BSM Flavor Physics at LHC

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Talk is limited to work by ATLAS and CMS. Mostly ATLAS, but have included some CMS work (thanks to Albert de Roeck).

Will emphasize SUSY: well studied and clear implications for flavor physics. But will also discuss "Little Higgs" and other models.

All LHC physics studies start with pQCD cross section plus event generator. Typically parton shower + hadronization + underlying event (Pythia, Herwig, Isajet). Simulate detector for signal and backgrounds:

- "Fast:" Parameterization of ideal response.
- "Full:" Detailed GEANT-based simulation of detector response, reconstruction using (approximately) software for real data.

SUSY

SUSY at TeV mass scale is perhaps most attractive extension of Standard Model. Provides naturally light Higgs, grand unification, and cold dark matter.

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

$$\begin{aligned} \text{Each massless gauge boson} &\quad\Leftrightarrow\quad \text{Massless gaugino} \\ \text{Each chiral fermion} &\quad\Leftrightarrow\quad \text{Massless sfermion} \end{aligned}$$

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, $\ldots \Rightarrow$ Number of parameters severely restricted.

Will assume here invariance under R-parity, where

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

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 $\operatorname{sgn}\mu = \pm 1$ of Higgsino mass-squared.

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.

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

Masses for ATLAS point SU3:
mSUGRA with

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

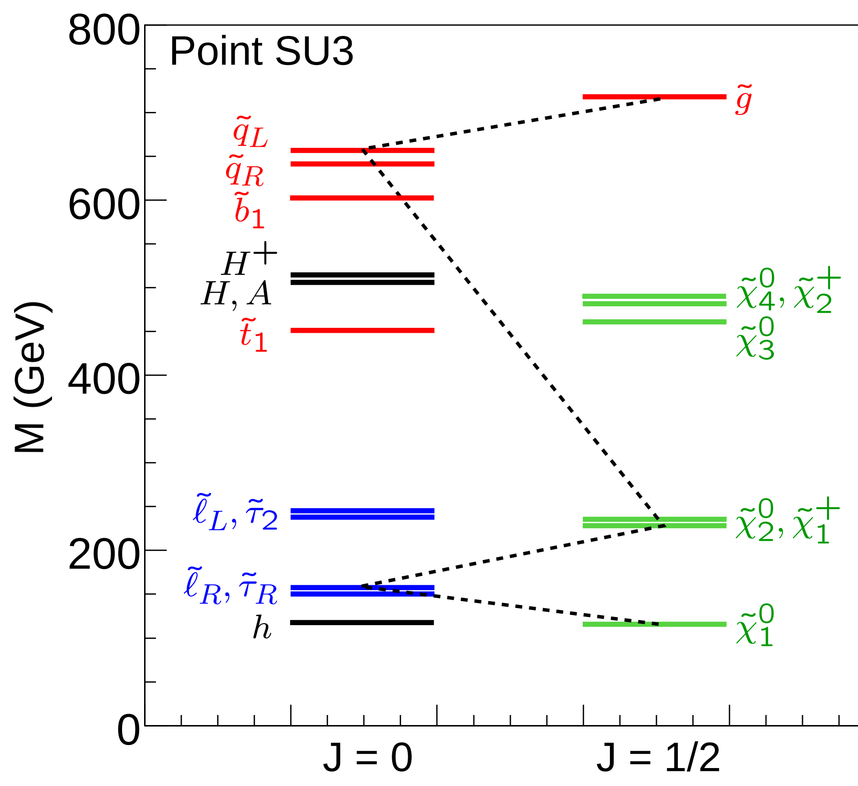
$$A_0 = -300\,\mathrm{GeV}, \ \tan\beta = 6, \ \mu > 0$$

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.



Various benchmark points in mSUGRA studied

Recent ATLAS full-simulation studies on a set of Points (SUx), using as a guide regions giving correct amount of LSP Dark Matter

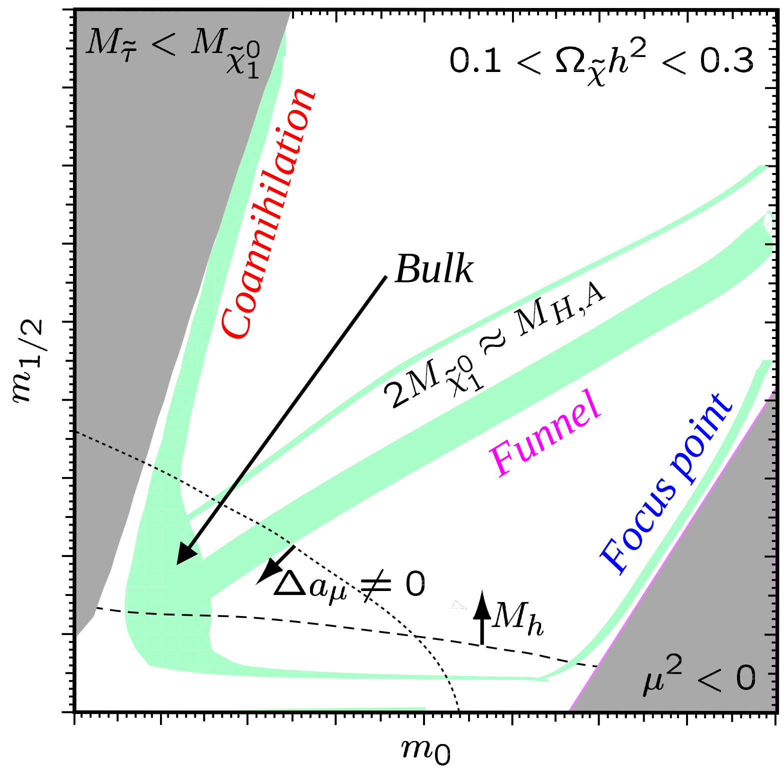
Coannihilation: Light $\tilde{\tau}_1$ in equilibrium with $\tilde{\chi}_1^0$, so annihilate via $\tilde{\chi}_1^0 \tilde{\tau}_1 \to \gamma\tau$ (SU1)

Bulk: bino $\tilde{\chi}_1^0$; light $\tilde{\ell}_R$ enhances annihilation. (SU3, SPS1a)

Funnel: H, A poles enhance annihilation for $\tan\beta \gg 1$. (SU6)

Focus point: Small μ^2, so Higgsino $\tilde{\chi}_1^0$ annihilate. Heavy s-fermions, so small FCNC. (SU2)

Most available studies focused on bulk.



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.

Experimentally need to rely on b and τ-tagged jets, or top reconstructed from decays: $\longrightarrow$ more complex experimental analysis, less results to date

Concentrate here on reviewing the techniques developed for measuring SUSY parameters at the LHC, basis for any detailed flavour study.

Only brief overview of available results in the field of SUSY flavour, some more detail in talks this afternoon in WG1 parallel session (T. Lari, I. Borjanovic)

Inclusive SUSY Searches

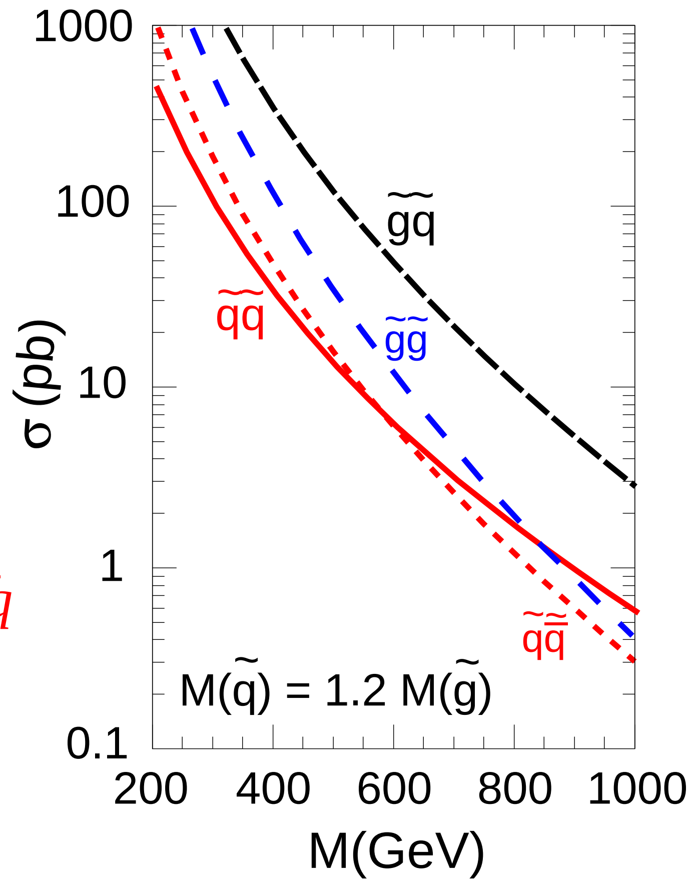
"Typical" SUSY model has gluinos and squarks at $\mathcal{O}(1\,\mathrm{TeV})$ decaying to $\tilde{\chi}_1^0$ at $\mathcal{O}(100\,\mathrm{GeV})$.

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

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

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

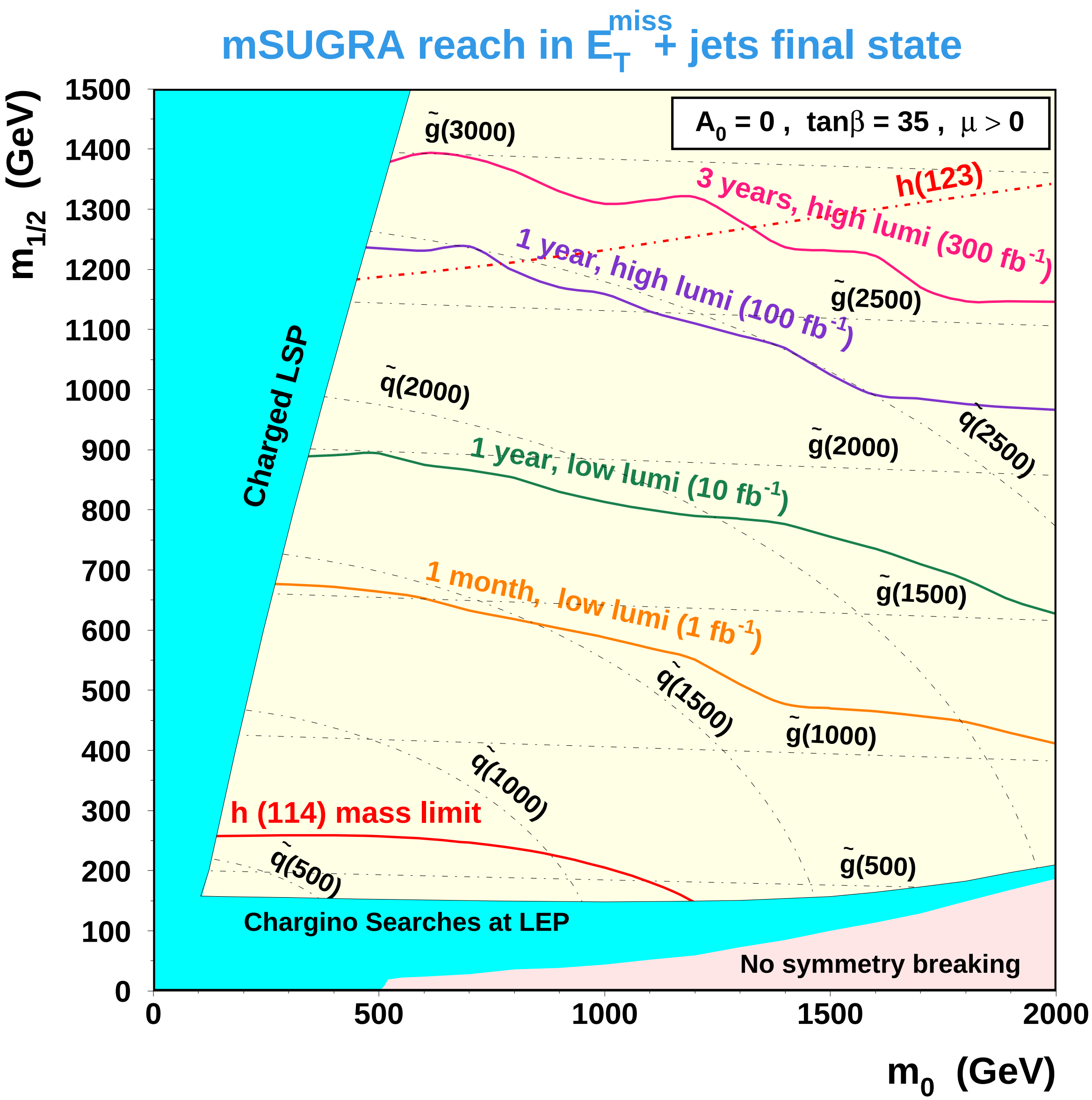
Hence expect multiple jets plus large $\not{E}_T$ from $\tilde{\chi}_1^0$. May also have leptons or τ's.



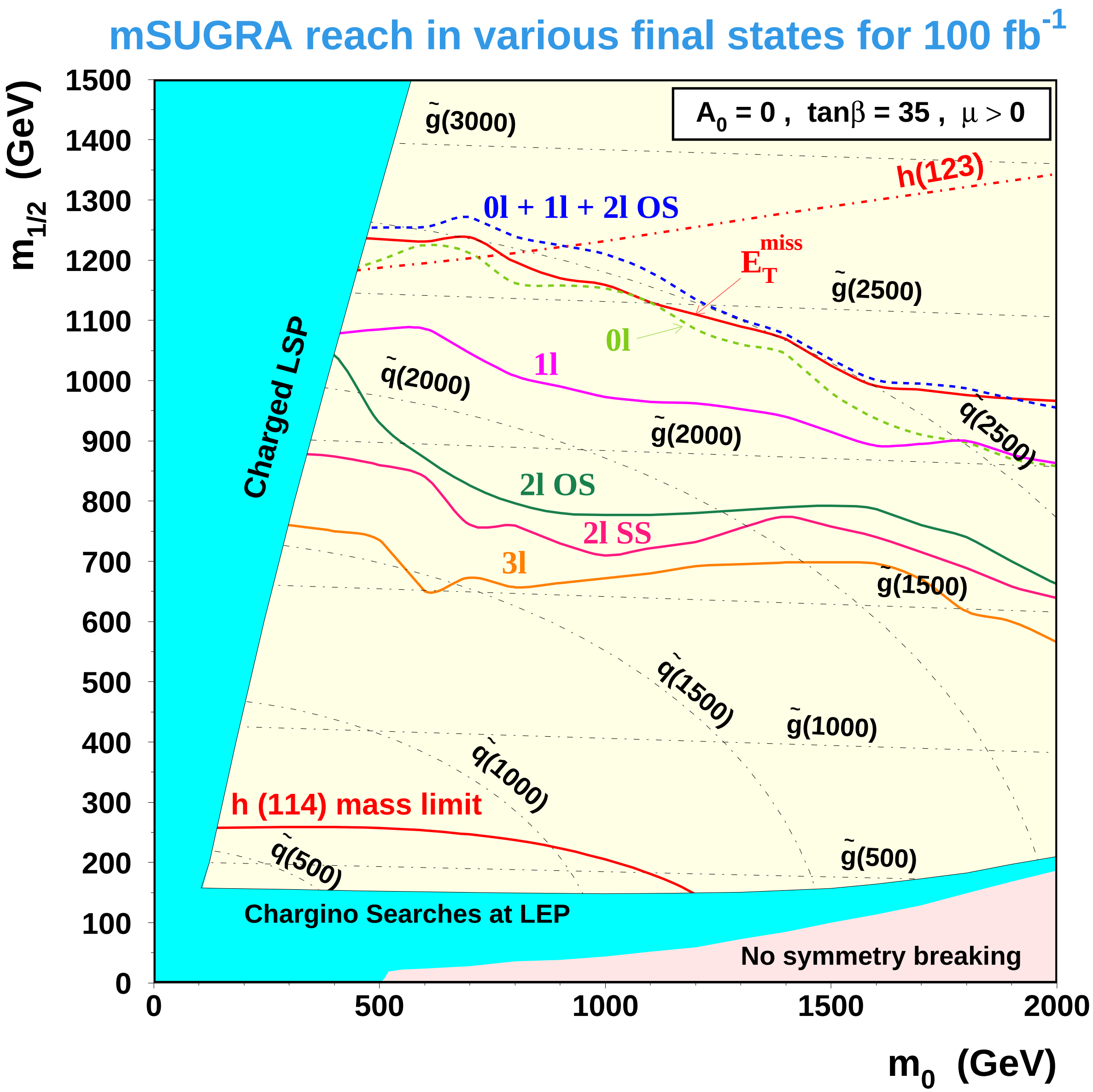
Standard Model backgrounds include $Z \to \nu\bar{\nu} +$ jets, $W +$ jets, $t\bar{t}$, b jets with $b \to \nu X$, etc. Also backgrounds from mismeasured events.

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]:



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 $\tilde{\chi}_1^0 e^\pm \mu^\mp$.

(different for $\mu\tau \Rightarrow$ see below)

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

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

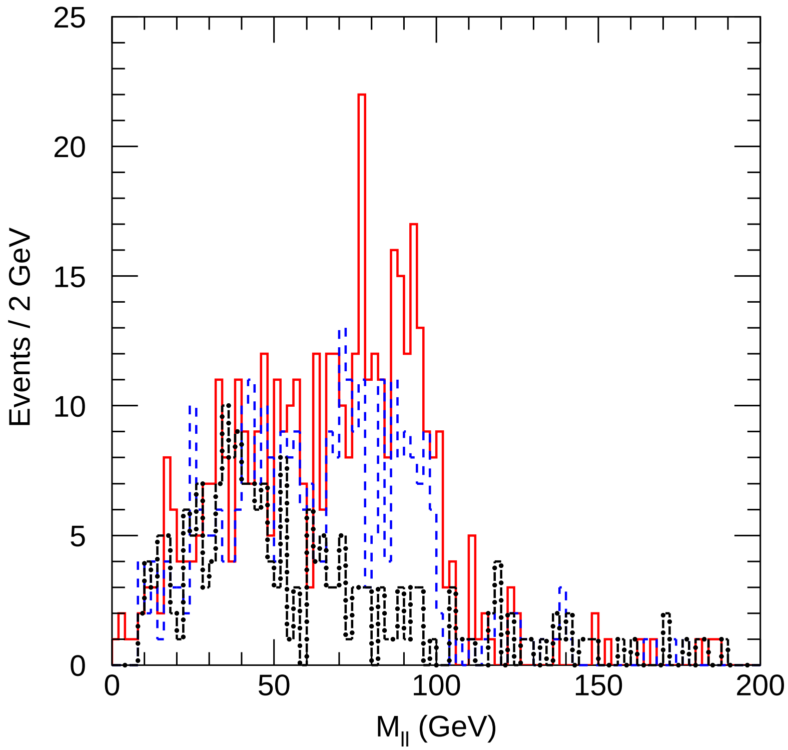
cancels backgrounds up to statistics and acceptance differences.

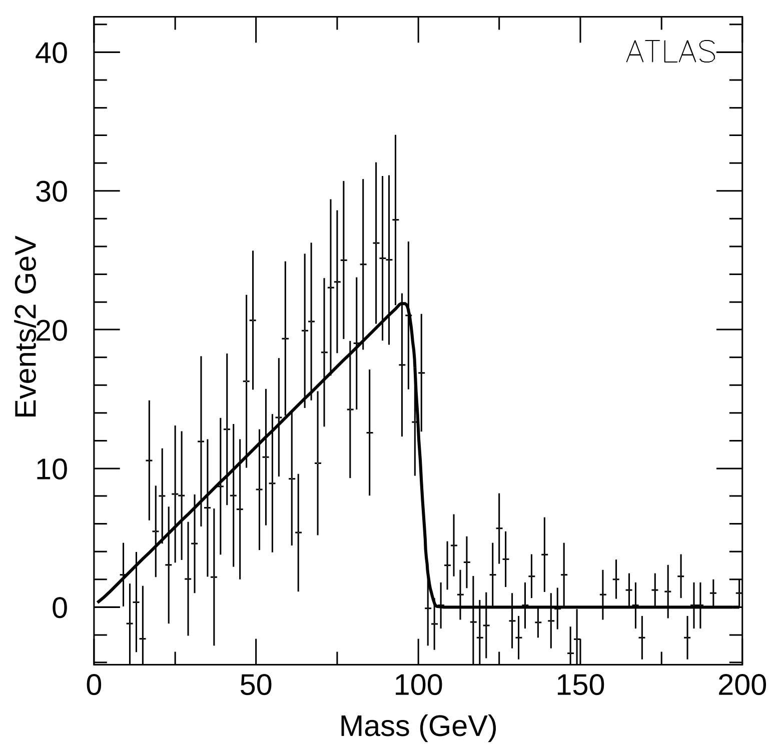
ATLAS and CMS have comparable acceptance for e and μ. Details are different.

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

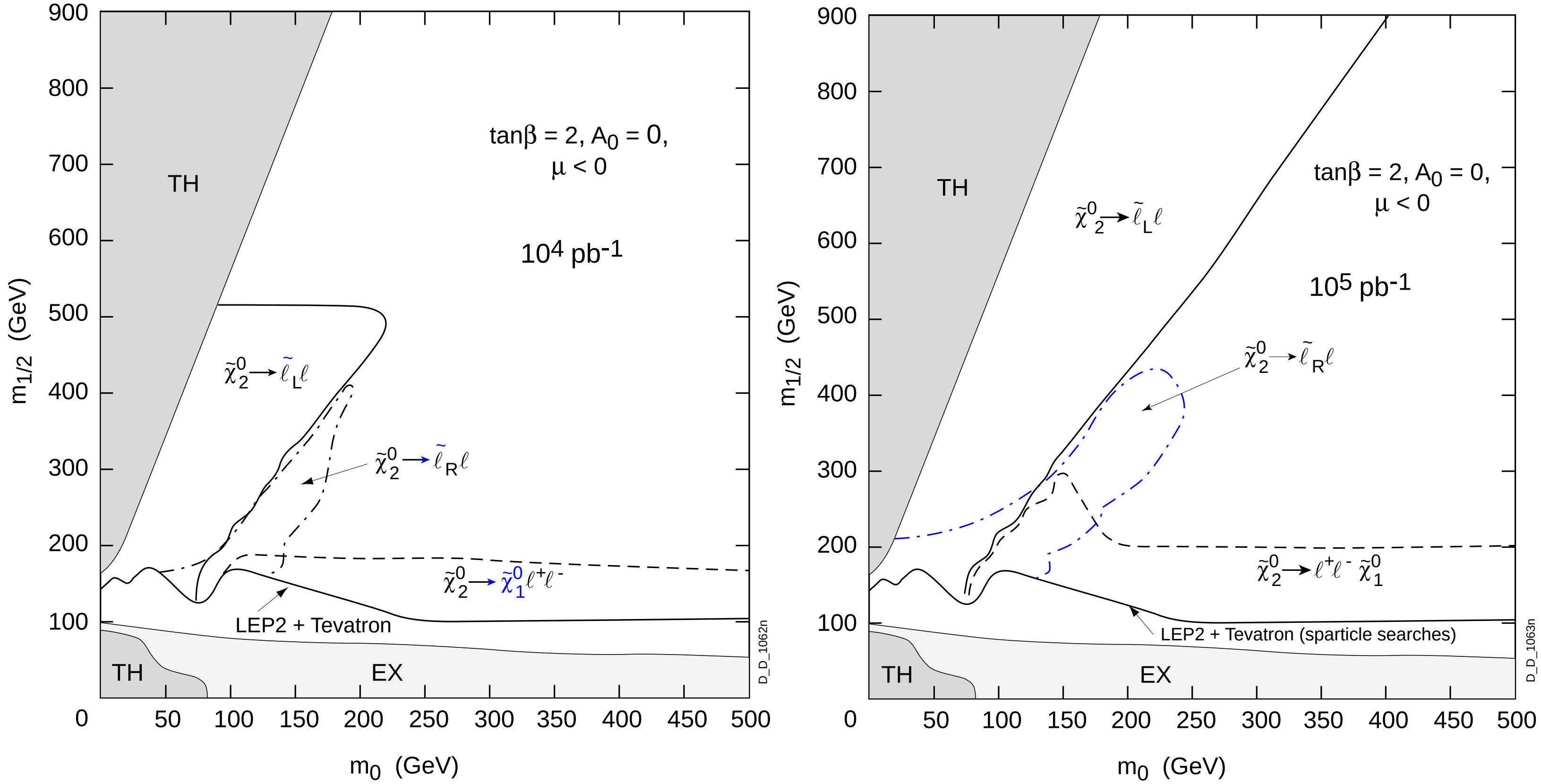
$$m_0 = 100\,\mathrm{GeV},\ m_{1/2} = 300\,\mathrm{GeV},\ A_0 = -300\,\mathrm{GeV},\ \tan\beta = 10,\ \mu > 0\,.$$

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 $100.31\,\mathrm{GeV}$:





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



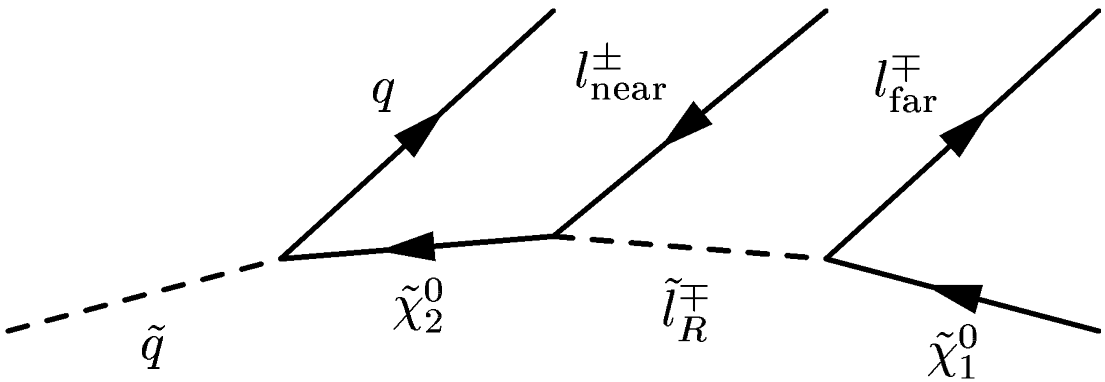
Next step: combine leptons with jets for “bulk” ATLAS point SU3.

Dominant source of $\tilde{\chi}_2^0$ is $\tilde{q}_L$ decay:

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

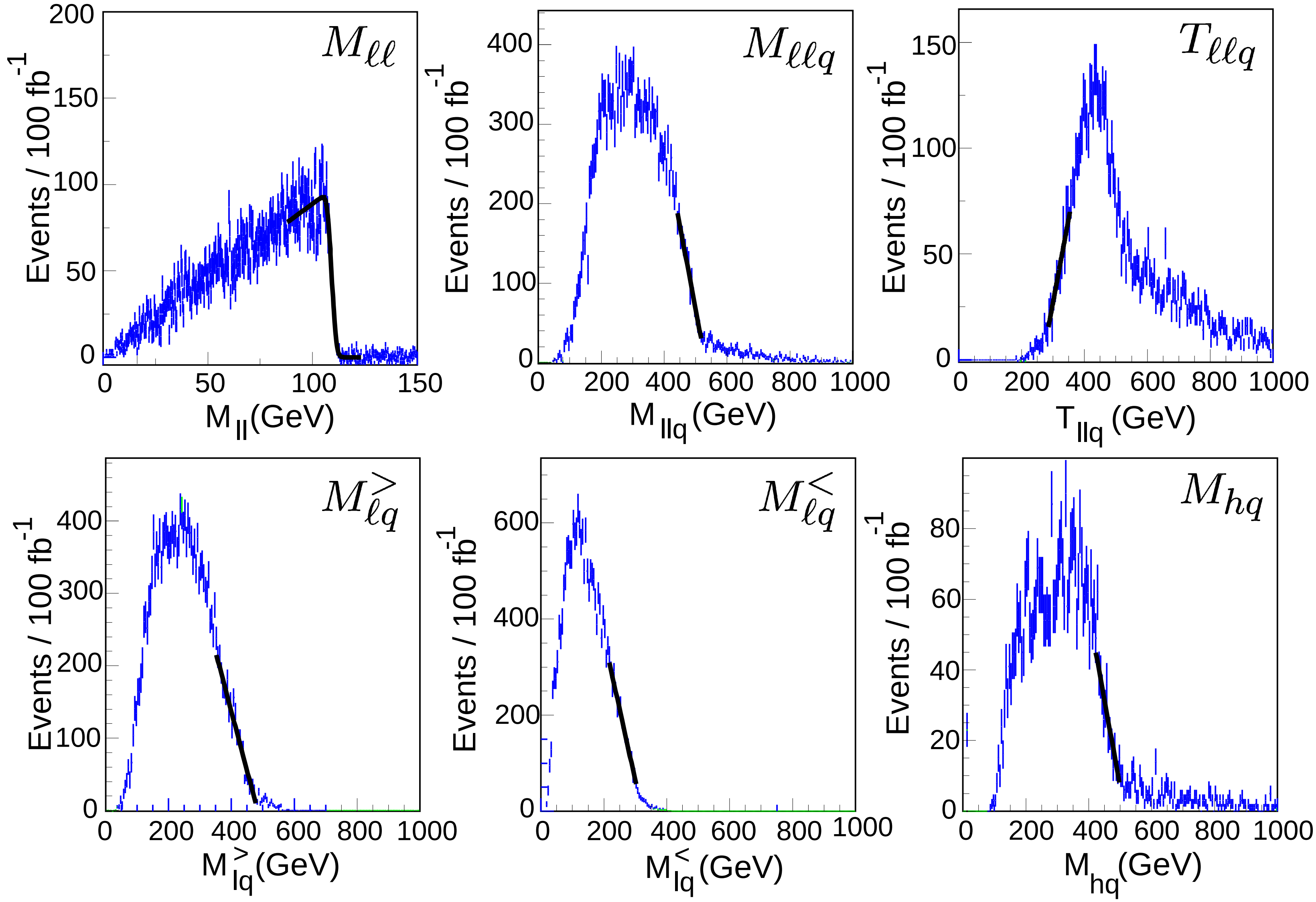
Can make $\tilde{q}_L$ either directly or via $\tilde{g}$ decay. In either case expect hardest jets to be from $\tilde{q}_L$.

For above decay chain can calculate invariant masses of visible particles: ℓ, ℓ, q [Bachacou,TDR]

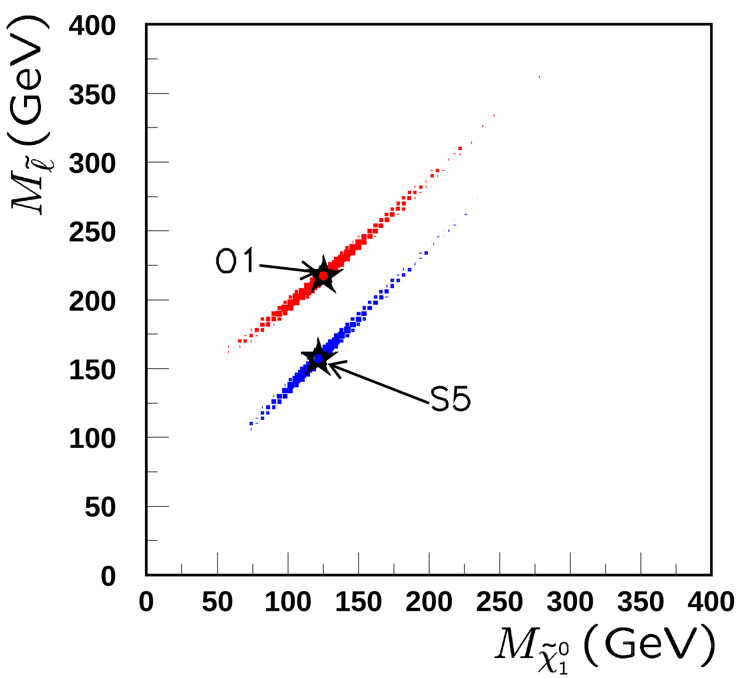


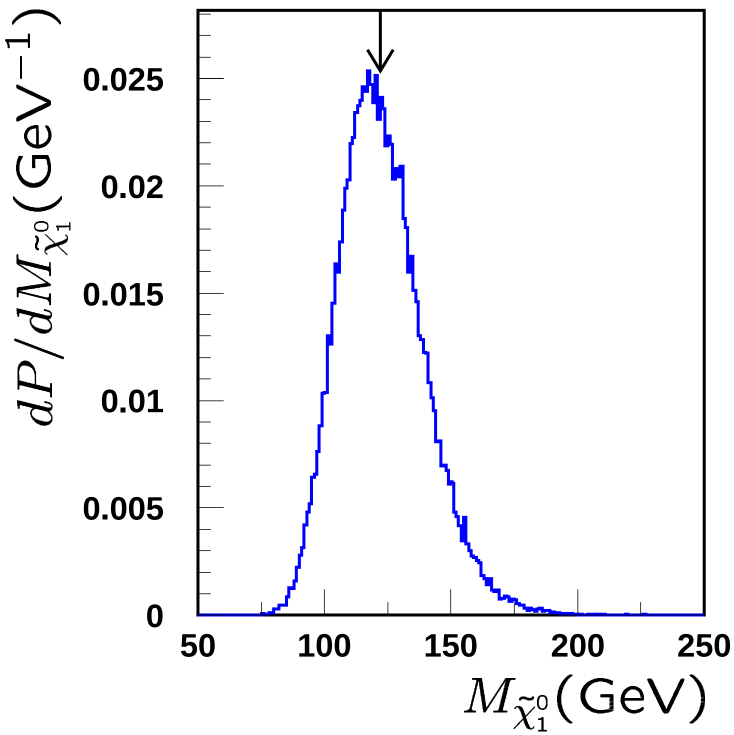
Values of end-points and thresholds of invariant mass distributions depend on relative masses of involved sparticles [Allanach].

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



Create MontCarlo experiments by smearing edges according to experimental resolution, and for each experiment solve edge constraints for sparticle masses. 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. Work in progress.

(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.

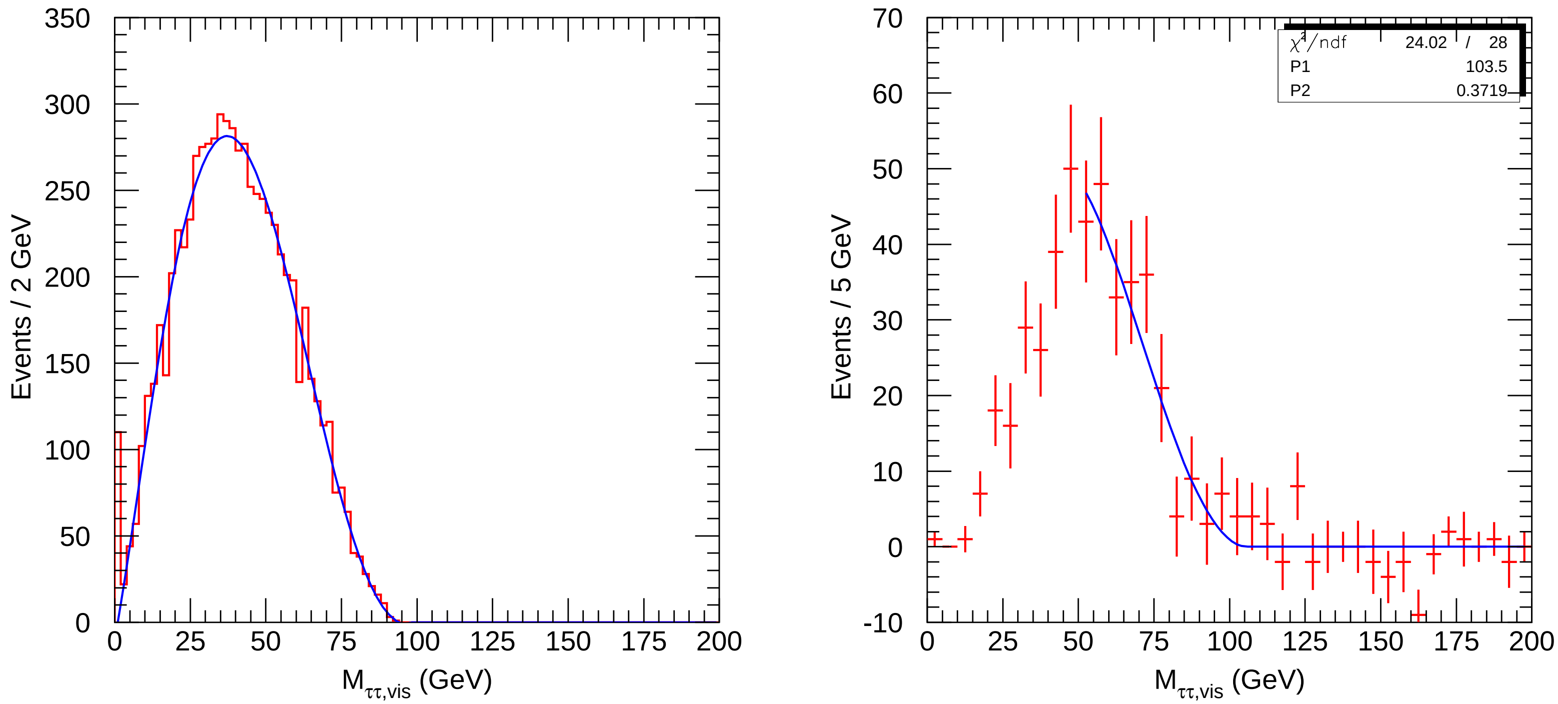
Even in mSUGRA model with unification at GUT scale, τ decays provide independent information because:

- 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 $R \sim 40\,\mathrm{mm}$, 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.

ATLAS full simulation analysis (SU3 Point): 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 $\tau \to \pi\nu$:

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

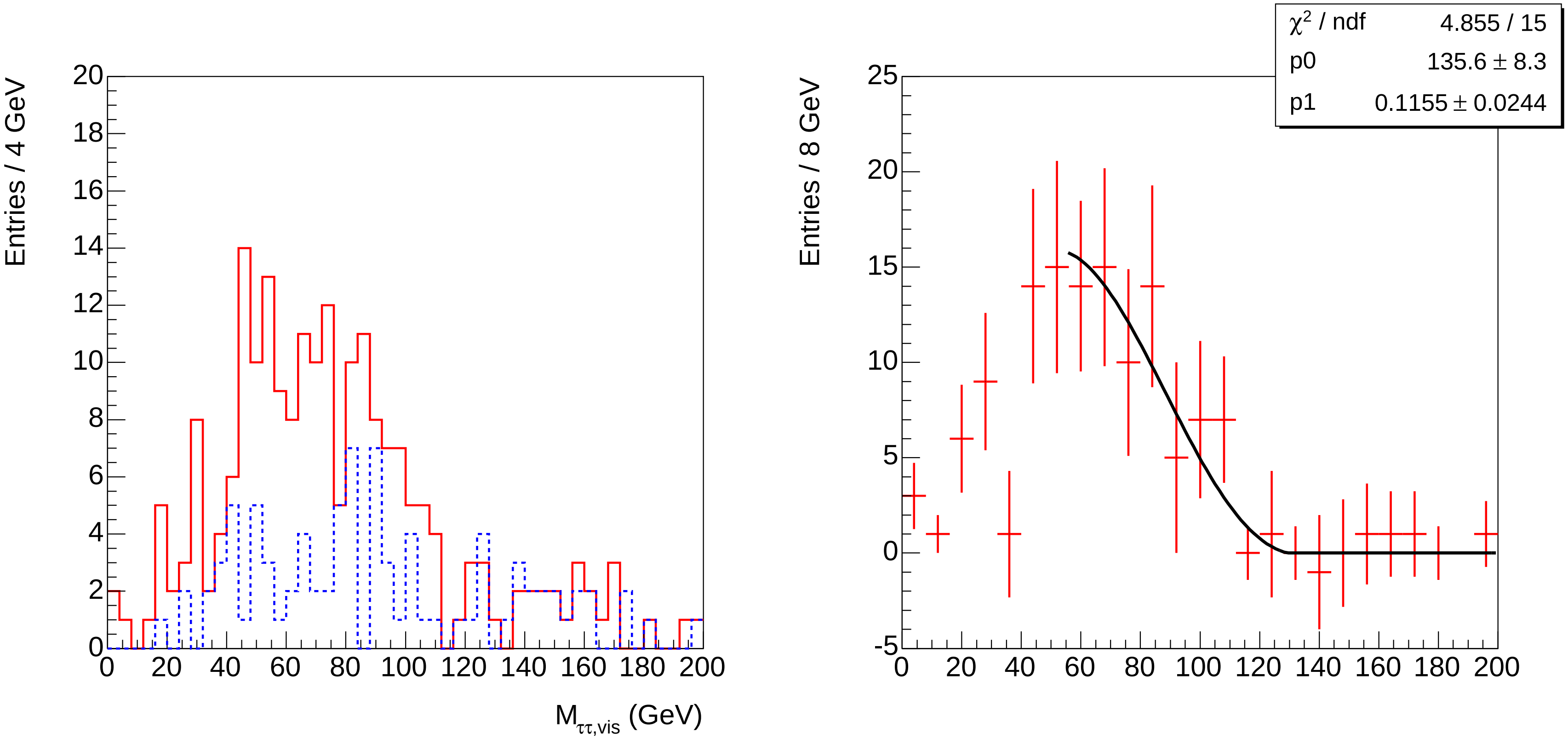
I.e., single pi is soft for τ_L, hard for τ_R.

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 ($3.6\,\mathrm{fb}^{-1}$) gives $135.6 \pm 8.3\,\mathrm{GeV}$ compared to true $126.5\,\mathrm{GeV}$:



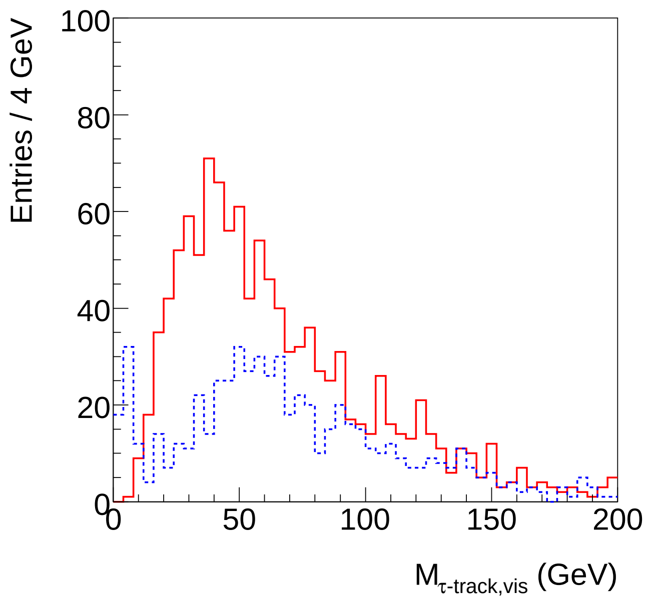
Consider Point SU1 in coannihilation region: $m(\tilde{\tau}_1) - m(\tilde{\chi}_1^0) = 10$ GeV.

Small mass gaps give soft τ's. Very low efficiency for $\tau\tau$ mass.

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

See clear OS/SS excess.

More experimental work needed to understand how to handle very soft τ hadronic decays.



In conclusion: possible to measure $\tilde{\tau}_1$ mass from $\tilde{\chi}_2^0$ decays, but high experimental uncertainties

Ratio of events in $\tau\tau$ edge and $\ell\ell$ can be used to measure $BR(\tilde{\chi}_2^0) \to \tilde{\tau}_1\tau / BR(\tilde{\chi}_2^0) \to \tilde{\ell}_R\ell$, and thence τ mixing angle.

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 $m_b \tan\beta$.

Main tool is the tagging of b-jets. Build likelihood function based on the impact parameters of the tracks in jets and the presence of secondary vertex.

Crucially based on excellent performance and systematic control of pixel detectors of the two experiments

Typical figure used in analysis is 60% efficiency for b-jets, factor 100 rejection on light jets, factor 10 rejection on c jets.

Most studies concentrate on $\tilde{t}$ and $\tilde{b}$ in gluino decays, favored in considered bulk models, rather than direct production

Gluino-sbottom mass reconstruction

From reconstruction of $\tilde{q}_L$ decay chain know $m(\tilde{\chi}_1^0)$, $m(\tilde{\chi}_2^0)$.

Building on this information go up the decay chain: study $\tilde{g} \to \tilde{b}_1 b$

Select events with OS-SF lepton pair. For $m_{\ell^+\ell^-}$ near edge, $\tilde{\chi}_1^0$ essentially at rest $\Rightarrow \vec{p}(\tilde{\chi}_2^0) \simeq (1 - \frac{m(\tilde{\chi}_1^0)}{m(\ell\ell)})\vec{p}_{\ell\ell}$ with $\vec{p}_{\ell\ell} = \vec{p}_{\ell 1} + \vec{p}_{\ell 2}$

SPS1a Point:

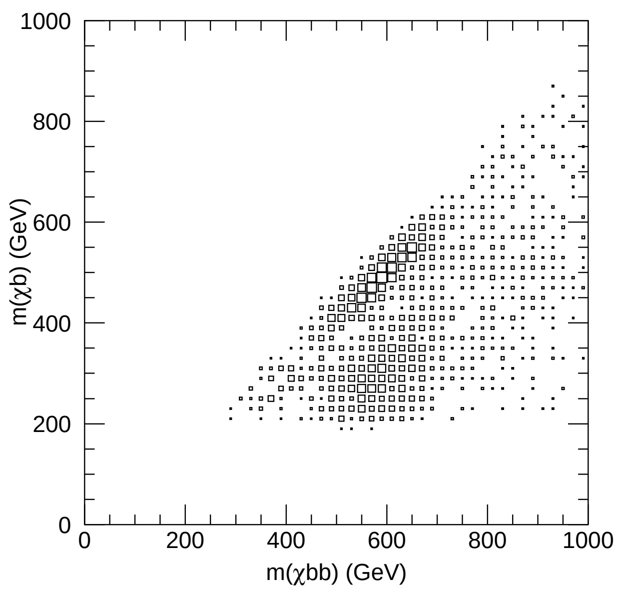
Require $65 < m_{\ell\ell} < 78$ GeV ($\ell\ell$ edge)

Reconstruct approximate $\tilde{\chi}_2^0$ momentum

Require two jets tagged as b

Plot $m(\tilde{\chi}_2^0 b)$ versus $m(\tilde{\chi}_2^0 bb)$ (two entries per event) $\Rightarrow$ observe structure

Select peak region in scatter plot by choosing $\tilde{\chi}_0^2$ coupling such that $m(\tilde{\chi}_2^0 bb)$-$m(\tilde{\chi}_2^0 b) < 150$ GeV

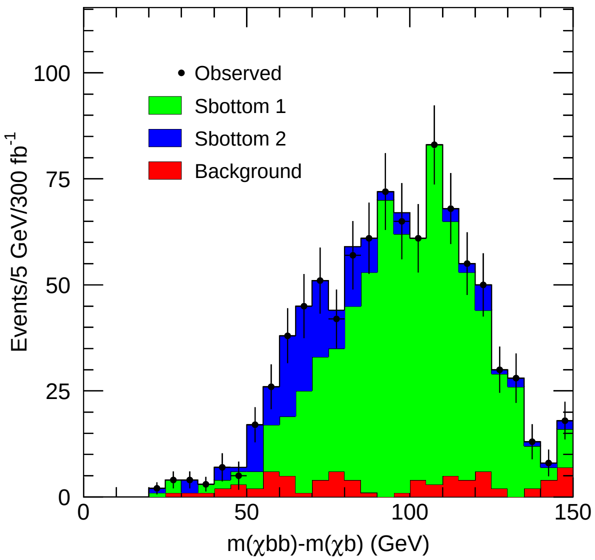


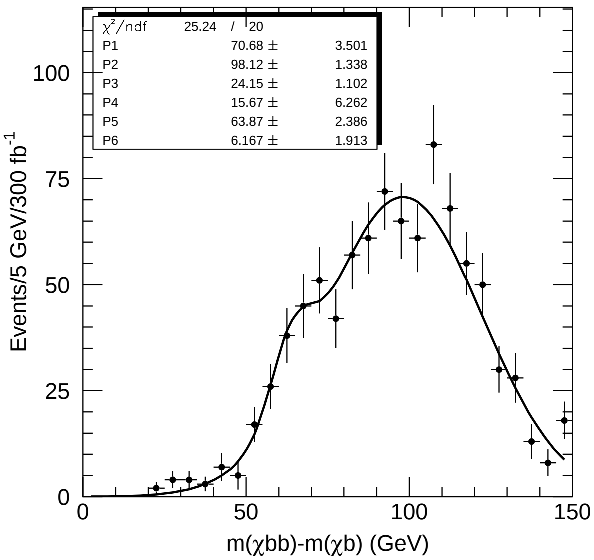
$m(\tilde{\chi}_2^0 bb)$: $\tilde{g} \to \tilde{b} b$ decay; $m(\tilde{\chi}_2^0 b)$: $\tilde{b} \to \tilde{\chi}_2^0 b$ decay

Selected events are a mixture of $\tilde{g} \to \tilde{b}_1 b$ and $\tilde{g} \to \tilde{b}_2 b$

As shown in scatter plot, $m(\tilde{\chi}_2^0 b)$ strongly correlated with $m(\tilde{\chi}_2^0 bb)$

Can factor out the spread due to $p(\tilde{\chi}_2^0)$ by plotting $m(\tilde{\chi}_2^0 bb)$-$m(\tilde{\chi}_2^0 b)$





With 100 fb^{-1} two contributions probably indistinguishable

With 300 fb^{-1}, if excellent control of b-jet measurement is achieved, two peaks can be distinguished, and relative rate measured

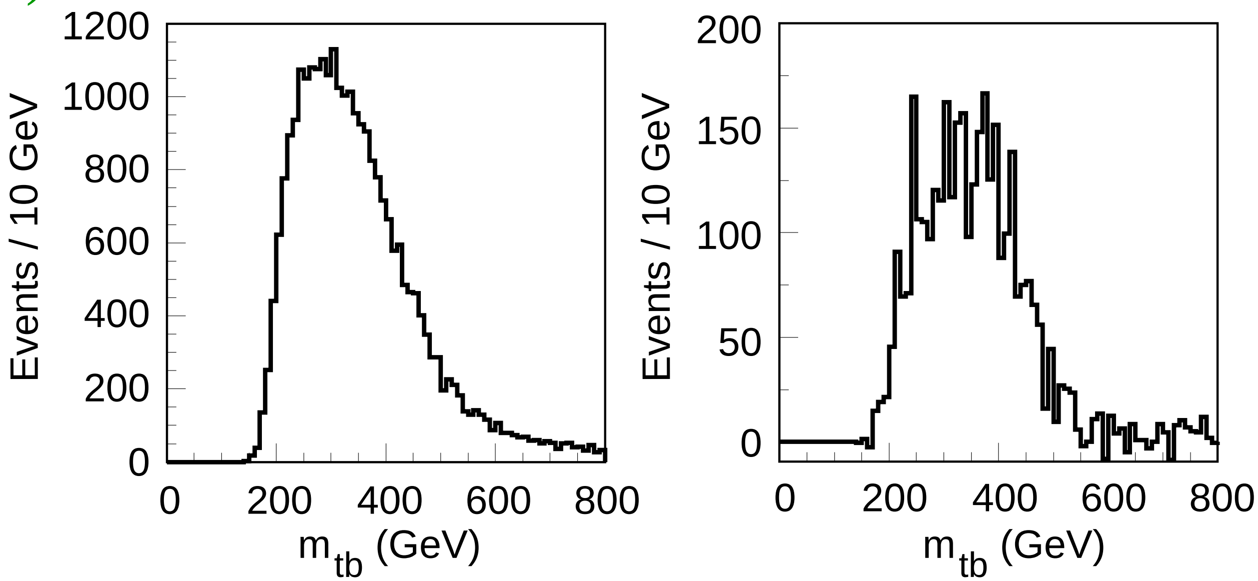
Stop mass measurement

Study the decay chain $\tilde{g} \to \tilde{t}_1 \bar{t} \to \tilde{\chi}_j^+ b \bar{t}$

Start from fully reconstructed the top hadronic decay $t \to Wb \to q\bar{q}b$

Then $b\bar{t}$ invariant mass has endpoint sensitive to $M(\tilde{g})$, $M(\tilde{t}_1)$, $M(\tilde{\chi}_1^\pm)$ [Hisano].

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

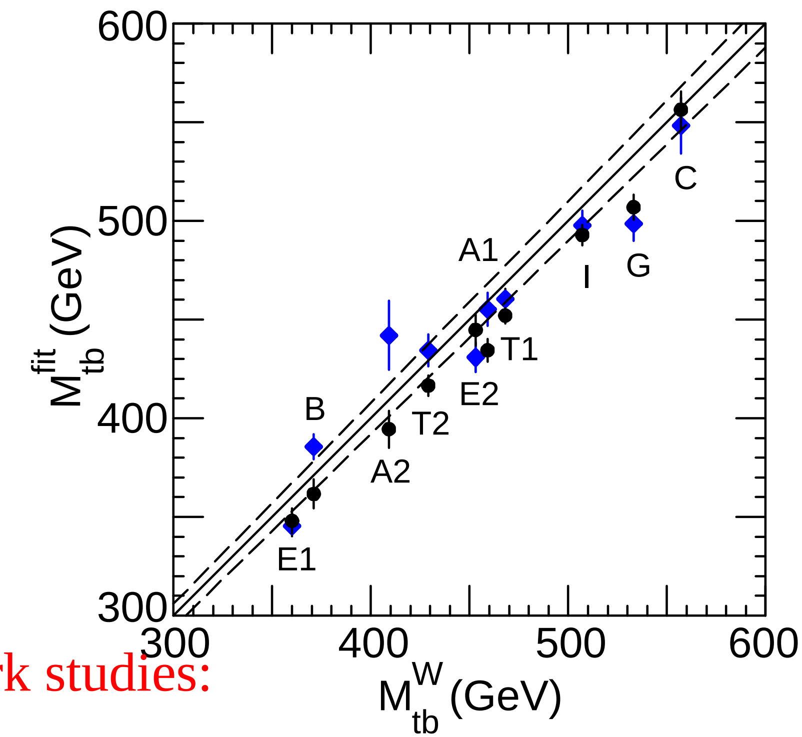


Same signature from $\tilde{g} \to \tilde{b}_1 b \to tb\tilde{\chi}_1^\pm$, end-point complex function of masses and BR

Analysis repeated for 10 points for both Herwig and Pythia.

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

Height of observed excess can be related to stop mixing



Conclusions on third generation squark studies:

From cascade decays of gluinos can extract information on masses and couplings of $\tilde{b}_1$, $\tilde{b}_2$, and $\tilde{t}_1$ for favorable models. Need to systematize work to take in all possible combinations of decay chains.

Lepton Flavour Violation in SUSY decays

Motivation: SuperKamiokande results:

ν_μ and ν_τ fully mixed, mass difference $\Delta m^2 \sim 10^{-3}$ eV^2

Lepton flavour mixing can happen in SUSY models through off-diagonal terms in the slepton mass matrix:

$\nu_\mu - \nu_\tau$ mixing imply a non-zero $M_{\mu\tau}$ term in matrix:

SuperKamiokande measurements suggest:

$$\delta = \frac{M_{\mu\tau}^2}{M_L^2} = \mathcal{O}(1)$$

with $M_L \sim \tilde{l}_L$ mass

Large flavour violation could be observed indirectly via the decay $\tau \to \mu\gamma$ (e.g. Ellis et al. hep-ph/9911459)

For some values of SUSY model parameters direct search for lepton flavour violation (LFV) in $\tilde{\chi}_2^0$ decays can provide better sensitivity

Example mSUGRA model

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

Identical to bulk points shown previously

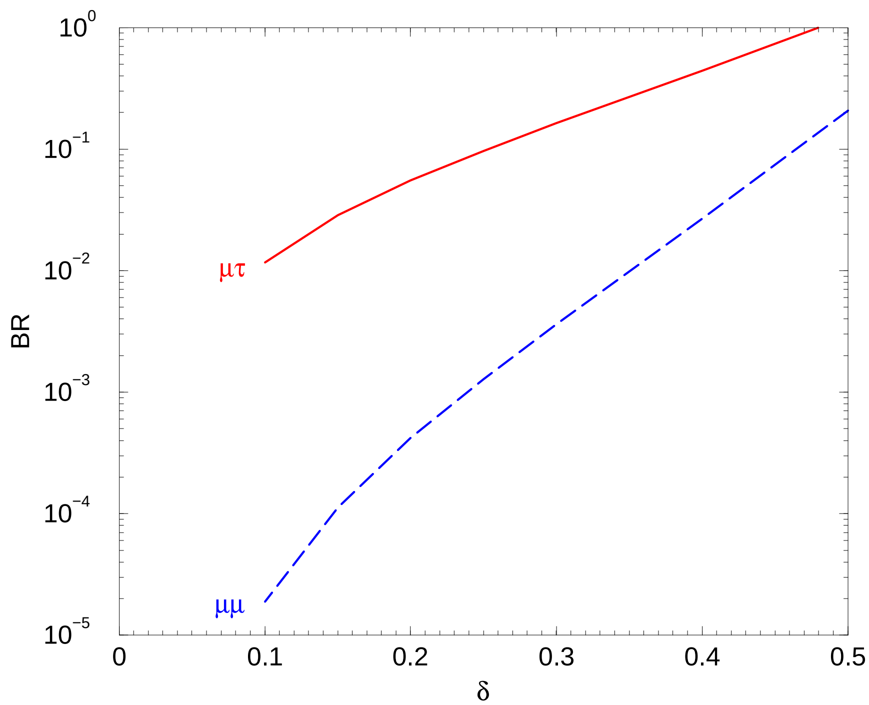
Main source of sleptons are $\tilde{\chi}_0^2$ from $\tilde{q}_L$ decays:

$\mathrm{BR}(\tilde{\chi}_2^0 \to \tilde{\tau}_1\tau) \simeq 66\%$, $\mathrm{BR}(\tilde{\chi}_2^0 \to \tilde{l}_R l) \simeq 12.8\%$ $(l = e, \mu)$

$\delta \neq 0 \Rightarrow \quad \tilde{\mu}_L$ component in $\tilde{\tau}_1 \Rightarrow \quad$ Two LFV decays: $\tilde{\chi}_2^0 \to \tilde{\tau}_1\mu$, $\tilde{\tau}_1 \to \mu\tilde{\chi}_1^0$

Branching fraction for:

- $\tilde{\chi}_2^0 \to \tau\mu\tilde{\chi}_1^0$
- $\tilde{\chi}_2^0 \to \mu\mu\tilde{\chi}_1^0$
  via intermediate τ_1 state.



Search for $\ell^\pm\tau_h^\mp$

For $\delta = 0$ (no LFV), $\ell^\pm\tau_h^\mp$ rate from:

- τ pairs from $\tilde{\chi}_2^0 \to \tilde{\tau}_1\tau \to \tau^+\tau^-\tilde{\chi}_1^0$ (one τ decaying leptonically)
- Two independent chargino decays (both $\ell^\pm\tau^\mp$ and $\ell^\pm\tau_h^\pm$)

Additional $\mu\tau$ pairs from LFV identified as $\mu^\pm\tau_h^\mp$ in 92% of cases

Assume BR($\tilde{\chi}_2^0 \to \tau^\pm\mu^\mp$)=10%, corresponding to δ=0.25

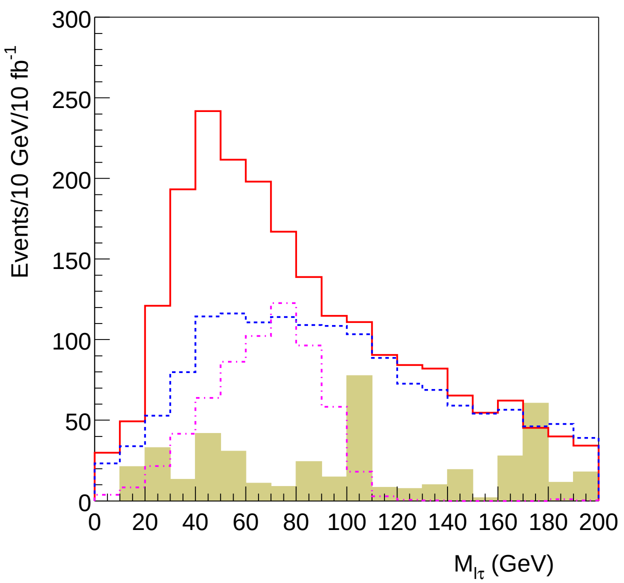
$M_{\ell\tau}$ distribution for:

Opposite-Sign background

Same-Sign background

Signal

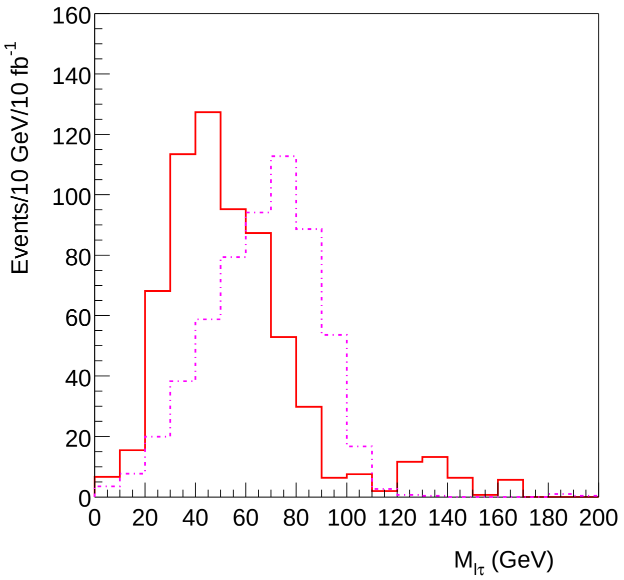
Fake τ



Mass distribution for:

- Sign-subtracted background $(\ell^\pm\tau^\mp - \ell^\pm\tau^\mp)$
- Signal

Background should cancel subtracting $e^\pm\tau^\mp$ from $\mu^\pm\tau^\mp$ because LFV signal only occurs in $\mu\tau$



For $50 < M_{\ell\tau} < 100\,\text{GeV}$, for 10 pb^{-1}

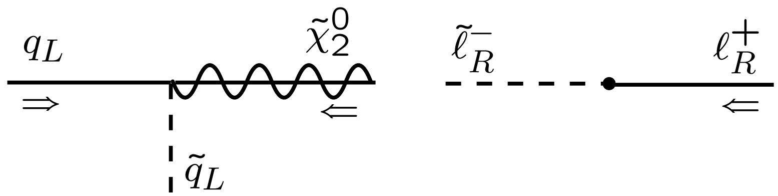
$$N(\mu^\pm\tau^\mp) - N(e^\pm\tau^\mp) = 476 \pm 39$$

5σ limit on BR$(\tilde{\chi}_2^0 \to \tau\mu\tilde{\chi}_1^0)$ for 30 fb^{-1} is 2.3% $(\delta \approx 0.1)$

Sensitivity better than for direct measurement of $BR(\tau \to \mu\gamma)$ using $W \to \tau\nu$ events.

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 $\lambda = -1$:



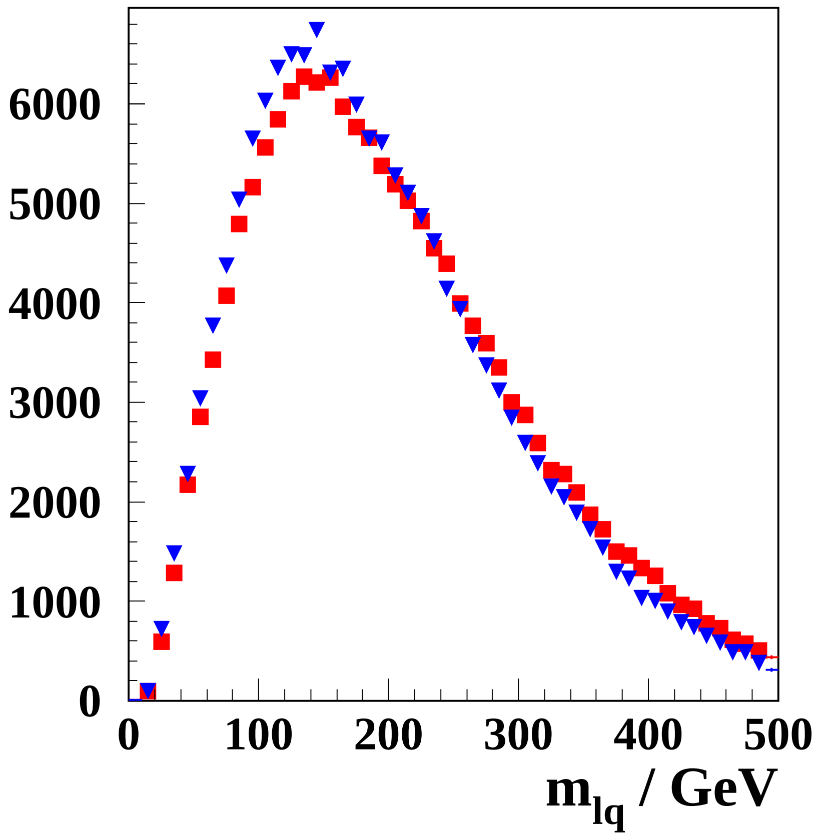
Hence $\tilde{\chi}_2^0 \to \tilde{\ell}_R^{\mp} \ell^{\pm}$ distribution $\sim \left[d^{(\frac{1}{2})}_{-\frac{1}{2}\pm\frac{1}{2}}(\theta) \right]^2 \propto 1 \pm \cos\theta$.

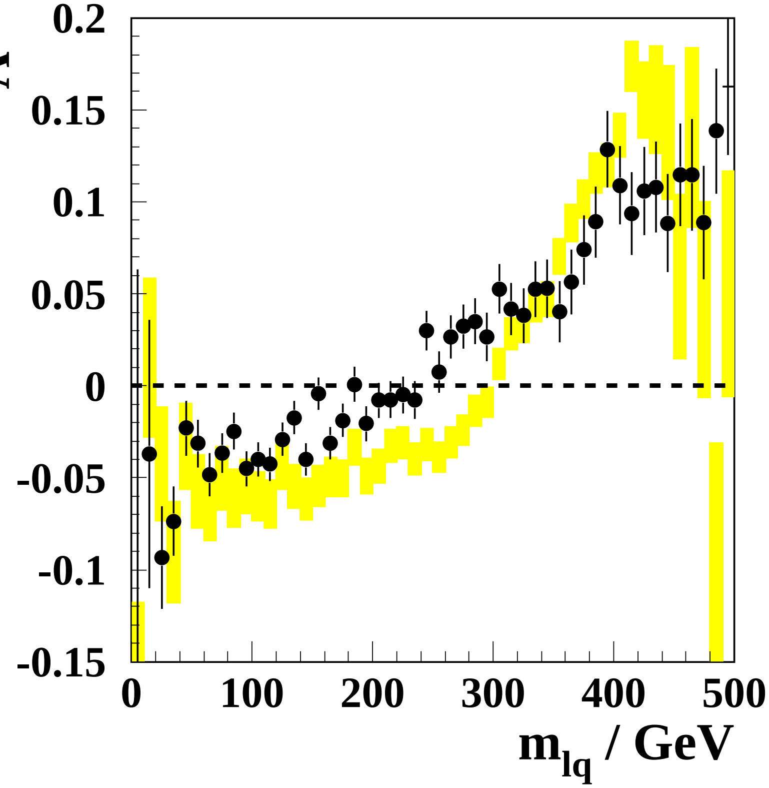
Basic asymmetry suppressed by:

- 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 SU3). Pass through fast detector simulation 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]:





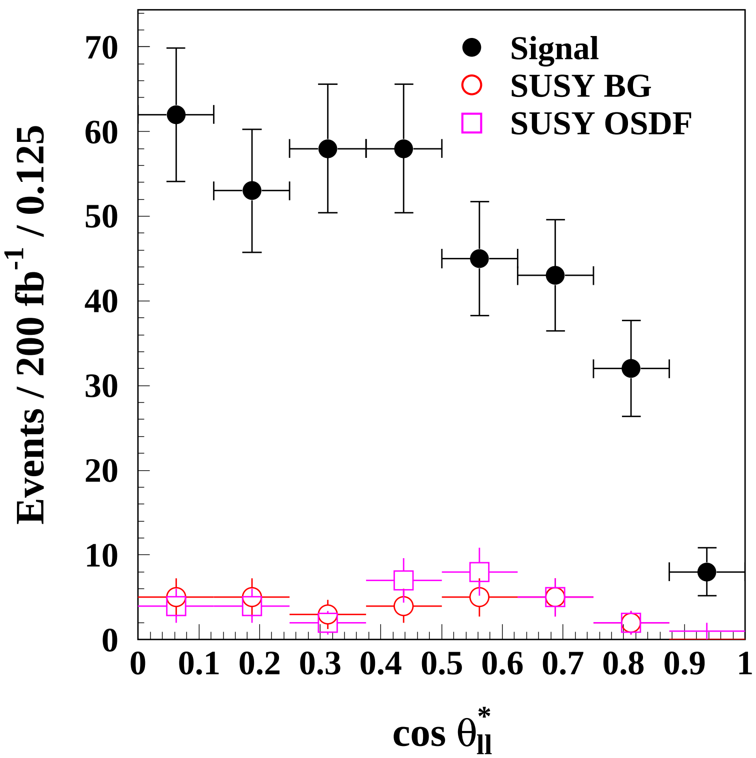
(Yellow rectangles show rescaled parton level distribution.)

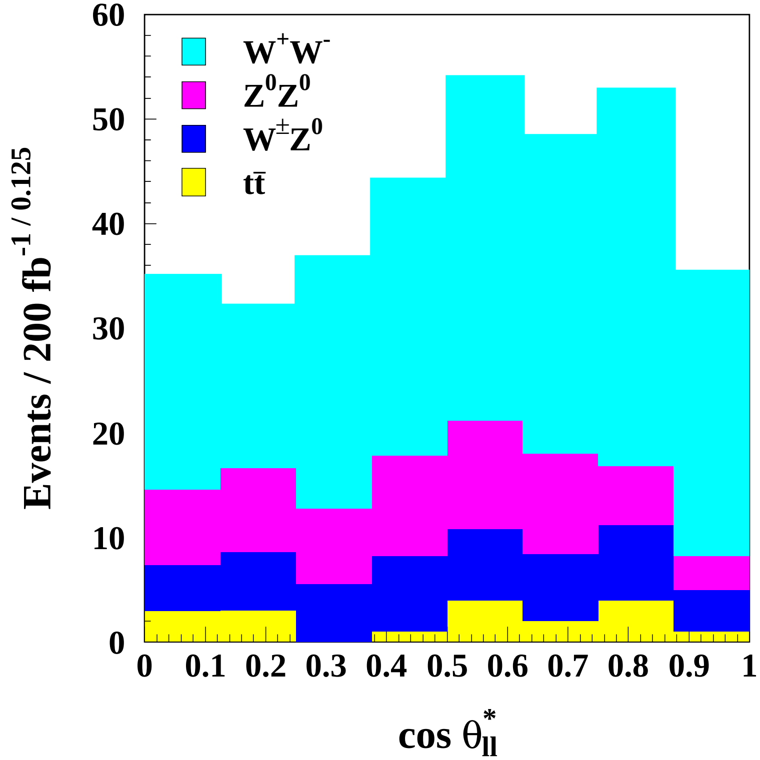
Shows non-zero spin consistent with SUSY expectations. . . .

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]

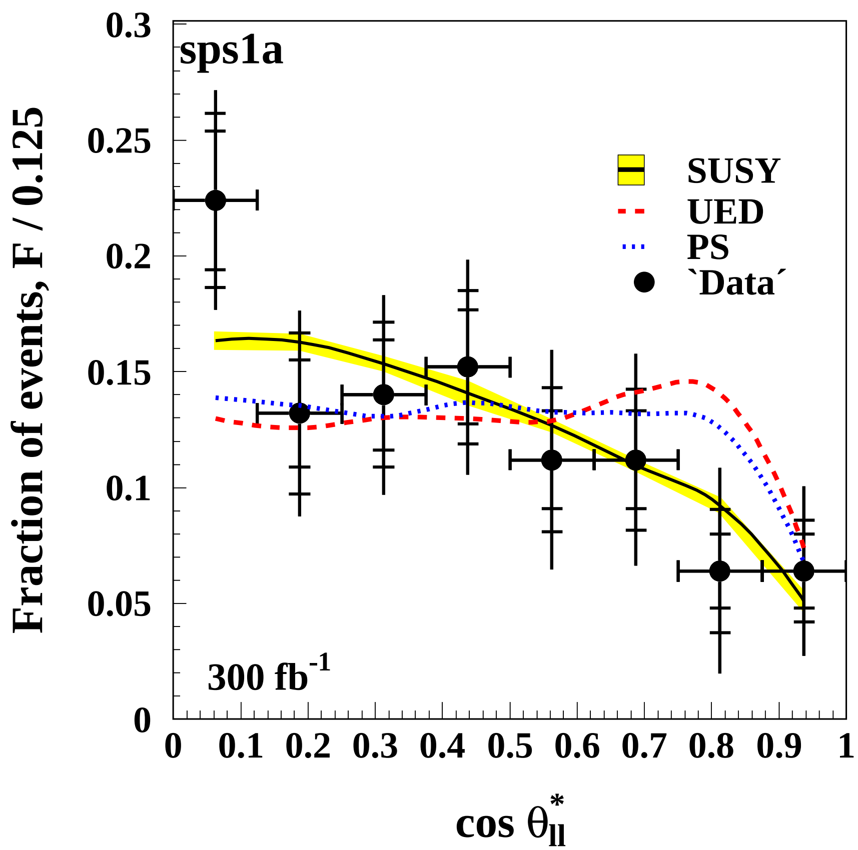
$$\cos\theta^*_{\ell\ell} \equiv \cos\left(2\tan^{-1}\exp(\Delta\eta_{\ell\ell}/2)\right) = \tanh(\Delta\eta_{\ell\ell}/2)$$

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:





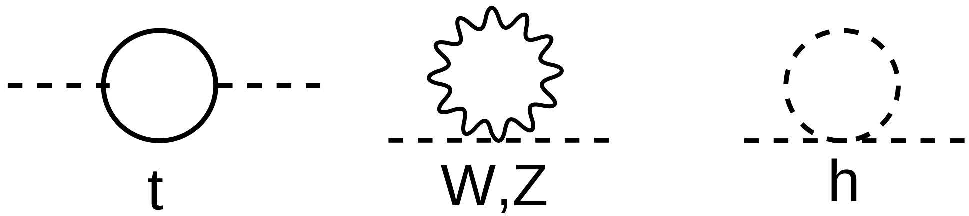
Background-subtracted distributions for Point SPS1a:



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

Little Higgs Models

Only three large 1-loop quadratic divergences for Higgs mass:



$$\delta m_H^2 = -\frac{3y_t^2}{8\pi^2}\Lambda^2 + \frac{g^2}{16\pi^2}\Lambda^2 + \frac{\lambda^2}{16\pi^2}\Lambda^2$$

Little Higgs models arrange to cancel these $\Rightarrow$ push cutoff to $\sim 10\,\mathrm{TeV}$.

Studies have used "Littlest" Higgs. Break $SU(5)$ to $SO(5)$, giving 14 Goldstone bosons:

$$X(3,0),\ Y(1,0),\ h(2,\tfrac{1}{2}),\ h^\dagger(2,-\tfrac{1}{2}),\ \phi(3,1),\ \phi^\dagger(3,-1)$$

Gauge $SU(2)\times U(1)\times SU(2)\times U(1)$ and break to $SU(2)_L\times U(1)$. Remaining $SU(2)\times U(1)$ combines with $X,Y \Rightarrow$ massive $W_H^\pm, Z_H, A_H$. Also generate ϕ mass, but h mass protected by two symmetries.

Add vector-like $SU(2)_L$ singlet T_L, T_R with $SU(3)$ symmetry to guarantee cancellation of top loop.

Result is “naturally” light Higgs h: cancellation with particles of same spin, unlike SUSY. Have new particles at TeV scale:

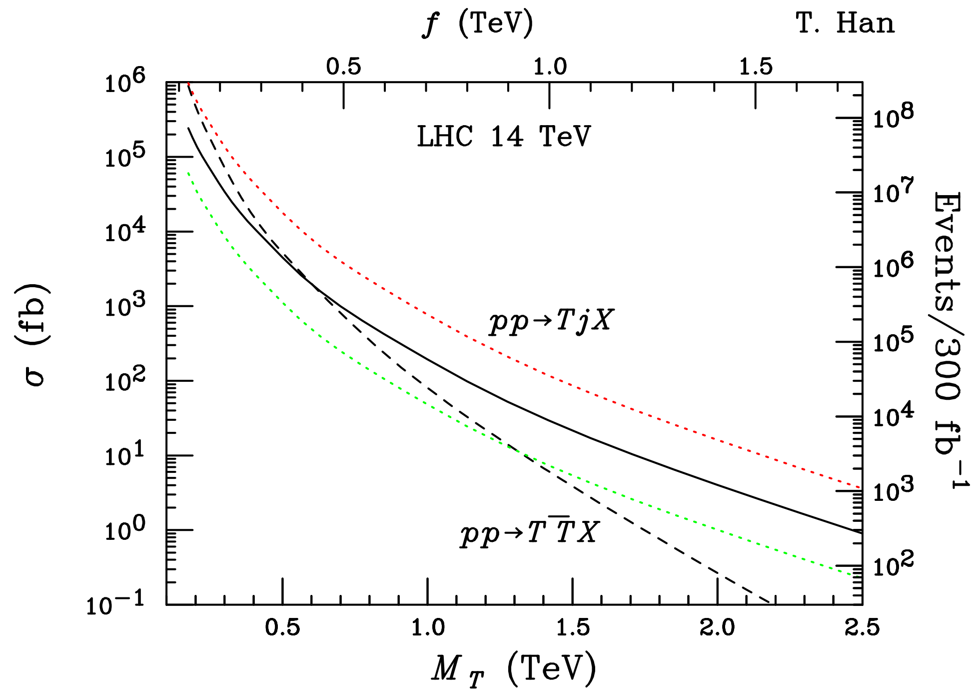
- T with $T \to Zt, Wb, ht$ in ratio $1:2:1$.
- New gauge bosons $W_H^{\pm}, Z_H, A_H$.
- Higgs triplet ϕ produced by WW fusion or in pairs.

Signatures studied with fast simulation by ATLAS [Azuelos].

Presence of new heavy quark, either scalar (SUSY) or fermion is common feature of models trying to tame top loop correction to higgs mass $\Rightarrow$ concentrate here on T discovery

First consider T. Can have both $T\bar{T}$ production via QCD and single T production via W exchange.

Rate for single T is model dependent but dominates for large mass.



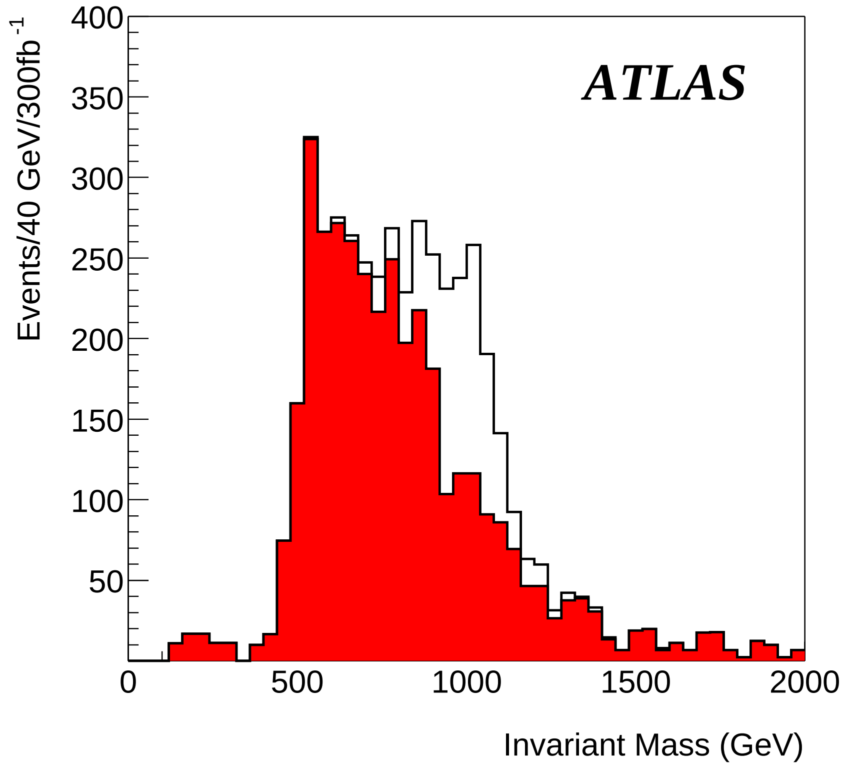
Initial T signature would be $T \to Wb \to \ell\nu b$. Similar to sequential quark. Backgrounds from $t\bar{t}$, single t, and $Wb\bar{b}$.

Signature similar to sequential t', but (perhaps) too heavy and (in minimal model) no b'.

Note rates are small for $M_T = 1\,\mathrm{TeV}$: few hundred events/bin for $300\,\mathrm{fb}^{-1}$ with $S/B \sim 1$.

Need good understanding of SM background.

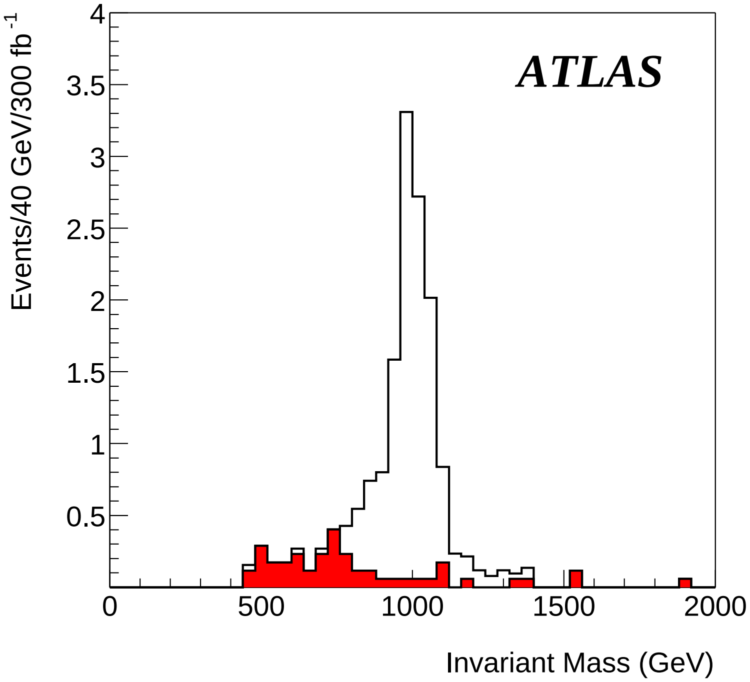
Not observable with low luminosity.

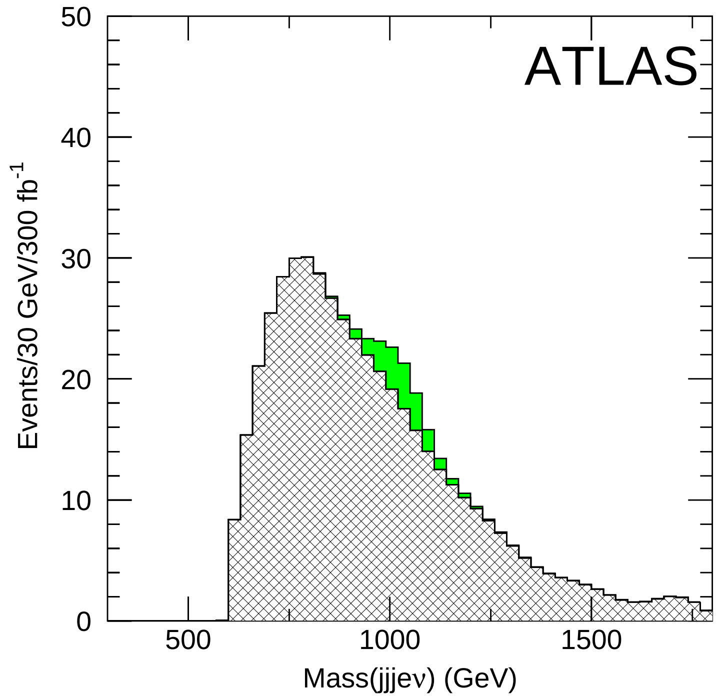


Look for other modes. For $T \to Zt \to \ell^+\ell^-\ell\nu b$, require three isolated leptons, $\not\!\!E_T > 100\,\mathrm{GeV}$, and at least one tagged b jet with $p_T > 30\,\mathrm{GeV}$.

For $T \to ht$ assume $M_h = 120\,\mathrm{GeV}$ so $h \to b\bar{b}$. Require one isolated e, μ with $p_T > 100\,\mathrm{GeV}$, $|\eta| < 2.5$, three jets with $p_T > 130\,\mathrm{GeV}$, at least one tagged as a $b-$jet.

Can observe $T \to tZ$ with low statistics for $300\,\mathrm{fb}^{-1}$. Higgs signal is $\sim 4\sigma$ *if* mass and $t\bar{t}$ background are known:





Extra Dimensions

Hierarchy problem comes from mismatch between reduced Planck scale ($\overline{M}_{\rm Pl} = M_{\rm Pl}/\sqrt{8\pi} = 2.43 \times 10^{18}\,{\rm GeV}$) and weak scale ($246\,{\rm GeV}$). Extra (space-like) dimensions alleviate this by reducing effective Planck scale. Several scenarios. . . .

ATLAS and CMS have concentrated on searches. Examples:

- KK gauge boson resonances to e^+e^-, $\mu^+\mu^-$ in TeV-scale extra dimensions[Polesello].
- $\tilde{G} \to e^+e^-$ in RS-1 model [Collard] with full simulation and corrections for readout saturation. Can cover full range of parameters.
- $\tilde{G}$ emission $\Rightarrow \not{E}_T$ in large extra dimensions[Vacavant].
- Black hole production in large extra dimensions [Harris]. Includes "grey-body" factors [Charybdis]. Would produce very complex events.

But little work so far related to flavor physics. . . .

Summary

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.

Large effort of the ATLAS and CMS Collaborations on new physics signatures and Standard Model backgrounds

SUSY models investigated in detail and technique developed to measure model parameters in case of discovery

Results mostly in first two generations, but significant work also in $\tilde{\tau}$, $\tilde{b}$ and $\tilde{t}$ sectors, important benchmarks for key elements of detector performance

More work needed to prepare us to extract all the useful information from the forthcoming LHC data

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