The DUNE Experiment: Status and Physics Prospects

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On behalf of the DUNE collaboration

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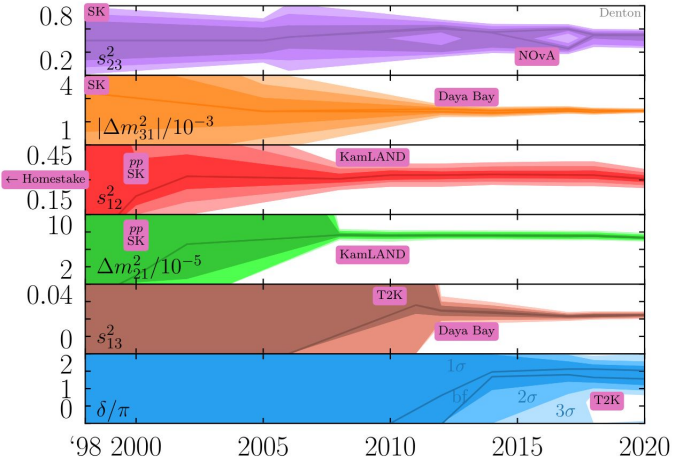
cnrs NUCLÉAIRE & PARTICULES
LAPP Laboratoire d'Annecy de Physique des Particules
UNIVERSITÉ SAVOIE MONT BLANC

DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT

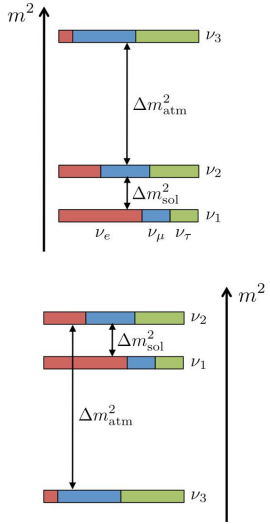
Neutrino physics: The current picture

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = U_{PMNS}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

$$U_{PMNS} = \underbrace{\begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}}_{\text{Atmospheric Accelerator}} \underbrace{\begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta}\\ 0 & 1 & 0\\ s_{13}e^{i\delta} & 0 & c_{13}\end{pmatrix}}_{\text{Reactor Accelerator}} \underbrace{\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}}_{\text{Solar Reactor}} \underbrace{\begin{pmatrix}i & 0 & 0\\ 0 & e^{i\alpha} & 0\\ 0 & 0 & e^{i\beta}\end{pmatrix}}_{0\nu\beta\beta}$$



arXiv: 2212.00809



So far data can be **"described"** in the **3ν framework**
Most of the parameters have been **determined** ✔
But …
CP violating phase?
Mass ordering?
Octant of θ_{23}?
Sterile neutrinos?
Is the 3-flavor model correct?
Dirac or Majorana?
Absolute mass scale?

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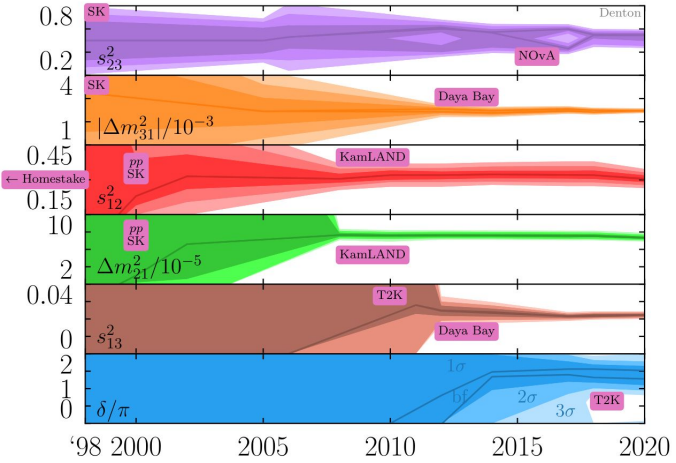
Reactor Accelerator



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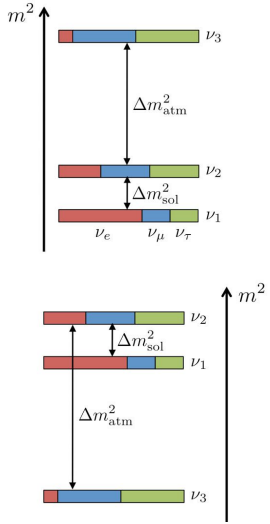

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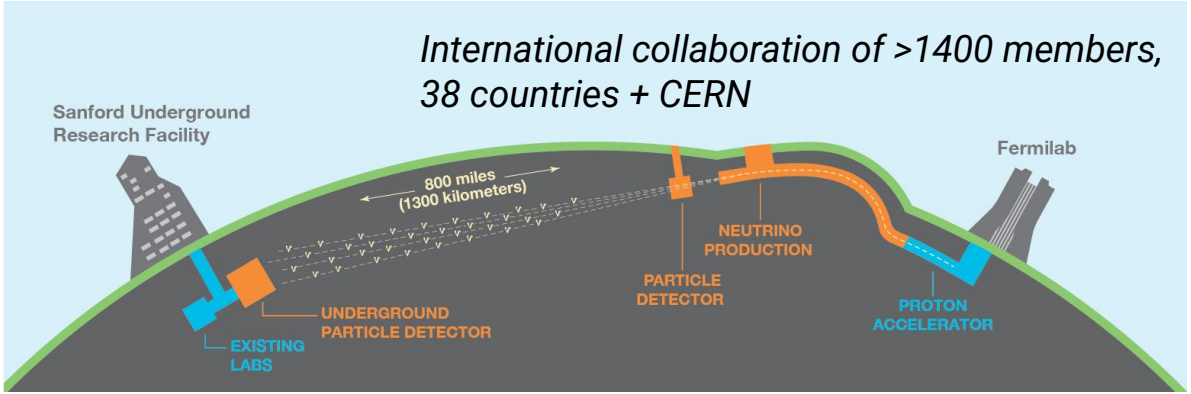
DUNE scope

- **CP violating phase?**
- **Mass ordering?**
- **Octant of θ_{23}?**
- **Sterile neutrinos?**
- **Is the 3-flavor model correct?**
- **Dirac or Majorana?**
- Absolute mass scale?

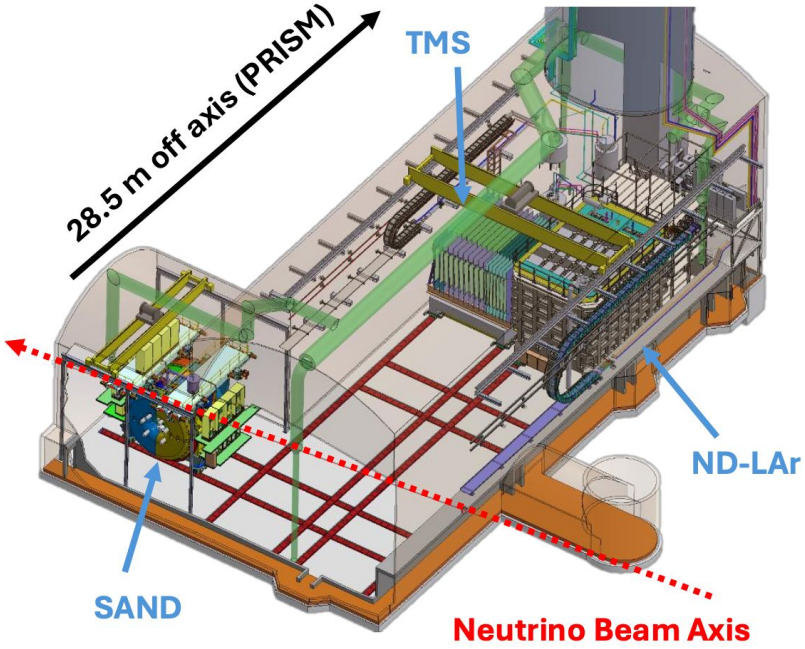
The Deep Underground Neutrino Experiment



- **DUNE – Next-Generation Long-Baseline Neutrino Experiment**
  - **Baseline:** 1300 km from Fermilab to SURF (South Dakota) → enables ***unambiguous*** neutrino mass ordering determination
  - **Far Detector Location:** **1.5 km underground** at the Sanford Underground Research Facility
  - Project Structure: Developed in **two phases**
  - **Beam Power:** World's most powerful neutrino beam – **2 MW ν beam** from Fermilab
  - **Wide-band neutrino energy spectrum** allows **precise measurement of oscillation parameters**
- Detector systems:
  - **Near Detector (ND)**: 574 m from source; measures unoscillated neutrino flux
  - **Far Detector (FD)**: 3 × 17 kton **Liquid Argon TPC** modules + module of opportunity (LArTPC or other) at SURF

Near detectors

The Near Detector complex will constrain DUNE's flux and cross section systematic uncertainties



Three detectectors located 574 m from the beam & 60 m underground

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

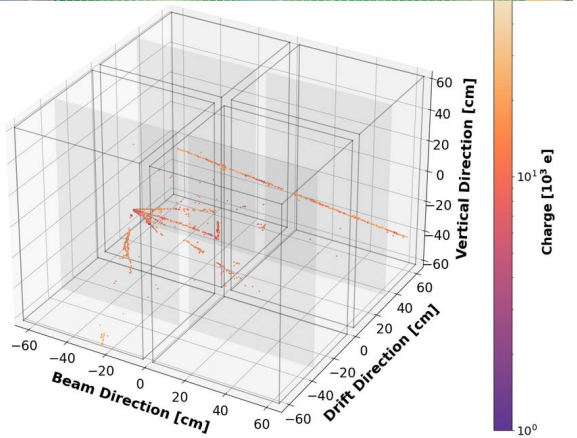
Talk by D. Casazza

ND-LAr and TMS are movable detectors: This is the DUNE-PRISM concept

Near detector prototype: 2x2 ND-LAr

Goals: *Demonstrate modular design with natively 3D pixelated readout*

- 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 at FERMILAB
  - Four TPC modules installed in former location of MINOS-ND
  - Includes upstream/downstream trackers from MINERvA
  - Development of **neutrino analysis pipelines**
  - **Performance demonstrations**

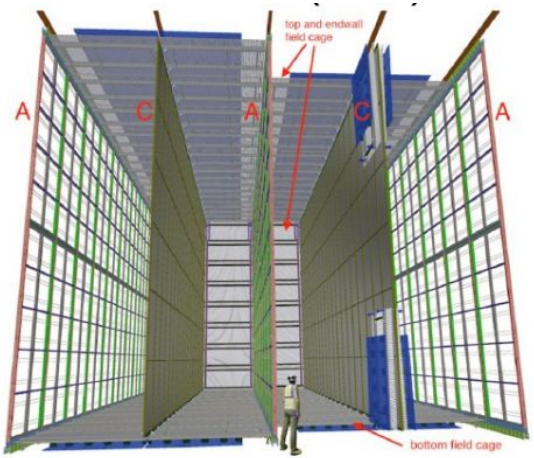


Far detector technologies: HD vs VD

Horizontal drift:

- Wire readout planes (**APAs**)
- **Four drift regions** of ~3.5 m
- X-ARAPUCA light readout

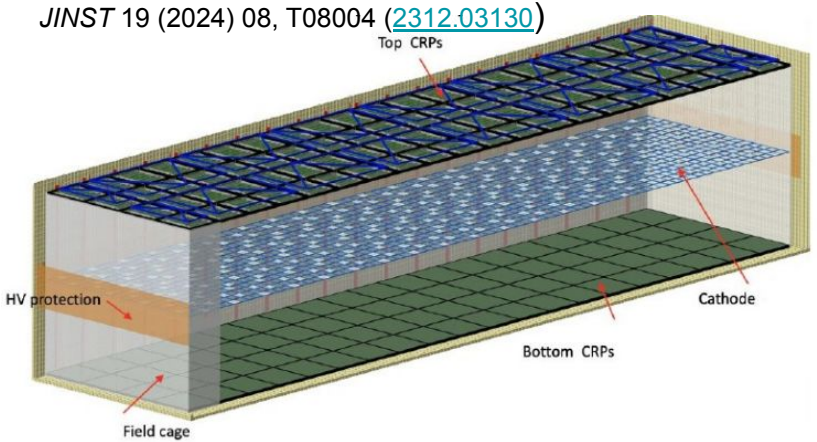
JINST 15 (2020) 08, T08010 (2002.03010)



Vertical drift:

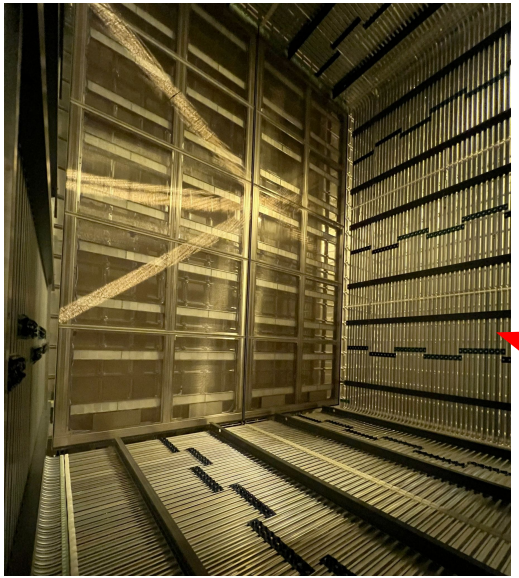
- Charge readout planes (**CRPs**) with PCB-based anodes
- **Two 6.25 m drift regions** and central cathode
- X-ARAPUCA light readout

JINST 19 (2024) 08, T08004 (2312.03130)

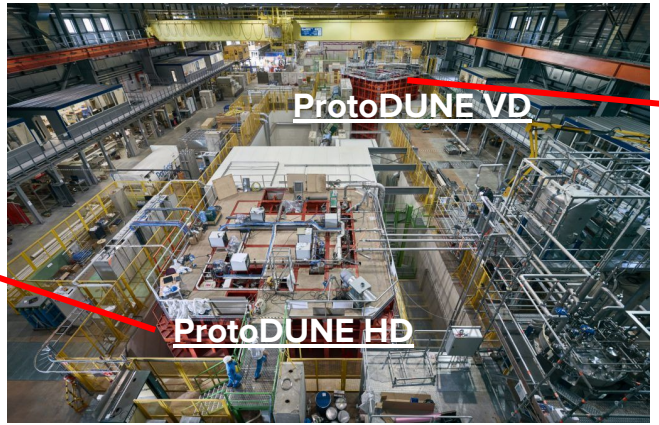


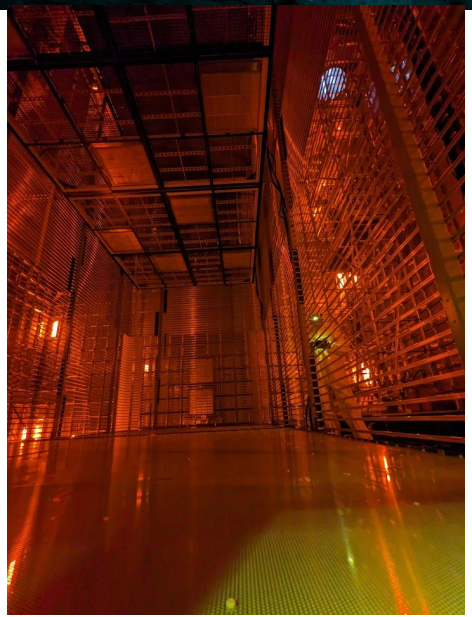
VD simpler to install → first DUNE FD module will use vertical drift

Far detector prototypes: ProtoDUNEs at CERN



CERN neutrino platform

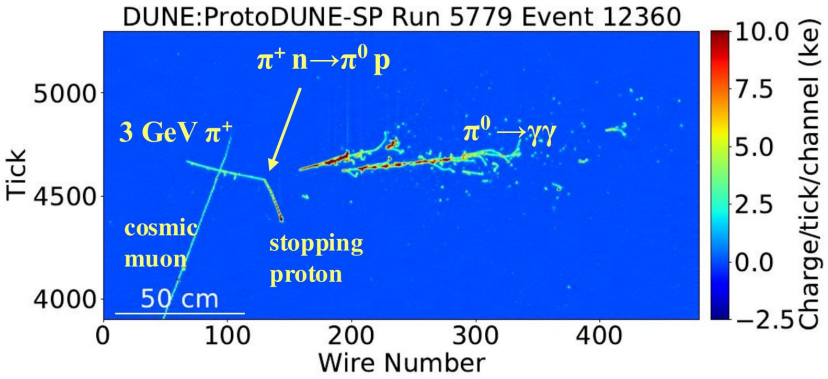




- Two 750 t LAr detectors with **real-size** readout elements (**APA, CRP, PDS**)
- **Validate the procurement & installation** sequence with 1:1 components
  - Estimate future resources needed and approve **final detector components design**
  - Cosmic and hadron **beam data** to allow **physics studies** and assess the **LArTPC performances**

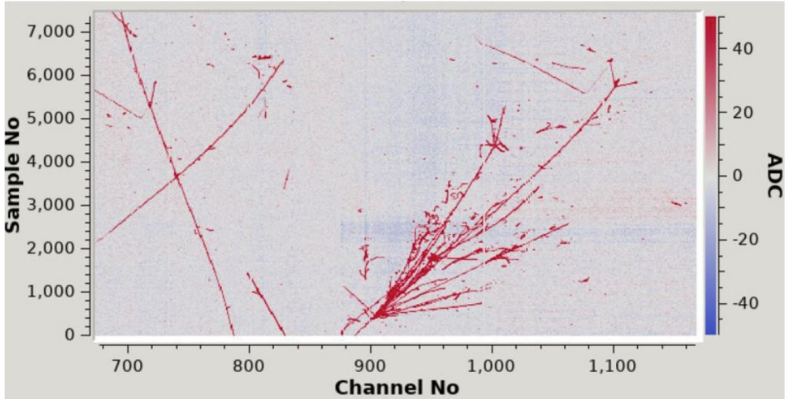
Far detector prototypes: ProtoDUNEs at CERN

ProtoDUNE-HD



- ProtoDUNE-HD completed LAr filling on April 30th, 2024
  - Physics data taking for several months with beam + cosmics + radioactive sources
- Excellent LAr purity: **>30 ms e^- lifetime!**
  - DUNE requirement: 3 ms
- Physics analysis ongoing

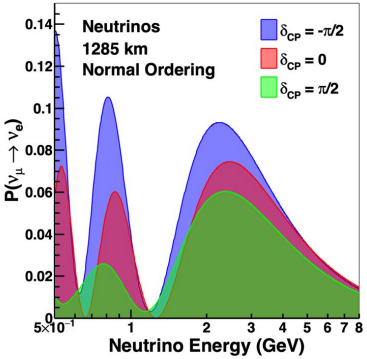
ProtoDUNE-VD

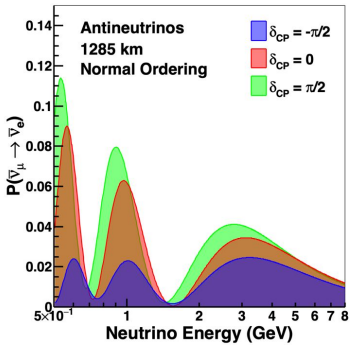


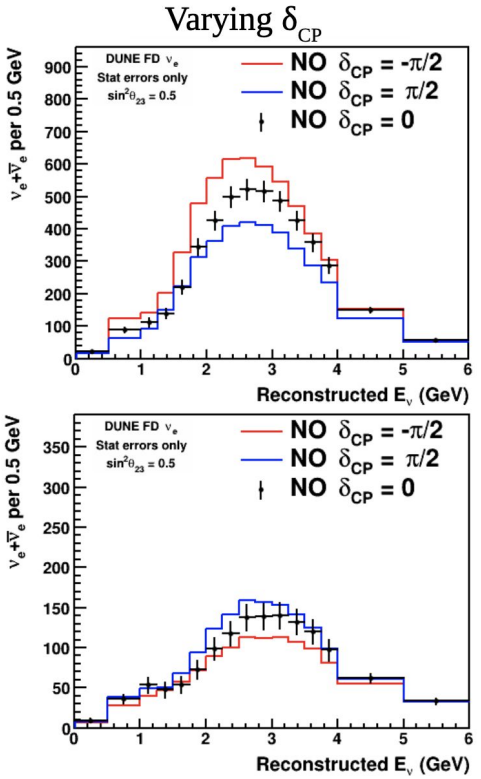
- Test of the **VD concept** for the first time at **large scale**
- LAr transferred from ProtoDUNE-HD completed on December 2025
- Commissioning being completed
  - **First data with nominal operational conditions already taken**
  - Cosmics tracks nicely reconstructed

Neutrino energy at the far detectors

- If $\delta_{CP} \sim -\pi/2$
  - DUNE will measure an **enhancement** in electron **neutrino appearance**, and a **reduction** in electron **antineutrino appearance**

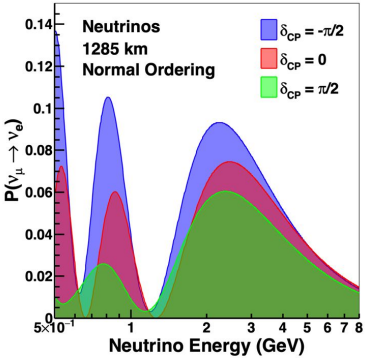


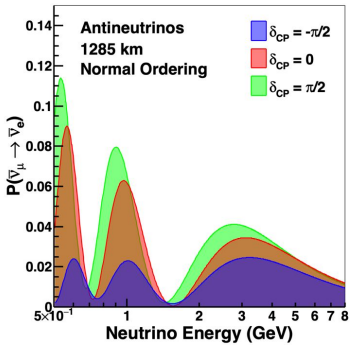




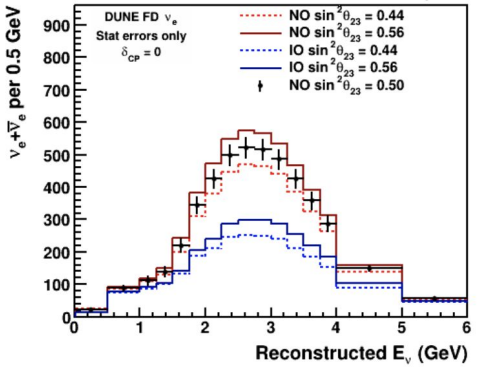
Neutrino energy at the far detectors

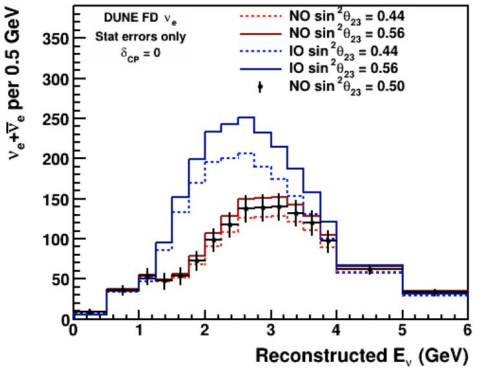
- If $\delta_{CP} \sim -\pi/2$
  - DUNE will measure an **enhancement** in electron **neutrino appearance**, and a **reduction** in electron **antineutrino appearance**
- If the **mass ordering** is normal
  - DUNE will measure a much **larger enhancement** in electron neutrino appearance, and a reduction in electron antineutrino appearance
- **MO, δ_{CP}, and θ_{23}** all affect spectra with different shape
  - → additional handle on resolving degeneracies
- **If new physics is present**
  - There may be no combination of MO, δ_{CP}, and θ_{23} that fits data





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





CP sensitivity

- DUNE can establish CPV
  - >3σ in 3.5 years for best scenario
  - Over 50% of δCP values at >5σ
  - Over 75% of δCP values at >3σ (worst case scenario)
- After 10 years of exposure, strong CP violation discovery potential for both mass ordering options

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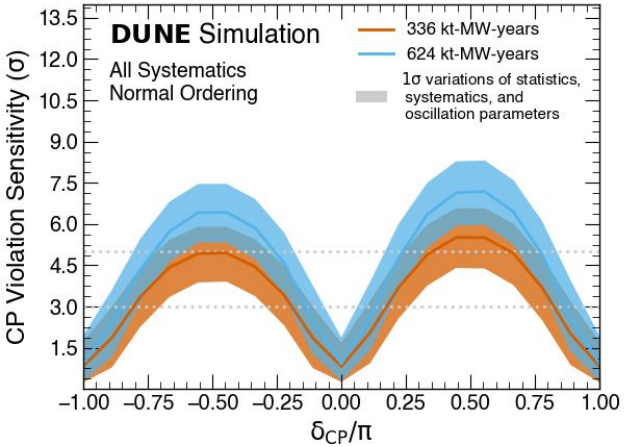

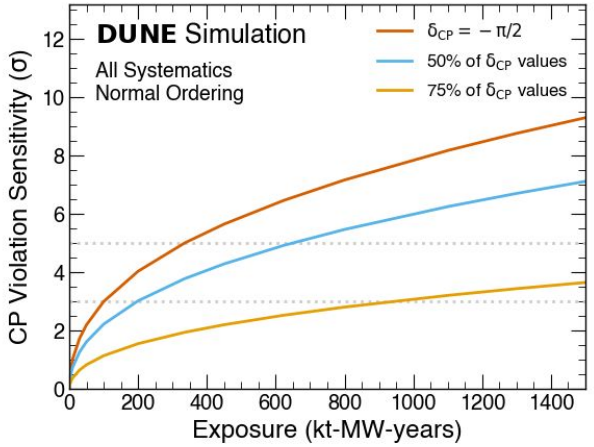

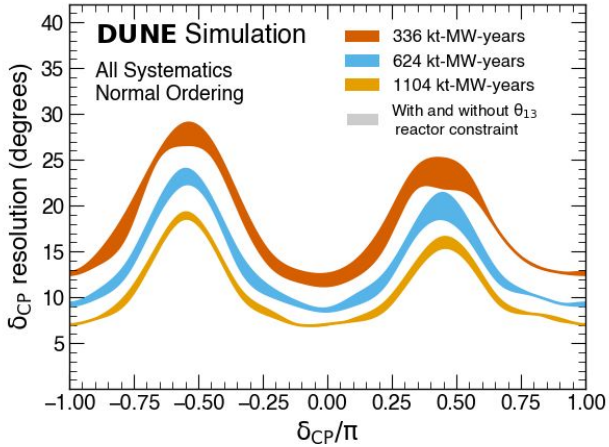

Mass ordering sensitivity

Regardless of the values of the other oscillation parameters:

- DUNE can establish **mass ordering at > 5σ in 1 year** (best case scenario)
- DUNE can establish **mass ordering at > 5σ in 3 year** (worst case scenario)

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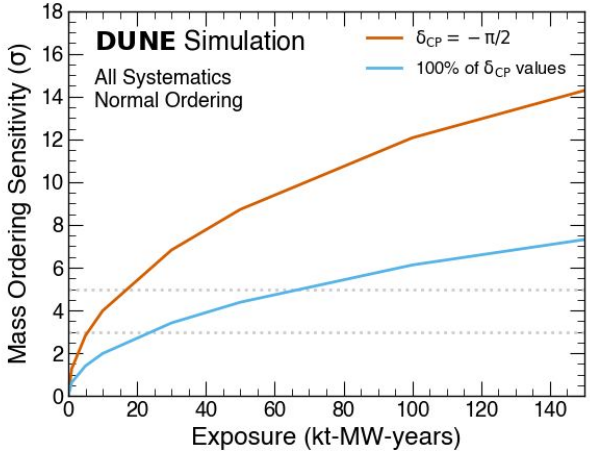
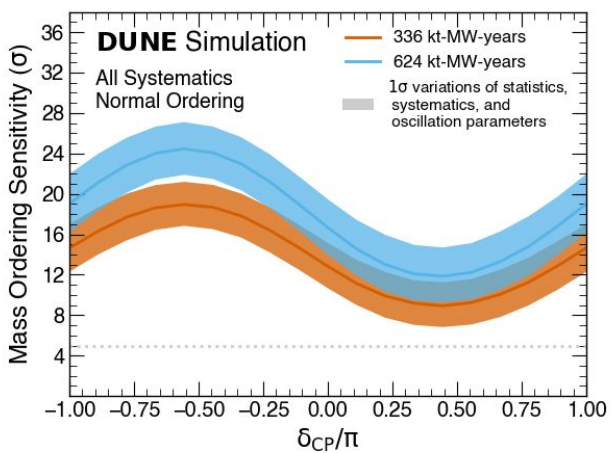
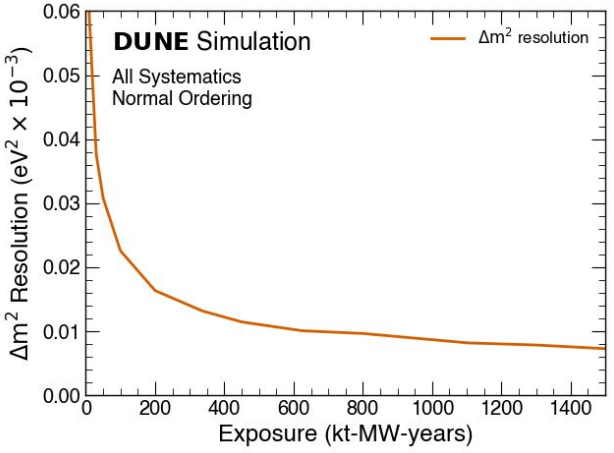


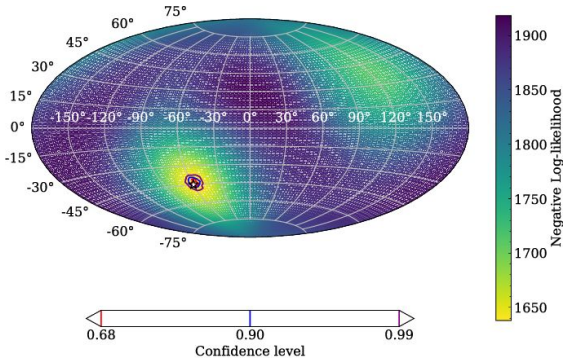




Astrophysical neutrinos

- **Ar target** provides unique sensitivity to MeV electron neutrinos
  - **CC channel**: $\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$
  - **ES channel**: $\nu_x + e^- \rightarrow \nu_x + e^-$ (pointing)
- Neutrinos from **core-collapse supernovae**
  - Neutronization burst measurements → mass ordering measurement
  - ES channel enables ~5° pointing resolution (40 kt, 10 kpc)
- **Solar neutrinos**
  - Discovery sensitivity to the **hep solar flux**
  - **Improve upon existing solar oscillation measurements** via day-night asymmetry induced by Earth matter effects

Poster by S. Butchart



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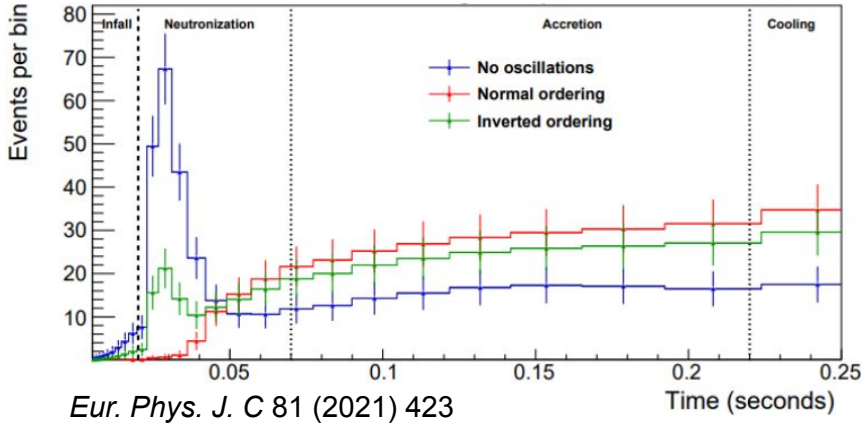

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Construction status

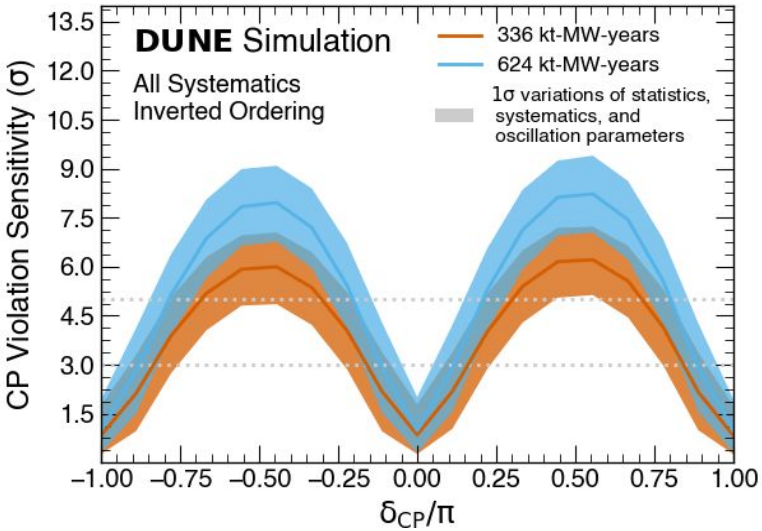
- Cryostat installation starting in 2026
- Inner detector components installation starting in ~2027
- Physics data taking starting in ~2030

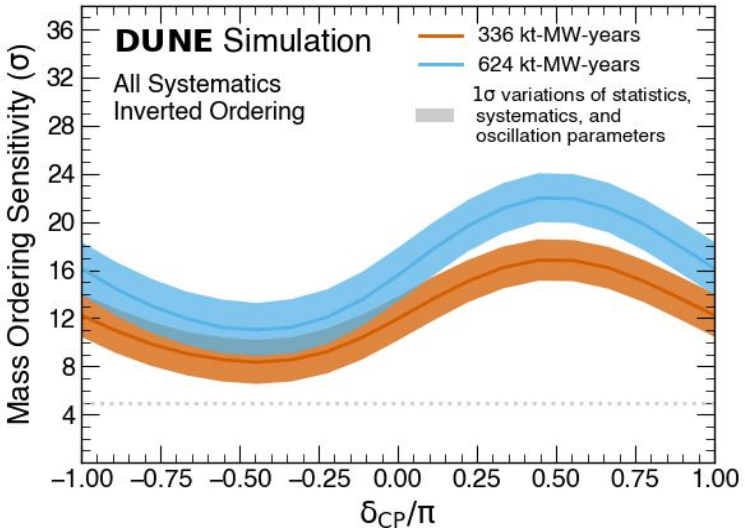
DUNE: Summary & Outlook

- World-leading long-baseline neutrino experiment under construction in the U.S. aimed at major discoveries:
  - **Neutrino mass ordering**
  - **Leptonic CP violation**
- Unique sensitivity to MeV-scale neutrinos:
  - Excellent **detection of supernova ν_e**
  - Potential to observe **hep solar flux**
  - Precision on solar neutrino parameters
- Complementary to the global neutrino effort
- Active prototyping at CERN & Fermilab
- **DUNE science starts this decade!**


Thank you for your attention!

Inverted ordering





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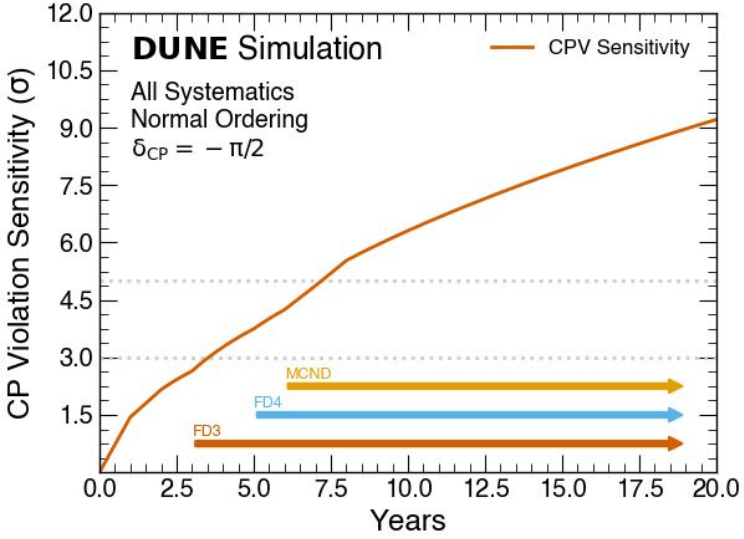
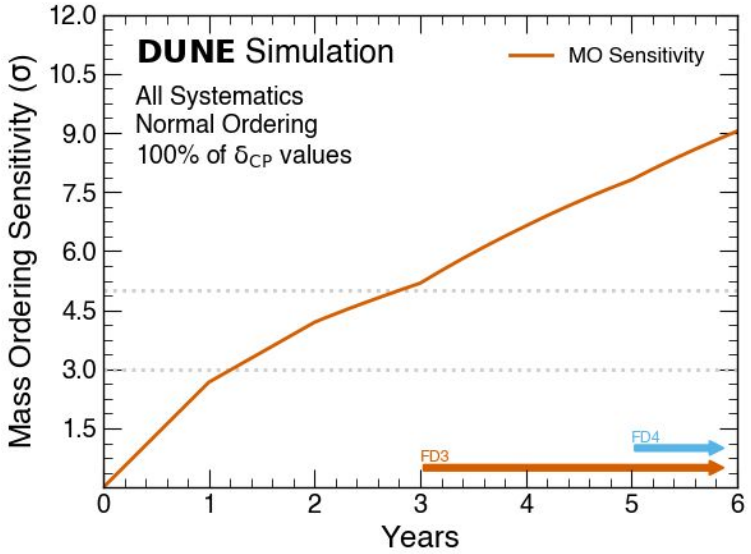
Sensitivity and FD modules





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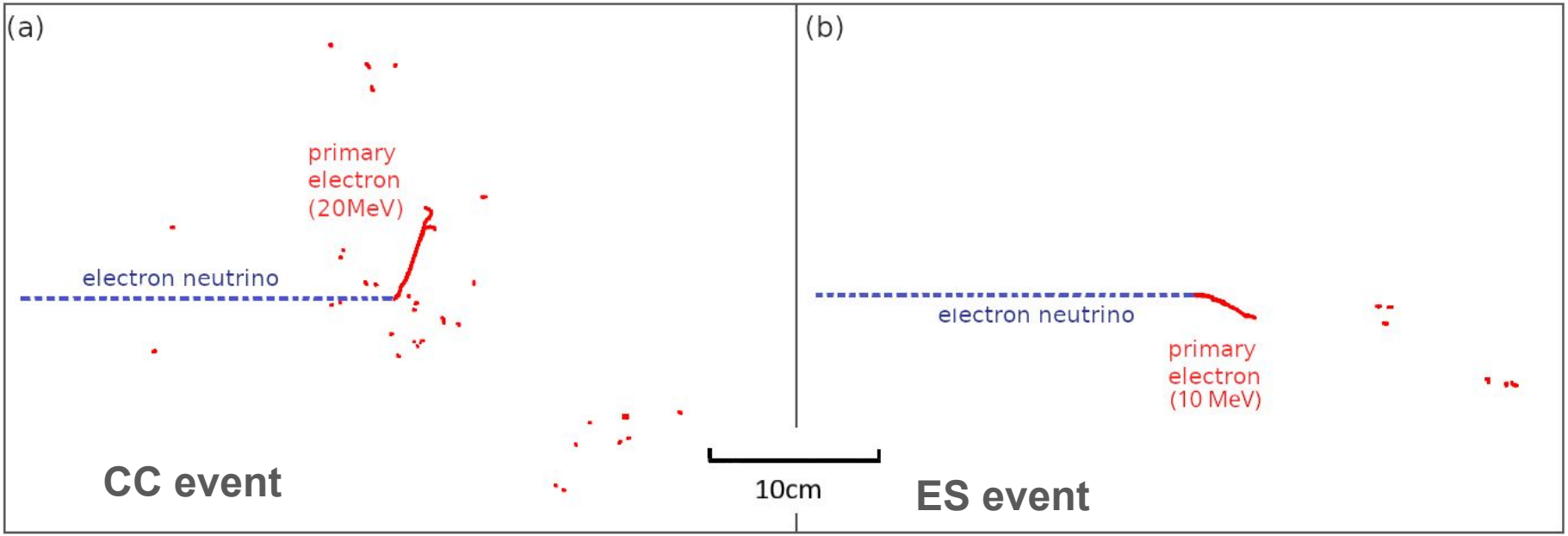
MeV neutrinos



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