Kaon rare decays: theory overview

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Based on 2206.14748 and 2311.04878 in collaboration with G. D'Ambrosio, A. Iyer, F. Mahmoudi

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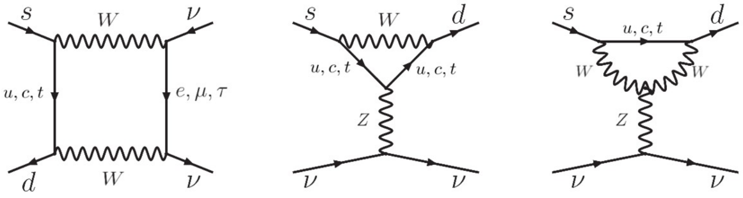
Rare kaon decays

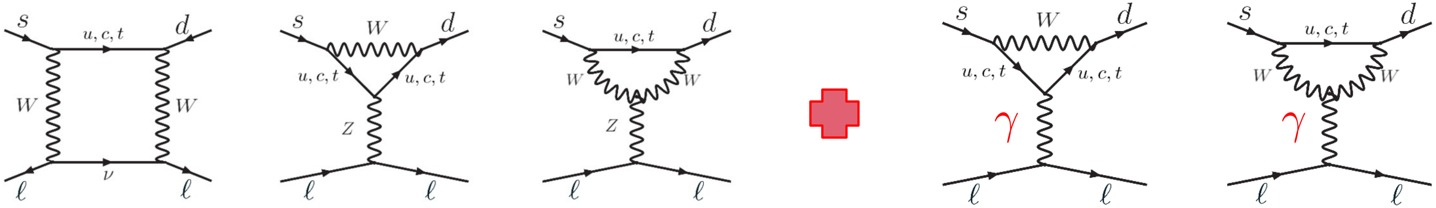
- Take place via FCNC
- Suppressed in the Standard Model
- Interesting probe of New Physics

  ↪ Requires reliable prediction in the SM

- 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 $K_L \to \pi^0 \ell\ell, \ldots$



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

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

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

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

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

- 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 $\to$ included in κ_+ [Mescia, Smith '17]
- $\Gamma_{\mathrm{SD}}/\Gamma > 90\%$

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

Sources of uncertainty:

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

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

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$$\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu})_{\mathrm{NA62}} = (10.6^{+4.0}_{-3.5} \pm 0.9) \times 10^{-11}$$ [D'Ambrosio, Iyer, Mahmoudi, SN '22]

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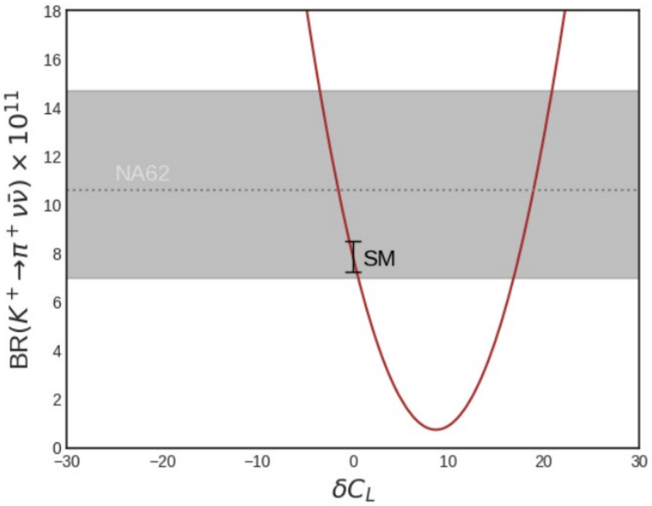
New Physics effects:

Lepton flavour universal



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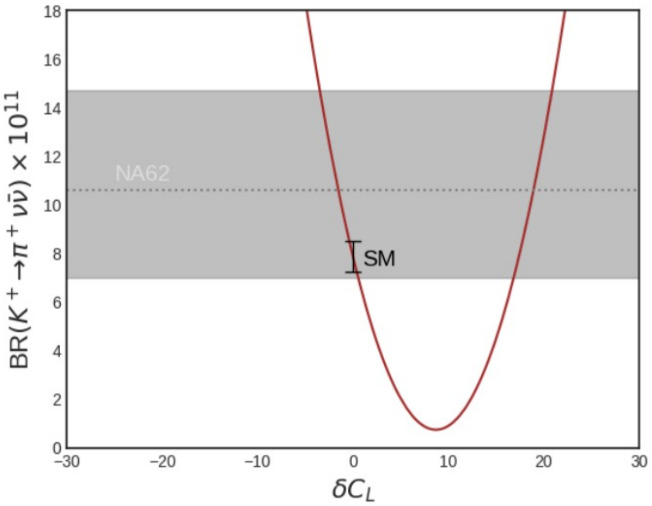
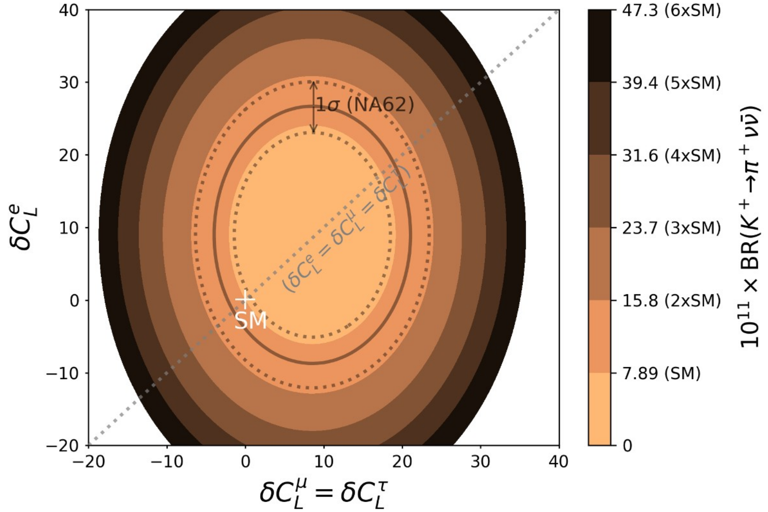


Lepton flavour universality violation



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

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

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

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

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

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

$$\mathrm{BR}(K_L \to \pi^0 \nu\bar{\nu})_{\mathrm{KOTO}} < 3.0 \times 10^{-11} \text{ at } 90\% \text{ CL}$$ [KOTO Coll., Ahn et al. '18]

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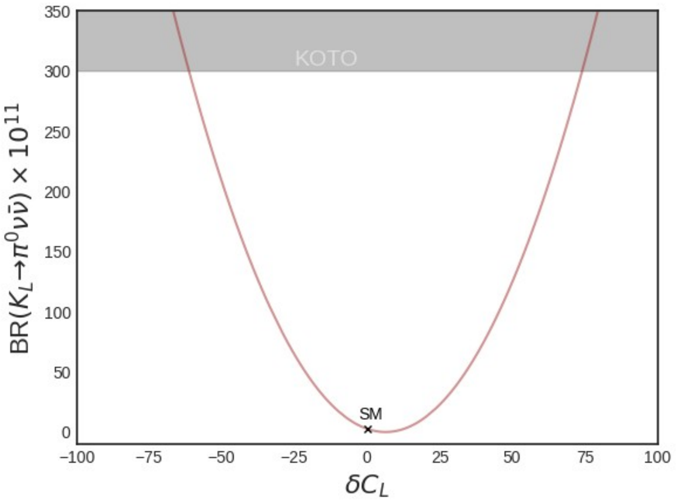

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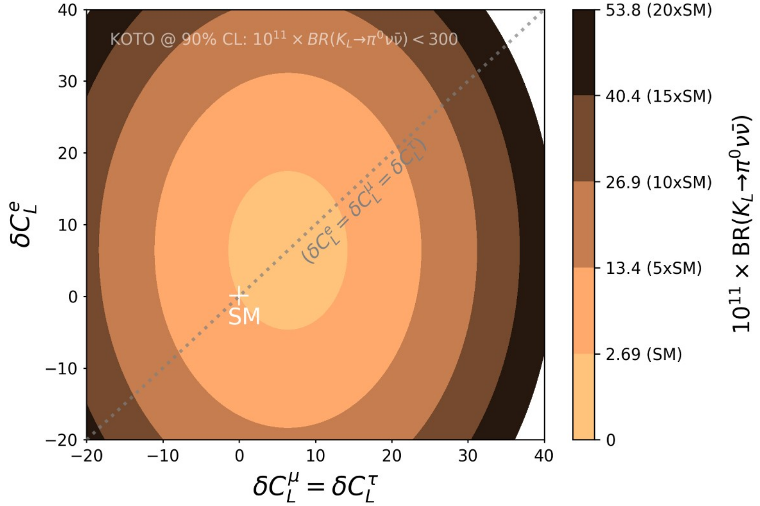
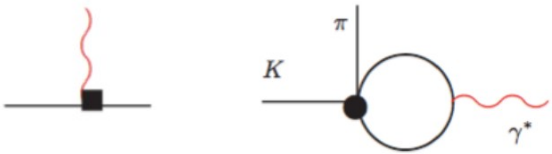
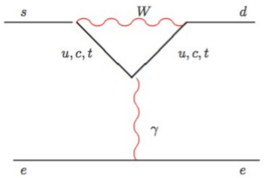


LFUV in $K^+ \to \pi^+ \ell \ell$

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



LD >> SD



$\Longrightarrow$ precise SM prediction not yet possible

$$\mathcal{A}(z) \propto G_F M_K^2 (a + bz) + W^{\pi\pi}(z) \qquad z = m^2(\ell\ell) \,/\, M_K^2$$

form factors (a, b)

loop term ($W^{\pi\pi}(z)$)

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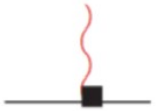

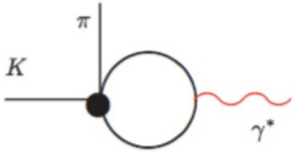

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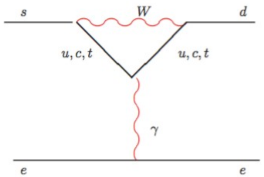

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LFU predicts the same form factors a and b, for $\ell = e, \mu$

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

[Crivellin et al. '16]

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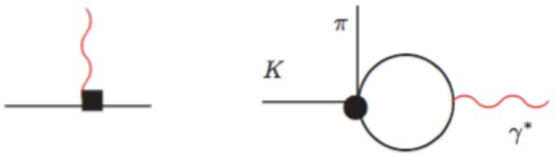

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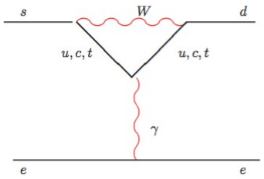

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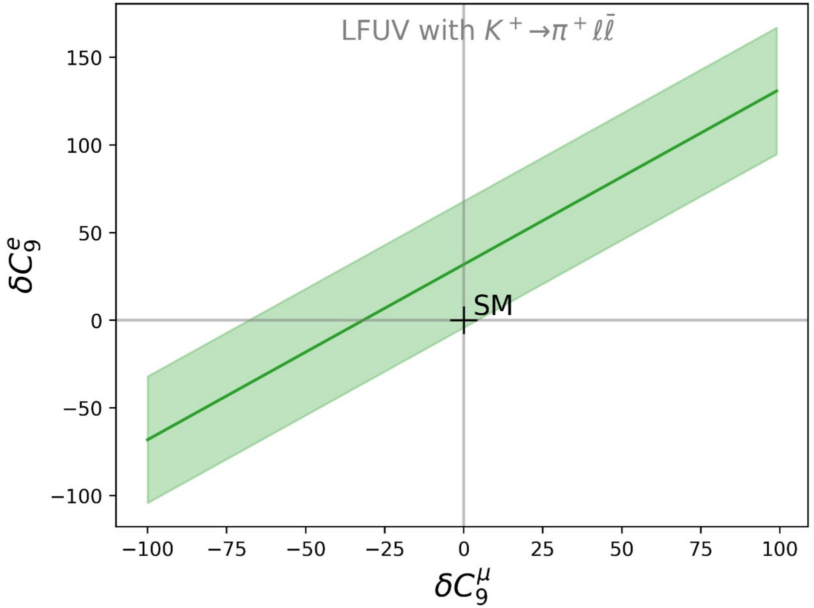
Channel	a_+	b_+	Reference
ee	-0.561 ± 0.009	-0.694 ± 0.040	E865 '99 and NA48/2 '09 comb. [D'Ambrosio, Greynat, Knecht '18]
$\mu\mu$	-0.575 ± 0.013	-0.722 ± 0.043	NA62 Coll. '22



$K_L \to \mu\,\mu$

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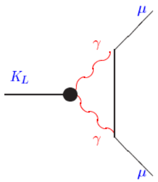
$$\mathrm{BR}(K_L \to \mu\bar{\mu}) = \tau_L \frac{f_K^2 m_K^3 \beta_\mu}{16\pi} \left| N_L^{\mathrm{LD}} - \left(\frac{2m_\mu}{m_K}\frac{G_F \alpha_e}{\sqrt{2}\pi}\right) \mathrm{Re}\left[-\lambda_c \frac{Y_c}{s_W^2} + \lambda_t C_{10}^{\ell}\right]\right|^2$$



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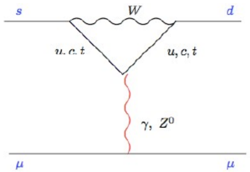

$$N_L^{\mathrm{LD}} \propto (\chi_{\mathrm{disp}} + i\chi_{\mathrm{abs}}) \longrightarrow N_L^{\mathrm{LD}} = \pm\,[0.54(77) - 3.95i] \times 10^{-11}\,(\mathrm{GeV})^{-2}$$

[D'Ambrosio et al. '86 '97;
Gomez Dumm, Pich '98;
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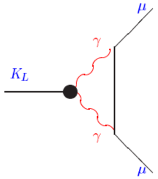

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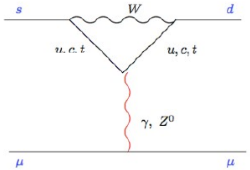

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Prediction depends on the sign of $A(K_L \to \gamma\gamma)$ contribution
determining the effect of the SD-LD interference

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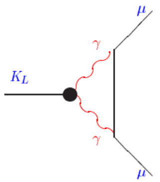

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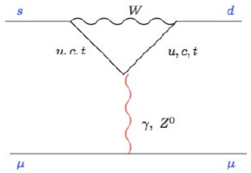

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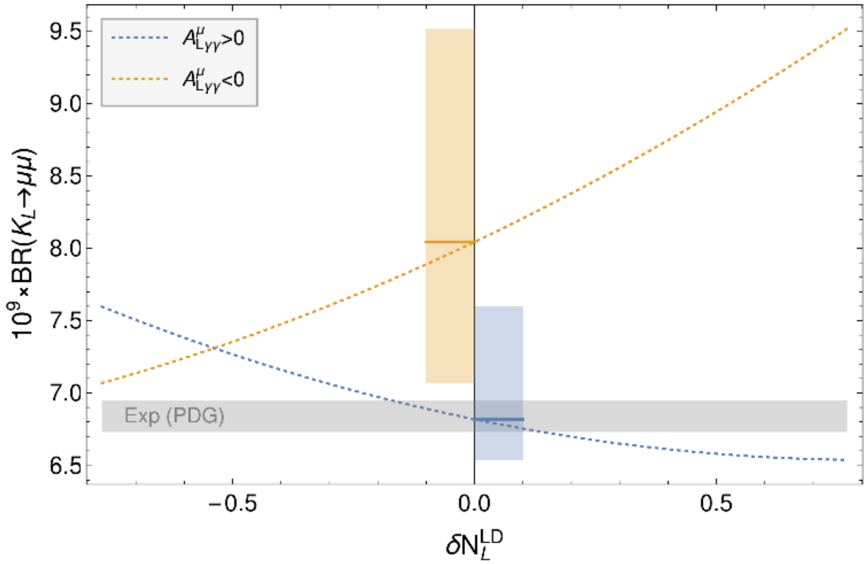

$$\mathrm{BR}(K_L \to \mu\bar{\mu})_{\mathrm{SM}} = \begin{cases} \mathrm{LD}(+): & (6.82^{+0.77}_{-0.24} \pm 0.04) \times 10^{-9} \\ \mathrm{LD}(-): & (8.04^{+1.46}_{-0.97} \pm 0.09) \times 10^{-9} \end{cases}$$

[D'Ambrosio, Iyer, Mahmoudi, SN '22]

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

[PDG]

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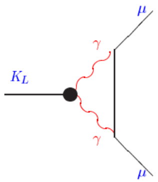

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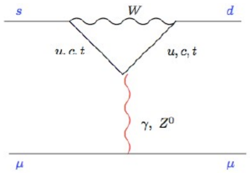

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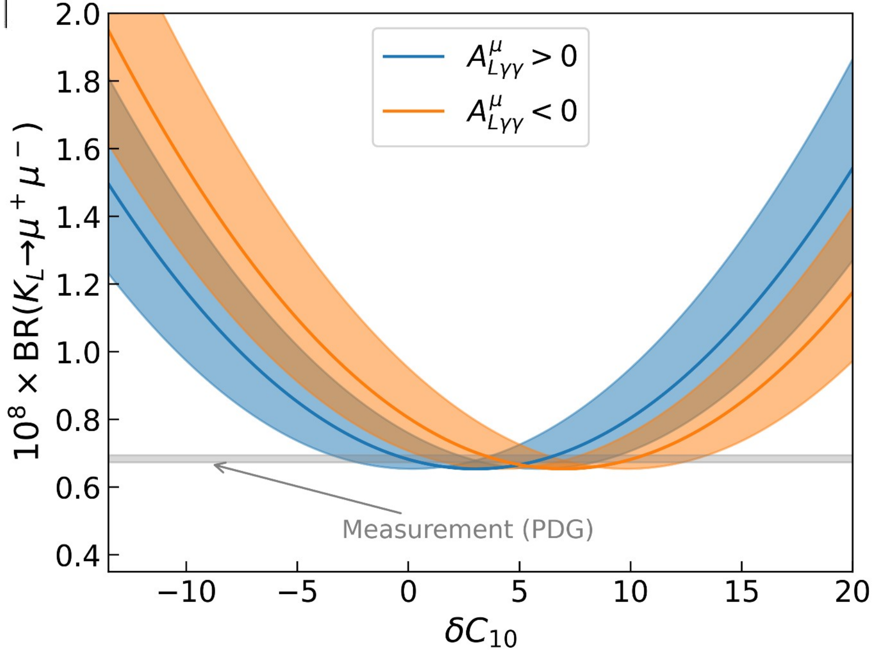
$$\mathrm{BR}(K_L \to \mu\bar{\mu})_{\mathrm{SM}} = \begin{cases} \mathrm{LD}(+): & (6.82^{+0.77}_{-0.24} \pm 0.04) \times 10^{-9} \\ \mathrm{LD}(-): & (8.04^{+1.46}_{-0.97} \pm 0.09) \times 10^{-9} \end{cases}$$

[D'Ambrosio, Iyer, Mahmoudi, SN '22]

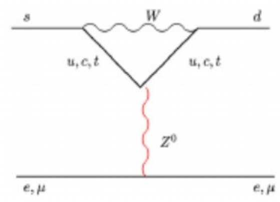


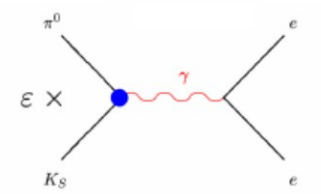
$$\mathrm{BR}(K_L \to \mu\bar{\mu})_{\mathrm{exp}} = (6.84 \pm 0.11) \times 10^{-9}$$

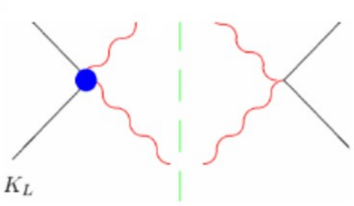
[PDG]

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

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







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

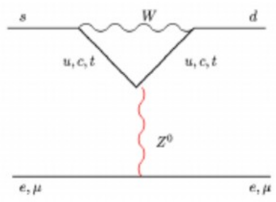
	$C^\ell_{\rm dir}$	$C^\ell_{\rm int}$	$C^\ell_{\rm mix}$	$C^\ell_{\gamma\gamma}$
$\ell = e$	$(4.62 \pm 0.24)(w_{7V}^2 + w_{7A}^2)$	$(11.3 \pm 0.3) w_{7V}$	14.5 ± 0.5	≈ 0
$\ell = \mu$	$(1.09 \pm 0.05)(w_{7V}^2 + 2.32 w_{7A}^2)$	$(2.63 \pm 0.06) w_{7V}$	3.36 ± 0.20	5.2 ± 1.6

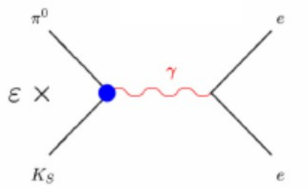
[Mescia, Smith, Trine ‘06]

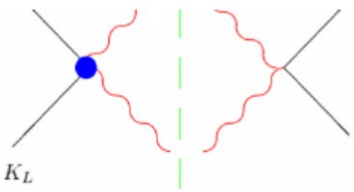
$$w_{7V} = \frac{1}{2\pi}\mathrm{Im}\left[\frac{\lambda_t^{sd}}{1.407 \times 10^{-4}} C_9\right], \quad w_{7A} = \frac{1}{2\pi}\mathrm{Im}\left[\frac{\lambda_t^{sd}}{1.407 \times 10^{-4}} C_{10}\right]$$

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

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







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

	$C^\ell_{\rm dir}$	$C^\ell_{\rm int}$	$C^\ell_{\rm mix}$	$C^\ell_{\gamma\gamma}$
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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]

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

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

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

[D’Ambrosio, Iyer, Mahmoudi, SN ‘22]

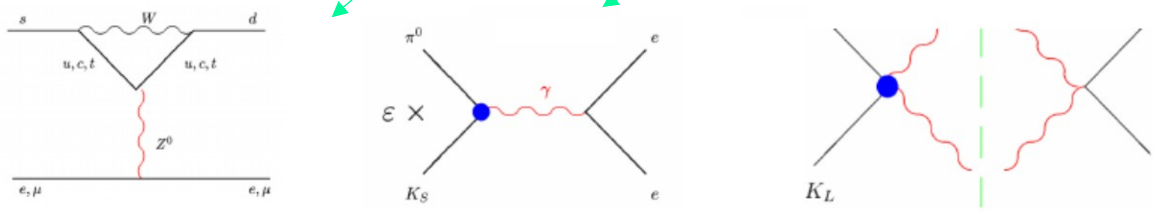
$$\mathrm{BR}^{\rm exp}(K_L \to \pi^0 e\bar{e}) < 28 \times 10^{-11} \quad \text{at } 90\% \text{ CL}$$

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

[KTeV ‘00 and ‘03]

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

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



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

	C^ℓ_{dir}	C^ℓ_{int}	C^ℓ_{mix}	$C^\ell_{\gamma\gamma}$
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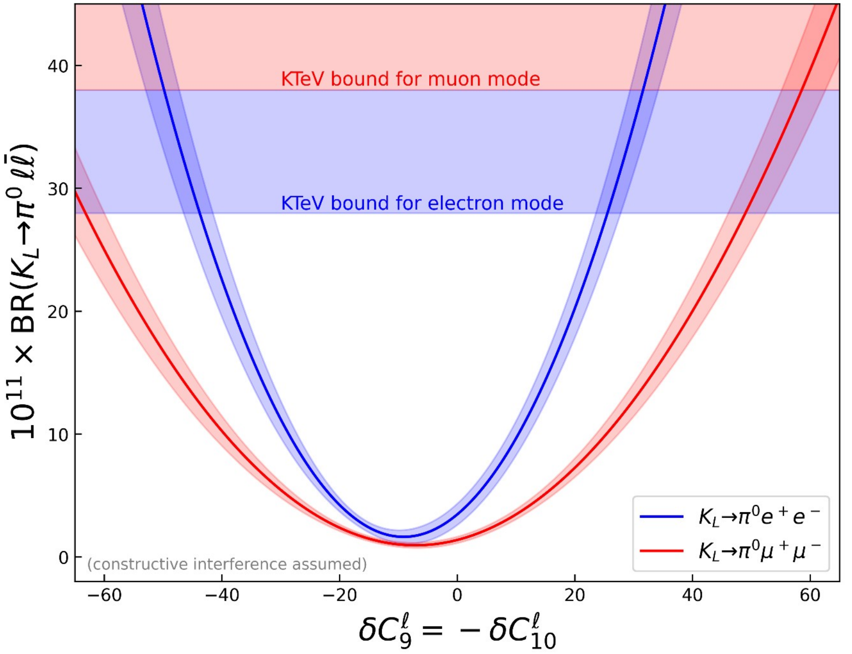
[Mescia, Smith, Trine '06]

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



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

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[D'Ambrosio, Iyer, Mahmoudi, SN '22]

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

[KTeV '00 and '03]

Global analysis

All observables

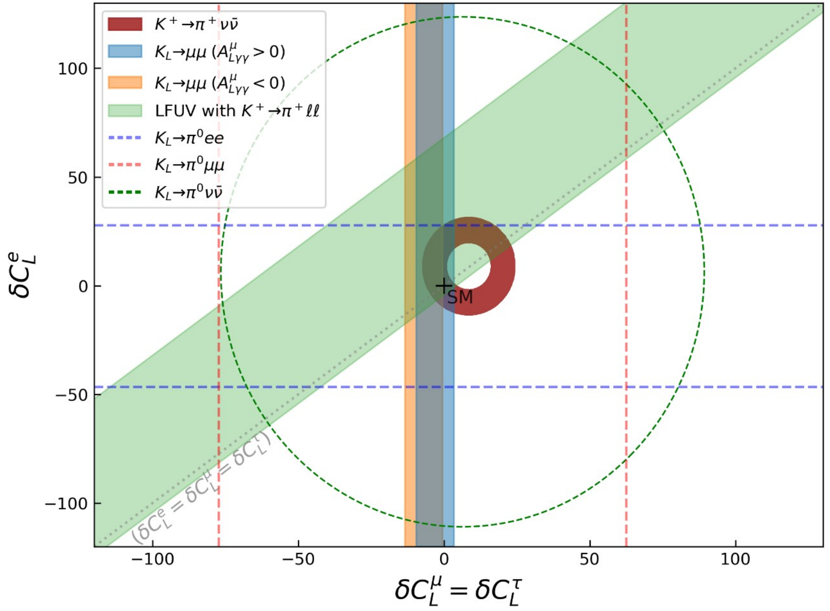
Rare kaon observables

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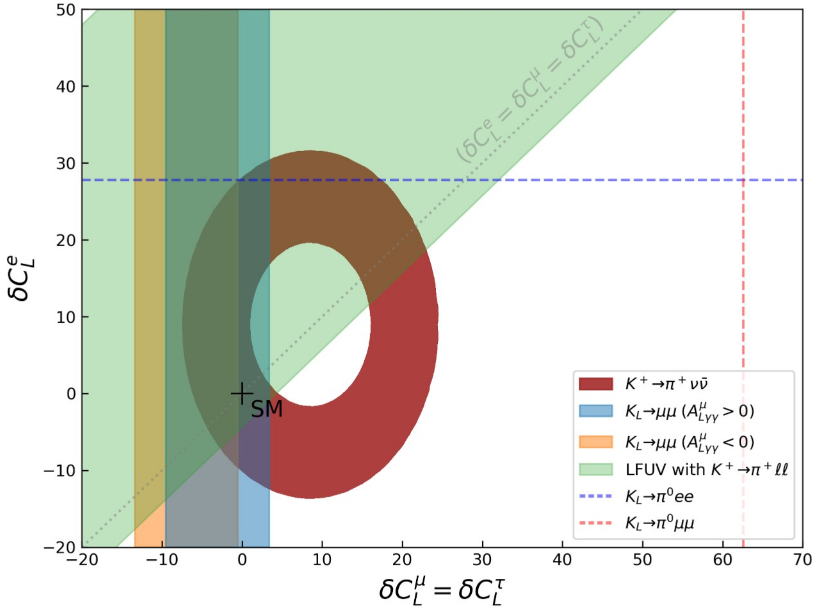
~~$\mathrm{BR}(K_L \to \pi^0 ee)(-)$~~	~~$(1.55^{+0.60}_{-0.48}) \times 10^{-11}$~~	
$\mathrm{BR}(K_L \to \pi^0 \mu\mu)(+)$	$(1.38^{+0.27}_{-0.25}) \times 10^{-11}$	$< 38 \times 10^{-11}$ @90% CL
~~$\mathrm{BR}(K_L \to \pi^0 \mu\mu)(-)$~~	~~$(0.94^{+0.21}_{-0.20}) \times 10^{-11}$~~	

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

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

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

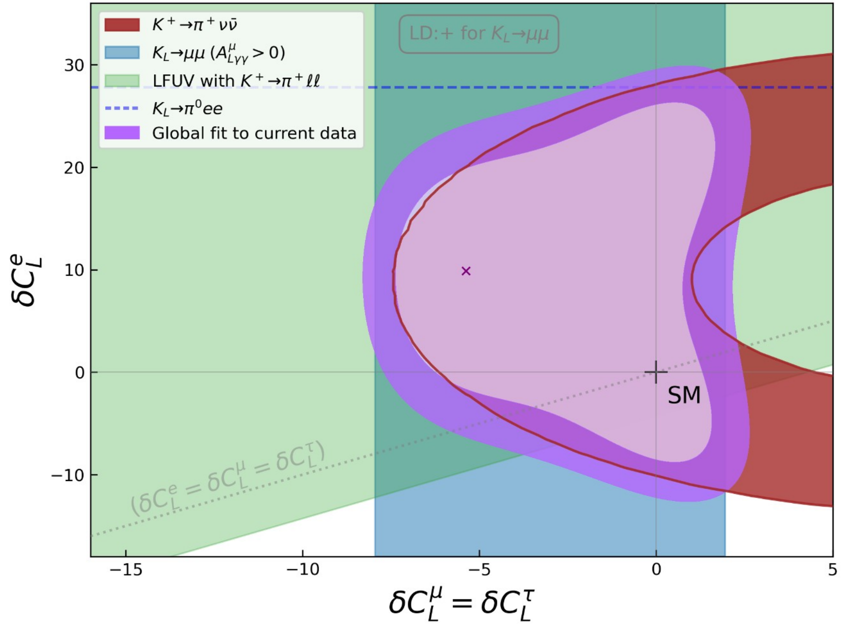


Bounds from individual observables:

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

All observables / 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($K_L \to \mu\mu$)

Prospects for future measurements

Numerical values used in the projections

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

Numerical values used in the projections

Observable	SM prediction	Experimental results	NA62 final	HIKE Phase 2	HIKE P2 + KOTO-II
$\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu})$	$(7.86 \pm 0.61) \times 10^{-11}$	$(10.6^{+4.0}_{-3.5} \pm 0.9) \times 10^{-11}$	20%	5%	5%
$\mathrm{BR}(K^0_L \to \pi^0 \nu\nu)$	$(2.68 \pm 0.30) \times 10^{-11}$	$< 3.0 \times 10^{-9}$ @90% CL	current	current	20%
$\mathrm{LFUV}(a_+^{\mu\mu} - a_+^{ee})$	0	-0.014 ± 0.016	current	± 0.007	± 0.007
$\mathrm{BR}(K_L \to \mu\mu)$ (+)	$(6.82^{+0.77}_{-0.29}) \times 10^{-9}$	$(6.84 \pm 0.11) \times 10^{-9}$	current	1%	1%
$\mathrm{BR}(K_L \to \mu\mu)$ (−)	$(8.04^{+1.47}_{-0.98}) \times 10^{-9}$				
$\mathrm{BR}(K_S \to \mu\mu)$	$(5.15 \pm 1.50) \times 10^{-12}$	$< 2.1(2.4) \times 10^{-10}$ @90(95)% CL	current	current	current
$\mathrm{BR}(K_L \to \pi^0 ee)(+)$	$(3.46^{+0.92}_{-0.80}) \times 10^{-11}$	$< 28 \times 10^{-11}$ @90% CL	current	20%	20%
~~$\mathrm{BR}(K_L \to \pi^0 ee)(-)$~~	~~$(1.55^{+0.60}_{-0.48}) \times 10^{-11}$~~				
$\mathrm{BR}(K_L \to \pi^0 \mu\mu)(+)$	$(1.38^{+0.27}_{-0.25}) \times 10^{-11}$	$< 38 \times 10^{-11}$ @90% CL	current	20%	20%
~~$\mathrm{BR}(K_L \to \pi^0 \mu\mu)(-)$~~	~~$(0.94^{+0.21}_{-0.20}) \times 10^{-11}$~~				

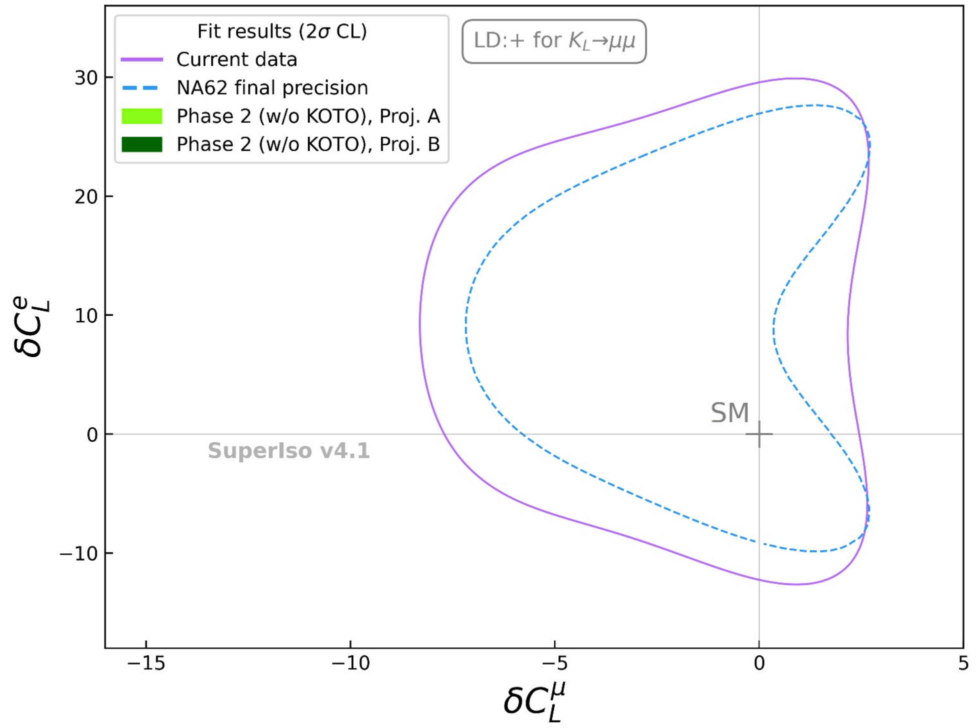
Projection A

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

Projection B

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

NA62 final precision



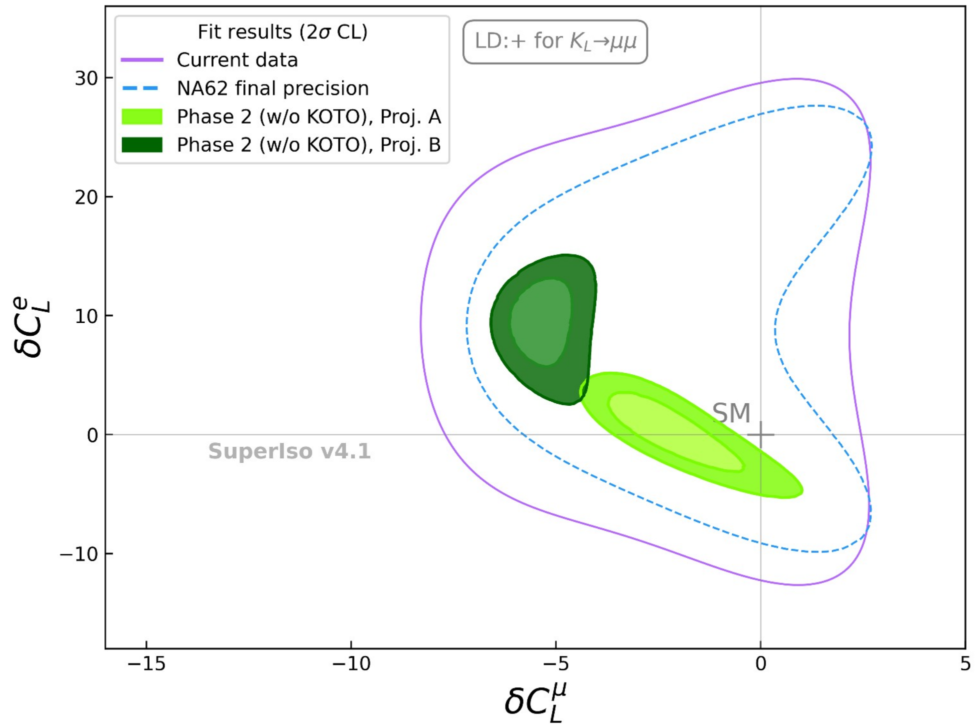
Projection A

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

Projection B

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

HIKE without KOTO



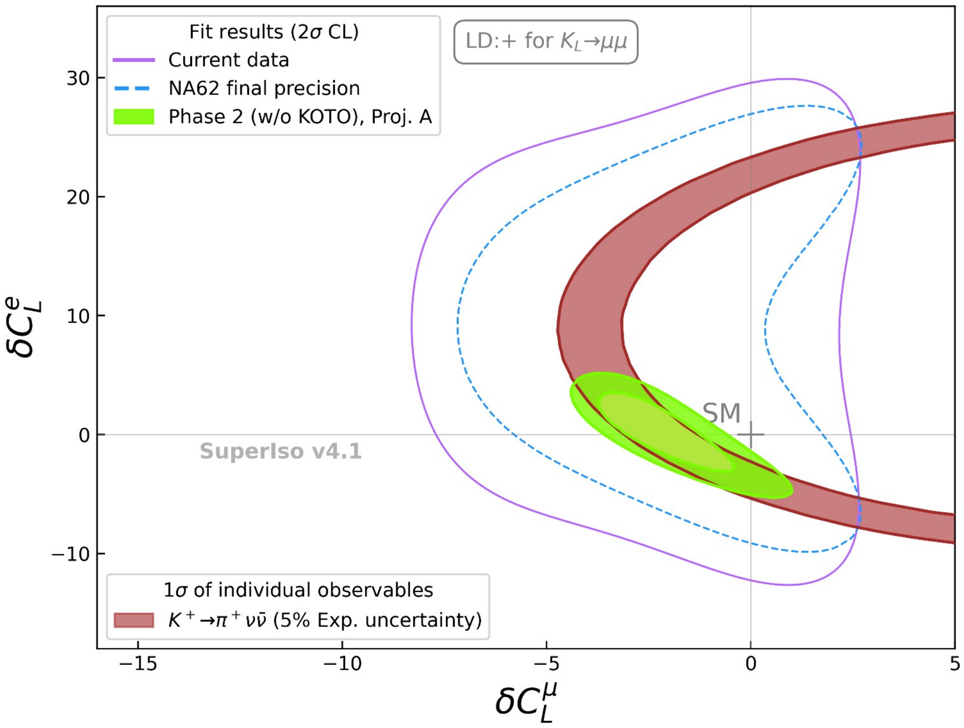
Projection A

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

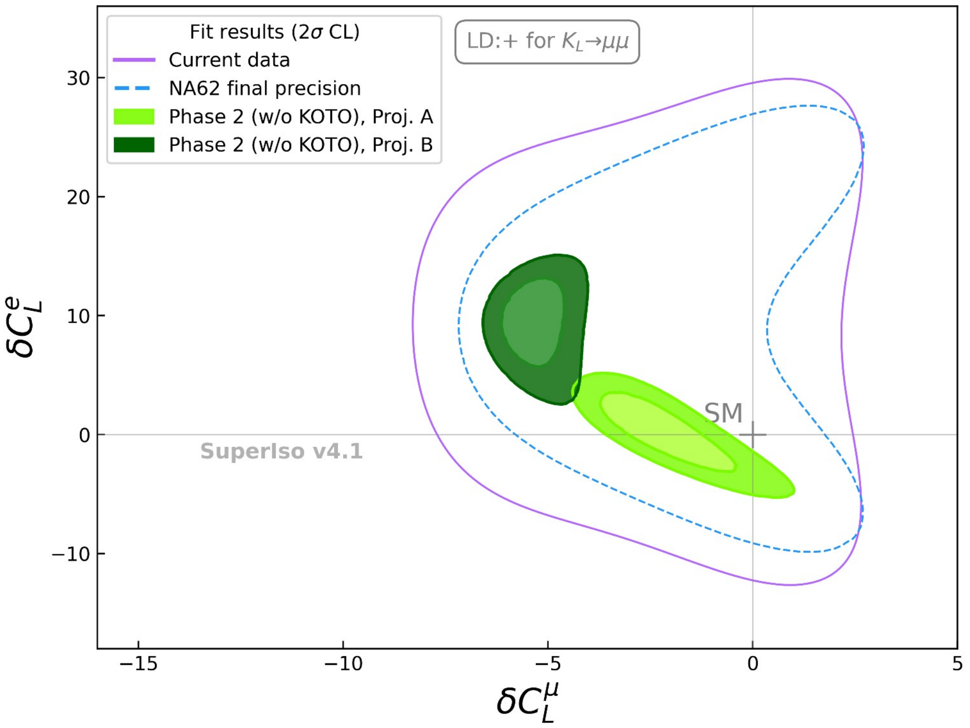
Projection B

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

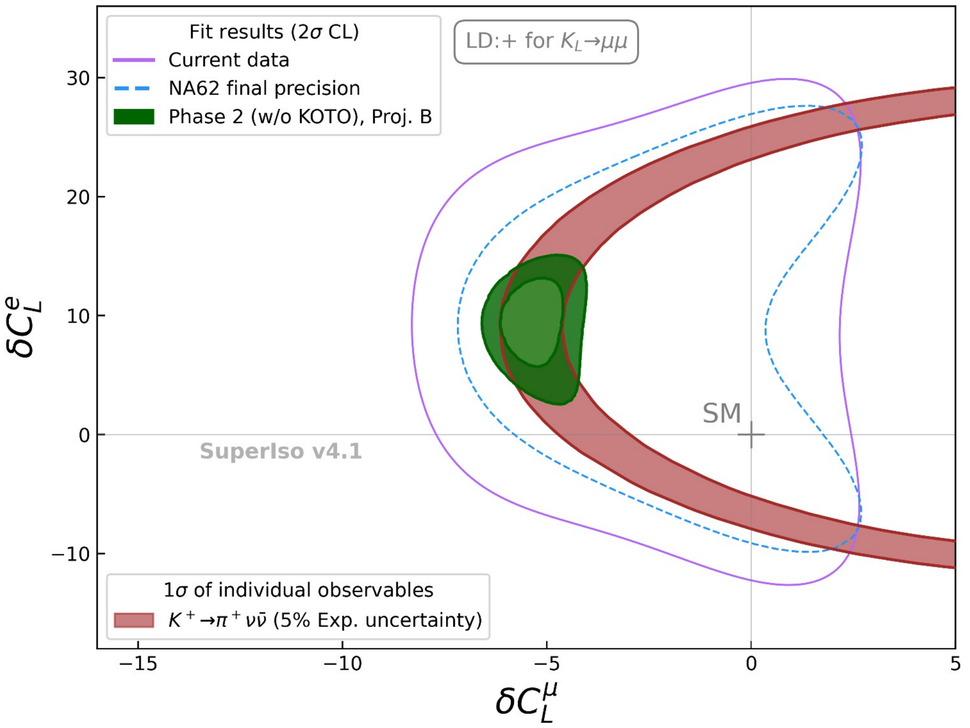
HIKE without KOTO – impact of $K^+ \to \pi^+ \nu\nu$



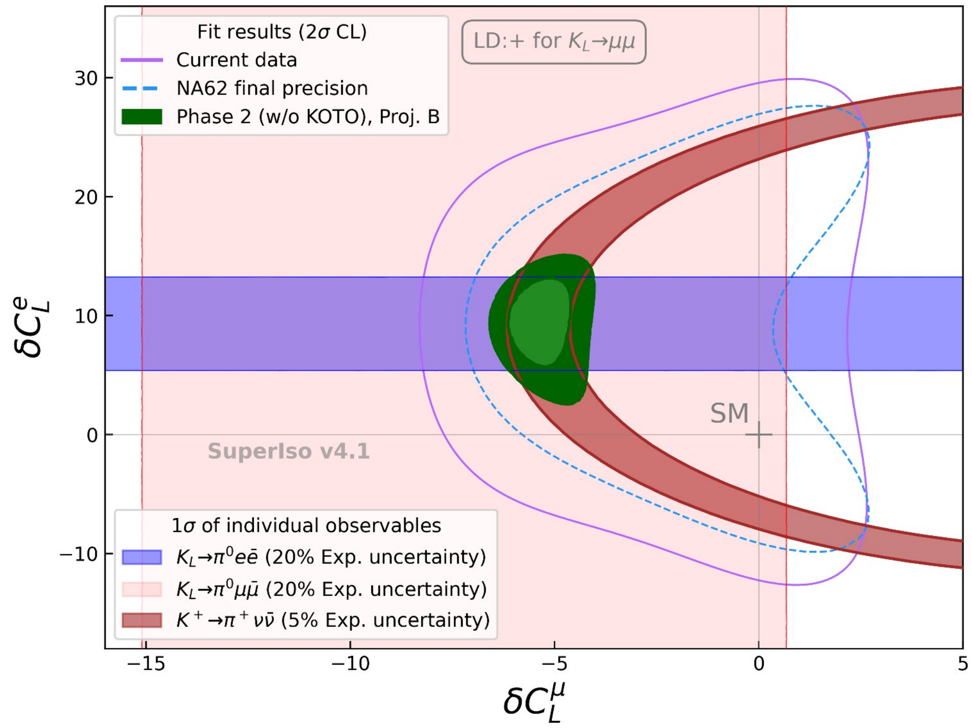
HIKE without KOTO



HIKE without KOTO – impact of $K^+ \to \pi^+ \nu \nu$

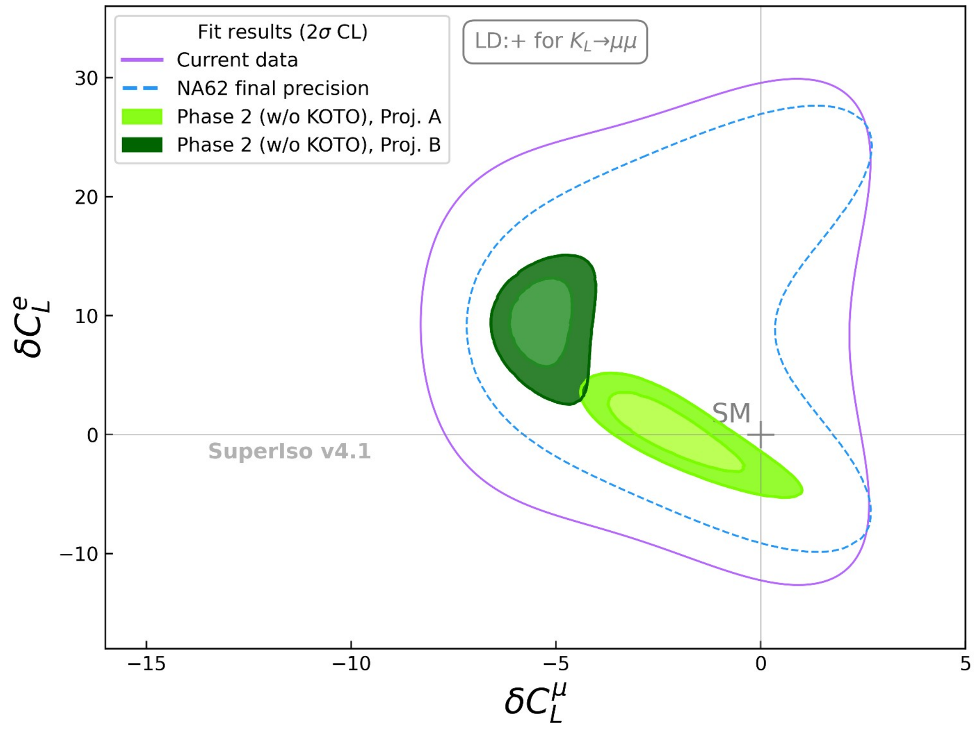


HIKE without KOTO – impact of $K^+ \to \pi^+ \nu\nu$ and $K_L \to \pi^0 \ell\ell$

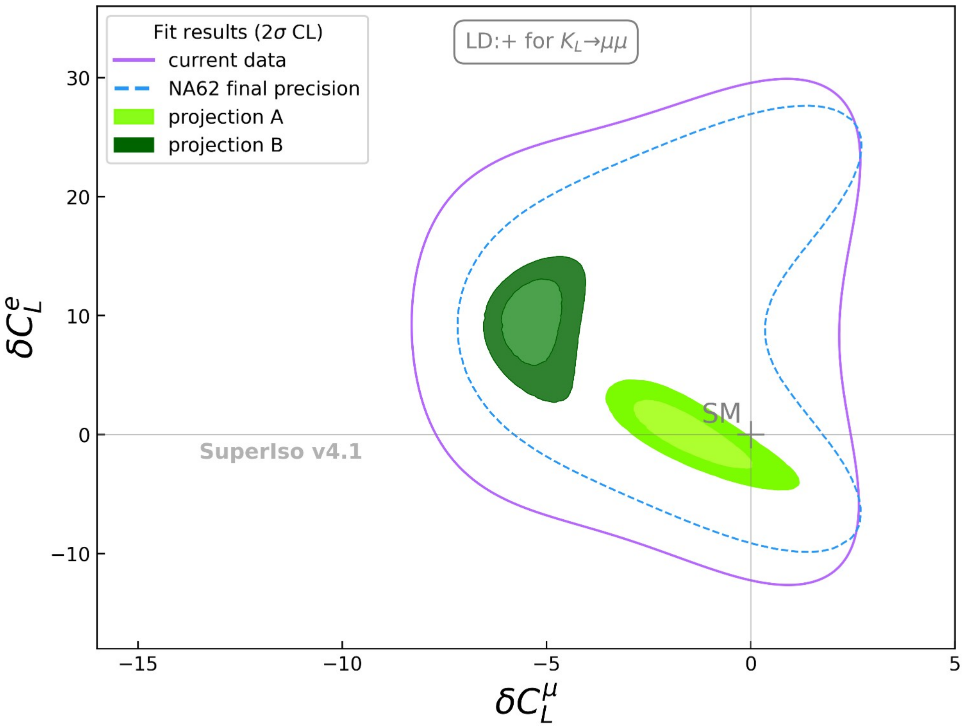


Main constraining observables BR($K^+ \to \pi^+ \nu\nu$) followed by BR($K_L \to \pi^0 e^+ e^-$)

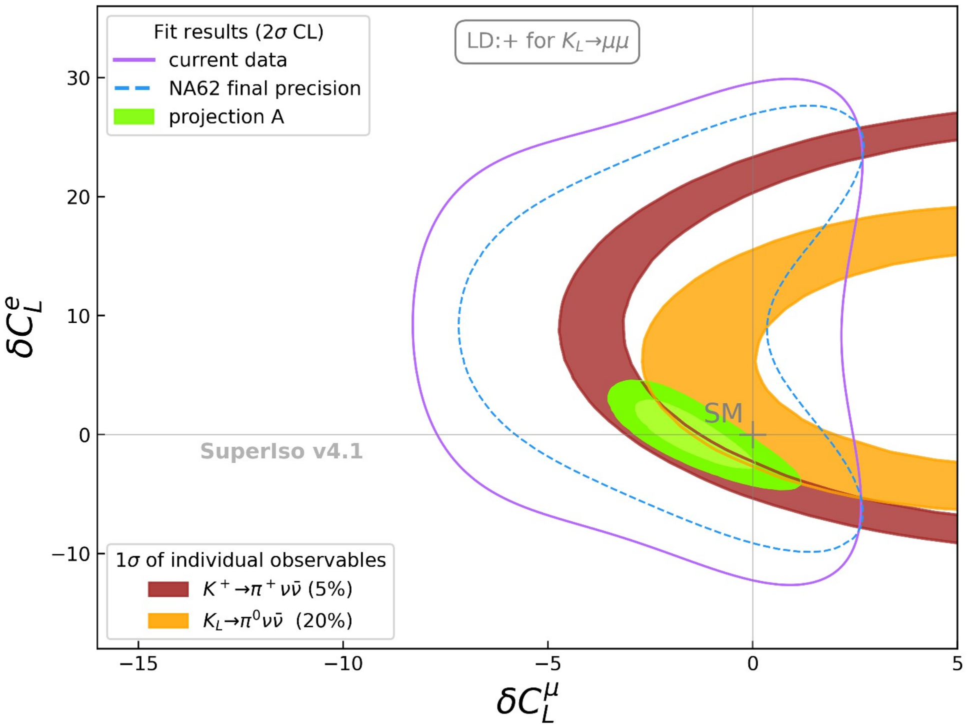
HIKE without KOTO



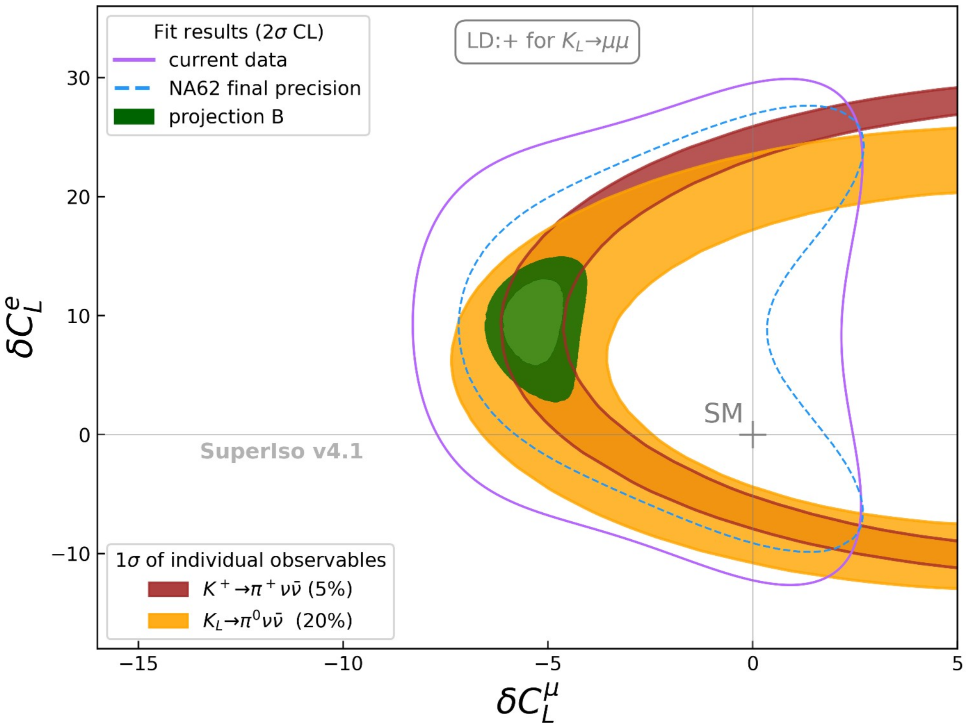
HIKE with KOTO



HIKE with KOTO – impact of $K^+ \to \pi^+ \nu\nu$ and $K_L \to \pi^0 \nu\nu$



HIKE with KOTO – impact of $K^+ \to \pi^+ \nu\nu$ and $K_L \to \pi^0 \nu\nu$



Summary

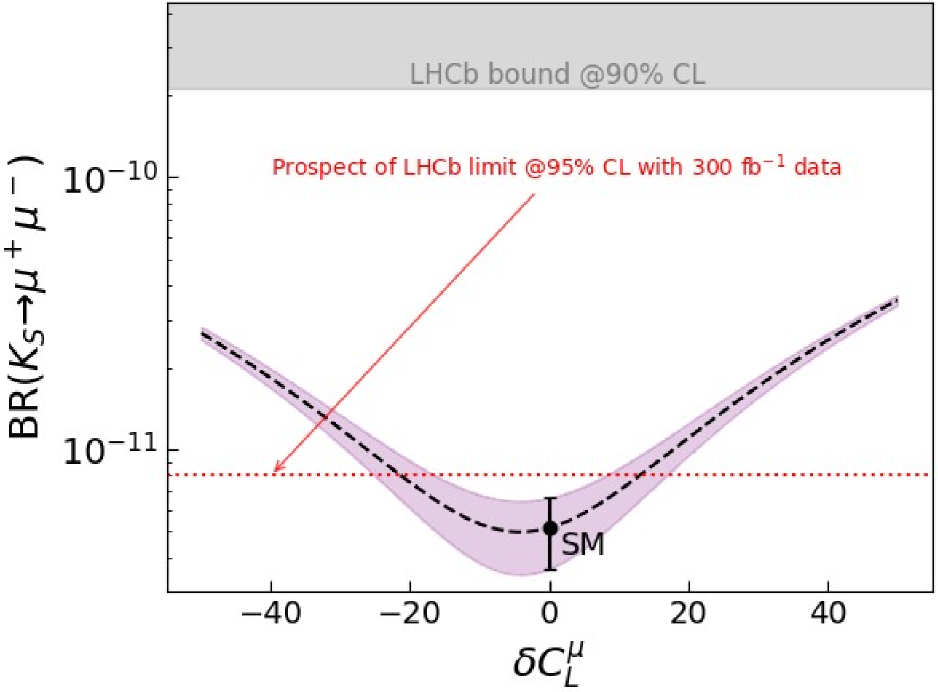
- Rare kaon decays offer interesting information on short distance physics, even those which are long-distance dominated
- Hike (Phase 1 and 2) offers excellent sensitivity to new physics
- KOTO-II measurement of $K_L \to \pi^0 \nu\nu$ will improve this sensitivity
- Measurement of $K_L \to \pi^0 \ell \ell$, especially in the electron sector gives a very effective probe of new physics

Backup

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

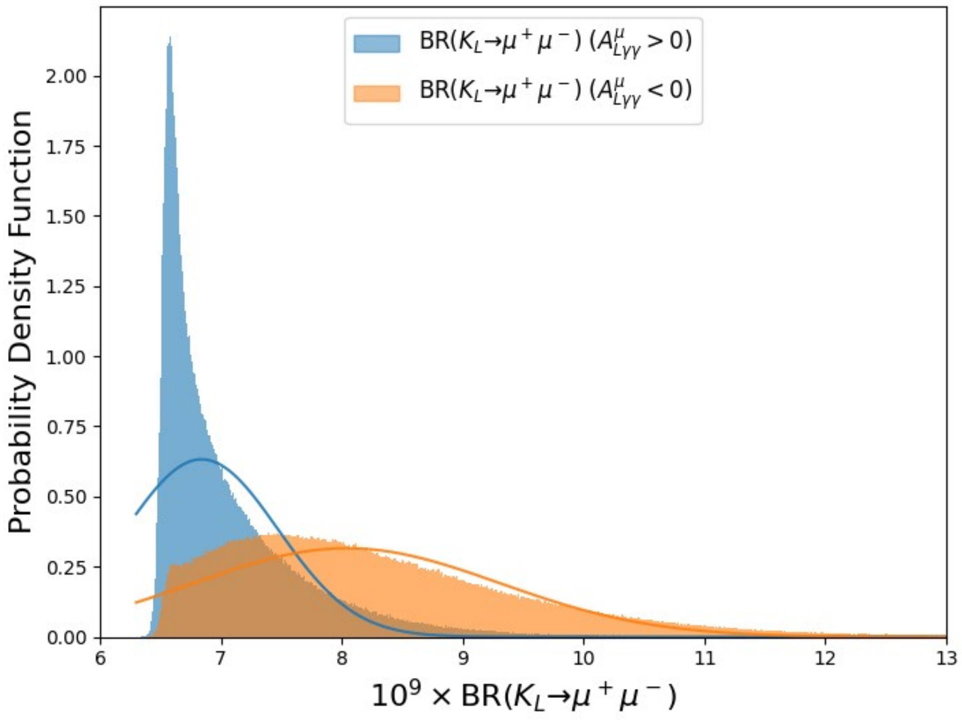
$$N_S^{\mathrm{LD}} = (-2.65 + 1.14i) \times 10^{-11}\,(\mathrm{GeV})^{-2}$$

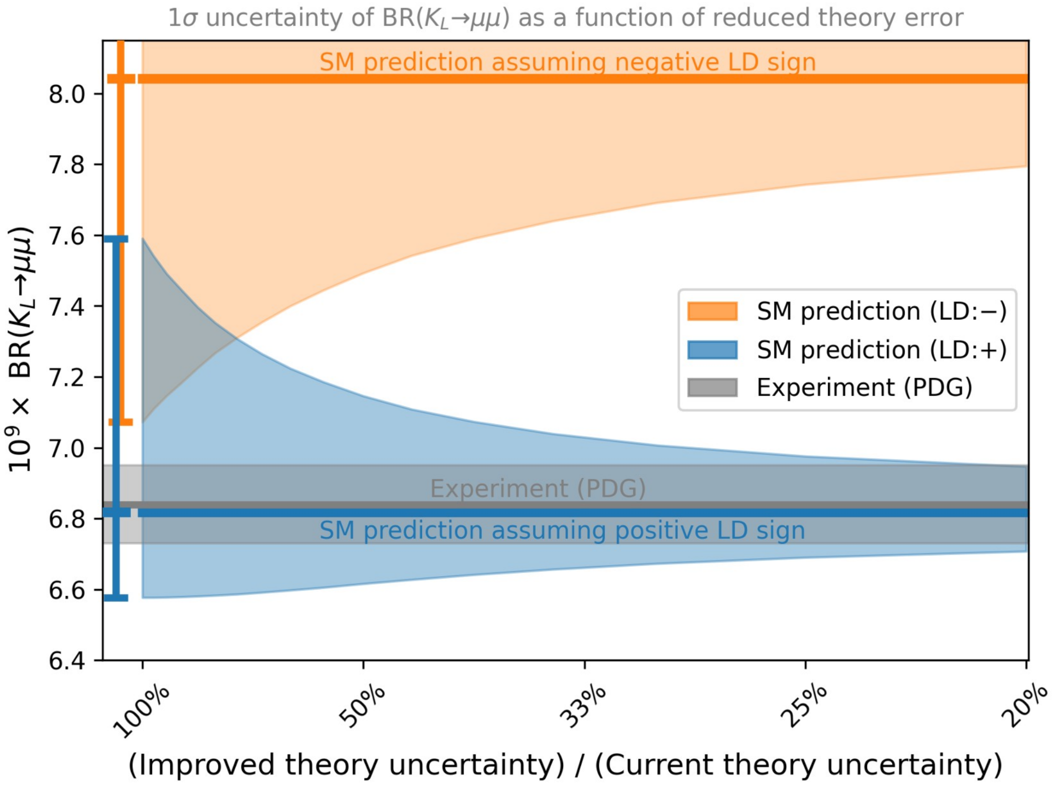
$$\mathrm{BR}(K_S \to \mu\bar{\mu})^{\mathrm{SM}} = (5.15 \pm 1.50) \times 10^{-12}$$



Backup

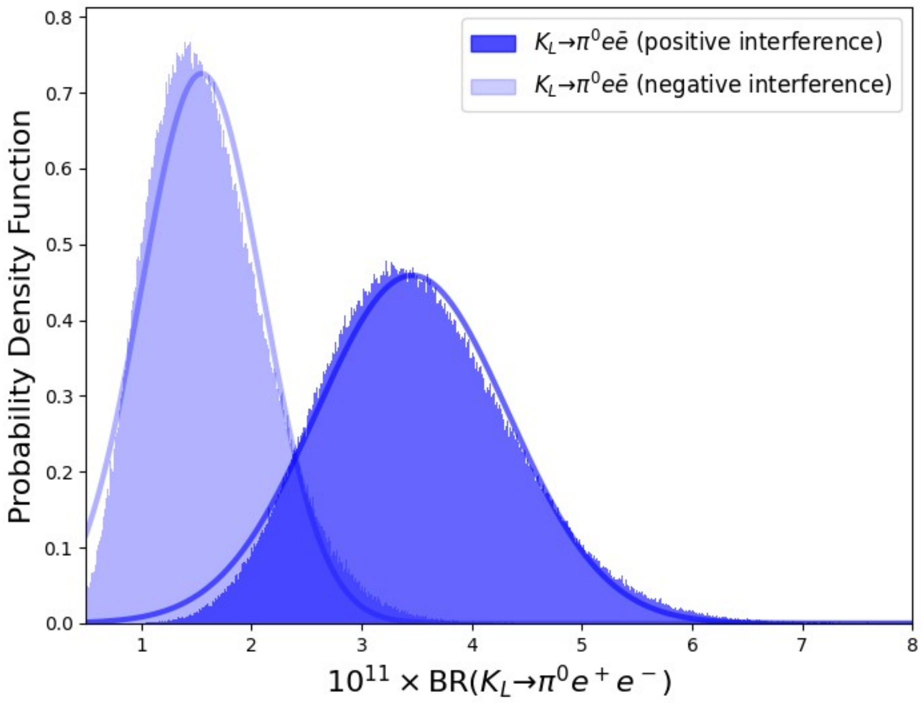
Asymmetric theoretical uncertainty of $K_L \to \mu\mu$

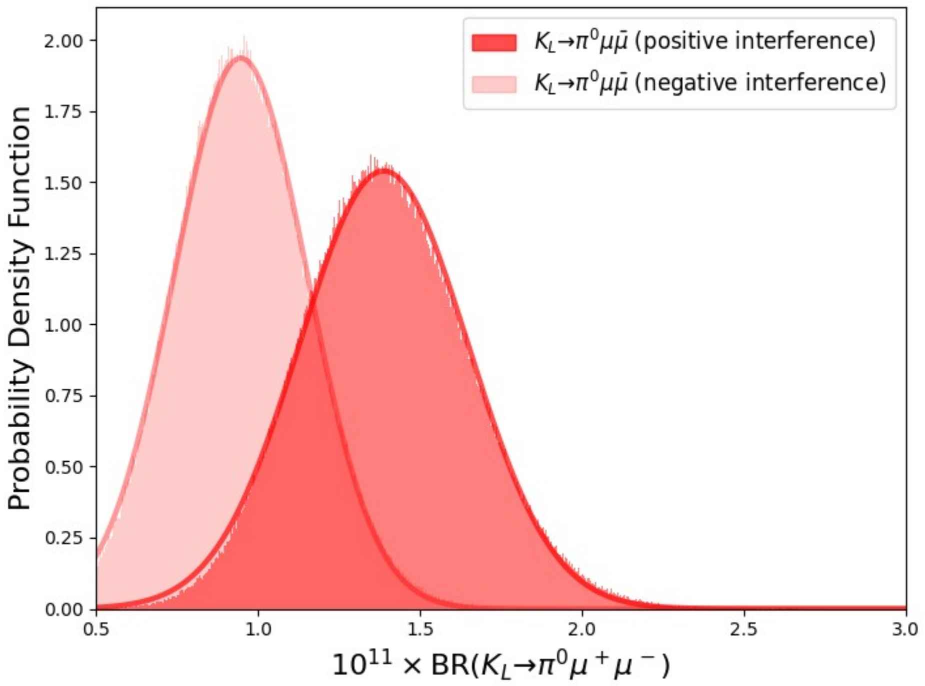




Backup

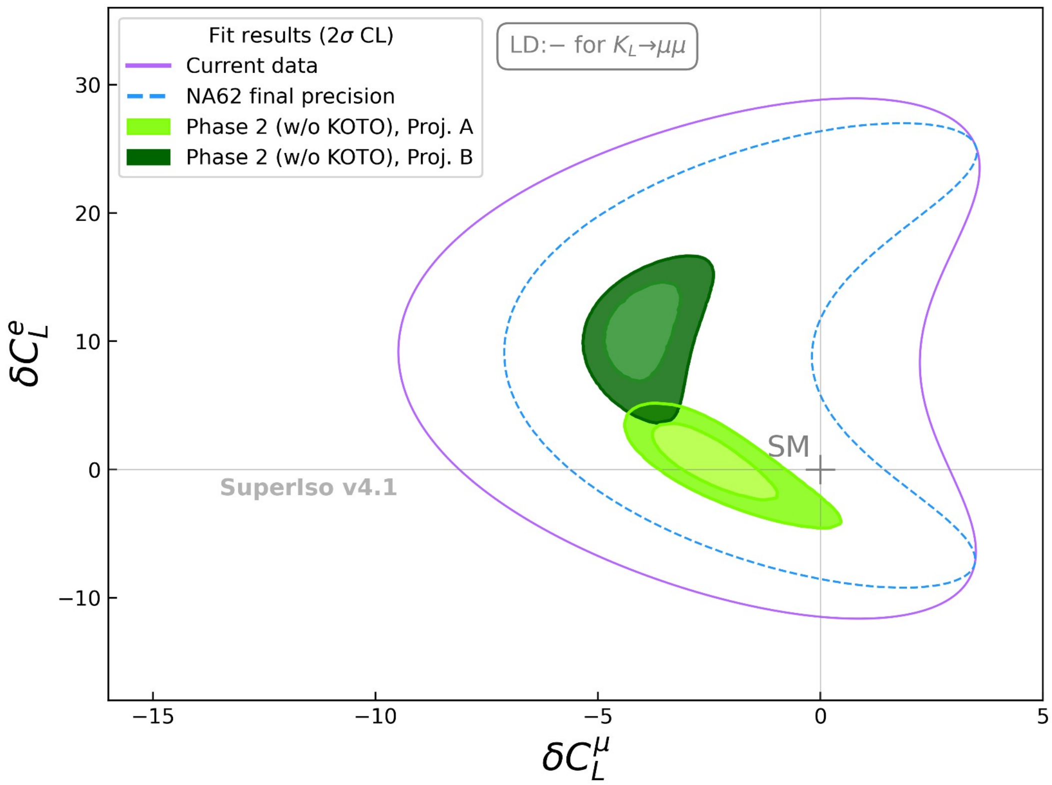
Asymmetric theoretical uncertainty of $K_L \to \pi^0 \ell\ell$





Backup

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



Backup

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