$K \to \pi\nu\bar{\nu}$ Spectra and NA62 Interpretations

based on [arXiv: 2312.06494] and updates

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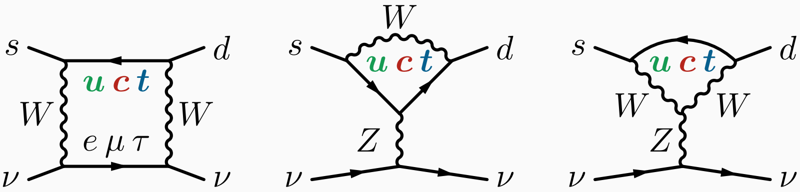
Motivation

Why Kaons?

Motivation: The Golden Kaon Modes

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



[diagrams taken from Stamou, FPCP '25]

Here:

- loop suppressed
- CKM suppressed
- hard GIM mechanism

Theory Prediction vs. Experiment

SM [Brod et al., '21]

$$\mathrm{Br}(K^+ \to \pi^+ \nu\nu)^{\mathrm{SM}} = (7.73 \pm 0.16_{\mathrm{SD}} \pm 0.25_{\mathrm{LD}} \pm 0.54_{\mathrm{param}}) \times 10^{-11}$$

$$\mathrm{Br}(K_{\mathrm{L}} \to \pi^0 \nu\nu)^{\mathrm{SM}} = (2.59 \pm 0.06_{\mathrm{SD}} \pm 0.02_{\mathrm{LD}} \pm 0.28_{\mathrm{param}}) \times 10^{-11}$$

NA62 & KOTO

$$\mathrm{Br}(K^+ \to \pi^+ \nu\nu) = (13.0^{+3.0}_{-2.7}|_{\mathrm{stat}}{}^{+1.3}_{-1.3}|_{\mathrm{syst}}) \times 10^{-11}$$ [NA62, '24]

$$\mathrm{Br}(K_{\mathrm{L}} \to \pi^0 \nu\nu) < 3.0 \times 10^{-9} \text{ @ } 90\,\%\ \mathrm{CL}$$ [KOTO, '19]

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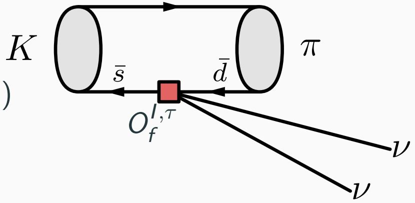
Here: New Physics analysis using the full experimental information

Theory: New Physics



Weak Effective Theory

$$\mathcal{L}^{\text{dim}-6}_{s\to d\nu\nu} = \sum_{f,I,\tau} C_f^{I,\tau} O_f^{I,\tau} (+\,\text{h.c.})$$

Dirac

$$O_{ijsd}^{V,L/R\,L/R} = \left(\bar{\nu}_{Di}\gamma_\mu P_{L/R}\nu_{Dj}\right)\left(\bar{d}\gamma^\mu P_{L/R}s\right)$$
$$O_{ijsd}^{S,L\,L/R} = \left(\bar{\nu}_{Di}P_L\nu_{Dj}\right)\left(\bar{d}P_{L/R}s\right)$$
$$O_{ijsd}^{T,LL} = \left(\bar{\nu}_{Di}\sigma_{\mu\nu}P_L\nu_{Dj}\right)\left(\bar{d}\sigma^{\mu\nu}P_Ls\right)$$

⇒ 90 independent complex Wilson coefficients

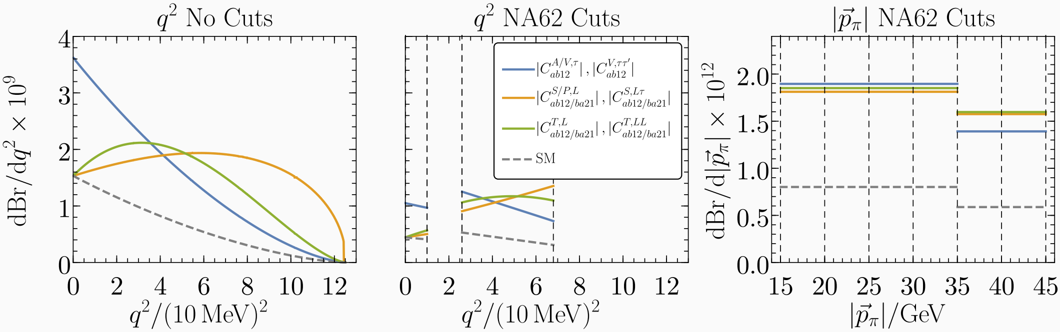
Majorana

$$O_{ijsd}^{V(A),L/R} = \frac{1}{2}\left(\bar{\nu}_{Mi}\gamma_\mu(\gamma_5)\nu_{Mj}\right)\left(\bar{d}\gamma^\mu P_{L/R}s\right)$$
$$O_{ijsd}^{S(P),L} = \frac{1}{2}\left(\bar{\nu}_{Mi}(i\gamma_5)\nu_{Mj}\right)\left(\bar{d}P_Ls\right)$$
$$O_{ijsd}^{T,L} = \frac{1}{2}\left(\bar{\nu}_{Mi}\sigma_{\mu\nu}\nu_{Mj}\right)\left(\bar{d}\sigma^{\mu\nu}P_Ls\right)$$

⇒ 48 independent complex Wilson coefficients

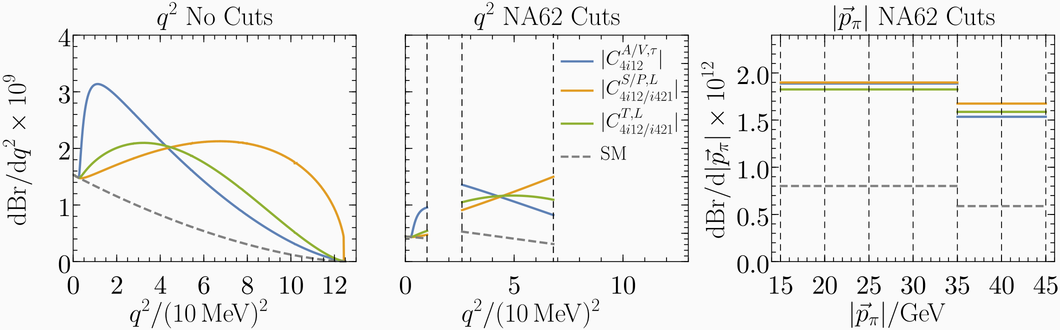
Theory: Spectra I

3 massless (Dirac or Majorana) neutrinos [Gorbahn et al., '23]



$C_f^{l,\tau}$ saturate limits @ 90 % CL (2016–2018 data) [NA62, '21]

Additional sterile neutrino with $m_{\nu,4} = 50\,\text{MeV}$ [Gorbahn et al., '23]



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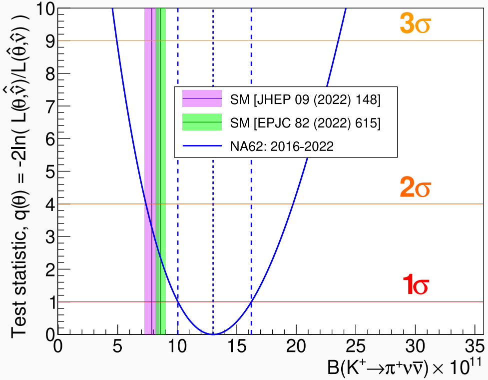
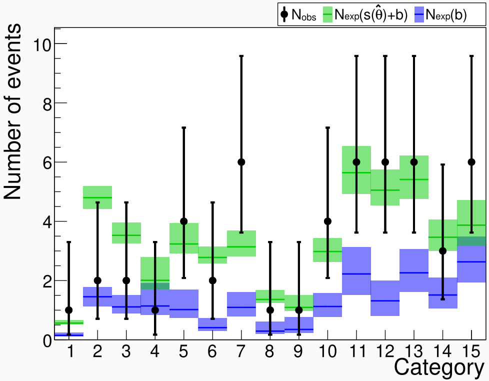
Experimental Results

Combination of data samples 2016–2022 [NA62, '24]





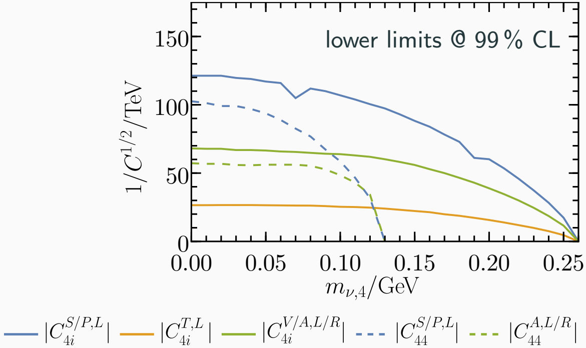
Results: New Physics Sensitivities

3 SM Majorana neutrinos and 1 additional sterile neutrino with mass $m_{\nu,4}$

(quark flavour indices suppressed in the following)

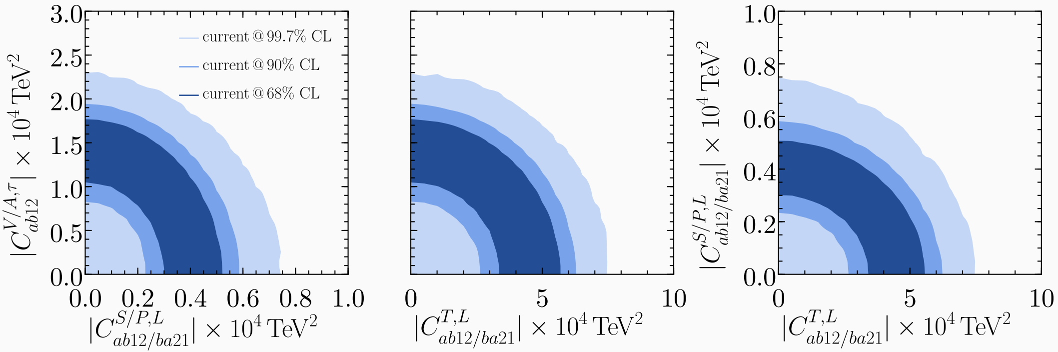
$\rightarrow$ Current reach:

New Physics scale $\gtrsim \mathcal{O}(100\,\text{TeV})$



Results: New Physics Correlations

For example new off-diagonal Majorana neutrino couplings



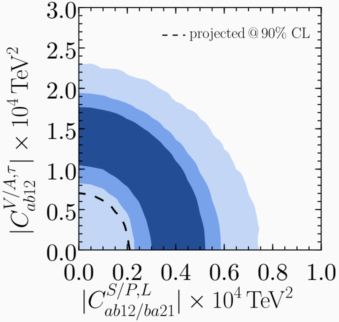
$\rightarrow$ e.g. for this specific setup: 2.1–2.7 σ preference depending on SM prediction.

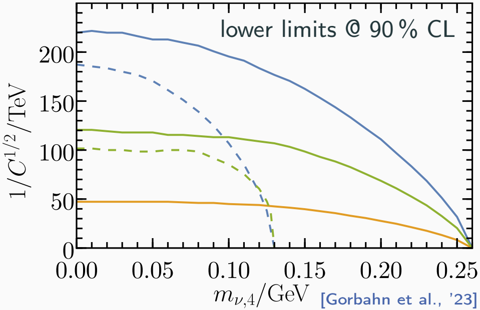
What could have been: HIKE

- If slight excess confirmed

→ projected final statistical uncertainty allows $5\,\sigma$ rejection of SM hypothesis [2503.22256]

SM like projections:



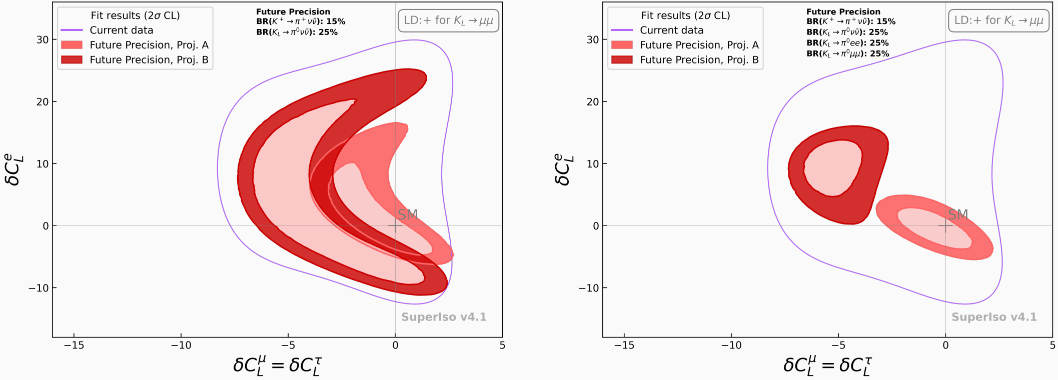


[Gorbahn et al., '23]

→ Potential reach: New Physics scale $\gtrsim \mathcal{O}(300\,\mathrm{TeV})$

Future Opportunities: KOTO and KOTO II

e.g. taken from [D'Ambrosio et al, '24]:



Summary and Outlook

- Studied impact of a massive sterile neutrino on the invisible mass spectrum
- Model-independent constraints on various New Physics scenarios
- Currently sensitive to New Physics up to $\mathcal{O}(100\,\text{TeV})$

  $\Rightarrow$ strong motivation for future Kaon programs

Outlook

- SMEFT or specific UV models $\rightarrow$ correlations between different operators

  $\Rightarrow$ distinguish between Majorana and Dirac neutrinos
- correlations with other Kaon modes