SUSY Breaking

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Outline

- Mass Scales and SUSY
- Breaking schemes and characteristic spectra
  SuperGravity Mediation
  Gauge Mediation
  Anomaly Mediation
  Gaugino Mediation
  Extra dim boundary condition
- How to sort it out.

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Scales and SUSY

All data consistent with SM ($g-2???$)

SM constrained at the loop level by precise data from LEP, W mass $etc.$

New particles of mass $\lesssim 10\mathrm{TeV}$ are constrained: EW fits, FCNC limits etc unless their couplings are very well prescribed.

Calculate with a cut off $\Lambda = 10TeV$; its much worse if you want $\Lambda = M_{Plank}$

Consider radiative corrections to the Higgs mass: calculate with a cut off $\Lambda = 10TeV$

top loop $\delta m_h^2 = \frac{3}{8\pi^2}\lambda_t^2\Lambda^2 \sim (2TeV)^2$

W/Z loops $\delta m_h^2 \sim \alpha_w\Lambda^2 \sim -(750GeV)^2$

Higgs loop $\delta m_h^2 \sim \frac{\lambda}{16\pi^2}\Lambda^2 \sim -(1.25m_h/100GeV)^2$

But the full fits to the SM imply $m_h^2 \sim (100GeV)^2$

Fine tuning of Higgs mass seems to require something else $\sim 1\mathrm{TeV}$

But adding new stuff can cause a conflict

It must be added in such a way that it solves the hierarchy problem without making a mess. Most extensions to the standard model fail this

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SUSY to the rescue

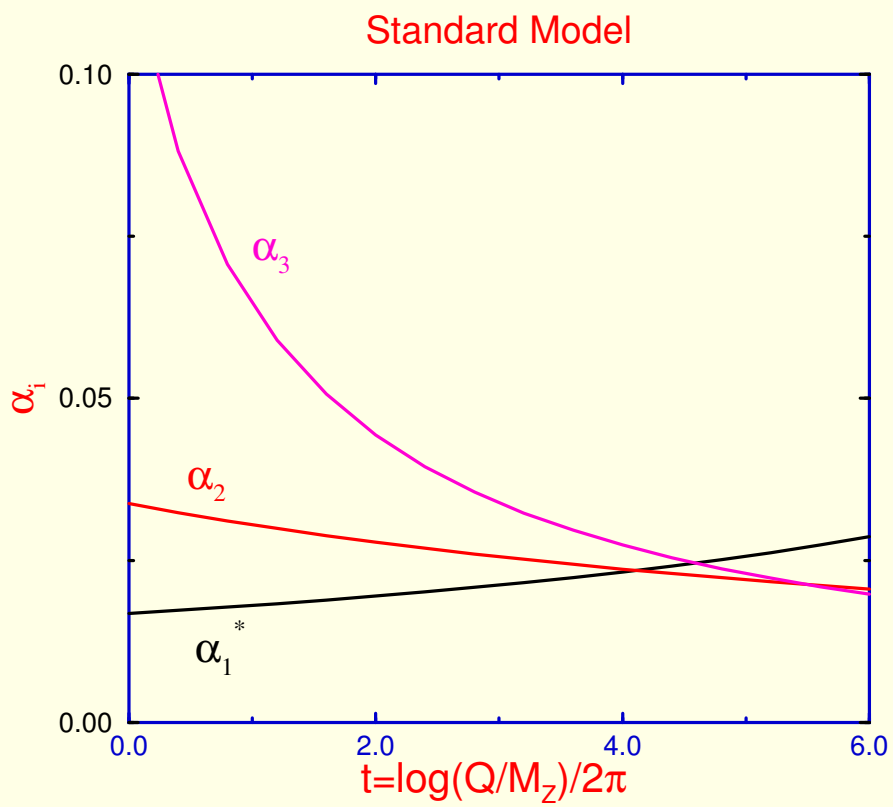
SUSY solves it up to $\sim M_{Planck}$ by removing all quadratic divergences. This may be overkill; Most dangerous terms are top loop, Higgs loop, W/Z loops

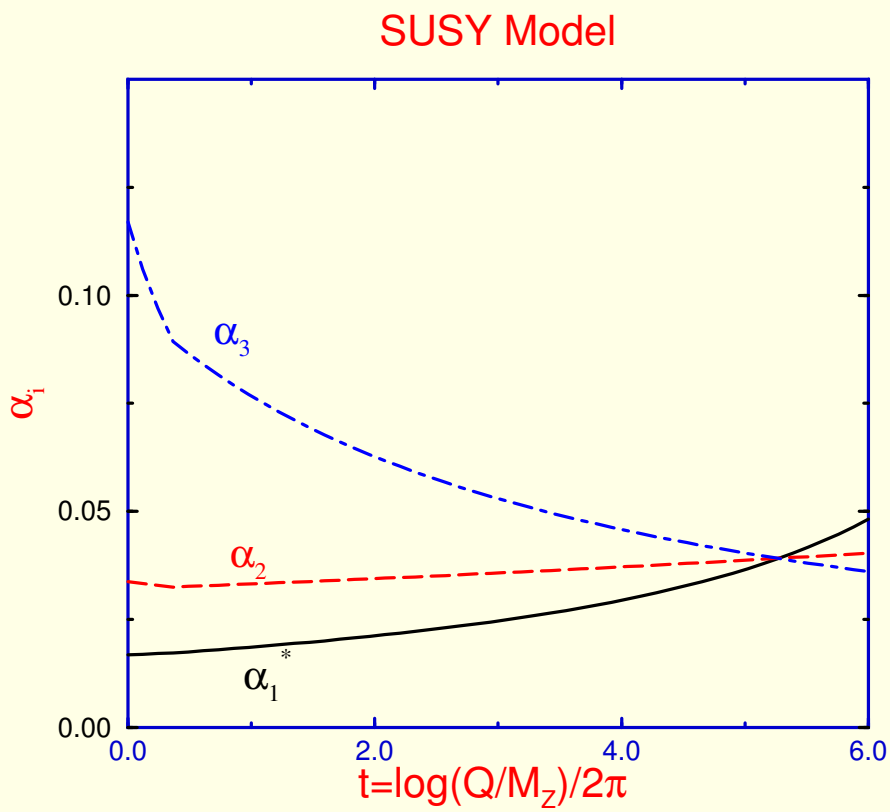
This argument implies that some SUSY particles must have mass below 1 TeV or so, specifically, Stop, Wino.

Minimal particle content is the partners of all particles (N=1 Susy)
Scalars, one partner for each fermion spin state: Squarks (12), Sleptons (6) and sneutrinos (3 or 6)
Fermions to partner gauge bosons: gluinos(8), gauginos(4)

Two Higgs doublets and their partner fermions (4): SM anomaly from one doublet cancels the other.
Higgsino and gaugino states are mixed by EW symmetry breaking to give 2 charged ($\tilde{\chi}_i^+$) and 4 neutral states ($\tilde{\chi}_i^0$)
mixings determine decay properties

Susy helps unification





. without susy

. with susy

What other stuff is (not) needed?

Avoid other fields with EW coupling. (LEP constraints)

Unbroken SUSY model has exact cancellations and mass degeneracy.

It contains gauge interactions plus Yukawa's expressed as a superpotential. Most general consistent with $SU(2) \times U(1)$

$$\begin{aligned} W &= \epsilon_{ij}\mu \hat{H}_1^i \hat{H}_2^j + \epsilon_{ij}\left[\lambda_L \hat{H}_1^i \hat{L}^{cj} \hat{E}^c + \lambda_D \hat{H}_1^i \hat{Q}^j \hat{D}^c + \lambda_U \hat{H}_2^j \hat{Q}^i \hat{U}^c\right] \\ &\quad + \epsilon_{ij}\left[\lambda_1 \hat{L}^i \hat{L}^j \hat{E}^c + \lambda_2 \hat{L}^i \hat{Q}^j \hat{D}^c\right] + \lambda_3 \hat{U}^c \hat{D}^c \hat{D}^c, \end{aligned}$$

One less parameter than SM if $\lambda_i = 0$

SUSY cannot be broken spontaneously with only this particle content due to sum rules

$$\sum_i (-1)^F m_i^2 = 0$$

But

$$\sum_i (-1)^F m_i^2 > (TeV)^2$$

for known particles and their partners.

SUSY is broken in some "hidden sector" and then communicated to SM somehow. Models are classified by the communication mechanism.

Many pitfalls to avoid

- No electroweak symmetry breaking
- Large baryon or lepton number violation. (need $\lambda_1 = \lambda_2 = 0$ and/or $\lambda_3 = 0$)
- μ is not Susy breaking, what sets its value?
- Too much CP violation
- Tachyons all $m_i^2 > 0$ except for Higgs.
- Stable heavy particles (can be good – Dark Matter)
- Problems with current constraints such as $K \to \mu\mu$, E-W constraints

R parity

Most SUSY breaking schemes conserve R parity.

All particles even

Sparticles odd

Forces $\lambda_1 = \lambda_2 = \lambda_3 = 0$

Lightest SUSY particle (LSP) stable

R parity can be broken — but have to conserve B or L

Most general susy breaking

Very large number of parameters in the low energy theory controlled by SUSY breaking
Parametrized as coefficients of operators describing (s)particle interactions and masses.
Many new couplings
Many complex parameters $\Rightarrow$ CP violation

$$
\begin{aligned}
-\mathcal{L}_{soft} \;=\; & m_1^2 \mid H_1 \mid^2 + m_2^2 \mid H_2 \mid^2 - B\mu\epsilon_{ij}(H_1^i H_2^j + \text{h.c.}) + \tilde{M}_Q^2(\tilde{u}_L^* \tilde{u}_L + \tilde{d}_L^* \tilde{d}_L) \\
& + \tilde{M}_u^2 \tilde{u}_R^* \tilde{u}_R + \tilde{M}_d^2 \tilde{d}_R^* \tilde{d}_R + \tilde{M}_L^2(\tilde{e}_L^* \tilde{e}_L + \tilde{\nu}_L^* \tilde{\nu}_L) + \tilde{M}_e^2 \tilde{e}_R^* \tilde{e}_R \\
& + \frac{1}{2}\left[M_3 \bar{\tilde{g}}\tilde{g} + M_2 \overline{\tilde{\omega}_i}\tilde{\omega}_i + M_1 \bar{\tilde{b}}\tilde{b}\right] + \frac{g}{\sqrt{2}M_W}\epsilon_{ij}\left[\frac{M_d}{\cos\beta} A_d H_1^i \tilde{Q}^j \tilde{d}_R^* \right. \\
& \left. + \frac{M_u}{\sin\beta} A_u H_2^j \tilde{Q}^i \tilde{u}_R^* + \frac{M_e}{\cos\beta} A_e H_1^i \tilde{L}^j \tilde{e}_R^* + \text{h.c.}\right] \quad .
\end{aligned}
$$

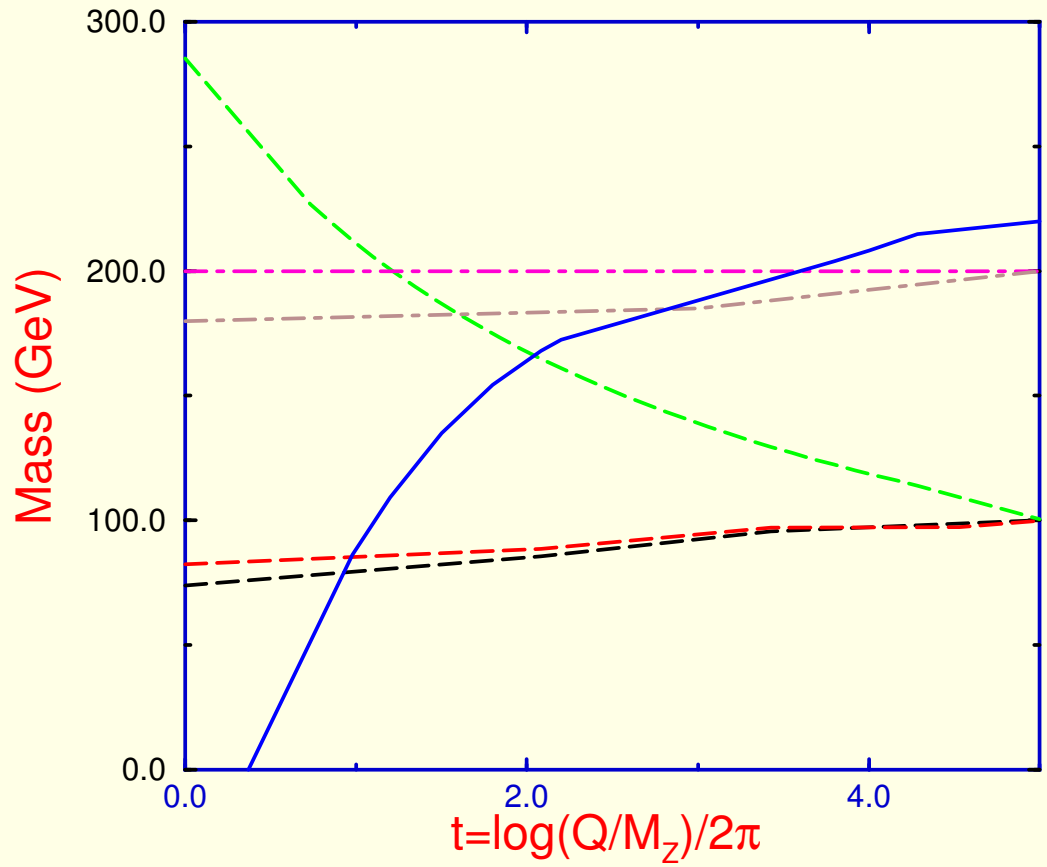
Theory has to predict this lot and experiment to measure them!

Getting EW symmetry breaking

Need $m_1^2 < 0$ or $m_2^2 < 0$

Can get this "for free"

Supposed at some high (GUT?) scale all $M_i^2 > 0$, interaction of H_2 with T via large Yukawa can drive $M_2^2 < 0$.
Requires (predicts) large top quark mass
Will work if there is "room to run"



Smallest set of extra parameters

$M_{1/2}$: gaugino masses; all related to each other

m_0: scalar masses;

A relevant only for 3rd generation

B and μ

Higgs VeV's given by these; so B and $|\mu|$ are traded for physical parameters $\tan\beta$ and M_Z

B and μ cannot be zero

Higgs particles and masses

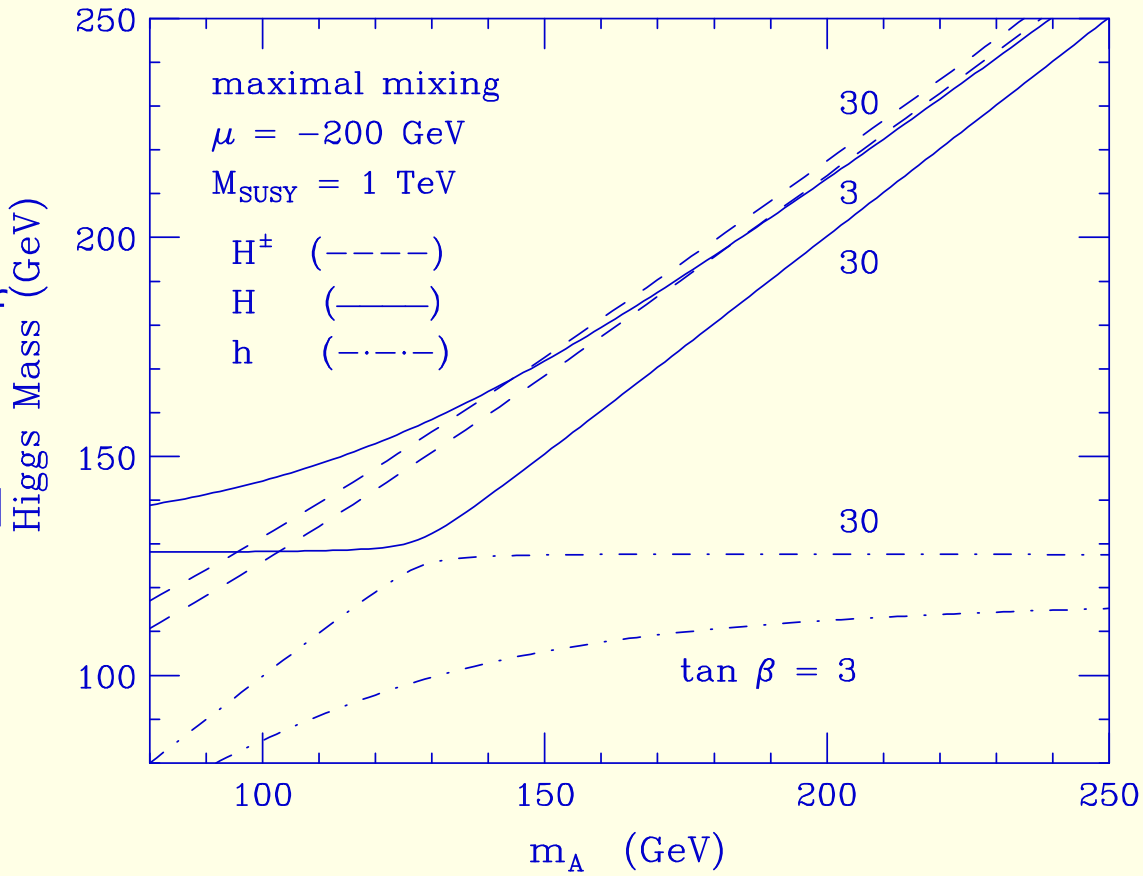
Three mass eigenstates h, H, A and $H^{\pm}$

Properties predicted in terms of above parameters.

Lightest h is bounded independent of susy breaking

Not far above LEP limit

Properties of h similar to standard model



SUGRA models

Oldest idea: Try to use Gravity as the communication mechanism since we know it exists.

SUSY is broken in some sector with very heavy particles

Gravitino acquires a mass $\sim TeV$

Gravity knows nothing about E-W interactions so might guess

Unification all scalar masses (m_0) at GUT scale

Unification all gaugino masses ($M_{1/2}$) at GUT scale universal Trilinear term A and B term with all related to gravitino mass;

Masses must then evolve to EW scale where they are observed.

Spectrum is given by 4 parameters.

$\tan\beta = v_1/v_2$, m_0, $m_{1/2}$

$sign(\mu)$ and universal Trilinear term A, important only for 3rd generation

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

If μ large then $\tilde{\chi}_1^0$ is $\tilde{B}$ and $\tilde{\chi}_2^0$ is $\tilde{W}$; heavier $\tilde{\chi}$ are Higgsino

Can relax unification assumption – more parameters

Certain regions of parameter space excluded by

Expt searches

No EW breaking

Charged LSP (assuming it's stable)

Many search limits quoted for this model

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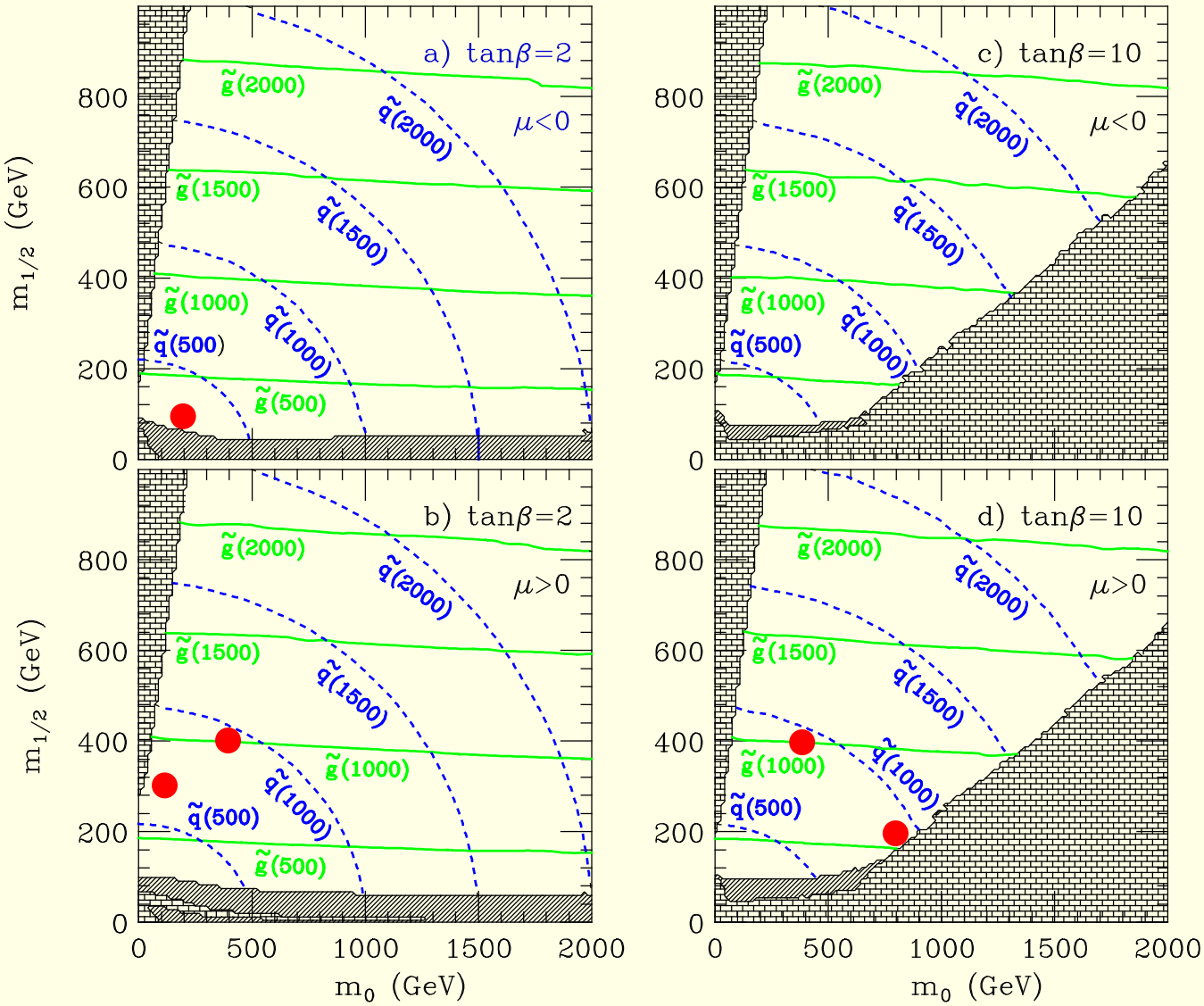
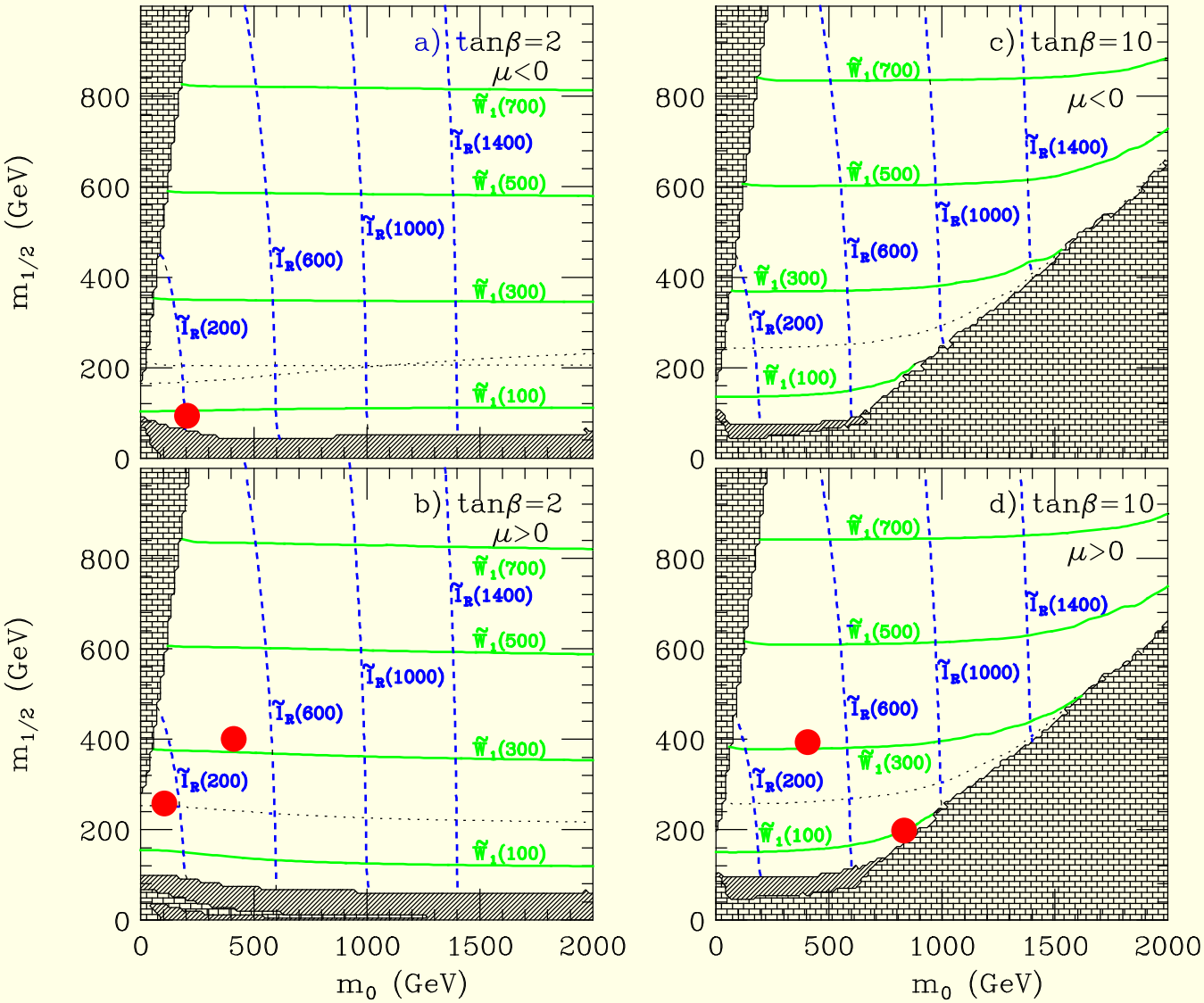


Contours of fixed *gluino* and squark mass



Contours of fixed *wino* and slepton mass

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 and stau lightest slepton.

Lightest SUSY particle (LSP) stable if R-parity good.

LSP must be neutral if stable; its usually $\tilde{B}$

SUSY particles produced in pairs even if R-parity broken.

SUSY production at LHC 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.

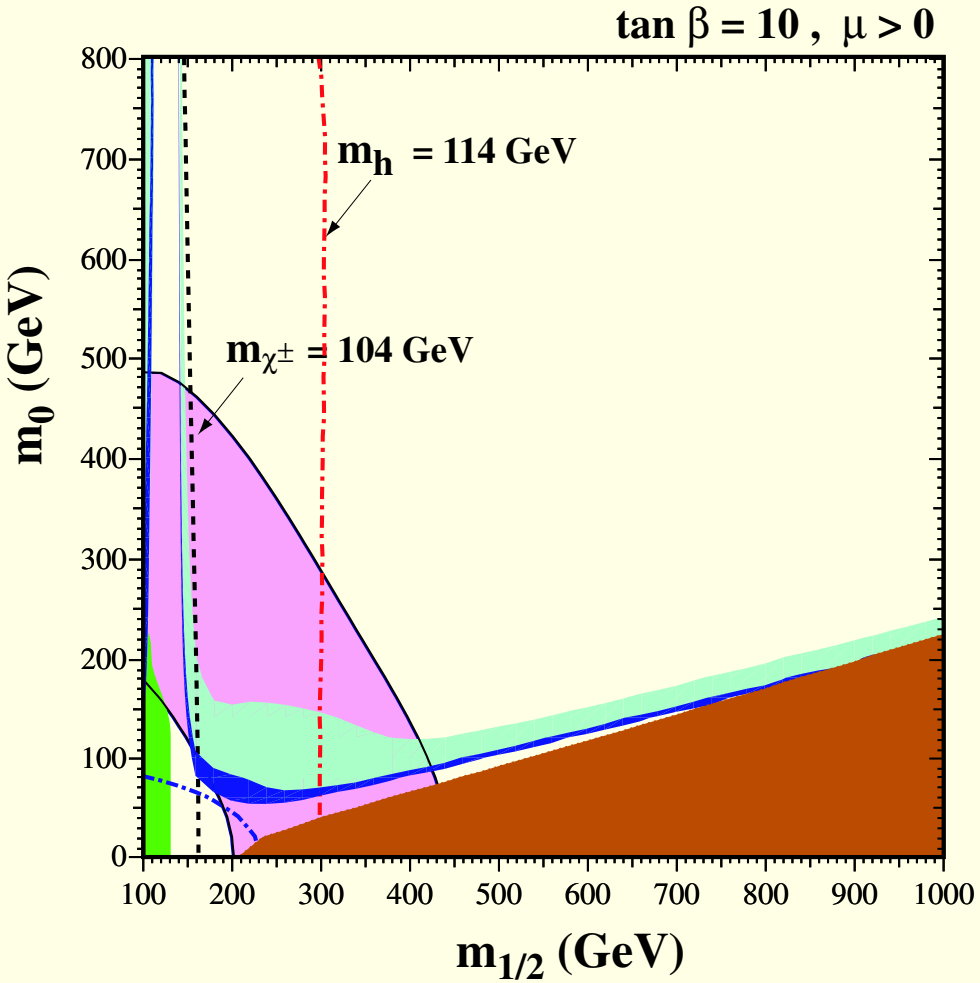
Complicated final states will dominate LHC $e.g.$

$$\tilde{g} \to \overline{q}\tilde{q} \to \overline{q}q\tilde{\chi}_2^0 \to \overline{q}q\tilde{\tau}\tau \to \overline{q}q\tilde{\chi}_2^0 \to \overline{q}q\tau\tilde{\chi}_1^0\tau$$

Nice features of SUGRA model

Natural dark matter candidate with right properties
Neutral LSP can be Cold Dark Matter

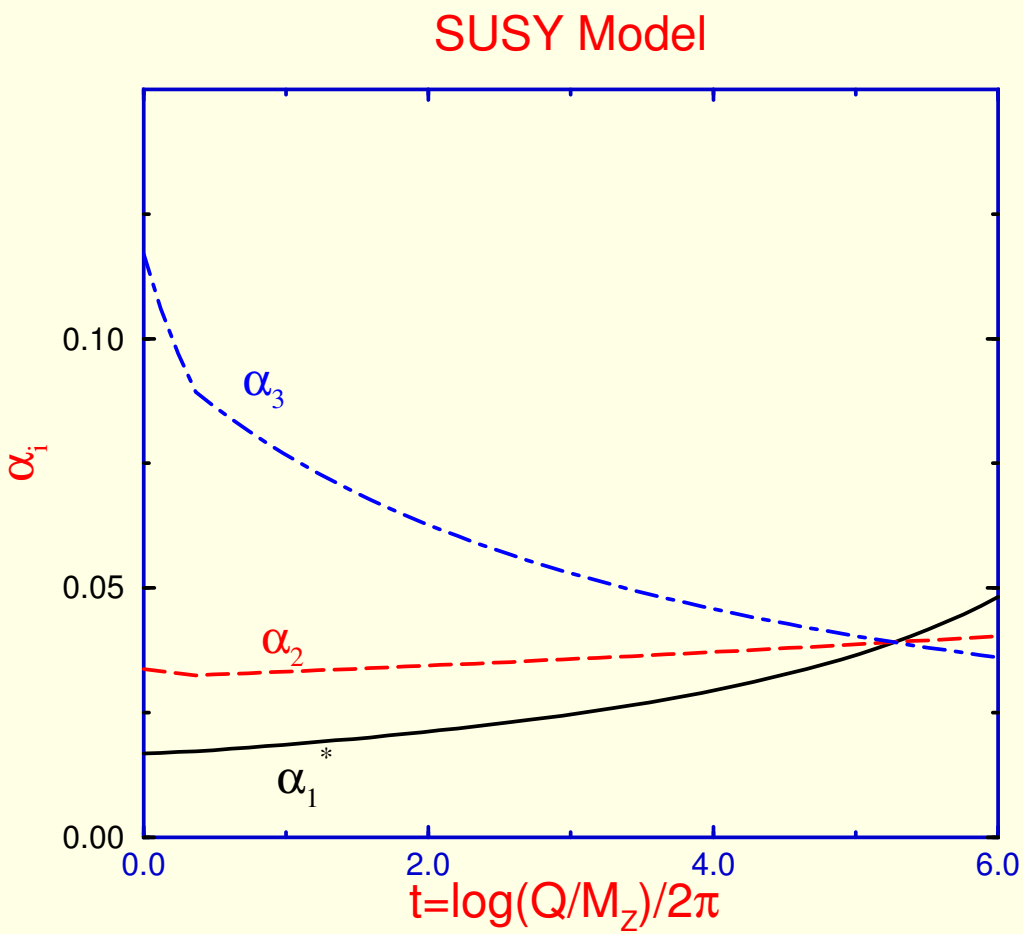
But parameter space is getting restricted by WMAP (small blue region) Ellis, Olive...
details rather model dependent



Nice features of SUGRA model II

Coupling constant unification is not bad.

But it's not perfect



Gauge Mediated breaking

Problem with SUGRA is that gravity knows nothing about EW interactions.
Why do the flavors align?: quark flavor states are determined by EW structure; squarks by both SUSY breaking and EW. In general expect large flavor changing neutral currents and lepton disasters like $\mu \to e\gamma$
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, but its $mass^2$ so

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

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; can be long lived

Lacks a natural dark matter candidate.

Unification still possible.

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.

Charateristic 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 ("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.

Anomaly mediated breaking

Superconformal anomaly always present
predicts sparticle masses in terms of $m_{3/2}$ Randall, Sundrum, Luty, Giudice, Wells, Murayama, Jones...
Generates gaugino masses with very differant structure

$$M_i = \frac{\beta(g_i)}{2g_i^2} m_{3/2}$$

Simplest version predicts tachyonic sleptons!
Some other SUSY breaking mechanism must be present to get realistic spectrum
Add universal squark masses (mAMSB) or new very heavy fields (DAMSB)
AMSB only – Most important feature $M_3 > M_1 > M_2 \Rightarrow$ LSP is a $\tilde{W}^0$ and almost degenerate with $\tilde{\chi}_1^+$
Critical prediction $\tilde{\chi}_1^+ \to \tilde{\chi}_1^0 \pi^+$ with $c\tau < 10$ cm But very model dependent.
Sleptons are lighter than squarks $\tilde{q}_r \to \tilde{\chi}_2^0 q$ and $\tilde{q}_l \to \tilde{\chi}_1^0 q$, *i.e. opposite* to SUGRA and GMSB.
Gravitino mass is $\sim$ TeV, irrelevant to terrestrial experiments.
$\tilde{q}_r \to \tilde{\chi}_2^0 q$ and $\tilde{q}_l \to \tilde{\chi}_1^0 q$, *i.e. opposite* to SUGRA and GMSB.

Timeout – some typical spectra

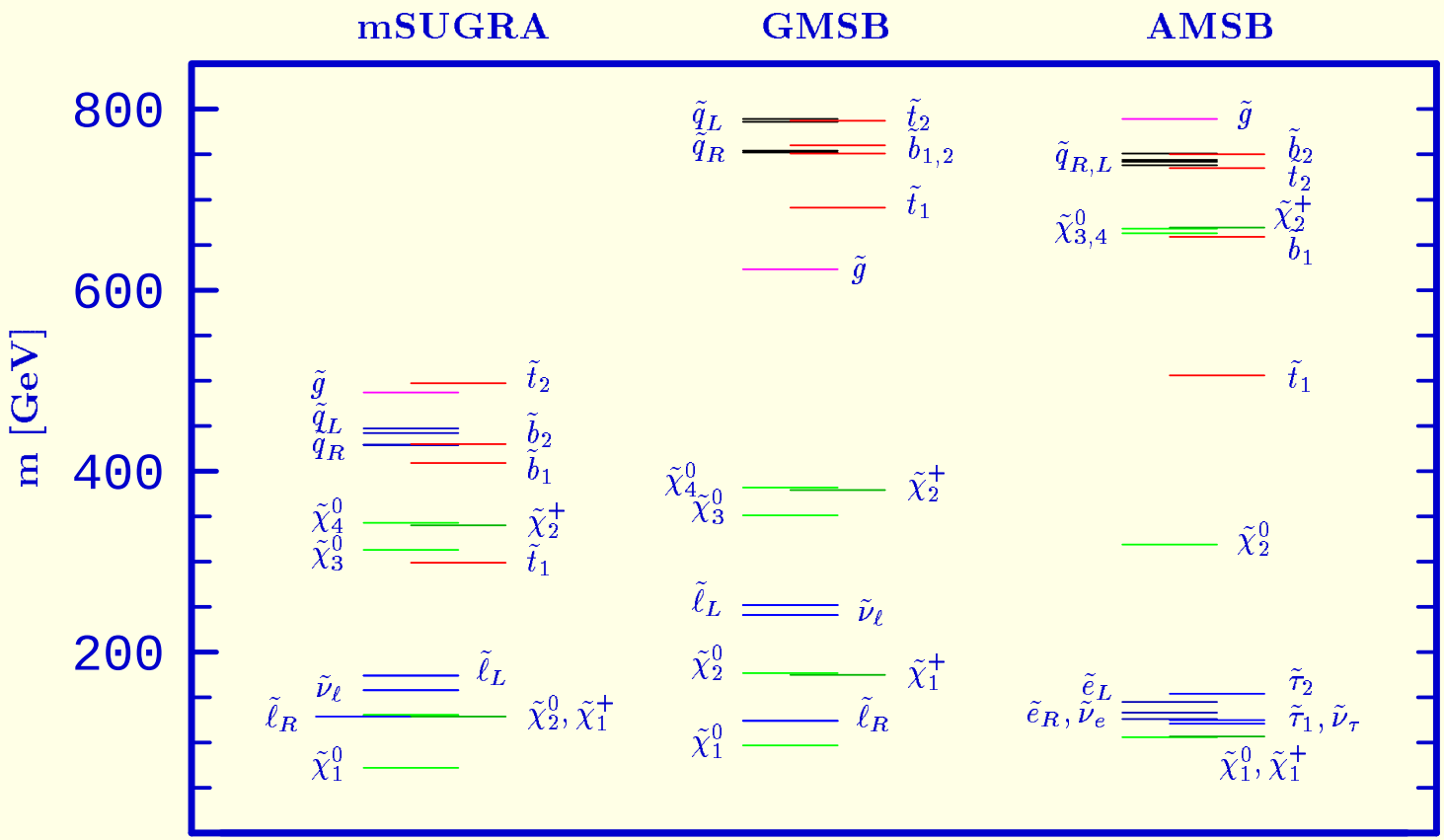


Figure 3.0.1: *Examples of mass spectra in mSUGRA, GMSB and AMSB models for* $\tan\beta = 3$, *sign* $\mu > 0$. *The other parameters are* $m_0 = 100$ *eV*, $m_{1/2} = 200$ *GeV for mSUGRA;* $M_{\rm mess} = 100$ *TeV*, $N_{\rm mess} = 1$, $\Lambda = 70$ *TeV for GMSB; and* $m_0 = 200$ *GeV*, $m_{3/2} = 35$ *TeV for AMSB.*

Out of this world breaking I – gaugino mediation

Motivated by theory of extra dimensions. Recall that strings need extra dim, so may not be totally crazy.

5D theory with 2 4-d boundaries (branes). We live on one. SUSY is spontaneously broken on the other.

Quarks and leptons trapped on our brane. Gauge fields propagate in all 5-d.

Gauginos get mass since they interact with the other brane.

At some compactification scale $m_0 = A = 0$, natural to assume a unification so only parameter is $M_{1/2}$

Scalar masses arise at one loop from gaugino interactions hence "gaugino mediated".

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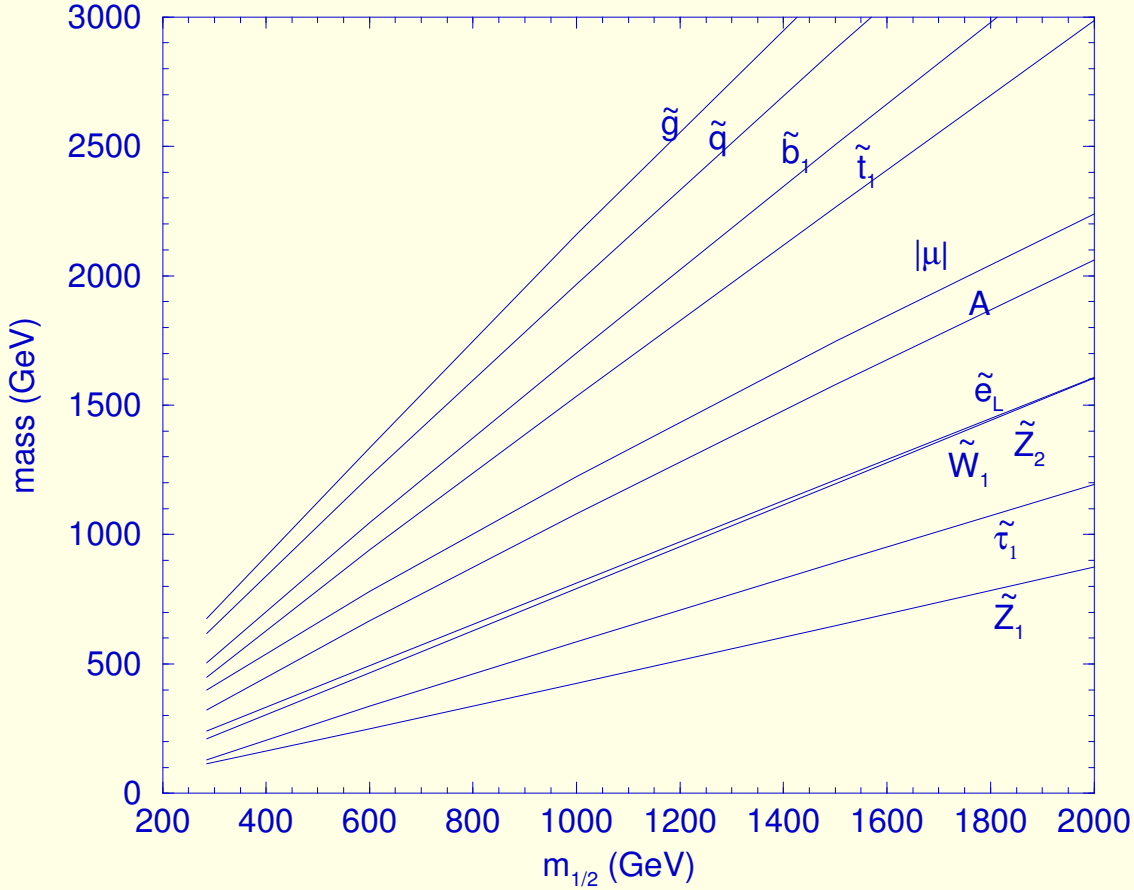
No flavor problem

Stau is light: may be the only slepton is gluino decay



Out of this world breaking II – boundary conditions

Again theory of extra dimensions. Barbieri, Hall, Ratazzi, Nomuara....

$5th$ dimension is compactified with boundary conditions that violate SUSY.

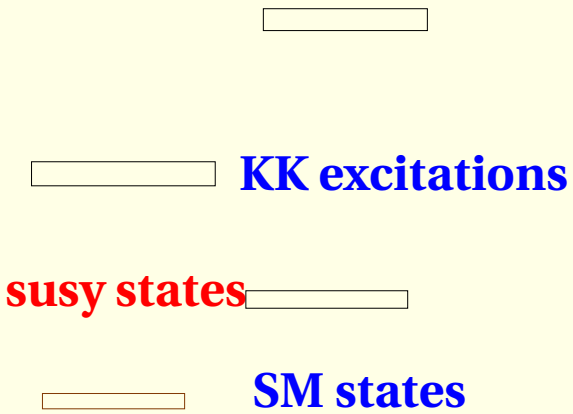
SUSY is explicitly broken but only at a single point

Low energy spectrum is not MSSM (h violates the bound discussed above)

SUSY spectrum is compressed

Quasi-stable stop

Dark matter?



How do we sort it out?

SUSY breaking sector not observable directly

Must be inferred from pattern of susy breaking parameters, masses and couplings.

Critical tests

Is there missing E_T? "yes" $\rightarrow$ No Rparity

Do gaugino masses fit a GUT unification scheme? "no" $\rightarrow$ not SUGRA

Yukawa couplings and mixings of third generation squarks and sleptons?

Is there flavor violation in the slepton sector? "yes" $\rightarrow$ Neutrino masses?

Is there an inverted hierarchy in the squark sector?

Are there quasi stable charged particles? "yes" $\rightarrow$ GMSB

Will require large number of measurements at differant facilities, LHC, Boulby, $g-2$, Tevatron, NLC

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Experimental searches

Easiest to discuss in e^+e^- (most theory lives here)

LEP limits are almost model independent. $M(charged) > 90GeV$

Future experiments very powerful. SUSY particles pair produced masses and properties can be sorted out.

Given the expected mass spectra NLC is focused on EW sparticles.

Hardest to discuss in hadron colliders (most experiment will live here)

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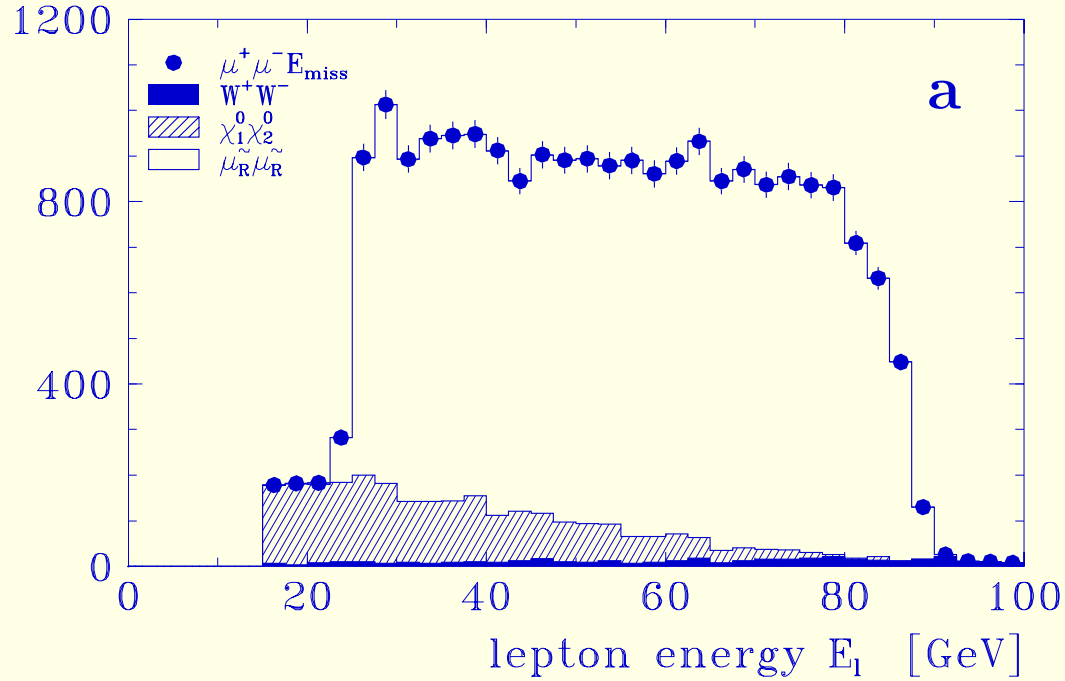
$\tilde{\mu} \to \tilde{\chi}_1^0 \mu$

Pair production
Events have $\mu^+\mu^-$ and missing energy
Note small SM background

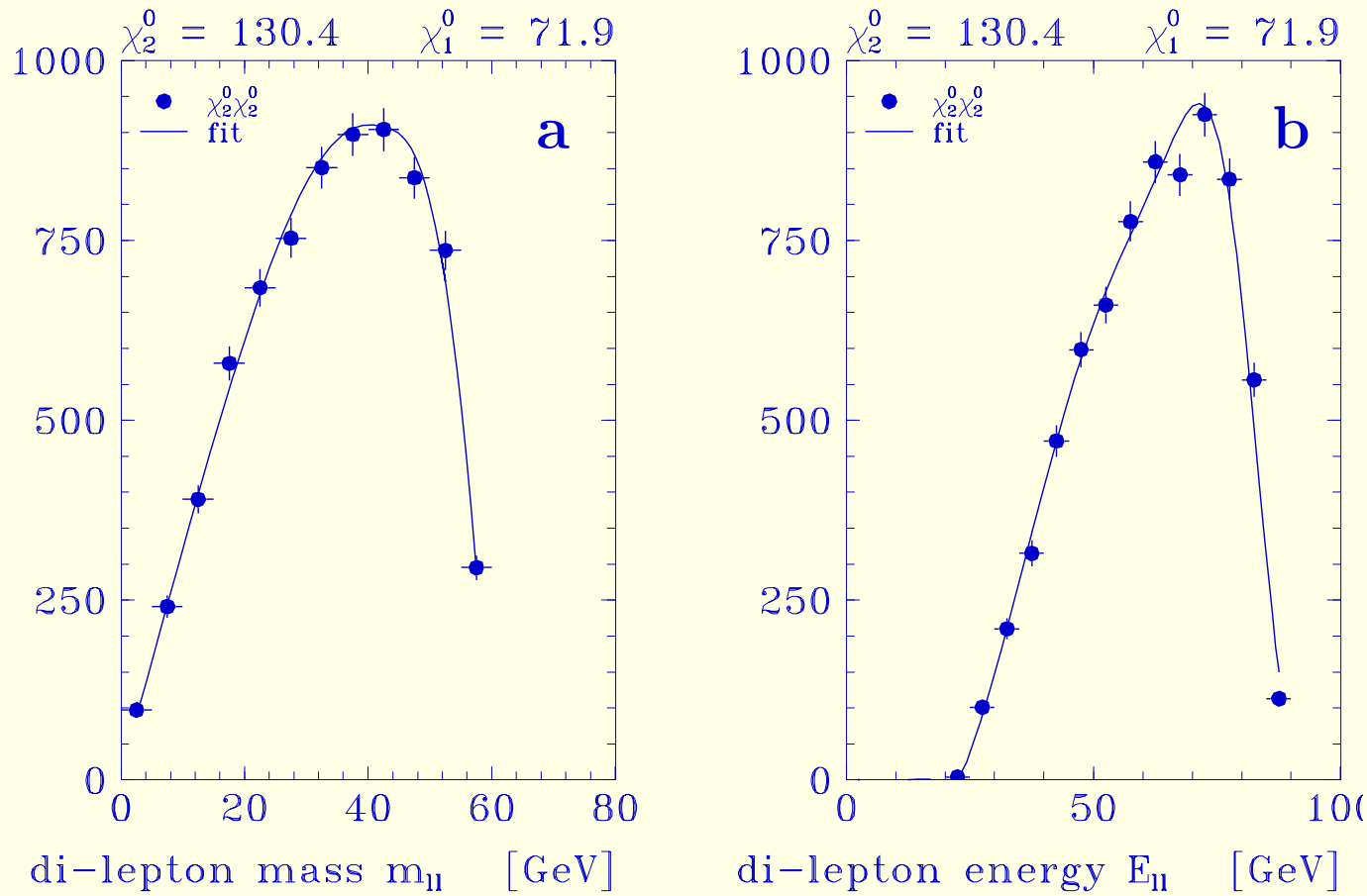


Can determine both $\tilde{\chi}_1^0$ and $\tilde{\mu}$ mass to $\sim 0.5\%$

SUSY background is zero in this study as machine is below threshold for other sparticles.

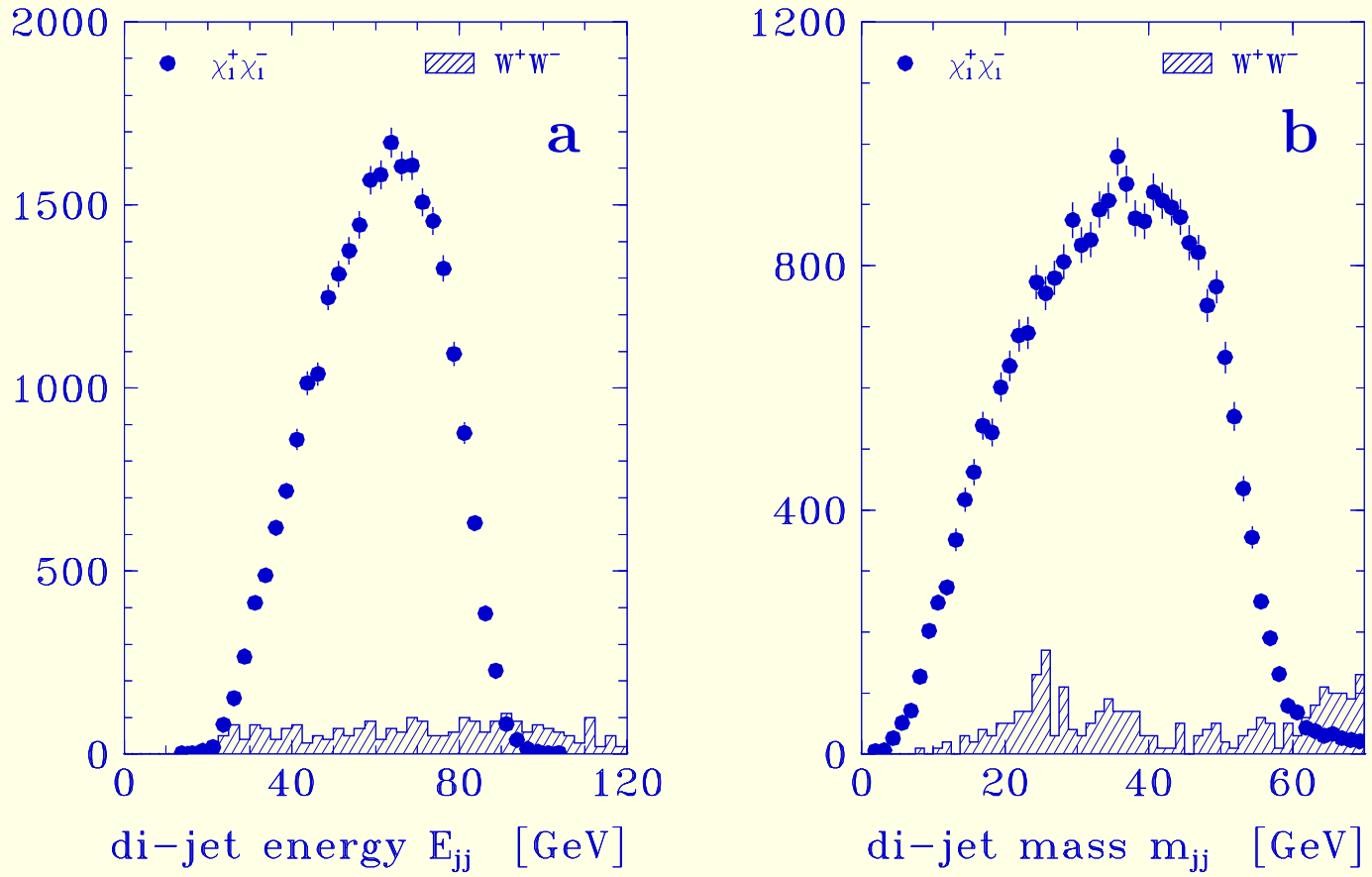
Polarization can measure amount of left and right slepton in mass eigenstate

At larger energy can produce heavier gauginos $e^+e^- \to \widetilde{\chi}_2^0\widetilde{\chi}_2^0 \to \ell^+\ell^-\ell^+\ell^-\widetilde{\chi}_1^0\widetilde{\chi}_1^0$



Measures both $\widetilde{\chi}_2^0$ and $\widetilde{\chi}_1^0$ masses

$e^+e^- \to \widetilde{\chi}_1^+\widetilde{\chi}_1^- \to \ell^+\nu q\overline{q} - \widetilde{\chi}_1^0\widetilde{\chi}_1^0$



Tevatron and LHC

Everything is produced at once.

In hadron colliders squarks and gluinos have largest rates if $\sqrt{s}$ big enough

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

Dominant backgrounds at LHC are combinatorial from SUSY events themselves.

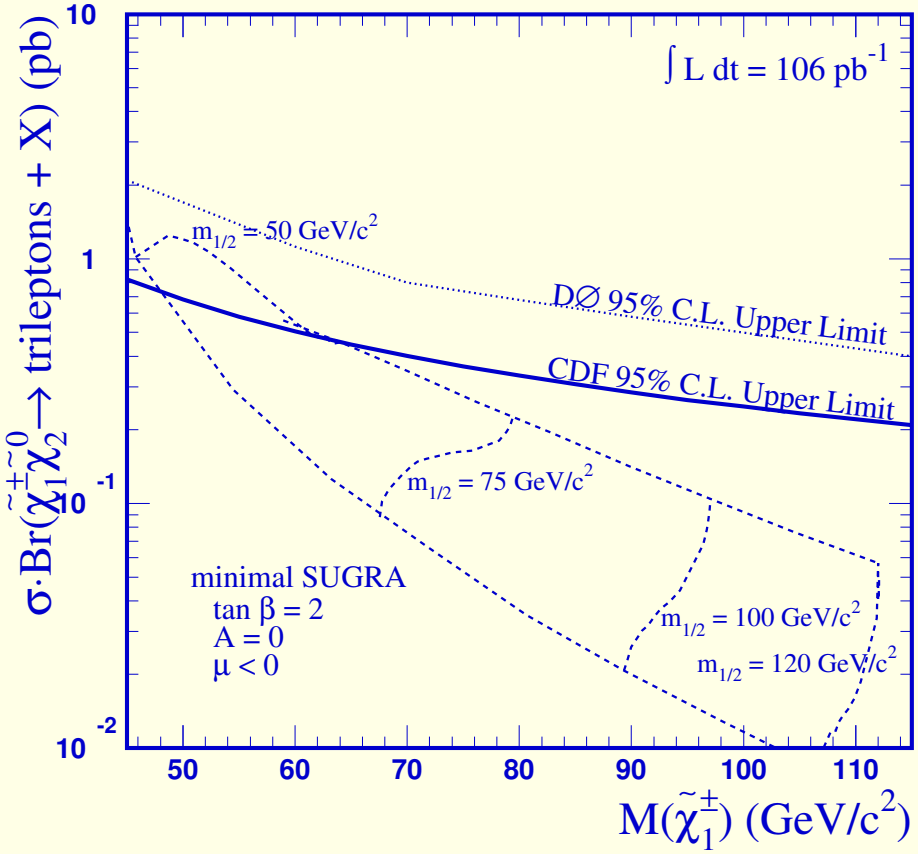
Strategies different at LHC from Tevatron where weak gaugino production probably dominates and $\tilde{\chi}_1^+ \tilde{\chi}_2^0 \to 3\ell + X$ is important.

Tevatron

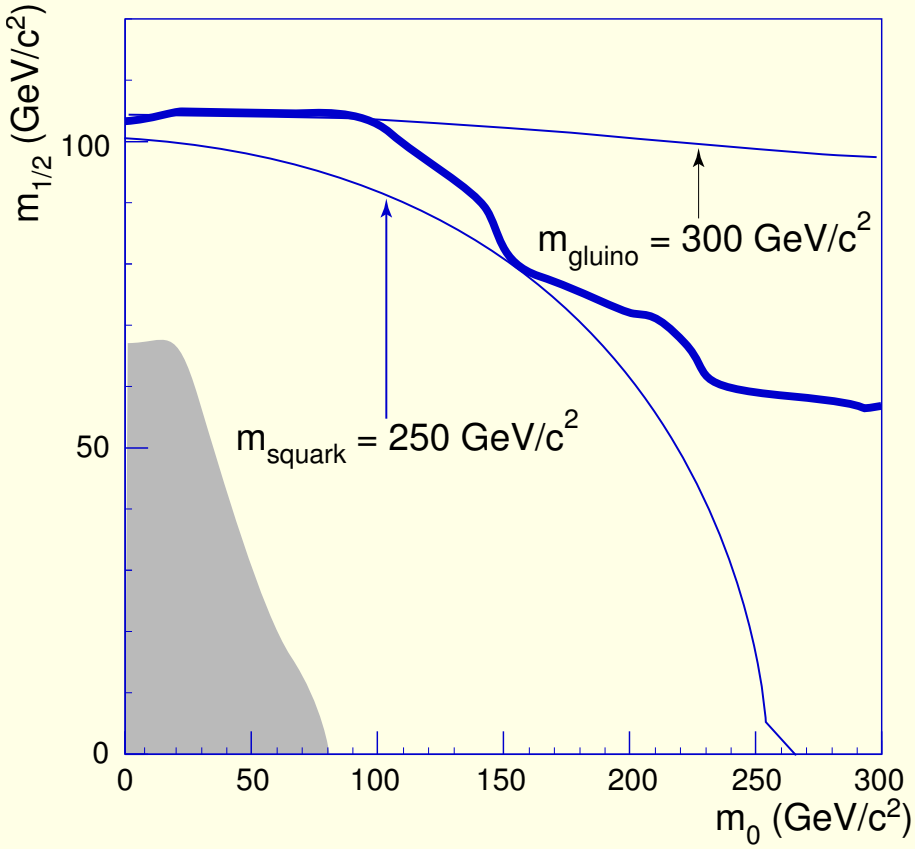
No signal claimed by an experiment

Inclusive signals based on Leptons jets and $\not{E}_T$ show no signal.

Limits are model dependent. These are for SUGRA



. $\ell^+\ell^+\ell^-$



. D0 from $jets + \not{E}_T$

TeVII will extend mass range, $\sqrt{S} = 2\,\mathrm{TeV}$ and $\sim 100\times$ luminosity

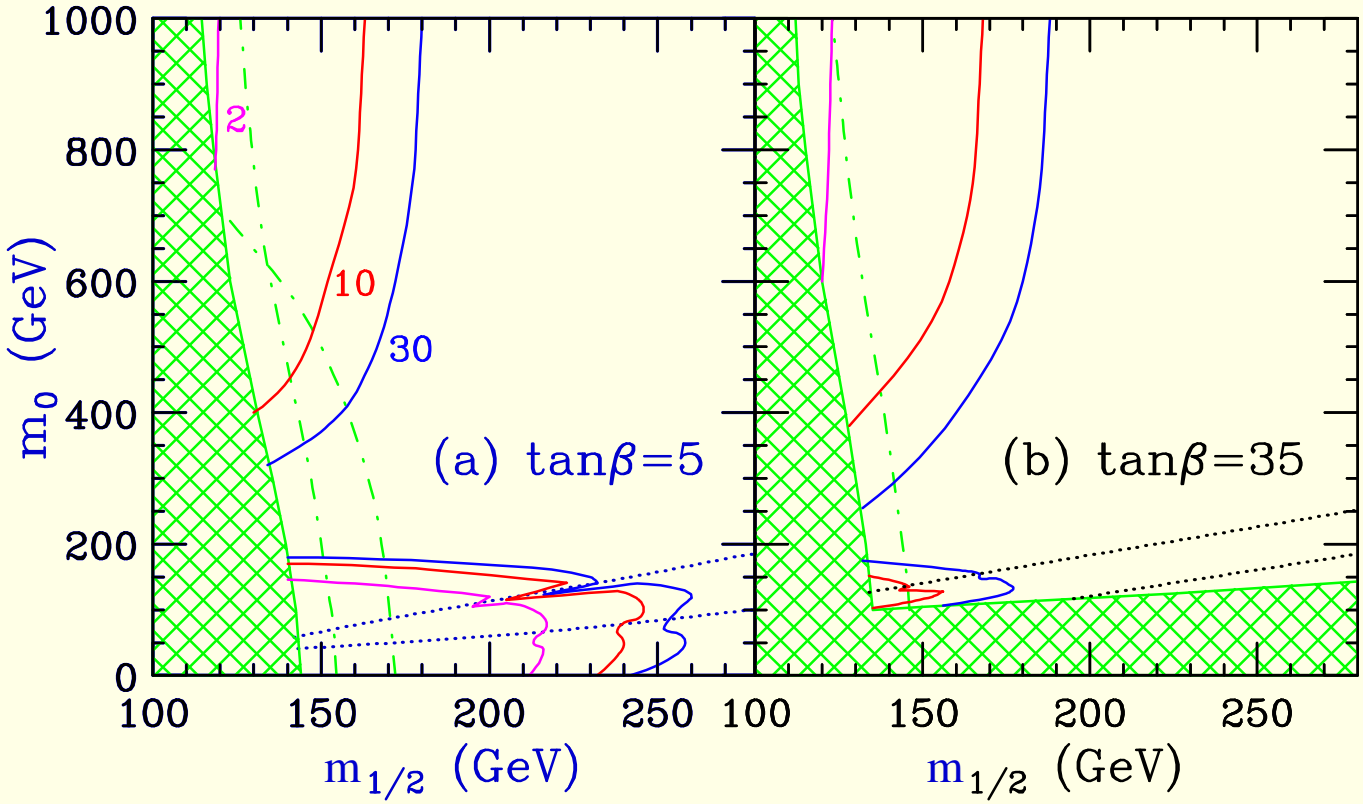
But reach is limited

Squark and gluino production may not dominate

Best hope is production of $\widetilde{\chi}_2^0\widetilde{\chi}_1^+ \to \ell^+\ell^-\widetilde{\chi}_1^0\ell^+\nu\widetilde{\chi}_1^0$

Background dominated by WZ^*

Tevatron study hep-ph/0003154



3σ contours.

Accessible masses at LHC

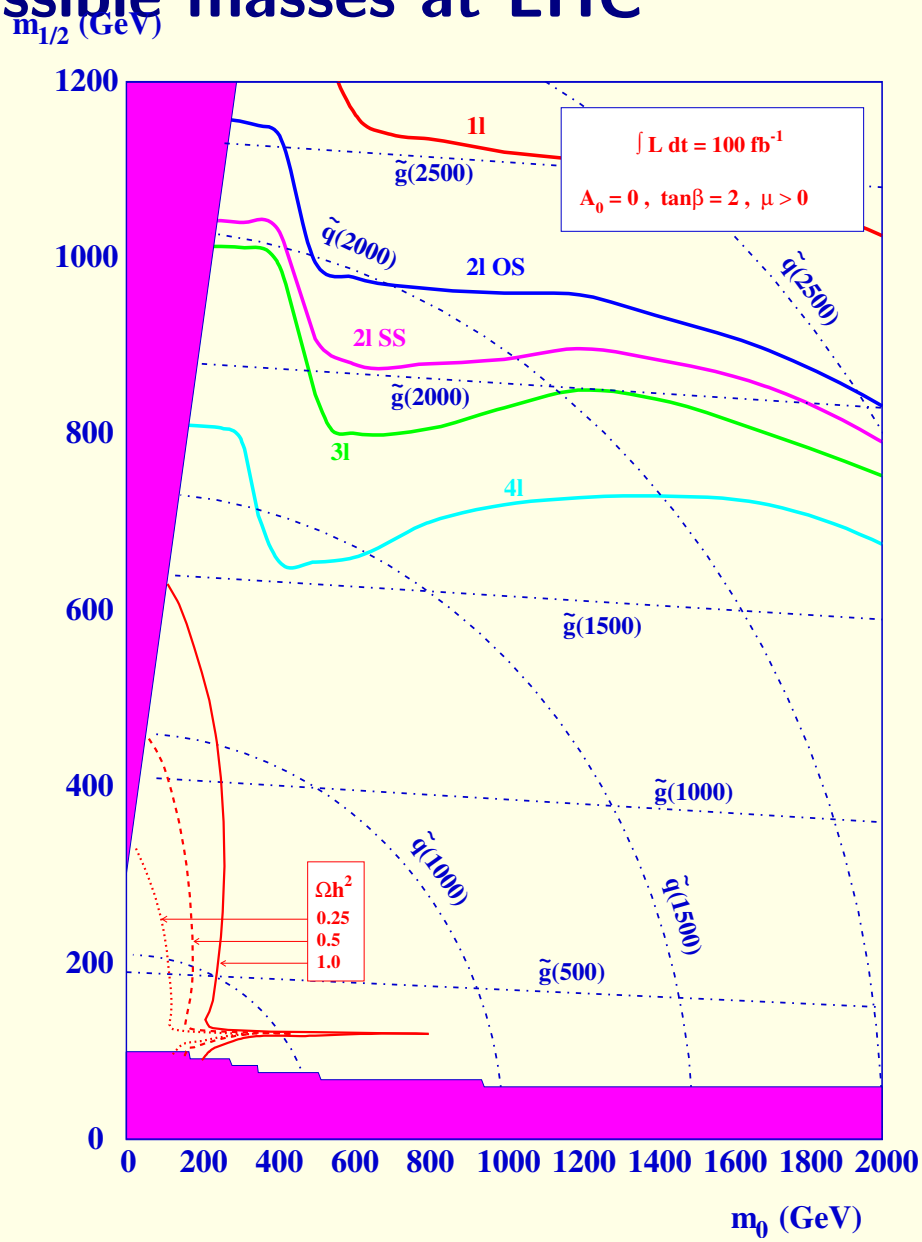
Very large range of accessible masses in inclusive signals

$jets + \not{E}_T \; etc$

Plot shows SUGRA mass reach (CMS)

Covers all interesting theoretical range

$m_{\tilde{g}} \lesssim 2.5\,\mathrm{TeV}$



Characteristic 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. $e.g.$ $\widetilde{q_L} \to \widetilde{\chi}_2^0 q_L$

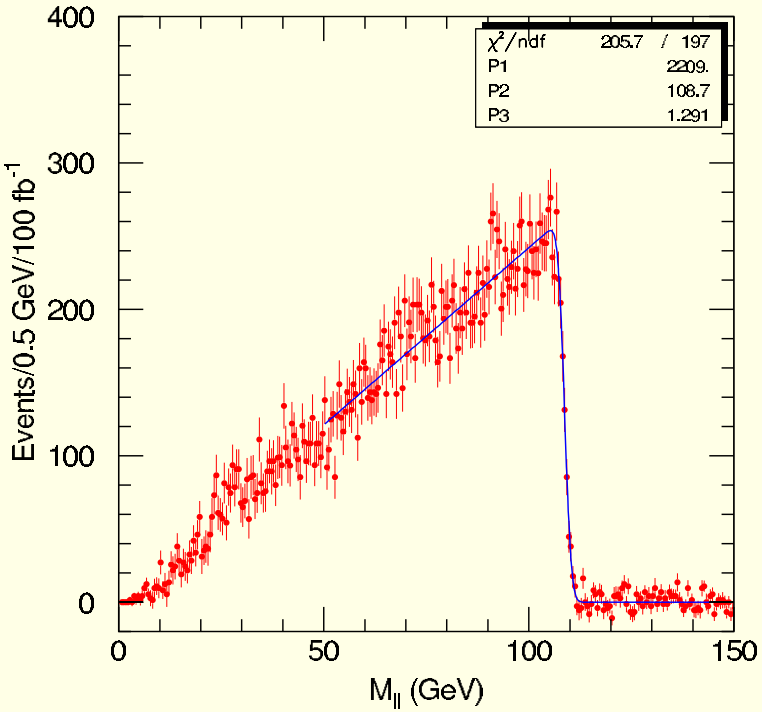
Two generic features
$\chi_2^0 \to \chi_1^0 h$ or
$\chi_2^0 \to \chi_1^0 \ell^+\ell^-$ possibly via intermediate slepton $\chi_2^0 \to \widetilde{\ell^+}\ell^- \to \chi_1^0 \ell^+\ell^-$
Former tends to dominate if kinematically allowed.

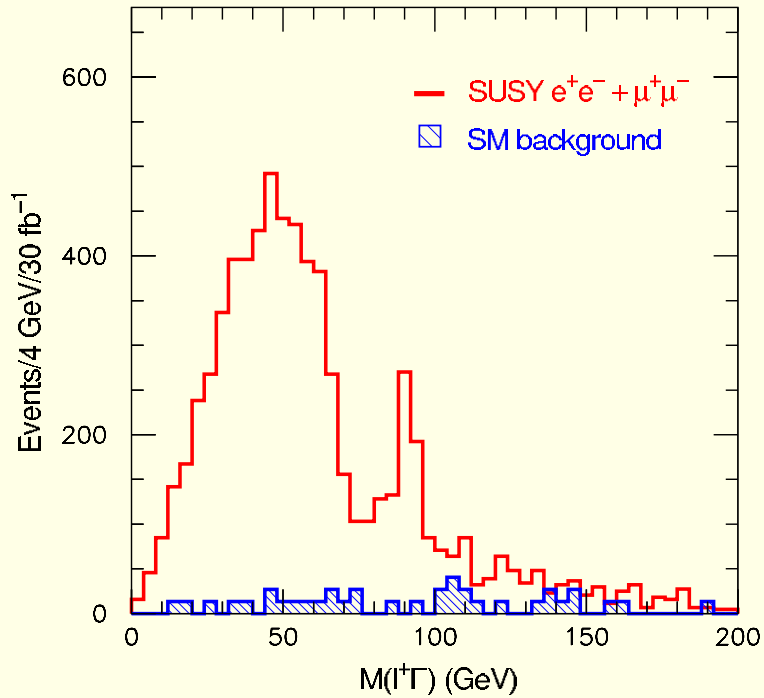
Use these characteristic decays as a starting point for mass measurements

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

an LHC example

Isolated leptons indicate presence of t, W, Z, weak gauginos or sleptons
Key decays are $\widetilde{\chi}_2 \to \widetilde{\ell}^+\ell^-$ and $\widetilde{\chi}_2 \to \widetilde{\chi}_1\ell^+\ell^-$
Mass of opposite sign same flavor leptons is constrained by decay



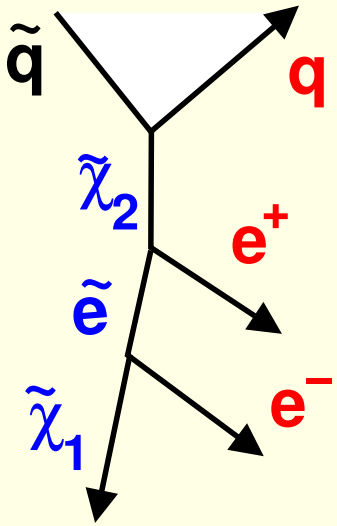


Decay via real slepton: $\widetilde{\chi}_2 \to \widetilde{\ell}^+\ell^-$
Plot shows $e^+e^- + \mu^+\mu^- - e^\pm\mu^\mp$

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

Building on Leptons

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



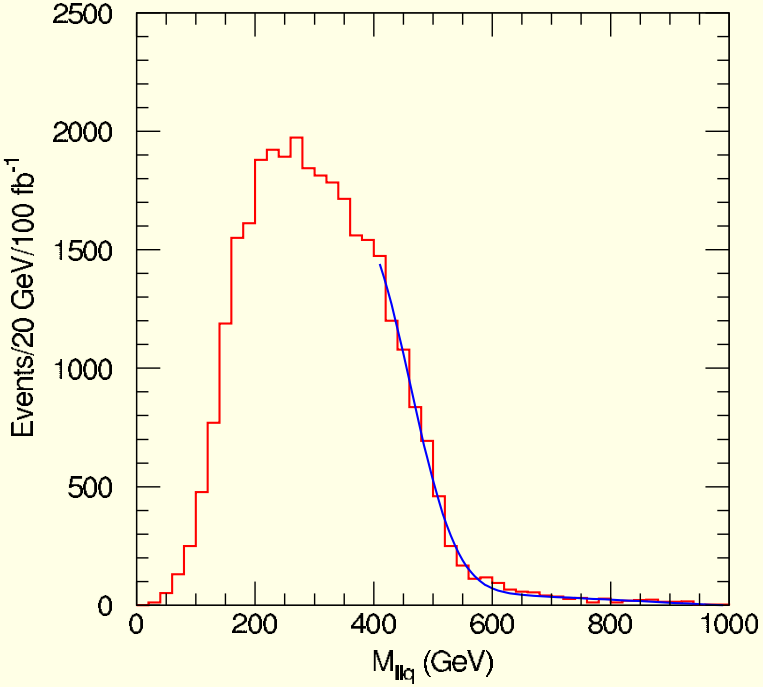
Identify and measure decay chain

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

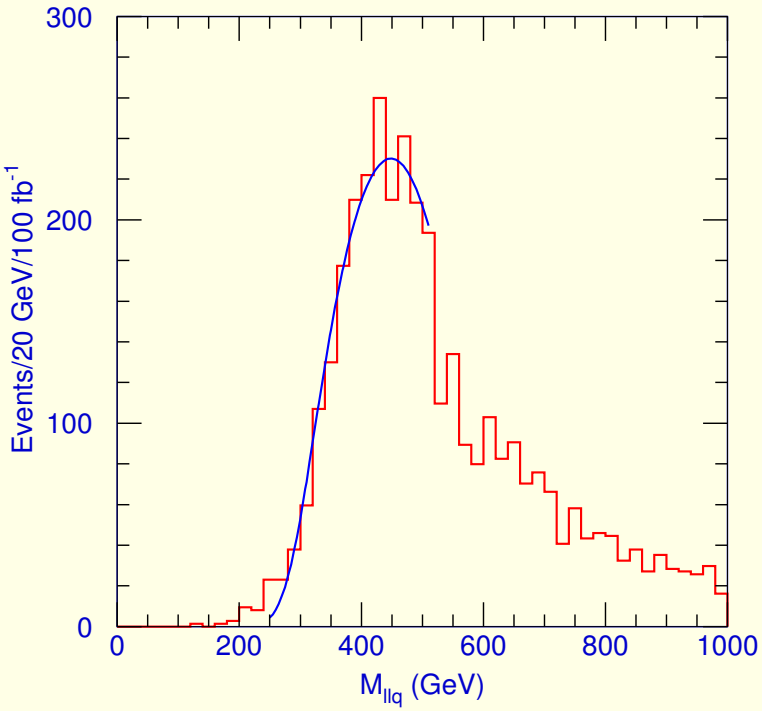
Mass of $q\ell\ell$ system has max at

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

and min at 271 GeV



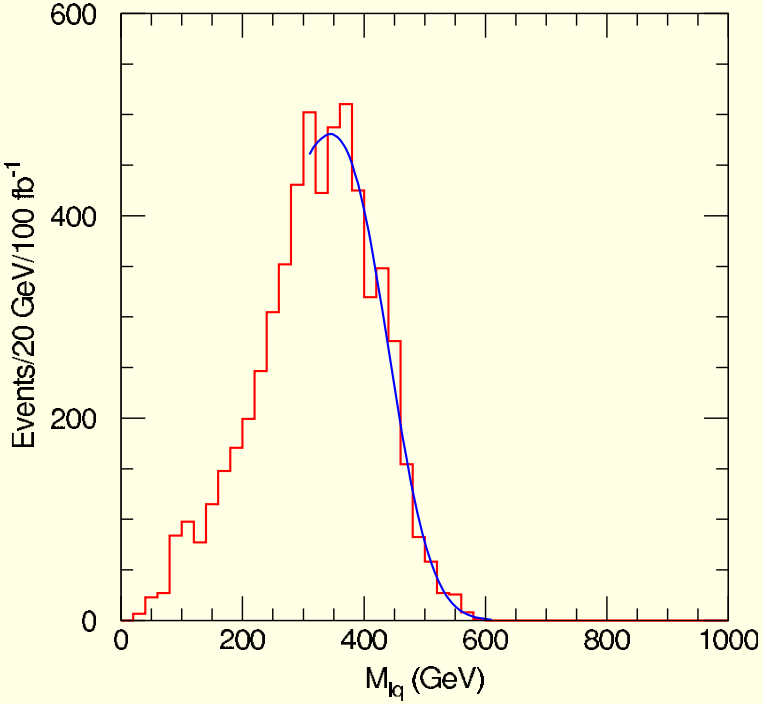
smallest mass of possible $\ell\ell jet$ combinations



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

Kinematic structure clearly seen

Can also exploit ℓjet mass

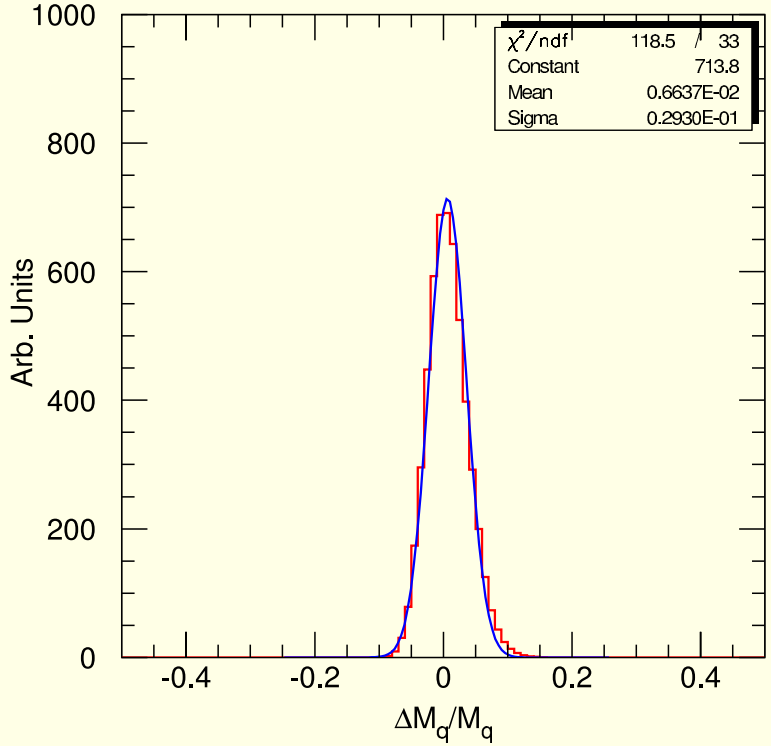


Can now solve for the masses. Note that no model is needed

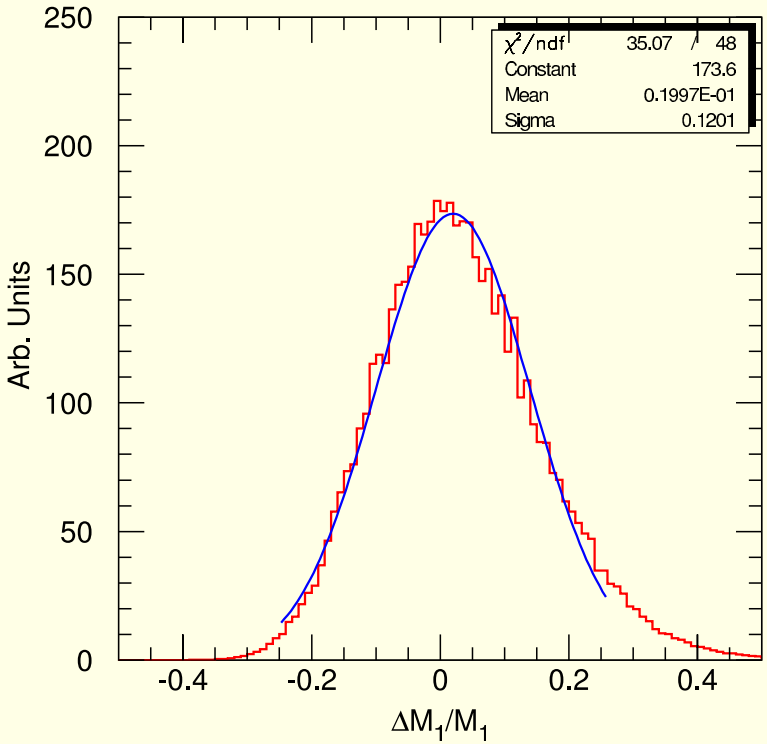
Very naive analysis has 4 constraints from $lq, llq_{upper}, llq_{lower}, ll$ masses

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



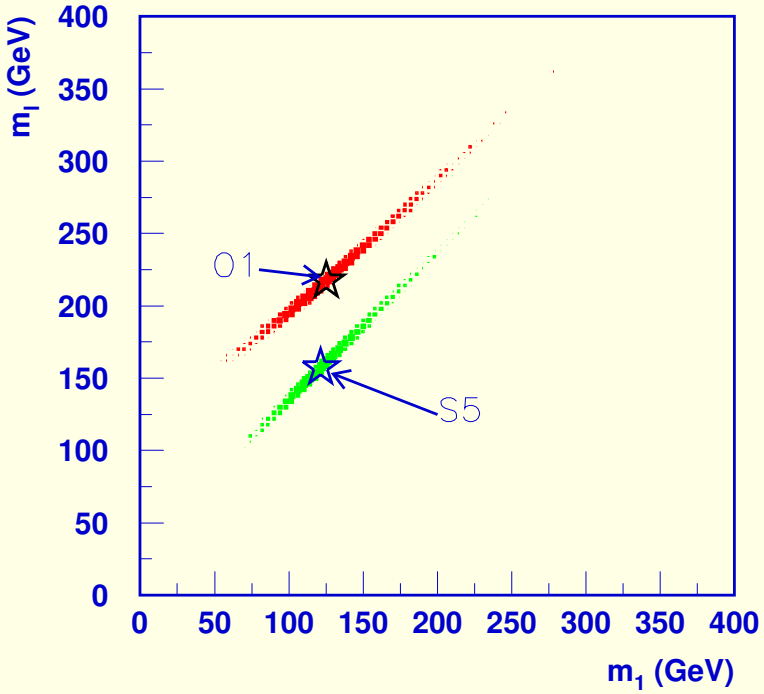
. Squark mass



. LSP mass

Mass of unobserved LSP is determined

Errors are strong correlated and a precise independent determination of one mass reduces the errors on the rest. Allanach *et.al.*



Discovery cannot be far off

"The train is already late" (Altarelli): Fine tuning is a problem already.

We expected gauginos in the LEP range

Tevatron "window" is small but low masses are more likely

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.