Probing Light Sterile Neutrino

in

its exclusive semileptonic decays

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NCTS

arXiv: 1801.03624, Claudio Dib, C.S. Kim, Nicolás Neill, XY

Motivation

Displaced Vertices

- mainly $\mathcal{O}(10)\,\mathrm{cm} < c\tau < \mathcal{O}(1)\,\mathrm{m}$ — displaced vertices inside detectors
- possible for $c\tau \sim \mathcal{O}(1)\,\mathrm{mm}$ — e.g., CMS, PRD95,012009

NP particle's lifetime long enough — not too long

- small couplings — symmetry/its breaking, e.g., various SUSY particles
- small mass: few GeV or maller — e.g., see Ishida and Sming Tsai's talk

Searching for GeV NP particle — light sterile neutrino

- inclusive mode: $X_{\mathrm{NP}} \to \mathrm{jets} + \mathrm{leptons}$
- exclusive mode: $X_{\mathrm{NP}} \to \pi s + \mathrm{leptons}$

Most GeV SM particles are established via their exclusive decays
e.g., $\Omega_b^-(6046) \to \pi^-(\Omega_c^0 \to pK^-K^-\pi^+)$@LHCb, $\Upsilon(11020) \to \Upsilon(nS)\pi^+\pi^-$@BELLE

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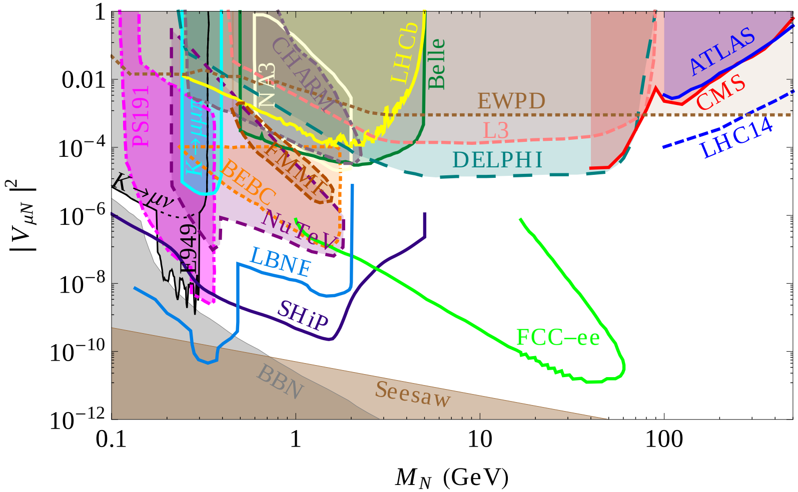
Motivation for sterile neutrino

- 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 searches in different mass regions

$pp \to W^{(*)} \to \ell^\pm \ell^\pm jj$ 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
- $20\,\mathrm{GeV} < m_N < m_W$: $\not{E}_T$, fake lepton, displaced vertex

B, D **and** K **decays** Dirac, Majorana

- $m_N < 5\,\mathrm{GeV}$: Kim, et al, 1005.4282, 1705.09403

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

- $5\,\mathrm{GeV} < m_N < 20\,\mathrm{GeV}$

Exclusive decays of N

$$pp \to W^+ \to \ell^+ N_{\hookrightarrow \pi^-\ell^+,\ \pi^0\pi^-\ell^+,\ \pi^-\pi^-\pi^+\ell^+}$$

Dirac, Majorana

- $m_N \in [5,\ 20]\,\mathrm{GeV}$
- 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 $\tau^- \to \pi^-\pi^-\pi^+\nu_\tau$,
  but without missing energy
  possible to use smilar τ determination tech@LHC
- most GeV SM particles are established via their exclusive decays
  $\Omega_b^-(6046) \to \pi^-(\Omega_c^0 \to pK^-K^-\pi^+)$@LHCb
  $\Upsilon(11020) \to \Upsilon(nS)\pi^+\pi^-$@BELLE
- measuring the exclusive mode $B \to K^*\gamma$ is much easier than the inclusive mode $B \to X_s\gamma$

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Basic setup

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

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

- 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: $r \sim 0.6\%$ for $m_N = 10\,\mathrm{GeV}$

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

- The exclusive single-pion mode is suppressed with respect to the inclusive process. This suppression is clearly milder for lower masses of the sterile neutrino. (The formation of a single pion require the two produced quarks to remain close together.)

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

- similar to $\tau^- \to \pi^0\pi^-\nu$ decay
- 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

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

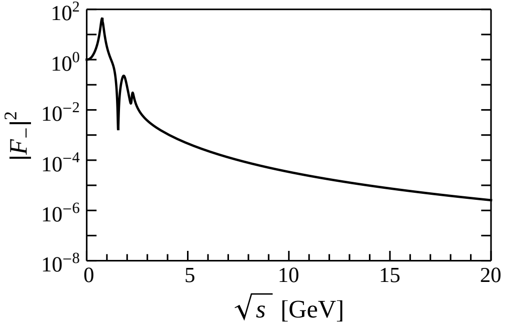
$$\langle \pi^-(p)\pi^+(p')|\bar{u}\gamma_\mu u|0\rangle = -\langle \pi^-(p)\pi^+(p')|\bar{d}\gamma_\mu d|0\rangle = F_0(s)(p-p')_\mu$$

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

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

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

- extrapolated to $\sqrt{s} > 3\,\mathrm{GeV}$ region (no other meson's contribution)
- shape determined by the ρ, ρ', ρ'', ρ''' and ω meson



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

- similar to $\tau^- \to \pi^- \pi^- \pi^+ \nu$
- decay width

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

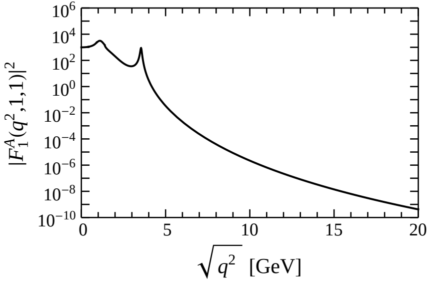
- input: form factor

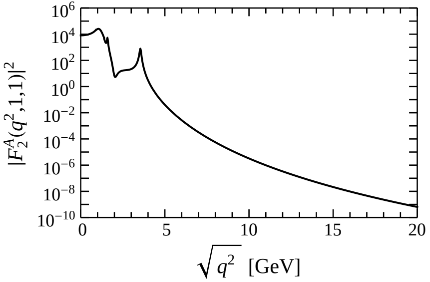
$$\langle h_1(p_1) h_2(p_2) h_3(p_3) | (V-A)^\mu | 0 \rangle = V_1^\mu F_1^A + V_2^\mu F_2^A + q^\mu F_3^P + i V_3^\mu F_4^V$$

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

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

- CLEO τ decay data
- We use the so-called CLEO parametrization
- 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 (no other meson's contribution)





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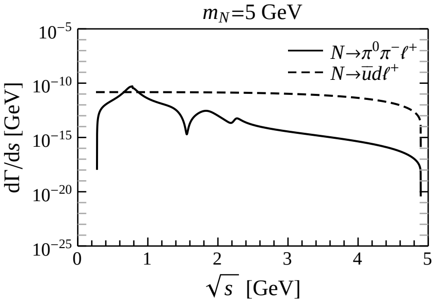
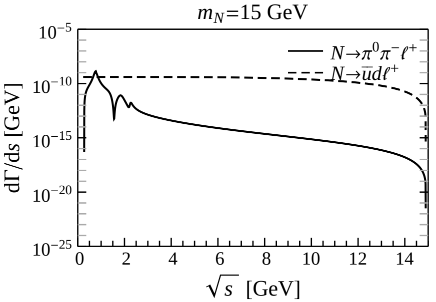
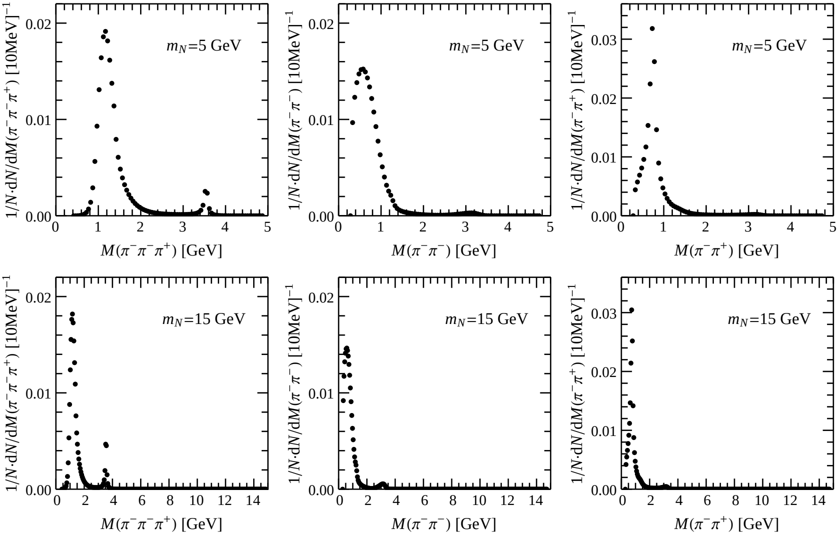
Distribution: $N \to \pi^0\pi^-\ell^+$ and $N \to \bar{u}d\ell^+$





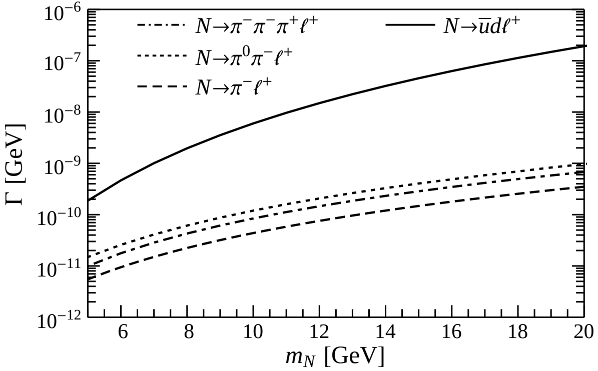
- $|V_{\ell N}| = 1$ assumed
- $\sqrt{s} = M(\pi^0\pi^-)$ or $M(\bar{u}d)$
- shape similar to $\tau^- \to \pi^0\pi^-\nu_\tau$
- shape dominated by ρ, ρ', ρ'', ρ''' and ω meson

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



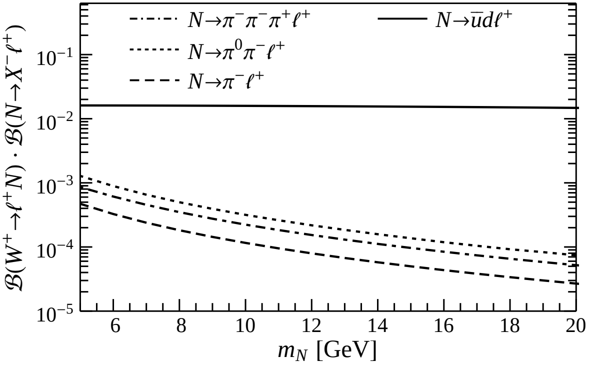
- shape similar to $\tau^- \to \pi^-\pi^-\pi^+\nu_\tau$

Total decay width



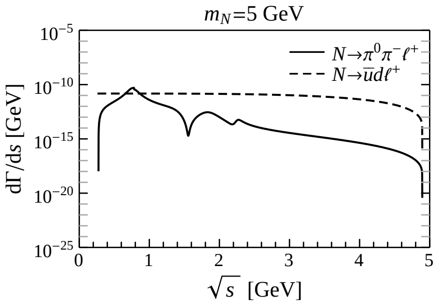
- total width: $\Gamma(N \to \bar{u}d\ell^+) \gg \Gamma(N \to 2\pi) > \Gamma(N \to 3\pi) > \Gamma(N \to \pi)$
- inclusive mode $N \to \bar{u}d\ell^+$ suffer frome large QCD background
- small m_N makes the neutrino could have enough life time to travel a measurable distance before decay, which can help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

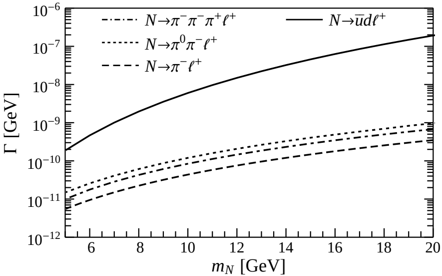
Branching ratio



- Assuming 10^9 $W^\pm$ boson, expected by the end of LHC Run II.
- Benchmark mass $m_N = 10\,\mathrm{GeV}$
- In order to obtain 5 events of $W^+ \to n\pi\mu^+\mu^-$, $|U_{\mu N}|^2 \sim 10^{-5}$ is needed.
- In order to obtain 5 events of $W^+ \to n\pi\ell^+\ell^-$, $|U_{\ell N}|^2 \sim 10^{-6}$ is needed.
- ideal results, without cuts and backgrounds
- The current DELPHI bound is $|U_{\ell N}|^2 < 2.1 \times 10^{-5}$.

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 $|V_{us}|$

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- We have investigated the possibility to probe light sterile neutrino with the mass $5\,\mathrm{GeV} < m_N < 20\,\mathrm{GeV}$ 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 analytically.
- We find for $5\,\mathrm{GeV} < m_N < 20\,\mathrm{GeV}$, total width: $\Gamma(N \to \bar{u} d \ell^+) \gg \Gamma(N \to 2\pi) > \Gamma(N \to 3\pi) > \Gamma(N \to \pi)$
- Assuming 10^9 $W^\pm$ produced by the end of LHC Run II, a ideal analysis shows $|U_{\ell N}|^2 \sim 10^{-6}$ can be probed, which is one order of magnitude more stringent than the DELPHI bounds.
- Our study is still quite preliminary. More detailed simulation is needed. (displaced vertices technology. modified TAUOLA package ? etc.)

Thank You !

Backup

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