Flavor and CP Violations

– as probes of heavy SUSY scenario –

Takeo Moroi (Tokyo)

Refs:

TM & Nagai, PLB 723 ('13) 107

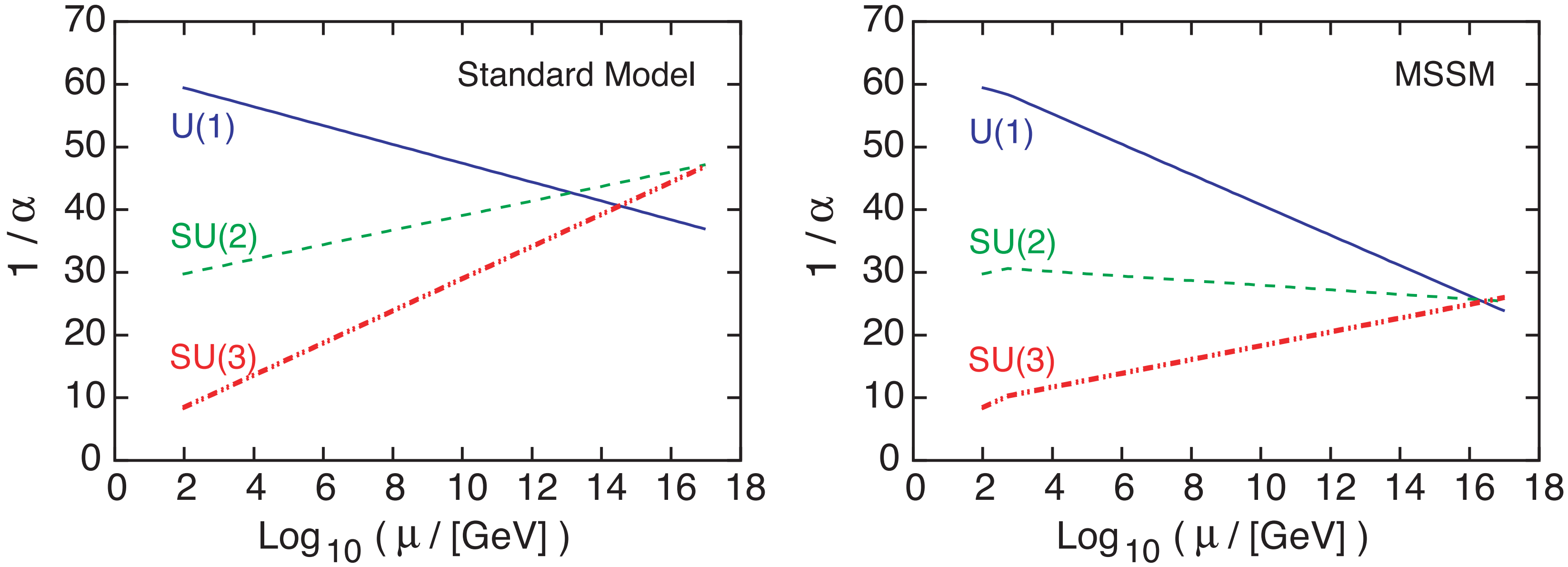
TM, Nagai & Yanagida, PLB 728 (2014) 342

Toyama, Japan, Feb. 2014

1. Introduction

Supersymmetry: good & bad

- Gauge coupling unification can be realized



- Dark matter candidate exists (neutralino, gravitino, $\cdots$)
- SUSY particles have not been discovered yet

  $\Rightarrow$ For e.g., $m_{\tilde{q}} \gtrsim 1.8$ TeV & $m_{\tilde{g}} \gtrsim 1.4$ TeV in mSUGRA

- $m_h \simeq 125 - 126$ GeV looks heavier than naive expectation

One possibility: Heavy sfermions: $m_{\tilde{f}} \sim O(10 \text{ TeV})$

- Focus-point

  [Feng, Matchev & TM ('99)]

- (Some class of) anomaly-mediation

  [Giudice, Luty, Murayama & Rattazzi ('99)]

- Split SUSY

  [Giudice & Romanino ('04); Arkani-Hamed, Dimopoulos ('04); Wells ('04)]

- Minimal gravity mediation

  [Ibe, TM & Yanagida ('06); Ibe & Yanagida ('11)]

- $\cdots$

LHC may not find the SUSY signals in heavy SUSY scenario

$\Rightarrow$ Flavor and CP physics may be useful

Today, I will talk about:

- Flavor and CP violations in SUSY model (paying particular attention to the case with heavy SUSY particles)

<u>Outline</u>

1. Introduction
2. K^0-$\bar{K}^0$ Mixing
3. Leptonic Flavor and CP Violations
4. Summary

2. K^0-$\bar{K}^0$ Mixing

K^0-$\bar{K}^0$ system: CP and Hamiltonian eigenstates differ

- $|K_L\rangle \simeq |K_{CP=-}\rangle - \epsilon_K |K_{CP=+}\rangle$
- $|K_S\rangle \simeq |K_{CP=+}\rangle + \epsilon_K |K_{CP=-}\rangle$

$$CP|K^0\rangle = |\bar{K}^0\rangle \quad \Rightarrow \quad |K_{CP=\pm}\rangle = \frac{1}{\sqrt{2}}(|K^0\rangle \pm |\bar{K}^0\rangle)$$

Hamiltonian and ϵ_K parameter

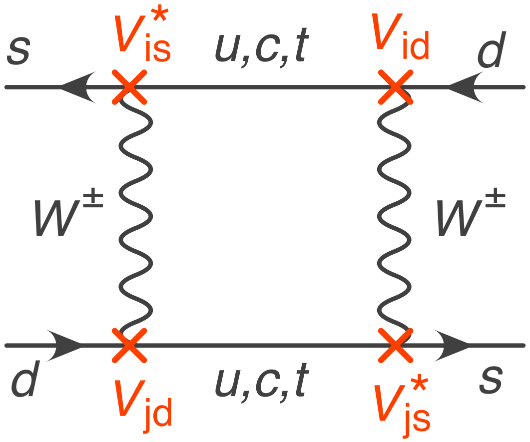
$$\mathcal{H}_K = \begin{pmatrix} \langle K^0|\hat{\mathcal{H}}|K^0\rangle & \langle K^0|\hat{\mathcal{H}}|\bar{K}^0\rangle \\ \langle \bar{K}^0|\hat{\mathcal{H}}|K^0\rangle & \langle \bar{K}^0|\hat{\mathcal{H}}|\bar{K}^0\rangle \end{pmatrix} = \begin{pmatrix} M_{11} + \frac{i}{2}\Gamma_{11} & M_{12} + \frac{i}{2}\Gamma_{12} \\ M_{12}^* + \frac{i}{2}\Gamma_{12}^* & M_{11} + \frac{i}{2}\Gamma_{11} \end{pmatrix}$$

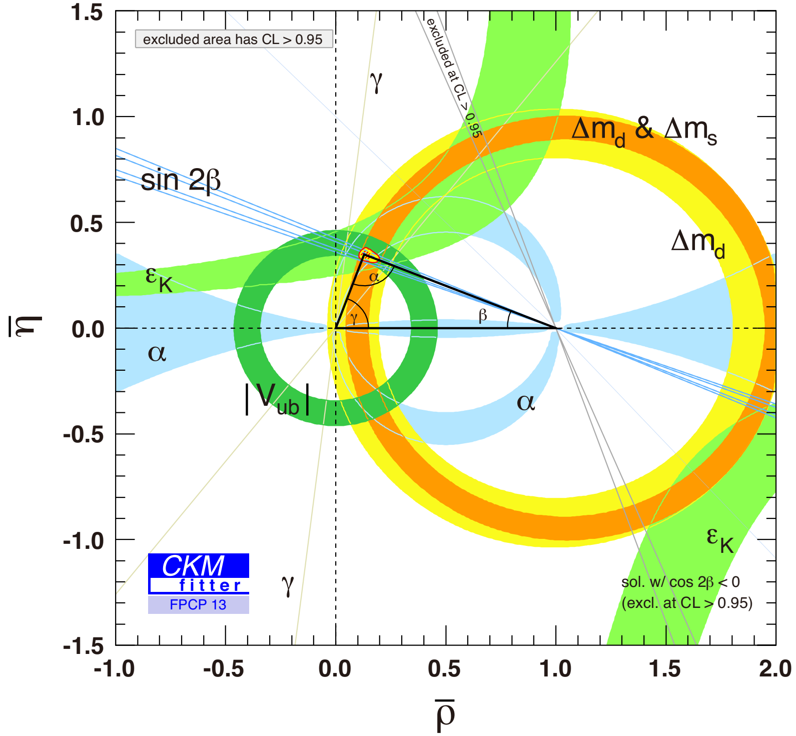
We take Wu-Yang phase convention: $\langle (2\pi)_{I=0} | K_{CP=-}\rangle = 0$

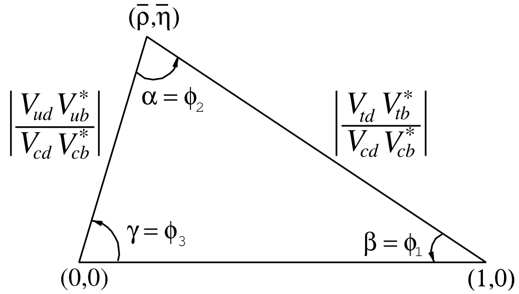
$$\Rightarrow \epsilon_K \simeq \frac{i}{2} \frac{\Im M_{12} - i\Im\Gamma_{12}/2}{\Re M_{12} - i\Re\Gamma_{12}/2}$$

$\Rightarrow$ CP violation, if $\Im M_{12} \neq 0$ or $\Im \Gamma_{12} \neq 0$

In the SM, K^0-$\bar{K}^0$ mixing originates from $W^\pm$-boson loop







[CKMfitter ('13)]

- $|\epsilon_K^{(\text{exp})}| = (2.228 \pm 0.011) \times 10^{-3}$
- $|\epsilon_K^{(\text{exp})}| - |\epsilon_K^{(\text{SM})}| = (3.8 \pm 2.7) \times 10^{-4} \quad \Rightarrow |\epsilon_K^{(\text{extra})}| < 9.2 \times 10^{-4}\ (2\sigma)$

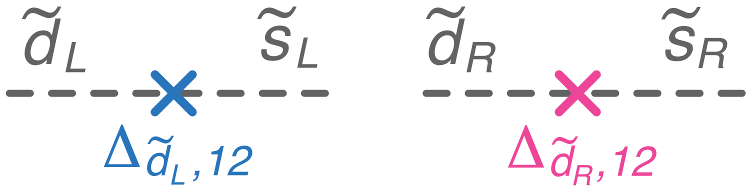
In SUSY model, new sources of flavor and CP violations exist

$\Rightarrow$ Off-diagonal elements of sfermion mass matrices

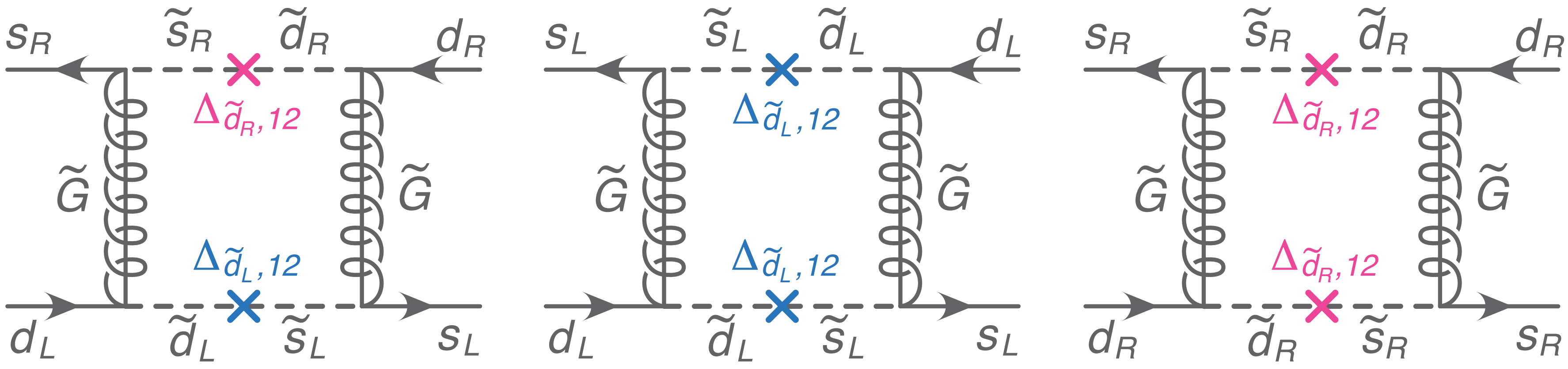
$$\mathcal{M}^2_{\tilde{Q}} = m^2_{\tilde{q}} \begin{pmatrix} \Delta_{\tilde{Q},11} & \Delta_{\tilde{Q},12} & \Delta_{\tilde{Q},13} \\ \Delta_{\tilde{Q},21} & \Delta_{\tilde{Q},22} & \Delta_{\tilde{Q},23} \\ \Delta_{\tilde{Q},31} & \Delta_{\tilde{Q},32} & \Delta_{\tilde{Q},33} \end{pmatrix} \qquad \tilde{Q} = \tilde{u}_L, \tilde{u}^{c*}_R, \tilde{d}_L, \tilde{d}^{c*}_R$$

$$\mathcal{M}^2_{\tilde{L}} = m^2_{\tilde{l}} \begin{pmatrix} \Delta_{\tilde{L},11} & \Delta_{\tilde{L},12} & \Delta_{\tilde{L},13} \\ \Delta_{\tilde{L},21} & \Delta_{\tilde{L},22} & \Delta_{\tilde{L},23} \\ \Delta_{\tilde{L},31} & \Delta_{\tilde{L},32} & \Delta_{\tilde{L},33} \end{pmatrix} \qquad \tilde{L} = \tilde{e}_L, \tilde{e}^{c*}_R, \tilde{\nu}_L$$

Mass terms: $\mathcal{L}_{\text{mass}} = -[\mathcal{M}^2_{\tilde{d}_L}]_{ij} \tilde{d}^*_{L,i} \tilde{d}_{L,j} - [\mathcal{M}^2_{\tilde{d}^c_R}]_{ij} \tilde{d}^c_{R,i} \tilde{d}^{c*}_{R,j} - \cdots$



Diagrams contributing to ϵ_K & Δm_K



(LR) (LL) (RR)

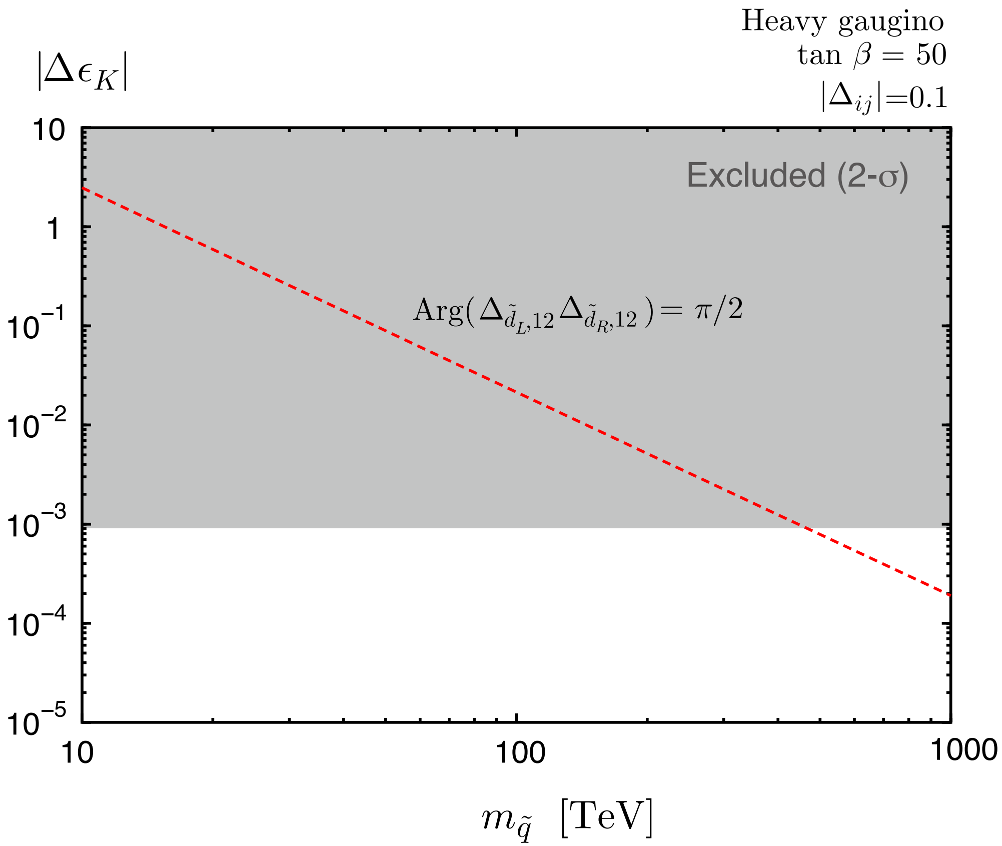
⇒ Important parameters: $\Delta_{\tilde{d}_L,12}$ & $\Delta_{\tilde{d}_R,12}$

K-$\bar{K}$ mixing gives serious constraints on the MSSM

⇒ It often requires $m_{\rm SUSY} \gtrsim O(100\ \text{TeV})$, if off-diagonal elements of the squark mass matrices are sizable

[Gabbiani, Gabrielli, Masiero & Silvestrini ('96)]

Numerical result



- $M_3 = m_{\tilde{q}}$
- $\Delta_{\tilde{d},12} = 0.1$
- $\mathrm{Arg}(\Delta_{\tilde{d}_L,12}\Delta_{\tilde{d}_R,12}) = \pi/2$

$\Rightarrow$ ϵ_K often gives a serious constraint on the MSSM

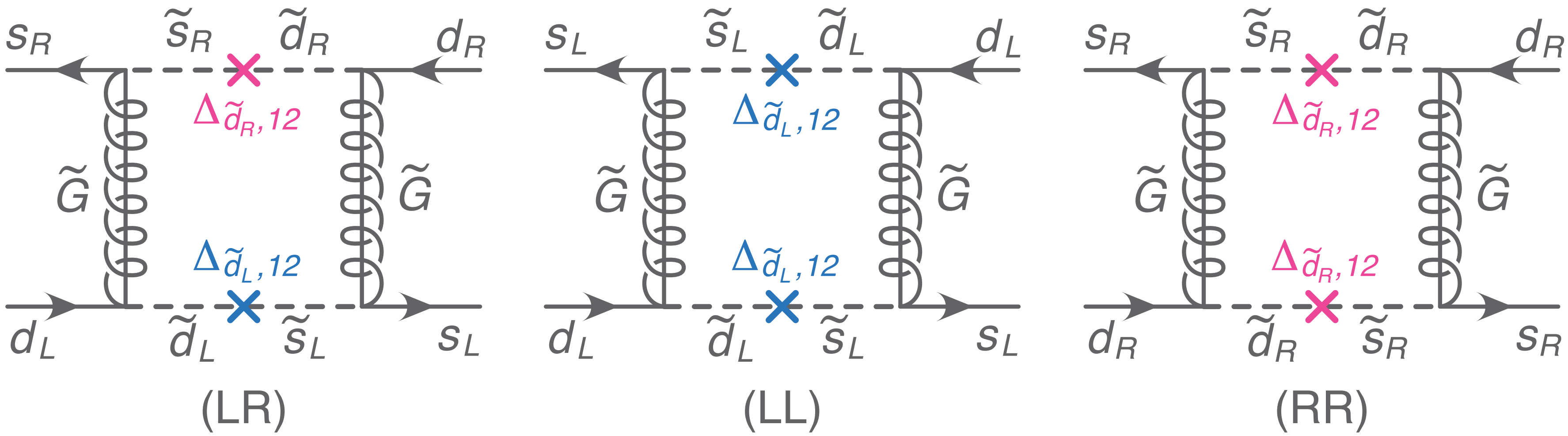
$\Rightarrow$ Constraints from Δm_K and Δm_B are less stringent (assuming maximal CP violation)

$\epsilon_K^{(\text{SUSY})}$ may be suppressed, if $\mathcal{M}^2_{\tilde{d}_L} \simeq \mathcal{M}^2_{\tilde{d}_R}{}^* \;\Rightarrow\; \Delta_{\tilde{d}_L} \simeq \Delta^*_{\tilde{d}_R}$

[TM & Nagai ('13)]

⇒ This may be realized in $SO(10)$-GUT (if D-term contribution is small enough)

If $\mathcal{M}^2_{\tilde{d}_L} \simeq \mathcal{M}^2_{\tilde{d}_R}{}^*$, sum of the following diagrams becomes real



Lagrangian (the most important part):

$$\mathcal{L} = -i\sqrt{2}g_3(\tilde{d}_L^\dagger T^a d_L)\tilde{G}^a + i\sqrt{2}g_3(\tilde{d}_R^c T^a \bar{d}_R^c)\bar{\tilde{G}}^a$$
$$+ \tilde{d}_{L,I}^\dagger \mathcal{M}^2_{\tilde{d}_L,IJ}\tilde{d}_{L,J} + \tilde{d}_{R,I}^c \mathcal{M}^2_{\tilde{d}_R,IJ}\tilde{d}_{R,J}^{c\dagger} + \cdots$$

If $\mathcal{M}^2_{\tilde{d}_L} = \mathcal{M}^2_{\tilde{d}_R}{}^*$, C invariance approximately holds

- $\tilde{d}_L \leftrightarrow \tilde{d}_R^c$
- $d_L \leftrightarrow d_R^c$

ϵ_K is suppressed due to this (approximate) C invariance

$\Rightarrow \epsilon_K \neq 0$, due to:

- Violation of $\mathcal{M}^2_{\tilde{d}_L} = \mathcal{M}^2_{\tilde{d}_R}{}^*$
- $SU(2)_L$ and $U(1)_Y$ interactions

The relation $\mathcal{M}^2_{\tilde{d}_L} = \mathcal{M}^{2\,*}_{\tilde{d}_R}$ is affected by RG effects

Effects of third-generation Yukawas may be important

Case with (almost) universal scalar mass at the GUT scale

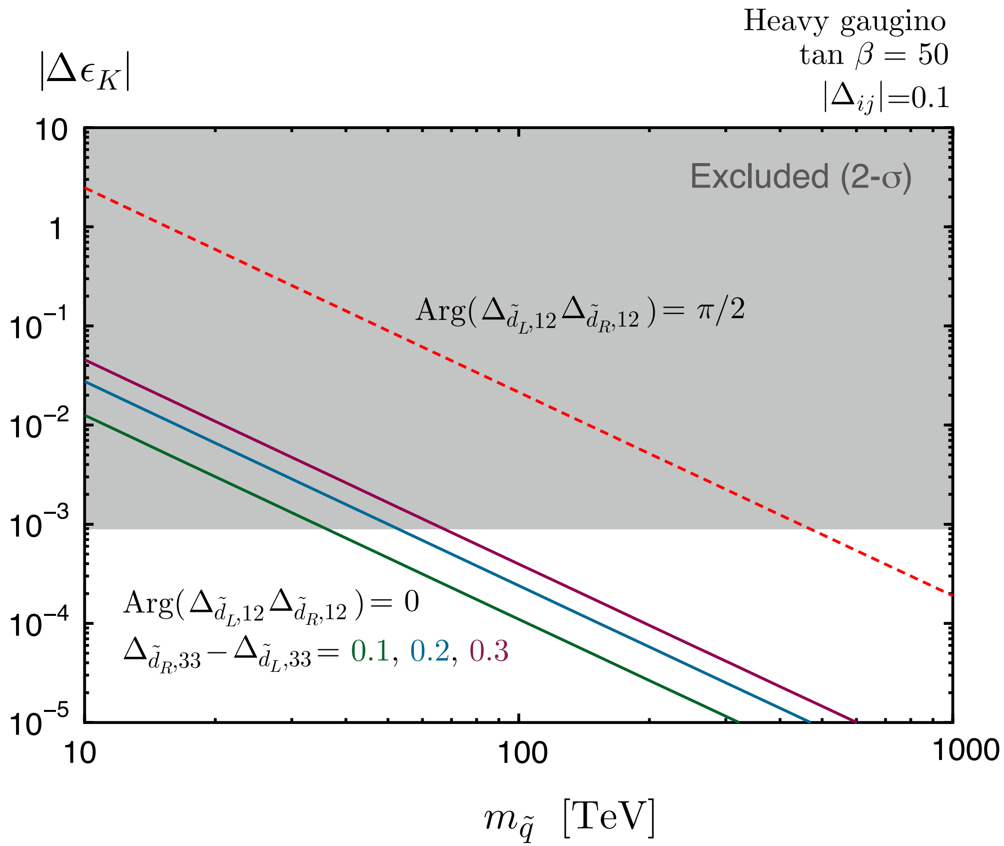
$$\Rightarrow \mathcal{M}^2_{\tilde{d}_L} \sim m^2_{\tilde{q}} \begin{pmatrix} 1 & \Delta_{12} & \Delta_{13} \\ \Delta_{21} & 1 & \Delta_{23} \\ \Delta_{31} & \Delta_{32} & \Delta^L_{33} \end{pmatrix}, \quad \mathcal{M}^2_{\tilde{d}_R} \sim m^2_{\tilde{q}} \begin{pmatrix} 1 & \Delta^*_{12} & \Delta^*_{13} \\ \Delta^*_{21} & 1 & \Delta^*_{23} \\ \Delta^*_{31} & \Delta^*_{32} & \Delta^R_{33} \end{pmatrix}$$

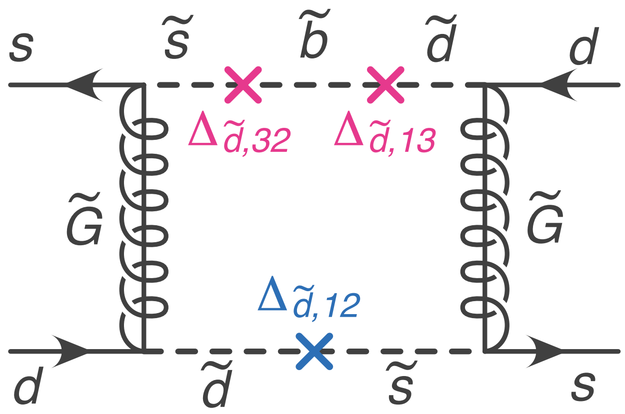
$\Rightarrow$ Breaking of the $SO(10)$-like relation at the MSSM scale

$\tan\beta$	Δ^L_{33}	Δ^R_{33}
10	0.7	1.0
30	0.7	0.8
50	0.5	0.5

$\Delta^{L,R}_{33}(\text{GUT}) = 1$

$\epsilon_K^{(\mathrm{SUSY})}$ for the case with $\mathcal{M}^2_{\tilde{d}_L} \simeq \mathcal{M}^{2\,*}_{\tilde{d}_R}$ (except for 33 elements)





$\Rightarrow$ Constraint from ϵ_K may be relaxed

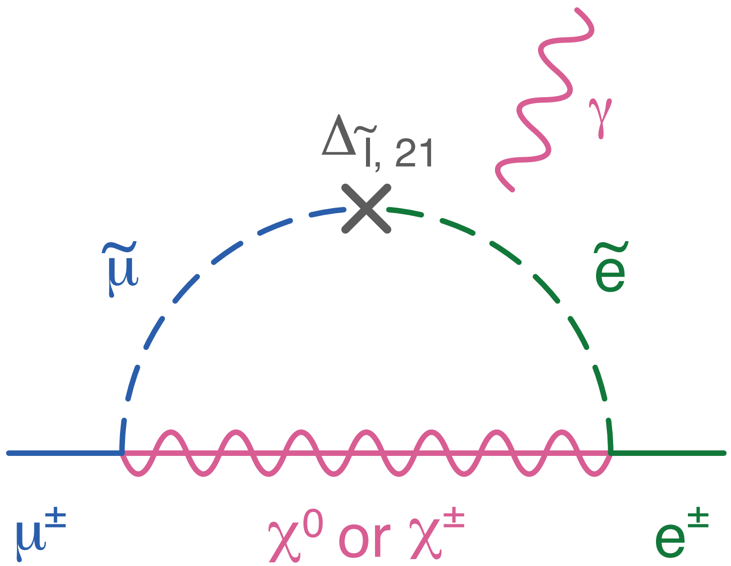
$\Rightarrow$ Other observables are also important (like LFV)

3. Leptonic Flavor and CP Violations

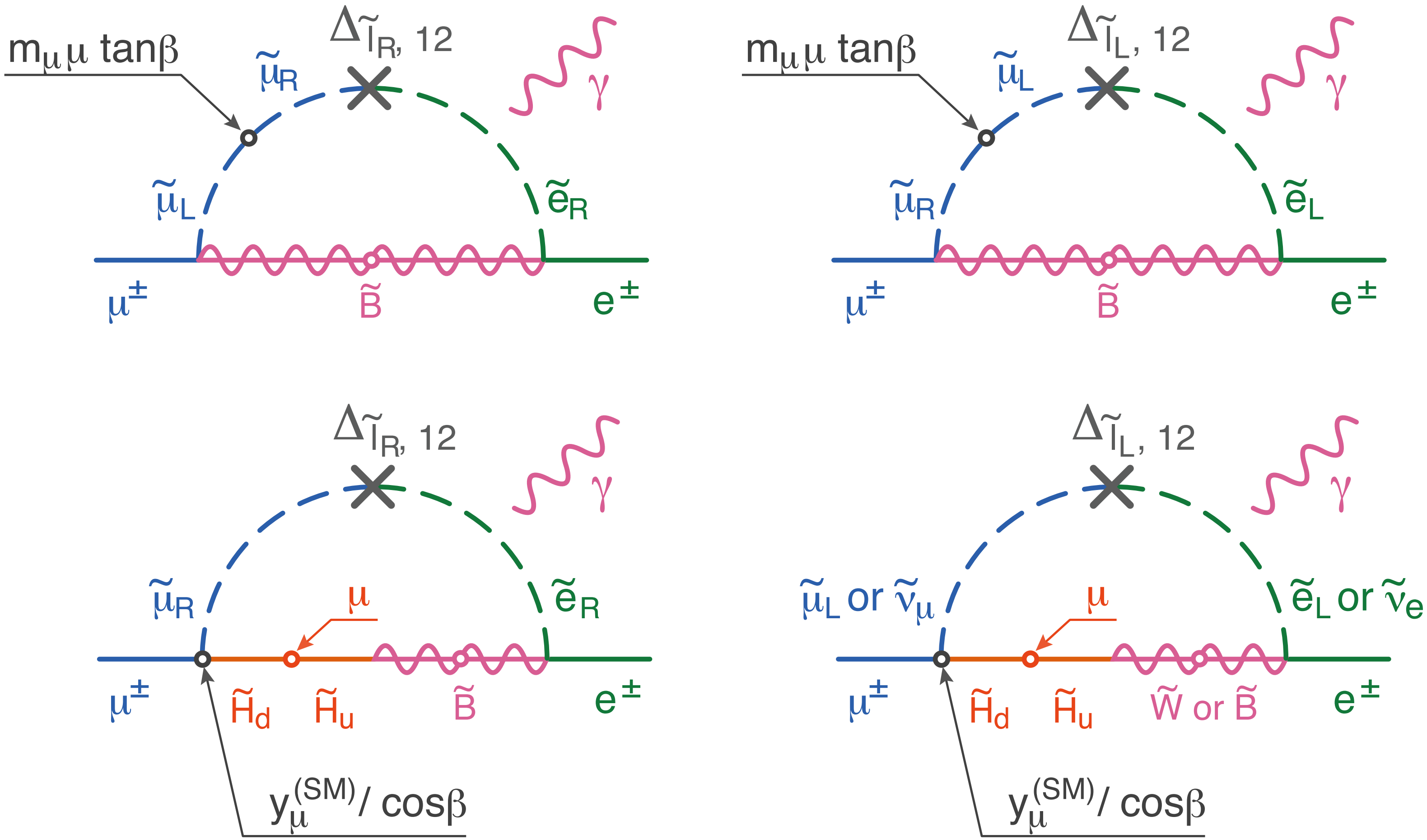
LFVs in SUSY models: (probably) due to $\Delta_{\tilde{l}_L}$ and $\Delta_{\tilde{l}_R}$

$$\mathcal{M}^2_{\tilde{l}_{L,R}} = m^2_{\tilde{l}_{L,R}} \begin{pmatrix} \Delta_{\tilde{l}_{L,R},11} & \Delta_{\tilde{l}_{L,R},12} & \Delta_{\tilde{l}_{L,R},13} \\ \Delta_{\tilde{l}_{L,R},21} & \Delta_{\tilde{l}_{L,R},22} & \Delta_{\tilde{l}_{L,R},23} \\ \Delta_{\tilde{l}_{L,R},31} & \Delta_{\tilde{l}_{L,R},32} & \Delta_{\tilde{l}_{L,R},33} \end{pmatrix}$$

Off-diagonal elements of the mass matrices induce LFVs

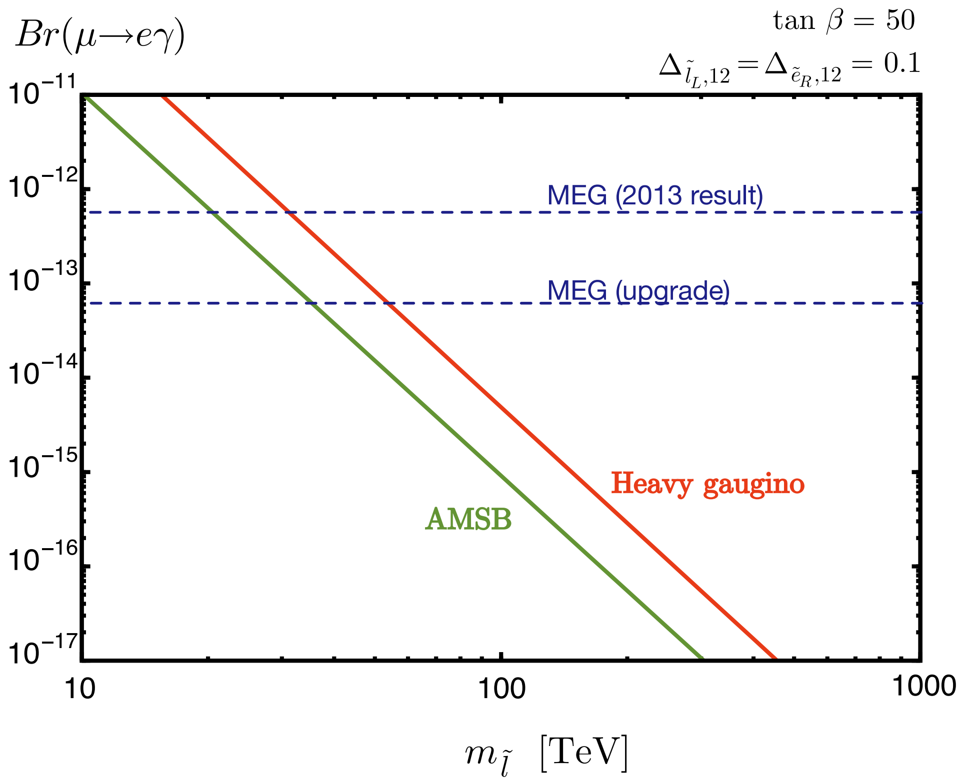


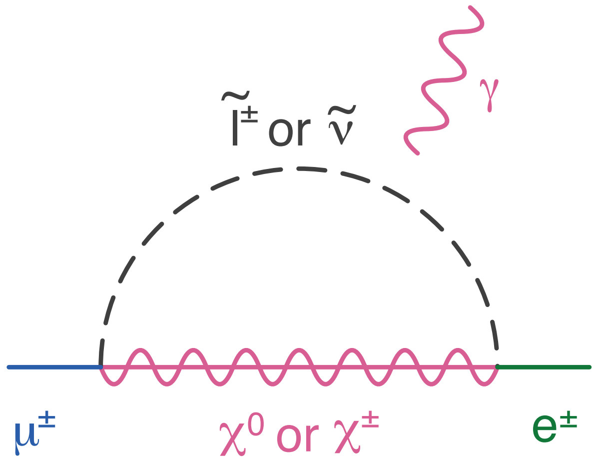
In the MSSM, LFV processes are enhanced by $\tan\beta$



$\Rightarrow$ LFV rates are (approximately) proportional to $\tan^2\beta$

$\mu \to e\gamma$ (with $\Delta^L_{e\mu} = \Delta^R_{e\mu} = 0.1$, $\tan\beta = 50$, $\cdots$)





[TM & Nagai ('13)]

- MEG (current bound): $Br < 5.7 \times 10^{-13}$

  [MEG experiment ('13)]

- MEG upgrade: $Br \lesssim 6 \times 10^{-14}$

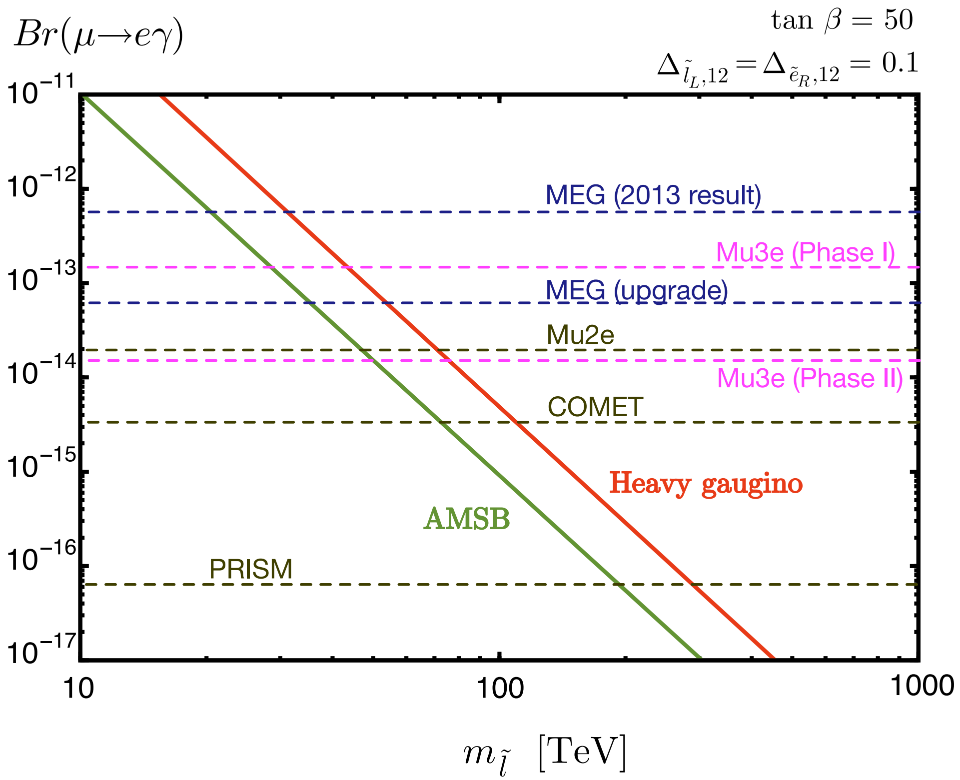
Of course, other LFV processes may occur

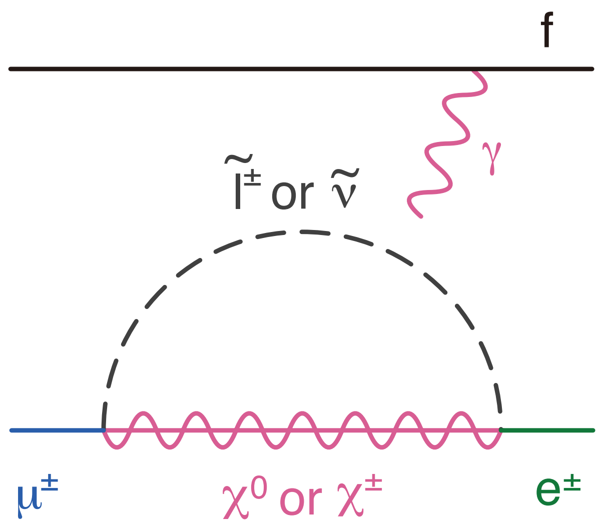
- $\mu \to 3e$
  - Current bound: $Br < 1 \times 10^{-12}$
  - Mu3e (Phase I): $Br \lesssim 10^{-15}$
  - Mu3e (Phase II): $Br \lesssim 10^{-16}$
- μ-e conversion
  - Current bound: $R_{\mu e} < 7 \times 10^{-13}$ (with Au)
  - Mu2e: $R_{\mu e} \lesssim 6 \times 10^{-17}$ (with Al)
  - COMET: $R_{\mu e} \lesssim 10^{-17}$ (with Al)
  - PRISM: $R_{\mu e} \lesssim 10^{-19}$

In the case of dipole dominance:

- $\mu \to 3e$: $Br(\mu \to 3e) \simeq 7 \times 10^{-3} \times Br(\mu \to e\gamma)$
- μ-e conversion: $R_{\mu e} \sim$ (a few) $\times 10^{-3} \times Br(\mu \to e\gamma)$

Comparison (with the naive rescalings)

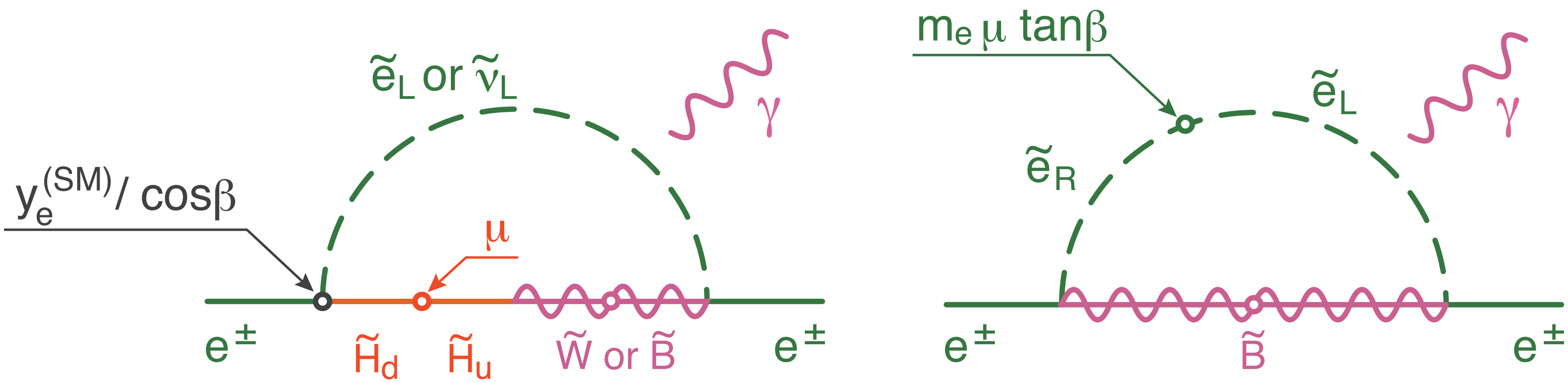




Another possible probe of heavy SUSY scenario

Electric dipole moments (EDMs)

Electron EDM, for example

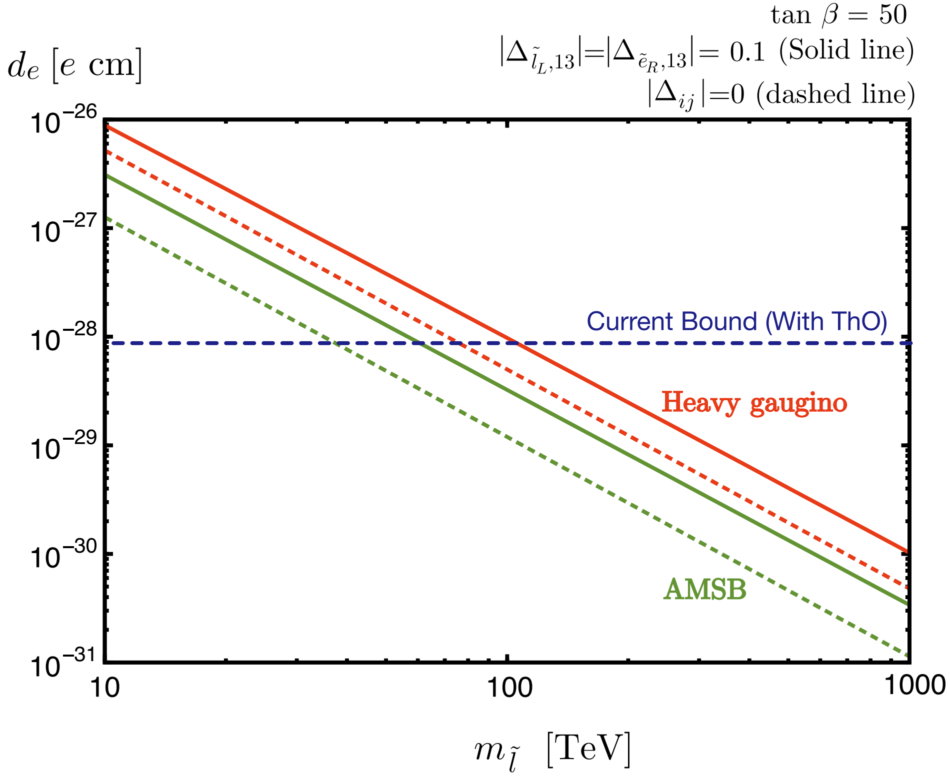


- $\mu\tan\beta$ can be complex

  $\Rightarrow d_e^{(\mathrm{SUSY})}$ is approximately proportional to $\Im(\mu\tan\beta)$

- Phases in the sfermion mass matrices may also contribute

Numerical result with $\mu = m_{\tilde{l}}$ & $\arg(\mu) = \pi/2$:



- Current bound

$$|d_e| < 8.7 \times 10^{-29} e \text{ cm}$$

[ACME collaboration ('13)]

[TM & Nagai ('13)]

$\Rightarrow$ Electron EDM covers the sfermion mass of ~ 100 TeV

4. Summary

Today, I considered:

- Flavor and CP violations in heavy SUSY scenario

I have discussed:

- There exist new sources of flavor and CP violations in the MSSM
- We may see a signal of BSM physics in flavor and CP violating processes
  - LFVs, like $\mu \to e\gamma$, $\mu \to 3e$, μ-e conversion, etc
  - Electron EDM

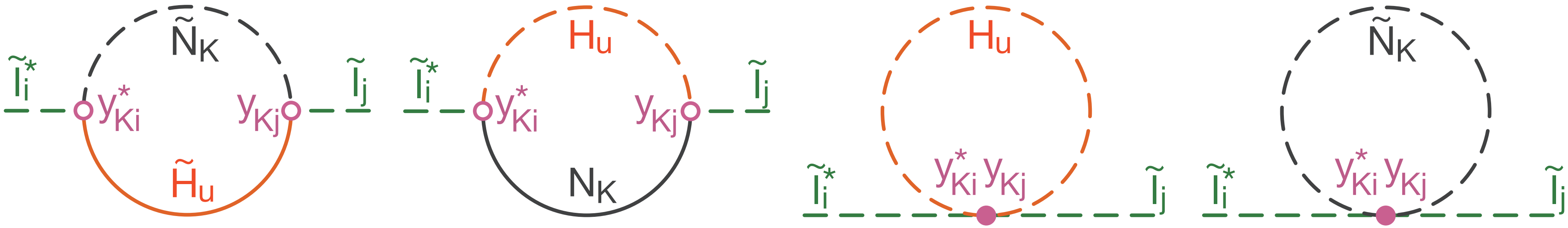
Backups

Off-diagonal elements may be generated by RG effects

$\Rightarrow$ Even if scalar masses are universal at the GUT scale, off-diagonal elements may be generated

In particular, the right-handed (s)neutrinos are important

[Borzumati & Masiero ('86); Hisano, TM, Tobe & Yamaguchi ('95)]

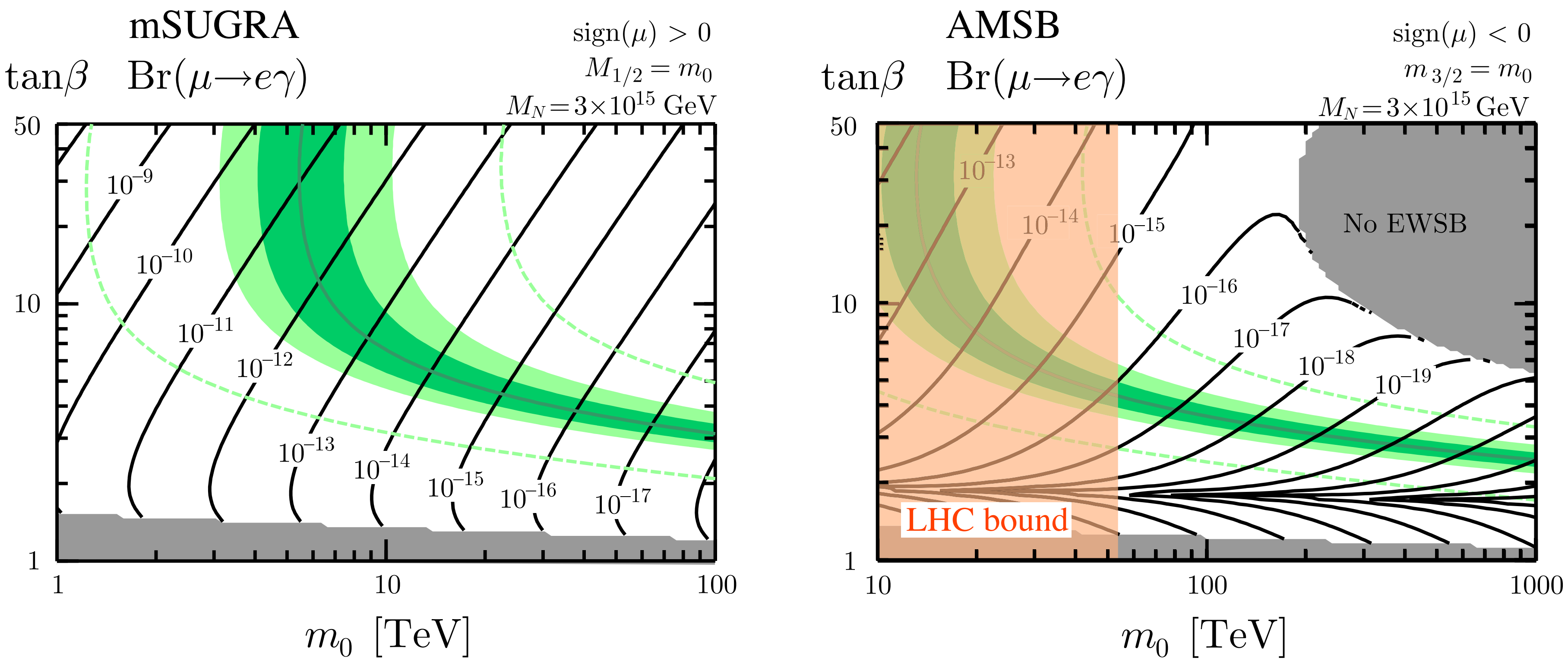


$$\Rightarrow \Delta\mathcal{M}^2_{\tilde{l}_L,ij} \simeq -\frac{6m_0^2}{16\pi^2}(y_\nu^\dagger y_\nu)_{ij} \ln\frac{M_{\mathsf{GUT}}}{M_N}$$

$$y_{\nu,Ij} \simeq \frac{\sqrt{2M_N m_{\nu_L,I}}[U_{\mathsf{PMNS}}]_{Ij}}{v\sin\beta} \quad \text{(when } M_{N,IJ} = M_N\delta_{IJ}\text{)}$$

$Br(\mu \to e\gamma)$ in SUSY model with right-handed neutrinos

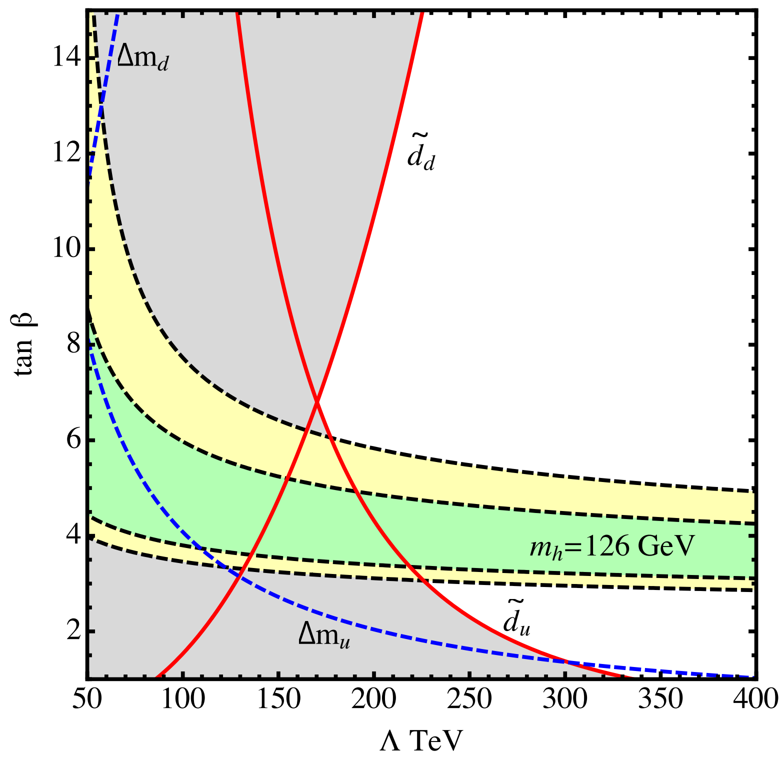
- Universal scalar mass at the GUT scale is assumed



[TM, Nagai & Yanagida ('13)]

- Dark green: $125 \leq m_h \leq 127$ GeV
- Light green: $124 \leq m_h \leq 128$ GeV

EDMs of hadrons



Gray region:

Constraint on CEDMs (Hg)

($|\tilde{d}_u - \tilde{d}_d| < 5.75 \times 10^{-27}$ cm)

[McKeen, Pospelov & Ritz ('13)]

$\Rightarrow$ Hadronic EDMs are also important