SUSY at LHC

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SUSY with $M \lesssim 1\,\mathrm{TeV}$ is attractive extension of SM, providing:

- Natural explanation for $M_h \sim 100\,\mathrm{GeV}$ since $\Delta M_h \sim g^2(1\,\mathrm{TeV}) \lesssim M_h$;
- Consistency of EW data from LEP, SLC, Tevatron with coupling constants needed for grand unification;
- Natural candidate ($\tilde{\chi}_1^0$) for cold dark matter;
- Decoupling of virtual corrections for low-energy processes.

But SUSY is not without problems:

- ○ Must break SUSY "by hand" $\Rightarrow$ many parameters generally breaking SM accidental symmetries;
- ○ No explanation for cosmological constant $\Lambda \sim (10^{-3}\,\mathrm{eV})^4$.

SUSY is also good testing ground for detectors and reconstruction. Hence extensive work by ATLAS and CMS. Will limit talk to this work.

Emphasis on results from full simulation and reconstruction, but also results from fast parameterized simulations.

Am collaborator on ATLAS, so inevitable bias. Thanks to Albert de Roeck for help with CMS material.

Outline:

- Brief review of MSSM.
- Inclusive SUSY searches.
- Techniques for measuring (combinations of) masses.
- Outlook

Minimal SUSY Standard Model (MSSM)

For each Standard Model particle X, MSSM has partner $\tilde{X}$ with $\Delta J = \pm\frac{1}{2}$:

Each massless gauge boson	$\Leftrightarrow$	Massless gaugino
Each chiral fermion	$\Leftrightarrow$	Massless sfermion

Also two Higgs doublets and corresponding $J = \frac{1}{2}$ Higgsinos.

No realistic dynamical SUSY breaking using just MSSM. Can break by hand: all SUSY particles have $SU(2) \times U(1)$ invariant mass terms. But most general breaking has 105+45 new parameters.

Random choice violates Standard Model accidental symmetries: gives weak scale proton decay, $\mu \to e\gamma$ and other flavor violation, new CP violation, ...

New physics — even SUSY — might not look like *a priori* expectations. Important to retain sensitivity to surprises.

Will assume here invariance under R-parity, where

$$R \equiv (-1)^{3B-3L+2S}$$
$$= +1 \quad \text{(all SM particles)}$$
$$= -1 \quad \text{(all SUSY particles)}$$

R-parity eliminates 45 parameters and implies:

- No proton decay.
- SUSY particles produced in pairs and decay to stable Lightest SUSY Particle (LSP), usually $\tilde{\chi}_1^0$. Must be neutral and weakly interacting, so escapes detector.

Conservation of just B or L rather than R possible, giving unstable LSP. But WMAP results indicate cold dark matter:

$$\Omega_b = 0.044 \pm 0.004, \quad \Omega_m = 0.27 \pm 0.04, \quad \Omega_\Lambda = 0.73 \pm 0.04$$

LSP is good candidate: naturally gives about observed $\Omega_m h^2$.

Would like to break SUSY dynamically. Not possible just with MSSM; must communicate breaking in hidden sector via gravity or gauge interactions. Must avoid large flavor violation.

Many LHC studies use mSUGRA (or CMSSM) model. Has simplest possible gravity-mediated breaking with just four parameters:

- Common scalar mass m_0 at GUT scale;
- Common gaugino mass $m_{1/2}$ at GUT scale;
- Common trilinear coupling parameter A_0 (not very important);
- Common ratio $\tan\beta$ of Higgs VEV's at weak scale.

Also sign $\mathrm{sgn}\,\mu = \pm 1$ of Higgsino mass.

Not generic prediction of gravity mediation. But does provide weak-scale spectrum consistent with low-energy constraints.

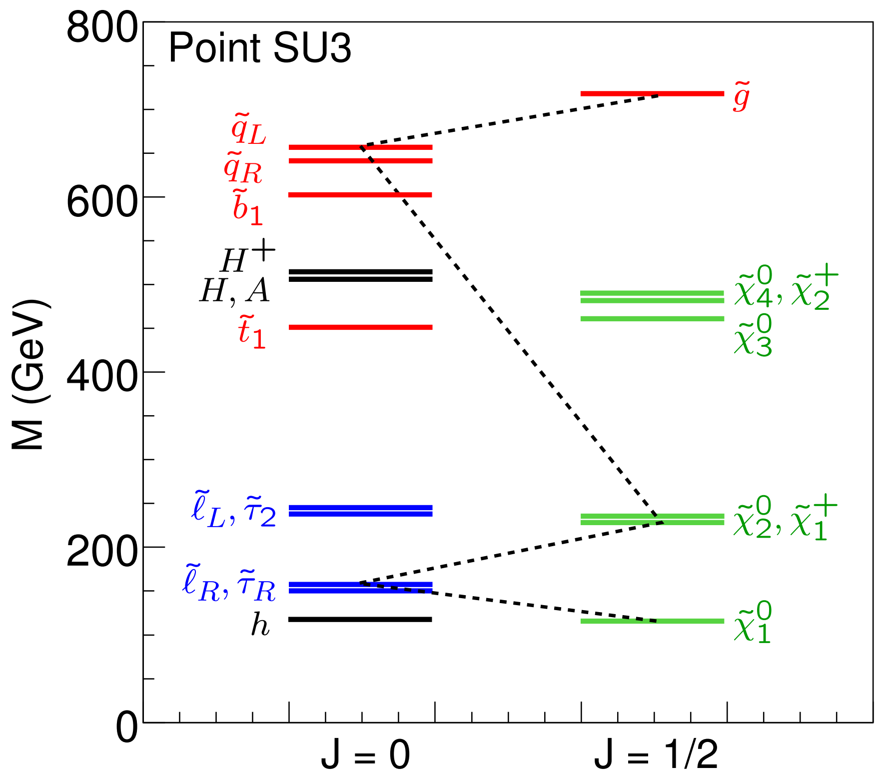
Must solve RGEs' to relate GUT and weak scale masses. Need iterative solution to handle thresholds from SUSY particles.

Find complex spectrum at weak scale even for simple one at GUT scale.

Masses for ATLAS point SU3: mSUGRA with

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

$$A_0 = -300\,\mathrm{GeV}, \ \tan\beta = 6, \ \mu > 0$$



Typically find in simple models

$$m_1 : m_2 : m_3 \approx \alpha_1 : \alpha_2 : \alpha_3$$

$$M(\tilde{\ell}) \sim m_0, \quad M(\tilde{q}) \gtrsim 0.9 M(\tilde{g})$$

But many patterns possible.

Generically expect $\tilde{g}$ and $\tilde{q}$ to be heavy, $\sim 1\,\mathrm{TeV}$. In many cases, $\tilde{\chi}_3^0$, $\tilde{\chi}_4^0$, $\tilde{\chi}_2^\pm$, H, A, and $H^\pm$ also heavy. But model dependent.

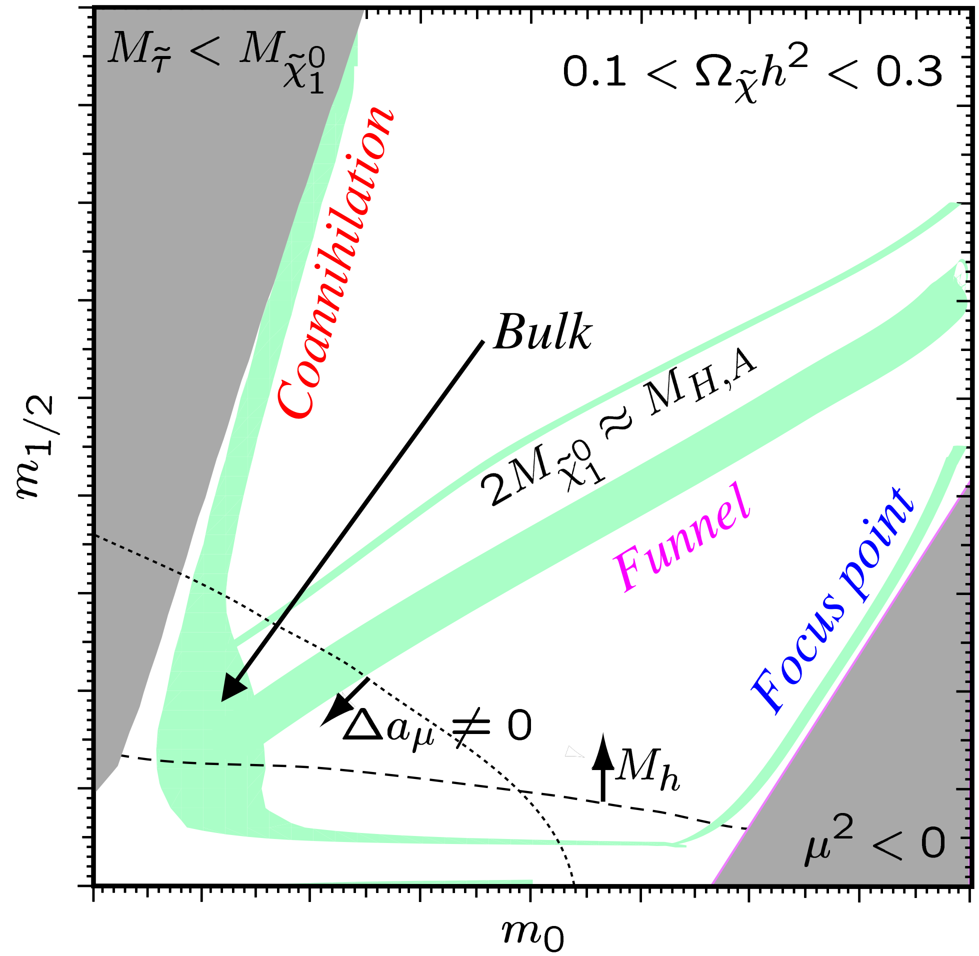
While TeV-scale SUSY gives qualitatively right cold dark matter, detailed calculations ⇒ need enhanced annihilation. Use mSUGRA as guide (qualitative picture — no mass scale):

Coannihilation: Light $\tilde{\tau}_1$ in equilibrium with $\tilde{\chi}_1^0$, so annihilate via $\tilde{\chi}_1^0\tilde{\tau}_1 \to \gamma\tau$.

Bulk: bino $\tilde{\chi}_1^0$; light $\tilde{\ell}_R$ enhances annihilation.

Funnel: H,A poles enhance annihilation for $\tan\beta \gg 1$.

Focus point: Small μ^2, so Higgsino $\tilde{\chi}_1^0$ annihilate. Heavy s-fermions, so small FCNC.



Third generation is always different even in simple mSUGRA model:

- Larger $\tilde{f}_L - \tilde{f}_R$ mixing $\propto m_f$;
- Yukawa couplings in RGE;
- Effects of gaugino-Higgsino mixing.

Essential to study third-generation SUSY particles ($\tilde{t}_i$, $\tilde{b}_i$, and $\tilde{\tau}_i$) to understand SUSY model.

GMSB communicates SUSY breaking via gauge interactions at scale $\ll M_{\rm Pl}$ (e.g., $100\,\rm TeV$). Hence predicts

- Degeneracy among SUSY particles with same $SU(3) \times SU(2) \times U(1)$ quantum numbers, so no FCNC or CP violation.
- Light $\tilde{G}$ ($M \gtrsim 1\,\rm eV$) is LSP. Phenomenology depends on nature of NLSP ($\tilde{\chi}_1^0$, $\tilde{\tau}_1$) and its lifetime for $\tilde{G}$ decay.
- $\tilde{\chi}_1^0$ is no longer dark matter.

Inclusive SUSY Searches

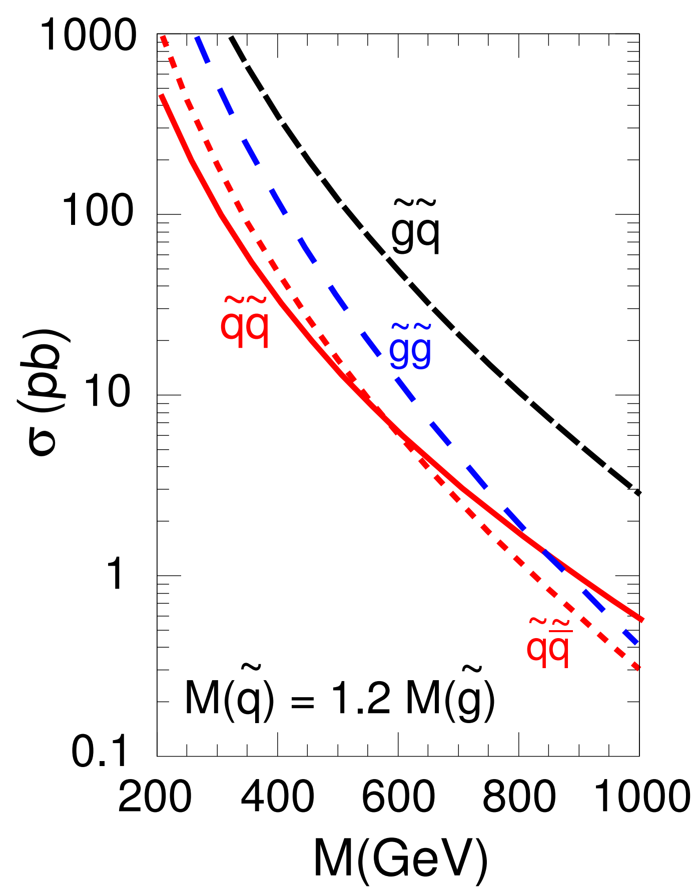
"Typical" SUSY model has gluinos and squarks at $O(1\,\mathrm{TeV})$ decaying to $\tilde{\chi}_1^0$ at $O(100\,\mathrm{GeV})$.

Cross sections known to NLO; typically $\gtrsim 1\,\mathrm{pb}$ [Beenakker].

Generally decay to $\tilde{\chi}_1^0$ via several steps,

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

Hence expect multiple jets plus large $\not{E}_T$ from $\tilde{\chi}_1^0$. May also have leptons or τ's.



Standard Model backgrounds include $Z \to \nu\bar{\nu}$ + jets, W + jets, $t\bar{t}$, b jets with $b \to \nu X$, etc. Also backgrounds from mismeasured events.

Typical cuts: at least four jets with $p_T > 100, 50, 50, 50\,\mathrm{GeV}$ and $\not{E}_T > 100\,\mathrm{GeV}$. Then plot

$$M_{\mathrm{eff}} \equiv \not{E}_T + \sum_j p_{T,j}$$

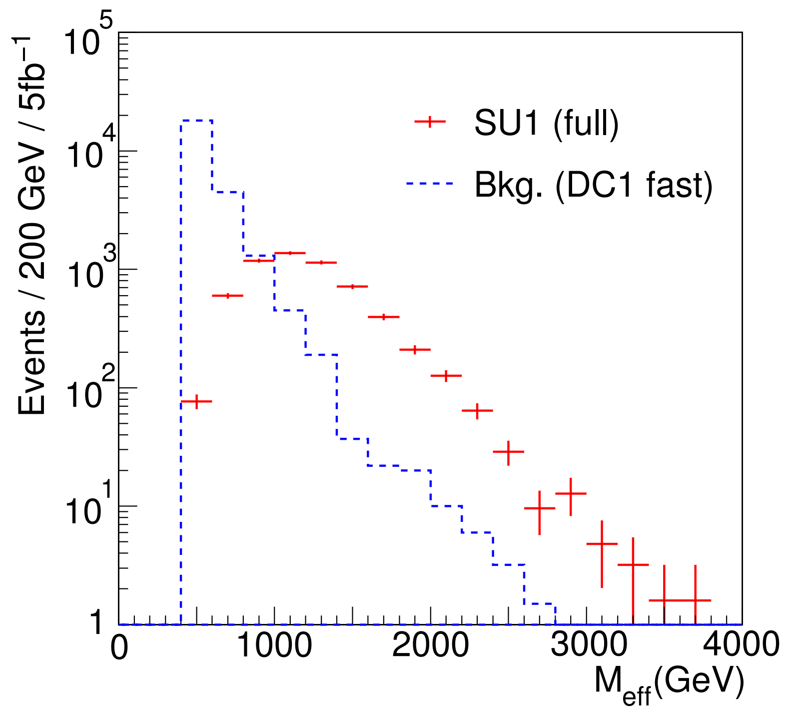
Scalar p_T sum measures hardness of interaction better than invariant mass, which is sensitive to low-p_T forward jets.

M_{eff} distribution for mSUGRA with

$$m_0 = 70\,\mathrm{GeV},\ m_{1/2} = 350\,\mathrm{GeV},$$
$$\tan\beta = 10$$

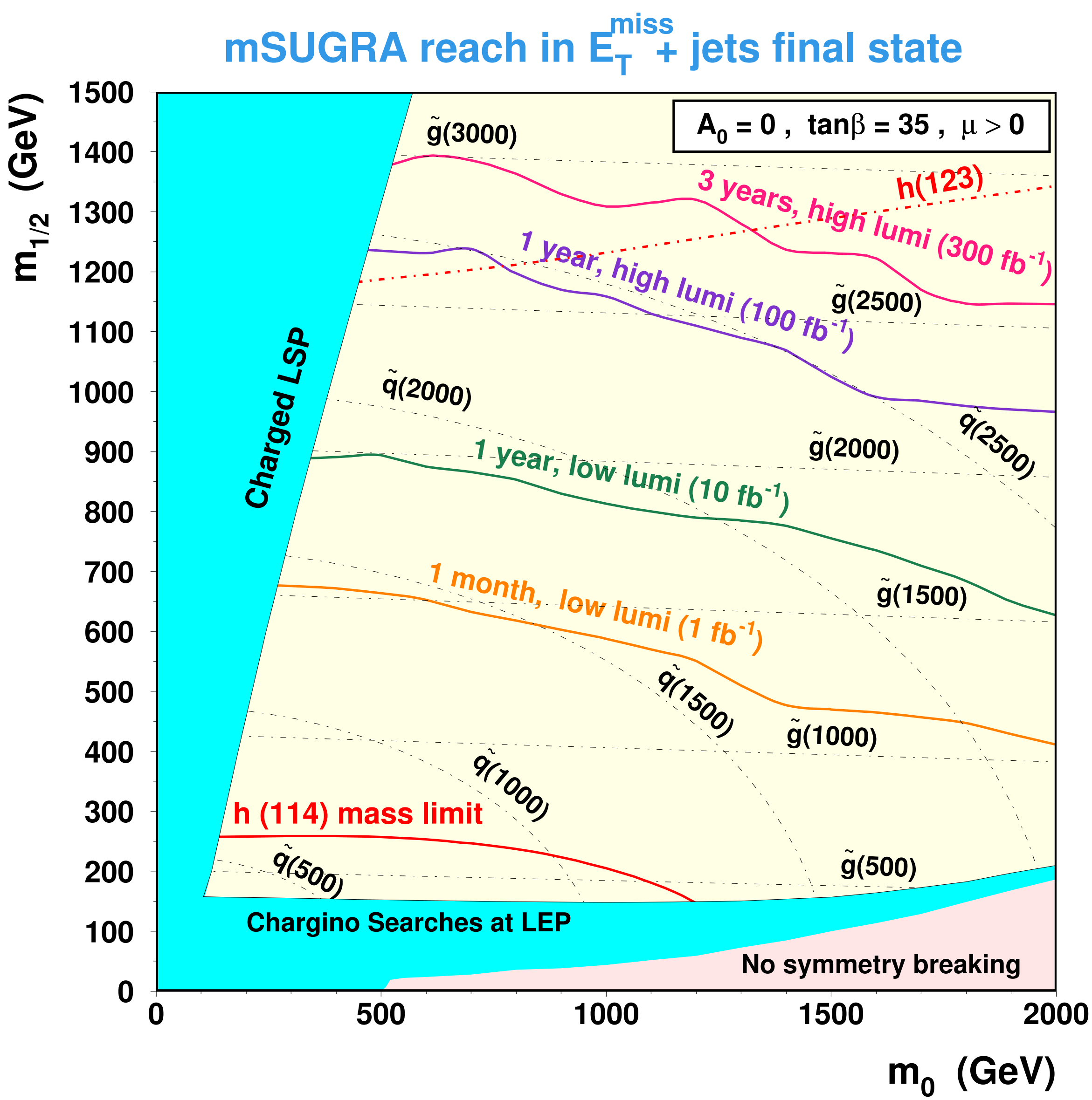
and full reconstruction.

Standard Model backgrounds from parton shower Monte Carlo and fast simulation.

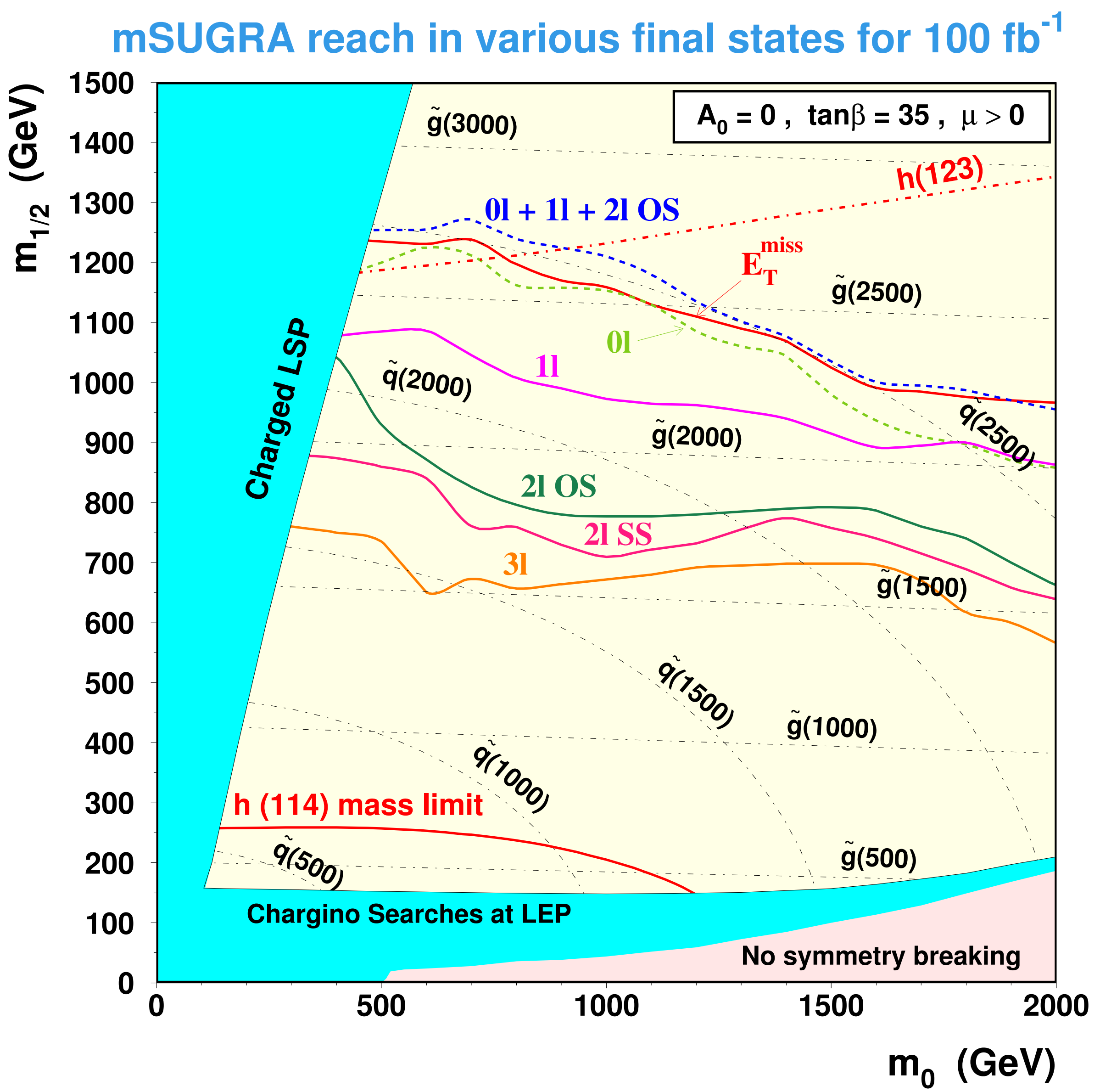


Note $S/B > 10$ for large M_{eff}, so search limits depend mainly on signal, not on SM background.

mSUGRA 5σ search limits vs. luminosity shown based on parton showers and fast simulation [CMSSUSY].

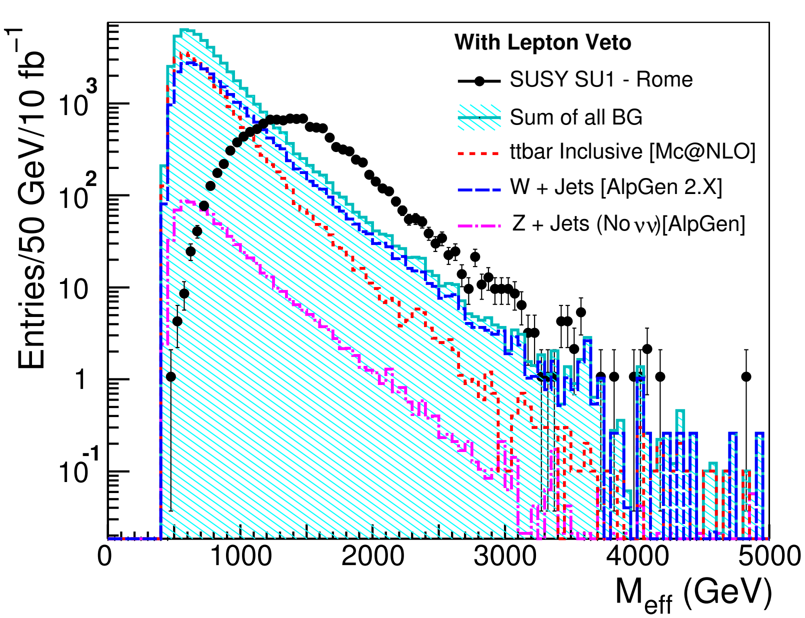


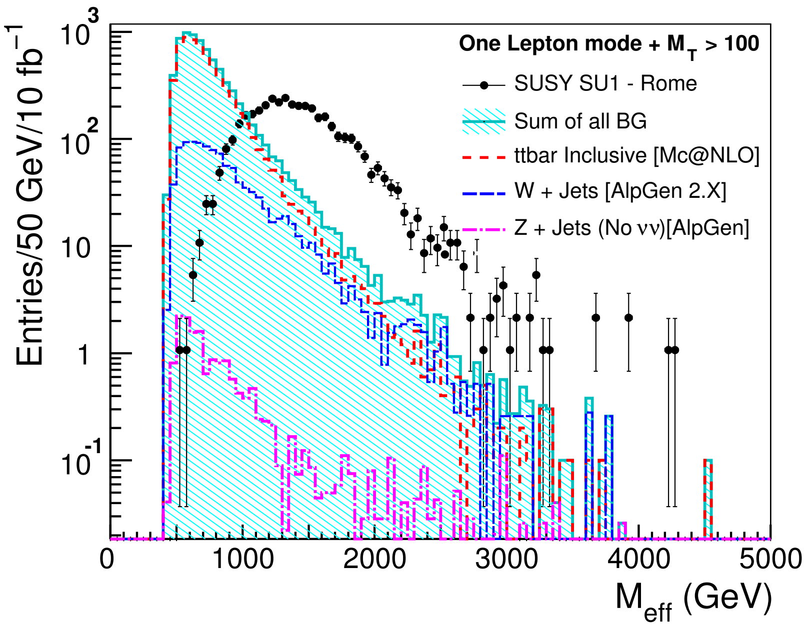
Search limits in various lepton channels on same basis [CMSSUSY]:



Full $2 \to n$ matrix elements in ALPGEN give larger background than parton showers, especially for $W + n$ jets, $Z + n$ jets [Asai].

Require $M_T(\ell, \not{E}_T) > 100\,\mathrm{GeV}$ to reduce $W + n$ jets. Preliminary result with lepton veto (left) and requiring ≥ 1 lepton (right) [Padhi]:





Background for ≥ 1 lepton dominated by $t\bar{t}$. Less sensitive to high-order QCD effects and generally has comparable sensitivity.

Leptonic Endpoint Measurements

In mSUGRA and most SUSY models, all SUSY particles decay to invisible $\tilde{\chi}_1^0 \Rightarrow$ no mass peaks. Can often identify specific decays, use kinematic endpoints to measure mass combinations [Hinchcliffe,TDR].

Backgrounds dominated by other SUSY processes. Must choose SUSY model points and generate all processes consistently.

Very unlikely that any such point is real. Goal is to develop analysis techniques and reconstruction for complex events.

Simplest (trivial) endpoint example: for $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \ell^+ \ell^-$,

$$M(\ell^+\ell^-) \le M(\tilde{\chi}_2^0) - M(\tilde{\chi}_1^0)\,.$$

For $\tilde{\chi}_2^0 \to \tilde{\ell}^\pm \ell^\mp \to \tilde{\chi}_1^0 \ell^+ \ell^-$ find triangular mass distribution with

$$M(\ell^+\ell^-) \le \sqrt{\frac{\left(M^2(\tilde{\chi}_2^0) - M^2(\tilde{\ell})\right)\left(M^2(\tilde{\ell}) - M^2(\tilde{\chi}_1^0)\right)}{M^2(\tilde{\ell})}}\,.$$

Must avoid e and μ flavor violation in $\tilde{\chi}_2^0$ decays to avoid $\mu \to e\gamma$ at 1-loop level. (Problem for SUSY model building.) Hence expect $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 e^+ e^-$ and $\tilde{\chi}_1^0 \mu^+ \mu^-$ with equal rates but no $\tilde{\chi}_1^0 e^\pm \mu^\mp$.

Backgrounds from two independent decays, either Standard Model (e.g., $t\bar{t}$) or SUSY (e.g., $\tilde{\chi}_1^+ \tilde{\chi}_1^-$) produce e^+e^-, $\mu^+\mu^-$, and $e^\pm\mu^\mp$ equally. Hence flavor subtraction

$$e^+e^- + \mu^+\mu^- - e^\pm\mu^\mp$$

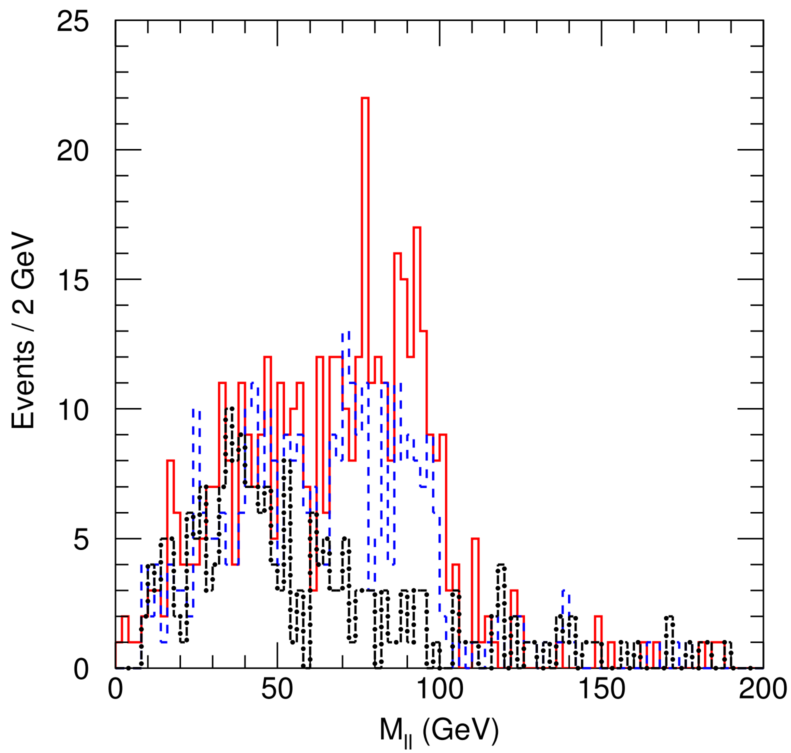
cancels backgrounds up to statistics and acceptance differences.

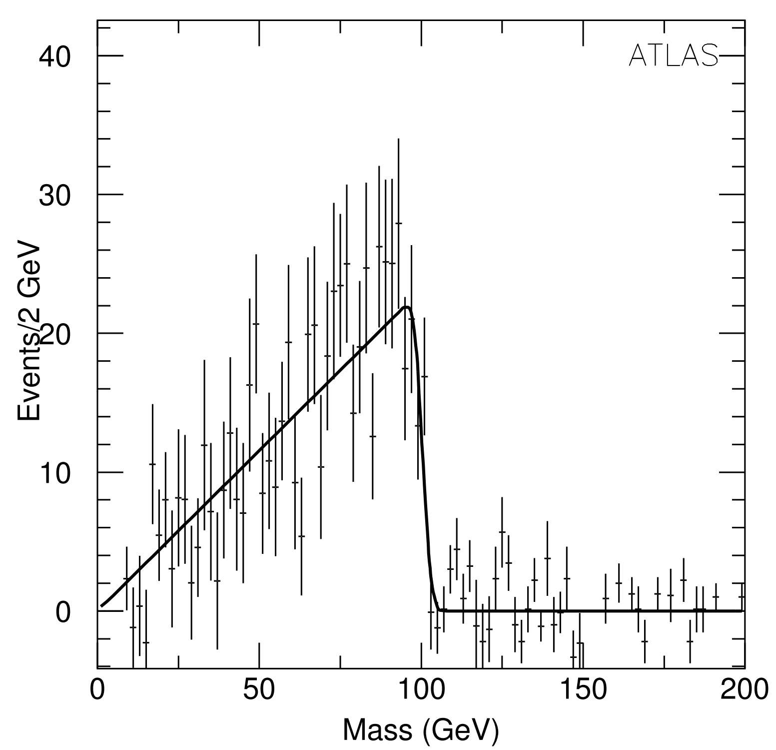
ATLAS and CMS have comparable acceptance for e and μ. Details are different: cracks in EM calorimeter vs. gaps in muon chambers.

ATLAS point SU3 is mSUGRA model in "bulk" region:

$$m_0 = 100\,\mathrm{GeV},\ m_{1/2} = 300\,\mathrm{GeV},\ A_0 = -300\,\mathrm{GeV},\ \tan\beta = 10,\ \mu > 0\,.$$

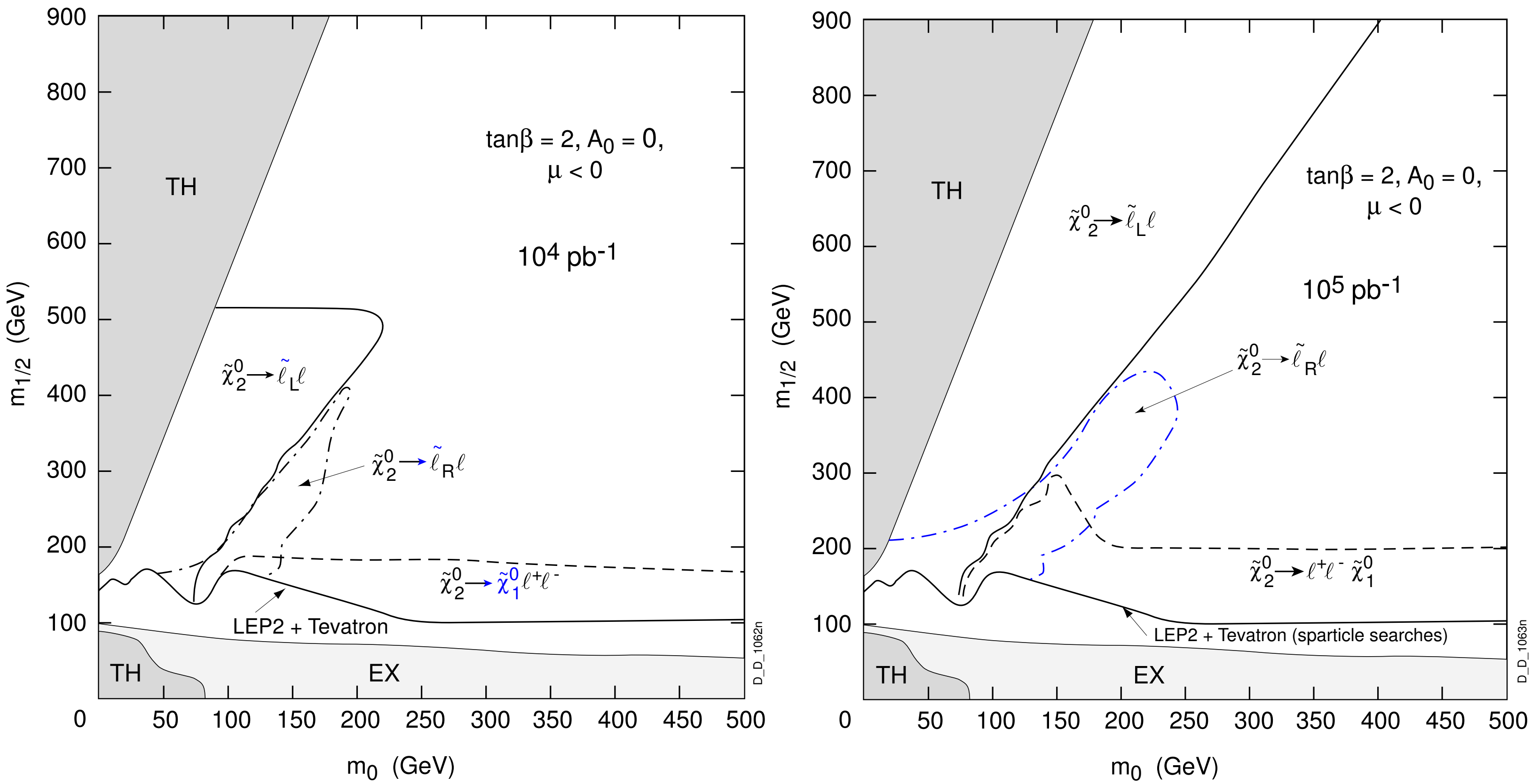
DC1 full simulation results for $5\,\mathrm{fb}^{-1}$ [DC1]. Left: $\mu^+\mu^-$ (solid), e^+e^- (dash), and $\mu^\pm e^\mp$ (dash-dot). Right: $e^+e^- + \mu^+\mu^- - e^\pm\mu^\mp$. Fitted endpoint is $100.25 \pm 1.14\,\mathrm{GeV}$; c.f. expected $100.31\,\mathrm{GeV}$:





Similar results at Rome [Aracena, Ozturk].

Dilepton endpoints observable over wide range of mSUGRA parameter space scanned with fast simulation [CMSSUSY]:



Sometimes have multiple endpoints. ATLAS point SU1 is mSUGRA Point in coannihilation region:

$$m_0 = 70\,\mathrm{GeV},\ m_{1/2} = 350\,\mathrm{GeV},\ A_0 = 0,\ \tan\beta = 10,\ \mu > 0$$

Small mass splitting for *both* $\tilde{\ell}_L$ and $\tilde{\ell}_R$:

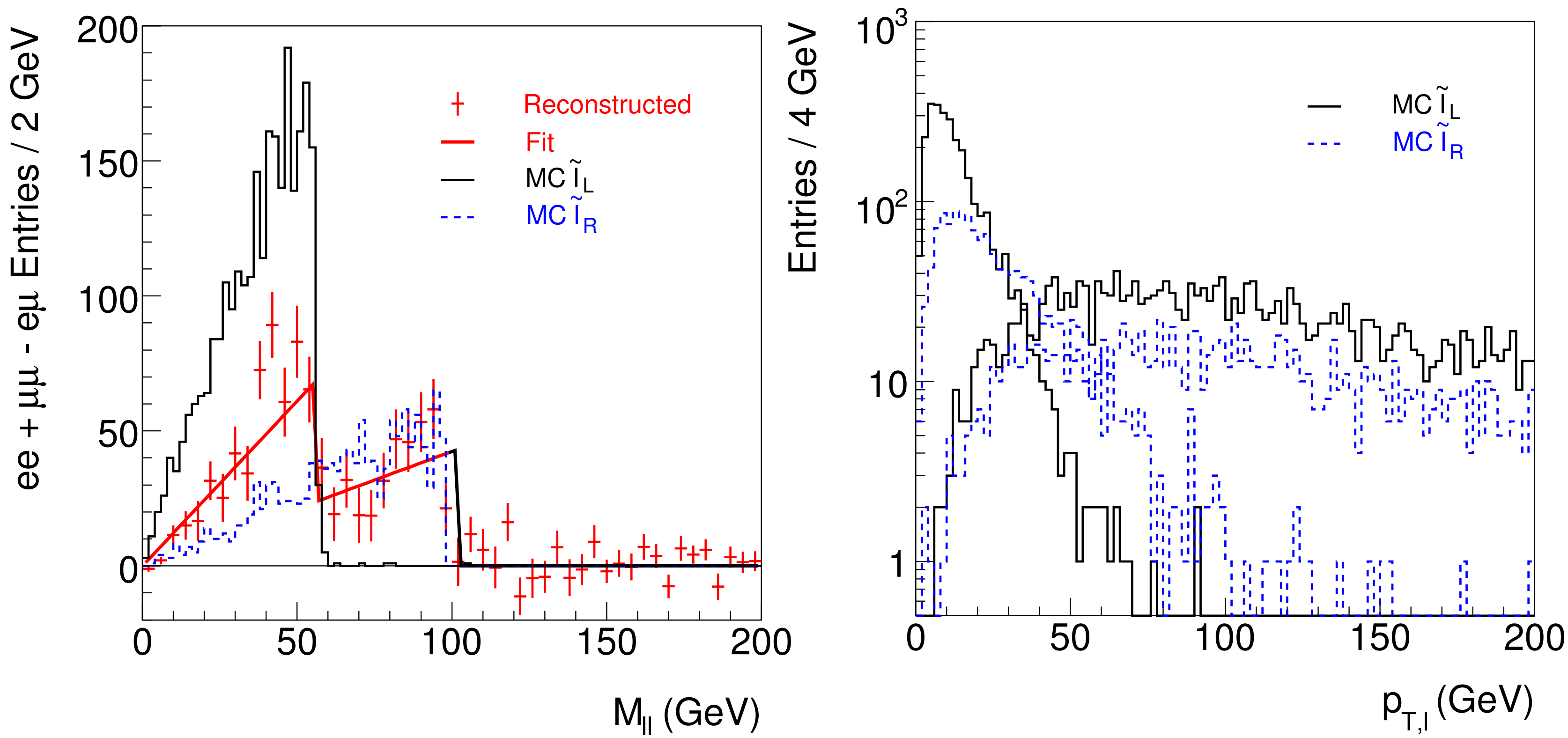
$$M(\tilde{\chi}_2^0) - M(\tilde{\ell}_L) = 8.5\,\mathrm{GeV},\ \ M(\tilde{\ell}_R) - M(\tilde{\chi}_1^0) = 17\,\mathrm{GeV}$$

Problem is to reconstruct soft leptons. Muons limited by minimum p_T needed to penetrate calorimeter and make track through muon system: $p_T > 6\,\mathrm{GeV}$ for ATLAS.

Low-p_T electrons have backgrounds from jet fluctuations. Default ATLAS reconstruction is seeded from calorimeter, optimized for $p_T \gtrsim 20\,\mathrm{GeV}$. Can do better using neural net and/or likelihood.

Should also try track-seeded algorithm for low-p_T electrons.

Results for SU1 after first attempt to optimize soft electrons:



Reconstruction (points with errors) finds both edges. But poor efficiency for $\tilde{\ell}_L$ edge because "near" (first) lepton for this edge is very soft.

With small mass gaps, reconstruction is harder, but distinguishing which electron is "near" (first) and "far" (second) is easier.

Now combine leptons with jets for “bulk” point ATLAS point SU3.
Dominant source of $\tilde{\chi}_2^0$ is $\tilde{q}_L$ decay:

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

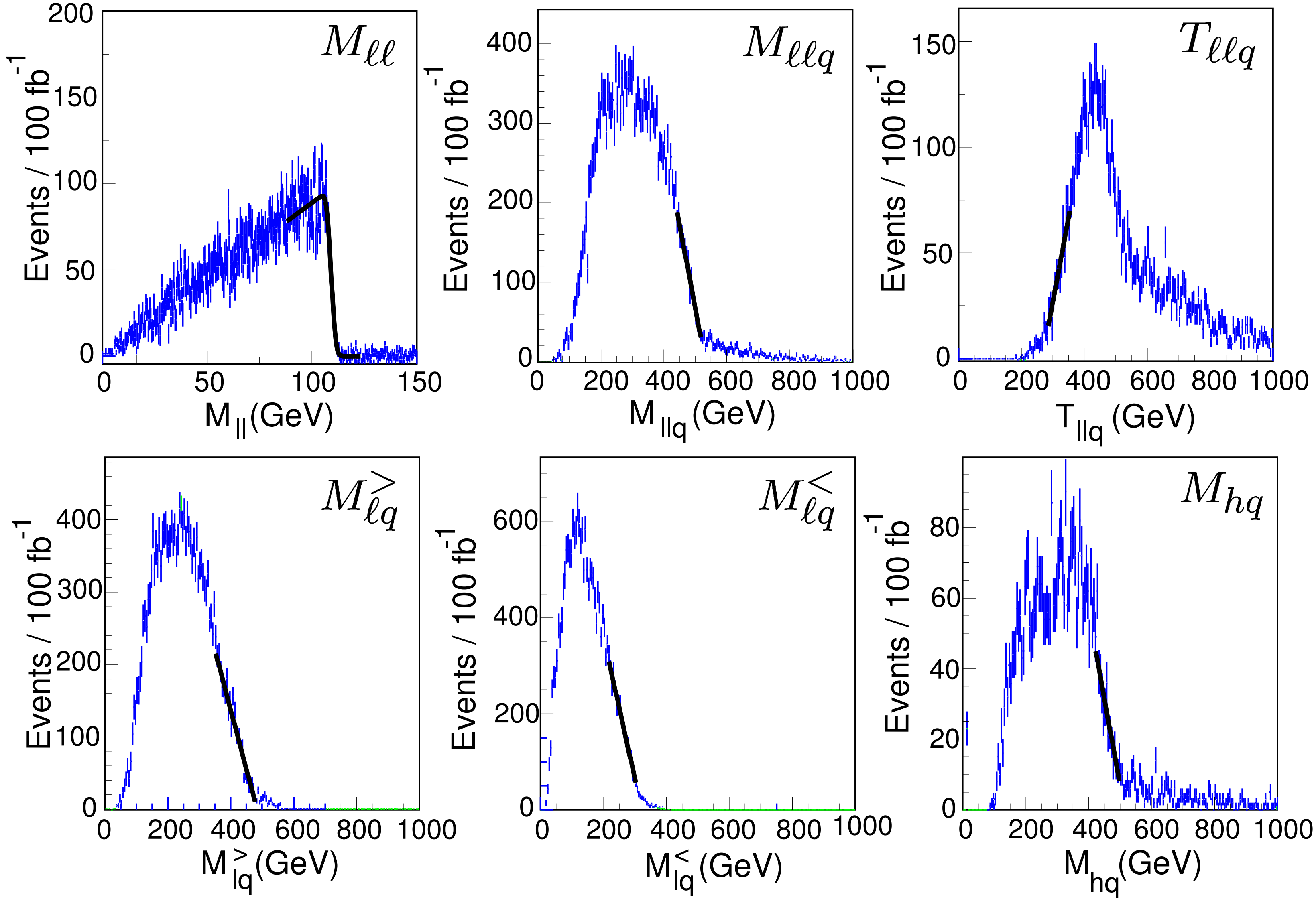
Can make $\tilde{q}_L$ either directly or via $\tilde{g}$ decay. In either case expect hardest jets to be from $\tilde{q}_L$.

For above decay chain can calculate [Bachacou,TDR]

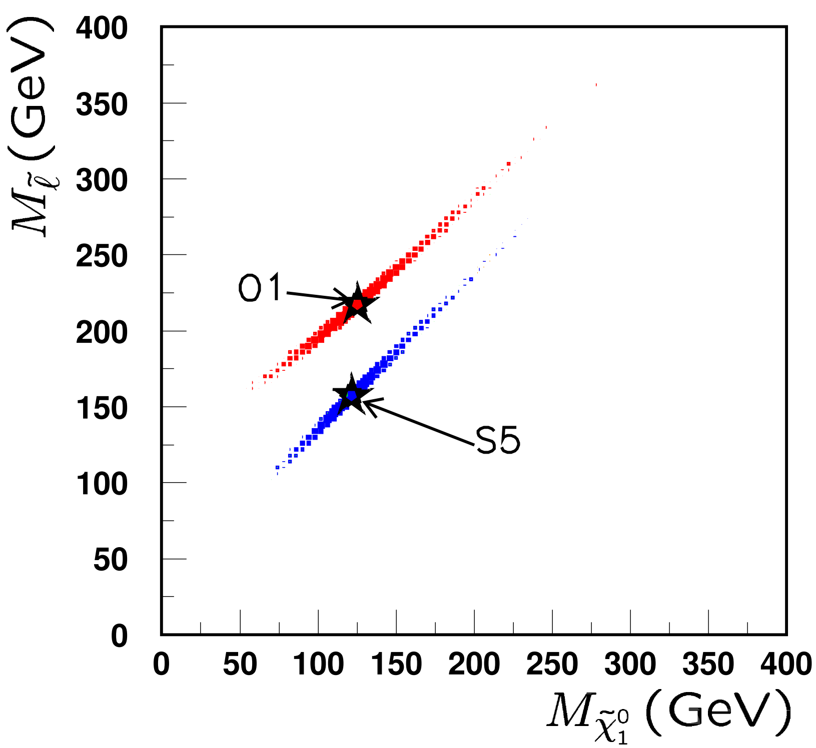
- $\ell\ell q$ endpoint $M_{\ell\ell q}$;
- Larger and smaller ℓq endpoints $M_{\ell q}^<$, $M_{\ell q}^>$;
- $\ell\ell q$ threshold $T_{\ell\ell q}$ given $M_{\ell\ell}$ cut. ($T_{\ell\ell q} = 0$ without any $M_{\ell\ell}$ cut.)

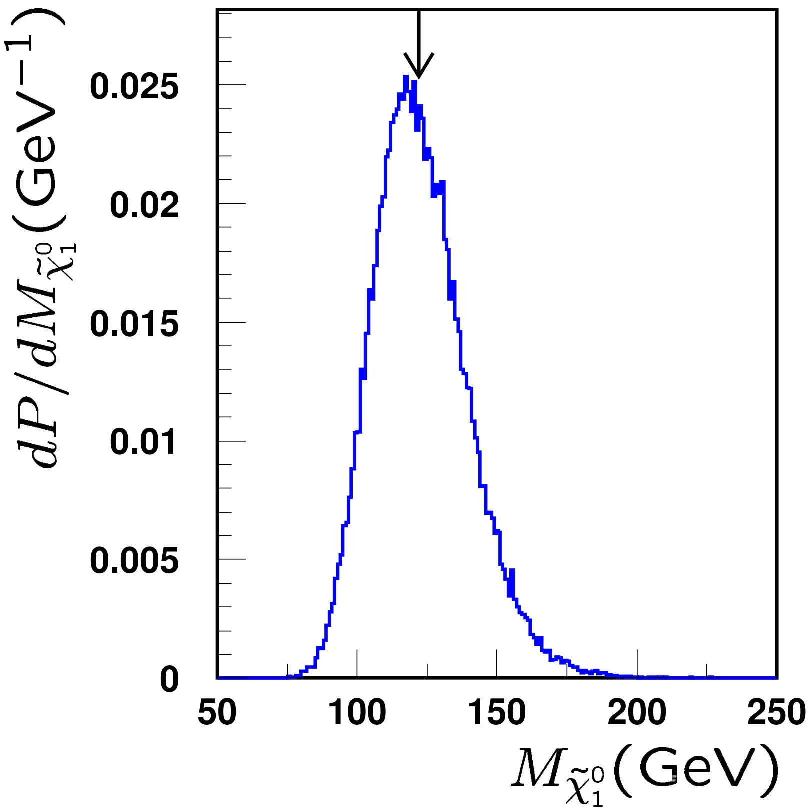
Expressions depend on relative mass values [Allanach].

Distributions for various $\ell^+\ell^-$ plus jet distributions [Allanach]:



Generate masses in $\tilde{q}_L$ decay chain at random, compute edges, and compare with measured values and estimated errors. Result [Allanach]:

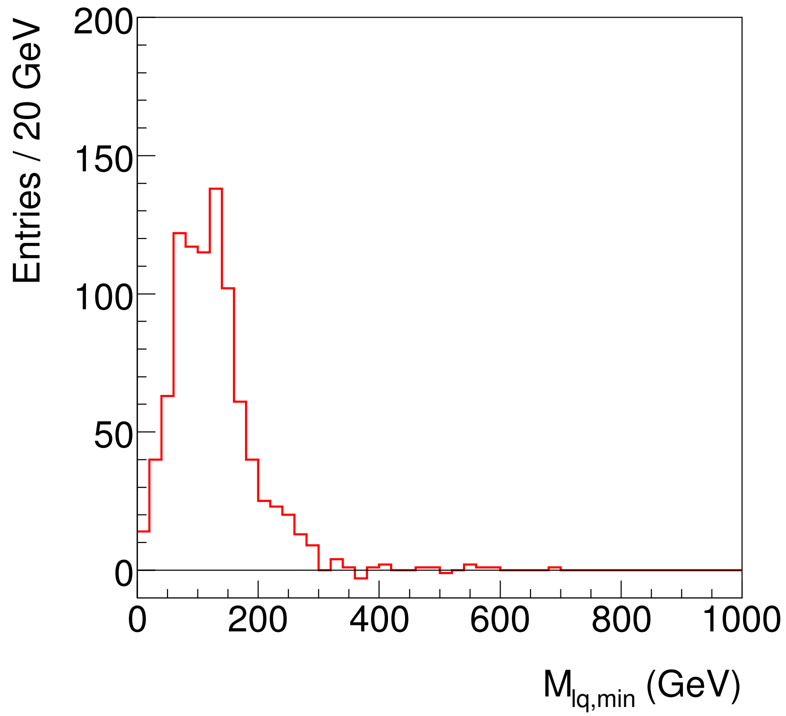


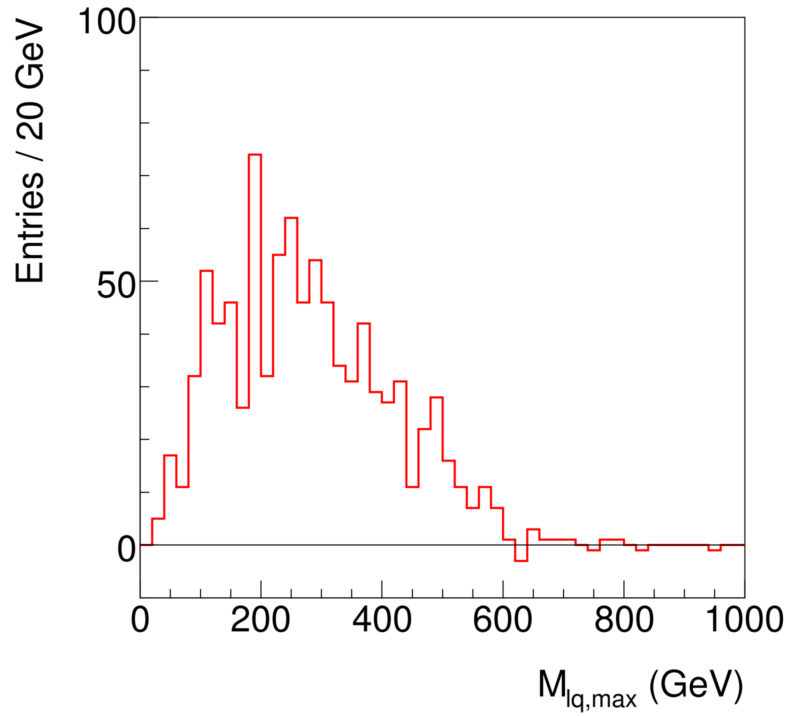


Measure relative masses to $\sim 1\%$, absolute $\tilde{\chi}_1^0$ mass to $\sim 10\%$.

Full simulation $\Rightarrow$ more background below $T_{\ell\ell q}$ threshold in ATLAS DC1 and Rome data. Not understood.

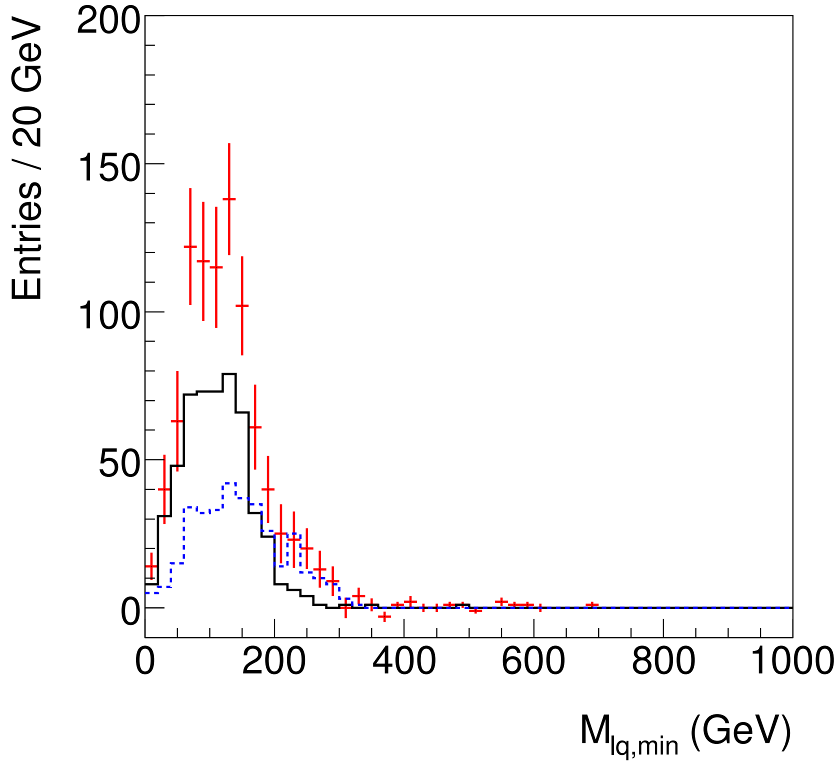
Can do similar analysis for Point SU1 with two dilepton edges. Instructive to look at $M_{\ell q}^{<}$ (left) and $M_{\ell q}^{>}$ (right) distributions:





Soft lepton from $\tilde{\ell}_L$ is "near" (first) and gives triangular distribution smeared by resolution. Soft lepton from $\tilde{\ell}_R$ is "far" (second). Maximum $M_{\ell q}$ also requires maximum $M_{\ell\ell}$, so endpoint vanishes linearly.

Decompose measured distribution (points with errors) into contribution from $58.2 < M_{\ell\ell} < 100.9\,\mathrm{GeV}$ ($\tilde{\ell}_R$, dashed) and $M_{\ell\ell} < 58.2\,\mathrm{GeV}$ (mainly $\tilde{\ell}_L$, solid):



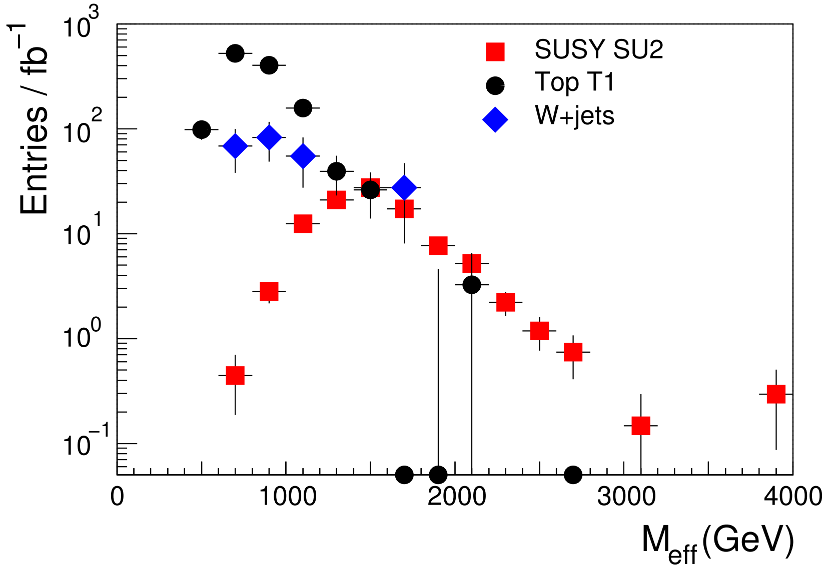
Clearly see both structures consistent with expected endpoints at 186.7 GeV and 338.5 GeV. No error analysis yet.

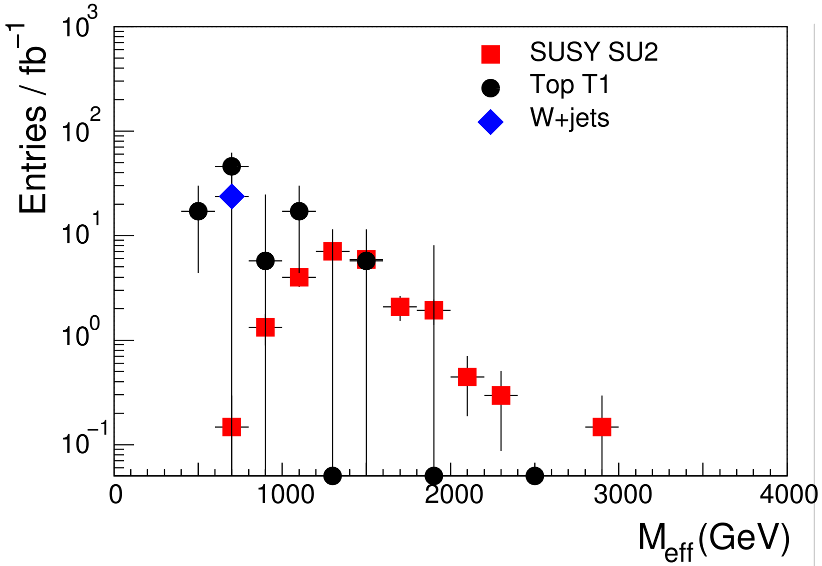
ATLAS point SU2 is in focus point region:

$$m_0 = 3550\,\mathrm{GeV},\ m_{1/2} = 300\,\mathrm{GeV},\ A_0 = 0,\ \tan\beta 10,\ \mu > 0$$

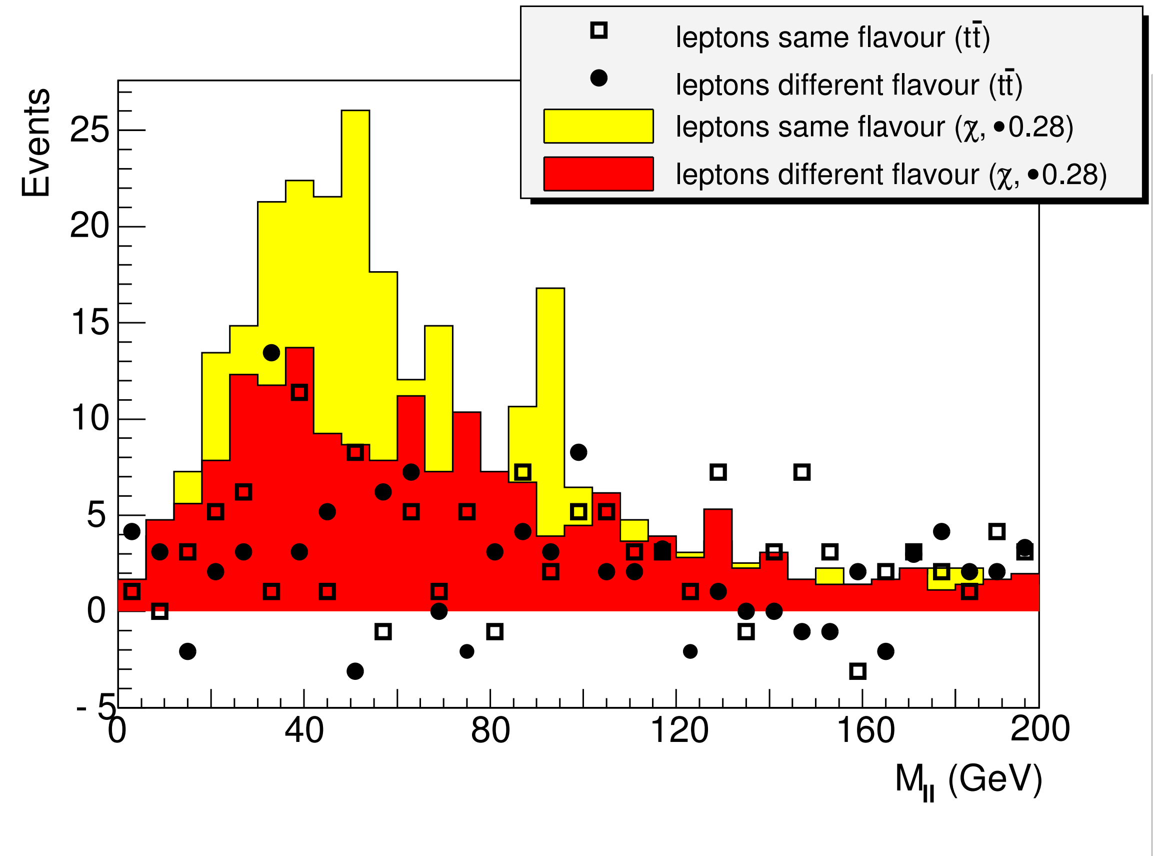
Considerably harder: only $\tilde{g}$ and $\tilde{\chi}_i^{\pm,0}$ accessible.

Large gaugino-Higgsino mixing, so $\tilde{g} \to \tilde{\chi}_i^0 t\bar{t}, \chi_i^- t\bar{b}$. Get $S/B \sim 1$ requiring ≥ 2 tagged b jets and zero (left) or one (right) leptons plus standard $\not\!\!E_T$ and multijet cuts [Lari]:





$\tilde{\chi}_i^0 \to \tilde{\chi}_1^0 \ell^+ \ell^-$ decays dominated by virtual Z. Require two OSSF leptons, $\not{E}_T > 80\,\mathrm{GeV}$, six jets with $p_T > 150, 3 \times 50, 2 \times 30\,\mathrm{GeV}$. Result for $10\,\mathrm{fb}^{-1}$:



Have in principle additional information from shape — difficult.

Heavy Gaugino Signatures

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. 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:

$\tilde{q}_L \to \tilde{\chi}_4^0 q$, $\tilde{\chi}_4^0 \to \tilde{\ell}_R^\pm \ell^\mp$, $\tilde{\ell}_R^\pm \to \tilde{\chi}_1^0 \ell^\pm$ [$D1$]

$\tilde{q}_L \to \tilde{\chi}_4^0 q$, $\tilde{\chi}_4^0 \to \tilde{\ell}_L^\pm \ell^\mp$, $\tilde{\ell}_L^\pm \to \tilde{\chi}_1^0 \ell^\pm$ [$D2$], $\tilde{\ell}_L^\pm \to \tilde{\chi}_2^0 \ell^\pm$ [$D3$]

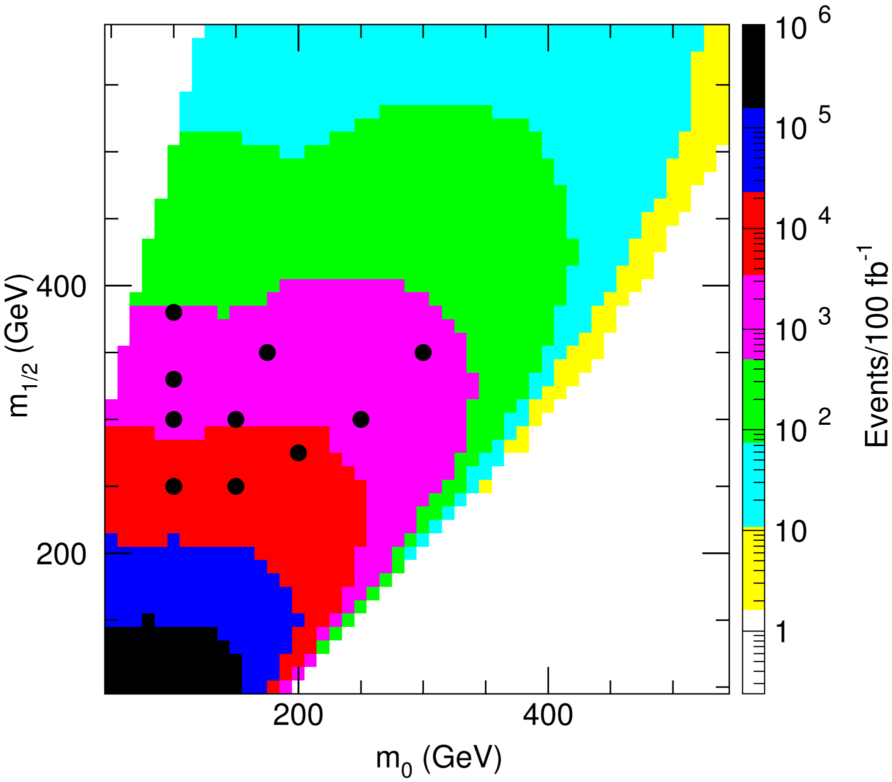
$\tilde{q}_L \to \tilde{\chi}_2^\pm q'$, $\tilde{\chi}_2^\pm \to \tilde{\nu}_\ell \ell^\pm$, $\tilde{\nu}_\ell \to \tilde{\chi}_1^\pm \ell^\mp$ [$D4$]

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 $M_{\mathrm{eff}} > 600\,\mathrm{GeV}$.

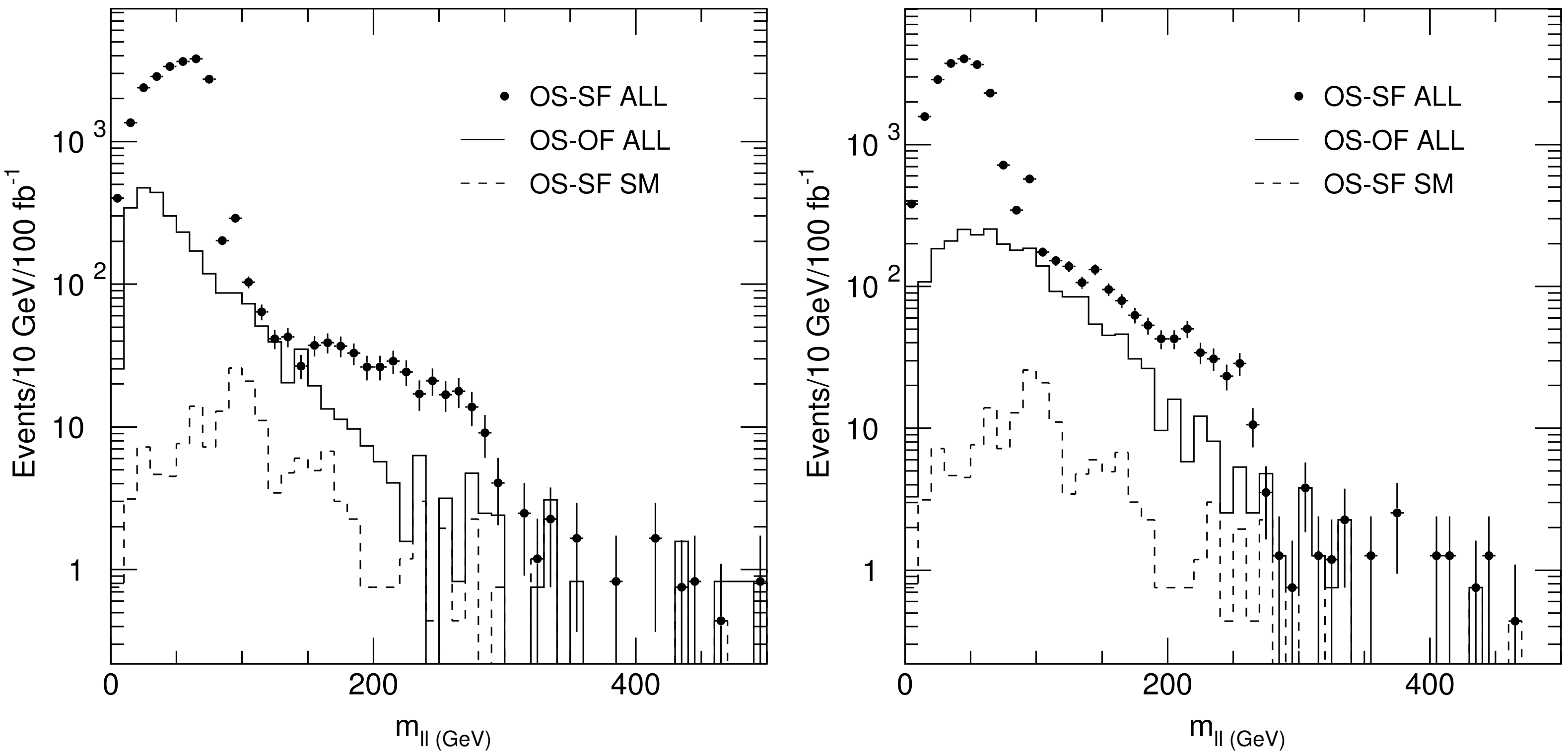


To suppress SM backgrounds, also require $M_{T2} > 80\,\mathrm{GeV}$ for minimum "stransverse" mass for $\ell + \not\!\!E_T$, where

$$M_{T2}^2 \equiv \min_{\not p_1 + \not p_2 = \not p_T} \left[\max\left\{m_T(p_{T\ell_1}, \not p_1), m_T(p_{T\ell_2}, \not p_2)\right\}\right]$$

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

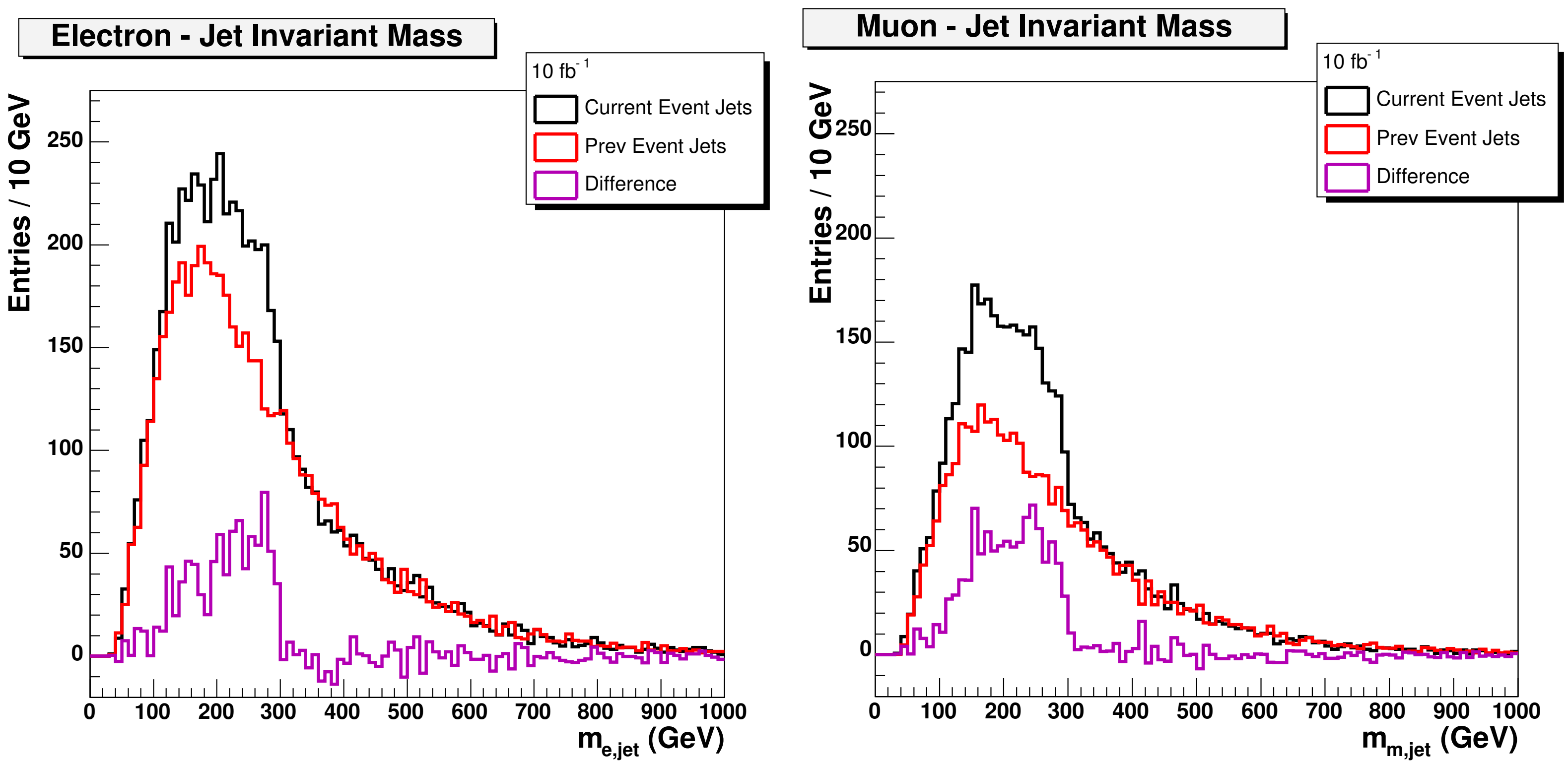
Results for Point A (100,250) and Point E(150,250):



Observe small but clear excess over OS,OF SUSY and SM backgrounds. Can measure endpoints to $\sim 4\,\mathrm{GeV}$ for Points A,E. Cannot resolve various endpoints.

Heavy gaugino signals are hard but not impossible.

New result: SU1 has ℓq triangular edge from $\tilde{q}_L \to \tilde{\chi}_1^\pm q \to \ell^\pm \tilde{\nu}_\ell q$ [Cooke]. (Note $B(\tilde{\chi}_1^\pm \to \ell^\pm \tilde{\nu}_L) = 20.2\%$.) Use mixed events (scaled by 90%) to subtract SUSY background:



Not kinematically allowed for DC1/SU3; provides additional constraint.

(Hadronic) τ Signatures

τ decays can dominate over e/μ decays, especially for $\tan\beta \gg 1$, if light $\tilde{\tau}_1$ provides only 2-body mode.

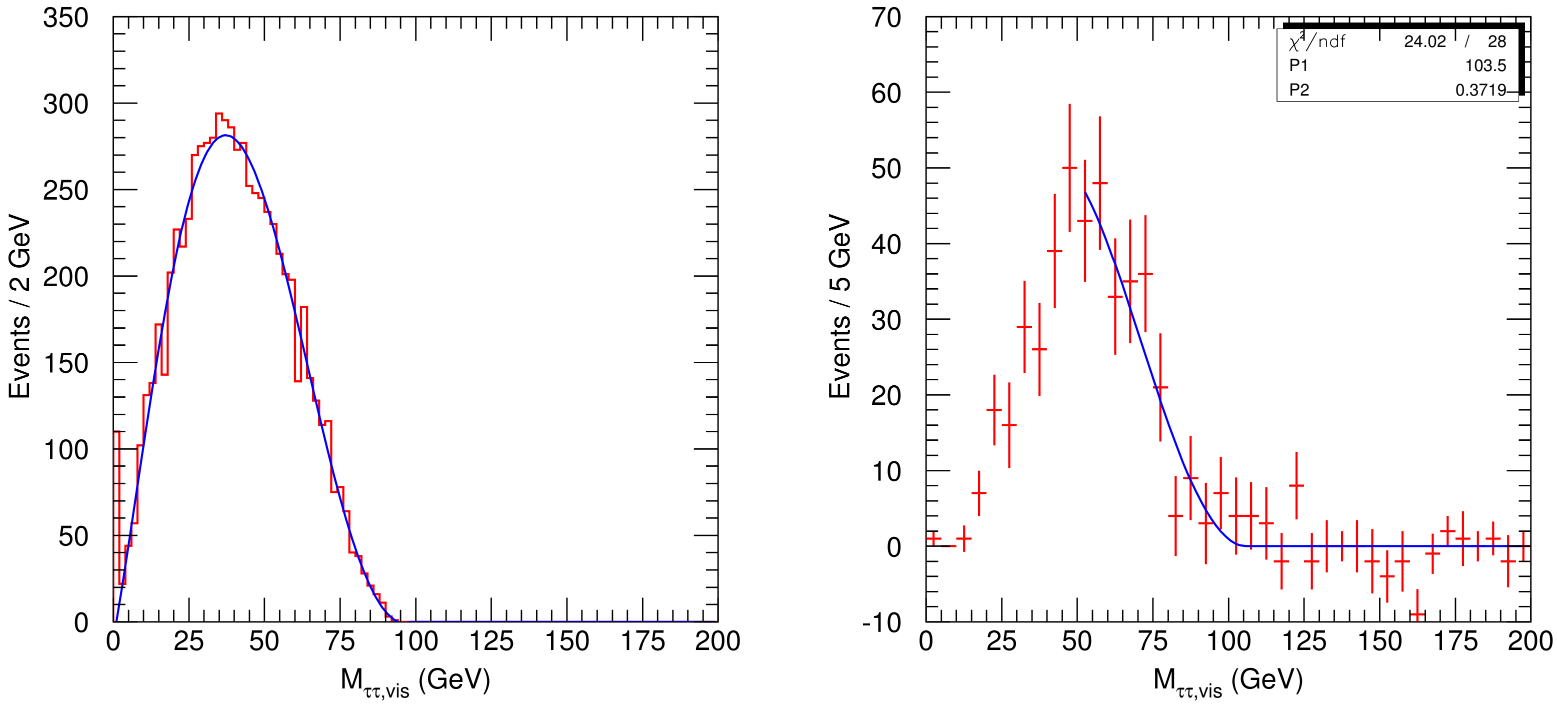
Even in mSUGRA model with unification at GUT scale, τ decays provide independent information because:

- ◦ Yukawa terms in RGE running;
- ◦ Gaugino/Higgsino mixing for charginos/neutralinos;
- ◦ τ_L–τ_R mixing ($\propto m_\tau \tan\beta$).

Inner layer of LHC vertex detectors at $R \sim 40\,\mathrm{mm}$ to avoid radiation damage, so cannot tag $\tau \to \ell\nu\nu$. Must rely on hadronic τ decays $\to$ narrow, low-multiplicity jets. Background from QCD fluctuations.

Have $\not{E}_T$ from both $\tilde{\chi}_1^0$ and ν, so can only measure visible hadronic τ momentum. Must deduce true p_τ from this.

DC1 full simulation analysis: parameterize visible $\tau\tau$ mass from $\tilde{\chi}_2^0 \to \tilde{\tau}_1 \tau$ decays and fit to reconstructed $\tau^+\tau^- - \tau^\pm\tau^\pm$ distribution:



Sign subtraction assumes that fake tau background (mainly) random in sign. Fitted endpoint is $103.5 \pm 4.9\,\mathrm{GeV}$ compared to true $98.3\,\mathrm{GeV}$.

Caveat 1: Reconstructed $\tau\tau$ mass has different shape at low $M_{\tau\tau}$. Need to make acceptance correction for low-p_T τ's — not done.

Caveat 2: Shape of Monte Carlo template distribution depends on τ polarization. Largest effect is for $\tau \to \pi\nu$:

$$\frac{dN}{d\cos\theta^*}(\tau^-_{L,R} \to \pi\nu) \propto 1 \mp \cos\theta^* \,.$$

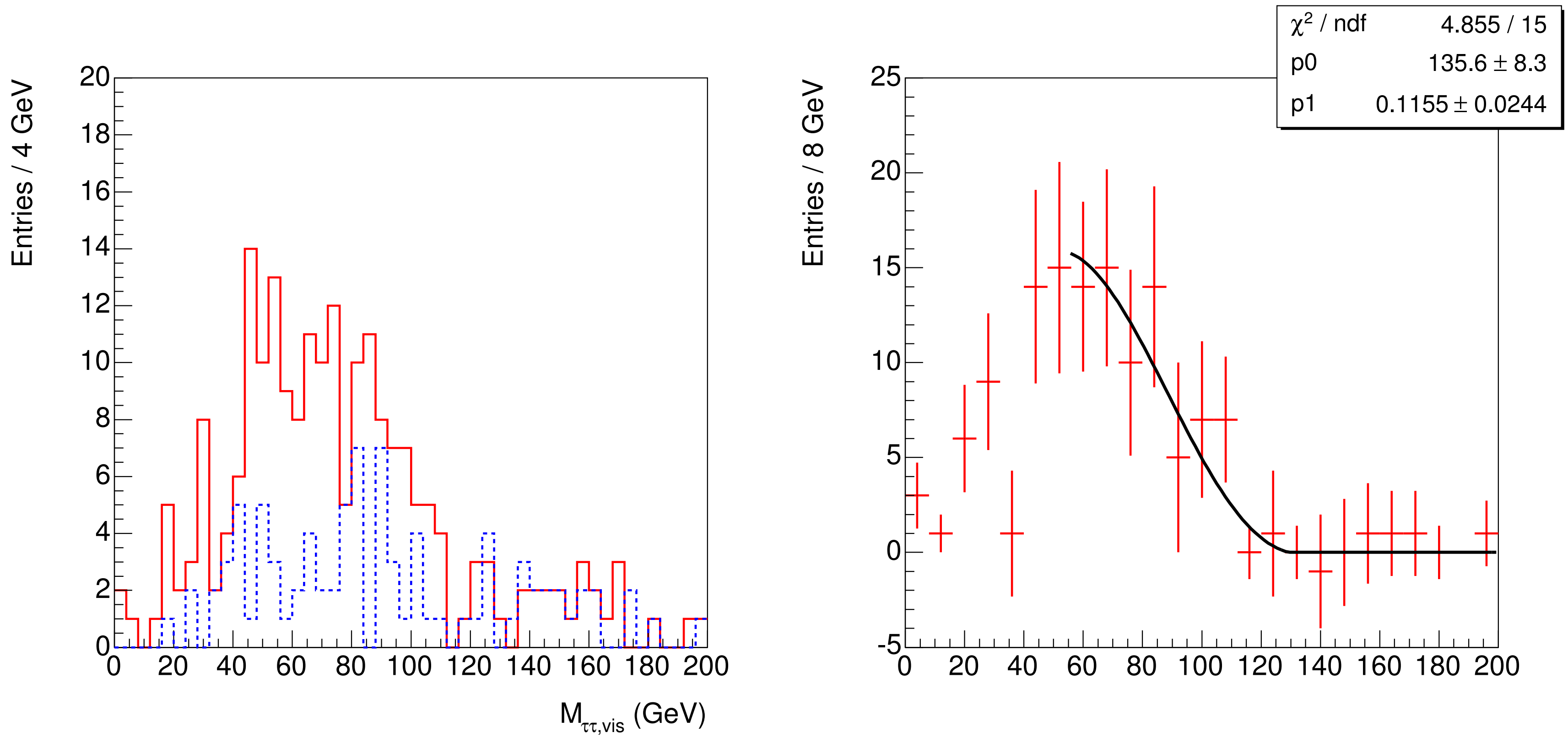
I.e., single pi is soft for τ_L, hard for τ_R.

Polarization hard to measure $\Rightarrow$ not important for $M_{\tau\tau}$?

Still want to measure it: best handle on chiral structure at LHC. Perhaps possible: identify $\pi\nu$ decays using $E = p$ and compare with all decays [Vacavant]. Needs study.

τ decays can dominate, e.g., mSUGRA Point SU6 in funnel region, $(m_0 = 320\,\mathrm{GeV},\ m_{1/2} = 375\,\mathrm{GeV},\ A_0 = 0,\ \tan\beta = 50,\ \mu > 0)$ has 2-body decays only to τ's, so $B(\tilde{\chi}_2^0 \to \tilde{\tau}_1^\pm \tau^\mp) = 95.6\%$, $B(\tilde{\chi}_1^\pm \to \tilde{\tau}_1^\pm \nu_\tau) = 94.6\%$.

Fit to $\tau^+\tau^- - \tau^\pm\tau^\pm$ for 16k events ($3.6\,\mathrm{fb}^{-1}$) using DC1/SU3 parameterization gives $135.6 \pm 8.3\,\mathrm{GeV}$ compared to true $126.5\,\mathrm{GeV}$:

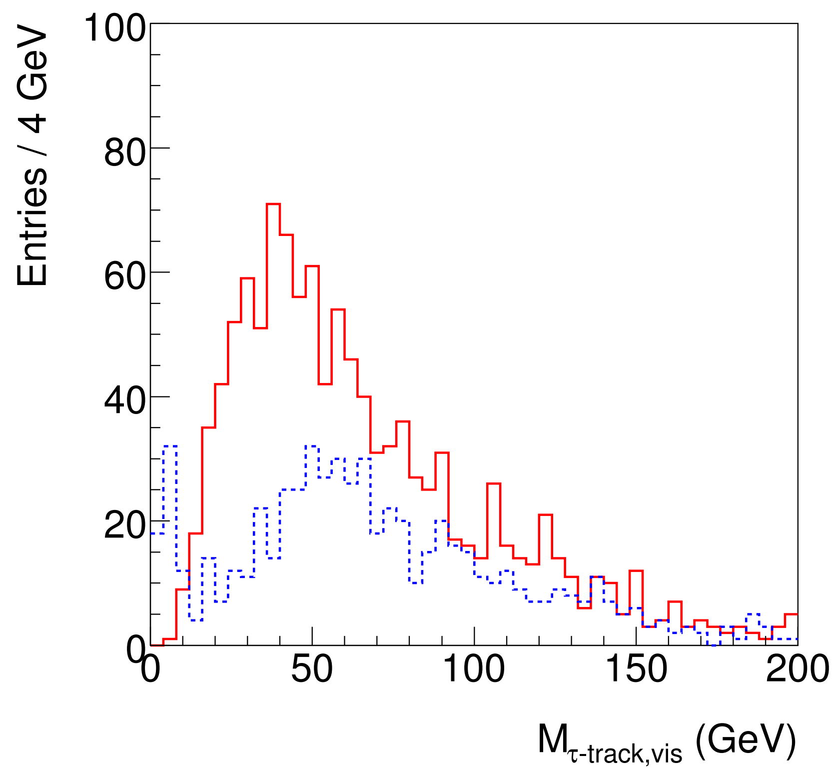


Finally consider Point SU1 in coannihilation region: small mass gaps give soft τ's. Reconstructed $\tau\tau$ mass has dismal efficiency.

Try instead combining hard reconstructed τ with *any* isolated track with $p_T > 6\,\mathrm{GeV}$.

See clear OS/SS excess.

Crude version of track-seeded τ reconstruction for soft τ's. Need something like this for similar cases.



New `tau1p3p` algorithm for ATLAS uses track seeds and looks for matching calorimeter clusters. Works better for low-p_T τ's.

Third Generation Squarks

Like $\tilde{\tau}$'s, third generation squarks $\tilde{t}_i, \tilde{b}_i$ are special:

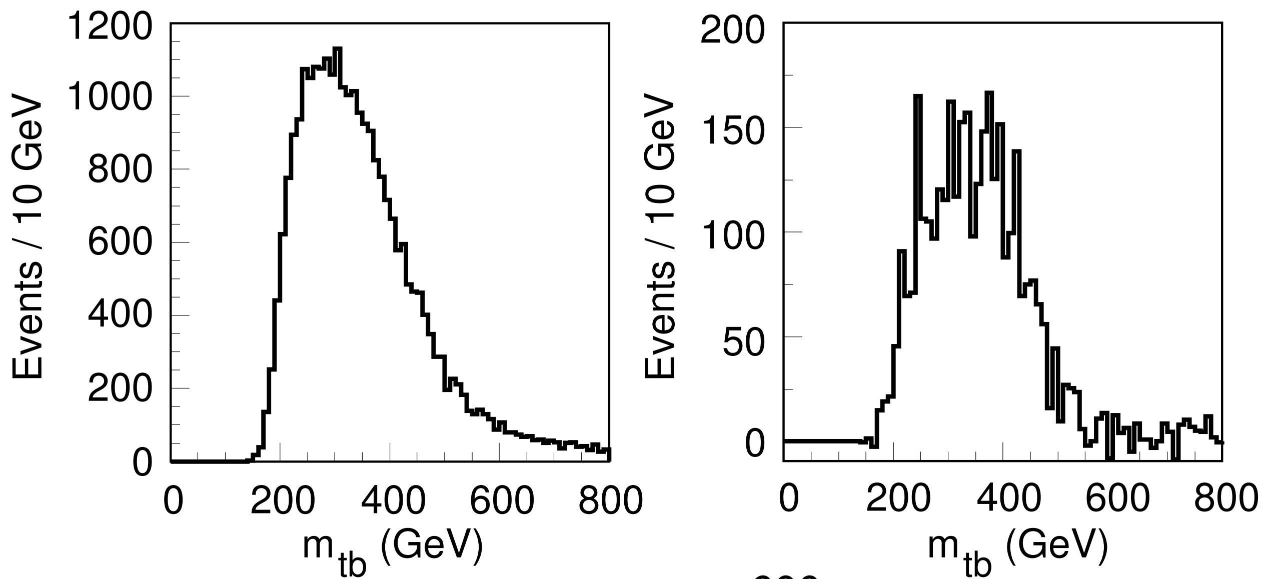
- Large Yukawa terms in RGE's and couplings.
- Large left-right mixing proportional to m_t or $m_b \tan\beta$.

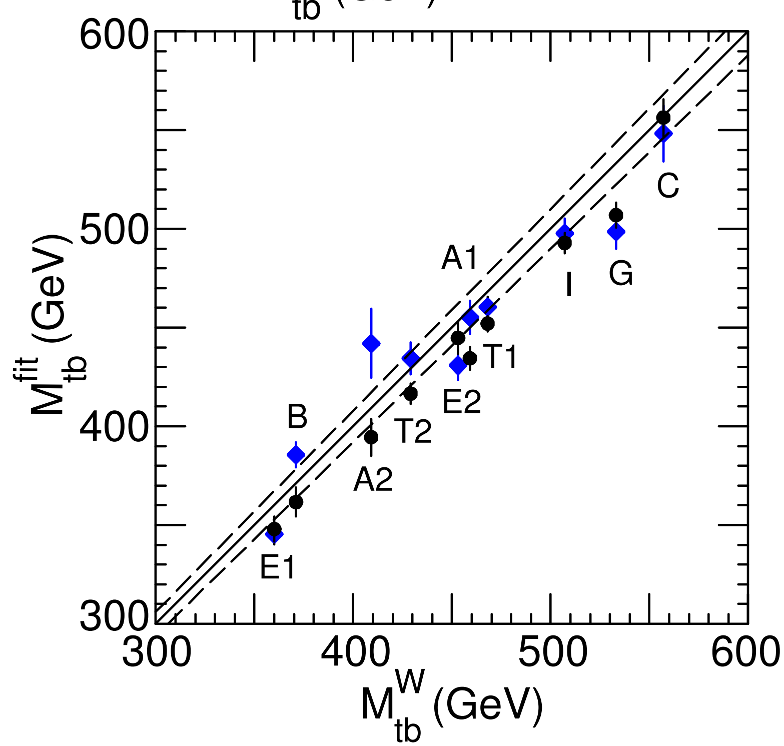
Crucial for understanding SUSY model — needs work.

Rely on vertex detector to tag b jets. Problems are efficiency/mistags and combinatorics.

Typical decay chain is $\tilde{g} \to \tilde{t}_1 \bar{t} \to \tilde{\chi}_j^+ b\bar{t} + \mathrm{h.c.}$. Then $b\bar{t}$ endpoint with $t \to q\bar{q}b$ measures $M(\tilde{g}) - M(\tilde{\chi}_1^\pm)$ [Hisano].

Fast simulation analysis. Large combinatorial background $\Rightarrow$ see nothing initially. But after sideband subtraction, endpoint emerges at right place (471 GeV):





Analysis repeated for 10 points for both Herwig and Pythia.

Consistently find right endpoint to about $\pm 2\%$ (lines in figure).

Should try similar studies with full simulation.

"Stransverse Mass"

In mSUGRA $B(\tilde{q}_R \to \tilde{\chi}_1^0 q) \approx 1$. Generally expect some squarks to decay directly to $\tilde{\chi}_1^0$. If $M(\tilde{q}) < M(\tilde{g})$, expect events with two hard jets and $\not\!\!E_T$.

Form "stransverse mass" including $M(\tilde{\chi}_1^0)$:

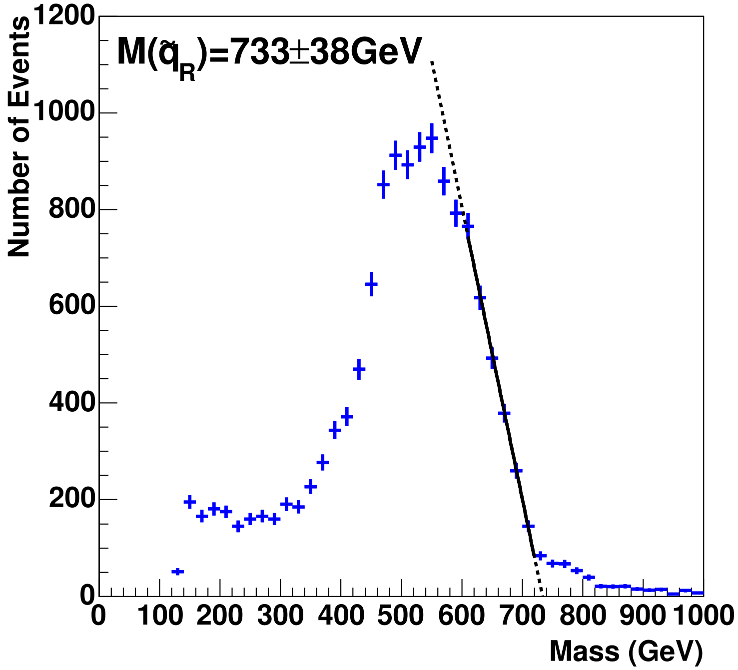
$$M_{T2}^2 \equiv \min_{\not p_1 + \not p_2 = \not p_T} \left[\max \left\{ m_T(p_{T\ell_1}, \not p_1; M(\tilde{\chi}_1^0)), m_T(p_{T\ell_2}, \not p_2; M(\tilde{\chi}_1^0)) \right\} \right]$$

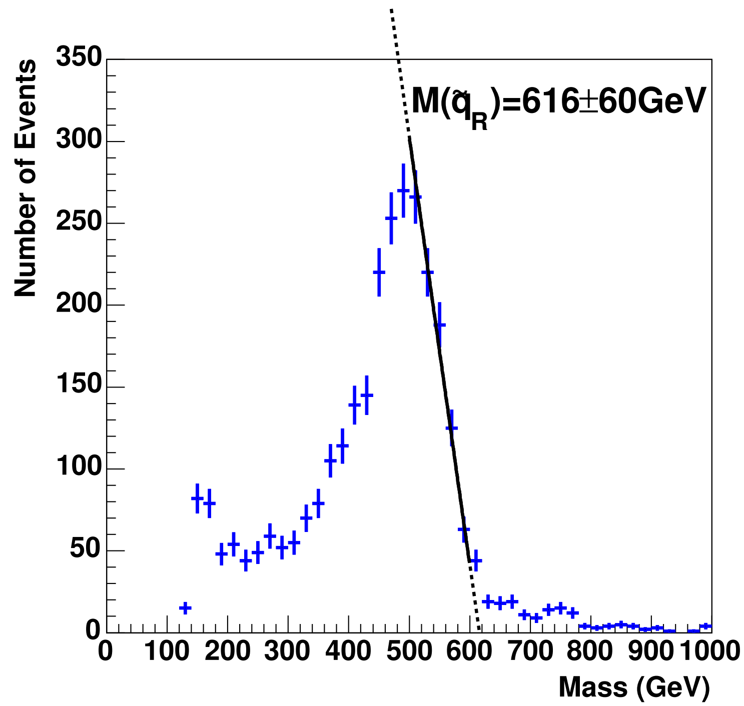
Partition $\not\!\!E_T$ in all possible ways, form two M_T for each partition, take larger, and minimize over all partitions.

Partitions include correct one, so M_{T2} has endpoint at $M(\tilde{q})$. (Must be careful not to get stuck in false minima.)

Very useful for signal and also to reject backgrounds with two neutrinos, e.g., $t\bar{t}$ or W^+W^-.

M_{T2} distributions for mSUGRA points SU1 and SU3 with correct $M)\tilde{\chi}_1^0)$ and fitted endpoints:

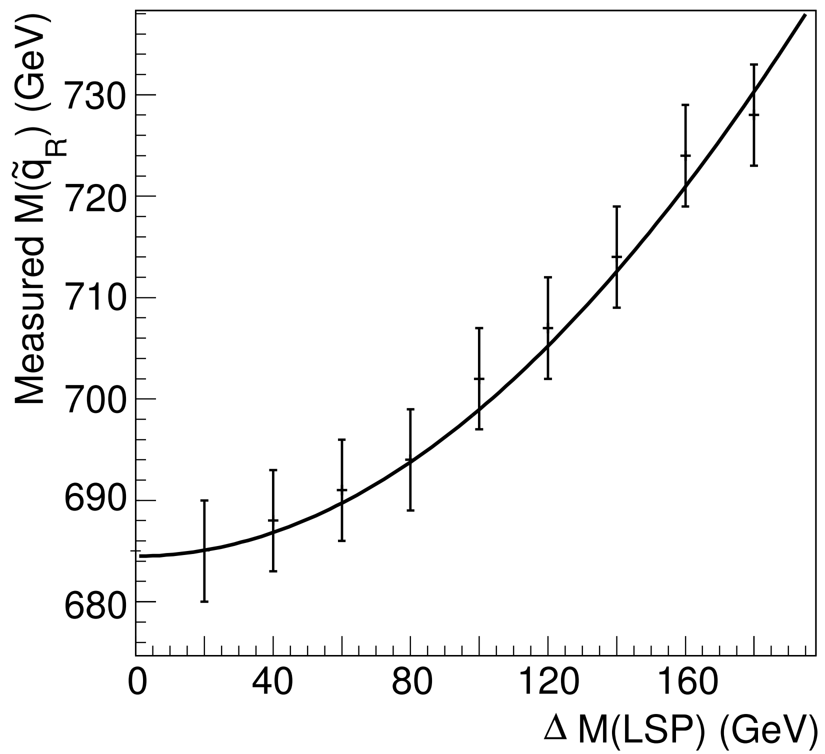




Compare with $\langle M(\tilde{q}_R) \rangle = 729$ and $638\,\mathrm{GeV}$ respectively.

Of course $M(\tilde{\chi}_1^0)$ not well known, at least from early data. . . .

Vary assumed $M(\tilde{\chi}_1^0)$ and redo fit:

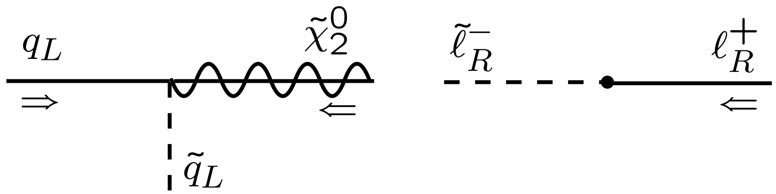


Quadratic dependence $\Rightarrow$ not very sensitive if $M(\tilde{\chi}_1^0) \ll M(\tilde{q}_R)$. But need better understanding of what M_{T2} endpoint really measures.

Needs work.

Measuring Spins

Can get some spin information: decay $\tilde{q}_L \to \tilde{\chi}_2^0 q$ produces q_L and hence $\tilde{\chi}_2^0$ with helicity $\lambda = -1$:



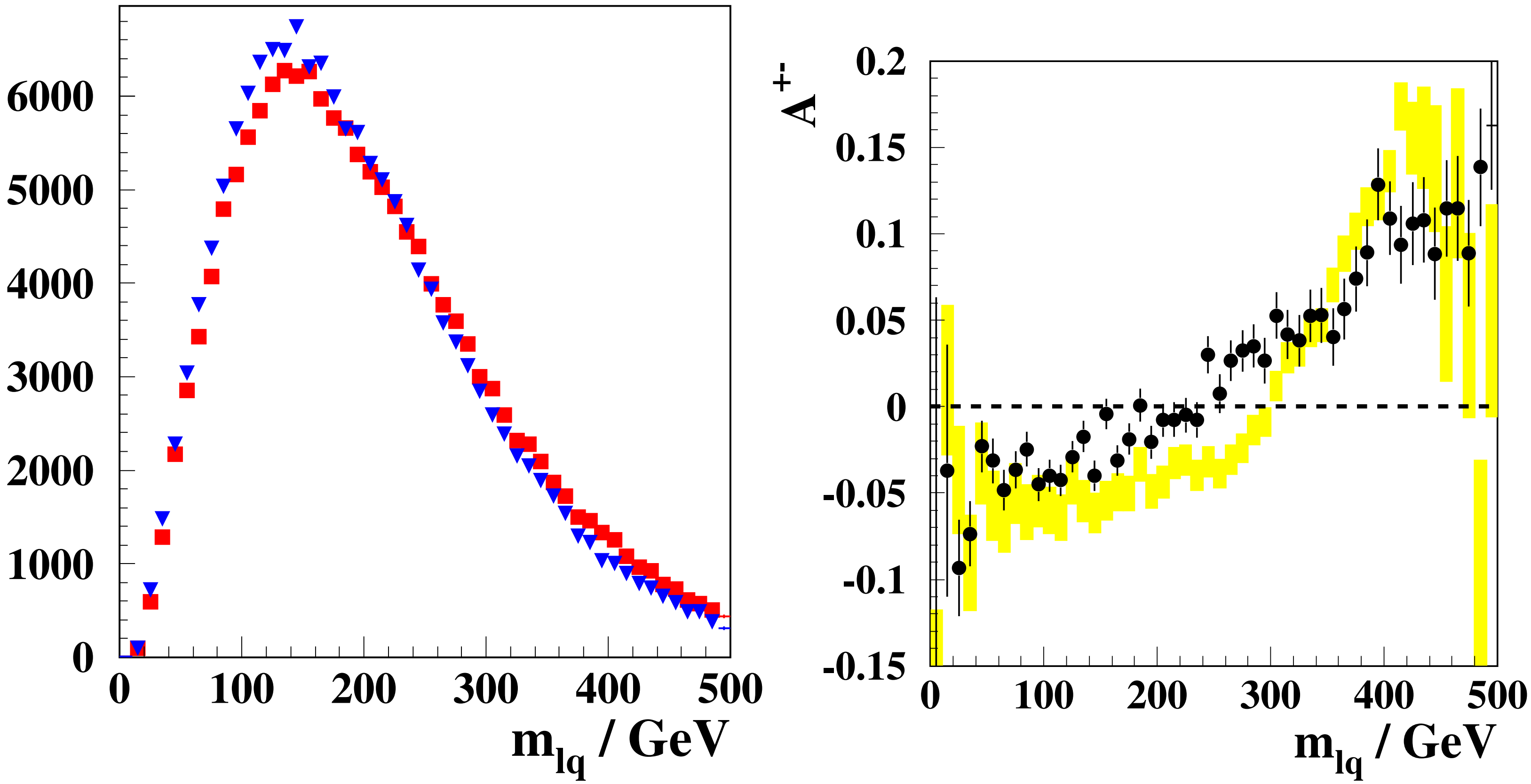
Hence $\tilde{\chi}_2^0 \to \tilde{\ell}_R^{\mp} \ell^{\pm}$ distribution $\sim \left[d^{\left(\frac{1}{2}\right)}_{-\frac{1}{2}\pm\frac{1}{2}}(\theta) \right]^2 \propto 1 \pm \cos\theta$.

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 SU3). 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 $150\,\mathrm{fb}^{-1}$ [Barr]:



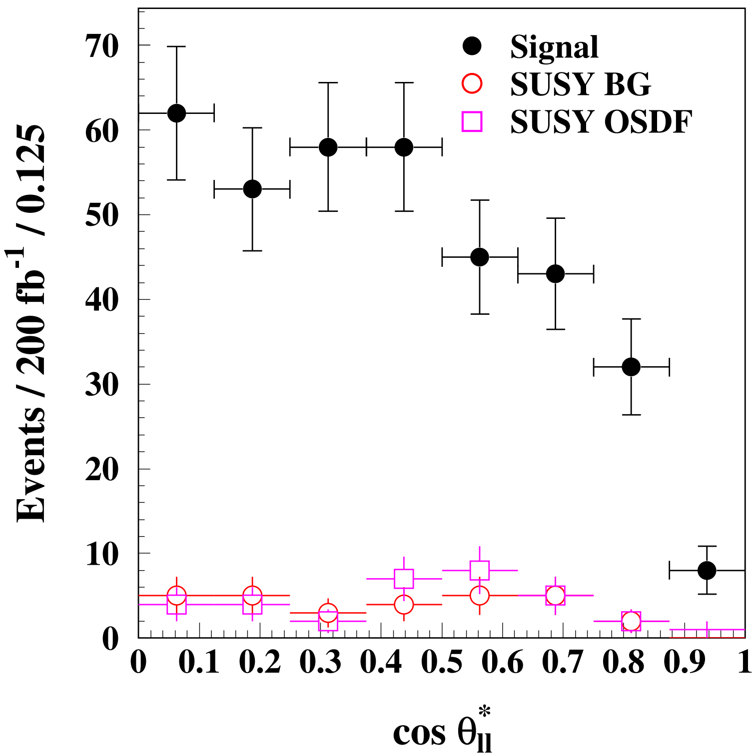
(Yellow rectangles show rescaled parton level distribution.)

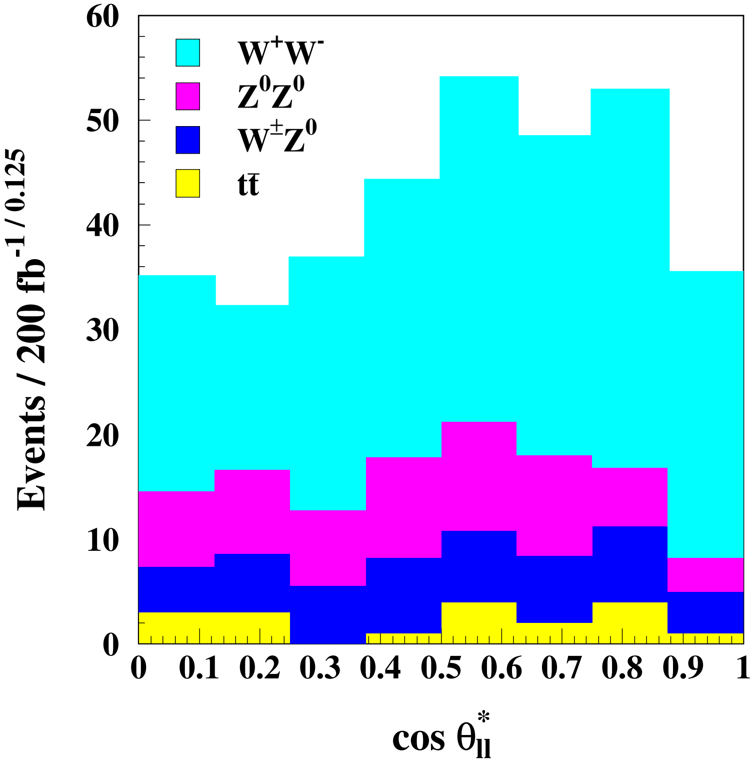
Shows non-zero spin consistent with SUSY expectations. . . .

More general method is based on $q\bar{q} \to \gamma/Z \to \tilde{\ell}^+\tilde{\ell}^-$. Would give $\sin^2\theta^*$ in COM for $J=0$, $1+\cos^2\theta^*$ for $J=1$. For boost-invariance use [Barr05]

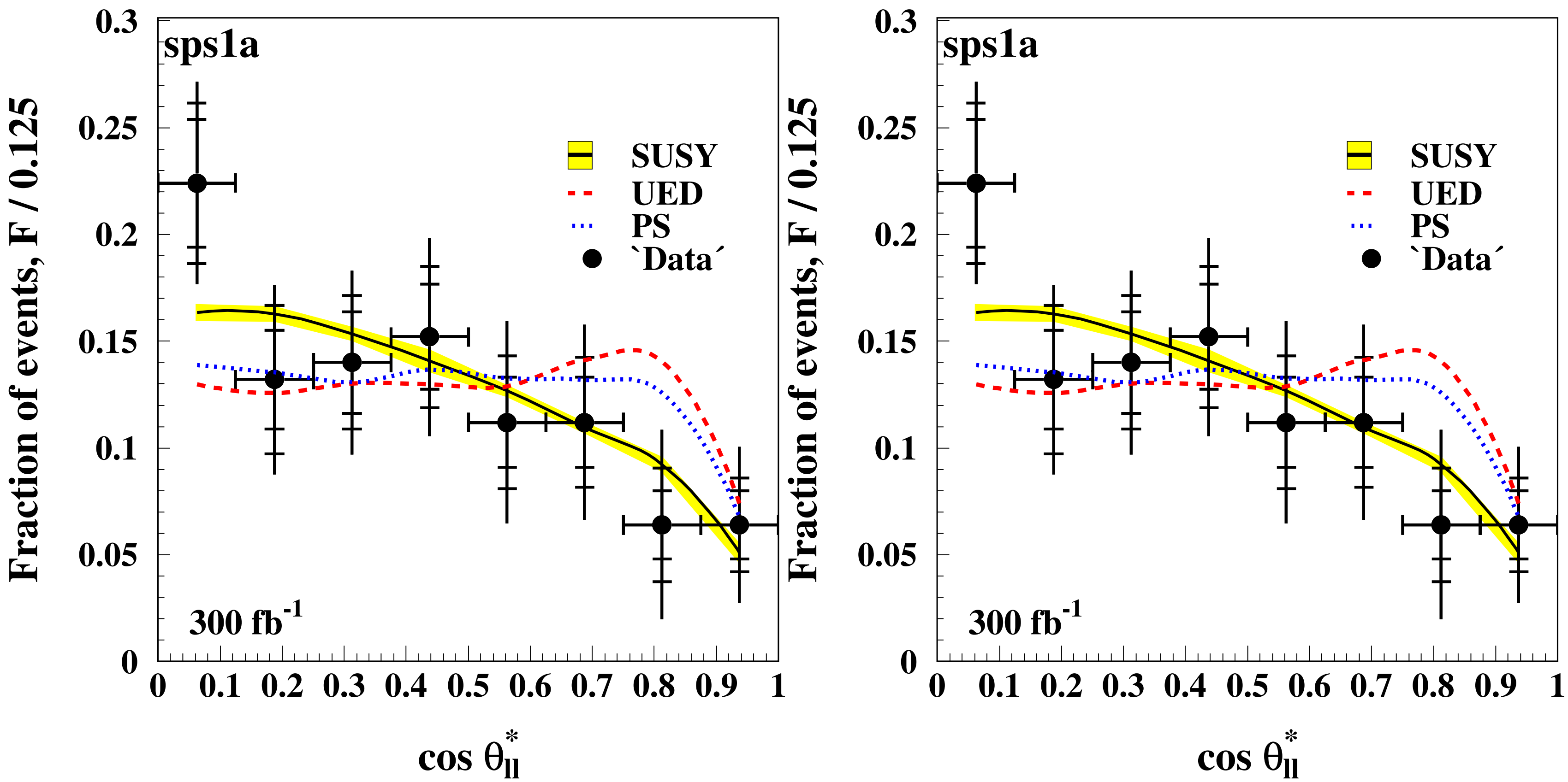
$$\cos\theta^*_{\ell\ell} \equiv \cos\left(2\tan^{-1}\exp(\Delta\eta_{\ell\ell}/2)\right) = \tanh(\Delta\eta_{\ell\ell}/2)$$

Select events with 2 leptons, $M_{T2} < M_W$, no jet with $p_T > 100\,\mathrm{GeV}$, no tagged b jet, and $\left|\not{\mathbf{p}}_{\mathbf{T}} + \mathbf{p}_{\mathbf{T},1} + \mathbf{p}_{\mathbf{T},2}\right| < 100\,\mathrm{GeV}$. Results for TDR Point 5:





Background-subtracted distributions for Point 5 and SPS1a:



Also works for several other cases.... Quite general, but does need 200–300 fb^{-1}.

GMSB Models

SUSY breaking in GMSB communicated by $SU(3) \times SU(2) \times U(1)$ gauge interactions at low scale ($\sim 100\,\mathrm{TeV}$) $\Rightarrow$ no FCNC.

LSP is gravitino $\tilde{G}$ with $M \sim 1\,\mathrm{eV}$–$1\,\mathrm{keV}$. Phenomenology depends on nature of NLSP ($\tilde{\chi}_1^0$, $\tilde{\tau}_1$) and lifetime for $\tilde{G}$ decay (prompt, long-lived). Typically longer decay chains, e.g.,

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

No recent work, but generally expect less background and easier analysis [TDR].

Possible exotic signatures if NLSP is long-lived:

- Non-pointing photons from $\tilde{\chi}_1^0 \to \tilde{G}\gamma$.
- Quasi-stable charged particles ($\tilde{\tau}_1$, perhaps $\tilde{\ell}_R$).

Quasi-Stable Charged Particles

Exotic atom limits $\Rightarrow$ stable particles must be neutral and weakly interacting. But long-lived charged particles possible. Possible SUSY scenarios:

- GMSB Model: If $N_5 > 1$, NLSP is $\tilde{\tau} \to \tilde{G}\tau$, with $1\,\mathrm{mm} \lesssim c\tau \lesssim 1\,\mathrm{km}$.
- Co-NLSP quasi-stable $\tilde{e}$, $\tilde{\mu}$, $\tilde{\tau}$ possible.
- In split-SUSY, $M(\tilde{q}) \sim M(\tilde{\ell}) \sim 10^{12}\,\mathrm{GeV} \Rightarrow \tilde{g}$ forms quasi-stable R-hadrons, giving soft interactions in calorimeter.

Quasi-stable charged particles speculative but possible.

ATLAS muon system $\Rightarrow$ TOF system with $R \sim 10\,\mathrm{m}$ and $\Delta t \sim 1\,\mathrm{ns}$. "Compact" CMS not dissimilar.

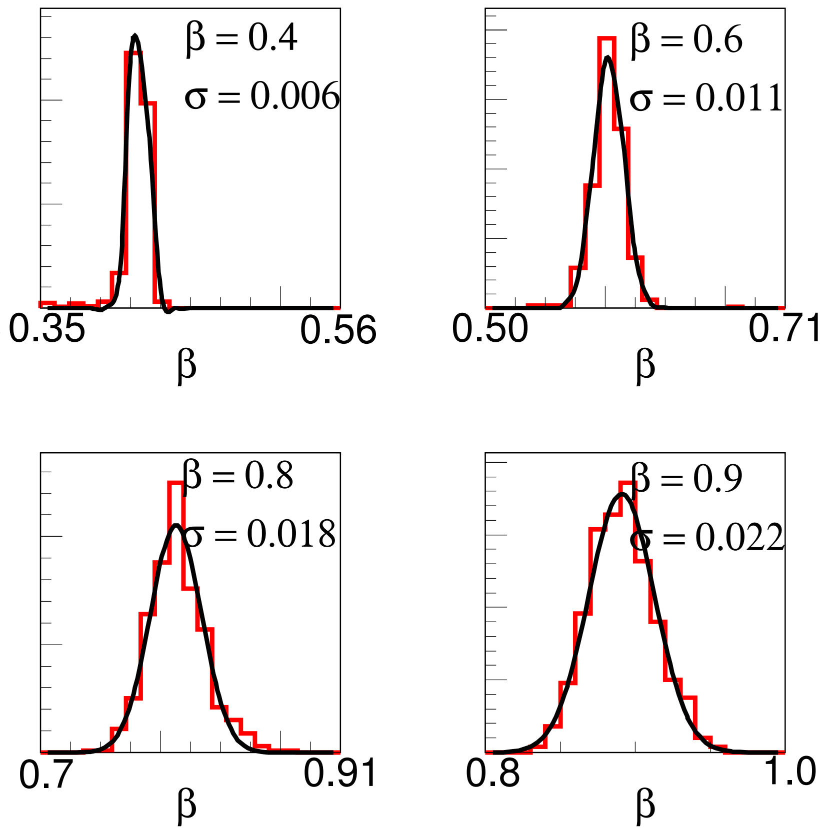
Trigger and reconstruction should allow such exotic possibilities.

Know from LEP $M \gtrsim 100\,\mathrm{GeV}$. Generally expect $p \gtrsim M$, so $0.7 \lesssim \beta < 1$. Should be associated with right bunch crossing.

ATLAS study for TDR found good resolution for $\beta < 1$, comparable to $\Delta t \sim 1\,\mathrm{ns}$ over $R \sim 10\,\mathrm{m}$.

Based on old software; not in current reconstruction.

Essential to allow for slow particles in trigger and reconstruction. Can ssume $p \lesssim 100\,\mathrm{GeV} \Rightarrow$ nearly straight tracks.



Should allow $\beta < 1$ in standard muon trigger/reconstruction.

Outlook

Standard Model is very successful but fails to address several crucial issues. Speculation about physics beyond the Standard Model at TeV mass scale has been ongoing for at least 25 years.

Can only resolve such speculation by experiments capable of probing TeV mass scale. LHC can do this starting in about two years.

ATLAS and CMS are expending a lot of effort to understand how to extract physics from data. Have only discussed specific SUSY scenarios here. Crucial question: can we find "any" new physics?

Must be produced $\Leftrightarrow$ coupling to SM quanta with sufficient strength. Then decay either to SM quanta or to charged/neutral (quasi)-stable particles. All are detectable by ATLAS/CMS.

But, e.g., charged particles ("muons" with $\beta < 1$) might have bad χ^2 and be discarded.

Balance between rejection of junk and acceptance of possible exotic signatures requires careful thought. Not enough attention.

Current emphasis is more mundane: what to do with initial data sample, perhaps $100\,\mathrm{pb}^{-1}$. Would give 100k $Z \to ee$, 100k $t\bar{t}$, and perhaps $\gtrsim$ 1k SUSY events.

Even $100\,\mathrm{pb}^{-1}$ at LHC might yield major discoveries! Playing with simulated data has been fun ... looking forward to real data soon.

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