DUNE: science & status

Francisco Martínez López,
on behalf of the DUNE collaboration

PIC 2024
43rd International Symposium on Physics in Collision
Athens, 24 October 2024

Particle Physics
STFC Rutherford Appleton Laboratory

Queen Mary
University of London

DUNE

Long baseline neutrino oscillations

Reactor/accelerator sector

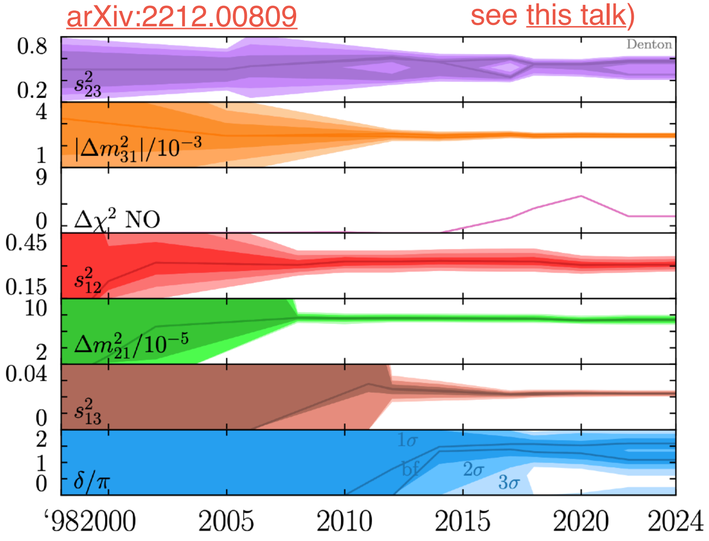
Majorana phases

$$U_{\mathrm{PMNS}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

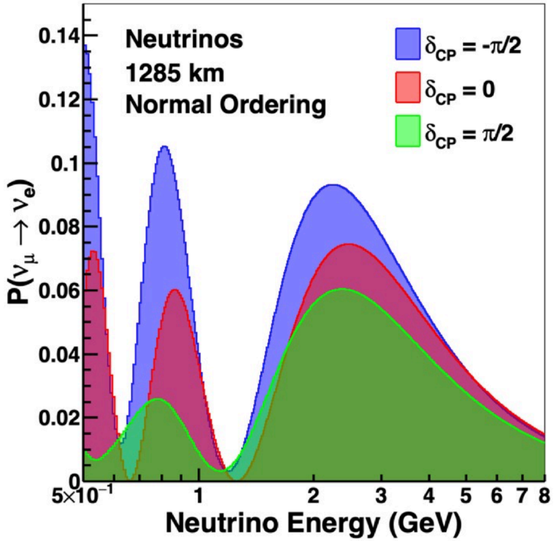
Atmospheric sector

Solar sector

(for updated version see this talk)

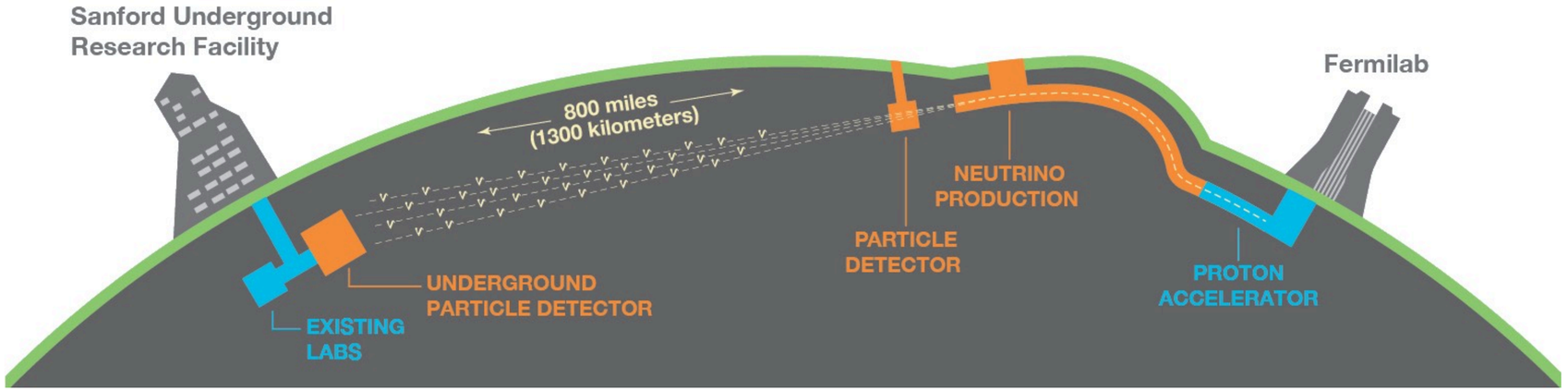


- Next-generation long-baseline oscillation experiments:
  - Determine the **neutrino mass ordering**.
  - Determine the **octant** of θ_{23} (greater/less than $45°$).
  - Determine if **CP is violated in the leptonic sector** and measure δ_{CP}.
- Is the 3 flavour model correct?
  - Precision measurements of neutrino/antineutrino oscillations as a function of L/E.

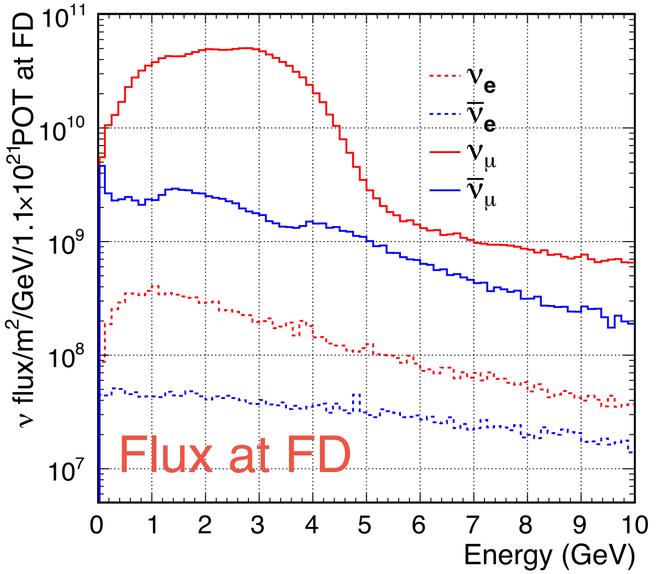


Particle Physics STFC Rutherford Appleton Laboratory · Queen Mary University of London · DUNE

The Deep Underground Neutrino Experiment

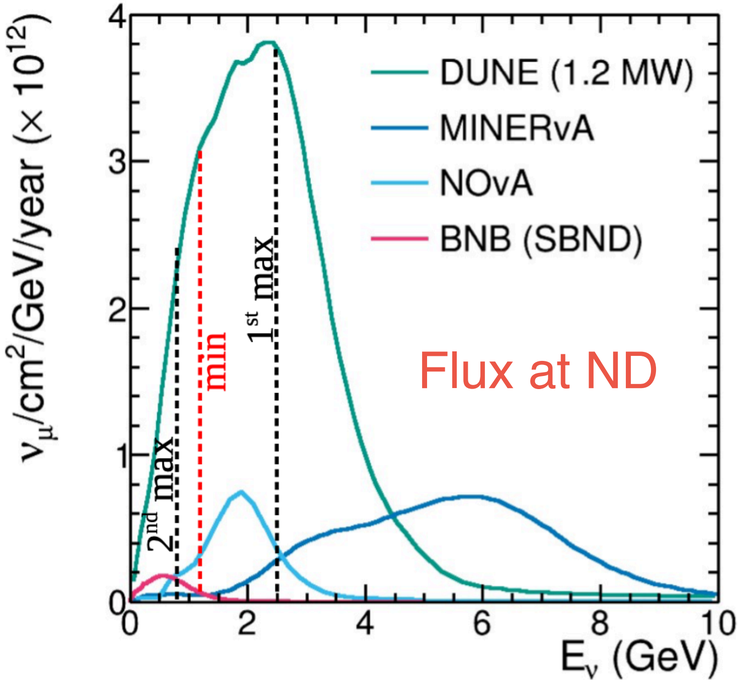


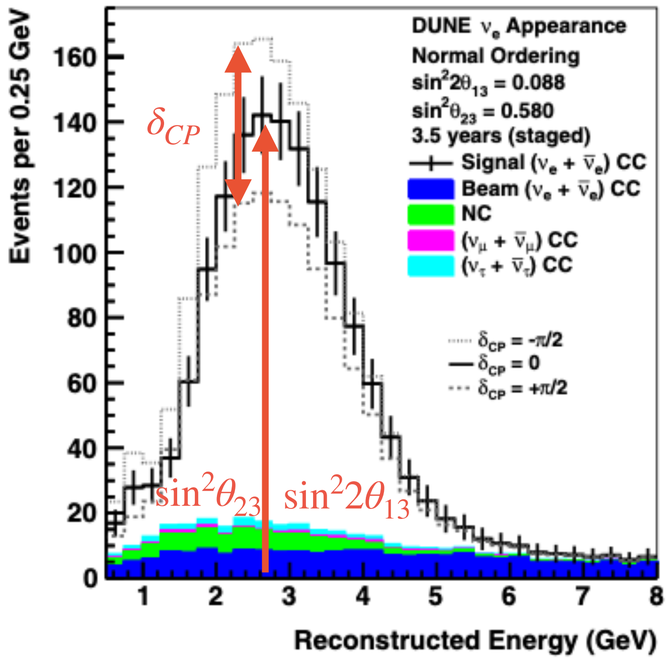
- New broad-band (anti)neutrino beam at Fermilab with $\geq$ 2 MW intensity.
- **Far Detector** (FD) @ SURF.
  - Underground modular LArTPC with $\geq$ 40 kton fiducial mass.
- **Near Detector** (ND) @ FNAL.
  - Multiple technologies to control systematic uncertainties.

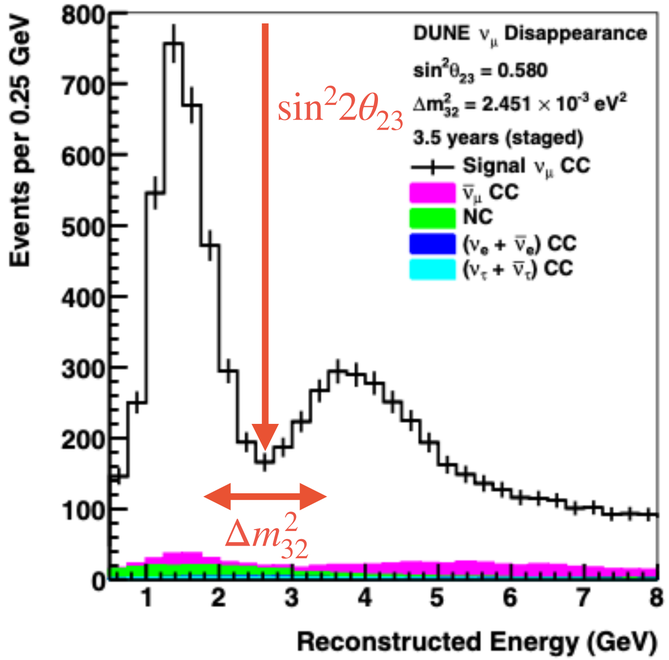


LBL neutrino oscillations

Long-baseline neutrino oscillation physics potential of the DUNE experiment
Eur.Phys.J.C 80 (2020) 10, 978



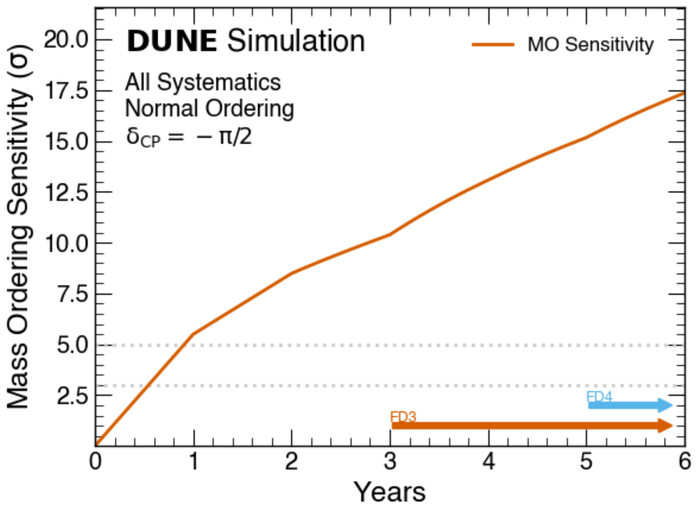


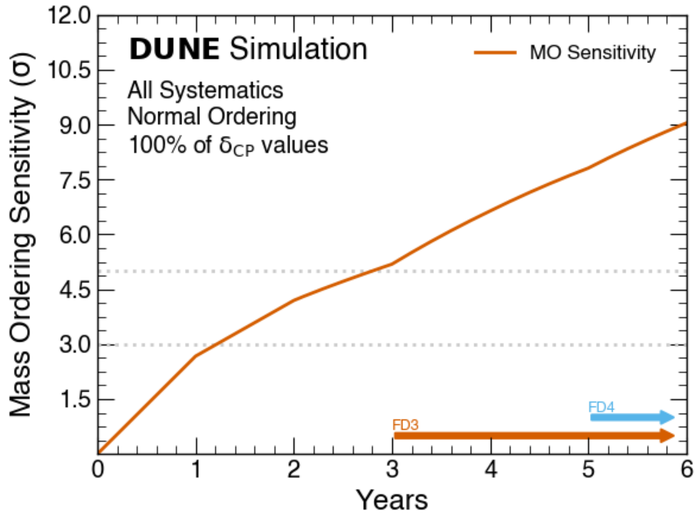


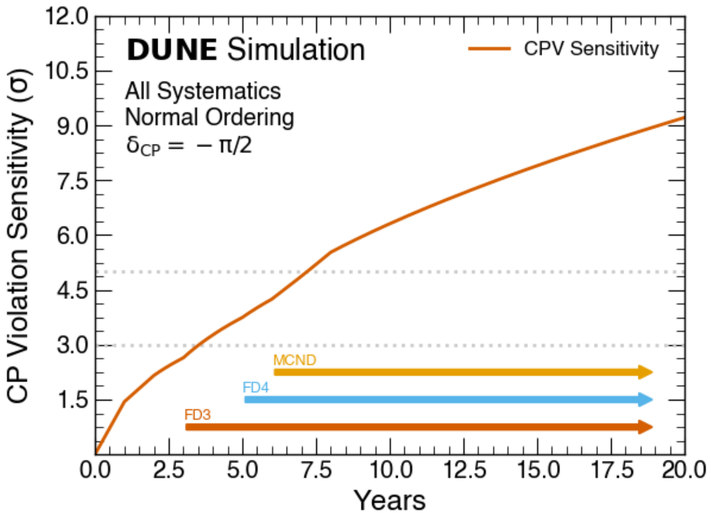
- Very high flux of neutrinos between oscillation minimum (1.27 GeV) and maximum (2.54 GeV), with coverage of the second maximum (0.80 GeV).
- MO, δ_{CP} and θ_{23} affect shape of the spectra in different ways, useful to resolve degeneracies.

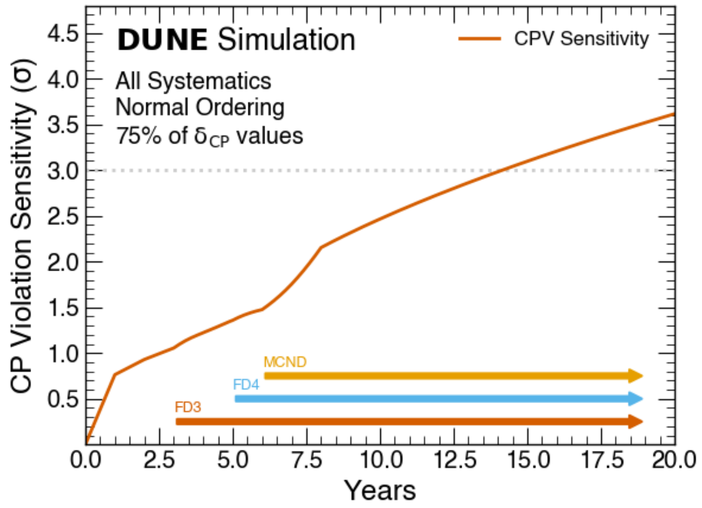
DUNE sensitivity

Long-baseline neutrino oscillation physics potential of the DUNE experiment
Eur.Phys.J.C 80 (2020) 10, 978









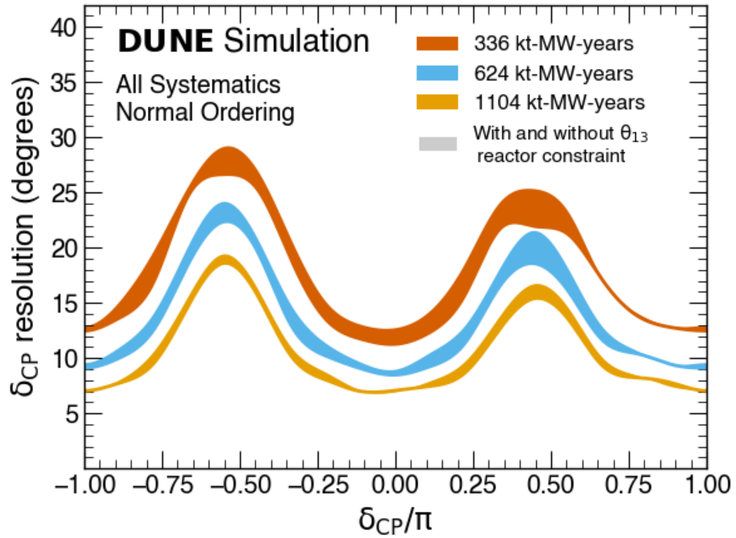
For **best-case** oscillation scenarios, DUNE has:

- $> 5\sigma$ mass ordering sensitivity after 1 year.
- $> 3\sigma$ CPV sensitivity in 3.5 years.

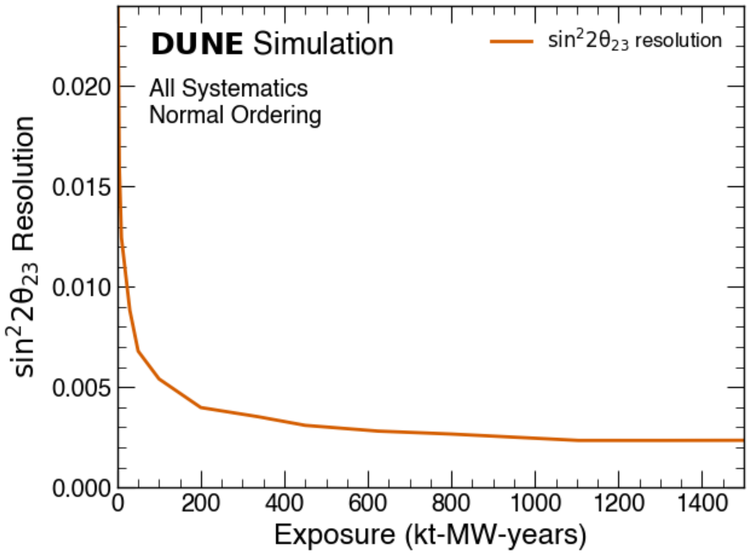
- For **worst-case** oscillation scenarios, DUNE has $> 5\sigma$ mass ordering sensitivity in 3 years.
- In the **long term**, DUNE can establish CPV over 75% of δ_{CP} values at $> 3\sigma$.

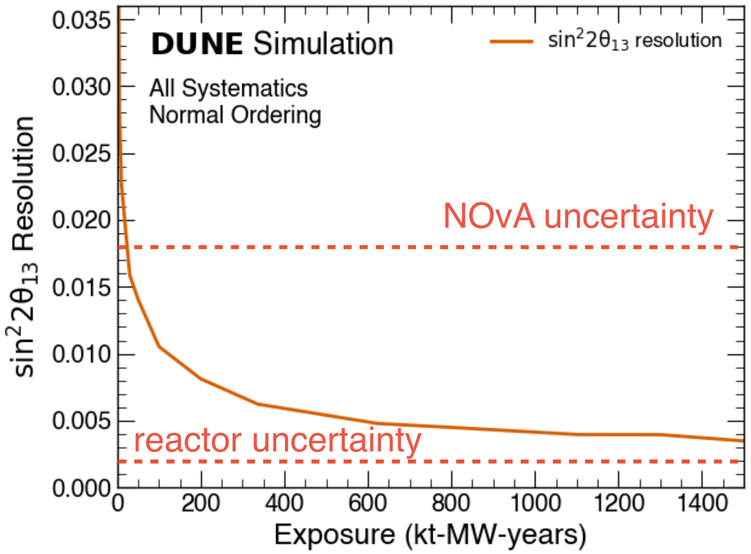
Precision measurements

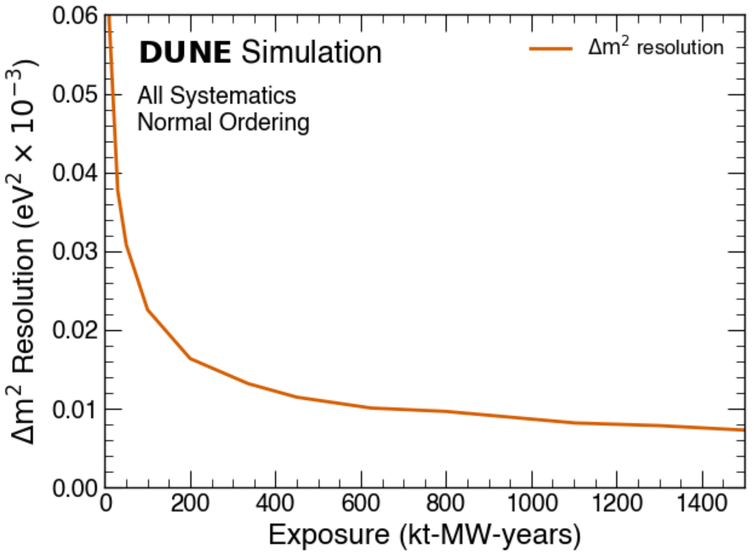
Long-baseline neutrino oscillation physics potential of the DUNE experiment
Eur.Phys.J.C 80 (2020) 10, 978



- Ultimate precision $6 - 16^{\circ}$ in δ_{CP}.
- World leading precision for Δm^2 and θ_{13} in accelerator experiment.
  - Comparisons to reactor measurements are sensitive to new physics.



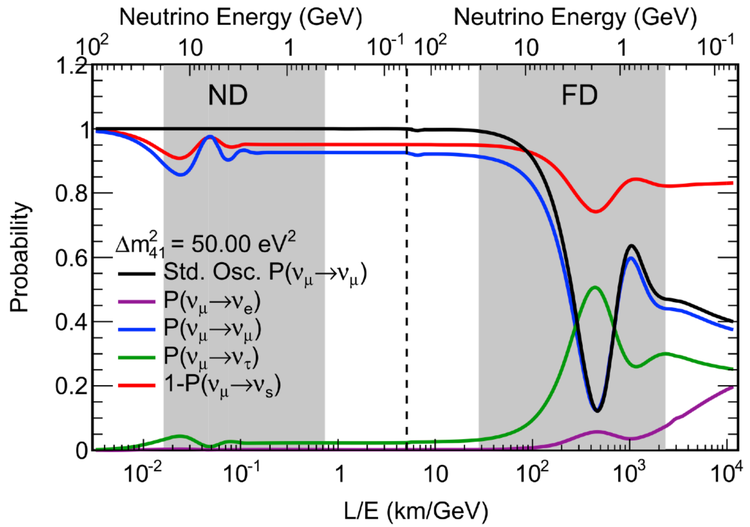




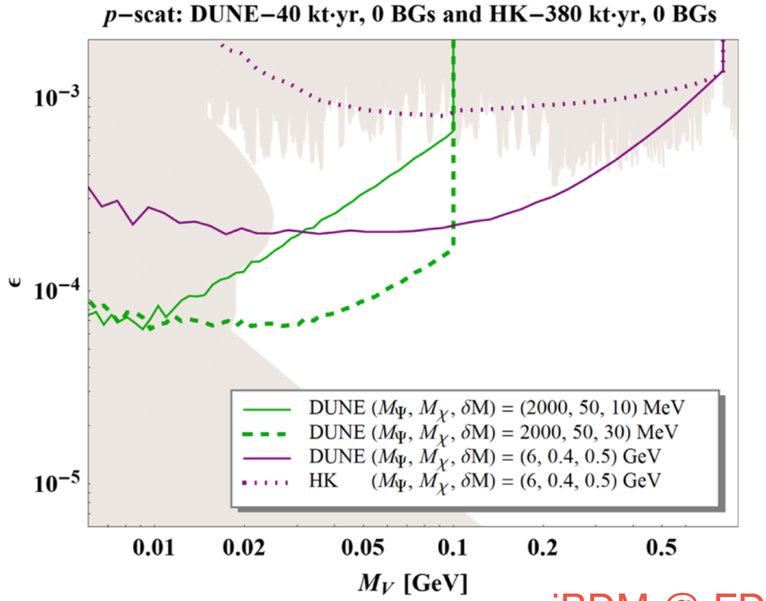
Beyond the Standard Model

Prospects for beyond the Standard Model physics searches at the Deep Underground Neutrino Experiment
Eur.Phys.J.C 81 (2021) 4, 322

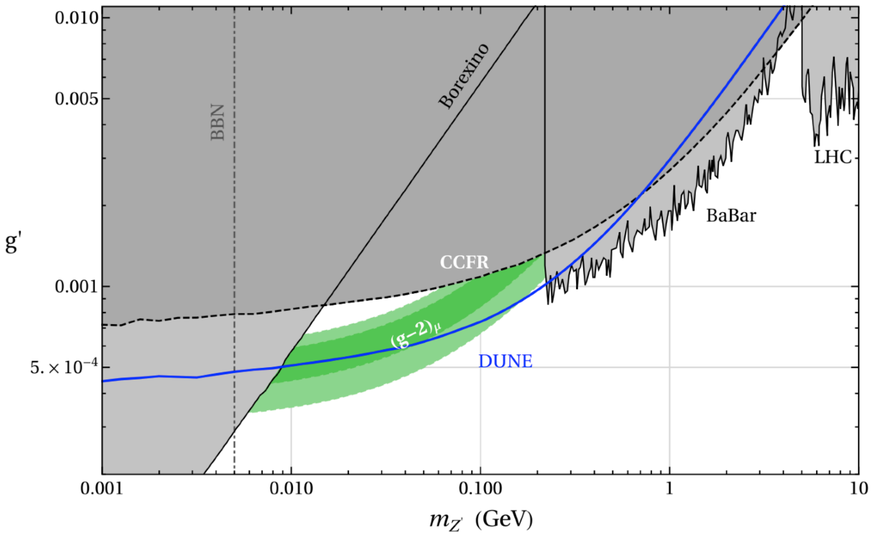
- DUNE covers a broad L/E range both at the ND and FD **new physics in neutrino oscillations** (sterile mixing, CPT violation, NSI, …).
- FD sensitive to other rare processes (iBDM, nucleon decay, …) thanks to its low energy and directionality capabilities.
- ND is sensitive to exotic physics from the beam (light DM, HNL, …) and BSM contributions to neutrino interactions (neutrino tridents).



Sterile neutrino mixing



iBDM @ FD

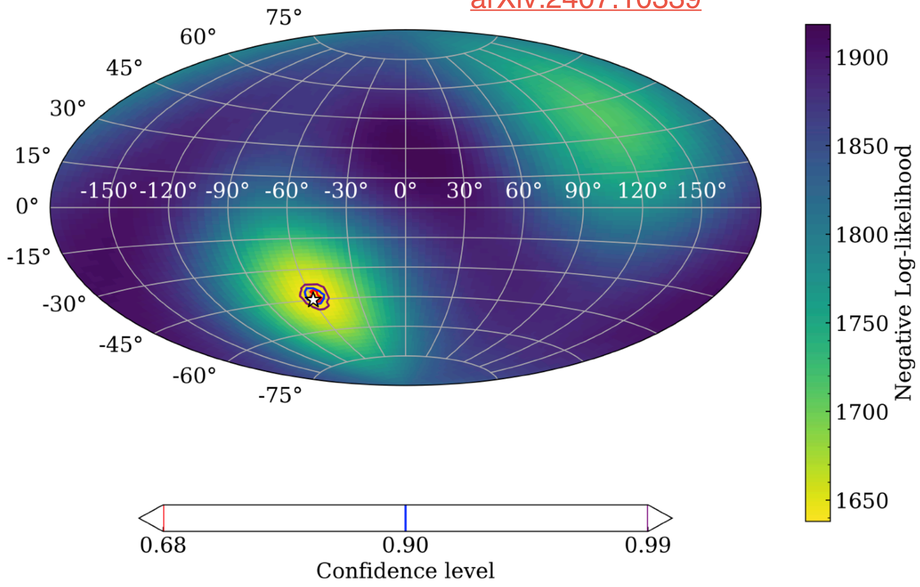


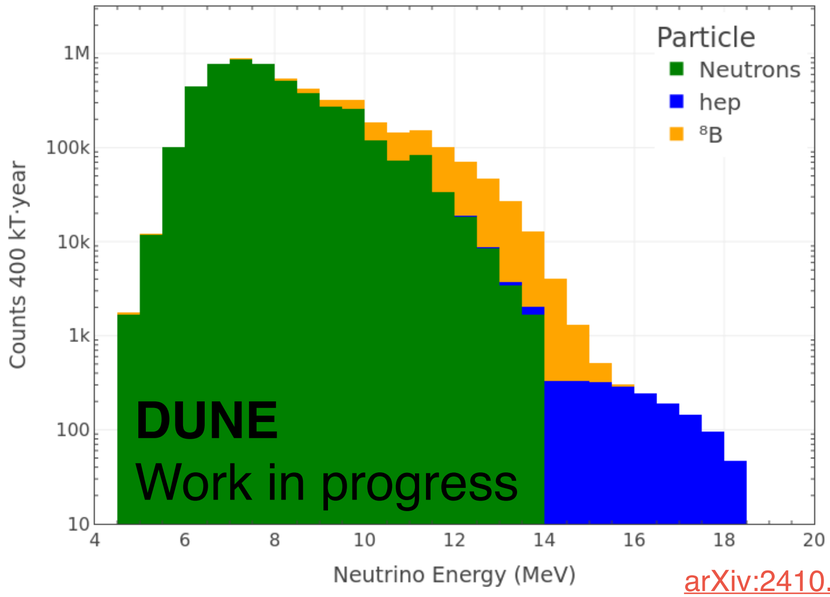
Z'-mediated neutrino tridents

Astrophysical neutrinos

- DUNE has a unique sensitivity to MeV electron neutrinos.
- Neutrinos from core-collapse supernovae.
  - Able to extract mass ordering from neutronisation burst measurement.
  - Estimated 5° pointing resolution.
- Excellent sensitivity to $^{8}\mathrm{B}$ 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.

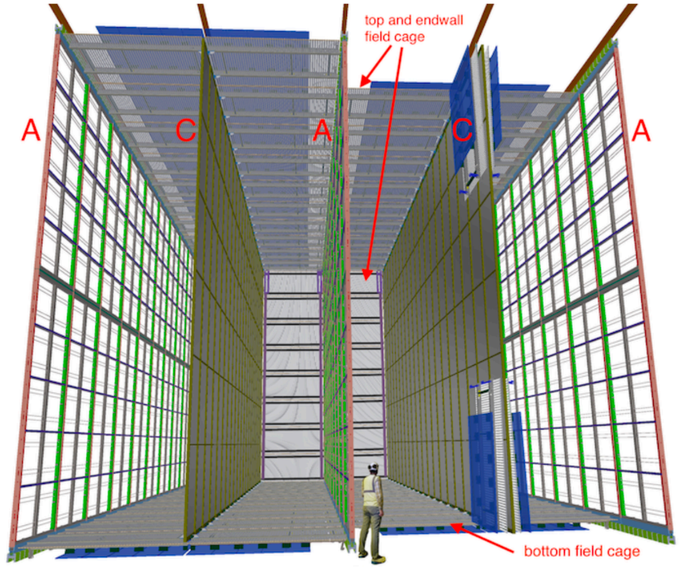
Supernova Pointing Capabilities of DUNE
arXiv:2407.10339





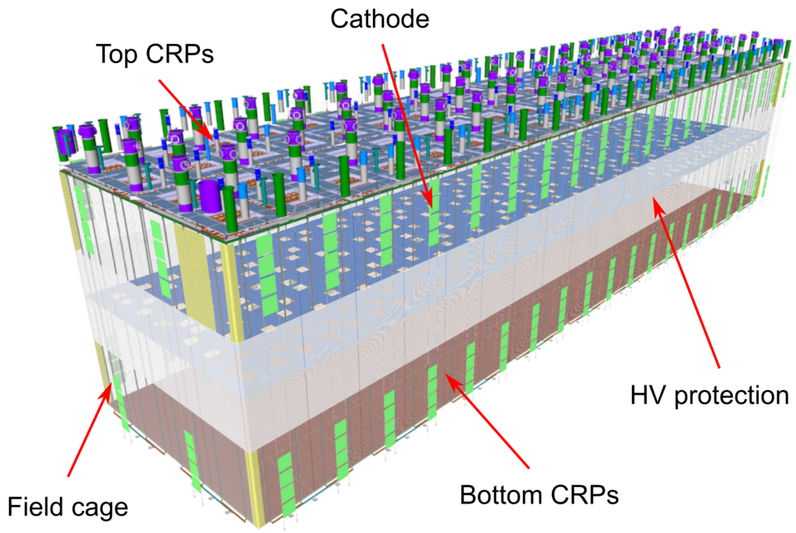
arXiv:2410.08251

Far Detector technology

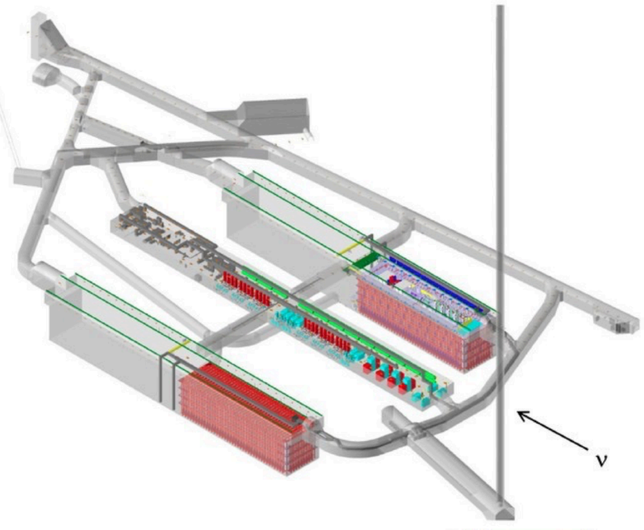


DUNE FD TDR Vol IV
JINST 15 T08010 (2020)

Horizontal drift (HD)



Phase I



DUNE FD VD TDR
JINST 19 T08004 (2024)

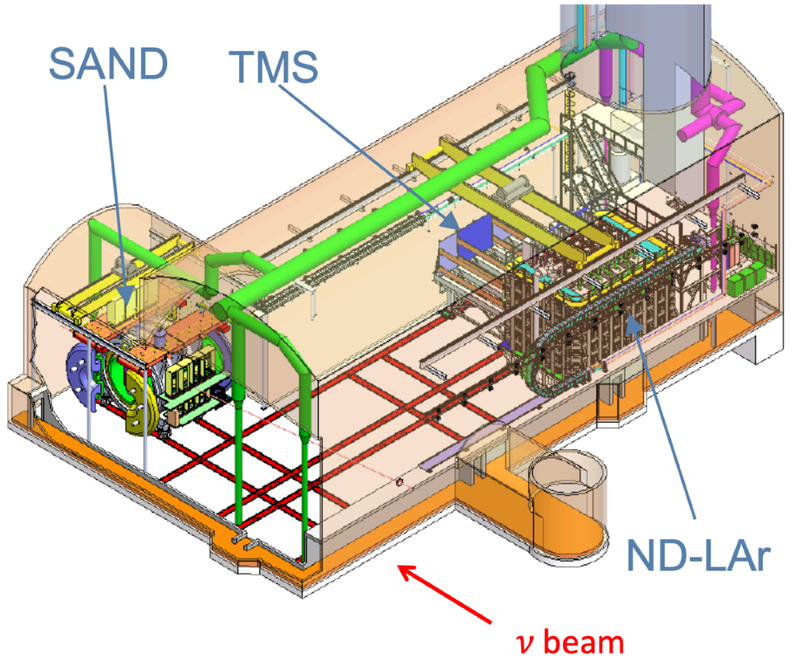
Vertical drift (VD)

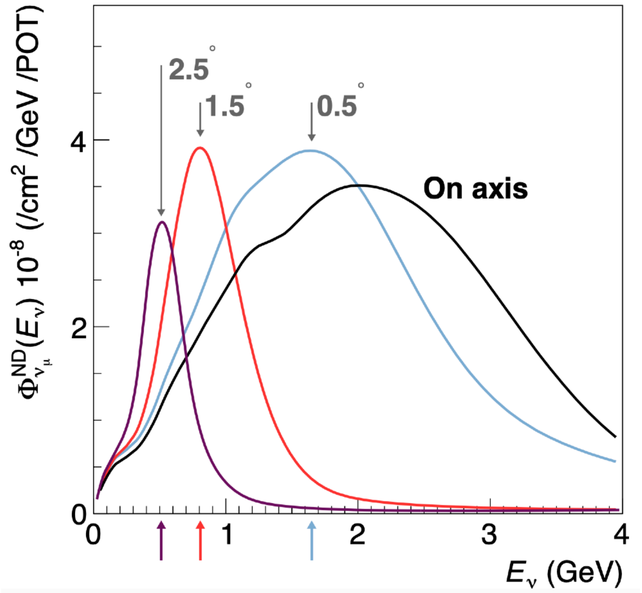
- Two (four) LArTPCs, each with 17 kton of LAr (10 kton fiducial).
- Horizontal drift uses wire readout planes, distributed in four 3.6 m drift regions.
- Vertical drift with two 6.25 m drift regions and a central cathode.

Near Detector complex

DUNE ND CDR
Instruments 5 (2021) 4, 31

- Main role is to measure beam rate and spectrum to predict unoscillated event rates at the FD.
- Constrain systematic uncertainties (flux, cross section, detector response) for oscillation measurement.
- Independent physics programme, including cross sections and BSM.



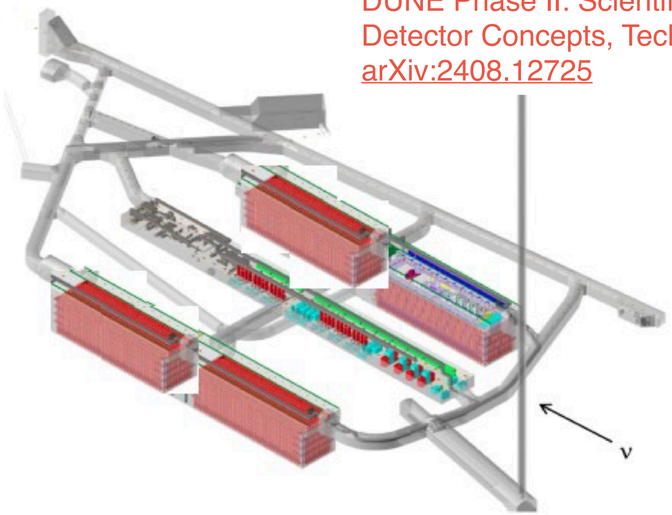


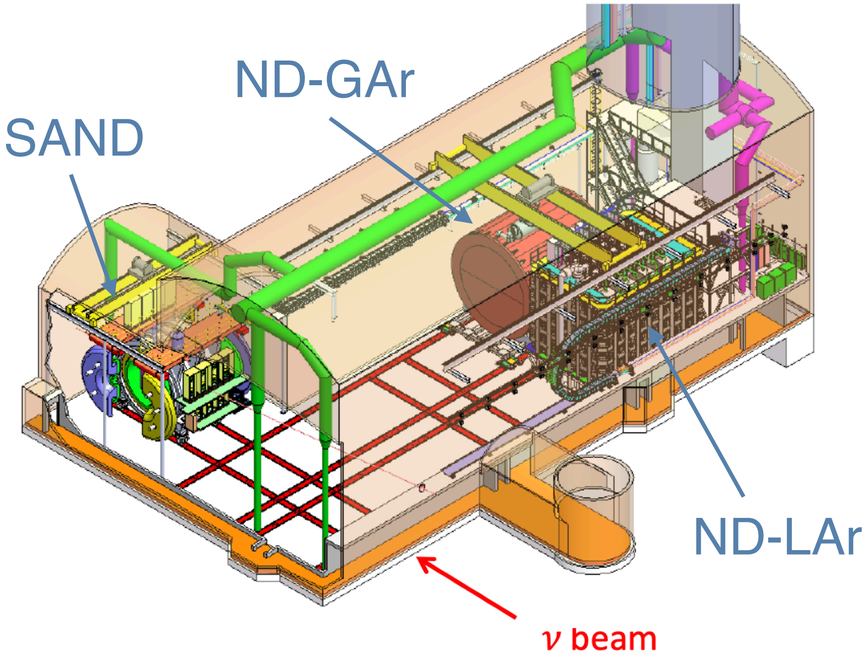
- Same main target and technology (LArTPC), cancels systematics and allows for model-tuning.
- Moveable detector system (PRISM) help constrain energy dependence of cross sections.
- On-axis magnetised detector (SAND) for beam monitoring and neutrino measurements.

Phases of DUNE

- **DUNE Phase I** (2029 start of physics, 2031 beam + ND):
  - Two 17 kton LArTPC modules.
  - Upgradeable 1.2 MW neutrino beam.
  - Moveable LArTPC with muon spectrometer in ND.
  - On-axis near detector.
- **DUNE Phase II**:
  - Two additional FD modules (≥40 kton total).
  - Beam upgrade to >2 MW (ACE-MIRT).
  - More capable near detector (ND-GAr).

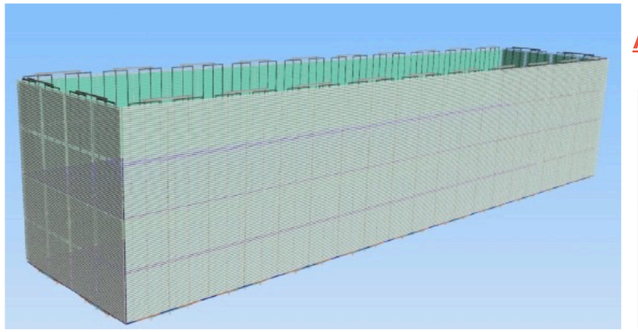
DUNE Phase II: Scientific Opportunities, Detector Concepts, Technological Solutions
arXiv:2408.12725



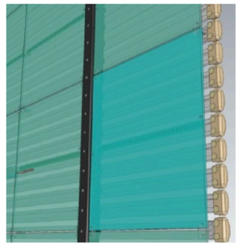


FD Phase II options

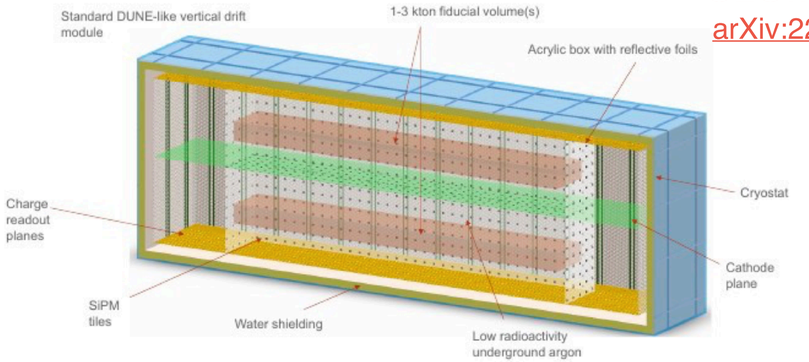
- VD is the baseline design for the Phase II FD modules.
- **Phased construction** allows the technological developments to **expand the physics** of DUNE (solar and supernova neutrinos, $0\nu\beta\beta$, DM, …).
- Pursuing improvements to light collection for FD3, including Aluminium Profiles with Embedded X-ARAPUCA (APEX).
- For **FD4** (the “Module of Opportunity”) more **ambitious designs** are being considered:
  - Pixel readout, integrated charge-light readout, low backgrounds, Xe doping, non-LAr options, etc.



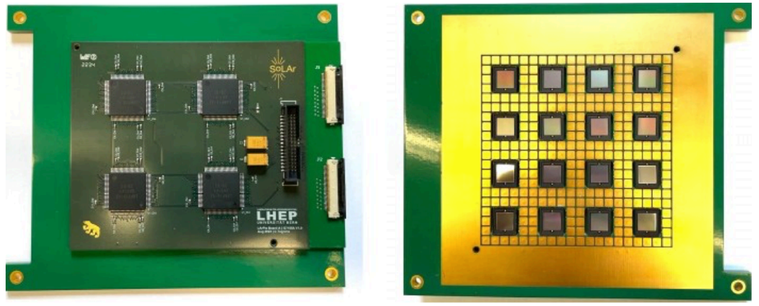
APEX for FD3



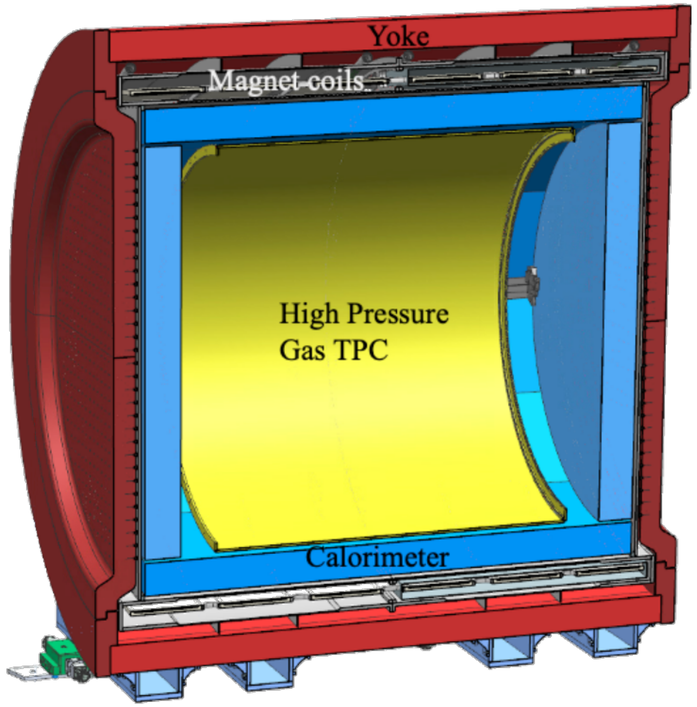
SLOMO
arXiv:2203.08821



SoLAR
arXiv:2203.07501

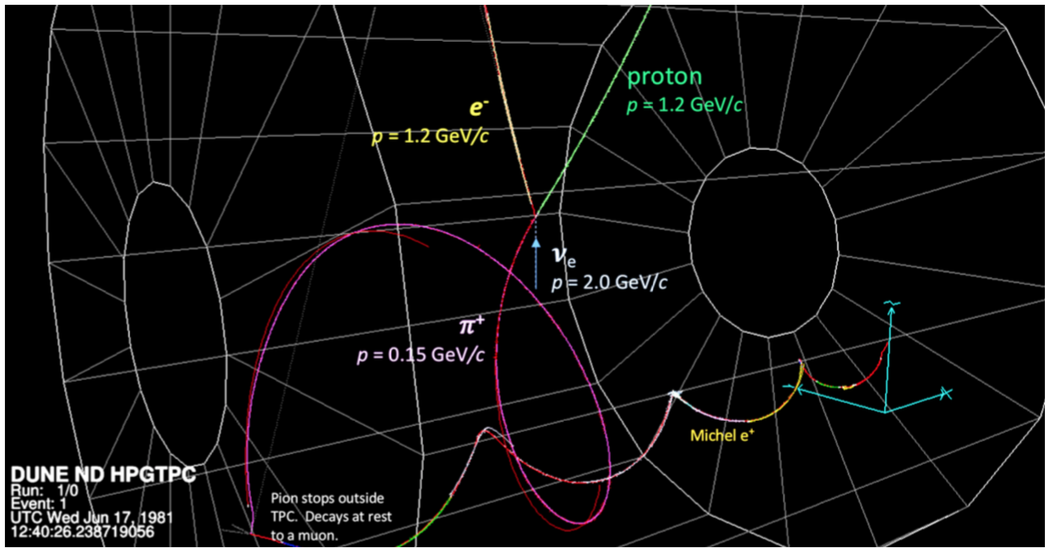


ND-GAr



- Leading option for Phase II ND is ND-GAr.
- ND-GAr is a magnetised high-pressure gaseous argon TPC, surrounded by an ECal and a muon tagger.
- The B field and the ECal allow for **particle identification** and **momentum** and **sign reconstruction**.

DUNE ND CDR
Instruments 5 (2021) 4, 31

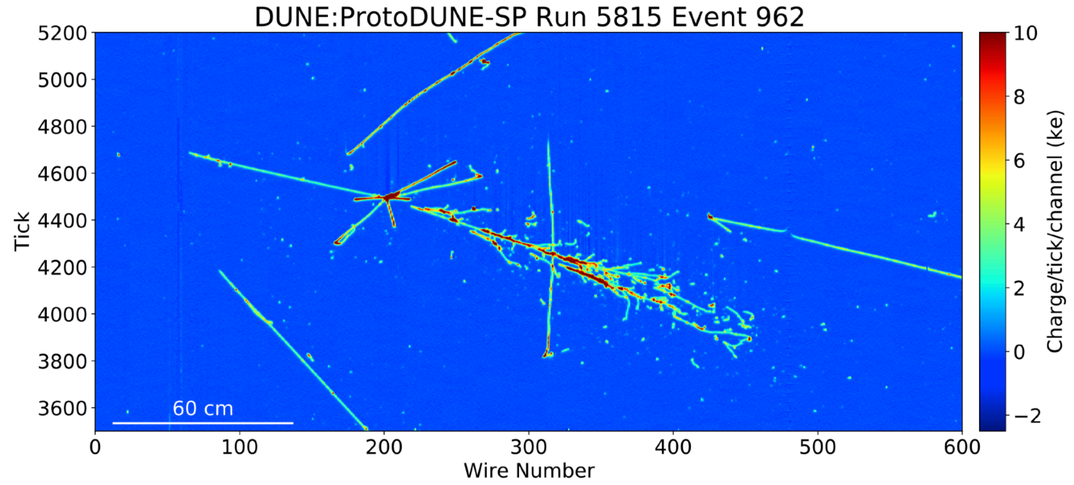


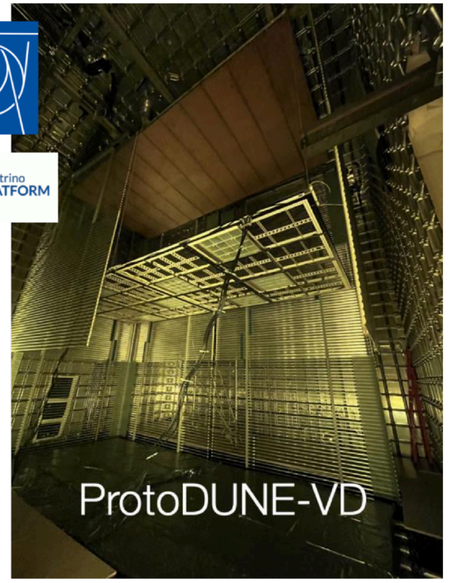
- ND-GAr provides **low tracking thresholds** and a **uniform event acceptance**.
- Detector design currently being optimised, active R&D programme.

ProtoDUNEs @ CERN

- ProtoDUNE Phase I (2018-2020):
  - Successful demonstration of the DUNE LArTPC HD technology (ProtoDUNE-SP).
  - Several analyses ongoing (hadron-Ar cross sections, calibrations, …).
- ProtoDUNE Phase II (2020-):
  - Construction of HD and VD modules completed (2020-2023).
  - ProtoDUNE-HD successfully completed beam operations last month.
  - LAr being transfer to ProtoDUNE-VD imminently, start data taking in early 2025.

Separation of track- and shower-like energy deposits in ProtoDUNE-SP using a convolutional neural network
Eur.Phys.J.C 82 (2022) 10, 903



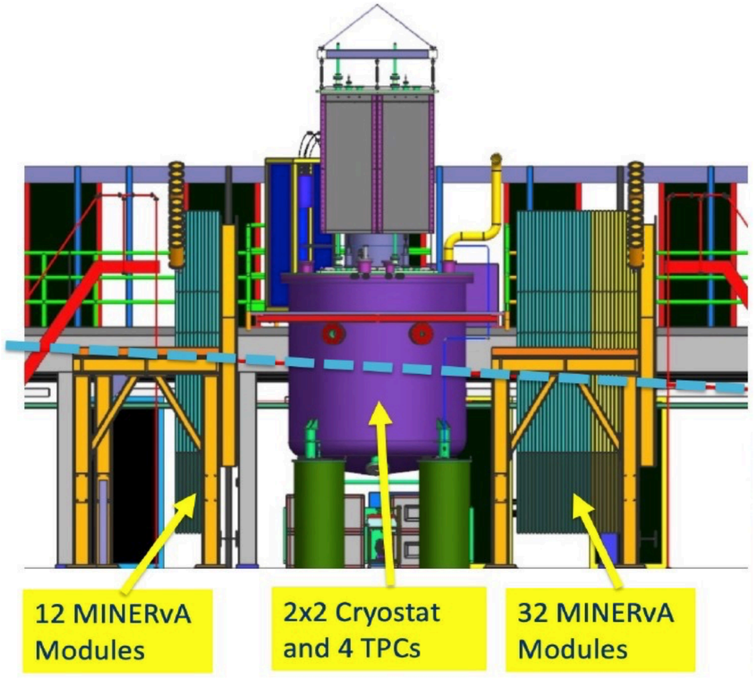


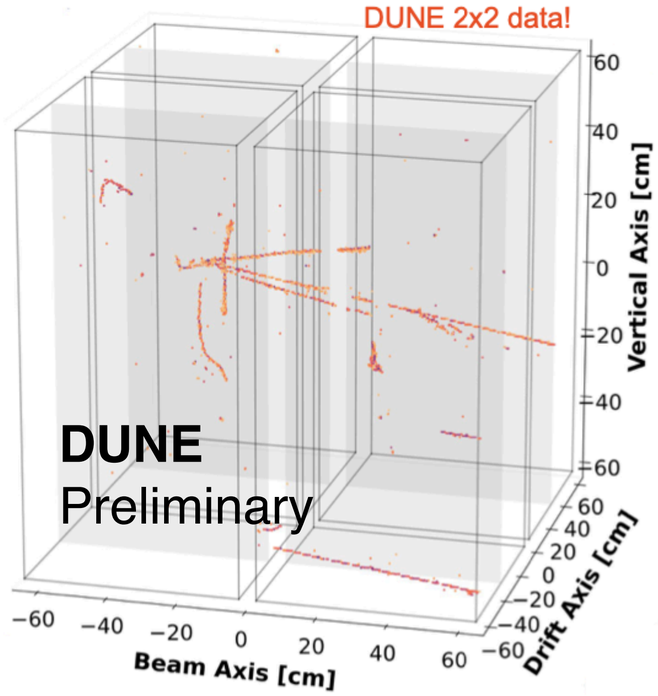
2x2 demonstrator @ FNAL

See recent NuFact talks on the topic:
- The Near Detector Liquid Argon (ND-LAr) 2x2 prototype of DUNE
- The DUNE 2x2 Demonstrator physics prospects and plans with neutrino data

- Very high rate at ND (~51 neutrinos/spill) motives pixel readout and optical modularity.
- Four LArTPC modules with pixelated readout, installed in the MINOS-ND cavern.
  - Includes upstream and downstream tracking planes, repurposed from MINERvA.

- Cooldown and filling finished May 31, operating in NuMI beam since July 8.
- Goal: demonstrate reconstruction with a natively 3D readout in a neutrino beam, with similar event rates to DUNE.
- First (anti)neutrino data of DUNE!





Summary

- DUNE is a long-baseline neutrino oscillation experiment and neutrino observatory.
- DUNE has potential to deliver ground-breaking results, like the unambiguous **determination of the neutrino mass hierarchy** and the discovery of **leptonic CP violation**.
- DUNE also has a rich programme on **astrophysical neutrinos**, and **BSM** both at the ND and FD.
- **Active large-scale prototyping efforts** at CERN and Fermilab.
  - R&D programme for DUNE Phase II detectors.
- **DUNE science begins this decade!**

International collaboration of >1400 members, 38 countries + CERN