Search for Sterile Neutrino Mixing
- Status and Plans -

Alex Sousa, Mattias Blennow, Enrique Fernandez-Martinez, Salvador Rosauro-Alcaraz, Jacob Todd

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Sterile Neutrinos

- Like other current and past LBL experiments, DUNE will be able to probe active-to-sterile neutrino mixing:
  - Look for CC and NC disappearance between ND and FD (and anomalous FD $\nu_e$ appearance)
  - Sensitivity to $\nu_\mu$ disappearance and $\nu_e$ appearance at the ND baselines
Deep Underground Neutrino Experiment (DUNE)

DRAFT Technical Design Report

Volume 2:
DUNE Physics

Chapter 1: Beyond the Standard Model Physics Program

1.4 Sterile Neutrino Searches

Experimental results in tension with the three-neutrino-flavor paradigm [51, 52, 53, 54], which may be interpreted as mixing between the known active neutrinos and one or more sterile states, have led to a rich and diverse program of searches for oscillations into sterile neutrinos. Having a longer baseline, a more intense beam, and a high-resolution large-scale FD, compared to previous experiments, DUNE provides a unique opportunity to improve significantly on the sensitivities of existing probes, and to enhance the ability to map the extended parameter space if a sterile neutrino is discovered.

1.4.1 Probing Sterile Neutrino Mixing with DUNE

Long-baseline experiments like DUNE can look for sterile neutrino oscillations by measuring disappearance of the beam neutrino flux between the ND and FD. This results from the quadratic suppression of the sterile mixing angle measured in appearance experiments, $\theta_{\mu\nu}$, with respect to its disappearance counterparts, $\theta_{\mu 2}$ for long-baseline (LBL) experiments, and $\theta_{\mu 3}$ for reactor experiments. These disappearance effects have not yet been observed and are in tension with appearance results [55] when global fits of all available data are carried out. Its high-intensity and high-resolution FD will allow DUNE to perform direct measurements of nonstandard electron (anti)neutrino disappearance.

- Contributed text to TDR BSM Physics section on Nov. 30, 2018 and Jan. 18, 2019
- Now under review by LBNC
Sterile Neutrino Search Setup

- GLoBES implementation with simultaneous fit of near and far detector (4×3×5 m³, 83.76 ton LArTPC ND @ 574 m)

- Using GLoBES plugin for steriles and NSI by J. Kopp. Assuming 3+1 model with one sterile neutrino:
  - [https://www.mpi-hd.mpg.de/personalhomes/globes/tools/snu-1.0.pdf](https://www.mpi-hd.mpg.de/personalhomes/globes/tools/snu-1.0.pdf)

- 300 Kt.MW.years CDR exposure

- 80 GeV reference beam flux as in CDR

- Same reconstruction efficiencies as in CDR

- More realistic systematics (significantly larger) with respect to those considered in the CDR

- Account for uncertainty in neutrino production point (or pion decay point) between target and ND by applying a 20% energy smearing obtained by integrating gaussian in reco. energy \(E'\):

  \[
  R^c(E, E') \equiv \frac{1}{\sigma(E)\sqrt{2\pi}} e^{-\frac{(E-E')^2}{2\sigma^2(E)}}, \quad \sigma(E) = 0.2E
  \]

### Previous Systs. CDR - Table 3.8

<table>
<thead>
<tr>
<th>Source of Uncertainty</th>
<th>MINOS</th>
<th>T2K</th>
<th>DUNE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam Flux after N/F extrapolation</td>
<td>0.3%</td>
<td>3.2%</td>
<td>2%</td>
</tr>
<tr>
<td>Interaction Model</td>
<td>2.7%</td>
<td>5.3%</td>
<td>~2%</td>
</tr>
<tr>
<td>Energy scale ((\nu_e))</td>
<td>3.5%</td>
<td>included above</td>
<td>(2%)</td>
</tr>
<tr>
<td>Energy scale ((\nu_e))</td>
<td>2.7%</td>
<td>2.5%</td>
<td>includes all FD effects</td>
</tr>
<tr>
<td>Fiducial volume</td>
<td>2.4%</td>
<td>1%</td>
<td>1%</td>
</tr>
<tr>
<td>Total</td>
<td>5.7%</td>
<td>6.8%</td>
<td>3.6%</td>
</tr>
</tbody>
</table>

Systematic errors included (new):

- Signal flux errors (+/-): 8%
- Background flux errors (+/-): 15%
- F/N flux e: 2%
- F/N flux mu: 0.4%
- CC x-sec error: 15%
- NC x-sec error: 25%
- F/N x-secs (separate flav & nu/antinu): 2%
- Fiducial volume FD: 1%
- Fiducial volume ND: 1%

E. Fernandez-Martinez, M. Blennow, S. Rosauro, J. Todd, A.S.
Light Sterile Neutrino Results

$\nu_\mu$ CC + NC Disappearance

$\nu_e$ CC App./Disapp. + $\nu_\mu$ CC Disapp.

$\Delta m^2_{41}$ (eV$^2$)

$\sin^2(\theta_{24})$

$\sin^22\theta_{\mu e} = 4|U_{e4}|^2|U_{\mu 4}|^2$

DUNE Simulation

Work in Progress!

Alex Sousa, University of Cincinnati

DUNE BSM Physics Session - January 29, 2019
Light Sterile Neutrino Results

**NC Disappearance**

\[ \sin^2 2\theta_{\mu\tau} \equiv 4|U_{\tau 4}|^2|U_{\mu 4}|^2 = \cos^4 \theta_{14} \sin^2 2\theta_{24} \sin^2 \theta_{34} \]

**Table 1.4:** The projected DUNE 95% CL upper limits on sterile mixing angles and matrix elements compared to the equivalent 90% CL upper limits from NOνA [60], MINOS [61], Super-Kamiokande [62], IceCube [63], and IceCube-DeepCore [64]. The limits are shown for \( \Delta m_{41}^2 = 0.5 \text{ eV}^2 \) for all experiments, except for IceCube-DeepCore, where the results are reported for \( \Delta m_{41}^2 = 1.0 \text{ eV}^2 \).
ND and FD Contributions to Limits

Large $\Delta m_{41}^2$ (ND-dominated):
- Rapid oscillations at FD average out
- ND spectral distortions affect extrapolation to FD
- ND stats error negligible, limit determined by systematic uncertainties

Intermediate $\Delta m_{41}^2$ (Counting Expt):
- Rapid oscillations at FD average out
- No ND oscillations, ND flux/cross section syst. constraint, FD statistics dominate

Small $\Delta m_{41}^2$ (FD-dominated):
- FD spectral distortions above 3-flavor max.
- No ND oscillations, ND flux/cross section syst. constraint, FD statistics dominate
Tech Note Comment

Comment by M. Shaevitz: One needs to measure an appearance rate at the 1 in a million level with all the backgrounds and mis-IDs that would have to be known at the $10^{-6}$ absolute level.
Tech Note Comment

Signal $\nu_e$ app.

$\sin^2(2\theta_{\mu e}) = 3 \cdot 10^{-6}$

$\Delta m_{41}^2 = 10 \text{ eV}^2$

Can’t get $10^{-6}$ sensitivity from here!!

Background $\nu_e$ app.

$\sin^2(2\theta_{\mu e}) = 3 \cdot 10^{-6}$

$\Delta m_{41}^2 = 10 \text{ eV}^2$
However, sensitivity to nue appearance is a linear combination of sensitivity to nue disappearance and to numu disappearance, so appearance sensitivity of 1 in $10^6$, given how good those are, is not unreasonable.
Tech Note Comment

- Why are the disappearance sensitivities so good in the ND-dominated region?
  - DUNE ND energy resolution is very good (125 MeV bins in flux*cross section input histograms)
  - By default, GLoBES treats all systematics as normalization shifts and not shifts to the shape of the spectrum
    - ND can then exclude most sterile-induced shapes or "wiggles", which do not look like normalization shifts, except at very high $\Delta m^2_{41}$ where normalization dominates

- Have shown that using shape-distorting systematics does degrade sensitivity
  - In this example, changed the GLoBES implementation of the CC x-sec syst. to allow bin-by-bin decorrelated 15% randomly up or down shifts in the energy spectrum
Understanding fit in ND region

- Salva reran the numu disappearance fit under different energy shape shift assumptions
  - Present result (pink)
  - Energy shift described by 7 bins, 15% in CC and 25% in NC (green)
  - Energy shift described by 14 bins, 15% in CC and 25% in NC (purple)
  - Energy shift described by 14 bins, 30% in CC and 40% in NC (red I)
  - Energy shift described by 28 bins, 15% in CC and 25% in NC (blue)
    - (~250 MeV bins)
  - FD-only fit using glb file from Elizabeth with already correlated systematics (red II)

- 3+1-flavor oscillation-induced wiggles can now be reproduced by this fine-grained energy shape shift systematic, so the sensitivity in the ND-dominated region is washed out, as expected
- However, it is not clear such systematic makes sense from a physics point of view. Can perhaps be justified as a conservative empirical shift accounting for all potential shape systematics?
TDR End Game

- In the process of recomputing all sensitivities with the TDR-recommended files
  - 120 GeV flux
  - Migration matrices for detector response
  - Signal and background efficiencies
  - New ND fiducial volume/mass

- Unless we reach a clear understanding of the ND-dominated region fit behavior in the next week or so (and associated systematics), we plan to show the FD-only version of the sensitivities mentioned above

- On more trivial changes, need to convert figures and tables to DUNE formats

- Hoping to have final draft ready by Feb. 15, will incorporate TDR editors, Anne H., (and LBNC?) feedback as it becomes available

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|         | $\theta_{24}$ | $\theta_{34}$ | $|U_{\mu 4}|^2$ | $|U_{\tau 4}|^2$ |
|---------|---------------|---------------|----------------|----------------|
| DUNE    | 2.6°          | 14.2°         | 0.002          | 0.06           |
| NOvA    | 20.8°         | 31.2°         | 0.126          | 0.268          |
| MINOS   | 7.3°          | 26.6°         | 0.016          | 0.20           |
| SuperK  | 11.7°         | 25.1°         | 0.041          | 0.18           |
| IceCube | 4.1°          | 22.8°         | 0.11           | 0.15           |
| IceCube-DeepCore | 19.4° | 22.8° | 0.11 | 0.15 |

Table 1.4: The projected DUNE 95% CL upper limits on sterile mixing angles and matrix elements compared to the equivalent 90% CL upper limits from NOvA [60], MINOS [61], Super–Kamiokande [62], IceCube [63], and IceCube-DeepCore [64]. The limits are shown for $\Delta m_{41}^2 = 0.5 \text{ eV}^2$ for all experiments, except for IceCube-DeepCore, where the results are reported for $\Delta m_{41}^2 = 1.0 \text{ eV}^2$.  

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| IceCube | -             | -             | 0.005          | -              |
| IceCube-DeepCore | 19.4° | 22.8° | 0.11 | 0.15 |

Table 1.4: The projected DUNE 95% C.L. upper limits on sterile mixing angles and matrix elements compared to the equivalent 90% C.L. upper limits from NOvA [13], MINOS [14], Super–Kamiokande [15], IceCube [16], and IceCube-DeepCore [17]. The limits are shown for $\Delta m_{41}^2 = 0.5 \text{ eV}^2$ for all experiments, except for IceCube-DeepCore, where the results are reported for $\Delta m_{41}^2 = 1.0 \text{ eV}^2$. 
Post-TDR Prospects

- Continue GLoBES studies to understand further two-detector fit implementation and shape systematics treatment
  - Could be a very interesting limited authorship/DUNE paper for GLoBES user community

- Adapt fully-realistic LBL 3-flavor framework developed for TDR to use 3+N flavor model (new people needed!)
  - Should be easy for an FD-only fit with $\Delta m_{41}^2 < 1 \text{ eV}^2$
  - Would need to add a two-detector fit to include ND oscillations. Can learn from MINOS/MINOS+ and NOvA implementations (e.g. NOvA now has a CAFana two-detector sterile fit)

- Develop dedicated ND searches for nue and nutau appearance using combined fits to nue/nutau and numu samples (new people needed!)
  - Working examples from NOvA and T2K

- Determine sensitivity to sterile neutrinos using DUNE’s atmospheric samples (new people needed!)
  - Working examples from IceCube and SuperK

- Your ideas are welcome! Talk to me or e-mail me if interested in contributing: alex.sousa@uc.edu