LBNF/DUNE: The Science, The Facility, The Experiment

Sam Zeller
Fermilab Colloquium
February 22, 2023

“one experiment to test the 3-neutrino paradigm”
Outline

• History
• The Science
• The Facility
• The Experiment
Some History

- In 2011, discussion centered around value of the (then unknown) smallest $\nu$ mixing angle ($\theta_{13}$) and its implications
- What are our next steps in $\nu$ oscillation physics?
- What we know now: $\theta_{13}$ is large …

Fermilab W&C June 2011: [https://indico.fnal.gov/event/4546/sessions/9058/#20110617](https://indico.fnal.gov/event/4546/sessions/9058/#20110617)
Big Questions in Neutrino Physics

We are missing some important information about neutrinos:

• What are the masses of the neutrinos?
• What kind of masses do neutrinos have? Are neutrinos their own antiparticles?
• Are there more than 3 kinds of neutrinos?
• How are the neutrino masses ordered? (implications for GUTs, cosmology, $0\nu\beta\beta$)
• Do neutrinos and antineutrinos oscillate differently? Do neutrinos violate CP? (neutrinos could play a role in the generation of the matter/anti-matter asymmetry in the early universe)
• Is our 3-flavor picture of oscillations complete?

possible to answer given that $\theta_{13} \neq 0$

this has been the focus of an intense global effort
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Main Physics Goals of DUNE

- unambiguous, high precision measurements of neutrino mixing in a single experiment
  - *DUNE does not rely on inputs from other experiments*

- determine the neutrino mass ordering, observe and measure CP violation in the (if it is present) in the neutrino sector over the entire possible parameter space

- serve as a large underground neutrino observatory with sensitivity to neutrinos from astrophysical sources (solar, atmospheric, supernova burst) and BSM physics
• **2014 P5 report** prioritized DUNE’s physics program as one of the primary goals for U.S. particle physics. It is the first “*internationally conceived, constructed, and operated mega-science project hosted by the Department of Energy in the United States*” (DOE).

• **DUNE** has the potential for multiple major discoveries and is bringing together the world to do this physics …
DUNE Discovery Potential

Neutrino CP violation
- The origin of matter in the universe

Supernova neutrinos
- Origins of neutron stars and black holes

Neutrino surprises
- New forces, particles, or laws of nature connected to neutrinos

Proton decay
- Unified origins of particles and forces

Lia Merminga, special Director’s Colloquium, June 8, 2022
DUNE Collaboration

- DUNE has attracted the world
- DUNE Science Collaboration is currently 1,402 collaborators from 206 institutions in 37 countries including CERN

DUNE Collaboration meeting at CERN, January 2023
Three Unique Features of DUNE

- 1300 km baseline
  - unambiguously measure mass ordering, CPV
  - do not have to look for inputs from other places
- on-axis, wide band beam
  - very powerful on-axis beam, both $\nu$ and $\bar{\nu}$
  - better oscillation physics, increased BSM sensitivity
- liquid argon detectors
  - near and far LAr TPC detectors
  - higher resolution, higher efficiency $\rightarrow$ less mass needed
  - enables wide band beam physics

There is no other experiment in the world like this.
Why Is This the Best Configuration for the Experiment?

- neutrino baseline is optimized
  - 1000-1500 km is the optimal distance for MO, CP
  - 1300 km is in a “sweet spot” for this physics

- beam spectrum covers the full neutrino oscillation curve
  - this is not a counting experiment
  - enables detailed fitting of the \( \nu \) oscillation parameters

- LAr TPC is a game-changer
  - enables precise reconstruction of the entire neutrino interaction

other \( \nu \) LBL experiments probe shorter baselines, narrow band beam, not LAr TPC
How Does this Work? Neutrino Oscillations in DUNE

Far site → measure ν’s after they’ve oscillated:

ν_e, ν_e
appearance

ν_µ, ν_µ
disappearance

Near site ← measure ν’s before they have had a chance to oscillate

ν_µ, ν_µ
State of the Art: NOvA and T2K

• Current lay of the land:
  • T2K sees an asymmetry in $\nu_e$ versus $\bar{\nu}_e$ data. NOvA does not. The two experiments are not giving a consistent picture. All eyes are on continued analysis of this data!

+ NOvA/T2K combinations in progress
DUNE will be able to resolve this

T2K 75 $\nu_e$ events

NOvA 82 $\nu_e$ events
• DUNE will be able to unambiguously and simultaneously measure MO, CP given the baseline and on-axis beam

• in the 1st year alone, DUNE will collect ~150 oscillated $\nu_e$ events. We immediately hit the ground running.
  - assuming a beam ramp-up to 1.2 MW, 2 FDs, normal ordering, $\delta_{CP}=0$
  - expected range is 70-180 $\nu_e$ events in FHC, depending on true MO, CP
Using this Data …

- DUNE is designed to resolve degeneracies by measuring $\nu$ flavor transitions over more than a full oscillation period.
  - spectrum contains dual information about the MO and CP

- DUNE will be able to determine the MO and $\delta_{CP}$ across the entire range of possible outcomes.
  - DUNE’s capability to quickly and unambiguously determine the MO is unique among existing & planned experiments
  - $\delta_{CP}$ measurement capability is better than any other experiment

- The broad beam is also uniquely sensitive to new physics. We have not had a wide band beam since MINOS.
  - DUNE is able to simultaneously measure all the pars governing $\nu_1$-$\nu_3$ & $\nu_2$-$\nu_3$ mixing in a single exp w/o an external $\theta_{13}$ constraint
  - can discriminate between flavor versus BSM models and test the unitarity of the PMNS matrix
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Underground Facilities in South Dakota

- Ross Shaft: 1.5km to surface
- Expanded Drift
- Maintenance Shop
- 4850 ft level of Sanford Underground Research Facility (SURF)

2 x Detector Caverns:
- 475' L x 65' W x 92' H
- 145m L x 20m x 28m

1 x Central Utility Cavern (CUC):
- 624' L x 64' W x 37' H
- 180m L x 20m W x 11m H

neutrinos from Fermilab

North Detector Cavern
Central Utility Cavern: facility & cryogenic support systems
South Detector Cavern
Spray Chamber
Visit by Dr. Asmeret Berhe, DOE Director of Office of Science

Ross shaft area on 4850L
Chris Mossey (L), Lia Merminga (L), Dr. Berhe (R)

July 2022

North cavern
Lia Merminga (L), Dr. Berhe (M), Chris Mossey (M), Mary Convery (R)
Total Excavation Complete to Date: 54% (February 13)

- Excavation of the DUNE drifts and caverns is more than \( \frac{1}{2} \) way complete
Cavern Excavation

February 13, 2023

North Cavern

South Cavern

we have entered a new phase now
Far Site Excavation: North Cavern

Location of photo in North Cavern

Photo taken about halfway point of the north detector cavern looking east (see blue arrow)
Far Site Excavation: South Cavern
Far Site Excavation: Spray Chamber

Photos taken in Spray Chamber (facility to reject heat from cryogenics systems and transfer up the raise bore)
4850-22N: concrete drains complete, right outside the South Detector Cavern

Starting "Bench D" at the North Detector Cavern. This is #2 of 5 benches to create the full 93’ cavern height.
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DUNE Far Detectors (Phase I)

- LBNF is providing caverns for 4 detector modules at SURF and 2 far detector modules, each 10 kton of liquid argon (fiducial mass), the largest LAr TPCs ever constructed.
  - **FD1**: to be installed in NE cavern, horizontal drift (*like ICARUS, MicroBooNE*)
  - **FD2**: to be installed in SE cavern, vertical drift (*capitalizing on dual phase development*)

- Order of magnitude more mass than has been deployed up to now from all LAr detectors
- DUNE science begins as soon as the far detectors are operational (*more on this later*)
Far Detector Partners

- Multiple international partners have invested significant resources

Our partners are getting ready to send detectors and detector components

Gina Rameika, CD1-RR Review, July 2022
Far Site Logistics Planning

• In November, Anode Plane Assembly (APA) test lift was successfully completed at SURF demonstrating that largest detector components can be successfully moved to 4850L.
  – Test included handling and lowering of the APA shipping container (holding 2 APAs) to the 4850L.
  – “Slung load” traveled at 100 ft/min to the 4850 level, which takes ~45 minutes.
  – The APAs are now at Fermilab for wire fidelity and tension testing – critical validation test.
Cryostats for the Far Detectors

Fabrication of the 1st cryostat is underway at CERN!
Agreement for CERN to Provide 2nd Cryostat

September 2022

ceremony at CERN

agreement signed by Fabiola Gianotti (CERN DG), Dr. Asmeret Berhe (DOE Director of Office of Science)

photo credit: Jacques Fichet, CERN
Prototypes of the Far Detector

- Successful operation of prototypes of the far detector at CERN, Neutrino Platform
  - protoDUNE

- Getting physics out of these prototypes through their exposure to the CERN testbeam

- Not only testing the technology but also providing vital calibration measurements + important e, π, K re-scattering data on argon

JINST, P12004 (2020), 100+ pages
Why Liquid Argon?

• This really sets DUNE apart. Can see the hadronic side the interaction. This means that we can measure both the hadronic and leptonic parts of the $\nu$ event with extremely high precision leading to much better event classification & determination of $E_\nu$.

LAr $\rightarrow$ TPC

Water $\rightarrow$ Cerenkov

DUNE far detector has unmatched capability

LAr also a fertile playground for AI/ML
We Have Come a Long Way with LAr TPCs

- There have been major technological advances in recent years. An explosion of innovation.
  - charge readout (CRPs, pixels)
  - light collection (X-ARAPUCA, power over fiber)
  - Xe doping
  - cryogenic (in-liquid) electronics
  - membrane cryostats
  - argon purification (without evacuation)
  - achievement of long drift distances (meters)
  - sophisticated event reconstruction (AI/ML)
    (to name a few)
- with a fire hose of high-caliber data coming from operating LAr TPC detectors & demonstrators …

these are not your grandmother’s LAr TPCs
Liquid Argon Detectors Work And They Work Extremely Well

- Combination of ProtoDUNE detectors at CERN Neutrino Platform, MicroBooNE, ICARUS, and ArgoNeuT have clearly demonstrated that LAr TPCs have lived up to their promise.

- One of the best examples (so far) is from MicroBooNE ...
  - DUNE-like $\nu_e$ analysis included 3 different event reco, 4 final states
  - these initial results went far beyond what was originally proposed/planned

- MicroBooNE, to date:
  - 52 publications, 82 public notes

- More to come from SBN!
  - SBND, ICARUS

Are these detectors all they are cracked up to be? Yes!
Far Detector (Non-Beam) Physics

- DUNE science begins as soon as the far detectors turn on.
- DUNE will collect large samples of astrophysical neutrinos: earth’s atmosphere, the sun, and from a Galactic core-collapse supernovae. We want to use as many of our neutrino sources to learn as much as we can.
- LAr TPCs have demonstrated the ability to detect such MeV-scale activity:

ArgoNeuT Collaboration, PRD 99, 012002 (2019)

Solar Neutrinos

- The sun produces a large flux of neutrinos that will interact in DUNE.
- The solar $^8\text{B}$ and hep flux is very large in DUNE: several tagged events/day/kton.
  - *need to control and understand backgrounds, of course*
- DUNE will have the potential to measure the yet-unobserved hep solar neutrino flux.
  - *5σ discovery possible in the first 20 kt-yrs of exposure*
- With the ability to measure solar oscillations, DUNE will be able to measure all of the neutrino mixing parameters in a single experiment.
Supernova Burst Neutrinos

• DUNE far detectors will be able to detect a large sample of neutrinos (~1k) from the next Galactic core-collapse supernova.
  - past experiments and Hyper-K, JUNO are sensitive to $\overline{\nu}_e$
  - because of the LAr detector, DUNE provides unique sensitivity to $\nu_e$

• With the advent of gravitational waves and high energy $\nu$ detection in IceCube, the next core-collapse supernova will be an even more spectacular multi-messenger observation.

• DUNE will be a part of SNEWS as soon as the far detectors are live

"gravity-powered neutrino bomb": SN release nearly all (99%) of their energy in the form of $\nu$'s in a short burst

Atmospheric Neutrinos

- DUNE will collect 10’s of thousands of atmospheric neutrino interactions. New types of analyses are possible because of the use of a LAr detector (can reconstruct hadrons).

- Atmospheric neutrinos become a tool for studying neutrino oscillations and can give us another handle on the complicated $\nu$ oscillation landscape. May even be able to measure the matter profile of the earth.

![Graph](image1.png)


![Graph](image2.png)


Neutrino Beam

• Horn-focused wide-band beam, builds on the success of NuMI
  • *broad spectrum of* $\nu$’s (& anti-$\nu$’s) *peaked at* $2.5$ GeV
  • *focusing parameters optimized to maximize sensitivity to CPV*
  • *1.2 MW, upgradeable to 2.4 MW*

• Final designs for the beamline and near detector complexes have been completed. The beamline design is at ~70% final design and on track.
Near Detector Complex

- **Where?** ND hall is located 550m from proton target, 215ft deep, on-site at Fermilab
- **Why?** Purpose of the ND is to measure the rate & spectrum of $\nu$’s before they make their journey west and to the FD. The ND measures the $\nu$’s before oscillations.
DUNE Near Detector

• DUNE ND is optimized with the same technology as FD
• Design follows that of most long-baseline $\nu$ experiments
  - near detector matches the far detector
  - example: MINOS and NOvA employ near detectors that are functionally identical to their far detectors
    • same target material
    • work to cover same phase space of events as FD

• For DUNE, this means having a LAr tracking calorimeter at the near site that is capable of handling the LBNF rate
  - $\geq 50$ neutrino interactions per beam spill
  - unique environment requires innovation
  - DUNE LAr-base ND is designed with pixelated readout and optical segmentation

• near detector measurements both on & off axis
Near Detector (Phase I)

- Two main detector components:
  - ND-LAr + TMS
  - SAND

- ND that is functionally identical to the FD (moveable off-axis)
Near Detector (Phase I)

• Just as with the FD, there are multiple partners contributing to the ND as well

the on-axis neutrino detector (stationary)
DUNE Near Detector

- We are also building prototypes of the near detector
  - 2x2 Demonstrator (NuMI beam at Fermilab)
  - Full Scale Demonstrator (FSD)
- Important to test the pixelated, modular design
- Just like with the protoDUNEes, we will be getting physics out of the ND prototypes through their exposure to cosmic rays (Bern) and the NuMI neutrino beam (Fermilab)
- ND 2x2 demonstrator is being installed in the NuMI beam →
- Also, KLOE magnet is currently being disassembled in Frascati for shipment to Fermilab for SAND!

Dan Dwyer, Brooke Russell, and LBNL colleagues won the 2022 R&D 100 award for the I/O used to readout the network of ASICs used in these prototypes
Building on the Shoulders of Giants

- We’ll have access to information in DUNE that we have never had access to before, so we need to be ready, armed both with a DUNE near detector and a strong foundation.
- There is a very active neutrino interaction program at the lab, both theory and experiment.

- **MINERvA** has $\nu, \bar{\nu}$ data on a large number of nuclear targets (He, C, Fe, Pb, H$_2$O) across a very broad range of energies (NuMI LE, ME)
- **MicroBooNE** has recently measured a large # of $\nu$ cross sections on Ar, many first-of-their kind
- **SBND** is about to turn on and will soon have the largest-ever $\nu$ data set on Ar
- plus, new ideas for light target bubble chambers
  Bryan Ramson (LDRD), Snowmass whitepaper, arXiv:2203.11319
- continued advancement of neutrino-nucleus theory and event generator work is critical

All is deeply connected to DUNE.
BSM Physics

- DUNE is a machine for discovery. Using both near and far detectors, DUNE can probe a diverse range of phenomenology beyond the Standard Model.
- LAr TPC detectors open up new windows for discovery → exquisite imaging, low particle detection thresholds, sensitivity to hadronic side.

![Diagram showing light dark matter and extra Z' bosons]

V. Romeri, K. Kelly, P. Machado, PRD 100, 095010 (2019)


+ EW physics
What’s Next?

• The 2014 P5 report strongly endorsed the DUNE physics program and laid out a phased approach to realizing the experiment. We are already thinking ahead to Phase II.
  
  • *doubling the mass at the far site: FD3, FD4*
  • *doubling the beam power (> 2MW)*
  • *upgrade to the ND to further constrain systematics*

  ➔ DUNE *Module of Opportunity Workshop* held in Valencia, Spain, November 2022

• Phase II is important for realizing the full P5 vision of DUNE and is being actively discussed as part of the current Snowmass process.

• Encourage you to attend the *Looking Ahead of Snowmass* seminar series
  
  • *Thursdays 4pm, coffee starting at 3:30pm*
  • *presentations by Steve Brice and Louise Suter in March*
Things Did Not Have to Work Out As Well As They Did

• Why is there so much excitement and anticipation for DUNE? If anything, the science case is even more compelling now. And well, the world could have worked out much differently, but it didn’t.

✓ $\theta_{13}$ is large

✓ LAr TPCs work
  - we made the right choice in choosing the LAr TPC technology
  - series of successful prototypes, recent success from MicroBooNE
  - membrane cryostats have made large LAr TPCs & hence DUNE possible
  - argon purity is not an issue (LAPD, MicroBooNE, protoDUNE, ICARUS)

✓ Fermilab is the best place to do this physics
  - we made the right choice being on-axis and sending a beam to SD
  - $1300 \text{ km baseline is optimal}$ (better MO, CP + underground detectors $\rightarrow$ much more physics possible)
  - wide band beam is unmatched (choice of LAr makes this possible $\rightarrow$ better oscillation physics, increased BSM sensitivity)

• Major breakthrus, a lot of hard work from a lot of people (+ a bit of luck) made this possible!
Some More Good News

last Thursday, DOE Under Secretary of Science, Dr. Geri Richmond, approved the LBNF/DUNE US Project CD1-RR critical decision milestone

Chris Mossey (LBNF/DUNE-US Project Director):

"thanks to everyone’s extraordinary efforts, Fermilab is on track to deliver world-class facilities supporting the best-in-class neutrino experiment in the world"

Onwards! - B. Hewes

Message from the LBNF/DUNE-US Project Director

CD-1RR critical decision milestone approved

Dear colleagues,

DOE Under Secretary of Science and Innovation Dr. Geri Richmond officially approved the LBNF/DUNE-US CD-1RR critical decision milestone on Feb. 16. This fantastic outcome is the direct result of the hard work and dedicated efforts over the past several years by the LBNF/DUNE team with critical support from across the lab, as well as from the Fermilab Site Office, the DOE Office of Science and High Energy Physics program, our international partners, the DUNE collaboration, and our partner national laboratories.

The CD-1RR approval reaffirms the Department of Energy’s commitment to LBNF/DUNE. It implements a subproject structure, establishes a strong funding profile, and sets a new point estimate and cost range.

This good news caps significant recent progress across our flagship international neutrino project. Working closely with our partners over the past several months, we have:

- Safely advanced excavation of the caverns at Sanford Underground Research Facility to 54% complete.
- Finalized plans to baseline the Far Site Building and Site Infrastructure subproject next month.
- Finalized plans for the CD-2/3 review for the Far Detectors and Cryogenic Infrastructure subproject later this year.
- Progressed the beamline design to >70% and successfully completed a CD-3a review for long-lead procurements and site preparation work in wetland-impacted areas at the near site.
- Advanced plans to test the 2x2 prototype of the ND-LAr Near Detector in the NuMI beam later this year.

Thanks to everyone’s extraordinary efforts, Fermilab is on track to deliver world-class facilities supporting the best-in-class neutrino experiment in the world!

All the best,

Chris
Summary

• There is no other experiment in the world like LBNF/DUNE.

• DUNE is a best-in-class $\nu$ experiment that is unparalleled in its ability to measure oscillations (MO, CP) using intense beams of neutrinos and antineutrinos. Plus, DUNE will capture astrophysical $\nu$’s and be sensitive to physics beyond the standard model in new ways.

• DUNE is truly unique in its approach to making these science measurements, with its key features being the long-baseline, wide-band beam, and liquid argon detector technology.
  • this “triple threat” is leading to our ability to do the best neutrino physics in the world

• The facilities provided by LBNF are world class and provide opportunities for decades of discovery beyond what we even contemplate today.

• And as we know, no one does accelerator-based neutrino physics better than this laboratory.

• So get ready. There is a lot of science coming!

  S. Parke: “DUNE may very well be the next revolution”