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SCHOOL ON PHYSICS AT LHC: "EXPECTING LHC"
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Supersymmetry at LHC
Part III
(Reconstructing SUSY)

Ian HINCHLIFFE
Lawrence Berkeley Laboratory, Physics Group,
94720 Berkeley, CA, U.S.A.

Reconstructing SUSY

Ian Hinchliffe
LBNL

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Berkeley Lab

Recall Inclusive analysis

Select events with at least 4 jets and Missing E_T

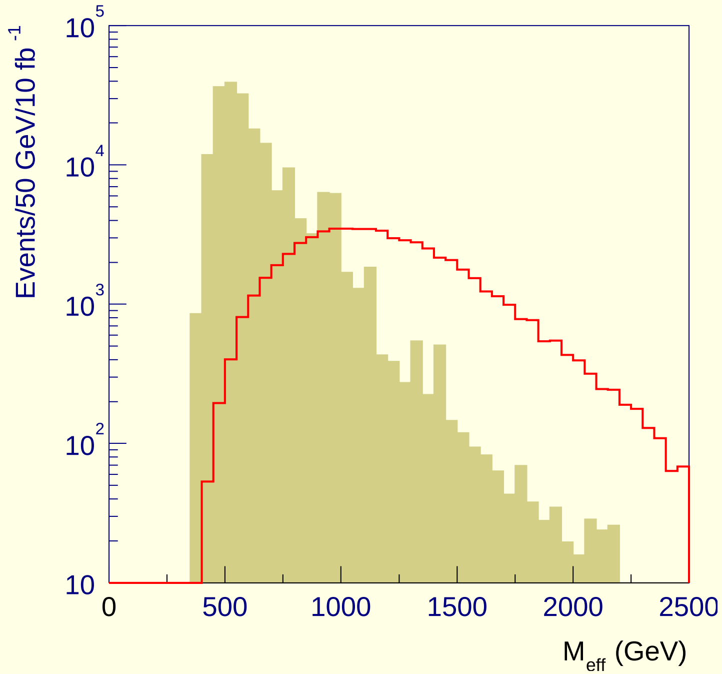
A simple variable

$M_{\rm eff} = P_{t,1} + P_{t,2} + P_{t,3} + P_{t,4} + \not\!\!E_T$

At high $M_{\rm eff}$ non-SM signal rises above background note scale

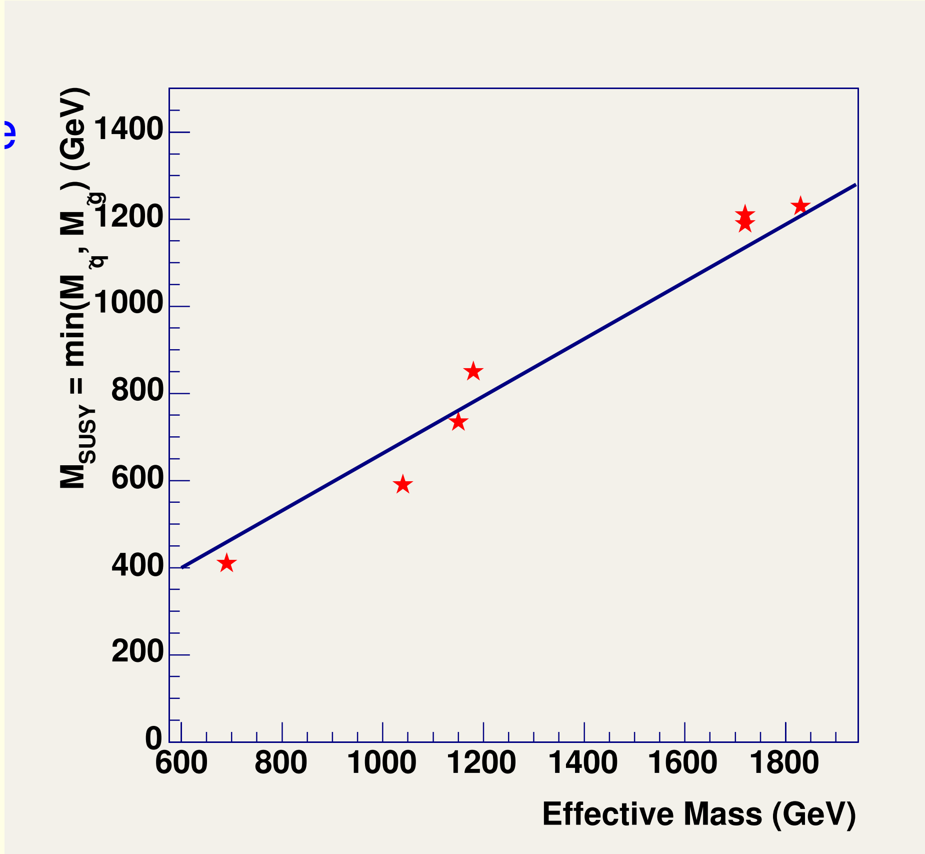
Peak in $M_{\rm eff}$ distribution correlates well with SUSY mass scale

$M_{\rm SUSY} = \min(M_{\tilde{u}}, M_{\tilde{g}})$



Will determine gluino/squark masses to $\sim 15\%$

Peak in $M_{\rm eff}$ distribution correlates well with SUSY mass scale



$$M_{\rm SUSY} = \min(M_{\widetilde{u}}, M_{\widetilde{g}})$$

Use this and similar global distributions to establish that new physics exists and determine its mass scale

Method is slightly model dependent

Generalizations to other models

Similar method works in GMSB and MSSM

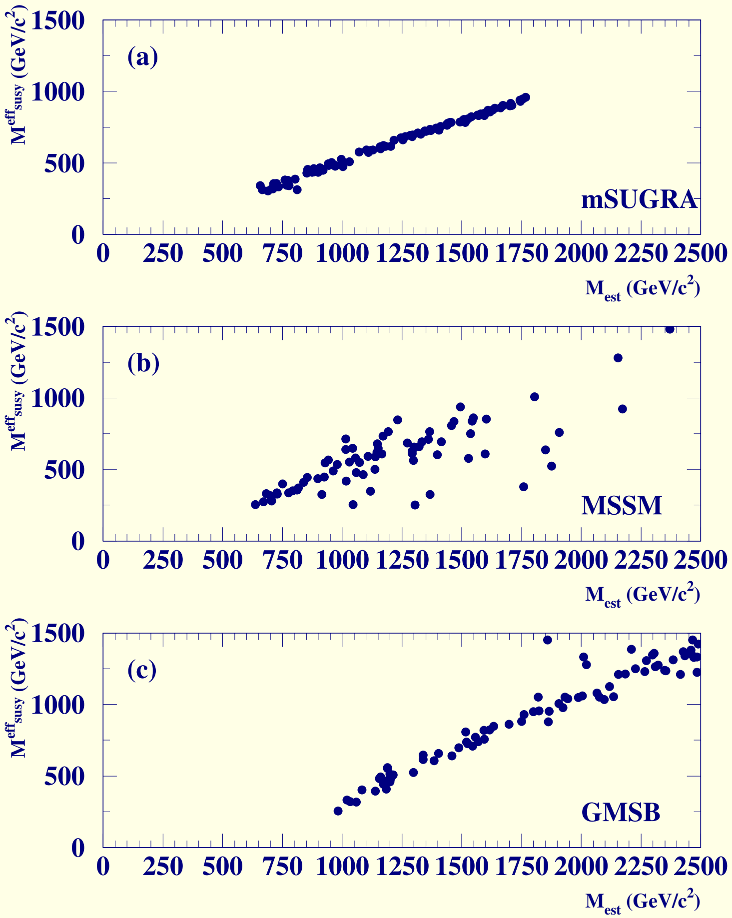
In MSSM, 15 parameters were varied

Events selected to have no isolated leptons, at least 4 jets, large missing E_T

More global variables were used; best is

$$\sum_{jets} |E_T| \text{ or } \sum_{jets} |E_T| + \not{E}_T$$

Error is bigger in MSSM



Model	Var	$\bar{x}$	σ	$\sigma/\bar{x}$	Prec. (%)
mSUGRA	1	1.585	0.049	0.031	2.9
	2	0.991	0.039	0.039	3.8
	3	1.700	0.043	0.026	2.1
	4	1.089	0.030	0.028	2.5
	5	1.168	0.029	0.025	2.1
MSSM	1	1.657	0.386	0.233	23.1
	2	0.998	0.214	0.215	21.1
	3	1.722	0.227	0.132	12.8
	4	1.092	0.143	0.131	12.8
	5	1.156	0.176	0.152	14.8
GMSB	1	1.660	0.149	0.090	8.1
	2	1.095	0.085	0.077	6.6
	3	1.832	0.176	0.096	9.0
	4	1.235	0.091	0.074	6.1
	5	1.273	0.109	0.086	7.9

$\sigma(M_{susy} < 13\%)$

Not optimized

Leptonic channels not used

More work on "global signatures" needed

Characteristic SUSY Decays

Illustrate techniques by choosing examples from case studies.

Both $\widetilde{q}$ and $\widetilde{g}$ produced; one decays to the other

Weak gauginos ($\widetilde{\chi_i^0}, \widetilde{\chi_i^\pm}$) then produced in their decay. $e.g.$ $\widetilde{q_L} \to \widetilde{\chi}_2^0 q_L$

Two generic features
$\chi_2^0 \to \chi_1^0 h$ or
$\chi_2^0 \to \chi_1^0 \ell^+ \ell^-$ possibly via intermediate slepton $\chi_2^0 \to \widetilde{\ell^+} \ell^- \to \chi_1^0 \ell^+ \ell^-$
Former tends to dominate if kinematically allowed.

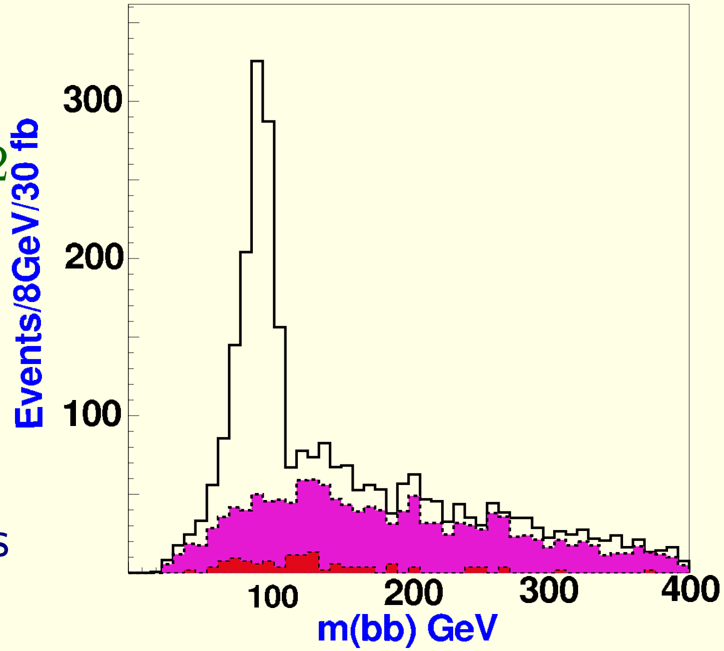
Use these characteristic decays as a starting point for mass measurements

Many SUSY particles can then be identified by adding more jets/leptons

Decays to Higgs bosons

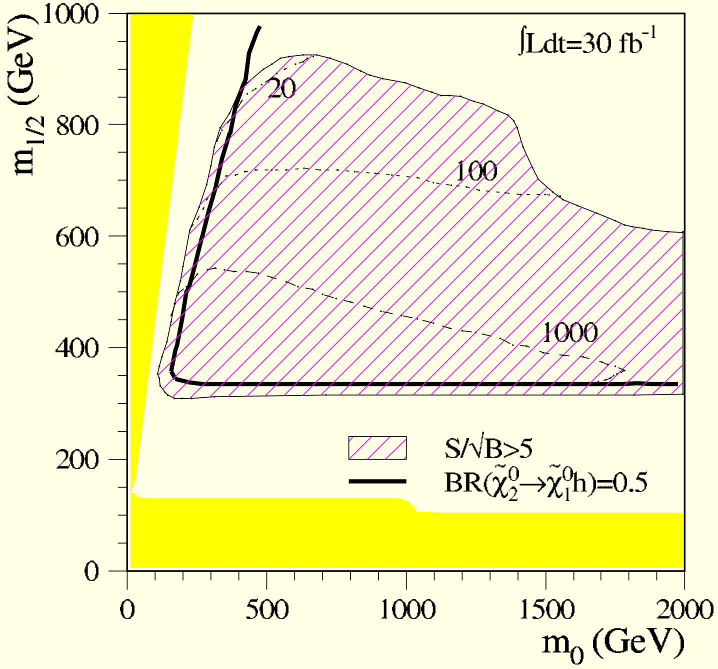
If $\chi_2^0 \to \chi_1^0 h$ exists then this final state followed by $h \to b\bar{b}$ results in discovery of Higgs at LHC.
In these cases $\sim 20\%$ of SUSY events contain $h \to b\bar{b}$

Event selection
$\not{E}_T > 300\,\mathrm{GeV}$
≥ 2 jets with $p_T > 100\,\mathrm{GeV}$ and ≥ 1 with $|\eta| < 2$
No isolated leptons (suppresses $t\bar{t}$)
Only 2 b-jets with $p_{T,b} > 55$ GeV and $|\eta| < 2$
$\Delta R_{b\bar{b}} < 1.0$ (suppresses $t\bar{t}$)
Clear peak in $b\bar{b}$ mass
Very small standard model background (pale)
Dominant background is other SUSY decays (dark)



Generally applicable

This method works over a large region of parameter space in the SUGRA Model
Hatched region has $S/\sqrt{B} > 5$
Contours show number of reconstructed Higgs
Channel is closed at low $m_{1/2}$



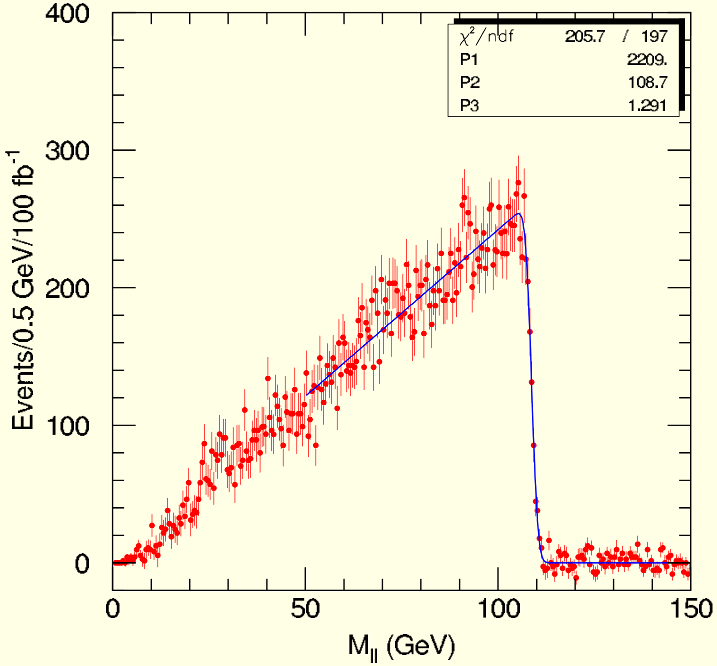
Over rest of parameter space, leptons are the key...

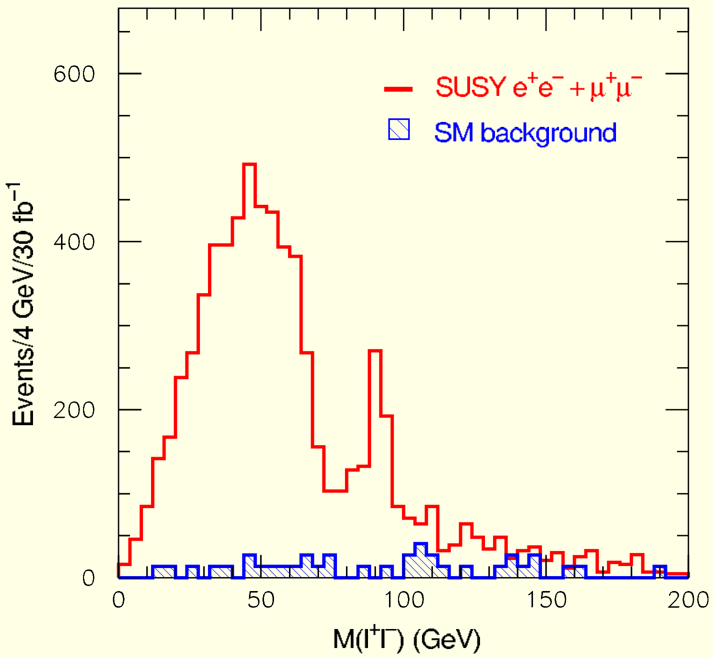
Starting with Leptons

Isolated leptons indicate presence of t, W, Z, weak gauginos or sleptons

Key decays are $\tilde{\chi}_2 \rightarrow \tilde{\ell}^+ \ell^-$ and $\tilde{\chi}_2 \rightarrow \tilde{\chi}_1 \ell^+ \ell^-$

Mass of opposite sign same flavor leptons is constrained by decay





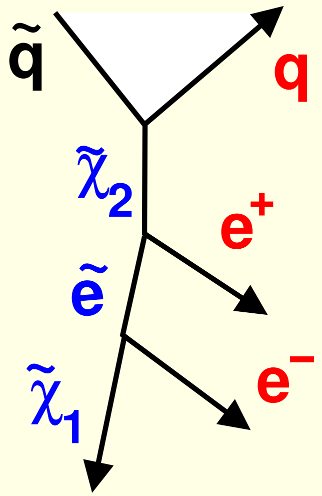
Decay via real slepton: $\tilde{\chi}_2 \rightarrow \tilde{\ell}^+ \ell^-$

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

Decay via virtual slepton: $\tilde{\chi}_2 \rightarrow \tilde{\chi}_1 \ell^+ \ell^-$ and Z from other SUSY particles

Building on Leptons

Decay $\tilde{q}_L \to q\widetilde{\chi}_2^0 \to q\widetilde{\ell}\ell \to q\ell\ell\widetilde{\chi}_1^0$



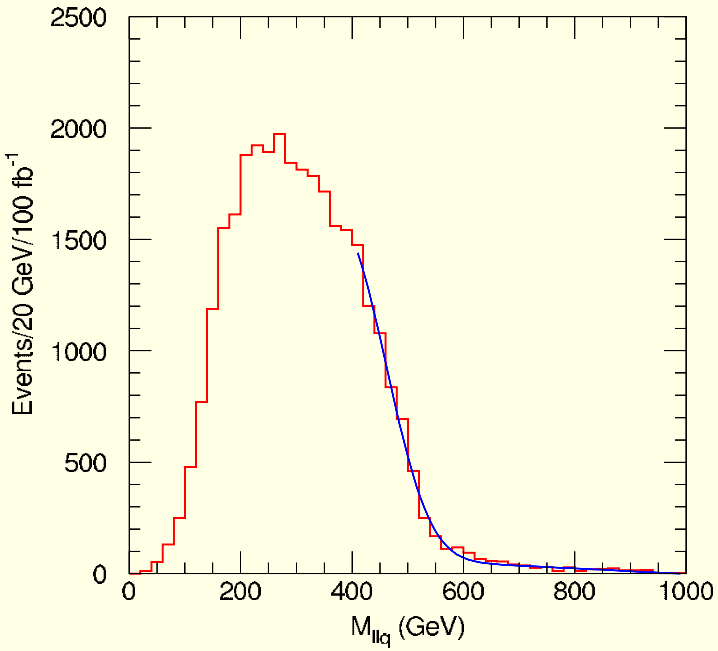
Identify and measure decay chain

- 2 isolated opposite sign leptons; $p_t > 10$ GeV
- $\boldsymbol{\geq 4}$ jets; one has $\boldsymbol{p_t > 100\ GeV}$, rest $\boldsymbol{p_t > 50}$ GeV
- $\boldsymbol{\not{E}_T > max(100, 0.2M_{eff})}$

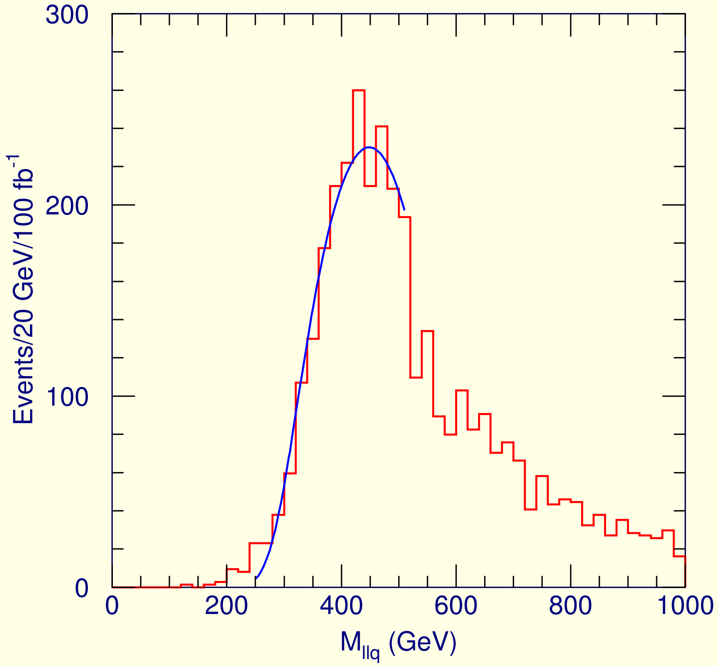
Mass of $q\ell\ell$ system has max at

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

and min at 271 GeV



smallest mass of possible $\ell\ell jet$ combinations



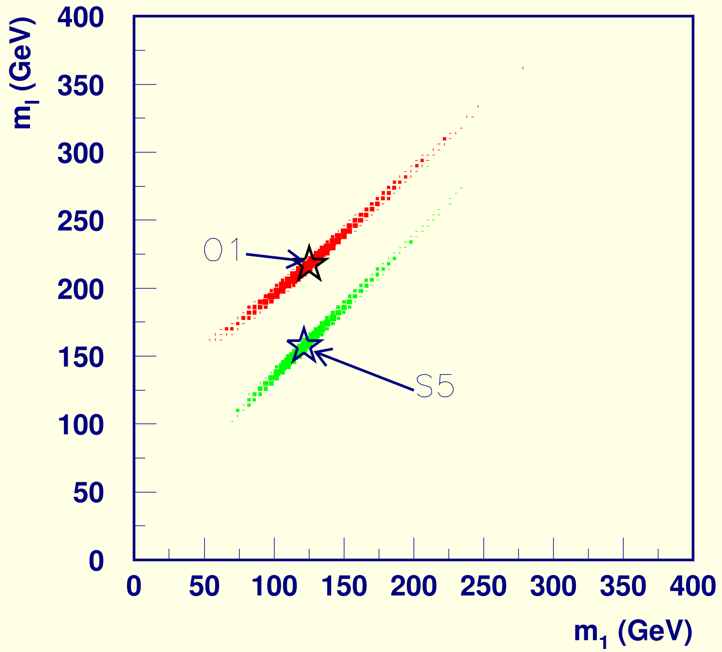
largest mass of possible $\ell\ell jet$ combinations

Kinematic structure clearly seen
Can also exploit ℓjet mass

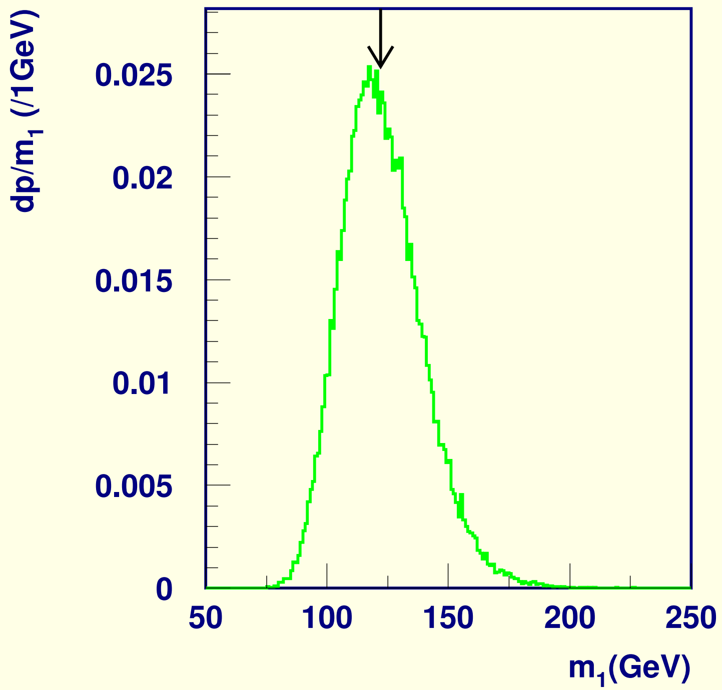
Can now solve for the masses. Note that no model is needed

Very naive analysis has 4 constraints from $lq, llq_{upper}, llq_{lower}, ll$ masses
4 Unknowns, $m_{\tilde{q}_L}, m_{\tilde{e_R}}, m_{\tilde{\chi}_2^0}, m_{\tilde{\chi}_1^0}$

Errors are 3%, 9%, 6% and 12% respectively



correlations $m_{\tilde{e_R}}$ vs. $m_{\tilde{\chi}_1^0}$



LSP mass

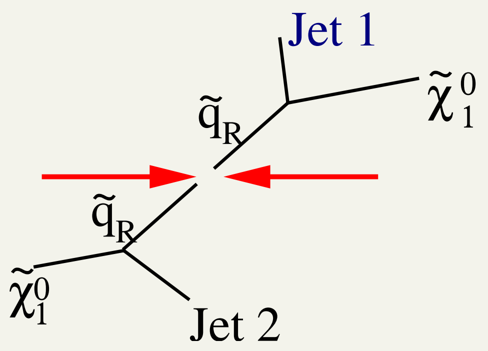
Mass of unobserve determined
Errors are strong and a precise i determination of reduces the errors on

s-tranverse mass. Definition

- Select Events:

$pp \to X + \tilde{q}_R\tilde{q}_R \to X + q\bar{q}\tilde{\chi}_1^0\tilde{\chi}_1^0$

  - 2 Jets with $P_T >$200GeV
  - Δ(j1-j2)$>$1
  - Missing $E_T >$400GeV



- Partition $\vec{\not{E}}_T = \vec{\not{E}}_{T,1} + \vec{\not{E}}_{T,2}$ in all possible ways and compute:

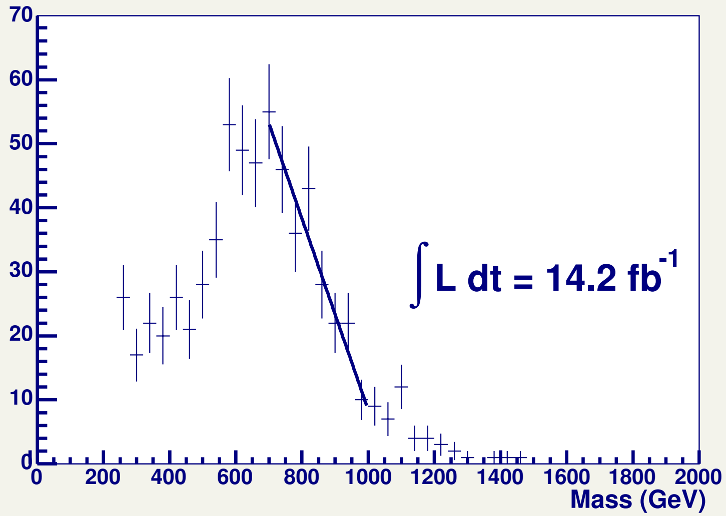
$$M_T^2 = \min_{\vec{\not{E}}_{T,1},\vec{\not{E}}_{T,2}} \left[\max\{m_T^2(P_{T,j1}, \not{E}_{T,1}, M_{\tilde{\chi}_1^0}), m_T^2(P_{T,j2}, \not{E}_{T,2}, M_{\tilde{\chi}_1^0})\}\right]$$

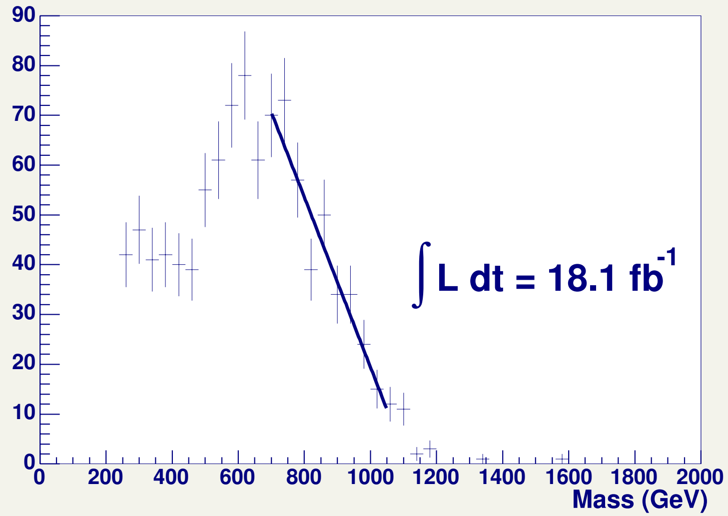
- M_T^2 depends on the choice of $M(\tilde{\chi}_1^0)$

s-tranverse mass for the SU5 point

Fit the end-point with a straight line and extrapolate to the x-axis
Use "true" value of M$(\tilde{\chi}_1^0)$

(Ola Kristoff Oye)





From the fit: $M(\tilde{q}_R) = 1056 \pm 181$GeV
Generator: $M(\tilde{q}_R) = 1190$GeV

From the fit: $M(\tilde{q}_R) = 1113 \pm 164$GeV
Generator: $M(\tilde{q}_R) = 1210$GeV

Again Limited by LSP mass uncertainty

Final states with taus

Large $\tan\beta$ implies that $m(\tilde{\tau}) < m(\tilde{\mu})$

Taus may be the only produced leptons in gaugino decay.

Leptonic tau decays are of limited use – where did lepton come from?

Use Hadronic tau decays, using jet shape and multiplicity for ID and jet rejection.

Full simulation study used to estimate efficiency and rejection

Rely on Jet and $E_t(miss)$ cuts to get rid of SM background

Measure "visible" tau energy

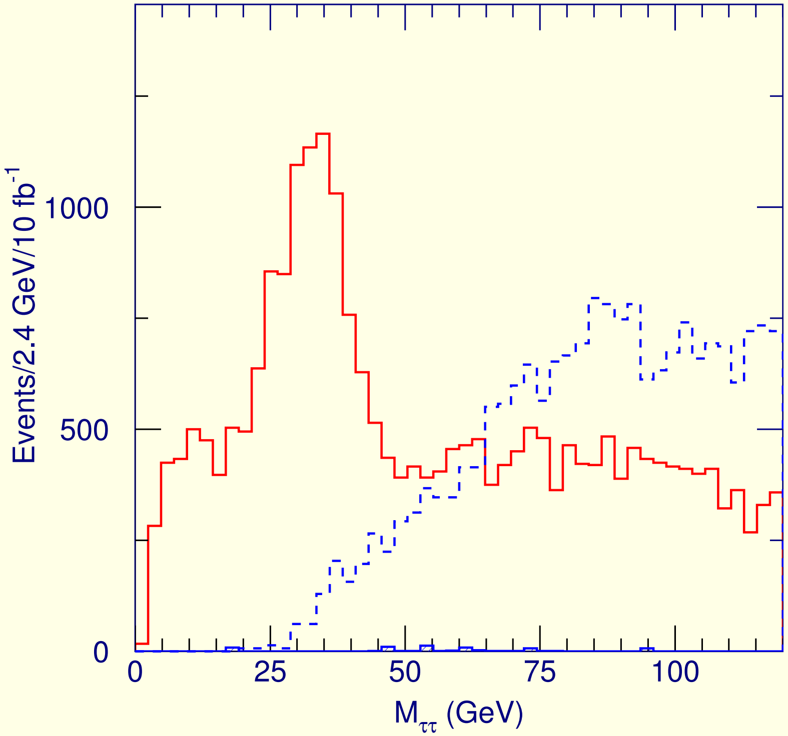
Event selection

≥ 4 jets, one has $p_t > 100$ GeV, rest $p_t > 50$ GeV

No isolated leptons with $p_t > 10$ GeV

$\not{E}_T > max(100, 0.2M_{eff})$

Look at mass of observed tau pairs



Real signal visible above fakes (dashed) and SM (solid)

Can use peak position to infer end point in decay $\widetilde{\chi}_2^0 \to \tau\tau\widetilde{\chi}_1^0$ (61 GeV)

Estimate 5% error

Large $\tan\beta \Rightarrow$ light sbottom – Look for these

$$\tilde{g} \to b\tilde{b} \to bb\tau^{\pm}\tau^{\mp}\widetilde{\chi}_1^0$$

Previous sample with 2 $b-$jets having $p_t > 25$ GeV

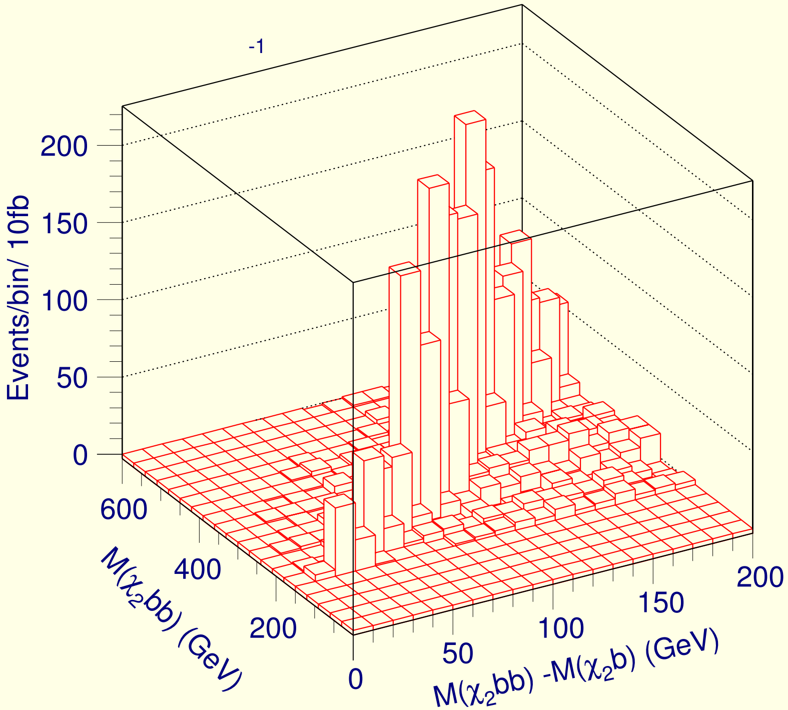
Lots of missing E_T: tau decays and $\widetilde{\chi}_1^0$'s

Select $40 < m_{\tau\tau} < 60$ GeV

Combine with b jets

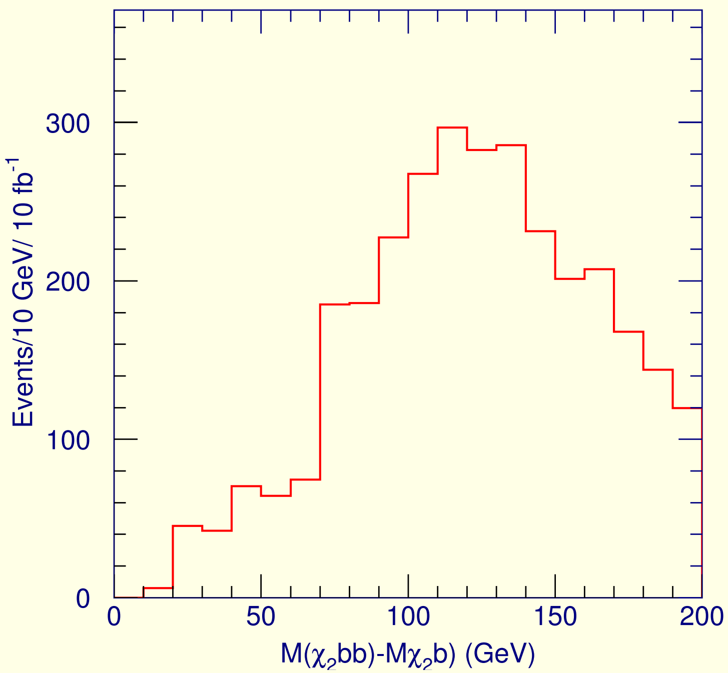
Look at $\tau\tau bb$ and $\tau\tau b$: should approximate gluino and sbottom use partial reconstruction technique assuming mass of $\widetilde{\chi}_1^0$

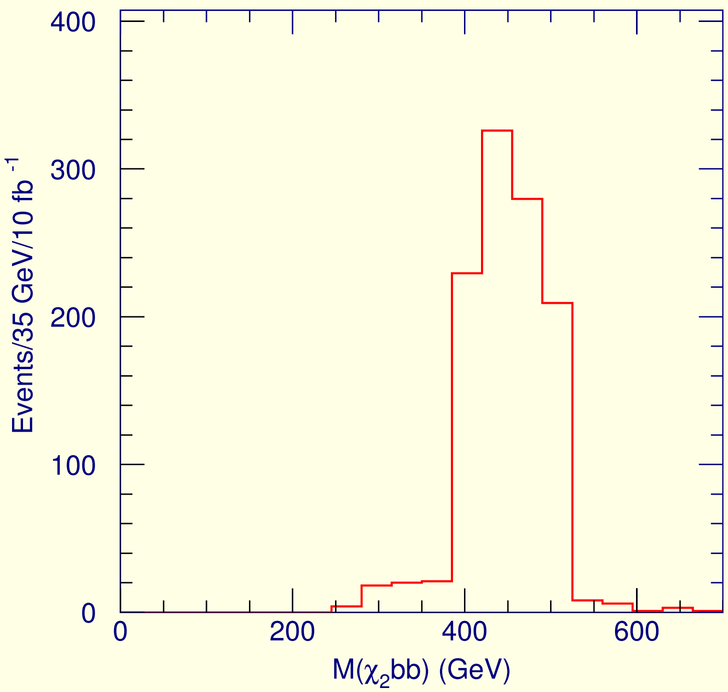
Peaks are low; should be expected due to missing energy



Plot of $m(\widetilde{\chi}_2^0 bb)$ vs $m(\widetilde{\chi}_2^0 bb) - m(\widetilde{\chi}_2^0 b)$

Projections





gluino-sbottom
should be 160 GeV

gluino
540 GeV

Gauge Mediated Model

Aims to solve FCNC problem by using gauge interactions instead of Gravity to transmit SUSY breaking

Messenger Sector consists of some particles (X) that have SM interactions and are aware of SUSY breaking.

$M_i^2 = M^2 \pm F_A$ Simplest X is complete SU(5) **5** or **10** to preserve GUT

Fundamental SUSY breaking scale $F > F_A$, but $\sqrt{F} \lesssim 10^{10}$ GeV or SUGRA breaking will dominate Gaugino masses at 1-loop

$$M_{\widetilde{g}} \sim \alpha_s N_X \Lambda$$

Squark and Slepton masses at 2-loop

$$M_{\widetilde{e}} \sim \alpha_W \sqrt{N_X} \Lambda$$

True LSP is a (almost) massless Gravitino

Sparticles decay as in SUGRA, then "NLSP" decays to $\tilde{G}$

lifetime model dependent

NLSP does not have to be neutral

6 parameters

Λ, M, N_5, $\tan\beta$,

$sign\mu$

$10\,\mathrm{TeV} \lesssim \Lambda \equiv F_A/M \lesssim 400\,\mathrm{TeV}$: Scale for SUSY masses.

$M > \Lambda$: Messenger mass scale.

$N_5 \geq 1$: Number of equivalent $5 + \bar{5}$ messenger fields.

$1 \lesssim \tan\beta \lesssim m_t/m_b$: Usual ratio of Higgs VEV's.

$\mathrm{sgn}\,\mu = \pm 1$: Usual sign of μ parameter.

$C_{\mathrm{grav}} \geq 1$: Ratio of $M_{\tilde{G}}$ to value from F_A, controls lifetime of NLSP.

Point	Λ (TeV)	M_m (TeV)	N_5	$\tan\beta$	$\mathrm{sgn}\,\mu$	$C_{\mathrm{grav}} \geq 1$	σ (pb)
G1a	90	500	1	5.0	$+$	1.0	7.6
G1b	90	500	1	5.0	$+$	10^3	7.6
G2a	30	250	3	5.0	$+$	1.0	23
G2b	30	250	3	5.0	$+$	5×10^3	23

Sparticle	G1	G2	Sparticle	G1	G2
$\widetilde{g}$	747	713			
$\widetilde{\chi}_1^\pm$	223	201	$\widetilde{\chi}_2^\pm$	469	346
$\widetilde{\chi}_1^0$	119	116	$\widetilde{\chi}_2^0$	224	204
$\widetilde{\chi}_3^0$	451	305	$\widetilde{\chi}_4^0$	470	348
$\widetilde{u}_L$	986	672	$\widetilde{u}_R$	942	649
$\widetilde{d}_L$	989	676	$\widetilde{d}_R$	939	648
$\widetilde{t}_1$	846	584	$\widetilde{t}_2$	962	684
$\widetilde{b}_1$	935	643	$\widetilde{b}_2$	945	652
$\widetilde{e}_L$	326	204	$\widetilde{e}_R$	164	103
$\widetilde{\nu}_e$	317	189	$\widetilde{\tau}_2$	326	204
$\widetilde{\tau}_1$	163	102	$\widetilde{\nu}_\tau$	316	189
h^0	110	107	H^0	557	360
A^0	555	358	$H^\pm$	562	367

Mass spectrum more spread out than in SUGRA

$m(squark)/m(slepton)$ bigger

New signals in GMSB

Lightest superpartner is unstable and decays to Gravitino ($\tilde{G}$)

Either neutral

$\chi_1^0 \to \gamma\tilde{G}$: $c\tau \sim C^2(100\text{ GeV}/M_{\chi_1^0})^5(\Lambda/180\text{TeV})^2(M_M/180\text{TeV})^2$mm

$\Rightarrow$ extra photons or similar signals to SUGRA depending on lifetime

Or charged

Almost always slepton: $\tilde{e_R} \to e\widetilde{G}$

No Missing E_T if $c\tau$ large, events have a pair of massive stable charged particles (“G2b”)

Large lepton multiplicity if $c\tau$ small (“G2a”).

Discovery and measurement in these cases is trivial

In case “G2b”, every decay product can be measured

In case “G1a” $\widetilde{G}$ momenta can be inferred and events fully reconstructed.

GMSB case 1a: Event selection (not optimized)

Decay $\widetilde{\chi}_2^0 \to \ell^+\ell^-\widetilde{\chi}_1^0 \to \ell^+\ell^-\gamma\tilde{G}$ is key
Lifetime of $\widetilde{\chi}_1^0$ is short

Find jets

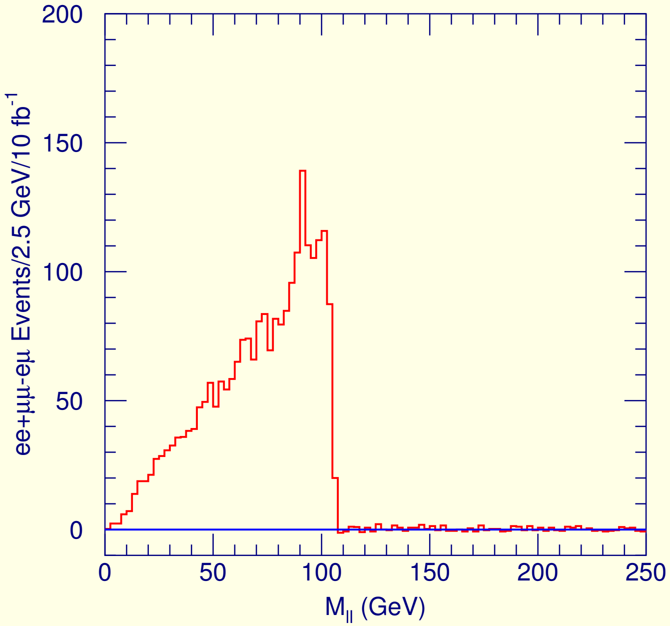
$$M_{\text{eff}} \equiv \not{E}_T + p_{T,1} + p_{T,2} + p_{T,3} + p_{T,4}\,.$$

Require
$M_{\text{eff}} > 400\,\text{GeV}$;
$\not{E}_T > 0.1 M_{\text{eff}}$.
Looking for

$$\widetilde{\chi}_2^0 \to \widetilde{\ell}^{\pm}\ell^{\mp} \to \widetilde{\chi}_1^0\ell^{\pm}\ell^{\mp} \to \widetilde{G}\gamma\ell^{\pm}\ell^{\mp}\,,$$

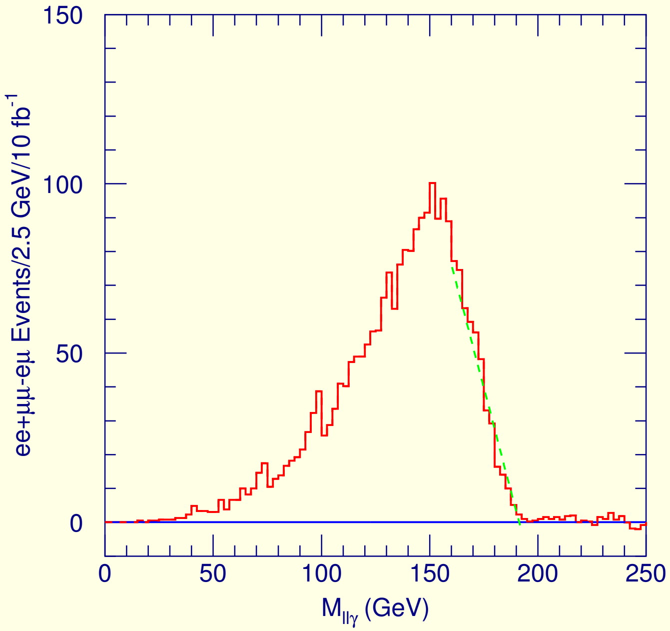
Electrons and photons : $p_T > 20\,\text{GeV}$
Muons : $p_T > 5\,\text{GeV}$.
Require at least 2 photons and two leptons.

Dilepton mass distribution, flavor subtracted $e^+e^- + \mu^+\mu^- - e^\pm\mu^\mp$



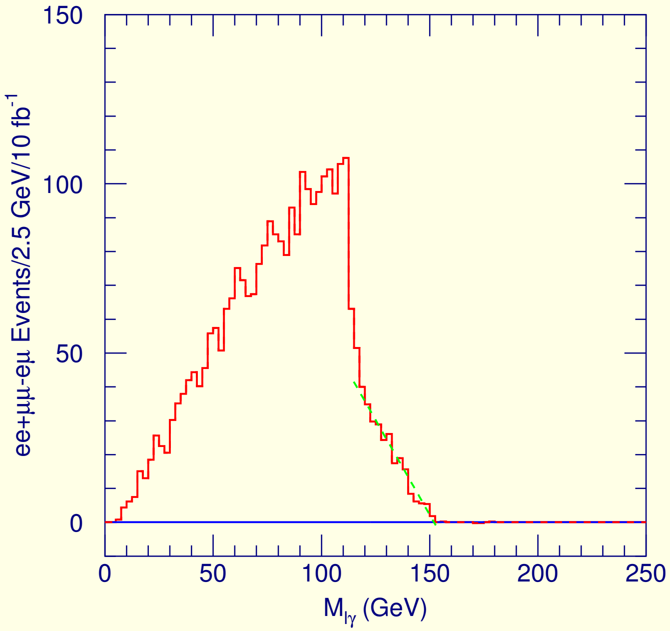
End is at

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



Form $\ell^+\ell^-\gamma$ mass and take smallest combination. Linear vanishing at

$$\sqrt{M^2_{\widetilde{\chi}^0_2} - M^2_{\chi^0_1}} = 189.7\,\mathrm{GeV}\,,$$



Form $\ell^{\pm}\gamma$ mass also. Two structures at

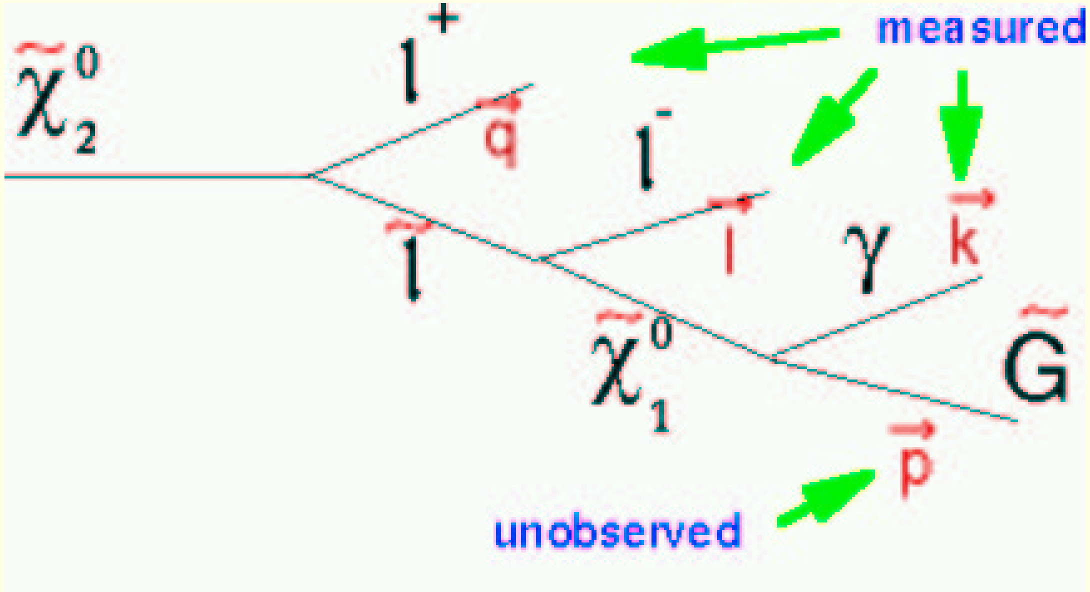
$$\sqrt{M^2_{\tilde{\ell}_R} - M^2_{\chi^0_1}} = 112.7\,\mathrm{GeV}$$

and

$$\sqrt{M^2_{\chi^0_2} - M^2_{\tilde{\ell}_R}} = 152.6\,\mathrm{GeV}$$

These four measurements are sufficient to determine the masses of the particles ($\widetilde{\chi}_2^0$, $\widetilde{\ell}_R$, and $\widetilde{\chi}_1^0$) in this decay chain without assuming any model of SUSY breaking.

Now use this to reconstruct the decay chain and measure the $\widetilde{G}$ momenta despite the fact that there are two in each event and both are invisible!



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

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

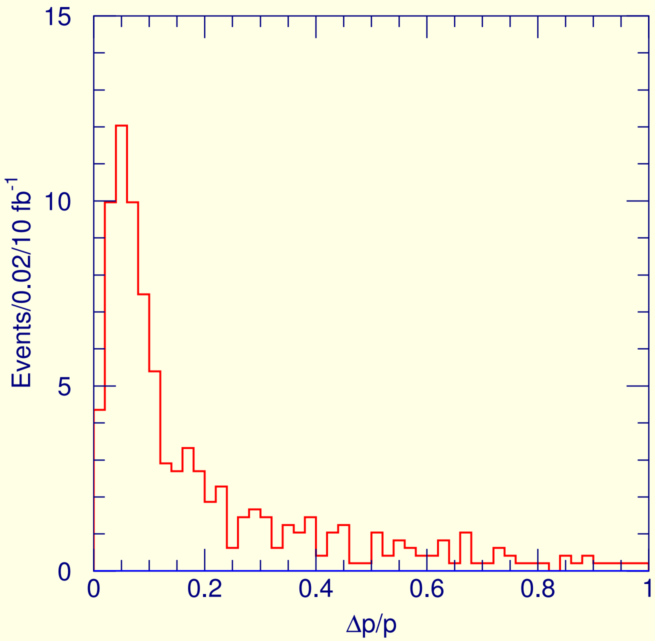
0C fit with 2×2 solutions.

Event has two of these decays so require 4 leptons and 2 gammas

Calculate missing E_T
Form a χ^2 using measured missing E_T to resolve ambiguities

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

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



Compare to generated $\widetilde{G}$ momenta
Plot shows all solutions with $\chi^2 < 10$
$\Delta\vec{p} = \vec{p}_{\tilde{G}} - \vec{p}_{reconst}$
$\Delta|\vec{p}|/|\vec{p}| \sim 10\%$

Squark and Gluino Masses

Use measured $\widetilde{\chi}_2^0$ momenta and combine with jets

$\widetilde{q} \to \widetilde{g}q \to \widetilde{\chi}_2^0\overline{q}qq$

Require at least 4 jets with $p_T > 75\,\mathrm{GeV}$

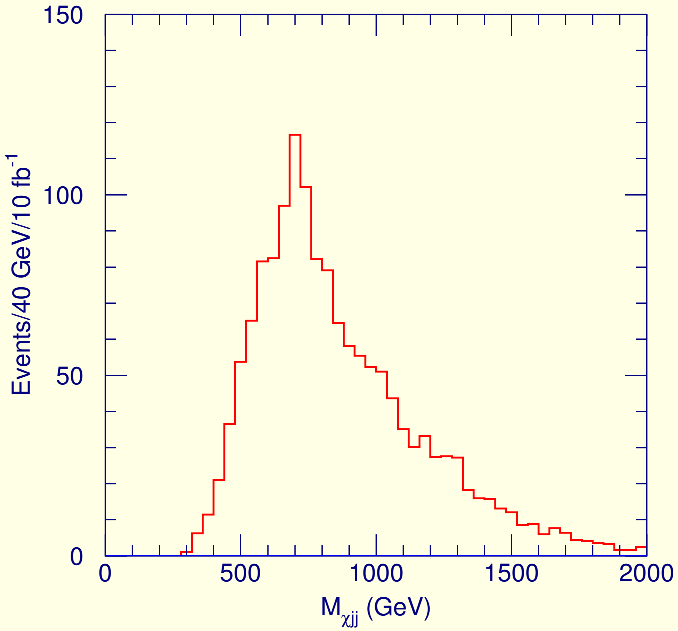


Figure shows mass of $\widetilde{\chi}_2^0$+2 jets;
peak is below gluino mass (747 GeV);
no correction applied for small jet cone.

Much easier than the SUGRA cases; masses measured directly

Measuring the fundamental scale of SUSY breaking

Lifetime of $\widetilde{\chi}_1^0 \to \tilde{G}$ is important as it measures the fundamental scale of SUSY breaking

Measure lifetime of χ_1^0 ($\to \widetilde{G}\gamma$) using Dalitz decay $\chi_1^0 \to e^+e^-\gamma\widetilde{G}$

Works for short lived $\widetilde{\chi}_1^0$

Statistics limited (∼few-K events)

Measure lifetime of χ_1^0 ($\to \widetilde{G}\gamma$): photon pointing.

Angular resolution of photons from primary vertex (ATLAS)

$\Delta\theta \sim 60mr/\sqrt{E}$ Detailed study of efficiency for non-pointing photons

Important for long lived $\widetilde{\chi}_1^0$

Decays are uniformly distributed in the detector

Cross check from time delay of decay

Failure to see photons $\Rightarrow c\tau > 100$ km or $\sqrt{F} \geq 10^4$ TeV

Mass measurement of quasi-stable sleptons – ATLAS

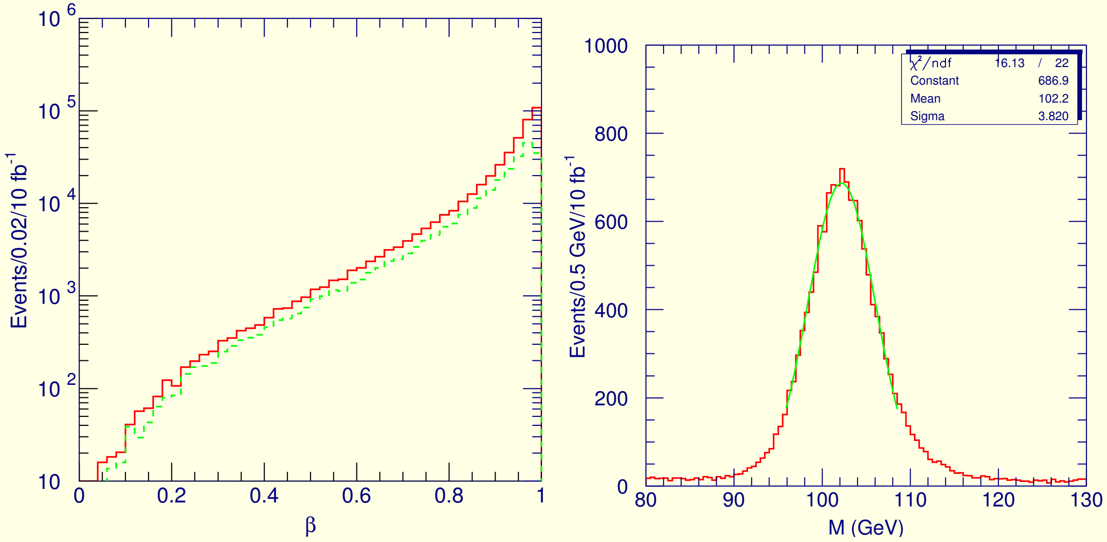
Sleptons are produced at the end of decay chains ⇒ large velocity

Most of these will pass the Muon Trigger

Measure the velocity using TOF in Muon system, then infer mass

Time resolution ~ 65 ns

$\Rightarrow \Delta M/M \sim 3\%$ for $M = 100$ GeV



velocity $\qquad\qquad\qquad\qquad \Delta M/M$

R-parity broken

Implies either Lepton number or Baryon number is violated and LSP decays

Either $\widetilde{\chi}_1^0 \to qqq$, or $\widetilde{\chi}_1^0 \to q\overline{q}\ell$ or $\widetilde{\chi}_1^0 \to \ell^+\ell^-\nu$

First two have no $\not{E}_T$, last 2 have more leptons and are straightforward

First case is hardest, Global S/B is worse due to less $\not{E}_T$ Example, SUGRA with $\widetilde{\chi}_1^0 \to qqq$ Leptons are essential to get rid of QCD background

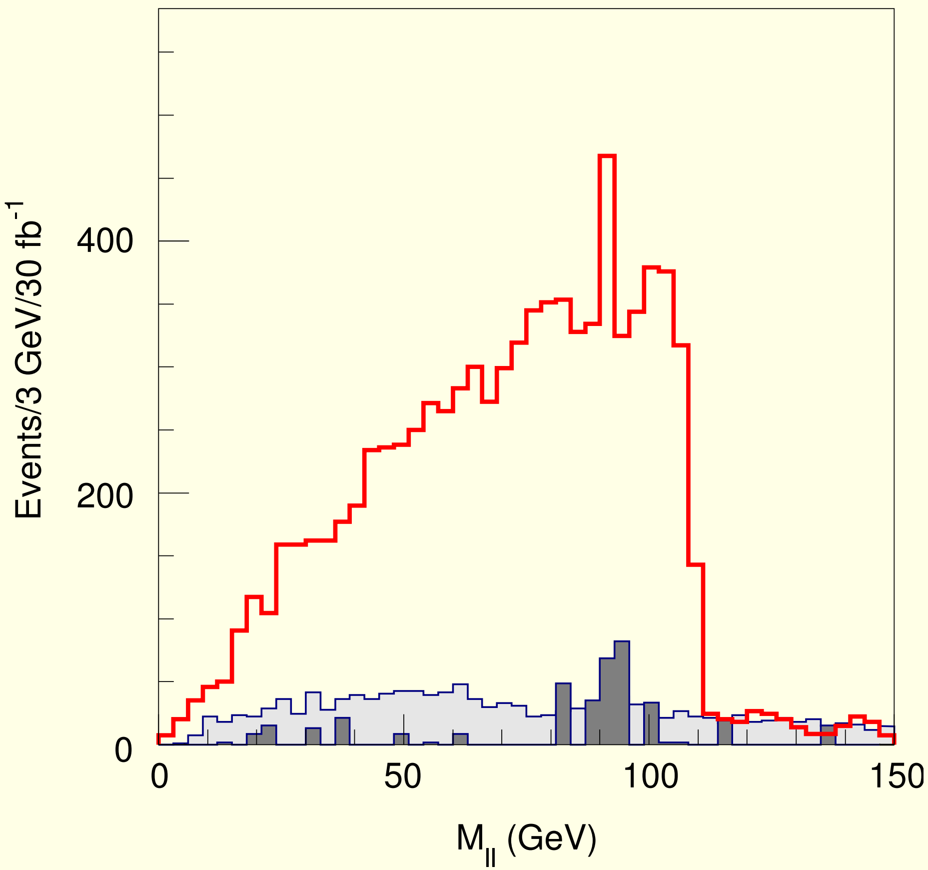
≥ 8 jets with $p_t > 50$ GeV

2 OSSF isolated leptons.

$S_T > 0.2$, selects "ball like" events

$\Sigma_{jets+leptons} E_T > 1$ TeV

Dilepton mass still shows clear structure with small background from $\widetilde{\chi}_2^0 \to \ell^+\ell^-\widetilde{\chi}_1^0$



As nothing is lost, should be possible to reconstruct $\widetilde{\chi}_1^0$

Difficult because jet multiplicity is very high and $\widetilde{\chi}_1^0$ mass is usually small, so jets are soft

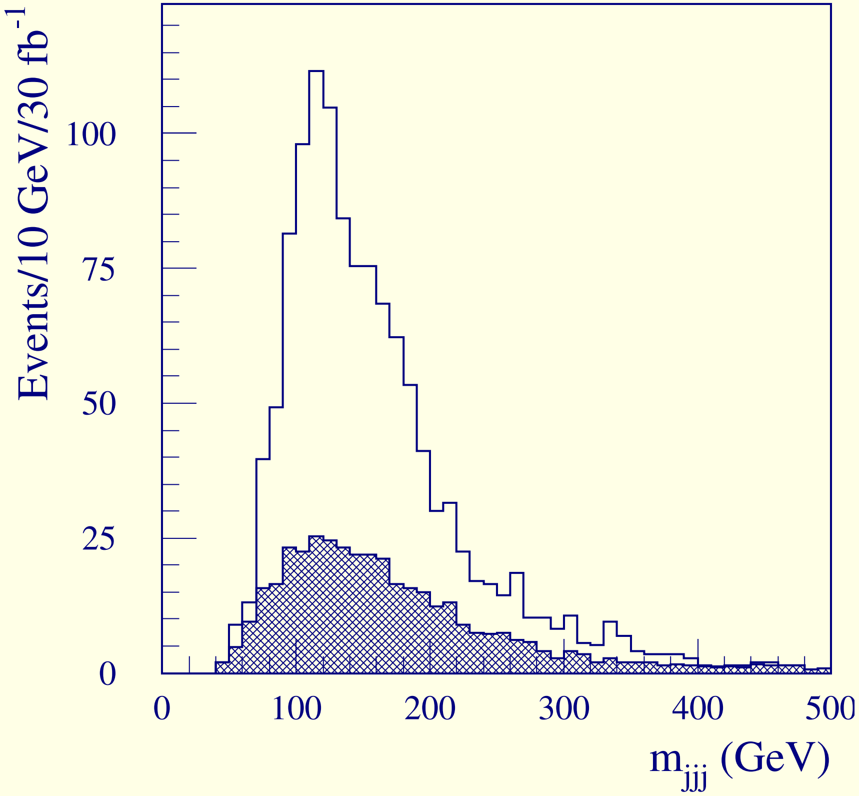
≥ 8 jets with $p_t > 17.5$ GeV, ≤ 8 jets with $p_t > 25$ GeV

2 jets with $p_t > 100(200)$ GeV and $\mid \eta \mid< 2$

1 or 2 leptons with $p_t > 20$ GeV

Sphericity cut

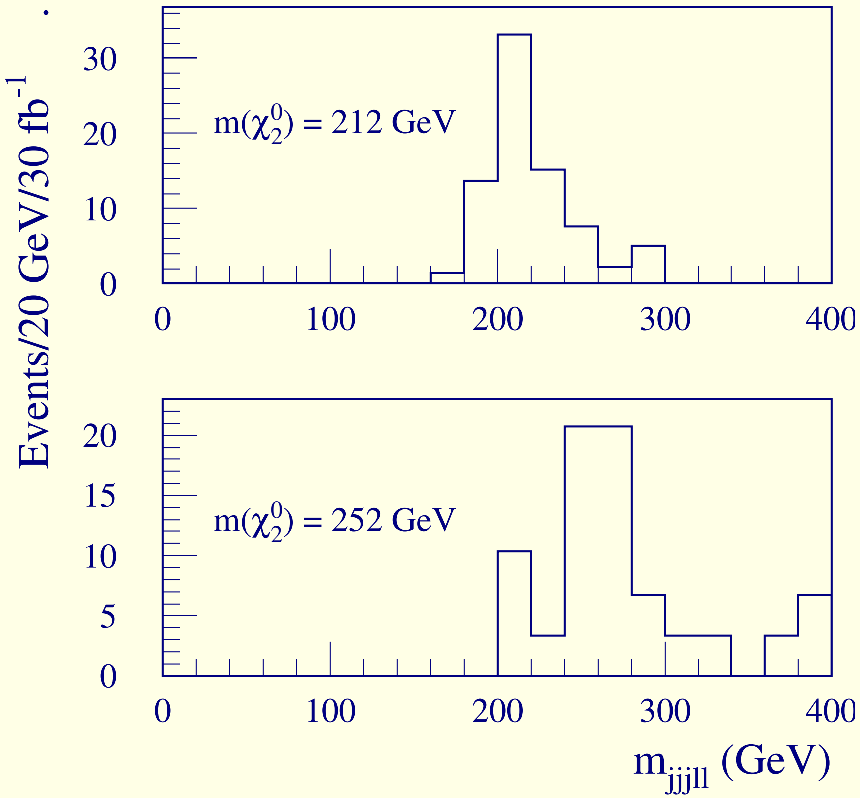
combine 6 slowest jets into 2 sets of 3; require $M(jjj)_1 - M(jjj)_2 < 20$ GeV



Nominal mass 122 GeV

Can cut around peak and combine with either leptons or quarks

reconstruct $\tilde{q}_R \to q\widetilde{\chi}_1^0(\to qqq))$ and $\chi_2^0 \to \ell\ell\widetilde{\chi}_1^0$



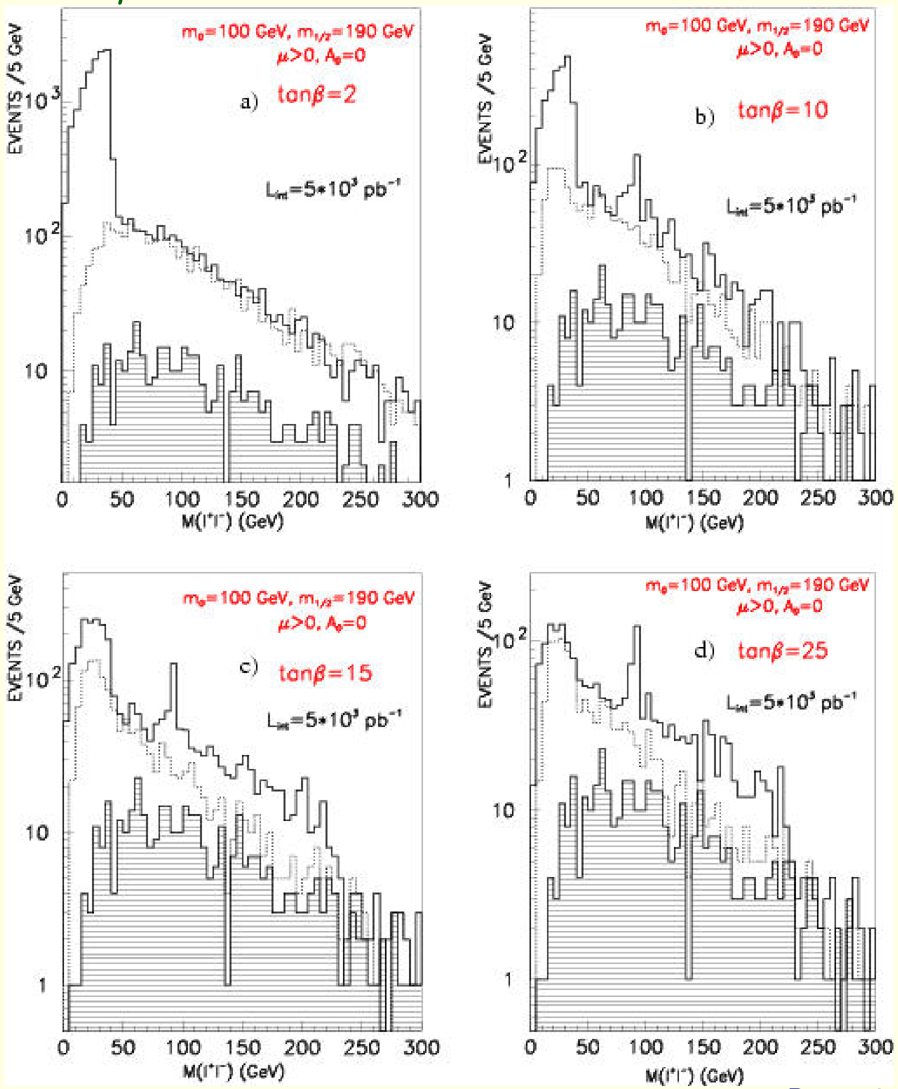
Plot shows $\widetilde{\chi}_2^0$

Note that tight cuts imply low event rate (analysis not optimized)

Lepton Universality

$e/\mu/\tau$ universality must be tested Large $\beta \Rightarrow m_{\tilde{\tau}} < m_{\tilde{e}}$
Expect larger rate of $\tau^+\tau^-$ and hence μ^+e^-

Plot of invariant mass distributions
μ^+e^- (dashed) and $\mu^+\mu^-$ (solid) from SUSY cascades *vs.* $\tan\beta$
$\mu^+\mu^-$ structure less distinct at large $\tan\beta$



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Denegri, Majerotto, Rurua

Explicit flavor violation is also possible

Neutrino oscillations imply lepton number is violated

Atmospheric muon neutrino deficit implies $\nu_{mu} \leftrightarrow \nu_\tau$ with maximal mixing

In a SUSY model, expect significant flavor violation in slepton sector

Simplest model of lepton number violation involves addition of right handed neutrino N with SUSY conserving Majorana mass mNN and coupling to lepton left doublet and Higgs of the form LNH

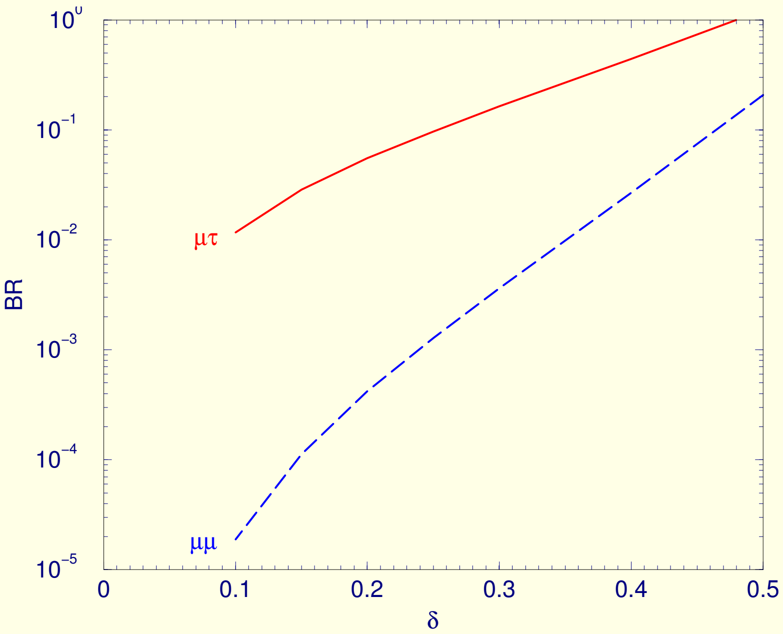
Including only $\mu \leftrightarrow \tau$ mixing gives

$$M^2_{\tilde{\ell}\tilde{\ell}} = \begin{bmatrix} M_L^2 + D_L & 0 & 0 & 0 & 0 & 0 \\ 0 & M_L^2 + D_L & M^2_{\mu\tau} & 0 & 0 & 0 \\ 0 & M^2_{\mu\tau} & M^2_{\tau_L} + D_L & 0 & 0 & m_\tau \bar{A}_\tau \\ 0 & 0 & 0 & M_R^2 + D_R & 0 & 0 \\ 0 & 0 & 0 & 0 & M_R^2 + D_R & 0 \\ 0 & 0 & m_\tau \bar{A}_\tau & 0 & 0 & M^2_{\tau_R} + D_R \end{bmatrix}$$

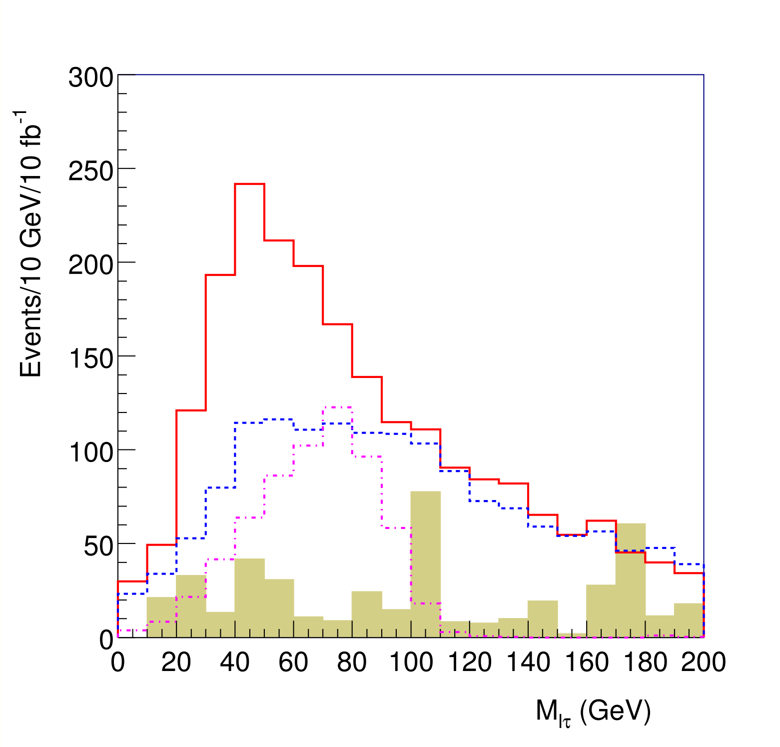
Atmospheric neutrinos suggest maximal mixing $i.e.\quad \delta = \mathcal{O}(1)$

Two types of flavor violation production ($\widetilde{\chi}_2^0 \to \tilde{\tau}\mu$) and decay ($\tilde{\tau} \to \widetilde{\chi}_1^0\mu$).

Branching ratio for $\widetilde{\chi}_2^0 \to \widetilde{\chi}_1^0\mu\tau$ and for $\widetilde{\chi}_2^0 \to \widetilde{\chi}_1^0\mu\mu$ through an intermediate $\tilde{\tau}_1$
Must use hadronic tau decays to distinguish



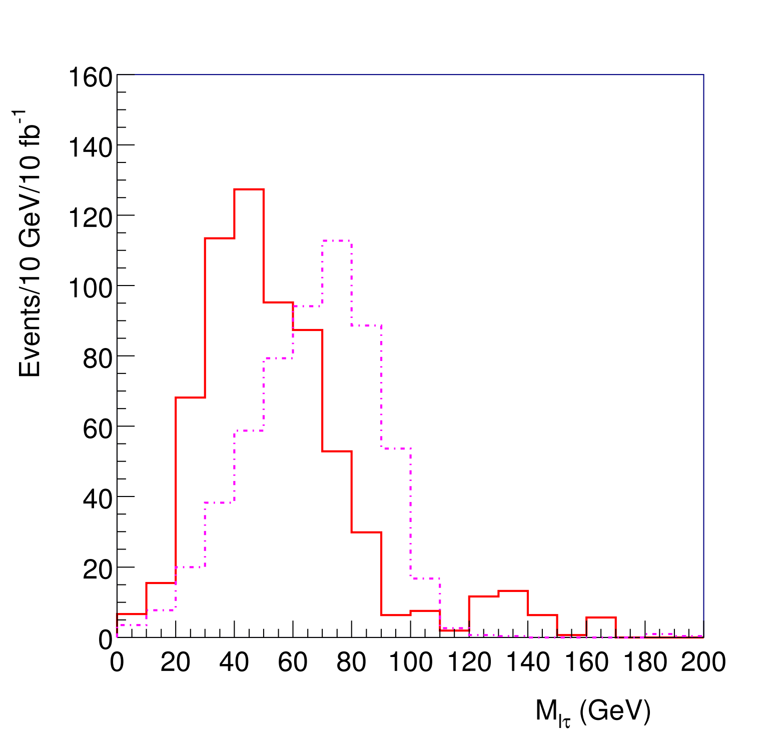
Signal for lepton number violation comes by comparing $\mu\tau_h$ and $e\tau_h$ final states



$\ell^\pm \tau_h^\mp$ signal (red), $\ell^\pm \tau_h^\pm$ signal (blue), $\mu^\pm \tau_h^\mp$ from LFV decays with $BR = 10\%$ (magenta), and Standard Model $\ell^\pm \tau_h^\mp$

Lepton number violating decay $\widetilde{\chi}_2^0 \to \mu \tau_h \widetilde{\chi}_1^0$ give harder $\mu\tau$ mass distribution than that from $\widetilde{\chi}_2^0 \to \tau\tau\widetilde{\chi}_1^0 \to \mu\tau_h\widetilde{\chi}_1^0$

Subtraction removes background

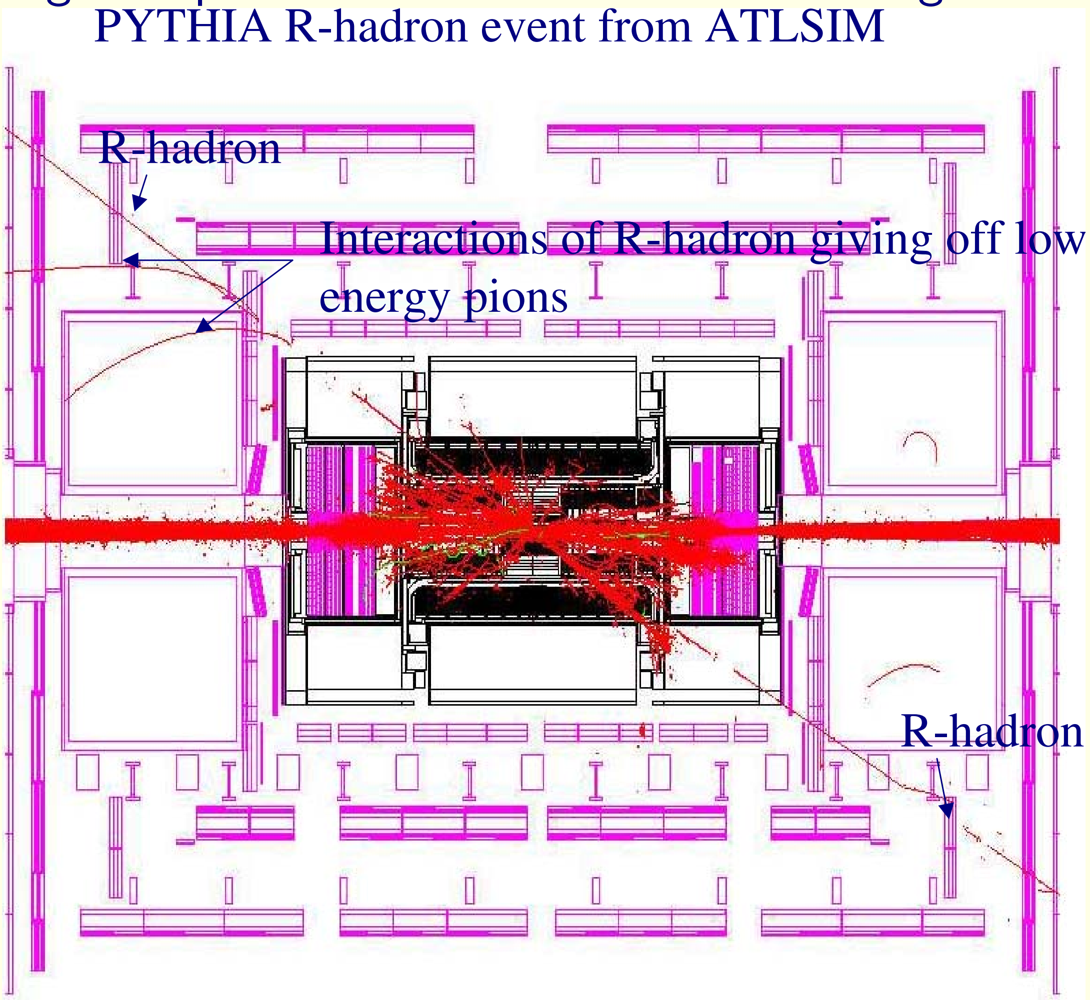


$\ell^\pm\tau_h^\mp - \ell^\pm\tau_h^\pm$ (red) and $\mu^\pm\tau_h^\mp$ from LFV decays with $BR = 10\%$ (magenta)
Signal is established from $E = N(\mu^\pm\tau_h^\mp) - N(e^\pm\tau_h^\mp)$
10 fb^{-1} and 5σ implies BR=2.3% or $\delta \sim 0.1$ well within value needed for neutrino data

Sensitive provided that $\widetilde{\chi}_2^0$ production is large enough (large fraction of parameter space More sensitive than $\mu \to e\gamma$

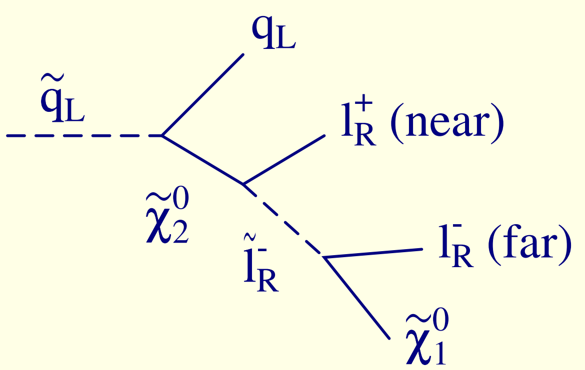
Odd Ball: R-hadron (split susy)

Long lived or quasi stable gluino produces "cannon ball" that charge exchanges as it passes through detector



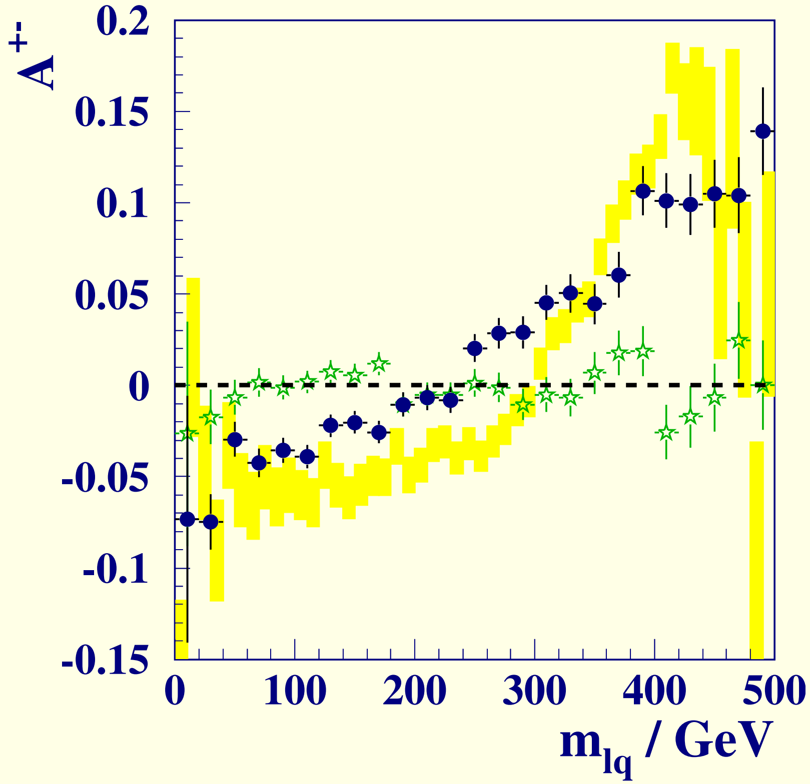
Spin measurements at LHC?

Conventional wisdom says that you need LC for this but...



Angle between q and e^- in $\tilde{\chi}^0_2$ rest frame is sensitive to spin correlations.
But effect washes out if we do not know which lepton comes out first: Use kinematics
But effect washes out if average over q and $\overline{q}$: LHC is a pp machine: more $\tilde{q}$ than $\tilde{\overline{q}}$

Form an asymmetry from invariant mass distribution of lepton and jet



$A = \frac{(l^+q)-(l^-q)}{(l^+q)+(l^-q)}$

Green:spin correlation off
Yellow: No detector $(\times 0.6)$
Needs at least 100fb^{-1}

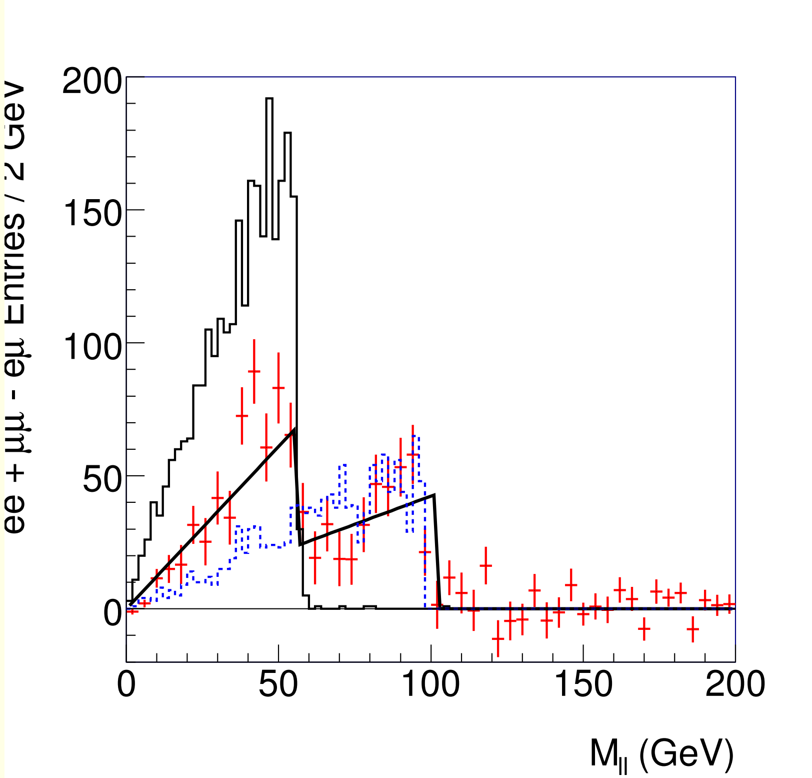
Barr

Difficult cases I: Small mass gaps

Co-annihilation region: Near degeneracy between LSP and sleptons.Soft leptons and more messy decays.

$\tilde{q}_L \rightarrow q\widetilde{\chi}_2^0$ then $\widetilde{\chi}_2^0(260) \rightarrow \widetilde{\ell}_R(153)\ell \rightarrow \ell\ell\widetilde{\chi}_1^0(136)$ and $\widetilde{\chi}_2^0 \rightarrow \widetilde{\ell}_L(255)\ell \rightarrow \ell\ell\widetilde{\chi}_1^0(136)$

Leptons can still be found despite small mass gaps



ATLAS

An era is about to end

Low energy SUSY has provided employment for > 20 years
It will be discovered or die in the next 6 years.