Prospects for New Physics in Rare Kaon Decays

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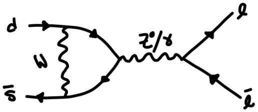
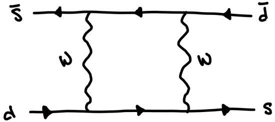
Kaons historically vital for new physics discoveries!

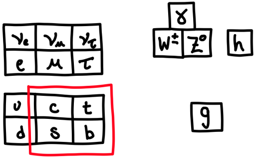
FCNCs/GIM



CP-violation



$\approx$ 23.5% of SM



	Kaons	B-mesons
GIM Suppression:	$\lvert V_{ts}^* V_{td}\rvert \sim \lambda^5$	$\lvert V_{tb}^* V_{td(s)}\rvert \sim \lambda^{3(2)}$
Decay Suppression:	$\Gamma \sim M_K^5/M_W^4$	$\Gamma \sim M_B^5/M_W^4$
Light NP:	$\mathcal{B} \sim (M_W/M_K)^n$	$\mathcal{B} \sim (M_W/M_B)^n$

Promising Observables

(See talks from Xu Feng, Silvia Martellotti, Yu-Chen Tung, and Rainer Wanke for more details!)

$K \to \pi\bar{\nu}\nu$

$$\mathcal{H}_{\text{eff}} = \frac{4G_F}{\sqrt{2}} \frac{\alpha}{2\pi \sin^2 \Theta_W} \sum_{\ell=e,\mu,\tau} \Big(V_{cs}^* V_{cd} X_c^\ell + V_{ts}^* V_{td} X_t \Big) (\bar{s}_L \gamma^\mu d_L)(\bar{\nu}_L^\ell \gamma_\mu \nu_L^\ell) + \text{h.c.}$$

- Re $V_{ts}^* V_{td} \sim$ Im $V_{ts}^* V_{td} \sim \lambda^5$, Re $V_{cs}^* V_{cd} \sim \lambda$, Im $V_{cs}^* V_{cd} \sim \lambda^5$

$K_L \to \pi^0 \bar{\nu}\nu$: A Theorist's Dream Decay

$$|K_L\rangle = p\,|K^0\rangle - q\,|\bar{K}^0\rangle \quad \Rightarrow \quad \langle \pi^0\bar{\nu}\nu|\mathcal{H}_{\text{eff}}|K_L\rangle = \frac{4G_F}{\sqrt{2}}\frac{\alpha}{2\pi\sin^2\Theta_W}\,\text{Im}\left(V_{ts}^* V_{td} X_t\right)\langle Q_\nu\rangle + \mathcal{O}\left(\lambda^5 \frac{m_c^2}{M_W^2}\right)$$

- Nearly pure *CP*-violating $\Rightarrow$ Top-quark dominated (tiny long-distance)

$$\mathcal{B}(K_L \to \pi^0\bar{\nu}\nu)_{\text{SM}} = \left(2.59(6)_{\text{SD}}(2)_{\text{LD}}(28)_{\text{param}}\right) \times 10^{-11}$$

[Brod, Gorbahn, Stamou; 2105.02868], [Mescia, Smith; 0705.2025], [Buchalla, Buras; 9607447]

- Very challenging experimentally (fully neutral final state)

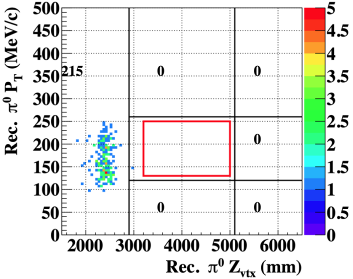
$K_L \to \pi^0 \bar{\nu}\nu$: KOTO at J-PARC

2015 dataset results:

$$\mathcal{B}(K_L \to \pi^0 \bar{\nu}\nu) < 3.0 \times 10^{-9} \ (90\% \ \text{CL})$$

[KOTO, 1810.09655]

- Charged-K veto counter and reduction of halo $K_L \to 2\pi^0$

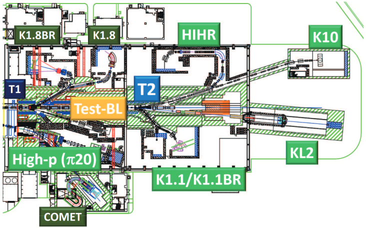


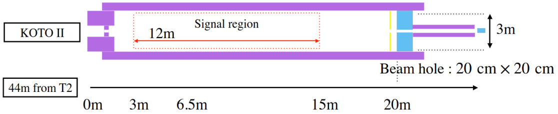
[KOTO, 2311.02923]

Updated analysis:

$$\mathcal{B}(K_L \to \pi^0 \bar{\nu}\nu) < 2.0 \times 10^{-9} \ (90\% \ \text{CL})$$

$K_L \to \pi^0 \bar{\nu}\nu$: KOTO-II at J-PARC



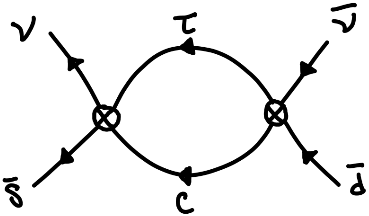


[KOTO, 2311.02923]

- Expected $\sim$ 25% sensitivity for SM BR

$K^+ \to \pi^+ \bar{\nu}\nu$

- Real part of $\mathcal{H}_{\text{eff}}$ plays non-negligible role
  $\Rightarrow$ charm contributions compete
  $(\lambda\, m_c^2/M_W^2$ vs. $\lambda^5)$
- More dependent on long-distance than K_L case; $\mathcal{O}(5\%)$ [Isidori, Mescia, Smith; 0503107]
- Future lattice calculations
  [Bai et al.; 1806.11520]



$$\mathcal{B}(K^+ \to \pi^+ \bar{\nu}\nu)_{\text{SM}} = \big(7.73(16)_{\text{SD}}(25)_{\text{LD}}(54)_{\text{param}}\big) \times 10^{-11}$$

[Brod, Gorbahn, Stamou; 2105.02868],[Mescia, Smith; 0705.2025]

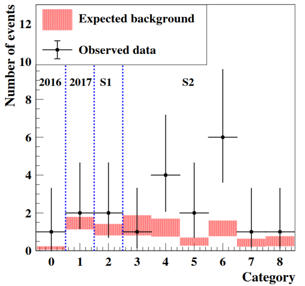
$K^+ \to \pi^+ \bar{\nu}\nu$: NA62

Run I results:

$$\mathcal{B}(K^+ \to \pi^+ \bar{\nu}\nu) = \left(10.6^{+4.0}_{-3.4}\big|_{\text{stat}} \pm 0.9\big|_{\text{syst}}\right) \times 10^{-11}$$

Run II:

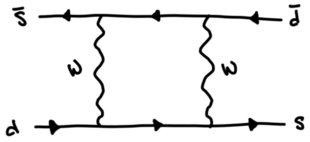
- 2022 signals $\sim$ all Run I [2023 NA62 Status Report]
  $\Rightarrow$ 15% precision (similar data taking up to LS3)



[NA62, 2103.15389]

ϵ_K: Experiment Ahead of Theory

- Measure of indirect CP-violation in $K^0 - \bar{K}^0$ mixing
- Theoretical uncertainty $\sim \mathcal{O}(1\%)$
  - Perturbative
    [Brod, Gorbahn, Stamou; 1911.06822], [Brod, Kvedaraitė, **ZP**; 2108.00017], [Brod, Kvedaraitė, **ZP**, Youssef; 2207.07669]
  - Hadronic ME [FLAG; 2111.09849]
  - m_c power corrections [Ciuchini, et al.; 2111.05153]



$$|\epsilon_K|_{\text{th}} = (2.170(65)_{\text{pert}}(76)_{\text{nonpert}}(153)_{\text{param}})\times 10^{-3}$$

- Experimentally measured to per-mil accuracy
  [PDG 2022]

$$|\epsilon_K|_{\text{ex}} = (2.228\pm 0.011)\times 10^{-3}$$

Theory calculation will be improved with 3loop QCD top, NLO RI/SMOM-$\overline{\text{MS}}$ matching and improved lattice calculations!

$K \to \mu^+\mu^-$

- Large LD contaminations from *CP*-even parts of decays: hard to control
- *Interference* effects dominated by SD $\Rightarrow$ theoretically clean [D'Ambrosio, Kitahara; 1707.06999]
- Mostly *CP*-violating $\mathcal{B}(K_S \to (\mu\mu)_{\ell=0})$ can be determined from*
  [Dery, Ghosh, Grossman; 2104.06427]

$$\mathcal{B}(K_S \to (\mu\mu)_{\ell=0}) = \mathcal{D}_F \mathcal{B}(K_L \to \mu\mu) \frac{\tau_S}{\tau_L} \left(\frac{C_{\rm int}}{C_L} \right)^2$$

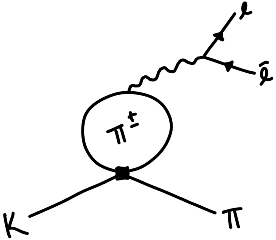
- LD effects from mixing can be enhanced by $|\mathcal{A}_L^0|/|\mathcal{A}_S^0| \sim 10$ ($\lesssim$ few %)
  [Brod, Stamou; 2209.07445]
- Experimentally challenging: $C_{\rm int}$ only seen in $K^0 - \bar{K}^0$-asymmetric beam

The Golden Mode: $K \to \pi\bar{\ell}\ell$

- Need to extract ChPT FFs from data
- $K_{L/S} \to \pi^0\bar{\ell}\ell$: both depend on same FF
  $\Rightarrow$ Measuring K_S decay can help prediction of K_L (LHCb)
  [LHCb; 2001.10354]
- $K^+ \to \pi^+\bar{\ell}\ell$: FF difference b/n $\ell = e, \mu$ gives LFUV test

$$\text{LFUV}(a_+^{\mu\mu} - a_+^{ee}) = -0.014 \pm 0.016$$

[D'Ambrosio, Mahmoudi, Neshatpour; 2209.07445], [E865; 9907045], [NA62; 2209.05076]



Heavy New Physics

Heavy New Physics

- Treated in model-independent* way with corrections to WCs: $C \to C_{\mathrm{SM}} + \delta C$
- Heavy GIM suppressions $\Rightarrow$ high-scale/weakly coupled heavy NP

$$\frac{4G_F}{\sqrt{2}} \frac{\alpha}{2\pi \sin^2 \Theta_W} \lambda_t \sim -\left(130 \text{ TeV}\right)^{-2} + i\left(200 \text{ TeV}\right)^{-2}$$

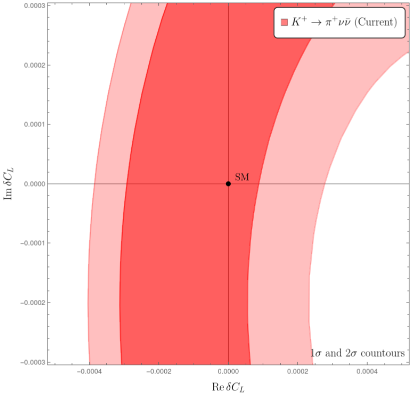
HNP in $K \to \pi\bar{\nu}\nu$: Current Status

- Compatible with SM at 1σ
- Charged Decay (90% CL):

$$|\,\mathrm{Re}\,\delta C_L| \lesssim (120\ \mathrm{TeV})^{-2}, \quad |\,\mathrm{Im}\,\delta C_L| \lesssim (70\ \mathrm{TeV})^{-2}$$

- Neutral Decay (90% CL):

$$|\,\mathrm{Im}\,\delta C_L| \lesssim (50\ \mathrm{TeV})^{-2}$$

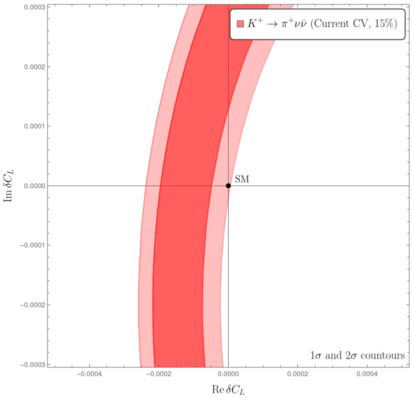


HNP in $K \to \pi\bar{\nu}\nu$: Future Prospects

- Projected $\sim$ 15% from NA62
- SM-like Central Value (90% CL):

$$|\,\mathrm{Re}\,\delta C_L| \lesssim (225\ \mathrm{TeV})^{-2}, \quad |\,\mathrm{Im}\,\delta C_L| \lesssim (100\ \mathrm{TeV})^{-2}$$

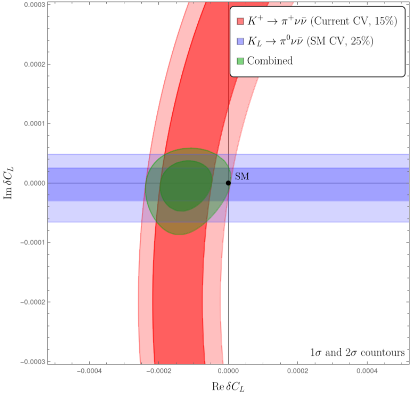
- Unchanged Central Value: Compatible at 2σ



- Projected $\sim$ 25% KOTO-II sensitivity
- SM-like Central Value (90% CL):

$$|\,\mathrm{Re}\,\delta C_L| \lesssim (240\ \mathrm{TeV})^{-2}, \quad |\,\mathrm{Im}\,\delta C_L| \lesssim (280\ \mathrm{TeV})^{-2}$$

- Unchanged NA62 Central Value: Compatible at 2σ

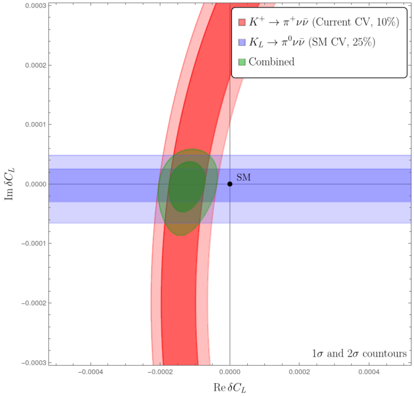


HNP in $K \to \pi\bar{\nu}\nu$: Future Prospects

- Extra NA62 data-taking: $\sim 10\%$ (optimistic)
- SM-like Central Value (90% CL):

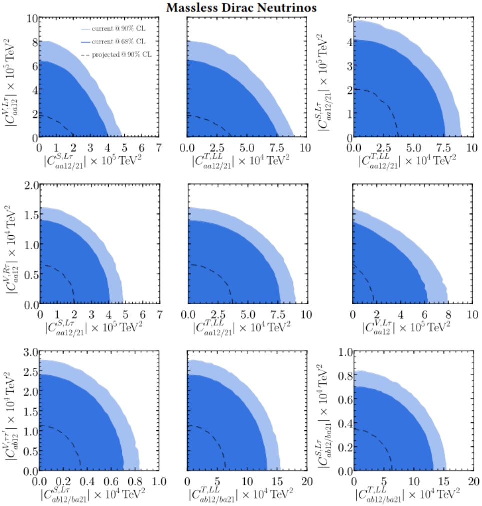
$$|\,\mathrm{Re}\,\delta C_L| \lesssim (290\ \mathrm{TeV})^{-2}, \quad |\,\mathrm{Im}\,\delta C_L| \lesssim (280\ \mathrm{TeV})^{-2}$$

- Unchanged NA62 Central Value: $\sim 3\sigma$ tension



Other BSM Operators

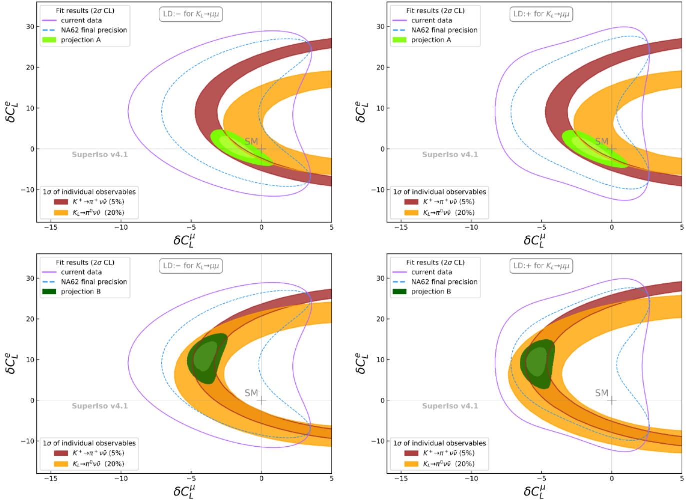
- Currently $C_i \lesssim (\sim\text{few } 10\text{s-}100\ \text{TeV})^{-2}$: will be improved in future



[Gorbahn, et al.; 2312.06494]

Other (Semi-)Leptonic Decays

- $SU(2)_L$ symmetry: $(\bar{s}_L \gamma_\mu d_L)(\bar{\ell}_L \gamma^\mu \ell_L) \Rightarrow K \to \pi\nu\bar{\nu},\ K \to \pi\ell\bar{\ell},\ K \to \ell\bar{\ell}$ complimentary



[D'Ambrosio, Mahmoudi, Neshatpour; 2311.04878]

Light New Physics

Light New Physics

- Searches less model-independent than heavy case (can "see" light dynamics)
- Plethora of possible NP models: see review [Goudzovski, et al.; 2201.07805]
- Light flavored NP can appear in many solutions to other SM problems:
  - Inflation
  - Strong CP
  - Baryogenesis
  - Dark Matter (via dark photons/Higgs portals)
  - Flavor puzzle
  - Neutrino oscillations/masses
  - And combinations thereof!

Light New Physics

- Light NP benchmarks (Physics Beyond Colliders BSM study group):

  [Beacham, et al.; 1901.09966]

1. Minimal dark photon
2. Light DM-coupled dark photon
3. Millicharged particles
4. Higgs-mixed scalar
5. Higgs-mixed scalar + pair production
6. Single HNL (U_{eN})
7. Single HNL ($U_{\mu N}$)
8. Single HNL ($U_{\tau N}$)
9. Photon-coupled ALP
10. Fermion-coupled ALP
11. Gluon-coupled ALP

$K^+ \to \pi^+ X_{\rm inv}$

- Generalized Grossman-Nir bound:

$$\mathcal{B}(K_L \to \pi^0 X) \leq 4.3 \times \mathcal{B}(K^+ \to \pi^+ X)$$

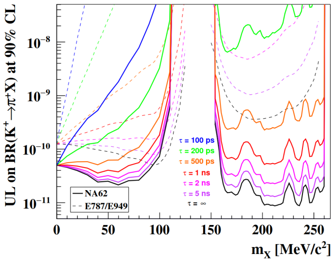
[Grossman, Nir; 9701313]

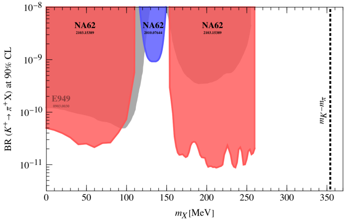
$\Rightarrow$ Stronger bounds from charged decays

- NA62 sensitive in $K^+ \to \pi^+ \bar{\nu}\nu$ signal regions: $m_X = 0 - 110$ MeV, $160 - 260$ MeV

- Can also probe $K^+ \to \pi^+(\pi^0 \to X_{\rm inv})(\gamma)$ in intermediate region [NA62; 2010.07644]

[NA62; 2103.15389]

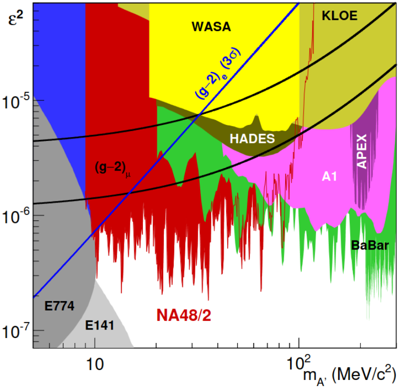




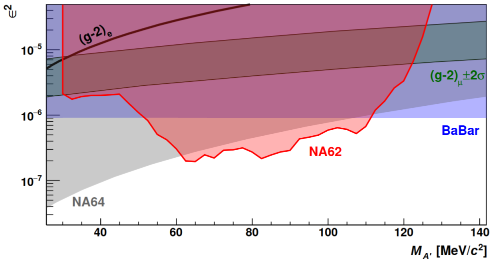
[Goudzovski, et al.; 2201.07805]

Dark Photon

[NA48/2; 1504.00607]



[NA62; 1903.08767]

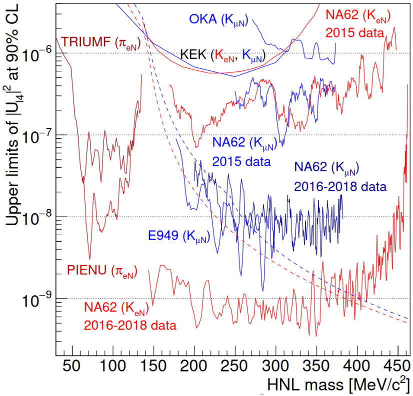


$$K^+ \to \pi^+(\pi^0 \to \gamma(A' \to e^+e^-))$$

$$K^+ \to \pi^+(\pi^0 \to \gamma A')$$

Heavy Neutral Leptons

[NA62; 2101.12304]



$$K^+ \to \ell^+ N \; (\ell = e, \mu)$$

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$$K^+ =$$

Generalized GN-violating NP

- Violations of generalized GN bound possible (almost universally light):
  1. Additional CPV in Decay (challenging to make work)
  2. New states enhance $\Delta I = 3/2$ transition [He, et al.; 2005.02942]
  3. Charge conservation: $K_L \to X^2$ vs $K^+ \to X^2 \pi^+$ [Gori, Perez, Tobioka; 2005.05170], [Hostert, Kaneta, Pospelov; 2005.07102]
  4. Charged vs neutral mass difference: $m_{K^+} - m_{\pi^+} < 2m_X < m_{K_L} - m_{\pi^0}$ [Fabbrichesi, Gabrielli; 1911.03755]
  5. Variety of experimental loopholes (blind spots, unstable $X \to$ SM, etc.)
- K_L still very important for LNP searches!

Moral of the Story

- We don't control where or what NP is!
- Kaon decays cast wide BSM net (GIM suppression/$\not{\mathcal{B}}$ enhancement)
- Simultaneously test theoretically well-understood hadronic decays
- $K^{\pm}$ and $K_{L/S}$ provide complimentary information for both HNP and LNP

Thank you!