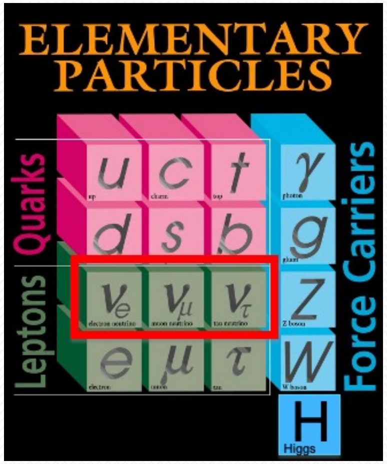
DUNE Update

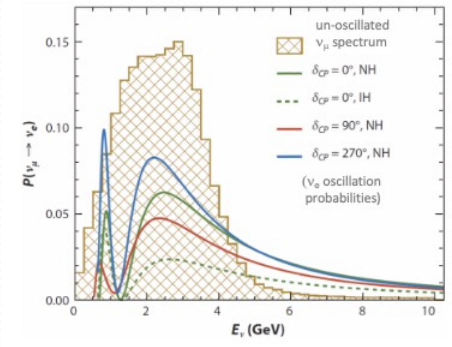
Jelena Maricic, University of Hawaii
for DUNE Collaboration
US-Japan Hawaii Meeting
May 22, 2023

DUNE
Deep Underground Neutrino Experiment
Outline

Motivation

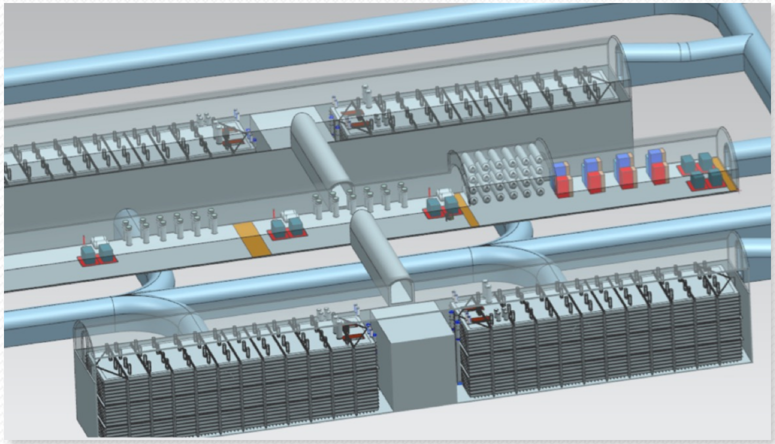


Science



Facility

Experiment



DUNE: Motivation

Open Questions in Neutrino Physics

- What are the masses of the neutrinos?

- What kind of masses do neutrinos have? Are neutrinos their own antiparticles?

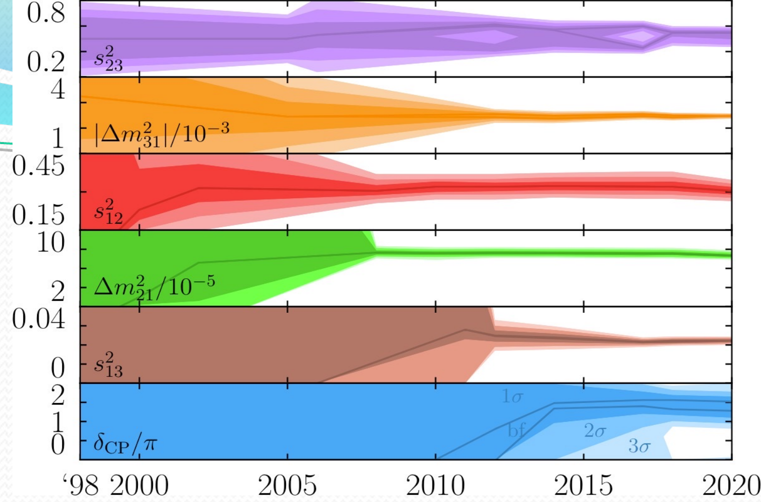
- Are there more than 3 kinds of neutrinos?

- How are the neutrino masses ordered? *(implications for GUTs, cosmology, 0nbb)*

- Do neutrinos and antineutrinos oscillate differently? Do neutrinos violate CP symmetry (CPV)? *(neutrinos could play a role in the generation of the matter/anti-matter asymmetry in the early universe)*

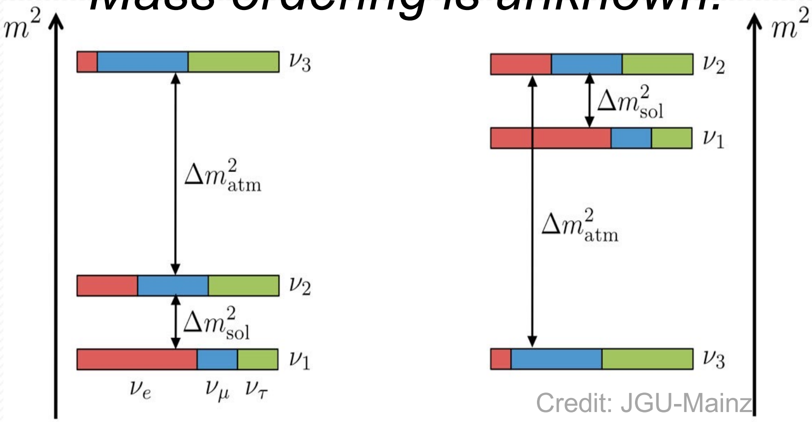
- Is our 3-flavor picture of oscillations complete?

Evolution of neutrino oscillation parameters

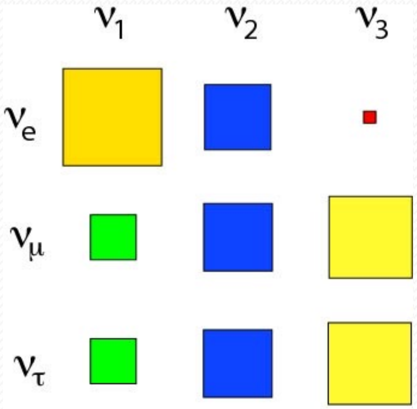


Snowmass NF01 Topical Report, *arXiv:2212.00809*

Mass ordering is unknown.



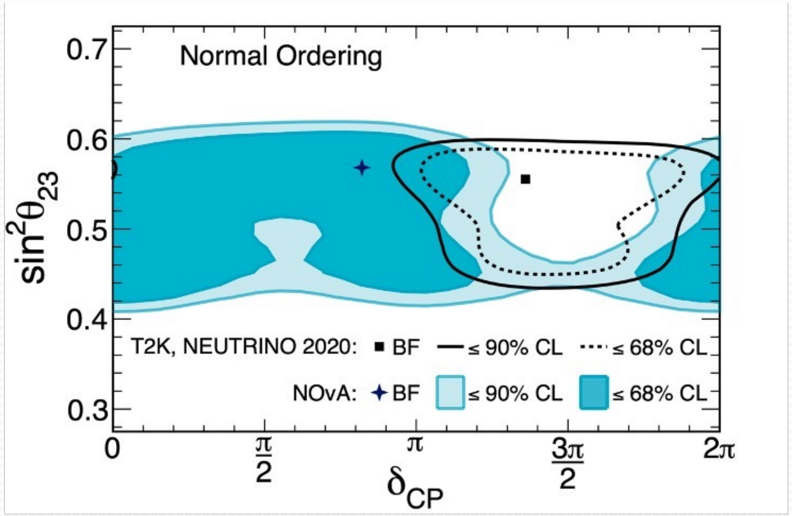
Credit: JGU-Mainz

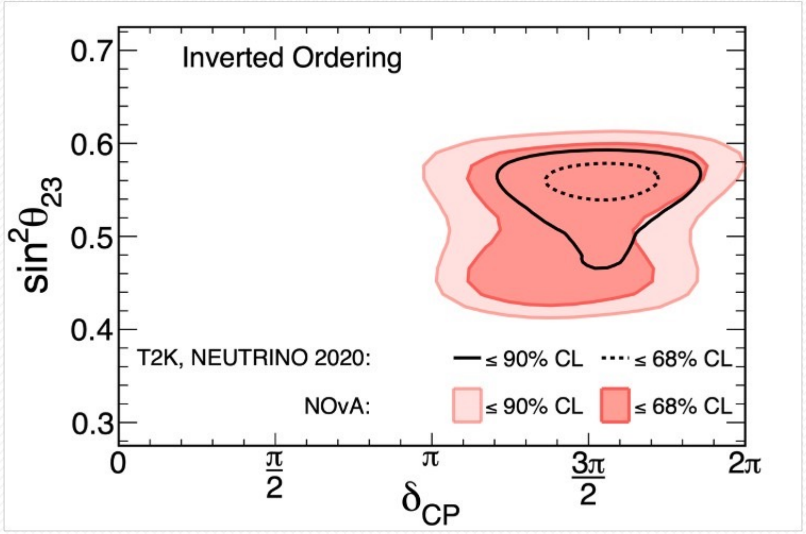


Credit: Sheldon Stone

Current Understanding of MO and CP-δ Phase

https://doi.org/10.5281/zenodo.6683827

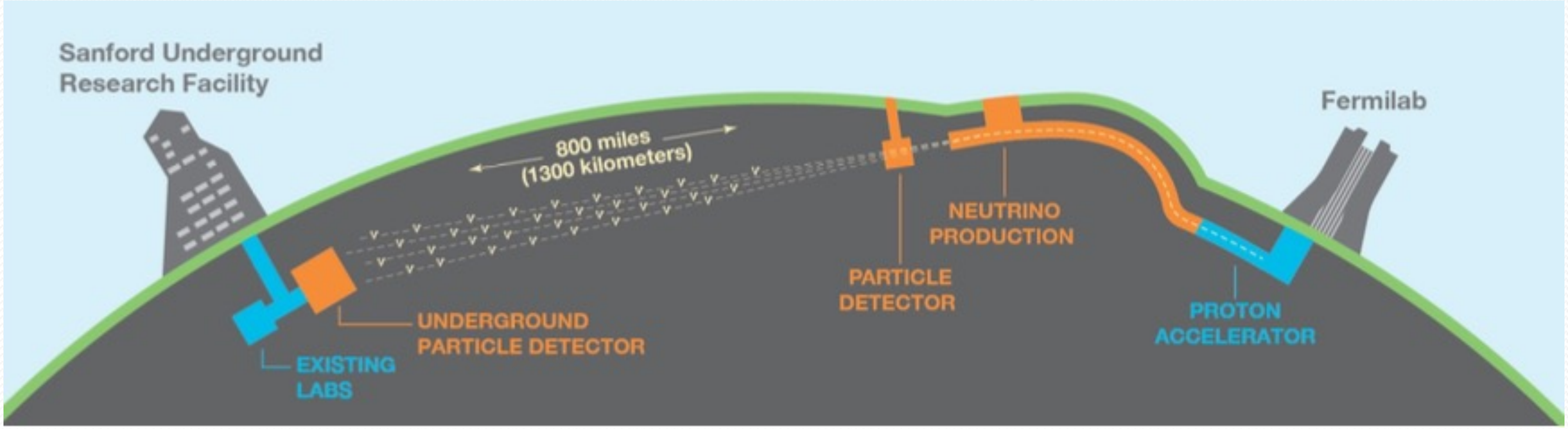




- Weak preferences for normal ordering from atmospheric & long-baseline experiments
- Some regions of joint MO-δ_{CP}-θ_{23} space are excluded at >90% by NOvA and T2K
- NOvA and T2K best fit in NO, consistent at ~1σ, but mutually allowed region in IO at <1σ
- **In summary: MO and δ_{CP} remain unknown**
- **Definitive experiments needed**

DUNE: Science

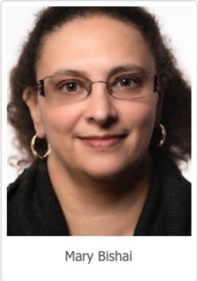
DUNE Science Program



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

DUNE Collaboration

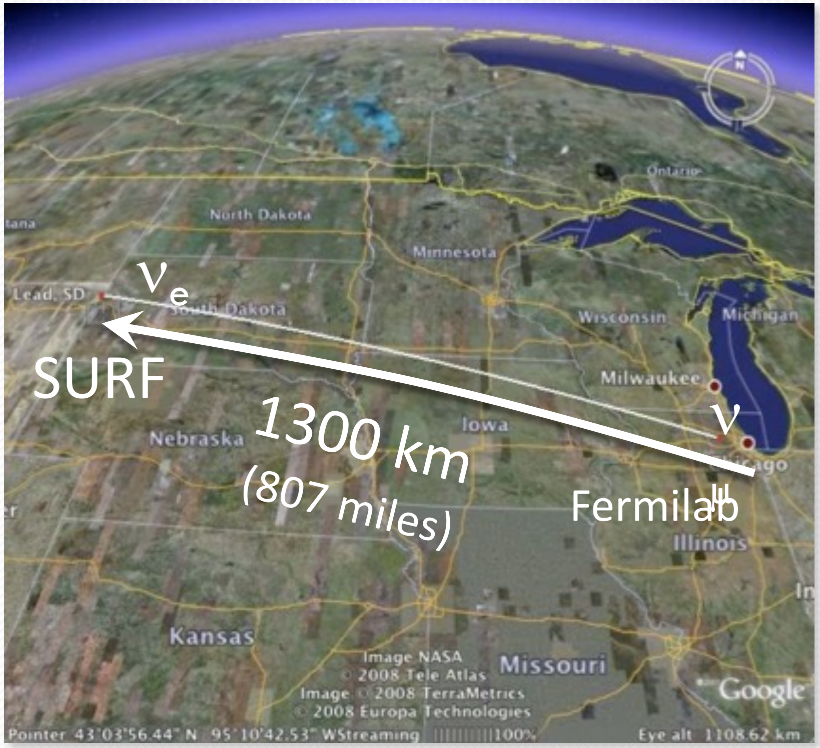
- Strong, international collaboration (from 2014):
- 1400+ collaborators!
- 206+ institutions!
- 37 countries and CERN!


Mary Bishai


Sergio Bertolucci

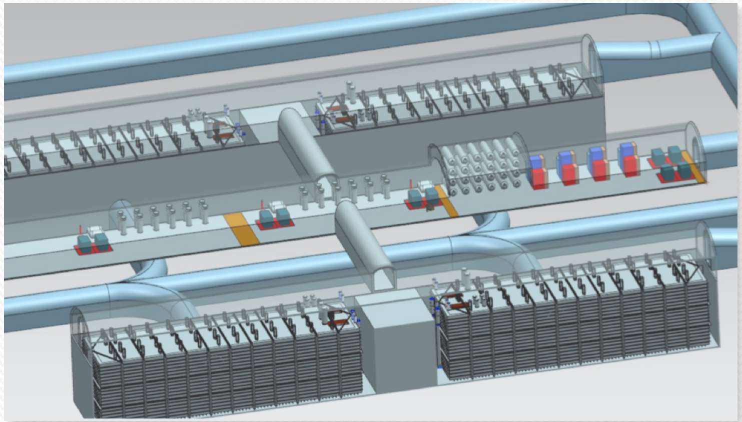

CERN, January 2023

Extraordinary Experimental Setup



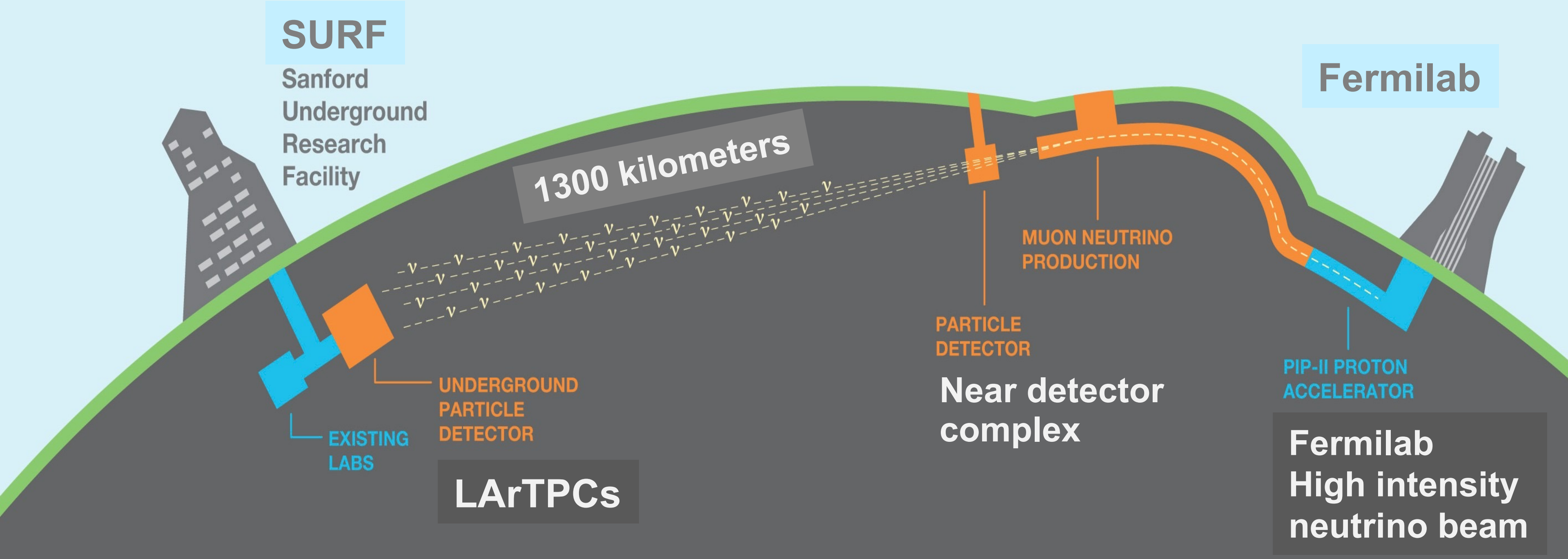
- 1300 km baseline → long baseline → large matter effects
  - *unambiguously measure MO, CPV*
- On-axis, wide band beam (ν, $\bar{\nu}$)
  - *High statistics over full period*
  - *Increased BSM sensitivity*

40 ktons of LAr far detector a mile underground:



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

Deep Underground Neutrino Experiment



SURF

Fermilab

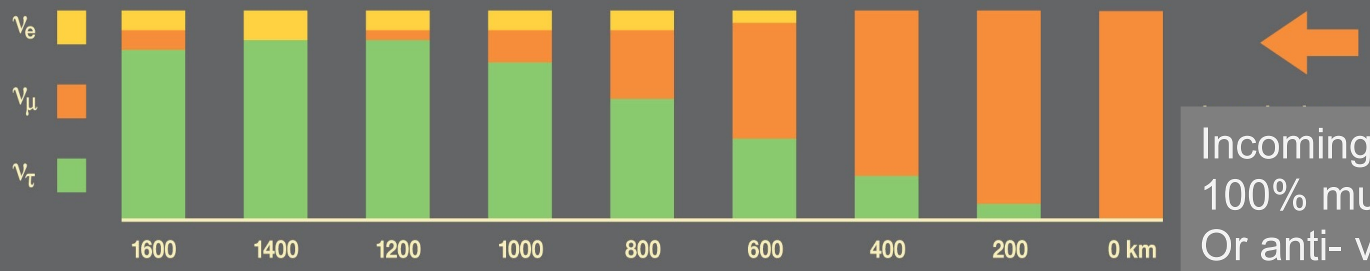
LArTPCs

Near detector complex

Fermilab
High intensity
neutrino beam

Disappearance
ν_μ, $\bar{\nu}_\mu$

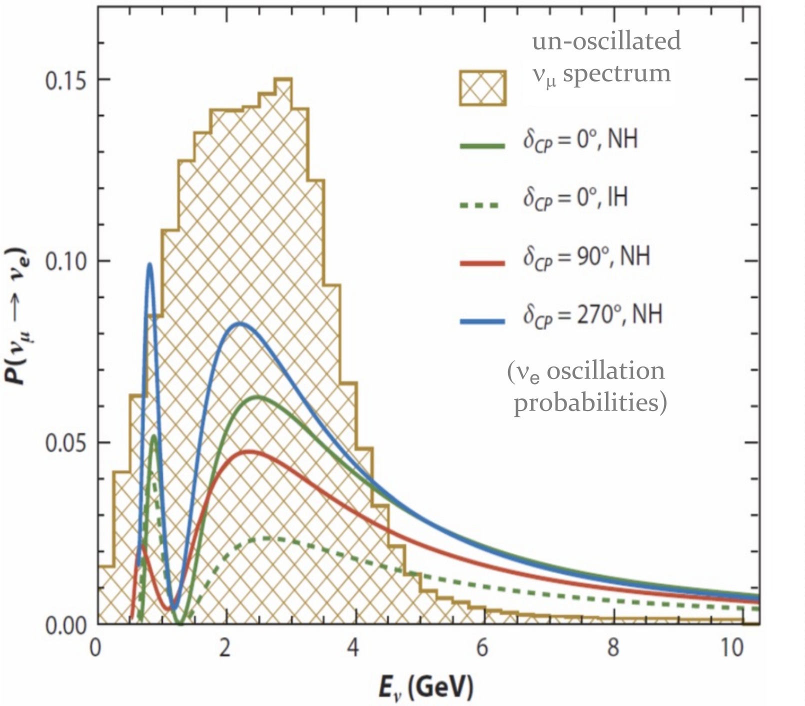
Appearance
ν_e, $\bar{\nu}_e$



Incoming beam:
100% muon ν's
Or anti- ν's

Probability of detecting electron, muon and tau neutrinos

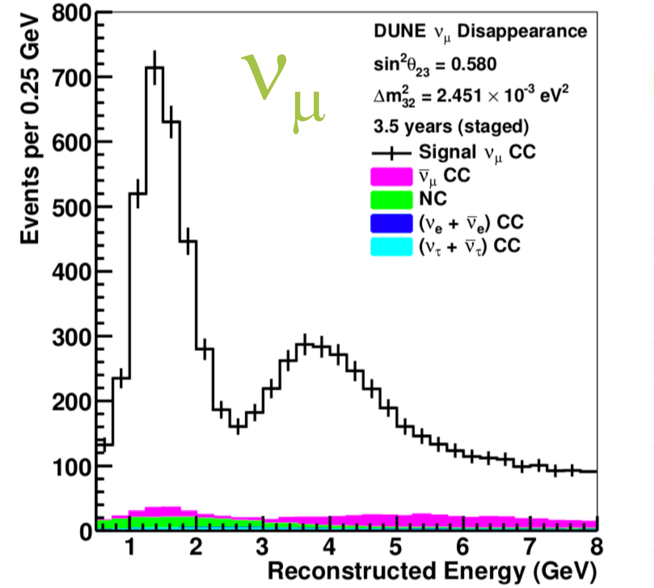
DUNE Physics

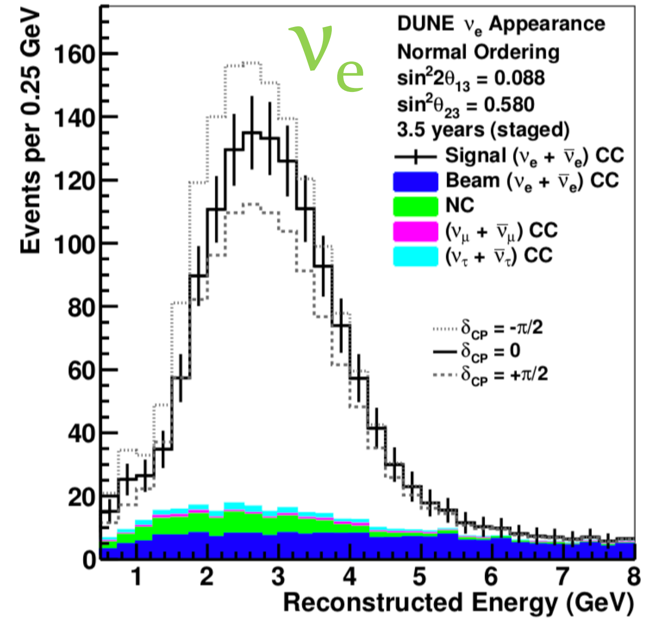


disappearance

$\nu_\mu \rightarrow \nu_e$

appearance





- DUNE will be able to unambiguously and simultaneously measure MO, CP given the baseline and on-axis beam

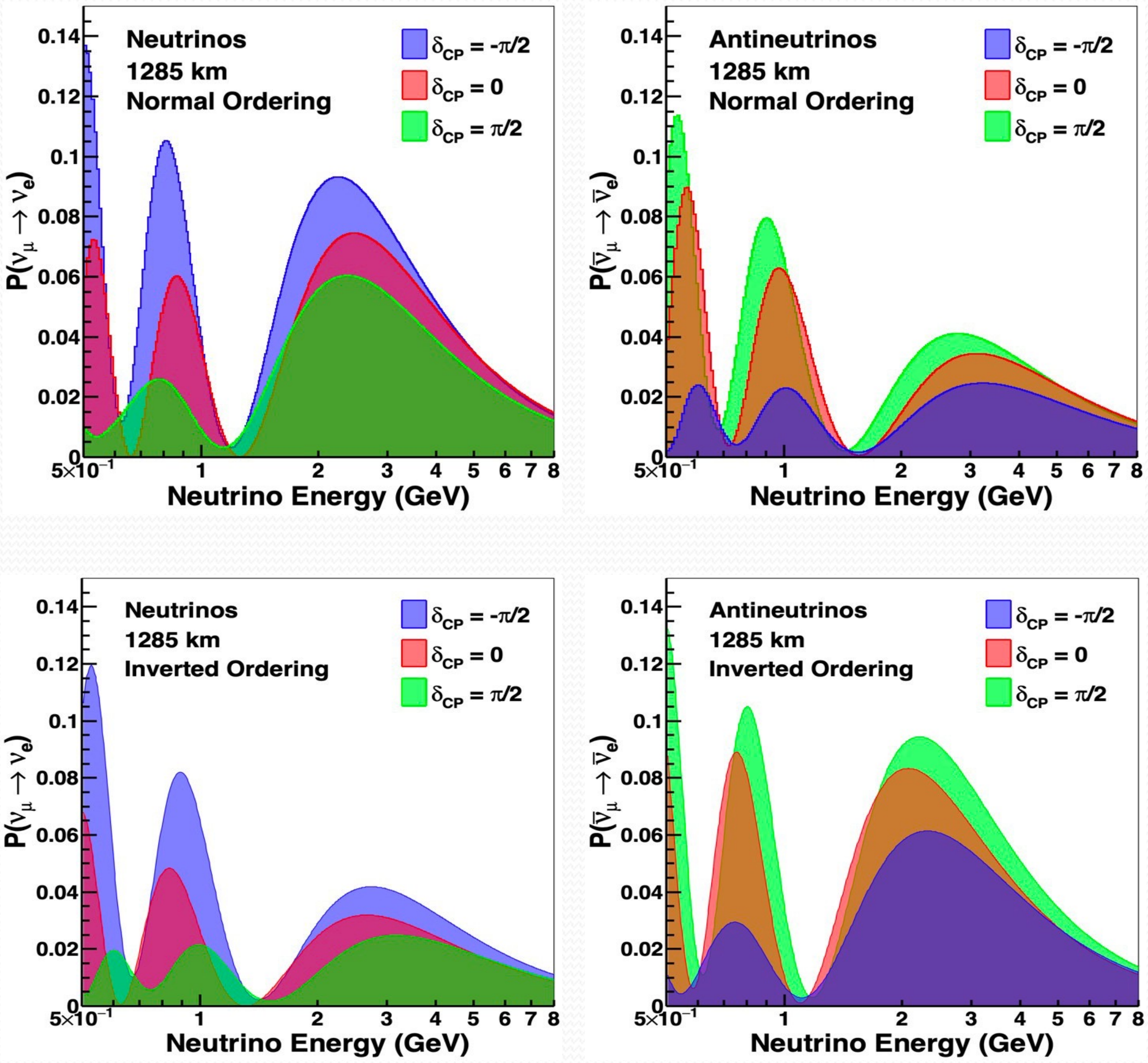
- in the 1st year alone, DUNE will collect ~150 oscillated ν_e events.

  - 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

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

Simultaneous Measurement of MO, CPV and Mixing Parameters in DUNE

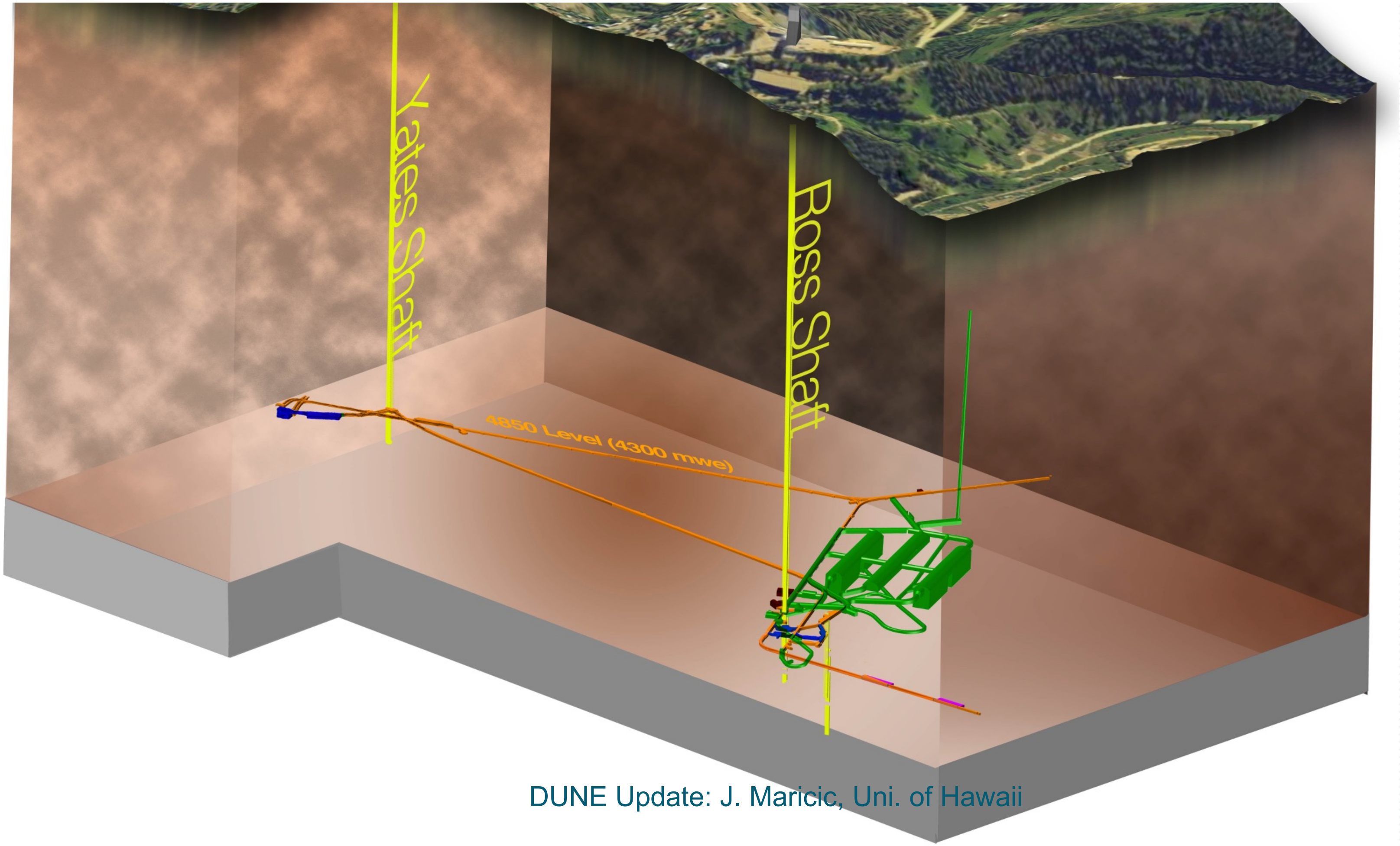


- Effects of MO and CPV have different shape as a function of L/E
- DUNE measures oscillations over more than a full period, which helps resolve degeneracies
- This is unique to DUNE, and complementary to other experiments with narrow flux spectra

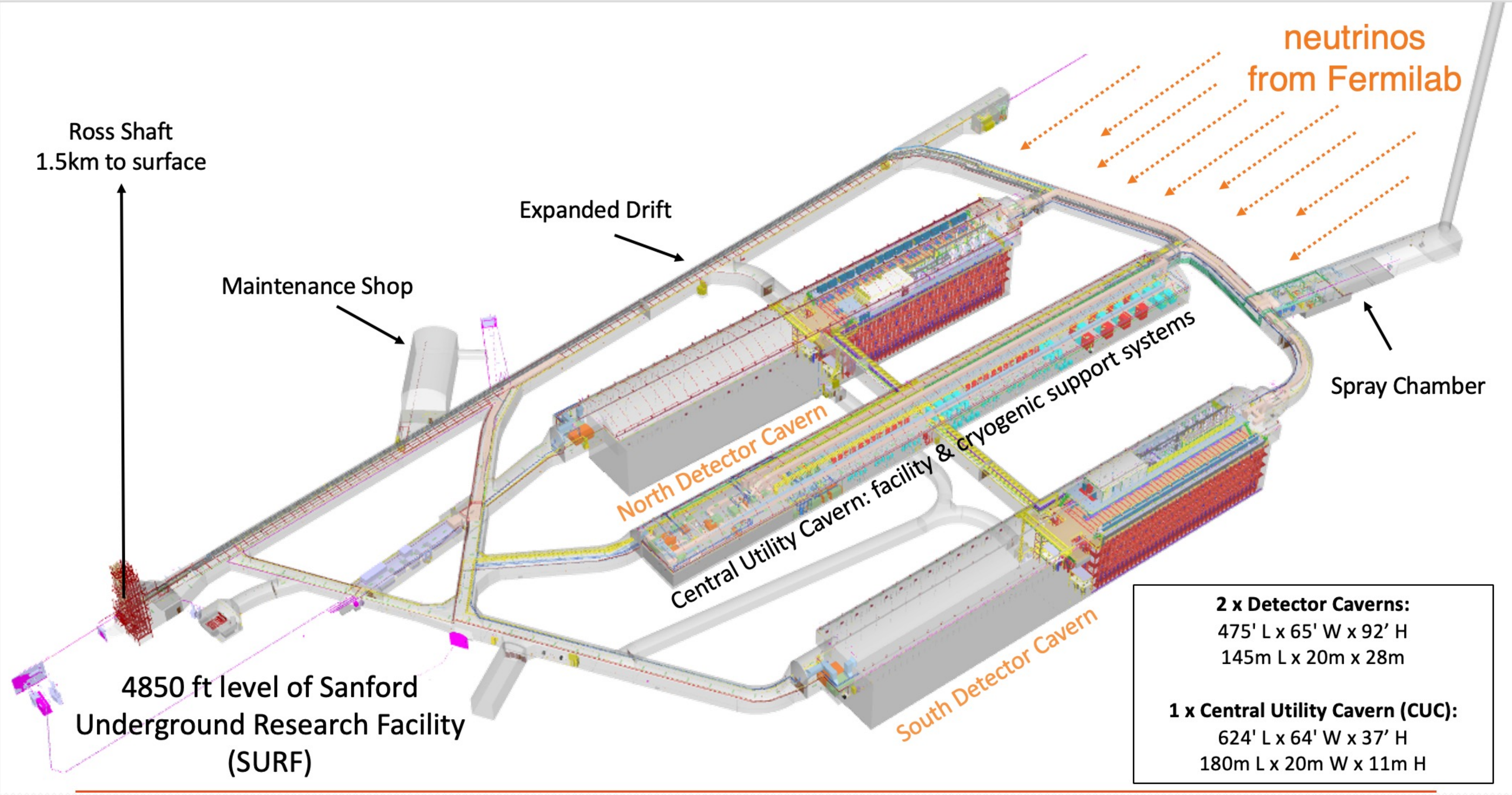
Long Baseline Neutrino Facility (LBNF)

Sanford Underground Research Facility (SURF) South Dakota

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



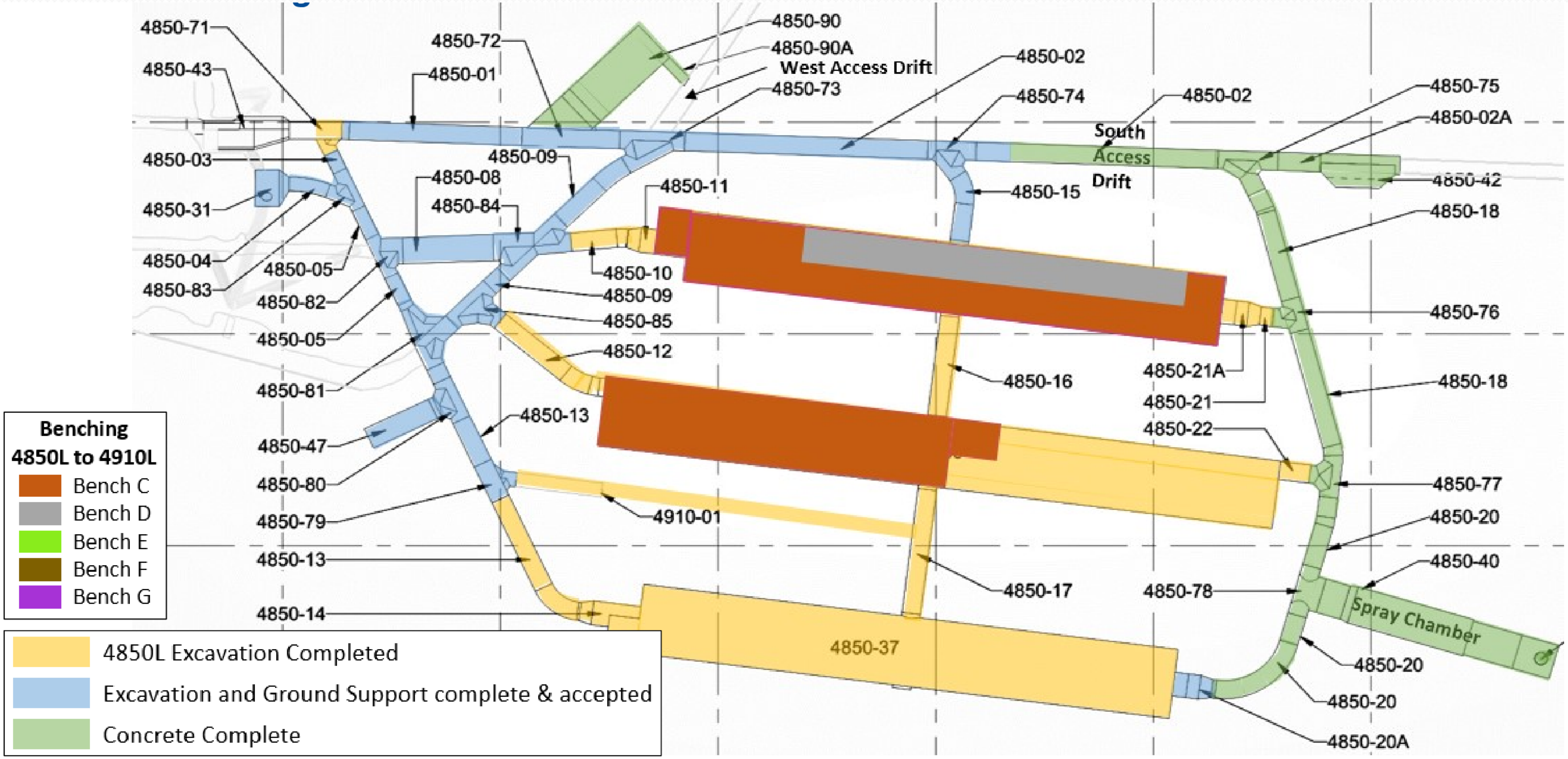
Facilities Underground



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

Excavation Progress > 60%

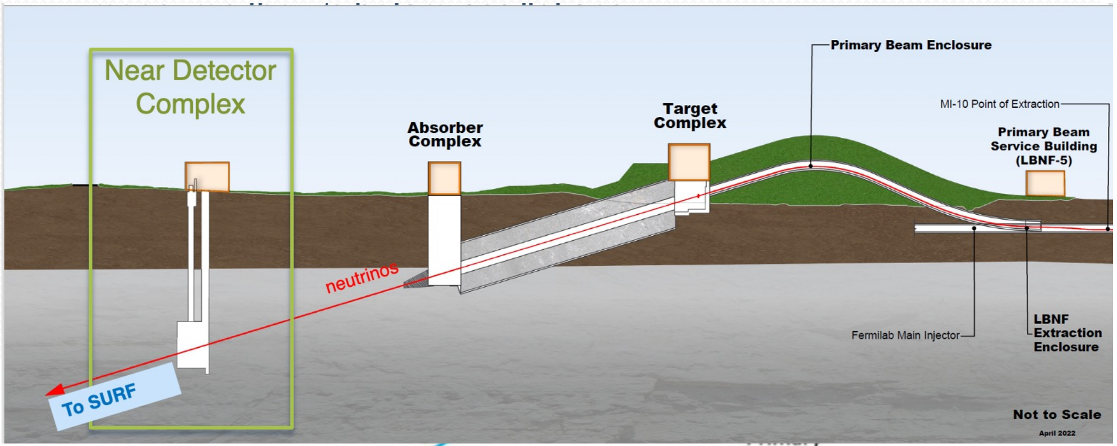


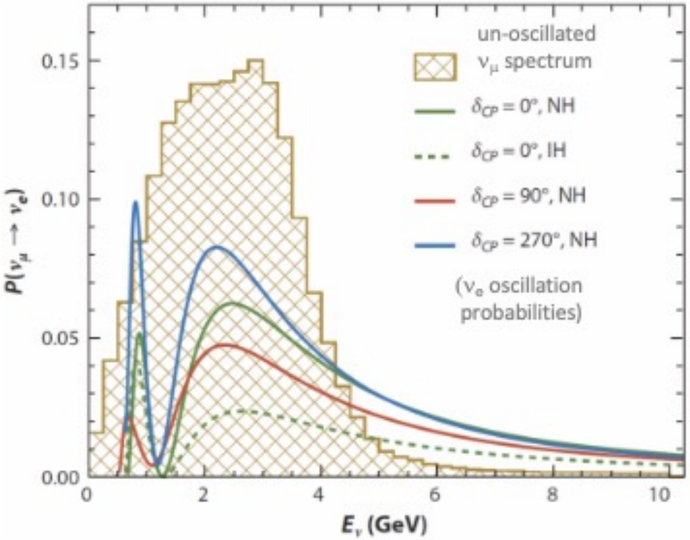
All excavation work is under firm-fixed price construction contract and proceeding on cost and on schedule


mec 3084RT SPEED LEVEL

LBNF Near Site: Beam + ND Complex

- Horn-focused wide-band beam, builds on the success of NuMI
  - *broad spectrum of ν's (& anti-ν's) peaked at 2.5 GeV*
  - *focusing parameters optimized to for maximum sensitivity to CPV*
  - *1.2 MW, upgradeable to 2.4 MW*
- Beamline design at 70% final design status. Final design of near detector complex have been completed.

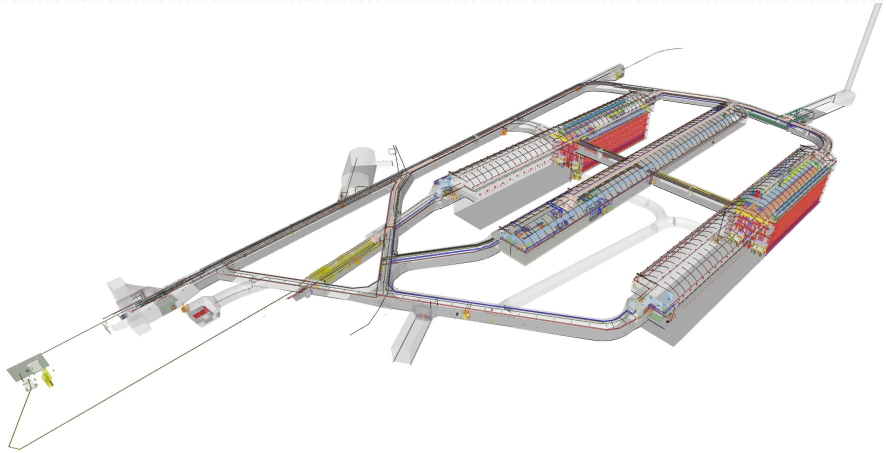


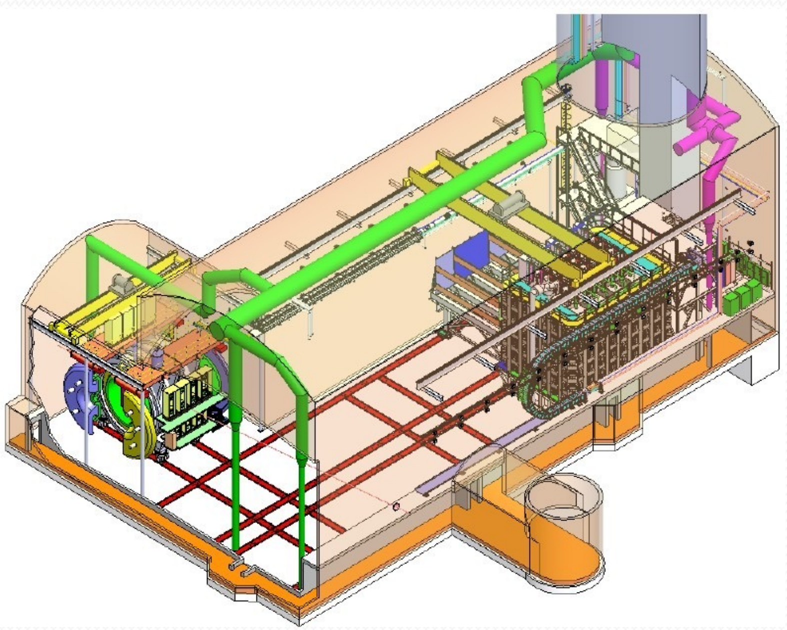


Beamline Complex: Upstream end view of Primary Beamline, Target Hall, Decay Pipe, and Absorber

DUNE: Experiment

DUNE Phased Approach





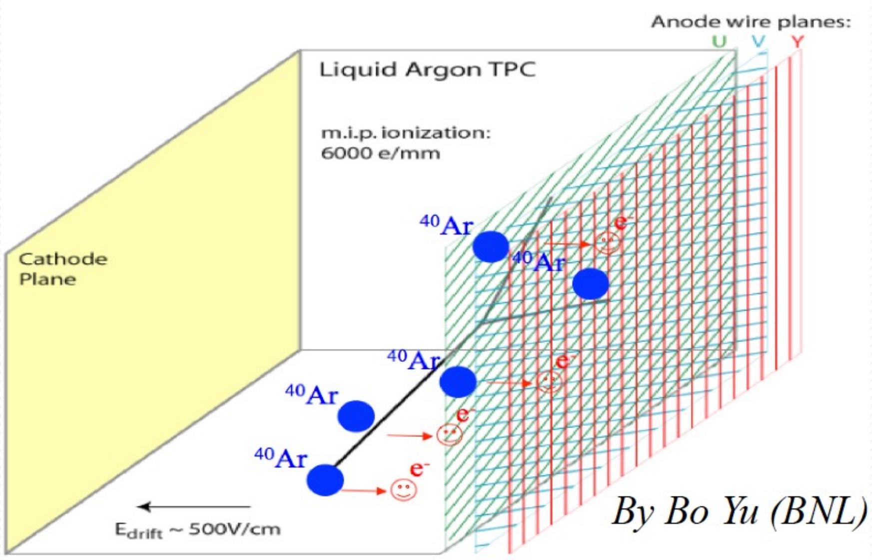
DUNE Phase I:

- Full near + far site facility and infrastructure
- Upgradeable 1.2 MW beam
- Two 17kt LArTPC modules
- Movable LArTPC near detector with muon catcher
- On-axis near detector

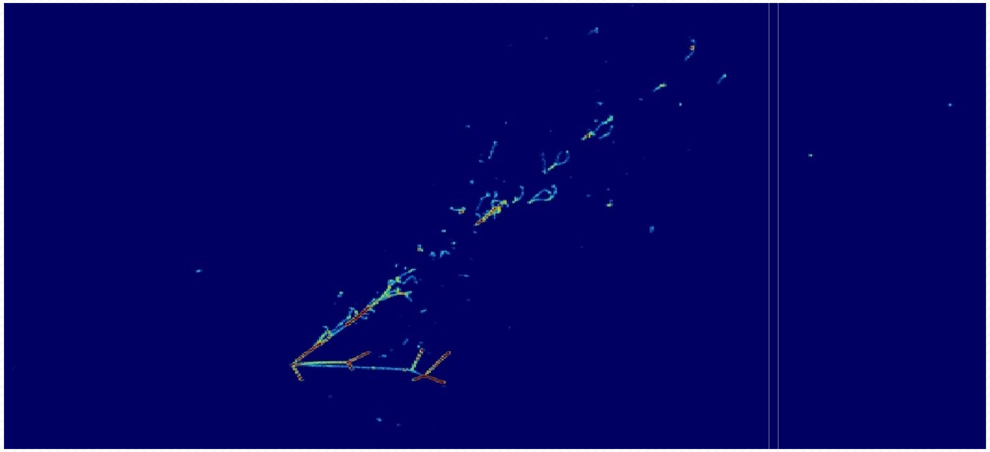
DUNE Phase II:

- Two additional FD modules
- Beam upgrade to > 2MW
- More capable Near Detector

Detector Technology – Liquid Argon Time Projection Chamber



By Bo Yu (BNL)



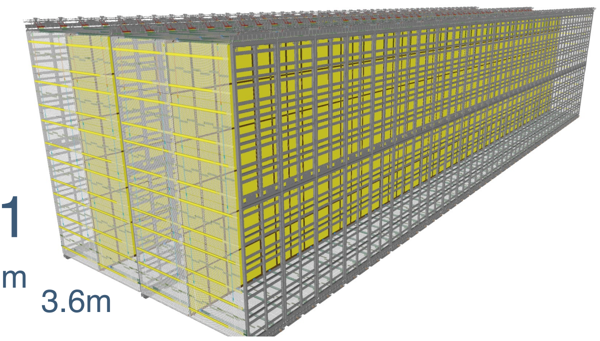
Identify as ν_e CC from EM shower

Measure E_ν by summing energy of e^- and hadrons (1 π and 2 p^+, here)

- LAr TPC: excellent tracking and calorimetry (hadrons and electrons)
- Suitable for very large detectors – high signal eff. and bkg. discrimination
- High resolution 3D reconstruction – charged particles ionize Ar; electrons drift to anode wires (~ms) for xy coordinate; drift time – z coordinate
- Argon scintillation light (~ns) detected by photon detectors – provides t_0

DUNE Far Detectors (Phase I)

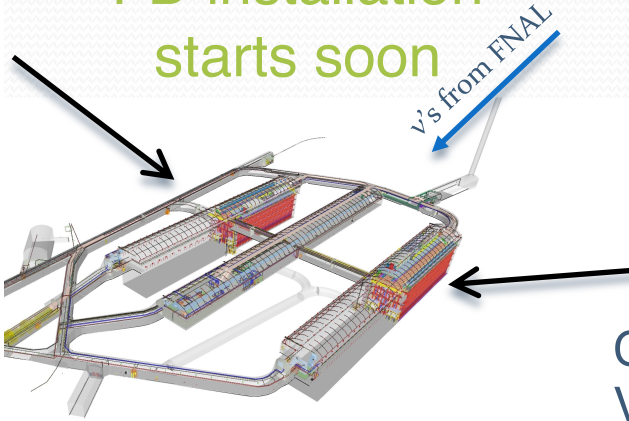
- LBNF provides caverns for 4 detector modules at SURF and 2 far detector modules, each 10 kton of liquid argon (fiducial mass), the largest LAr TPCs ever constructed.
  - *FD1: horizontal drift (like ICARUS, MicroBooNE)*
  - *FD2: vertical drift (capitalizing on dual phase development)*

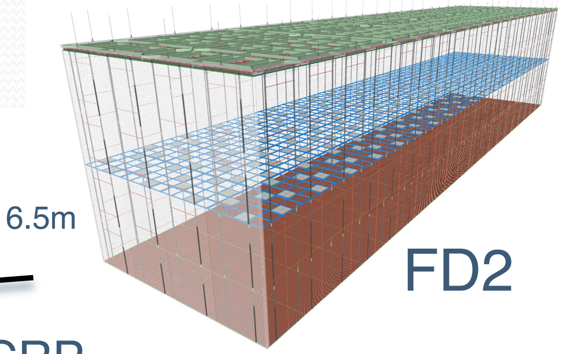


APA, Horizontal Drift

APA = Anode Plane Assemblies

FD installation starts soon



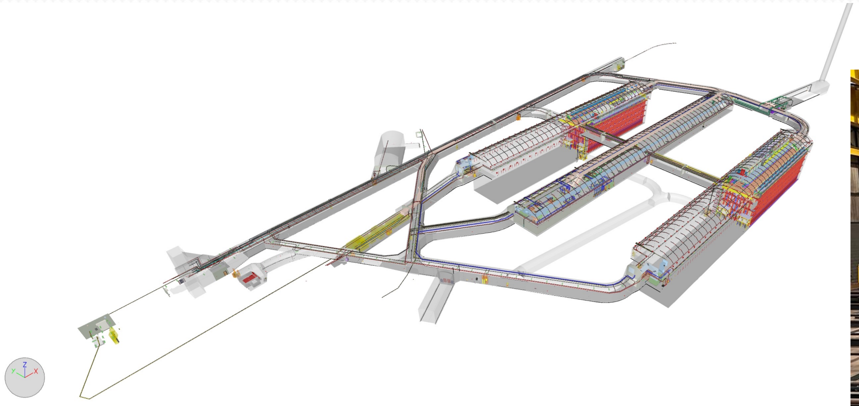


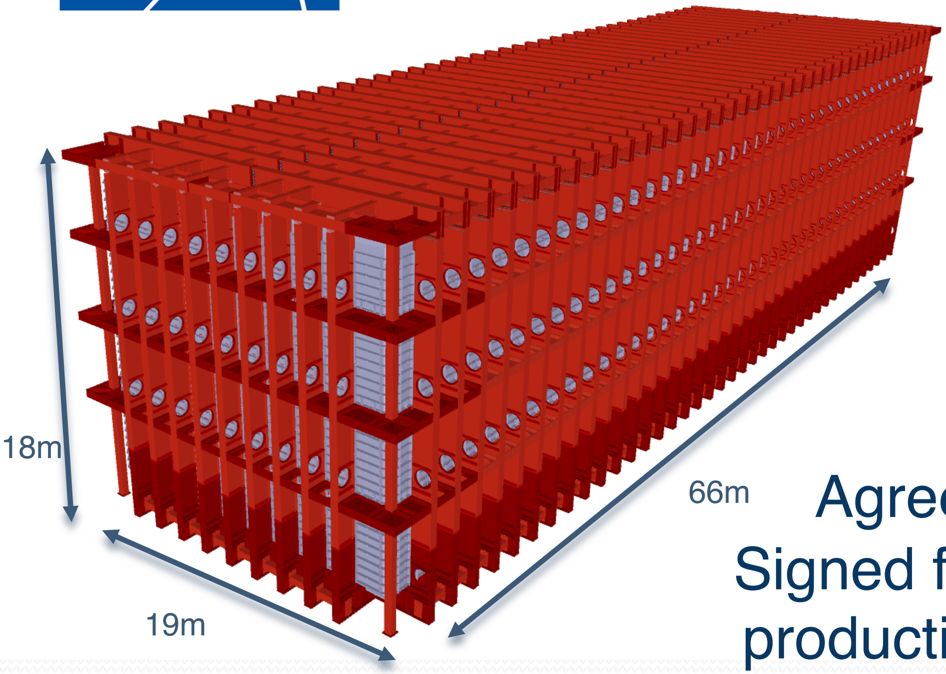
CRP, Vertical Drift

CRP = Charge Readout Planes

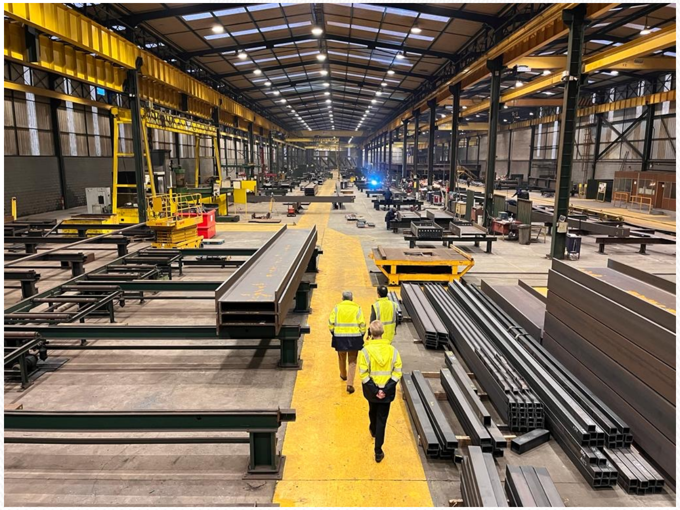
- Order of magnitude more mass than has been deployed up to now from all LAr detectors
- DUNE science begins as soon as the far detectors are operational

Cryostats For Far Detectors



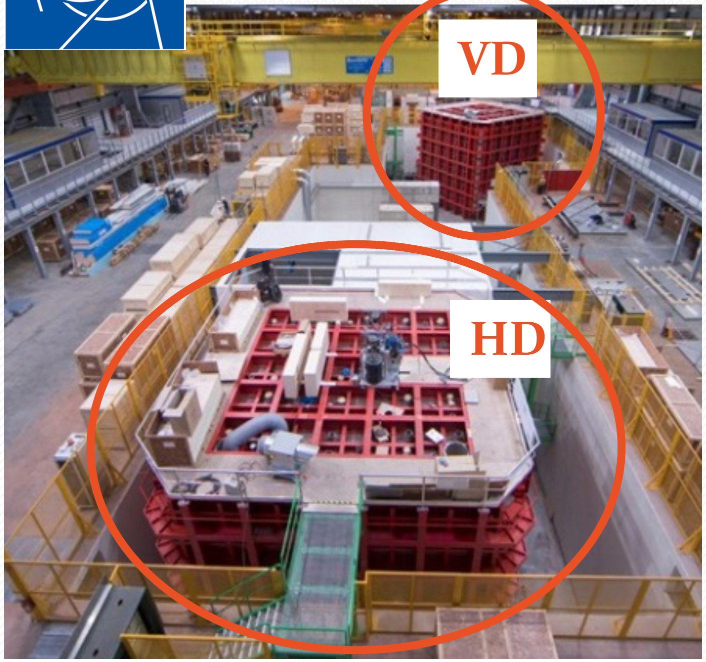


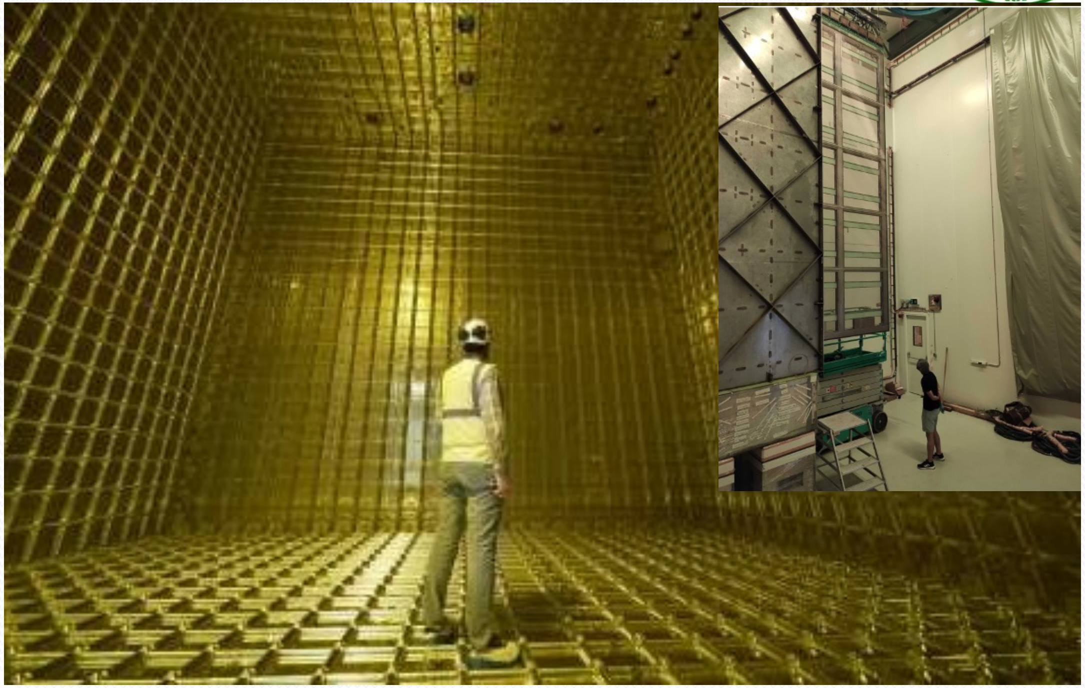
Agreement Signed for CERN production of 2nd cryostat.

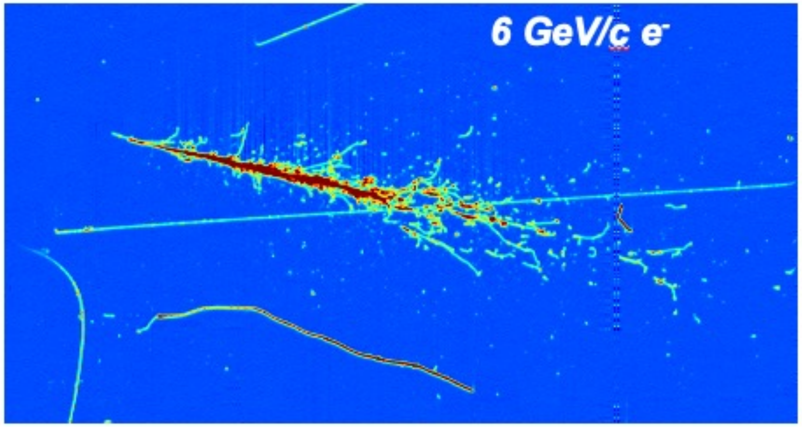


Fabrication of the 1st cryostat is underway at CERN

Far Detector Prototypes





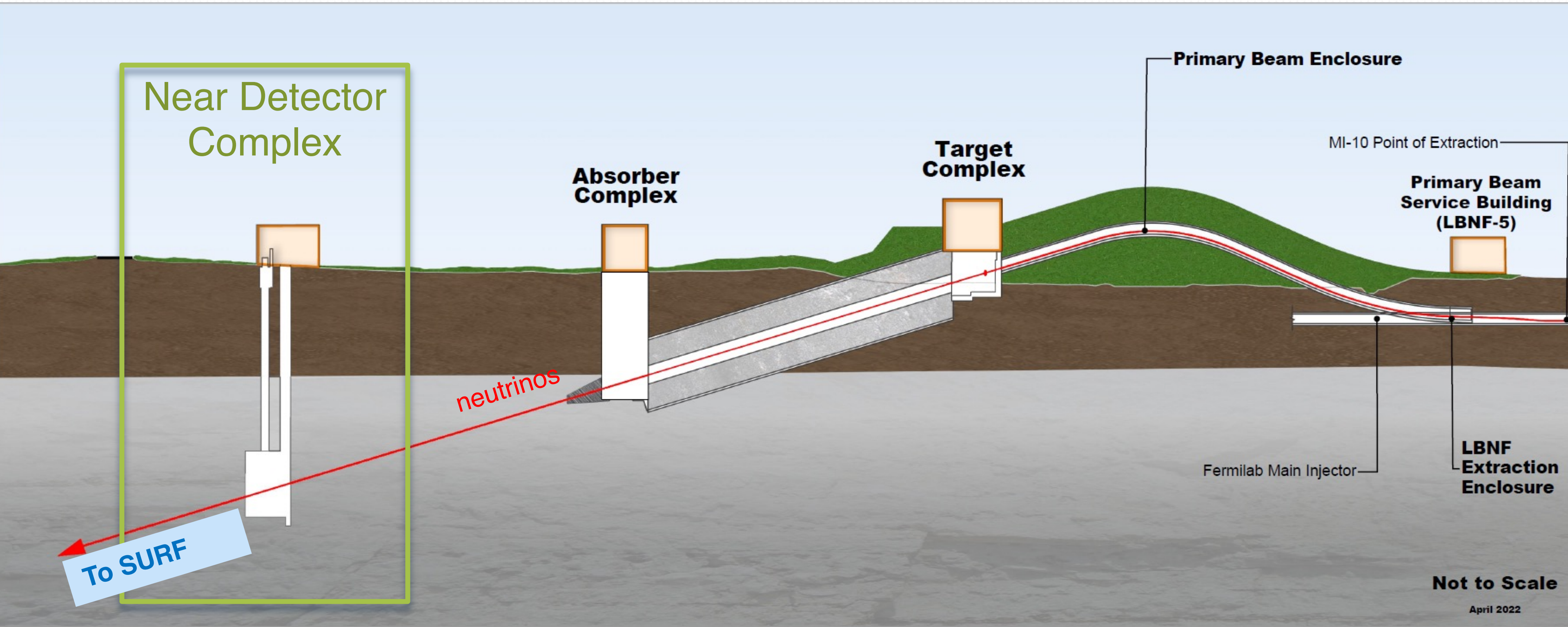


Eur. Phys. J. C82, 903 (2022)

- 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

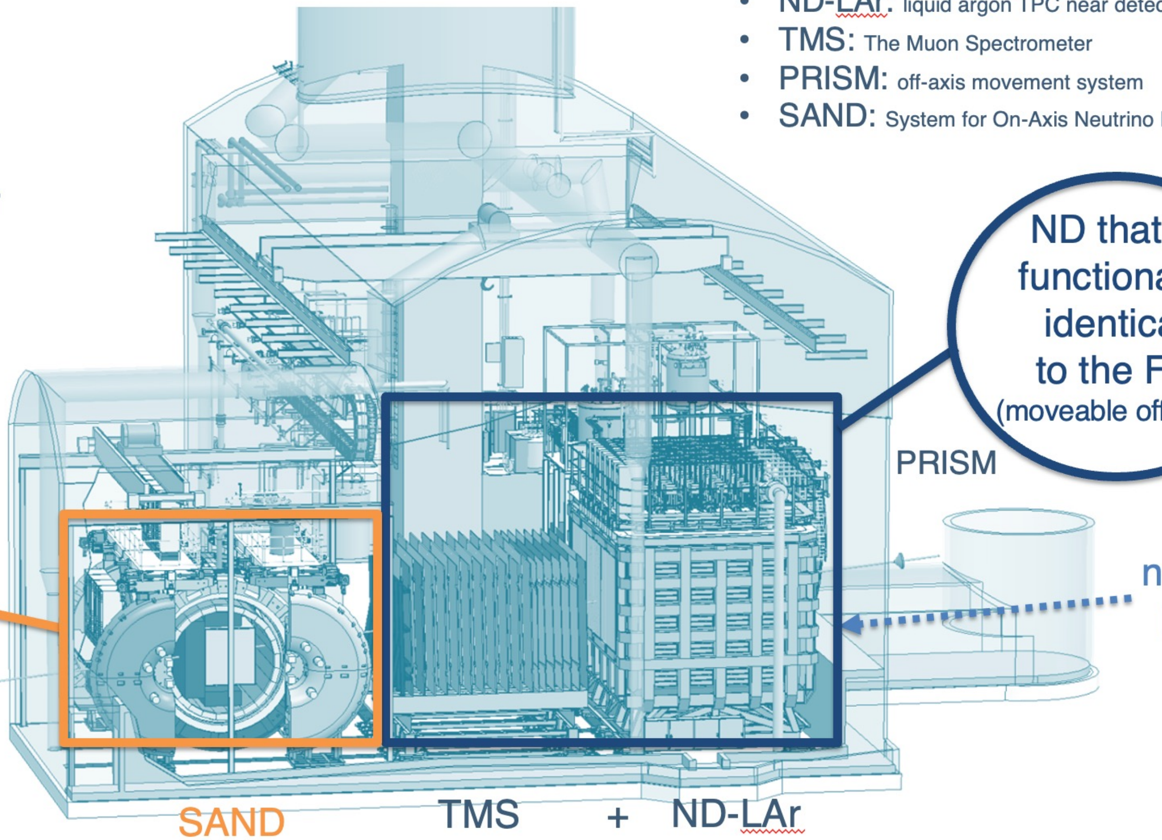
Near Detector Complex

- ND hall is located 550m from proton target, 215ft deep, on-site at Fermilab
- Purpose of the ND is to measure rate & spectrum of ν's before they make their journey west and to the FD. The ND measures ν's before oscillations.



DUNE Near Detector

- DUNE ND is optimized with the same technology as FD
- ND LAr is tracking calorimeter, capable of handling beam rate
  - > 50 neutrino interactions per beam spill (pixelated readout and optical segmentation
- **Near detector measurements both on & off axis**



- ND-LAr: liquid argon TPC near detector
- TMS: The Muon Spectrometer
- PRISM: off-axis movement system
- SAND: System for On-Axis Neutrino Detection

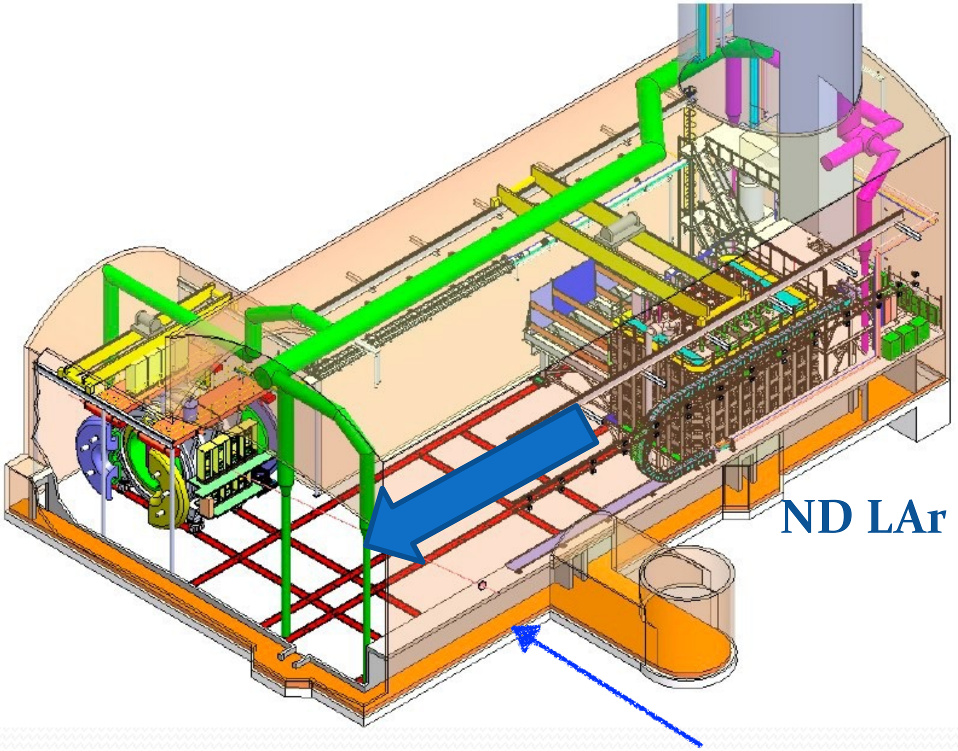
- Two main detector components:
  - ND-LAr + TMS
  - SAND

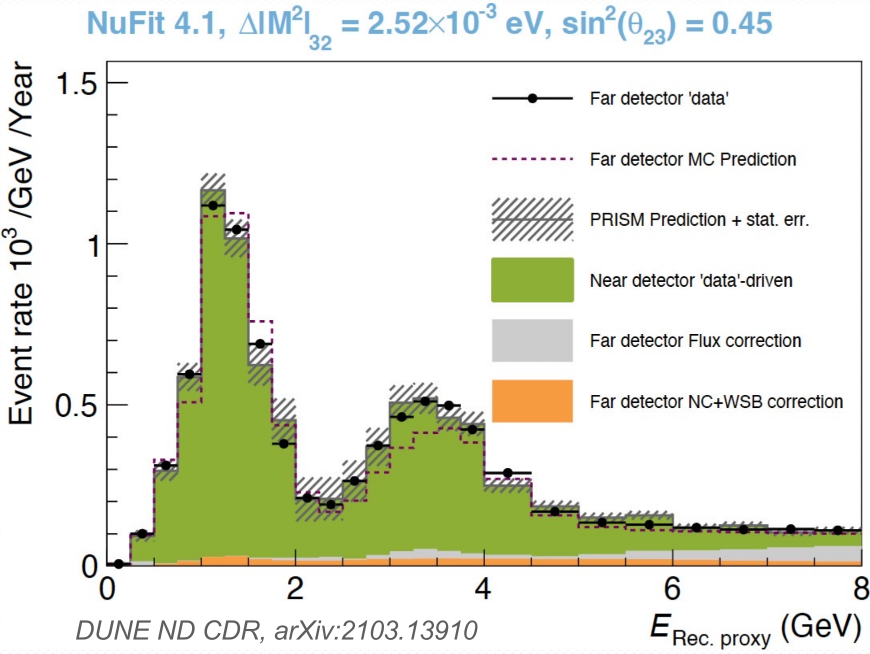
the on-axis neutrino detector (stationary)

ND that is functionally identical to the FD (moveable 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



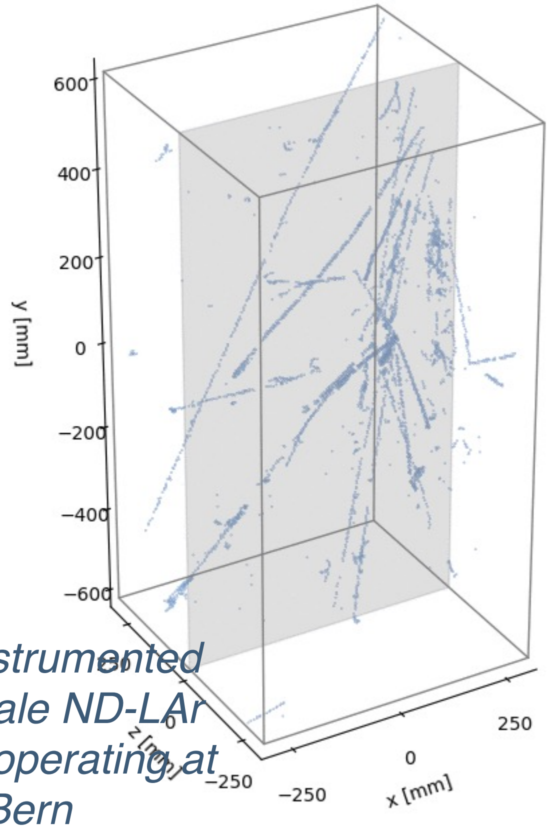

NuFit 4.1, $\Delta|M^2|_{32} = 2.52\times10^{-3}$ eV, $\sin^2(\theta_{23}) = 0.45$

DUNE ND CDR, arXiv:2103.13910

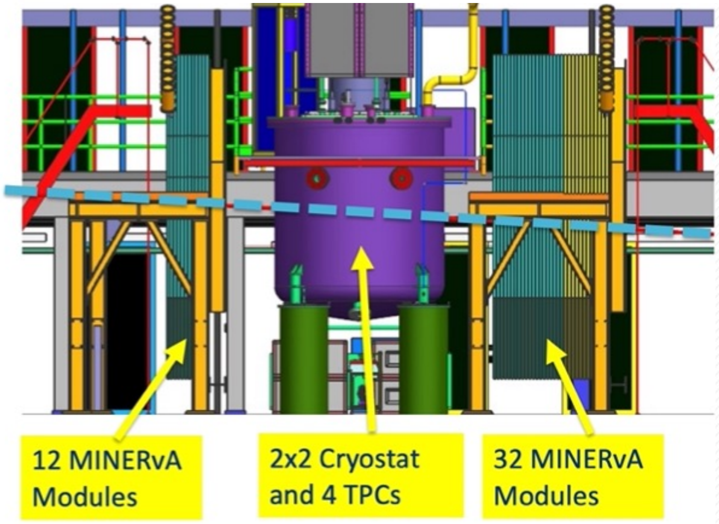
Near Detector Prototypes

- 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.



Fully instrumented 20% scale ND-LAr module operating at Bern



Source: Jen Raaf

DUNE: Science Reach

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

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

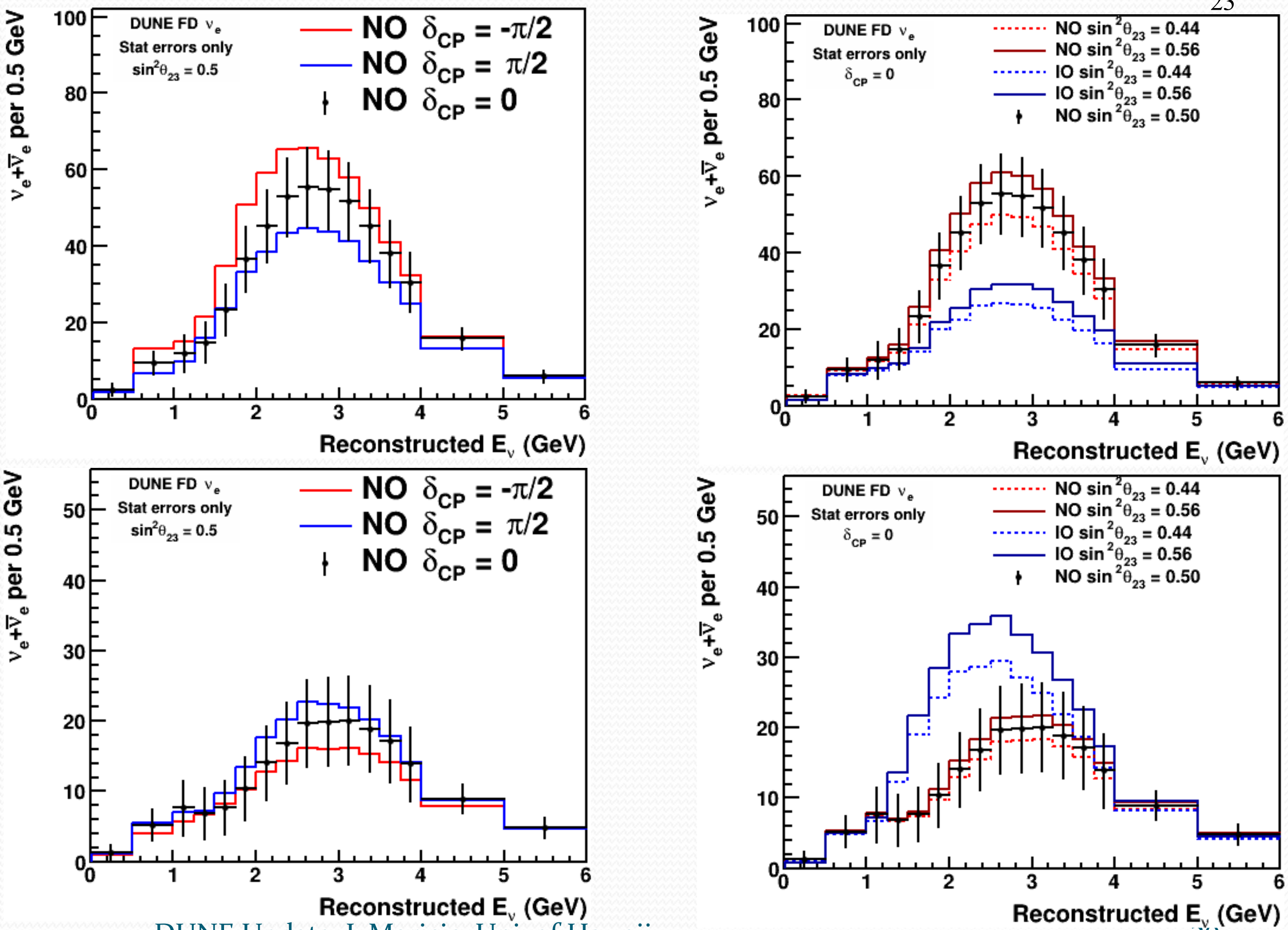
Neutrino mode

Phase I

Antineutrino mode

Varying δ_{CP}

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



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

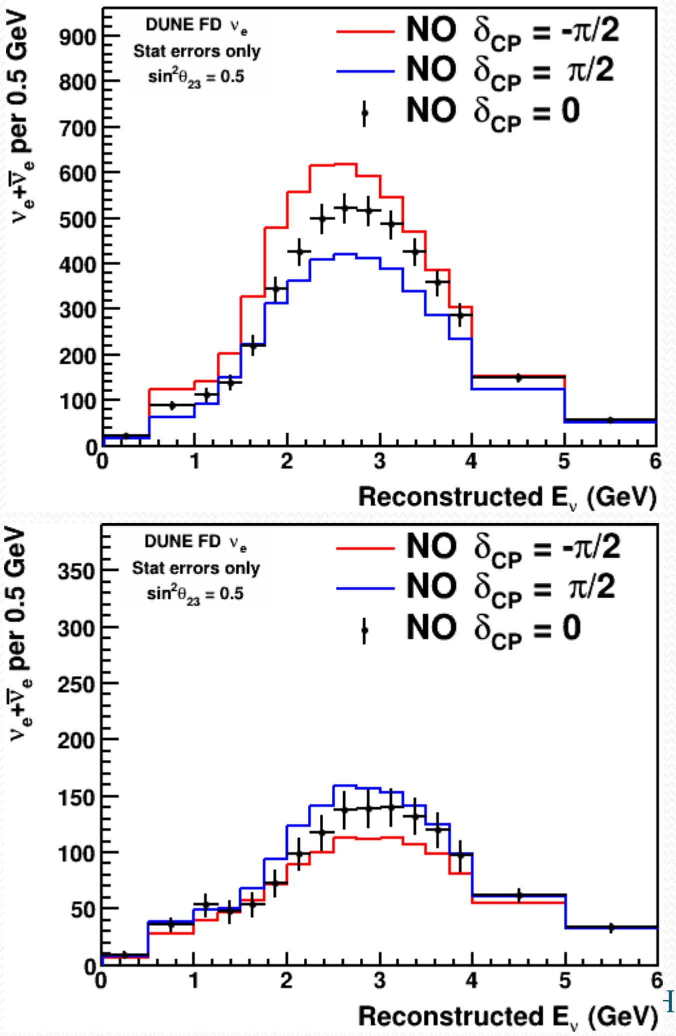
Data points show NO, $\delta_{CP} = 0$, $\sin^2\theta_{23} = 0.5$

Neutrino mode

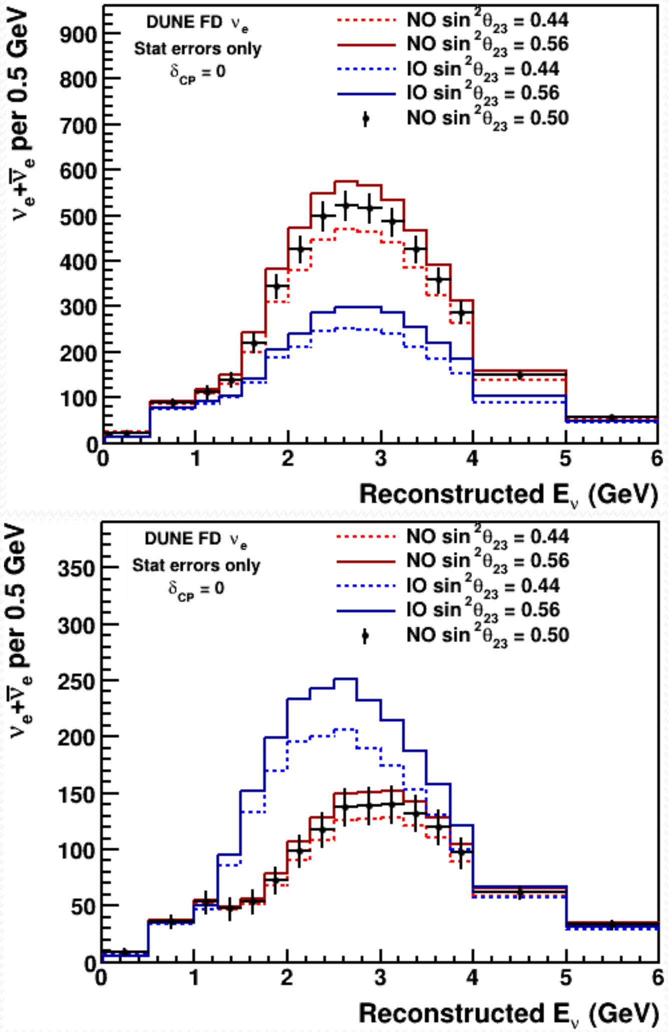
Phase II

Antineutrino mode

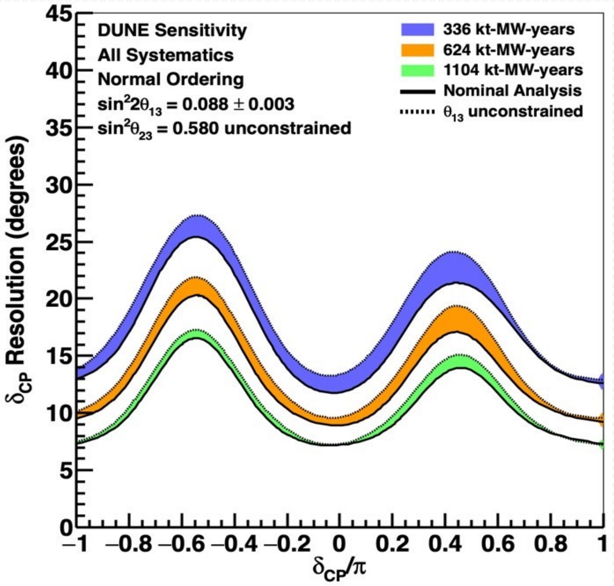
Varying δ_{CP}

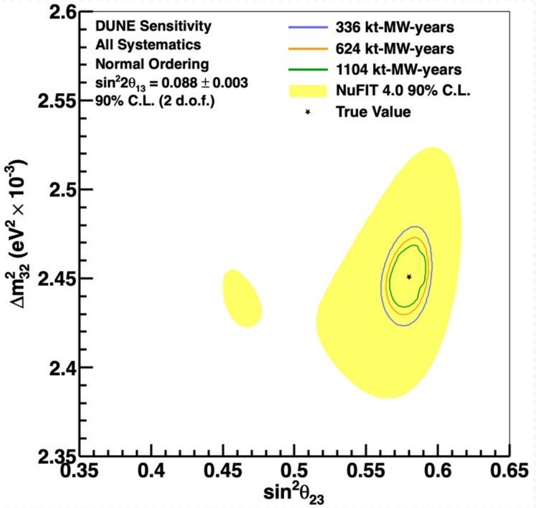


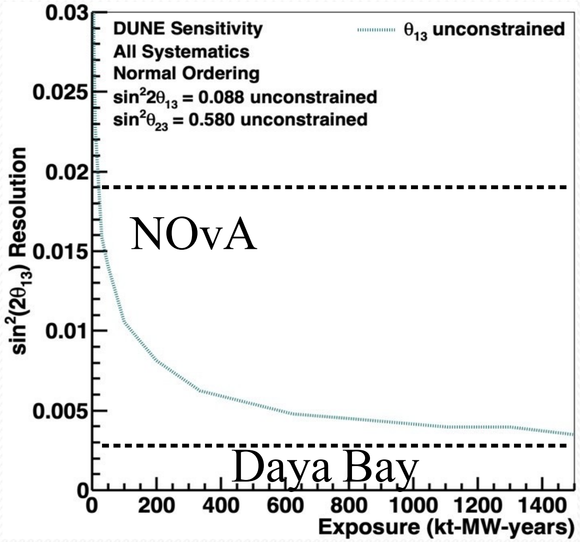
Varying MO and $\sin^2\theta_{23}$



DUNE Phase II: Precision Long Baseline Physics

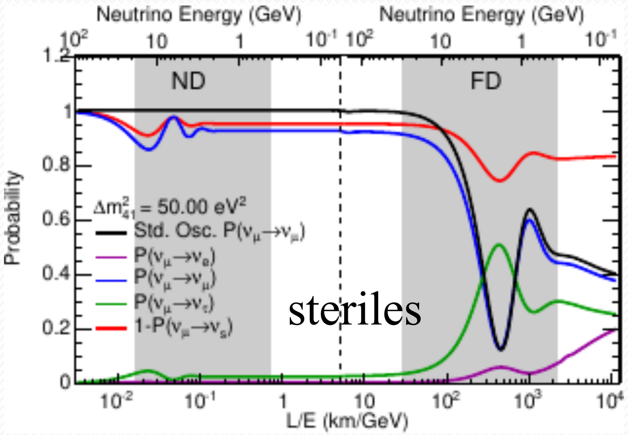


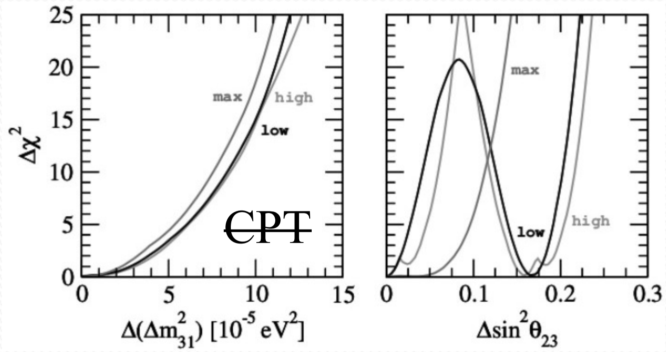


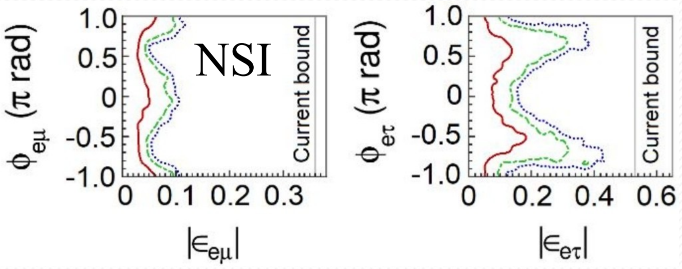


- Resolution to δ_{CP} is ~6-16° depending on true value, and sensitivity to CPV even if Nature is relatively unkind
- Excellent resolution to θ_{23}, including octant discovery potential
- Resolution to θ_{13} approaches Daya Bay, DUNE-reactor comparison is sensitive to new physics

DUNE is Sensitive to New Physics in Neutrino Oscillations

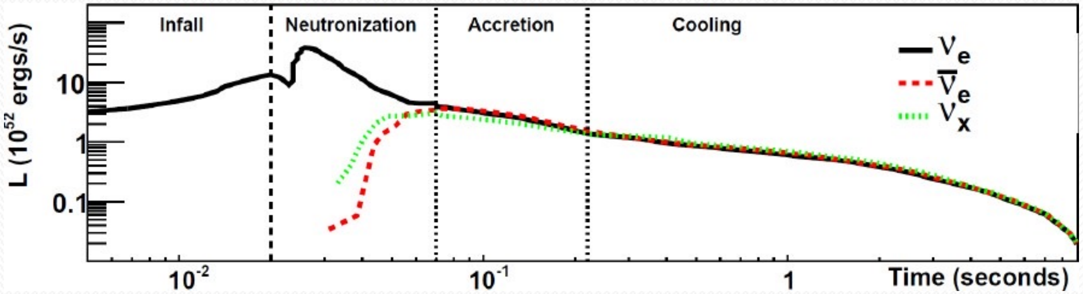


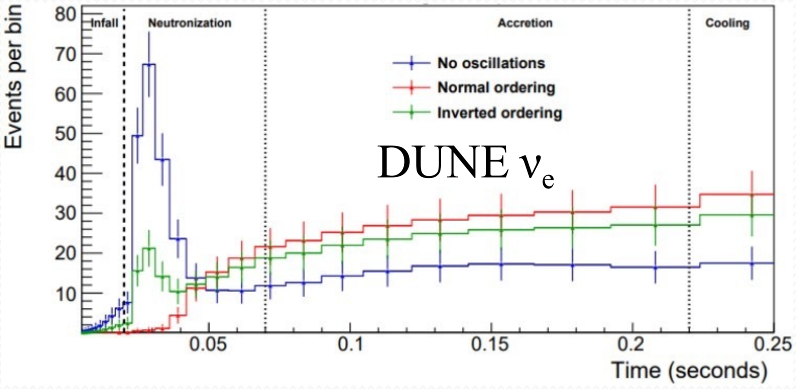




- If ν and $\bar{\nu}$ spectra are inconsistent with three-flavor oscillations, it could be due to sterile neutrinos (top), CPT violation (middle), or NSI (bottom)
  - DUNE covers a very broad range of L/E at both the ND and FD
  - DUNE can measure parameters like Δm^2_{32} with neutrinos and with antineutrinos
  - DUNE has unique sensitivity to NSI matter effects due to long baseline
- Characterizing new physics will be challenging: precise measurements with small matter effect in Hyper-K **and** large matter effect in DUNE Phase II likely required

Supernova Physics: Unique Sensitivity to Electron Neutrinos





	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)

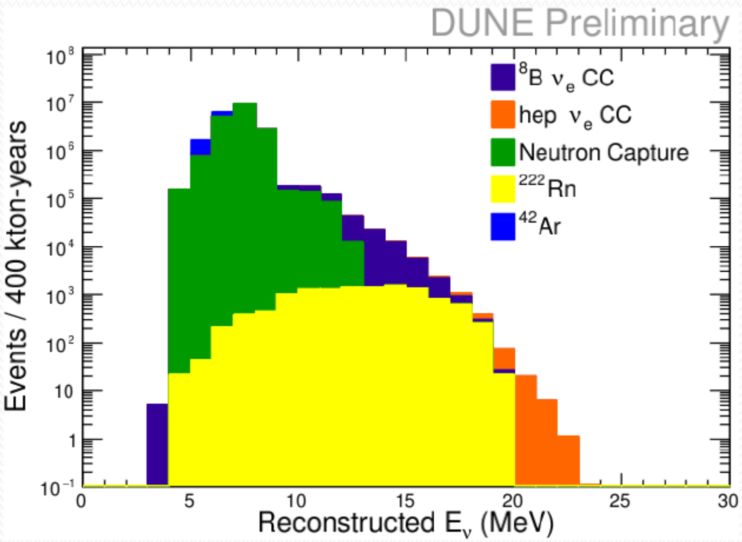
- Time (and energy) profile of the flux is rich in supernova astrophysics

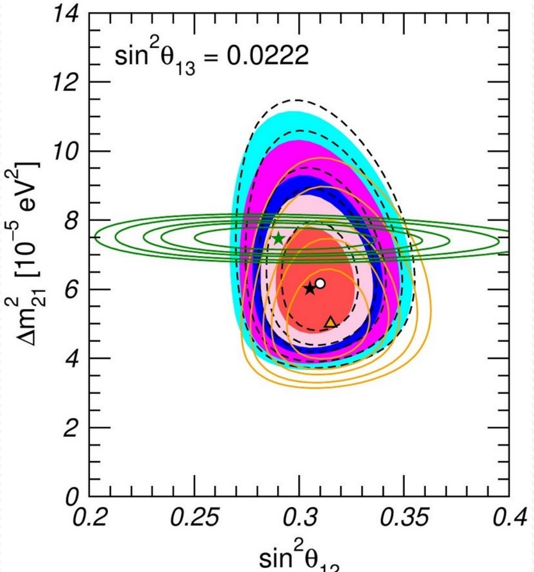
Flux contains ν_e and $\bar{\nu}_e$ as well as a component of the other flavors (ν_x) – DUNE has **unique sensitivity to ν_e** component

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

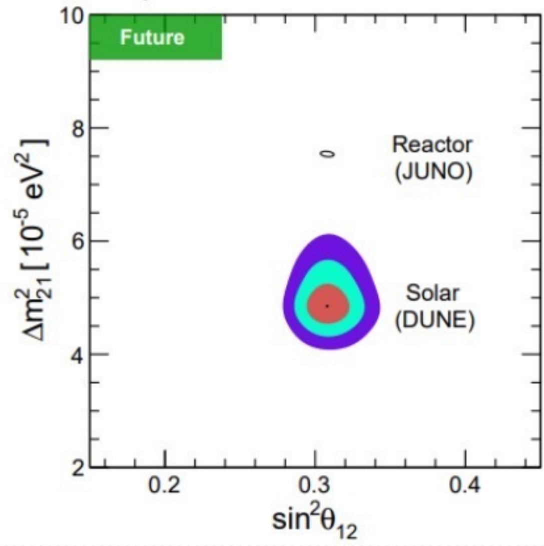
Phase II: Reach extends beyond the Milky Way

Solar Neutrinos: Search for New Physics with DUNE and JUNO





Capozzi et al., PRL **123** 131803



- Despite large neutron background below ~10 MeV, DUNE can measure ^{8}B solar flux and observe hep flux

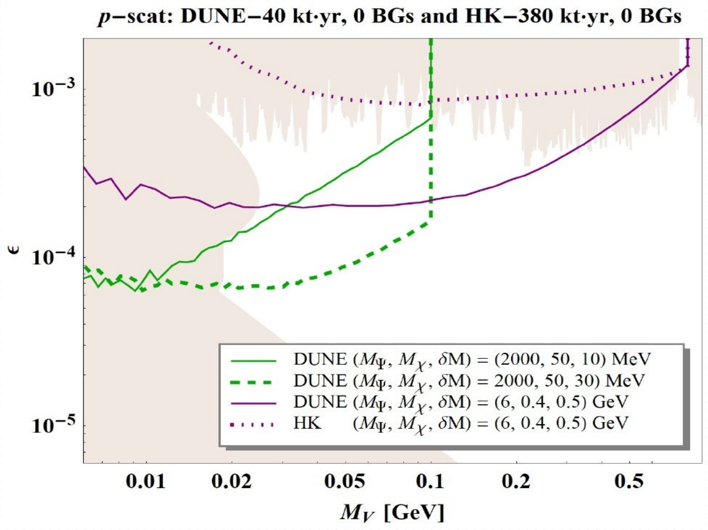
Phase I: >5σ sensitivity to hep flux

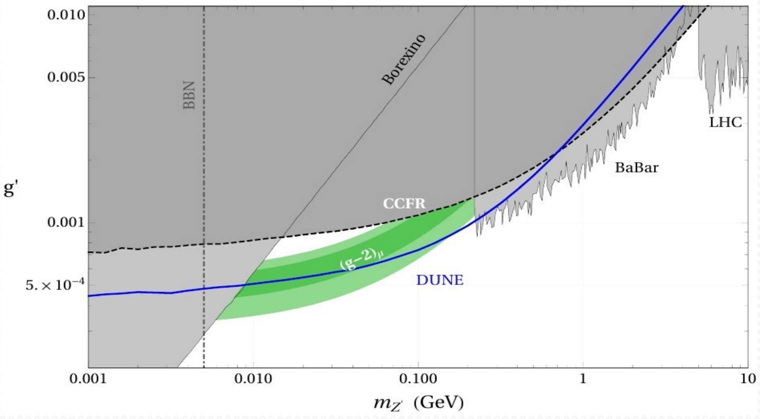
Phase II: DUNE can improve existing θ_{12} and Δm_{21} measurements with solar neutrinos

JUNO will have by far the best precision in θ_{12} and Δm_{12}^2 DUNE-JUNO comparison is sensitive to new physics

aii

BSM physics: unique capabilities of DUNE FD and ND



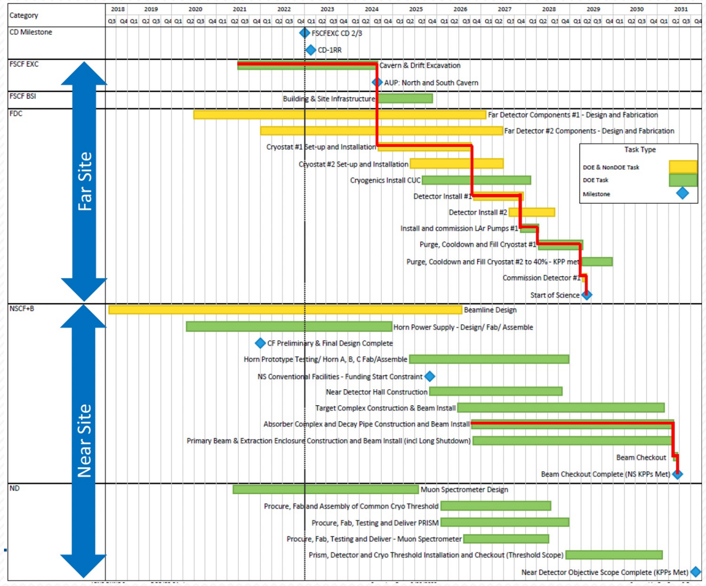


- Hyper-K will have higher statistics, but DUNE’s imaging and spatial resolution are critical for some signals
- Inelastic dark matter scattering gives a signature of two low-energy electron tracks, and a detached low-energy electron or proton
- DUNE can see all of these tracks, and the displacement → world leading sensitivity at low mass already in Phase I

- DUNE ND-LAr will see ~100 μμ tridents per year (at 1.2 MW; XS scales with energy and Z^2)
- DUNE ND: Heavy neutral leptons, boosted dark matter

DUNE Schedule

- Detailed Scheduled developed and tracked by project.
- Physics runs start as soon as FDs are operation (before beam starts)
- ***FD1 LAr filled and commissioned 2029 →*** ***Science (underground) starts***
- FD2 LAr filled and commissioned 2030
- ND filled and commissioned 2031
- ***Beam starts 2031 →*** ***Beam physics starts***
- FD3 LAr filled and commissioned 2034
- FD 4 LAr filled and commissioned 2036



Summary

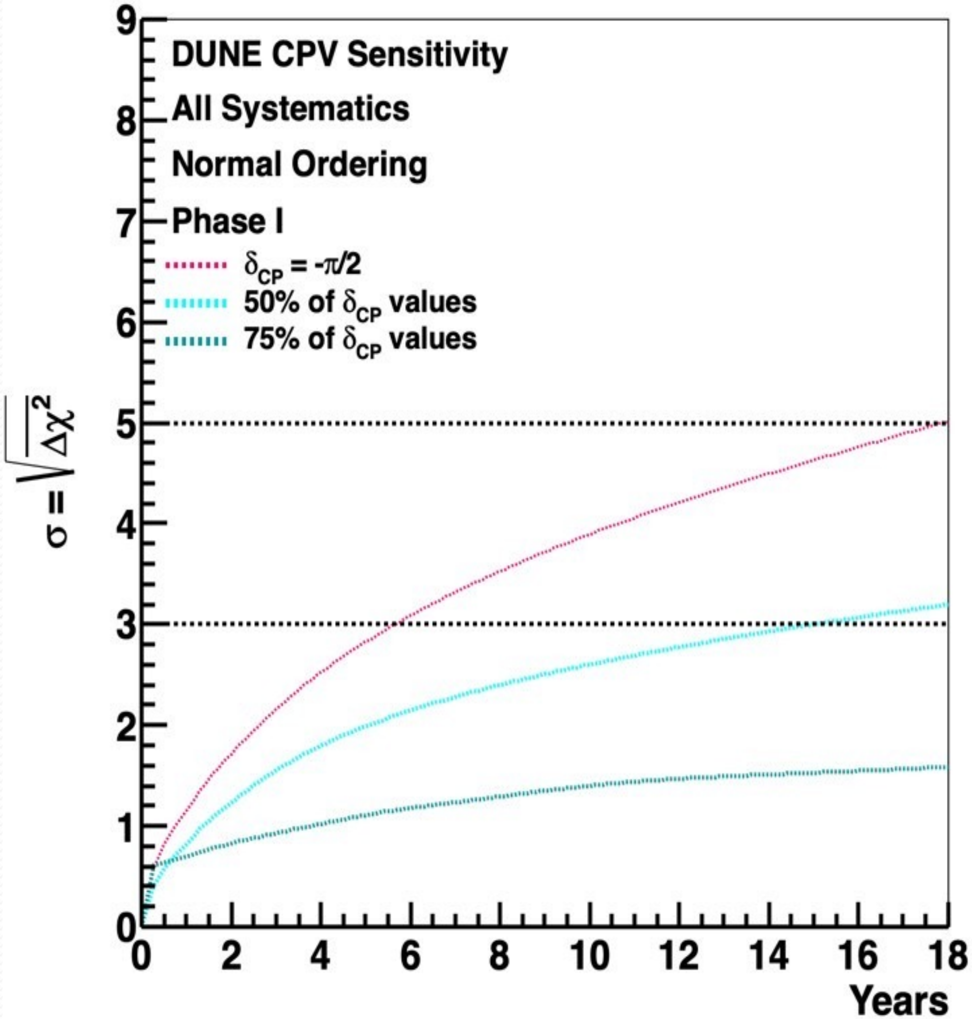
- What makes DUNE unique is extra long baseline, wide band intense neutrino and antineutrino beam, Liquid Argon TPC detector technology and deep underground location

- LBNF provides world-class facilities that will provide for decades to come

- 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

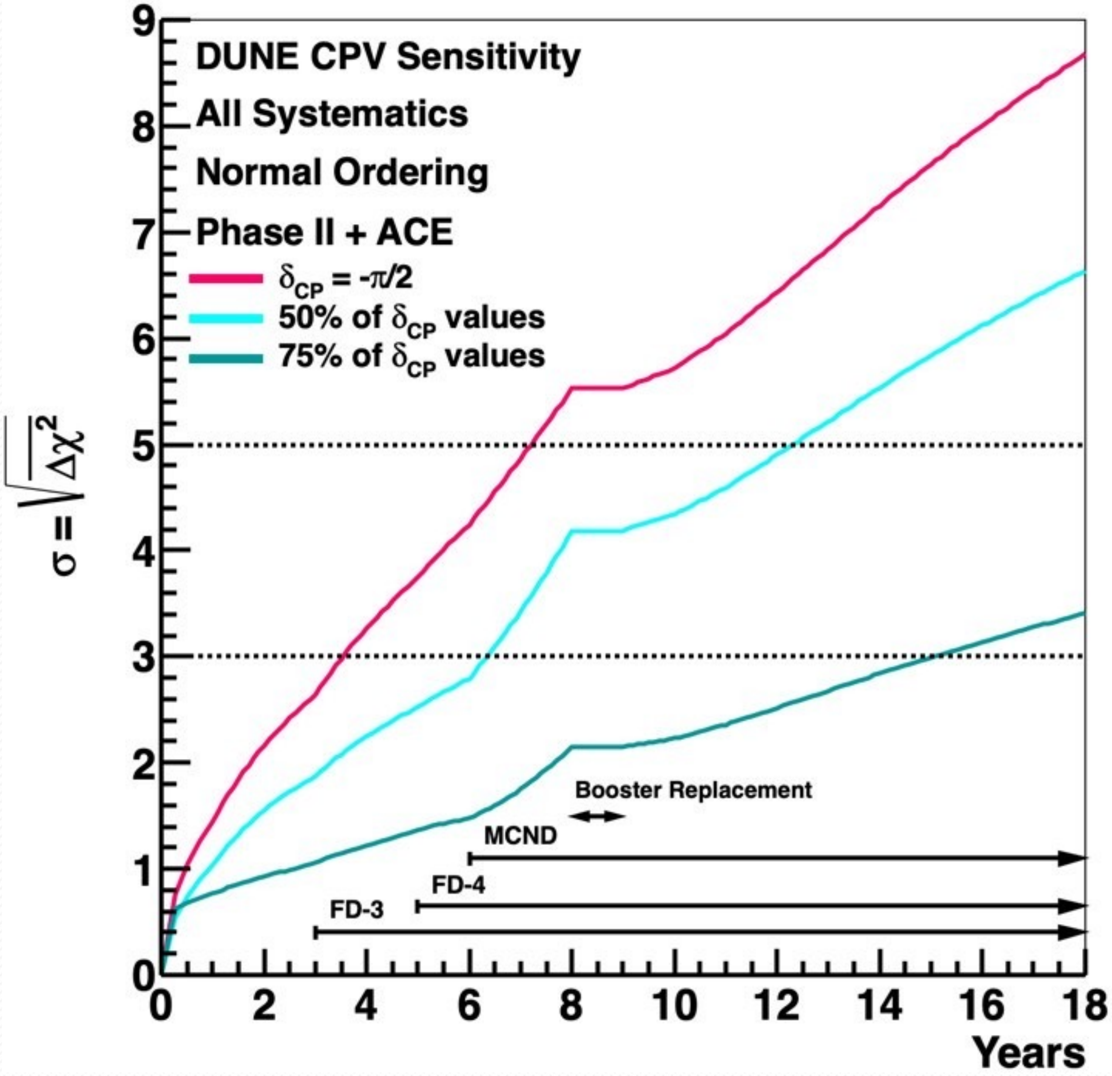
Thank you!

Phase II is required to establish CP violation at high significance



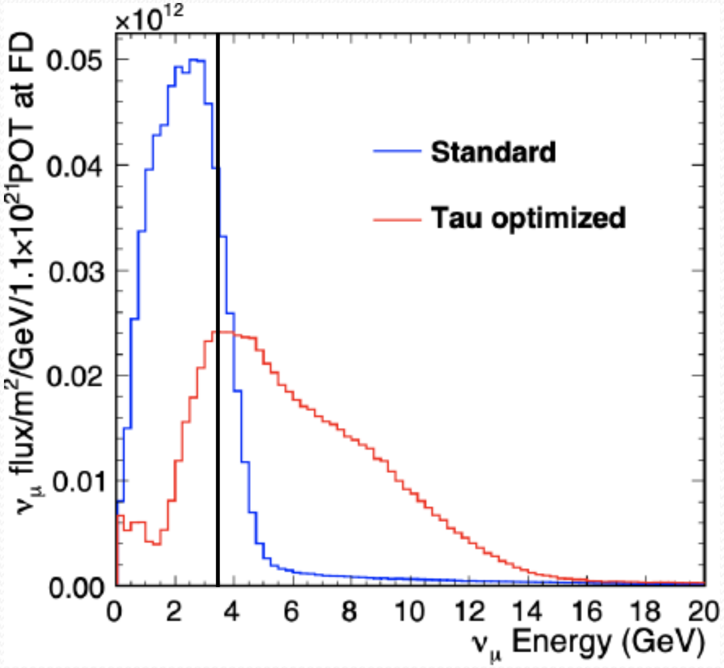
- If δ_{CP} = ±90°, DUNE can establish CP violation at 3σ in Phase I
- For all other oscillation scenarios, DUNE requires Phase II to establish CP violation

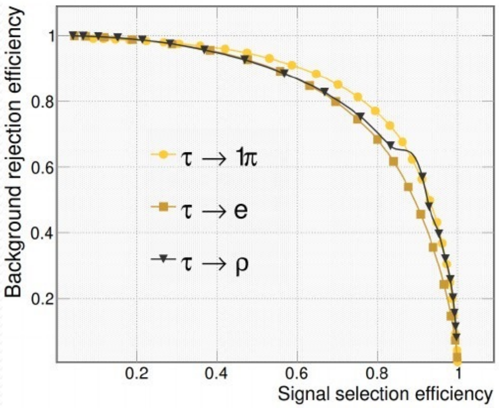
Timeline for CP violation: it depends on the value of δ



- If δ_{CP} = ±90°, DUNE reaches 3σ CPV in 3.5 years, 5σ in 7 years
- HyperK will likely get there first, if/when the mass ordering is known
- If δ_{CP} = ±23°, it is extremely challenging to establish CP violation at 3σ → DUNE and HyperK are competitive and complementary

Unique to DUNE: three-flavor measurements, including taus





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 flux above the τ 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 τ physics that is accessible in IceCube