

Sterile neutrinos in leptonic and semi-leptonic decays

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Neutrino oscillations

- Best fit (nu-fit.org)

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

$$\text{atmospheric } \nu_\mu \rightarrow \nu_\tau: \quad \theta_{23} \simeq 42^\circ \quad |\Delta m_{23}^2| \simeq 2.4 \times 10^{-3} \text{ eV}^2$$

$$\text{reactor } \bar{\nu}_e \rightarrow \bar{\nu}_{\text{others}}: \quad \theta_{13} \simeq 8.8^\circ$$

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

- Oscillations \Rightarrow Non-diagonal charged currents

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

- 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

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

[Schael et al., 2006]

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

- Deviations from LFU \Rightarrow Evidence of New Physics

Lepton universality tests

- Couplings to different bosons can be tested: γ, Z^0, W^\pm
→ 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 → sensitive to New Physics
 - Decay width plagued by QCD uncertainties ⇒ **Ratios**

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

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

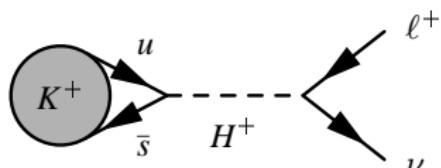
$$\Delta r_K = (4 \pm 4) \times 10^{-3}$$

- Similar prospects for R_π

Deviations from the SM

- Origin of LFU violation in R_K :

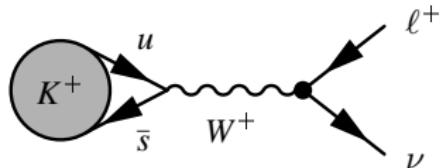
- New Lorentz structure in the four-fermion interaction



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

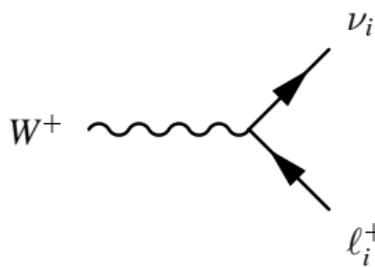
e.g. Additional neutrinos: low-scale seesaw, inverse seesaw

Modified $W\ell\nu$ vertex

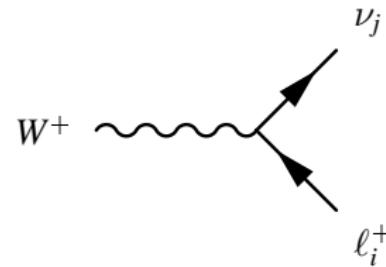
- Naturally arises when leptonic mixing is added to the SM

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

SM: $gP_L \delta^{ij}$



SM + massive ν : $gP_L \mathbf{U}^{ij}_\nu$



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

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

Deviation from universality

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

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

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

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

The inverse seesaw mechanism

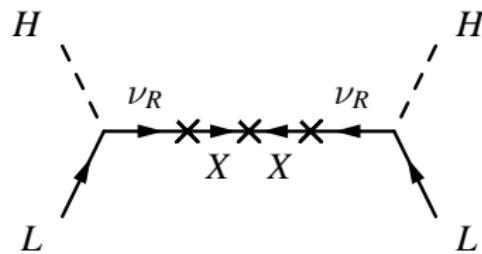
- Inverse seesaw \Rightarrow Consider fermionic gauge singlets ν_{Ri} ($L = +1$) and X_i ($L = +1$) [Mohapatra and Valle, 1986]

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

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 $M_R \sim 1 \text{ TeV}$
⇒ testable at the LHC and low energy experiments
- LHC/ILC signatures
 - single lepton + dijet + missing energy [Das and Okada, 2012]
 - di-lepton + missing p_T [Bhupal Dev et al., 2012, Bandyopadhyay et al., 2013]
 - tri-lepton + missing E_T [Das and Okada, 2012, Mondal et al., 2012]
 - invisible Higgs decays [Banerjee et al., 2013]
- 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, Abada and Luente, 2014]

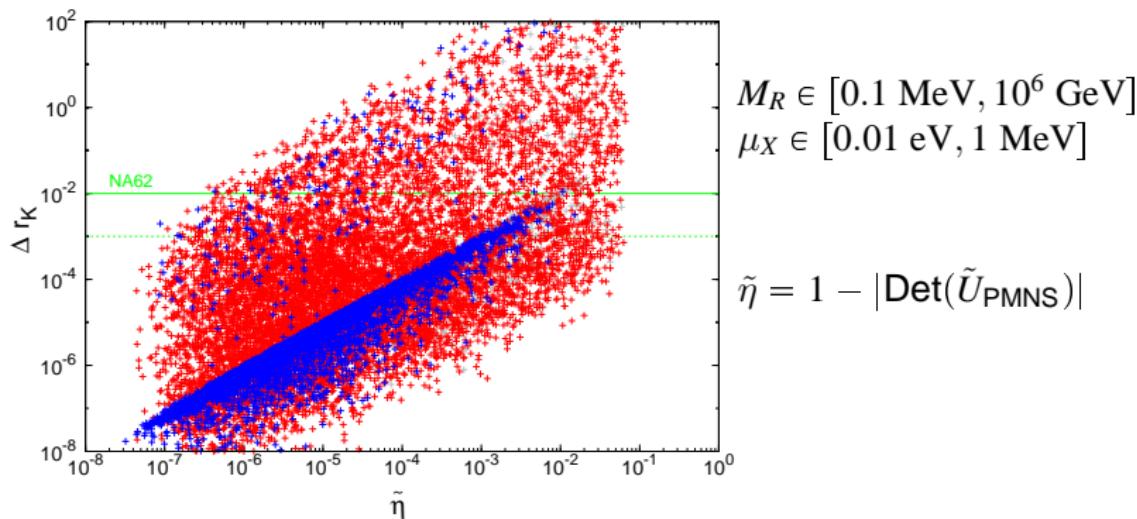
Constraints on the inverse seesaw

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

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]
→ can be evaded with non-standard cosmology (e.g. low reheating temperature [Gelmini et al., 2008])

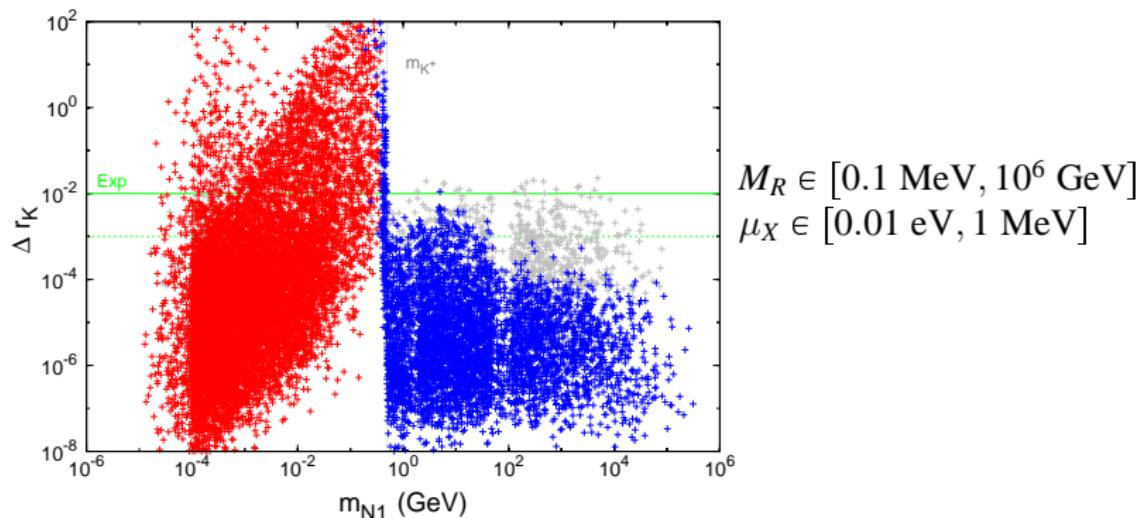
R_K in the inverse seesaw



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

R_K in the inverse seesaw

- Scenario (A) vs (B)

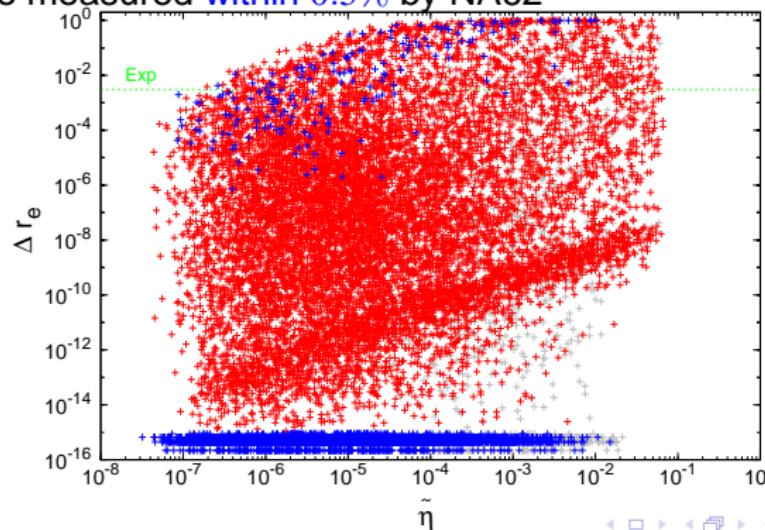


- In both scenarios: Non-unitarity effects
- Scenario (A): Extra phase-space effects
- Large deviations in scenario (B): specific to the inverse seesaw

R_e in the inverse seesaw

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

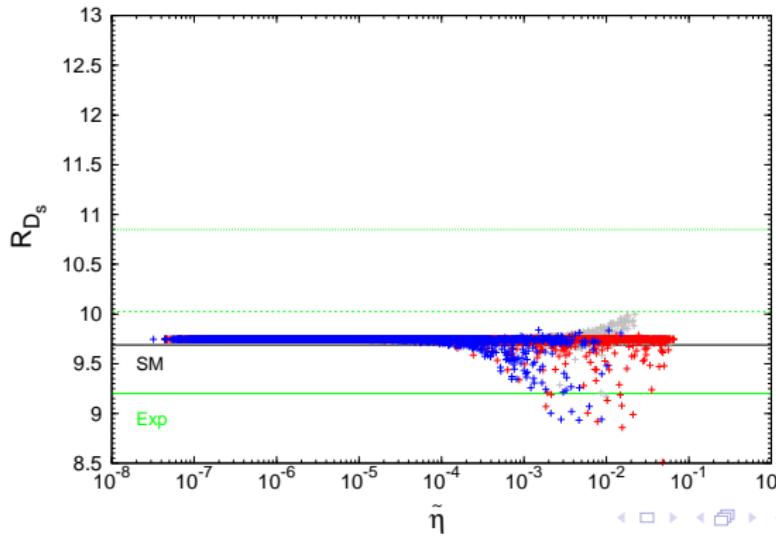
- Current experimental limit:
 $\Delta r_e = -0.003 \pm 0.006$ [Beringer et al., 2012]
- Can be measured **within 0.5%** by NA62



R_{D_s} in the inverse seesaw

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

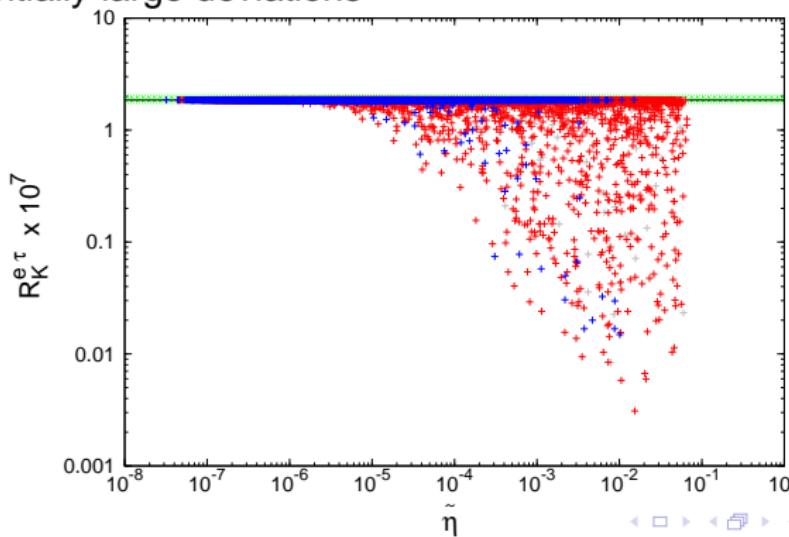
- Roughly 1σ away from the SM prediction
 $R_{D_s}|_{SM} \simeq 10.1$ [Beringer et al., 2012, Charles et al., 2011]
- Sterile neutrinos can reduce the tension



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

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

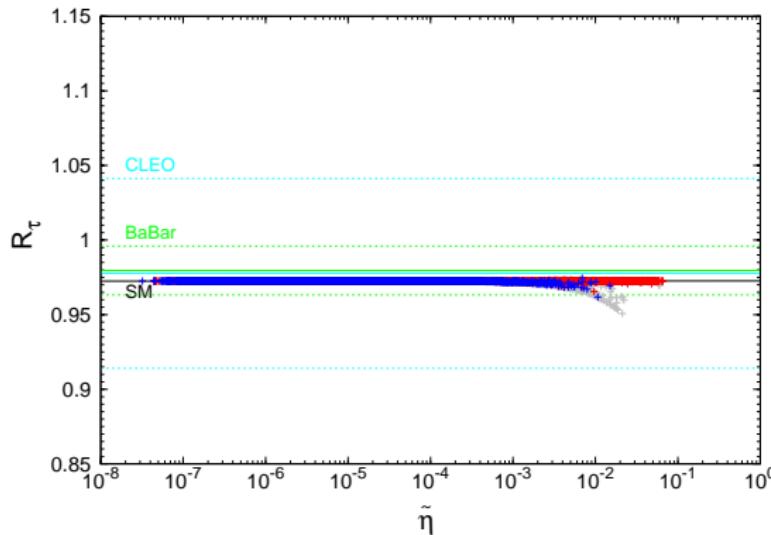
- Within 1σ of the SM prediction
 $R_K^{e\tau}|_{SM} \simeq 1.853 \times 10^7$ [Beringer et al., 2012]
- Potentially large deviations



3-body lepton decays in the inverse seesaw

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

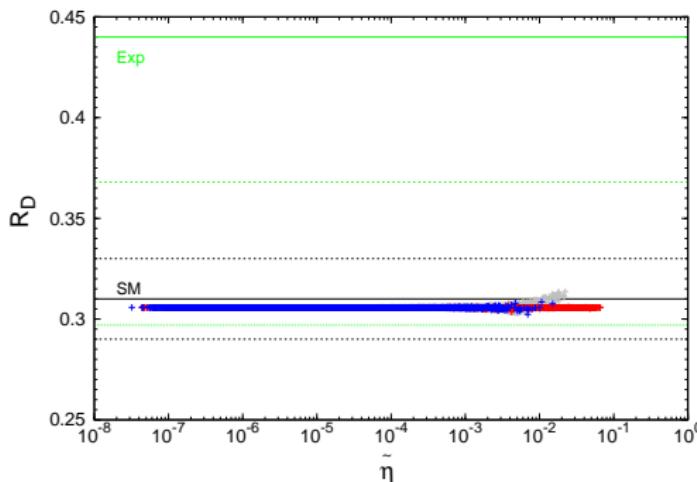
- within 2σ of the SM prediction $R_\tau|_{SM} \simeq 0.9726$ [Beringer et al., 2012]
- Any sizeable deviation forbidden by $\mu \rightarrow e\gamma$



Semileptonic meson decays

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

- 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 \tilde{U}_{PMNS}
- Large LFU violation in the inverse seesaw
 \Rightarrow Constraint on the parameter space from $R_K, R_\pi, R_e, R_K^{\ell\tau}$
- May reduce the tension for R_{D_s}
- Minor effects on three-body decays

Backup slides

Scan method

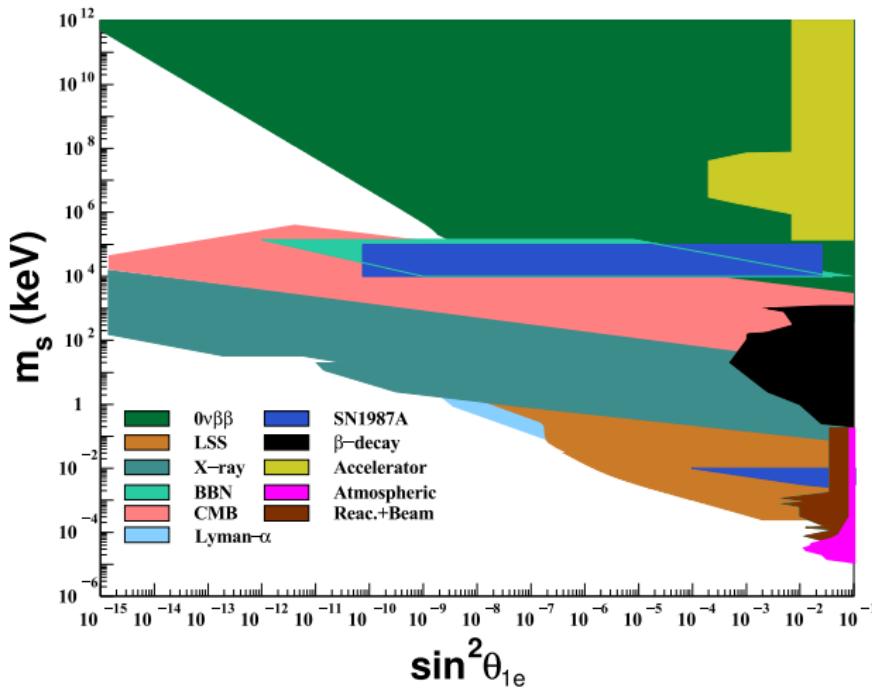
- Inverse seesaw as an illustrative example, only one among other possibilities
- Random scan on M_R and μ_X entries
- Y_ν obtained from neutrino data via the Casas-Ibarra parametrization [Casas and Ibarra, 2001]

$$Y_\nu^T = \frac{\sqrt{2}}{v} V^\dagger \text{diag}(\sqrt{m_1}, \sqrt{m_2}, \sqrt{m_3}) R \text{diag}(\sqrt{M_1}, \sqrt{M_2}, \sqrt{M_3}) U_{PMNS}^\dagger$$

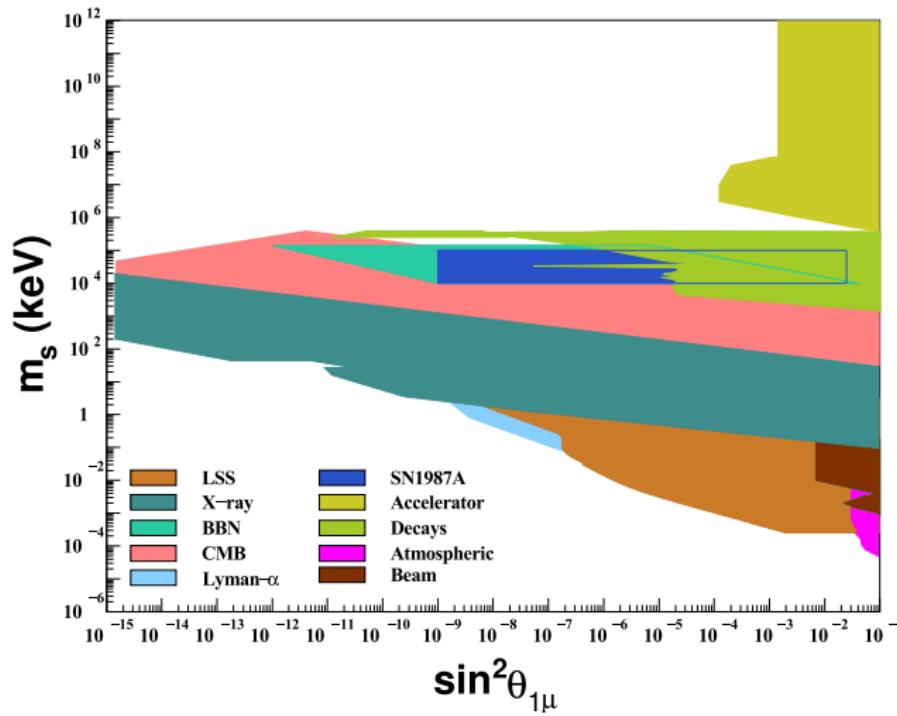
where R is a complex orthogonal matrix and V a unitary matrix that decompose $M = M_R \mu_X^{-1} M_R^T$ according to
 $M = V^\dagger \text{diag}(M_1, M_2, M_3) V^*$.

- Apply the constraints

Constraints on sterile neutrinos [Kusenko, 2009]



Constraints on sterile neutrinos [Kusenko, 2009]



Constraints on sterile neutrinos [Kusenko, 2009]

