Measuring virtual slepton masses at the LHC

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Outline

- Introduction: SUSY at the LHC
- Neutralino decays and distribution endpoints
- Proof of technique study
- Recent work towards reality
- Future

Who cares about the slepton mass?

- Important to measure all parameters after SUSY discovery
- Slepton mass affects $\tilde{\chi}_1^0$ annihilation cross section.
  - Light slepton$\longrightarrow$ slepton mediated annihilation diagrams may be important to $\tilde{\chi}_1^0$ annihilation. (Need slepton mass to calculate relic abundance)
  - Heavy slepton$\longrightarrow$ slepton diagrams do not enhance $\tilde{\chi}_1^0$ annihilation
- With no experimental constraints on slepton mass, there may be a significant uncertainty on the relic abundance calculation.

SUSY phenomenology at the LHC

●If SUSY exists at the TeV scale, squarks and gluinos will be produced most abundantly at the LHC.

$\longrightarrow$Large cross section$\longrightarrow$Good statistics$\longrightarrow$Precision measurements

● Every SUSY initial state will "cascade" down to the lightest superpartner (LSP) via a chain of decays.

$\longrightarrow$Many particles and jets

● The LSP is stable and does not interact with the detector.

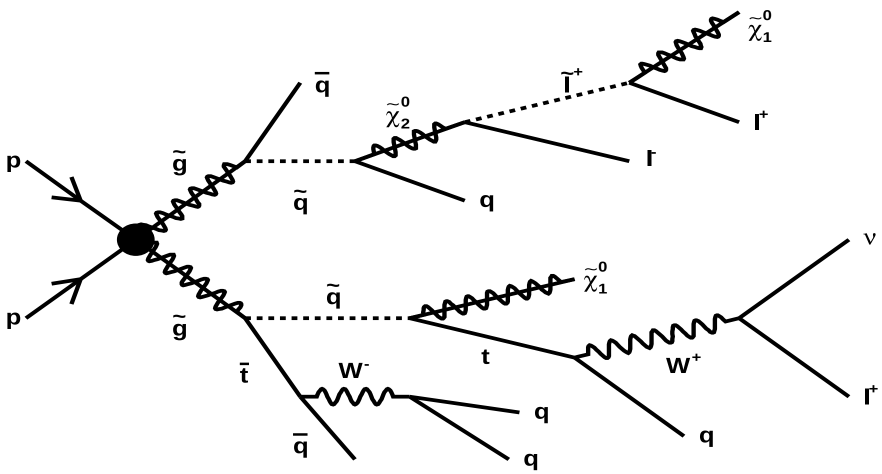
$\longrightarrow$Large missing P_T

Typical SUSY analysis steps

- Establish a deviation from the Standard Model.
- Is it SUSY?
- Identify characteristic observables occurring near the end of the SUSY cascade.
- Use advanced analysis techniques to extract SUSY masses from these observables.

Extracting SUSY masses is not easy

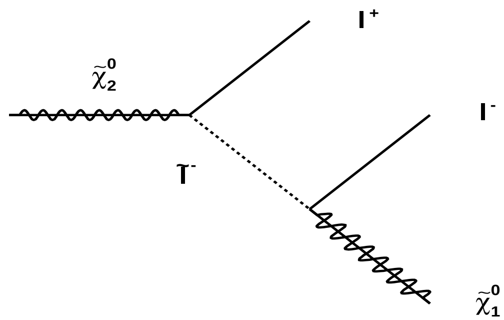
- In each SUSY event two LSP's escape detection. There are not enough kinematical constraints to construct the momenta of the LSP's.
- It is not clear from what point in the cascade the observable quantities originate.

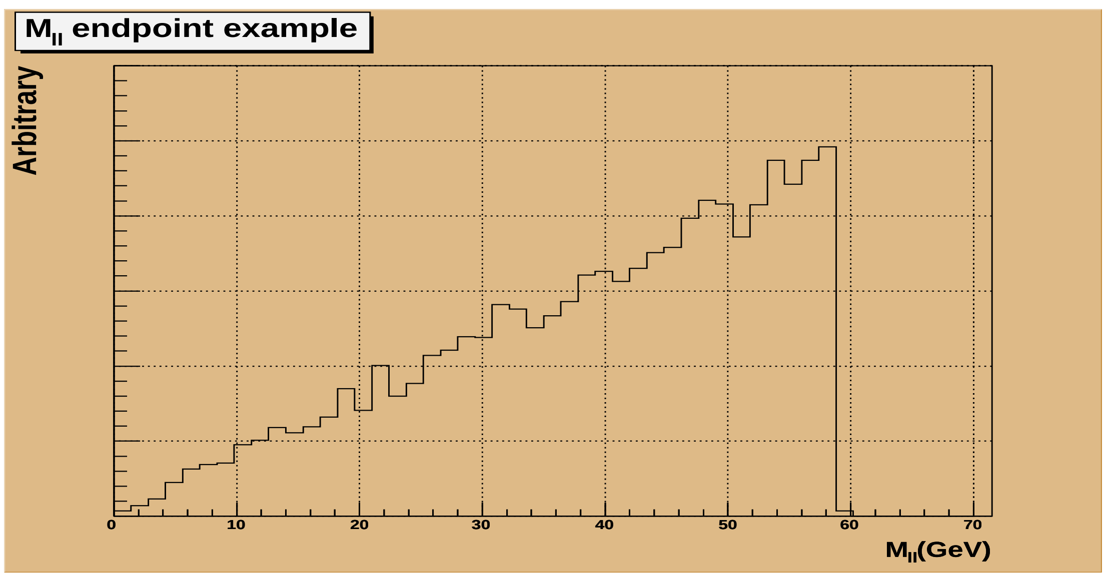


Distribution endpoints

One technique is to study the kinematic endpoints of invariant mass distributions of various combinations of lepton pairs and leptons with a jet...

$$M_{ll_{max}} = \frac{\sqrt{(M^2_{\tilde{\chi}_2} - M^2_{\tilde{l}})(M^2_{\tilde{l}} - M^2_{\tilde{\chi}_1})}}{M_{\tilde{l}}}$$





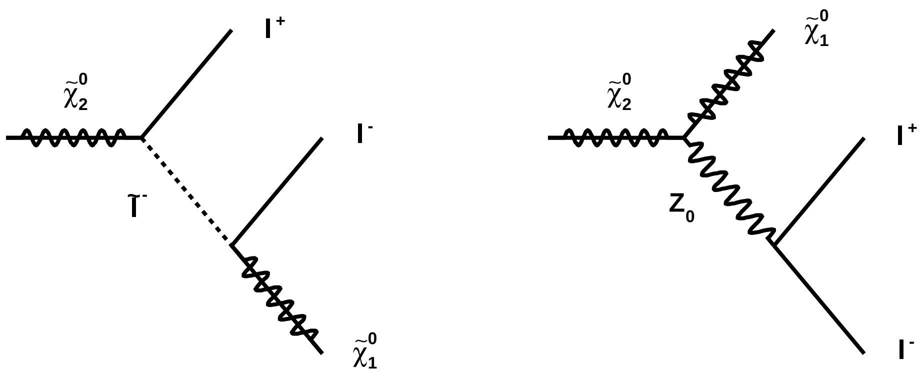
$\tilde{\chi}_2^0$ decay modes

The final state $\tilde{\chi}_1^0 l^+ l^-$ may be realized by two $\tilde{\chi}_2^0$ decays:

$$\tilde{\chi}_2^0 \to \tilde{l}^{\pm}_{R/L} l^{\pm} \to \tilde{\chi}_1^0 l^+ l^- \qquad (1)$$

$$\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 Z_0 \to \tilde{\chi}_1^0 l^+ l^- \qquad (2)$$

The relevant Feynman diagrams are shown below.



These decays may be real or virtual.

M_{ll} distribution endpoints

The $\tilde{\chi}_2^0$ decay through the slepton decay has the following well known endpoints...

- virtual decay:

$$M_{ll_{max}} = M_{\tilde{\chi}_2^0} - M_{\tilde{\chi}_1^0} \tag{3}$$

- real decay:

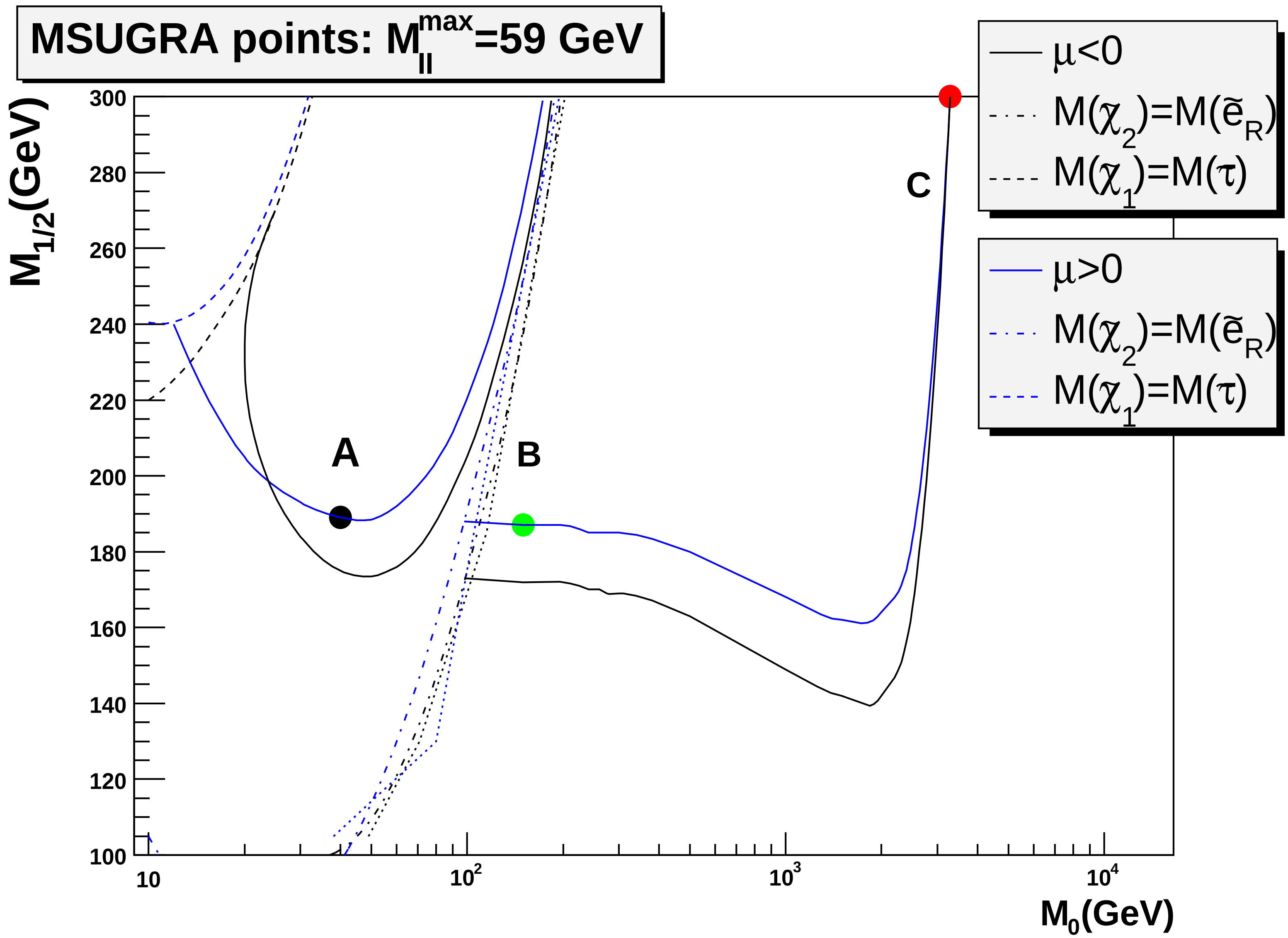
$$M_{ll_{max}} = \frac{\sqrt{(M^2_{\tilde{\chi}_2} - M^2_{\tilde{l}})(M^2_{\tilde{l}} - M^2_{\tilde{\chi}_1})}}{M_{\tilde{l}}} \tag{4}$$

Notice: On-shell decays with

$$M_{\tilde{l}} = \sqrt{M_{\tilde{\chi}_2^0} M_{\tilde{\chi}_1^0}} \tag{5}$$

have the same endpoint as off-shell slepton decays!

Confined mSUGRA parameter space ($A_0 = 0, tan(\beta) = 10$)



Origin of M_{ll} distributions shape differences

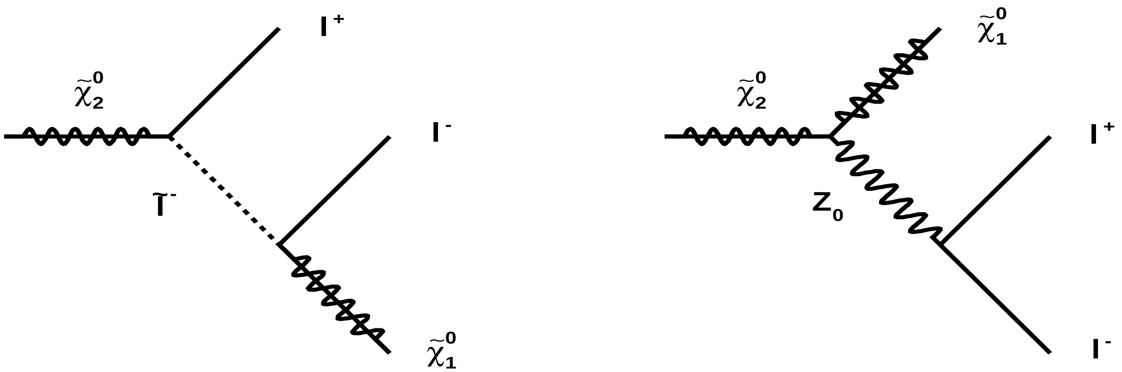
The new element in this analysis is to compare the shapes of the M_{ll} distributions at various points in parameter space to constrain experimentally allowed regions.

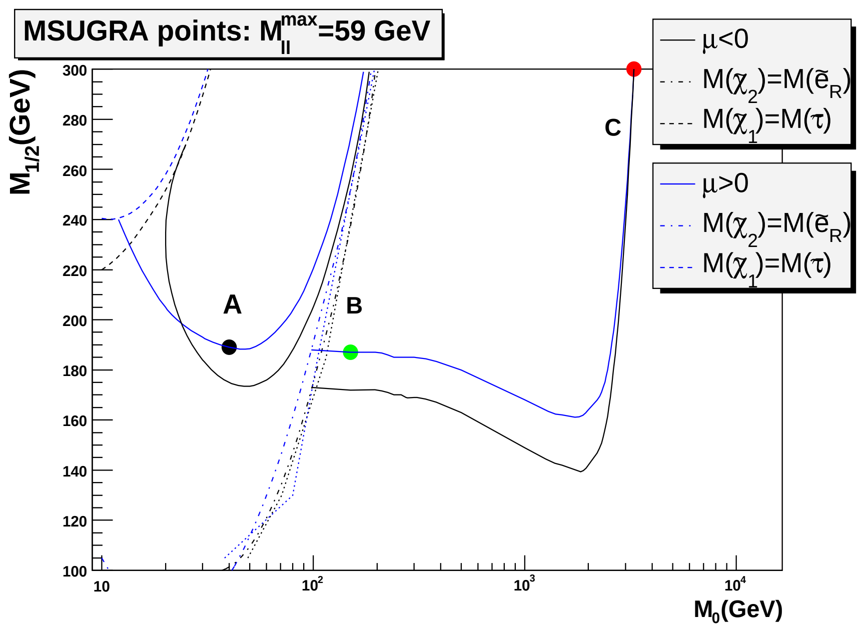
- virtual decay modes: 3 body decays

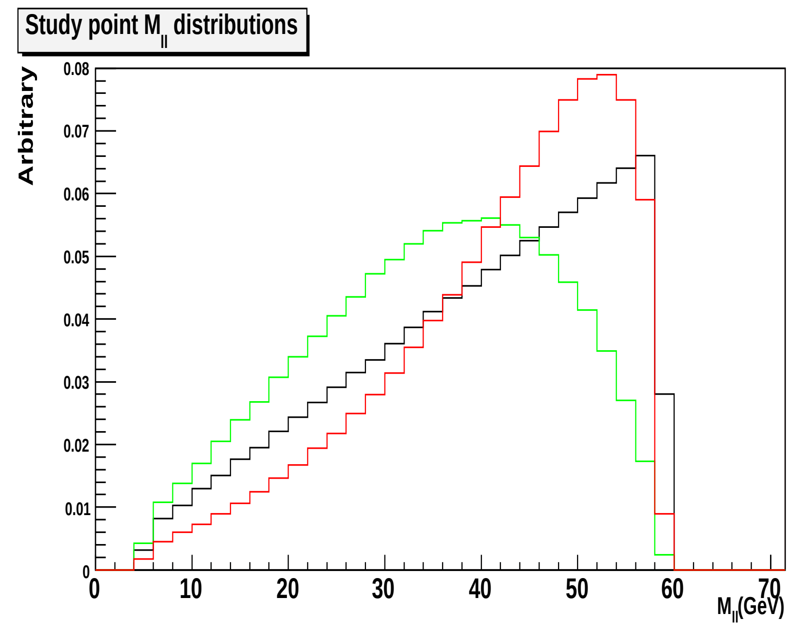
$\longrightarrow$High slepton mass

$\longrightarrow$Low slepton mass

- real decay modes: series of 2 2-body decays.







The three distributions above are clearly different to the naked eye. We need a tool to quantify these differences.

Kolmogorov-Smirnov Test

The K-S test may be used to quantify differences in shape in a systematic way.

$\longrightarrow$ The K-S test looks at the maximum difference between the cumulative distribution functions.

$\longrightarrow$ A null hypothesis is made that the two samples come from the same underlying distributions.

$\longrightarrow$ The K-S test then calculates the confidence level with which the null hypothesis can be falsified.

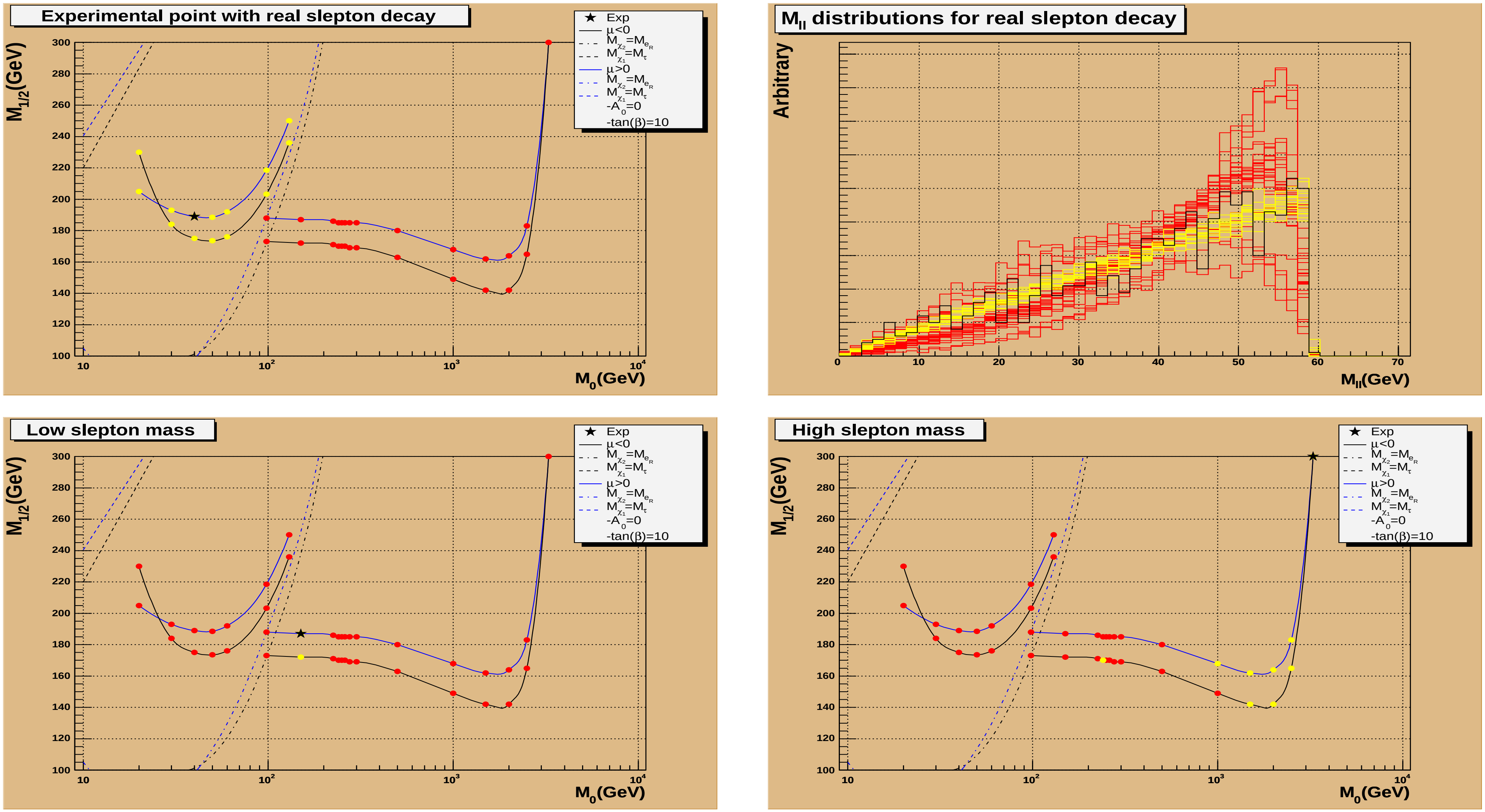
Theoretical Distributions

- Found set of points with same kinematic endpoint (M_{ll}^{max}).
- 10,000 events were then generated for each point with ISAJET.
- Distributions represent theoretical curves that are compared with hypothetical experimental results.

Caveats

- 1000 events for experimental point.
- 10,000 events for the theoretical distributions: Only limited by CPU.
- The following plots do not contain any background or cuts. SM background should not be a problem.
- We have only considered the slice of mSUGRA parameter space defined by $tan(\beta) = 10$ and $A_0 = 0$.

Results from proof of technique study



Conclusions from proof of technique study

- Point A: the slepton is directly discovered, and an upper limit may be put on its mass.
- Point B: the slepton is indirectly discovered and the slepton mass is tightly constrained.
- Point C: a lower limit may be put on the slepton mass.
- This shape analysis of neutralino decay distributions can be used to constrain the underlying SUSY parameters. We have illustrated this for the special case of mSUGRA.

The LHC environment is not ideal

- In the previous slides I showed that in a perfect world we could use the shapes of M_{ll} distributions to discover something about a virtual slepton's mass at the LHC.

- Will this effect survive the real world environment of the LHC?
  $\longrightarrow$ I ignored just a few physical effects in the "perfect world" analysis
  - Backgrounds
  - Cuts
  - Signal rates
  - Detector resolution
  - ID efficiencies
  - ...

Backgrounds

There are 2 main types of backgrounds in this study...

- Standard Model: $t\bar{t}$ is the dominant producer of 2 opposite sign leptons,jets, and missing energy in the Standard Model.
- SUSY: Uncorrelated lepton pairs from different SUSY particle decays

How do we suppress these backgrounds?

Base Cuts

Variable	Cuts
N_{jets}(P$_T$ >50GeV, $\|\eta\|$ <2)	4
N_{jets}(P$_T$ >100GeV, $\|\eta\|$ <2)	1
$\not{E}_T$	max(100GeV,.2M_{eff})
N_{leps}(P$_T$ >20GeV, $\|\eta\|$ <2.5)	2 (opposite sign)

- Jets: Stable hadronic particles are clustered using an iterative cone algorithm with $R_{cone} = .7$.
- $\not{E}_T$: Vector E_T sum of jets, leptons, and photons.
- $M_{\text{eff}} \equiv \not{E}_T + \sum_{i=1}^{4} P_{T_i}$

Cuts similar to those in I. Hinchliffe, *et al.* Phys. Rev D55 (1997) 5520.

SUSY backgrounds

- The cuts described above work well for most Standard Model backgrounds but are designed to minimally reduce the SUSY signal.
- The lepton pairs of the backgrounds are uncorrelated in the since that they do not come from the same decay.
- The uncorrelated background can be determined from the opposite sign opposite flavor rate($\mu^+ e^- + \mu^- e^+$).

$$\left.\frac{d\sigma}{dM}\right|_{\rm sub} = \left.\frac{d\sigma}{dM}\right|_{e^+e^-} + \left.\frac{d\sigma}{dM}\right|_{\mu^+\mu^-} - \left.\frac{d\sigma}{dM}\right|_{e^+\mu^-} - \left.\frac{d\sigma}{dM}\right|_{e^-\mu^+} \qquad (6)$$

The subtracted distribution above yields a sharp endpoint and eliminates the majority of the SUSY/SM background from uncorrelated leptons.

Detectors are not perfect!

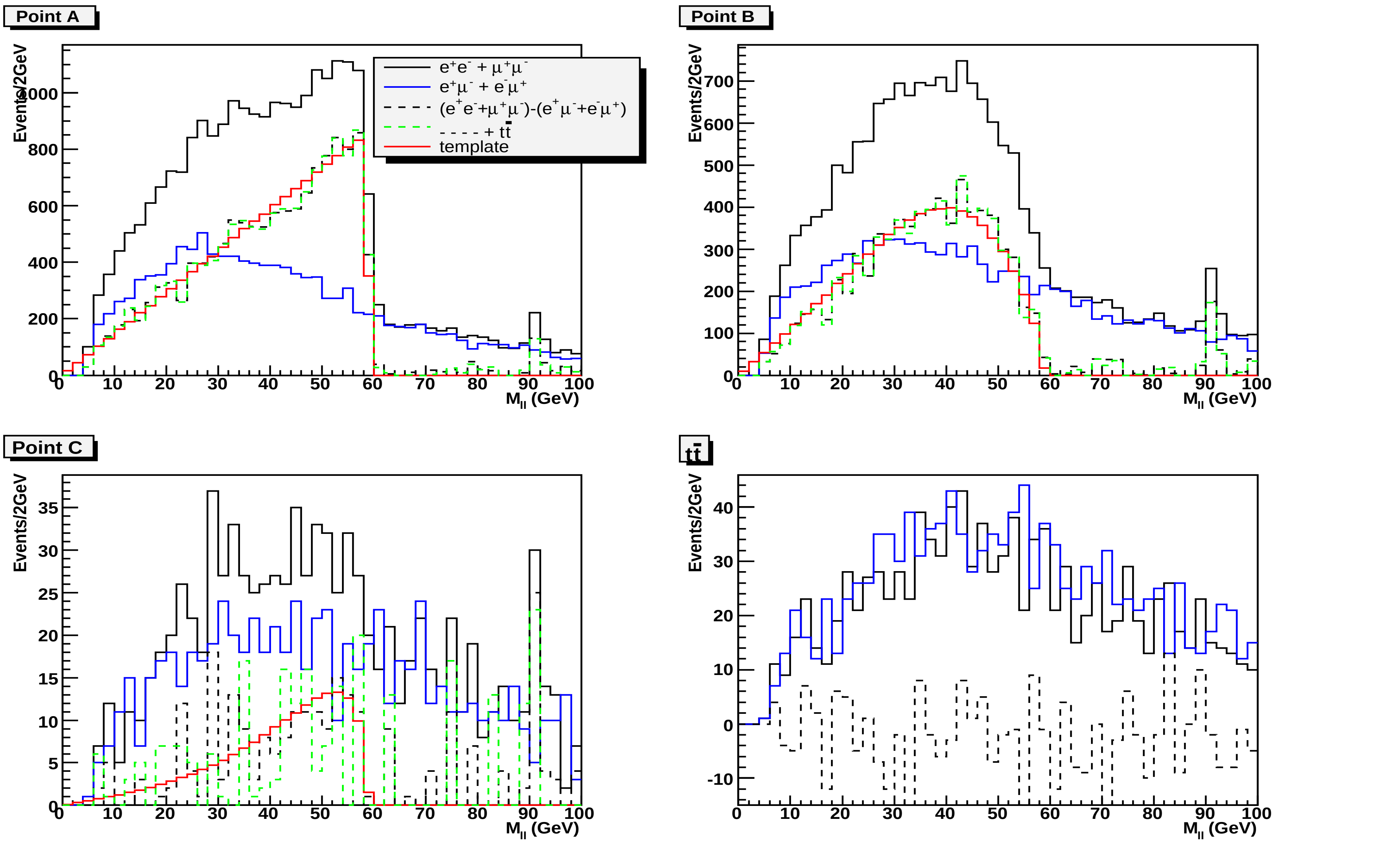
- Smearing effects similar to those expected for CMS included...
  - Jet smearing: $\frac{\Delta E}{E} = \frac{120\%}{\sqrt{E}} + 7\%$
  - e and γ smearing: $\frac{\Delta E}{E} = \frac{5\%}{\sqrt{E}} + 0.5\%$
  - μ ($\eta < 1$) smearing: $\frac{\Delta P}{P} = .01\% P + 1\%$
  - μ ($\eta > 1$) smearing: $\frac{\Delta P}{P} = .04\% P + 2\%$
- 90% lepton ID efficiencies are assumed

Approximate event rates

Table 1: All SUSY points have $\mu > 0$, $A_0 = 0$, $tan(\beta) = 10$.

Point	M_0	$M_{\frac{1}{2}}$	$M_{\tilde{\ell}}$	σ	N(10fb^{-1})
A	40GeV	189 GeV	92 GeV	170 pb	$1.7 * 10^6$
B	150GeV	187 GeV	96 GeV	150 pb	$1.5 * 10^6$
C	3280GeV	300 GeV	3277 GeV	4.4 pb	$44,000$
$t\bar{t}$ (SM background)	NA	NA	NA	425 pb	$4.25 * 10^6$

Preliminary Distributions with $10\,fb^{-1}$



Future work

- Make new template distributions
- Do study with 300 fb^{-1} of data
- Compare Kolmogorov test and χ^2 test results

When will this be useful?

Before this analysis can begin on real data...

- An excess of events over the standard model must be identified that is consistent with SUSY.
- The endpoint for the M_{ll} distribution must be measured.

Then...

- Theoretical M_{ll} distributions for points on the constrained parameter space must be generated with relevant backgrounds and full detector simulation for the SUSY model of interest.
- The K-S test can be used to further reduce the allowed parameter space and measure or place limits on the slepton mass.

Advantages of this study

- Precision measurements of M_{ll} distributions, and M_{ll}^{max} can be made at the LHC.
- One set of cuts will be used for all points in reduced parameter space.
- Only use jets to cut out SM background.
- This is not a counting experiment. Only shape is important, so all efficiencies need not be quantitatively understood.
- Information about the slepton mass can be extracted even when it is not produced directly.