Flavor violations in SUSY Grand Unified Models

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Collaboration with Bhaskar Dutta

(based on PRL**97**,241802; PRD**75**,015006; arXiv:0708.3080)

1. Introduction & Basic Scenario
2. Possible discrepancies from SM
3. FCNCs in GUT models (SU(5), SO(10))
4. Relations in flavor violations
5. Conclusion

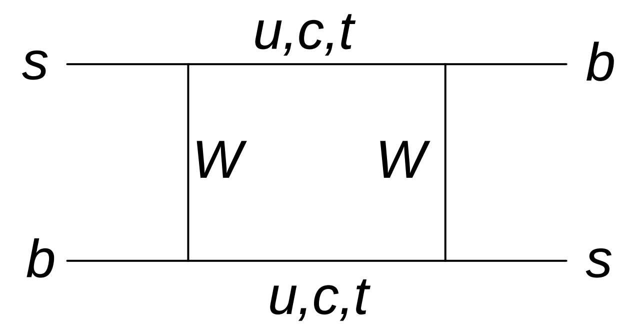
Talk at KEK Theory meeting (KEKPH0712), 12.12.2007

Introduction

Recent result: B_s-$\bar{B}_s$ mass difference (D0, CDF)

$$\Delta M_s = 17.77 \pm 0.10 \pm 0.07 \ \mathrm{ps}^{-1}$$

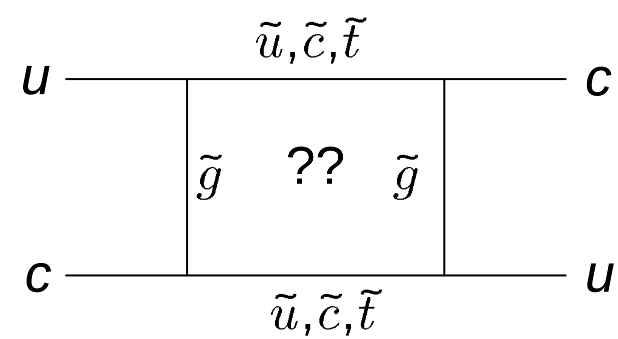
(CDF, hep-ex/0609040)



Recent result: D-$\bar{D}$ mixing (Babar, Bell, 2007)

$$x_D = 8.7^{+3.0}_{-3.4} \times 10^{-3}, \qquad y_D = (6.6 \pm 2.1) \times 10^{-3} \quad \text{(HFAG)}$$

$$x_D \equiv \frac{\Delta M_D}{\Gamma_D}, \qquad y_D \equiv \frac{\Delta \Gamma_D}{2\Gamma_D},$$



Additional FCNC constraints

Basic Scenario

Too much FCNCs in general SUSY breaking masses.

⇒ Flavor universality of SUSY breaking is assumed.

Even if so, FCNCs are induced by RGEs.

In MSSM, the quark FCNCs are small due to tiny CKM mixings.

If there is a heavy particle, the loop corrections can induce sizable FCNCs.

(e.g. right-handed neutrino)

(Borzumati-Masiero)

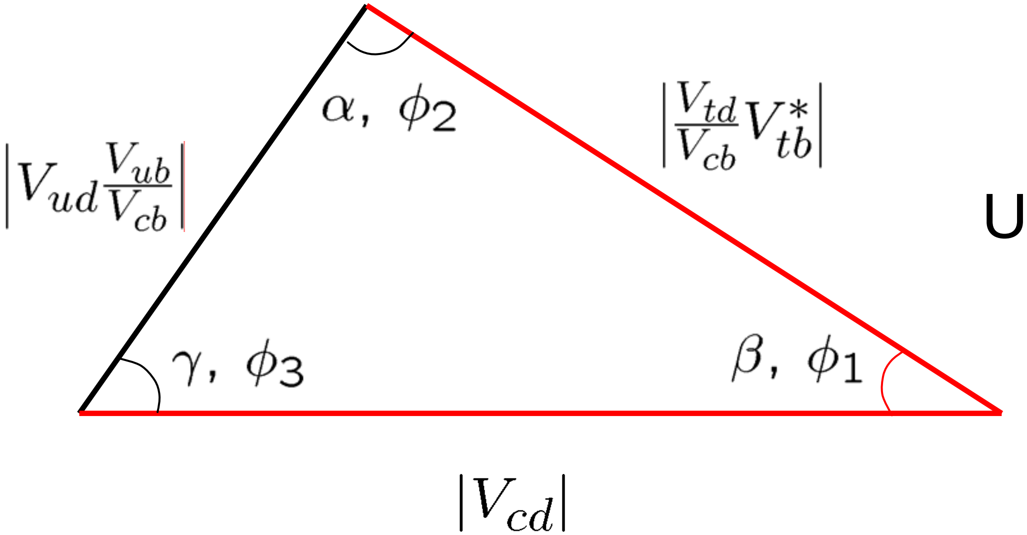
Investigating accurate measurement of FCNCs in quarks and leptons is very important to find a footprint of the GUT models.

This talk: we study FCNCs from grand unified models SU(5), SO(10)

In this talk, we feature

1. $\sin 2\phi_1$-V_{ub} discrepancy in unitarity triangle
2. phase of B_s-$\bar{B}_s$ mixing

   CP violation of $B_s \to J/\psi\phi$ decay



Unitarity Triangle

$$\sin 2\phi_1 = 0.680 \pm 0.026$$ (World average, Belle and Babar)

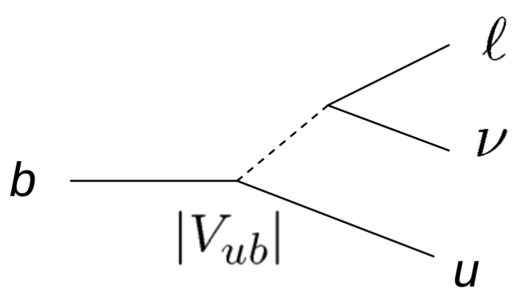
$$\left|\frac{V_{td}}{V_{ts}}\right| = 0.206^{+0.008}_{-0.006} \qquad \frac{\Delta M_s}{\Delta M_d} = \xi^2 \frac{M_{B_s}}{M_{B_d}} \left|\frac{V_{td}}{V_{ts}}\right|^2 \qquad \left(\xi^2 = \frac{B_{B_s} f_{B_s}^2}{B_{B_d} f_{B_d}^2} = (1.21 \pm 0.06)^2\right)$$

$$|V_{cd}| = 0.2258, \quad |V_{cb}| = (41.6 \pm 0.6) \times 10^{-3}, \quad |V_{ts}| \simeq |V_{cb}|, \quad |V_{tb}| \simeq 1$$

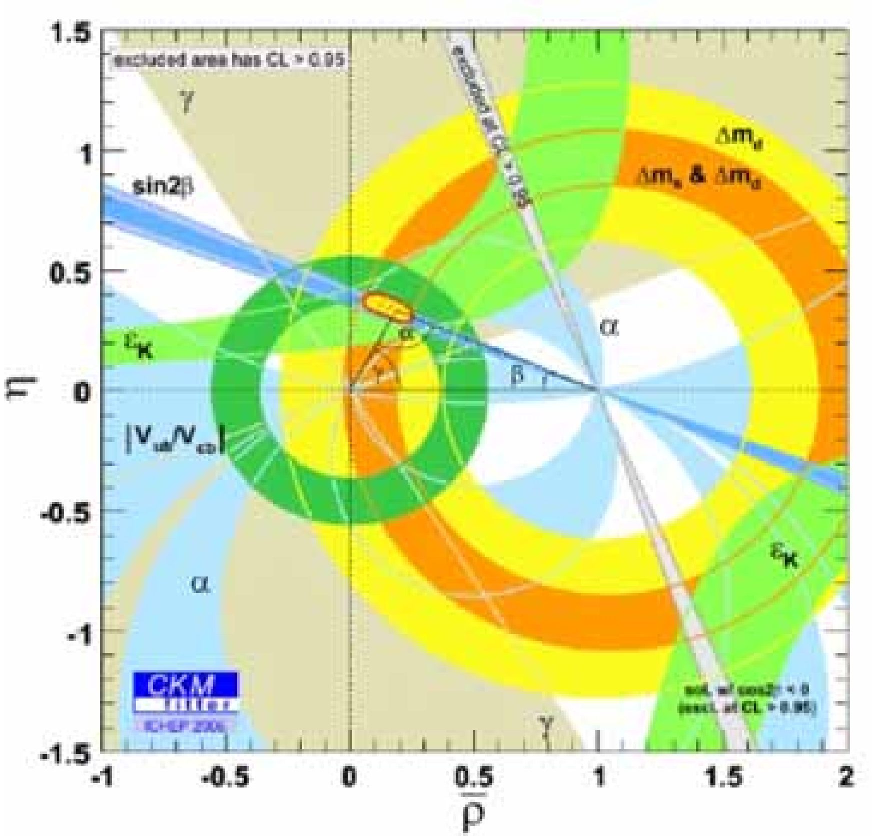
$$|V_{ub}| = (3.52 \pm 0.17) \times 10^{-3}$$ (Unitarity)

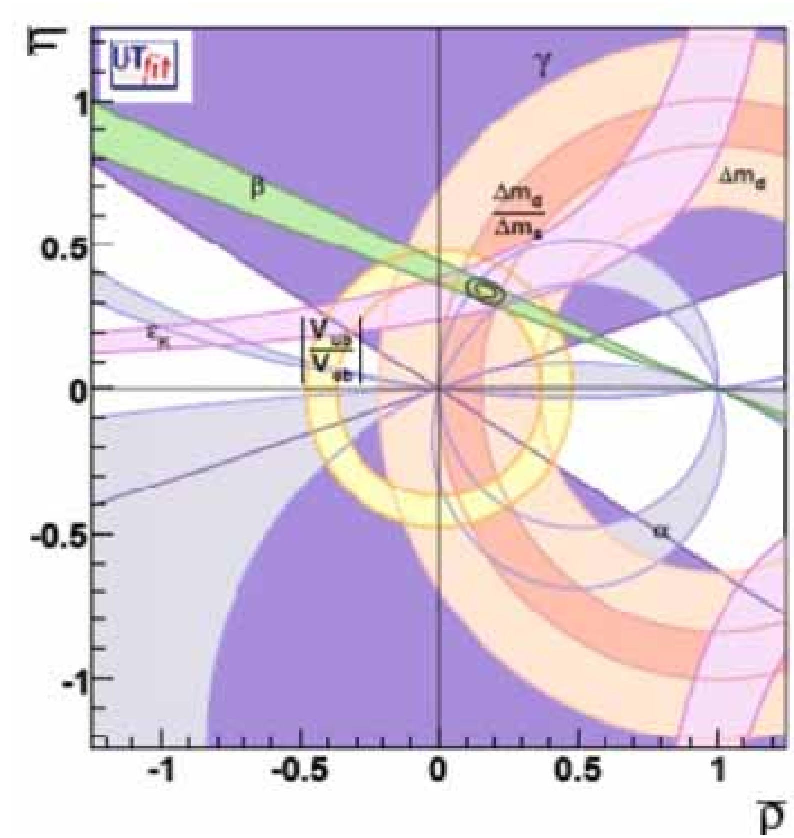
Experimental measurement of $|V_{ub}|$ (Tree-level dominant)

PDG average : $|V_{ub}| = (4.31 \pm 0.30) \times 10^{-3}$



(Recently, inclusive decay data become accurate.)





Global fit :

Consistent with SM

But 1.5-2 sigma discrepancy in $\sin 2\phi_1$-V_{ub}

New physics is hiding there ? Or statistical phantom ?

2. phase of B_s-$\bar{B}_s$ mixing

CP violation in $B_s \to J/\psi\phi$ decay

$$M_{12} = \langle B_s | H | \bar{B}_s \rangle$$

$$\Delta M_s = 2|M_{12}| \qquad M_{12} = |M_{12}| e^{-2i\beta_s}$$

SM prediction : $2\beta_s = 0.03 - 0.04 \ \text{(rad)}$

DØ preliminary : $2\beta_s = -0.79^{+0.47}_{-0.39} \ \text{(rad)}$

(hep-ex/0702030)

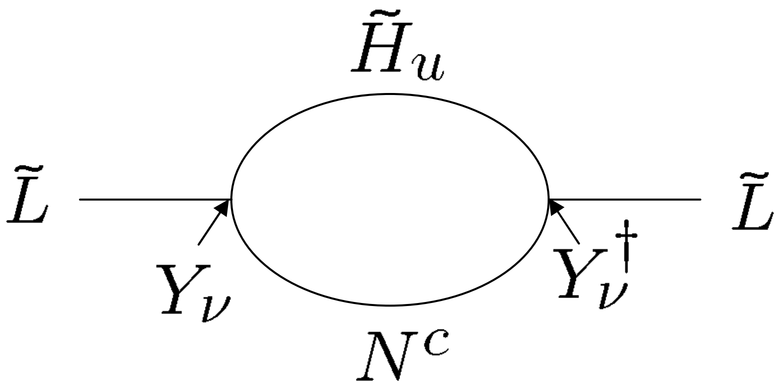
Waiting for more statistics.

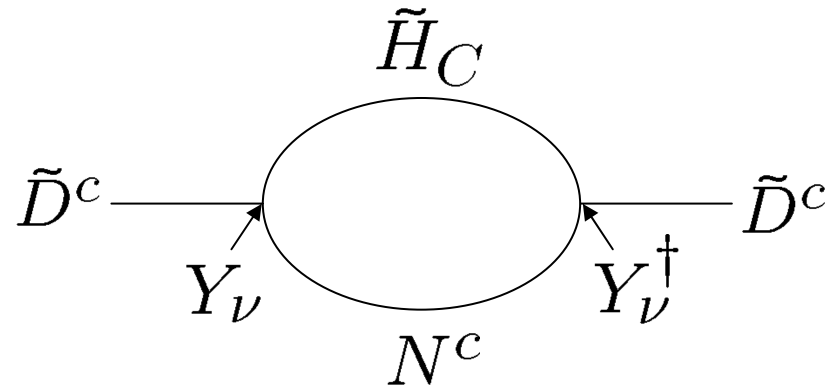
SU(5) GUT

Down quarks (D^c) and lepton doublet (L) are unified in $\bar{\mathbf{5}}$.

$Q, U^c, E^c \;:\; \mathbf{10}$ Right-handed neutrino : N^c

$$Y_u\,\mathbf{10}\cdot\mathbf{10}\,H_5 + Y_d\,\mathbf{10}\cdot\bar{\mathbf{5}}\,H_{\bar{5}} + Y_\nu\,\bar{\mathbf{5}}\,N^c\,H_5$$





Both RH down-squarks and sleptons can have sizable FCNC effects.

(Moroi, Akama-Kiyo-Komine-Moroi, Baek-Goto-Okada-Okumura, …)

SO(10) GUT

All Q, U^c, D^c, L, E^c, N^c are unified in $\mathbf{16}$.

$$h\,\mathbf{16}\cdot\mathbf{16}\,H_{10} + f\,\mathbf{16}\cdot\mathbf{16}\,H_{\overline{126}} + h'\mathbf{16}\cdot\mathbf{16}\,H_{120}$$

$$Y_u = h + r_2 f + r_3 h'$$
$$Y_d = r_1(h + f + h')$$
$$Y_e = r_1(h - 3f + c_e h')$$
$$Y_\nu = h - 3r_2 f + c_\nu h'$$

$$M_\nu^{\text{light}} = \underbrace{M_L}_{\text{Type II}} - \underbrace{Y_\nu M_R^{-1} Y_\nu^{\mathsf{T}} v_u^2}_{\text{Type I}}$$

$$M_L = f_L \langle \Delta_L^0 \rangle \qquad M_R = f_R \langle \Delta_R^0 \rangle$$

Naively, $V_{L,R}^e \sim \mathbf{1}$. $\quad (Y_\nu = V_L^e Y_\nu^{\text{diag}} V_R^{e\dagger})$

The right-handed neutrino loop effects are not very large.

However, $f\,\mathbf{16}\cdot\mathbf{16}\,H_{\overline{126}}$ coupling has large mixings.

The coupling includes the Majorana couplings : $f_L L L \Delta_L + f_R L^c L^c \Delta_R$

$$m_{16}^2 \simeq m_{\tilde{Q}}^2 \simeq m_{\tilde{U}^c}^2 \simeq m_{\tilde{D}^c}^2 \simeq m_{\tilde{L}}^2 \simeq m_{\tilde{E}^c}^2 \simeq m_{\tilde{N}^c}^2$$

$$m_{16}^2 \simeq m_0^2 \left(\mathbf{1} - \kappa\, U \begin{pmatrix} k_1 & & \\ & k_2 & \\ & & 1 \end{pmatrix} U^\dagger \right)$$

Threshold parameter : $\kappa \simeq \frac{(f_{33}^{\mathrm{diag}})^2}{8\pi^2} \left(3 + \frac{A_0^2}{m_0^2} \right) \ln \frac{M_*}{M_{\mathrm{GUT}}}$

M_*: String/Planck scale

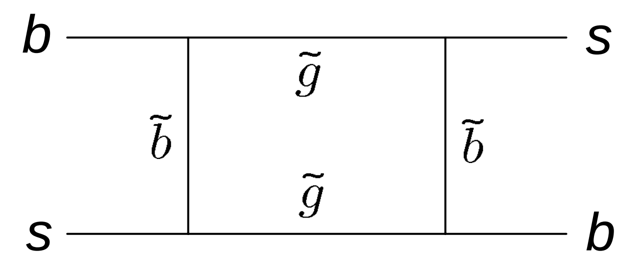
$$f = U f^{\mathrm{diag}} U^{\mathsf{T}} \qquad U \simeq U_{\mathrm{MNSP}}^* \qquad k_2 \simeq \frac{\Delta m_{\mathrm{sol}}^2}{\Delta m_{\mathrm{atm}}^2}$$

Both left- and right-squarks have sizable FCNC effects!

SUSY contributions in B-$\bar{B}$ mixings

$$M_{12} = \langle B|H|\bar{B}\rangle \qquad \Delta M = 2|M_{12}|$$

The gluino box diagram dominates.



Mass insertion approximation:

$$\frac{M_{12}^{\mathrm{SUSY}}}{M_{12}^{\mathrm{SM}}} \simeq a[(\delta^d_{LL})^2_{3i} + (\delta^d_{RR})^2_{3i}] - b(\delta^d_{LL})_{3i}(\delta^d_{RR})_{3i} + \cdots$$

$i = 1$ for B_d, $i = 2$ for B_s

$a \sim O(1)$, $b \sim O(100)$ for $m_{\mathrm{SUSY}} \sim 1$ TeV (Ball-Khalil-Kou)

$$\delta^d_{LL,RR} = (M^2_{\tilde{d}})_{LL,RR}/\tilde{m}^2 \qquad \tilde{m}\ :\ \text{average squark mass}$$

$$(\tilde{d}_L, \tilde{d}_R)\begin{pmatrix} (M^2_{\tilde{d}})_{LL} & (M^2_{\tilde{d}})_{LR} \\ (M^2_{\tilde{d}})_{RL} & (M^2_{\tilde{d}})_{RR} \end{pmatrix}\begin{pmatrix} \tilde{d}^\dagger_L \\ \tilde{d}^\dagger_R \end{pmatrix}$$

$$(M^2_{\tilde{d}})_{LL} = m^2_{\tilde{Q}} + \cdots$$

$$(M^2_{\tilde{d}})_{RR} = (m^2_{\tilde{D}^c})^{\mathsf{T}} + \cdots$$

Both left- and right-squarks have sizable FCNC effects in SO(10).

$$\frac{M_{12}^{\text{SUSY}}}{M_{12}^{\text{SM}}} \simeq a[(\delta^d_{LL})^2_{3i} + (\delta^d_{RR})^2_{3i}] - b(\delta^d_{LL})_{3i}(\delta^d_{RR})_{3i} + \cdots$$

$i = 1$ for B_d, $i = 2$ for B_s

$a \sim O(1)$, $b \sim O(100)$ for $m_{\text{SUSY}} \sim 1$ TeV

Flavor violating effects are larger in the box diagram in SO(10).

Cf. Only δ^d_{RR} is large in SU(5).

Remark :

Accurate measurement of mass difference is consistent with SM.

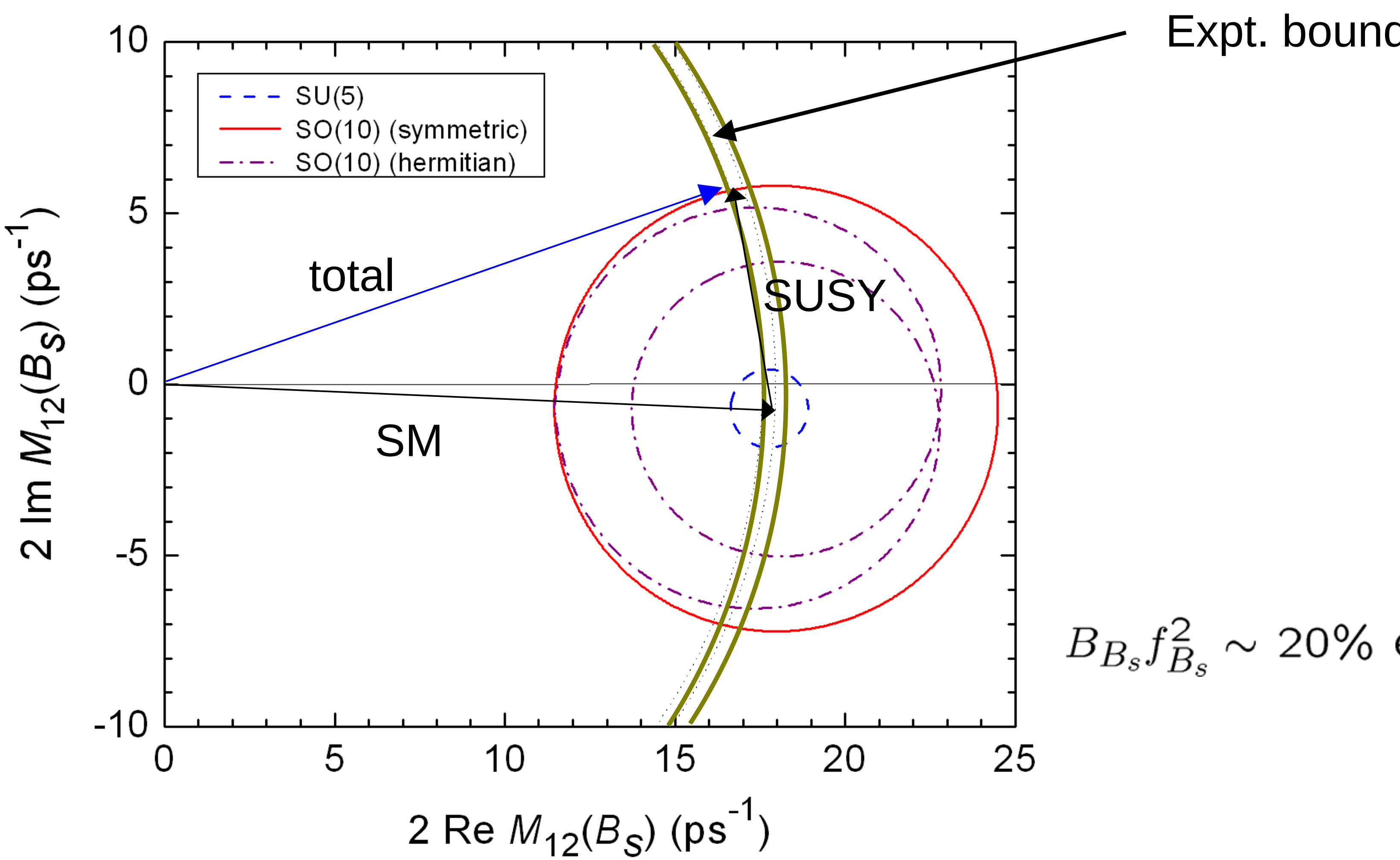
However, experimental result of $\Delta M_s = 2|M_{12}(B_s)|$
does not constrain size of SUSY contribution $|M_{12}^{\mathrm{SUSY}}|$ much.

$$M_{12} = M_{12}^{\mathrm{SM}} + M_{12}^{\mathrm{SUSY}}$$

arg M_{12}^{SUSY} is a free parameter in the model:

due to free phase in Yukawa couplings

There is room for sizable SUSY contribution. → Next page



$B_{B_s} f_{B_s}^2 \sim 20\%$ error

One can always find a solution as long as $|M_{12}^{\mathrm{SUSY}}| < 2|M_{12}^{\mathrm{SM}}|$.

Accurate measurement of not only the mass difference but also the B_s-$\bar{B}_s$ phase is very important.

$$\frac{M_{12}^{\mathrm{SUSY}}}{M_{12}^{\mathrm{SM}}} \propto (\delta_{LL}^d)_{ji}(\delta_{RR}^d)_{ji}$$

$ji = 12 : K\text{-}\bar{K}$

$ji = 13 : B_d\text{-}\bar{B}_d$

$ji = 23 : B_s\text{-}\bar{B}_s$

$$(M_{\tilde{d}}^2)_{LL} = m_{\tilde{Q}}^2 + \cdots, \qquad (M_{\tilde{d}}^2)_{RR} = (m_{\tilde{D}^c}^2)^{\mathsf{T}} + \cdots$$

$$m_{\tilde{Q}}^2 \simeq m_{\tilde{U}^c}^2 \simeq m_{\tilde{D}^c}^2 \simeq m_0^2 \left(\mathbf{1} \underbrace{\boxed{- \kappa\, U \begin{pmatrix} k_1 & & \\ & k_2 & \\ & & 1 \end{pmatrix} U^\dagger}}_{\delta_{ji}} \right)$$

Parameterization of phase:

$$U = P U_q \qquad P = \begin{pmatrix} e^{i\alpha_1} & & \\ & e^{i\alpha_2} & \\ & & e^{i\alpha_3} \end{pmatrix}$$

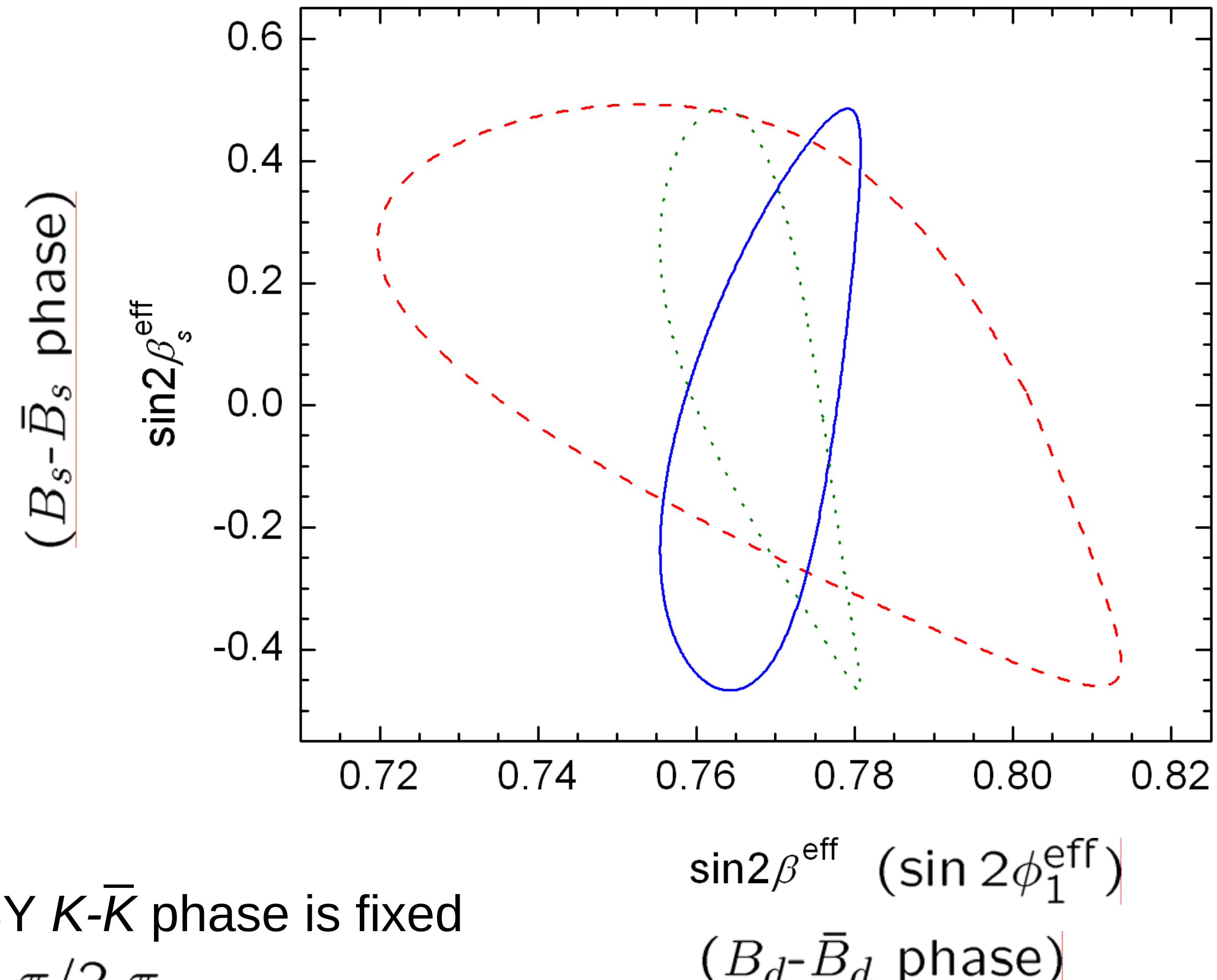
Phases in *P* are cancelled in the SUSY contribution.

$$Y_u = V_{\mathrm{CKM}}^{\mathsf{T}} Y_u^{\mathrm{diag}} P_u V_{\mathrm{CKM}} \qquad Y_d = Y_d^{\mathrm{diag}} P_d$$

P_d provides the phase of SUSY contribution of $K\text{-}\bar{K}$, $B_d\text{-}\bar{B}_d$, $B_s\text{-}\bar{B}_s$

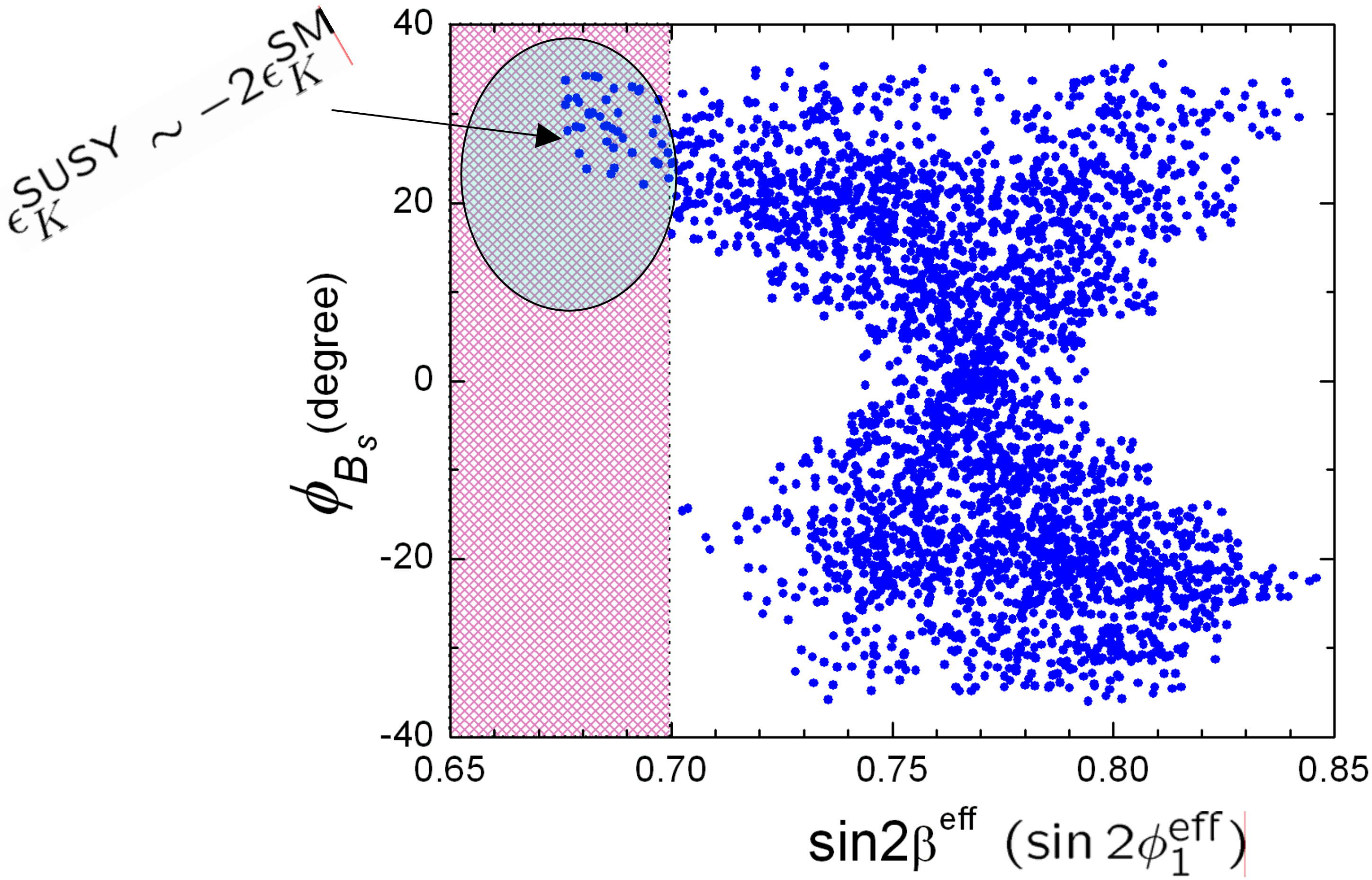
There are only two phase freedom (approximately) for SUSY contributions to K-$\bar{K}$, B_d-$\bar{B}_d$, B_s-$\bar{B}_s$ mixing amplitudes.

The SUSY modifications of the phases are related.



SUSY K-$\bar{K}$ phase is fixed as $0, \pi/2, \pi$.

ϕ_{B_s} vs $\sin 2\beta$ with ϵ_K constraint



$\beta_s^{SM} \simeq 1^\circ$ $\qquad$ $\beta_s^{eff} = \beta_s^{SM} - \phi_{B_s} = (-23 \pm 16)^\circ$

DØ preliminary

$$m^2_{\tilde{Q}} \simeq m^2_{\tilde{U}^c} \simeq m^2_{\tilde{D}^c} \simeq \; m_0^2 \left(\mathbf{1} - \kappa\, U \begin{pmatrix} k_1 & & \\ & k_2 & \\ & & 1 \end{pmatrix} U^\dagger \right)$$

$$U = PU_q \qquad U_q = (\theta^q_{12}, \theta^q_{13}, \theta^q_{23}, \delta^q)$$

K-$\bar{K}$: $\quad |\delta^d_{12}| \simeq \kappa \left| \frac{1}{2} k_2 \sin 2\theta^q_{12} \cos\theta^q_{23} + e^{i\delta^q} \sin\theta^q_{13} \sin\theta^q_{23} \right|$

B_d-$\bar{B}_d$: $\quad |\delta^d_{13}| \simeq \kappa \left| \frac{1}{2} k_2 \sin 2\theta^q_{12} \sin\theta^q_{23} - e^{i\delta^q} \sin\theta^q_{13} \cos\theta^q_{23} \right|$

B_s-$\bar{B}_s$: $\quad |\delta^d_{23}| \simeq \frac{1}{2} \kappa \sin 2\theta^q_{23}$

SUSY contribution of K-$\bar{K}$ mixing can be cancelled when $\delta^q \simeq \pi$.

D-$\bar{D}$ mixing amplitude can be calculated in a similar formula, but it is calculated in the up-type quark Yukawa diagonal basis.

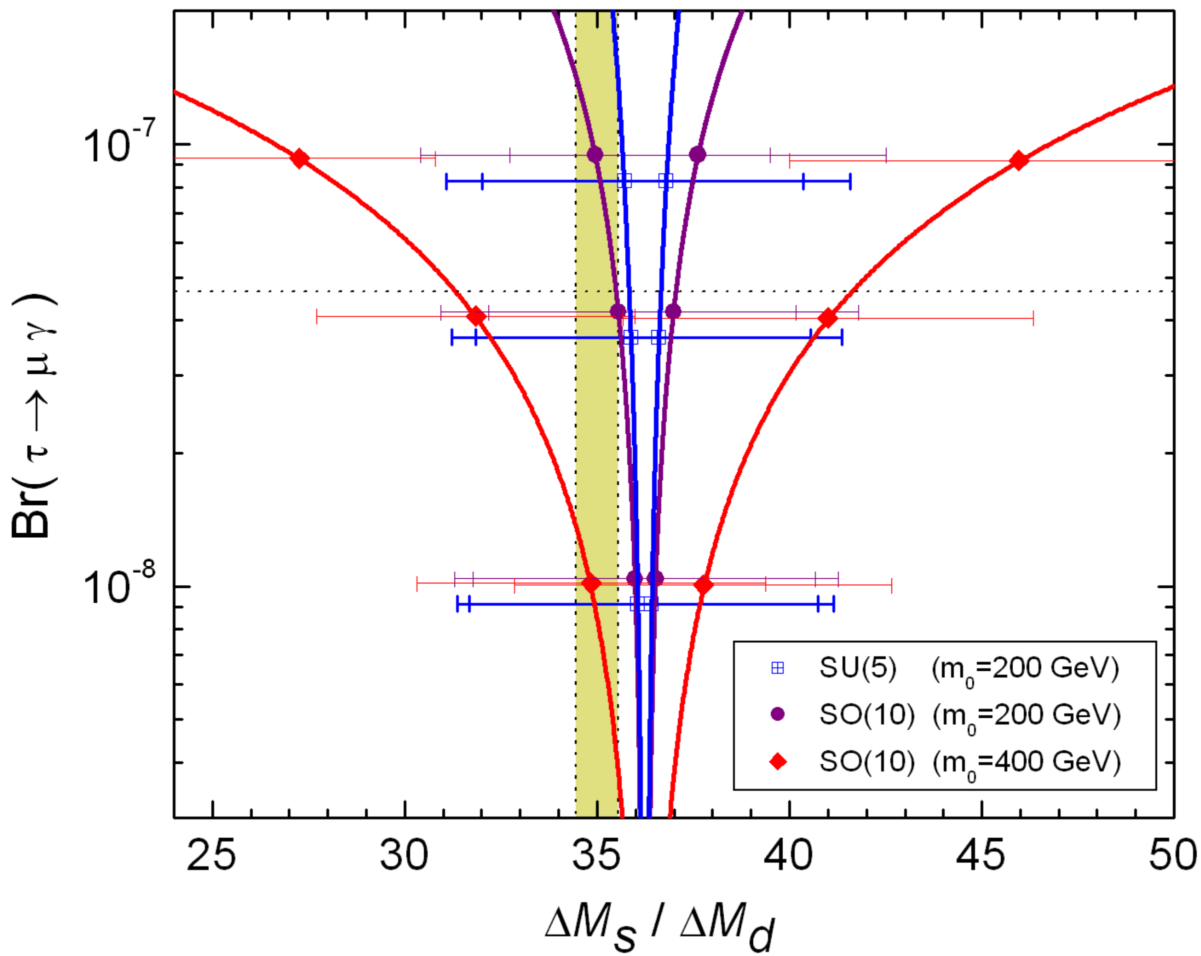
$$\delta^u_{12} \simeq [V^*_{\mathrm{CKM}}(\delta^d)V^{\mathrm{T}}_{\mathrm{CKM}}]_{12} \simeq \delta^d_{12} + V_{us}\kappa \sin^2\theta^q_{23}$$

K-$\bar{K}$ and D-$\bar{D}$ cannot be cancelled simultaneously if $\kappa \sin^2\theta^q_{23}$ is sizable.

$\bar{D}$-$\bar{D}$ data constrain $\kappa \sin^2\theta^q_{23}$. (arXiv:0708.3080)

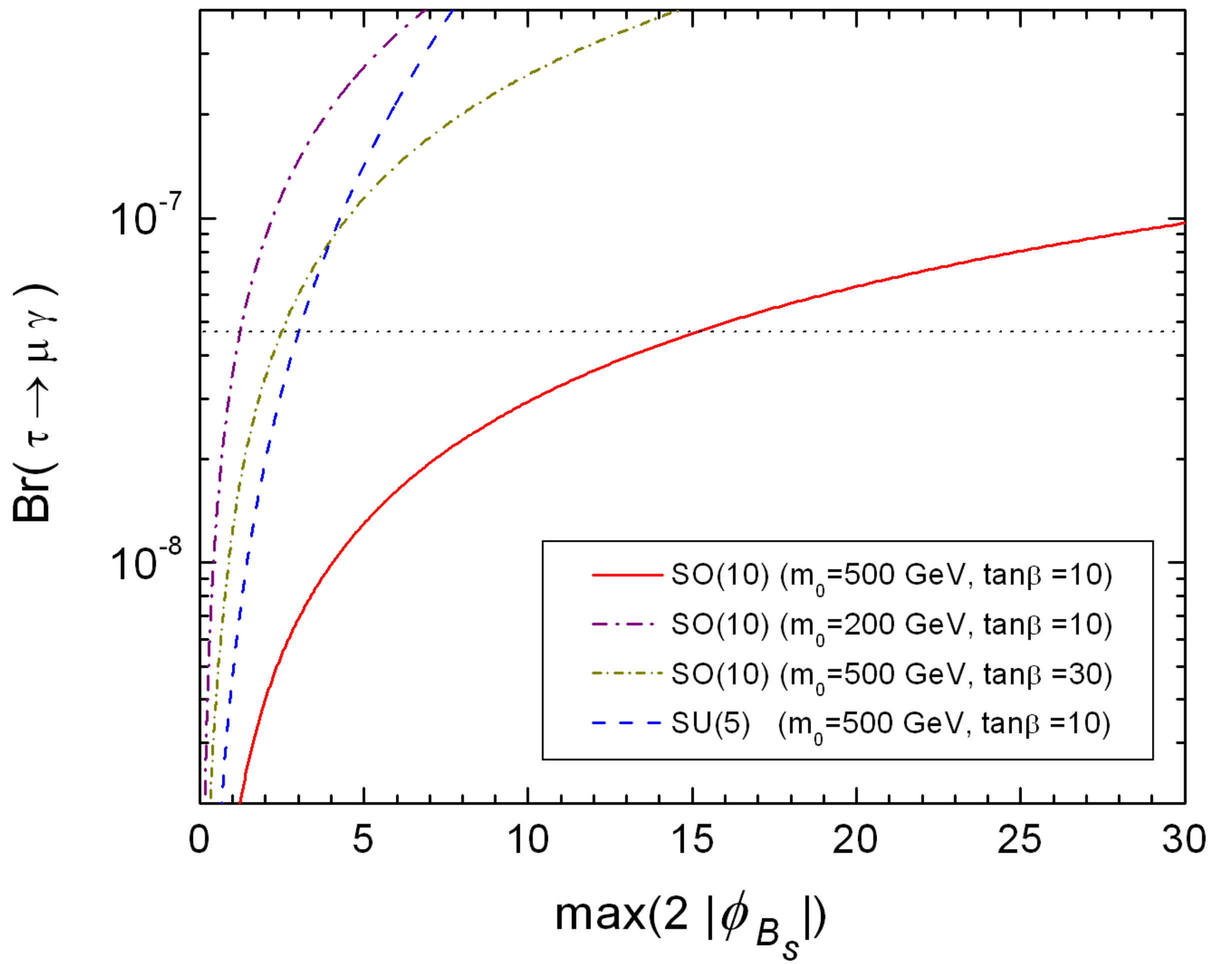
In the scenario where $\sin 2\phi_1$ and V_{ub} discrepancy is solved by the SUSY contribution, SUSY contribution may also affect to the recently measured D-$\bar{D}$ mixing.

B_s-$\bar{B}_s$ mixing and $\tau \to \mu\gamma$



$m_{1/2} = 300$ GeV, $\tan\beta = 10$

$\mathrm{Br}(\tau \to \mu\gamma)$ constrains the CP phase of B_s decay



$\mathrm{BR} < 4.5 \times 10^{-8}$

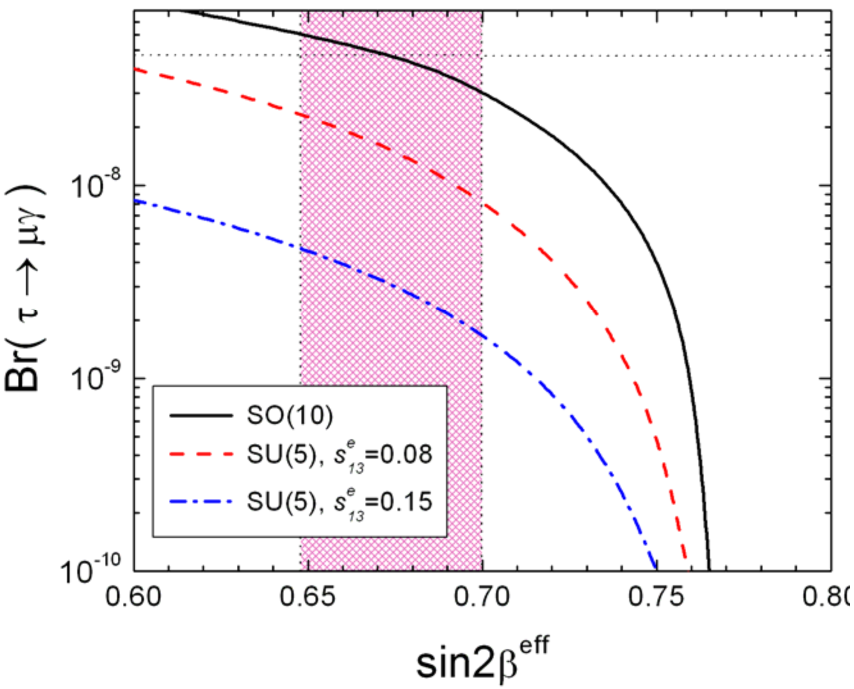
(Belle)

$$C_{B_s} e^{2i\phi_{B_s}} = \frac{M_{12}^{\mathrm{full}}}{M_{12}^{\mathrm{SM}}}$$

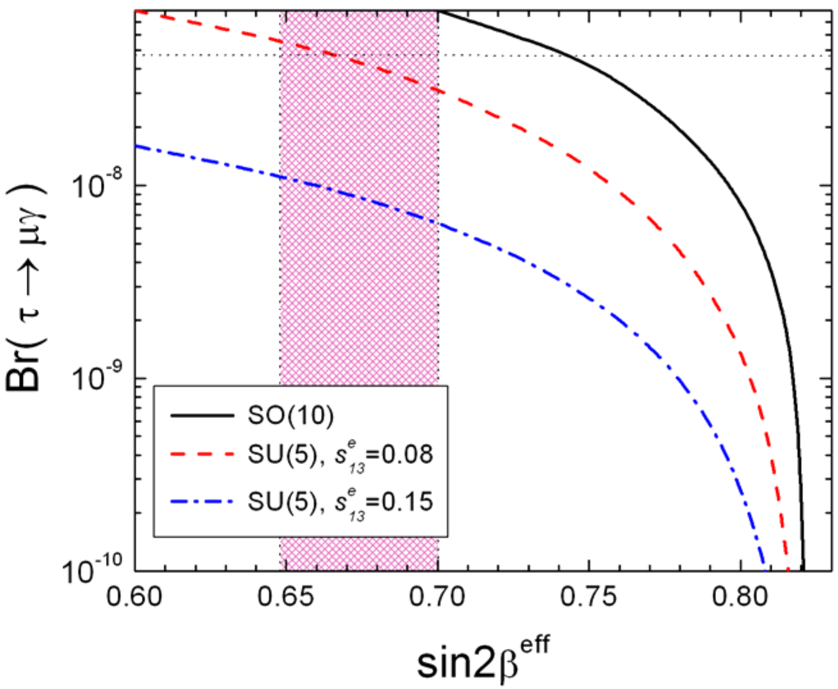
$$\beta_s^{\mathrm{SM}} \simeq 1^\circ, \qquad \beta_s^{\mathrm{eff}} = \beta_s^{\mathrm{SM}} - \phi_{B_s} = (-23 \pm 16)^\circ$$

DØ preliminary

$\text{Br}(\tau \to \mu\gamma)$ vs $\sin 2\phi_1$



$|V_{ub}| = 0.0041$



$|V_{ub}| = 0.0045$

$m_0 = 1.2$ TeV, $m_{1/2} = 300$ GeV, $\tan\beta = 10$, $A_0 = 0$

We have assumed

$$m_{16}^2 \simeq m_{\tilde{Q}}^2 \simeq m_{\tilde{U}^c}^2 \simeq m_{\tilde{D}^c}^2 \simeq m_{\tilde{L}}^2 \simeq m_{\tilde{E}^c}^2 \simeq m_{\tilde{N}^c}^2$$

$$m_{16}^2 \simeq m_0^2 \left(\mathbf{1} - \kappa\, U \begin{pmatrix} k_1 & & \\ & k_2 & \\ & & 1 \end{pmatrix} U^\dagger \right)$$

But, κ may depend on the fermion species when (some of) decomposed fields from 126 and 120 Higgses split from the others.

Variety of induced FCNCs depends on the light decomposed field.

Accurate measurement of quark-lepton FCNCs deviation from SM

$\Downarrow$

Information of GUT breaking vacua

quark-quark-Higgs coupling

$(qq)_s$	$(\bar{\mathbf{3}}, \mathbf{1}, \frac{1}{3})$	colored Higgs	
$(qq)_a$	$(\bar{\mathbf{3}}, \mathbf{3}, \frac{1}{3})$	cause proton decay	
$(qq)_s$	$(\mathbf{6}, \mathbf{3}, \frac{1}{3})$	light in flipped-$SU(5)$	
$(qq)_a$	$(\mathbf{6}, \mathbf{1}, \frac{1}{3})$	favorable to suppress p decay	(*)
qu^c, qd^c	$(\mathbf{1}, \mathbf{2}, \pm\frac{1}{2})$		
qu^c, qd^c	$(\mathbf{8}, \mathbf{2}, \pm\frac{1}{2})$	favorable to suppress p decay	(*)
$u^c u^c$	$(\mathbf{3}, \mathbf{1}, -\frac{4}{3})$	cause proton decay	
$u^c d^c$	$(\mathbf{3}, \mathbf{1}, -\frac{1}{3})$	colored Higgs	
$d^c d^c$	$(\mathbf{3}, \mathbf{1}, \frac{2}{3})$	PS higgsino	
$u^c u^c$	$(\bar{\mathbf{6}}, \mathbf{1}, -\frac{4}{3})$		
$u^c d^c$	$(\bar{\mathbf{6}}, \mathbf{1}, -\frac{1}{3})$	favorable to suppress p decay	(*)
$d^c d^c$	$(\bar{\mathbf{6}}, \mathbf{1}, \frac{2}{3})$	light in flipped-$SU(5)$	

(*) arXiv:0712.1206 (Dutta-YM-Mohapatra)

lepton-lepton-Higgs coupling

$(\ell\ell)_s$	$(\mathbf{1},\mathbf{3},-1)$	important in type II seesaw
$(\ell\ell)_a$	$(\mathbf{1},\mathbf{1},-1)$	$SU(2)_R$ higgsino
$\ell\nu^c, \ell e^c$	$(\mathbf{1},\mathbf{2},\pm\frac{1}{2})$	important in type I seesaw
$\nu^c\nu^c$	$(\mathbf{1},\mathbf{1},0)$	
$\nu^c e^c$	$(\mathbf{1},\mathbf{1},1)$	$SU(2)_R$ higgsino
$e^c e^c$	$(\mathbf{1},\mathbf{1},2)$	light in PS & LR vacua

quark-lepton-Higgs coupling

$q\ell$	$(\mathbf{3},\mathbf{1},-\frac{1}{3})$	colored Higgs
$q\ell$	$(\mathbf{3},\mathbf{3},-\frac{1}{3})$	cause proton decay
$q\nu^c$	$(\mathbf{3},\mathbf{2},\frac{1}{6})$	flipped-$SU(5)$ higgsino
qe^c	$(\mathbf{3},\mathbf{2},\frac{7}{6})$	
ℓu^c	$(\bar{\mathbf{3}},\mathbf{2},-\frac{7}{6})$	
ℓd^c	$(\bar{\mathbf{3}},\mathbf{2},-\frac{1}{6})$	flipped-$SU(5)$ higgsino
$u^c\nu^c$	$(\bar{\mathbf{3}},\mathbf{1},-\frac{2}{3})$	PS higgsino
$u^c e^c$	$(\bar{\mathbf{3}},\mathbf{1},\frac{1}{3})$	colored Higgs
$d^c\nu^c$	$(\bar{\mathbf{3}},\mathbf{1},\frac{1}{3})$	important in lopsided structure
$d^c e^c$	$(\bar{\mathbf{3}},\mathbf{1},\frac{4}{3})$	cause proton decay

If a field from **120** Higgs is light, the FCNC inducing fermion coupling is antisymmetric.

$$h'h'^{\dagger} = \begin{pmatrix} 0 & c & b \\ -c & 0 & a \\ -b & -a & 0 \end{pmatrix} \begin{pmatrix} 0 & -c^* & -b^* \\ c^* & 0 & -a^* \\ b^* & a^* & 0 \end{pmatrix}$$

$$= (a^2 + b^2 + c^2) I - \begin{pmatrix} a^2 & a^* b & a^* c \\ ab^* & b^2 & b^* c \\ ac^* & bc^* & c^2 \end{pmatrix}$$

$b \sim c \sim \lambda a$

$\lambda \sim 0.2$

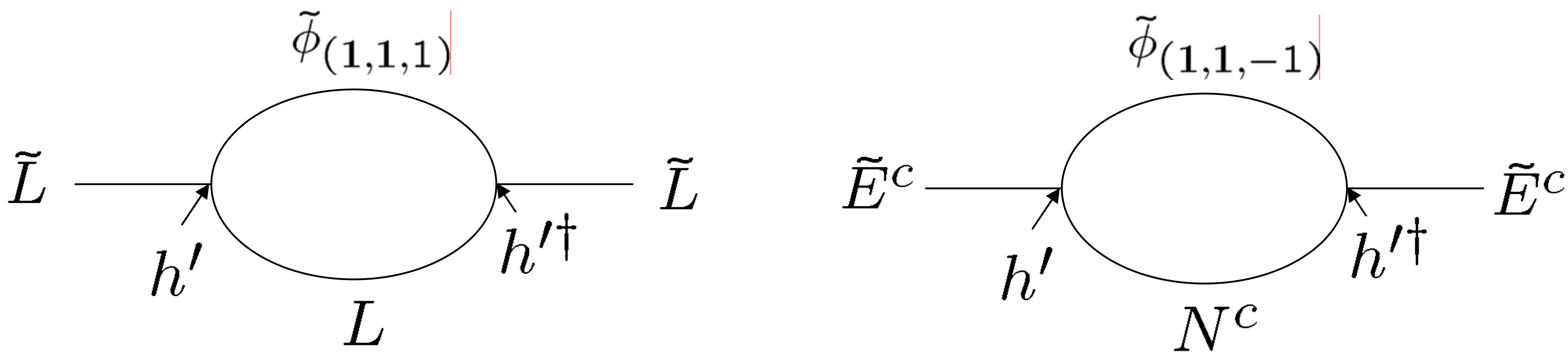
Hierarchy is inverted.

E.g. If (8,2,1/2) splits from **120** or **126**, flavor violations are induced for both left- and right-handed squarks.

$$q u^c \phi_{(\mathbf{8},\mathbf{2},1/2)} + q d^c \phi_{(\mathbf{8},\mathbf{2},-1/2)}$$

If it comes from **120**, contribution to B_s-$\bar{B}_s$ is small, but V_{ub}-$\sin 2\phi_1$ discrepancy can be solved.

E.g. If $\mathrm{SU}(2)_R$ remains below SO(10) breaking scale, and right-handed chargino $(\mathbf{1},\mathbf{1},\pm 1)$ comes from **120** mainly, $BR(\tau \to e\gamma)$ is enhanced rather than $BR(\tau \to \mu\gamma)$.



Cf. In usual scenario, $BR(\tau \to e\gamma)$ is much suppressed since 13 neutrino mixing is small.

Detail of induced FCNC is related to the SO(10) breaking pattern.

Summary

- We study the flavor violation in the context of SUSY GUTs.
- SO(10) model has impact on the modification of meson mixing amplitudes since both left- and right-handed squarks can have sizable flavor violation.
- The future observation of FCNCs for both quarks and leptons as well as sfermion mass (maybe for upcoming decade from 2010) can probe GUT scale physics.