An Experimental Program in Neutrinos, Nucleon Decay and Astroparticle Physics Enabled by the Fermilab Long-Baseline Neutrino Facility

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The Deep Underground Neutrino Experiment collaboration is 750 scientists from 150 institutions in 23 countries
Who Are We?

• The collaborations formerly known as LBNE and LBNO, with some new participants
  – Mark Thomson (Cambridge) and André Rubbia (ETH Zurich) are our spokesfolk
  – First collaboration meeting was last April, new Conceptual Design Report (CDR) and “CD1 refresh” passed last week
  – Shared DoE and international funding, CERN involvement
• The beam and infrastructure are now known as Long-Baseline Neutrino Facility (LBNF)
What Will We Do?

• Build a large (40 kt) liquid argon TPC on the 4850’ level of the Sanford Underground Lab in the Homestake Mine, and bask in a new, intense neutrino beam from Fermilab
  – Longer baseline, more intense, tunable energy
With What?

- **Staged** 10 kt LArTPC modules at Homestake

  Two 10kt Single-phase modules ala ICARUS
  Gaining experience with LARIAT, MicroBoone, CAPTAIN, SBND at FNAL
  First module reference design

- **Final goal is 40kt total Far Detector mass**

  Dual-phase design catches ionization in gas above liquid
  Prototyping with WA105 at CERN
  Later modules could use this mode
• Near Detector near the beam source at FNAL
  – Precisely measure pre-oscillation $\nu$ beam spectra and flavor
  – Reference design is fine-grained straw tube tracker
  – Calorimeters, 0.6T magnet
  – Will also do neutrino interaction physics
Stephen Parke’s famous visualization of things, as annotated by Gary Feldman
So What Might We Learn?

- Does the $\nu_3$ mass state have a $\nu_e$ component?
  - Is $\theta_{13} \neq 0$? YES! (*without which nothing else works*)

- Is there CP violation in the lepton sector?
  - Is $\delta_{CP} \neq 0$?

- Is the $\nu_3$ mass state more massive than $\nu_1$ and $\nu_2$ (*normal hierarchy*) or less massive (*inverted hierarchy*)?
  - Absolute mass values need $\beta$ and $\beta\beta$ decay experiments to nail down

- Does the $\nu_3$ mass state have a larger $\nu_\mu$ or $\nu_\tau$ component?
  - Is $\theta_{23} \neq \pi/4$?

In my biased opinion, that’s 1.5 of the remaining fundamental 2 things we don’t yet know about the standard model ($\theta_{13}$, Higgs mass were #3, #4)
How Well?

- Primary goal: precision measurement of neutrino oscillation parameters
  - $3\sigma$ sensitivity to $\delta_{\text{CP}}$ for 75% of the possible values of $\delta_{\text{CP}}$ after 850-1300 kt-MW-years
  - $5\sigma$ sensitivity neutrino mass hierarchy for all possible values of $\delta_{\text{CP}}$ after 400 kt-MW-years
What’s the Signal?

- Measure probability of $\nu_\mu \rightarrow \nu_e$ oscillation for both neutrinos and antineutrinos
  - Compare to expectations for different $\delta_{CP}$, mass hierarchies
Proton Decay

- GUTs predict protons are unstable at very long lifetimes, beyond what we have probed so far
- A LArTPC has the spatial resolution for good efficiency on popular modes involving Kaons
Atmospheric $\nu$

- Neutrinos from cosmic ray interactions in the atmosphere probe a wide range of oscillation parameter space, complementary to the more intense (but narrow band) LBNF beam.
Core-collapse supernova release 99% of their binding energy in a blast of neutrinos (*1% in as kinetic energy, only 0.1% as light!*)
- Observing this in 1987 revolutionized two fields

The next time it happens (*in our galaxy*) we want a complete picture
- Both for astrophysics and particle physics
- Observing that density of neutrinos in detail will shed light on neutrino properties via collective effects not possible to probe in a lab
All the flavors

- Existing experiments would mostly see anti-electron neutrinos
  - Super-K, IceCube: mostly anti-electron neutrinos
  - LVD, NOvA, Kamland, Daya Bay, Borexino: anti-electron neutrinos and NC (all flavor)
  - HALO: electron neutrinos, but is small
- Measuring all flavors paints the complete picture needed to extract all the results

Garching flux seen in DUNE as calculated by SNoWGLoBES
• We’ll have 40kt of high resolution detector deep underground, an intense beam, and a fine-grained near Detector! Can probe many more things:
  – Neutrino interaction physics
  – Indirect dark matter searches
  – Cosmic ray physics
  – Lorentz and CPT violation, extra dimensions
  – Non-standard interactions, sterile neutrinos

• Exploring potential of lower energy neutrino studies:
  – Solar neutrinos
  – Diffuse supernova neutrino background
LBNF/ DUNE Schedule Summary Overview

- Jul-15 CD-1 Refresh Review
- Jan-16 CD-3a
- May-18 CD-3b
- Dec-19 CD-2/3c Project Baseline/ Construction Approval
- CFFS Preliminary & Final Design
- CFFS Excavation and Caverns
- Cryostat and Cryogenics Construction
- FD Detector Design and Prototyping
- FD Detector 1-4 Procurement
- FD Detector assembly, installation, filling, commissioning
- CFNS Preliminary & Final Design
- Near Detector & Beamline Design
- Near Detector Procurement and Assembly
- Beamline Conventional Facilities and Component Installation
- N.D. Hall & Install of Near Detector in Hall
- ND Commissioning
- FY15
- FY16
- FY17
- FY18
- FY19
- FY20
- FY21
- FY22
- FY23
- FY24
- FY25
- FY26
- FY27

- Detector #1 Commissioned
- Beamline Complete
Summary

- While existing long-baseline experiments (T2K, NOvA) might give us hints of $\delta_{CP}$ and neutrino mass hierarchy, DUNE is designed to cover most of parameters space with discovery sensitivity.
- DUNE will greatly enhance the world’s ability to decipher Supernova neutrinos and search for nucleon decay.
- Project has a busy but doable schedule and new international cooperation.
Backups
• \(\nu\) are leptons, interact only weakly
  – interact as flavor eigenstates \(\{\nu_e, \nu_\mu, \nu_\tau\}\)
  – but propagate as mass eigenstates \(\{\nu_1, \nu_2, \nu_3\}\)
• Different m’s make mass states slide in and out of phase as they travel
  – So a \(\nu\) created as one flavor might be detected as another later

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix} = \begin{pmatrix}
U_{e1} & U_{e2} & U_{e3} \\
U_{\mu1} & U_{\mu2} & U_{\mu3} \\
U_{\tau1} & U_{\tau2} & U_{\tau3}
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
\]

Useful Approximations:

\(\nu_\mu\) Disappearance (2 flavors):
\[
P(\nu_\mu \rightarrow \nu_x) = \sin^2 2\theta_{23} \sin^2 (1.27 \Delta m^2_{32} L/E)
\]

\(\nu_e\) Appearance:
\[
P(\nu_\mu \rightarrow \nu_e) \approx \sin^2 \theta_{23} \sin^2 2\theta_{13} \sin^2 (1.27 \Delta m^2_{31} L/E)
\]

Where L, E are experimentally optimized and \(\theta_{23}, \theta_{13}, \Delta m^2_{32}\) are to be determined
Mass Hierarchy

- Unlike quarks and the other leptons, we do not even know which $\nu$ is more massive than the next!
\( \nu_e \) appearance

- We will start off with few \( \nu_e \) in a beam of \( \nu_\mu \) and see if more \( \nu_e \) pop up after some L/E
  - This isn’t simply the converse of the reactor case which measures \( \nu_e \) disappearance and thus \( \theta_{13} \)
- Back to the oscillation approximations we use for \( \nu_\mu \) disappearance:
  - Note that while experimentally \( \theta_{23} \) is close to \( \pi/4 \), if it’s not exactly \( \pi/4 \) we can’t tell if it’s > or <
  - And that “\( \approx \)” wipes away a lot more terms which result from multiplying out the mixing matrix properly

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Where L, E are experimentally optimized and \( \theta_{23}, \theta_{13}, \Delta m^2_{32} \) are to be determined
\( \nu_e \) appearance

\[
P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \approx \sin^2 2\theta_{13} \sin 2\theta_{23} \frac{\sin^2 (A-1)\Delta}{(A-1)^2} \\
+ \alpha \sin \theta_{13} \sin \delta_{\text{CP}} \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin \Delta \alpha}{\Delta} \frac{\sin (A-1)\Delta}{(A-1)} \sin \Delta \\
+ \alpha \sin \theta_{13} \cos \delta_{\text{CP}} \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin \Delta \alpha}{\Delta} \frac{\sin (A-1)\Delta}{(A-1)} \cos \Delta
\]

\[
\alpha = \Delta m^2_{21}/\Delta m^2_{31} \quad \Delta = \Delta m^2_{31} L/(4E) \quad A = \frac{\alpha}{\Delta} G F n_e L/(\sqrt{2}\Delta)
\]

- Note there are \( \theta_{23} \) terms that are not squared, introducing sensitivity to \( \theta_{23} > \pi/4 \) or \( < \pi/4 \)
- CP-violating \( \delta \) is present
- Matter effects are in there, differ in sign for \( \nu \) and anti-\( \nu \), so a comparison could allow sorting out the mass hierarchy
- But if \( \theta_{13} \) is near zero, we learn nothing (all terms \( \rightarrow 0 \))

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