Effects of singlet neutrinos on lepton universality tests

JHEP02(2013)048 & article in preparation

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35th International School of Nuclear Physics
Erice, September 20th, 2013

Neutrino oscillations

- Best fit (nu-fit.org)

  solar $\nu_e \to \nu_{\text{others}}$: $\theta_{12} \simeq 34^\circ$ $\Delta m^2_{12} \simeq 7.5 \times 10^{-5}\text{eV}^2$

  atmospheric $\nu_\mu \to \nu_\tau$: $\theta_{23} \simeq 41^\circ$ $|\Delta m^2_{23}| \simeq 2.4 \times 10^{-3}\text{eV}^2$

  reactor $\bar{\nu}_e \to \bar{\nu}_{\text{others}}$: $\theta_{13} \simeq 8.7^\circ$

  accelerator $\nu_\mu \to \nu_{\text{others}}$

- Oscillations $\Rightarrow$ Non-diagonal charged currents

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

- Impact on low-energy observables, e.g. lepton flavour violation, deviation from lepton universality

Lepton flavour universality

- Lepton flavour universality (LFU): independence of gauge boson couplings from lepton flavours

- Searches for LFU violation among most precise tests of SM

$$\frac{\mathcal{B}(Z^0 \to \mu^+\mu^-)}{\mathcal{B}(Z^0 \to e^+e^-)} = 1.0009 \pm 0.0028$$

$$\frac{\mathcal{B}(Z^0 \to \tau^+\tau^-)}{\mathcal{B}(Z^0 \to e^+e^-)} = 1.0019 \pm 0.0032$$

[Schael et al., 2006]

- Deviations from LFU $\Rightarrow$ Evidence of New Physics

Lepton universality tests

- Couplings to different bosons can be tested: γ, Z^0, $W^\pm$
  $\rightarrow$ Focus on $W^\pm$ couplings

- Many observables can be used
  - Gauge boson decays (e.g. $W \rightarrow \ell\bar{\nu}$)
  - Leptonic and semileptonic meson decays (e.g. $K \rightarrow \ell\bar{\nu}$, $\overline{B} \rightarrow D\ell^-\bar{\nu}$)
  - Lepton decays (e.g. $\ell \rightarrow \ell'\nu\bar{\nu}$, $\tau \rightarrow K\nu$)

- Consider light meson decays: pions and kaons
  SM decay width is chirally suppressed $\rightarrow$ sensitive to New Physics
  Decay width plagued by QCD uncertainties $\Rightarrow$ Ratios

$$R_P = \frac{\Gamma(P^+ \rightarrow e^+\nu)}{\Gamma(P^+ \rightarrow \mu^+\nu)}\,, \qquad P = K, \pi$$

R_K and R_π

- Well measured by the NA62 collaboration [Lazzeroni et al., 2013]:

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

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

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

- SM prediction is very precise [Finkemeier, 1996, Cirigliano and Rosell, 2007]:

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

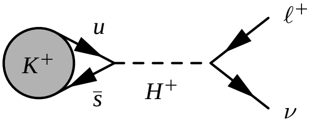
- New Physics: $R_K = R_K^{\text{SM}} (1 + \Delta r_K)$

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

- Similar prospects for R_π

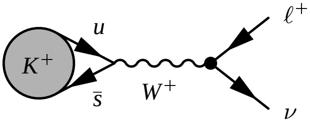
Deviations from the SM

- Origin of LFU violation in R_K:
  - New Lorentz structure in the four-fermion interaction



New fields, new couplings
e.g. 2 Higgs doublet models [Hou, 1993], Supersymmetry [Masiero et al., 2006, Fonseca et al., 2012]

  - Corrections to the SM $W\ell\nu$ vertex



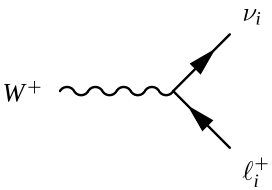
New states, Higher-order effects
e.g. Additional neutrinos: low-scale seesaw, inverse seesaw

Modified $W\ell\nu$ vertex

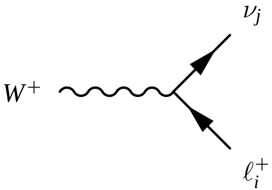
- Naturally arises when leptonic mixing is added to the SM

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

SM: $g P_L \delta^{ij}$



SM + massive ν: $g P_L U_\nu^{ij}$



$$i = e, \mu, \tau; \quad j = 1, \ldots, n_\nu$$

- If $n_\nu > 3$ (e.g. fermionic singlets) $\rightarrow U_\nu \neq U_{\text{PMNS}}$
  $\rightarrow 3 \times 3$ submatrix $\tilde{U}_{\text{PMNS}}$ is not unitary
- Tree-level corrections to R_K

Deviation from universality

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

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

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

- In SM + 3 massive ν, recover $R_K^{SM} = \frac{m_e^2}{m_\mu^2}\frac{(m_K^2 - m_e^2)^2}{(m_K^2 - m_\mu^2)^2}$
  - $m_\nu \ll m_\ell \Rightarrow G^{i1} \simeq G^{j1}$
  - $U_\nu = U_{\text{PMNS}} \Rightarrow \sum_{i=1}^{n_\nu} |U_\nu^{1i}|^2 = (U_\nu U_\nu^\dagger)_{11} = 1$

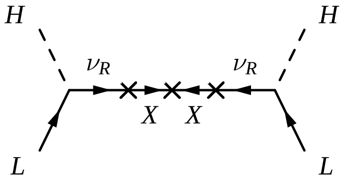
- Mass regimes and LFU:
  - (A) sterile neutrinos are lighter than m_K, with $m_\nu^{\text{active}} \ll m_{\nu_s} \lesssim m_K$
    $\rightarrow \widetilde{U}_{\text{PMNS}}$ non-unitary + Phase space effect
  - (B) sterile neutrinos are heavier than the kaon, $m_{\nu_s} > m_K$
    $\rightarrow \widetilde{U}_{\text{PMNS}}$ non-unitary [Shrock, 1980, 1981]

The inverse seesaw mechanism

- Inverse seesaw $\Rightarrow$ Consider fermionic gauge singlets ν_{Ri} ($L = +1$) and X_i ($L = +1$) [Mohapatra and Valle, 1986]

$$\mathcal{L}_{inverse} = Y_\nu^{ij}\overline{L_i}\tilde{H}\nu_{Rj} - M_R^{ij}\overline{\nu_{Ri}}X_j - \frac{1}{2}\mu_X^{ij}\overline{X_i^C}X_j + \text{h.c.}$$

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



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

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

2 scales: μ_X and M_R

The inverse seesaw mechanism

- Inverse seesaw: $Y_\nu \sim \mathcal{O}(1)$ and $M_R \sim 1\,\mathrm{TeV}$
  $\Rightarrow$ testable at the LHC and low energy experiments
- Could provide a sterile neutrino at the eV scale (accelerator and short baseline anomalies)
- LHC/ILC signatures [Bhupal Dev et al., 2012, Bandyopadhyay et al., 2013, Mondal et al., 2012, Das and Okada, 2012]
- Low energy:
  - deviations from lepton universality [Abada et al., 2013]
  - charged lepton flavour violation [Bernabéu et al., 1987, Deppisch et al., 2006]
  - neutrinoless double beta decay [Awasthi et al., 2013]

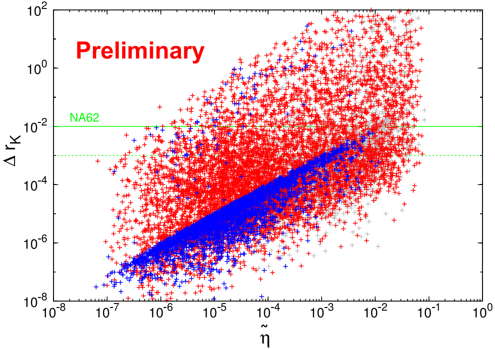
Constraints on the inverse seesaw

- Depend on the mass regime and the Yukawa couplings
  - Direct searches of sterile neutrinos (e.g. monochromatic lines in $\pi \to \mu\nu$) [Atre et al., 2009, Kusenko, 2009]
  - Non-unitarity constraints [Antusch et al., 2009]
  - Lepton flavour violation (e.g. $\mu \to e\gamma$): [Deppisch and Valle, 2005]
  - B Physics (e.g. $B \to \ell\nu$)

Constraints on the inverse seesaw

- Depend on the mass regime and the Yukawa couplings
  - LHC Higgs searches (e.g. invisible decays) [Bhupal Dev et al., 2012, Cely et al., 2013]
  - Electroweak precision data [del Aguila et al., 2008, Atre et al., 2009]
  - Cosmological observations (e.g. LSS, Lyman-α, CMB, BBN, X-ray) [Smirnov and Zukanovich Funchal, 2006, Kusenko, 2009]
    $\rightarrow$ can be evaded with non-standard cosmology (*e.g.* low reheating temperature [Gelmini et al., 2008])

R_K in the inverse seesaw



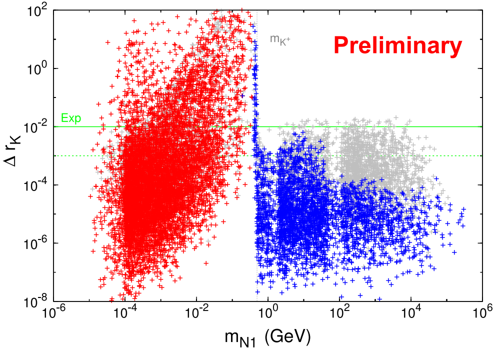
$M_R \in [0.1\ \text{MeV}, 10^6\ \text{GeV}]$
$\mu_X \in [0.01\ \text{eV}, 1\ \text{MeV}]$

$\tilde{\eta} = 1 - |\text{Det}(\tilde{U}_{\text{PMNS}})|$

- Blue=Comply with all constraints, Gray=Excluded by $\mu \to e\gamma$, Red=Comply with all but cosmological bounds
- Large LFU violation $\Delta r_K > 1$ can be reached
- Possibly large $Y_\nu \Rightarrow \mathcal{B}(\mu \to e\gamma)$ is within MEG reach

R_K in the inverse seesaw

- Scenario (A) vs (B)



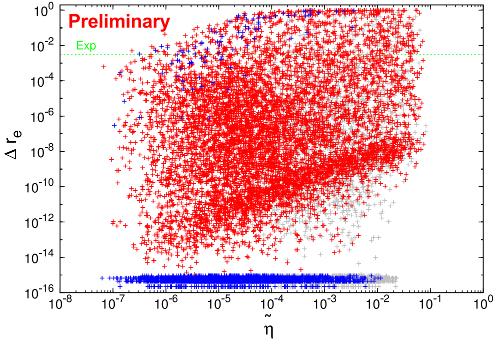
$$M_R \in [0.1\ \text{MeV}, 10^6\ \text{GeV}]$$
$$\mu_X \in [0.01\ \text{eV}, 1\ \text{MeV}]$$

- In both scenarios: Non-unitarity effects
- Scenario (A): Extra phase-space effects
- Large deviations in scenario (B): specific to the inverse seesaw

R_e in the inverse seesaw

$$R_e = \frac{\Gamma(\pi^+ \to e^+\nu)}{\Gamma(K^+ \to e^+\nu)}\,, \qquad \Delta r_e = \frac{R_e|_{exp}}{R_e|_{SM}} - 1$$

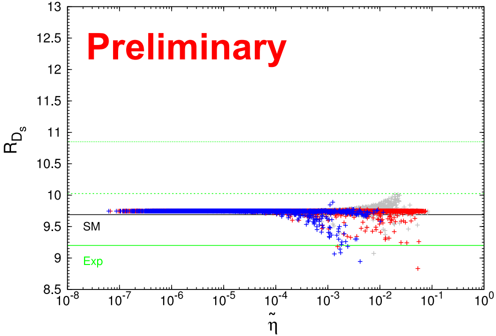
- Current experimental limit:
  $\Delta r_e = -0.003 \pm 0.006$ [Beringer et al., 2012]
- Can be measured within 0.5% by NA62



R_{D_s} in the inverse seesaw

$$R_{D_s}\big|_{exp} = \frac{\Gamma(D_s^+ \to \tau^+\nu)}{\Gamma(D_s^+ \to \mu^+\nu)} \simeq 9.2$$

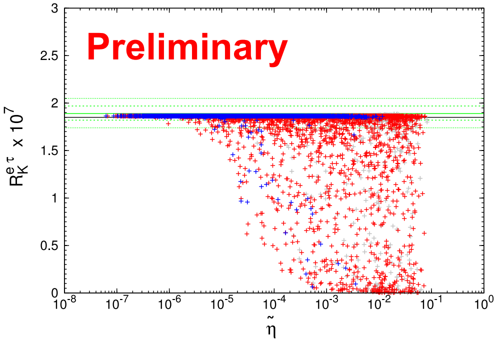
- Roughly 1σ away from the SM prediction $R_{D_s}\big|_{SM} \simeq 10.1$ [Beringer et al., 2012, Charles et al., 2011]
- Sterile neutrinos can reduce the tension



$R_K^{e\tau}$ in the inverse seesaw

$$R_K^{e\tau}\big|_{exp} = \frac{\Gamma(\tau \to K\nu)}{\Gamma(K \to e\nu)} \simeq (1.886 \pm 0.078) \times 10^7$$

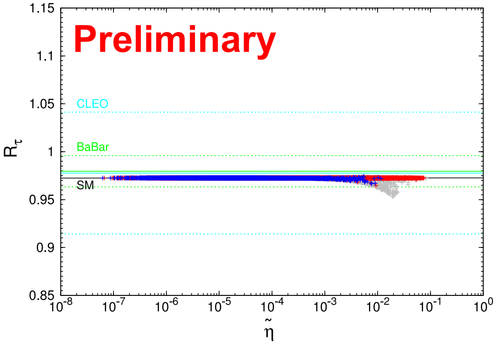
- Within 1σ of the SM prediction
  $R_K^{e\tau}\big|_{SM} \simeq 1.853 \times 10^7$ [Beringer et al., 2012]
- Potentially large deviations



3-body lepton decays in the inverse seesaw

$$R_\tau = \frac{\Gamma(\tau^- \to \mu^- \nu\nu)}{\Gamma(\tau^- \to e^- \nu\nu)} = 0.9764 \pm 0.0030$$

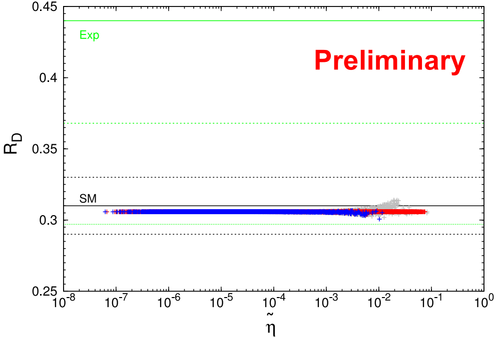
- within 2σ of the SM prediction $R_\tau|_{SM} \simeq 0.9726$ [Beringer et al., 2012]
- Any sizeable deviation forbidden by $\mu \to e\gamma$



Semileptonic meson decays

$$R(D) = \frac{\mathcal{B}(\overline{B} \to D\tau^- \bar{\nu}_\tau)}{\mathcal{B}(\overline{B} \to D\ell^- \bar{\nu}_\ell)} = 0.440 \pm 0.072$$

- 1.7σ away from the SM prediction $R(D)|_{SM} = 0.31 \pm 0.02$
  [Lees et al., 2012, Becirevic et al., 2012]
- Depend on hadronic matrix elements



Conclusion

- Source: modified $W\ell\nu$ vertex from extra sterile neutrinos
- Mechanism: phase space effect
  non-unitarity of $\widetilde{U}_{\text{PMNS}}$
- Large LFU violation in the inverse seesaw
  $\Rightarrow$ Constraint on the parameter space from R_K, R_π, R_e, $R_K^{\ell\tau}$
- May reduce the tension for R_{D_s}
- Minor effects on three-body decays