Reconstructing SUSY at LHC

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Remarks about SUSY at Hadron Colliders.

Remarks about models, SUGRA, GMSB, R-parity breaking

Examples of methodology – characteristic decays, $h^0 \to b\bar{b}$ and dileptons

Masses reconstructible in some cases with NO model assumptions

R-Parity breaking: Missing Transverse energy is not essential

"Stable" slepton signals, isolated photons and other odd-balls.

Constraining Models and parameters

http://www-theory.lbl.gov/∼ianh/susy/fnal.ps

Atlas Physics TDR and refs therein.

Comments about SUSY at Hadron colliders

If SUSY is relevant to electro-weak symmetry breaking then
LHC is a SUSY factory *Theorists should give up on Weak scale SUSY if LHC does not find it*

Everything is produced at once; squarks and gluinos have largest rates.

Production of Sparticles with only E-W couplings (e.g sleptons, Higgs) may be dominated by decays not direct production.

Must use a consistent model for simulation;
cannot discuss one sparticle in isolation.

Strategies different from Tevatron where weak gaugino production probably dominates

Studies shown here are not optimized;
large event rates are used to cut hard to get rid of standard model background.

Dominant backgrounds are combinatorial from SUSY events themselves.

Characteristic SUSY signatures at LHC

Not all present in all models

- $\not\!\!E_T$
- High Multiplicity of large p_t jets
- Many isolated leptons
- Copious b production
- Large Higgs production
- Isolated Photons
- Quasi-stable charged particles

No SUSY study has yet revealed a signal that would have been missed by a prexisting “trigger menu”

Comments about Models

Huge number of theoretical models

Most general SUSY model has > 100 parameters

Several FTE-months to study a particular case assuming that is it available in an event generator.

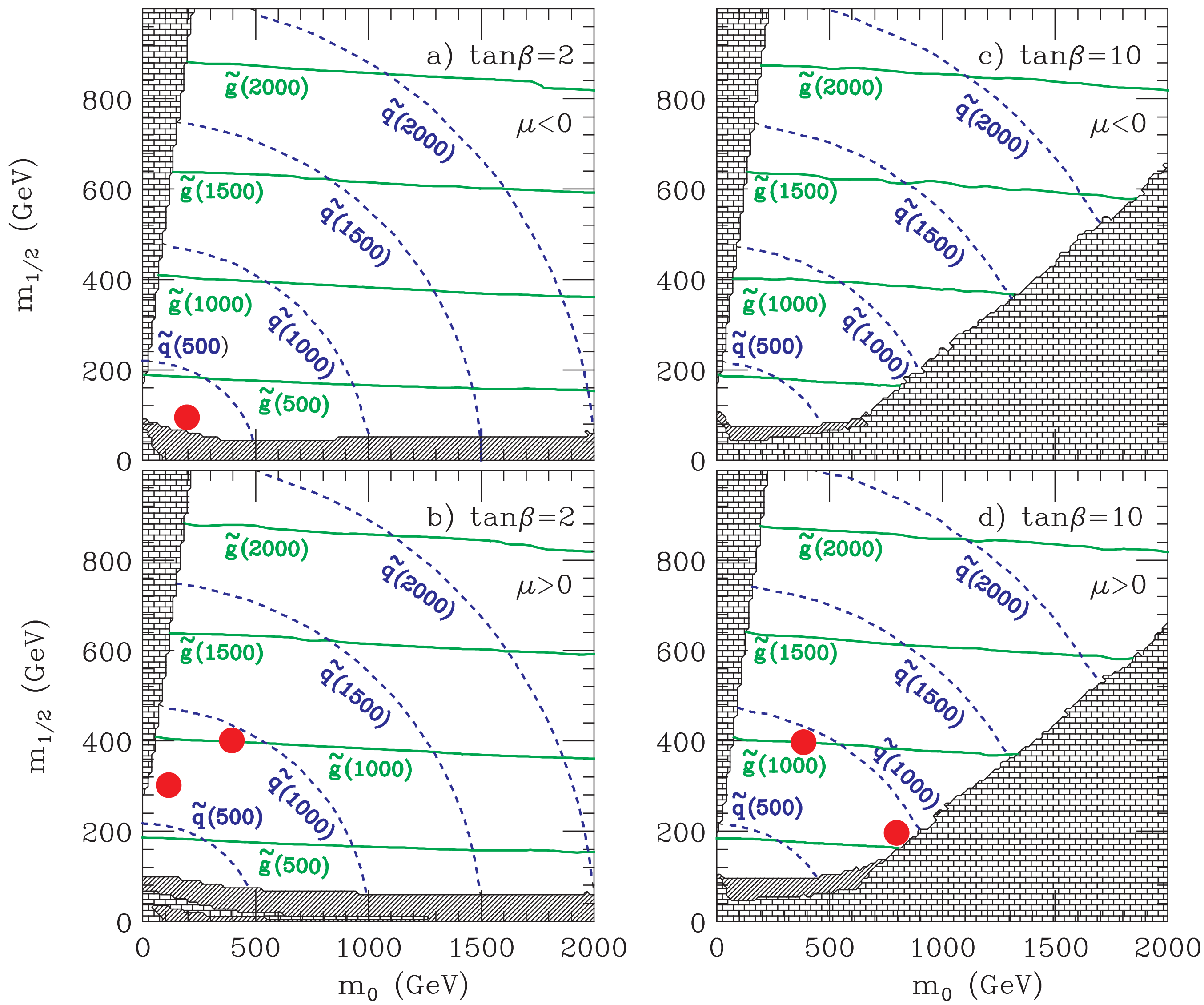
Work has concentrated on cases that are qualitatively different; some examples were chosen in the expectation that they would be hard.

Model determines the masses, decays and signals.

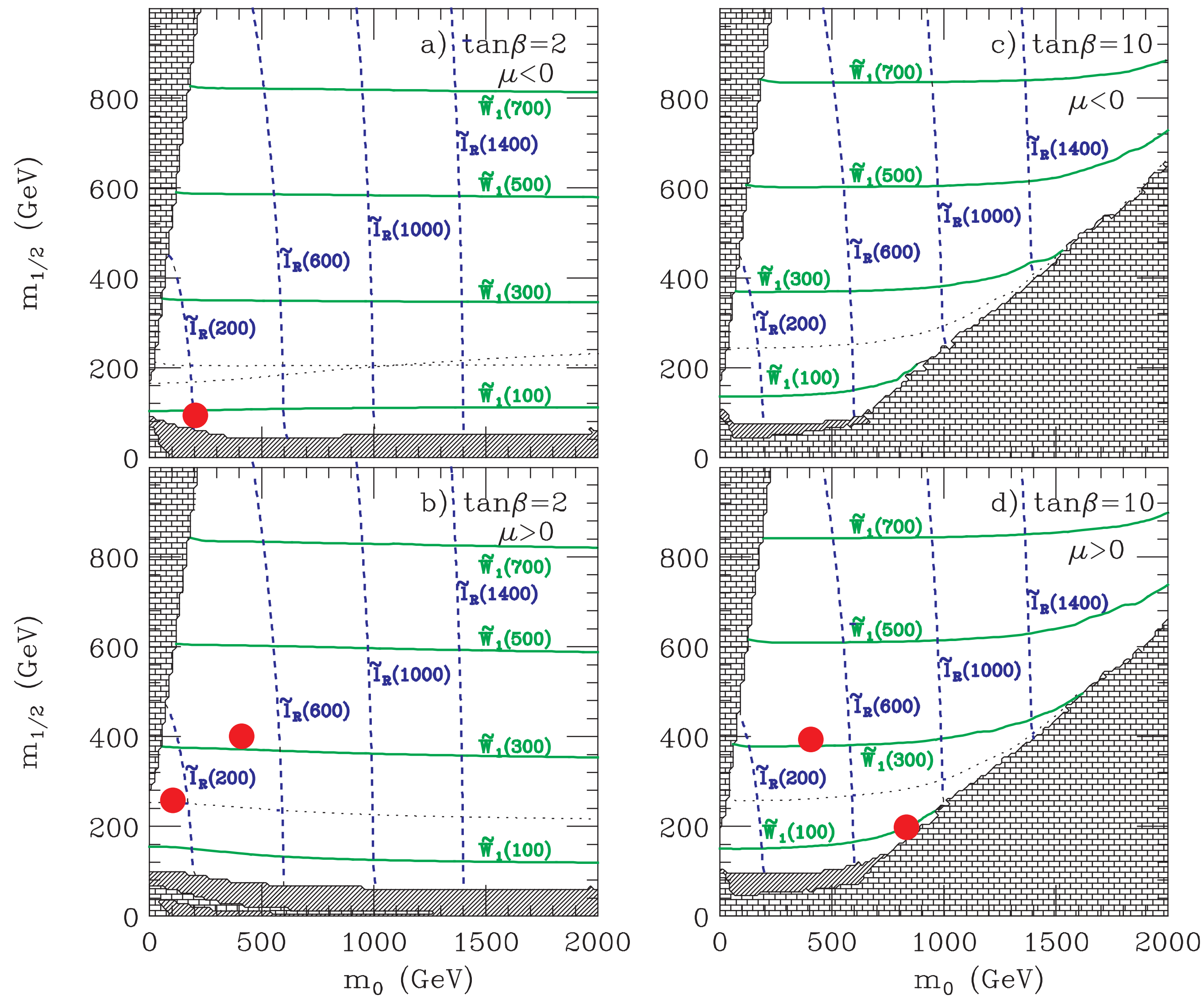
Detailed studies of 12 models; general conclusions difficult; mine are possibly too conservative?

SUGRA Model

- Grandaddy of SUSY models
- Unification all scalar masses (m_0) at GUT scale
- Unification all gaugino masses ($m_{1/2}$) at GUT scale
- Three more parameters $\tan\beta = v_1/v_2$
  $sign(\mu)$ (superpotential has $\mu H_1 H_2$) and
- Trilinear term A, important only for 3rd generation
- Full mass spectrum and decay table predicted
- Gluino mass strongly correlates with $m_{1/2}$, slepton mass with m_0.
- R parity good – neutral LSP stable – all events have 2 LSP's in them
  $\Rightarrow$ missing E_T
- Can relax unification assumption – more parameters



Contours of fixed gluino and squark mass



Contours of fixed wino and slepton mass

6 SUGRA cases studied in detail

In one case unification assumptions were relaxed to investigate how signals changed (New signals appeared, old ones stayed)

3 cases were restudied assuming that R-Parity was broken
$\Rightarrow$ LSP decayed inside detector.

Worst case cross section is ~ 3 pb

Table I: SUGRA parameters for the six LHC points.

Point	m_0 (GeV)	$m_{1/2}$ (GeV)	A_0 (GeV)	$\tan\beta$	sgn μ	σ (pb)
1	400	400	0	2.0	$+$	2.9
2	400	400	0	10.0	$+$	2.9
3	200	100	0	2.0	$-$	1300
4	800	200	0	10.0	$+$	28
5	100	300	300	2.1	$+$	15
6	200	200	0	45	$-$	99

General Features

- In general $m_{squark} > m_{slepton}$, $m_{gluino} > m_{\widetilde{W}}$
- Splitting between $m_{\widetilde{e}_l}$ and $m_{\widetilde{e}_r}$
- Stop is usually lightest squark
- Lightest SUSY particle (LSP) stable if R-parity good.
- LSP must be neutral if stable
- SUSY particles produced in pairs even if R-parity broken.
- SUSY production is dominated by gluinos and squarks.
  Not necessarily true for Tevatron.
- Stable LSP $\Rightarrow$ Missing E_T
- Background for SUSY usually other SUSY, not Standard Model.

Table II: Masses of the superpartners, in GeV, at the six SUGRA points. Note that the first and second generation squarks and sleptons are degenerate and so are not listed separately.

Point	1	2	3	4	5	6
$\tilde{g}$	1004	1009	298	582	767	540
$\tilde{\chi}_1^{\pm}$	325	321	96	147	232	152
$\tilde{\chi}_2^{\pm}$	764	537	272	315	518	307
$\tilde{\chi}_1^0$	168	168	45	80	122	81
$\tilde{\chi}_2^0$	326	321	97	148	233	152
$\tilde{\chi}_3^0$	750	519	257	290	497	286
$\tilde{\chi}_4^0$	766	538	273	315	521	304
$\tilde{u}_L$	957	963	317	918	687	511
$\tilde{u}_R$	925	933	313	910	664	498
$\tilde{d}_L$	959	966	323	921	690	517
$\tilde{d}_R$	921	930	314	910	662	498
$\tilde{t}_1$	643	710	264	594	489	365
$\tilde{t}_2$	924	933	329	805	717	517
$\tilde{b}_1$	854	871	278	774	633	390
$\tilde{b}_2$	922	930	314	903	663	480
$\tilde{e}_L$	490	491	216	814	239	250
$\tilde{e}_R$	430	431	207	805	157	219
$\tilde{\nu}_e$	486	485	207	810	230	237
$\tilde{\tau}_1$	430	425	206	797	157	132
$\tilde{\tau}_2$	490	491	216	811	239	259
$\tilde{\nu}_\tau$	486	483	207	806	230	218
h^0	111	125	68	117	104	112
H^0	1046	737	379	858	638	157
A^0	1044	737	371	859	634	157
$H^{\pm}$	1046	741	378	862	638	182

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

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

- Squark and Slepton masses at 2-loop

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

- 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 TeV $\lesssim \Lambda \equiv F_A/M \lesssim 400$ 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.
- sgn $\mu = \pm 1$: Usual sign of μ parameter.
- $C_{\text{grav}} \geq 1$: Ratio of $M_{\tilde{G}}$ to value from F_A, controls lifetime of NLSP.

Table III: Parameters for the four GMSB case studies in this paper.

Point	Λ (TeV)	M_m (TeV)	N_5	$\tan\beta$	sgn μ	$C_{\text{grav}} \geq 1$	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

Table IV: Masses of the superpartners, in GeV, for the cases to be studied. Note that the first and second generation squarks and sleptons are degenerate and so are not listed separately.

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

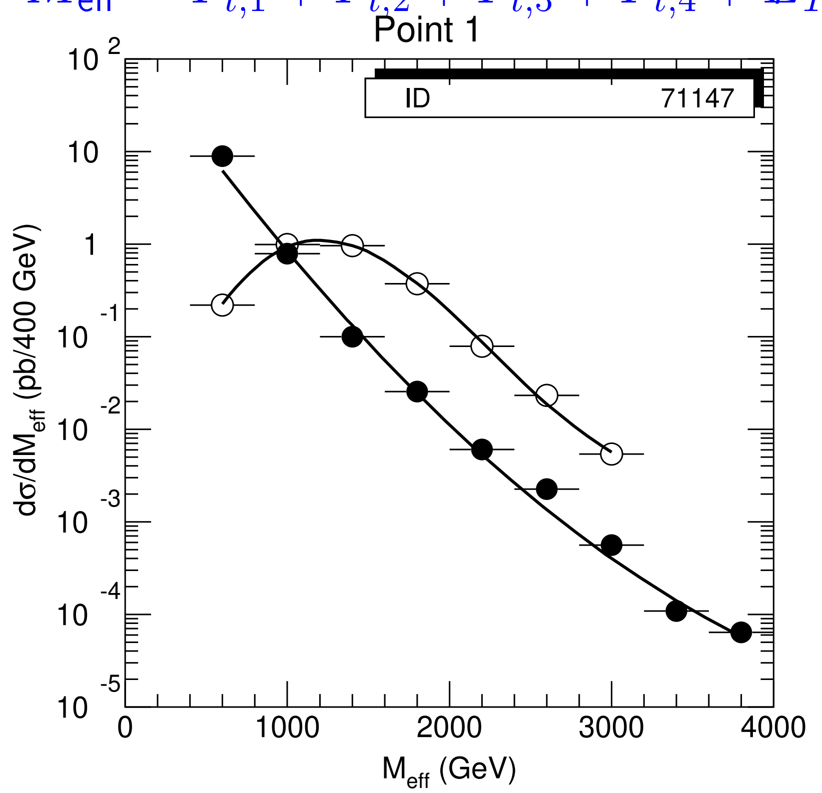
Establishing the SUSY Mass scale

Select events with at least 4 jets and Missing E_T

A simple variable

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

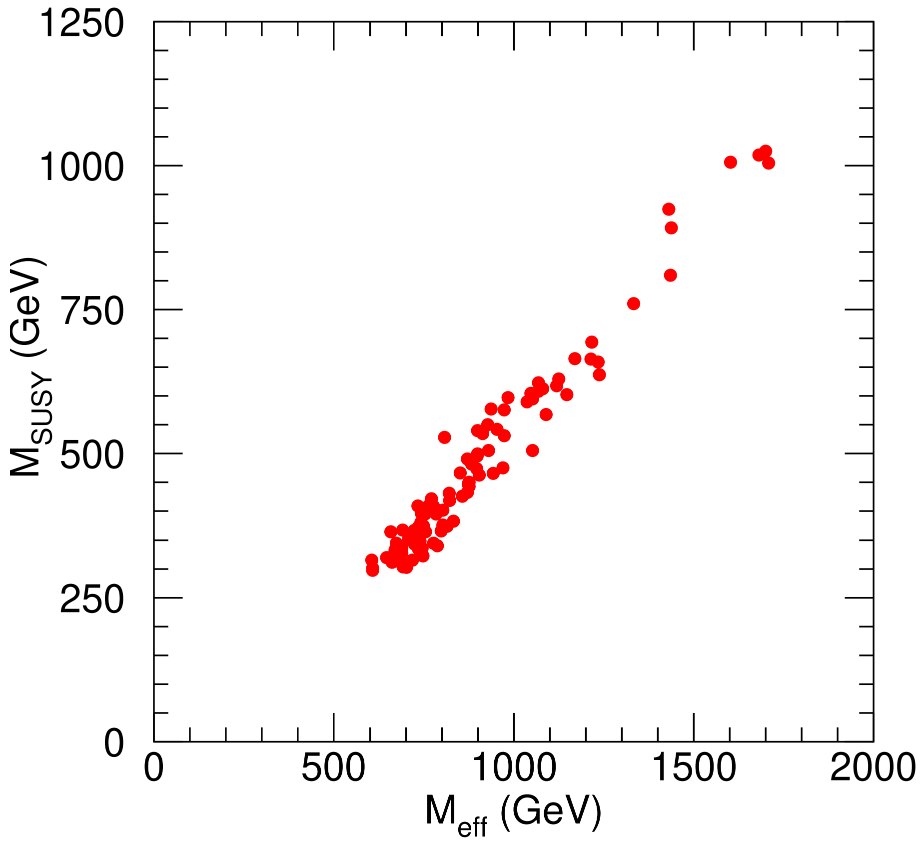
SUGRA



At high $M_{\rm eff}$ see non-SM signal (open points) emerging from SM background (solid points)

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

SUGRA



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

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

Characteristic Decays

Will illustrate techniques by choosing examples from each case study.

Both $\tilde{q}$ and $\tilde{g}$ 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 $\chi_2^0 \to \widetilde{\ell^+} \ell^-$
Former tends to dominate if kinematically allowed.

Use these charateristic decays as a starting point

Many SUSY particles can then be identified

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.

SUGRA Point 1, $\sim 20\%$ of SUSY events contain $h \to b\bar{b}$

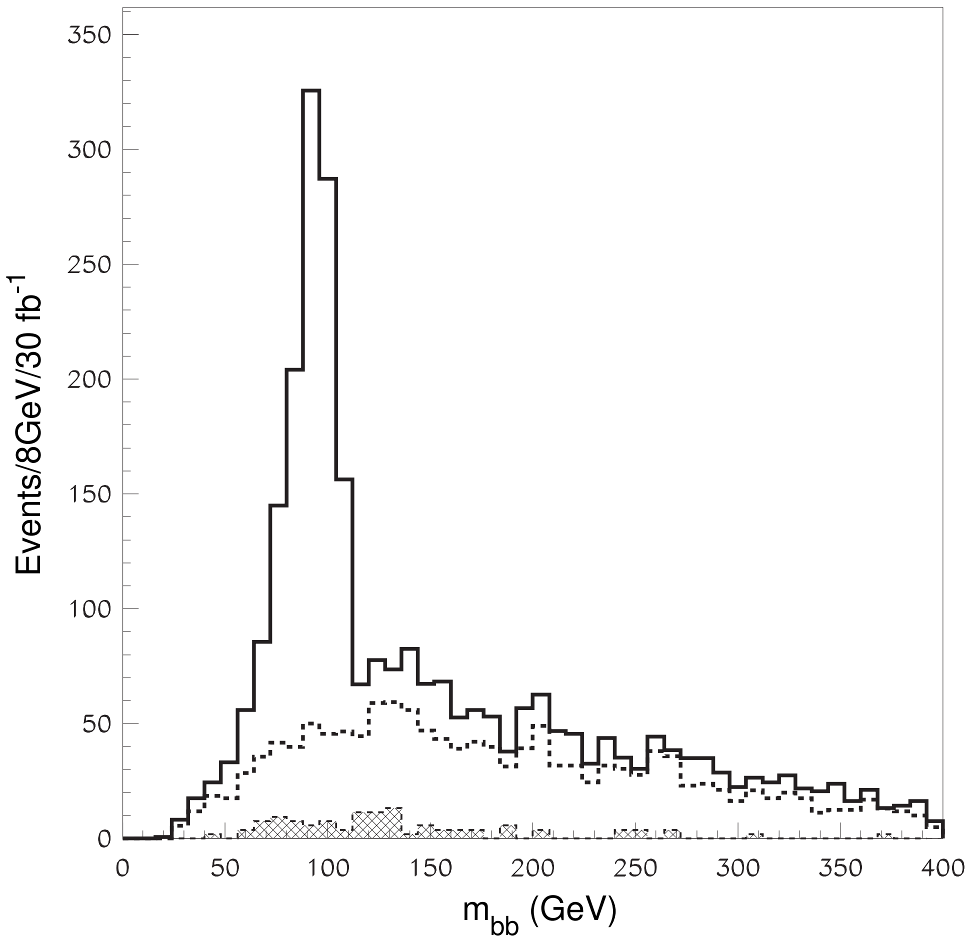
Squarks and gluinos are heavy (~ 1 TeV) – small rates

Event selection

- $\not{E}_T > 300$ GeV
- ≥ 2 jets with $p_T > 100$ 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 $t\bar{t}$)

$b\bar{b}$ mass distribution

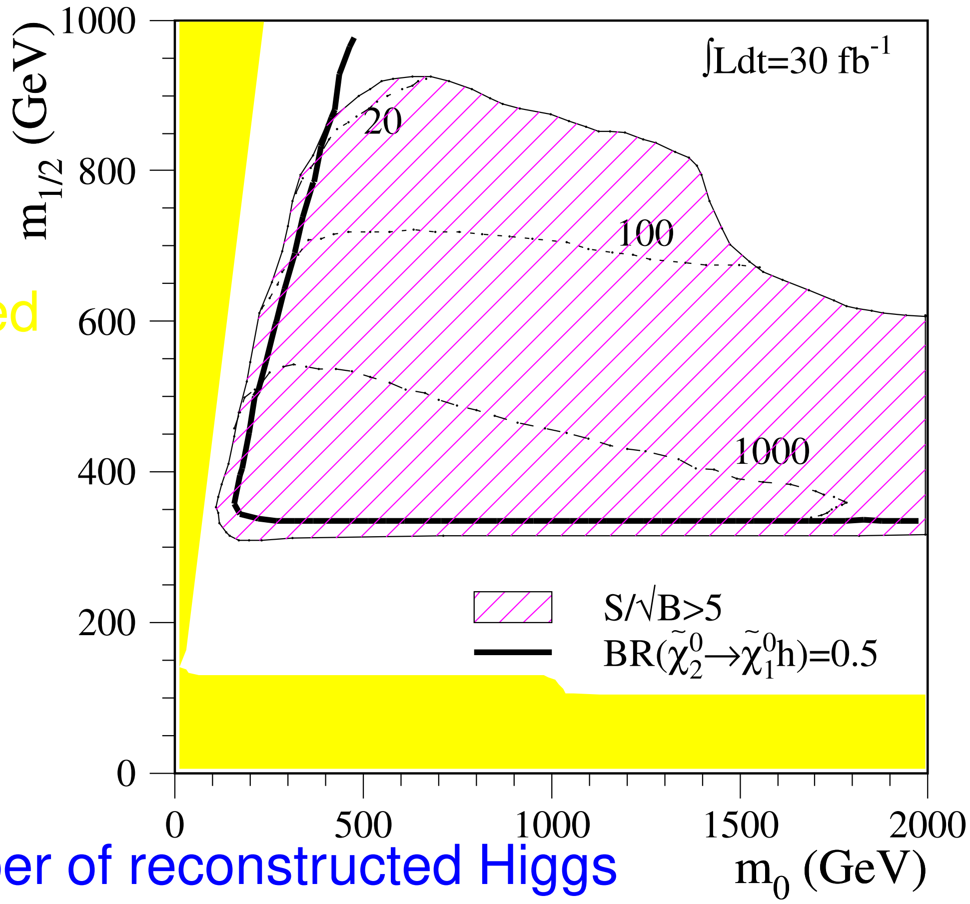
Large Higgs peak
30 fb^{-1}



Very small standard model background (filled histogram)

Dominant background is other SUSY events (dashed)

This method works over a large region of parameter space in the SUGRA Model



Cuts vary
across the plot

.
Yellow region excluded
by current data
Hatched region
has $S/\sqrt{B} > 5$

Contours show number of reconstructed Higgs
Channel is closed at low $m_{1/2}$
Run out of events at large masses ($m(\tilde{g}) \sim 2$ TeV)
interesting SUSY not in this region

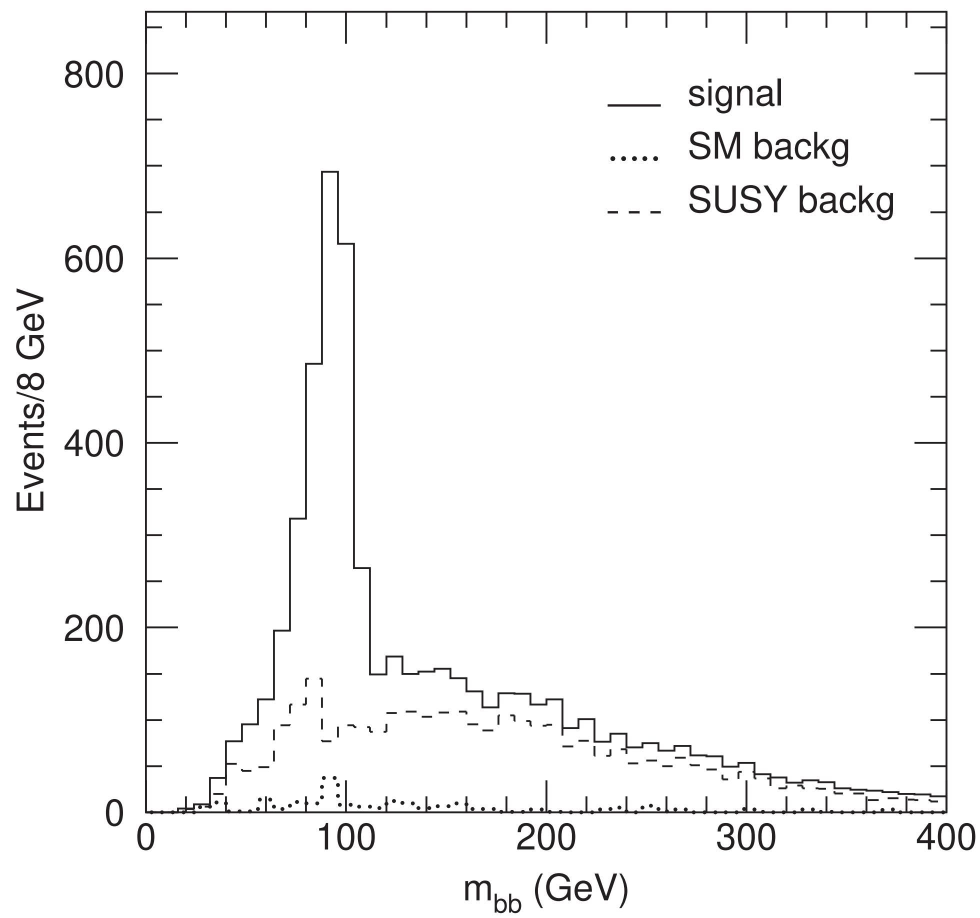
Building on the Higgs

Same $b\bar{b}$ at "SUGRA 5"

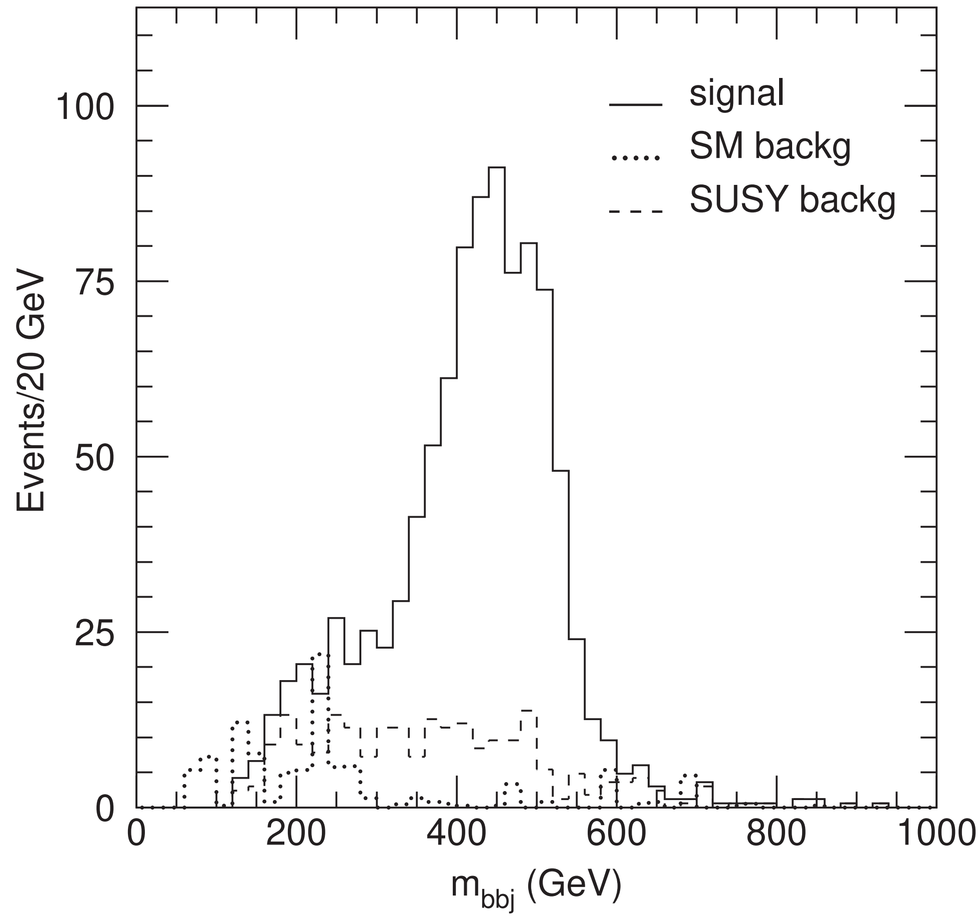
– Lower masses but smaller BR since $\chi_2^0 \to \widetilde{\ell^+}\ell^-$ is significant (see later)

$\Longrightarrow$ more events

30 fb^{-1}



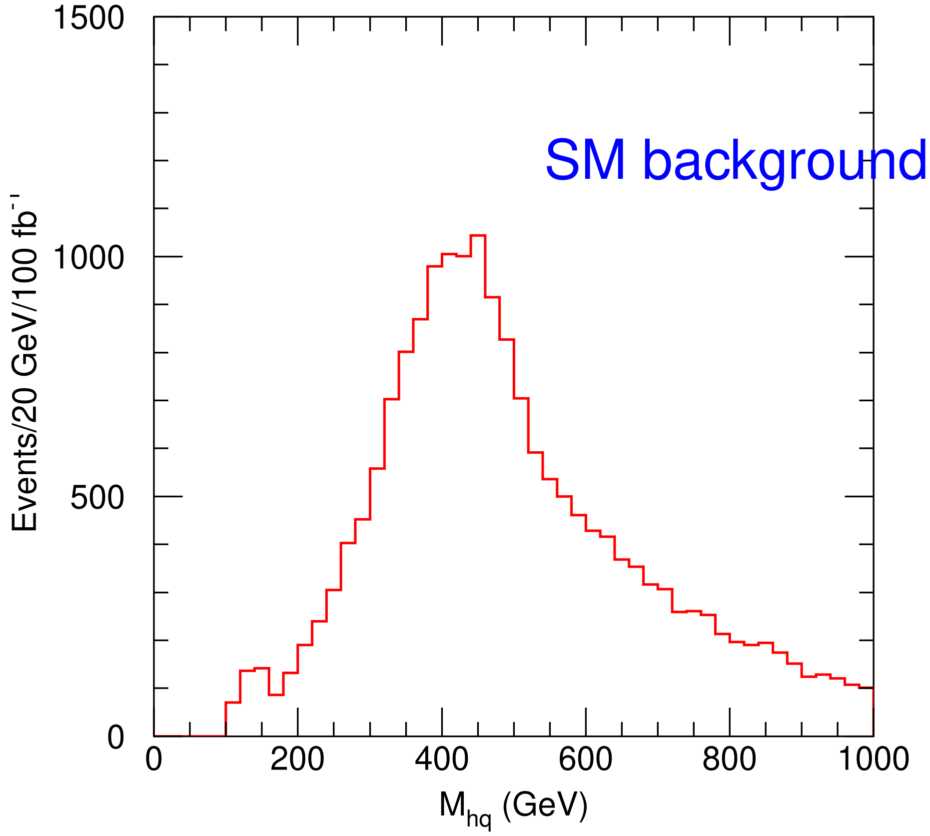
Select $b\bar{b}$ in a 50 GeV window around peak, combine with each of two highest p_T jets. Plot shows lower of two $jb\bar{b}$ masses



Kinematic end point from $\widetilde{q_L} \to q\chi_2^0 \to q\chi_1^0 h$ should be at 552 GeV
3 unknown masses ($\widetilde{q_L}, \chi_2^0$ and χ_1^0) $\Longrightarrow$ need more info or a model

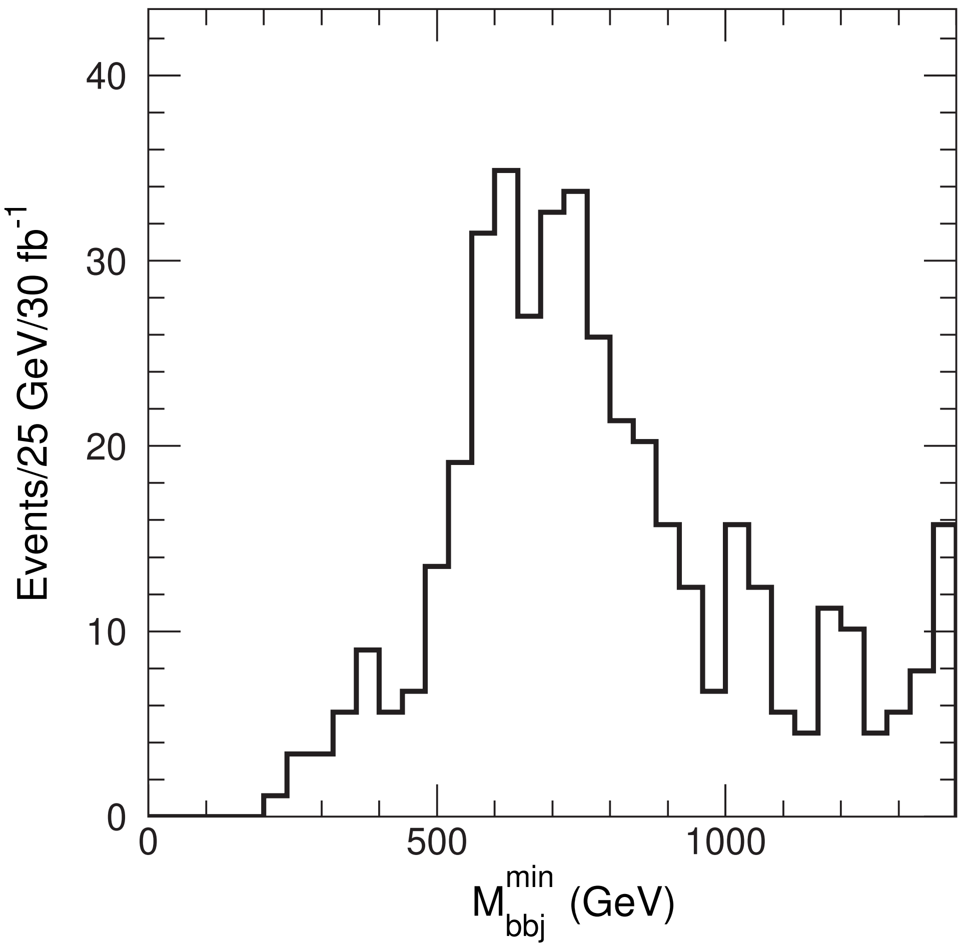
If jets are correctly identified, there is a minimum mass for $jb\bar{b}$ – gives another constraint
Could be distorted by selection cuts. Plot shows larger of $jb\bar{b}$ combinations

SM background not shown (very small)



"threshold" should be at 271 GeV, distorted but visible
Similar technique used by NLC folks

Same plot at “Point1”



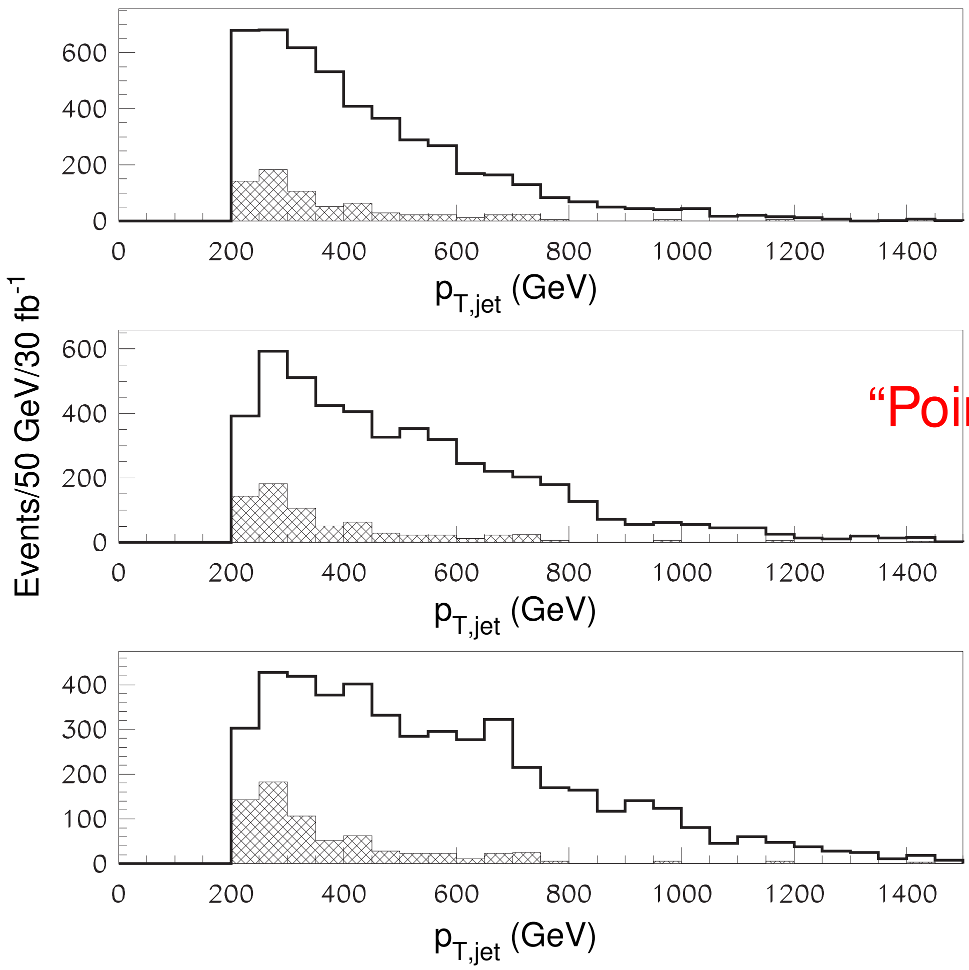
“threshold” should be at 352 GeV

Squarks without Higgs
30 fb^{-1}

Large BR for
$\tilde{q}_r \to \tilde{\chi}_1^0 q$

Pair production
$\Rightarrow$ 2 jets $+\not{E}_T$

- $\not{E}_T > 400 GeV$
- 2 jets
  $p_t > 200$
  $|\ \eta\ |< 2$
- No other jets
  with $p_t > 15$ GeV



$m(\tilde{q}_r) = 750$ GeV

"Point 1" $m(\tilde{q}_r) = 950$ GeV

$m(\tilde{q}_r) = 1150$ GeV

background small (filled hist, mainly other SUSY)

p_t (jet) *shape* is sensitive to $m(\tilde{q}_r)$

Starting with Leptons

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

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

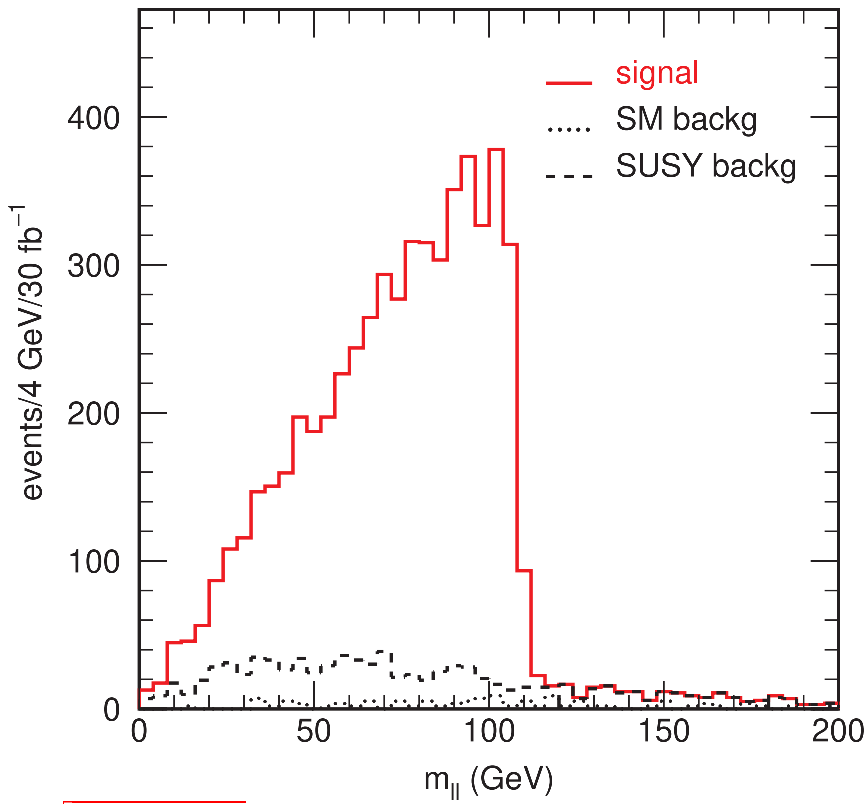
- Former dominates if channel is open
- Decays are important when gauginos are close in mass and Higgs channel is closed
- Leptons are could be all taus (discussed below)

Very good S/B and very precise measurements

Covers region at low $m_{1/2}$ where $\widetilde{\chi}_2^0 \to \widetilde{\chi}_1^0 h$ closed

Example of $\chi_2 \to \tilde{\ell}_R^+ \ell^- \to \chi_1 \ell^+ \ell^-$ – “Point 5”

$\not{E}_T > 300$ GeV; ≥ 2 jets with $p_t > 150$ GeV;
2 isolated opposite sign, same flavor leptons, $p_t > 10$ GeV.
Dilepton mass distribution.

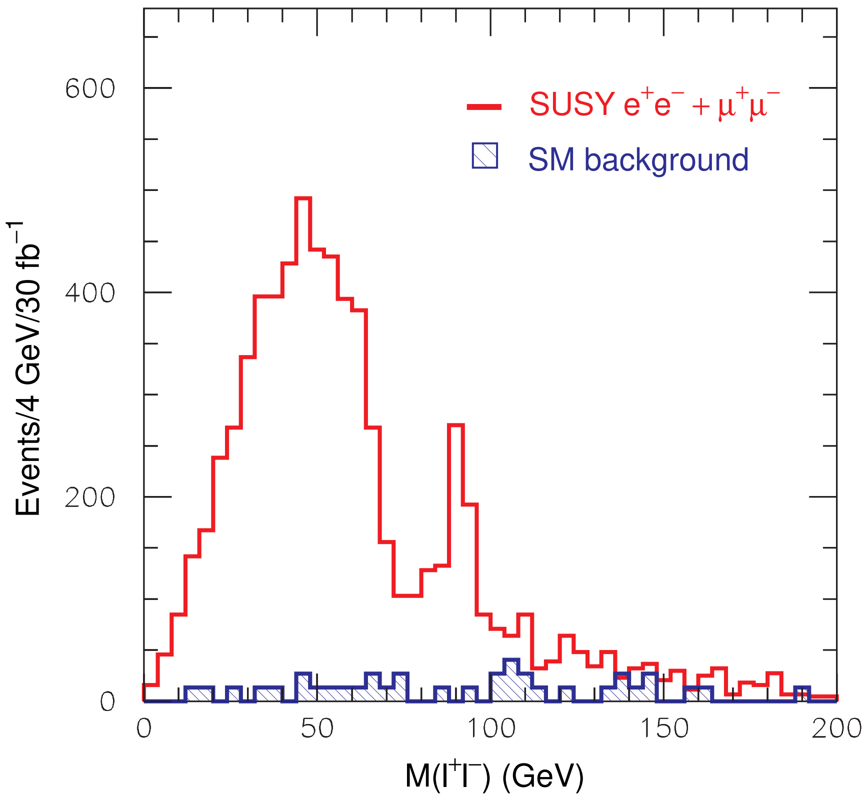


end point at $m_{\chi_2^0}\sqrt{1-\frac{M_{\tilde{\ell}}^2}{M_{\tilde{\chi}_2^0}^2}}\sqrt{1-\frac{M_{\tilde{\chi}_1^0}^2}{M_{\tilde{\ell}}^2}} = 108.1$ GeV

Again very little SM background

“Point4”, more information

Similar event selection



Direct decay $\chi_2 \to \chi_1 \ell^+ \ell^-$ measures $M_{\tilde{\chi}_2} - M_{\tilde{\chi}_1}$

Z peak from $\widetilde{\chi}_i^0 \to \widetilde{\chi}_1^0 Z$

flavor subtraction can elliminate SM background

Leptons and jets – Model independent masses?

Decay $\tilde{q}_L \to q\widetilde{\chi}_2^0 \to q\tilde{\ell}\ell \to q\ell\ell\widetilde{\chi}_1^0$ at “SUGRA 5”

Event selection

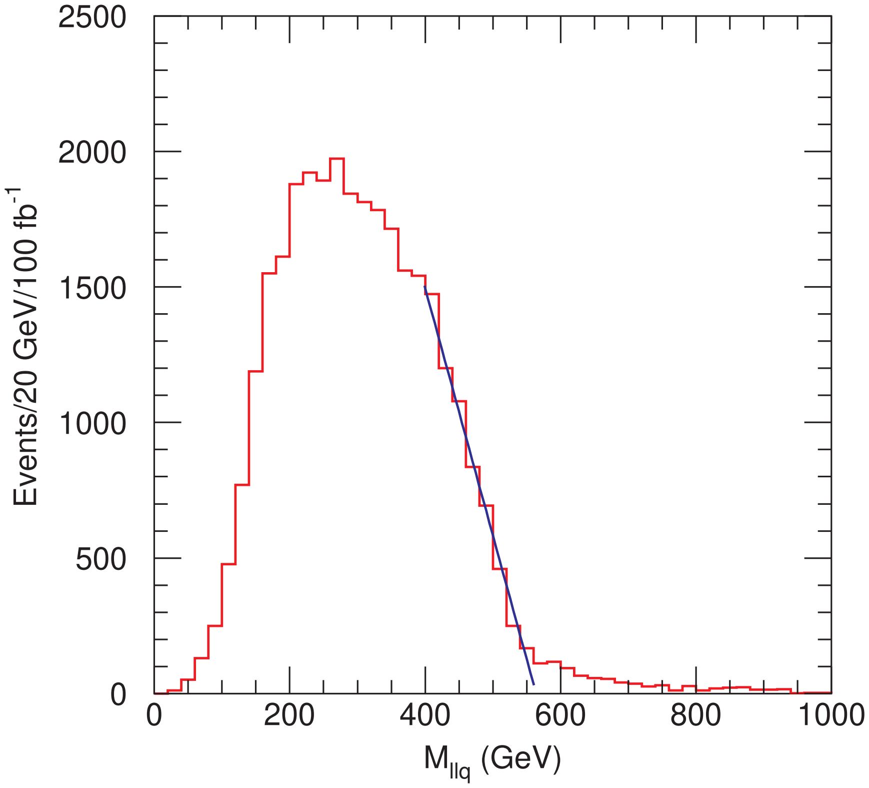
- 2 isolated opposite sign leptons; $p_t > 10$ GeV
- ≥ 4 jets; one has $p_t > 100$ GeV, rest $p_t > 50$ GeV
- $\not{E}_T > max(100, 0.2M_{eff})$

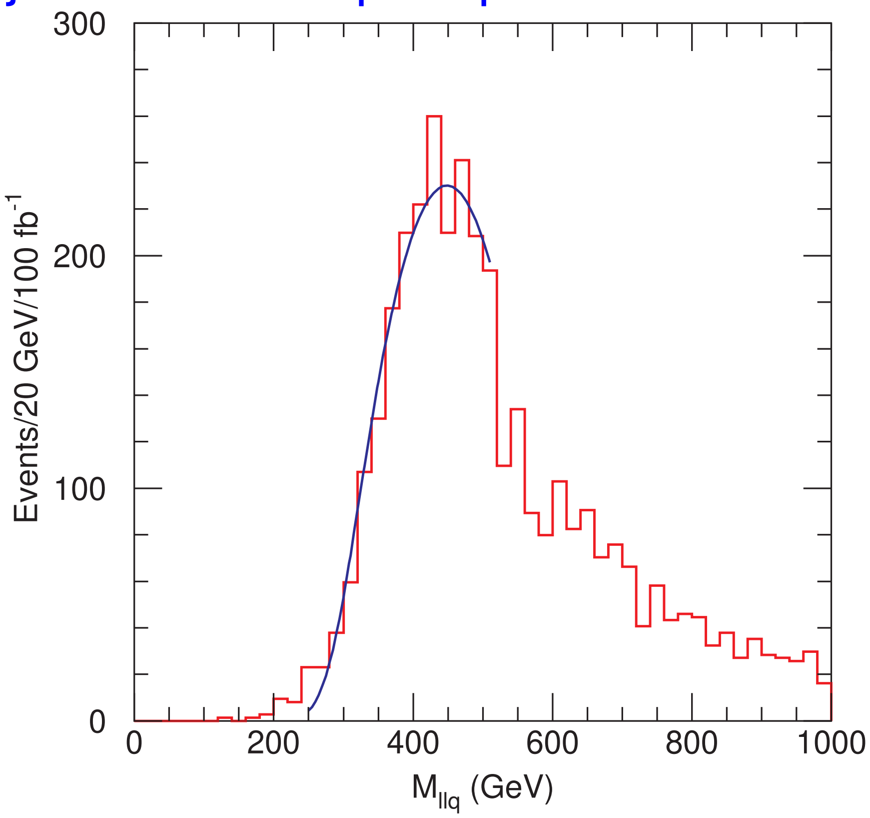
Mass of $q\ell\ell$ system has max at

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

and min at 271 GeV

combine each of the two highest p_t jets with the lepton pair





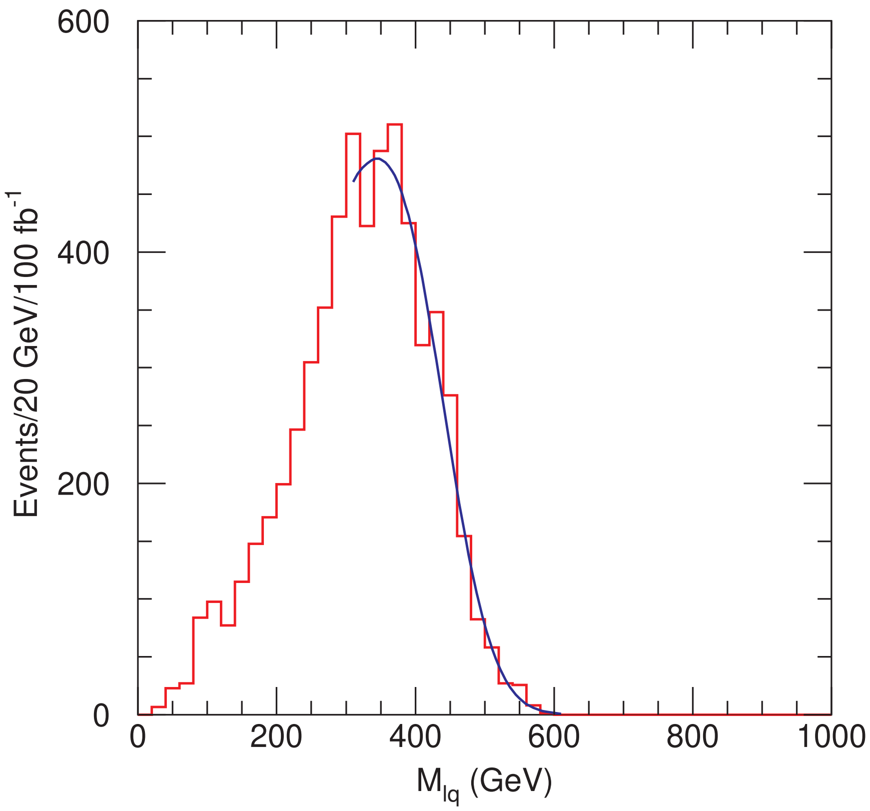
Smaller mass

Both are visible

larger mass ($m_{\ell\ell} > 80$ GeV)

Mass of $q\ell$ system has max at

$$M_{\ell q}^{\text{max}} = \left[\frac{\left(M_{\tilde{q}_L}^2 - M_{\tilde{\chi}_2^0}^2\right)\left(M_{\tilde{\chi}_2^0}^2 - M_{\ell_R}^2\right)}{M_{\tilde{\chi}_2^0}^2}\right]^{1/2} = 479.3\,\text{GeV}$$



Shows ℓq masses if $m_{\ell\ell q} < 600 GeV$

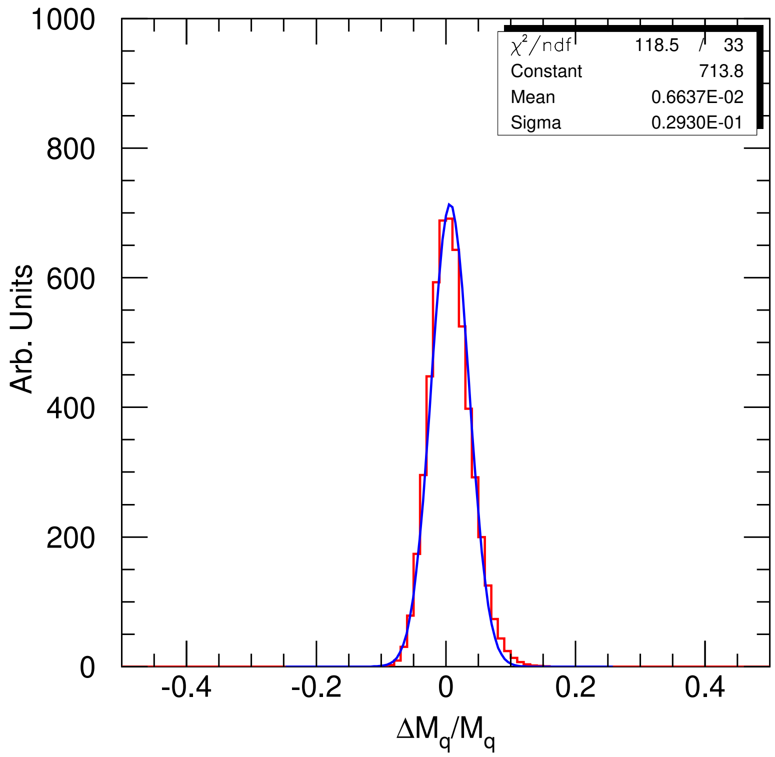
Fit is linear smeared with Gaussian;
gives end at 433 GeV (due to small jet cone used)

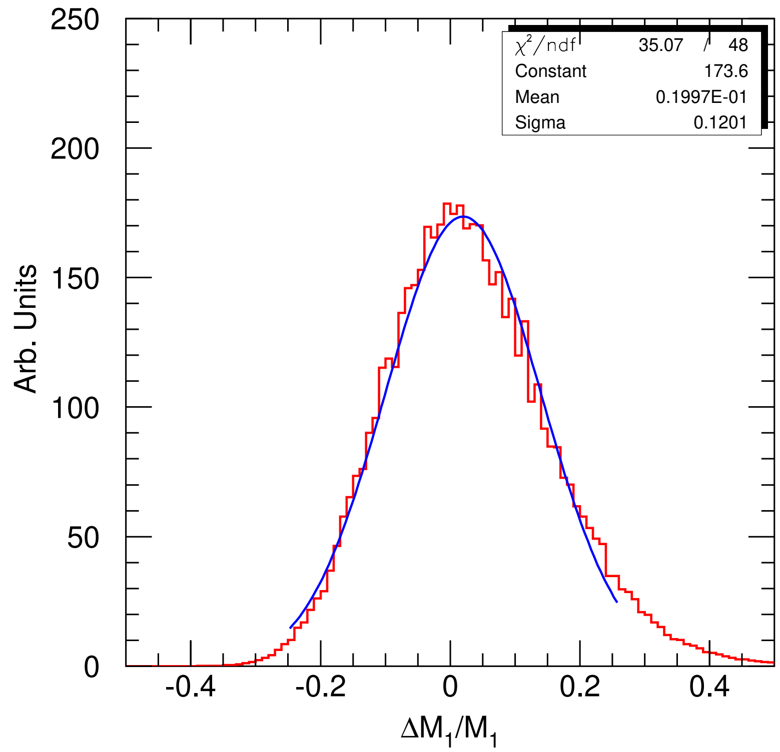
5 constraints, from $hq, lq, llq_{upper}, llq_{lower}, ll$ masses

4 Unknowns, $m_{\tilde{q}_L}, m_{\tilde{e}_R}, m_{\tilde{\chi}_1^0}, m_{\tilde{\chi}_2^0}$

Should be able to determine masses without a model

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





. squark mass $\tilde{\chi}_1^0$ mass

Direct Slepton production

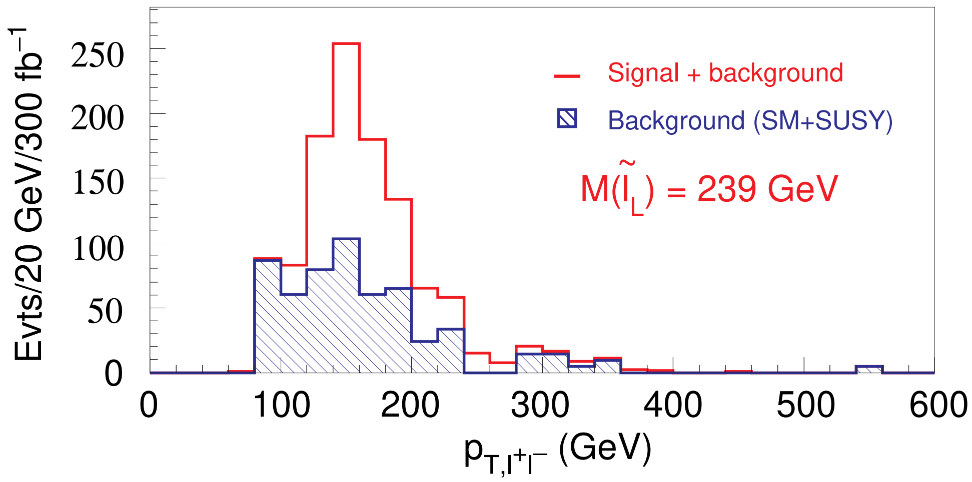
If sleptons are not produced in squark/gluino decay must rely on direct production

- Low rate.
- Must use jet veto to reduce background
- Hardest case is where some sleptons are produced in SUSY decays and must find the others

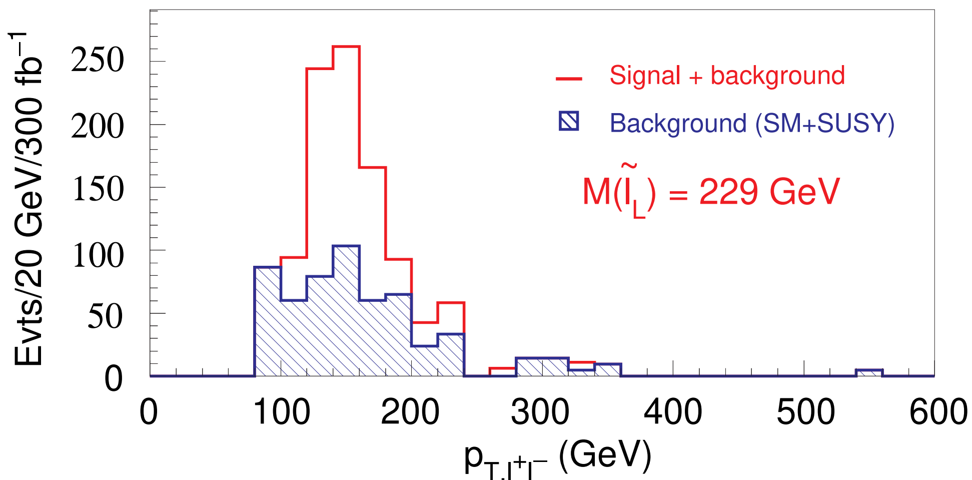
Example $\tilde{\ell}_L$ at "Point 5"; look for $\tilde{\ell}_L \to \ell \widetilde{\chi}_1^0$
Huge background from previous stuff ($\tilde{\ell}_R$)

- 2 same flavor, opposite sign leptons
- No jets with $p_t > 40$ GeV

Sensitivity to mass from shape of p_t distribution of lepton pair



Nominal mass



SUSY background dominates

Full Luminosity needed, masses must be below ~ 350 GeV

Hold everything

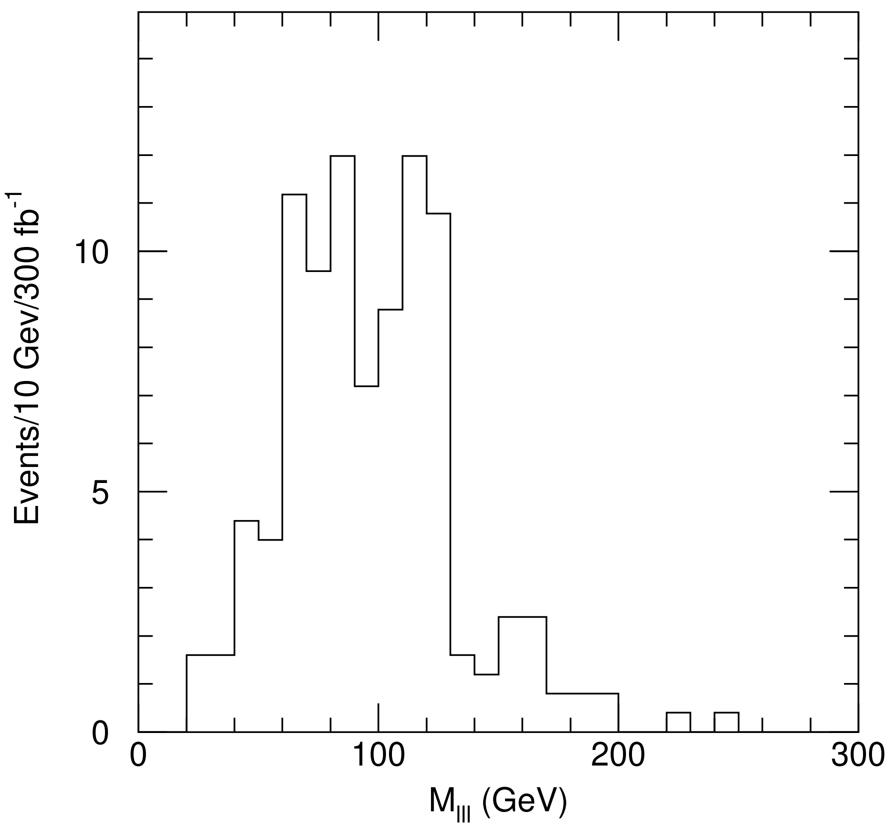
We changed the mass of one particle and did nothing else. Is this sensible?

You must look at everything

As mass goes up new channel opens $\widetilde{e_L} \to \widetilde{\chi}_2^0 e \to e\mu^-\mu^+\widetilde{\chi}_1^0$

- 4 isolated leptons, $p_t > 10$ GeV making two flavorless pairs
- No jets with $p_t > 40$GeV
- $M(pair) < 108$ GeV (to pick the $\widetilde{\chi}_2^0$ decay)

Plot of mass of three lepton system



$m(\tilde{e_L}) = 250$ GeV

No signal at $m(\tilde{e_L}) = 229$ GeV

No background and a clearer structure.

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

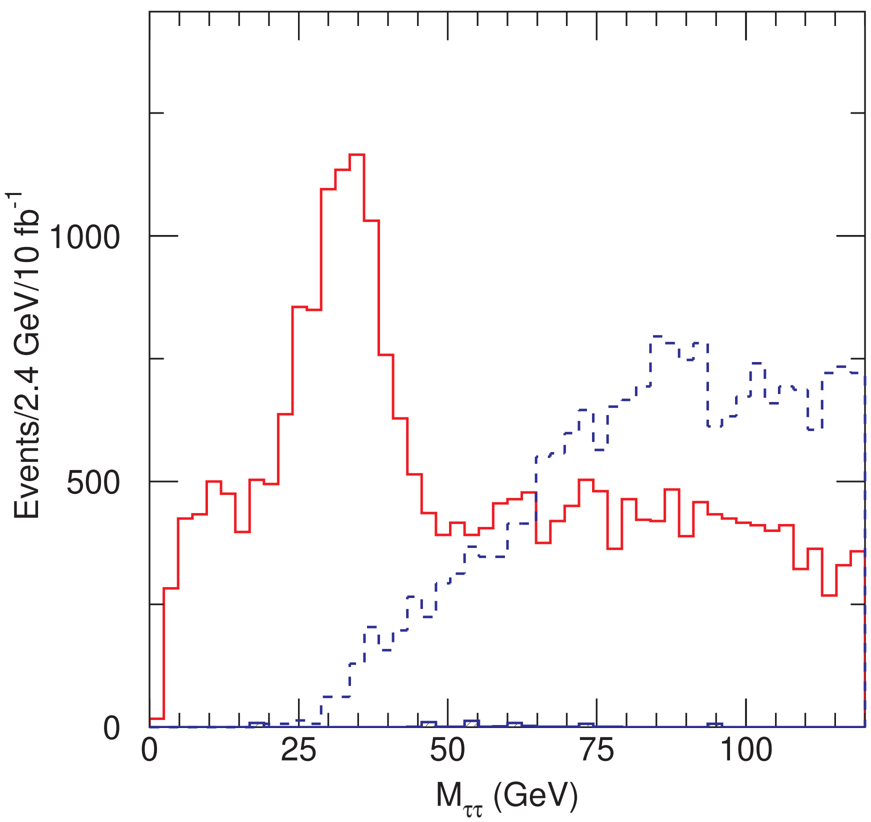
Measure “visible” tau energy

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

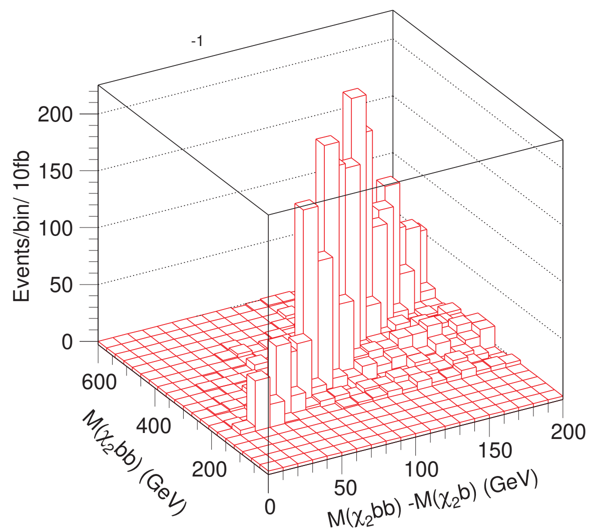
$$\tilde{g} \to b\tilde{b} \to bb\tau^{\pm}\tau^{\mp}\tilde{\chi}_1^0$$

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

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

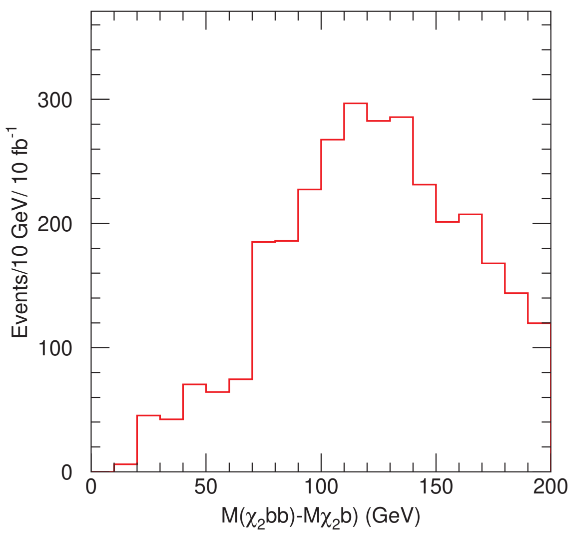
- Select $40 < m_{\tau\tau} < 60$ GeV
- Combine with b jets
- Look at $\tau\tau bb$ and $\tau\tau b$: should approximate gluino and sbottom
- use partial reconstruction technique assuming mass of $\tilde{\chi}_1^0$

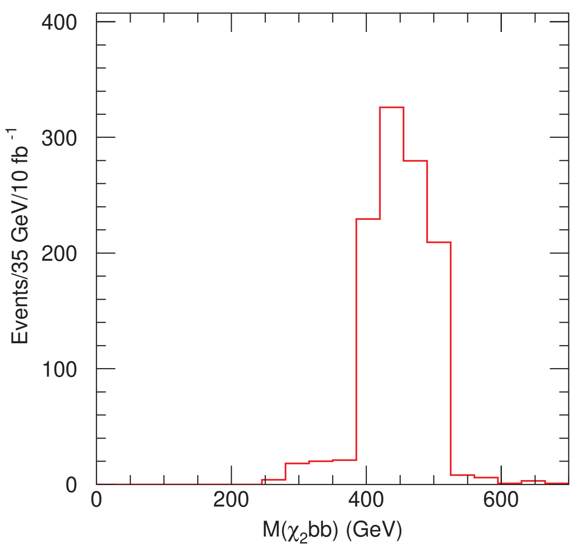
Peaks are low; should be expected due to missing energy



.

plot of $m(\tilde{\chi}_2^0 bb)$ vs $m(\tilde{\chi}_2^0 bb) - m(\tilde{\chi}_2^0 b)$
projections





gluino-sbottom
should be 160 GeV

gluino
540 GeV

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

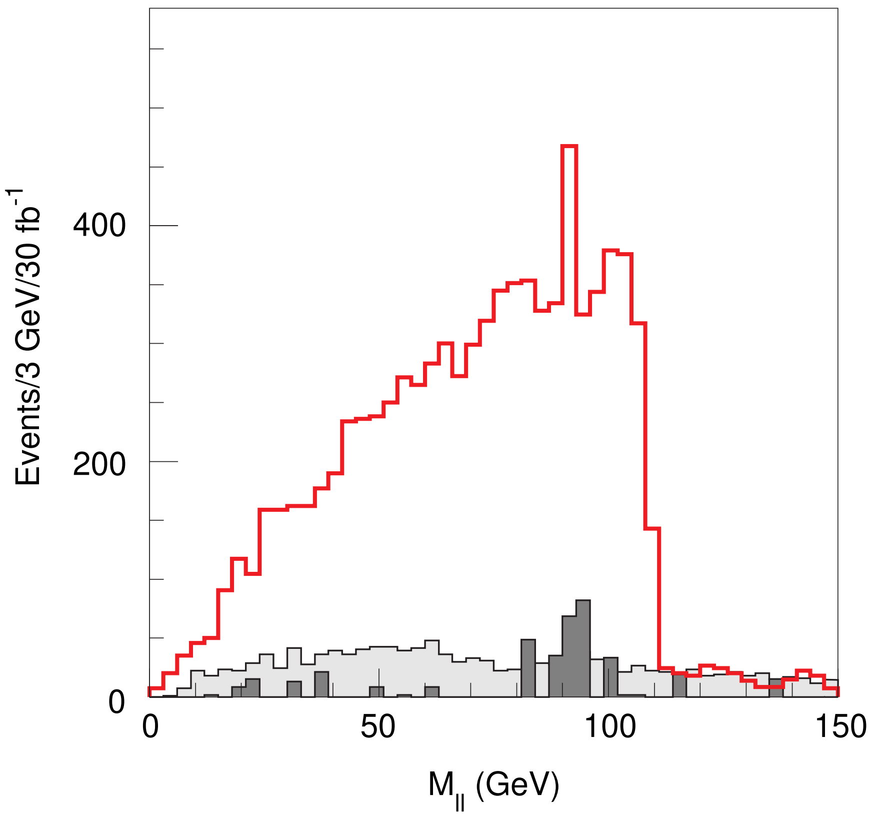
First case is hardest, Global S/B is worse due to less $\not\!\!E_T$

Example, SUGRA "Point 5" 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

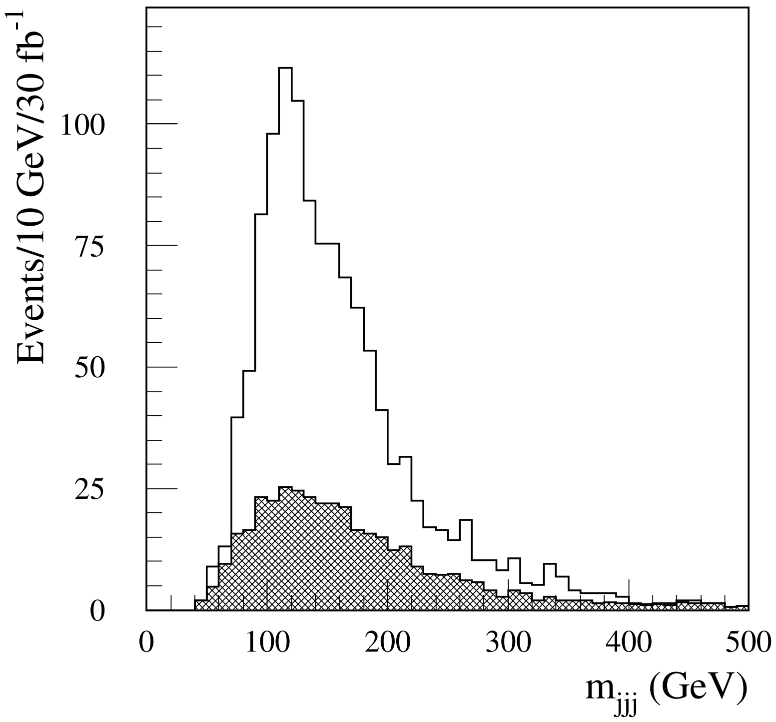
Dilepton mass still shows clear structure with small background from $\widetilde{\chi}_2^0 \to \ell^+\ell^-\widetilde{\chi}_1^0$



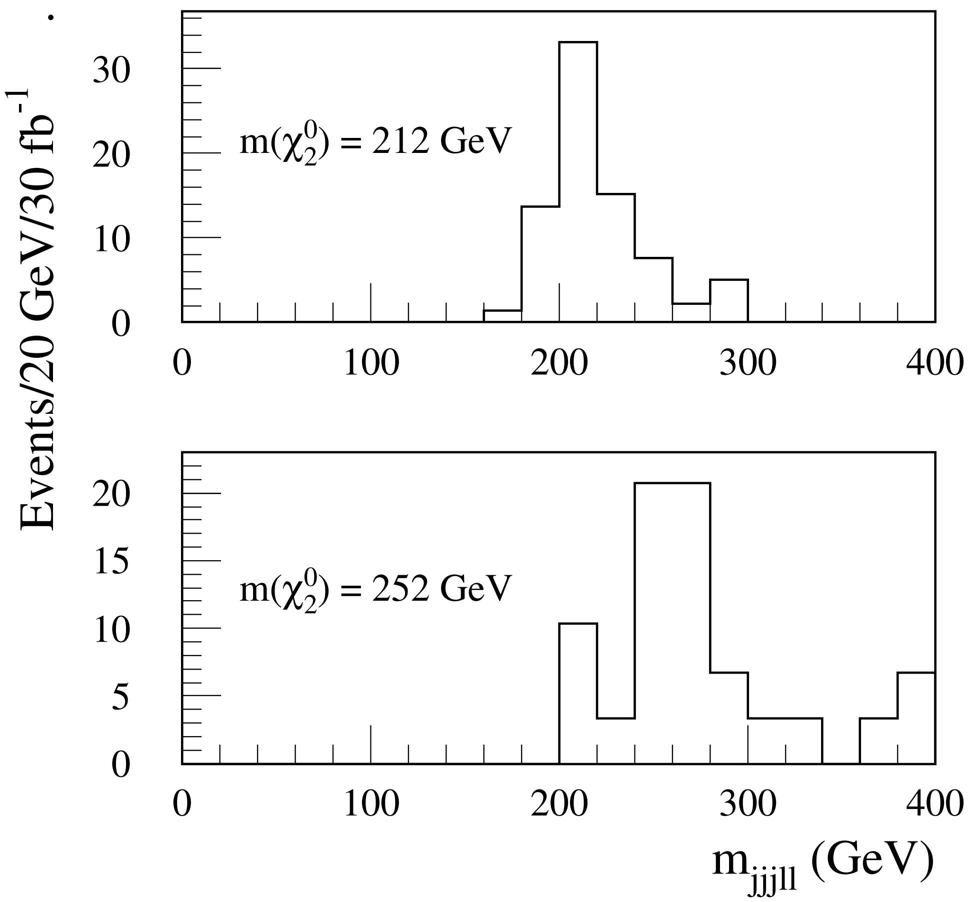
As nothing is lost, should be possible to reconstruct $\tilde{\chi}_1^0$
Difficult because jet multiplicity is very high and $\tilde{\chi}_1^0$ mass is usually small, so jets are soft

- ≥ 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
SM background
significant



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)

New signals in GMSB

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

Either neutral

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

$\Rightarrow$ extra photons ("G1a") or similar signals to SUGRA ("G1b") 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

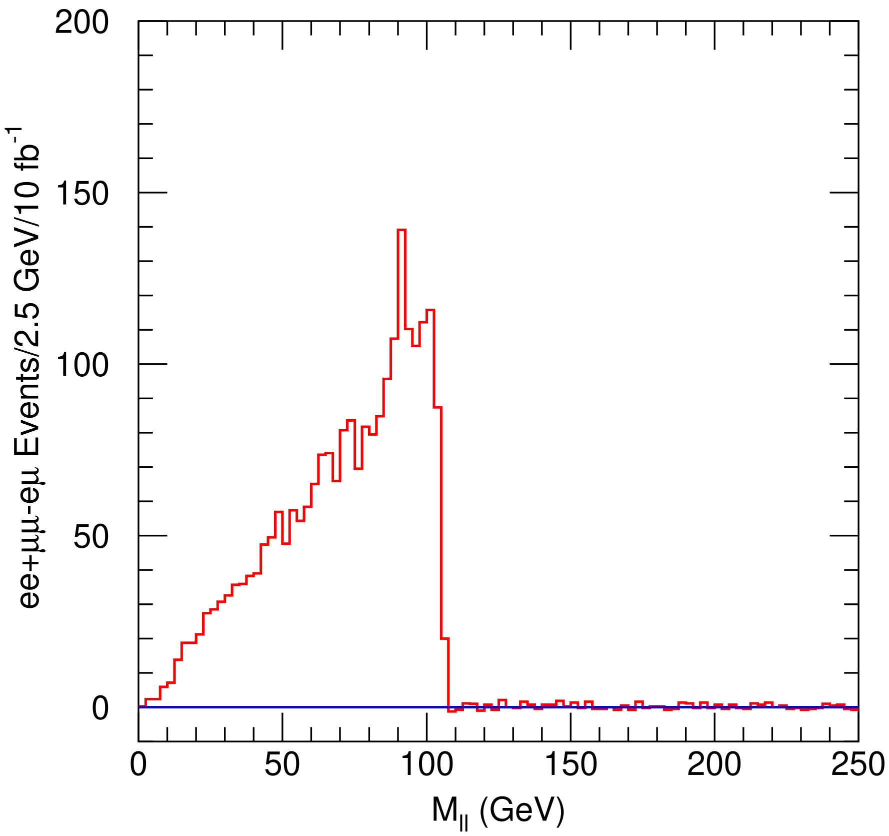
- $M_{\text{eff}} > 400$ GeV;
- $\not{E}_T > 0.1 M_{\text{eff}}$.

Looking for

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

- Electrons and photons : $p_T > 20$ GeV
- Muons : $p_T > 5$ GeV.
- Require at least 2 photons and two leptons.

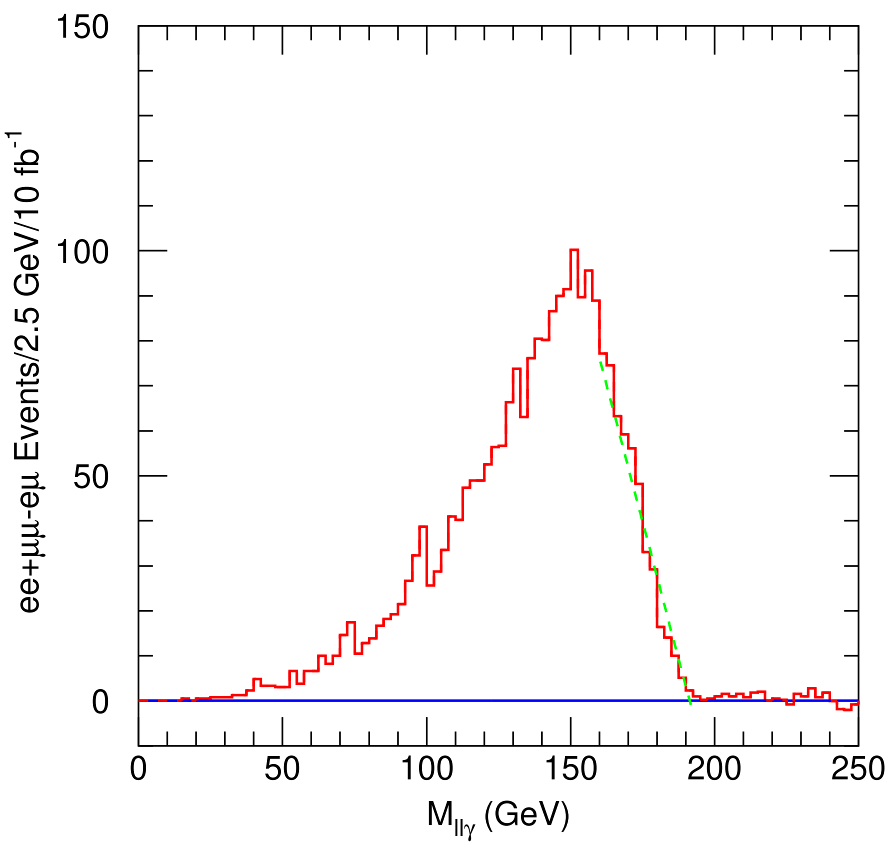
Dilepton mass distribution, flavor subtracted $e^+e^- + \mu^+\mu^- - e^\pm\mu^\mp$



End is at

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

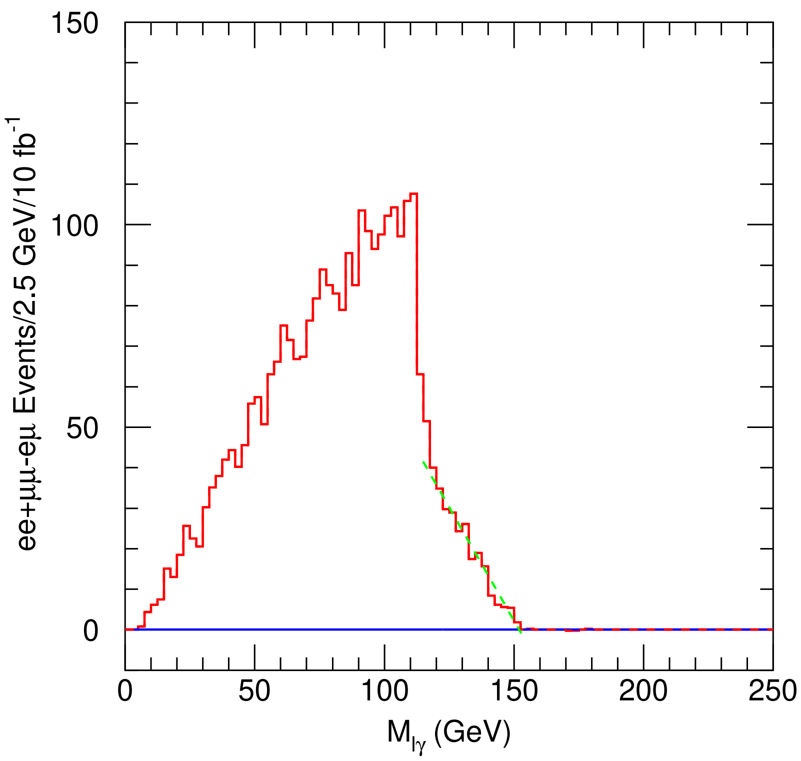
Form $\ell^+\ell^-\gamma$ mass and take smallest combination



Linear vanishing at

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

Form $\ell^{\pm}\gamma$ mass also



Two structures at

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

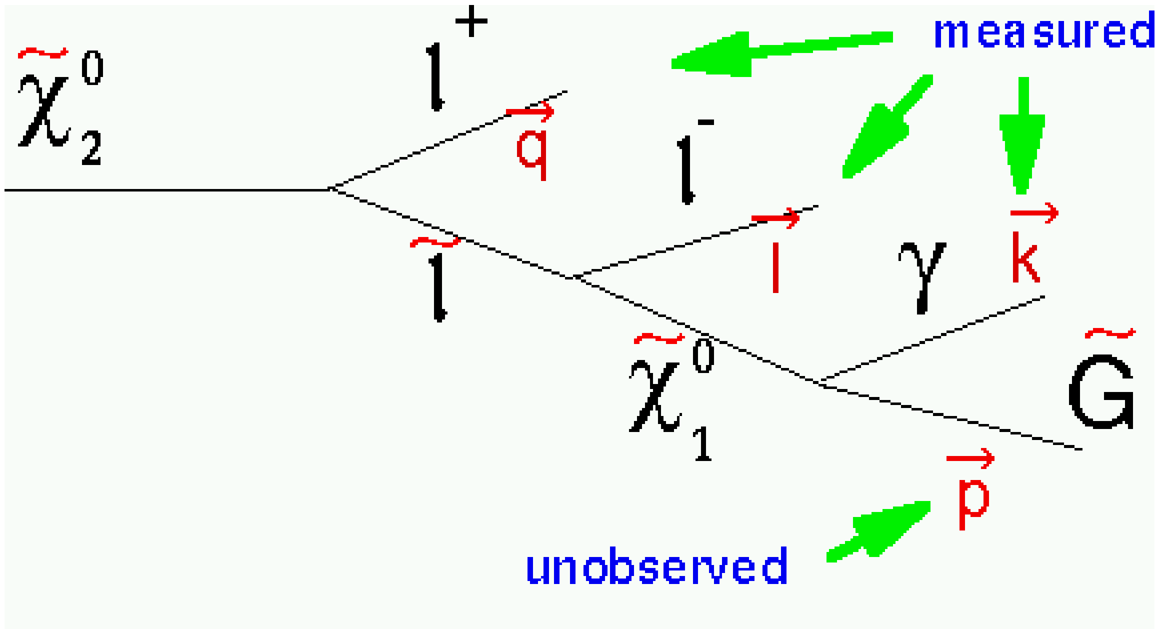
and

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

These four measurements are sufficient to determine the masses of the particles ($\widetilde{\chi}_2^0$, $\tilde{\ell}_R$, 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!

Full reconstruction of SUSY events



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

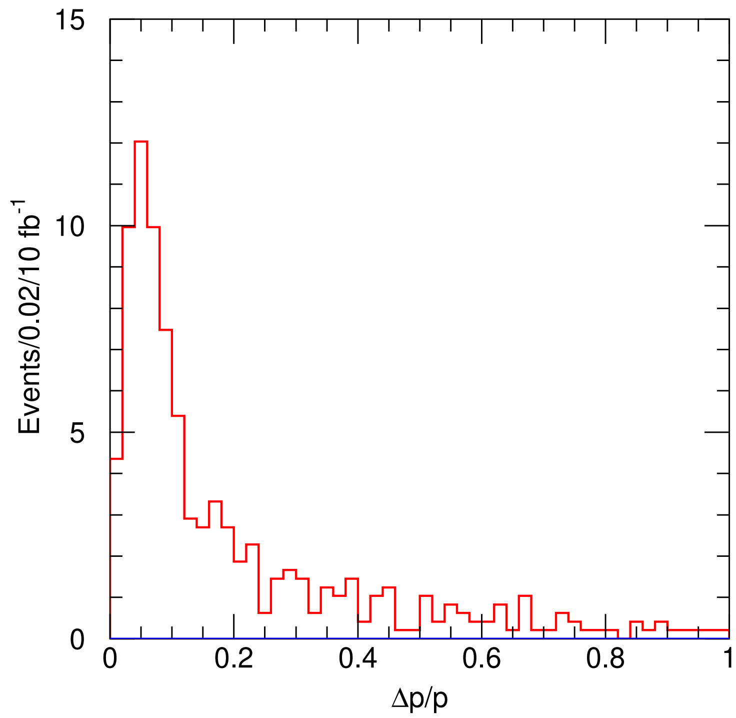
$$\begin{aligned}
2p_0k_0 - 2\vec{p}\cdot\vec{k} &= M^2_{\tilde{\chi}^0_1} \\
2p_0l_0 - 2\vec{p}\cdot\vec{l} &= M^2_{\tilde{\ell}_R} - M^2_{\tilde{\chi}^0_1} - 2k\cdot l \\
2p_0k_0 - 2\vec{p}\cdot\vec{q} &= M^2_{\tilde{\chi}^0_2} - M^2_{\tilde{\ell}_R} - 2(k+l)\cdot q
\end{aligned}$$

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

- $\tilde{q} \to \widetilde{g} q \to \widetilde{\chi}_2^0 \overline{q} q q$
- Require at least 4 jets with $p_T > 75\,\mathrm{GeV}$

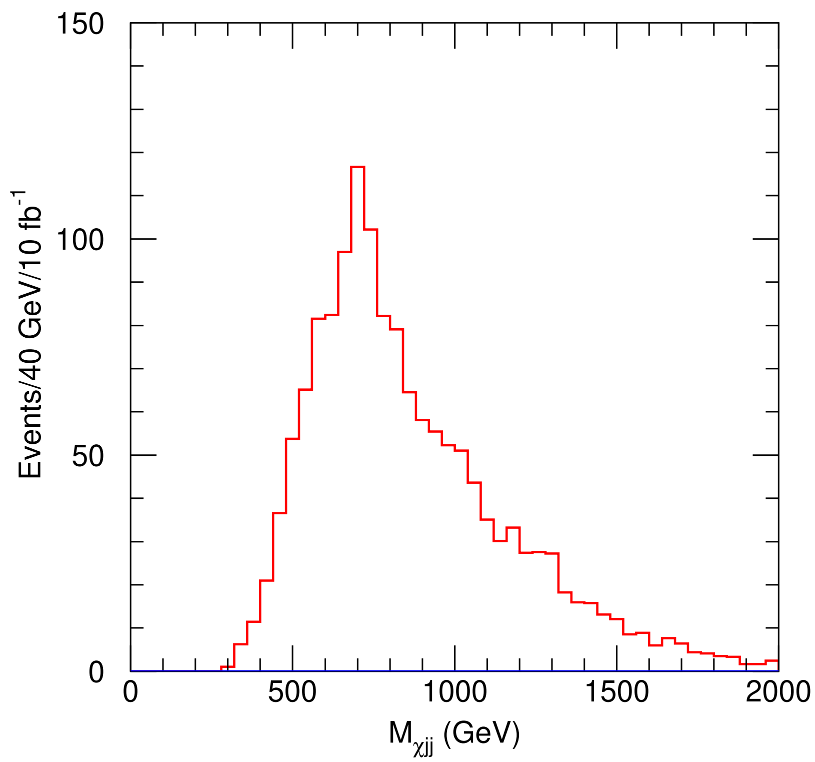
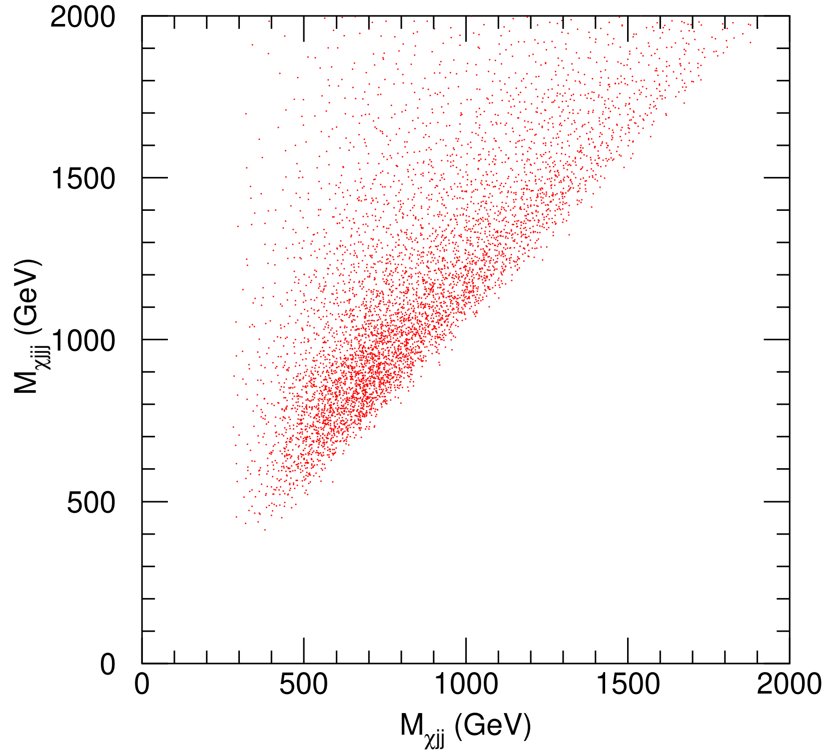


Figure shows mass of $\widetilde{\chi}_2^0$+2 jets;
peak is below gluino mass (747 GeV);
no correction applied for small jet cone.

Look for correlations

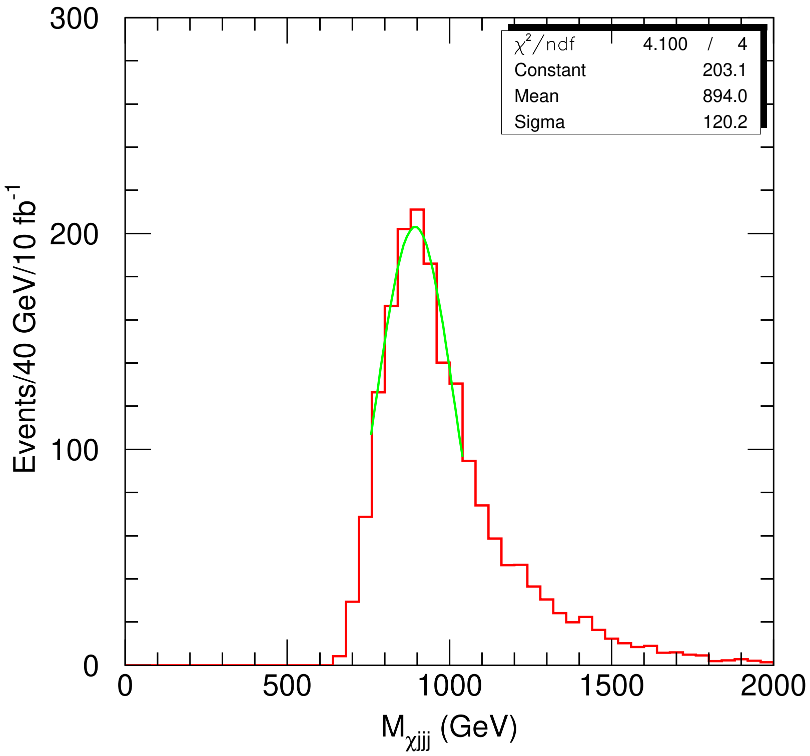
$\tilde{\chi}_2^0$+3 jets



$\tilde{\chi}_2^0$+2 jets

Peaks clearly visible in projections

Cut $600\ \mathsf{GeV} < M(\tilde{\chi}_2^0 jj) < 800\ \mathsf{GeV}$
Project



Peak below Squark mass (940 GeV)
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 ($\sim$few-K events)
- No detailed study

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

- Angular resolution of photons from primary vertex $\Delta\theta \sim 60mr/\sqrt{E}$
- 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

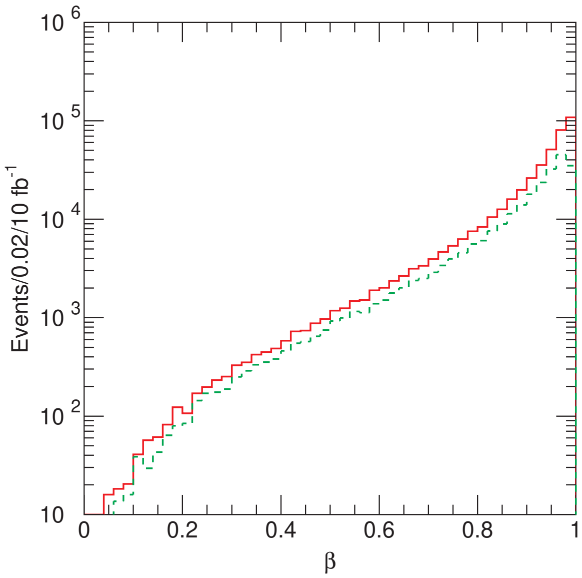
Mass measurement of quasi-stable sleptons

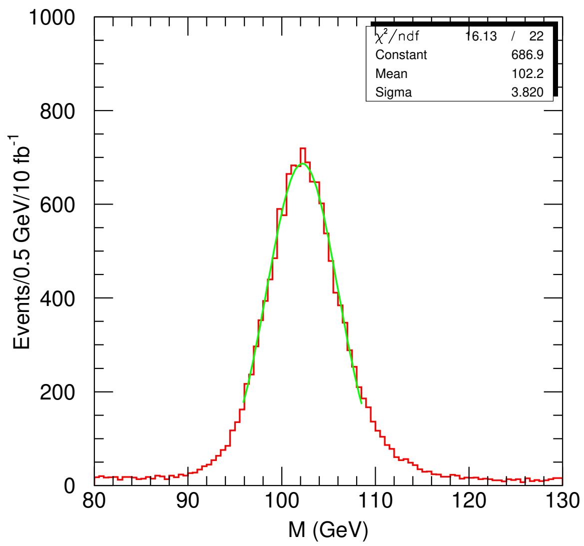
Sleptons are produced at the end of decay chains $\Rightarrow$ large velocity

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 $\qquad$ $\Delta M/M$

What precision can one expect?

Depends whether fitting individual masses or a model; ultimately it will be the latter.

Qualitative signals will rule out classes of models *e.g*

- Stable heavy charged particle $\Rightarrow$ not SUGRA
- No missing $E_T \Rightarrow$ not unbroken R-Parity

Where events are fully reconstructed, masses are *measured directly* and then *masses are fitted to model*

Other cases need a guess of the model and then a fit to it

Examples of easy and hard cases
– Warning – only naive fits have been done,
event rates are not used,
multivariate fits to distributions have not been used

Easy case– "G1a" (30 fb^{-1})

$\tilde\chi_1^0 \to \tilde G \gamma$ with short lifetime.

- $M_{\tilde\chi_2^0}\sqrt{1-\left(\frac{M_{\tilde\ell_R}}{M_{\tilde\chi_2^0}}\right)^2}\sqrt{1-\left(\frac{M_{\tilde\chi_1^0}}{M_{\tilde\ell_R}}\right)^2} = 105.1 \pm 0.10$ GeV ,
  - $\sqrt{M^2_{\tilde\chi_2^0} - M^2_{\chi_1^0}} = 189.7 \pm 0.30$ GeV,
  - $\sqrt{M^2_{\ell_R} - M^2_{\chi_1^0}} = 112.7 \pm .15$ GeV
  - $\sqrt{M^2_{\chi_2^0} - M^2_{\ell_R}} = 152.6 \pm .30$ GeV
  - $m_{h^0} = 109.47 \pm 3$ GeV,

First 4 determine masses directly and imply

- $\Lambda = 90000 \pm 1700$ GeV,
- $M_m = 500000 \pm 170000$ GeV,
- $\tan\beta = 5.0 \pm 1.3$,
- $N_5 = 1 \pm 0.014$.

Note that measured squark and gluino masses do not improve accuracy, they provide strong consistency checks.

A bit harder "G1b"

$\tilde{\chi}_1^0 \to \tilde{G}\gamma$ with long lifetime; no photons visible
qualitatively similar to SUGRA.

- $M_{\tilde{\chi}_2^0}\sqrt{1-\left(\frac{M_{\tilde{\ell}_R}}{M_{\tilde{\chi}_2^0}}\right)^2}\sqrt{1-\left(\frac{M_{\tilde{\chi}_1^0}}{M_{\tilde{\ell}_R}}\right)^2} = 105.1 \pm 0.10$ GeV,
  - $m_{\tilde{g}} - m_{\tilde{\chi}_2^0} = 523 \pm 30$ GeV; $m_{\tilde{q}_R} = 990 \pm 50$ GeV
  - $m_{h^0} = 109.47 \pm 3$ GeV,

Note squark mass is needed as first is not sensitive to $m(\tilde{e_L})$!

- $\Lambda N_5 = 90000 \pm 880$ GeV,
- $\Lambda = 90000 \pm 11500$ GeV,
- $M_m < 7 \times 10^8$ GeV (95% confidence)
- $\tan\beta = 5.0^{+2.7}_{-1.8}$

These "data" cannot be fit to SUGRA model

A tough case "SUGRA 2"

m_0 is poorly constrained as we have no slepton signal ($m > 430$ GeV)
All sparticles are heavy – gluinos and squarks $\sim$ 1 TeV

- $m_0 = 400 \pm 100$ GeV
- $m_{1/2} = 400 \pm 8$ GeV
- $\tan\beta = 10. \pm 2.$
- A is not constrained; it's an "irrelevant" parameter
- $A_b = -1100 \pm 200$ GeV and $A_t = -800 \pm 55$GeV

Are we in a model?

General discussion impossible

Use a Model and add parameters asking how well they can be constrained.

"SUGRA Point 5" 30 fb^{-1}

- $m_0 = 100^{+4.1}_{-2.2}$ GeV
- $m_{1/2} = 300 \pm 2.7$ GeV
- $\tan\beta = 2. \pm 0.1$

Soft Higgs masses differ at GUT scale, can only constrain $M_H < 400$ GeV; Must measure H and A (630 GeV) masses to 20 GeV in order to improve.
Very hard.

Relax squark/slepton mass unification, assume different SU(5) reps have different masses: $m_{d_R} = m_L = m_5$; rest m_0
above errors increase a bit and $m_5 = 100^{+15}_{-10}$ GeV

Where might we be? A guess at what LHC will do

- Find SUSY or stop people taking about it
- Measure gluino and squark masses to a few percent
- Measure some Slepton masses
- Measure $\widetilde{\chi}_1^0$ mass ????
- Severely constrain the underlying model
- Best case – all sparticle masses predicted with small errors
- Worse case – a few masses well known, rest inferred with big errors
- Model independent limits are hard

A guess at what LHC will not do

- Find sleptons with mass $\geq\sim 300$ GeV unless they are present in squark/gluino decays
- Find the Heavier gauginos unless they are produced in squark/gluino decay
- Find all of the Higgs Bosons