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BSM Sensitivity of Rare Kaon Decays

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Rare kaon decays offer a sensitive probe of short-distance physics and physics beyond the Standard Model. We study several key modes, including $K^+ \to \pi^+ \nu\bar{\nu}$, $K_L \to \pi^0 \nu\bar{\nu}$, and $K_L \to \pi^0 \ell^+ \ell^-$, focusing on new physics contributions mediated by semileptonic $(V - A) \otimes (V - A)$ operators. A global analysis of current data is presented together with projections based on future sensitivities expected from NA62 and KOTO-II. We show that charged-lepton modes play an essential role in lifting degeneracies present in neutrino observables and significantly enhance sensitivity to short-distance effects.

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1. Introduction

Rare kaon decays provide a powerful probe of the Standard Model (SM) [1–4]. The "golden modes," $K^+ \to \pi^+ \nu\bar{\nu}$ and $K_L \to \pi^0 \nu\bar{\nu}$, are particularly important as they are dominated by short-distance contributions within the SM. An especially crucial aspect of our work concerns the subtle role of lepton-flavour universality violation in neutrino modes. Since the branching ratios of these decays experimentally involve sums over neutrino flavours, sizeable new physics contributions in individual lepton channels can cancel in the total rate, leading to SM-like measurements despite the presence of beyond the Standard Model (BSM) effects. This motivates the need for complementary observables involving charged leptons, where such cancellations do not occur and lepton-flavour-dependent effects can be disentangled.

Complementary information is provided by decays with charged leptons in the final state such as $K_L \to \ell^+\ell^-$, $K^+ \to \pi^+\ell^+\ell^-$, and $K_L \to \pi^0\ell^+\ell^-$. These modes receive significant long-distance contributions from photon exchange and are typically predicted with lower theoretical precision. Despite this limitation, they offer valuable sensitivity to short-distance effects from potential new physics (NP) and play an essential role in testing lepton-flavour-dependent scenarios. In this work, we focus on NP contributions mediated by the $(V-A)\otimes(V-A)$ operators, which are also present in the SM effective Hamiltonian. We do not consider scalar or pseudoscalar structures, which are explored separately in our related studies [5, 6]. Our analysis builds directly on the framework established in [7–9].

For the description of $d \to s$ transitions we adopt the effective Hamiltonian

$$\mathcal{H}_{\rm eff} = -\frac{4G_F}{\sqrt{2}}\lambda_t \frac{\alpha_e}{4\pi}\sum_k C_k^\ell O_k^\ell \,, \tag{1}$$

with

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

where $\lambda_t = V_{td}V_{ts}^*$. We do not consider the chirality-flipped counterparts of these operators, which are highly suppressed in the SM. We work in the chiral basis where $\delta C_9 = -\delta C_{10}$. Furthermore, a key theoretical assumption is the preservation of $SU(2)_L$ gauge invariance, which correlates charged-lepton and neutrino operators. Consequently, the new physics contributions satisfy

$$\delta C_9^\ell = -\delta C_{10}^\ell = \delta C_L^\ell \,, \tag{2}$$

allowing us to express all results in terms of the single coefficient δC_L^ℓ for each lepton flavour. To reduce the dimensionality of the parameter space while keeping sensitivity to lepton-flavour non-universality, we assume

$$\delta C_L^\mu = \delta C_L^\tau \neq \delta C_L^e \,. \tag{3}$$

This defines a two-dimensional parameter space $(\delta C_L^e, \delta C_L^\mu)$, which is well suited for graphical interpretation and global analysis.

2. Decay Modes

Within the operator framework outlined above, a variety of rare kaon decays provide sensitivity to the Wilson coefficients δC_L^ℓ. Some of these observables are already measured with good precision, while for others only upper bounds are currently available. They probe different combinations of short-distance and long-distance dynamics and therefore play complementary roles in the global analysis.

The decays $K^+ \to \pi^+ \nu\bar{\nu}$ and $K_L \to \pi^0 \nu\bar{\nu}$ are theoretically clean observables. Long-distance effects are subleading and the amplitudes are dominated by short-distance physics (see e.g. [10–20]). As a result, these modes offer direct access to the effective operators governing $s \to d\nu\bar{\nu}$ transitions. The branching ratios involve a sum over neutrino flavours, implying that lepton-flavour non-universal NP effects can remain hidden through cancellations. This property makes it essential to combine these channels with charged-lepton modes.

The decay $K^+ \to \pi^+ \ell^+ \ell^-$ is dominated in the SM by single-photon exchange and is described by a vector form factor [21, 22]. Although the short-distance contribution is subleading, this mode provides sensitivity to lepton-flavour universality through comparisons of the electron and muon channels [7, 23], offering a complementary probe of lepton-flavour-dependent effects.

The purely leptonic modes $K_L \to \mu^+\mu^-$ and $K_S \to \mu^+\mu^-$ are also included in the analysis. In both cases the decay amplitudes are dominated by long-distance contributions, leading to sizeable theoretical uncertainties. Nevertheless, short-distance effects can still be numerically relevant and allow constraints on new physics contributions to be extracted. This is particularly true for $K_L \to \mu^+\mu^-$, whose branching ratio has been measured with very high precision. The interpretation of this observable is however limited by an ambiguity in the interference between the short-distance amplitude and the long-distance contribution mediated by $K_L \to \gamma\gamma$, which depends on the unknown sign of the corresponding amplitude [24–26]. For $K_S \to \mu^+\mu^-$ the theoretical prediction is not affected by this sign ambiguity. On the experimental side, however, the current upper bound is about two orders of magnitude above the Standard Model expectation [27]. In the operator setup considered here, this mode provides relatively weak additional constraints, even when accounting for the LHCb upgrade projection [28], but it is kept in the global fit for completeness.

A central focus of this work is the decay $K_L \to \pi^0 \ell^+ \ell^-$, which receives contributions from direct CP violation, indirect CP violation through kaon mixing, and CP-conserving two-photon effects [21, 29, 30]. Despite these complications, the short-distance component is theoretically well controlled and directly sensitive to the operators under consideration. Although the current experimental limits are about one order of magnitude larger than the Standard Model expectations [31, 32], these modes are already sensitive to the operators considered in this work and are therefore particularly promising for future measurements. Their inclusion is essential for lifting degeneracies that remain when only neutrino modes are considered, especially in the electron channel.

The experimental inputs and theoretical uncertainties used in our analysis are summarised in Table 1 from Ref. [5][1]. The following section details the current global analysis as well as projection scenarios built upon these observables.

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[1] We note that newer experimental results for the neutrino modes have since been reported by NA62 [33] and KOTO [34].

Observable	**SM prediction**	**Experimental result**	**Reference**	**Precision for projections**
$\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu})$	$(7.86 \pm 0.61) \times 10^{-11}$	$(10.6^{+4.0}_{-3.5} \pm 0.9) \times 10^{-11}$	[35]	15% [36]
$\mathrm{BR}(K^0_L \to \pi^0 \nu\bar{\nu})$	$(2.68 \pm 0.30) \times 10^{-11}$	$< 1.99 \times 10^{-9}$ @90% CL	[37]	25% [36]
$\mathrm{LFUV}(a^{\mu\mu}_+ - a^{ee}_+)$	0	-0.014 ± 0.016	[22, 38]	Current
$\mathrm{BR}(K_L \to \mu^+\mu^-)\ (+)$	$(6.82^{+0.77}_{-0.29}) \times 10^{-9}$	$(6.84 \pm 0.11) \times 10^{-9}$	[39]	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 $\left(0.9^{+0.7}_{-0.6} \times 10^{-10}\right)$	[27]	$< 6.4 \times 10^{-12}$ @95% CL (LHCb@300 fb^{-1} [28, 40])
$\mathrm{BR}(K_L \to \pi^0 e^+ e^-)(+)$	$(3.46^{+0.92}_{-0.80}) \times 10^{-11}$	$< 28 \times 10^{-11}$ @90% CL	[31]	25% [36]
$\mathrm{BR}(K_L \to \pi^0 e^+ e^-)(-)$	$(1.55^{+0.60}_{-0.48}) \times 10^{-11}$			
$\mathrm{BR}(K_L \to \pi^0 \mu^+ \mu^-)(+)$	$(1.38^{+0.27}_{-0.25}) \times 10^{-11}$	$< 38 \times 10^{-11}$ @90% CL	[32]	25% [36]
$\mathrm{BR}(K_L \to \pi^0 \mu^+ \mu^-)(-)$	$(0.94^{+0.21}_{-0.20}) \times 10^{-11}$			

Table 1: This table lists Standard Model predictions alongside current experimental measurements and future precision targets. The label "Current" in the last column indicates scenarios where the experimental precision or limit is assumed to remain at its present level. The upper bound on $\mathrm{BR}(K_L \to \pi^0 \nu\bar{\nu})$ given in Ref. [37] has been updated to $< 2.1 \times 10^{-9}$ @90% CL, agreeing with the published result in Ref. [34].

3. Current Fit and Projections

To obtain a global picture of the constraints arising from the rare kaon decays discussed above, we perform a global fit. The analysis follows a frequentist approach and is implemented using the `SuperIso` program [41–43]. The resulting bounds in the $(\delta C^e_L, \delta C^\mu_L)$ plane of Wilson coefficients, obtained from a global analysis of the current rare kaon measurements, are illustrated in Fig. 1. Throughout this fit, we assume a positive sign for the long-distance contribution to $K_L \to \mu^+\mu^-$. The purple bands represent the 68% and 95% confidence level regions, shown with lighter and darker shades, respectively, while the purple cross denotes the best-fit point.

To assess the impact of future experimental progress, in Fig. 2, we perform a set of projected global fits based on realistic precision goals for upcoming experiments, while keeping theoretical uncertainties at their current levels.

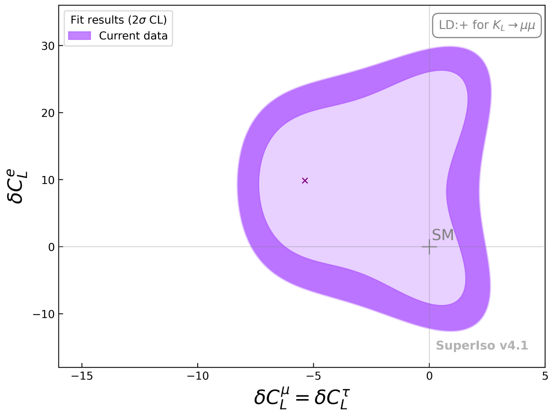

Figure 1: Global fit to $(\delta C^e_L, \delta C^\mu_L)$ using current data. The purple cross indicates the best-fit point. The sign of the long-distance contribution to $K_L \to \mu\bar{\mu}$ is assumed to be positive.

We consider future improvements in three successive steps. For each step, we explore two illustrative assumptions for the future central values: **Projection A**) future measurements are assumed to be centred on the Standard Model predictions; **Projection B**) future measurements are taken to coincide with the current best-fit point obtained from existing data.

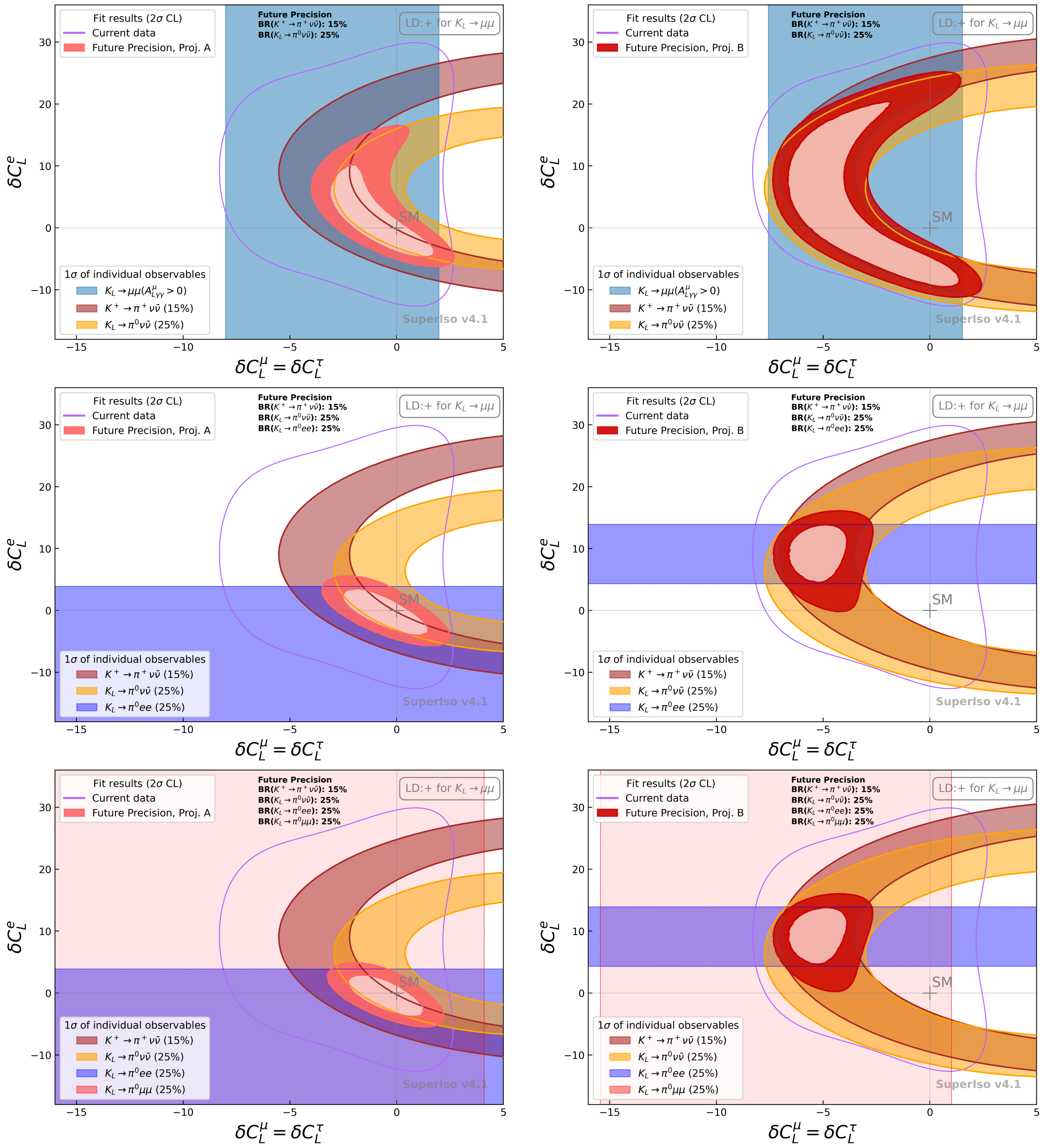

Figure 2: Impact of future experimental precisions for projection A (left) and projection B (right). The top row illustrates the impact on the parameter space when only the golden kaon decay modes are included at their projected precisions. The middle row shows the additional impact of including a future measurement of BR($K_L\to\pi^0e^+e^-$). The bottom row illustrates the impact of further including a future measurement of BR($K_L\to\pi^0\mu^+\mu^-$).

In the first step, only the golden modes are assumed to be measured with improved precision. We take a 15% precision for $K^+ \to \pi^+\nu\bar{\nu}$, motivated by the final NA62 sensitivity [35], and a 25% precision for $K_L \to \pi^0\nu\bar{\nu}$, as anticipated at KOTO-II [36, 44]. This scenario already leads to a significant reduction of the allowed region in the $(\delta C_L^e, \delta C_L^\mu)$ plane compared to the present situation.

In the second step, we add a projected 25% measurement of $K_L \to \pi^0 e^+ e^-$. The inclusion of this observable results in a substantial further reduction of the allowed parameter space. This demonstrates that even a moderately precise measurement of this mode can strongly enhance sensitivity to short-distance new physics and constrain lepton-flavour non-universal effects.

The third step incorporates, in addition, a projected 25% measurement of $K_L \to \pi^0\mu^+\mu^-$. While the overall size of the allowed region is not dramatically reduced compared to the previous step, the combined information from the electron and muon channels improves the ability to discriminate between the two different projection assumptions. This highlights the complementarity of the two charged-lepton modes.

4. Conclusions

Rare kaon decays continue to provide a uniquely sensitive window on short-distance flavour physics. While the golden neutrino modes remain central to this programme, their interpretation can be affected by cancellations among lepton flavours. This motivates a broader approach that includes charged-lepton modes, despite their larger long-distance contributions.

In this work, we have studied the impact of future measurements within a $(V-A)\otimes(V-A)$ operator framework, highlighting in particular the role of $K_L \to \pi^0\ell^+\ell^-$. By performing projected global fits under a series of well-defined scenarios, we have shown that measurements of these modes at the level expected from KOTO-II can substantially improve constraints on the relevant Wilson coefficients. Already the inclusion of the electron mode leads to a marked reduction of the allowed parameter space, while the muon mode provides additional discrimination between competing hypotheses.

Our results make a clear case for pursuing a comprehensive kaon physics programme with an emphasis on rare K_L decays into both neutrinos and charged leptons. Combined with ongoing and future efforts to improve theoretical precision, such measurements have the potential to significantly sharpen tests of the Standard Model and to probe new physics in the flavour sector.

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