Flavor Physics in SUSY

Masahiro Yamaguchi (Tohoku U.)

Nov.25, 2005 @Higgs&SUSY conference

- **"New" Flavor Problem in Beyond-SM**
- **Flavor Mixing in SUSY**
- **Lepton Flavor Violation**
- **B-physics**
- **Summary**

“NEW” Flavor Problem in Beyond-SM

Standard Model

- Current Understanding of the fundamental elements of matter and their interaction:

- **Gauge Sector:**
  - $SU(3)_C x SU(2)_L x U(1)_Y \rightarrow SU(3)_C x U(1)_{em}$
  - Spontaneous symmetry breaking: Higgs mechanism

- **Flavor Sector:**
  - 3 generations of quarks and leptons
  - FCNC suppressed: **GIM mechanism**

Standard Model is not complete!

- Naturalness Problem (Gauge hierarchy problem) ← Gauge Sector
  - Why electroweak scale << Planck scale?
  - How is EW scale stabilized against radiative corrections?

- Mysteries of Flavors ← Flavor Sector
  - Why 3 generations?
  - Why such masses?
  - Neutrino masses

- Other questions ……..

- Gauge Hierarchy Problem
  - Probably a real problem (cf. cosmological constant)
  - Moreover the solution should be around EW scale (Terascale)
  - Many proposals: supersymmetry, extra dimensions …

- Questions on Flavor
  - We don’t know at which scale these questions should be answered.

"New" Flavor Problem in Beyond SM

- SM is too good to suppress FCNC

  GIM mechanism

  - No tree level FCNC
  - FCNC at loop level: suppressed by small quark mass

  - **No Lepton Flavor Violation (LFV)**

    ← Massless neutrino

- **FCNC from Beyond SM**
  - No GIM suppression
  - New particles & new interaction → too large FCNC
    - Examples:
      - extended technicolor
      - supersymmetry with arbitrary squark masses

- FCNC constraints
- Naïve dimensional analysis Λ>O(100-1000)TeV
  - Loop factor etc → **Λ_{NP}>O(10-100) TeV**

- Conflicts with the naturalness **Λ_{NP} <1 TeV**

→ **New Flavor Problem!**

Flavor Physics in Beyond-SM

- New paradigm of Beyond-SM should
  - **1. solve the gauge hierarchy problem**
  - **2. solve the new flavor problem**

- Expect the solution of the flavor problem gives a hint on the mysteries of flavor.

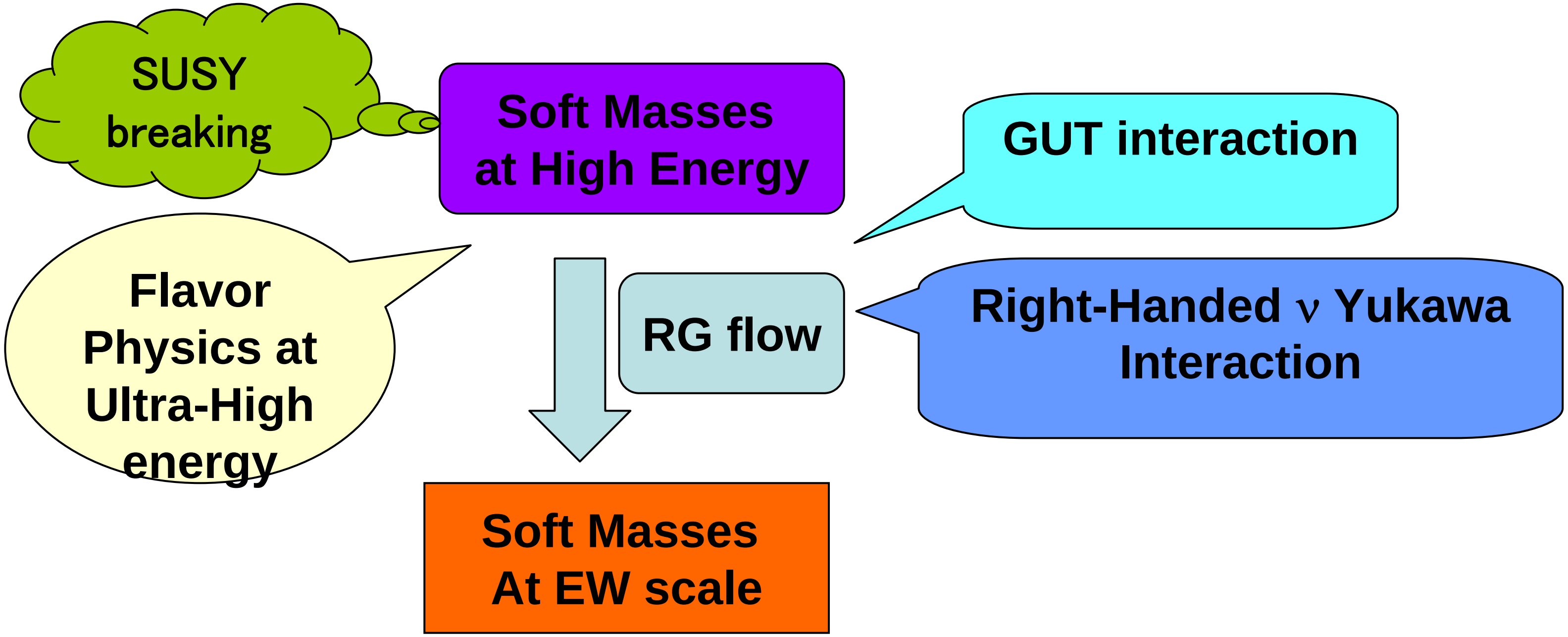
- Nature may be so kind to us that flavor mixing is not completely hided, but marginally revealed.
  - Chance to observe at the forthcoming experiments.
  - This seems the case in many scenarios of Beyond-SM.

- In the following, I consider Supersymmetric Standard Model.
  - A promising candidate for BSM
  - Interaction known: calculable
  - Conclusions will be shared with other BSM candidates.

Flavor Mixing in SUSY

Squark & Slepton Masses

- **Treasure** which may carry various information on physics at Ultra-High Energy



Flavor Mixing in Sfermion Masses

- **Squark/Slepton masses with arbitrary flavor mixing**
  → too large FCNC/LFV if masses are (sub-) TeV.
  SUSY flavor problem

- **Mechanisms of SUSY breaking &mediation**
  - **Minimal SUGRA**
    - **Universal scalar masses**
      - **not always be justified from theoretical viewpoint. Should be critically tested experimentally**
    - **RG flow-→ regenerates flavor mixing in general**
  - **Flavor Symmetry (or geometry of extra dimensions)**
    - **Broken flavor sym generates flavor mixing in sfermion masses.**

  - **Gauge mediation**
  - **Anomaly mediation**
    - **Insensitive to UV flavor physics. Too good solution to SUSY flavor problem.**
    - **Flavor physics may be boring in these cases.**

Two sources of flavor mixing

- **Renormalization Group flow** (Radiative correction)
  - Flavor mixing (Yukawa) interaction generates flavor mixing in sfermion masses.
    - GUT interaction
    - right-handed ν Yukawa in See-saw mechanism
- **Imprint at Ultra-High Energy**
  - e.g. Flavor symmetry
- These two sources will give different pattern of flavor mixings. → distinguishable!

Lepton Flavor Violation

Lepton Flavor Violation (LFV)

- LFV in charged leptons: clear signal of Beyond-SM

- Neutrino oscillation → Lepton flavor is not a sacred conservation law in nature

- In Many Extensions of SM (including SUSY), sizable LFV effects are expected.

Various LFV processes

- Muon
  - $\mu \rightarrow e\,\gamma$
  - $\mu \rightarrow eee$
  - $\mu A \rightarrow eA$ (conversion)
- Tau
  - $\tau \rightarrow \mu\gamma,\ \mu\eta$ (super)B factory
  - $\tau \rightarrow \mu\mu\mu$ etc LHCb

$$\mu^+ \rightarrow e^+\gamma$$
$$B < 1.2 \times 10^{-11}$$
$$\rightarrow 0(10^{-14})\ (\mathrm{MEG})$$

LFV in SUSY

$$(\Delta m^2_{\tilde{l}})_{ij}$$

- **SU(5) GUT**

  Barbieri-Hall 94
  Hisano-Moroi-Tobe-MY 96

  - RG effects above GUT scale

    → flavor mixing in RH sleptons: $\underline{10}$ in SU(5)

    ← Large top quark Yukawa

- **SUSY see-saw Models**

  Borzumati-Masiero 87
  HIsano-Moroi-Tobe-MY
  -Yanagida 95
  ……

  - RG from Heavy Right-Handed ν Yukawa

    → flavor mixing in LH sleptons

LFV from RH ν Yukawas

Ellis,Hisano,Raidal,Shimizu '02

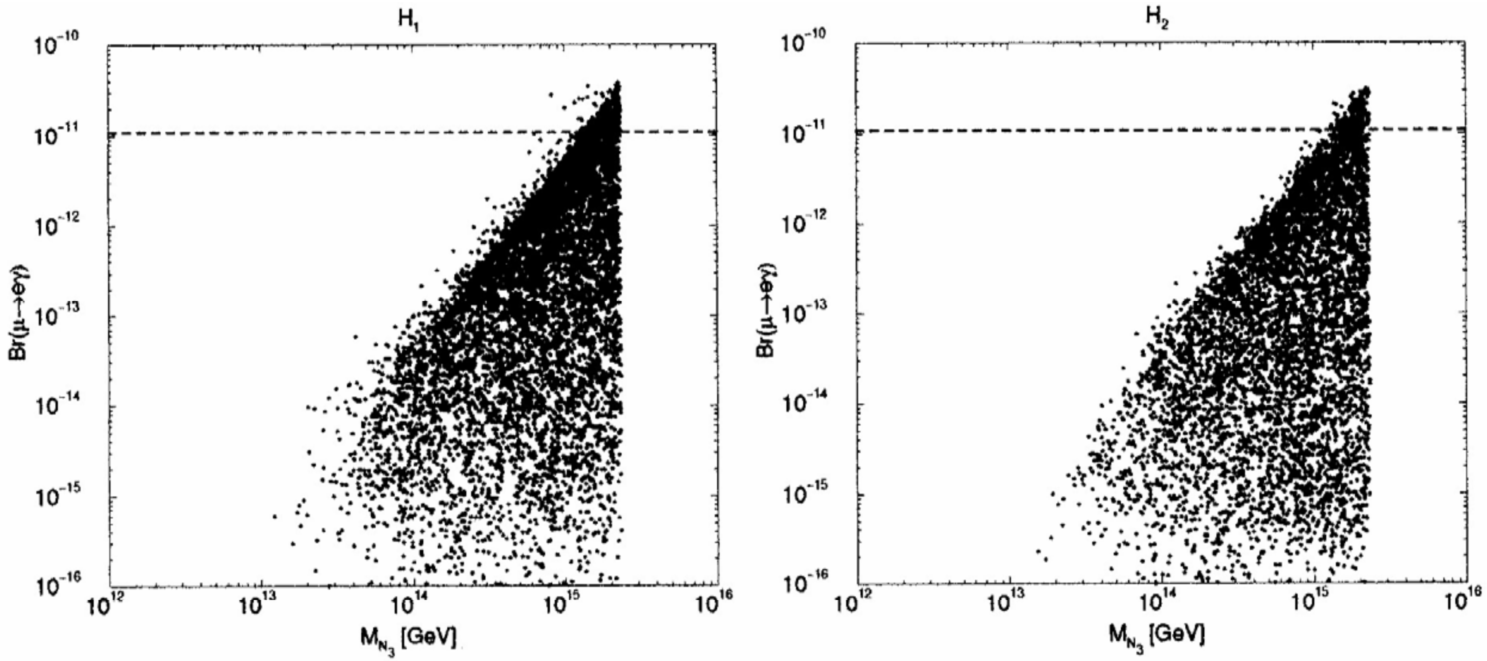


Figure 1: *Scatter plot of* $Br(\mu \to e\gamma)$ *against the heaviest singlet neutrino mass* M_{N_3} *for the ansatz (a)* H_1 *and (b)* H_2. *We take* $m_{1/2} = 300$ *GeV,* $m_0 = 100$ *GeV,* $A_0 = -300$ *GeV,* $\tan\beta = 10$ *and* $sign(\mu) = +1$. *Other input parameters are specified in the text.*

Yet another source ← flavor symmetry

- Broken flavor symmetry imprints flavor mixing in slepton masses.

- e.g.) democratic approach (permutation sym S3)
  - Quark masses — Fritzch&Xing 96
  - Neutrino masses — Fukugita-Tanimoto-Yanagida 98
  - Apply this to sfermion sector — Hamaguchi-Kakizaki-MY 02

$$m_{ij}^2 = m_0^2 \left[\begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} + \rho \frac{1}{3} \begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix} \right]$$

Non-zero ρ → flavor mixing

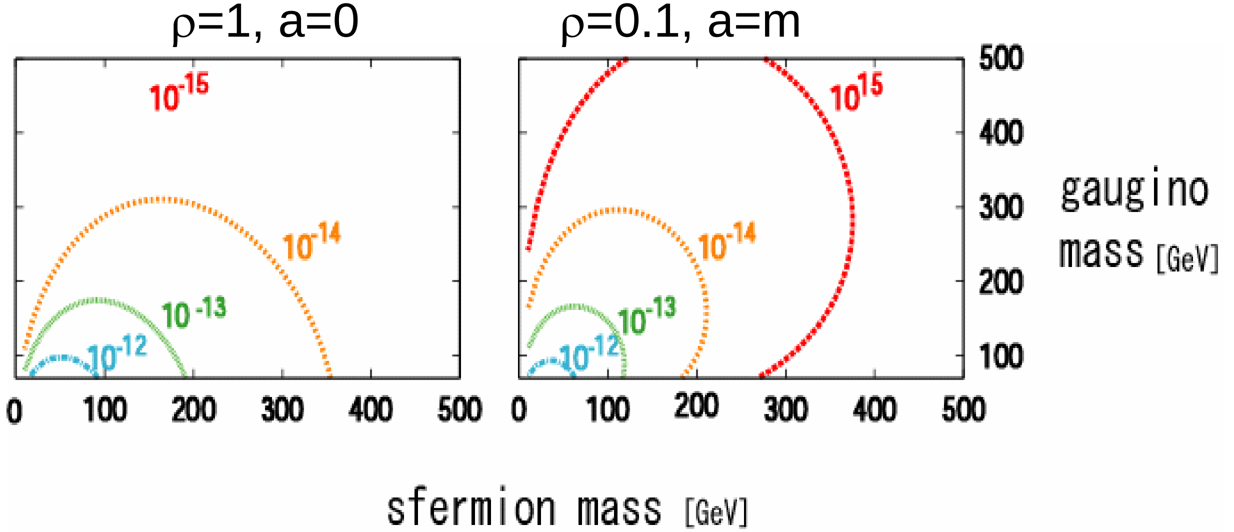
Unique Predictions

- Collider Physics

$$m_{\tilde{e}R} = m_{\tilde{\mu}R} \neq m_{\tilde{\tau}R} \qquad m_{\tilde{e}L} = m_{\tilde{\mu}L} = m_{\tilde{\tau}L}$$

  - This is testable in future collider experiments!

- Lepton Flavor Violation (LFV)
  - $\mu \rightarrow e\,\gamma$ from RH slepton exchanges.



Comparison:

Synergy between collider and flavor experiments

Minimal SUGRA © RG from NR Yukawa	Democratic Approach
LH stau is lighter than others.	RH stau is either lighter or heavier than others
LH sleptons have LFV $\Rightarrow \mu_R^- \rightarrow e_L^- + \gamma$	RH sleptons have LFV. $\Rightarrow \mu_L^- \rightarrow e_R^- + \gamma$

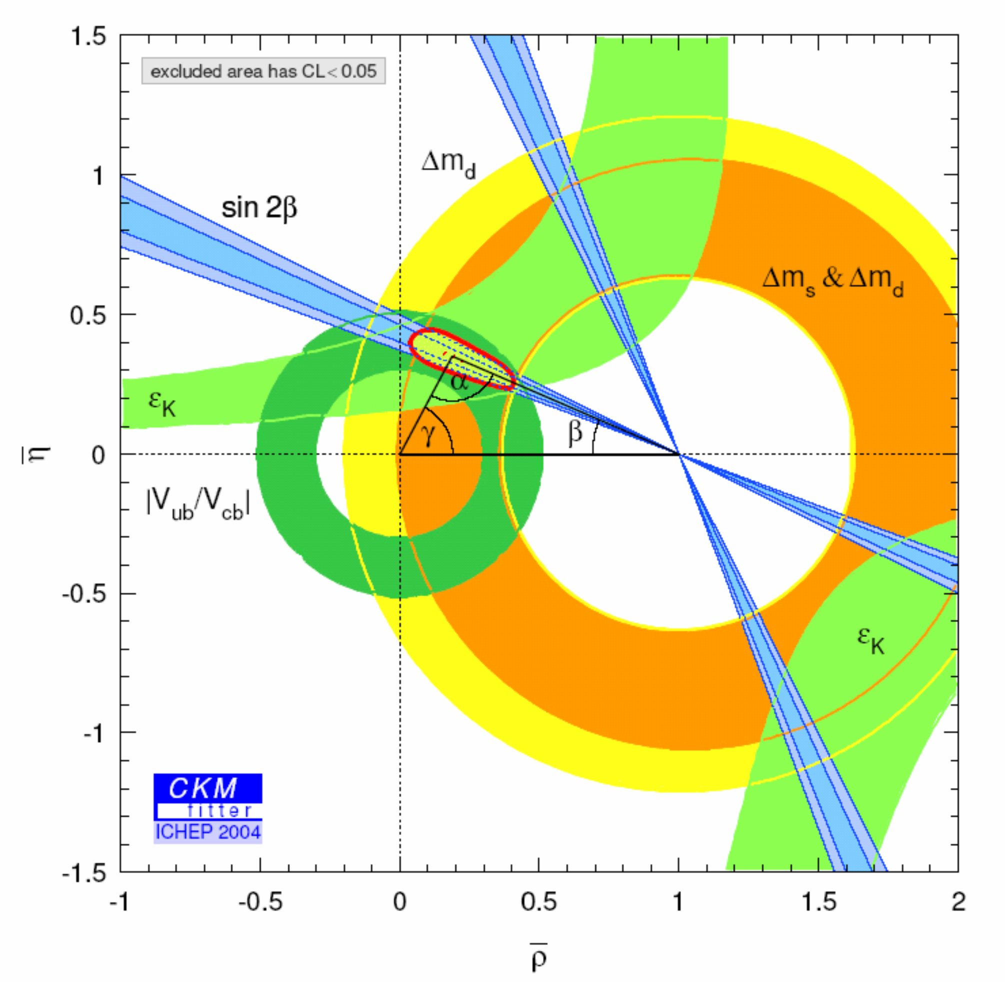
testable in collider exp

Polarized muon may be important to distinguish each other.

B-physics in SUSY

Flavor Mixing and CP in SM

Cabbibo-Kobayashi-Maskawa (CKM) scheme has been established!



Flavor Mixing in Quark Sector: Beyond-SM

- b→s seems most interesting
  - b→c measured by B→J/ΨK: SM contribution (startring from tree level) dominant
  - b→s no SM at tree level: easy to see new physics effects
  - Other mixings already give stringent constraints on SUSY flavor mixing. e.g.) K-Kbar, B-Bbar
  - Prejudice: 3-2 mixing may be large as suggested by atmospheric neutrino

Beauty → Strange in SUSY GUT see-saw models

Large 2-3 RH sdown mixing

in SUSY GUT see-saw models

SU(5) Moroi

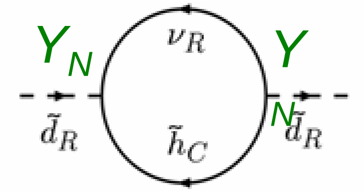
SO(10) Chang,Masiero&Murayama

Atmospheric ν implies large 2-3 mixing in Right-handed ν Yukawa

$$\begin{pmatrix} b_R^c \\ \tau_L \end{pmatrix} \leftrightarrow \begin{pmatrix} s_R^c \\ \mu_L \end{pmatrix}$$

SUSY GUTs→ large 2-3 mixing in RH sdown sector via RG flow

$$\tilde{b}_R \leftrightarrow \tilde{s}_R$$



Large contribution to b→s transition

Cf. $\tilde{b}_L \leftrightarrow \tilde{s}_L$

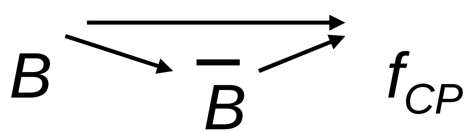
- RG Flow: does not give significant flavor mixing with new CP phase

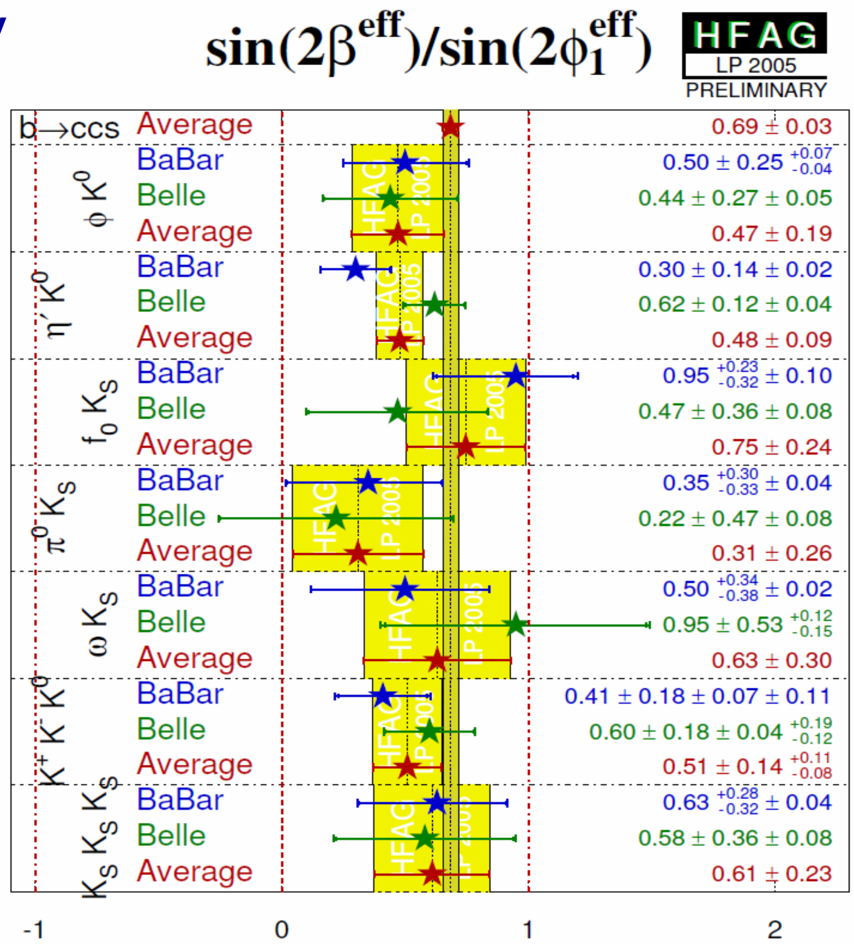
- May be imprinted at Ultra-High Energy Scale.
  - e.g. Flavor symmetry!?

b→s: Current Status 2005

mixing-induced CP asymmetry

$$a_{CP}(t) \equiv \frac{\Gamma(\bar{B}(t) \to f_{CP}) - \Gamma(B(t) \to f_{CP})}{\Gamma(\bar{B}(t) \to f_{CP}) + \Gamma(B(t) \to f_{CP})}$$
$$= \frac{|\lambda|^2 - 1}{|\lambda|^2 + 1} \cos \Delta m t + \frac{2 \mathrm{Im} \lambda}{|\lambda|^2 + 1} \sin \Delta m t.$$



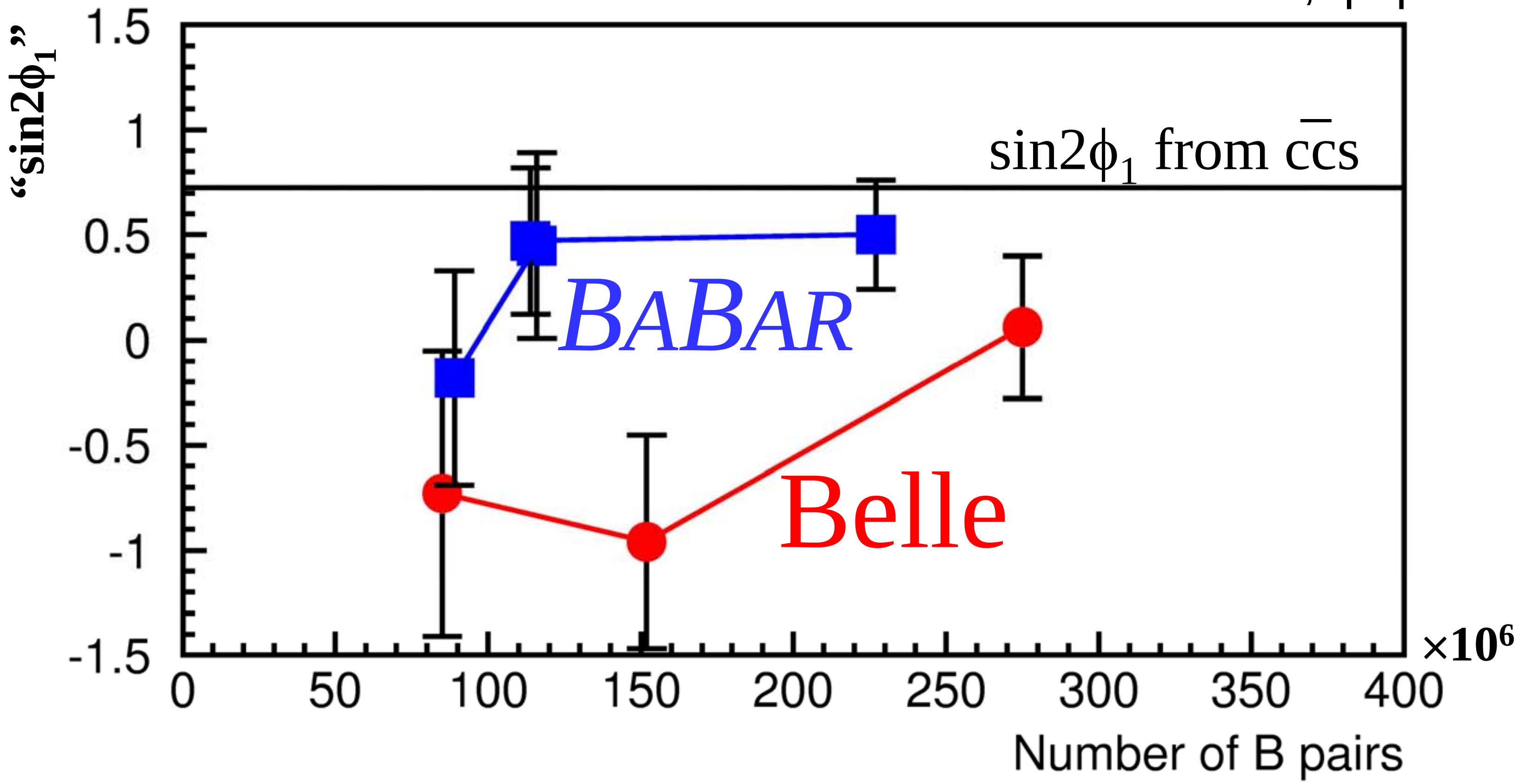


Deviation from SM?

ϕ K, η' K: slightly smaller than SM expectation, but within 2 σ

History of "$\sin 2\phi_1$" with ϕK^0

Hazumi, fpcp2004



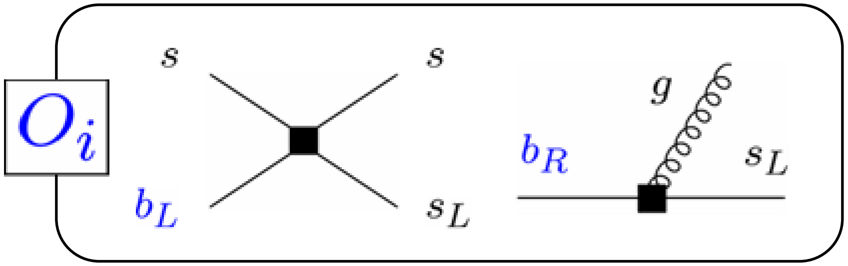
- Deviation is not very evident. But let’s take it seriously.
  - Or suppose that the deviation becomes more evident in future, (with the same central values).
  - What implications to new physics?

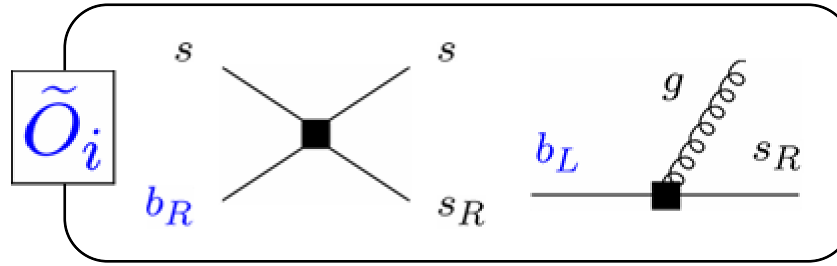
- Pattern of suggested deviation:

  Both ϕK, $\eta' K$ smaller than SM expectation

Sign of Contributions: Final-state Parity

- Effective Hamiltonian $H_{\text{eff}} \sim C_i O_i \; + \; (\tilde{C}, \tilde{O} : R \leftrightarrow L)$





- Decay Amplitude $\langle f|\tilde{O}_i|B_d\rangle = -(-1)^{P_f}\langle f|O_i|B_d\rangle$

$$A \sim \left[\, C_i - (-1)^{P_f}\tilde{C}_i \,\right]\; \langle f|O_i|B_d\rangle$$

Kagan; Khalil&Kou

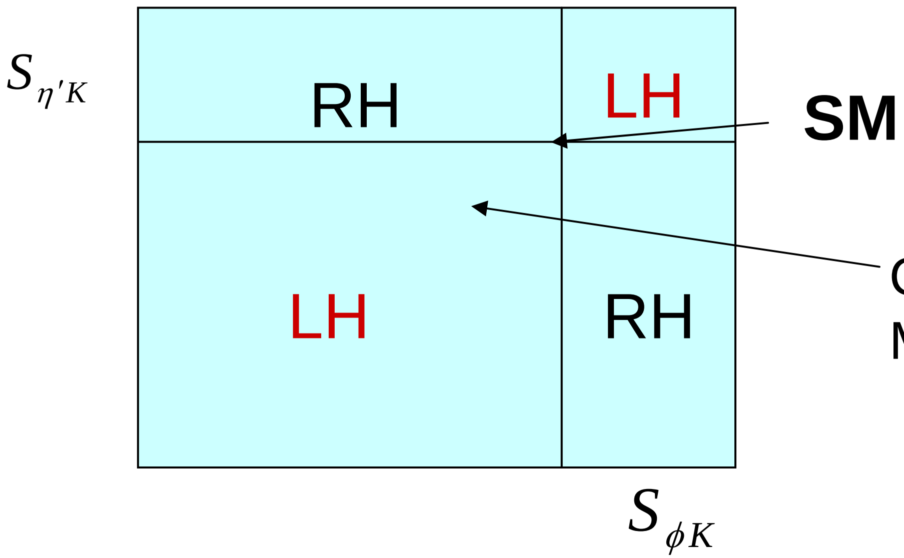
$$A_i^{\text{NP}}(\phi K) \propto [\, C_i^{\text{SM}} + C_i^{\text{NP}} + \tilde{C}_i^{\text{NP}} \,]\langle \phi K|O_i|B_d\rangle \quad \textbf{(odd)}$$

$$A_i^{\text{NP}}(\eta' K) \propto [\, C_i^{\text{SM}} + C_i^{\text{NP}} - \tilde{C}_i^{\text{NP}} \,]\langle \eta' K|O_i|B_d\rangle \quad \textbf{(even)}$$

LH

Schematic View of SUSY contributions

Sf : Mixing Induced CP Asymmetry



Endo, Mishima & MY 04

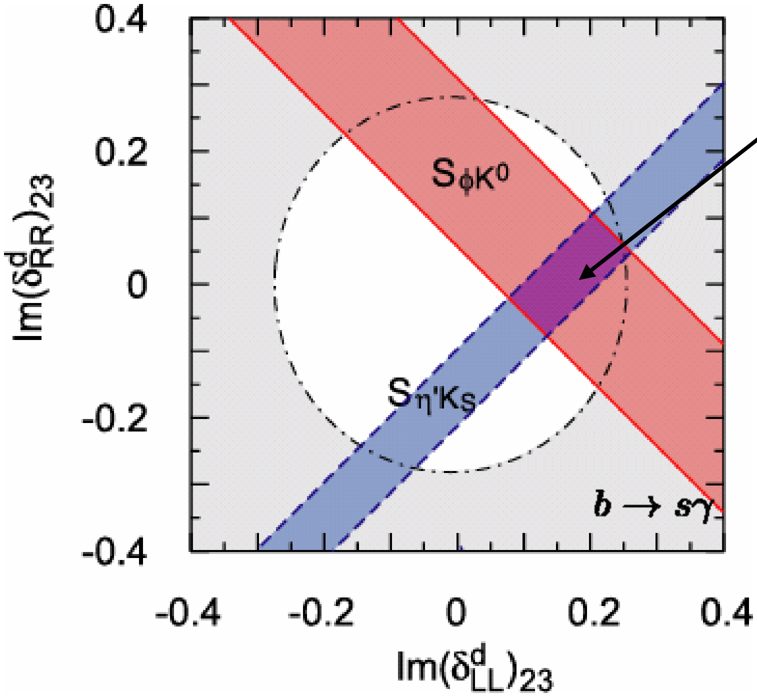
Central values of Experimental Data:
May prefer LH.

	2004 (summer)	2005(summer)
All charmonium	0.726 ± 0.037	0.687 ± 0.032
ϕK^0	0.34 ± 0.20	0.47 ± 0.19
$\eta' K^0$	0.47 ± 0.19	0.50 ± 0.09

Numerical Evaluation in MSSM

Endo, Mishima & MY 04

2005



favored by current data from B-factories (1σ)

$(\delta^d_{LL,RR})_{23} = (m^2_{\tilde{d}_{L,R}})_{23}/m^2_{\tilde{q}}$

$m_{\mathrm{soft}} = 500\ \mathrm{GeV},\ \tan\beta = 10$

GF: $q^2 = m_b^2/2$

The current data prefers LH dominant case!

Caution: deviation less than 2 sigmas. Premature to conclude

Future Prospects

More Data on b→ s penguins: wait and watch!

Correlation with other B decay processes

e.g. $B_S - \bar{B}_S$ mixing: $\Delta m_S \geq 20 - 100\, ps^{-1}$ Endo&Mishima 04

$Br(B \to \mu^+ \mu^-)$ can be $10^{-7} >> 10^{-9}$ (SM)

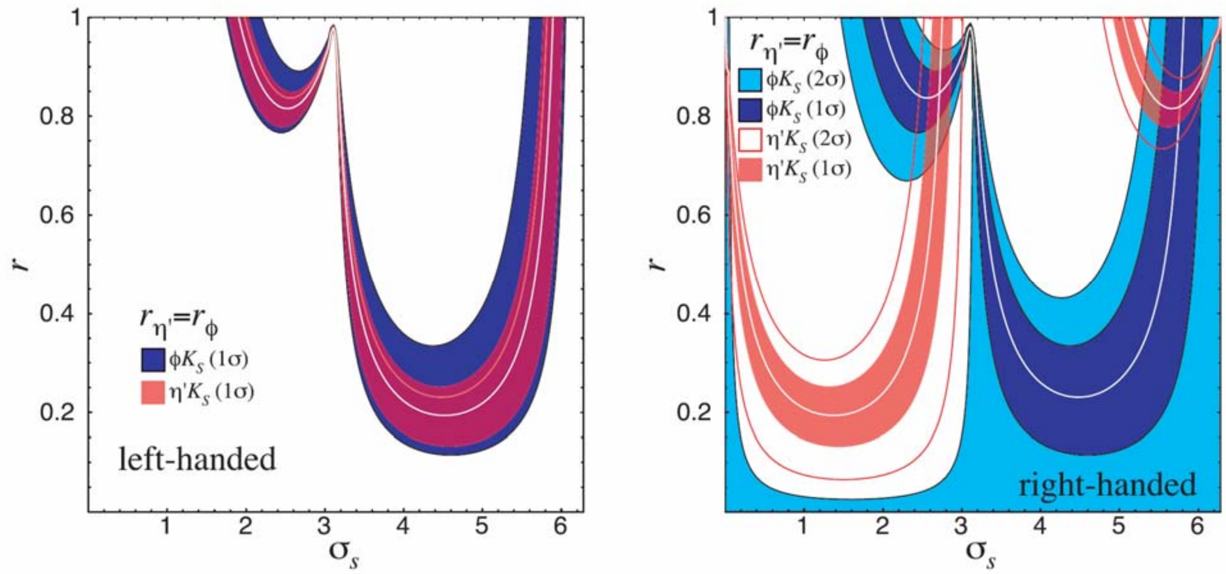
→ **LHC**

Correlation with Lepton Flavor Violation

$\tau \to \mu\gamma, \tau \to \mu\eta$ etc

$\mu \to e\gamma$ etc

Comments on RH/LH



Larson, Murayama & Perez 04

$$\mathcal{A}(B^0 \to \phi, \eta') = \mathcal{A}^{\rm SM}_{\phi,\eta'} \left(1 \pm r_{\phi,\eta'} e^{i\sigma_s}\right)$$

LH interpretation:

OK for generic choice of CP phase

RH interpretation:
may marginally work for special choice of CP phase and SUSY/SM~1
(danger of b→s gamma etc)

← detailed study (Endo,Mishima &MY, in preparation)

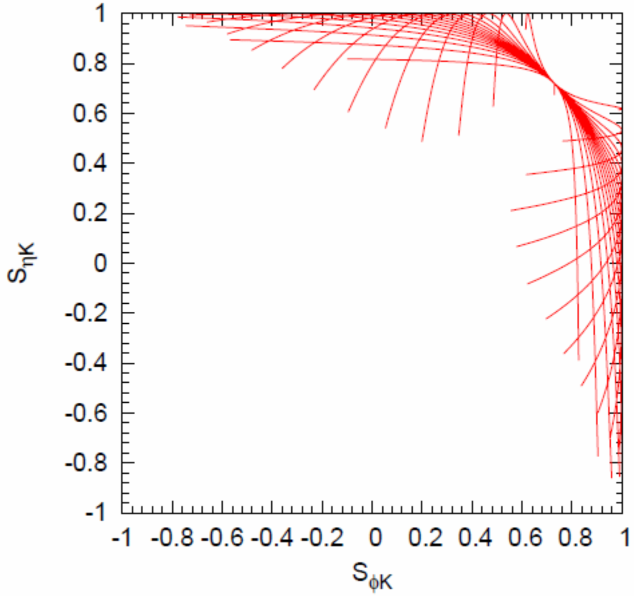
Endo, Mishima & MY
In preparation

- RH interpretation requires large SUSY contributions comparable to SM.
  - Generically excluded by b→s gamma

- Way to escape b→ s gamma
  - Suppression of C7/C8 Wilson coefficients
  - Can be achieved for Light gluino, heavy squarks

  →clear signal at LHC

preliminary



Gluino mass ~300 GeV
Squark mass~1500 GeV

Interplay between flavor physics and collider searches/measurements

Summary

Synergy between collider and flavor physics

→ Reveal the nature of New Paradigm beyond SM