CP Violating Lepton Asymmetry from B Decays in Supersymmetric Grand Unified Theories

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in Collaboration with B. Dutta and Y. Santoso
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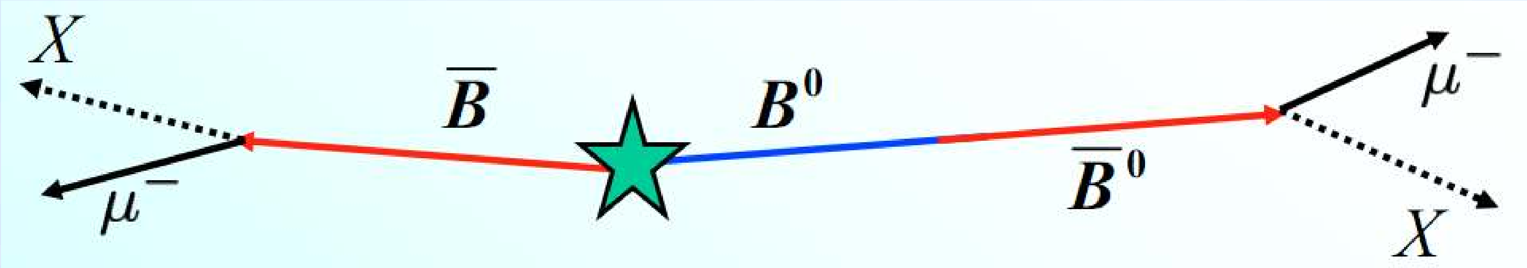
Menu

1. Introduction
2. FCNC scenario in GUTs
3. SUSY contributions to the mixing amplitude of B_s-$\bar{B}_s$
4. SU(5) with type I seesaw vs. SO(10) with type II seesaw
5. Constraints from $\tau \to \mu\gamma$, $B_s \to \mu\mu$ and $b \to s\gamma$

Dimuon charge asymmetry of semileptonic B decay [D0]



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

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

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

3.2 sigma deviation from SM

A hint of a large CP violating phase in B_s system!

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.

Basic Scenario of flavor violation in 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)

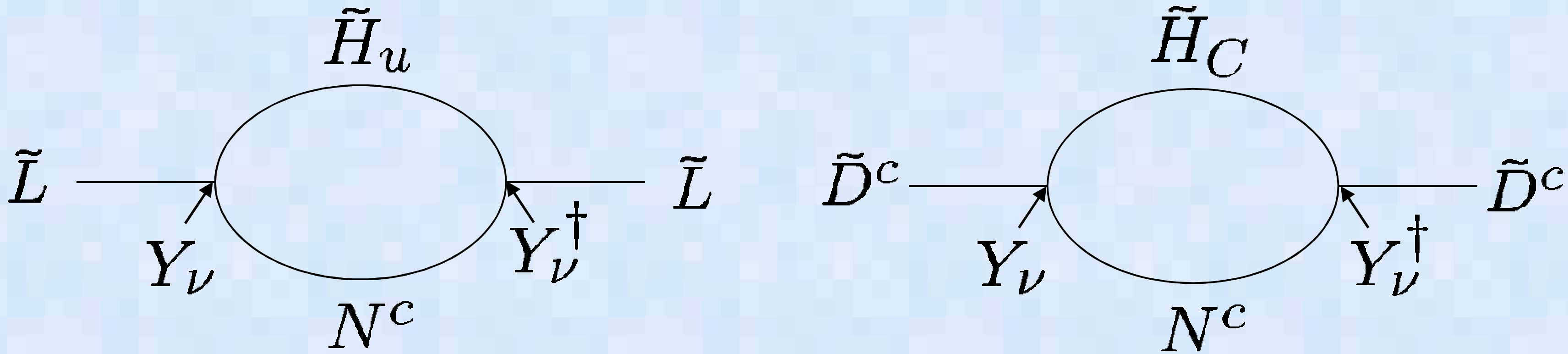
Investigating accurate measurement of FCNCs in quarks and leptons is very important to find a footprint of the GUT models.

SU(5) GUT

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

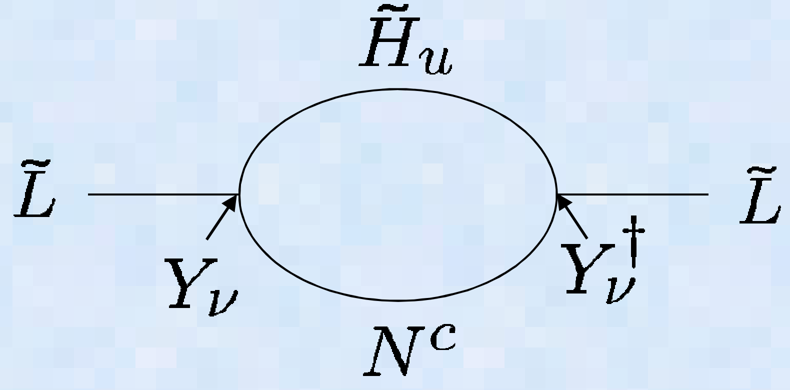
$Q, U^c, E^c \;:\; \mathbf{10}$ Right-handed neutrino : N^c

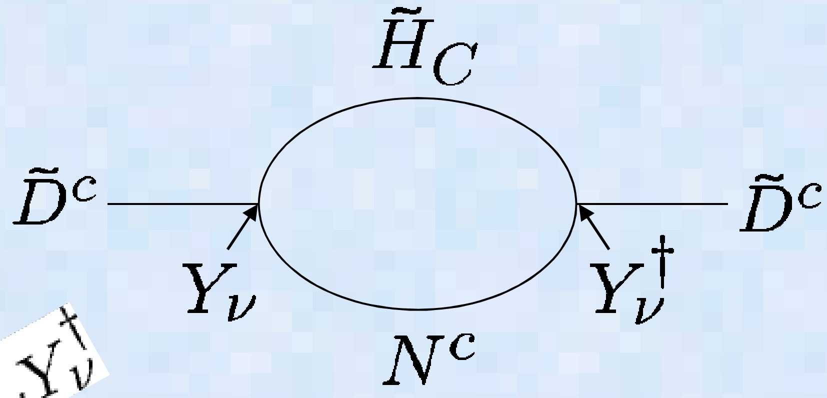
$$W_Y = Y_u\, \mathbf{10} \cdot \mathbf{10}\, H_5 + Y_d\, \mathbf{10} \cdot \bar{\mathbf{5}}\, H_{\bar{5}} + Y_\nu\, \bar{\mathbf{5}}\, N^c\, H_5$$



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.

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

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

size of A_s^{NP}

Origin of ϕ_s^{NP}

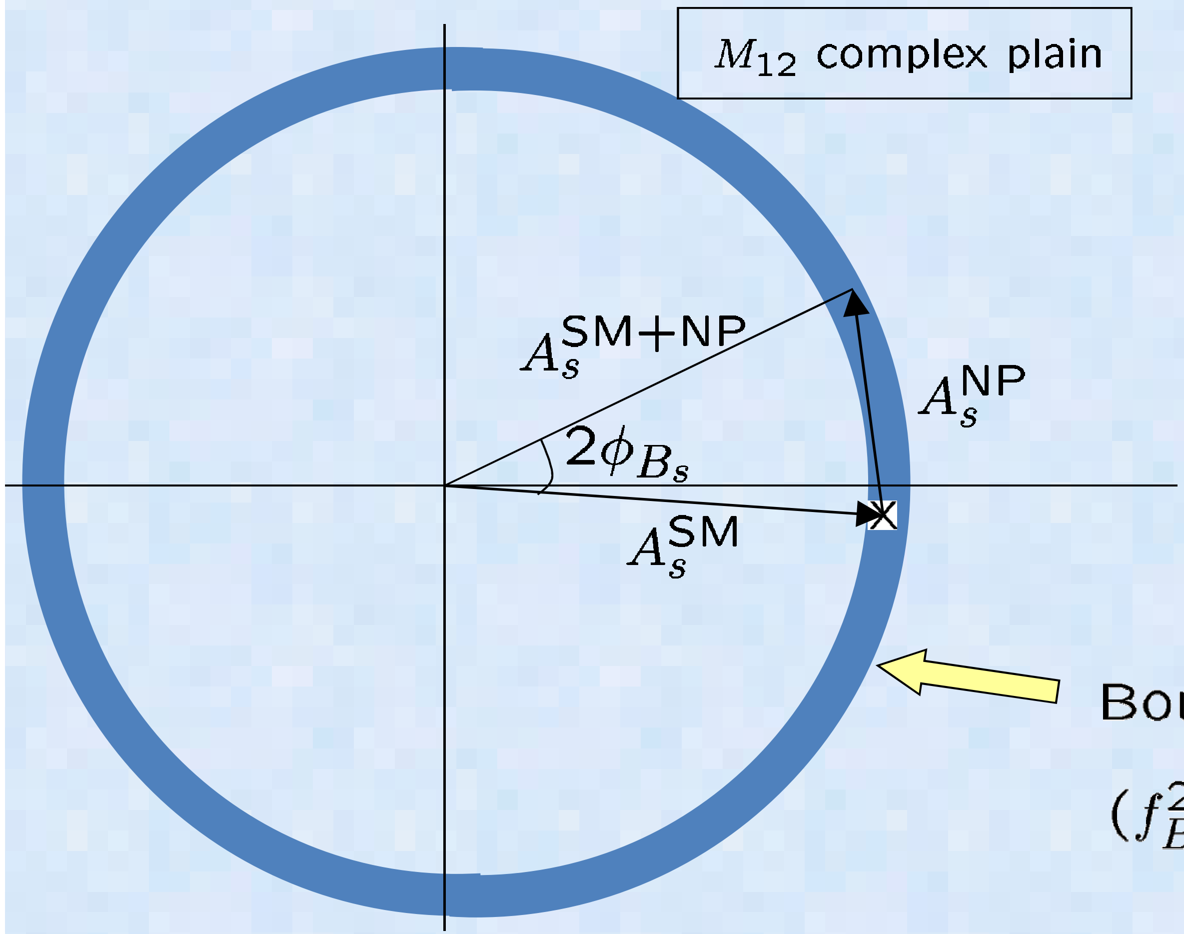
Definition

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

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

Cf.

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



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

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

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

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

Note:

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

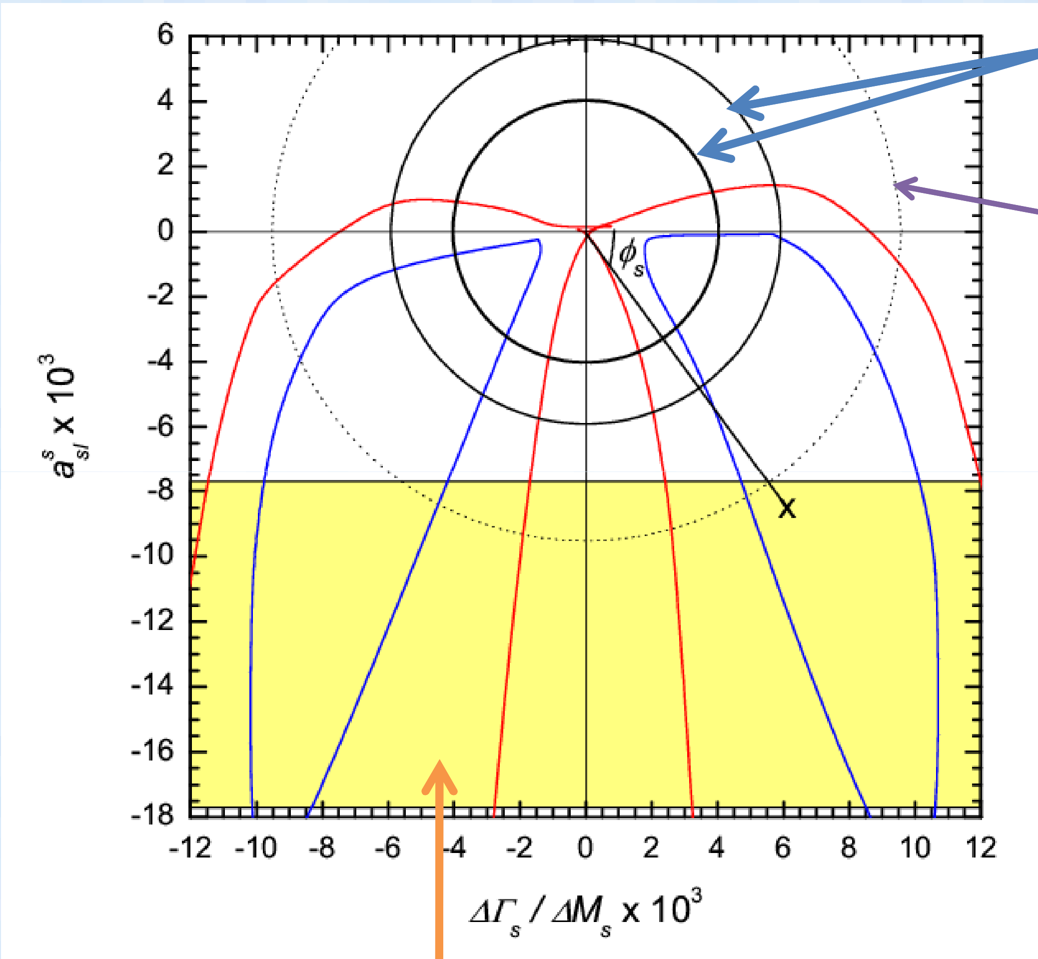
(More accurate)

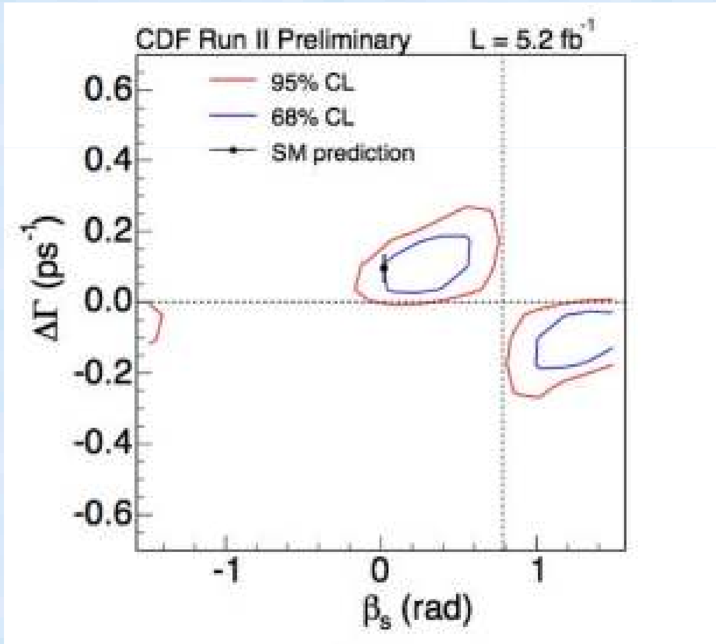
$$a_{sl}^s = \left|\frac{\Gamma_s^{12}}{M_s^{12}}\right| \sin\phi_s = \frac{\Delta\Gamma_s}{\Delta M_s} \tan\phi_s \qquad (a_{sl}^s)^2 + \left(\frac{\Delta\Gamma_s}{\Delta M_s}\right)^2 = \left|\frac{\Gamma_s^{12}}{M_s^{12}}\right|^2$$

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

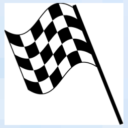
Lenz-Nierste

$$\left|\frac{\Gamma_s^{12}}{M_s^{12}}\right| = \frac{1}{C_{B_s}} \left|\frac{\Gamma_{12}^s}{M_{12}^s}\right|_{\mathrm{SM}}$$





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

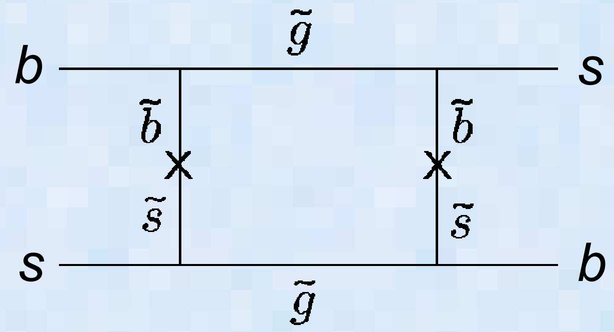


Check the scheme in this talk.

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

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

◆Gluino box contribution.



Mass insertion approximation:

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

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

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

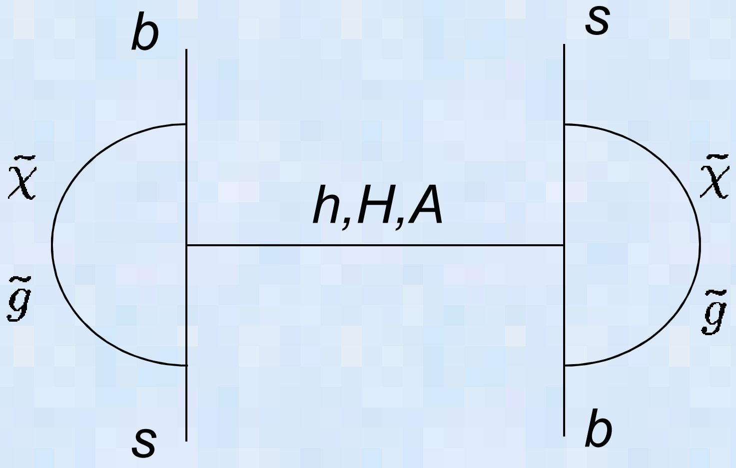
$\tilde{m}$: average squark mass

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

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

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

◆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

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

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

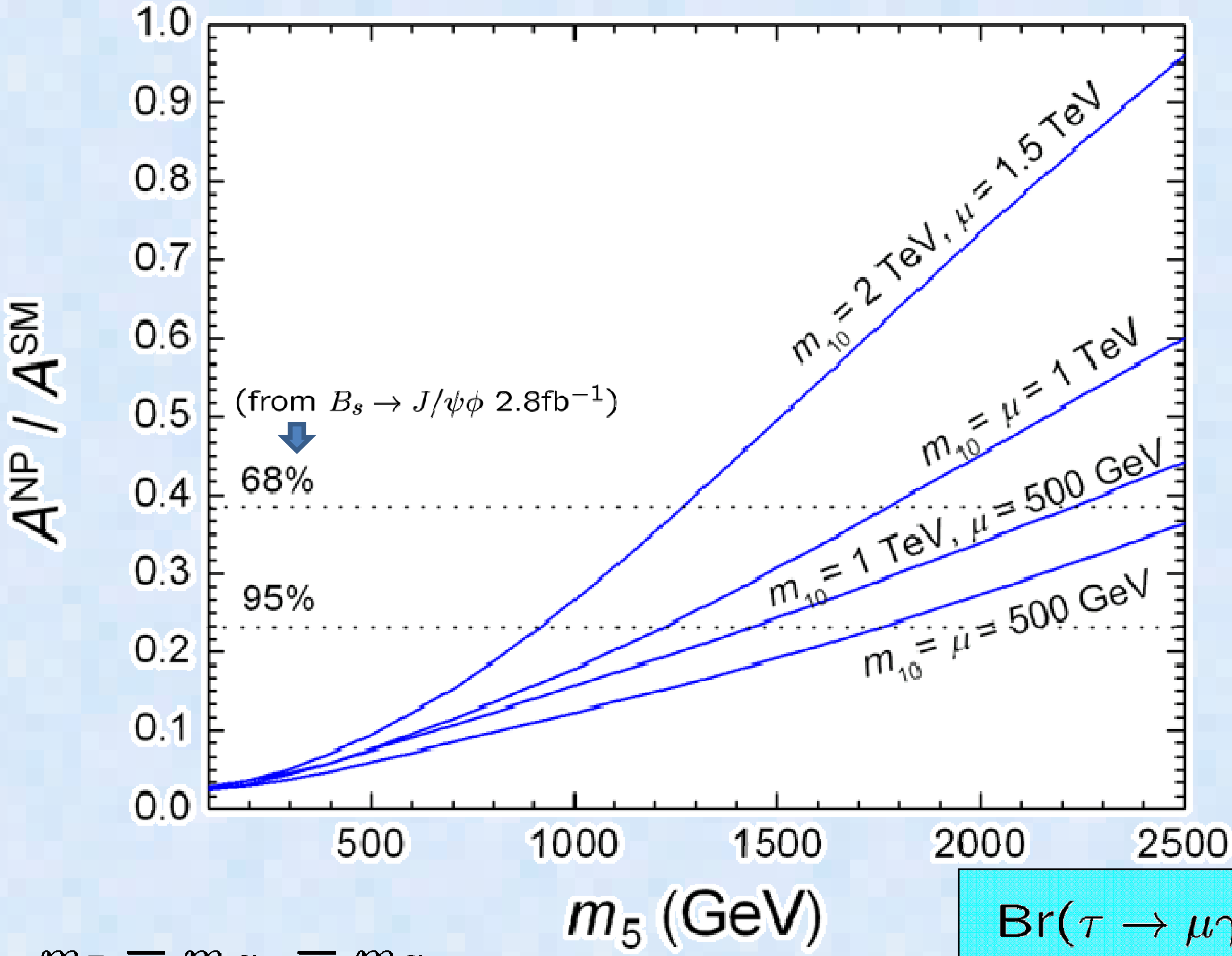
$$M^2_{\tilde{D}^c} \sim \begin{pmatrix} (1\mathrm{TeV})^2 + m_0^2 & & \\ & (1\mathrm{TeV})^2 + m_0^2 & \kappa m_0^2 \\ & \kappa m_0^2 & (1\mathrm{TeV})^2 + m_0^2 \end{pmatrix}$$

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

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 $\tau \to \mu\gamma$



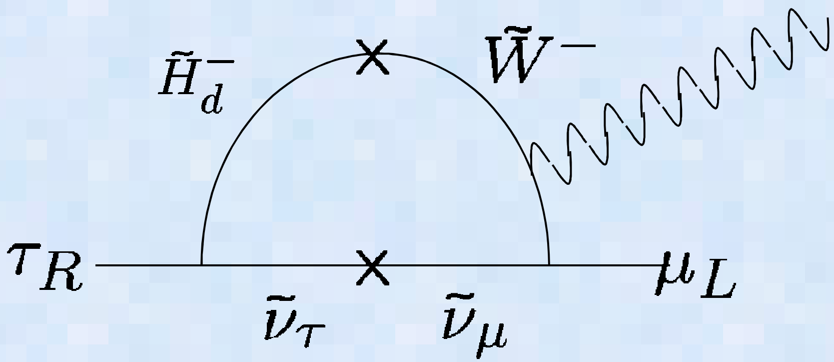
$$m_5 = m_{\tilde{D}^c} = m_{\tilde{L}}$$

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

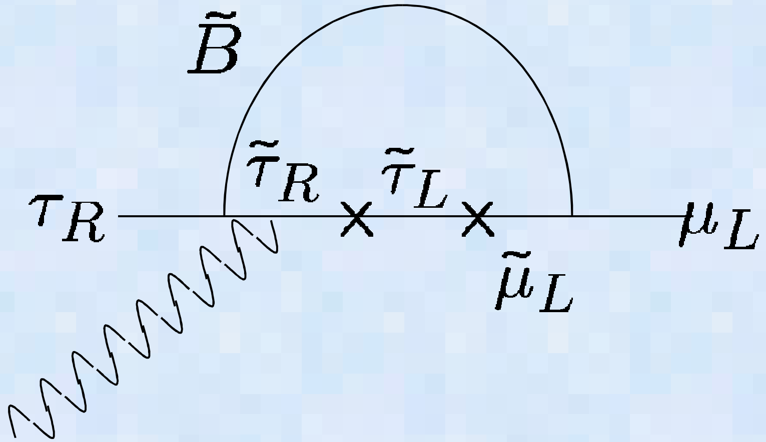
$\mathrm{Br}(\tau \to \mu\gamma) < 4.4 \times 10^{-8}$

$\tan\beta = 10$

$m_{1/2} = 300$ 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

SO(10) GUT

All Q, U^c, D^c, L, E^c, N^c are unified in **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: $M_L = f_L \langle \Delta_L^0 \rangle$ (Δ_L^0: SU(2)$_L$ triplet)

Type I: $M_R = f_R \langle \Delta_R^0 \rangle$

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

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

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

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

M_*: String/Planck scale

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

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

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

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

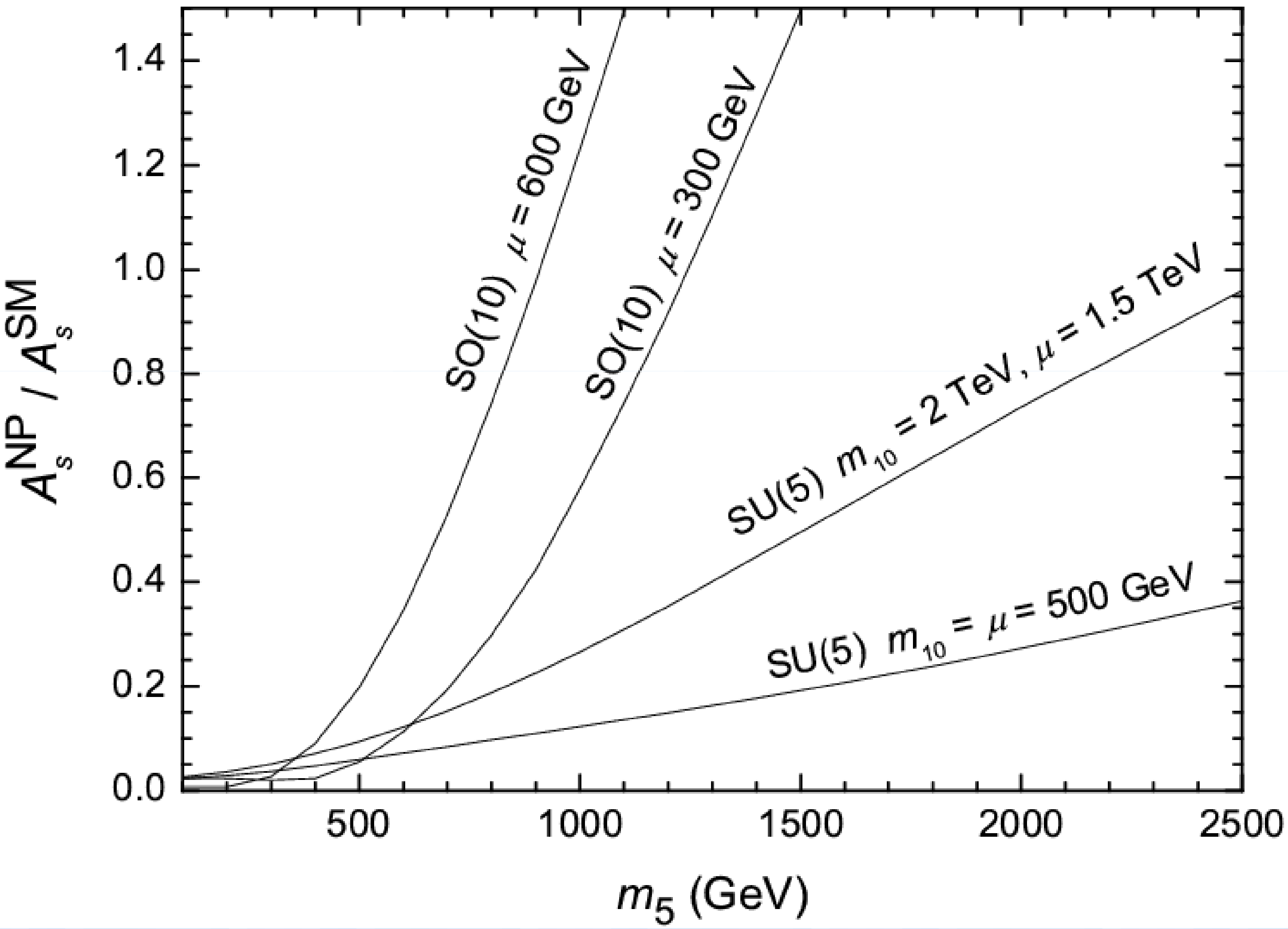
Flavor violating effects are larger in the box diagram in SO(10).

Cf. Only δ^d_{RR} is large in SU(5).

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

$\tan\beta = 10$

$m_{1/2} = 300$ GeV



Check the scheme in this talk.

- 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)

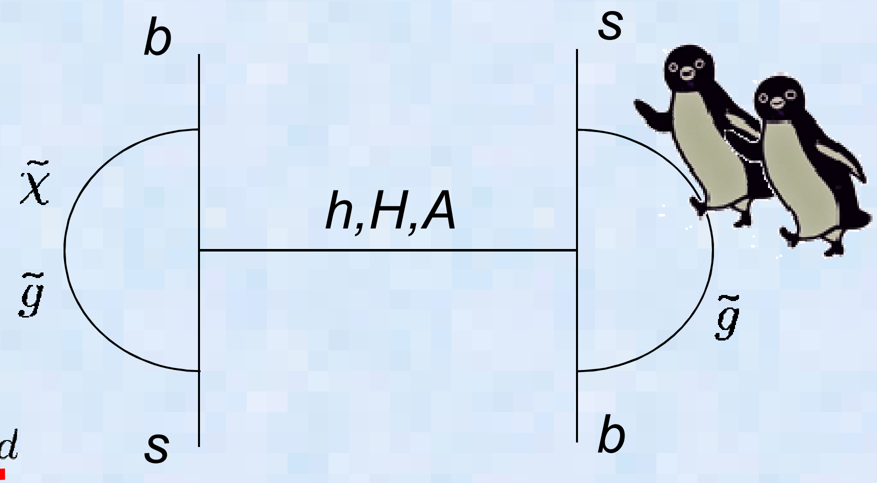
Both δ^d_{LL} and δ^d_{RR} is large in SO(10).

“SO(10) > SU(5)” for box contribution

◆Double penguin contribution

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

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



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

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

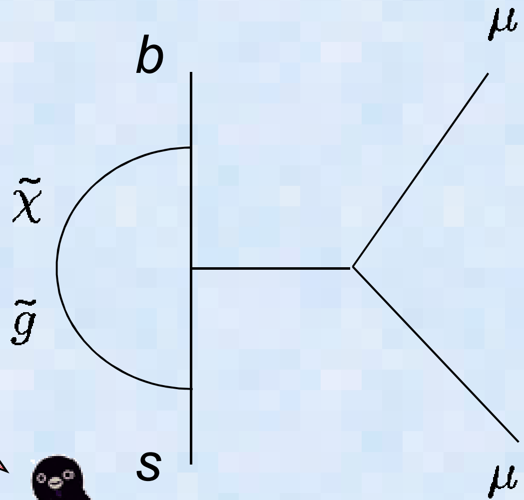
$$\epsilon_{32} \propto \qquad + \delta^{\tilde{d}}_{RR,23}(\text{gluino})$$

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

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

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

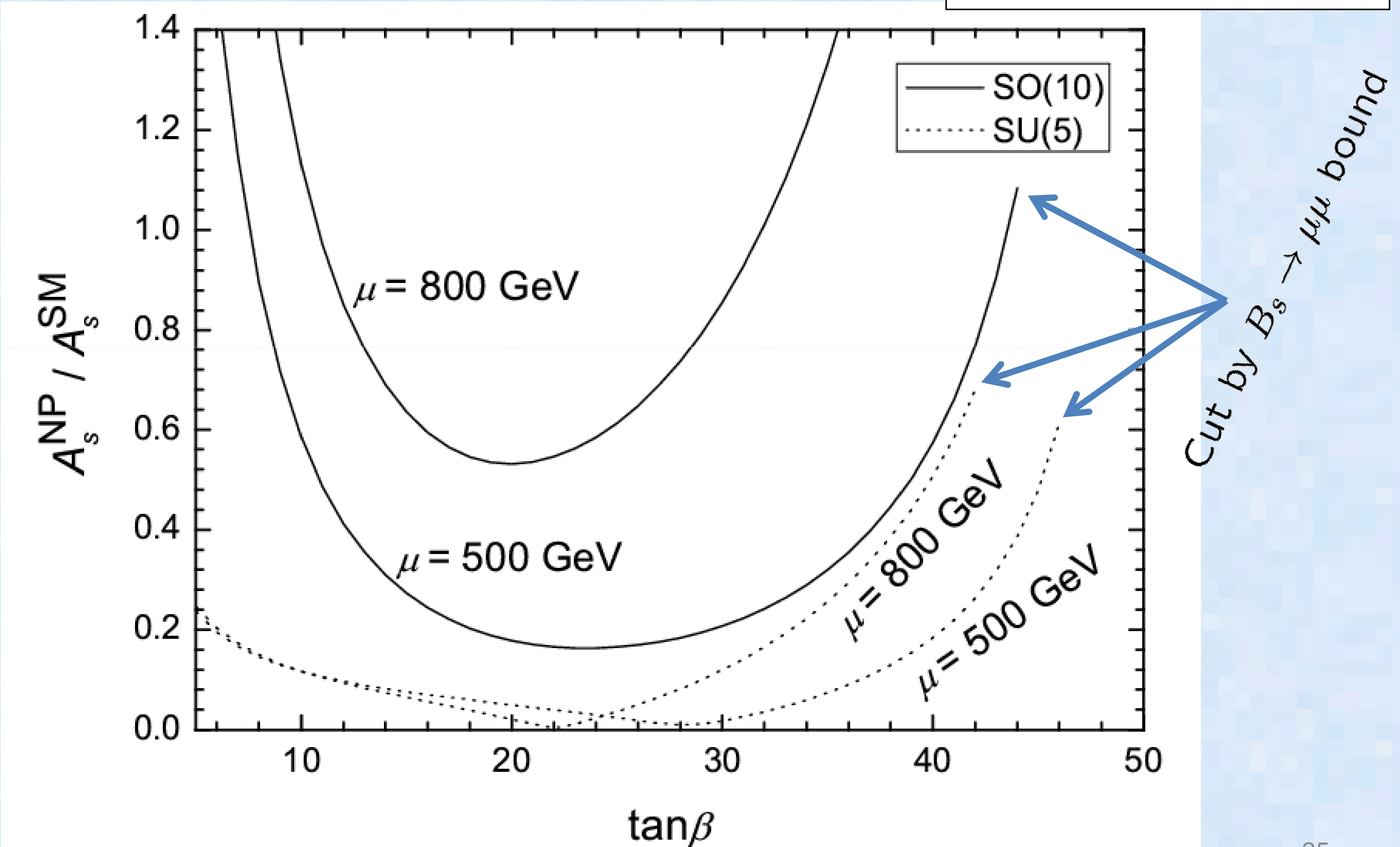
For large $\tan\beta$ and small m_A,
the large CP phase is possible.



However,

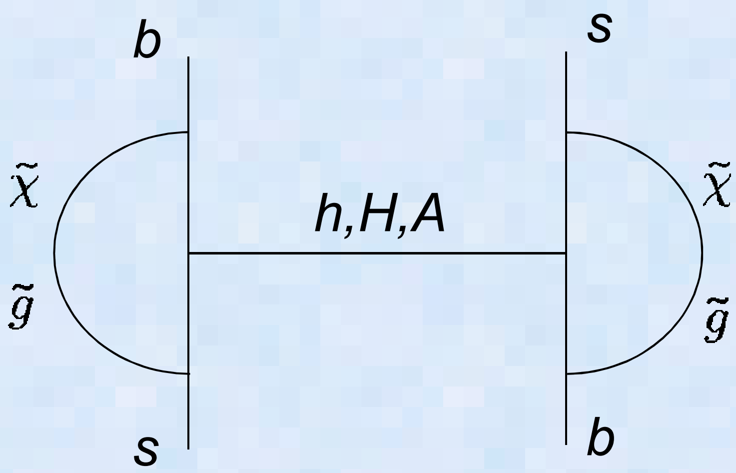
$$\mathrm{Br}(B_s \to \mu\mu) \propto \tan^6\beta/m_A^4$$

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



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

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



"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.

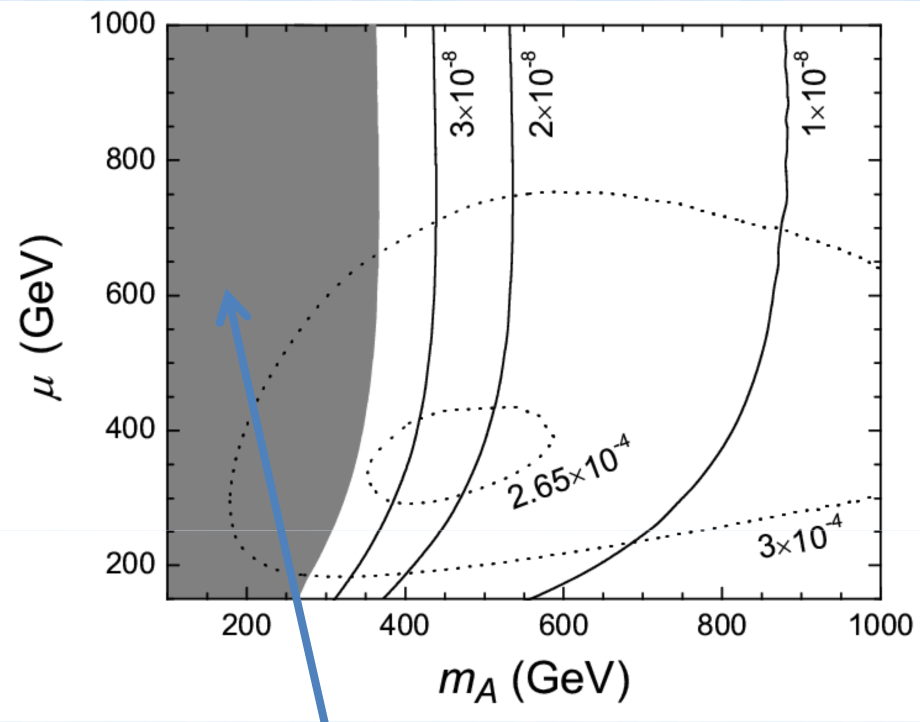
$$C_{7L}^{b\to s\gamma} \propto O(V_{ts})(\text{chargino}) - \delta^{\tilde{d}}_{LL,23}(\text{gluino})$$

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

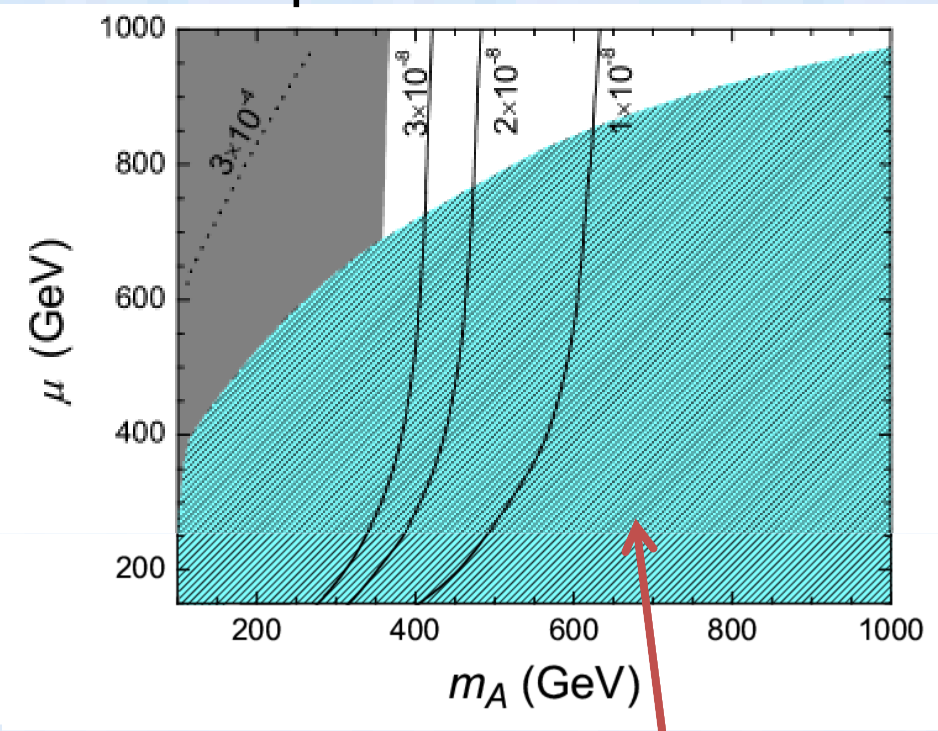
(Buras-Chankowski-Rosiek-Slawianowska)

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

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.

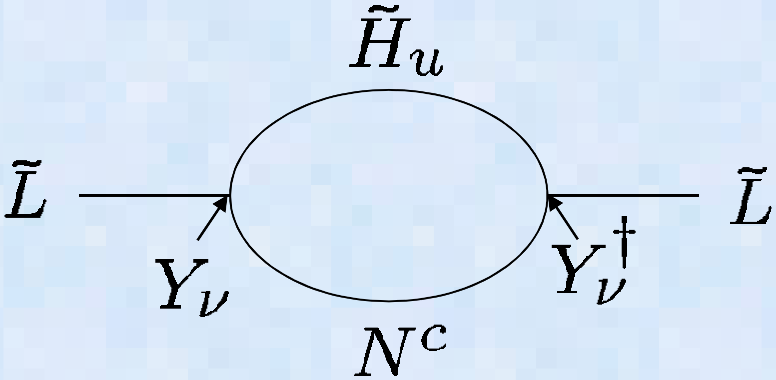
Possible violation of the quark-lepton unification

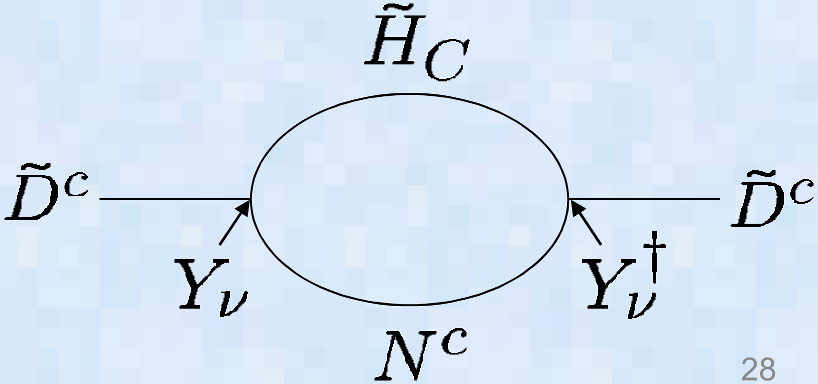
To relax the constraint, one needs $\kappa_{\rm quark} > \kappa_{\rm lepton}$.

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.

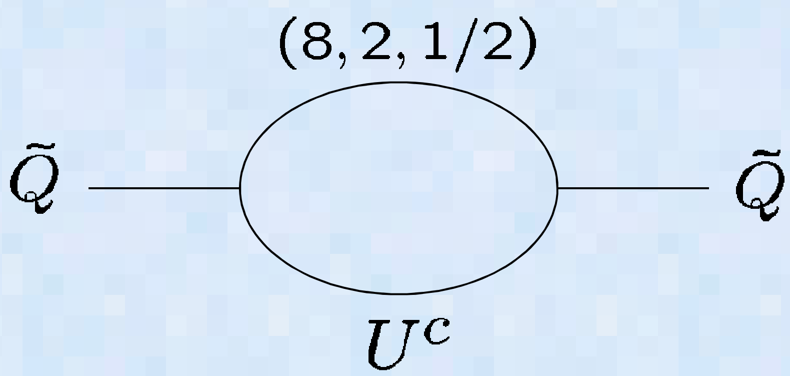
If $SU(2)_R$ remains below the SO(10) breaking scale, $SU(2)_R$ Higgsino induces κ_ℓ rather than κ_q. Wrong direction!

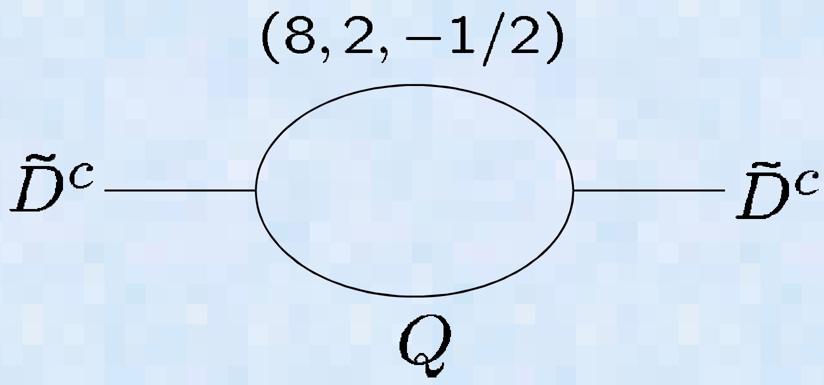
If (**8**,**2**,1/2) (in **126** Higgs) is light, it generates only κ_q.

Right direction!

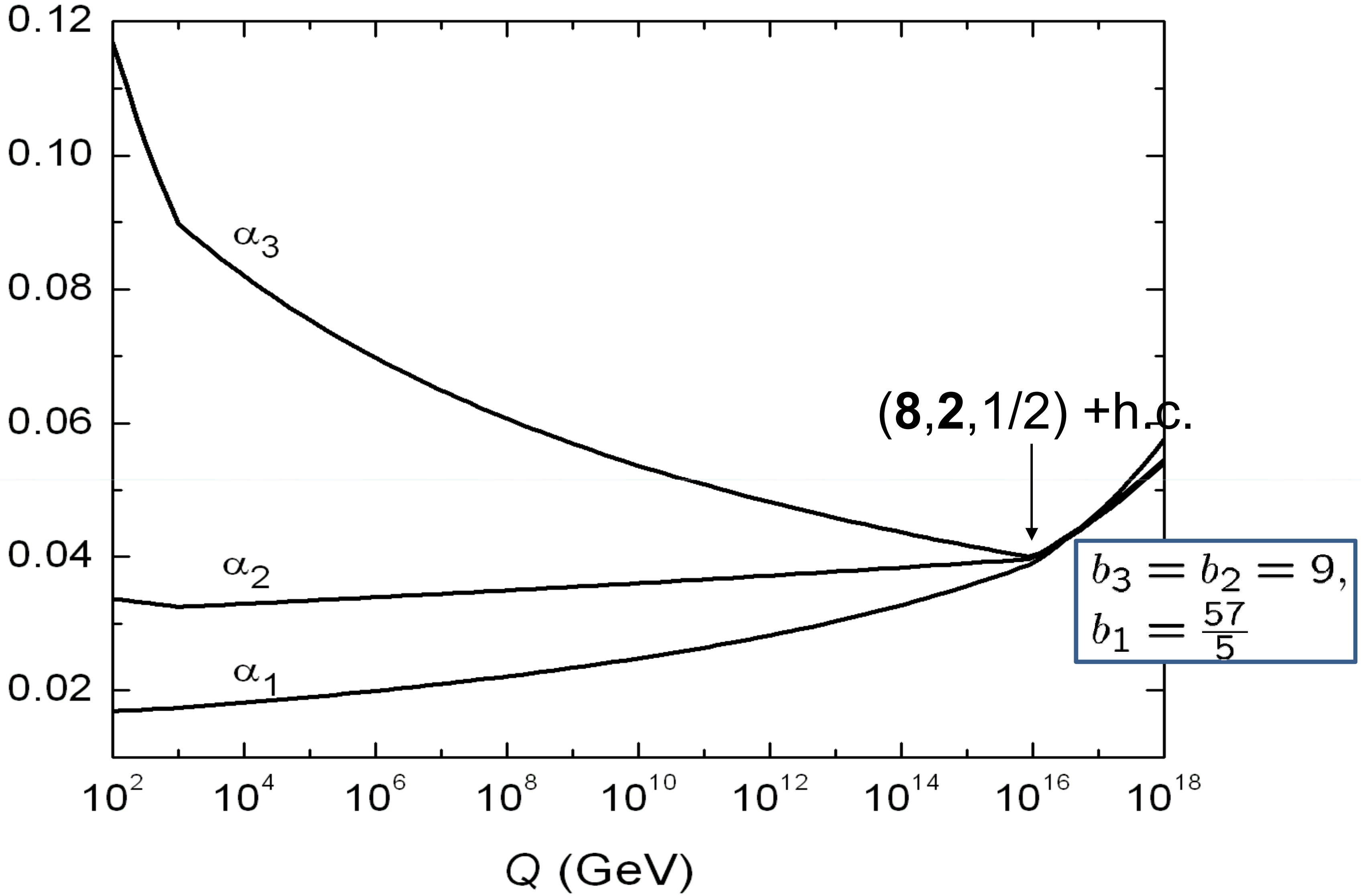
Light (**8**,**2**,1/2) is also proper direction to suppress proton decay.

(Dutta-YM-Mohapatra, arXiv: 0712.1206)





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

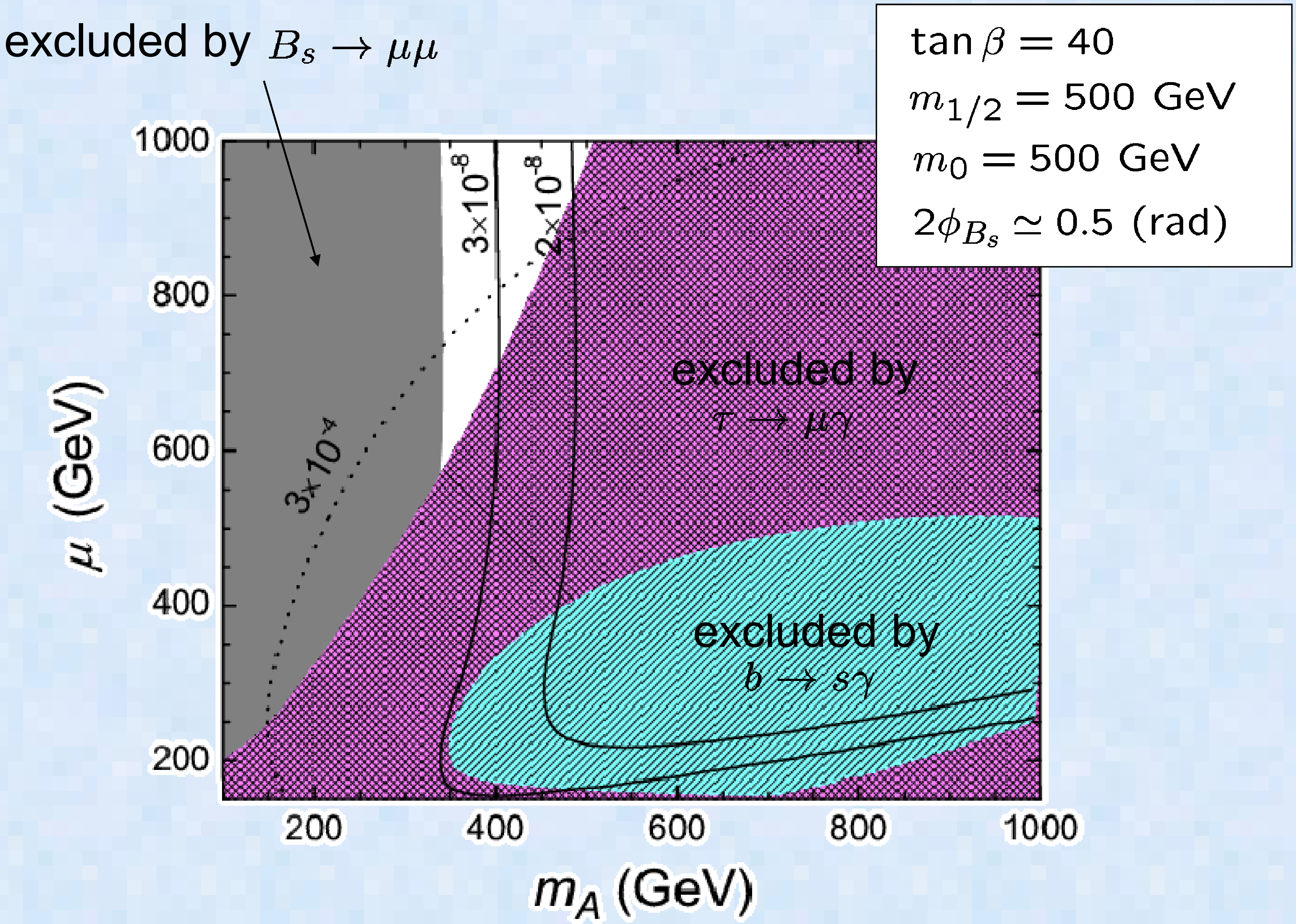


Gauge symmetry does not recover, but couplings run almost unitedly.

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
3×10⁻⁴
excluded by
$\tau \to \mu\gamma$
excluded by
$b \to s\gamma$
200
400
600
800
1000
m_A (GeV)

For a given large CP phase,
there is a lower bound of $\mathrm{Br}(B_s \to \mu\mu)$.

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 $\mathrm{Br}(B_s \to \mu\mu)$
$m_0 = m_{1/2} = 500$ 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,
it is expected that
$B_s \to \mu\mu$ is observed soon.

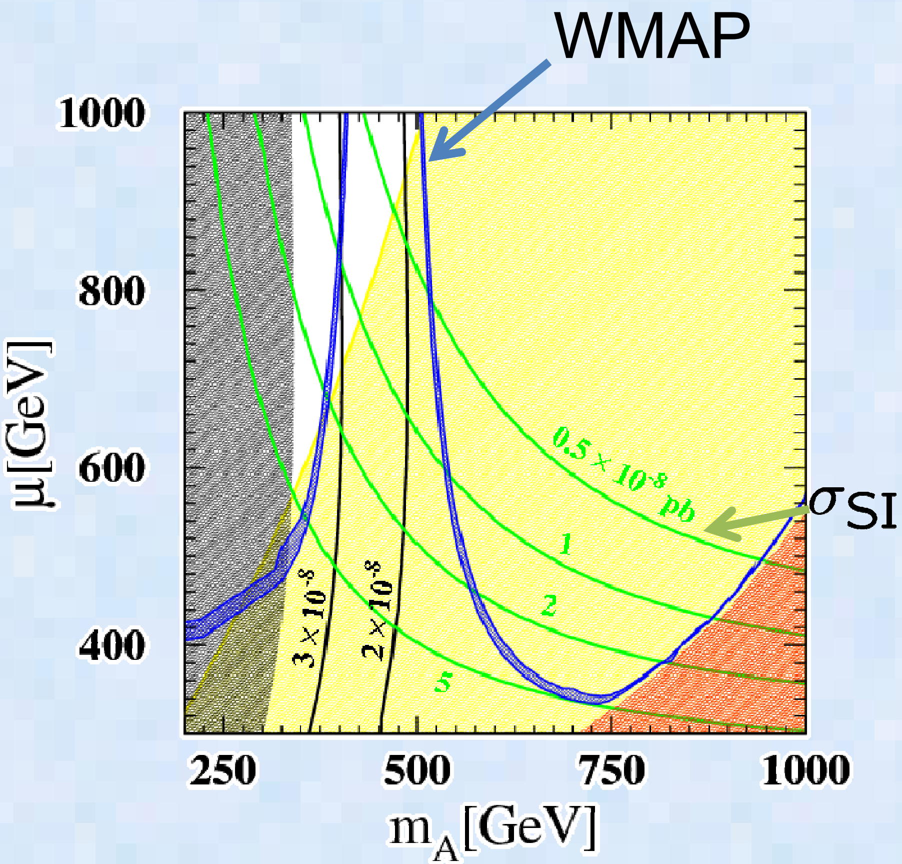
$\tan\beta = 40$

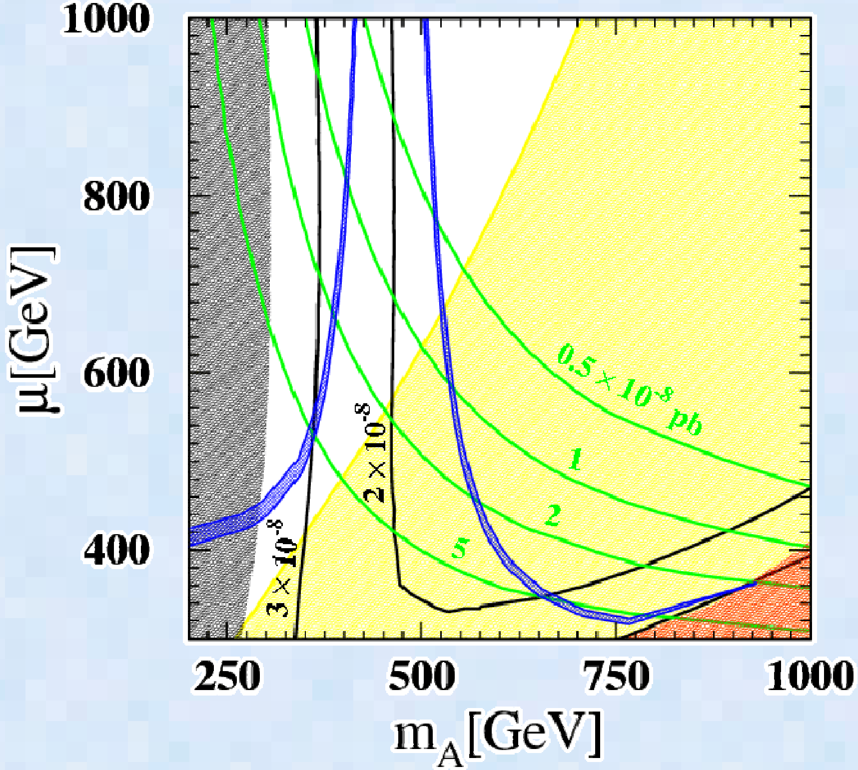
$\mu < 1$ TeV

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

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

$2\phi_{B_s} \simeq 0.5$ (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.

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

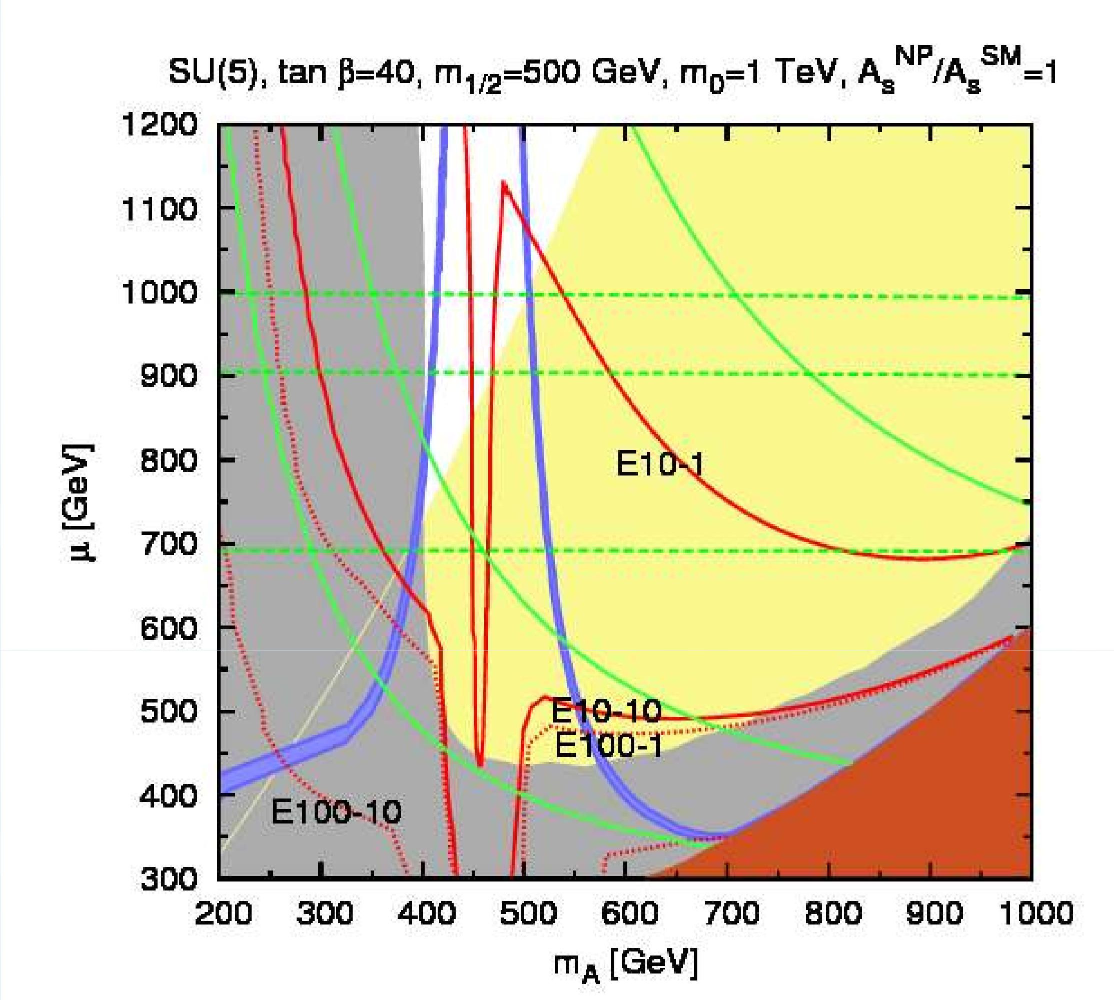
Summary

- We study the CP phase ϕ_{B_s} in the mixing amplitude in SUSY GUT models.

- SUSY spectrum is restricted in SU(5) model. This result is important for LHC era.

- The phase is enhanced in SO(10), and large phase can be allowed by a choice of vacua.

- 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 $km^{-2}\ yr^{-1}$