Neutrino mass models:
Experimental reach vs. theoretical predictions

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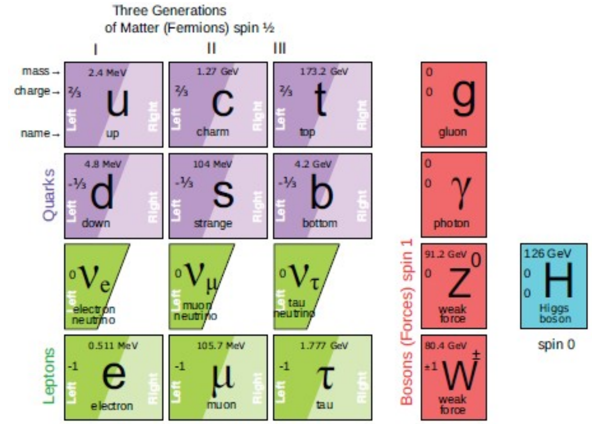
Theory of elementary particle physics and beyond

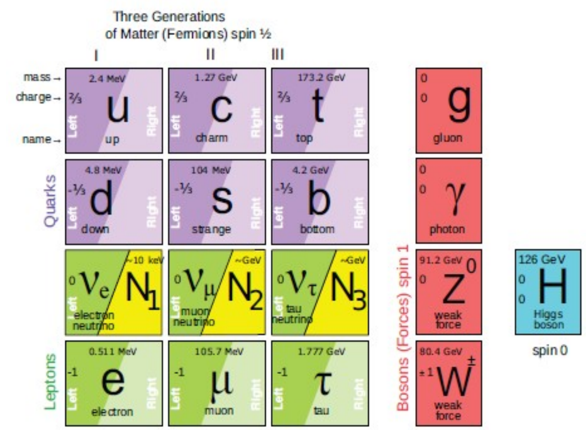
- The Standard Model (SM)
- Shortcomings: Neutrino masses, dark matter and baryon asymmetry



- Possible extension: The Neutrino Minimal Standard Model (nuMSM)

[Asaka, Shaposhnikov (2005); Canetti, Drewes, Frossard,Shaposhnikov (2012); Drewes, Garbrecht (2015); Hernandez, Kekic, Lopez-Pavon, Racker, Salvado (2016)..]

- Other possibilities [See Ballesteros's talk]
- N_1 is dark matter candidate with keV mass [See Merle's and Campos's talk]
- N_2 and N_3 with 100 MeV-100 GeV mass: Origin of neutrino masses and baryon asymmetry [See Klaric's talk]



Our motivation

- The Lagrangian becomes

$$L_{\text{Seesaw}} = L_{\text{SM}} + \overline{N}_I i \partial_\mu \gamma^\mu N_I - Y_{\alpha I} \overline{L}_\alpha N_I \Phi - \frac{1}{2} M_R \overline{N}_I^C N_I + h.c.$$

- nuMSM: Mass degeneracy $\Delta M / M \leqslant 10^{-3}$ for successful baryon asymmetry [Canetti, Drewes, Frossard, Shaposhnikov (2012)]
- **We will consider 3 sterile neutrinos at the GeV scale**: No mass degeneracy needed [Drewes, Garbrecht (2012)]
- Essentially, we only need three Yukawa/mass matrices to calculate the observables

$$M_l = v Y_l, (M_D)_{\alpha I} = v Y_{\alpha I} \text{ and } M_R$$

Observables relations to mass matrices

- Seesaw mechanism [Minkowski (1977); Gell-Mann, Ramond, Slansky (1979); Yanagida (1980); Mohapatra (1980); Schechter, Valle (1980)]

$$m_\nu = -M_D M_R^{-1} M_D^T \text{ and } M_N = M_R$$

- The PMNS mixing matrix

$$U_{PMNS} = U_l^H U_\nu \qquad U_l^H := (U_l^*)^T$$

- The active-sterile mixing matrix

$$U_{\alpha I} = (U_l^H M_D M_R^{-1} U_N)_{\alpha I}$$

- Decay rates depend on [Gorbunov, Shaposhnikov (2007)]

$$\Gamma(N_I \to l_\alpha X) \propto |U_{\alpha I}|^2 \qquad X = \text{hadron}$$

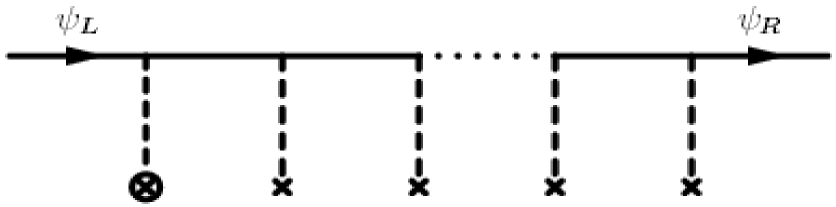
- We will focus on the individual mixing element $|U_{\alpha I}|^2$ and total mixing $|U_I|^2 = \sum_\alpha |U_{\alpha I}|^2$ for sterile neutrino

Classes of models

- We studied two classes of models: We will focus on flavor symmetric mass models since generic assumptions generate the whole parameter space [Drewes, Garbrecht (2015)]

- Flavor symmetric mass models in the Froggatt-Nielsen (FN) framework [Froggatt, Nielsen (1979)]

- Pictorial diagram of generating fermion mass terms with flavons acquiring universal VEVs v_f and heavy fermions with universal mass M_F



- Integrating out the heavy fermions, leads to the Lagrangian with $\varepsilon = v_f / M_F$

$$-L_Y = \prod_{k=1}^{m} \varepsilon^{\alpha_{ij}^k} x_{ij} H^* L_i (e_R)_j + \prod_{k=1}^{m} \varepsilon^{\beta_{ij}^k} y_{ij} \tilde{H} L_i N_j + \frac{1}{2} m_R \prod_{k=1}^{m} \varepsilon^{\gamma_{ij}^k} z_{ij} N_i N_j^c + h.c.$$

- Exponents α_{ij}^k, β_{ij}^k and γ_{ij}^k are controlled by the quantum numbers of the leptons

Classes of models continued

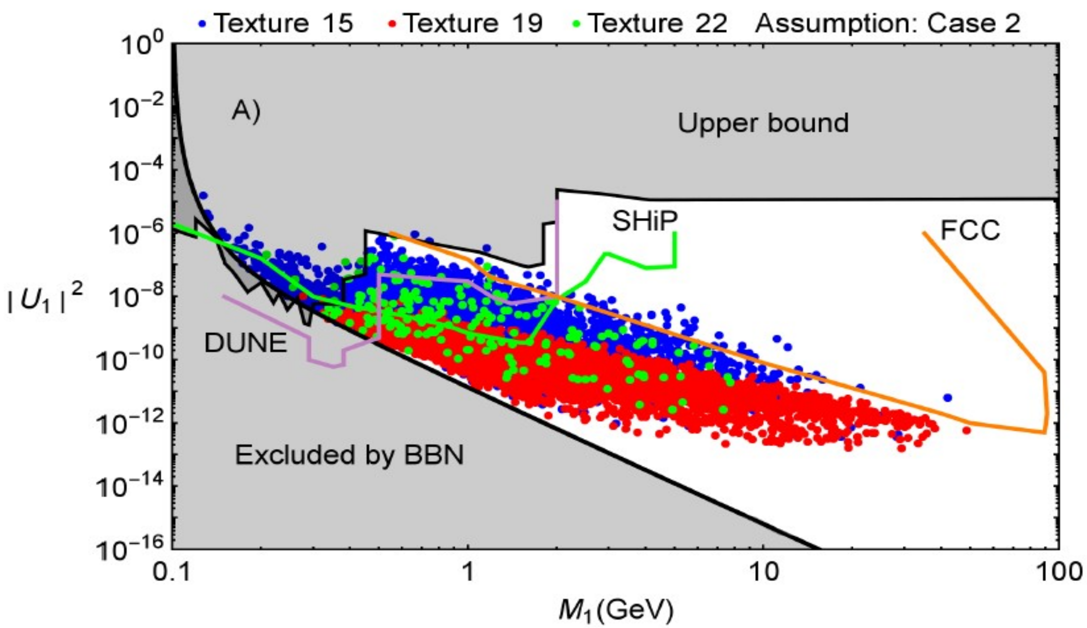
- We assume $\varepsilon \approx 0.2$ since
  $$m_u : m_c : m_t \approx \varepsilon^8 : \varepsilon^4 : 1 \;,\; m_d : m_s : m_b \approx \varepsilon^5 : \varepsilon^2 : 1 \text{ and } m_e : m_\mu : m_\tau \approx \varepsilon^5 : \varepsilon^2 : 1.$$
- Additionally, this value also appears in the CKM mixing matrix and it can possibly explain the neutrino mass ratio due to $\Delta m_{21}^2 / |\Delta m_{32}^2| = \varepsilon^2$
  $$m_1 : m_2 : m_3 \approx \varepsilon^2 : \varepsilon : 1 \;,\; m_1 : m_2 : m_3 \approx 1 : 1 : \varepsilon \text{ and } m_1 : m_2 : m_3 \approx 1 : 1 : 1.$$
  (Normal hierarchy) (Inverted hierarchy) (Quasi-degenerate)
- Therefore, it could be interesting to incorporate this quantity into the neutrino sector
  $$Y_l = \begin{pmatrix} \varepsilon^4 & \varepsilon^5 & \varepsilon^2 \\ \varepsilon^2 & \varepsilon^2 & \varepsilon^2 \\ \varepsilon^4 & \varepsilon^4 & 1 \end{pmatrix} \quad M_D = m_D \begin{pmatrix} \varepsilon & \varepsilon^2 & \varepsilon \\ \varepsilon & 1 & \varepsilon \\ \varepsilon^2 & 1 & \varepsilon \end{pmatrix} \quad M_R = m_R \begin{pmatrix} \varepsilon & \varepsilon^2 & \varepsilon \\ \varepsilon^2 & 1 & \varepsilon^3 \\ \varepsilon & \varepsilon^3 & 1 \end{pmatrix}$$

[Plentinger, Seidl, Winter (2007)]

- Experimental constraints: Neutrino oscillation data, neutrinoless double beta mass, LFV, direct searches, Big Bang nucleosynthesis

The total active-sterile mixing for the lightest sterile neutrino

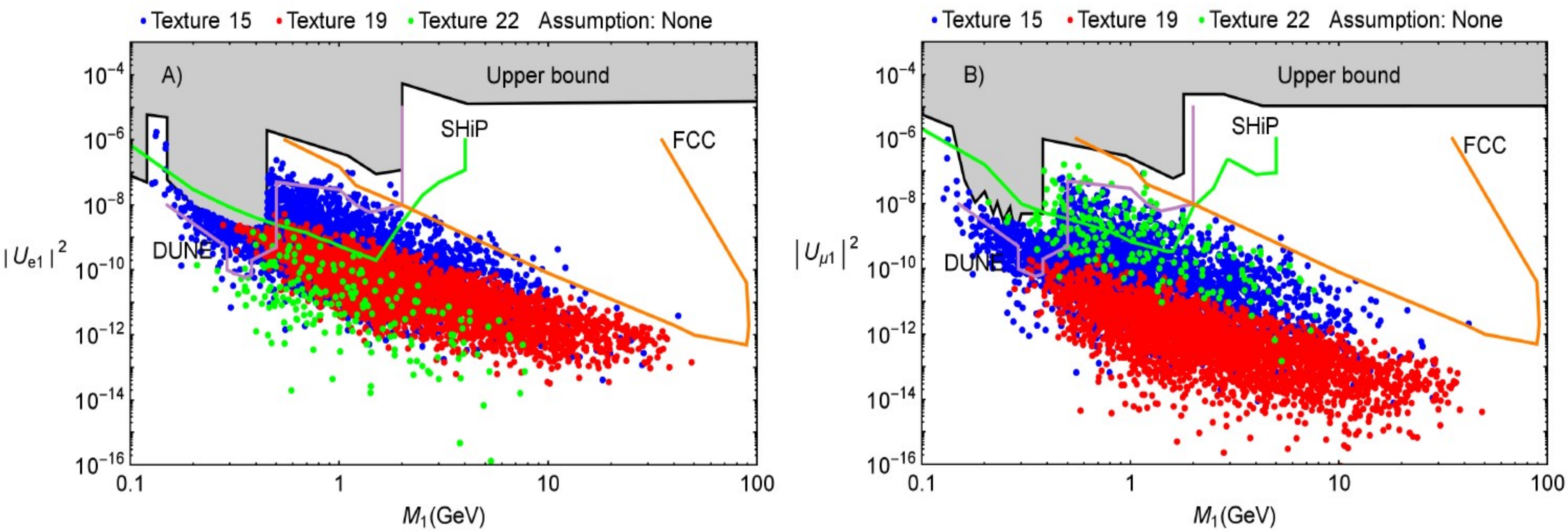
- Total mixing is partially within reach
  [RWR, Winter (2016)]



- Future Circular Collider (FCC) – possible successor to the LHC
  [Blondel, Graverini, Serra, Shaposhnikov (2014)]
- Deep Underground Neutrino Experiment (DUNE) – proposed long-baseline neutrino experiment in the US
  [Adams et. al. (2013)]
- Search for Hidden Particles (ShiP) – proposed beam-dump experiment at CERN, searching for "hidden particles" such as sterile neutrinos [Alekhin et. al. (2015); Anelli et al. (2015)]

Individual mixing elements for the lightest sterile neutrino

- Structure in mass matrices leads to refined mixing



- Therefore, channels such as $N \rightarrow e\pi / eK$ [RWR, Winter (2016)]

  and $N \rightarrow \mu\pi / \mu K$ can resolve this mixing pattern

Summary

> Sterile neutrinos are theoretically motivated and can solve many of the problems in the SM

> Generic assumptions generates the whole parameter space

> Flavor symmetric predictions are more refined in comparison to generic assumptions

> Potential to exclude parameter space of models by measuring the total mixing

> Important to measure the individual mixing elements

Back-up

Total mixing for N3

- FCC constrains the parameter space for heavier sterile neutrinos