ε'/ε and new physics

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Introduction

- Kaon decays with $s \to d$ flavor-changing-neutral-current (FCNC) transitions are sensitive to NP beyond the SM.

  - CKM and loop suppressions;

  - GIM suppression;

  - small phase for CP violation.

  ⇨ sensitive to very high scale NP:

$$\frac{\Lambda_{\rm NP}}{g_i} \sim 10^3 - 10^5\,\mathrm{TeV}$$

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CPV in $K \to \pi\pi$

- CPV in $K \to \pi\pi$ is parameterized by ϵ and ϵ', where the former represents indirect CPV in $\Delta S = 2$, while the latter is direct CPV in $\Delta S = 1$.

$$\frac{A(K_L \to \pi^+\pi^-)}{A(K_S \to \pi^+\pi^-)} = \epsilon + \epsilon', \qquad \frac{A(K_L \to \pi^0\pi^0)}{A(K_S \to \pi^0\pi^0)} = \epsilon - 2\epsilon'$$

- Experimentally tiny CPVs have been found:

$$|\epsilon| = (2.228 \pm 0.011) \times 10^{-3}$$ *[PDG]*

$$\frac{\epsilon'}{\epsilon} = (16.6 \pm 2.3) \times 10^{-4}$$ *[PDG (NA48, KTeV)]*

ϵ'/ϵ

- Defining isospin amplitudes $\sqrt{2}\,A_{0,2} = \langle (\pi\pi)_{I=0,2} | \mathcal{H} | K \rangle$,

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

- ϵ'/ϵ is highly suppressed due to the $\Delta I = 1/2$ rule, $\mathrm{Re}A_0/\mathrm{Re}A_2 \approx 22$:

  - a suppression from the prefactor $\mathrm{Re}A_2/\mathrm{Re}A_0$;

  - an accidental cancellation between $I=0$ and $I=2$.

⇨ very sensitive to NP !

Theoretical calculation

- Short-distance contributions:

  - NLO result has been available since early 90's.

  - NNLO calculation is in progress.

  [Cerdà-Sevilla et al., 1611.08276]

- Long-distance contributions:

  - two analytic approaches based on

    large-Nc dual QCD (DQCD) *[Bardeen, Buras & Gérard; …]*

    chiral perturbation theory (ChPT) *[Bertolini, Eeg, Fabbrichesi & Lashin; Pallante, Pich & Scimemi; Gisbert & Pich; ….]*

  - a numerical lattice calculation from RBC-UKQCD.

RBC-UKQCD lattice result

[1] Buras, et al., 1507.06345
[3] RBC-UKQCD, 1505.07863
[15] RBC-UKQCD, 1502.00263

Amplitude	Lattice QCD	Exp. data
$\mathrm{Re}A_0$ $[10^{-7}$ GeV$]$	$4.66 \pm 1.00 \pm 1.26$ [3]	3.322 ± 0.001 [1]
$\mathrm{Im}A_0$ $[10^{-11}$ GeV$]$	$-1.90 \pm 1.23 \pm 1.08$ [3]	—
$\mathrm{Re}A_2$ $[10^{-8}$ GeV$]$	$1.50 \pm 0.04 \pm 0.14$ [15]	1.479 ± 0.003 [1]
$\mathrm{Im}A_2$ $[10^{-13}$ GeV$]$	$-6.99 \pm 0.20 \pm 0.84$ [15]	—

- The real parts are consistent with those extracted from the data.
- Scattering phase-shifts are determined from the two-pion energy levels in a finite Euclidean volume on the lattice.

  [Lellouch & Lüscher]
- Caveat: The calculated $I = 0$ $\pi\pi$ phase-shift is smaller than the data:

$$\delta_0 = 23.8(4.9)(1.2)^\circ \quad \Leftrightarrow \quad (\delta_0)_{\rm exp} = 38.3(1.3)^\circ$$

B6 and B8

- ϵ'/ϵ requires calculations of two important matrix elements:

chirally enhanced!

$$\langle(\pi\pi)_{I=0}|\mathcal{O}_6|K\rangle \propto B_6^{(1/2)} \times \left(\frac{2m_K^2}{m_s+m_d}\right)^2 \qquad \mathcal{O}_6 = 4(\bar{s}_\alpha\gamma^\mu P_L d_\beta)\sum_q(\bar{q}_\beta\,\gamma_\mu P_R q_\alpha)$$

$$\langle(\pi\pi)_{I=2}|\mathcal{O}_8|K\rangle \propto B_8^{(3/2)} \times \left(\frac{2m_K^2}{m_s+m_d}\right)^2 \qquad \mathcal{O}_8 = 6(\bar{s}_\alpha\gamma^\mu P_L d_\beta)\sum_q e_q(\bar{q}_\beta\,\gamma_\mu P_R q_\alpha)$$

$$\frac{\epsilon'}{\epsilon} \propto 24.7\, B_6^{(1/2)} - 10.4\, B_8^{(3/2)} + \cdots$$

- The Lattice results imply

[Buras, et al., 1507.06345]

$$B_6^{(1/2)}(m_c) = 0.57 \pm 0.19\,, \qquad B_8^{(3/2)}(m_c) = 0.76 \pm 0.05\,,$$

which are consistent with an expectation in DQCD,

$$B_6^{(1/2)}(m_c) \leq B_8^{(3/2)}(m_c) < 1\,.$$

[Buras & Gérard, 1507.06326]

Recent SM results for ϵ'/ϵ

$$\left(\frac{\epsilon'}{\epsilon}\right)_{\rm SM} = \begin{cases} (1.38 \pm 6.90) \times 10^{-4} & \text{[RBC-UKQCD, 1505.07863]} \\ (1.9 \pm 4.5) \times 10^{-4} & \text{[Buras et al., 1507.06345]} \\ (1.06 \pm 5.07) \times 10^{-4} & \text{[Kitahara et al., 1607.06727]} \\ (15 \pm 7) \times 10^{-4} & \text{[Gisbert \& Pich, 1712.06147]} \end{cases}$$

- Buras *et al.* have used the matrix elements extracted from the data in addition to the RBC-UKQCD ones and taken into account the effects of isospin breaking.
- Kitahara *et al.* have further improved it by including subleading contributions.
- They deviate from the data at $2.8 - 2.9\,\sigma$ level, while Gisbert & Pich's result based on ChPT is consistent with the data.

$$(\epsilon'/\epsilon)_{\rm exp} = (16.6 \pm 2.3) \times 10^{-4}$$

Recent SM results for ϵ'/ϵ

- DQCD and ChPT yield different conclusions, where the former supports the RBC-UKQCD result.
- ChPT predicts $B_6^{(1/2)} \sim 1.5$ in contrast to $B_6^{(1/2)} < 1$ in DQCD, where the smaller value in the latter is caused by meson evolution from $\mathcal{O}(m_\pi)$ to $\mathcal{O}(1\,\mathrm{GeV})$.
- FSI is important in ChPT, but not in DQCD.

[Buras & Gérard, 1603.05686]

- Improvements of the lattice calculation and independent confirmations by other lattice groups will settle those issues, including that on the $I = 0$ $\pi\pi$ phase-shift in the RBC-UKQCD result.

New physics?

$$\left(\frac{\epsilon'}{\epsilon}\right)_{\rm SM} = \begin{cases} (1.9 \pm 4.5) \times 10^{-4} & \text{[Buras et al., 1507.06345]} \\ (1.06 \pm 5.07) \times 10^{-4} & \text{[Kitahara et al., 1607.06727]} \end{cases}$$

$\Leftrightarrow$ $(\epsilon'/\epsilon)_{\rm exp} = (16.6 \pm 2.3) \times 10^{-4}$ **$2.8 - 2.9\,\sigma$**

littlest Higgs with T-parity	*[Blanke et al., 1507.06316]*
modified Z couplings	*[Buras et al., 1507.08672; Buras, 1601.00005; Endo et al., 1612.08839; Bobeth et al., 1703.04753]*
Z' models	*[Buras et al., 1507.08672; Buras, 1601.00005]*
331 models	*[Buras & De Fazio., 1512.02869; 1604.02344]*
SUSY models	*[Tanimoto & Yamamoto 1603.07960; Kitahara et al., 1604.07400; Endo et al., 1608.01444; Crivellin et al., 1703.05786; Endo et al., 1712.04959]*
vector-like quarks	*[Bobeth et al., 1609.04783]*
RH charged current	*[Cirigliano et al., 1612.03914; Alioli et al., 1703.04751]*
leptoquarks	*[Bobeth & Buras, 1712.01295]*
a LR symmetric model	*[Haba et al., 1802.09903]*
a two-Higgs doublet model	*[Chen & Nomura, 1804.06017; 1805.07522]*
chiral-flavorful vector bosons	*[Matsuzaki et al., 1806.02312]*

NP interpretation of ϵ'/ϵ

- NP in ϵ'/ϵ $(\Delta S = 1)$ also affects ΔM_K & ϵ $(\Delta S = 2)$.

  ➡ severe constraints on NP models

- Since SM uncertainty is smaller in ϵ compared to ΔM_K, the former generally gives a quite strong constraint on the NP models that solve the ϵ'/ϵ anomaly.

- Because of the large prefactor, NP contributions to $\mathrm{Im}A_2$ have been often considered in the literature.

$$\frac{\epsilon'}{\epsilon} \propto \mathrm{Im}A_0 - 22.4\,\mathrm{Im}A_2$$

- Moreover, NP in $\mathrm{Im}A_0$ is likely to result in a huge contribution to ϵ.

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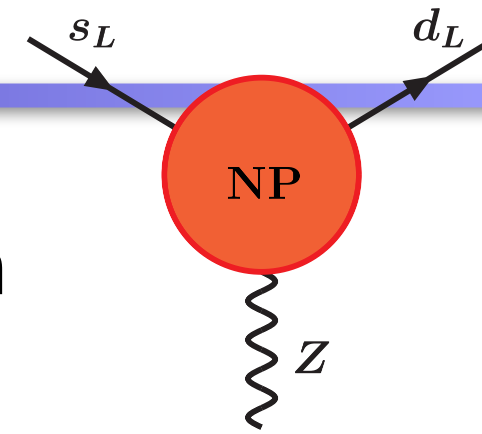
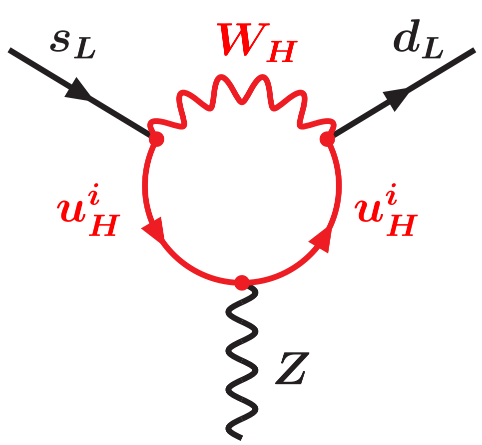
Modified Z couplings



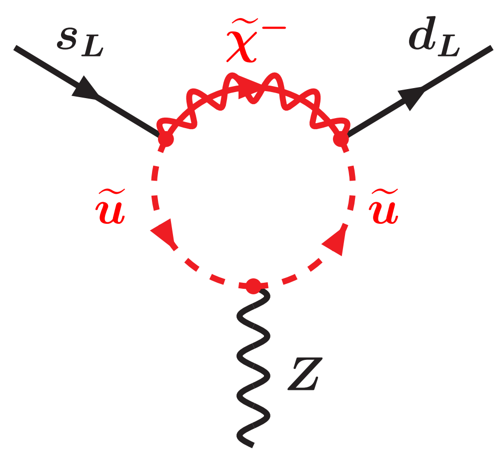
- Modified Z-coupling scenarios are realized in various UV models: e.g.,

Littlest Higgs with T-parity
[Blanke et al., 1507.06316]



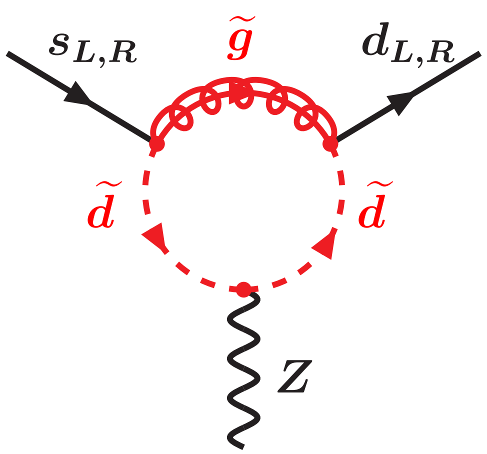
only LH

Chargino Z penguin
[Endo et al., 1608.01444]



only LH

Gluino Z penguin
[Tanimoto et al., 1603.07960; Endo et al., 1712.04959]



both LH & RH

(See also the vector-like quark model in *[Bobeth et al., 1609.04783]*)

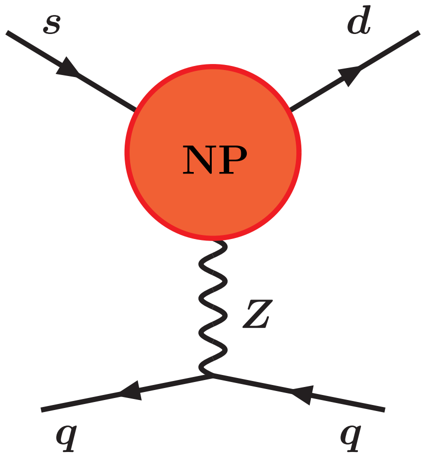
- ϵ'/ϵ exhibits interesting correlations with other observables, depending on the chiral structure of the couplings.

Modified Z couplings

- Kaon observables have the following dependences on the LH and RH couplings:

[Buras et al., 1211.1896; Buras et al., 1408.0728; Buras et al., 1507.08672; Buras, 1601.00005]

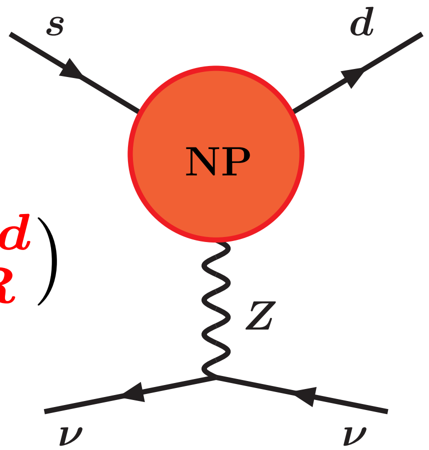
$$\mathrm{Re}\left(\frac{\epsilon'}{\epsilon}\right) \propto -\mathrm{Im}\,\Delta_L^{sd} - 3\,\mathrm{Im}\,\Delta_R^{sd} + \cdots$$



$$\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu}) \propto |X + \cdots|^2$$

$$\mathrm{BR}(K_L \to \pi^0 \nu\bar{\nu}) \propto (\mathrm{Im}\,X)^2$$

$$X = X(x_t)_{\mathrm{SM}} + \frac{\pi^2}{2M_W^2 G_F^2}\frac{\Delta_L^{\nu\nu}}{V_{ts}^* V_{td} M_Z^2}(\Delta_L^{sd} + \Delta_R^{sd})$$

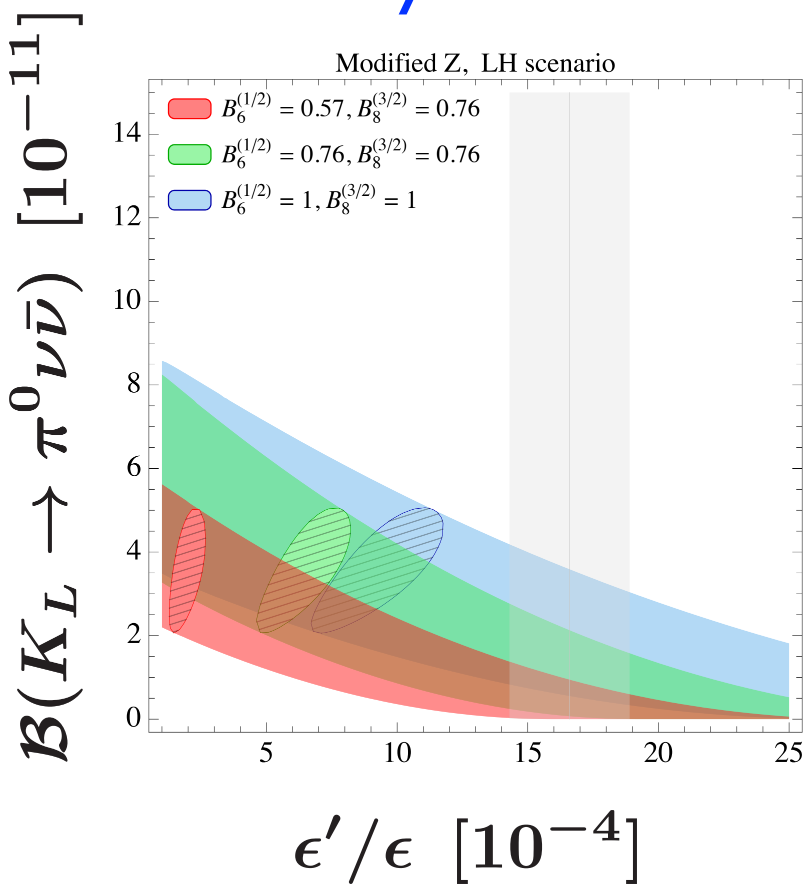


$$|\epsilon_K| \propto \mathrm{Im}\left[(\Delta_L^{sd})^2 + (\Delta_R^{sd})^2 - 240\Delta_L^{sd}\Delta_R^{sd}\right]$$

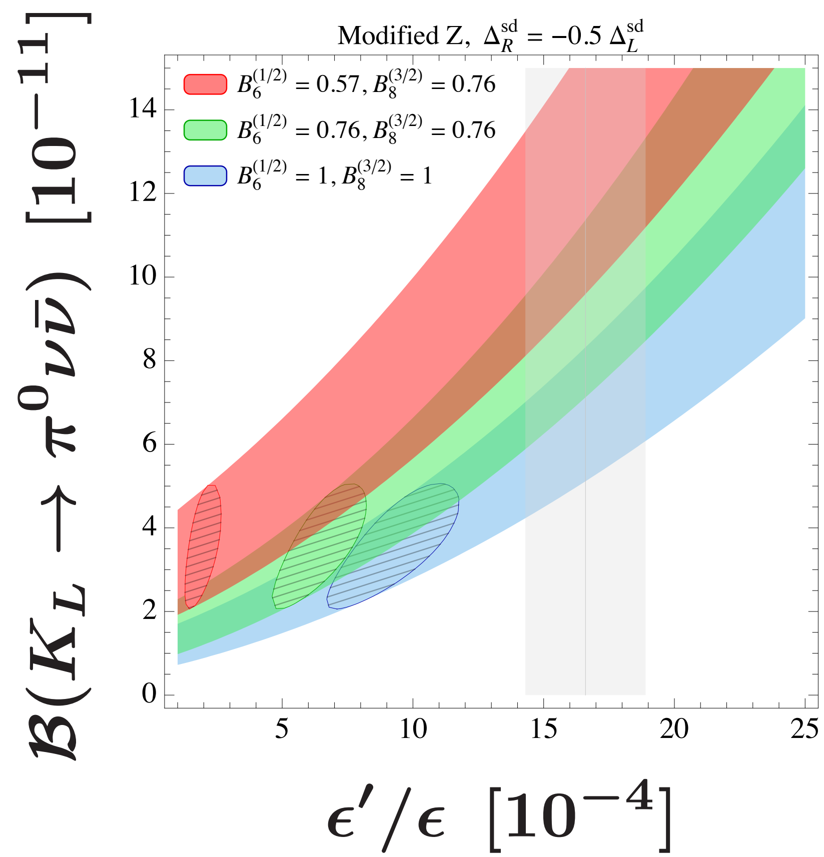
Modified Z couplings

- In the LH scenario, $\mathcal{B}(K_L \to \pi^0 \nu\bar{\nu})$ is suppressed when the ϵ'/ϵ anomaly is resolved, while it can be enhanced with the presence of LH and RH. *[Buras et al., 1507.08672]*

only LH



both LH & RH



$\mathcal{B}(K_L \to \pi^0 \nu\bar{\nu})_{\rm exp}$

$< 2.6 \times 10^{-8}$

[KEK E391a (2010)]

↓

$< 3 \times 10^{-9}$

[KOTO (ICHEP2018)]

↓

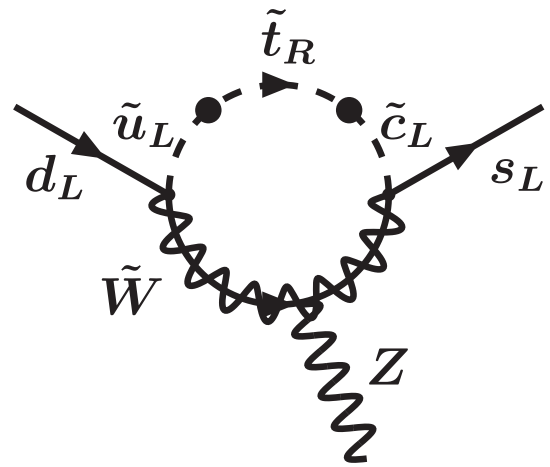
KOTO will reach the SM sensitivity:

3×10^{-11}

- A correlation to $\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})$ depends on the real part of the couplings, and thus more model dependent.

An example of the LH scenario

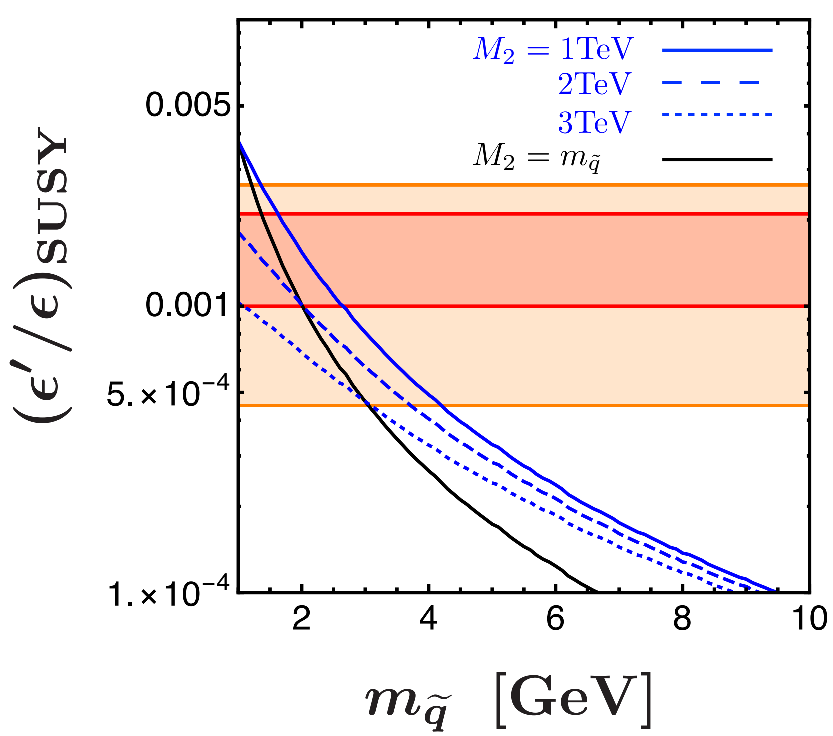
- The chargino Z penguin gets enhanced when the scalar trilinear couplings $(T_U)_{13}$ and $(T_U)_{23}$ are large.

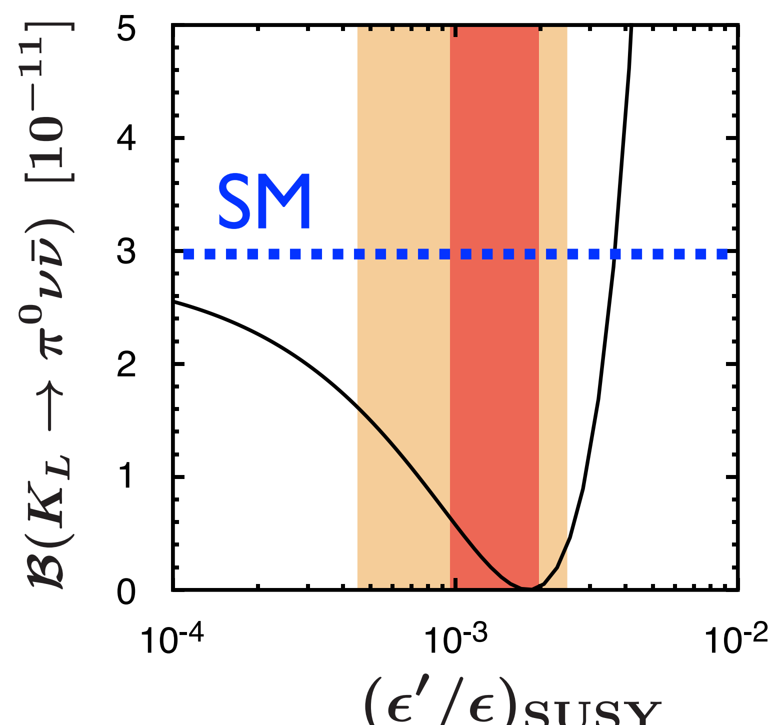


$$\propto (T_U)^*_{23}(T_U)_{13}$$

- Too large trilinear couplings make the EW vacuum unstable.

➡ upper bounds on the couplings *[Endo et al., 1608.01444]*





$$m_{\tilde{q}} \lesssim 3 - 4\ \text{TeV}$$

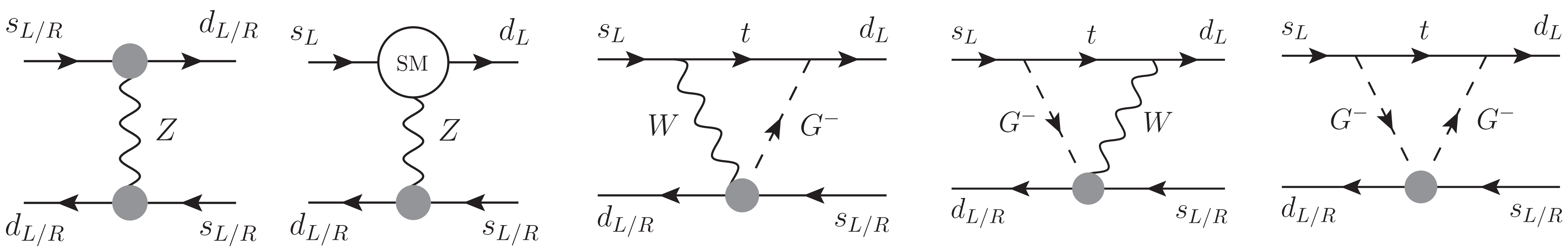
$$\frac{\mathcal{B}(K_L \to \pi^0\nu\bar{\nu})}{\mathcal{B}(K_L \to \pi^0\nu\bar{\nu})_{\rm SM}} \lesssim 60\,\%$$

Modified Z couplings in SMEFT

- Above the EW scale, modified Z couplings are described by the following dimension-six operators in the SMEFT:

$$Q_{Hd}^{ij} = (H^\dagger\, i\overleftrightarrow{D}_\mu\, H)(\bar{d}_{Ri}\,\gamma^\mu\, d_{Rj})$$
$$Q_{Hq}^{(1)\,ij} = (H^\dagger\, i\overleftrightarrow{D}_\mu\, H)(\bar{q}_{Li}\,\gamma^\mu\, q_{Lj})$$
$$Q_{Hq}^{(3)\,ij} = (H^\dagger\, i\overleftrightarrow{D}_\mu^a\, H)(\bar{q}_{Li}\,\tau^a\gamma^\mu\, q_{Lj})$$

- These operators generate $\Delta S = 2$ contributions:



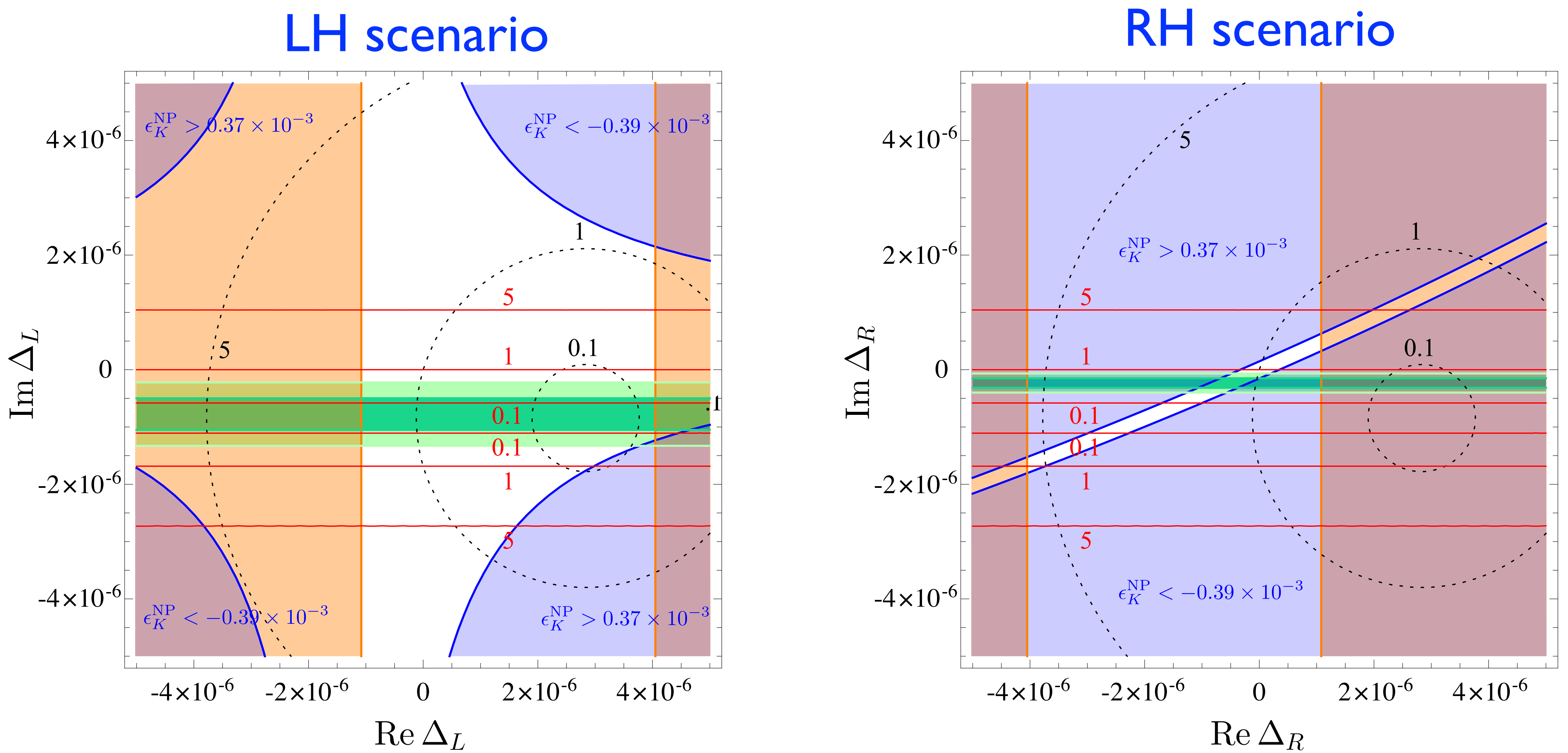
- top-Yukawa enhanced RG evolution

- RH Z NP gets a strong constraint from $\Delta S = 2$.

[Endo et al., 1612.08839; Bobeth et al., 1703.04753]

Stronger constraint in the RH scenario

Endo et al., 1612.08839

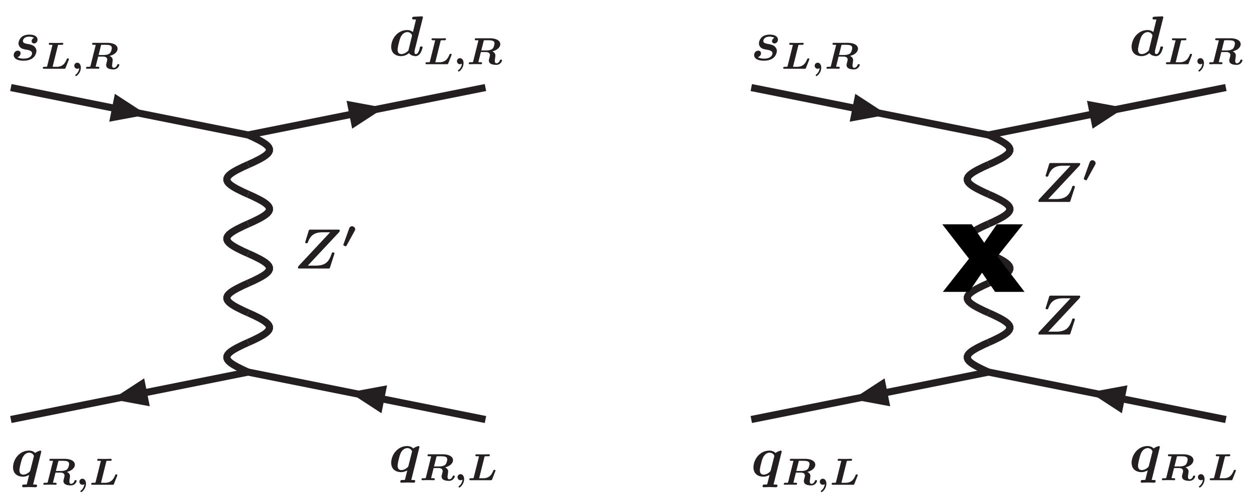


green: ϵ'/ϵ
blue: excluded regions by ϵ
orange: excluded regions by $\mathcal{B}(K_L \to \mu^+\mu^-)$
red solid contours: $\mathcal{B}(K_L \to \pi^0\nu\bar{\nu})/\mathcal{B}(K_L \to \pi^0\nu\bar{\nu})_{\rm SM}$
black dashed contours: $\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})/\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})_{\rm SM}$

Other types of contributions to ϵ'/ϵ

- Z'-induced FCNC: [Buras et al., 1507.08672; Buras, 1601.00005]

VLQ models with $U(1)_{L_\mu - L_\tau}$ [Bobeth et al., 1609.04783]
Z' models [Buras et al., 1507.08672; Buras, 1601.00005]
331 models [Buras & De Fazio., 1512.02869; 1604.02344]
chiral-flavorful vector bosons [Matsuzaki et al., 1806.02312] (with g', W' and LQs)



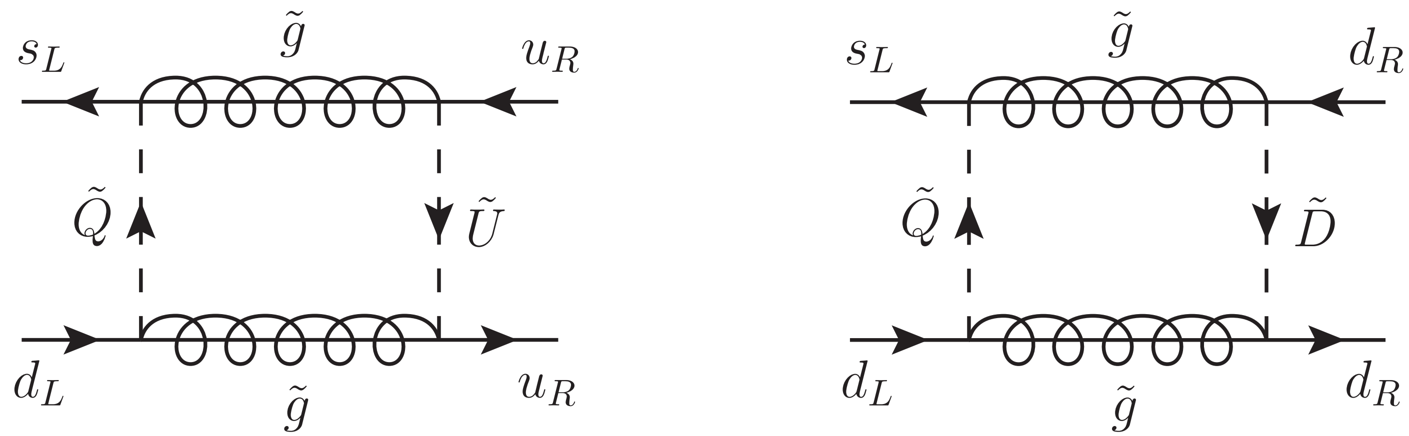
- The size of each coupling and that of the $Z - Z'$ mixing depend on the details of the model.

- Each model shows distinct correlations between ϵ'/ϵ and other observables.

Other types of contributions to ϵ'/ϵ

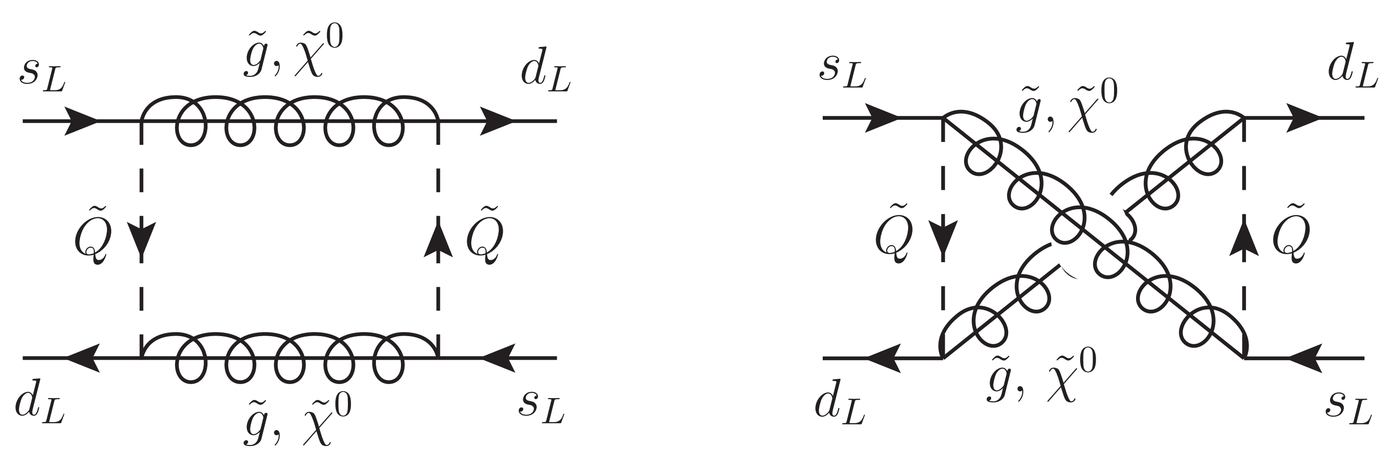
- SUSY gluino box ("trojan penguin"):

[Kitahara et al., 1604.07400; Crivellin et al., 1703.05786]



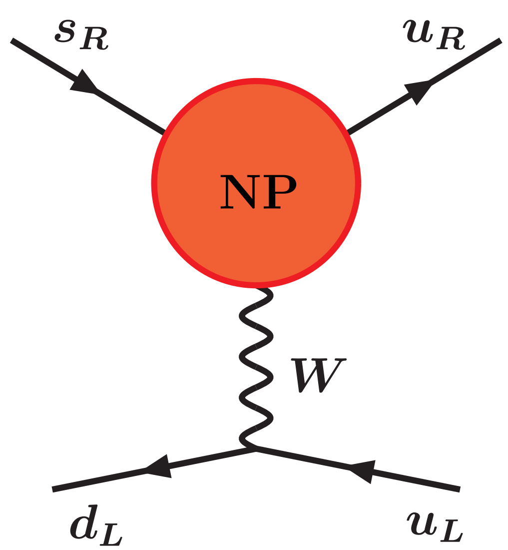
which generate contribution to the EW penguin $\mathcal{O}_8$ for $m_{\tilde{U}} \neq m_{\tilde{D}}$, and the ϵ'/ϵ anomaly can be solved.

Here the ϵ constraint can be avoided by a cancellation between the two diagrams for $m_{\tilde{g}} \sim 1.5\, m_{\tilde{q}}$.



Other types of contributions to ϵ'/ϵ

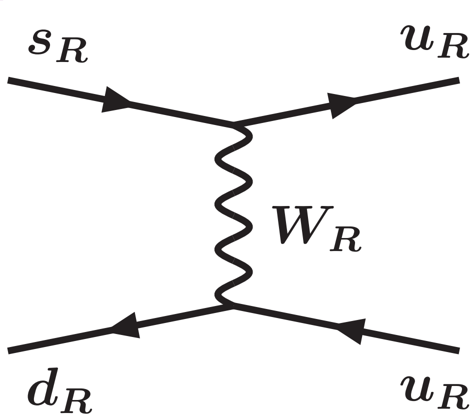
- RH charged current model: *[Cirigliano et al., 1612.03914;Alioli et al., 1703.04751]*



➡ LR current-current operators, which are related to LR EW penguin operators.

- a left-right symmetric model: *[Haba et al., 1802.09903]*

In addition to the above LR current-current contributions, RR ones are also generated.



In both models, a significant contribution to ϵ'/ϵ is possible, while $\Delta S = 2$ is loop suppressed.

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Other types of contributions to ϵ'/ϵ

- Leptoquarks: *[Bobeth & Buras, 1712.01295]*

  - Non-leptonic decays are loop-suppressed.

  - Non-leptonic operators mix into semi-leptonic ones through EW RG evolutions, and are generated at one-loop level at the LQ scale.

  - ϵ'/ϵ can be explained with a LQ which couples to both LH and RH quarks. $\boldsymbol{R_2,\ S_1,\ U_1,\ V_2}$

  - However, they conflict with experimental bounds on semi-leptonic & leptonic Kaon decays.

  - LQs are likely not responsible for the ϵ'/ϵ anomaly.

Other types of contributions to ϵ'/ϵ

- a two-Higgs doublet model: *[Chen & Nomura, 1804.06017]*

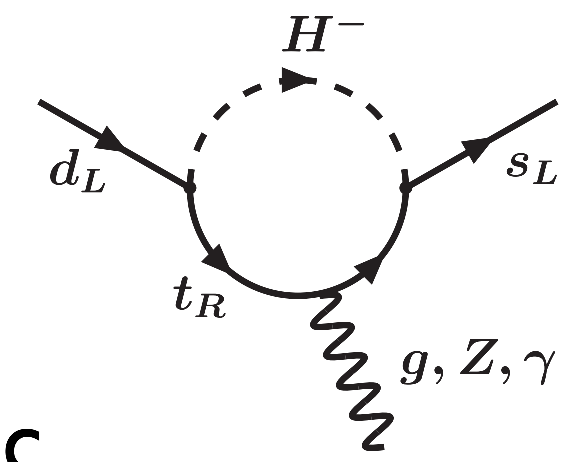
type-III THDM
+
Cheng-Sher ansatz for FCNC Higgs couplings

$$X_{ij}^f \propto \frac{\sqrt{m_{f_i} m_{f_j}}}{v}$$

- CPV phase only from CKM.

- charged-Higgs contribution to ϵ'/ϵ .

$$\left(\frac{\epsilon'}{\epsilon}\right)_{H^\pm} \sim 8 \times 10^{-4}$$



- $H^\pm$ contributions to the chromomagnetic operator have also been studied recently.

[Chen & Nomura, 1805.07522]

Chromomagnetic operator

- ETM collaboration has reported the first Lattice result for the $K \to \pi$ matrix element of the chromomagnetic operator. *[1712.09824]*

$$\mathcal{O}_g^{\pm} = \frac{g_s}{16\pi^2}\left(\bar{s}_L \sigma^{\mu\nu} G_{\mu\nu} d_R \pm \bar{s}_R \sigma^{\mu\nu} G_{\mu\nu} d_L\right)$$

- DQCD gives a similar result for $K \to \pi$. *[Buras & Gérard, 1803.08052]*

- DQCD also predicts a small value for the $K \to \pi\pi$ matrix element:

$$B_{\text{CMO}} \approx 0.33\,.$$

- The CMO contribution is not significant in the SM, but it could be important in some NP models.

BSM hadronic matrix elements

- The NP models considered for the ϵ'/ϵ anomaly can be described only with the hadronic matrix elements (HMEs) that are present in the SM.

- However, in general, more HMEs appear in NP beyond the SM (BSM).

  e.g., *chirally-enhanced HMEs for scalar-scalar and tensor-tensor operators.*

- The BSM HMEs have been calculated for the first time with DQCD recently. *[Aebischer, Buras & Gérard, 1807.01709]*

- The results are implemented in the open source code ***flavio***. *[Aebischer et al., 1807.02520]*

Summary

- ϵ'/ϵ deviates from the SM predictions by Buras et al. and Kitahara et al. at $2.8 - 2.9\,\sigma$ level.
- Improvements of the RBC-UKQCD calculation and independent confirmations by other lattice groups are highly important.
- The deviation in ϵ'/ϵ can be explained in several NP models.
- Each model shows various correlations among Kaon (and B) observables, which will be useful for model discrimination.