Prospects for SUSY at LHC

Frank E. Paige

If SUSY exists at TeV scale, production at LHC dominated by $\tilde{g}$ and $\tilde{q}$. Production comparable to jets at similar Q^2.

Discovery is easy. Select events with large

$$M_{\text{eff}} = p_{T,1} + p_{T,2} + p_{T,3} + p_{T,4} + \not{E}_T \,.$$

plus multiple jets, $\not{E}_T$, leptons, etc.

Problem is to extract SUSY from SUSY background. Typical events are complex, e.g.,

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

Strategy is to identify characteristic decay at bottom of chain, e.g., $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \ell^+ \ell^-$.

Then work up decay chain, using endpoints of distributions to determine combinations of masses.

Need new analysis for each case. Have studied

- SUGRA Points 1–5: Starting points are $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \ell^+ \ell^-$, $\tilde{\ell}_R^\pm \ell^\mp$, or $\tilde{\chi}_1^0 h$.
- SUGRA Point 6: $\tan\beta \gg 1 \Rightarrow \tilde{\chi}_2^0 \to \tilde{\tau}_1^\pm \tau^\mp \to \tilde{\chi}_1^0 \tau^+ \tau^-$. Must rely on τ hadronic decays.
- GMSB points with prompt and long-lived $\tilde{\chi}_1^0$ and $\tilde{\ell}_R$. Different signatures in each case.

Will concentrate on new results:

- 4-body decays for SUGRA Point 5.
- GMSB with prompt $\tilde{\chi}_1^0 \to \tilde{G}\gamma$.
- GMSB with long-lived $\tilde{\ell}_R$.

For earlier work see Phys. Rev. D55, 5520 and ATLAS-PHYS-No-108, 109, 110, 111, [112].

SUGRA Point 5

Parameters chosen to give cold dark matter:

$$m_0 = 100, \mathrm{GeV}, m_{1/2} = 300\,\mathrm{GeV}, A_0 = 300\,\mathrm{GeV},$$

$$\tan\beta = 2, \mathrm{sgn}\,\mu = +.$$

$(M_{\tilde{g}} = 767\,\mathrm{GeV},\ M_{\tilde{q}_L} = 688\,\mathrm{GeV},\ M_{\tilde{\chi}_1^0} = 122\,\mathrm{GeV}.)$

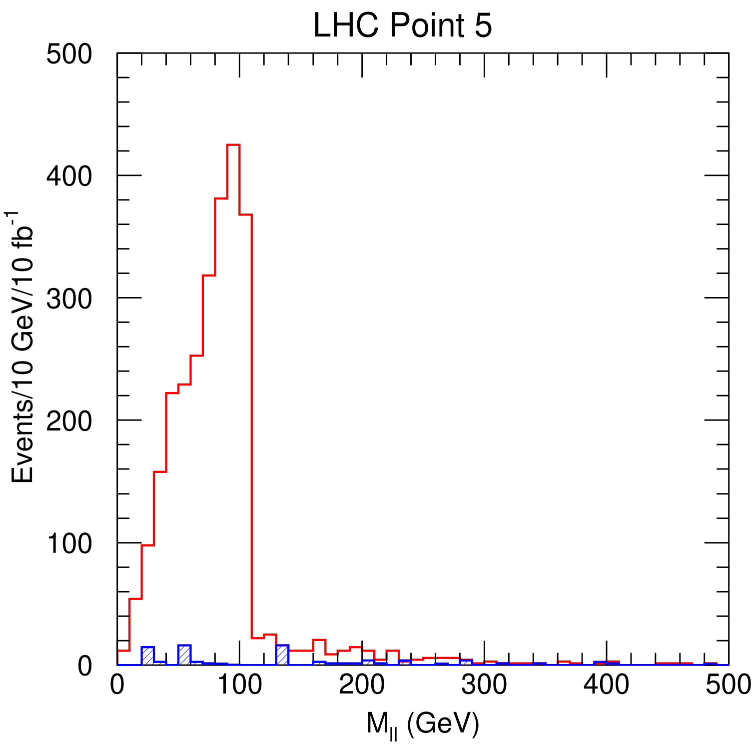
Generate signal and SM backgrounds with ISAJET (or PYTHIA). Apply simple detector simulation and fixed cone jet algorithm with $R = 0.4$.

Event selection to suppress SM background:

- $\not{E}_T > 100\,\mathrm{GeV}$;
- ≥ 4 jets with $p_T > 50\,\mathrm{GeV}$ and $p_{T,1} > 100\,\mathrm{GeV}$;
- Transverse sphericity $S_T > 0.2$;
- $M_{\mathrm{eff}} > 800\,\mathrm{GeV}$;
- $\not{E}_T > 0.2 M_{\mathrm{eff}}$.

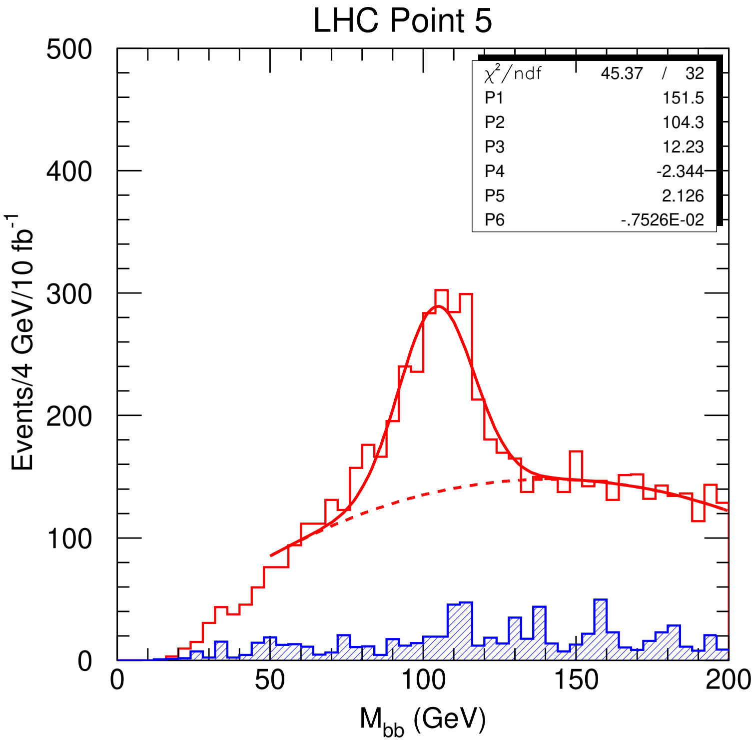
$\tilde{\chi}_2^0 \to \tilde{\ell}_R^\pm \ell^\mp$ produces sharp dilepton edge at

$$M_{\ell\ell}^{\max} = M_{\tilde{\chi}_2^0} \sqrt{1 - \frac{M_{\tilde{\ell}}^2}{M_{\tilde{\chi}_2^0}^2}} \sqrt{1 - \frac{M_{\tilde{\chi}_1^0}^2}{M_{\tilde{\ell}}^2}} \approx 108.6\,\mathrm{GeV}\,,$$



Can measure to $\sim 0.1\%$ with $100\,\mathrm{fb}^{-1}$.

Also have $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 h$. Can reconstruct $h \to b\bar{b}$ (discovery mode for h!).



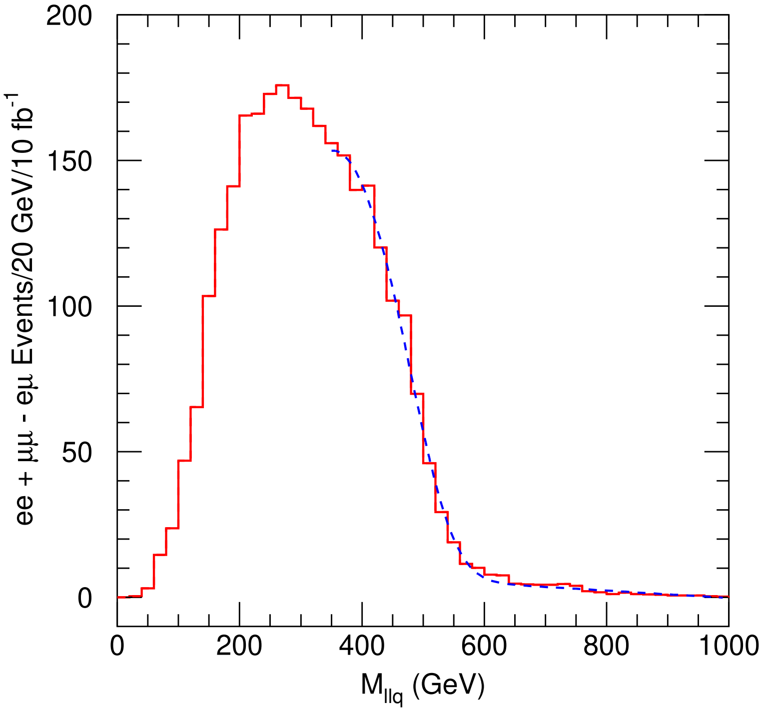
Combine with hard jet $\Rightarrow$ handle on squark masses.

Can also use 4-body phase space, e.g.

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

Gives linear vanishing of $\ell^+\ell^- q$ mass at

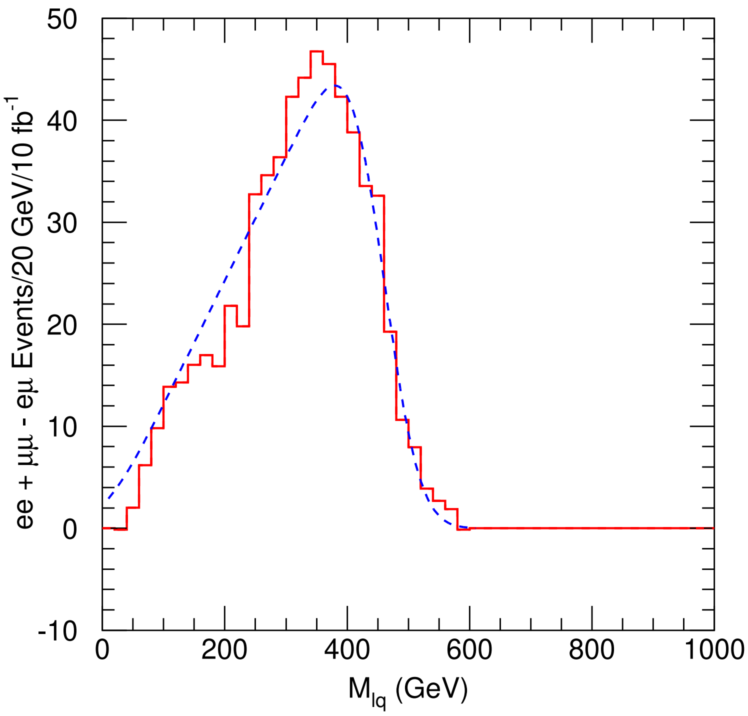
$$M_{\ell\ell q} = \left[\frac{\left(M_{\tilde{q}_L}^2 - M_{\tilde{\chi}_2^0}^2\right)\left(M_{\tilde{\chi}_2^0}^2 - M_{\tilde{\chi}_1^0}^2\right)}{M_{\tilde{\chi}_2^0}^2}\right]^{1/2} = 552.4\,\mathrm{GeV}\,.$$



Also find edge in ℓq mass from "right" lepton:

$$M_{\ell q} = \left[\frac{\left(M^2_{\tilde{q}_L} - M^2_{\tilde{\chi}^0_2}\right)\left(M^2_{\tilde{\chi}^0_2} - M^2_{\ell_R}\right)}{M^2_{\tilde{\chi}^0_2}} \right]^{1/2} = 479.3\,\mathrm{GeV}\,.$$

Fitting edge smeared with Gaussian gives $457.4\,\mathrm{GeV}$ with $\sigma = 46\,\mathrm{GeV}$.



ℓq endpoint from "wrong" lepton not visible.

Have $\ell\ell$, $\ell\ell q$, ℓq and hq endpoints to determine $\tilde{q}_L$, $\tilde{\chi}_2^0$, $\tilde{\ell}_R$, and $\tilde{\chi}_1^0$ masses $\Rightarrow$ model independent masses!

Fit gives 0.866 for

$$\frac{M_{\ell q}}{M_{\ell\ell q}} = \sqrt{\frac{M_{\tilde{\chi}_2^0}^2 - M_{\ell_R}^2}{M_{\tilde{\chi}_2^0}^2 - M_{\tilde{\chi}_1^0}^2}} = 0.868\,,$$

Less sensitive to jet energy scale.

Gauge Mediated SUSY Breaking

GMSB is alternative to SUGRA: no FCNC. Very different signatures. Model parameters:

- $10\,\mathrm{TeV} \lesssim \Lambda \equiv F_m/M_m \lesssim 400\,\mathrm{TeV}$: Scale for SUSY masses.
- $M_m > \Lambda$: Messenger mass scale.
- $N_5 \ge 1$: Number of equivalent $5+\bar{5}$ messenger fields.
- $1 \lesssim \tan\beta \lesssim m_t/m_b$: Usual ratio of Higgs VEV's.
- $\mathrm{sgn}\,\mu = \pm 1$: Usual sign of μ parameter.
- $C_{\mathrm{grav}} \ge 1$: Ratio of $M_{\tilde{G}}$ to value from F_m.

Lightest SUSY particle is gravitino:

$$M_{\tilde{G}} = F_b/M_{\mathrm{Planck}} \ll 1\,\mathrm{GeV}$$

where $F_b \ge F_m$ is total SUSY breaking scale. NLSP decays to $\tilde{G}$ can be prompt or slow if $F_b \gg F_m$.

NLSP $= \tilde\chi_1^0$, $c\tau \ll 1\,\mathrm{m}$:

Point G1a with prompt $\tilde\chi_1^0 \to \tilde G \gamma$ decay:

$$\Lambda_m = 90\,\mathrm{TeV},\ M_m = 500\,\mathrm{TeV},\ N_5 = 1,$$

$$\tan\beta = 5,\ \mathrm{sgn}\,\mu = +,\ C_{\mathrm{grav}} = 1$$

Representative masses (in GeV) from ISAJET:

$$M_{\tilde g} = 744,\ M_{\tilde q_L} = 983,\ M_{\tilde q_R} = 937,$$

$$M_{\tilde\chi_4^0} = M_{\tilde\chi_2^\pm} = 468,\ M_{\tilde\chi_3^0} = 449,$$

$$M_{\tilde\chi_2^0} = M_{\tilde\chi_1^\pm} = 223,$$

$$M_{\tilde\ell_R} = 164,\ M_{\tilde\chi_1^0} = 119$$

$$M_h = 109$$

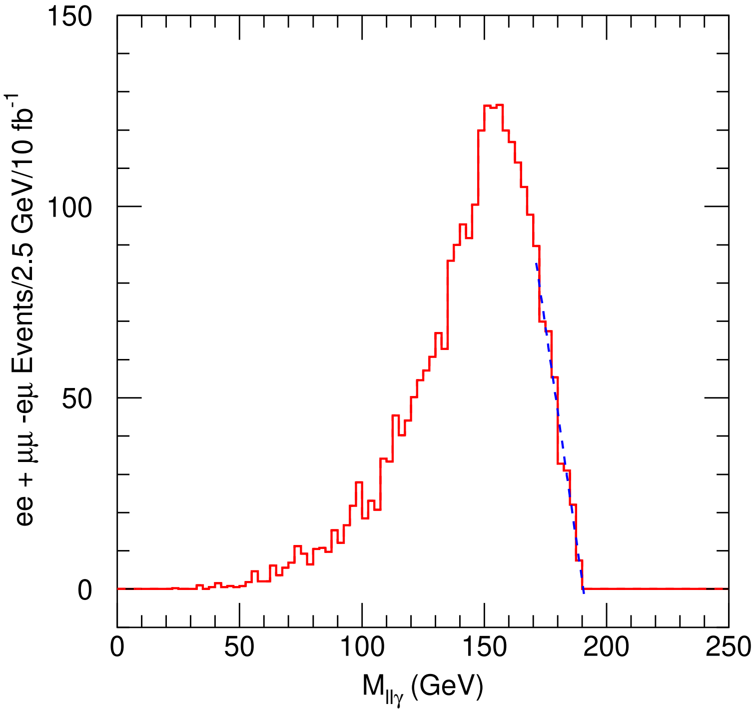
Every event tagged with two photons.

Consider decay chain $\tilde\chi_2^0 \to \tilde\ell_r \ell \to \tilde\chi_1^0 \ell\ell \to \tilde G \gamma \ell\ell$.

Select $\ell\ell\gamma\gamma$ events. Then smaller $\gamma\ell\ell$ mass has 4-body endpoint vanishing linearly at

$$\sqrt{M_{\tilde\chi_2^0}^2 - M_{\tilde\chi_1^0}^2} = 189.7\,\mathrm{GeV}.$$

Make linear fit near endpoint:

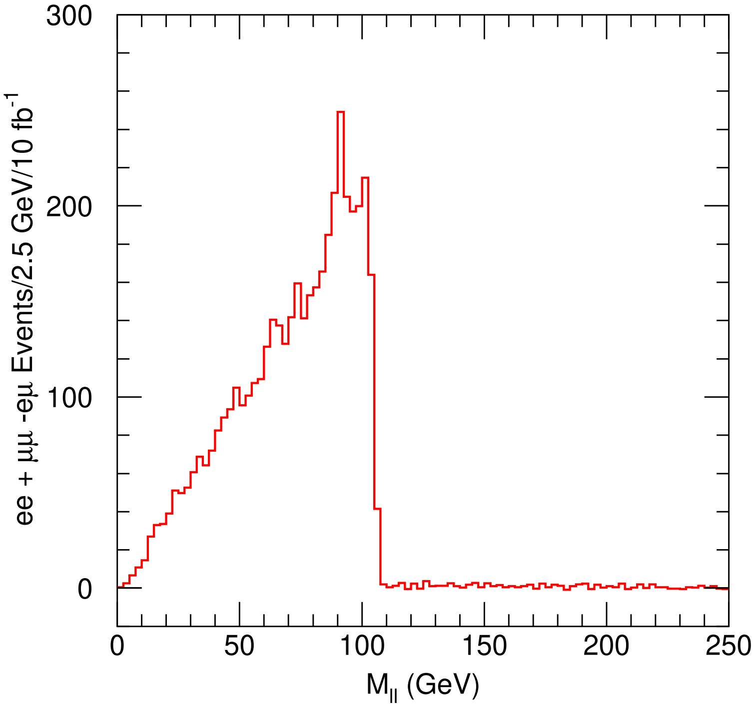


Select events with one $\gamma\ell\ell$ mass above and other below endpoint.

$\ell^+\ell^-$ edge determines

$$M_{\tilde{\chi}_2^0}\sqrt{1-\frac{M_{\tilde{\ell}_R}^2}{M_{\tilde{\chi}_2^0}^2}}\sqrt{1-\frac{M_{\tilde{\chi}_1^0}^2}{M_{\tilde{\ell}_R}^2}} = 105.1\,\mathrm{GeV}.$$

Also have Z peak — partly from heavy gauginos.

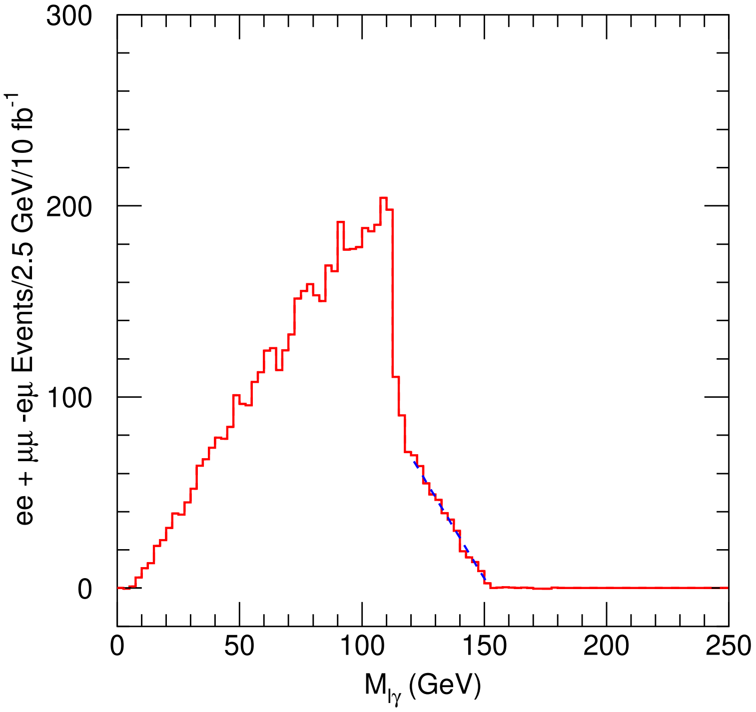


$\ell\gamma$ distribution determines both "right" edge

$$\sqrt{M_{\tilde\ell_R}^2 - M_{\tilde\chi_1^0}^2} = 112.6\,\mathrm{GeV},$$

and "wrong" lepton endpoint

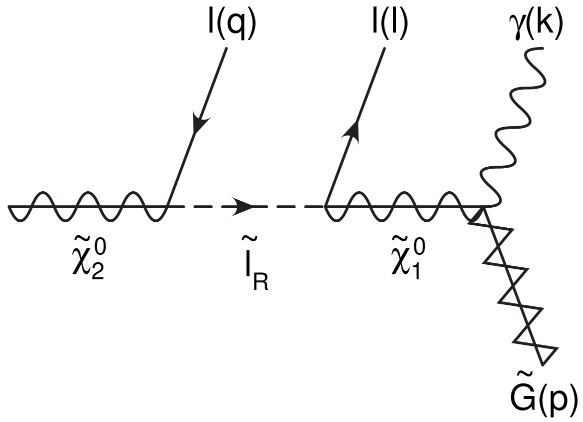
$$\sqrt{M_{\tilde\chi_2^0}^2 - M_{\tilde\ell_R}^2} = 152.7\,\mathrm{GeV}.$$



Determine 4 combinations of $\tilde{\chi}_2^0$, $\tilde{\ell}_R$, $\tilde{\chi}_1^0$ masses using 3-body and 4-body distributions $\Rightarrow$ can again extract masses without assuming model.

Full Reconstruction

Can reconstruct long decay chains. Consider



Know masses $\Rightarrow$ can calculate p assuming $p^2 = 0$:

$$
\begin{aligned}
2p_0k_0 - 2\vec{p}\cdot\vec{k} &= M_{\tilde{\chi}_1^0}^2 \\
2p_0l_0 - 2\vec{p}\cdot\vec{l} &= M_{\tilde{\ell}_R}^2 - M_{\tilde{\chi}_1^0}^2 - 2k\cdot l \\
2p_0k_0 - 2\vec{p}\cdot\vec{q} &= M_{\tilde{\chi}_2^0}^2 - M_{\tilde{\ell}_R}^2 - 2(k+l)\cdot q
\end{aligned}
$$

0C fit with 2×2 solutions.

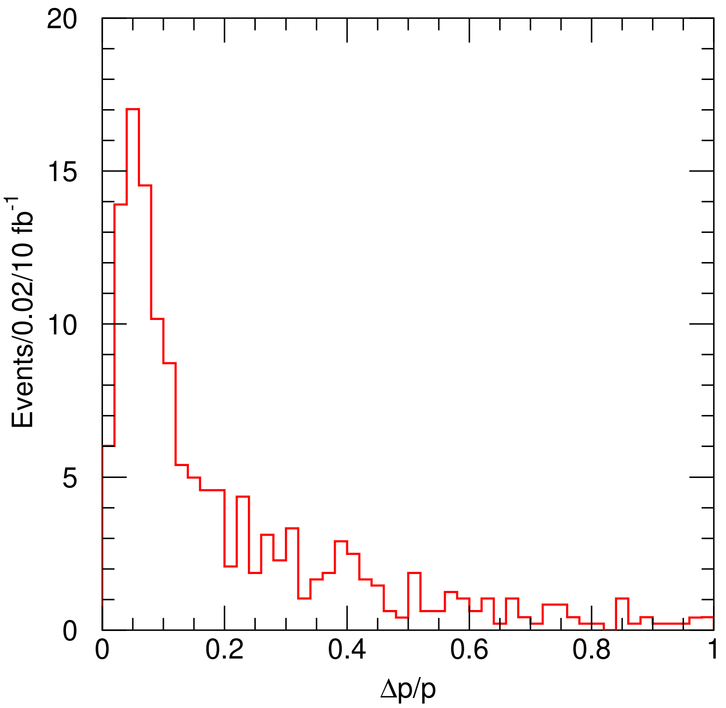
Require $4\ell + 2\gamma$ with unique $\ell^+\ell^-\gamma$ pairing.

Calculate for 16 solutions:

$$\chi^2 = \left(\frac{\not{E}_x - p_{1x} - p_{2x}}{\Delta\not{E}_x}\right)^2 + \left(\frac{\not{E}_y - p_{1y} - p_{2y}}{\Delta\not{E}_y}\right)^2 .$$

using $\Delta\not{E}_x = \Delta\not{E}_x = 0.6\sqrt{E_T} + 0.03E_T$.

For $\chi^2 < 10$ find $\Delta|\vec{p}|/\vec{p}| \sim 10\%$ compared with generated $\tilde{G}$ momenta:

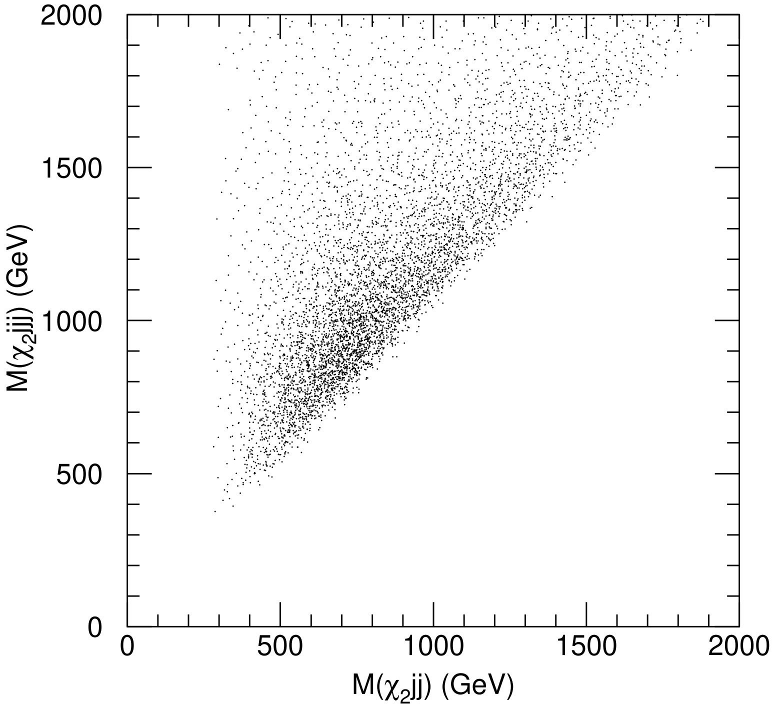


Limited statistics $\Rightarrow$ want high $\mathcal{L}$. Also can determine $\tilde{\chi}_2^0$ momenta.

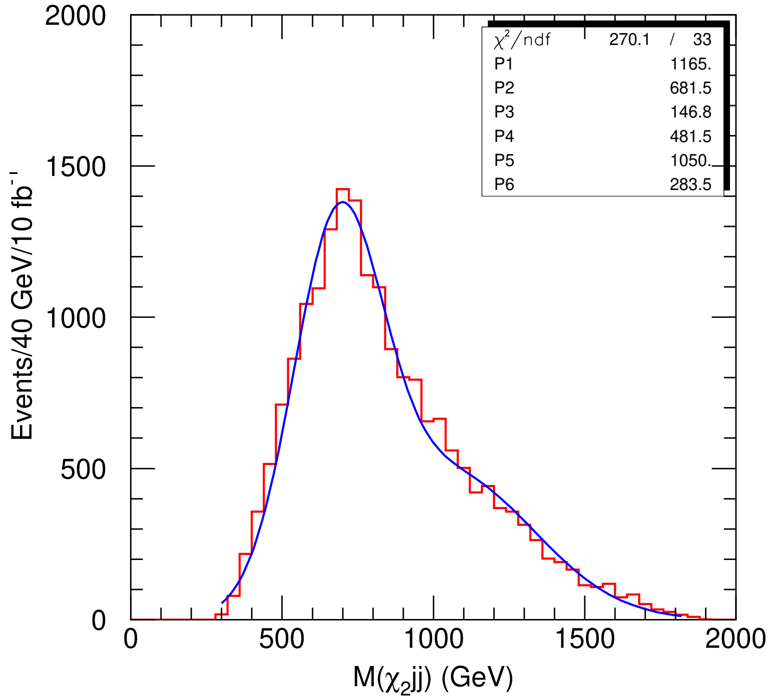
Use fully reconstructed events to determine gluino and squark masses — may not be optimal.

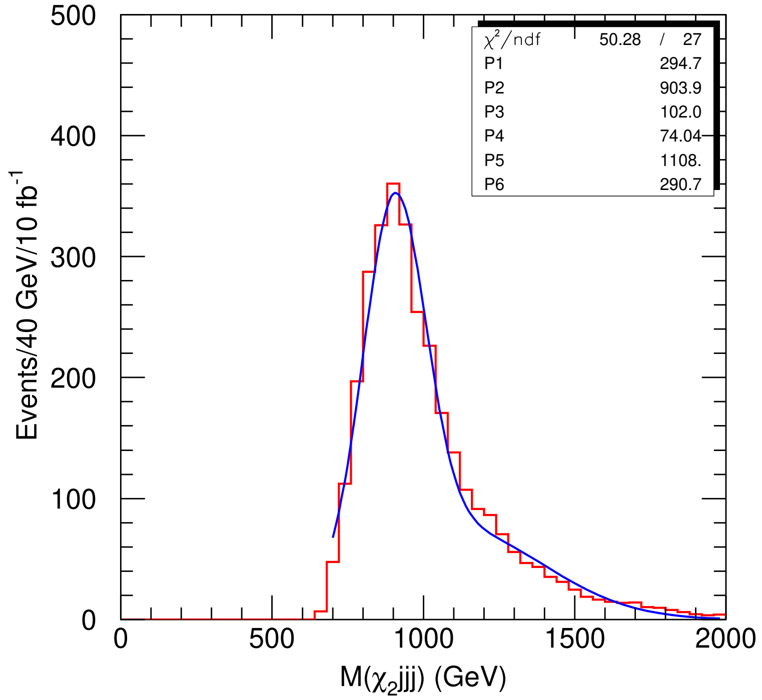
While $M_{\tilde{q}} > M_{\tilde{g}}$, $\tilde{g}$ and $\tilde{q}$ production comparable, so reconstructing two equal $\tilde{\chi}_2^0 jj$ massses failed.

Better to look at scatter plot of $\tilde{\chi}_2^0 jj$ vs.$\tilde{\chi}_2^0 jjj$ using all jets with $p_T > 75\,\mathrm{GeV}$:



Projection on $M(\tilde{\chi}_2^0 jj)$ axis gives peak near gluino mass. Projection on $M(\tilde{\chi}_2^0 jjj)$ axis after cut around gluino peak, $600\,\mathrm{GeV} < M(\tilde{\chi}_2^0 jj) < 800\,\mathrm{GeV}$, gives peak near squark mass:





Need more work to understand mass shifts and errors.

NLSP $= \tilde\tau_1$, $c\tau \gg 1\,\mathrm{m}$:

Two sub-cases:

- $\tan\beta \gg 1$: mass splitting $> M_\tau$, so $\tilde\ell \to \tilde\tau_1 \tau \ell$.
- $\tan\beta \sim 1$: splitting $< M_\tau$, and both $\tilde\ell_R$ and $\tilde\tau_1$ are quasi-stable.

Point G2b with $\tilde\ell \not\to \tilde\tau_1 \tau \ell$:

$$\Lambda = 30\,\mathrm{TeV}, M_m = 250\,\mathrm{TeV}, N_5 = 3,$$

$$\tan\beta = 5,\ \mathrm{sgn}\,\mu = +,\ C_{\mathrm{grav}} = 10^4$$

Representative masses (in GeV) from ISAJET:

$$M_{\tilde g} = 713,\ M_{\tilde q_L} = 672,\ M_{\tilde q_R} = 648,$$

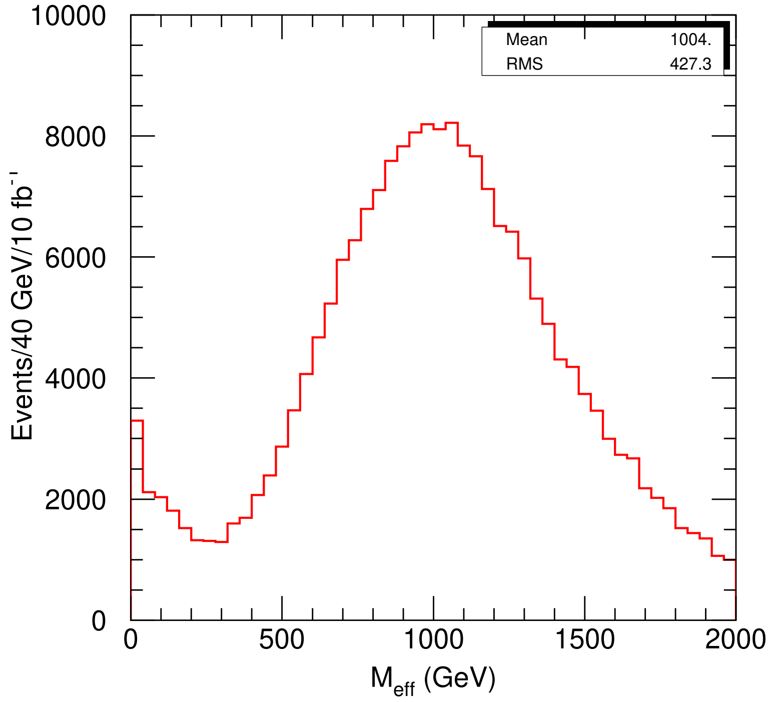
$$M_{\tilde\chi_4^0} = M_{\tilde\chi_2^\pm} = 347,\ M_{\tilde\chi_3^0} = 304,$$

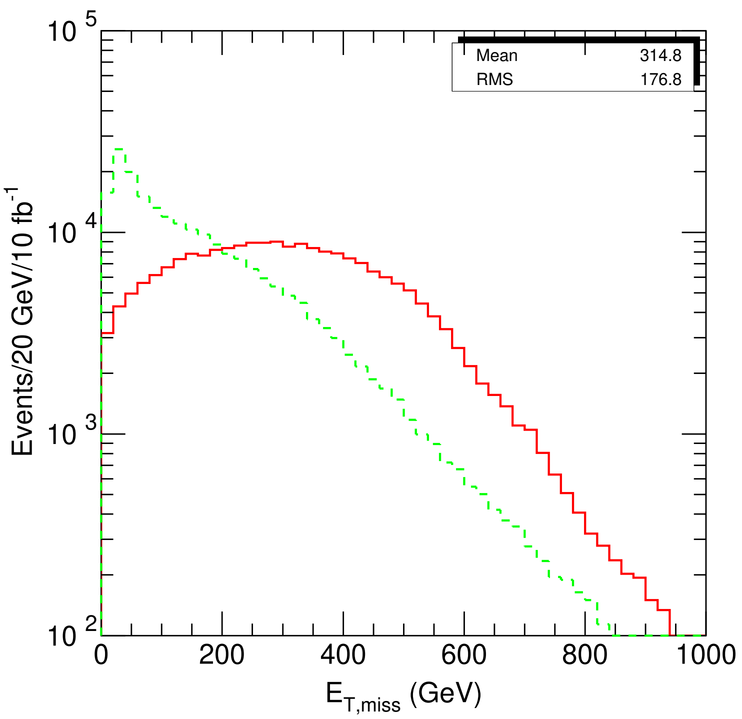
$$M_{\tilde\chi_2^0} = M_{\tilde\chi_1^\pm} = 201,\ M_{\tilde\chi_1^0} = 115$$

$$M_h = 107$$

$$M_{\tilde\ell_R} = M_{\tilde\tau_1} = 101\ [c\tau = 5\,\mathrm{km}]$$

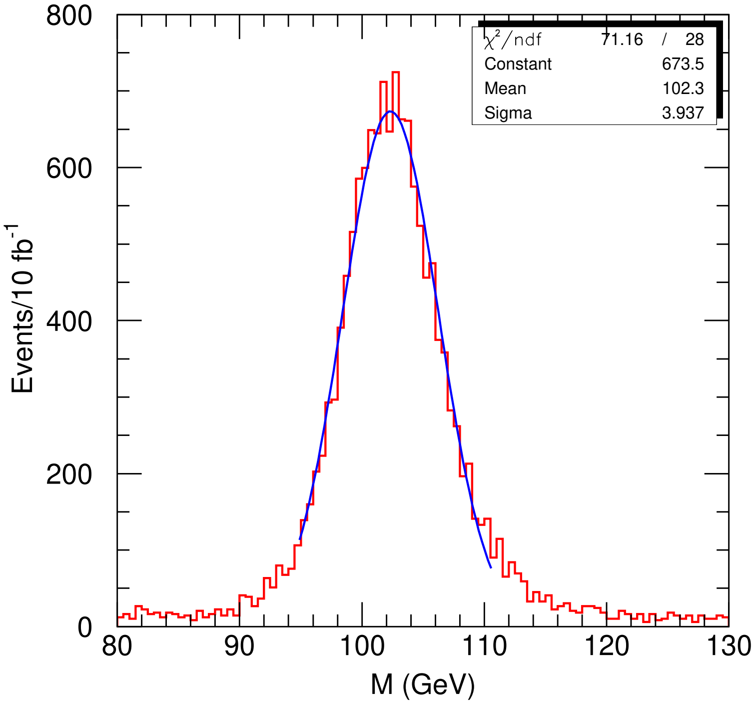
Large $M_{\rm eff}$ and calorimetric $\not\!\!E_T$ provide trigger:



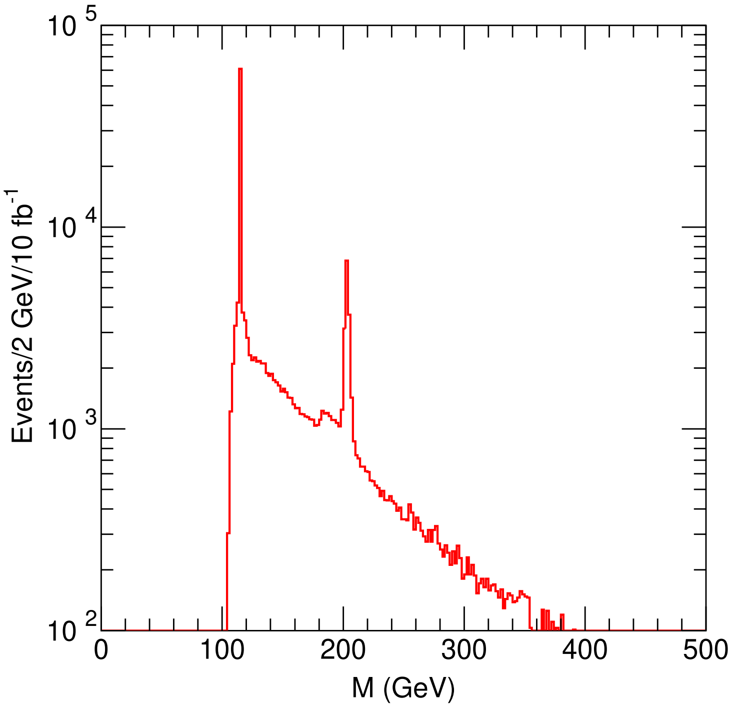


Events contain quasi-stable sleptons with $\langle\beta\rangle = 0.9$.

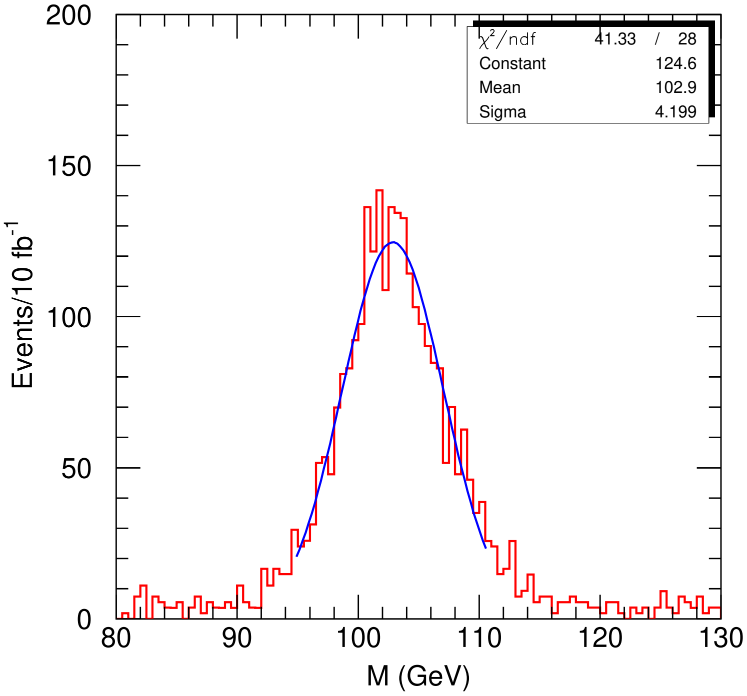
Use $\pm 1\,\mathrm{ns}$ TOF to measure average $M_{\tilde{\ell}}$ for $10\,\mathrm{ns} < \Delta t < 50\,\mathrm{ns}$. Small improvement for larger Δt; cannot separate $M_{\tilde{\ell}_R} = 102.7\,\mathrm{GeV}$ and $M_{\tilde{\tau}_1} = 101.4\,\mathrm{GeV}$.



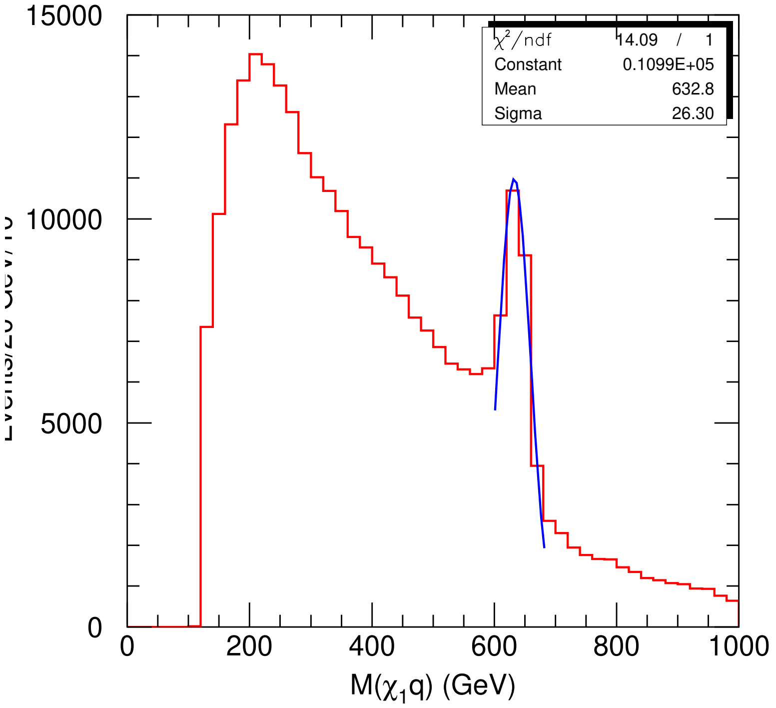
Assume 2 highest p_T muon tracks are sleptons and combine them with electron or muon:

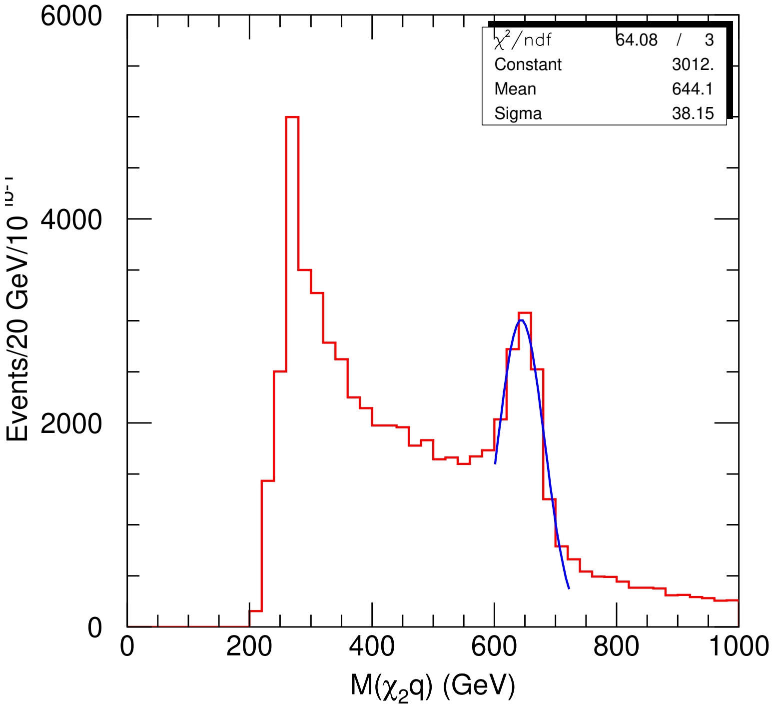


Use events in $\tilde{\chi}_1^0$ peak to measure $M_{\tilde{\ell}_R} = 102.9\,\mathrm{GeV}$:



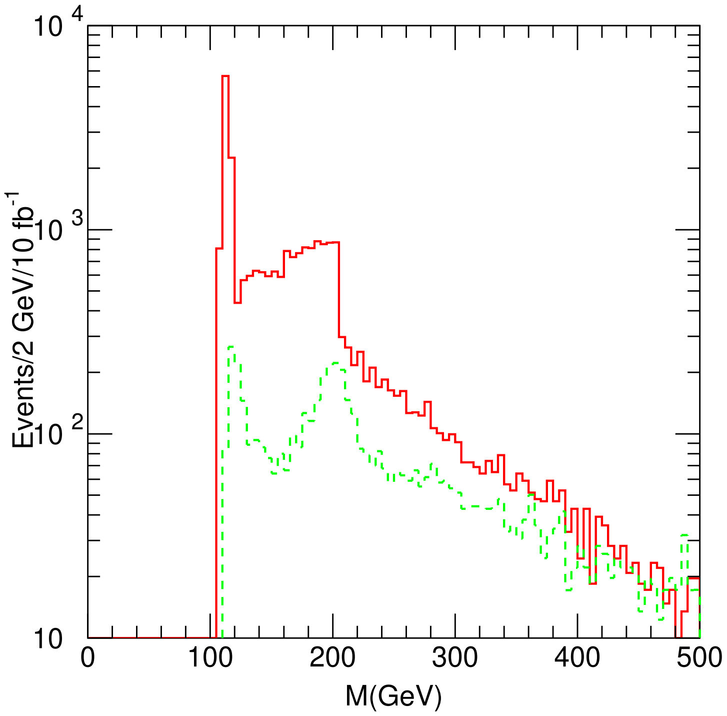
Combine $\tilde{\chi}_1^0$ and $\tilde{\chi}_2^0$ with 2 highest p_T jets:





Difference is 11 GeV, while $\tilde{q}_L$-$\tilde{q}_R$ splitting is 26 GeV. Have mixture of $\tilde{q}_R \to \tilde{\chi}_1^0 q$, $\tilde{q}_L \to \tilde{\chi}_i^0 q$, and $\tilde{b}_{1,2}$.

Can also reconstruct τ–$\tilde{\tau}_1$. Select hadronic τ's with $p_T > 20\,\mathrm{GeV}$, $\eta < 2.5$. Solid curve uses visible p_τ from generator. Dotted curve uses highest p_T τ and requires $\Delta\phi(\tau, \not{E}_T) < 0.1\pi$:



Need to add τ reconstruction and resolution.

Implications for NLC

If SUSY exists at weak scale, LHC should discover it easily. Precise measurements also possible:

- Kinematic endpoints with high statistics can determine mass combinations.
- Long decay chains help — may determine some masses without relying on model.
- GMSB models generally easier than SUGRA.
- Can find model parameters just using endpoints in simple cases. Much more information available.

Have only studied a few points. Each has required new thinking, even knowing the answer.

Backgrounds dominated by other SUSY channels, so cannot just scan branching ratios.

Lack resources to analyze many points.

NLC with $\sqrt{s} \sim 500\,\mathrm{GeV}$ probably limited to light gauginos and sleptons. Should concentrate on things that seem hardest at LHC:

- Sleptons, especially for $M_{\tilde{\ell}} > M_{\tilde{\chi}_2^0}$.
- Hadronic decays. (Good hadronic calorimetry?)
- τ decays, e.g., for $\tan\beta \gg 1$. (τ tagging?)
- Light Higgs.

Importance depends on complexity of model.

Eventually want to study whole spectrum:

- Heavy gauginos — mainly Higgsino.
- Heavy Higgs bosons.
- Flavor mixing, CP violation, ...

May require $\sqrt{s} \sim 2\,\mathrm{TeV}$.