Phenomenology of supersymmetric models

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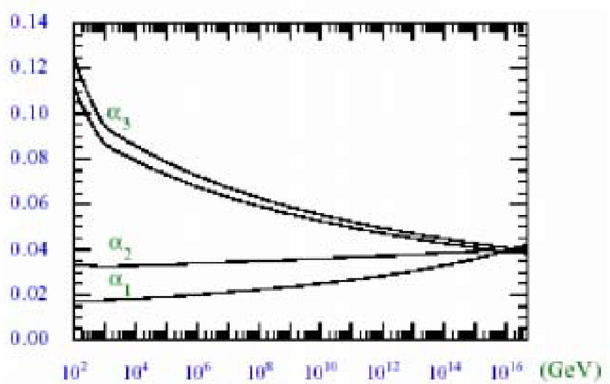
2003.5.20 at ICRR

Introduction

- Supersymmetry (SUSY) was introduced in 1970's as an extension of the special relativity. (extension of space-time concept)
- It was soon realized that remarkable cancellations occurs in renormalization of vacuum energy, scalar mass terms, etc, in SUSY theories.
- SUSY extensions of the SM and SUSY GUT were proposed in early 80's as a solution of hierarchy problem.
- Anomaly cancellation was found for superstring theory in 1984.
- Three gauge coupling constants determined precisely at LEP/SLC in 1990's turned out to be consistent with SUSY GUT unification.



If SUSY is discovered, we will be most likely led to a fundamental change of the space-time concept.

Poincare algebra -> Super-Poincare algebra

Space-time (x^μ) $\rightarrow$ Superspace (x^μ, θ)

SUSY transformation:

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

The origin of the electroweak mass scale may be understood in connection with the SUSY breaking scale.

Phenomenology of SUSY models

- Direct search
  A light Higgs boson (a necessary condition for SUSY)
  SUSY particle search (Tevatron, LHC, LC)
- Indirect search
  Quark flavor physics (squark mass matrixes)
  Lepton flavor violation (slepton mass matrixes)
  muon g-2 (enhanced muon Yukawa coupling)
  Neutron, electron, muon EDM (SUSY CP phases)
  Proton decay (GUT interaction)
- Each indirect search is sensitive to a different aspect of SUSY models.

Plan of this talk

- SUSY model
- SUSY at energy frontier
  (LHC and role of LC)
- SUSY and flavor physics
  (Role of Super B factory)

SUSY model

Minimal SUSY Standard Model (MSSM)

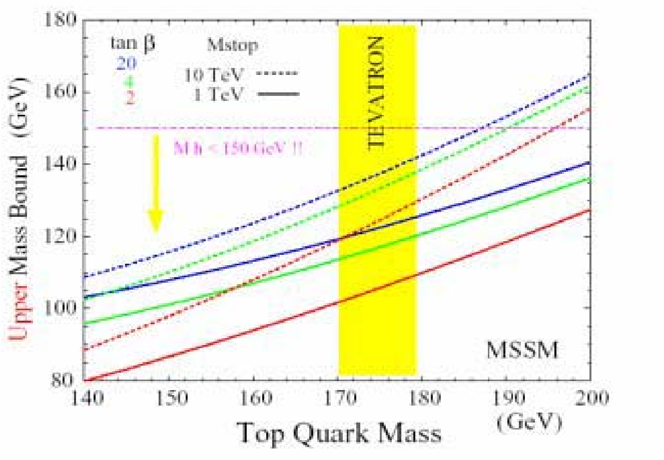
A SUSY partner is introduced
for each particle in the SM.
Two Higgs doublets are necessary.

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

MSSM Lagrangian

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

SUSY invariant Lagrangian
Gauge coupling constants, Yukawa coupling constants. -> Various relations among fermionic and bosonic couplings.
No independent Higgs self-coupling constant.
-> Mh < 135 GeV



SUSY breaking terms

- Mass terms for SUSY particles.
- Origin of SUSY breaking.= Spontaneous SUSY breaking in supergravity. (Super Higgs mechanism)
- Various possibilities.

Origin of SUSY breaking
(mSUGRA, AMSB, GMSB,
Flavor symmetry, etc.)

↓ ← Renormalization
(SUSY GUT, neutrino Yukawa couplings etc.)

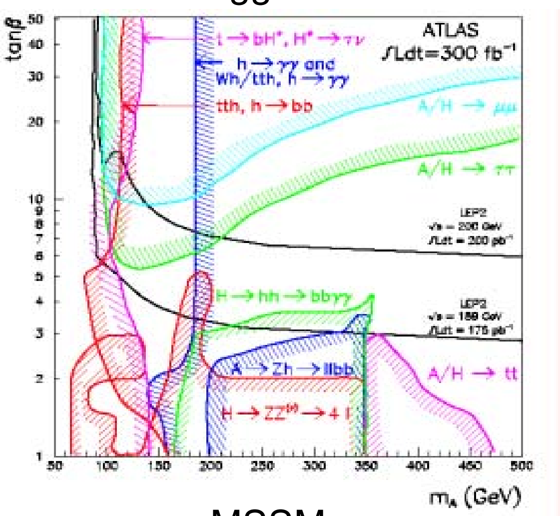
SUSY breaking terms at the Mw scale
(squark, slepton, chargino, neutralino, gluino masses)

- Electroweak symmetry breaking may be understood from SUSY breaking. (Radiative electroweak symmetry breaking scenario)

SUSY at energy frontier

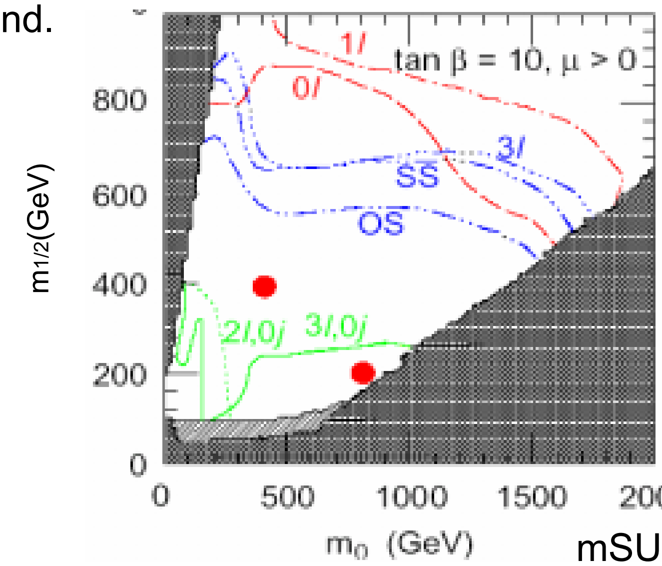
LHC experiments will provide a crucial test for SUSY.
(1) Mass reach of squark and gluino search is about 2 TeV.
(2) A light Higgs boson below 135 GeV must exist for MSSM.

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



MSSM

SUSY search: Cascade decay.

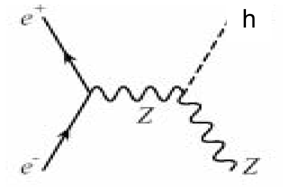


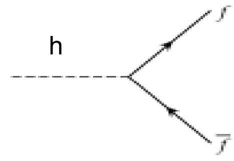
~gluino
2 TeV

mSUGRA

Role of LC

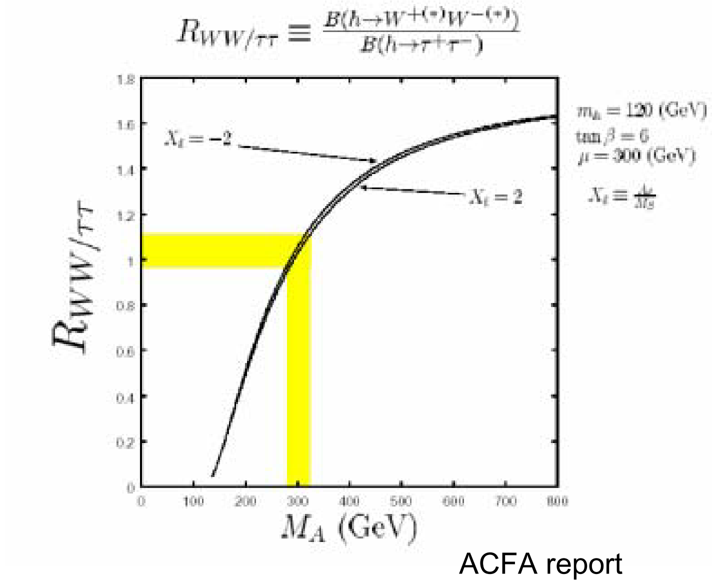
(1) SUSY Higgs sector



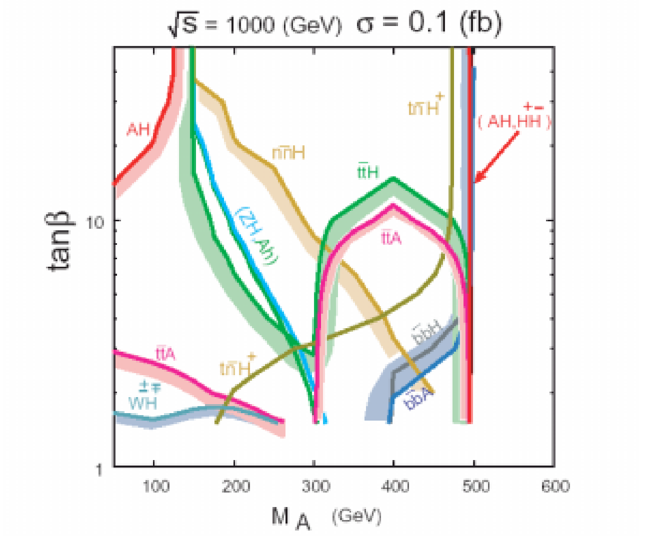


Higgs-coupling measurements from the cross section and branching ratios of the light Higgs boson (h) .

Direct and indirect search for heavy Higgs bosons (H, A, $H^{\pm}$).



ACFA report

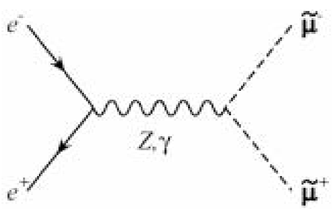


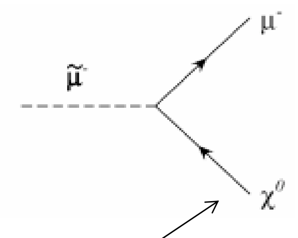
S. Kiyoura, et.al, (ACFA Higgs WG)

(2) SUSY particle search

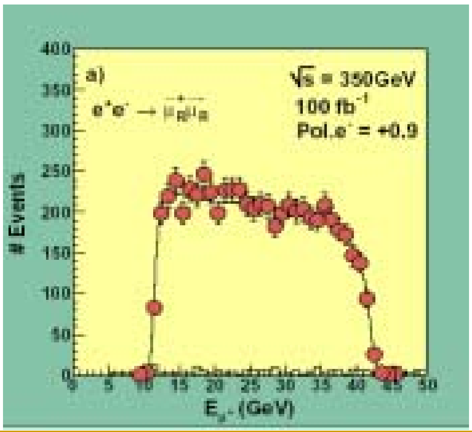
Slepton, chargino, neutralino production.
Precise determination of mass, spin, coupling.
Crucial to prove a new symmetry principle.

Smuon production and decay





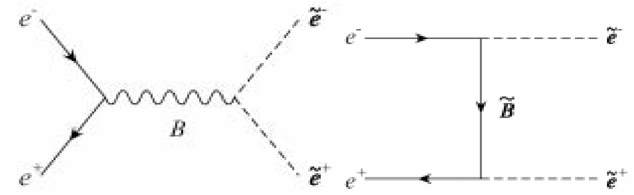
Dark matter candidate?

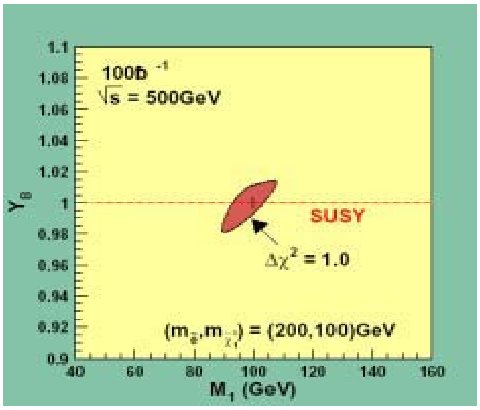


Test of a SUSY relation

Selectron production

$g_{eeB} = g_{\tilde{e}\tilde{e}\tilde{B}}$?





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

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

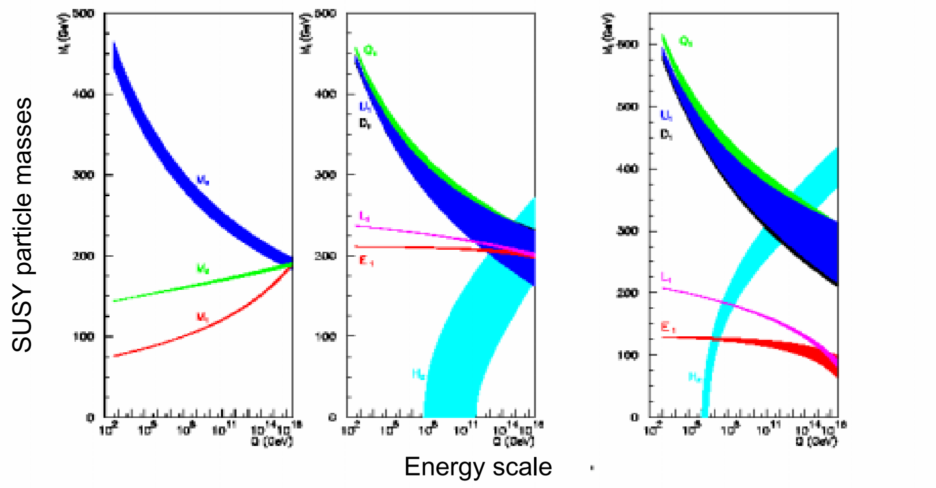
LHC: Squark and gluino production and cascade decay

JLC: Slepton, neutlarino, and chargino pair-production

Combined analysis

↓

SUSY breaking scenario



mSUGRA RGE evolution GMSB RGE evolution

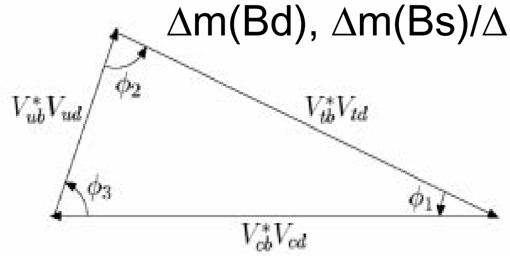
G.A.Blair, W.Porod,and P.M.Zerwas

SUSY at Super B factory

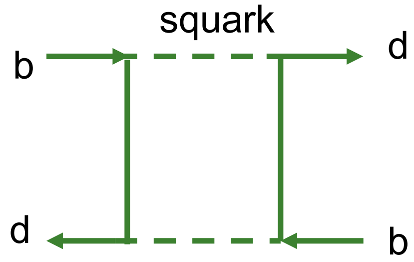
- Both KEK and SLAC have an update plan of increasing the luminosity of the current B factory by a factor of 10 – 100 in 10 years.
- Main motivation is a search for "New Physics" effects. There are a variety of ways to search for new physics.

1. Consistency among the Bd unitarity triangle, ε, and the Bs mixing. (New contributions to box diagrams)

Δm(Bd), Δm(Bs)/Δm(Bd), ε



A few % level at a Super B factory



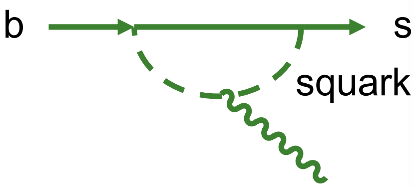
2. Comparison of CP violation in different decay modes (New phases in the b-s-g transition)

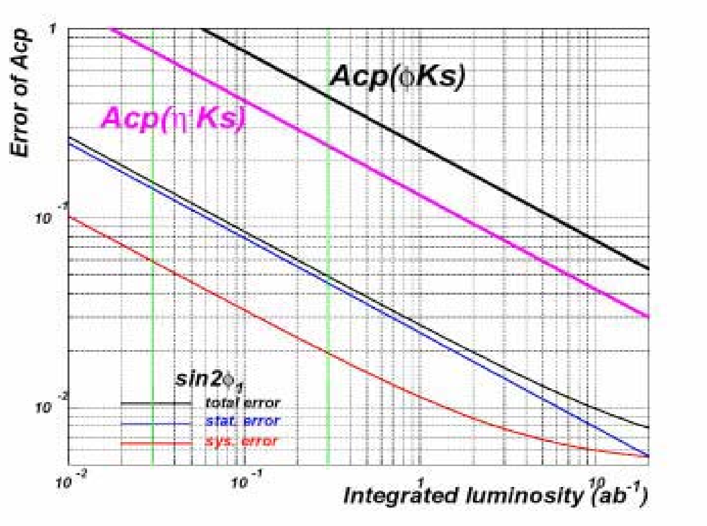
$\sin(2\phi_1)$ from

$B \to J/\psi\ Ks$

$B \to \phi Ks$

$B \to \eta' Ks$





Super KEKB EoI

Current date

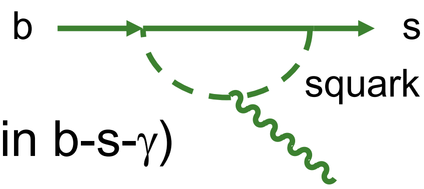
$B \to J/\psi\ Ks$

$$\sin(2\phi_1) = 0.719 \pm 0.074 \pm 0.035 (Belle)$$
$$0.741 \pm 0.067 \pm 0.034 (BABAR)$$

$B \to \phi Ks$

$$'\sin(2\phi_1)' = -0.73 \pm 0.64 \pm 0.18 \quad (Belle)$$
$$-0.19^{+0.52}_{-0.50} \pm 0.09 \quad (BABAR)$$

3. Rare decay processes



Direct CP violation in b->s γ. (New phase in b-s-γ)

$$A_{CP} = \frac{B(b \to s\gamma) - B(\bar{b} \to s\gamma)}{B(b \to s\gamma) + B(\bar{b} \to s\gamma)}$$

|Acp|<1% in SM

Mixing induced CP violation in B->Msγ. (b->sγR)

$$A_{CP}^{mix}(B \to K_1\gamma) = \frac{2Im(e^{-i\phi_M} C_7 C_7')}{|C_7|^2 + |C_7'|^2}$$

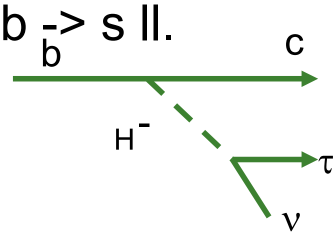
$$H = \frac{4G_F}{\sqrt{2}} \{C_7'(\bar{s}_R \sigma^{\mu\nu} b_L) F_{\mu\nu} + C_7(\bar{s}_L \sigma^{\mu\nu} b_R) F_{\mu\nu} + h.c\}$$

Acp~O(ms/mb) in SM

Branching ratio and lepton FB asymmetry in b -> s ll.

b-> s νν, B->ττ, B->ll,

B->D τν (Charged Higgs exchange)



Role of Flavor Physics

- Determine flavor structure of squark mass matrices.
(New flavor mixing and new CP phases.)
- Quark mass -> Yukawa coupling
Squark mass -> SUSY breaking terms
- SUSY breaking terms depend on SUSY breaking mechanism and interaction at the GUT/Planck scale.

Diagonal tem: LHC/LC
Off diagonal term:
Flavor Physics

$$(m_{\tilde{q}}^2)_{ij} = \begin{pmatrix} m_{\tilde{1}1}^2 & m_{\tilde{1}2}^2 & m_{\tilde{1}3}^2 \\ m_{\tilde{2}1}^2 & m_{\tilde{2}2}^2 & m_{\tilde{2}3}^2 \\ m_{\tilde{3}1}^2 & m_{\tilde{3}2}^2 & m_{\tilde{3}3}^2 \end{pmatrix}$$

B physics in three SUSY models

T.Goto, Y.O. Y.Shimizu, T.Shindou, and M.Tanaka, 2002,2003

- In order to illustrate how B physics is useful to explore the SUSY breaking sector, we take three models.

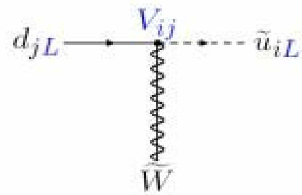
1. Minimal supergravity model
2. SU(5) SUSY GUT with right-handed neutrino
3. MSSM with U(2) flavor symmetry

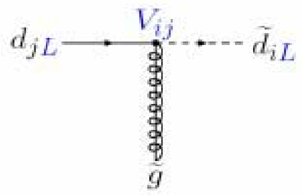
Minimal supergravity model

S.Belrolini, F.Borzumati, A.Masiero, and G.Ridorfi, 1991, …..

- All squarks are degenerate at the Planck scale.
- Flavor mixings and mass-splittings are induced by renormalization. Flavor mixing in the d_L sector.
- As a consequence,

$$(V_{squark})_{ij} \simeq (V_{quark})_{ij}$$



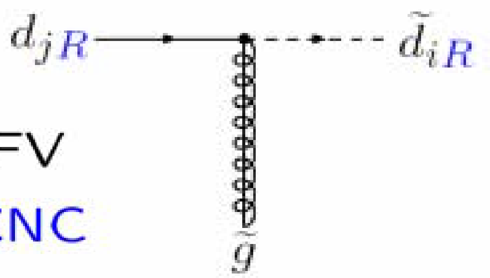


The CKM matrix is the only source of flavor mixing.
SUSY CP phases (A-term, μ–term) constrained by EDM experiments.

SU(5) SUSY GUT with right-handed neutrino

S.Baek,T.Goto,Y.O, K.Okumura, 2000,2001;T.Moroi,2000; N.Aakama, Y.Kiyo, S.Komine, and T.Moroi, 2001, D.Chang, A.Masiero, H.Murayama,2002; J.Hisano and Y.Shimizu, 2003;….

- Large flavor mixing in the neutrino sector can be a source of flavor mixing in the right-handed sdown sector.



$$\nu \text{ mixing} \;\; \underset{GUT}{\rightarrow} \;\; \begin{array}{l} \tilde{l} \text{ mixing} \rightarrow \text{LFV} \\ \tilde{q} \text{ mixing} \rightarrow \text{FCNC} \end{array}$$

Correlation with LFV processes (μ –> eγ, etc) is important.
New CP phases in the GUT embedding. (T.Moroi)

The LFV constraint depends on neutrino parameters

Neutrino mass $$m_\nu = y_\nu^T \frac{1}{M_R} y_\nu (v^2 \sin^2 \beta / 2)$$

LFV mass terms for slepton (and sdown).

$$(\delta m_L^2)^{ij} \cong -(y_\nu^+ y_\nu)^{ij} \cdot (3 + |A_0|^2) \ln(M_p / M_R) / 8\pi^2$$

Two cases considered for M_R.

(1) Degenerate case

$(M_R)_{ij} = M \delta_{ij}$

Severe $\mu \to e\gamma$ constraint

(2) Non-degenerate case

$$y_\nu^\dagger y_\nu = \begin{pmatrix} Y_{11} & 0 & 0 \\ 0 & Y_{22} & Y_{23} \\ 0 & Y_{23}^* & Y_{33} \end{pmatrix}$$

$\mu \to e\gamma$ suppressed

(Casas and Ibarra, Ellis-Hisano-Raidal-Shimizu)

MSSM with U(2) flavor symmetry

A.Pomarol and D.Tommasini, 1996; R.Barbieri,G.Dvali, and L.Hall, 1996; R.Barbieri and L.Hall; R.Barbieri, L.Hall, S.Raby, and A.Romonino; R.Barbieri,L.Hall, and A.Romanino 1997; A.Masiero,M.Piai, and A.Romanino, and L.Silvestrini,2001; ….

- The quark Yukawa couplings and the squark mass terms are governed by the same flavor symmetry.
- 1st and 2nd generation => U(2) doublet
  3rd generation => U(2) singlet

$$U(2) \xrightarrow{\epsilon} U(1) \xrightarrow{\epsilon'} \text{“No symmetry”}$$

$$(Y)_{ij} \simeq y \begin{pmatrix} 0 & O(\epsilon') & 0 \\ O(\epsilon') & O(\epsilon) & O(\epsilon) \\ 0 & O(\epsilon) & 1 \end{pmatrix},$$

$$(m_{\tilde{q}}^2)_{ij} \simeq \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1+O(\epsilon^2) & O(\epsilon) \\ 0 & O(\epsilon) & O(1) \end{pmatrix},$$

for $\epsilon' \ll \epsilon \ll 1$.

Numerical results

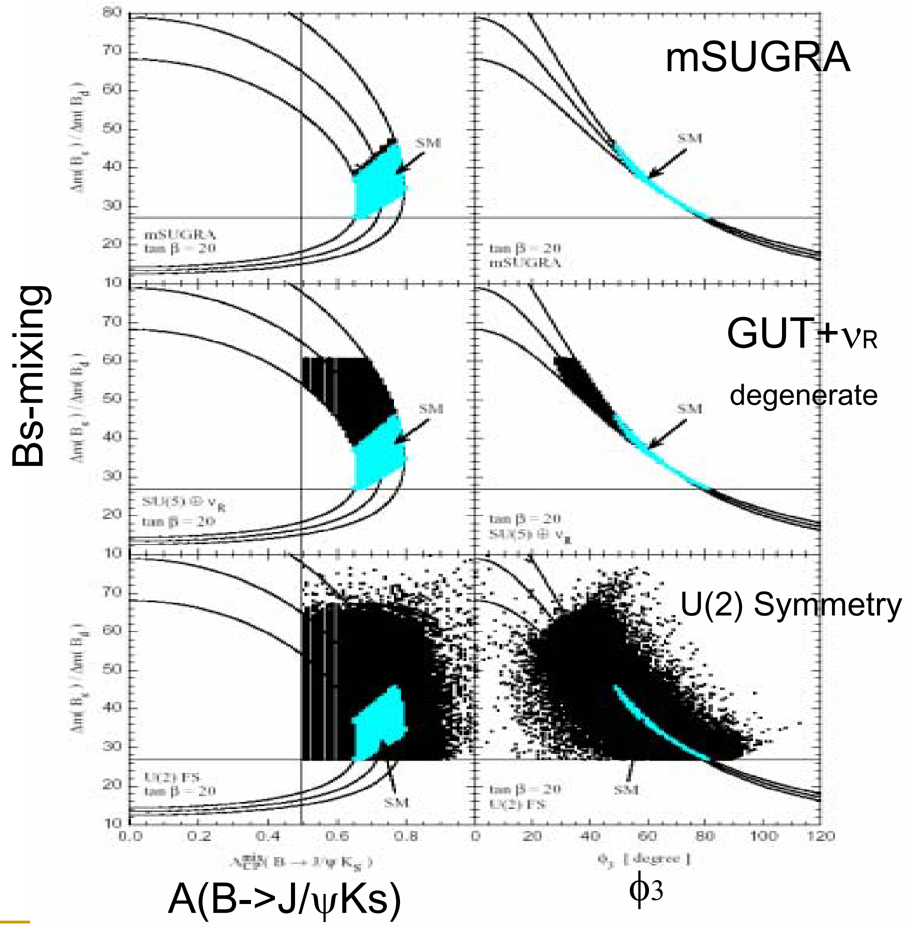
- We calculated SUSY effects to the following observables in the three models.
- CP violation in K-K mixing (ε).
- Bd-Bd mixing, Bs-Bs mixing.
- Mixing-induced CP violation in B ->J/ψKs, B->φKs, B->Ms γ .
- Direct CP violation in b->s γ.

Unitarity Triangle

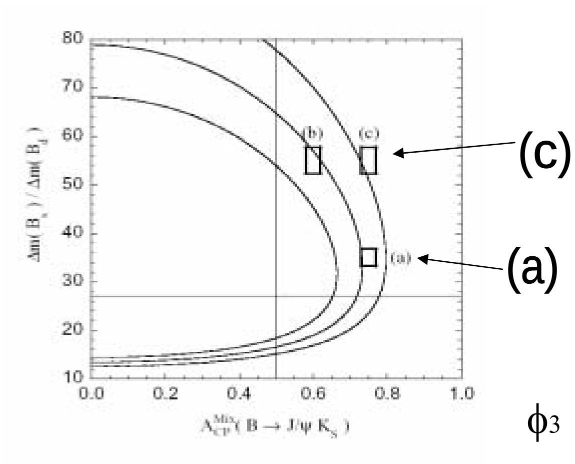
1. Minimal SUGRA:
   The deviation from the SM is less than 10%.

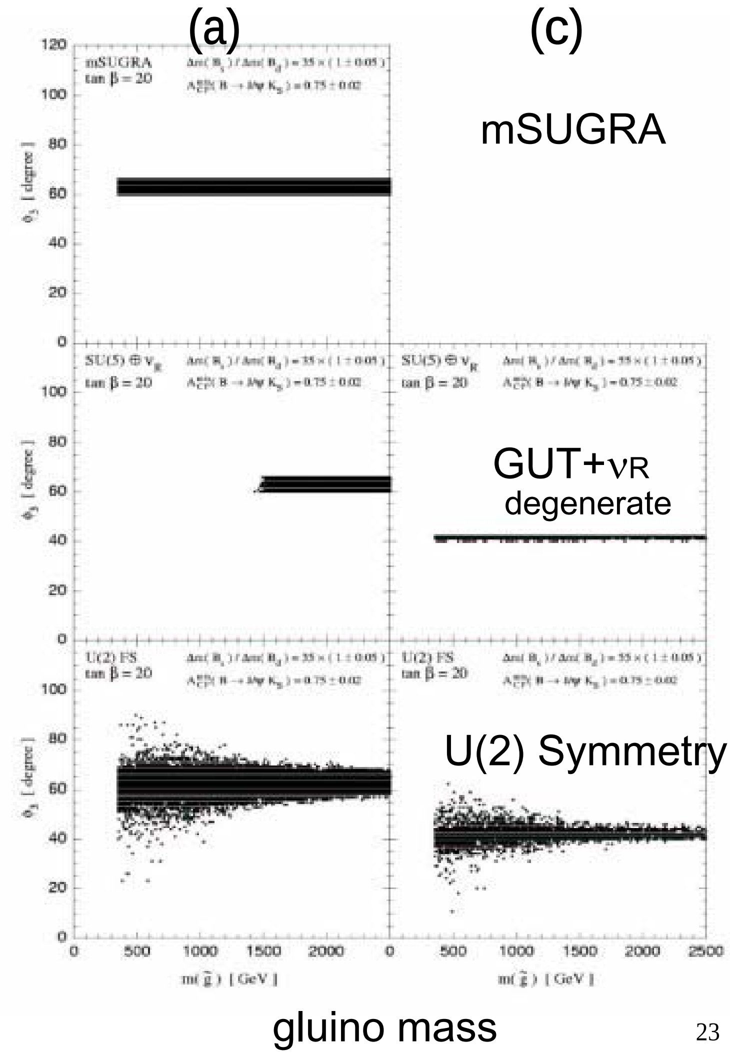
2. SUSY GUT with ν_R :
   ($M_{R\,ij}$= $M\delta_{ij}$)
   degenerate-case
   Bs-mixing can be different from the SM.
   B-unitarity triangle is closed.

3. U(2) flavor symmetry:
   Large SUSY corr. to K, Bd, and Bs mixings.
   B-unitarity triangle may not be closed.



ϕ_3 (γ) determination

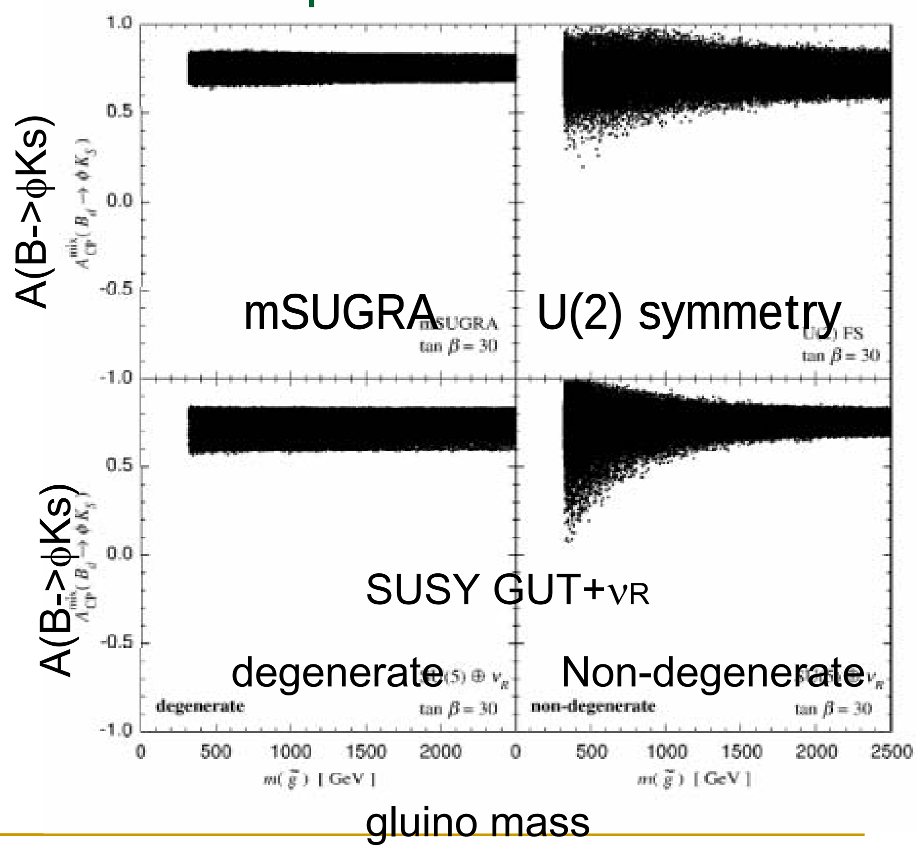




Even if Bs-mixing is consistent with the SM, ϕ3 measurement could show the deviation for the U(2) model.

CP asymmetry in B ->ϕKs

CP asymmetry can be different from that of the B->J/ψ Ks mode in U(2) and SUSY GUT (non-degenerate case).

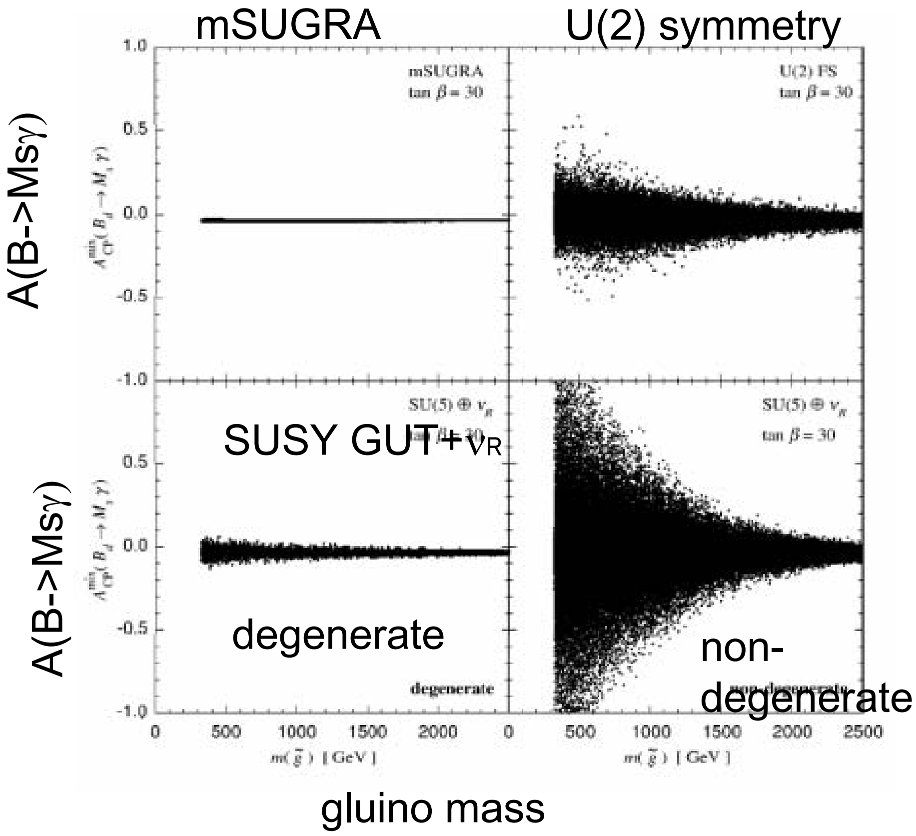


Recent works:
Hiller, Ciuchini-Silvesrini, Kahalil-Kou, Kane-Ko-Wang-Kolda-Park-Wang, Harnik-Larson-Murayama-Pierce, Ciuchini-Franco-Masiero-Slivestrini, Hisano-Shimizu, …

Mixing-induced asymmetry in B->Msγ

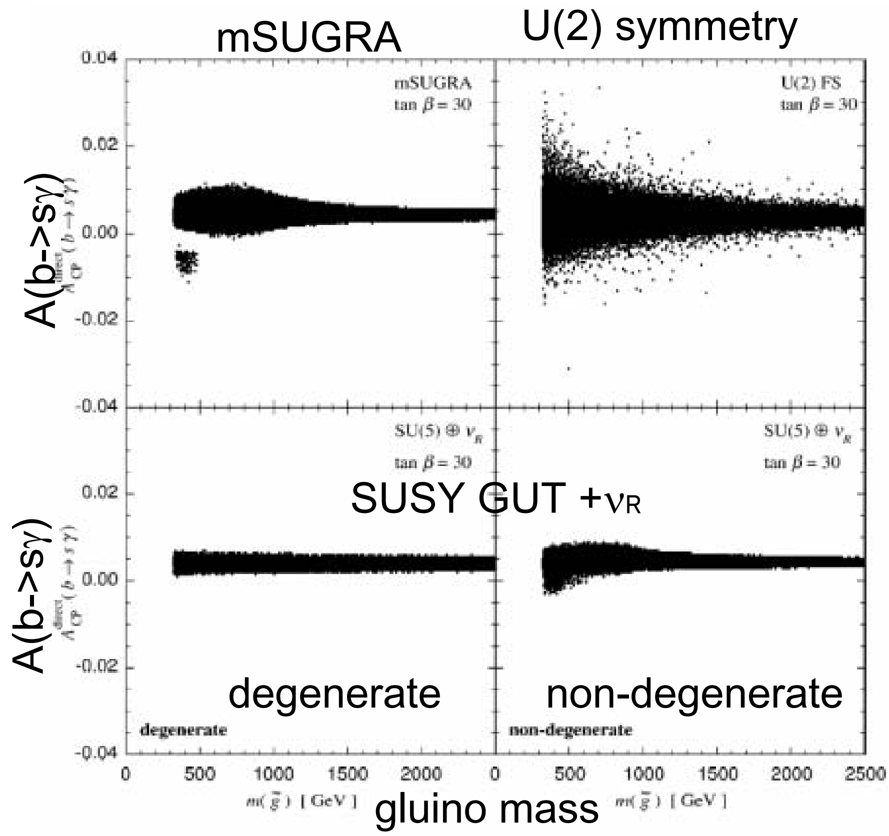
Signal of b->sγ_R;

Large for SU(5) SUSY GUT (non-degenerate) and the U(2) flavor symmetry model.



Direct CP asymmetry of b->s γ

- A signal of a new phase in the b-> s γ_L transition.
- The deviation can be large for the U(2) model.



- Deviation from the SM is at most 10% level for the mSUGRA model.
- In the SU(5) GUT with ν_R, 1-2 flavor mixing is large for the degenerate case.

  -> Inconsistency between ε and the B-triangle.
- 2-3 mixing signals for the non-degenerate case. -> Mixing induced CP asymmetries in B-> ϕKs, B->Msγ.
- Various new physics signals for the MSSM with U(2) flavor symmetry.

Pattern of the deviation from the SM prediction

	Unitarity triangle			Rare decay		
	Bd-unitarity	ε	Δ m(Bs)	B->ϕKs	B->Msγ indirect CP	b->sγ direct CP
mSUGRA	closed	small	small	small	small	small
SU(5)SUSY GUT + ν_R (degenerate)	closed	large	small	small	small	small
SU(5)SUSY GUT + ν_R (non-degenerate)	closed	small	large	large	large	small
U(2) Flavor symmetry	large	large	large	large	large	sizable

Summary

- If SUSY is a true symmetry, we are led to a big change of concept on space-time and particle physics.
- LHC will provide a crucial test concerning existence or non-existence of SUSY.
- LC is necessary to establish a new symmetry principle.
- Role of flavor physics is to explore the SUSY breaking sector from flavor changing and CP violating processes.
- Flavor and CP structure of squark mass matrixes will be determined at Super B factory. We expect different patterns of deviations from SM predictions for different SUSY breaking scenarios and unification models.