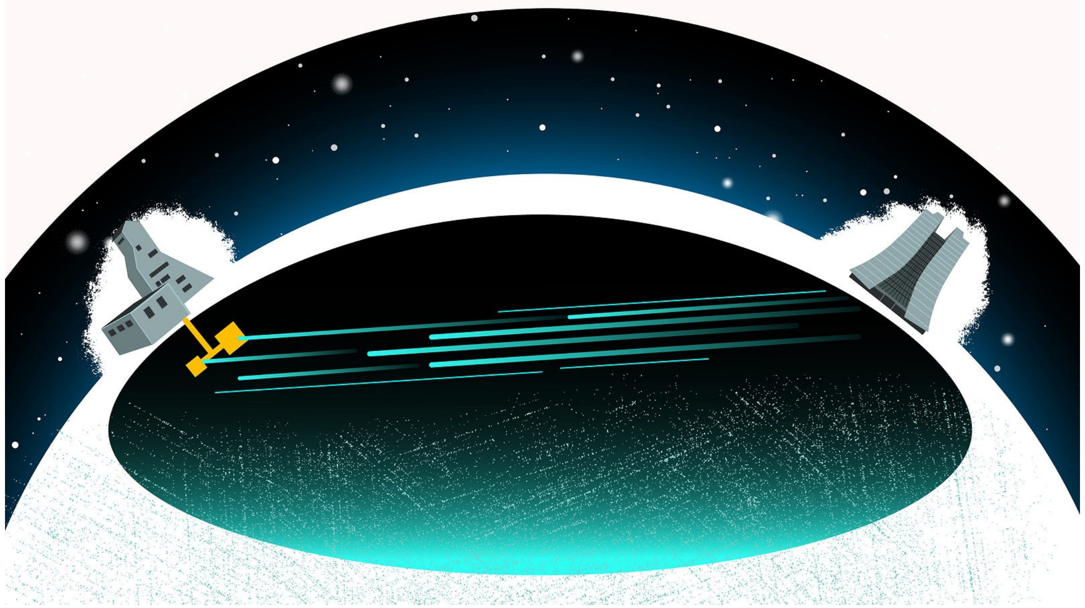
The DUNE Physics Program

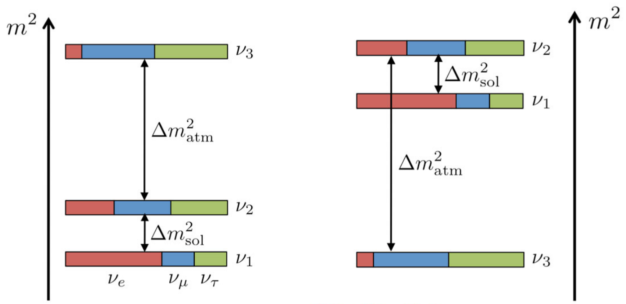
Inés Gil-Botella (CIEMAT)

MidTerm Review of SENSE

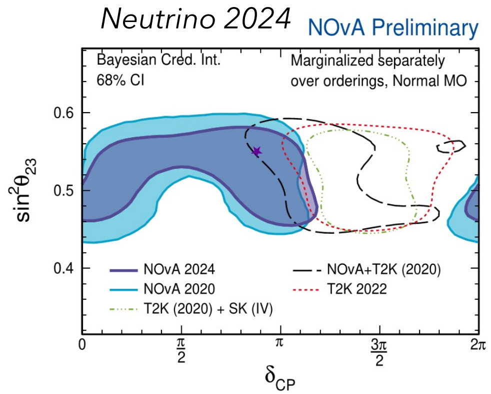


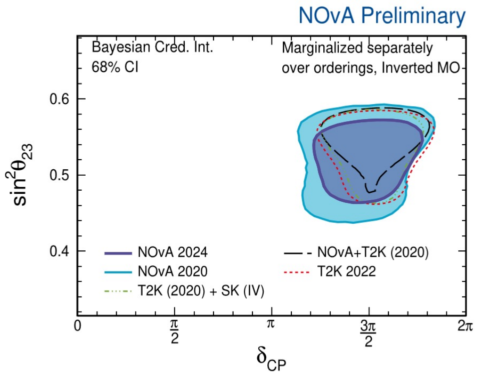
Long-baseline neutrino oscillations

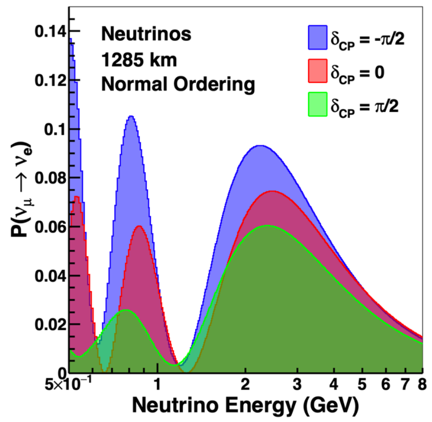
$$U_{\rm PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & e^{-i\delta_{\rm CP}} s_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{\rm CP}} s_{13} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

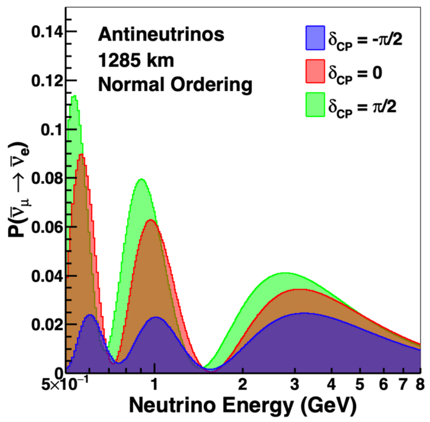


- **Goals** for next generation experiments:
  - Determine the neutrino mass ordering
  - Determine the octant of θ_{23}
  - Measure δ_{CP} and determine if CP is violated
- **Is the 3-flavor model correct?**
  - Provide precise measurements of neutrino and antineutrino oscillations as a function of L/E
- **Complementary** approaches are needed: different neutrino energies, matter effects, systematics…

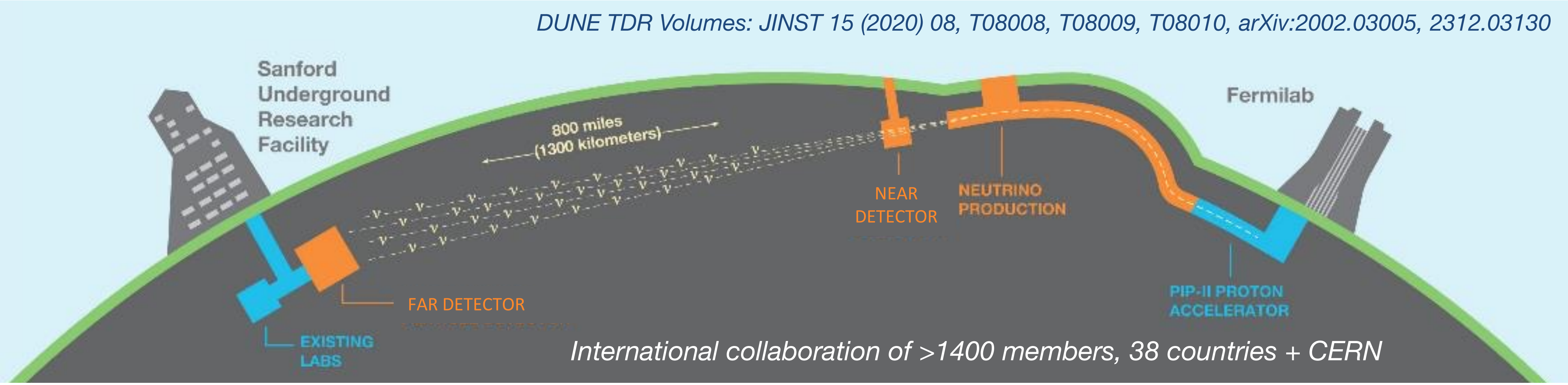








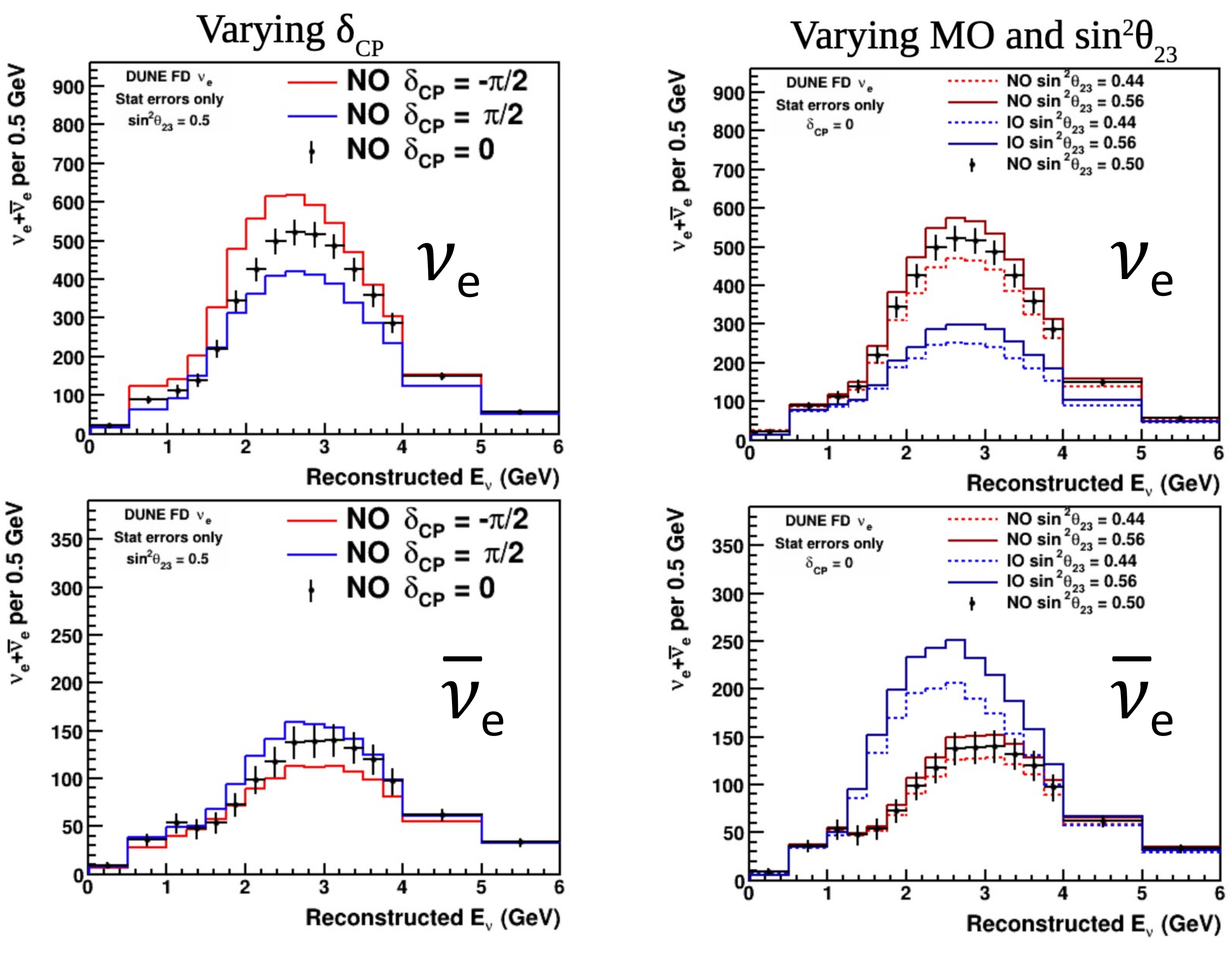
The Deep Underground Neutrino Experiment



- The **most powerful neutrino beam in the world** (>2 MW) will be sent from Fermilab (Chicago) to SURF (South Dakota) along 1300 km distance to be detected by four liquid argon **far detector** modules (70 kton LAr) at 1.5 km deep underground and a **near detector** complex at 560 m from the neutrino source
  - The **long baseline** enables an unambiguous measurement of the neutrino mass ordering
  - The **wide-band energy spectrum** of neutrinos enables detailed fitting of the oscillation parameters
  - **LArTPC technology** enables precise reconstruction of the neutrino interactions
  - The FD **underground location** enables astrophysical measurements
  - The **ND complex** enables unprecedented control of systematic uncertainties

Neutrino energy spectra at the Far Detector

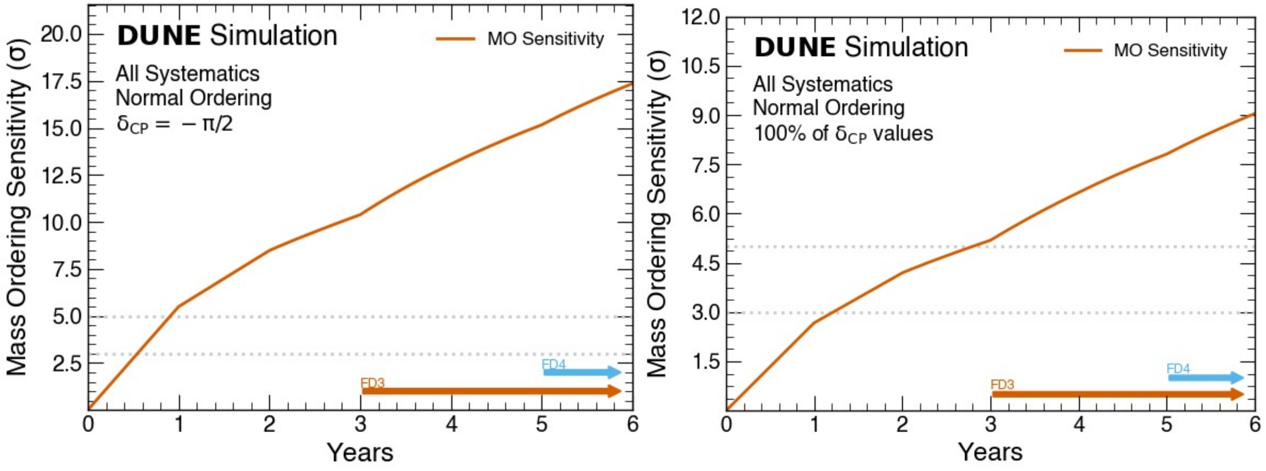
- Sensitivity to δ_{CP}
  - If δ_{CP} ~ $-\pi/2$, DUNE will measure an enhancement in electron neutrino appearance, and a reduction in electron antineutrino appearance
- Sensitivity to mass ordering (**MO**)
  - If MO is normal, DUNE will measure a <u>much larger</u> enhancement in electron neutrino appearance, and a reduction in electron antineutrino appearance
- MO, δ_{CP}, and θ_{23} all affect spectra with different shape → additional handle on resolving degeneracies



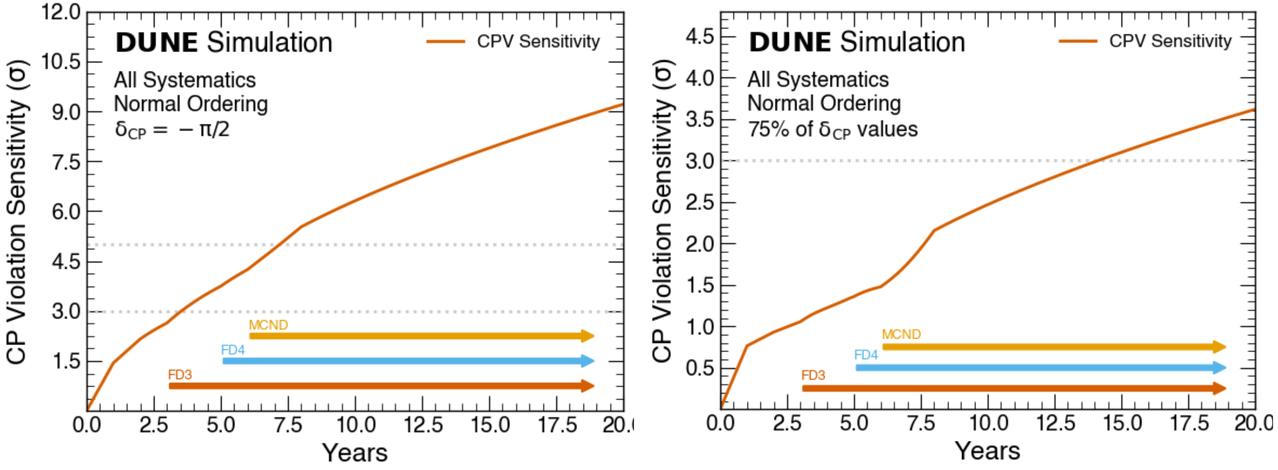
DUNE sensitivity

Neutrino mass ordering

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



CP violation sensitivity



- For best-case oscillation scenarios, DUNE has

  >5σ mass ordering sensitivity in 1 year

  >3σ CPV sensitivity in 3.5 years

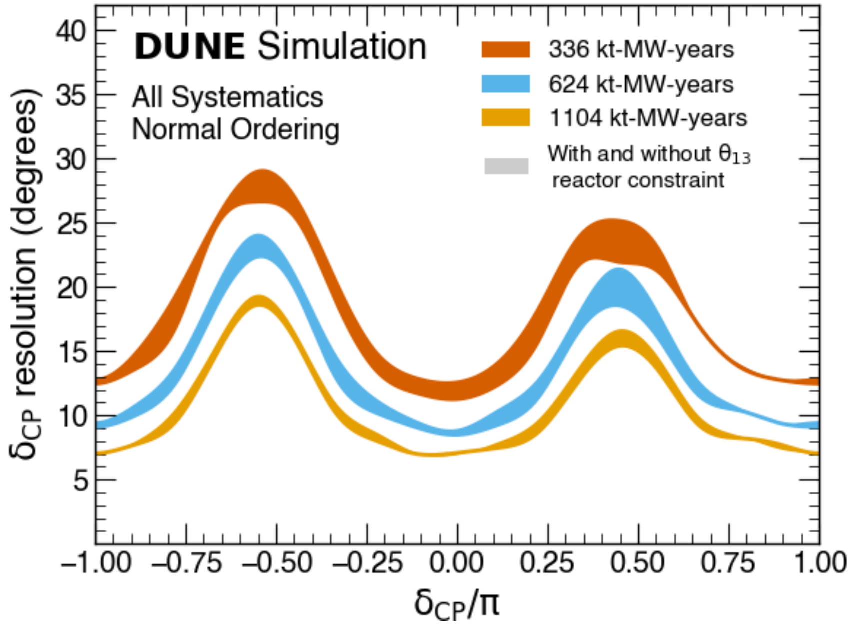
- For worst-case oscillation scenarios, DUNE has >5σ mass ordering sensitivity in 3 years

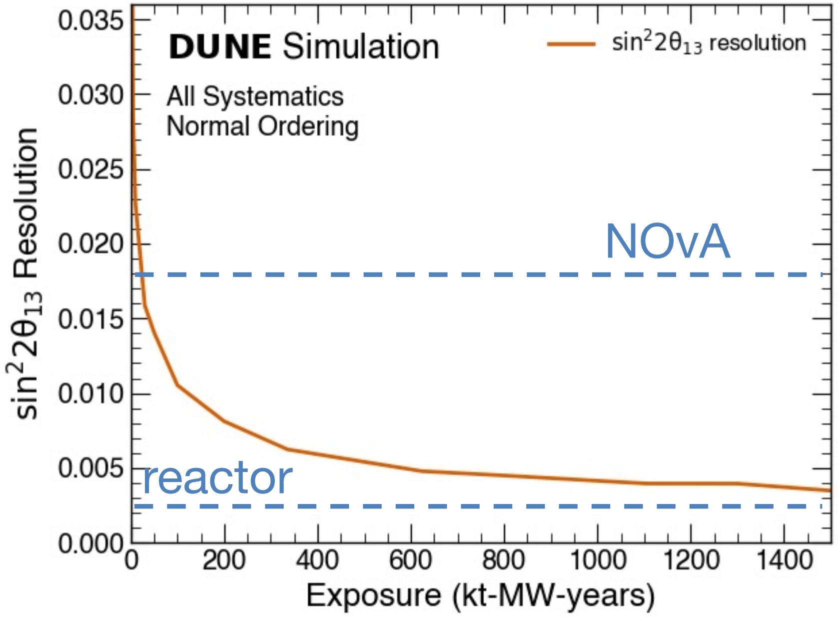
- In long term, DUNE can establish CPV over 75% of δ_{CP} values at >3σ

DUNE precise measurements

- Ultimate precision 6-16° in $\boldsymbol{\delta_{CP}}$
- World-leading precision (for long-baseline experiment) in $\boldsymbol{\theta_{13}}$ → comparisons with reactor measurements are sensitive to new physics

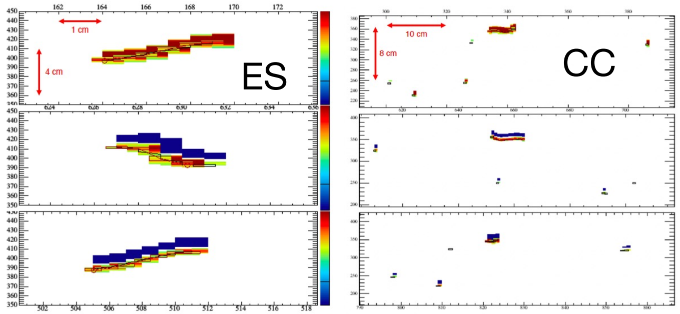
δ_{CP}





θ_{13}

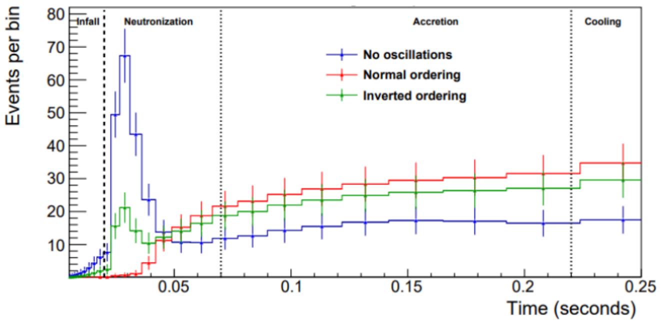
Astrophysical neutrinos in DUNE



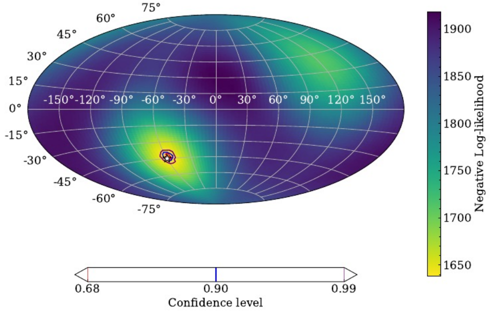
Unique sensitivity to MeV electron neutrinos: CC $\nu_e + Ar \rightarrow e^- + {}^{40}K^*$ *(main channel)*
ES $\nu_x + e^- \rightarrow \nu_x + e^-$ *(pointing)*

Neutrinos from core-collapse supernovae

- **Neutronization** burst measurements → mass ordering measurement *Eur. Phys. J. C 81 (2021) 5, 423* *Phys.Rev.D 107 (2023) 11, 112012*



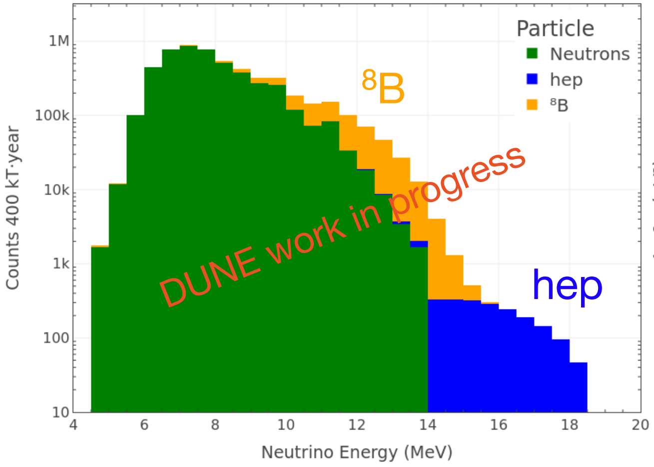
- **Pointing** capabilities: ES channel ~5° pointing resolution



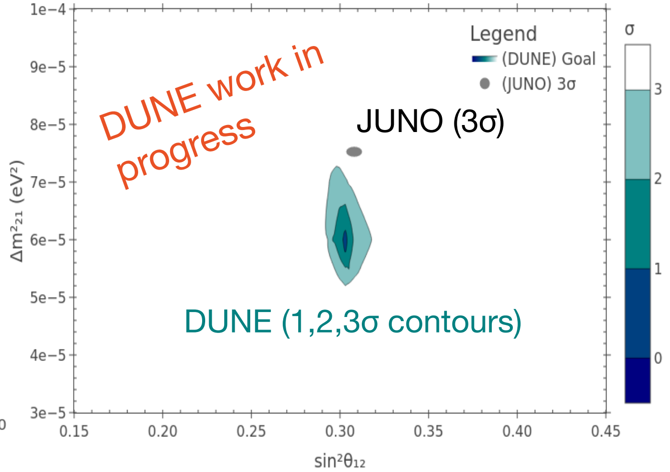
Neutrinos from the Sun

- DUNE has excellent sensitivity to **^{8}B solar neutrinos** above ~10 MeV, and discovery sensitivity to the **hep solar flux**
- DUNE can improve upon existing solar oscillation measurements via **day-night asymmetry** induced by matter effects → comparison with JUNO

Reco solar ν_e spectrum in DUNE



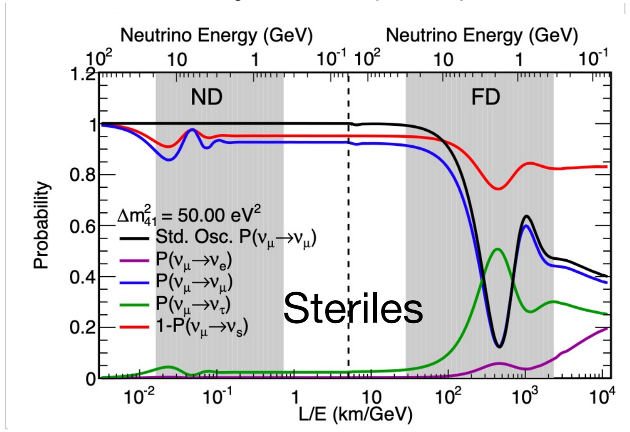
DUNE goal contours for solar best-fit

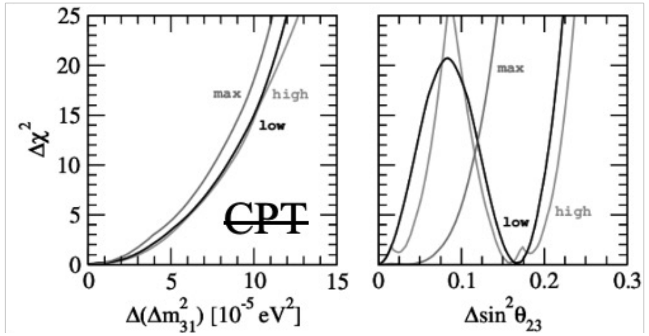


Beyond of Standard Model searches

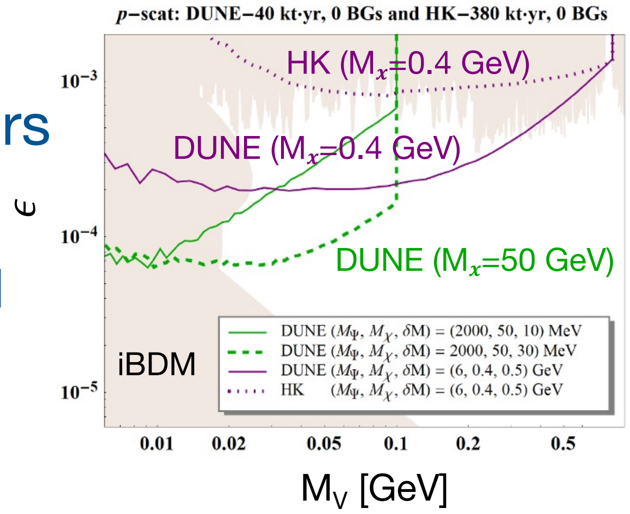
- **New physics in neutrino oscillations**: If ν and $\bar{\nu}$ spectra are inconsistent with three-flavor oscillations, it could be due to sterile neutrino mixing, CPT violation, Non Standard Interactions (NSI)…
  - DUNE covers a very broad range of L/E at both the ND and FD
  - High statistics in ν & $\bar{\nu}$ measurements → search for CPT violation
  - DUNE has unique sensitivity to NSI matter effects due to long baseline

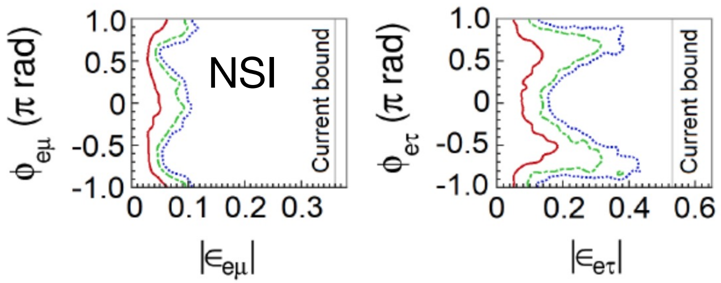
Eur. Phys. J. C (2021) 81:322



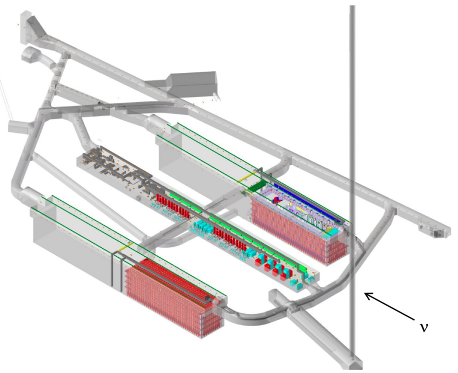


- Other **BSM** in Far and Near Detectors
  - Dark matter at FD & ND, nucleon decay, n-$\bar{n}$ oscillations, heavy-neutral leptons, neutrino tridents, ...

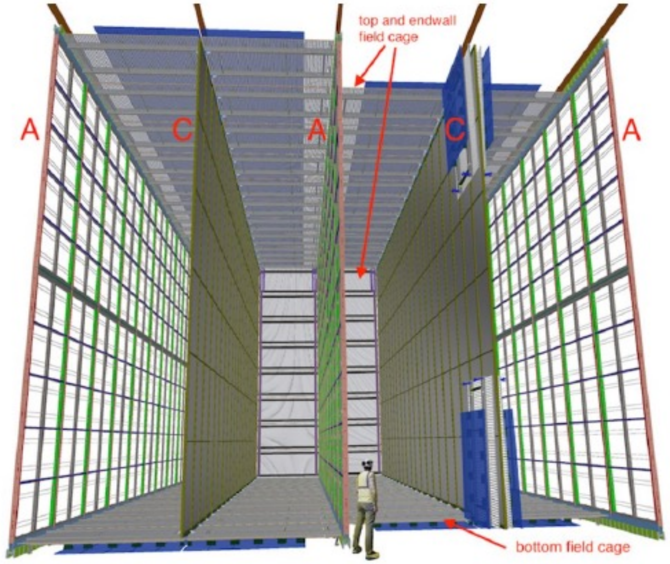




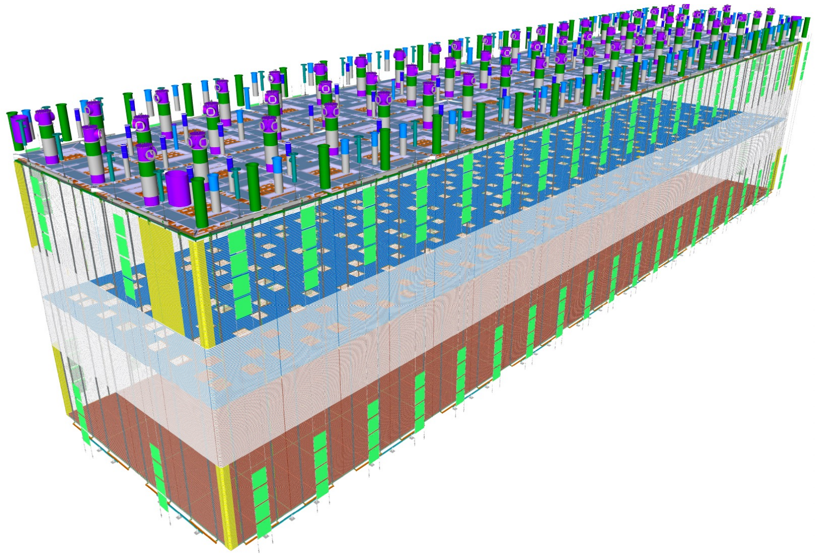
Far Detector Technologies



***FD-HD**: JINST 15 T08010 (2020)*

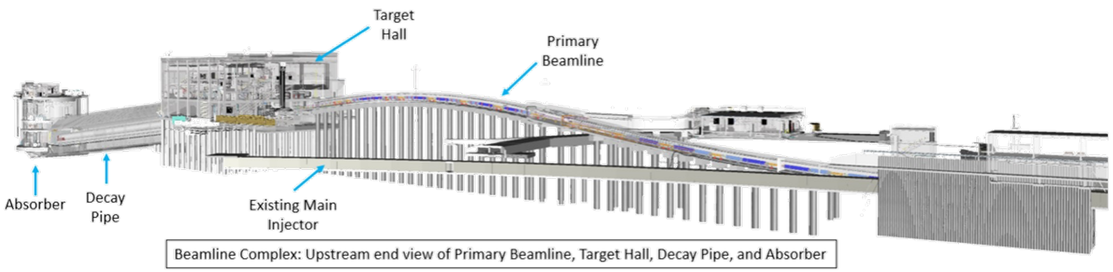


***FD-VD**: arXiv:2312.03130 (2023)*



- Horizontal drift (FD-HD) using wire readout planes, four drift regions (3.6m)
- Vertical drift (FD-VD) using two 6.25m drift regions and central cathode
  - Simpler to install → first DUNE FD module will use vertical drift
  - VD is baseline design for FD modules 3 and 4

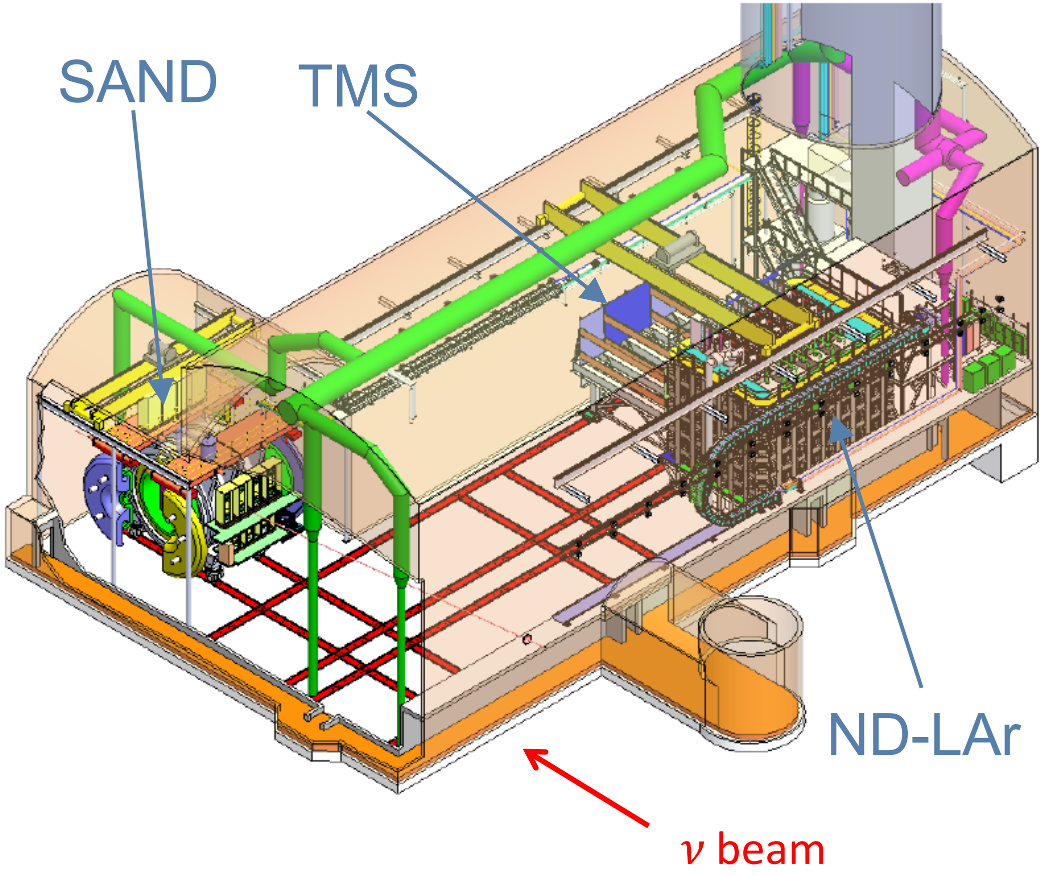
Near Detector Complex



- Main purpose: enable prediction of Far Detector reconstructed spectra

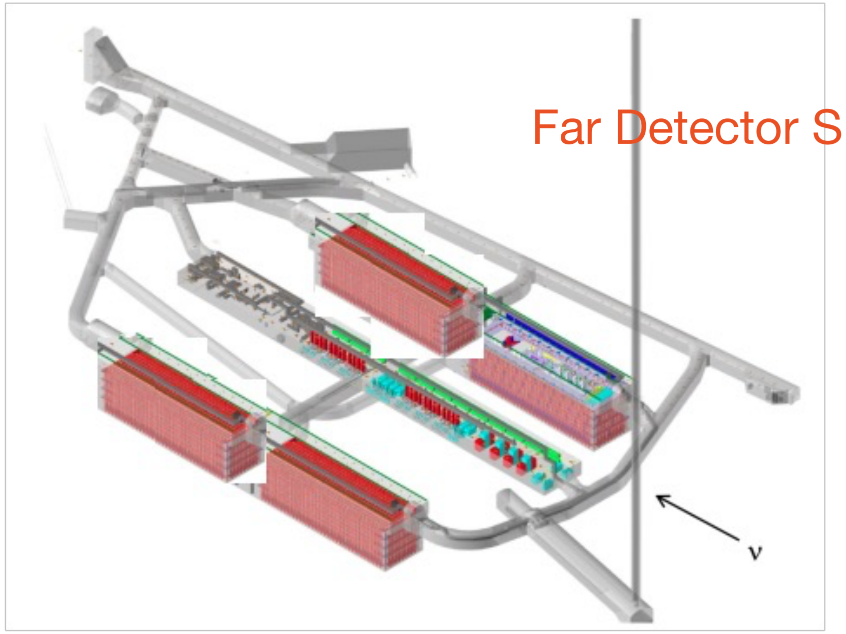
- Movable detector system: LArTPC (**ND-LAr**) with muon spectrometer (**TMS**)
  - Off-axis data in different neutrino fluxes constrains energy dependence of neutrino cross sections
  - Same target, same technology → inform predictions of reconstructed E_ν in Far Detector

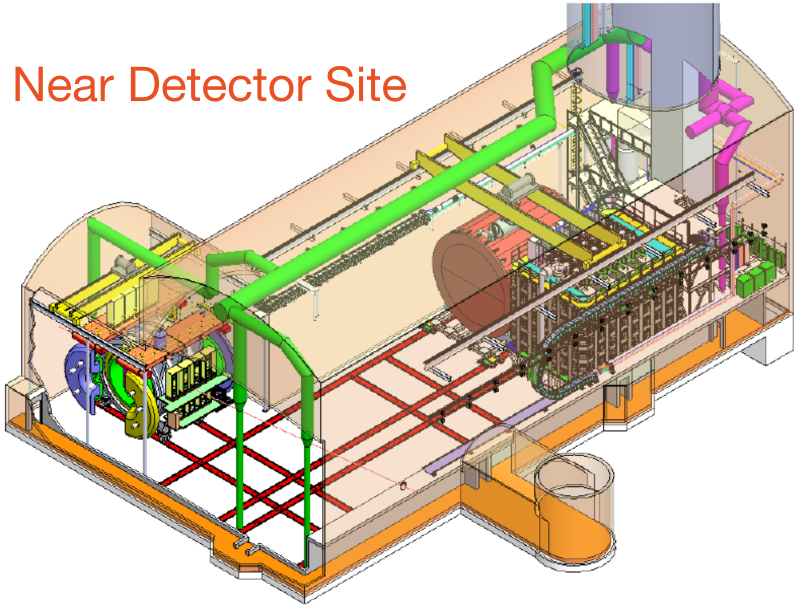
- On-axis magnetized detector (**SAND**) for beam monitoring and neutrino measurements



DUNE Phases

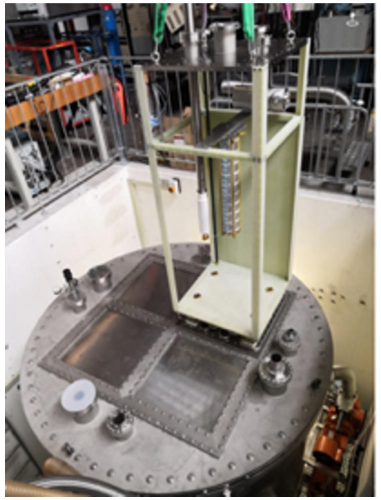
- **DUNE Phase I** (2026 start detector installation; 2029 physics; 2031 beam + ND)
  - Full near + far site facility and infrastructure
  - Two 17 kt LArTPC modules
  - Upgradeable 1.2 MW neutrino beamline
  - Movable LArTPC near detector with muon catcher
  - On-axis near detector
- **DUNE Phase II**:
  - Two additional FD modules (≥40 kt fiducial in total)
  - Beamline upgrade to >2 MW (ACE-MIRT)
  - More capable Near Detector (ND-GAr)

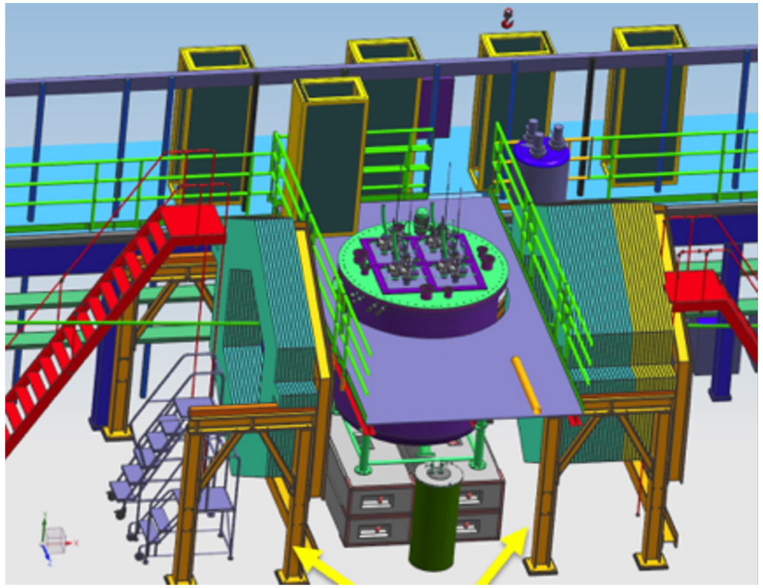




2x2 ND-LAr demonstrator at Fermilab

- **ND challenge**: neutrino pile-up (several dozens of neutrinos per spill)
  - Very high rate at near site motivates pixelated readout and optical modularity
- **Four LArTPC modules** built and operated in LAr in Bern with a total of ~330k pixel channels
- Operation of **2x2 ND-LAr in NuMI Neutrino Beam**
  - Four TPC modules installed in former location of MINOS-ND
  - Includes upstream/downstream trackers, repurposed from MINERvA
- **Goals**: Demonstrate reconstruction with natively 3D readout in a neutrino beam with similar event rate to DUNE

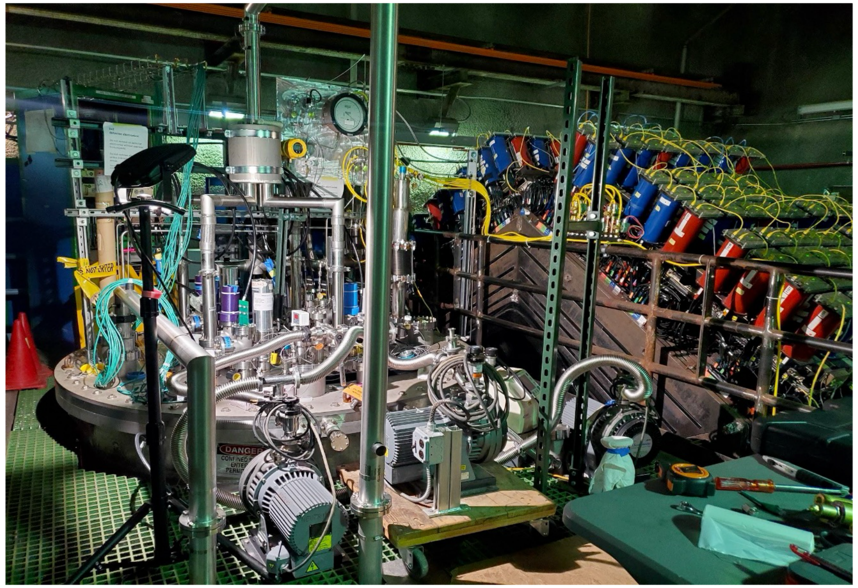


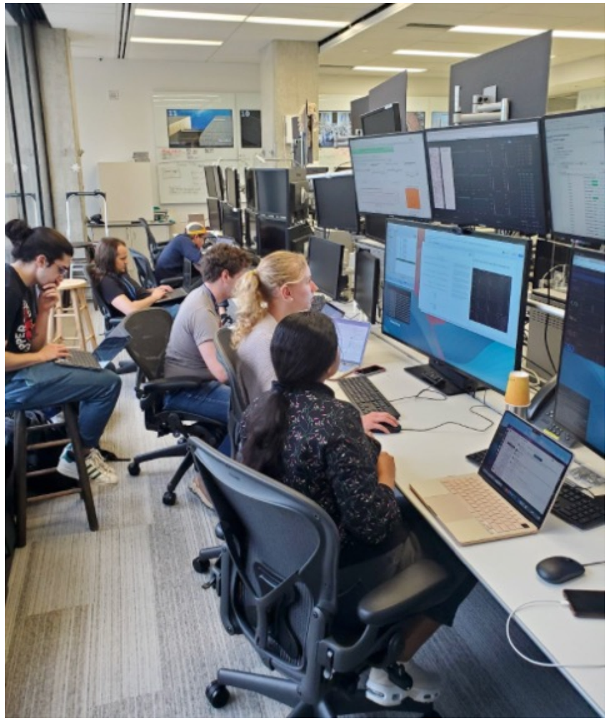


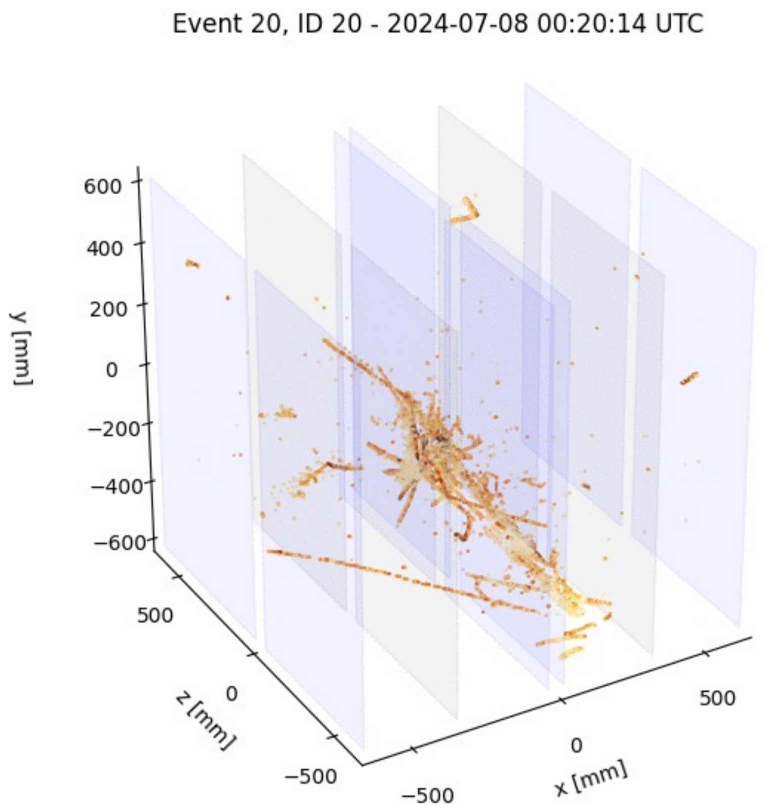
2x2 ND-LAr demonstrator at Fermilab

- Cooldown and argon filling finished May 31
- 24/7 shifts since early June
- Operating since July 8 at NuMI

First DUNE Near Detector 2x2 Demonstrator neutrino events (July 2024)

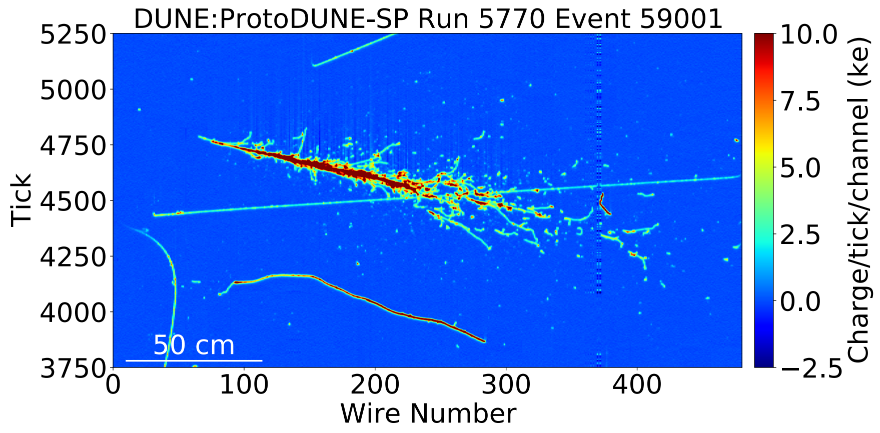


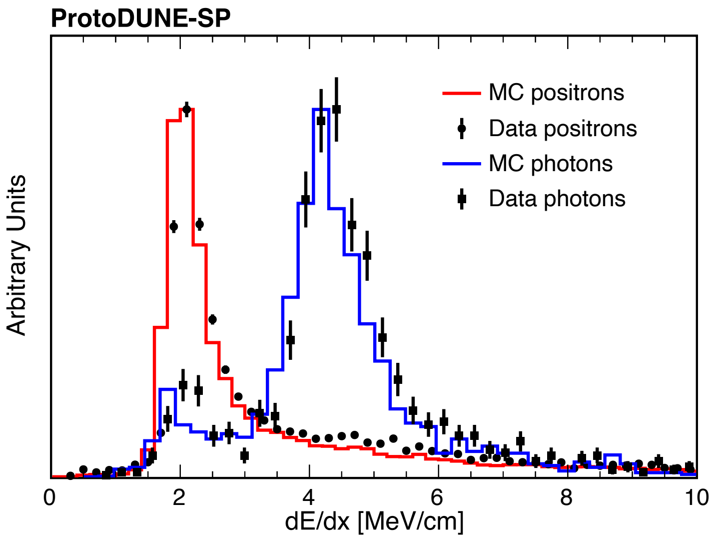


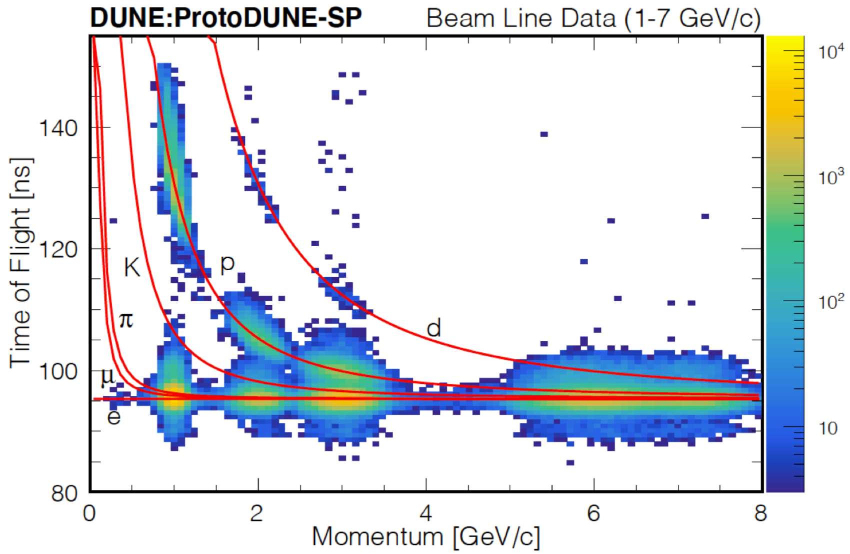


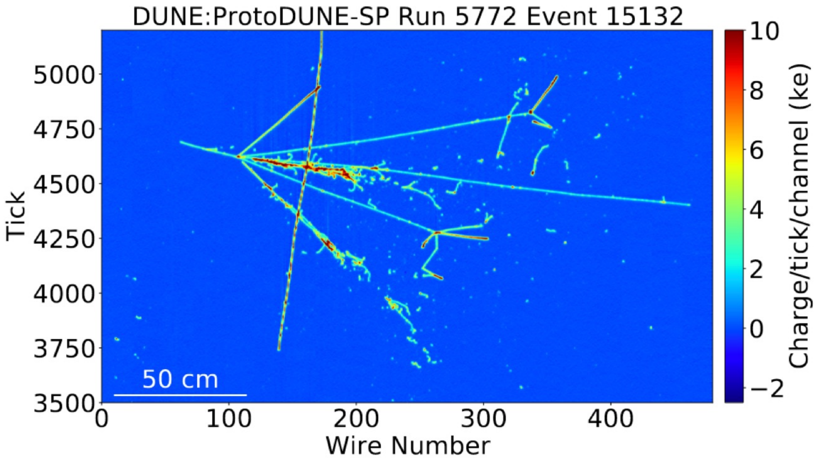
FD: ProtoDUNEs at CERN (1st Phase)

- **1st Phase of ProtoDUNEs**
  - Construction and operation of ProtoDUNEs at CERN (2018-2020)
  - Successful demonstration of the DUNE LAr TPC performance
  - Several ongoing analyses (hadron-Ar cross sections…)









FD: ProtoDUNEs at CERN (2nd phase)

- 2nd Phase of ProtoDUNEs (2020-2023 construction + operation ≥2024)

  <u>ProtoDUNE-HD</u>

  - Final technical solutions for all FD-HD subdetectors
  - Data taken with charged-particle test-beam and cosmic muons at CERN

  <u>ProtoDUNE-VD</u>

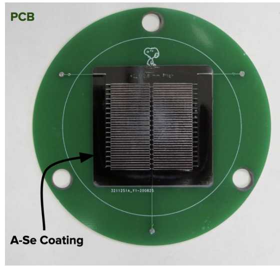
  - Realization of a Module-0 detector in 2022-2023
  - Detector filled and ready to take data in early 2025

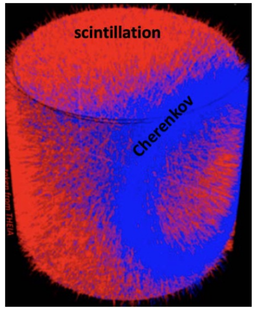
CERN

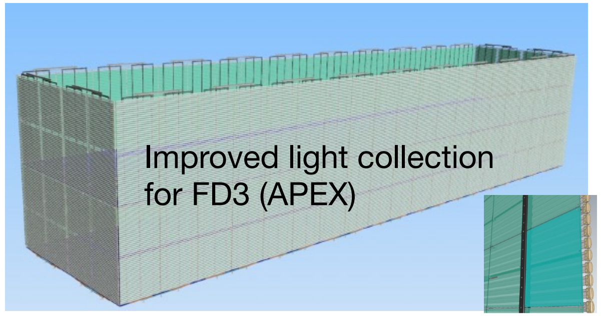
Neutrino PLATFORM

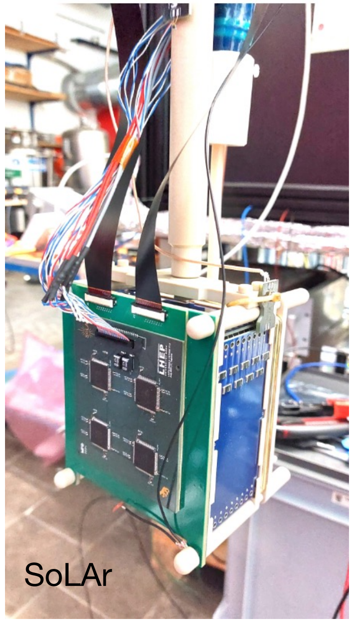
More opportunities for Phase II detectors

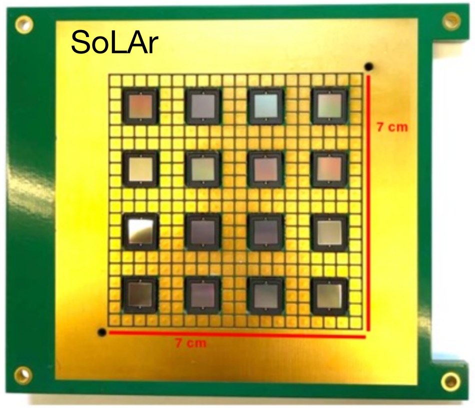
- Vertical Drift module is the baseline design for Phase II FD modules
- Pursuing improvements to light collection for FD3, including Aluminum Profiles with Embedded X-ARAPUCA (APEX)
- The phased construction program allows the development of the technology to expand the DUNE physics scope (solar, supernova neutrinos, $0\nu\beta\beta$, dark matter…)
- FD4 is the “Module of Opportunity”, and more ambitious designs are being considered, including pixel readout, integrated charge-light readout, low background modules, and non-LAr technologies











Summary

- DUNE is a **best-in-class long-baseline neutrino oscillation experiment** currently under construction in US
  - DUNE has the potential to deliver groundbreaking results as the unambiguous determination of the neutrino mass ordering and the discovery of leptonic CP violation
- DUNE has **unique sensitivity to MeV-scale neutrinos**
  - Excellent sensitivity to SN ν_e, potential to discover hep solar flux & measure the solar neutrino parameters
  - Opportunities to greatly enhance the detector performance and extend the low-E physics reach in Phase II
- DUNE has a **rich and broad BSM program** including search for BSM oscillations with large L/E range and large matter effect
- DUNE is both **competitive** with, and **complementary** to the global experimental program
- A very active **prototyping program** at large scale is **underway at CERN and Fermilab** together with an **ongoing R&D program** for DUNE Phase II detectors
- **DUNE science begins in this decade!**

Thanks

DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT