Prospects for Beyond the Standard Model Physics in Long Baseline Neutrino Experiments

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Mary Bishai
Brookhaven National Lab

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Outline

1. Long-Baseline $\nu$ Experiments
2. Non-Standard Interactions
3. Large Extra Dimensions
4. LBL Sterile Searches
5. BSM with $\nu_\tau$ Appearance
6. Summary and Next Steps
Introduction to Long Baseline Neutrino Experiments
BSM and Neutrino Oscillations

Due to the very small masses and large mixing of neutrinos, their oscillations over a long distance act as an *exquisitely precise interferometer with high sensitivity to very small perturbations caused by new physics phenomena*, for e.g.:

- **Non-standard interactions** in matter that manifest in long-baseline oscillations as deviations from the three-flavor mixing model
- **Sterile neutrino states** that mix with the three known active neutrino states
- **New long-distance potentials** arising from discrete symmetries that manifest as small perturbations on neutrino and antineutrino oscillations over a long baseline
- **Large compactified extra dimensions** from String Theory models that manifest through mixing between the Kaluza-Klein states and the three active neutrino states
- **Non-unitarity** of the 3-flavor mixing matrix due to BSM of unknown origin
Sources of Neutrinos

Big Bang

- $10^{-4}$ eV
- $56/cm^3$

Reactors

- few MeV
- $10^{21}/GW_{th}/s$

Sun

- 0.1-14 MeV
- $10^{10}/cm^2/s$

SuperNova

- $\sim 10$ MeV
- $10^9/cm^2/s$

Atmosphere

- $\sim 1$ GeV
- few/cm$^2$/s

Accelerators

- 1-20 GeV
- $10^6/cm^2/s/MW$ (at 1km)

Extragalactic

- TeV-PeV
- varies
Sources of Neutrinos
Oscillations of $\nu_\mu \rightarrow \nu_e$ at different baselines

$$P(\nu_\mu \rightarrow \nu_e) \text{ maxima: } E_\nu^n (\text{GeV}) \sim \text{Baseline (km)}/(515 \times (2n - 1))$$

for $\Delta m^2_{31} = 2.4 \times 10^{-3} \text{ eV}^2$
Oscillations of $\nu_\mu \rightarrow \nu_e$ at different baselines

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Oscillations of $\nu_\mu \rightarrow \nu_e$ at different baselines

$P(\nu_\mu \rightarrow \nu_e)$ maxima: $E_\nu^0(\text{GeV}) \sim \text{Baseline(\text{km})}/(515 \times (2n - 1))$

for $\Delta m^2_{31} = 2.4 \times 10^{-3}$ eV$^2$
Atmospheric Neutrino Oscillations

$\nu_\mu \rightarrow \nu_e$

$P(\sin^2 \theta_{13} = 0.04)$ (NH)

$E_\nu / \text{GeV}$

$\cos \theta_z$

$10^{-1}$ $10^{-0.6}$ $10^{-0.2}$ $10^{0}$ $10^{0.2}$ $10^{0.4}$ $10^{0.6}$

$10^{1}$ $10^{1.2}$ $10^{1.4}$ $10^{1.6}$ $10^{1.8}$ $10^{2}$

$\nu_\mu \rightarrow \nu_e$

$P(\sin^2 \theta_{13} = 0.04)$ (IH)

$E_\nu / \text{GeV}$

$\cos \theta_z$

$10^{-1}$ $10^{-0.6}$ $10^{-0.2}$ $10^{0}$ $10^{0.2}$ $10^{0.4}$ $10^{0.6}$

$10^{1}$ $10^{1.2}$ $10^{1.4}$ $10^{1.6}$ $10^{1.8}$ $10^{2}$

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Long-Baseline $\nu$ Experiments

Non-Standard Interactions

Large Extra Dimensions

LBL Sterile Searches

BSM with $\nu_\tau$ Appearance

Summary and Next Steps
Conventional horn-focused neutrino beams (decay-in-flight):

Source | Oscillation | Detection
--- | --- | ---
$\pi, K$ | $\nu_\mu$ | $\mu^-$
$>99\%$ | $\nu_e$ | $e^-$
$<1\%$ | $\nu_\mu$ | $\mu^-$

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Summary and Next Steps
Neutrinos from High Power Proton Sources

Muon Storage Rings:

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Summary and Next Steps
Neutrino fluxes with perfect focusing

$\nu_\mu$ fluxes from pion decay-in-flight (DIF) beams assuming perfect focusing and charge selection:

120 GeV, decay channel lengths from 200m to 1km

Flux at 1000km, perfect focusing, different decay pipe lengths

Gain with longer decay channels, BUT excavation is challenging/expensive.
Expected Appearance Signal Event Rates

The total number of electron neutrino appearance events expected for a given exposure from a muon neutrino source as a function of baseline is given as

$$N_{\nu_e}^{\text{appear}}(L) = N_{\text{target}} \int \Phi^{\nu\mu}(E_\nu, L) \times P^{\nu\mu \rightarrow \nu e}(E_\nu, L) \times \sigma^{\nu e}(E_\nu) dE_\nu$$

Assume the neutrino beam source produces a wide coverage that is flat in energy in the oscillation region and approximate the probability with the dominant term for $P(\nu_\mu \rightarrow \nu_e)$

$$\Phi^{\nu\mu}(E_\nu, L) \approx \frac{C}{L^2}, \quad C = \text{number of } \nu_\mu/m^2/\text{GeV}/\text{MW/yr at 1 km}$$

$$P^{\nu\mu \rightarrow \nu e}(E_\nu, L) \approx \frac{\sin^2 \theta_{23} \sin^2 \theta_{13} \sin^2 (1.27\Delta m^2_{31} L/E_\nu)}{P_0}$$

$$\sigma^{\nu e}(E_\nu) = 0.7 \times 10^{-42} (m^2/\text{GeV}/N) \times E_\nu, \quad E_\nu > 1 \text{ GeV}$$

$$N_{\text{target}} = 6.022 \times 10^{32} \text{N/kt}$$

Assuming constant flux: $C \approx 1.2 \times 10^{17} \nu_\mu/m^2/\text{GeV}/(\text{MW}/\text{yr})$ at 1 km:

$$N_{\nu_e}^{\text{appear}}(L) \approx (2 \times 10^6 \text{events/(kt/MW/yr)})(\text{km/GeV})^2 \times \int_{x_0}^{x_1} \frac{\sin^2(ax)}{x^3} dx,$$

$$x \equiv L/E_\nu, \quad a \equiv 1.27\Delta m^2_{31}.$$

For $x_0 = 100 \text{ km/GeV}$ and $x_1 = 2000 \text{ km/GeV}$ (1st and 2nd oscillation maxima)

$$N_{\nu_e}^{\text{appear}}(L) \sim \mathcal{O}(20) \text{ events/(kt/MW/yr)}$$

constant for $L \geq 300 \text{ km in vacuum}!$
To get below 1 GeV from an $\pi$ DIF accelerator source, go off-axis to a high energy proton beam - the JPARC beam for T2K (295 km baseline). This produces a narrow-band beam:
## Neutrino CC Event Rates - Various Experiments

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Baseline</th>
<th>$\nu_\mu \rightarrow \nu_\mu$</th>
<th>$\nu_\mu \rightarrow \nu_\tau$</th>
<th>$\nu_\mu \rightarrow \nu_e$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Super Beams</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T2K</td>
<td>295km (off-axis)</td>
<td>900</td>
<td>$&lt; 1$</td>
<td>40 - 70</td>
</tr>
<tr>
<td>30 GeV, 750 kW</td>
<td>$9 \times 10^{20}$ POT/year</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MINOS LE</td>
<td>735km</td>
<td>11,000</td>
<td>115</td>
<td>230-340</td>
</tr>
<tr>
<td>120 GeV, 700 kW</td>
<td>$6 \times 10^{20}$ POT/year</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NO$\nu$A</td>
<td>810km (off-axis)</td>
<td>1500</td>
<td>10</td>
<td>120 - 200</td>
</tr>
<tr>
<td>120 GeV, 700 kW</td>
<td>$6 \times 10^{20}$ POT/year</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LBNE (LBNF) LE</td>
<td>1,300km</td>
<td>4300</td>
<td>160</td>
<td>350 - 600</td>
</tr>
<tr>
<td>80 GeV, 1.1MW</td>
<td>$1.5 \times 10^{21}$ POT/year</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LBNE (LBNF) ME</td>
<td>1,300km</td>
<td>12,000</td>
<td>690</td>
<td>290 - 430</td>
</tr>
<tr>
<td>120 GeV, 1.2MW</td>
<td>$1.1 \times 10^{21}$ POT/year</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>$\nu$ Factory at Fermilab</strong></td>
<td></td>
<td>$\nu_\mu \rightarrow \nu_\mu$</td>
<td>$\nu_\mu \rightarrow \nu_\tau$</td>
<td>$\nu_e \rightarrow \nu_\mu$</td>
</tr>
<tr>
<td>NuMAX I</td>
<td>1,300km</td>
<td>340</td>
<td>30</td>
<td>70 - 120</td>
</tr>
<tr>
<td>3 GeV, 1MW</td>
<td>$0.94 \times 10^{20}$ $\mu$/year</td>
<td>(no $\mu$ cooling)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NuMAX II</td>
<td>1,300km</td>
<td>2000</td>
<td>300</td>
<td>420 - 700</td>
</tr>
<tr>
<td>3 GeV, 3MW</td>
<td>$5.6 \times 10^{20}$ $\mu$/year</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Facility duty factor taken into consideration
Probing new physics beyond 3-flavor oscillations: Non Standard Interactions
Prospects for Beyond the Standard Model Physics in Long Baseline Neutrino Experiments

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High-Baseline \(\nu\) Experiments
Non-Standard Interactions
Large Extra Dimensions
LBL Sterile Searches
BSM with \(\nu_{\tau}\) Appearance
Summary and Next Steps

NSI in Long-Baseline Oscillations

- In the Standard Model,
  \[ L_{CC} = (\bar{\nu}_e \gamma^\mu P_L \nu_\alpha) (\bar{f} \gamma_\mu P_L f') \]

- With new physics, we could have
  \[ L_{CC} = (\bar{\nu}_e \gamma^\mu P_L \nu_\beta) (\bar{f} \gamma_\mu P_{L,R} f'') \]

\text{CC NSI production, detection}

\text{NC NSI propagation}

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

\[ \nu_{\text{MSW}} = \sqrt{2} G_F N_e \begin{pmatrix} 1 + \epsilon_{\text{ee}}^m & \epsilon_{e\mu}^m & \epsilon_{e\tau}^m \\ \epsilon_{e\mu}^* & \epsilon_{\mu\mu}^m & \epsilon_{\mu\tau}^m \\ \epsilon_{e\tau}^* & \epsilon_{\mu\tau}^* & \epsilon_{\tau\tau}^m \end{pmatrix} \]
NSI impact on Atmospheric Long Baseline
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NSI limits from Current Experiments

P. Coloma et. al. JHEP 04 (2017) 116:
Standard solution with $\theta_{12} < 45^\circ$
Degenerate solution with $\theta_{12} > 45^\circ$ and large $|\epsilon_{ee}|$

[Graphs showing NSI limits with up and down quarks]
CP Asymmetry vs $E_\nu$ and $\delta_{cp}$

$$A = \frac{P(\nu_\mu \rightarrow \nu_e) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)}{P(\nu_\mu \rightarrow \nu_e) + P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)}$$

Asymmetries caused by CPV and matter are a complex phenomena.
Asymmetries caused by CPV and matter are a complex phenomena
NSI could also impact interpretation of observed CP asymmetries in long-baseline:

(M. Masud, A. Chatterjee, P. Mehta arXiv:1510.08261)
Extricating NSI from 3-flavor Oscillations

Study NSI sensitivity with GLoBeS using $\nu_\mu \rightarrow \nu_{\mu,e}$ and 3 sample LBNF-like beam tunes: LE, ME and HE$^\ast$.

NSI parameters used:
$|\epsilon_{e\mu}| = 0.04, |\epsilon_{e\tau}| = 0.04, \epsilon_{ee} = 0.4, \phi_{e\mu} = 0, \phi_{e\tau}$

NSI effects in $\nu_\mu \rightarrow \nu_e$ are larger at higher energy

$^\ast$ 2 NuMI horns, 230kA, 6.6m apart and horns were not moved for higher energy beam tunes (non-optimal beams). Decay pipe was assumed to be 250m.

Extricating NSI from 3-flavor Oscillations

Fraction of SI $\delta_{cp}$ for which SI/NSI can be separated at the $3/5\sigma$ level:

Can achieve $3\sigma$ separation for $>80\%$ of true $\delta_{cp}$

No beam optimization attempted yet!

Search for Large Extra Dimensions with MINOS/MINOS+
In some models of LED, sterile neutrinos arise as Kaluza-Klein states in an extra dimension compactified on a circle with radius $R$. Using the MINOS detector energy resolution the impact on the $\text{P}(\nu_\mu \rightarrow \nu_\mu)$ oscillation probability for a given $R$ and $m_0$ the mass of the lightest neutrino state:
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Results from MINOS/MINOS+ search for LED

Wide-band beams, long baselines, high efficiency/purity $\nu_\mu$ selection and combination of CC and NC channels start to constrain LED models.
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Probing new physics beyond 3-flavor oscillations: Sterile neutrinos
Impact of Sterile Neutrinos on Long-Baseline $\nu$ Oscillations

$\Delta m^2_{41} = 0.05 \text{ eV}^2$

- Std. Osc. $P(\nu_\mu \rightarrow \nu_\mu)$
- $P(\nu_\mu \rightarrow \nu_e) \times 5$
- $P(\nu_\mu \rightarrow \nu_\mu)$
- $P(\nu_\mu \rightarrow \nu_\tau)$
- $1-P(\nu_\mu \rightarrow \nu_s)$

A. Sousa, U. Cincinatti
Impact of Sterile Neutrinos on Long-Baseline $\nu$ Oscillations

\[ \Delta m_{41}^2 = 0.50 \text{ eV}^2 \]

- Black: Std. Osc. $P(\nu_\mu \rightarrow \nu_\mu)$
- Purple: $P(\nu_\mu \rightarrow \nu_e) \times 5$
- Blue: $P(\nu_\mu \rightarrow \nu_\mu)$
- Green: $P(\nu_\mu \rightarrow \nu_\tau)$
- Red: $1 - P(\nu_\mu \rightarrow \nu_s)$

\[ L/E \text{ (km/GeV)} \]

- ND
- FD

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A. Sousa, U. Cincinnati
Impact of Sterile Neutrinos on Long-Baseline $\nu$ Oscillations

\[ \Delta m_{41}^2 = 5.0000 \text{ eV}^2 \]

- ND
- SD
- FD

- $\nu_e \rightarrow \nu_{\mu}$
- $\nu_{\mu} \rightarrow \nu_{\mu}$
- $\nu_{\mu} \rightarrow \nu_{\tau}$
- $1 - P(\nu_{\mu} \rightarrow \nu_s)$

A. Sousa, U. Cinccinati
Sensitivities to 3+1 from SBL/LBL Appearance and Disappearance

Tension between LBL $\nu_\mu$ disappearance and SBL $\nu_e$ appearance
Probing new physics beyond 3-flavor oscillations: $\nu_\mu \rightarrow \nu_\tau$
NuMI-like reference design could be tuned to higher energy to observe $\nu_\mu \rightarrow \nu_\tau$ with high statistics.

*2015 two horn optimized design $E_p = 66$ GeV:*

$\nu_\mu \rightarrow \nu_e$ Appearance at 1300 km

$\nu_\mu \rightarrow \nu_\tau$ Appearance at 1300 km

$\nu_\mu \rightarrow \nu_e$ 290 events $\quad$ $\nu_\mu \rightarrow \nu_\tau$ 60 events in 40 ktons, 1 year at 1.2 MW
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Higher $\nu$ Energy Beam Tunes with DUNE (M. Bishai proposal)

NuMI-like reference design could be tuned to higher energy to observe $\nu_\mu \to \nu_\tau$ with high statistics.

LBNF target -2m from horn 1, NuMI focusing 230 kA, horns 17m apart

$\nu_\mu \to \nu_e$ Appearance at 1300 km

$\nu_\mu \to \nu_\tau$ Appearance at 1300 km

$\nu_\mu \to \nu_e$ 330 events in 40 ktons, 1 year at 1.2 MW

$\nu_\mu \to \nu_\tau$ 700 events

Increase $\nu_\tau$ appearance 10x!!!

Increase high energy $\nu_e$ appearance - good for NSI/Sterile searches
Using $\nu_\tau$ appearance for precision oscillation measurements is difficult. For $\nu_\tau$ CC interactions where the $\tau$ decays hadronically there is a lot of smearing:

$P(E_{\nu}^{\text{reco}} | E_{\nu}^{\text{true}})$

\begin{figure}
\centering
\includegraphics[width=\textwidth]{diagram.png}
\end{figure}
Using some optimistic assumptions about $\nu_\tau$ CC events in DUNE with $\tau$ hadronic decays a possible signal in 3.5 yrs running in CPV optimized beam and 1 yr in HE beam:
Simple Unitarity Tests with $\nu_\tau$ Appearance in DUNE

Run in 3.5 ($\nu$) + 3.5 ($\bar{\nu}$) years with $\nu_\mu$ disappearance, $\nu_e$ appearance and $\nu_\tau$ appearance in the default low-energy beam or combine all 3 modes with 3+3 years in LE + 1 year in HE beam:

U: Unitary matrix, N: non-unitary matrix

$$U \rightarrow NU = \begin{pmatrix} \alpha_{11} & 0 & 0 \\ \alpha_{21} & \alpha_{22} & 0 \\ \alpha_{31} & \alpha_{32} & \alpha_{33} \end{pmatrix} U$$

Summary and Next Steps
Followup talks on BSM in LBL Expts

- **Saturday 12:00:** Long Baseline Neutrino Oscillation Physics at DUNE. Speaker: Hanyu Wei
- **Sunday 10:30:** Neutrino Cross-sections. Speaker: Steve Dytman
- **Monday 12:10:** Experimental Overview of Reactor Experiments. Speaker: Xin Qian
- **Monday 15:00:** The many faces of non-standard neutrino interactions. Speaker: Danny Marfatia
- **Monday 16:00:** Non-Standard Interactions of Neutrinos and where to find them. Speaker: Tatsu Takeuchi
- **Tuesday 15:35:** Dark Matter and Physics Beyond the Standard Model at DUNE. Speaker: Valentina De Romeri
The Snowmass process has started in the US and the \( \nu \) BSM community is planning a year long effort. Community activities so far:

- **Workshop on New Opportunities at the Next Generation Neutrino Experiments** 12-13 April 2019 University of Texas, Arlington. Explored Dark Matter Searches at Neutrino Experiments and BSM Physics with Neutrinos.


- 2nd workshop planned April 2-4, 2020 in **Pittsburgh, PA**
Long-baseline experiments are entering an era of precision oscillation measurements with most 3-flavor oscillation parameters - like the mixing angles and mass differences - now measured at the few % level of precision.

This opens up a new frontier of using precision oscillation measurements to search for physics beyond the Standard Model and beyond the 3-flavor $\nu$ model.

Long-baseline oscillation experiments using high purity well known neutrino sources from accelerators are particularly sensitive to NC NSI, new interactions in matter, compactified large extra dimensions and low mass sterile neutrinos.

Future LBL experiments like DUNE are also opening up a new frontier of new physics searches using $\nu_\tau$ appearance. This promises tighter constraints on unitarity tests.
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THANK YOU