Next-Generation Neutrino Physics with **DUNE**

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DEEP UNDERGROUND NEUTRINO EXPER





Deep Underground Neutrino Experiment



MeV-scale neutrino physics, BSM searches,



DUNE Collaboration

- DUNE has attracted the world
- DUNE has currently >1400 collaborators from 206 institutions in 37 countries including CERN



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DUNE Collaboration meeting at CERN, January 2023



Neutrino Oscillations: Motivation

Standard model has been highly successful, but we know it's not complete



The basic building blocks are the six leptons, six quarks, four force carriers, and the Higgs boson. Credit: Fermilab

The allowed ranges of neutrino oscillation parameters have been narrowed through tremendous effort





Neutrino Oscillations: Motivation

- Many questions remain unanswered
 - 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?
 - Do neutrinos follow a "normal ordering" or an "inverted ordering"?
 - Do neutrino oscillations violate chargeparity?

.



Credit: JUNO Collaboration / JGU-Mainz





Credit: Sheldon Stone



1300 km baseline, unambiguously measure mass ordering and CPV



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1.2 MW proton beam, upgradeable to 2.4 MW

* On axis, wide band beam



- * Dedicated near detector complex



40 ktons (fiducial mass) of LAr far detectors, 1490 m underground



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- - Four detectors
 - Each of them have a different design
 - Phase I
 - First two detectors will start operation around 2027
 - Both of them are liquid argon TPCs
 - FD1 Horizontal Drift LArTPC
 - FD2 Vertical Drift LArTPC
 - Other two detectors are to be determined for Phase II





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- Effects of mass ordering, CP violation have different shape as a function of L/E
- DUNE measures oscillations over more than a full period, which helps resolve degeneracies
- This is unique to DUNE, and complementary to other experiments with narrow flux spectra



Liquid Argon TPC



- LArTPC provides precise 3D spatial location of energy deposition for particle ID
 - Clean separation of ν_{μ} and ν_{e} CC events
- range, benefits from its low thresholds for charged particles

LArTPC also provides good neutrino energy reconstruction over a broad energy



What DUNE actually measures



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 Oscillation sensitivities are obtained by simultaneously fitting the disappearance and appearance spectra

$$\begin{array}{ccc} \nu_{\mu} \rightarrow \nu_{\mu}, \nu_{\mu} \rightarrow \nu_{e}, \\ \bar{\nu}_{\mu} \rightarrow \bar{\nu}_{\mu}, \bar{\nu}_{\mu} \rightarrow \bar{\nu}_{e} \end{array}$$

- ND sample is incorporated in order to constrain flux/ xsec uncertainties

Eur. Phys. J. C 80, 978 (2020)





DUNE Near Detector Complex

- Large uncertainties on flux, cross sections, and detector response are constrained to the few percent level by the suite of detectors in ND
- ND-LAr+TMS: measure neutrino interactions on the same Ar target, with same detector technology as FD
 - System moves up to 30 m off axis
- SAND: on-axis detector measures neutrino interactions on various targets and monitors beam stability







DUNE-PRISM



- PRISM: Precision Reaction-Independent Spectrum Measurement
- Use off-axis data to uncover interaction modeling problems that might induce an unexpected bias in the extracted oscillation parameters
- GENIE-based FD prediction is a poor predictor for the FD data, where as the linear combination of ND data correctly predicts the FD spectrum



UCIRVINE DUA



Mass Ordering: Definitive Resolution



- Long term $\rightarrow >10\sigma$ for any parameter combination

DUNE is sensitive to the mass ordering from very low exposures: ~97% correct after ~1-2 years



CP Violation: δ resolution 6-16°



sensitivity to CP violation over a broad range of possible values



PhysRevD.105.072006 Snowmass: "DUNE Physics Summary", arXiv:2203.06100

• 6-16° resolution to δ_{CP} without dependence on other experiments, discovery



Precision Measurements



- Excellent on Δm_{32}^3 and θ_{23} , including octant, and unique PRISM measurement technique that is less sensitive to systematic effects
- reactor directly tests PMNS unitarity



Eur. Phys. J. C 80, 978 (2020)

Ultimate reach does not depend on external θ_{13} measurements, and comparison with





Low Energy Events in DUNE

$\nu - e$ Elastic Scattering (10.25 MeV electron)



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 ν_{ρ} CC event (20.25 MeV neutrino)





Supernova Burst Neutrinos



- Core-collapse supernovae within our Galaxy are expected to occur once every few decades
- The flavor content and spectra of neutrinos change throughout different phases
 - Neutronization burst is primarily ν_{ρ}
- SNB is driving the design of the DAQ and trigger system
- 100s to 1000s from galactic SNB

Large uncertainty due to SN model



Supernova Burst Neutrinos



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- Liquid argon has a particular sensitivity to the ν_e component via the CC interaction on nuclei
 - Observable: electron and de-excitation photons
 - Offers a new opportunity to measure the ν_{ρ} content of the burst with high statistics and good event reconstruction

• Very forward scattering $\rightarrow 5^{\circ}$ resolution on the SN direction



Solar Neutrinos



- DUNE sees a huge number of solar neutrinos
- Ability to measure hep flux



inspired by the work in PhysRevLett.123.131803

Swamped by neutron capture backgrounds below about 9 MeV, but high rate of ⁸B neutrinos





DUNE Plans and Installation

this decade

Parameter	Phase I		Phase II			Impact	
FD mass	20 kt fiducial		40 kt fiducial			FD	statistics
Beam power	up to 1.2 I	ММ		2.4 MW		FD	statistics
ND config	ND-LAr TMS,	SAND	ND-LAr,	ND-GAr,	SAND	Syst.	constraints

- Far and near detector prototyping and validation underway
 - ProtoDUNEs successfully operated at CERN, and are preparing for the phase 2 running
 - ND prototype tested at BERN with cosmic rays and being tested at Fermilab with neutrino beam
- Far site civil construction to be complete in 2024 with far detector installation starting right after
- Near site and beamline are fully designed, and in construction in parallel with far site activities



• DUNE construction is phased to provide continuous progress towards physics goals beginning

Snowmass: "DUNE Physics Summary", arXiv:2203.06100





ProtoDUNEs at CERN

- ProtoDUNE-HD and VD are DUNE's large scale prototypes (~1 kton-scale) of its far detector modules at CERN Neutrino Platform
 - HD is the single phase detector
 - VD is the successor to the dual phase detector

Dual Phase (DP) \rightarrow Vertical Drift (VD)

- LArTPC 6 m vertical drift + charge amplification in gas Ar + photon detection
- Cosmic-muon data in 2019 2020
- VD is now under installation for this year's running





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ProtoDUNE Tour Mar. 15 (Wed.)

ProtoDUNE Single Phase (SP) → Horizontal Drift (HD)

- LArTPC 3.6 m horizontal drift + photon detection
- Beam data taken in 2018 & cosmic data in 2018 2020
- HD is now under installation for this year's running



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Excavation at far detector site SURF SD January 2023 C.: M. Kapust

Excavation now more than 50% complete



Summary

- a broad range of parameter space
- paradigm
- DUNE also has potential to probe (not covered in this talk)
 - atmospheric neutrinos

 - for new particles, including dark matter
 - More

• DUNE will resolve the neutrino mass ordering, and measure δ_{CP} with CP violation sensitivity over

• DUNE will precisely measure θ_{13} , θ_{23} , and Δm_{32}^2 , and 3-flavor oscillations to test the 3-flavor

• The far detector technology and location deep underground will facilitate study of low-energy neutrinos, including sensitivity to neutrinos from a core-collapse supernova and solar neutrinos

baryon number violating processes, such as proton decay and neutron-antineutron annihilation

physics beyond the Standard Model, including both searches for BSM processes and direct searches

Stay tuned !





Backup Materials

Event CVN







Event Selection Efficiency







Energy resolution



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ν_{μ} CC with exiting tracks





Atmospheric Neutrinos

Atmoshperic Neutrinos



- can give us another point of view on the neutrino oscillation landscape



DUNE will collect 10's of thousands of atmospheric neutrino interactions

Atmospheric neutrinos become a tool for studying neutrino oscillations and

Non-standard Oscillation Effects

- searches
- experiments with shorter baselines

• Combination of ND+FD, and broad energy spectrum \rightarrow broad Δm^2 coverage for sterile

DUNE baseline provides an advantage in the detection of NSI relative to existing beam-based

