Lepton universality in K decays

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Cédric Weiland
in collaboration with A. Abada, D. Das, A.M. Teixeira and A. Vicente

Laboratoire de Physique Théorique d'Orsay, Université Paris-Sud 11, France

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Neutrino oscillations and masses

- Neutrino oscillations:
  - solar $\nu_e \to \nu_{\text{others}}$: $\theta_{12} \simeq 33^\circ$, $\Delta m^2_{12} \simeq 7.5 \times 10^{-5}\text{eV}^2$ (best fit)
  - atmospheric $\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_\tau$: $\theta_{23} \simeq 40^\circ$ or 50°, $\Delta m^2_{23} \simeq 2.4 \times 10^{-3}\text{eV}^2$ (best fit)
  - reactor $\bar{\nu}_e \to \bar{\nu}_{\text{others}}$: $\theta_{13} \simeq 8.7^\circ$ (best fit)
  - accelerator $\nu_\mu \to \nu_{\text{others}}$

- Oscillations $\Rightarrow$ Non-diagonal charged currents

$$\mathcal{L}_{\text{int}} = -\frac{g}{\sqrt{2}} \boldsymbol{U_\nu^{ji}} \bar{\ell}_j \gamma^\mu P_L \nu_i W^-_\mu + \text{h.c.}$$

- 3 mass eigenstates $\nu_i = \nu_1, \nu_2, \nu_3$ different from the interaction eigenstates $\nu_\alpha = \nu_e, \nu_\mu, \nu_\tau$

$$\nu_\alpha = \boldsymbol{U_\nu^{\alpha i}} \nu_i$$

$\Rightarrow$ $\boldsymbol{U_\nu}$ is a 3×3 unitary matrix, the PMNS matrix

Leptonic kaon decays

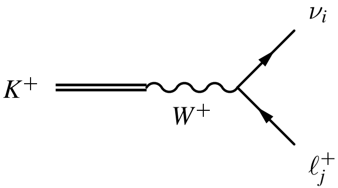
- Focus on $K \to \ell\nu$ decays, more precisely on:

$$R_K \equiv \frac{\Gamma(K^+ \to e^+\nu)}{\Gamma(K^+ \to \mu^+\nu)}$$

- Well measured by the NA62 collaboration [Lazzeroni et al., 2013]:
  $R_K^{\text{exp}} = (2.488 \pm 0.010) \times 10^{-5}$
- SM prediction is very precise [Finkemeier, 1996, Cirigliano and Rosell, 2007]:
  $R_K^{\text{SM}} = (2.477 \pm 0.001) \times 10^{-5}$
- New Physics: $R_K^{\text{NP}} = R_K^{\text{SM}}(1 + \Delta r_K)$
  - tree-level corrections are usually lepton universal
  - higher-order corrections are limited by other observables (*e.g.* $\Delta r_K \lesssim 10^{-3}$ in unconstrained minimal SUSY models [Fonseca et al., 2012])

Impact of singlet neutrinos

- Singlet neutrino = Interaction eigenstate with no coupling to gauge bosons (*e.g.* fermionic singlet in type-I seesaw)
- Modification of the charged weak current: U_ν becomes a $3 \times n_\nu$ non-unitary matrix with $n_\nu > 3$
- Could affect at tree-level many observables containing a $W - \ell - \nu$ vertex [Schrock, 1980, 1981]



Deviation from universality

- Summing over all the kinematically accessible neutrinos (from 1 to $N^{(e)}_{\text{max}}$, $N^{(\mu)}_{\text{max}}$ the heaviest kinematically allowed neutrino) :

$$R_K = \frac{\sum_{i=1}^{N^{(e)}_{\text{max}}} |U_\nu^{1i}|^2 G^{i1}}{\sum_{k=1}^{N^{(\mu)}_{\text{max}}} |U_\nu^{2k}|^2 G^{k2}} \quad \text{with}$$

$$G^{ij} = \left[m_K^2(m_{\nu_i}^2 + m_{l_j}^2) - (m_{\nu_i}^2 - m_{l_j}^2)^2\right]\left[(m_K^2 - m_{l_j}^2 - m_{\nu_i}^2)^2 - 4m_{l_j}^2 m_{\nu_i}^2\right]^{1/2}$$

- In the SM, $R_K^{SM} = \frac{m_e^2}{m_\mu^2}\frac{(m_K^2-m_e^2)^2}{(m_K^2-m_\mu^2)^2}$

  because $G^{i1} = G^{j1}$ and $\sum_{i=1}^{n_\nu} |U_\nu^{1i}|^2 = (U_\nu U_\nu^\dagger)_{11} = 1$

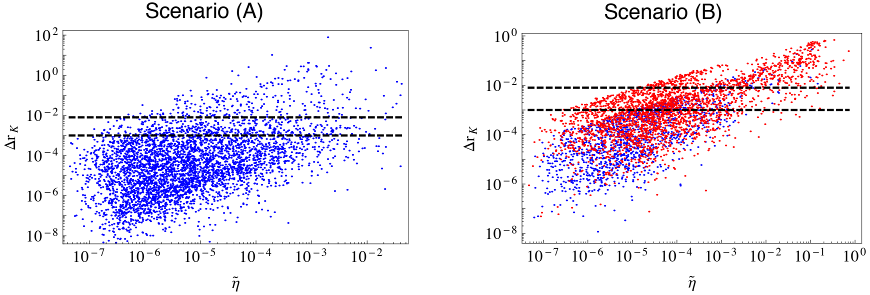
- 2 ways to deviate from universality:
  - (A) sterile neutrinos are lighter than m_K, with $m_\nu^{\text{active}} \ll m_{\nu_s} \lesssim m_K$
  - (B) sterile neutrinos are heavier than m_K

Δr_K in the inverse seesaw model

- Inverse seesaw: low-scale seesaw mechanism
  - Add fermionic singlets
  - Smallness of the active neutrino mass related to the smallness of the Majorana mass μ_X

$$\mathcal{L}_{\text{ISS}} = \mathcal{L}_{SM} - Y_\nu^{ij}\bar{L}_i\tilde{H}\nu_{Rj} - M_{R_{ij}}\,\bar{\nu}_{Ri}X_j - \frac{1}{2}\mu_{X_{ij}}\bar{X}_i^c X_j + \text{h.c.}$$

$$R_K^{\text{NP}} = R_K^{\text{SM}}\,(1 + \Delta r_K)$$



Contributions to Δr_K in the inverse seesaw as a function of $\tilde{\eta} = 1 - |\text{Det}(\tilde{U}_{\text{PMNS}})|$

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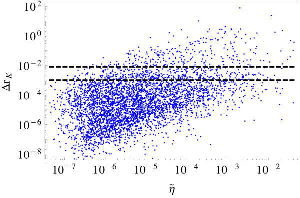
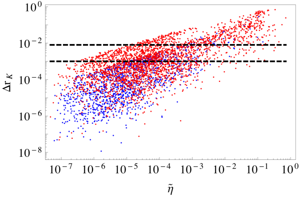
Scenario (A)



Scenario (B)



Contributions to Δr_K in the inverse seesaw as a function of $\tilde{\eta} = 1 - |\text{Det}(\tilde{U}_{\text{PMNS}})|$

Conclusion

- Sterile neutrinos can lead to a large violation of lepton universality at tree-level
- R_K particularly well-suited for this search
- Large deviations from the SM can be found ($\Delta r_K \sim \mathcal{O}(1)$, already excluded by NA62)
- Can appear in other leptonic or semileptonic meson decays

Backup–Constraints

- Direct sterile neutrino searches (monochromatic lines in meson decays): scenario (A) and (B)
- Non-unitarity of the leptonic mixing matrix: scenario (B)
- Lepton flavour violation: scenario (A) and (B)
- LHC SM scalar searches and electroweak precision data: scenario (B)
- Cosmological observations: scenario (A) and (B) but disappear in non-standard cosmology (*e.g.* low reheating temperature)

The Inverse Seesaw Mechanism

- Inverse seesaw: $M_R \simeq 1$ TeV with natural Yukawa $Y_\nu \sim \mathcal{O}(1)$
  $\Rightarrow$ cLFV is much less suppressed
  $\rightarrow$ Might be testable at the LHC and future B factories (Belle II)
- Inverse seesaw $\Rightarrow$ Consider fermionic gauge singlets ν_{Ri} ($L = -1$, $i = 1, 2, 3$) and X_i ($L = +1$, $i = 1, 2, 3$)
  [Mohapatra and Valle, 1986]

$$\mathcal{L}_{\text{ISS}} = \mathcal{L}_{SM} - Y_\nu^{ij} \bar{L}_i \tilde{H} \nu_{Rj} - M_{R_{ij}} \bar{\nu}_{Ri} X_j - \frac{1}{2} \mu_{X_{ij}} \bar{X}_i^c X_j + \text{h.c.}$$

With $m_D = Y_\nu \mathrm{v}$, $\mathcal{M} = \begin{pmatrix} 0 & m_D & 0 \\ m_D^T & 0 & M_R \\ 0 & M_R^T & \mu_X \end{pmatrix}$

$$m_\nu \approx \frac{m_D^2 \mu_X}{m_D^2 + M_R^2}$$

$$m_{1,2} \approx \mp\sqrt{m_D^2 + M_R^2} + \frac{M_R^2 \mu_X}{2(m_D^2 + M_R^2)}$$