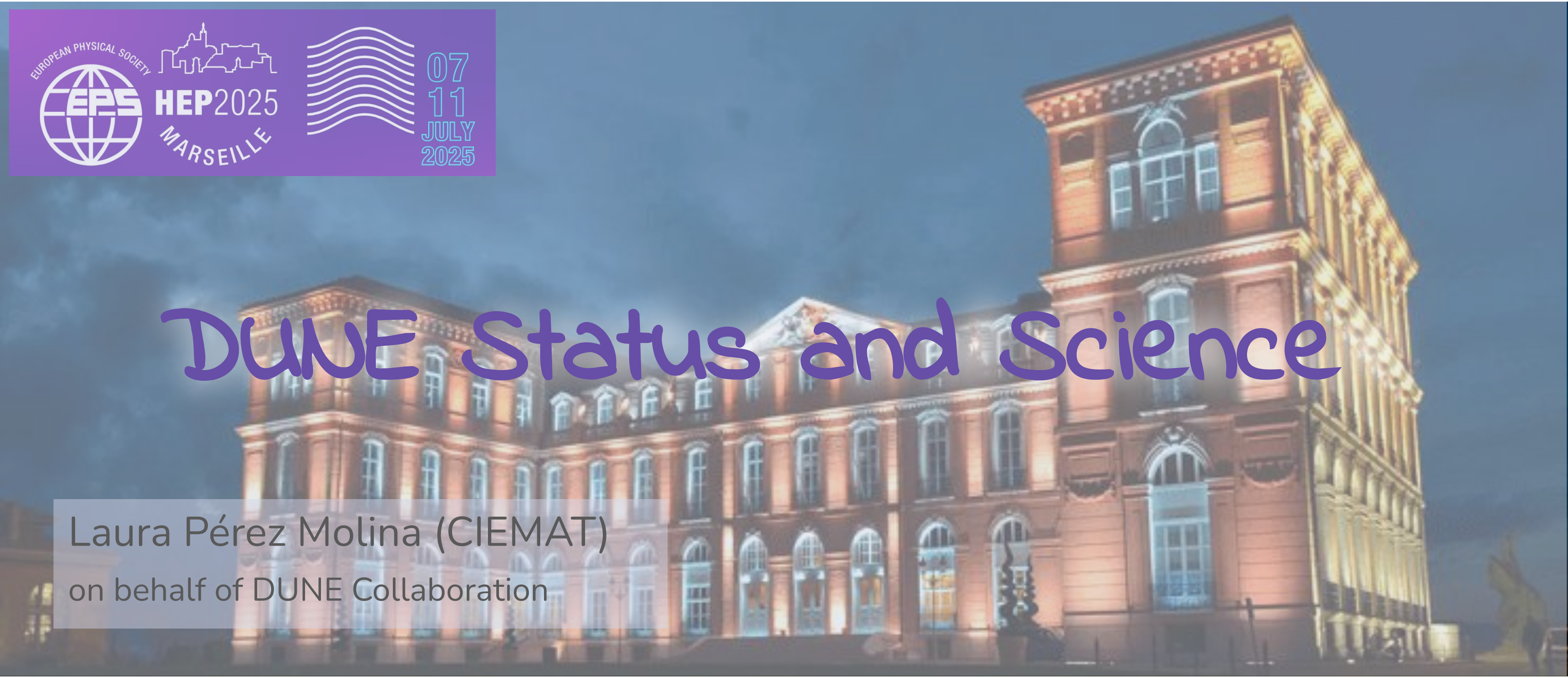
EUROPEAN PHYSICAL SOCIETY EPS HEP2025 MARSEILLE 07 11 JULY 2025



DUNE Status and Science

Laura Pérez Molina (CIEMAT)

on behalf of DUNE Collaboration

Neutrino Physics

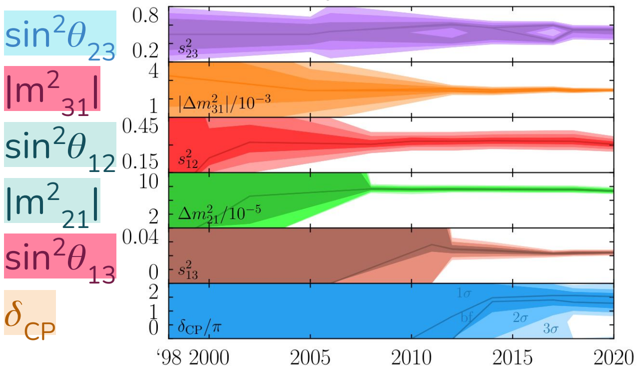
PMNS Parameterisation: 3 mixing angles (θ_{12}, θ_{13}, θ_{23}) and 1 CP-violating phase (δ_{CP})

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\text{Atmospheric}} \underbrace{\begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix}}_{\text{Reactors}} \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{Solar + KamLAND}} \underbrace{\begin{pmatrix} e^{-i\alpha_1} & 0 & 0 \\ 0 & e^{-i\alpha_2} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{Majorana (?)}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Atmospheric: $\nu_\mu \rightarrow \nu_\tau$ | Reactors: $\nu_\mu \rightarrow \nu_e$ | Solar + KamLAND: $\nu_e \rightarrow \nu_{\mu,\tau}$ | Majorana (?)

- Known: θ_{12}, θ_{23}, θ_{13}, Δm^2_{21}, $|\Delta m^2_{31}|$
- **Unknown:** mass ordering (sign of Δm^2_{31}) and δ_{CP}

P. Denton, arXiv:2212.00809



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★ Neutrino nature: Dirac or Majorana particles
★ Absolute mass scale
★ Mass generation mechanism
★ Mass ordering
★ Leptonic CP violation (δ_{CP})

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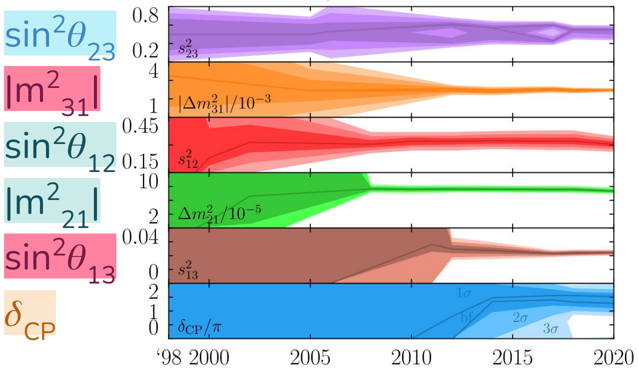

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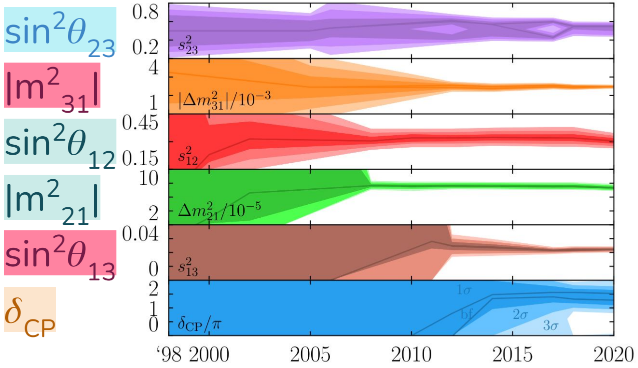
DUNE SCOPE

P. Denton, arXiv:2212.00809

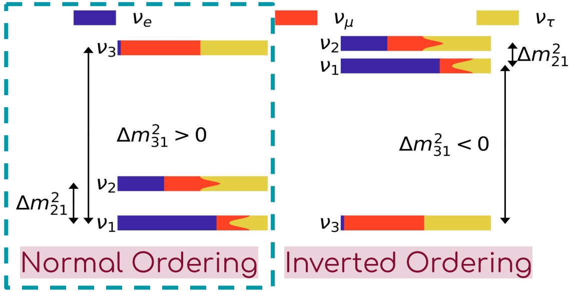


DUNE Science Program

Taking advantage of the **long-baseline,** DUNE will perform **precision** measurements on:

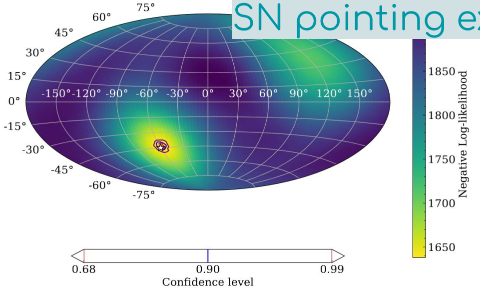
- Leptonic **CP violation**
- **Three neutrino mixing parameters**
- Neutrino **mass ordering** (5σ)

2 Possible scenarios:



- Searches for physics beyond the Standard Model (BSM)
  - Proton Decay search ($p \to K^+ \overline{\nu}$)
- Atmospherics neutrinos see C. Sironneau's talk
- **Low energy neutrino astrophysics:**
  - Solar neutrinos
  - Core-collapse supernovae

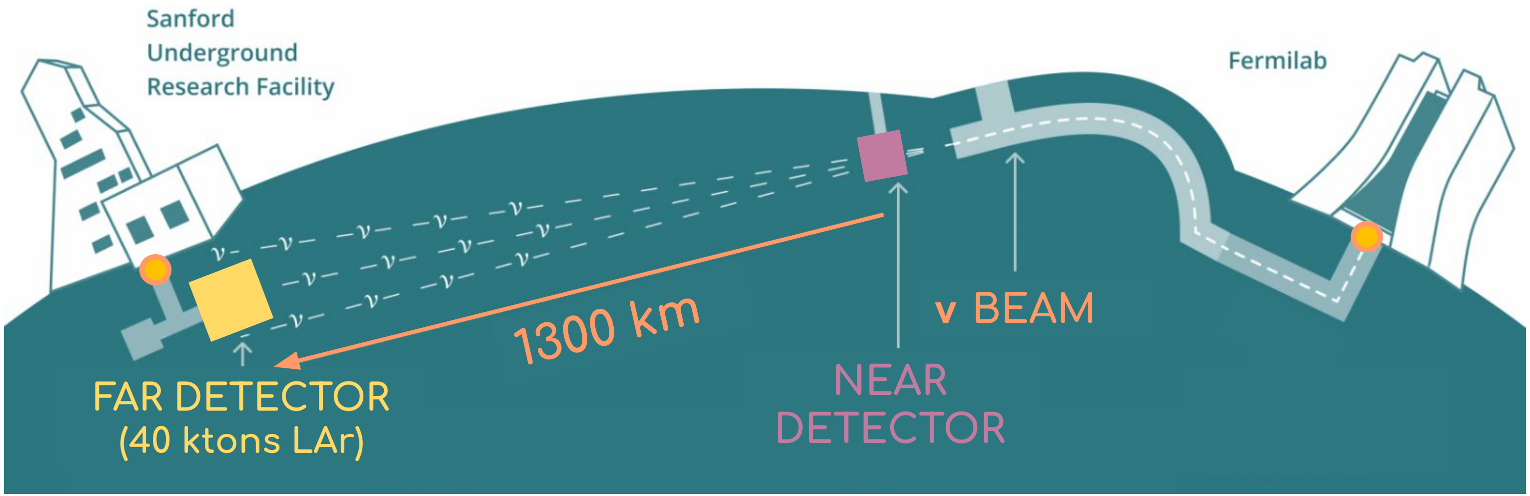
SN pointing example



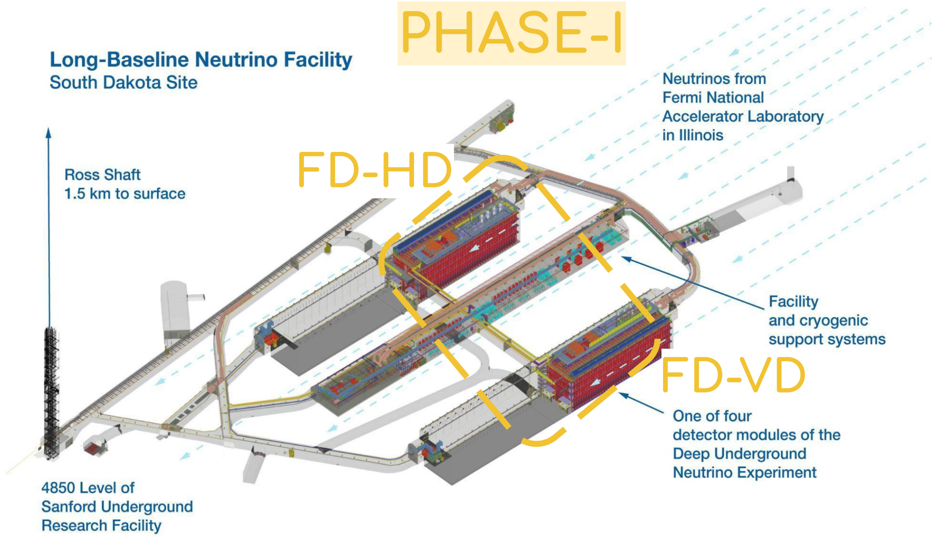
Deep Underground Neutrino Experiment

Next-generation long-baseline (**1300 km**) oscillation experiment **between Fermilab** (Illinois) and the **Sanford** Underground Research Facility (South Dakota, **1.5 km to surface**) consisting of:

1. **Muon neutrino beam:** **1.2 MW neutrino beamline** (LBNF)
2. **Near Detector (ND):** 574 m from the beam for **monitoring** the unoscillated flux
3. **Far Detector (FD):** measurement of oscillated neutrinos with four 17-kT LArTPC modules



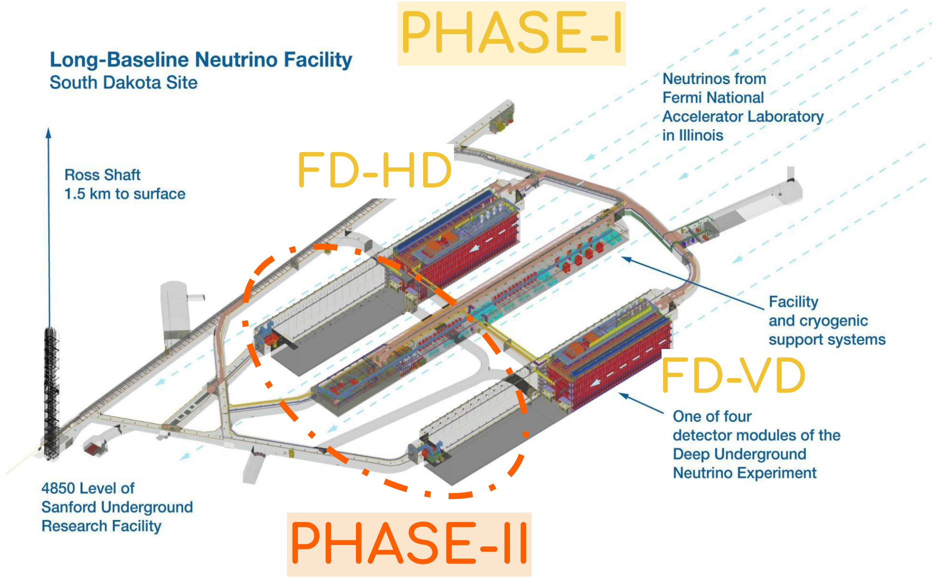
Phase Approach



PHASE-I

- **Full** Near and Far site facilities
- 1.2 MW **upgradable** neutrino beamline
- Far Detector (FD): **two** LArTPCs modules (17 kt each)
- Near Detector (ND): **three** detectors including a LArTPC and a temporary muon spectrometer

Phase Approach



PHASE-II

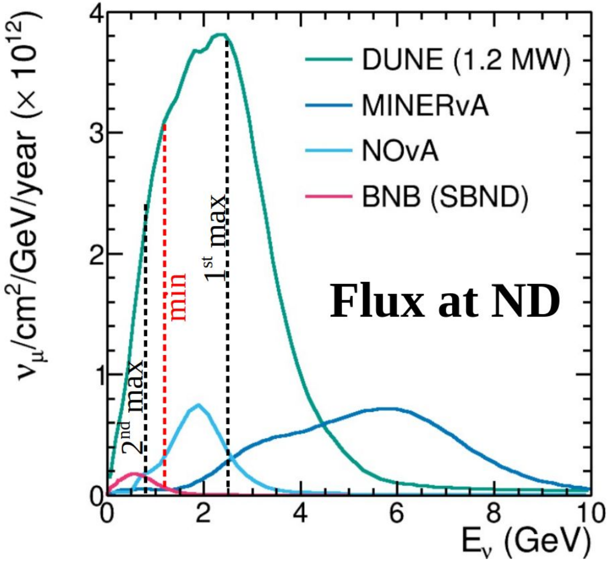
- Beamline upgrade to **> 2MW**
- **Two additional** FD modules (four in total for 40 kt of active volume)
- A more capable ND

DUNE beam and oscillation probability

Precision measurements of the oscillation parameters from $P(\nu_\mu \rightarrow \nu_e)$ and $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$

- Neutrino and Anti-neutrino mode
- **World-leading intensity:** 1.2 MW → 2.4 MW
- Very high flux peaked at **2.5 GeV** neutrino energy
- The oscillation probability has a strong dependence on both δ_{CP} and **mass ordering** for L=1300 km
- **Wide band beam:** coverage of first and second oscillation maximum will be crucial to resolve the degeneracy

DUNE collaboration. Neutrino 2024



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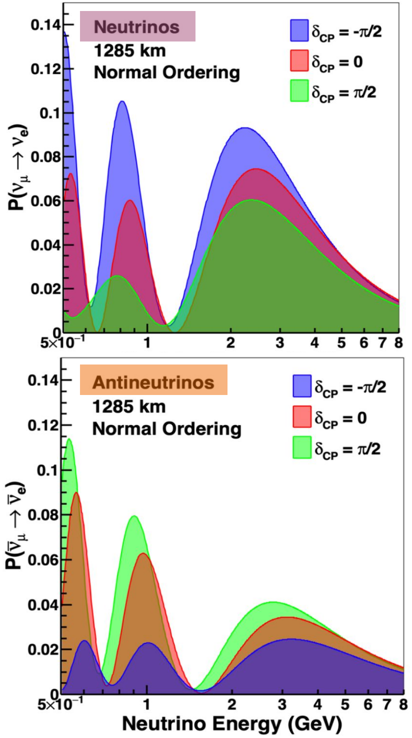
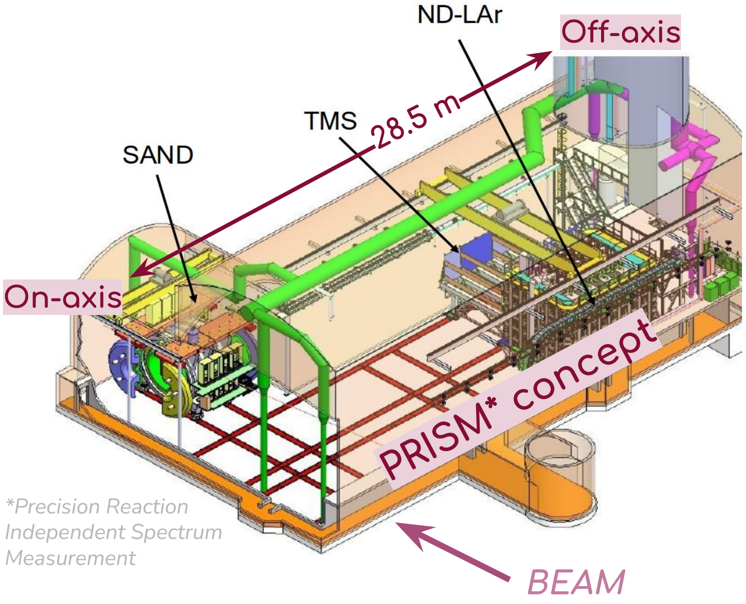


DUNE collaboration. EPJC (2020) 80:978

DUNE Near Detector (ND) - Phase I

Constrain uncertainties for oscillation measurements
- → Monitor unoscillated neutrino flux
- → Measure ν-Ar cross section
- → **Prediction on neutrino spectra at FD**



*Precision Reaction Independent Spectrum Measurement

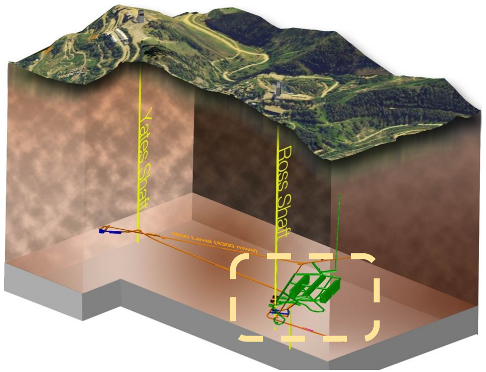
DUNE collaboration. Instruments 5 (2021) 4, 31

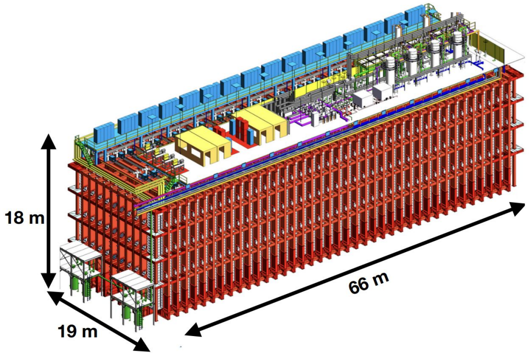
Located 574 m from the beam & 60 m underground

1. **ND-LAr: 50t fiducial volume detector**
   - Primary target, FD technology + pixelated readout
2. **The muon spectrometer (TMS)**
   - Measure μ's escaping the first detector
3. **SAND (tracker surrounded by an electromagnetic calorimeter and magnet)**
   - Monitor the neutrino beam

DUNE Far Detector (FD)

A massive 70 kt detector deployed in 4 modules



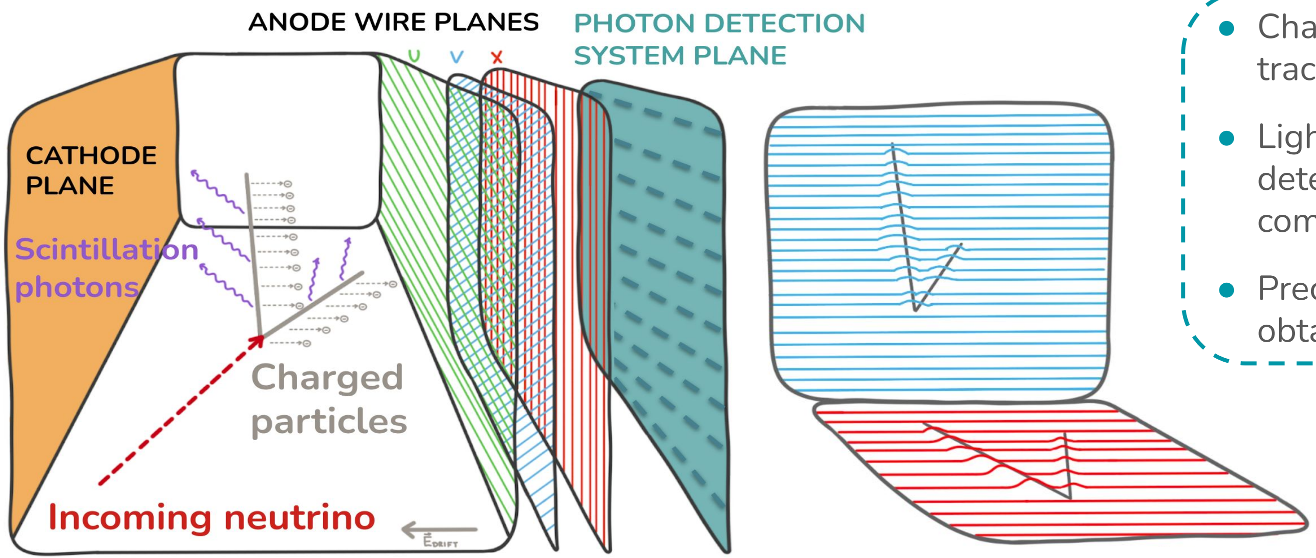


- Sanford Underground Research Facility (SURF)
- 1300 km apart from ND (Baseline)
- 1500 m underground (Background)
- 4 modules in two different caverns
  - Modules 1, 2 and 3 → LArTPCs
  - Module 4 → Module of Opportunity

The phase approach allows to:
- ➔ Consider different technologies for the fourth module
- ➔ Improvements can be applied in the second phase

LArTPC technology

Interaction in LAr
- Ionization electrons (~27k e$^-$/MeV) → drifted & collected by **anodes planes**
- Scintillation photons (~24k γ/MeV) → detected by the **photon collectors**

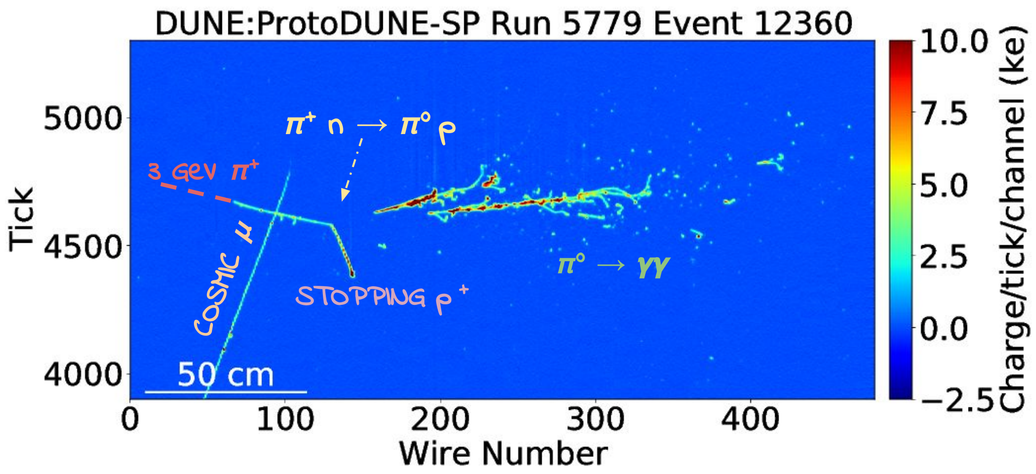


- Charge provide a precise tracking and calorimetry
- Light is crucial for t_0 determination and can complement calorimetry
- Precise **images** can be obtained

LArTPC images

- ➔ 60% of interactions at DUNE energy have final state pions
  - ◆ Measuring them will constrain DUNE interaction models!
- ➔ LArTPC enables precise hadron reconstruction
- ➔ Excelent e/μ and e/γ separation
- ➔ High quality **particle ID** and **energy reconstruction**
- ➔ Spatial resolution ~mm

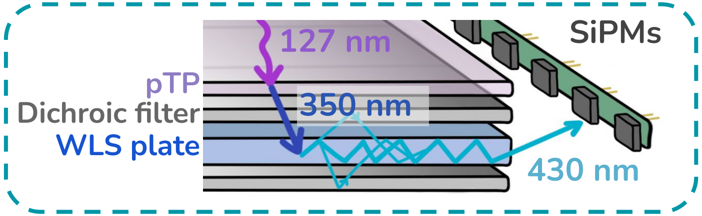
1st ProtoDUNE run - Beam Event Example

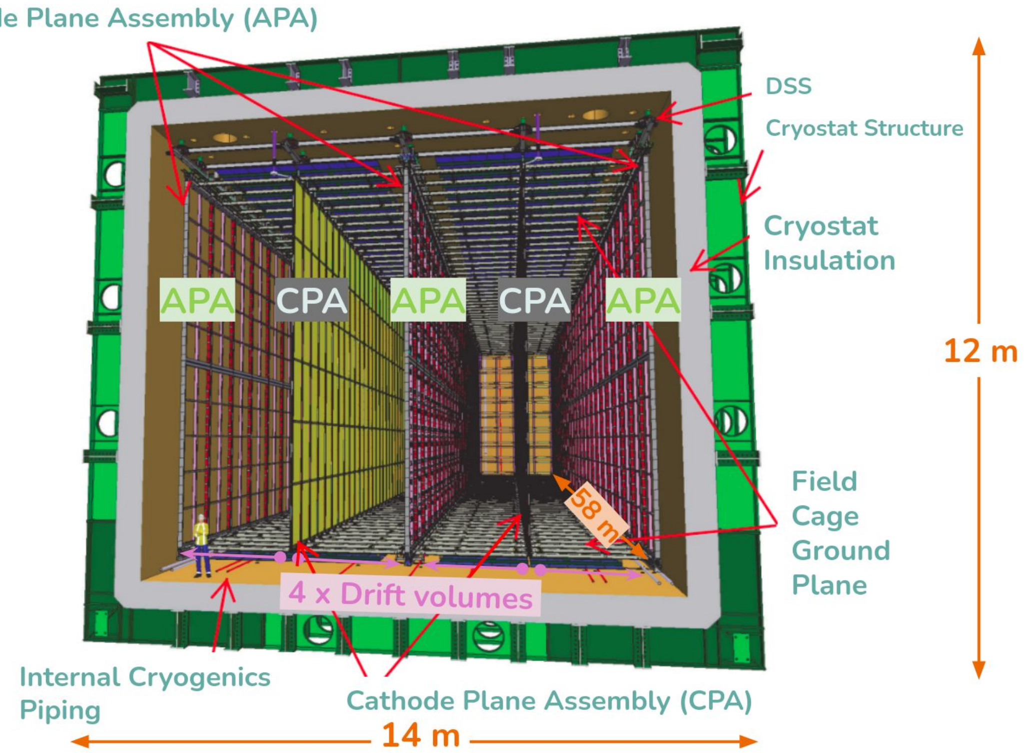


ProtoDUNE-SP. JINST 15 (2020) P12004

Far Detector Horizontal Drift (FD-HD)

- Established and validated technology
- TPC size: $(12 \times 14 \times 58.2)\ m^3$
- 4 horizontal drift regions (3.5 m)
- Drift Voltage 500 V/cm
- Vertical cathode and anode planes
- Photon detectors on the anode planes
- Photon detection based on X-ARAPUCAs

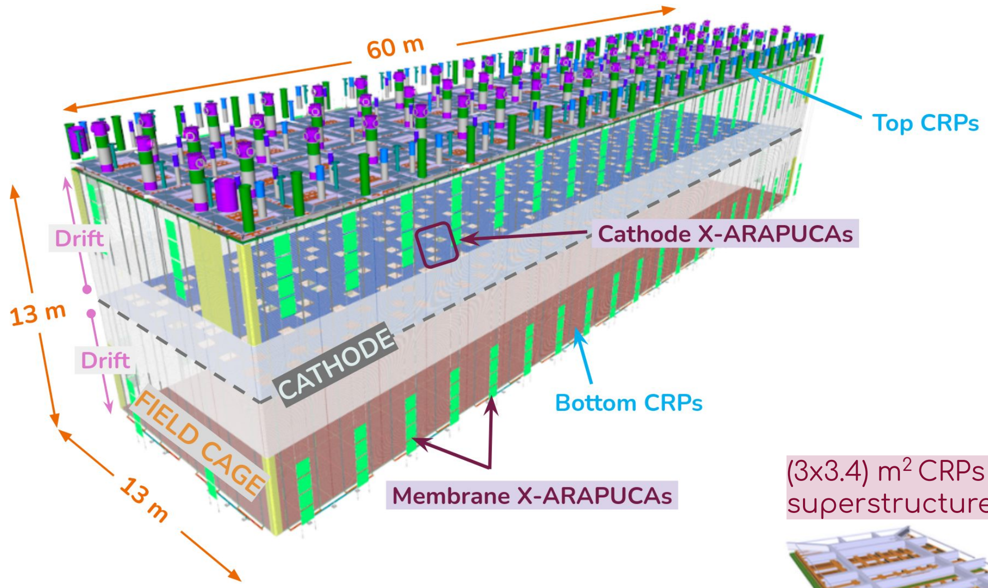




DUNE collaboration. JINST 15 (2020) T08010

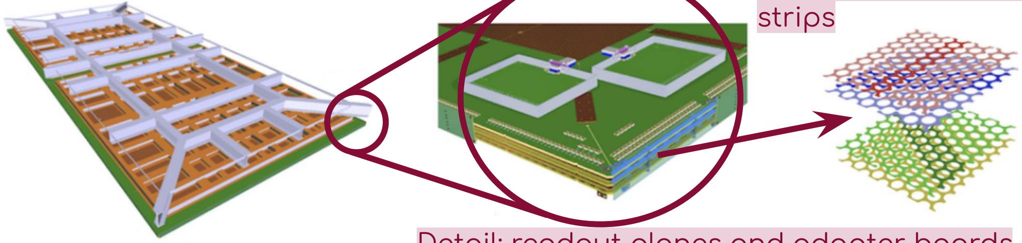
see P. Sánchez-Lucas' talk

Far Detector Vertical Drift (FD-VD)



- Simpler construction
- 2 volumes separated by a cathode
- 6.5 m drift distance (drift field 450 V/cm)
- 2 anode planes (top & bottom)
- X-ARAPUCAs on the cathode plane and membrane walls
- PCB-based charge readout

see F. Boran's talk



Baseline design for modules 3 and 4

DUNE collaboration. JINST 19 (2024) 08 T08004

ProtoDUNEs at CERN (HD & VD)

- 750 t LAr total (1/20 of one FD module)
- **Real-size** readout elements (APA, PDS, CRP)
- Successful phase-I (2018 - 2020)
- ProtoDUNE-HD campaign in 2024
  - Test upgraded components in **their final design** and take more beam data
- ProtoDUNE-VD campaign in 2025
  - Test the VD concept for the first time at large scale

Building DUNE: schedule

2025

Building & Site Infrastructure

2026 Cryostat installation

2027

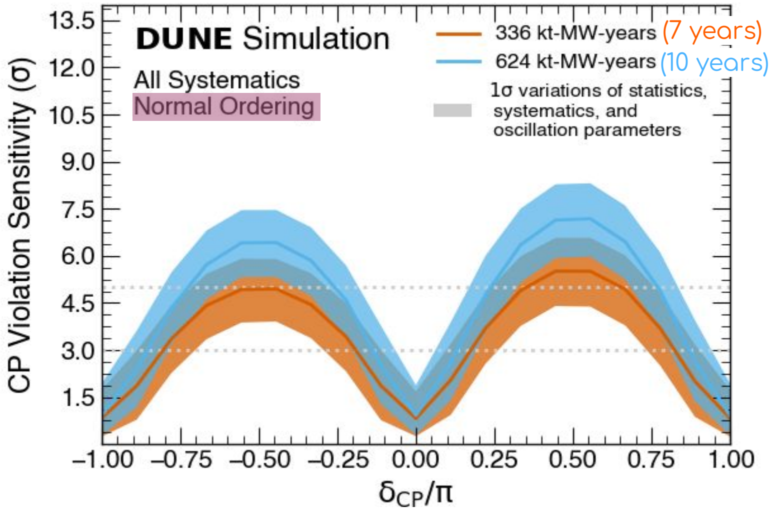
FD Installation

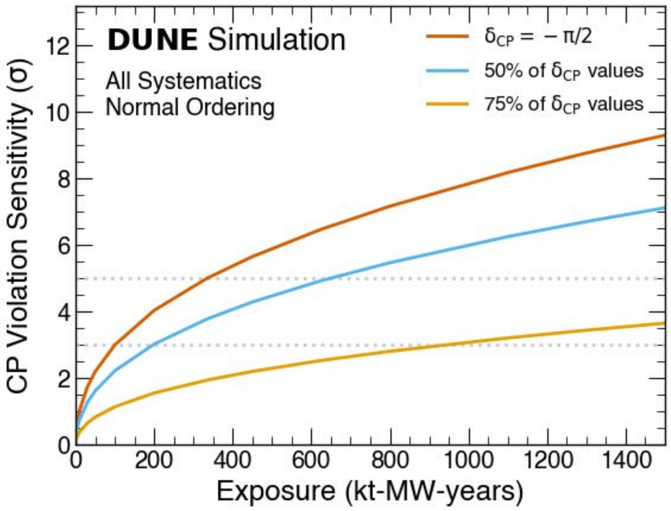
2030 PHYSICS

- Solar, atmospheric and astrophysics
- Full beam physics

CP Sensitivity

- After **10 years** exposure there is significant CP violation ($\delta_{CP} \neq 0, \pi$) discover potential across true values of δ_{CP} and for both hierarchies
- DUNE can establish CPV **over 75% of δ_{CP} values** at >3σ *(worst case scenario)*
- DUNE can establish CPV **over 50% of δ_{CP} values** at >5σ



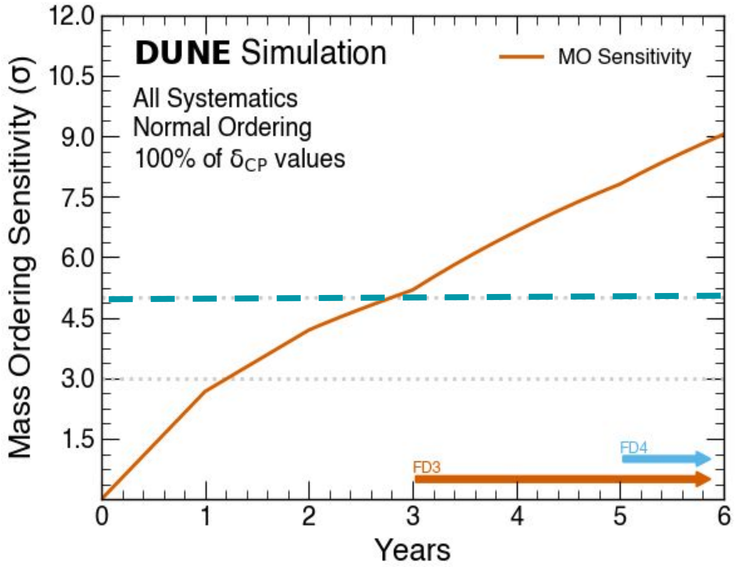


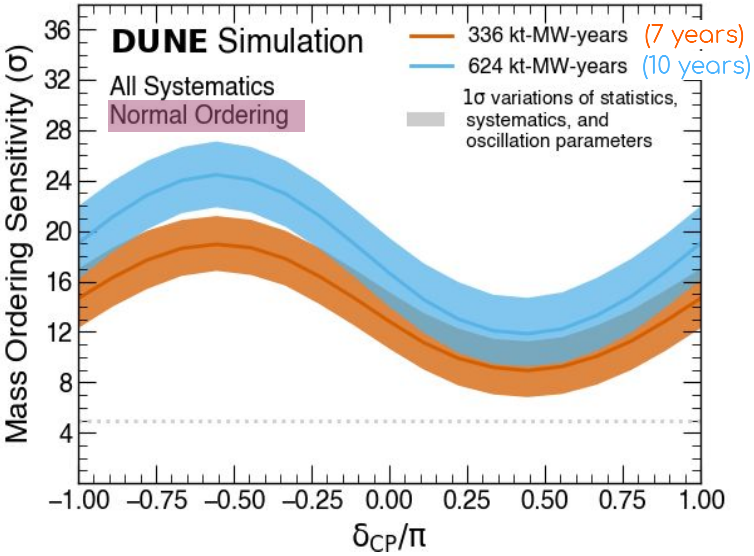
DUNE collaboration. EPJC (2020) 80:978 & Neutrino 2024

Mass Ordering Sensitivity

Regardless of the values of the other oscillation parameters:

- DUNE can establish mass ordering at $> 5\sigma$ in **3 years** (worst case scenario)
- Obtain a definitive answer for the mass hierarchy within **7 years**

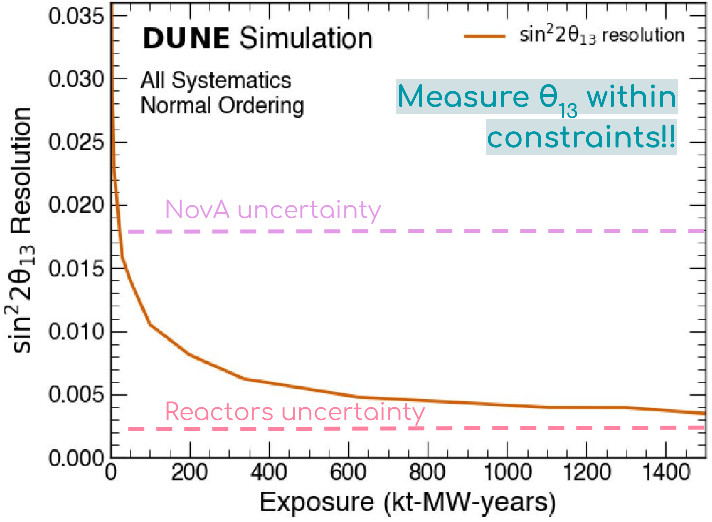


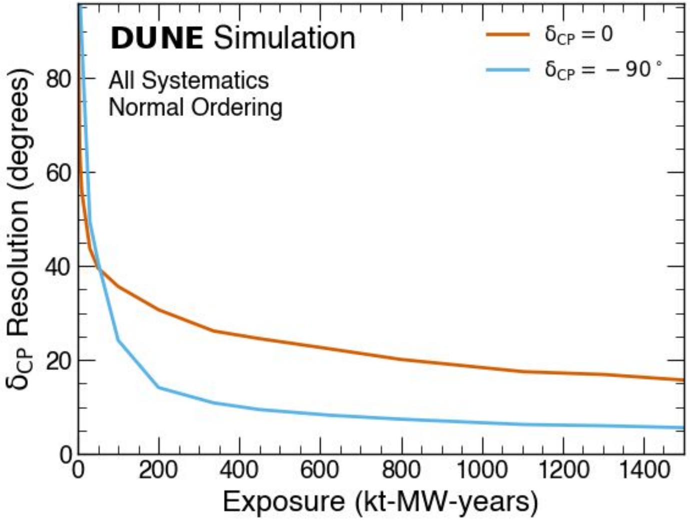


DUNE collaboration. EPJC (2020) 80:978 & Neutrino 2024

Resolution to oscillation parameters

- **World-leading precision** (for long-baseline experiment) in θ_{13} and $\Delta m^2 \rightarrow$ comparisons with reactor measurements are sensitive to new physics
- Ultimate precision 6°-16° in δ_{CP}

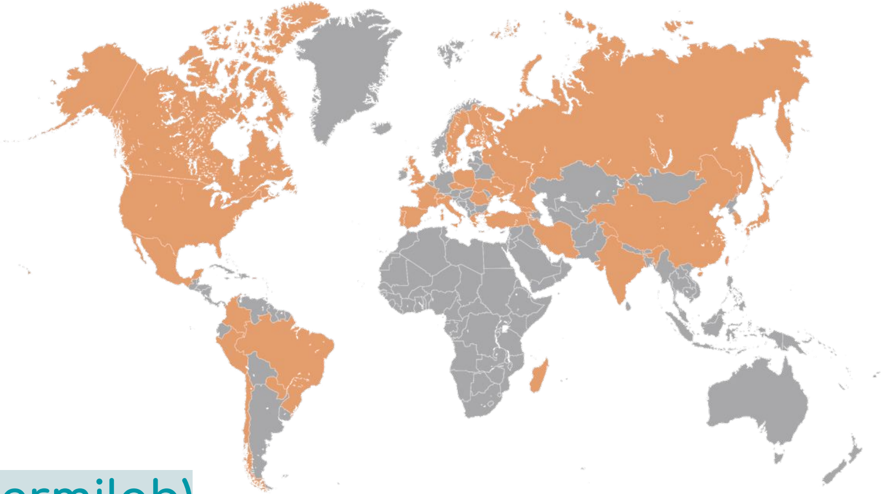




DUNE collaboration. EPJC (2020) 80:978 & Neutrino 2024

DUNE Collaboration

- 1400 collaborators
- 200 institutions
- 30 countries + CERN



DUNE Collaboration Meeting May 2025 (Fermilab)

Summary

- DUNE is a long-baseline oscillation experiment & neutrino observatory 🔭

➔ **Mass ordering & δ_{CP}, MeV-scale astrophysical neutrinos and proton decay & BSM**

- Prototyping program very active and successful ✅
- Construction work ongoing 🏗️
- Start of Science by the end of this decade 🧮

DUNE talks/posters in the EPS 2025

Wednesday 9th July (T03 - Neutrino Physics)

- 16:20 → DUNE Astrophysical and Atmospheric Neutrinos - C. Sironneau (APC)
- 18:00 → Analysis and simulation of low energy Michel electrons in ProtoDUNE - T. Houdy (IJCLab)

Friday 11th July (T11 - Detectors)

- 8:30 → The DUNE Photon Detection System - P. Sánchez Lucas (UGR)
- 9:06 → The Charge Readout Planes of the DUNE Vertical Drift TPC - F. Boran (CERN)
- 9:24 → Signal and Power transmission over Fiber in the DUNE Far Detector - S. Sacerdoti (APC)

Backup slides

Inverted Ordering Sensitivities