SUSY Measurements at LHC

Frank E. Paige, BNL

If SUSY exists at TeV scale, “easy” to discover at LHC: $\tilde{g}$ and $\tilde{q}$ are strongly produced and have distinctive decays.

Problem is not discovery but precise measurements.

ATLAS and CMS have studied potential to make such measurements for specific examples of:

- Minimal SUGRA models;
- Minimal GMSB models;
- R-parity violating models.

Will cover small fraction of work, emphasising implications for e^+e^- colliders.

References:

ATLAS *Physics TDR*, Chapter 22 (May 1999).

CMS Note 1998/006 (April 1998).

SUGRA Point 5

Minimal SUGRA model with

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

$$\tan\beta = 2.1,\ \mathrm{sgn}\,\mu = +.$$

Gives right cold dark matter ⇔ light sleptons.

Point 5 has two characteristic $\tilde{\chi}_2^0$ decays:

$$\tilde{\chi}_2^0 \to \tilde{\ell}_R^\pm \ell^\mp \to \tilde{\chi}_1^0 \ell^+ \ell^- \quad \text{and} \quad \tilde{\chi}_2^0 \to \tilde{\chi}_1^0 h \to \tilde{\chi}_1^0 b\bar{b}$$

"Effective mass" measures interaction hardness:

$$M_{\mathrm{eff}} = \not\!\!E_T + p_{T,1} + p_{T,2} + p_{T,3} + p_{T,4}$$

Basic cuts on jets and $\not\!\!E_T$:

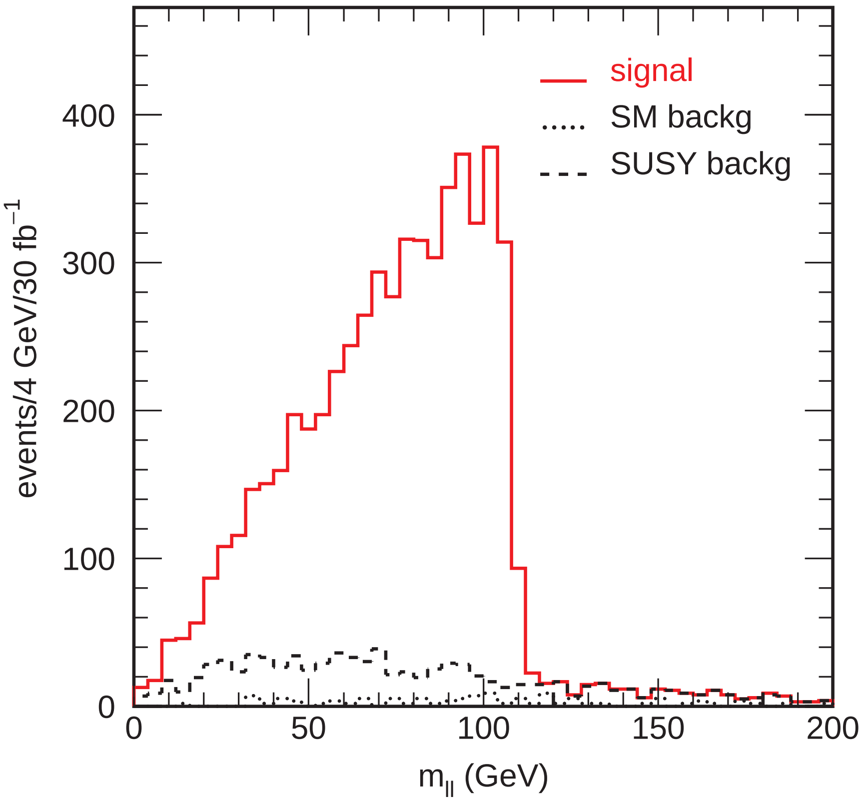
- $N_{\mathrm{jet}} \ge 4$ with $p_T > 100, 50, 50, 50\,\mathrm{GeV}$;
- $M_{\mathrm{eff}} > 400\,\mathrm{GeV}$;
- $\not\!\!E_T > \max(100\,\mathrm{GeV}, 0.2 M_{\mathrm{eff}})$.

Then Standard Model background is small.

Also require $\ell^+\ell^-$ $(\ell = e, \mu)$ with $p_T > 10\,\mathrm{GeV}$, $|\eta| < 2.5$. Then $\tilde\chi_2^0 \to \tilde\ell_R \ell$ dominates $\Rightarrow$ endpoint

$$M_{\ell\ell}^{\max} = M_{\tilde\chi_2^0} \sqrt{1 \Leftrightarrow \frac{M_{\tilde\ell_R}^2}{M_{\tilde\chi_2^0}^2}} \sqrt{1 \Leftrightarrow \frac{M_{\tilde\chi_1^0}^2}{M_{\tilde\ell_R}^2}} = 108.93\,\mathrm{GeV}.$$

Other backgrounds small:



Fit to $e^+e^- + \mu^+\mu^- \Leftrightarrow e^\pm\mu^\mp$ mass for $100\,\mathrm{fb}^{-1}$ gives

$$M_{\ell\ell}^{\max} = 108.71^{+0.087}_{-0.088}\,\mathrm{GeV}.$$

Sensitive to $\tilde e_R \Leftrightarrow \tilde\mu_R$ mass difference of $\sim 0.1\%$.

Four-Body Distributions

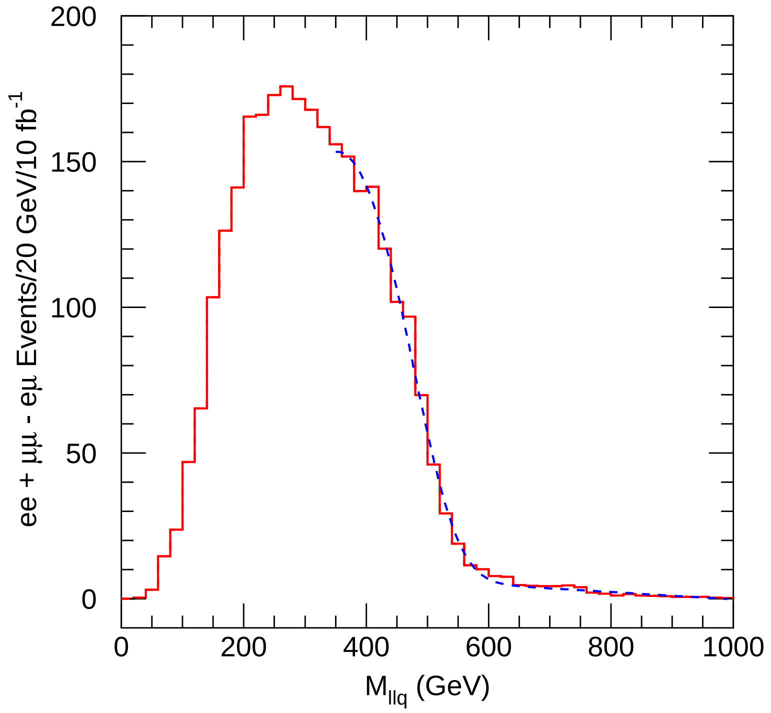
Main source of dileptons is

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

Four-body phase space gives endpoint at

$$M_{\ell\ell q} = \left[\frac{\left(M_{\tilde{q}_L}^2 \Leftrightarrow M_{\tilde{\chi}_2^0}^2 \right) \left(M_{\tilde{\chi}_2^0}^2 \Leftrightarrow M_{\tilde{\chi}_1^0}^2 \right)}{M_{\tilde{\chi}_2^0}^2} \right]^{1/2} = 552\,\mathrm{GeV}\,.$$

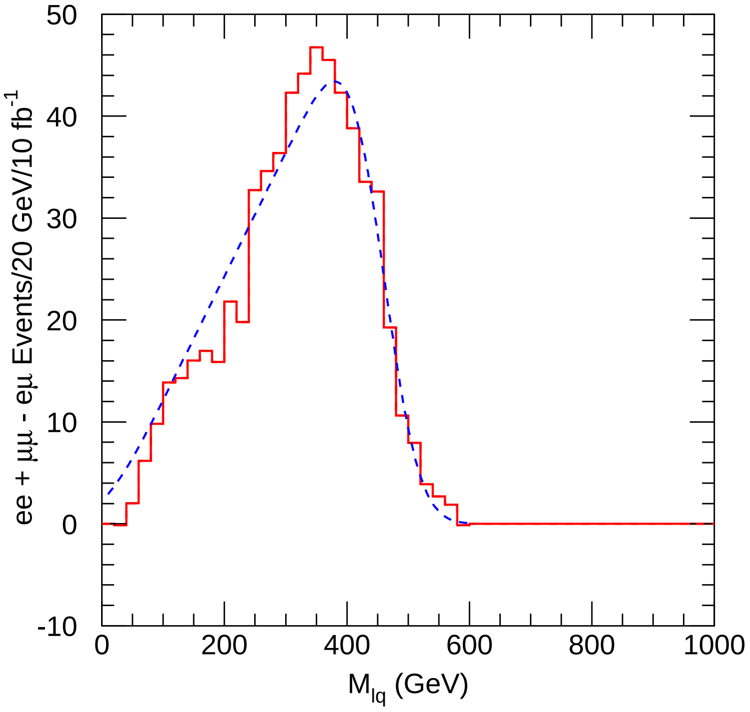
Plot smaller $\ell\ell q$ mass using 2 hardest jets:



Select events with only one $\ell\ell q$ mass below 600 GeV.

Have edge in ℓq mass from “right” lepton at

$$M_{\ell q} = \left[\frac{\left(M^2_{\tilde{q}_L} \Leftrightarrow M^2_{\tilde{\chi}^0_2}\right)\left(M^2_{\tilde{\chi}^0_2} \Leftrightarrow M^2_{\ell_R}\right)}{M^2_{\tilde{\chi}^0_2}} \right]^{1/2} = 479\,\mathrm{GeV}\,.$$



Can fit edges with good precision.

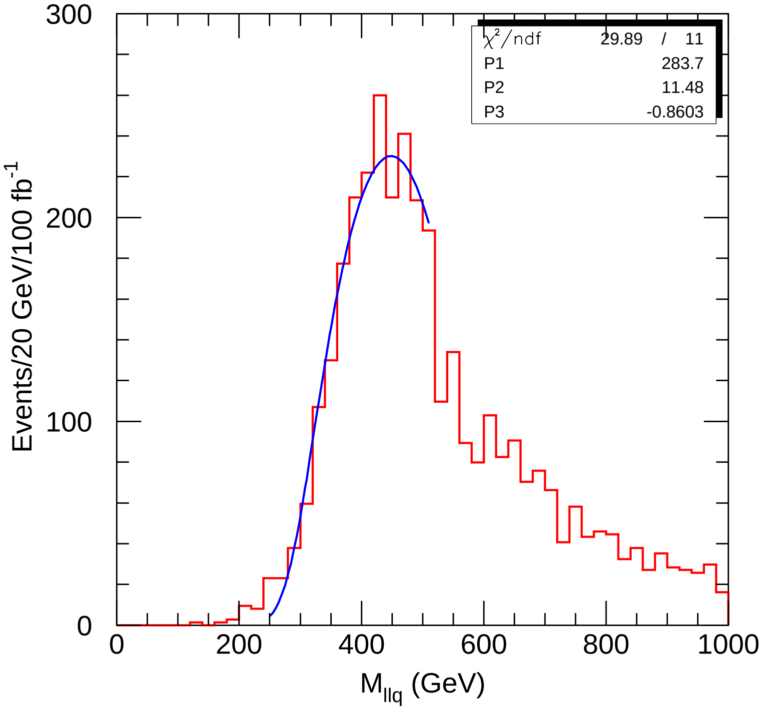
Not sufficient to determine masses.

Backwards Edges

Similar to e^+e^- strategy: use minimum $\ell\ell q$ mass from $\tilde{q}_L$ decay. Depends on minimum $M_{\ell\ell} \Leftrightarrow \cos\theta^*$.

Select events with $M_{\ell\ell} > M_{\ell\ell}^{\max}/\sqrt{2}$. Larger $\ell\ell q$ mass with two hardest jets gives backwards edge at

$$M_{\ell\ell q}^{\min} = F(M_{\tilde{q}_L}, M_{\tilde{\chi}_2^0}, M_{\tilde{\ell}_R}, M_{\tilde{\chi}_1^0}) = 346.5\,\mathrm{GeV}$$

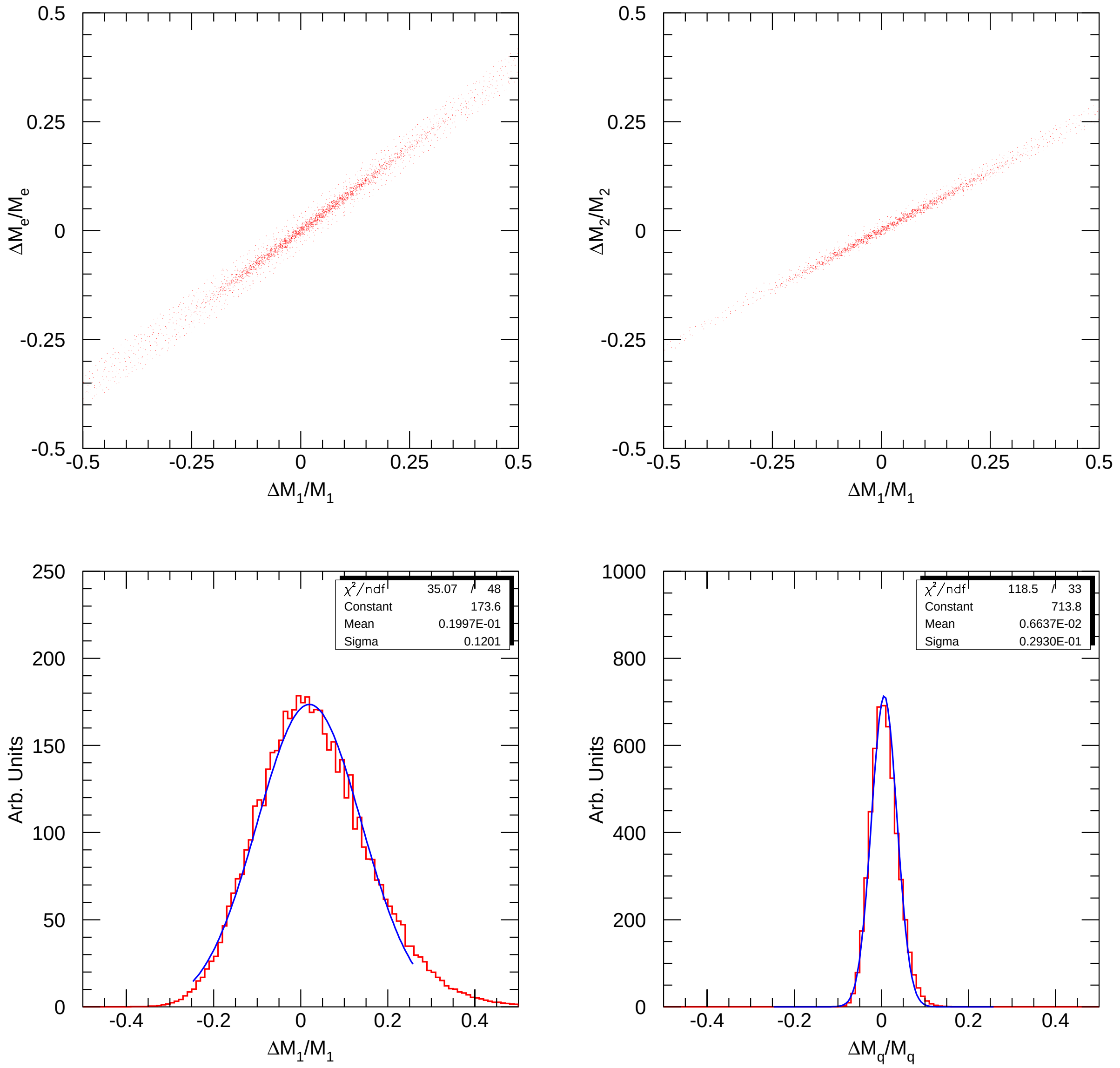


Must constrain resolution for stable fit:

$$M_{\ell\ell q}^{\min} = 283.7^{+4.4}_{-4.5}\,\mathrm{GeV}$$

Model-Independent Masses

Can now determine masses without fitting to minimal SUGRA. Solve constraints numerically:



Can determine masses using only kinematics.

Masses highly correlated with $M_{\tilde{\chi}_1^0}$. Errors range from ±12% on $M_{\tilde{\chi}_1^0}$ to ±3% on $M_{\tilde{q}_L}$. Error on $M_{\tilde{\chi}_1^0}$ controlled by ±2% error on backwards $\ell\ell q$ edge.

Can also fit to minimal SUGRA model:

- $m_0 = 100.0 \pm 1.4\,\mathrm{GeV}$ (1.4%),
- $m_{1/2} = 300.0 \pm 2.7\,\mathrm{GeV}$ (0.9%),
- $\tan\beta = 2.00 \pm 0.11$ (5.5%),
- $\mu = +1$;

Do not constrain A_0 — weak scale A_t insensitive to it. Smaller theory error on $M_h \Rightarrow$ smaller $\Delta\tan\beta$.

But poor constraints on, e.g.,

$$M_{\tilde{d}_R} = M_{\tilde{\ell}_L} = M_{\tilde{\nu}} = m_5 \neq m_0$$

Need $\tilde{\ell}_L$. May be possible at LHC but hard.

Obvious role for NLC.

SUGRA Point 6

For $\tan\beta \lesssim 10$ usually have at least one of

$$\tilde\chi_2^0 \to \tilde\chi_1^0 \ell^+\ell^-,\ \tilde\ell^\pm\ell^\mp,\ \tilde\chi_1^0 h.$$

But for $\tan\beta \gg 1$ only allowed 2-body decay may be

$$\tilde\chi_2^0 \to \tilde\tau_1^\pm\tau^\mp \to \tilde\chi_1^0\tau^+\tau^-$$

Must rely on τ signatures.

Point 6 has $m_{1/2}$ small enough that $\tilde\chi_2^0 \not\to \tilde\chi_1^0 h$, m_0 large enough that $\tilde\chi_2^0 \not\to \tilde\ell_R\ell$, and $\tan\beta$ small enough that $\tilde\chi_2^0 \to \tilde\tau_1^\pm\tau^\mp$:

$$m_0 = 200\,\mathrm{GeV},\ m_{1/2} = 200\,\mathrm{GeV},\ A_0 = 0,$$

$$\tan\beta = 45,\ \mathrm{sgn}\,\mu = \Leftrightarrow$$

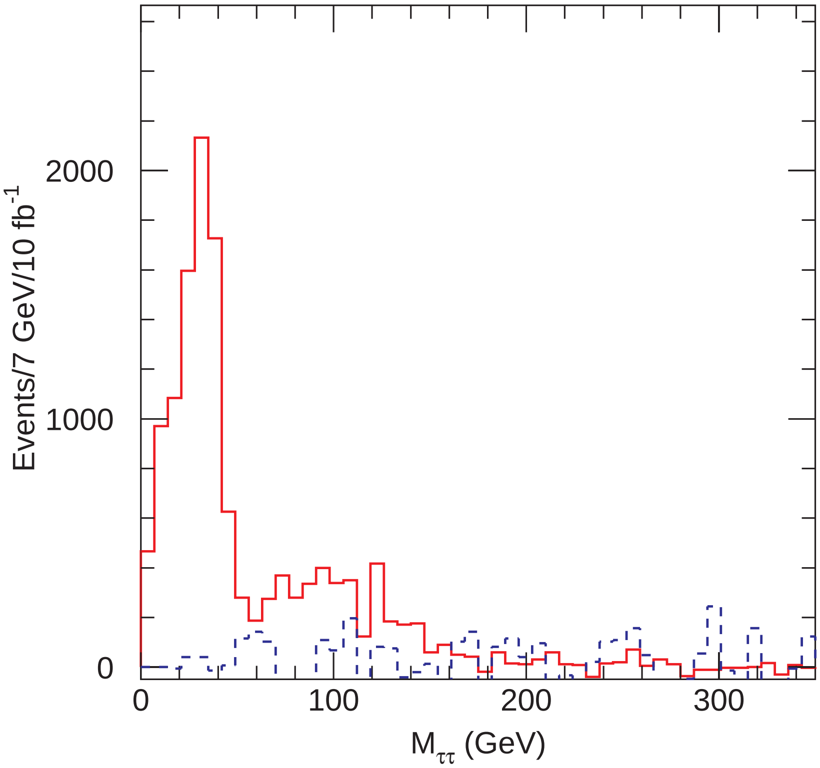
Must measure $\tau\tau$ pairs. Need modest τ identification, so use hadronic τ decays biased towards high mass, for which $M_{\text{visible}} \approx M_{\tau\tau}$.

Algorithm developed using full simulation of ATLAS for $Z \to \tau\tau$ events. Use tracking + EM calorimeter + minimum and maximum jet mass cuts. Result:

- $\langle M_{\rm visible}\rangle = 0.66 M_{\tau\tau}$;
- $(\sigma/M)_{\rm visible} = 0.12$.
- τ/q rejection ≈ 15 — adequate for this case.

Combine with fast simulation.

SUSY dominated by $\tilde{g}\tilde{g}$ and $\tilde{g}\tilde{q} \Rightarrow$ backgrounds from two independent decays cancel in $\tau^+\tau^- \Leftrightarrow \tau^\pm\tau^\pm$:



True $\tau\tau$ edge is at

$$M_{\tau\tau}^{\max} = M_{\tilde{\chi}_2^0} \sqrt{1 \Leftrightarrow \frac{M_{\tilde{\tau}_1}^2}{M_{\tilde{\chi}_2^0}^2}} \sqrt{1 \Leftrightarrow \frac{M_{\tilde{\chi}_1^0}^2}{M_{\tilde{\tau}_1}^2}} = 59.64\,\mathrm{GeV}.$$

Estimated error is $\pm 3\,\mathrm{GeV}$ for $30\,\mathrm{fb}^{-1}$.

Can combine $\tau\tau$ with jets to partially reconstruct gluinos and squarks.

Can also partially reconstruct $\tilde{g} \to \tilde{\chi}_2^0 b\bar{b}$.

Point 6 hard compared to Point 5 but still possible.

Measurements possible at LHC but probably easier at e^+e^- collider.

Should study such cases for NLC.

$\tan\beta$ Dependence

Can also use $e\mu$ events to study τ's. Consider

$$m_0 = 100\,\text{GeV},\ m_{1/2} = 190\,\text{GeV},\ A_0 = 0,\ \text{sgn}\,\mu = +$$

for various $\tan\beta$.

Event selection with CMS detector:

- $\not\!\!E_T > 150\,\text{GeV}$;
- ≥ 3 jets with $p_T > 60\,\text{GeV}$, $|\eta| < 4.5$;
- 2 leptons with $p_T > 10\,\text{GeV}$, $|\eta| < 2.4$.

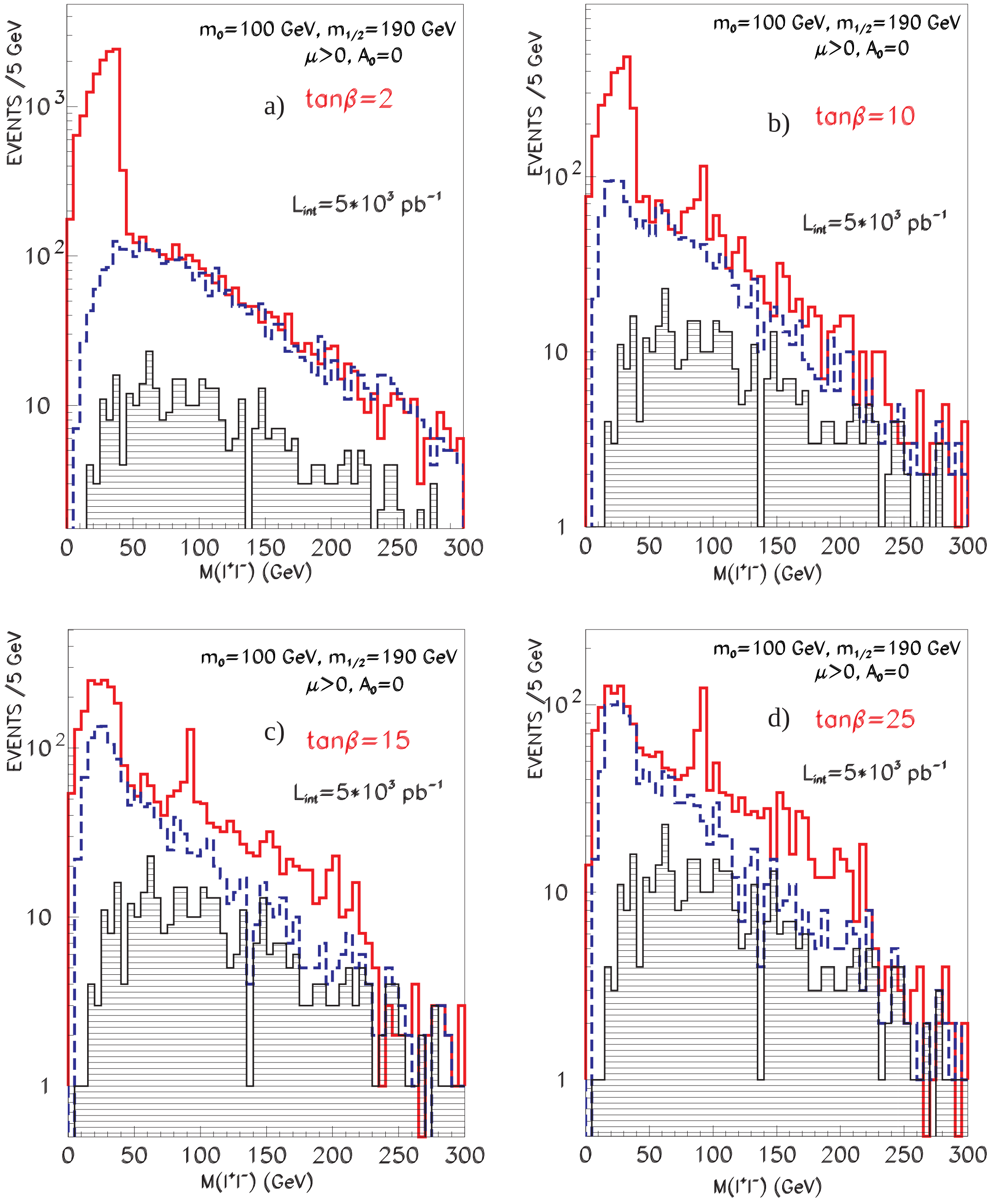
Compare $e^+e^- + \mu^+\mu^-$ (solid), $e^\pm\mu^\mp$ (dashed), and SM $e^+e^- + \mu^+\mu^-$ background (shaded):

$\tan\beta = 2$: Dominant OS-SF edge.

$\tan\beta = 10$: OS-SF edge and Z peak.

$\tan\beta = 15$: Small OS-SF edge, Z peak, and $\tilde\chi_{3,4}^0 \to \tilde\ell_{L,R}^\pm \ell^\mp$ "edge".

$\tan\beta = 25$: Z peak and $\tilde\chi_{3,4}^0 \to \tilde\ell_{L,R}^\pm \ell^\mp$ "edge".


m₀=100 GeV, m₁/₂=190 GeV
μ>0, A₀=0
a) tanβ=2
L_int=5*10³ pb⁻¹
EVENTS /5 GeV
10³
10²
10
0 50 100 150 200 250 300
M(l⁺l⁻) (GeV)
m₀=100 GeV, m₁/₂=190 GeV
μ>0, A₀=0
b) tanβ=10
L_int=5*10³ pb⁻¹
EVENTS /5 GeV
10²
10
1
0 50 100 150 200 250 300
M(l⁺l⁻) (GeV)
m₀=100 GeV, m₁/₂=190 GeV
μ>0, A₀=0
c) tanβ=15
L_int=5*10³ pb⁻¹
EVENTS /5 GeV
10²
10
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0 50 100 150 200 250 300
M(l⁺l⁻) (GeV)
m₀=100 GeV, m₁/₂=190 GeV
μ>0, A₀=0
d) tanβ=25
L_int=5*10³ pb⁻¹
EVENTS /5 GeV
10²
10
1
0 50 100 150 200 250 300
M(l⁺l⁻) (GeV)

GMSB Models

Phenomenology depends on NLSP nature and its lifetime.

Prompt $\tilde{\chi}_1^0 \to \tilde{G}\gamma$ or $\tilde{\ell} \to \tilde{G}\ell$ decays $\Rightarrow$ longer decay chains, hence more constraints.

Compare with $\tilde{q}_L \to \tilde{\chi}_2^0 \to \tilde{\ell}_R \to \tilde{\chi}_1^0$ chain at SUGRA Point 5.

Long-lived NLSP $\tilde{\ell} \Rightarrow$ full reconstruction.

Important to reconstruct muon-like tracks with $\beta < 1$ and to measure mass with TOF or dE/dx.

Long-lived NLSP $\tilde{\chi}_1^0$ qualitatively like SUGRA. Could distinguish case studied from minimal SUGRA.

Rare $\tilde{\chi}_1^0 \to \tilde{G}\gamma$ decays measure true SUSY breaking scale. ATLAS EM calorimeter provides good γ angle measurement. Sensitive to $\sim 100\,\mathrm{km}$.

Status and Outlook

If SUSY exists at TeV scale, discovery at LHC seems stKrightforward for all cases considered.

LHC produces many SUSY channels. Background to SUSY is SUSY. Measurements are model dependent.

Hard to draw general conclusions, but reasonably expect to make many precise measurements.

Recent results from LHC SUSY studies:

- Long decay chains provide multiple constraints.
- Such multiple constraints make determination of masses and full reconstruction possible.
- GMSB models generally easier than SUGRA models.
- New signatures identified including non-pointing γ's and stable $\tilde{\ell}$'s.
- Complete study needs full range of ATLAS/CMS capabilities and full LHC luminosity.

ATLAS analyses mainly use kinematic endpoints. Small fraction of total information available.

Plausibly expect to do better.

NLC should concentrate on aspects of SUSY models that seem difficult to study at LHC:

- Heavy Higgs bosons.
- Heavy Higgsinos, unless strong gaugino-Higgsino mixing from small μ or large $\tan\beta$.
- Sneutrinos and sleptons with $M_{\tilde{\ell}} > M_{\tilde{\chi}_2^0}$.
- Dominant τ decays.