Pôle Théorie - IJCLAB-Orsay

Heavy neutral fermions and neutrino physics

Contribution of A.A, A.M. Teixeira

- Neutrino data calls for New Physics
- Which BSM? Neutrino mass models
- Many BSM (with m_ν): neutrino mass generation mechanisms
- Bottom-up approach: extra neutral fermions like right-handed neutrinos
- Extensive impact and thus many searches at different energy scales

Journée prospectives, juin 2021

Asmaa Abada

Indisputable: νs are massive and mix

$\Rightarrow$ **Lepton mixing & massive neutrinos: unique signal for NP**

☞ SM has other issues that call for BSM

- observational problems (ν masses & mixings): BAU and Dark Matter
- theoretical caveats: fine-tuning, hierarchy and flavour problems ....

☞ ν-SM = New Physics just to explain ν masses and mixings

- New d.o.f, for example Right-Handed Neutrinos, $\boldsymbol{H\, Y^{\nu}\, \nu_L\, \nu_R + ...} \longrightarrow \boldsymbol{m_\nu}$
- What is the neutrino mass generation mechanism?
- $\boldsymbol{\nu \leftrightarrow \bar{\nu}}$ the **only particle** that can have *both* **Dirac or Majorana** descriptions

☞ ν-SM will allow for many new phenomena

- **LFV** in neutral sector. Why not in the charged sector? $\ell_i \to \ell_j\, \ell_k\, \ell_l$, $\ell_i \to \ell_j \gamma$, ...
- If ν is a Majorana particle $\longrightarrow$ **LNV observables, ...**
- Contributions to $g-2$, lepton EDMs
- Signatures of the new heavy states at colliders, ...

☞ **Determination of ν-SM/BSM model requires combinations of many $\neq$ observables**

$m_\nu \neq 0 \Rightarrow$ New Physics Scale

Standard Model

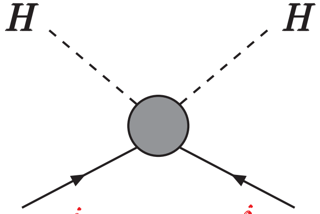
- ν_L only and no ν_R $\Longrightarrow$ No Dirac mass term: $\mathcal{L}_{m_D} = m_D\left(\overline{\nu_L}\nu_R + \overline{\nu_R}\nu_L\right)$
- No Higgs triplet $\Longrightarrow$ No Majorana mass term: $\mathcal{L}_{m_M} = \frac{1}{2}M\overline{\nu_L^c}\nu_L + h.c.$
- Lepton number symmetry is accidental $\Longrightarrow$ Non-renormalisable operators dim 5, 6 ..

SM $\equiv$ Effective theory of a larger one valid at a scale M

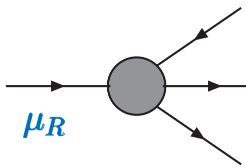
$\downarrow$

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{1}{M}c^{d=5}\mathcal{O}^{d=5} + \frac{1}{M^2}c^{d=6}\mathcal{O}^{d=6} + \cdots$$

$$\Delta\mathcal{L}^{d\geq 5} = \frac{c^{d=5}}{M} \times$$



$$+ \frac{c^{d=6}_{\mu eee}}{M^2} \times$$



$$+ \frac{c^{d=6}_{\ell_i\ell_j\gamma}}{M^2} \ldots$$

$$\mathcal{O}^{d=5} = \frac{1}{M}\left\{\left(\phi\ell\right)^{\mathrm{T}}\left(\phi\ell\right) + h.c.\right\} \xrightarrow{\langle\phi\rangle = v} m_\nu \sim c^{d=5}v^2/M$$

Depending on $c^{d=5}$ (thus on NP model) $\Rightarrow M \in [..., \mathrm{MeV}, \mathrm{GeV}, \mathrm{TeV}, ..., \mathrm{GUT}, ...]$

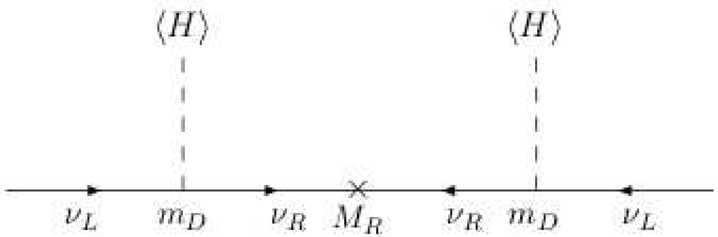
See-Saw mechanism, SM + ν_R

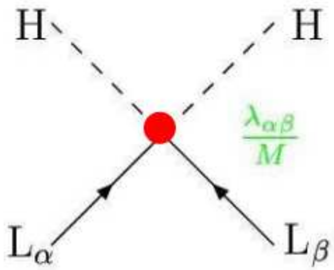
$$\mathcal{L} = \mathcal{L}_{SM} + Y_{Jk}\bar{L}_k \nu_{R_J} H - \tfrac{1}{2}\bar{\nu}_{R_J} M_{R_J} \nu^c_{R_J} + \lambda_\alpha H^c \bar{e}_{R_\alpha}\ell_\alpha \ , \quad m_D = \lambda^\nu \ v$$

Majorana states(3×3) : $\begin{cases} \nu = L + L^c = \nu^c \ , & \rightarrow \ \tilde{\mathrm{m}}_{\mathrm{L}} \sim -m_D \frac{1}{M_R} m_D^T \\ N = R + R^c = N^c, & \rightarrow \ \tilde{M}_R \sim M_R \end{cases}$

- **Dimension 5 for m_ν**

$$\delta\mathcal{L}^{d=5} = \frac{1}{2}\, c^{d=5}_{\alpha\beta} \left(\overline{\ell^c_L}_\alpha \tilde{\phi}^*\right)\left(\tilde{\phi}^\dagger\, \ell_{L\beta}\right) + \text{h.c.}$$





$$m_\nu = \frac{v^2 Y^\dagger Y}{M_R}$$

$$m_\nu = c^{d=5} v^2, \quad c^{d=5} = \frac{Y^\dagger Y}{M_R}$$

- **Dimension 6: $c^{d=6} \sim (c^{d=5})^2$** $\Rightarrow$ small m_ν preclude observable effects from $\mathcal{O}_i^{d=6}$

→ Need variants or other seesaw mechanisms?

☞ **Extending the SM with sterile fermions**: (testable!) **theoretical frameworks**

▶ **Incorporating ν_R - low scale seesaws: type I seesaw [TeV]** ➔ **small Y_ν**

$$\mathcal{M}_\nu = \begin{pmatrix} 0 & v\,Y_\nu^T \\ v\,Y_\nu & M_R \end{pmatrix}$$

type I seesaw variants ➔ **"large" Y_ν**

νMSM [GeV] ➔ **tiny Y_ν**

$$m_\nu \approx -v^2 Y_\nu^T \frac{1}{M_R} Y_\nu$$

☞ **Extended seesaw: Inverse and Linear Seesaw**

▶ **Incorporating ν_R and additional steriles ν_S: Inverse seesaw (ISS)** ➔ **sizeable Y_ν**

Linear seesaw (LSS) ➔ **sizeable Y_ν**

[in the basis $\left(\nu_L, \nu_R^c, \nu_S\right)^T$]

$$\mathcal{M}_{\text{ISS}} = \begin{pmatrix} 0 & Y_\nu^T v & 0 \\ Y_\nu v & 0 & M_R \\ 0 & M_R^T & \mu_X \end{pmatrix}$$

$$m_\nu \approx \frac{(Y_\nu v)^2}{M_R}\mu_X$$

$$\mathcal{M}_{\text{LSS}} = \begin{pmatrix} 0 & Y_\nu^T v & M_L^T \\ Y_\nu v & 0 & M_R \\ M_L & M_R^T & 0 \end{pmatrix}$$

$$m_\nu \approx (vY_\nu)\,(M_L {M_R}^{-1})^T + (M_L {M_R}^{-1})\,(vY_\nu)^T$$

▶ **Heavy physical states** ➔ **pseudo-Dirac pairs: $m_{N\pm} \approx M_R \pm \mu_X$**

Sterile fermions or heavy neutral fermions

- **Extending the SM with other "sterile fermions"**: **singlets** under $SU(3)_c \times SU(2)_L \times U(1)_Y$

  Interactions with SM fields: through **mixings** with **active neutrinos**

  A priori, **no bound** on the **number** of sterile states, **no limit** on their **mass scale(s)**

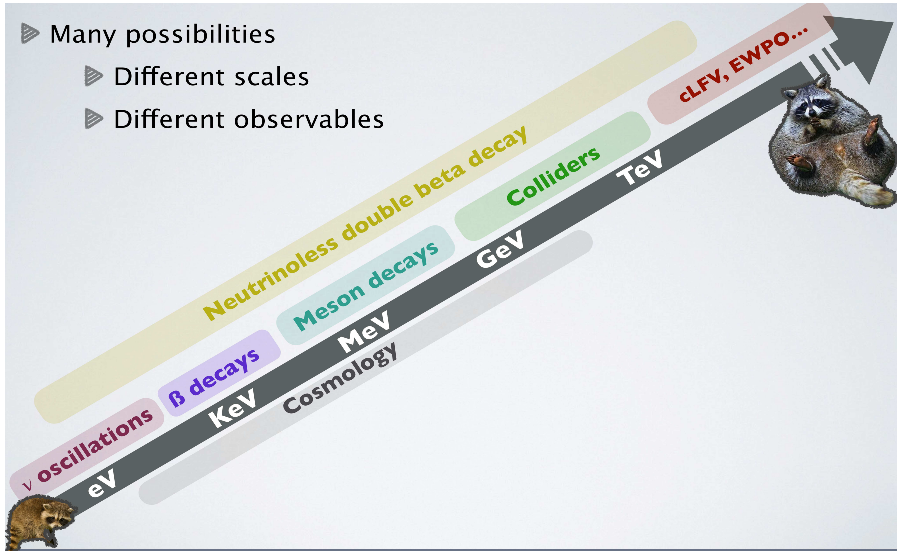
- **Interest/phenomenological implications of new "neutrinos" (ν_R) dependent on their mass!**

  eV scale $\leftrightarrow$ extra neutrinos suggested by reactor (& short baseline?) ν-oscil. anomalies

  keV scale $\leftrightarrow$ warm dark matter candidates; explain pulsar velocities (kicks); 3.5 keV line..

  MeV - TeV scale $\leftrightarrow$ experimental testability, i.e. **high-intensity/colliders** (+ BAU, DM, ...)

  Beyond 10^9 GeV $\leftrightarrow$ theoretical appeal: standard seesaw, BAU, GUTs



m_{ν_s}	Motivation	ν-oscillations	laboratory searches
$\lesssim$ eV	ν-oscil. anomalies, dark radiation	massses by seesaw, explain anomalies	oscillation anomalies, β-decays
keV	DM	no if DM	direct searches? , nuclear decays?
MeV	testability	masses by seesaw	intensity frontier, $0\nu\beta\beta$
GeV	testability, minimality	masses by seesaw	intensity frontier, EW precision data, $0\nu\beta\beta$
TeV	minimality, testability	masses by seesaw	LHC
$\gtrsim 10^9$ GeV	grand unification, "naturality"	masses by seesaw	–

m_{ν_s}	CMB	BBN	DM	Leptogenesis
$\lesssim$ eV	explain $N_{\text{eff}} > 3$	may explain $N_{\text{eff}} > 3$	no	no
keV	act as DM, no effect on N_{eff}	effect on N_{eff} too small if DM	good candidate	no
MeV	unaffected	constrains $m_{\nu_s} \gtrsim 200$ MeV	no	possible (finetuning)
GeV	unaffected	unaffected	no	possible
TeV	unaffected	unaffected	no	possible
$\gtrsim 10^9$ GeV	unaffected	unaffected	no	natural

Extending SM with "sterile" fermions: phenomenological consequences

- **Modified charged ($W^{\pm}$) and neutral (Z^0) current interactions:**

$$\mathcal{L}_{W^\pm} \sim -\frac{g_w}{\sqrt{2}} W^-_\mu \sum_{\alpha=e,\mu,\tau} \sum_{i=1}^{3+N_S} \mathbf{U}_{\alpha i}\, \bar{\ell}_\alpha\, \gamma^\mu\, P_L\, \nu_i$$

$$\mathcal{L}_{Z^0} \sim -\frac{g_w}{2\cos\theta_w} Z_\mu \sum_{i,j=1}^{3+N_S} \bar{\nu}_i\, \gamma^\mu \left[P_L\, (\mathbf{U}^\dagger\mathbf{U})_{ij} - P_R\, (\mathbf{U}^\dagger\mathbf{U})^*_{ij}\right] \nu_j$$

$\mathbf{U}_{\alpha i}$ ➞ modified lepton mixing - now encodes also **active-sterile mixings**

(for $N_s = 0$, $\mathbf{U}_{\alpha i} = U_{\text{PMNS}}$)

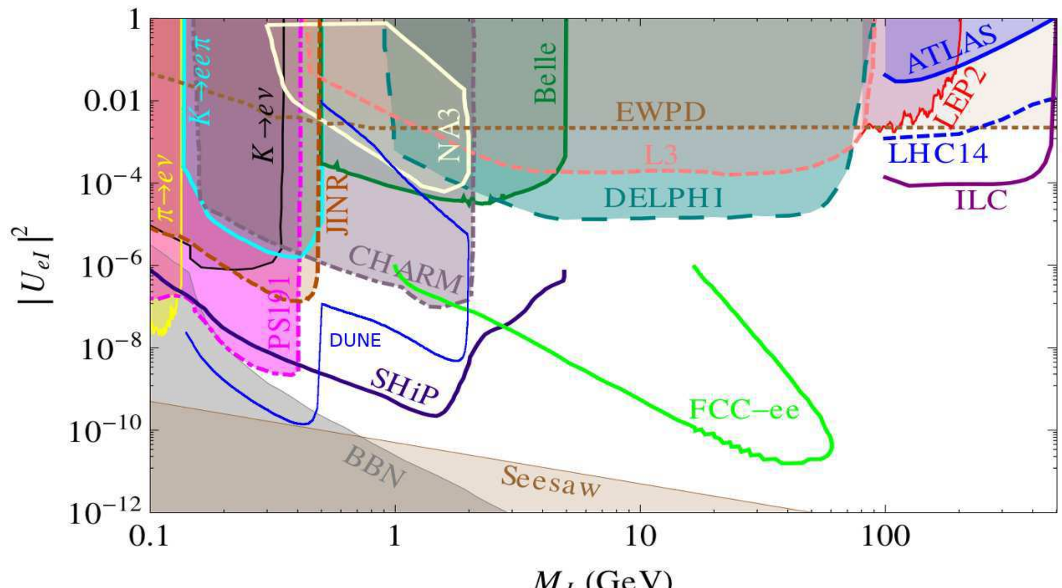
- If sufficiently light, sterile ν_S can be **produced as final states**

☞ **Many new searches proposed ➞ Huge impact for numerous observables!**

But also abundant constraints !!

[Deppisch et al, '15,]

[updated 2018: AA et al, 1712.03984]



Sterile fermions impact on

- **Oscillation parameters:** $\tilde{U}_{\text{PMNS}}$ comply with observed mixings, mass ordering, δ CPV phase
- **Electroweak precision tests:** invisible Z width; leptonic Z width; Weinberg angle...
- **Searches at the LHC:** invisible Higgs decays $H \to \nu_L \nu_R$; direct searches, ...
- **Peak searches in meson decays:** monochromatic lines in $\ell^\pm$ spectrum from $X_M^\pm \to \ell^\pm \nu_s$
- **Beam dump experiments:** ν_s decay products (light mesons, $\ell^\pm$) from $X_M^\pm$ decays
  [PS191, CHARM, NuTeV, ...]
- **Neutrinoless double beta decays - $|m_{ee}|$**
- **Rare meson decays:** Lepton Number Violating (LNV) e.g. $K^+ \to \ell^+ \ell^+ \pi^-$
  Lepton Universality Violating (leptonic decays) e.g. R_{X_M}, $R(D)$, R_τ
- **Lepton Flavour Violation:** 3 body decays among most stringent...

On going well motivated studies and questions

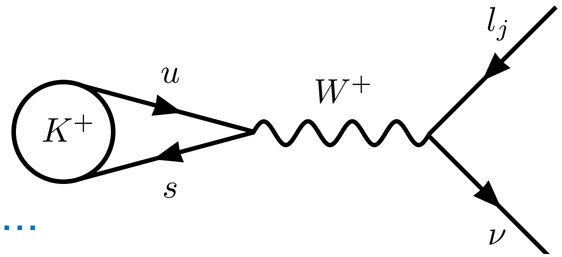
➜ **Cosmology and astroparticle** (Jérémie Quévillon)

⇒ BAU from leptogenesis (oscillations): ARS mechanism

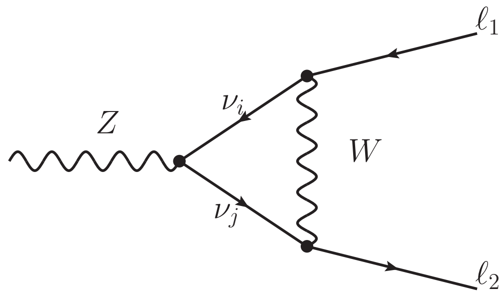
⇒ (Warm) dark matter candidates, astrophysical puzzles: pulsar kicks, ...

➜ **Particle physics**

Lepton properties:
- Leptonic CPV phases
- Electric and magnetic moments
- Neutrinoless double beta decay (LNV)
- Violation of flavour universality (e.g. $\boldsymbol{\Delta r_K}$), ...



Rare decays:
- Lepton number violation
- cLFV with high intensity observables
- cLFV $\boldsymbol{Z}$ and $\boldsymbol{H}$ decays
- Collider signatures, ...



- Case of more than one sterile : interference effect to be deeply explored (flavour)
- New CPV phases appear to have huge impact regarding predictions
- Explore $\tau - \mu$ sector