CP violating lepton asymmetry from semileptonic *B* decays in supersymmetric grand unified theories

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Based on
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Phys. Rev. D**80**, 095005 (2009); ibid. **82**, 055017 (2010)
in Collaboration with B. Dutta, S. Khalil, and Q. Shafi
in prepearation

NCTS, Hsinchu (2011.4.12)

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↑ Review

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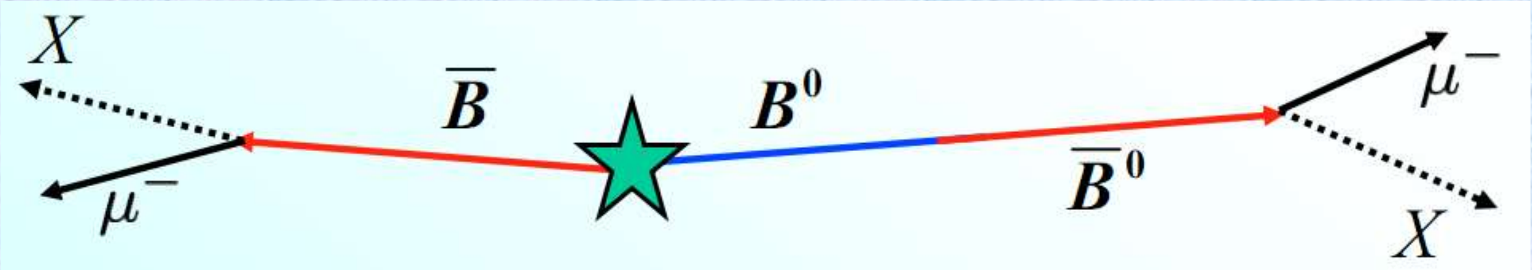
5. Constraints from $\tau \to \mu\gamma$ in SUSY GUTs

Dimuon charge asymmetry of semileptonic *B* decay [D0]



$$A^b_{sl} \equiv \frac{N_b^{++} - N_b^{--}}{N_b^{++} + N_b^{--}}$$

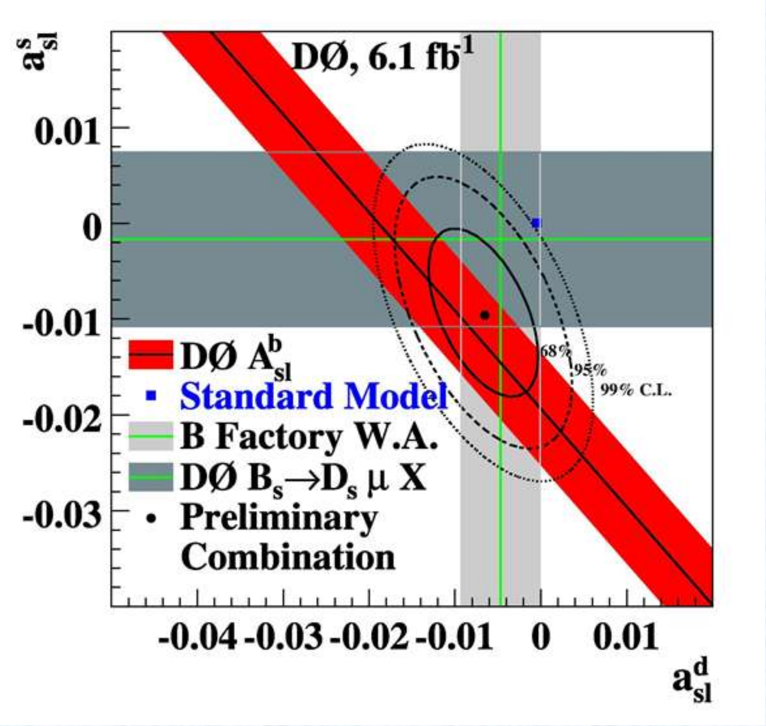
$$b \to \mu^- \bar{\nu} X$$
$$\bar{b} \to \mu^+ \nu X$$

$$A^b_{sl} = -0.00957 \pm 0.00251(\mathrm{stat}) \pm 0.00146(\mathrm{syst})$$

$$A^b_{sl}(\mathrm{SM}) = (-2.3^{+0.5}_{-0.6}) \times 10^{-4}$$

3.2 sigma deviation from SM

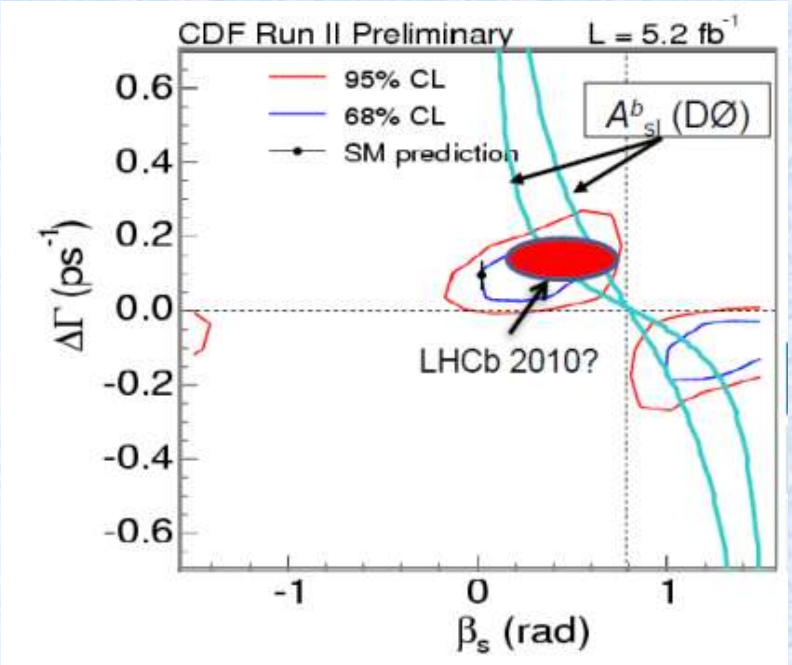
Asymmetry from semi-leptonic decay

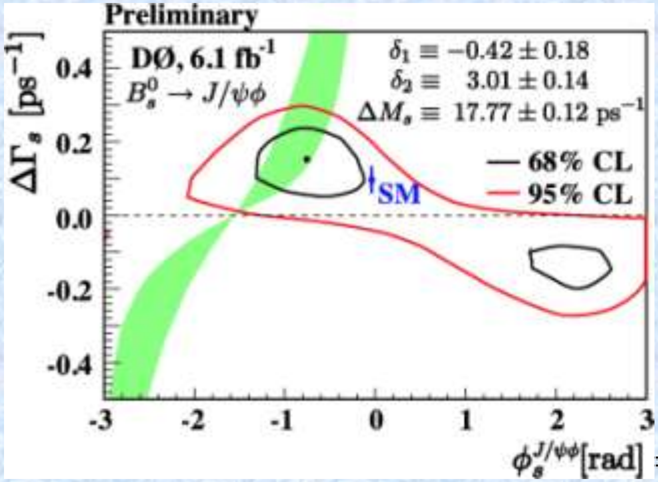


$$a^q_{sl} \equiv \frac{\Gamma(\bar{B}^0_q \to \mu^+ X) - \Gamma(B^0_q \to \mu^- X)}{\Gamma(\bar{B}^0_q \to \mu^+ X) + \Gamma(B^0_q \to \mu^- X)}$$

$$a^q_{sl} = \text{Im}\,\frac{\Gamma^{12}_q}{M^{12}_q} = \left|\frac{\Gamma^{12}_q}{M^{12}_q}\right| \sin\phi_q$$

From $B_s \to J/\psi\phi$ decay



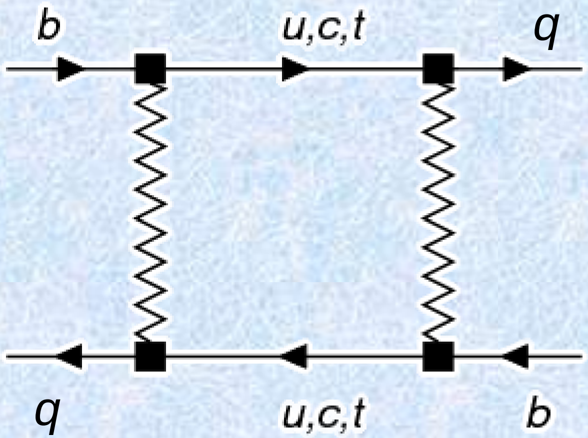


$= -2\beta_s$

A hint of a large CP violating phase in *Bs* system!

B_q-$\bar{B}_q$ oscillations $(q = d, s)$

$$i\frac{d}{dt}\begin{pmatrix} B_q(t) \\ \bar{B}_q(t) \end{pmatrix} = \left(\begin{pmatrix} M^q_{11} & M^q_{12} \\ M^q_{21} & M^q_{22} \end{pmatrix} - \frac{i}{2}\begin{pmatrix} \Gamma^q_{11} & \Gamma^q_{12} \\ \Gamma^q_{21} & \Gamma^q_{22} \end{pmatrix}\right)\begin{pmatrix} B_q(t) \\ \bar{B}_q(t) \end{pmatrix}$$



$$\frac{q}{p} = \sqrt{\frac{M^*_{12} - \frac{i}{2}\Gamma^*_{12}}{M_{12} - \frac{i}{2}\Gamma_{12}}}$$

$$r \equiv \frac{P(\bar{B}\to B)}{P(\bar{B}\to\bar{B})} = \left|\frac{q}{p}\right|^2 \frac{x^2+y^2}{2+x^2-y^2}$$

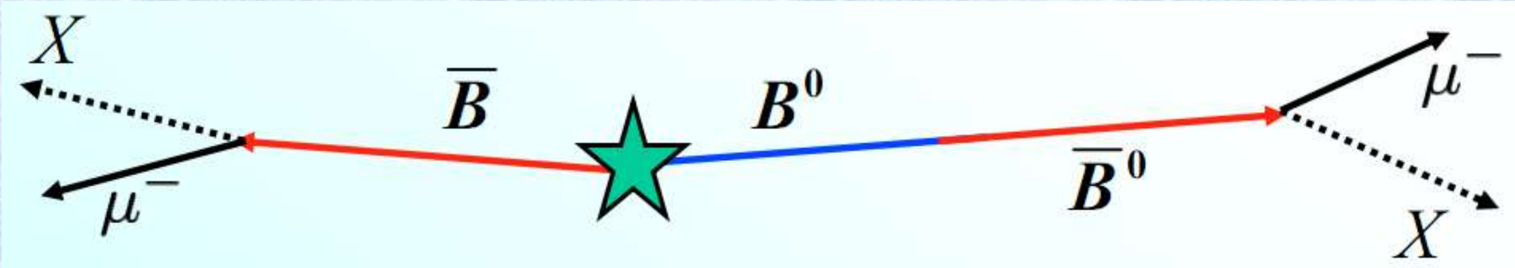
$$\bar{r} \equiv \frac{P(B\to\bar{B})}{P(B\to B)} = \left|\frac{p}{q}\right|^2 \frac{x^2+y^2}{2+x^2-y^2}$$

$$x = \frac{\Delta M}{\Gamma} \qquad y = \frac{\Delta\Gamma}{2\Gamma}$$

$$\Delta M_q = 2|M^q_{12}|$$

$$\Delta\Gamma_q = 2|\Gamma^q_{12}|\cos\phi_q$$

$$\phi_q \equiv \arg\left(-\frac{M^q_{12}}{\Gamma^q_{12}}\right)$$



$$a_{sl}^q = \frac{n(B_q B_q) - n(\bar{B}_q \bar{B}_q)}{n(B_q B_q) + n(\bar{B}_q \bar{B}_q)} = \frac{r - \bar{r}}{r + \bar{r}} = \frac{\left|\frac{q}{p}\right|^2 - \left|\frac{p}{q}\right|^2}{\left|\frac{q}{p}\right|^2 + \left|\frac{p}{q}\right|^2}$$

$$= \frac{\mathrm{Im}\,\frac{\Gamma_{12}^q}{M_{12}^q}}{1 + \frac{1}{4}\left|\frac{\Gamma_{12}^q}{M_{12}^q}\right|^2}$$

$$\simeq \mathrm{Im}\,\frac{\Gamma_{12}^q}{M_{12}^q}$$

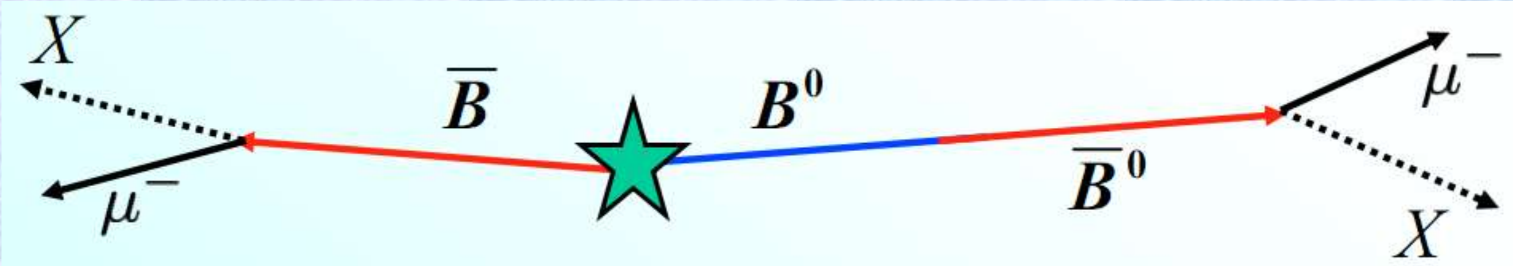
$$= \left|\frac{\Gamma_{12}^q}{M_{12}^q}\right| \sin\phi_q = \frac{\Delta\Gamma_q}{\Delta M_q} \tan\phi_q$$

$$\frac{q}{p} = \sqrt{\frac{M_{12}^* - \frac{i}{2}\Gamma_{12}^*}{M_{12} - \frac{i}{2}\Gamma_{12}}}$$

$$\Delta M_q = 2|M_{12}^q|$$

$$\Delta\Gamma_q = 2|\Gamma_{12}^q| \cos\phi_q$$

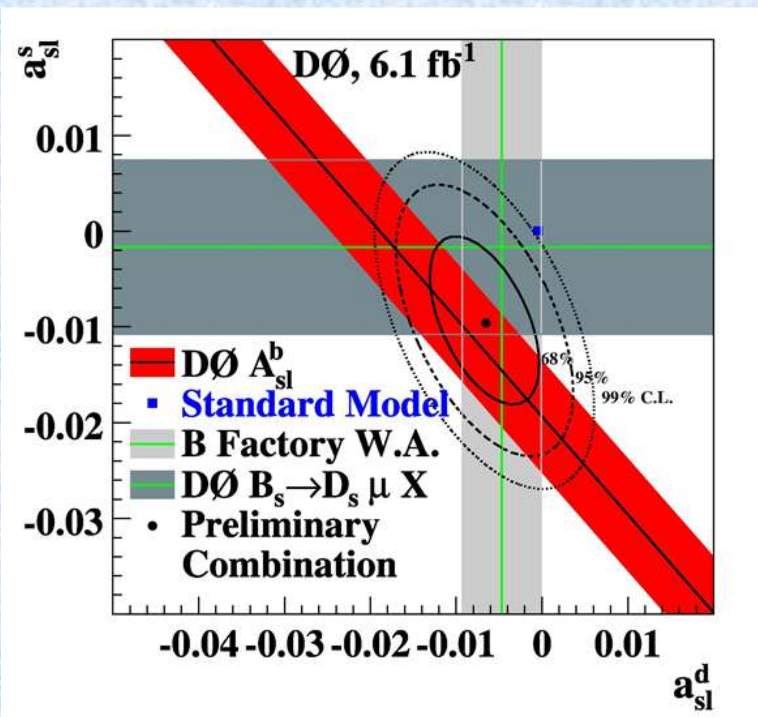
$$\phi_q \equiv \arg\left(-\frac{M_{12}^q}{\Gamma_{12}^q}\right)$$



$$A^b_{sl} = \frac{n(B_dB_d)-n(\bar{B}_d\bar{B}_d)+n(B_sB_s)-n(\bar{B}_s\bar{B}_s)}{n(B_dB_d)+n(\bar{B}_d\bar{B}_d)+n(B_sB_s)+n(\bar{B}_s\bar{B}_s)}$$

$$= (0.506 \pm 0.043)a^d_{sl} + (0.494 \pm 0.043)a^s_{sl}$$

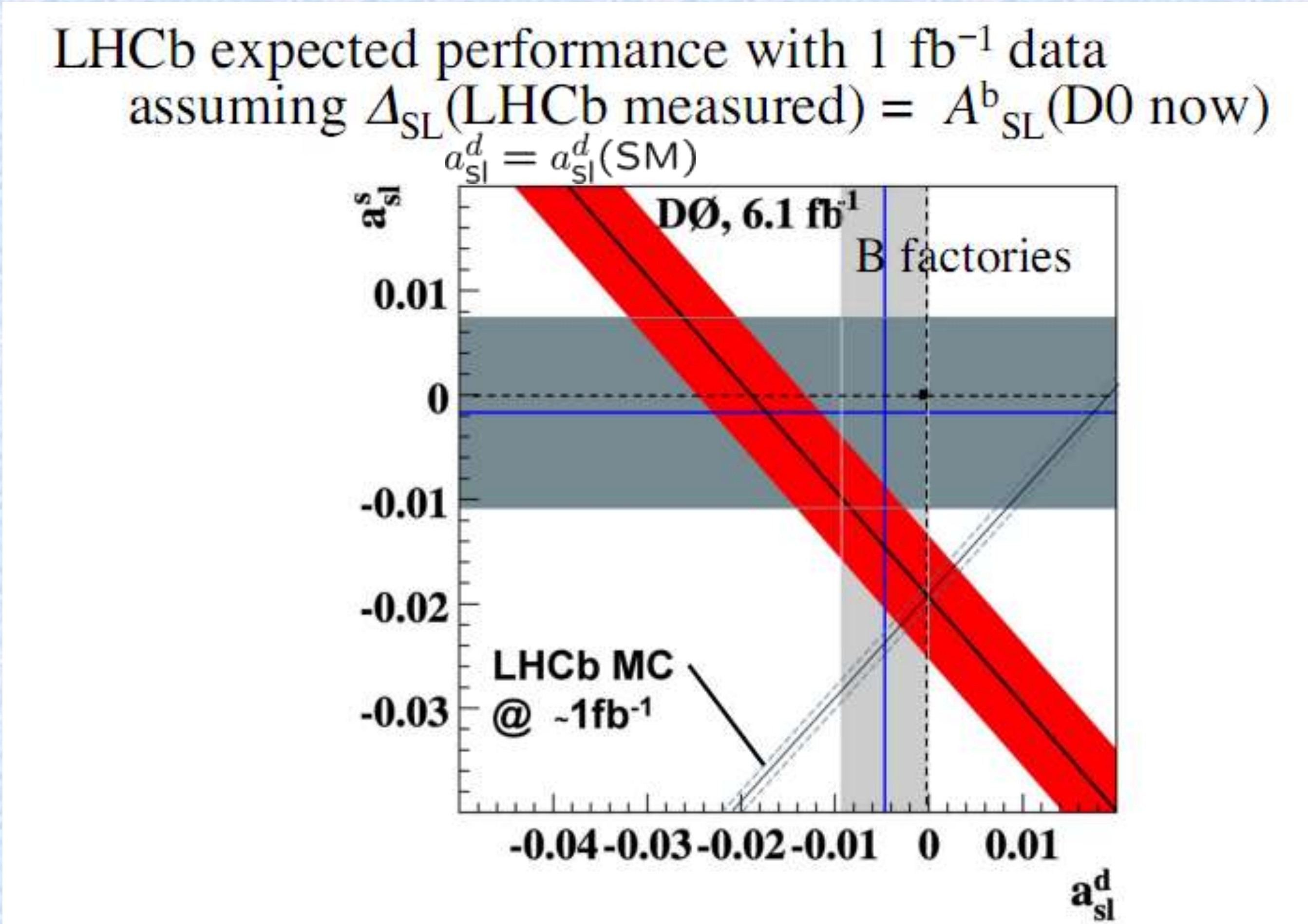
(Tevatron)



$$a^d_{sl}(\mathrm{SM}) = (-4.8^{+1.0}_{-1.2}) \times 10^{-4}$$
$$a^s_{sl}(\mathrm{SM}) = (2.1 \pm 0.6) \times 10^{-5}$$

(Lenz-Nierste)

$$A^b_{sl}(\mathrm{SM}) = (-2.3^{+0.5}_{-0.6}) \times 10^{-4}$$



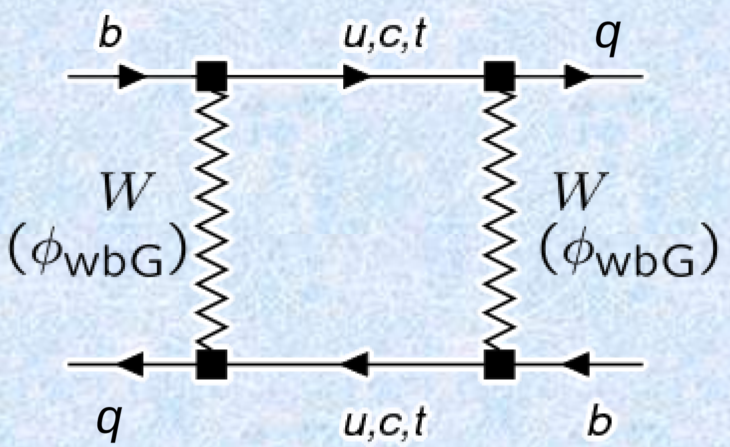
(picked up from T.Nakada's talk at CPV conf. at Tohoku U)

It will be tested very accurately at LHCb.

Why is SM prediction so small?

➡ Because of unitarity of CKM matrix.

Standard model prediction



$$M_{12}^q \propto \sum_{i,j=u,c,t} \lambda_i^q \lambda_j^q E(x_i, x_j)$$

$$M_{12}^q \propto (V_{tb}V_{tq}^*)^2$$

$$\lambda_i^q = V_{ib}V_{iq}^* \qquad x_i = \frac{m_i^2}{M_W^2}$$

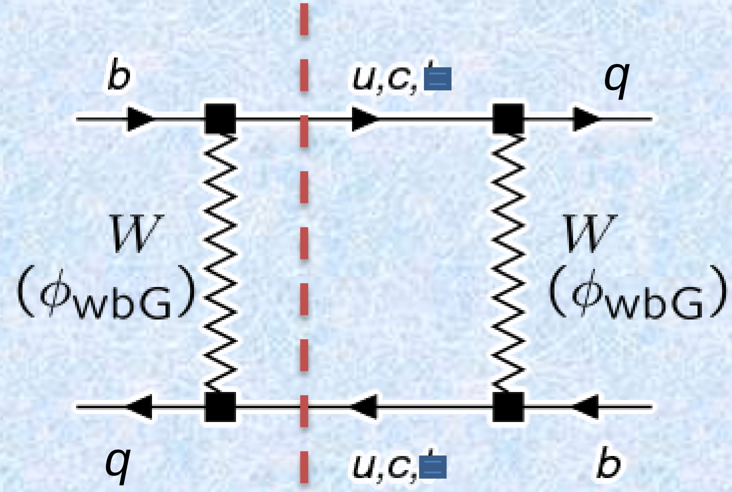
$$\lambda_u^q + \lambda_c^q + \lambda_t^q = 0$$

$$M_{12}^q \propto \sum_{i,j=c,t} \lambda_i^q \lambda_j^q \left(E(x_i, x_j) - E(x_u, x_j) - E(x_i, x_u) + E(x_u, x_u)\right)$$

$$x_i x_j \left(\frac{(4-8x_i+x_i^2)\ln x_i}{4(1-x_i)^2(x_i-x_j)} + \frac{(4-8x_j+x_j^2)\ln x_j}{4(1-x_j)^2(x_j-x_i)} - \frac{3}{4(1-x_i)(1-x_j)} \right)$$

(Inami-Lim function)

Standard model prediction



$$\Gamma_{12}^q \propto \sum_{i,j=u,c} \lambda_i^q \lambda_j^q \gamma_{ij}$$

(Leading order)

$$\Gamma_{12}^q \propto (V_{tb}V_{tq}^*)^2$$

$$\lambda_i^q = V_{ib}V_{iq}^*$$

$$\lambda_u^q + \lambda_c^q + \lambda_t^q = 0$$

$$\Gamma_{12}^q \propto (\lambda_u^q)^2 + 2\lambda_u^q\lambda_c^q + (\lambda_c^q)^2 = (\lambda_u^q + \lambda_c^q)^2$$

up to $O(m_c^2/m_b^2)$

$$\gamma_{uu} \simeq 1,\ \gamma_{uc} \simeq 1 - \frac{4m_c^2}{3m_b^2},\ \text{and}\ \gamma_{cc} \simeq 1 - \frac{8m_c^2}{3m_b^2}$$

1 Unitarity: $\lambda_u^q + \lambda_c^q + \lambda_t^q = 0$

$\Rightarrow$ ϕ_q : small

$$\Delta M_q = 2|M_{12}^q|$$

$$\Delta\Gamma_q = 2|\Gamma_{12}^q|\cos\phi_q$$

$$\phi_q \equiv \arg\left(-\frac{M_{12}^q}{\Gamma_{12}^q}\right)$$

$$a_{sl}^q = \left|\frac{\Gamma_{12}^q}{M_{12}^q}\right|\sin\phi_q$$

2 $$\frac{\Gamma_{12}}{M_{12}} \sim -\frac{3\pi}{2}\frac{m_b^2}{m_t^2}\frac{1}{F_{IL}(x_t)} \times (1 + O(m_c^2/m_b^2))$$

Smallness of the dimuon asymmetry is an important prediction in the standard model (with 3 generations).

Lenz-Nierste's calculations $[O(\alpha_s)$ and $O(\Lambda/m_b)]$

$$\Delta M_q = 2|M_{12}^q|$$

$$\Delta\Gamma_q = 2|\Gamma_{12}^q|\cos\phi_q$$

$$\phi_q \equiv \arg\left(-\frac{M_{12}^q}{\Gamma_{12}^q}\right)$$

$$a_{sl}^q = \left|\frac{\Gamma_{12}^q}{M_{12}^q}\right|\sin\phi_q$$

$$\frac{\Delta\Gamma_d}{\Delta M_d} = (52.6^{+11.5}_{-12.8}) \times 10^{-4}$$

$$\phi_d = -0.091^{+0.026}_{-0.038}$$

$$\frac{\Delta\Gamma_s}{\Delta M_s} = (49.7 \pm 9.4) \times 10^{-4}$$

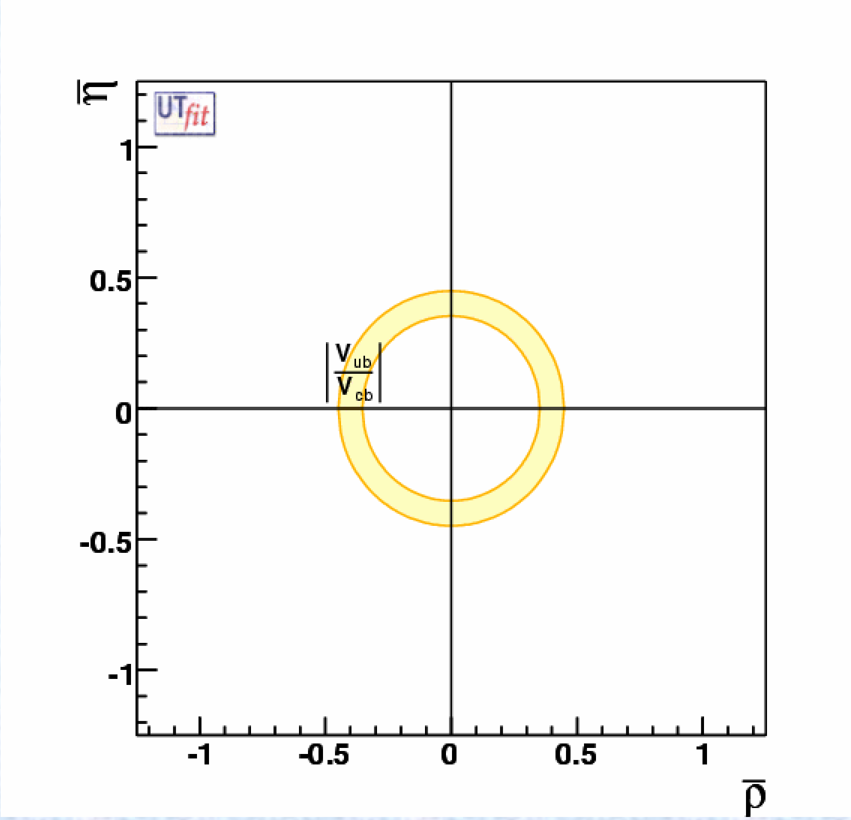
$$\phi_s = 0.0042 \pm 0.0014$$

When new particles propagate in the loop, the phase can be generically large.

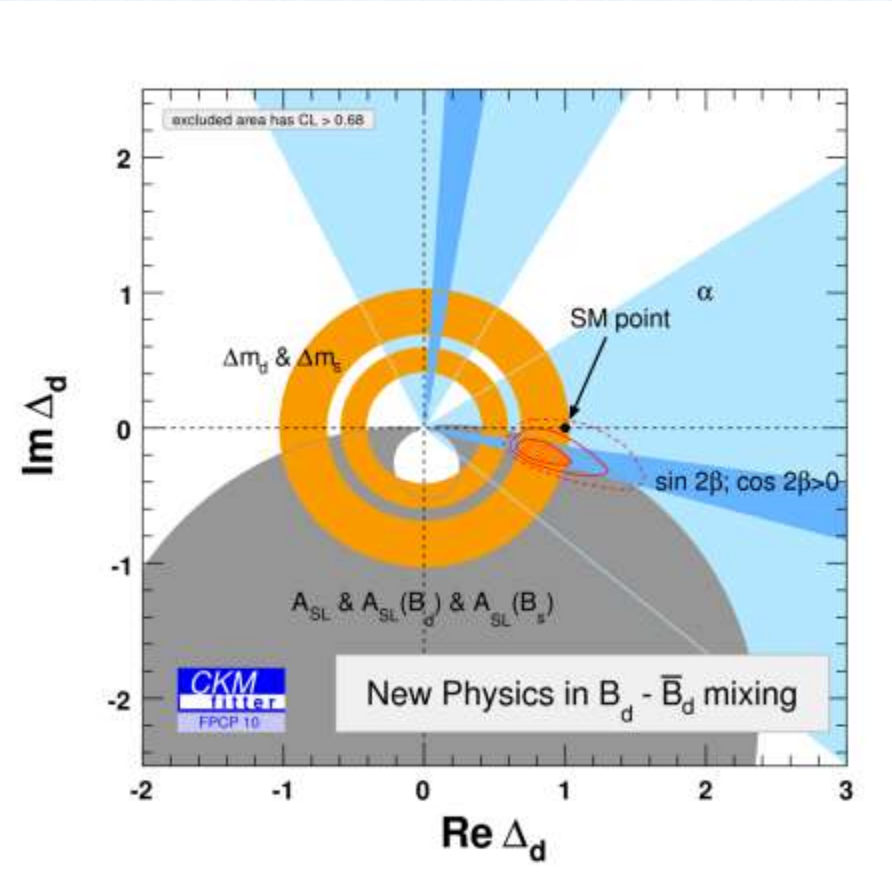
⇨ Important probe of new physics.

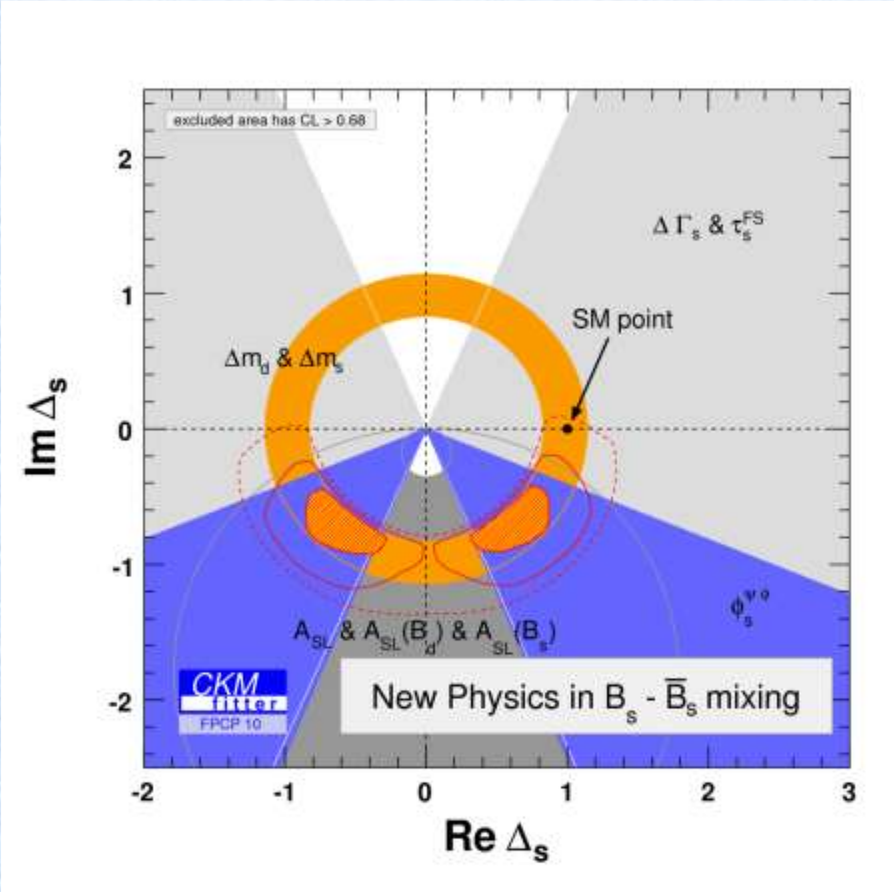
What kinds of new physics are possible?

Unitary triangle $(\lambda_u^d + \lambda_c^d + \lambda_t^d = 0)$ seems to be closed.



There may be no much room for new physics in B_d system.



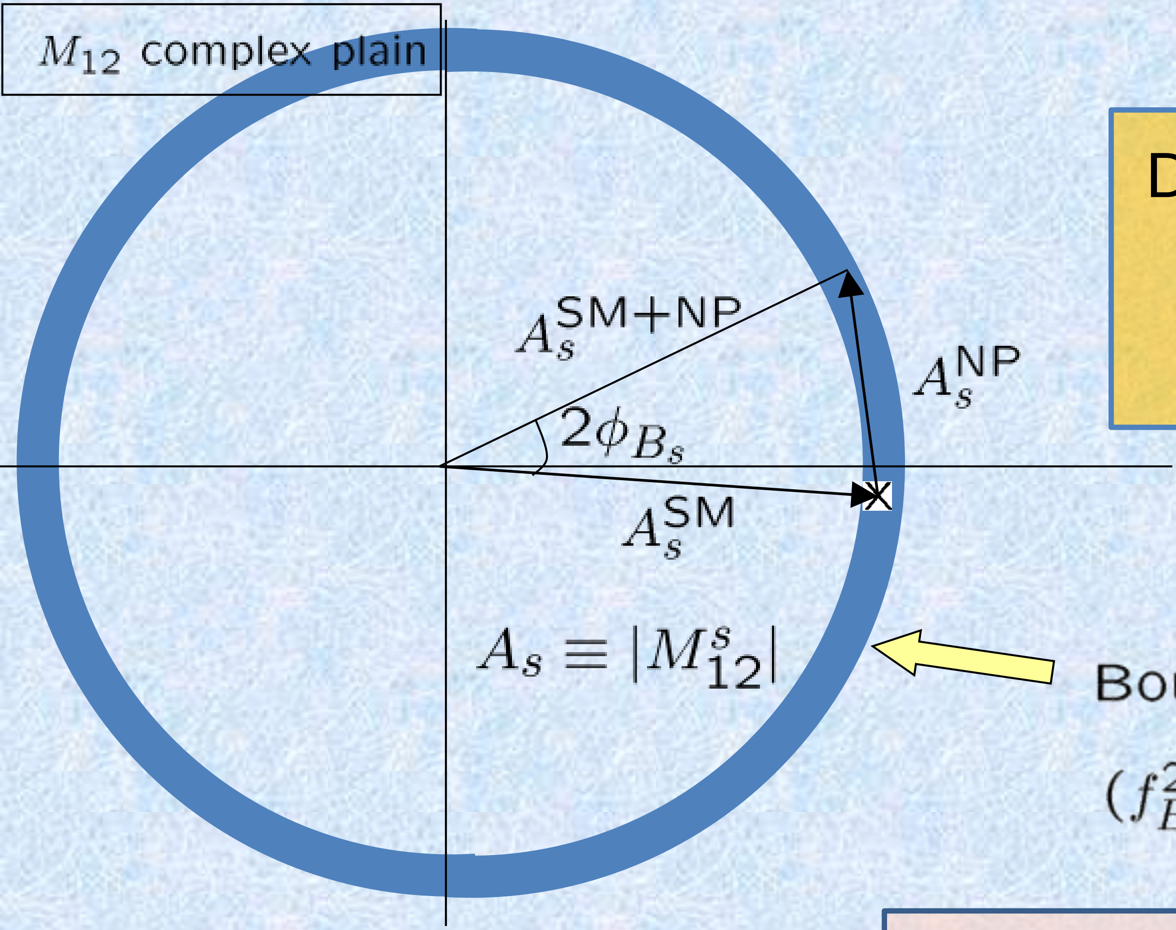


[sin 2β-V_{ub} descrepancy?]

Definition:

$$|\Delta_q| e^{i2\phi_{B_q}} = \frac{M_{12}^{q,\text{full}}}{M_{12}^{q,\text{SM}}}$$

B_s system still has room for new physics due to phase freedom.



Definition:

$$\Delta_s e^{i2\phi_{B_s}} = \frac{M_{12}^{\mathrm{full}}}{M_{12}^{\mathrm{SM}}}$$

Bound from $\Delta M_s = 2|M_{12}^s|$

($f_{B_s}^2 B_{B_s}$ ambiguity)

$$M_{12}^{\mathrm{full}} = M_{12}^{\mathrm{SM}} + M_{12}^{\mathrm{NP}}$$

When $A_s^{\mathrm{SM}} \simeq A_s^{\mathrm{SM+NP}}$,

$$\sin\phi_{B_s} \simeq \frac{1}{2}\frac{A_s^{\mathrm{NP}}}{A_s^{\mathrm{SM}}}$$

$$\Delta M_s^{\rm exp} = (17.77 \pm 0.10 \pm 0.07)\ {\rm ps}^{-1}$$

$$\Delta M_s^{\rm SM} = (19.30 \pm \underline{6.74})\ {\rm ps}^{-1}$$

Now improving!

$\sim 15\%$

$$\Delta_s = \frac{\Delta M_s^{\rm exp}}{\Delta M_s^{\rm SM}} = 0.92 \pm \underline{0.32}$$

(mainly $f_{B_s}^2 B_{B_s}$ ambiguity)

When there is no NP in *Bd* system,

$$\Delta M_s^{\rm SM} = \frac{M_{B_s}}{M_{B_d}} \left|\frac{V_{ts}}{V_{td}}\right|^2 \frac{f_{B_s}^2 B_{B_s}}{f_{B_d}^2 B_{Bd}} \Delta M_d^{\rm exp}$$

$$= (18.3 \pm 1.3)\ {\rm ps}^{-1}$$

$$\Delta_s = \frac{\Delta M_s^{\rm exp}}{\Delta M_s^{\rm SM}} = 0.95 \pm 0.095$$

Is the M_{12} phase modification sufficient to achieve the center value of D0 result?

→ No.

$$a^s_{sl} = \left|\frac{\Gamma_s^{12}}{M_s^{12}}\right| \sin\phi_s = \frac{\Delta\Gamma_s}{\Delta M_s}\tan\phi_s$$

$$(a^s_{sl})^2 + \left(\frac{\Delta\Gamma_s}{\Delta M_s}\right)^2 = \left|\frac{\Gamma_s^{12}}{M_s^{12}}\right|^2 = \frac{1}{\Delta_s^2}\left|\frac{\Gamma_s^{12}}{M_s^{12}}\right|^2_{\mathrm{SM}}$$

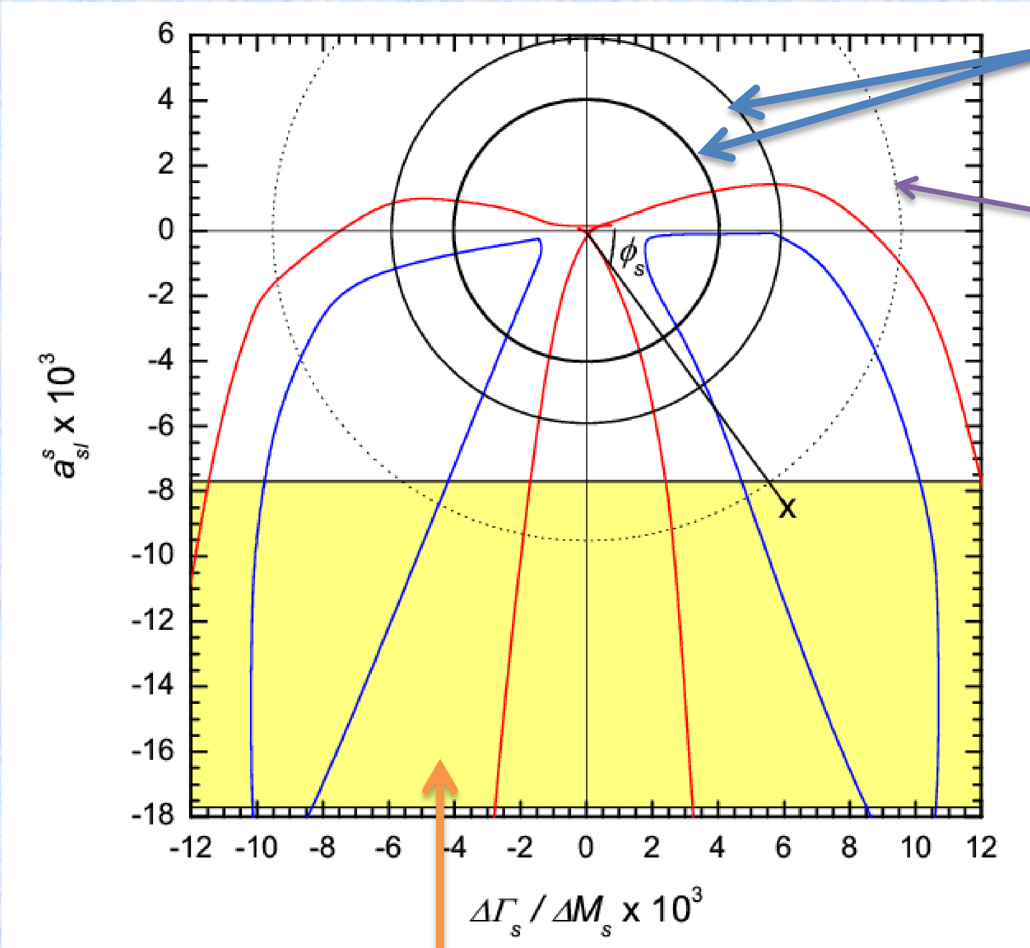
$$\left|\frac{\Gamma^s_{12}}{M^s_{12}}\right|_{\mathrm{SM}} = (4.97 \pm 0.94) \times 10^{-3}$$ (Lenz-Nierste)

$\Gamma_{12} = \Gamma_{12}^{\mathrm{SM}}$ is assumed.

$$(a_{sl}^s)^2 + \left(\frac{\Delta\Gamma_s}{\Delta M_s}\right)^2 = \left|\frac{\Gamma_s^{12}}{M_s^{12}}\right|^2 = \frac{1}{\Delta_s^2}\left|\frac{\Gamma_s^{12}}{M_s^{12}}\right|_{\text{SM}}^2$$

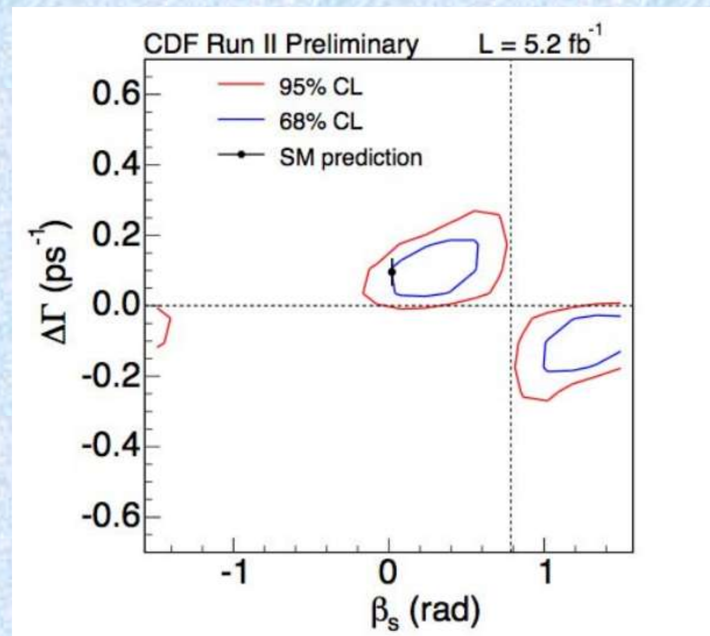
$$\left|\frac{\Gamma_{12}^s}{M_{12}^s}\right|_{\text{SM}} = (4.97 \pm 0.94) \times 10^{-3}$$

$$\Delta_s = 1$$



Conservative region

$$\Delta_s = 0.6$$



$$a_{\text{sl}}^s = (-12.7 \pm 5.0) \times 10^{-3}$$ (Combined data)

assuming $a_{sl}^d = a_{sl}^d(\text{SM})$

M_{12}^s modification

by $\Delta b = 2$ interaction   Loop processes

It is easy to modify its phase in many FCNC models.

CPV in $B_s \to J/\psi\phi$ decay is large.

Γ_{12}^s modification

by $\Delta b = 1$ interaction

Necessary to achieve the center value of D0 result.

But it is not so easy because of experimental constraints.

Long distance QCD contribution?

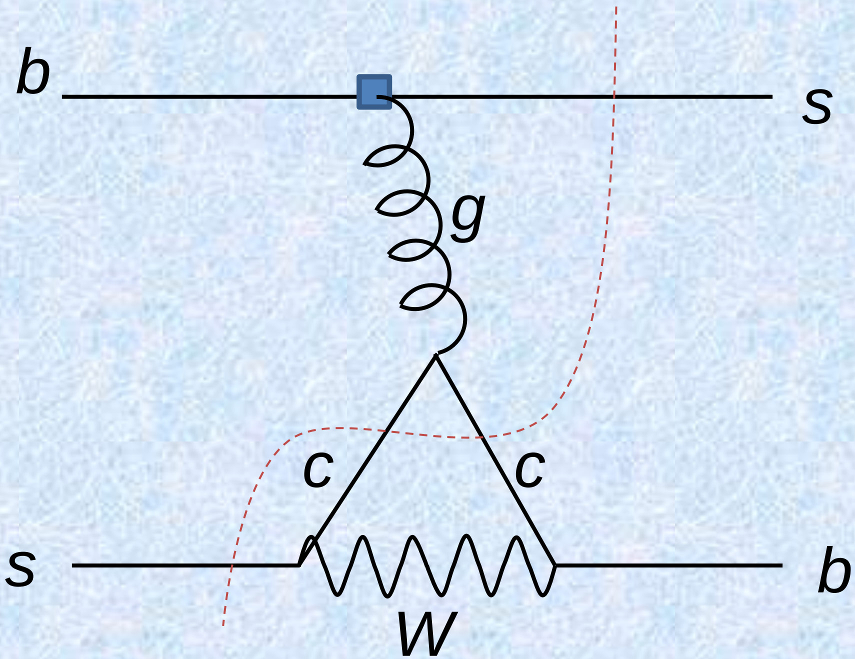
M_{12}^{s} modification

- SUSY
- 4th generation
- TeV scale vector-like family
- multiple Higgs
- horizontal gauge symmetry
- right-handed *W*
- extra U(1)
- axigluon
- warped model
- ……

Γ_{12}^{s} modification

- *R*-parity violating SUSY
- leptoquark
- diquark
- multiple Higgs
- light bosons
- unparticle
- CPT violation
- ……

Modification of Γ_{12} in MSSM?



bs gluon penguin

$$b \to sc\bar{c}$$

However, $b \to ss\bar{s}$, $b \to sd\bar{d}$, $b \to su\bar{u}$ are constrained from $B_d \to \phi K$, πK.

➡ Only O(10) % modification

Allowed $\Delta b = 1$ operators (Bauer-Dunn)

- $(\bar{b}\gamma_\mu s)(\bar{c}\gamma^\mu c)$
- $(\bar{b}\gamma_\mu s)(\bar{\tau}\gamma^\mu \tau)$
- $(\bar{b}\gamma_\mu d)(\bar{u}\gamma^\mu c)$
- $(\bar{b}d)(\bar{u}c)$

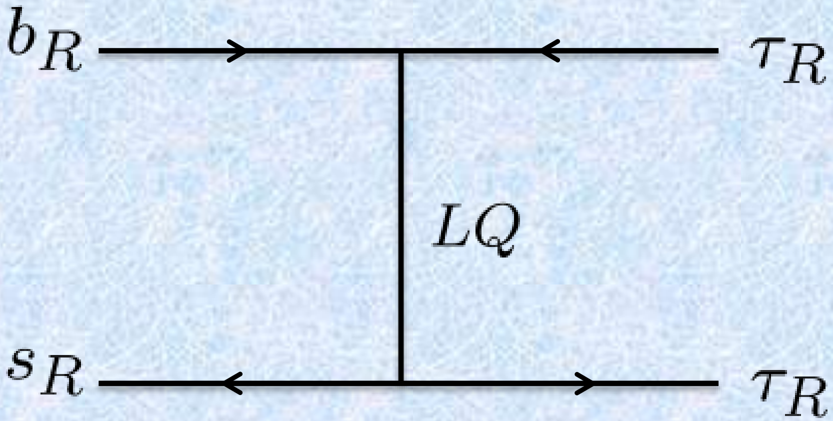
constraints

- $B \to M_1 M_2,\ B \to \ell^+\ell^-$
- $b \to s\gamma$

Ex)

leptoquark

(Dighe-Kundu-Nandi)



In general, it is not easy due to the constraint of lifetime ratio.

Fine-tune is needed. $\tau_{B_s}/\tau_{B_d} = 0.99 \pm 0.03$

(arXiv: 1103.1864)

The scheme in PRD **82**, 055017 (2010)

(Dutta-YM-Santoso)

- Dimuon asymmetry comes from the mixing amplitude M_{12}^{s}
- Modification from Γ_{12} (by Lenz-Nierste) is not considered. (giving up the center value of D0 result).
- We do not touch the modification of B_d mixing.
- We will investigate the constraints to have the large CP phase in SUSY GUT FCNC scenarios.

Basic Scenario of flavor violation in SUSY GUTs

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.

In GUT models,

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

Experimental data for Lepton Flavor Violation (LFV)

$$\mathrm{Br}(\tau \to \mu\gamma) < 4.4 \times 10^{-8}$$ (Babar & Belle)

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

(YM-Dutta, Parry, Hisano-Shimizu, Park-Yamaguchi, Goto et.al. …)

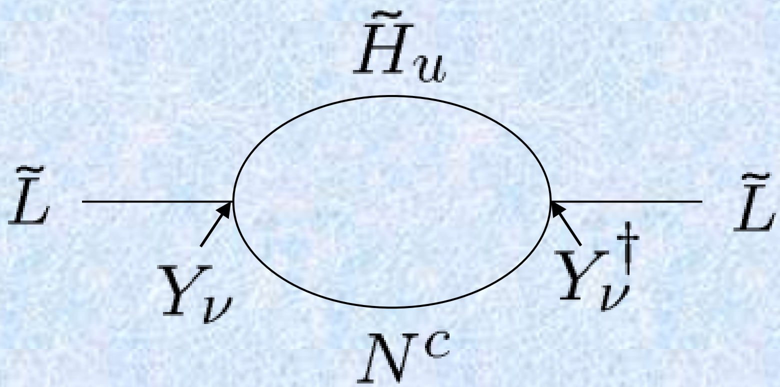
We will study the constraints to obtain the large CP phase and the correlation to the other observables (e.g. $B_s \to \mu\mu$) in SU(5) and SO(10) GUT models.

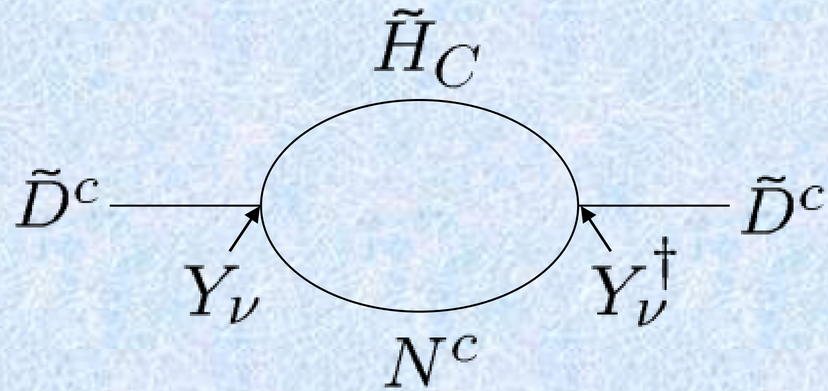
SU(5) GUT

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

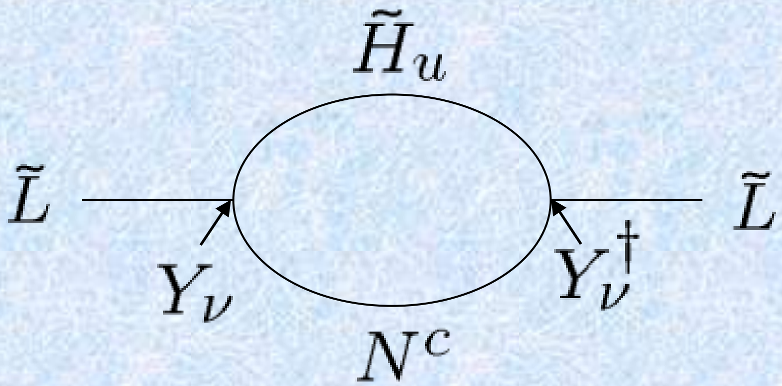
$$W_Y = Y_u\,\mathbf{10}\cdot\mathbf{10}\,H_5 + Y_d\,\mathbf{10}\cdot\bar{\mathbf{5}}\,H_{\bar{5}} + Y_\nu\,\bar{\mathbf{5}}\,N^c\,H_5$$

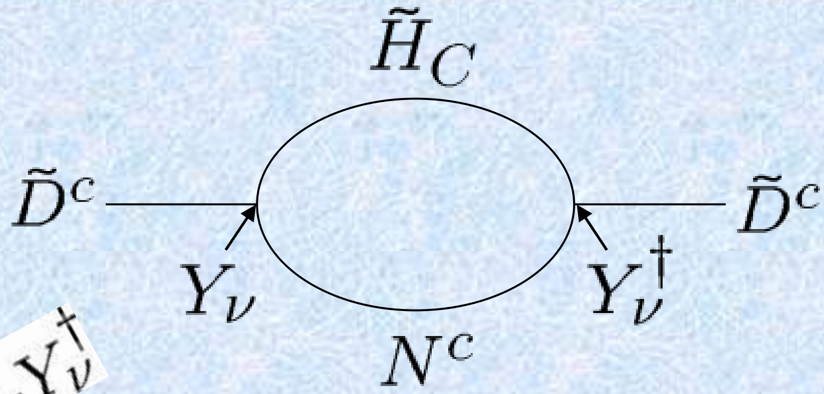




Both RH down-squarks and LH sleptons can have FCNC effects.

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





$\propto Y_\nu Y_\nu^\dagger$

$$m_5^2 \simeq m_0^2 \left(\mathbf{1} - \kappa\, U \begin{pmatrix} k_1 & & \\ & k_2 & \\ & & 1 \end{pmatrix} U^\dagger \right)$$

$$k_1, k_2 \ll 1$$

base

$$Y_e = Y_e^{\mathrm{diag}}$$
$$Y_\nu = U Y_\nu^{\mathrm{diag}} U_R^\dagger$$
$$M_N = M_N^{\mathrm{diag}}$$

U : unitary mixing matrix

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

If $U_R = \mathbf{1}$, U is the PMNS neutrino mixing matrix.

$$m^2_{\tilde{D}} \simeq m^2_{\bar{5}} \simeq m^2_0 \left(\mathbf{1} - \kappa\, U \begin{pmatrix} k_1 & & \\ & k_2 & \\ & & 1 \end{pmatrix} U^\dagger \right)$$

κ : coefficient

U : unitary matrix

$$(m^2_{\bar{5}})_{23} = -\frac{1}{2} m^2_0\, \kappa \sin 2\theta_{23}\, e^{i\alpha}$$

size of A_s^{NP}

Origin of ϕ_s^{NP}

$$A_s = |M_{12}^s|$$

$$\frac{M_{12}^{\mathrm{full}}}{M_{12}^{\mathrm{SM}}} = \frac{A_s^{\mathrm{SM}} e^{-2i\beta_s} + A_s^{\mathrm{NP}} e^{2i(\phi_s^{\mathrm{NP}} - \beta_s)}}{A_s^{\mathrm{SM}} e^{-2i\beta_s}} \equiv \Delta_s e^{2i\phi_{B_s}}$$

Cf.

$$(m^2_{\bar{5}})_{13} = m^2_0 \kappa \left(-\frac{1}{2} k_2 \sin 2\theta_{12} \sin\theta_{23} + e^{i\delta} \sin\theta_{13} \cos\theta_{23}\right) e^{i\beta}$$

$$(m^2_{\bar{5}})_{12} = m^2_0 \kappa \left(-\frac{1}{2} k_2 \sin 2\theta_{12} \cos\theta_{23} - e^{i\delta} \sin\theta_{13} \sin\theta_{23}\right) e^{i(\beta-\alpha)}$$

SO(10) GUT

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

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

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

$$M_\nu^{\text{light}} = M_L - Y_\nu M_R^{-1} Y_\nu^{\mathsf{T}} v_u^2$$

Type II | Type I

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

$SU(2)_L$ triplet

Naively, $U_{L,R} \sim \mathbf{1}$. $\quad (Y_\nu = U_L Y_\nu^{\text{diag}} U_R^\dagger)$

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

However, $f\,\mathbf{16}\cdot\mathbf{16}\,H_{\overline{126}}$ coupling can have a source of large mixings.

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

The relative mixings between *h* and *f* couplings give the large neutrino mixings.

$$h = \begin{pmatrix} c \\ b \\ a \end{pmatrix} \begin{pmatrix} c & b & a \end{pmatrix}, \qquad f = \begin{pmatrix} f_1 & & \\ & f_2 & \\ & & f_3 \end{pmatrix}$$

$$\tan\theta_s = -\frac{c}{b}$$

$$\tan\theta_a = \frac{\sqrt{b^2+c^2}}{a}$$

$$U_0 h U_0^t = \mathrm{diag}(0,0,h_3)$$ (*h*: rank 1)

$$U_0 = \begin{pmatrix} \cos\theta_s & \sin\theta_s & 0 \\ -\cos\theta_a \sin\theta_s & \cos\theta_a \cos\theta_s & -\sin\theta_a \\ -\sin\theta_a \sin\theta_s & \sin\theta_a \cos\theta_s & \cos\theta_a \end{pmatrix}$$

$$U_{\mathrm{MNSP}} = \tilde{V}_e^* U_0 \qquad \tilde{V}_e^* \sim V_{\mathrm{CKM}}$$

Neglecting threshold effects:

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

$$m^2_{16} \simeq m^2_0 \left(\mathbf{1} - \kappa\, U \begin{pmatrix} k_1 & & \\ & k_2 & \\ & & 1 \end{pmatrix} U^\dagger \right)$$

Threshold parameter : $\kappa \simeq \frac{15}{4} \frac{(f^{\mathrm{diag}}_{33})^2}{8\pi^2} \left(3 + \frac{A_0^2}{m_0^2} \right) \ln \frac{M_*}{M_{\mathrm{GUT}}}$

M_*: String/Planck scale

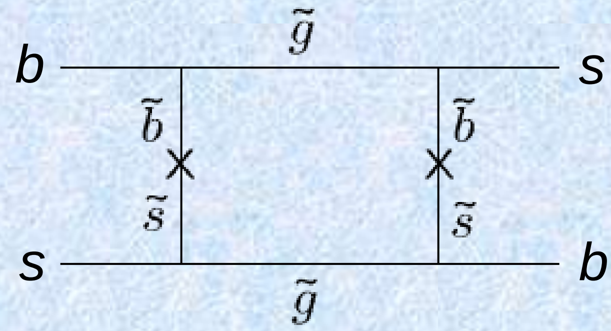
$$f = U f^{\mathrm{diag}} U^{\mathrm{T}}$$

$$k_2 \simeq \frac{\Delta m^2_{\mathrm{sol}}}{\Delta m^2_{\mathrm{atm}}}$$

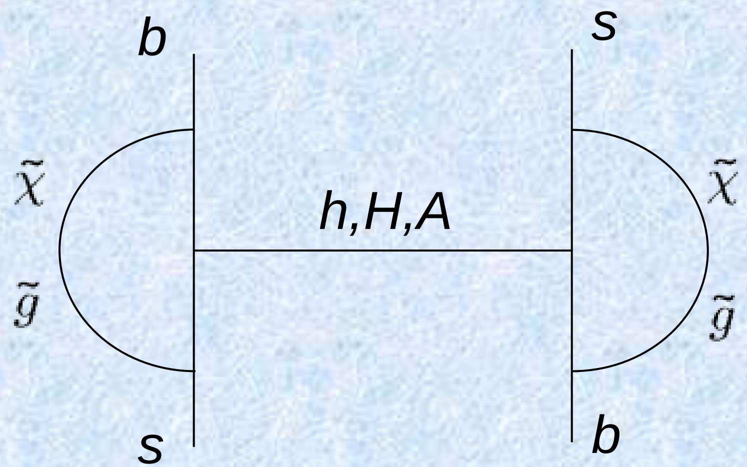
Both left- and right-squarks have sizable FCNC effects!

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

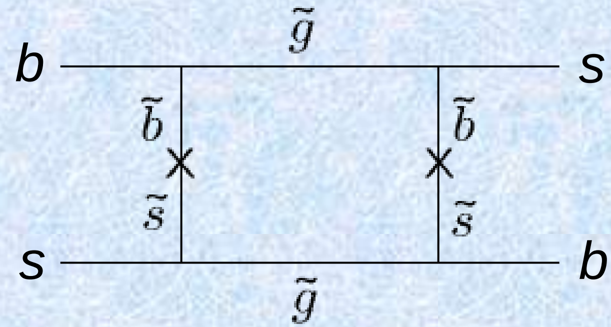
- Gluino box contribution.



- Double Higgs penguin contribution.



◆Gluino box contribution.



Mass insertion approximation:

$$\frac{M_{12}^{\mathrm{SUSY}}}{M_{12}^{\mathrm{SM}}} \simeq a[(\delta^d_{LL})^2_{32}+(\delta^d_{RR})^2_{32}]-b(\delta^d_{LL})_{32}(\delta^d_{RR})_{32} + \cdots$$

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

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

$$(\tilde{d}_L, \tilde{d}_R)\begin{pmatrix} (M^2_{\tilde{d}})_{LL} & (M^2_{\tilde{d}})_{LR} \\ (M^2_{\tilde{d}})_{RL} & (M^2_{\tilde{d}})_{RR} \end{pmatrix}\begin{pmatrix} \tilde{d}_L^\dagger \\ \tilde{d}_R^\dagger \end{pmatrix} \qquad \begin{aligned} (M^2_{\tilde{d}})_{LL} &= m^2_{\tilde{Q}} + \cdots \\ (M^2_{\tilde{d}})_{RR} &= (m^2_{\tilde{D}^c})^{\mathrm{T}} + \cdots \end{aligned}$$

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

$$\frac{M_{12}^{\mathrm{SUSY}}}{M_{12}^{\mathrm{SM}}} \simeq a[(\delta^d_{LL})^2_{32}+(\delta^d_{RR})^2_{32}]-b(\delta^d_{LL})_{32}(\delta^d_{RR})_{32}+\cdots$$

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

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

Cf. Only δ^d_{RR} is large in SU(5).

- SU(5) GUT with type I seesaw (FCNC source = Y_ν)

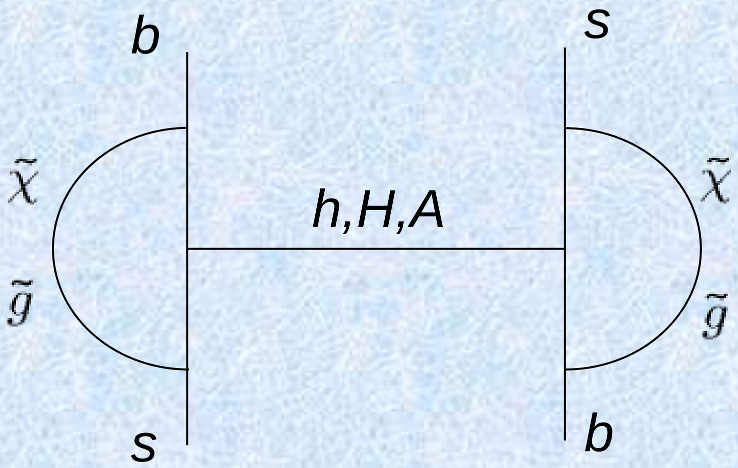
Only δ^d_{RR} is large in SU(5).

- SO(10) GUT with type II seesaw (triplet term dominant) (FCNC source = $\mathbf{16}\ \mathbf{16}\ \overline{\mathbf{126}}$ coupling)

Both δ^d_{LL} and δ^d_{RR} is large in SO(10).

"SO(10) > SU(5)" for box contribution

Double penguin contribution. (Hamzaoui-Pospelov-Toharia, Buras et.al., Bobeth et.al. ,…)



$$\propto \tan^4 \beta$$

FCNC Higgs-Penguin operator comes from finite mass correction.

$$\mathcal{L}^{\text{eff}} = Y_d Q D^c H_d + \epsilon\, Q D^c H_u^*$$

$$\mathcal{L}^{\text{FCNC}} = \epsilon Q D^c H_u^* - (\epsilon \tan\beta) Q D^c H_d$$

(in the basis where the eff. mass is diag.)

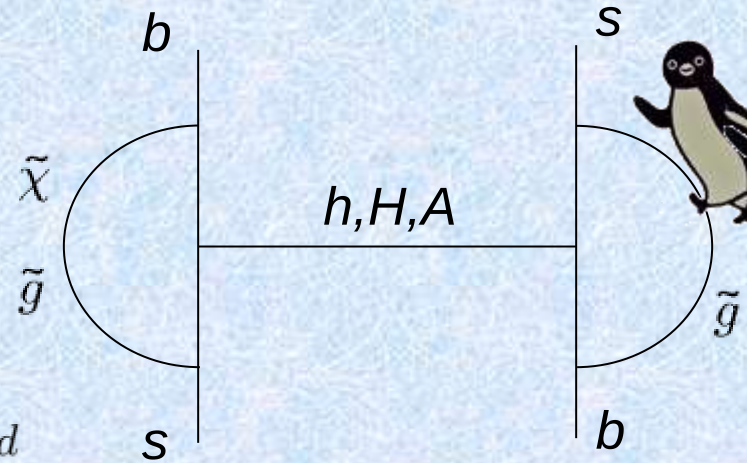
$$(\delta_{LL})_{32}(\delta_{LL})_{32}\left(\frac{\sin^2(\alpha-\beta)}{m_H^2} + \frac{\cos^2(\alpha-\beta)}{m_h^2} - \frac{1}{m_A^2}\right) \to 0$$

$$(m_A > M_Z, \tan\beta \gg 1)$$

$$(\delta_{LL})_{32}(\delta_{RR})_{32}\left(\frac{\sin^2(\alpha-\beta)}{m_H^2} + \frac{\cos^2(\alpha-\beta)}{m_h^2} + \frac{1}{m_A^2}\right)$$

Dominant contribution

◆Double penguin contribution



$$\mathcal{L}^{\rm eff} = Y_d Q D^c H_d + \epsilon\, Q D^c H_u^*$$

$$\mathcal{L}^{\rm FCNC} = \epsilon Q D^c H_u^* - (\epsilon \tan\beta) Q D^c H_d$$

$$\propto \epsilon_{32}\epsilon_{23}$$

"Left-handed" penguin $\epsilon_{23} s_L b_R^c H^0$

$$\epsilon_{23} \propto O(V_{ts})(\text{chargino}) + \delta^{\tilde{d}}_{LL,23}(\text{gluino})$$

"Right-handed" penguin $\epsilon_{32} b_L s_R^c H^0$

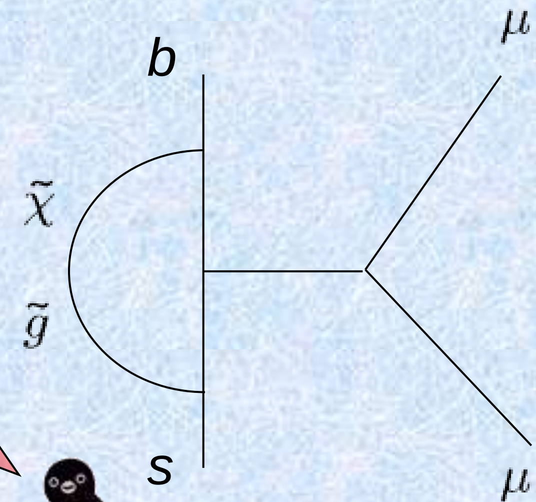
$$\epsilon_{32} \propto \qquad\qquad + \delta^{\tilde{d}}_{RR,23}(\text{gluino})$$

"SO(10) ~ SU(5)" for double penguin contribution

$$\mathrm{Br}(\tau \to \mu\gamma) \quad \propto \tan^2\beta$$

$$A_s^{\mathrm{NP}}(\text{double penguin}) \propto \tan^4\beta/m_A^2$$

For large $\tan\beta$ and small m_A,
the large CP phase is possible.



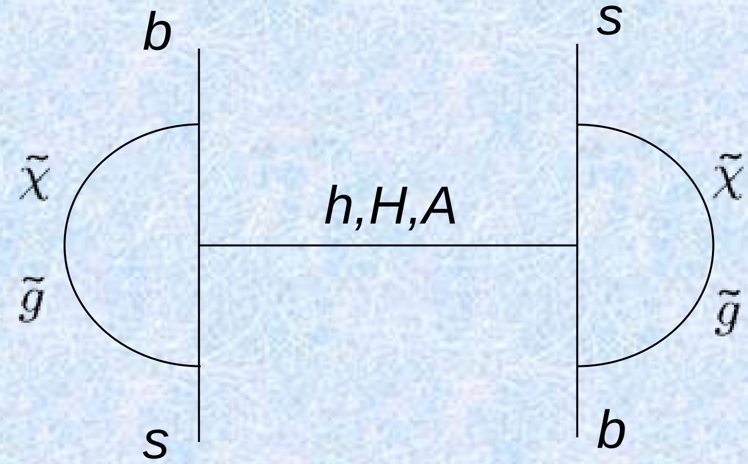
However,

$$\mathrm{Br}(B_s \to \mu\mu) \propto \tan^6\beta/m_A^4$$

$\mathrm{Br}(\tau \to 3\mu)$, too.

$$\mathcal{L}^{\text{eff}} = Y_d Q D^c H_d + \epsilon Q D^c H_u^*$$

$$\mathcal{L}^{\text{FCNC}} = \epsilon Q D^c H_u^* - (\epsilon \tan\beta) Q D^c H_d$$



"Left-handed" penguin $\epsilon_{23} s_L b_R^c H^0$

$$\epsilon_{23} \propto O(V_{ts})(\text{chargino}) + \delta^{\tilde{d}}_{LL,23}(\text{gluino})$$

SO(10) b.c. can provide an additional contribution to the amplitude.

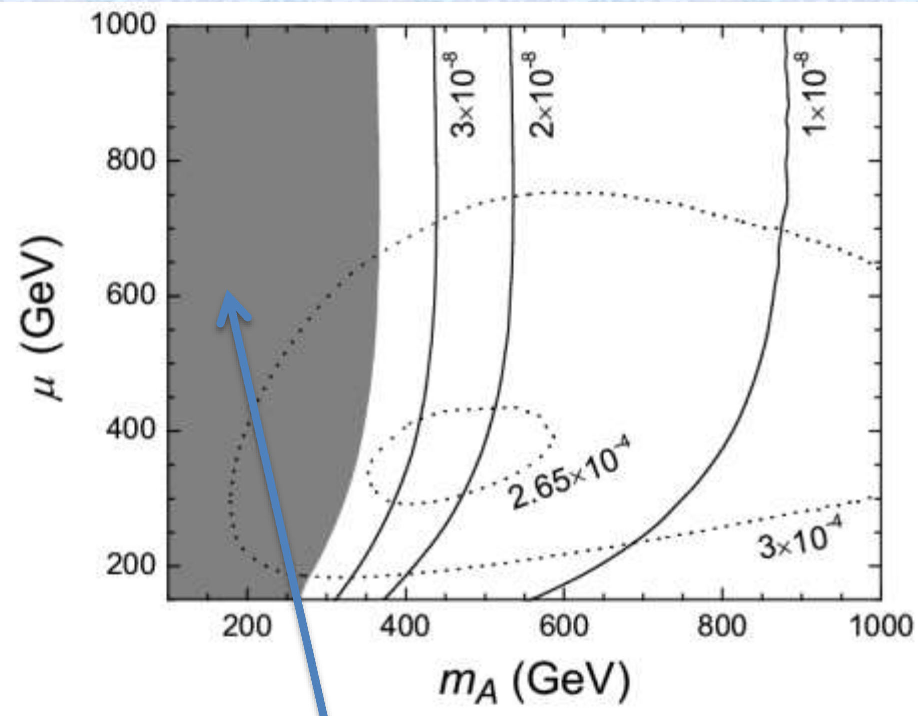
$$C_{7L}^{b\to s\gamma} \propto O(V_{ts})(\text{chargino}) - \delta^{\tilde{d}}_{LL,23}(\text{gluino})$$

When the B_s mixing amplitude is constructive,
SUSY contribution of $b \to s\gamma$ is destructive.

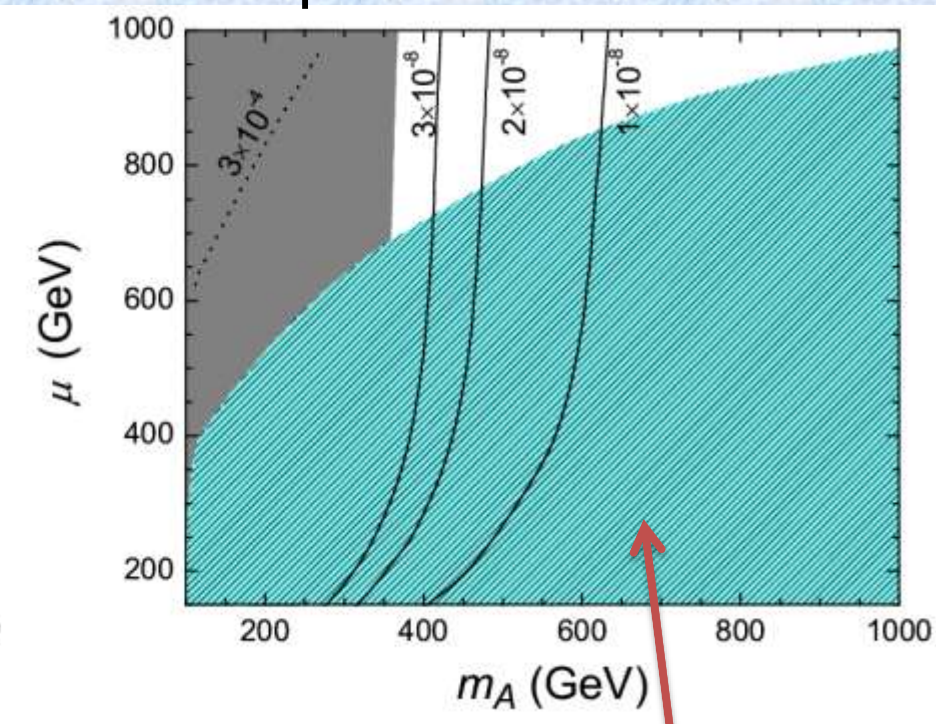
(Buras-Chankowski-Rosiek-Slawianowska)

$A^{\mathrm{NP}}/A^{\mathrm{SM}} = 0.5$

Bs amplitude is constructive.



Bs amplitude is destructive.



excluded by $B_s \to \mu\mu$

excluded by $b \to s\gamma$

Note:

The phases of $\delta^{\tilde{d}}_{LL,23}$ and $\delta^{\tilde{d}}_{RR,23}$ are independent due to a phase from the down-type quark Yukawa coupling.

The phase of M_{12}(doublePenguin) is still free.

Suppression of $\tau \to \mu\gamma$

$$M^2_{\tilde{D}^c} \sim \begin{pmatrix} (1\text{TeV})^2 + m_0^2 & & \\ & (1\text{TeV})^2 + m_0^2 & \kappa m_0^2 \\ & \kappa m_0^2 & (1\text{TeV})^2 + m_0^2 \end{pmatrix}$$

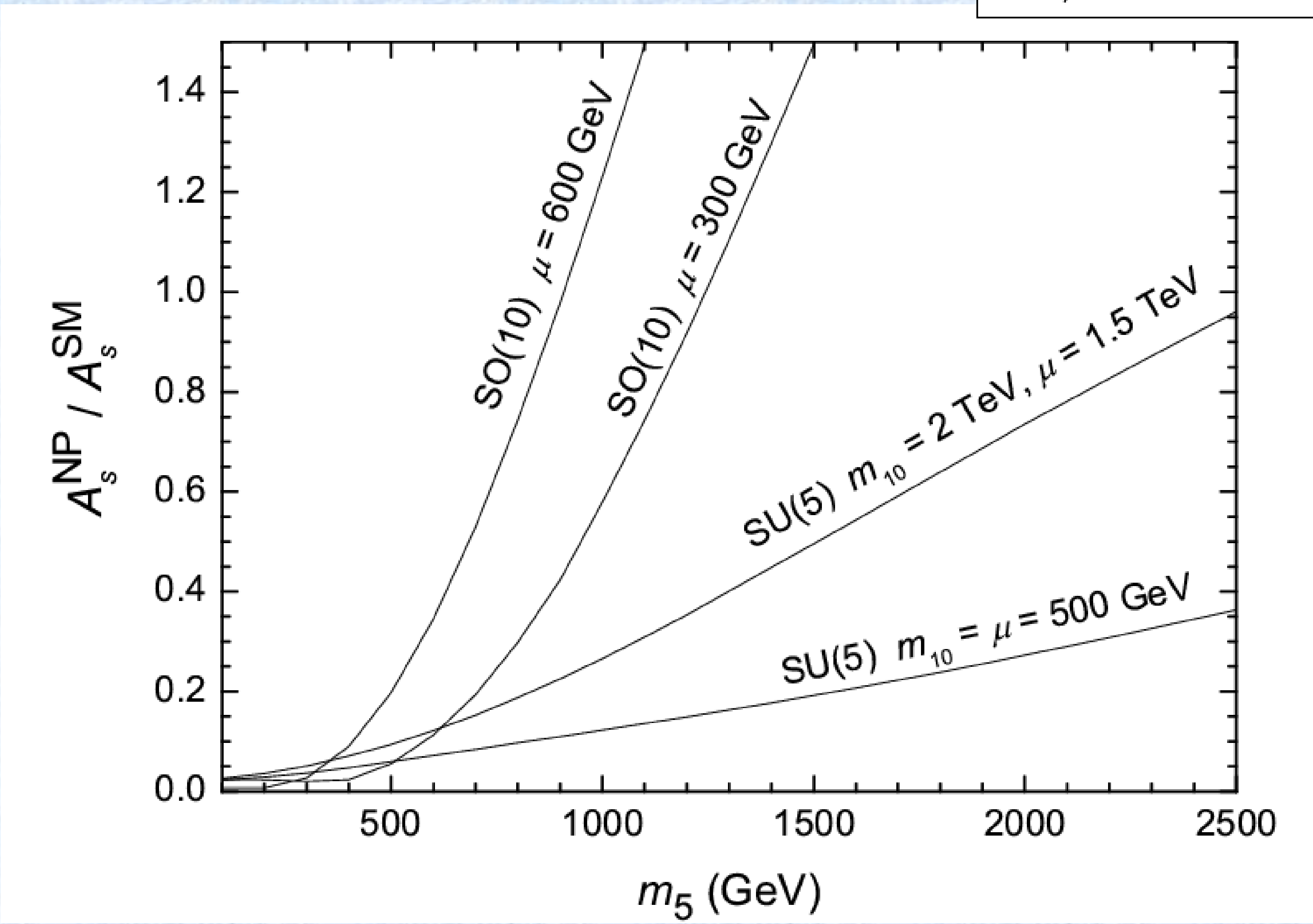
$$M^2_{\tilde{L}} \sim \begin{pmatrix} (0.2\text{TeV})^2 + m_0^2 & & \\ & (0.2\text{TeV})^2 + m_0^2 & \kappa m_0^2 \\ & \kappa m_0^2 & (0.2\text{TeV})^2 + m_0^2 \end{pmatrix}$$

Diagonal elements are enlarged by gaugino loops.

⬇

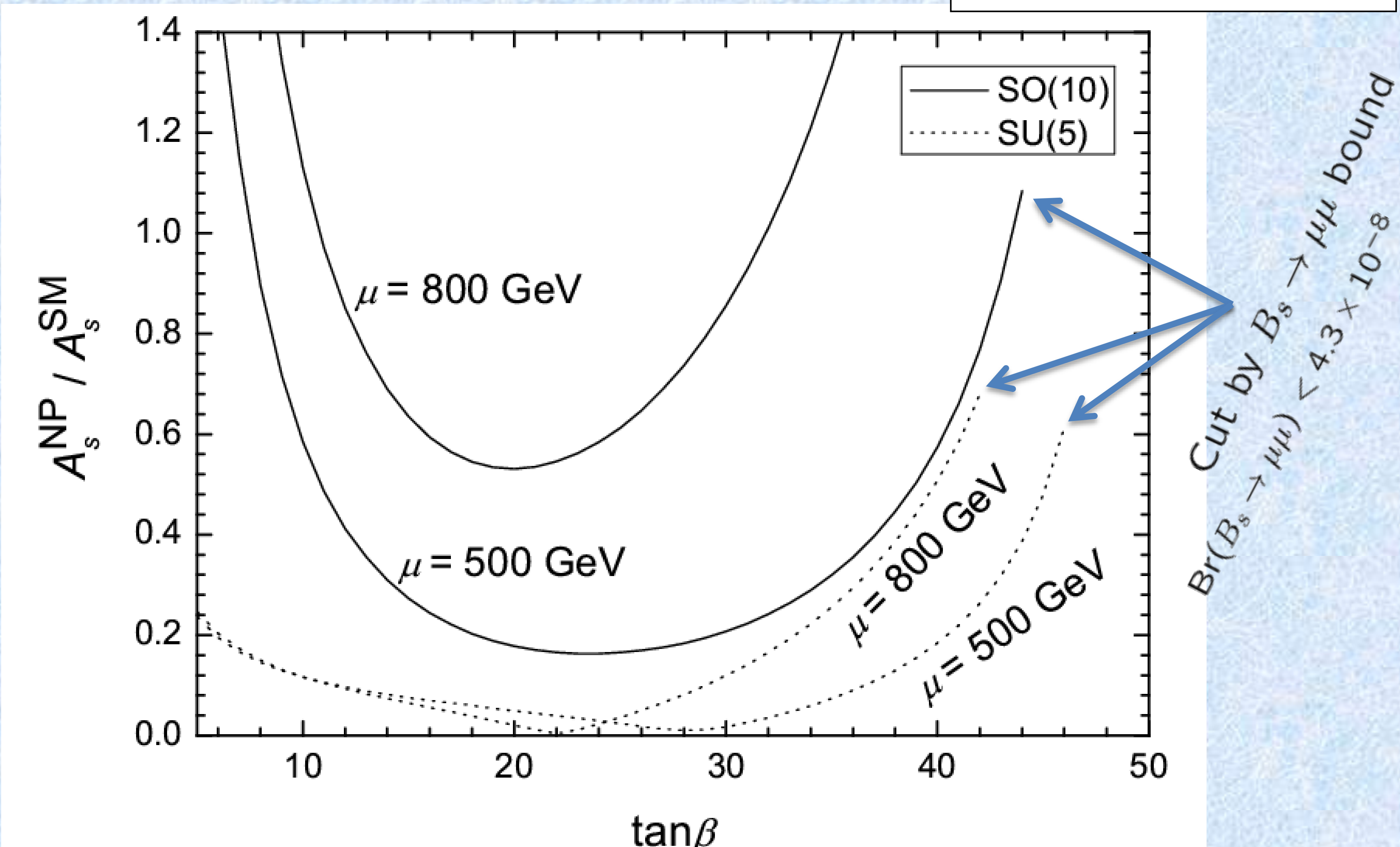
Large m_0 affects to $\tau \to \mu\gamma$ suppression more effectively rather than A_s^{NP} suppression.

$\mathrm{Br}(\tau \to \mu\gamma) < 4.4 \times 10^{-8}$
$\tan\beta = 10$
$m_{1/2} = 300$ GeV



$Br(\tau \to \mu\gamma) < 4.4 \times 10^{-8}$
$m_0 = 800$ GeV
$m_{1/2} = 300$ GeV

$A_s = |M_{12}^s|$



For a given large CP phase,
Br($B_s \to \mu\mu$) needs to be large in SU(5).

Larger m_A for a given CP phase $\longrightarrow$ Larger κ is needed. $\longrightarrow$ Excluded by $\tau \to \mu\gamma$
(Br($B_s \to \mu\mu$) is smaller)

m_0, $m_{1/2}$	Minimal value of Br($B_s \to \mu\mu$)
$m_0 = m_{1/2} = 500$ GeV	1.8×10^{-8}
$m_0 = m_{1/2} = 1$ TeV	1.3×10^{-8}
$m_0 = 500$ GeV, $m_{1/2} = 1$ TeV	2.8×10^{-8}

In SU(5) GUT model where quark-lepton unif. is manifested, it is expected that $B_s \to \mu\mu$ is observed soon.

$\tan\beta = 40$
$\mu < 1$ TeV
$2\phi_{B_s} \simeq 0.5$ (rad)
Br($\tau \to \mu\gamma$) $< 4.4 \times 10^{-8}$

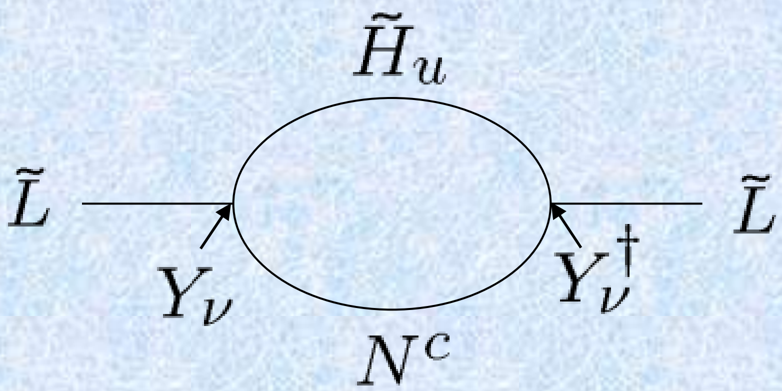
Possible violation of the quark-lepton unification

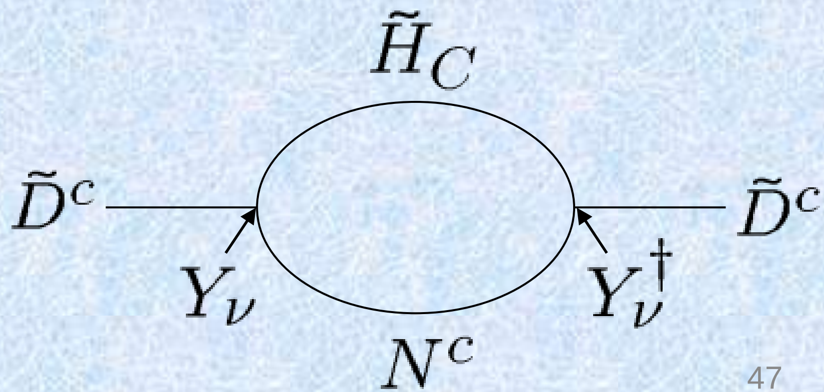
To relax the constraint, one needs $\kappa_{\text{quark}} > \kappa_{\text{lepton}}$.

In SU(5) model in which neutrino Dirac Yukawa coupling is the origin of the flavor violation,

$$\kappa_q \propto \ln \frac{M_*}{M_{H_C}}, \qquad \kappa_\ell \propto \ln \frac{M_*}{M_N},$$

and thus, $\kappa_q < \kappa_\ell$.





In SO(10) model, it depends on the SO(10) breaking vacua.

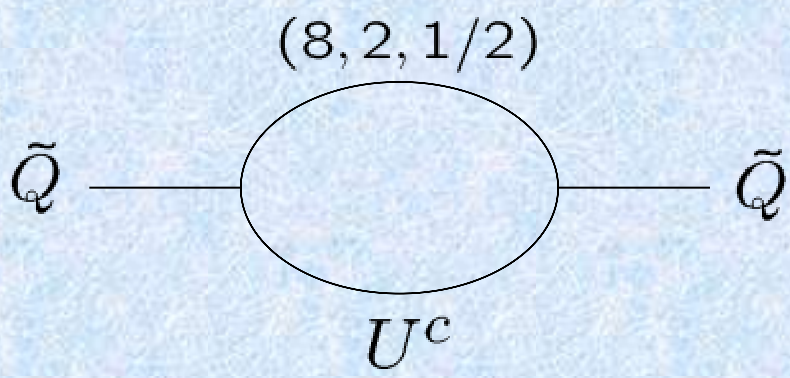
If $SU(2)_R$ remains below the SO(10) breaking scale, $SU(2)_R$ Higgsino induces κ_ℓ rather than κ_q. Wrong direction!

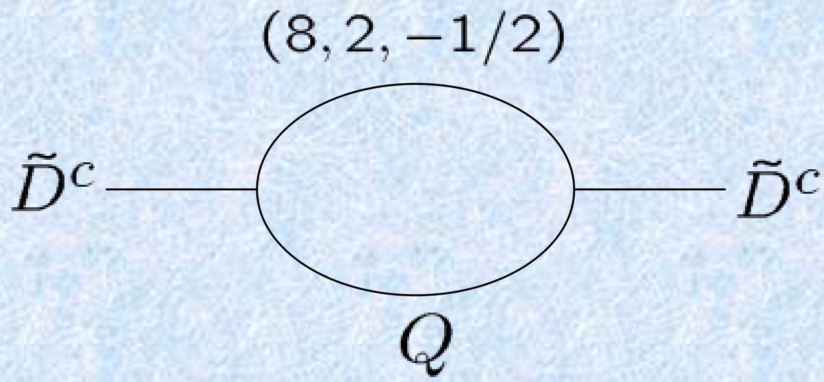
If (**8**,**2**,1/2) (in **126** Higgs) is light, it generates only κ_q.

Right direction!

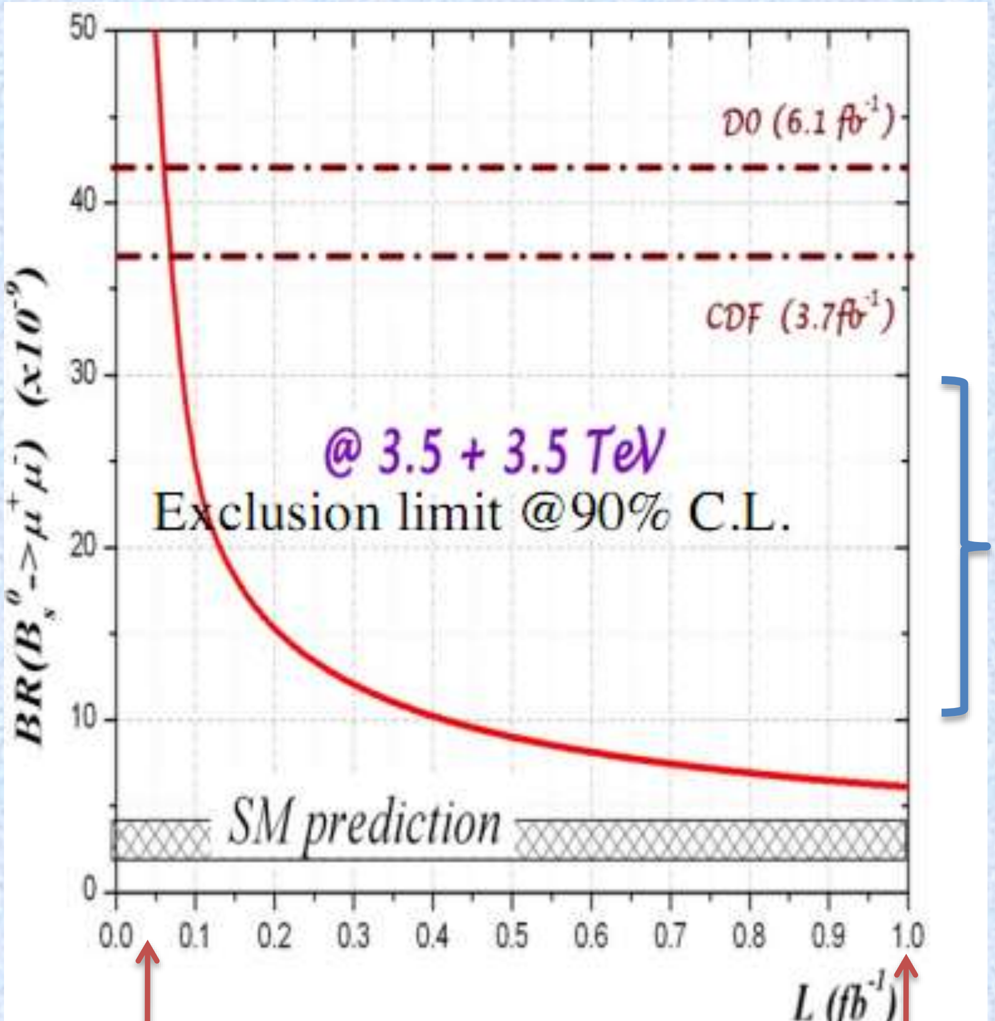
Light (**8**,**2**,1/2) is also proper direction to suppress proton decay.

(Dutta-YM-Mohapatra)





$B_s \to \mu^+\mu^-$ at LHCb

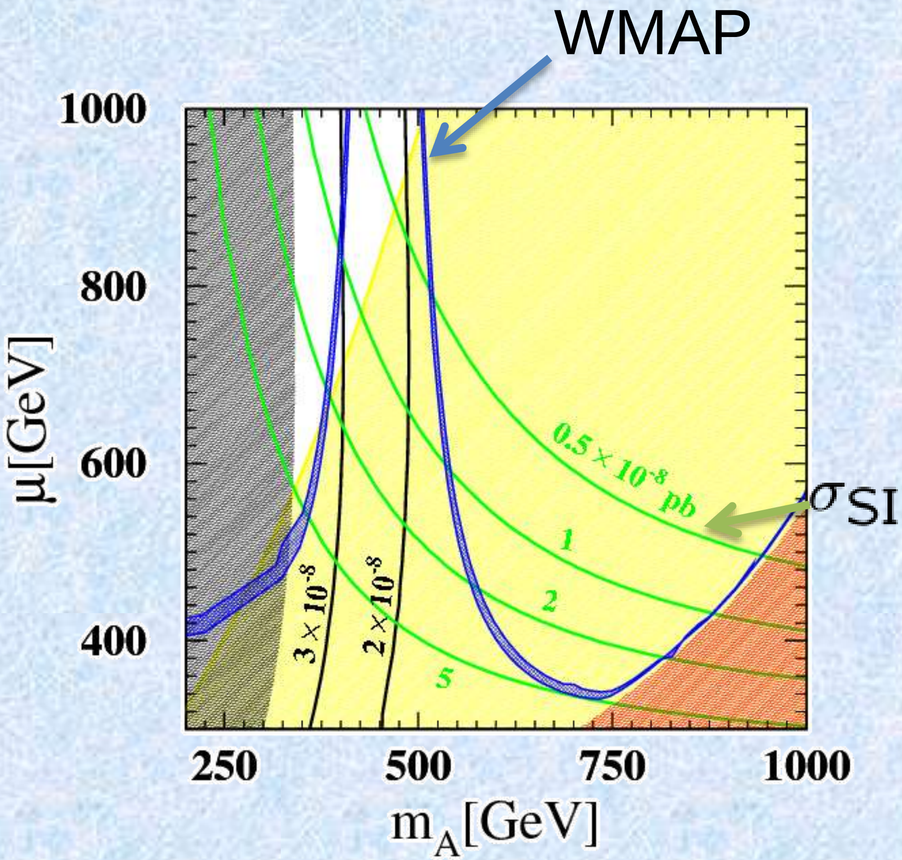


SU(5) prediction

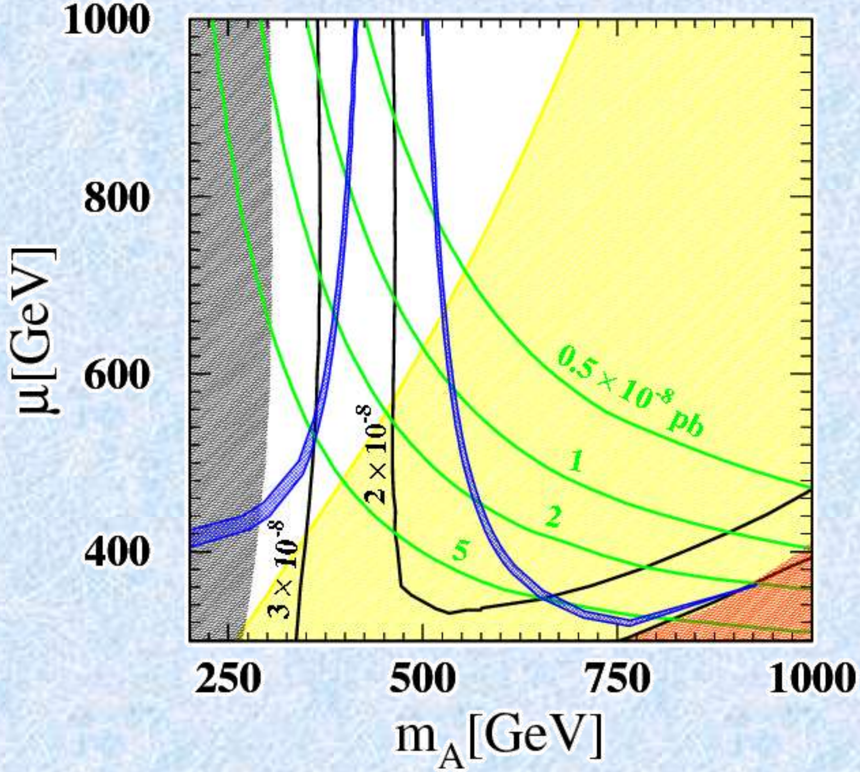
Now

2011 June?

$2\phi_{B_s} \simeq 0.5$ (rad)



$\tan\beta = 40$ $m_{1/2} = 500$ GeV $m_0 = 500$ GeV



$\tan\beta = 40$ $m_{1/2} = 500$ GeV $m_0 = 1$ TeV

A-funnel solution for neutralino dark matter relic density is preferred.

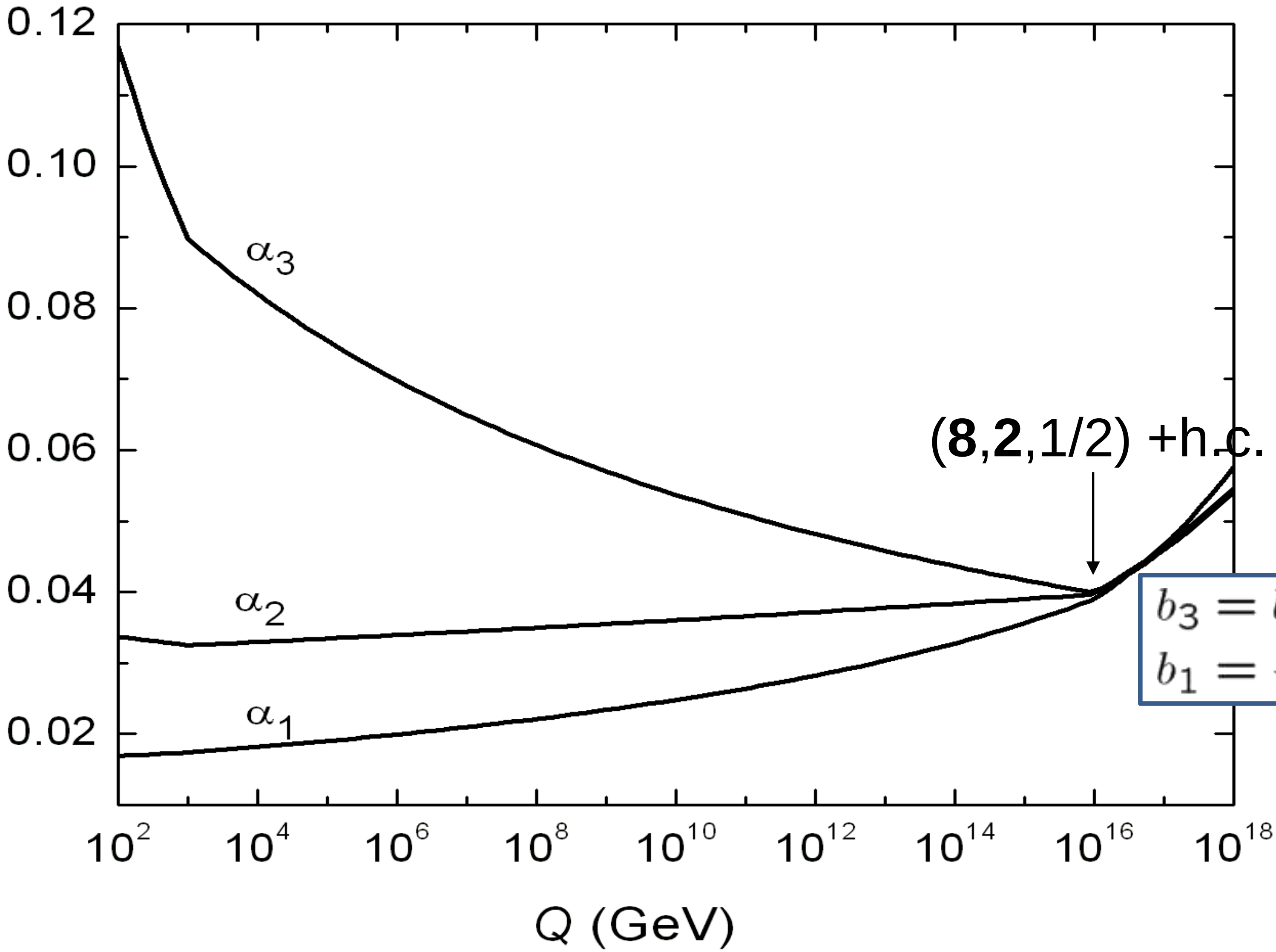
$m_A \sim 2m_{\tilde{\chi}_1^0}$

Summary

- The dimuon asymmetry is a good probe of NP.
- Dispersive part of the mixing amplitude can be easily modified in NP, but absorptive part is not easy.
- We study the CP phase in the mixing amplitude in SUSY GUT models.
- The phase is more enhanced in SO(10) rather than in SU(5).
- Especially in SU(5), $\mathrm{Br}(B_s \to \mu\mu)$ is expected to be large in order to allow a large phase.

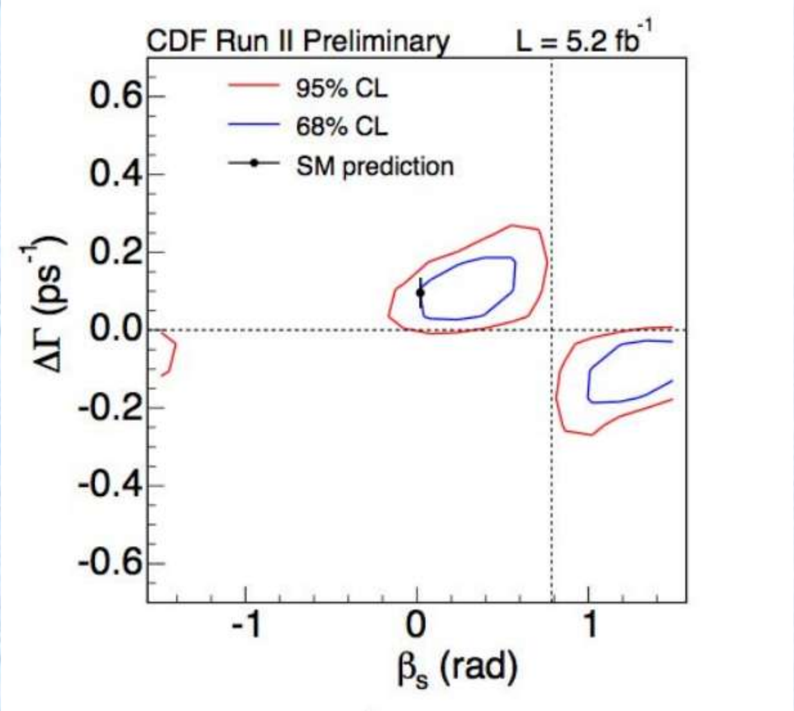
Back up Slides

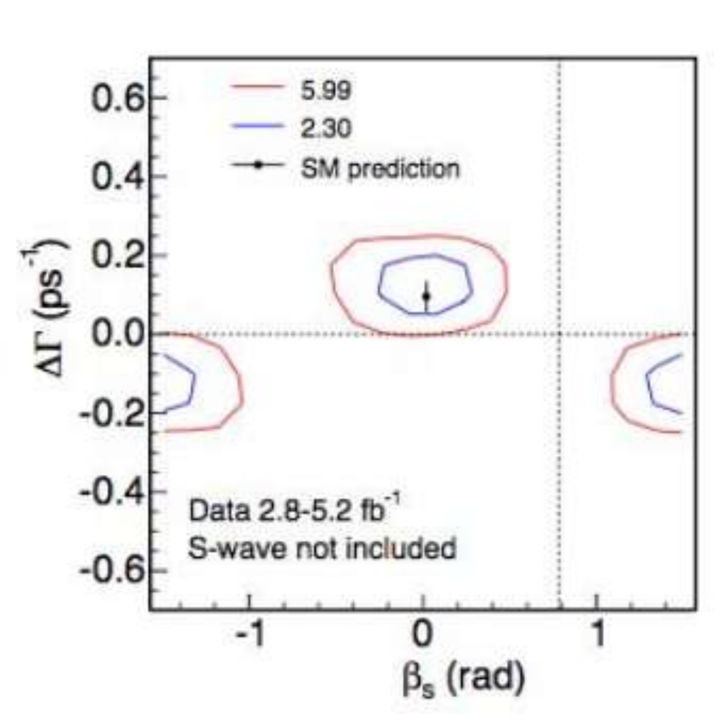
MSSM+(**8**,**2**,1/2) threshold



$b_3 = b_2 = 9,$
$b_1 = \frac{57}{5}$

Gauge symmetry does not recover, but couplings run almost unitedly.


CDF Run II Preliminary
L = 5.2 fb-1
95% CL
68% CL
SM prediction
ΔΓ (ps-1)
βs (rad)


5.99
2.30
SM prediction
Data 2.8-5.2 fb-1
S-wave not included
ΔΓ (ps-1)
βs (rad)

Large Phase of B_s-$\bar{B}_s$ mixing

CP violation in $B_s \to J/\psi\phi$ decay $(b \to sc\bar{c})$.

$$S_{b\to sc\bar{c}} = \sin\phi_s$$

SM prediction : $\phi_s = -2\beta_s \simeq -0.04$ (rad) small!

$$\beta_s \equiv \arg\left(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right)$$

Measurements :

$$-\phi_s(\text{CDF}) = [0.32, 2.82]\ (68\%\ \text{CL}) \quad (1.35\ \text{fb}^{-1})$$

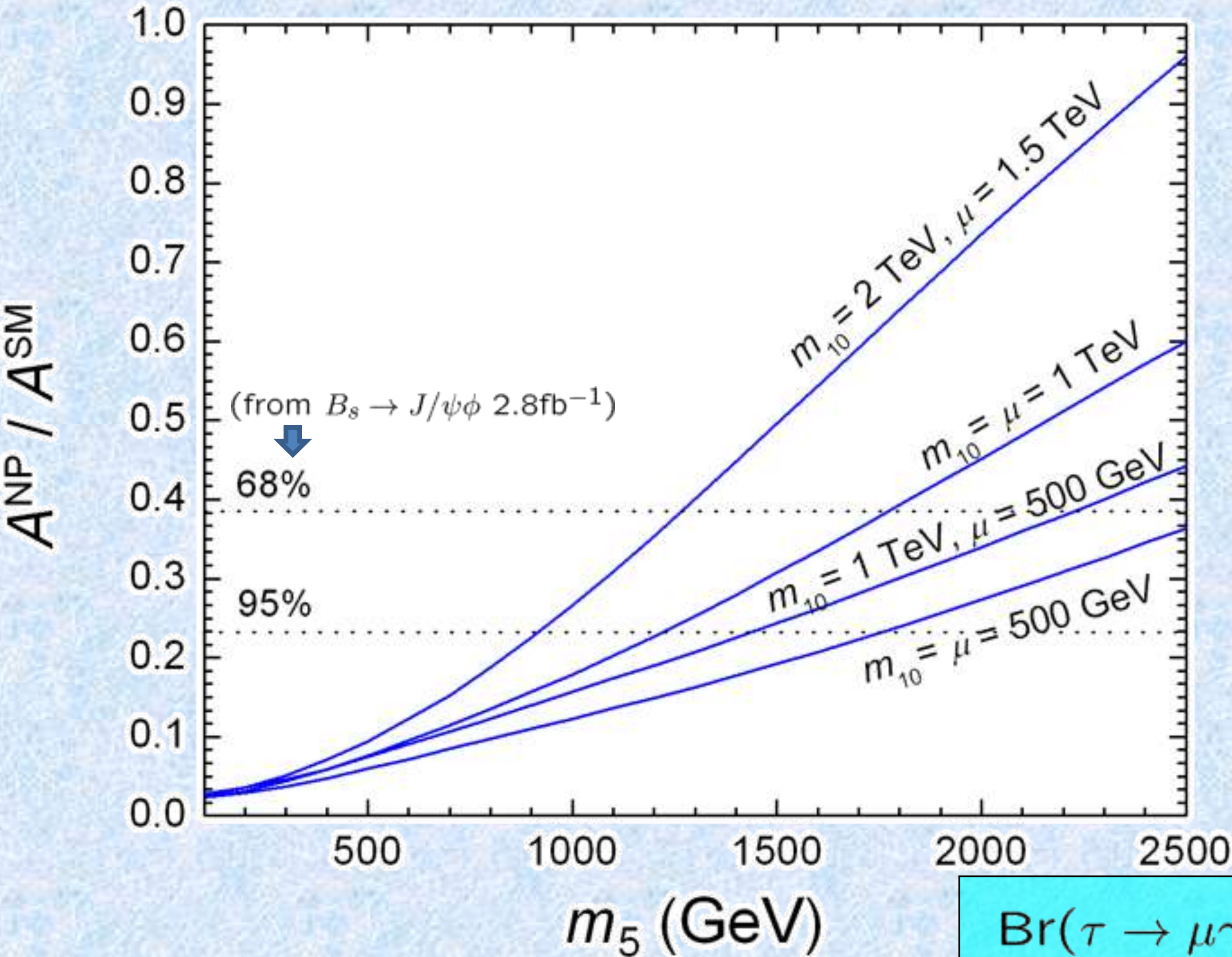
(arXiv: 0712.2397)

$$-\phi_s(\text{D0}) = 0.57^{+0.30}_{-0.24}(\text{stat})^{+0.02}_{-0.07}(\text{syst}) \quad (2.8\ \text{fb}^{-1})$$

(arXiv: 0802.2255)

2.2 sigma deviation from SM

A^{NP}/A^{SM} bound from $\tau \to \mu\gamma$



$$m_5 = m_{\tilde{D}^c} = m_{\tilde{L}}$$

$$m_{10} = m_{\tilde{Q}} = m_{\tilde{U}^c} = m_{\tilde{E}^c}$$

Br($\tau \to \mu\gamma$) $< 4.4 \times 10^{-8}$
$\tan\beta = 10$
$m_{1/2} = 300$ GeV