The Deep Underground Neutrino Experiment

Status and Prospects

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TAU 2023
Dec. 7th, 2023
Outline

• Neutrino Oscillations
• Scientific Reach
• The DUNE Experiment
• LBNF Beam
• DUNE Near Detector
• LBNF Far Site and DUNE Far Detector
• ProtoDUNE – DUNE prototype
• DUNE Physics.
• Conclusion and Future
Neutrino Oscillations

Phenomenon of neutrino flavor transmutation at a distance traveled. For 3-flavor model

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix} = U_{\text{PMNS}}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
\]

• Neutrinos are produced as flavor eigenstates and propagate as mass eigenstates

\[
U_{\text{PMNS}} = \begin{pmatrix}
c_{12} & s_{12} & 0 \\
-s_{12} & c_{12} & 0 \\
0 & 0 & 1
\end{pmatrix}
\begin{pmatrix}
c_{13} & 0 & s_{13}e^{-i\delta} \\
0 & 1 & 0 \\
-s_{13}e^{i\delta} & 0 & c_{13}
\end{pmatrix}
\begin{pmatrix}
1 & 0 & 0 \\
0 & c_{23} & s_{23} \\
0 & -s_{23} & c_{23}
\end{pmatrix}
\]

• PMNS matrix – transforms from mass to flavor eigenstates – 3 mixing angles and phases

\[
P(\nu_\alpha \to \nu_\beta) \sim \sin^2(2\theta) \sin^2 \left( \frac{\Delta m_{ij}^2 L}{4E} \right)
\]

• Two flavor oscillation probability depends on the distance L and neutrino energy E.

• Governed by the mixing angles and mass splitting.
Neutrino Oscillations Measurements

- Fast progress in 25 years.

- Neutrinos have non-zero masses and they are different.

arXiv:2212.00809
Neutrino Oscillations – Open Questions

- How the mass eigenstates ordered?
  - \( q_{23} \) maximal?
    - \( q_{23} \sim 45^\circ \)
  - Is PMNS unitary?

- Is \( \theta_{23} \) maximal?
  - \( \theta_{23} \sim 45^\circ \)

- Is CP symmetry violated?
  - \( \delta_{CP}=0? \)

- If yes, does it explain the matter anti-matter asymmetry?

- Are there sterile neutrinos?

Symmetry Magazine
DUNE/LBNF/SURF

- DUNE collaboration is an international team of 1400+ scientists and engineers.
- LBNF is the facility combining the beamline and the near detector complex at Fermilab and the far detector complex at SURF.
- SURF experimental facility at the far site.
The Dune Collaboration

- 1450 Collaborators
- 215 institutions
- 35 countries

January Collaboration Meeting at CERN
DUNE Concept

- Long baseline ~ 1300km
- Wide-band $\nu/\bar{\nu}$ beam ~ 2GeV peak with 1.2 MW power (2.4MW with upgrade)
- Near detector complex to analyze the beam and control systematics.
- 70 kt LArTPC far detector complex at SURF ~ 1.5km below the surface.

\[
A_{CP} = \frac{P(\nu_\mu \rightarrow \nu_e) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)}{P(\nu_\mu \rightarrow \nu_e) + P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)} \sim \frac{\cos \theta_{23} \sin 2\theta_{12} \sin \delta_{CP}}{\sin \theta_{23} \sin \theta_{13}} \left( \frac{\Delta m_{21}^2 L}{4E_\nu} \right) + \text{matter effects}
\]
LBNF Beamline – PIP-II

- Proton Improvement Plan
- New proton source with 800MeV H⁻ at Fermilab
- LINAC line to inject into Booster
- MI with 1.2MW (phase-I) and up to 2.4MW (phase-II)

LBNF Neutrino Beam

- Protons from MI impinging on a graphite target
- Magnetic focusing horns with reversible current to produce $\nu$ mode (FHC) and $\bar{\nu}$ mode (RHC).
- Beamline entering Earth at a 5.8° and pointing to the far site producing wide-band beam.

Making a neutrino beam
Near Detector Complex

Versatile complex tasked with neutrino beam characterization and control of systematic uncertainties. Comprise of

- ND-LAr – same target and detection technology as the far detector modified for higher rate

- TMS – The Muon Spectrometer – magnetized spectrometer to analyze muons produced in $\nu_\mu$ CC interactions.

- DUNE-PRISM – moving ND-LAr and TMS to 30m off axis.

- SAND – on-axis tracking spectrometer with Ar target GRAIN and STT with ECAL utilizing the KLOE magnet.
DUNE PRISM Concept

- Different off-axis angles result in different neutrino beam spectra.
- Linear combination for different angles can reproduce the far detector oscillated flux.
- Similarly, it can be used to get a Gaussian narrow beam for cross section measurements.
DUNE Far Site

- Excavation expected to finish in 2024
- 80% done.
- Facility to be completed in 2025
DUNE Far Detector - LArTPC

- Liquid Ar Time Projection Chamber
- Low detection threshold ~MeV
- High resolution (mm) tracking
- Energy reconstructed for calorimetry -
- Particle ID – good separation between $\nu_\mu$ and $\nu_e$ events
DUNE Far Detector

Module 1 - Horizontal drift.

- 150 wire APAs – total of 384k channels
- About 180kV on the cathode
- Max drift distance of 3.5m (CPA->APA)
- Photo detection system (PDS) – 6000 PDS

Module 2 - Vertical drift.

- CRP based on perforated PCB
- About 300kV on the cathode
- Max drift distance of 6.4m
- Photo detection system (PDS) – on cathode
DUNE Far Detector

• Two 17kt LArTPC modules – 1 each of horizontal and vertical drift.

• 17.8m(H) x 19m(W) x 65.9m(L) Cryostat with internal volume of 28’500 m³

• 17.5kt of LAr when filled.

• Membrane with passive insulation.

  Design by CERN and GTT
Comprehensive R&D Program - ProtoDUNE

- Two Prototypes at CERN – 770t
- 1/25\(^{th}\) of DUNE
- DUNE size components 8mx8mx8m cryostat
- Test beam with muons, pions, protons, kaons, etc.
- Multiple beam momenta.
- Characterization of detector components performance and detector response.
- Development and tuning of reconstruction.
- Physics measurements.
ProtoDUNE II

ProtoDUNE-HD (NP04)

• ProtoDUNE-HD is installed
• Module – 1 components

• Expected to take data later in 2024

ProtoDUNE-VD (NP02)

• ProtoDUNE-VD is being installed
• Module – 2 components

Excellent SN and image quality
ProtoDUNE I Physics – 2018/20 Run

- ProtoDUNE single phase beam and cosmics.
- Successful long-term run.
- Evaluate the performance of first version of DUNE’s components and reconstruction tools.
- Physics results are already coming out.

Michel energy reconstruction:

Phys. Rev. D 107, 092012 (2023)
arXiv:2211.01166

Pandora reconstruction validation with beam and cosmic muons:

arXiv:2206.14521
Physics Results in the Works

- Number of hadron cross section results for pion, proton, and kaons
- Important input to neutrino event generators
- Used to tune the modeling of nuclear effects in neutrino interactions.
DUNE Physics – Neutrino Oscillations

In about 7 years of running we expect
• ~10,000 disappearance events
• ~1,000 appearance events

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DUNE Physics – CP Violation Sensitivity

![Graph showing CP Violation Sensitivity]
Rich Physics Program

• Precise measurement of 3-flavor neutrino oscillation parameters with both neutrinos and anti-neutrinos
  - Would be competitive to Daya Bay $\theta_{13}$ measurement with complete data set
• Neutrino interaction cross sections.
• SN physics – detect $\nu_e$ from galactic super-novae with $\sim 5\degree$ pointing capability.
• HEP solar flux observation at more that 5$\sigma$ and measurement of solar oscillation parameters.
• Test of 3-flavor oscillation limits – search for sterile n, PMNS non-unitarity, NSI, CPT violations
• Proton decay and GUT model tests. Search for $p \rightarrow K^+ \bar{\nu}$.
• Other BSM physics.
• LArTPC can reconstruct $\nu_\tau$ interactions as the beam is above $\tau$ production threshold.
Tau Neutrinos

- Configurable beam allows for high energy tune (phase-II)
- Needed to overcome the 3.5 GeV $\tau$ production threshold
- Achieved by moving the magnetic horns.
- Expected $\nu_\tau$ statistics per year:
  - 130 with default beam
  - 800 with high energy tune.
- For $\bar{\nu}_\tau$ the rate is about 30 events/year in low energy mode.

Phys. Rev. D 102, 053010 (2020)
Conclusions and Future

- DUNE is a next generation long-baseline neutrino oscillation experiment with rich physics program
  - Precise measurement of neutrino oscillation parameters
  - Astrophysical measurements with SN and other ~MeV energy neutrinos
  - BSM physics both neutrino and non-neutrino.
- ProtoDUNE is a successful testbed with many physics results right around the corner.
- LBNF construction is progressing rapidly with expectation to have occupancy at the far site at the end of 2024.
- First module starts taking data in 2028.
- First beam is expected to start in 2031.

DUNE Talk on 3D-Reconstruction of Tau Neutrinos in LArTPC Detectors

By Barbara Yaeggy Alvarez

Thursday, Dec 7th, at 5:40PM.
Thank you!
Backups
DUNE Concept

- Near detector

- 1490m underground (4300 mwe)
- Space for 70kt LAr detector

Beamline
DUNE Timeline and Phasing

DUNE phase-I:

• LBNF completed
  - PIP-II and neutrino beamline by 2031
  - full near detector site and facilities by 2028
  - far site with facilities and caverns for 2 modules – total of 70kt FD
    complete by the end of 2024
• Two FD modules – 17kt LArTPC each of HD and VD
  - HD starts installation in 2026, complete and commissioned by 2028
  - VD starts installation in 2029
• LAr-ND w/ TMS and on-axis SAND by 2031

DUNE phase-II:

• Fermilab beamline: Booster and other upgrade allowing for 2.1MW
• ND – additional sub-detectors – ND-Gar, calorimeter
• FD – FD3 and FD4 – technology TBD.
Data points show NO, $\delta_{\text{CP}} = 0$, $\sin^2\theta_{23} = 0.5$

Neutrino mode

Phase I

Antineutrino mode
DUNE Physics – $\nu_e/\bar{\nu}_e$ Phase-II Statistics

Data points show NO, $\delta_{\text{CP}} = 0$, $\sin^2\theta_{23} = 0.5$

Neutrino mode

Phase II

Antineutrino mode
LBNF Far Site

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