Rare Kaon Decays in SMEFT: $K \to \pi\bar{\nu}\nu$, $K \to (\pi)\ell^+\ell^-$ ΔM_K and ε'/ε

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Outline

1. Motivation
2. Z' Model
3. Results
4. Z from Z'
5. Summary

based on: 2006.01138, in collaboration with Andrzej Buras and Jacky Kumar

Outline

New Measurements: $K \to \pi\nu\bar{\nu}$

$K^+ \to \pi^+\nu\bar{\nu}$

$\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})_{\text{exp}} = (4.7^{+7.2}_{-4.7}) \times 10^{-11}$ Ruggiero: KAON2019

$\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})_{\text{SM}} = (8.5^{+1.0}_{-1.2}) \times 10^{-11}$ Buras/Buttazzo/Girrbach-Noe/Knegjens:1503.02693

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

$\mathcal{B}(K_L \to \pi^0\nu\bar{\nu})_{\text{KOTO}} = 2.1^{+2.0(+4.1)}_{-1.1(-1.7)} \times 10^{-9}$ Shinohara: KAON2019

$\hookrightarrow$violation of GN bound

$\mathcal{B}(K_L \to \pi^0\nu\bar{\nu})_{\text{SM}} = (3.2^{+1.1}_{-0.7}) \times 10^{-11}$ Buras/Buttazzo/Girrbach-Noe/Knegjens:1503.02693

New lattice results: ΔM_K , ε'/ε

From RBC-UKQCD

For ε'/ε RBC-UKQCD: 2004.09440

For ΔM_K RBC-UKQCD: 1406.0916,1504.01170

ε'/ε

$(\varepsilon'/\varepsilon)_{\text{exp}} = (16.6 \pm 2.3) \times 10^{-4}$ NA48, KTeV: hep-ex/0208009, hep-ex/0208007

$(\varepsilon'/\varepsilon)_{\text{SM}} = (13.9 \pm 8.4) \times 10^{-4}$ JA/Buras/Bobeth: 2005.05978

ΔM_K

$(\Delta M_K)_{\text{exp}} = 3.484(6) \times 10^{-15}\,\text{GeV}$

$(\Delta M_K)_{\text{SM}} = 7.7(2.1) \times 10^{-15}\,\text{GeV}$ RBC-UKQCD: Lattice 2017

Pattern

$\boldsymbol{K \to \pi\nu\bar{\nu}}$

$K^+ \to \pi^+\nu\bar{\nu} \ \downarrow$

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

$\boldsymbol{\Delta M_K}$

$\Delta M_K \downarrow$

$\hookrightarrow$ need $\not{CP}$ phase, since:

$$(\Delta M_K)_{\rm BSM} = c\,{\rm Re}[\Delta_{sd}^2] = c\,[({\rm Re}[\Delta_{sd}])^2 - ({\rm Im}[\Delta_{sd}])^2]\,, \qquad c > 0.$$

Constraints from ε'/ε , ε_K

$$\left(\frac{\varepsilon'}{\varepsilon}\right)^{\rm BSM} = \kappa_{\varepsilon'} \cdot 10^{-3}, \qquad -1.0 \le \kappa_{\varepsilon'} \le 1.0,$$

$$(\varepsilon_K)^{\rm BSM} = \kappa_{\varepsilon} \cdot 10^{-3}, \qquad -0.2 \le \kappa_{\varepsilon} \le 0.2$$

Outline

Z' model: $s \to d$

New FV coulings to quarks

$\mathcal{L}_{Z'} = \Delta_{Z'}(\bar{s}\gamma^{\mu} d) Z'_{\mu}$ + h.c.

	$\mathrm{Im}\Delta$	$\mathrm{Re}\Delta$
$K_L \to \pi^0 \nu\bar{\nu}$	$*$	
$K^+ \to \pi^+ \nu\bar{\nu}$	$*$	$*$
$K_L \to \mu^+\mu^-$		$*$
$K_S \to \mu^+\mu^-$	$*$	
$K_L \to \pi^0 \ell^+\ell^-$	$*$	
ε'/ε	$*$	
ε_K	$*$	$*$
ΔM_K	$*$	$*$

Table: The dependence of rare Kaon decay observables on the imaginary and/or real parts of Z' and Z flavour-violating couplings.

Setup

Z'

Matching onto SMEFT

SMEFT running and matching onto WET

Including full 1-loop running

WET

1-loop runnig and computation of observables

Setup

$\mathcal{L}_{Z'}$: Z' **model**

↓ **matching**

$\mu = \Lambda$ — $\mathcal{C}_i(\Lambda)$: **SMEFT**

⇣ **SMEFT running**

$\mathcal{C}_i(\mu_{\text{ew}})$: **SMEFT**

$\mu = \mu_{\text{ew}}$ — ↓ **matching**

$C_i(\mu_{\text{ew}})$: **WET**

⇣ **WET running**

$\mu = \mu_{\text{Low}}$ — $C_i(\mu_{\text{Low}})$: **WET** wilson

JA/Kumar/Straub: 1804.05033

A Phyton package, which includes

SMEFT running

Complete 1-loop RGEs — Alonso/Jenkins/Manohar/Trott: 1312.2014, 1308.2627, 1310.4838

Matching

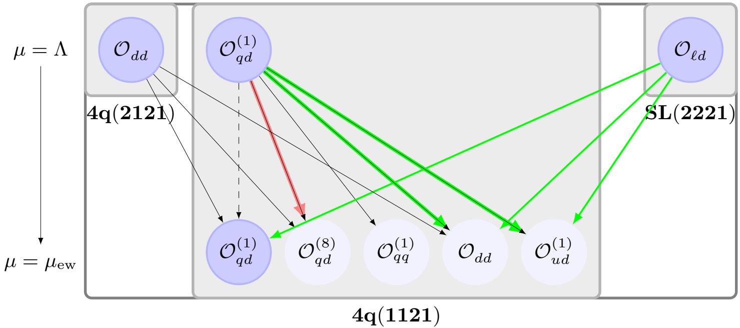
Complete tree-level matching — JA/Crivellin/Fael/Greub:1512.02830, Jenkins/Manohar/Stoffer:1709.04486

Complete one-loop matching — Dekens/Stoffer:1908.05295

WET running

Complete 1-loop running — JA/Fael/Greub/Virto:1704.06639, Jenkins/Manohar/Stoffer:1711.05270

RG chart



red: QCD
green: Weak
black: Yukawa
dashed: Self-mixing

Procedure

Step 1

$\mathrm{Im}[\Delta_{sd}]$: fixed by ε'/ε

Step 2

$\mathrm{Re}[\Delta_{sd}]$: fixed by ε_K

Step 3

$\mathrm{Im}[\Delta_{sd}] > \mathrm{Re}[\Delta_{sd}]$: from ΔM_K

Step 4

Prediction of other observables

Scenarios

Left-handed scenario (LHS)

$\Delta_{sd}^{L} \neq 0$

Right-handed scenario (RHS)

$\Delta_{sd}^{R} \neq 0$

LR

LHS+RHS

Plotted ratios

$K \to \pi\nu\bar{\nu}$

$$R^{+}_{\nu\bar{\nu}} = \frac{\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})}{\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})_{SM}}\,,\; R^{0}_{\nu\bar{\nu}} = \frac{\mathcal{B}(K_L \to \pi^0 \nu\bar{\nu})}{\mathcal{B}(K_L \to \pi^0 \nu\bar{\nu})_{SM}}$$

ΔM_K

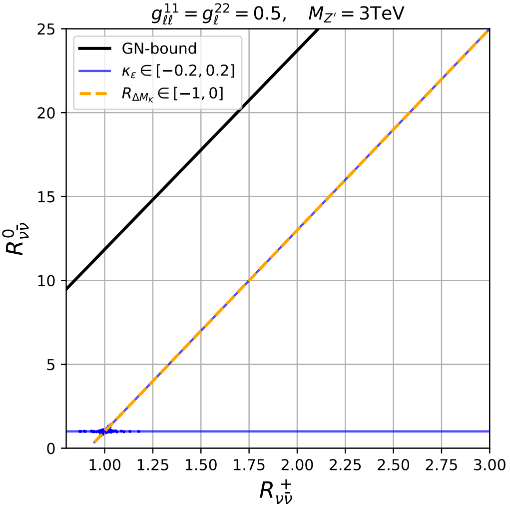
$$R_{\Delta M_K} = \frac{\Delta M_K^{BSM}}{\Delta M_K^{exp}}$$

Rare Kaon decays

$$R^{S}_{\mu^+\mu^-} = \frac{\mathcal{B}(K_S \to \mu^+\mu^-)}{\mathcal{B}(K_S \to \mu^+\mu^-)_{SM}}\,, \quad R^{0}_{\pi\ell^+\ell^-} = \frac{\mathcal{B}(K_L \to \pi^0 \ell^+\ell^-)}{\mathcal{B}(K_L \to \pi^0 \ell^+\ell^-)_{SM}}$$

Outline

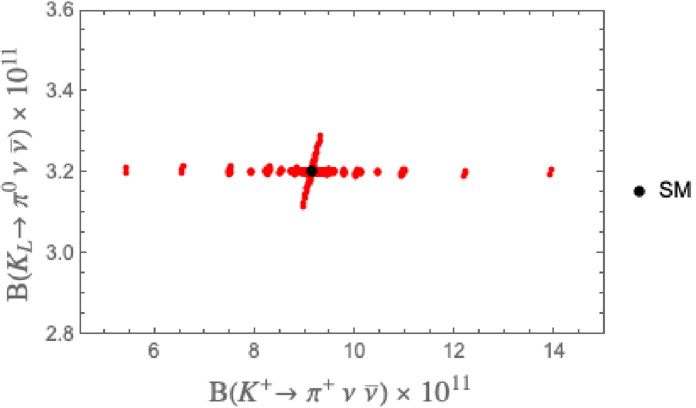
LHS



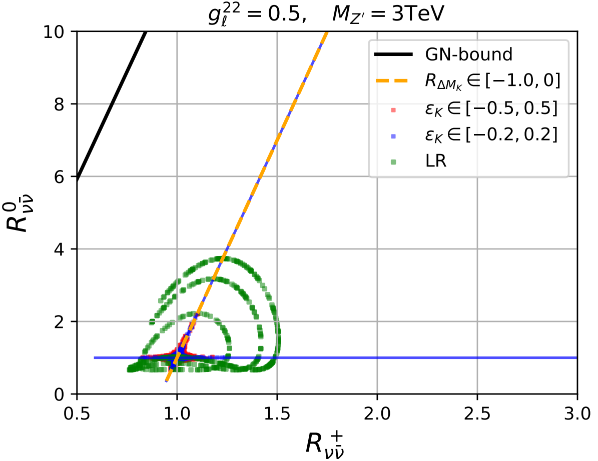
$g_{\ell\ell}^{11} = g_{\ell}^{22} = 0.5, \quad M_{Z'} = 3\text{TeV}$
GN-bound
$\kappa_\varepsilon \in [-0.2, 0.2]$
$R_{\Delta M_K} \in [-1, 0]$
$R^0_{\nu\bar{\nu}}$
$R^+_{\nu\bar{\nu}}$
0
5
10
15
20
25
1.00
1.25
1.50
1.75
2.00
2.25
2.50
2.75
3.00

With anomaly cancellation

JA/Buras/Cerdà-Sevilla/De Fazio: 1912.09308

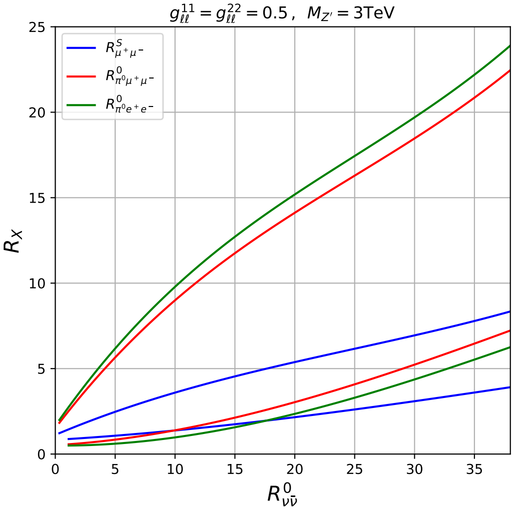


LHS and LR



$g_\ell^{22} = 0.5, \quad M_{Z'} = 3\text{TeV}$
GN-bound
$R_{\Delta M_K} \in [-1.0, 0]$
$\varepsilon_K \in [-0.5, 0.5]$
$\varepsilon_K \in [-0.2, 0.2]$
LR
$R^0_{\nu\bar{\nu}}$
$R^+_{\nu\bar{\nu}}$
0
2
4
6
8
10
0.5
1.0
1.5
2.0
2.5
3.0

Rare Kaon decays



Outline

Z' and Z

New coulings to quarks

$\mathcal{L}_{Z'+Z} = \Delta_{Z'}(\bar{s}\gamma^{\mu}d)Z'_{\mu} + \Delta_{Z}(\bar{s}\gamma^{\mu}d)Z_{\mu}$ + h.c.

$\Delta_{Z'}$

Directly generated (as before)

Δ_{Z}

Generated through top-yukawa RG effects

RG induced Δ_Z

Modified Z-coupling in SMEFT

$$[\mathcal{O}_{Hd}]_{ij} = (H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{d}^i\gamma^\mu d^j)$$

LL running

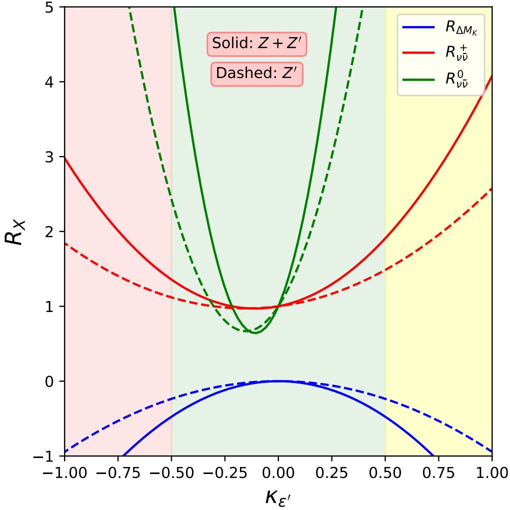
$$\left[\mathcal{C}_{Hd}\right]_{ij}(\mu_{\rm ew}) = \frac{N_c y_t^2}{8\pi^2}\left(\left[\mathcal{C}_{qd}^{(1)}\right]_{33ij}(\Lambda) - \left[\mathcal{C}_{ud}^{(1)}\right]_{33ij}(\Lambda)\right)\ln\left(\frac{\mu_{\rm ew}}{\Lambda}\right)$$

FV Z coupling

$$[\Delta_Z^d]_{ij} = -\frac{g_Z}{2}v^2\left[\mathcal{C}_{Hd}\right]_{ij}$$

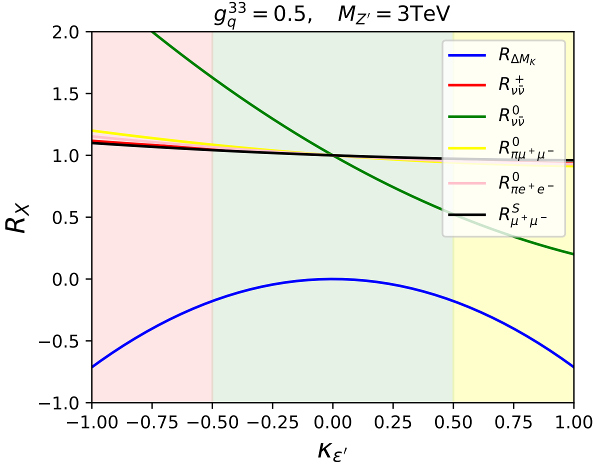
and similar for $\left[\mathcal{C}_{Hq}^{(1)}\right]_{ij}$, $\left[\mathcal{C}_{Hq}^{(3)}\right]_{ij}$, $\left[\mathcal{C}_{Hu}\right]_{ij}$, $\left[\mathcal{C}_{H\ell}^{(1)}\right]_{ij}$, $\left[\mathcal{C}_{He}\right]_{ij}$

NP in Z and Z'



Solid: $Z+Z'$
Dashed: Z'
$R_{\Delta M_K}$
$R^+_{\nu\bar{\nu}}$
$R^0_{\nu\bar{\nu}}$
R_X
$\kappa_{\varepsilon'}$
5
4
3
2
1
0
−1
−1.00
−0.75
−0.50
−0.25
0.00
0.25
0.50
0.75
1.00

NP in Z only



$g_q^{33} = 0.5, \quad M_{Z'} = 3\text{TeV}$
$R_{\Delta M_K}$
$R^+_{\nu\bar{\nu}}$
$R^0_{\nu\bar{\nu}}$
$R^0_{\pi\mu^+\mu^-}$
$R^0_{\pi e^+e^-}$
$R^S_{\mu^+\mu^-}$
R_X
$\kappa_{\varepsilon'}$
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.00
−0.75
−0.50
−0.25
0.00
0.25
0.50
0.75
1.00

Outline

Summary

Z' in SMEFT

$\Delta M_K \downarrow$ with constraints from ε'/ε, ε_K

Interesting correlations

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

$K_S \to \mu^+\mu^-$, $K_L \to \pi^0 e^+ e^-$ and $K_L \to \pi^0\mu^+\mu^-$

Z FCNCs from Z'

Through Yukawa running effects

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

Grossman-Nir Bound

Grossman/Nir: hep-ph/9701313

$\mathcal{B}(K_L \to \pi^0\nu\bar{\nu}) \leq 4.3\,\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})$

New KOTO measurement

$\mathcal{B}(K_L \to \pi^0\nu\bar{\nu})_{\text{KOTO}} = 2.1^{+2.0(+4.1)}_{-1.1(-1.7)} \times 10^{-9}$ Shinohara: KAON2019

$\hookrightarrow$violation of GN bound

Explanations

Heavy/light NP — Kitahara/Okui/Perez/Soreq/Tobioka:1909.11111

$\Delta I = 3/2$ — He/Ma/Tandean/Valencia:2002.05467,2005.02942

Z' and $L_\mu - L_\tau$ — Fuyuto/Hou/Kohda:1412.4397

$K_S \to \mu^+\mu^-$, $K_L \to \pi^0 e^+ e^-$ and $K_L \to \pi^0\mu^+\mu^-$

Coputations

NNLO — Gorbahn/Haisch:hep-ph/0605203

Long-distance contributions — Isidori/Unterdorfer:hep-ph/0311084
D'Ambrosio/Kitahara:1707.06999
Mescia/Smith/Trine:hep-ph/0606081
D'Ambrosio/Greynat/Knecht:1812.00735,1906.03046

SM prediction

$$\mathcal{B}(K_S \to \mu^+\mu^-)_{\rm SM} = (5.2 \pm 1.5) \times 10^{-12}$$

Isidori/Unterdorfer:hep-ph/0311084
D'Ambrosio/Kitahara:1707.06999

$$\mathcal{B}(K_L \to \pi^0 e^+ e^-)_{\rm SM} = 3.54^{+0.98}_{-0.85}(1.56^{+0.62}_{-0.49}) \times 10^{-11}$$

$$\mathcal{B}(K_L \to \pi^0 \mu^+\mu^-)_{\rm SM} = 1.41^{+0.28}_{-0.26}(0.95^{+0.22}_{-0.21}) \times 10^{-11}$$

Mescia/Smith/Trine:hep-ph/0606081

Experimental bounds

$$\mathcal{B}(K_S \to \mu^+\mu^-)_{\rm LHCb} < 0.8(1.0) \times 10^{-9}$$

LHCb:1706.00758

$$\mathcal{B}(K_L \to \pi^0 e^+ e^-)_{\rm KTeV} < 28 \times 10^{-11}$$

KTeV:hep-ex/0309072

$$\mathcal{B}(K_L \to \pi^0 \mu^+\mu^-)_{\rm KTeV} < 38 \times 10^{-11}$$

KTeV:hep-ex/0001006