

# Light sterile neutrinos and $R_K$

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Based on work in collaboration with  
A. Abada, D. Das, A. M. Teixeira and C. Weiland

ArXiv:1211.XXXX

# Introduction

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

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

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

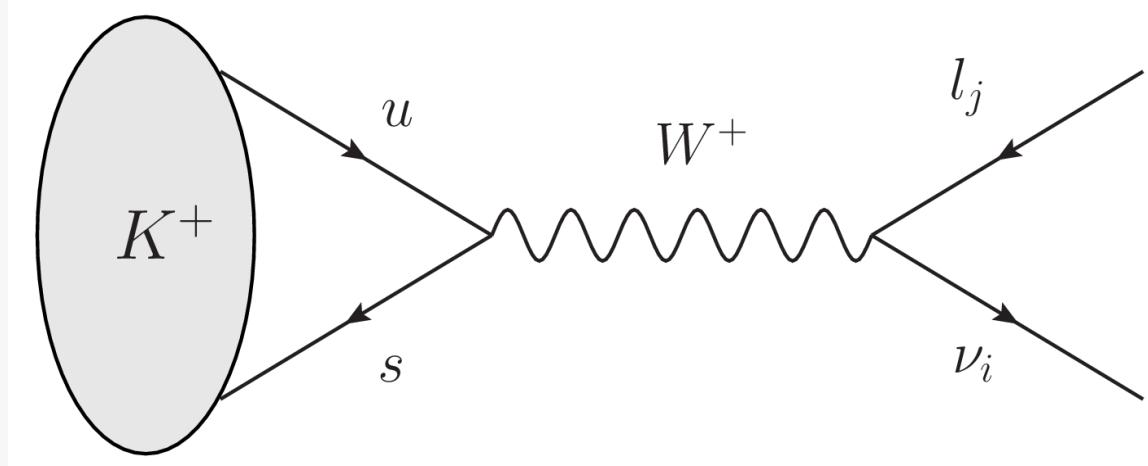
Current experimental error:

$$\frac{\delta R_K}{R_K} \sim 0.4\%$$

Expected sensitivity:

$$\frac{\delta R_K}{R_K} \sim 0.1\%$$

# $R_K$ in the SM



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

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

↑  
Helicity suppression

↑  
Small QED corrections

SM result

# $R_K$ in the SM

Experimental value:  
(2011)  $R_K^{exp} = (2.488 \pm 0.010) \times 10^{-5}$

NA62 Collaboration

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

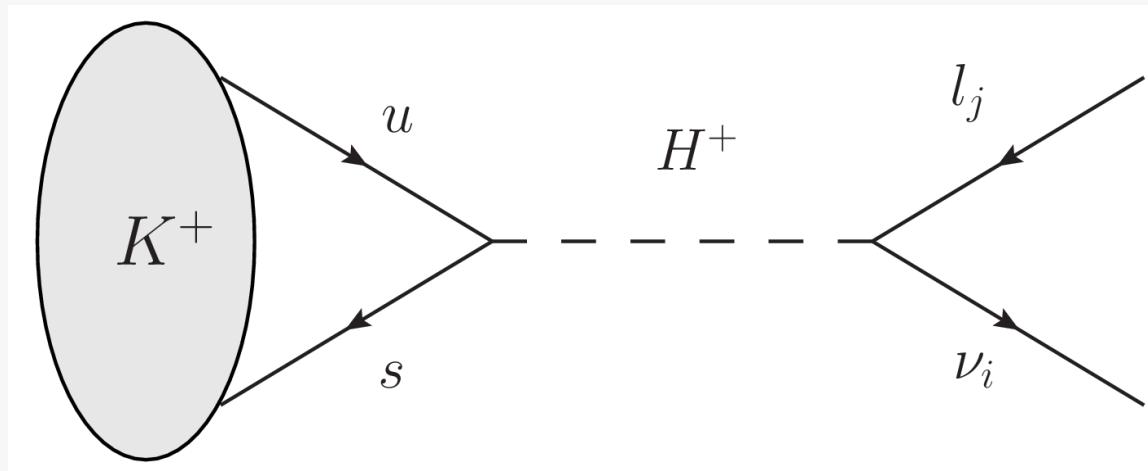
$$R_K = R_K^{SM} (1 + \Delta r)$$

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

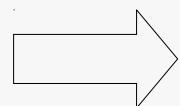
# How to modify $R_K$ ?

- In a 2HDM:

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



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



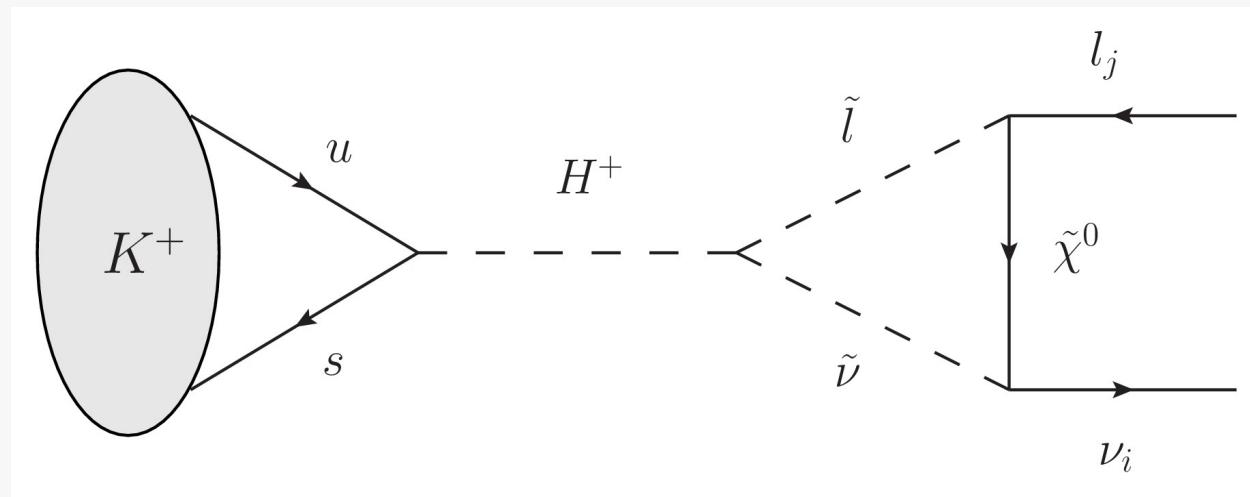
The correction is **lepton universal**  
 $R_K$  is **not** modified

# How to modify $R_K$ ?

Higher order corrections are required

- In SUSY:

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



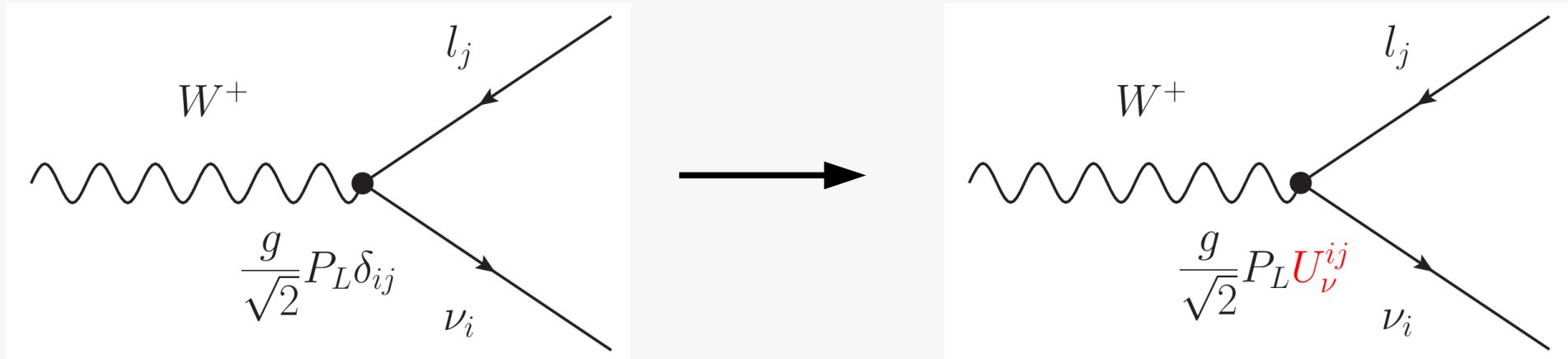
R. M. Fonseca, J. C. Romão, A. M. Teixeira, arXiv:1205.1411

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

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

# A different scenario

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



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

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

# A different scenario

However, under the **assumptions**...

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

$$\begin{aligned} G^{ij} &= (m_K^2 - m_{l_j}^2 - m_{\nu_i}^2) \left[ (m_K^2 - m_{l_j}^2 - m_{\nu_i}^2)^2 - 4m_{l_j}^2 m_{\nu_i}^2 \right]^{1/2} \\ &\simeq (m_K^2 - m_{l_j}^2)^2 \end{aligned}$$

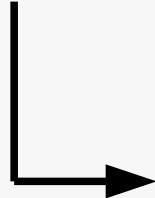
$$\Delta r_K \simeq \frac{\sum_m |U_\nu^{m1}|^2}{\sum_n |U_\nu^{n2}|^2} - 1$$

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

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

# Dropping the assumptions

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



Additional neutrino states can be produced in the kaon decay

Sterile neutrinos with masses  $m_N \lesssim m_K$

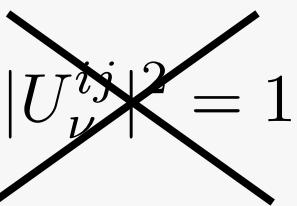
2)  $\sum_i |U_\nu^{ij}|^2 = 1$

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



Deviation from **unitarity**  
**Large mixings** are necessary

# Constraints

There are, however, some **constraints**...

## 1) Lepton flavor violation

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

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

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

## 2) Non-unitarity bounds

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

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



Strongly **constrained**  
if  $m_N > m_{EW}$

# Constraints

## 3) Laboratory bounds: direct searches for sterile neutrinos

Bounds from decays like

$$\pi^\pm \rightarrow \mu^\pm \nu$$

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

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

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

## 4) B physics

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

$$\text{Br}(B \rightarrow \mu\nu) < 10^{-6}$$

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

# Constraints

## 5) LHC bounds

Indirect bounds from **Higgs searches**

P. S. Bhupal Dev et al, arXiv:1207.2756

C. García Cely et al, arXiv:1208.3654

P. Bandyopadhyay et al, arXiv:1209.4803

$$h \rightarrow \nu_R \nu_L$$

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- $\alpha$  limits
- BBN
- CMB
- X-ray constraints (from  $\nu_i \rightarrow \nu_j \gamma$ )

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  $\nu^c$  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  $\mu_X$  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

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

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

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

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

$$m_N \lesssim m_K$$

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

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

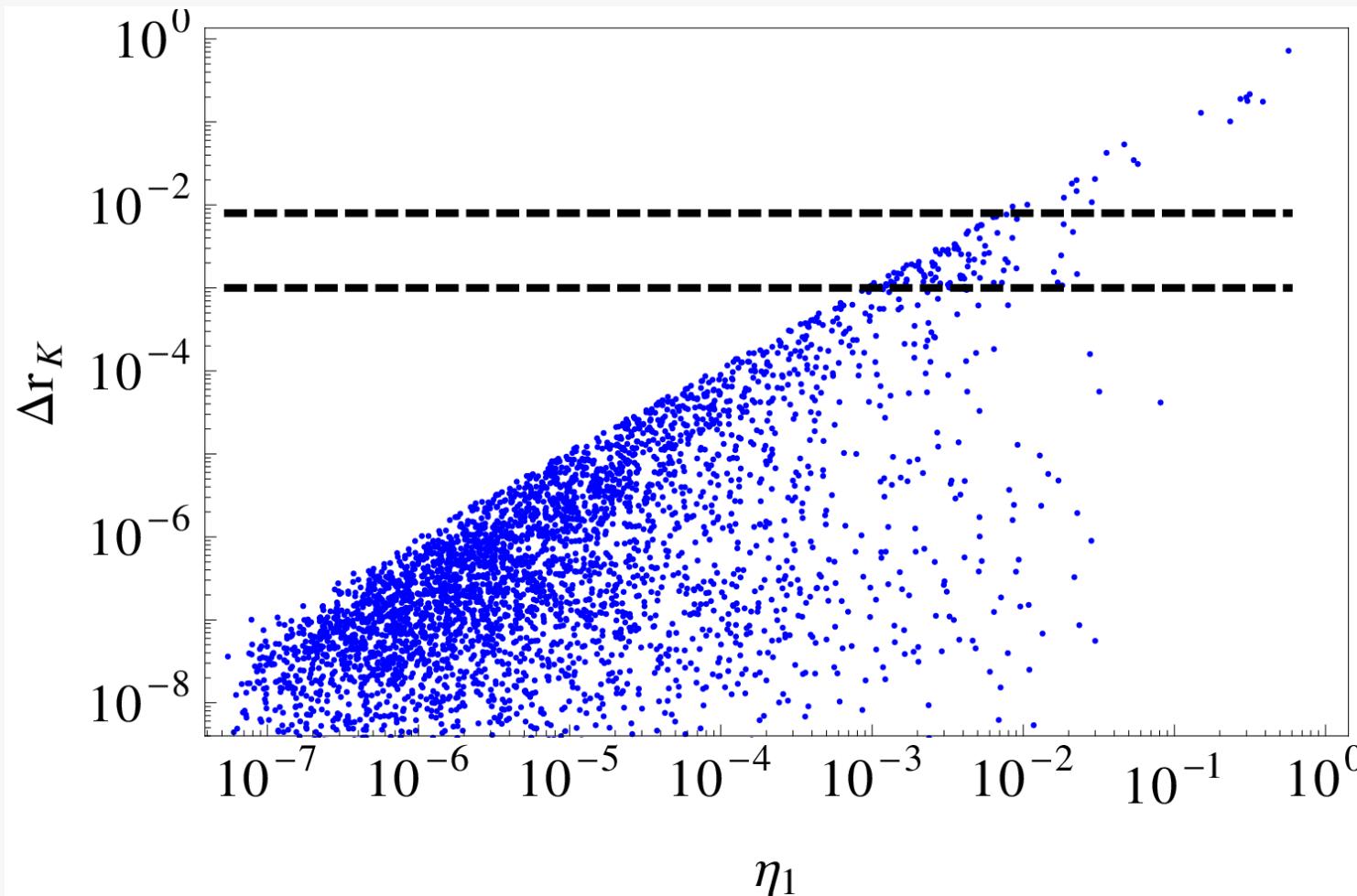
## Scenario 2

$$m_N > m_K$$

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

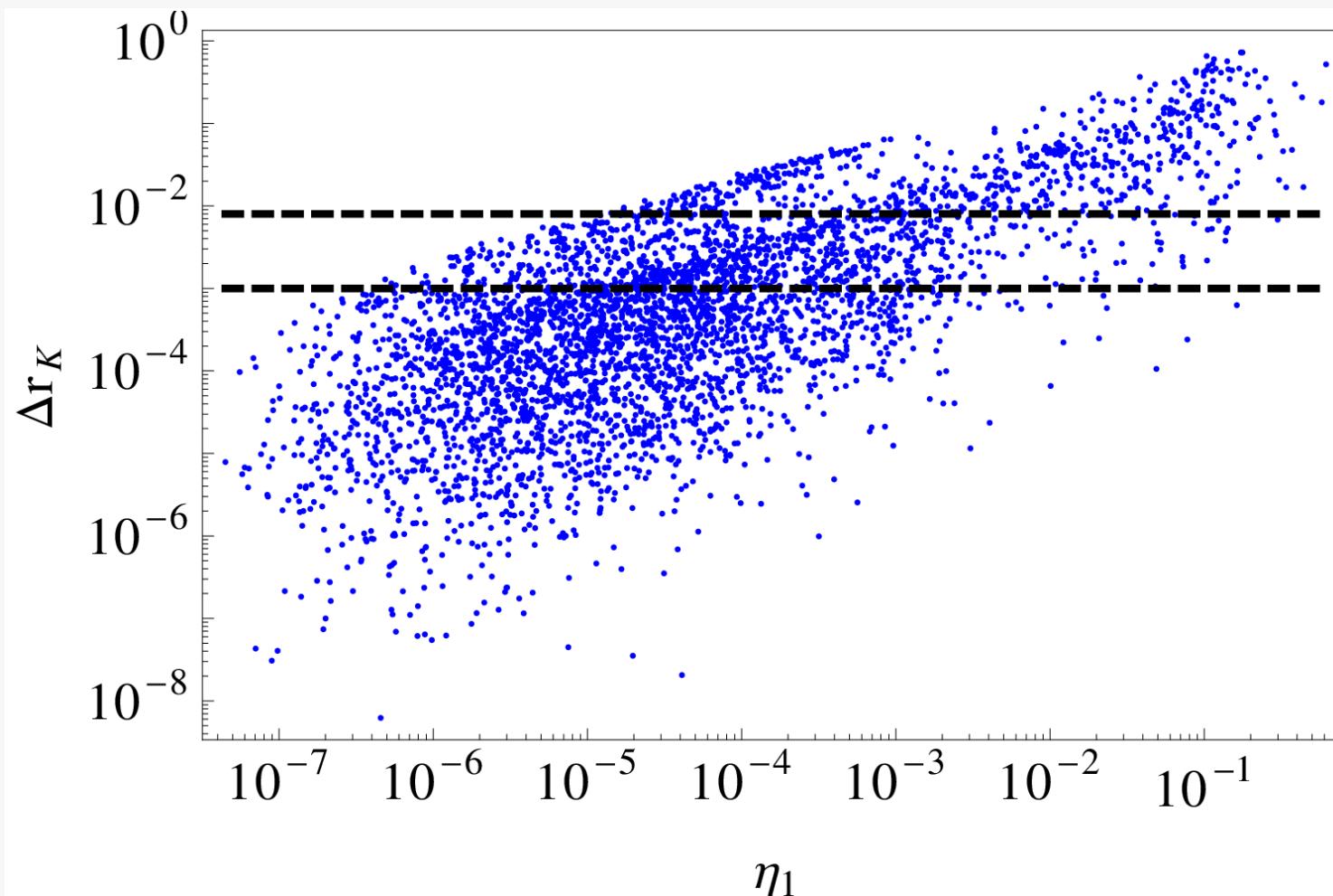
$$\mu_X \in [0.01 \text{ eV}, 1 \text{ MeV}]$$

# Scenario 1 : $m_N \lesssim m_K$



- Here  $\eta_1 = 1 - \text{Det}(U_{3 \times 3})$  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!