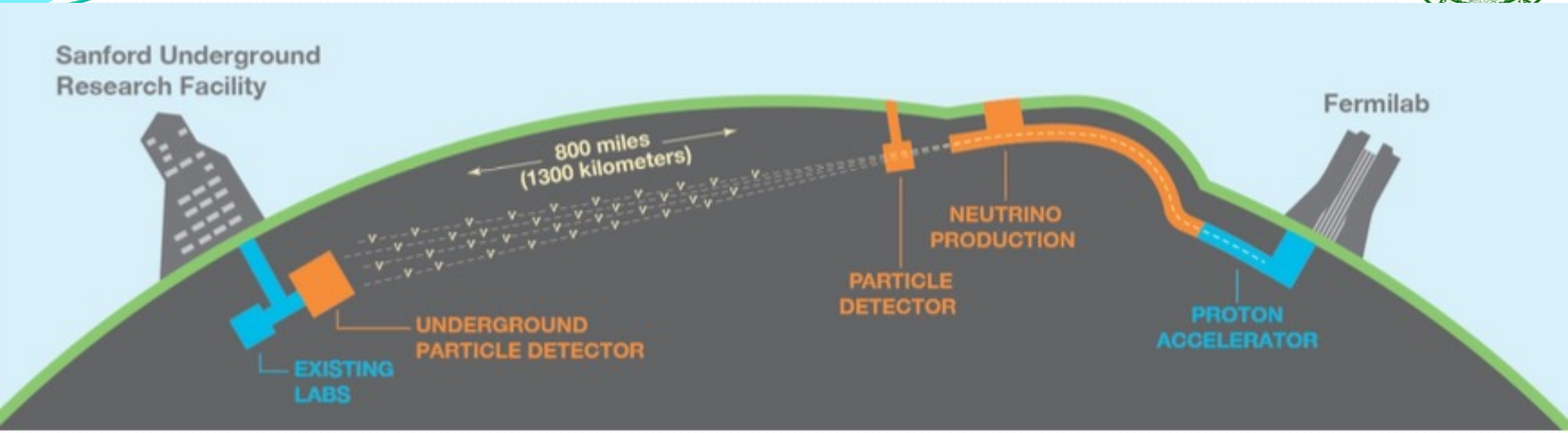
Jelena Maricic, University of Hawaii
for the DUNE Collaboration
Lake Louis Winter Institute
February 22, 2024

DUNE - Status

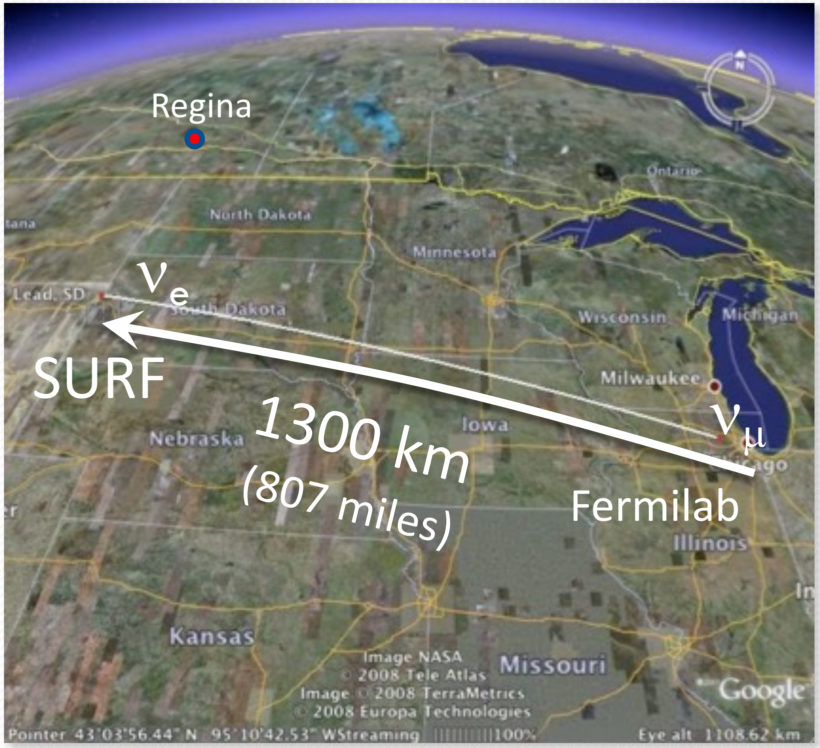
Strong, international collaboration since 2014
1400+ collaborators!
36 countries and CERN!

DUNE Science Program



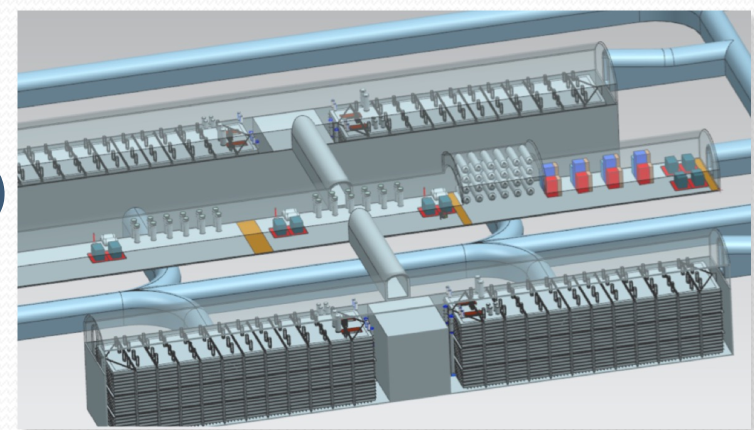
- Several opportunities for major scientific discoveries:
  - High precision measurement of neutrino oscillation parameters in a **single experiment**
  - Determination of the ***neutrino mass ordering (MO)***, observation and ***measurement of CP violation (CPV)*** in the neutrino sector over the ***entire possible parameter space***
  - Large, underground neutrino observatory for neutrinos of astrophysical origin (***supernovae neutrino burst, solar, atmospheric***) and plethora of ***BSM physics with near and far detectors.***

Extraordinary Experimental Setup



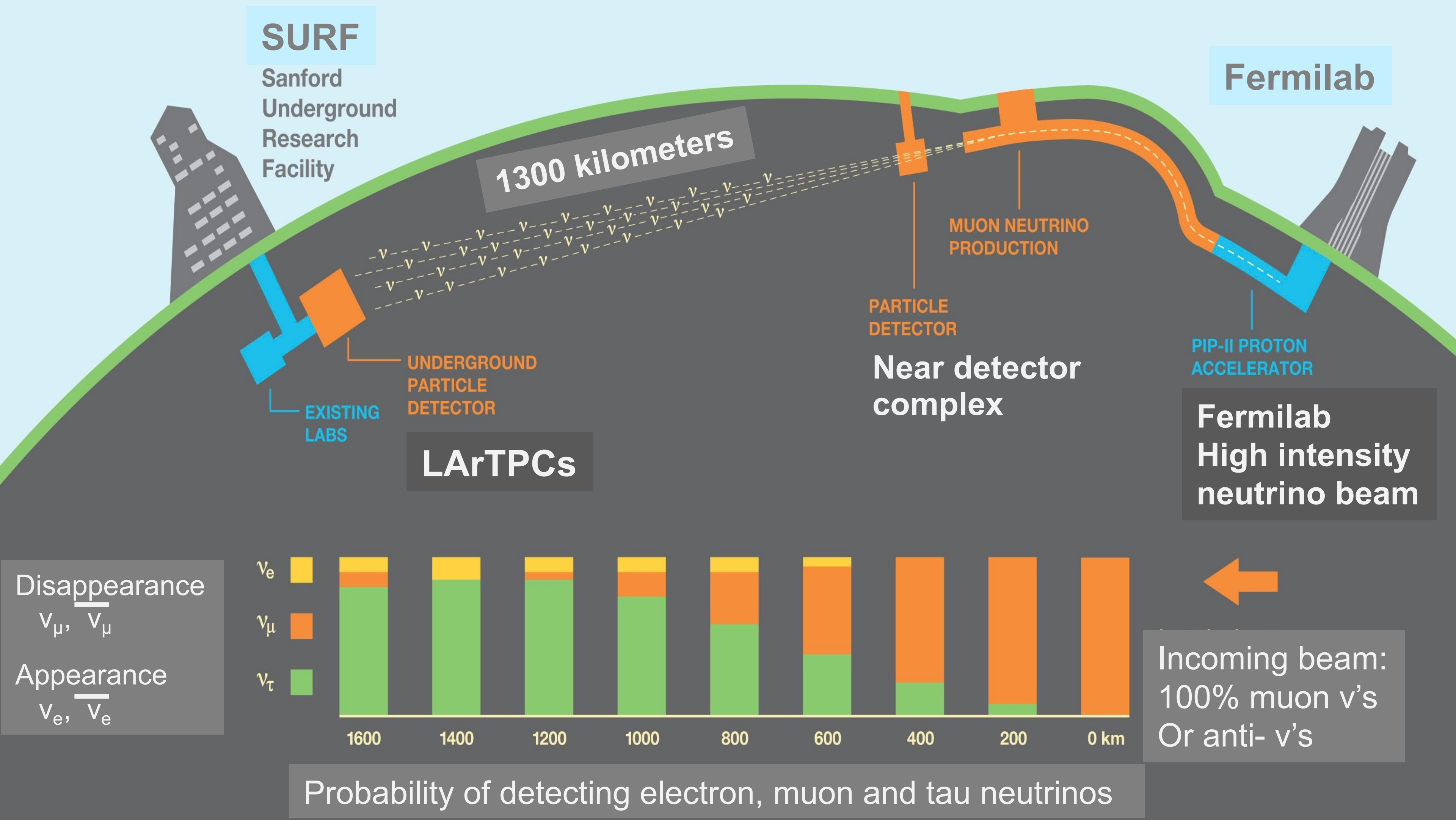
- 1300 km baseline → long baseline → large matter effects
  - *unambiguously measure MO and CPV phase*
- On-axis, wide band beam (ν, $\bar{\nu}$)
  - *High statistics over full osc. period*
  - *Increased BSM sensitivity*

17 kton LAr far detector modules a mile underground:



- Liquid argon (LAr) detectors
  - *near ND and far (FD) LAr Time Projection Chambers (LAr TPC detectors)*
  - *Reconstruct E_ν over broad range: imaging + calorimetry*
  - *Higher resolution, higher efficiency*
  - *Systematic errors constraints with ND*

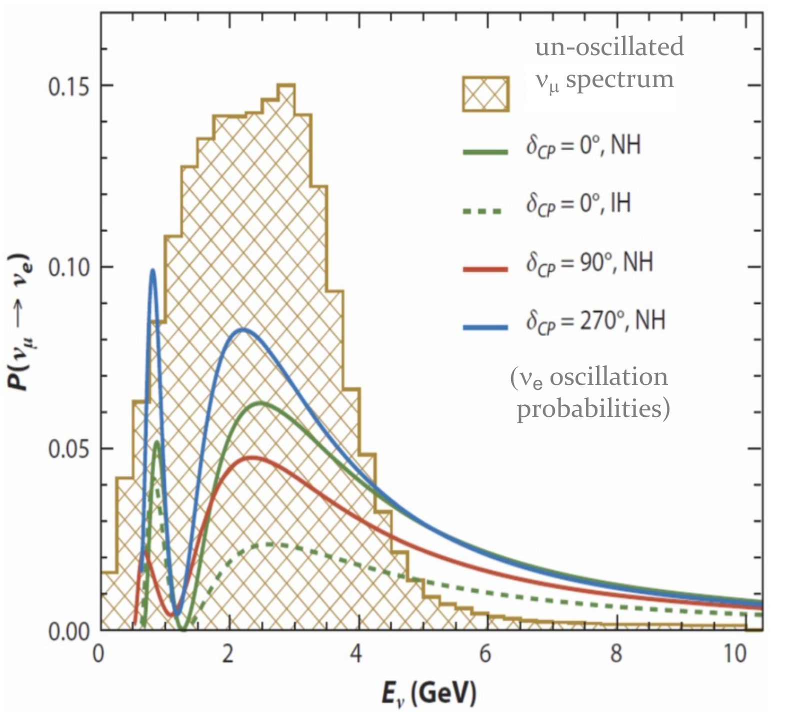
Deep Underground Neutrino Experiment



Broad spectrum of muon n's (& anti-n's) peaked at 2.5 GeV

1.2 MW, up to 2.1 MW with early implementation

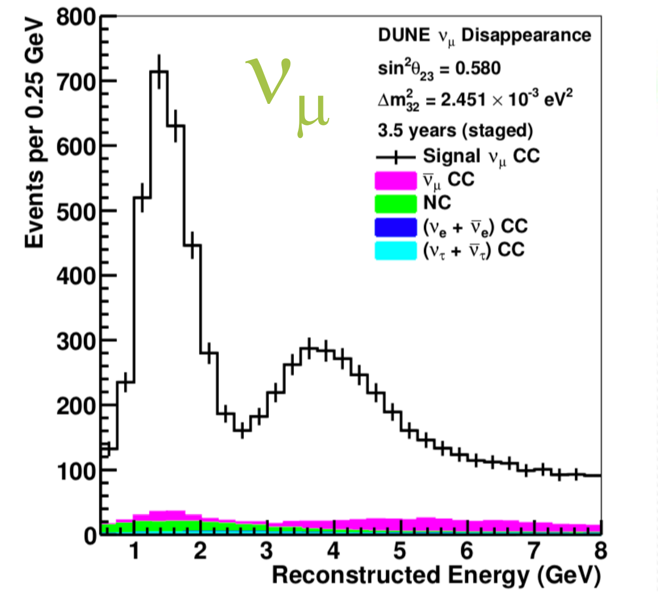
DUNE Physics

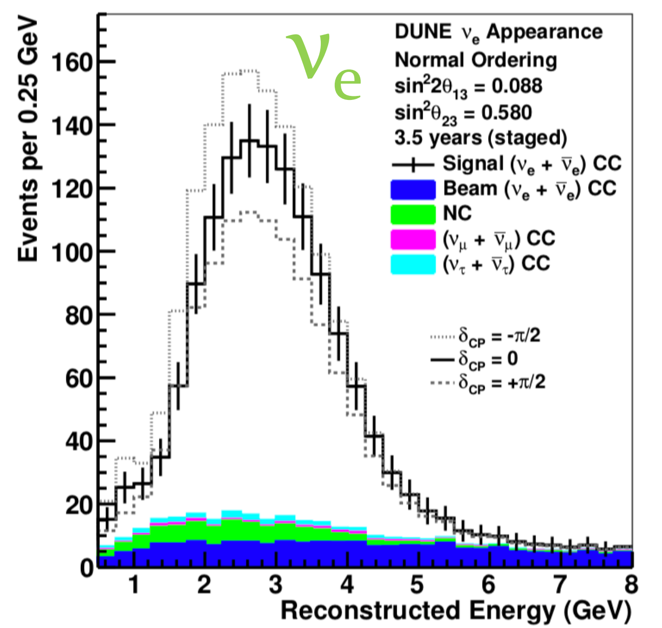


disappearance

$\nu_\mu \rightarrow \nu_e$

appearance



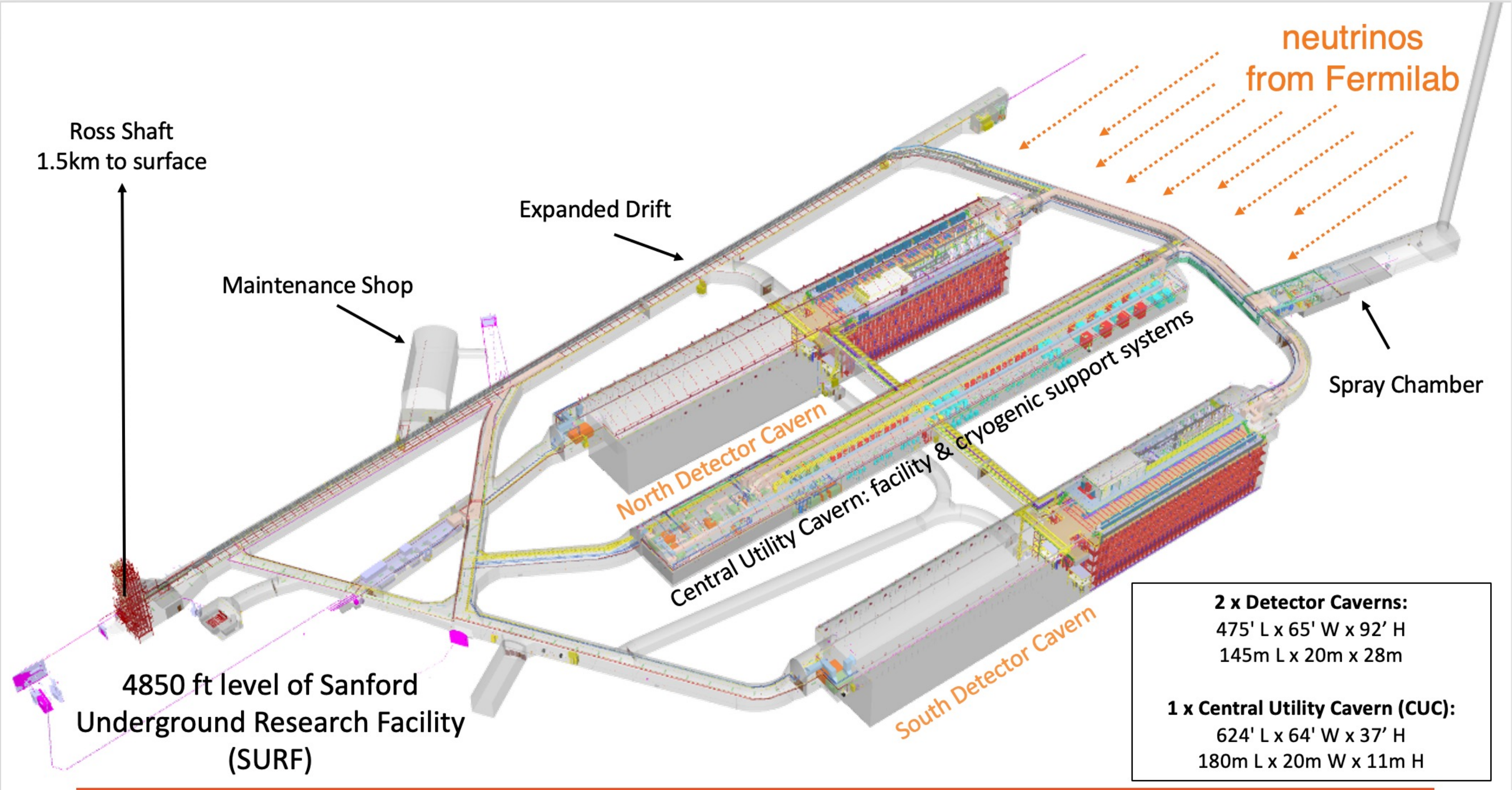


- DUNE will be able to unambiguously and simultaneously measure MO, CP given the long baseline and on-axis wide-band beam to measure oscillations over > a full period: **unique to DUNE and complimentary to experiments with narrow beam spectra.**
- in the 1st year alone, DUNE will collect ~150 oscillated ν_e events (*assuming a beam ramp-up to 1.2 MW, 2 FDs, NO, δ_{CP}=0; expected range is 70-180 ν_e events, depending on true MO, CP phase)*

DUNE Collaboration, Eur. J. Phys. C80, 978 (2020)

Sanford Underground Research Facility (SURF) South Dakota: Facilities Underground

- Attractive deep site: 4300 mwe
- Hosted Homestake neutrino experiment
- Accommodates 4 detector chambers and accompanying utilities
- Built-in flexibility to accommodate all detector needs

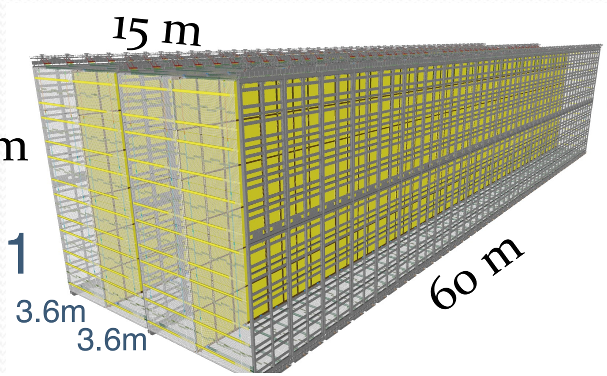


Excavation Completed - February 1st, 2024

- Total size: eight soccer fields
- Almost 800,000 tons of rock excavated
- Next step: outfitting the caverns to receive the detectors

DUNE Far Detectors (Phase I & II)

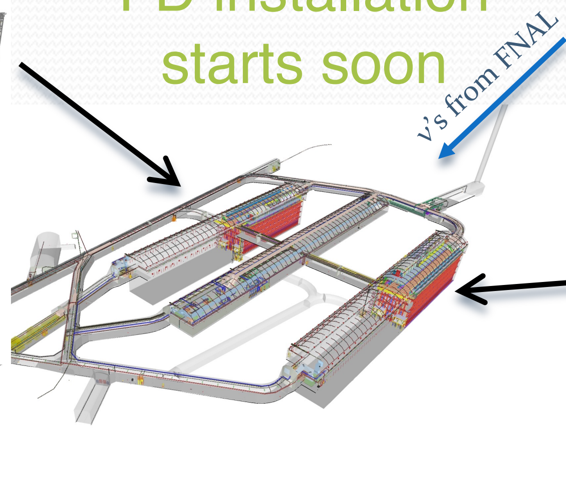
- Phase I: 2 far detector modules, each 10 kton of liquid argon (fiducial mass), the largest LAr TPCs ever constructed (to be followed by FD3 in phase II + Module of Opportunity with wider physics program).
  - *FD1: horizontal drift (like ICARUS, MicroBooNE)*
  - *FD2: vertical drift (capitalizing on dual phase development)*

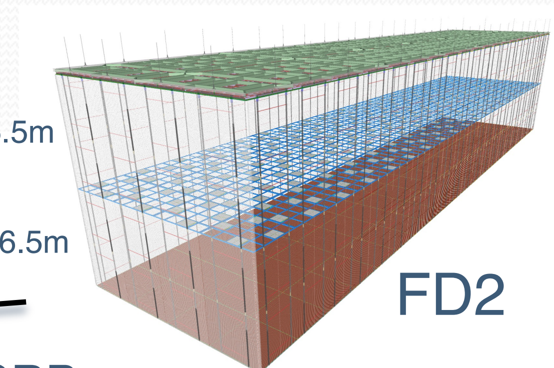


APA, Horizontal Drift

APA = Anode Plane Assemblies

FD installation starts soon



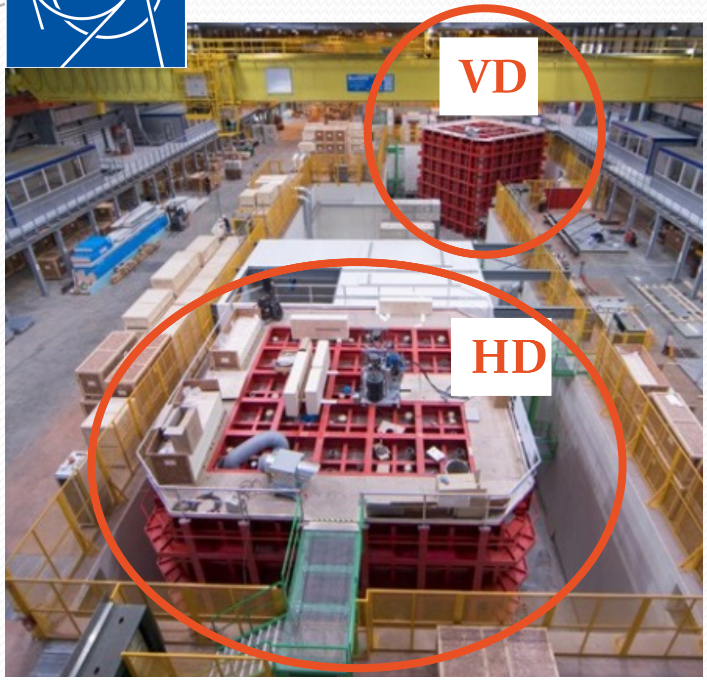


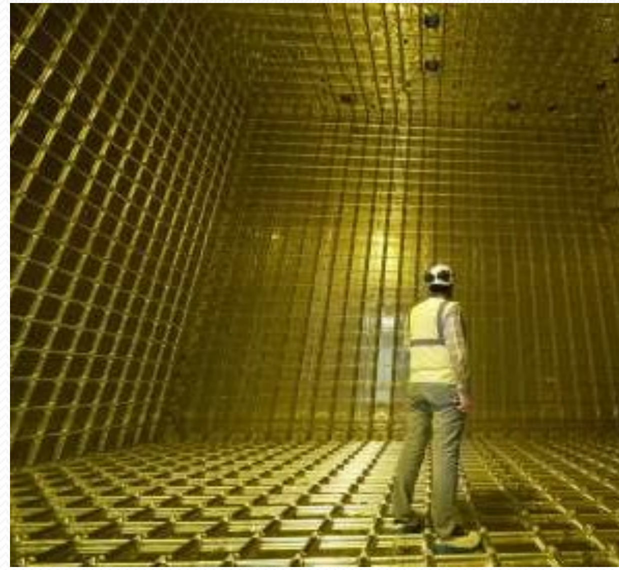
CRP, Vertical Drift

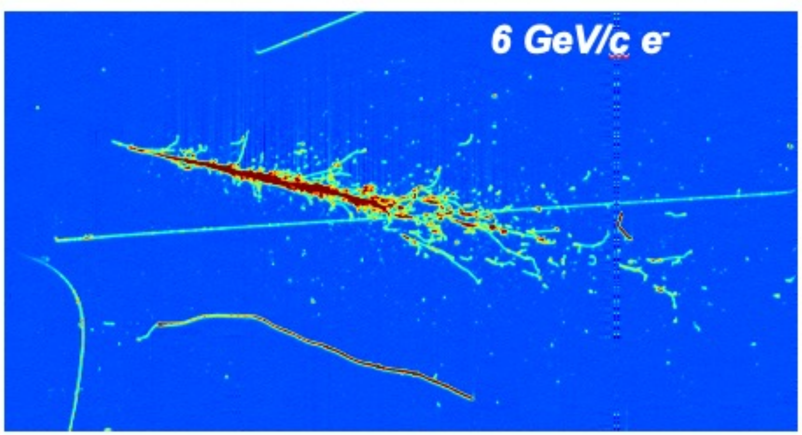
CRP = Charge Readout Planes

- 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
-  involvement extending DAQ capabilities for low energy events
- Many more opportunities for involvement: calibration, low energy upgrades, new technologies...

Far Detector Prototypes





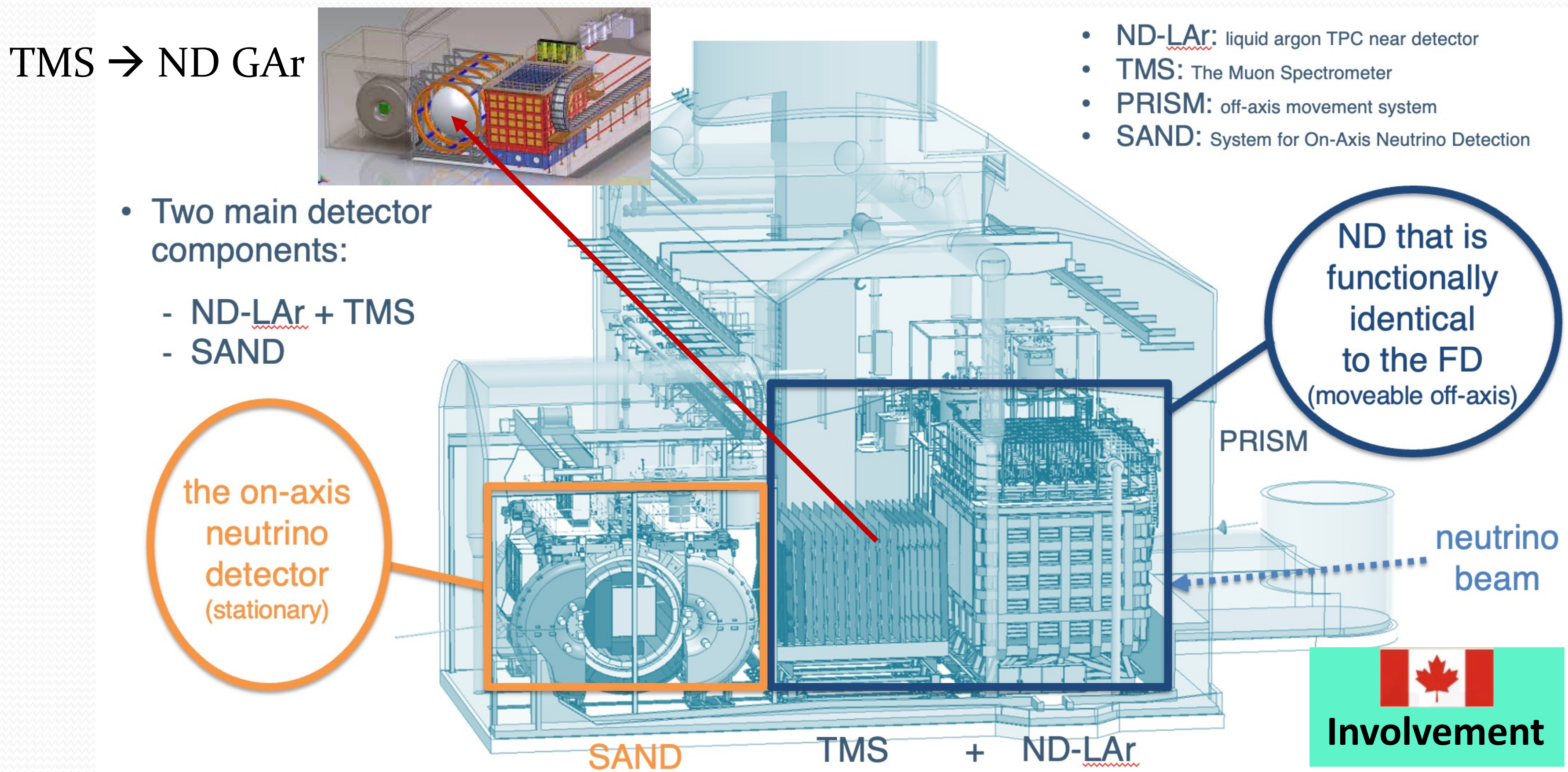


Eur. Phys. J. C82, 903 (2022)

- Successful operation of prototypes of FD at CERN, Neutrino Platform protoDUNEs
- Physics from prototypes from exposure to CERN test beam
- Technology test + calibration measurements + e,p,K re-scattering data on Ar
- Second physics run with HD and VD in April 2024 and 2025

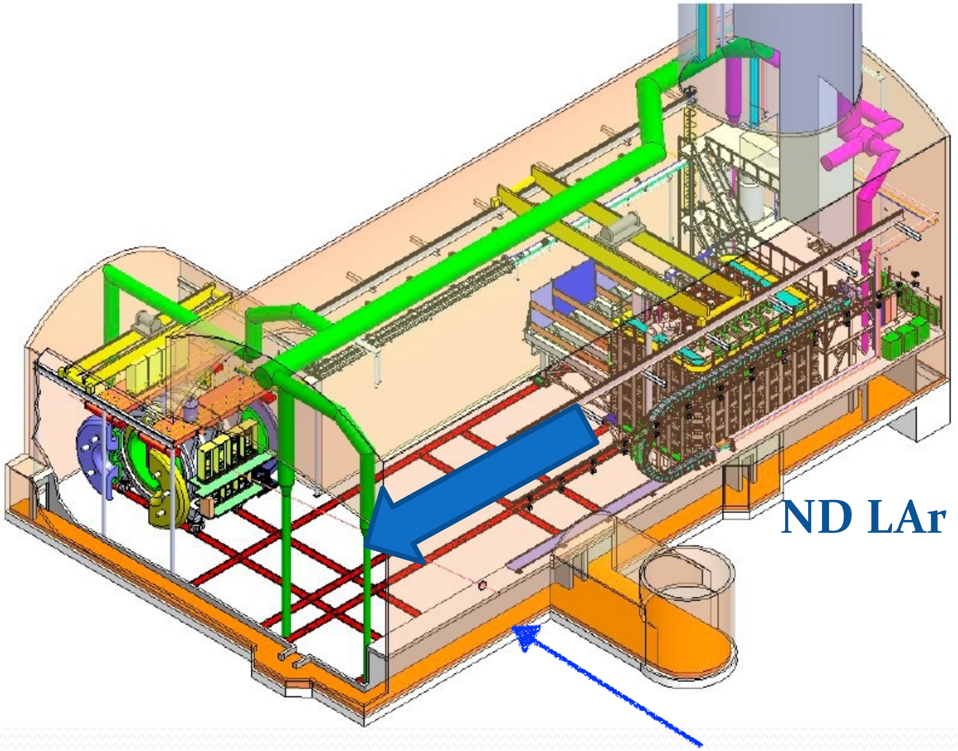
DUNE Near Detector (ND)

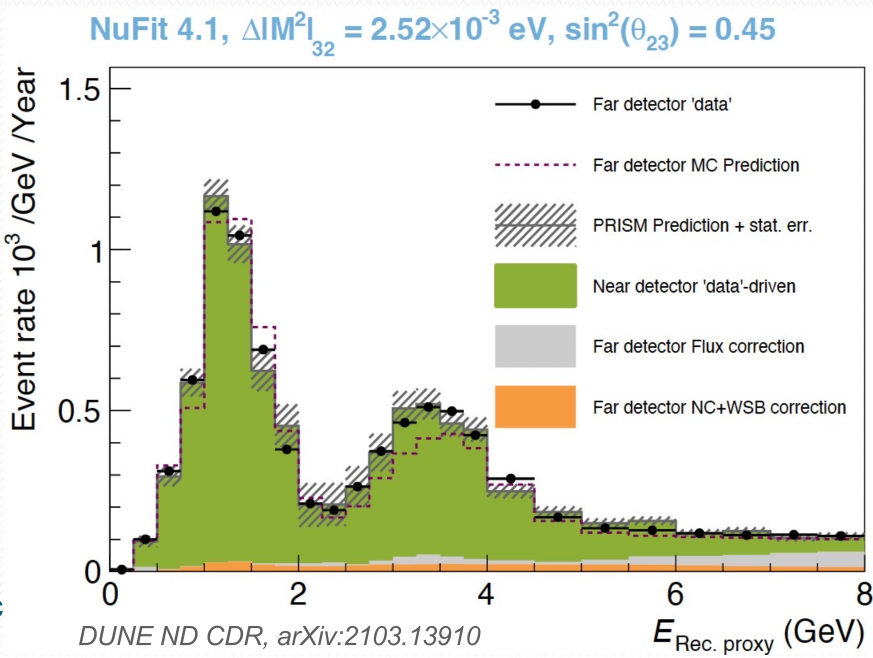
- ND hall is located 550m from proton target, 215ft deep, on-site at Fermilab
- ND LAr is tracking calorimeter, capable of handling beam rate
  - > 50 neutrino interactions per beam spill (pixelated readout and optical segmentation); (upgrade to MCND (More Capable ND) for higher beam power)
- **Near detector measurements both on & off axis**



DUNE PRISM

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

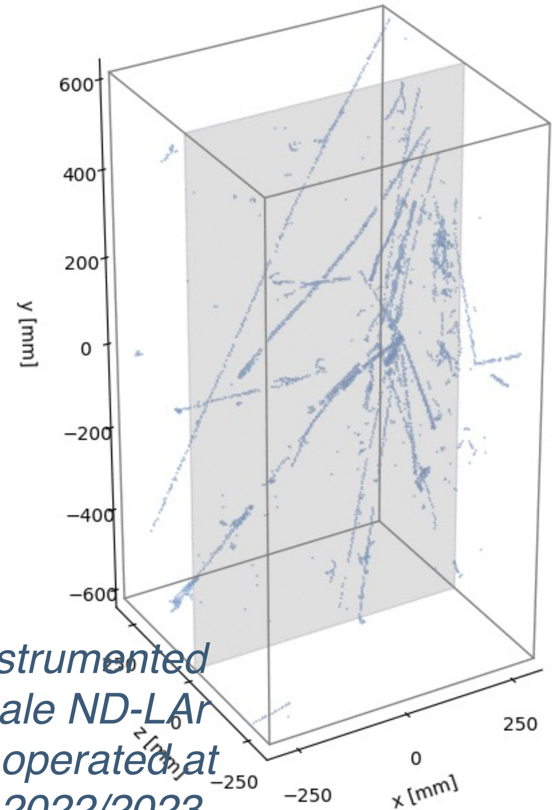




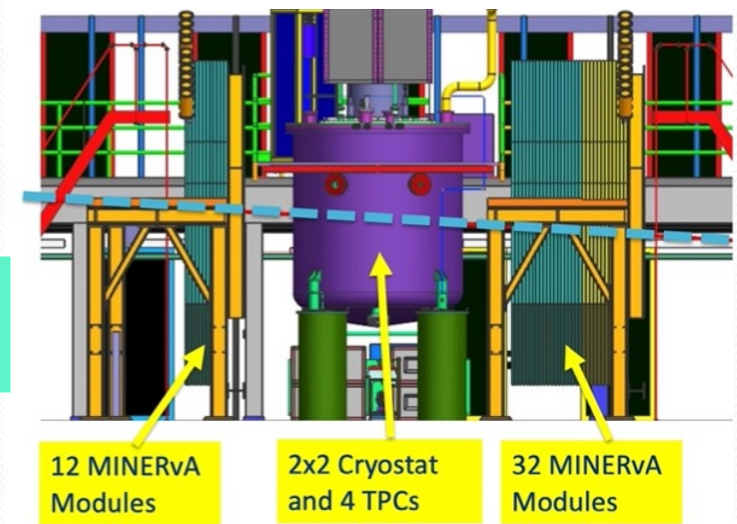
Near Detector Prototypes

- 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
- Physics results from prototypes at Bern, and in NuMI beam at FNAL
- ND 2x2 demonstrator being installed in NuMI beam at Fermi lab – neutrino run in Spring 2024 and 2025.
- <u>Opportunities for neutrino c-s measurements.</u>
- FSD to run in August 2024 at U of Bern.

Involvement



Fully instrumented 20% scale ND-LAr module operated at Bern in 2022/2023.



Source: Jen Raaf

DUNE ν_e and $\overline{\nu}_e$ spectra can Distinguish MO in Phase I

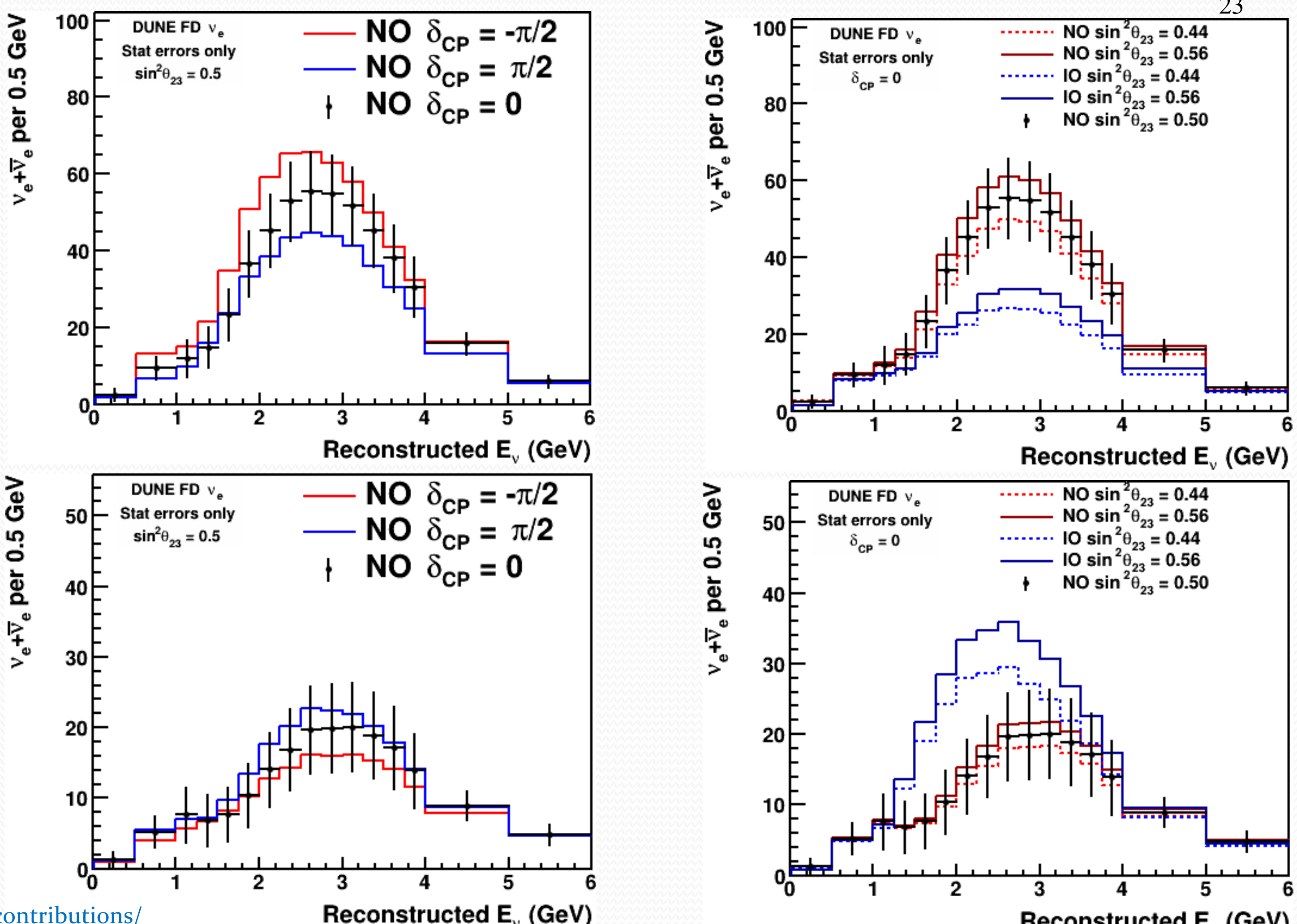
Data points show NO, $\delta_{CP} = 0$, $\sin^2\theta_{23} = 0.5$

Varying δ_{CP} | Varying MO and $\sin^2\theta_{23}$

Neutrino mode

Phase I

Antineutrino mode



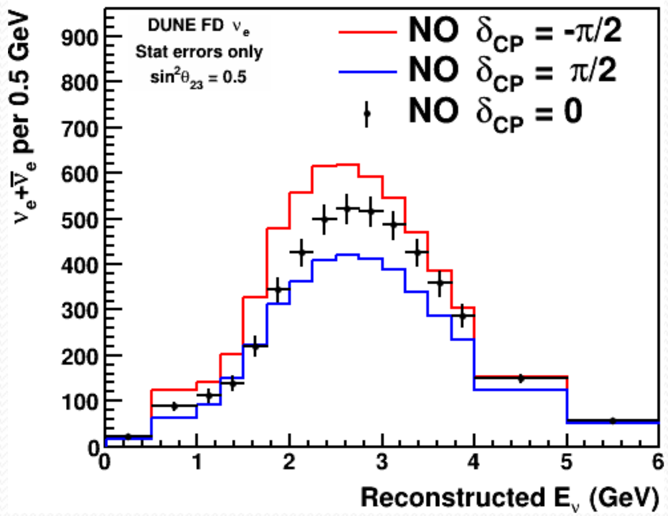
DUNE ν_e and $\bar{\nu}_e$ spectra can measure δ_{CP} and θ_{23} Octant in Phase II

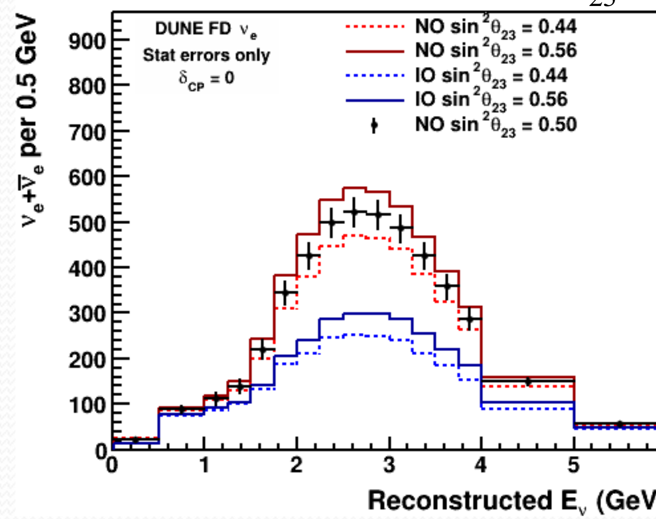
Data points show NO, $\delta_{CP} = 0$, $\sin^2\theta_{23} = 0.5$

Varying δ_{CP}

Varying MO and $\sin^2\theta_{23}$

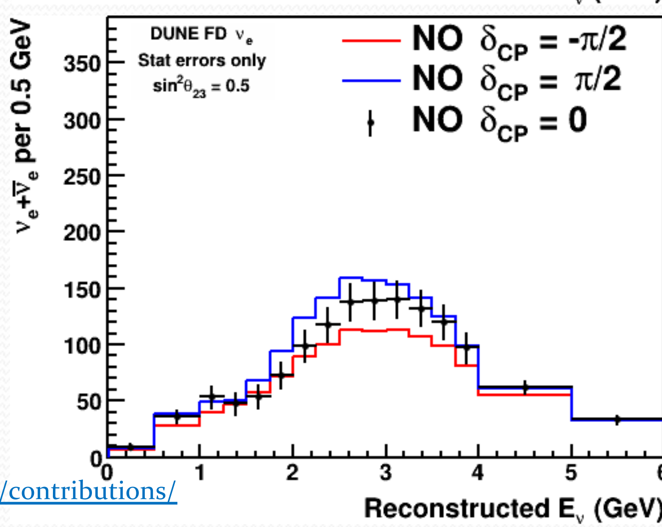
Neutrino mode

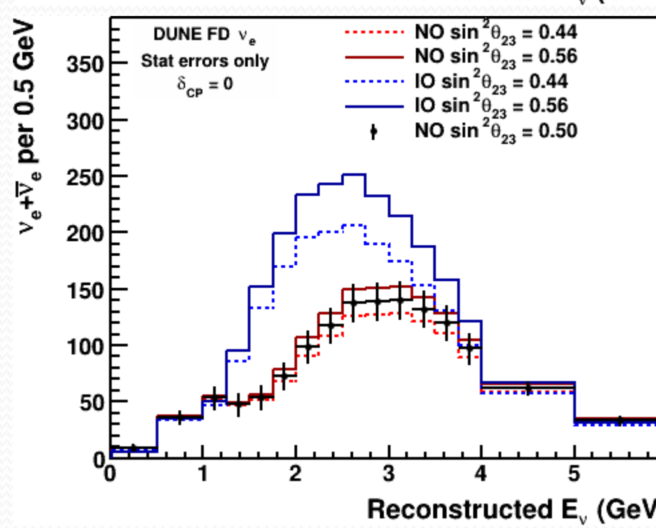




Phase II

Antineutrino mode

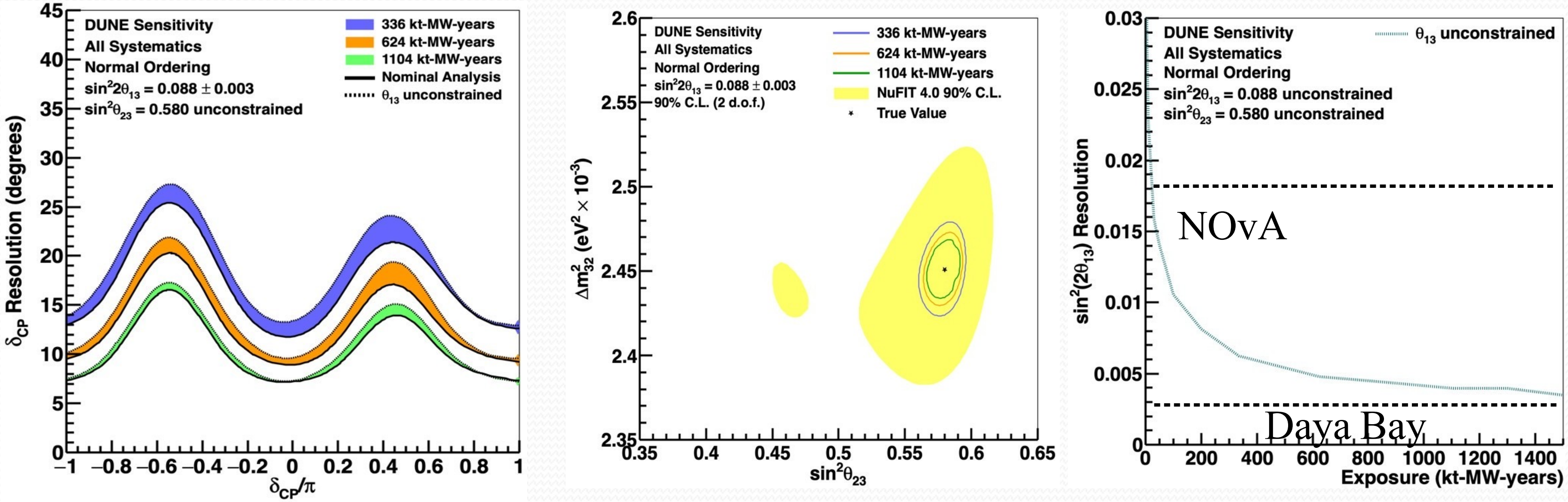




https://indico.fnal.gov/event/58272/contributions/262187/attachments/165088/219229

DUNE Phase II (3rd FD + 4th Module of Opportunity): Precision Long Baseline Physics

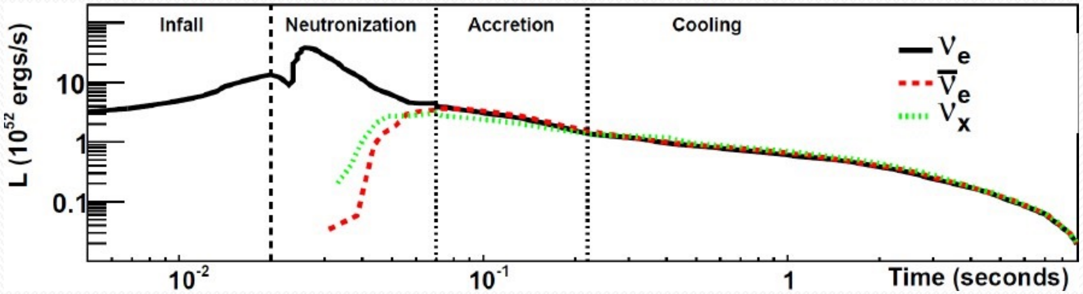
DUNE Collaboration,
Eur. J. Phys. C80, 978 (2020)

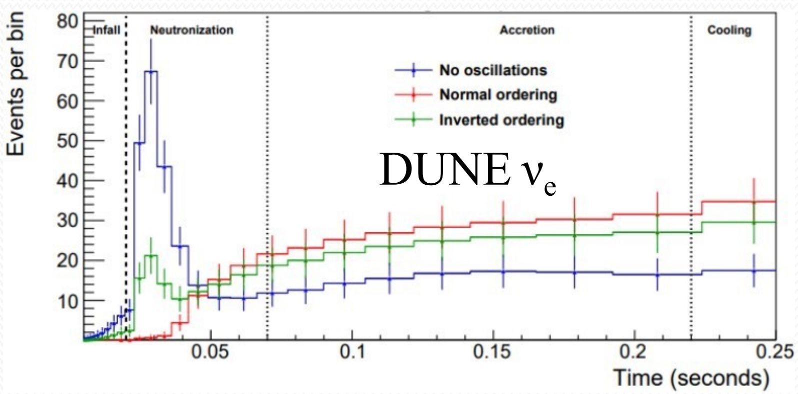


- Resolution to δ_{CP} is ~6-16° depending on true value, and sensitivity to CPV even if Nature is relatively unkind
- Excellent resolution to θ_{23}, including octant discovery potential
- Resolution to θ_{13} approaches Daya Bay, DUNE-reactor comparison is sensitive to new physics

Supernova Physics: Unique Sensitivity to Electron Neutrinos

arXiv:2002.03005 [hep-ex]





	ν_e	$\bar{\nu}_e$	ν_x
DUNE	89%	4%	7%
SK[1]	10%	87%	3%
JUNO[2]	1%	72%	27%

[1]Super-Kamiokande, *Astropart. Phys.* **81** 39-48 (2016)
[2]Lu, Li, and Zhou, *Phys Rev. D* **94** 023006 (2016)

- Time (and energy) profile of the flux is rich in supernova astrophysics

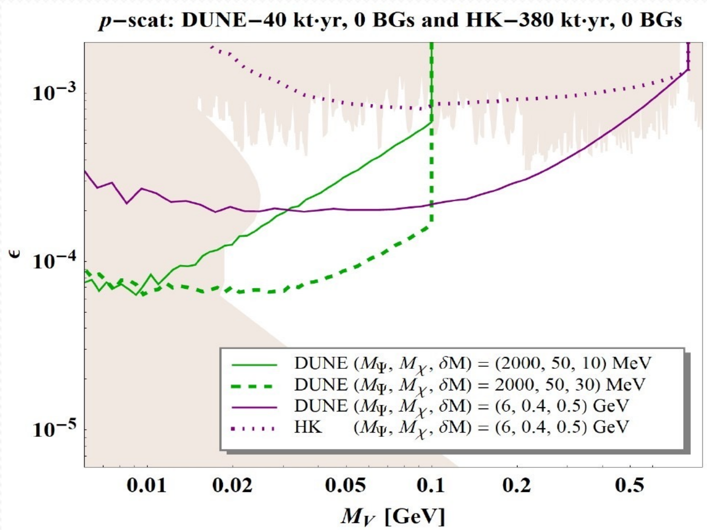
Flux contains ν_e and $\bar{\nu}_e$ as well as a component of the other flavors (ν_x) – DUNE has **unique sensitivity to ν_e** component

Phase I: O(100s) events per FD module for galactic SNB

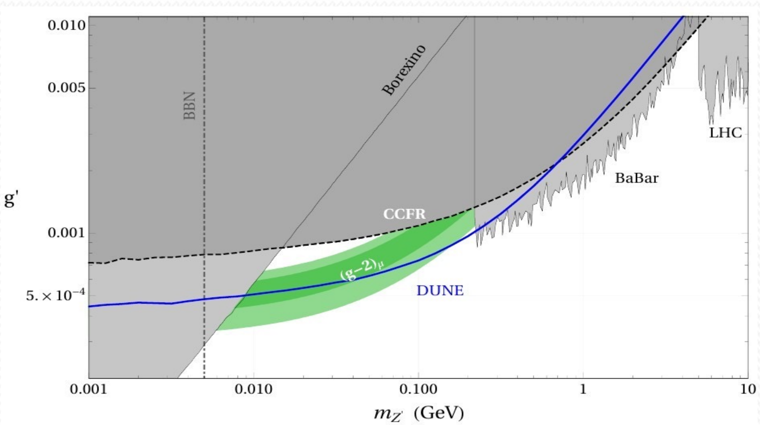
Phase II: Reach extends beyond the Milky Way

Involvement

BSM physics: unique capabilities of DUNE FD and ND



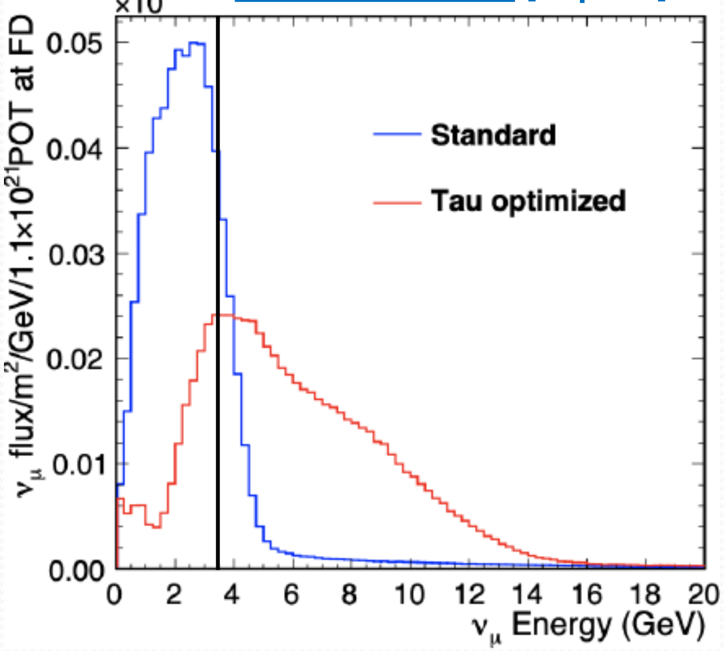
arXiv:2002.03005 **[hep-ex]**

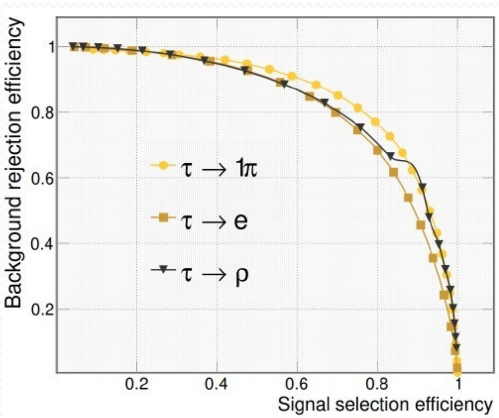


- Hyper-K will have higher statistics, but DUNE's imaging and spatial resolution are critical for some signals
- Inelastic dark matter scattering gives a signature of two low-energy electron tracks, and a detached low-energy electron or proton
- DUNE can see all of these tracks, and the displacement → world leading sensitivity at low mass already in Phase I
- DUNE ND-LAr will see ~100 $\nu_\mu \rightarrow \nu_\mu \mu^+\mu^-$ tridents per year (at 1.2 MW; XS scales with energy and Z^2)
- DUNE ND: Heavy neutral leptons, low mass DM
- DUNE FD: boosted dark matter

Unique to DUNE: three-flavor measurements, including tau neutrinos!

arXiv:2002.03005 [hep-ex]





Three-flavor unitarity tests are limited by the dearth of ν_τ data

LArTPC presents a unique opportunity to image hadrons and improve the reconstruction of ν_τ CC interactions

LBNF has significant ν_τ flux above the tau production threshold, and the beam could be re-optimized (by moving the focusing components) to enhance ν_τ CC

This is unique for accelerator beams, and complementary to atmospheric tau physics that is accessible in IceCube

Involvement

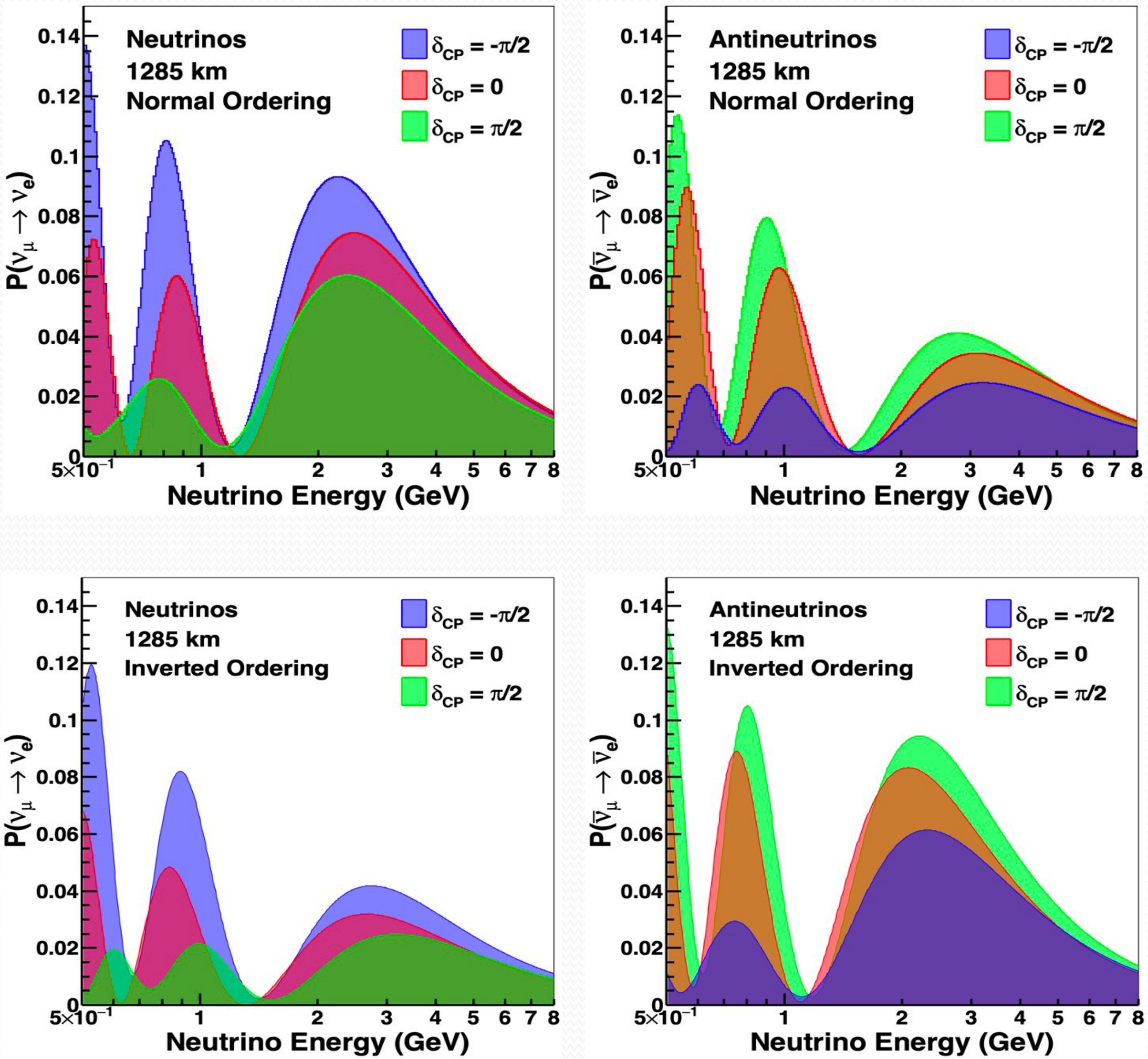
Summary

- ✓ What makes DUNE unique is extra long baseline, wide band intense neutrino and antineutrino beam, Liquid Argon TPC detector technology and deep underground location
- ✓ LBNF provides world-class facilities that will provide for decades to come (*underground physics start in 2029; beam physics in 2031*)
- ✓ DUNE is world-class long-baseline neutrino oscillation experiment, with outstanding ability to:
  - ✓ Resolve MO and measure CPV over broad range of parameters
  - ✓ Precisely measure θ_{13}, θ_{23}, and Δm^2, and 3-flavor oscillations to test the 3-flavor paradigm
  - ✓ DUNE FD deep underground will capture astrophysical neutrinos, and has extraordinary sensitivity to BSM physics

- ✓ Many opportunities for involvement; *for more details on DUNE-Canada please contact Deborah Harris (deborahh@yorku.ca)*

Thank you!

Simultaneous Measurement of MO, CPV and Mixing Parameters in DUNE



DUNE Collaboration, Eur. J. Phys. C80, 978 (2020)

- Effects of MO and CPV 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