

# Rare Kaon Decays:

$$K \rightarrow \pi \bar{\nu} \nu \text{ and } K \rightarrow (\pi) \ell^+ \ell^-$$

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# Outline

- 1 Motivation
- 2 Feynman diagrams
- 3 Decays
- 4 New Physics
- 5 Summary

Lol of: [JA](#), [Andrzej Buras](#) and [Jacky Kumar](#)

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# Motivation

## Rare

$K \rightarrow \pi \bar{\nu} \nu$ : Theoretically clean, Sensitivity to high scales

$K \rightarrow (\pi) \ell \ell$ : Bounds on NP models

## CKM parameters

$K \rightarrow \pi \bar{\nu} \nu$ :  $V_{td}$ ,  $V_{ts}^* V_{td}$ ,  $\beta$

$\hookrightarrow$  CP violation

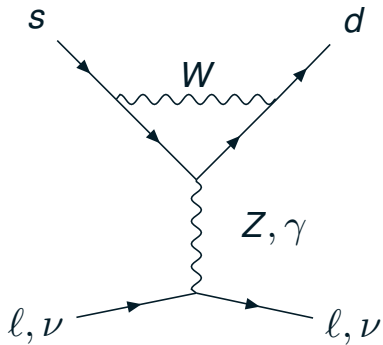
## Sensitivity to NP

Correlations amongst each other and  $\Delta M_K$ ,  $\varepsilon'/\varepsilon$  and  $\varepsilon_K$

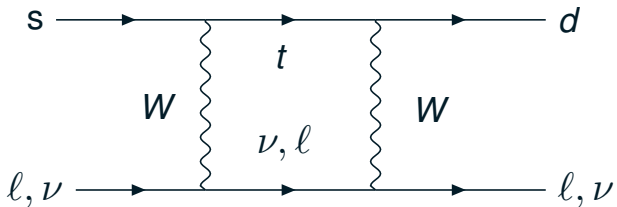
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$s \rightarrow d$ : Penguin diagrams



$s \rightarrow d$ : Box diagram



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

## Coputations

NNLO

Buras/Gorbahn/Haisch/Nierste:hep-ph/0508165  
Buras/Gorbahn/Haisch/Nierste:hep-ph/0603079  
Gorbahn/Haisch:hep-ph/0411071

Isospin breaking

Mescia/Smith:0705.2025

Non-perturbative effects

Isidori/Mescia/Smith:hep-ph/0503107

## SM prediction

Buras/Buttazzo/Girrbach-Noe/Knegjens: 1503.02693

$$\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu})_{\text{SM}} = (8.5_{-1.2}^{+1.0}) \times 10^{-11}$$

$$\mathcal{B}(K_L \rightarrow \pi^0 \nu \bar{\nu})_{\text{SM}} = (3.2_{-0.7}^{+1.1}) \times 10^{-11}$$

## Measurement

$$\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu})_{\text{exp}} = (11.0_{-3.5}^{+4.0} \pm 0.3) \times 10^{-11}$$

NA62:2007.08218

$$\mathcal{B}(K_L \rightarrow \pi^0 \nu \bar{\nu})_{\text{exp}} \leq 3.0 \times 10^{-9}$$

KOTO:1810.09655

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

## Grossman-Nir Bound

Grossman/Nir: hep-ph/9701313

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

## New KOTO measurement

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

Shinohara: KAON2019

↪ 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

$$K_S \rightarrow \mu^+ \mu^-, K_L \rightarrow \pi^0 e^+ e^- \text{ and } K_L \rightarrow \pi^0 \mu^+ \mu^-$$

## Computations

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

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

Isidori/Unterdorfer:hep-ph/0311084

D'Ambrosio/Kitahara:1707.06999

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

Mescia/Smith/Trine:hep-ph/0606081

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

## Experimental bounds

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

LHCb:1706.00758

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

KTeV:hep-ex/0309072

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

KTeV:hep-ex/0001006

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# NP in $Z$ and $Z'$

## New couplings to quarks

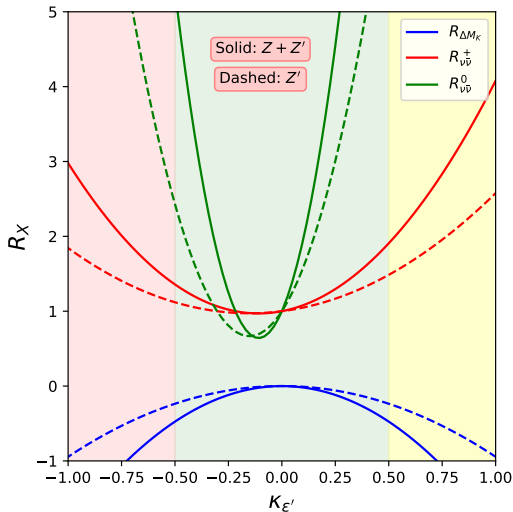
$$\mathcal{L}_{Z+Z'} = \Delta_Z (\bar{s} \gamma^\mu d) Z_\mu + \Delta_{Z'} (\bar{s} \gamma^\mu d) Z'_\mu + \text{h.c.}$$

	Im $\Delta$	Re $\Delta$
$K_L \rightarrow \pi^0 \nu \bar{\nu}$	*	
$K^+ \rightarrow \pi^+ \nu \bar{\nu}$	*	*
$K_L \rightarrow \mu^+ \mu^-$		*
$K_S \rightarrow \mu^+ \mu^-$	*	
$K_L \rightarrow \pi^0 \ell^+ \ell^-$	*	
$\varepsilon'/\varepsilon$	*	
$\varepsilon_K$	*	*
$\Delta M_K$	*	*

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

# NP in $Z$ and $Z'$

JA/Buras/Kumar: 2006.01138



$$\text{with: } R_{\Delta M_K} = \frac{\Delta M_K^{\text{BSM}}}{\Delta M_K^{\text{exp}}}, R_{\nu\bar{\nu}}^+ = \frac{\mathcal{B}(K^+ \rightarrow \pi^+ \nu\bar{\nu})}{\mathcal{B}(K^+ \rightarrow \pi^+ \nu\bar{\nu})_{\text{SM}}}, R_{\nu\bar{\nu}}^0 = \frac{\mathcal{B}(K_L \rightarrow \pi^0 \nu\bar{\nu})}{\mathcal{B}(K_L \rightarrow \pi^0 \nu\bar{\nu})_{\text{SM}}}, \left(\frac{\epsilon'}{\epsilon}\right)^{\text{BSM}} = \kappa_{\epsilon'} \cdot 10^{-3}$$

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# Summary

## Rare Kaon decays

Sensitive to CKM, CP violation, NP, high scales

## Upcoming experimental results

Expected in coming years

## Strong correlations among decays

Example:  $Z$  and  $Z'$



