Neutrino & Dark Matter Connections

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Precision understanding of Lepton Mixing, CP Violation, etc.

New Physics in Neutrino Oscillations

Connections to Dark Sector Physics
Precision understanding of Lepton Mixing, CP Violation, etc.

New Physics in Neutrino Oscillations
(A. Aurisano’s talk after this!)

Connections to Dark Sector Physics
Tau Neutrinos for Three-Flavor Oscillation Physics
\[ L = 1300 \text{ km (DUNE)} \]

\[ 0.5 < \sin^2 (2\theta_{\mu\tau}) < 1 \]

\[ P_{\mu\tau} \propto \sin^2 \left(2\theta_{\mu\tau}\right) \sin^2 \left(\frac{\Delta m^2 L}{4E}\right) \]
Three-flavor: \( \sin^2 (2\theta_{\mu\tau}) = 4 |U_{\mu3}|^2 |U_{\tau3}|^2 = 4 |U_{\mu3}|^2 \left(1 - |U_{\mu3}|^2 - |U_{e3}|^2\right) \)
\[ \sin^2 (\theta_{12}) = 0.310 \text{ (fixed)} \]
\[ \sin^2 (\theta_{13}) = 0.0224 \text{ (free)} \]
\[ \sin^2 (\theta_{23}) = 0.582 \text{ (free)} \]

\[ \Delta m^2_{32} = 7.39 \times 10^{-5} \text{ eV}^2 \text{ (fixed)} \]
\[ \Delta m^2_{32} = 2.525 \times 10^{-3} \text{ eV}^2 \text{ (free, ordering fixed)} \]
\[ \delta_{CP} = -2.496 \text{ rad } 217 \text{ (free)} \]

DUNE 7 yr. data collection

\[ \sin^2 \left( \frac{1}{2} \theta_{12} \right) = 0 \text{ (fixed)} \]
\[ \sin^2 \left( \frac{1}{2} \theta_{13} \right) = 0.58 \text{ (free)} \]
\[ \sin^2 \left( \frac{1}{2} \theta_{23} \right) = 0.45 \text{ (free)} \]

de Gouvêa, Kelly, Pasquini, Stenico [1904.07265]
\[ \sin^2 \left( \frac{2}{\sqrt{2}} \mu \theta \right) \]

**3.5 yr. \( \nu + 3.5 \text{ yr.} \bar{\nu} \)**

- **DUNE 7 yr. data collection**
- \( \sin^2 \theta_{12} = 0.310 \) (fixed)
- \( \sin^2 \theta_{13} = 0.02240 \) (free)
- \( \sin^2 \theta_{23} = 0.582 \) (free)
- \( \Delta m^2_{21} = \pm 7.39 \times 10^{-5} \text{ eV}^2 \) (fixed)
- \( \Delta m^2_{31} = \pm 2.525 \times 10^{-3} \text{ eV}^2 \) (free, ordering fixed)
- \( \delta_{CP} = -2.496 \text{ rad} = 217^\circ \) (free)

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de Gouvêa, Kelly, Pasquini, Stenico [1904.07265]
Why Stress-test?

Tour de force results on quark mixing from the CKMfitter group

Closure tests allow for honest evaluation of our models — is the “three massive neutrinos” paradigm good or not?
Analogue to the Lepton Sector

\[ \rho_{e\mu} + i\eta_{e\mu} = -\frac{U_{e1}U_{\mu1}^*}{U_{e3}U_{\mu3}^*} \]

\[ \rho_{23} + i\eta_{23} = -\frac{U_{\tau2}U_{\tau3}^*}{U_{e2}U_{e3}^*} \]
Tau Neutrinos and Dark Sectors
1) Charged and Neutral Mesons are produced in the high-energy/high-intensity proton collisions.
Neutrino Facilities as Dark Sector Machines

1) Charged and Neutral Mesons are produced in the high-energy/high-intensity proton collisions.

2) Mesons undergo rare decays into dark sector mediators that are long-lived. Some fraction of them travel in the forward direction.
Neutrino Facilities as Dark Sector Machines

1) Charged and Neutral Mesons are produced in the high-energy/high-intensity proton collisions.

2) Mesons undergo rare decays into dark sector mediators that are long-lived. Some fraction of them travel in the forward direction.

3) Dark Sector particles decay/interact inside the neutrino detector, leaving a striking signature.
Neutrino Facilities as Dark Sector Machines

1) Charged and Neutral Mesons are produced in the high-energy/high-intensity proton collisions.
2) Mesons undergo rare decays into dark sector mediators that are long-lived. Some fraction of them travel in the forward direction.
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ArgoNeuT

Tabletop ton-scale liquid-argon detector at Fermilab that took data in the NuMI beamline (120 GeV protons)

HNL production possible through D-meson production: $D^\pm \to \tau^\pm$, $\tau^\pm \to N$
ArgoNeuT

HNLs produced in $D^\pm \rightarrow \tau^\pm$, $\tau^\pm \rightarrow NX$

Decay in/near ArgoNeuT via $N \rightarrow \nu_\tau \mu^+ \mu^-$

ArgoNeuT 1.25 $\times 10^{20}$ POT

ArgoNeut Collab. (With AdG, KJK) [2106.13684] $|U_{eN}|^2 = |U_{\mu N}|^2 = 0$

Belle from Sourav's talk yesterday
Full Disclosure… [Heavy-Neutrino-Limits]
Complementarity of Neutrino Detectors

Liquid Detectors (SBND, ICARUS, etc.)

- Large mass for rare-particle scattering
- Excellent particle ID, energy resolution, etc.

Gaseous Detectors (DUNE NDGAr)

- Decay Signal \( \propto \) Volume
- Neutrino Scattering Backgrounds \( \propto \) Mass
Complementarity of Neutrino Detectors

Liquid Detectors (SBND, ICARUS, etc.)

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Gaseous Detectors (DUNE NDGAr)

Decay Signal $\propto$ Volume
Neutrino Scattering Backgrounds $\propto$ Mass

Magnetic Field (charge ID)
Electromagnetic Calorimeter (measures exiting particles)
DUNE NDGAr’s HNL Capability

Berryman, de Gouvêa, Fox, Kayser, KJK, Raaf [1912.07622]

More on HNLs at DUNE? Ballett et al [1905.00284], Coloma et al [2007.03701], Breitbach et al [2102.03383]
Looking Ahead…
What do we do with a discovery?
Is the new particle a Dirac or Majorana Fermion?

Do the new particle’s interactions preserve or violate Lepton Number conservation?

$K^+ \rightarrow \mu^+ N$

Heavy Neutrino Source

$N \rightarrow \pi^+ \pi^- \\ N \rightarrow \mu^+ \\ N \rightarrow \mu^-$

Heavy Neutrino Decay

• Do these two chains occur with equal probability?
Next-Generation Prospects

Berryman, de Gouvêa, Fox, Kayser, KJK, Raaf [1912.07622]
What if we’re not lucky?

• What if the HNL is lighter than the pion? Then there are no fully-visible final states to decay into, and Lepton Number can’t be identified on an event-by-event basis.

Still, there are differences between Dirac/Majorana fermions: Measure the distribution of outgoing (visible) particles.
Dirac vs. Majorana in Three-Body Decays

If \( N \) is a Majorana fermion, its decays are forward/backward symmetric if either:

- The final-state charged leptons are identical (e.g. electron/positron pair).
- Whatever detection mechanism being used is charge-blind (can’t distinguish electron from positron or muon from antimuon)

\[
\mathcal{M}_1 = G_{NL} \left[ \bar{u}_\nu \Gamma_N P \Sigma u_N \right] \left[ \bar{u}_\alpha \Gamma_L \nu_\beta \right]
\]

de Gouvêa, Fox, Kayser, KJK [2104.05719] (Building off Balantekin, de Gouvêa, Kayser [1808.10518])
Takeaways
Takeaways
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\[ \tau^+ \rightarrow \nu_\tau \]

\[ \rho_{\tau\mu} + i\eta_{\tau\mu} = \frac{U_{e1}U_{\mu1}^*}{U_{e3}U_{\mu3}^*} \]

\[ \rho_{23} + i\eta_{23} = \frac{U_{e2}U_{\tau2}^*}{U_{e3}U_{\tau3}^*} \]

\[ |U_{eN}|^2 = |U_{\mu N}|^2 = 0 \]

ArgoNeuT 1.25 \times 10^{20} \text{ POT}

\[ m_N \text{ [GeV]} \]

CHARM

DELPHI

Observed

Expected ± 1σ

All Current Data

All Future Data, Unitarity Assumed

All Future Data
Takeaways

With a wealth of $\nu_{\tau}$ and rich detectors now and in the coming decade, there’s substantial new territory ahead. Stay tuned for results, and hopefully discoveries!