Supersymmetry, the ILC & the LHC Inverse Problem: Project Summary

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0711.1374 & 0712.2965

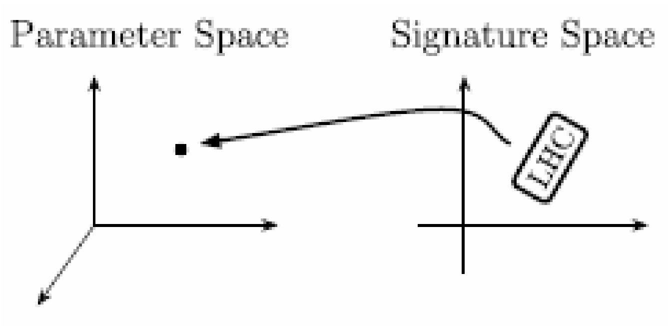
The goals of this project were twofold:

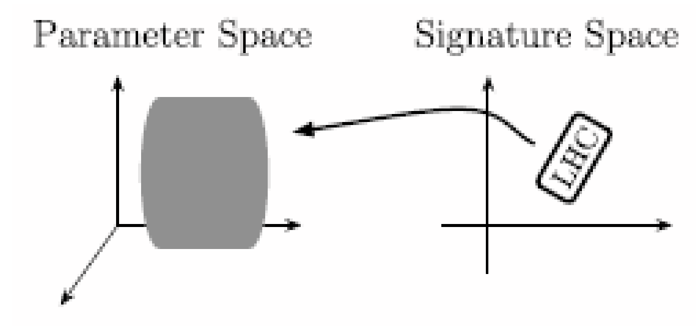
- Study in as realistic a way as possible the capability of the ILC to examine the physics of a large number of random points in MSSM parameter space. Such a large-scale study of points *not* tied to a specific model, e.g., MSUGRA, has never been done.

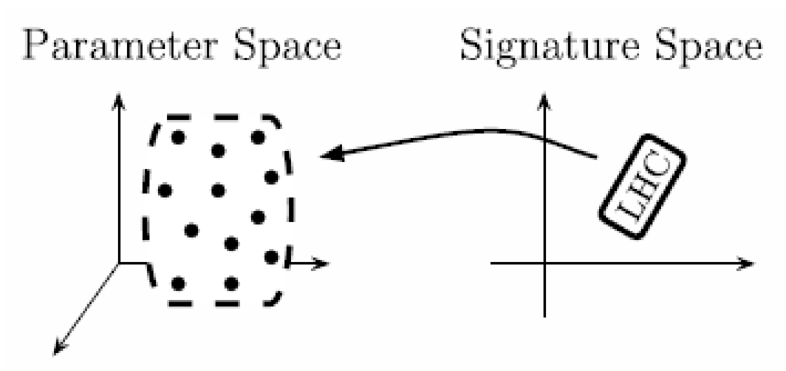
  → We don't know how SUSY is broken so an analysis which is as model-independent as possible is extremely valuable

- Examine the capability of the ILC to distinguish points in parameter space which lead to essentially identical, so called `degenerate', signatures at the LHC.

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

This 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:

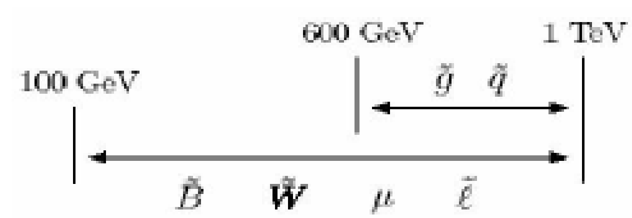
Inos : $M_1,\ M_2,\ M_3,\ \mu$

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

A Few Comments on AKTW Model Generation

- There are certainly other ways one could have chosen to generate a set of models: parameter ranges, prior `tilts', etc... We are studying these alternatives now.

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

- To be specific and to deal with LHC distinguishability issues we will use these models for our study.

- We are now making our own *much* larger model set satisfying all the known constraints. This requires *many* different codes to talk to each other & lots of time for code testing & development & for actual model generation.

- Recall there is major filtering required: generate 10^8 models to get a few thousand (??)

Opening Comments:

After some filtering, we begin our study with 242 models in 162 pairs; some models are in more than one pairing.

A \`weakness' of this analysis, as you will see, is that it makes use of a huge set of SM backgrounds generated by Tim Barklow at $\sqrt{s}$=500 GeV. Since these backgrounds are not available for other random energies we cannot perform \`energy scans' to find particle thresholds as part of our analysis and we lose a valuable ILC tool.

We also employ a cut-based analysis that may be improved by using neural-nets.

How :

- Pick one of the models. Simulate SUSY signal events with PYTHIA and CompHEP feeding in Whizard/GuineaPig generated beam spectrum for ILC
- 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 the java-based SiD fast detect simulation org.lcsim (vanilla version)
- Assuming E_{cm}=500 GeV, L=500 fb^{-1} with P_{e-} =80%, 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…& >1 CPU century

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

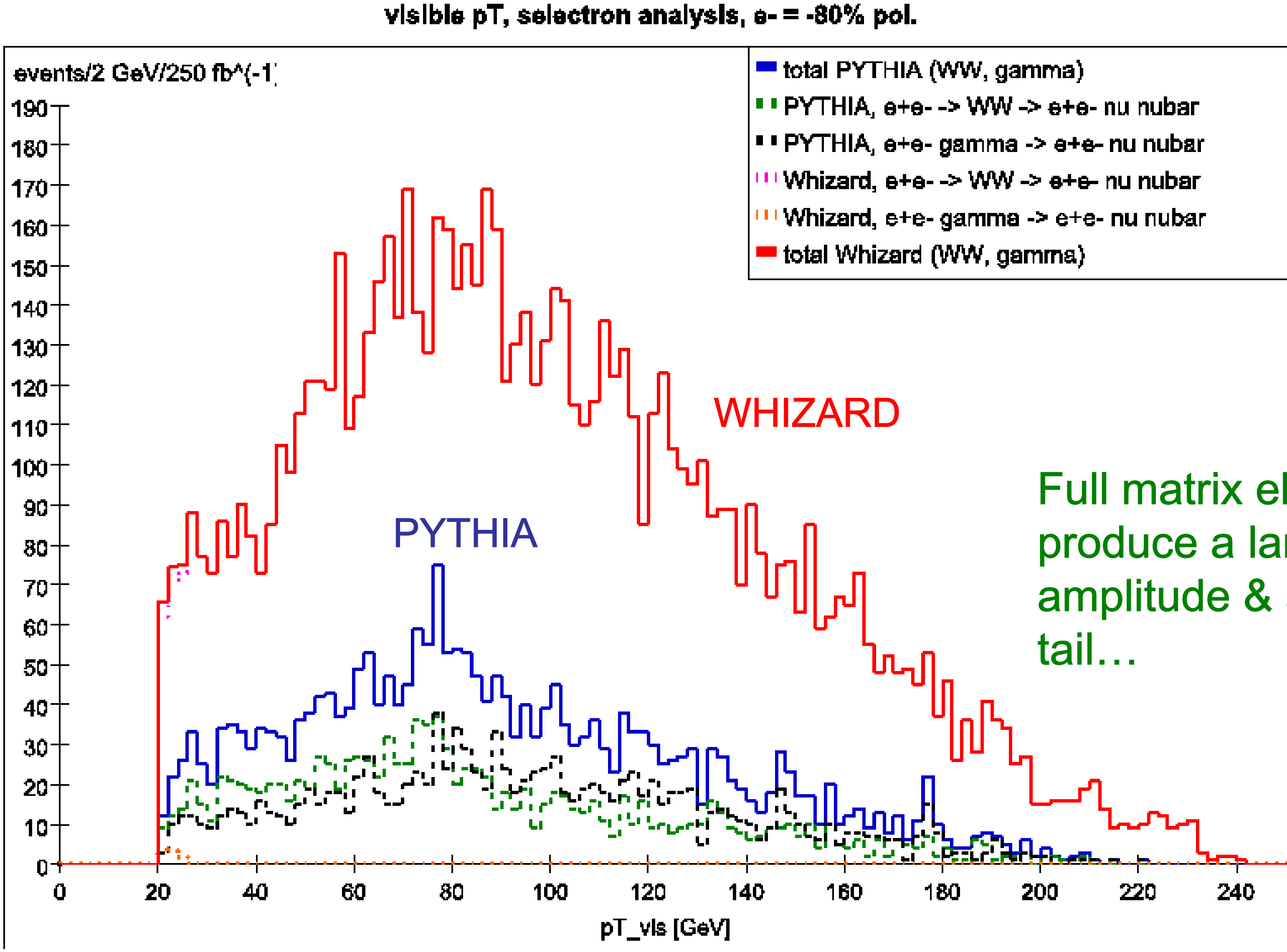
Table 12:

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 can underestimates backgrounds…



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

Kinematic Accessibility ($\neq$ 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 trivially observable signal at the ILC…the percentage will 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!

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

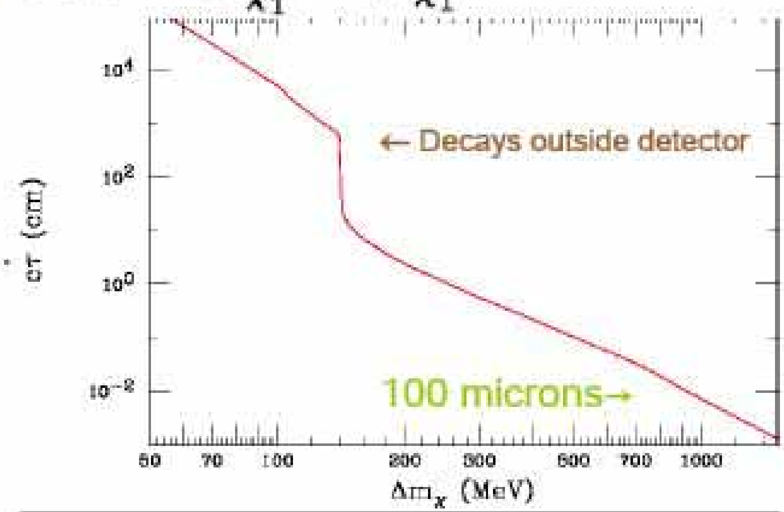
(iii) $\chi_2^0\,\chi_1^0$ → missing E + Z/H (jj /l^+l^-)

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

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

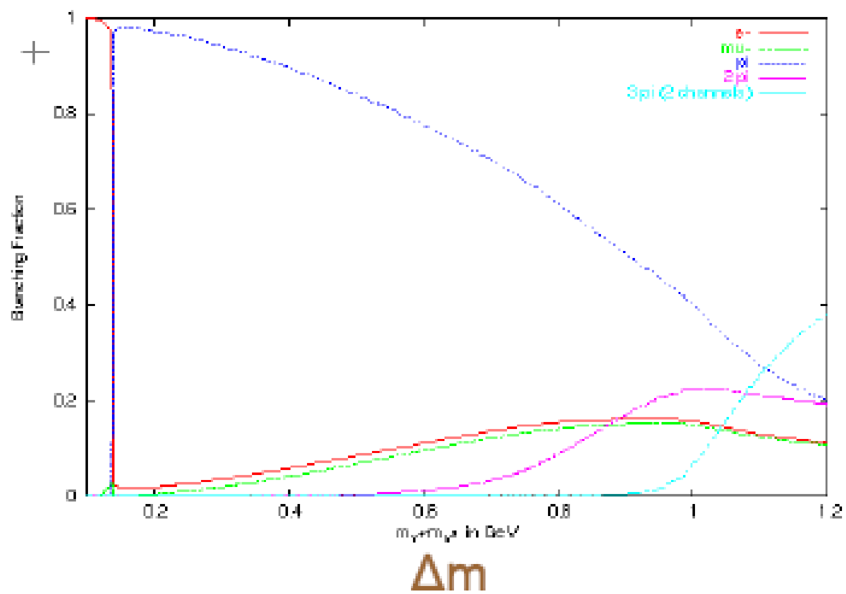
Critical parameter for charginos: $\Delta m = m_{\chi_1^\pm} - m_{\chi_1^0}$

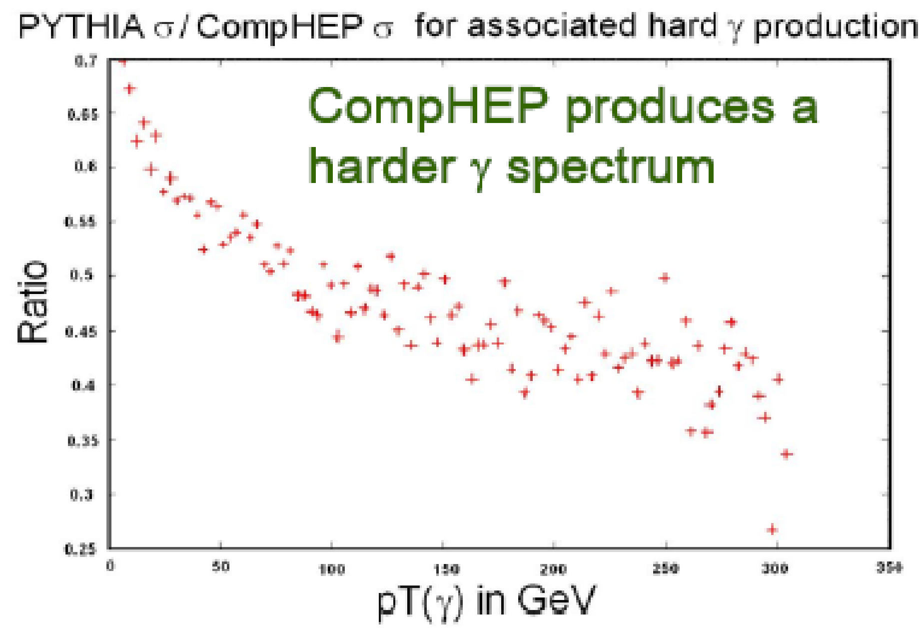
(a) → if $\Delta m < m_\pi$ we need to do a stable charged particle search ..



Analyses Continued :

(b) When m_π < Δm < ~1 GeV the chargino decays to soft hadrons which we tag by a hard photon. A full matrix element calculation is important here...





(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.....

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:

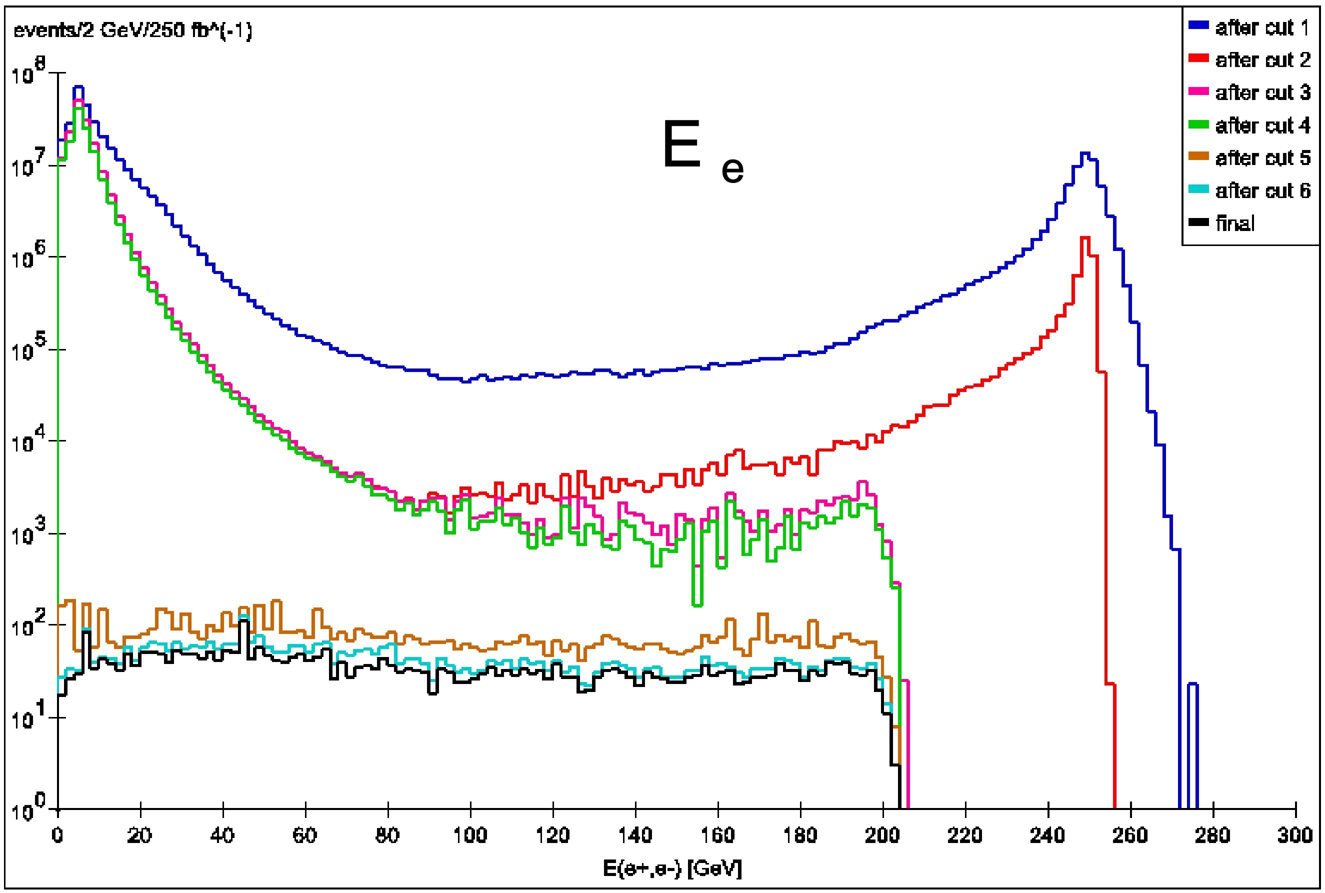
Minimal quality cuts applied

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 $\not{E}_T$, 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, $\Delta\phi^{e^+e^-} = \pi - \theta_T$,

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.

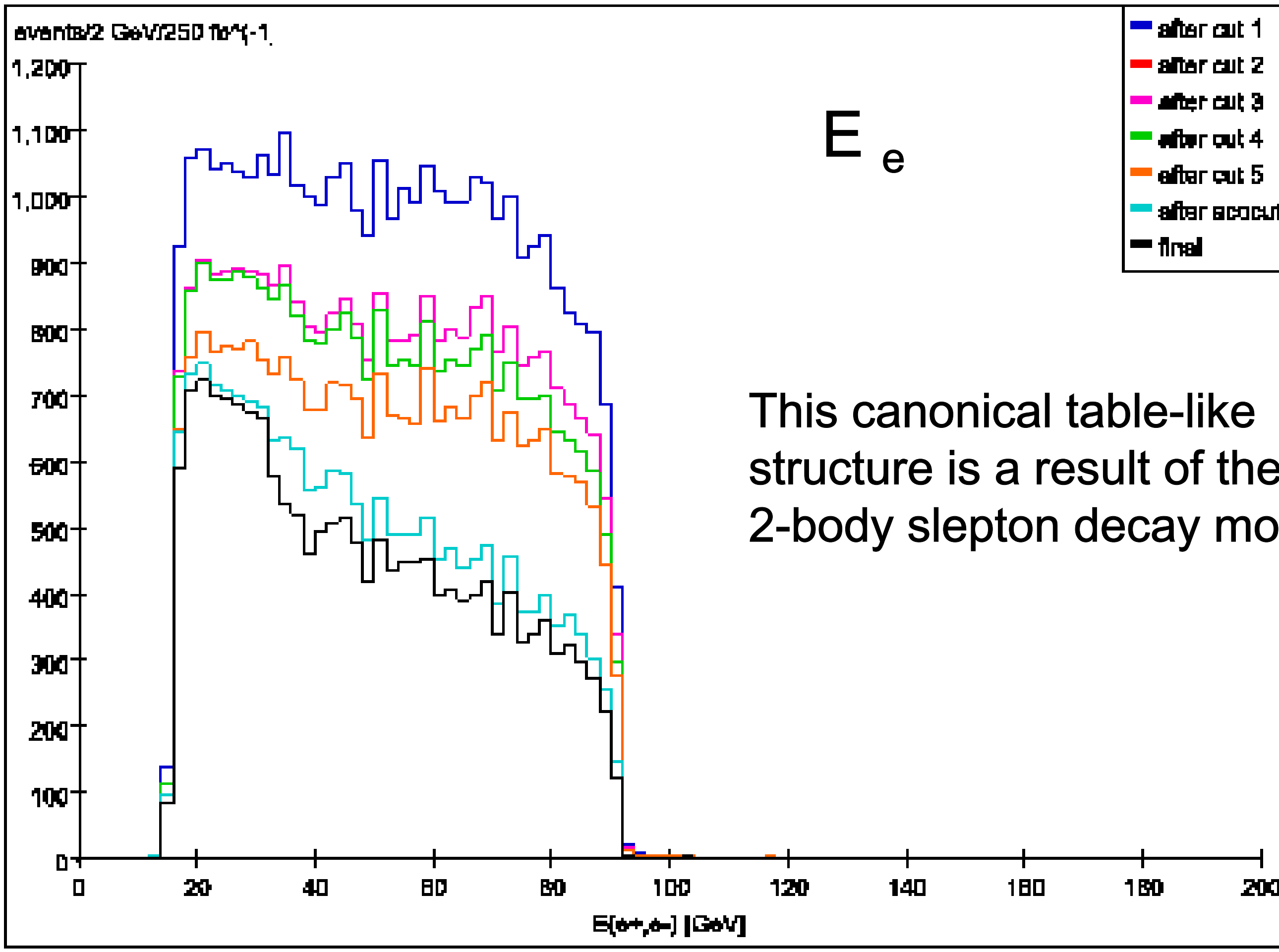
7. $M_{e^+e^-} < M_Z - 5$ GeV or $M_{e^+e^-} > M_Z + 5$ GeV.
This is to cut out events from Zs, that is, $e^+e^- \to ZZ \to e^+e^-\nu\bar{\nu}$.



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

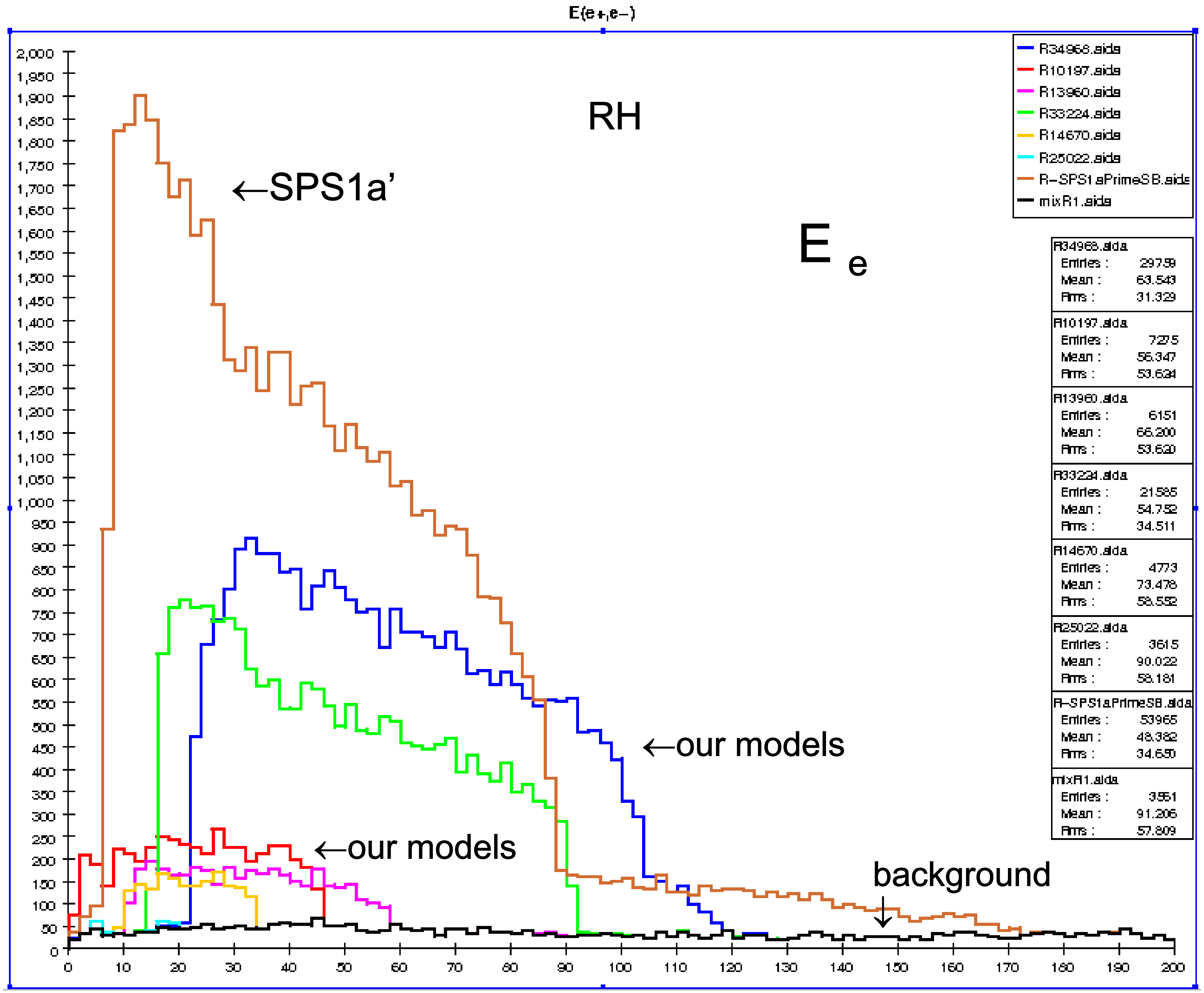
Sample Analysis Cuts : Selectrons (cont.)

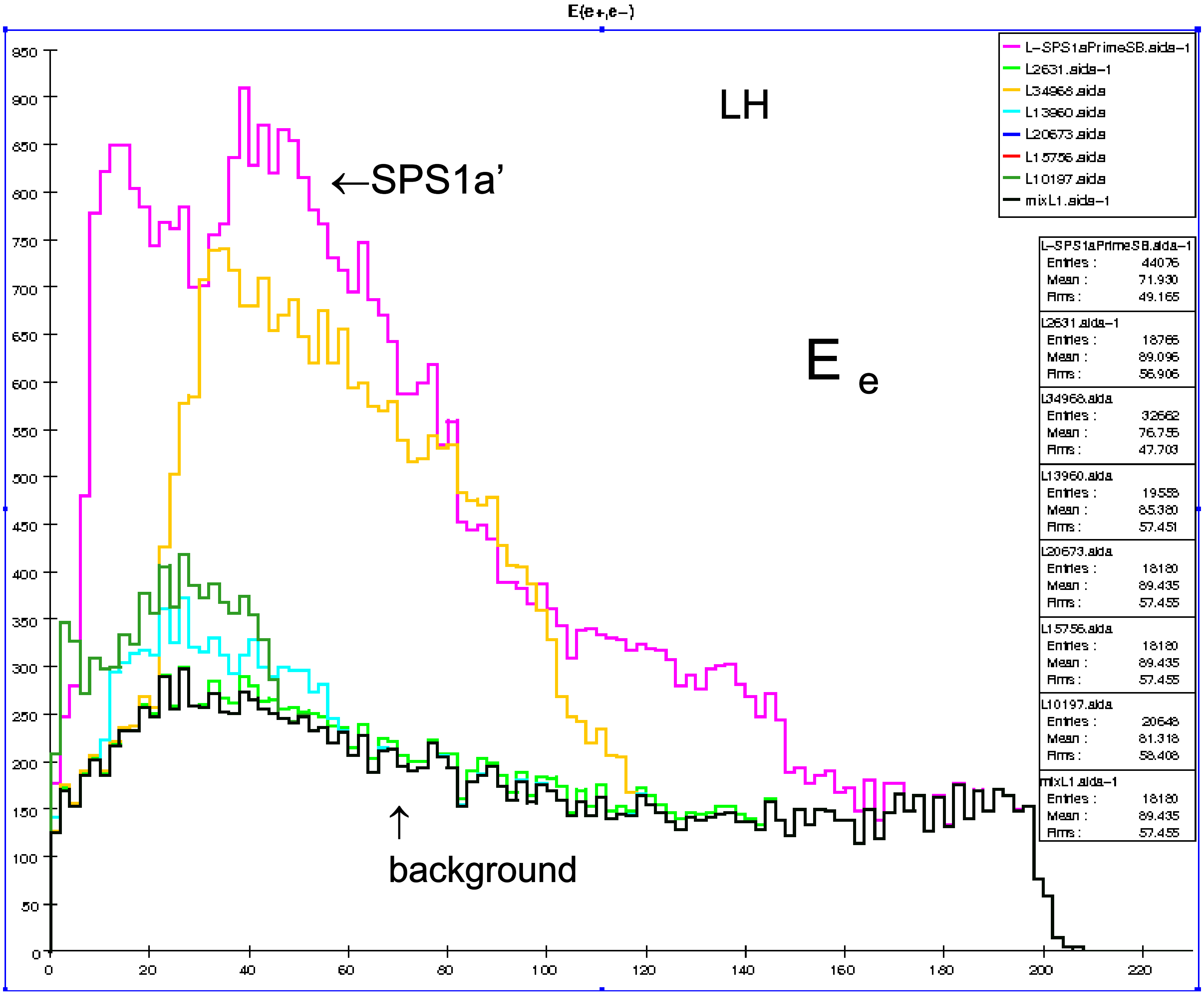
..but the signal is only reduced by a factor of ~2!!!



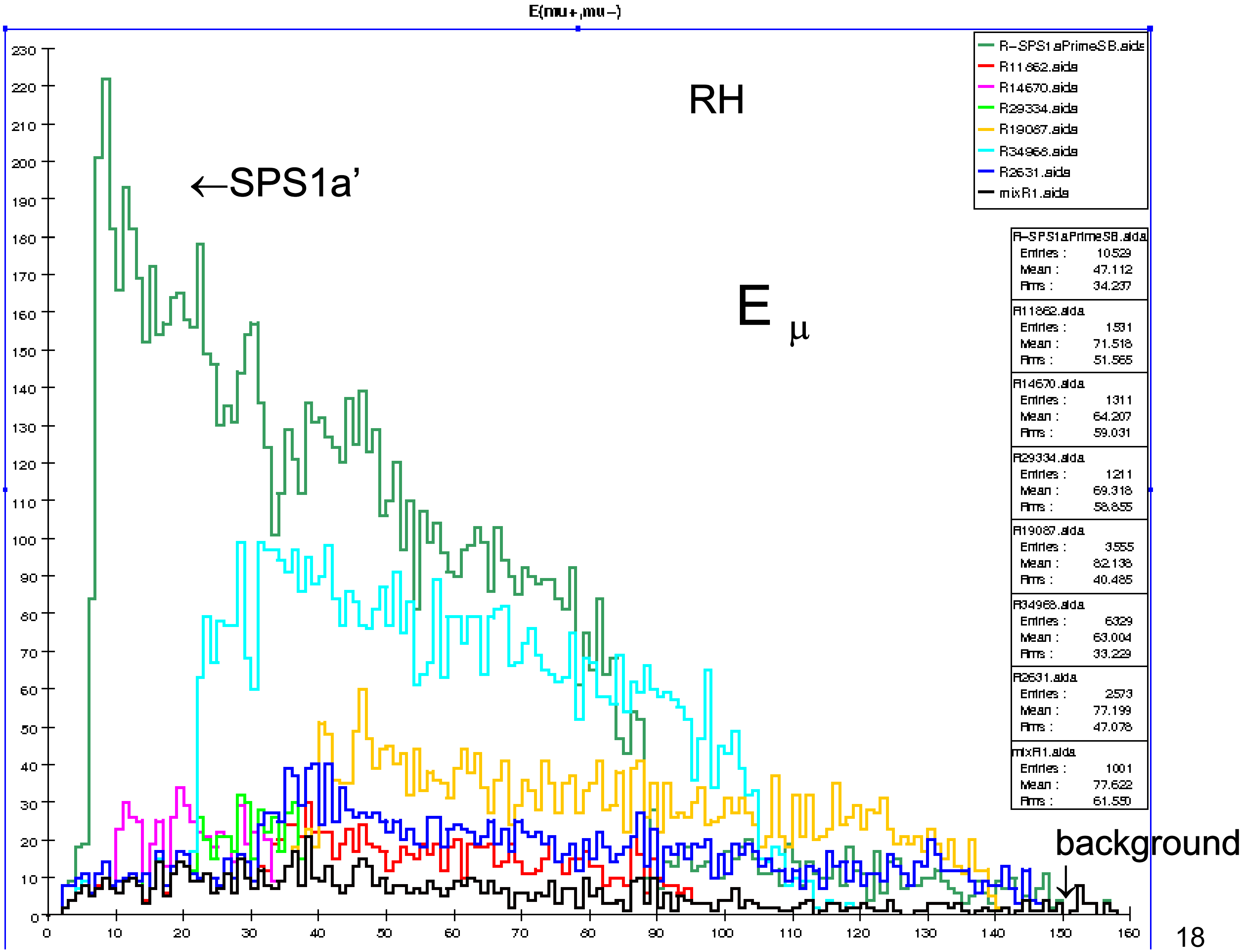
This canonical table-like structure is a result of the 2-body slepton decay mode

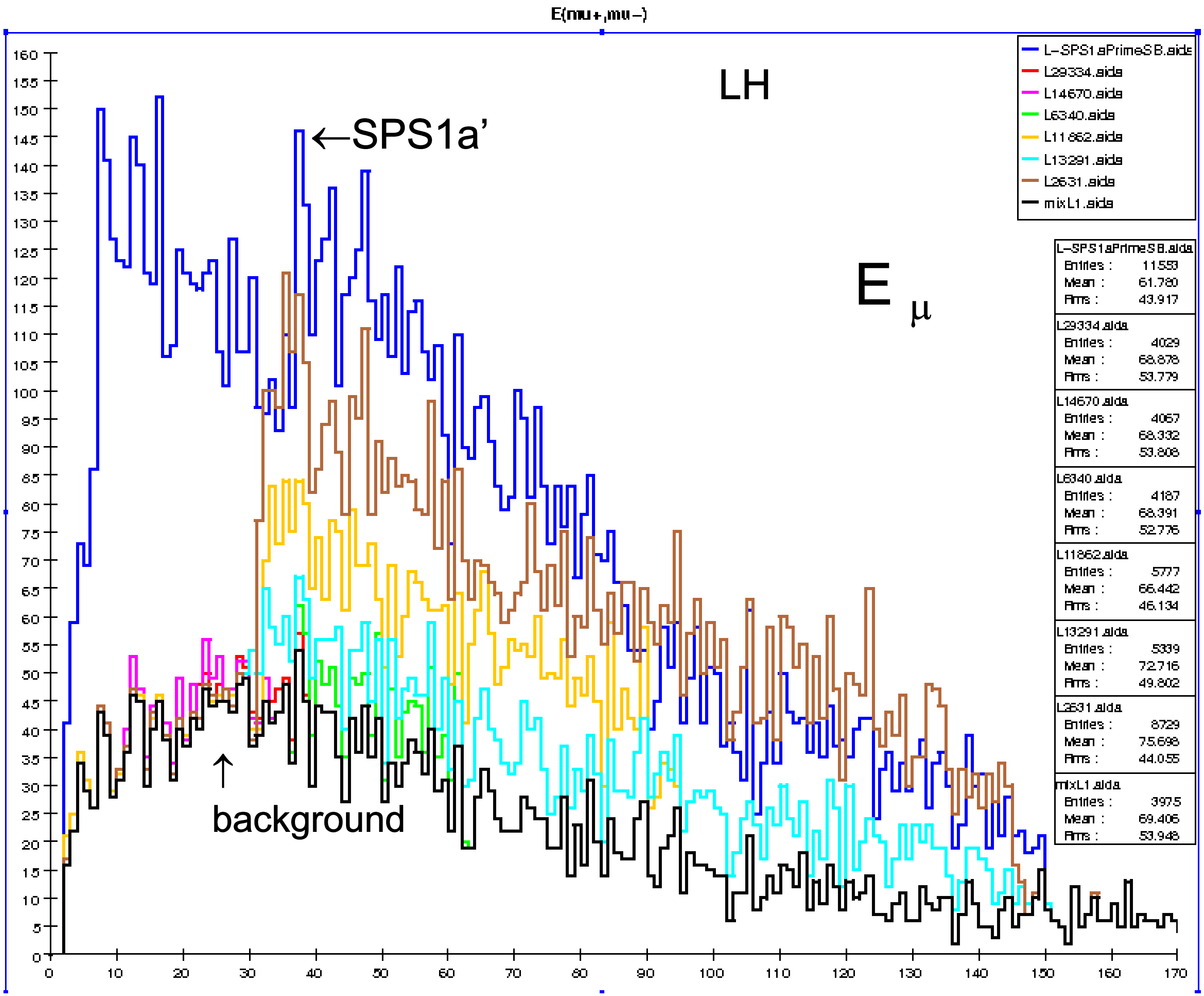
Now for some analyses…

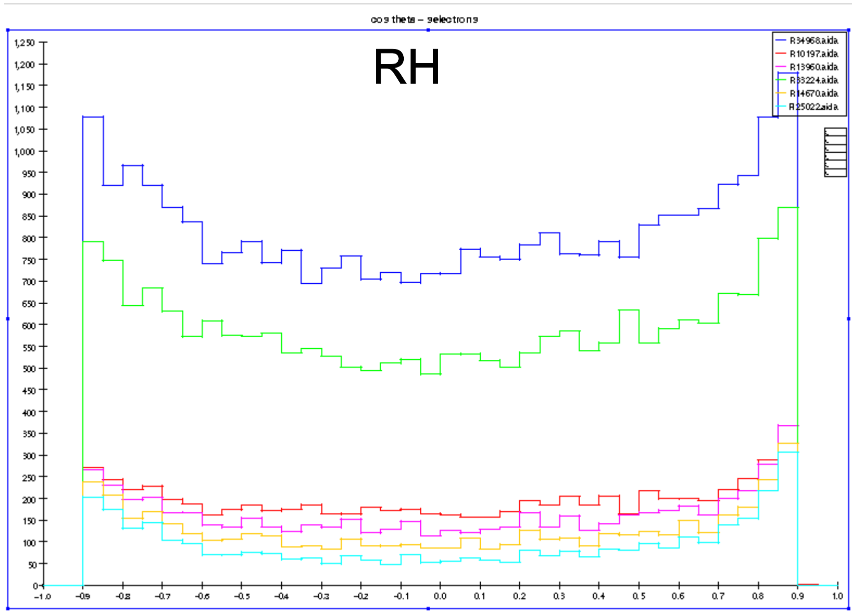

E(e+,e−)
RH
←SPS1a'
E e
←our models
←our models
background
R34968.aida
R10197.aida
R13960.aida
R33224.aida
R14670.aida
R25022.aida
R-SPS1aPrimeSB.aida
mixR1.aida
R34968.aida Entries : 29759 Mean : 63.543 Rms : 31.329
R10197.aida Entries : 7275 Mean : 56.347 Rms : 53.634
R13960.aida Entries : 6151 Mean : 66.200 Rms : 53.620
R33224.aida Entries : 21585 Mean : 54.752 Rms : 34.511
R14670.aida Entries : 4773 Mean : 73.478 Rms : 58.552
R25022.aida Entries : 3615 Mean : 90.022 Rms : 58.181
R-SPS1aPrimeSB.aida Entries : 53965 Mean : 48.382 Rms : 34.650
mixR1.aida Entries : 3551 Mean : 91.206 Rms : 57.809

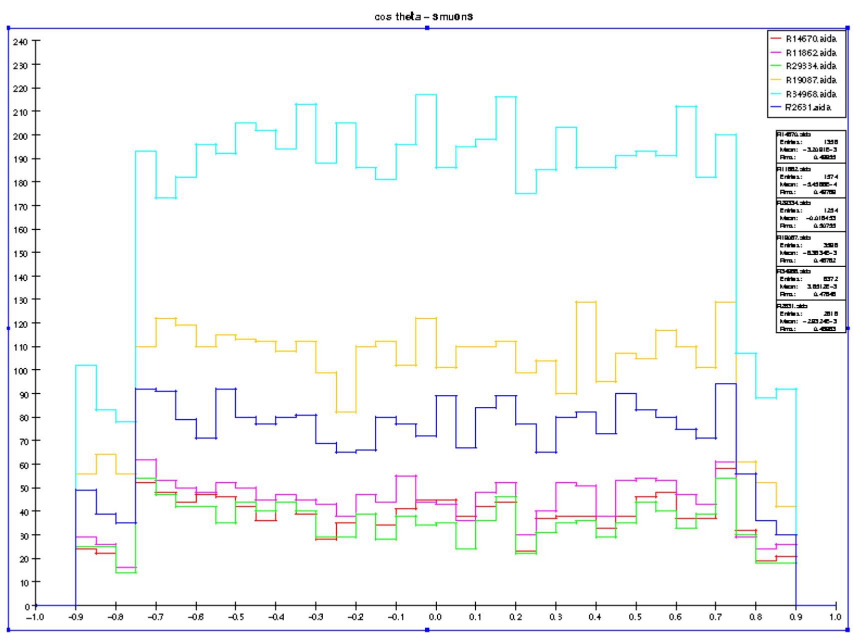


E(e+,e−)
LH
←SPS1a'
E e
background
L-SPS1aPrimeSB.aida-1
L2631.aida-1
L34968.aida
L13960.aida
L20673.aida
L15756.aida
L10197.aida
mixL1.aida-1
L-SPS1aPrimeSB.aida-1 Entries : 44076 Mean : 71.930 Rms : 49.165
L2631.aida-1 Entries : 18766 Mean : 89.096 Rms : 56.906
L34968.aida Entries : 32662 Mean : 76.755 Rms : 47.703
L13960.aida Entries : 19559 Mean : 85.380 Rms : 57.451
L20673.aida Entries : 18180 Mean : 89.435 Rms : 57.455
L15756.aida Entries : 18180 Mean : 89.435 Rms : 57.455
L10197.aida Entries : 20648 Mean : 81.318 Rms : 58.408
mixL1.aida-1 Entries : 18180 Mean : 89.435 Rms : 57.455


E(mu+,mu-)
RH
←SPS1a'
E μ
background
R-SPS1aPrimeSB.aida
R11862.aida
R14670.aida
R29334.aida
R19087.aida
R34968.aida
R2631.aida
mixR1.aida
R-SPS1aPrimeSB.aida Entries : 10529 Mean : 47.112 Rms : 34.237
R11862.aida Entries : 1531 Mean : 71.518 Rms : 51.565
R14670.aida Entries : 1311 Mean : 64.207 Rms : 59.031
R29334.aida Entries : 1211 Mean : 69.318 Rms : 58.855
R19087.aida Entries : 3555 Mean : 82.138 Rms : 40.485
R34968.aida Entries : 6329 Mean : 63.004 Rms : 33.229
R2631.aida Entries : 2573 Mean : 77.199 Rms : 47.078
mixR1.aida Entries : 1001 Mean : 77.622 Rms : 61.550


E(mu+,mu-)
LH
←SPS1a'
E μ
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





Angular distributions of final state leptons in the decay of selectrons (top) and smuons (bottom) assuming RH beam polarization.

These are not obviously useful for spin determination which will require a threshold measurement

Some Immediate Lessons:

- SPS1a’ produces rates significantly larger than all our models

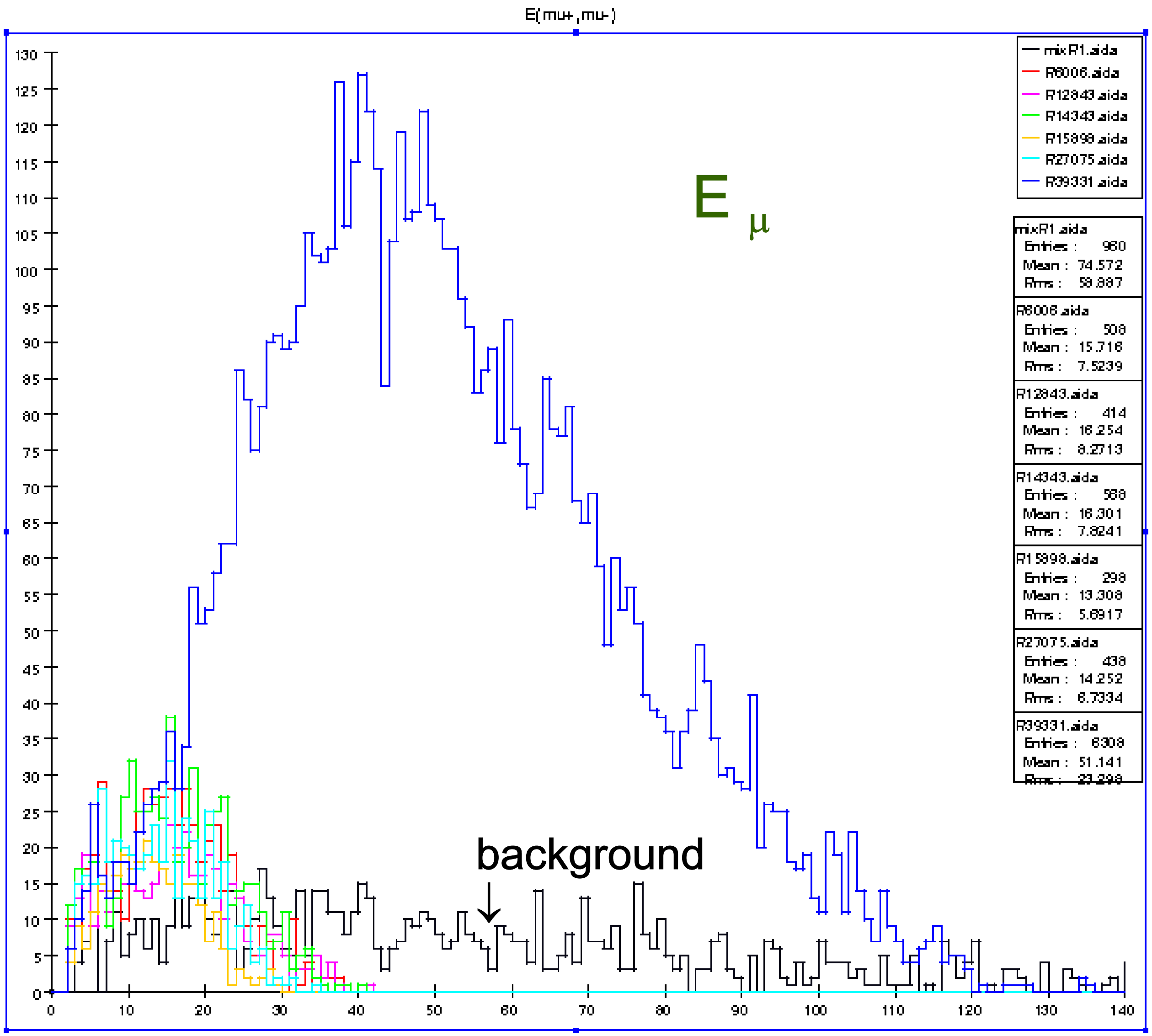
- The variation in rates is by up to a factor of ~50! Clearly models with smaller rates will be challenging…

- Spin determinations will likely require threshold scans

- The ratio of signals to 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…

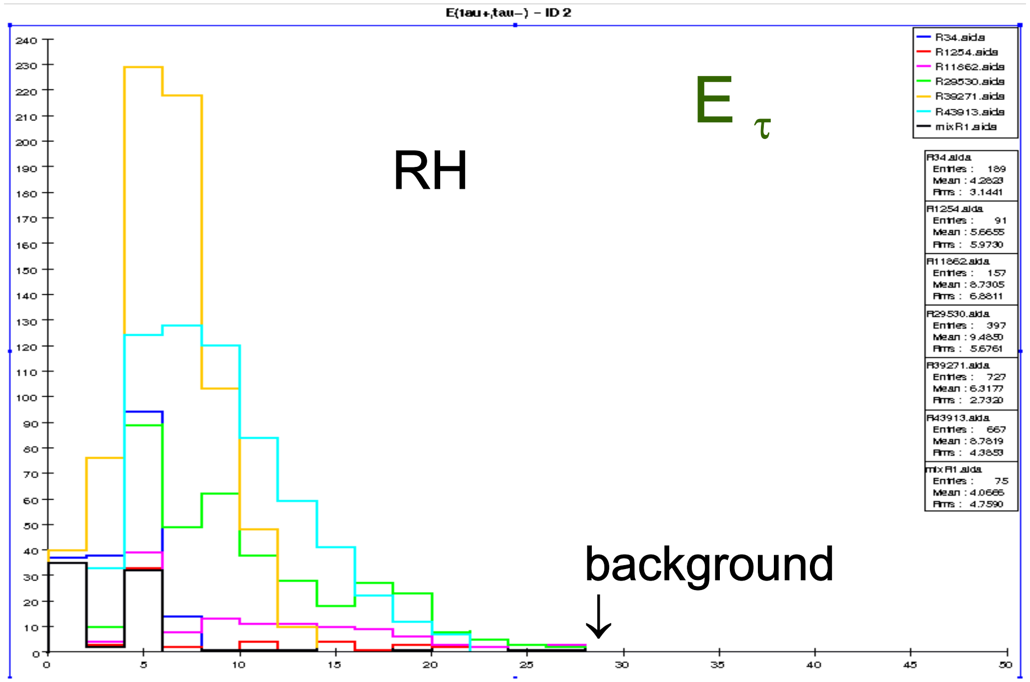
More smuons? Here are 6 models passing the smuon search criteria that are NOT smuons but feed-down from other SUSY particles...note the different spectrum structure.

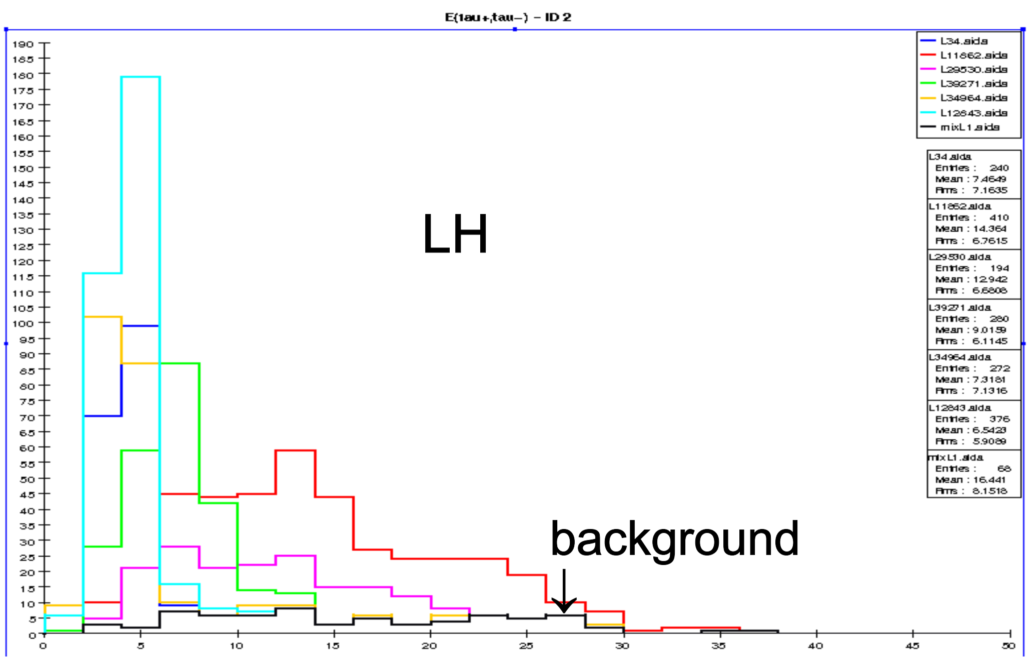


RH Polarization

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





Staus

….cleanliness at the cost of efficiency…

♠ 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

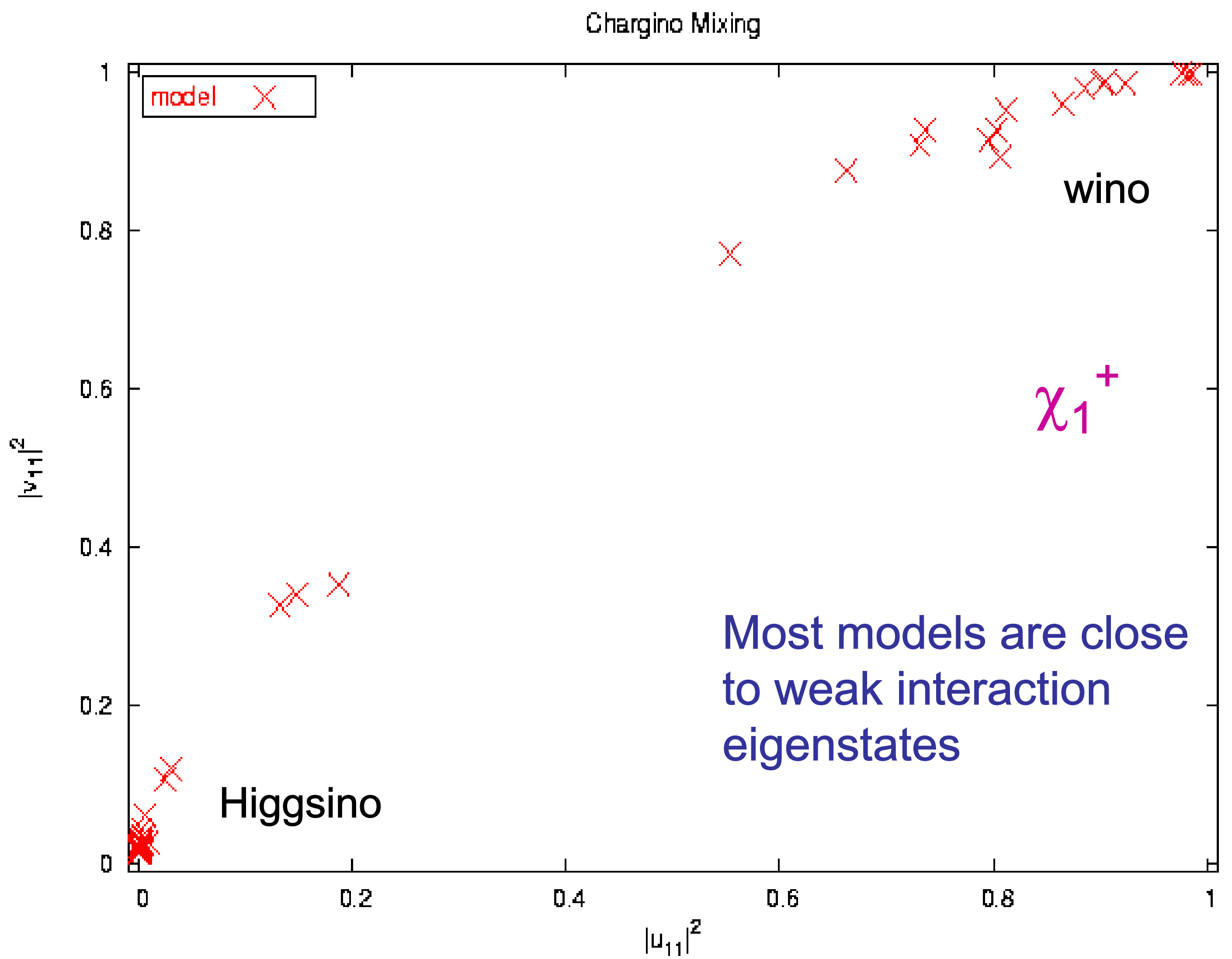
(*iii*) sneutrino → χ_1^+ + lepton → jj +lepton +LSP : allowed in only one model and the resulting jets are rather soft….. X

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

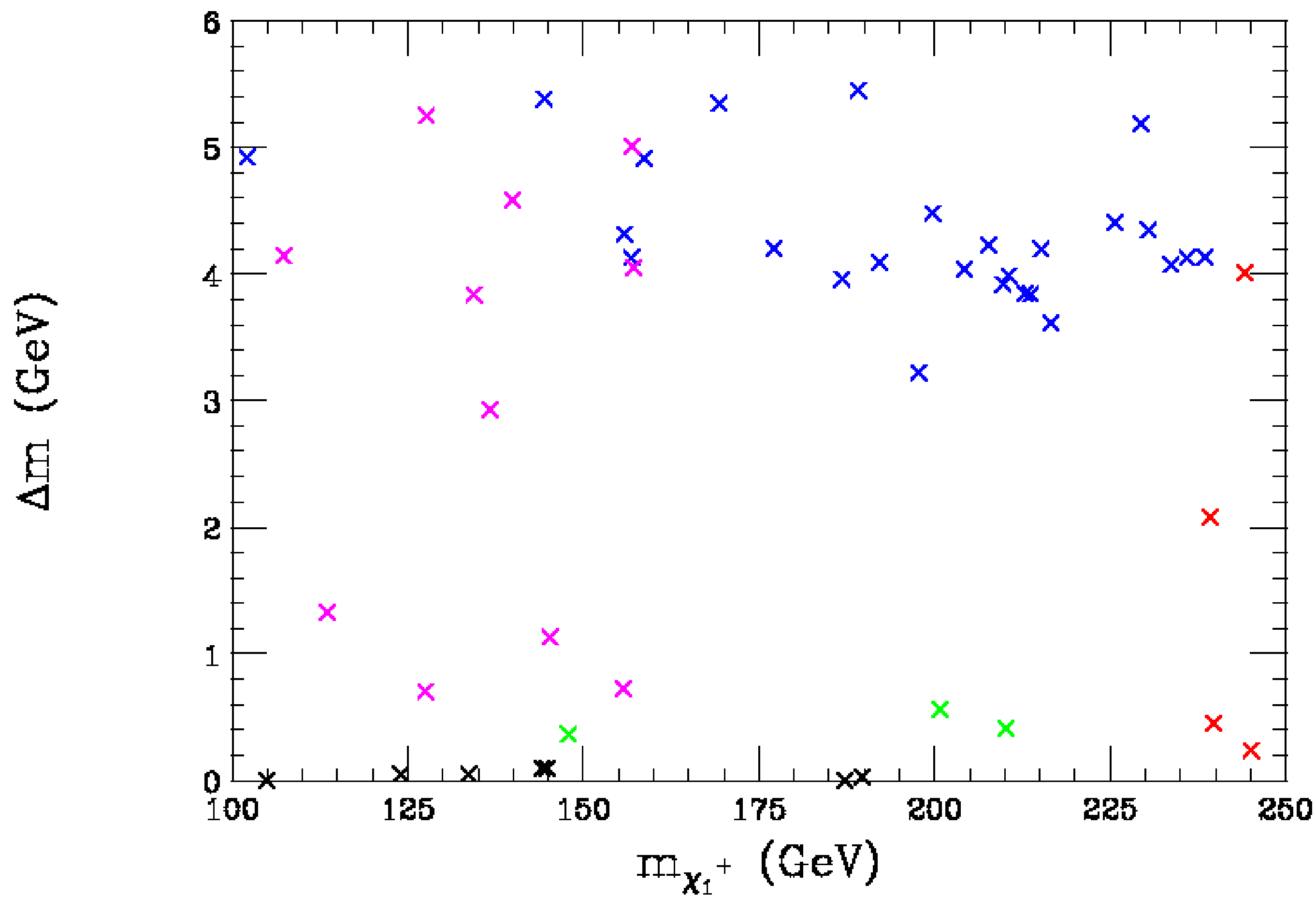
♣ → sneutrinos are not observable at 500 GeV in any model…..

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

CHARGINOS : MULTIPLE ANLAYSES REQUIRED



Charginos are seen in many different analyses…



Green = radiative only

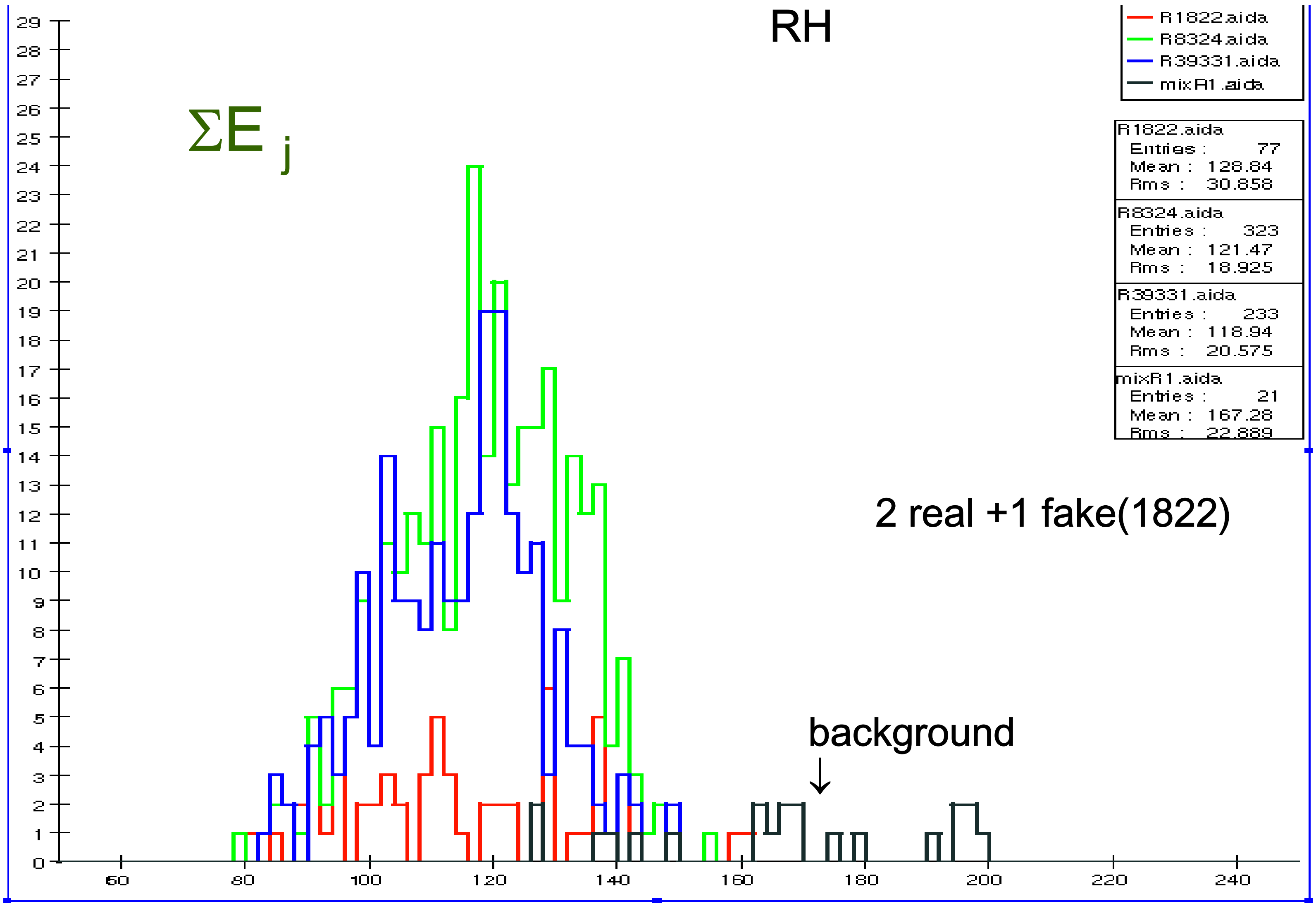
Black = stable only

Blue = off-shell W

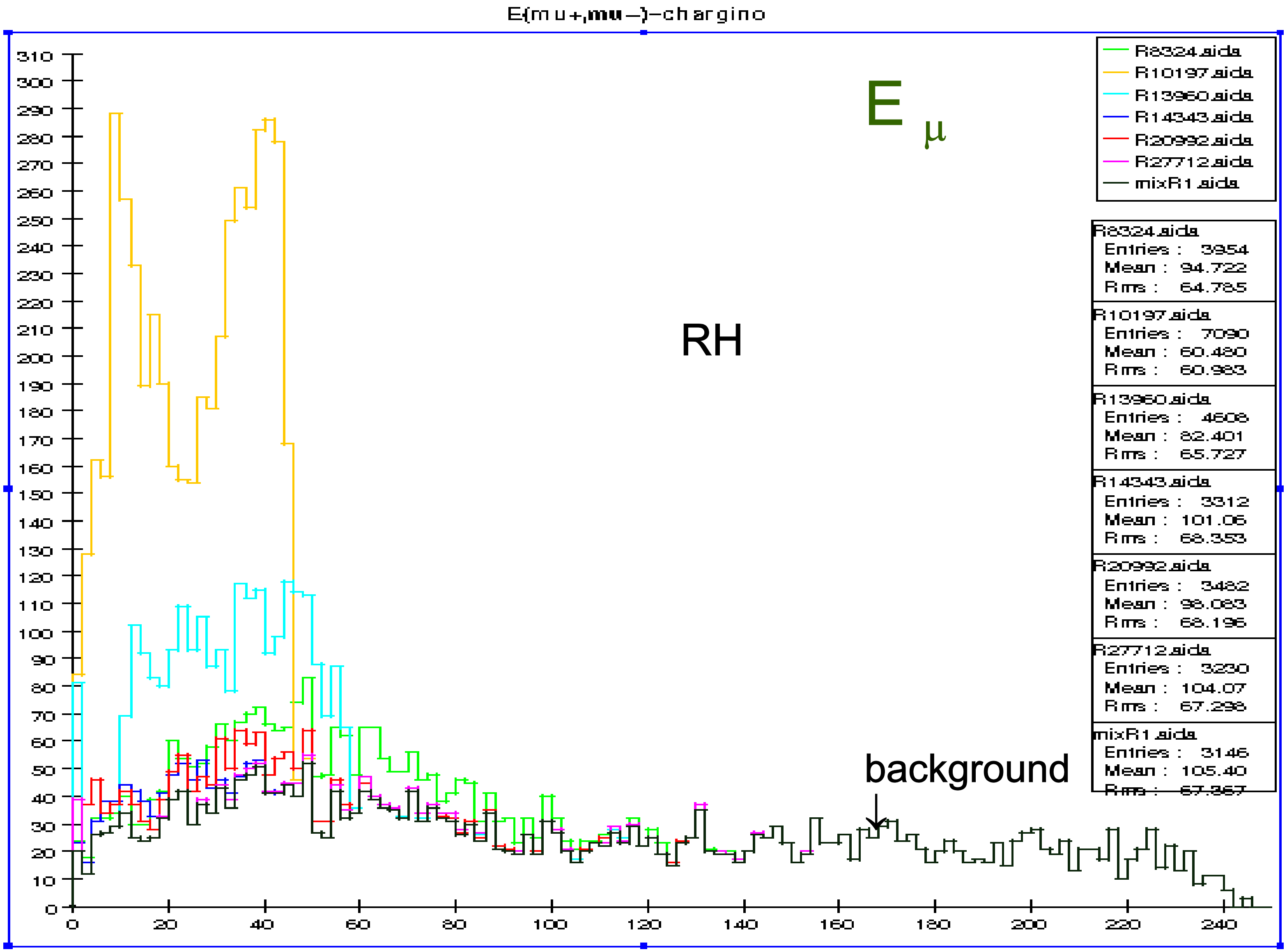
Magenta = off-shell W & radiative

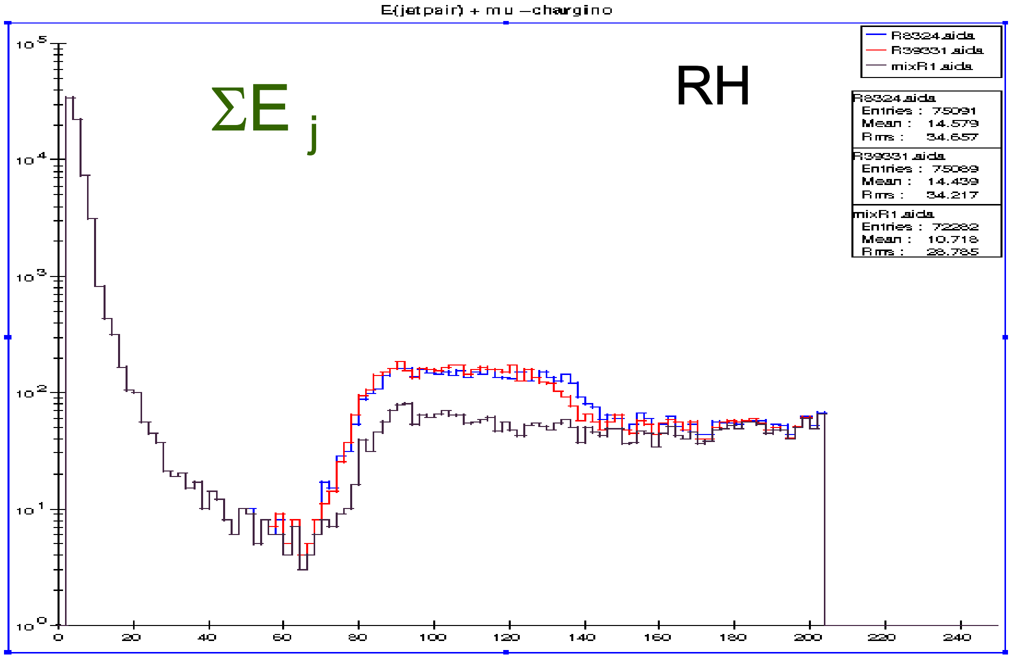
Red = missed

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

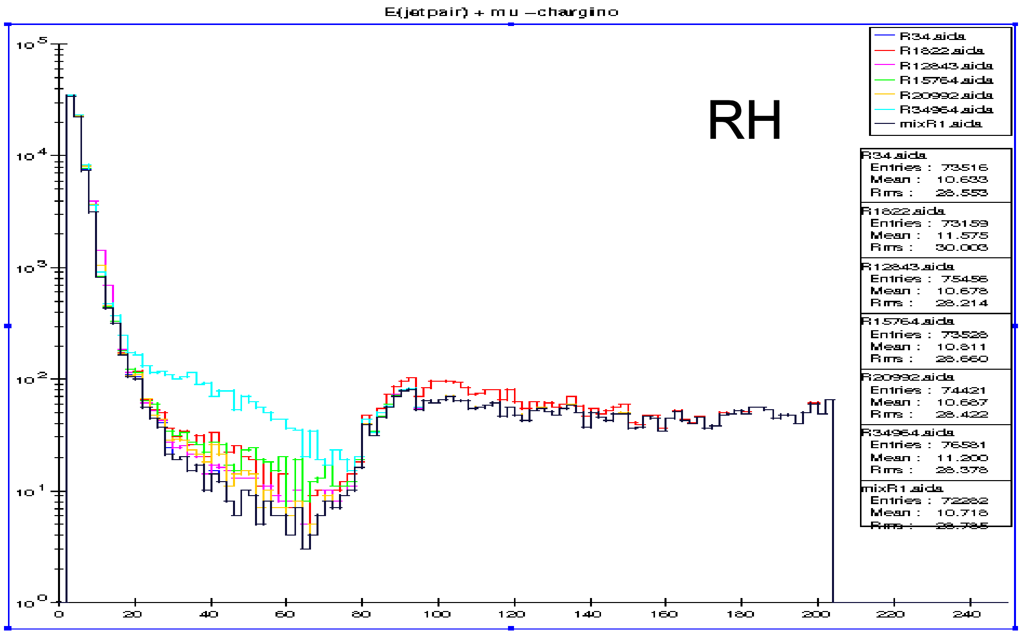


Chargino--2μ + missing E analysis : Muon Energy Analysis



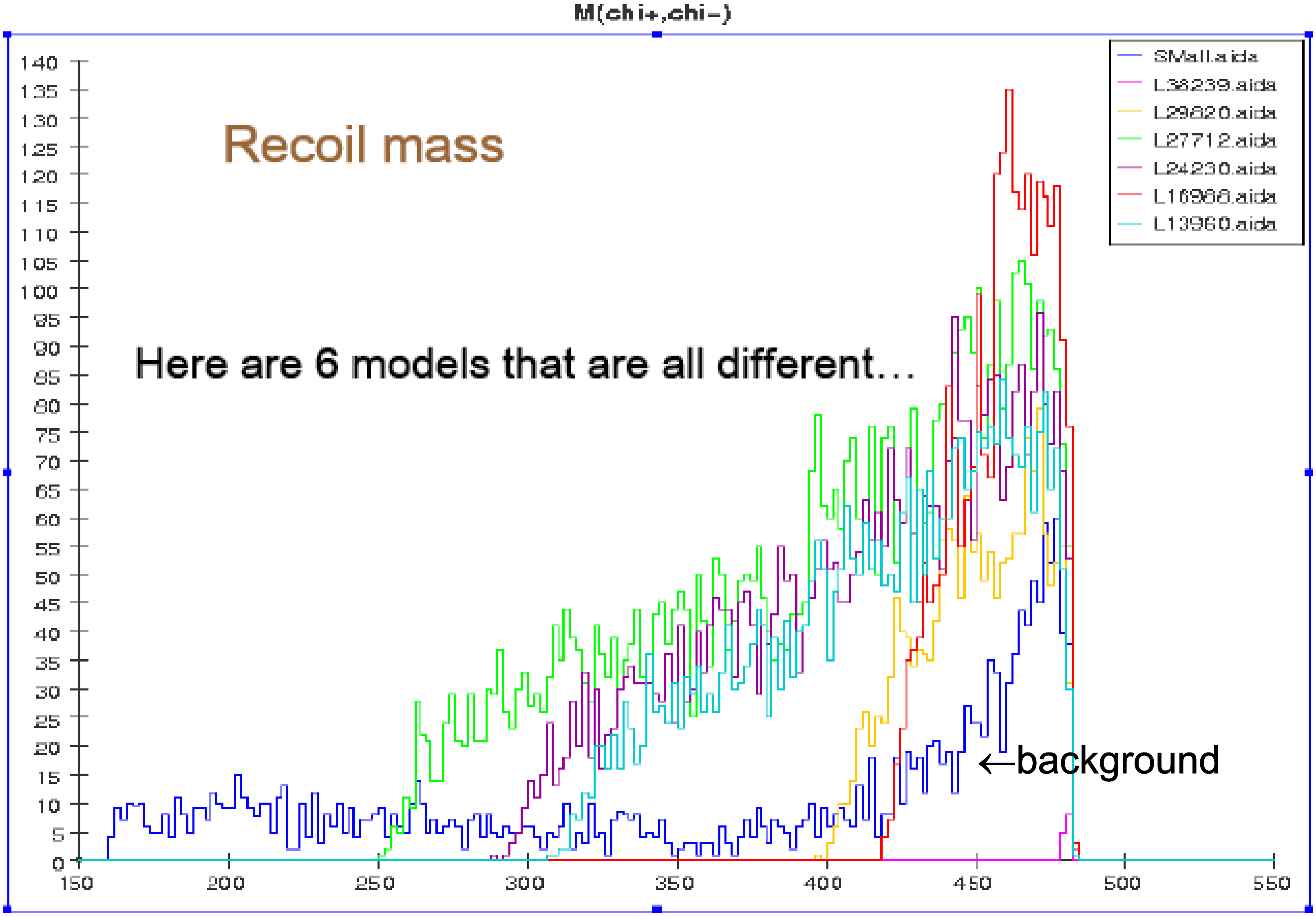


Charginos--2 jet+ muon +missing E Analysis: Jet Pair Energy

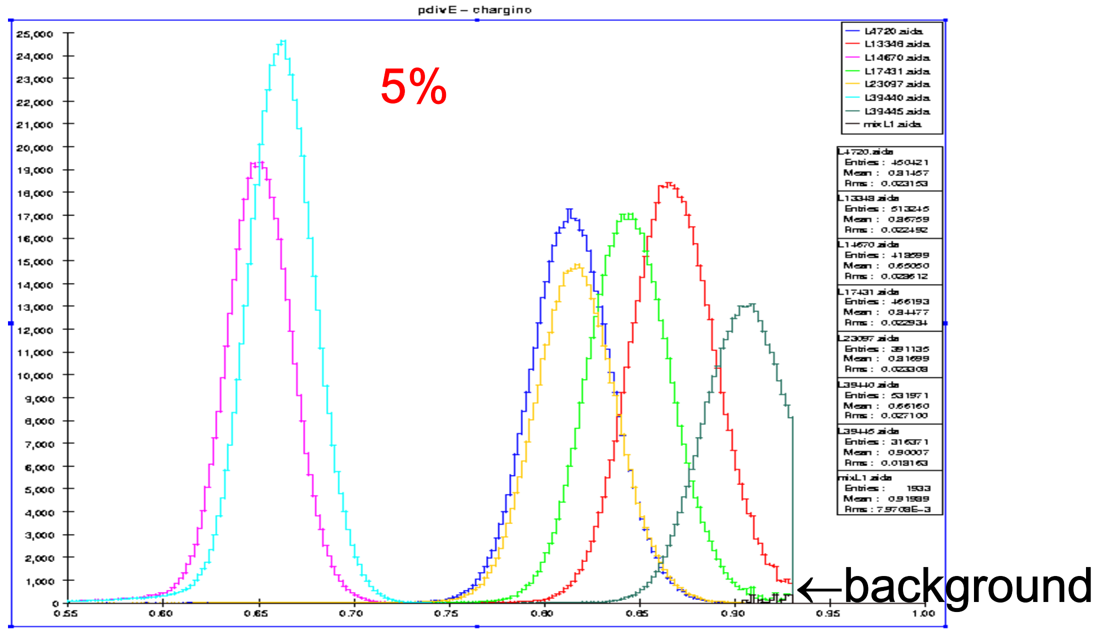


Both on- and off-shell W's are captured by this analysis

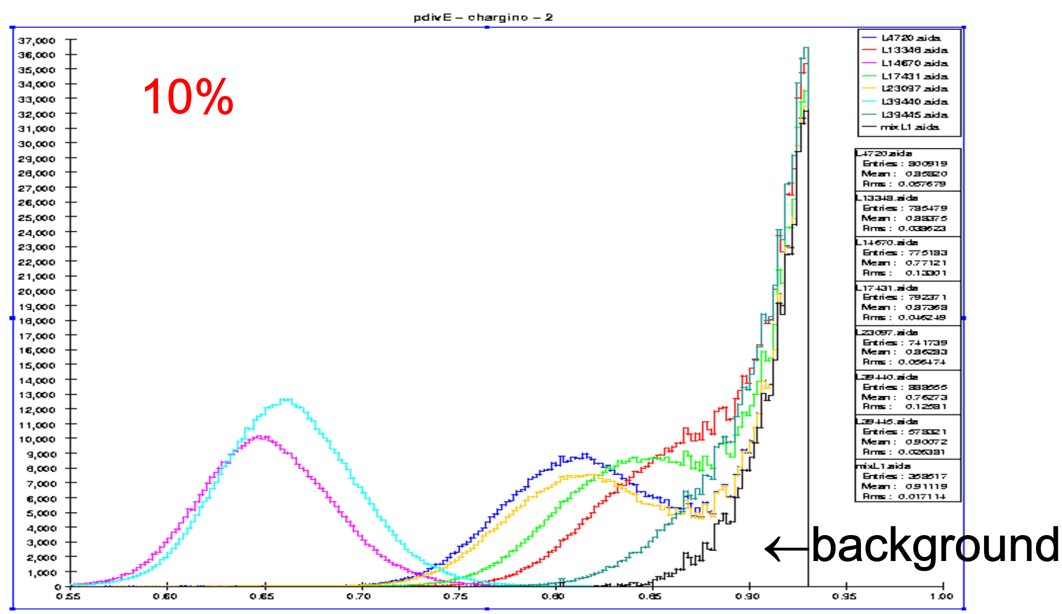
Small Δm ~ 1 GeV, Charginos: soft hadrons + photon tag



.2



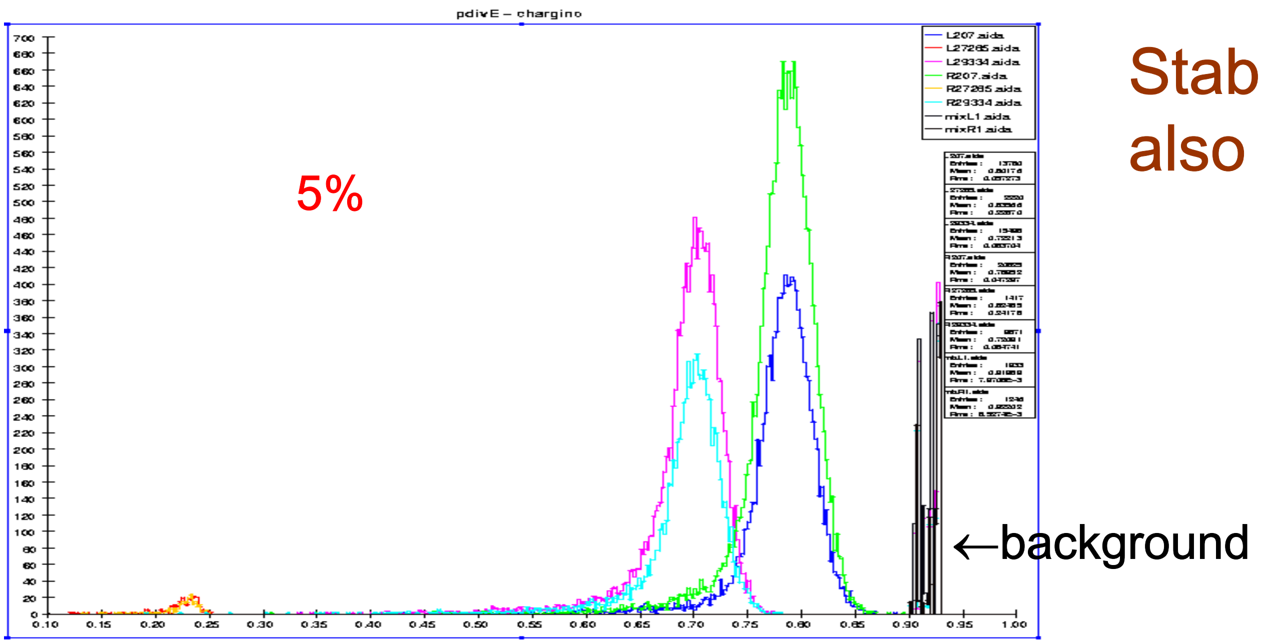
β



Stable charginos are quite easy to see with reasonable resolution

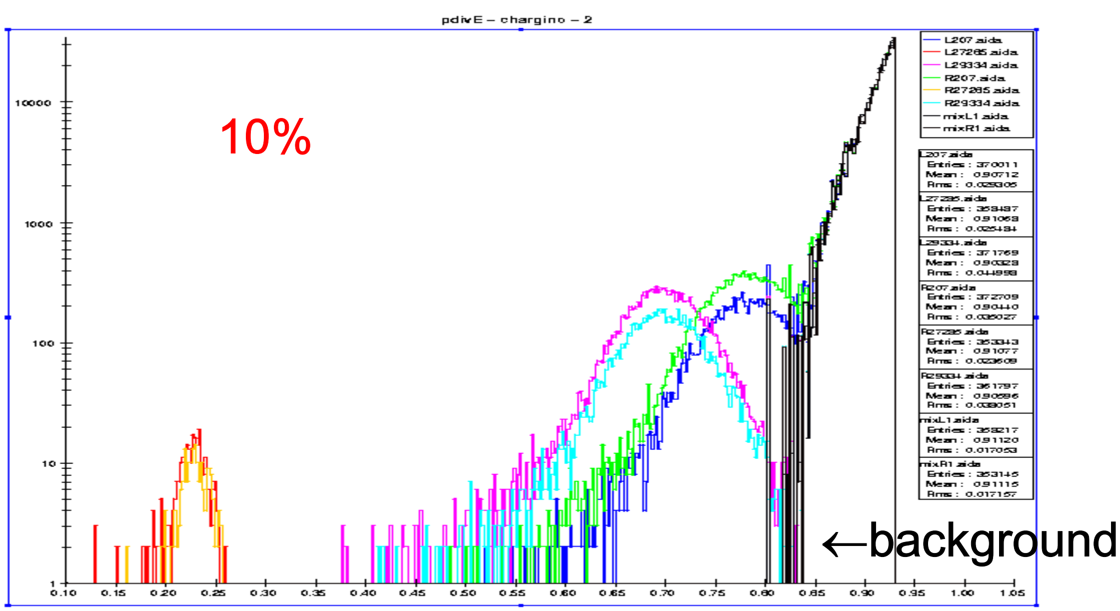
Note that ATLAS(CMS) achieves a resolution on β better than 5(3)% so we should expect an ILC detector to do as well or better

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



Stable staus are also easy to see..

β



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

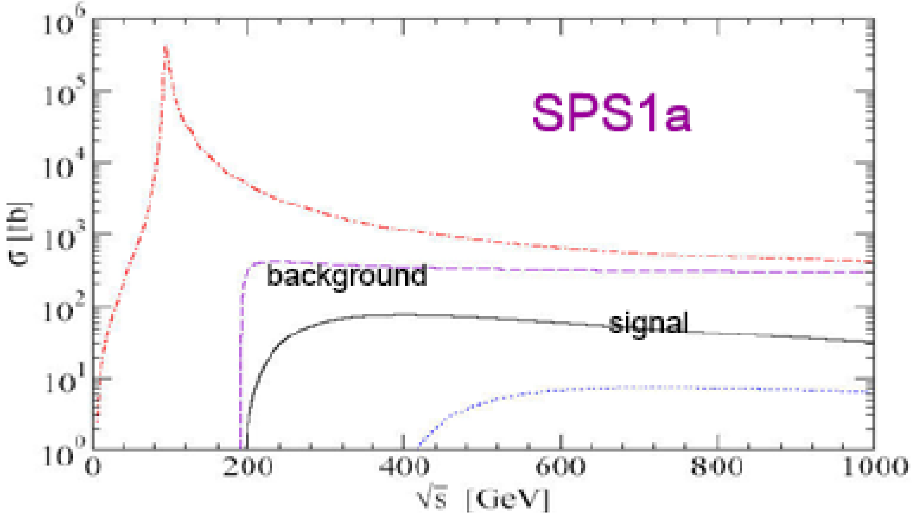
Radiative Neutralino Production

$e^+e^- \to \chi_1^0\chi_1^0$ 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
:

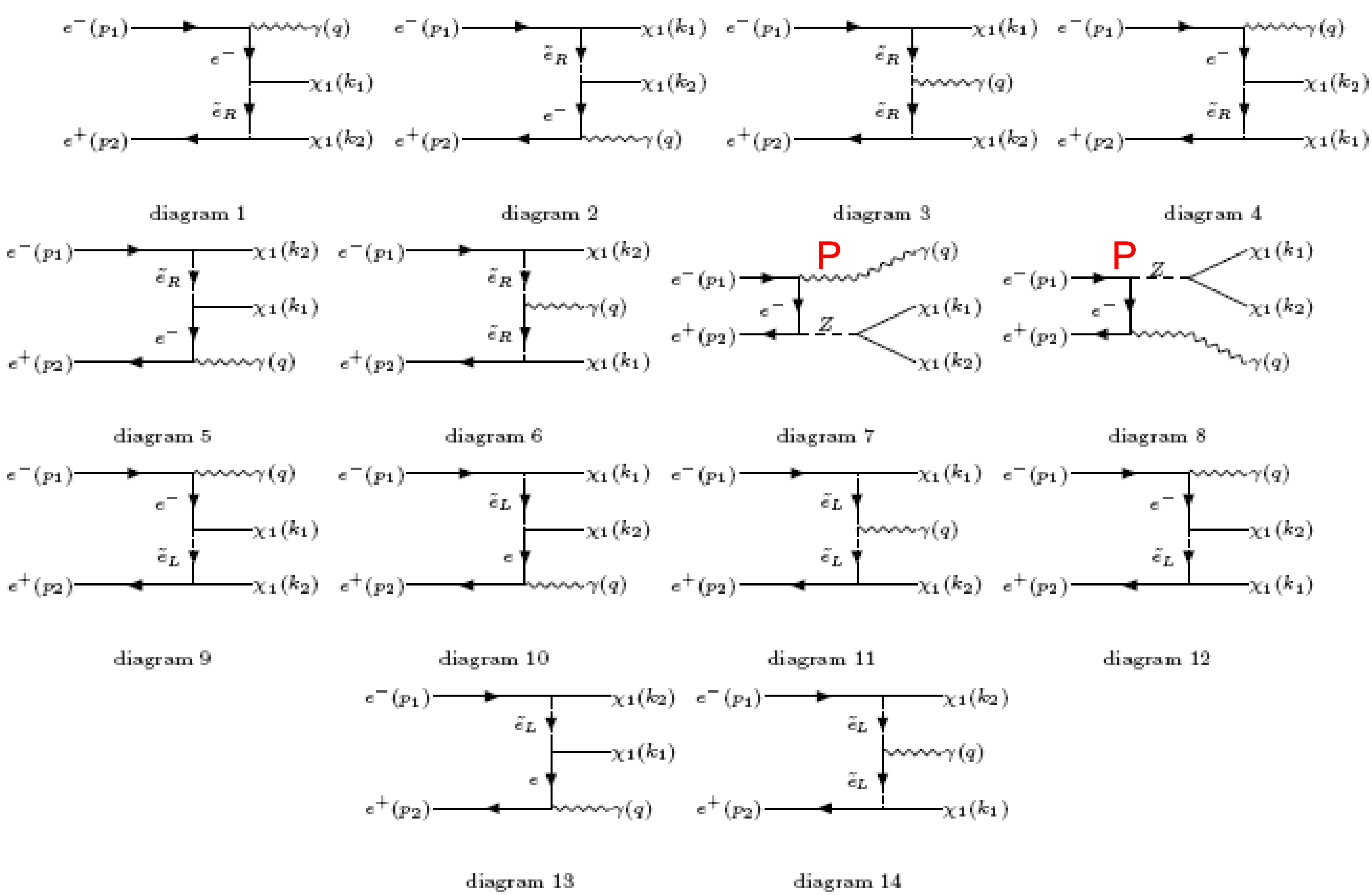
1. One γ and nothing else visible in the event
2. $E_T^\gamma = E^\gamma \sin\theta^\gamma > 0.03\sqrt{s}$, θ^γ is γ angle w/ beam axis
3. $\sin\theta^\gamma > 0.1$
4. $E^\gamma < 160.0$ GeV (removes radiative return to the Z)
5. Use CompHEP to generate hard matrix element



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

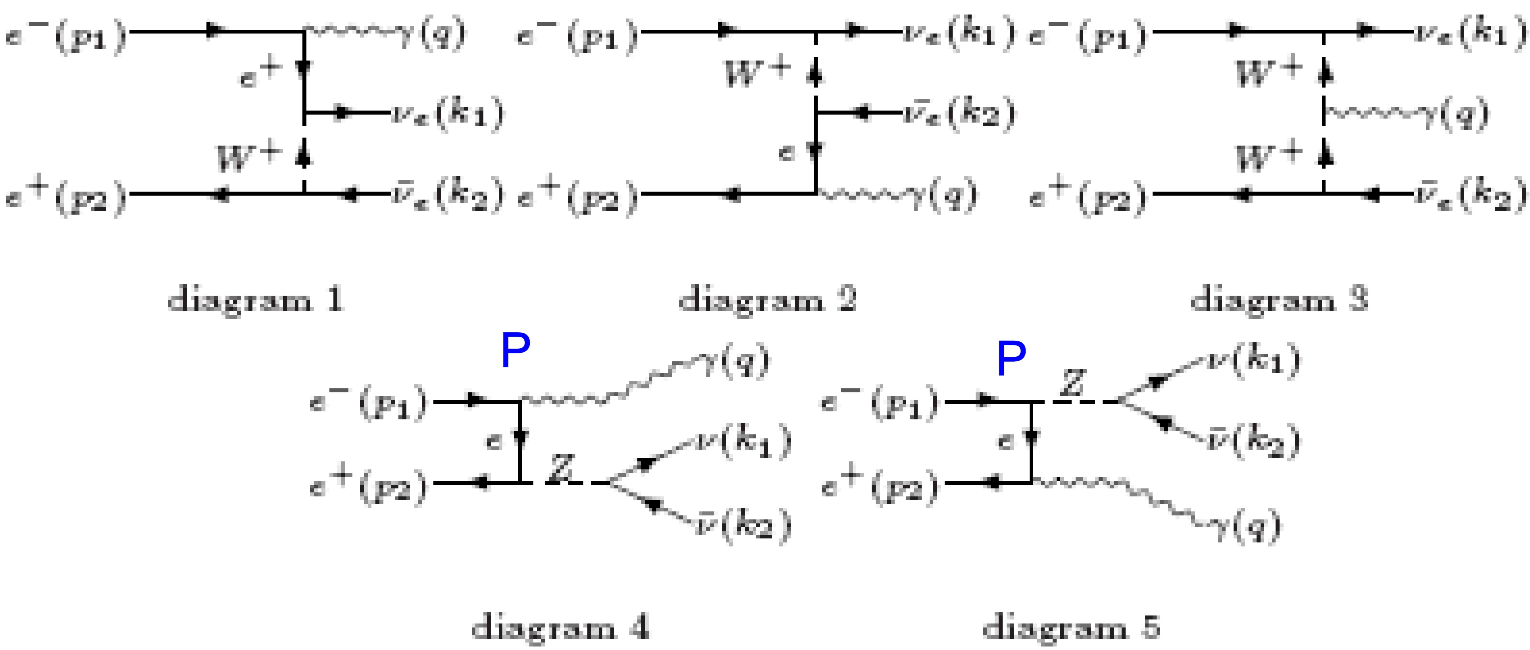
Dreiner et al., hep-ph/0610020

Signal Processes



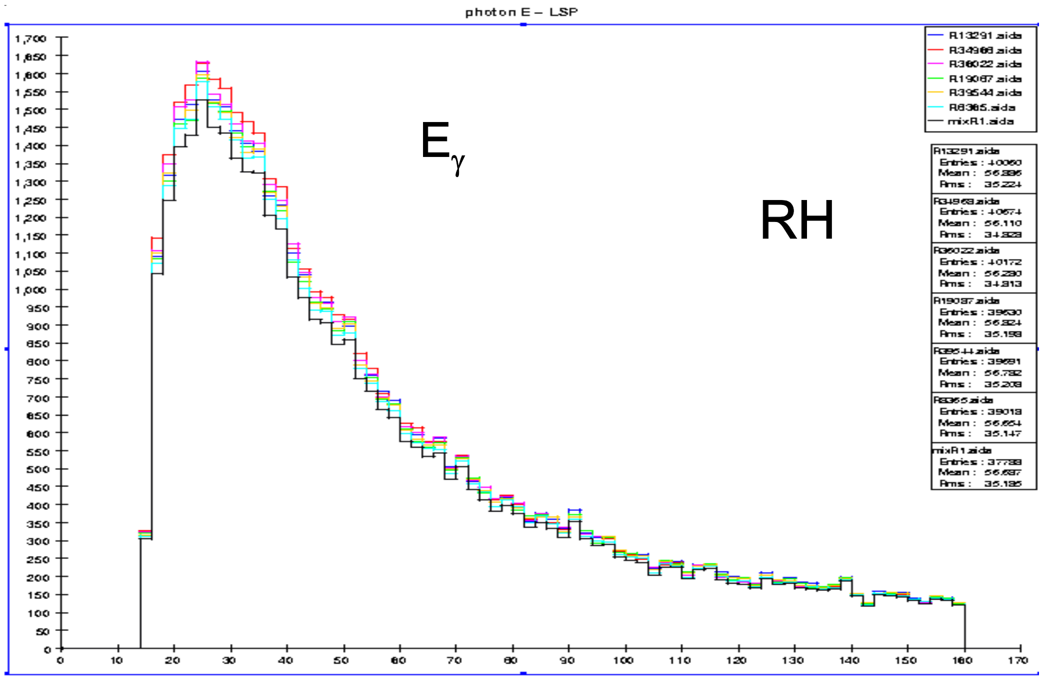
P = included in PYTHIA

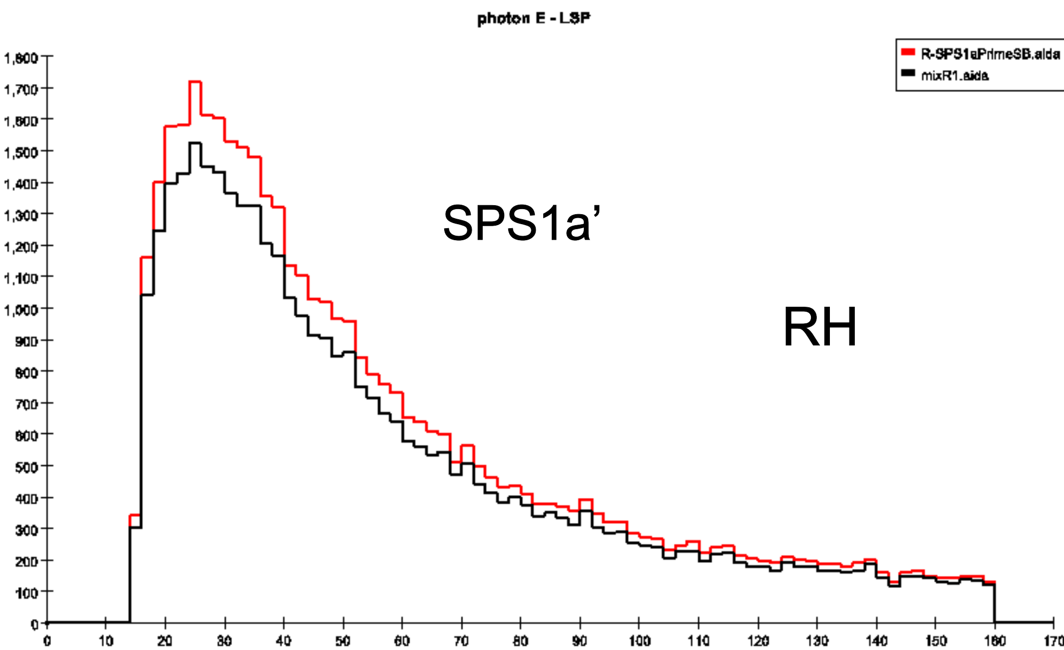
Standard Model Background



SM graphs are dominated by W exchanges and so can be significantly reduced by employing RH electron and LH positron beam polarization.

P = included in PYTHIA



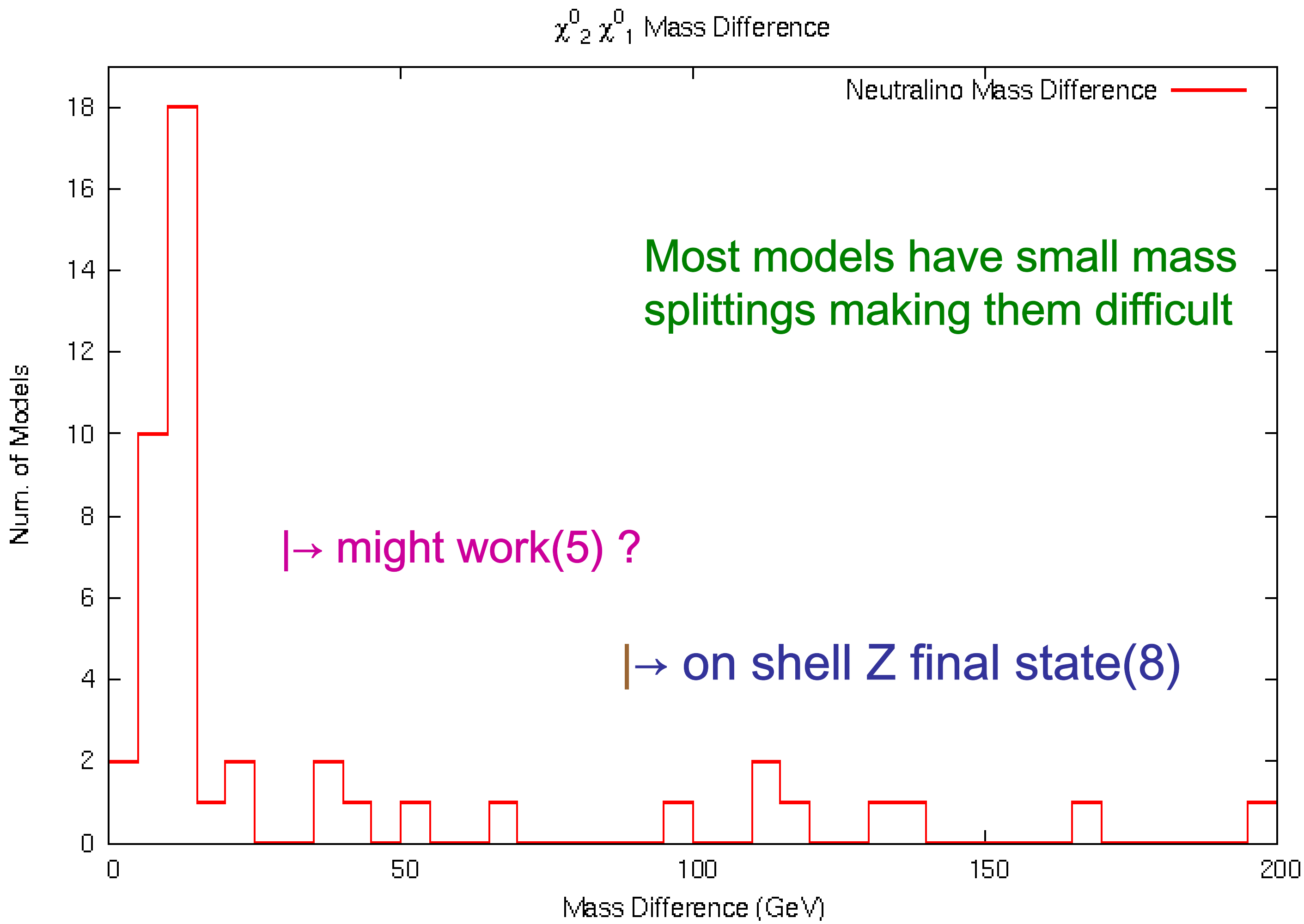


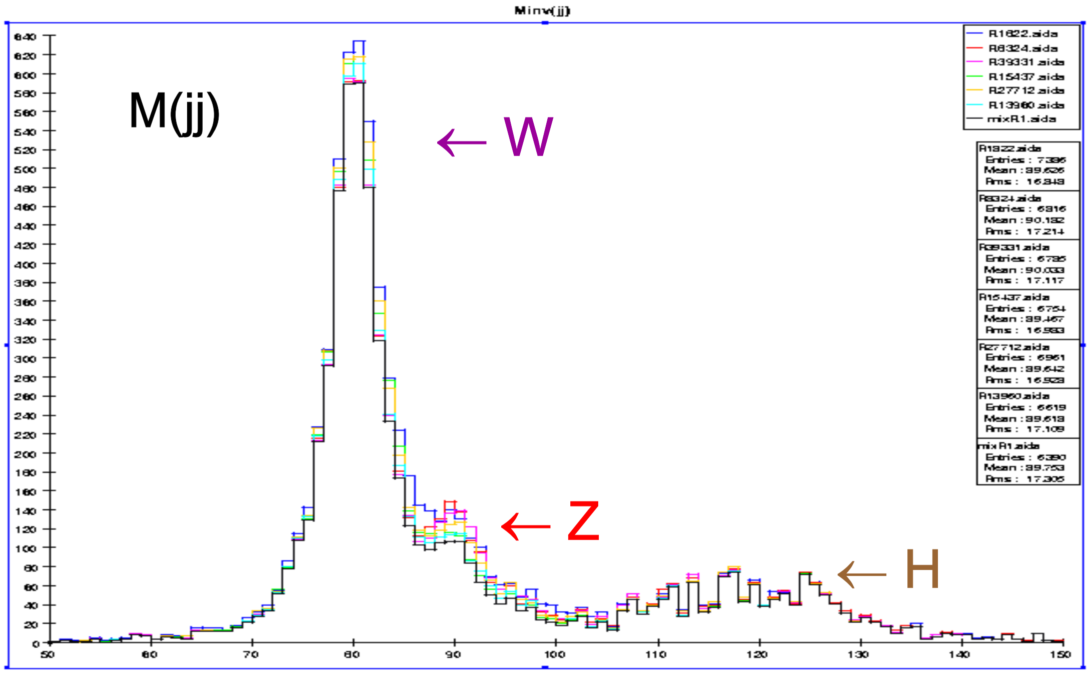
Photon tagging is quite efficient.. we see this final state for 17/242 models. Sneutrino pollution is important in some cases.

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

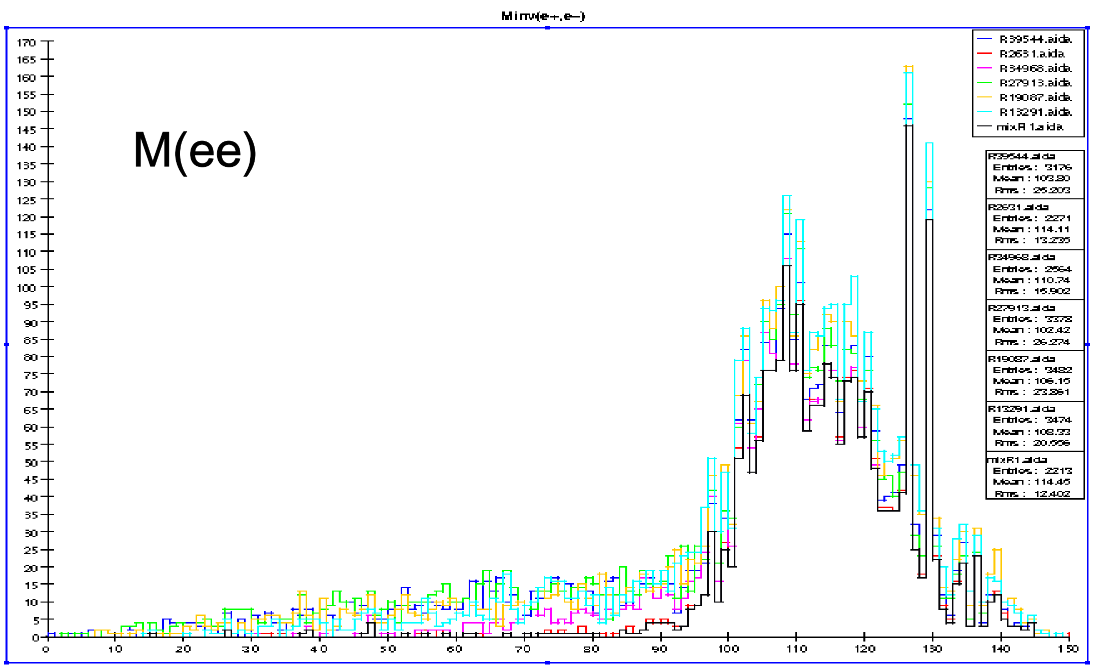
SPS1a' produces a rate far larger than all our models but is contaminated by sneutrino production

$\chi_2^0\ \chi_1^0$ 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 $\mu\mu$



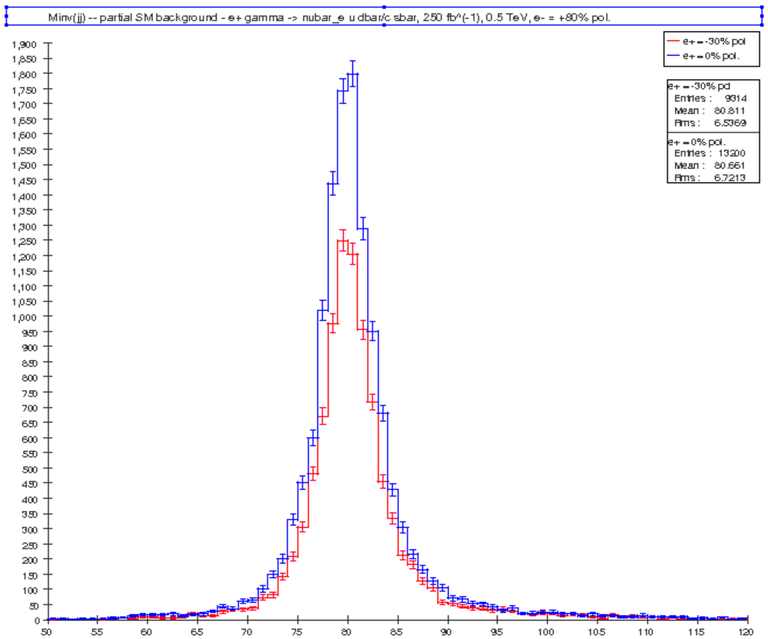


In the jj channel we *do* see an excess at the Z (5 models) but also a huge W peak from both backgrounds as well as from other sparticles such as the charginos… we also see the Higgs.

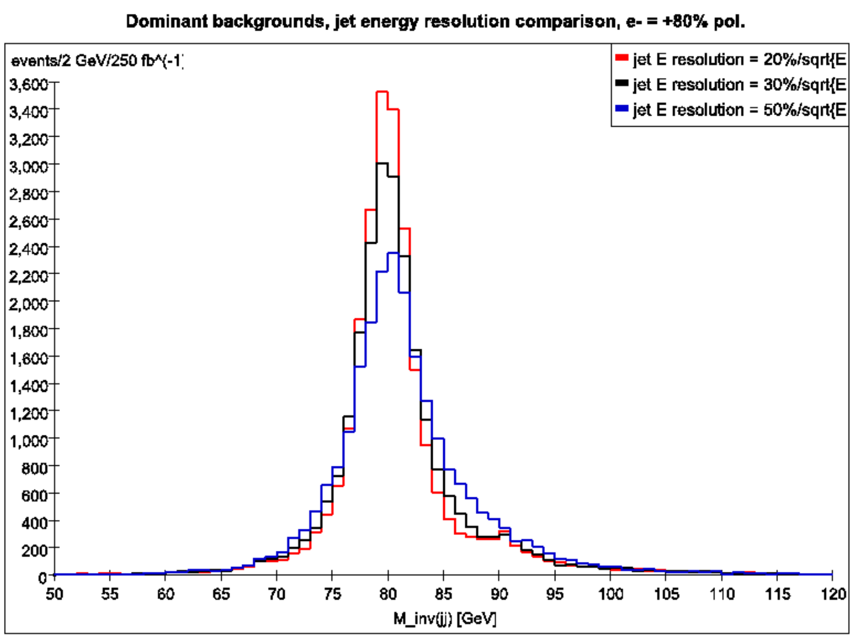


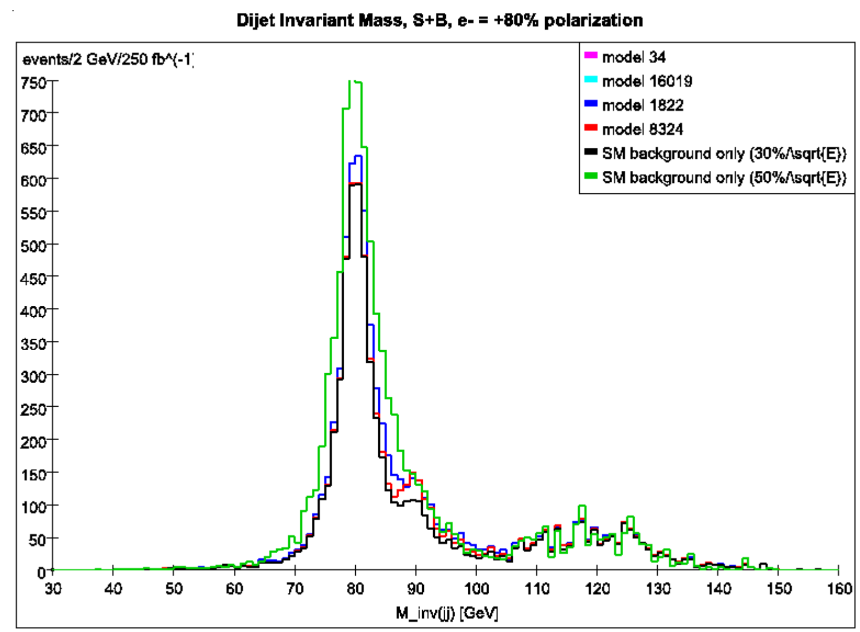
This signal can be cleaned up with better mass resolution and/or positron polarization

In the ee channel we have mostly fakes..



Here we see the response to both positron polarization and changes in the jet energy resolution…these changes are necessary to improve this channel





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 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….

In the case of charged sparticles, the missed models are due to either phase space rate suppression or, e.g., stau mixing

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 that we have a set of 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

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.

How can we improve our batting average?

• In the charged sector, overall we do rather well but we could do a somewhat better job seeing taus and distinguishing them from charginos with small mass splittings from the LSP. Low angle tracking to ID muons would be useful.

• The biggest problem is in the neutral sector especially as many models and pairs of models only have the lightest neutralino accessible. Observing photon–tagged LSPs is already quite difficult due to low rates & the large SM background. At fixed $\sqrt{s}$, increased luminosity & positron polarization will be helpful. One can also use the fact that signal & background have a different $\sqrt{s}$ behavior.

• Better access to χ_2^0 would be useful but the W-induced dijet background is very large. Both positron polarization and/or better jet E resolution is needed is this case.

SUMMARY AND OUTLOOK

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

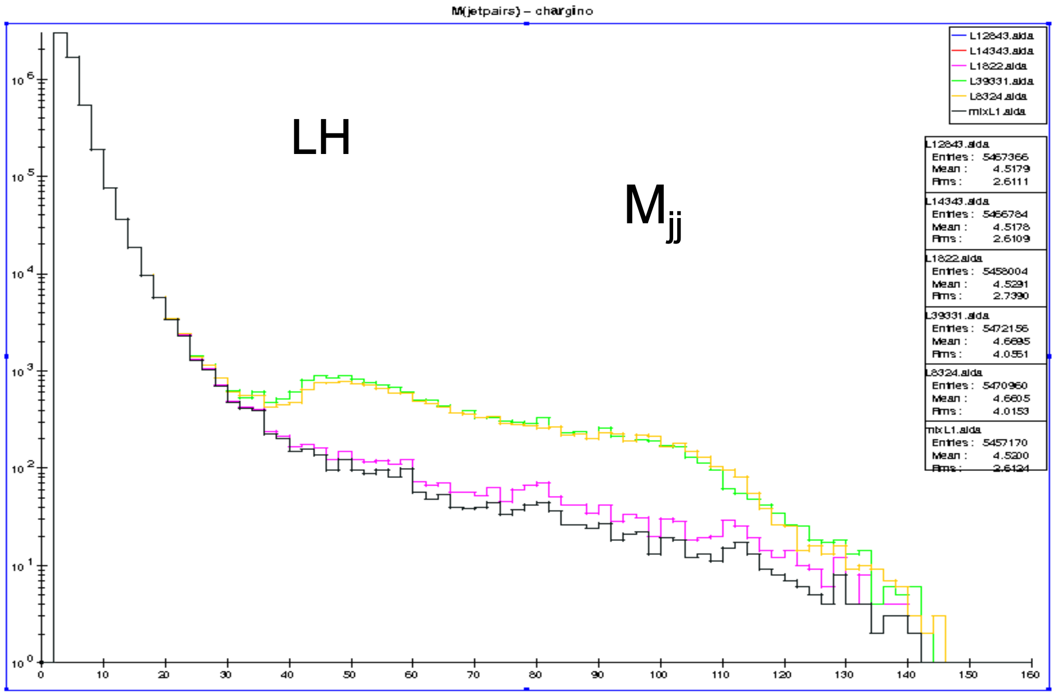
(*i*) Study higher energy colliders and the influence of positron polarization on both signals and backgrounds (+more channels to look at). Do threshold scans of some kind, include vertex detector analyses…

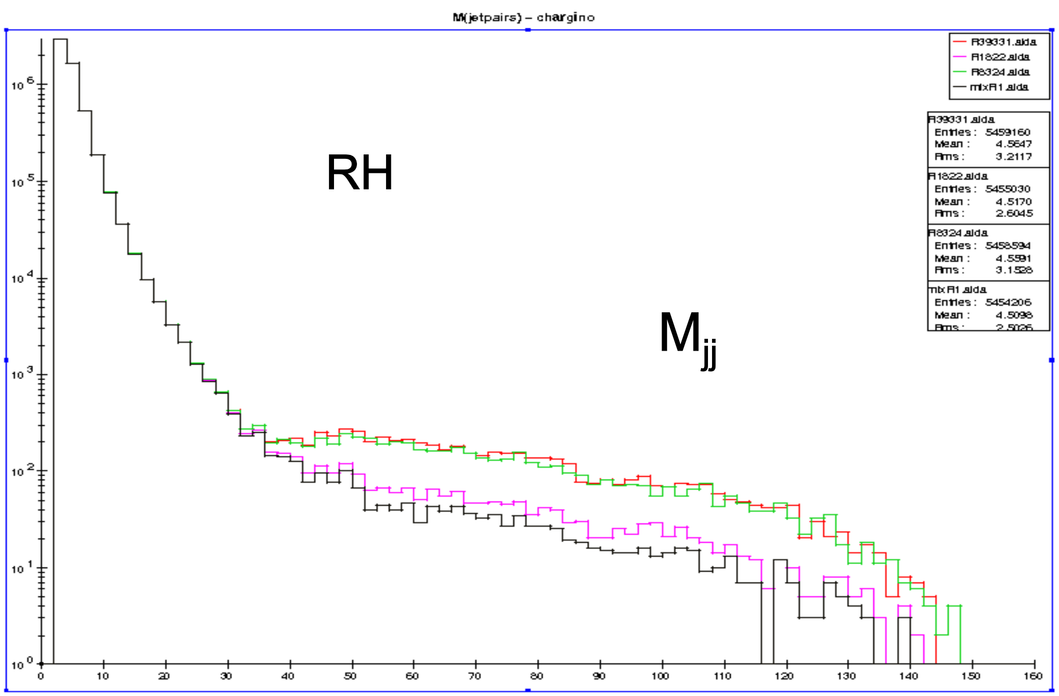
(*ii*) Explore using CompHEP/MADGRAPH to generate SUSY signal events for all analysis channels & use SDECAY to access more final states

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

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

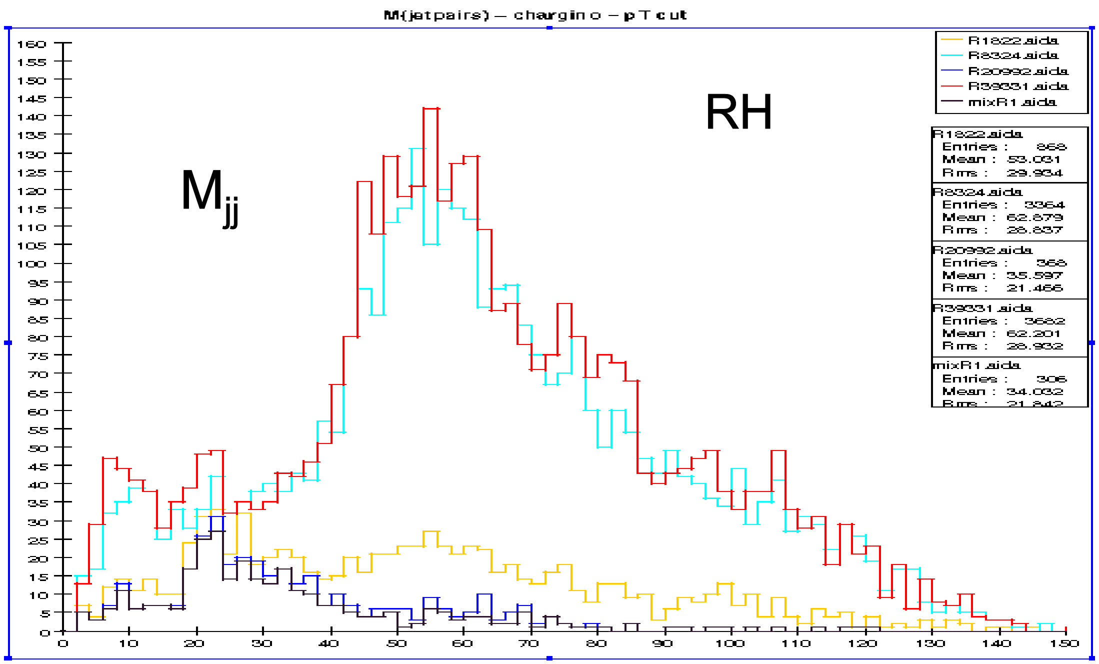
BACKUP SLIDES

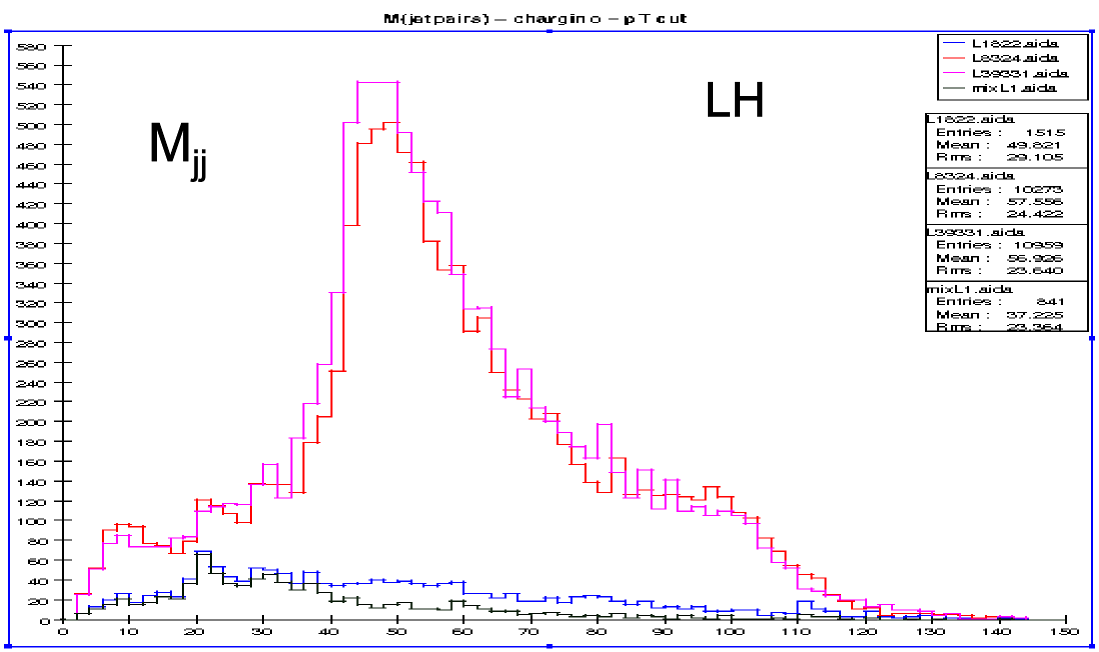




Chargino 4-jet+Missing Energy Analysis

2 real + 1 fake models



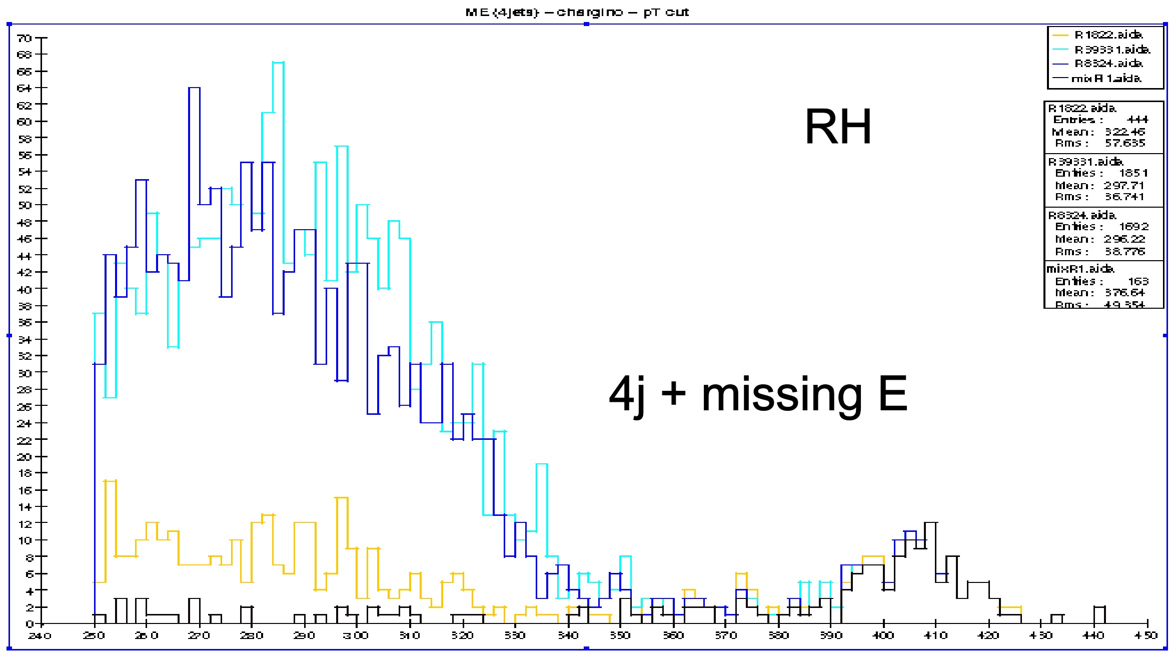


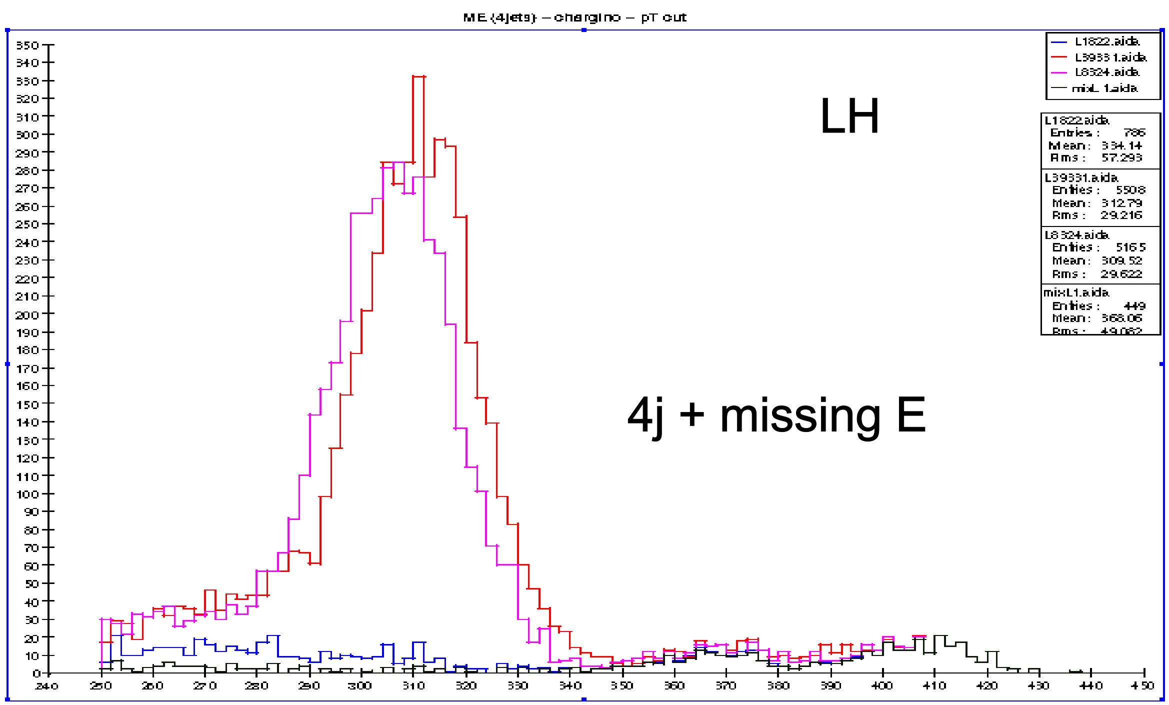
Chargino 4-jet+Missing Energy Analysis

AFTER p_T CUT…

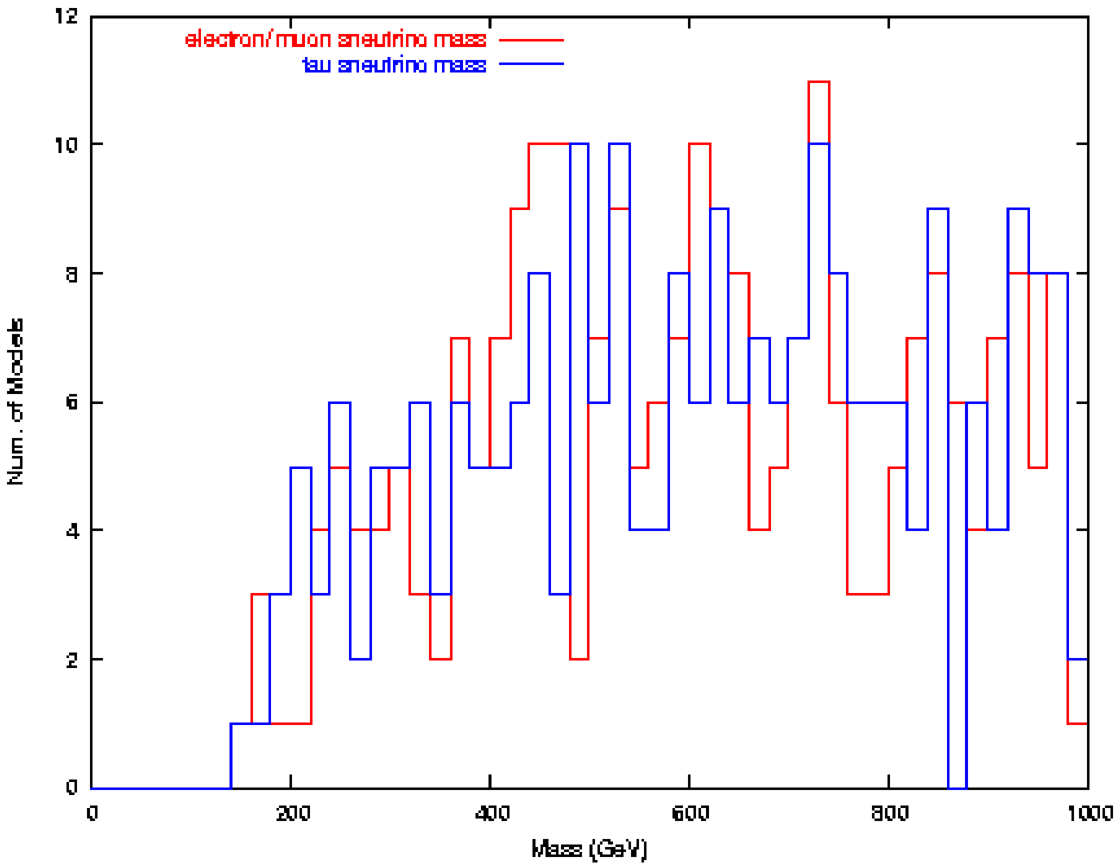
Much cleaner!

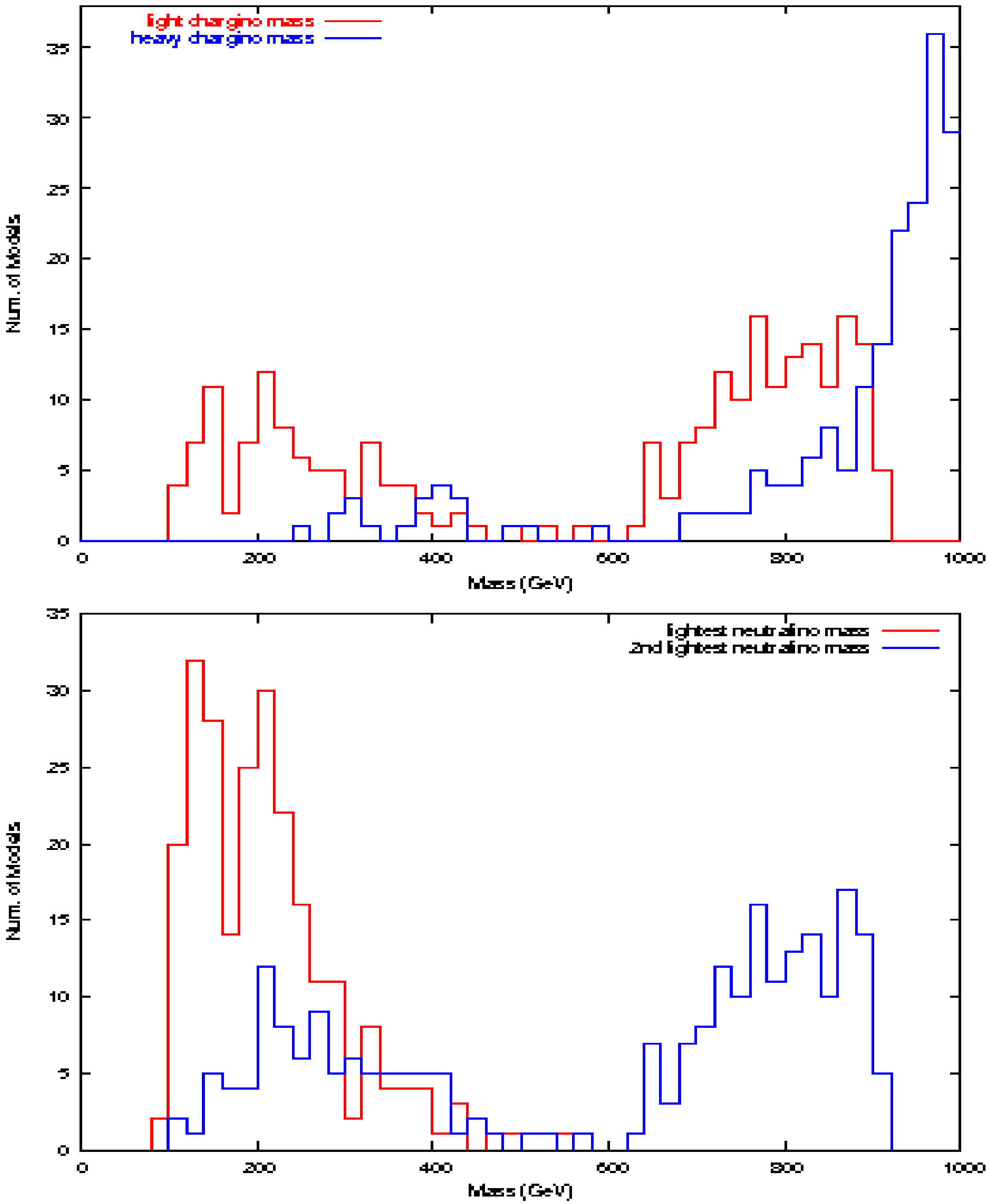
2 real + 2 fake models


ME (4jets) – chargino – pT cut
R1822.aida
R39331.aida
R8324.aida
mixR1.aida
R1822.aida Entries : 444 Mean : 322.46 Rms : 57.635
R39331.aida Entries : 1851 Mean : 297.71 Rms : 36.741
R8324.aida Entries : 1692 Mean : 296.22 Rms : 38.776
mixR1.aida Entries : 163 Mean : 376.64 Rms : 49.354
RH
4j + missing E

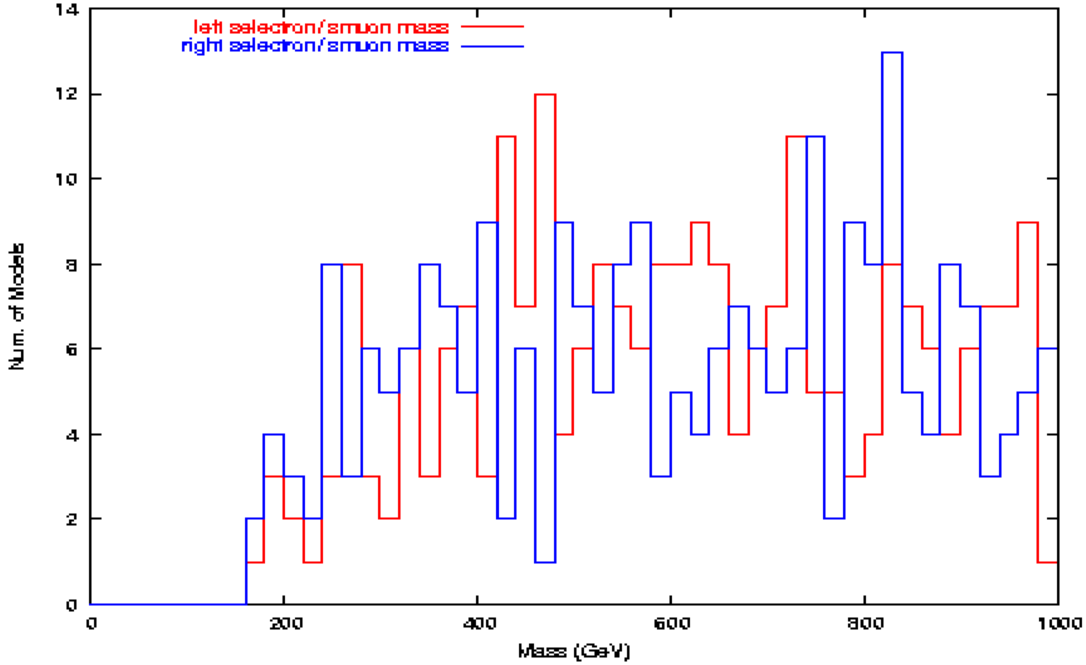

ME (4jets) – chargino – pT cut
L1822.aida
L39331.aida
L8324.aida
mixL1.aida
L1822.aida Entries : 786 Mean : 334.14 Rms : 57.293
L39331.aida Entries : 5508 Mean : 312.79 Rms : 29.216
L8324.aida Entries : 5165 Mean : 309.52 Rms : 29.622
mixL1.aida Entries : 449 Mean : 368.06 Rms : 49.062
LH
4j + missing E

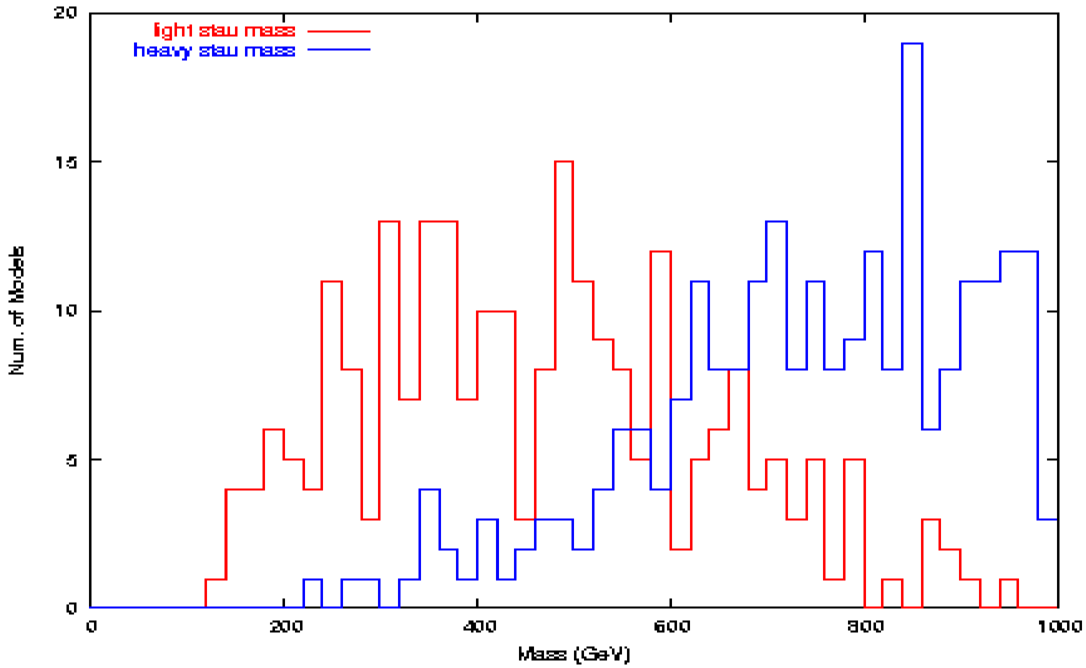
Slepton Spectra





Particle mass spectrum for charginos and neutralinos





Particle mass spectrum for selectrons, smuons and staus

Essentials of MSSM Parameters and Mixings

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

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

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

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

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

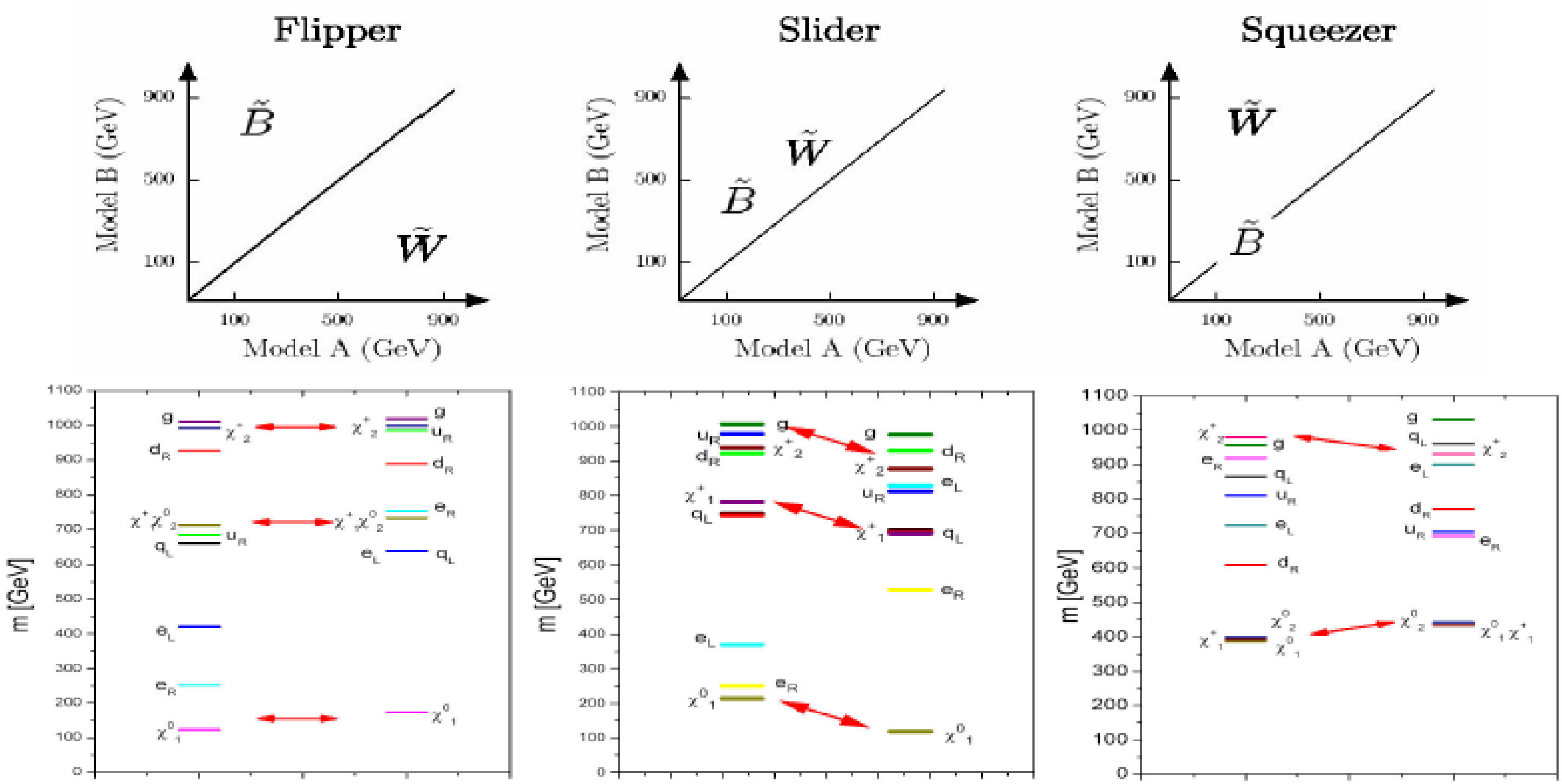
$$\begin{aligned} M^2_{LL} &= m^2_f + m^2_{L,\tilde{f}} + M^2_Z \cos 2\beta (I^f_3 - Q^f s^2_W), \\ M^2_{RR} &= m^2_f + m^2_{R,\tilde{f}} + M^2_Z \cos 2\beta \, Q^f s^2_W, \\ X_f &= A_f - \mu^* \{\cot\beta, \tan\beta\} \end{aligned}$$

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

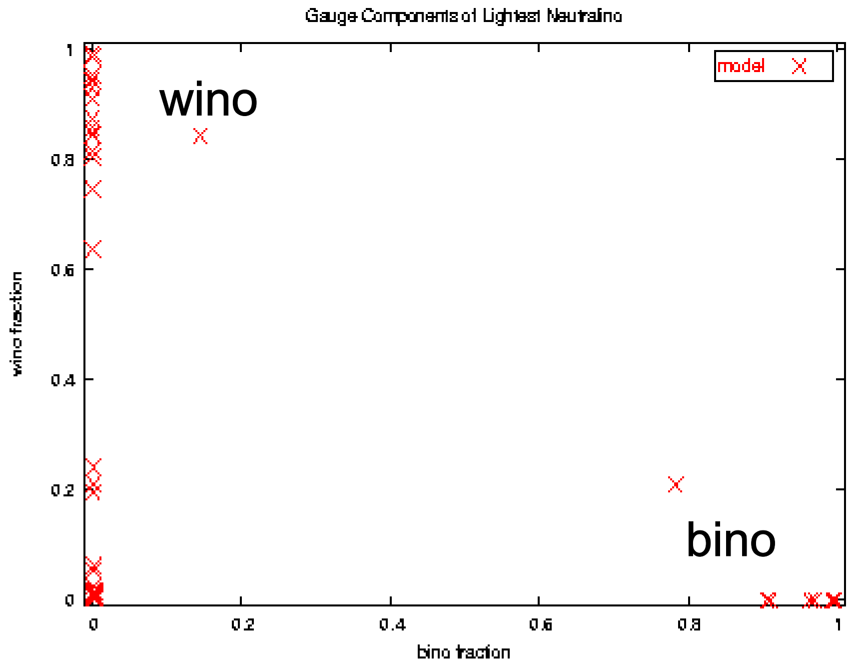
Characteristics of Degenerate Models

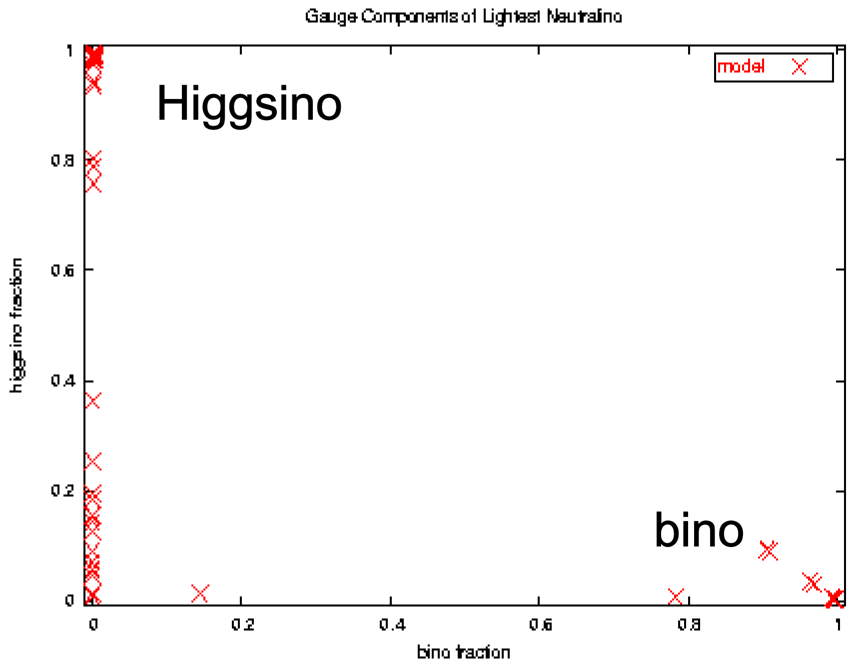
LHC: measures mass differences in cascade decays quite well…

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



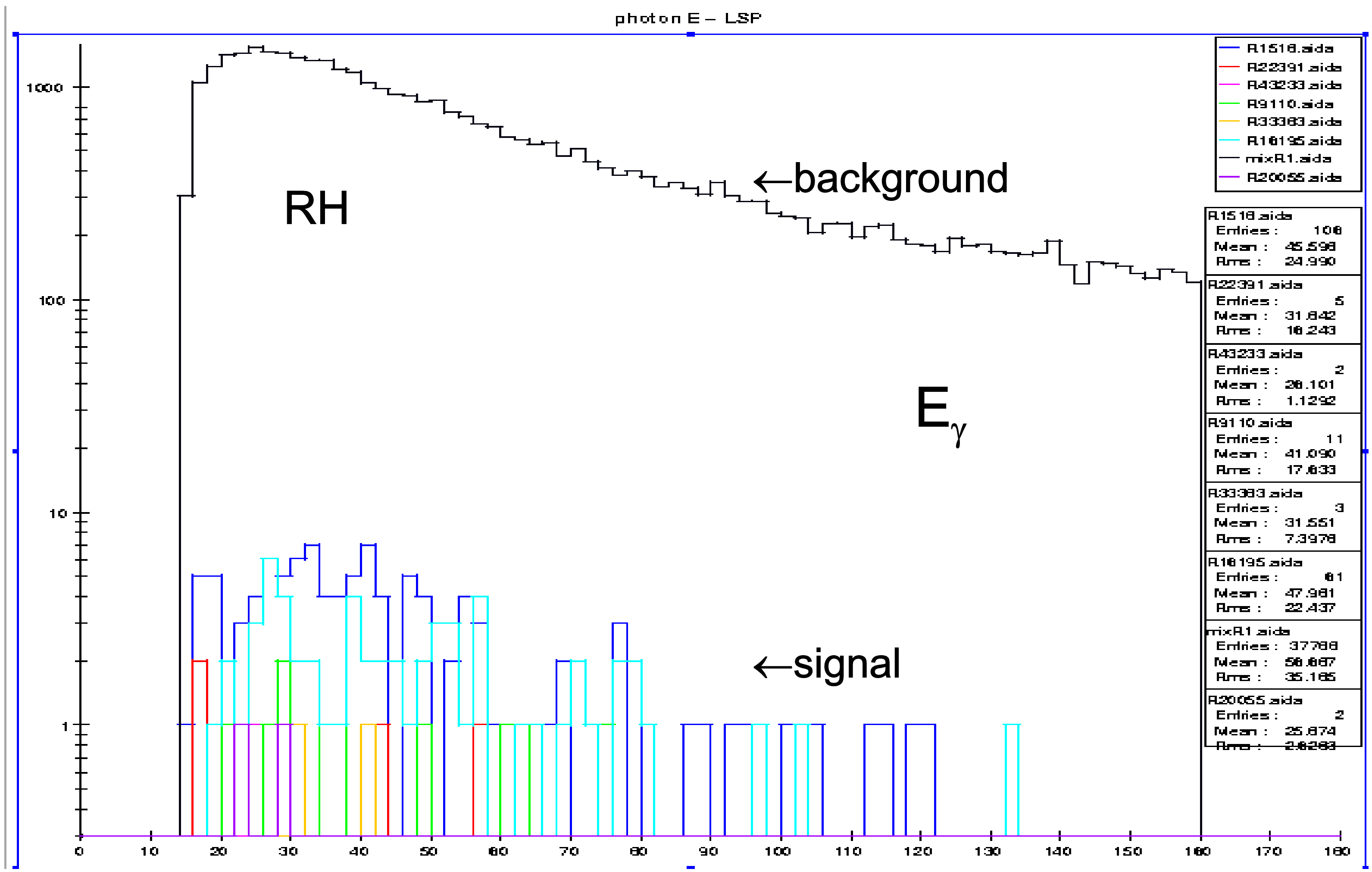
NEUTRALINOS



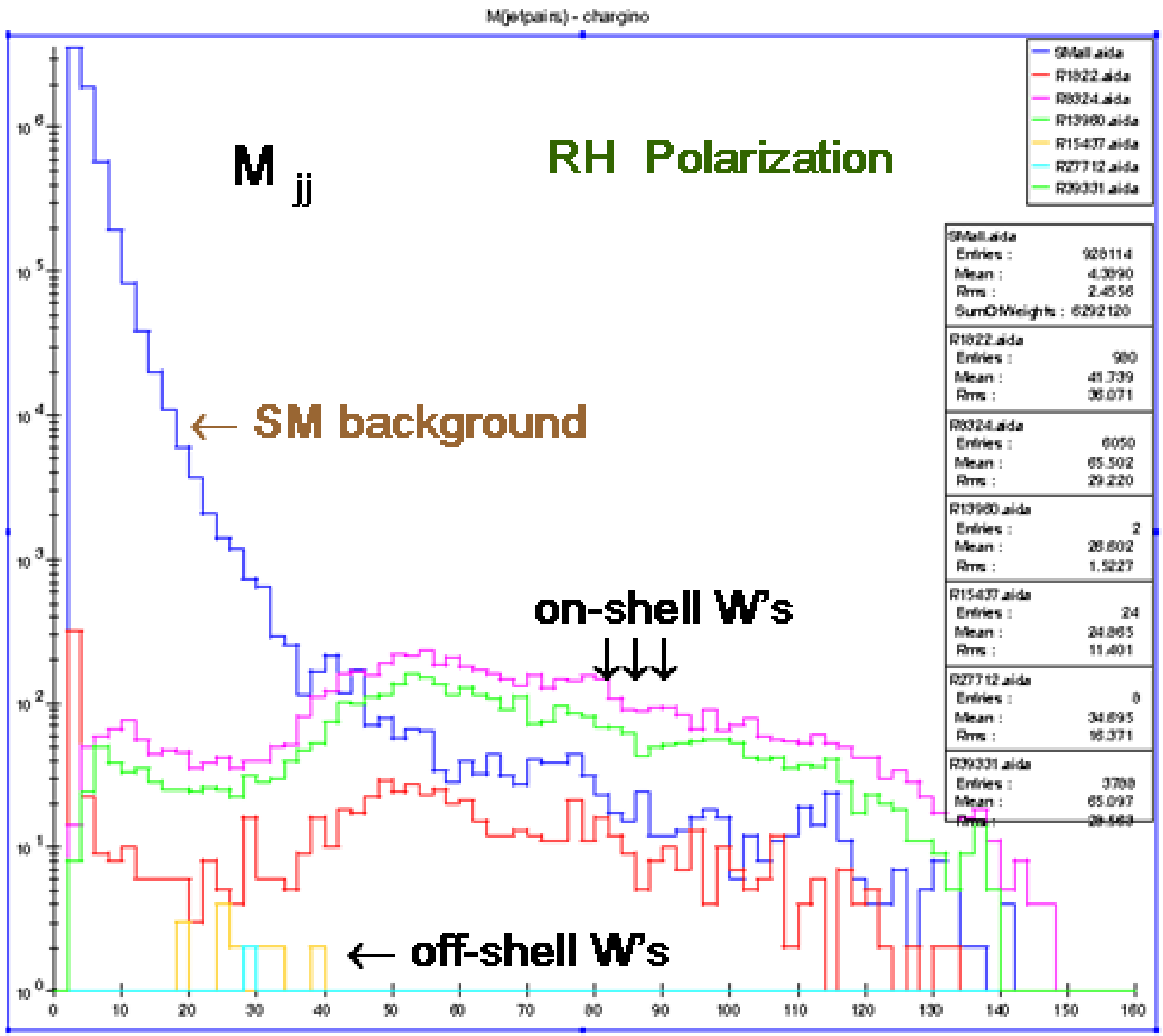


χ_1^0 's in our models are almost all weak eigenstate fields… these figures break down their wino, bino and Higgsino contents. This has to do with how the relevant parameters were scanned..

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



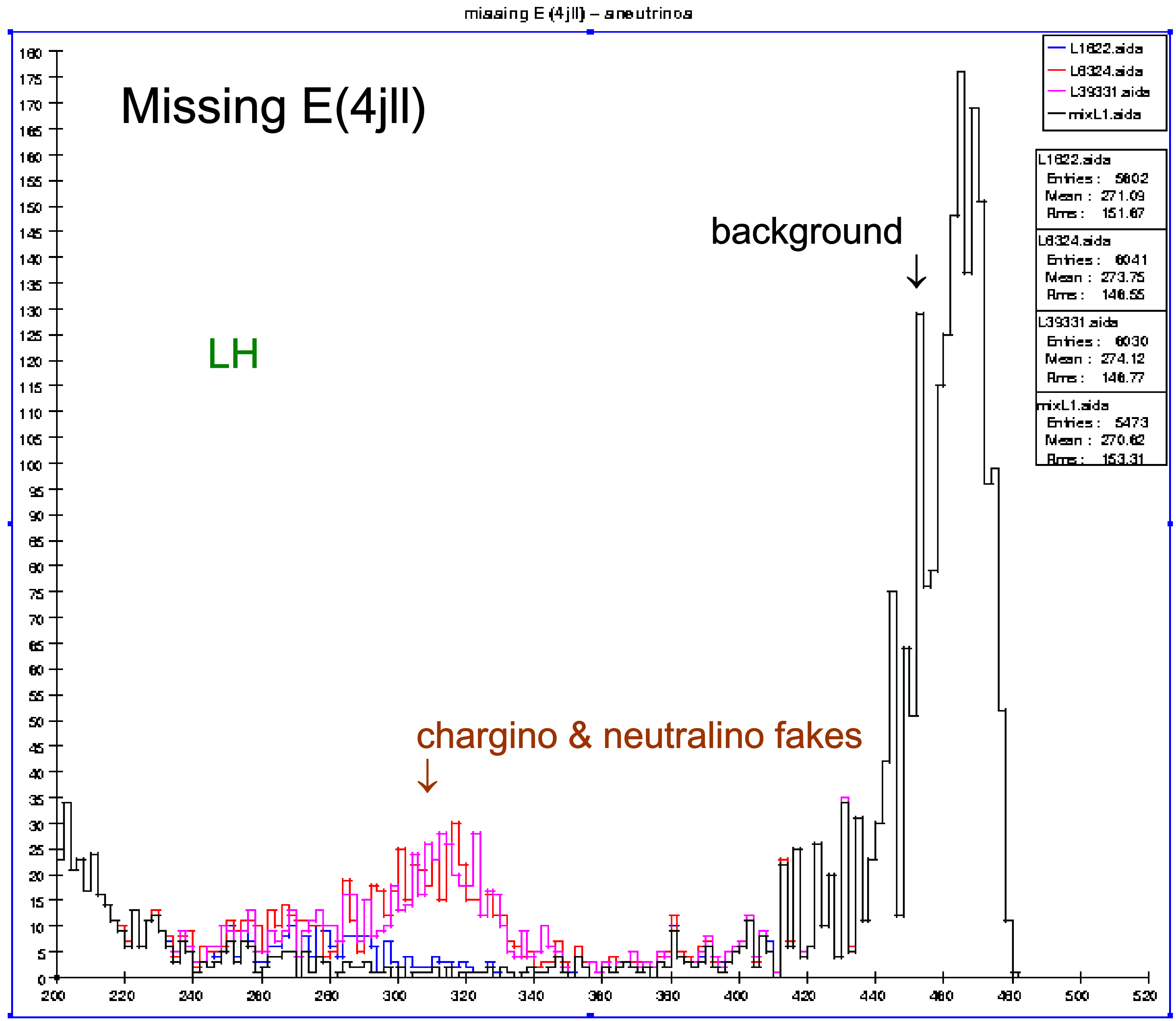
Chargino--4j + missing E analysis (off-shell): Jet Pair Mass



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

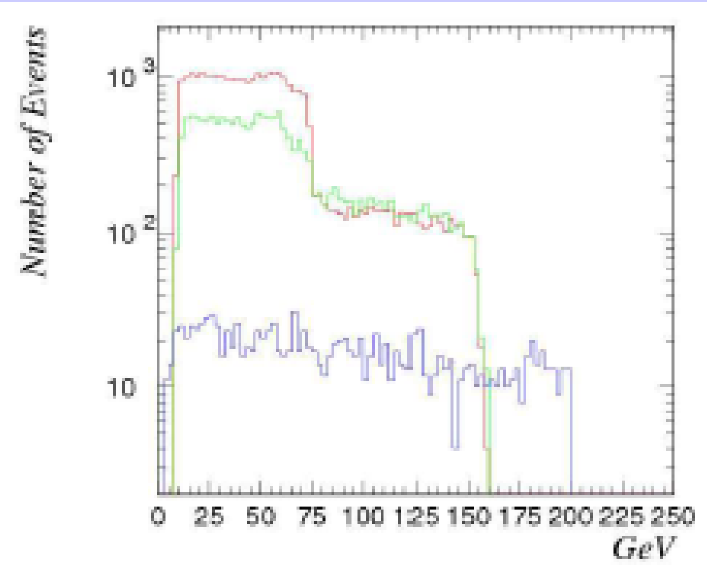
fake

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


missing E (4jll) – sneutrinos
Missing E(4jll)
LH
background
chargino & neutralino fakes
L1622.aida
L6324.aida
L39331.aida
mixL1.aida
L1622.aida Entries : 5802 Mean : 271.09 Rms : 151.67
L6324.aida Entries : 6041 Mean : 273.75 Rms : 146.55
L39331.aida Entries : 6030 Mean : 274.12 Rms : 146.77
mixL1.aida Entries : 5473 Mean : 270.62 Rms : 153.31

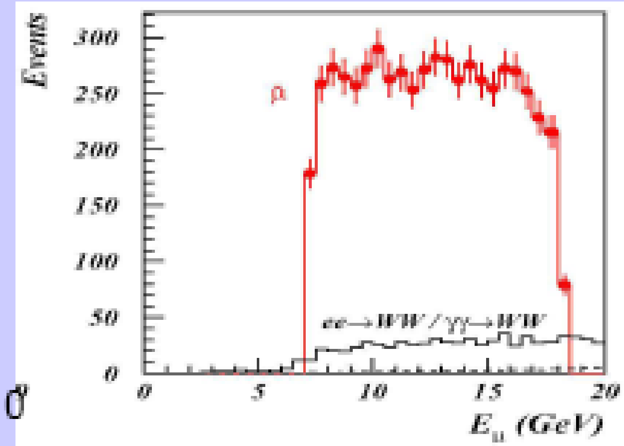
Is it REALLY this easy ??? Yes (sort of) with SPS1a..

Previous ILC SUSY Studies

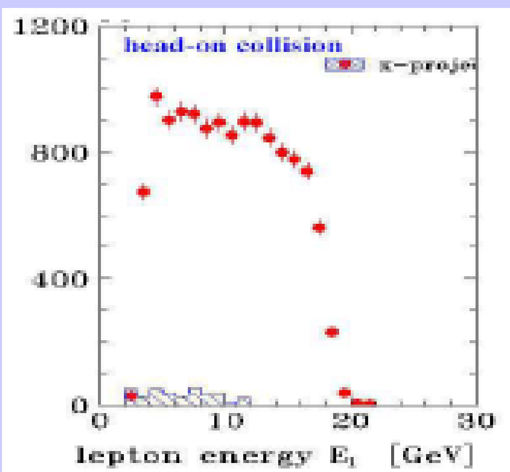


Colorado Group
Goodman etal

Bambade etal
hep-ph/0406010



Choi etal, hep-ph/0612301



Martyn
hep-ph/0408226