DARK NEUTRINO SECTORS & LOW ENERGY EXPERIMENTS

Brookhaven Neutrino Theory Virtual Seminars
BNTVS

Matheus Hostert
University of Minnesota,
William I. Fine Institute & Perimeter Institute
DARK NEUTRINO SECTORS
&
LOW ENERGY EXPERIMENTS

Based on work with:
Silvia Pascoli & Peter Ballett
@ Durham University

Outline

PRD99, 091701(R)

1903.07590
*extended v2
submitted to PRD
Based on work with:
Silvia Pascoli & Peter Ballett
@ Durham University

Outline

- Heavy neutral leptons in seesaw extensions with dark U(1)' symmetries
DARK NEUTRINO SECTORS & LOW ENERGY EXPERIMENTS

Based on work with:
Silvia Pascoli & Peter Ballett @ Durham University

Outline

• Heavy neutral leptons in seesaw extensions with dark U(1)' symmetries

• Overview of new signatures at neutrino, collider, and kaon experiments.
DARK NEUTRINO SECTORS & LOW ENERGY EXPERIMENTS

Based on work with:
Silvia Pascoli & Peter Ballett @ Durham University

Outline

• Heavy neutral leptons in seesaw extensions with dark U(1)' symmetries
• Overview of new signatures at neutrino, collider, and kaon experiments.
• New ideas to search for dark neutrinos at NA62.

PRD99, 091701(R)

1903.07590 *extended v2 submitted to PRD
Well-motivated extension of the SM

- Type-I seesaw (and variants) for neutrino masses
- Generic renormalizable coupling to singlet fermions
- $M_N$ need not be large. Nu masses may be small due to small Yukawas.
Under the lamppost meson decays & beam dumps
But how robust is this picture against enlarging the dark sector? e.g., if open-minded about BRs and decays of N.

\[ L_{\text{SM}} \]

\[ \nu_\alpha \rightarrow N \]

[Diagram showing the Standard Model and Hidden Sector, with a question mark indicating uncertainty in the decay \( N \rightarrow X \).]

---

de Gouvea et al, 1511.00683
New local U(1) gauge symmetry with Type-I-like HNL

Gauged \((B - L)\)


Gauged \((L_a - L_b)\)


this talk ➔ Gauged \((Q_X)\) — dark quantum number, not shared by SM


Dark fermion \(\nu_D\) no longer a complete singlet.

\[(LH_D)\nu_D\] in extended SM-charged scalar sectors (e.g. 2HDM, richer scalar pheno)

but can have much simpler model.
New dark U(1)' symmetry spontaneously broken by SM-singlet scalar field

\[ \mathcal{L} = \mathcal{L}_{\text{SM}} + (D_\mu \Phi) \dagger (D^\mu \Phi) - V(\Phi, H) \]

\[ - \frac{1}{4} X^{\mu \nu} X_{\mu \nu} + \bar{N} i \Phi N + \bar{\nu}_D i \Phi \nu_D \]

\[ - \left[ y_\nu (\bar{L}_\alpha \cdot \bar{H}) N^c + \frac{\mu'}{2} \bar{N} N^c + y_N \bar{N} \nu_D \Phi + \text{h.c.} \right], \]

Two-step mixing with SM-like neutrinos.

- **Kinetic mixing**: \( B_{\mu \nu} X^{\mu \nu} \)
- **Scalar mixing**: \( |\Phi|^2 |H|^2 \)
- **Neutrino mixing**: \( (\bar{L} \bar{H}) N \)
New dark U(1)' symmetry spontaneously broken by SM-singlet scalar field

\[ \mathcal{L} = \mathcal{L}_{\text{SM}} + \left( D_\mu \Phi \right)^\dagger (D^\mu \Phi) - V(\Phi, H) \]

\[ - \frac{1}{4} X^{\mu \nu} X_{\mu \nu} + \bar{N} i \slash D N + \bar{\nu}_D i \slash D \nu_D \]

\[ - \left[ y^\alpha_v \left( \bar{L}_\alpha \cdot \tilde{H} \right) N^c + \frac{\mu'}{2} \bar{N} N^c + y_N \bar{N} \nu_D^c \Phi + \text{h.c.} \right], \]

<table>
<thead>
<tr>
<th></th>
<th>SU(2)_L</th>
<th>U(1)_Y</th>
<th>U(1)'</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>\nu_D</td>
<td>1</td>
<td>0</td>
<td>Q</td>
</tr>
<tr>
<td>\Phi</td>
<td>1</td>
<td>0</td>
<td>Q</td>
</tr>
</tbody>
</table>

**Anomaly freedom and extensions w/ fermionic DM candidates:**

- **Option 1)** Vector-like \( \nu_D \) and DM, where \( \chi_{L,R} \sim (1, 0, Q/2) \) stable

\[ y_R \chi_R^c \chi_R \Phi^* + y_L \chi_L^c \chi_L \Phi^* + m_\chi \chi_L \chi_R \]

- **Option 2)** Cancellation between \( \nu_D \) and dark matter \( \chi_L \sim (1, 0, 0) \), \( \chi_R \sim (1, 0, Q) \)

with residual dark parity (e.g., from lepton number).

\[ \mu_L \chi_L^c \chi_L + y \chi_L \chi_R \Phi^* \]

see also:
J. Gherlelein & M. Pierre
JHEP02 (2020) 068
Inverse, Extended and Linear seesaws — Pair of HNL with opposite L

\[ -\mathcal{L}_{\nu-\text{mass}} \supset \frac{1}{2} (\nu_L \quad N \quad \nu_D) \begin{pmatrix} 0 & m & \epsilon' \\ m & \mu' & \Lambda \\ \epsilon' & \Lambda & \mu \end{pmatrix} \begin{pmatrix} \nu_L^c \\ N^c \\ \nu_D^c \end{pmatrix} + \text{h.c.} \]

\[ m_1 = \frac{\mu m^2 - 2\epsilon' m \Lambda + \epsilon'^2 \mu'}{\Lambda^2 - \mu \mu'}. \]

Light neutrino masses proportional to LNV parameters.
Minimal Radiative Inverse Seesaw (MRISS)

When $\mu = \epsilon = 0$

$$-L_{\nu\text{-mass}} \supset \frac{1}{2} \left( \bar{\nu}_L \ N \ \bar{\nu}_D \right) \left( \begin{array}{ccc} 0 & m & 0 \\ m & \mu' & \Lambda \\ 0 & \Lambda & 0 \end{array} \right) \left( \begin{array}{c} \nu_L^c \\ N^c \\ \nu_D^c \end{array} \right) + \text{h.c.}$$

Easy to see when integrating out N: $\mu' \to \infty$

$$\frac{1}{2\mu'} \left( \bar{\nu}_\alpha \ N \ \bar{\nu}_D \right) \left( \begin{array}{cc} m^2 & m \Lambda \\ m \Lambda & \Lambda^2 \end{array} \right) \left( \begin{array}{c} \nu_\alpha^c \\ \nu_D^c \end{array} \right)$$

Massless SM-like neutrinos at tree-level

(holds provided $#N = #S$)

n.b.

**ESS-like scenario relevant for:**

- light steriles w/ secret interactions,
- neutrino self-interactions

$$m_{\text{dark}} = \frac{m^2 + \Lambda^2}{2\mu'}$$

$$m_\nu = 0$$

P.S.B. Dev et al., 1209.4051
J. Lopez-Pavon et al, 1209.5342

P.S.B. Dev et al., 1209.4051
J. Lopez-Pavon et al, 1209.5342

P.S.B. Dev et al., 1209.4051
J. Lopez-Pavon et al, 1209.5342
After $U(1)'$ and EW group are broken, no longer protected.

With light new particles, NP loops dominate: neutrino masses are small because $m_D$ is small.

**ISS-like:** $\mu' \ll \Lambda$

$$m_\nu \sim \frac{g'^2}{8\pi^2} \frac{m_D^2}{m_{Z'}^2} \mu' \left(3 \ln \frac{m_{Z'}^2}{\Lambda^2} + \ln \frac{m_{\phi'}^2}{\Lambda^2} - 4\right)$$

where $m_{Z'}, m_{\phi'} \ll \Lambda$

**ESS-like:** $\mu' \gg \Lambda$

$$m_\nu \sim \frac{g'^2}{8\pi^2} \frac{m_D^2}{\mu'} \left(3 \ln \frac{m_{Z'}^2}{\Lambda^2} + \ln \frac{m_{\phi'}^2}{\Lambda^2} - 4\right)$$

where $m_{Z'}, m_{\phi'} \gg \mu'$
Ignoring kinetic and scalar mixing

Provided neutrino mixing is small:

**ISS-limit:** both steriles behave “standard” HNL

\[ \Gamma(\nu_5 \to \nu_4 + \ldots) \propto (\mu')^3(5) \]

**ESS-limit:** Heavy steriles cascade to \( \nu_4 \), which in turn behaves as “standard” HNL.

\[ \nu_5 \to \nu_4 Z' \to \nu_4 \nu_4 \nu_4 \]

\( m_{Z'}, m_{\phi} < m_4 \): HNL decay invisibly.

Best way to search for such HNL is still via **decay-in-flight** exps.

P. Ballett et al, 1905.00284
J. M. Berryman et al, 1912.07622
UV completion for “neutrino-philic” interactions & explains the zero in the MRISS mass matrix…

…but phenomenology is somewhat “boring”.

This changes when we turn on additional portal couplings.
Focus on dark photon + HNL case, and neglect the dark scalar for now.

New “stronger-than-weak” neutrino-charged matter interactions!

\[ \nu_\alpha \rightarrow \nu_h \]

\[ e \chi q_f \]

\[ U_{\alpha h}^* g' \]

SM + heavy neutrino

Quarks and charged leptons

Mixing x O(1) coupling

Kinetic mixing

SM neutrinos only

Doubly suppressed
Explaining MiniBooNE
MiniBooNE Coll., PRL.121.221801

4.7σ excess observed in nu + nubar mode
— data/MC disagreement beyond statistical doubt —

Neutrinos up-scatter into HNL, which promptly decays into e+e-.

E. Bertuzzo et al., 1807.09877

P. Ballett et al., 1808.02915
Several scenarios discussed so far

nu4 fine tuned to be long lived

nu5 much shorter-lived, 

(m5-m4) max inv masses, 

nu4 fine tuned to be long lived 

to avoid PS-191 bounds.

Coherent scattering, 

fast decays, 

forward signal

Less forward, 

but too large scattering 

cross section for nutaus.

E. Bertuzzo et al., 1807.09877

P. Ballett et al., 1808.02915

P. Ballett, MH, S. Pascoli, 1903.07589
Light Dark Photon case

C. Argüelles, MH, Y. Tsai, PRL123, 261801 (2019)

\[ m_{Z'} = 30 \text{ MeV}, \alpha \varepsilon^2 = 2 \times 10^{-10}, \alpha_D = 1/4 \]

New bounds from single-photon sample in nu-e scattering analyses.

Conclusion:
HNL mass cannot be too large, MiniBooNE signal typically very forward.
Currently studying all such cases in LAr together with microBooNE single-photon group @ Nevis Labs, Columbia University.

Asli Abdullahi
Durham Uni.

4 topologies currently under consideration: 

- **0p⁺ 1γ**
- **0p⁺ 2e**
- **1p⁺ 1γ**
- **1p⁺ 2e**

Pioneering study of genuine dielectron pairs in LAr.

**Light Dark Photon**: no proton so smaller efficiencies, but enhanced in LAr (\(A^2\) coherent.)

**Heavy Dark Photon**: shower displaced from proton. *Mostly photon-like showers.*
Minimal dark photon model

P. Foldenhauer et al, JHEP07(2018)094

Invisible dark photon

J.P. Lees, PRL.119.131804

Signal: mono-photon + $E_T$

Muon (g-2) is excluded, but only by mono-photon searches at BaBar

$$M_{Z'}^2 = s - 2E_\gamma \sqrt{s}$$

In a 2-fermion dark sector, one may relax such bounds if the heaviest fermion decays visibly.

Proven for an inelastic DM model.
Even more relevant for dark neutrinos

$$\Delta = 0.4 \ m_{\chi 1}, \ m_A = 3 \ m_{\chi 1}, \ \alpha_D = 0.1$$

$$\Gamma(Z' \rightarrow \nu_h \nu) \approx |U_{\alpha h}|^2 \frac{g'^2 m_{Z'}}{12\pi}$$

$$m_{Z'} \sim 1 \ GeV$$

$$m_A \sim 800 \ MeV$$

$$\chi \sim 2.2 \times 10^{-2}$$

Now final states are even harder to miss:

pair of electrons, muons or pions!

$$\Gamma(\nu_4 \rightarrow \nu_\alpha e^+ e^-) \approx |U_{\alpha 4}|^2 \frac{(e e W \chi g')^2}{384 \pi^3} \ \frac{m_4^5}{m_{Z'}^4}$$
A smoking gun signature at NA62
Searches for HNL at NA62 @ CERN

Usual peak searches based on kinematical argument:

\[ m_{p_K-p_\alpha}^2 \equiv (p_K - p_\alpha)^2 = m_{\nu h}^2, \]

Stringent vetoes on additional photons or charged particles to avoid backgrounds such as \( K^+ \to \mu^+ \nu \gamma \).

Provided the detection *inefficiency* to additional particles is not too small, can be relaxed significantly!

HNL + light dark photon \( \rightarrow K^+ \to \mu^+ \nu_h \to \mu^+ \nu Z' \to \mu^+ ve^+ e^- \) is vetoed from sample.

75 GeV Kaons

*special thanks to Evgueni Goudzovski for discussion on NA62*
But this is in itself is quite a striking prediction:

\[ K^+ \rightarrow \ell_\alpha^+ \nu_h \rightarrow \ell_\alpha^+ \nu Z' \rightarrow \ell_\alpha^+ \nu \ell_\beta^+ \ell_\beta^- \]

Production is still controlled:

\[ \text{BR}(M^+ \rightarrow \ell_\alpha^+ \nu_h) = |U_{\alpha h}|^2 \rho_\alpha(m_{\nu_h}) \text{BR}(M^+ \rightarrow \ell_\alpha^+ \nu_{\alpha}) \]

“Multi-dimensional bumps” from 2-body kin:

\[
\begin{align*}
    m_{\beta\beta}^2 & \equiv (p_{\beta^+} + p_{\beta^-})^2 = m_{Z'}^2, \\
    m_{pK-p_\alpha}^2 & \equiv (p_K - p_\alpha)^2 = m_{\nu_h}^2, \\
    m_{\text{miss}}^2 & \equiv (p_K - p_\alpha - p_{\beta^+} - p_{\beta^-})^2 = 0 \\
    m_{\alpha\beta\beta}^2 & + m_{\alpha\nu}^2 + m_{pK-p_\alpha}^2 = m_K^2 + m_{\alpha}^2 + m_{\text{miss}}^2 + m_{\beta\beta}^2,
\end{align*}
\]

Directly measure dark state masses
With perfect resolution this constitutes a zero-background search!

Main challenge comes from pion Dalitz decays at $m_{ee} < 140$ MeV

missed soft photon from $K^+ \rightarrow \mu^+ \nu_\mu (\pi^0 \rightarrow \gamma e^+ e^-)$

Bkgs such as $K^+ \rightarrow (\pi^+ \rightarrow \mu^+ \nu)e^+ e^-$ can be reduced from additional cuts:

$$m_{\mu\nu} > 150 \text{ MeV}$$

M. S. Atiya et al., PRL.63, 2177 (1989)

Ultimately, depends on resolution, but at very small mixing, NA62 can also reduce bkgs by searching for displaced vertices when $c\tau > 10$ ps

Existing measurements

$$\text{BR}(K^+ \rightarrow \mu^+ e^+ e^-) = (7.81 \pm 0.21 \text{ stat.}) \times 10^{-8} \ @ \ NA48/2$$

$$\text{BR}(K^+ \rightarrow \mu^+ \nu \mu^+ \mu^-) < 4.7 \times 10^{-7} \ @ \ E787$$

Both SM process will be measured by NA62.
$g' = 0.375$, $m_{Z'} = 150$ MeV, $\chi^2 = 10^{-8}$

Other bounds:

- Peak searches relaxed due to visible events (very conservative 0.5% ineff.)
- Upscattering cannot be much larger than nu-e scattering in the SM
- Existing bound based on NA48/2 measurement.

NA62 S.E.S. assuming background-free search.

Assumptions matched to LNV search in $K^+\rightarrow\pi^-e^+e^+$ and $K^+\rightarrow\pi^-\mu^+\mu^+$

Total of 1.6e12 useful Kaon decays (only 30% of NA62 dataset!)

4% acceptance of ee
8% acceptance for $\mu\mu$

NA62 Coll., j.physletb.2019.07.041
If zero-bkg assumption correct, provides direct test of MiniBooNE explanation with light dark photons

E. Bertuzzo et al., 1807.09877
CONCLUSIONS

Presented a “harmless” and minimal UV completion for neutrino-phillic interactions.
Presented a “harmless” and minimal UV completion for neutrino-phillic interactions.

Neutrino masses in MRISS. Loop-level masses arise due to new U(1)' symmetry.
CONCLUSIONS

Presented a “harmless” and minimal UV completion for neutrino-phillic interactions.

Neutrino masses in MRISS. Loop-level masses arise due to new U(1)’ symmetry.

Interplay of portals offers a fertile ground for phenomenology

- MiniBooNE explanations from upscattering and decay.
- Semi-visible dark photons/scalars, poorly constrained parameter space.
Presented a “harmless” and minimal UV completion for neutrino-phillic interactions.

Neutrino masses in MRISS. Loop-level masses arise due to new U(1)’ symmetry.

Interplay of portals offers a fertile ground for phenomenology
  • MiniBooNE explanations from upscattering and decay.
  • Semi-visible dark photons/scalars, poorly constrained parameter space.

New searches for such dark neutrino sectors at NA62. “Smoking-gun” signature in

\[ K^+ \rightarrow \ell^+ \nu e^+ e^- \]