CKM and New Physics

An Overview

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1. Introduction

A new era in flavor physics
Valuable outputs from B factories

e.g. CPV in $B \longrightarrow (c\bar{c})K^{(*)}$, ICHEP2002

$$\sin 2\phi_1 = \begin{cases} 0.719 \pm 0.074 \pm 0.035 & \text{Belle (KEK)} \\ 0.741 \pm 0.067 \pm 0.033 & \text{BaBar (SLAC)} \end{cases}$$

cf. ICHEP2000

$$\sin 2\phi_1 = \begin{cases} 0.45 \pm 0.44 \pm 0.08 & \text{Belle} \\ 0.12 \pm 0.37 \pm 0.09 & \text{BaBar} \end{cases}$$

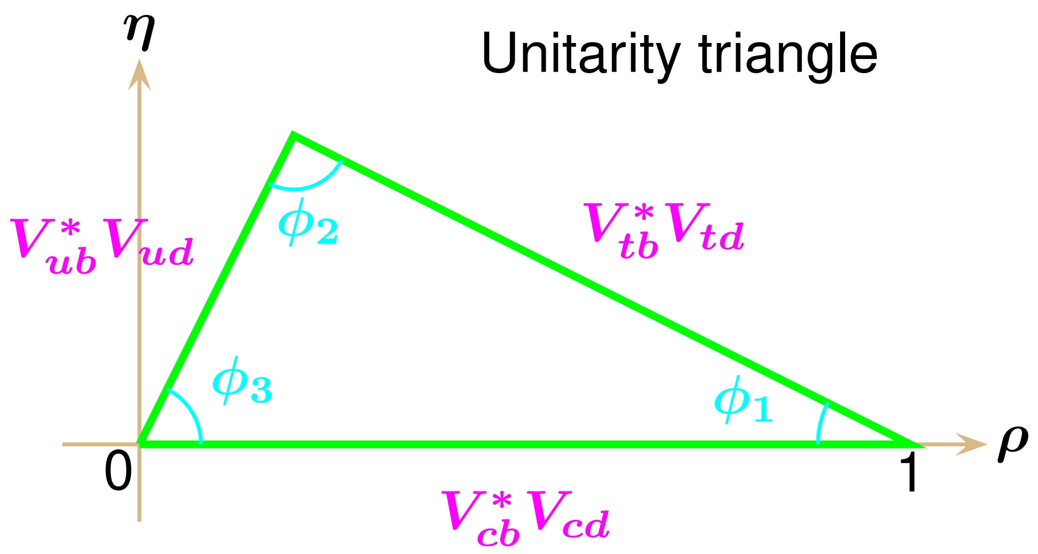
$\Rightarrow$ Precision test of the standard model
$\Rightarrow$ New physics search

PLAN

1. Introduction
2. Present status of the unitarity triangle
3. Soft SUSY breakings
4. An illustration of new physics
5. Summary and discussion

2. Present status of the unitarity triangle

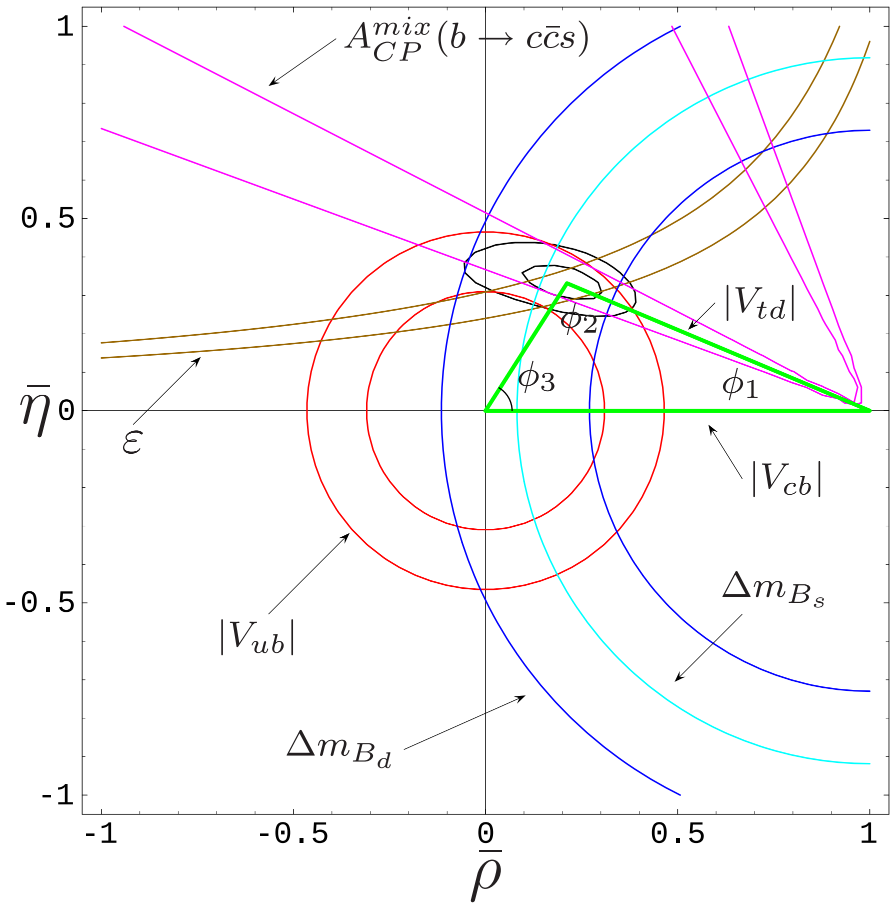
Unitarity of KM matrix $\Rightarrow V_{ub}^* V_{ud} + V_{cb}^* V_{cd} + V_{tb}^* V_{td}$=0



- 3 parameters in the triangle
  the apex (ρ, η) and the overall scale (A)
- Measuring the sides and the angles
  $\Rightarrow$ test for the SM
  $\Rightarrow$ search for new physics

Present status

ICHEP2002 Belle+Babar, PDG2002, . . .



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

The unitarity triangle looks closed.
All of these (and others) are consistent with the SM.

But, this is not the whole story.

Theoretical uncertainties

More precise experimental data

$$\Updownarrow$$

More precise theoretical calculations

B physics tends to suffer from hadronic uncertainties.

$$\boxed{\text{theoretical uncertainty} > \text{experimental error}}$$

does happen. New physics may be hidden by the uncertainties.

We have to

- evaluate how large the uncertainties are,
- reduce the uncertainties.

New physics effects

In the SM,

$$\boxed{\rho, \eta, A \Longleftrightarrow \text{the observables}}$$

If new physics exists

$$\boxed{\rho, \eta, A, \text{new parameters} \Longleftrightarrow \text{the observables}}$$

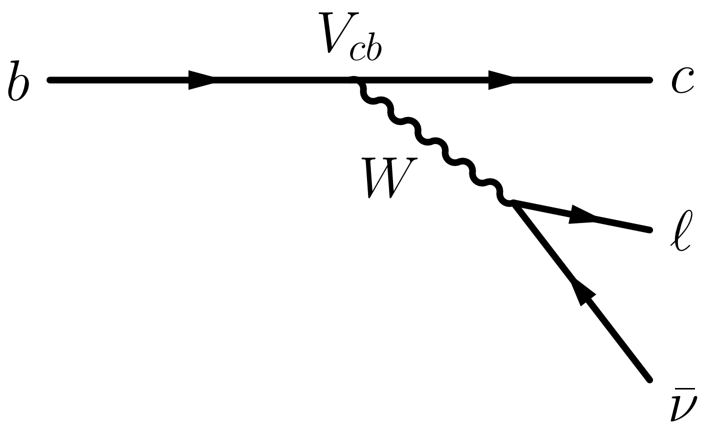
Supersymmetry (with R parity)

- Tree level processes are hardly affected.
  The SM relation holds.
- Loop processes tend to be affected in general.
  The SM relation may be altered.

$\Rightarrow$ Be careful to extract the CKM parameters.

Semileptonic B decays: $|V_{cb}|$

$b \to c l \nu_l$



- $B \to D^* l \nu$:
  $|V_{cb}| = (41.9 \pm 1.1 \pm 1.9) \times 10^{-3}$ ICHEP2002 World Av.
  $\sim$ 5% theoretical uncertainty
- $B \to X_c l \nu$:
  $|V_{cb}| = (40.7 \pm 0.6 \pm 0.8) \times 10^{-3}$ ICHEP2002 World Av.
  $\sim$ a few % theoretical uncertainty

$\Rightarrow$ A tree level process, no new physics contribution.

Semileptonic B decays: $|V_{ub}|$

$b \to u l \nu_l$

- $B \to (\pi, \rho) l \nu$

$$|V_{ub}| = \begin{cases} (3.23 \pm 0.14 \pm 0.26 \pm 0.65) \times 10^{-3} \text{ Belle}(\pi) \\ (3.69 \pm 0.23 \pm 0.27 \pm 0.50) \times 10^{-3} \text{ BaBar}(\rho) \end{cases}$$

  $\sim 20\%$ theoretical uncertainty

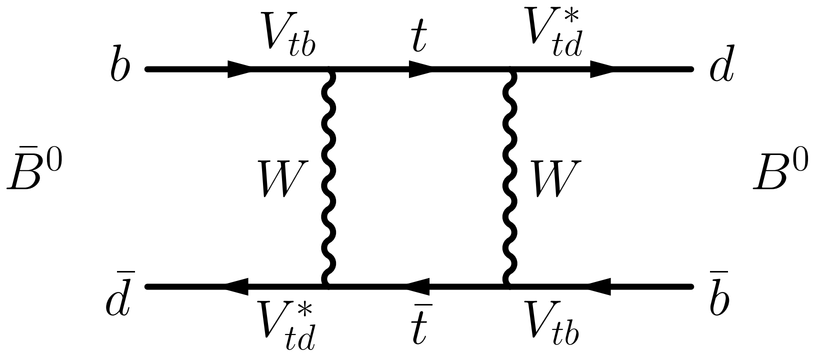
- $B \to X_u l \nu$
  $|V_{ub}| = (4.05 \pm 0.18 \pm 0.63 \pm 0.60) \times 10^{-3}$ CLEO M_x-q^2
  $\sim 15\%$ theoretical uncertainty

$\Rightarrow$ A tree level process, no new physics contribution.

$\Rightarrow$ Need to reduce theoretical uncertainties.

B_d–$\bar{B}_d$ mixing: $|V_{td}|$

$\Delta m_{B_d} = 2|M_{12}(B_d)| \Leftarrow$ a loop process



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

- Hadronic uncertainty
  $f_{B_d}\sqrt{B_{B_d}} = 235 \pm 33^{+0}_{-24}\ \mathrm{MeV}$ (lattice)
- Possible new physics contribution

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

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

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

B_s–$\bar{B}_s$ mixing: $|V_{td}|$

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

- Hadronic uncertainty

  $f_{B_s}\sqrt{B_{B_s}} = 276 \pm 38\,\mathrm{MeV}$ (lattice)

  Taking a ratio $\Delta m_{B_s}/\Delta m_{B_d}$ reduces the hadronic uncertainty. $\Leftarrow$ SU(3) symmetry.

  $f_{B_s}\sqrt{B_{B_s}}/f_{B_d}\sqrt{B_{B_d}} = 1.18 \pm 0.04^{+0.12}_{-0}$ (lattice)

  $\Rightarrow$ The result from CDF is important.

  But, the SU(3) breaking may be larger.

- Possible new physics contribution

  $M_{12}(B_s) = M_{12}(B_s)|_{\mathrm{SM}} + M_{12}(B_s)|_{\mathrm{NP}}$

  The effect might be large.
  cf. large 2–3 mixing in the ν sector

CP violation in neutral B decays

$$
\begin{aligned}
A_{\mathrm{CP}} &\equiv \frac{\Gamma(B^0(t)\to f)-\Gamma(\bar{B}^0(t)\to f)}{\Gamma(B^0(t)\to f)+\Gamma(\bar{B}^0(t)\to f)} \\
&= \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2}\cos\Delta m\, t+\frac{2\mathrm{Im}\lambda_f}{1+|\lambda_f|^2}\sin\Delta m\, t
\end{aligned}
$$

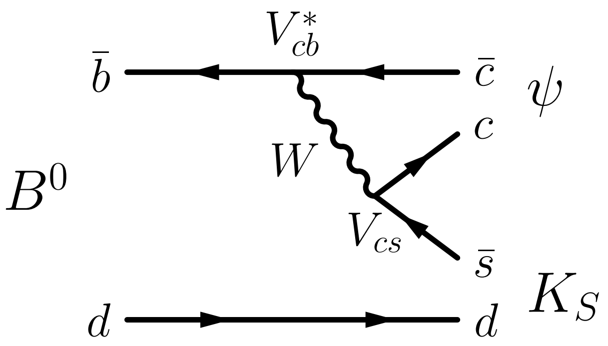
$$
\lambda_f \equiv \frac{q}{p}\frac{\bar{A}}{A},\quad \frac{q}{p}=\frac{M_{12}^*}{|M_{12}|},\quad A\equiv\langle f|B^0\rangle,\ \bar{A}\equiv\langle f|\bar{B}^0\rangle
$$

- the $\sin$ term
  $\Rightarrow$ interference between the mixing and the decay
- the $\cos$ term
  $\Rightarrow$ interference among decay amplitudes (Direct CPV)

CP asymmetry in $B_d \to \psi K_S, \cdots$

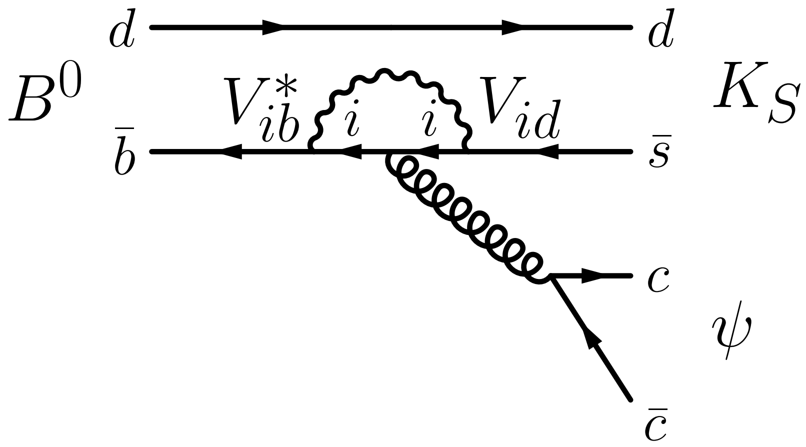
$A_{\rm CP}^{\rm mix}(B_d \to (c\bar{c})K^{(*)})$

tree



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

penguin



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

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

- Almost free from hadronic uncertainties
- If $M_{12}(B_d)|_{\rm NP}$ exists, $-{\rm Im}\lambda_{\psi K_S} \neq \sin 2\phi_1$.

Implication of $B_d \longrightarrow \psi K_S, \cdots$

- Belle
  $(\mathrm{CP})_f \mathrm{Im}\lambda_{c\bar{c}s} (\stackrel{\mathrm{SM}}{=} \sin 2\phi_1) = 0.719 \pm 0.074 \pm 0.035$
  $|\lambda_{c\bar{c}s}| = 0.950 \pm 0.049 \pm 0.026$
- BaBar
  $(\mathrm{CP})_f \mathrm{Im}\lambda_{c\bar{c}s} (\stackrel{\mathrm{SM}}{=} \sin 2\phi_1) = 0.741 \pm 0.067 \pm 0.033$
  $|\lambda_{c\bar{c}s}| = 0.948 \pm 0.051 \pm 0.017$ $((\mathrm{CP})_f = -1$ only)

$\Rightarrow$ If no new phase in the $b \longrightarrow c\bar{c}s$ amplitude,
$\sin\phi_M$ is measured. But, it might not be $\sin 2\phi_1$.

$\Rightarrow$ $|\lambda_{c\bar{c}s}| \simeq 1$ What does this mean?
No direct CP violation?
No new physics in $b \longrightarrow c\bar{c}s$?

CP violation in $K \to \pi\pi$

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

$$\varepsilon \equiv \frac{A_{0,L}}{A_{0,S}} \simeq \frac{e^{i\pi/4}}{\sqrt{2}} \frac{\mathrm{Im}(M_{12}e^{2i\omega_0})}{\Delta m}$$

ω_0: weak phase of $A(K^0 \to (\pi\pi)_{I=0})$

Interference between K^0–$\bar{K}^0$ mixing and $K \to (\pi\pi)_{I=0}$
$\Rightarrow$ relative phase between $M_{12}(K)$ and A_0

- Hadronic uncertainty
  $\hat{B}_K = 0.86 \pm 0.06 \pm 0.14$ (lattice)
- New physics
  - ⋆ $M_{12}(K)$: box $\Rightarrow$ New physics may contribute.
  - ⋆ A_0: tree and penguin (dominant, $\Delta I = 1/2$)
    But, no new phase. ($\Leftarrow \varepsilon'$)

  $\Rightarrow$ $\mathrm{Im}M_{12}(K)(\neq \mathrm{Im}M_{12}(K)|_{\mathrm{SM}})$ is measured.

3. Soft SUSY breakings

Scalar masses, scalar trilinear couplings

$\Rightarrow$ New sources of flavor violation

- Squark mass matrix (6×6)

$$\tilde{M}_q^2 = \begin{pmatrix} \tilde{M}^2_{q,LL} & \tilde{M}^2_{q,LR} \\ \tilde{M}^{2\dagger}_{q,LR} & \tilde{M}^2_{q,RR} \end{pmatrix}, \quad (q = u, d)$$

- Quark mass matrix (3×3)

$$V_L^q M_q V_R^{q\dagger} = \hat{M}_q \text{ (diagonal)}$$

FV is caused by non-vanishing and off-diagonal

$$(\delta^q_{MN})_{ij} \equiv \frac{(V_M^q \tilde{M}^2_{q,MN} V_N^{q\dagger})_{ij}}{\tilde{m}^2}$$

Typical constraints

Nir and Seiberg, hep-ph/9304307

- K–$\bar{K}$ mixing

  $\sqrt{(\delta^d_{LL})_{12}(\delta^d_{RR})_{12}} < 0.006,\ (\delta^d_{MM})_{12} < 0.05$

  $\sqrt{(\delta^u_{LL})_{12}(\delta^u_{RR})_{12}} < 0.04,\ (\delta^u_{MM})_{12} < 0.1$

- B–$\bar{B}$ mixing

  $\sqrt{(\delta^d_{LL})_{13}(\delta^d_{RR})_{13}} < 0.04,\ (\delta^d_{MM})_{13} < 0.1$

- $b \longrightarrow s\gamma$

  $(\delta^d_{LR})_{23} < 0.04$

$$\Rightarrow (\delta^q_{MN})_{ij} < 0.01 \sim 0.1 \quad (\tilde{m} \sim 1\mathrm{TeV})$$

We need some mechanism to suppress δ's.

Possible mechanisms

Several ideas in the market

- Universal soft breakings
  Gravity mediation of SUSY breaking (SUGRA),
  Gauge mediation
  Phenomenology depends on the scale of SUSY breaking and extra interaction below it (GUT, ν Yukawa).
- Flavor symmetry
  Must explain the fermion masses and mixings.
  Depends on the breaking sector.
- Alignment
- Effective SUSY

4. An illustration of new physics

T. Goto, Y. Okada, Y. Shimizu, T. Shindou, M.T.
Phys. Rev. D 66, 035009 (2002)

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

⇒ 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)
  $\mathrm{BR}(\mu \to e\gamma)$ gives a tight constraint in our specific choice of $M_R \sim I$.

Models (cont'd)

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

  Hierarchical breaking:

  $\mathrm{U}(2) \xrightarrow{\epsilon\sim\lambda^2} \mathrm{U}(1) \xrightarrow{\epsilon'\sim\lambda^3} 1$ (no symmetry)
  $\Rightarrow$ Reproduces the quark masses and mixings.

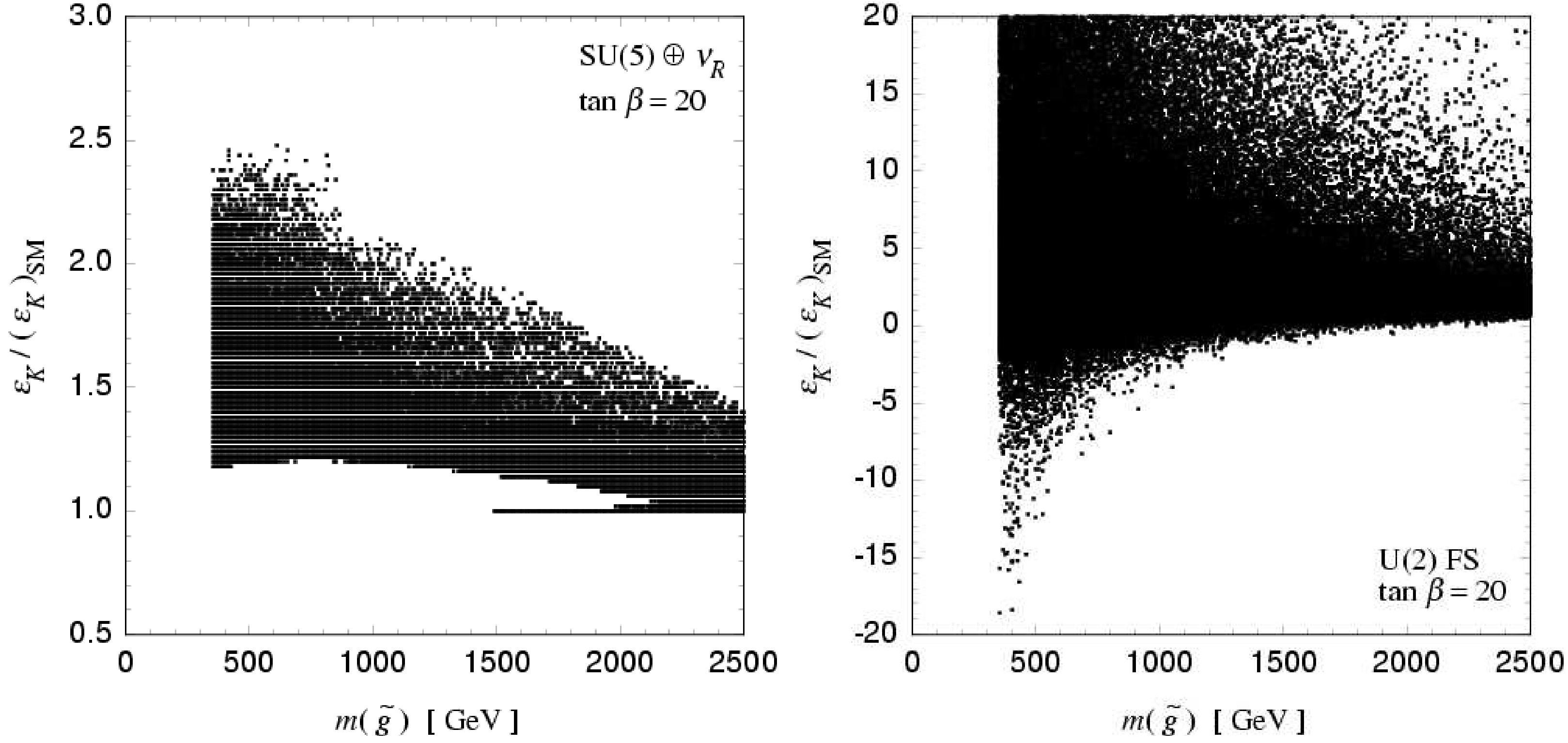
  Soft breaking masses:

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

Numerical results

Effect in ε

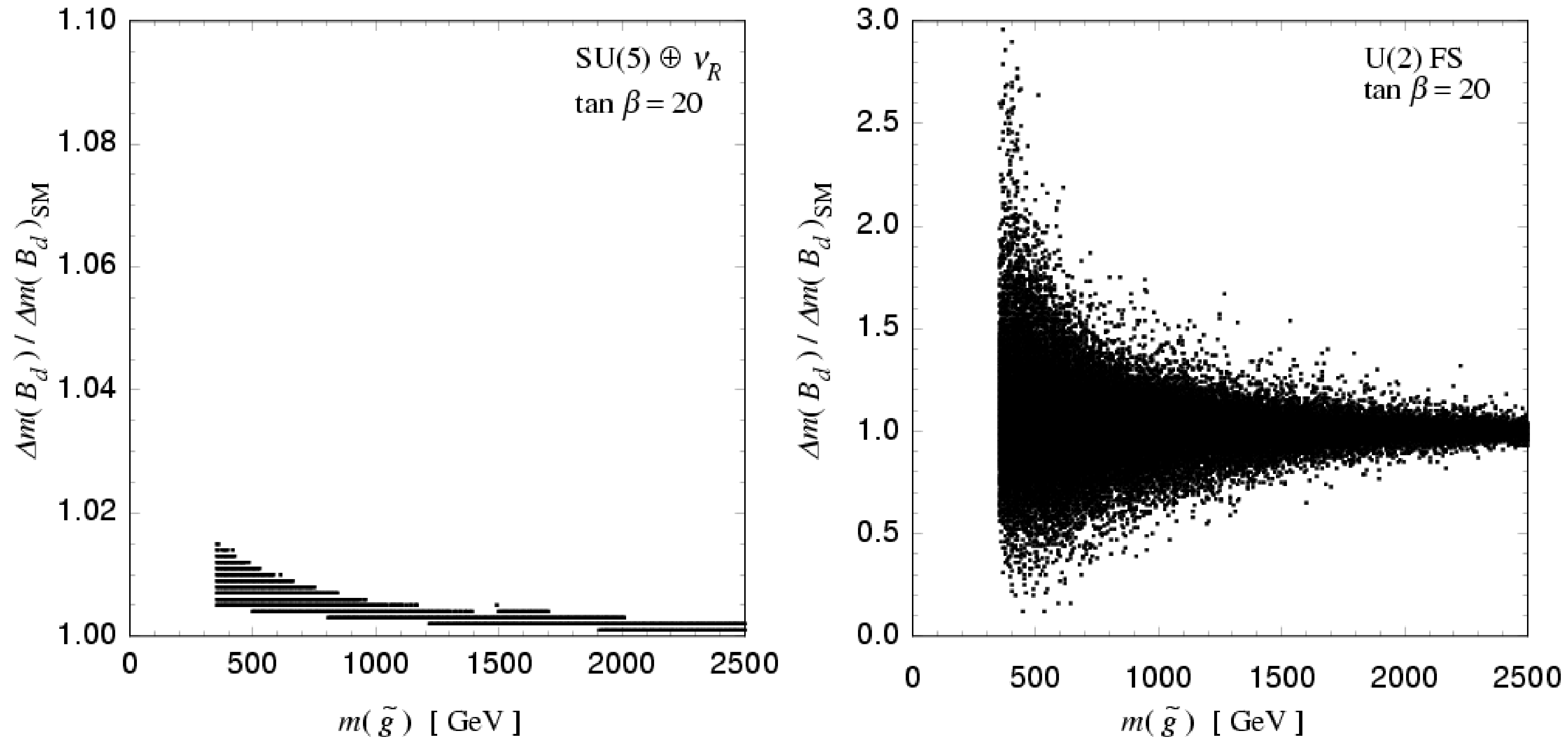
mSUGAR $\sim \boldsymbol{O(0.01)}$, SU(5) $\sim \boldsymbol{O(1)}$, U(2) $\sim \boldsymbol{O(10)}$



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

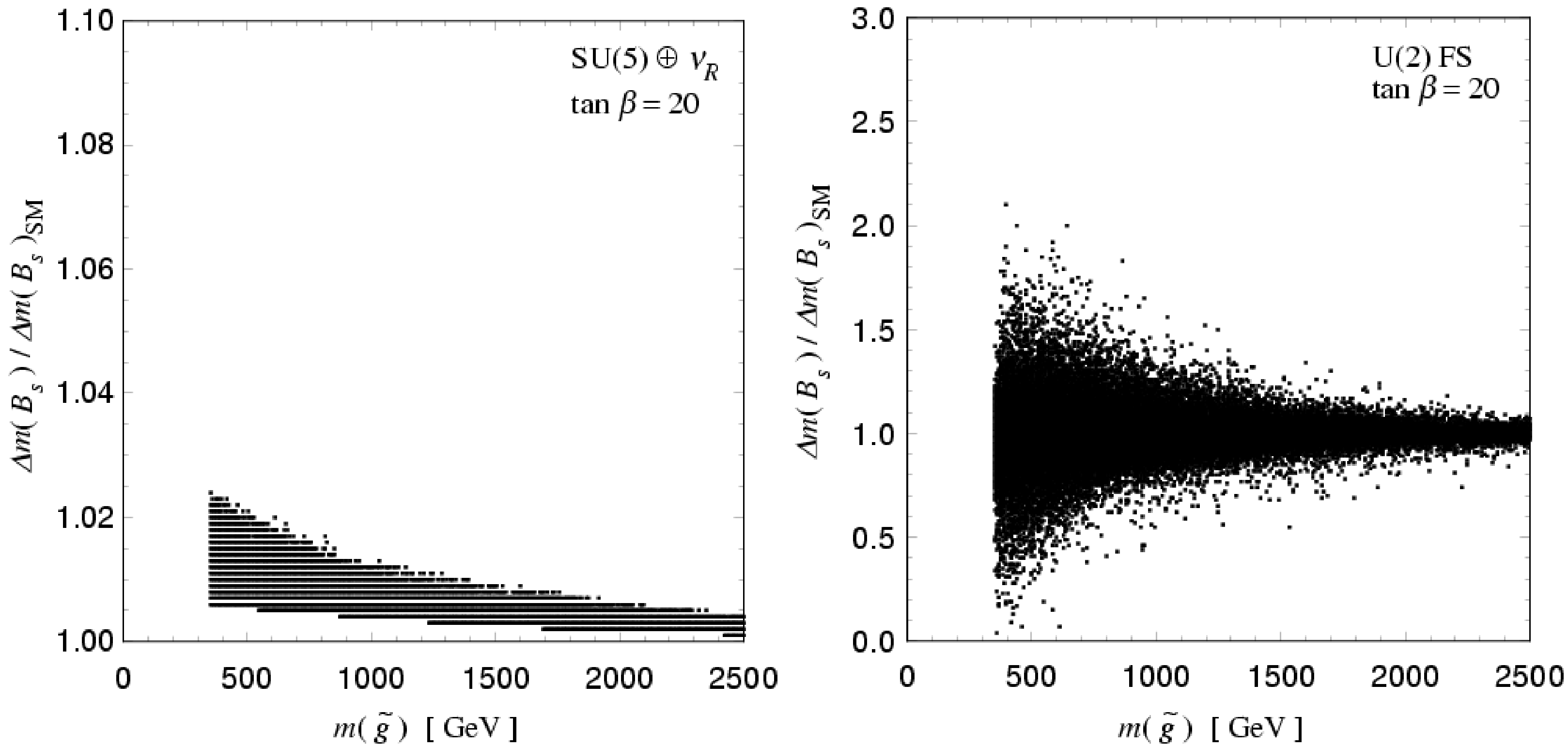
Effect in Δm_{B_d}

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

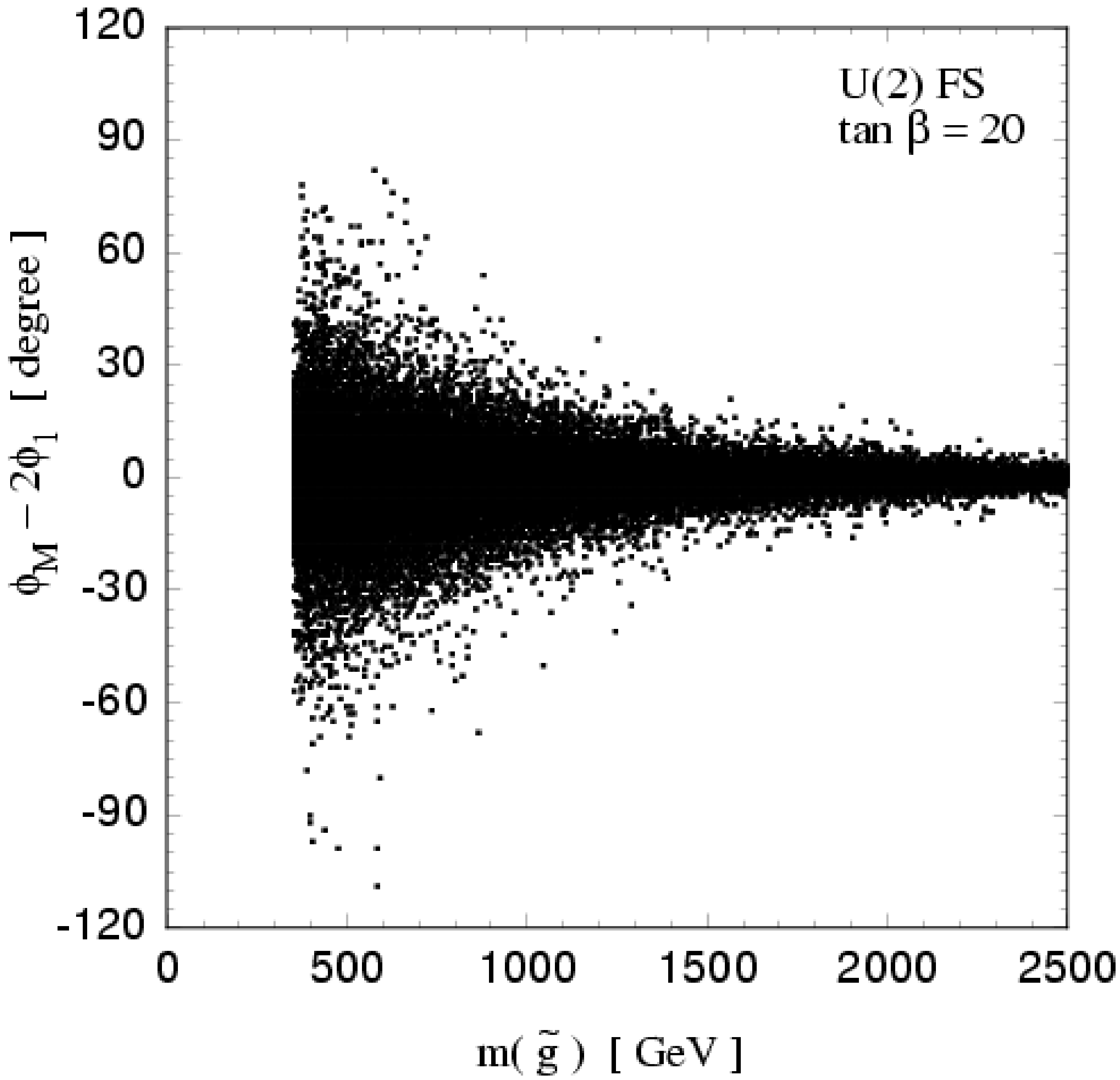


Effect in Δm_{B_s}

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

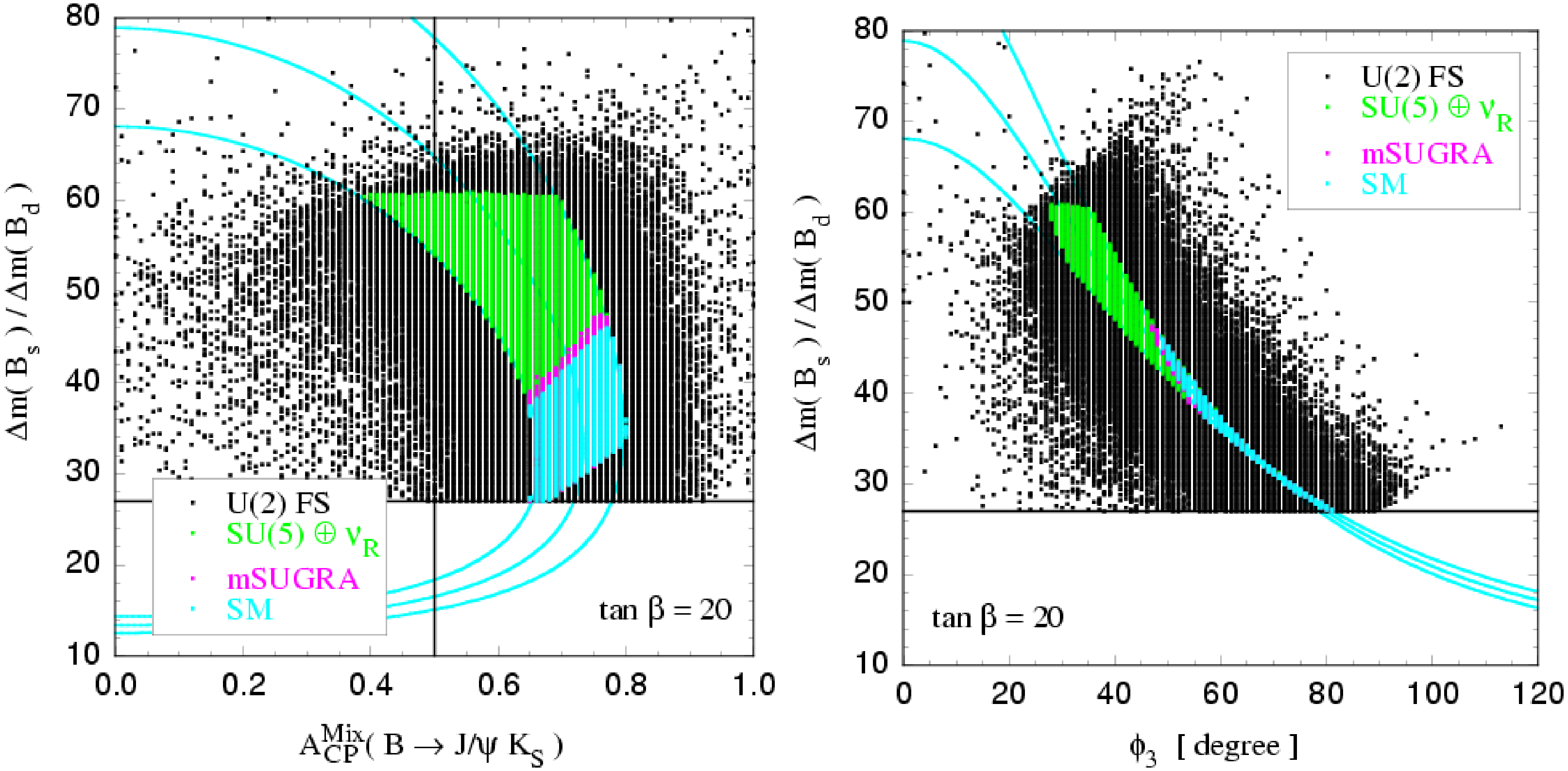


Effect on ϕ_1 measurement in U(2)



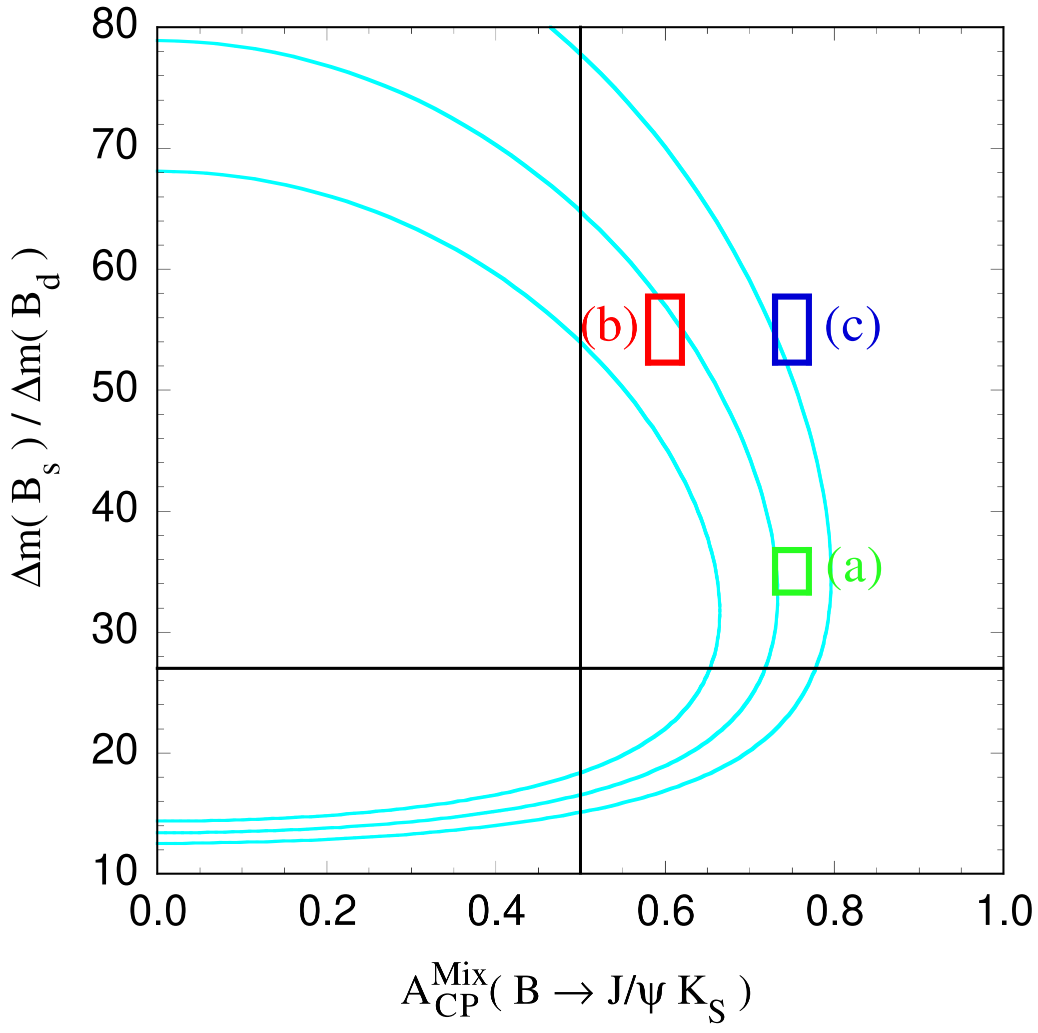
Correlations

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

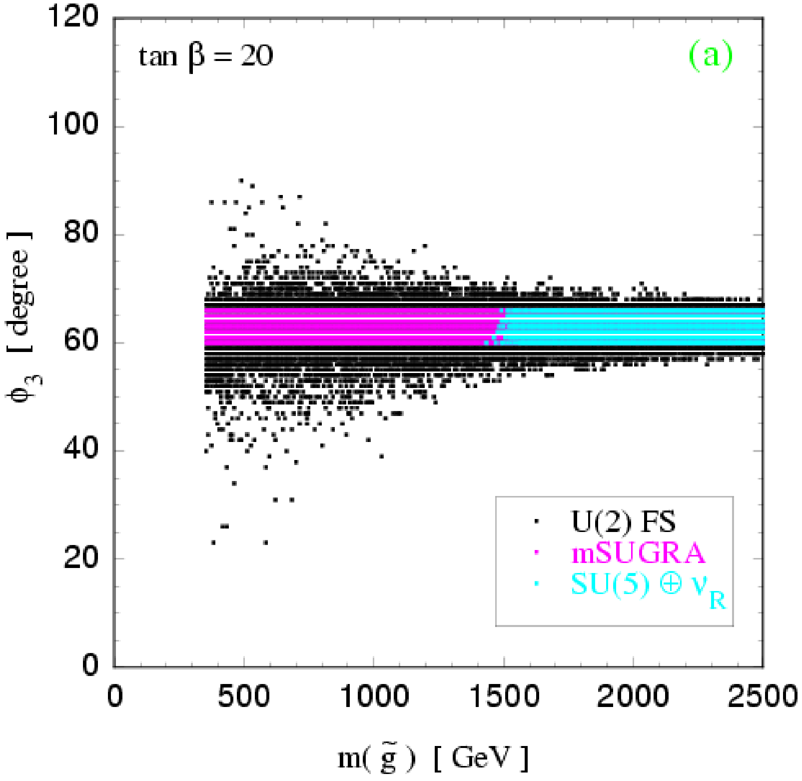


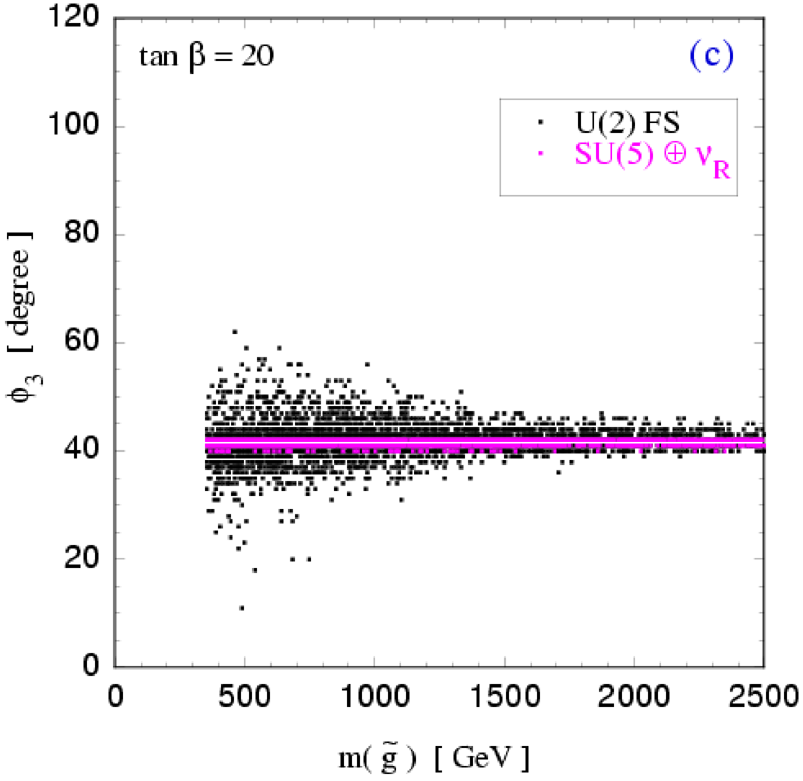
Possible implication on ϕ_3

$A^{\mathrm{mix}}_{\mathrm{CP}}(B \to \psi K_S)$ and $\Delta m_{B_s}/\Delta m_{B_d}$ measurements



Possible implication on ϕ_3 (cont'd)





5. Summary and discussion

- The CKM mechanism has been non-trivially tested.
- Still large room for new physics. $O(0.1) \sim 1$ effects are allowed.
- Δm_{B_s} is an important step. $\Leftarrow$ hadron machine
  But with caution in the hadronic uncertainty.
- A clean ϕ_3 determination is requisite. $B \longrightarrow DK$, ...
  (Super) B factories
  $\Rightarrow$ Uncover the flavor structure of SUSY breakings
- $B \longrightarrow \phi K_S$: $b \longrightarrow s\bar{s}s$ (no tree)
  The same CP asymmetry as ψK_S in the SM
  Deviation $\Rightarrow$ new physics
- $b \longrightarrow s\gamma$, $b \longrightarrow sll$, ...
  loop induced $\Rightarrow$ potentially sensitive to new physics.