New physics implication from Kaon physics

WIN2019 (Bari Italy) 4th June 2019

Kei Yamamoto

(University of Zurich/Hiroshima University)

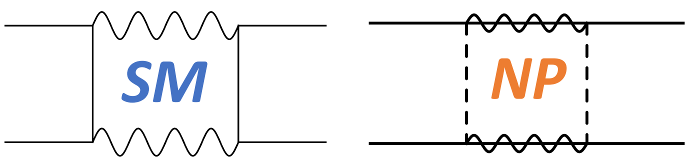
Universität Zürich UZH

Why Kaon? & What's new?

- Kaon observables are sensitive to NP at a very high scale, which is not accessible at the LHC

  - FCNC and CP violation in Kaon system are suppressed in the SM

c.f. meson mixing



$$\mathcal{L}_{eff} = \mathcal{L}^{SM} + \frac{1}{\Lambda_{NP}^2} \sum_i C_i \mathcal{O}_i^{\mathrm{dim6}}$$

If $|C_{\mathrm{NP}}| \sim 1$

$$\Lambda_{\mathrm{NP}} \sim \begin{cases} \mathcal{O}(10^5 \mathrm{TeV}) & : K^0 \\ \mathcal{O}(10^4 \mathrm{TeV}) & : D^0 \\ \mathcal{O}(10^3 \mathrm{TeV}) & : B_{d,s} \end{cases}$$

- Several on-going experiments for Kaon observables (KOTO/NA62…)

★ Using recent result of lattice calculation, there is discrepancy in ε'/ε between SM value and data

ε and ε’

1964 $K_L \to 2\pi$ was observed *Discovery of CP violation*

CP odd CP even

$$|K_L\rangle = |K_2\rangle + \epsilon|K_1\rangle$$

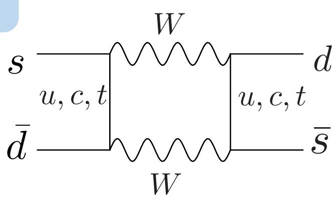
Indirect CPV (mixing) ϵ → CP even $|2\pi\rangle$

Direct CPV (decay) ϵ' → CP even $|2\pi\rangle$

$$\eta_{00} \equiv \frac{A(K_L \to \pi^0\pi^0)}{A(K_S \to \pi^0\pi^0)} \equiv \epsilon - 2\epsilon' \qquad \eta_{+-} \equiv \frac{A(K_L \to \pi^+\pi^-)}{A(K_S \to \pi^+\pi^-)} \equiv \epsilon + \epsilon'$$

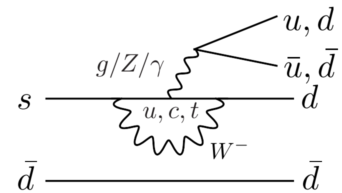
Indirect CPV (mixing) ϵ

$$|\epsilon| \simeq \frac{1}{3}\left(|\eta_{00}| + 2|\eta_{+-}|\right)$$



Direct CPV (decay) ϵ'

$$\left|\frac{\eta_{00}}{\eta_{+-}}\right|^2 \simeq 1 - 6\mathrm{Re}\left(\frac{\epsilon'}{\epsilon}\right)$$



$$\epsilon = \mathcal{O}(10^{-3}) \quad \mathrm{Re}\left(\frac{\epsilon'}{\epsilon}\right) = \mathcal{O}(10^{-3}) \quad \epsilon' = \mathcal{O}(10^{-6})$$

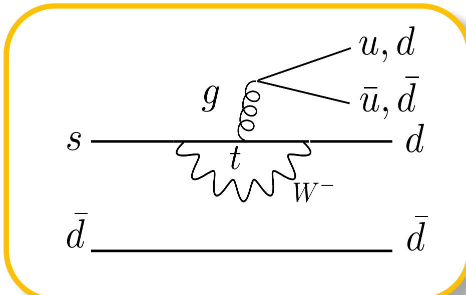
Highly suppressed and sensitive to NP

ε'/ε

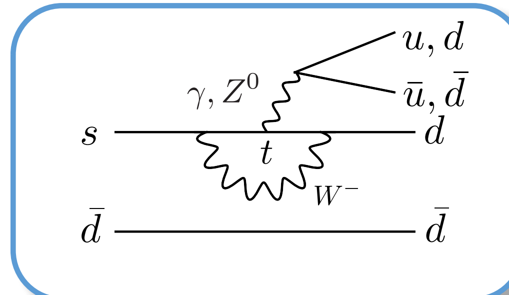
$$A(K^0 \to (\pi\pi)_{I=0,2}) = A_{0,2}e^{i\delta_{0,2}}$$

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

QCD penguin operator



EW penguin operator



ΔI=1/2 rule

$$\frac{\mathrm{Re}A_0}{\mathrm{Re}A_2} \equiv \frac{1}{\omega} = 22.46 \quad \text{(exp.)}$$

In the SM, there is accidental cancellation between $\mathrm{Im}A_0$ and $\mathrm{Im}A_2$ due to the enhancement factor $1/\omega$

EW penguin is comparable to QCD penguin due to the enhancement factor

ε'/ε discrepancy

Short distance Matrix element

$$\langle (\pi\pi)_I | \mathcal{H} | K^0 \rangle = \sum_n C_n \langle (\pi\pi)_I | \mathcal{O}_n | K^0 \rangle$$

- Short distance
  - NLO result has been available since early 90's
  - NNLO QCD calculation is in progress *Cerda-Sevilla, Gorbahn, Jager, Kokulu 1611.08276*
- Long distance (Matrix elements)
  - First lattice result by **RBC-UKQCD** in 2015 *1502.00263 1505.07863*

From the lattice result, ε'/ε has been calculated in SM using data for Re$A_{0,2}$

SM with Lattice

$$\left(\frac{\epsilon'}{\epsilon}\right)_{\rm SM} = (1.06 \pm 5.07) \times 10^{-4}$$

Kitahara, Nierste and Tremper, 1607.06727

c.f. RBC-UKQCD / Buras, Gorbahn, Jager and Jamin 1507.06345

Exp

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

average of NA48 and KTeV

2.8σ difference **NP in ε'/ε ?**

ε'/ε discrepancy

SM with Lattice

$$\left(\frac{\epsilon'}{\epsilon}\right)_{\rm SM} = (1.06 \pm 5.07) \times 10^{-4}$$

2.8σ difference

Exp

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

- O_6 & O_8 have dominant effects on ε'/ε due to chiral enhancement

$$\langle(\pi\pi)_0|\mathcal{O}_6|K\rangle \propto B_6^{(1/2)}$$
$$\langle(\pi\pi)_2|\mathcal{O}_8|K\rangle \propto B_8^{(3/2)}$$

Non-perturbative parameter

QCD penguin $O_6 = (\bar{s}_\alpha d_\beta)_{V-A} \sum_q (\bar{q}_\beta q_\alpha)_{V+A}$

EW penguin $O_8 = \frac{3}{2}(\bar{s}_\alpha d_\beta)_{V-A} \sum_q e_q (\bar{q}_\beta q_\alpha)_{V+A}$

- Values extracted from the lattice result

Buras, Buttazzo, Girrbach-Noe and Knegjens 1503.02693

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

- Error for ε'/ε is dominated by $B_6^{(1/2)}$

- Two ways of analytic approaches

Large N_C Dual QCD approach — *Buras and Gérard 1507.06326*

$$B_6^{(1/2)} \leq B_8^{(3/2)} < 1 \qquad \left(\frac{\epsilon'}{\epsilon}\right)_{\rm SM} < (6.0 \pm 2.4) \times 10^{-4}$$

1805.11096

ChPT (FSI) — *Gisbert and Pich 1712.06147, hep-ph/0007208*

$$B_6^{(1/2)} \sim 1.5 \qquad B_8^{(3/2)} \sim 0.9 \qquad \left(\frac{\epsilon'}{\epsilon}\right)_{\rm SM} = (15 \pm 7) \times 10^{-4}$$

Result in DQCD approach gives support to lattice result. On the other hand, result in ChPT is consistent with data

- Wait for improved lattice results

ε'/ε at Lattice study

Amplitude	Exp. data	Lattice QCD
$\mathrm{Re}A_0$ $[10^{-7}$ GeV$]$	3.322 ± 0.001 [1]	$4.66 \pm 1.00 \pm 1.26$ [2]
$\mathrm{Im}A_0$ $[10^{-11}$ GeV$]$	—	$-1.90 \pm 1.23 \pm 1.08$ [2]
$\mathrm{Re}A_2$ $[10^{-8}$ GeV$]$	1.479 ± 0.003 [1]	$1.50 \pm 0.04 \pm 0.14$ [3]
$\mathrm{Im}A_2$ $[10^{-13}$ GeV$]$	—	$-6.99 \pm 0.20 \pm 0.84$ [3]

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

- ReA0, ReA2 are consistent with exp. Data → Δ*I*=1/2 rule is confirmed

- Calculated *I*=0 ππ scattering phase shift of was smaller than measured value

$$\delta_0 = 23.8(4.9)(1.2)^\circ$$ *2015* $$(\delta_0)_{\mathrm{exp}} = 38.3(1.3)^\circ$$

→ New preliminary result *RBC-UKQCD preliminary, 2018*

$$\delta_0 = 30.9(1.5)(3.0)^\circ$$ "Puzzle is resolved"

- Lattice update with higher statistics will appear soon

ε'/ε beyond the SM

- Motivated by ε'/ε discrepancy, several new physics models have been studied

Little Higgs Model with T-parity	*Blanke, Buras and Recksiegel 1507.06316*
Modified Z scenario	*Buras, Buttazzo and Knegjens1507.08672/Buras, 1601.00005*
	Endo, Kitahara, Mishima and KY 1612.08839/Bobeth, Buras, Celis and Jung 1703.04753
Z' models	*Buras, Buttazzo, Knegjens 1507.08672 /Buras 1601.00005*
331 model	*Buras and De Fazio 1512.02869/1604.02344*
MSSM Chargino Z penguin	*Endo, Mishima, Ueda and KY 1608.01444*
Gluino Z penguin	*Tanimoto and KY 1603.07960*
	Endo, Goto, Kitahara, Mishima, Ueda and KY 1712.04959
Gluino Box	*Kitahara, Nierste and Tremper 1604.07400,1703.05786*
	Crivellin, D'Ambrosio, Kitahara, Nierste 1712.04959
	Chobanova, D'Ambrosio,Kitahara, Martínez, Santos, Fernández and KY 1711.11030
Vector-like quarks	*Bobeth, Buras, Celis and Jung 1609.04783*
Right handed current	*Cirigliano, Dekens, Vries and Mereghetti 1612.03914*
	Alioli, Cirigliano, Dekens, de Vries and Mereghetti 1703.04751
Leptoquark	*Bobeth and Buras 1712.01295*
LR symmetric model	*Haba,Umeeda and Yamada 1802.09903/1806.0342*
Type-III 2HDM	*Chen and Nomura 1804.06017/ 1805.07522*
Flavorful composite vectors	*Matsuzaki, Nishiwaki and KY 1806.02312*
Diquark model	*Chen and Nomura 1808.04097*
3HDM	*Marzola and Raidal 1901.08290*
General 2HDM	*Iguro and Omura, 1905.11778*

ε'/ε beyond the SM

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

22.4

- CPV effect
- ImA2 is enhanced by enhancement factor 1/ω
- SM effect is small due to this accidental cancellation

- NP in ImA_0 or (and) ImA_2

ImA_2 … have enhancement factor 1/ω

ImA_0 … likely to result in huge contribution to ϵ_K

→ NP in ImA_2 is likely

ε’/ε beyond the SM

- Master formulae for ε’/ε   *Aebischer, Bobeth, Buras, Gérard and Straub 1807.02520*

Master formula including BSM operators is derived with DQCD

$$\left(\frac{\varepsilon'}{\varepsilon}\right)_{\rm BSM} = \sum_i P_i(\mu_W)\,{\rm Im}\left[C_i(\mu_W) - C'_i(\mu_W)\right]$$

P_i : Hadronic matrix elements + RG effects

Most efficient operators explaining ε′/ε anomaly

NP scenario

$$O^u_{VLR} = (\bar{s}^\alpha \gamma_\mu P_L d^\alpha)(\bar{u}^\beta \gamma^\mu P_R d^\beta)$$
$$\tilde{O}^u_{VLR} = (\bar{s}^\alpha \gamma_\mu P_L d^\beta)(\bar{u}^\beta \gamma^\mu P_R d^\alpha)$$
$$O^d_{VLR} = (\bar{s}^\alpha \gamma_\mu P_L d^\alpha)(\bar{d}^\beta \gamma^\mu P_R d^\beta)$$
$$\tilde{O}^d_{VLR} = (\bar{s}^\alpha \gamma_\mu P_L d^\beta)(\bar{d}^\beta \gamma^\mu P_R d^\alpha)$$

SM type operators
HME calculated by Lattice & DQCD

Generate O6(ImA0) & O8(ImA2)

New heavy vectors
Modified Z penguin
(MSSM,VLQ,LHT,,,)

$$O^u_{TLL} = (\bar{s}^\alpha \sigma_{\mu\nu} P_L d^\alpha)(\bar{u}^\beta \sigma^{\mu\nu} P_L d^\beta)$$
$$\tilde{O}^u_{TLL} = (\bar{s}^\alpha \sigma_{\mu\nu} P_L d^\beta)(\bar{u}^\beta \sigma^{\mu\nu} P_L d^\beta)$$
$$O^d_{TLL} = (\bar{s}^\alpha \sigma_{\mu\nu} P_L d^\alpha)(\bar{d}^\beta \sigma^{\mu\nu} P_L d^\beta)$$
$$O^u_{SLR} = (\bar{s}^\alpha P_L d^\alpha)(\bar{u}^\beta P_R u^\beta)$$

New scalar & tensor Operators
HME calculated by only DQCD

Heavy scalars

※Chrome magnetic operator <O_{8g}> (calculated by Lattice & DQCD) would be suppressed

ETM collaboration, 1712.09824
Buras and Gérard 1803.08052

ε'/ε beyond the SM

- SMEFT study : *(SM effective field theory) [SU(2) × U(1) inv.]* $(\mu_{EW} < \mu < \mu_{NP})$

-Model independent approach *Aebischer, Bobeth, Buras and Straub 1808.00466*

The constraints from K^0 and D^0 mixing as well as EDM are potentially important

- Z penguin scenario *Bobeth, Buras, Celis and Jung 1703.04753*
Endo, Kitahara, Mishima and KY 1612.08839/ Endo, Goto, Kitahara, Mishima, Ueda and KY 1712.04959

ΔS=1 operators generate ΔS=2 contributions, through top-Yukawa enhanced RG evolution

$$\left(H^\dagger i \overleftrightarrow{D}_\mu H\right)(\bar{s}_R \gamma^\mu d_R)$$

RG evolution →

$$(\bar{s}_R \gamma^\mu d_R) Z_\mu$$

ΔF=2 operator

$$(\bar{s}_L \gamma_\mu d_L)(\bar{s}_R \gamma^\mu d_R)$$

ε'/ε beyond the SM

- NP in ε'/ε also affect other observables

  - ΔS=2 process ϵ_K and ΔM_K give severe constraint

    Some model need tuning to avoid this constraint

  - Kaon rare decay $K_L \to \pi^0 \nu \bar{\nu}$ and $K^+ \to \pi^+ \nu \bar{\nu}$ could be good probe

    Pure imaginary. Strong correlation with ε'/ε

  - B observables have correlation (and become constraint) in some models

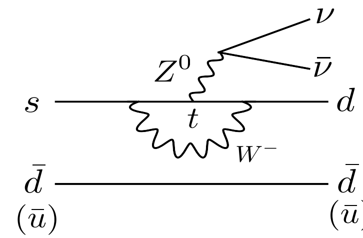
  - Other observables (EDM)

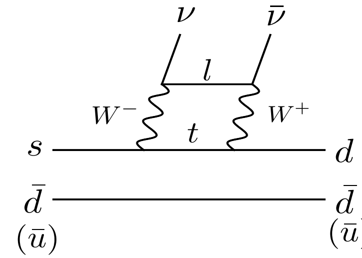
- Different implications (correlations & predictions) for other observables appear depending on models ⇒ Possibility of model discriminations

★ $K \to \pi \nu \bar{\nu}$

★ Correlation with B anomalies

$K_L \to \pi^0 \nu\bar{\nu}$ and $K^+ \to \pi^+ \nu\bar{\nu}$





- Highly suppressed in SM : $BR_{SM} \sim 10^{-11}$
- Theoretically clean (Hadronic matrix element can be estimated using isospin sym.)
- $K_L \to \pi^0 \nu\nu$ is purely CP violating mode

$K^+ \to \pi^+ \nu\bar{\nu}$ — *NA62@CERN*

- NA62 at CERN observed one event in 2016 data

$$BR(K^+ \to \pi^+ \nu\bar{\nu})_{\rm SM} = (9.11 \pm 0.72) \times 10^{-11}$$

$$BR(K^+ \to \pi^+ \nu\bar{\nu})_{\rm exp} = (1.73^{+1.15}_{-1.05}) \times 10^{-10}$$ *BNL 949/E787*

$$< 14 \times 10^{-10} (95\% {\rm C.L.})$$ ***New 2018***

- Expected about 20 SM events from the 2017-2018 data sample

$K_L \to \pi^0 \nu\bar{\nu}$ — *KOTO@J-PARC*

- KOTO at J-PARC reported result from the 2015 data last summer

$$BR(K_L \to \pi^0 \nu\bar{\nu})_{\rm SM} = (3.00 \pm 0.30) \times 10^{-11}$$

$$BR(K_L \to \pi^0 \nu\bar{\nu})_{\rm exp} < 2.6 \times 10^{-8}\ (90\% {\rm C.L.})$$ *E391a*

$$< 3.0 \times 10^{-9} (90\% {\rm C.L.})$$ ***New 2018***

- KOTO-phase2 aims to measure at 10% accuracy

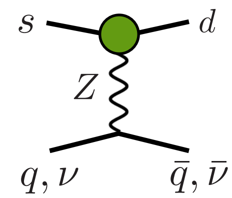
ε'/ε ⇔ K→πνν *- Examples -*

Z scenario

Buras, Buttazzo and Knegjens 1507.08672 / Buras 1601.00005 / Bobeth, Buras, Celis and Jung 1703.04753

There are interesting correlations between Kaon observables depending on the chiral structure of coupling (LH and/or RH)

Δ_L and/or Δ_R



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

CPV ⇒ Strong correlation

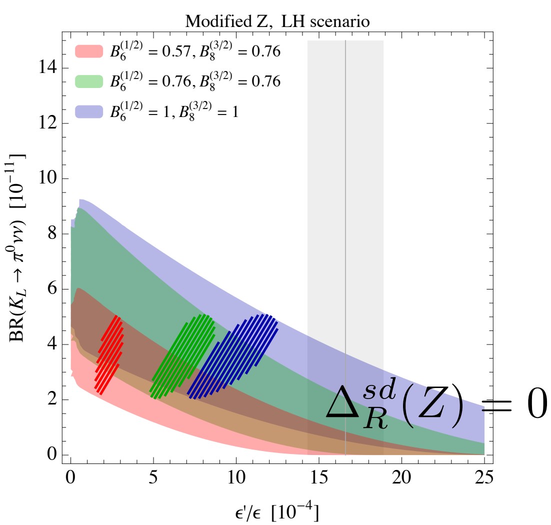
$$\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu}) \propto |X + \cdots|^2$$

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

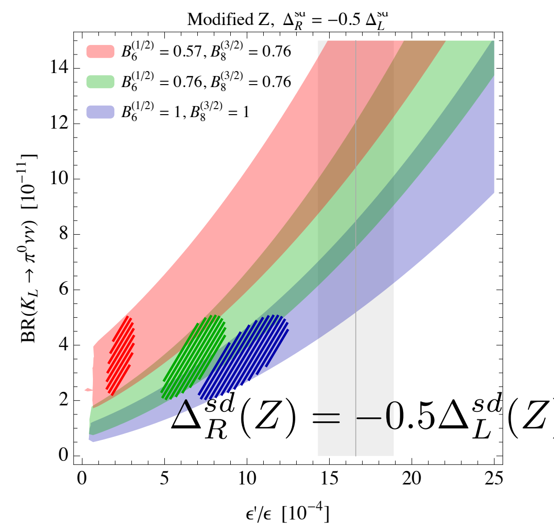
$$X = X(x_t)_{\mathrm{SM}} + \frac{\pi^2}{2M_W^2 G_F^2}\frac{\Delta_L^{\nu\nu}}{V_{ts}^* V_{td} M_Z^2}(\Delta_L^{sd} + \Delta_R^{sd})$$

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

LH Scenario
⇒ negative correlation



LH+RH Scenario
⇒ positive correlation

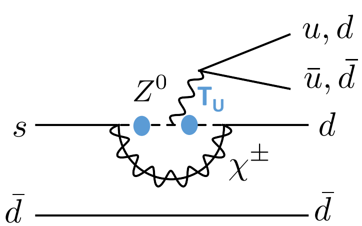


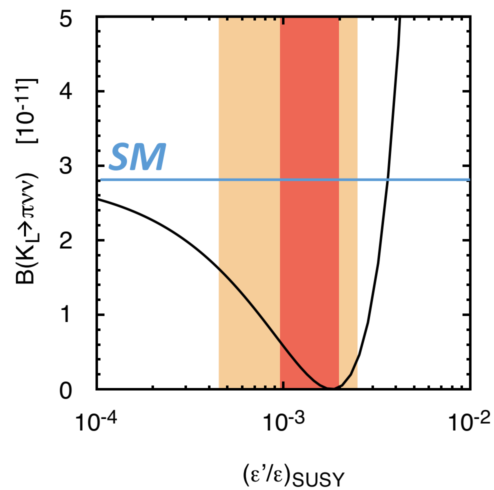
ε'/ε ⇔ K→πνν *- Examples -*

Chargino Z penguin *Endo, Mishima, Ueda and KY 1608.01444*

Large trilinear couplings bring enhancement of ε'/ε

LH Z scenario ⇒ negative correlation btwn ε'/ε and KL→π0νν

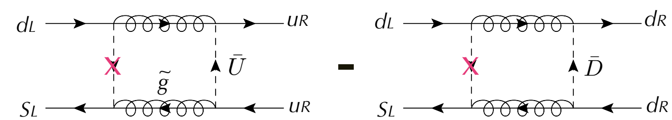


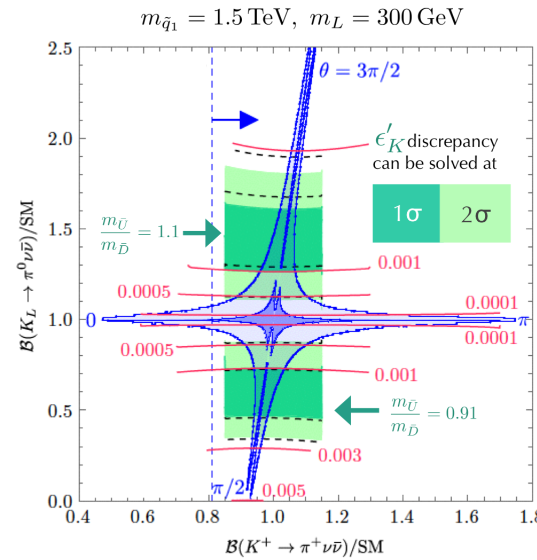


ε'/ε ⇔ SUSY scale < 4-6 TeV

Gluino box *Crivellin, D'Ambrosio, Kitahara and Nierste 1703.05786*

Large isospin breaking ($m_{\tilde{U}} \neq m_{\tilde{D}}$) gives effect on ImA2





$BR(K_L \to \pi^0 \nu\bar{\nu})$	< 0.6 SM	< 1.4 SM	→ ***KOTO***
$BR(K^+ \to \pi^+ \nu\bar{\nu})$	O(10~100%) effect	< 1.2 SM	→ ***NA62***

Different correlations between ε'/ε and K→πνν may allow to distinguish among models

B anomalies

Lepton flavor universality Violation (LFUV) in semi-leptonic **B** decays

$$b \to c\tau\nu$$

$$R_{D^{(*)}} = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu)}{\mathcal{B}(B \to D^{(*)}\ell\nu)}$$

~ 3σ excess over the SM

$$b \to s\ell\ell$$

$$R_{K^{(*)}} = \frac{\mathcal{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B \to K^{(*)}e^+e^-)}$$

~ 2.5σ less over the SM

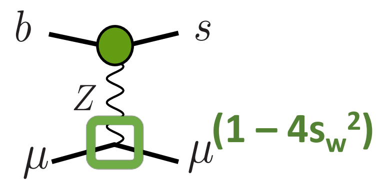
Correlation with ε'/ε ?

ε'/ε ⇔ B anomalies

Possibility of simultaneous explanation of them are discussed in several models

- Z model is not favored by anomalies in b → s transitions, which suggest large C_9^{NP}

$$O_9 = (\bar{s}_L \gamma_\mu b_L)(\bar{\mu}\gamma^\mu \mu)$$



In Z model, it is hard to produce large C_9^{NP} due to smallness of the vector coupling to charged lepton

- In Leptoquark model, which is one of strong candidate of NP model realizing B anomalies , it is difficult to explain ε'/ε because of bounds from rare Kaon decays *Christoph and Buras 1712.01295*

- 2HDM + νR can address $R_{K(*)}$ and ε'/ε *Iguro and Omura, 1905.11778*

  3HDM + νR can access RD(*),RK(*) and ε'/ε *Marzo, Marzola and Raidal 1901.08290*

- Composite model can access $R_{K(*)}$ and ε'/ε *Matsuzaki, Nishiwaki and KY 1806.02312*

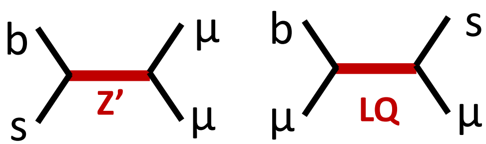
ε'/ε ⇔ B anomalies *- Example -*

Flavorful composite vectors

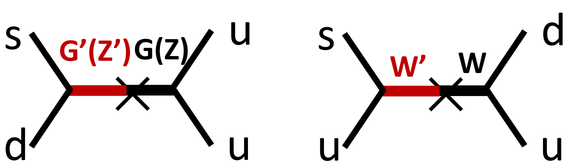
Matsuzaki, Nishiwaki and KY 1806.02312

New vector particles : G', Z', W', Leptoquark(LQ) are included as composite vectors

b→sμμ



ε'/ε (K→π π)



Flavor texture: Assume pure imaginary

(to avoid ε_K constraint)

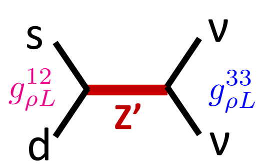
ε'/ε

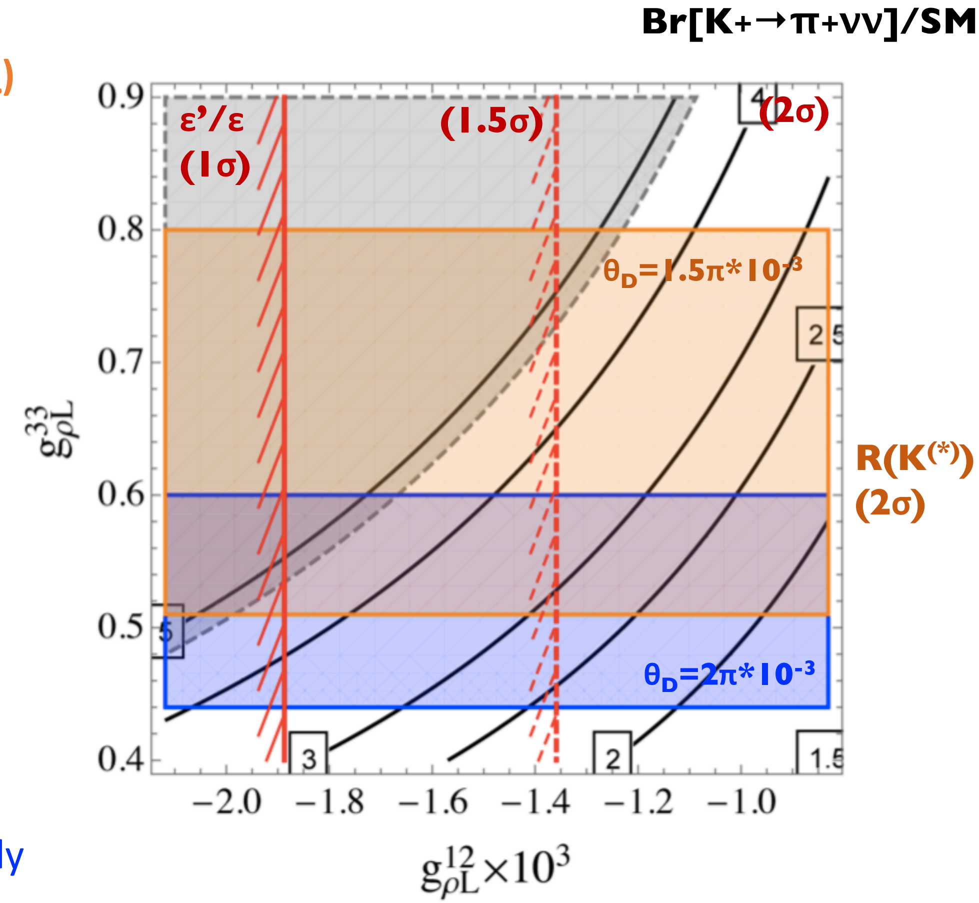
$$g_{\rho L}^{ij} = \begin{pmatrix} 0 & i g_{\rho L}^{12} & 0 \\ i(g_{\rho L}^{12})^* & 0 & 0 \\ 0 & 0 & g_{\rho L}^{33} \end{pmatrix}^{ij}$$

B anomaly

The correlation b/w ε'/ε and B obs. appear in K→πνν

K→πνν





R(K) & ε'/ε (2σ)*

⇔ 1.5 < BR($K^+ \to \pi^+ \nu\nu$)/SM

⇔ 10 < BR($K_L \to \pi^0 \nu\nu$)/SM

Summary

Kaon physics is highly suppressed and sensitive to NP

2.8σ discrepancy in direct CPV of Kaon ε'/ε

NP in ϵ' / ϵ ?

Lattice
New result coming soon

Different implications
(correlations & predictions)

Kaon rare decays

$$\begin{cases} K_L \to \pi^0 \nu \bar{\nu} \\ K^+ \to \pi^+ \nu \bar{\nu} \end{cases}$$

B anomalies

$$\begin{cases} R_{D^{(*)}} \\ R_{K^{(*)}} \end{cases}$$

Many experiments are on-going, and could allow us to discriminate NP models

Kaon physics will continue to offer a powerful probe for NP!