SUSY Signatures at LHC

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SUSY is promising candidate for physics beyond Standard Model. Well studied by ATLAS and CMS:

- *ATLAS Detector and Physics Performance TDR*, Chap. 20, CERN/LHCC 99-15;
- *Discovery potential for supersymmetry in CMS*, Note 1998/006.

Work is actively continuing.

If SUSY exists at TeV scale, LHC should find it easily: sensitive to $\sim 2\,\mathrm{TeV}$ for $10\,\mathrm{fb}^{-1}$.

Problem is to make precision measurements.

Strategy: select particular decay chains and use kinematics to determine mass combinations.

General approach for ATLAS and CMS studies:

- Generate signal for given SUSY point with shower event generator (HERWIG, ISAJET, PYTHIA).
- Do same for SM backgrounds (Wj, Zj, $t\bar{t}$, jj,...).
- Simulate detector response with parameterized simulation (based on detailed GEANT simulation of engineering design).
- Apply same analysis to signal and background.

ATLAS and CMS generally find comparable results.

Typical analysis involves a few people working 1–2 months. Impractical to study many models.

Given hint of SUSY, analysis of real data would simulate and compare large numbers of models.

SUSY Search

$\tilde{g}$ and $\tilde{q}$ strongly produced, so cross sections comparable to QCD at same Q^2.

If R conserved, cascade decays produce distinctive events: multiple jets, leptons, and $\not\!\!E_T$. Typical cuts:

- $N_{\rm jet} \geq 4$ with $E_T > 100, 50, 50, 50\,{\rm GeV}$;
- $\not\!\!E_T > 100\,{\rm GeV}$.

S/B is then good at large Q, so reach is limited mainly by $\tilde{g}$, $\tilde{q}$ cross sections. SUGRA results:

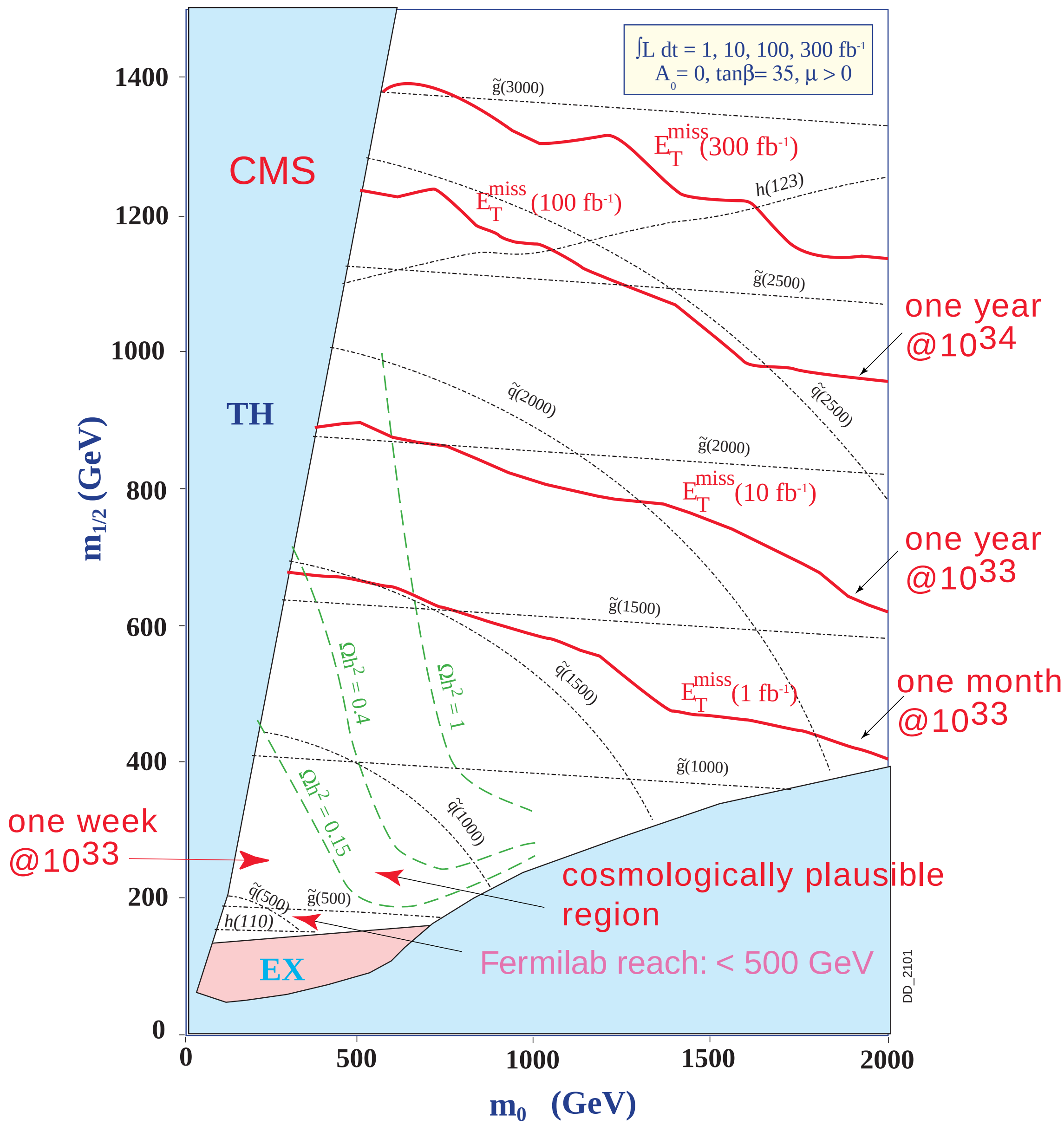
$$1\,{\rm fb}^{-1} \Rightarrow M \sim 1500\,{\rm GeV}$$

$$10\,{\rm fb}^{-1} \Rightarrow M \sim 2000\,{\rm GeV}$$

$$100\,{\rm fb}^{-1} \Rightarrow M \sim 2500\,{\rm GeV}$$

Could find TeV scale SUSY quickly!

LHC reach [Denegri]:



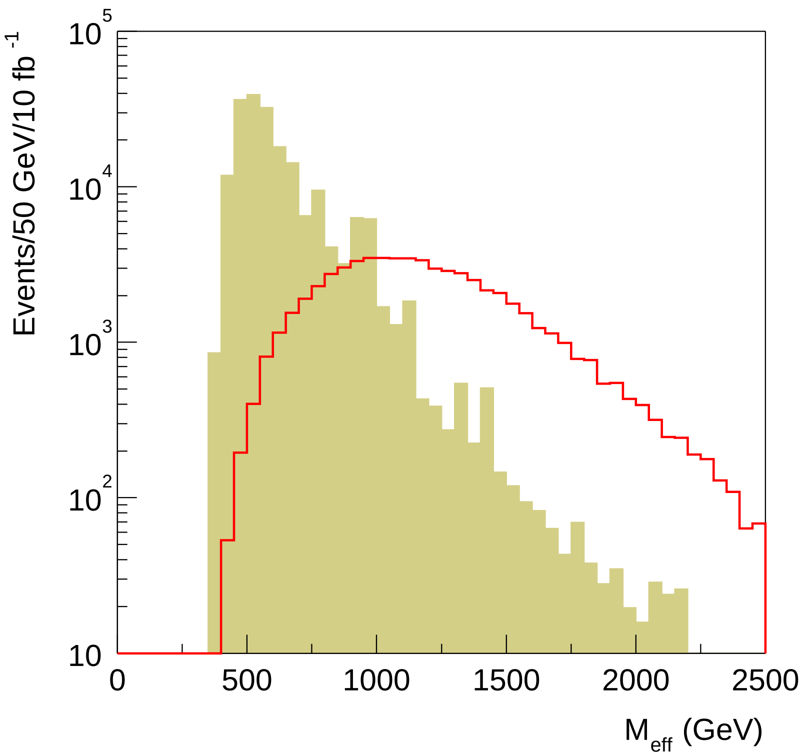
Catania 18

SUSY08 talk on *"Observation of Multijet + $\not\!\!E_T$ Events at LHC"*??

Require ≥ 4 jets plus $\not\!\!E_T$. Plot "effective mass"

$$M_{\rm eff} = \not\!\!E_T + \sum_j p_{T,j}$$

for SUGRA with $m_0 = 100\,{\rm GeV}$, $m_{1/2} = 300\,{\rm GeV}$, $A_0 = 0$, $\tan\beta = 10$, $\mu > 0$:



Simple cuts can give rather pure SUSY sample.

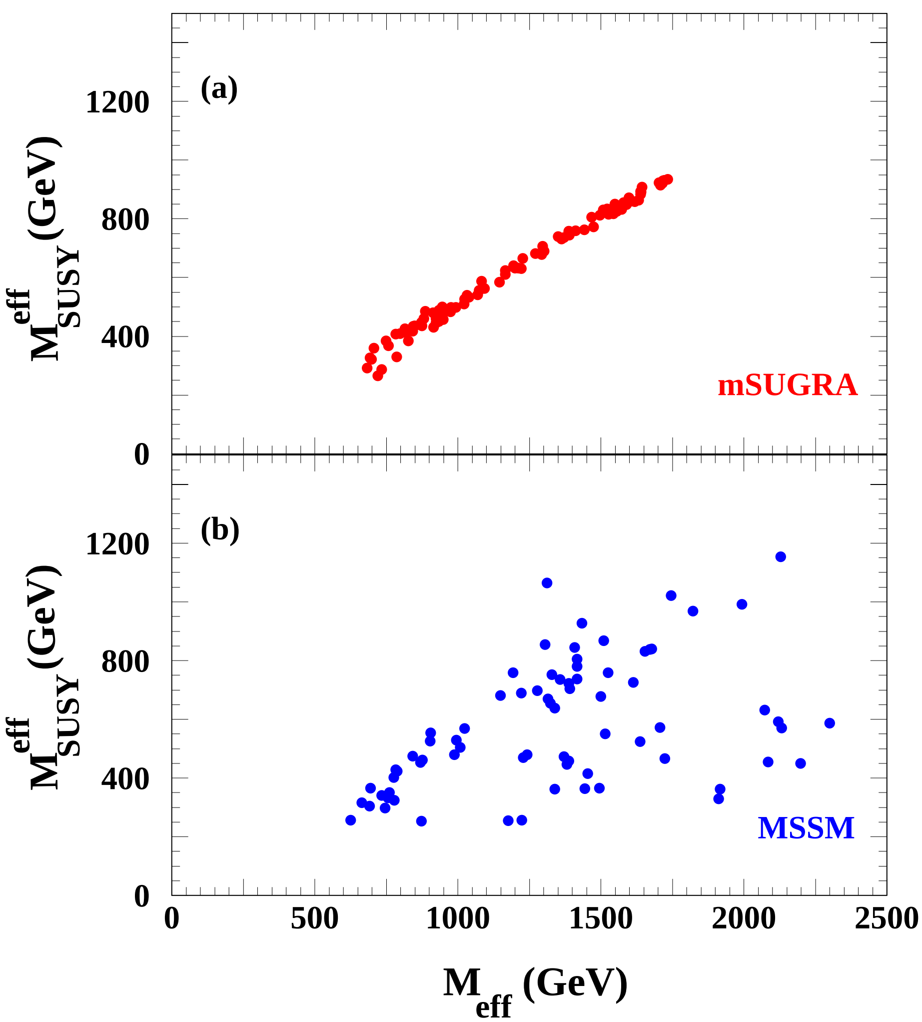
Main background for SUSY is SUSY.

Define average produced SUSY mass [Tovey]:

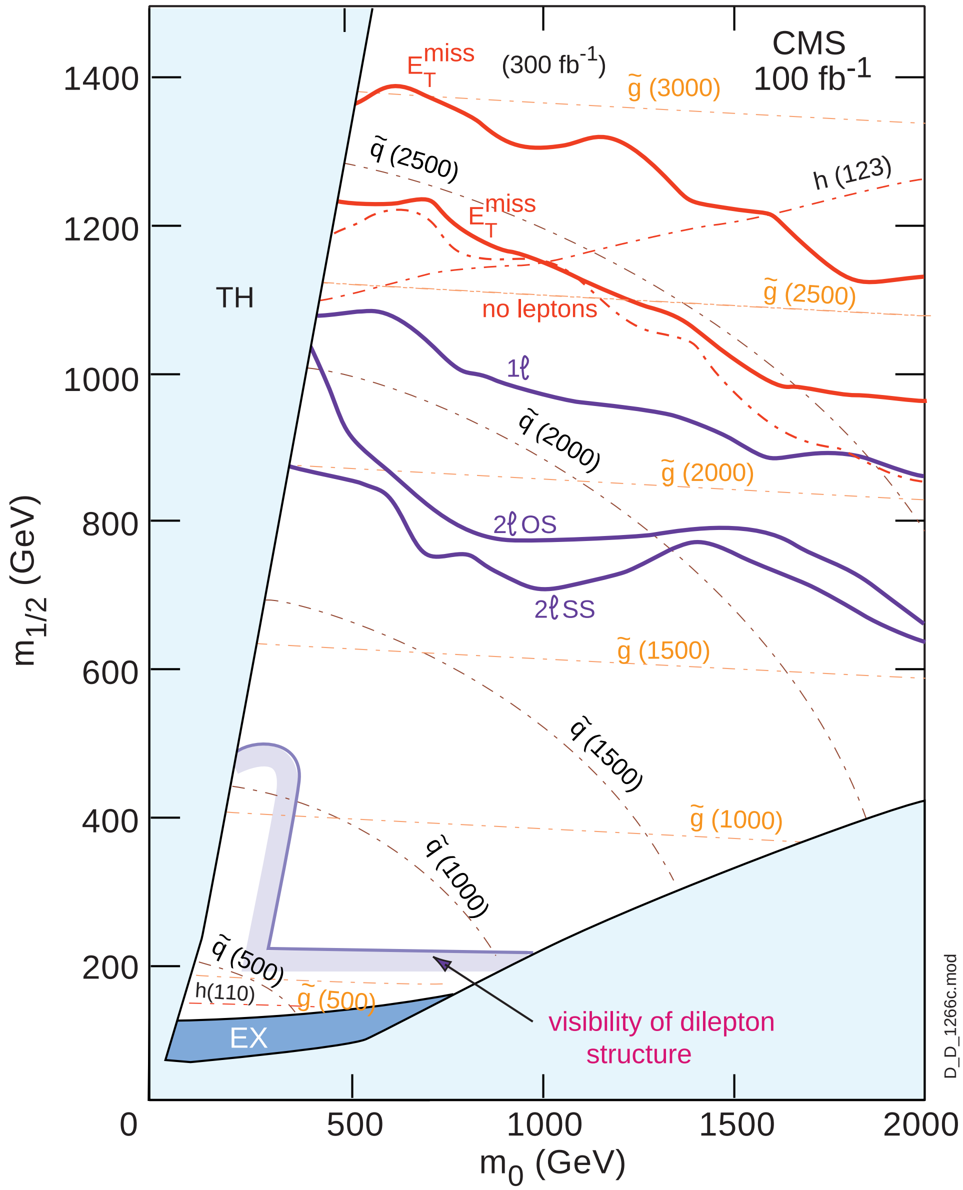
$$M_{\rm SUSY} \equiv \frac{\sum_i M_i \sigma_i}{\sum_i \sigma_i}$$

$$M_{\rm SUSY}^{\rm eff} \equiv M_{\rm SUSY} - \frac{M^2(\tilde\chi_1^0)}{M_{\rm SUSY}}$$

Good correlation with $M_{\rm eff}$ for SUGRA; not bad even for MSSM [Tovey]:



SUSY cascade decays give rise to many inclusive signatures: leptons, b jets, τ's, ... [CMS]:



Expect multiple signatures for TeV-scale SUSY.

Models other than SUGRA have been studied:

GMSB with prompt NLSP $\tilde{\chi}_1^0$ or $\tilde{\ell}_R$ decays give additional handles and are easier.

GMSB with quasi-stable $\tilde{\ell}_R$ is trivial: muon system provides excellent TOF.

AMSB gives few single leptons but more $\not{E}_T$.

R-violation via $\tilde{\chi}_1^0 \to \ell^+\ell^-\nu$ or $q\bar{q}\ell, q\bar{q}\nu$ gives additional leptons and/or $\not{E}_T$.

R-violation via $\tilde{\chi}_1^0 \to cds$ is probably hardest case: c tagging is poor and QCD N-jet background is poorly known. Probably must rely on leptonic cascade decays.

Fine tuning arguments are only qualitative, and cold dark matter constraint cannot exclude heavy masses.

3 TeV is *much* harder than 1 TeV.

SUGRA Measurements

Invisible LSP $\Rightarrow$ no mass peaks. But kinematic endpoints $\Rightarrow$ mass combinations.

Simplest case: $\tilde\chi_2^0 \to \tilde\chi_1^0 \ell^+\ell^-$ has endpoint

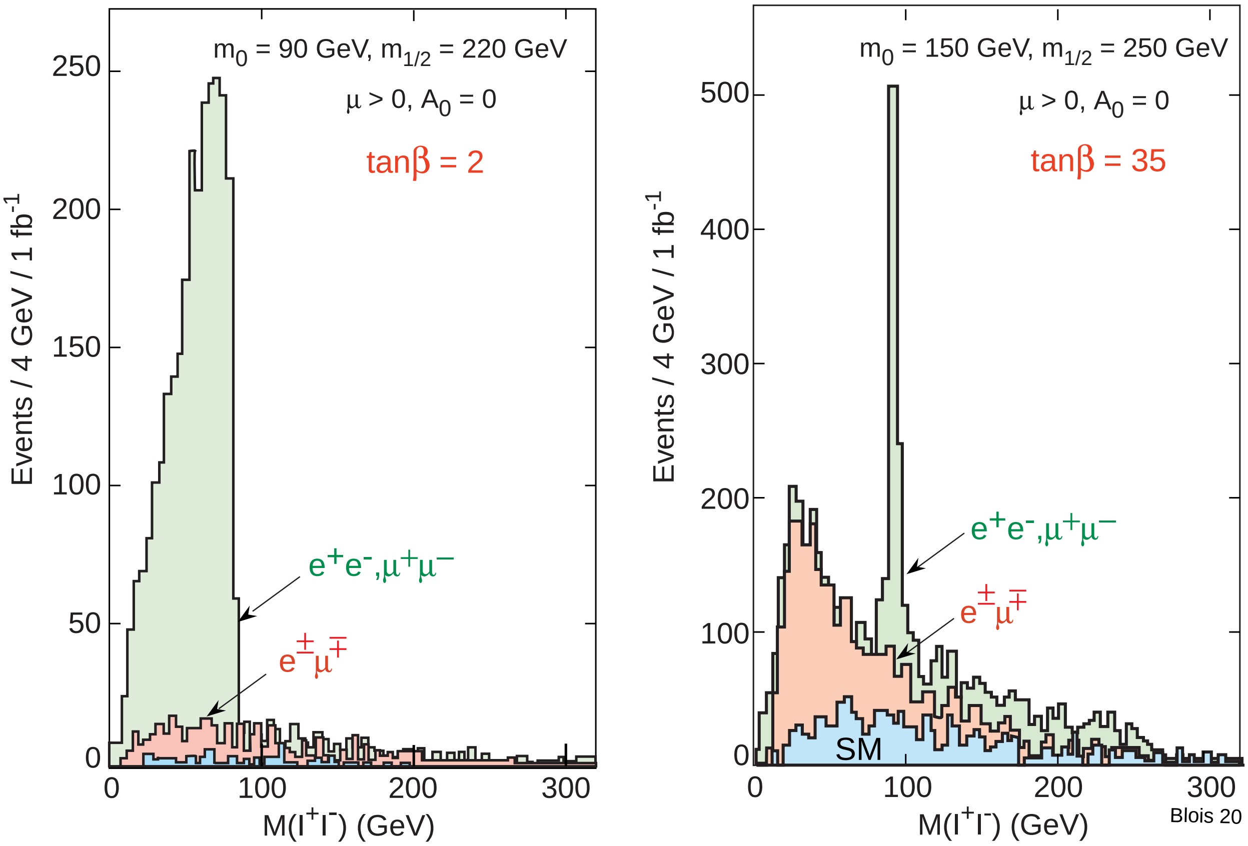
$$M_{\ell\ell} = M_{\tilde\chi_2^0} - M_{\tilde\chi_1^0}$$

Significant mode if $\tilde\chi_2^0 \not\to \tilde\chi_1^0 Z, \tilde\chi_1^0 h, \tilde\ell\ell$.

Require 2 isolated leptons, multiple jets, and large $\not\!\!E_T$. $\Rightarrow$ main SM background is $t\bar t$. Combination $e^+e^- + \mu^+\mu^- - e^\pm\mu^\mp$ cancels independent decays from SM or SUSY.

Can have 3-body $\tilde\chi_2^0 \to \tilde\chi_1^0 \ell^+\ell^-$ decay, cascade decay $\tilde\chi_2^0 \to \tilde\ell^\pm\ell^\mp \to \tilde\chi_1^0\ell^+\ell^-$, or decay via Z.

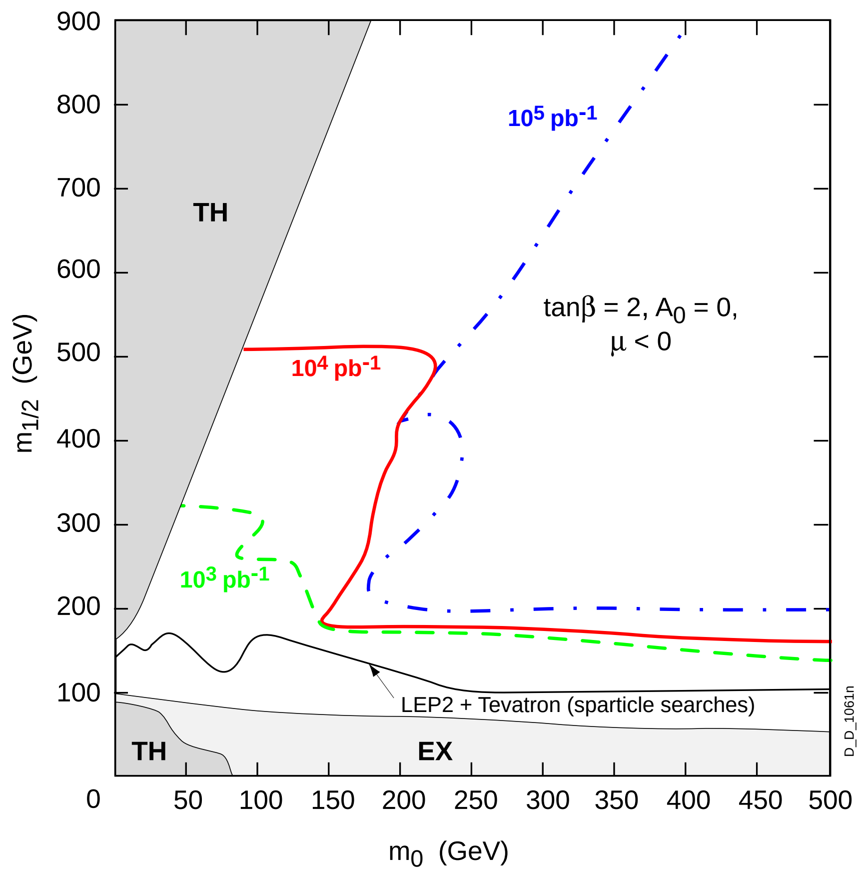
Typical $\ell^+\ell^-$ distributions [Denegri]:



Can distinguish modes possible using shape of $\ell^+\ell^-$ mass distribution.

"Generic" SUGRA region with acceptable cold dark matter has light sleptons $\Rightarrow$ enhanced $\ell^+\ell^-$ decays.

Can observe such $\ell^+\ell^-$ endpoints over significant fraction of SUGRA parameter space [Abdullin]:



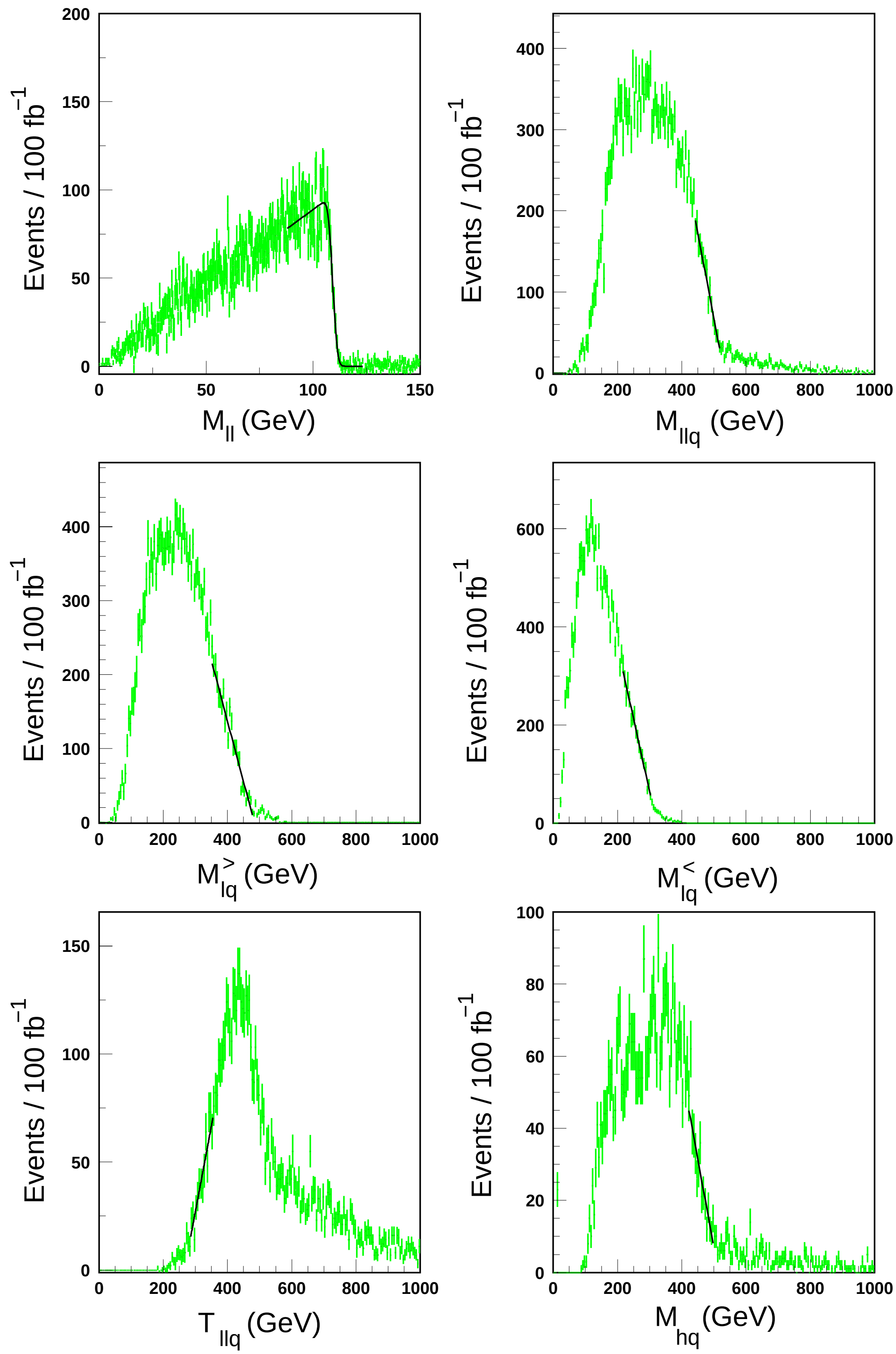
Long decay chains allow more measurements.

Dominant source of $\tilde\chi_2^0$ at SUGRA Point 5 is

$$\tilde q_L \to \tilde\chi_2^0 q \to \tilde\ell_R^\pm \ell^\mp q \to \tilde\chi_1^0 \ell^+ \ell^- q$$

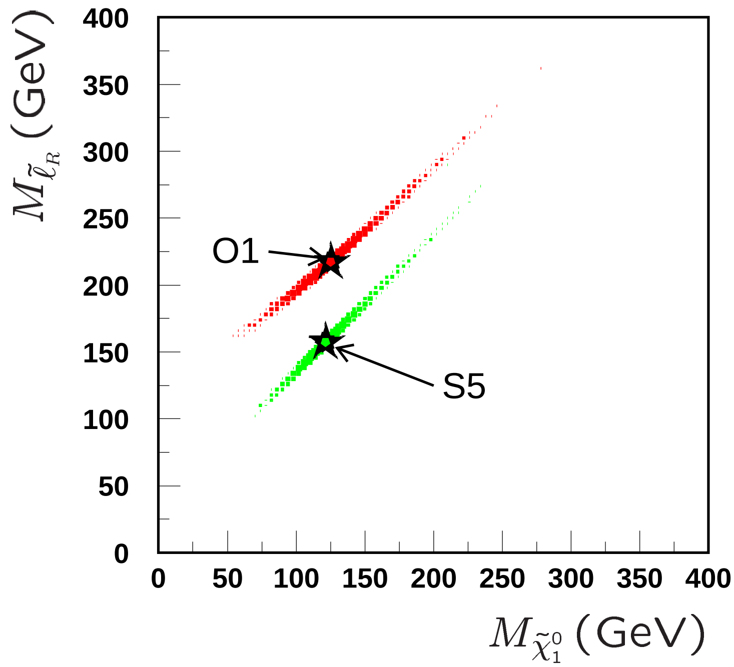
Assume 2 hardest jets come from squarks and combine them with leptons to form:

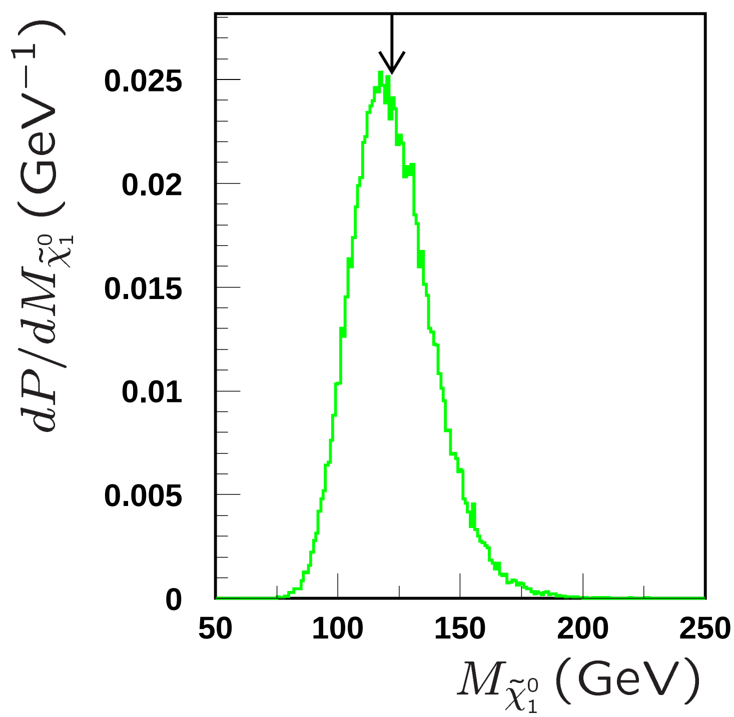
- Endpoints $M_{\ell\ell q}$, $M_{\ell q}^{(1)}$, $M_{\ell q}^{(2)}$;
- Threshold $T_{\ell\ell q}$ from $M_{\ell\ell} > cM_{\ell\ell}^{\max}$.



Enough constraints to determine all masses without model assumptions(!).

Results for Point 5 and “Optimized String Model” with similar masses [Allanach]:





Models are clearly distinguished, but LSP mass is not well determined. Two reasons:

- LSP mass is small, and its effect on kinematics vanishes as $M_{\tilde{\chi}_1^0} \to 0$.
- QCD radiation smears $\ell\ell q$ threshold.

Measurement of $M_{\tilde{\chi}_1^0}$ from $e^+e^- \to \tilde{\ell}^+\tilde{\ell}^-$ would greatly improve errors on other masses.

"Generic" SUGRA model giving acceptable cold dark matter has light sleptons to annihilate $\tilde{\chi}_1^0$'s efficiently, so same analysis should be applicable.

Alternative is to reconstruct $\tilde{\chi}_2^0$ momentum using

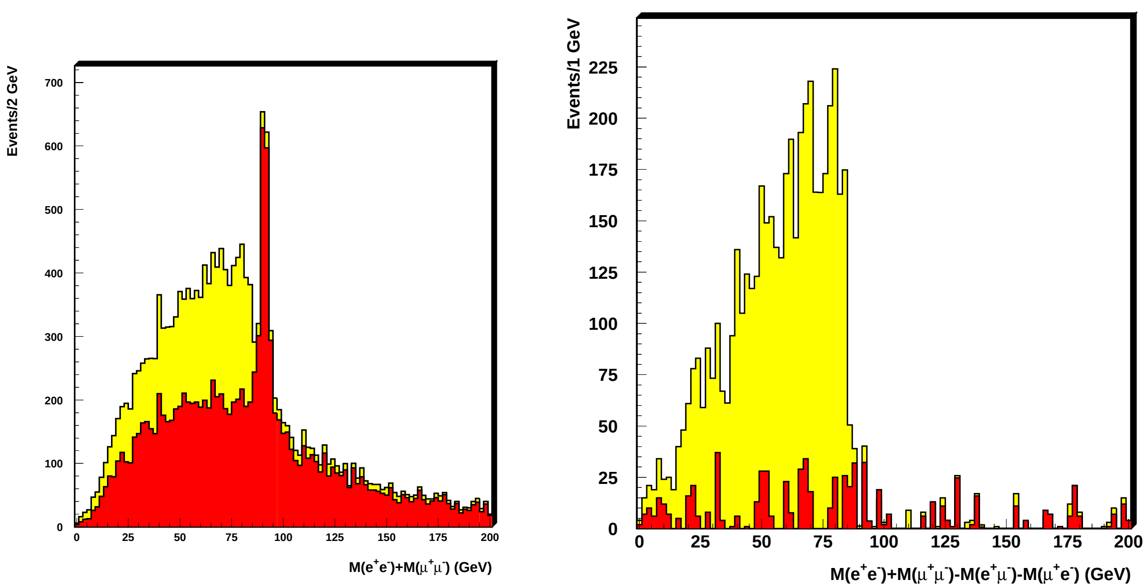
$$\vec{p}_{\tilde{\chi}_2^0} = \vec{p}_{\ell\ell}\left(1 + \frac{M_{\tilde{\chi}_1^0}}{M_{\ell\ell}}\right)$$

Exact only for $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \ell\ell$ at endpoint.

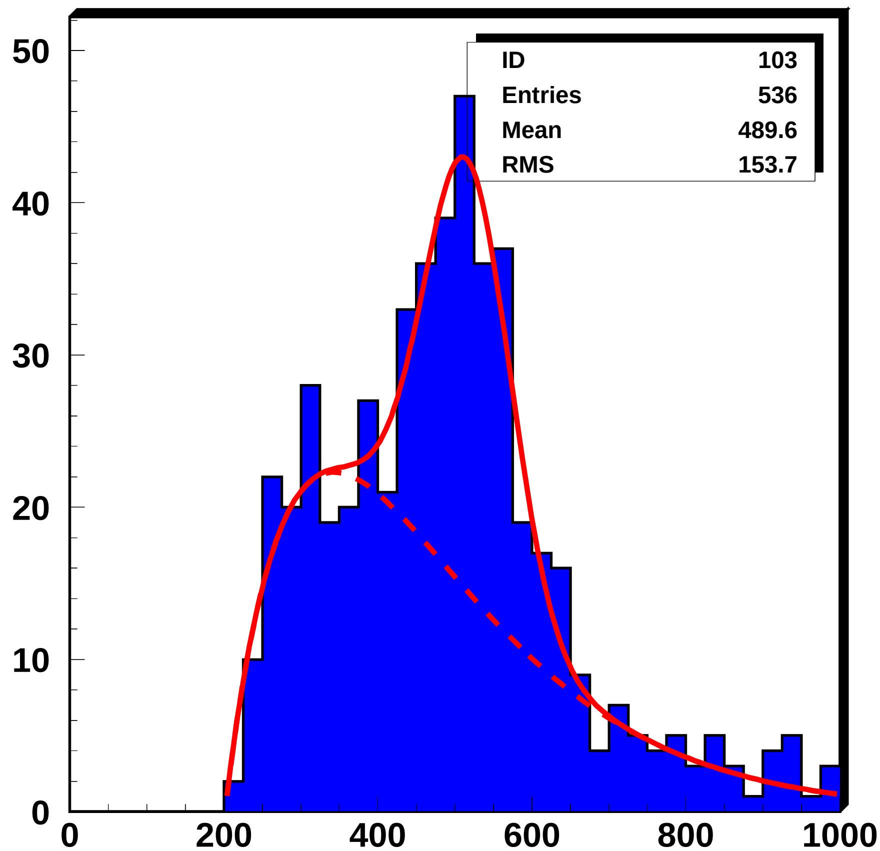
Analysis for SUGRA Point B ($m_0 = 100\,\mathrm{GeV}$, $m_{1/2} = 250\,\mathrm{GeV}$, $A_0 = 0$, $\tan\beta = 10$, $\mu > 0$) looks for

$$\tilde{g} \to \tilde{b}\bar{b} \to \tilde{\chi}_2^0 b\bar{b} \to \tilde{\ell}\ell b\bar{b} \to \tilde{\chi}_1^0 \ell\ell b\bar{b}$$

First find dileptons. Left: minimal cuts. Right: with $\not{E}_T > 50\,\mathrm{GeV}$ and flavor subtraction cuts [Chiorboli]:



Combine $\tilde{\chi}_2^0$ from $75 < M_{\ell\ell} < 92\,\mathrm{GeV}$ with one b jet to form $\tilde{b}$ [Chiorboli]:

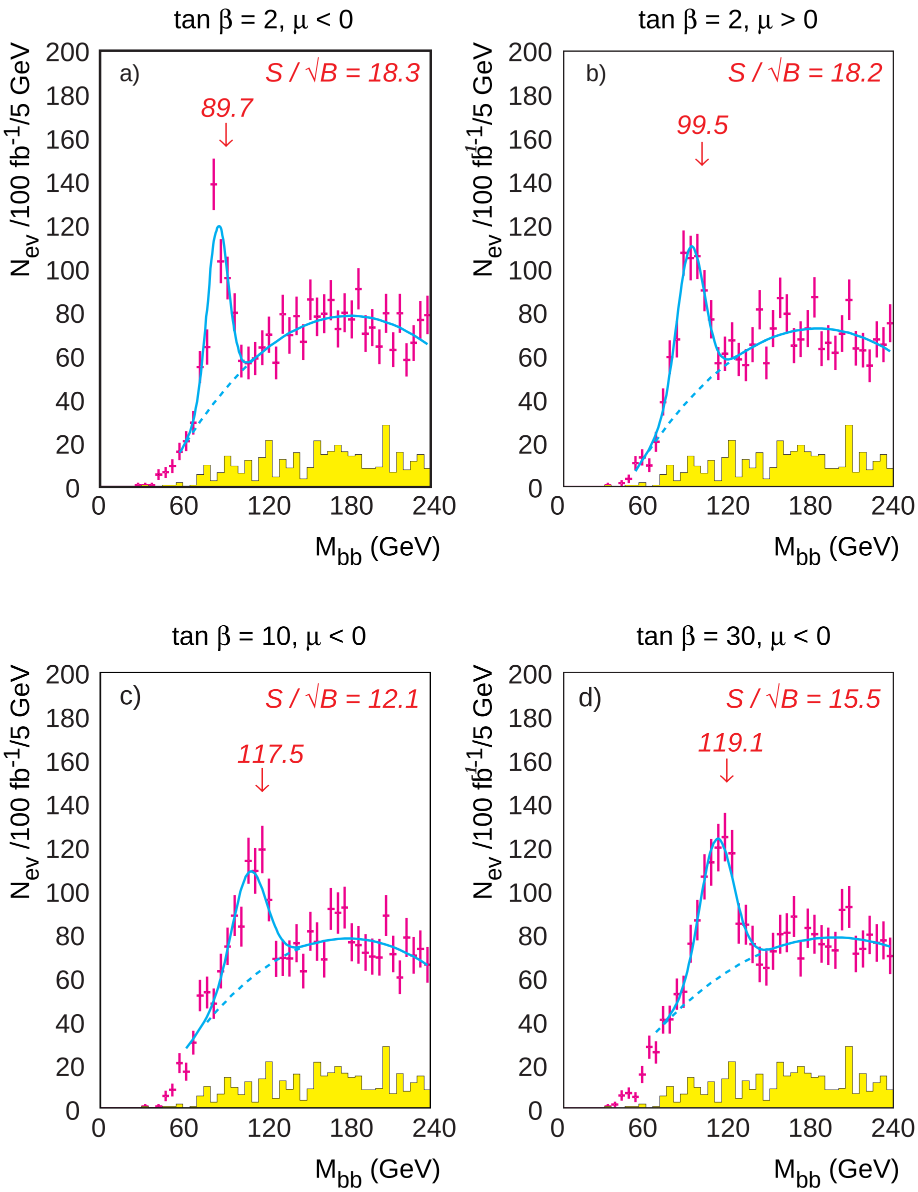


For $M(\tilde{b}_L) = 523\,\mathrm{GeV}$, $M(\tilde{b}_R) = 550\,\mathrm{GeV}$, reconstruct

$$M(\tilde{b}) = 516 \pm 8\,\mathrm{GeV}$$

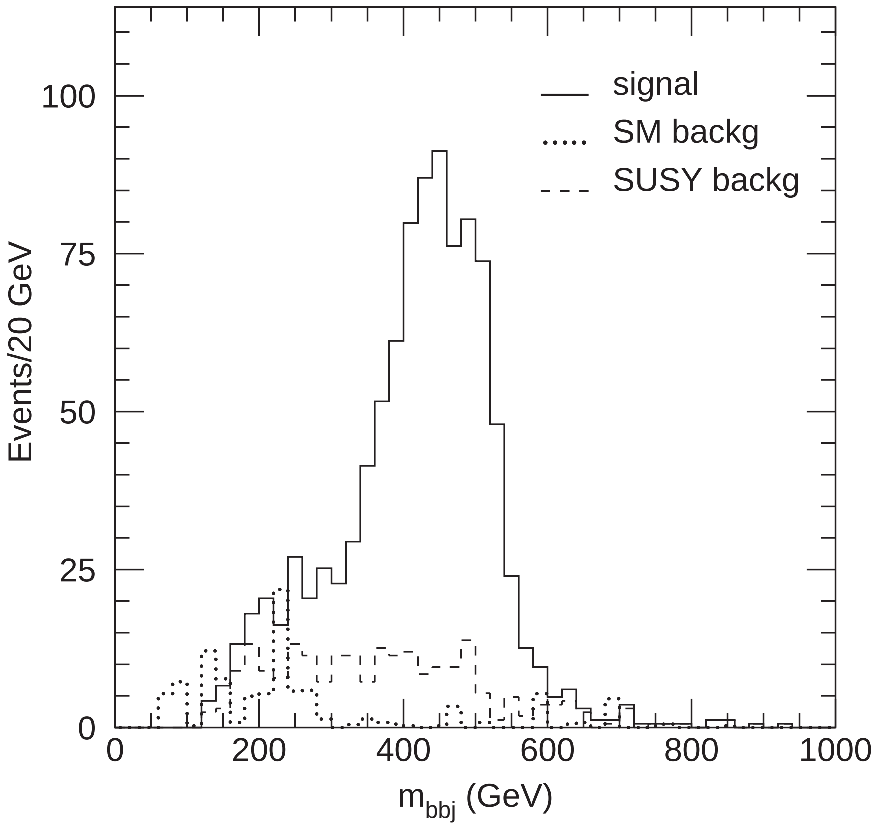
Combine with second b to reconstruct $\tilde{g}$; see talk by Tricomi for details.

$h \to b\bar{b}$: May have small rate for $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \ell\ell$ but much larger rate for $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 h$. Can reconstruct $b\bar{b}$ peak in many cases [Abdullin]:



Could be Higgs discovery mode!

Can combine $h \to b\bar{b}$ with jets to determine other masses. Example for "Point 5": smaller of bbj_1, bbj_2 is less than $\tilde{q} \to \tilde{\chi}_1^0 hq$ endpoint [ATLAS TDR]:



Less precise than $\ell^+\ell^- q$ endpoint, but applicable in cases for which leptonic decays are small.

Complex Cases

SUSY events can be quite complex.

"Focus Point" region near $\mu = 0$ boundary. Gives Higgsino LSP, so OK for cosmology.

For $m_0 = 1500\,\mathrm{GeV}$, $m_{1/2} = 300\,\mathrm{GeV}$, $A_0 = 0$, $\tan\beta = 10$, $\mu > 0$, produce mainly $\tilde{g}\tilde{g}$ events with

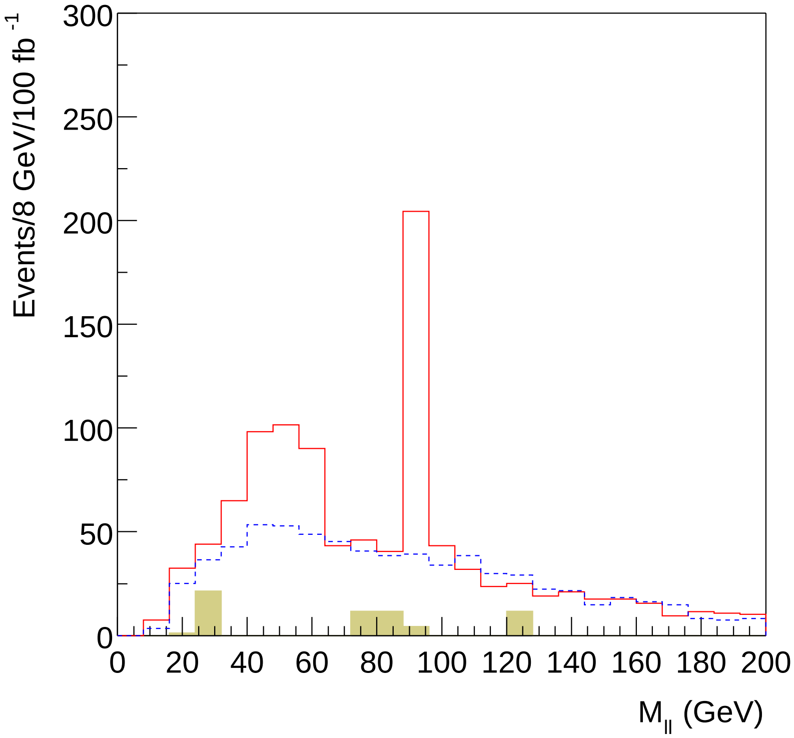
$$B(\tilde{g} \to \tilde{\chi}_1^- t\bar{b} + \mathrm{h.c.}) \approx B(\tilde{g} \to \tilde{\chi}_2^- t\bar{b} + \mathrm{h.c.}) \approx 23\%.$$

Implies events with 12–16 jets + leptons!

General search methods work fine.

Sorting out combinatorial background with many jets, even many b jets, needs work. But can use similar starting points.

E.g., $e^+e^- + \mu^+\mu^- - e^\pm\mu^\mp$ mass distribution shows 3-body endpoint plus Z peak [Hinchliffe]:



R violation with $\tilde{\chi}_1^0 \to qqq$ also gives many jets.

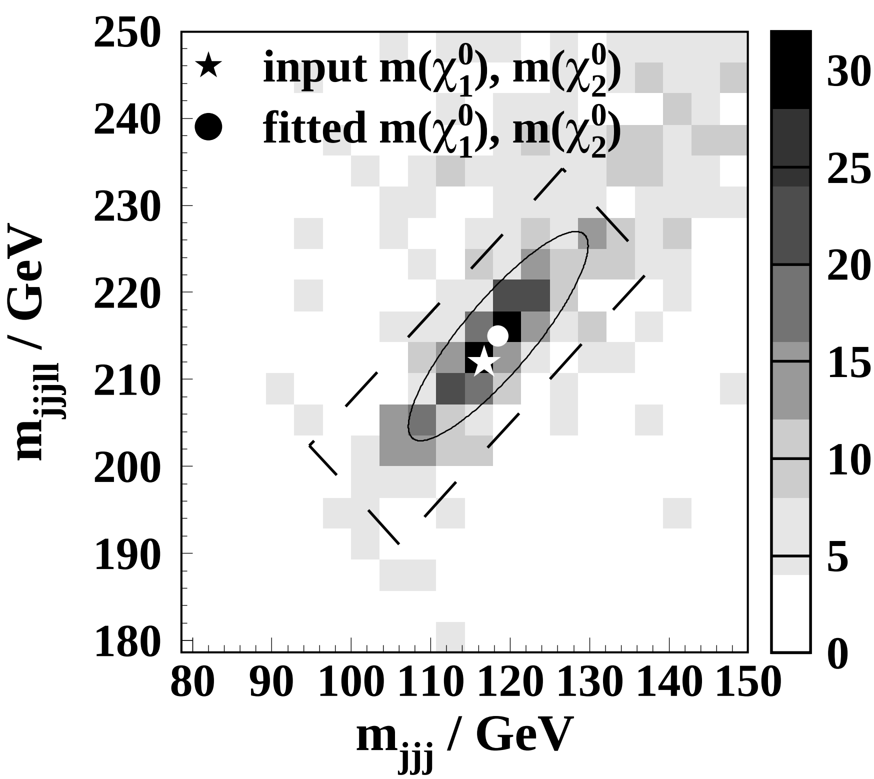
$\not{E}_T$ is small, so poorly known QCD background.

Probably must use cascade decays involving leptons, e.g.,

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

Then reconstruct mass peaks.

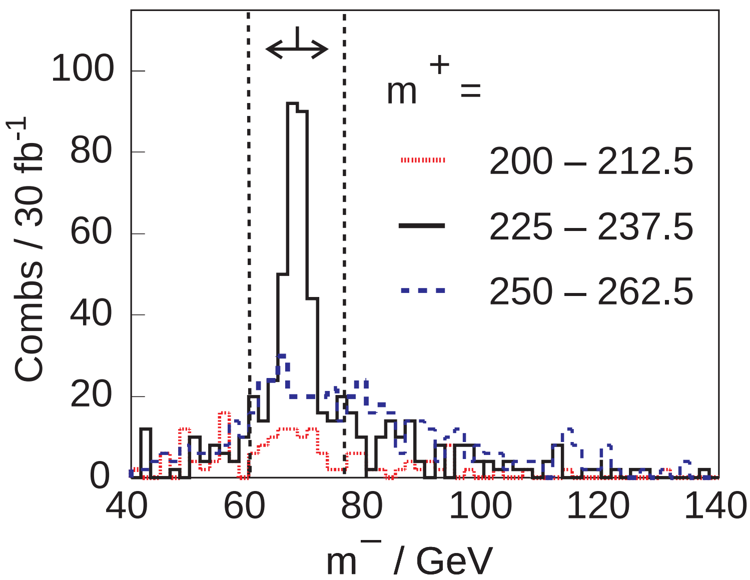
Mass resolution is only $\sim 10\%$ and some jets are soft. Look at correlation [Allanach]:

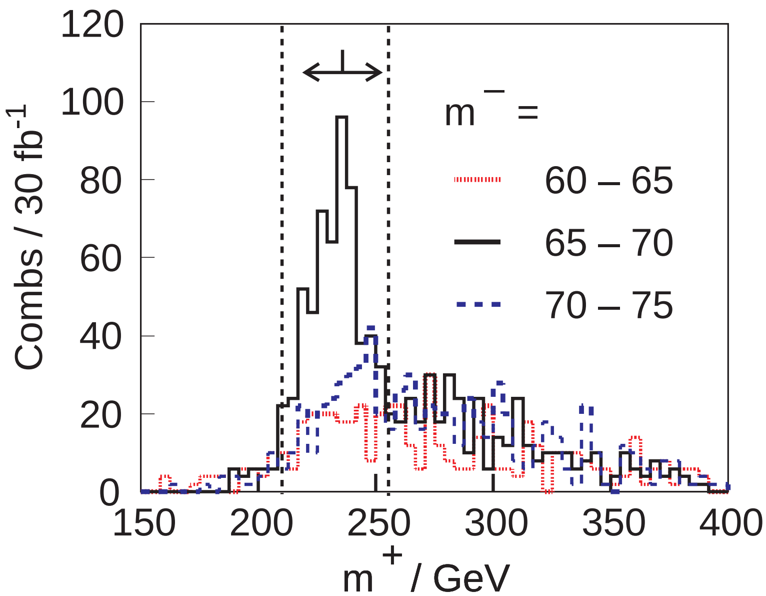


Advantageous to use

$$M^{\pm} = M(qqq\ell^+\ell^-) \pm M(qqq)$$

Resulting projections in each variable cut around the other shows nice signal:





Need more study of complex events like these.

τ Signatures

Initial motivation came from SUGRA models with large $\tan\beta$ giving dominant decays

$$\tilde{\chi}_2^0 \to \tilde{\tau}_1 \tau \quad \tilde{\chi}_1^\pm \to \tilde{\tau}_1^\pm \nu_\tau$$

Simplest version gives large $g_\mu - 2$ contribution.

Want $\tilde{e}_{L,R} \approx \tilde{\mu}_{L,R}$ but expect $\tilde{\tau}$ to differ:

- Mixing of $\tilde{\tau}_L$-$\tilde{\tau}_R$ ($\propto m_\tau$).
- Yukawa contributions to gauginos, RGE's.

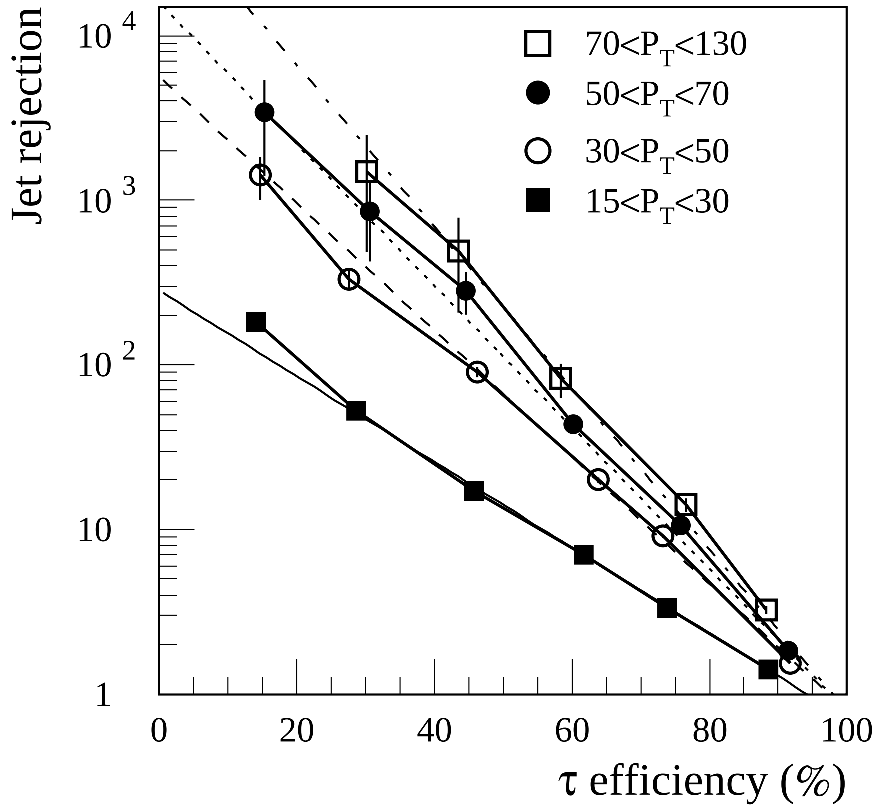
Enhanced for $\tan\beta \gg 1$; c.f., LEP Higgs limit.

τ's are difficult but give unique information.

First problem is to identify τ's. Cannot tag with vertex, so select narrow 1-prong jets.

More background than e, μ but need only select τ's from jets in SUSY events.

Typical $R_{\rm jet} \sim 100$ at $\epsilon_\tau \sim 50\%$ [ATLAS TDR]:

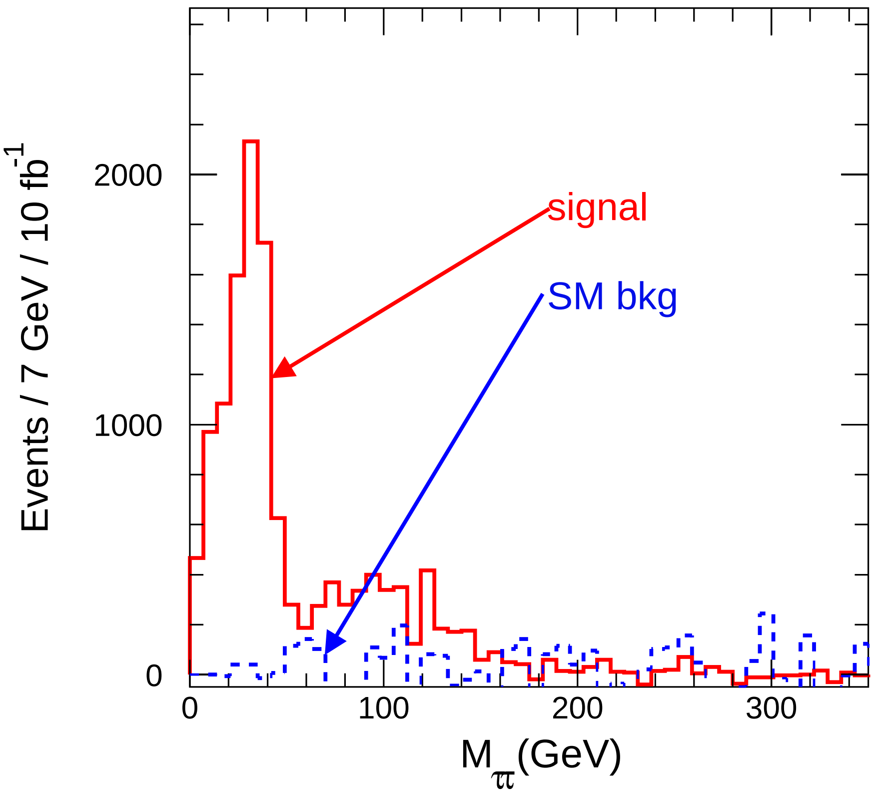


Have $\not\!\!E_T$ from both ν_τ's and $\tilde\chi_1^0$'s. Must rely on visible $\tau\tau$ mass.

SUGRA model with $m_0 = m_{1/2} = 200\,{\rm GeV}$, $A_0 = 0$, $\tan\beta = 45$ would give dominant

$$\tilde\chi_2^0 \to \tilde\tau_1 \tau, \qquad \tilde\chi_1^\pm \to \tilde\tau_1 \nu_\tau$$

Sharp $\tau\tau$ edge at $59.64\,{\rm GeV}$ becomes [ATLAS TDR]:



Visible τ momentum depends on both $\vec{p}_\tau$ and λ_τ; for $\tau \longrightarrow \pi\nu$

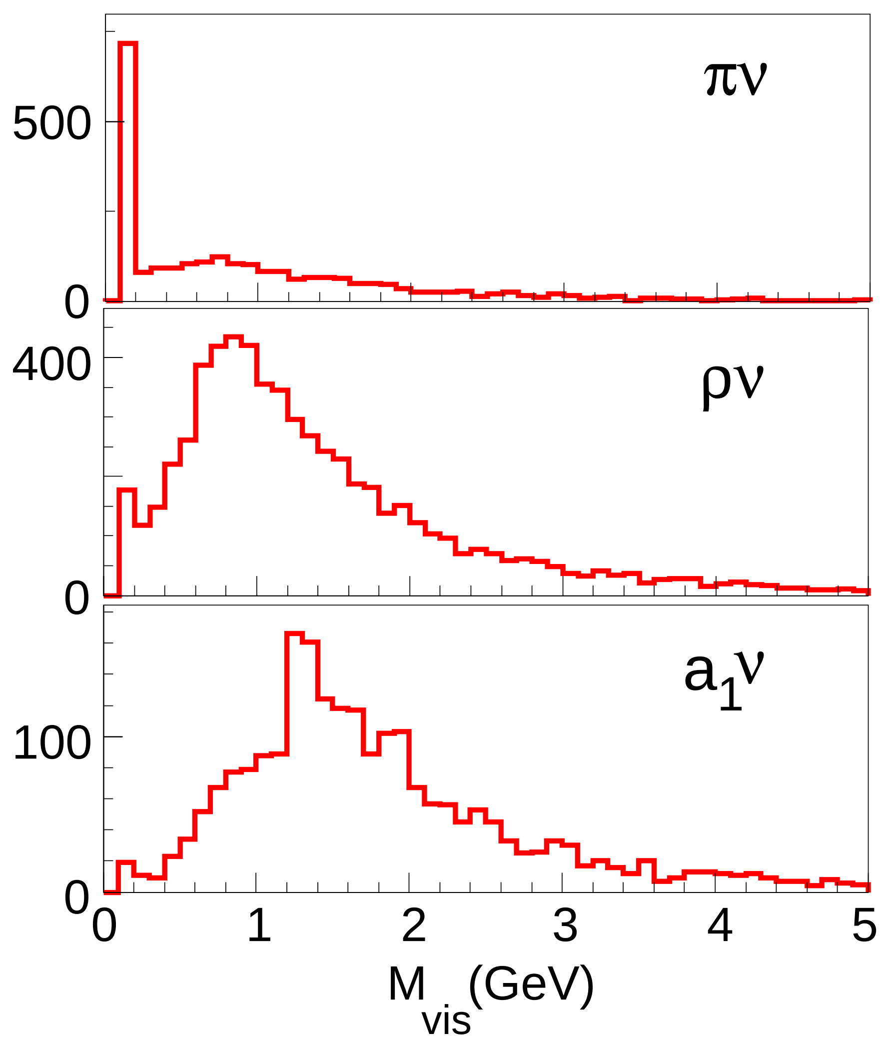
$$\frac{dN}{d\cos\theta^*} = \frac{1}{2}(1 + \lambda_\tau \cos\theta^*)$$

while $\tau \longrightarrow a_1\nu$ weakly dependent on λ_τ.

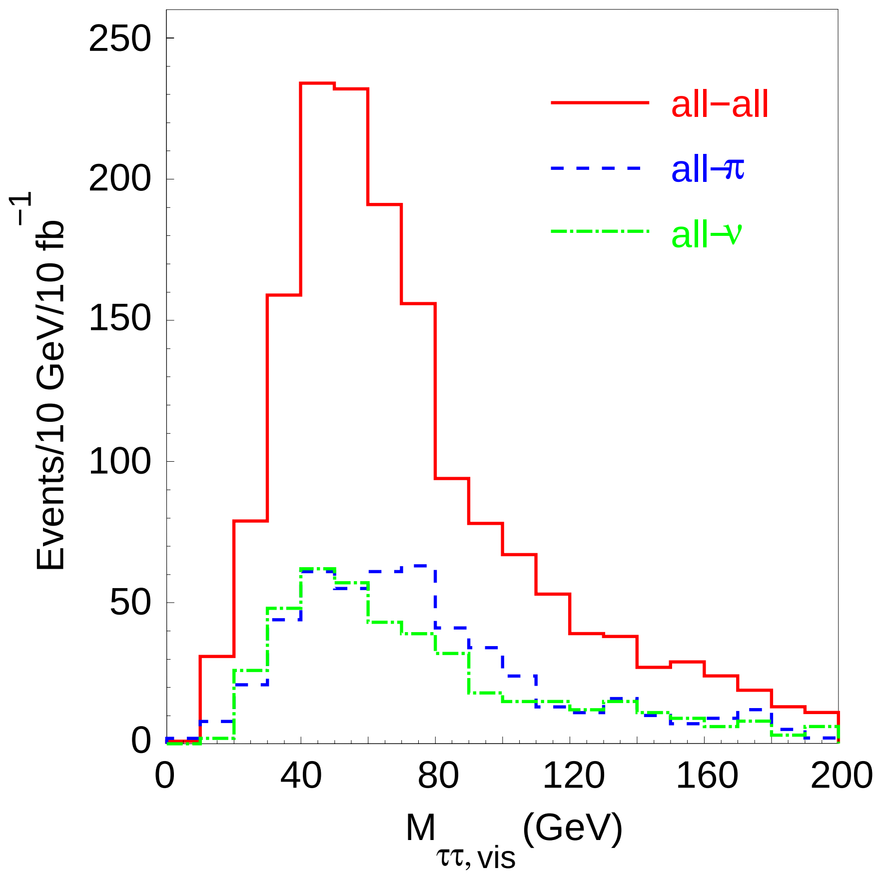
Want to separate τ decay modes. Requires full GEANT simulation.

Full GEANT takes $\sim$1h/event. Simulate just cones around parent τ's for 100k events with $m_0 = 100\,\mathrm{GeV}$, $m_{1/2} = 300\,\mathrm{GeV}$, $\tan\beta = 10$.

Can identify $\tau \to \pi\nu$ using small EM energy and $E = p$. Or combine tracks with EM cells to estimate mass [Hinchliffe]:



To reverse helicity let $\pi \leftrightarrow \nu$ [Hinchliffe]:



Still in progress – after a year. But Komogorov test suggests sensitivity is $\sim 10\%$.

GMSB Signatures

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

Generally longer decay chains, e.g.,

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

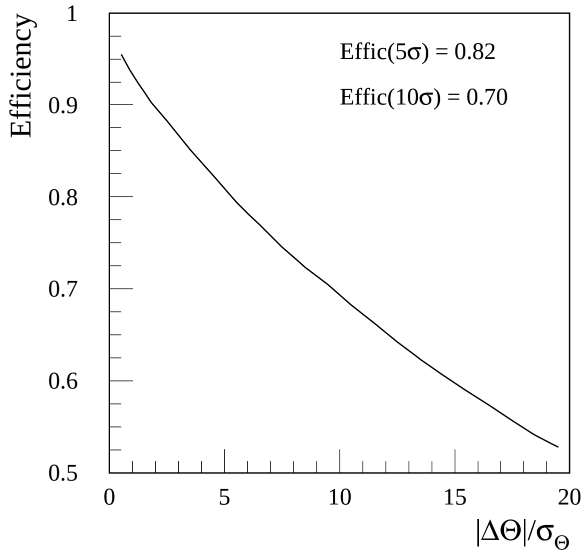
Hence easier than SUGRA.

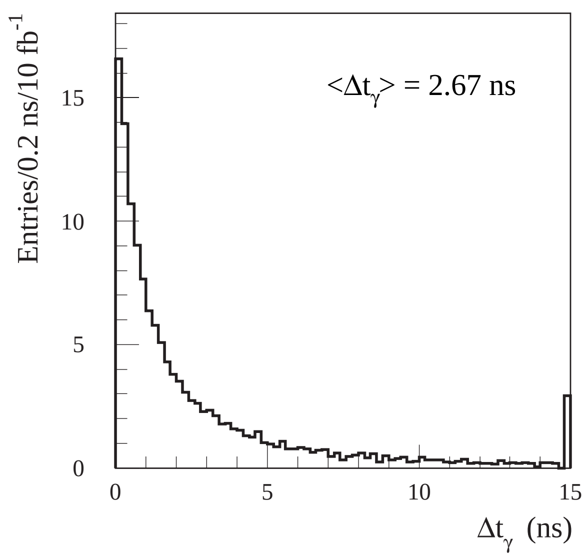
Important to measure NLSP lifetime $\Leftrightarrow$ SUSY breaking scale. For $\tilde{\chi}_1^0 \to \tilde{G}\gamma$, can measure short lifetimes with Dalitz decays.

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

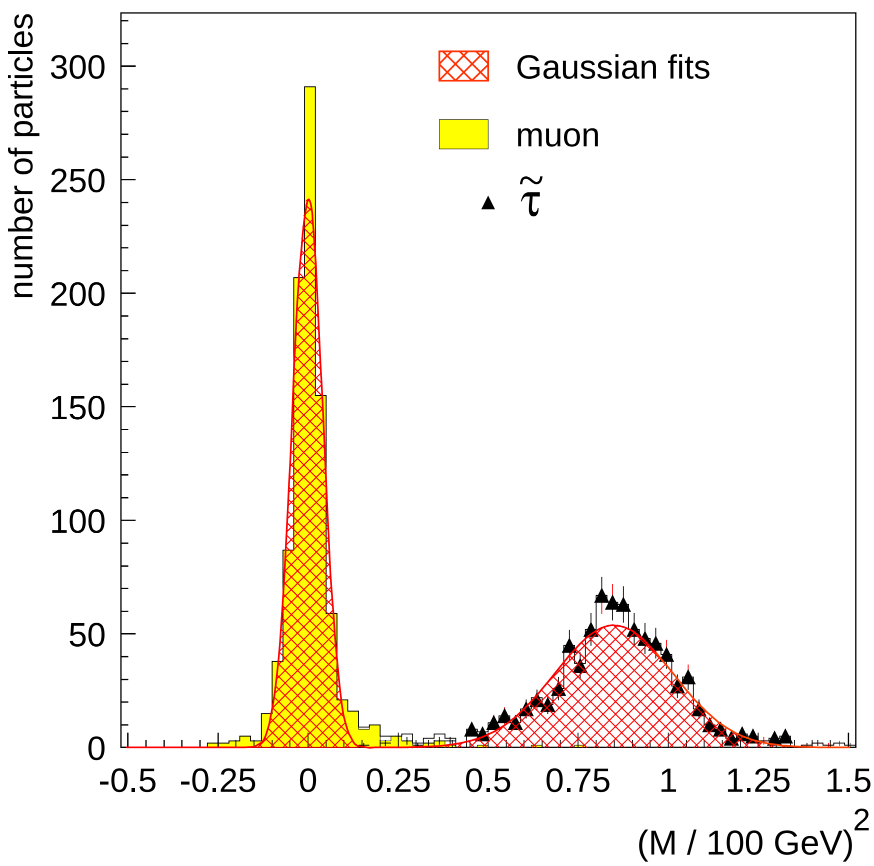
$$\Delta\theta \approx \frac{60\,\mathrm{mr}}{\sqrt{E}}, \qquad \Delta t \approx 100\,\mathrm{ps}$$

Could be sensitive to $c\tau \sim 100\,\mathrm{km}$ [ATLAS TDR]:

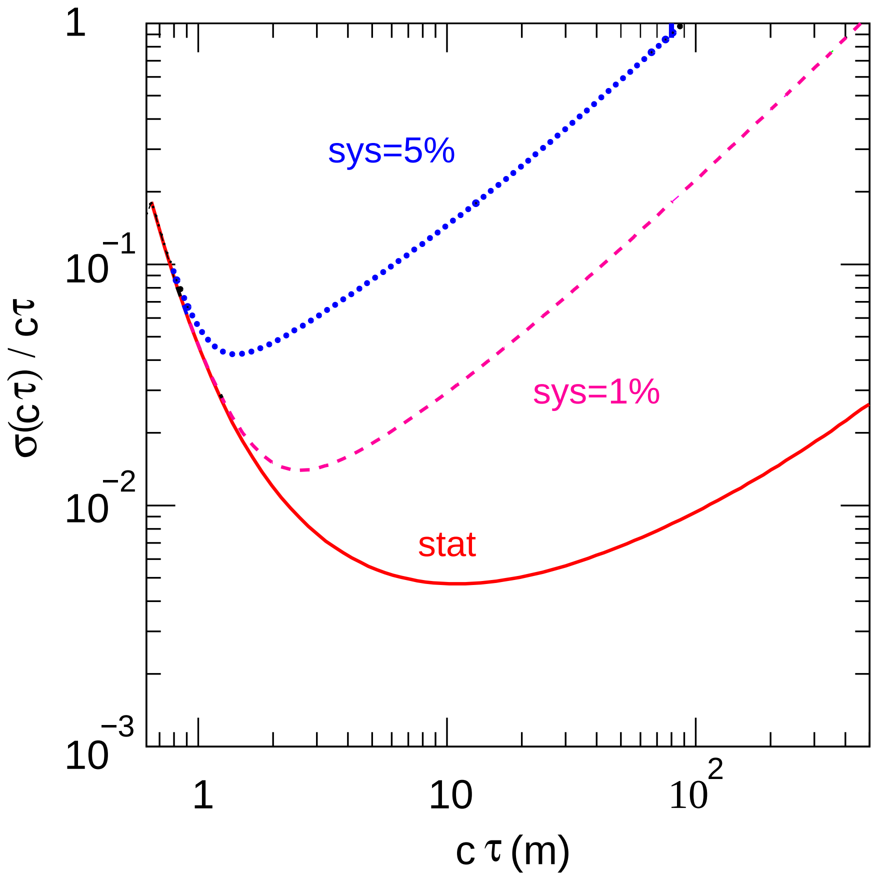




Can use TOF to reconstruct $\tilde{\tau}$ or $\tilde{\ell}$ [Kazana]:



Ratio of 1 vs. 2 sleptons in muon system sensitive to decays. Sensitivity limited by systematic error on acceptance [Polesello]:



Kinks in tracker, e.g., $\tilde{\tau}_1 \to \tilde{G}\tau$, might also be used. Pattern recognition problem not trivial.

Outlook

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

Despite missing $\tilde{\chi}_1^0$'s, have several tools for precision measurements, especially of masses.

Can sketch broad outline of initial SUSY program:

1. Search for multijet + $\not{E}_T$ excess over Standard Model.
2. If found, can select SUSY sample with simple cuts.
3. Look for special features (e.g., γ's or long-lived $\tilde{\ell}$).
4. Look for $\ell^\pm$, $\ell^+\ell^-$, $\ell^\pm\ell^\pm$, b jets, hadronic τ's, etc.
5. Try simple endpoint-type analyses.

Seems quite feasible. Will use results to guide further analyses and eventually global fits to all distributions.