SUSY at LHC

Frank E. Paige, Brookhaven National Laboratory

TeV-scale SUSY is attractive extension of Standard Model (SM):

- Natural explanation for $M_h \sim 100\,\mathrm{GeV}$ *(but not for* $\Lambda \sim 10^{-3}\,\mathrm{eV}$*)*;
- Consistency of EW data from LEP, SLC, Tevatron with GUTs;
- Natural candidate ($\tilde{\chi}_1^0$) for cold dark matter.

SUSY gives complex signatures: jets, $\not{E}_T$, e, μ, τ, and b-tagging.

Cold dark matter well established by WMAP, so will only consider models with R parity.

Main background for SUSY is other SUSY processes, so must assume complete model. Often use mSUGRA with parameters

$$m_0, \quad m_{1/2}, \quad A_0, \quad \tan\beta, \quad \mathrm{sgn}\,\mu = \pm 1.$$

But have also considered GMSB, AMSB, etc.

Search for SUSY Particles at LHC

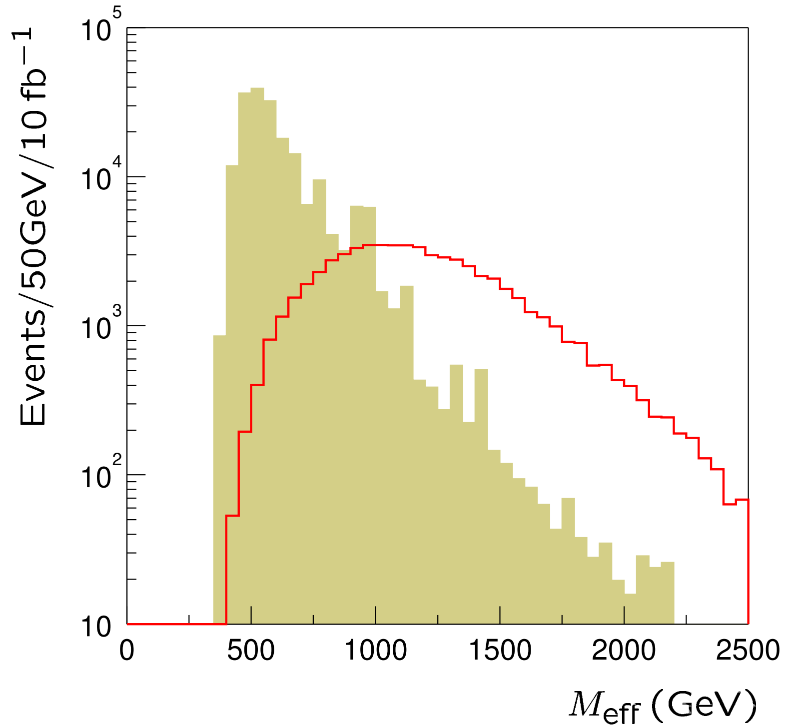
SUSY production at LHC dominated by $\tilde{g}$ and $\tilde{q}$ if masses $\lesssim 1\,\mathrm{TeV}$.

Strongly produced, so cross sections comparable to jets at similar Q^2. Decays to $\tilde{\chi}_1^0$ give large $\not{E}_T$.

Example: mSUGRA with $m_0 = 100\,\mathrm{GeV}$, $m_{1/2} = 300\,\mathrm{GeV}$, $A_0 = 0$, $\tan\beta = 10$, $\operatorname{sgn}\mu = +$.

Require $\not{E}_T > 100\,\mathrm{GeV}$, ≥ 4 jets with $E_T > 100, 50, 50, 50\,\mathrm{GeV}$, and plot

$$M_{\mathrm{eff}} = \not{E}_T + \sum_j E_{T,j}$$



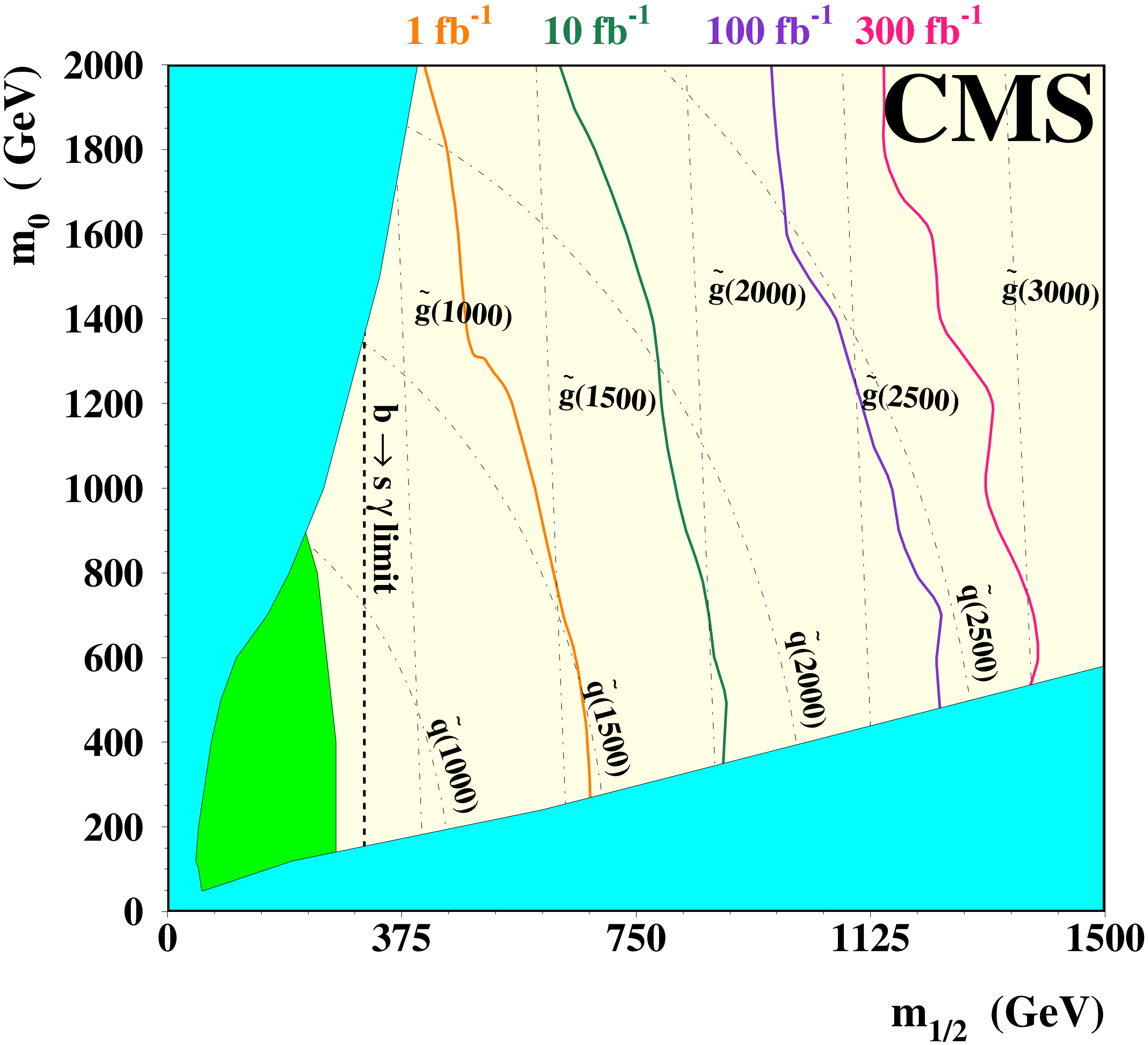
Clean SUSY signal for large M_{eff} with reasonable efficiency.

5σ discovery reach for gluinos and squarks [CMS98]:

$M > 1\,\mathrm{TeV}$ with $1\,\mathrm{fb}^{-1}$;

$M > 2\,\mathrm{TeV}$ with $10\,\mathrm{fb}^{-1}$;

$M > 2.5\text{–}3\,\mathrm{TeV}$ with $300\,\mathrm{fb}^{-1}$.



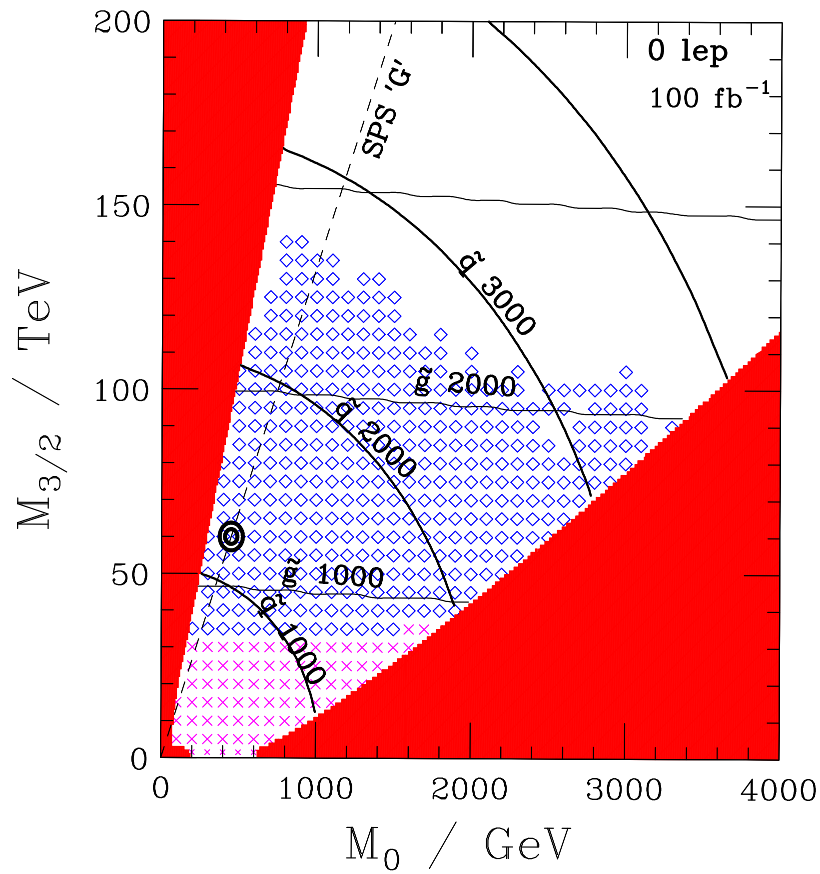
Could find SUSY quickly, but must first understand detectors.

Similar $M_{\tilde{g}}, M_{\tilde{q}}$ reach in AMSB model, $M > 2\,\mathrm{TeV}$ for $100\,\mathrm{fb}^{-1}$ with lepton veto [Barr03]:

MSSM particle masses in AMSB are produced from $\tilde{G}$ mass $m_{3/2}$ via anomalies. May dominate if other contributions vanish.

Pure AMSB model gives tachyons. Add scalar mass m_0 to fix problem.

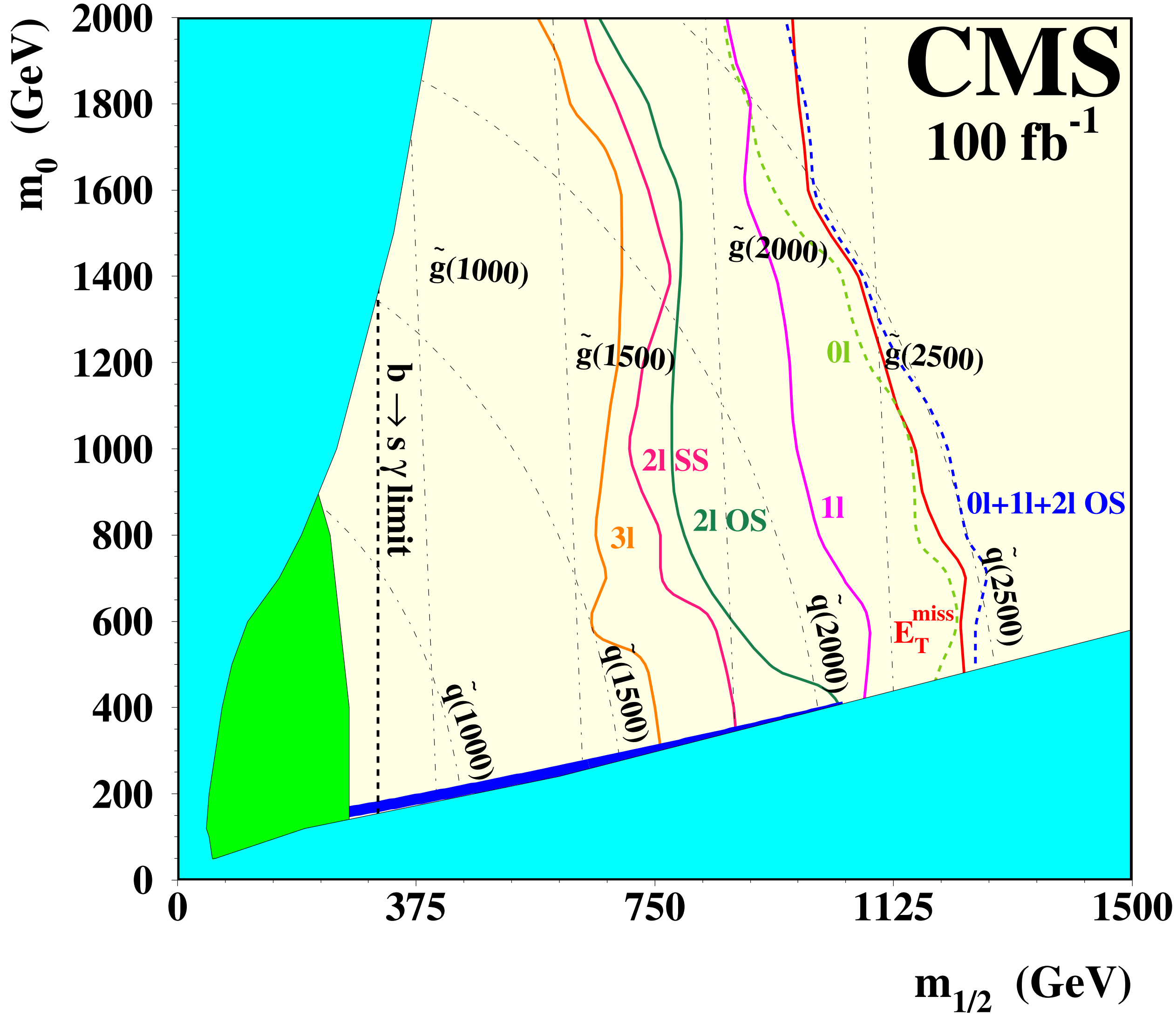
Gaugino spectrum is quite different than mSUGRA.



Reach depends mainly on $\sigma(M_{\tilde{g}}, M_{\tilde{q}})$ and $M_{\tilde{\chi}_1^0} \ll M_{\tilde{g}}, M_{\tilde{q}}$. Expect similar result in most R-conserving models.

If gluinos and squarks have $M \lesssim 1.5\text{–}2\,\mathrm{TeV}$, can observe multi-lepton signatures

[CMS98]



Even if SUSY is discovered quickly, will need complete detectors and full LHC luminosity to understand SUSY properties.

SUSY Measurements from Endpoints

After "Observation of anomalous multijet + $\not{E}_T$ events at LHC"....

R parity $\Rightarrow$ invisible LSP, so no mass peaks. But can measure kinematic endpoints $\Rightarrow$ mass combinations. Will discuss many examples.

Simplest case: $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \ell^+ \ell^-$ gives dilepton endpoint at

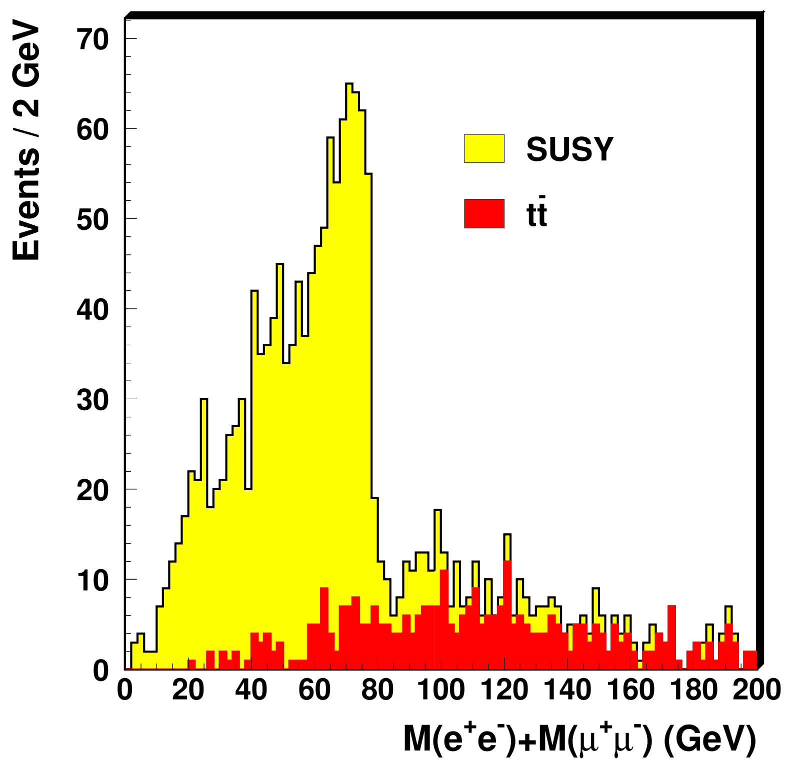
$$M_{\ell\ell}^{\max} = M_{\tilde{\chi}_2^0} - M_{\tilde{\chi}_1^0}$$

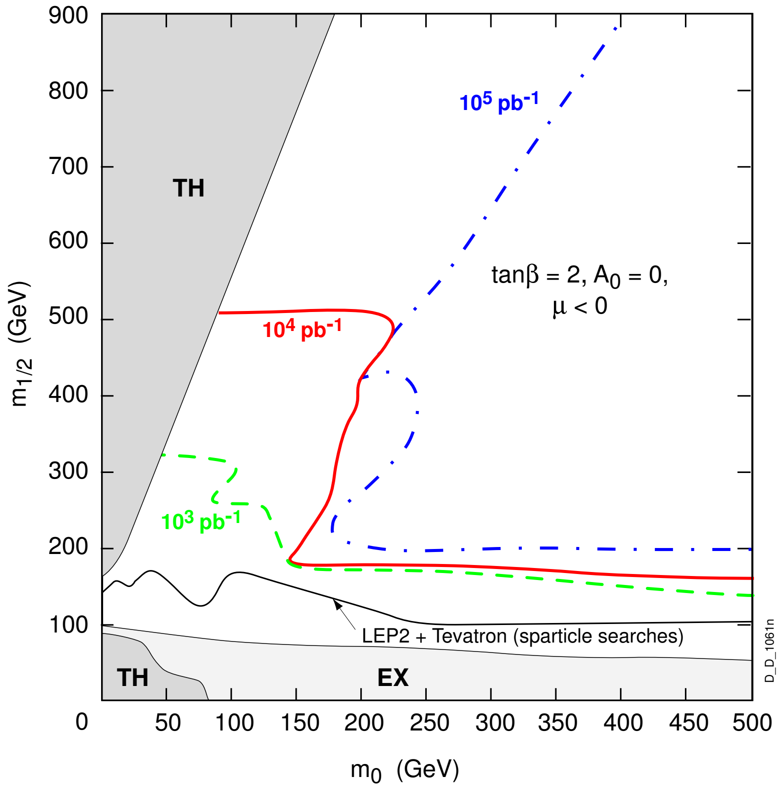
Cascade decay $\tilde{\chi}_2^0 \to \tilde{\ell}^\pm \ell^\mp \to \tilde{\chi}_1^0 \ell^+ \ell^-$ gives endpoint at

$$M_{\ell\ell}^{\max} = \frac{1}{M_{\tilde{\ell}}} \sqrt{(M_{\tilde{\chi}_2^0}^2 - M_{\tilde{\ell}}^2)(M_{\tilde{\ell}}^2 - M_{\tilde{\chi}_1^0}^2)}$$

Require 2 isolated leptons, multiple jets, and large $\not{E}_T \Rightarrow$ main SM background is $t\bar{t}$. Form combination $e^+e^- + \mu^+\mu^- - e^\pm\mu^\mp$ to cancel independent decays from SM or SUSY.

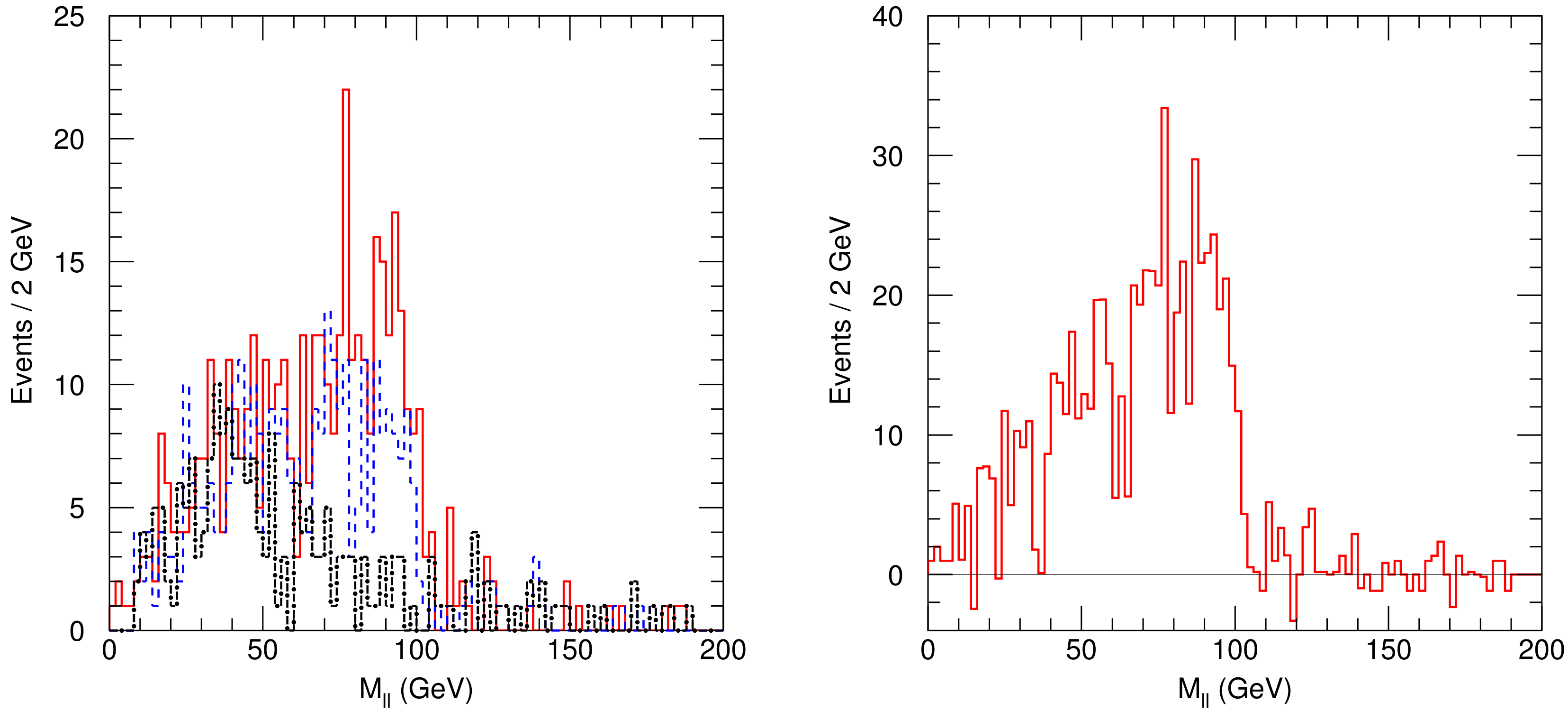
Example of OSSF $M_{\ell\ell}$ distribution for $\not{E}_T > 150\,\mathrm{GeV}$ and reach for edge measurement [Tricomi]:





Note that subtracting $e^{\pm}\mu^{\mp}$ events would cancel $t\bar{t}$ background.

$\mu^+\mu^-$, e^+e^-, $e^\pm\mu^\mp$, and weighted $e^+e^- + \mu^+\mu^- - e^\pm\mu^\mp$ masses from ATLAS full simulation and reconstruction ($5\,\mathrm{fb}^{-1}$) [fullsusy]:



Better acceptance for muons than electrons. EM scale set for γ — is $\sim 1.5\%$ low for e.

Long decay chains allow more measurements. Use mSUGRA point SPS1a for illustration:

$$m_0 = 100\,\mathrm{GeV},\ m_{1/2} = 250\,\mathrm{GeV},\ A_0 = -100\,\mathrm{GeV},\ \tan\beta = 10,\ \mu > 0$$

Dominant source of $\tilde{\chi}_2^0$ is [TDR]

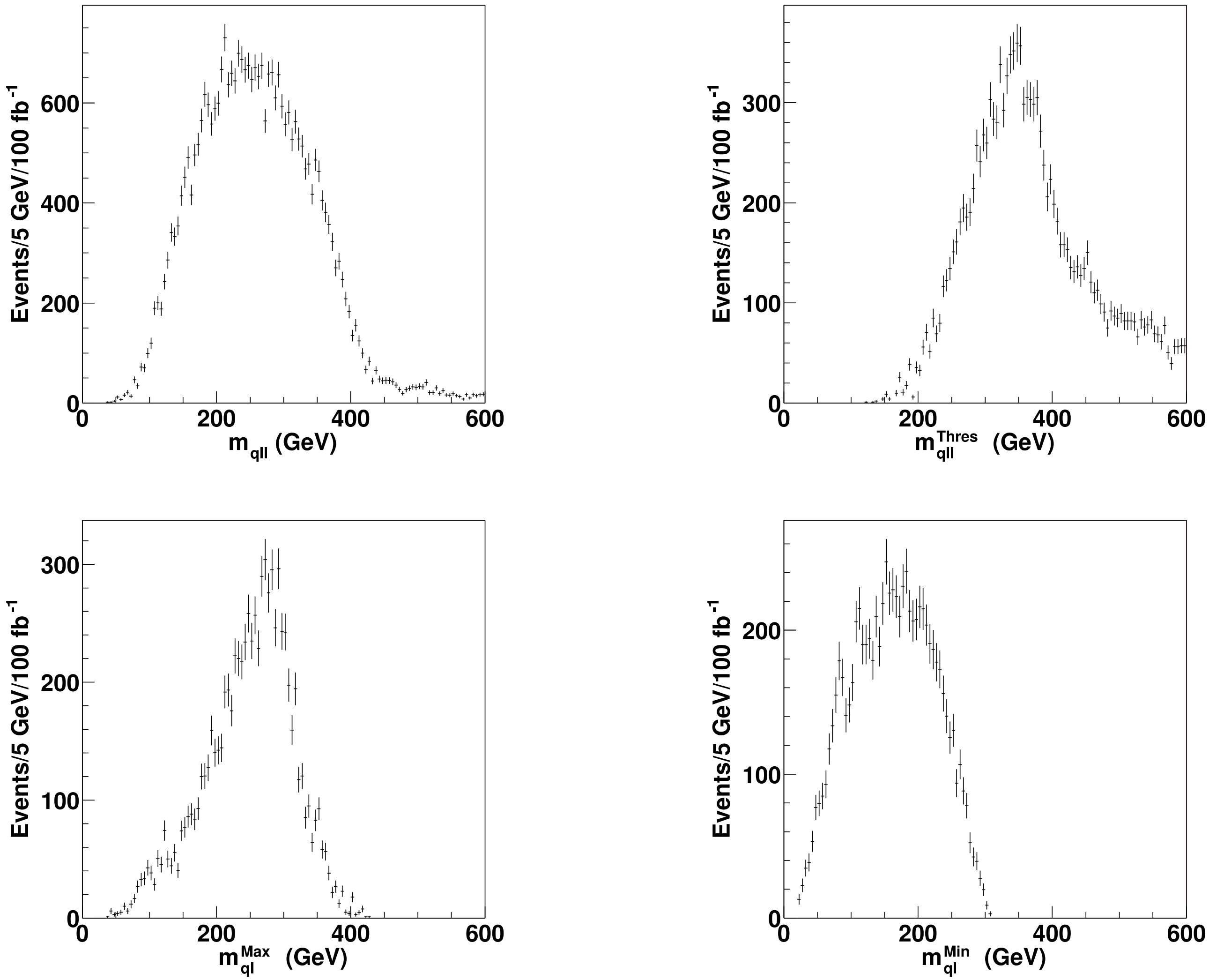
$$\tilde{q}_L \to \tilde{\chi}_2^0 q \to \tilde{\ell}_R^{\pm} \ell^{\mp} q \to \tilde{\chi}_1^0 \ell^+ \ell^- q$$

Assume 2 hardest jets are from squarks; combine each of these with leptons to form beside dilepton endpoint:

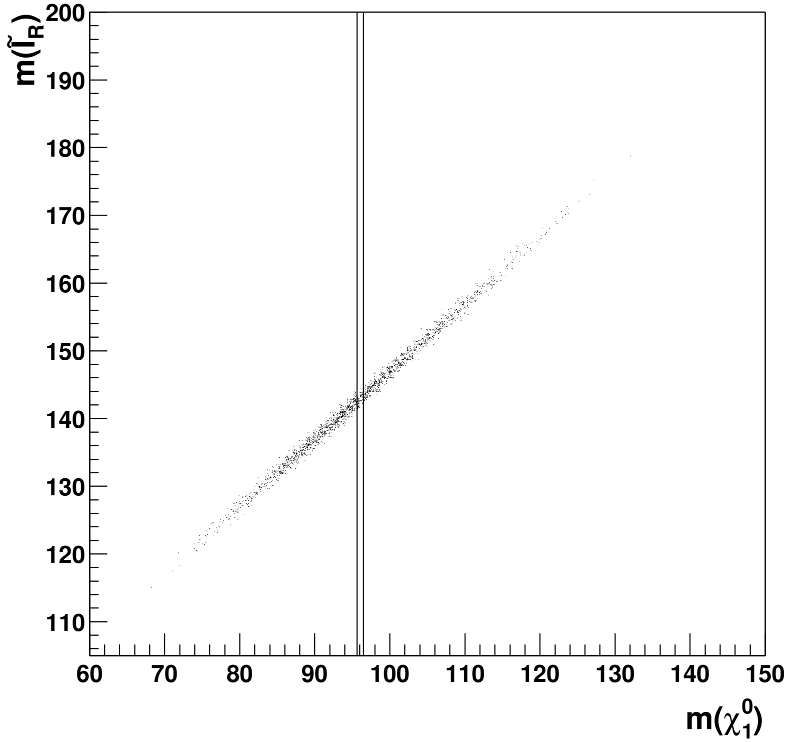
- $\ell\ell q$ endpoint using the smaller $M_{\ell\ell q}$;
- Both ℓq endpoints, $M_{\ell q}^{(>)}$, $M_{\ell q}^{(<)}$;
- Threshold $T_{\ell\ell q}$ requiring $M_{\ell\ell} > c M_{\ell\ell}^{\max}$ ($c = 1/\sqrt{2}$).

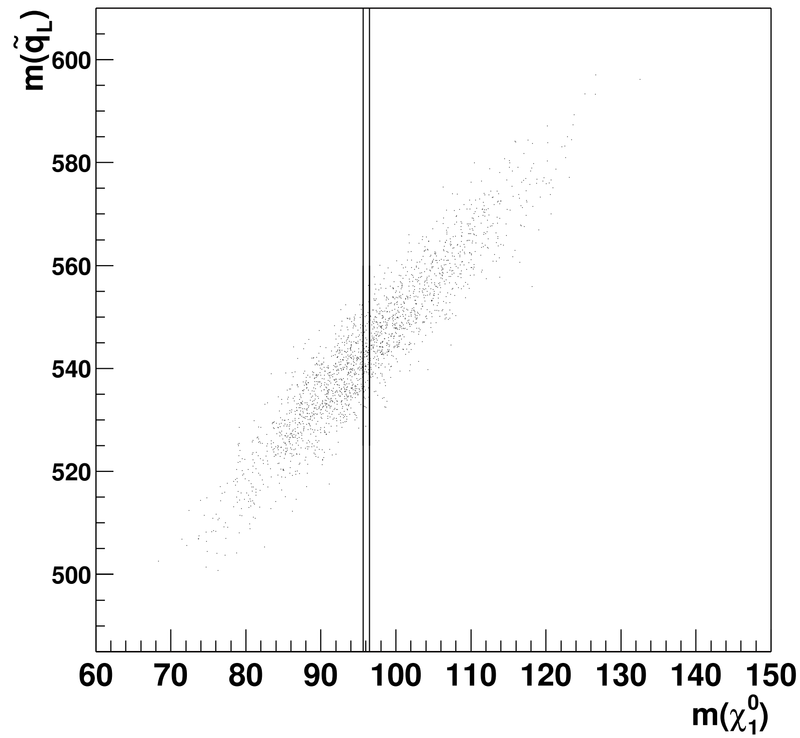
Enough constraints to determine all masses involved(!). Can measure mass relations to $\sim 1\%$ as functions of LSP mass, determined to $\sim 10\%$.

Plots of $M_{\ell\ell q}$, $T_{\ell\ell q}$, $M_{\ell q}^{\max}$, and $M_{\ell q}^{\min}$ for Point SPS1a [LesHouches]:



Can fit for $\tilde{q}_L$, $\tilde{\chi}_2^0$, $\tilde{\ell}_R$, and $\tilde{\chi}_1^0$ masses from measurements:





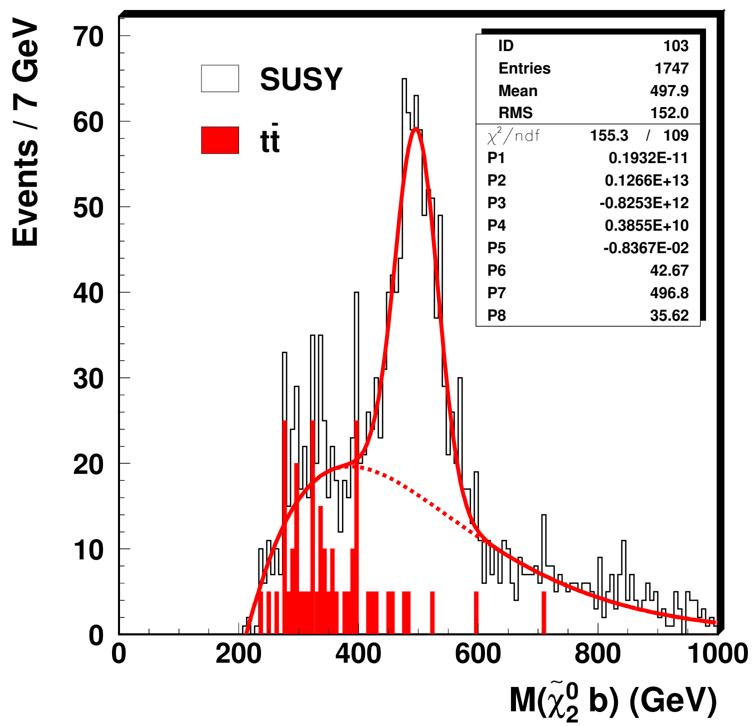
Since $M_{\tilde{\chi}_1^0} \ll M_{\tilde{q}}$, only determine $\tilde{\chi}_1^0$ mass to $\sim 10\%$. Knowing it from linear collider would help a lot.

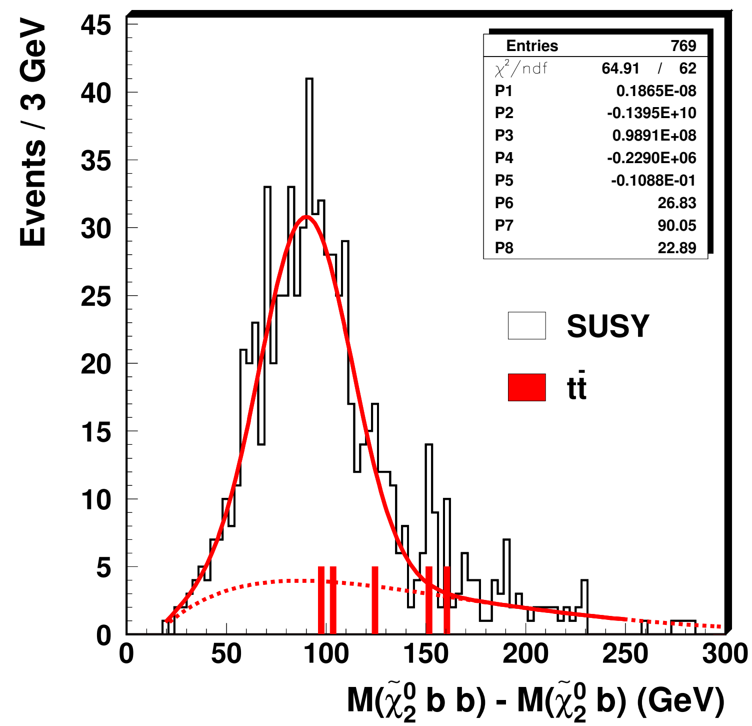
Gluino Reconstruction

$M^2_{\tilde{\ell}_R} \approx M_{\tilde{\chi}^0_1} M_{\tilde{\chi}^0_2}$ for SPS1a, so $\tilde{\chi}^0_1$ is nearly at rest in $\tilde{\chi}^0_2$ frame [Tricomi]:

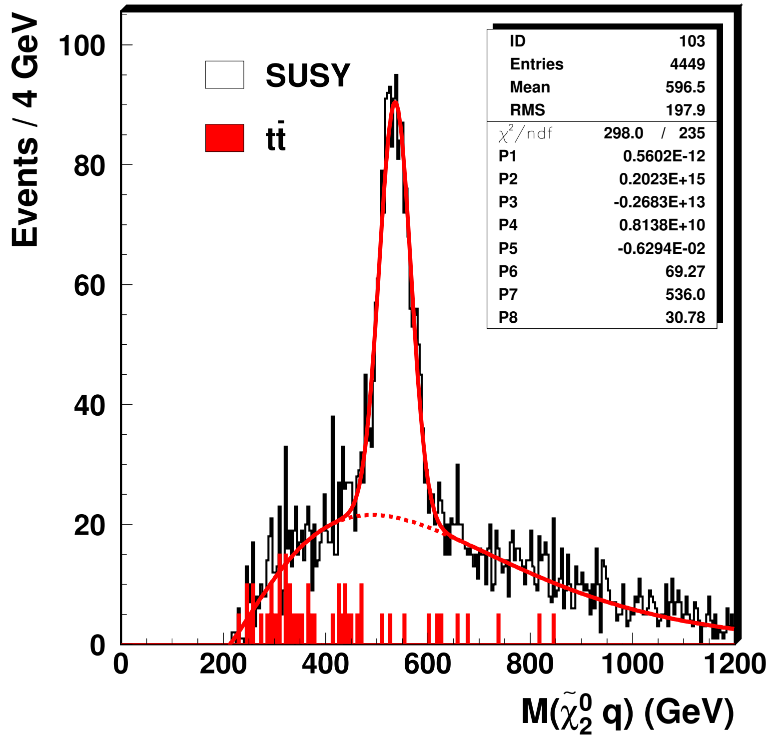
$$\vec{p}_{\tilde{\chi}^0_2} \approx \left(1 + M_{\tilde{\chi}^0_1}/M_{\ell\ell}\right) \vec{p}_{\ell\ell}\,.$$

Then reconstruct $M_{\tilde{b}}$ and $M_{\tilde{g}} - M_{\tilde{b}}$ from $\tilde{g} \to \tilde{b}_i b$, $\tilde{b}_i \to \tilde{\chi}^0_2 b$ decay chain:





Similar analysis works for $\tilde{g} \to \tilde{q}\bar{q}$ despite more background:



Method depends on $\tilde{\chi}_1^0$ being at rest in $\tilde{\chi}_2^0$ frame close to $\ell\ell$ endpoint. Hence requires either direct $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0\ell\ell$ or $\tilde{\chi}_2^0 \to \tilde{\ell}\ell \to \tilde{\chi}_1^0\ell\ell$ with $\tilde{\ell}$ mass close to geometric mean of $M_{\tilde{\chi}+2^0}$ and $M_{\tilde{\chi}_1^0}$.

Heavy Gaugino $\ell^+\ell^-$ Signature

Light gauginos typically dominate cascade decays:

$$B(\tilde{q}_L \to \tilde{\chi}_2^0 q) \sim 1/3, \quad B(\tilde{q}_L \to \tilde{\chi}_1^\pm q') \sim 2/3, \quad B(\tilde{q}_R \to \tilde{\chi}_1^0 q) \sim 1.$$

While heavy gauginos mainly Higgsino, mSUGRA gives some $\tilde{\chi}_4^0$ and $\tilde{\chi}_2^\pm$ decays. New analysis looks for dileptons beyond $\tilde{\chi}_2^0$ edge [LesHouches]:

Four $\tilde{\chi}_4^0/\tilde{\chi}_2^\pm$ decay chains give OS, SF dileptons:

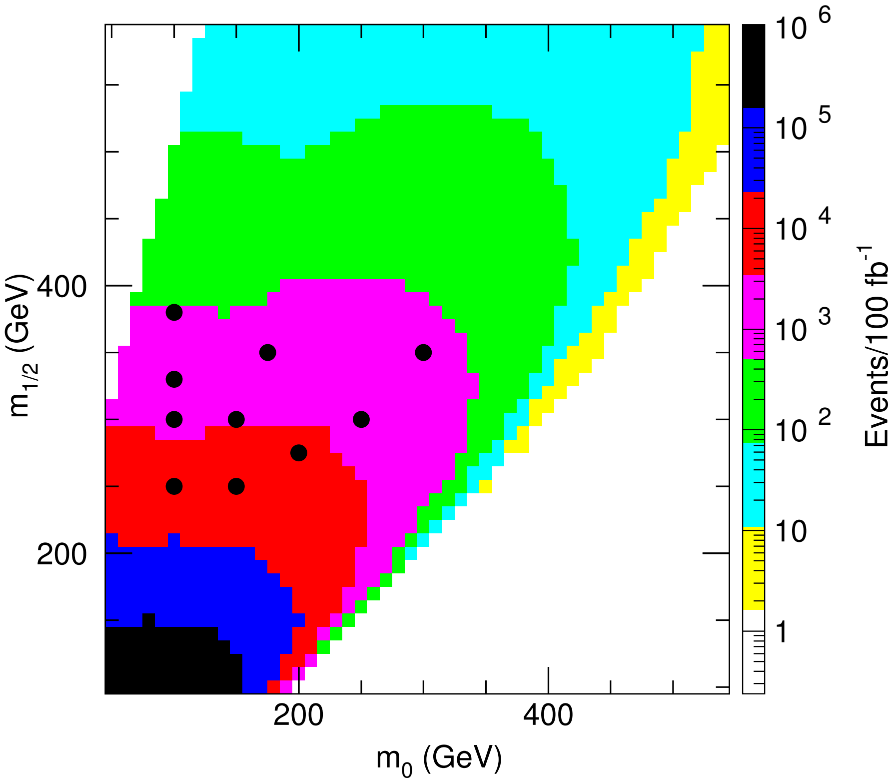
$$\begin{array}{l} \tilde{q}_L \to \tilde{\chi}_4^0\, q \\ \quad \hookrightarrow \tilde{\ell}_R^\pm \ell^\mp \\ \qquad \hookrightarrow \tilde{\chi}_1^0 \ell^\pm \; [D1] \end{array} \qquad \begin{array}{l} \tilde{q}_L \to \tilde{\chi}_4^0\, q \\ \quad \hookrightarrow \tilde{\ell}_L^\pm \ell^\mp \\ \qquad \hookrightarrow \tilde{\chi}_1^0 \ell^\pm \; [D2] \\ \qquad \hookrightarrow \tilde{\chi}_2^0 \ell^\pm \; [D3] \end{array} \qquad \begin{array}{l} \tilde{q}_L \to \tilde{\chi}_2^\pm\, q' \\ \quad \hookrightarrow \tilde{\nu}_\ell \ell^\pm \\ \qquad \hookrightarrow \tilde{\chi}_1^\pm \ell^\mp \; [D4] \end{array}$$

Again can use $e^+e^- + \mu^+\mu^- - e^\pm\mu^\mp$ to cancel backgrounds.

Have $> 10^3$ $\ell^+\ell^-$ events from heavy gauginos over substantial range of mSUGRA parameters.

Analyze specific points: $\tilde{\chi}_4^0$ dominates for low m_0, while $\tilde{\chi}_2^\pm$ dominates for diagonal line.

Require $\ell^+\ell^-$, $M_{\ell\ell} > 100\,\mathrm{GeV}$, $\not{E}_T > 100\,\mathrm{GeV}$, ≥ 4 jets, and $M_{\mathrm{eff}} > 600\,\mathrm{GeV}$.

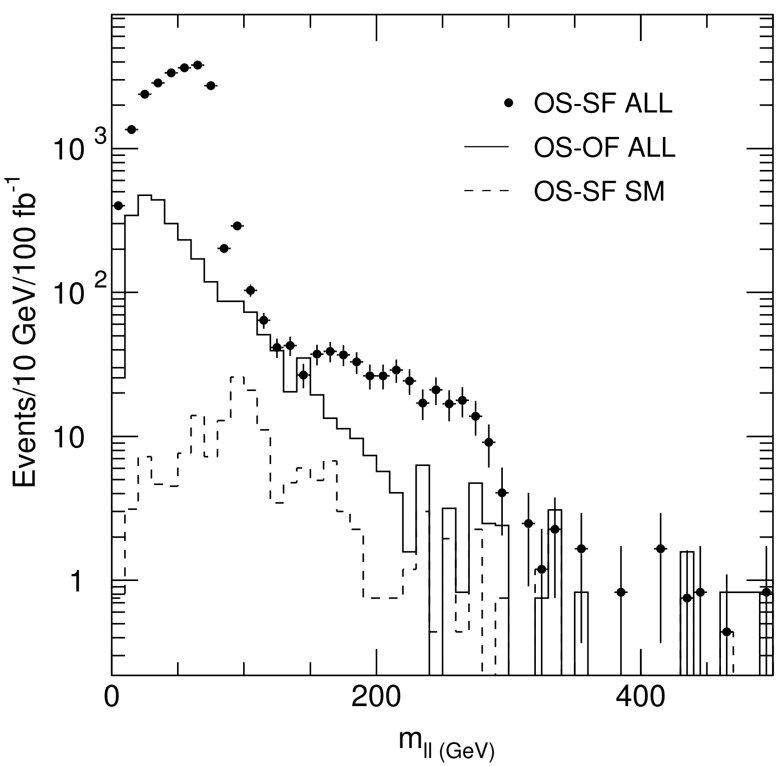


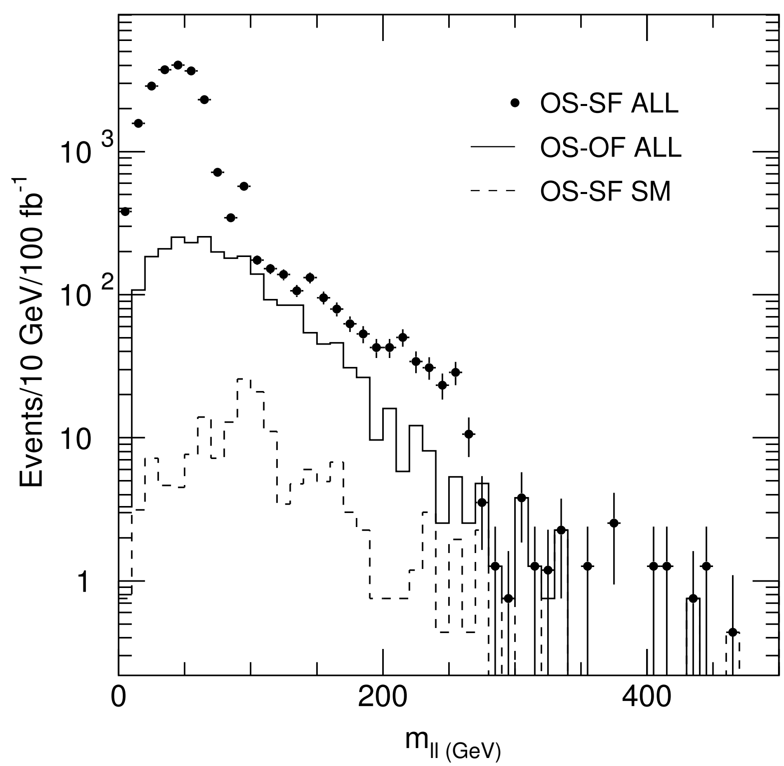
To suppress SM backgrounds, also require $M_{T2} > 80\,\mathrm{GeV}$ for minimum transverse mass for $\ell + \not{E}_T$, where

$$M_{T2}^2 \equiv \min_{\not{p}_1 + \not{p}_2 = \not{p}_T} \left[\max\left\{m_T(p_{T\ell_1}, \not{p}_1), m_T(p_{T\ell_2}, \not{p}_2)\right\}\right]$$

Note $M_{T2} < M_W$ for t and W backgrounds.

Results for Point A (100,250) and Point E(150,250):





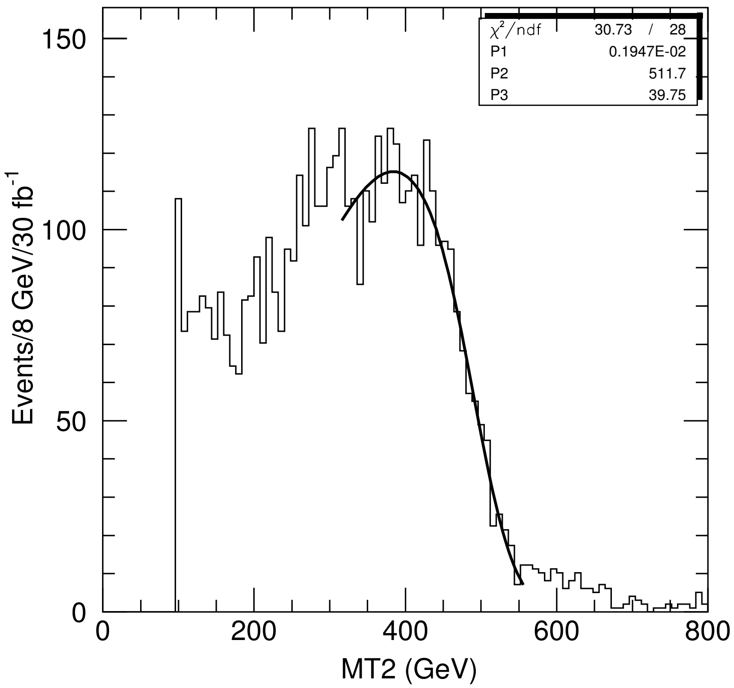
Observe small but clear excess over OS,OF SUSY and SM backgrounds.

Can measure endpoints to $\sim 4\,\mathrm{GeV}$ for Points A,E.

Heavy gaugino signals are hard but not impossible.

$\tilde{q}_R\tilde{q}_R$ Dijet + $\not{E}_T$ Signature

In mSUGRA $\tilde{\chi}_1^0$ is mainly bino, so $B(\tilde{q}_R \to \tilde{\chi}_1^0 q) \approx 100\%$. Hence $\tilde{q}_R\tilde{q}_R$ gives two jets + $\not{E}_T$. Use modified M_{T2} including $\tilde{\chi}_1^0$ mass [LesHouches]:



Endpoint measures $M_{\tilde{q}_R} - M_{\tilde{\chi}_1^0}$ with $\sim 10\,\mathrm{GeV}$ uncertainty.

Third-Generation Squark Signatures

$\tilde{b}_{1,2}$ and $\tilde{t}_{1,2}$ are important for understanding SUSY model, but signatures are typically complex [Kawagoe].

Main source is $\tilde{g}$ decays. Consider for mSUGRA with $m_0 = 100\,\mathrm{GeV}$, $m_{1/2} = 300\,\mathrm{GeV}$, $A_0 = -300\,\mathrm{GeV}$, $\tan\beta = 10$, $\mathrm{sgn}\,\mu = +$:

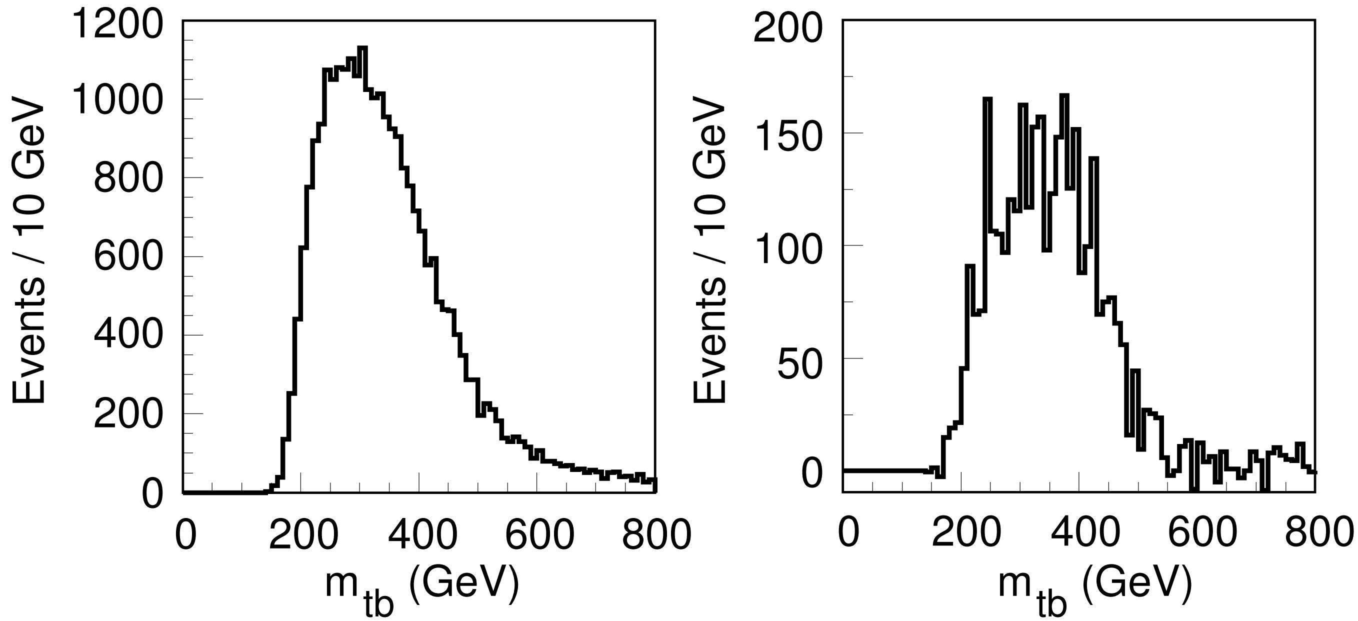
$$\tilde{g} \to t\tilde{t}_1^* \to t\bar{b}\tilde{\chi}_1^-, \qquad \tilde{g} \to \bar{b}\tilde{b}_1 \to \bar{b}t\tilde{\chi}_1^- .$$

Then $M(t\bar{b})$ endpoint measures combination $M_{\tilde{g}} - M_{\tilde{\chi}_1^-}$.

Analysis outline: Select SUSY events using cuts like those above. Require 2 b-tagged jets and two non-b jets j consistent with $t\bar{b} \to jjb\bar{b}$. Resulting $M_{jjb\bar{b}}$ distribution dominated by combinatorial background.

Select sidebands around $M_{jj} = M_W$, rescale their momenta to M_W, and subtract to determine $t\bar{b}$ signal.

$M(t\bar{b})$ mass distributions before and after subtraction [Kawagoe]:



Fitted endpoint is $443.2 \pm 7.4\,\mathrm{GeV}$ compared to expected $459\,\mathrm{GeV}$. Similar agreement between reconstructed and expected endpoints for 12 points studied.

Important to investigate similar sideband-subtraction methods for other multi-jet SUSY signatures.

τ Signatures

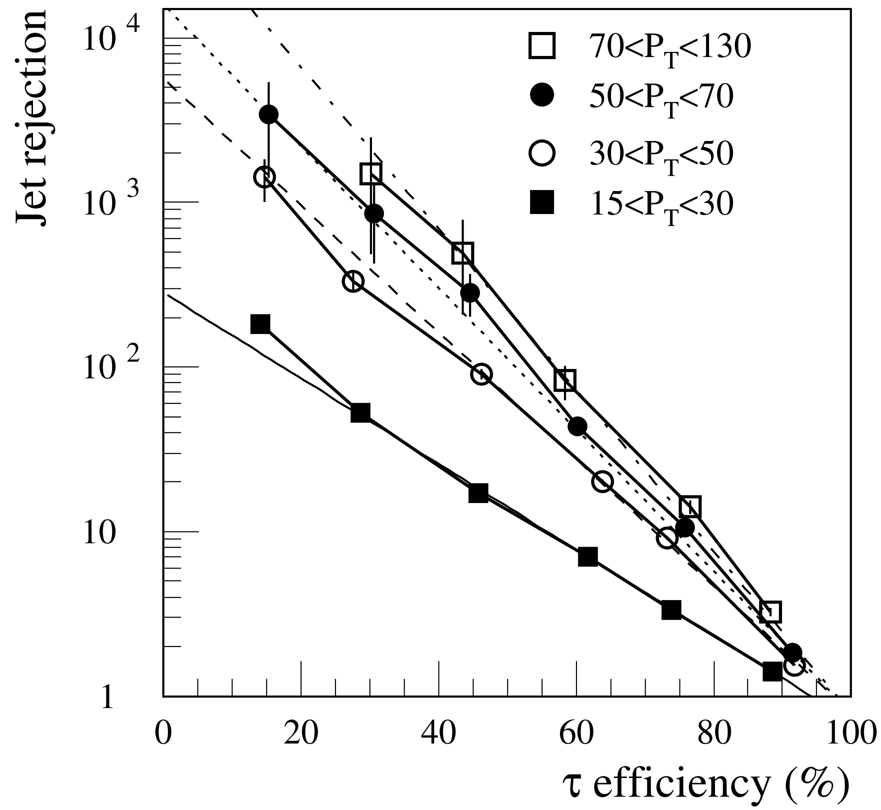
Expect $\tilde{e}$-$\tilde{\mu}$ universality since $\mu \not\to e\gamma$, but $\tilde{\tau}$ split by Yukawa contributions to RGE's, gaugino-Higgino mixing, and $\tilde{\tau}_L$-$\tilde{\tau}_R$ ($\propto m_\tau$).

τ's provide unique information, e.g., chirality, and might even be dominant, especially for $\tan\beta \gg 1$.

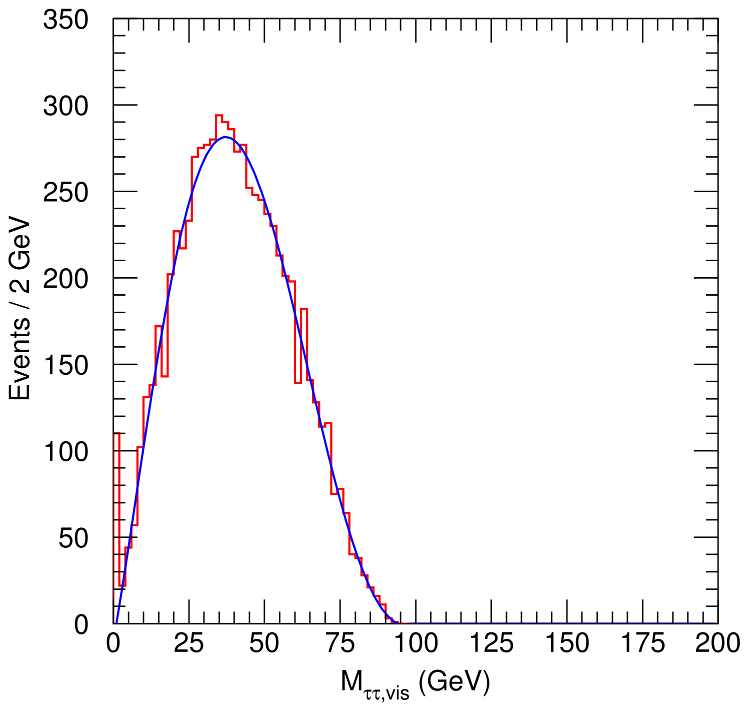
LHC vertex detectors cannot cleanly identify $\tau \to \ell\nu\bar{\nu}$.

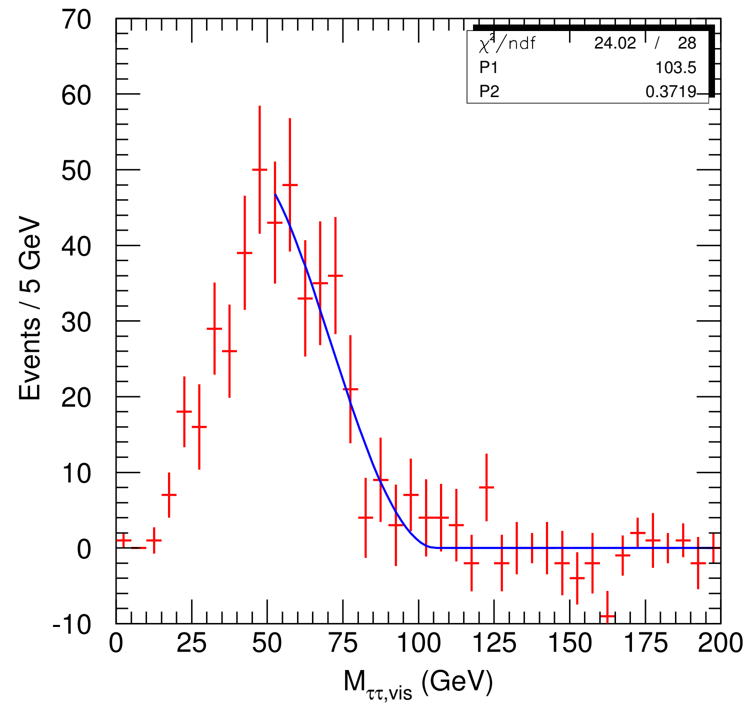
Must rely on hadronic decays $\Rightarrow$ narrow, 1-prong jets. Large QCD background.

Can typically achieve $\tau/\text{jet} \sim 100$ for $\varepsilon_\tau \sim 50\%$ [TDR]. Much worse than for e, μ.



Reconstruct hadronic τ's using full simulation/reconstruction. Fake background is mostly random in sign, so fit shape of ττ visible mass distribution to $\tau^+\tau^- = \tau^\pm\tau^\pm$ [fullsusy]:





Analysis assumes correct τ polarization. Can measure in principle by comparing $\tau \to \pi\nu$ and $\tau \to$ all, but difficult

Mass Relation Method

Each decay involves three unknowns, $\vec{p}_{\tilde{\chi}_1^0}$. If > 3 mass constraints, can solve for $\vec{p}_{\tilde{\chi}_1^0}$ by requiring same masses in several events.

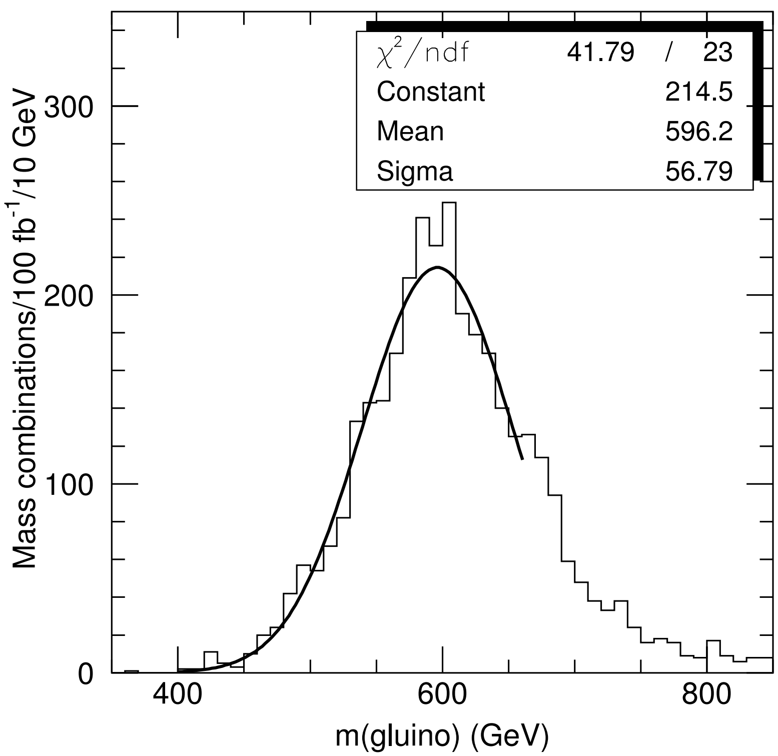
Example: $\tilde{g} \to \tilde{b}\bar{b} \to \tilde{\chi}_2^0 b\bar{b} \to \tilde{\ell}\ell b\bar{b} \to \tilde{\chi}_1^0 \ell\ell b\bar{b}$ for SPS1a. Have 4 mass constraints: $M_{\tilde{g}}$, $M_{\tilde{q}}$, $M_{\tilde{\chi}_2^0}$, and $M_{\tilde{\ell}}$.

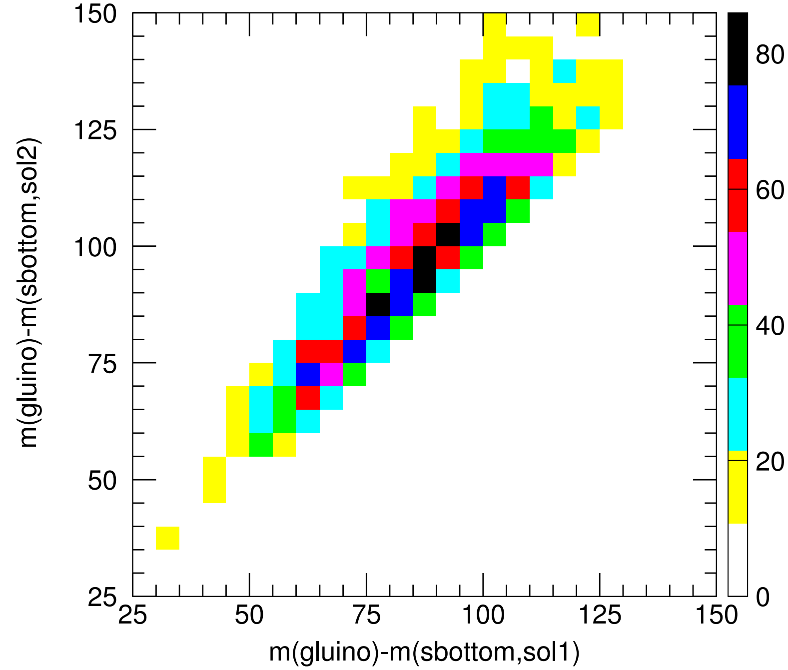
Require 3 jets, $\not{E}_T$, and 2 OS-SF leptons with $40 < M_{\ell\ell} < 88\,\mathrm{GeV}$. Assume $M_{\tilde{\chi}_2^0}$, $M_{\tilde{\ell}}$, and $M_{\tilde{\chi}_1^0}$ already known. Then have for each event

$$M_{\tilde{g}} = F_0 + F_1 M_{\tilde{b}}^2 \pm F_2 \sqrt{D_0 + D_1 M_{\tilde{b}}^2 + D_2 M_{\tilde{b}}^4}$$

Apply for pairs of $bb\ell\ell$ events with only one lepton assignment and difference $> 100\,\mathrm{GeV}$ between gluino solutions.

Plot smaller $M_{\tilde{g}}$ and then two solutions for $M_{\tilde{g}} - M_{\tilde{b}}$ [Nojiri]:



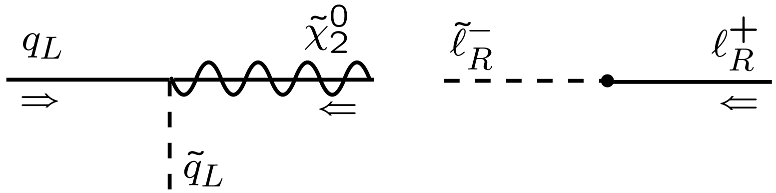


Find for 100 fb^{-1} statistical errors of 2 GeV on $M_{\tilde{g}}$ and 1–2.5 GeV on $M_{\tilde{b}} - M_{\tilde{b}}$. Must add at least $\sim 1\%$ scale error.

Exploits long decay chains using all events, not just those near endpoints. Does not depend on $\tilde{\chi}_1^0$ being (nearly) at rest at endpoint.

SUSY Spin Measurements

Decay $\tilde{q}_L \to \tilde{\chi}_2^0 q$ produces q_L and hence $\tilde{\chi}_2^0$ with helicity $\lambda = -1$:



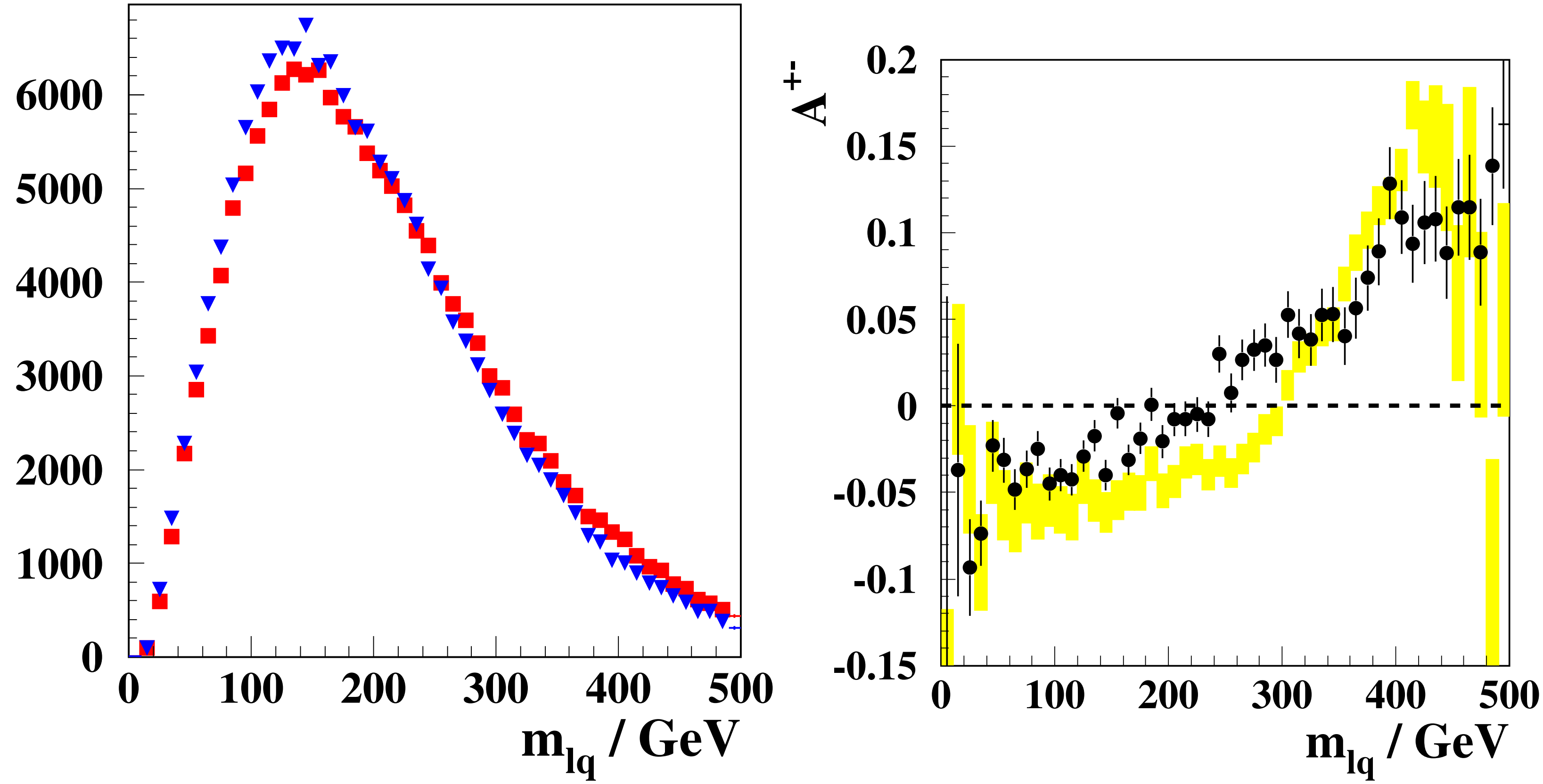
Hence $\tilde{\chi}_2^0 \to \tilde{\ell}_R^{\mp} \ell^{\pm}$ distribution $\sim \left[d^{(\frac{1}{2})}_{-\frac{1}{2}\pm\frac{1}{2}}(\theta) \right]^2 \propto 1 \pm \cos\theta$.

Basic asymmetry suppressed by:

- Cancellation between $\tilde{q}$ and $\bar{\tilde{q}}$. But for pp machine valence quarks give excess of $\tilde{u}$ and $\tilde{d}$. (Suppresses effect of Higgsino mixing.)
- Contribution of far (second) lepton.

Analysis done only for TDR Point 5 (fairly similar to SPS1a). Simulate detector response with Atlfast and make standard event selection cuts.

Even after dilutions, see difference between $\ell^+ q$ (red squares) and $\ell^- q$ (blue triangles). Clear asymmetry for $150\,\mathrm{fb}^{-1}$ [Barr04]:



(Yellow rectangles show rescaled parton level distribution.)

Analysis clearly shows non-zero spin for $\tilde{\chi}_2^0$ consistent with SUSY expectations. Important result, albeit only for one case.

Should examine for other cases, including especially $\tilde{\chi}_2^0 \to \tilde{\tau}^{\mp}\tau^{\pm}$.

GMSB Signatures

LSP in GMSB is light gravitino $\tilde{G}$. Phenomenology depends on nature and lifetime of NLSP ($\tilde{\chi}_1^0$ or $\tilde{\ell}$). Generally long decay chains:

$$\tilde{\chi}_2^0 \to \tilde{\ell}^\pm \ell^\mp \to \tilde{\chi}_1^0 \ell^+ \ell^- \to \tilde{G} \gamma \ell^+ \ell^-$$

Hence easier than SUGRA.

Might also give special signatures from long-lived particles.

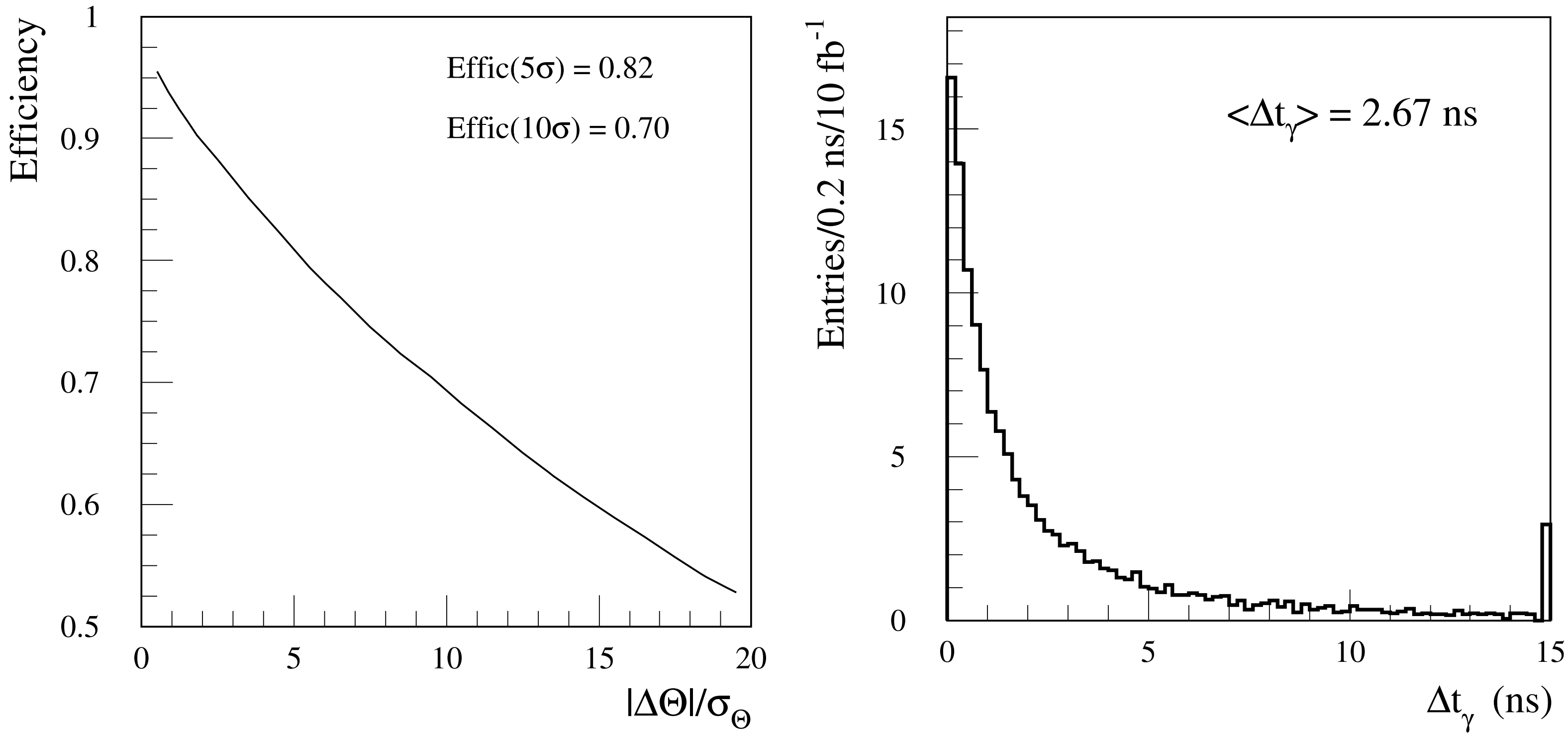
Important to measure NLSP lifetime $\Leftrightarrow$ SUSY breaking scale. For $\tilde{\chi}_1^0 \to \tilde{G}\gamma$, can measure short lifetimes with Dalitz decays.

For $c\tau_{\tilde{\chi}_1^0} \gg 1\,\mathrm{m}$, look for (rare) non-pointing photons. ATLAS EM calorimeter gives

$$\Delta\theta \approx \frac{60\,\mathrm{mr}}{\sqrt{E}}, \qquad \Delta t \approx 100\,\mathrm{ps}$$

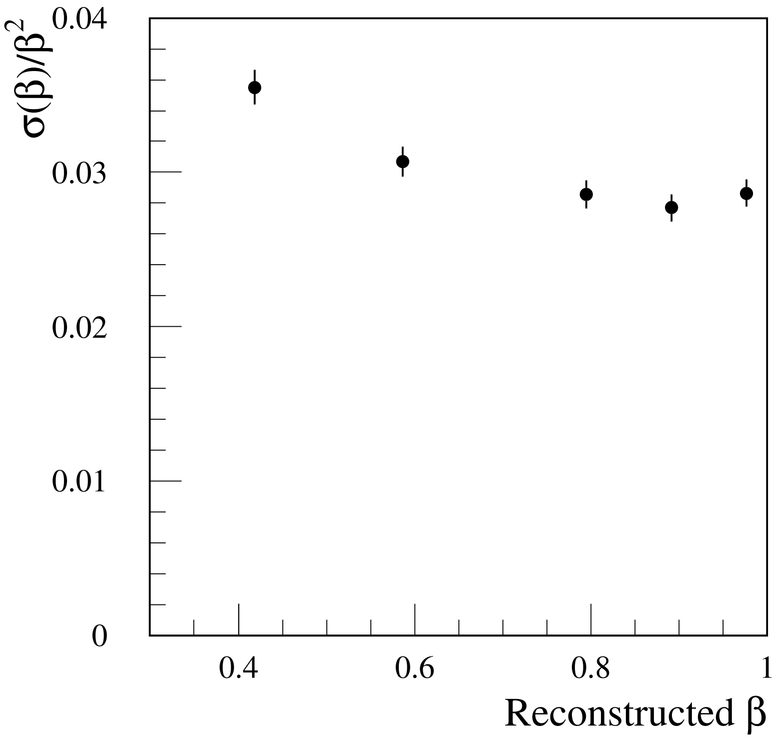
Can use both to identify non-pointing photons.

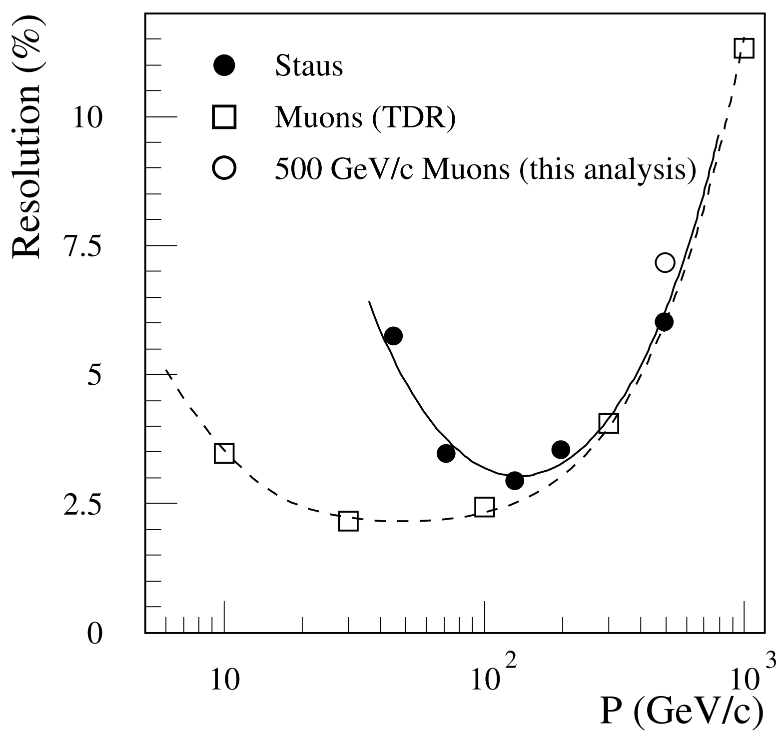
Efficiency for $\Delta\theta > 5\sigma_\theta$ is 82% for typical model, while mean time delay is 2.67 ps [TDR]:



Could be sensitive to $c\tau \sim 100$ km [TDR]. Rate would determine lifetime if acceptances known.

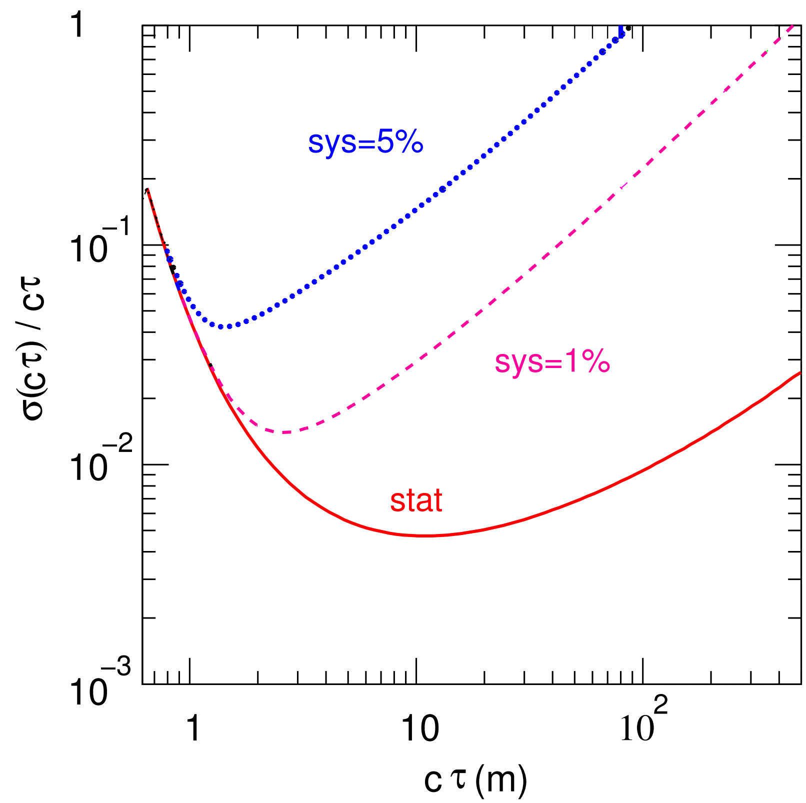
GMSB model might also give long-lived sleptons. Look like muons with $\beta < 1$. Muon chambers give TOF $\Rightarrow$ measure both p and β:





Then can fully reconstruct events for $\tilde{\ell}$ NLSP. Only small smearing for $\tilde{\tau}_1$ NLSP.

NLSP lifetime important for understanding SUSY breaking. Ratio of 1 vs. 2 sleptons in muon system sensitive to decays. Limited by systematic error on acceptance [Rimoldi]:



Could also look for decays in central tracker. Requires difficult study of pattern recognition for such events.

Outlook

If TeV scale SUSY exists, ATLAS and CMS should find it at LHC using inclusive measurements.

Must first understand detectors and Standard Model backgrounds. Implies reconstructing $Z+$jets, $t\bar{t}$, etc., with SUSY background. Just started.

Have developed many tools for precision SUSY measurements despite missing $\tilde{\chi}_1^0$.

Methods typically use decay chains, so what can be done depends on whole pattern of masses and mixings.

Have mainly discussed recent work on SPS1a and similar points. Probably easier than average, but harder than GMSB.

Two talks on harder mSUGRA cases in parallel sessions:

- Coannihilation region $\left(M_{\tilde{\tau}} - M_{\tilde{\chi}_1^0} \ll M_{\tilde{\chi}_1^0}\right)$ [Gianluca Commune]
- Focus point region (heavy scalars, Higgsino LSP) [Tommaso Lari]

Much more work on SUSY analysis at fast simulation level is needed. Some examples:

- Study $M_{\tilde{\chi}_1^0}$ measurement for whole SUGRA range allowed by CDM.
- Develop techniques for difficult modes, e.g., τ decays, $\tilde{g} \to t\bar{b}\tilde{\chi}_i^-$.
- Learn to measure cross sections and branching ratios.

Need to develop full simulation/reconstruction and to address more difficult cases.

LHC is currently expected expected to start in Spring 2007.

If SUSY at TeV scale exists, might reasonably hope for "Observation of SUSY-like Signatures at LHC" in 2008.

References

[CMS98] CMS Collaboration, hep-ph 9806366.

[Barr03] A.J. Barr, et al., hep-ph/0208214, JHEP **0303**, 045 (2003).

[Tricomi] A. Tricomi, hep-ex/0406020.

[fullsusy] M. Biglietti, et al., ATL-PHYS-2004-011.

[TDR] ATLAS Collaboration, *Detector and Physics Performance Technical Design Report*, CERN/LHCC 99-14.

[LesHouches] B.C. Allanach, et al., hep-ph/0402295.

[Kawagoe] J. Hisano, K. Kawagoe, M. Nojiri, hep-ph/0304214.

[Nojiri] M.M Nojiri, G. Polesello, and D.R. Tovey, hep-ph/0312237.

[Barr04] A.J. Barr, hep-ph/0404052.

[Rimoldi] S. Ambrosanio, et al., ATL-PHYS-2002-006.