Anomalous $\nu_\tau$ Appearance from Light Mediators in Short-Baseline $\nu$ Experiments

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Introduction

• New Physics: Dark Matter (DM), Neutrino masses and mixing, various anomalies, e.g., g-2 of muon, MiniBooNE etc

  Are they all correlated? Is there a model?

• Where is the new physics scale?

• Many experiments are probing new physics scales: DM direct and indirect detections, LHC, neutrino experiments, beam dump experiments, rare decays etc.

• LHC, direct and indirect detections are mostly probing scales with high sensitivities above 1 GeV
This talk: Investigates scales below 1 GeV

- This region is not well searched
- Anomalies, puzzles can be addressed
- There are many new ideas

Models (a lot of ongoing activities):
Light mediators: scalar, pseudo-scalar, vector; sub-GeV DM

We will utilize: a few specific well-motivated scenarios

- involve tau neutrinos at short baseline neutrino experiments for probing
Beam dump-based Neutrino experiments can be versatile

Beam dump-based (proton beam) [ongoing]: 800 MeV-3 GeV: COHERENT (Oakridge), CCM (LANL), JSNS2 (JPARC) Detectors, CsI, LAr, NaI, Ge

Fermilab SBN program: 120 GeV NuMI, 8 GeV BNB beams (ongoing)

- Many experiments with proton beams have different beam energies using various detectors at different locations
- FASER, FASERv, SND are ongoing at the LHC
New physics at $\nu$ experiments

From $\gamma$:

- $A'$: Vector
- $\phi$: scalar
- $a$: pseudo-scalar

Coherent scattering for $\gamma$ exchange

$$L \supset -\frac{\varepsilon}{4} F^{\mu\nu}F_{\mu\nu}^{(i)} - g_{a,\phi}\gamma(Z') \frac{(a, \phi)}{4} F^{\mu\nu} \tilde{F}_{\mu\nu}^{(i)}$$

Primakoff
New physics at $\nu$ experiments

From $e^\pm$:

$$L \supset -g_{\phi(a)ee\bar{e}} (i\gamma^5)e \phi(a) - g_{Aee\bar{e}} \gamma^\mu e A'$$

**Compton**

**Resonance**

**Associated**

**Bremsstrahlung**
New physics at $\nu$ experiments

\[ L \supset -g_{\phi(a)}f_f \bar{f}(i\gamma^5)f_{\phi(a)} - g_{A_{ee}}f_{A'} \gamma^\mu f_{A' \mu} \]

- Charged meson decay: quarks and lepton couplings
  - Not helicity suppressed $\Rightarrow$ both electron and muon final states contribute
  - Needs to include all the internal bremsstrahlung diagrams $IB_i$ ($i=1,23$)

- Satisfy the experimental constraint from PIENU (pions) and NA62 (Kaons)

Form factor uncertainties associated with $\pi \rightarrow l_{\nu} A'$ decay mode, Khodjamirian, Wyler, hep-ph/0111249

\[ \eta^0, \pi^0 \rightarrow \gamma A'_{\mu} \]

Neutral meson decays

- Charged pion contribution can be larger than the neutral pion even without the focusing horns

- Important for stopped pion and mesons decay-in-flight experiments
New physics

Proton bremsstrahlung

Parton interactions

- There can be more production processes, e.g., $\nu + N \rightarrow \nu_s + N$ (coherently enhanced) using $\bar{\nu}_s \sigma_{\mu\nu} F^{\mu\nu} \nu$

- Nuclear de-excitation lines at lower mass target (lower beam energy)

- Neutrons can be used: Bremsstrahlung, neutrons on target: light mediators

Dev, Dutta, Han, Karthikeyan, Kim, Kim, 2311.10078
Final states

Short-lived mediators: $V, \phi, a$

Longer-lived mediators: Decays

Scattering

$A'$
$N$

$a, \phi, \pi$

Inverse -Primakoff

$\gamma$
$N$

$a, \phi$

Inverse -Compton

$e^-$
$N$

$\gamma$

$e^-$
$N$

$a, \phi$

Bethe-Heitler pair production

This talk

Decays

$e^-, \mu^-, \tau^-$

$e^+, \mu^+, \tau^+$

$e^-$

$e^+$

$\gamma$

$A'$

$\gamma$

$N$

$A'$

$\gamma$

$N$

$\gamma$

$N$

$\gamma$
Various flux spectra at DUNE

\[ \gamma: \frac{20}{\text{POT}} \]
\[ e^-: \frac{700}{\text{POT}} \]
\[ e^+: \frac{20}{\text{POT}} \]

\[ \pi^+: \frac{10}{\text{POT}} \]
\[ \pi^0: \frac{10}{\text{POT}} \]
\[ k^+: \frac{1}{\text{POT}} \]

$120 \text{ GeV}$

$10^{21} \text{ POT}$

\[ \text{Number/POT} \]
Example: DUNE, ICARUS...

**ALP at DUNE using photon, electron/positron flux**

Brdar, Dutta, Jang, Kim, Shoemaker, Tabrizi, Thompson, Yu, Phys.Rev.Lett. 126 (2021) 20, 201801

**HNLs via dark pions**

Abdullah, De Gouvea, Dutta, Shoemaker, Tabrizi, arXiv:2311.07713

Dutta, Karthikeyan, Kim, 2308.01491
**\( \nu_\tau \) final states**

\[
\mathcal{L}_{\text{int}} \supset \sum_f g_V x_f A'_\mu \bar{f} \gamma^\mu f
\]

\[A' \rightarrow \nu_\tau \bar{\nu}_\tau\]

**\( A' \) productions:** Charged mesons, neutral mesons, proton, neutron bremsstrahlung

\((\nu_\tau\)-optimized mode can produce more events through charged mesons\)

- \( \nu_\tau \) produces \( \tau \) via charged current interactions
- \( \tau \) leptons can be detected via hadronic (mesons), leptonic final states (e, \( \mu \) etc.)

**\( \tau \) decay modes**

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>Branching ratio (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \pi^- \pi^0 \nu_\tau )</td>
<td>25.49</td>
</tr>
<tr>
<td>( \bar{e}^- \bar{\nu}<em>e \nu</em>\tau )</td>
<td>17.82</td>
</tr>
<tr>
<td>( \mu^- \bar{\nu}<em>\mu \nu</em>\tau )</td>
<td>17.39</td>
</tr>
<tr>
<td>( \pi^- \nu_\tau )</td>
<td>10.82</td>
</tr>
<tr>
<td>( \pi^- 2\pi^0 \nu_\tau )</td>
<td>9.26</td>
</tr>
</tbody>
</table>
Background

- $\nu_\mu \rightarrow \nu_\tau$ oscillation

$$P_{\mu \rightarrow \tau} = \sin^2(2\theta_{23}) \sin^2\left[1.27 \left(\frac{\Delta m^2_{31}}{eV^2}\right) (\frac{L}{km})\right]$$

- $D$ mesons decays: $B(D^+ \rightarrow \tau^+ \nu_\tau) = (1.2 \pm 0.24) \times 10^{-3}$

  Berryman, de Gouvea, Fox, Kayser, Kelly, Raaf, JHEP 02 (2020) 174

- Hadronic final states: background due to neutral current
- Leptonic final states: charged current

- Misidentification is a problem
- What would be the signal detection efficiencies for $\tau \rightarrow e, \mu$, hadron final states?
Investigation of $\nu_\tau$-identification and related backgrounds in all three major $\tau$-decay channels utilizing multivariable analysis, machine-learning techniques + additional event information from the SAND detector in the ND complex [ongoing]

The level of hadronic activities induced by $\nu_\tau$ scattering vs. $\nu_\mu/e$ scattering can be a good discriminator.

The $\tau$ tagging and background rejection efficiencies perform better with increasing energy ➔ measurements in the $\nu_\tau$-optimized mode

$\nu_\tau$ from charged pion decays will benefit from this configuration
Various Models

\textit{B-L vector mediators}

\textit{v-philic mediators}

\textbf{U(1)}_{\text{B-3L}_\tau}: J. Heeck, M. Lindner, W. Rodejohann, and S. Vogl, Sci Post, 2019

Similar parameter space also exists for \textbf{U(1)}_{\text{T3R}} model

Dutta, Ghosh, Kumar, PRD2019

Dev, Dutta, Han, Kim, 2304.02031 [hep-ph]
Outlook

- Light mediator models can explain various anomalies and puzzles
- $M(\text{new physics}) < \text{GeV}$ is not easy to probe, e.g., LHC, direct and indirect detection experiments mostly probe $M > \text{GeV}$
- Various experiments provide interesting possibilities for searching low-scale models
- Light mediators can be produced using photon, electron-positron, mesons, protons, neutrons and neutrino fluxes
- Light mediators can be probed using tau neutrinos
- The probing can be difficult at the near detector