New physics in B and K meson systems

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1. Introduction

- A new era in flavor physics is dawning.

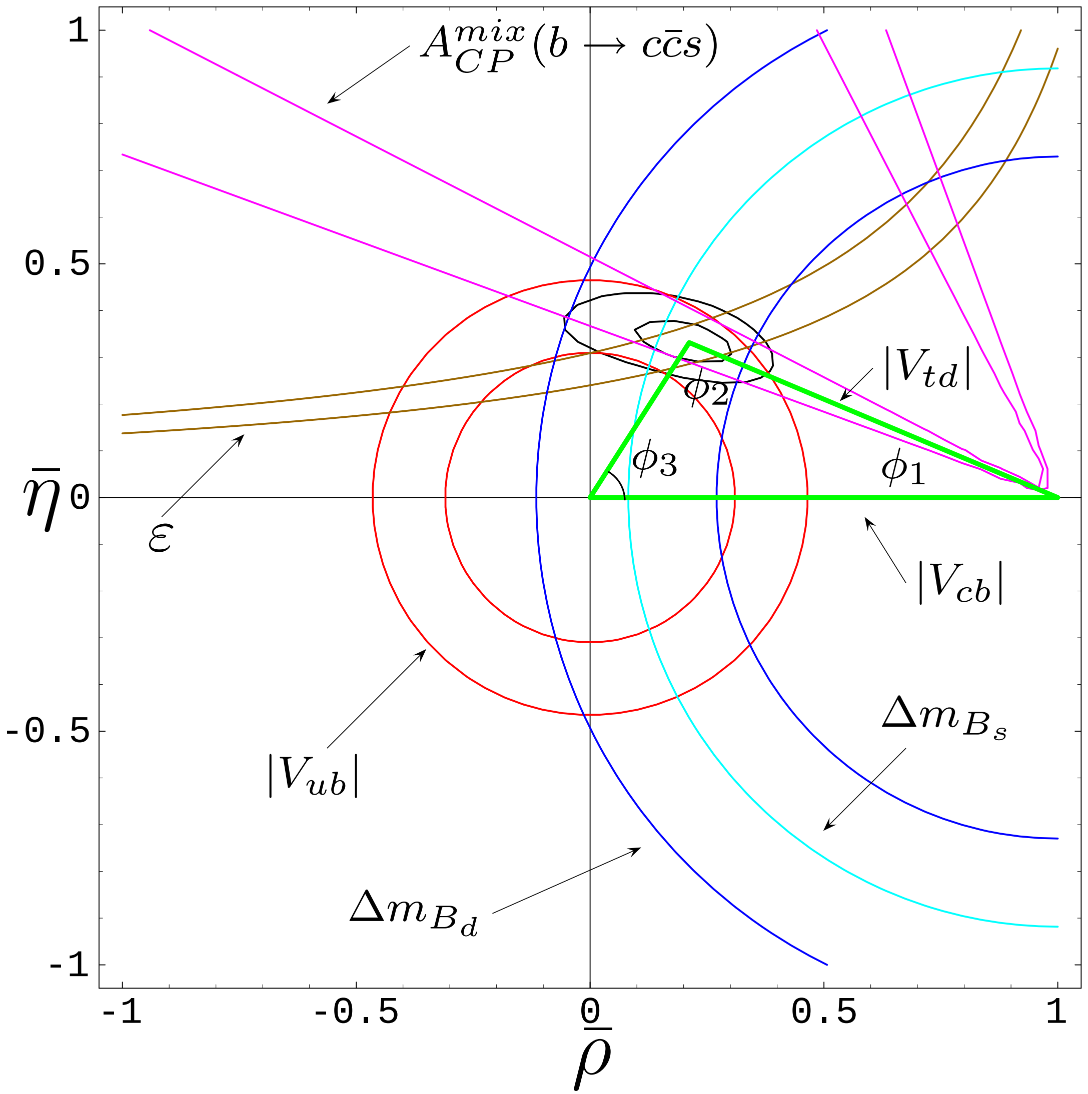
  B factories are giving valuable outputs. (Hazumi)

- The CKM paradigm looks OK.

  - ε parameter: CPV in $K \to \pi\pi$
  - $|V_{cb}|$, $|V_{ub}|$: $b \to c, u$ transition
  - Δm_{B_d}: B_d–$\bar{B}_d$ mixing $\Rightarrow |V_{td}|$
  - Δm_{B_s}: B_s–$\bar{B}_s$ mixing (lower bound) $\Rightarrow |V_{td}|$
  - $A_{CP}^{mix}(b \to c\bar{c}s)$: CP asymmetry in $B_d \to \psi K_s, \psi K_L, \cdots$
    $\Rightarrow \sin 2\phi_1$

  All of these (and others) are consistent with the standard model.

Present status of the unitarity triangle



Belle + BaBar

(ICHEP 2002)

PDG 2002

Any room for new physics?

YES!

- What kind of new physics?

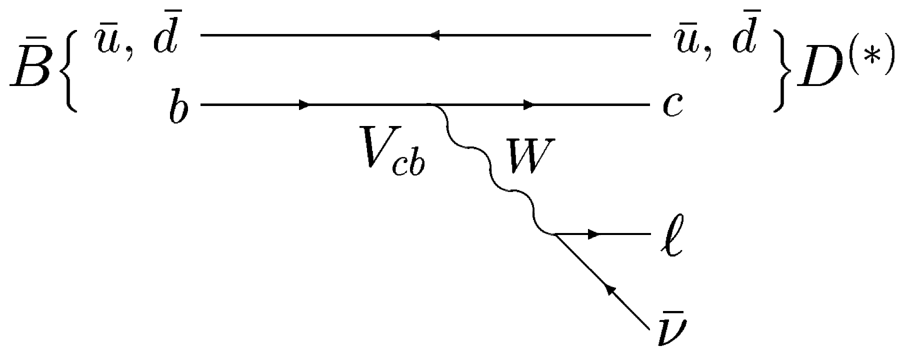
  We consider SUSY here.

- New sources of flavor mixing and CPV in soft SUSY breaking terms.

- B and K physics can probe them.

2. B physics

- $|V_{cb}|$: $b \to c l \nu_l \Leftarrow$ a tree level process

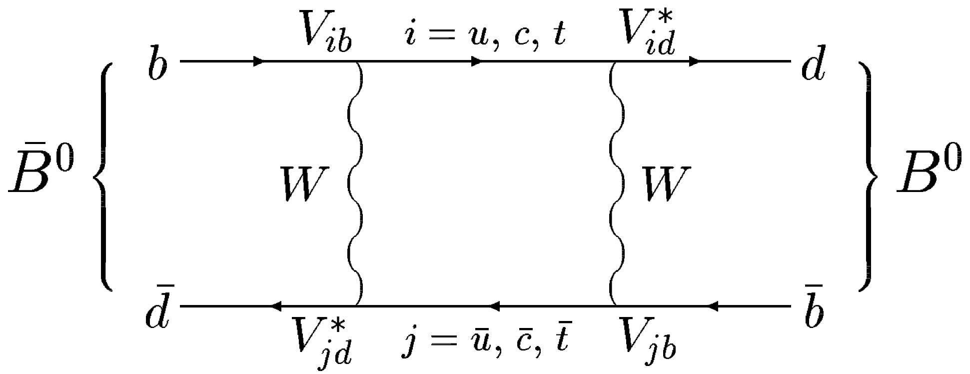


New physics hardly contributes.

- $|V_{ub}|$: $b \to u l \nu_l$, similar as $|V_{cb}|$

But more difficult to extract from experimental data. (Hashimoto)

- $\Delta m_{B_d} = 2|M_{12}(B_d)|$: B^0–$\bar{B}^0$ mixing $\Leftarrow$ a loop process



$= M_{12}(B_d)|_{SM}$

Internal quarks and gauge bosons $\xrightarrow{SUSY}$ squarks and gauginos

$M_{12}(B_d) = M_{12}(B_d)|_{SM} + M_{12}(B_d)|_{NP}$

New physics may contribute to both $|M_{12}|$ and $\phi_M (\equiv \arg M_{12})$.

- $\Delta m_{B_s} = 2|M_{12}(B_s)|$: Similar as Δm_{B_d}.

  But taking a ratio $\Delta m_{B_s}/\Delta m_{B_d}$ reduces the hadronic uncertainty. $\Rightarrow$ The result from CDF is crucial. (Ukegawa)

● CP violation in neutral B decays

$$\Gamma(B^0(t) \to f) = \frac{|A|^2}{2} e^{-\Gamma t} \Big[1 + |\lambda_f|^2 + (1 - |\lambda_f|^2) \cos \Delta m\, t + 2 \mathrm{Im} \lambda_f \ \sin \Delta m\, t \Big]$$

$$\Gamma(\bar{B}^0(t) \to f) = \left|\frac{p}{q}\right|^2 \frac{|A|^2}{2} e^{-\Gamma t} \Big[1 + |\lambda_f|^2 - (1 - |\lambda_f|^2) \cos \Delta m\, t - 2 \mathrm{Im} \lambda_f \ \sin \Delta m\, t \Big]$$

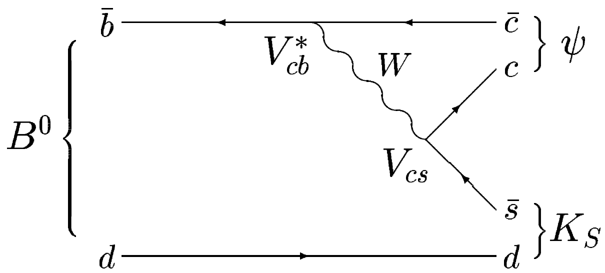
$$\lambda_f \equiv \frac{q}{p}\frac{\bar{A}}{A}, \quad \frac{q}{p} = \frac{M_{12}^*}{|M_{12}|}, \quad A \equiv \langle f | B^0 \rangle,\ \bar{A} \equiv \langle f | \bar{B}^0 \rangle$$

sin term ⇒ interference between the mixing and the decay

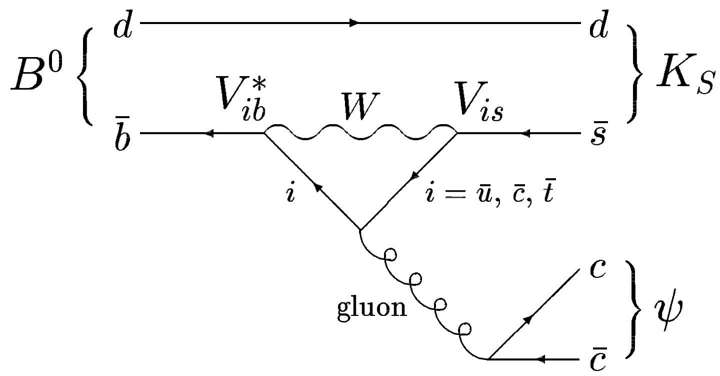
cos term ⇒ interference among decay amplitudes (Direct CPV)

- $A_{CP}^{mix}(B_d \to \psi K_S)$: CP asymmetry in $B_d \to \psi K_S, \cdots$

tree



penguin



$$\sim V_{cb}^* V_{cs}$$

$$\sim V_{tb}^* V_{ts} F_t + V_{cb}^* V_{cs} F_c + V_{ub}^* V_{us} F_u$$

$$\simeq V_{cb}^* V_{cs} (F_c - F_t)$$

$$\frac{\bar{A}}{A} = +\frac{V_{cb} V_{cs}^*}{V_{cb}^* V_{cs}} = +1 \;\Rightarrow\; \lambda_{\psi K_S} = +e^{-2i\phi_1}$$

- Belle

$$-\mathrm{Im}\lambda_{c\bar{c}s}(=\sin 2\phi_1) = 0.719 \pm 0.074 \pm 0.035$$

$$|\lambda_{c\bar{c}s}| = 0.950 \pm 0.049 \pm 0.026$$

- BaBar

$$-\mathrm{Im}\lambda_{c\bar{c}s}(=\sin 2\phi_1) = 0.741 \pm 0.067 \pm 0.033$$

$$|\lambda_{c\bar{c}s}| = 0.948 \pm 0.051 \pm 0.017$$

$\Rightarrow$ No evidence for direct CP violation.

Suggests no new physics in $b \to c\bar{c}s$.

$\Rightarrow$ ϕ_M is measured. It might not be $2\phi_1$.

3. K physics

● CP violation in $K \longrightarrow \pi\pi$

$K \longrightarrow \pi\pi$ amplitudes:

$\langle \pi\pi(I)|K^0\rangle \equiv A_I e^{i\delta_I},\ I = 0, 2,\ \delta_I =$ strong phase shift

CPT invariance $\Downarrow$ A_I contains CP violating weak phase.

$\langle \pi\pi(I)|\bar{K}^0\rangle = -A_I^* e^{i\delta_I}$

no change in the CP conserving strong phase

If CP is conserved, $A_I = A_I^*$ (real).

Physical amplitudes: $A_{I,L} \equiv \langle \pi\pi(I)|K_L\rangle,\ A_{I,S} \equiv \langle \pi\pi(I)|K_S\rangle$

● ε parameter: CPV in the $I = 0$ channel

$$\varepsilon \equiv \frac{A_{0,L}}{A_{0,S}} \qquad A_I = |A_I| e^{i\omega_I}$$

$$= \frac{2i\mathrm{Im}(M_{12}e^{2i\omega_0}) + \mathrm{Im}(\Gamma_{12}e^{2i\omega_0})}{2\mathrm{Re}(M_{12}e^{2i\omega_0}) - i\mathrm{Re}(\Gamma_{12}e^{2i\omega_0}) + \Delta m - \frac{i}{2}\Delta\Gamma}$$

$$\simeq \frac{e^{i\pi/4}}{\sqrt{2}} \frac{\mathrm{Im}(M_{12}e^{2i\omega_0})}{\Delta m} \qquad \text{(rephasing invariant)}$$

Interference between K^0–$\bar{K}^0$ mixing and $K \to \pi\pi(I = 0)$

$\Rightarrow$ the relative phase between $M_{12}(K)$ and A_0 (cf. $B \to \psi K_S$)

◇ $M_{12}(K)$: box $\Rightarrow$ New physics may contribute.

◇ A_0: tree and penguin (dominant, $\Delta I = 1/2$). No new phase.

- ε' parameter: Difference of CPV in $I = 0$ and $I = 2$ channels

$$\varepsilon' \equiv \frac{1}{\sqrt{2}} \frac{A_{2,S}}{A_{0,S}} \left(\frac{A_{2,L}}{A_{2,S}} - \frac{A_{0,L}}{A_{0,S}} \right)$$

$$\simeq \frac{1}{\sqrt{2}} e^{i(\pi/2+\delta_2-\delta_0)} \left| \frac{A_2}{A_0} \right| \sin(\omega_2 - \omega_0)$$

$\Rightarrow$ Interference between A_0 and A_2 (direct CPV)

Experiment: $\mathrm{Re}(\epsilon'/\epsilon) = (16.6 \pm 1.6) \times 10^{-4}$ (2002 World Avg)

◇ A_2: Tree (apart from EW penguin) $\Rightarrow$ No new physics.

◇ $|\varepsilon'/\varepsilon| \ll 1 \Rightarrow$ No large new phase in A_0.

$\Longrightarrow \varepsilon$ gives $\arg M_{12}(K)$.

- $K \to \pi\nu\bar{\nu}$: $s \to d\nu\bar{\nu}$, virtually no hadronic uncertainty

  (Komatsubara)

$$\frac{\Gamma(K_L \to \pi^0\nu\bar{\nu})}{\Gamma(K^+ \to \pi^+\nu\bar{\nu})} \simeq \sin^2\theta, \qquad \frac{q}{p}\frac{A(\bar{K}^0 \to \pi^0\nu\bar{\nu})}{A(K^0 \to \pi^0\nu\bar{\nu})} \simeq e^{2i\theta}$$

  In the SM,

  ◇ $K^+ \to \pi^+\nu\bar{\nu}$

  clean, 7% theoretical uncertainty

  $\Rightarrow |V_{td}V_{ts}^*|^2 \propto \eta^2 + (1-\rho)^2$

  ◇ $K_L \to \pi^0\nu\bar{\nu}$

  very clean, 1% theoretical uncertainty

  $\Rightarrow (\mathrm{Im}V_{td}V_{ts}^*)^2 \propto \eta^2$

4. New physics: An illustration

T. Goto, Y. Okada, Y. Shimizu, T. Shindou, M.T.

hep-ph/0204081, to appear in Phys. Rev. D.

- How large could new physics effects be?
- Can B and K physics distinguish several SUSY models?

$\Rightarrow$ An illustration with three SUSY models:

- ◇ Minimal SUGRA
- ◇ SU(5) SUSY GUT with ν_Rs (see-saw)
- ◇ U(2) flavor symmetry model

Models

- Minimal SUGRA

  Source of flavor mixing: Quark Yukawa couplings only (MFV).

  $\Rightarrow$ Flavor mixing (and CPV) is controlled by V_{CKM}.

- SU(5) SUSY GUT with ν_Rs

  Mixing in the ν sector $\longrightarrow$ Mixing in the $\tilde{d}_R$ sector

  $\Rightarrow$ Controlled by V_{CKM} and V_{MNS} (and additional matrices).

  $BR(\mu \rightarrow e\gamma)$ gives a tight constraint for our specific choice of $M_R \sim I$.

- U(2) model

  1st and 2nd gen. $\in$ U(2) doublets, 3rd gen. $\in$ U(2) singlets.

  Hierarchical breaking: $\mathrm{U}(2) \stackrel{\epsilon\sim\lambda^2}{\longrightarrow} \mathrm{U}(1) \stackrel{\epsilon'\sim\lambda^3}{\longrightarrow} 1$ (no symmetry)

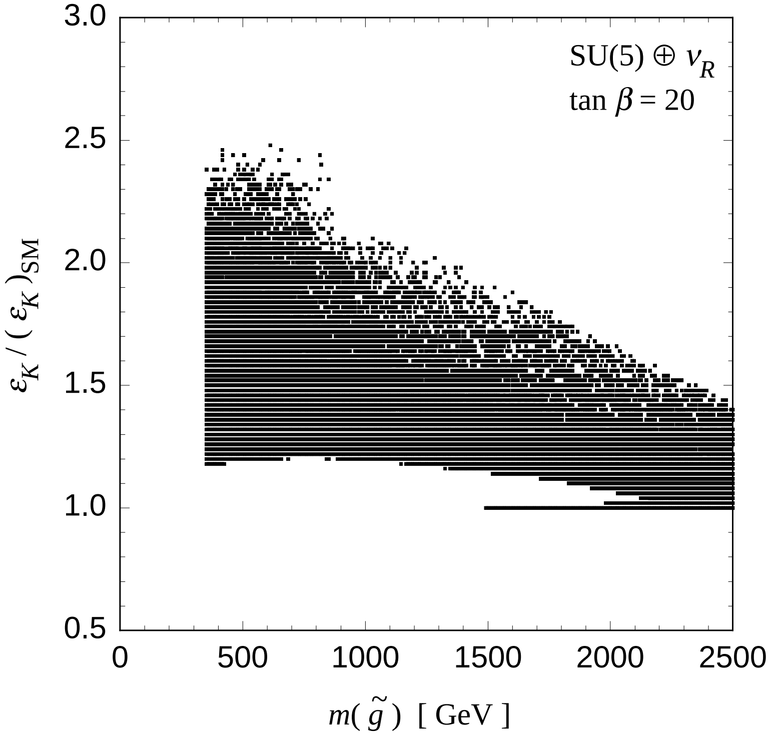
  $\Rightarrow$ Reproduces the fermion masses and mixings.

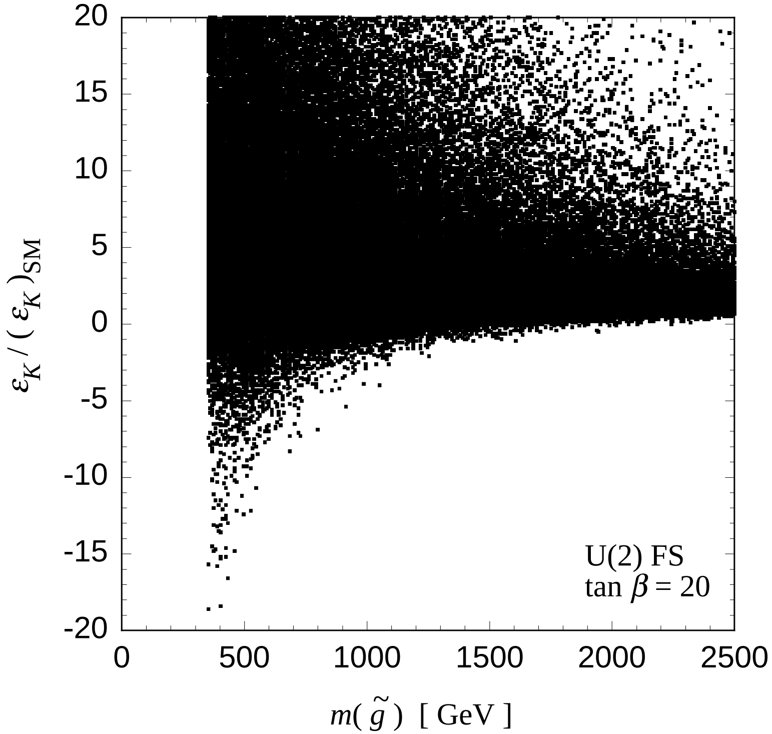
  Soft breaking masses:

$$\tilde{m}^2 = m_0^2 \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 + r_{22}\epsilon^2 & r_{23}\epsilon \\ 0 & r_{23}^*\epsilon & r_{33} \end{pmatrix}, \quad r_{ij} \sim O(1).$$

Numerical results

- Effect in ε: mSUGAR $\sim O(0.01)$, SU(5) $\sim O(1)$, U(2) $\sim O(10)$

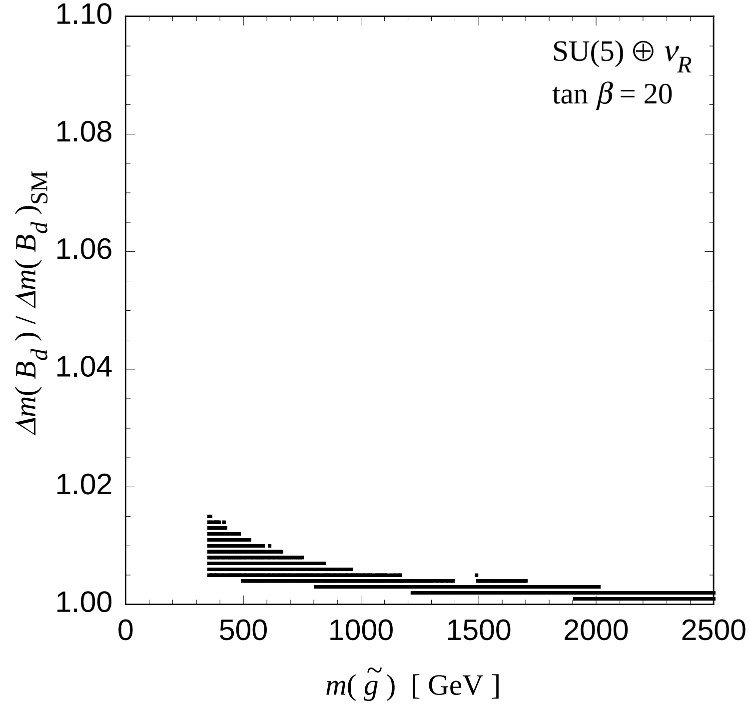


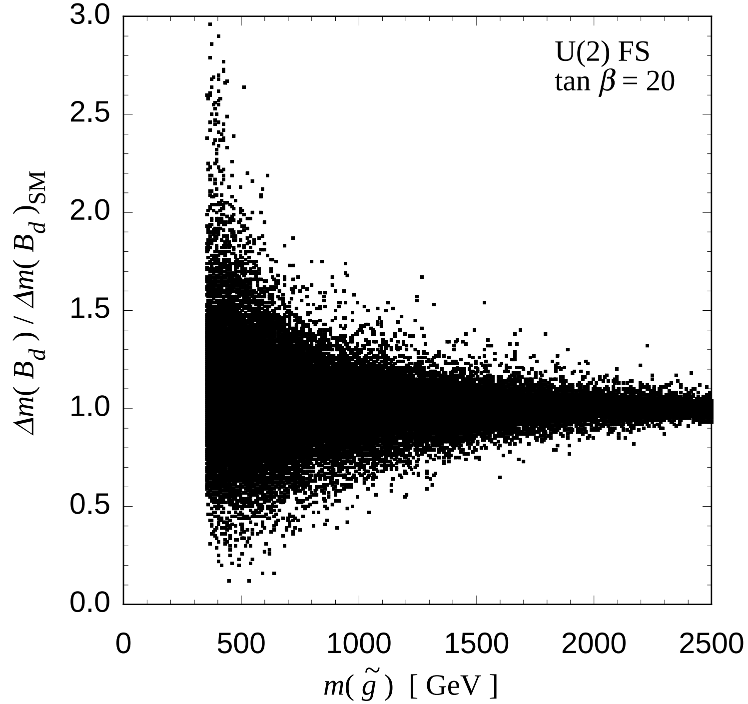


Potentially large contribution from $S \pm P$ operators due to the chiral enhancement.

- Effect in Δm_{B_d}

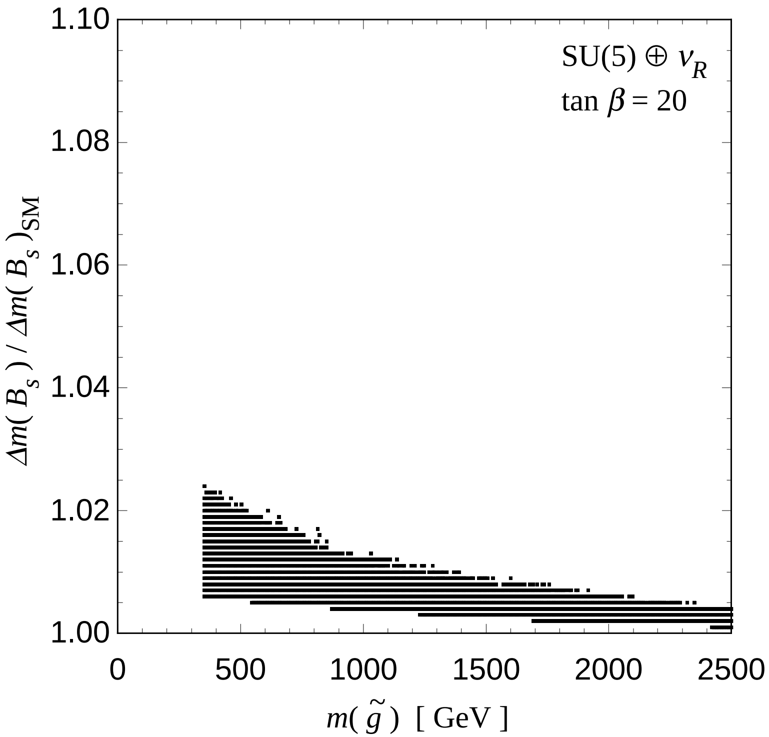
mSUGAR $\sim O(0.01)$, SU(5) $\sim O(0.01)$, U(2) $\sim O(1)$

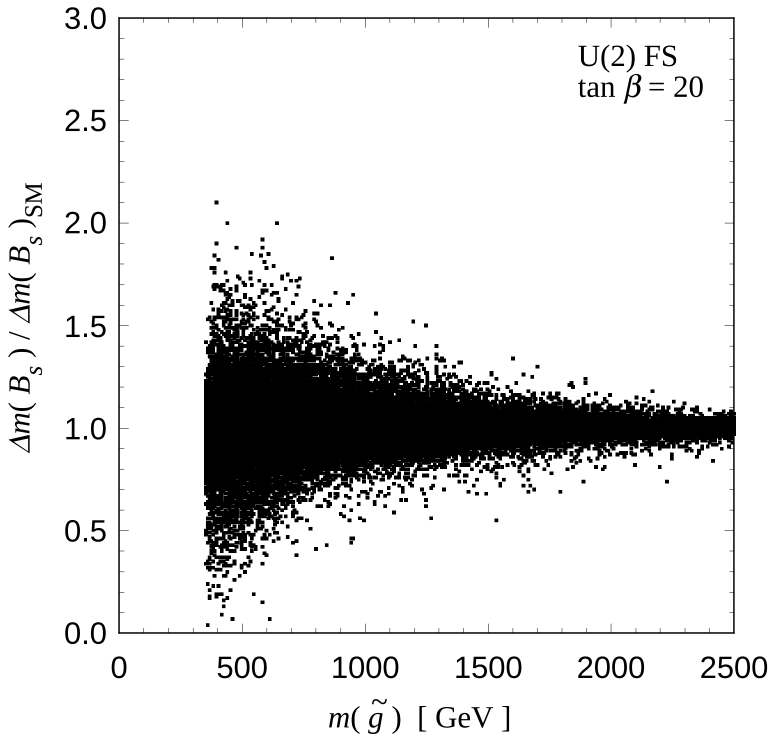




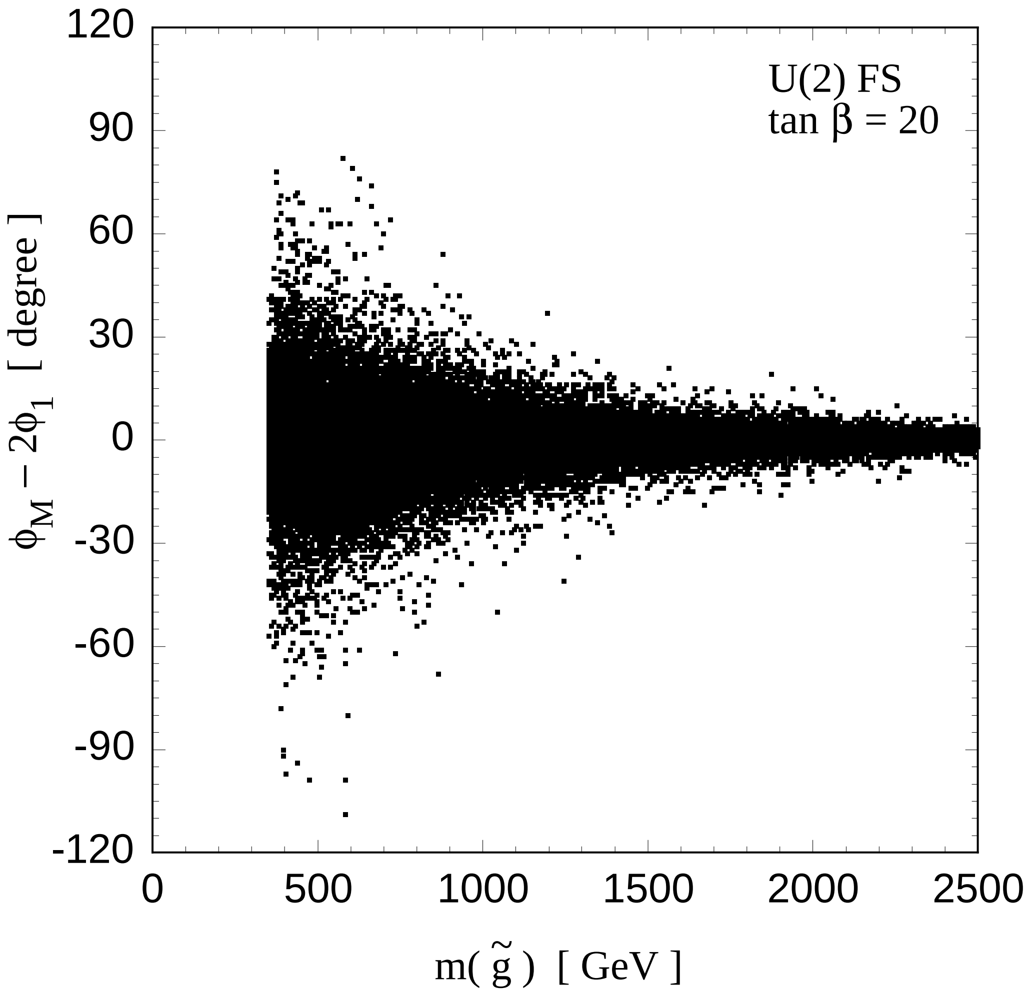
- Effect in Δm_{B_s}

  mSUGAR $\sim O(0.01)$, SU(5) $\sim O(0.01)$, U(2) $\sim O(1)$

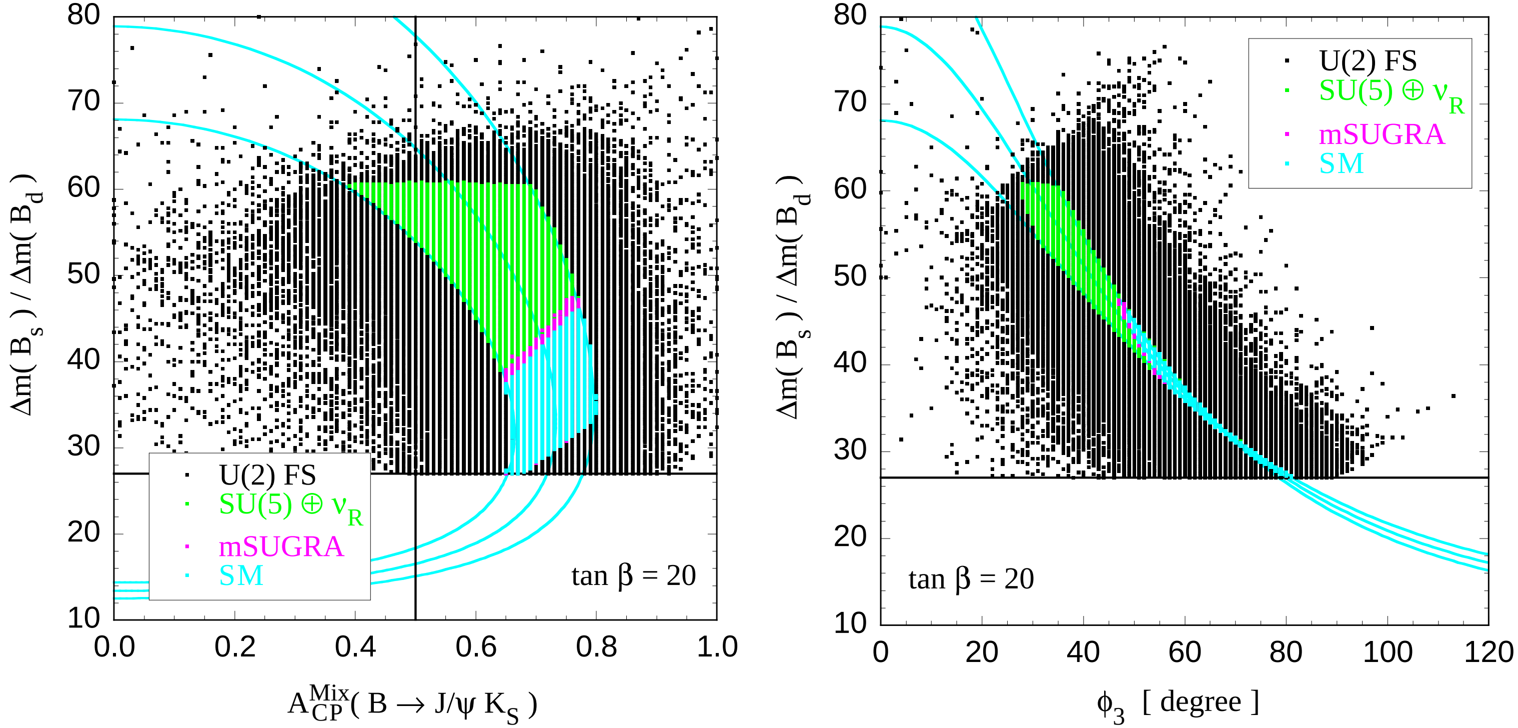




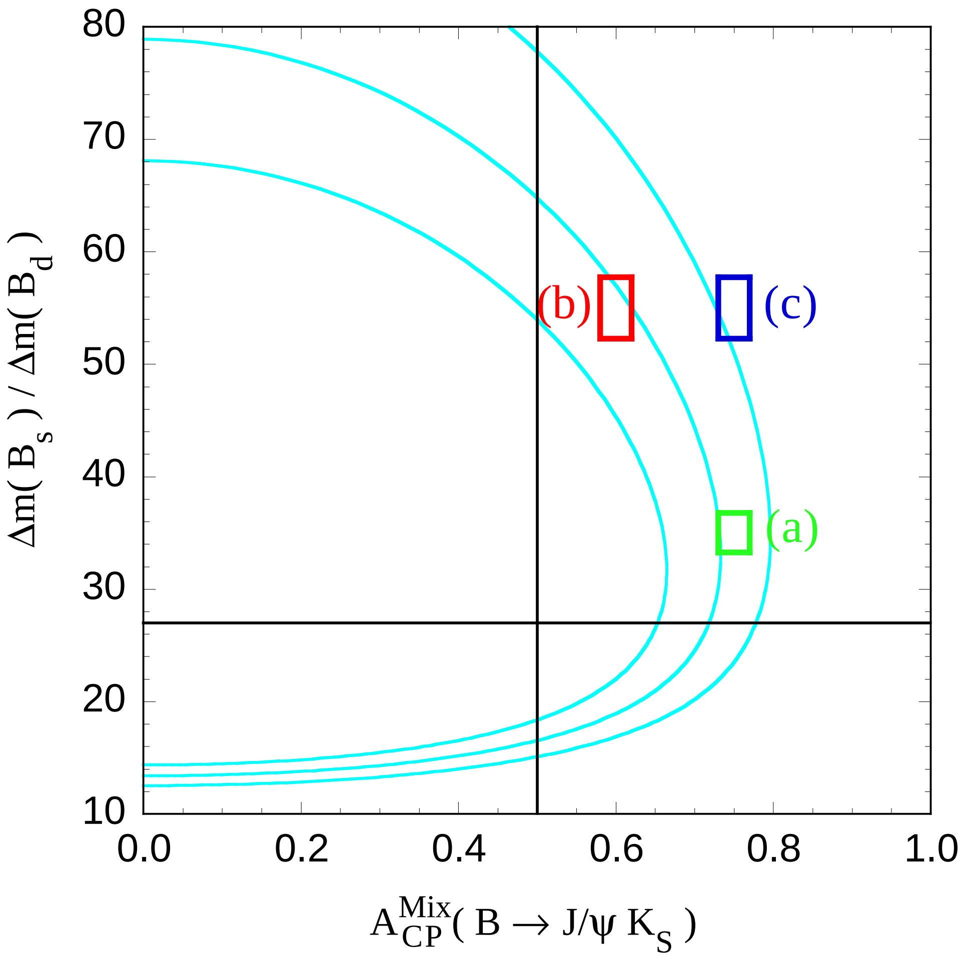
- Effect on ϕ_1 measurement in U(2)

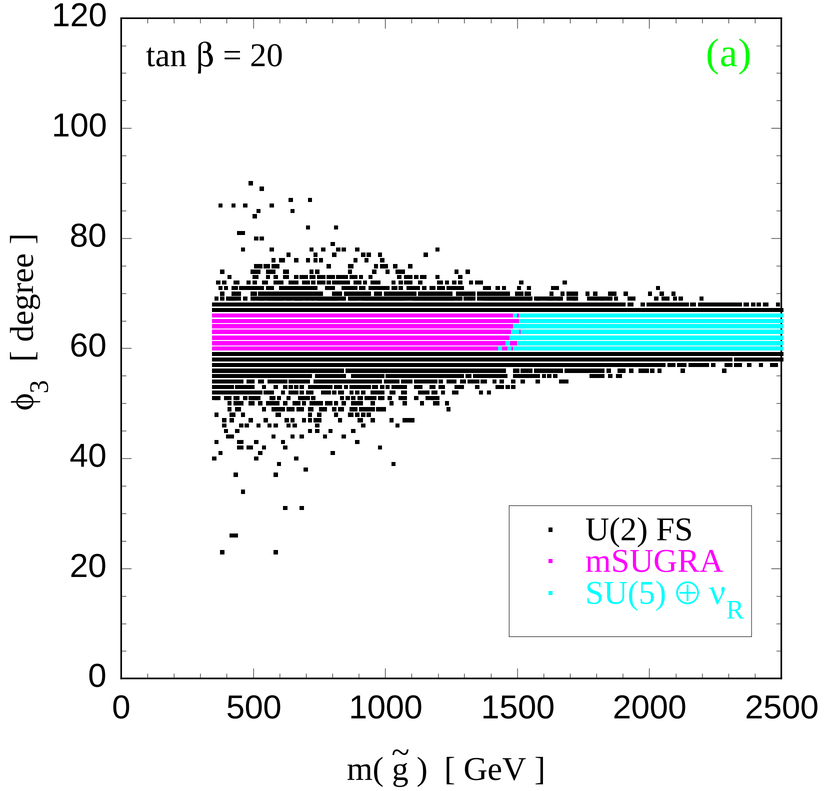


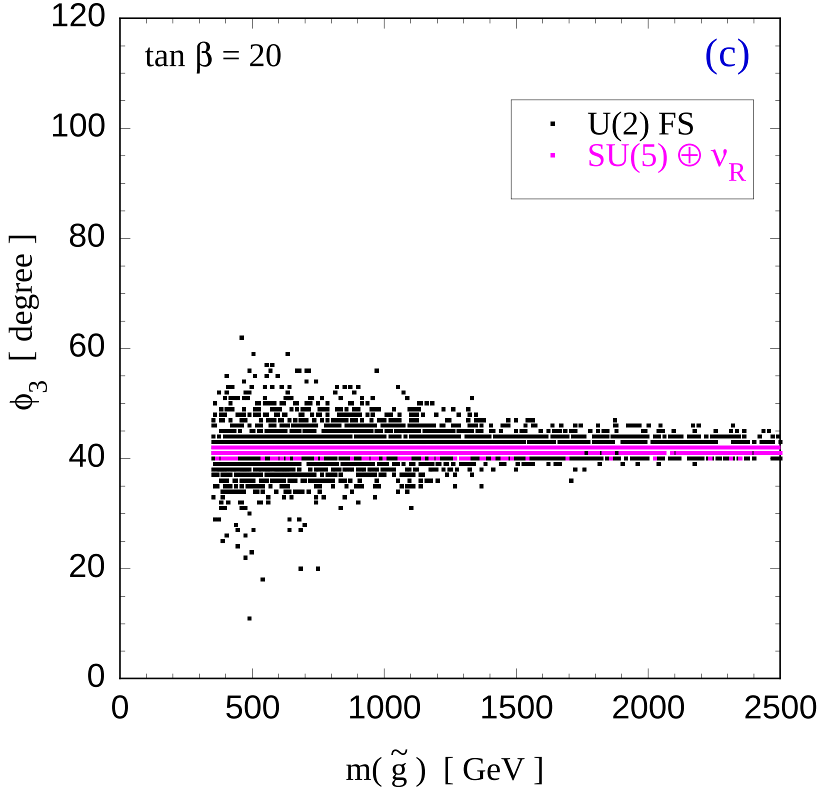
- Effects in $\Delta m_{B_s}/\Delta m_{B_d}$, $A_{\rm CP}^{\rm mix}(B \to \psi K_S)$, and ϕ_3



- Possible implication of $A_{\rm CP}^{\rm mix}(B \to \psi K_S)$ and $\Delta m_{B_s}/\Delta m_{B_d}$ measurements




tan β = 20
(a)
U(2) FS
mSUGRA
SU(5) ⊕ ν_R
φ_3 [degree]
m(g̃) [GeV]
0
20
40
60
80
100
120
0
500
1000
1500
2000
2500


tan β = 20
(c)
U(2) FS
SU(5) ⊕ ν_R
φ_3 [degree]
m(g̃) [GeV]
0
20
40
60
80
100
120
0
500
1000
1500
2000
2500

5. Summary and discussion

- Δm_{B_s} is the next important step.

  Hadron machine

- A clean ϕ_3 determination is requisite. $B \to DK$, ...

  (Super) B factories (Katayama)

- $B \to \phi K_S$: $b \to s\bar{s}s$

  the same CPA as ψK_S in the SM,

  possible deviation in SUSY GUT.

- $b \to s\gamma$, $b \to sll$, ... (Iijima)

  loop induced $\Rightarrow$ potentially sensitive to new physics.