Physics at LC: SUSY and QCD

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Some references

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2) T.~Abe et al. (2001)
[American Linear Collider Working Group Collaboration],
``Linear collider physics resource book for Snowmass 2001,''
SLAC-R-570.

3) K.~Abe et al. [ACFA Linear Collider Working Group Collaboration], (2001)

4) R.M. Godbole ," SUSY and SUSY breaking scale at Linear Collider",Proceedings of the International Linear Collider Workshop LCWS 2000, FNAL, 2000.

5) J.L. Feng and M.M. Nojiri, hep-ph/0210390.

Outline

- Will discuss some selected topics in SUSY and QCD that can be studied at the LC.
- Also mention about some of the phenomenological work in India in the cotnext of LC in these two areas.

Outline

1) How LC will aid in establishing SUSY as a viable theory

2) How LC will help gleen information about the scale and the mechanism of SUSY breaking.

3)Summary of some of the Indian work in the context.

4) How will LC crucially completment/extend the achievemnets of the LHC.

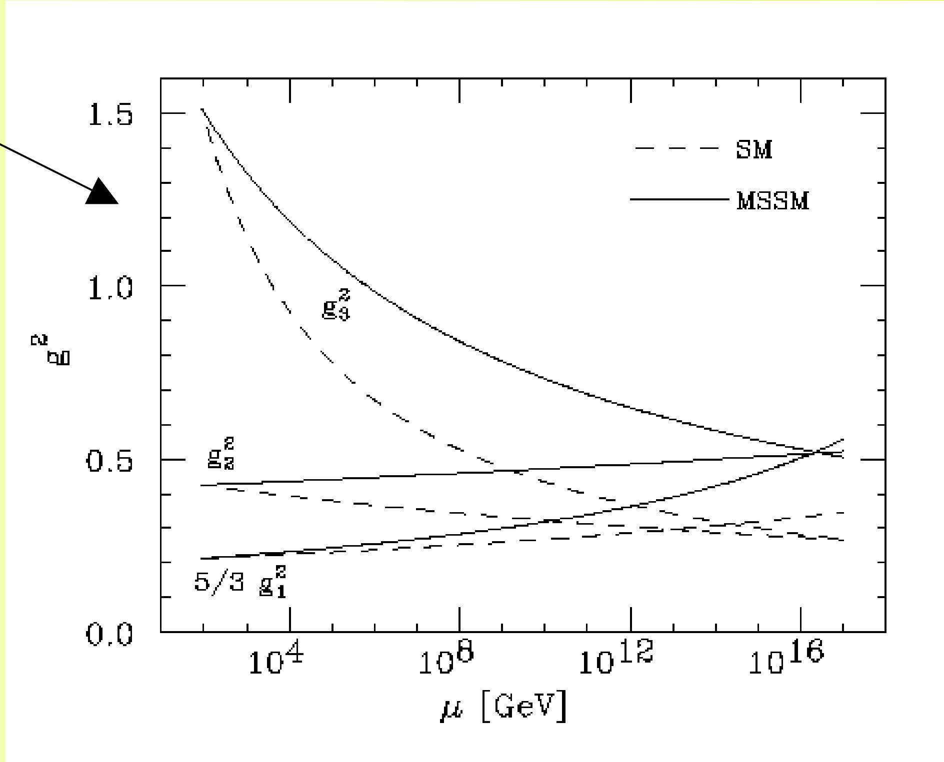
5) Mention some aspects of QCD studies, mainly the two photon studies.

Introduction

TeV Scale Supersymmetry (SUSY)

1) Stabilizes m_h at electroweak scale.
2) The only concrete and worked out solution to the hierarchy problem.
SUSY Provides a natural, elegant mechanism for the SSB of EW symmetry

3) Unification of Couplings:
Indicative(?) of Supersymmetry.

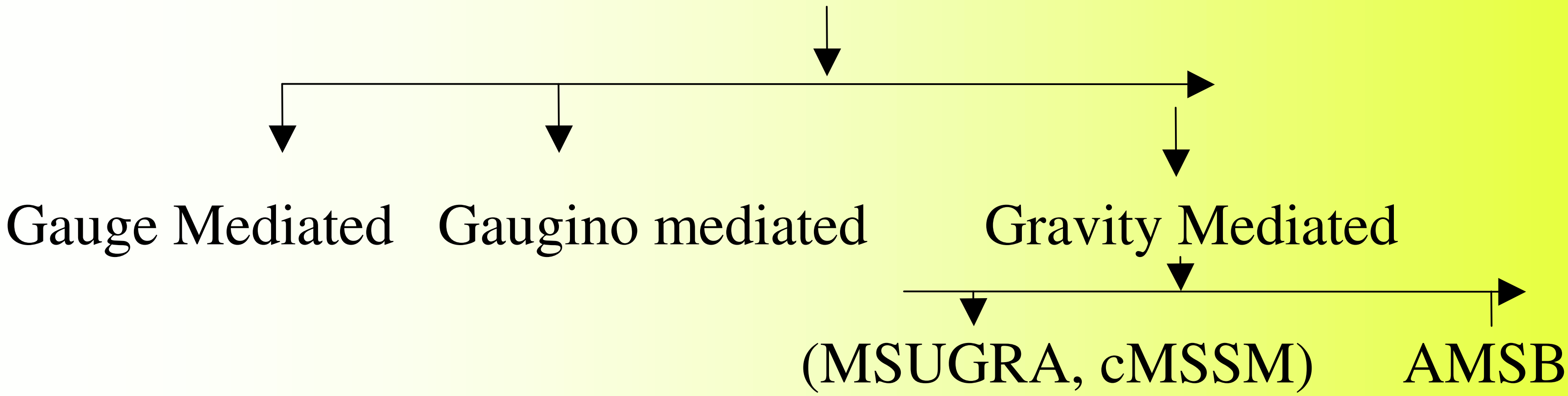


BUT
It is clear that Supersymmetry, if it is a symmetry of the theory, is broken in real life and SUSY breaking is not really understood theoretically completely.

SUSY breaking

Theoretical ideas for Supersymmetry breaking involves high scale physics.

Mediation of this supersymmetry breaking to our TeV scale world:



SUSY breaking scale can be any where between 10^4 GeV and M_{pl} depending on the SUSY breaking *and* mediation mechanism.

Clues from high scale physics?

Sparticles masses at the EW scale (for all sparticles) and couplings (for some of them) depend on this mechanism.

This is the clue provided to us to point to high scale physics
question is how do the colliders help us unravel the physics from this clue?

For example for GMSB,mSUGRA the gaugino masses follow approximately M1 : M2 :M3 = 1:2:7 where as for the AMSB case they are in the ratio 2.8:1:8.3.

Clues in sparticle properties?

The three breaking mechasnisms differ crucially in their

1) expectation of lepton mass hierarchy, e.g.,
in mSUGRA sleptons generally expected to be lightest sfermions

2) couplings of the lightest supersymmetric particle (LSP), the next lightest sparticle NLSP and that of the chargino, e.g.,
The LSP is U(1) gaugino for mSUGRA , SU(2) gaugino for AMSB and the LSP is invisible in the detector.
The LSP is gravitino for GMSB and the NLSP is the neutralino, which can have a decay length between 10^{-4} cm to 10^{5} cm and decays into final state containing photons.

3) the mass differences between chargino and neutralino
These are degenerate for AMSB.

How to establish SUSY?

SUSY phenomenology in its gory detail looks formidable. Important to try and extract 'model independent' information as far as possible.

We need to (LHC will do things written in **blue**)

- **find sparticles**, establish quantum numbers.

- check the interactions and establish coupling equalities implied by supersymmetry.

- **determine sfermion masses**, gaugino-higgsino mising, **some gaugino masses**

- Mixing between sfermions of the third generation.

The last two can then provide information on parameters of SUSY model which will give a handle on SUSY breaking parameters.

Few facts about SUSYsearches at LHC

- If SUSY has been realized by nature, LHC will for sure provide proof for its 'Naturalness'

- If theories are 'natural' some sparticles must be accessible at LHC. (Gauginos/higgsinos)
- The strongly interacting heavier sparticles are produced first, lighter sparticles in decays. 'top-down'

- Worst background for SUSY is SUSY itself.

Hopes for SUSY from LHC?

- Very nice analysis methods developed make possible measurement of a variety of sparticle masses such as squarks, gluinos, LSP etc.
- Possible to get a good idea of effective SUSY breaking scale
- Model independent determination of the LSP mass to 10% level possible

BUT

- Accurate information about SUSY breaking scale and mechanism seems gererally not easily extractable,
- determination of quantum numbers not quite possible.

Hopes for SUSY from LC?

Hope : To build on the results obtained by LHC

- Determine sparticles masses, mixing to high precision

- Determine quantum numbers such as spin, hypercharge

- Measure equality of couplings predicted by SUSY

- **Along with the information from LHC use the sparticle mass and coupling measurements to get information about SUSY breaking at high scale.**

Hopes for SUSY from LC?

What are the special features which help extra ?

- Energy can be tuned : bottom up approach. Start with lightest. Input from LHC will of course help in choices of energy.

- Use of polarisation : SUSY deals with chiral fermions & their partners. Important information can be projected. WW background can be killed.

- Running in e^-e^-,$e\gamma$ and $\gamma\gamma$ mode can add to useful information (example later)

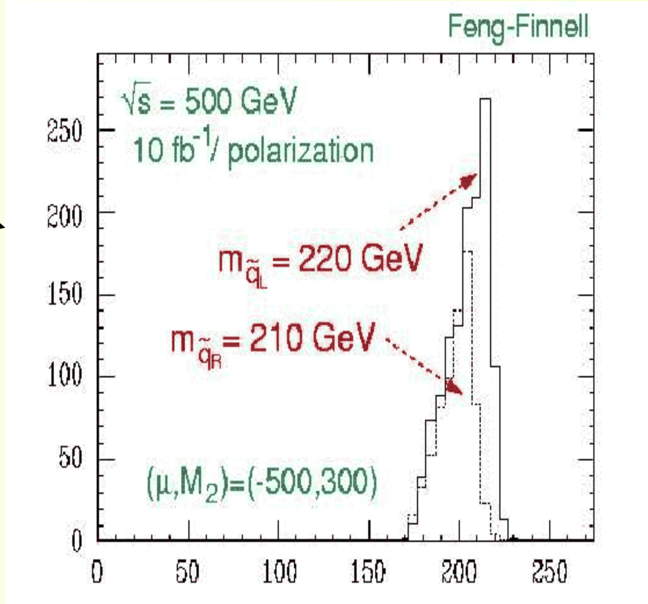
What can LC measure?

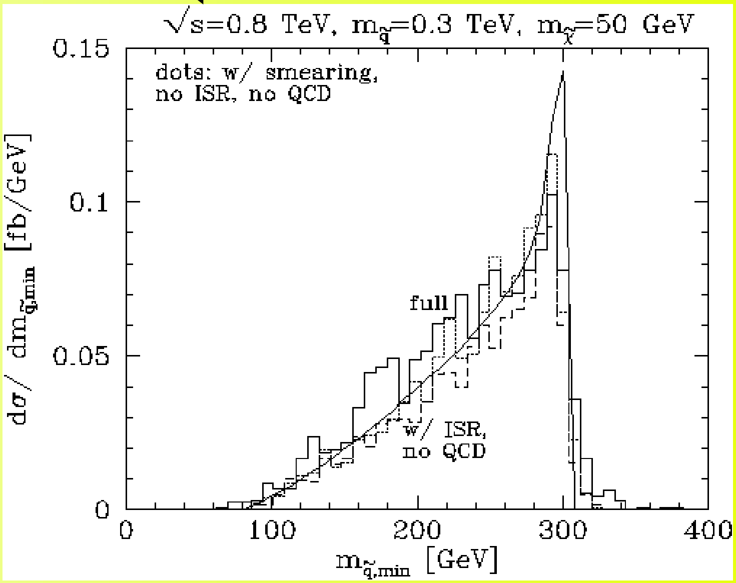
Precision determination of masses from threshold scans and kinematics, using accuarte knowledge of the beam energy already discussed. Martyn et al : quote per mil accuracy for all, Tata et al think it is an overestimate.

Theorists calculating effects of higher order corrections.

Effect of radiative corrections
Godbole, Drees, Kraml

Kinematic determination of the squark mass: Finnel and Feng





Using these to determine SUSY parameters

Knowing both chargino masses can give information on M2 and μ, and tan β. All neutralino masses will give M1 in addition. To determine all the four, e.g., measurements of the couplings of these to leptons are essential. Thus determination of Quantum Numbers of the sparticles is essential.

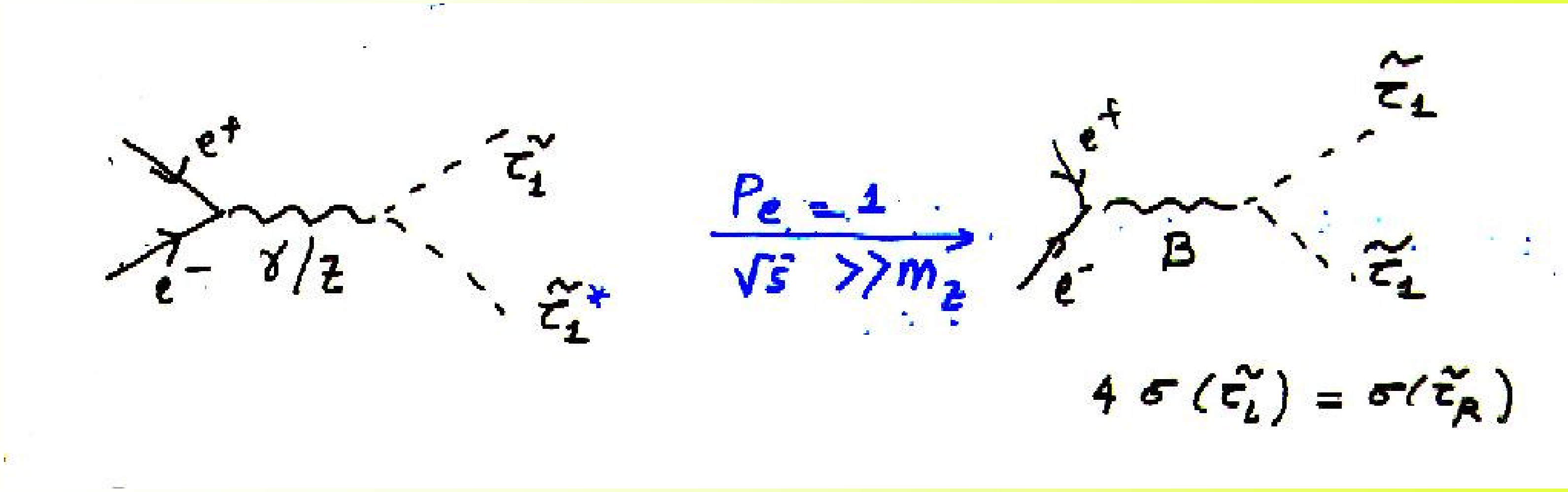
This can be done at LC using polarisation of the incoming lepton beams or polarisation of the final state decay products.

Quantum number determination

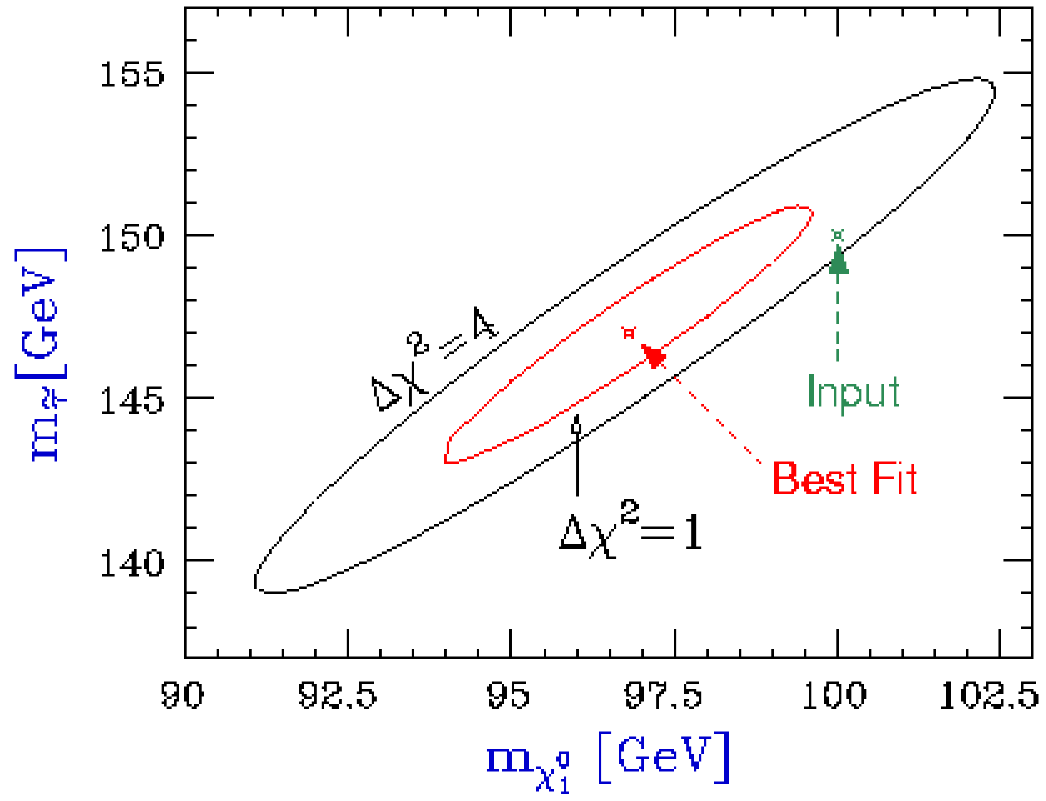
Third generation staus (M. Nojiri)

Mass eignestates are a mixture of L and R states.

Determination of production cross-section and kinematic determination of the mass of the stau gives a measurement of the mixing angle directly.

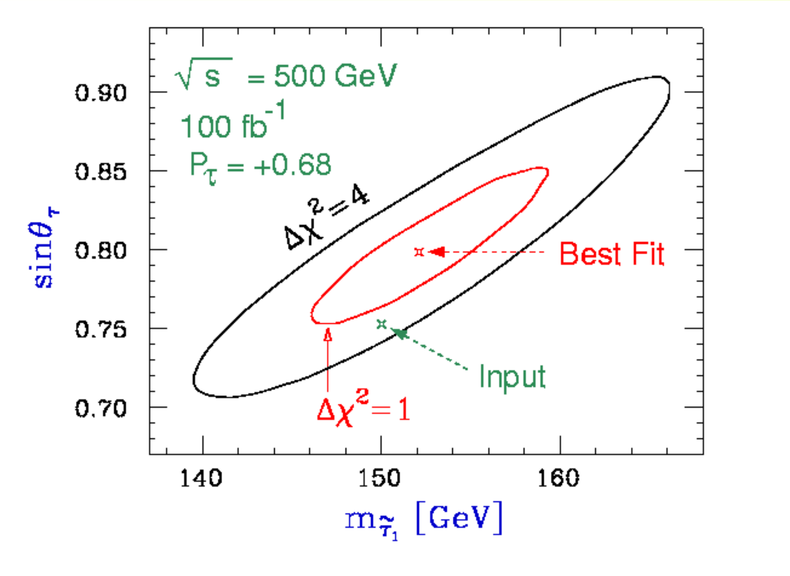


Quantum number determination



Determine mass of the stau and the LSP from kinematic fits.

Quantum number determination

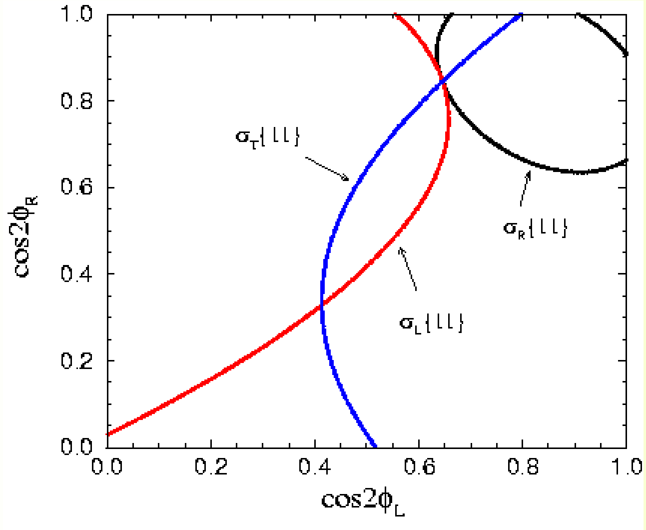


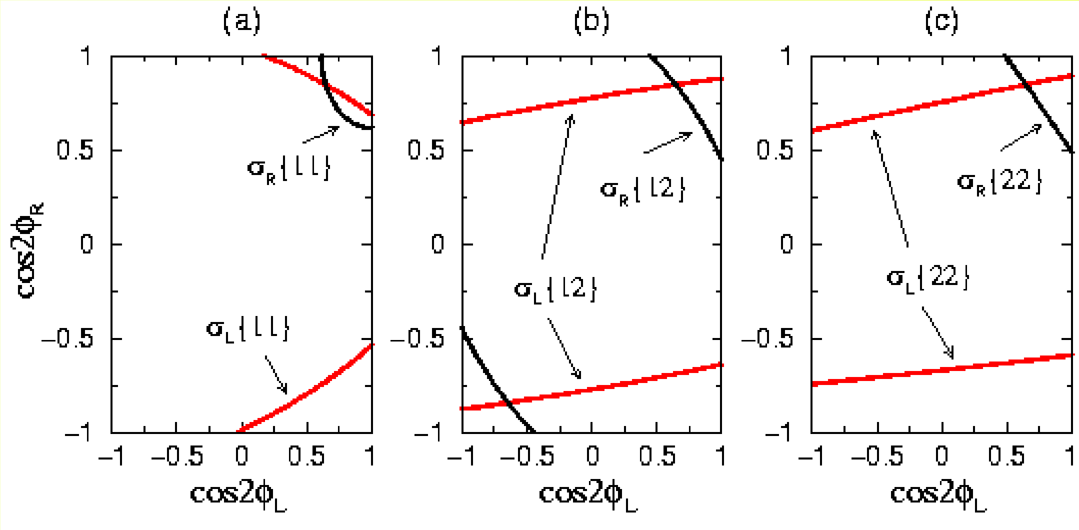
Determine the mixing angle from the production cross-section measurement which is a function of the masses and θ_τ .

Decay of the stau into a LSP + τ: the polarisation of the decay τ depends on the gaugino-higgsino mixing in the neutralino sector.

Thus for the staus, just the measurement of the production cross-section and polarisation of the decay τ , can give information on the mixing .

Quantum number determination

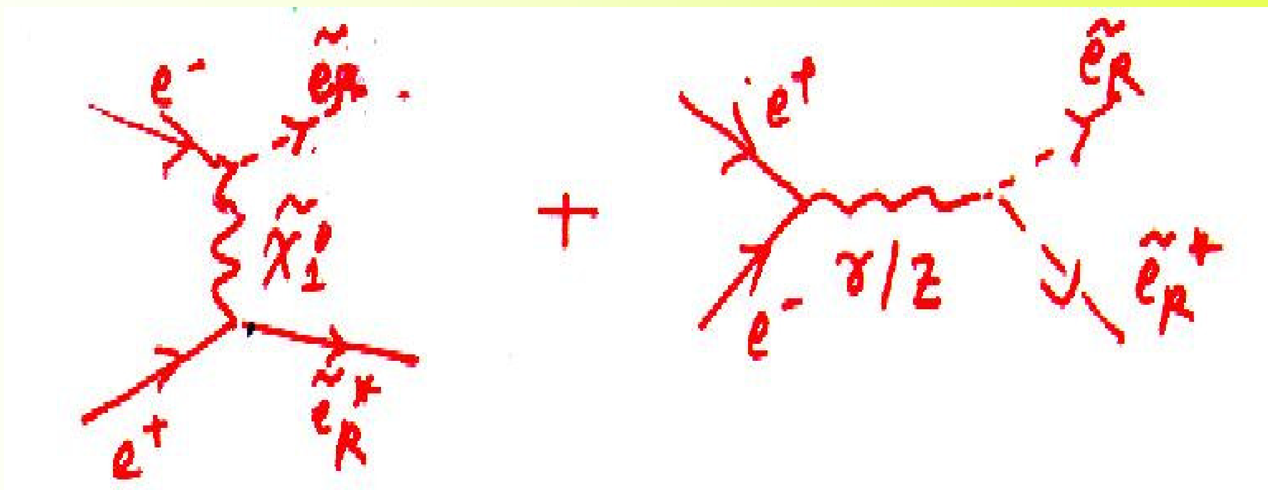




Use of beam polarisation to determine the mixing in the chargino secttor. If both the charginos are available kinematically, the parameters M2, μ and tan β, can be determined accurately. (Guchait, Zerwas, Choi, Kalinowski)

Testing coupling equality

Equality of Selectron selectron U(1) gaugino coupling
with
eeB coupling:



Use slepton production to test this.

Indian contributions 1: parameter determination

- Determination of parameters of chargino sector
  - Y.Choi, M.Guchait, J.Kalinowski, P.MZerwas (hep-ph/0001175)
  - Y.Choi, A.Djouadi, M.Guchait, J.Kalinowski, H.S.Song, P.M.Zerwas (hep-ph/0002033)
  - They consider $e+e- \rightarrow \chi^+_i \chi^-_j$ $(i,j = 1,2)$
  - Measure 3 cross-sections
  - Measure several spin-correlations
  - Use these data to pin down parameters of chargino sector, viz.
    - M_1, M_2, μ, $\tan\beta$
  - Discuss relative merits of different combinations of these
  - Consider radiatively-corrected cross-sections
- Determination of mixing angles of stau sector:
  - M.Guchait, J.Kalinowski, P.Roy (hep-ph/0103161)
  - SuperK results indicate mixing between muon neutrino & tau neutrino: seems to indicate mixing between corresponding superfields, I.e. between muon and tau sneutrinos and smuon and stau through RG evolution
  - Treat mixing angles as free parameters and measure from cross-sections for smuon pair production and stau pair production

Indian contributions 2: `invisible' sparticles

- Single photon signals for `virtual LSP' scenarios
  - A.Datta, A.K.Datta, SR (hep-ph/9605432)
  - Consider scenario when next-to-LSP is the sneutrino
  - Decays to neutrino + neutralino (both invisible)
  - Consider radiative neutralino and sneutrino pair-production
  - Signal is photon + missing E, p
  - Should be observable over SM background ($\nu\bar{\nu}$ with ISR γ)
  - Extend to scenario when next heavier sparticle is second neutralino
  - Invisible decays to neutrino + sneutrino, LSP + Z* (neutrinos)
- Consider AMSB-inspired scenario when next-to-LSP is the chargino:
  - A.Datta, S.Maity (hep-ph/0104086)
  - Chargino decays to neutralino + soft pions (unobservable)
  - Consider radiative (ISR) chargino production
  - Again signal is photon + missing E, p
- Consider same AMSB scenario at a $\gamma\gamma$ collider
  - D.Choudhury, B.Mukhopadhyaya, S.Rakshit (hep-ph/0205103)
  - Final state is either photon + missing E, p or photon + $\pi^+\pi^-$

Indian contributions 3: GMSB signals

- Single photon signals in e+e- collisions:
  - A.Datta, A.K.Datta, A.Kundu, B.Mukhopadhyaya, S.Roy (hep-ph/9707239)
  - They consider neutralino pair production e+e- $\rightarrow \chi^0_1 \chi_1^0$
  - One neutralino decays $\chi^0_1 \rightarrow \gamma \breve{G}$
  - Other neutralino decays $\chi^0_1 \rightarrow Z \breve{G} \rightarrow \nu \underline{\nu} \breve{G}$
  - Final state is photon + missing *E*, *p*
  - Use polarized beams
  - A.Ghoshal, A.Kundu, B.Mukhopadhyaya (hep-ph/9709431)
  - Consider left-right asymmetry in above signal
  - Use to probe photon-photino-gravitino & Z-Zino-gravitino couplings
- Tri-electron signals for GMSB at eγ colliders:
  - A.Ghoshal, A.Kundu, B.Mukhopadhyaya (hep-ph/9709431)
  - They consider $e\gamma \rightarrow \chi^0_1 \breve{e}_R \rightarrow e\, \breve{e}_R \breve{e}_R$
  - Each selectron goes to electron + gravitino
  - Very small backgounds from SM and MSSM;
  - `smoking gun' for GMSB

Indian contributions 4: AMSB signals

- AMSB signals in selectron pair-production:
  - D.K. Ghosh, P.Roy, S.Roy (hep-ph/0004127)
  - They consider e+e- → $\tilde{e}_L \tilde{e}_L$
  - One $\tilde{e}_L$ → electron + neutralino (LSP), one → neutrino + chargino
  - Chargino decays to pion + neutralino LSP
  - Two possibilities:
    - Chargino leaves a heavy track in the detector
    - Chargino decays to pion with a displaced vertex
  - Trigger on hard electron, missing E, p and look for heavy tracks or displaced vertices (claim `smoking gun' for AMSB)
- AMSB signals in pair-production of sparticles:
  - D.K. Ghosh, A.Kundu, P.Roy, S.Roy (hep-ph/0104217)
  - More comprehensive study: They consider e+e- → pairs of
  - Selectrons (L-L, L-R, R-R), Sneutrinos, Neutralinos (12, 22), Charginos
  - Final decay signal will still involve heavy tracks/displaced vertices
- AMSB signals in eγ colliders:
  - D.Choudhury, D.K.Ghosh, S.Roy (hep-ph/0208240)
  - They consider eγ → sneutrino + chargino (rest is similar)

Indian contributions 5: R-parity violation

- Signals for LSP decay at e+e- collider
  - D.K. Ghosh, R.M. Godbole, SR (hep-ph/990233)
  - In R-violating scenario LSP neutralino decays
    - LLE: dilepton + neutrino
    - LQD: dijet + neutrino, dijet + charged lepton
    - UDD: three jets
  - Produce neutralino and chargino pairs: consider all possible cascade decays (84 channels !)
    - LLE has very clear multi-lepton signals
    - LQD has interesting like-sign dilepton signals (Majorana LSP)
    - UDD must be detected in multijet scenarios
  - Possibility of neutralino/chargino mass reconstruction
- Signals for LSP decay at $e\gamma$ collider:
  - D.K. Ghosh, SR (hep-ph/ 9711473)
  - Very similar study
- Bilinear R-parity violation:
  - B.Mukhopadhyaya, S.Roy (hep-ph/9612447)

Testing SUSY breaking mechanism

- Use measured masses, mixing angles to determine the lagrangian parameters. Use the RG equation to evolve them to a high scale and test the high enervgy behaviour of the SUSY parameters which are different (say) for AMSB and mSUGRA.

- Study of LSP pair production and final state coming from the decay of the LSP to γ + gravitino, can give accurate information on the SUSY breaking scale in GMSB.

QCD studies at a LC

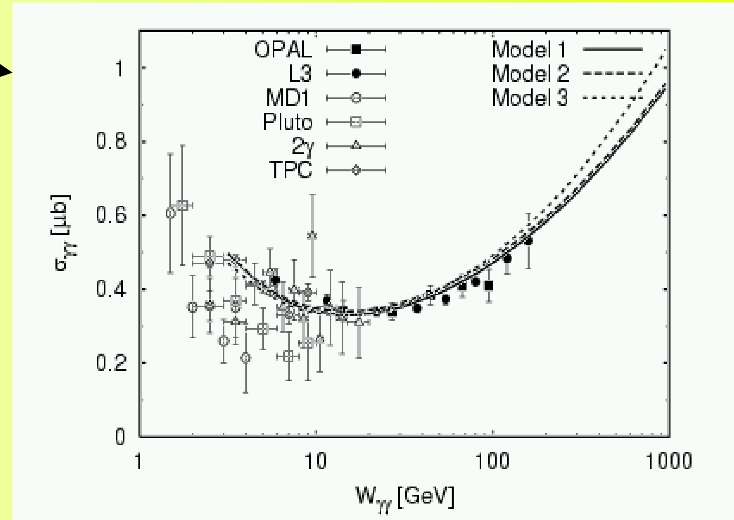
Kwiecinski et al

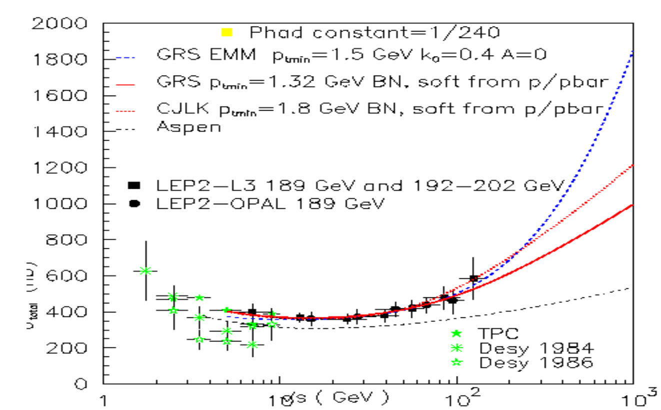
Total cross-sections

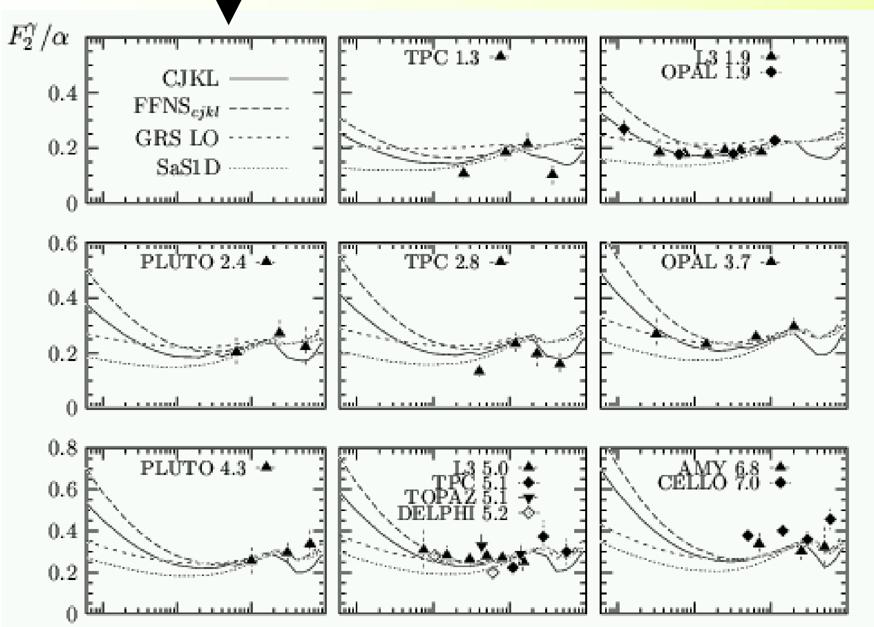
Grau,Godbole Pancheri, De Roeck

Photon Structure

M. Krawczyk et al







Conclusions

- To get precision information about the SUSY, SUSY scale and SUSY mechanism, a LC is absolutely essential.

- A high luminosity e^+e^- collider upto TeV energy can go a long way towards putting SUSY in text books.

- Information on the LSP mass from LC, if available will increase the accuarcy of LHC determination of masses of the gluino and the squarks, aiding further in the reconstruction of the high scale theory.