CP violating lepton asymmetry from semileptonic *B* decays as a probe of new physics

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Based on
in Collaboration with B. Dutta and Y. Santoso
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↑ Review

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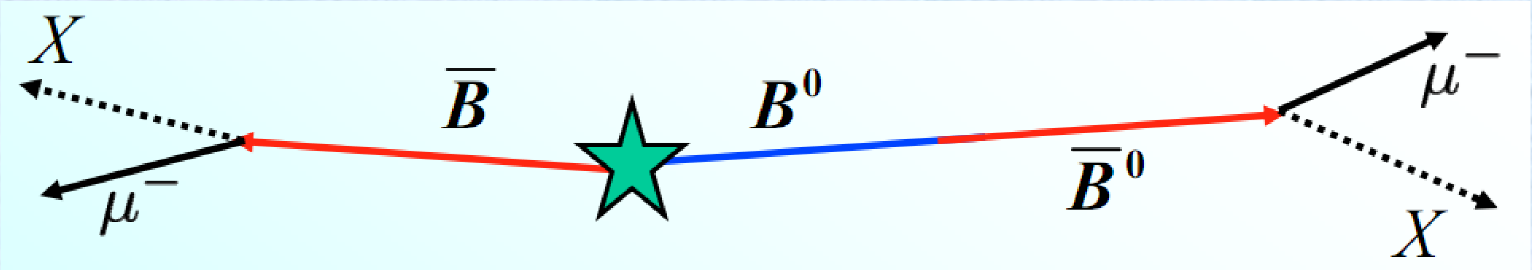
Dimuon charge asymmetry of semileptonic *B* decay [D0]



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

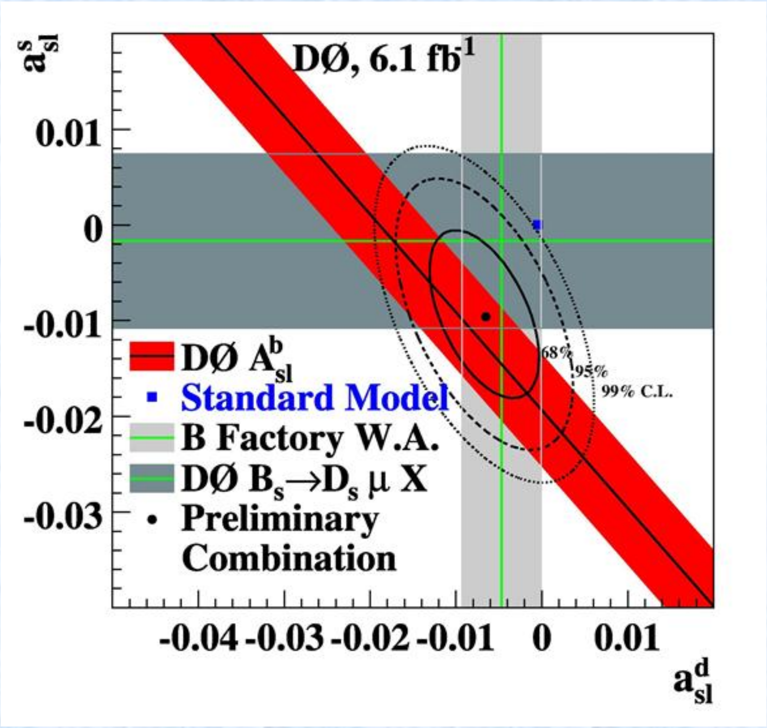
$$b \to \mu^- \bar{\nu} X$$
$$\bar{b} \to \mu^+ \nu X$$

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

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

3.2 sigma deviation from SM

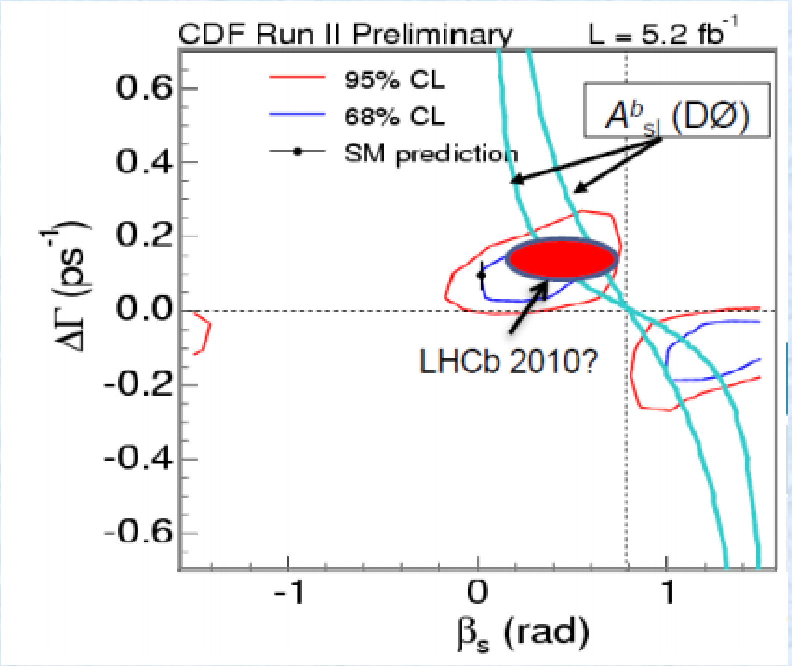
Asymmetry from semi-leptonic decay

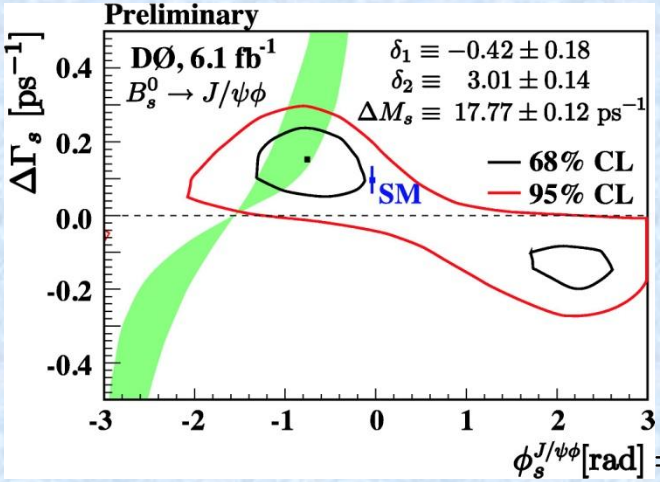


$$a_{sl}^q \equiv \frac{\Gamma(\bar{B}_q^0 \to \mu^+ X) - \Gamma(B_q^0 \to \mu^- X)}{\Gamma(\bar{B}_q^0 \to \mu^+ X) + \Gamma(B_q^0 \to \mu^- X)}$$

$$a_{sl}^q = \text{Im}\,\frac{\Gamma_q^{12}}{M_q^{12}} = \left|\frac{\Gamma_q^{12}}{M_q^{12}}\right| \sin\phi_q$$

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



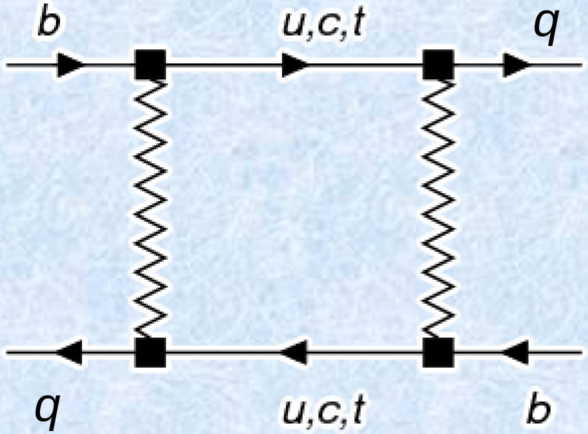


$= -2\beta_s$

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

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

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



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

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

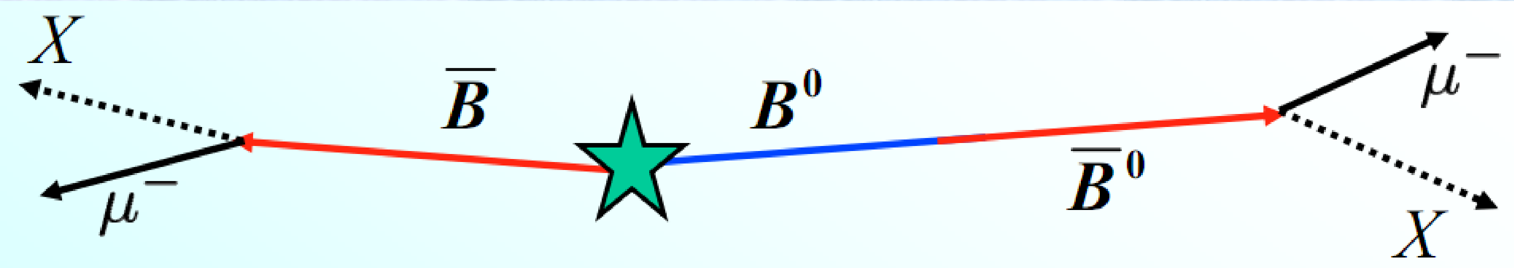
$$\bar{r} \equiv \frac{P(B\to\bar{B})}{P(B\to B)} = \left|\frac{p}{q}\right|^2 \frac{x^2+y^2}{2+x^2-y^2}$$

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

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

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

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



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

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

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

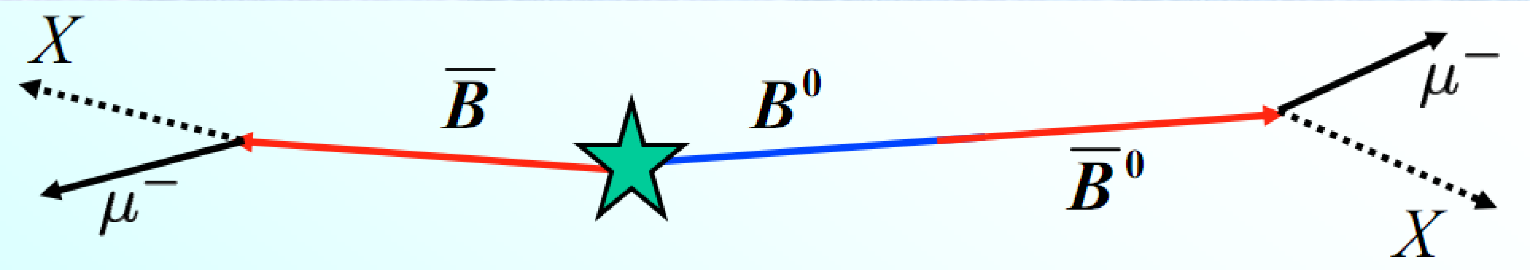
$$= \left|\frac{\Gamma_{12}^q}{M_{12}^q}\right| \sin\phi_q = \frac{\Delta\Gamma_q}{\Delta M_q}\tan\phi_q$$

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

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

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

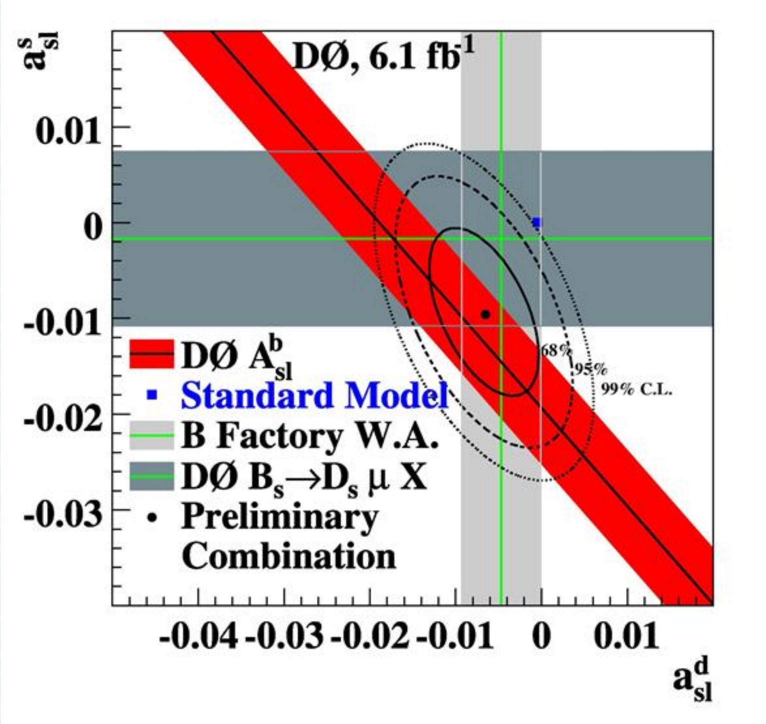
$$\phi_q \equiv \arg\left(-\frac{M_{12}^q}{\Gamma_{12}^q}\right)$$



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

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

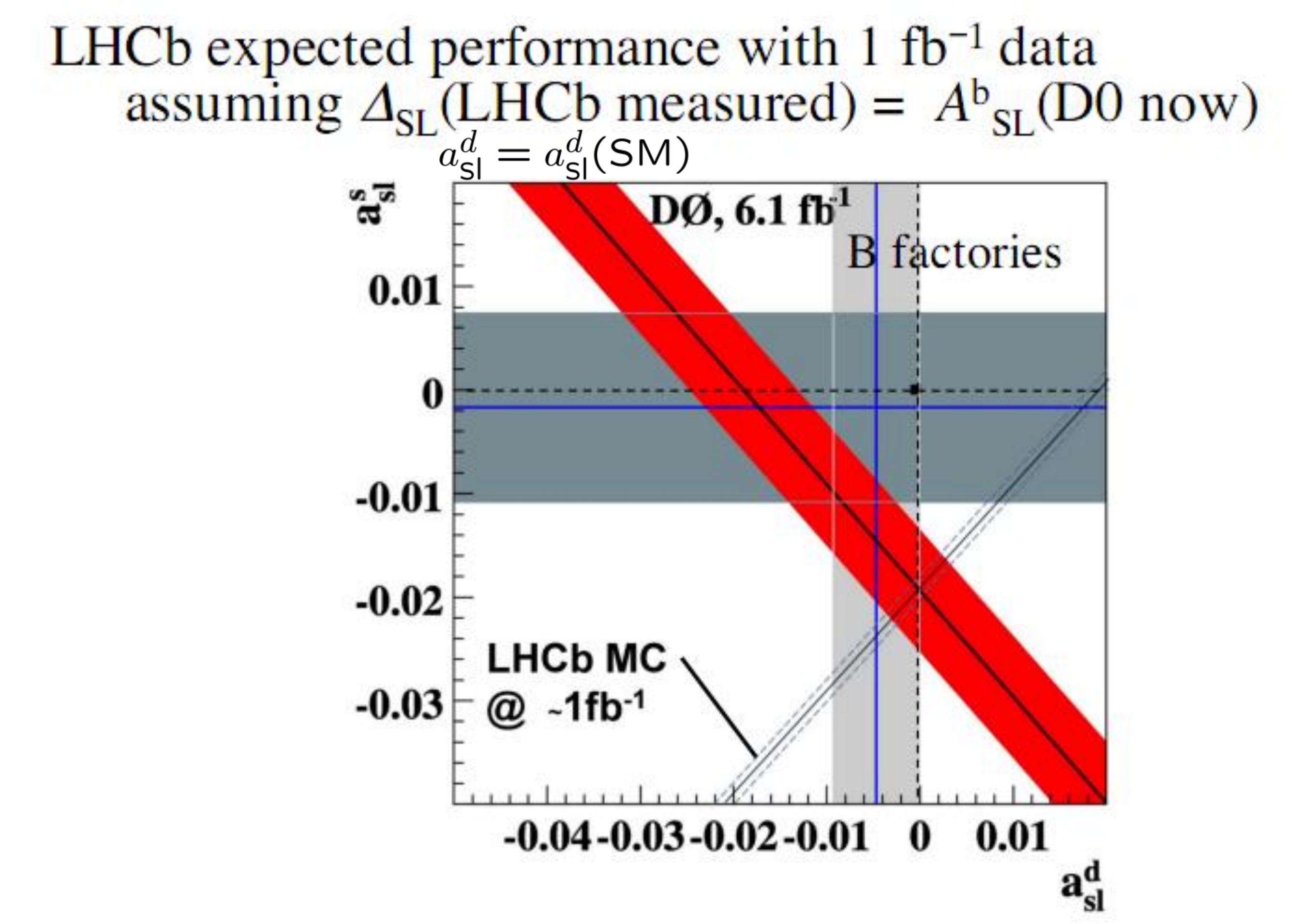
(Tevatron)



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

(Lenz-Nierste)

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



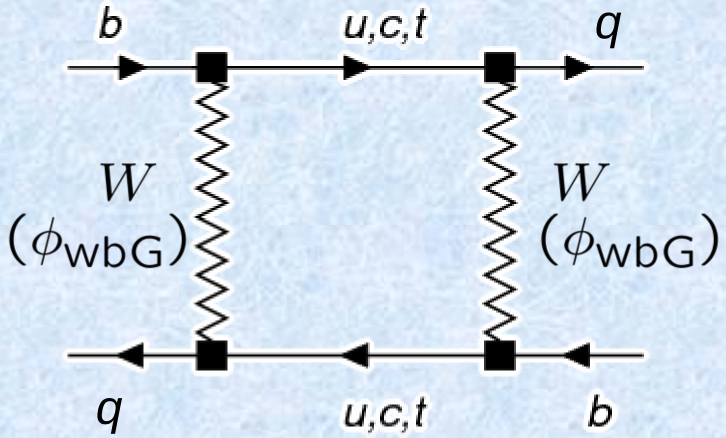
(picked up from T.Nakata's talk at CPV conf. at Tohoku U)

It will be tested very accurately at LHCb.

Why is SM prediction so small?

➡ Because of unitarity of CKM matrix.

Standard model prediction



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

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

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

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

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

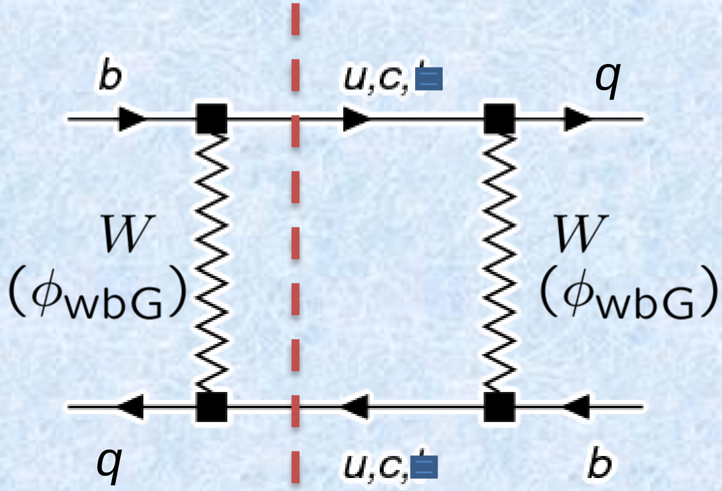
$$x_i x_j \left(\frac{(4-8x_i+x_i^2)\ln x_i}{4(1-x_i)^2(x_i-x_j)} + \frac{(4-8x_j+x_j^2)\ln x_j}{4(1-x_j)^2(x_j-x_i)} - \frac{3}{4(1-x_i)(1-x_j)} \right)$$

(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 $O(\Lambda/m_b)]$

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

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

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

$$\phi_s = 0.0042 \pm 0.0014$$

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

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

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

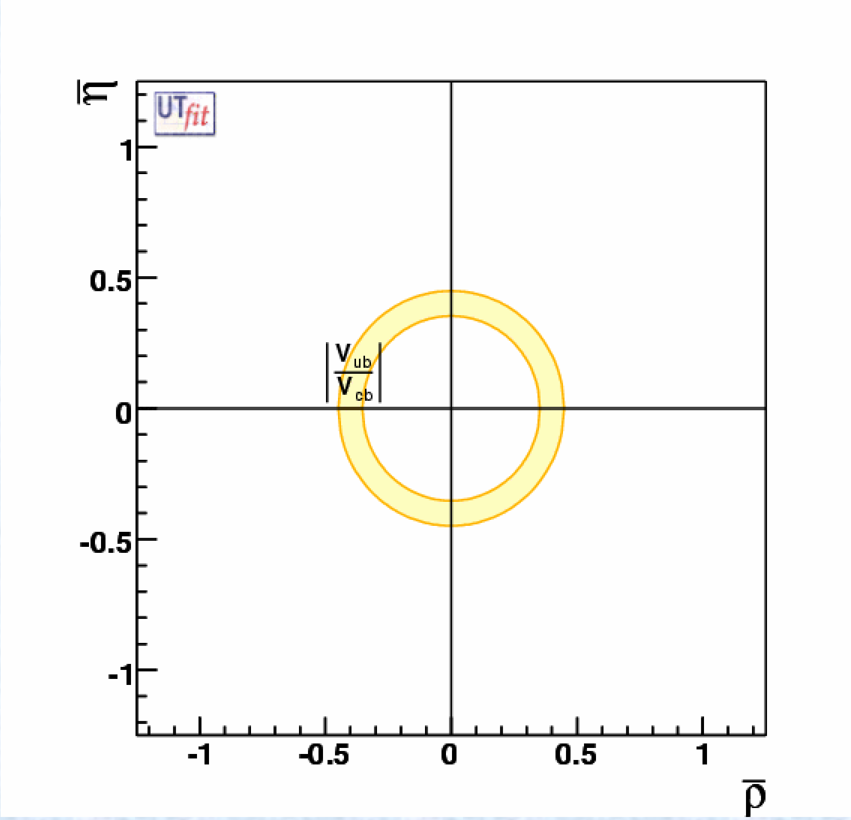
$$a_{sl}^q = \left|\frac{\Gamma_{12}^q}{M_{12}^q}\right| \sin\phi_q$$

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

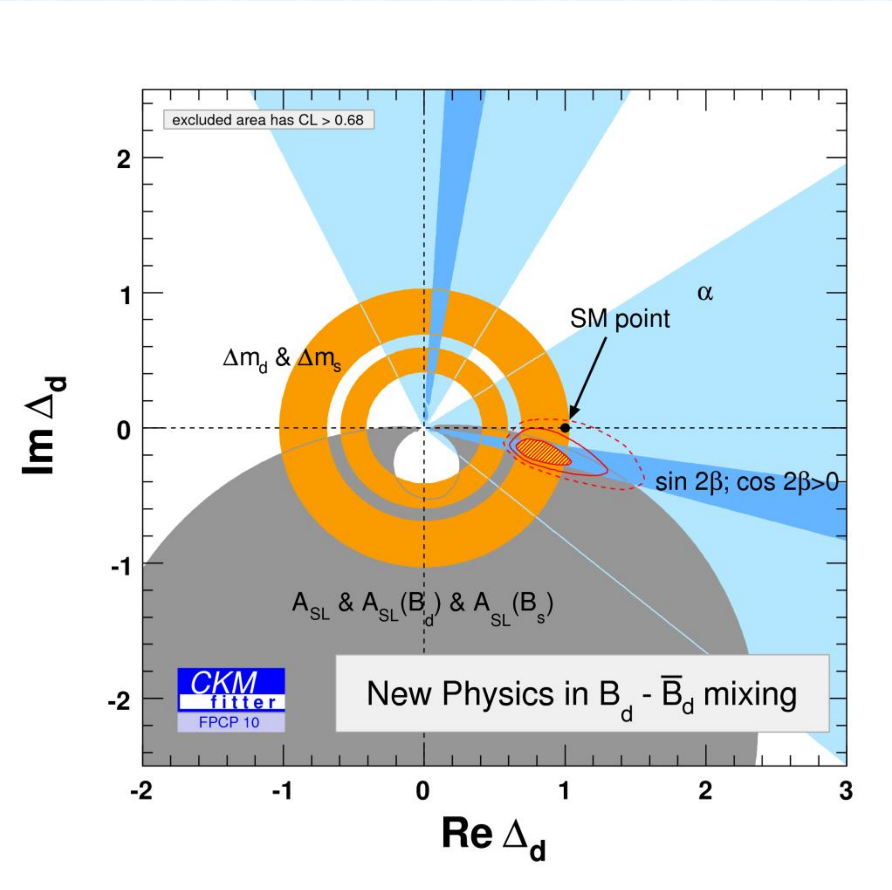
→ Important probe of new physics.

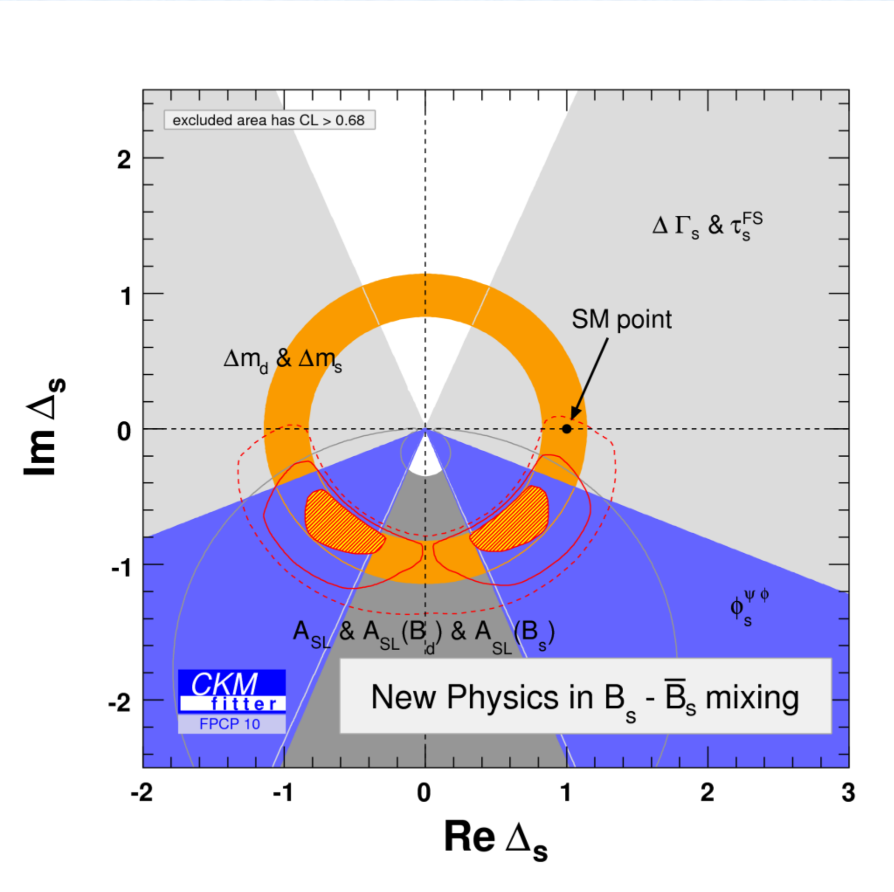
What kinds of new physics are possible?

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.



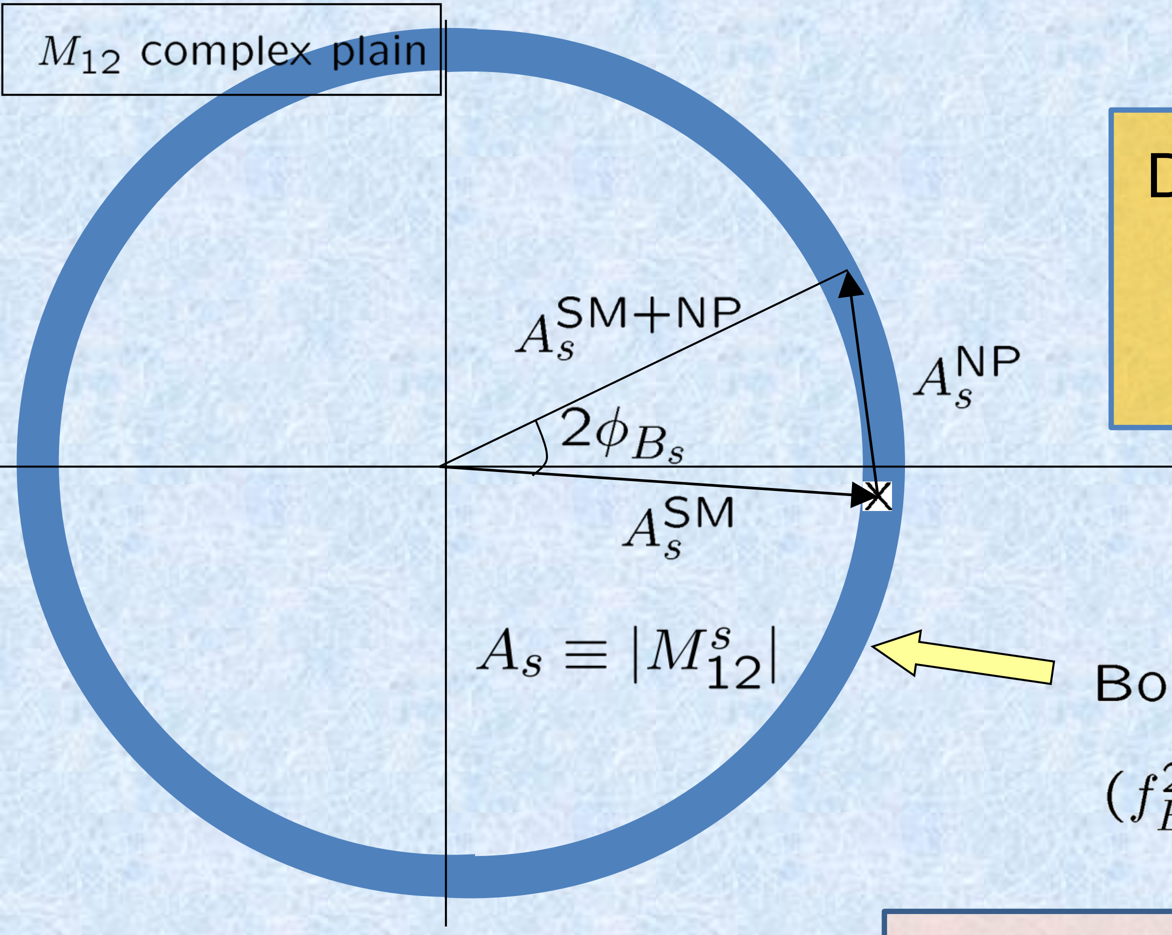


[$\sin 2\beta$-V_{ub} descrepancy?]

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.



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

Definition:

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

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

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

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

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

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

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

Now improving!

$\sim 15\%$

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

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

When there is no NP in *Bd* system,

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

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

$$\Rightarrow \quad \Delta_s = \frac{\Delta M_s^{\text{exp}}}{\Delta M_s^{\text{SM}}} = 0.95 \pm 0.095$$

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

➡ No.

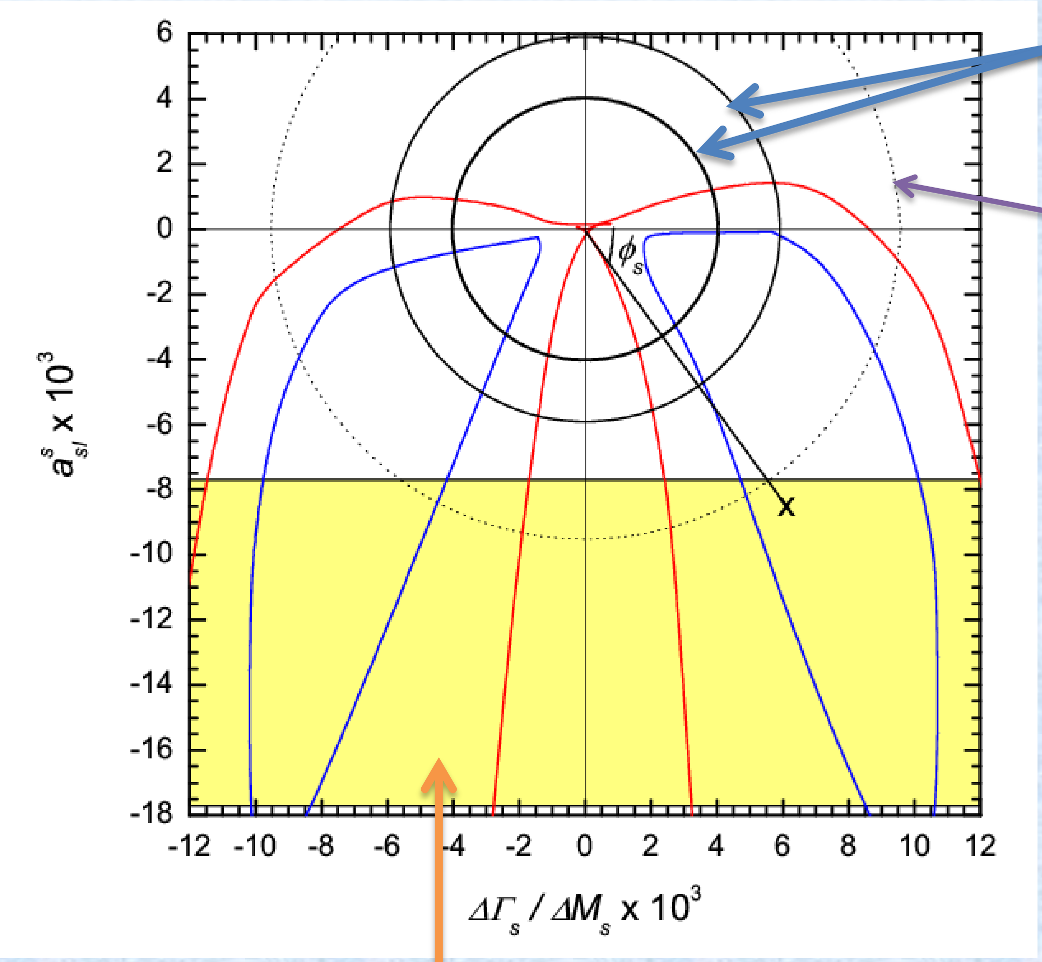
$$a^s_{sl} = \left|\frac{\Gamma^{12}_s}{M^{12}_s}\right| \sin\phi_s = \frac{\Delta\Gamma_s}{\Delta M_s}\tan\phi_s$$

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

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

$\Gamma_{12} = \Gamma^{\text{SM}}_{12}$ is assumed.

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

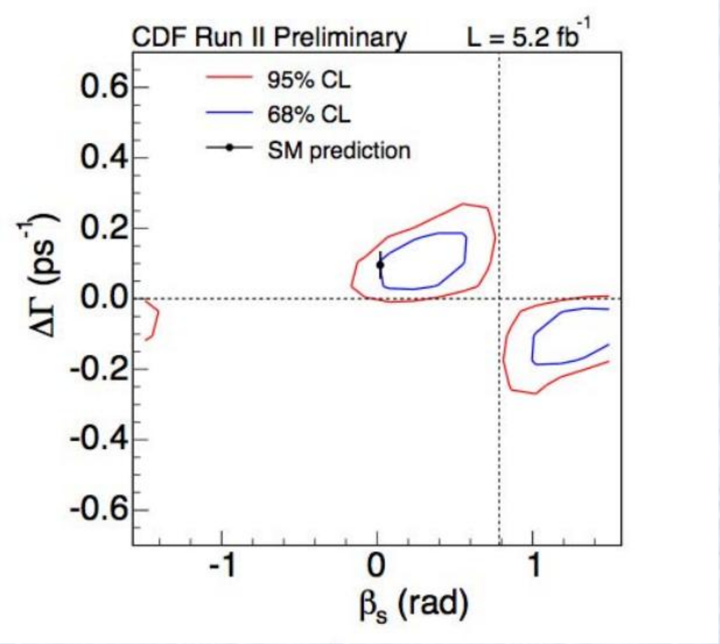


$$\left|\frac{\Gamma_{12}^s}{M_{12}^s}\right|_{\mathrm{SM}} = (4.97 \pm 0.94) \times 10^{-3}$$

$$\Delta_s = 1$$

Conservative region

$$\Delta_s = 0.6$$



$$a^s_{\mathrm{sl}} = (-12.7 \pm 5.0) \times 10^{-3}$$ (Combined data)

assuming $a^d_{sl} = a^d_{sl}(\mathrm{SM})$

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?

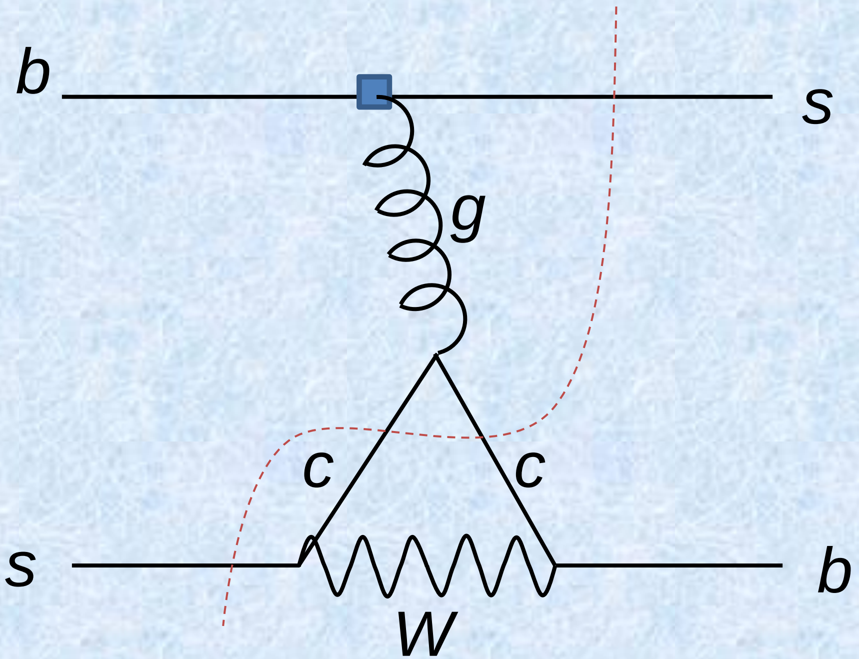
M^s_{12} modification

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

Γ^s_{12} 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)

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

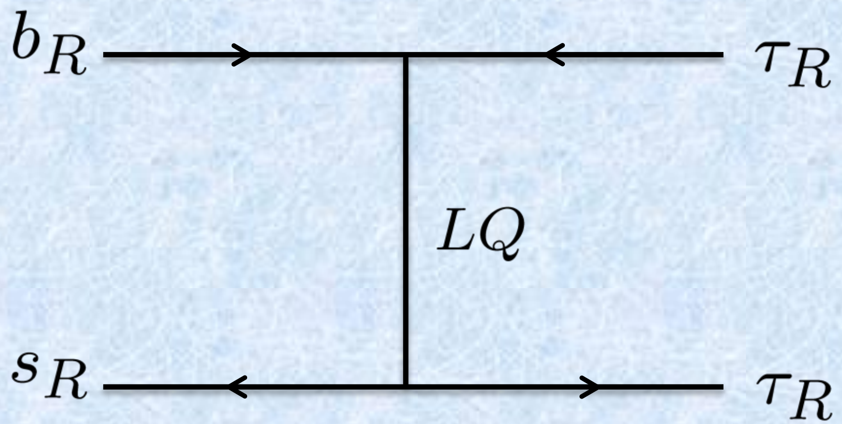
constraints

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

Ex)

leptoquark

(Dighe-Kundu-Nandi)



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

Fine-tune is needed. τ_{B_s}/τ_{B_d}=0.965±0.017

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. …)

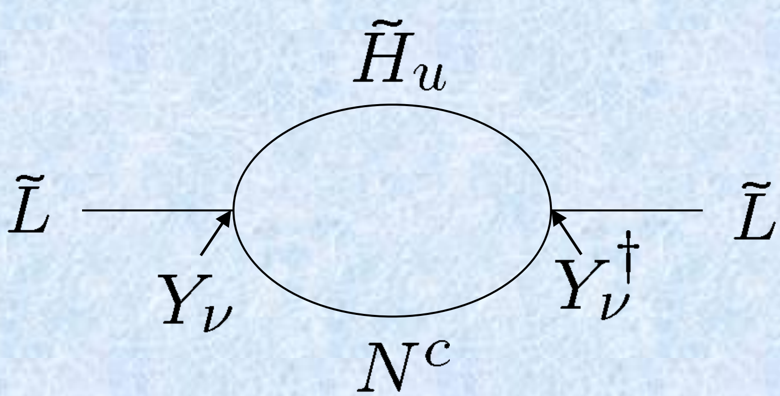
We will study the constraints to obtain the large CP phase and the correlation to the other observables (e.g. $B_s \to \mu\mu$) in SU(5) and SO(10) GUT models.

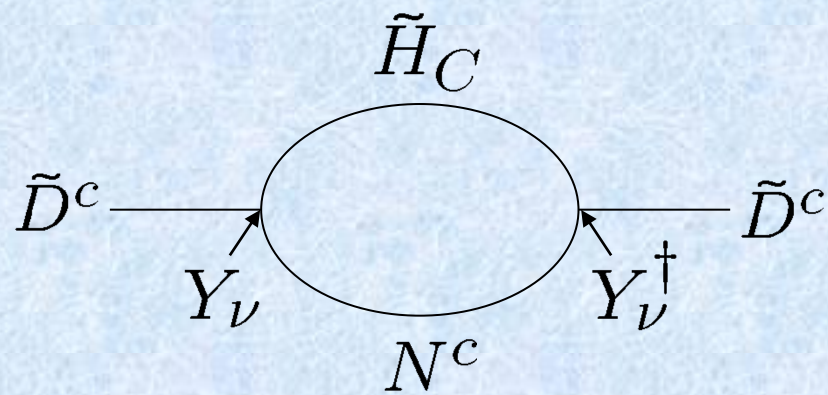
SU(5) GUT

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, …)

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

κ : coefficient

U : unitary matrix

$$(m_5^2)_{23} = -\tfrac{1}{2} m_0^2\, \kappa \sin 2\theta_{23}\, e^{i\alpha}$$

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.

$$(m_5^2)_{13} = m_0^2 \kappa \left(-\tfrac{1}{2} k_2 \sin 2\theta_{12} \sin\theta_{23} + e^{i\delta} \sin\theta_{13} \cos\theta_{23}\right) e^{i\beta}$$

$$(m_5^2)_{12} = m_0^2 \kappa \left(-\tfrac{1}{2} k_2 \sin 2\theta_{12} \cos\theta_{23} - e^{i\delta} \sin\theta_{13} \sin\theta_{23}\right) e^{i(\beta-\alpha)}$$

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

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

$SU(2)_L$ triplet

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

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 : $f_L LL\Delta_L + f_R L^c L^c \Delta_R$

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:

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

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

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

M_*: String/Planck scale

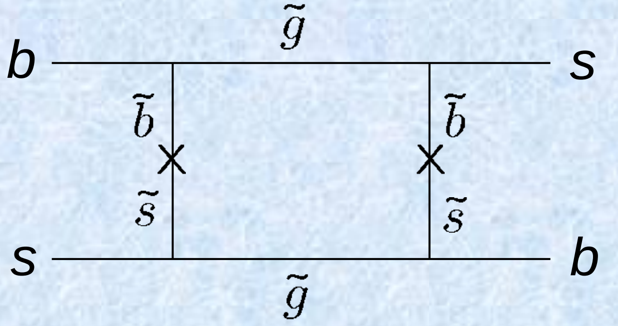
$$f = U f^{\mathrm{diag}} U^{\mathsf{T}}$$

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

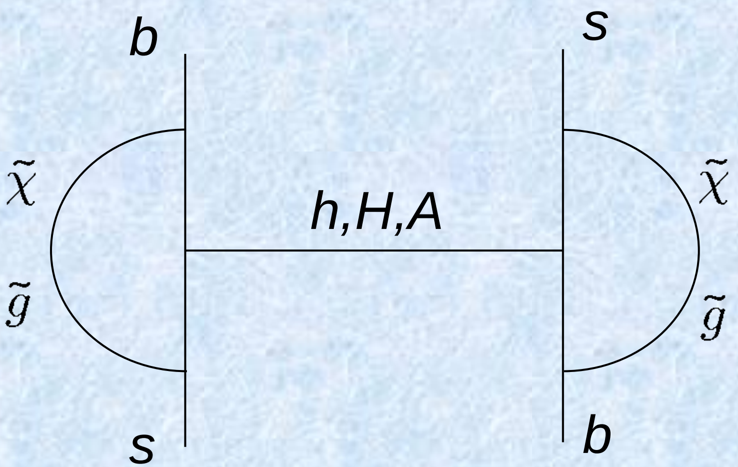
Both left- and right-squarks have sizable FCNC effects!

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

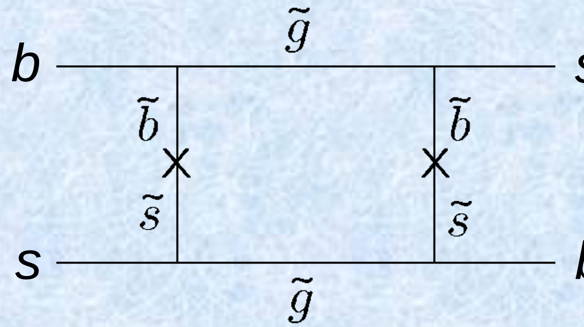
- Gluino box contribution.



- Double Higgs penguin contribution.



◆Gluino box contribution.



Mass insertion approximation:

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

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

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

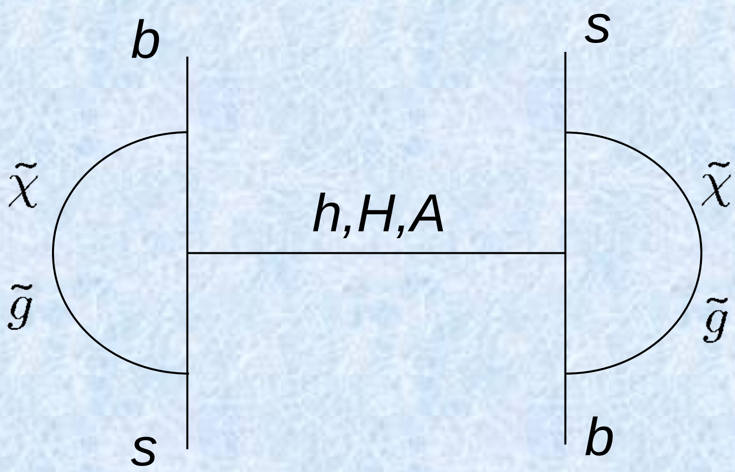
Only δ^d_{RR} is large in SU(5).

- 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.

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

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

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

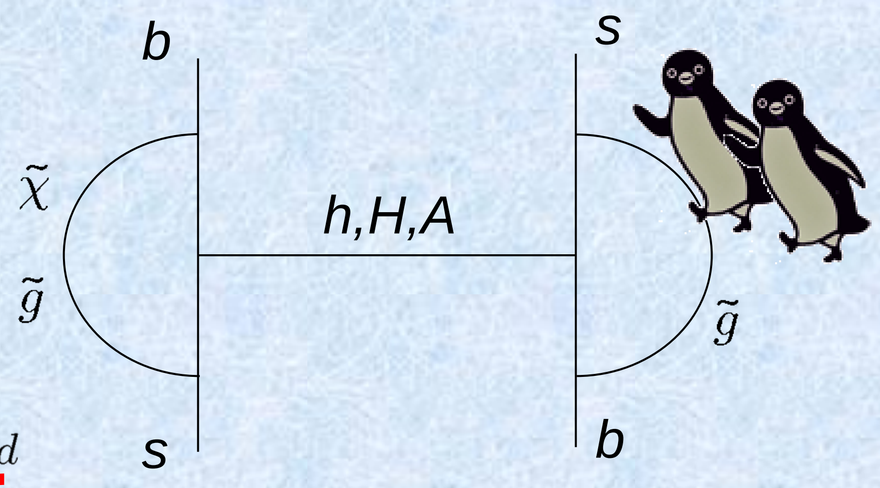
$$(\delta_{LL})_{32}(\delta_{LL})_{32}\left(\frac{\sin^2(\alpha-\beta)}{m_H^2}+\frac{\cos^2(\alpha-\beta)}{m_h^2}-\frac{1}{m_A^2}\right)\to 0$$

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

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

Dominant contribution

◆Double penguin contribution



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

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

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

"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 $\epsilon_{32} b_L s_R^c H^0$

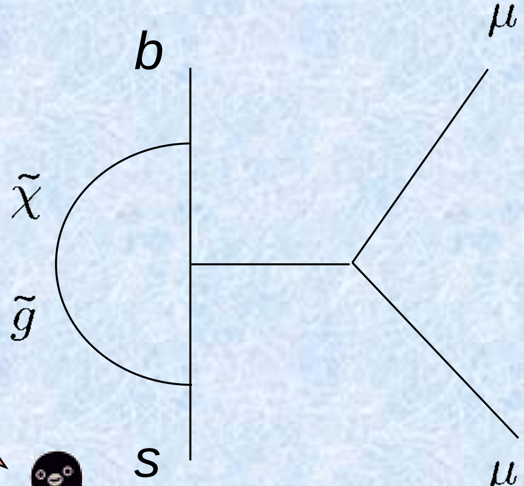
$$\epsilon_{32} \propto \qquad\qquad + \delta^{\tilde{d}}_{RR,23}(\text{gluino})$$

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

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

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

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



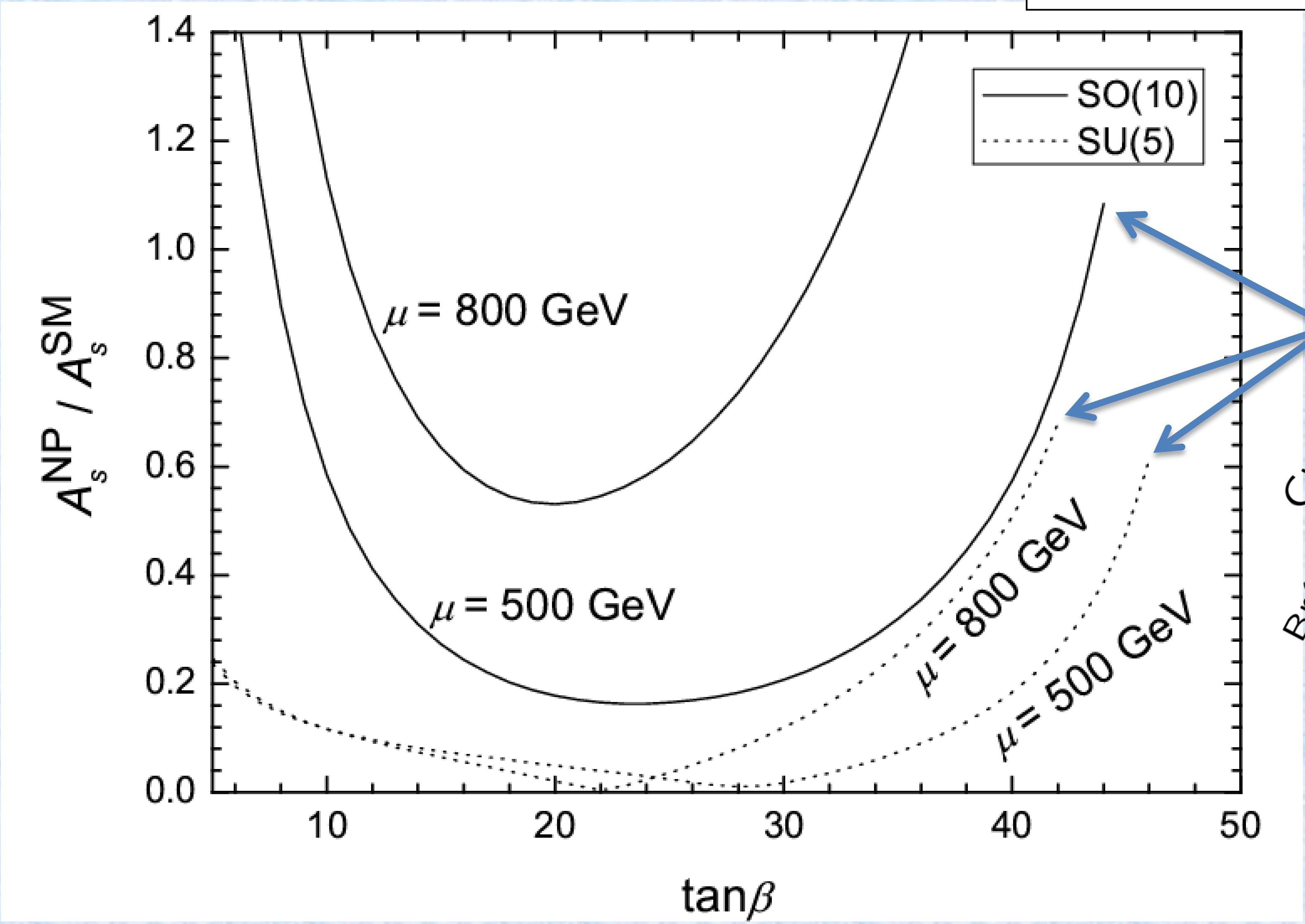
However,

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

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

$A_s = |M^s_{12}|$

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



Cut by $B_s \to \mu\mu$ bound
$Br(B_s \to \mu\mu) < 4.3 \times 10^{-8}$

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.

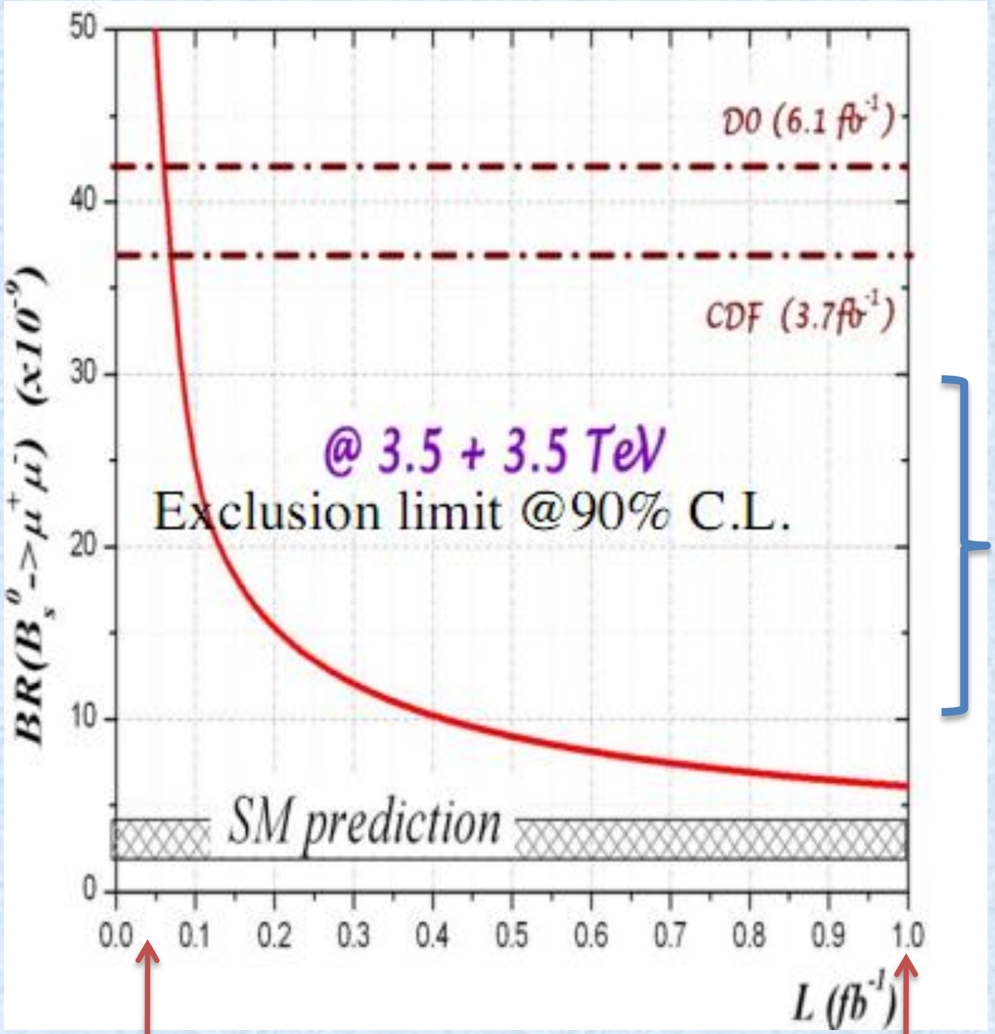
$\tan\beta = 40$

$\mu < 1$ TeV

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

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

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

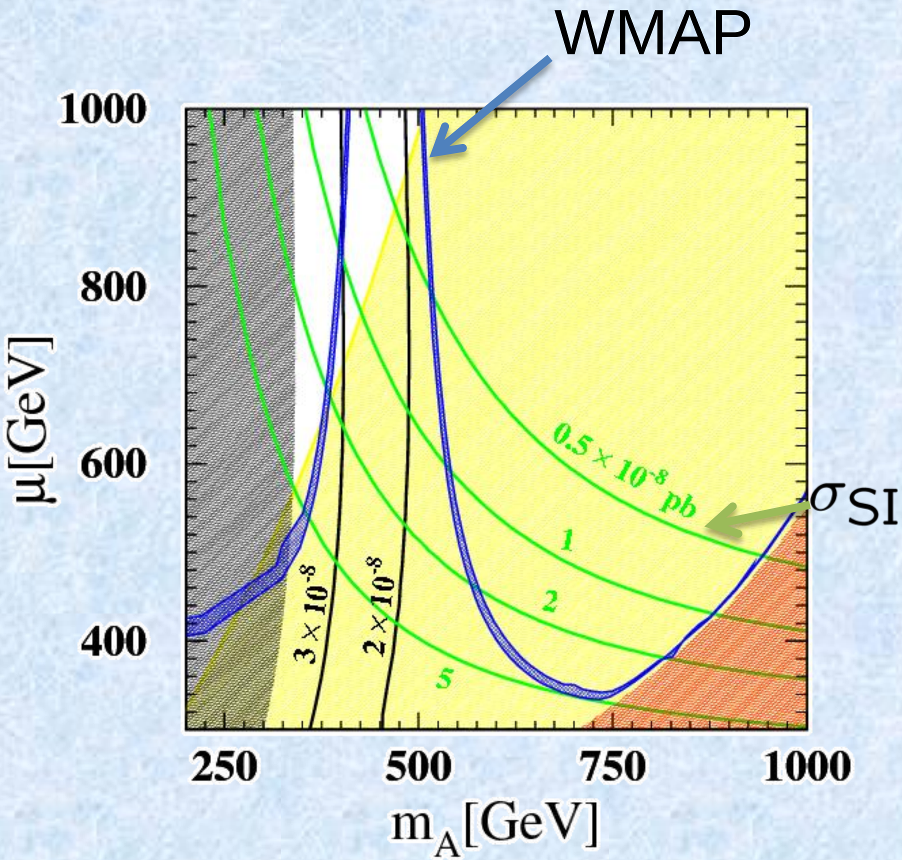


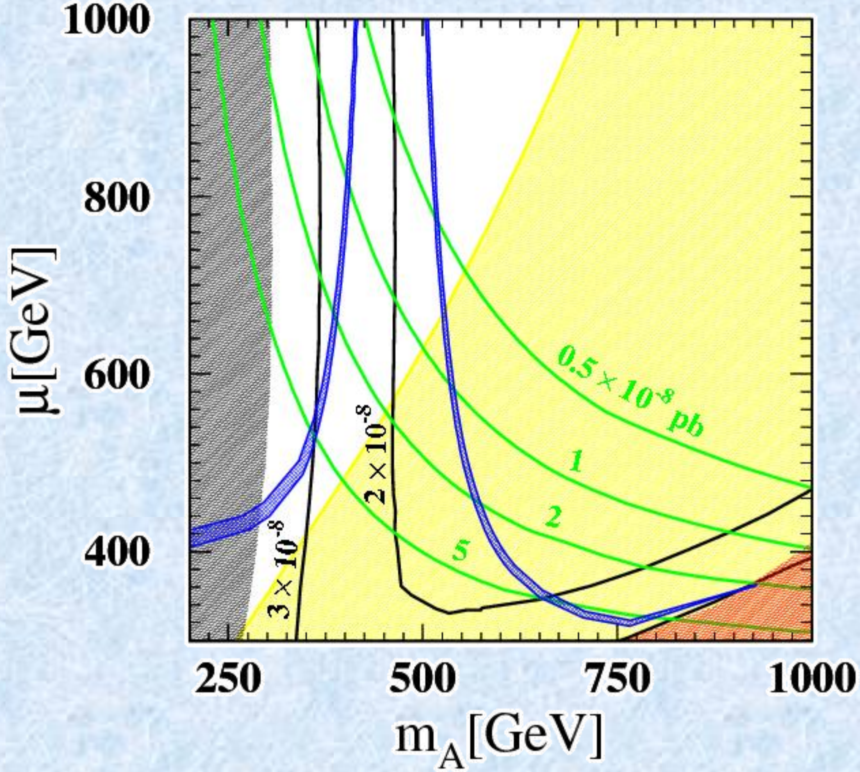
SU(5) prediction

Now

End of 2011

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





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

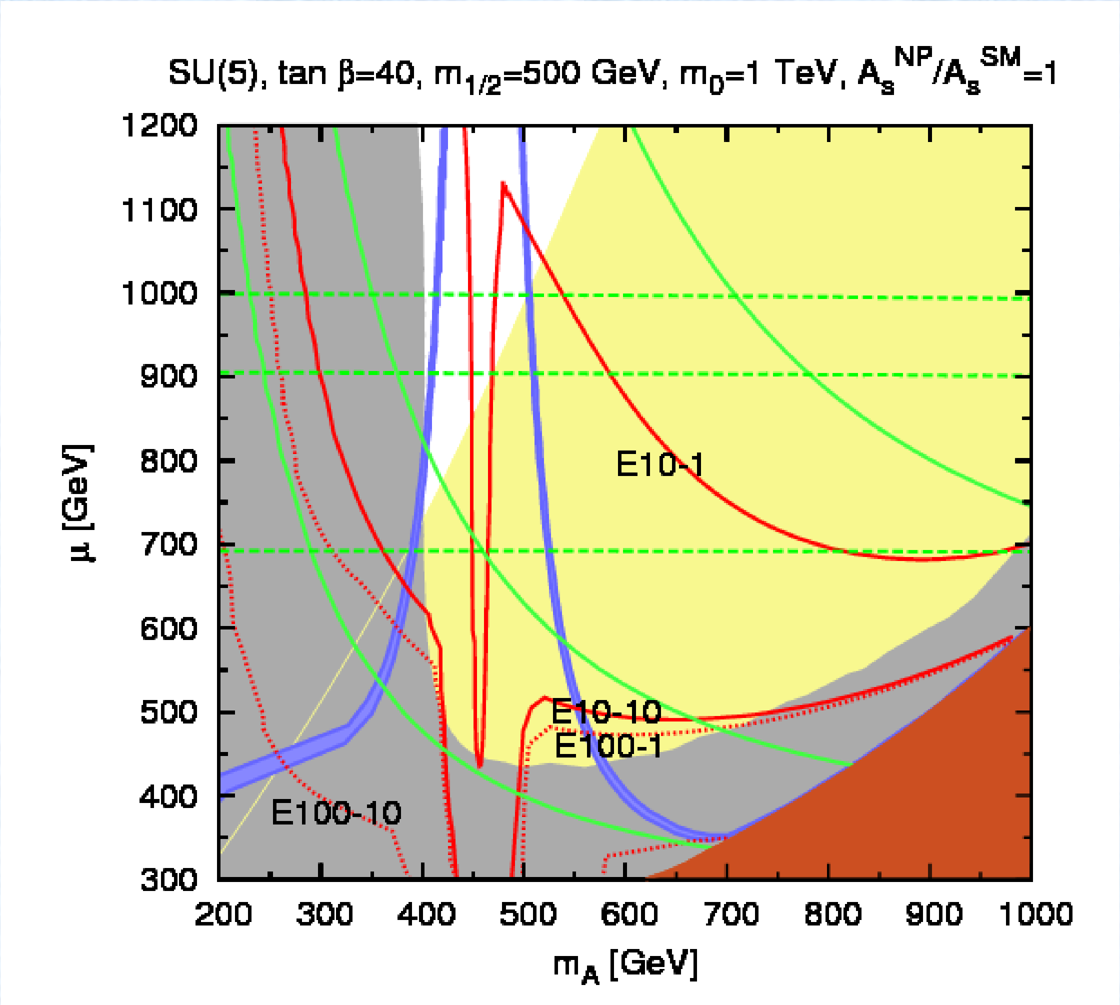
$\tan\beta = 40$
$m_{1/2} = 500$ GeV
$m_0 = 1$ TeV

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

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

Summary

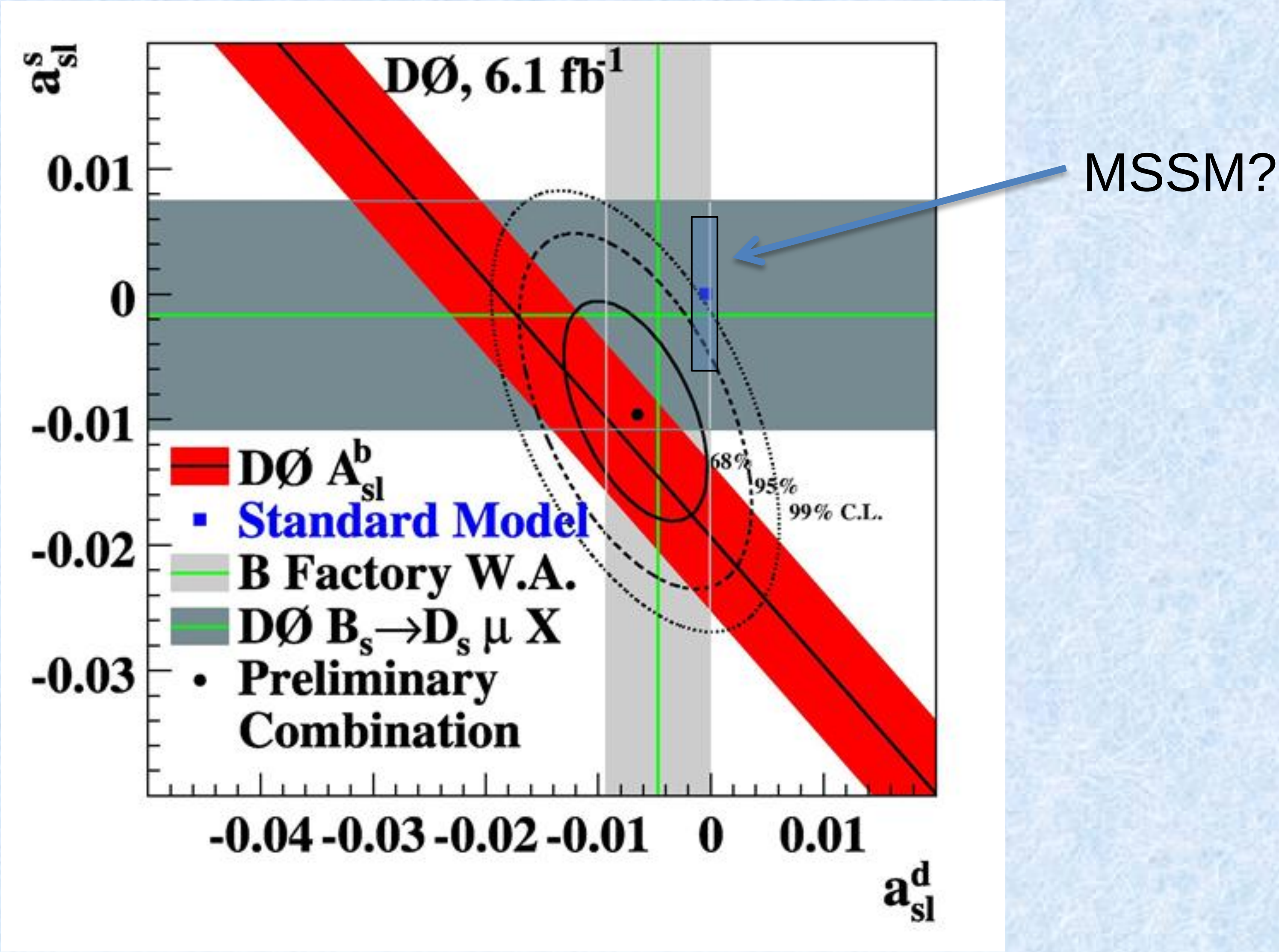
- The dimuon asymmetry is a good probe of NP.
- Dispersive part of the mixing amplitude can be easily modified in NP, but absorptive part is not easy.
- We study the CP phase in the mixing amplitude in SUSY GUT models.
- The phase is more enhanced in SO(10) rather than in SU(5).
- Especially in SU(5),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

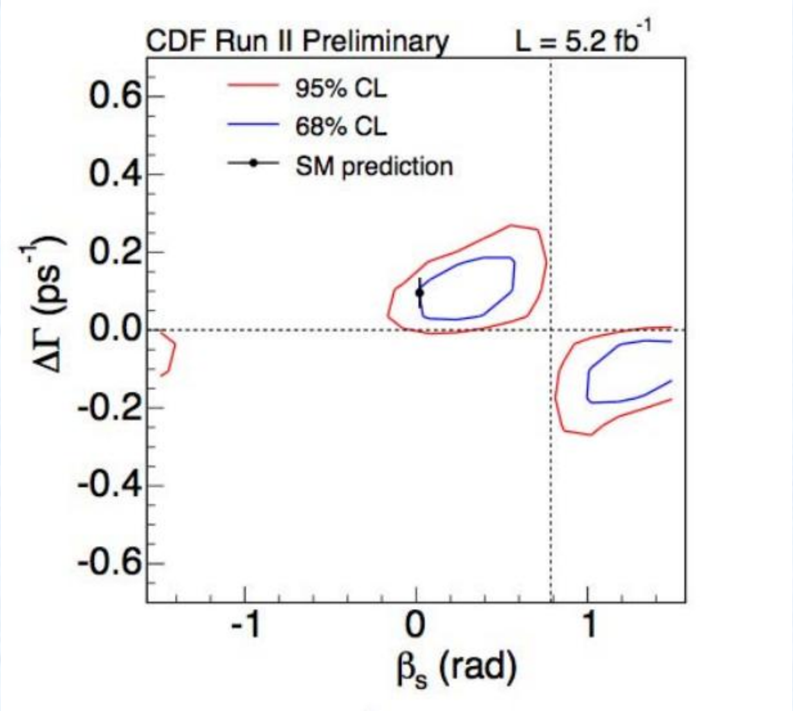


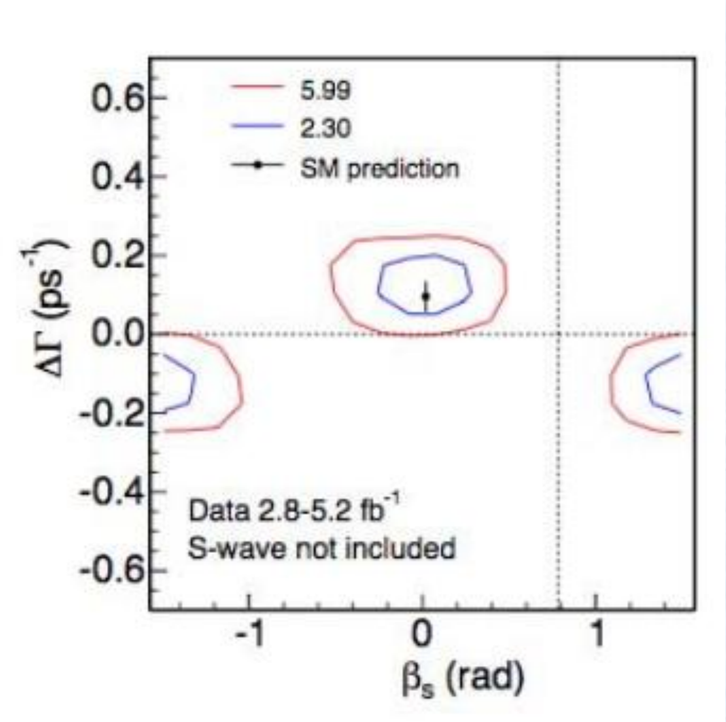
Muon flux from the sun

Ex-y : x is the assumed detector energy threshold in GeV

y is the flux in $\mathrm{km}^{-2}\ \mathrm{yr}^{-1}$


DØ, 6.1 fb-1
0.01
0
-0.01
-0.02
-0.03
-0.04 -0.03 -0.02 -0.01 0 0.01
68%
95%
99% C.L.
DØ A b sl
Standard Model
B Factory W.A.
DØ Bs→Ds μ X
Preliminary
Combination
MSSM?


CDF Run II Preliminary
L = 5.2 fb^{-1}
95% CL
68% CL
SM prediction
$\Delta\Gamma$ (ps^{-1})
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-1
0
1
β_s (rad)


5.99
2.30
SM prediction
Data 2.8-5.2 fb^{-1}
S-wave not included
$\Delta\Gamma$ (ps^{-1})
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-1
0
1
β_s (rad)

Back up Slides

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 :

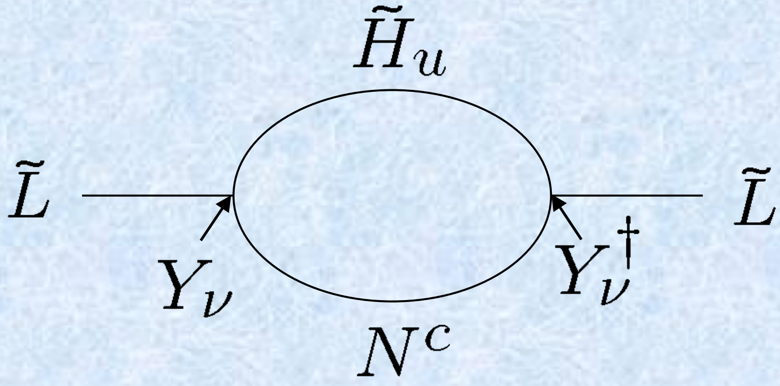
$$-\phi_s(\text{CDF}) = [0.32, 2.82] \ (68\% \ \text{CL})$$ $(1.35\ \text{fb}^{-1})$

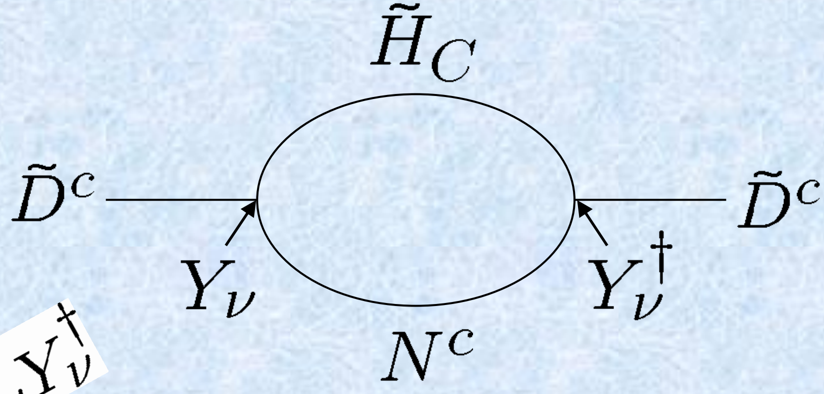
(arXiv: 0712.2397)

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

(arXiv: 0802.2255)

2.2 sigma deviation from SM





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

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

$$k_1, k_2 \ll 1$$

base

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

U : unitary mixing matrix

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

If $U_R = 1$, U is the PMNS neutrino mixing matrix.

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

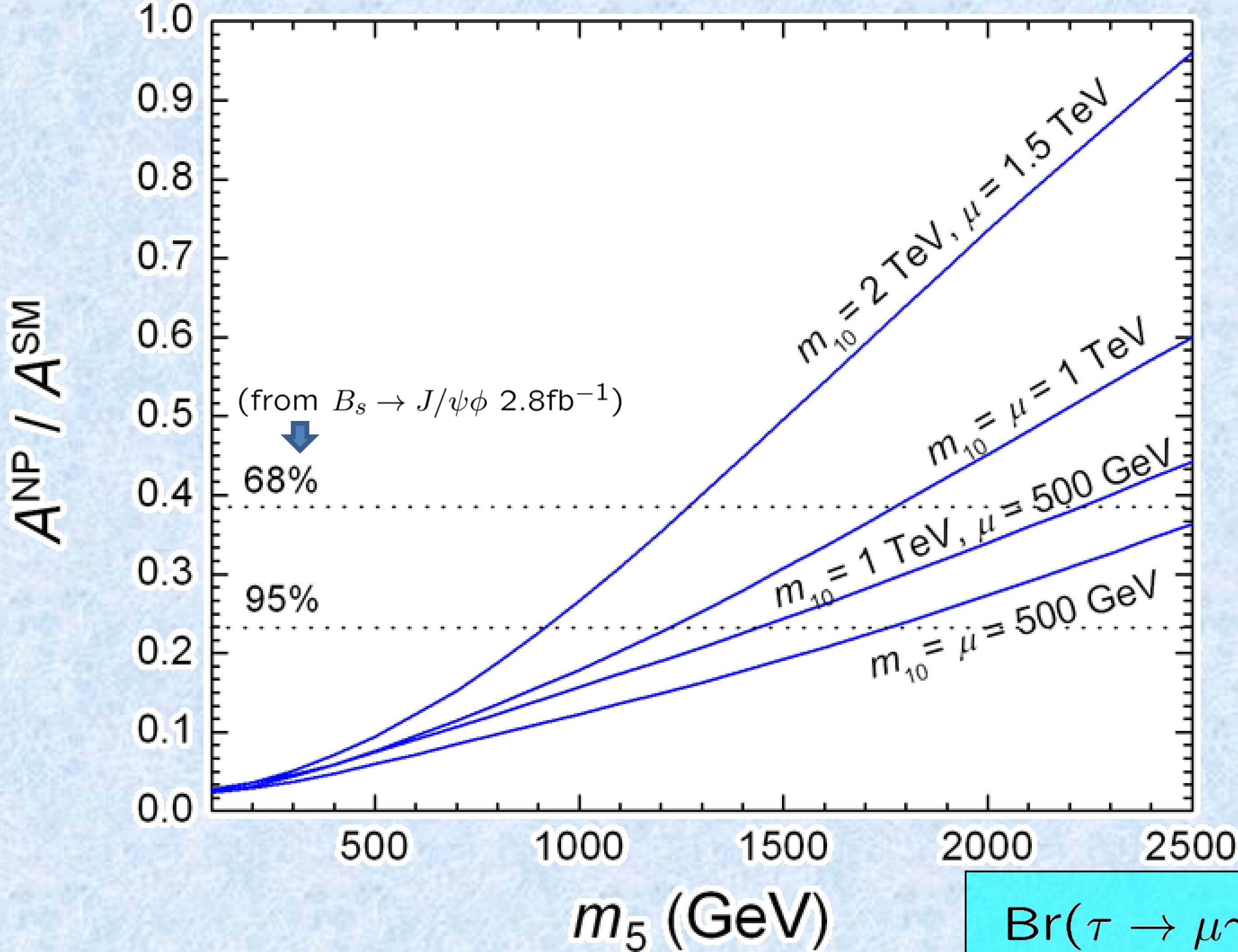
$$M^2_{\tilde{D}^c} \sim \begin{pmatrix} (1\text{TeV})^2 + m_0^2 & & \\ & (1\text{TeV})^2 + m_0^2 & \kappa m_0^2 \\ & \kappa m_0^2 & (1\text{TeV})^2 + m_0^2 \end{pmatrix}$$

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

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.

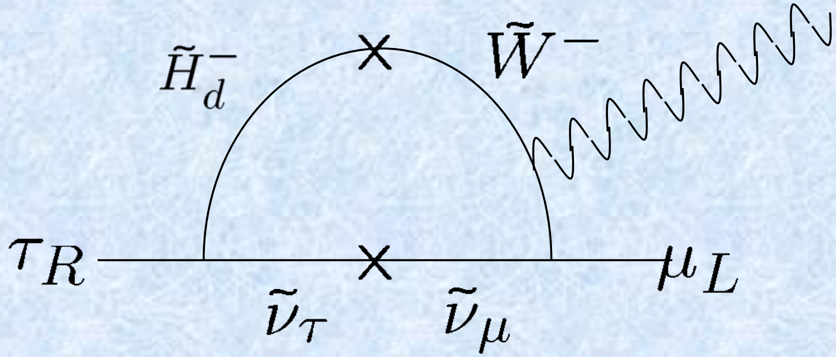
A^{NP}/A^{SM} bound from $\tau \to \mu\gamma$



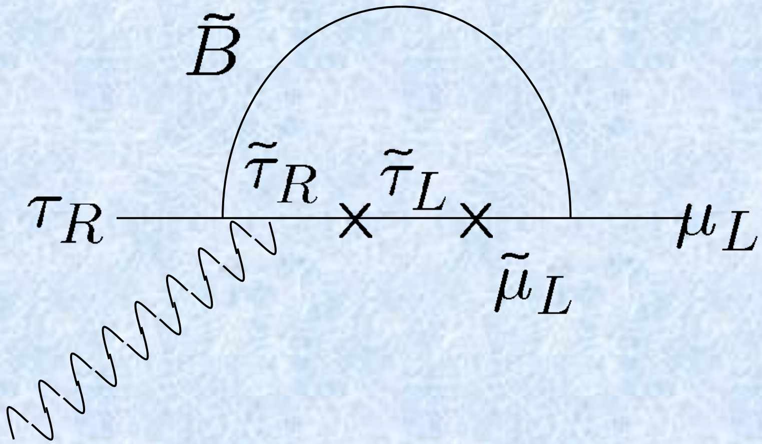
$m_5 = m_{\tilde{D}^c} = m_{\tilde{L}}$

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

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



$$\propto \kappa \, \frac{1}{m_5^2} \, \frac{M_W}{\mu} \tan\beta$$

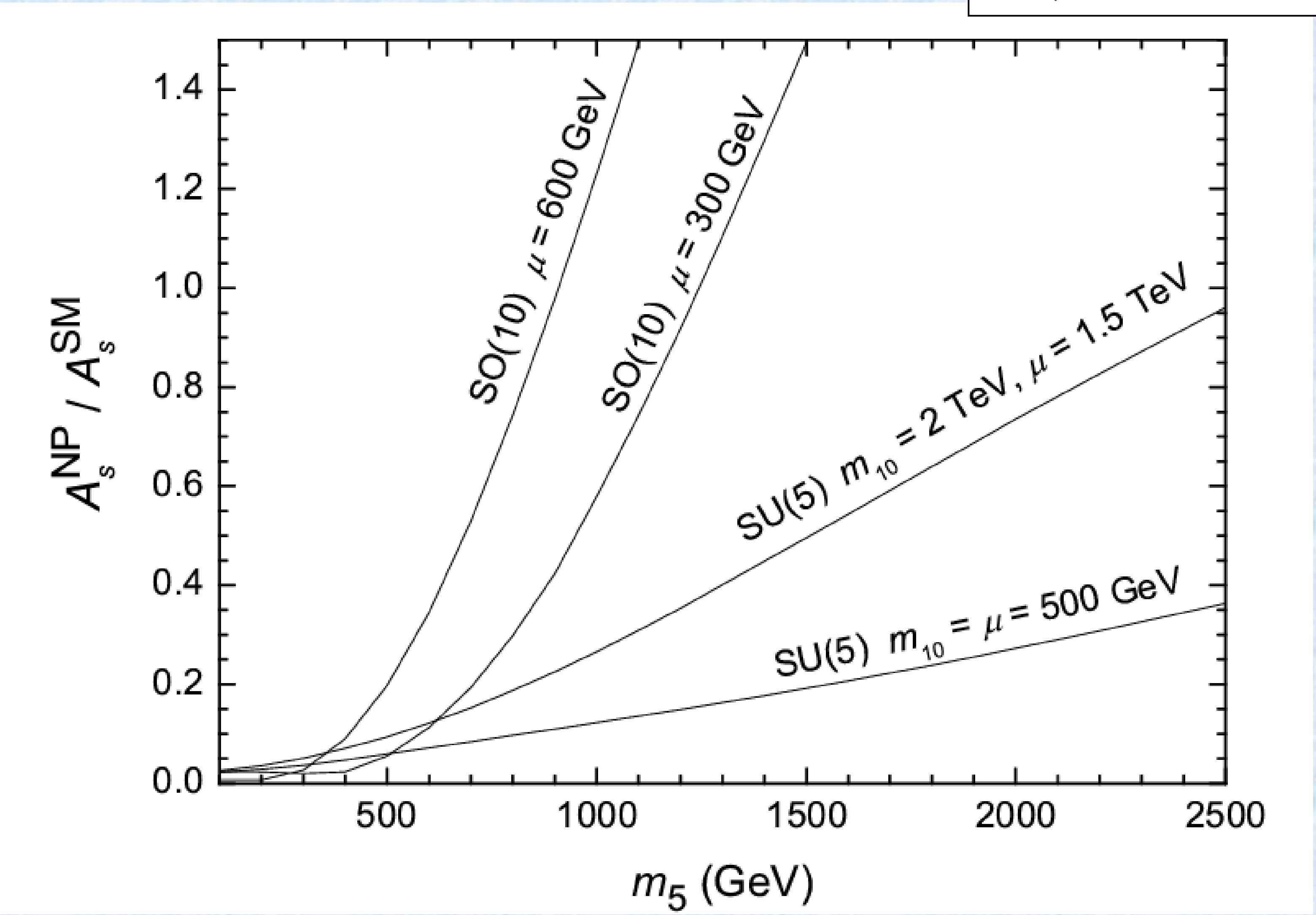


$$\propto \kappa \, \frac{1}{m_{10}^2} \, \frac{\mu \tan\beta \, m_\tau}{m_5^2}$$

Large m_5, m_{10}, μ are needed to suppress $\tau \to \mu\gamma$.

Sparticle spectrum is restricted. → LHC

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



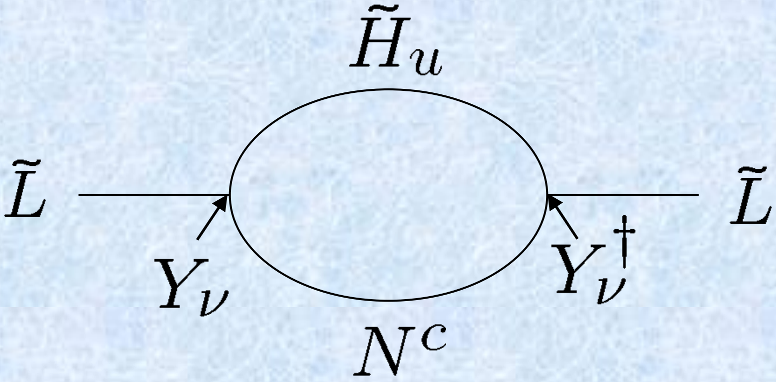
Possible violation of the quark-lepton unification

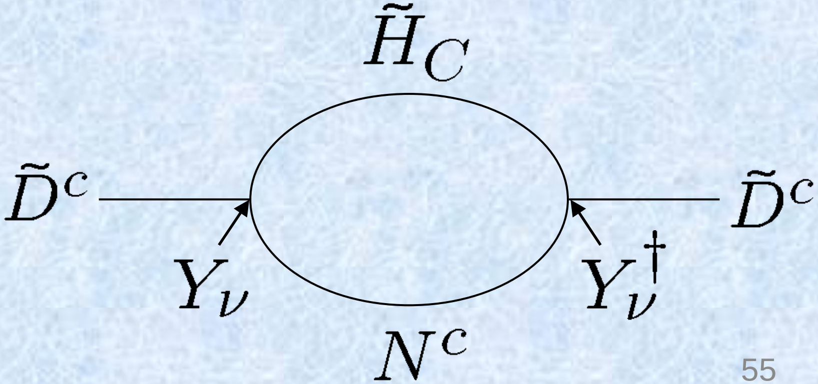
To relax the constraint, one needs $\kappa_{\text{quark}} > \kappa_{\text{lepton}}$.

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

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

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





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

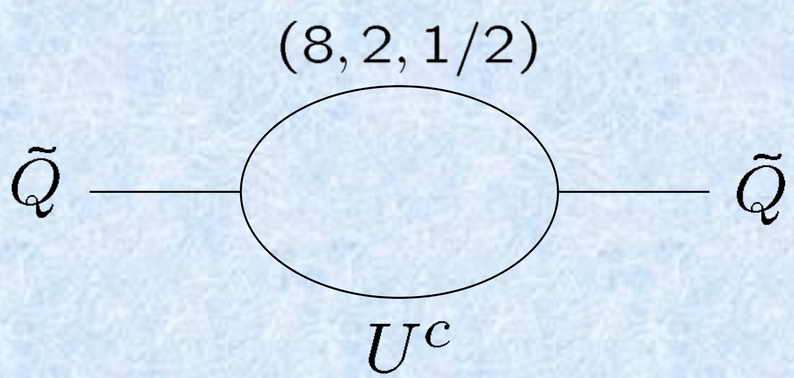
If $SU(2)_R$ remains below the SO(10) breaking scale,
$SU(2)_R$ Higgsino induces κ_ℓ rather than κ_q. Wrong direction!

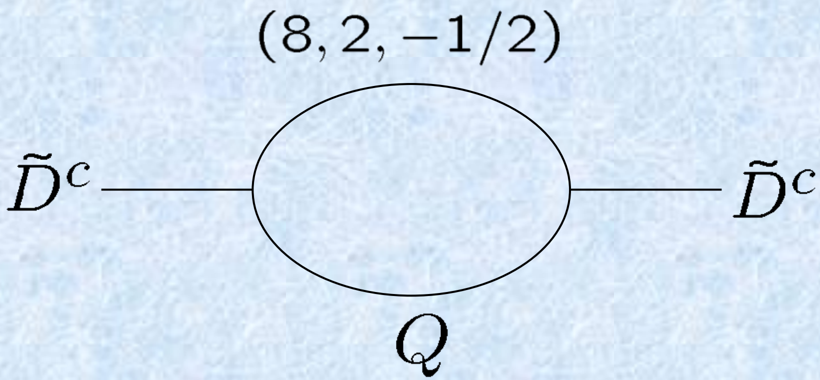
If (**8**,**2**,1/2) (in **126** Higgs) is light, it generates only κ_q.

Right direction!

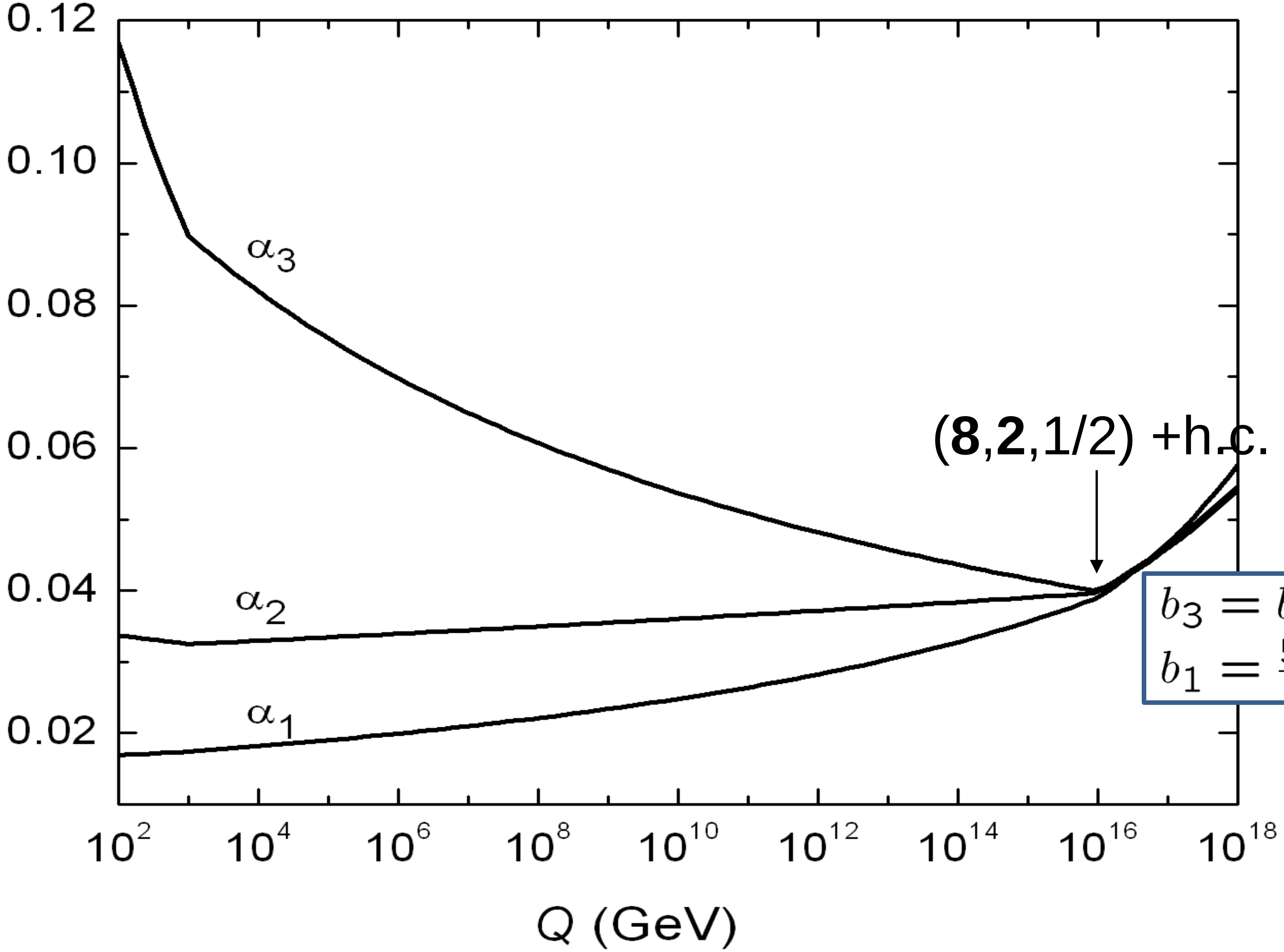
Light (**8**,**2**,1/2) is also proper direction to suppress proton decay.

(Dutta-YM-Mohapatra)





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



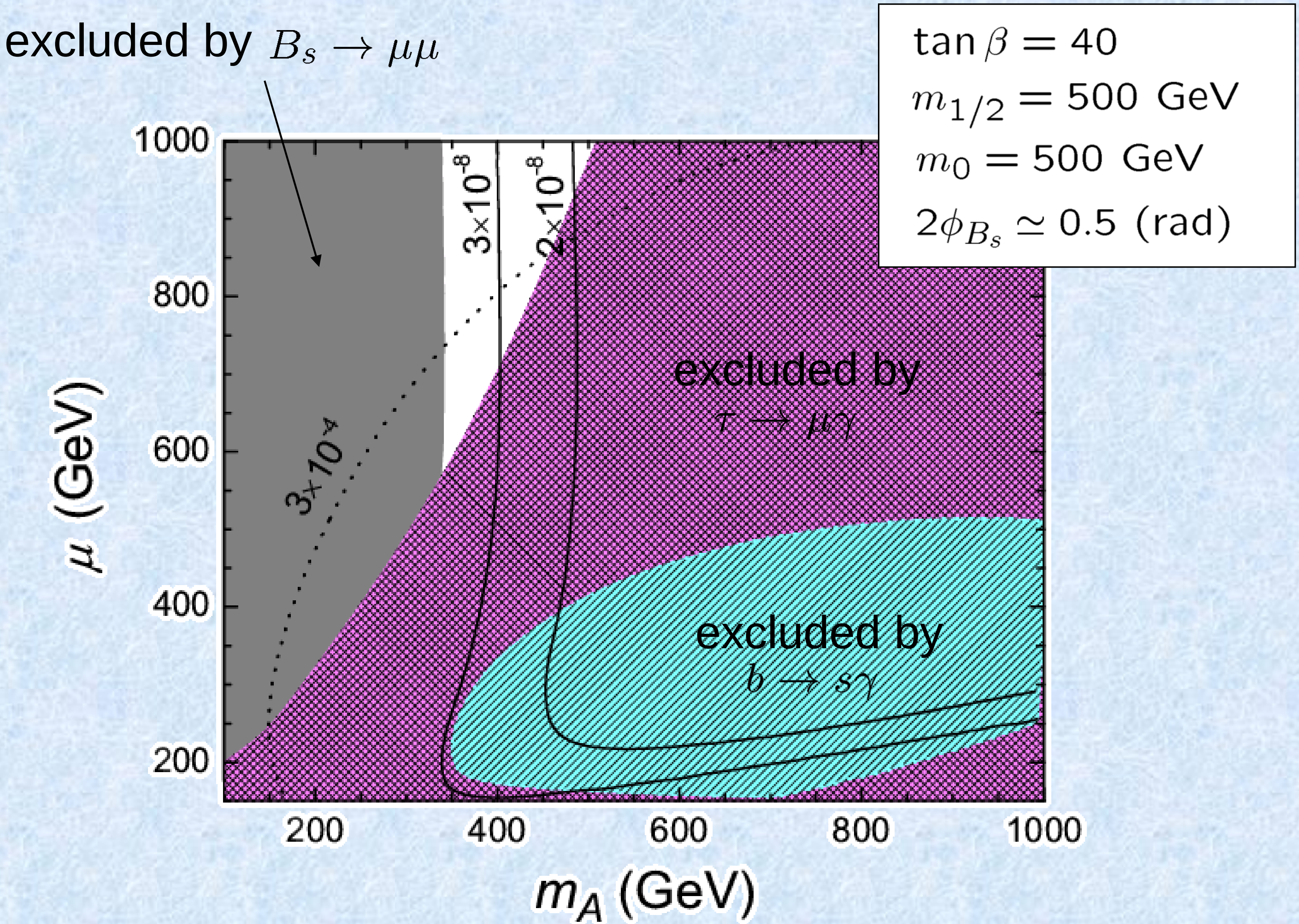
$b_3 = b_2 = 9,$
$b_1 = \frac{57}{5}$

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

In the SO(10) GUT model,
ϕ_{B_s} can be large due to the left-handed FCNC source.

Besides, $\tau \to \mu\gamma$ can be suppressed by a choice of vacua.

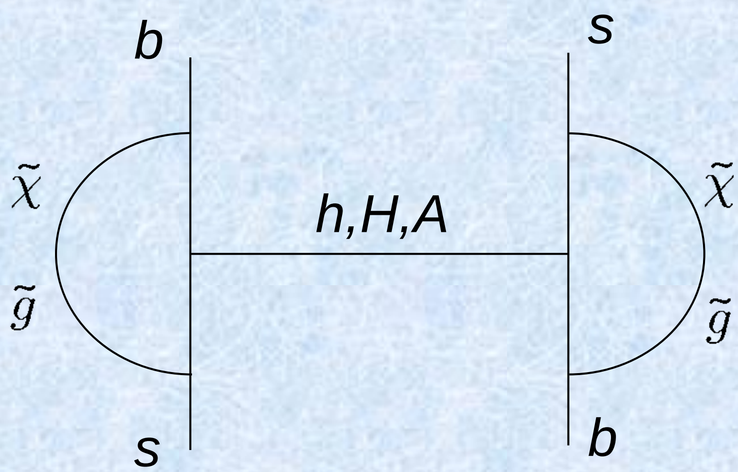
In the SU(5) GUT model,
$\tau \to \mu\gamma$ bound restricts the SUSY mass spectrum when the CP phase is large.


excluded by $B_s \to \mu\mu$
$\tan\beta = 40$
$m_{1/2} = 500$ GeV
$m_0 = 500$ GeV
$2\phi_{B_s} \simeq 0.5$ (rad)
1000
800
600
400
200
μ (GeV)
3×10^{-8}
2×10^{-8}
3×10^{-8}
excluded by $\tau \to \mu\gamma$
excluded by $b \to s\gamma$
200
400
600
800
1000
m_A (GeV)

	Wino box	Gluino box	Double Penguin
mSUGRA Minimal FV $(\kappa = 0)$	Win! (but small)		
$\kappa \neq 0$ $\tan\beta \sim 10$		Win!	
$\kappa \neq 0$ $\tan\beta \sim 40$ H, A: light			Win!

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

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



"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.

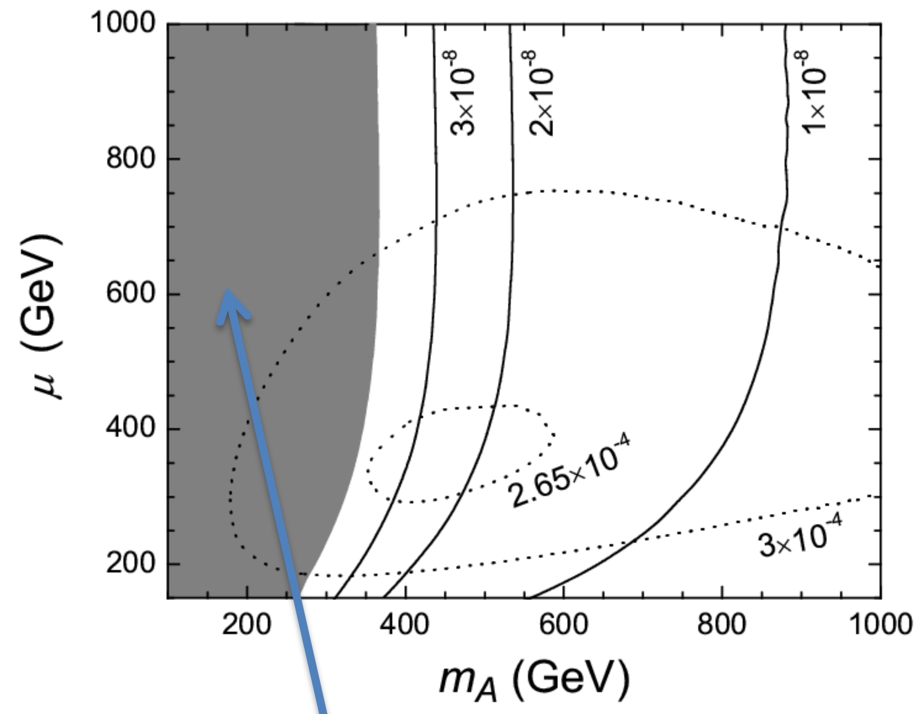
$$C_{7L}^{b\to s\gamma} \propto O(V_{ts})(\text{chargino}) - \delta^{\tilde{d}}_{LL,23}(\text{gluino})$$

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

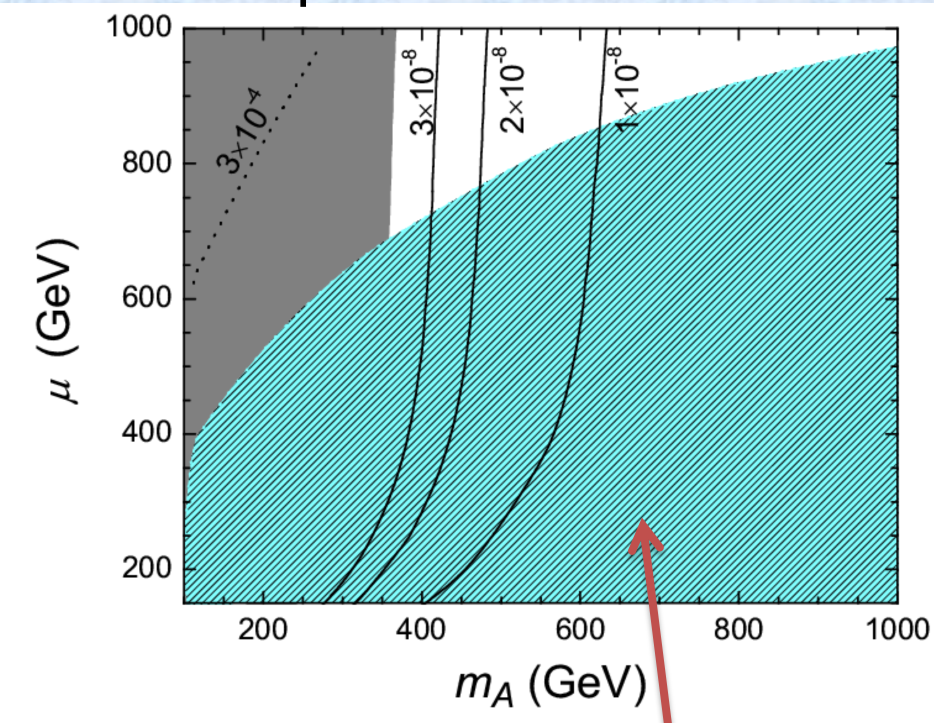
(Buras-Chankowski-Rosiek-Slawianowska)

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

*B*s amplitude is constructive.



*B*s 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.