

SUSY and Colliders - II.

- Particle spectra for different SUSY breaking scenarios and generic signatures.
- Non observation of SUSY – so far
- **Wish list**
- What can LHC do for SUSY search?
- What can LHC tell us about SUSY (**breaking**)?
- What can the ILC do?; LHC-ILC interplay.
- Interplay between Colliders and Cosmology?

Main ideas discussed here: Gravity mediation (mSUGRA), moduli mediation, GMSB and AMSB. $10 \text{ TeV} < \Lambda_s \leq M_M \leq M_{Pl}$ and $M_M \simeq \Lambda_s^2/M_s$

Mediation mechanism	Model	Gravitino mass $m_{3/2}$	Gaugino mass M_α	Sfermion mass squared m_i^2
Gravity mediated	mSUGRA	$\leq \mathcal{O}(\text{TeV})$	$(g_\alpha/g_2)^2 M_2$	$m_0^2 + G_i M_{1/2}^2 + \text{D-terms}$
	$\tilde{\text{C}}\text{MSSM}$	$\leq \mathcal{O}(\text{TeV})$	$(g_\alpha/g_2)^2 M_2$	$\tilde{q}_L: m_{\tilde{q}_L}^2 + G_{\tilde{q}_L} M_{1/2}^2 + \text{D-terms}$ $\tilde{l}_L: m_{\tilde{l}_L}^2 + G_{\tilde{l}_L} M_{1/2}^2 + \text{D-terms}$ $\tilde{e}_R: m_{\tilde{e}_R}^2 + G_{\tilde{e}_R} M_{1/2}^2 + \text{D-terms}$ $\tilde{u}_R: m_{\tilde{u}_R}^2 + G_{\tilde{u}_R} M_{1/2}^2 + \text{D-terms}$ $\tilde{d}_R: m_{\tilde{d}_R}^2 + G_{\tilde{d}_R} M_{1/2}^2 + \text{D-terms}$
	AMSB	20–100 TeV	$(g_\alpha b_\alpha/g_2 b_2)^2 M_2$	$m_0^2 + C_i (16\pi^2)^{-2} m_{3/2}^2$
Gauge mediated	mGMSB	$10^{-5} \text{ eV} - 1 \text{ keV}$	$(g_\alpha/g_2)^2 M_2$	$\tilde{q}_L: M_3^2 G'_{\tilde{q}_L} + \text{D-terms}$ $\tilde{l}_L: M_2^2 G'_{\tilde{l}_L} + \text{D-terms}$ $\tilde{e}_R: M_2^2 G'_{\tilde{e}_R} + \text{D-terms}$ $\tilde{u}_R: M_3^2 G'_{\tilde{u}_R} + \text{D-terms}$ $\tilde{d}_R: M_3^2 \tilde{G}'_{\tilde{d}_R} + \text{D-terms}$

mSUGRA $M_1 : M_2 : M_3 \simeq 1 : 2.8 : 7$, $m_0, M_{1/2}, A, \tan \beta, \text{sgn}(\mu)$

mGMSB : similar, subject to some corrections depending on couplings of the messenger fields. $M_M, \Lambda_s, \text{sgn}(\mu), \tan \beta, n_q, n_l$ and $m_{3/2}$.

AMSB: $M_1 : M_2 : M_3 \simeq 2.8 : 1 : 8.3$, $m_0, M_{3/2}, \tan \beta, \text{sgn}(\mu)$.

mSUGRA: LSP is $\tilde{\chi}_1^0$.

mGMSB Gravitino is LSP, NLSP: $\tilde{\chi}_1^0, \tau_1, \tilde{e}_R$. NLSP can be long lived and quasi stable! Cosmological constraints on $m_{3/2}$ and hence on scale of SUSY breaking.

mSUGRA, mGMSB: Once LEP constraints are imposed, $\tilde{\chi}_1^0$ is an almost pure $U(1)$ gaugino and $\tilde{\chi}_2^0 \sim$ pure $SU(2)$ gaugino. ($|M_1| < |\mu|$).

Note : These things have important implications for viability of the LSP as the DM. Higgsinos annihilate too efficiently and can be a good DM candidate only if heavier than \sim TeV.

AMSB: Both $\tilde{\chi}_1^\pm, \tilde{\chi}_1^0$ are pure $SU(2)$ gauginos and degenerate. Loop effects need to be included to lift the degeneracy.

Most of the constraints come in the form of inequalities.

The first two generation squarks can not be much lighter than the gluinos.

$$(m_{\tilde{q}}/m_{\tilde{t}}) |_{GMSB} > (m_{\tilde{q}}/m_{\tilde{t}}) |_{mSUGRA} ;$$

$$m_{\tilde{e}} < m_{\tilde{q}} \text{ for mSUGRA};$$

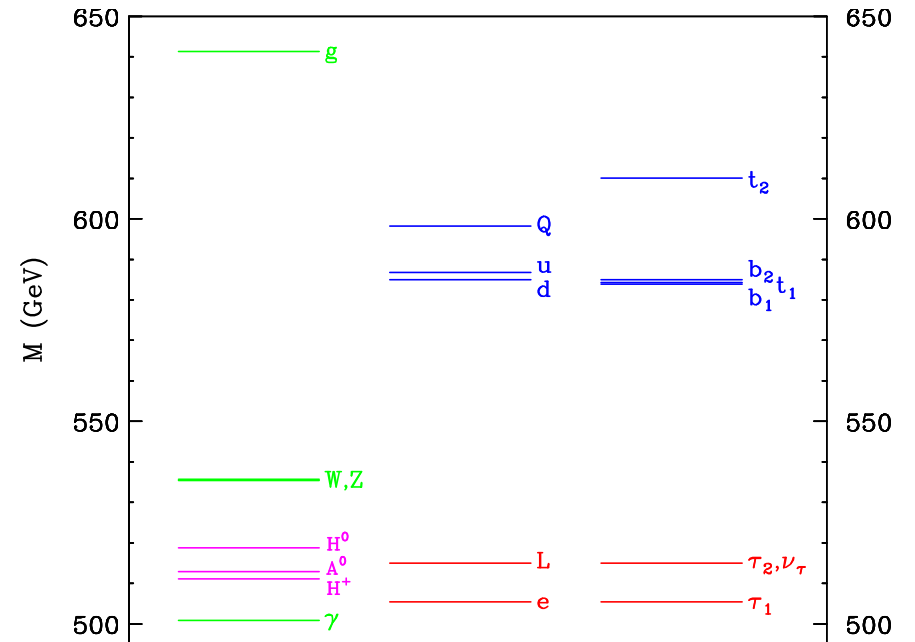
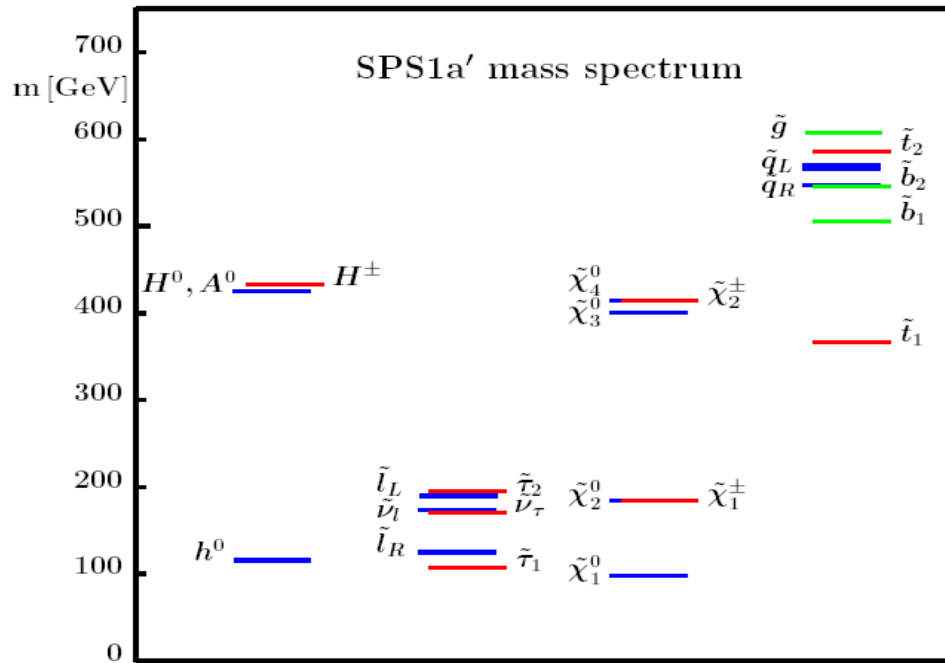
$$m_{\tilde{e}_L} \simeq m_{\tilde{e}_R} \text{ for GMSB};$$

$$m_{\tilde{e}_R} < m_{\tilde{e}_L} \text{ for mSUGRA.}$$

Third generation sfermions are lighter than the other two due to the larger Yukawa coupling contribution to the running.

It is already indicative that a lepton collider will be, in fact, a much better probe to discriminate between different SUSY breaking ideas.

A representative spectrum. One of the benchmark points for LHC analyses. In fact the UED models predict similar spectra. So one needs to determine the spins then!



$$R_p = (-1)^{(3(B-L)+2S)} = (-1)^{(3B-L+2S)}$$

▷ Supersymmetry and Gauge Invariance allow \mathcal{R}_p terms in the Superpotential

$$\mathcal{W}_{\mathcal{R}_p} = -\epsilon_i L_i \cdot H_2 + \frac{1}{2} \lambda_{ijk} L_i \cdot L_j \bar{E}_k + \lambda'_{ijk} L_i \cdot Q_j \bar{D}_k + \frac{1}{2} \lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k$$

Conservation: Sparticles produced in pairs and lightest Sparticle (LSP) is absolutely stable, giving rise to missing E_T .

With \mathcal{R}_p DM candidate is lost, as the $\tilde{\chi}_1^0$ not stable.

- Proton will decay **very rapidly** for TeV scale SUSY breaking.
- The latter can be cured by adopting B conservation $\lambda'' = 0$.

▷ Actually B, L symmetries of the SM but **NOT** of the MSSM.

- Neither \mathcal{R}_p , nor R_p conservation is mandatory from theoretical point of view.

Some compactifications in unified, string based models actually seem to prefer models with B conservation and R_p violation.

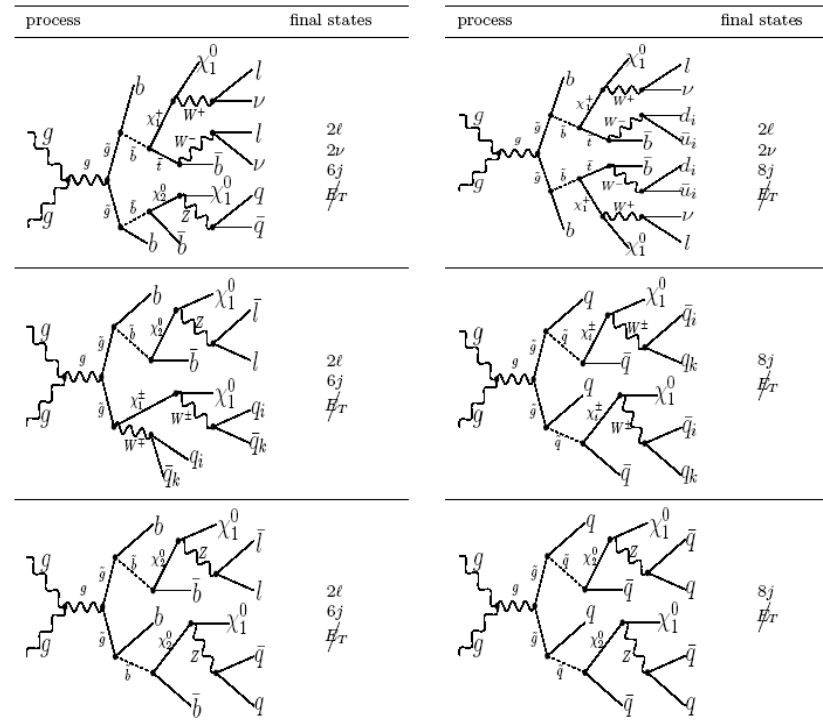
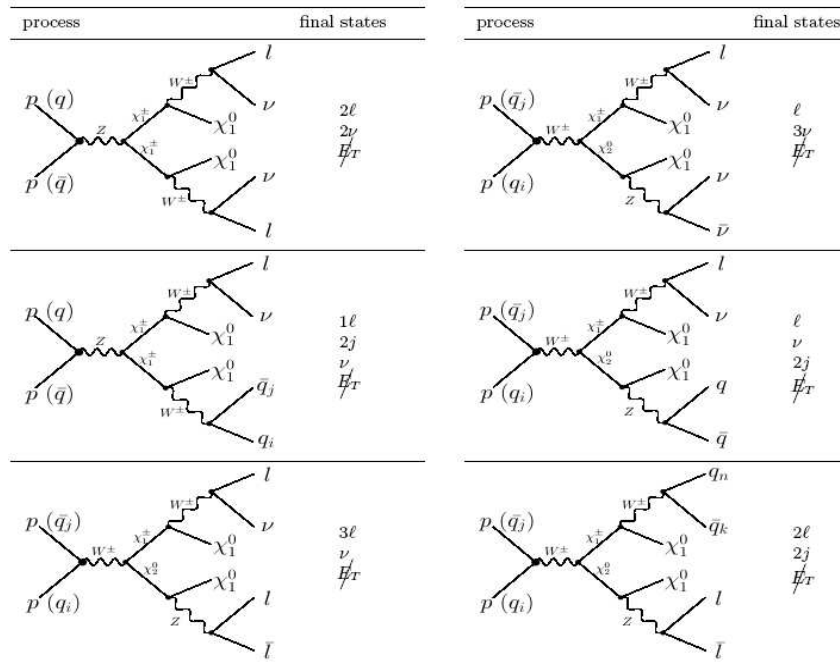
These models treat the Lepton and the Quark fields differently and finally have two discrete (Z_2) symmetries, one of them has to be broken. One option in there is to break R_p and B conservation. This eliminates not just the dimension 4 operators for proton decay BUT also dimension 5.

Interesting models of ν mass generation using \mathcal{R}_p .

- **Discovery of sparticles** and determination of their quantum numbers.
- **Quantitative verification of coupling equalities implied by supersymmetry.**
- **Measurement of the masses of scalars (including Higgs) as well as gauginos.**
- Determination of the gaugino-higgsino mixing parameters.
- Study of the properties of third generation sfermions including *L-R* mixing.

One would then like to use these to reconstruct the lagrangian parameters of SUSY.

LHC can address highlighted points to some extent and also point 2 indirectly. To achieve the rest we need ILC and LHC + ILC.



- **Missing transverse energy signature:** \cancel{E}_T Because of R_p conservation sparticles are produced in pairs and will contain LSP which is **neutral and stable**. At e^+e^- colliders it can be just missing energy: \cancel{E}
- Decay patterns of $\tilde{\chi}_i^0/\tilde{\chi}_j^\pm$ very important.
- Generically m jets, n leptons and \cancel{E}_T .
- In case of GMSB: hard photons which come from decays of the NLSP $\tilde{\chi}_1^0 \rightarrow \gamma\tilde{G}$. Large life times of the NLSP can give rise to pointing photons. So all the above + photons! If $\tilde{\tau}_1$ is the NLSP, heavy longlived charged particle tracks is the signature.
- AMSB : difficult. $165MeV < \Delta M(m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0}) < 1$ GeV and $\tilde{\chi}_1^\pm \rightarrow \tilde{\chi}_1^0 + \pi$. Stopping track in the vertex detector or the soft pion is to be detected.
- R_p : Even then due to very energetic neutrinos missing ET signal is not gone + large number of jets and leptons.

Where do the limits come from?

Direct searches:

NEWS!! No sparticle has been observed yet!

Analysis done in the context of mSUGRA, Pheno. MSSM, mGMSB, AMSB, R_p .

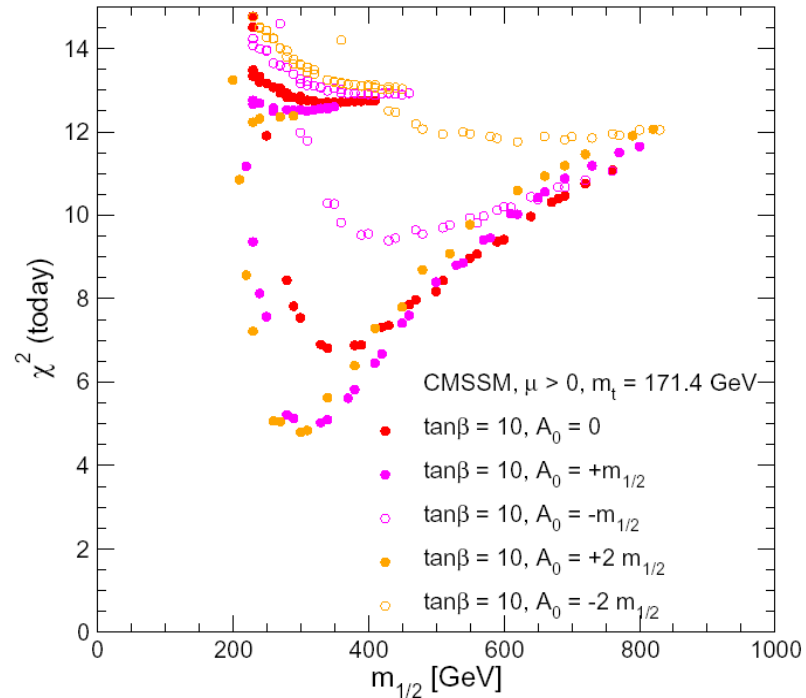
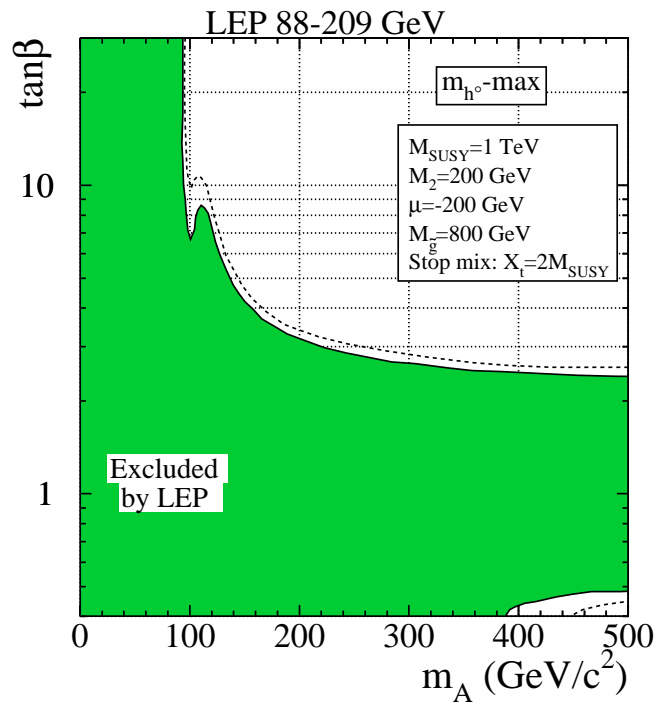
Tevatron: gluinos, squark searches. $m_{\tilde{g}} > 300$ GeV, $m_{\tilde{q}} > 260$ GeV for all flavours but top, $m_{\tilde{t}_1} > 90 - 100$ GeV. Stop different as it can not decay into a t and $\tilde{\chi}_1$

LEP: direct searches for $\tilde{\chi}, \tilde{l}$, Supersymmetric Higgs. $m_{\tilde{\chi}^\pm} > 103$ GeV, $m_{\tilde{t}_1}, m_{\tilde{l}} \gtrsim 90$ GeV.

Large M_A : $m_h > 114$ GeV $M_A \simeq M_Z$: $m_h, m_A > 92$ GeV. This means a bound on M_{H^\pm} . Can be relaxed in NMSSM.

Constraints from $B \rightarrow s\gamma$. **Expt. agrees with the SM.** Constraints on the mSUGRA, may be alleviated with small amount of flavour violation.

Higgs limits can also be translated on limits on SUSY parameter space which determines the Higgs sector, sensitively depend on m_t used. Theoretical activity in calculating Higgs mass accurately to do draw these conclusions. Limits from Higgs mass limits and precision measurements.



Long decay chains:

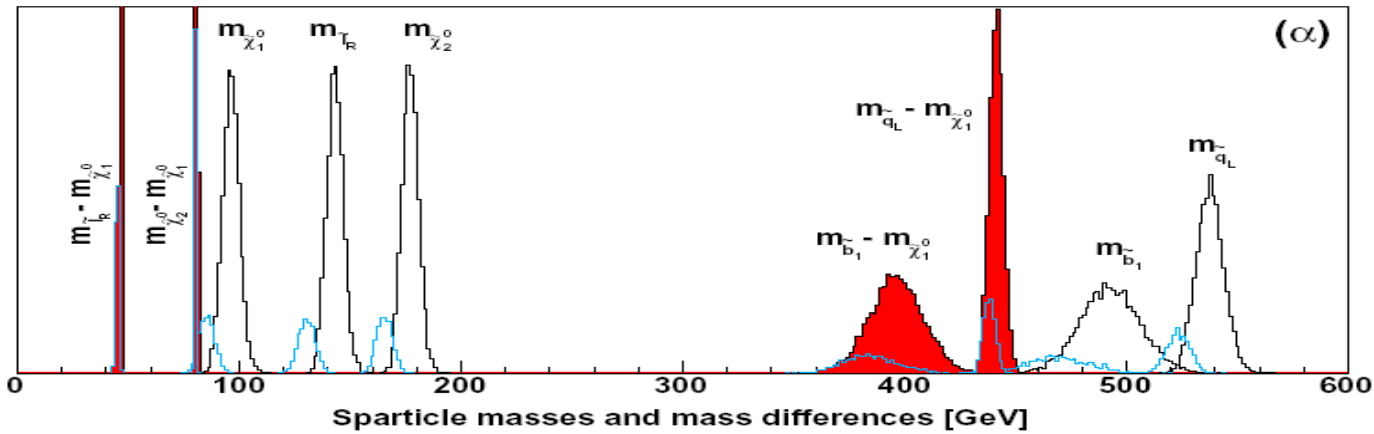
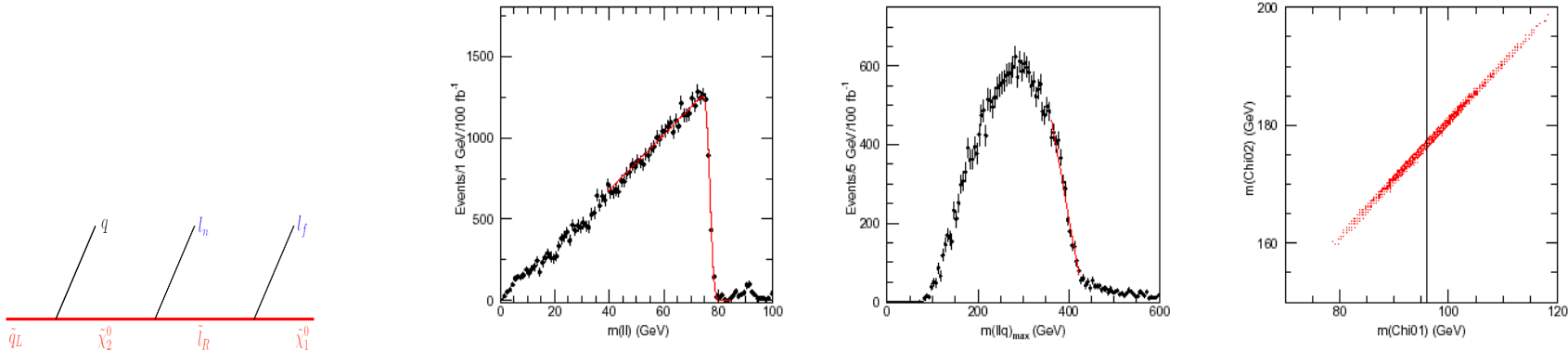
$\tilde{q}_L \rightarrow q\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 f \bar{f}'$ Use kinematics and features of distributions in kinematic variables to determine **mass differences**.

Example:

The distribution in dilepton invariant mass for $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 \ell^- \ell^+$, $m_{\ell^+ \ell^-}$ can be used to decide mass differences.

For $M_{\tilde{\chi}_2^0} < m_{\tilde{\ell}}$, $m_{\ell^+ \ell^-}$ develops a sharp upper edge at $m_{\ell^+ \ell^-}^{\max} = M_{\tilde{\chi}_2^0} - M_{\tilde{\chi}_1^0}$.

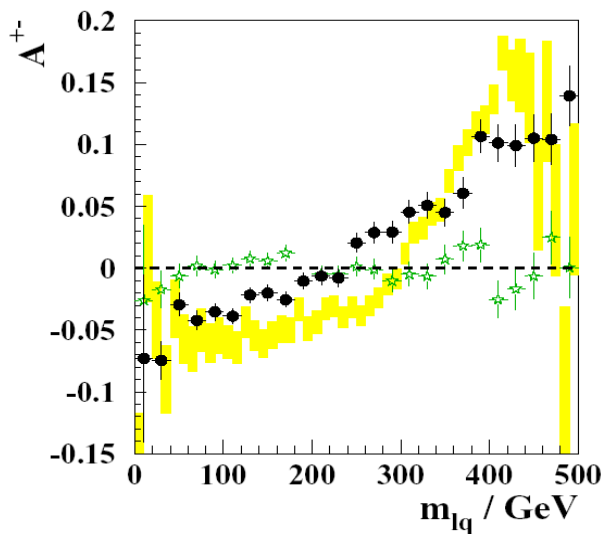
For $M_{\tilde{\chi}_2^0} > m_{\tilde{\ell}}$, the decay is $\tilde{\chi}_2^0 \rightarrow \tilde{\ell}^\pm \ell^\mp \rightarrow \ell^\pm \tilde{\chi}_1^0 \ell^\mp$ the upper edge comes $m_{\ell^+ \ell^-}^{\max} = M_{\tilde{\chi}_1^0} \left(1 - m_{\tilde{\ell}}^2/M_{\tilde{\chi}_2^0}^2\right)^{1/2} \left(1 - M_{\tilde{\chi}_1^0}^2/m_{\tilde{\ell}}^2\right)^{1/2}$.



LHC can determine mass differences with high precision but not absolute masses
 Biggest uncertainty

Equality of the couplings: Qualitative : relationship between rates and masses. Accurate cross-section calculations (including NLO effects etc) available. A qualitative conclusion could be drawn.

Determination of spin? The spin spin correlations will determine the angular distributions of the decay products. Some clever variables have been constructed which could distinguish between spin 0 and spin 1/2 particle being exchanged in the chain. The game is beginning.



If we find events with pointing photons or quasi stable, heavy charged stau we will know we have GMSB.

In that case it is possible to access the symmetry breaking scale directly through the measurement of mass of $\tilde{\chi}_1^0$ and its life time.

In general LHC can

1) give accurate information about sparticle Mass differences and some not so accurate information on actual masses

2) discussions about how to establish spin have now started. May be possible to get information on spin of sparticle involved in decay chains.

3) But for anything more we have to turn to ILC.

4) Most of the analyses were in the framework of a model. Model indep. analyses have begun now.

- 1) An LC should provide **precision** measurement of sparticle masses and mixing. Of course for that one needs $\sqrt{s} > 2m_s$, where m_s is sparticle mass. Desirable energy range for the ILC from the point of view of SUSY searches should extend at least upto 1000 GeV.
- 2) The ILC should provide determination of quantum numbers such as spin, hypercharge and establish the equality of couplings predicted by SUSY.
- 3) Information from LHC, along with measurements in (2) can then be used to get information about the SUSY breaking at high scale

There was an international study group which studied this issue of ILC-LHC synergy. (phys. reports. 2006)

Needless to say that with polarised electron, positron beams and the possibility of measuring the polarisation of the final state particles like τ, t ILC can determine the lagrangian parameters $\mu, \tan \beta, M_1, M_2$ from a study of chargino, neutralino and slepton production.

The polarisation plays an important role because SUSY has chiral fermions and scalars are partners of chiral fermions.

$\sigma(e^+e^- \rightarrow f\bar{f})$ and $\sigma(e^+e^- \rightarrow s^+s^-)$ have different energy dependence near the threshold, as one is a p wave excitation and one is an s-wave excitation. Thus very clear determination of spin.

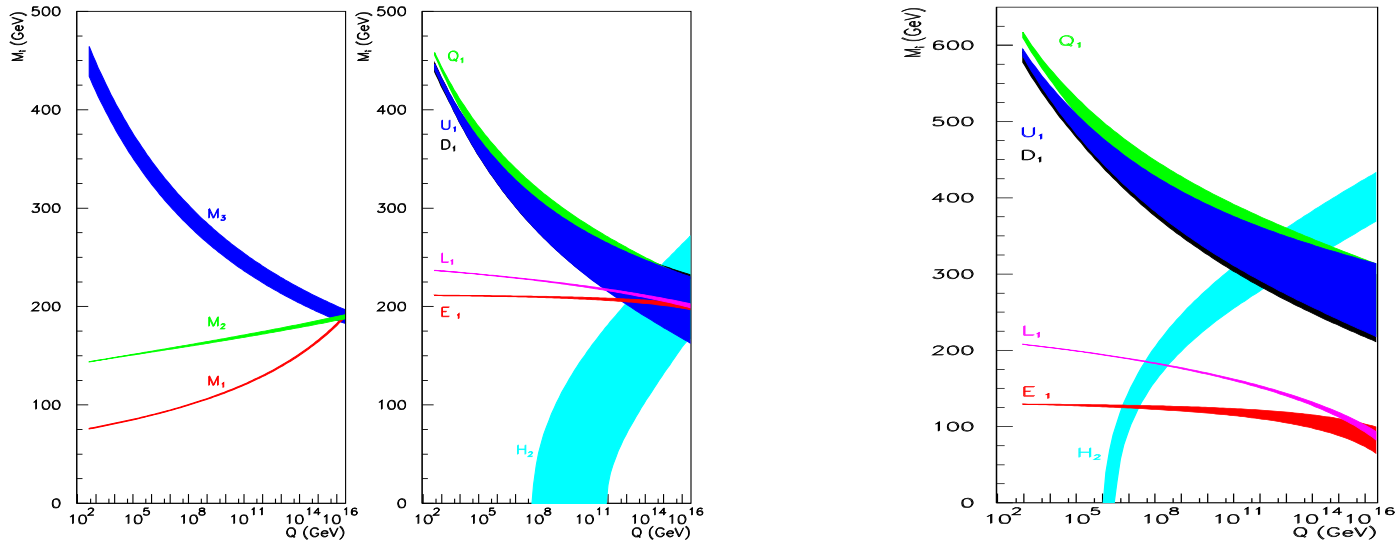
Even in the decoupling regime for the Higgs sector of the SUSY Higgs, accurate determination of the couplings can give access to the contribution of Sparticles in the loops even if they are above the energy reach of the collider.

Of course one caveat: we still have to get this collider.

Two approaches:

Determine the parameters $M_1, M_2, \mu, \tan \beta$ and m_0 *at the high scale* by fitting these **directly** to the various experimental observables such as the polarisation dependent production cross-sections of the sparticles, angular distributions of the decay products.

Use experimental observables such as cross-sections, angular distributions to determine the physical parameters of the system such as masses and mixings and then use these to determine the lagrangian parameters $M_1, M_2, \mu, \tan \beta$ at the *EW scale itself*. Now evolve these lagrangian parameters in the framework of an assumed model and test the model of symmetry breaking.



Left panel for mSUGRA and the right for GMSB.

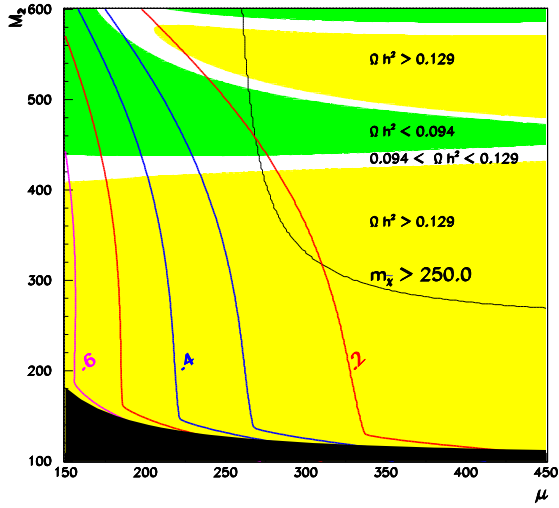
Multidimensionality of SUSY phenomenology:

Direct search for extra Higgses of course. The search strategies depend on SUSY breaking parameters, just like other sparticles. There are regions where only the lightest state can be seen and has properties very similar to the SM Higgs. Decoupling limit. LHC studies wont be able to probe this region for SUSY.

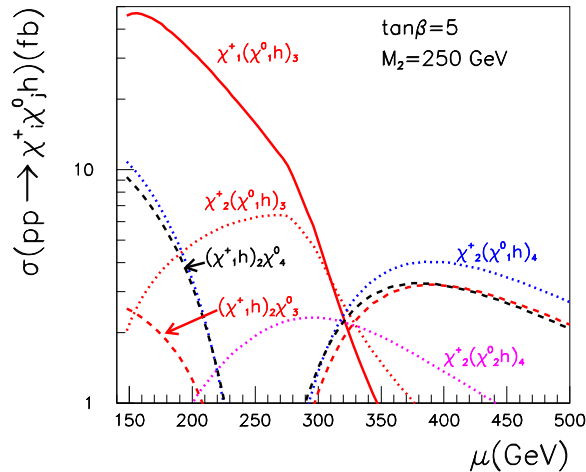
SUSY changes lightest higgs production rate away from the SM.

NMSSM, CP violation can affect the couplings of the lightest higgs to a Z pair so as to reduce production rate at LEP. LEP limits are then invalid. May be SUSY will show itself up through such effects.

But then these effects are large only if **some** sparticle is light enough, so it should be seen at LHC.



The left panel shows contours of 'invisible' branching ratio of the h , for a particular choice of the **non-universality of the Gaugino masses**, along with the Dark Matter and LEP constraints. The nonuniversality threatens to reduce the c.sections in the usual channels. Requirements that adequate DM should be present removes a big chunk of that region. But some region is still left.



Higgs yield through charginos and neutralinos decays as a function of μ is shown in the right panel.

Luckily both LHC and the Tevatron will be able to see enhanced signals for $\tilde{\chi}$ sector .

Example of the interplay between Higgs-LHC-Cosmology:

References: Theory and Phenomenology of sparticles: Drees, Godbole, Roy

TeV scale SUSY: Tata and Baer

Physics Reports:LHC-ILC interplay (Eds. G. Wieglein, R. Godbole...)

DCR for ILC. hep-ph (Djoaudi et al)