# Supersymmetry

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# Motivations for introducing SUSY

- SUSY is an extension of space-time concept.
- Superstring requires SUSY
- A solution to the hierarchy problem
- Gauge coupling unification in SUSY GUT

# SUSY: an extension of space-time

- Supersymmetry (SUSY): a symmetry between bosons and fermions.
- Introduced in 1973 as a part of an extension of the special relativity.
- Super Poincare algebra.

$$
\begin{aligned}
&P_\mu && (translation), \\
&M_{\mu,\nu} && (rotation\ and\ Lorentz\ tranformation), \\
&Q_\alpha && (SUSY\ transformation)
\end{aligned}
$$

$$\{Q_\alpha, Q_\beta\} = (\gamma^\mu)_{\alpha\beta} P_\mu$$

- SUSY = a translation in Superspace.

Space-time $(x^\mu)$ $\rightarrow$ Superspace $(x^\mu, \theta)$

SUSY transformation:

$$
\begin{aligned}
x^\mu &\rightarrow x'^\mu = x^\mu + \frac{i}{2}\bar{\epsilon}\gamma^\mu\theta \\
\theta &\rightarrow \theta' = \theta + \epsilon
\end{aligned}
$$

- Supergravity was formulated in 1976.

# Superstring

- The only known way to unify gravity and gauge theory.
- SUSY is an essential ingredient of the superstring theory.
- Low-energy SUSY or SUSY GUT  can be an effective theory below the Planck scale (, but not necessarily so).

# Hierarchy problem and SUSY

String and GUT unification -> A cutoff scale ~ Planck scale (10^19 GeV).
SUSY is the only known symmetry to avoid the fine tuning in the renormalization of the Higgs boson mass at the level of O(10^34).

$$M_h^2 = M_{h,tree}^2 + c\frac{g^2}{4\pi^2}M_{pl}^2 \qquad (w/o\ SUSY)$$

$$M_h^2 = M_{h,tree}^2\left(1 + c'\frac{g^2}{4\pi^2}\ln(M_{pl}/M_W)\right) \qquad (with\ SUSY)$$

Three possibilities:

1. Some new dynamics associated with the electroweak symmetry breaking exists just above the TeV scale.
2. SUSY exists.
3. Fine-tuning is realized by unknown reason.

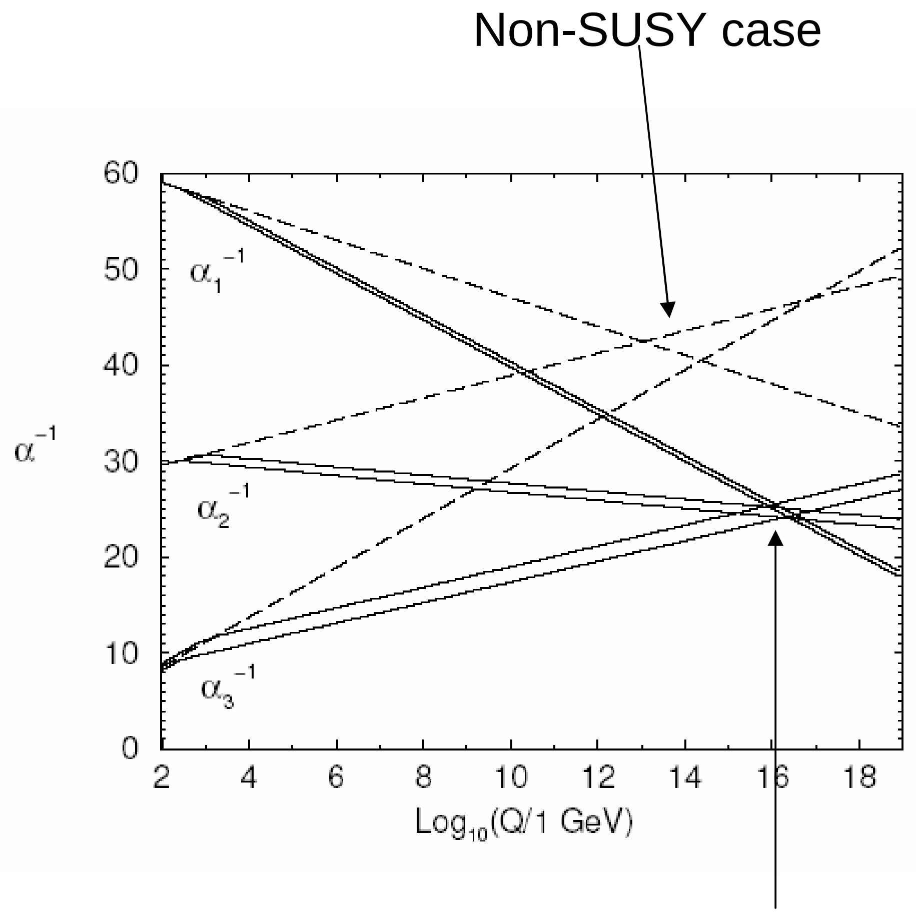
=> LHC will provide a hint on which is the correct direction.

# SUSY GUT

GUT was introduced independently of SUSY, but SUSY and GUT are closely connected.

GUT assumes the desert between the EW scale and the GUT scale, so that the hierarchy problem is real.

Gauge coupling unification works for SU(5) and SO(10) SUSY GUT.



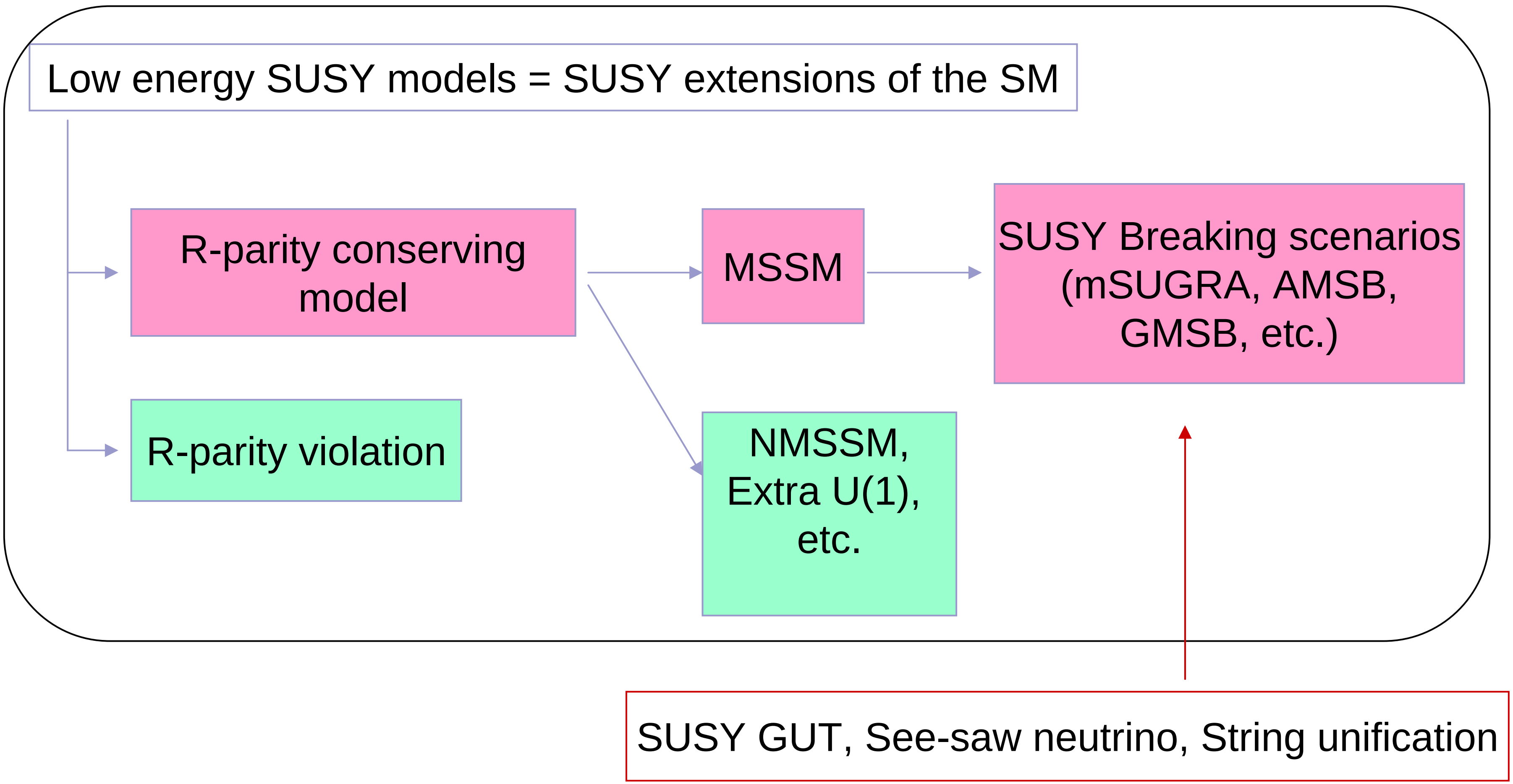

Puzzles in GUT models associated colored Higgs fields
Triplet-doublet splitting, Non-observation of proton decay
=> Depends on details of the GUT model.

# Structure of SUSY models

- Existence of SUSY partners
- SUSY-invariant Lagrangian
- SUSY breaking terms.

# SUSY models

A SUSY model is not a single model, rather collection of models.
The number of free parameters of the minimal supersymmetric standard model (MSSM) is about 100.




No strong motivations to consider beyond the MSSM.

# MSSM

The particle content of MSSM = Two Higgs doublet SM + scalar SUSY partners and fermionic SUSY partners

| | |
|---|---|
| gluon | gluino ($\tilde{g}$) |
| $W, Z, \gamma,$ | chargino ($\chi_i^{\pm}$), |
| Higgs fields ($H_i$) | neutralino ($\chi_i^{0}$) |
| quark ($q$) | squark ($\tilde{q}$) |
| lepton ($l$) | slepton ($\tilde{l}$) |

Two Higgs doublets are necessary for fermion Yukawa couplings.

$H_1$: down-type-quark and lepton Yukawa couplings
$H_2$: up-type-quark Yukawa couplings

# MSSM Lagrangian

$$\mathcal{L} = \mathcal{L}_{SUSY\ inv} + \mathcal{L}_{SUSY\ breaking}$$

SUSY invariant Lagrangian

- Coupling constants.

$$g_1, g_2, g_3, y_{ij}$$

- Lightest Higgs boson mass bound

$$m_h < 135\ \mathrm{GeV}$$

- R parity conservation

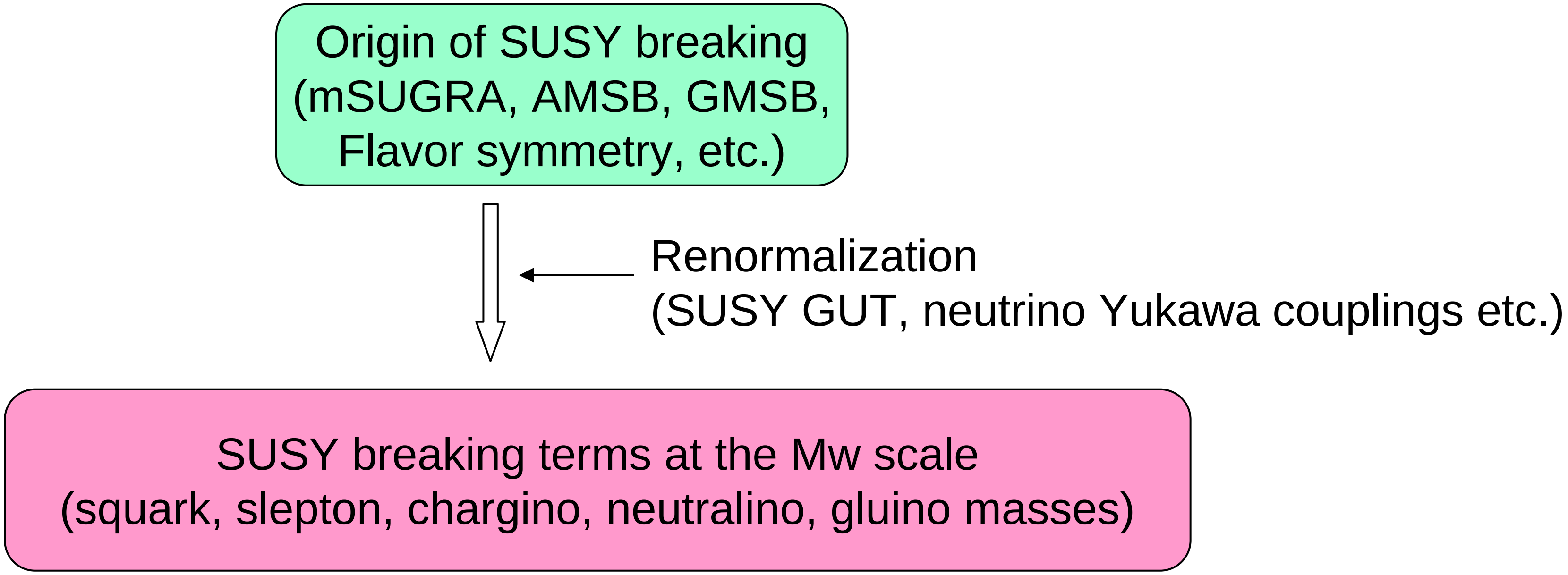
  Missing energy signal. Dark matter candidate.

# SUSY breaking terms

- Mass terms for SUSY particles.
- Origin of SUSY breaking.

= Spontaneous SUSY breaking in supergravity. (Super Higgs mechanism)

- Various possibilities.




- Origin of electroweak scale may be understood from SUSY breaking. (Radiative electroweak symmetry breaking scenario)

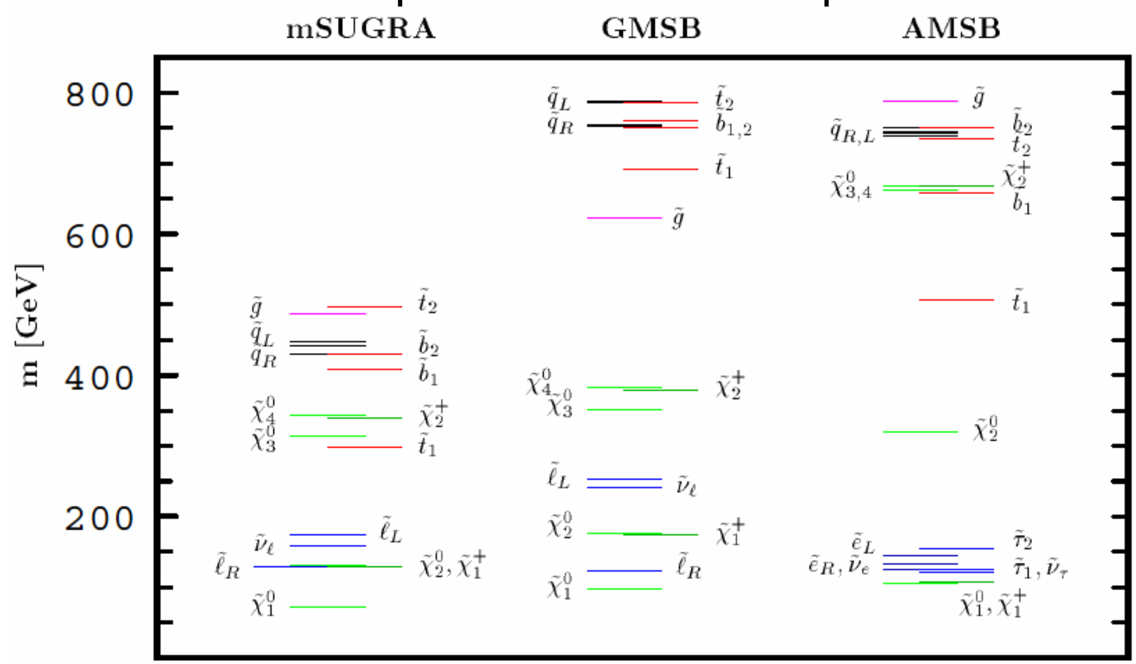
# SUSY mass spectrum

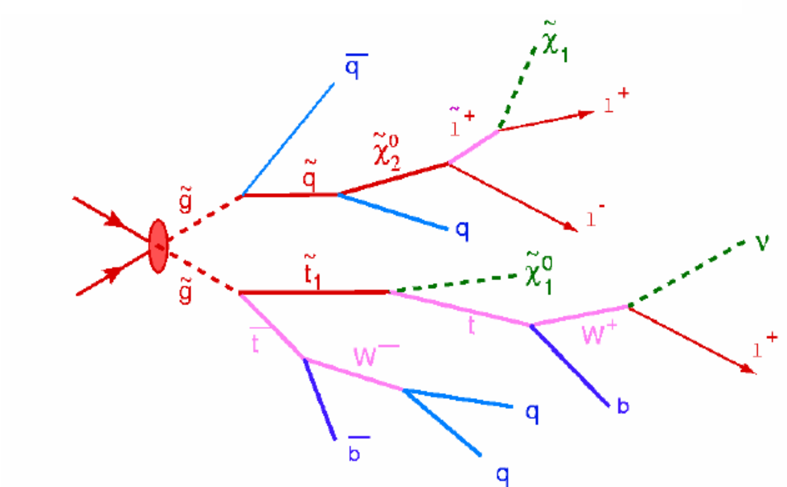
Pattern of the SUSY mass spectrum depends on SUSY breaking scenarios.

Generic feature:
 Colored particles: heavy
 Non-colored particles: light
The overall scale is a free parameter.

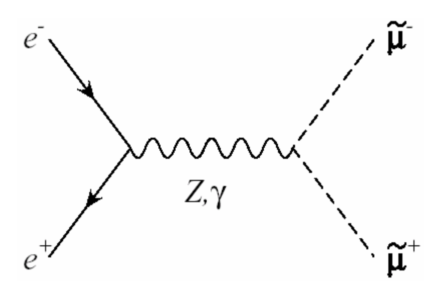
 LHC: cascade decays from colored SUSY particles.

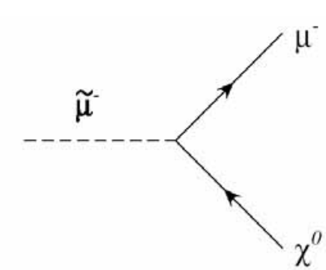
Example of SUSY mass spectrum




LC: pair production of SUSY particles



# Flavor mixing in squark and slepton

- Squark/slepton matrixes:

new sources of flavor mixing and CP violation.

- Quark/lepton mass -> Yukawa coupling
  Squark/slepton mass -> SUSY breaking terms

$$(m_q)_{ij} = Y_{ij} v$$
$$(m^2_{\tilde{q}})_{ij} = (Y^\dagger Y)_{ij} v^2 + m^2_{ij}$$

- SUSY breaking terms depend on SUSY breaking mechanism and interaction at the GUT/Planck scale.

Diagonal tem: LHC/LC
Off diagonal term:
Quark Flavor Physics
Lepton Flavor Violation

$$(m^2_{\tilde{q}})_{ij} = \begin{pmatrix} m^2_{11} & m^2_{12} & m^2_{13} \\ m^2_{21} & m^2_{22} & m^2_{23} \\ m^2_{31} & m^2_{32} & m^2_{33} \end{pmatrix}$$

# Cosmology and SUSY

- Good : Dark matter
- Bad: Gravitino problem
- Interesting: Baryogenesis
  Leptogenesis
  Affleck-Dine baryogensis (Q-ball)
  Electroweak baryogensis

These issues depend on the cosmological scenario and are related to each other.

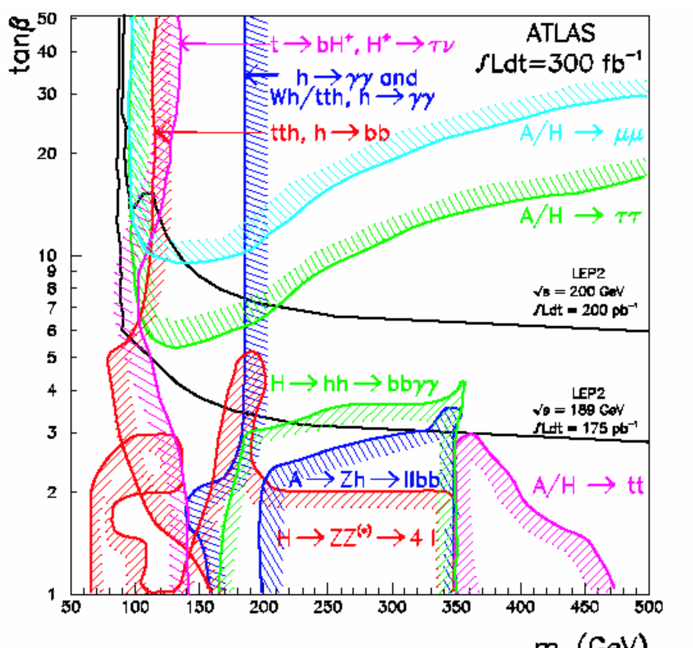
# SUSY phenomenology

1. Discover SUSY particles
2. Establish the symmetry property.
3. Determine SUSY breaking mechanism.
4. Clarify the meaning in unification and the cosmological connection.

# SUSY at LHC

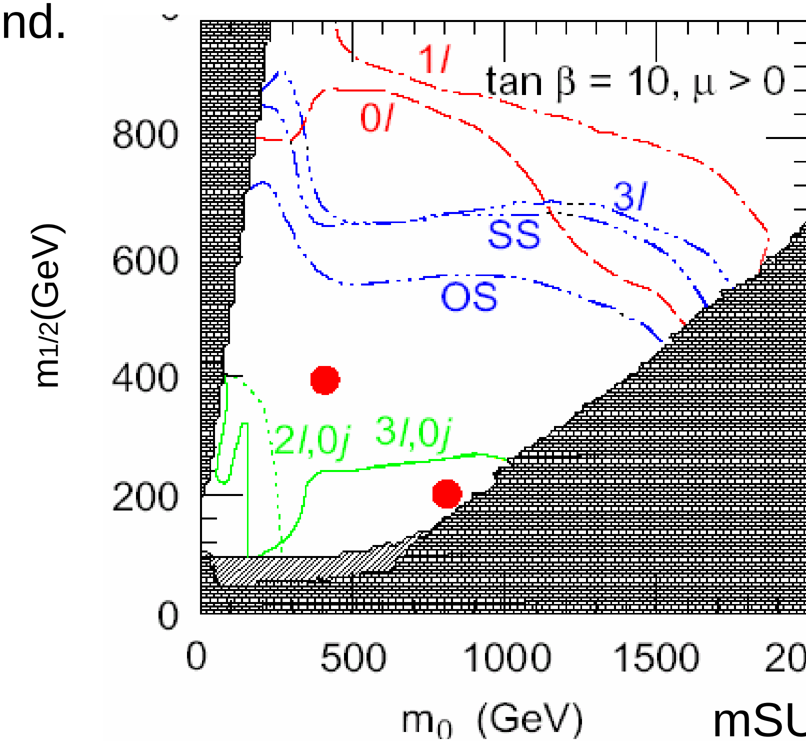
LHC experiments will provide a crucial test for SUSY.
(1) Mass reach of squark and gluino search is about 2 TeV.
(2) A light Higgs boson below 135 GeV must exist for MSSM.

Higgs search:
At least one Higgs boson can be found.




MSSM

SUSY search: Cascade decay.




~gluino
2 TeV

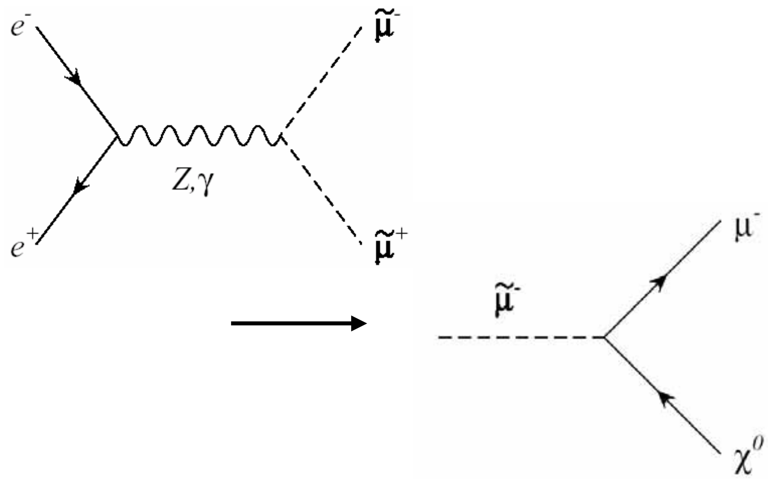
mSUGRA

# LC studies on SUSY

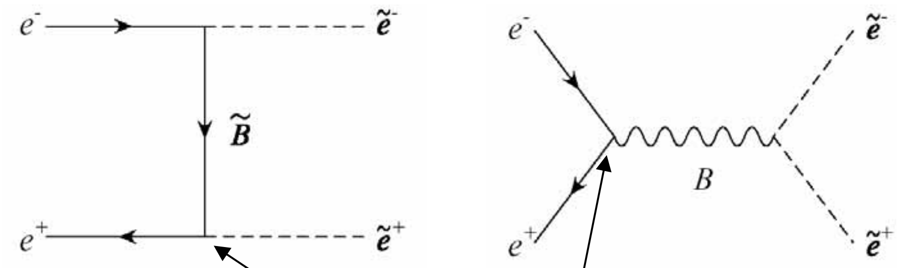
- Determine mass, spin and quantum numbers of SUSY particles. Beam polarization and energy scan are very useful tools.
- Determine chargino and neutralino mixings.
- Test SUSY coupling relations.
- Test the gaugino GUT relation.
- Determine properties of the dark matter candidate.
- Search for lepton flavor violation in slepton production and decays.

Smuon production and decay

# Test of a SUSY relation

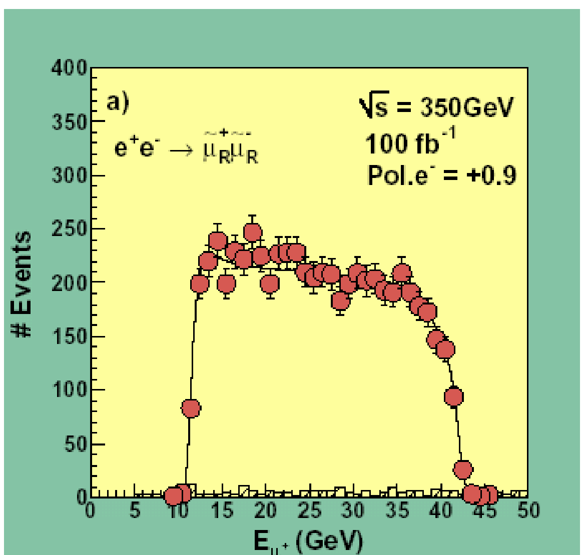


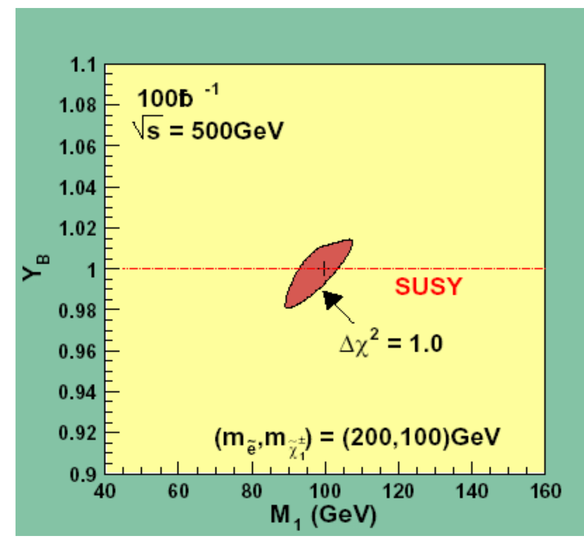

Selectron production




$$g_{\tilde{B}\bar{e}_R e} = g_{Bee}$$

Dark matter candidate?




M.M.Nojiri, K. Fujii and T. Tsukamoto

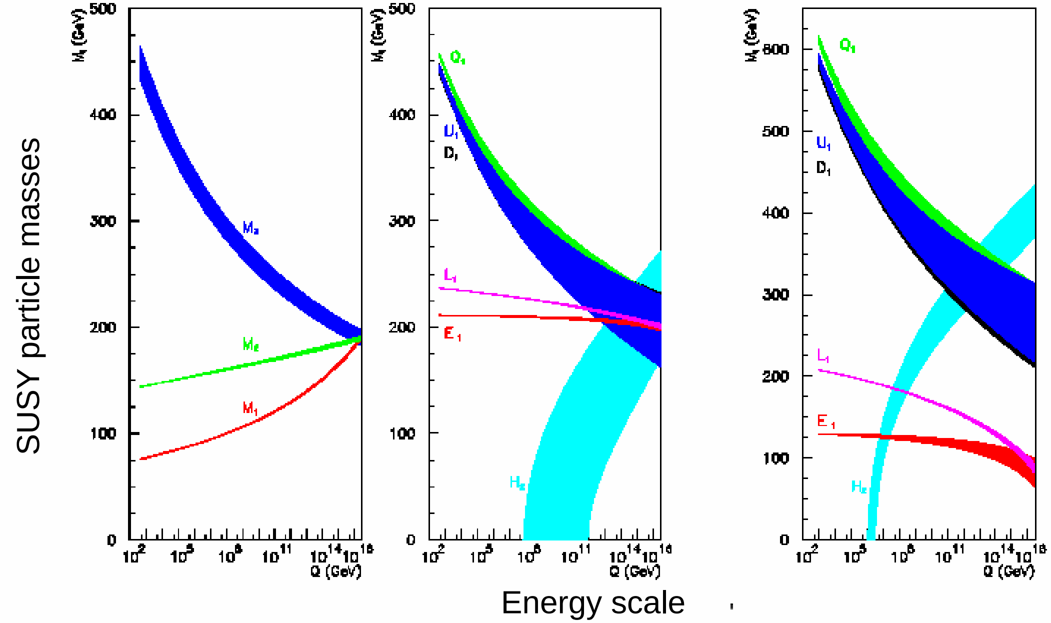
# Combined analysis of LHC and LC provide a hint on a SUSY breaking scenario.

LHC: Squark and gluino production and cascade decay
LC: Slepton, neutlarino, and chargino pair-production

Combined analysis

↓

SUSY breaking scenario

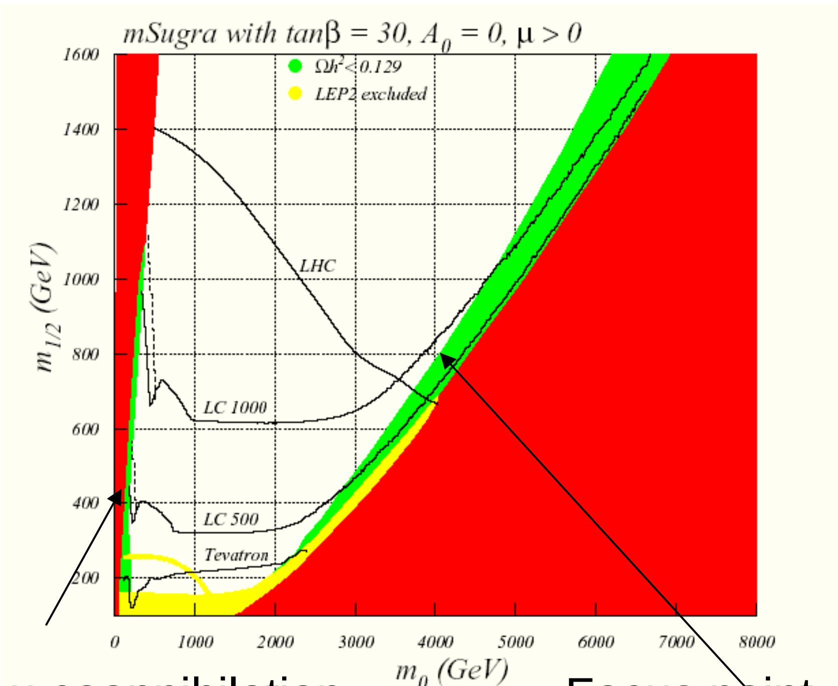



mSUGRA RGE evolution    GMSB RGE evolution

G.A.Blair, W.Porod,and P.M.Zerwas

# Dark matter and LHC／LC

H.Baer, A.Belyaev, T.Krupovnickas, X.Tata




Stau coannihilation

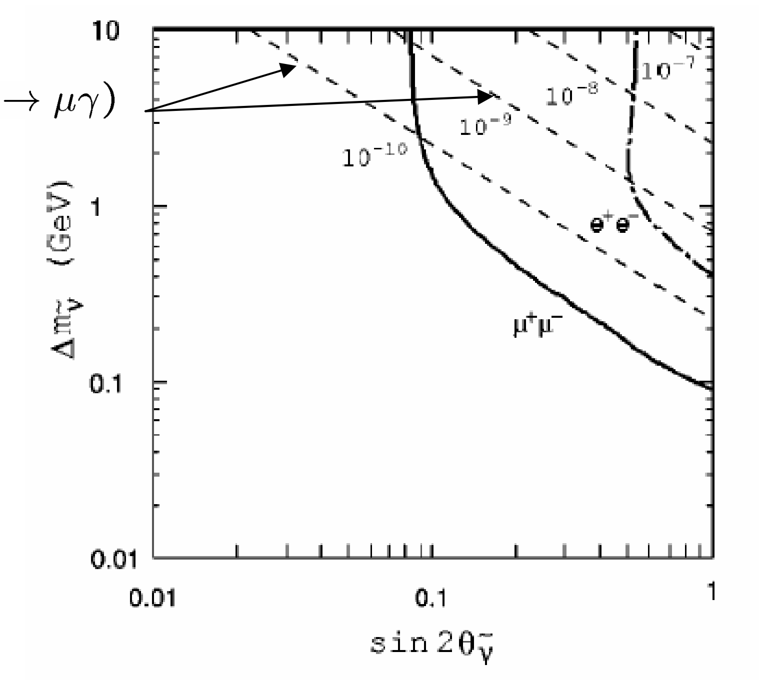
Focus point

# Search for LFV in the SUSY Seesaw model

J.Hisano, M.M.Nojiri, Y.Shimizu, M.Tanaka

$$e^+e^- \to \tilde{l}\bar{\tilde{l}} \to \tau\mu X$$

$B(\tau \to \mu\gamma)$




Neutrino mixing
-> Slepton mixing
-> LFV in slepton production and decay

# Summary

- Discovery of SUSY, if it occurs, would be a revolution of physics in $21^{st}$ century.
- SUSY is a key to unification and cosmology.
- SUSY discovery reach will be extended by an order of magnitude from the current mass bound at LHC.
- LC is necessary in order to establish the new symmetry.