Beyond Three-Flavor v Oscillations with DUNE

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University of Cincinnati, on behalf of the DUNE Collaboration

Snowmass 2021 Community Summer Study, Seattle
July 19, 2022
DUNE is a Machine for Discovery!

- High-intensity wide-band LBNF neutrino beam
  - 1.2 MW upgradeable to 2.4 MW

- Far Detector 1500m underground at SURF
  - 1300 km baseline
  - up to 4×17 kton modules, LArTPC technology

- Highly-capable Near Detector complex
  - 574 m baseline
  - High-Res. Detectors, PRISM

DUNE Simulation

\[ v^2/(m^2 GeV) \times (1.1 \times 10^{22} \text{ POT}) \]

Neutrino energy (GeV) vs. \( v^2/(m^2 GeV) \times (1.1 \times 10^{22} \text{ POT}) \)

DUNE FD1-HD simulated 2.5 GeV \( v_e \)

Highly-capable Near Detector complex

Phase I ND
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- Highly-capable Near Detector complex
  - 574 m baseline
  - High-Res. Detectors, PRISM

DUNE FD1-HD simulated 2.5 GeV $v_e$
DUNE is a Machine for Discovery!

- **Non-standard short-baseline and long-baseline oscillation phenomena**
  - Mixing with light sterile neutrinos
  - Large extra-dimensions
  - Non-unitarity of the mixing matrix
  - Non-standard neutrino interactions
  - Violation of CPT Symmetry

- **Searches for new phenomena/particles at the ND**
  - Neutrino trident interactions
  - Heavy neutral leptons
  - Low-mass dark matter
  - Axion-like particles

- **Searches for new phenomena at the FD benefitting from its large mass and high resolution**
  - Inelastic boosted dark matter from the galactic core
  - Boosted dark matter from the Sun
  - Nucleon decay

In this talk!

See next talk by Jae Yu!
More than Three Neutrinos?

- The LSND experiment measured a 3.8σ excess of $\nu_e$ in a DAR $\nu_\mu$ beam over a very short baseline (~30 m).
- Oscillation explanation requires 4th neutrino state with $\Delta m^2_{41} \sim 1 \text{ eV}^2$
  - $Z^0$ width measured at LEP => only 3 light active neutrinos
  - 4th neutrino is very heavy or has no weak interactions

=> Sterile neutrino ($\nu_s$)

$\nu_4$

$\Delta m^2_{41}$

$\nu_3$

$\Delta m^2_{32}$

$\nu_2$

$\Delta m^2_{21}$

$\nu_1$

$\nu_e$, $\nu_\mu$, $\nu_\tau$, $\nu_s$

$\Delta m^2$

$\nu_4$

$\nu_3$

$\nu_2$

$\nu_1$

$\nu_e$, $\nu_\mu$, $\nu_\tau$, $\nu_s$

$\Delta m^2$

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More than Three Neutrinos?

- The LSND experiment measured a $3.8\sigma$ excess of $\nu_e$ in a DAR $\nu_\mu$ beam over a very short baseline ($\sim 30$ m).
- Oscillation explanation requires 4th neutrino state with $\Delta m_{41}^2 \sim 1$ eV$^2$
  - $Z^0$ width measured at LEP => only 3 light active neutrinos
  - 4th neutrino is very heavy or has no weak interactions

$\Rightarrow$ Sterile neutrino ($\nu_s$)

- In a 3+1 model, have 1 new mass scale, $\Delta m_{41}^2$, 3 new mixing angles, $\theta_{14}$, $\theta_{24}$, $\theta_{34}$, and 2 new CP phases $\delta_{14}$, $\delta_{24}$

- Further motivated by MiniBooNE, Reactor, Gallium anomalies

\[ U = \begin{pmatrix} \begin{array}{cccc} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} & U_{\mu4} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} & U_{\tau4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{array} \end{pmatrix} \]
Looking for Light Sterile Neutrinos

- $\nu_e, \bar{\nu}_e$ CC appearance (LSND, KARMEN, mBooNE, $\mu$BooNE, etc.): $\theta_{14}, \theta_{24}$

$$P_{\mu e} \approx 2 \sin^2 2\theta_{14} \sin^2 \theta_{24} \times \sin^2 \frac{\Delta m_{41}^2 L}{E}$$

$$4 |U_{e4}|^2 |U_{\mu4}|^2$$

- $\bar{\nu}_e$ CC disappearance (Reactor experiments): $\theta_{14}$

$$P_{ee} \approx 1 - 2 \sin^2 2\theta_{14} \times \sin^2 \frac{\Delta m_{41}^2 L}{E}$$

$$|U_{e4}|^2$$

- $\nu_\mu, \bar{\nu}_\mu$ CC disappearance (mBooNE, MINOS(+), NOvA, T2K, IceCube, etc.): $\theta_{24}$

$$P_{\mu\mu} \approx 1 - 2 \sin^2 2\theta_{24} \times \sin^2 \frac{\Delta m_{41}^2 L}{E}$$

$$|U_{\mu4}|^2$$

- NC disappearance (MINOS(+), NOvA, T2K, etc.): $\theta_{24}, \theta_{34}$

$$1 - P_{\mu s} \approx 1 - \sin^2 2\theta_{24} \sin^2 \frac{\Delta m_{41}^2 L}{E} - \sin^2 \theta_{34} \sin^2 \theta_{23} \sin^2 \frac{\Delta m_{31}^2 L}{E}$$

$$SBL \quad LBL \quad |U_{\mu4}|^2, |U_{\tau4}|^2$$

- Thanks to the intense LBNF neutrino beam and exquisite detector spatial resolution of its detectors, DUNE is sensitive to all of these channels in a single experiment!

- Also sensitive to atmospheric measurements due to large FD, 1500 m deep at SURF
Active-sterile mixing would distort standard oscillation probabilities

- DUNE will be sensitive to this effect through both the Near and Far detectors
- Wide-band LBNF beam enables probes over large regions of parameter space
- Plot shows distortion of standard oscillation probabilities for L/E or ν energies at ND and FD

\[ \Delta m^2 = 5.00 \text{ eV}^2 \]

- \[ P(\nu_\mu \rightarrow \nu_\mu) \]
- \[ P(\nu_\mu \rightarrow \nu_e) \]
- \[ P(\nu_\mu \rightarrow \nu_\mu) \]
- \[ P(\nu_\mu \rightarrow \nu_\tau) \]
- \[ 1 - P(\nu_\mu \rightarrow \nu_s) \]

\[ \theta_{14} = 0.16 \]
\[ \theta_{24} = 0.2 \]
\[ \theta_{34} = 0.6 \]
Looking for Light Sterile Neutrinos

Distortions of standard oscillation probabilities change for different values of $\Delta m_{41}^2$

- **Small $\Delta m_{41}^2$**: slow oscillations visible at FD only (FD-dominated region)

- **Intermediate $\Delta m_{41}^2$**: rapid oscillations average out at FD but still not visible at ND (Counting experiment)

- **Large $\Delta m_{41}^2$**: oscillations average out at FD and distortions are visible at the ND (ND-dominated region)

![Diagram illustrating the probability of neutrino oscillations for different values of $\Delta m_{41}^2$.](image)

- For $\Delta m_{41}^2 = 0.05 \text{ eV}^2$:
  - Slow oscillations visible at FD only (FD-dominated region).
  - Probability curves for different neutrino transitions.

- For $\Delta m_{41}^2 = 0.50 \text{ eV}^2$:
  - Rapid oscillations average out at FD but still not visible at ND (Counting experiment).
  - Probability curves for different neutrino transitions.

- For $\Delta m_{41}^2 = 5.00 \text{ eV}^2$:
  - Oscillations average out at FD and distortions are visible at the ND (ND-dominated region).
  - Probability curves for different neutrino transitions.

- 3+1 Model:
  - $\theta_{14} = 0.16$
  - $\theta_{24} = 0.2$
  - $\theta_{34} = 0.6$
Assuming 300 kton.MW.year exposure (Phase I ND) for 3+1 model with simultaneous fit to oscillations at ND and FD

- GLoBES sensitivities include normalization-only systematics, so the two DUNE lines represent best (black) and worst (gray) scenarios
- On its own, DUNE can potentially probe the sterile mixing parameter space at same level or better than present and future experiments, depending on $\Delta m_{41}^2$
Assuming 300 kton.MW.year exposure (Phase I ND) for 3+1 model with simultaneous fit to oscillations at ND and FD
- PRISM and Phase II ND will help control systematics in ND-dominated region, $\Delta m_{41}^2 \gtrapprox 0.5$ eV$^2$
- Strong complementarity with SBN program, thanks to ND measurement, while extending probes to lower values of $\Delta m_{41}^2$ via the FD measurement
Assuming 300 kton.MW.year exposure (Phase I ND) for 3+1 model with simultaneous fit to oscillations at ND and FD

- DUNE can extend probes of ντ-sterile mixing to lower values of Δm²_{41} and improve the limits on θ_{34}, the least constrained sterile mixing angle
- Can be further improved by combining beam + atmospheric measurements
Most of our knowledge of $\nu_\tau$ sector results from assuming unitarity of PMNS matrix and lepton universality for cross sections

- $\nu_\tau$ CC production threshold, $E_\nu > 3.5$ GeV, is very challenging for signal accumulation

DUNE is in a unique position to probe the $\nu_\tau$ sector using:

- High-energy tail of CP-optimized beam during Phases I and II (130 $\nu_\tau$ CC, 30 $\bar{\nu}_\tau$ CC/year in FD)
- **Dedicated $\nu_\tau$-optimized beam run during Phase II (800 $\nu_\tau$ CC/year in FD)**
- Also atmospheric neutrino measurements with FD, like SuperK and IceCube
Higher energy of $\nu_\tau$-optimized beam, BDT based on kinematic variables, and measurements of a wide range of muon momenta from curvature in DUNE ND Phase II’s ND-GAr, enable good statistics in selection of $\nu_\tau$ CC sample from $\nu_\mu$ CC backgrounds.
Anomalous $\nu_\tau$ Appearance at DUNE ND

- Sensitivities for 1 year of running with $\nu_\tau$ - optimized beam (not expected during Phase I)
  - Including an overall 10% syst. uncertainty; smearing according to each detector’s resolution

- Potential leading sensitivity in difficult to probe parameter space during DUNE Phase II
  - Further improvements possible by using the SAND detector in the ND complex
  - Complementary to $\nu_\tau$-sterile mixing probes with FASERnu and FPF@LHC Bai et al., arXiv:2002.0301

See H. Razafinime’s talk, Saturday NF EC parallel
## DUNE and the Experimental ν Anomalies

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<tbody>
<tr>
<td>Reactor</td>
<td>DANSS Upgrade, JUNO-DAO, NEOS-II, Neutrino-4 Upgrade, PROSPECT-II</td>
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<td>Radioactive Source</td>
<td>BEST-2, IsoDAR, THEIA, Jinping</td>
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<td>Atmospheric</td>
<td>IceCube Upgrade, KM3NET ARCA, DUNE, Hyper-Kamiokande, THEIA</td>
<td>ORCA and Jinping</td>
<td></td>
<td>IceCube Upgrade, KM3NET, ORCA and ARCA, DUNE, Hyper-Kamiokande, THEIA</td>
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<tr>
<td>Pion/Kaon Decay-At-Rest</td>
<td>JSNS², COHERENT, Coherent-Captain-Mills, KPIPE</td>
<td>JSNS², COHERENT, Coherent-Captain-Mills, KPIPE, PIP2-BD</td>
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<td>COHERENT, Coherent-Captain-Mills, KPIPE, PIP2-BD, SBN-BD</td>
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<td>Beam Short Baseline</td>
<td>SBN</td>
<td>SBN, FASERν, SND@LHC, FLArE</td>
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<td>Beam Long Baseline</td>
<td>DUNE, Hyper-Kamiokande, ESSnuSB</td>
<td>DUNE, Hyper-Kamiokande, ESSnuSB</td>
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<td>Muon Decay-In-Flight</td>
<td>nuSTORM</td>
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<tr>
<td>Beta Decay and Electron Capture</td>
<td>KATRIN/TRISTAN, Project-8, HUNTER, BeEST, DUNE (³⁷Ar), PTOLEMY, 2νββ</td>
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- Pure 3+N sterile mixing disfavored as explanation for global neutrino data due to tension between appearance signals and null disappearance results
- With its strong multi-channel sensitivity and wide-band beam, DUNE will test more exotic scenarios

NF02 White Paper, hep-ex/2203.07323

NF02 Session on Expt. ν Anomalies, Thurs, 10 am
Large Extra-Dimensions

- Large Extra-Dimensions would cause distortions of 3-flavor oscillations from mixing of neutrinos with Kaluza-Klein (KK) modes
  - For LED model, Davoudiasl et al., PRD 65, 105015 (2002), assuming one LED in the bulk, KK modes in 3+1 spacetime brane behave like sterile neutrinos
  - Showing DUNE sensitivity for 300 kton.MW.year (Phase I) compared to MINOS published results

See D. V. Forero’s talk, Saturday NF EC parallel
Non-Unitary Mixing

- If new heavy states mix with active neutrinos (e.g. if neutrinos acquire mass through a type I seesaw mechanism), the mixing matrix need not be unitary

\[
N = \begin{pmatrix}
1 - \alpha_{ee} & 0 & 0 \\
\alpha_{\mu e} & 1 - \alpha_{\mu\mu} & 0 \\
\alpha_{\tau e} & \alpha_{\tau\mu} & 1 - \alpha_{\tau\tau}
\end{pmatrix} U^{3\times3}
\]

- Allowed regions at the 1σ, 90%, and 2σ CL for non-unitary mixing parameters for DUNE-only (solid), and DUNE + existing constraints (dashed)
  - Assuming 300 kton.MW.year (Phase I ND)

- Potential impact of non-unitarity on the DUNE CP violation discovery potential
Non-Standard Neutrino Interactions (NSI)

- In the Standard Model,
  \[ \mathcal{L}_{CC} = (\bar{\ell}_\alpha \gamma^\mu P_L \ell_\alpha)(\bar{f} \gamma_\mu P_L f') \]
  \[ \mathcal{L}_{NC} = (\bar{\nu}_\alpha \gamma^\mu P_L \nu_\alpha)(\bar{f} \gamma_\mu P_L f') \]

- With new physics, we could have
  \[ \mathcal{L}_{CC} = (\bar{\ell}_\alpha \gamma^\mu P_L \ell_\alpha)(\bar{f} \gamma_\mu P_L R f') \]
  \[ \mathcal{L}_{NC} = (\bar{\nu}_\alpha \gamma^\mu P_L \nu_\alpha)(\bar{f} \gamma_\mu P_L R f') \]

New neutral-current-like interactions during neutrino propagation between the Near and Far detectors can be described as new contributions to the neutrino matter effect (MSW)

- These contributions are encoded by the new coefficients \( \varepsilon_{ij} \)

\[ H = U \begin{pmatrix} 0 & \Delta m^2_{21} / 2E \\ \Delta m^2_{31} / 2E \end{pmatrix} U^\dagger + \tilde{\mathcal{V}}_{MSW} \]

\[ \tilde{\mathcal{V}}_{MSW} = \sqrt{2} G_F N_e \begin{pmatrix} 1 + \varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau} \\ \varepsilon_{e\mu}^* & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\ \varepsilon_{e\tau}^* & \varepsilon_{\mu\tau} & \varepsilon_{\tau\tau} \end{pmatrix} \]
Non-Standard Neutrino Interactions (NSI)

- DUNE can improve current constraints on $|\varepsilon_{e\mu}|$ and $|\varepsilon_{e\tau}|$ by a factor of ~2


- 90% C.L. 1-dim. DUNE constraints compared with bounds from Gonzalez-Garcia, Maltoni, arXiv:1307.3092
Violations of CPT Symmetry

- DUNE can search for CPT violation by comparing $\nu_\mu$ and $\bar{\nu}_\mu$ disappearance between ND and FD.

$$P(\nu_\mu \rightarrow \nu_e) \neq P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \Rightarrow \text{CP violation}$$

$$P(\nu_\mu \rightarrow \nu_\mu) \neq P(\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu) \Rightarrow \text{CPT violation}$$

- With 300 kton.MW.year running, DUNE can improve limits on $\Delta(\Delta m^2_{31})$ by over a factor of 5 and, depending on the octant of $\theta_{23}$ (low, high, maximal), the limits on $\Delta(\sin^2\theta_{23})$.

$$\Delta(\Delta m^2_{31}) \equiv |\Delta m^2_{31} - \Delta m^2_{31}'| < 3.7 \times 10^{-4} \text{ eV}^2$$

$$\Delta(\sin^2\theta_{23}) \equiv |\sin^2\theta_{23} - \sin^2\bar{\theta}_{23}| < 0.32$$

Present limits

Summary and Outlook

- The highly-capable DUNE detectors and the powerful LBNF beam will enable a very rich and diverse program for New Physics probes in the next decades

- DUNE has powerful physics reach for a broad range of beyond three-flavor neutrino mixing models
  - Can probe most flavor transition channels over wide energy spectrum within single expt.
  - Deployment of Phase II essential for DUNE to achieve its full BSM physics potential
  - Highly complementary to other efforts, ongoing or projected for the next decade

- As a machine for discovery, DUNE will provide leading guidance to experimental and theoretical efforts involving neutrinos and/or new particles/interactions

- Stay tuned for the next talk on further exciting DUNE BSM Physics opportunities!
Supplements
Assuming 400 kton.years exposure

<table>
<thead>
<tr>
<th>Track-like events</th>
<th>Shower-like events</th>
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<tbody>
<tr>
<td>Reconstruction efficiency (CC)</td>
<td>80%</td>
</tr>
<tr>
<td>Reconstruction efficiency (NC)</td>
<td>0.5%</td>
</tr>
<tr>
<td>Neutrino energy resolution</td>
<td>18%</td>
</tr>
<tr>
<td>Neutrino direction resolution</td>
<td>10 degrees</td>
</tr>
</tbody>
</table>

T. Thakore, Neutrino '22
**ντ-Optimized Beam**

**FUTURE: DUNE**

Laura Fields, NuTau 2021

- **ντ-CC** interactions possible

- **Optimized νμ flux**
- **νμ flux**

- Beamline **can be tuned to higher energy** by using two NuMI horns and increasing horn separation

- Fairly **simple optimization**; can probably be improved on, but not dramatically

- **ντ Optimized Configuration**

- **Optimized & Engineered 2017 Configuration**

- **Sudeshna Ganguly**

- **DUNE Neutrino Flux**

- **Decay pipe**

- **Horn A**
- **Horn B**
- **Horn C**
- **Target**
- **Horn 1**
- **Horn 2**
- **Beam direction**
The signal and background separation is based on kinematic differences. Used a total of 18 variables.

<table>
<thead>
<tr>
<th>Ranking</th>
<th>Kinematic variables</th>
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<tbody>
<tr>
<td>1</td>
<td>$R_{\text{miss}} = \frac{P_{T\text{miss}}}{P_{T\text{miss}} + P_{T\text{muon}}}$</td>
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<tr>
<td>2</td>
<td>$P_{T\text{muon}}$: transverse lepton momentum</td>
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<tr>
<td>3</td>
<td>$\theta_{\nu \text{ Miss}}$: angle between beam direction and missing transverse momentum</td>
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<tr>
<td>4</td>
<td>$E_{\text{Tot}}$: total visible energy</td>
</tr>
<tr>
<td>5</td>
<td>$\Phi_{\nu \text{ hadron}}$: angle between transverse muon and hadron momentum</td>
</tr>
<tr>
<td>6</td>
<td>$P_{T\text{Tot}}$: total transverse momentum</td>
</tr>
</tbody>
</table>

Examples of $\nu_\tau$ signal (blue) and background (red) kinematic variables distribution.

H. Razafinime, Neutrino ’22
M. Rajaolisoa, APS ’21
Proton decay expected to occur in Grand Unified Theories with a lifetime of $\sim 10^{34} - 10^{36}$ years

- DUNE is most sensitive to proton decay in the $p \rightarrow K^+ + \bar{\nu}$ channel
  - Excellent calorimetric capabilities of LArTPCs enable good kaon identification, as well as high kaon/muon tracking efficiency
  - A lower limit on the proton lifetime of $1.3 \times 10^{34}$ yrs@90%CL is expected if no signal is observed in 10 years

World’s Best Limits from SuperK:

\[
\begin{align*}
\tau (p \rightarrow e^+\pi^0) & > 2.4 \times 10^{34} \text{ years} \\
\tau (p \rightarrow K^+\bar{\nu}) & > 8.2 \times 10^{33} \text{ years}
\end{align*}
\]

Proton Decay

Signal

Background