Gluino-mediated electroweak penguin with flavor-violating trilinear couplings

Daiki Ueda
(KEK theory center, SOKENDAI)

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in collaboration with
Motoi Endo, Toru Goto, Teppei Kitahara, Satoshi Mishima
and Kei Yamamoto

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Introduction

- ϵ'/ϵ_K: CP violating observable in $K_L \to \pi\pi$
- SM prediction based on LQCD:

$(\epsilon'/\epsilon_K)_{\rm SM} = (1.06 \pm 5.07) \times 10^{-4}$ [T.Kitahara, U.Nierste and P.Tremper]

c.f. [RBC-UKQCD], [A.J.Buras, M.Gorbahn, S.Jager and M.Jamin]

- experiment:

$(\epsilon'/\epsilon_K)_{\rm EXP} = (16.6 \pm 2.3) \times 10^{-4}$ [NA48, KTeV]

- discrepancy b/w SM and experiment:

$(\epsilon'/\epsilon_K)_{\rm EXP} > (\epsilon'/\epsilon_k)_{\rm SM}$ at 2.9 σ level

Can we explain this discrepancy by SUSY?

Outline

- Scenario:

  -MSSM

  -gluino contributions with large trilinear couplings

  -CP phase in trilinear couplings

- We evaluate maximum SUSY contributions to ϵ'/ϵ_K

- SUSY can explain the discrepancy

- SUSY contributions to $\mathcal{B}(K_L \to \pi^0 \nu\bar{\nu})$

CP violation in $K_L \to \pi\pi$

- CP violating observable in $K_L \to \pi\pi$:

$$\epsilon' \equiv \frac{\eta_{\pm} - \eta_{00}}{3} \quad \eta_{\pm} \equiv \frac{\langle \pi^+\pi^- | \mathcal{H} | K_L \rangle}{\langle \pi^+\pi^- | \mathcal{H} | K_S \rangle} \quad \eta_{00} \equiv \frac{\langle \pi^0\pi^0 | \mathcal{H} | K_L \rangle}{\langle \pi^0\pi^0 | \mathcal{H} | K_S \rangle}$$

- mass eigenstates and CP eigenstates :

$$|K_S\rangle = |K_+\rangle + \epsilon\,|K_-\rangle \qquad |K_L\rangle = \underset{\displaystyle\downarrow}{|K_-\rangle} + \epsilon\,|K_+\rangle$$

$|\pi\pi\rangle$:CP even

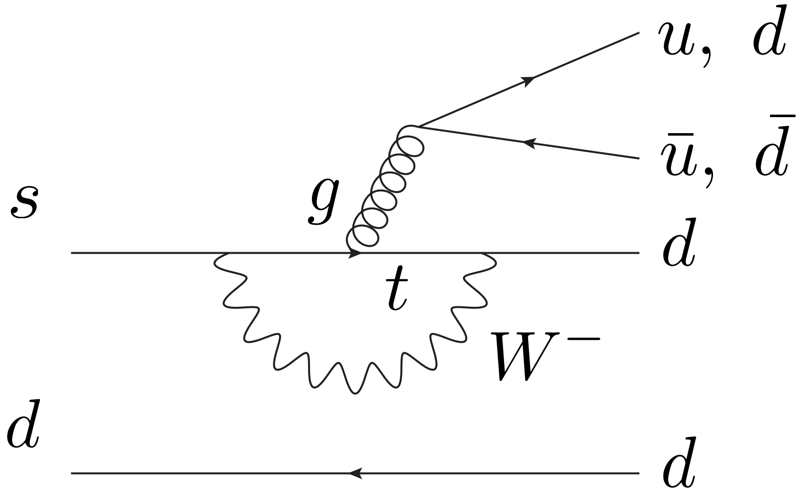
$|K_+\rangle$: CP even $|K_-\rangle$: CP odd

CP violation in $K_L \to \pi\pi$

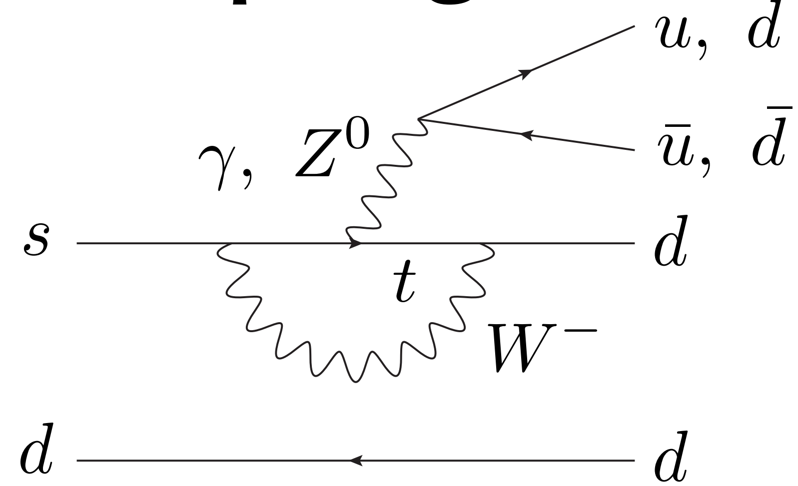
$$\frac{\epsilon'}{\epsilon_K} \propto \left(\mathrm{Im} A_0 - \frac{1}{\omega_{EXP}} \mathrm{Im} A_2 \right)$$

A_0, A_2: decay amplitude

QCD penguin



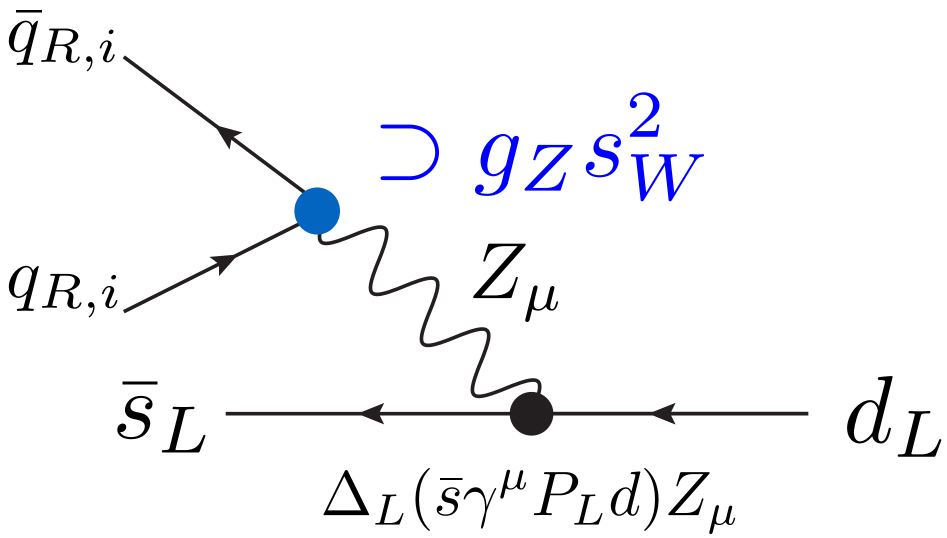
EW penguin

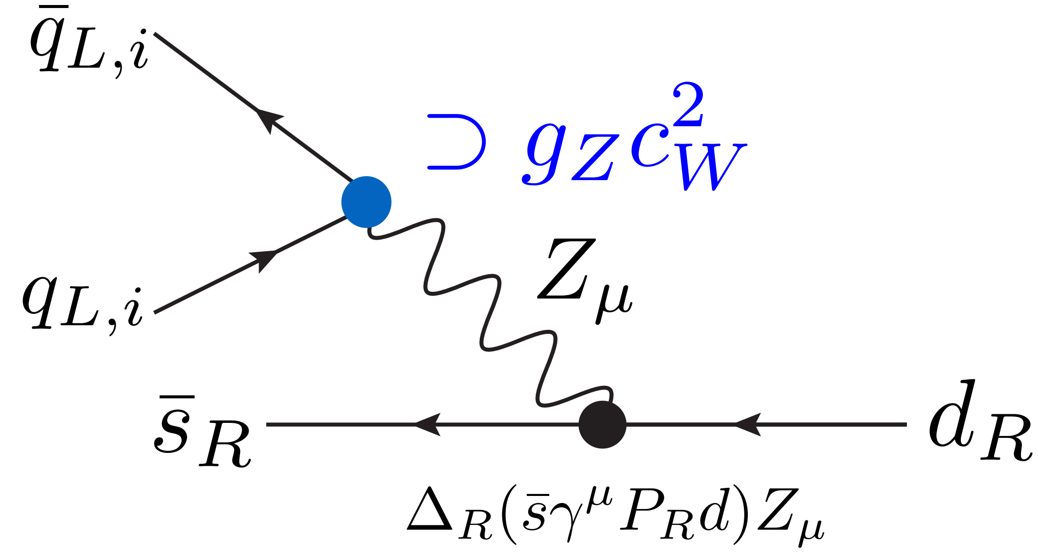


- $\Delta I = 1/2$ rule: $1/\omega_{\mathrm{EXP}} = 22.46$
- NP in $\mathrm{Im}A_2$ is **favored** because of $\Delta I = 1/2$

NP contribution to Z penguin

- Z penguin contribution:





$$\sim g_Z s_W^2 \frac{\Delta_L}{M_Z^2}[\bar{s}\gamma^\mu(1-\gamma_5)d][\bar{q}_i\gamma_\mu(1+\gamma_5)q_i]$$

$$\sim g_Z c_W^2 \frac{\Delta_R}{M_Z^2}[\bar{s}\gamma^\mu(1+\gamma_5)d][\bar{q}_i\gamma_\mu(1-\gamma_5)q_i]$$

- NP contributions to ϵ'/ϵ_K :

$$(\epsilon'/\epsilon_K)_{NP} \propto \left(s_W^2 \mathrm{Im}\Delta_L + c_W^2 \mathrm{Im}\Delta_R\right) \qquad c_W^2/s_W^2 \simeq 3.3$$

- NP contributions to right-handed Z-penguin is favored

Gluino contribution to Z penguin

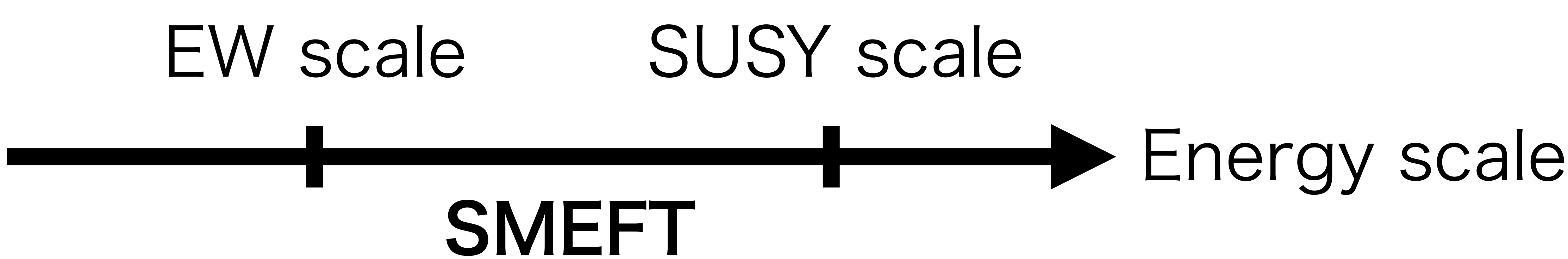
- we treat the gluino contribution in SMEFT(SU(2)×U(1))

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \sum_i \mathcal{C}_i \mathcal{O}_i^{d>4} \qquad \mathcal{O}_i^{d>4}\text{: SU(2)×U(1) inv}$$

-squark and gluino are much heavier than EW scale

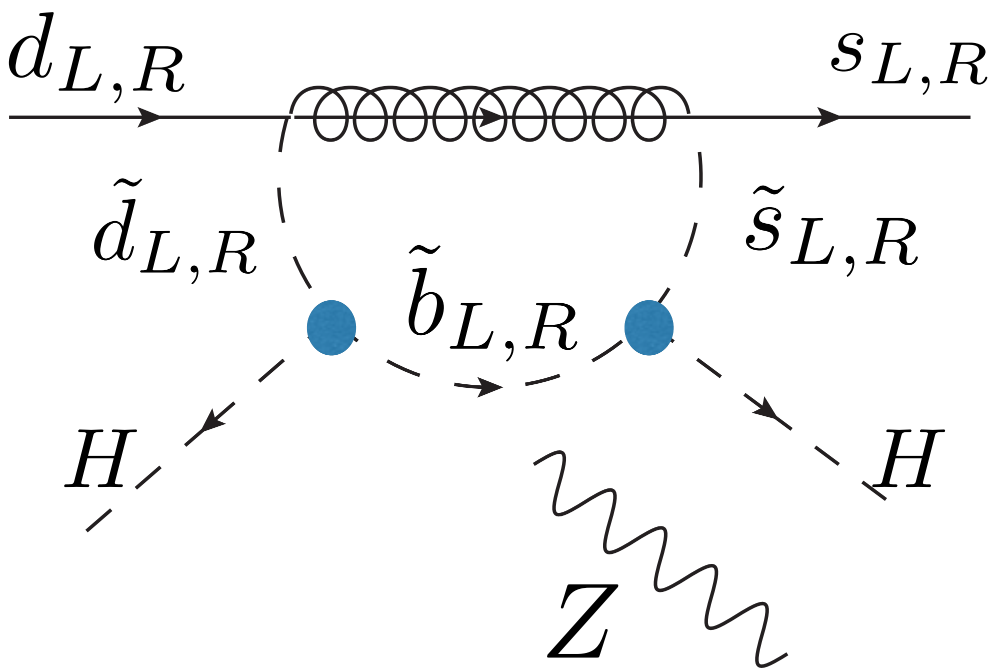
-SUSY particles are decoupled at SUSY scale

- SMEFT b/w SUSY scale and EW scale is suitable



Gluino contribution to Z penguin

- gluino contributions to SMEFT:



$$
\begin{aligned}
&= [\mathcal{C}^{(1)}_{HQ}]_{12}(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{d}\gamma^\mu P_L s) \\
&+ [\mathcal{C}^{(3)}_{HQ}]_{12}(H^\dagger i \tau^a \overleftrightarrow{D}_\mu H)(\bar{d}\tau^a\gamma^\mu P_L s) \\
&+ [\mathcal{C}_{HD}]_{12}(H^\dagger i \tau^a \overleftrightarrow{D}_\mu H)(\bar{d}\tau^a\gamma^\mu P_R s)
\end{aligned}
$$

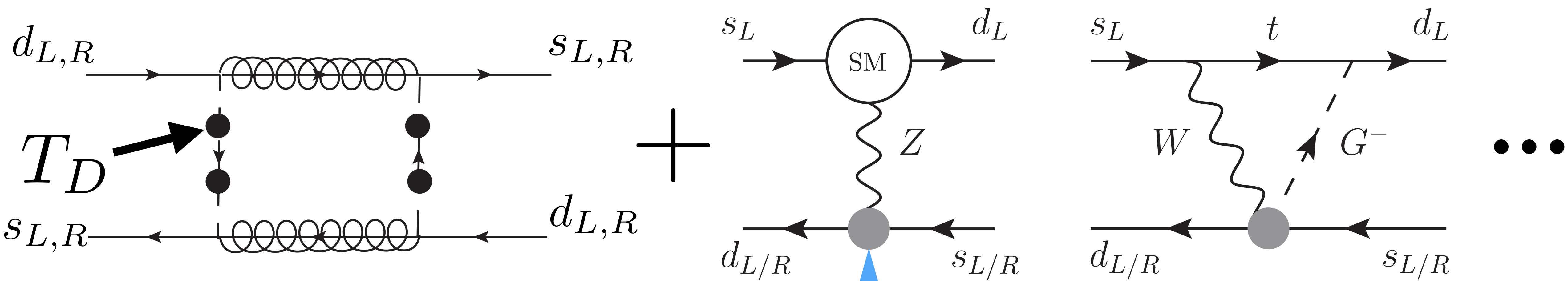
- gluino contributions to Z penguin after EW breaking:

$$\mathcal{L} = \Delta_L(\bar{s}\gamma^\mu P_L d)Z_\mu + \Delta_R(\bar{s}\gamma^\mu P_R d)Z_\mu$$

$\Delta_L \propto (T_D^*)_{13}(T_D)_{23}v^2/m^4_{\tilde{Q}}$ $\Delta_R \propto (T_D^*)_{32}(T_D)_{31}v^2/m^4_{\tilde{Q}}$

- **large trilinear couplings can amplify ε'/ε$_K$**

Constraint from εK



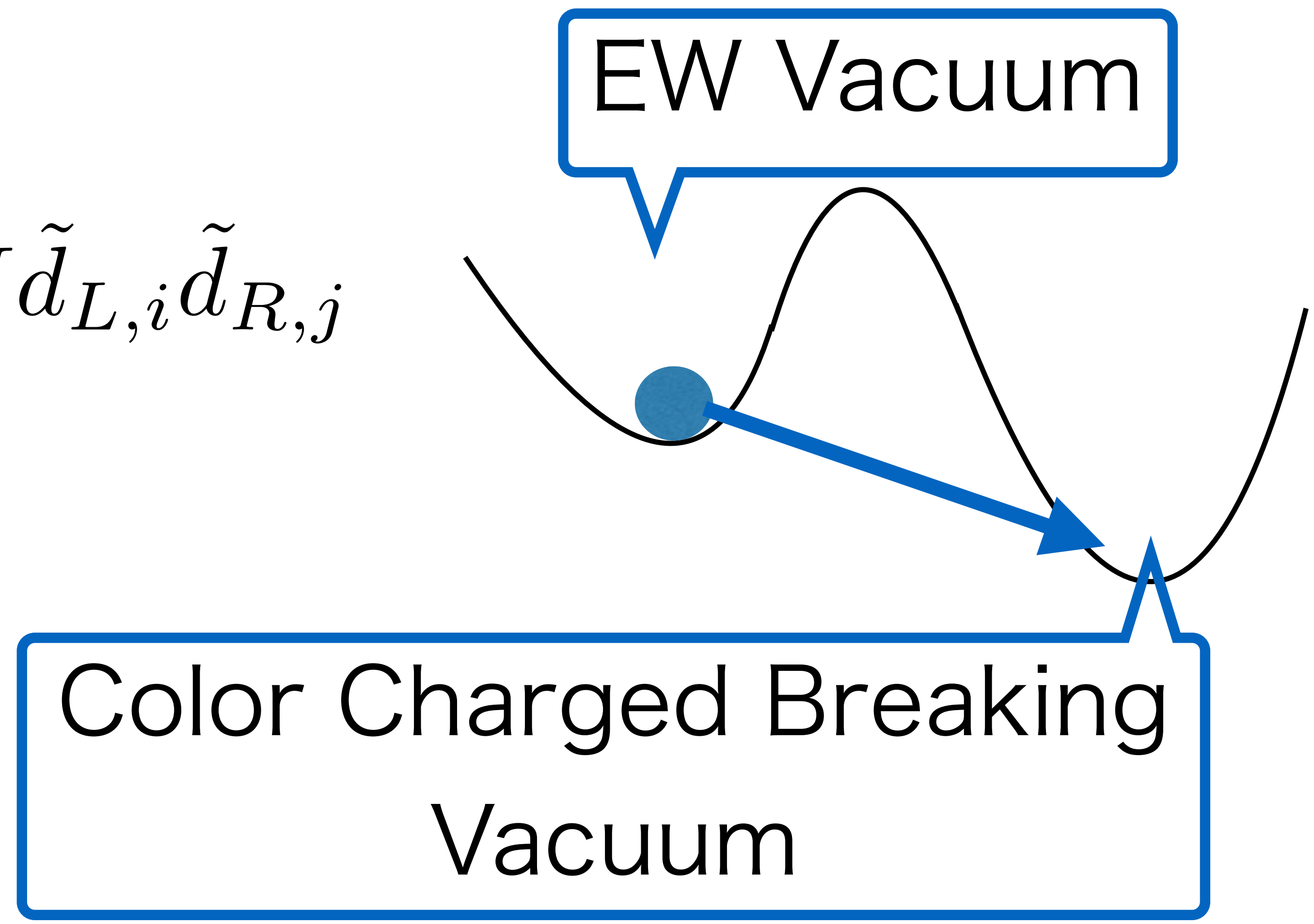
$$\boxed{\Delta_L(\bar{s}\gamma^\mu P_R d)Z_\mu,\ \ \Delta_R(\bar{s}\gamma^\mu P_L d)Z_\mu}$$

- $\mathcal{L} \supset \Delta_R(\bar{s}\gamma^\mu P_R d)Z_\mu$ generates $(\bar{d}\gamma_\mu P_L s)(\bar{d}\gamma^\mu P_R s)$
- right-handed Z-penguin is chiral-enhanced in ε K
- constraint from ϵ_K is severe

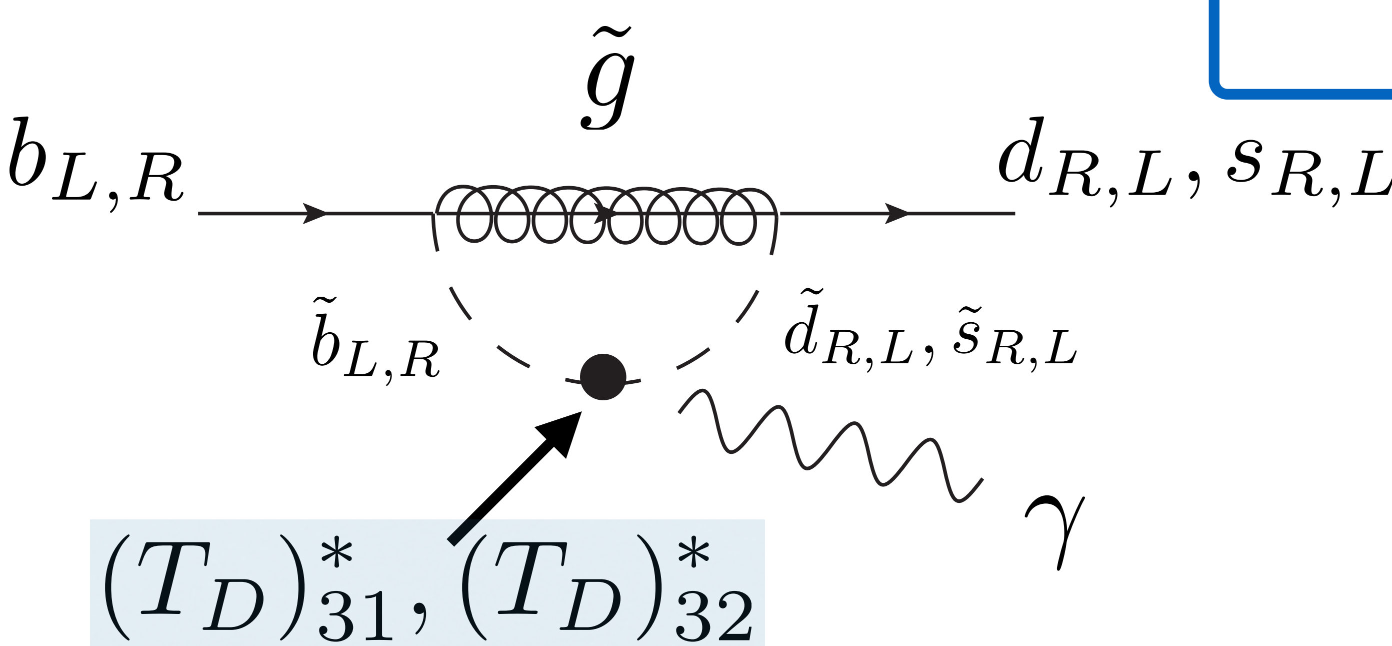
Other constraints

- Vacuum stability:

$$V_{scalar} \supset \frac{1}{\sqrt{2}} (T_D)_{ij} \cos\beta H \tilde{d}_{L,i} \tilde{d}_{R,j}$$



- $\mathcal{B}(b \to d\gamma),\ \mathcal{B}(b \to s\gamma)$:



Parameter scan(1)

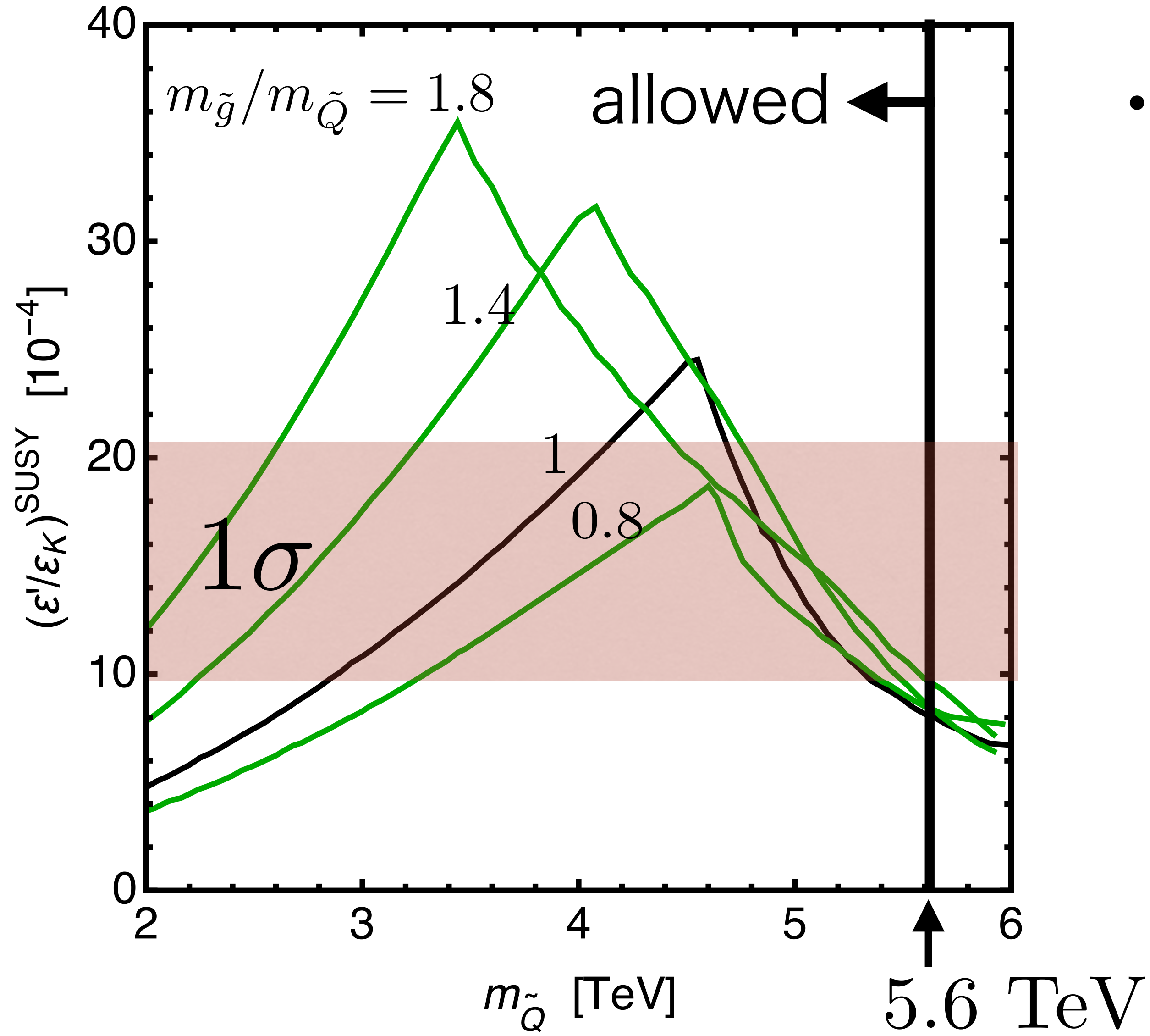
- maximum SUSY contributions to ϵ'/ϵ_K
  - ε_K:2σ level
  - B(b→dγ), B(b→sγ): 2σ level
  - vacuum stability:
    lifetime of EW vacuum > age of the universe
- trilinear couplings:

$$[(T_D)_{13}, (T_D)_{23}, (T_D)_{31}, (T_D)_{32}]$$

$$= [\mathrm{Re}(T_D)_{13}, \mathrm{Re}(T_D)_{23} + i\mathrm{Im}(T_D)_{23}, \mathrm{Re}(T_D)_{31}, \mathrm{Re}(T_D)_{32} + i\mathrm{Im}(T_D)_{32}]$$

- $\mathrm{Re}(T_D)_{13}/\mathrm{Im}(T_D)_{23} = \mathrm{Re}(T_D)_{31}/\mathrm{Im}(T_D)_{32}$: fixed
- $m_{\tilde{g}}/m_{\tilde{Q}}$: fixed

Maximum SUSY contributions to ε'/ε$_K$



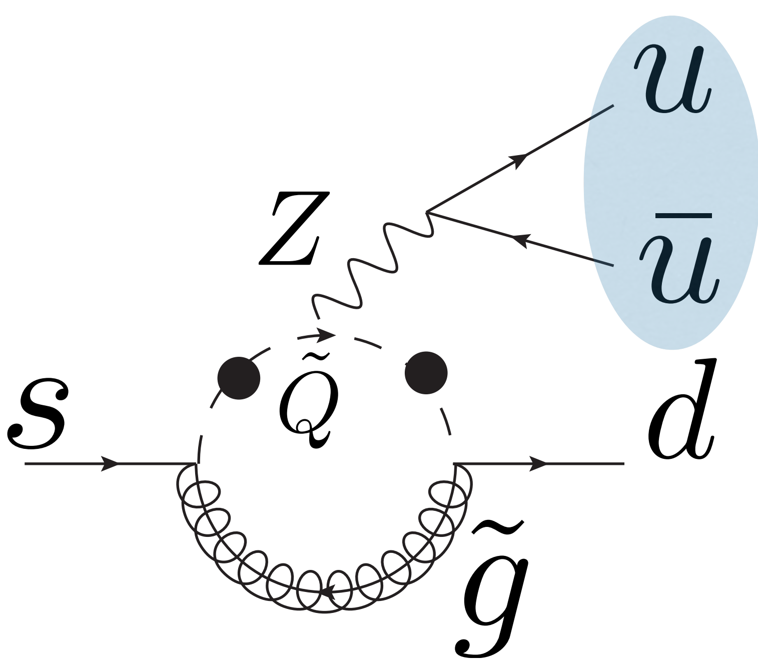
- $\mathrm{Re}(T_D)_{13}/\mathrm{Im}(T_D)_{23}$
  $= \mathrm{Re}(T_D)_{31}/\mathrm{Im}(T_D)_{32} = 1$

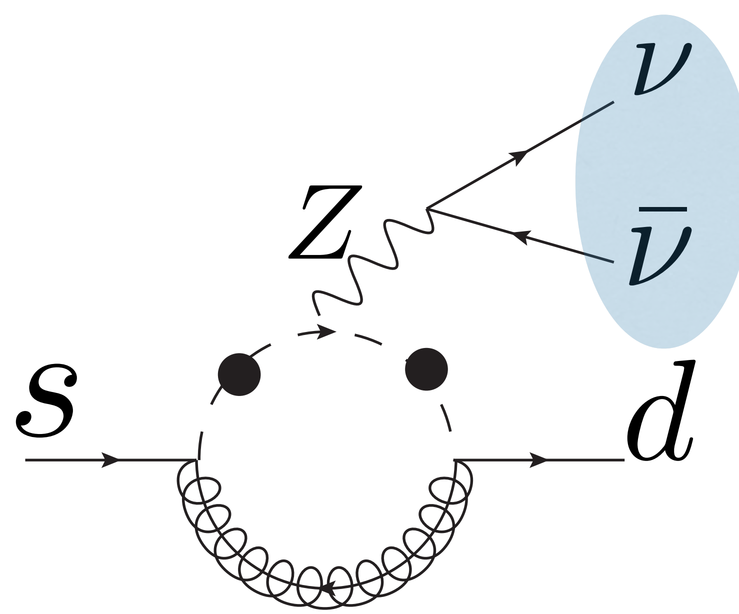
・gluino contributions can explain the discrepancy if the SUSY masses are smaller than $5.6\ \mathrm{TeV}$

Gluino contributions to $\mathcal{B}\left(K_L \to \pi^0 \nu\bar{\nu}\right)$

- SUSY also contribute to $\mathcal{B}(K_L \to \pi^0 \nu\bar{\nu})$

$K_L \to \pi\pi$ $\qquad\qquad$ $K_L \to \pi^0 \nu\bar{\nu}$





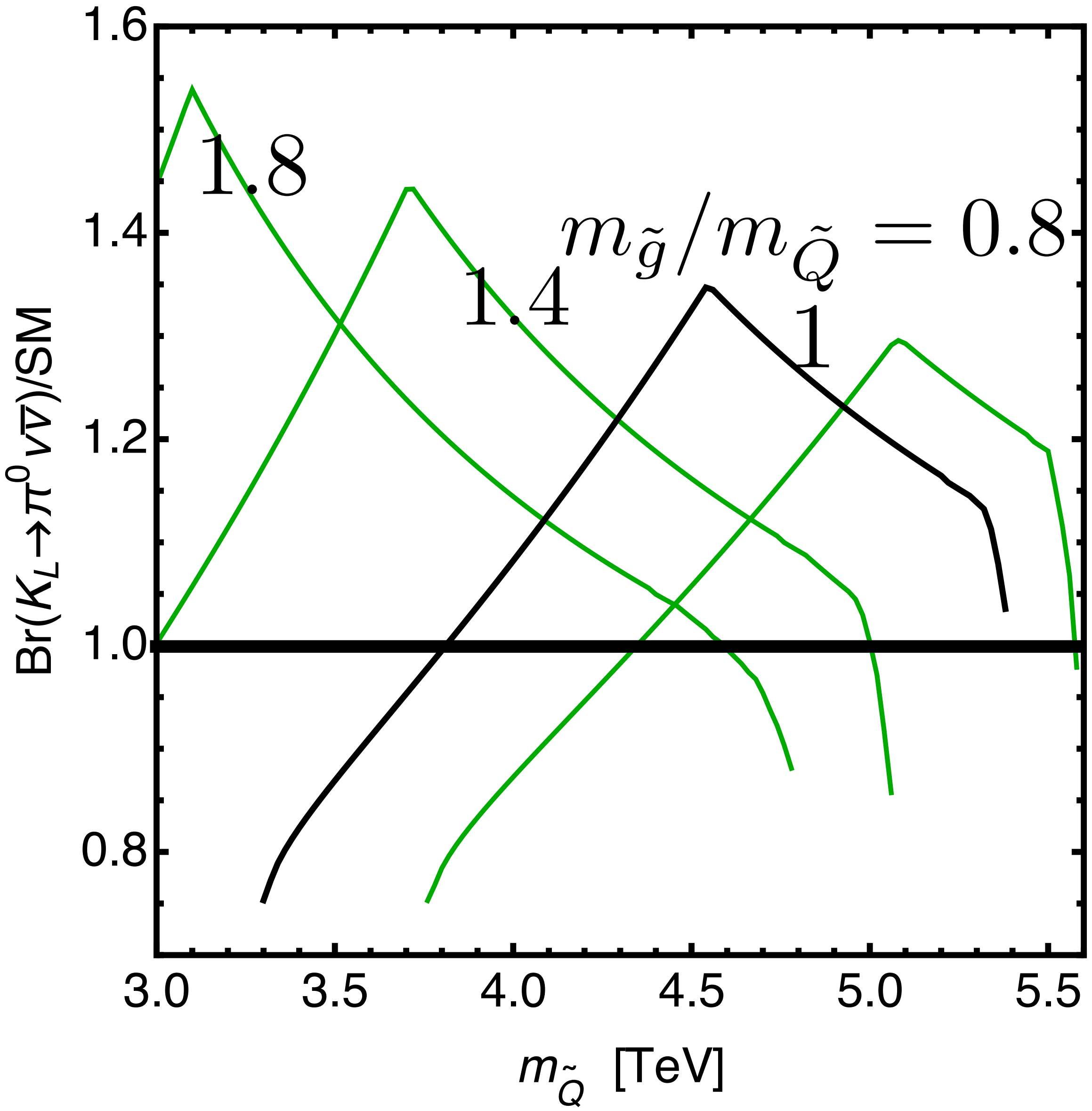
- $\mathcal{B}(K_L \to \pi^0 \nu\bar{\nu}) \propto$

$$\left(2.12 \times 10^{-4} - 2.51 \times 10^{2}(\mathrm{Im}[\Delta_L]_{12} + \mathrm{Im}[\Delta_R]_{12})\right)^2$$

Parameter scan(2)

- maximum SUSY contributions to $\mathcal{B}(K_L \to \pi^0 \nu \bar{\nu})$
  - ε K :2σ level
  - B(b→dγ), B(b→sγ): 2σ level
  - vacuum stability:
- trilinear couplings:
  $[(T_D)_{13}, (T_D)_{23}, (T_D)_{31}, (T_D)_{32}]$
  $= [\mathrm{Re}(T_D)_{13}, \mathrm{Re}(T_D)_{23} + i\mathrm{Im}(T_D)_{23}, \mathrm{Re}(T_D)_{31}, \mathrm{Re}(T_D)_{32} + i\mathrm{Im}(T_D)_{32}]$
- $\mathrm{Re}(T_D)_{13}/\mathrm{Im}(T_D)_{23} = -\mathrm{Re}(T_D)_{31}/\mathrm{Im}(T_D)_{32}$: fixed
- $m_{\tilde{g}}/m_{\tilde{Q}}$: fixed
- $(\epsilon'/\epsilon_K)^{\mathrm{SUSY}} = 10.0 \times 10^{-4}$: fixed

Maximum SUSY contribution to B(K$_L$→π^{0}νν)



- $\mathrm{Re}(T_D)_{13}/\mathrm{Im}(T_D)_{23}$
  $= -\mathrm{Re}(T_D)_{31}/\mathrm{Im}(T_D)_{32} = 1$
- $(\epsilon'/\epsilon_K)^{\mathrm{SUSY}} = 10.0 \times 10^{-4}$ is fixed

- $\mathcal{B}(K_L \to \pi^0 \nu\bar{\nu})$ can be about 1.5 times lager than the SM
- This branching ratio can be discovered in KOTO

Conclusion

・gluino contributions can explain the discrepancy of ϵ'/ϵ_K if the SUSY masses are smaller than $5.6\ \mathrm{TeV}$

・$\mathcal{B}(K_L \to \pi^0 \nu\bar{\nu})$ can be about 1.5 times lager than the SM

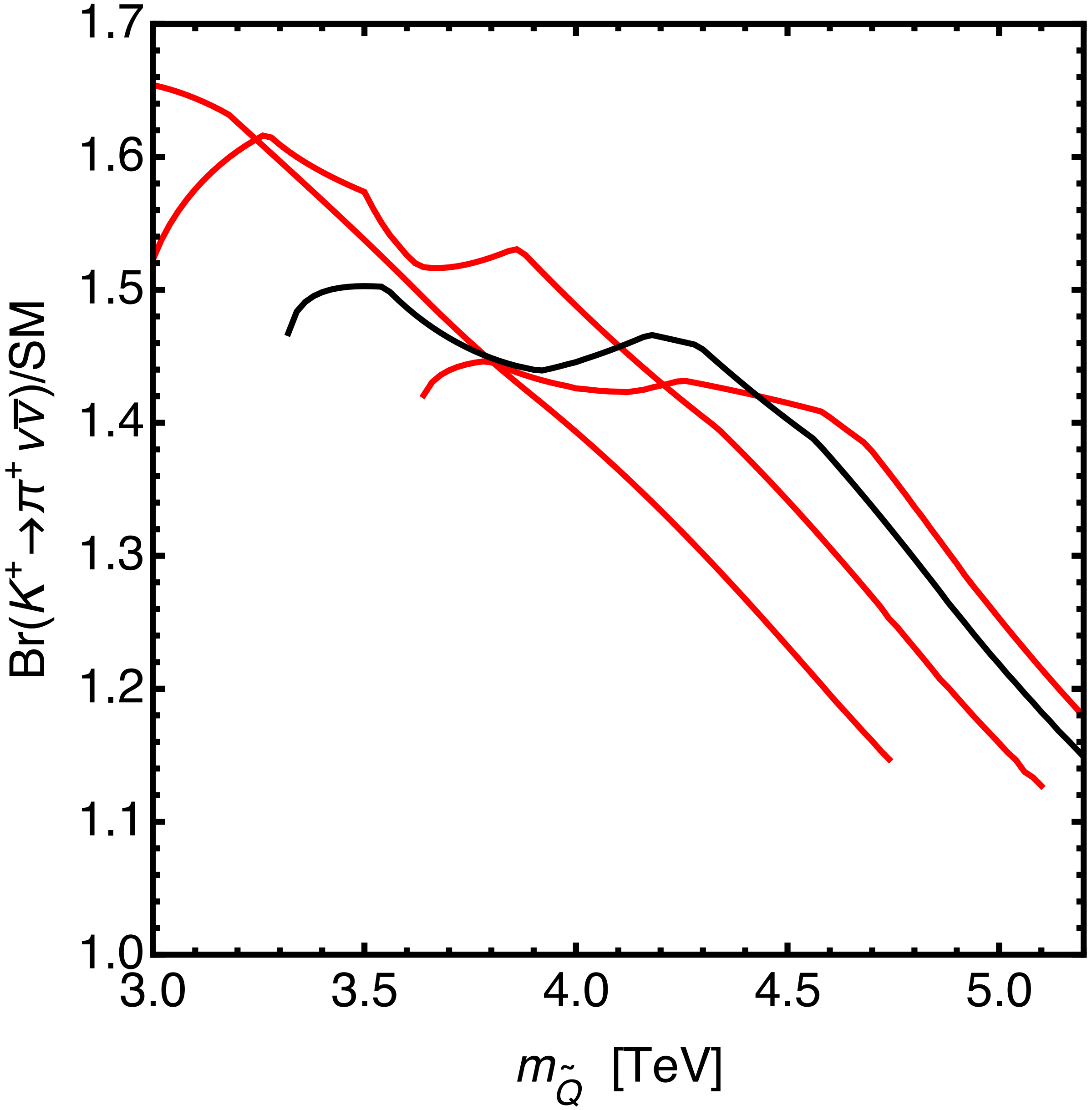
・This branching ratio can be discovered in future KOTO experiment

・SUSY contributions to

$\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu}) \quad \Delta A_{CP}(b \to s\gamma) \quad \mathcal{B}(K_S \to \mu^+\mu^-)_{\mathrm{eff}}$

can be also amplified

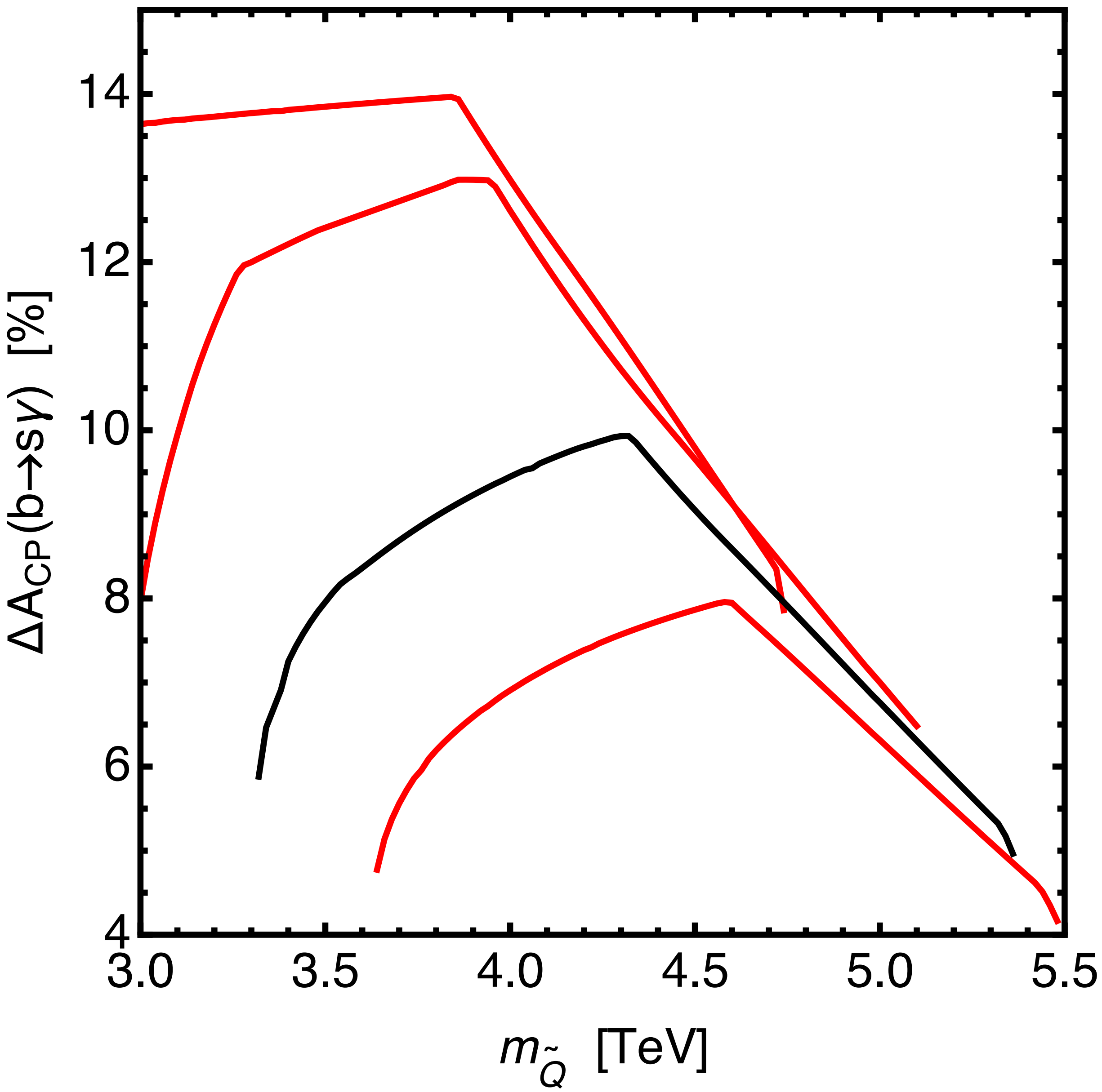
Maximum SUSY contributions to $\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})$



- $m_{\tilde{g}}/m_{\tilde{Q}} = 1$: fixed
- $(\epsilon'/\epsilon_K)^{\mathrm{SUSY}} = 10.0 \times 10^{-4}$ is fixed
- $\mathrm{Re}(T_D)_{13}/\mathrm{Im}(T_D)_{23}$
  $= -\mathrm{Re}(T_D)_{31}/\mathrm{Im}(T_D)_{32}$
  $=0.6, 0.8, 1, 1.2$

$\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})$ can be about 1.6-1.7 times later than the SM

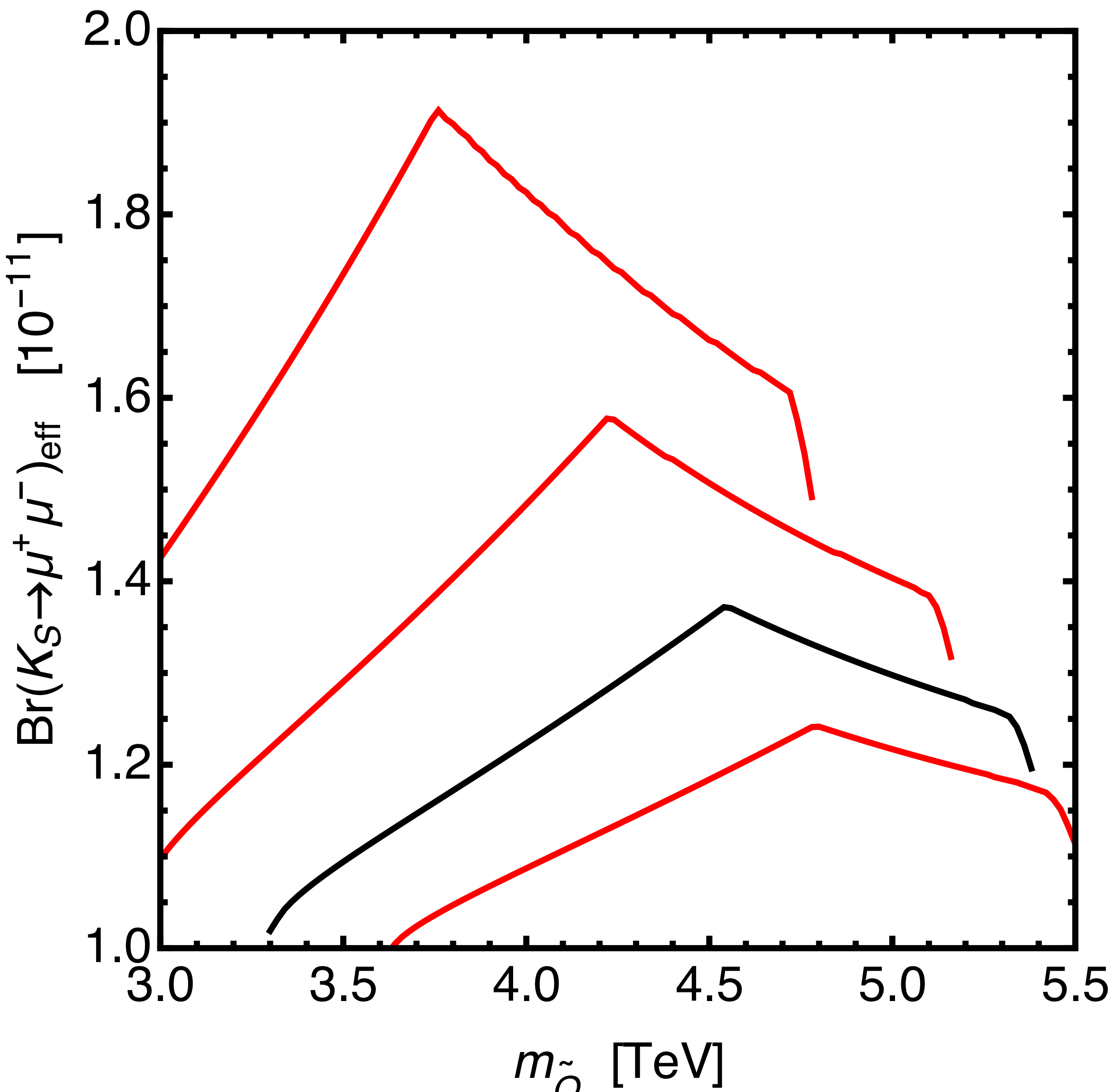
Maximum SUSY contributions to $\Delta A_{CP}(b \to s\gamma)$



- $m_{\tilde{g}}/m_{\tilde{Q}} = 1$: fixed
- $(\epsilon'/\epsilon_K)^{\rm SUSY} = 10.0 \times 10^{-4}$ is fixed
- $\mathrm{Re}(T_D)_{13}/\mathrm{Im}(T_D)_{23}$
  $= -\,\mathrm{Re}(T_D)_{31}/\mathrm{Im}(T_D)_{32}$
  $= 0.6, 0.8, 1, 1.2$

- $\Delta A_{CP}(b \to s\gamma)$ can be as large as 14%
- This asymmetry can be measured at Belle II with $50\mathrm{ab}^{-1}$

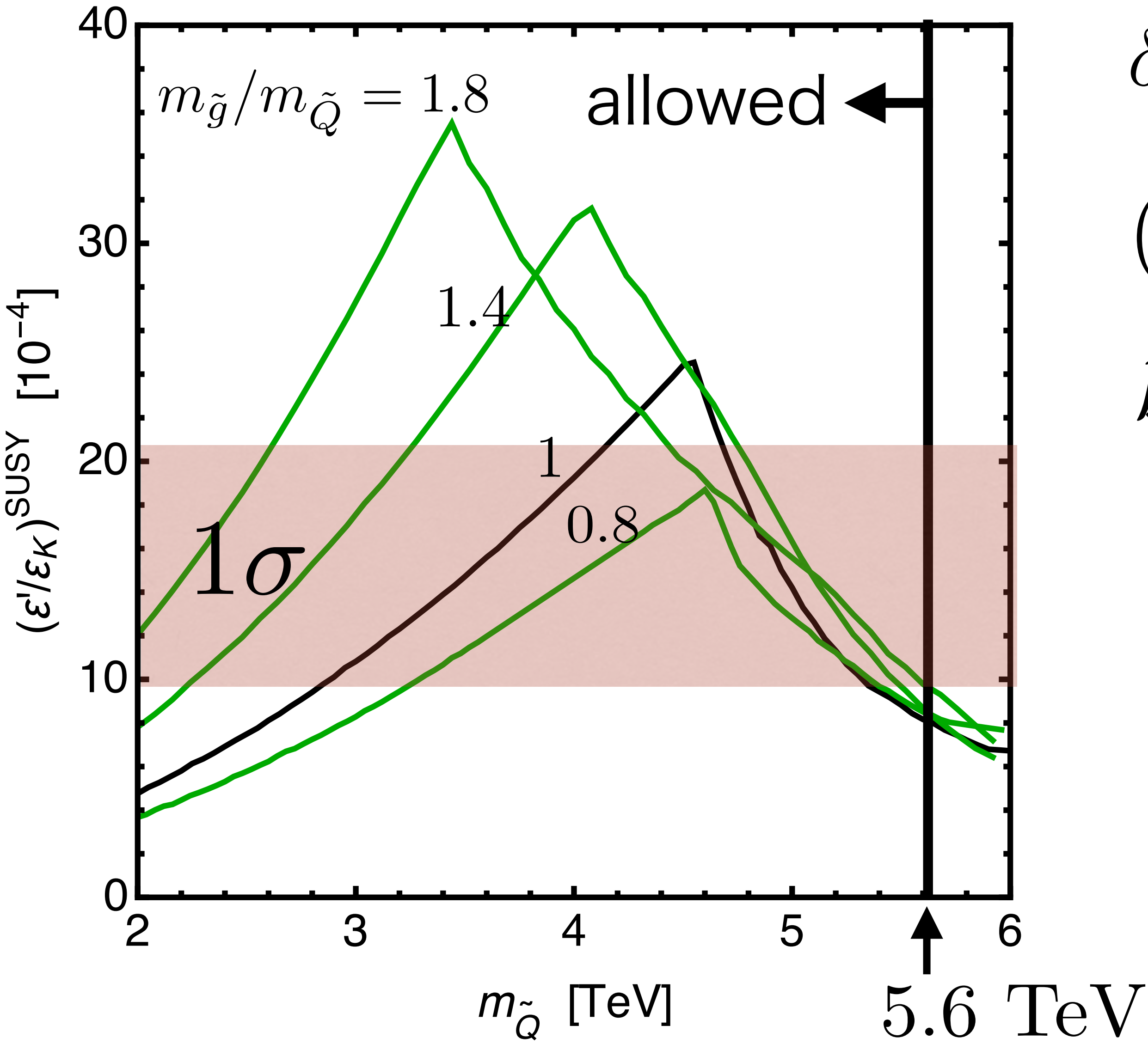
$$\mathcal{B}(K_S \to \mu^+\mu^-)_{\rm eff}$$



- $m_{\tilde{g}}/m_{\tilde{Q}} = 1$: fixed
- $(\epsilon'/\epsilon_K)^{\rm SUSY} = 10.0 \times 10^{-4}$ is fixed
- $\mathrm{Re}(T_D)_{13}/\mathrm{Im}(T_D)_{23}$
  $= -\mathrm{Re}(T_D)_{31}/\mathrm{Im}(T_D)_{32}$
  $=0.6, 0.8, 1, 1.2$
- D=1, η_A=-1

- branching ratio is evaluated in parameter space $\mathcal{B}(K_L \to \pi^0\nu\bar{\nu})$ is maximized
- effective branching ratio can be larger than SM
- this branching ratio might be measured by the end of the LHCb Run-2

Maximum SUSY contributions to ε'/ε$_K$



$$\delta_D \equiv (T_D)_{ij} v \cos\beta / m_{\tilde{Q}}^2$$

$$(\epsilon'/\epsilon)^{SUSY} \sim \delta_D^2$$

$$\mathcal{B}(\bar{B} \to X_d \gamma) \sim \delta_D / m_{\tilde{Q}}$$

・maximal value of ϵ'/ϵ increases as $m_{\tilde{Q}}$ becomes larger

Leading RG effects in SMEFT

- RG equation:

$$(4\pi)^2 \mu \frac{d\mathcal{C}_a}{d\mu} = \gamma_{ab} \mathcal{C}_b$$

γ_{ab} : anomalous dimension

e.g. $$(4\pi)^2 \frac{d[\mathcal{C}_{HQ}^{(1,3)}]_{12}}{d \ln \mu} = 6 Y_t^2 [\mathcal{C}_{HQ}^{(1,3)}]_{12}$$

- first leading logarithm:

$$\mathcal{C}_a(\mu_{\rm ew}) = \left[\delta_{ab} - \frac{\gamma_{ab}}{(4\pi)^2} \ln \frac{\mu_{\rm susy}}{\mu_{\rm ew}} \right] \mathcal{C}(\mu_{\rm susy})$$

Maximum SUSY contributions to ε'/ε$_K$

$$(\epsilon'/\epsilon_K)^{\rm SUSY} \propto -\Big[5.91\times 10^7 {\rm GeV}^2 {\rm Im}\left([\mathcal{C}_{HQ}^{(1)}]_{12} + [\mathcal{C}_{HQ}^{(3)}]_{12}\right)$$
$$+1.97\times 10^8 {\rm GeV}^2 {\rm Im}[\mathcal{C}_{HD}]_{12}\Big]$$

$${\rm Im}[\mathcal{C}_{HQ}^{(1,3)}]_{12} \propto -{\rm Im}\left[(T_D)^*_{13}(T_D)_{23}\right] = -{\rm Im}(T_D)_{23}{\rm Re}(T_D)_{13}$$

$${\rm Im}[\mathcal{C}_{HD}]_{12} \propto +{\rm Im}\left[(T_D)_{31}(T_D)^*_{32}\right] = -{\rm Im}(T_D)_{32}{\rm Re}(T_D)_{31}$$

- maximum SUSY contribution:

$${\rm Re}(T_D)_{13}/{\rm Im}(T_D)_{23} = {\rm Re}(T_D)_{31}/{\rm Im}(T_D)_{32}$$

Maximum SUSY contribution to B($K_L \to \pi^0 \nu\nu$)

$$\mathcal{B}(K_L \to \pi^0 \nu\bar{\nu}) \propto \Bigg(-4.83 \times 10^{-4}$$

$$-5.62 \times 10^{6} \mathrm{GeV}^2 \mathrm{Re}\left([\mathcal{C}_{HQ}^{(1)}]_{12} + [\mathcal{C}_{HQ}^{(3)}]_{12} + [\mathcal{C}_{HD}]_{12} \right) \Bigg)^2$$

$$\mathrm{Im}[\mathcal{C}_{HQ}^{(1,3)}]_{12} \propto -\mathrm{Im}\left[(T_D)^*_{13}(T_D)_{23}\right] = -\mathrm{Im}(T_D)_{23}\mathrm{Re}(T_D)_{13}$$

$$\mathrm{Im}[\mathcal{C}_{HD}]_{12} \propto +\mathrm{Im}\left[(T_D)_{31}(T_D)^*_{32}\right] = -\mathrm{Im}(T_D)_{32}\mathrm{Re}(T_D)_{31}$$

- maximum SUSY contribution:

$$\mathrm{Re}(T_D)_{13}/\mathrm{Im}(T_D)_{23} = -\mathrm{Re}(T_D)_{31}/\mathrm{Im}(T_D)_{32}$$

- right-handed contribution can amplify $\mathcal{B}$($K_L \to \pi^0 \nu \nu$)