LHC^{-1} = ILC ?? PROJECT UPDATE

- ♣ 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 could be distinguished at the 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., backgrounds, cuts, detector and simulation properties & our basic assumptions about SUSY signatures.

- ♠ We've had many surprises and have learned many lessons…

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

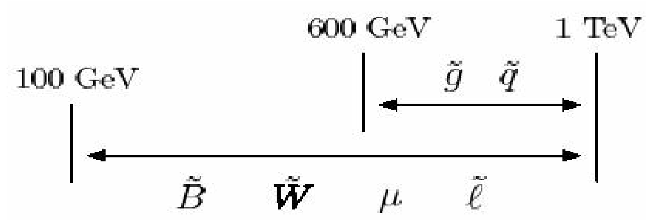
LHC Inverse Problem

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)**
- **For 15 parameters:**

$$\text{Inos}: \quad M_1,\ M_2,\ M_3,\ \mu$$
$$\text{Squarks}: \quad m_{\tilde{Q}_{1,2}},\ m_{\tilde{U}_{1,2}},\ m_{\tilde{D}_{1,2}},\ m_{\tilde{Q}_3},\ m_{\tilde{t}_R},\ m_{\tilde{b}_R} \qquad + \tan\beta$$
$$\text{Sleptons}: \quad m_{\tilde{L}_{1,2}},\ m_{\tilde{E}_{1,2}},\ m_{\tilde{L}_3},\ m_{\tilde{\tau}_R}$$

Within the constraints:



$2 < \tan\beta < 50$

kept 1st two scalar generations degenerate

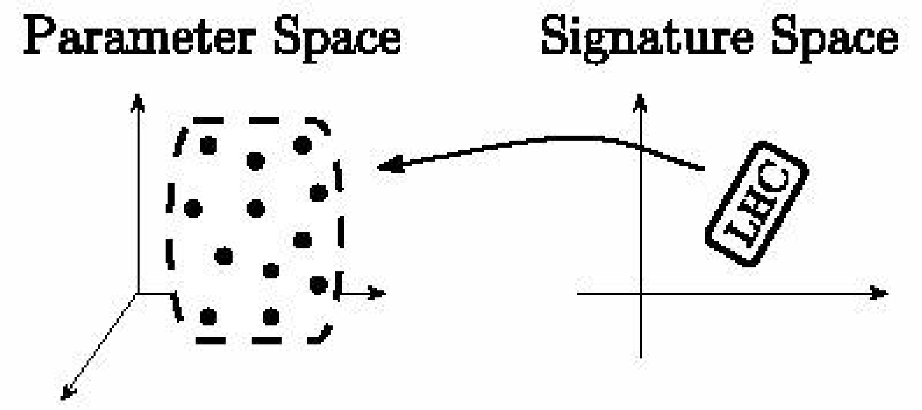
- **Used ~1808 LHC MSSM `Observables'**
  - **Rate counting, kinematic distributions**

- **NO SM Backgrounds!**

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

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..
  - A `signature' maps back into a number of small islands in parameter space

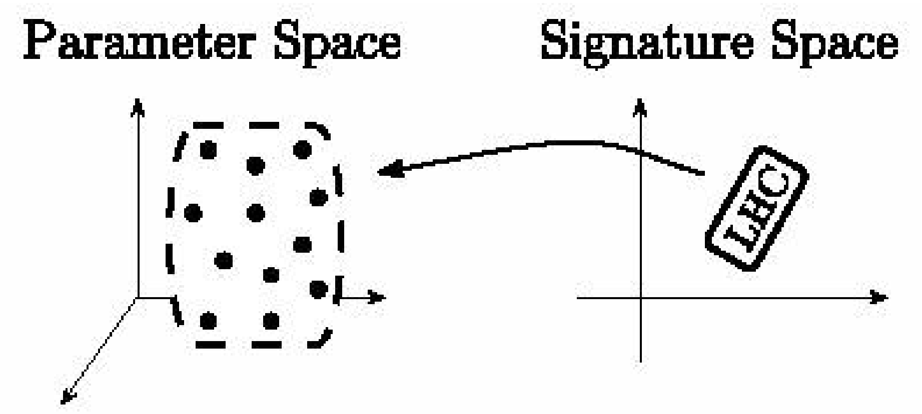


* as we will see only 242 models are physical

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

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..
  – A `signature' maps back into a number of small islands in parameter space



* as we will see only 242 models are physical

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

A Reminder :

From JoAnne

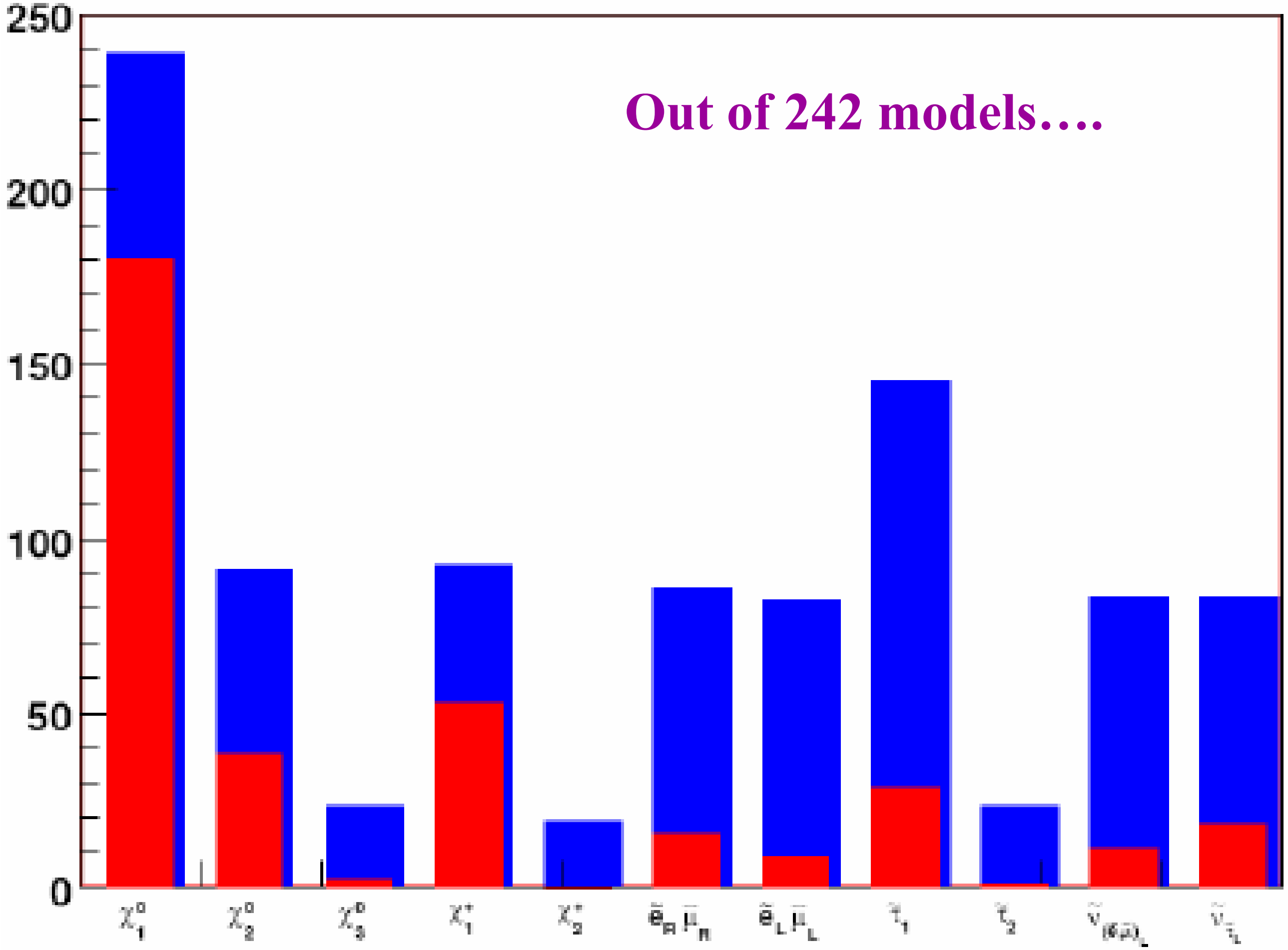
Our Analysis*

- We start with their 283 degenerate pairs (383 distinct models)
- Simulate signal events with Pythia & CompHEP, and feed in appropriate beamspectrum generated via Whizard/GuineaPig
- 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^{-1} "data" with 80% P_{e-} and appropriate cuts.
  Several iterations necessary to find best cuts!

→ **Compare models**

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

Lesson One: Many models do not produce visible signals at 500 GeV



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

Let's look at the numbers…

LESSON ONE :

	500 GeV	visible	1 TeV
selectrons or smuons	20	10?	116
staus	28	6?	125
All sleptons types	7	6?	55
χ^{+}_{1}	53	15?	78
χ^{+}_{1} + smuons	2	?	12
χ^{+}_{1} + staus	8	?	12
$\chi^{+}_{1}\chi^{-}_{2}$	0	0	16
$\chi^{0}_{1}\chi^{0}_{1}$ *only*	99	0	1
$\chi^{0}_{1}\chi^{0}_{2}$	46	4?	?
nothing	59	0	1

Kinematic accessibility does not equal observability of models :

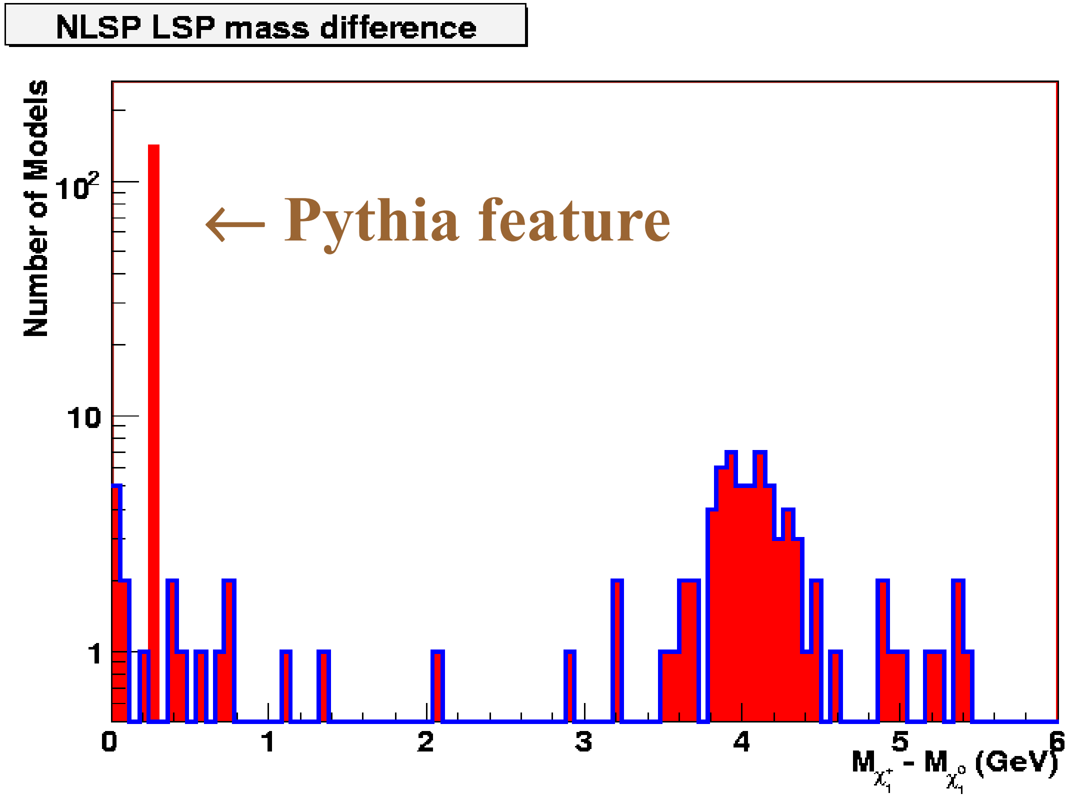
Out of 242 models, at 500 GeV, 59+99=158/242 = 65 % have NO signal observable…the percentage is actually higher (~90 % !) after some further investigation as we will see. But this fraction is much smaller at 1 TeV .

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

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

LESSON TWO :

BEWARE OF BLIND USE OF PYTHIA, PART I:



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, and without ANY warning, resets the χ_1^+ mass to that of the LSP+ $2m_\pi$. This happens in 141/383 original model cases !!

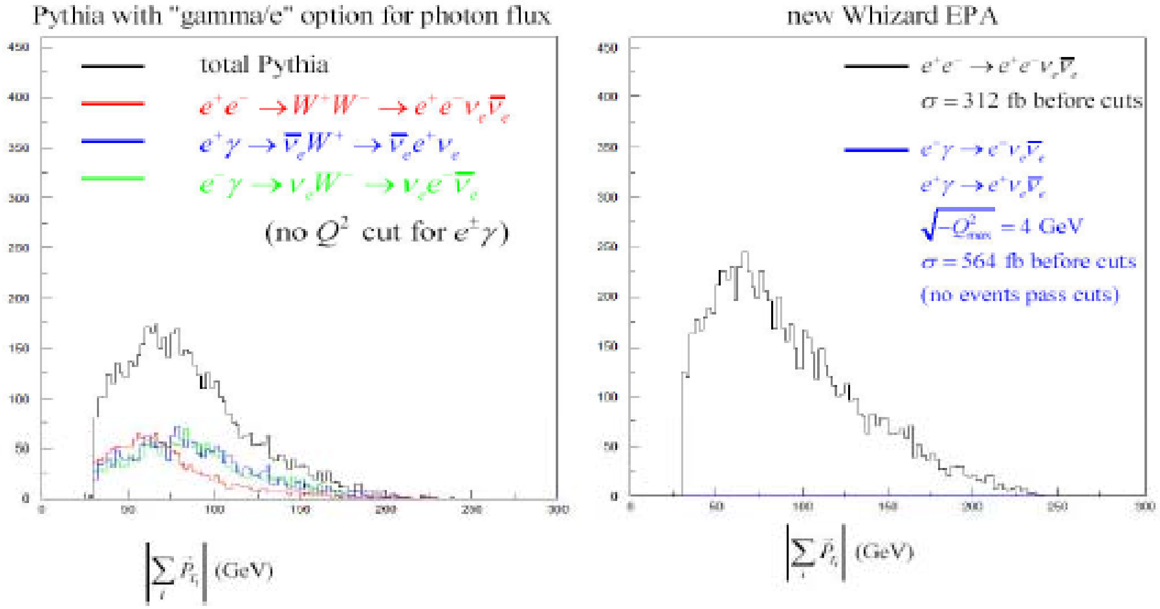
This reduces our sample: 383→242

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 UNDERESTIMA BACKGROUNDS

- Using full matrix elements makes a difference
  - Here we compare standard model background to our selectron analysis as calculated in PYTHIA and WHIZARD
  - 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

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



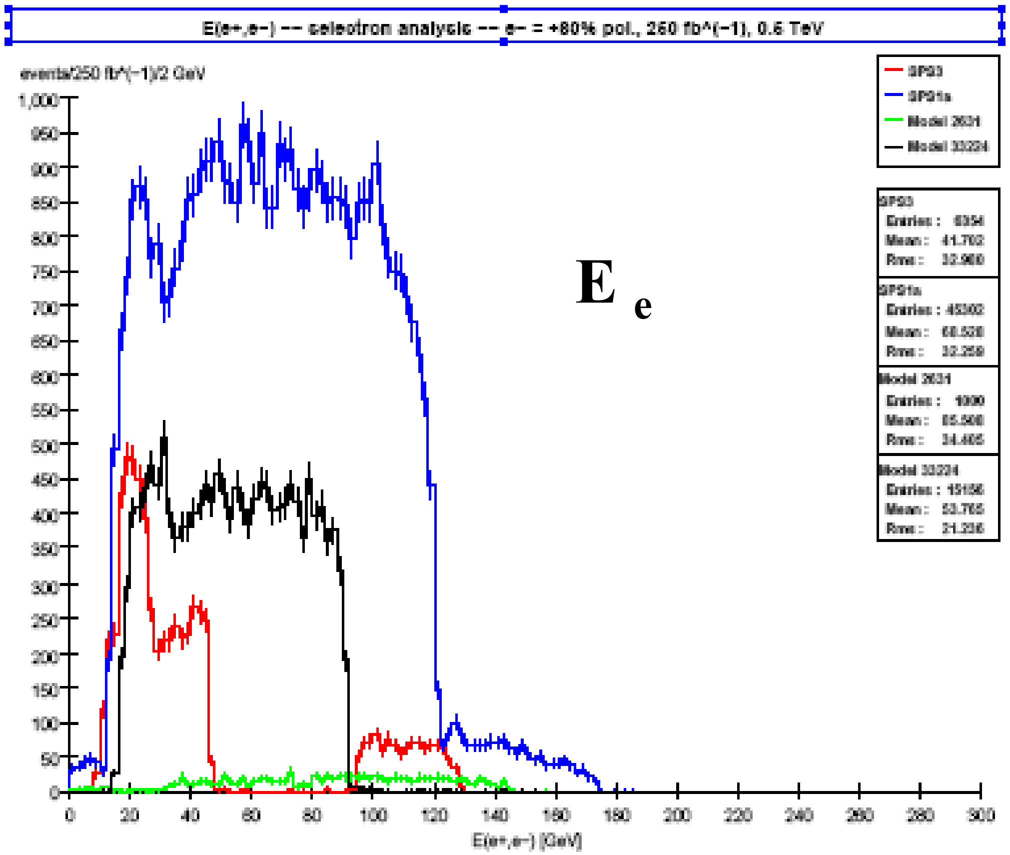
Thanks to Tim Barklow

$\rightarrow$ using full backgrounds is important !
Probably also true for the signal..

LESSON THREE :

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

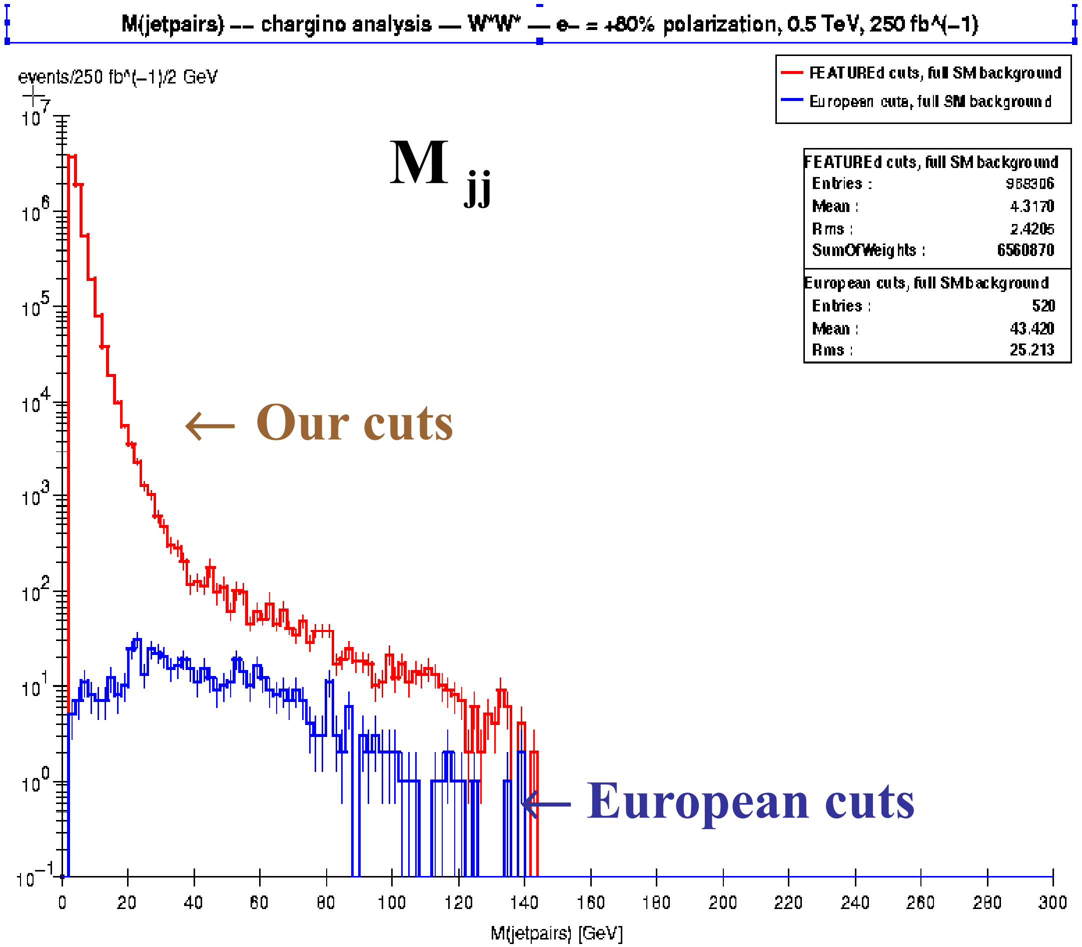


It will be much more difficult to see SUSY particles in general than in the well-studied specialized points…in some cases signal rates are over 50x smaller than in the SPS1a scenario…

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 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 need to develop and employ our own universal cuts that generally lead to larger SM backgrounds to SUSY…

LESSON FOUR :

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^{-1} 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: even with LCSIM priority it takes us ~3 weeks to generate a full background sample with a fixed set of cuts since the background files from TimB are so large (~ 1.7TB) even using the `toaster'…this drastically reduces the number of tests we can perform…

LESSON FIVE :

To cover all the possibilities many simultaneous analyses are required:

(i) Selectron/smuon/stau pairs → SM analogues + missing E

(ii) Radiative neutralino pairs using tagged γ's

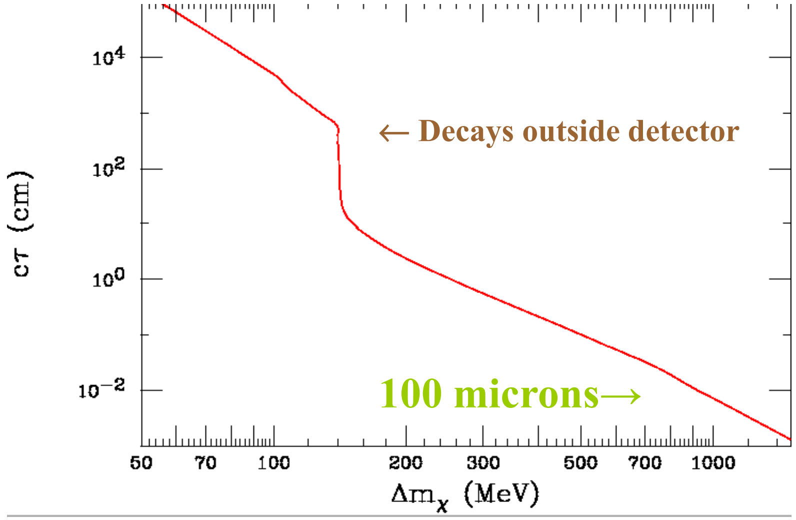
(iii) $\chi_2^0\,\chi_1^0$ → missing E + Z (jj /l^+l^-)…this analysis was added recently

(iv) Sneutrino pairs → 4jets+ lepton pair + missing E … another new one

(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 …

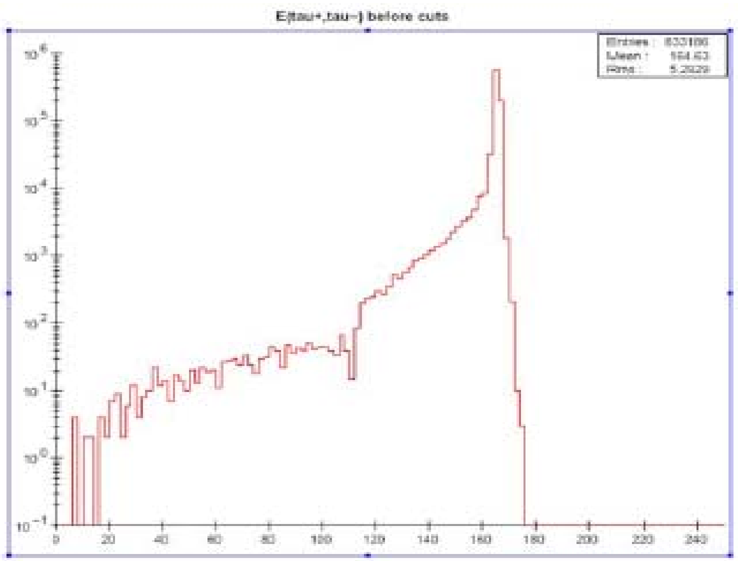


WHICH LEADS TO… LESSON SIX :

From Jamie

Watch out when these stable particles pass the cuts in other analyses as they lead to apparent violations of energy conservation….and funny background f

New heavy (~stable) particles are assigned random particle IDs (usually π or μ) and the corresponding energy is computed from measured momentum and incorrect mass instead of being set to the cluster energy.



Plot of jet events from specific SUSY model with 80% left-handed polarization.

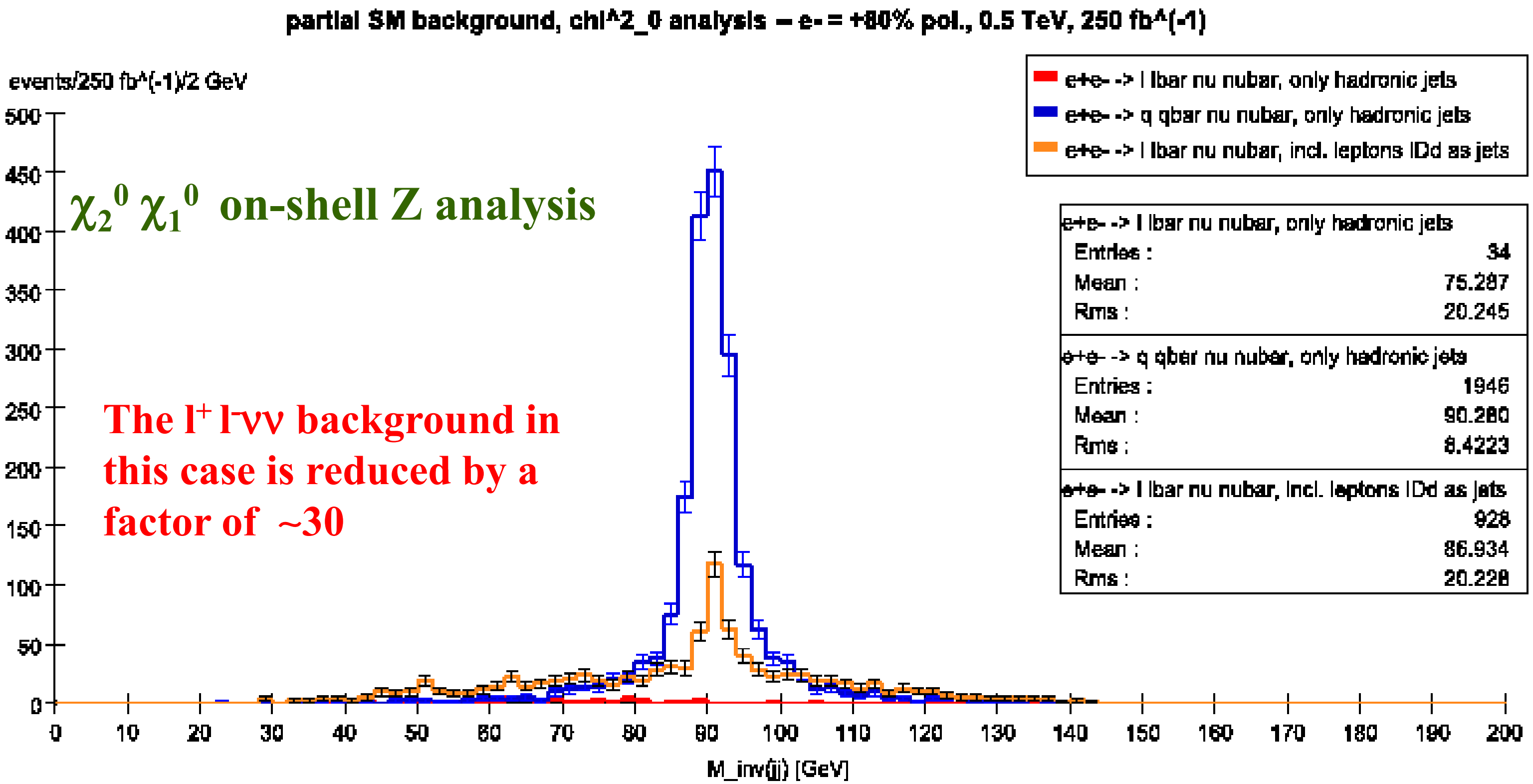
For example, in this stau analysis we are looking for jj+missing E. The stable χ_1^+ in this model yields a distribution with $<E_j>=164.69$ GeV while the LSP mass is 187.19 GeV. This violates energy conservation by ~20 GeV !!

But this also leads to…

LESSON SEVEN :

Electrons, muons, photons and any stable charged particles are tagged as \`jets' by the vanilla lcsim. These are not jets, i.e., they are not hadrons. This is a contamination in the stau, neutralino and chargino analyses to both the signal and backgrounds….this is what happened on the previous slide.

We needed to remove these fake jets with our own algorithms

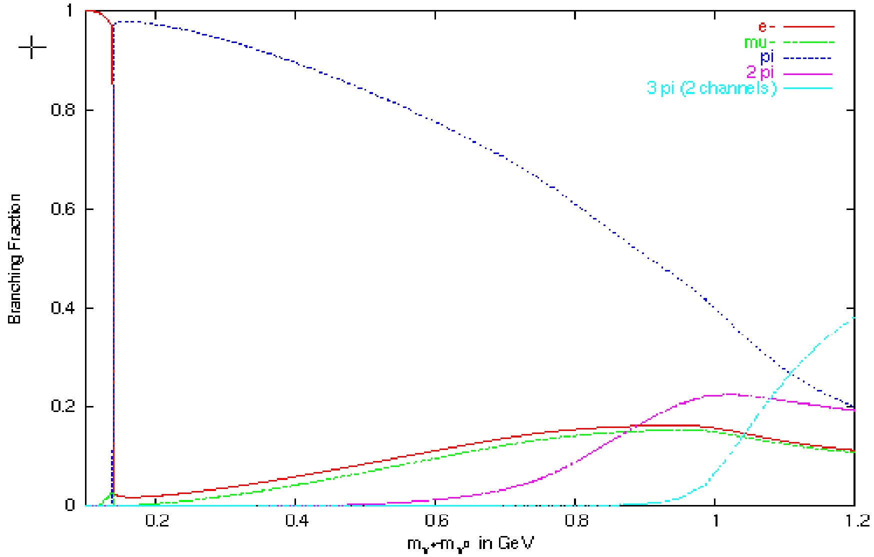


LESSON SEVEN : PART II

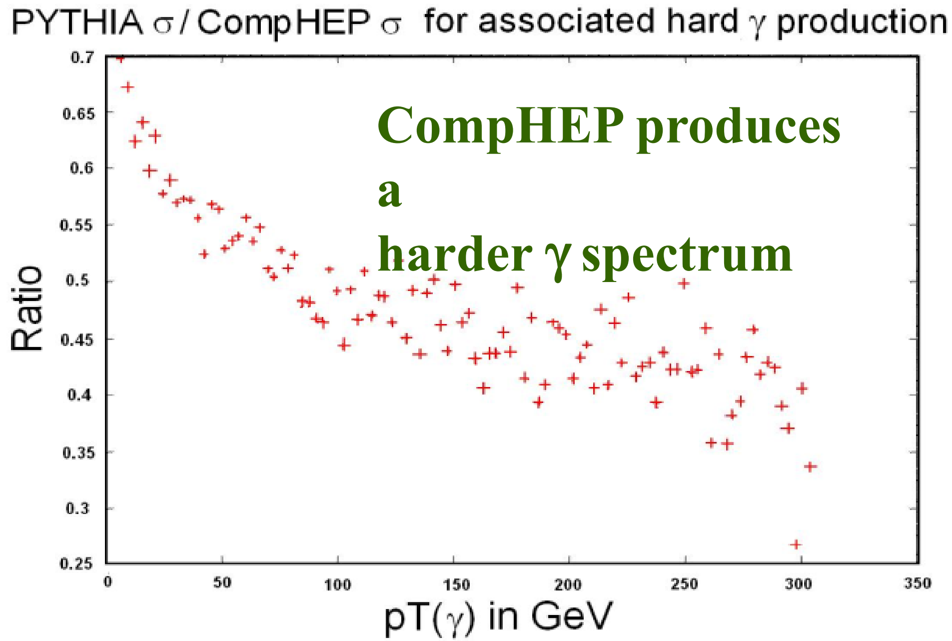
The vanilla version of lcsim has the y_{cut} value in the jet definition set too low and needs to be increased otherwise too many `jets' will be produced in both the signals and backgrounds.

Analyses Continued :

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



Δm



(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.

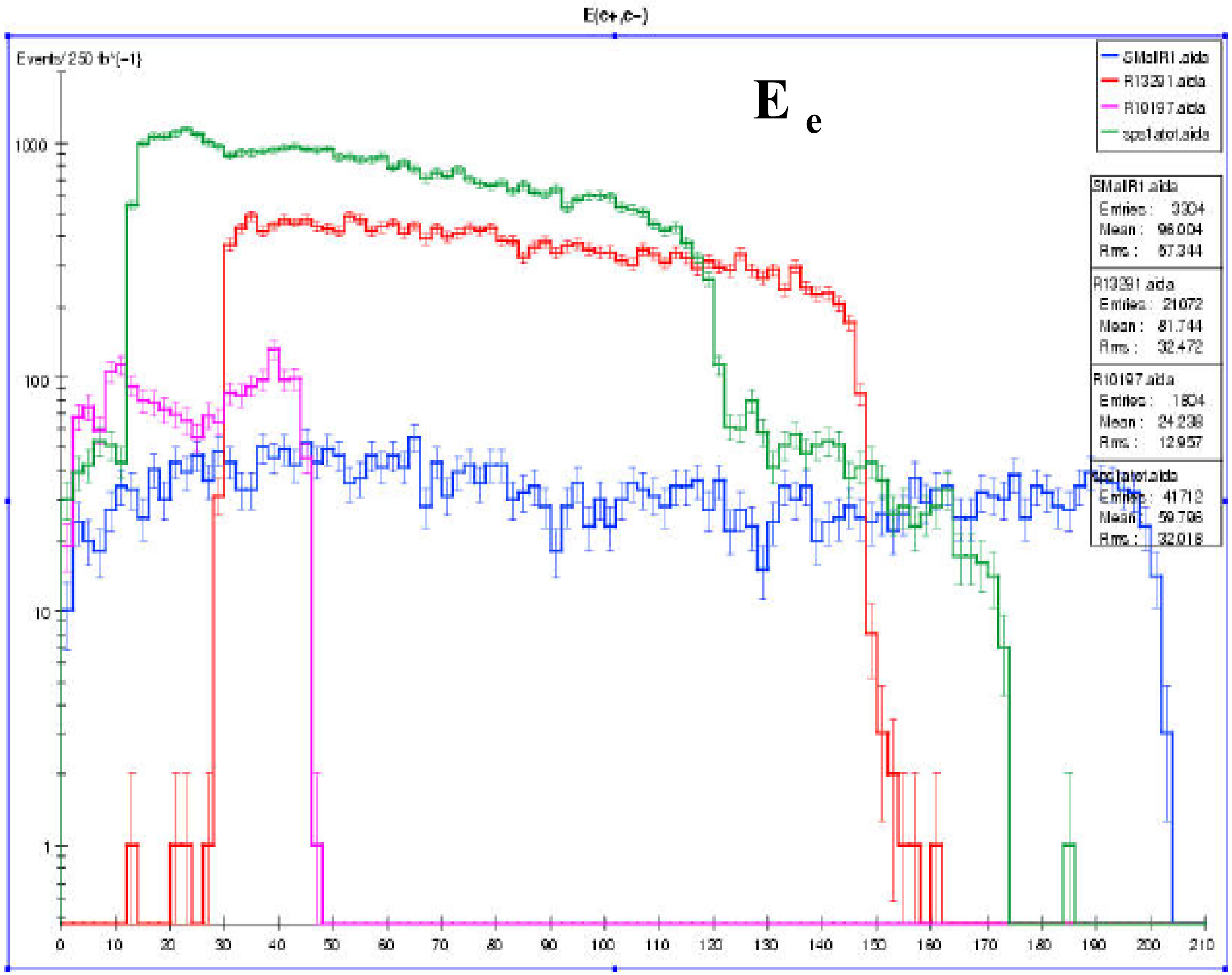
Now for some results…..

Selectron Example: Good S/B here…

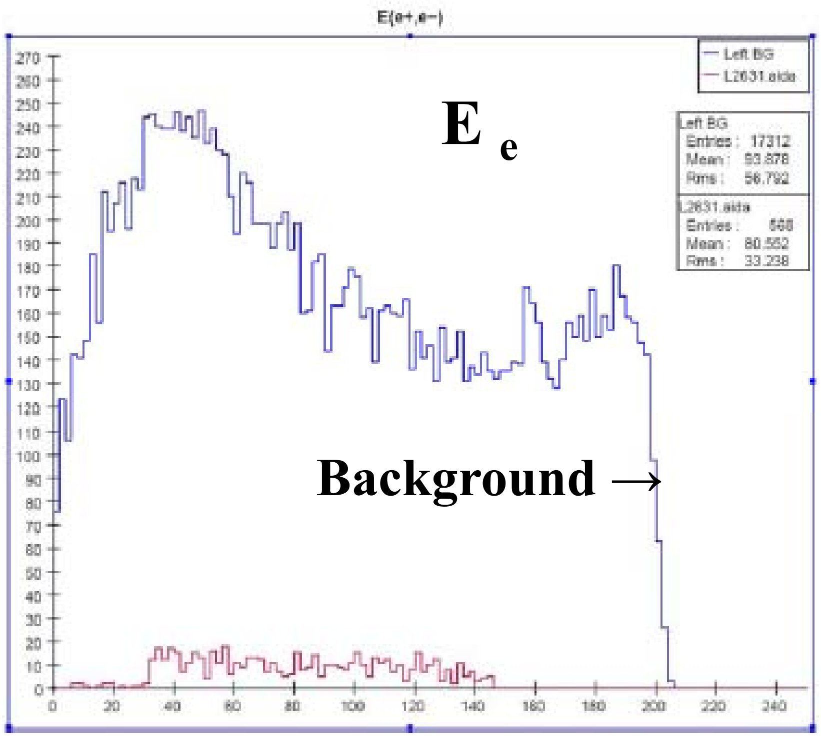
- Model 13291:
- Smuon Masses
  - L: 968.63 GeV
  - R: 187.02 GeV
- LSP Mass: 101.16 GeV

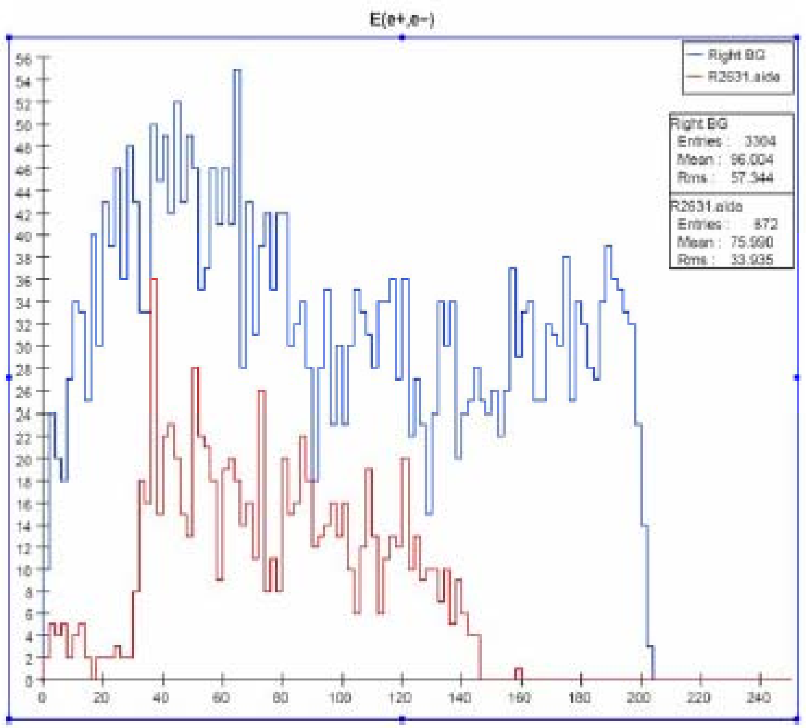
- Model 10197:
- Selectron Masses
  - L: 794.92 GeV
  - R: 170.88 GeV
- LSP Mass: 151.93 GeV

- 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:





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

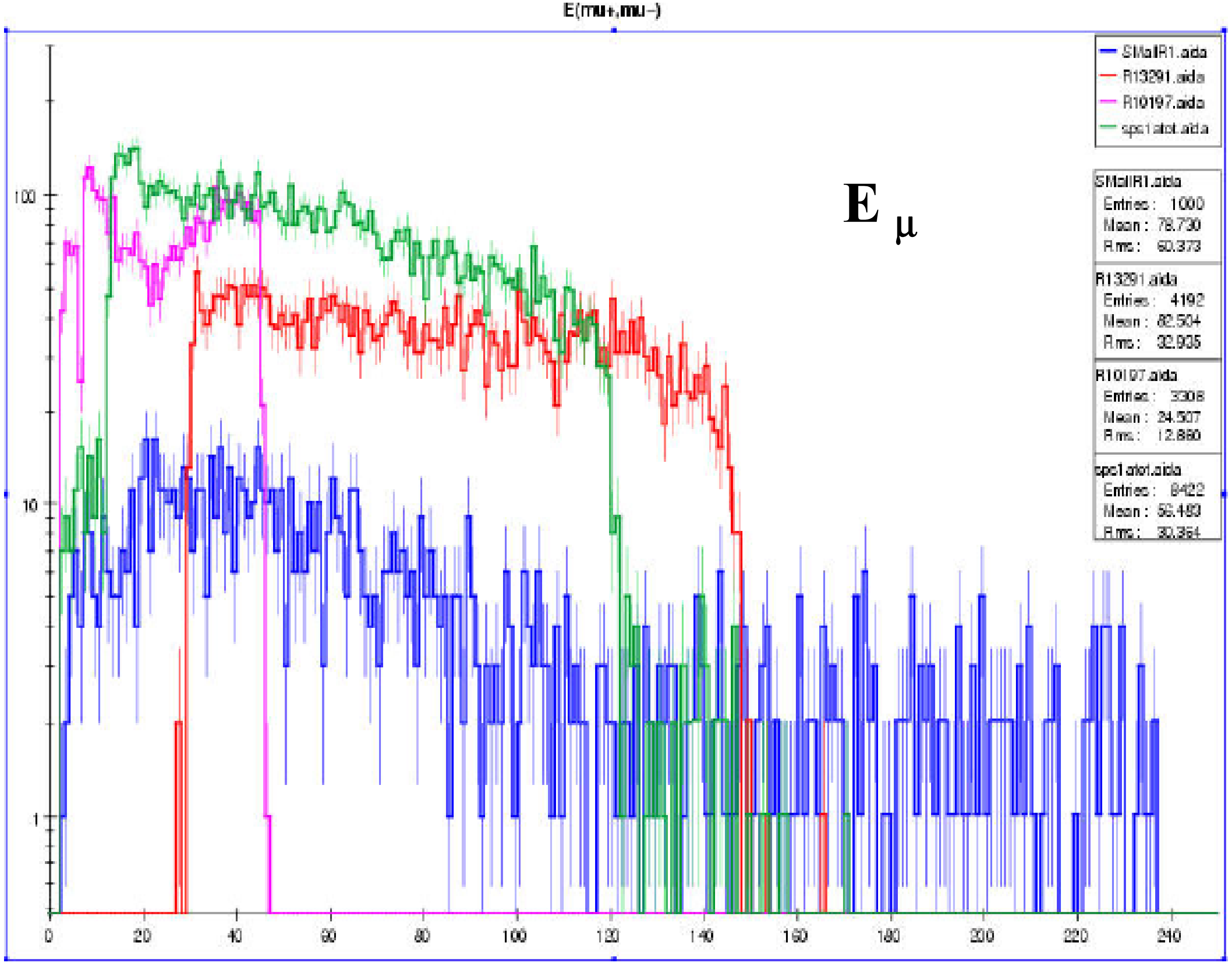
From Jamie

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

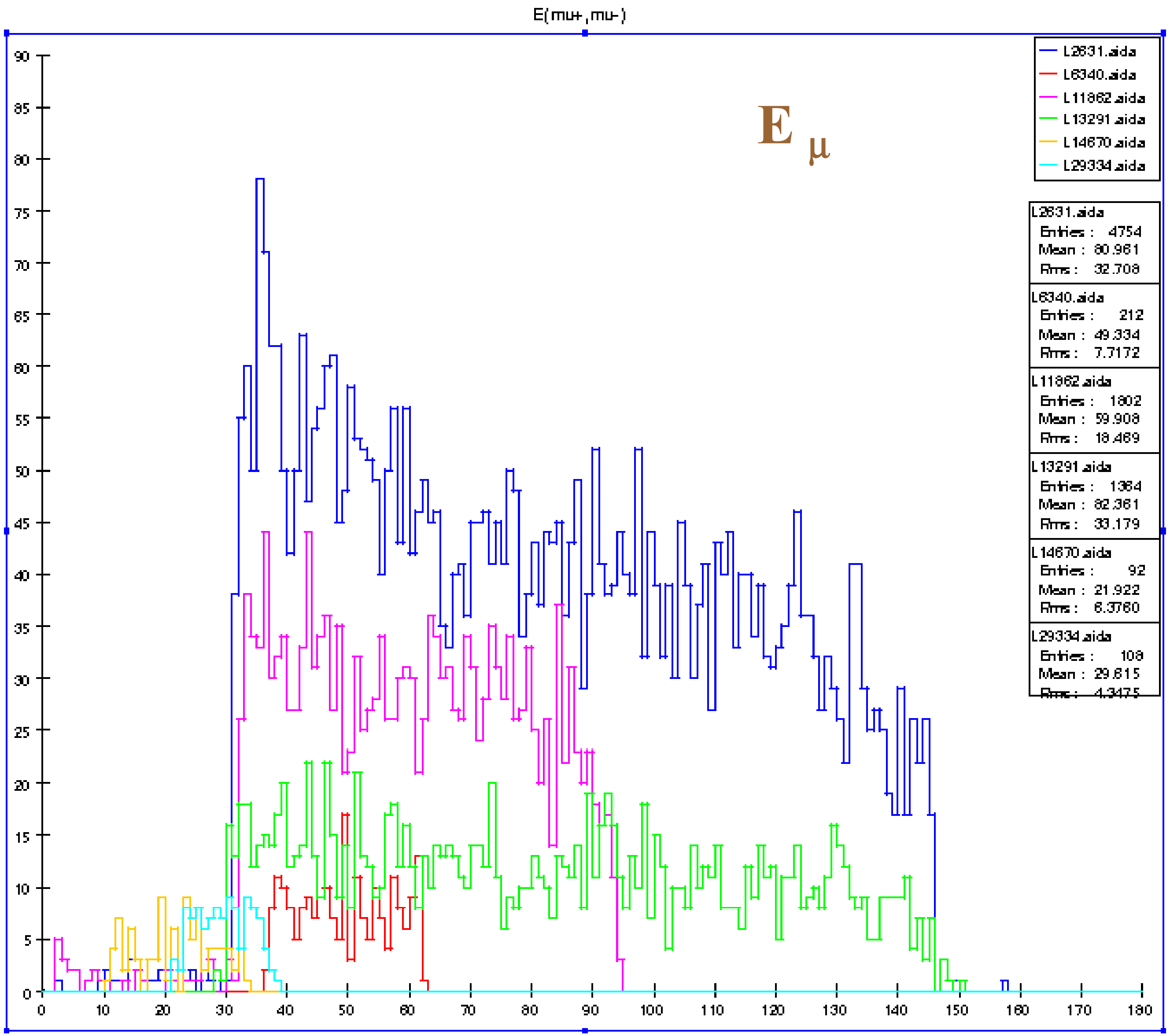
- SPS1A:
  - L: 202.14 GeV
  - R: 142.97 GeV
- LSP Mass: 96.05 GeV



However… some models are more difficult to see…

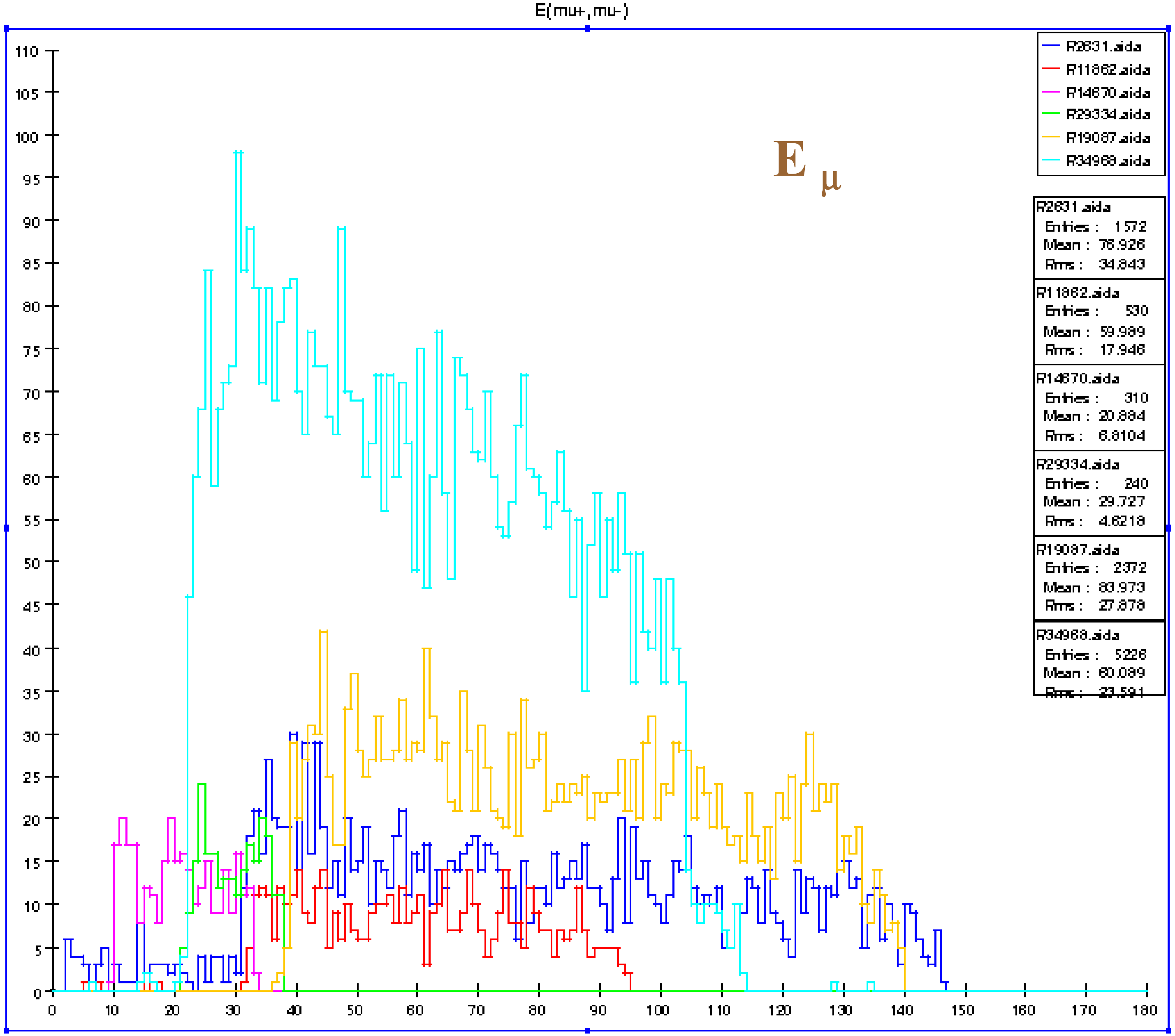
LH

ion

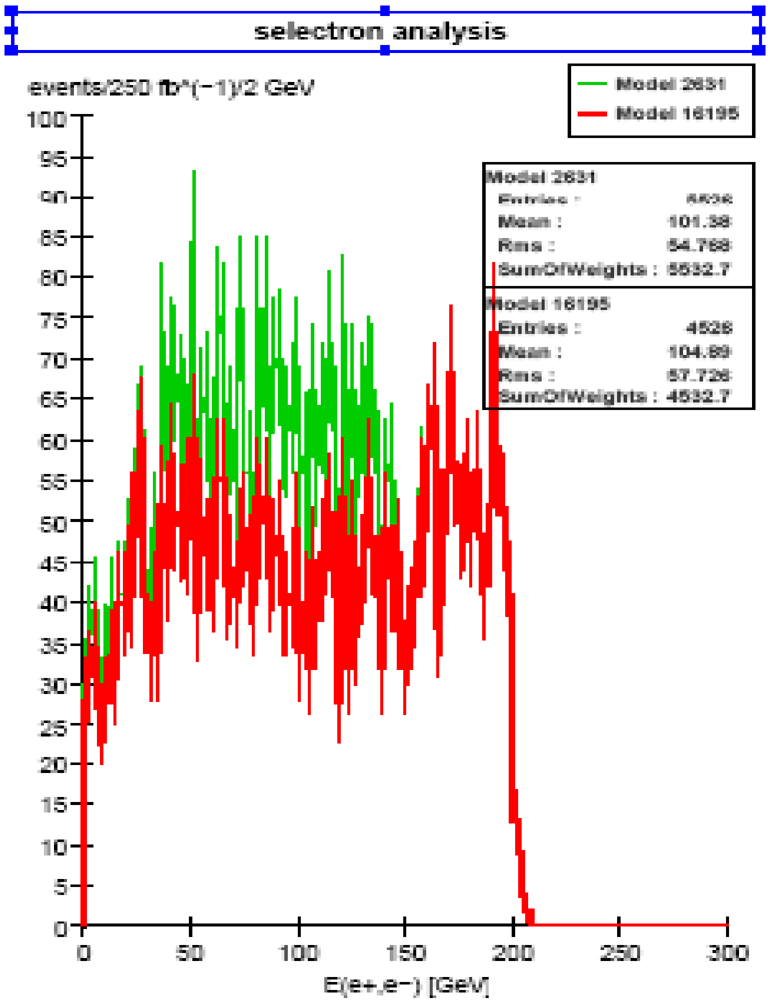


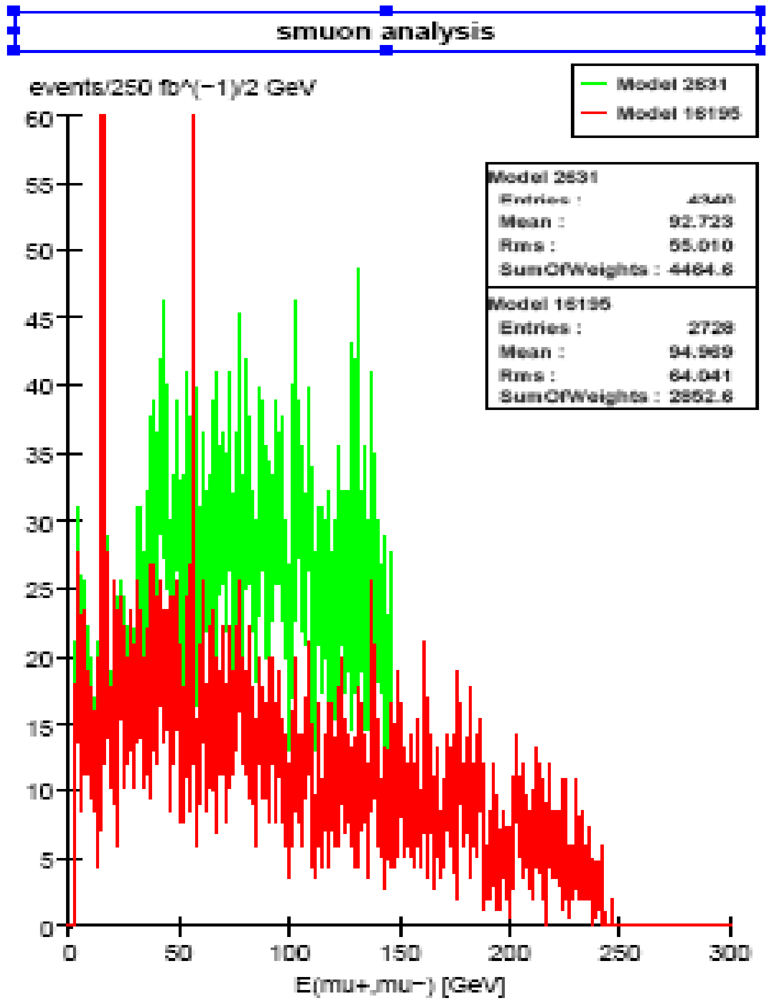
Note the event rates on these plot

RH Polarization



For some slepton cases it is RELATIVELY easy to distinguish model

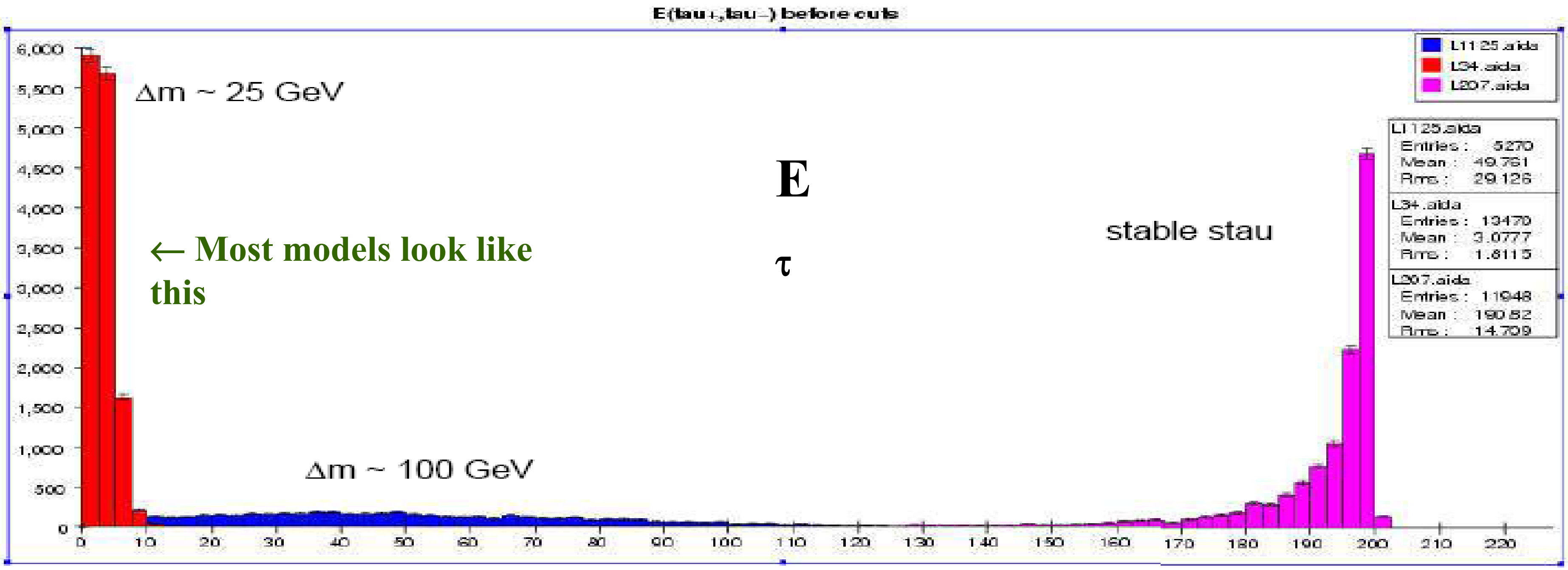




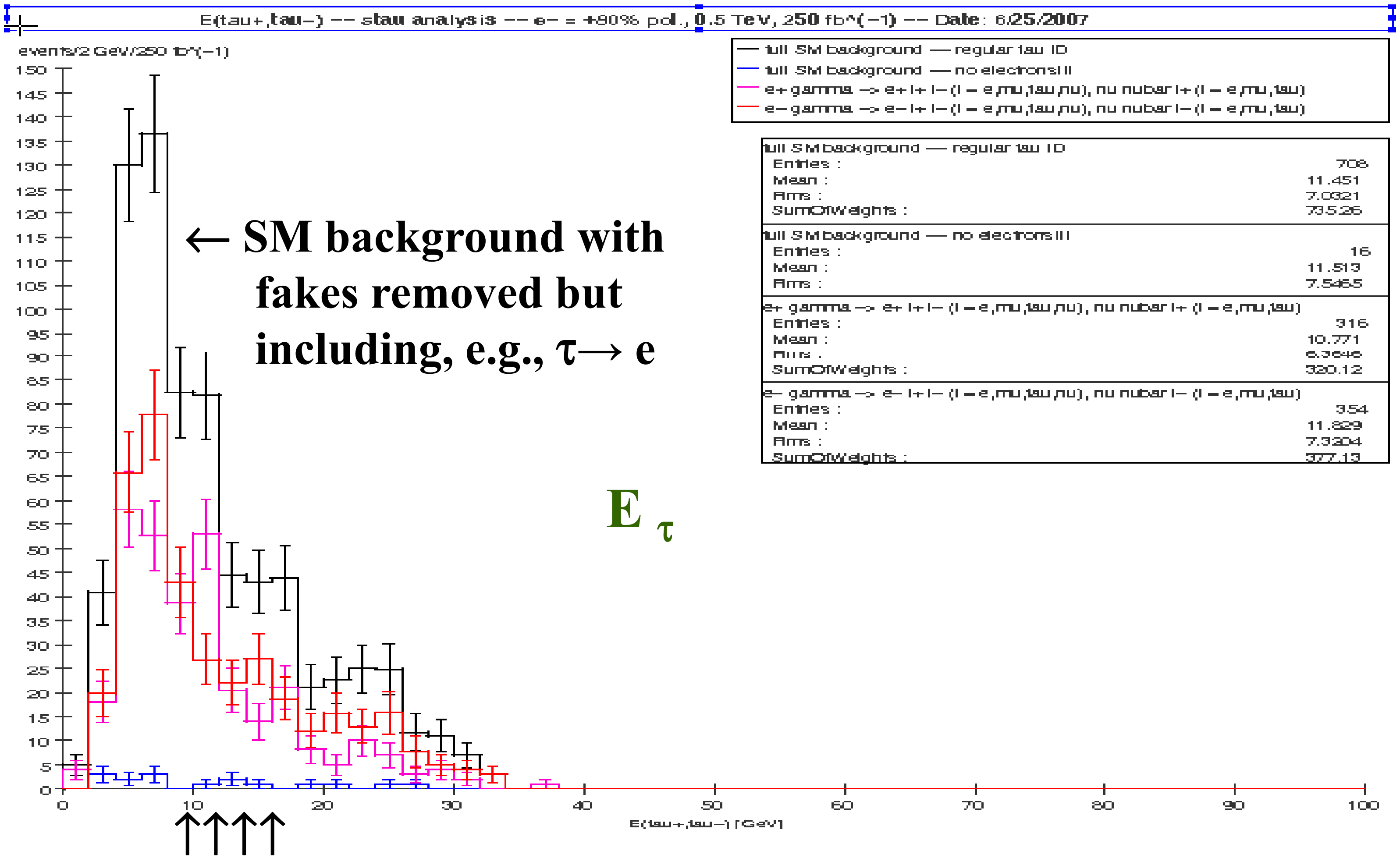
Staus are generally much harder :

For large Δm, 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'.

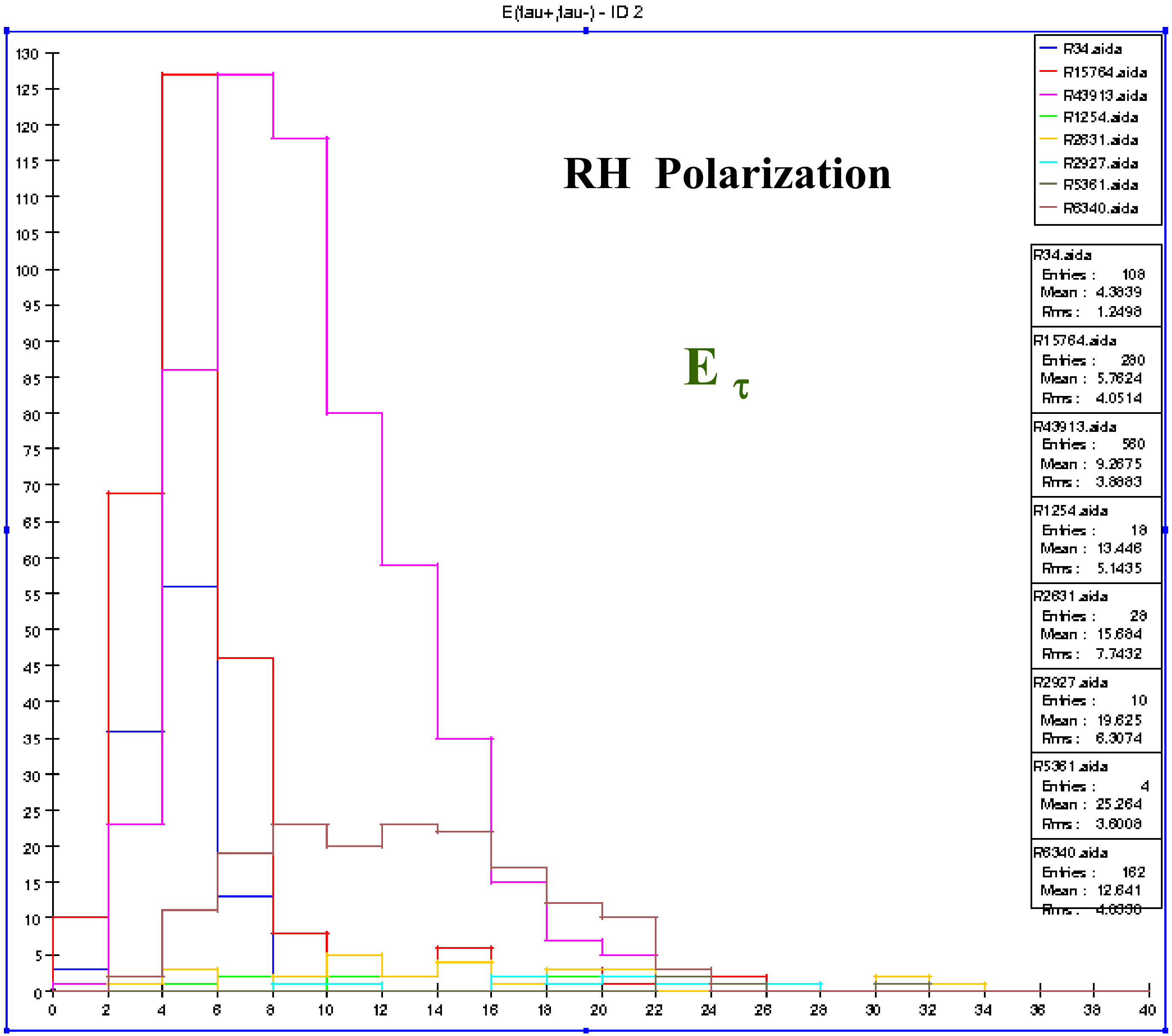


Stau backgrounds are quite reasonable once one finds suitable tau ID cuts and removes leptons faking jets…



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

(*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.

LESSON EIGHT :

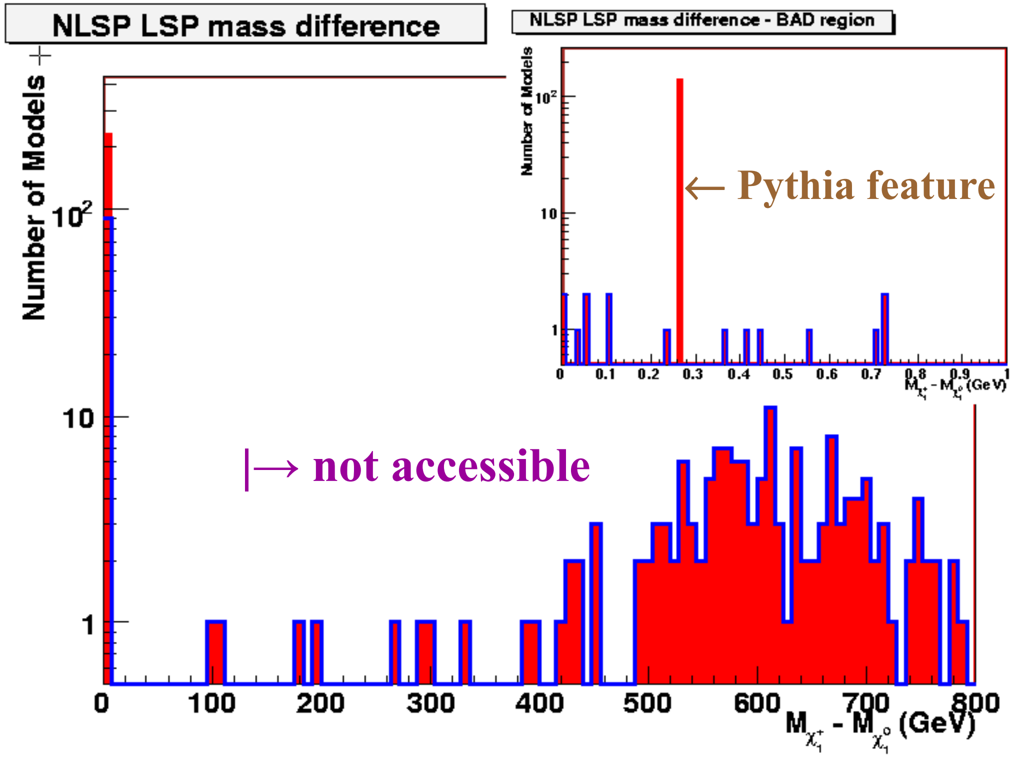
A healthy fraction of the backgrounds in the selectron, stau and, as we'll see, the chargino analyses arises from the lack of tracking/particle ID below ~140 mr in the default description of the SiD detector in the vanilla version of lcsim. Identifying the presence of EM clusters only is no substitute for knowing we have electrons or muons present in the final state at low angles. A user-friendly interface allowing for access to changeable detector parameters would be helpful for physics/detector studies.

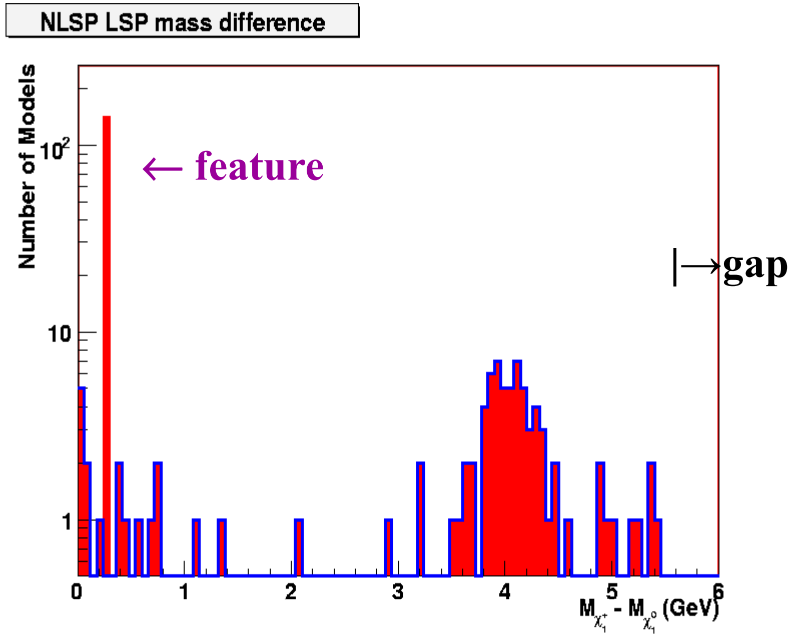
It would be helpful for new users if a notice appeared on the webpage describing the coverage and tunable parameters for the downloadable detectors .

Chargino Analyses:

Difficult spectrum

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



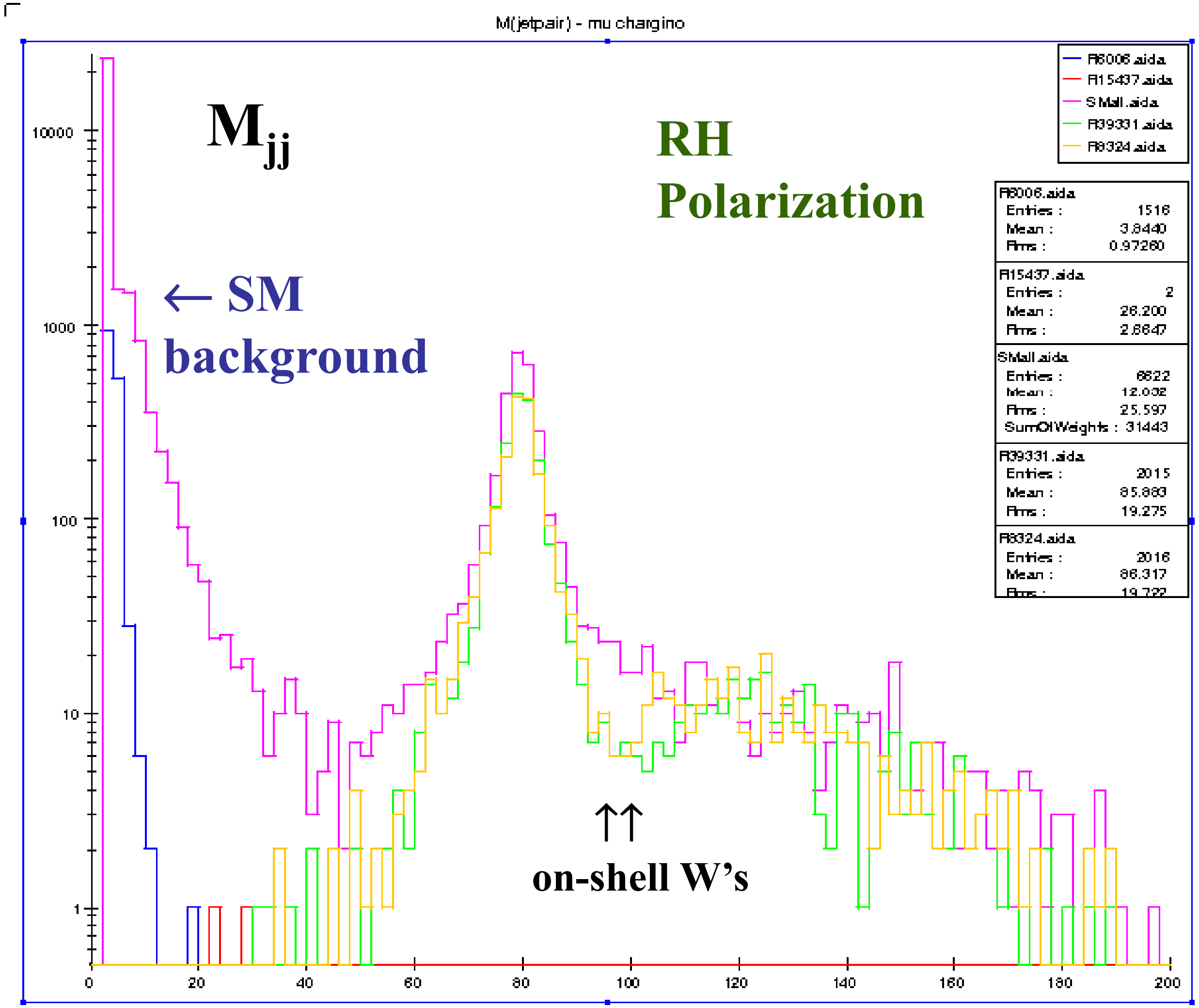


↑↑↑↑↑↑↑

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

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

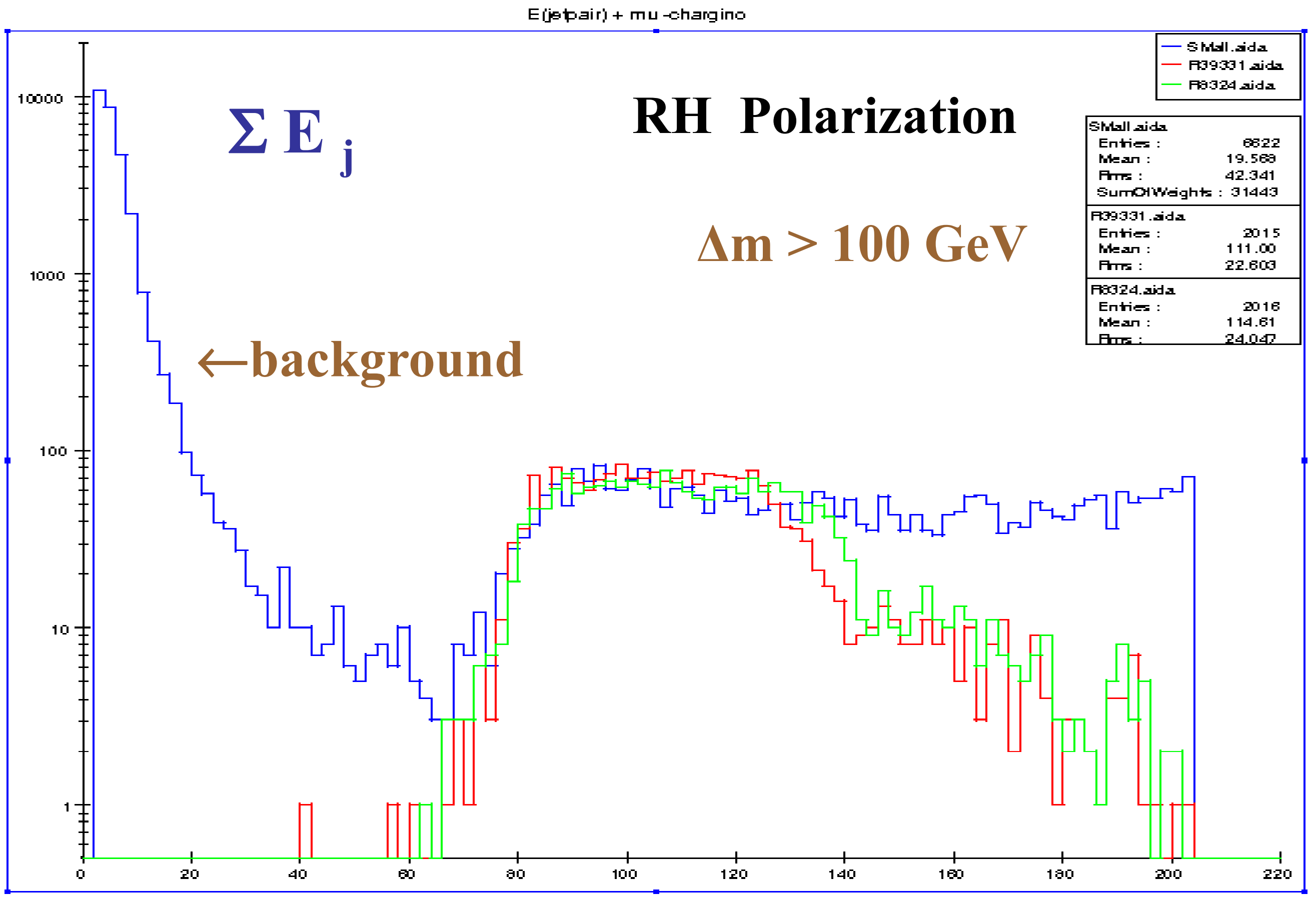
Some of the final state particles are much too soft in many of these models…



…except when $\Delta m > M_W$

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

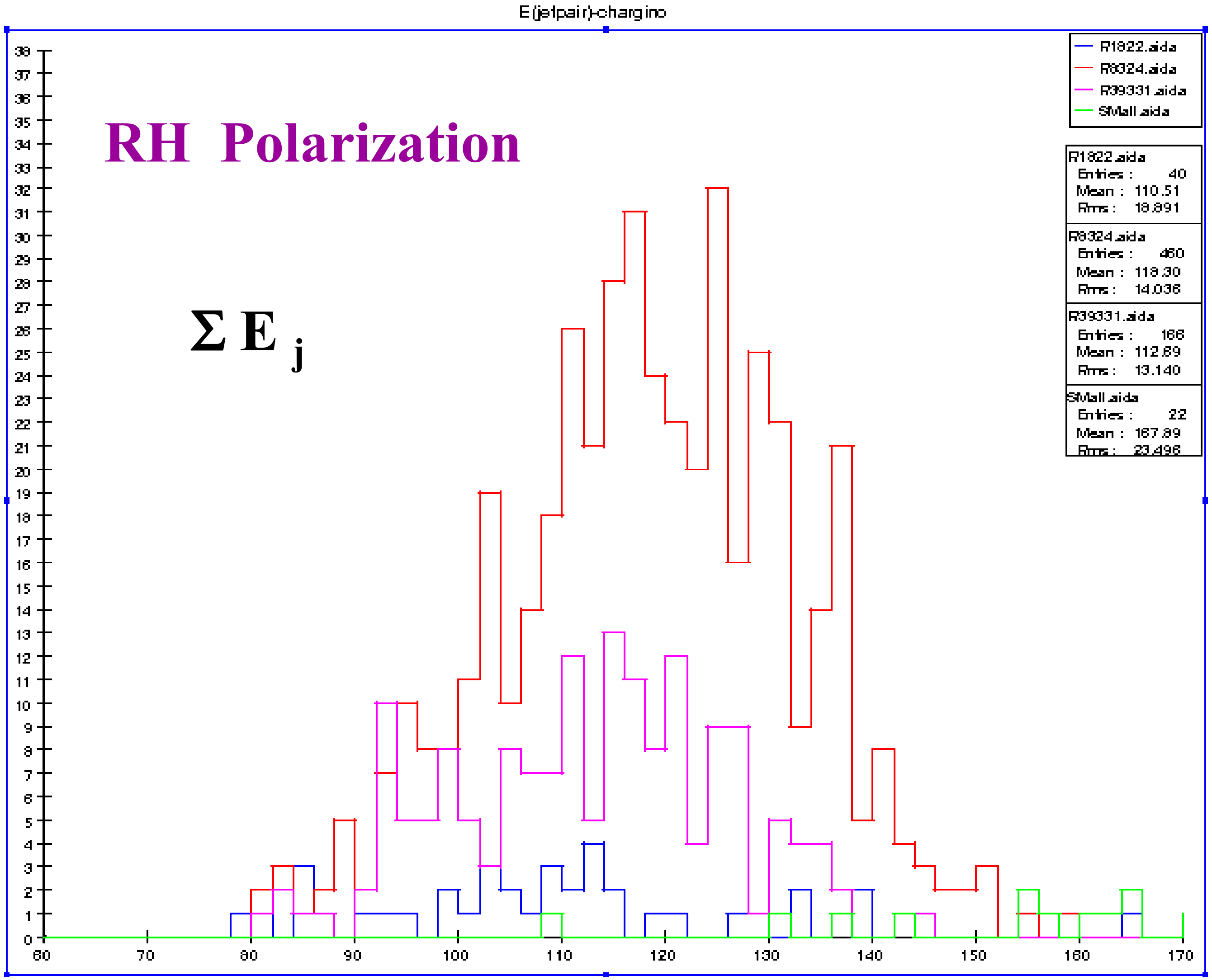
Signals are visible for on-shell W's as Δm is now large….



These models are rare…

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

Again, OK for the on-shell cases..

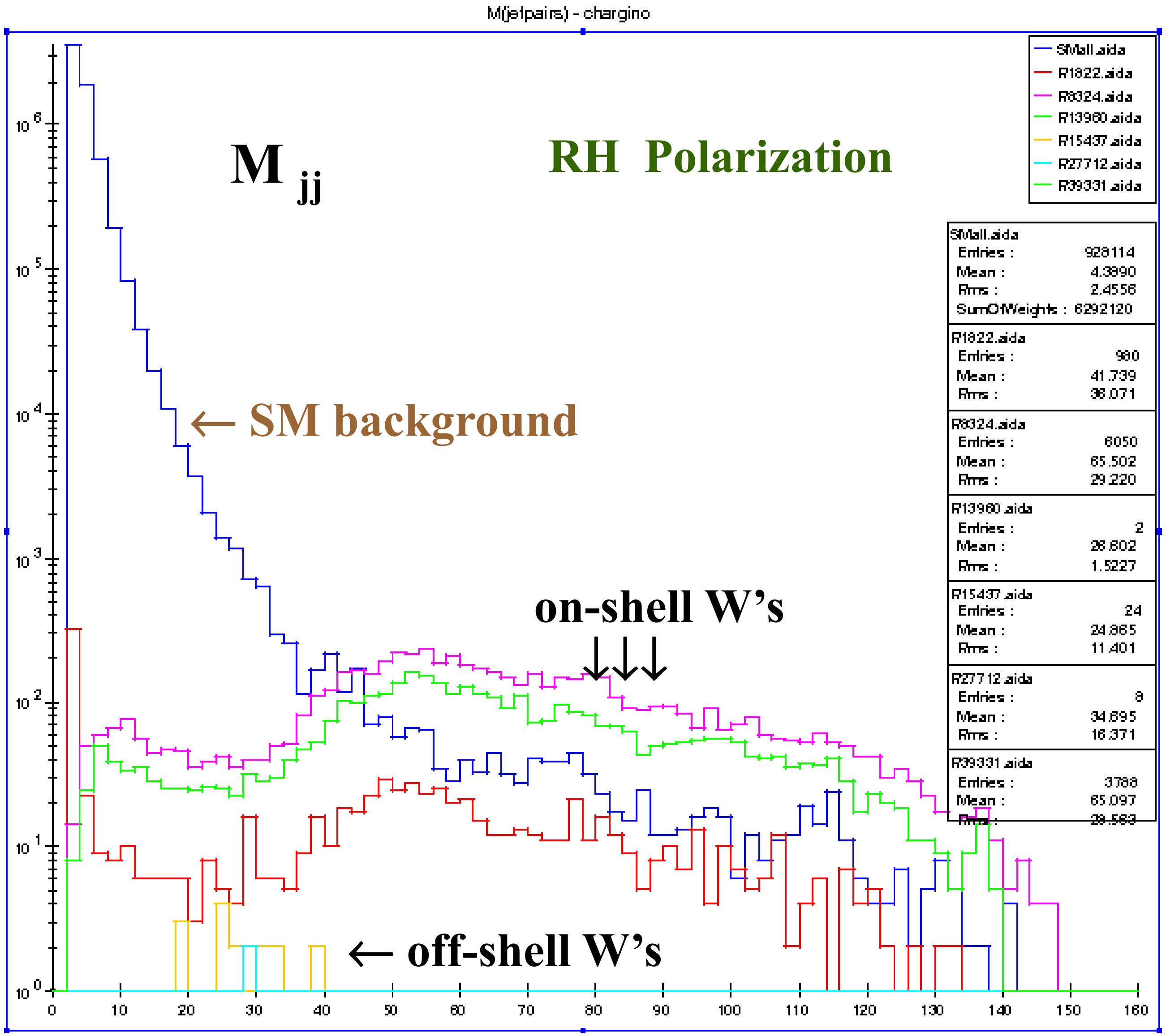


Model 39331
Δm= 103.85 GeV

Model 8324
Δm= 108.23 GeV

Model 1822
Δm=0.133 GeV !!
$2\chi_2^0 \rightarrow$ 4j+ Missing

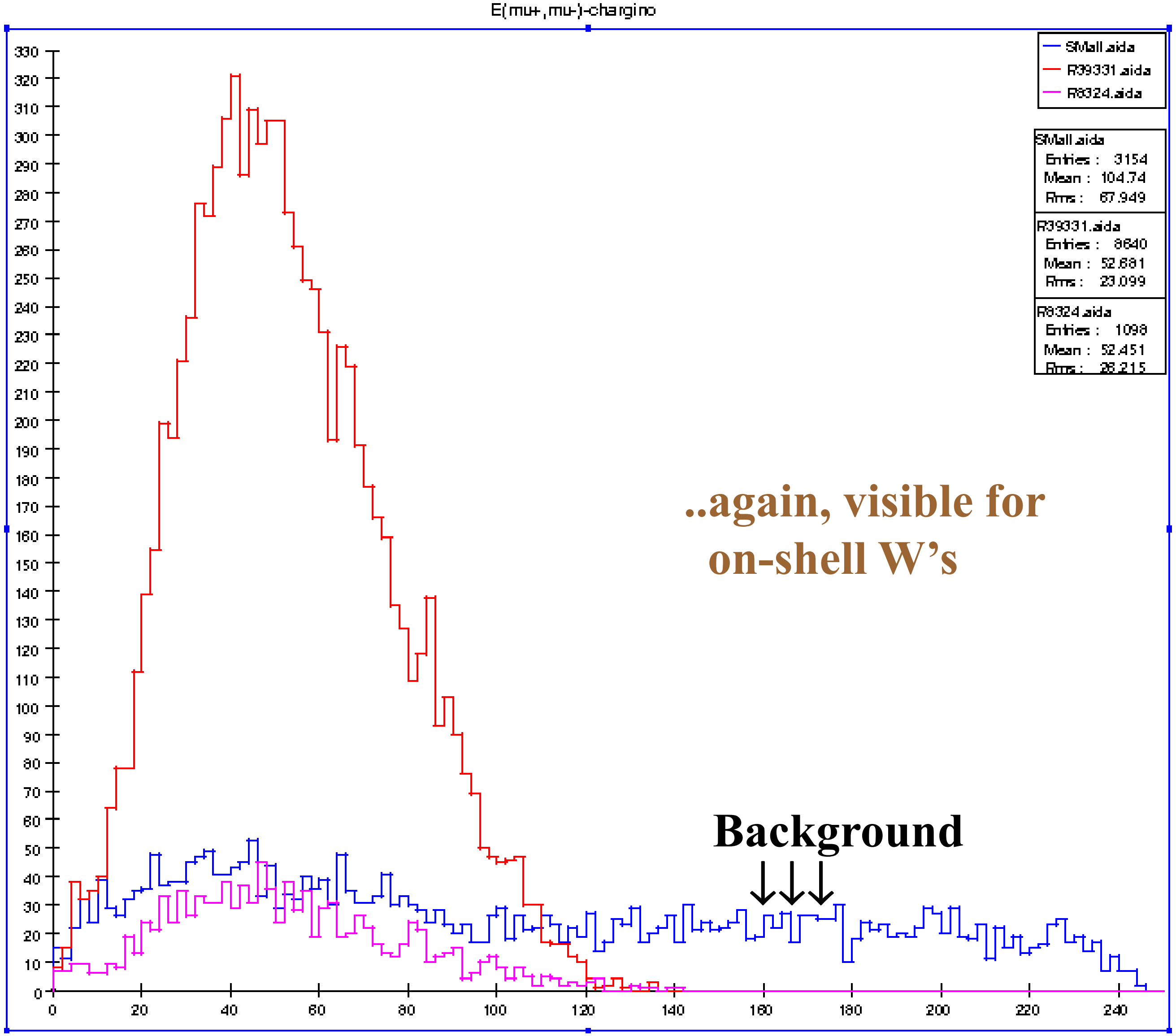
Chargino--4j + missing E analysis : Jet Pair Mass



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

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

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



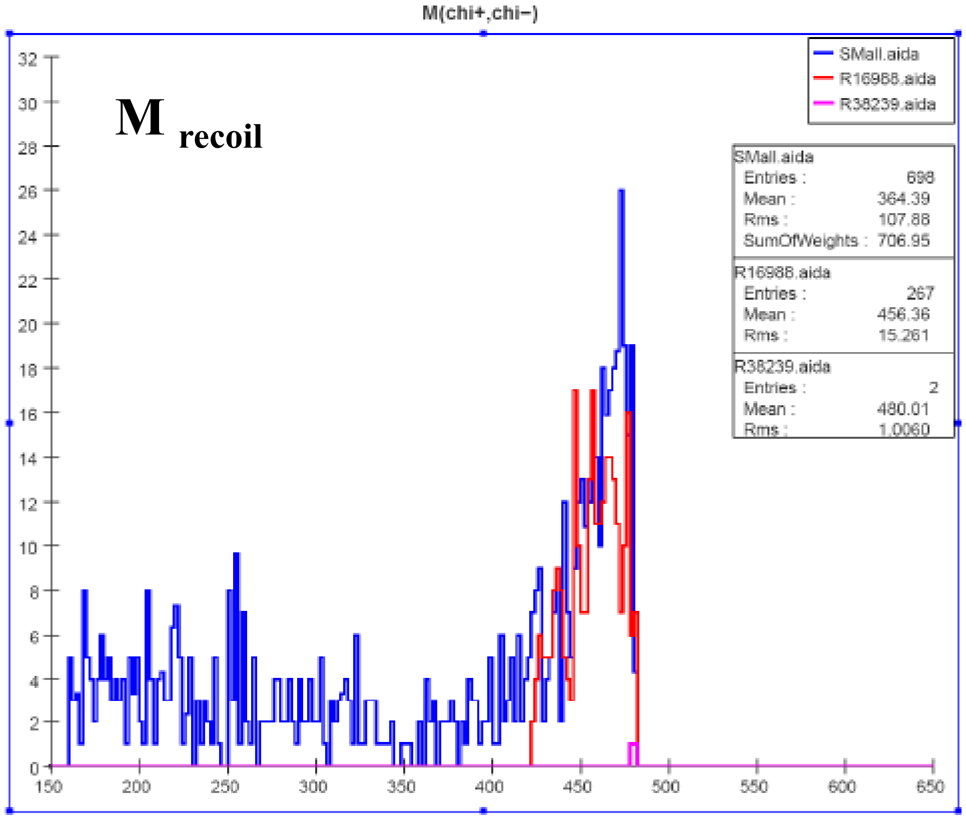
Small Δm ~ Few GeV, Charginos: soft hadrons + photon tag analysis

- Model 16988
  Δm = 413 MeV
  LSP mass:
  209.75 MeV

- Model 38239
  Δm = 450 GeV
  LSP mass:
  239.30 GeV

- We can see the signal from model 16988 easily from this analysis

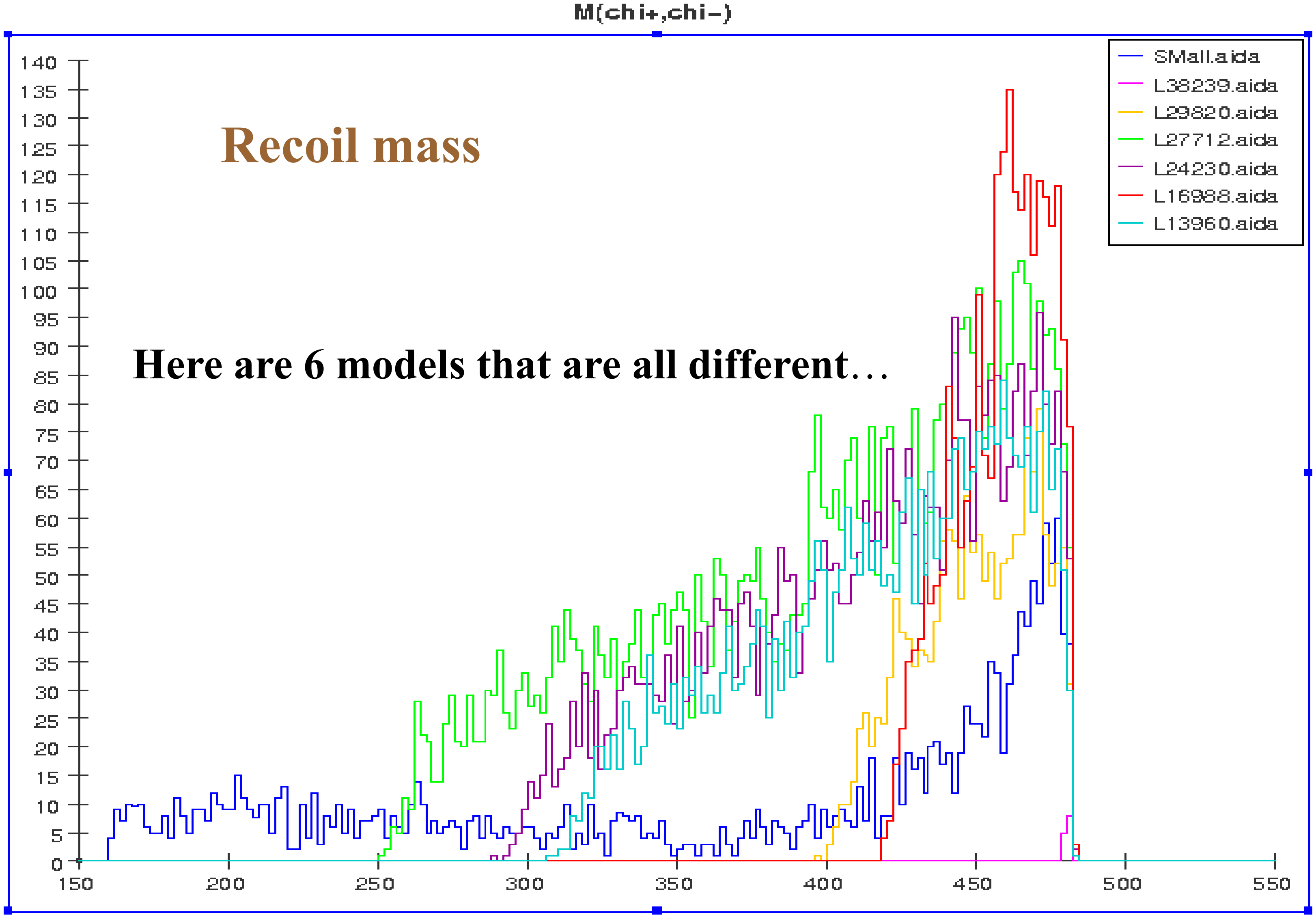
- There is effectively no signal from model 38239 do to the heavier LSP



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

from Jamie

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



Long-lived Chargino Analysis

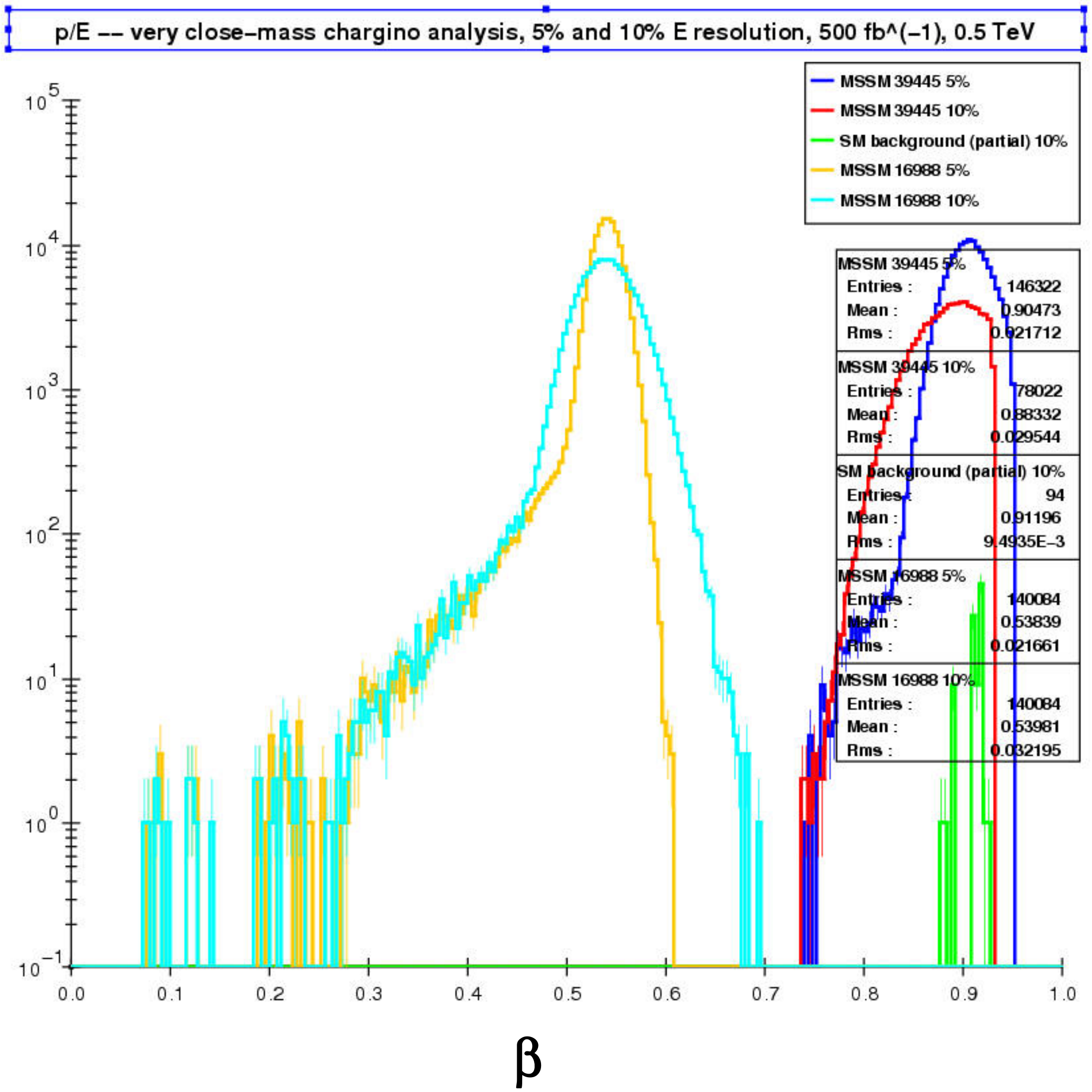
A surprisingly large number of our models have these particles

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).

$\beta = p/E$: 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

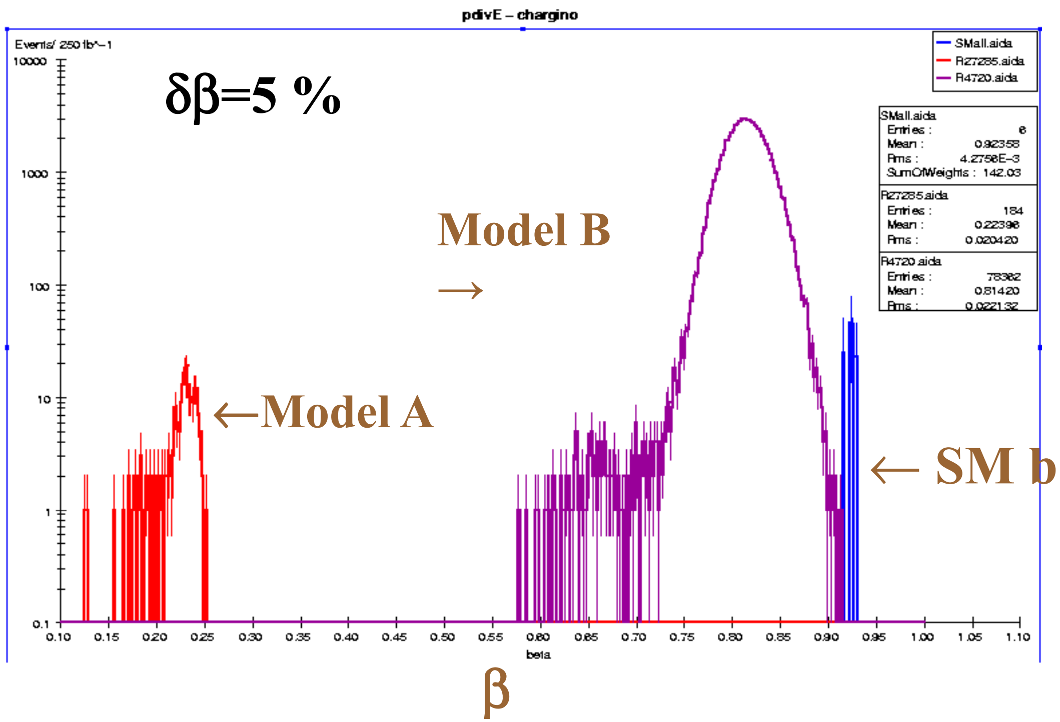
Background & Signal for Close Mass Case #2



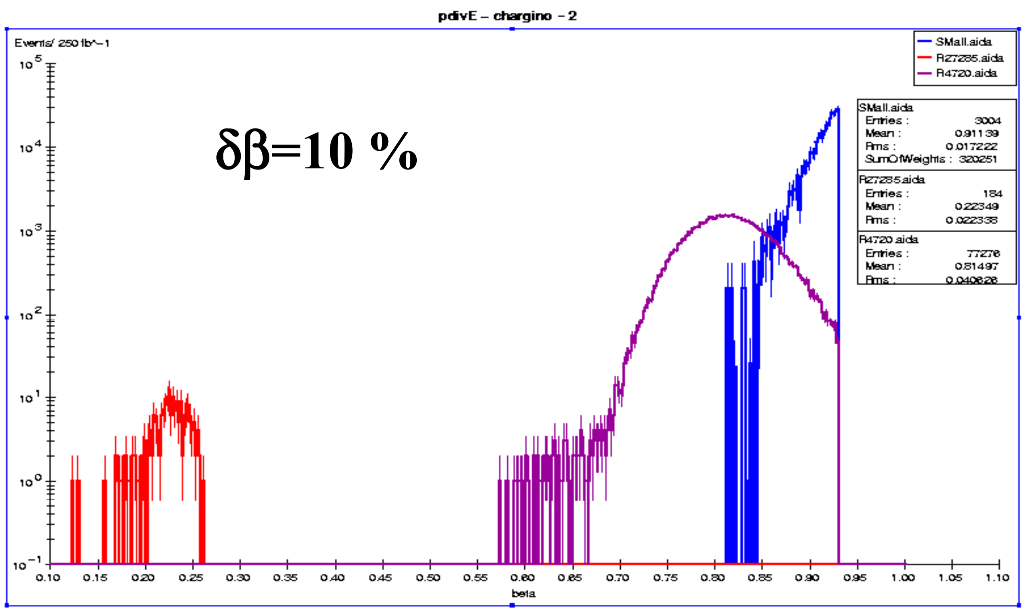
Looks pretty good!

Stable chargino Analysis

From JoA

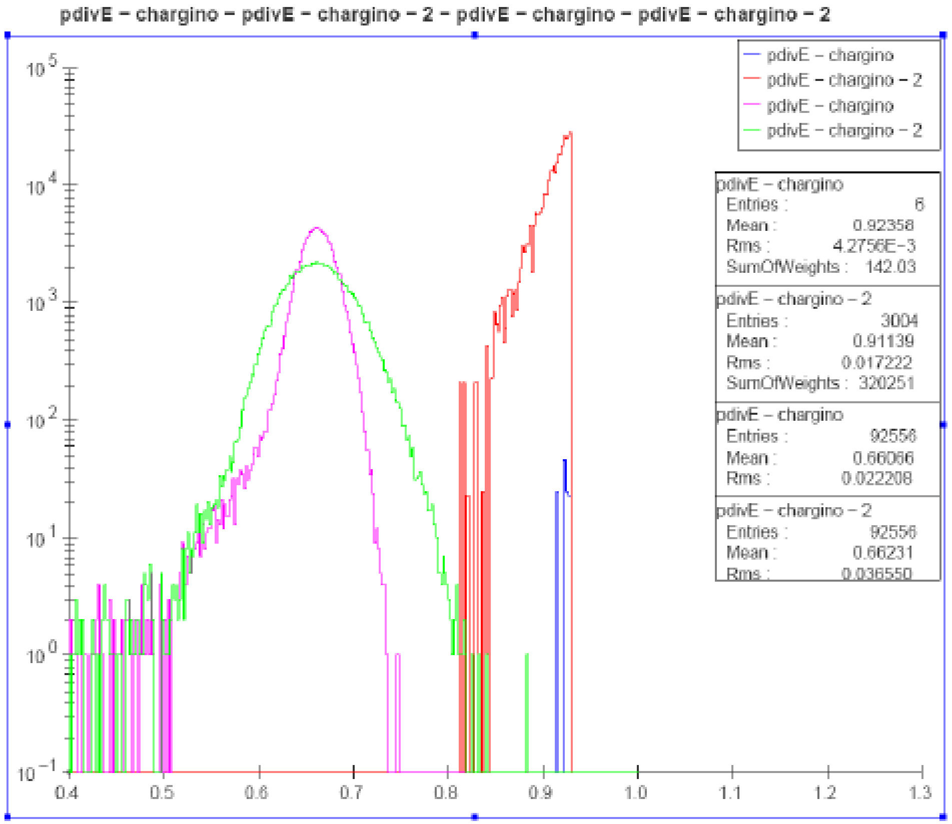


Stable Particle Searches



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

Long-lived Chargino Analysis (cont)



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

- Model 39445:

  Chargino Mass: 104.92 GeV

  Δm = 1.78 MeV

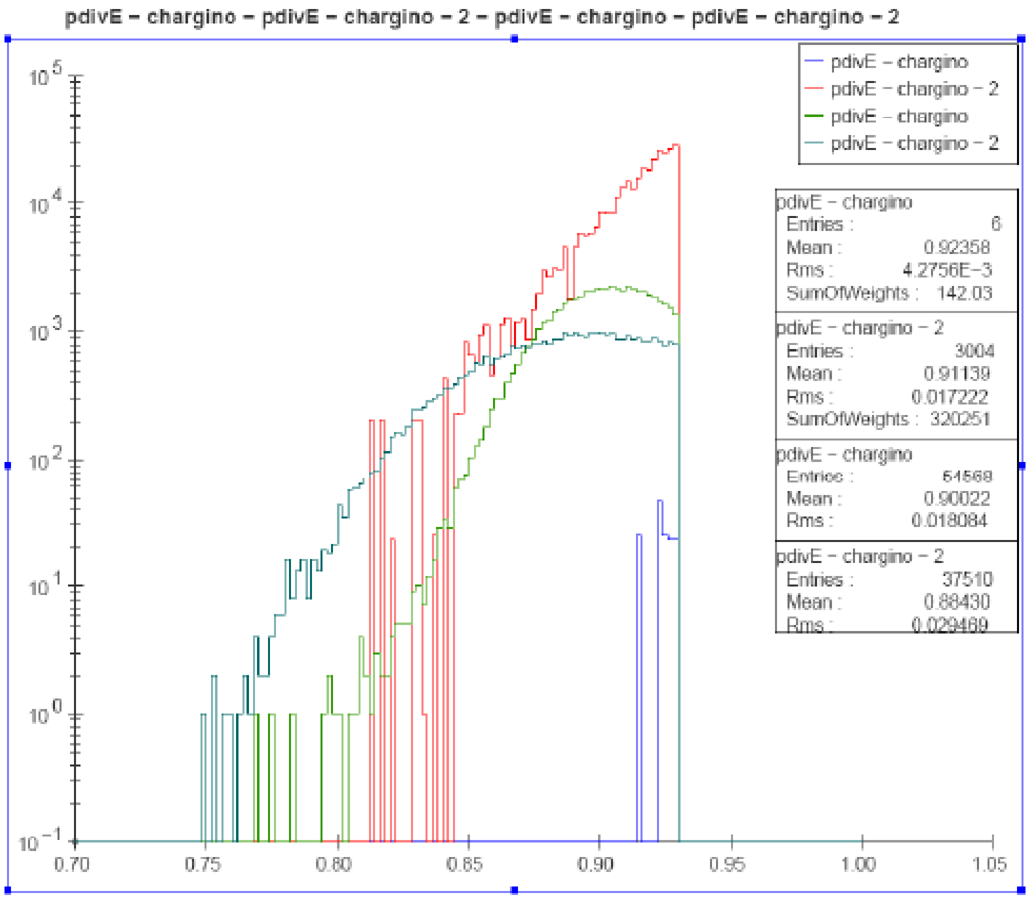
- Easy discovery, measurement of chargino mass for either energy spread

Some are easy…

From Jamie

Long-lived Chargino Analysis (cont) :

..some are a little harder



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

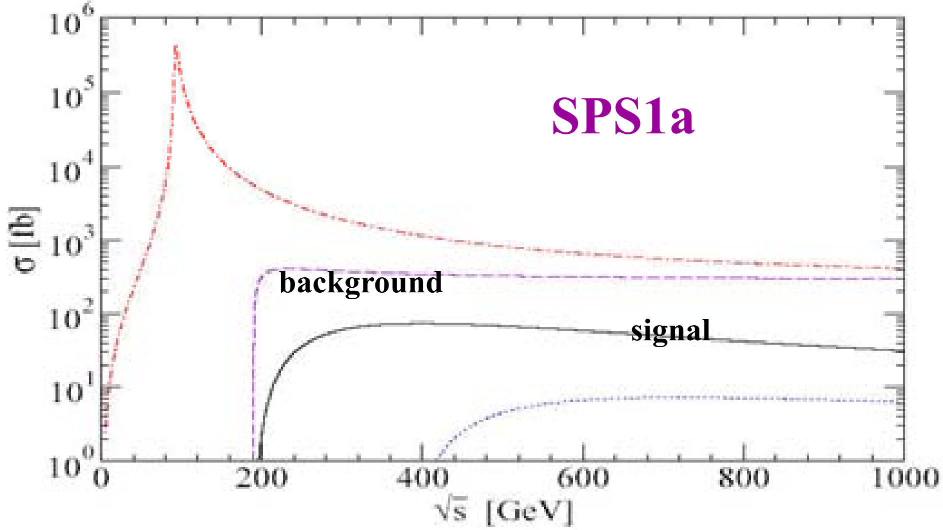
- Model 39445:
  Chargino Mass: 104.92 GeV
  Δm = 1.78 MeV
- S/B is huge for 5% smearing, but for 10% smearing the signal is harder to see (though probably visible due to low beta tail).
- Low sensitivity to light chargino masses if energy smearing is 10%

Radiative Neutralino Production

$e^+e^- \to \chi_1^0\chi_1^0$ is *invisible* so we employ the **γ-tag** again, i.e $e^+e^- \to \chi_1^0\chi_1^0 + \gamma$ 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 we explore… SM backgrounds from $e^+e^- \to \nu\nu\gamma(\gamma)$ are also very large and difficult to kill with standardized cuts

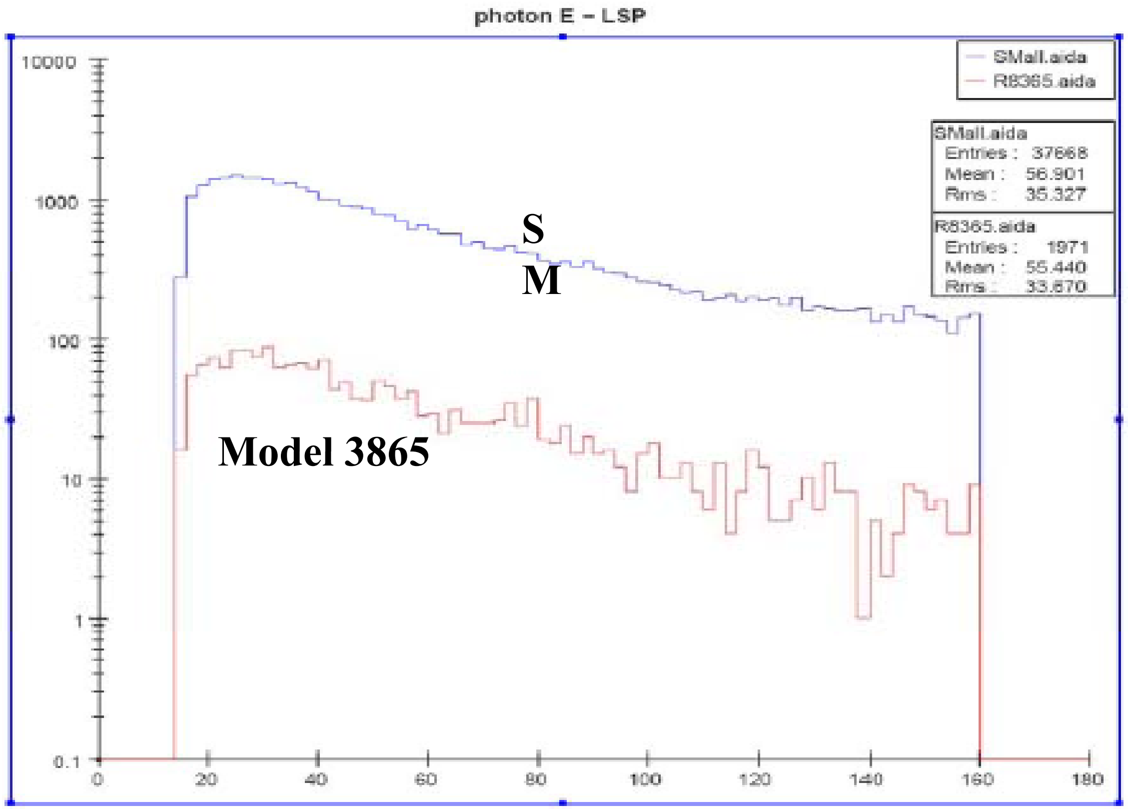
Dreiner et al., hep-ph/0610020

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….

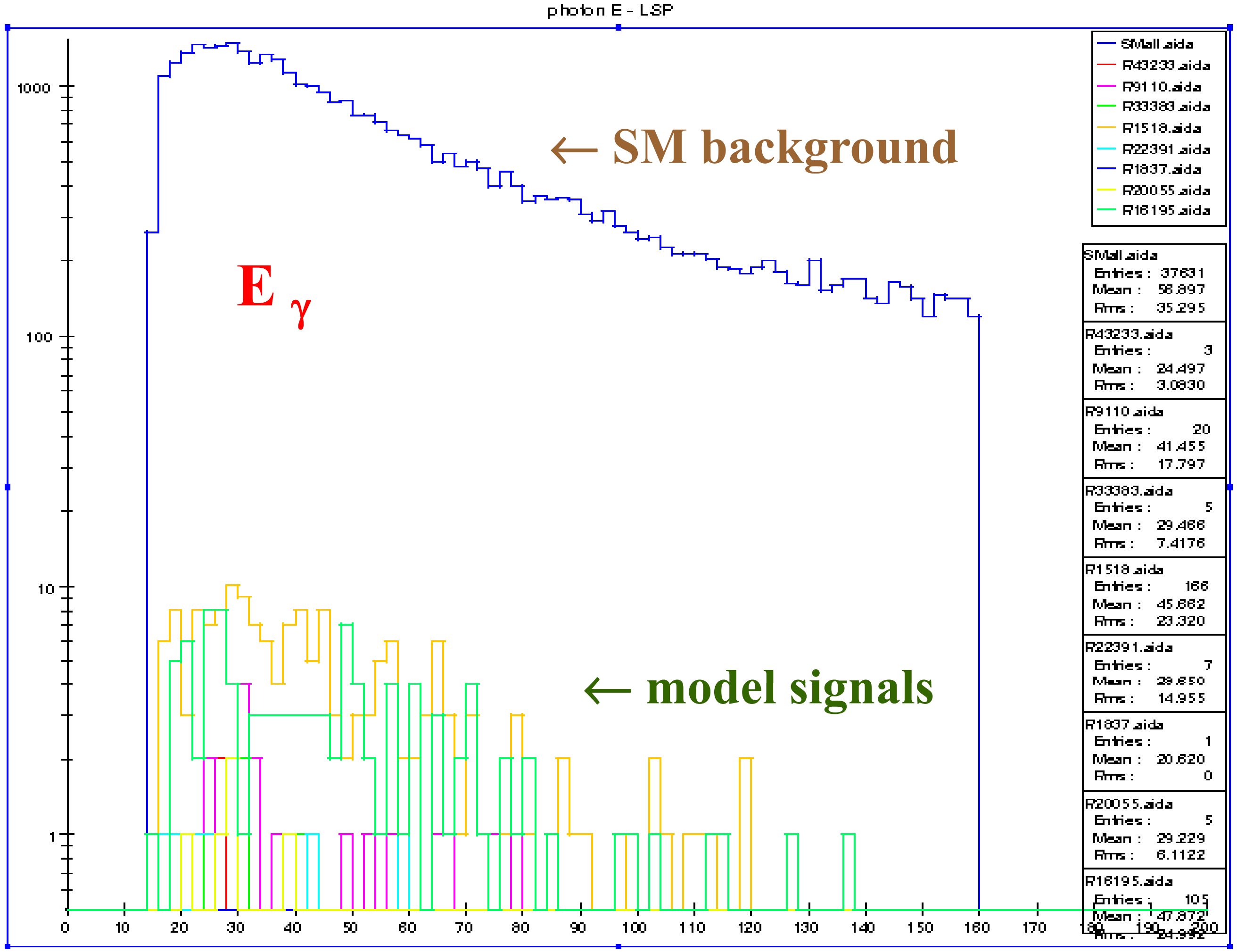
The background here is about 20x larger than the signal so these models look hopeless!!



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

..the situation is much worse in other random model cases…

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 $\sigma^B(e^-_L) \sim 50\ \sigma^B(e^-_R)$….

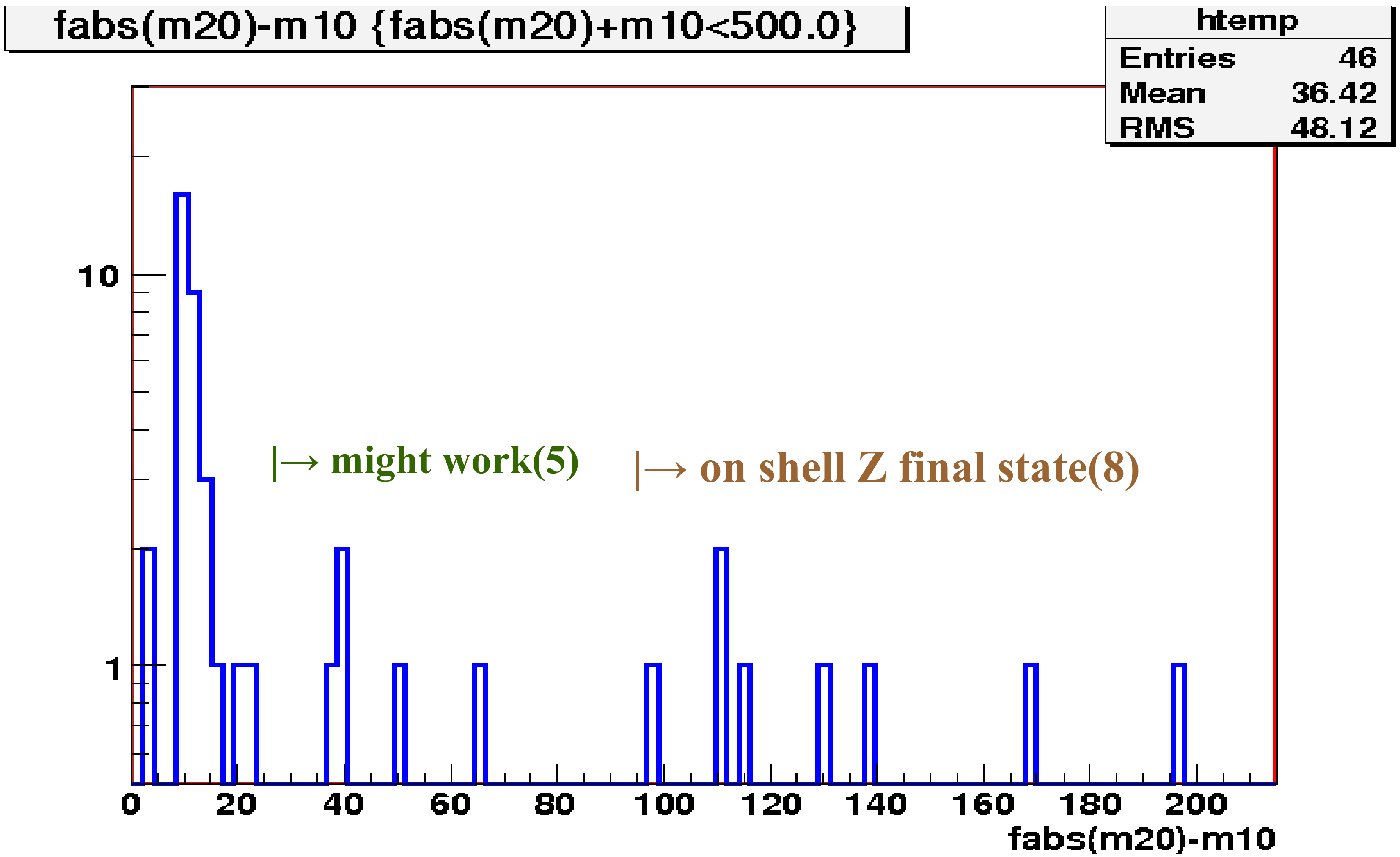
The best way to remove this background is with RH beam polarization and having both beams polarized is even *better* . For the signal, the models mostly cluster with either *(i)* $\sigma^S_L \sim \sigma^S_R$ or *(ii)* $\sigma^S_R >> \sigma^S_L$ This provides another good
reason to have positron polarization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

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

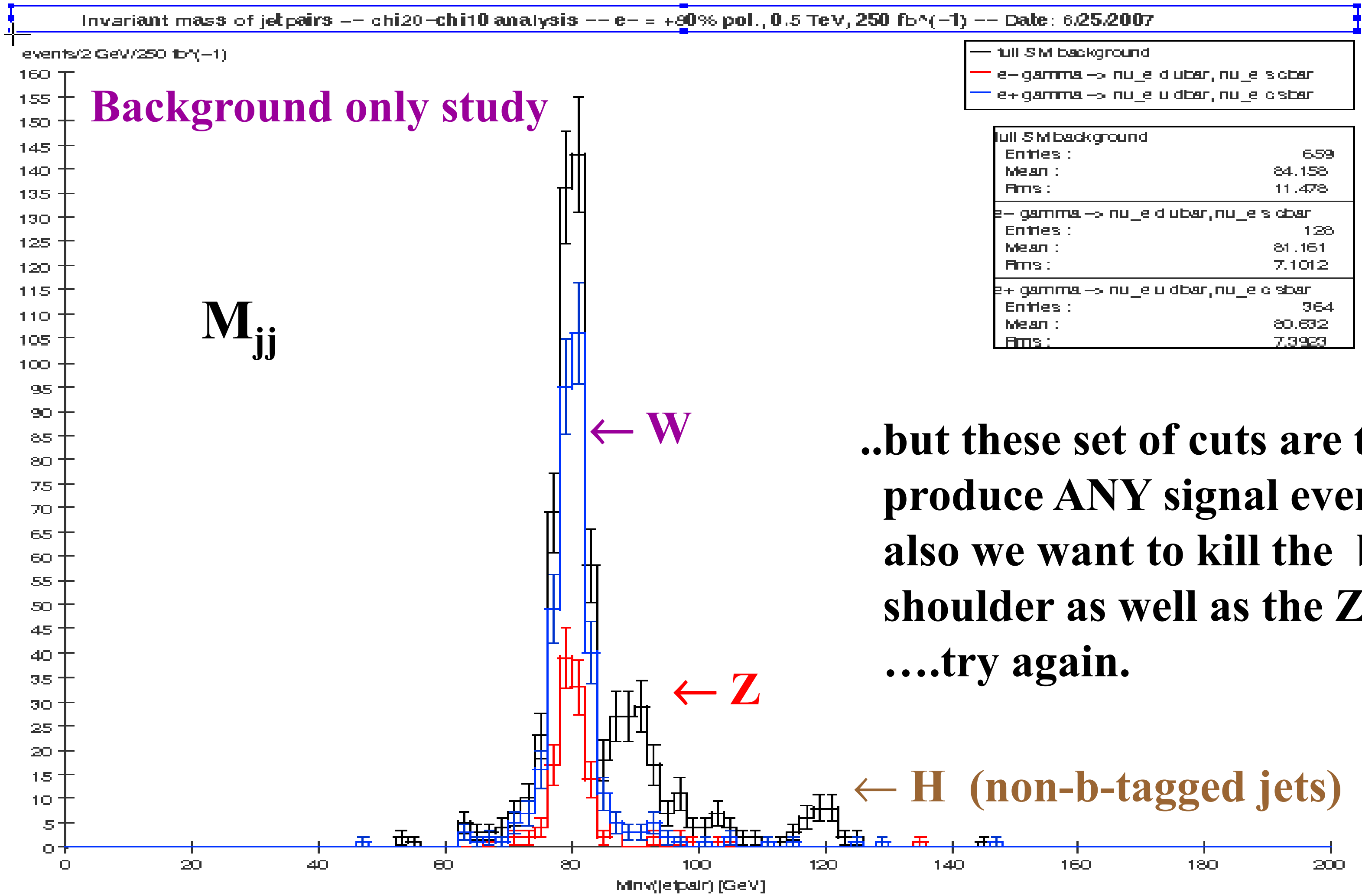
P_+	S_i	S_{ii}	B	S_i /B	S_{ii}/B
0.0	1	1.8	0.2	5.0	8.0
0.30	1.24	2.34	0.14	8.9	16.7
0.45	1.36	2.61	0.11	12.4	23.7
0.60	1.48	2.88	0.08	18.5	36.0

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

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



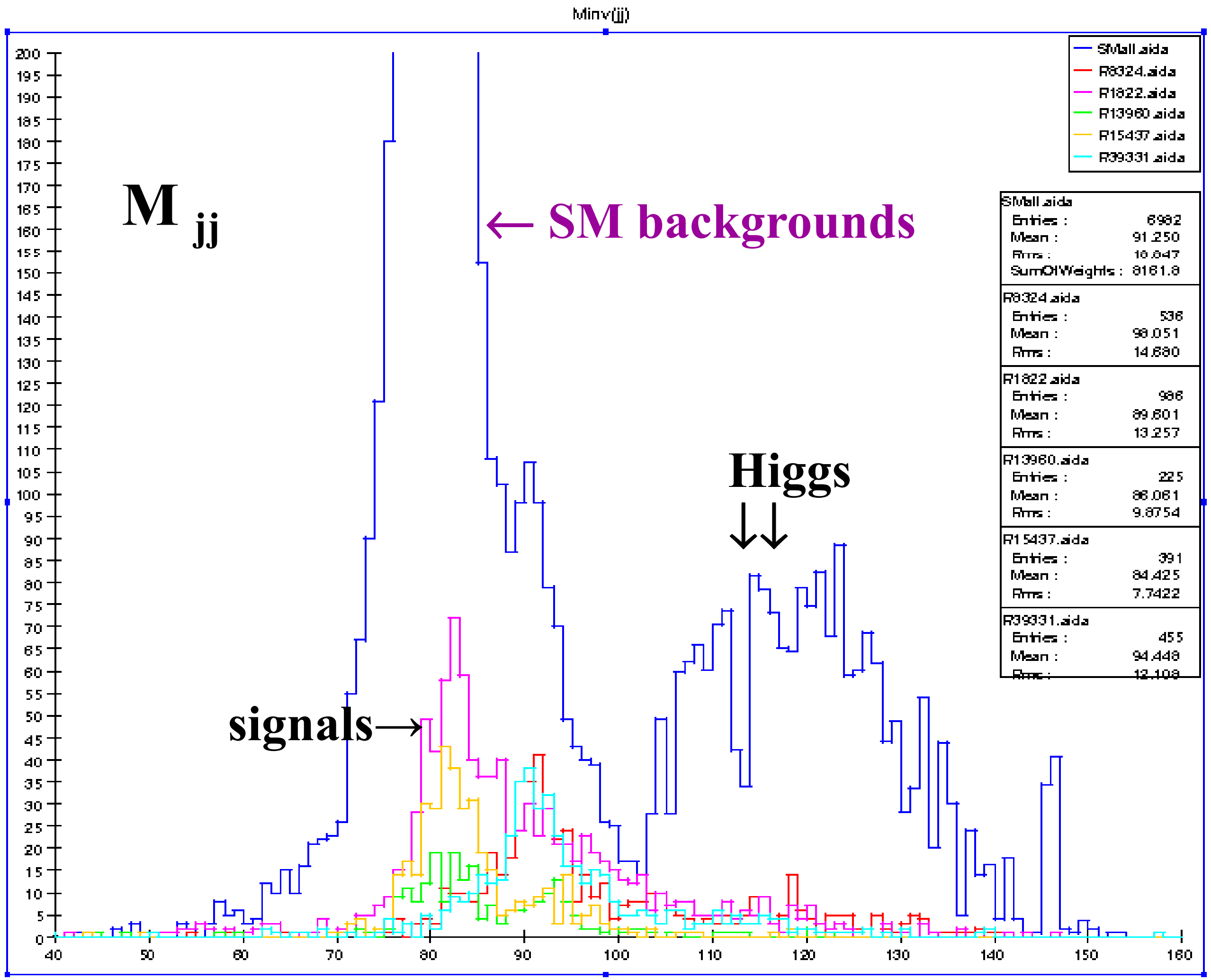
$\chi_2^0\,\chi_1^0\ \rightarrow$ jj + Missing E Analysis : Backgrounds are not bad ??



..but these set of cuts are too tight to produce ANY signal events and also we want to kill the 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…

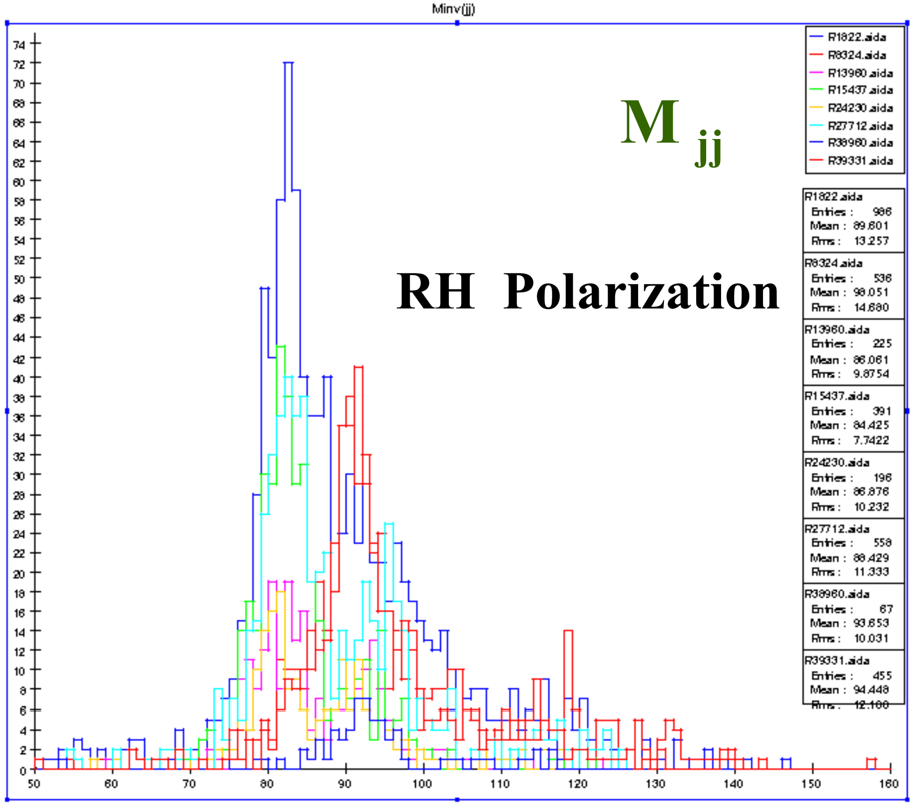


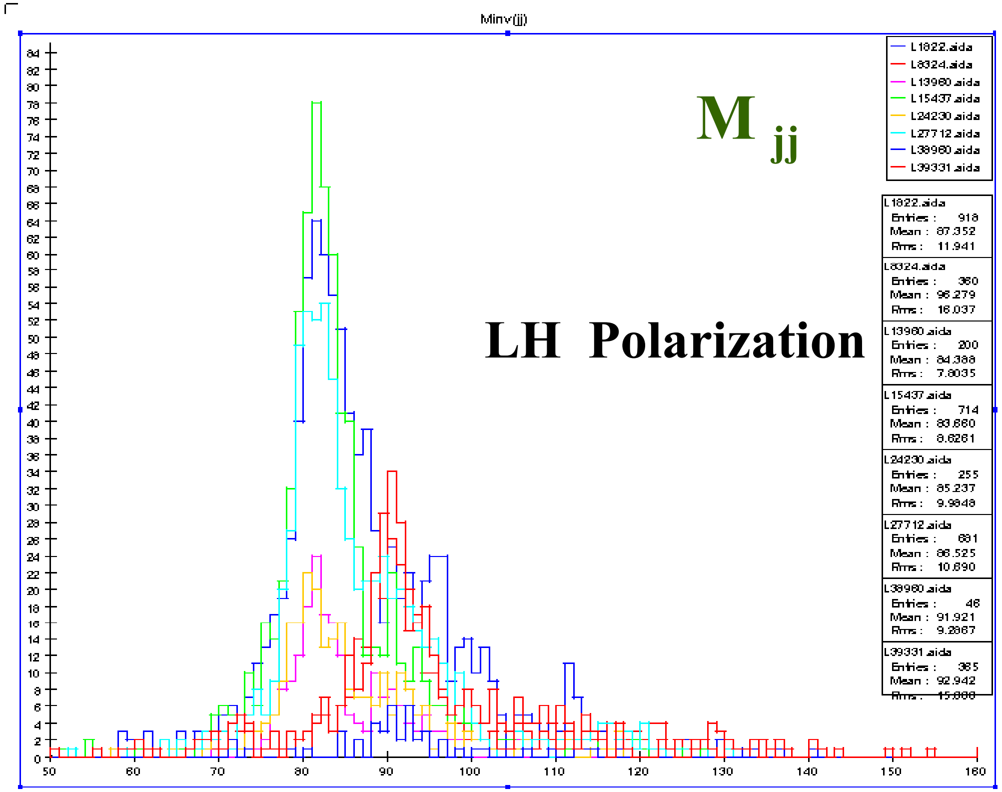
RH Polarization

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

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

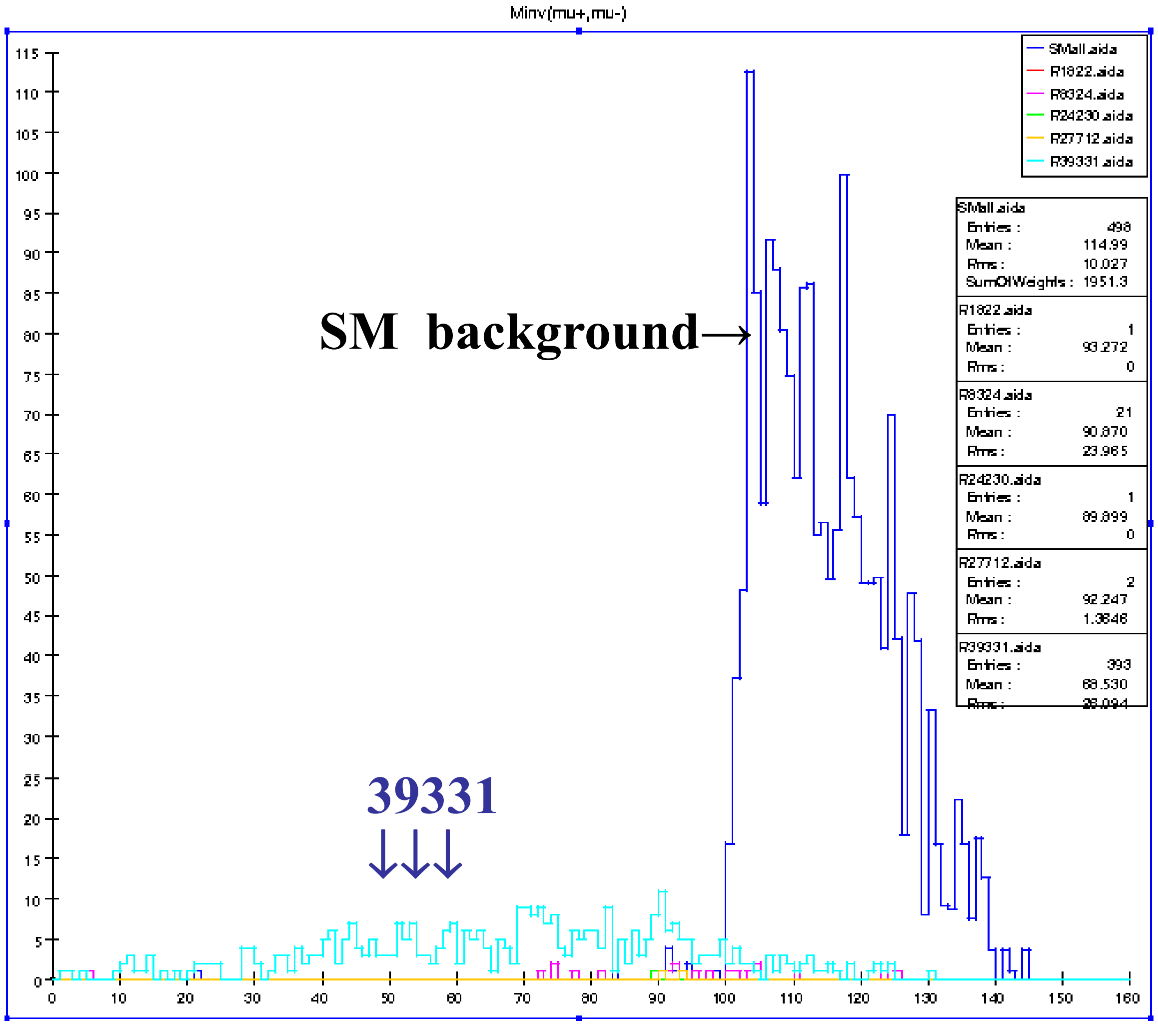
We see that the signals for either polarization are quite small but might still be visible…





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

$\chi_2^0\,\chi_1^0 \rightarrow\ \mu\mu$ + Missing E Analysis



The signal rate is very low…unfortunately

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

Analysis Procedure

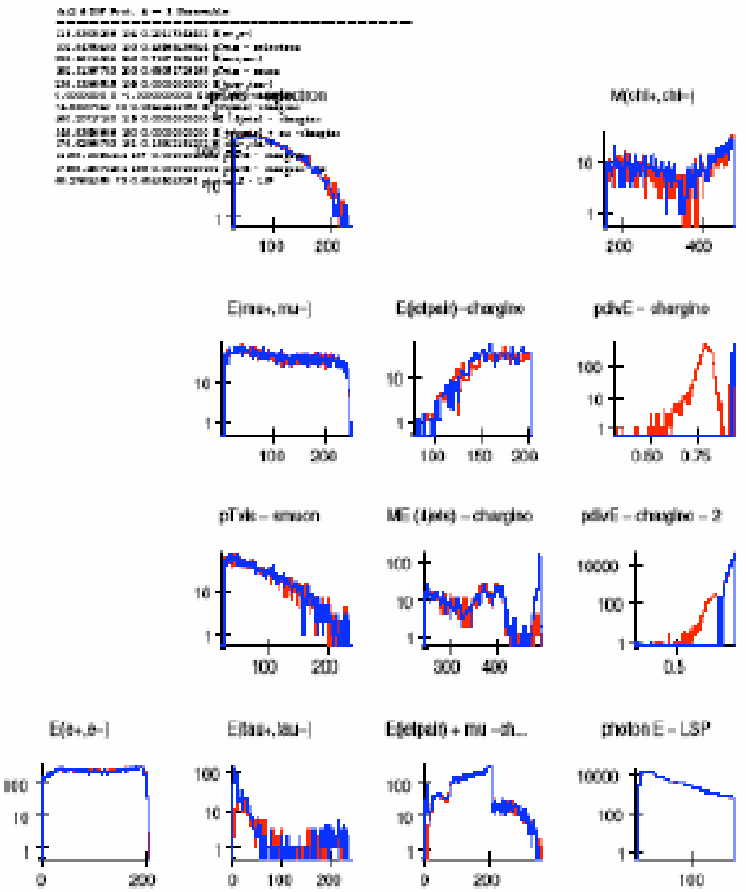
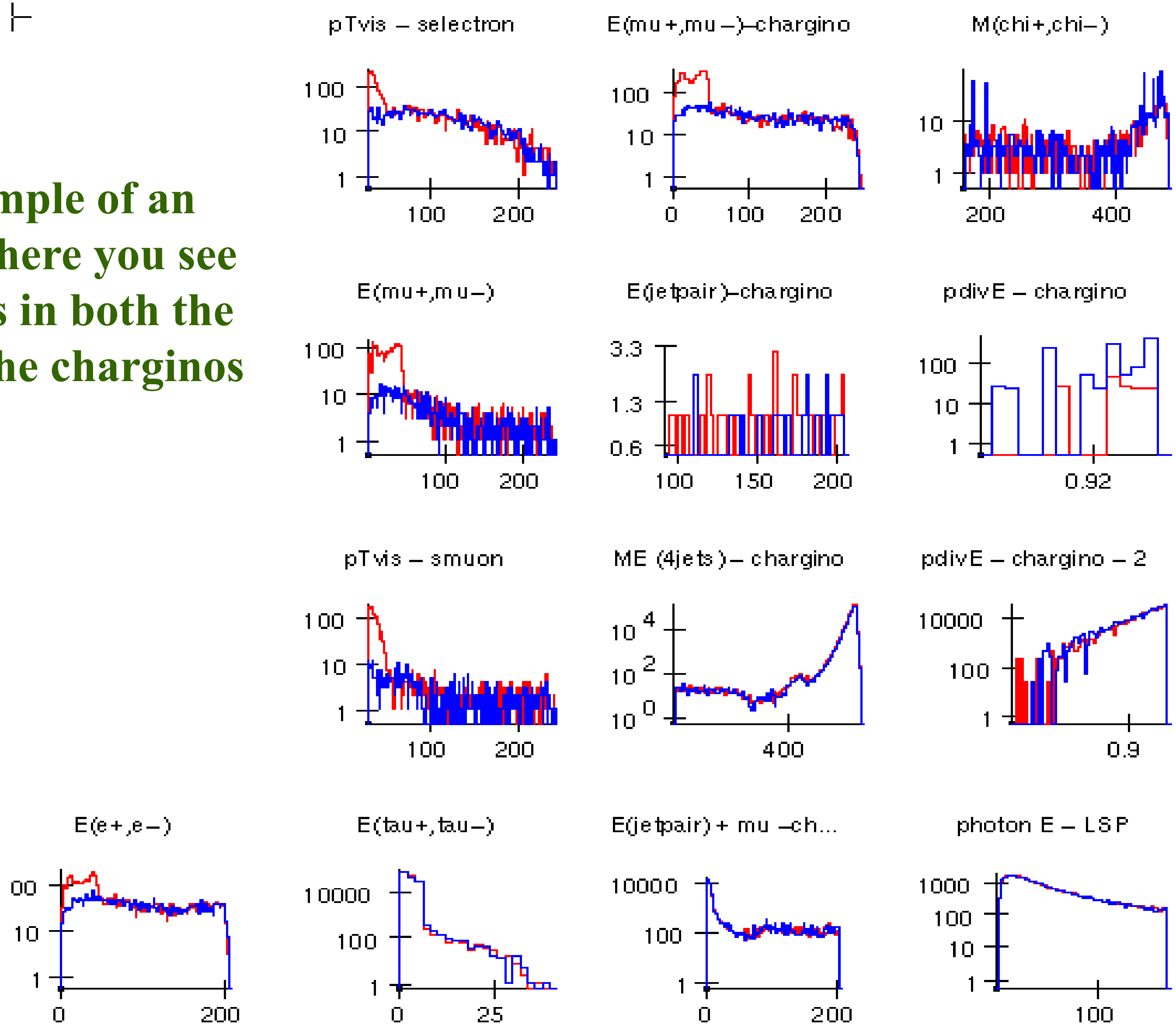


Figure 1: Left 207 (red) 3848 (blue)

- 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, 5σ
- We're just starting to do these comparisons

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



111

Figure 111: Right 10197 (red) 13274 (blue)

…and here is another case also showing significant differences…

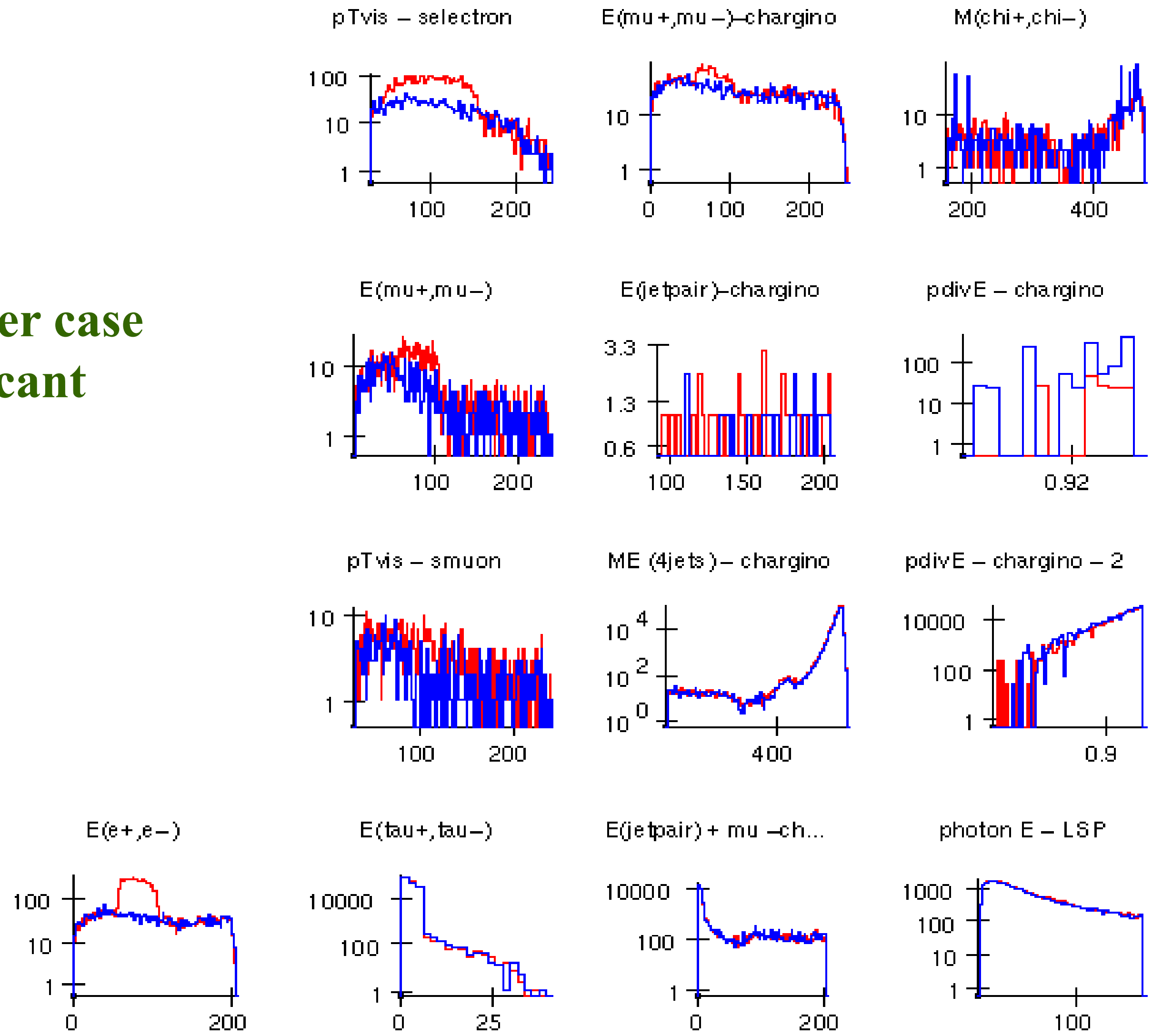


Figure 213: Right 27913 (red) 43006 (blue)

SUMMAR Y

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. Do threshold scans of some kind….

(*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 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.