FY2026 NPP LDRD Type B Pre-Proposal

A Flexible Open Source Neutrino Oscillation Global Fit

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FY2026 NPP LDRD Type B Pre-Proposal

Proposal title: A Flexible Open Source Neutrino Oscillation Global Fit

Primary Investigator: Peter Denton

Other Investigators:

Indicate if this is a cross-directorate proposal: Yes ___ No_X_

If yes, identify other directorates/organizations:

Proposal Term: From: Oct 2025 To: Sep 2027

Brookhaven National Laboratory

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Proposal title: A Flexible Open Source Neutrino Oscillation Global Fit

Abstract: Measuring the six neutrino oscillation parameters is of the utmost priority in physics. Experiments extract complicated mixtures of the parameters. A global fit is *necessary* to understand the nature of these fundamental physics parameters. I will develop the first open source, flexible global fit to neutrino oscillation data. This will allow for a transparent fitting procedure to the data, the ability for theorists and experimentalists to understand the impact of adding and subtracting experimental data.

Program: HEP

Return on Investment: Enhancing the DUNE physics case, leveraging institutional knowledge on long-baseline accelerator and reactor neutrino oscillation experiments, develop the world leading global fit for years to come.

Broader impact on the activities at the laboratory: A global fit will likely be the first to discover the neutrino mass ordering, CP violation, and the octant. The flexible nature will influence DUNE decisions such as neutrino vs. anti-neutrino run time

Total planned funding per year in FY26 and FY27: $500k

Description of the LDRD

Motivation:

It is essential for the advancement of particle physics to discover the nature of the parameters in neutrino oscillations; these represent the only particle physics evidence we have for physics beyond the Standard Model. Several key unknowns remain: notably 1) the *neutrino mass ordering* which has implications for cosmology, neutrinoless double beta decay, and elsewhere, 2) *CP violation* which is an innately interesting aspect of particle physics, and 3) the *octant* of θ_{23} which is essential for understanding flavor models. The next generation of neutrino oscillation experiments: DUNE (with a large BNL contribution), HyperK, and JUNO (building off a previous BNL experimental effort) aim to resolve these remaining mysteries.

Due to the interconnected nature of all the parameters, these unknowns will almost certainly be first resolved by a theorist performing a global fit, and it should be done at Brookhaven.

Description of the LDRD

Physics in the fit:

Input Data: We will include data from each neutrino oscillation measurement:

1. Solar:
   a) Homestake
   b) Gallium experiments: SAGE, GALEX, GNO
   c) SNO
   d) Borexino
   e) SuperK
   f) DUNE, JUNO, HK
2. Reactor:
   a) Daya Bay, RENO, Double CHOOZ
   b) KamLAND
   c) JUNO
3. Atmospheric:
   a) SuperK
   b) IceCube
   c) DUNE, HK, JUNO
4. Accelerator:
   a) MINOS
   b) NOvA
   c) T2K
   d) DUNE, HK

Interplay: Each experiment measures a complicated mixture of the parameters:

Solar: Measures mostly $\sin^2\theta_{12}$ and also Δm^2_{21} with a subleading contribution from $\sin^2\theta_{13}$

Reactor: Medium baseline measures mostly $\sin^2(2\theta_{13})$ and Δm^2_{31} with subleading effects from $\sin^2\theta_{12}$ and Δm^2_{21}

Long baseline measures $\sin^2(2\theta_{12})$ and Δm^2_{21} and will also measure the mass ordering and Δm^2_{31}

Atmospheric: Measures Δm^2_{31} and $\sin^2(2\theta_{23})$ and has sensitivity to the mass ordering

Accelerator: Measures Δm^2_{31}, $\sin^2(2\theta_{23}), \sin^2\theta_{23}$, $\delta_{\rm CP}$, and the mass ordering, and depends on all other oscillation parameters

Future experiments in green
Indicates BNL experimental involvement

Brookhaven National Laboratory

Description of the LDRD

Details in the analysis:

Systematics: We will consider **shared flux systematics**[1] and their theoretical uncertainties among multiple measurements for atmospheric, solar, and reactor.

Code: We will develop an **open source**[1] code in two layers. The first is a full fit to each experiment's published low-level data. This will be carefully **validated** against the experiment's own analysis. The second is a faster fit[1] that reproduces all the relevant physics but can be performed computationally quickly. This will allow for the easy addition and subtraction of experimental results and the ability to project sensitivities for future experiments like DUNE.

Statistical fit: Existing analyses assume Wilks' theorem to extract statistical significances. We will perform Bayesian[1] and frequentist[1] fits and quantify the significances using Monte Carlo (e.g. Feldman-Cousins) where necessary.

Usage:

1. Select which experiments to use:
   a) All existing
   b) Only the latest key measurements
   c) All existing plus anticipated future
   d) All existing minus one experiment
   e) …
2. Select the data level:
   a) Full data with all joint systematics
   b) Effective measurements (fast)
3. Select the statistical approach:
   a) Simple Wilks' theorem (industry standard)
   b) Bayesian regions
   c) Frequentist intervals (e.g Feldman-Cousins)
4. Return the confidence intervals for the six oscillation parameters and the overall goodness of fit[1]

[1]Never done before

Description of the LDRD

Deliverables: The main deliverable will be in the form of a **publicly available code** hosted and maintained on github.com. This will also be accompanied by **several publications** describing the physics input to the code, the validation procedure, the usage cases, as well the actual numerical results of the **best fits of all six oscillation parameters** and the statistical preference for the mass ordering, for the ability to reject CP conservation, and the ability to reject maximal θ_{23} mixing and the wrong octant.

ROI: This LDRD will establish **BNL as an international neutrino theory institution** and the code will be maintained throughout DUNE's run and will be a valuable asset to BNL, DUNE, and the community and aims to provide **the defacto standards for reviews such as the PDG.** It will provide an **early indication of key fundamental parameters** of nature before billion dollar experiments individually measure them. This flexible code will also allow for the expansion into **new physics** searches such as sterile neutrinos or non-standard neutrino interactions **expanding the physics reach of DUNE** and other experiments.

PI Capabilities: I have published many papers analyzing data from each class of experiments to be included in the fit: atmospheric, solar, reactor, and accelerator. I have written complicated neutrino oscillation codes before. I have publicly posted many of my neutrino codes online.

Budget justification: The majority of the budget will be to support a postdoc who will assist with experimental validation procedure and the code development. Some of the budget will also be spent on local computational resources for the final fit, and a small part of the budget will support the PI.

Summary Slide

- Neutrinos are the only particles that give us a known window into new physics
- Key foundational questions remain about the nature of neutrino oscillations, neutrino masses, and the flavor structure of neutrinos
- The remaining neutrino oscillation parameters will be first determined by a global fit
- Having an accessible and robust public code fitting neutrino oscillation will be an essential resource for the neutrino community
- My expertise in neutrino oscillation theory combined with the experimental group's experience with reactor and accelerator data make BNL the perfect place to perform such a fit
- Theory expertise will also be useful for interpreting the results in the context of flavor models and any tensions
- The code would be usable by theorists and experimentalists alike to understand the current and possible future scenarios
- This undertaking would establish BNL as a strong neutrino theory group for many years to come