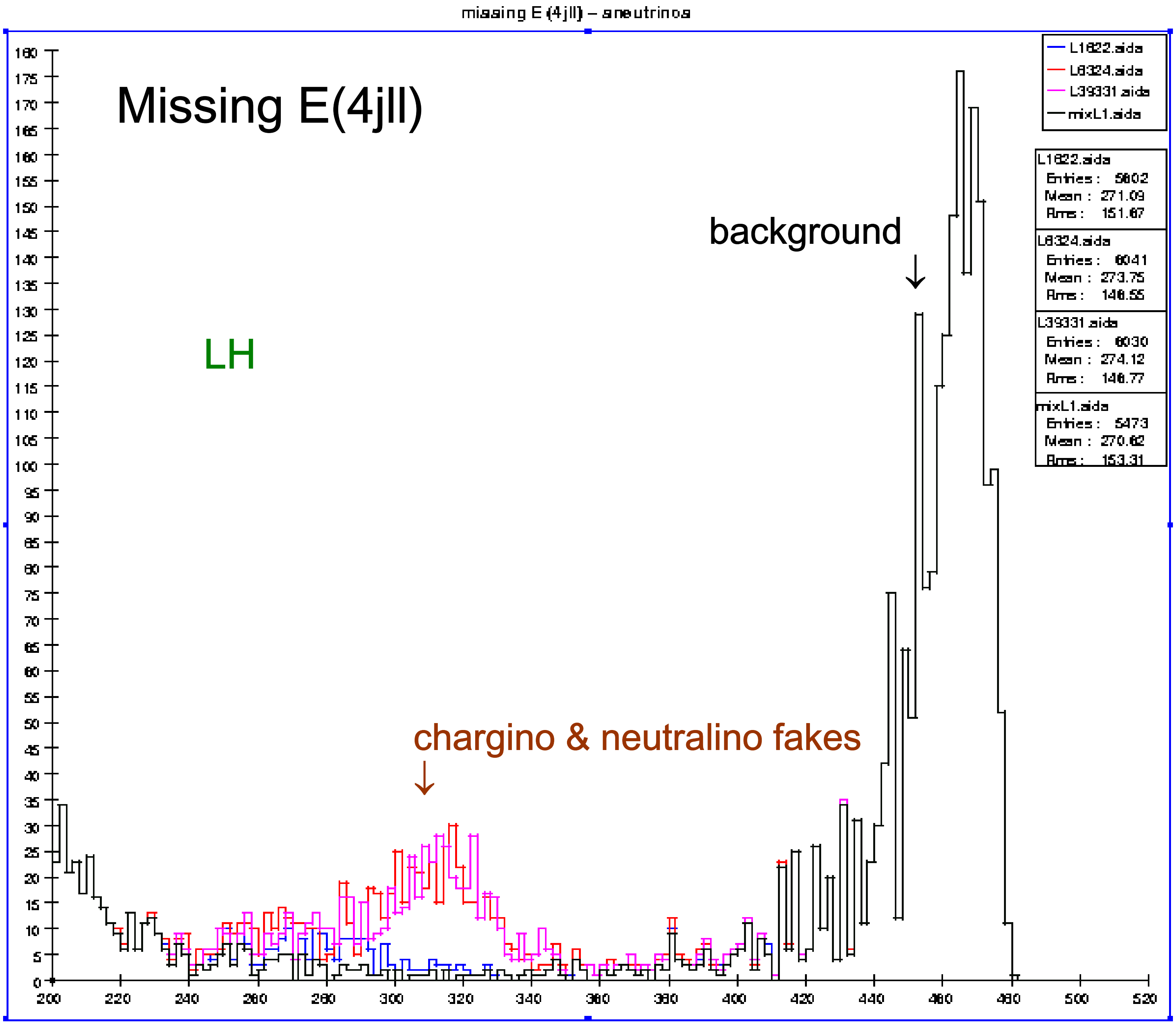
(*iii*) sneutrino → χ_1^+ + **lepton** → jj +lepton +LSP : allowed in only one model and the resulting jets are rather soft….. X

(*iv*) sneutrino → ν + χ_2^0 → jj +missing E : allowed only in one model and the jets are again too soft… X

♣ → sneutrinos are not observable at 500 GeV in any model…..

…and tagging the sneutrino final state with a γ doesn't work either.

Missing E(4jll)

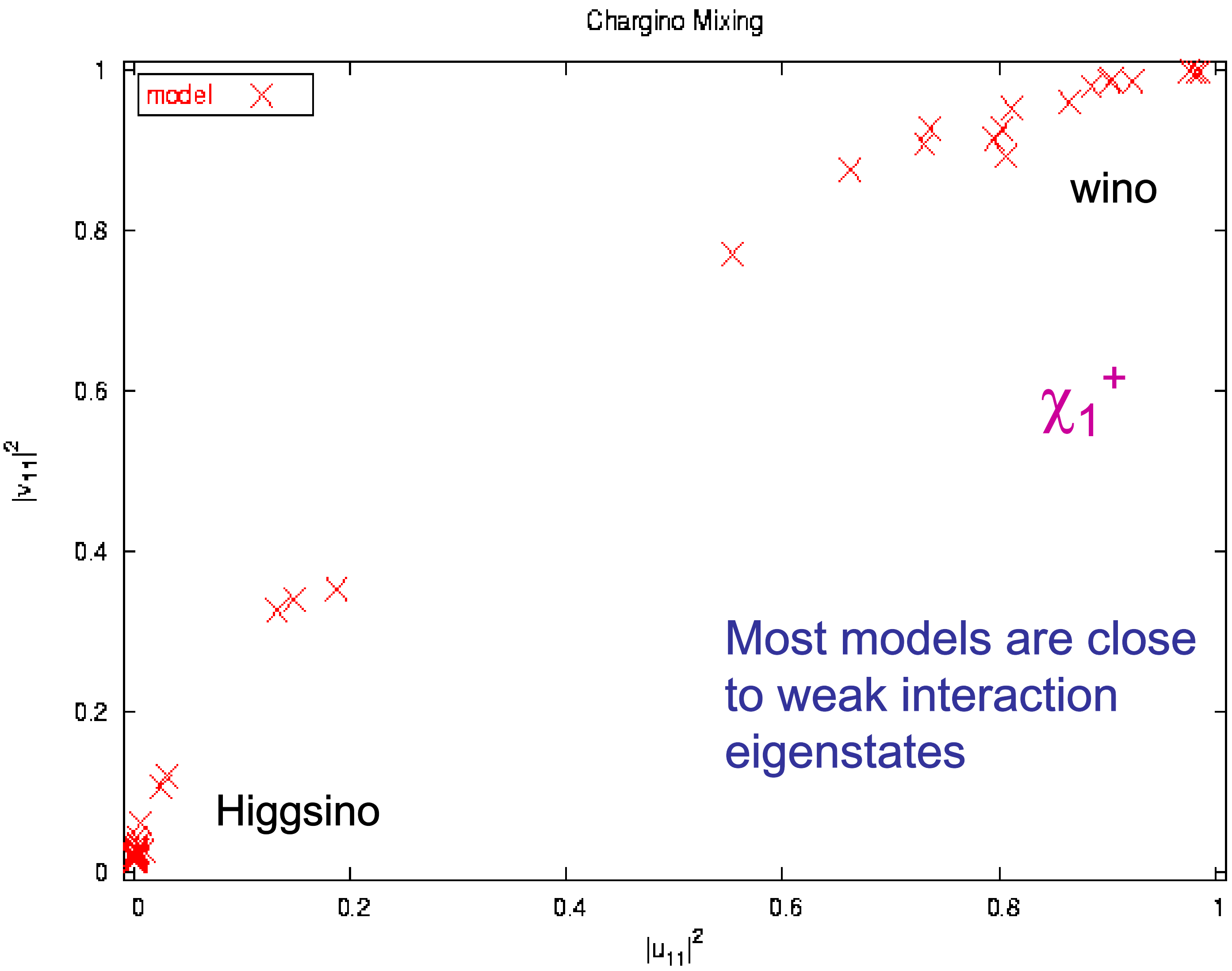


LH

background ↓

chargino & neutralino fakes ↓

CHARGINOS : MULTIPLE ANLAYSES REQUIRED

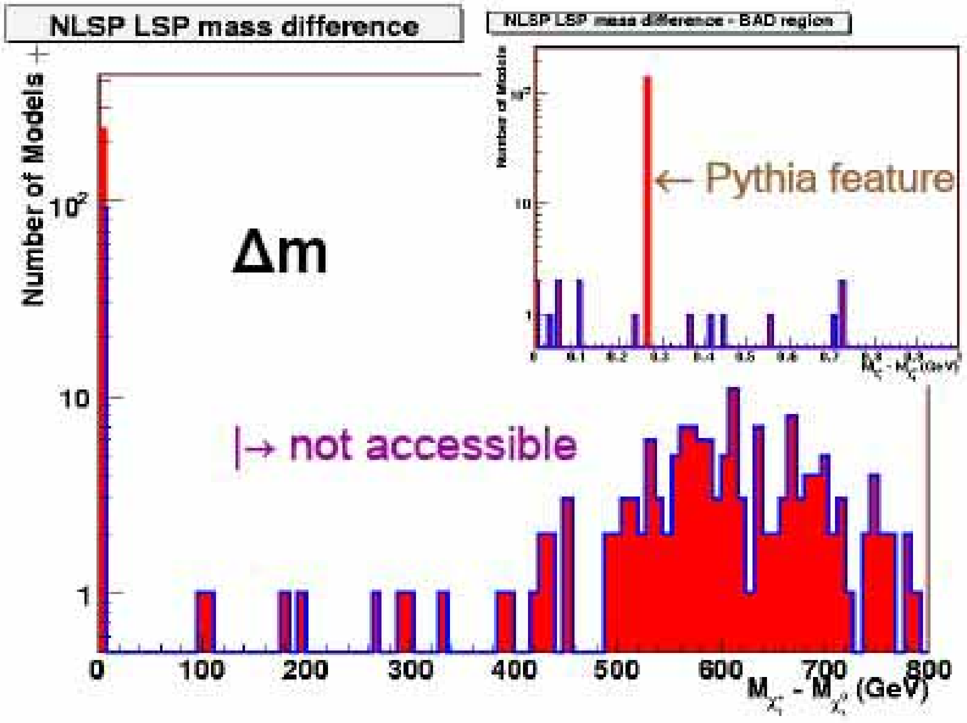


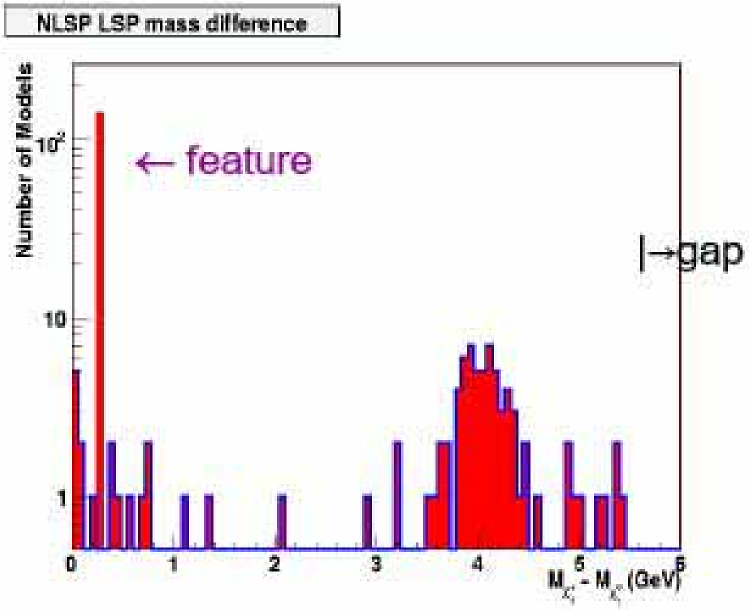
Most models are close to weak interaction eigenstates

Chargino Analyses:

Difficult spectrum

Δm is mostly either very small (leading to difficult signatures) or too large (not kinematically accessible).

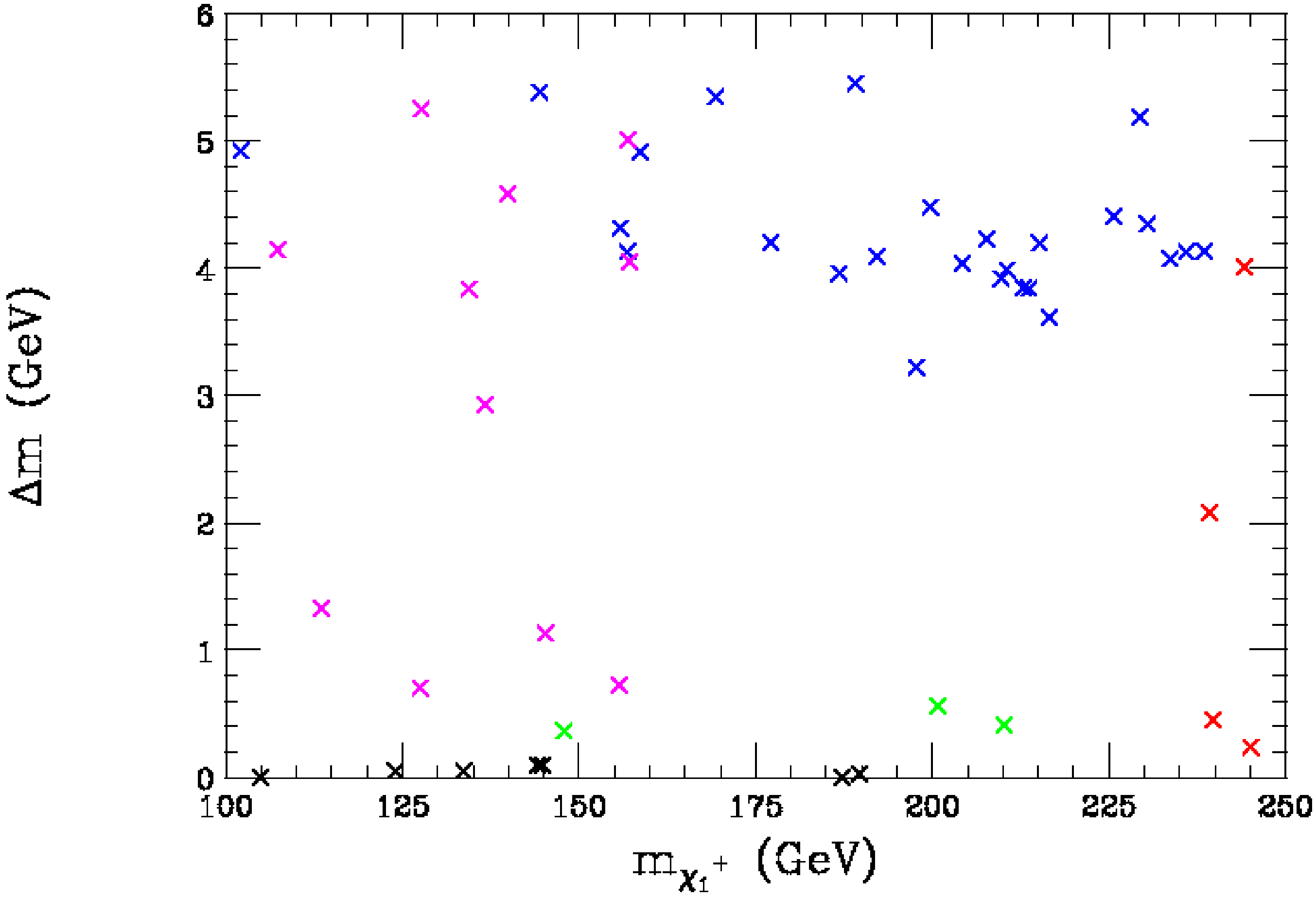




↑↑↑↑↑↑↑↑

Δm clusters in the few GeV mass region which has a lot of serious γγ/γe-induced backgrounds

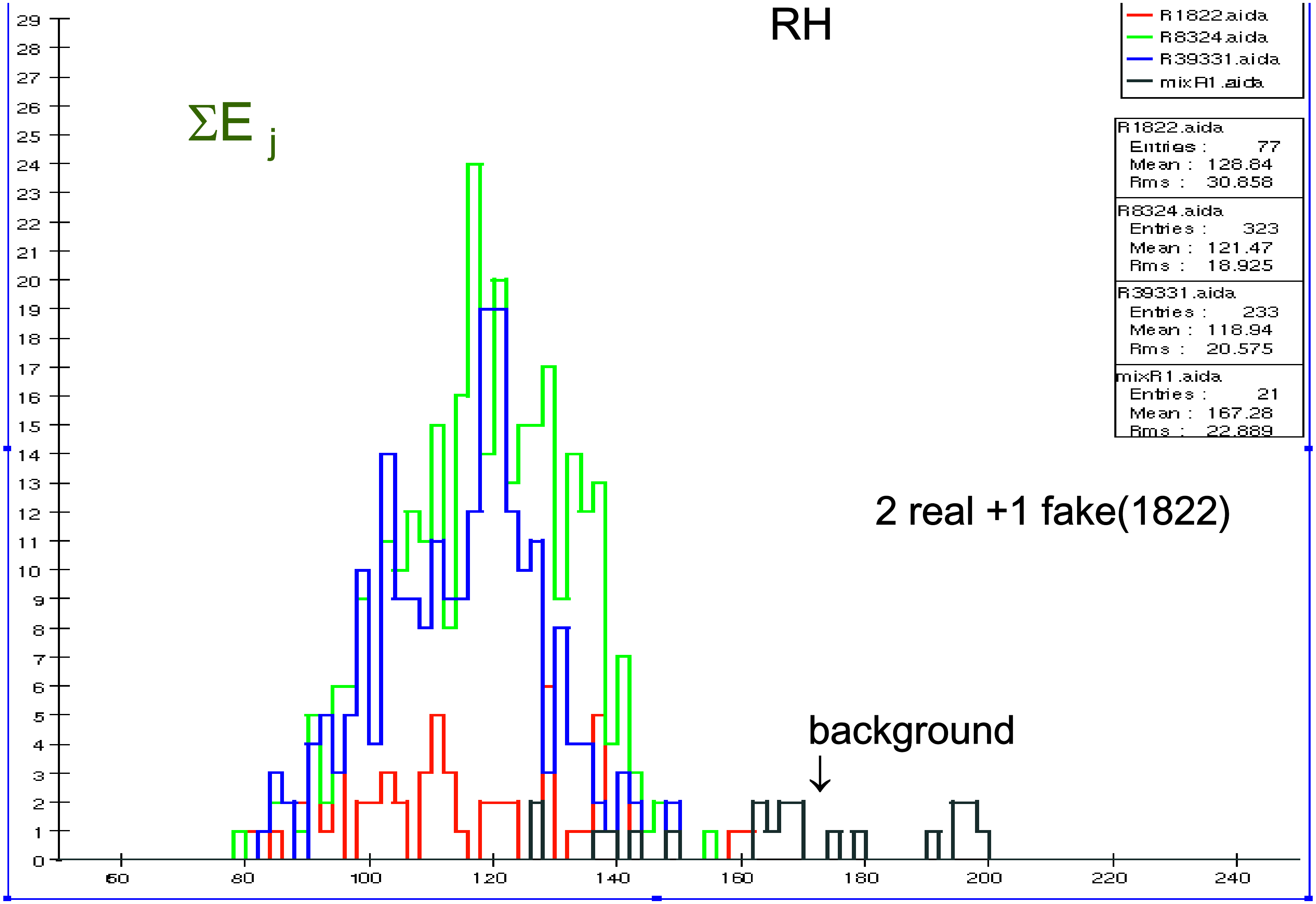
Charginos are seen in many different analyses…



Green = radiative only Blue = off-shell W Red = missed

Black = stable only Magenta = off-shell & radiative

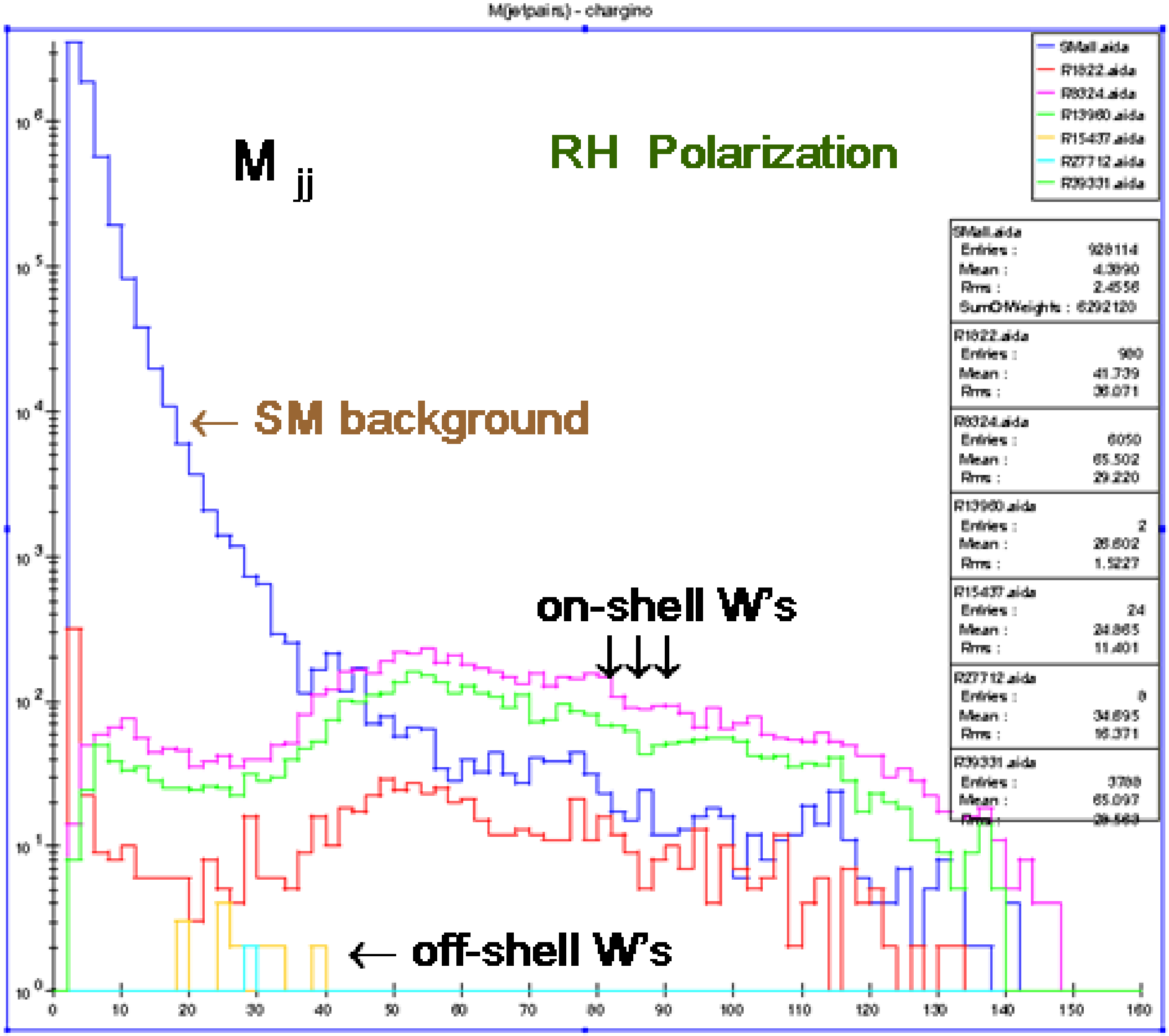
Chargino--4j + missing E analysis : Jet Pair Energy



2 real +1 fake(1822)

background ↓

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



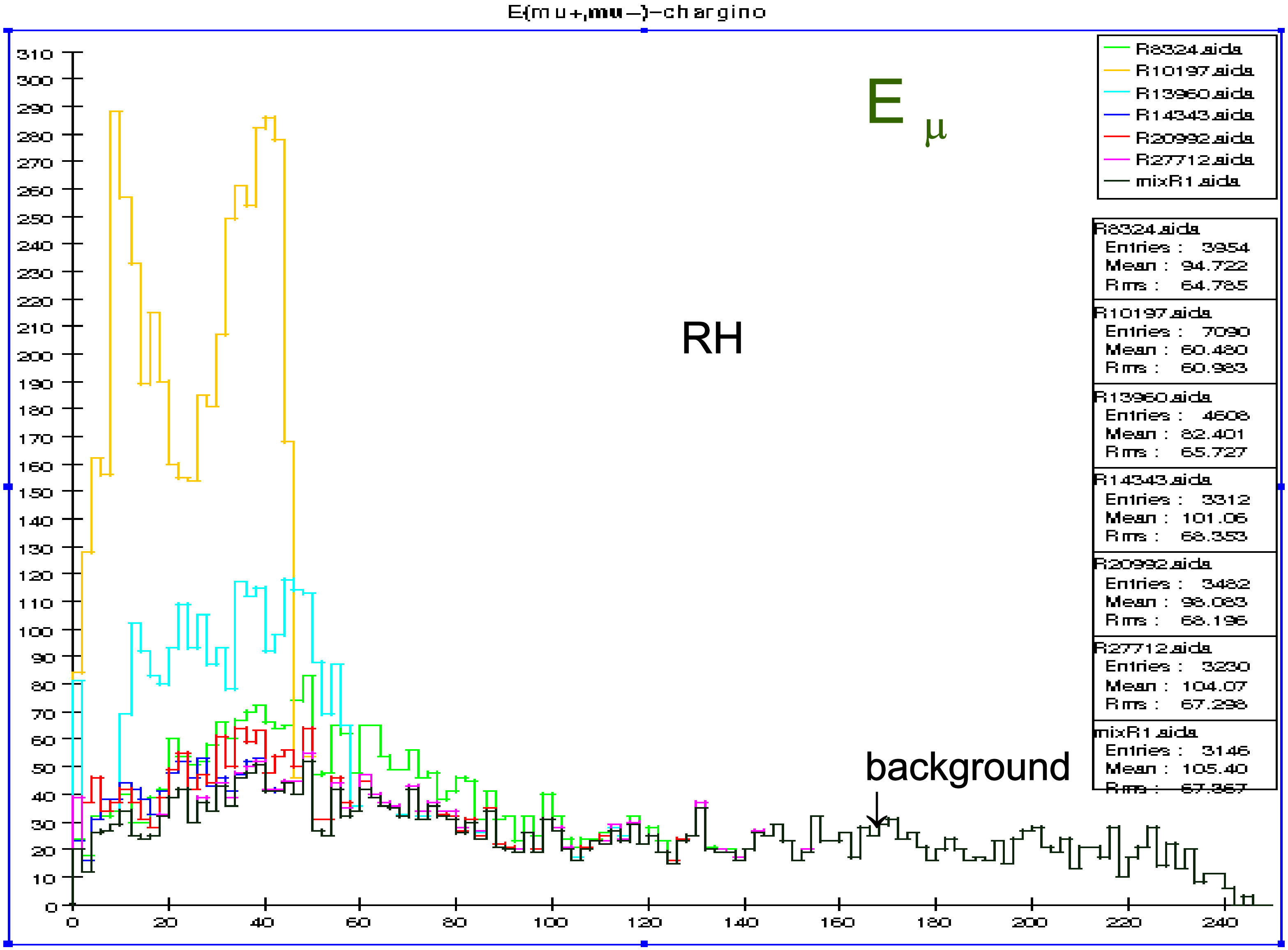
Again very difficult when off-shell W's are produced ….

fake

Model 1822 again,

$2\chi_2^0$ production

Chargino--2μ + missing E analysis : Muon Energy Analysis



R8324.aida
Entries : 3954
Mean : 94.722
Rms : 64.785

R10197.aida
Entries : 7090
Mean : 60.480
Rms : 60.983

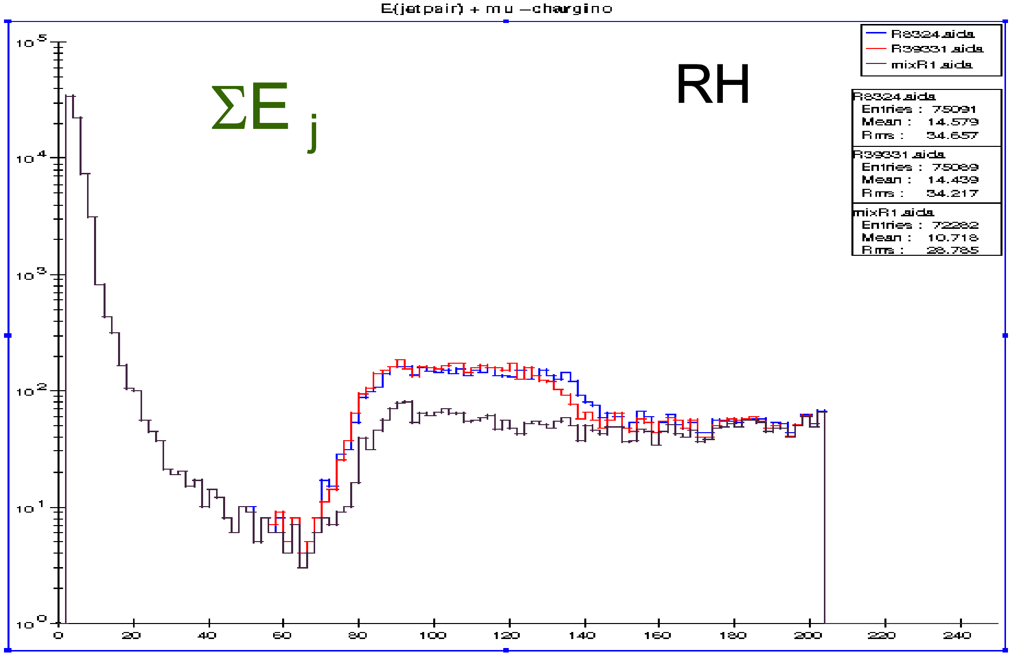
R13960.aida
Entries : 4608
Mean : 82.401
Rms : 65.727

R14343.aida
Entries : 3312
Mean : 101.06
Rms : 68.353

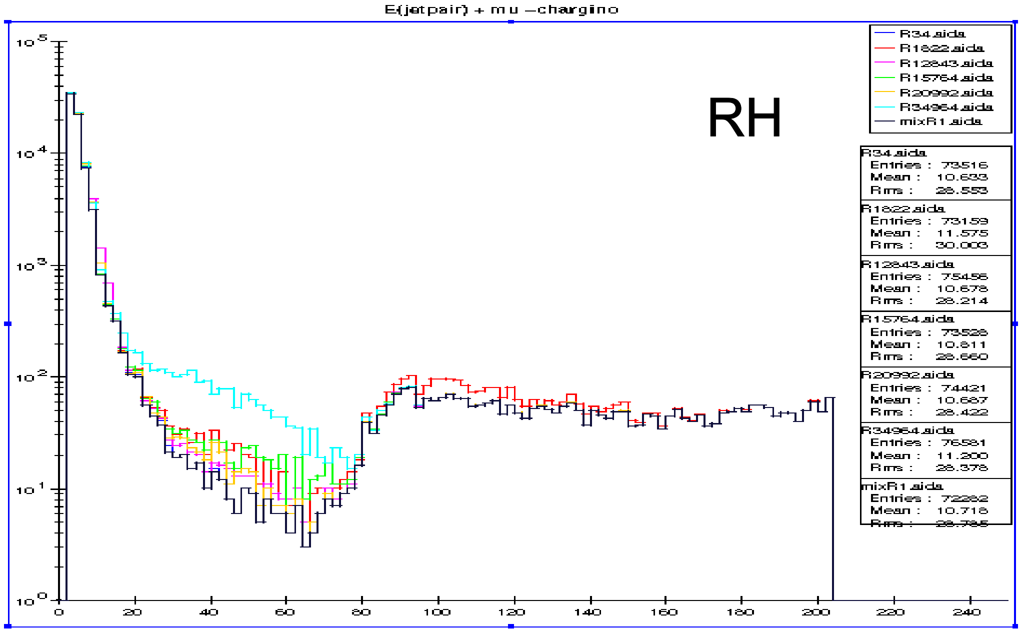
R20992.aida
Entries : 3482
Mean : 98.083
Rms : 68.196

R27712.aida
Entries : 3230
Mean : 104.07
Rms : 67.298

mixR1.aida
Entries : 3146
Mean : 105.40
Rms : 67.367

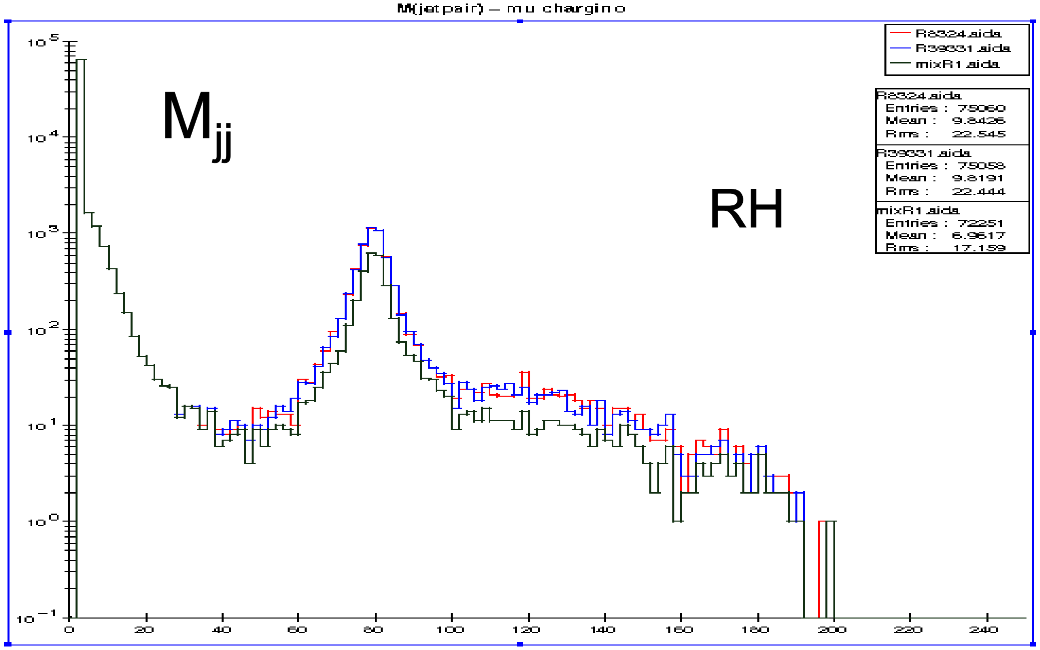


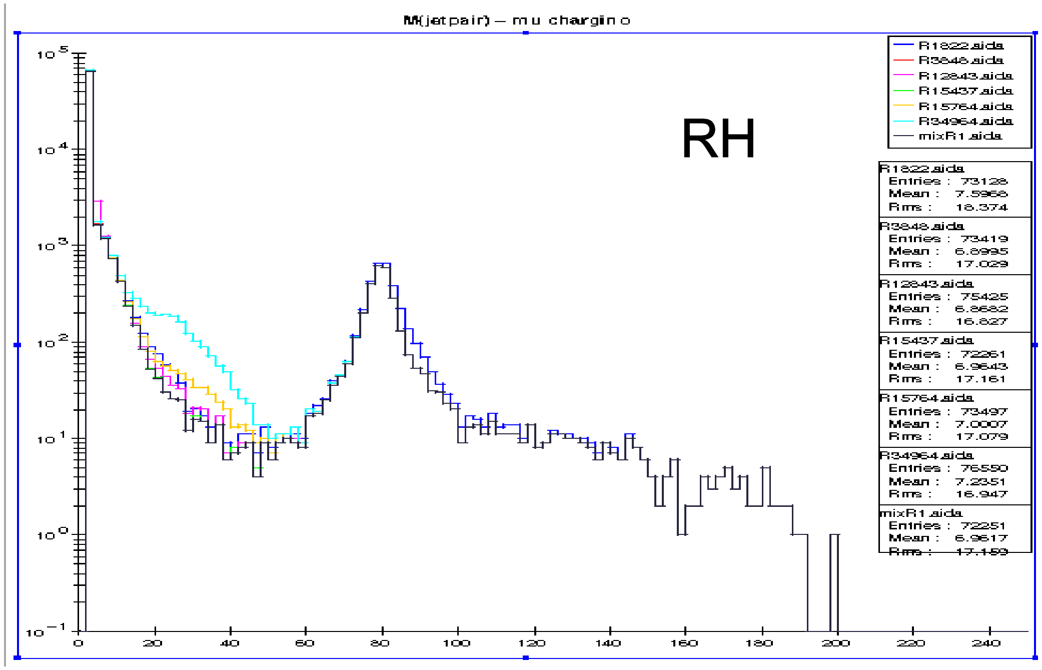
Charginos--2 jet+ muon +missing E Analysis: Jet Pair Energy



Both on- and off-shell W’s are captured by this analysis

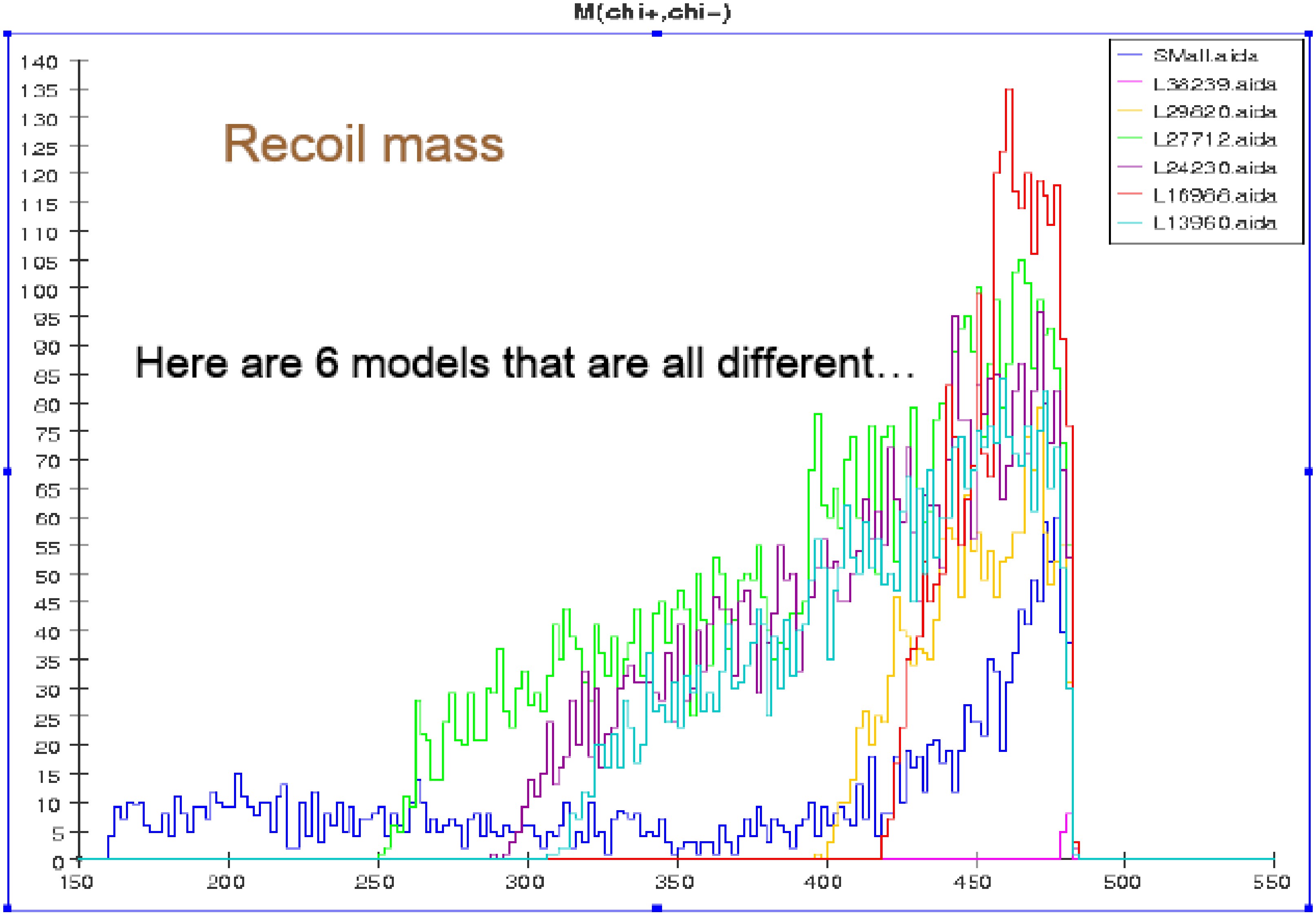
Charginos--2 jet+ muon +missing E Analysis: Jet Pair Energy





Again we see that both on- and off-shell W's are captured by this analysis

Small Δm ~ 1 GeV, Charginos: soft hadrons + photon tag

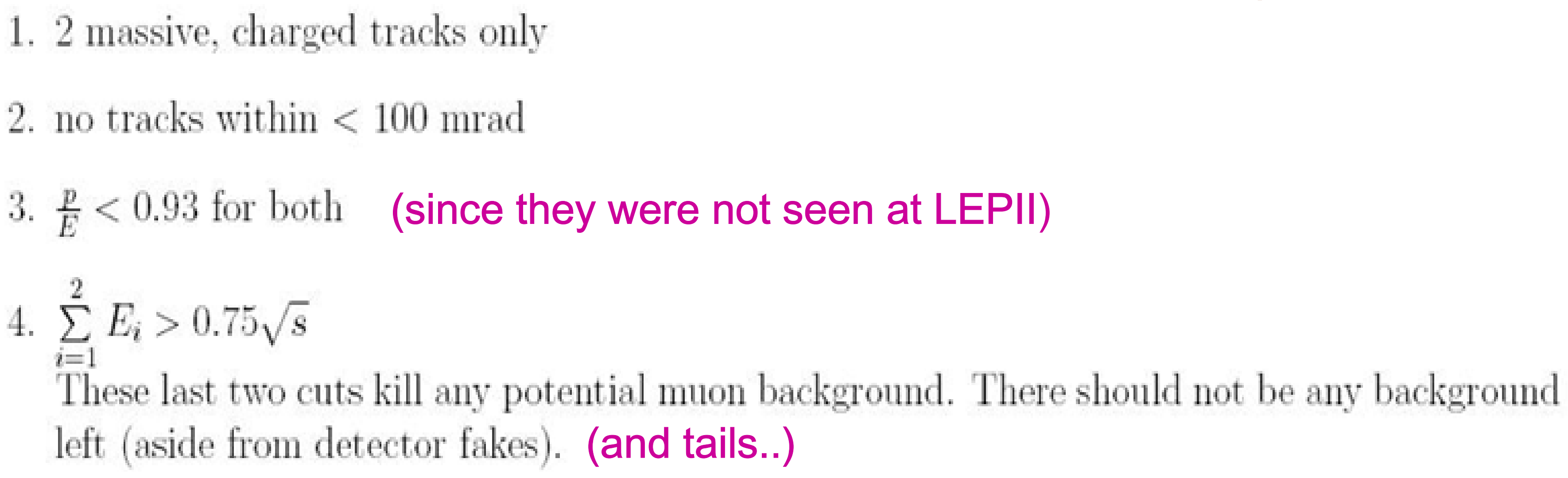


Recoil mass

Here are 6 models that are all different…

Long-lived `Chargino' Analysis

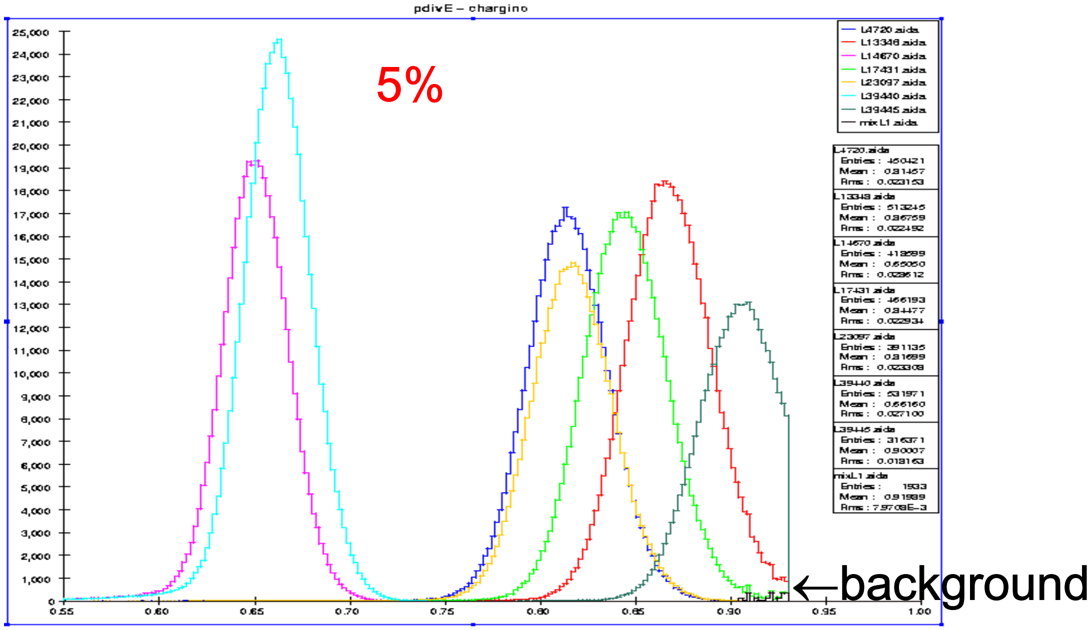
A surprisingly large number of our models have these particles



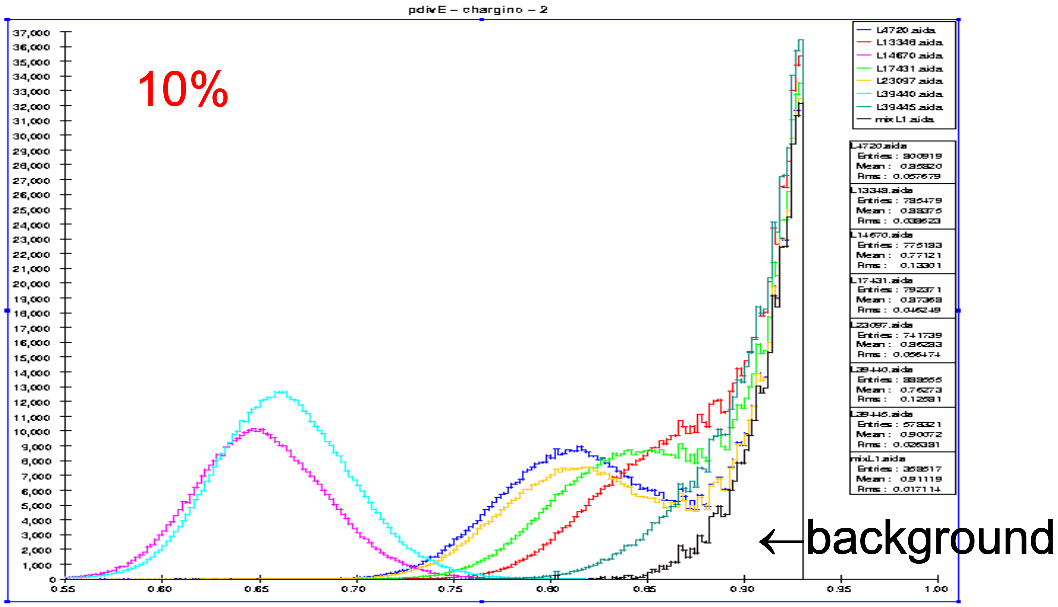
1. 2 massive, charged tracks only
2. no tracks within < 100 mrad
3. $\frac{p}{E} < 0.93$ for both (since they were not seen at LEPII)
4. $\sum_{i=1}^{2} E_i > 0.75\sqrt{s}$

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

β=p/E : p is determined by track curvature in the B field while E is determined by some other method. Note TOF and/or dE/dx, is *not yet in the vanilla lcsim…*To mimic this we assume β is determined with a track E smearing of $\delta E (\rightarrow \delta\beta)$=5 or 10% in our analysis before piping through lcsim, consistent with ILC detector models. (thanks to B. Schumm etal)



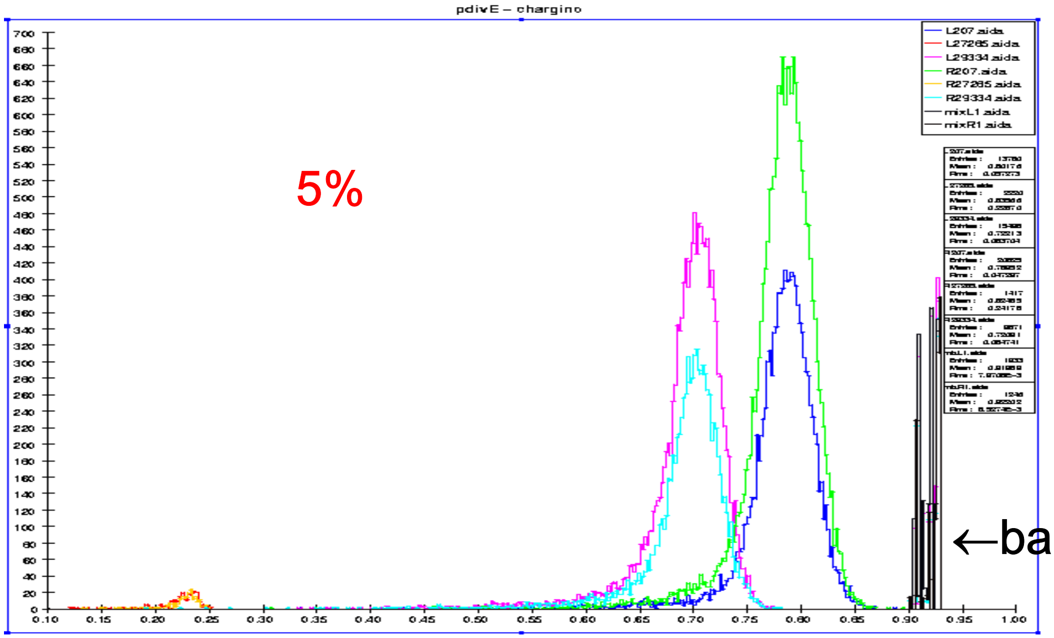
β



Stable charginos are quite easy to see with reasonable resolution

Note that ATLAS(CMS) achieves a resolution on β better than 5(3)% so we should expect an ILC detector to do as well or better

…other stable charged particles, in this case staus, are also captured by this analysis…

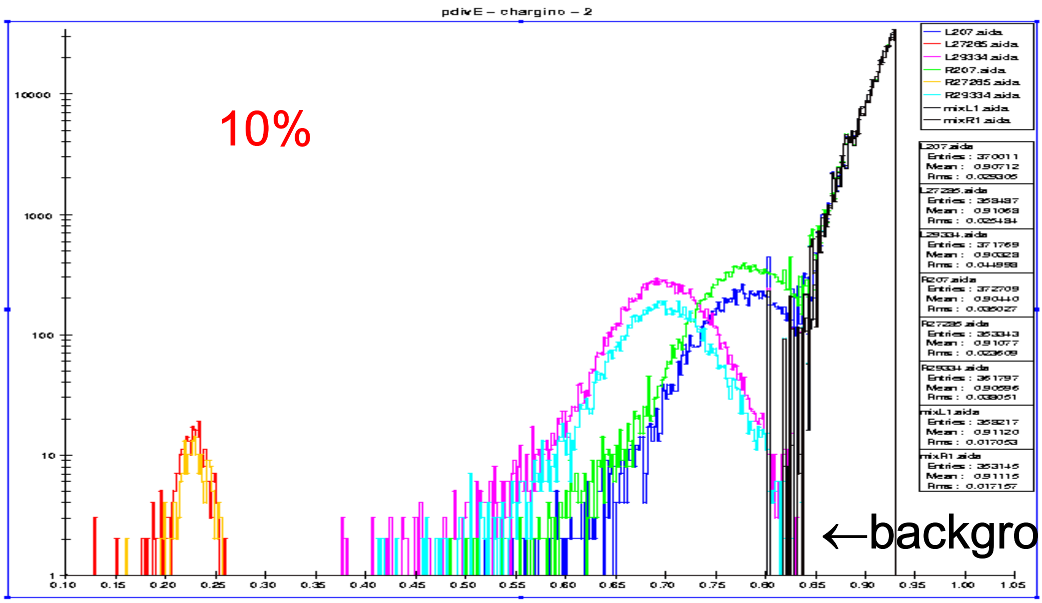


5%

←background

Stable staus are also easy to see..

β

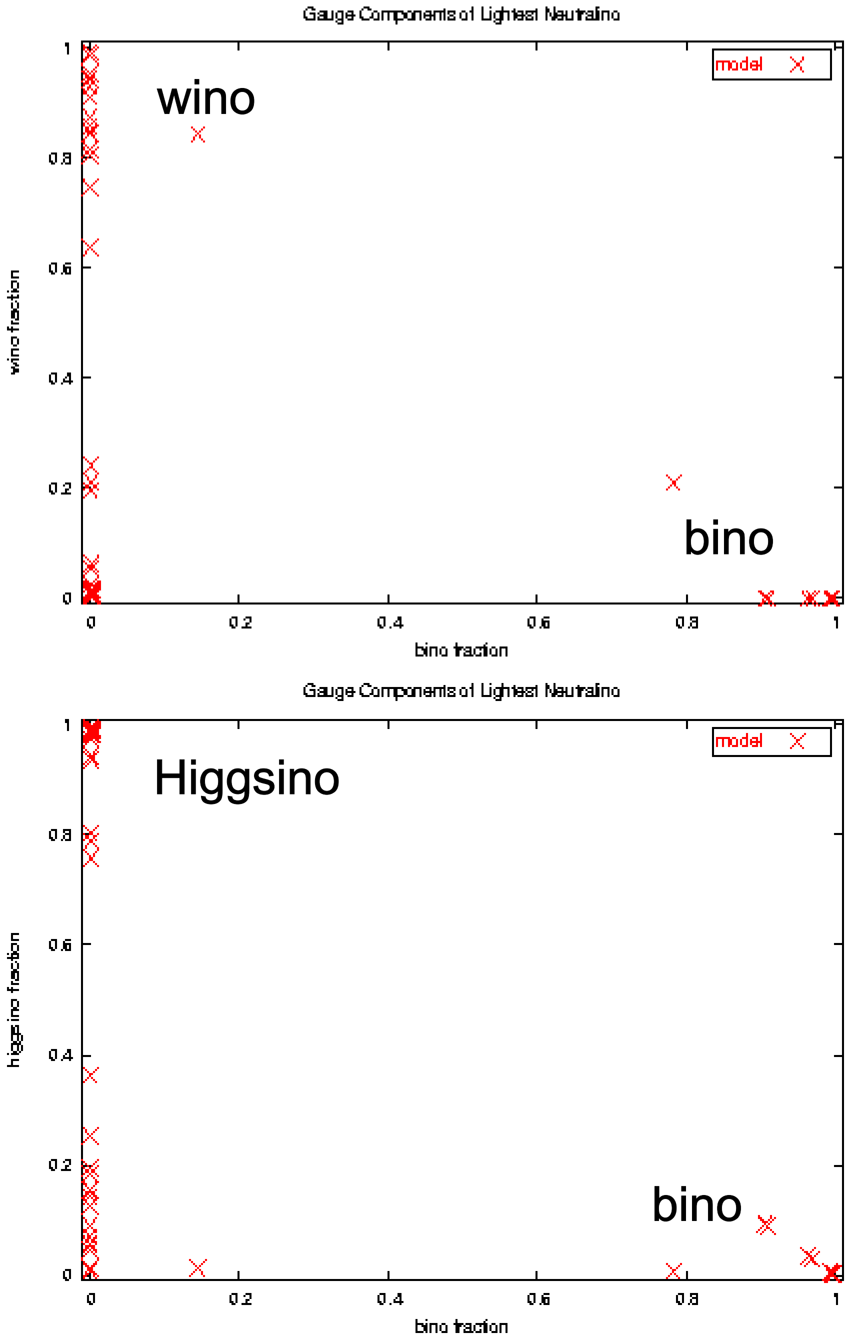


10%

←background

They can be easily distinguished from charginos by their angular distribution polarization asymmetries

NEUTRALINOS



χ_1^0 's in our models are almost all weak eigenstate fields… these figures break down their wino, bino and Higgsino contents. This has to do with how the relevant parameters were scanned..

Radiative Neutralino Production

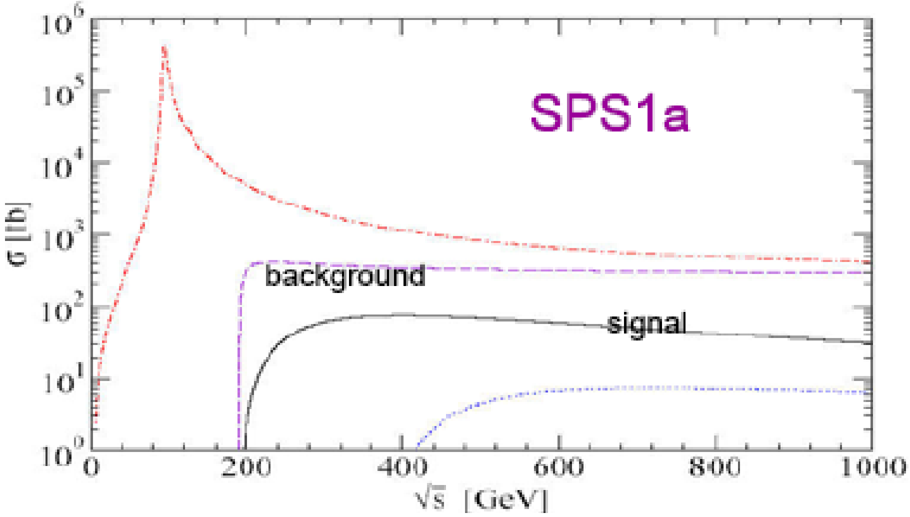
$e^+e^- \to \chi_1^0\chi_1^0$ is *invisible* so we employ the γ-tag again $e^+e^- \to \chi_1^0\chi_1^0 + \gamma$

which we calculate using CompHEP…..

ANALYSIS CUTS AT 500 GeV

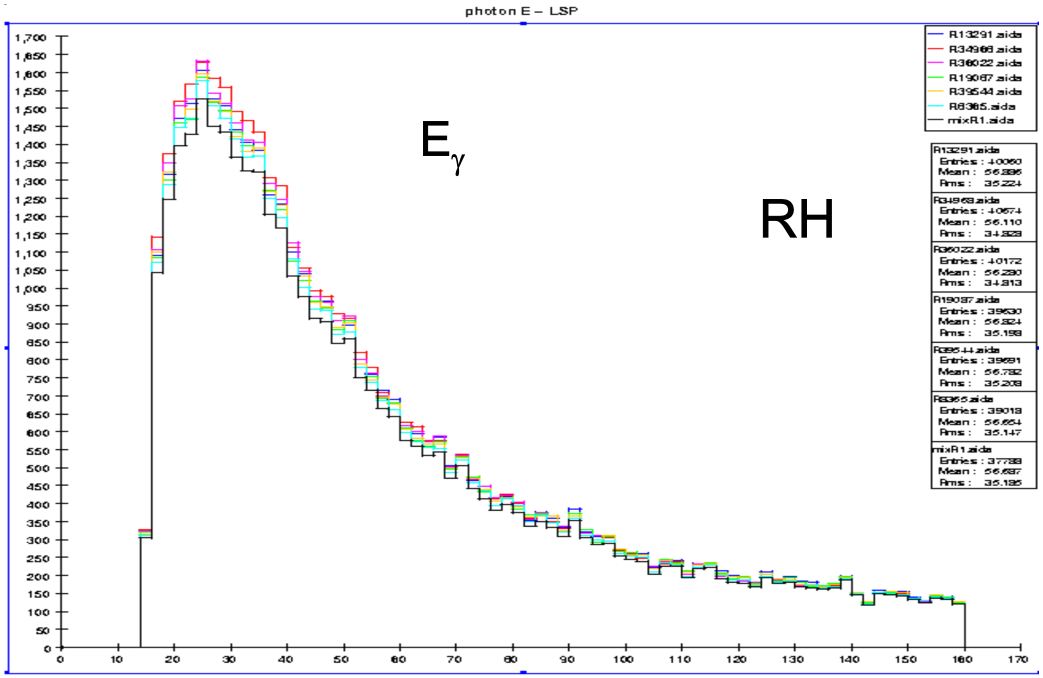
:

1. One γ and nothing else visible in the event
2. $E_T^\gamma = E^\gamma \sin\theta^\gamma > 0.03\sqrt{s}$, θ^γ is γ 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



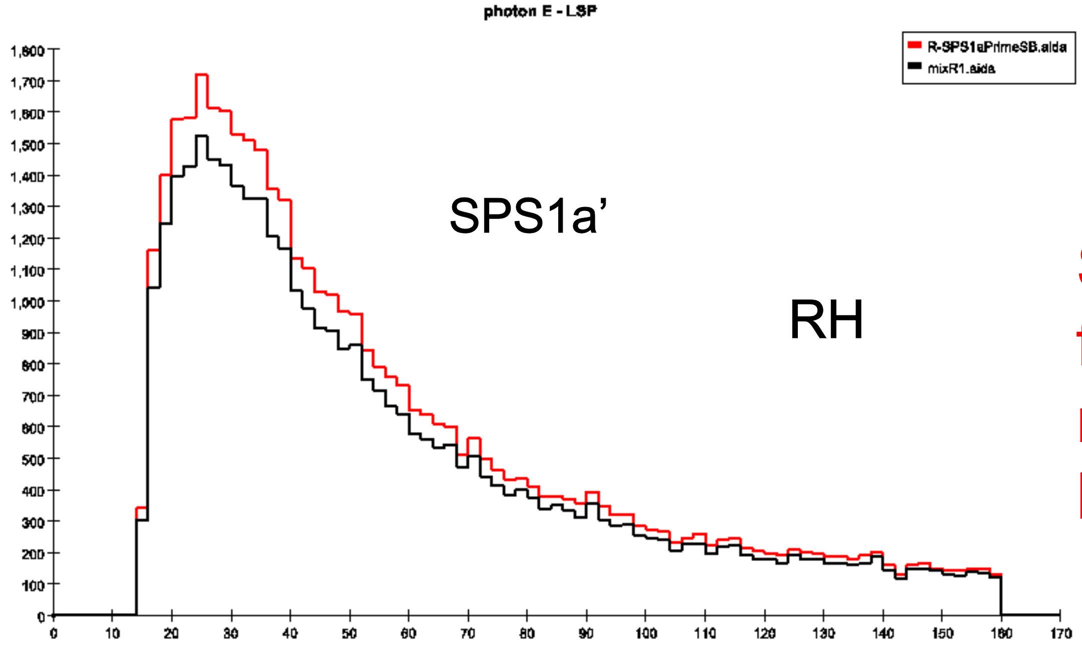
The signal is `big' for SPS1a but this is *not so* over the model space that we explore… SM backgrounds from $e^+e^- \to \nu\nu\gamma(\gamma)$ are also very large and difficult to kill with standardized cuts

Dreiner et al., hep-ph/0610020



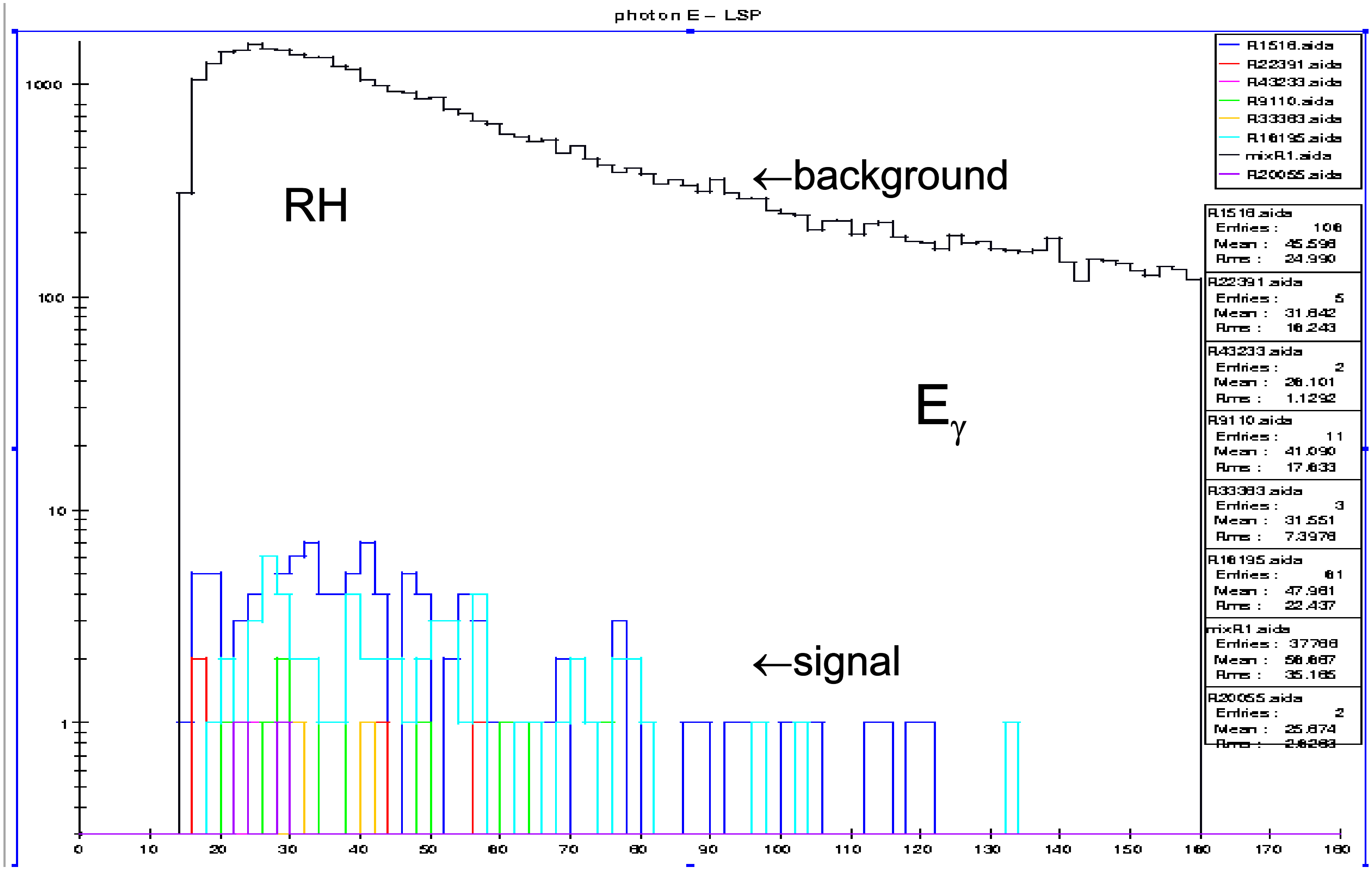
Photon tagging is quite efficient.. we see this final state for 17/242 models.

S/B can be substantially increased here by using positron polarization.

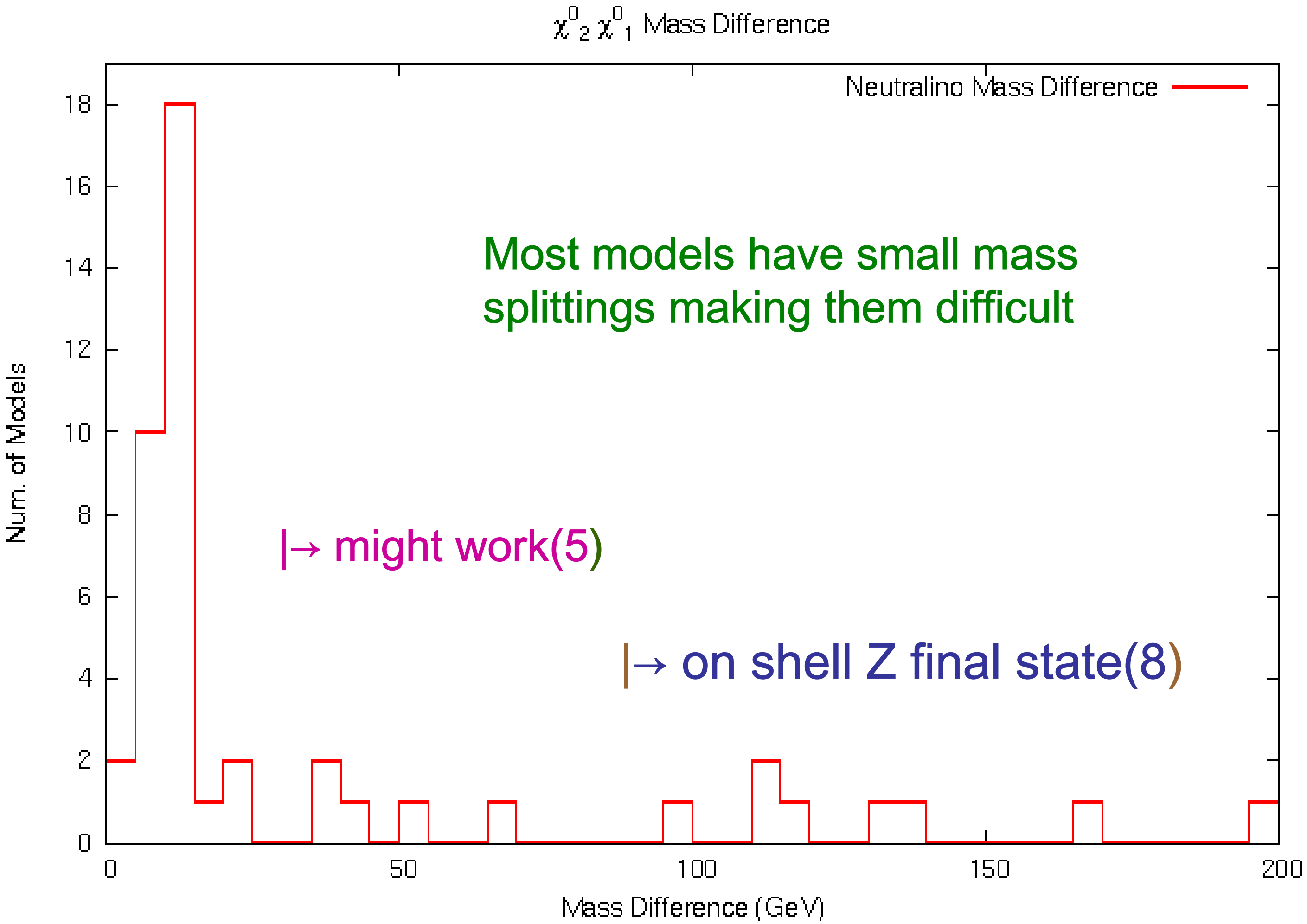


SPS1a' produces a rate far larger than all our models but is contaminated by sneutrino production

In most models the signal rate is so small there is no hope of observability…



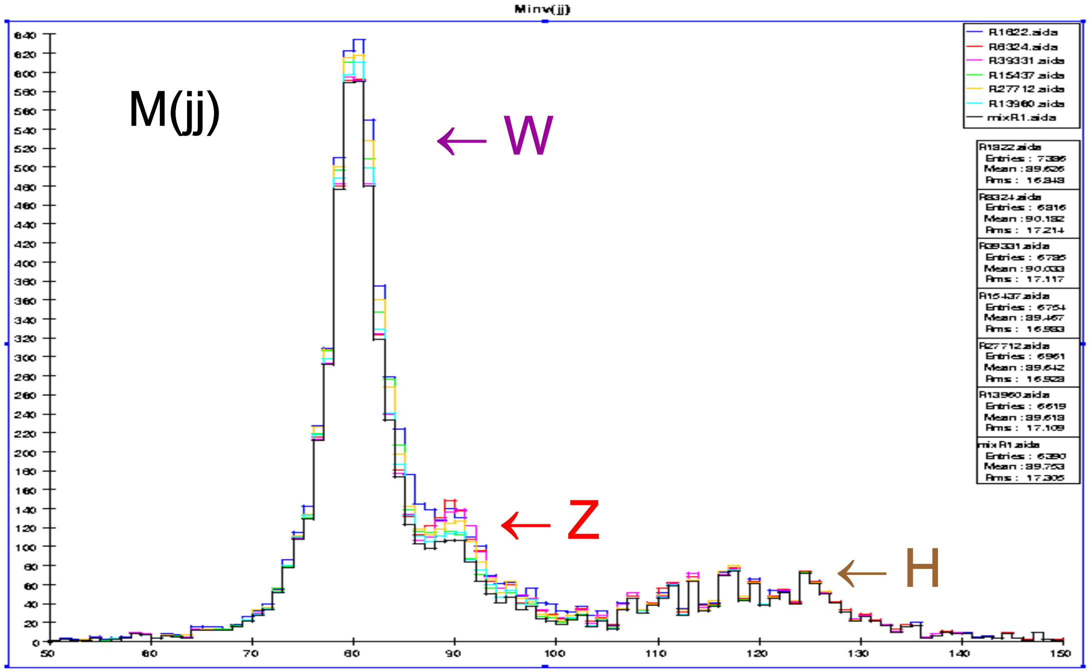
χ_2^0 χ_1^0 Analysis : most models accessible at 500 GeV have a smallish mass splitting and will be tough…look for an on/off-shell Z in jj, ee, and $\mu\mu$



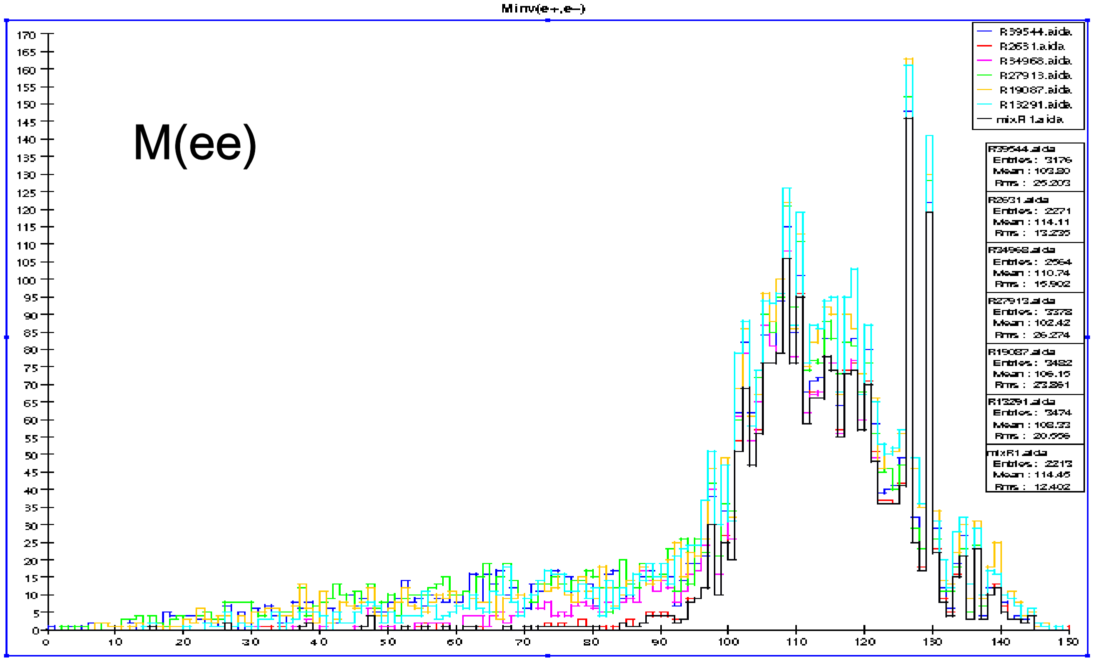
Most models have small mass splittings making them difficult

|→ might work(5)

|→ on shell Z final state(8)



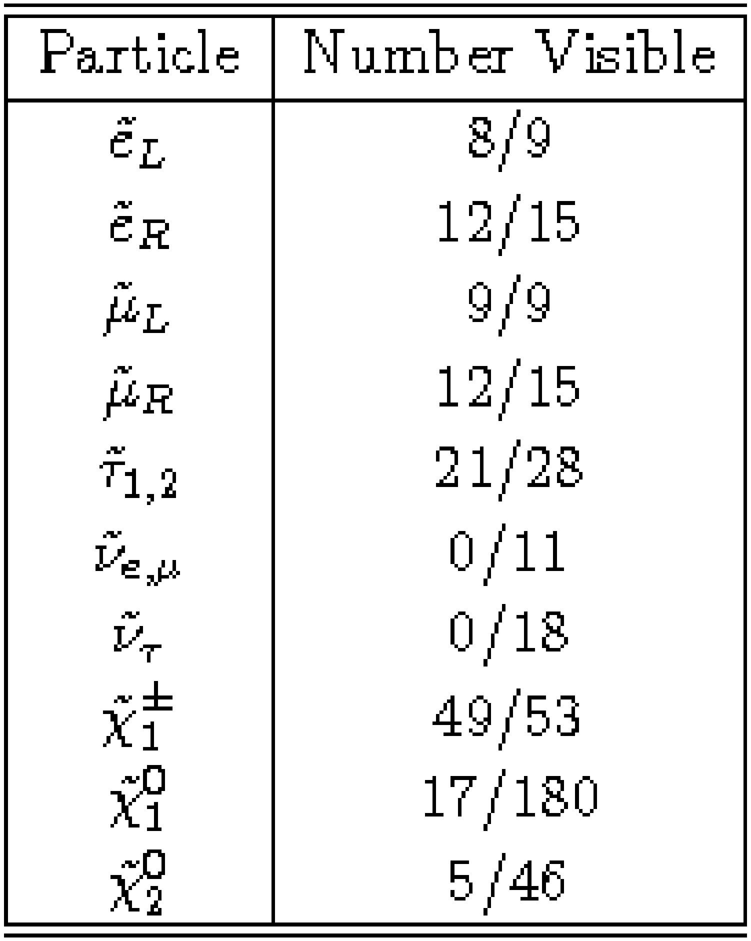
In the jj channel we *do* see an excess at the Z (5 models) but also a huge W peak from both backgrounds as well as from other sparticles such as the charginos… we also see the Higgs.



This signal can be cleaned up with better mass resolution and/or positron polarization

In the ee channel we have mostly fakes..

After all this our first goal is collect our results and determine just how many models lead to a visible signal at the 500 GeV ILC…



Particle	Number Visible
$\tilde{e}_L$	8/9
$\tilde{e}_R$	12/15
$\tilde{\mu}_L$	9/9
$\tilde{\mu}_R$	12/15
$\tilde{\tau}_{1,2}$	21/28
$\tilde{\nu}_{e,\mu}$	0/11
$\tilde{\nu}_{\tau}$	0/18
$\tilde{\chi}_1^{\pm}$	49/53
$\tilde{\chi}_1^0$	17/180
$\tilde{\chi}_2^0$	5/46

We do this by performing a likelihood ratio analysis based on Poisson statistics and require a significance greater than 5 to claim observability.

$$R=L(S+B1,B2)/L(B1,B2)$$

$$Sig=(2 \log R)^{1/2} > 5$$

This is done individually for each of our analysis histograms…

Recall that out of our sample of 242 remaining models

- 85 have at least one charged sparticle
- 61 have no kinematically accessible sparticles
- 96 have only neutral sparticles accessible, mostly just the LSP

Apparently, from looking at the table, we do reasonably well seeing charged sparticles but seeing neutrals is much harder….

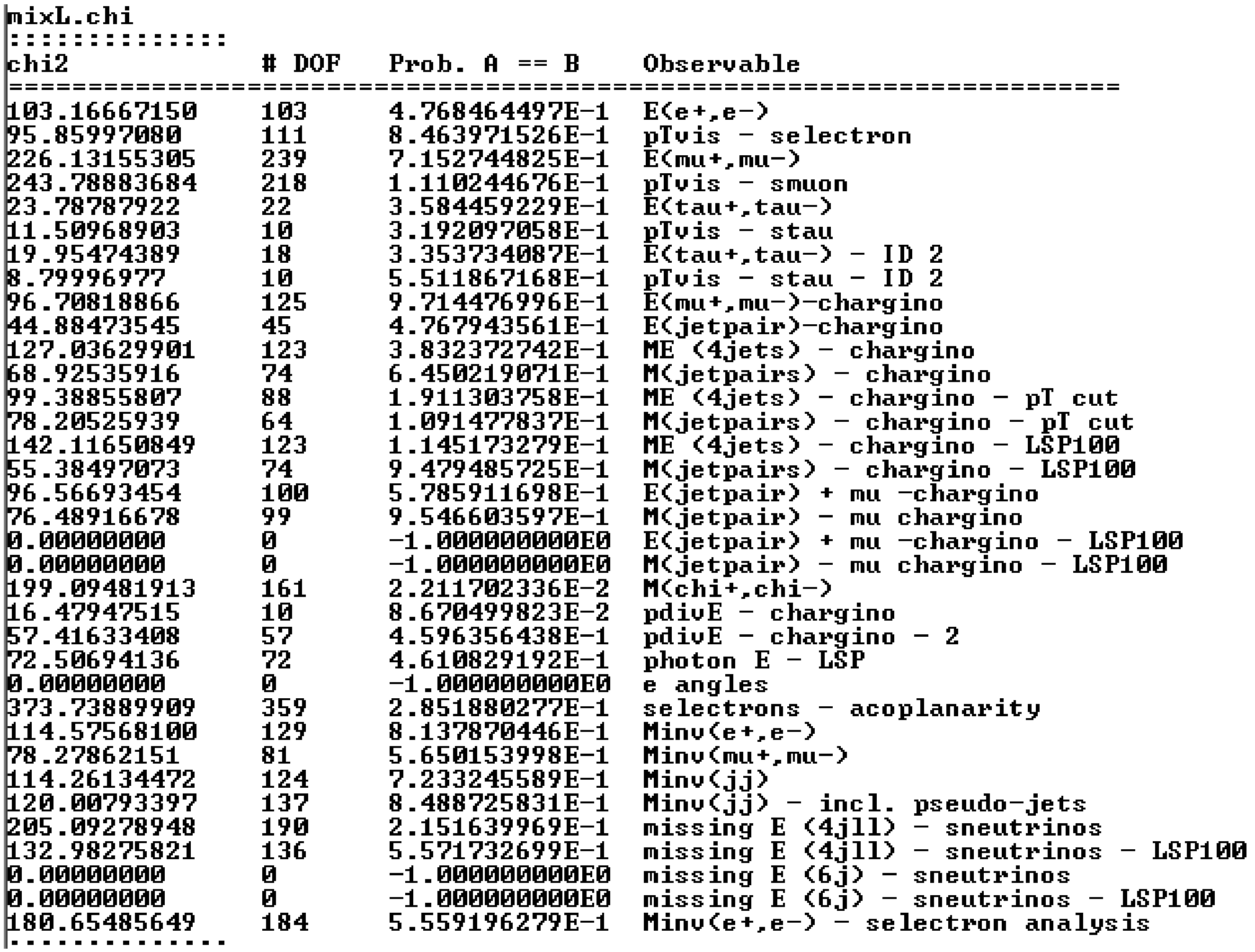
Once these results are known we next perform a χ^2 comparison of our model pairs employing the 2 statistically independent background samples requiring & distinguishability at 5(3)σ…

$$\chi^2 = \chi^2(S1+B1,S2+B2)$$

Here we take a combination of histograms, one from each analysis, i.e., one from selectrons, one from smuons, etc.

Recall 283 pairs – 121 removed by PYTHIA = 162 pairs… of these, 90 are `neutral’ vs `neutral’ and 72 are between models where at least one of the models has one or more kinematically accessible charged sparticle

It is important to compare, e.g., two SM background samples to make sure the χ^2 analysis procedures are correct….and no additional features are present. We pass this test with flying colors….



```
mixL.chi
::::::::::::::
chi2            # DOF   Prob. A == B    Observable
======================================================================
103.16667150    103     4.768464497E-1  E(e+,e-)
95.85997080     111     8.463971526E-1  pTvis - selectron
226.13155305    239     7.152744825E-1  E(mu+,mu-)
243.78883684    218     1.110244676E-1  pTvis - smuon
23.78787922     22      3.584459229E-1  E(tau+,tau-)
11.50968903     10      3.192097058E-1  pTvis - stau
19.95474389     18      3.353734087E-1  E(tau+,tau-) - ID 2
8.79996977      10      5.511867168E-1  pTvis - stau - ID 2
96.70818866     125     9.714476996E-1  E(mu+,mu-)-chargino
44.88473545     45      4.767943561E-1  E(jetpair)-chargino
127.03629901    123     3.832372742E-1  ME (4jets) - chargino
68.92535916     74      6.450219071E-1  M(jetpairs) - chargino
99.38855807     88      1.911303758E-1  ME (4jets) - chargino - pT cut
78.20525939     64      1.091477837E-1  M(jetpairs) - chargino - pT cut
142.11650849    123     1.145173279E-1  ME (4jets) - chargino - LSP100
55.38497073     74      9.479485725E-1  M(jetpairs) - chargino - LSP100
96.56693454     100     5.785911698E-1  E(jetpair) + mu -chargino
76.48916678     99      9.546603597E-1  M(jetpair) - mu chargino
0.00000000      0       -1.000000000E0  E(jetpair) + mu -chargino - LSP100
0.00000000      0       -1.000000000E0  M(jetpair) - mu chargino - LSP100
199.09481913    161     2.211702336E-2  M(chi+,chi-)
16.47947515     10      8.670499823E-2  pdivE - chargino
57.41633408     57      4.596356438E-1  pdivE - chargino - 2
72.50694136     72      4.610829192E-1  photon E - LSP
0.00000000      0       -1.000000000E0  e angles
373.73889909    359     2.851880277E-1  selectrons - acoplanarity
114.57568100    129     8.137870446E-1  Minv(e+,e-)
78.27862151     81      5.650153998E-1  Minv(mu+,mu-)
114.26134472    124     7.233245589E-1  Minv(jj)
120.00793397    137     8.488725831E-1  Minv(jj) - incl. pseudo-jets
205.09278948    190     2.151639969E-1  missing E (4jll) - sneutrinos
132.98275821    136     5.571732699E-1  missing E (4jll) - sneutrinos - LSP100
0.00000000      0       -1.000000000E0  missing E (6j) - sneutrinos
0.00000000      0       -1.000000000E0  missing E (6j) - sneutrinos - LSP100
180.65485649    184     5.559196279E-1  Minv(e+,e-) - selectron analysis
..............
```

The Final Score

Visibility: We see

78/85 models w/ at least one charged sparticle
17/96 models w/ neutral sparticles only
82/161 models w/ any accessible sparticle
82/242 of all models

As stated above we do well with charged sparticles. The ones we miss are *mostly* due to phase space suppression producing small cross sections or inability to pass kinematic cuts.

Models with only neutrals are far harder..

The Final Score (Part II) :

Distinguishability

57(63)/72 pairs w/ at least one charged sparticle at 5(3)σ

0/90 pairs where `neutral only' models are compared

57(63)/162 of all pairs at 5(3)σ

Some visible models are only `just so' and are thus hard to distinguish.. this is especially true for the chargino vs chargino case.

Again, `neutrals only' are very hard.. just to see.


SLEPTON
PHOTINO

SUMMARY AND OUTLOOK

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

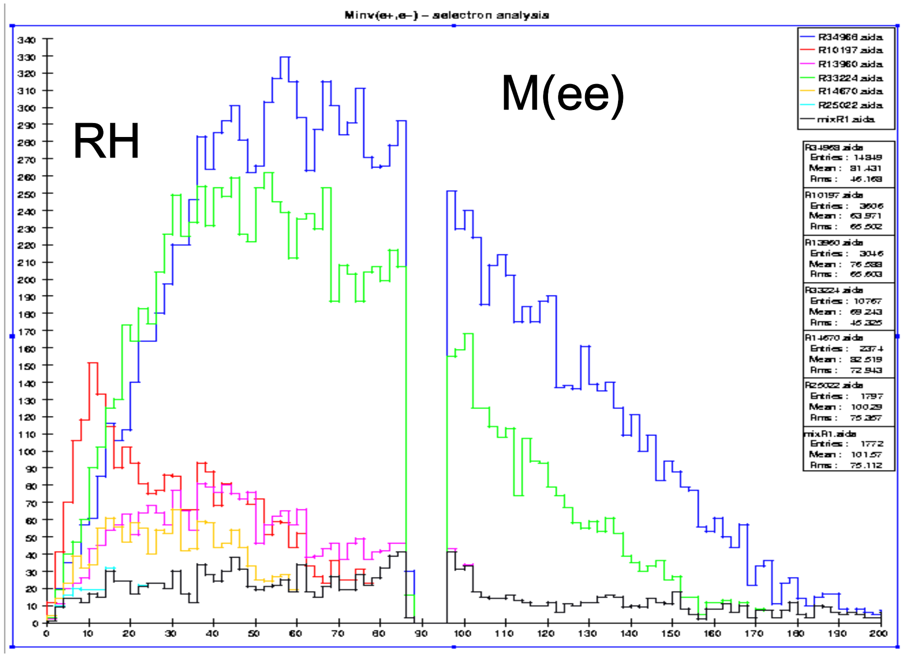
(*i*) Study the 1 TeV case and the influence of positron polarization on both signals and backgrounds (+more channels to look at). Do threshold scans of some kind, include vertex detector analyses…

(*ii*) Explore using CompHEP to generate SUSY signal events for all analysis channels which allows for interference.

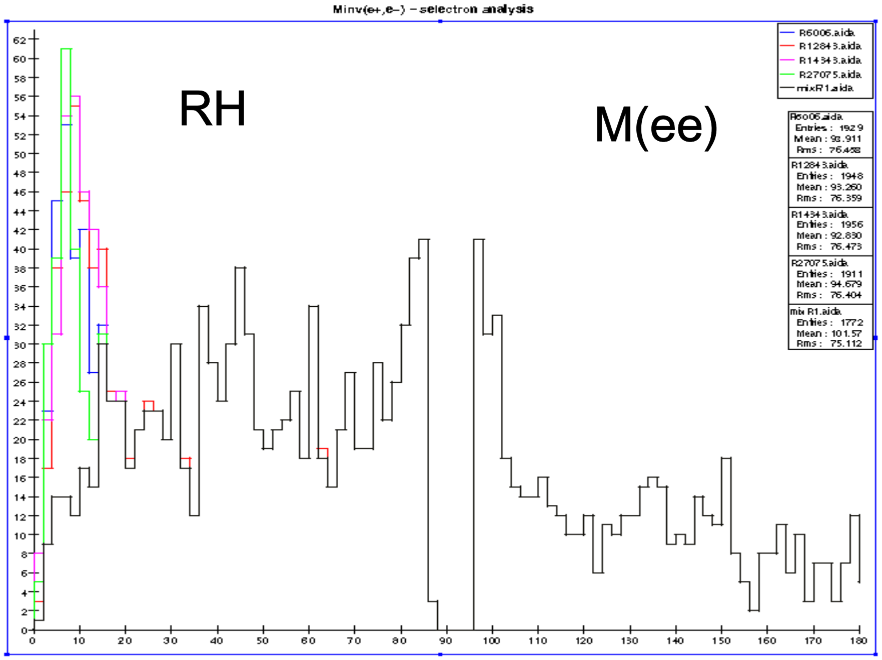
(*iii*) Study variations in the detector properties, in particular, the effect of introducing, e.g., low-angle muon ID below ~140 mr.

(*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, $b\to s\gamma$, dark matter searches, etc.

BACKUP SLIDES



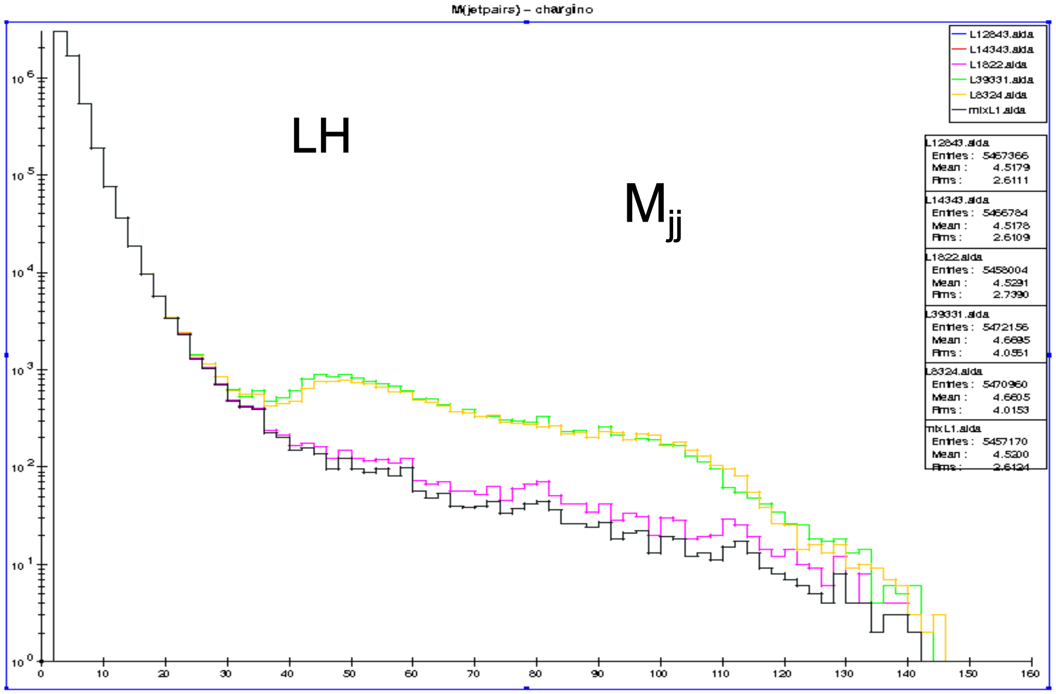
selectrons

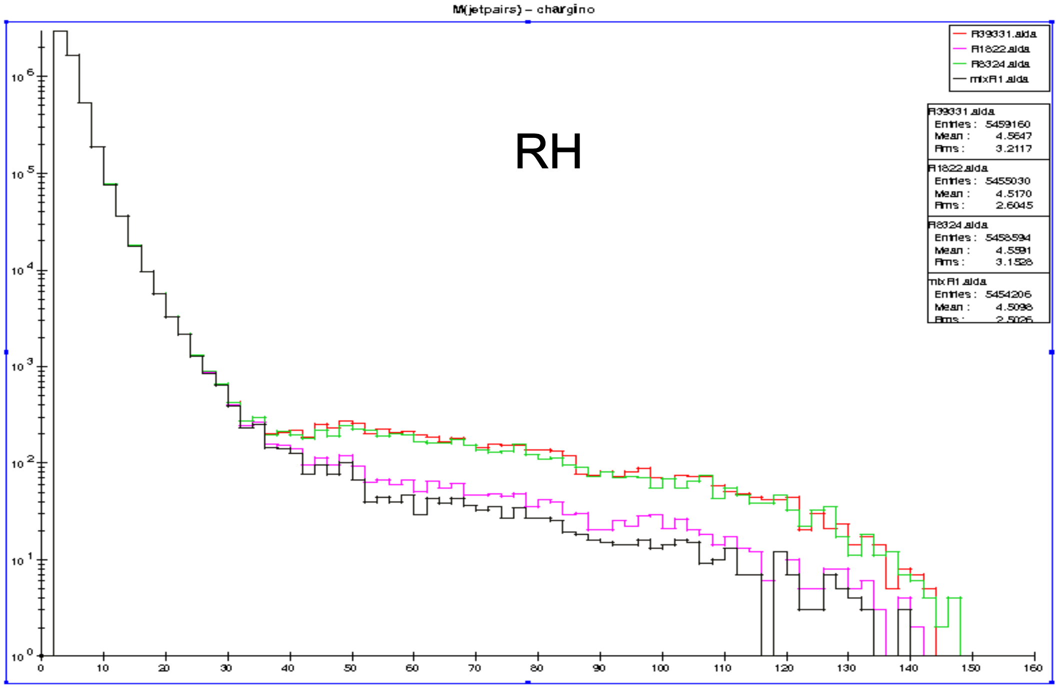


fakes

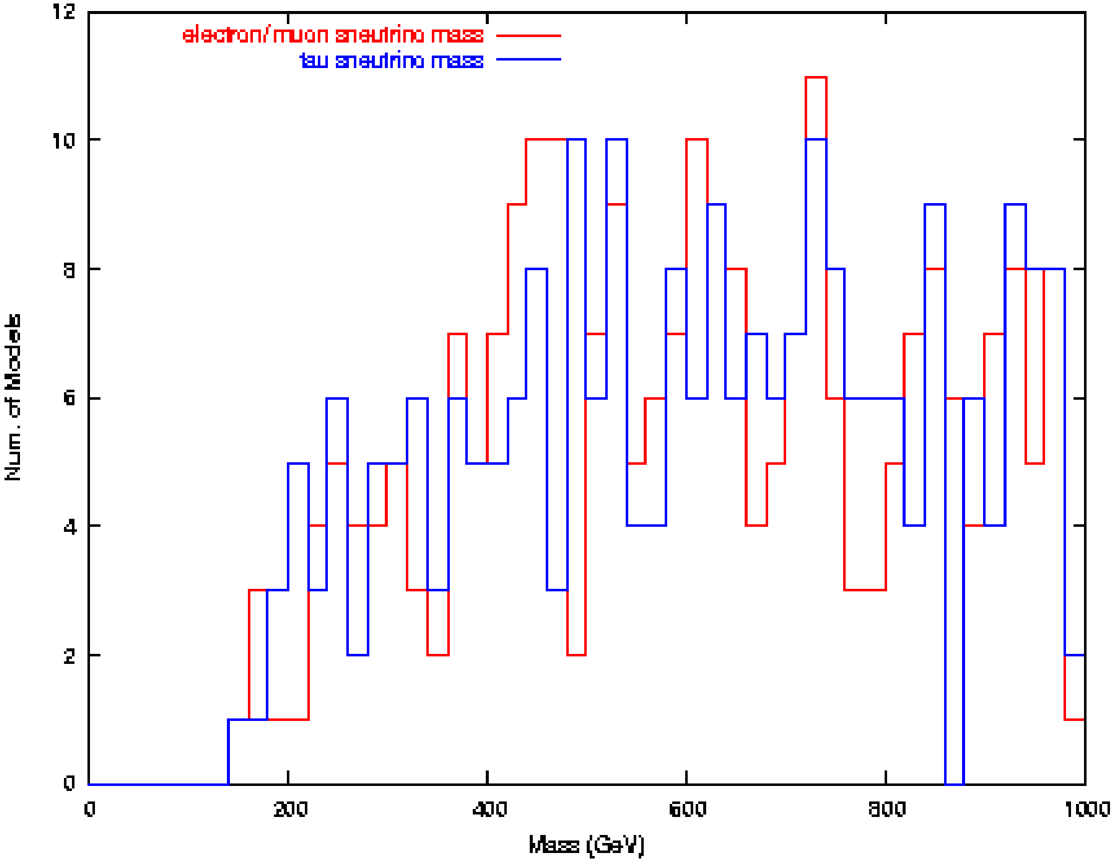
Using various distributions we can hopefully differentiate \`real’ models from fakes

Chargino 4-jet+Missing Energy Analysis





2 real + 1 fake models


electron/muon sneutrino mass
tau sneutrino mass
Num. of Models
Mass (GeV)
0
2
4
6
8
10
12
0
200
400
600
800
1000