SUSY at Hadron Colliders

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Outline

- Models and Signatures
- LHC
- Tevatron (a few remarks)
- Future colliders – when to give up.

All plots from ATLAS simulations unless otherwise noted

Models and Signatures

Will discuss model with minimal particle content
Two Higgs doublets (H_1 and H_2) and SUSY partners for SM fields plus Gravitino

Most general model has many parameters
- SUSY breaking masses for scalars(m_0) and gauginos ($M_{1/2}$)
- SUSY conserving μ parameter $(\mu H_1 H_2)$
- Soft A and B terms – $B\mu H_1 H_1$ and LEH_2 $etc.$

Trilinear term A, important only for 3^{rd} generation as in enters scaled by Yukawas
- M_Z is given in terms of these.

R parity – neutral LSP stable – all events have 2 LSP's in them $\Rightarrow$ missing E_T and pair production of sparticles
Sensible Model has far few parameters
Masses cannot be too high or SUSY is irrelevant to EWSB

Hadron Production of Sparticles

LHC is likely to be above threshold for many sparticles

A consistent model must be used for simulation. Most popular is SUGRA

Unification all scalar masses (m_0) at GUT scale

Unification all gaugino masses ($m_{1/2}$) at GUT scale

Universal A and B

$\mid \mu \mid$ and B are traded off for M_Z and $\tan\beta = v_1/v_2$

So five parameters $\tan\beta = v_1/v_2 \ sign(\mu) \ A$, $m_{1/2}$ and m_0 gives full mass spectrum and decays

Gluino mass strongly correlates with $m_{1/2}$, slepton mass with m_0.

Studies have also been done for Gauge, Anomaly mediated, and R-Parity breaking models.

Enough cases have now been studied that given a complete set of masses and decay rates, we can usually estimate what can be done at LHC.

SUSY in hadron colliders

Inclusive signatures provide evidence up to $2.5\ \mathrm{TeV}$ for squarks and gluinos.

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.

Makes studies somewhat complicated and general conclusions difficult to draw.

LHC 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.

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

Full program difficult to estimate, depends on masses and branching ratios

Characteristic SUSY signatures at hadron colliders

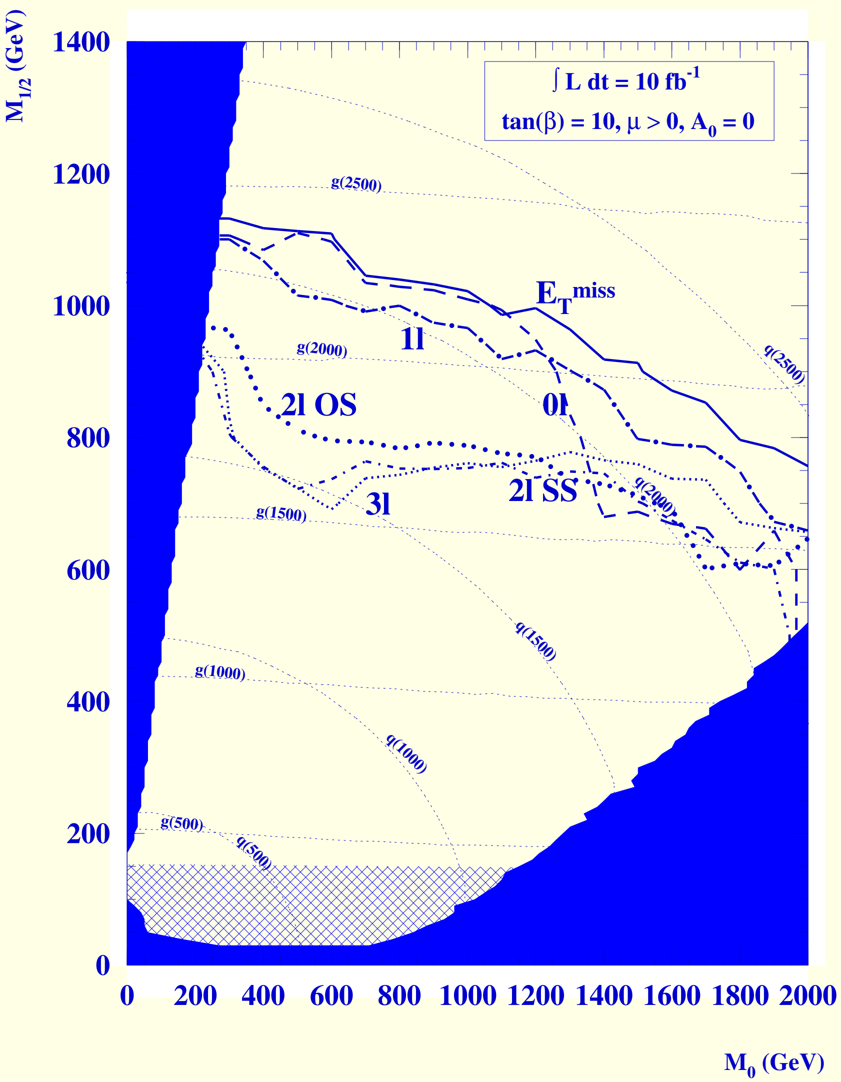
Not all present in all models

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

N.B.Production of heavy objects implies subset these signals
Important for triggering considerations in hadron colliders

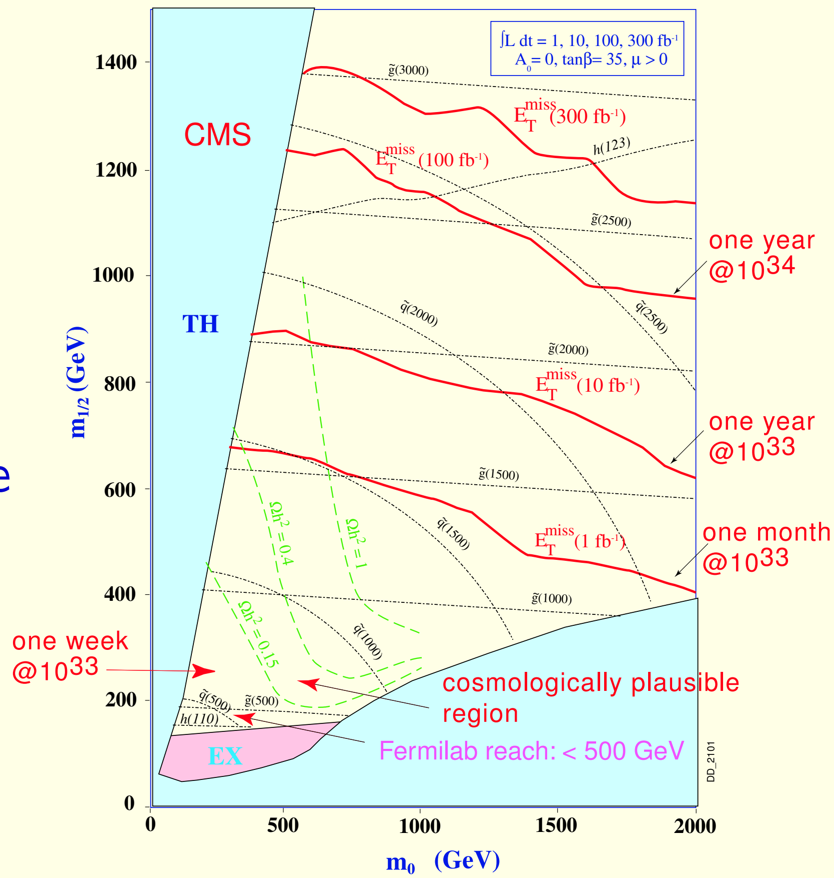
Inclusive analysis at LHC

These studies tend to be conservative



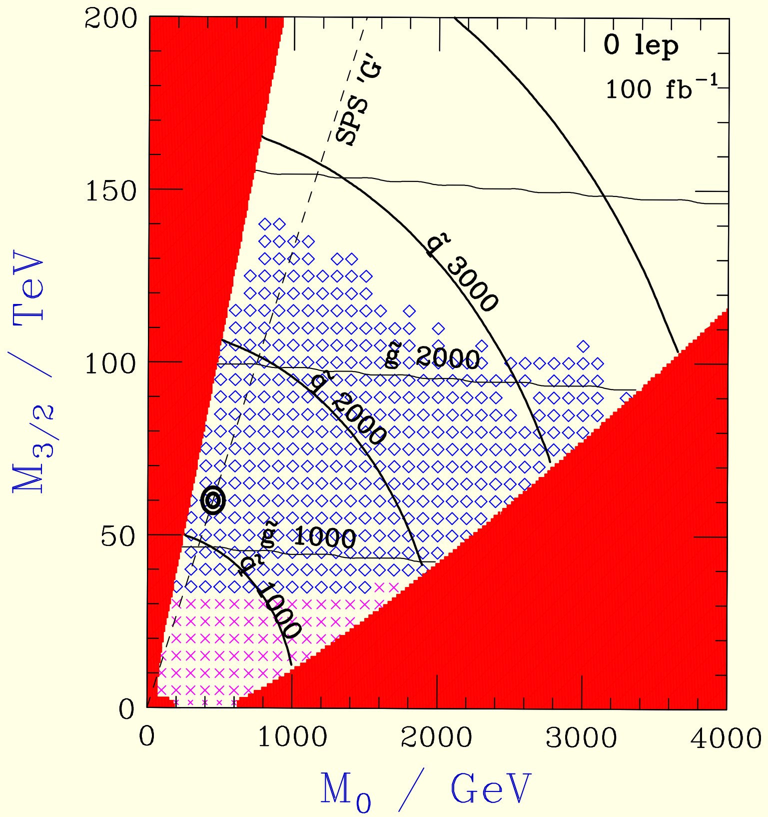
Reach is shown for various inclusive signals
Jets plus missing E_T
Multileptons of same and opposite sign
Shown for SUGRA
Shaded regions excluded by theory or LEP
Extends to gluino masses of over 2 TeV for 10fb^{-1}

Plot shows evolution of reach with luminosity
Notice that a few $\mathbf{0.1}\mathrm{fb}^{-1}$ covers most of the region favored by fine tuning arguments



Catania 18

Reach is similar in other models
Example of anomaly mediated model
Shaded pink region is excluded by LEP



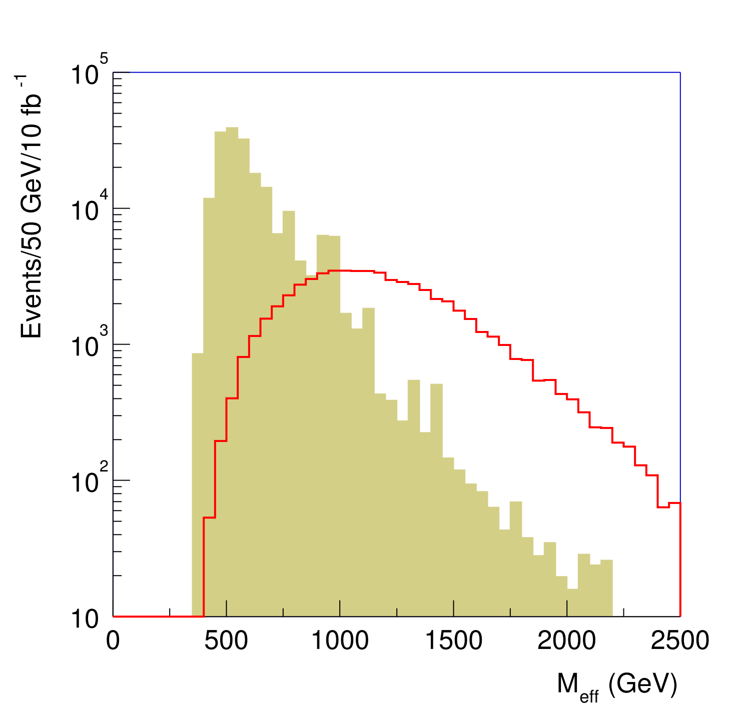
In general reach depends mainly on $M_{\tilde{g}}$ and $M_{\tilde{q}}$ provided $M_{\tilde{\chi}_1^0} \ll M_{\tilde{g}}, M_{\tilde{q}}$
rather model independent

Estimating the scale

Select events with at least 4 jets and Missing E_T
A simple variable

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

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

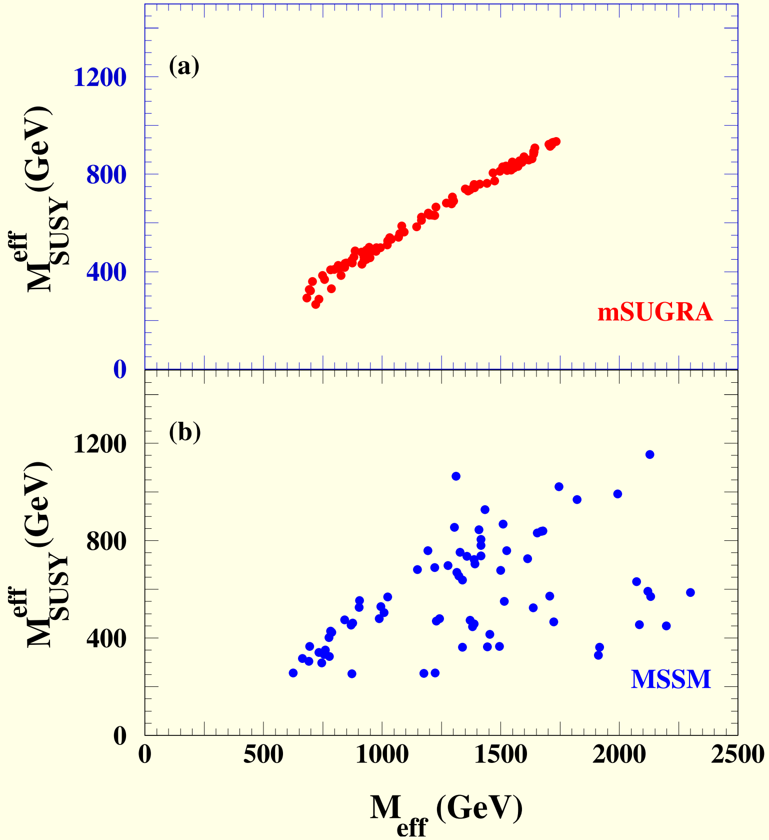


Peak in $M_{\rm eff}$ distribution correlates with SUSY mass scale

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

Will determine gluino/squark masses to $\sim 15\%$ in SUGRA, much poorer in a more general MSSM

15 parameters were varied



Note that rate information is difficult to use as BR are not known

Must reconstruct decays to get more information

Examples follow

Identifying typical decays

Assume $M_{\tilde{g}} > M_{\tilde{q}}$ (similar results in reverse case)
Then typically

$$B(\tilde{q}_L \to \tilde{\chi}_2^0 q) \sim 1/3, \quad B(\tilde{q}_L \to \tilde{\chi}_1^{\pm} q') \sim 2/3, \quad B(\tilde{q}_R \to \tilde{\chi}_1^0 q) \sim 1\,.$$

If channels are open, two body decays such as $\tilde{\chi}_2^0 \to \tilde{\ell}^+ \ell^-$, $\tilde{\chi}_2^0 \to Z\tilde{\chi}_1^0$, $\tilde{\chi}_2^0 \to h\tilde{\chi}_1^0$ usually dominate
Otherwise $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \ell^+ \ell^-$ via virtual slepton

So a good idea to look for leptons

Leptonic final states

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

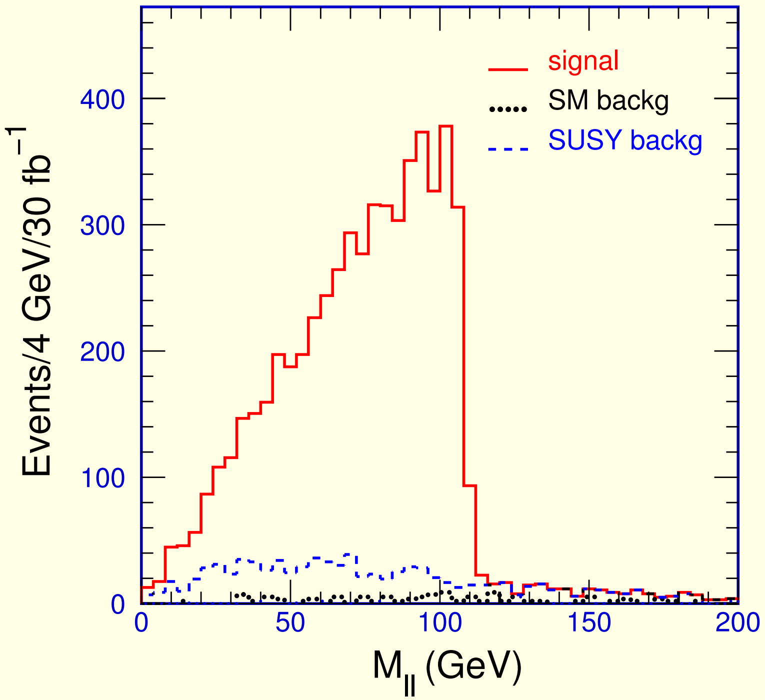
Straightforward case

Decay chain is $\widetilde{\chi}_2 \to \widetilde{\ell}^+\ell^- \to \widetilde{\chi}_1\ell^+\ell^-$

- 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 opposite sign same flavor leptons is constrained by decay

$$M_{\ell\ell} = \sqrt{(M^2_{\widetilde{\chi}^0_2} - M^2_{\widetilde{\ell}})(M^2_{\widetilde{\ell}} - M^2_{\widetilde{\chi}^0_1})}/M_{\widetilde{\ell}}.$$



Standard Model background is dominated by $t\bar{t}$

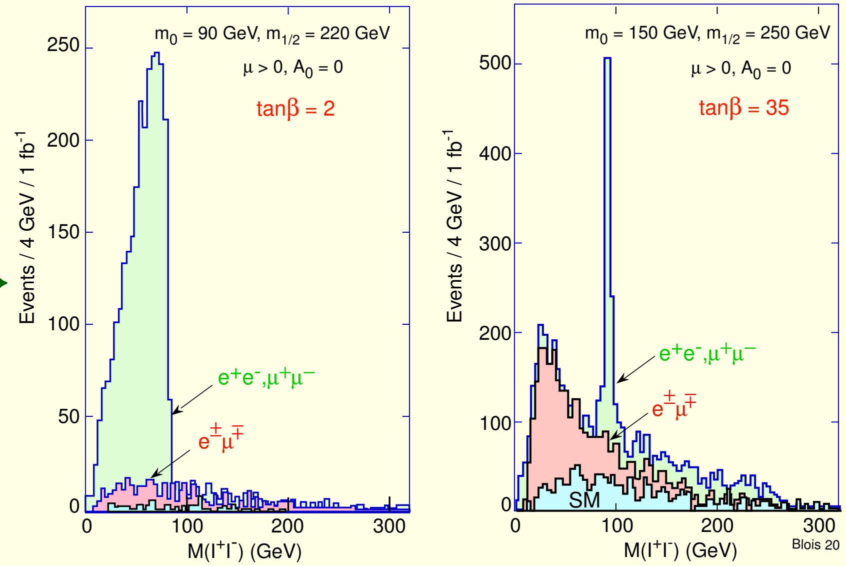
Other SUSY events (mainly $\widetilde{\chi}^\pm_1$ decays also contribute)

Others CMS Plots

$e\mu$ events arise from $\tau^+\tau^-$

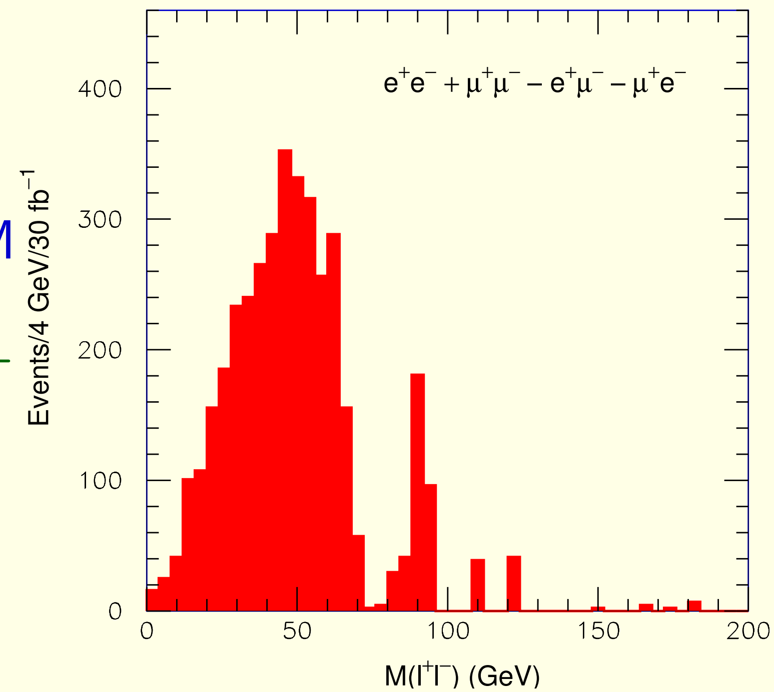
Note that right plot has only $\tilde{\chi}_2 \rightarrow \tilde{\tau}^+\tau^-$ and $\tilde{\chi}_2 \rightarrow Z\tilde{\chi}_1^0$ open

typical of large $\tan\beta$



Flavor subtraction remove the SM background and cleans up signal

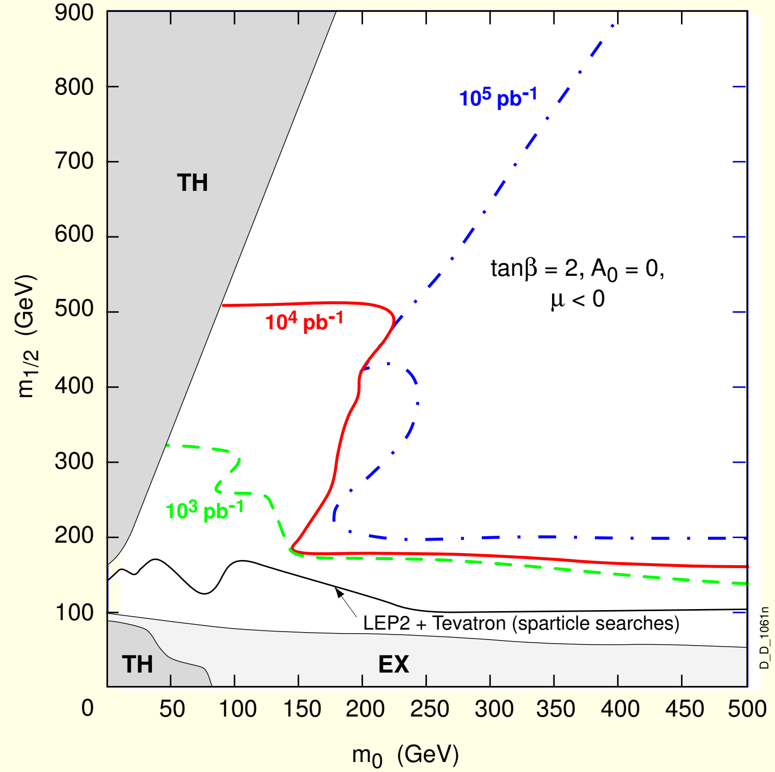
This example has both $\tilde{\chi}_2^0 \rightarrow \tilde{\ell}^+\ell^-$ and $\tilde{\chi}_2^0 \rightarrow Z\tilde{\chi}_1^0$,



Signal is visible over large part of parameter space

At large m_0 rates are suppressed by large slepton mass

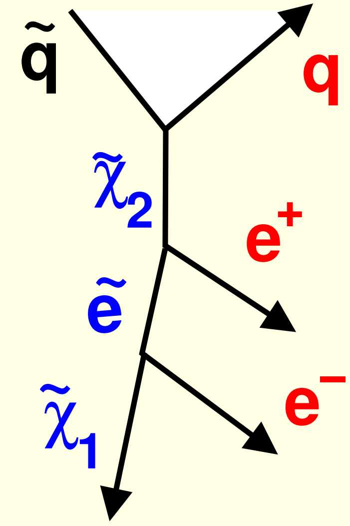
CMS plot



Must add jets to this to try to get full decay chains

Squark masses

Attempt to find $\tilde{q}_L \to q\tilde{\chi}_2^0 \to q\tilde{\ell}\ell \to q\ell\ell\tilde{\chi}_1^0$



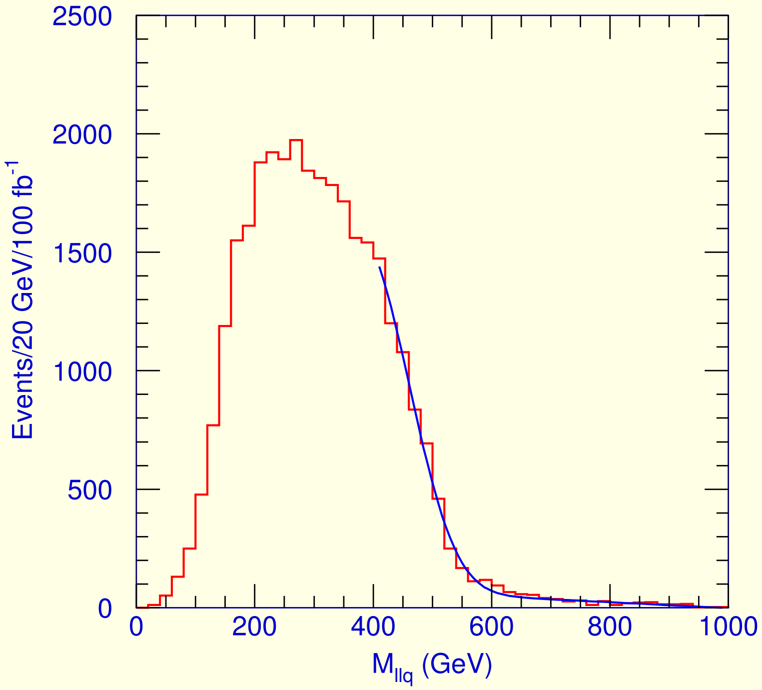
Identify and measure decay chain

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

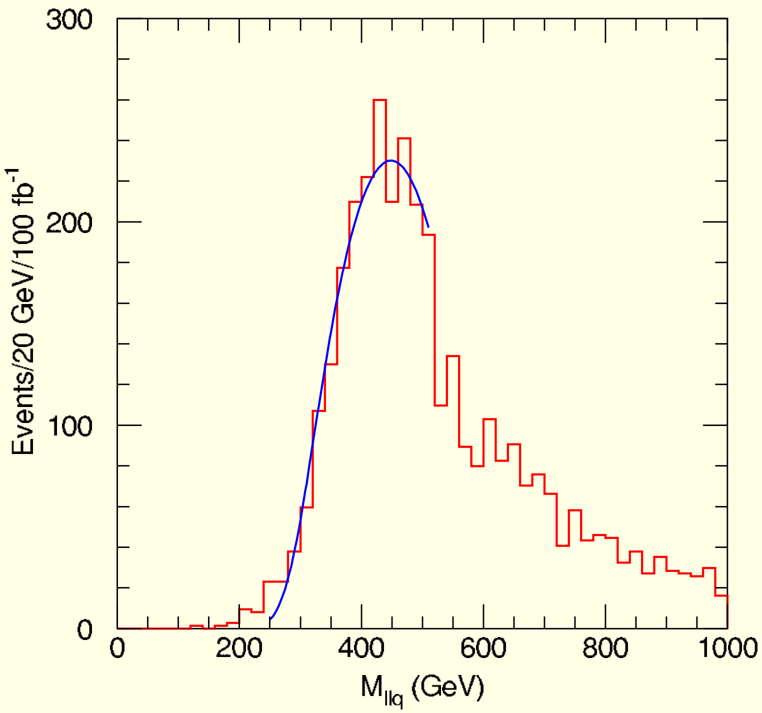
Mass of $q\ell\ell$ system has max at

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

and min at 271 GeV (in the example shown)



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



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

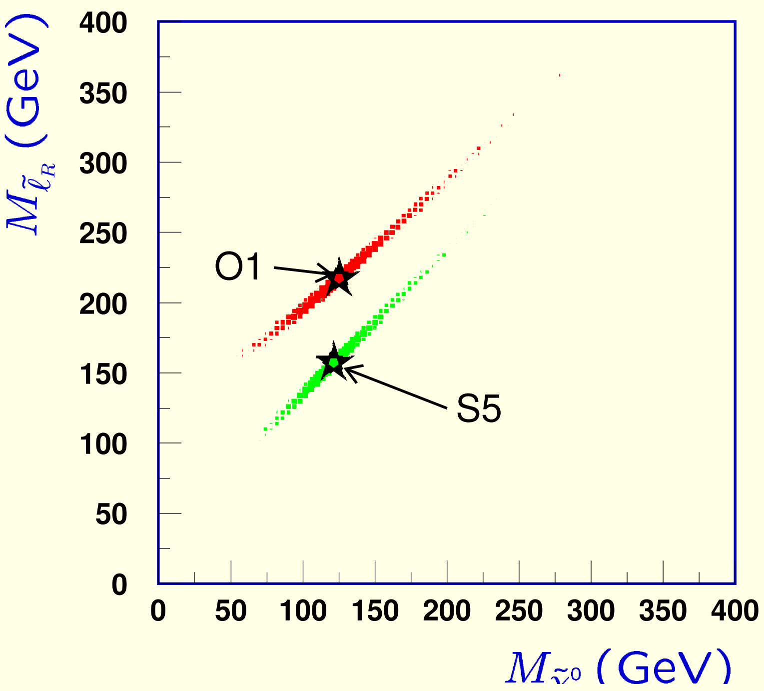
Kinematic structure clearly seen

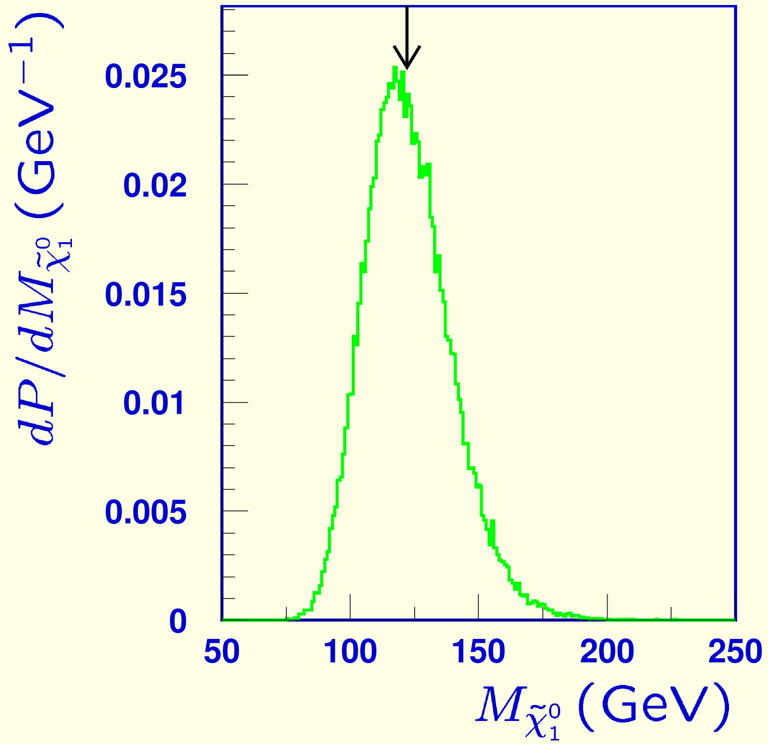
Can also exploit ℓjet mass

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 unobserved LSP is determined

Errors are strongly correlated and a precise independent determination of one mass reduces the errors on the rest.

What about $\tilde{q}_R$?

$\tilde{q}_r\tilde{q}_r \to qq\tilde{\chi}_1^0\tilde{\chi}_1^0$ produces clean events

$$m_{T2}^2(\chi) \equiv \min_{\not{q}_T^{(1)}+\not{q}_T^{(2)}=\not{E}_T} \left[\max\left\{m_T^2(\mathrm{p}_T^{j^{(1)}}, \not{q}_T^{(1)};\chi),\ m_T^2(\mathrm{p}_T^{j^{(2)}}, \not{q}_T^{(2)};\chi)\right\}\right]$$

Event selection

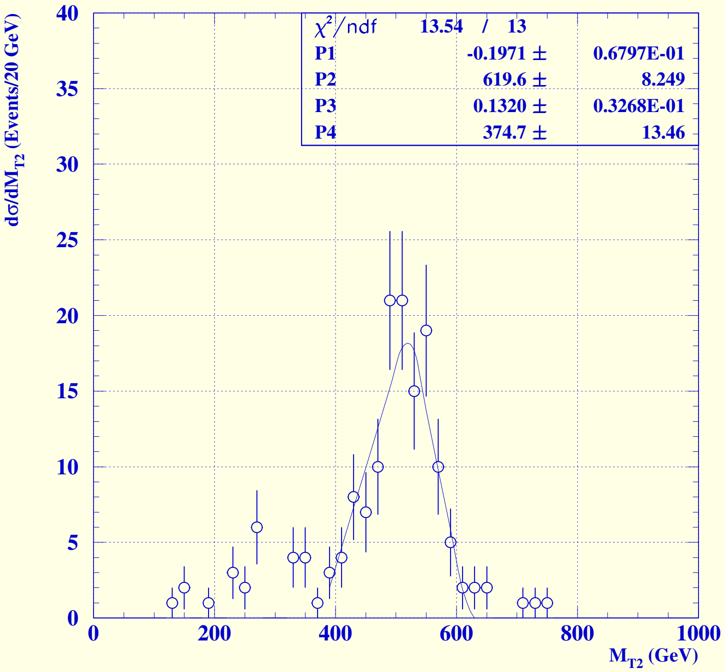
Two jets with $P_T > 150$ GeV

$\not{E}_T > 200$ GeV

No other jets with $P_T > 40$ GeV

Clear structure

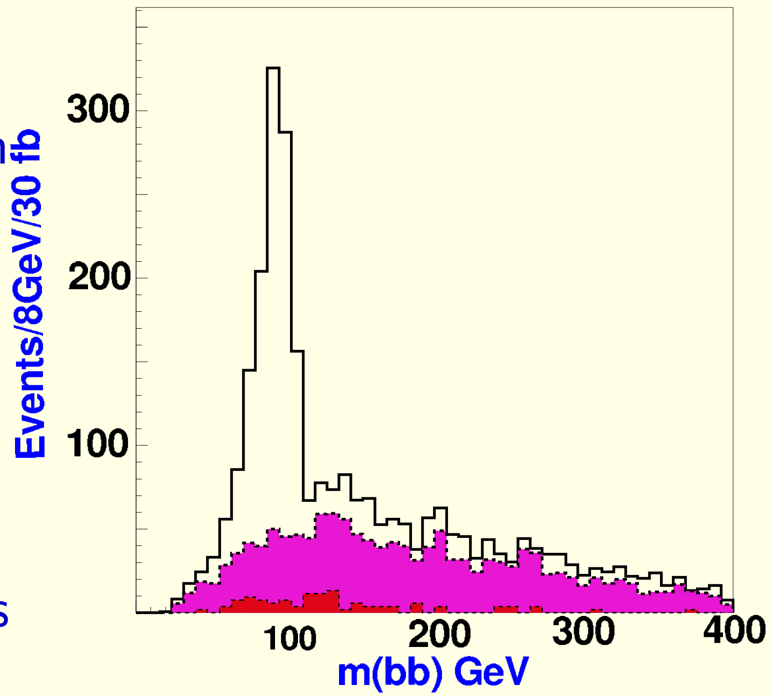
Determines a combination of M_{q_r} and $M_{\tilde{\chi}_1^0}$



Decays to Higgs

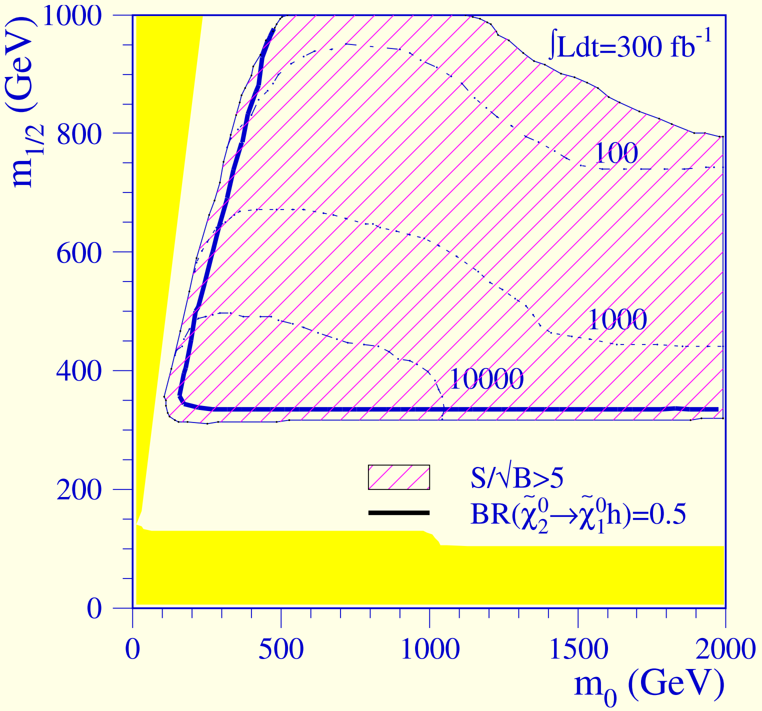
If $\chi_2^0 \to \chi_1^0 h$ exists then this final state followed by $h \to b\bar{b}$ results in discovery of Higgs at LHC.
In these cases $\sim 20\%$ of SUSY events contain $h \to b\bar{b}$

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

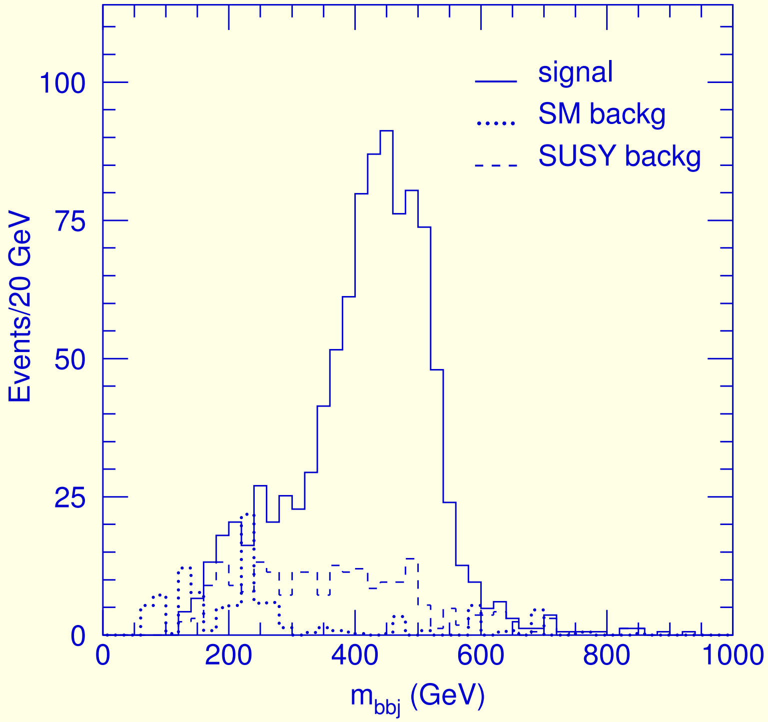


Generally applicable

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 $m_{1/2}$



Combine with a jet to attempt to get $\tilde{q} \rightarrow q\tilde{\chi}_2^0 \rightarrow qh\tilde{\chi}_1^0$



Take $b\bar{b}$ around the peak and combine with all jets
Plot the combination with the smallest mass
Again we see upper kinematic limit

Importance of Taus

Most models have e/μ universality, but $\tau' s$ are special

$\widetilde{\tau}_1$ is usually lightest slepton

Two $\widetilde{\tau}$ mass eigenstates are mixtures of $\widetilde{\tau}_L$ and $\widetilde{\tau}_R$.
Need to measure masses and mixings

Therefore τ rates are important

$m(\tilde{\tau}) < m(\tilde{\mu})$
Taus may be the only produced leptons in gaugino decay

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

Rely on Jet and $E_t(miss)$ cuts to get rid of SM background and obtain clean SUSY sample.

Tau background then arises from QCD jets in the SUSY event

Only need rejection $O(10)$

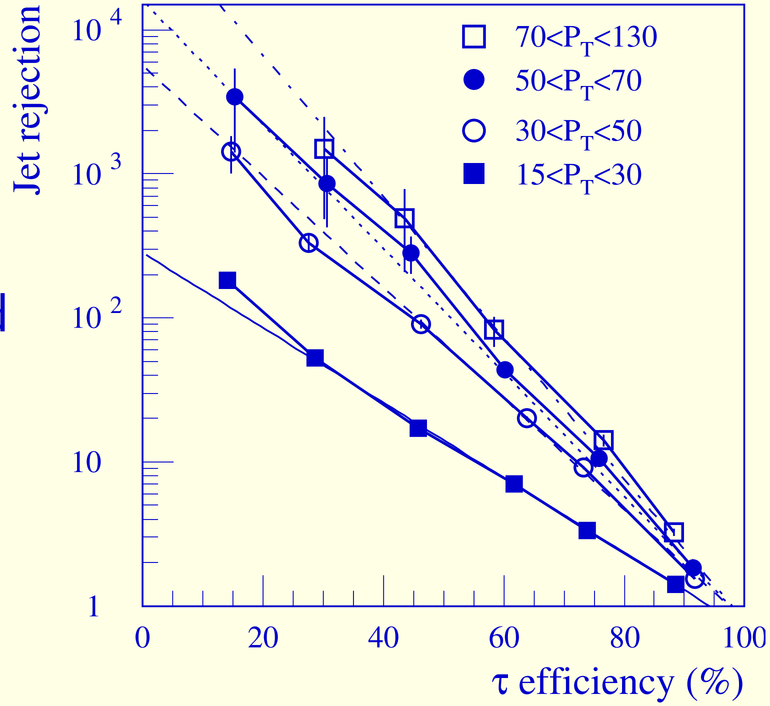
Measure "visible" tau energy. Can infer real end point from measured spectrum.

Real kinematic end point directly constrains masses.

$$M_{\tau\tau}^{\max} = M_{\tilde{\chi}_2^0}\sqrt{1-\frac{M_{\tilde{\tau}_1}^2}{M_{\tilde{\chi}_2^0}^2}}\sqrt{1-\frac{M_{\tilde{\chi}_1^0}^2}{M_{\tilde{\tau}_1}^2}}$$

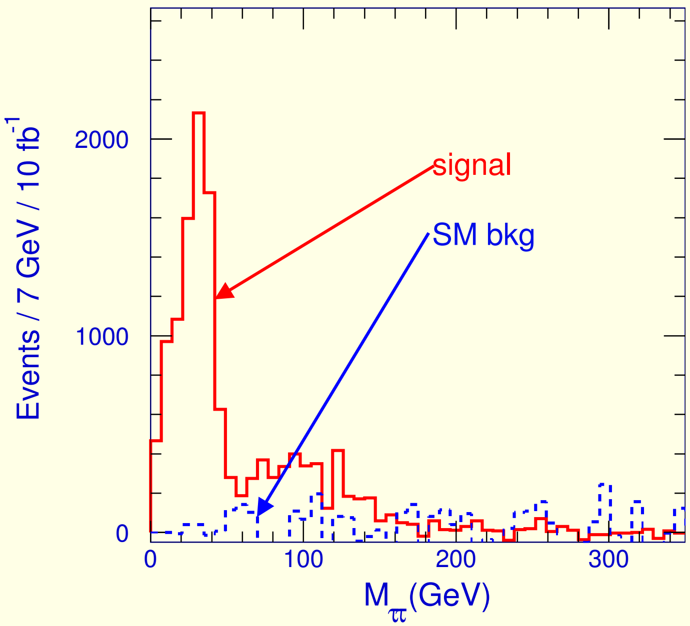
Then can reconstruct the decay chain by selecting these tau pairs

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



Example of decay to tau event

$\tilde{q}_L \rightarrow \tilde{\chi}_2^0 q \rightarrow q\tau^+\tau^-\tilde{\chi}_1^0$



≥ 4 jets
one has $p_t > 100$ GeV
rest $p_t > 50$ GeV
No isolated leptons with $p_t > 10$ GeV
$\not{E}_T > max(100, 0.2M_{eff})$
Plot mass of observed "tau" pairs

Red Solid': Signal
dashed: b- background from "real+fake"
Solid: background from "fake+fake"

In principle polarization information can be extracted
Vital to determine mixings

Heavier Gauginos

In some cases, heavier gaugino are "Higgsino" like and cannot be produced significantly in squark/gluino decay

But production of squarks can be huge so that even small BR may be observable

In some cases the Gauginos can all be mixed

then the heavier ones can be produced with significant rates

$\widetilde{\chi}_4^0/\widetilde{\chi}_2^\pm$ decay chains can give OS, SF dileptons:

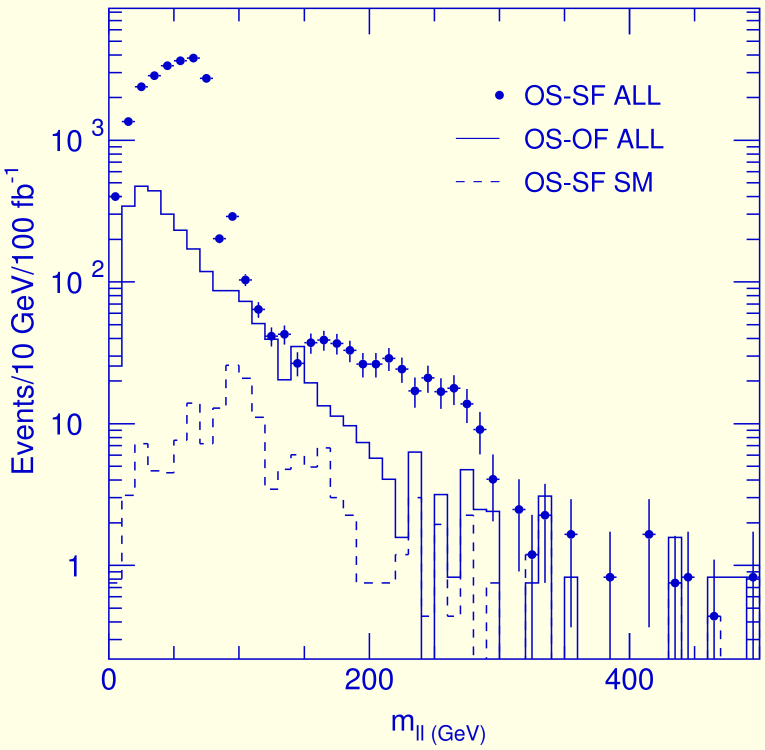
$\widetilde{q}_L \to \widetilde{\chi}_4^0 q \to \widetilde{\ell}_R^\pm \ell^\mp q \to \widetilde{\chi}_2^0 \ell^+ \ell^- q$

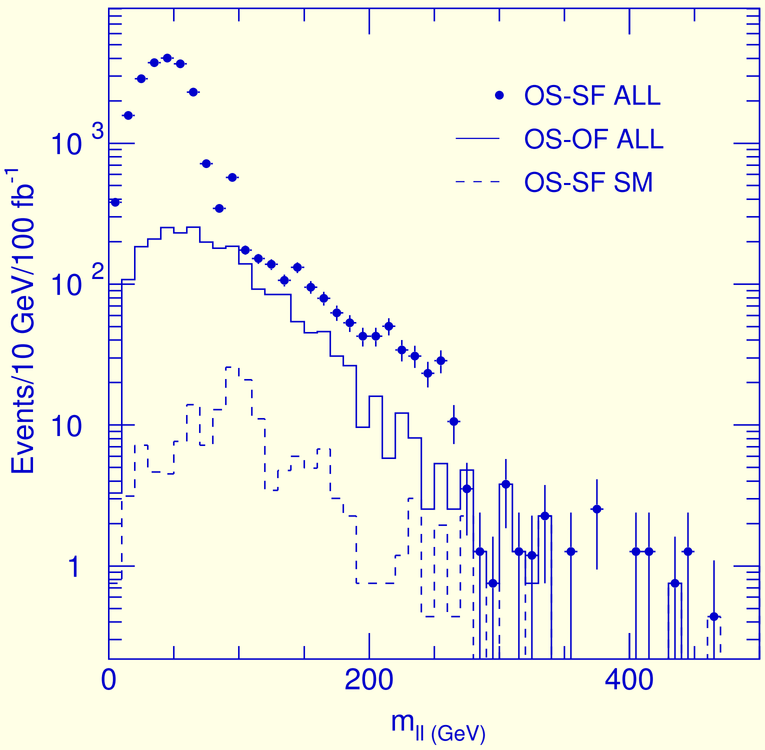
$\widetilde{q}_L \to \widetilde{\chi}_4^0 q \to \widetilde{\ell}_L^\pm \ell^\mp q \to \widetilde{\chi}_1^0 \ell^+ \ell^- q$

$\widetilde{q}_L \to \widetilde{\chi}_4^0 q \to \widetilde{\ell}_L^\pm \ell^\mp q \to \widetilde{\chi}_2^0 \ell^+ \ell^- q$

$\widetilde{q}_L \to \widetilde{\chi}_2^\pm q' \to \to_\ell \ell^\pm q' \to \widetilde{\chi}_1^\pm \ell^\mp q'$

more complicated dilepton signals

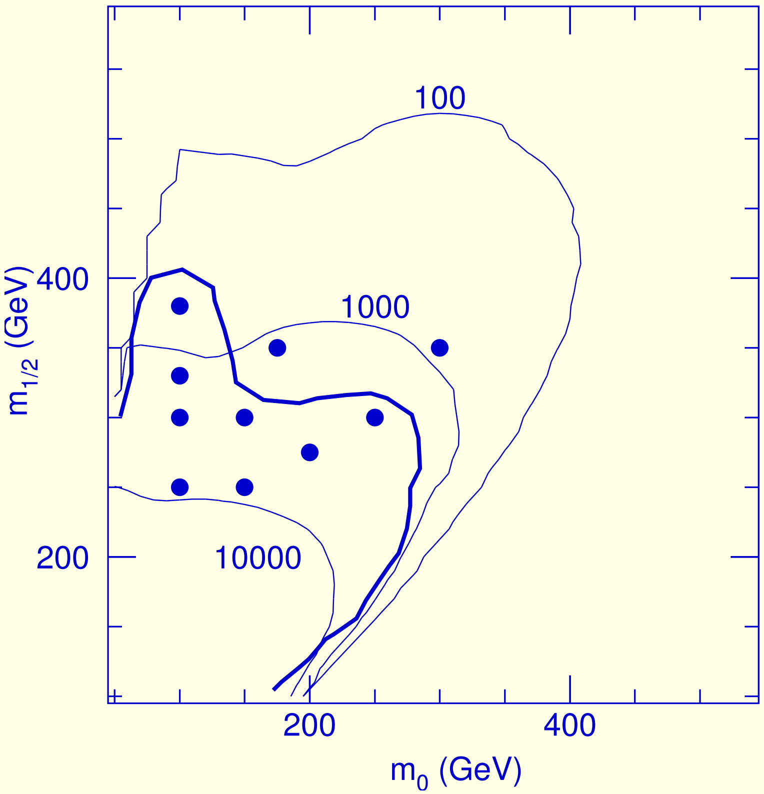




$m_0 = 100$ GeV, $m_{1/2} = 150$ GeV $m_0 = 100$ GeV, $m_{1/2} = 250$ GeV

Most events are from $\tilde{\chi}_2^0$ but event rates are large enough for higher end-points to be measured to ± 5 GeV

These heavier gauginos are visible over a large part of parameter space



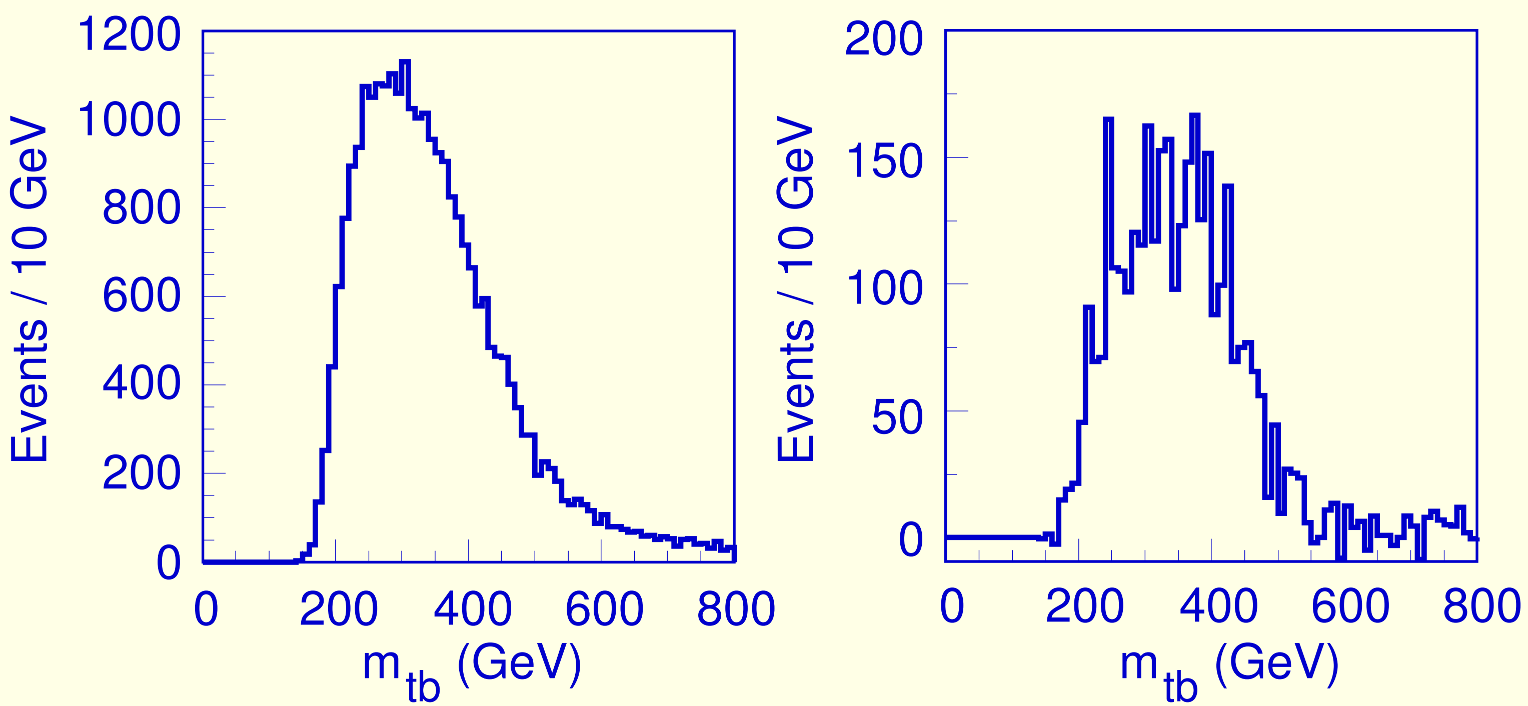
Plot shows event rates
Dark line shows reach for $\mathbf{100}\mathrm{fb}^{-1}$

Third Generation quarks

Measurement of $\tilde{b}$ gives vital information about SUSY breaking

$m_0 = 100\,\mathrm{GeV}$, $M_{1/2} = 300\,\mathrm{GeV}$, $A_0 = -300\,\mathrm{GeV}$, $\tan\beta = 10$, $\mathrm{sgn}\,\mu = +$

$$\tilde{g} \to t\tilde{t}_1^* \to t\bar{b}\tilde{\chi}_1^-, \qquad \tilde{g} \to \bar{b}\tilde{t}_1 \to t\bar{b}\tilde{\chi}_1^-$$



Reconstruct events with t and b and look for a kinematic end point

Even Messier cases

R-parity breaking
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

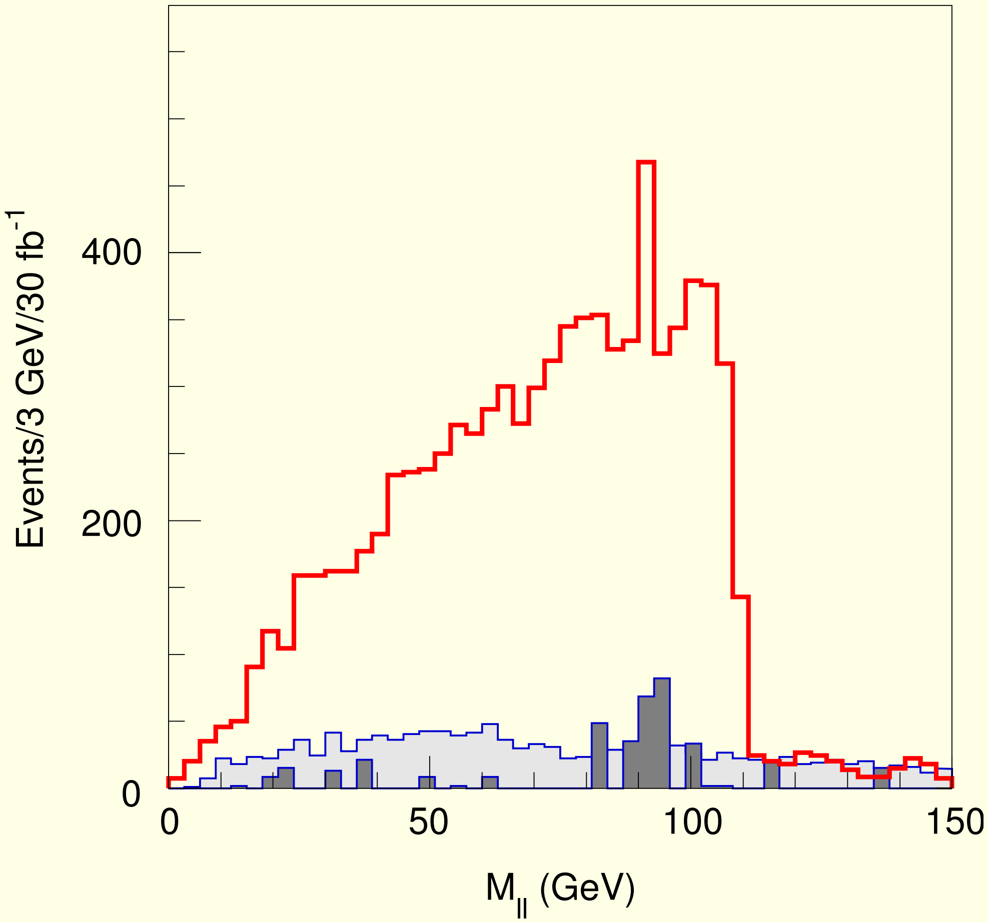
2 OSSF isolated leptons.

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

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

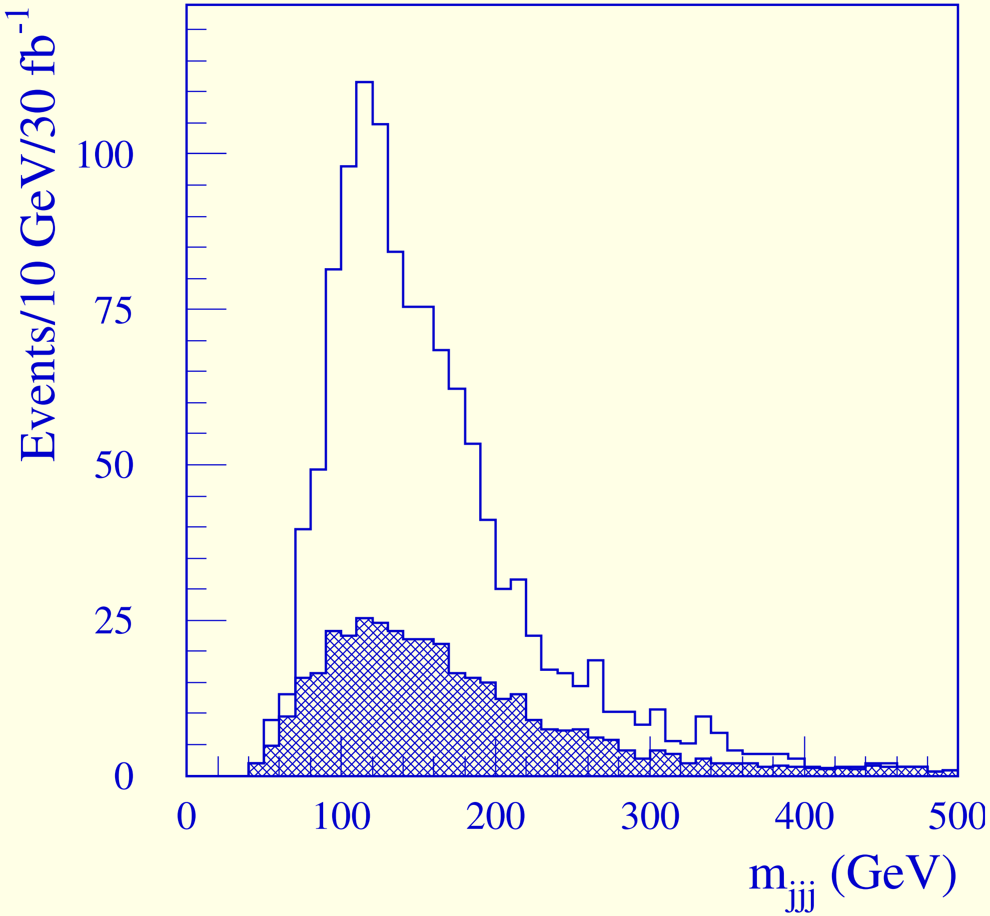
Dilepton mass still shows clear structure with small background from

$\widetilde{\chi}_2^0 \to \ell^+\ell^-\widetilde{\chi}_1^0$



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

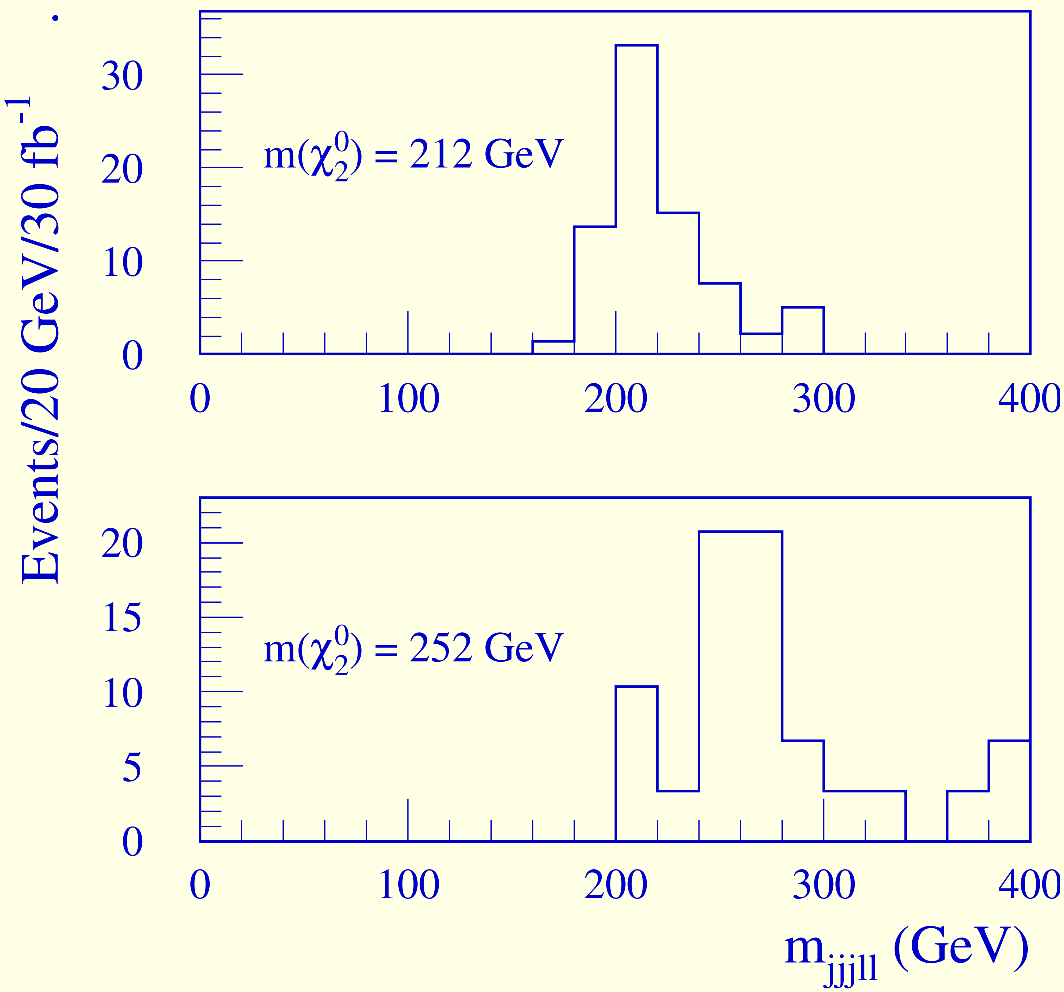
Can cut around peak and combine with either leptons or quarks reconstruct

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

$\chi_2^0 \to \ell\ell\tilde{\chi}_1^0$

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

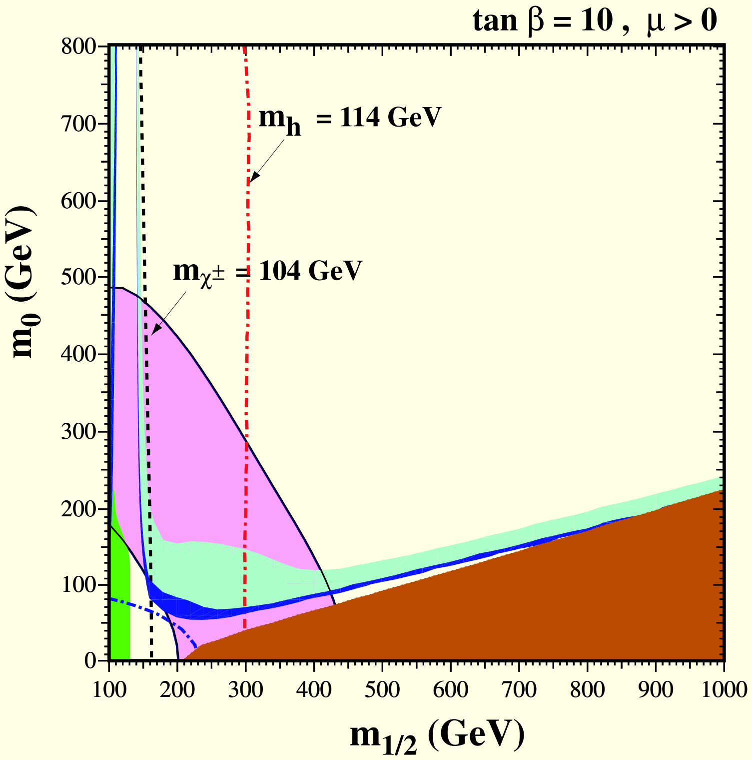
Note that tight cuts imply low event rate



Preferred regions?

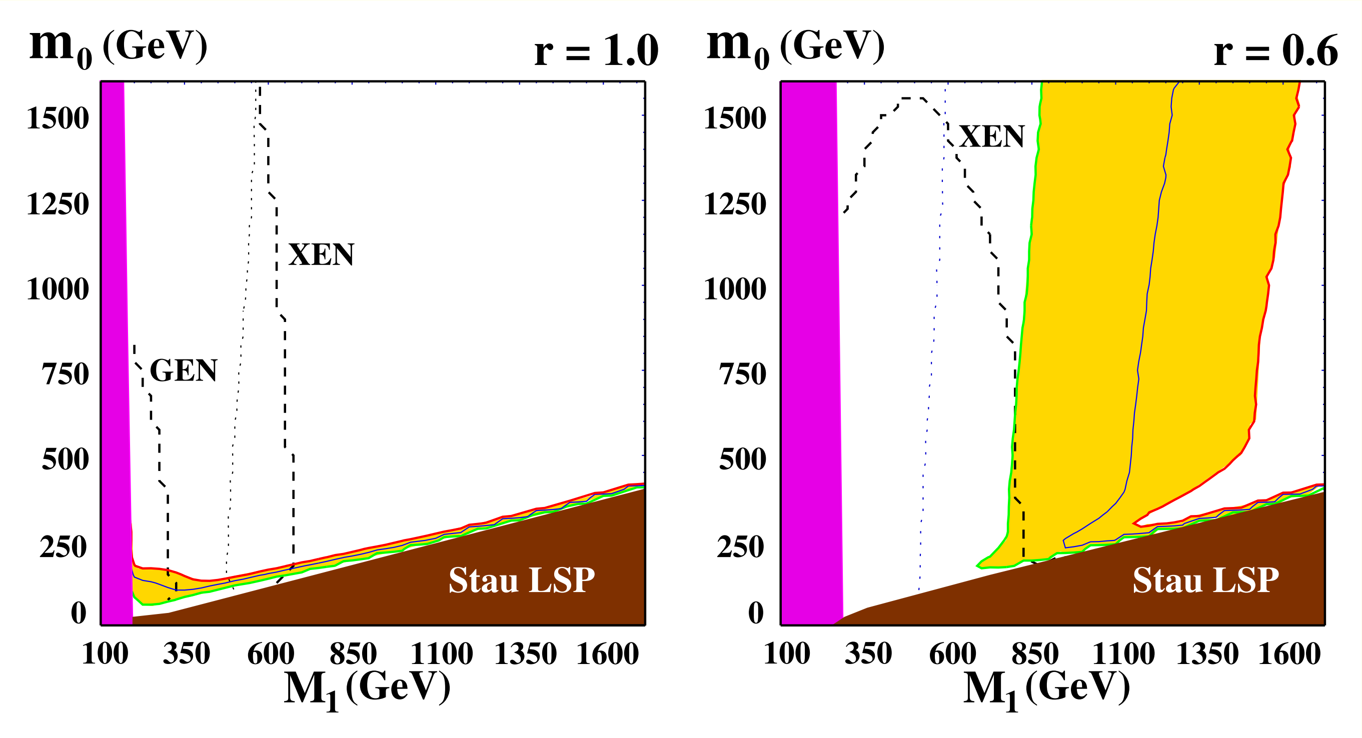
It would be nice to know where to look

If we really believe in minimal SUGRA then WMAP provides strong constraints
Even stronger if $g-2$ is included (with one value of $R(e^+e^-)$ at low energy)



But constraints weaken outside minimal sugra

$R = M_2/M_3$ at GUT scale.

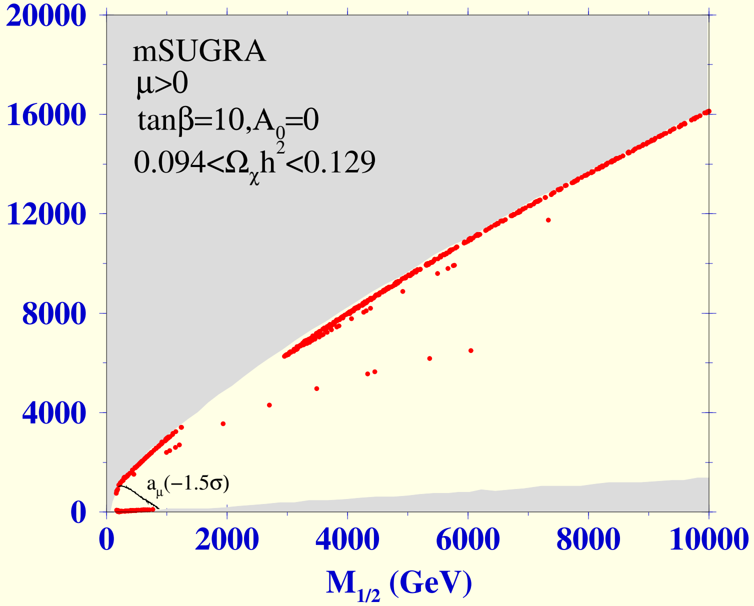


When to give up

Many arguments based on naturalness indicating that LEP/Tevatron should see something.

LHC should find something if squarks/gluinos less than $\sim \mathbf{3}$ TeV

You can always cook something up that LHC cannot find $(\boldsymbol{\Delta M = 1 GeV})$



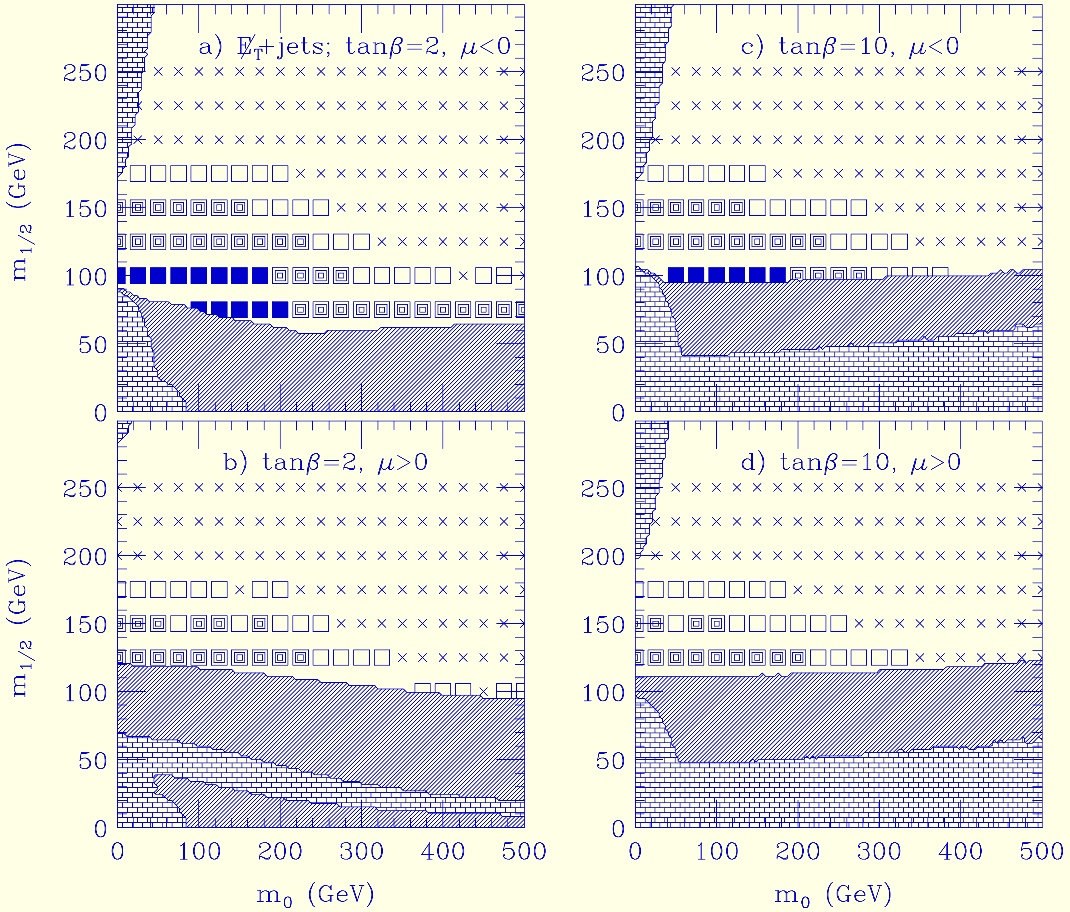
Tevatron

No signal claimed by an experiment

TeV will extend search range with more luminosity Reach is limited nut "the train is already late"

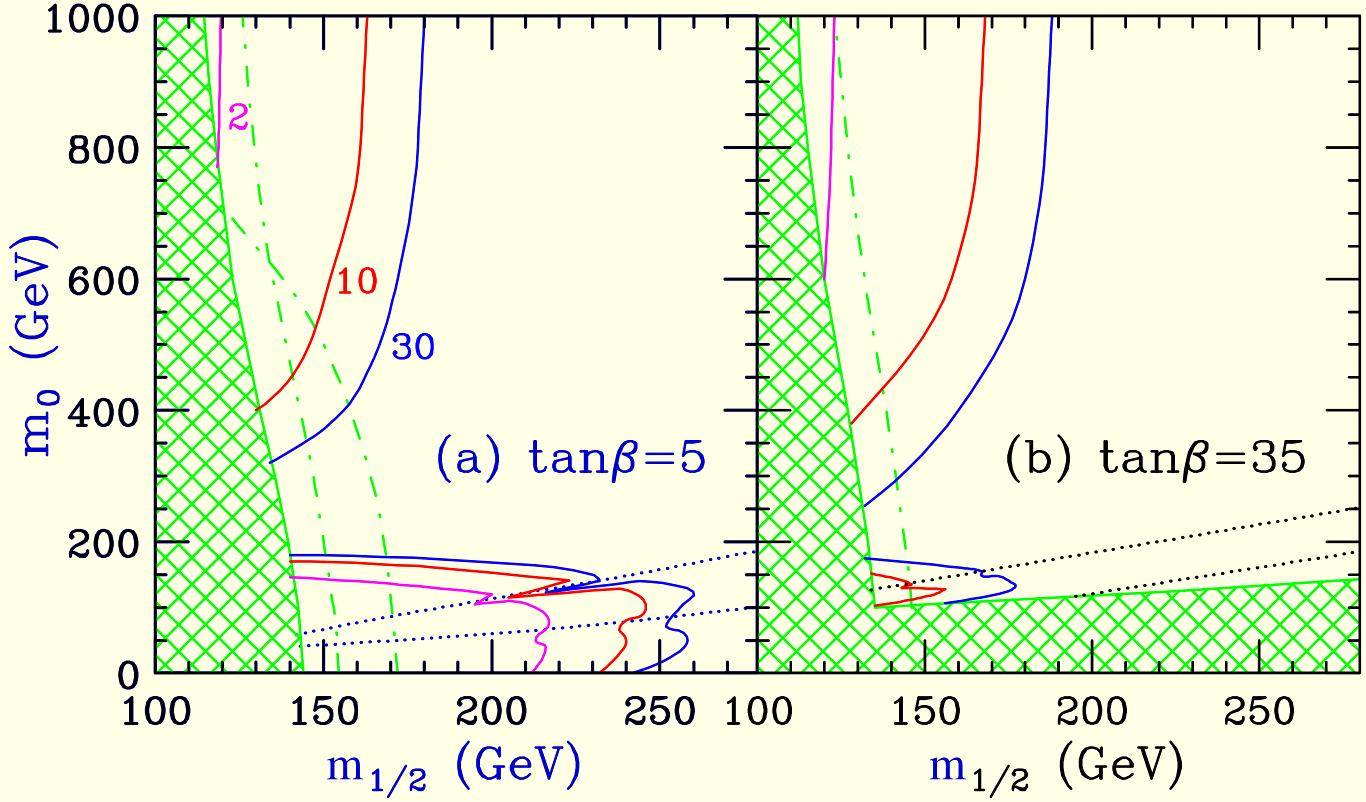
Squark and gluino production may not dominant

Global searches involving $\not\!\!E_T$ can extend search region
Plot from Tevatron study



Best hope is production of $\tilde{\chi}_2^0 \tilde{\chi}_1^+ \rightarrow \ell^+ \ell^- \tilde{\chi}_1^0 \ell^+ \nu \tilde{\chi}_1^0$
Background dominated by WZ^*

Tevatron study hep-ph/0003154



3σ contours.

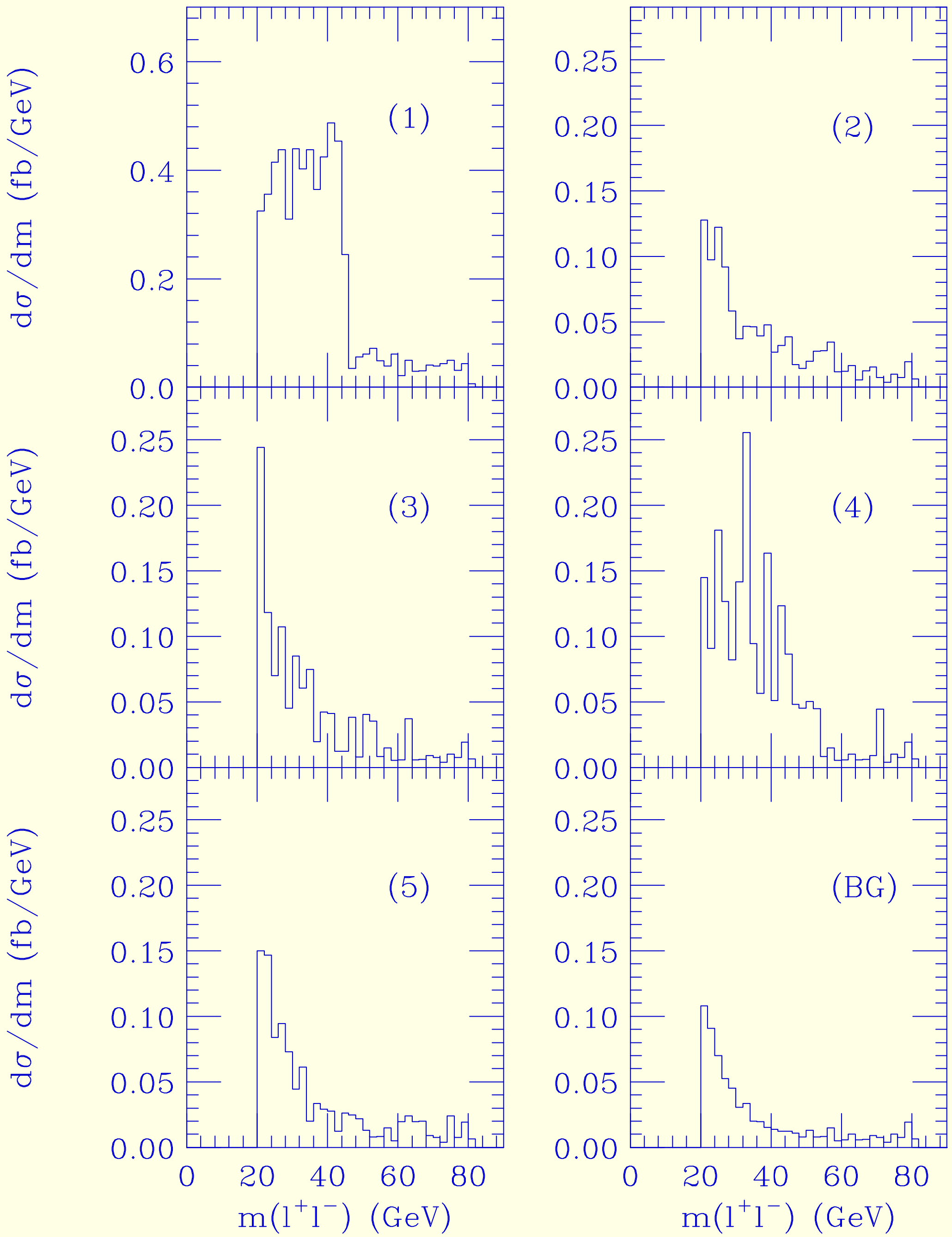
Berkeley Lab

If this signal is seen then structure in the $\ell^+\ell^-$ mass distribution will constrain $\widetilde{\chi}_2^0$ and $\widetilde{\chi}_1^0$ masses (see later)

Plot shows some typical cases

Note event rates

case (1) was ruled out by LEP!



If Tevatron finds SUSY it will determine the mass scale of some particles

Upgrades

Its very likely that LHC will discover SUSY.

But it's unlikely that it will measure everything

Studies of $\widetilde{\chi}_3$ and $\widetilde{\chi}_4$ likely rate limited.

In some models first two generation squarks can be very heavy.

For more on this see Albert's talk

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