SUSY contributions in light of recent ϵ'/ϵ

Daiki Ueda
(KEK theory center, SOKENDAI)

基研研究会　素粒子物理学の進展2017
於京都大学基礎物理学研究所
2017年7月31日-8月4日

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

Introduction

ϵ'/ϵ : $K_L \to \pi\pi$におけるdirect CP-violating observable

CP対称な系において

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

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

Introduction

標準理論

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

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

実験結果

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

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

SUSYによってこの不一致を説明できるか?

Kaon

$$CP\left|K^0\right\rangle = \left|\bar{K}^0\right\rangle$$

CP 固有状態

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

$$CP\left|K_+\right\rangle = +\left|K_+\right\rangle \quad CP\left|K_-\right\rangle = -\left|K_-\right\rangle$$

Kaon

系がCP対称のとき $[CP, \mathcal{H}] = 0$

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

$\left|K_+\right\rangle$, $\left|K_-\right\rangle$ は質量固有状態でもある

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

$\left|K_S\right\rangle$, $\left|K_L\right\rangle$:質量固有状態

KaonのCP破れ

CPが破れているとき $[CP, \mathcal{H}] \neq 0$

質量固有状態はCP固有状態ではない

質量固有状態 K_L, K_S は K_+, K_- の線形結合である

$$|K_S\rangle = |K_+\rangle + \underset{\substack{\uparrow \\ \sim 10^{-3}}}{\epsilon}\,|K_-\rangle \qquad |K_L\rangle = |K_-\rangle + \epsilon\,|K_+\rangle$$

KaonのCP破れ

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

$$\mathcal{H} = \begin{pmatrix} M - \frac{i}{2}\Gamma & \Delta_{12} \\ \Delta_{21} & M - \frac{i}{2}\Gamma \end{pmatrix}$$

$\Delta_{12} \sim \left\langle K^0\right| \hat{H} \left|\bar{K}^0\right\rangle$ $\Delta_{21} \sim \left\langle \bar{K}^0\right| \hat{H} \left|K^0\right\rangle$ で $K^0 \leftrightarrow \bar{K}^0$が生じる

CP violationがmixingによって生じるとき

Indirect CP violation

$$\epsilon \propto \mathrm{Im}\left\langle K^0\right| \hat{H} \left|\bar{K}^0\right\rangle$$

KaonのCP破れ

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

CP を破る相互作用

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

Direct CP violation

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

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

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

ϵ'/ϵ

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

この量を測ることができる

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

NA48実験 と KTeV実験 が測定を行った

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

ϵ'/ϵ

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

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

Isospin : $I = 0, 2$

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

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

ϵ'/ϵ

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

$$\epsilon = |\epsilon| \exp\left(i \mathrm{Tan}^{-1} \frac{2\Delta M}{\Delta \Gamma} \right)$$

← acidental cancellation
が起きる

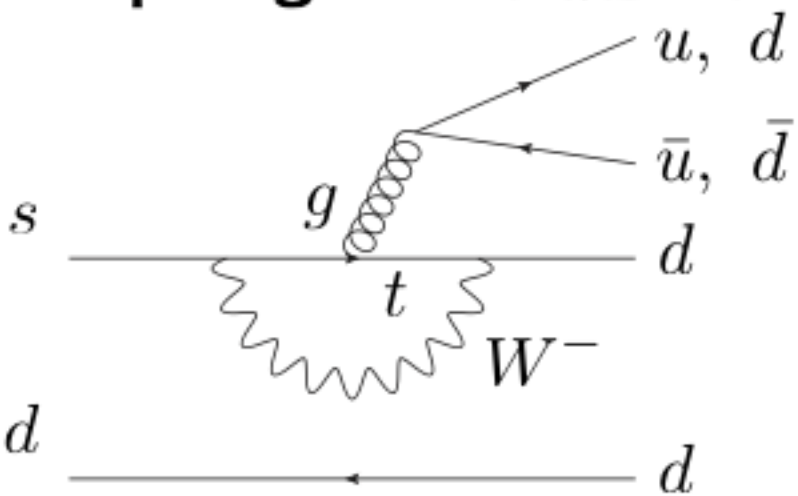
以下の量を評価する

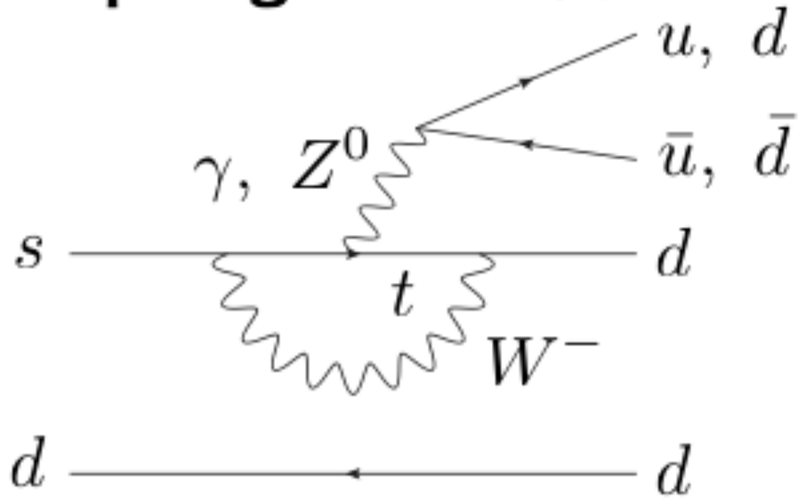
$$\frac{\epsilon'}{\epsilon} \simeq \frac{1}{\sqrt{2}\, |\epsilon|_{exp}} \frac{\omega_{exp}}{(\mathrm{Re}A_0)_{exp}} \left(\mathrm{Im}A_0 - \frac{1}{\omega_{exp}} \mathrm{Im}A_2 \right)$$

ϵ'/ϵ

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

QCD penguinに支配される **EW penguinに支配される**





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

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

$\mathrm{Im}A_2$におけるNPは$\Delta I = 1/2$ruleに支持される

Z penguinへのNPの寄与

SMEFT(SU(2)×U(1)対称)のEffective Lagrangian

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i C_i \mathcal{O}_i^{d>4}$$

e.g. d=6 operators

$$\mathcal{O}_i^{d=6} = \left(H^\dagger i \overleftrightarrow{D}_\mu H\right)\left(\bar{q}_i \gamma^\mu q_j\right)$$

$$\left(H^\dagger i \tau^a \overleftrightarrow{D}_\mu H\right)\left(\bar{q}_i \tau^a \gamma^\mu q_j\right)$$

$$\left(H^\dagger i \overleftrightarrow{D}_\mu H\right)\left(\bar{d}_i \gamma^\mu d_j\right)$$

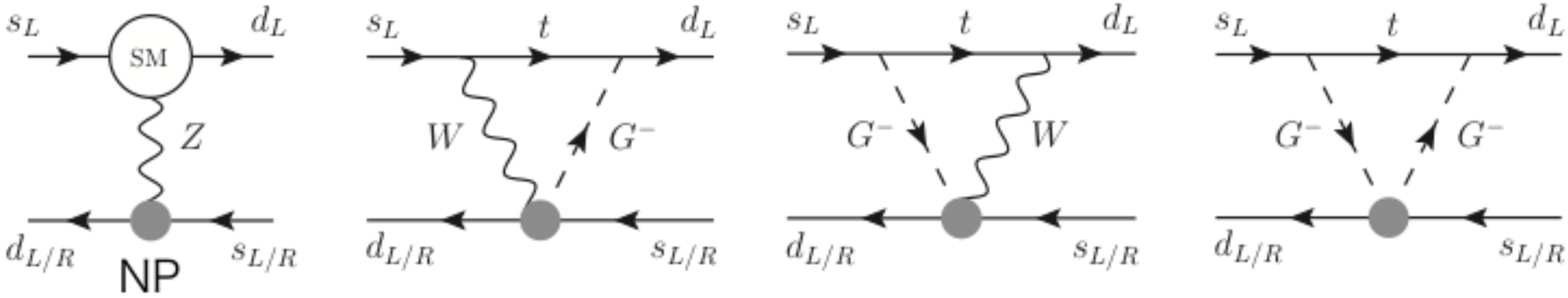
VEVをとる

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

$$+ \left(G_i, W^\pm - \mathrm{terms}\right)$$

Z penguinへのNPの寄与

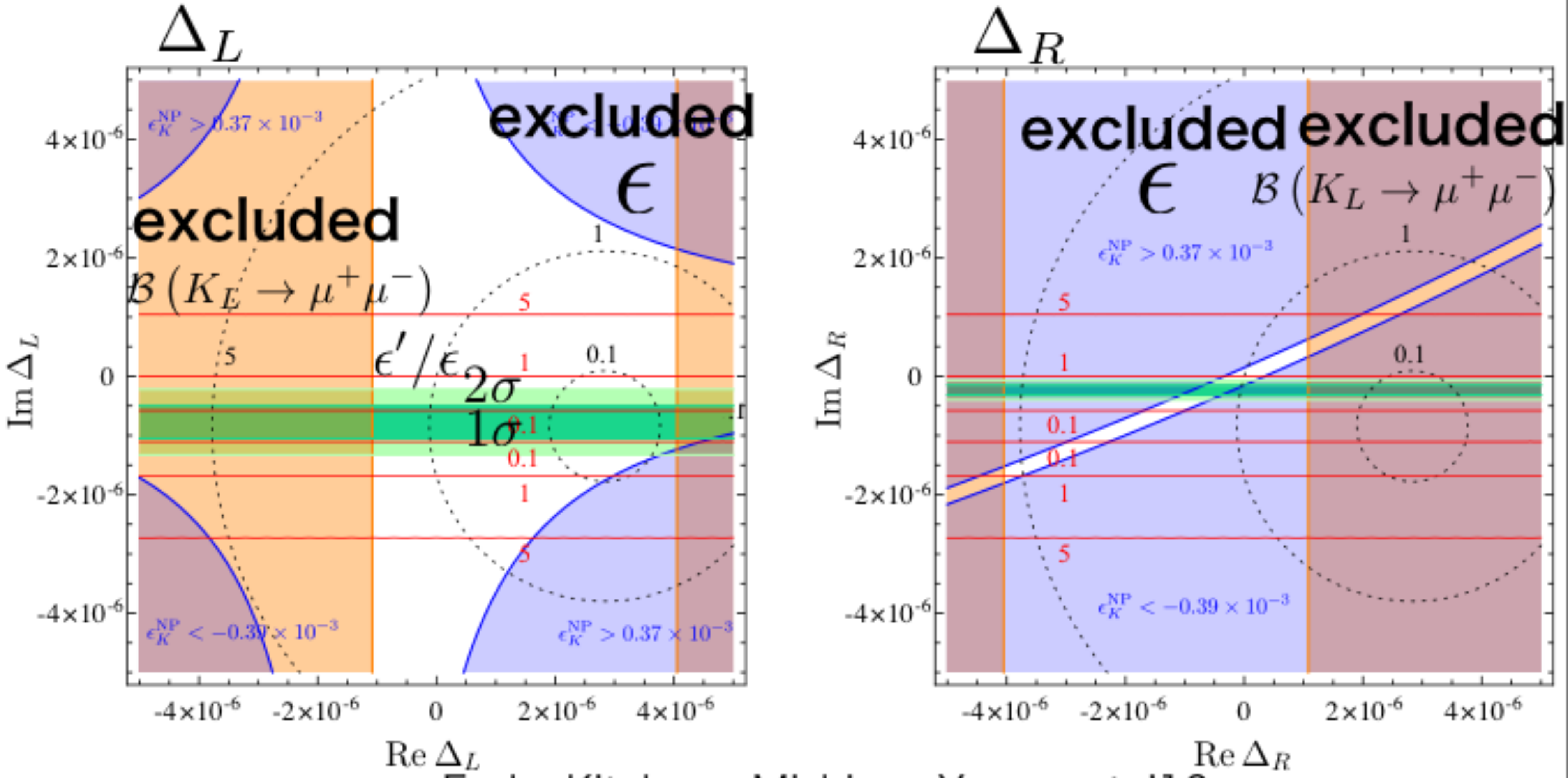
$\mathcal{L} \supset \Delta_R \left(\bar{s}\gamma^\mu P_R d\right) Z_\mu$ は $\left(\bar{d}\gamma_\mu P_L s\right)\left(\bar{d}\gamma^\mu P_R s\right)$を生成する



ϵにおいて$\left(\bar{d}\gamma_\mu P_L s\right)\left(\bar{d}\gamma^\mu P_R s\right)$の寄与は**chiral enhancement**

Z penguinへのNPの寄与

Z penguinへのNPの寄与



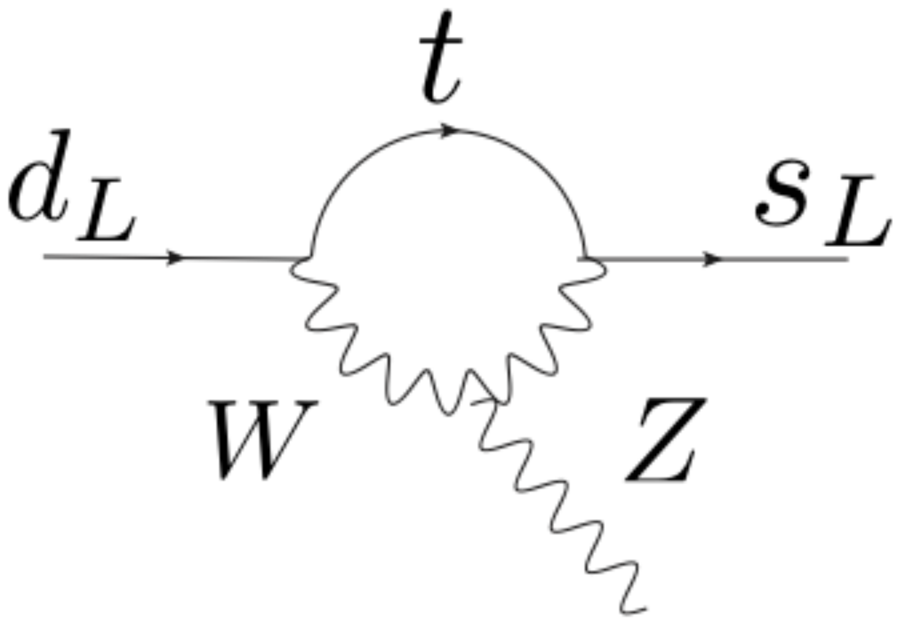
Endo, Kitahara, Mishima, Yamamoto'16

Δ_Rへの制限は**chiral enhancement**によって非常に厳しい

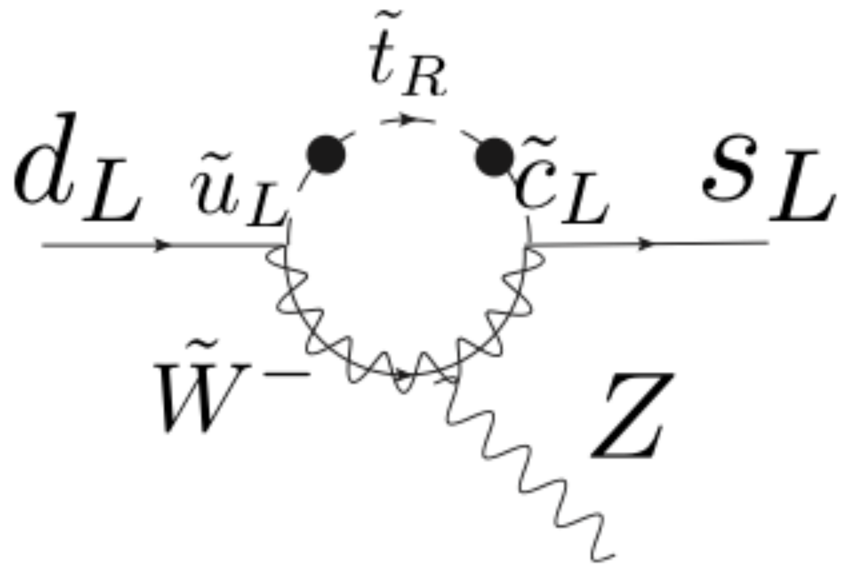
Δ_Lのシナリオが支持される　e.g. wino(chargino)の寄与

Z penguinへのCharginoの寄与

SMにおけるZ penguin

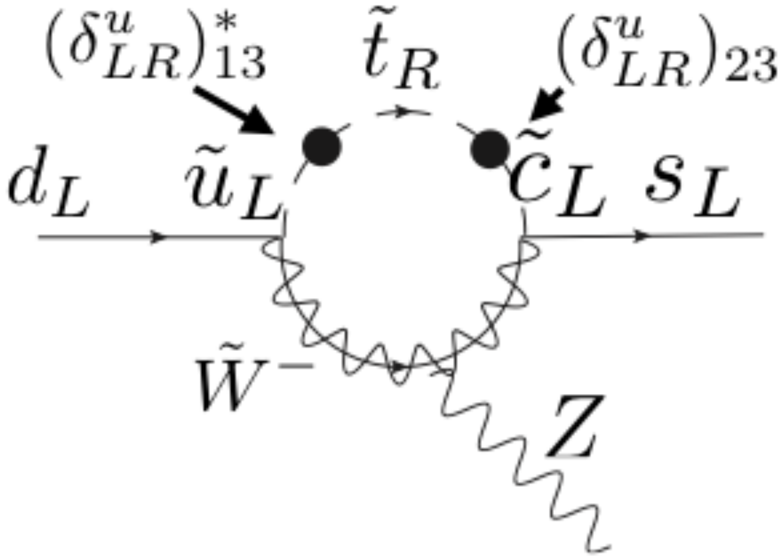


Charginoの寄与



Z penguinへのCharginoの寄与

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



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

$$V \supset (\hat T_U)_{ij} H^0_2 \tilde u_{iL} \tilde u^*_{jR}$$

$$\mathcal{L}_{eff} = \Delta_L \bar s_L \gamma_\mu d_L Z^\mu, \quad \Delta_L = \Delta_L^{(SM)} + \Delta_L^{(SUSY)}$$

$$\Delta_L^{(SUSY)} \propto (\delta^u_{LR})^*_{13} (\delta^u_{LR})_{23} \sim v_2^2 (\hat T_U)_{13} (\hat T_U)^*_{23} / m^4_{\tilde q}$$

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

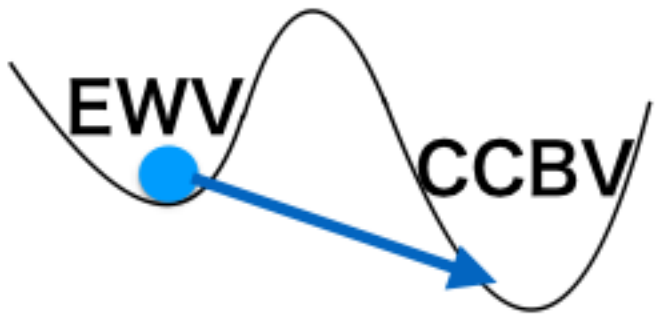
Vacuum stability

大きな $\left|(\hat{T}_U)_{ij}\right|$ electroweak vacuum(**EWV**)を不安定にする

soft SUSY breaking termsから生じるscalar potential

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

EWVはColor-Charge Breaking vacuum(**CCBV**)へ崩壊しうる



Vacuum stability

EW vacuumの寿命 > 宇宙年齢

単位体積あたりの真空の崩壊率

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

↑

崩壊率はS_Eに高い感度がある

半古典論では次元解析から

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

Vacuum stability

Vacuum stability

EW vacuumの寿命 > 宇宙年齢

↑

現在のHubble膨張率 $H_0 \sim 1.5 \times 10^{-42}\mathrm{GeV}$ を使う

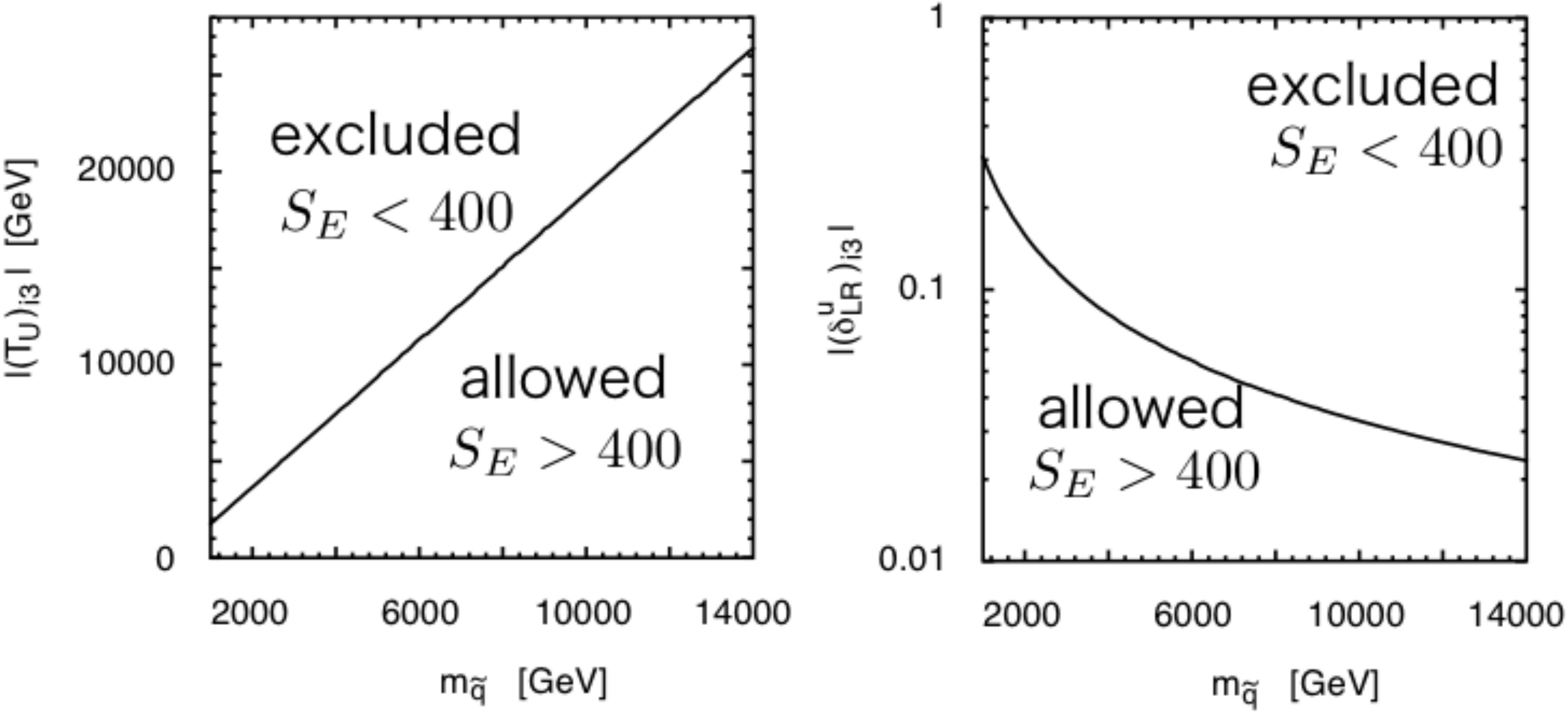
$$S_E > 400$$

trilinear couplingの上限値を得ることができる

Vacuum stability

Vacuum Stability

trilinear couplingと δ の上限値

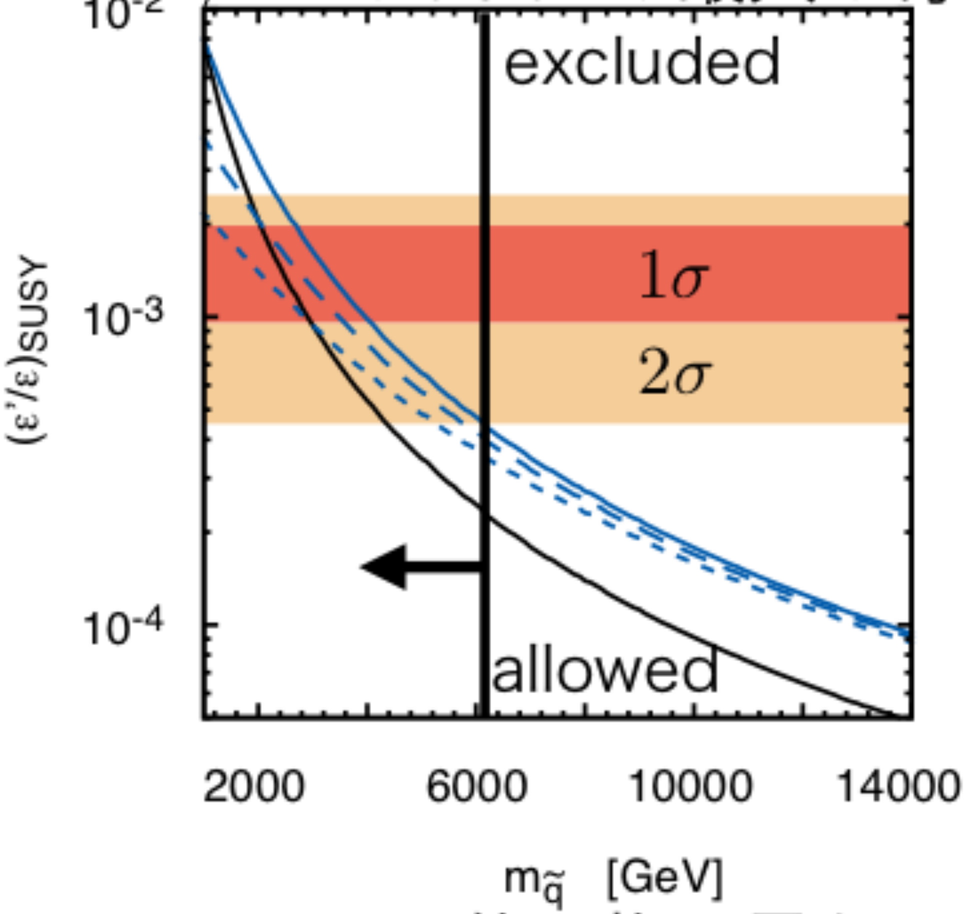


$$(\delta^u_{LR})_{ij} = \frac{v_2 (\hat{T}_U)^*_{ij}}{\sqrt{2} m^2_{\tilde{q}}}$$

Result(1)

Result(1)

ϵ'/ϵ へのSUSYの最大の寄与



$m_{\tilde{q}} \equiv m_{\tilde{Q}_i} = m_{\tilde{U}_3}$

$m_{\tilde{w}} = m_{\tilde{q}}$

$= 1TeV$

$= 2TeV$

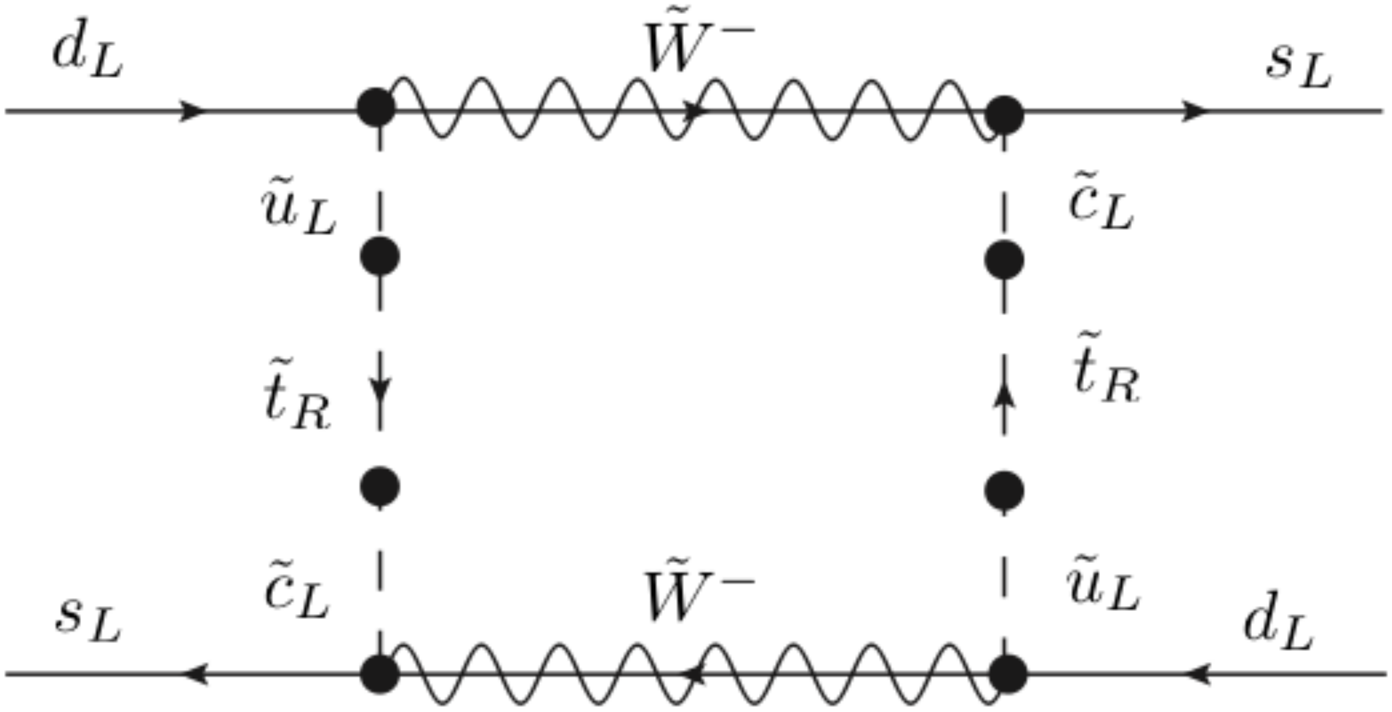
$= 3TeV$

SUSY の寄与は、SUSY質量が4-6TeV以下ならば標準理論と実験値との不一致を説明できる

他の物理量からの制限も満たせる

例えば ϵ , EDM, $\Delta m_d,\ \mathcal{B}(b \to s\gamma)$

ϵ



$$\epsilon \sim \delta^4/m^2_{SUSY} \quad \text{cf. } \epsilon'/\epsilon \sim \delta^2$$

Correlation with $B(K \to \pi^0 ...)$

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

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

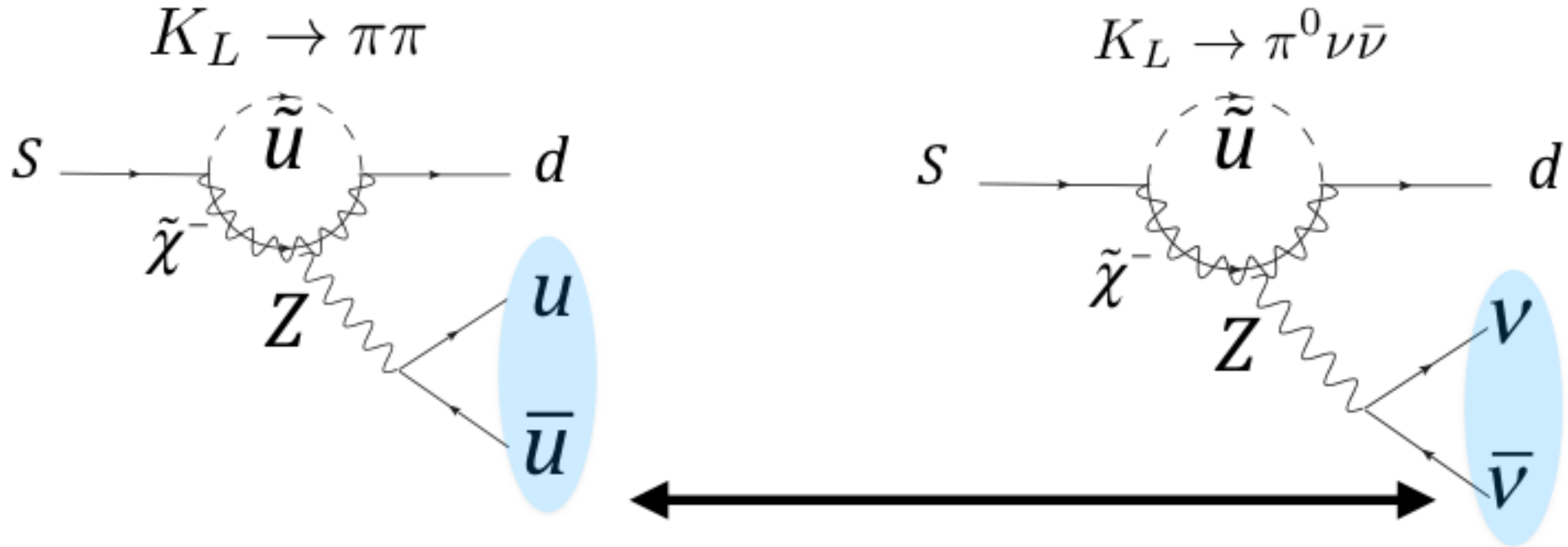
$$CP\,|\nu\bar{\nu}\rangle = -\,|\nu\bar{\nu}\rangle \quad CP\,|\pi^0\rangle = -\,|\pi^0\rangle \quad CP\,|\pi^0\nu\bar{\nu}\rangle = |\pi^0\nu\bar{\nu}\rangle$$

CP 対称な系において

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

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

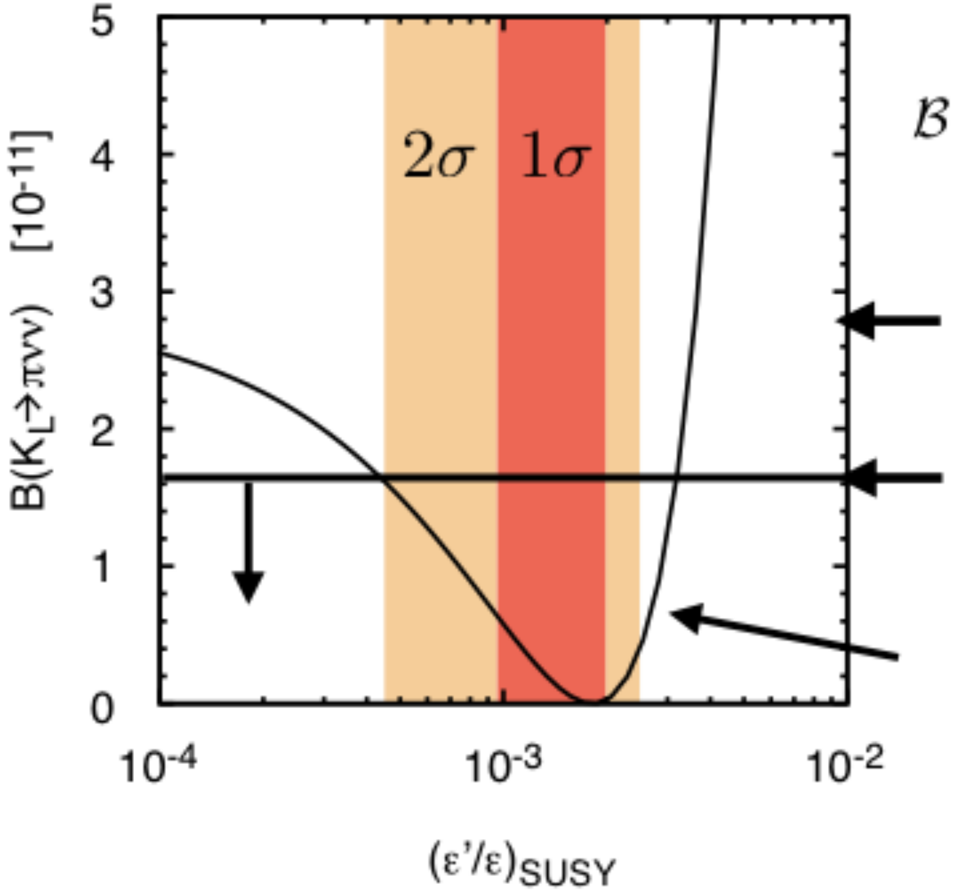
Correlation with $\mathcal{B}\left(K_L \to \pi^0 \nu\bar{\nu}\right)$



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

Result(2)

Result(2)



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

現在の標準理論と実験値との不一致は$\mathcal{B}\left(K_L \to \pi^0\nu\bar{\nu}\right)$が標準理論の予言の60%以下であることを示す

Conclusion

- SUSY質量が4-6TeVより小さいとき SUSY の寄与は標準理論と実験結果の不一致を説明できる
- 現在の標準理論と実験値との不一致は $\mathcal{B}\left(K_L \to \pi^0 \nu \bar{\nu}\right)$ が標準理論の予言の60%以下であることを示す
- 他のSUSY粒子の寄与は今後の仕事である

KaonのCPの破れ

$$|K_S\rangle = |K_+\rangle + \bar{\epsilon}\,|K_-\rangle \qquad |K_L\rangle = |K_-\rangle + \bar{\epsilon}|K_+\rangle$$

CP 対称な相互作用

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

CP violationがmixingによって生じるとき

Indirect CP violation

KaonのCPの破れ

$$|K_S\rangle = |K_+\rangle + \bar{\epsilon}\,|K_-\rangle \qquad |K_L\rangle = |K_-\rangle + \bar{\epsilon}\,|K_+\rangle$$

CP 対称な相互作用

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

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

CP の破れがindirectのみのとき $\eta_{00} = \eta_\pm = \bar{\epsilon}$

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]

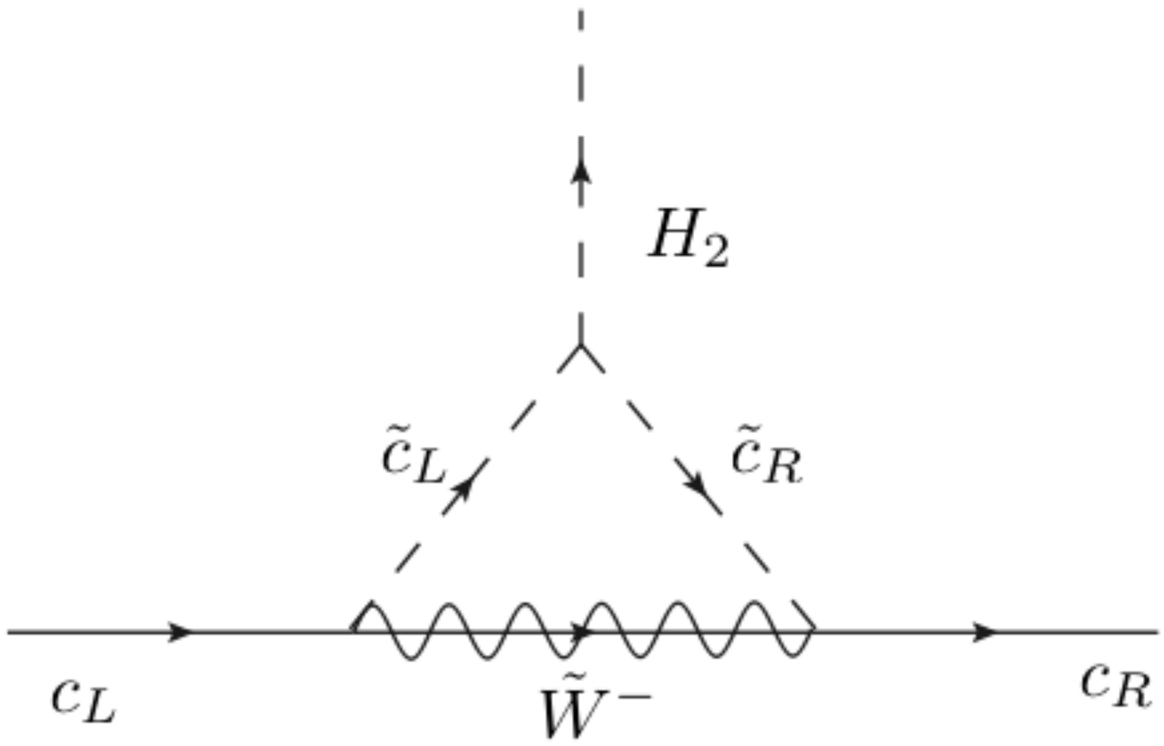
Vector-like quarks [C.Bobeth, A.J.Buras, A.Celis and M.Jung, JHEP1704(2017)079]

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]

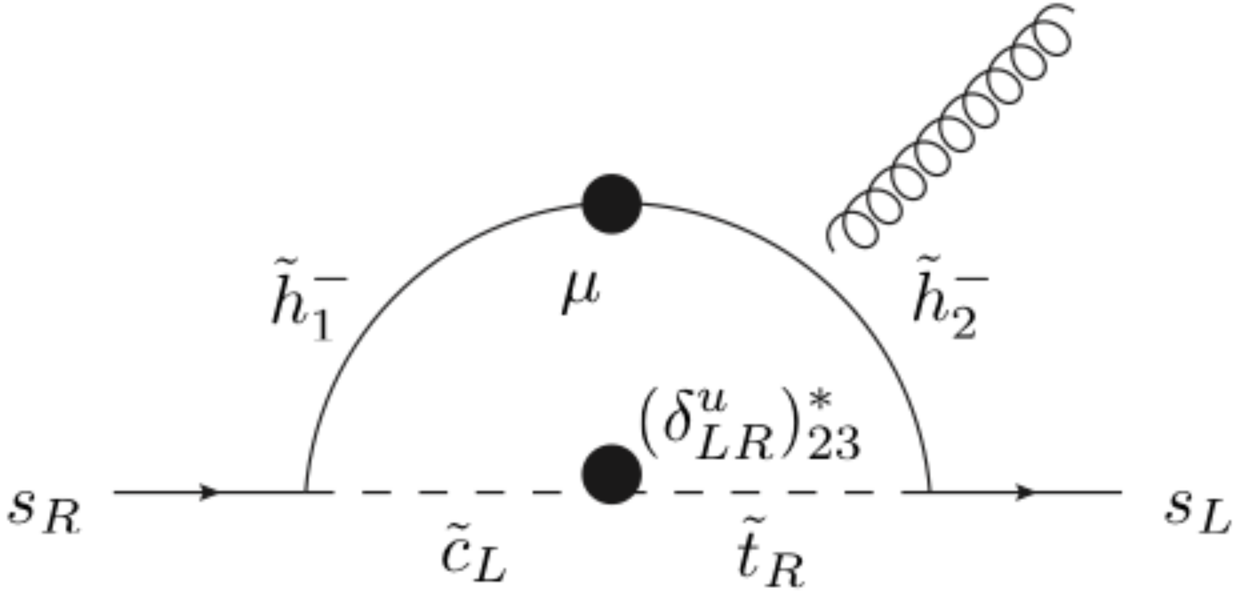
Right handed current [V.Cirigliano, W.Dekens, J.de Vries and E.Mereghetti, PLB
)17)1 S.Alioli, V.Cirigliano, W.Dekens, J.de Vries and E.Mereghetti, JHEP1705 (2017)086]

yukawaへの量子補正



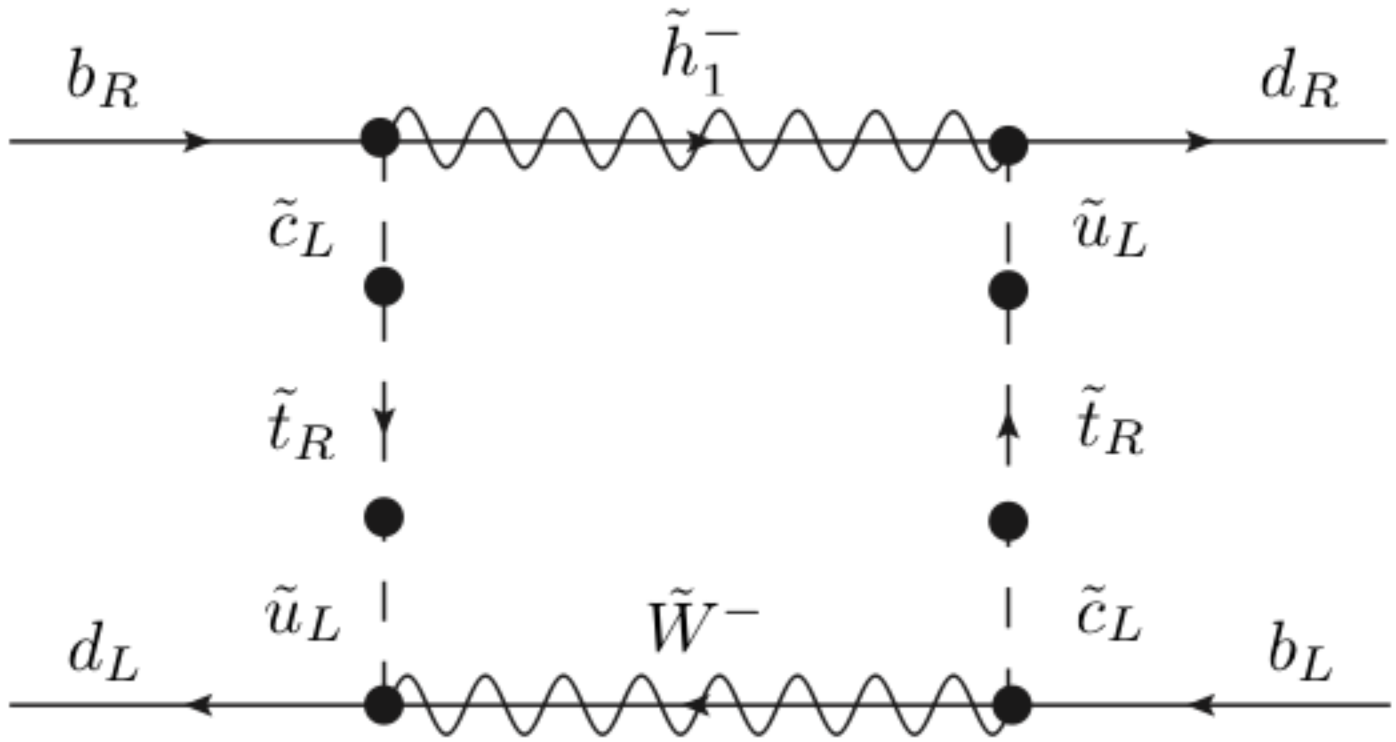
$$\sim 0.1 \frac{\alpha}{s_W^2} \delta \cdot m_{SUSY} \simeq 0.1 m_{SUSY}$$

EDM



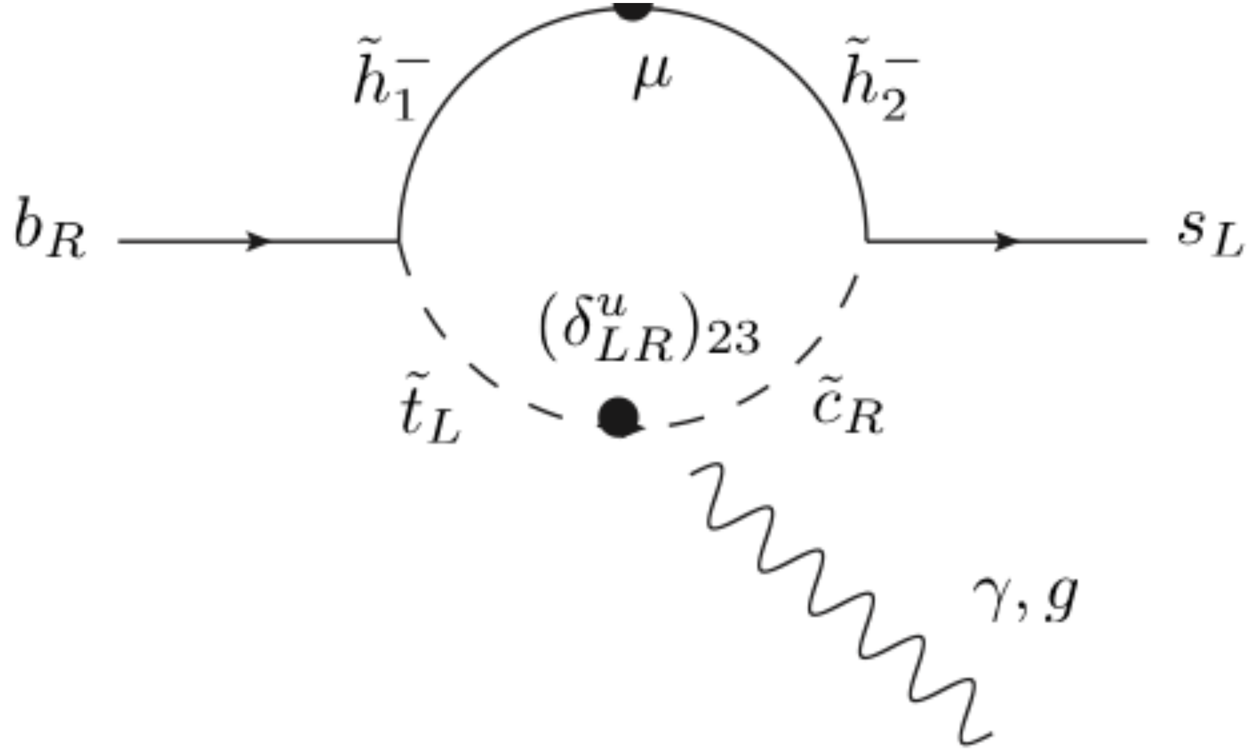
small yukawa and heavy higgsino suppress charging contribution.

$$\Delta m_d$$



Heavy higsino suppress chargino contribution.

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



Heavy higgsino suppress charging contribution.

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