Light sterile neutrinos and $\mathrm{R_K}$

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ArXiv:1211.3052

Introduction

Violations of lepton flavor universality are among the most precise tests of the Standard Model.

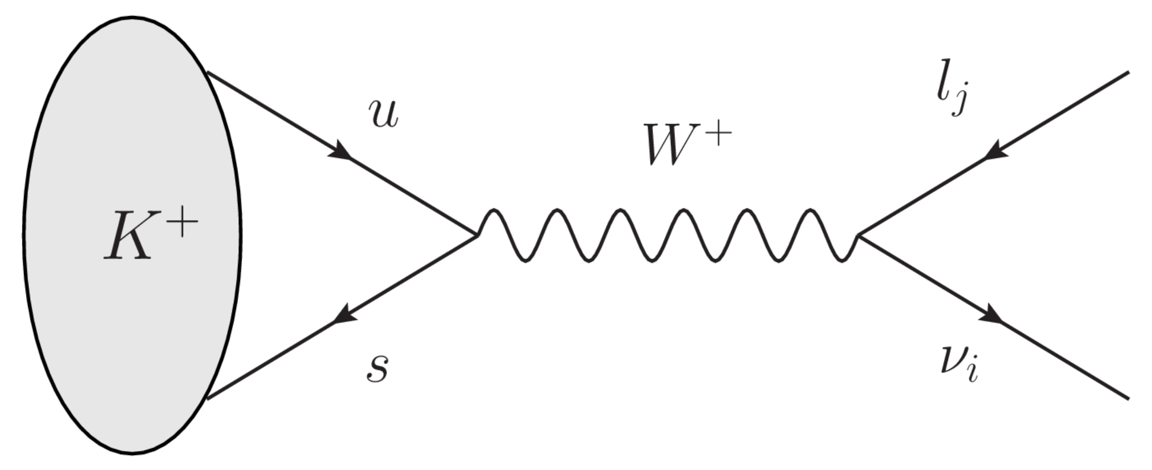
$$R_K = \frac{\Gamma(K^+ \to e^+\nu)}{\Gamma(K^+ \to \mu^+\nu)}$$

Measured in the NA62 experiment using a beam of kaons from the CERN SPS

Current experimental error: $\frac{\delta R_K}{R_K} \sim 0.4\%$

Expected sensitivity: $\frac{\delta R_K}{R_K} \sim 0.1\%$

R_K in the SM



V. Cirigliano, I. Rosell, PRL 99 (2007) 231801

$$R_K^{SM} = \left(\frac{m_e}{m_\mu}\right)^2 \left(\frac{m_K^2 - m_e^2}{m_K^2 - m_\mu^2}\right)^2 (1 + \delta R_{QED}) = (2.477 \pm 0.001) \times 10^{-5}$$

SM result

Helicity suppression

Small QED corrections

R_K in the SM

Experimental value:
(2011)

$$R_K^{exp} = (2.488 \pm 0.010) \times 10^{-5}$$

NA62 Collaboration

$$R_K^{SM} = (2.477 \pm 0.001) \times 10^{-5}$$

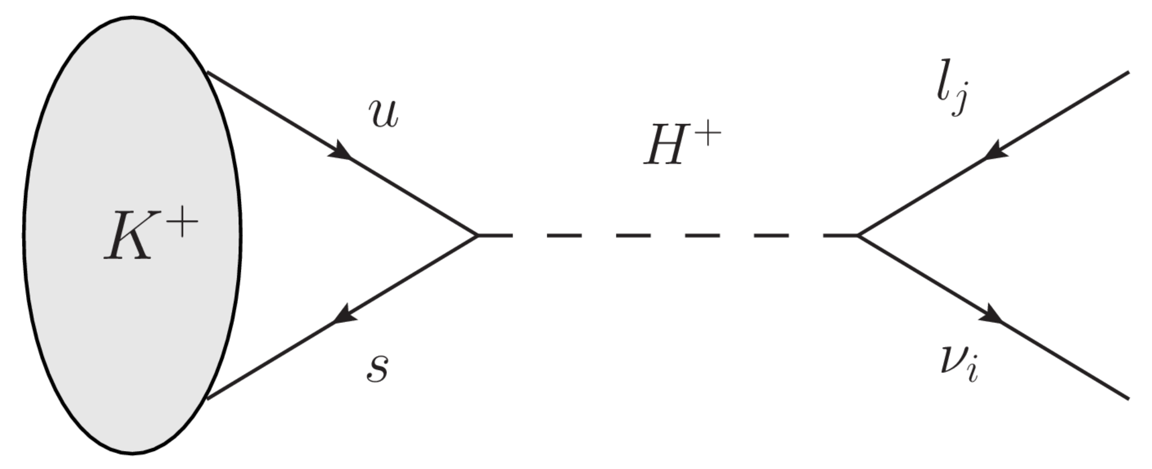
$$R_K = R_K^{SM}(1 + \Delta r)$$

$$\Delta r_K = (4 \pm 4) \times 10^{-3}$$

How to modify R_K?

- **In a 2HDM:**

W.-S. Hou, PRD 48 (1993) 2342



$$\Gamma(K^\pm \to l^\pm \nu) = \Gamma^{\rm SM}(K^\pm \to l^\pm \nu) \left(1 - \tan^2\beta \, \frac{m_K^2}{m_H^2} \frac{m_s}{m_s + m_u}\right)^2$$

⇨ The correction is lepton universal

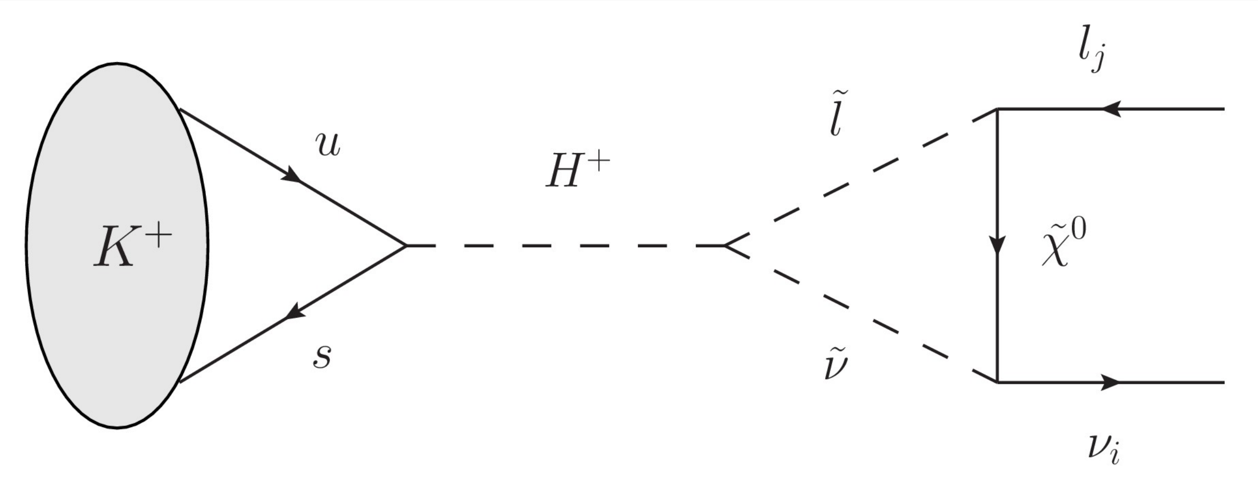
R_K is not modified

How to modify R_K?

Higher order corrections are required

- **In SUSY:**

A. Masiero, P. Paradisi, R. Petronzio, PRD 74 (2006) 011701



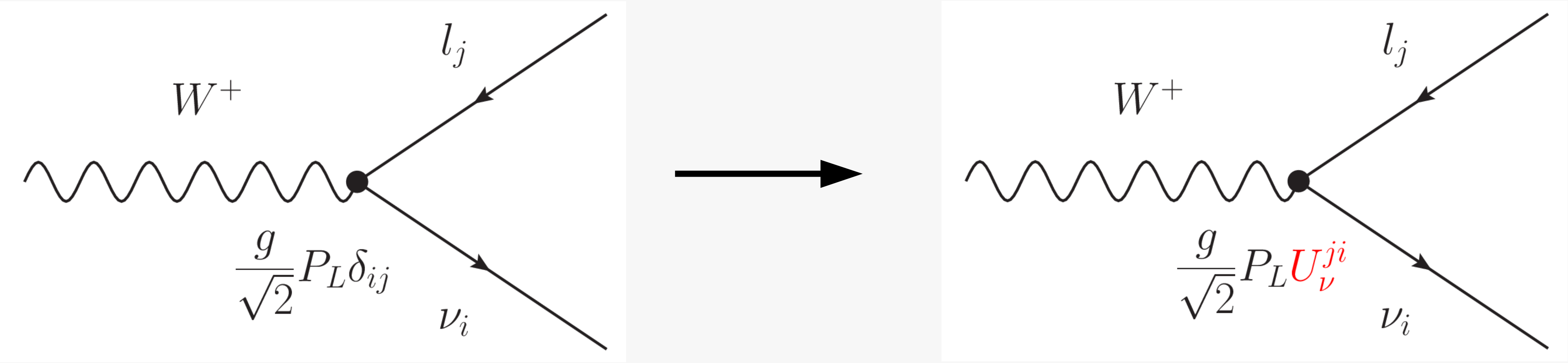
R. M. Fonseca, J. C. Romão, A. M. Teixeira, arXiv:1205.1411

Taking into account current constraints from $B \to \tau\nu$ one can go up to

$$\Delta r_K \lesssim 10^{-3}$$

A different scenario

Let us now consider non-zero neutrino masses and mixings...



$$\Delta r_K = \frac{m_\mu^2}{m_e^2} \frac{(m_K^2 - m_\mu^2)^2}{(m_K^2 - m_e^2)^2} \frac{\sum_m |U_\nu^{1m}|^2 G^{m1}}{\sum_n |U_\nu^{2n}|^2 G^{n2}} - 1$$

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

A different scenario

However, under the assumptions...

1) $m_{\nu_i}^2 \ll m_K^2, m_{l_j}^2$

$$\Rightarrow \quad G^{ij} \simeq m_{l_j}^2 (m_K^2 - m_{l_j}^2)^2$$

$$\Delta r_K \simeq \frac{\sum_m |U_\nu^{1m}|^2}{\sum_n |U_\nu^{2n}|^2} - 1$$

2) $\sum_i |U_\nu^{ji}|^2 = 1$

$\Delta r_K \simeq 0$ No deviation from the SM result

Dropping the assumptions

1) $m_{\nu_i}^2 \xcancel{\ll m_K^2}, m_{l_j}^2$

Additional neutrino states can be produced in the kaon decay

Sterile neutrinos with masses $m_N \lesssim m_K$

2) $\sum_i |U_\nu^{ji}|^2 = 1$

Dropping the assumptions

1) $m_{\nu_i}^2 \ll m_K^2, m_{l_j}^2$

Sterile neutrinos with masses $m_N > m_K$

2) $\sum_i \xcancel{|U_i^{ji}|^2} = 1$

Deviation from unitarity

Large mixings are necessary

Viable scenario?

This scenario was actually proposed more than 30 years ago...

R. E. Shrock, Phys. Lett. B 96 (1980) 159
R. E. Shrock, Phys. Rev. D 24 (1981) 1232

Things have changed a lot since then...

Is this scenario compatible with current constraints?

Constraints

There are, however, some constraints...

1) Lepton flavor violation

F. Deppisch, J. W. F. Valle, PRD 72 (2005) 036001

$$\mathrm{Br}(\mu \to e\gamma) = \frac{\alpha_W^3 s_W^2 m_\mu^5}{256\pi^2 m_W^4 \Gamma_\mu}|H_{\mu e}|^2 \quad , \quad H_{\mu e} = \sum_i U_\nu^{2i} U_\nu^{1i\,*} G_\gamma\left(\frac{m_{\nu,i+3}^2}{m_W^2}\right)$$

$$\mathrm{Br}(\mu \to e\gamma)_{\mathrm{MEG}} = 2.4 \cdot 10^{-12}$$

2) Non-unitarity bounds

S. Antusch et al, Nucl. Phys. B 810 (2009) 369

$$U_{3\times3} = (1-\eta)U_{PMNS}$$

Strongly constrained
if $m_N > m_{EW}$

Constraints

3) Laboratory bounds: direct searches for sterile neutrinos

A. Atre et al, JHEP 0905 (2009) 030

A. Kusenko, Phys.Rept. 481 (2009) 1

Bounds from decays like

$$\pi^\pm \to \mu^\pm \nu$$

(they would lead to monochromatic lines in the muon spectrum)

4) B physics

$$\mathrm{Br}(B \to e\nu) < 9.8 \cdot 10^{-7}$$

$$\mathrm{Br}(B \to \mu\nu) < 10^{-6}$$

$$\mathrm{Br}(B \to \tau\nu) = (1.65 \pm 0.34) \cdot 10^{-4}$$

Constraints

5) LHC bounds

P. S. Bhupal Dev et al, arXiv:1207.2756
C. García Cely et al, arXiv:1208.3654
P. Bandyopadhyay et al, arXiv:1209.4803

Indirect bounds from Higgs searches

$$h \to \nu_R \nu_L$$

Relevant for sterile neutrino masses around 100 GeV

6) EW precision data

F. Del Aguila et al, PRD 78 (2008) 013010

Leptonic mixing affects EW precision data fits

Apply to sterile neutrino masses $\gtrsim$ 1 TeV

Constraints

7) Cosmological bounds on sterile neutrinos

A. Y. Smirnov, R. Zukanovich Funchal, PRD 74 (2006) 013001

A. Kusenko, Phys.Rept. 481 (2009) 1

- Large scale structure
- Lyman-α limits
- BBN
- CMB
- X-ray constraints (from $\nu_i \to \nu_j \gamma$)

However, cosmological bounds can be evaded with a non-standard cosmology (for example, low reheating temperature)

G. Gelmini *et al*, JCAP 0810 (2009) 029

An example model

R. N. Mohapatra, J. W. F. Valle, PRD 34 (1986) 1642

An example model: Inverse Seesaw

$$-\mathcal{L}_{IS} \supset Y_\nu^{ij} \nu_i^c L_j \tilde{H} + M_{R_{ij}} \nu_i^c X_j + \frac{1}{2} \mu_{X_{ij}} X_i X_j$$

- 6 additional singlet states: 3 generations of ν^c and 3 generations of X
- Non-zero neutrino masses. In the limit $\mu_X \ll Y_\nu v \ll M_R$:

$$m_\nu \simeq \frac{v^2}{2} Y_\nu^T (M_R^T)^{-1} \mu_X M_R^{-1} Y_\nu$$

- The suppression by μ_X allows to have (in principle) $Y_\nu \sim \mathcal{O}(1)$

Large mixings and light sterile neutrinos are possible

An example model

The 9 neutrinos participate in the charged current interaction through their LH admixture

$$-\mathcal{L}_{cc} = \frac{g}{\sqrt{2}} U_\nu^{ji} \bar{l}_j \gamma^\mu P_L \nu_i W_\mu^- + \text{c.c.}$$

$$i = 1, \dots, 9$$

$$j = 1, \dots, 3$$

We have all the ingredients for a large contribution to R_K

Numerical results

Random scan of the parameter space of the inverse seesaw, filtered by all previous constraints.

We only fix active neutrino masses and mixings in order to reproduce neutrino oscillation data

Scenario 1

$$m_N \lesssim m_K$$

$$M_R \in [0.1, 200] \, \text{MeV}$$

$$\mu_X \in [0.01 \, \text{eV}, 1 \, \text{MeV}]$$

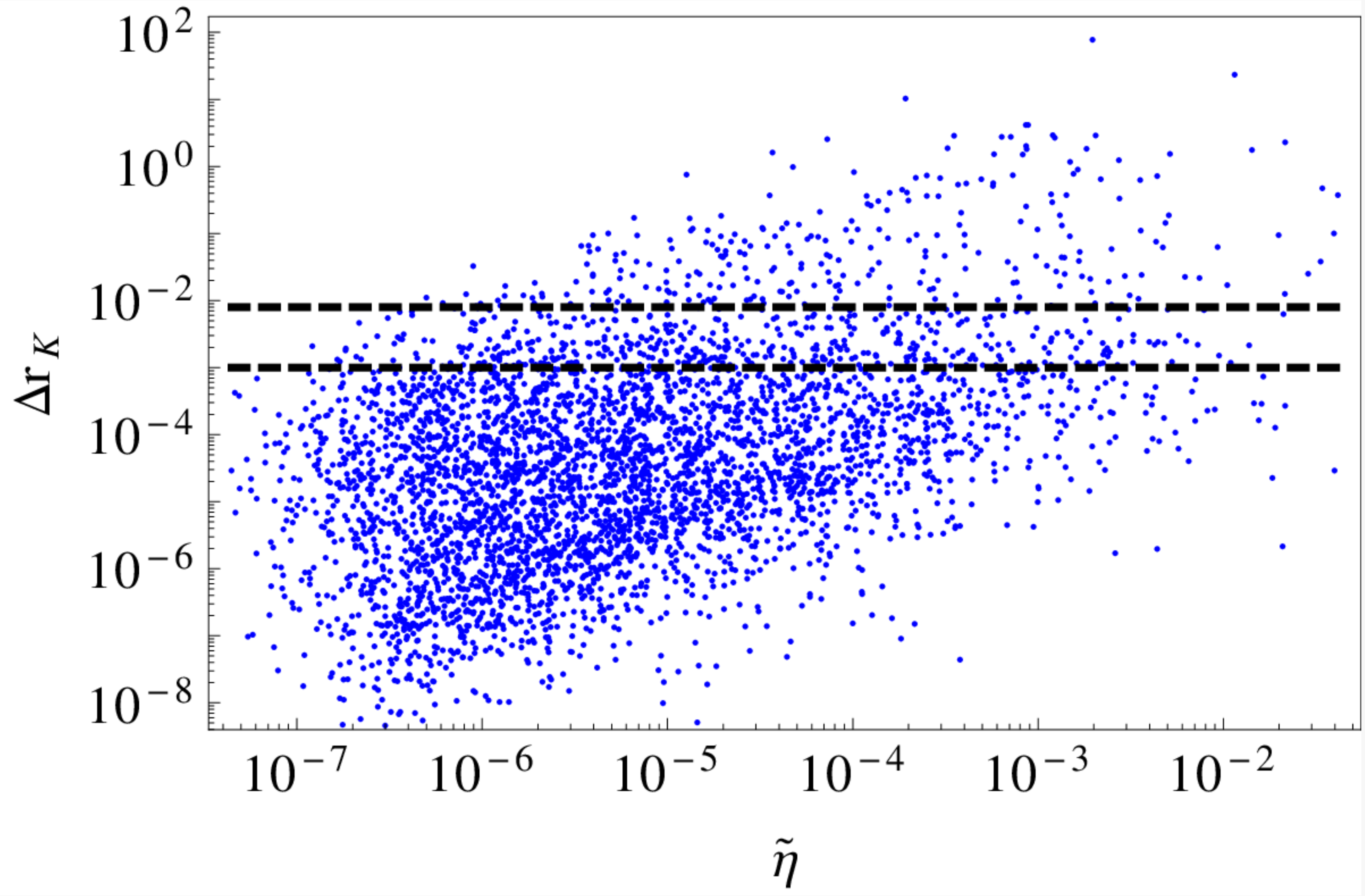
Scenario 2

$$m_N > m_K$$

$$M_R \in [1, 10^6] \, \text{GeV}$$

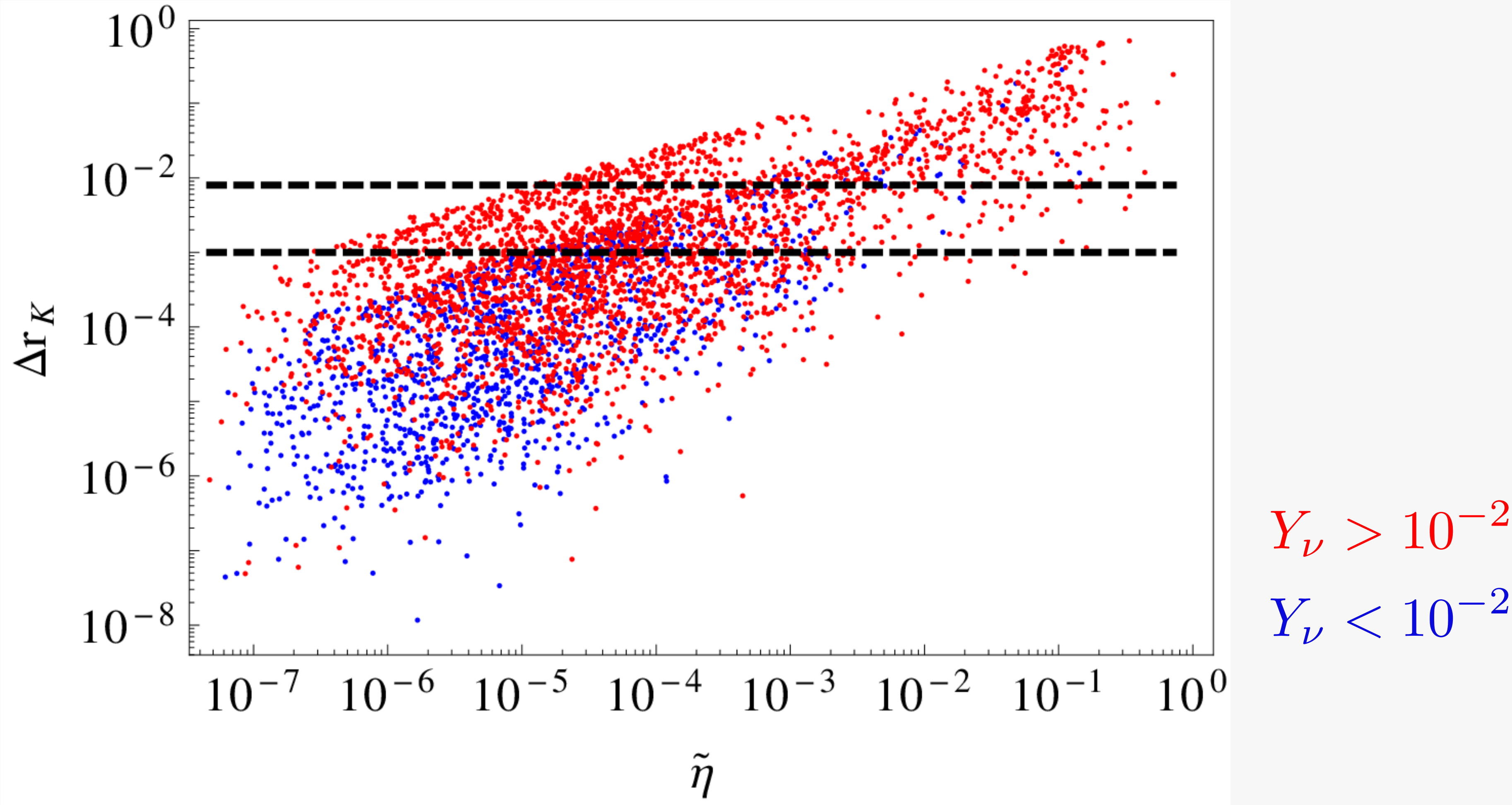
$$\mu_X \in [0.01 \, \text{eV}, 1 \, \text{MeV}]$$

Scenario 1 : $m_N \lesssim m_K$



- Here $\tilde{\eta} = 1 - \mathrm{Det}(U_{3\times3})$ measures the deviation from unitarity.
- $\Delta r_K \sim \mathcal{O}(1)$ can be reached: very good perspectives for NA62.

Scenario 2 : $m_N > m_K$



- In this scenario one can also go up to $\Delta r_K \sim \mathcal{O}(1)$
- Strong limits from non-unitarity and EW precision data apply in this case.

Conclusions

- Lepton universality violating observables are very good tests of the SM: high precision (theory & experiment)
- The presence of “light” sterile neutrinos can modify R_K in a very substantial way.
- Two scenarios have been considered: good perspectives in both!
- Stay tuned to NA62...

Thank you!