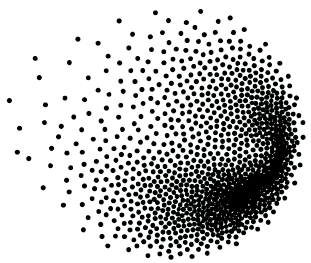
Kaon physics in the SM(EFT)

Presented by Jason Aebischer

Paul Scherrer Institute



PSI

Outline

1. Introduction
2. $\Delta S = 2$
3. $\Delta S = 1$
4. Rare decays
5. Summary

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The beauty of Kaons

CP violation

Direct or indirect

CKM parameters

V_{td}, V_{us}, β, γ, ...

New physics sensitivity

Rare decays

SM Effective Theory (SMEFT)

Symmetry

$SU(3)_C \times SU(2)_L \times U(1)_Y$

Fields

$u, d, c, s, b, t, \ell, \nu_\ell, g, W, Z, H$

Poincaré invariance

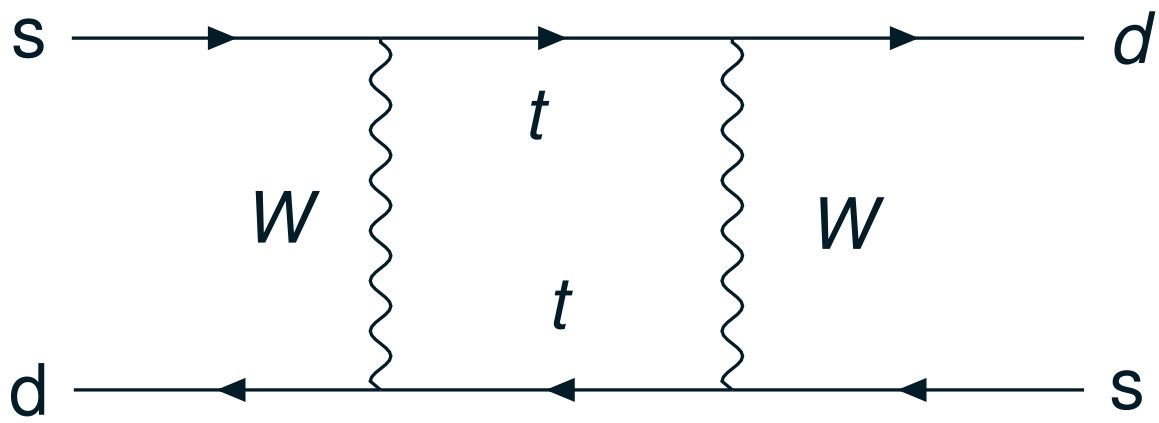
Dim 6 operators

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}^{(4)}_{\text{SM}} + \frac{1}{\Lambda} C^{(5)} \mathcal{O}^{(5)} + \frac{1}{\Lambda^2} \sum_i C^{(6)}_i \mathcal{O}^{(6)}_i + \mathcal{O}(\frac{1}{\Lambda^3})$$

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Kaon mixing



Kaon mass difference: ΔM_K

Computations

NNLO	Brod/Gorbahn: 1108.2036
DQCD	Buras/Gérard/Bardeen: 1401.1385 Bijnens/Gérard/Klein: PLB 257 (1991) 191-195
Lattice	Bai/Christ/Izubuchi/Sachrajda: 1406.0916 Christ/Feng/Martinelli/Sachrajda: 1504.01170 Bai/Christ/Sachrajda: EPJ Web Conf. 175 (2018) 13017

Measurement

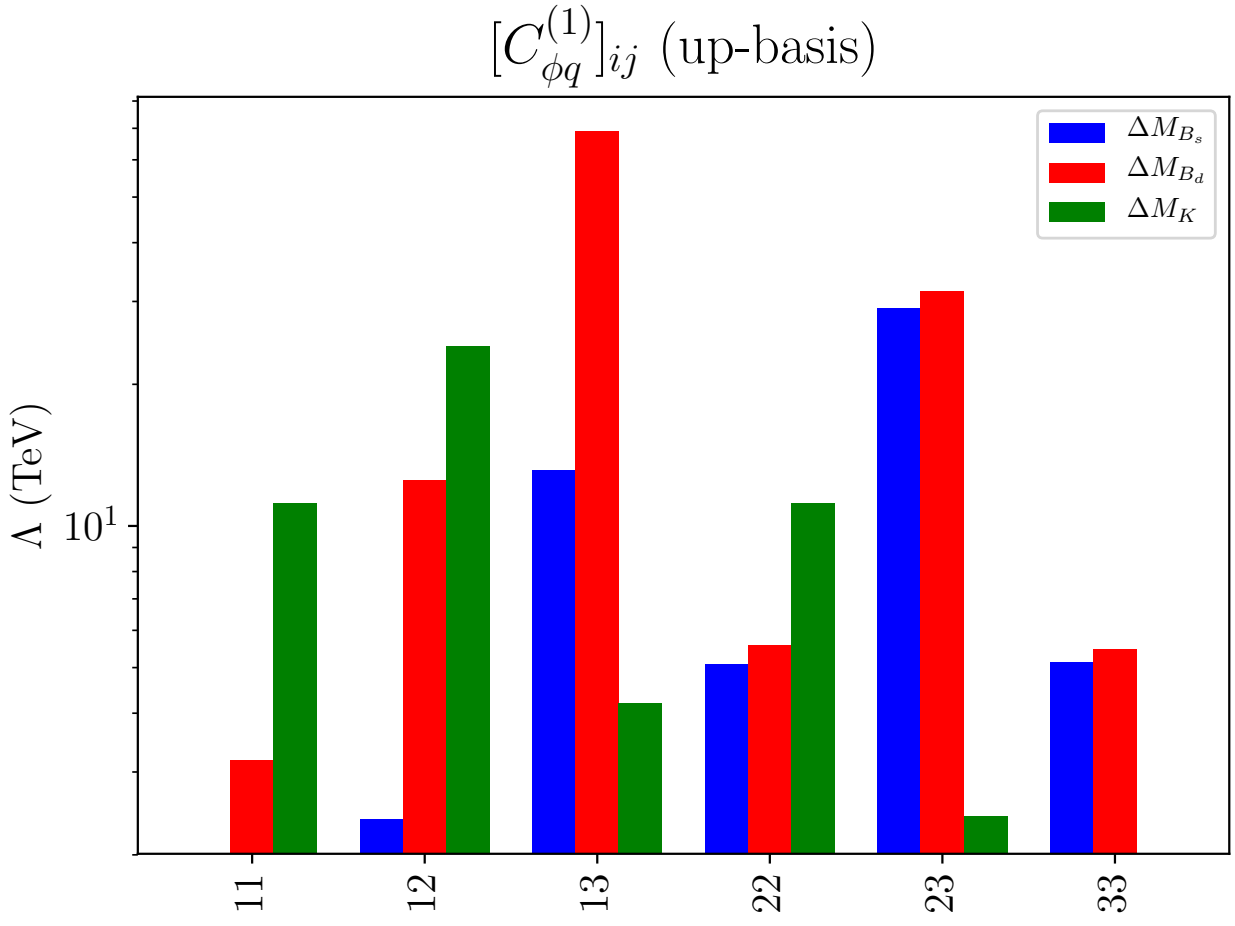
$(\Delta M_K)_{\text{exp}} = 3.484(6) \times 10^{-15}$ GeV — PDG

SM prediction

$(\Delta M_K)_{\text{SM}} = 5.8(0.6)(2.3) \times 10^{-15}$ GeV — RBC-UKQCD: 2301.01387

SMEFT bounds

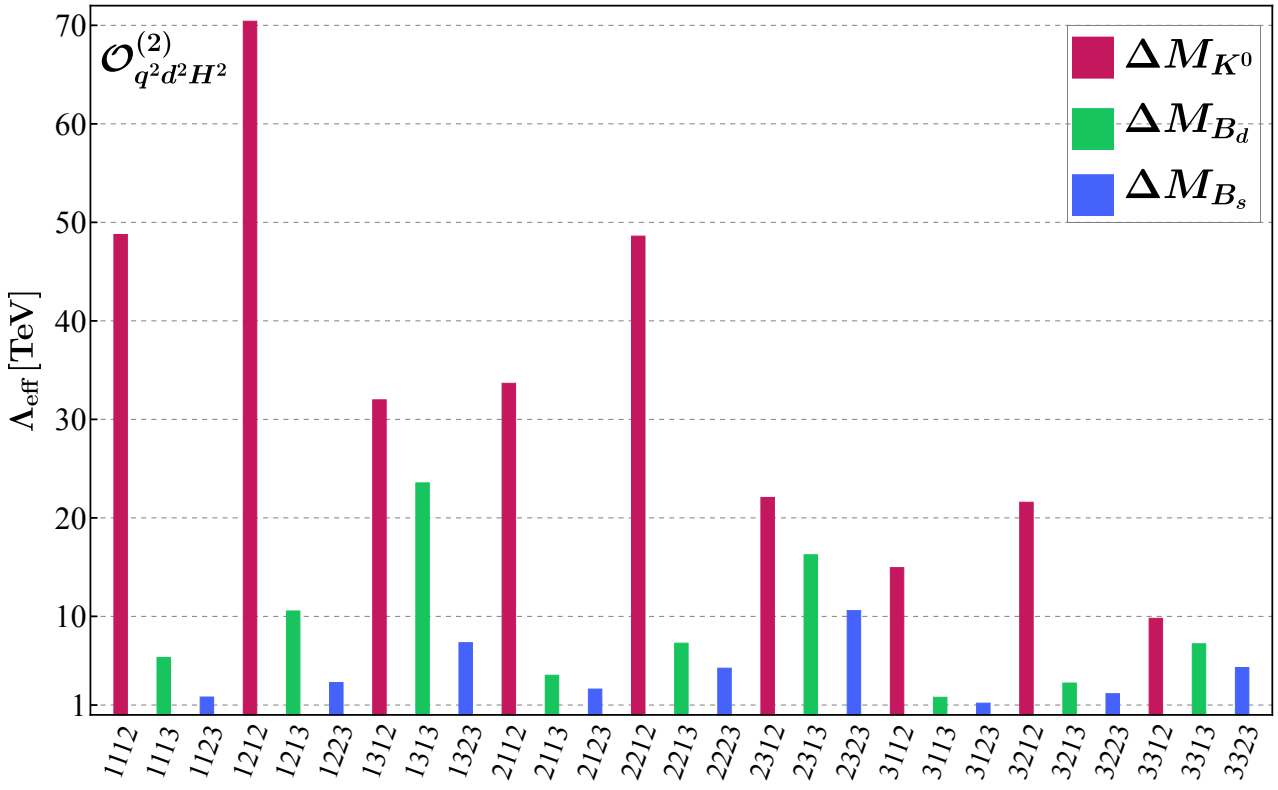
JA/Bobeth/Buras/Kumar: 2009.07276



$$\mathcal{O}_{\phi q}^{(1)} = (\phi^\dagger i \overleftrightarrow{\mathcal{D}_\mu} \phi)(\bar{q}_p \gamma^\mu q_r)$$

Dimension-8 effects

Liao/Ma/Wang: 2409.10305



$$\mathcal{O}^{(2)}_{q^2d^2H^2} = (\bar{q}\gamma_\mu \tau^I q)(\bar{d}\gamma^\mu d)(H^\dagger \tau^I H)$$

Kaon mixing parameter: ε_K

Computations

NNLO

Brod/Gorbahn: 1108.2036
Brod/Kvedaraite/Polonsky: 2108.00017
Brod/Kvedaraite/Polonsky/Youssef: 2207.07669

Long-distance

Buras/Guadagnoli/Isidori: 1002.3612
RBC-UKQCD: 2004.09440

Measurement

$|\varepsilon_K|_{\text{exp}} = 2.228(11) \times 10^{-3}$

PDG

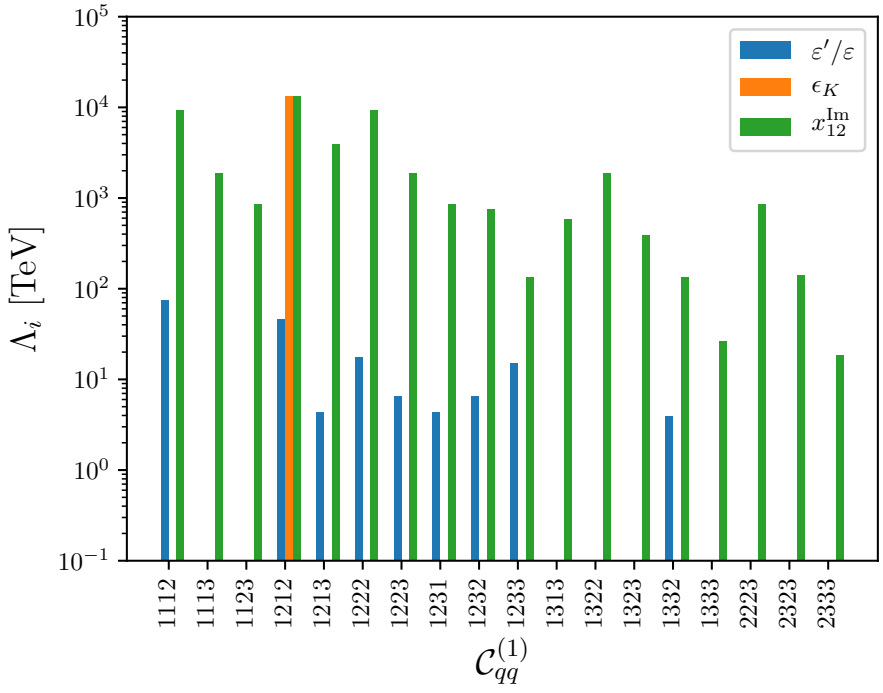
SM prediction

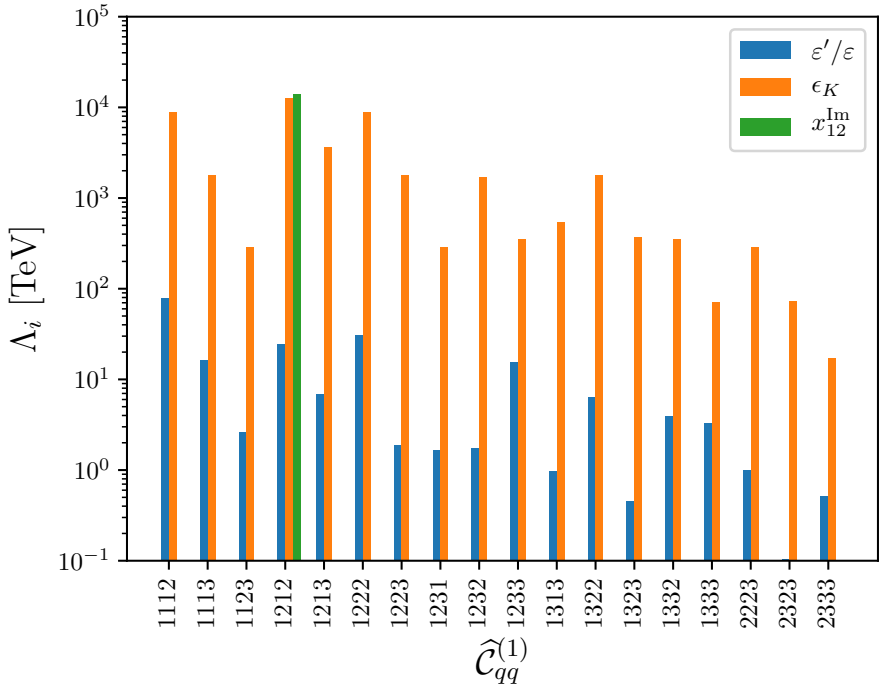
$|\varepsilon_K|_{\text{SM}} = 2.16(6)(8)(15) \times 10^{-3}$

Brod/Gorbahn/Stamou: 1911.06822

$K^0 - \bar{K}^0$ vs $D^0 - \bar{D}^0$

JA/Bobeth/Buras/Straub: 1808.00466





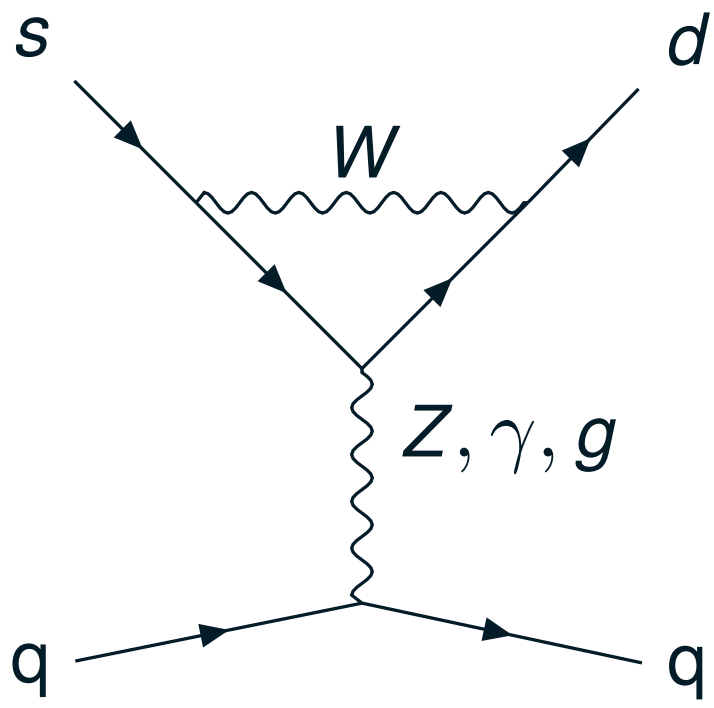
$$\mathcal{O}_{qq}^{(1)} = (\bar{q}_p \gamma_\mu q_r)(\bar{q}_s \gamma^\mu q_t)$$

$$[\hat{C}_{qq}^{(1)}]_{1212} = V_{ui} V_{cj}^* V_{uk} V_{cl}^* [C_{qq}^{(1)}]_{ijkl}$$

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$s \to d$: Penguin diagrams



ε'/ε

Isospin amplitudes

$A_{I,S} \equiv \mathcal{A}\left(K_S \to (\pi\pi)_I\right) , \quad I = 0, 2$

$A_{I,L} \equiv \mathcal{A}\left(K_L \to (\pi\pi)_I\right) , \quad I = 0, 2$

Definition

$\varepsilon' \equiv \frac{1}{\sqrt{2}} \left[\frac{A_{2,L}}{A_{0,S}} - \frac{A_{2,S}}{A_{0,S}} \frac{A_{0,L}}{A_{0,S}} \right]$

CP violation

ε': direct CP violation in $K_L \to \pi\pi$

ε : indirect CP violation in $K_L \to \pi\pi$

ε'/ε

Computations

NNLO

Buras/Gambino/Haisch: hep-ph/9911250
Cerdà-Sevilla/Gorbahn/Jäger/Kokulu: 1611.08276
Cerdà-Sevilla: Acta Phys. Polon. B49 (2018) 1087–1096

Long-distance

Buras/Gérard: 1507.06326
Gisbert/Pich: 1712.06147
RBC-UKQCD: 1502.00263, 1505.07863

Measurement

$(\varepsilon'/\varepsilon)_{\text{exp}} = (16.6 \pm 2.3) \cdot 10^{-4}$

NA48: hep-ex/0208009
KTeV: hep-ex/0208007

Theory predictions

Lattice

RBC-UKQCD: 2004.09440

$(21.7 \pm 8.4) \times 10^{-4}$

χPT

Cirigliano/Gisbert/Pich: 1911.01359

$(14 \pm 5) \times 10^{-4}$

DQCD

Buras/Gerard: 2101.00020

$(5 \pm 2) \times 10^{-4}$

$\Delta I = 1/2$

Definition

$R = Re(A_0)/Re(A_2)$

Measurement

PDG

$Re(A_0)_{\text{exp}} = 27.04(1) \cdot 10^{-8}\,\text{GeV}\,, \quad Re(A_2)_{\text{exp}} = 1.210(2) \cdot 10^{-8}\,\text{GeV}$

$\Rightarrow R = 22.35(4)$

Theory prediction

Lattice: $R = 19.9(2.3)(4.4)$ RBC-UKQCD: 2004.09440

DQCD: $R = 16(2)$ Buras/Gerard/Bardeen: 1401.1385

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Rare decays

Semi-leptonic

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

$K \to (\pi)\ell\ell$: less clean, bounds on NP models

CKM parameters

$K \to \pi\bar{\nu}\nu$: V_{td}, $V_{ts}^* V_{td}$, β

$\hookrightarrow$ CP violation

Sensitivity to NP

Correlations amongst each other and ΔM_K, ε'/ε and ε_K

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

Computations

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

Measurement

$\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})_{\text{exp}} = (9.6^{+1.9}_{-1.8}) \times 10^{-11}$

NA62: 2607.16413

$\mathcal{B}(K_L \to \pi^0 \nu\bar{\nu})_{\text{exp}} \leq 2.2 \times 10^{-9}$

KOTO: 2411.11237

SM prediction

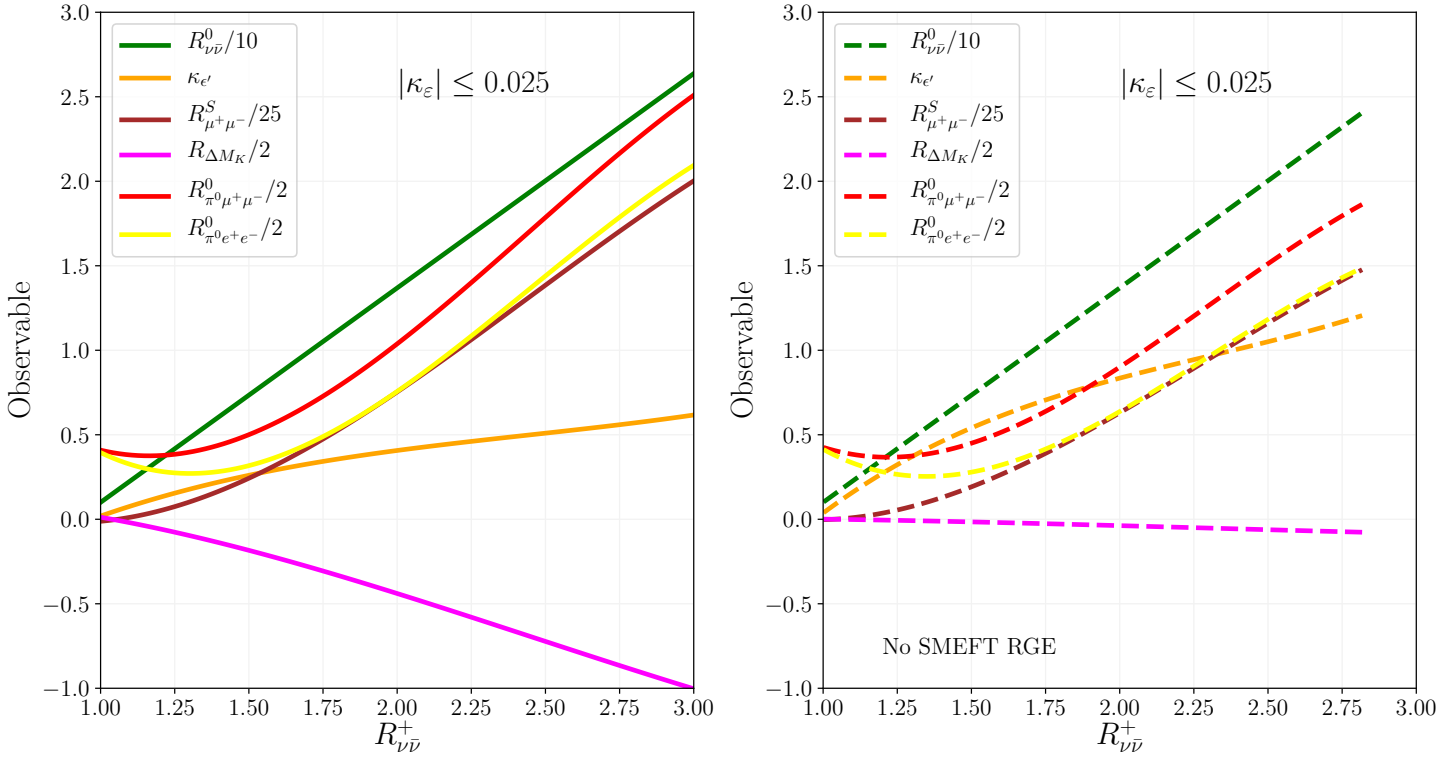
Brod/Gorbahn/Stamou: 2105.02868

$\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})_{\text{SM}} = (7.7 \pm 0.6) \times 10^{-11}$

$\mathcal{B}(K_L \to \pi^0 \nu\bar{\nu})_{\text{SM}} = (2.6 \pm 0.3) \times 10^{-11}$

No NP in ϵ_K

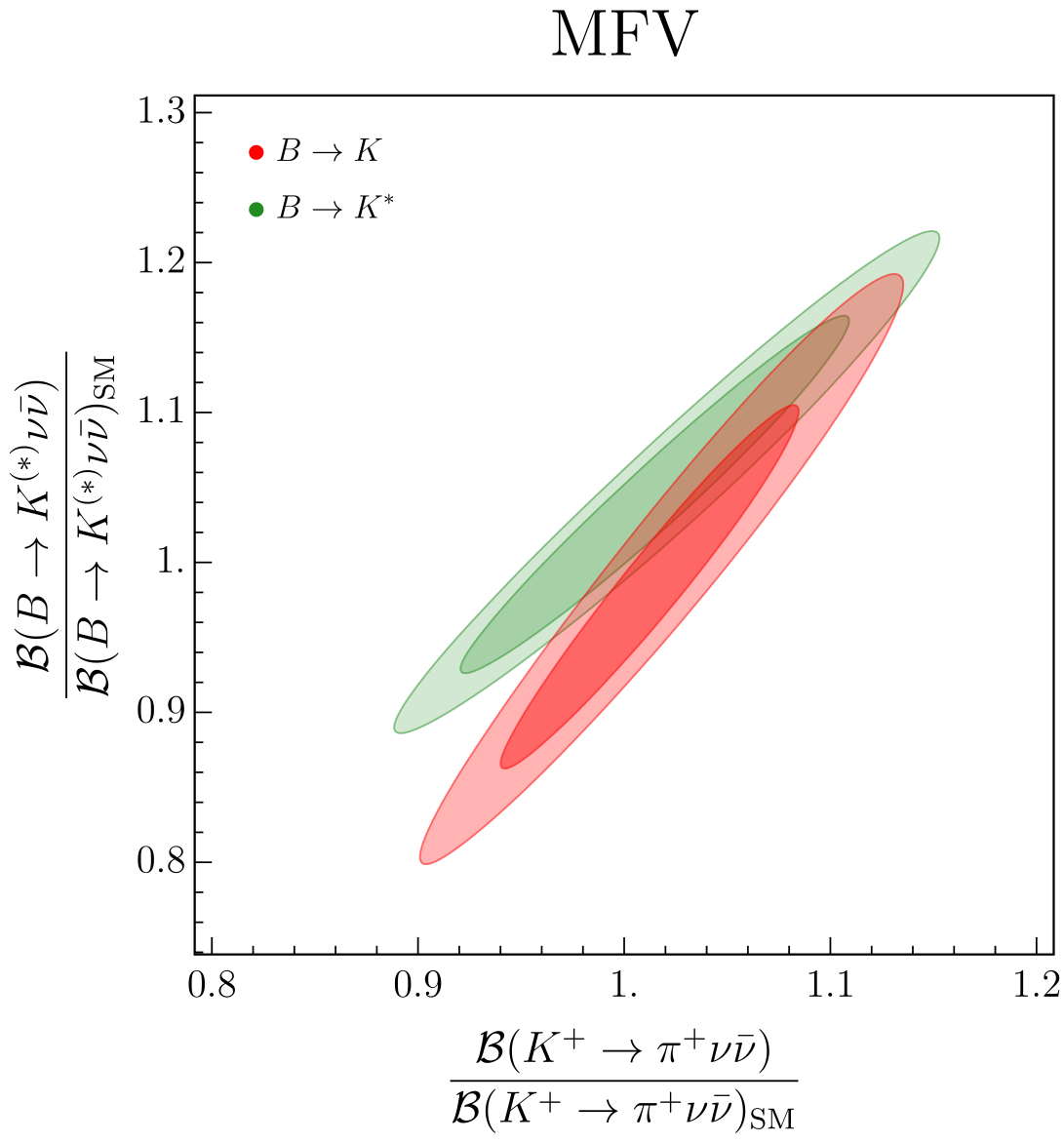
JA/Buras/Kumar: 2302.00013



$$R_{Obs} \equiv \frac{Obs}{Obs^{SM}}$$

Correlation to *B* physics

Allwicher/Bordone: 2607.24494



q^2 distribution for $K \to \pi\bar{\nu}\nu$

Theory prediction

$$\left[\frac{d\Gamma(K\to\pi\bar{\nu}\nu)}{dq^2}\right]_V, \qquad \left[\frac{d\Gamma(K\to\pi\bar{\nu}\nu)}{dq^2}\right]_S$$

Li/Ma/Schmidt: 1912.10433
Deppisch/Fridell/Harz: 2009.04494

Experiment

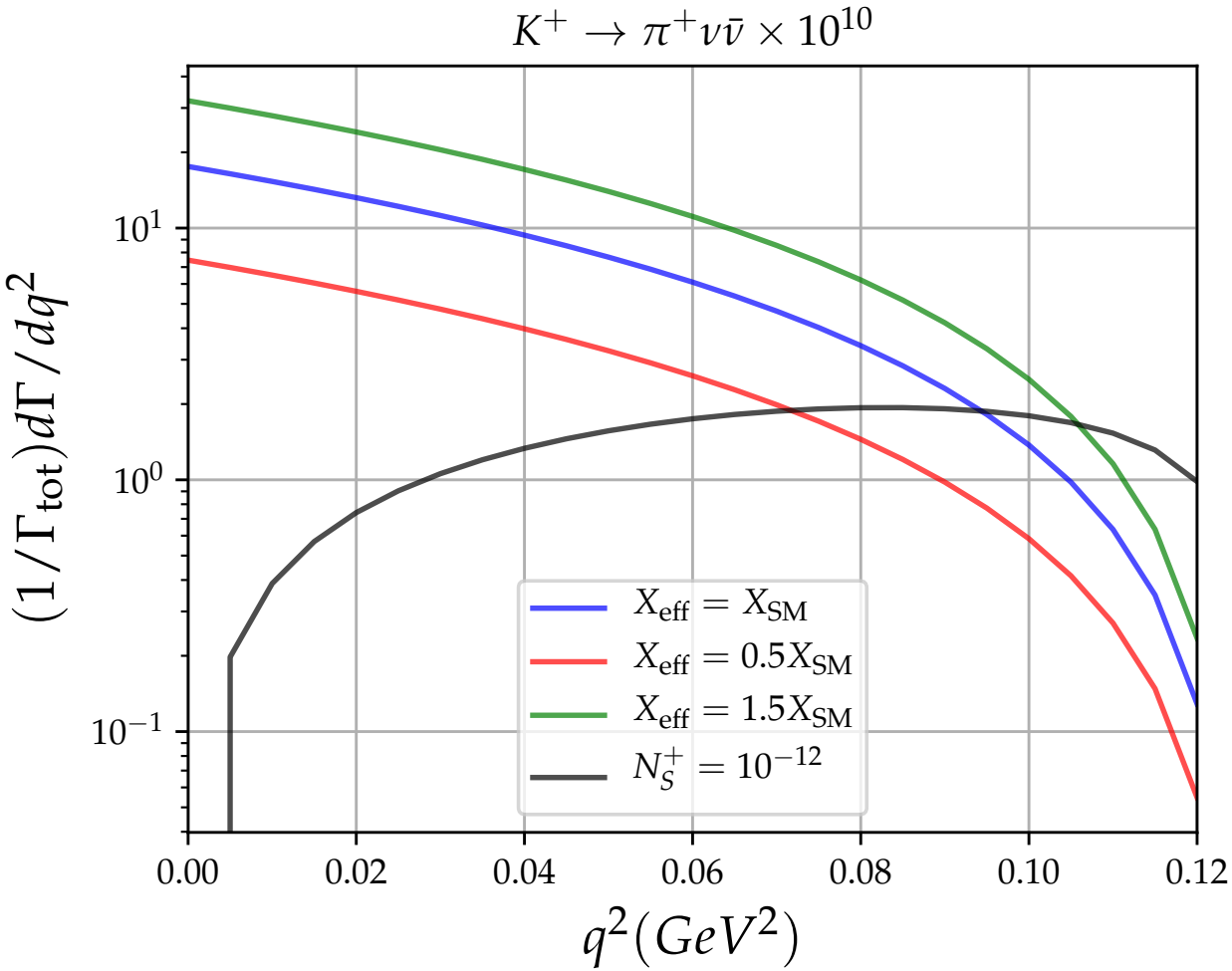
Experimentally accessible

NP

vector vs scalar

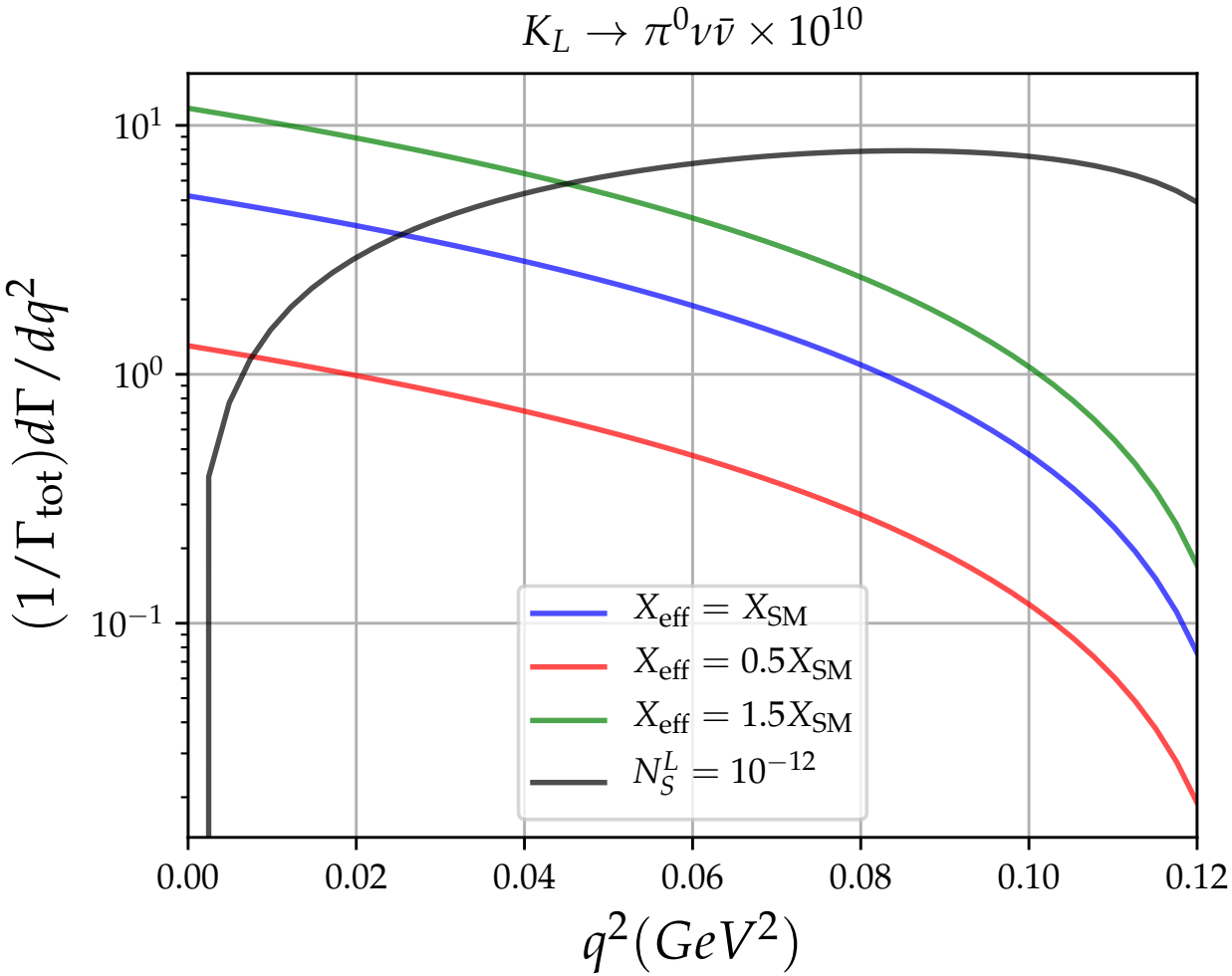
K^+: Scalar vs Vector

JA/Buras/Kumar: 2203.09524



K_L: Scalar vs Vector

JA/Buras/Kumar: 2203.09524



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

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

Experimental bounds

$\mathcal{B}(K_S \to \mu^+\mu^-)_{\text{LHCb}} < 2.1 \times 10^{-10}$ — LHCb: 2001.10354

$\mathcal{B}(K_L \to \pi^0 e^+ e^-)_{\text{KTeV}} < 28 \times 10^{-11}$ — KTeV: hep-ex/0309072

$\mathcal{B}(K_L \to \pi^0 \mu^+ \mu^-)_{\text{KTeV}} < 38 \times 10^{-11}$ — KTeV: hep-ex/0001006

SM prediction

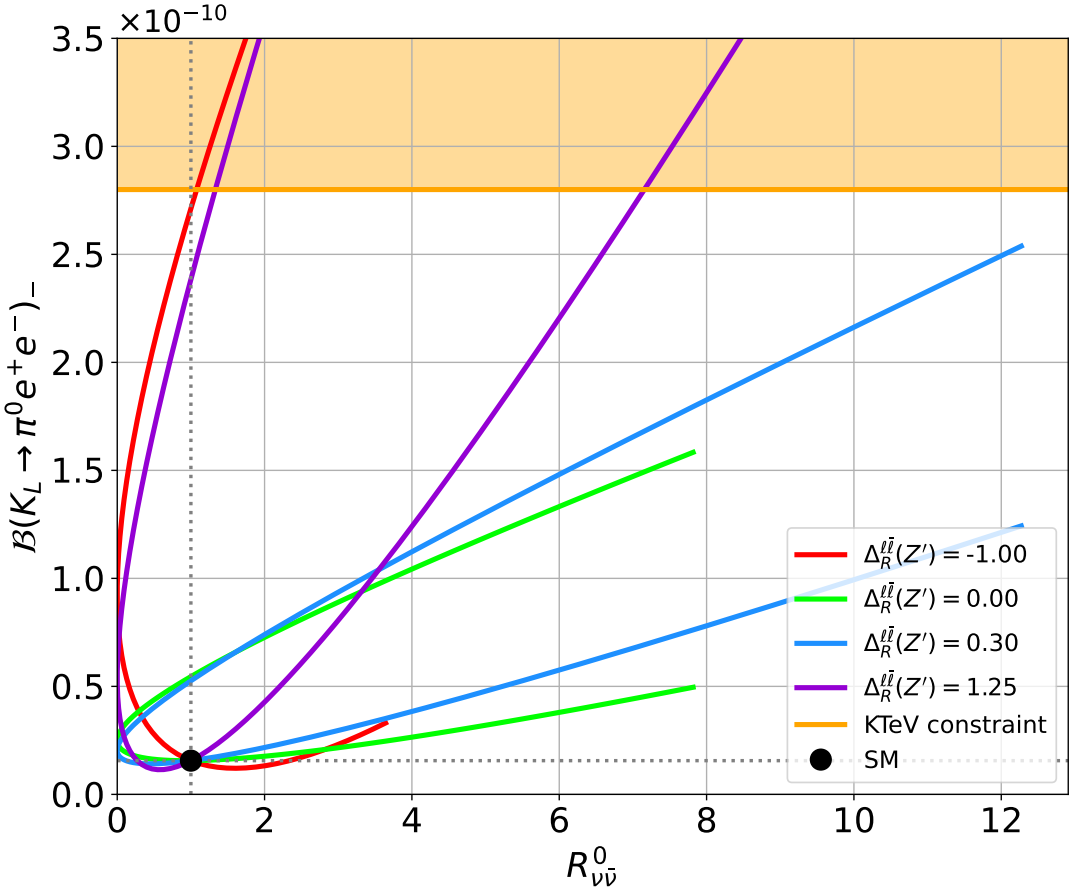
$\mathcal{B}(K_S \to \mu^+\mu^-)_{\text{SM}} = (5.2 \pm 1.5) \times 10^{-12}$ — Isidori/Unterdorfer: hep-ph/0311084; D'Ambrosio/Kitahara: 1707.06999

$\mathcal{B}(K_L \to \pi^0 e^+ e^-)_{\text{SM}} = 3.54^{+0.98}_{-0.85}(1.56^{+0.62}_{-0.49}) \times 10^{-11}$ — Mescia/Smith/Trine: hep-ph/0606081

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

Z' model

Blanke/Buras/Lazzeroni/Swallow: 2607.19055



$$R^0_{\nu\bar{\nu}} \equiv \frac{\mathcal{B}(K_L \to \pi^0 \overline{\nu}\nu)}{\mathcal{B}^{SM}(K_L \to \pi^0 \overline{\nu}\nu)}$$

$K_S \to \mu^+\mu^-$ from data

Dery/Ghosh/Grossman/Schacht: 2104.06427

Assumptions

CPV in mixing negligible

CPV only in $\mathcal{A}(K_S \to \mu^+\mu^-)_{\ell=0}$

Extract $\mathcal{B}(K_S \to \mu^+\mu^-)_{\ell=0}$

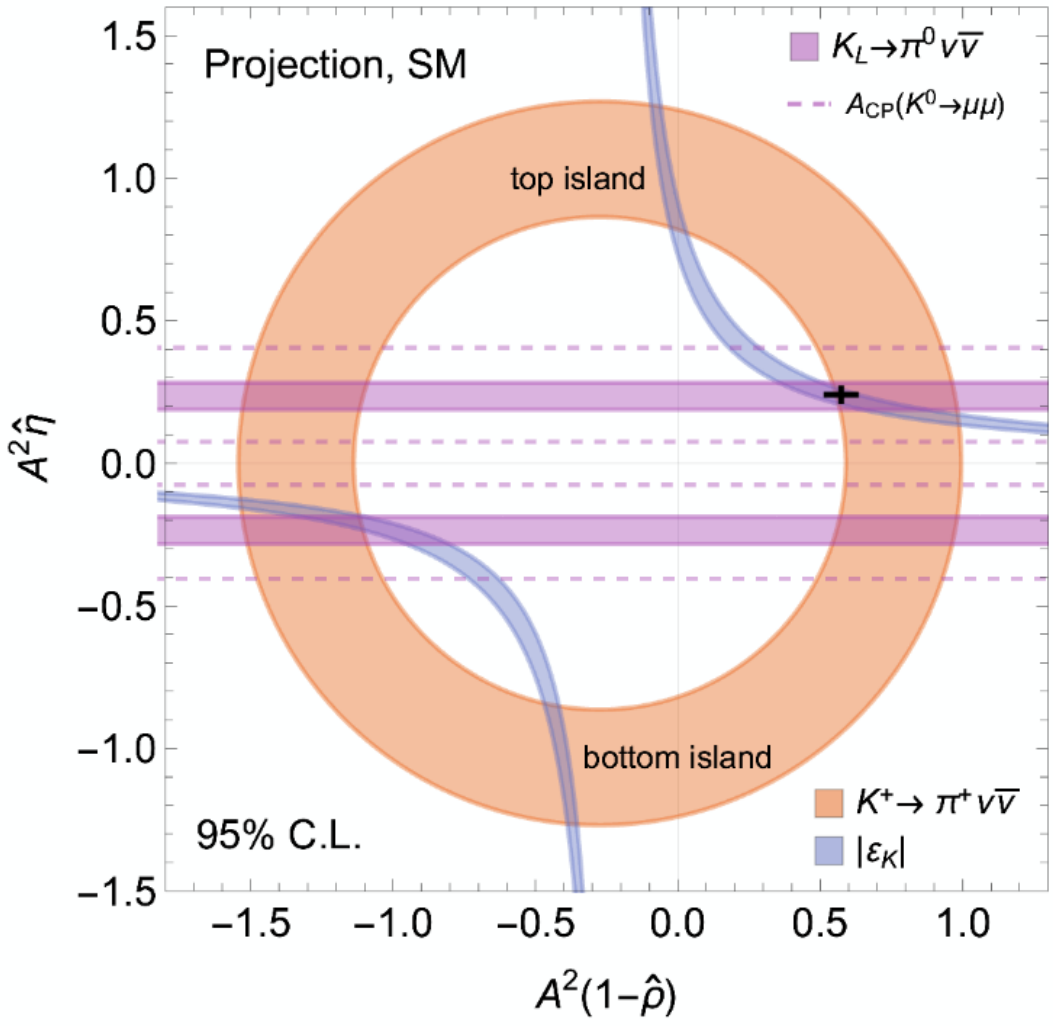
$\mathcal{B}(K_S \to \mu^+\mu^-)_{\ell=0} \sim \mathcal{B}(K_L \to \mu^+\mu^-)$

CKM parameters

$|V_{ts}V_{td}\sin(\beta+\beta_s)|$ up to 1%

$A_{CP}(K \to \mu^+\mu^-)$

Dery: 2504.12386



Proposals for upcoming experiments

LHCb

Implications

$\mathcal{B}(K_S \to \mu^+\mu^-)_{\mathrm{LHCb}} < (2.7 \pm (3.0)) \times 10^{-11}$

KOTO-II

KOTO II: 2501.14827

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

KOFFEE

Cesarotti/Homiller: 2608.27558

Kaon Observables at Future Fermilab Experimental Extensions

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Summary

Kaon physics

$\not{CP}$, CKM, NP

Correlations

$\Delta S = 1, 2$, rare decays

Future prospects

NA62, LHCb, KOTO-II, KOFFEE,...