

The Deep Underground Neutrino Experiment (DUNE) Program

Inés Gil-Botella
on behalf of the DUNE Collaboration

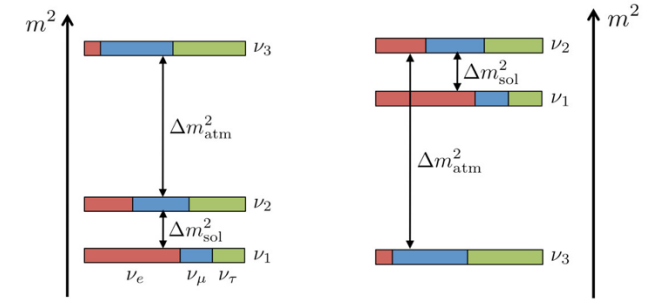
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Physics (ICHEP 2024)

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Long-baseline neutrino oscillations

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



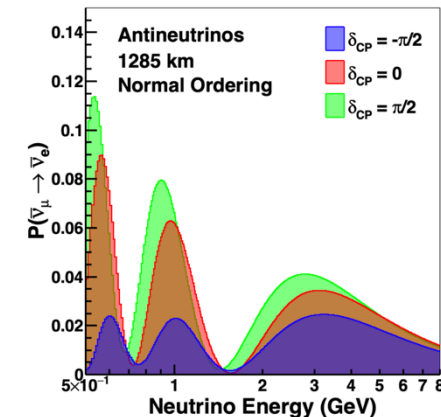
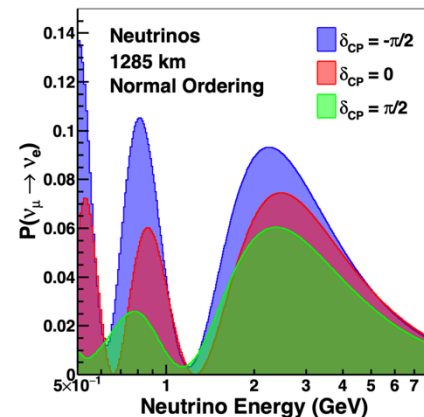
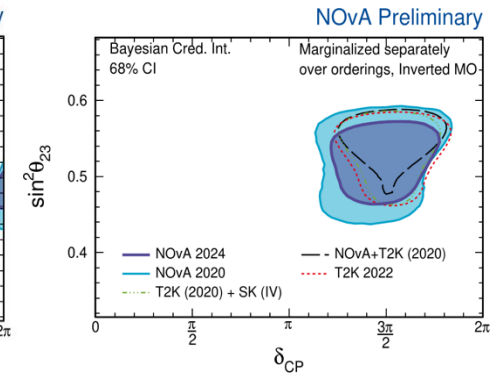
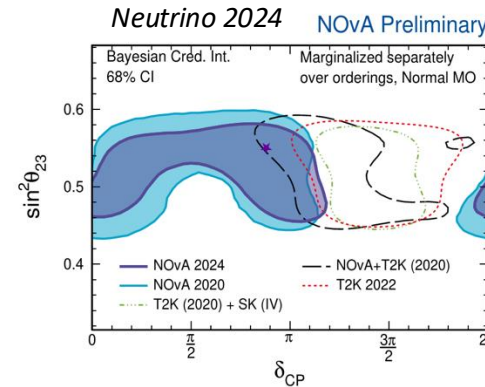
- **Goals** for next generation experiments:

- Determine the neutrino mass ordering
- Determine the octant of θ_{23}
- Measure δ_{CP} and determine if CP is violated

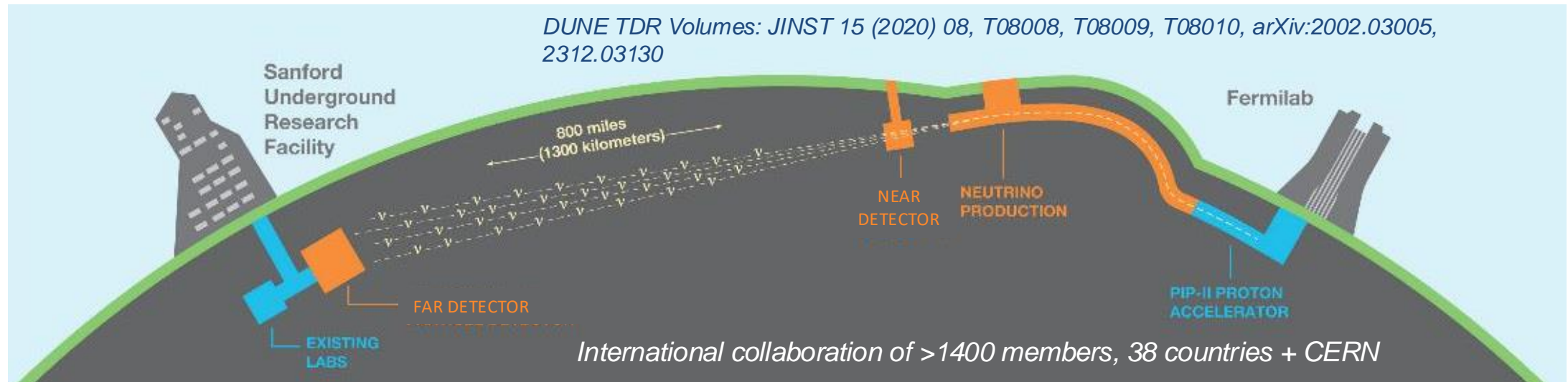
- **Is the 3-flavor model correct?**

- Provide precise measurements of neutrino and antineutrino oscillations as a function of L/E

- **Complementary** approaches are needed: different neutrino energies, matter effects, systematics...



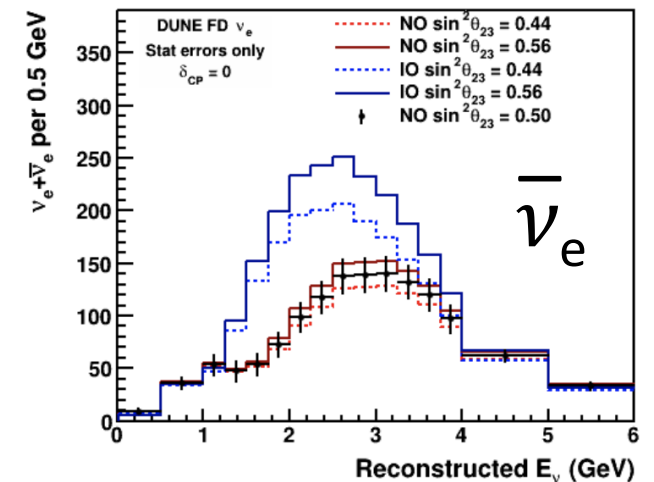
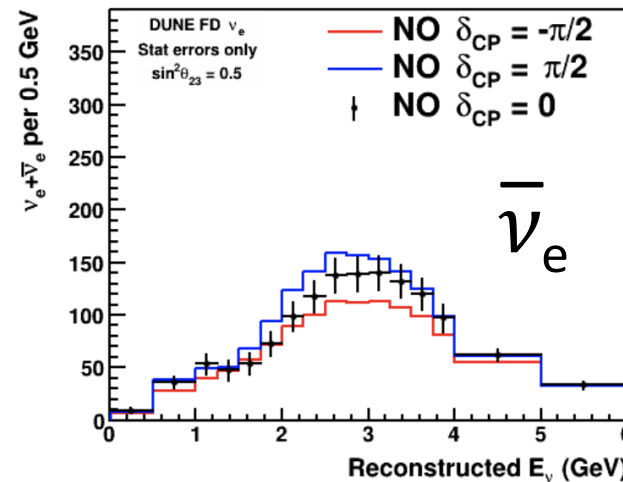
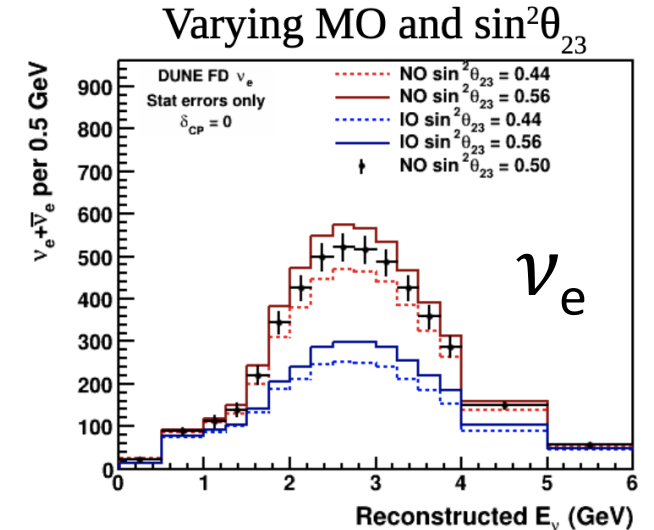
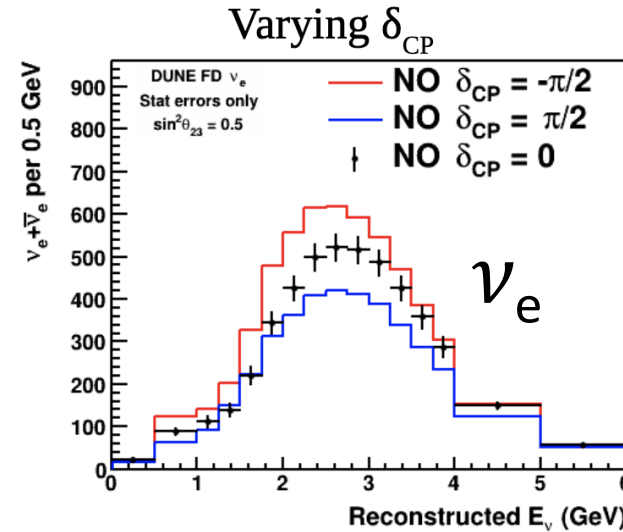
The Deep Underground Neutrino Experiment



- 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

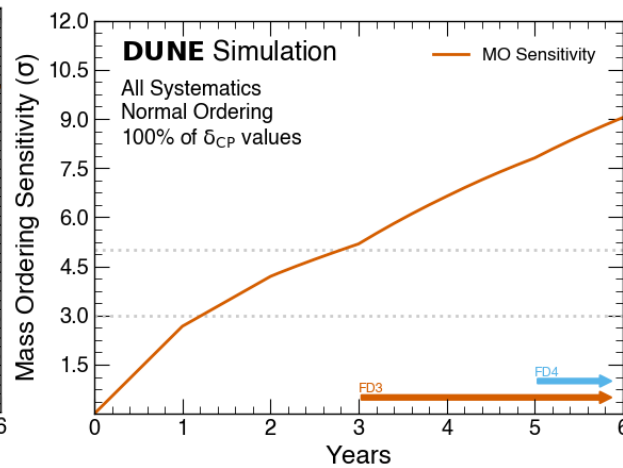
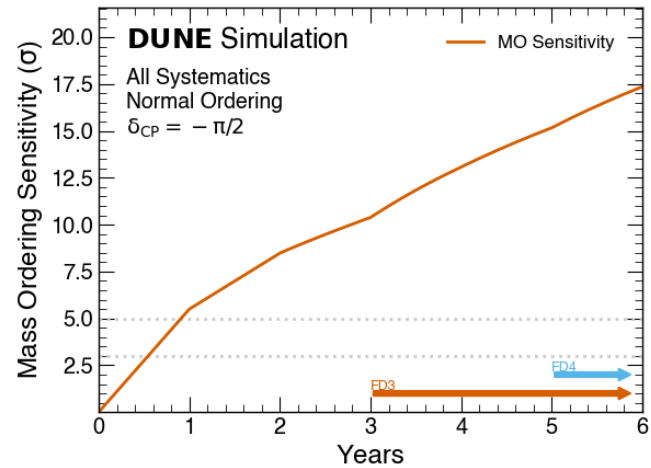
- Sensitivity to δ_{CP}
 - If $\delta_{CP} \sim -\pi/2$, DUNE will measure an enhancement in electron neutrino appearance, and a reduction in electron antineutrino appearance
- Sensitivity to mass ordering (MO)
 - If MO is normal, DUNE will measure a much larger enhancement in electron neutrino appearance,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



DUNE sensitivity

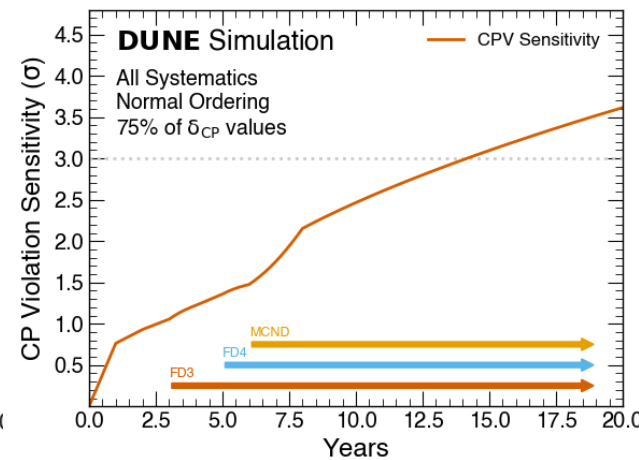
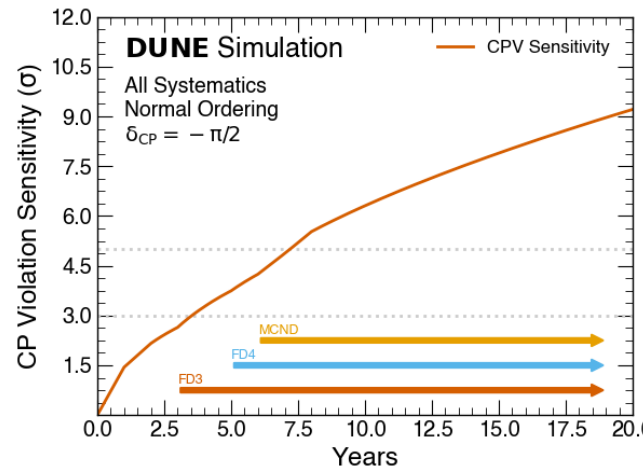
Neutrino mass ordering

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



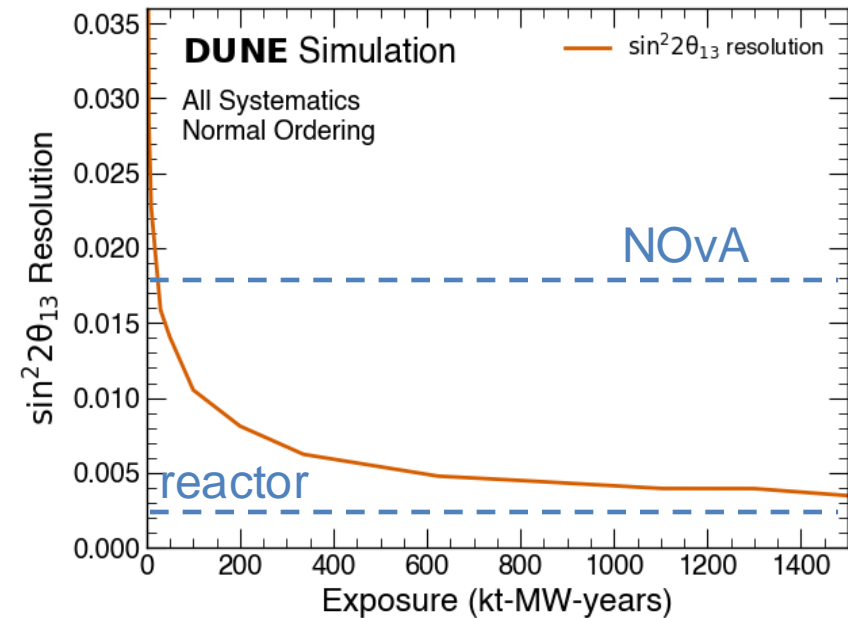
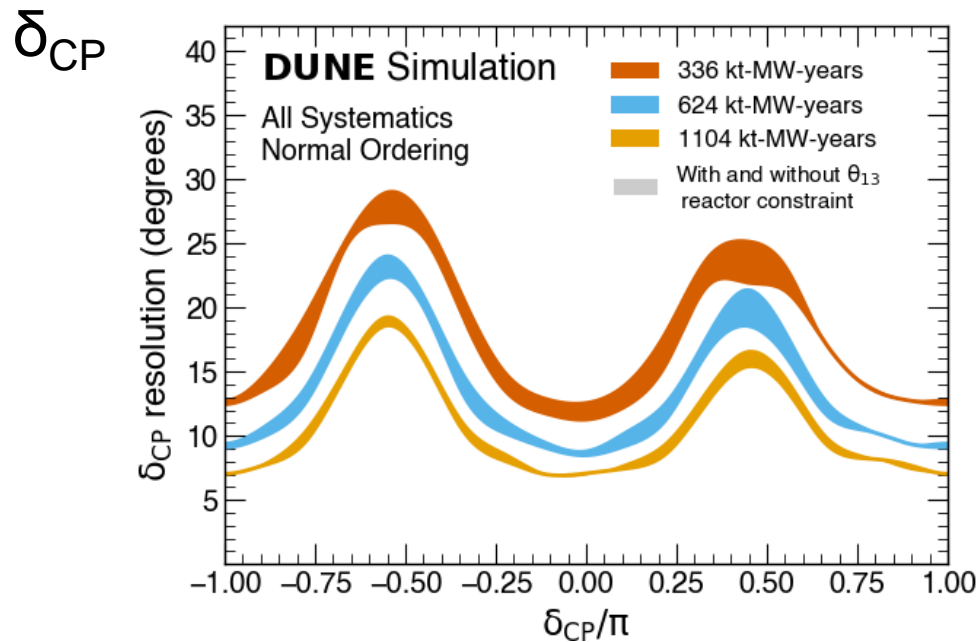
- For best-case oscillation scenarios, DUNE has
 - >5 σ mass ordering sensitivity in 1 year
 - >3 σ CPV sensitivity in 3.5 years
- For worst-case oscillation scenarios, DUNE has >5 σ mass ordering sensitivity in 3 years
- In long term, DUNE can establish CPV over 75% of δ_{CP} values at >3 σ

CP violation sensitivity



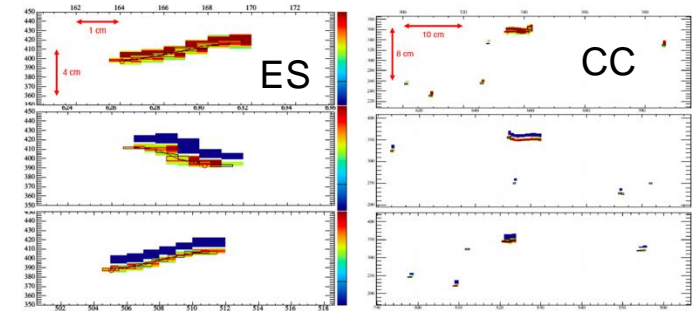
DUNE precise measurements

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



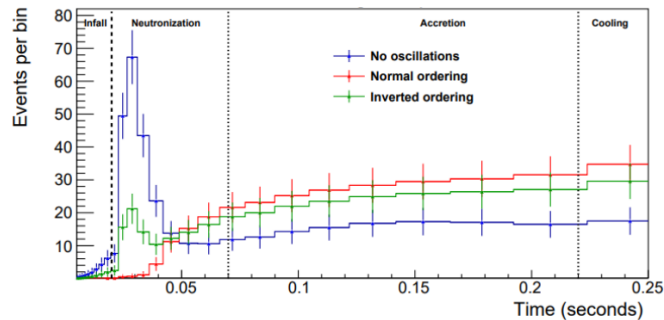
Astrophysical neutrinos in DUNE

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

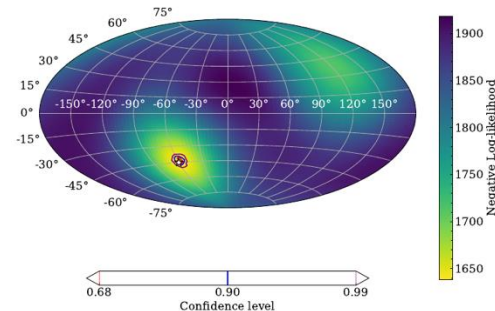


Neutrinos from core-collapse supernovae

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



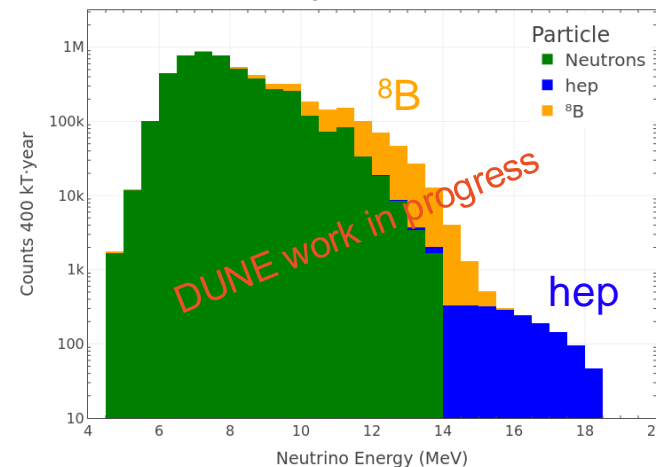
- Pointing capabilities: ES channel ~5° pointing resolution



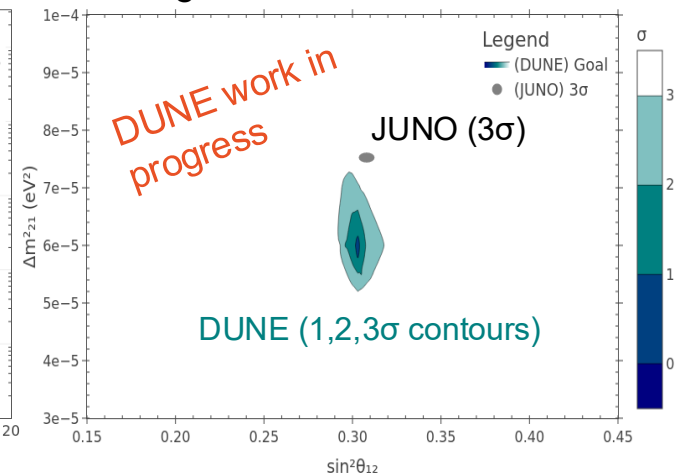
Neutrinos from the Sun

- DUNE has excellent sensitivity to ${}^8\text{B}$ 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



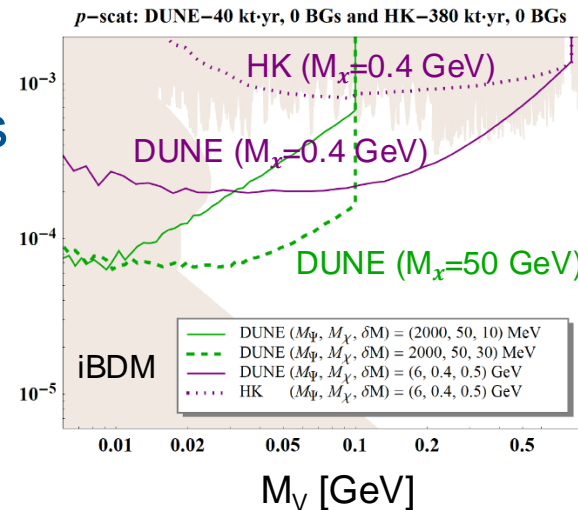
Beyond of Standard Model searches

- **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)...

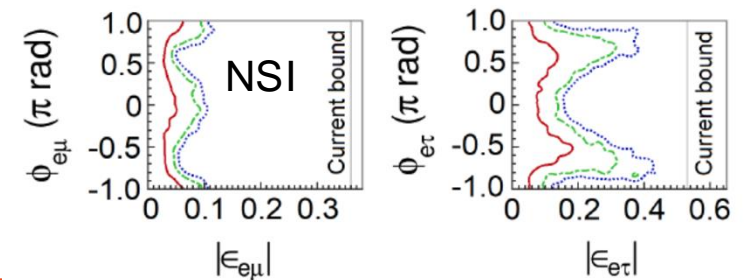
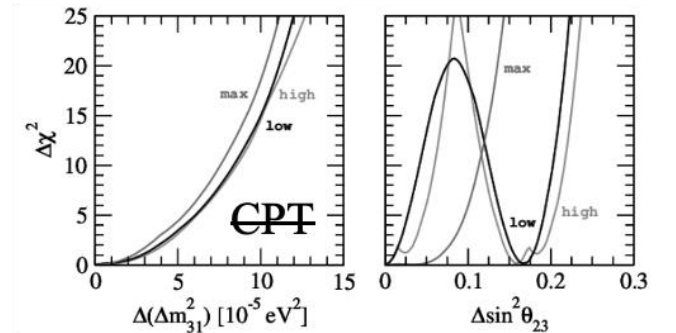
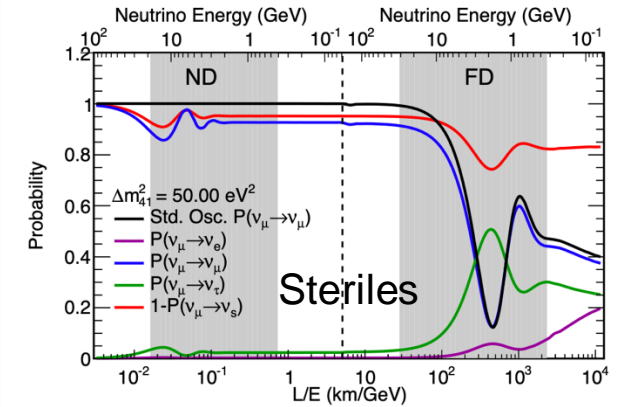
- DUNE covers a very broad range of L/E at both the ND and FD
- High statistics in ν & $\bar{\nu}$ measurements \rightarrow search for CPT violation
- DUNE has unique sensitivity to NSI matter effects due to long baseline

- **Other BSM in Far and Near Detectors**

- Dark matter at FD & ND, nucleon decay, n - \bar{n} oscillations, heavy-neutral leptons, neutrino tridents, ...

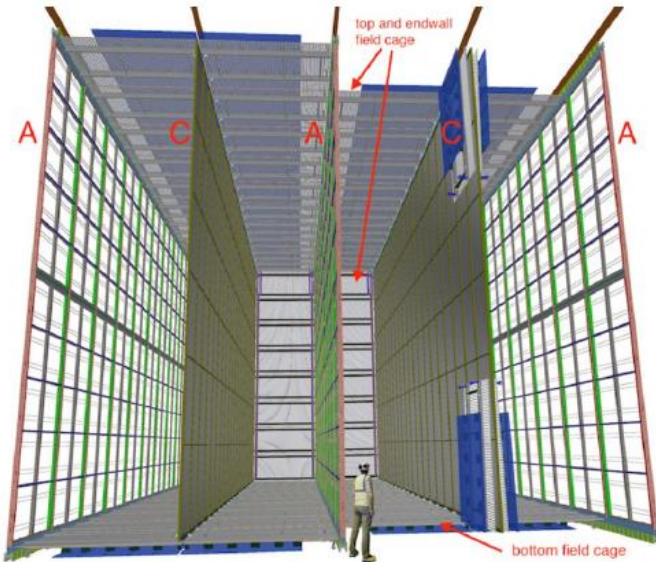


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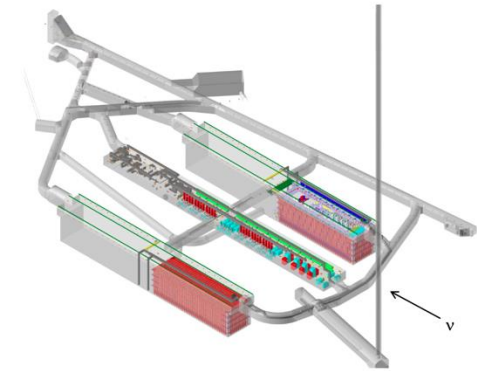
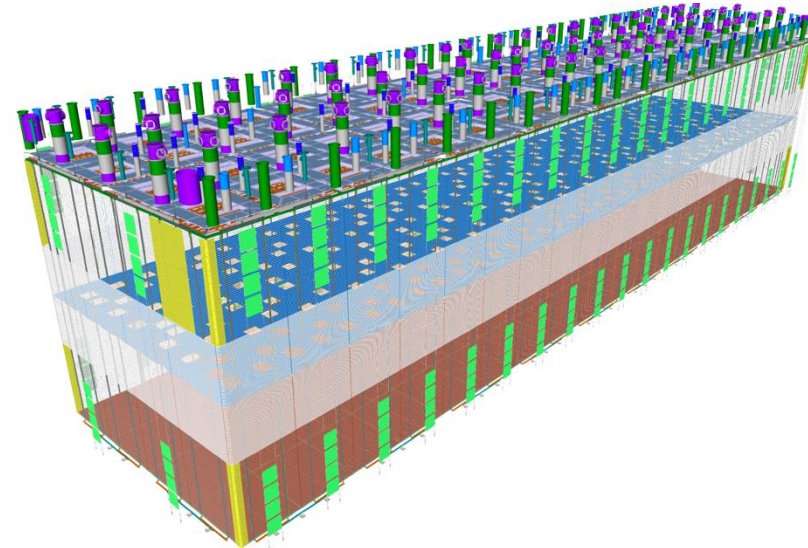


Far Detector Technologies

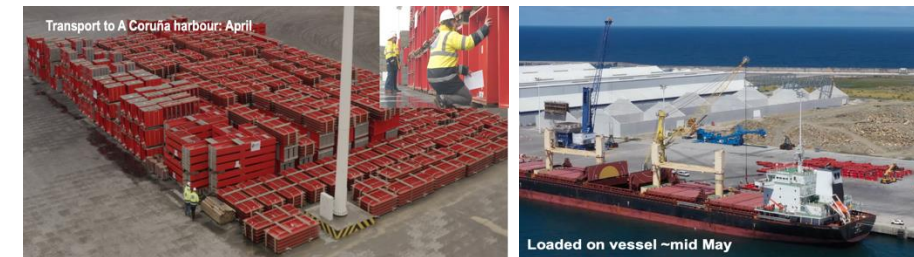
FD-HD: JINST 15 T08010 (2020)



FD-VD: arXiv:2312.03130 (2023)

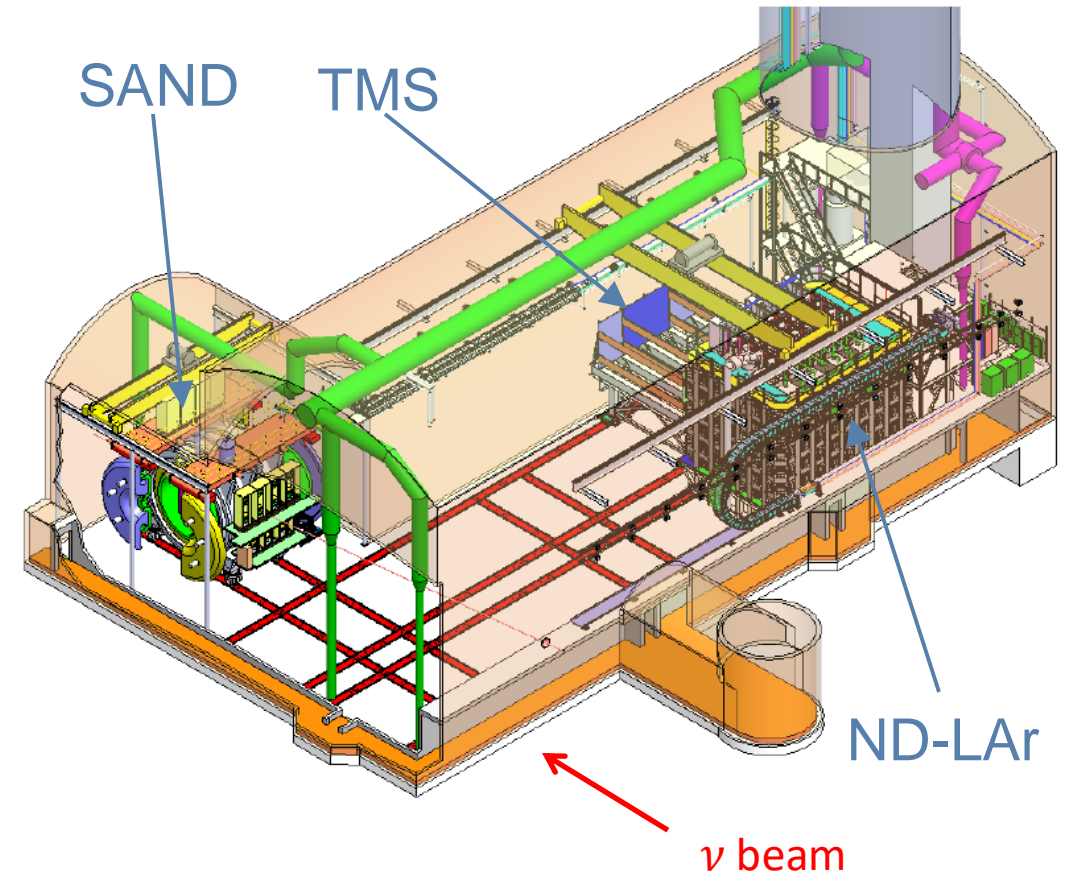
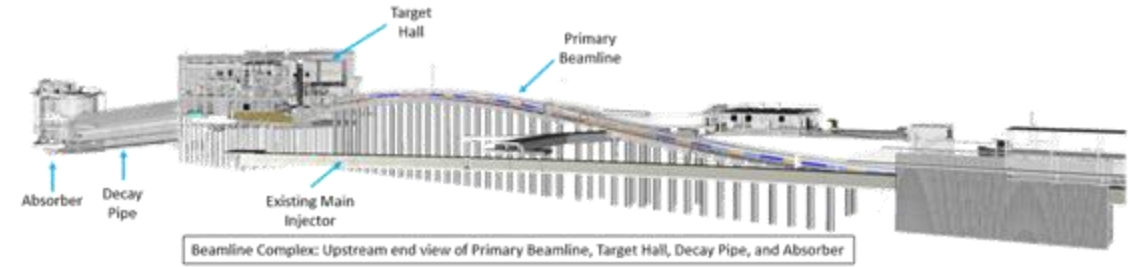


- Horizontal drift (FD-HD) using wire readout planes, four drift regions (3.6m)
- Vertical drift (FD-VD) using two 6.25m drift regions and central cathode
 - Simpler to install → first DUNE FD module will use vertical drift
 - VD is baseline design for FD modules 3 and 4



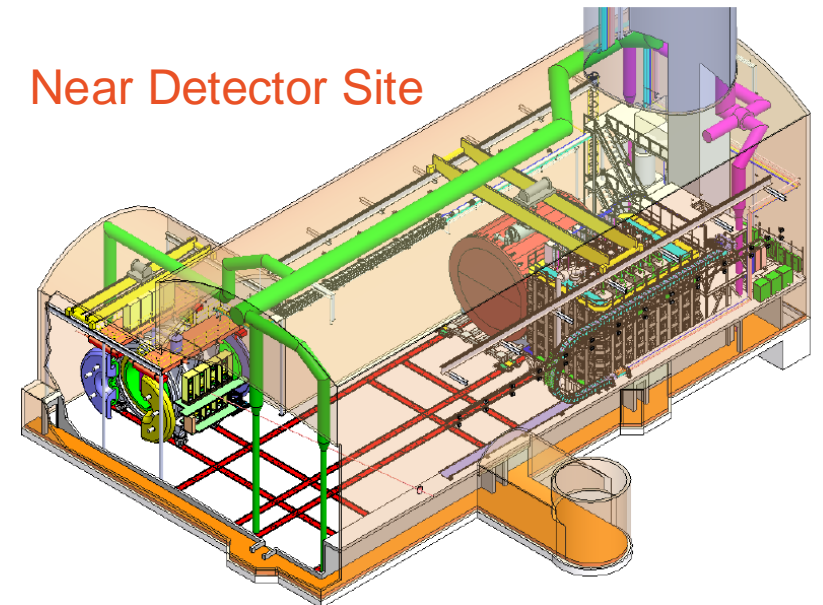
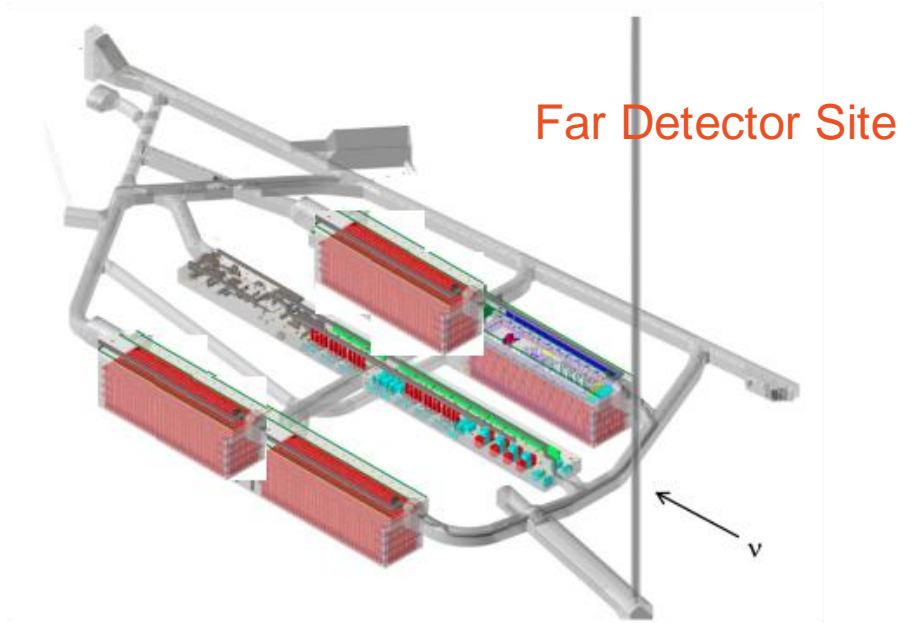
Near Detector Complex

- 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

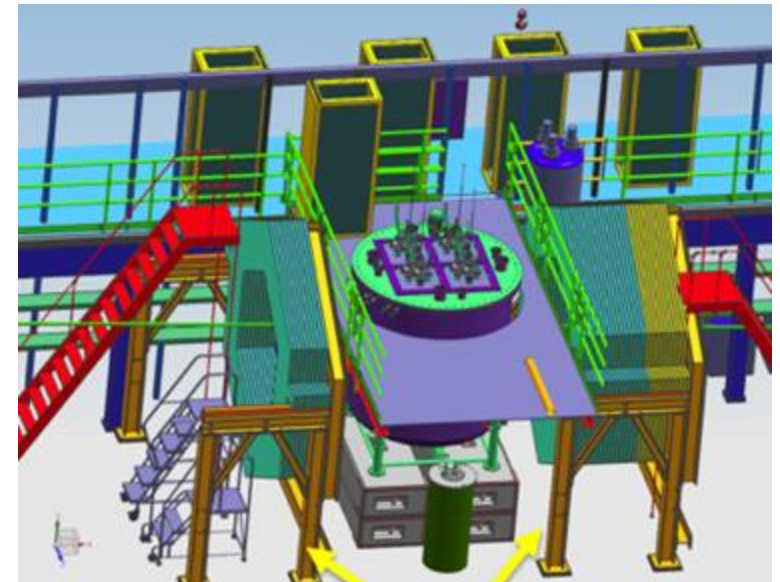
- **DUNE Phase I** (2026 start detector installation; 2029 physics; 2031 beam + ND)
 - Full near + far site facility and infrastructure
 - Two 17 kt LArTPC modules
 - Upgradeable 1.2 MW neutrino beamline
 - Movable LArTPC near detector with muon catcher
 - On-axis near detector
- **DUNE Phase II:**
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



P5 report endorses FD3, ACE-MIRT, and MCND in the next decade, and R&D toward FD4

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



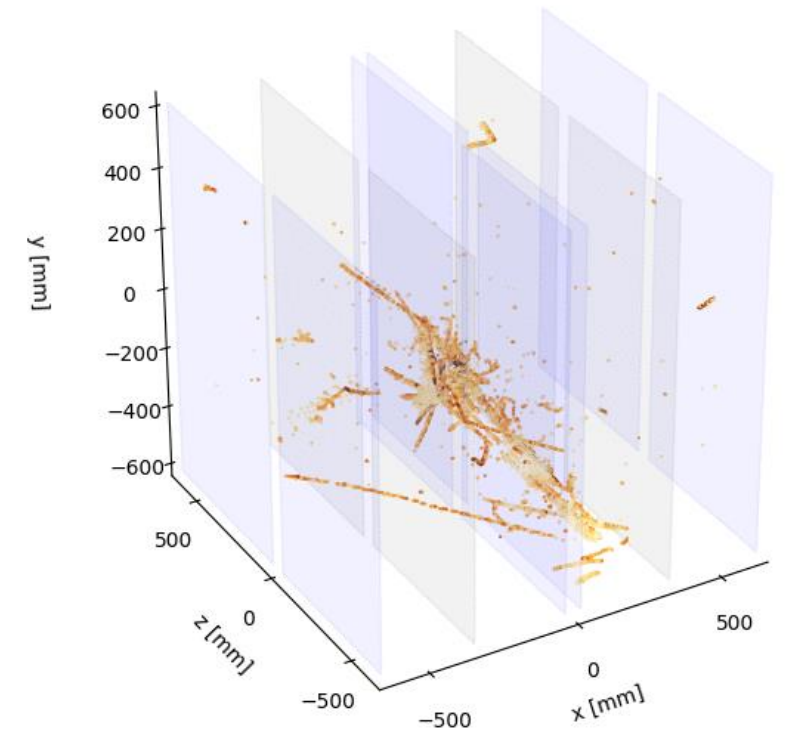
2x2 ND-LAr demonstrator at Fermilab

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



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

Event 20, ID 20 - 2024-07-08 00:20:14 UTC



ProtoDUNEs at CERN

- **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...)

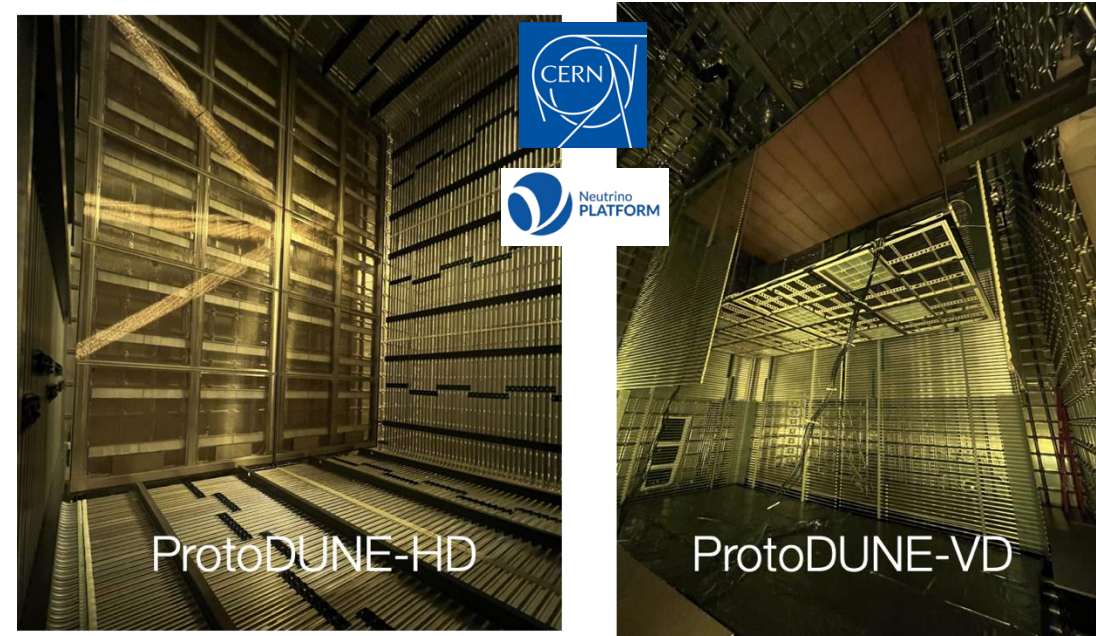
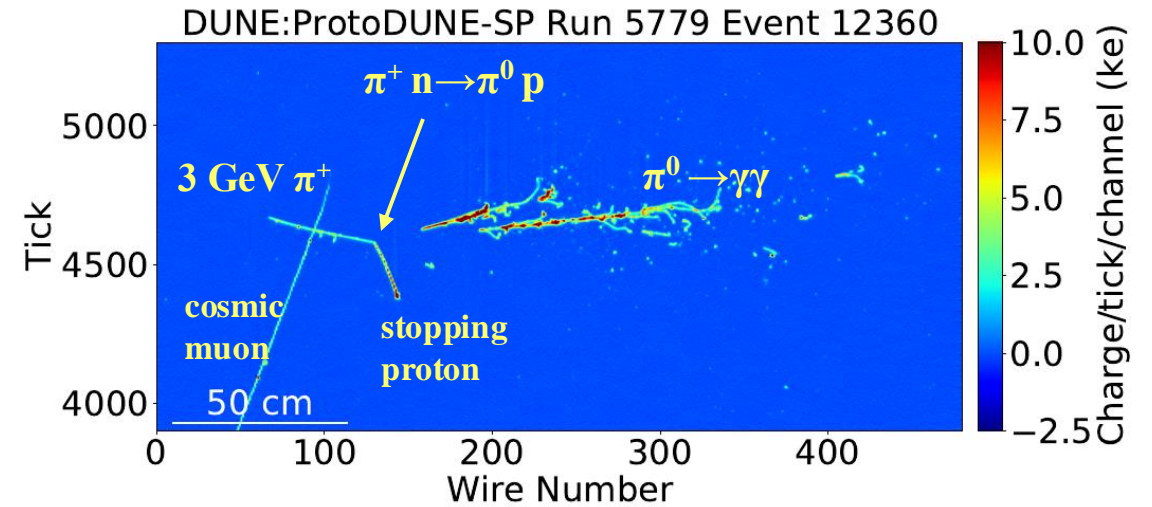
- **2nd Phase of ProtoDUNEs (2020-2023 construction + operation ≥2024)**

ProtoDUNE-HD

- Final technical solutions for all FD-HD subdetectors
- Detector filled and **currently taking data with charged-particle test-beam and cosmic muons at CERN**

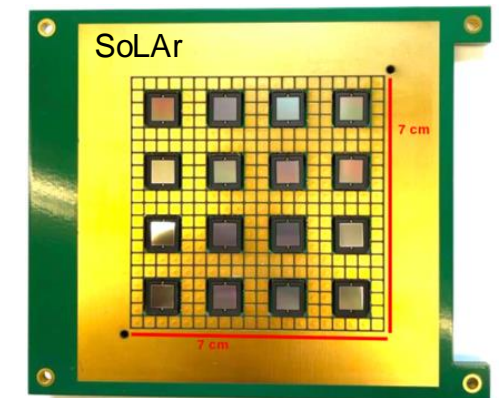
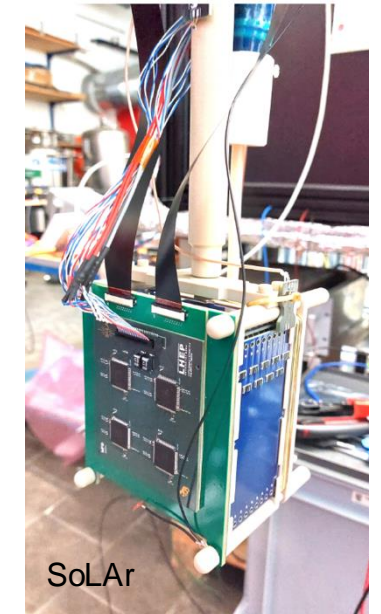
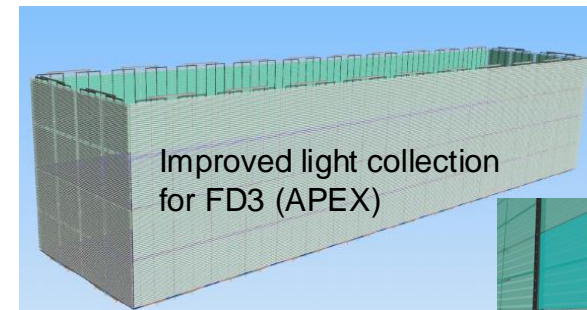
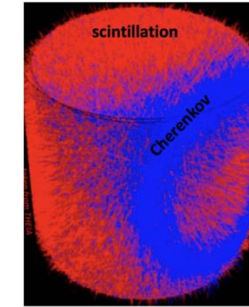
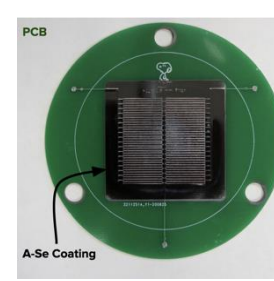
ProtoDUNE-VD

- Realization of a Module-0 detector in 2022-2023
- LAr will be transferred to ProtoDUNE-VD in October for running starting in early 2025



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!**

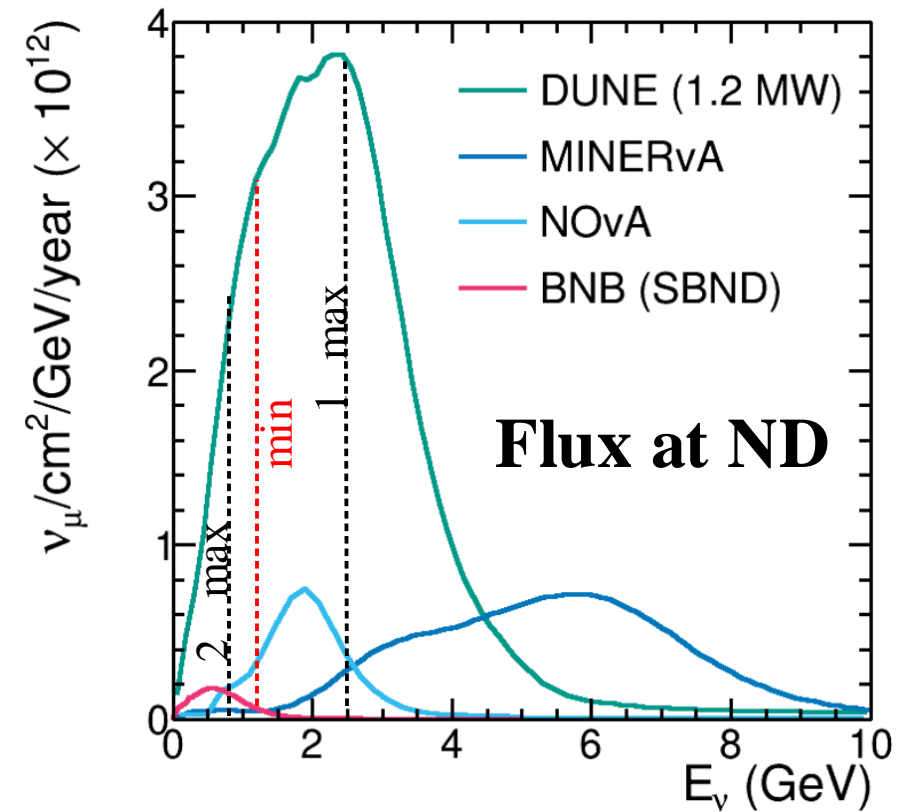
Děkuji



DEEP UNDERGROUND
NEUTRINO EXPERIMENT

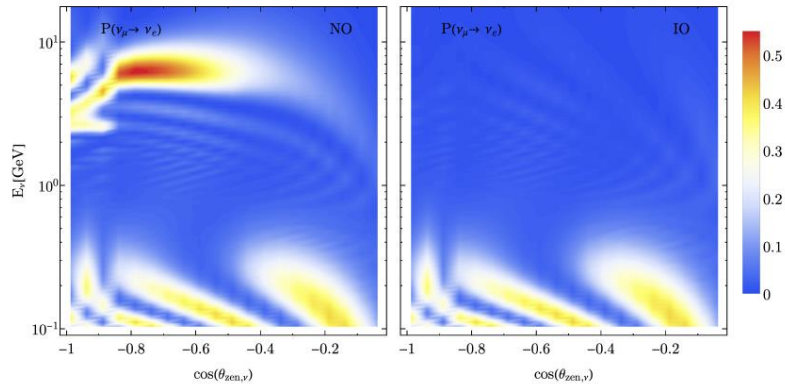
LBNF beamline: world-leading intensity

- Very high flux between oscillation minimum and maximum, with coverage of second maximum
- ACE-MIRT upgrade enables >2MW beam by ~doubling frequency of spills, and can be achieved before operations begin



Atmospheric neutrinos

Phys. Rev. X 13, 041055 (2023)



- Atmospheric neutrinos will be DUNE's first data; aim to combine with long-baseline
- Including reconstructed hadrons substantially improves angle resolution, especially at lower neutrino energies
- Potential to extend to low energies has been studied phenomenologically, see Phys. Rev. Lett. 123, 081801 (2019)
- DUNE analysis in progress

