Heavy neutral leptons

Lecture 3: long-lived HNLs

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$m_\nu \neq 0$

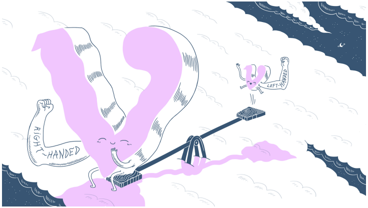
- $m_\nu = 0$ predicted in the SM, but ...
- ν oscillations $\Rightarrow$ $m_\nu \neq 0$ and very light and the SM is incomplete!
- No right-handed neutrino fields in the SM, forbidding the generation of a neutrino mass via the Higgs mechanism
- Add right-handed gauge-singlet spin-1/2 fields to the SM coupled to left-handed neutrinos and the Higgs field through Yukawa interactions $\Rightarrow$ Dirac neutrino mass after electroweak symmetry breaking
- Can also have Majorana mass term & Majorana mass eigenstates with LNV (type-I seesaw mechanism [Minkowski 1977, Gell-Mann, Ramond, Slansky 1979, Yanagida 1979, Mohapatra, Senjanovic 1980])

Type-I seesaw mechanism

$$\mathcal{L} \supset y\bar{L}HN + \frac{1}{2}m_N NN$$

$$m_\nu \sim \frac{y^2 v^2}{m_N}$$

$$U_{\ell N} \sim \frac{yv}{m_N} \text{ and } |U_{\ell N}|^2 \sim \frac{m_\nu}{m_N}$$



Symmetry magazine

- $m_\nu \sim 0.1$ eV $\Rightarrow m_N \sim 10^{15}$ GeV for $y \sim \mathcal{O}(1)$

Heavy, right-handed, "sterile" neutrinos for suppressing the active-neutrino masses

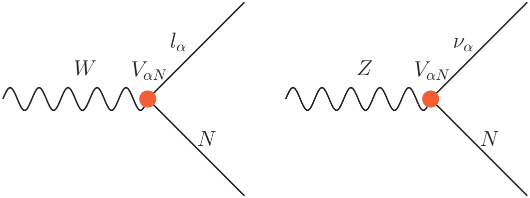
- neutrino masses
- dark matter
- baryon asymmetry via leptogenesis

$\Rightarrow$ highly motivated!

HNLs in the minimal scenario

- Type-I seesaw: active-sterile-neutrino mixings $|V_{\alpha N}|^2 \simeq m_\nu/m_N$
- More seesaw mechanisms: type-II, type-III, linear, inverse, ...
- In general, study HNLs: masses m_N and mixings $V_{\alpha N}$ decoupled
- HNL mass scales and mixing strengths unknown
- After EWSB:

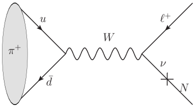
$$\mathcal{L} = \frac{g}{\sqrt{2}} V_{\alpha N_j} \bar{\ell}_\alpha \gamma^\mu P_L N_j W^-_{L\mu} + \frac{g}{2\cos\theta_W} \sum_{\alpha,i,j} V^L_{\alpha i} V^*_{\alpha N_j} \overline{N_j} \gamma^\mu P_L \nu_i Z_\mu$$



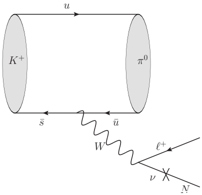
- All interactions are suppressed by $V_{\alpha N}$

Production

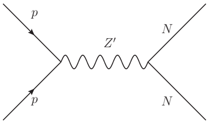
- Intensity frontier, meson: $m_N \sim$ MeV–GeV



  - $\pi^{\pm} \to \ell^{\pm} N$
  - $K \to \ell N(\pi)$
  - $D, B \to \ell N(M')$
  - Beam-dump, LHC, atmosphere, etc.



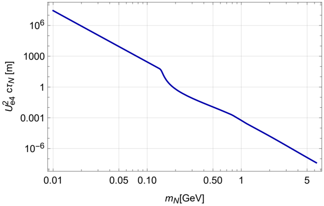
- Energy frontier, collider: $m_N \geq$ GeV
  - $W \to \ell N$, $Z \to \nu N$, and $h \to \nu N$
  - $Z' \to NN$, $W_R \to \ell N$, ...
  - Direct production
  - LHC, e^+e^-, e^-p, muon collider, etc.



- Production always suppressed by $U_{\ell N}$ in the minimal scenario

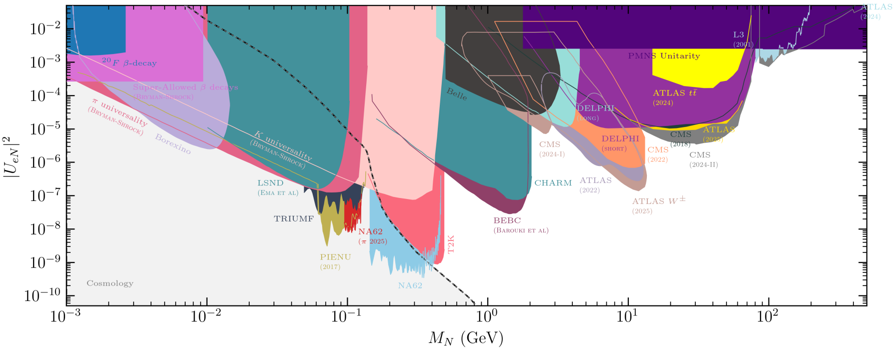
Decay

- Two-body decays dominant ($m_N \gtrsim m_W$)
  - $N \to \ell W$
  - $N \to \nu Z$
  - $N \to \nu h$
  - $\Gamma_N \propto |U_{\ell N}|^2 m_N^3$
  - $\Rightarrow c\tau_N \propto \frac{1}{|U_{\ell N}|^2 m_N^3}$



- Three-body decays dominant ($m_N \lesssim m_W$)
  - $N \to 3\nu, \ell\ell'\nu$
  - $N \to \nu M^0, \ell^\pm M^\mp$ or $N \to \nu jj', \ell jj'$ depending on m_N
  - $\Gamma_N \propto |U_{\ell N}|^2 m_N^5$
  - $\Rightarrow c\tau_N \propto \frac{1}{|U_{\ell N}|^2 m_N^5}$
- Also the Lorentz boost should be taken into account
- $\Rightarrow$ N can be easily long-lived for small mixings and small masses
- prompt, displaced, missing
- Various signatures for different final states

Existing bounds



[Heavy Neutrino Limits](#)

- HNLs are not *assumed* to be LLPs – they are predicted to be LLPs
- Different experiments probe different lifetimes and different masses

Conclusions

- Sterile neutrinos explain neutrino masses
- Different seesaw mechanisms
- HNLs, masses and mixings decoupled
- Various production and decay modes
- Existing bounds predict small mixings $\rightarrow$ LLP
- Rich experimental program across energy scales
- Next lecture: phenomenological results