BSM prospects for rare kaon decays

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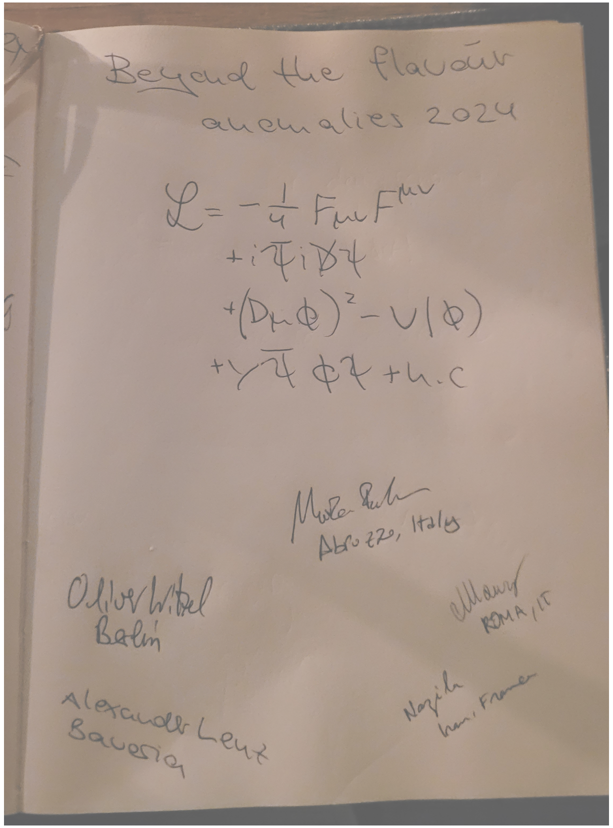
Based on 2206.14748, 2311.04878, 2404.03643, 2404.FORTH

In collaboration with G. D'Ambrosio, A. Iyer and S. Neshatpour

Beyond the Flavour Anomalies V – Siegen – 9-11 April 2024


Beyond the flavour anomalies 2024
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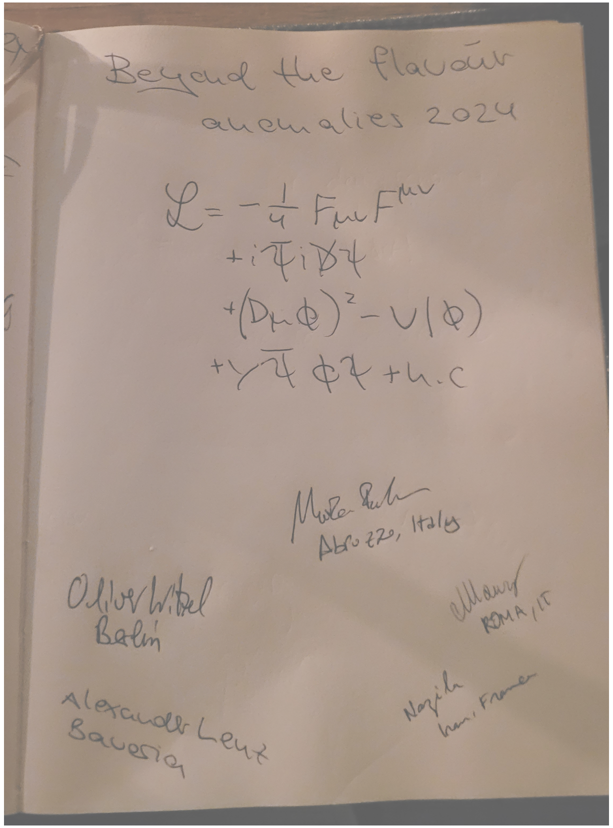
Bavaria



beauty is the new **strange**!

Motivations

Kaon physics

1. **CP Violation**: Kaons were crucial in the discovery of CP violation, a phenomenon where the laws of physics behave differently under the combined operations of charge conjugation (C) and parity transformation (P). The study of kaons contributed significantly to our understanding of this fundamental aspect of particle physics, which is essential for explaining the matter-antimatter asymmetry observed in the universe.
2. **Flavor Physics**: Kaons are mesons containing a strange quark and an up or down antiquark. Studying their behavior provides insights into the weak interaction, which governs processes such as particle decay. Understanding the properties and behavior of particles like kaons helps refine our understanding of the fundamental forces of nature.
3. **Rare Decays**: Kaon physics involves the study of rare decays of kaons, which occur through weak interactions. Investigating these decays allows physicists to probe the Standard Model of particle physics and search for deviations that could indicate new physics beyond our current understanding.
4. **Precision Measurements**: Experiments involving kaons often require high precision in measurements due to the rarity of certain decay processes. These experiments push the boundaries of technology and experimental techniques, leading to advancements in detector technology and data analysis methods.
5. **Cosmology and Astroparticle Physics**: Kaons and other particles produced in high-energy cosmic-ray interactions can provide information about cosmic-ray propagation and the properties of the universe. Understanding kaon interactions in cosmic rays can help us interpret data from astroparticle experiments and cosmic-ray observatories.

Overall, kaon physics plays a crucial role in our quest to understand the fundamental building blocks of the universe, the forces that govern their interactions, and the underlying symmetries and asymmetries that shape the cosmos.

Rare kaon decays

- The rare decays of a charged or neutral kaon into a pion plus a pair of charged or neutral leptons are strongly suppressed in the SM
  → historical tools to study Flavor Changing Neutral Currents (FCNC)

- The “gold-plated” rare kaon decays $K^+ \to \pi^+ \nu\nu$ and $K_L \to \pi^0 \nu\nu$ do not suffer from large hadronic uncertainties
  → rates very precisely predicted in SM
  → complementary to B physics

- Experimentally clean due to the limited number of possible decay channels
  → complementary probes of New Physics

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Weak effective Hamiltonian: $$\mathcal{H}_{\rm eff} = -\frac{4G_F}{\sqrt{2}} V_{ts}^* V_{td} \frac{\alpha_e}{4\pi} \sum_k C_k^\ell O_k^\ell$$

$$O_L^\ell = (\bar{s}\gamma_\mu P_L d)(\bar{\nu}_\ell \gamma^\mu (1-\gamma_5)\nu_\ell), \quad O_9^\ell = (\bar{s}\gamma_\mu P_L d)(\bar{\ell}\gamma^\mu \ell), \quad O_{10}^\ell = (\bar{s}\gamma_\mu P_L d)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$$

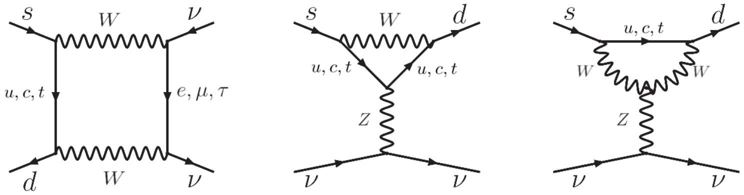
+ scalar and pseudoscalar operators

+ the chirality-flipped counterparts

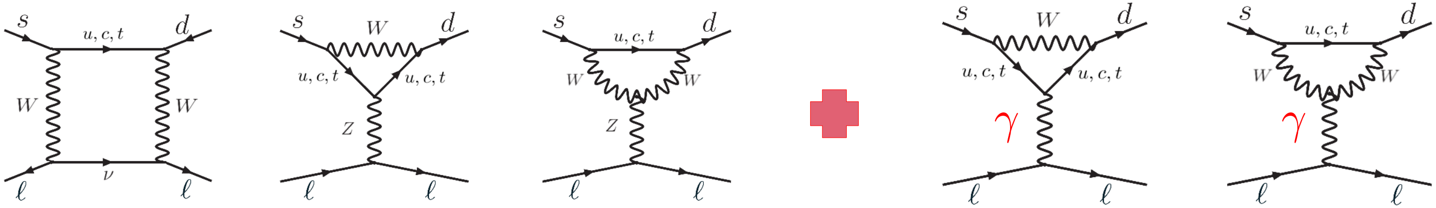
NP contributions: $C_k \to C_k^{\rm SM} + \delta C_k$

Rare kaon decays

- SD dominated
  - $K^+ \to \pi^+ \nu \nu$ and $K_L \to \pi^0 \nu \nu$ (**golden channels**)



- LD dominated
  - $K_L \to \mu\mu$, $K_S \to \mu\mu$, $K^+ \to \pi^+ \ell\ell$ and $K_L \to \pi^0 \ell\ell$, ...



$K^+ \to \pi^+ \nu\nu$

$$\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu}) = \frac{\kappa_+(1+\Delta_{\mathrm{EM}})}{\lambda^{10}} \frac{1}{3} s_W^4 \sum_\ell \left[\mathrm{Im}^2\left(\lambda_t C_L^\ell\right) + \mathrm{Re}^2\left(-\frac{\lambda_c X_c}{s_w^2} + \lambda_t C_L^\ell\right)\right]$$

($\lambda_i = V_{is}^* V_{id}$)

- top loop: $C^\ell_{L,\mathrm{SM}} = -X_{\mathrm{SM}}(x_t)/s_W^2$ NNLO QCD and 2-loop EW [Buchalla, Buras,'99; Misiak, Urban '99, Broad et al. '10]
- charm contribution: $X_c = \lambda^4[P_c^{\mathrm{SD}} + \delta P_{c,u}^{\mathrm{LD}}]$ SD: NNLO QCD and NLO EW; LD: ChPT SD:[Buras et al. '05; Brod et al. '08] LD:[Isidori et al.'05]
- O_L matrix elements known from $K_{3\ell}$ branching ratios → included in κ_+ [Mescia, Smith '07]
- $\Gamma_{\mathrm{SD}}/\Gamma$ >90%

$$\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu})_{\mathrm{SM}} = (7.86 \pm 0.61) \times 10^{-11}$$ [D'Ambrosio, Iyer, FM, Neshatpour '22]

Sources of uncertainty:

SD ~ 2%, LD ~ 3%, Parametric ~ 7%

$$\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu})_{\mathrm{SM}} = (7.73 \pm 0.61) \times 10^{-11}$$ [Brod, Gorbahn, Stamou '21]

$$\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu})_{\mathrm{SM}} = (8.60 \pm 0.42) \times 10^{-11}$$ [Buras, Venturini '22]

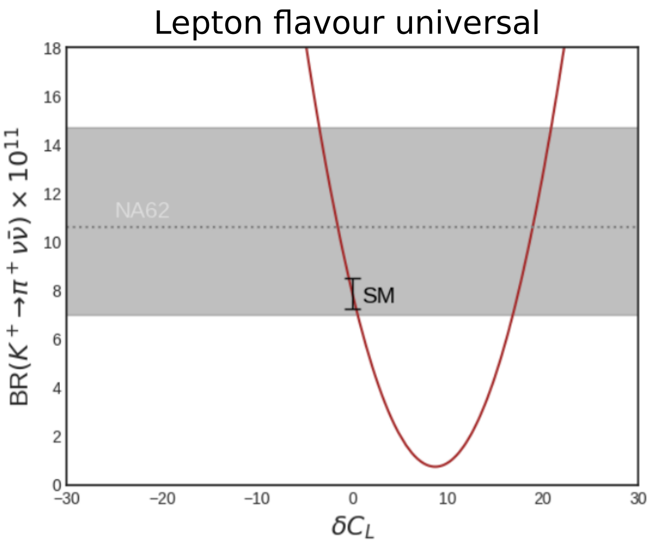
$K^+ \to \pi^+ \nu\nu$

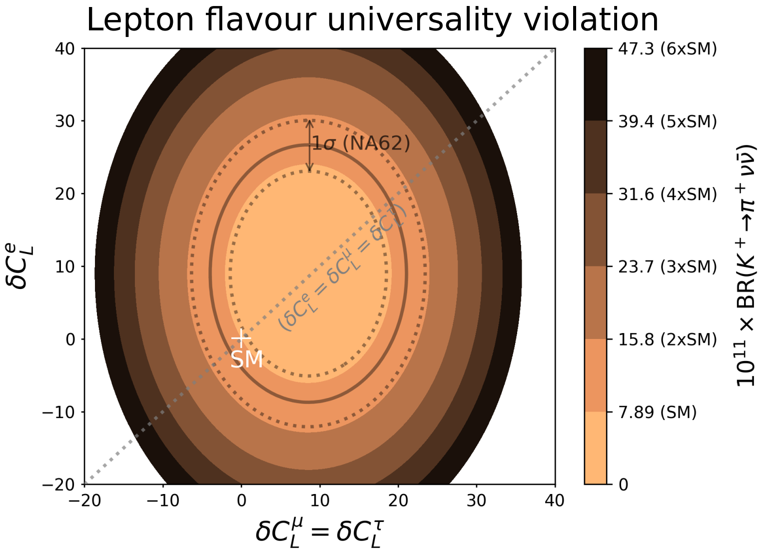
$$\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu}) = \frac{\kappa_+(1+\Delta_{\rm EM})}{\lambda^{10}} \frac{1}{3} s_W^4 \sum_\ell \left[\mathrm{Im}^2\left(\lambda_t C_L^\ell\right) + \mathrm{Re}^2\left(-\frac{\lambda_c X_c}{s_w^2} + \lambda_t C_L^\ell\right)\right]$$

$$\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu})_{\rm NA62} = (10.6^{+4.0}_{-3.5} \pm 0.9) \times 10^{-11}$$ [NA62 Coll., Cortina Gil et al. '21]

$$\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu})_{\rm SM} = (7.86 \pm 0.61) \times 10^{-11}$$ [D'Ambrosio, Iyer, FM, Neshatpour '22]

New Physics effects:





$K_L \to \pi^0 \nu\nu$

$$\mathrm{BR}(K_L \to \pi^0 \nu\bar{\nu}) = \frac{\kappa_L}{\lambda^{10}} \frac{1}{3} s_w^4 \sum_\ell \mathrm{Im}^2 \left(\lambda_t C_L^\ell\right)$$

- $C_{L,SM}$ same as for $K^+ \to \pi^+ \nu\nu$
- charm contributions below 1%
- 99% SD

$$\mathrm{BR}(K_L \to \pi^0 \nu\bar{\nu})_{\mathrm{SM}} = (2.68 \pm 0.30) \times 10^{-11}$$ [D'Ambrosio, Iyer, FM, Neshatpour '22]

Sources of uncertainty:

SD ~ 2%, LD ~ 1%, Parametric ~ 11%

$$\mathrm{BR}(K_L \to \pi^0 \nu\bar{\nu})_{\mathrm{SM}} = (2.59 \pm 0.29) \times 10^{-11}$$ [Brod, Gorbahn, Stamou '21]

$$\mathrm{BR}(K_L \to \pi^0 \nu\bar{\nu})_{\mathrm{SM}} = (2.94 \pm 0.15) \times 10^{-11}$$ [Buras, Venturini '22]

$K_L \to \pi^0 \nu\nu$

$$\text{BR}(K_L \to \pi^0 \nu\bar{\nu}) = \frac{\kappa_L}{\lambda^{10}} \frac{1}{3} s_w^4 \sum_\ell \text{Im}^2 \left(\lambda_t C_L^\ell\right)$$

$$\text{BR}(K_L \to \pi^0 \nu\bar{\nu})_{\text{KOTO}} < 3.0 \times 10^{-9} \text{ at } 90\% \text{ CL}$$ [KOTO Coll., Ahn et al. '18]

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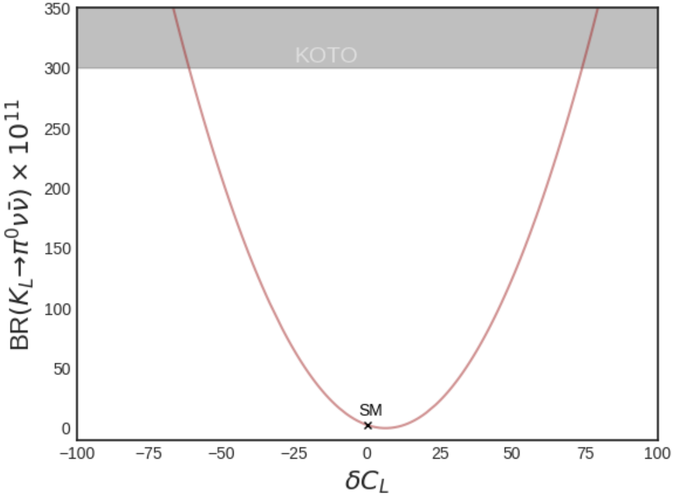
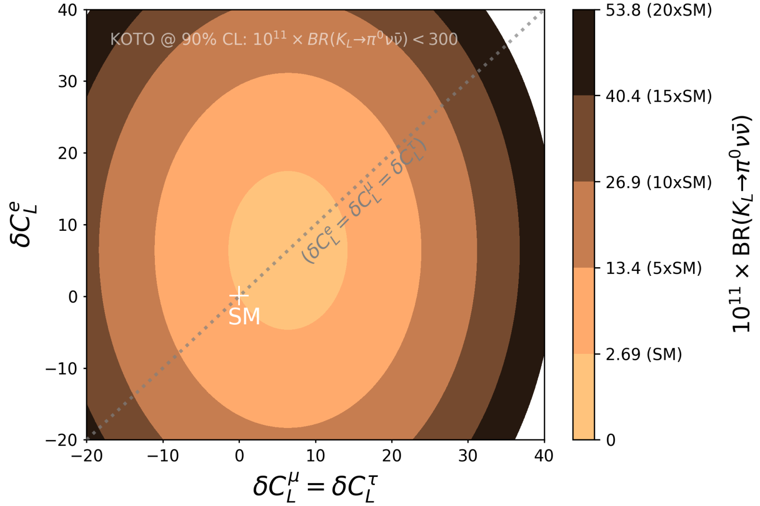
New Physics effects:

Lepton flavour universal

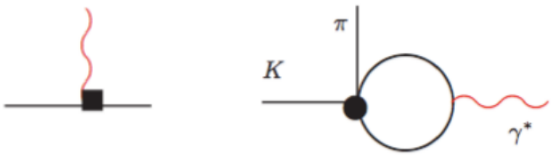


Lepton flavour universality violation

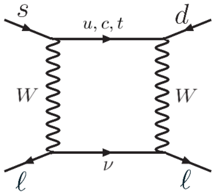


LFUV in $K^+ \to \pi^+\ell\ell$

$K^+ \to \pi^+\ell\ell$ is long distance dominated, mediated by single photon exchange $K^+ \to \pi^+\gamma^*$



LD >> SD



$\Longrightarrow$ precise SM prediction not yet possible

$$\mathcal{A}(z) \propto G_F M_K^2 (a + bz) + W^{\pi\pi}(z)$$

$z = m^2(\ell\ell) \,/\, M_K^2$

form factors — loop term

LFU predicts the same form factors a and b, for ℓ = e,μ

$a^{ee} \neq a^{\mu\mu}$ indicates LFUV NP: $a_+^{\mu\mu} - a_+^{ee} = -\sqrt{2}\,\mathrm{Re}\left[V_{td}V_{ts}^*(C_9^\mu - C_9^e)\right]$

[Crivellin et al. ‘16]

LFUV in $K^+ \to \pi^+ \ell\ell$

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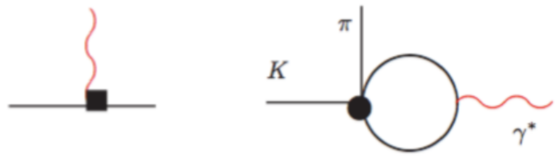
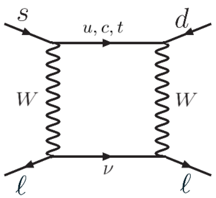


LD >> SD



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form factors (a, b) — loop term ($W^{\pi\pi}(z)$)

LFU predicts the same form factors a and b, for ℓ = e,μ

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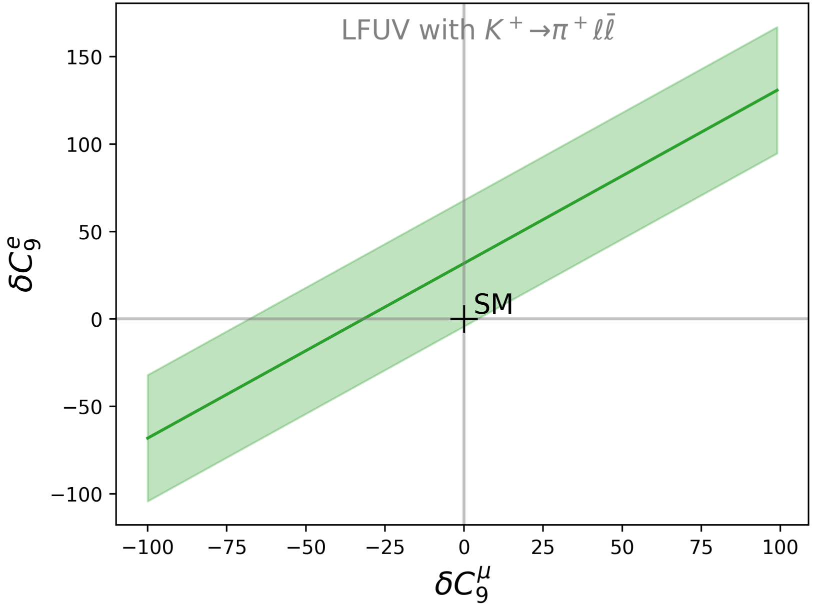
[Crivellin et al. '16]

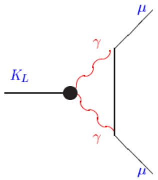
Channel	a_+	b_+	Reference
ee	-0.561 ± 0.009	-0.694 ± 0.040	E865 '99 and NA48/2 '09 comb. [D'Ambrosio, Greynat, Knecht '18]
$\mu\mu$	-0.575 ± 0.013	-0.722 ± 0.043	NA62 Coll. '22



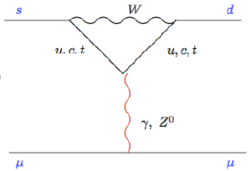
$K_L \to \mu\mu$

$K_L \to \mu\mu$ is long distance dominated, mediated by two photons via $K_L \to \gamma^* \gamma^*$

$$\mathrm{BR}(K_L \to \mu\bar{\mu}) = \tau_L \frac{f_K^2 m_K^3 \beta_\mu}{16\pi} \left| N_L^{\mathrm{LD}} - \left(\frac{2m_\mu}{m_K}\frac{G_F \alpha_e}{\sqrt{2}\pi}\right) \mathrm{Re}\left[-\lambda_c \frac{Y_c}{s_W^2} + \lambda_t C_{10}^\ell\right]\right|^2$$



LD >> SD



$$N_L^{\mathrm{LD}} \propto (\chi_{\mathrm{disp}} + i\chi_{\mathrm{abs}}) \longrightarrow \quad N_L^{\mathrm{LD}} = \pm[0.54(77) - 3.95i] \times 10^{-11}\,(\mathrm{GeV})^{-2}$$

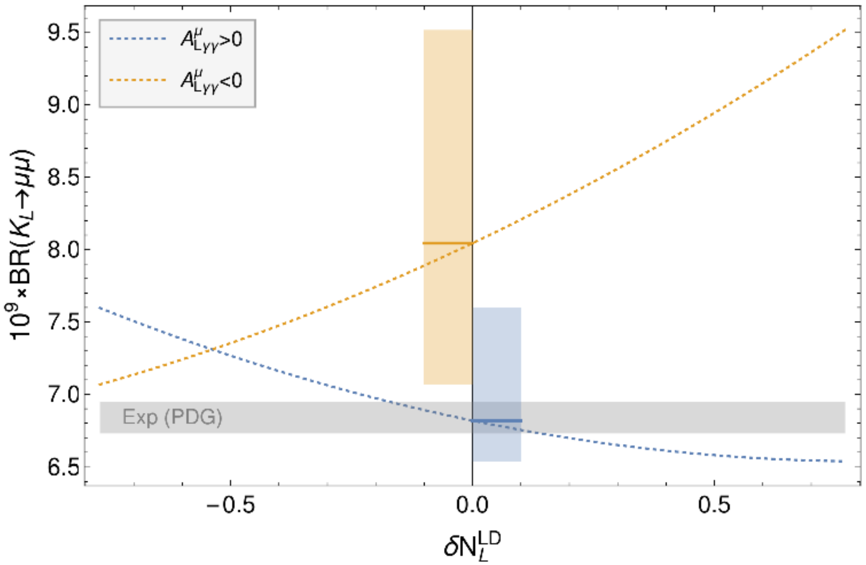
[D'Ambrosio et al. '86 '97;
Gomez Dumm, Pich '98;
Knecht et al. '99;
Isidori, Unterdorfer '03]

[D'Ambrosio et al. '17]
[Hoferichter et al. '23]

Prediction depends on the sign of $A(K_L \to \gamma\gamma)$ contribution determining the effect of the SD-LD interference

$$\mathrm{BR}(K_L \to \mu\bar{\mu})_{\mathrm{SM}} = \begin{cases} \mathrm{LD}(+): & (6.82^{+0.77}_{-0.24} \pm 0.04) \times 10^{-9} \\ \mathrm{LD}(-): & (8.04^{+1.46}_{-0.97} \pm 0.09) \times 10^{-9} \end{cases}$$

[D'Ambrosio, Iyer, FM, Neshatpour '22]



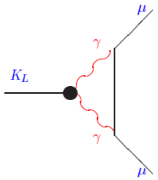
$$\mathrm{BR}(K_L \to \mu\bar{\mu})_{\mathrm{exp}} = (6.84 \pm 0.11) \times 10^{-9}$$

[PDG]

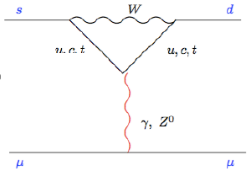
$K_L \to \mu\mu$

$K_L \to \mu\mu$ is long distance dominated, mediated by two photons via $K_L \to \gamma^* \gamma^*$

$$\mathrm{BR}(K_L \to \mu\bar{\mu}) = \tau_L \frac{f_K^2 m_K^3 \beta_\mu}{16\pi} \left| N_L^{\mathrm{LD}} - \left(\frac{2m_\mu}{m_K}\frac{G_F \alpha_e}{\sqrt{2}\pi}\right) \mathrm{Re}\left[-\lambda_c \frac{Y_c}{s_W^2} + \lambda_t C_{10}^\ell\right]\right|^2$$



LD >> SD



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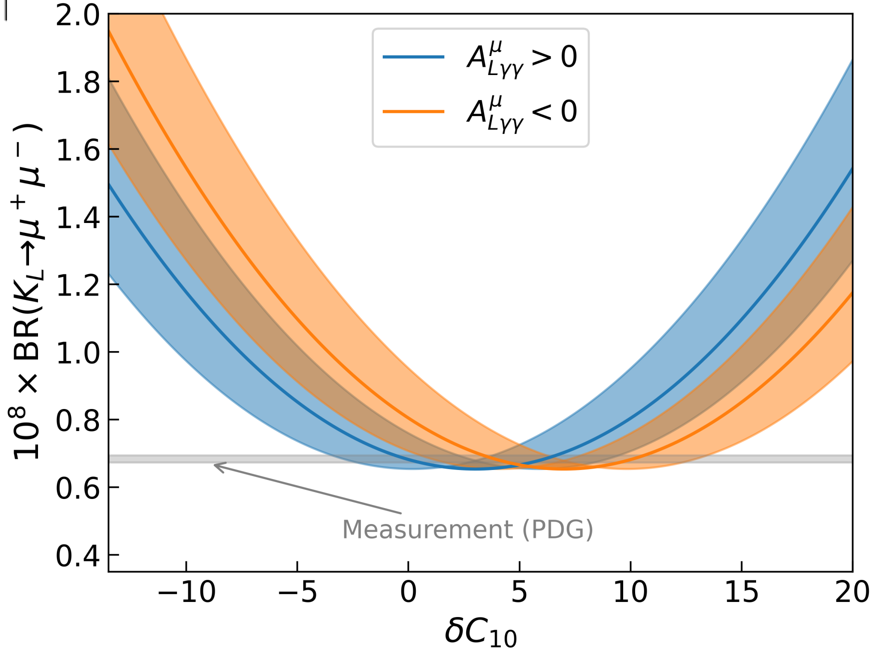


$$\mathrm{BR}(K_L \to \mu\bar{\mu})_{\mathrm{exp}} = (6.84 \pm 0.11) \times 10^{-9}$$

[PDG]

$K_S \to \mu\mu$

$$\mathrm{BR}(K_S \to \mu\bar{\mu}) = \tau_S \frac{f_K^2 m_K^3 \beta_\mu}{16\pi} \left\{ \beta_\mu^2 \left| N_S^{\mathrm{LD}} \right|^2 + \left(\frac{2m_\mu}{m_K} \frac{G_F \alpha_e}{\sqrt{2}\pi} \right)^2 \mathrm{Im}^2 \left[-\lambda_c \frac{Y_c}{s_W^2} + \lambda_t C_{10}^\ell \right] \right\}$$

$$N_S^{\mathrm{LD}} = (-2.65 + 1.14i) \times 10^{-11}\,(\mathrm{GeV})^{-2}$$

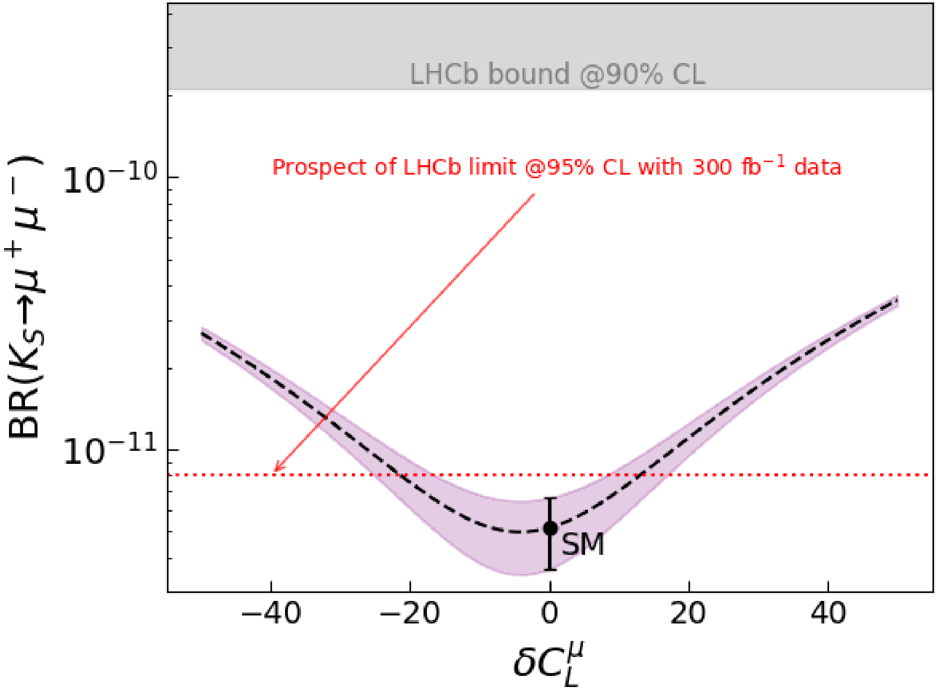
[D'Ambrosio et al. '86 '97;
Gomez Dumm, Pich '98;
Knecht et al. '99;
Isidori, Unterdorfer '03]

$$\mathrm{BR}(K_S \to \mu\bar{\mu})^{\mathrm{SM}} = (5.15 \pm 1.50) \times 10^{-12}$$

[D'Ambrosio, Iyer, FM, Neshatpour '22]

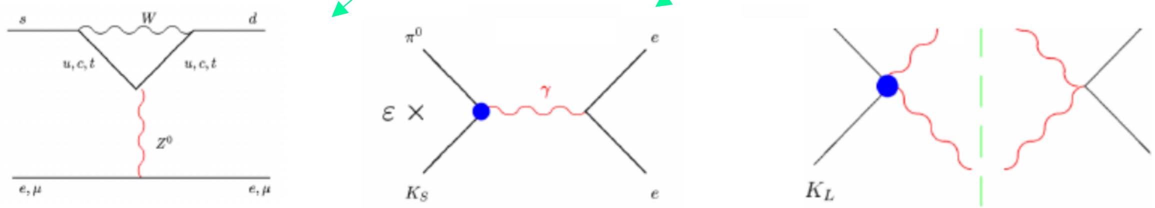
$$\mathrm{BR}(K_S \to \mu\mu) < 2.1(2.4) \times 10^{-10}\ @90(95)\%\ \mathrm{CL}$$

[LHCb, '20]



$K_L \to \pi^0 \ell\ell$

$$\mathrm{BR}(K_L \to \pi^0 \ell\bar{\ell}) = \left(C^\ell_{\rm dir} \pm C^\ell_{\rm int} |a_S| + C^\ell_{\rm mix} |a_S|^2 + C^\ell_{\gamma\gamma} \right) \cdot 10^{-12}$$



[Dambrosio et al. '98;Isidor et al. '04;Mescia, Smith, Trine '06]

	$C^\ell_{\rm dir}$	$C^\ell_{\rm int}$	$C^\ell_{\rm mix}$	$C^\ell_{\gamma\gamma}$
$\ell = e$	$(4.62 \pm 0.24)(w_{7V}^2 + w_{7A}^2)$	$(11.3 \pm 0.3) w_{7V}$	14.5 ± 0.5	≈ 0
$\ell = \mu$	$(1.09 \pm 0.05)(w_{7V}^2 + 2.32 w_{7A}^2)$	$(2.63 \pm 0.06) w_{7V}$	3.36 ± 0.20	5.2 ± 1.6

[Mescia, Smith, Trine '06]

$$w_{7V} = \frac{1}{2\pi} \mathrm{Im}\left[\frac{\lambda_t^{sd}}{1.407 \times 10^{-4}} C_9 \right] , \quad w_{7A} = \frac{1}{2\pi} \mathrm{Im}\left[\frac{\lambda_t^{sd}}{1.407 \times 10^{-4}} C_{10} \right]$$

$$\mathrm{BR}^{\rm SM}(K_L \to \pi^0 e\bar{e}) = 3.46^{+0.92}_{-0.80} \, (1.55^{+0.60}_{-0.48}) \times 10^{-11}$$

$$\mathrm{BR}^{\rm SM}(K_L \to \pi^0 \mu\bar{\mu}) = 1.38^{+0.27}_{-0.25} \, (0.94^{+0.21}_{-0.20}) \times 10^{-11}$$

[D'Ambrosio, Iyer, FM, Neshatpour '22]

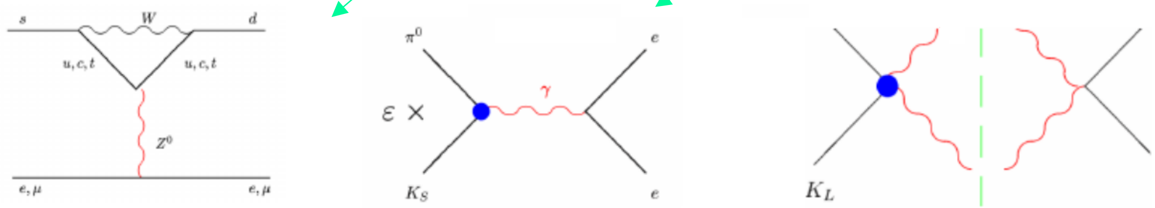
$$\mathrm{BR}^{\rm exp}(K_L \to \pi^0 e\bar{e}) < 28 \times 10^{-11} \quad \text{at 90\% CL}$$

$$\mathrm{BR}^{\rm exp}(K_L \to \pi^0 \mu\bar{\mu}) < 38 \times 10^{-11} \quad \text{at 90\% CL}$$

[KTeV '00 and '03]

$K_L \to \pi^0 \ell\ell$

$$\mathrm{BR}(K_L \to \pi^0 \ell\bar{\ell}) = \left(C^\ell_{\rm dir} \pm C^\ell_{\rm int}|a_S| + C^\ell_{\rm mix}|a_S|^2 + C^\ell_{\gamma\gamma}\right) \cdot 10^{-12}$$



[Dambrosio et al. '98;Isidor et al. '04;Mescia, Smith, Trine '06]

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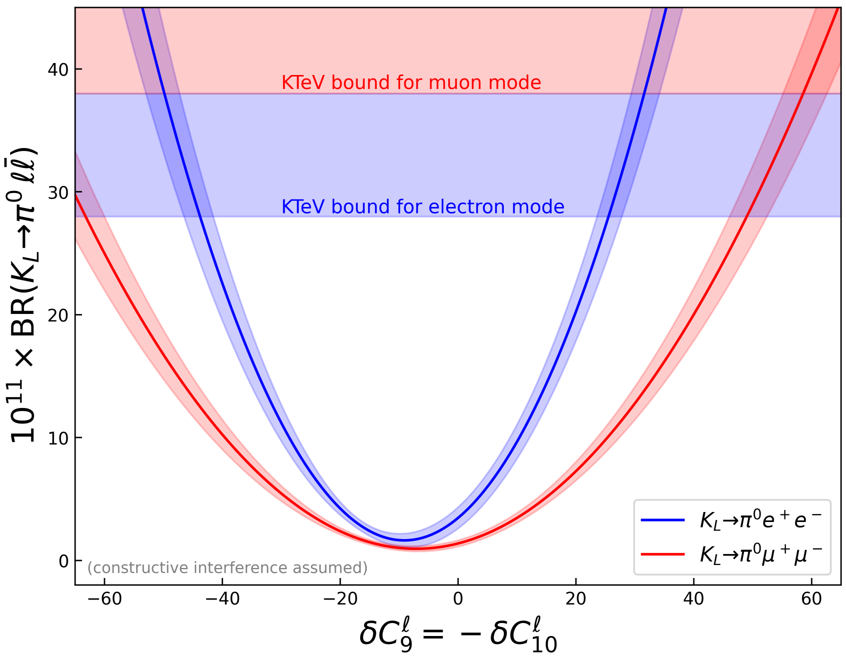
$\ell = \mu$	$(1.09 \pm 0.05)(w_{7V}^2 + 2.32 w_{7A}^2)$	$(2.63 \pm 0.06)w_{7V}$	3.36 ± 0.20	5.2 ± 1.6

[Mescia, Smith, Trine '06]

$$w_{7V} = \frac{1}{2\pi}\mathrm{Im}\left[\frac{\lambda_t^{sd}}{1.407 \times 10^{-4}} C_9\right], \quad w_{7A} = \frac{1}{2\pi}\mathrm{Im}\left[\frac{\lambda_t^{sd}}{1.407 \times 10^{-4}} C_{10}\right]$$



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[D'Ambrosio, Iyer, FM, Neshatpour '22]

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$$\mathrm{BR}^{\rm exp}(K_L \to \pi^0 \mu\bar{\mu}) < 38 \times 10^{-11} \quad \text{at 90\% CL}$$

[KTeV '00 and '03]

Global analysis

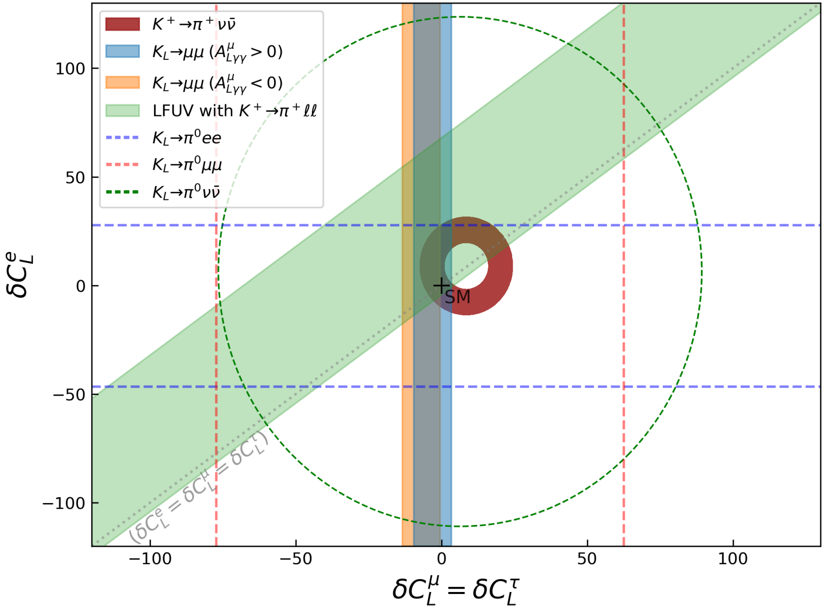
Rare kaon observables

Observable	SM prediction	Experimental results
$\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu})$	$(7.86 \pm 0.61) \times 10^{-11}$	$(10.6^{+4.0}_{-3.5} \pm 0.9) \times 10^{-11}$
$\mathrm{BR}(K_L^0 \to \pi^0 \nu\nu)$	$(2.68 \pm 0.30) \times 10^{-11}$	$< 3.0 \times 10^{-9}$ @90% CL
$\mathrm{LFUV}(a_+^{\mu\mu} - a_+^{ee})$	0	-0.014 ± 0.016
$\mathrm{BR}(K_L \to \mu\mu)\ (+)$	$(6.82^{+0.77}_{-0.29}) \times 10^{-9}$	$(6.84 \pm 0.11) \times 10^{-9}$
$\mathrm{BR}(K_L \to \mu\mu)\ (-)$	$(8.04^{+1.47}_{-0.98}) \times 10^{-9}$	
$\mathrm{BR}(K_S \to \mu\mu)$	$(5.15 \pm 1.50) \times 10^{-12}$	$< 2.1(2.4) \times 10^{-10}$ @90(95)% CL
$\mathrm{BR}(K_L \to \pi^0 ee)(+)$	$(3.46^{+0.92}_{-0.80}) \times 10^{-11}$	$< 28 \times 10^{-11}$ @90% CL
~~$\mathrm{BR}(K_L \to \pi^0 ee)(-)$~~	~~$(1.55^{+0.60}_{-0.48}) \times 10^{-11}$~~	
$\mathrm{BR}(K_L \to \pi^0 \mu\mu)(+)$	$(1.38^{+0.27}_{-0.25}) \times 10^{-11}$	$< 38 \times 10^{-11}$ @90% CL
~~$\mathrm{BR}(K_L \to \pi^0 \mu\mu)(-)$~~	~~$(0.94^{+0.21}_{-0.20}) \times 10^{-11}$~~	

We assume NP contributions of the charged and neutral leptons related to each other by the $SU(2)_L$ gauge symmetry and we work in the chiral basis

$$\delta C_L^\ell \equiv \delta C_9^\ell = -\delta C_{10}^\ell$$

$$\delta C_L^e \neq \delta C_L^\mu = \delta C_L^\tau$$



Bounds from individual observables:

Coloured regions: 68% CL measurements
Dashed lines: 90% upper limits

All observables

Rare kaon observables

Observable	SM prediction	Experimental results
$\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu})$	$(7.86 \pm 0.61) \times 10^{-11}$	$(10.6^{+4.0}_{-3.5} \pm 0.9) \times 10^{-11}$
$\mathrm{BR}(K^0_L \to \pi^0 \nu\nu)$	$(2.68 \pm 0.30) \times 10^{-11}$	$< 3.0 \times 10^{-9}$ @90% CL
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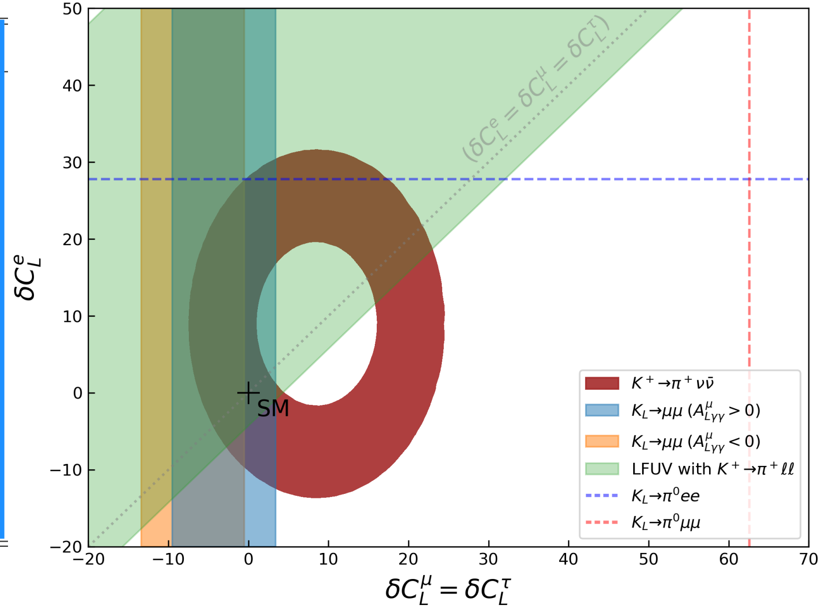
$$\delta C_L^e \neq \delta C_L^\mu = \delta C_L^\tau$$



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Bounds from individual observables:

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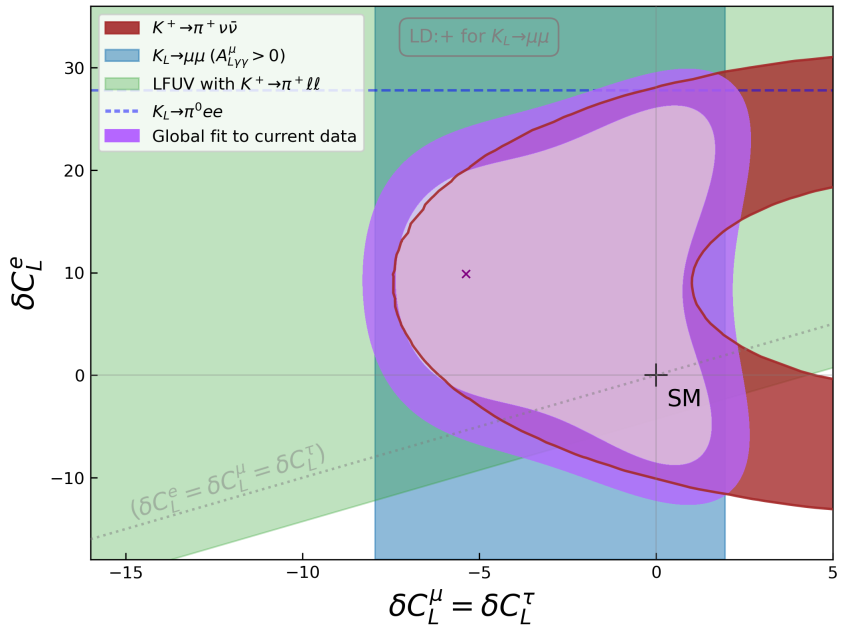
All observables / Global fit

Fit (with SuperIso public program) for positive LD contributions to $K_L \to \mu\mu$



Lighter / **darker** purple region: **68%** / **95%** CL of global fit

Main constraining observables BR($K^+ \to \pi^+ \nu\nu$) followed by BR($K_L \to \mu\mu$)

$K_S \to \mu\mu$

Add the scalar operator:

$$H_{eff}^{scalar} = C_s \mathcal{O} + \tilde{C}_s \tilde{\mathcal{O}}$$

$$\mathrm{BR}(K_S \to \mu\bar{\mu}) = \tau_S \frac{f_K^2 m_K^3 \beta_\mu}{16\pi} \left\{ \beta_\mu^2 \left| B_S^{\mathrm{LD}} \right|^2 + \left(\frac{2m_\mu}{m_K} \frac{G_F \alpha_e}{\sqrt{2}\pi} \right)^2 \mathrm{Im}^2 \left[-\lambda_c \frac{Y_c}{s_W^2} + \lambda_t C_{10}^\ell \right] \right\}$$

$$B_S = N_S^{\mathrm{LD}} - \frac{m_s M_K}{m_s + m_d} \mathrm{Re}(C_S - \tilde{C}_S)$$

[Chobanova et al ‘17]

How to get a handle on the scalar operator?

$K^+ \to \pi^+\ell\ell$

Let's go back to $K^+ \to \pi^+\ell\ell$

[Gao. '03,
Chen et al. '03]

$$\frac{d^2\Gamma}{dz\,d\cos\theta} = \frac{G_F^2 M_K^5}{2^8\pi^3}\beta_\ell\,\lambda^{1/2}(z)\times\Big\{|f_V|^2\,\frac{\alpha^2}{16\pi^2}\lambda(z)(1-\beta_\ell^2\cos^2\theta) + |f_S|^2\,z\beta_\ell^2$$

$$+\mathrm{Re}(f_V^* f_S)\frac{\alpha\,r_\ell}{\pi}\beta_\ell\lambda^{1/2}(z)\cos\theta\Big\}\,, \qquad r_\ell = m_\ell/M_K$$

$$A_{\rm FB}(z) = \frac{\alpha G_F^2 M_K^5}{2^8\pi^4} r_\ell\,\beta_\ell^2(z)\lambda(z)\mathrm{Re}\,(f_V^* f_S)\Big/\left(\frac{d\Gamma(z)}{dz}\right)$$

Difficult to do this for the electron mode

AFB is non-zero only in case there are simultaneously vector and scalar contributions!

Bounds on f_S

$(K^+ \to \pi^+\mu^+\mu^-)$		
NA48/2	exp	$\lvert f_S \rvert <$
A_{FB}	$(-2.4 \pm 1.8) \times 10^{-2}$	4.2×10^{-5}
BR	$(9.62 \pm 0.21) \times 10^{-8}$	1.0×10^{-4}
NA62	exp	$\lvert f_S \rvert <$
A_{FB}	$(0.0 \pm 0.7) \times 10^{-2}$	7.7×10^{-6}
BR	$(9.16 \pm 0.06) \times 10^{-8}$	5.6×10^{-5}

Our results

$(K^+ \to \pi^+ e^+ e^-)$		
E865	exp	$\lvert f_S \rvert <$
A_{FB}	–	–
BR	$(2.988 \pm 0.040) \times 10^{-7}$	6.8×10^{-5}
NA48/2	exp	$\lvert f_S \rvert <$
A_{FB}	–	–
BR	$(3.14 \pm 0.04) \times 10^{-7}$	6.8×10^{-5}

Our results

- we constrain the scalar interactions by examining both the BR and the AFB
- The upper bounds on f_S from both observables demonstrate the sensitivity of current experimental measurements
- The most stringent limit on f_S arises from the NA62 measurement of AFB, highlighting its potential to probe new physics scenarios involving scalar interactions.
- NA62 will also soon have results for $K^+ \to \pi^+\ell\ell$

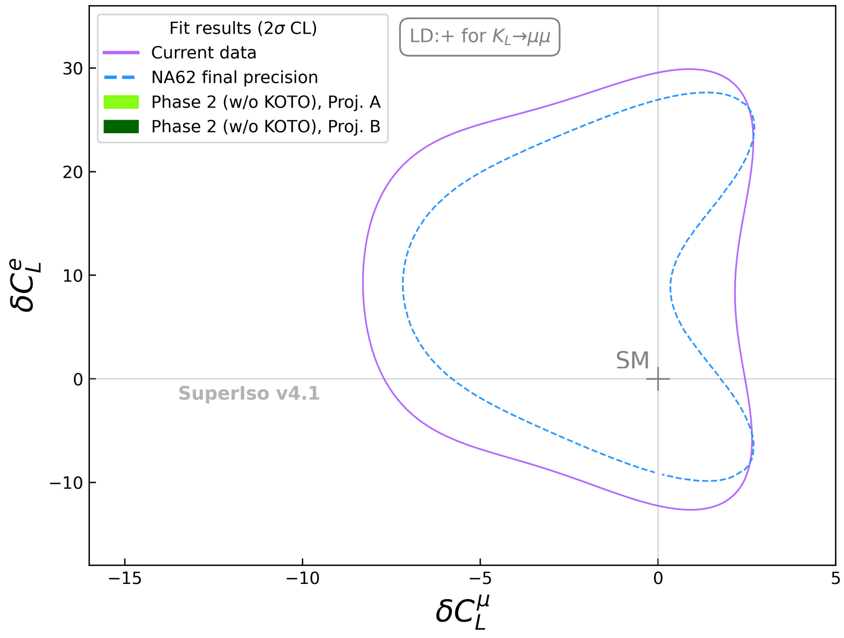
[D'Ambrosio, Iyer, FM, Neshatpour '24]

Prospects

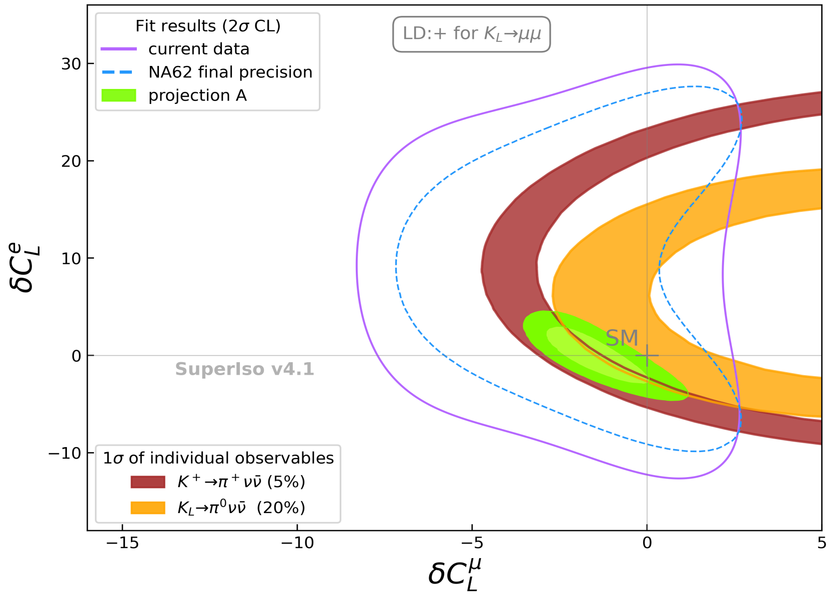
Prospects for future measurements

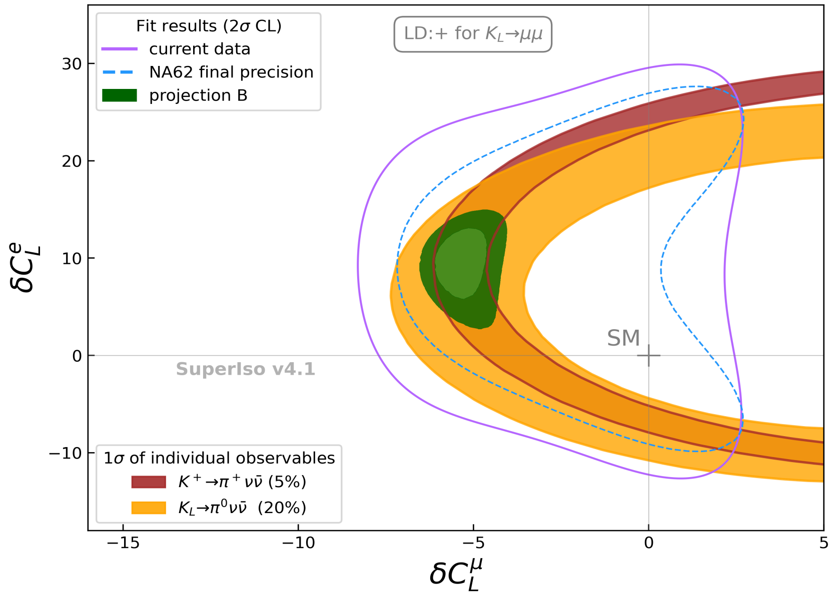
NA62 final precision

Observable	SM prediction	Experimental results	NA62 final
$\mathrm{BR}(K^+ \to \pi^+\nu\bar{\nu})$	$(7.86 \pm 0.61) \times 10^{-11}$	$(10.6^{+4.0}_{-3.5} \pm 0.9) \times 10^{-11}$	20%



Impact of $K^+ \to \pi^+ \nu \nu$ and $K_L \to \pi^0 \nu\nu$





Projection A

Observables already measured are kept, others assumed to be match SM, all with target precision of KOTO-II (+ HIKE)

Projection B

All measurements give current best-fit point with target precision of KOTO-II (+ HIKE)

Future experimental landscape

NA62 Run 2: Approved until LS3

Main goal is measure ultra rare kaon decay $K^+ \to \pi^+ \nu\nu$ with 10-20% precision

In total the largest K+ sample ever accumulated, analyses will continue for several years after LS3.

KOTO: Study of $K_L \to \pi^0 \nu\nu$ at J-PARC

Main goal is to reach a sensitivity below 10^{-10}

KOTO-II: aims to measure the branching ratio with a precision of 20%.

LHCb: Strong programme of K_S physics, in particular $K_S \to \mu\mu$

LHCb upgrade: Can reach the SM sensitivity

FCC: Strong flavour physics program

Future experimental landscape

HIKE: Study of rare kaon decays at very high precision

BDF/SHIP has been approved, instead of HIKE+SHADOWS, as the next project in ECN3. The HIKE physics case was considered to be excellent, as already established by the SPSC, but this was a strategic political decision of the Laboratory.

Other possibilities are being investigated:

→ join forces with KOTO-II and extend its physics case
→ PS at CERN, or other accelerators in the word
→ ...

Future experimental landscape

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- → join forces with KOTO-II and extend its physics case
- → PS at CERN, or other accelerators in the word
- → ...

The kaon physics community is disappointed but **NOT** dead!

The experimental kaon physics community is very much alive, and determined to look into the next thing on the horizon*.

* Cristina Lazzeroni