SUSY contributions in light of recent ϵ'/ϵ

Daiki Ueda
(KEK theory center, SOKENDAI)

EPSHEP 2017

Venice, Italy

8th. July 2017

M.Endo,S.Mishima,D.Ueda and K.Yamamoto,Phys.Lett. B762 (2016) 493-497

Introduction

ϵ'/ϵ : Direct CP-violating observable in $K_L \to \pi\pi$

$K_L \to \pi\pi$: CP-violating process

In CP symmetric system

$$CP\,|K_L\rangle = -\,|K_L\rangle \qquad CP\,|\pi\pi\rangle = +\,|\pi\pi\rangle$$

Introduction

The standard model prediction

$$(\epsilon'/\epsilon)_{SM} = (1.06 \pm 5.07) \times 10^{-4}$$

[T.Kitahara, U.Nierste and P.Tremper]

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

experimental result

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

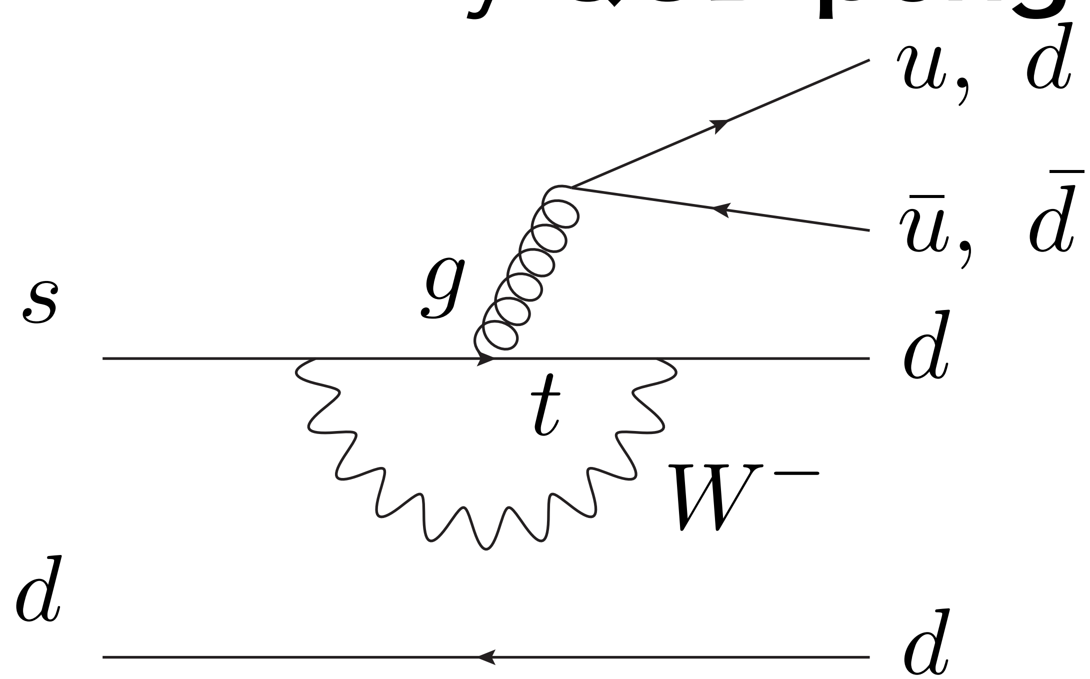
$$(\epsilon'/\epsilon)_{exp} > (\epsilon'/\epsilon)_{SM} \text{ at } 2.9\sigma \text{ level}$$

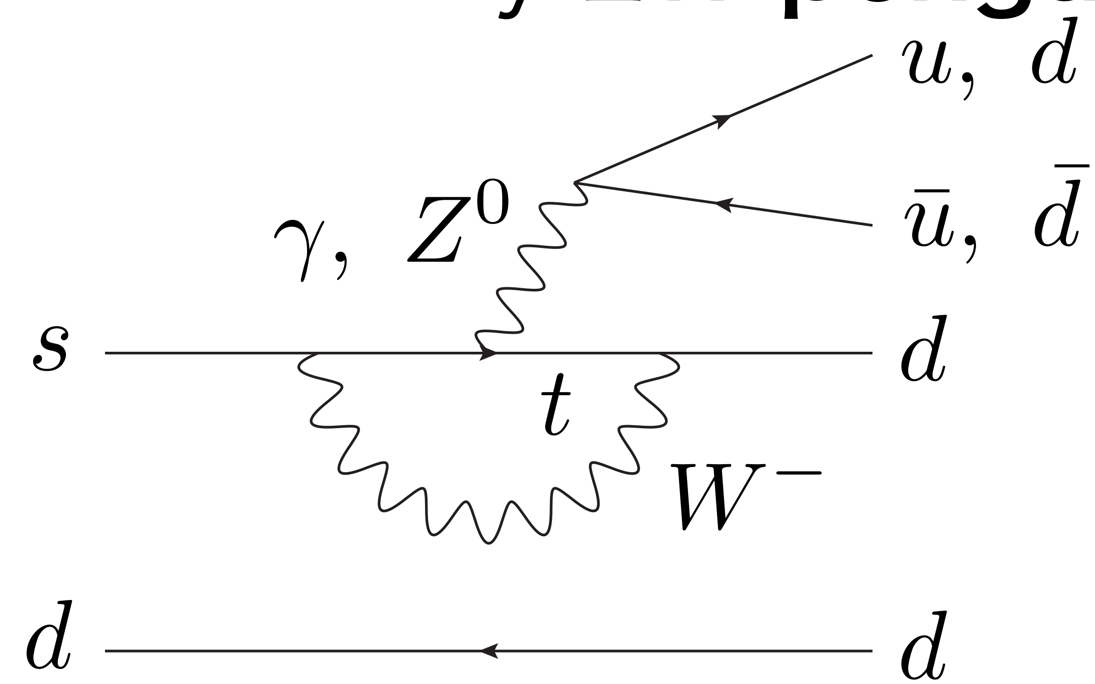
Can we explain this discrepancy by **SUSY**?

ϵ'/ϵ

$$\frac{\epsilon'}{\epsilon} = \frac{1}{\sqrt{2}\,|\epsilon|_{exp}} \frac{\omega_{exp}}{(\mathrm{Re}A_0)_{exp}} \left(\mathrm{Im}A_0 - \frac{1}{\omega_{exp}} \mathrm{Im}A_2 \right)$$

dominated by **QCD penguin** dominated by **EW penguin**





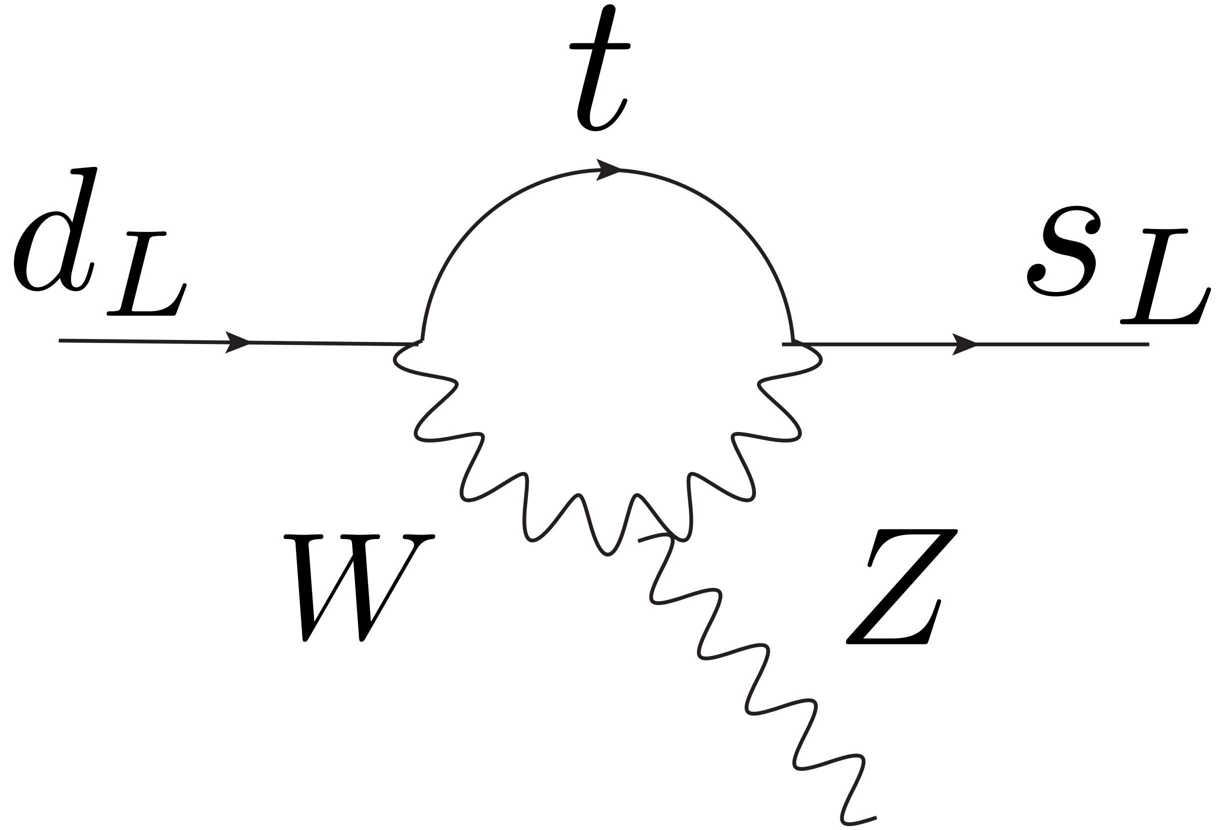
$$\langle (\pi\pi)_I | \mathcal{H} | K^0 \rangle = A_I e^{i\delta_I} \quad \text{Isospin} : I = 0, 2$$

$$\Delta I = 1/2 \text{ rule} : 1/\omega_{exp} = 22.46$$

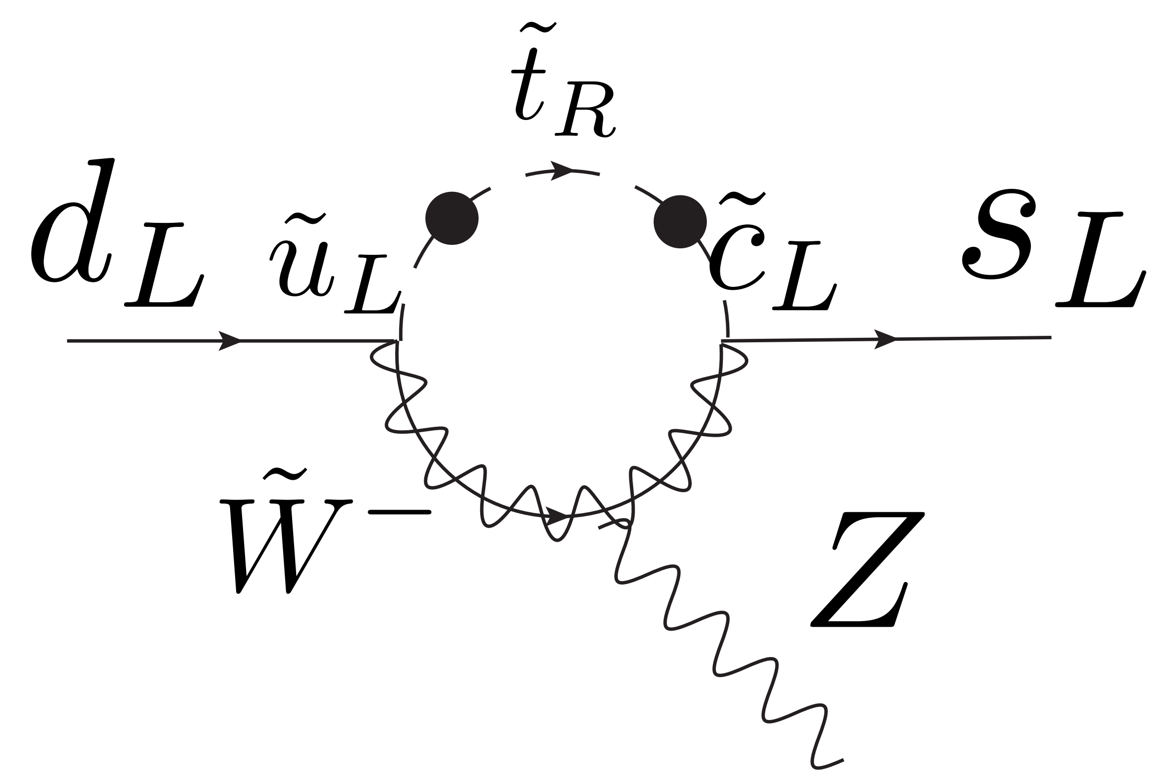
NP in $\mathrm{Im}A_2$ is favored because of $\Delta I = 1/2$

Chargino contributions to Z penguin

Z penguin in the SM

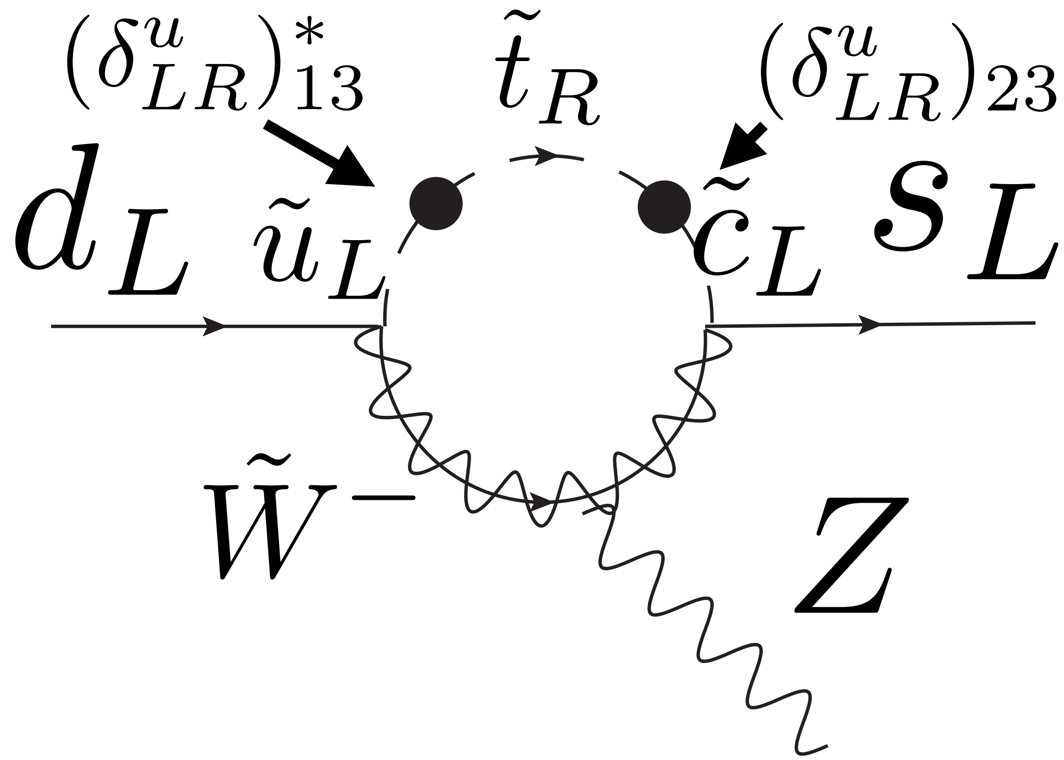


Chardino contribution



Chargino contributions to Z penguin

squark mass matrix: $\mathcal{M}^2_{\tilde{u}} = \mathrm{diag}(m^2_{\tilde{q}}) + m^2_{\tilde{q}} \begin{pmatrix} 0 & (\delta^u_{LR})_{ij} \\ (\delta^u_{RL})_{ij} & 0 \end{pmatrix}$



$$(\delta^u_{LR})_{ij} = \frac{v_2 (\hat{T}_U)^*_{ij}}{\sqrt{2} m^2_{\tilde{q}}}$$

$$\mathcal{L}_{eff} = Z_{ds} \bar{s}_L \gamma_\mu d_L Z^\mu + \mathrm{h.c.} \qquad Z_{ds} = Z^{(SM)}_{ds} + Z^{(SUSY)}_{ds}$$

$$Z^{(SUSY)}_{ds} \propto (\delta^u_{LR})^*_{13} (\delta^u_{LR})_{23} \sim \frac{v_2^2 (\hat{T}_U)_{13} (\hat{T}_U)^*_{23}}{m^4_{\tilde{q}}}$$

$$(\epsilon'/\epsilon)_{SUSY} \propto \mathrm{Im}\left(Z^{(SUSY)}_{ds}\right)$$

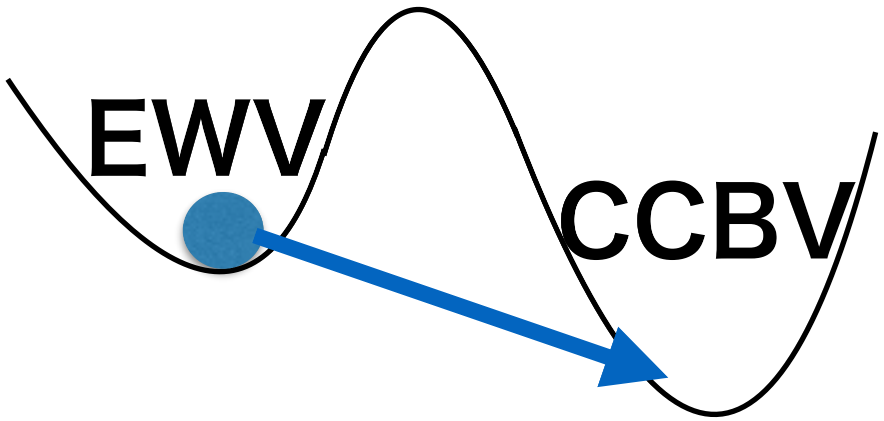
Vacuum stability

Large $\left|(\hat{T}_U)_{ij}\right|$ destabilizes electroweak vacuum(**EWV**)

scalar potential come from soft SUSY breaking terms

$$V_{scalar} \supset (\hat{T}_U)_{i3} H_2^0 \tilde{u}_{iL} \tilde{t}_R$$

EWV can decay to Color-Charge Breaking vacuum(**CCBV**)



Vacuum stability

(Lifetime of EW vacuum) > (Age of the universe)

Decay rate of the vacuum per unite volume

$$\Gamma/V = A \exp\left(-S_E\right)$$

↑

decay rate is sensitive to S_E

at semiclassical level

$$A \sim (100\mathrm{GeV})^4 - (10\mathrm{TeV})^4$$

from dimensional analysis

Vacuum stability

(Lifetime of EW vacuum) > (Age of the universe)

↑

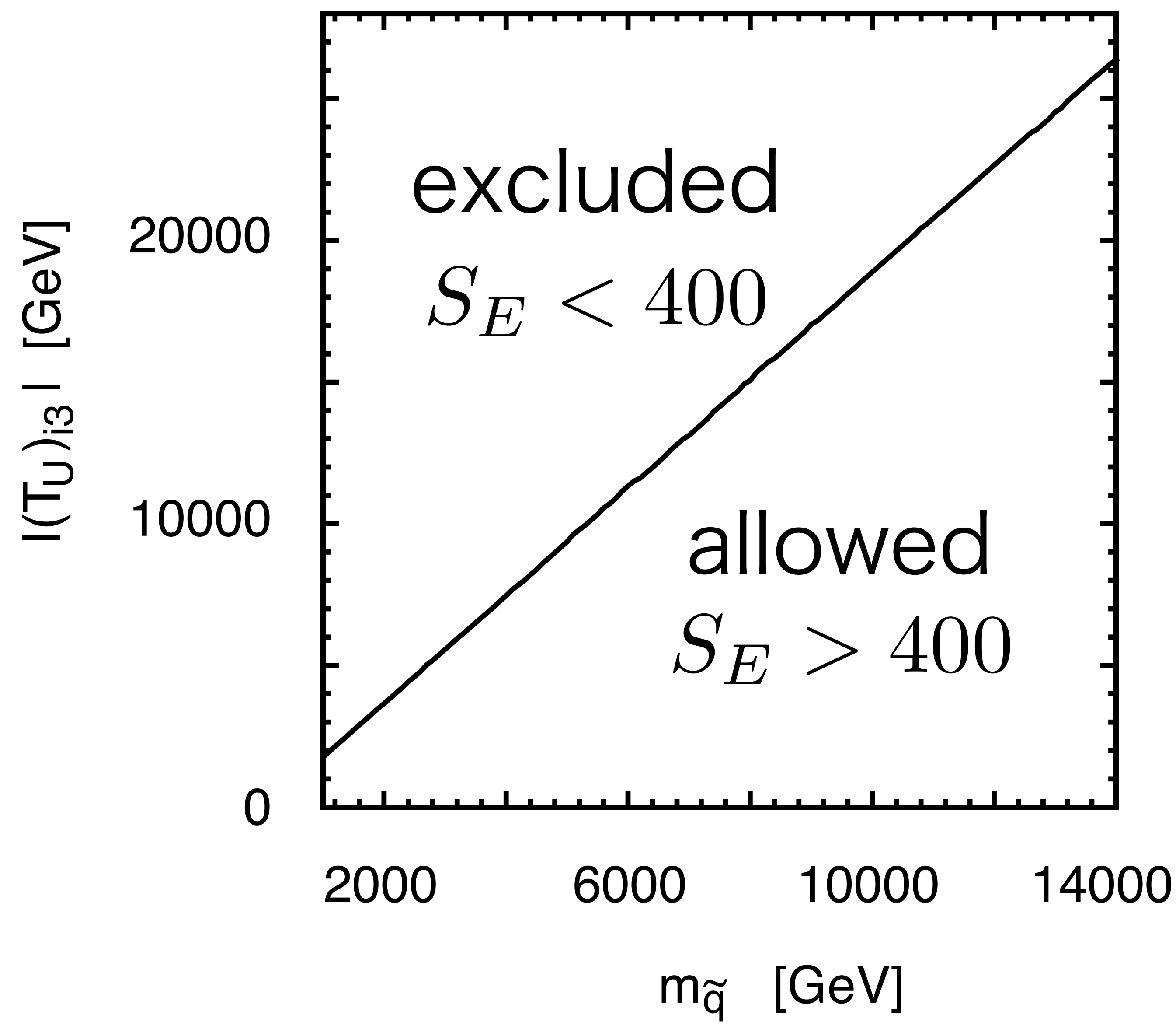
Using current Hubble constant $H_0 \sim 1.5 \times 10^{-42}\mathrm{GeV}$

$$S_E > 400$$

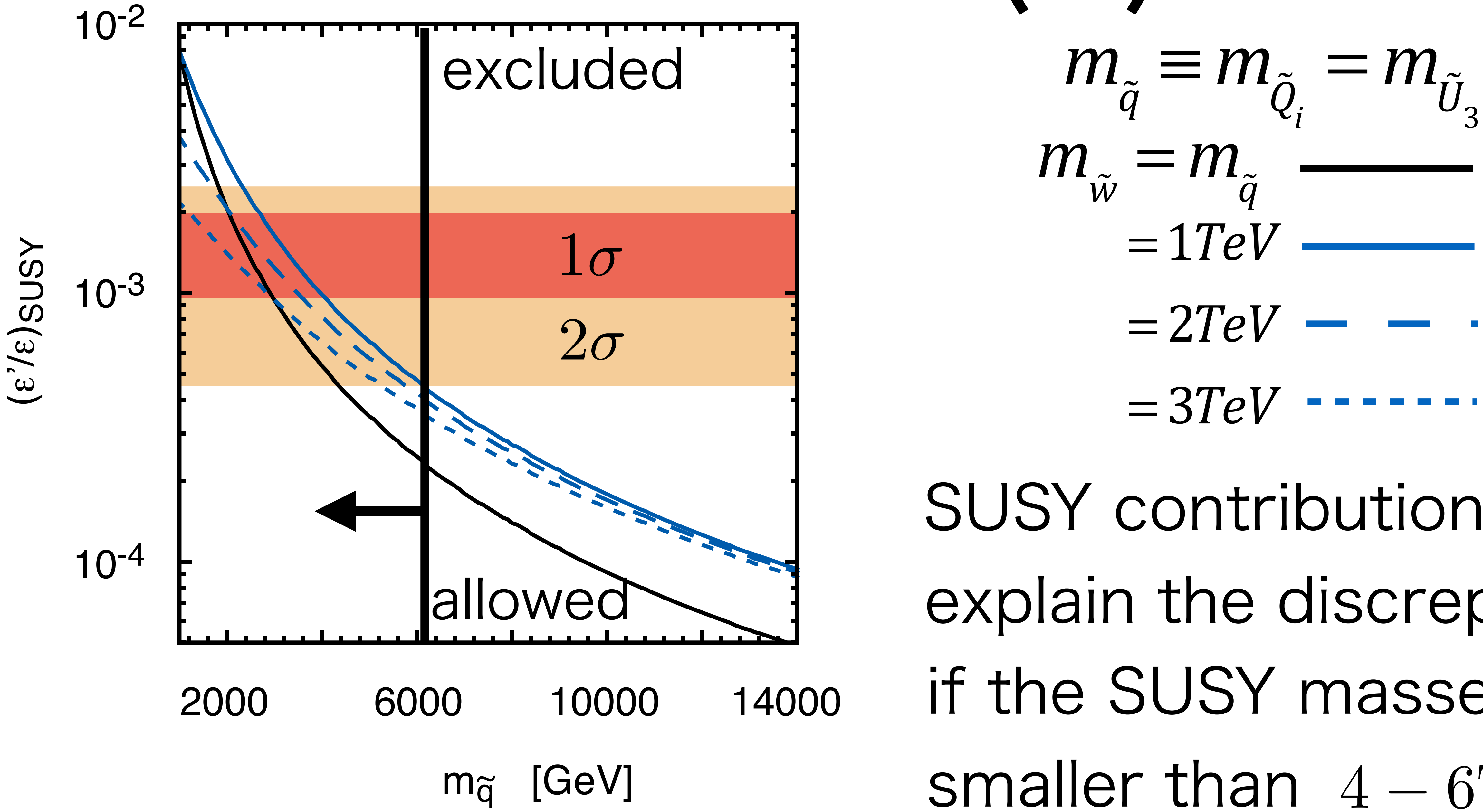
We can get the upper bound of trilinear coupling

Vacuum stability

upper limit of trilinear coupling



Result(1)



SUSY contributions can explain the discrepancy if the SUSY masses are smaller than $4 - 6\mathrm{TeV}$

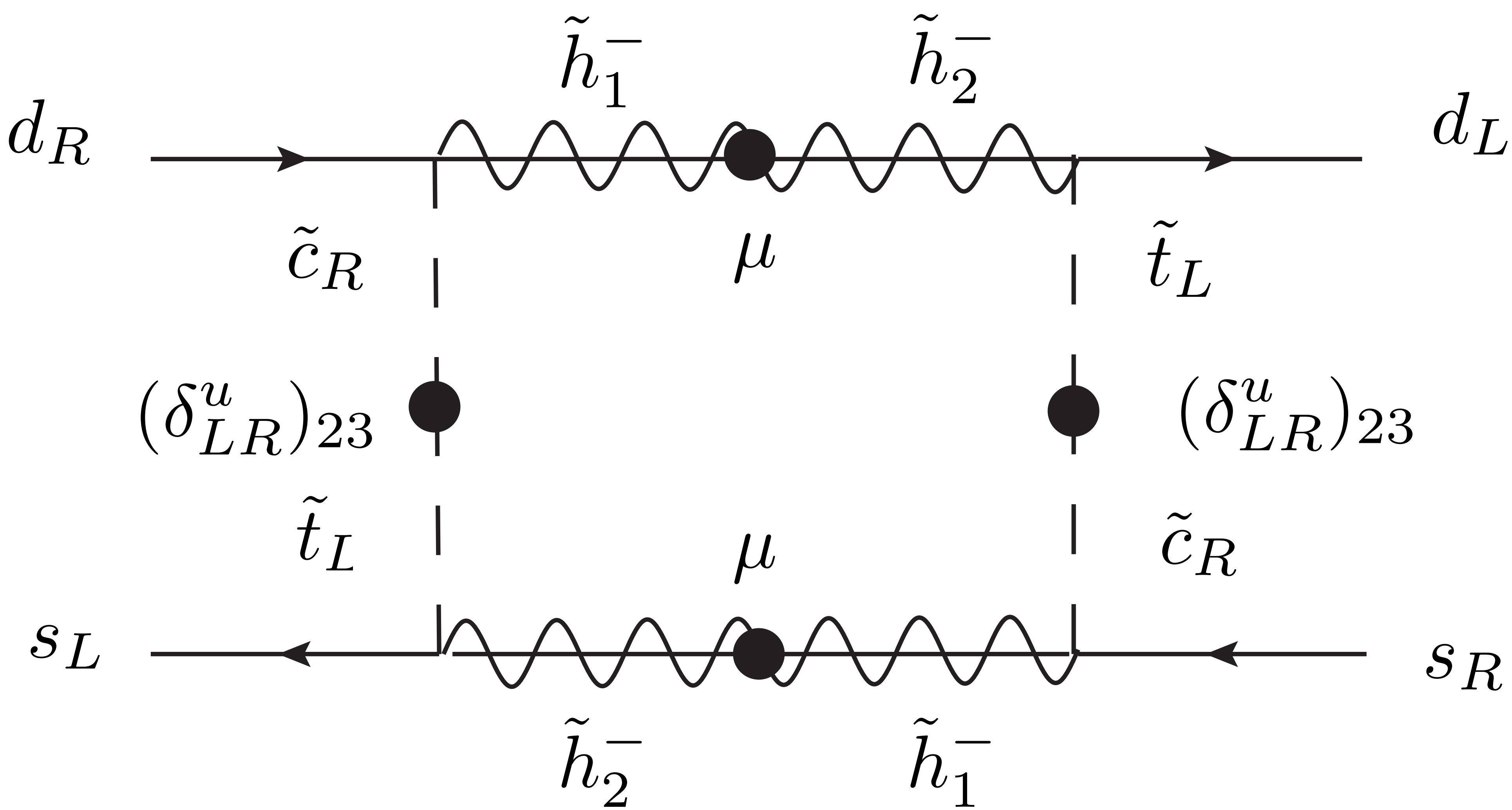
Other constraints is satisfied

For example, ϵ , EDM, Δm_d, $\mathcal{B}(b \to s\gamma)$

ϵ

In ϵ contribution from $(\bar{s}\gamma_\mu P_L d)(\bar{s}\gamma^\mu P_R d)$ is enhanced

chiral enhancement



But chargino contribution is suppressed by small yukawa

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

$K_L \to \pi^0 \nu\bar{\nu}$: CP-violating process

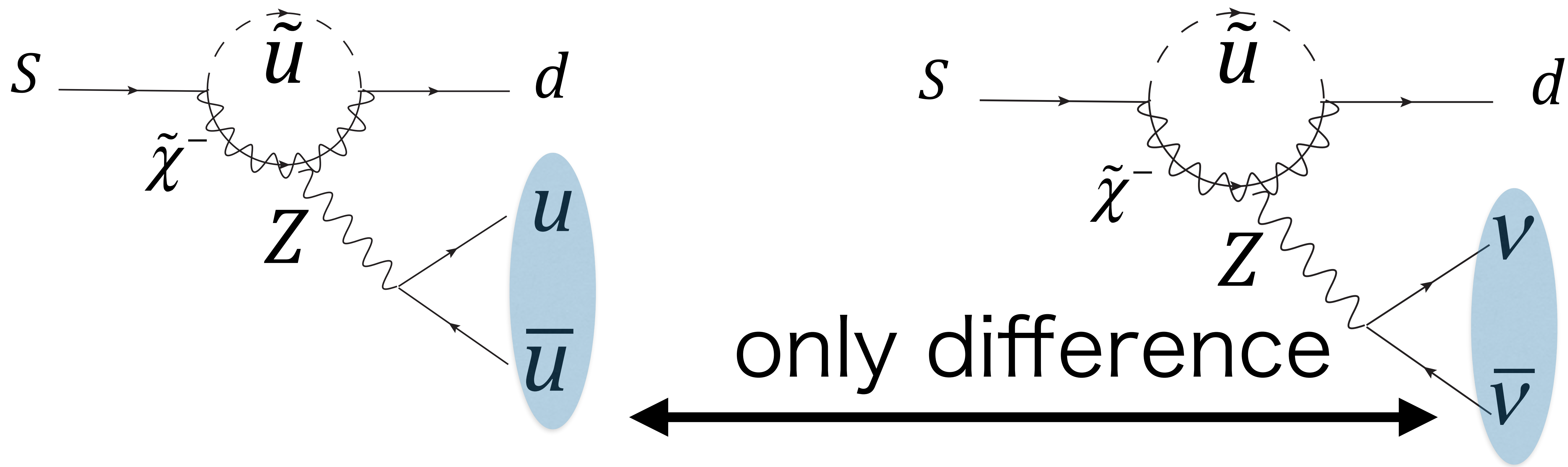
$$CP\left|\nu\bar{\nu}\right\rangle = -\left|\nu\bar{\nu}\right\rangle \quad CP\left|\pi^0\right\rangle = -\left|\pi^0\right\rangle \quad CP\left|\pi^0\nu\bar{\nu}\right\rangle = \left|\pi^0\nu\bar{\nu}\right\rangle$$

In CP symmetric system

$$CP\left|K_L\right\rangle = -\left|K_L\right\rangle$$

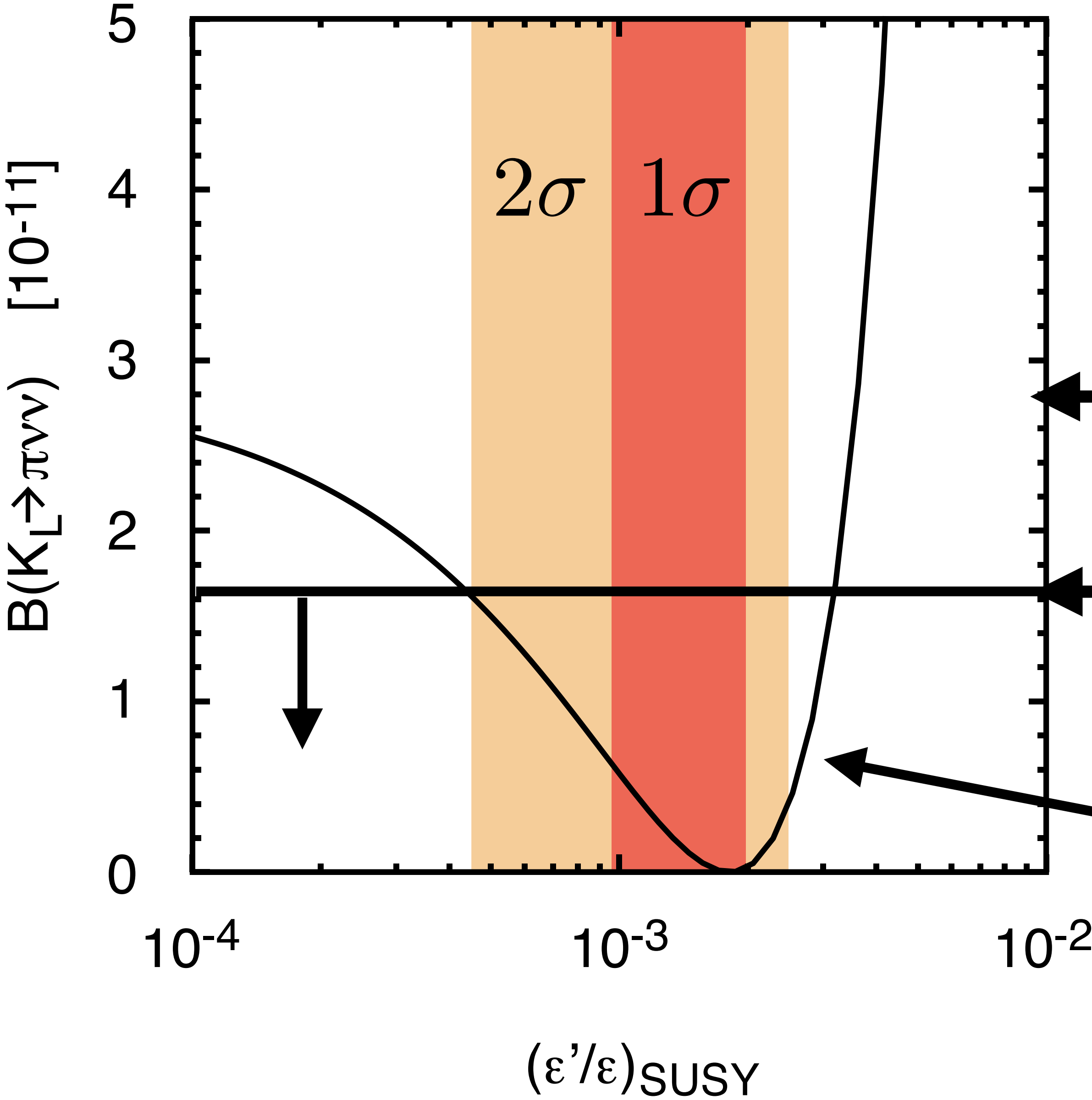
Correlation with $\mathcal{B}\left(K_L \to \pi^0 \nu\bar{\nu}\right)$

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



$$\mathcal{B}\left(K_L \to \pi^0 \nu\bar{\nu}\right) \propto \left(\mathrm{Im}\left(X^{(SM)}\right) + \mathrm{Im}\left(Z_{ds}^{(SUSY)}\right)\right)^2 \propto \left(Y^{(SM)} + (\epsilon'/\epsilon)_{SUSY}\right)^2$$

Result(2)



$$\mathcal{B}\left(K_L \to \pi^0 \nu \bar{\nu}\right) \propto \left(Y^{(SM)} + (\epsilon'/\epsilon)_{SUSY}\right)^2$$

SM prediction

60% of the SM prediction

chargino prediction

The current discrepancy implies that $\mathcal{B}\left(K_L \to \pi^0 \nu \bar{\nu}\right)$ is about less than 60% of the SM prediction

Conclusion

- SUSY contributions can explain the discrepancy if the SUSY masses are smaller than $4-6\mathrm{TeV}$
- The current discrepancy implies that $\mathcal{B}\left(K_L \to \pi^0\nu\bar{\nu}\right)$ is about less than 60% of the SM prediction.
- Other SUSY contributions are future works.

Kaon

Neutral kaon

Flavour eigenstate K^0 $\bar{K}^0$

$\updownarrow$ $\updownarrow$ quark level

$(d, \bar{s})$ $(\bar{d}, s)$

$\bar{K}^0$ is antiparticle of K^0 $CP\,|K^0\rangle = |\bar{K}^0\rangle$

Kaon

CP eigenstate

$$|K_+\rangle = \frac{1}{2}\left(|K^0\rangle + |\bar{K}^0\rangle\right) \qquad CP\,|K^0\rangle = |\bar{K}^0\rangle$$

$$|K_-\rangle = \frac{1}{2}\left(|K^0\rangle - |\bar{K}^0\rangle\right)$$

$$CP\,|K_+\rangle = +\,|K_+\rangle$$

$$CP\,|K_-\rangle = -\,|K_-\rangle$$

Kaon

If system is CP invariant $[CP, H] = 0$

$$i\frac{d}{dt}\left|\Phi(t)\right\rangle = H\left|\Phi(t)\right\rangle \qquad \left|\Phi(t)\right\rangle = a(t)\left|K^0\right\rangle + b(t)\left|\bar{K}^0\right\rangle$$

$\left|K_+\right\rangle,\ \left|K_-\right\rangle$ are also mass eigenstates.

$$\left|K_S\right\rangle \equiv K_+ = \frac{1}{\sqrt{2}}\left(\left|K^0\right\rangle + \left|\bar{K}^0\right\rangle\right) \quad \left|K_L\right\rangle \equiv K_- = \frac{1}{\sqrt{2}}\left(\left|K^0\right\rangle - \left|\bar{K}^0\right\rangle\right)$$

$\left|K_S\right\rangle,\ \left|K_L\right\rangle$:mass eigenstate

CP violation in Kaon

If system is CP invariant

$$|K_S\rangle = |K_+\rangle \rightarrow |\pi\pi\rangle$$

$$|K_L\rangle = |K_-\rangle \rightarrow |\pi\pi\rangle$$

$$CP\,|\pi\pi\rangle = |\pi\pi\rangle$$

$K_L \rightarrow \pi\pi$ is observed from experiment.

CP is violated.

CP violation in Kaon

If CP is violated $[CP, H] \neq 0$

mass eigenstates are not CP eigenstates.

mass eigenstates K_L, K_S are linear combination of K_+, K_-

$$|K_S\rangle = |K_+\rangle + \epsilon_K |K_-\rangle \qquad |K_L\rangle = |K_-\rangle + \epsilon_K |K_+\rangle$$

$\epsilon_K \sim 10^{-3}$

CP violation in Kaon

$|K_S\rangle = |K_+\rangle + \epsilon_K |K_-\rangle$ $\qquad$ $|K_L\rangle = |K_-\rangle + \epsilon_K |K_+\rangle$

CP invariant interaction

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

CP violation originate from mixing

Indirect CP violation

CP violation in Kaon

$$|K_S\rangle = |K_+\rangle + \epsilon_K |K_-\rangle \qquad |K_L\rangle = |K_-\rangle + \epsilon_K |K_+\rangle$$

CP invariant interaction

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

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

If CP violation is only indirect $\eta_{00} = \eta_\pm = \epsilon_K$

$$\epsilon_K \equiv \frac{2\eta_\pm + \eta_{00}}{3}$$

CP violation in Kaon

$$|K_S\rangle = |K_+\rangle + \epsilon_K |K_-\rangle \qquad |K_L\rangle = |K_-\rangle + \epsilon_K |K_+\rangle$$

CP violating interaction

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

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

Direct CP violation

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

$$\eta_\pm \neq \eta_{00}$$

$$\epsilon' \equiv \frac{\eta_\pm - \eta_{00}}{3}$$

Measurement of ϵ'/ϵ

$$\mathrm{Re}\frac{\epsilon'}{\epsilon} \simeq \frac{1}{6}\frac{|\eta_{\pm}|^2 - |\eta_{00}|^2}{|\eta_{\pm}|^2} = \frac{1}{6}\left(1 - \frac{\frac{\mathcal{B}(K_L\to\pi^0\pi^0)}{\mathcal{B}(K_S\to\pi^0\pi^0)}}{\frac{\mathcal{B}(K_L\to\pi^+\pi^-)}{\mathcal{B}(K_S\to\pi^+\pi^-)}}\right)$$

We can measure this value.

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

NA48 and KTeV measured it

$$(\epsilon'_K/\epsilon_K)_{exp} = (16.6 \pm 2.3)\times 10^{-4} \quad [\mathrm{PDG}]$$

ϵ'_K/ϵ_K

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

$$\left\langle (\pi\pi)_I|\mathcal{H}|K^0\right\rangle = A_I e^{i\delta_I} \qquad \left\langle (\pi\pi)_I|\mathcal{H}|\bar{K}^0\right\rangle = A_I^* e^{i\delta_I}$$

$$\text{Isospin} : I = 0, 2$$

$$\epsilon'_K \simeq \frac{1}{\sqrt{2}}\frac{\omega}{\mathrm{Re}A_0}\left(\mathrm{Im}A_0 - \frac{1}{\omega}\mathrm{Im}A_2\right)\exp\left(i\left(\frac{\pi}{2} + \delta_2 - \delta_0\right)\right)$$

$$\omega \equiv \frac{\mathrm{Re}A_2}{\mathrm{Re}A_0}$$

ϵ'_K/ϵ_K

$$\epsilon'_K \simeq \frac{1}{\sqrt{2}} \frac{\omega_{exp}}{(\mathrm{Re}A_0)_{exp}} \left(\mathrm{Im}A_0 - \frac{1}{\omega_{exp}} \mathrm{Im}A_2 \right) \exp\left(i \left(\frac{\pi}{2} + \delta_2 - \delta_0 \right)_{exp} \right)$$

$$\epsilon_K = |\epsilon_K| \exp\left(i \mathrm{Tan}^{-1} \frac{2\Delta M_K}{\Delta \Gamma_K} \right)$$

acidental cancellation occurs

We evaluate below quantity

$$\frac{\epsilon'_K}{\epsilon_K} \simeq \frac{1}{\sqrt{2}|\epsilon_K|} \frac{\omega_{exp}}{(\mathrm{Re}A_0)_{exp}} \left(\mathrm{Im}A_0 - \frac{1}{\omega_{exp}} \mathrm{Im}A_2 \right)$$

The SM prediction of ϵ'_K/ϵ_K

The standard model prediction

$$(\mathrm{Re}\,(\epsilon'_K/\epsilon_K))_{SM} = (1.38 \pm 6.90) \times 10^{-4} \quad \text{[RBC-UKQCD]}$$

$$(\mathrm{Re}\,(\epsilon'_K/\epsilon_K))_{SM} = (1.9 \pm 4.5) \times 10^{-4} \quad \text{[Buras et al.]}$$

$$(\mathrm{Re}\,(\epsilon'_K/\epsilon_K))_{SM} = (1.06 \pm 5.07) \times 10^{-4} \quad \text{[Kitahara et al.]}$$

The SM prediction of ϵ'_K/ϵ_K

RBC-UKQCD

$$\frac{\epsilon'_K}{\epsilon_K} \simeq \frac{1}{\sqrt{2}|\epsilon_K|} \frac{\omega_{exp}}{(\mathrm{Re}A_0)_{exp}} \left(\mathrm{Im}A_0 - \frac{1}{\omega_{exp}} \mathrm{Im}A_2 \right)$$

They determine $\mathrm{Im}A_0, \mathrm{Im}A_2$ by lattice QCD calculation.

The SM prediction of ϵ'_K/ϵ_K

Buras et al. A.J. Buras, M. Gorbahn, S. J¨ager and M. Jamin, JHEP 11 (2015) 202 [arXiv:1507.06345]

$$\frac{\epsilon'_K}{\epsilon_K} \simeq \frac{1}{\sqrt{2}|\epsilon_K|} \frac{\omega_{exp}}{(\mathrm{Re}A_0)_{exp}} \left(\mathrm{Im}A_0 - \frac{1}{\omega_{exp}} \mathrm{Im}A_2 \right)$$

$$\mathcal{H}_{eff} = \frac{G_F}{\sqrt{2}} \sum_{i=1}^{10} C_i(\mu) Q_i(\mu) \qquad A_I = \langle (\pi\pi)_I | \mathcal{H}_{eff} | K^0 \rangle$$

$$(\mathrm{Re}A_0)_{exp}, (\mathrm{Re}A_2)_{exp}$$

↓ determine

$$\langle Q_2(\mu) \rangle_0 , \langle Q_2(\mu) \rangle_2$$

↓ by using suitable relation

$$\langle Q_{4,10}(\mu) \rangle_0 , \langle Q_{1,9,10}(\mu) \rangle_2$$

$$\langle Q_i(\mu) \rangle_I \equiv \langle (\pi\pi)_I | Q_i(\mu) | K^0 \rangle$$

The SM prediction of ϵ'_K/ϵ_K

Kitahara et al.

$$\frac{\epsilon'_K}{\epsilon_K} \simeq \frac{1}{\sqrt{2}|\epsilon_K|} \frac{\omega_{exp}}{(\mathrm{Re}A_0)_{exp}} \left(\mathrm{Im}A_0 - \frac{1}{\omega_{exp}} \mathrm{Im}A_2 \right)$$

In addition to Buras's result they estimate subleading hadron matrix elements

$$\langle Q_3 \rangle_0 \,, \langle Q_5 \rangle_0 \,, \langle Q_7 \rangle_0$$

by using lattice QCD result.

Models solving ϵ'/ϵ anomaly

Several new physics models have been studied to explain ϵ'/ϵ anomaly

MSSM

chargino Z penguin [M.Endo, S.Mishima, D.Ueda and K.Yamamoto, PLB762(2016)493]

gluino Z penguin [M.Tanimoto and K.Yamamoto, PTEP(2016)no.12,123B02]

gluino box [T.Kitahara, U.Nierste and P.Tremper, PRL117(2016)no.9, 091802 A.Crivellin, G.D'Ambrosio, T.Kitahara and U.Nierste, 1703.05786]

Vector-like quarks [C.Bobeth, A.J.Buras, A.Celis and M.Jung, JHEP1704(2017)079]

Little Higgs Model with T-parity [M.Blanke, A.J.Buras and S.Recksiegel, EPJ.C76 (2016)no.4,182]

331 model [A.J.Buras and F.De Fazio, JHEP 1603(2016)010 & JHEP1608 (2016) 115]

Right handed current [V.Cirigliano, W.Dekens, J.de Vries and E.Mereghetti, PLB
017)1 S.Alioli, V.Cirigliano, W.Dekens, J.de Vries and E.Mereghetti, JHEP1705 (2017)086]

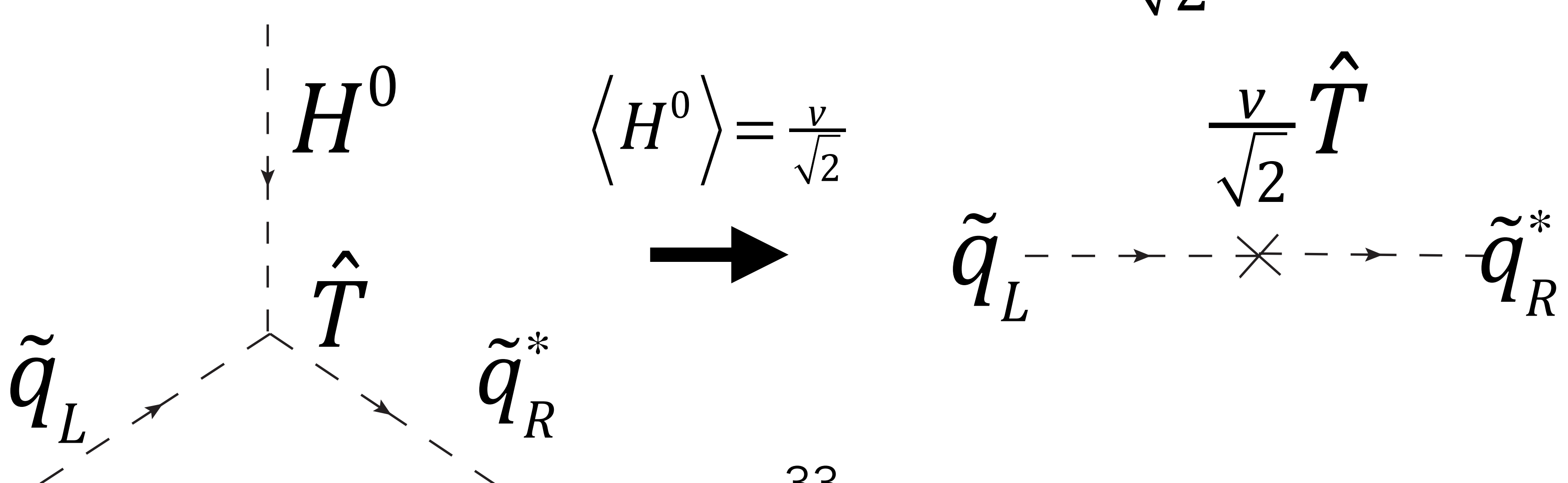
Chargino contributions to Z penguin

soft SUSY breaking terms

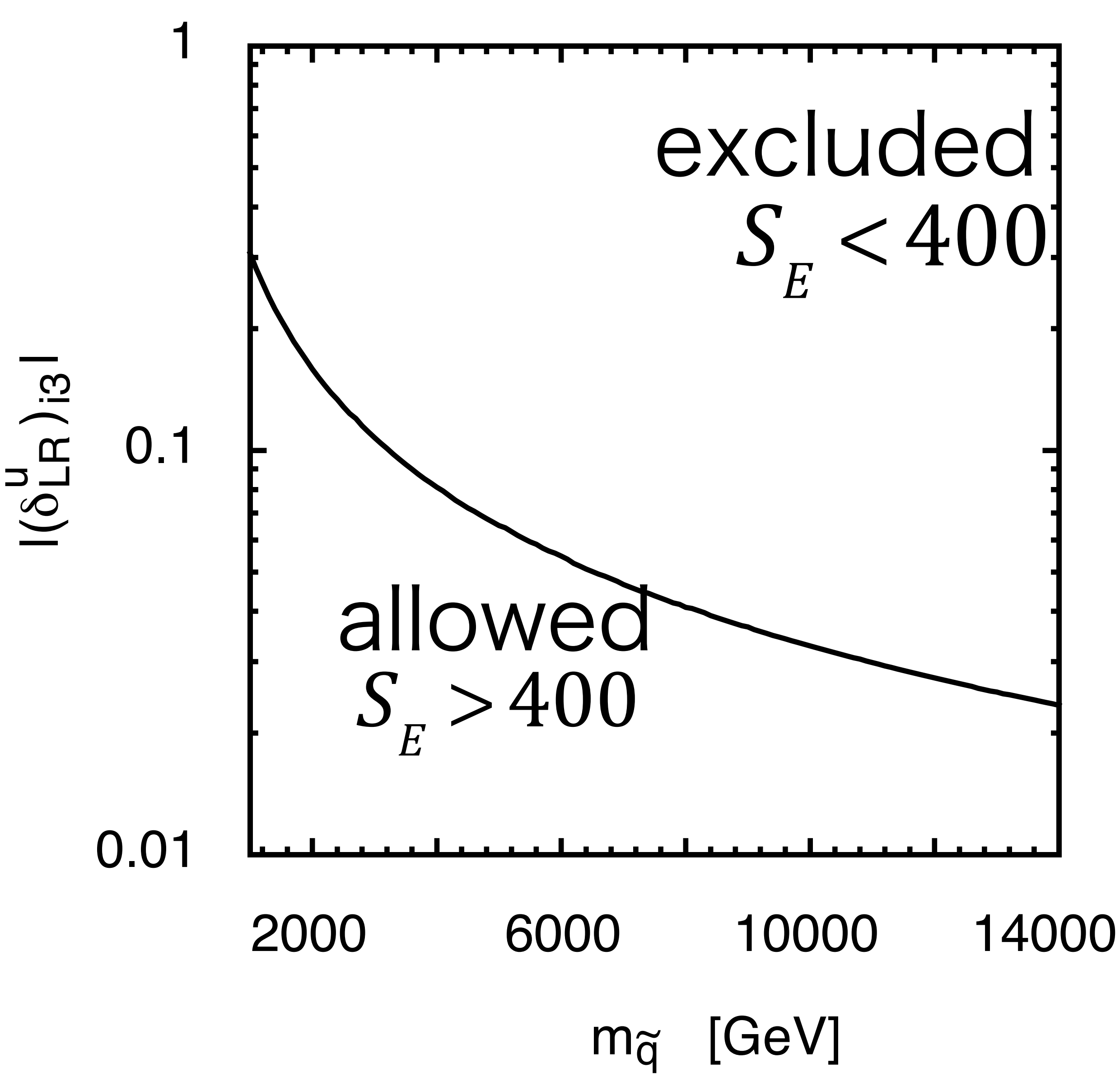
$$-\mathcal{L}_{soft} \supset (\hat{m}_{\tilde{Q}})^2_{ij}\tilde{u}^*_{iL}\tilde{u}_{jR} + (\hat{m}^2_{\tilde{u}})_{ij}\tilde{u}^*_{iR}\tilde{u}_{jR} + \left((\hat{T}_U)_{ij}H^0_2\tilde{u}_{iL}\tilde{u}_{jR} + \text{h.c.}\right)$$

trilinear term

EW symmetry breaking: $H_1^0 \to \frac{v_1}{\sqrt{2}}$ $H_2^0 \to \frac{v_2}{\sqrt{2}}$



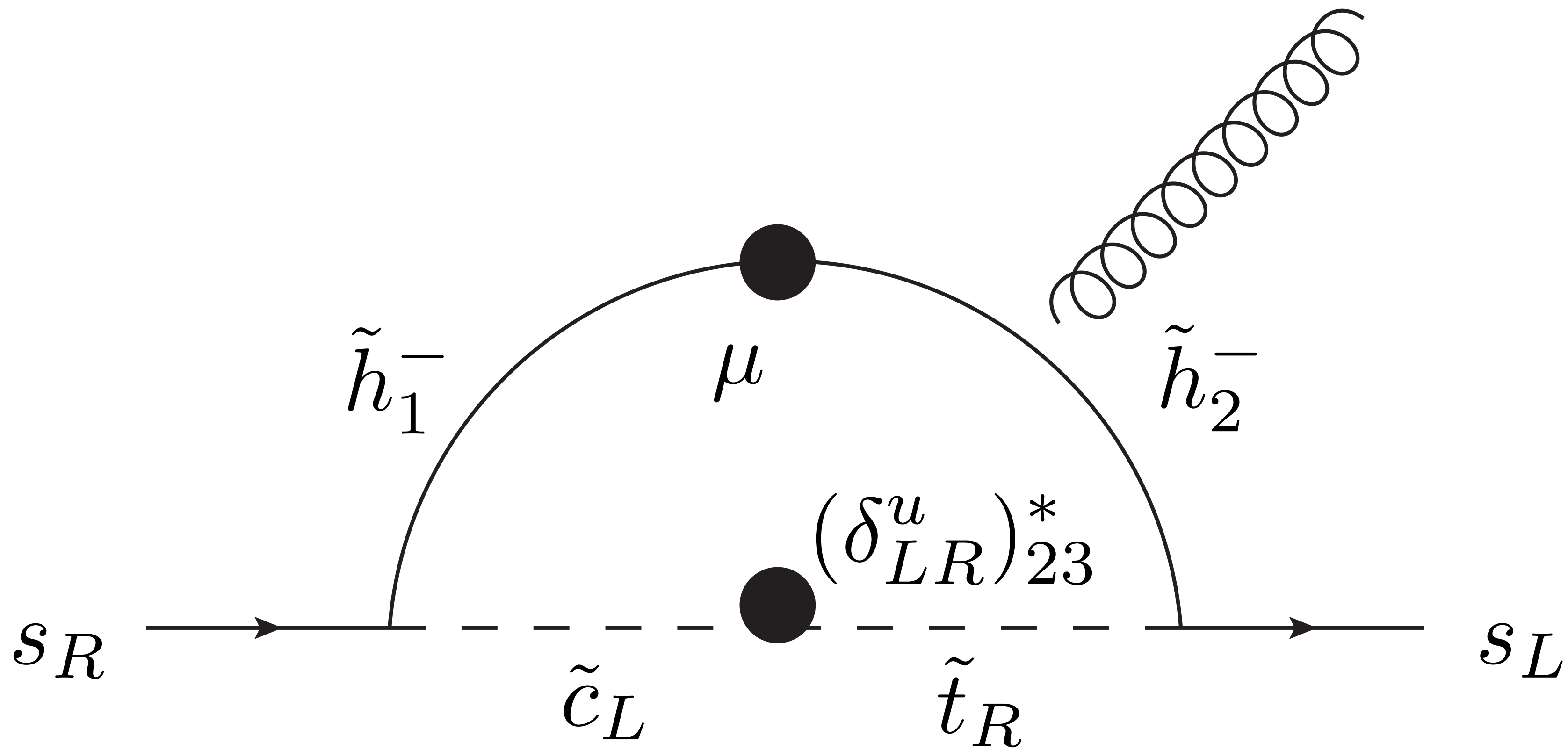
Vacuum stability



$$(\delta^u_{LR})_{ij} = \frac{v_2(\hat{T}_U)^*_{ij}}{\sqrt{2}m^2_{\tilde{q}}}$$

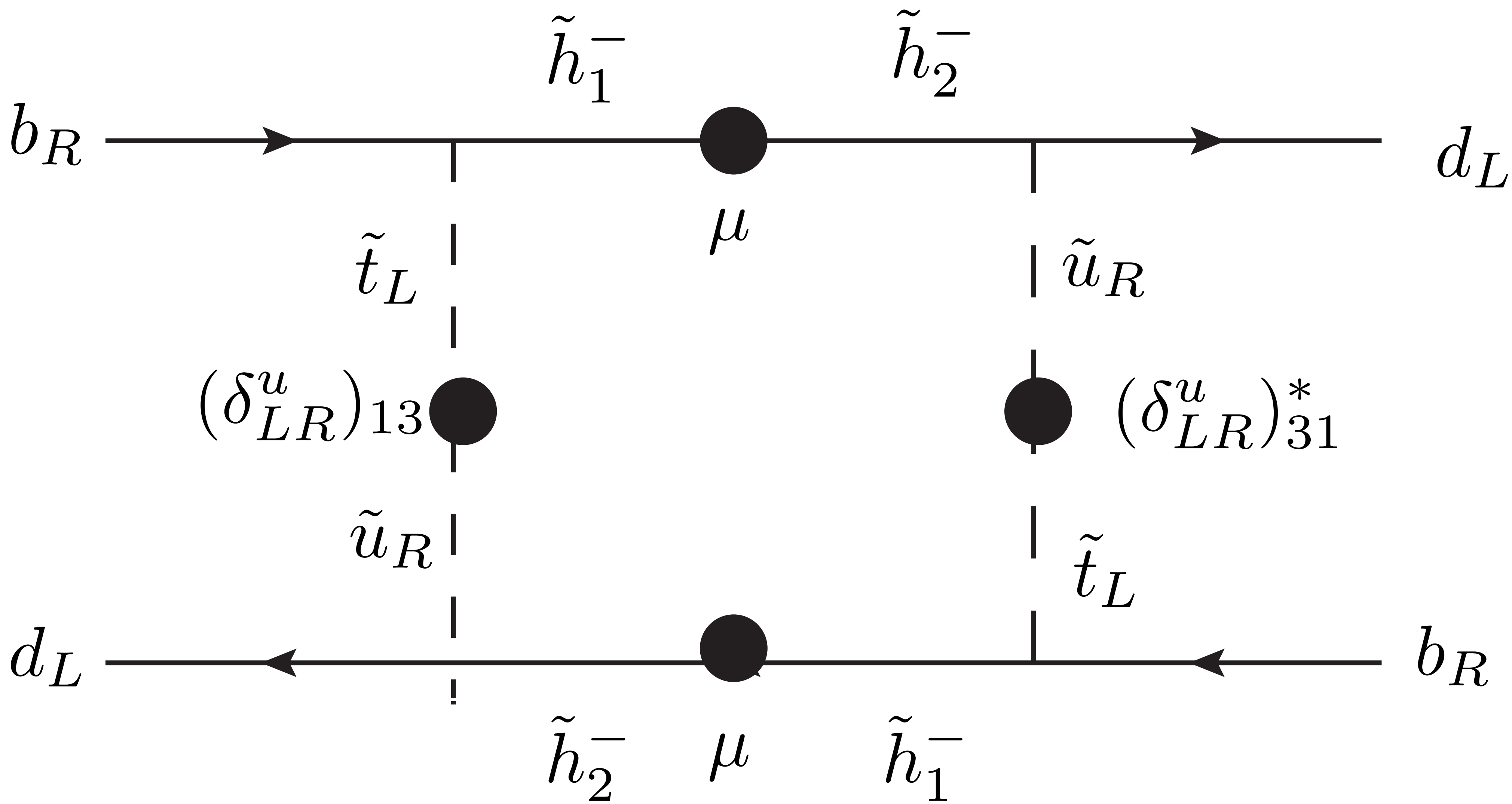
$$\left(\varepsilon'/\varepsilon\right)_{SUSY} \propto \mathrm{Im}\left(Z^{(SUSY)}_{ds}\right) \quad Z^{(SUSY)}_{ds} \propto (\delta^u_{LR})^*_{13}(\delta^u_{LR})_{23}$$

EDM



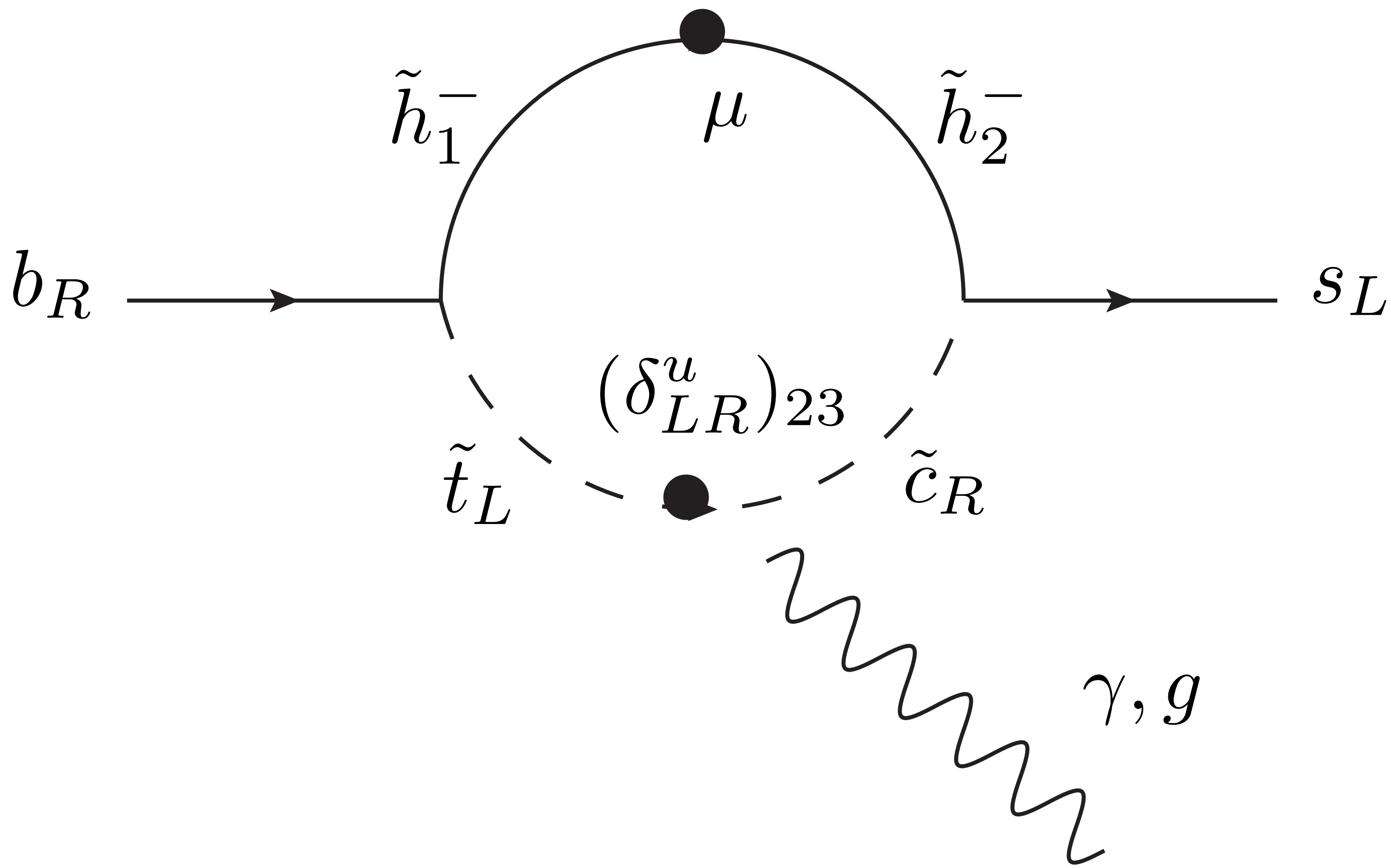
small yukawa and heavy higgsino suppress charging contribution.

Δm_d



Heavy higsino suppress chargino contribution.

$\mathcal{B}(b \to s\gamma)$



Heavy higgsino suppress charging contribution.

$(\epsilon'/\epsilon)_{SUSY}$ is sensitive to wino mass.