General Features of SUSY Signals at the ILC: Stau Problems

(due to lack of low-angle tracking)

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0711.1374 & 0712.2965

3/5/08

The goals of this (sub)project were twofold:

- Study in as realistic a way as possible the capability of the ILC to examine the physics of a large number(242) 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're now studying several thousand..)

  → 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 (162) pairs of points in parameter space which lead to essentially identical, so called \`degenerate', signatures at the LHC#.

#Arkani-Hamed etal., hep-ph/0512190

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

[@] To connect w/ LHC we use the models of Arkani-Hamed etal., hep-ph/0512190

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

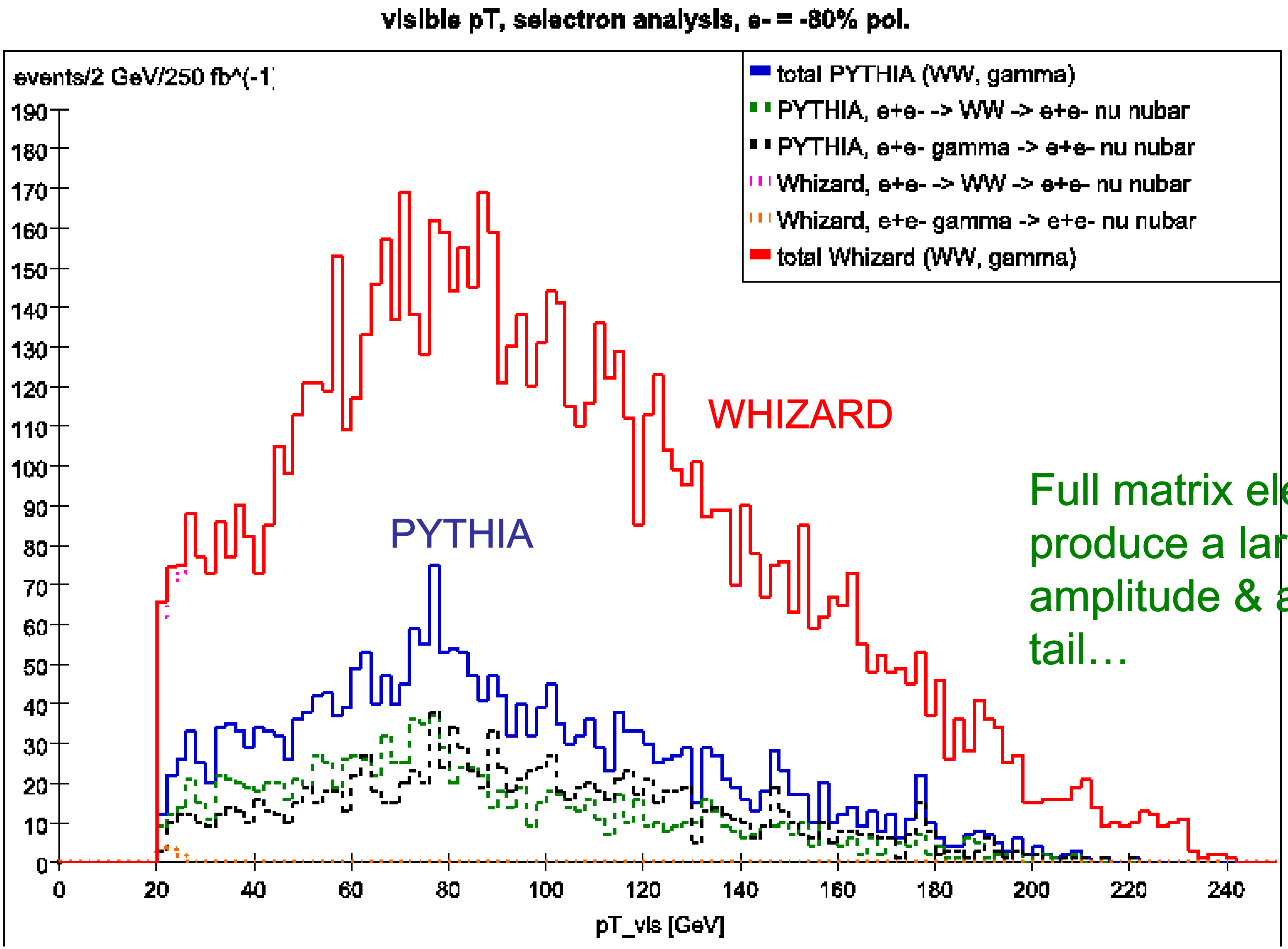
Table 12:

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…



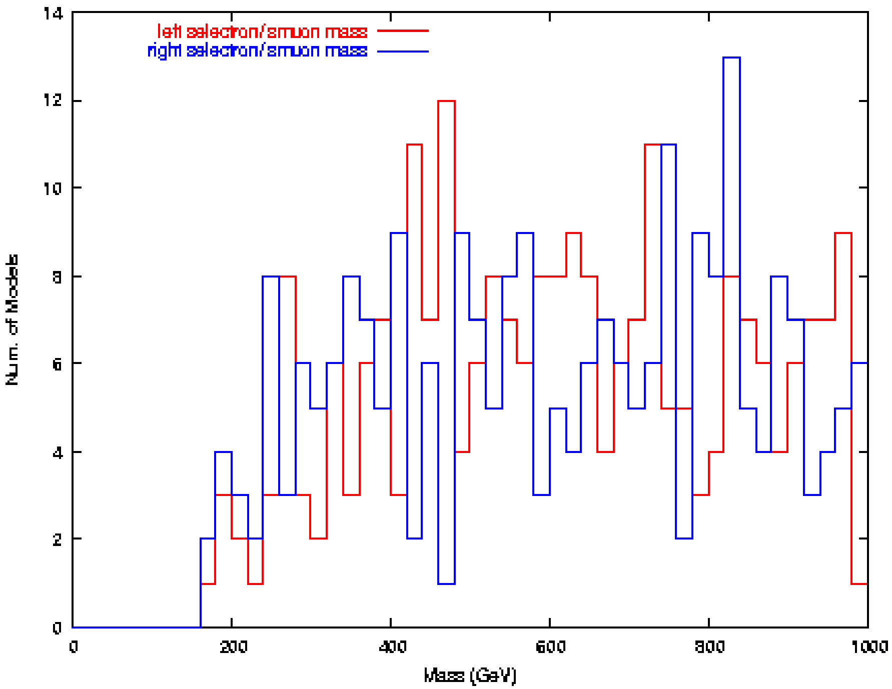
Full matrix elements produce a larger amplitude & a longer tail…

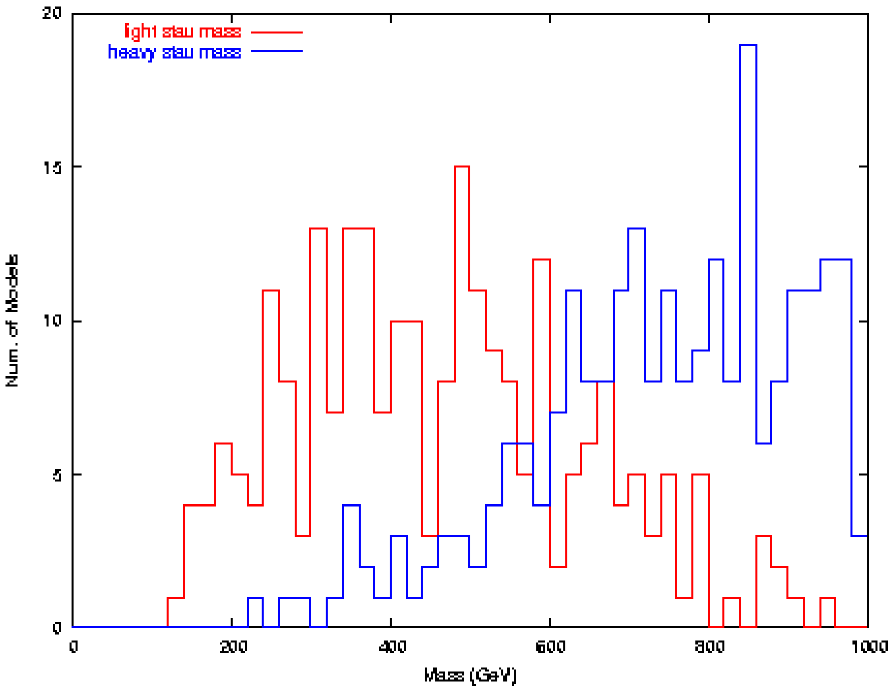
Kinematic Accessibility (≠ Observability)

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 ~ 7%

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





L- & R- selectrons & smuons

These are comparable spectra

Selectron/smuon and stau mass spectra for the set of models that we consider

Stau-1 & stau-2 spectra are quite different due to sizeable mixing

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

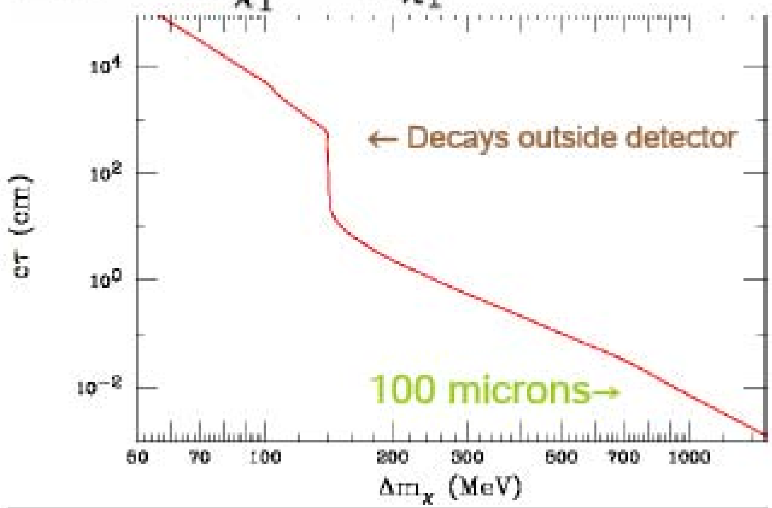
(iii) $\chi_2^0 \chi_1^0$ → missing E + Z/H (jj /l^+l^-)

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

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

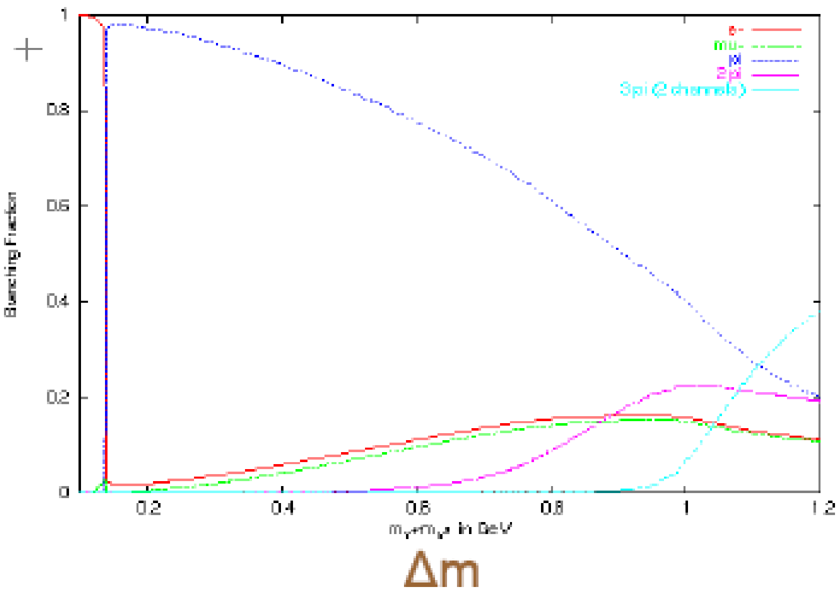
Critical parameter for charginos: $\Delta m = m_{\chi_1^\pm} - m_{\chi_1^0}$

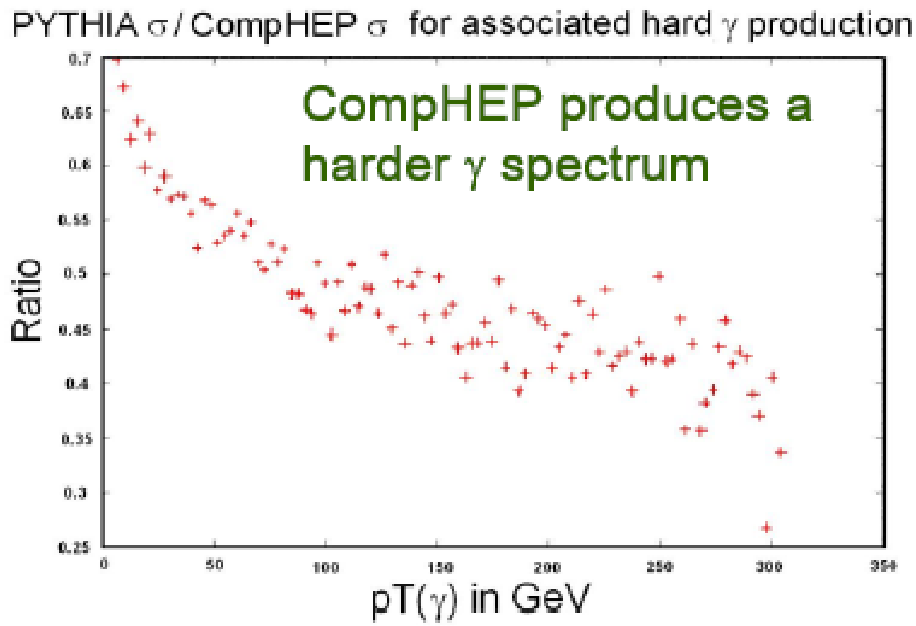
(a) → if $\Delta m < m_\pi$ we need to do a stable charged particle search …



Analyses Continued：

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





(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.....

Tau selection criteria

1. We require 2 jets in the event, each with charged multiplicity of 1 (where the tau decays into a lepton, ρ, π, or 3π-decay with $2\pi^0$s) or 3 (where the tau decays into 3 charged pions).

2. The invariant mass of tau-jet, *i.e.*, the visible tau decay products, must be < 1.8 GeV.

3. If the tau-jet is 3-prong (charged multiplicity of 3), then none of the charged particles should be an electron or muon.

4. If both tau-jets in the event are 1-prong, then we reject events where both jets are same flavor leptons, that is, an electron-positron or a muon pair. However we keep pairs of tau-jets that are, for example, an electron and a muon, or an electron and a pion, whereby a pion is defined as a charged track that is not identified as an electron or a muon. (ID1)

As an *alternative* analysis, we follow the above criteria and allow leptonic tau decays into muons, but reject taus that decay into electrons. This reduces contamination from photon-induced backgrounds. (ID2)

Stau observation cuts

1. No electromagnetic energy (or clusters) in the region $|\cos\theta| > 0.995$.

2. Two tau candidates as identified above, are weighted by their charge within the polar angle $-0.75 < Q_\tau \cos\theta_\tau < 0.75$. This reduces the W-pair background.

3. The acoplanarity angle must satisfy $\Delta\phi^{\tau\tau} > 40$ degrees. Here, since we demand two tau candidates, the acoplanarity angle is equivalent to π minus the angle between the p_T of the taus, $\Delta\phi^{\tau\tau} = \pi - \theta_T$. The above requirement then translates to $\cos\theta_T > 0.94$. This cut reduces the W-pair and $\gamma\gamma$-induced background.

4. $|\cos\theta_{missing}| < 0.8$.

5. The transverse momentum of the ditau system be in the range $0.008\sqrt{s} < p_T^{\tau\tau} < 0.05\sqrt{s}$. This decreases the $\gamma\gamma$-induced background.

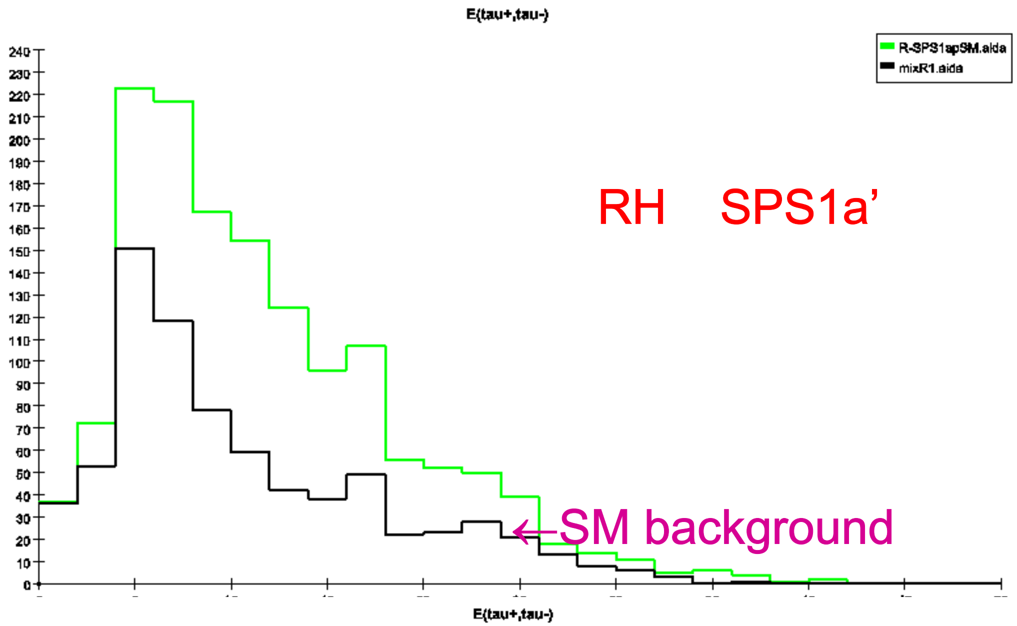
6. The transverse momentum of each of the tau candidates be $p_T > 0.001\sqrt{s}$. This cut is crucial to reduce the $\gamma\gamma$ and $e\gamma$ background.

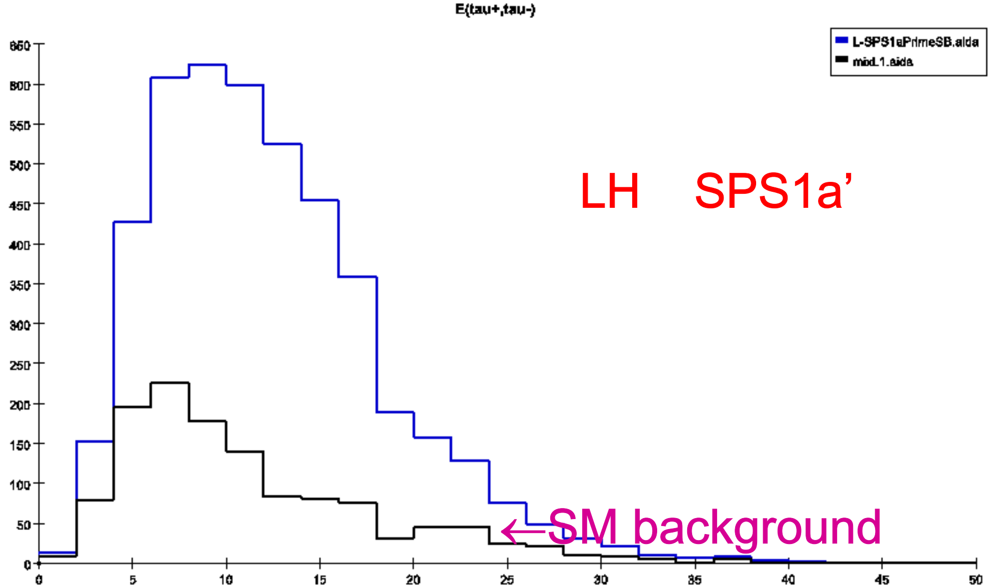
7. The combined cut on $\sum p^T_{\perp,\tau}$ and $\Delta\phi^{\tau\tau}$,

$$\begin{aligned} \sum p^T_{\perp,\tau} &< 0.00125\sqrt{s}(1 + 5\,\sin\Delta\phi^{\tau\tau}) \\ &= 0.00125\sqrt{s}\left(1 + 5\,\sqrt{1 - \cos^2\theta_T^{\tau\tau}}\right) \qquad (4.7) \end{aligned}$$

   is imposed. Here, $\sum p^T_{\perp,\tau}$ is the sum of the tau momenta projected onto the transverse thrust axis $\vec{T}_\perp$, where the transverse thrust axis is given by the xy-components of the thrust axis. This last cut is necessary in the tau decay channel to further decrease the $\gamma\gamma$ background.

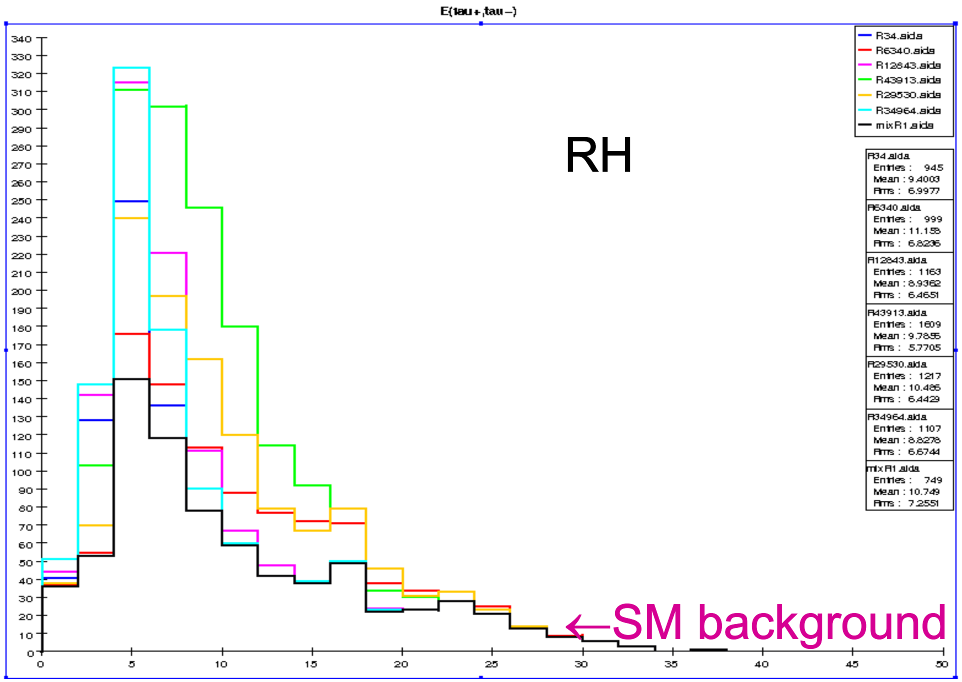
E_{vis} for each tau candidate

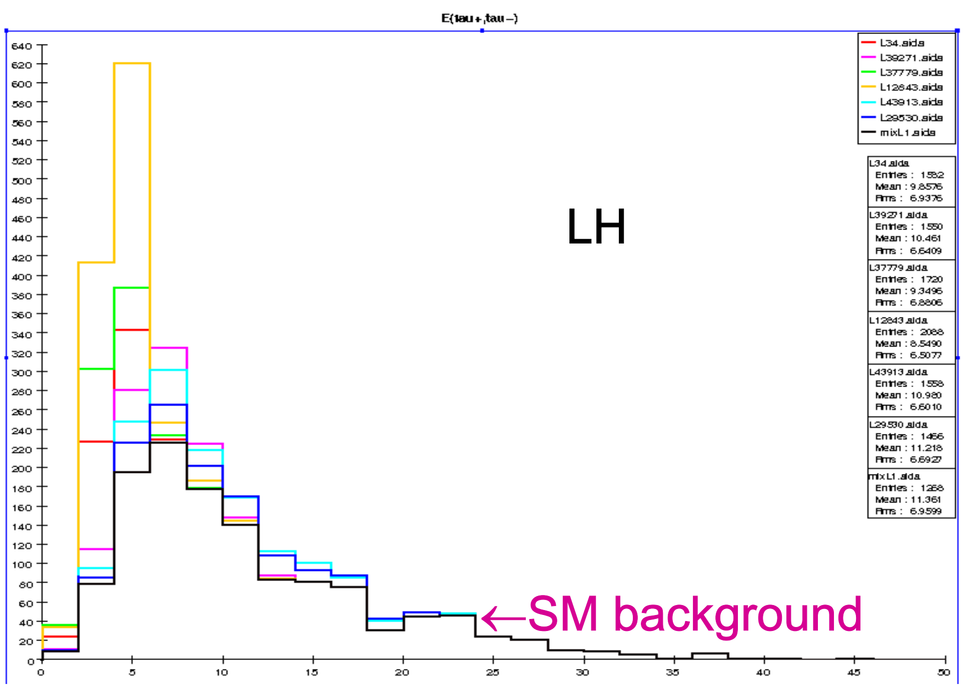




SPS1a’ :
An easy warm-up exercise as it leads to very large signal rates

For SPS1a’ the `standard’ analysis works just fine for both beam polarizations since the signal is far larger than the *significant* SM background





For our set of models, the signal rates can be far smaller compared to the significant SM backgrounds.

Out of the 28 models with kinematically accessible staus, only 12(11) are visible (with Sig > 5) for LH(RH) beam polarization. 13/28 are visible combining both polarization samples.

This is not great…

The main problem is the large SM background infecting the \`tau-jet' energy distribution & we need to find out where it comes from & how to deal with it…

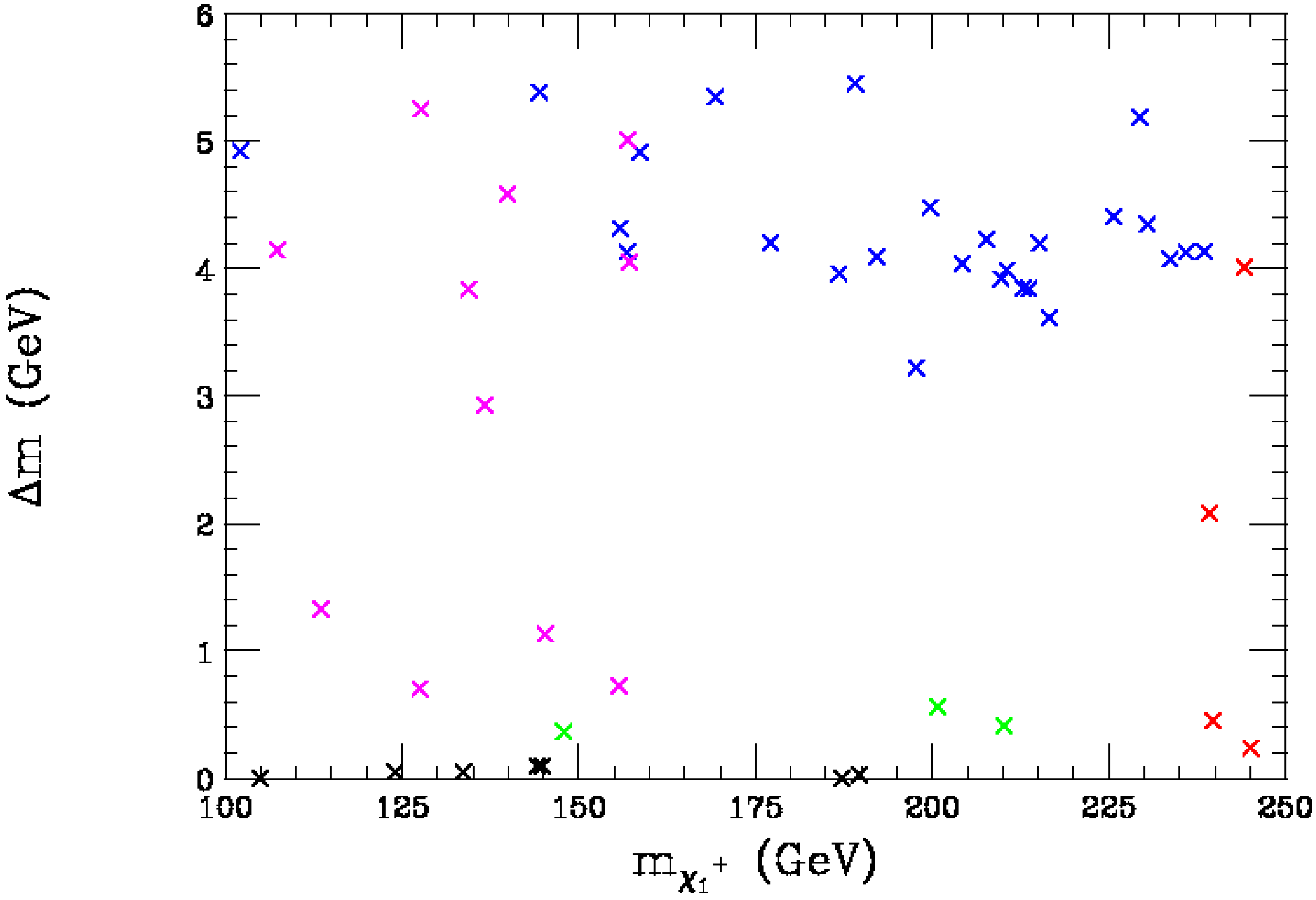
Another issue is that there can be \`fake' signals produced by the decay of other SUSY particles…a good example is provided by the decay of the lightest chargino through a virtual W

$$\chi^{+}_{1} \rightarrow \chi^{0}_{1}\, W^{*}$$

when the chargino-neutralino mass difference is small ~ a few GeV or less

The virtual W decay produces a τ-like final state so that the chargino looks like a stau. The large background also makes the separation of real from fakes difficult.

Charginos are seen in many different analyses…many have small mass splittings.



Green = radiative only

Black = stable only

Blue = off-shell W

Magenta = off-shell W & radiative

Red = missed

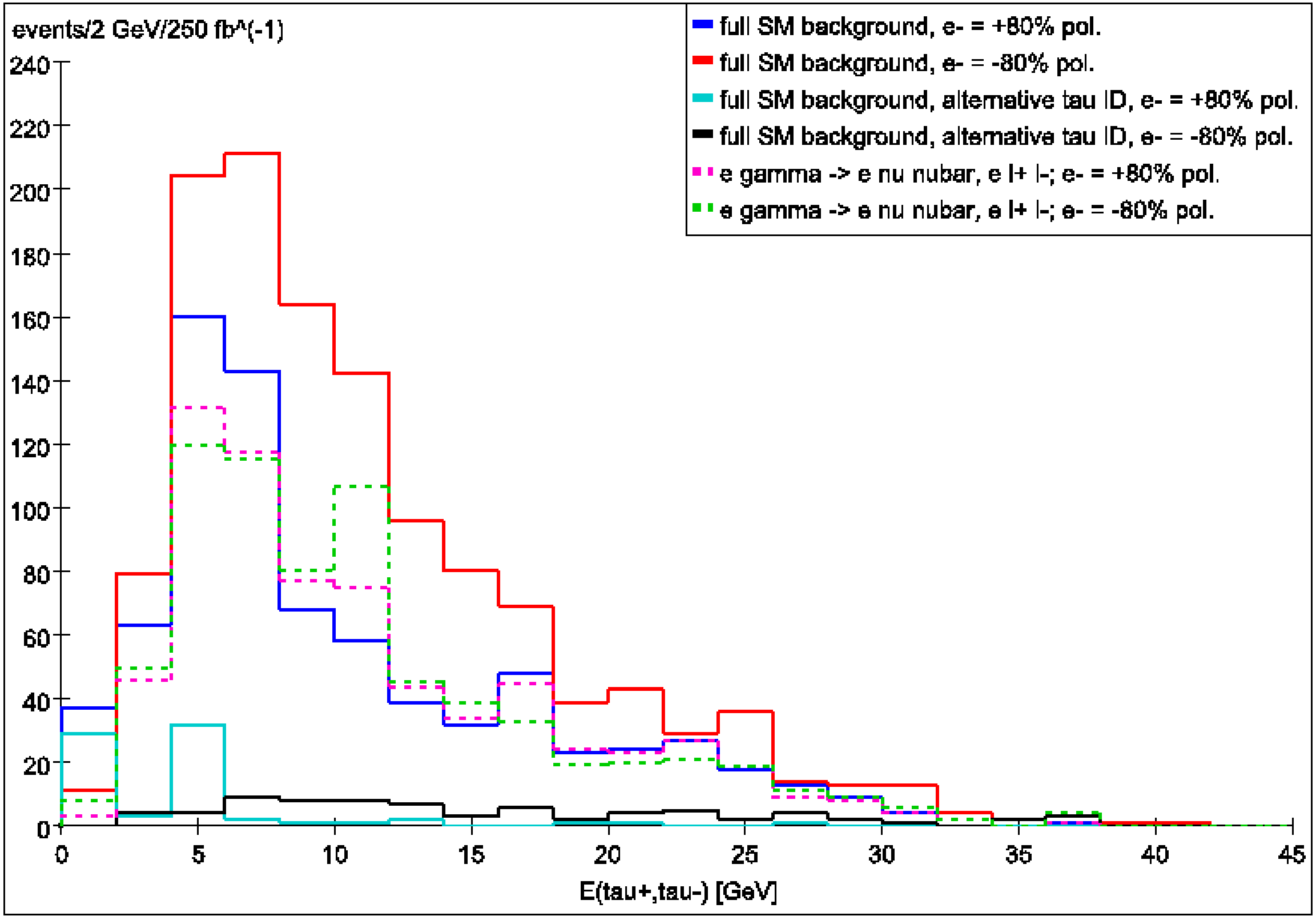
The current SiD vanilla detector design does not allow for low angle tracking, so doesn't have particle ID below ~140 mrad. Thus muons at low angles are completely missed if they are too energetic to deposit energy into EM clusters.

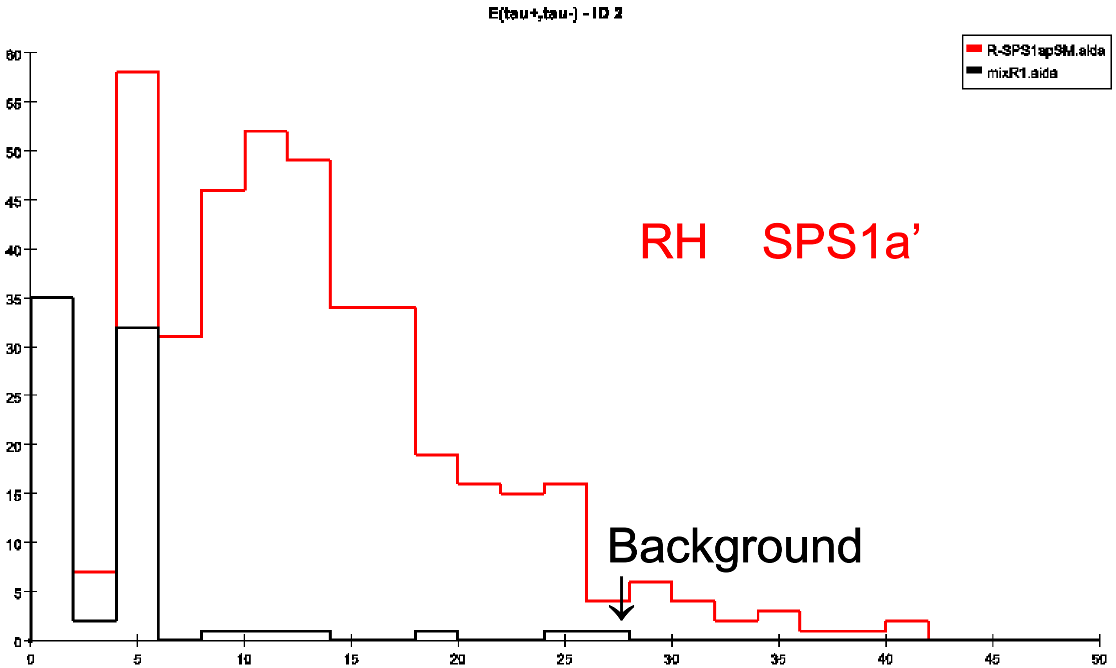
This implies that certain gamma-induced processes constitute a significant background to stau production, particularly in the case where such energetic muons are produced but one is not reconstructed and the beam electron/positron receives a sufficient transverse kick to be detected.

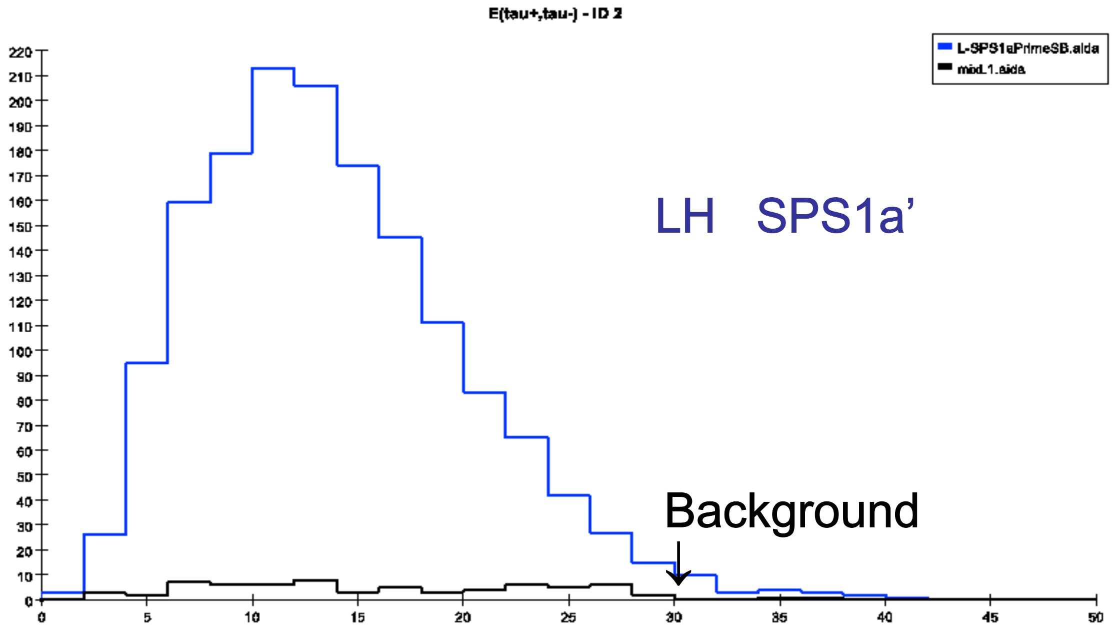
In this case, the final visible state is just an electron and a muon, which would pass the standard tau ID preselection. We can also employ an alternative tau preselection criteria, which rejects the electron decay channel, eliminating this background at the price of reducing the signal correspondingly by roughly 30%. → **ID2**

But this loss of signal is worth it as we'll see…

SM Backgrounds

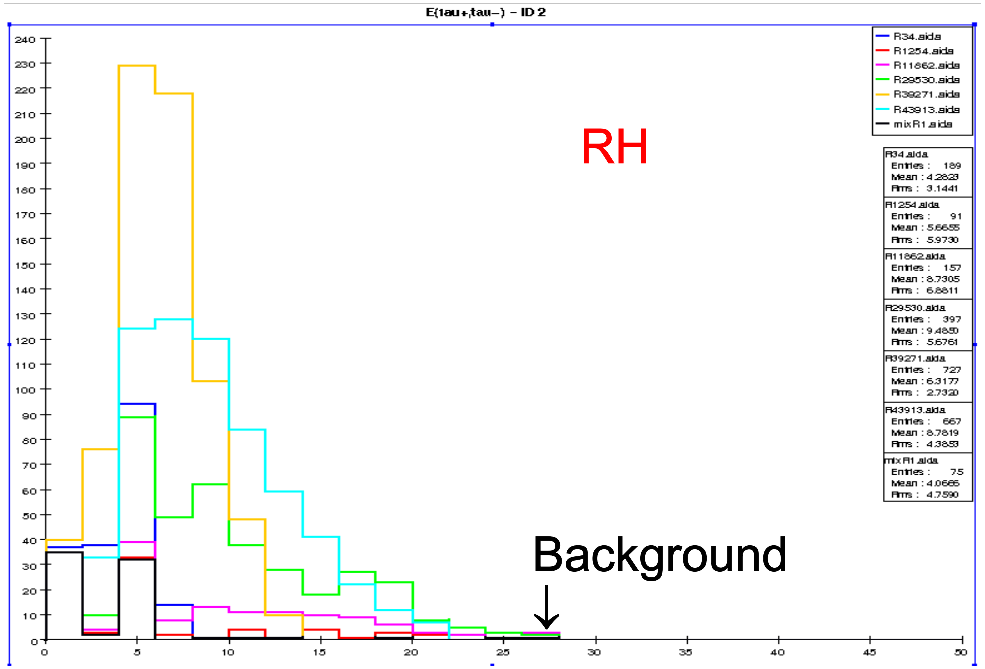


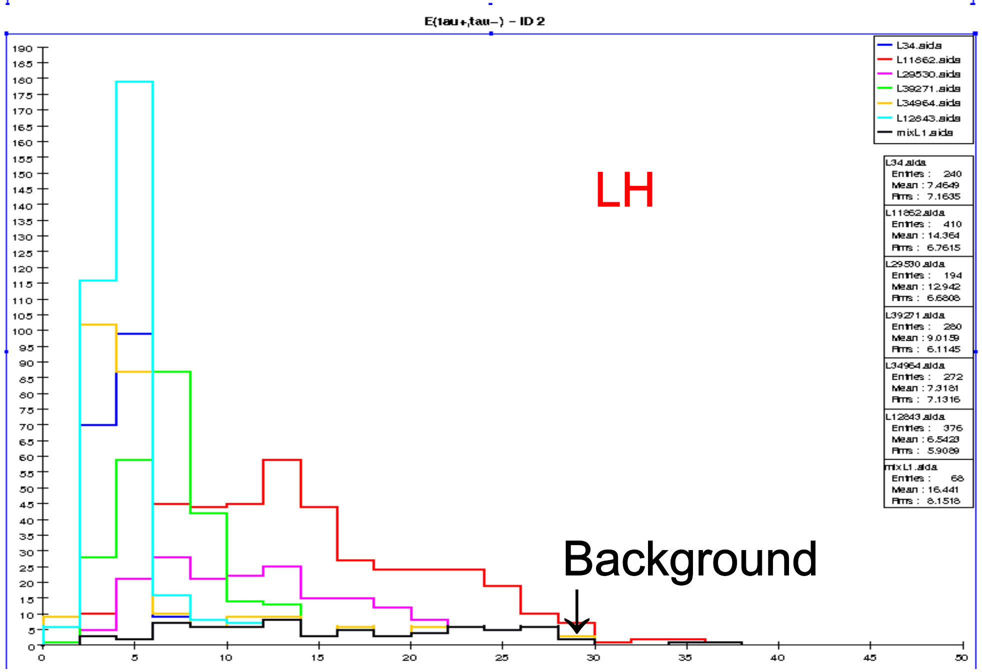




SPS1a' revisited with ID2

Using this new tau selection the SM backgrounds are now quite tiny & SPS1a' really stands out !

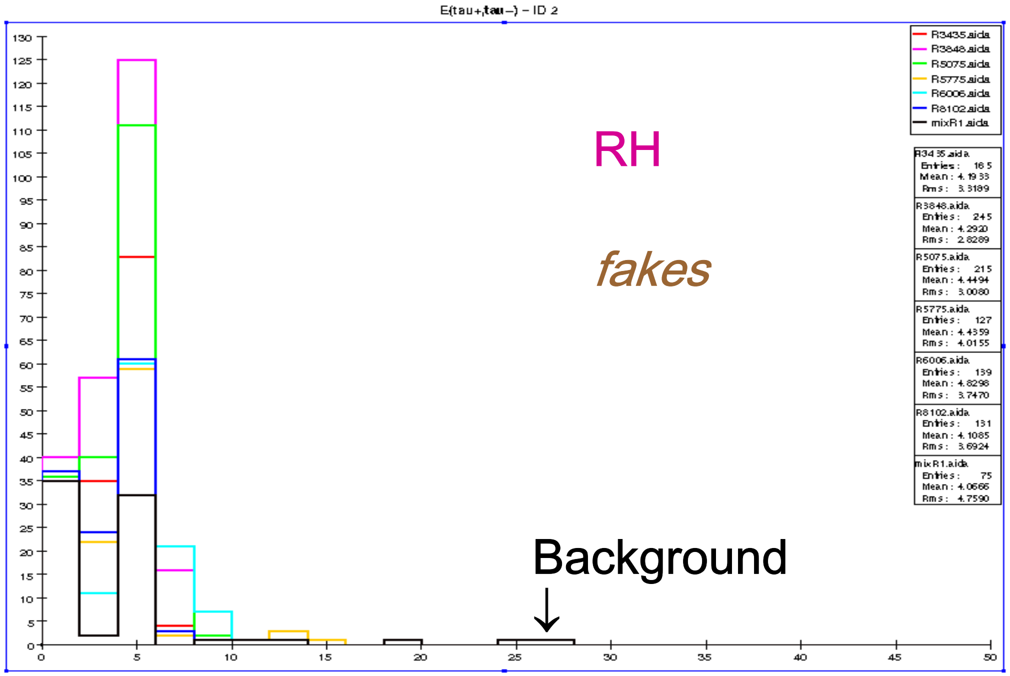


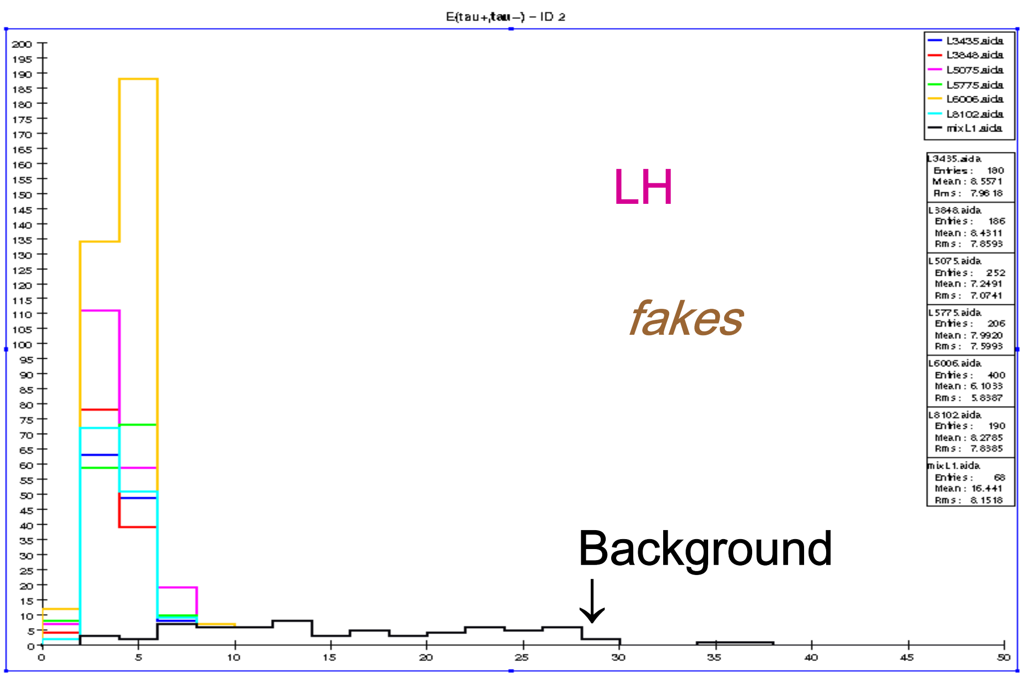


With the second ID criteria S/B is vastly improved for our model set as well

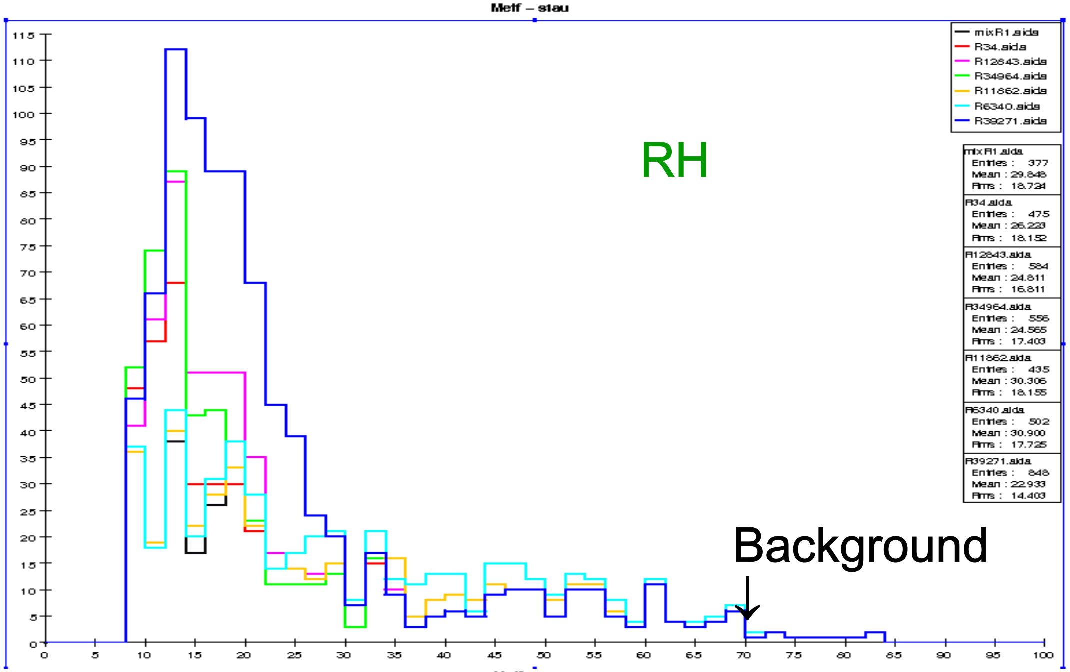
20/28 (14/28) are visible with LH(RH) polarization for a total of 21/28 when both samples are combined…which is a big improvement!

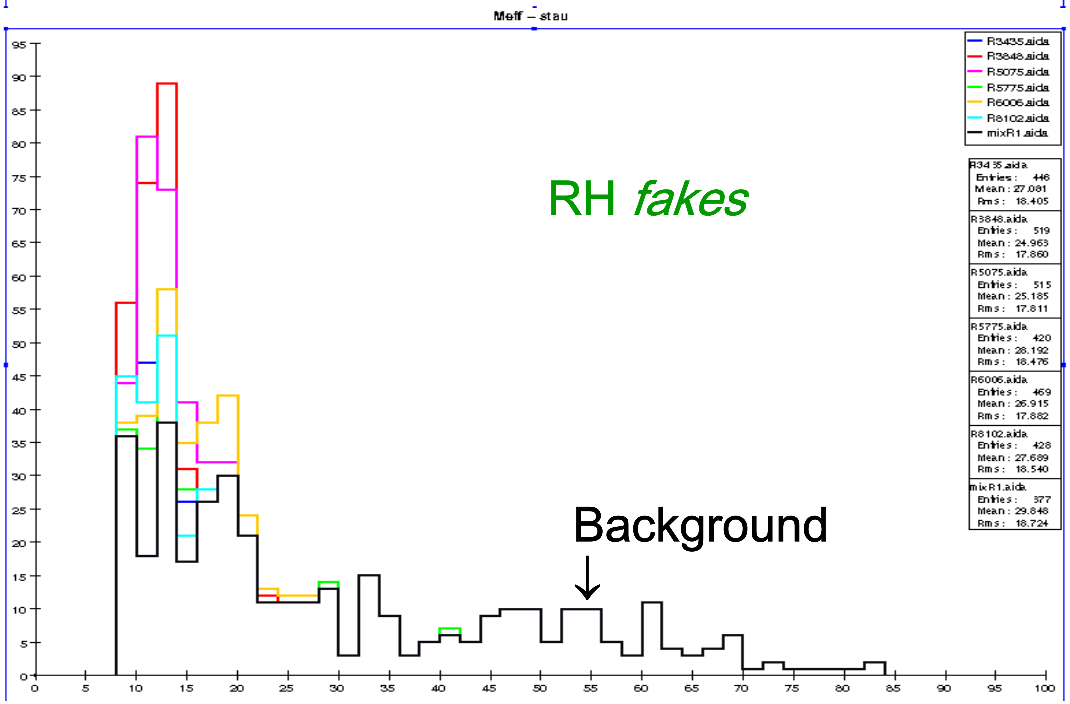
..however, there remains the issue of fakes…SPS1a' has no fakes in this channel





Going to ID2 does not help much with fakes *if* only this reconstructed tau energy observable is Used in the analysis… although the fake induced spectra are seen to be somewhat softer employing ID2



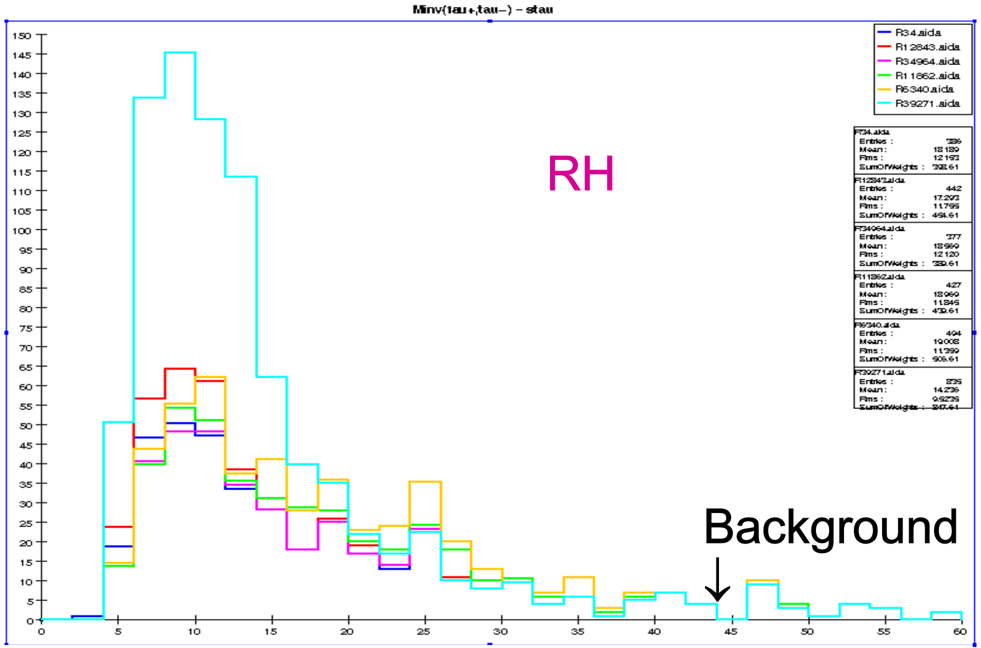


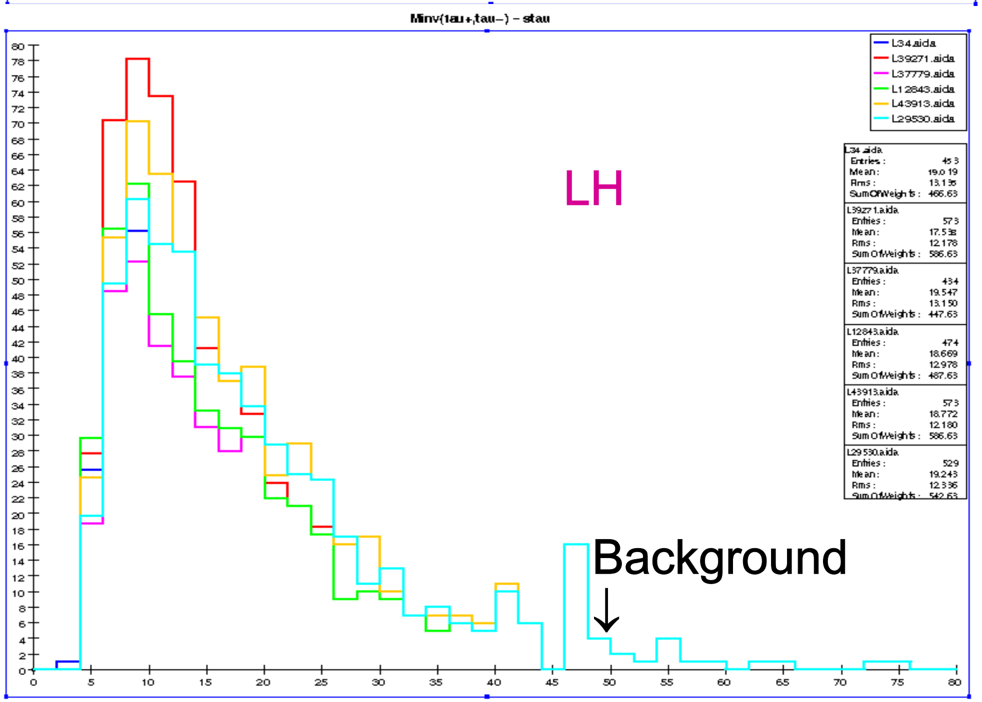
How about

$$M_{\rm eff} = E_T^{\rm miss} + \sum_{i=1,2} |E_T^{\tau_i}| \, .$$

The effective mass is also *not* a too useful an observable to remove fakes.

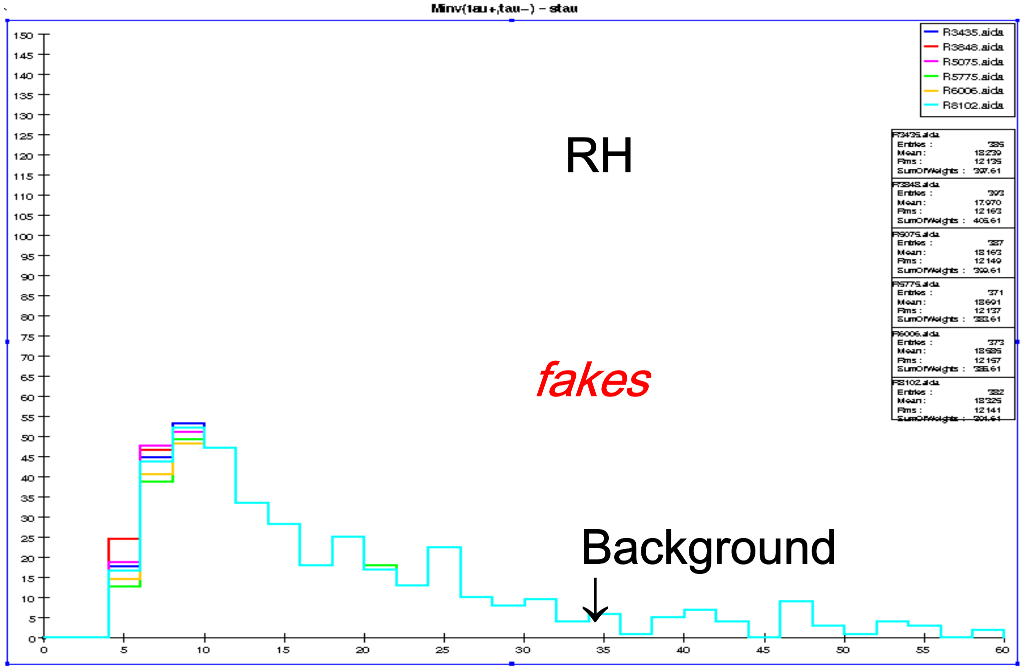
Too many similarities between the real and fake distributions if we have a wide spectrum of models

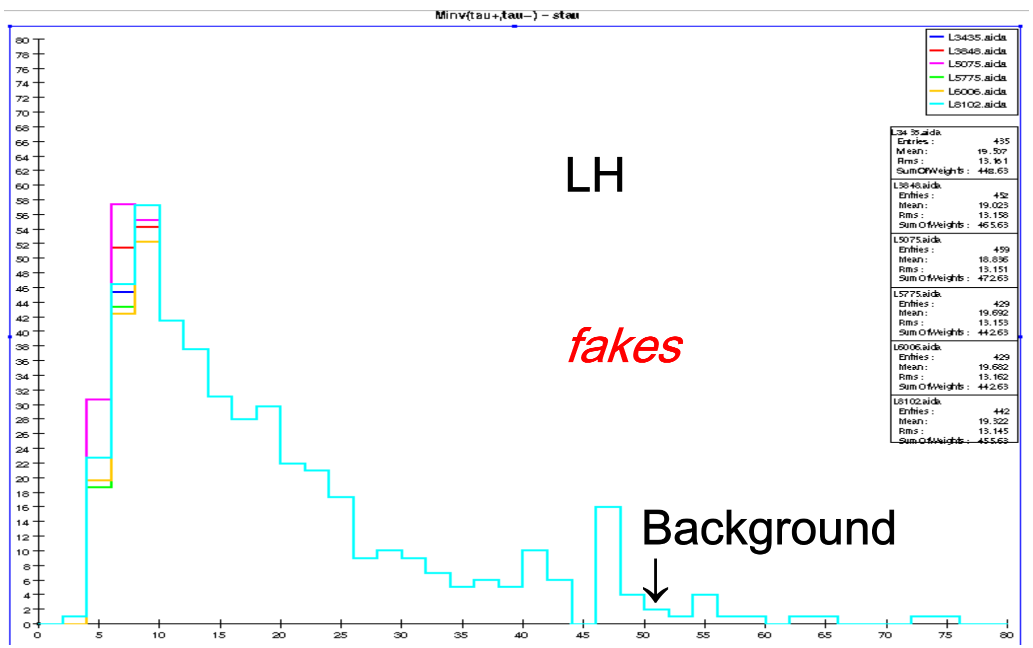




Another possibility…

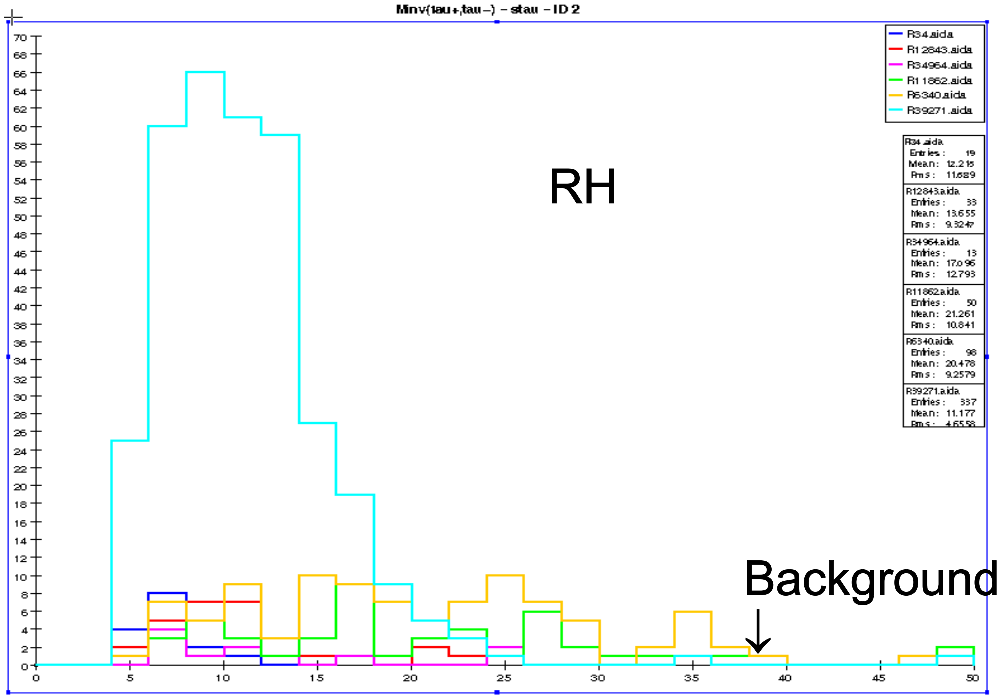
Here is the reconstructed invariant mass of all the visible particles from the tau decays using ID1

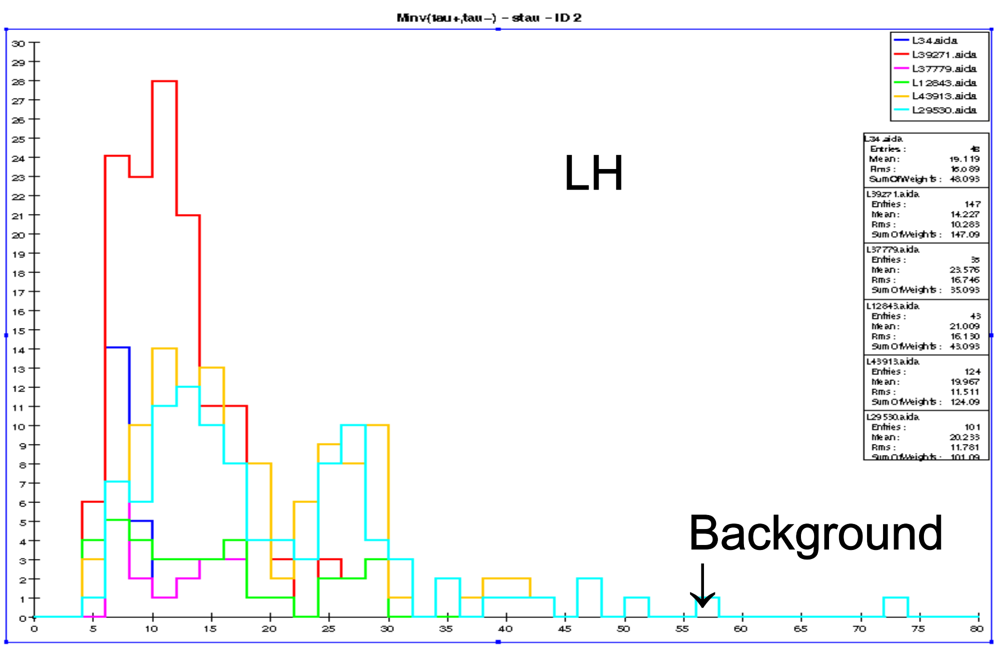




Here is the reconstructed invariant mass of all the visible particles using ID1 for *fakes*

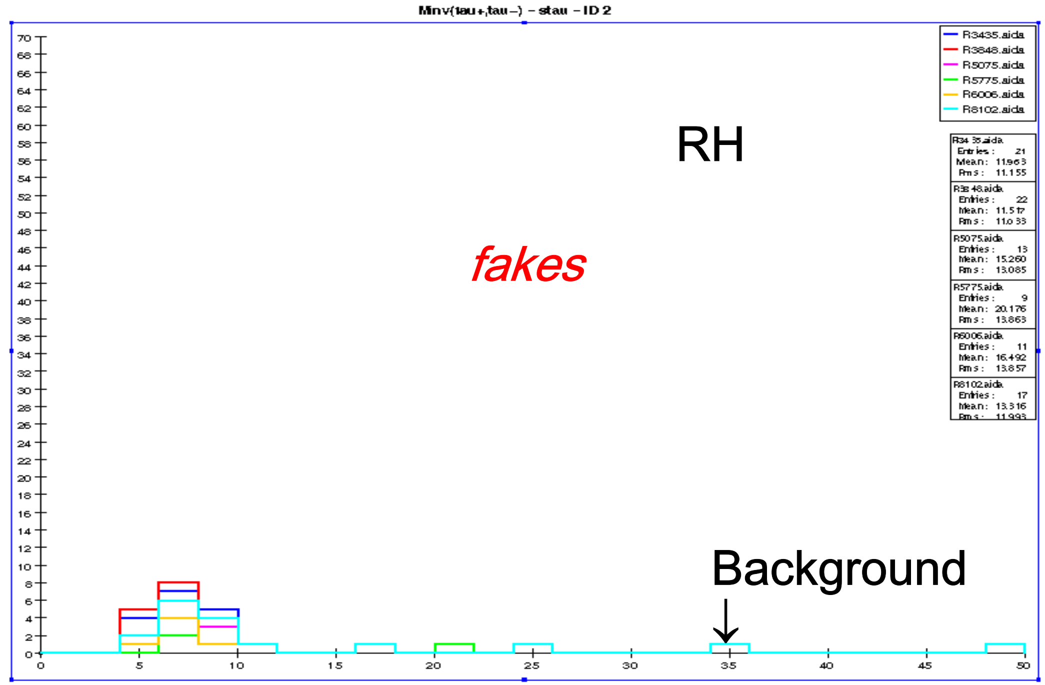
There is some separation power here but the backgrounds are too large using ID1…

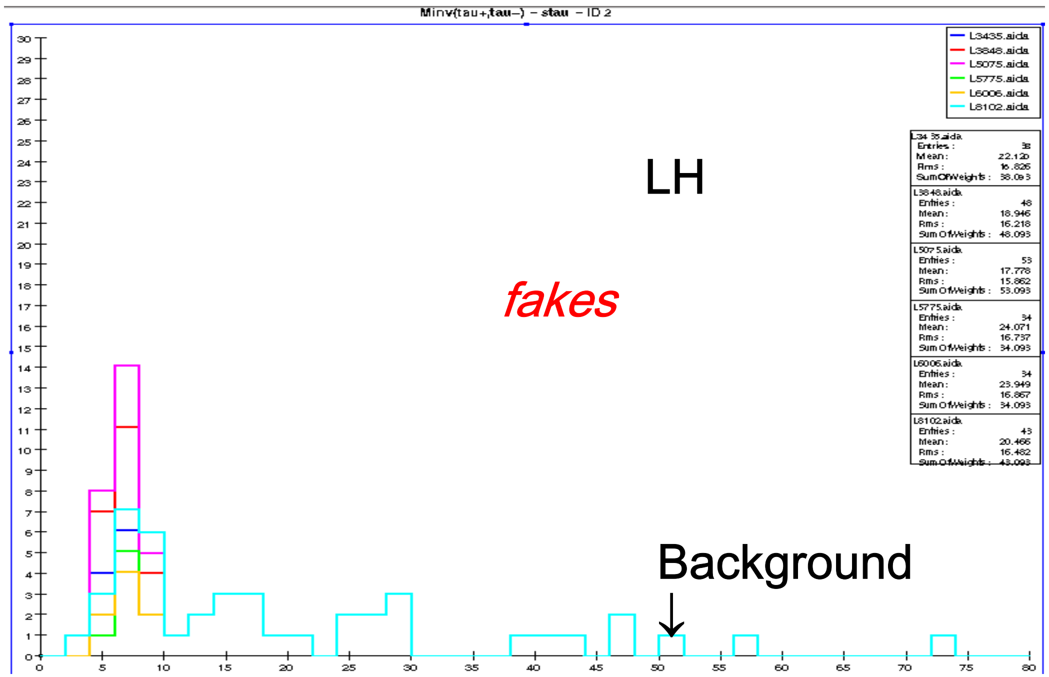




Going to ID2 with the invariant mass increases S/B substantially for real staus…

In the RH case the background is now almost absent





BUT going to ID2 with the invariant mass variable also removes fakes…

Thus ID2 not only helps with S/B for real staus but is extremely useful at removing fakes..

SUMMARY

For general MSSM models the visibility of staus is made somewhat problematic due to beam induced SM backgrounds arising from the lack of low angle tracking.

Furthermore it increases the possible confusion with other SUSY signals such as chargino production.

In our analysis we resolved both these issues but dropping tau decays to the electron final state which reduces the signal rate but substantially improves S/B.

However, having low angle tracking will allow for a substantial increase in statistics while maintaining signal cleanliness.

BACKUP SLIDES

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:

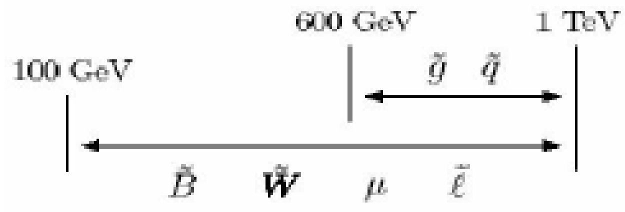
Inos : $M_1,\ M_2,\ M_3,\ \mu$

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

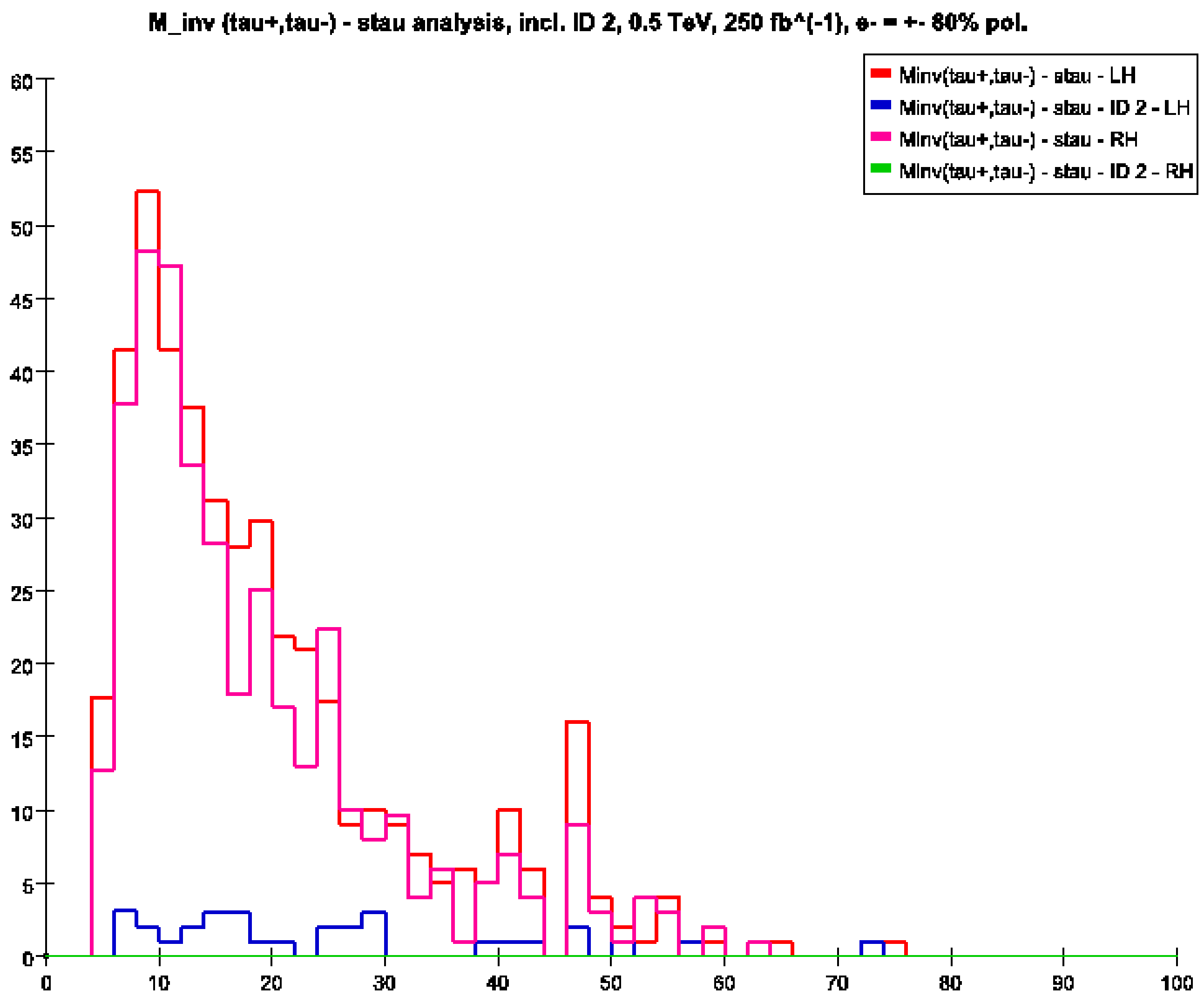
- There are certainly other ways one could have chosen to generate a set of models: parameter ranges, prior `tilts', etc... We are studying these alternatives now.

- These models satisfy the LEPII constraints as well as the Tevatron naïve squark and gluino bounds but not, e.g., WMAP, g-2, $b \to s\gamma$, 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 (??)


M_inv (tau+,tau-) - stau analysis, incl. ID 2, 0.5 TeV, 250 fb^(-1), e- = +- 80% pol.
Minv(tau+,tau-) - stau - LH
Minv(tau+,tau-) - stau - ID 2 - LH
Minv(tau+,tau-) - stau - RH
Minv(tau+,tau-) - stau - ID 2 - RH
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100