

# The DUNE experiment: overview and update

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on behalf of the DUNE Collaboration

Laboratoire Astroparticule et Cosmologie

IRN Neutrino 1-2 June 2026



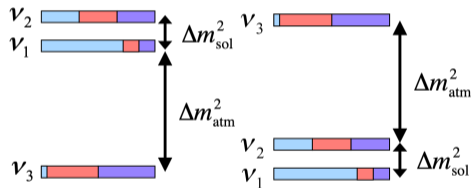
- ▶ Short Introduction
- ▶ DUNE Physics:
  - Beam physics
  - Off-beam physics
- ▶ DUNE Detector update
- ▶ ProtoDUNE program

# Introduction - neutrino physics unknowns

The good old list of unknowns in neutrino physics:

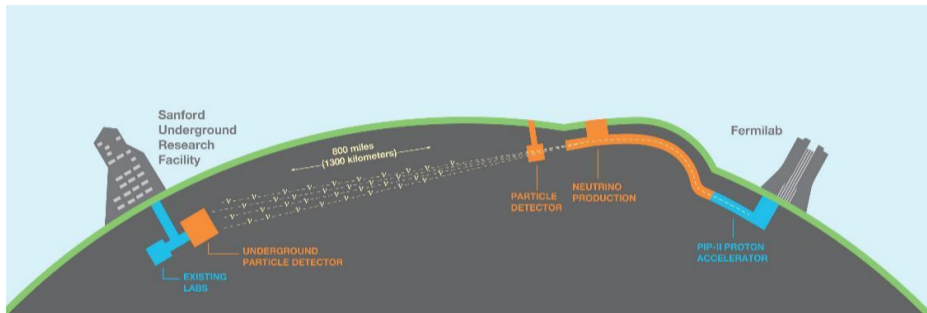
- ▶ Nature of neutrinos (Dirac or Majorana)
- ▶ The absolute value of neutrino masses

- ▶ Normal or Inverted Mass Ordering (MO)
- ▶ Whether there is charge-parity symmetry violation in the lepton sector
- ▶ Accuracy of the 3-neutrino model and unitarity of the PMNS matrix



→ To be measured in LBL neutrino experiments like DUNE

# The Deep Underground Neutrino Experiment



## DUNE TDR Volumes:

JINST 15 (2020) 08, T08008

JINST 15 (2020) 08, T08009

JINST 15 (2020) 08, T08010

JINST 19 (2024) 08, T08004

ND CDR : Instruments 5 (2021) 4, 31

DUNE is a long baseline neutrino oscillation experiment with unique features:

- ▶ A **1.2 MW proton beam** (upgradeable to  $> 2$  MW) will be produced at Fermilab, aimed towards the Sanford Underground Research Facility (SURF)
- ▶ **1300 km baseline** between Near and Far Detector sites
- ▶ A far detector placed on-axis, with a **1.5 km overburden** and **70 kton LAr**

# The DUNE Collaboration

- International collaboration
  - 1548 collaborators, 222 institutions
  - 40 countries incl. CERN



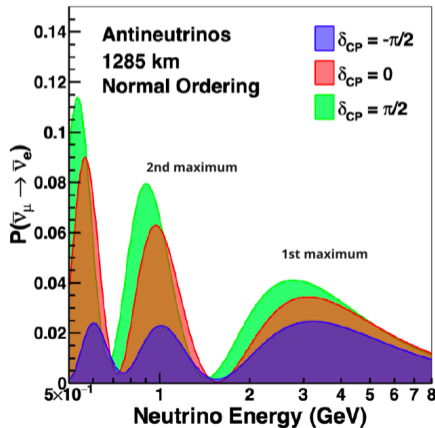
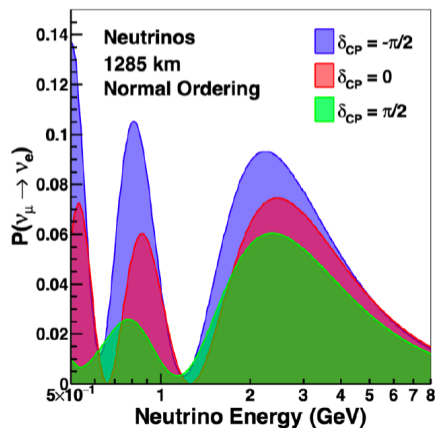
\* Collaboration Meeting at CERN 2025

# DUNE Physics

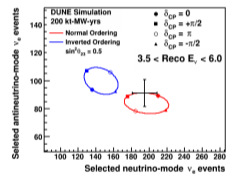
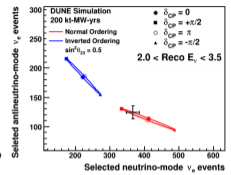
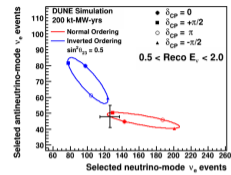
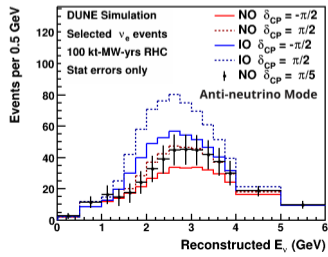
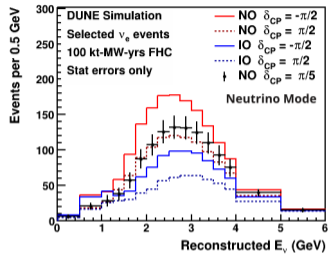


# DUNE Oscillation Physics

- ▶ DUNE will measure neutrino oscillations using a **wide-band beam** + **very long baseline**
  - exploit spectral information
  - access to **2<sup>nd</sup> oscillation maximum**
- ▶ Study of  $\nu_\mu \rightarrow \nu_e$  oscillations with neutrinos and anti-neutrinos



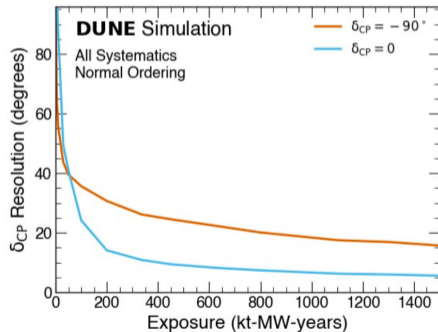
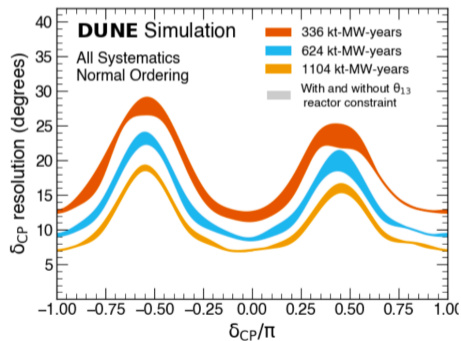
# DUNE strengths



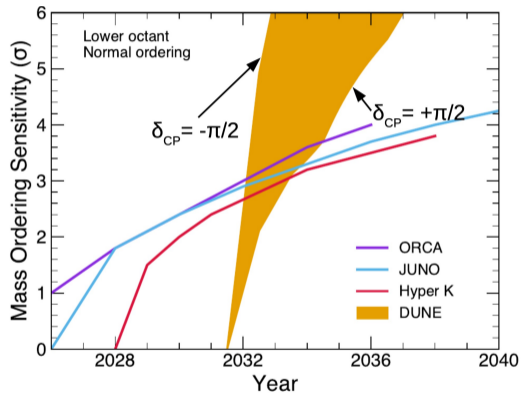
- Combining long baseline + wide-band beam allows to **break the degeneracy between  $\delta_{CP}$  and matter effects**
- Unique possibility to **measure all oscillation parameters within a single experiment, with high precision.**

# CP violation

- ▶ The ND allows to characterize the flux at different angles (energies) and control systematic effects (using PRISM technique)
- ▶ Best ultimate precision in  $\delta_{CP}$ , between 6-16° (15 years)



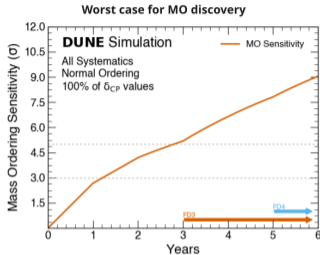
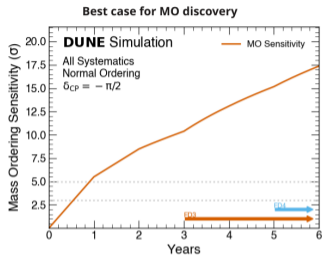
# Mass Ordering



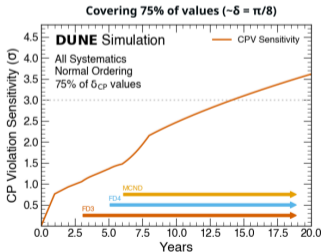
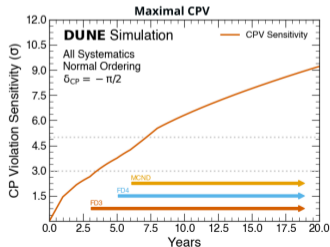
- ▶ Measurement of MO with both  $\nu$  and  $\bar{\nu}$  oscillations
- ▶ DUNE can reach **5 $\sigma$  sensitivity in MO in all scenarios**

# DUNE sensitivity - MO and CPV summary

Mass Ordering



CP Violation



- ▶ Staged sensitivity for best (left) and worst (right) scenarios for MO (top) and CPV (bottom)
- ▶ Best case oscillation scenario:
  - $> 5\sigma$  MO sensitivity with 1 year (Phase I)
  - $> 3\sigma$  CPV sensitivity in 3.5 years
- ▶ Worst case scenario:
  - $> 5\sigma$  MO sensitivity with 3 year
  - long term sensitivity to CPV  $> 3\sigma$  for over 75% of  $\delta_{CP}$  values

Phase I = FD1+FD2 + ND

Phase II = FD1+ FD2+FD3 + FD4 + MCND

JINST 19 (2024) 12, P12005

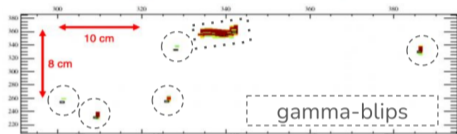
# DUNE off-beam program (a selection)

The DUNE FD will be sensitive to low energy  $\nu$  and have a high cross-section in the CC channel

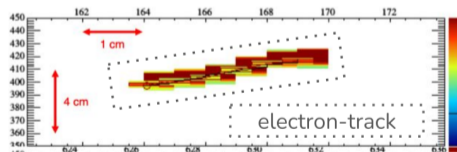
Sensitivity to MeV  $\nu_e$  via:

- ▶ **CC**  $\nu_e + Ar \rightarrow e^- + {}^{40}K^*$  (main channel)
- ▶ **ES**  $\nu_x + e^- \rightarrow \nu_x + e^-$  (pointing)

$\nu_e$  CC event (20.25 MeV  $\nu$ )



$\nu$ -e<sup>-</sup> ES event (10.25 MeV e<sup>-</sup>)

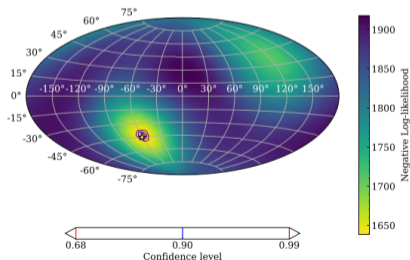


True Energy Deposits

## Supernova Neutrinos

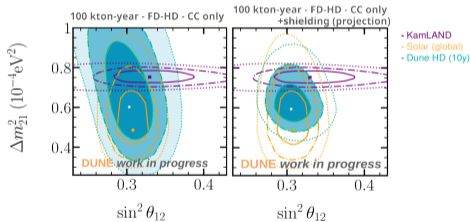
- ▶ measurement of the neutronisation burst  
→ flux vs time depends on MO
- ▶ Pointing capabilities: ES channel  $\sim 5^\circ$  resolution (40 kton, 10 kpc)

Phys. Rev. D 111, 092006



## Solar Neutrinos sensitivity

- ▶ Potential discovery of hep flux
- ▶  $^8B$  solar neutrinos above  $\sim 10$  MeV
- ▶ Solar oscillation measurements via day-night asymmetry (induced by matter effects)

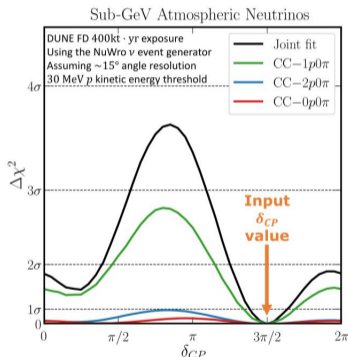


Potential boost shown by shielding studies and ProtoDUNE radiological background measurements - work at LAPP and IJCLAb

# Atmospheric Neutrinos

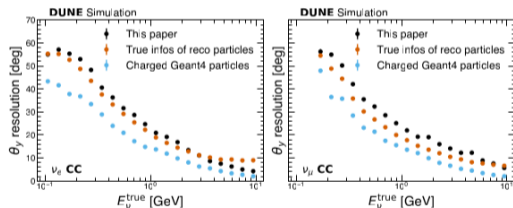
Will constitute the first DUNE data (between 2030 and 2032):

- ▶ Could exclude a large range of  $\delta_{CP}$  using sub-GeV neutrinos



- ▶ Potential use of few-GeV neutrinos for a MO measurement (complementary to beam)
- ▶ Sensitive for BSM searches (like sterile  $\nu$ )

A good evaluation of the physics reach requires an understanding of the **reconstruction performance**... [arXiv:2601.05697](https://arxiv.org/abs/2601.05697)



...and of **detector systematics**  
→ more details in Claire's talk tomorrow!

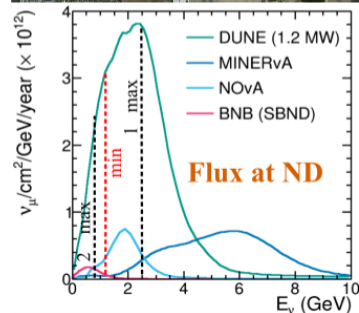
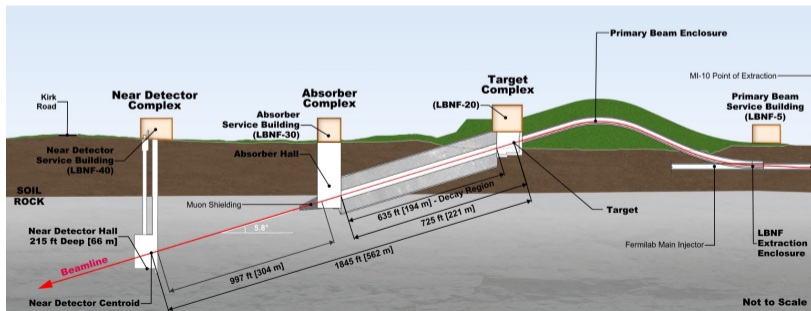
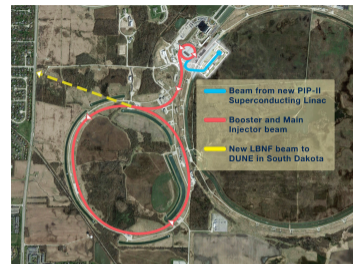
\*APC contribution

# Design/Construction status



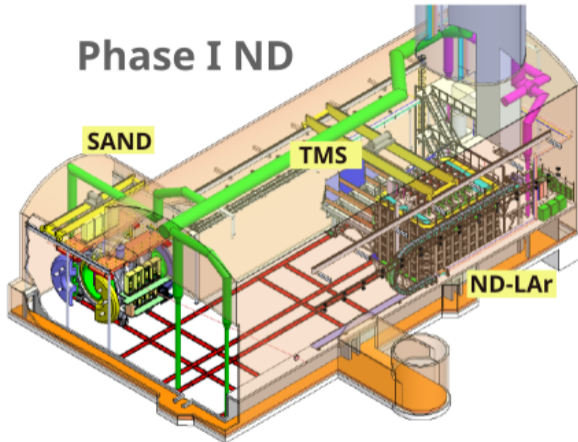
# Near Detector Site at Fermilab

- ▶ The Near Detector complex is located at Fermilab, 570 m from the beam target, 66 m deep
- ▶ Very high flux, covering **wide range of energy** - up to 10 GeV
- ▶ Possible to upgrade to  $> 2$  MW by doubling spill frequency
- ▶ Expecting final design by 2026



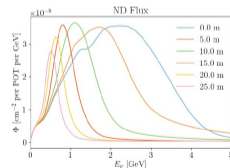
# The DUNE Near Detector

## Phase I ND



- ▶ **SAND**: on-axis magnetized detector
- ▶ **TMS**: The Muon Spectrometer
- ▶ **ND-LAr**: LArTPC with pixelated readout

- ▶ Main goal: measurement of unoscillated neutrino  $E_{rec}$  spectra at the ND to predict the flux at the Far Detector
- ▶ PRISM: ND-LAr and TMC detectors can move off-axis, up to 28.5 m
  - by measuring the off-axis flux, constrain energy dependence of  $\nu$  cross-sections
  - Same technology and target material as far detector  $\rightarrow$  unique opportunity to measure  $\nu$  interactions with Ar

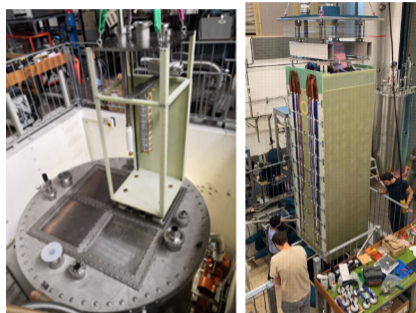


**PRISM is a key technology for the DUNE physics program**

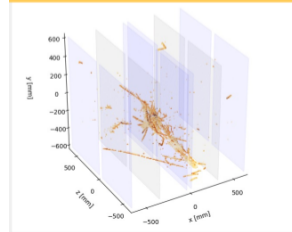
# Near Detector Prototypes

Prototyping activities on-going for 3 detectors and PRISM system in different institutions.

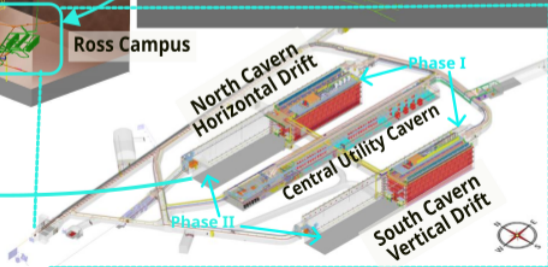
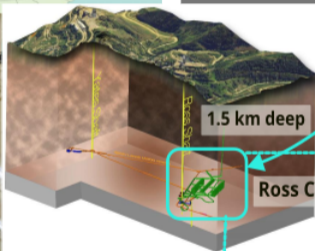
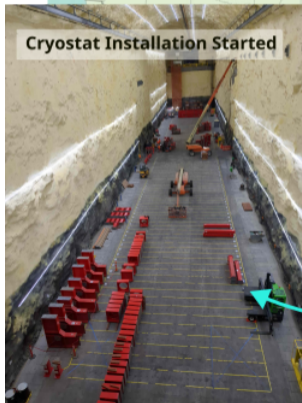
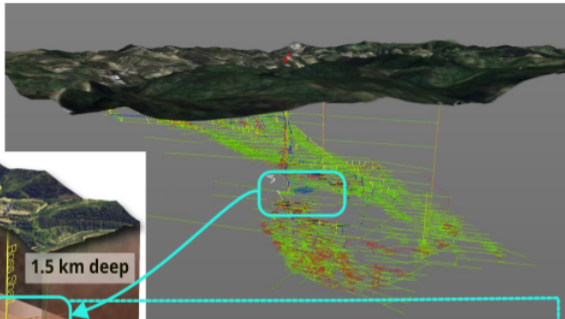
- ▶ TMS prototypes for detector modules, readout electronics and magnet coil  
→ path to final design
- ▶ Extraction and consolidation of SAND components, and prototypes for other components (LAr target, inner tracker)
- ▶ ND-LAr demonstrators at :
  - Fermilab:  $2 \times 2$  demonstrator collected 4.5 days of  $\bar{\nu}$  data in NuMI beam (2024) and  $\nu$  mode beam expected in 2026
  - Bern: full-scale module operated (70M cosmic ray events)



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

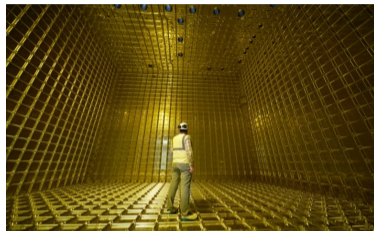
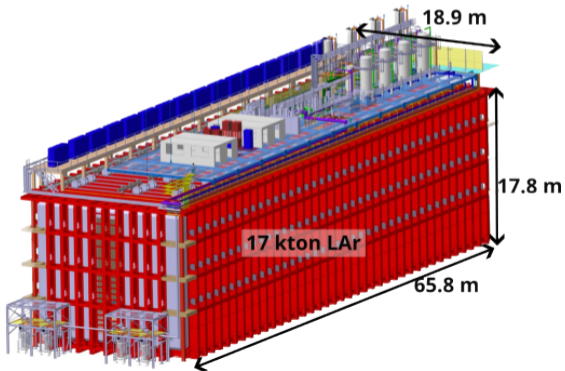


# Far Detector Site at SURF - South Dakota



# Far Detector Cryostats

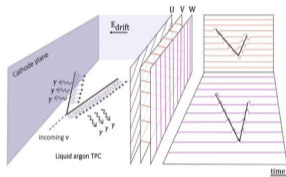
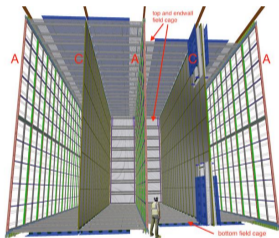
- ▶ CERN in-kind contribution: 2x FD cryostats, that's 6 ktons of steel!
- ▶ Membrane cryostat technology with passive insulation
- ▶ Most cryostat components at SURF already, being moved into the cavern!



# Far Detector Technology: LArTPC

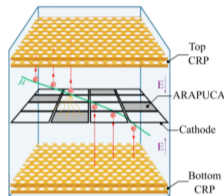
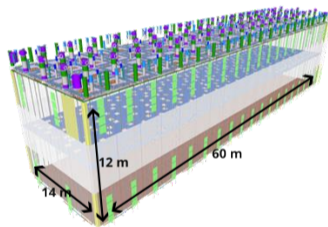
LAr is (relatively) cheap, dense and transparent to its own scintillation light.

## Horizontal Drift



- ▶ Four drift volumes, 3.6 m drift  $\rightarrow$  -180 kV
- ▶ Anodes are wire plane assemblies (APA)
- ▶ Cryogenic TPC readout

## Vertical Drift



- ▶ Two drift volumes, 6.25 m drift  $\rightarrow$  -300 kV
- ▶ Anodes are printed circuit boards (PCB)
- ▶ Bottom TPC: cryogenic readout, Top TPC: accessible cryo. electronics

# Photon Detection Systems

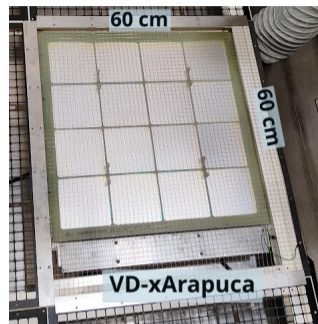
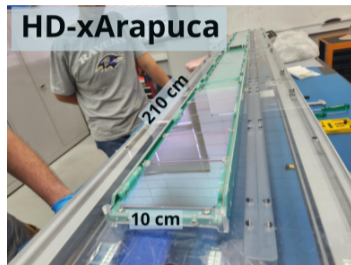
Light scintillation provides **time-stamp of neutrino interactions**:

## PDS requirements

- ▶  $\langle \text{light yield} \rangle > 20 \text{ PE/MeV}$ ,
- ▶  $\text{Min}(\text{light yield}) > 0.5 \text{ PE/MeV}$
- ▶  $\sigma_t < 100 \text{ ns}$
- ▶ Dynamic range /  $< 20\%$  saturation

## HD PDS:

- ▶ embedded in anodes
- ▶ xA-supercells of 96 SiPMs each (2 channels)  
→ 300000 total (in production)



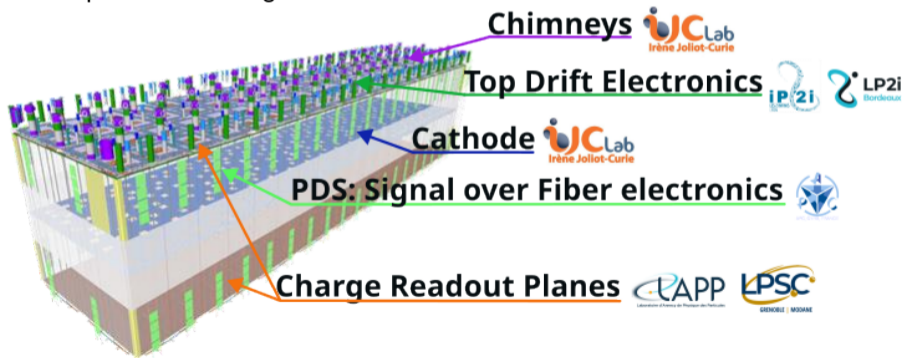
## VD PDS:

- ▶ xA-megacell with 160 SiPMs (2 channels)  
→ 10200 total
- ▶ PCB anodes are opaque → different xArapuca placement
  - 340 on cryostat membrane
  - 320 on cathode HV surface → **PoF and SoF technology**









# French Contributions to the VD FD

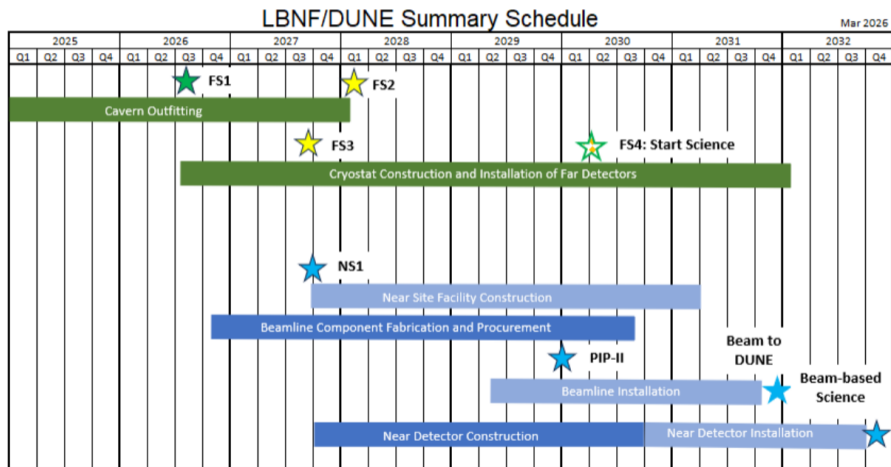
France has a large contribution to the Vertical Drift Far Detector via IN2P3:

- R&D of technological solutions
- Design of components
- Integration into the detector
- Production, QA/QC, shipping
- Computing: disk space and storage at CCIN2P3



# LBNF/DUNE Schedule

-  **FS1:** Start of far site cryostat construction
-  **FS2:** Far site conventional facility transition to operations complete
-  **FS3:** Start of far detector construction
-  **FS4:** Start Science - First far detector transition to operations
-  **NS1:** Start Near Site Civil
-  **NS2:** PIP-II Early CD-4
-  **NS3:** Deliver Beam to DUNE
-  **NS4:** Start Beam Based Science





## CERN Neutrino Platform



ProtoDUNE-VD  
(770 ton LAr)



ProtoDUNE-HD  
(770 ton LAr)

ProtoDUNE/DUNE ~1/20  
Full scale DUNE FD components

Unique cryogenic infrastructure for R&D  
on LArTPCs at large-scale

# ProtoDUNEs Phase I

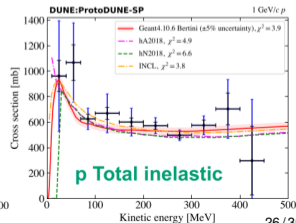
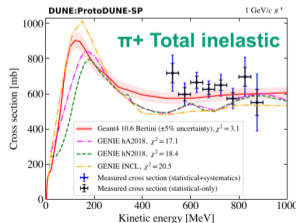
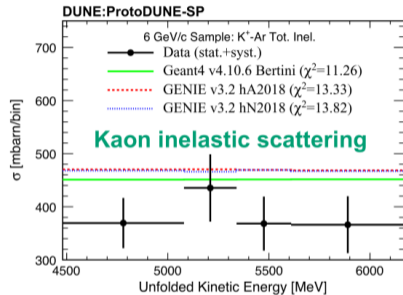
Largest LArTPC ever operated!

- ▶ ProtoDUNE-SP and DP constructed and operated (2018-2020)
- ▶ Successful demonstration of LAr-TPC technology at the kiloton scale
- ▶ and LAr purities that allow longer drift distances
- ▶ Lessons learned:
  - Vertical Drift LArTPC concept
  - final design components
- ▶ Large number of publications and on-going analysis:

Phys. Rev. D 110 (2024) no.9, 092011  
arxiv:2511.11925

arXiv:2511.13462

Measurement of  $p/\pi/K$  - Ar inclusive and exclusive cross-sections:



# ProtoDUNEs Phase II

Construction and operation of full-scale prototypes with  $\sim$  final design components

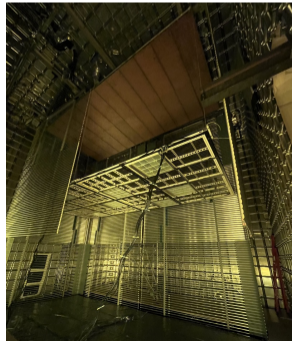
## ProtoDUNE-HD (NP04):

- ▶ Construction (2020-2023) with final technical solutions for all components
- ▶ Operation 2024 - 10 weeks of charged particle test beam from SPS and cosmics

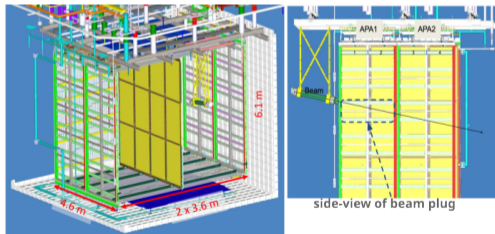


## ProtoDUNE-VD (NP02):

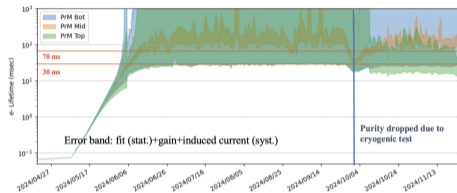
- ▶ All-new concept: prototype testing in  $3 \times 3 \times 1 \text{ m}^3$
- ▶ Construction (2023-2024) - first integrated test of VD technologies
- ▶ In operation since May 2025 - testbeam with charged particles in August 2025



- ▶ 2 APAs per wall (smaller than SP)
- ▶ longer beam pipe because detector is further away from cryostat wall
- ▶ New calibration systems: laser and  $^{207}\text{Bi}$

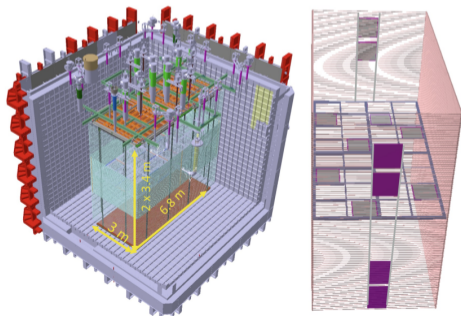


## Electron lifetime > 70 ms



- ▶ Successful demonstration of detector operation:
  - Excellent electronics noise performance
  - Stable HV operation
  - operation of photo-detection system
  - and of laser calibration

- ▶ 2 top and 2 bottom Charge Readout Planes
- ▶ Cathode at 3.4 m from anodes
- ▶ Photon-Detection System with 8 PD on cathode (HV surface: SoF and PoF) and 8 on membrane
- ▶ New beam-plug for SPS test beam



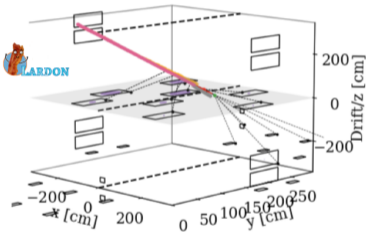
- ▶ LAr transferred from NP04  
→ electron lifetime at 25 ms
- ▶ on-going gradual Xe doping to reach 10 ppm  
- characterisation of light signal shape evolution as a function of Xe mix
- ▶ Pulsed neutron data acquisition on-going
- ▶ Demonstrated performance for all system:
  - stable operation of HV (300 kV bias test on-going)
  - Good SNR and performance for top and bottom readout, and PDS

Full-scale mockup installation in b.185@CERN

# ProtoDUNE analysis highlights (french bias)

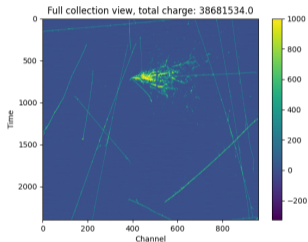
A non-exhaustive list of the many contributions to the analysis of ProtoDUNE-HD and VD data!

## ◆ Event reconstruction and TPC+light matching

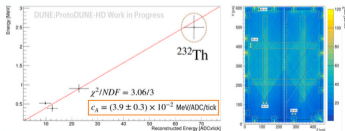


## ◆ Michel-e reconstruction → see Jeremy's talk

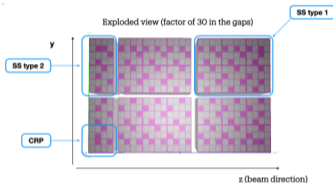
## ◆ Analysis of neutrino candidates



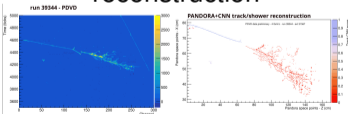
## ◆ Study of radiological backgrounds



## ◆ Study of CRP gap effects and tuning



## ◆ Implementation of SPINE AI/ML tool for track & shower reconstruction



# Conclusions

**DUNE will be a key experiment** in the next decade:

- ▶ High precision measurement of neutrino oscillations
- ▶ Unambiguous determination of mass hierarchy and CP violation in the leptonic sector
- ▶ Detection of SN and solar neutrinos
- ▶ Extended physics program with atmospheric

**Huge progress in Near and Far Detectors** design, prototyping and construction:

- ▶ The ND complex design is mature and prototypes are under test
- ▶ The FD1 and FD2 design has been fixed:
  - some components are already in production
  - (many) reviews to allow systems to move on to production
- ▶ The ProtoDUNE program is at its 2<sup>nd</sup> phase:
  - ProtoDUNE-HD (2024) 10 weeks of SPS beam, over 28 mill. triggers recorded
  - ProtoDUNE-VD (Jan 2025 - ongoing) was exposed to beam in August 25 and data taking is on-going with cosmics and calibration

Important French contributions both on detector design/construction and on analysis!

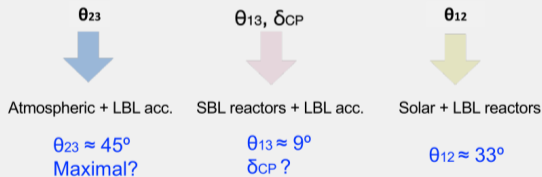
**Back Up**

# Neutrino oscillations

- Three neutrino mixing:  $| \nu_\alpha \rangle = \sum_{i=1}^3 U_{\alpha i} | \nu_i \rangle$

Pontecorvo, Maki, Nakagawa, Sakata (PMNS) 3x3 mixing matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$



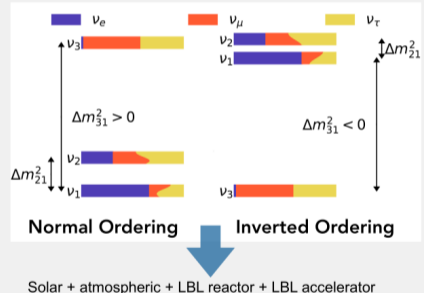
Current precision oscillation parameters ~6-20 %

Oscillation probability

$$P_{\nu_\alpha \rightarrow \nu_\beta}(L, E) = \delta_{\alpha\beta} - 4 \sum_{i>j} \text{Re} [U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*] \sin^2 \left( \frac{\Delta m_{ij}^2 L}{4E} \right) - 2 \sum_{i>j} \text{Im} [U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*] \sin \left( \frac{\Delta m_{ij}^2 L}{2E} \right)$$

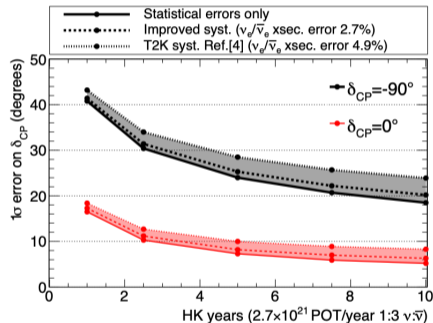
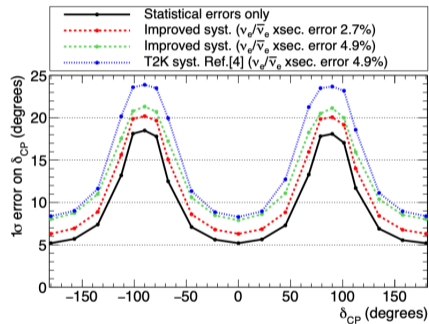
$$\Delta m_{ij}^2 = m_i^2 - m_j^2$$

Neutrino mass spectrum

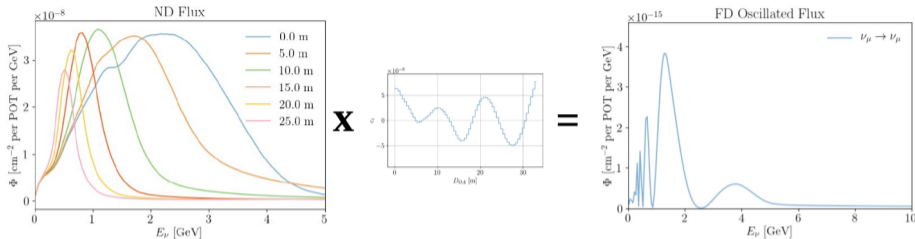


$$\Delta m_{21}^2 \approx 7.5 \times 10^{-5} \text{ eV}^2$$

$$|\Delta m_{31}^2| \approx 2.5 \times 10^{-3} \text{ eV}^2 \quad \text{Sign?}$$



# PRISM: how and why it works (3)



- Linearly combine ND distributions of **reconstructed energy** to produce a weighted distribution that corresponds to a different flux
- With enough basis vectors, one can make quite complicated “target” fluxes, for example the FD flux (for some oscillation hypothesis)
  - This only works if you scan the entire range; having two fixed detectors would not enable this technique

\*slide by Chris Marshall