Probing Light Sterile Neutrino
in
its exclusive semileptonic decays

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to appear on arXiv, Claudio Dib, C.S. Kim, Nicolás Neill, XY

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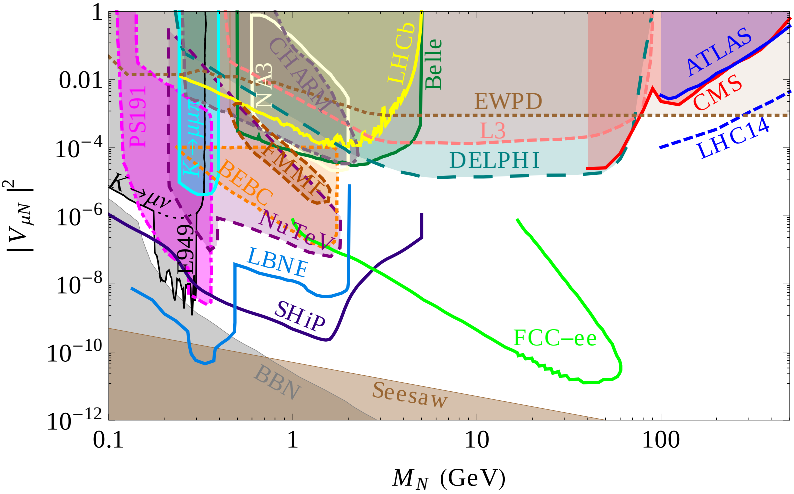
Motivation for sterile neutrino

- Recent neutrino oscillation data demonstrates that at least two active neutrinos are massive, which provide conclusive experimental evidence for the existence of BSM.
- In order to naturally explain the smallness of the observed neutrino masses, right-handed sterile neutrino is usually introduced in the SM extensions, such as the seesaw mechanism.
- In the past decades, many experiments have searched for the sterile neutrino of mass from eV to TeV scale.

Experimental searches



- current and future limits on the mixing between the muon neutrino and a single heavy neutrino.

  Taken from Deppisch, Bhupal Dev and Pilaftsis, arXiv:1502.06541

- constraints from $0\nu\beta\beta$ decay, (LNV) meson decays, Z decay, EWPT, direct search @electron/hadron collider

Direct collider searches

$pp \to W^{(*)} \to \ell^\pm \ell^\pm jj$ Majorana

- $m_N > m_W$: ☺ Atre, Han, et al, 0901.3589
- $m_N < m_W$: ☹ jet background

$pp \to W^{(*)} \to \ell^+\ell^+\ell'^-\bar{\nu}_{\ell'},\ \ell^+\ell^+\ell'^-\nu_\ell$ Dirac, Majorana

- $m_N > m_W$: Dib, Kim, et al, 1509.05981, 1605.01123
- $m_N < m_W$: $\not{E}_T$, fake lepton, displaced vertex

$pp \to W^+ \to \ell^+ N \hookrightarrow \pi^-\ell^+,\ \pi^0\pi^-\ell^+,\ \pi^-\pi^-\pi^+\ell^+$ Dirac, Majorana

- $m_N \in [5,\ 20]\,\mathrm{GeV}$
- $\Gamma(N \to \ell^+\pi^-)/\Gamma(N \to \ell\bar{q}q') \sim (f_\pi/m_N)^2$
- displaced vertex: lower masses make the sterile neutrino has enough time to travel a measurable distance before decaying.
- similar to τ decay, $\tau^- \to \pi^0\pi^-\nu_\tau$ and $\tau^- \to \pi^-\pi^-\pi^+\nu_\tau$
- Example: measuring the exclusive mode $B \to K^*\gamma$ is much easier than the inclusive mode $B \to X_s\gamma$

Basic setup

- SM+one right-handed singlet N_R
- Lagrangian after EWSB

$$\Delta\mathcal{L} = -\frac{g}{\sqrt{2}} V_{\ell N}^* W_\mu^+ \bar{N}\gamma^\mu P_L \ell - \frac{g}{2c_W} V_{\ell N}^* Z_\mu \bar{N}\gamma^\mu P_L \nu_\ell - \frac{g m_N}{2m_W} V_{\ell N}^* \bar{N} P_L \nu_\ell + h.c.$$

- sterile neutrino can't directly interact with other SM particles in the absence of any mixing with the active neutrino sector.
- In this setup, the sterile neutrino can be Dirac or Majorana fermion. However, since the nature of the sterile neutrino is not much relevant to the processes studied in this work, we only consider the case of the Majorana neutrino.

$N \to \pi^- \ell^+$

- decay width

$$\Gamma(N \to \pi^- \ell^+) = \frac{G_F^2}{16\pi} f_\pi^2 |V_{ud}|^2 |V_{\ell N}|^4 m_N^3 \lambda^{1/2}(1, m_\ell^2/m_N^2, m_{\pi^-}^2/m_N^2) \times \left[\left(1 + \frac{m_\ell^2}{m_N^2} - \frac{m_{\pi^-}^2}{m_N^2}\right) \left(1 + \frac{m_\ell^2}{m_N^2}\right) - 4\frac{m_\ell^2}{m_N^2} \right]$$

- input: f_π
- ratio:

$$\frac{\Gamma(N \to \ell^- \pi^+)}{\Gamma(N \to \ell^- u\bar{d})} \sim 4\pi^2 \frac{f_\pi^2}{m_N^2}$$

$N \to \pi^0\pi^-\ell^+$

- decay width

$$\frac{\mathrm{d}\Gamma(N\to\pi^0\pi^-\ell^+)}{\mathrm{d}s} = \frac{\Gamma_N^0|V_{ud}|^2|V_{\ell N}|^2}{2m_N^2}\frac{3s^3\beta_\ell\beta_\pi}{2m_N^6}F_-(s)^2 \times\left[\beta_\ell^2\left(\frac{(\Delta m_\pi^2)^2}{s^2}-\frac{\beta_\pi^2}{3}\right)+\left(\frac{(m_N^2-m_\ell^2)^2}{s^2}-1\right)\left(\frac{(\Delta m_\pi^2)^2}{s^2}+\beta_\pi^2\right)\right]$$

- input: form factor

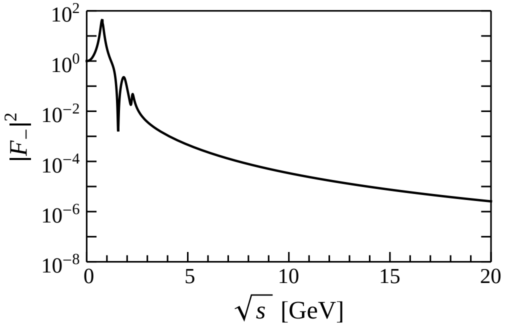
$$\langle\pi^-(p)\pi^0(p')|\bar{d}\gamma_\mu u|0\rangle = \sqrt{2}F_-(s)(p-p')_\mu$$

$N \to \pi^0 \pi^- \ell^+$

- conservation of vector current (CVC): $F_0(s) = F_-(s)$
- $e^- e^+ \to \pi^- \pi^+$ data at $\sqrt{s} < 3\,\mathrm{GeV}$
- VDM parametrization

$$F_0(s) = \frac{1}{1 + c_{\rho'} + c_{\rho''} + c_{\rho'''}} \left(\mathrm{BW}^{\mathrm{GS}}_{\rho}(s, m_\rho, \Gamma_\rho) \frac{1 + c_\omega \mathrm{BW}^{\mathrm{KS}}_{\omega}(s, m_\omega, \Gamma_\omega)}{1 + c_\omega} \right.$$
$$\left. + \; c_{\rho'} \mathrm{BW}^{\mathrm{GS}}_{\rho'}(s, m_{\rho'}, \Gamma_{\rho'}) + c_{\rho''} \mathrm{BW}^{\mathrm{GS}}_{\rho''}(s, m_{\rho''}, \Gamma_{\rho''}) + c_{\rho'''} \mathrm{BW}^{\mathrm{GS}}_{\rho'''}(s, m_{\rho'''}, \Gamma_{\rho'''}) \right)$$

- extrapolated to $\sqrt{s} > 3\,\mathrm{GeV}$ region
- shape determined by the ρ, ρ', ρ'', ρ''' and ω meson



$N \to \pi^- \pi^- \pi^+ \ell^+$

- decay width

$$\frac{\mathrm{d}\Gamma(N \to h_1 h_2 h_3 \ell^+)}{\mathrm{d}q^2} = \frac{G_F^2 |V_{ud}|^2 |V_{\ell N}|^2}{128(2\pi)^5\, m_N^3} \lambda^{1/2}(1, m_N^2/q^2, m_\ell^2/q^2) \Bigg[\left(\frac{(m_N^2 - m_\ell^2)^2}{q^2} - m_N^2 - m_\ell^2 \right) \omega_{SA}(q^2) + \frac{1}{3} \left(\frac{(m_N^2 - m_\ell^2)^2}{q^2} + m_N^2 + m_\ell^2 - 2q^2 \right) (\omega_A(q^2) + \omega_B(q^2)) \Bigg]$$

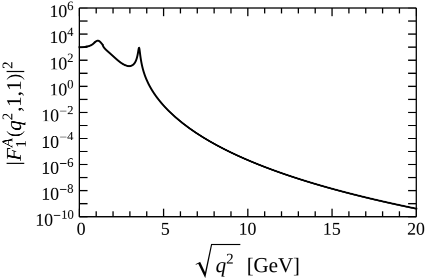
- input: form factor

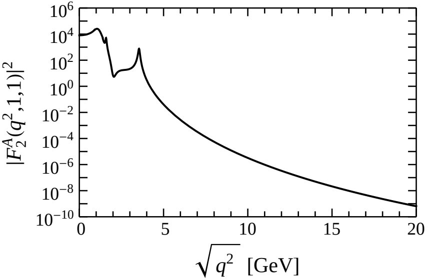
$$\langle h_1(p_1) h_2(p_2) h_3(p_3) | (V - A)^\mu | 0 \rangle = V_1^\mu F_1^A + V_2^\mu F_2^A + q^\mu F_3^P + i V_3^\mu F_4^V$$

  - F_3^P is suppressed (PCAC). $F_4^V = 0$ in the isospin limit.

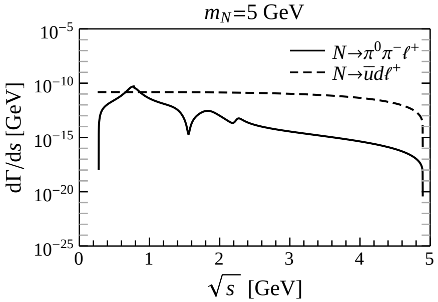
$N \to \pi^- \pi^- \pi^+ \ell^+$

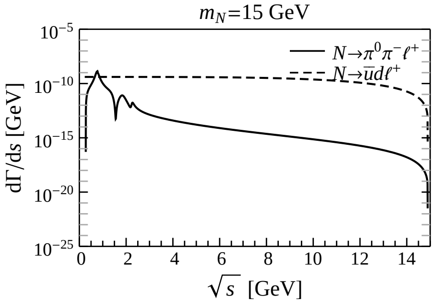
- CLEO τ decay data
- shape determined by the transitions $a_1(1260)/a_1'(1640) \to \pi + f_0(500), f_2(1270), f_0(1370), \rho(770), \rho'(1450)$, and $K^*(892)$.
- extrapolated to $q^2 > m_\tau^2$ region





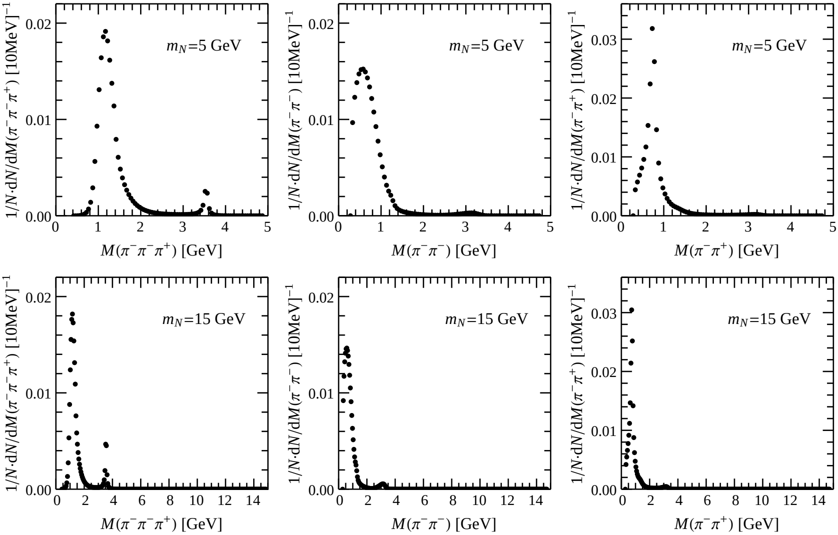
Distribution: $N \to \pi^0\pi^-\ell^+$ and $N \to \bar{u}d\ell^+$





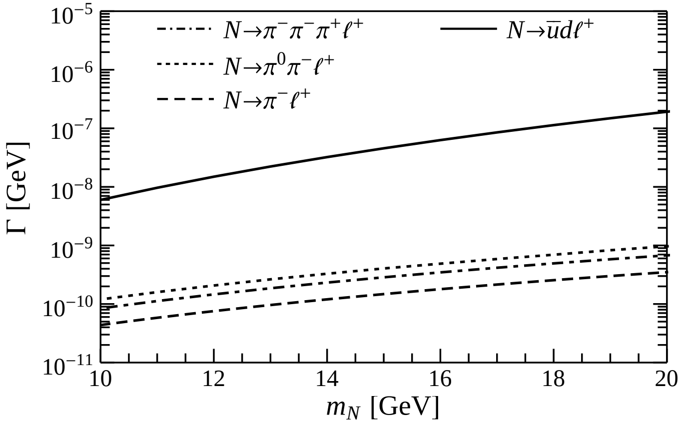
- $|V_{\ell N}| = 1$ assumed
- $\sqrt{s} = M(\pi^0\pi^-)$ or $M(\bar{u}d)$
- shape similar to $\tau^- \to \pi^0\pi^-\nu_\tau$
- shape dominated by ρ, ρ', ρ'', ρ''' and ω meson

Distribution: $N \to \pi^-\pi^-\pi^+\ell^+$



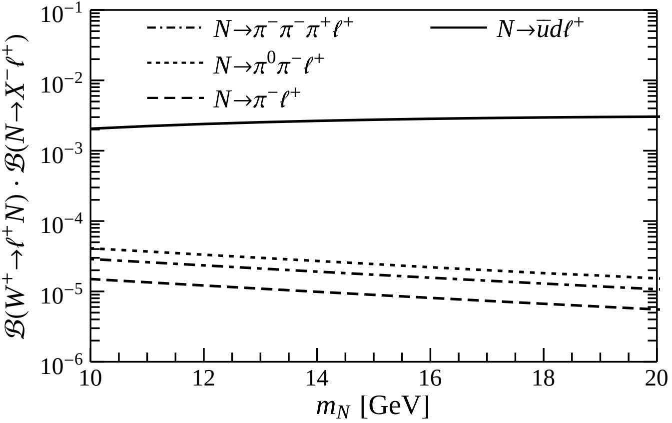
- shape similar to $\tau^- \to \pi^-\pi^-\pi^+\nu_\tau$

Total decay width

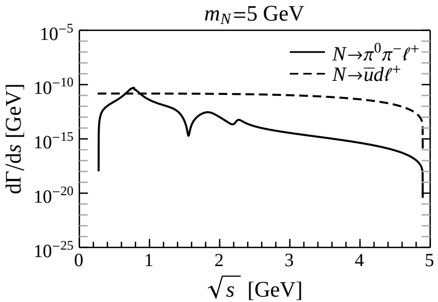


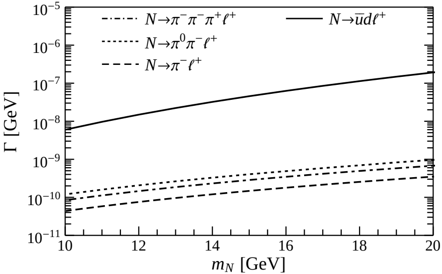
- total width: $\Gamma(N \to \bar{u}d\ell^+) \gg \Gamma(N \to 2\pi) > \Gamma(N \to 3\pi) > \Gamma(N \to \pi)$
- inclusive mode $N \to \bar{u}d\ell^+$ suffer frome large QCD background
- small m_N makes the neutrino has enough life time to travel a measurable distance before decay, which can help to suppress background in the exclusive mode.

Branching ratio



Quark-Hadron Duality





- $N \to \bar{u}d\ell^+$ is usually considered as inclusive, which should be larger than any exclusive mode.
- For the differential width, $N \to \bar{u}d\ell^+ < N \to \pi^0\pi^-\ell^+$ in some region
- quark-hadron duality: $\Gamma(N \to \text{hadrons} + \ell^+) \approx \Gamma(N \to \bar{u}d\ell^+)$
- reason: quark-hadron duality is always violated both locally and globally.
  $\Gamma_h = \Gamma_q + \Delta\Gamma$
  $\mathrm{d}\Gamma_h/\mathrm{d}s = \mathrm{d}\Gamma_q/\mathrm{d}s + \mathrm{d}\Delta\Gamma/\mathrm{d}s$
- duality violation: can't be calculated from first principle currently. can be estimated with some models
- e.g., $\tau^- \to \text{hadrons} + \nu_\tau$ decay applied to extract α_s and $|V_{us}|$

Summary

- We have investigated the possibility to probe light sterile neutrino by using the exclusive pionic decays:
  $N \to \pi^- \ell^+$, $N \to \pi^0 \pi^- \ell^+$, $N \to \pi^- \pi^- \pi^+ \ell^+$.
- Their differential and total decay width have been calculated.
- We find for $m_N \sim 10\,\mathrm{GeV}$, total width:
  $\Gamma(N \to \bar{u} d \ell^+) \gg \Gamma(N \to 2\pi) > \Gamma(N \to 3\pi) > \Gamma(N \to \pi)$
- These exclusive modes could be measured at the LHC, e.g., LHCb. In the next, a detailed collider simulation is needed.

Thank You !

Backup

$$\mathcal{B}(\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau) = 17.4\%$$
$$\mathcal{B}(\tau^- \to \pi^- \nu_\tau) = 18.0\%$$
$$\mathcal{B}(\tau^- \to \pi^- \pi^0 \nu_\tau) = 25.5\%$$
$$\mathcal{B}(\tau^- \to \pi^- \pi^+ \pi^- \nu_\tau) = 9.3\%$$
$$\mathcal{B}(\tau^- \to \text{hadrons} + \nu_\tau) \approx 64\%$$