Probing the Nature of Neutrinos with the Deep Underground Neutrino Experiment

Gianfranco Ingratta, YorkU (Toronto) on behalf of the DUNE collaboration

International Workshop on Next Generation Nucleon Decay and Neutrino Detectors (NNN25)

October 1-3, 2025 | **SNOLAB**

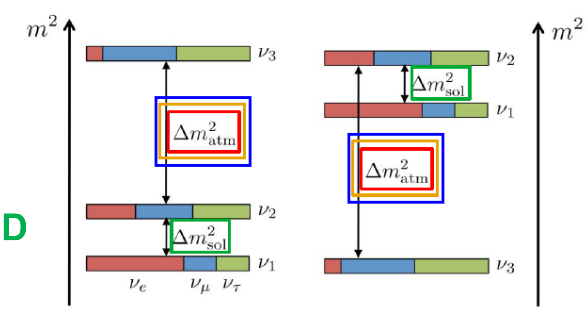
Neutrino Oscillations: open questions

- Assuming three flavor neutrinos, oscillations depend on **3** mixing **angles**, **2** mass **splitting** and **1 phase**
- Open questions:
  - **Is the 3-flavor neutrino picture correct?** Is PMNS unitary?
  - **Is ν_3 the heaviest** (normal ordering) **or the lightest** (inverted ordering)? What is the sign of Δm^2_{31}?
  - **Do ν and $\overline{\nu}$ oscillate differently?** What is the value of δ_{CP}?
  - **Does ν_3 contain more ν_τ or ν_μ?** What Is the θ_{23} octant?

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

Super-K T2K, NOvA Daya Bay, Reno SNO, KamLAND

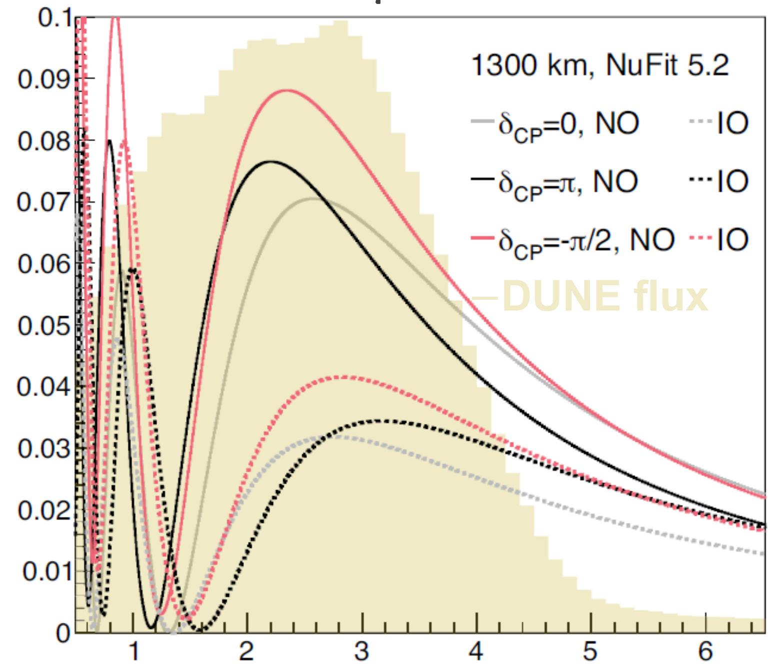
Current best measurements (solid) and complementary measurements (dashed)



DUNE's motivations

- Mixing angles are sufficiently large to design an experiment capable of measuring many oscillation parameters ($\Delta m^2_{32}, \theta_{13}, \theta_{23}, \delta_{CP}$) without degeneracy, enabling a **test** on the validity of **the three-neutrino model**!
- For **L=1300 km** and $\boldsymbol{E_\nu}$**=2.5 GeV**, the asymmetry in the matter effect on $\boldsymbol{P(\nu_\mu \to \nu_e)}$ is larger than the largest possible CP-violating difference → break parameters degeneracy!

$P(\nu_\mu \to \nu_e)$

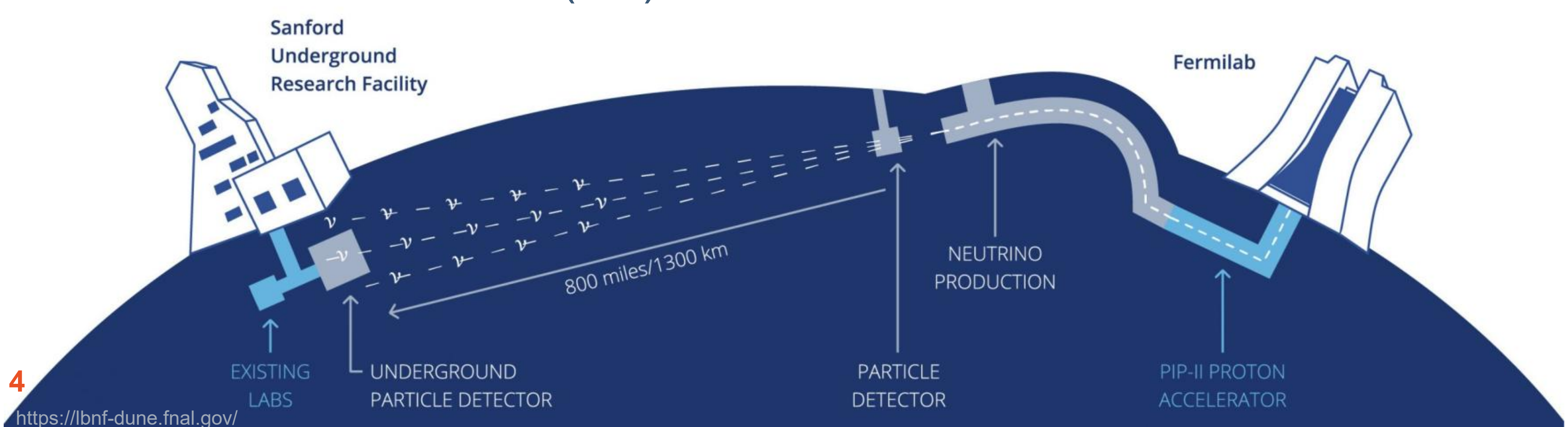


E_{ν_μ}(GeV)

Adapted from Harris, Ilic, Konaka, Canadian Journal of Physics (2025)

Deep Underground Neutrino Experiment

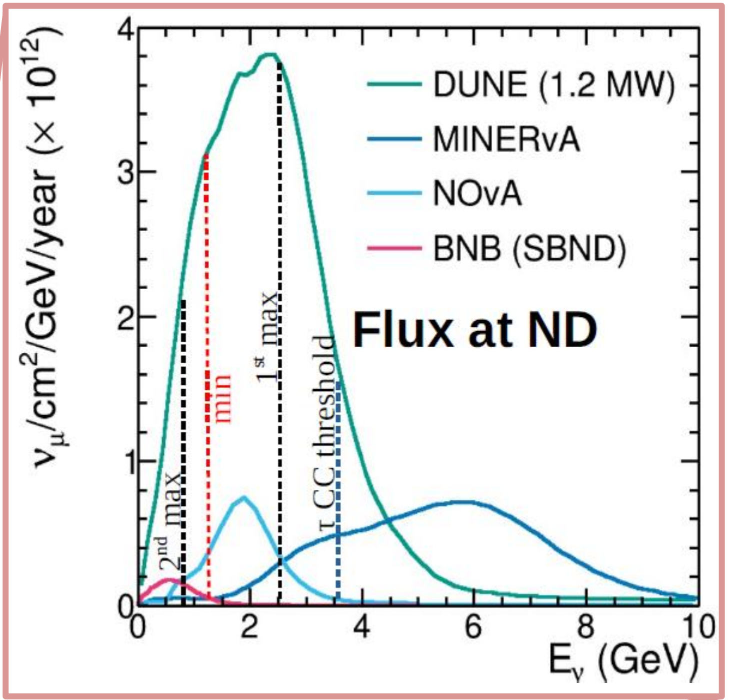
- Pillars of DUNE's design: a **large mass**, **high exposure**, **high precision**, deep **underground** accelerator experiment capable of measuring neutrino and antineutrinos over a **wide range of L/E covering two oscillations maxima**
- 1500 collaborators over 35 countries (including 🇨🇦)
- Sited in two facilities:
  - **FNAL:** Beam source and Near Detector (ND)
  - **SURF:** Far Detector (FD)

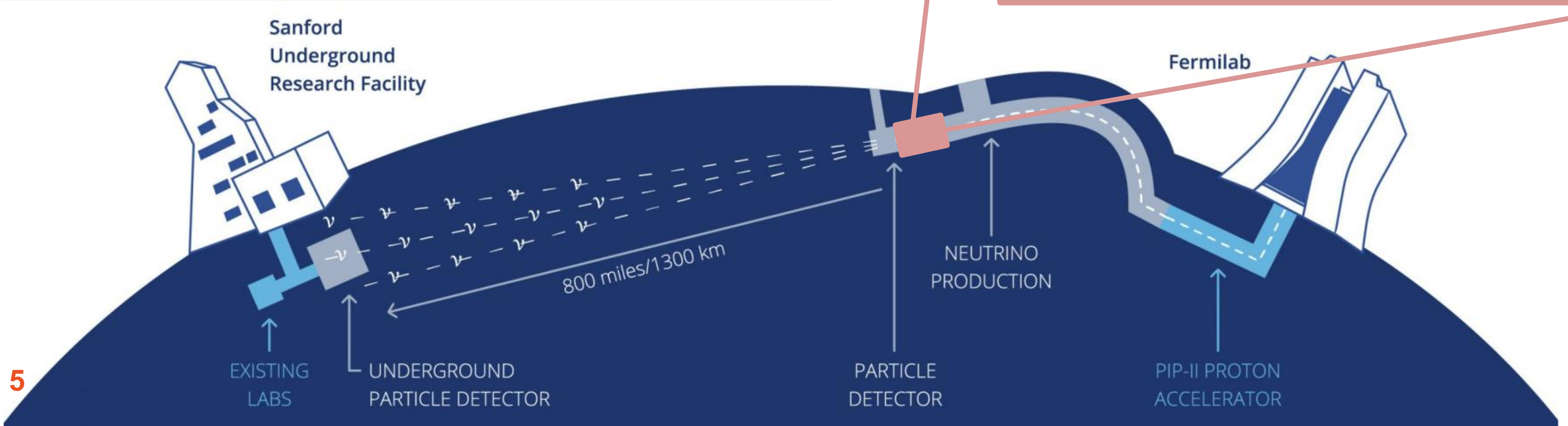


https://lbnf-dune.fnal.gov/

DUNE – what we measure

- Powerful neutrino beam of **1.2 MW** (DUNE phase I) upgradable to **2.4 MW** (DUNE phase II)
- Unique **broad band** beam covering **2 oscillation maxima**
- High-energy tail above ν_τ **CC threshold** → unique three flavor measurement opportunities (see contributions from W. Dallaway)

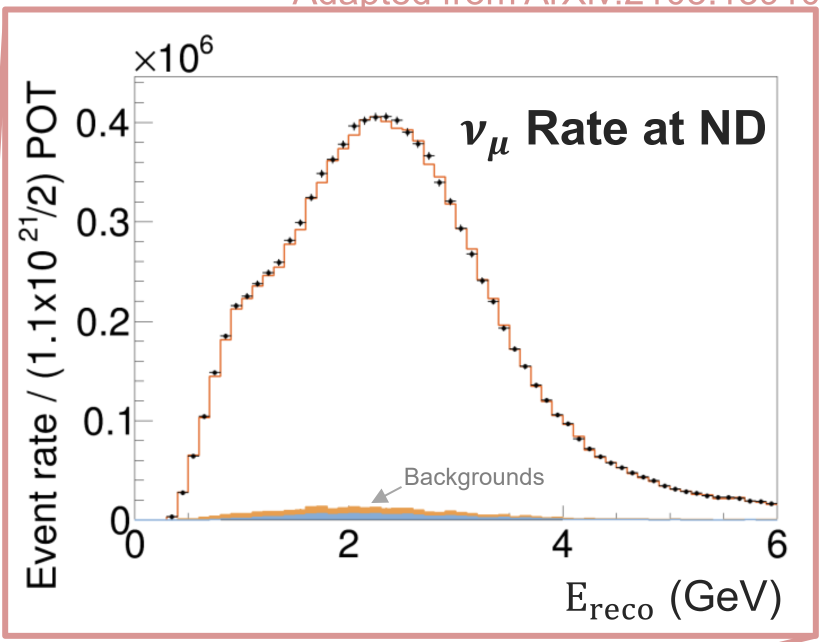


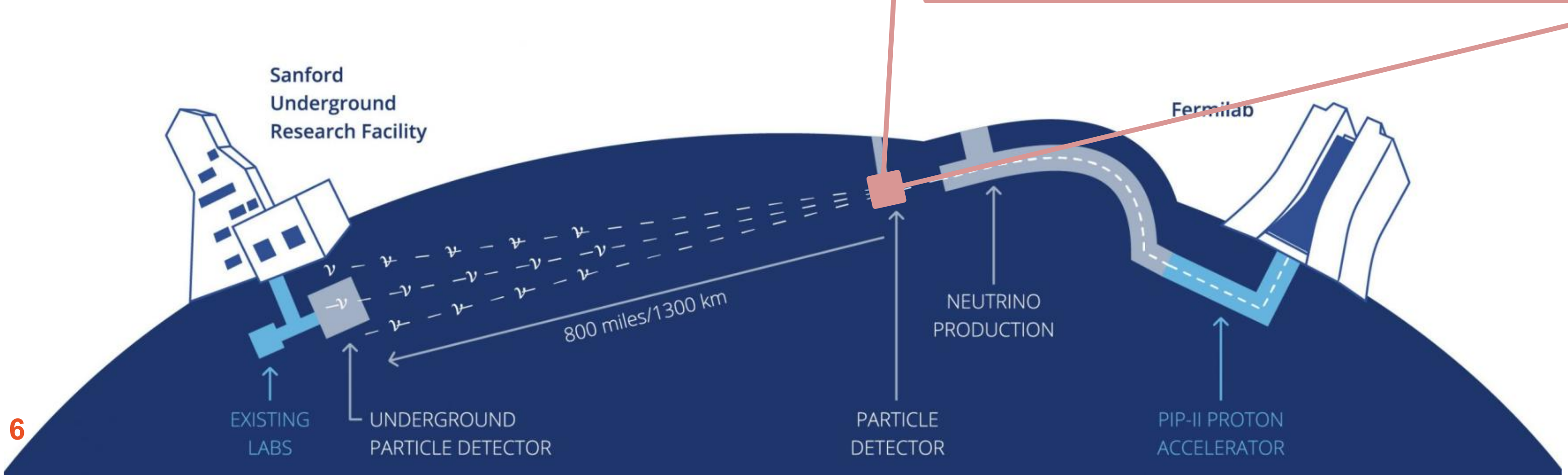


DUNE – what we measure

- The Near Detector (ND) measures the convolution of the (unoscillated) flux with the cross-section and the detector effects.
- ND **constrains** the systematic **uncertainties** and **predicts** the **event rate** at the Far Detector (FD)

Adapted from ArXiv:2103.13910

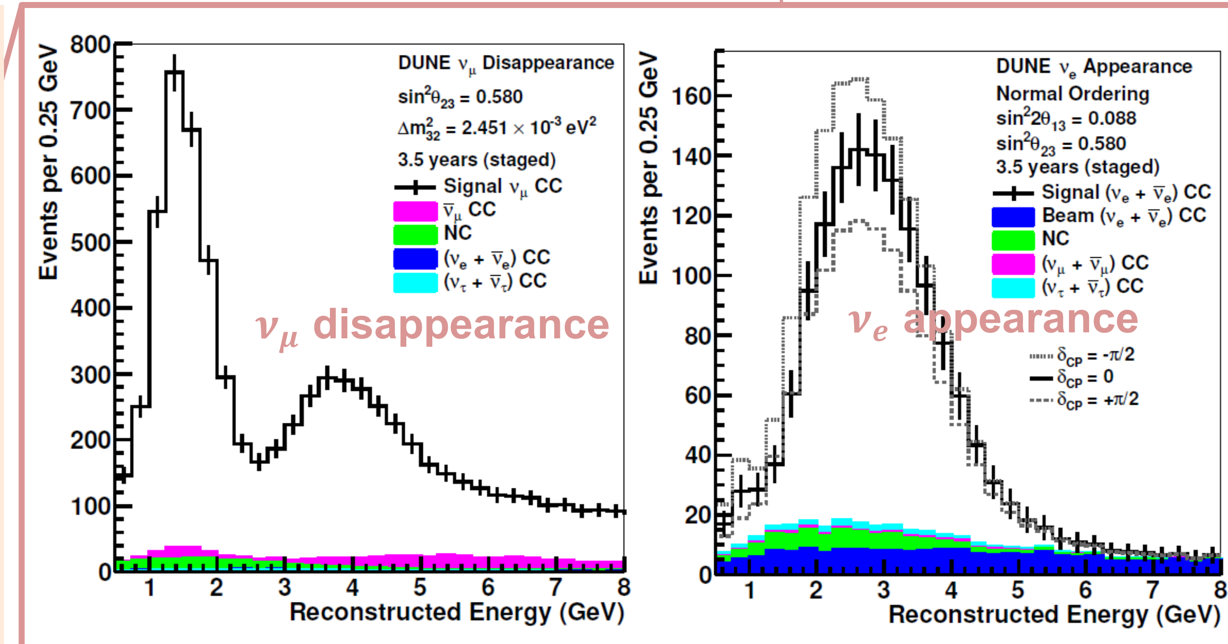


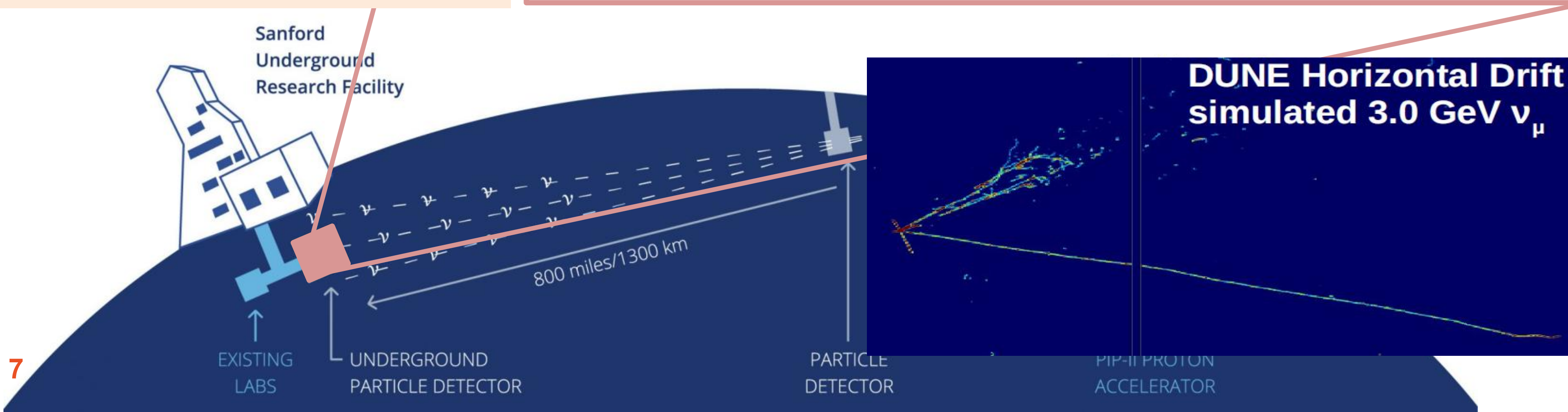


DUNE – what we measure

Adapted from ArXiv:2103.13910

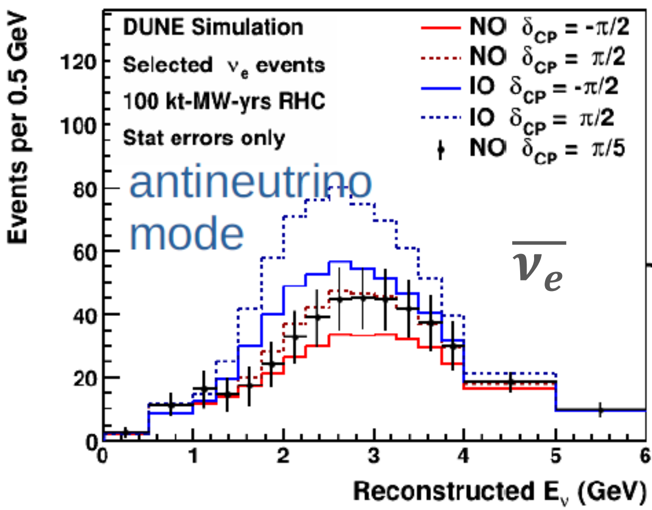
- The Far Detector (FD) measures the $\nu_\mu(\overline{\nu}_\mu)$ disappearance and the $\nu_e(\overline{\nu}_e)$ appearance over a **wide range of energy** using **multi-kiloton LArTPC** technology
- Repeat the measurement with **antineutrino beam**!

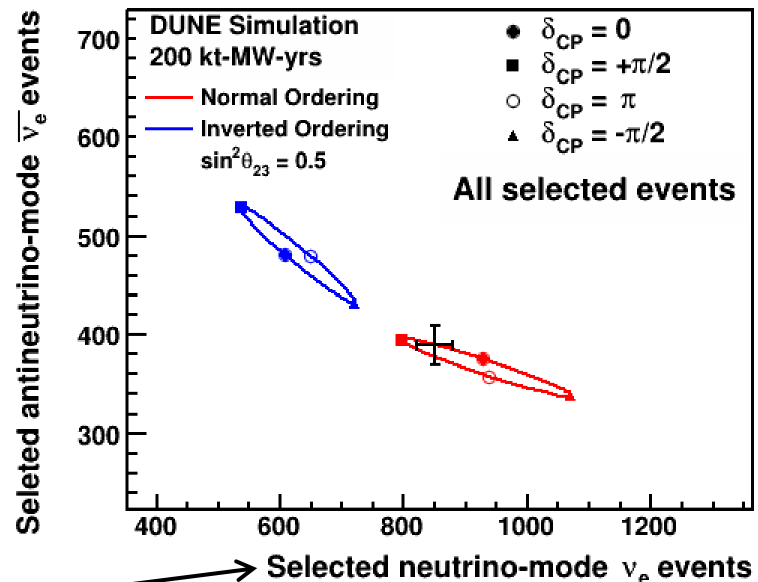


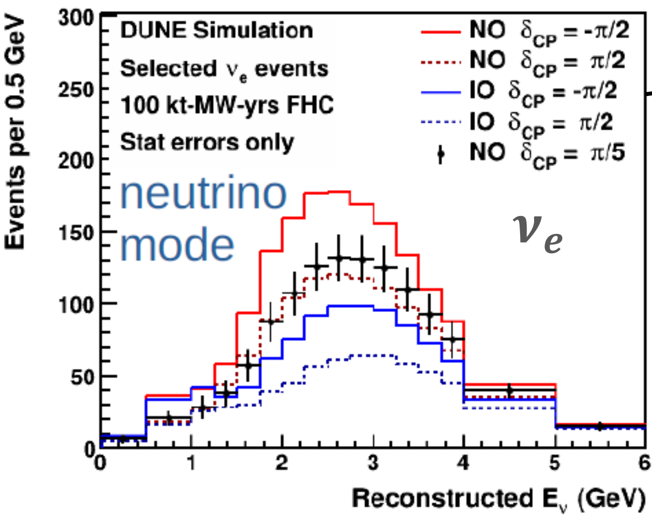


DUNE bi-event plots

Plots assume DUNE Phase I



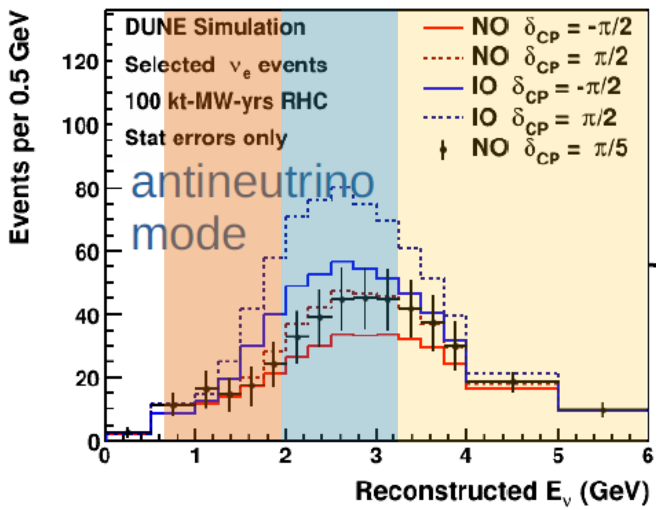


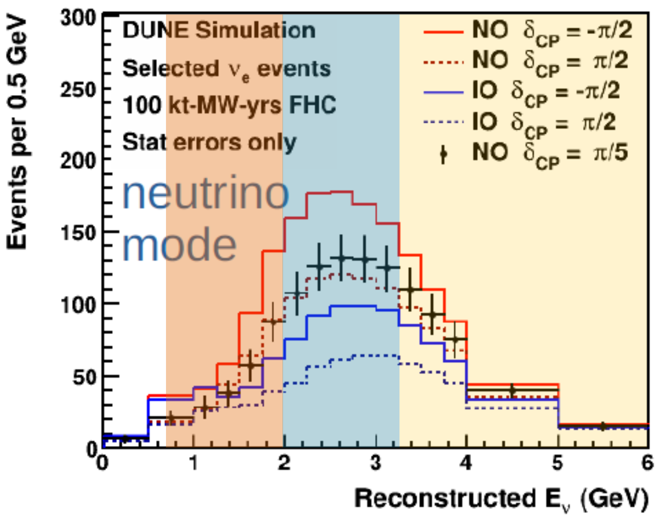


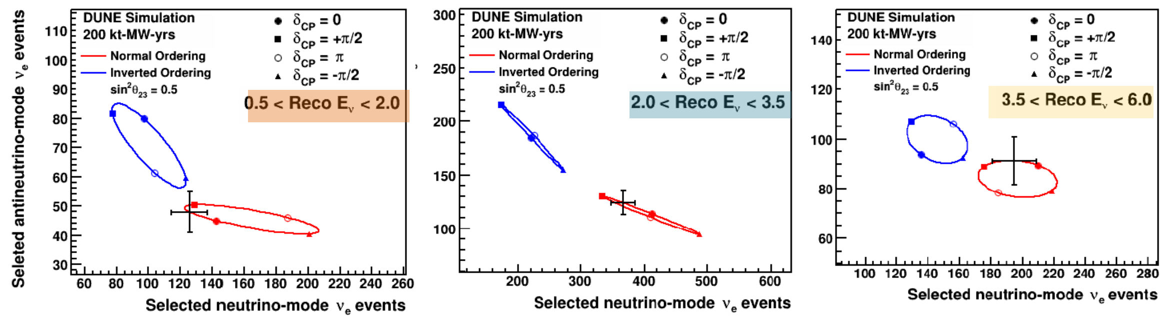
- A specific set of oscillation parameters corresponds to a point lying on one of two ellipses: normal or inverted ordering
- DUNE's ellipses are completely separated because of the **long baseline** → the matter effect is **not degenerate with** the (possible) **CP** violation effect

DUNE can do more

Plots assume DUNE Phase I



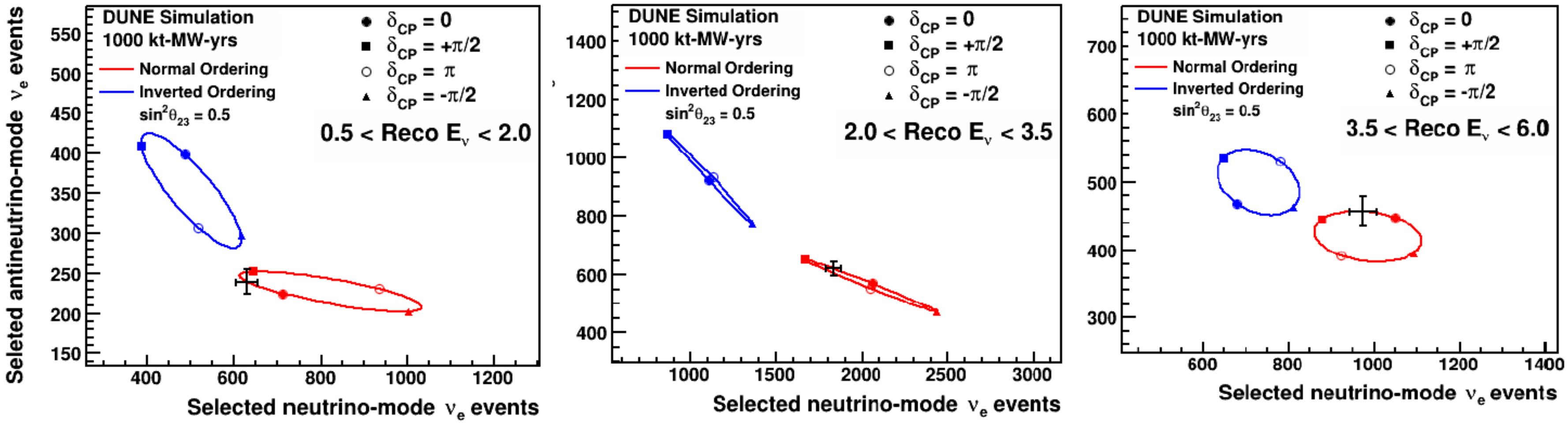




- The broad band beam covering two oscillation maxima allows DUNE to make **bi-event** plots for **multiple energy bins:**
  - **Test** the energy dependence of these ellipses predicted by the **3-neutrino standard model**
  - New physics would distort the L/E dependence

DUNE can do more

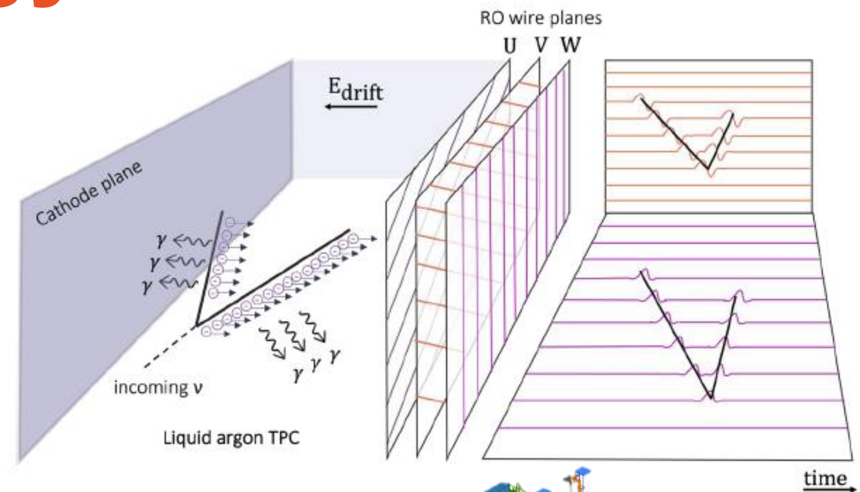
Plots assume DUNE Phase II

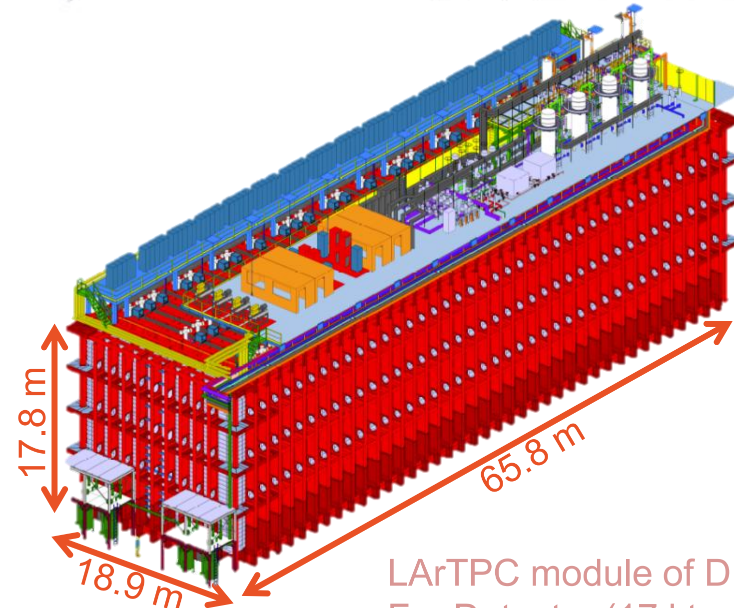


- DUNE will resolve the mass ordering for any δ_{CP} scenario
- In the long term, DUNE can:
  - establish whether CP is violated (for a range of values)
  - **measure** precisely the oscillation parameters, relying **minimally on external constrains** (i.e. input parameters from other experiments)

Detector technology - LArTPC

- Particles reconstructed from ionization and scintillation light
- **Ionization** drift in electric field towards sensing elements (**slow** signal, v~0.16 cm/μs):
  - Low threshold for ionization: 23.6 eV/e-
- **Scintillation** light (128 nm) with:
  - **fast** emission (**6 ns**) from argon dimers and slow emission (1.3 μs) from argon triplets
  - LAr is transparent to its own scintillation

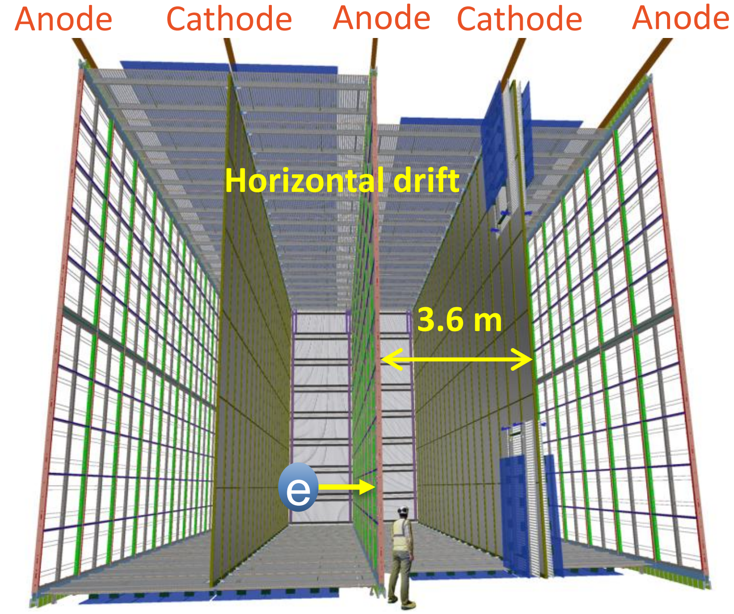


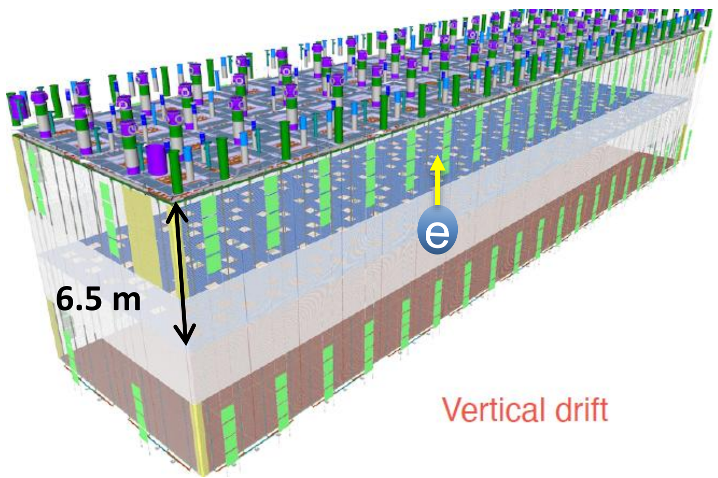


LArTPC module of DUNE Far Detector (17 kton)

DUNE's design – Far Detector

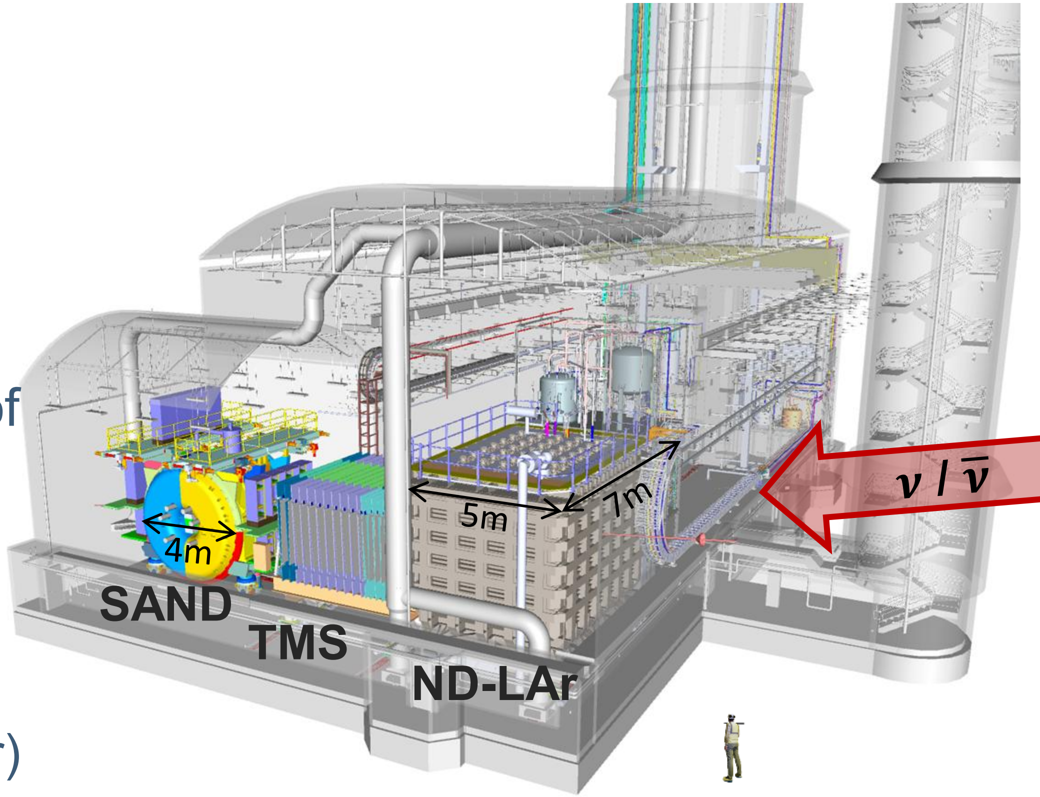
- DUNE will start with **2 FD modules**, each **17 kt** total volume 1 mile underground with different configuration
  - **Horizontal** drift (3.5 m), wire readout (5 mm wire spacing) providing high granularity (Canadian group heavily involved in the DAQ system)
  - **Vertical** drift (6.5 m)





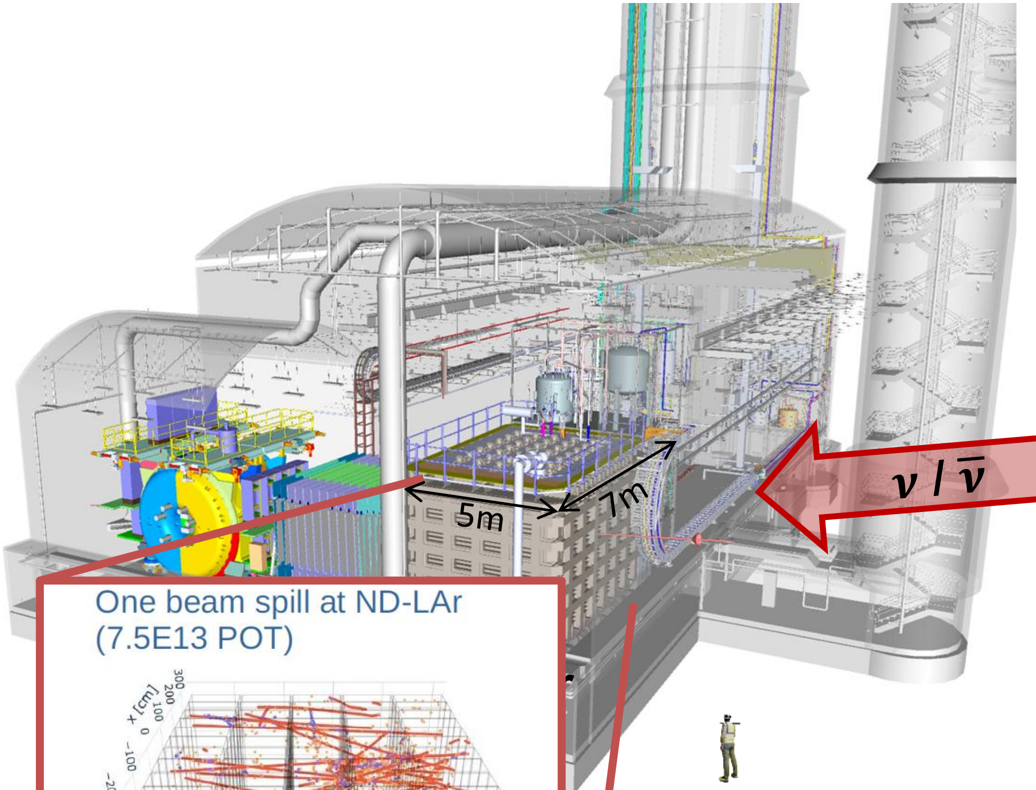
DUNE's design – Near Detector

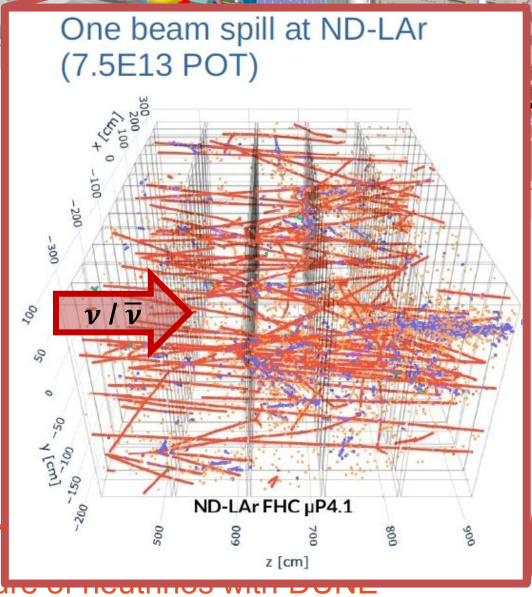
- Measures the unoscillated flux, constrains systematic uncertainties (xsec, flux, …) and predicts the far detector event rate
- Located 574 m downstream of neutrino beam source and includes three components:
  - **ND-LAr**: a 67 t LArTPC
  - **TMS**: The Muon Spectrometer (muon catcher)
  - **SAND**: **S**ystem for on **A**xis **N**eutrino **D**etection, a multipurpose magnetized detector



DUNE's design – ND-LAr

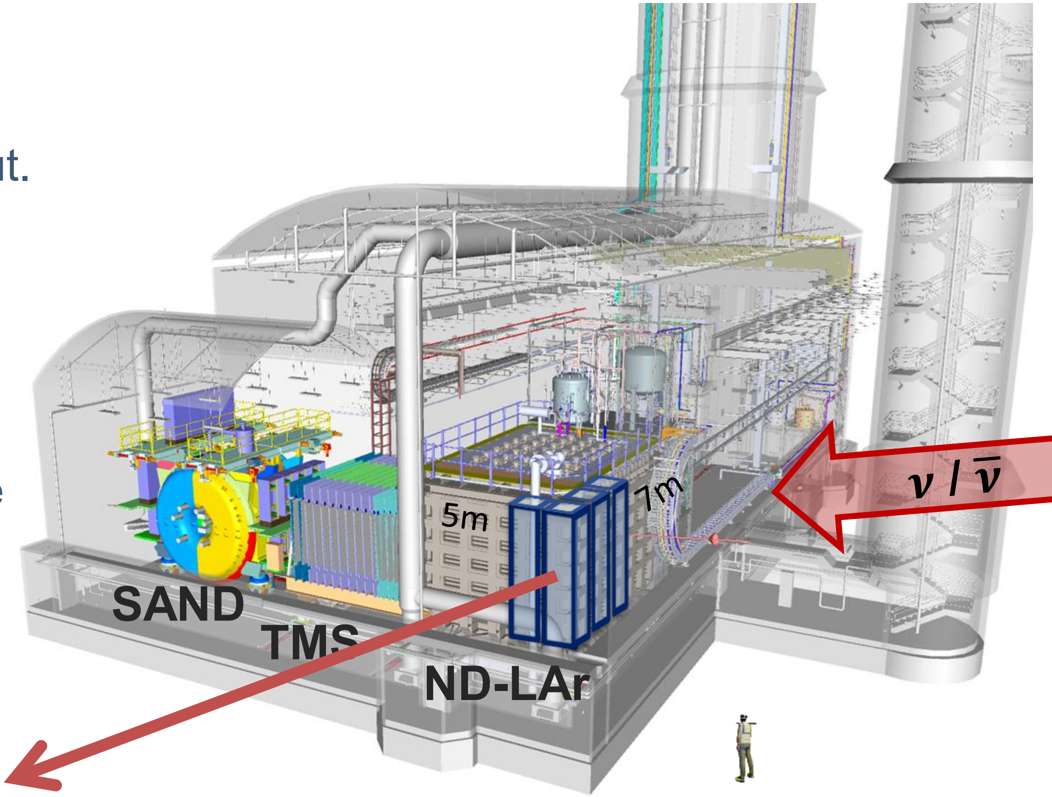
- The challenge is the event pileup:
  - **100-150** neutrino interactions (inside and nearby materials) within **10 μs spill** window
  - Traditional LArTPCs with wire-based readout are **slow** ($300\ \mu s$ max drift in ND-LAr) and too **many** (2D) **hits** on a **long wire** → confusion!

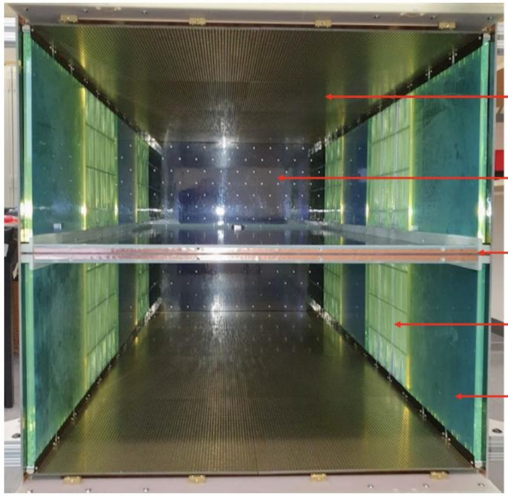




DUNE's design – ND-LAr

- Detector **segmented** into **35 modules** $1{\times}1{\times}3\ \mathrm{m}^3$, each with separated light and charge readout.
- **Charge** readout on the anode plane based on **pixels** providing native 3D hits with O(4mm) granularity
- **Light** readout: light traps coupled with SiPMs providing <10ns single hit timing resolution

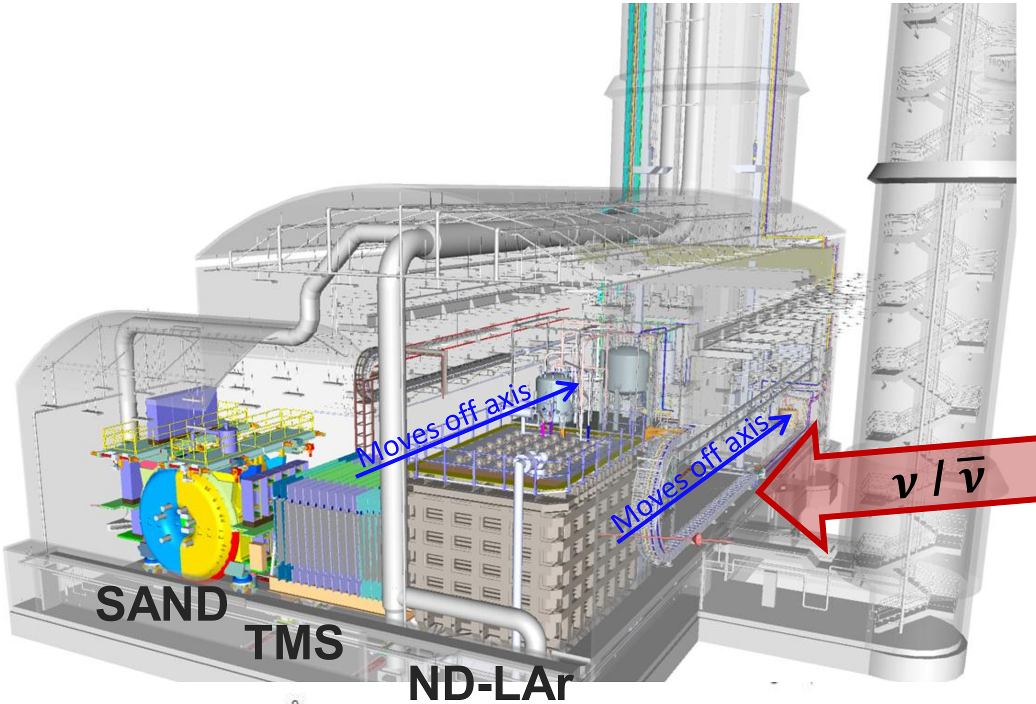


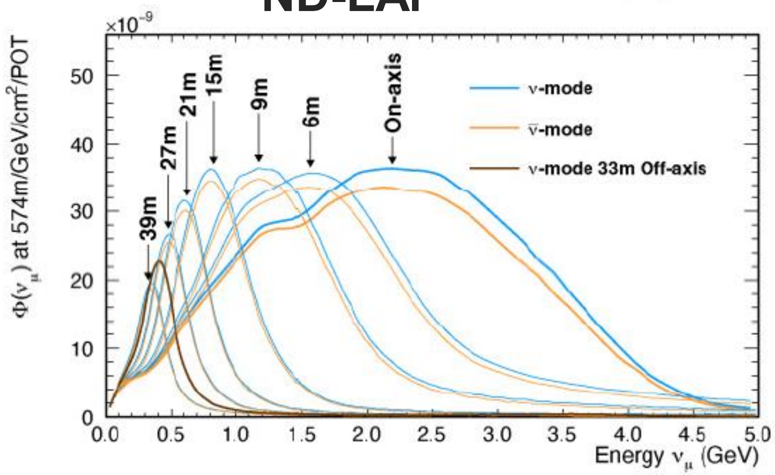


Top view into a small prototype module with the top panel removed *(Instruments 2024 8, 41)*

DUNE's design – PRISM concept

- Predicted rates at the Far Detector are affected by systematical uncertainties
- DUNE PRISM to make a robust prediction:
  - **TMS** and **ND-LAr move** off axis to measure the neutrino spectra at different off axis positions
  - **SAND** permanently **stays** on axis as monitor
- Build FD *oscillated* spectra from linear combination to match (very minimal dependence on interaction modeling)

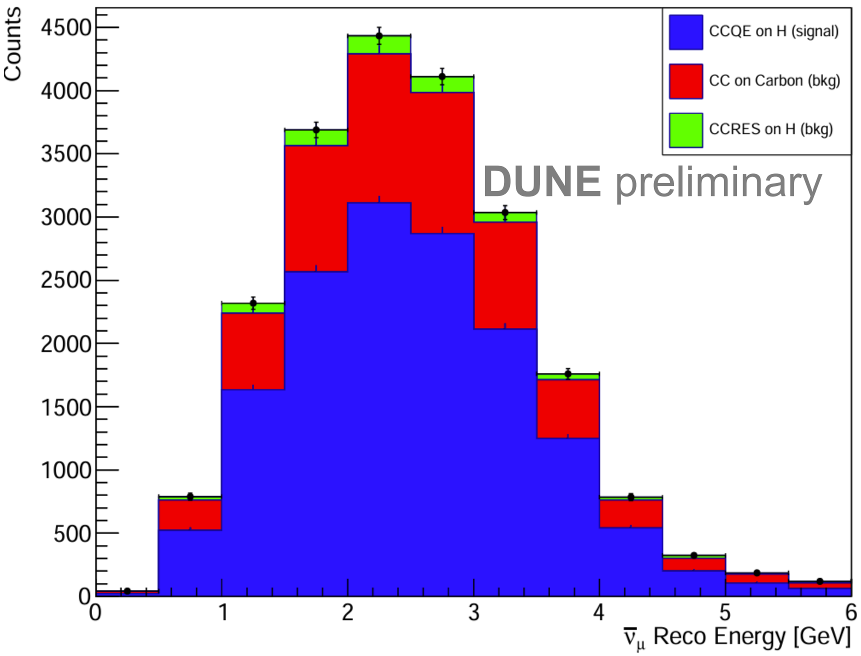




KLOE exp.: https://www.sciencedirect.com/science/article/pii/S0168900201015029
Solid Hydrogen technique: https://arxiv.org/html/1809.08752v3

DUNE's – SAND opportunities

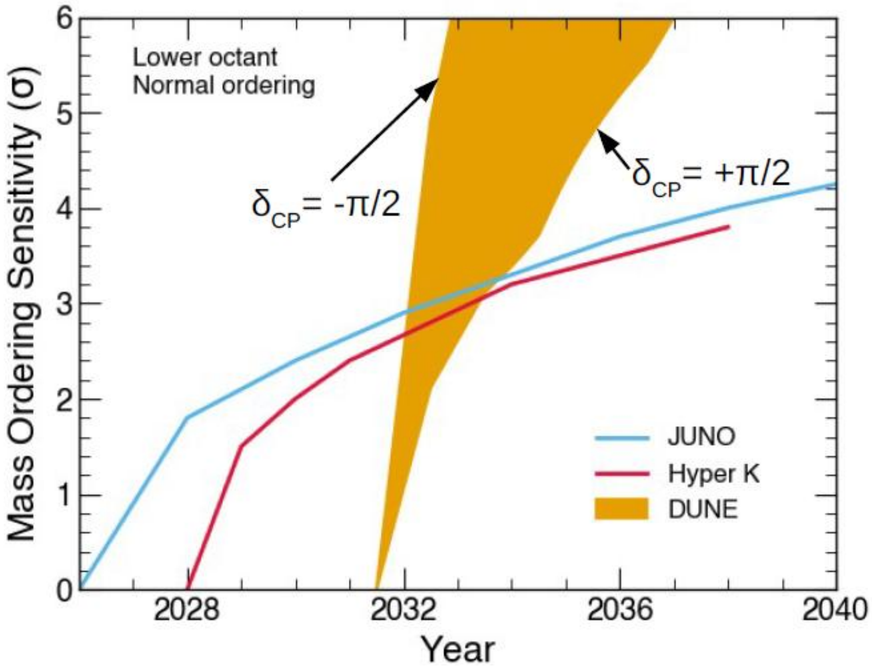
- SAND's design includes:
  - Magnetic field **0.6 T**
  - Modular **low-density** target-tracking system to retain **high momentum resolution** for muons
  - Existing ECAL with **time resolution 55 ps** $/\sqrt{E\ (GeV)}$
  - C, C_3H_6 and Argon target materials
- SAND provides a sample of $\boldsymbol{\nu(\overline{\nu})}$ **- H interactions** from subtraction of C from C_3H_6 → sample free from nuclear final state interactions (FSI) to **constrain systematic uncertainties** on cross-section!



Selected CCQE on Hydrogen events in SAND assuming reverse horn current and 1 year data taking

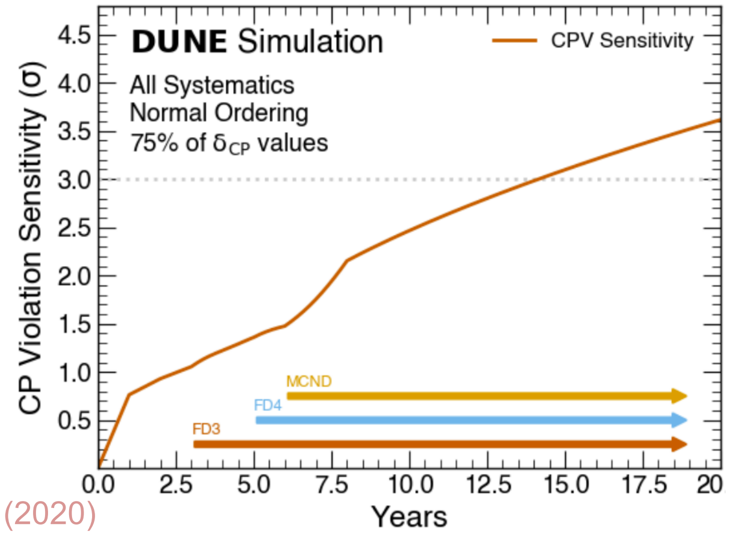
DUNE sensitivity – Mass Ordering

- Because of the **long baseline,** $\overline{\nu}/\nu$ asymmetry from **matter effect** is expected to be larger than the largest possible CP-violating difference
- DUNE is the only experiment to determine the mass ordering to 5σ (within 5 years **for any value of $\boldsymbol{\delta_{CP}}$**)
- DUNE MO determination is **crucially** important as **input** to experiments that measure:
  - neutrino absolute mass
  - **$\boldsymbol{\delta_{CP}}$ assuming MO is known**

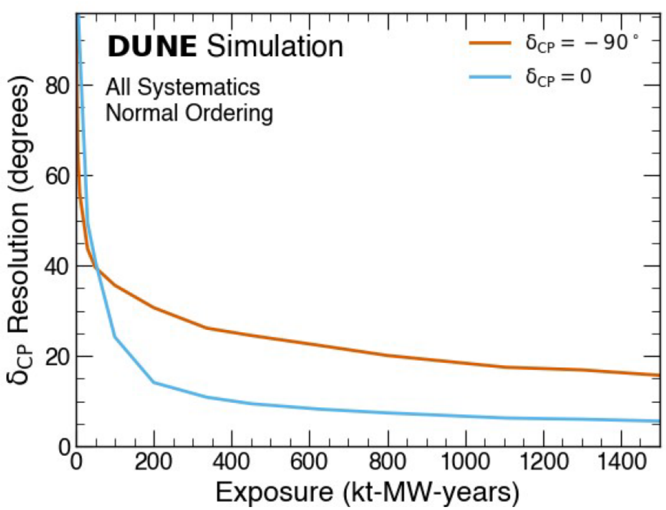


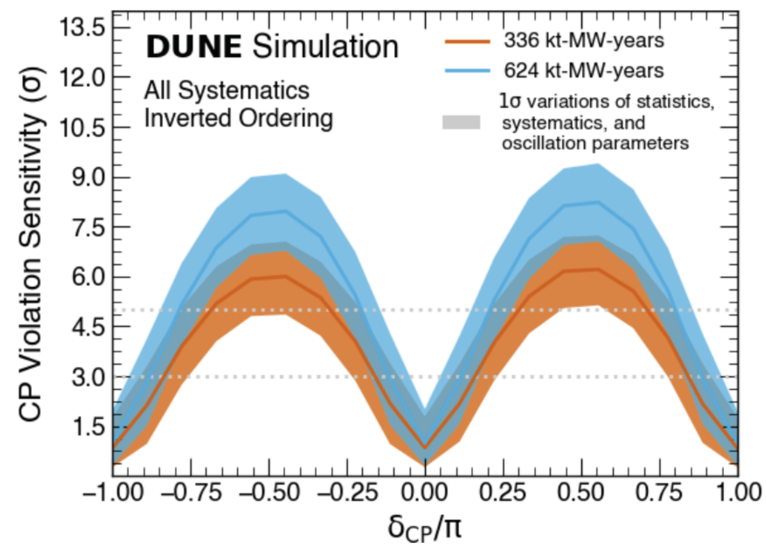
DUNE sensitivity – δ_{CP} phase

- In long term, DUNE can establish CP violation over 75% of δ_{CP} values at >3σ



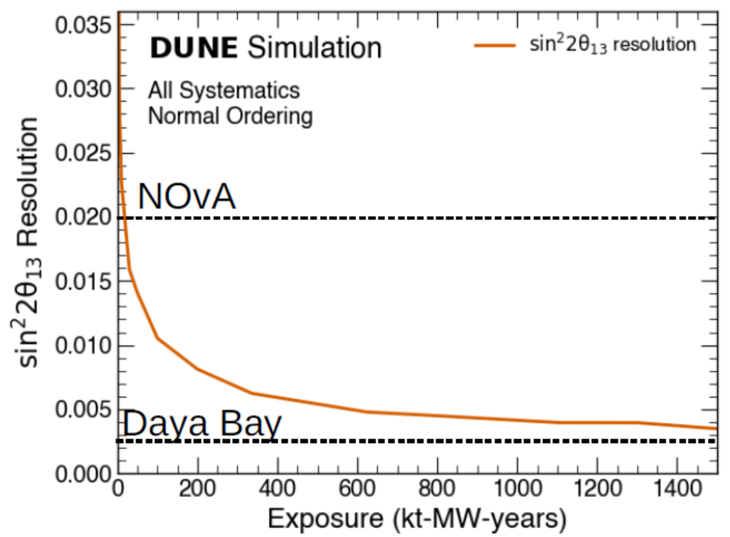
Eur. Phys. J. C 80, 978 (2020)

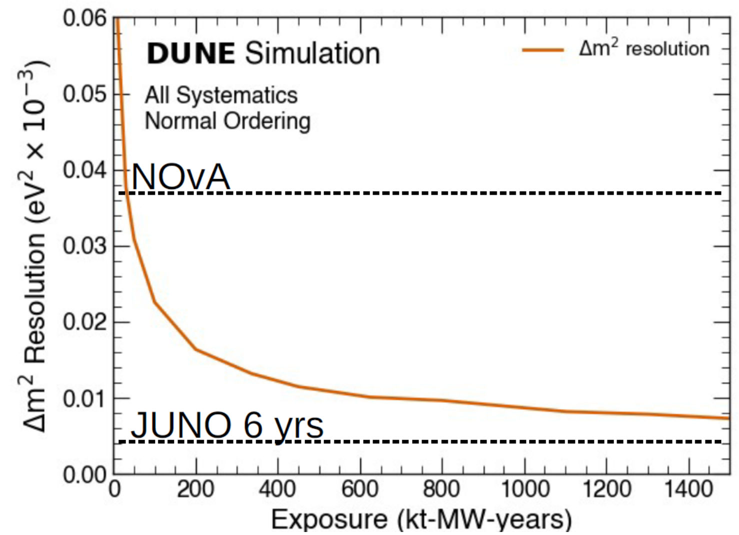




DUNE precise measurements

- DUNE will also **reach current generation sensitivity** on mixing angles being very well measured by **reactors** (θ_{13})
- DUNE measurements will rely minimally on external input parameters (model agnostic measurement)
- Comparisons with reactor measurements are sensitive to new physics





Supernova physics at DUNE FD

- DUNE FD is sensitive to ν_e from supernova burst (**neutronization phase**) through the dominant CC interaction:

$$\nu_e + {}^{40}Ar \rightarrow e^- + {}^{40}K^*$$

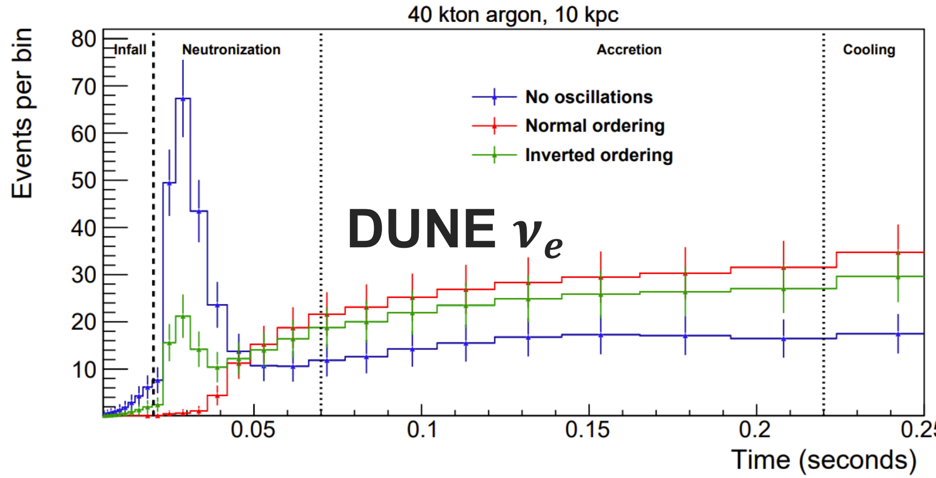
- 5° pointing resolution on supernova location using

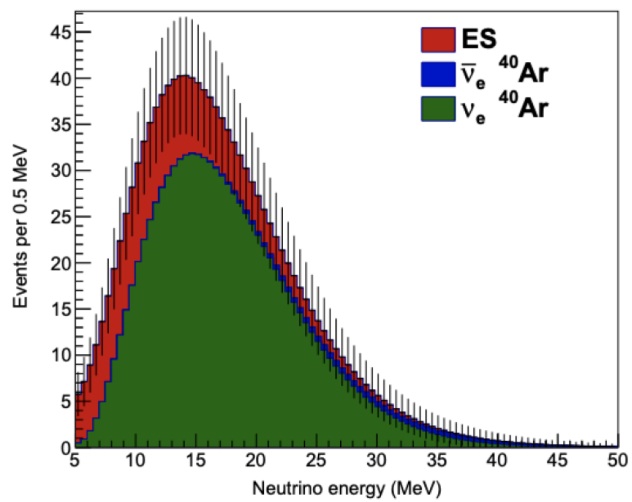
$$\nu_x + e^- \rightarrow \nu_x + e^-$$

- **Complementary** measurements to others experiments

Exp.	ν_e	$\bar{\nu}_e$	ν_x
DUNE	89%	4%	7%
SK[1]	10%	87%	3%
JUNO[2]	1%	72%	27%

1. SK Coll Astropart.Phys. 81 (2016)
2. Lu, Li & Zhou Phys.Rev.D 94 (2016)

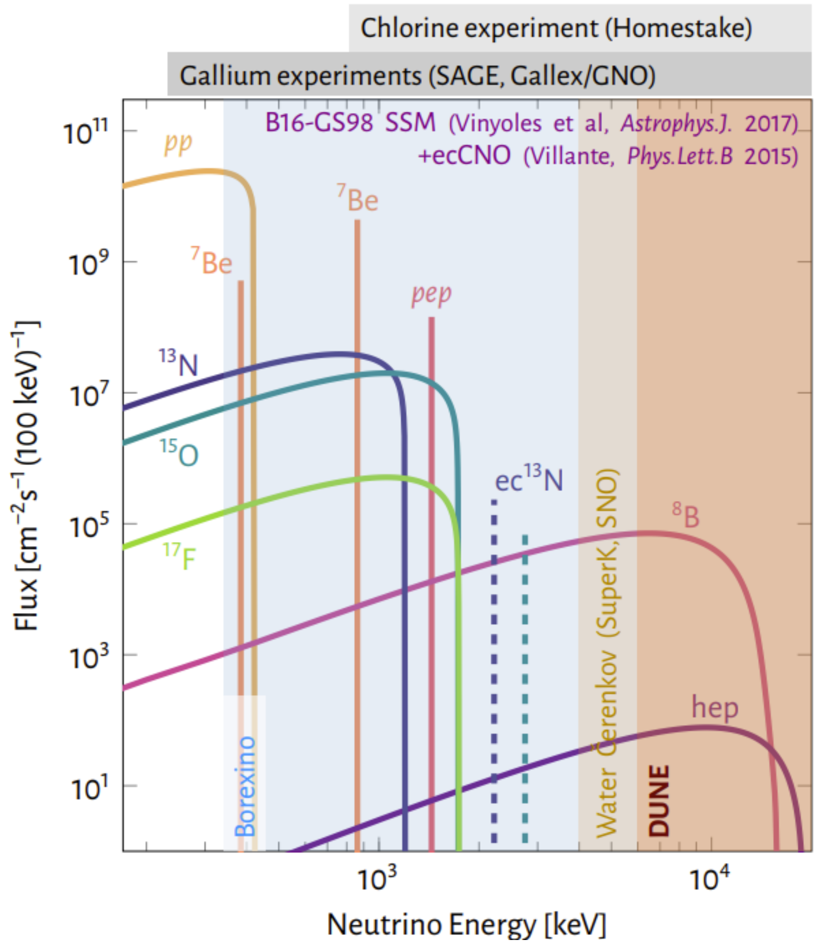




Expected ν_e rate for 10 kpc distant supernova assuming "Garching model"

Solar neutrinos in DUNE FD

- DUNE FD will have sensitivity to *hep* neutrinos flux with energy above ~ 5 MeV
- Control of background is crucial:
  - Most challenging backgrounds are **fast neutrons** from cavern and **gammas** from neutron activation in rock, that extend well beyond 5 MeV
- Passive shielding would help to reduce the background (studies ongoing)



LBNF/DUNE under construction

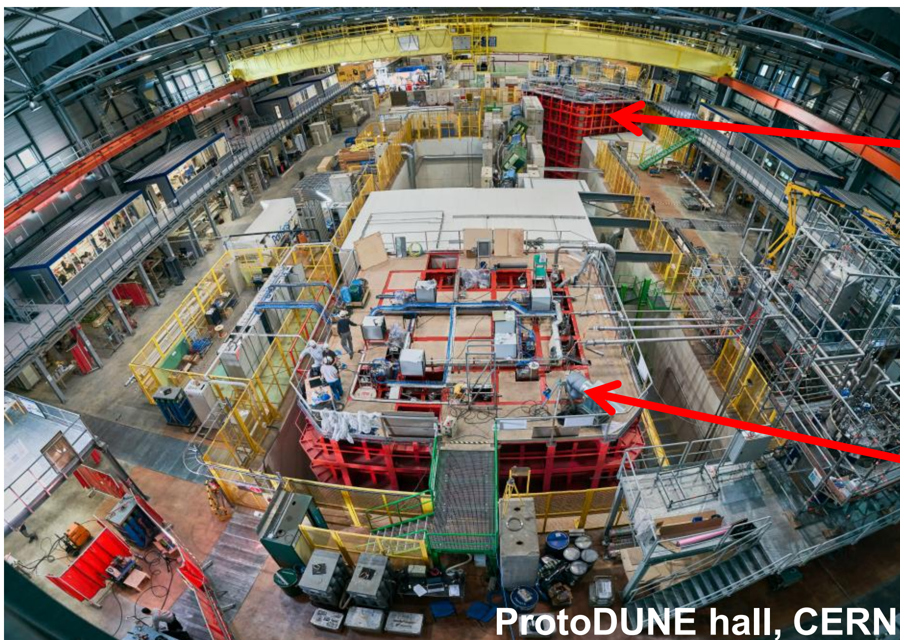
DUNE under construction

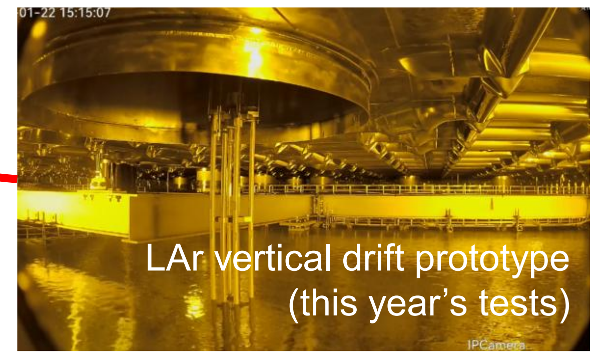
- DUNE Phase I:
  - DUNE Far Detector caverns completed in **2024**!
  - Cryostats constructed at CERN, shipped to South Dakota and ready for installation in **2026**
  - Far Detectors 1 and 2 installation expected to be complete and starting to operate ~**2029**
  - Physics in early **2030s**
- DUNE Phase II:
  - Far Detector Modules 3 and 4 within ~**5 years** from Phase I
  - Beam power upgrade

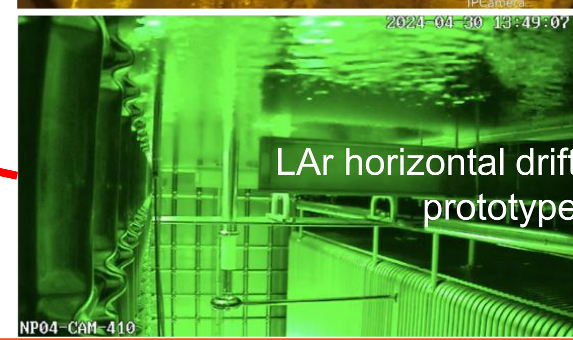
cavern excavated in Lead, South Dakota (news.fnal.gov)

ProtoDUNEs at CERN

- To test DUNE style horizontal and vertical drift detectors, two prototypes of about 700 tons have been operating in charged particle beam at CERN
- Horizontal drift produced the first physics publications in 2024 and vertical drift is ready for tests this year







DUNE Near Detector Prototypes

- Fermilab, **2x2 prototype** (2.2 t) : smaller segmented, pixelated LAr TPC
  - Operated in **NuMI neutrino beam** in summer 2024 DUNE has neutrino data!
  - Longer beam run planned for 2026

arXiv:2509.07012v1

- Bern, **F**ull **S**cale **D**emonstrator
  - 70M cosmic-ray events over several weeks of data-taking

DUNE Near Detector Prototypes

- Fermilab, **2x2 prototype** (2.2 t): smaller segmented, pixelated LAr TPC
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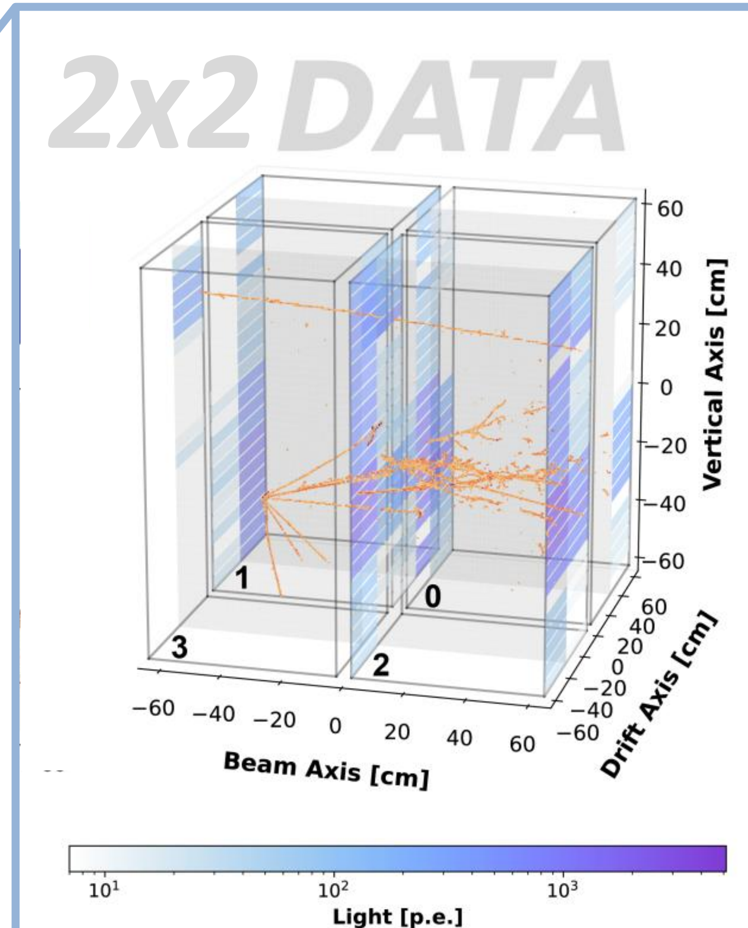


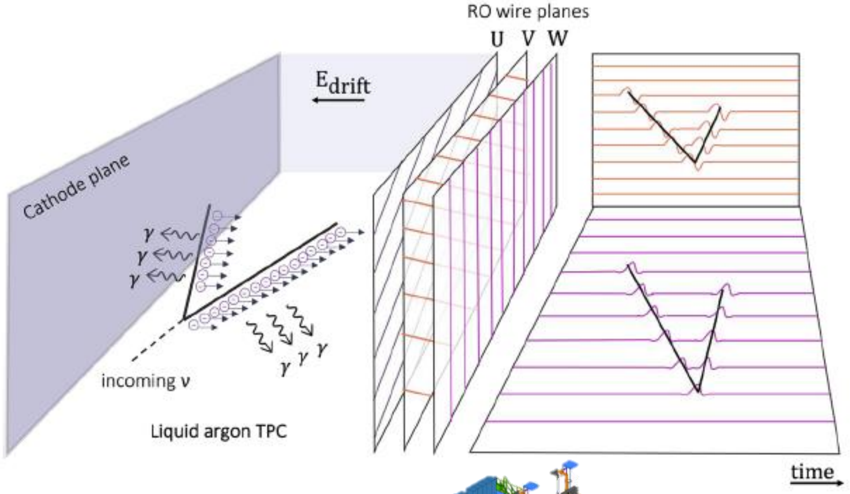
Conclusions

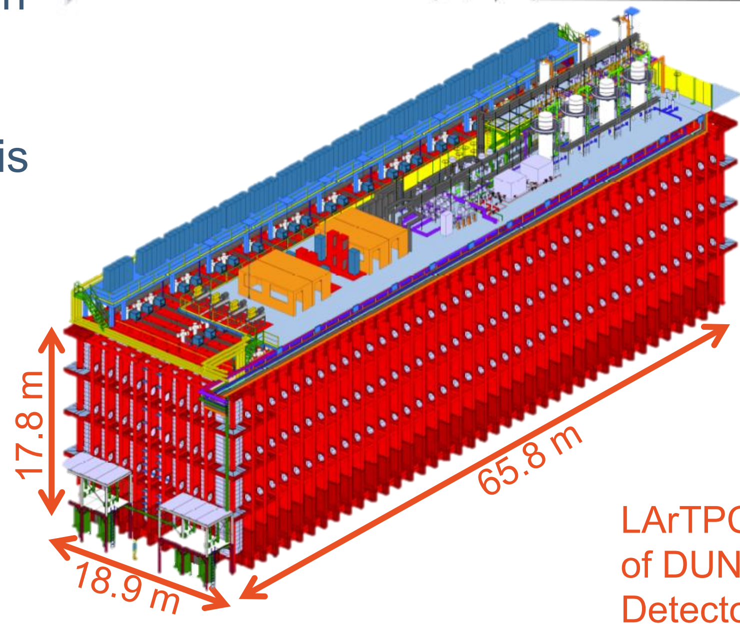
- DUNE is under construction and already doing science with its prototypes!
- DUNE is designed to test the three-neutrino model, estabish the mass ordering and make precise measurement of δ_{CP} phase and other oscillation parameters.
- If a supernova will occur nearby, DUNE will be there!
- Canada institutions are actively involved in both FD and ND! 🇨🇦

backup

Detector technology - LArTPC

- Particles are reconstructed from charge ionization and scintillation light
- **Ionization** drift in electric field towards sensing elements (**slow** signal, v~0.16 cm/us)
- **Scintillation** light (128 nm)
  - **fast emission** (6 ns) from excited argon dimers (about ¼ of total light for mip) provides track t0.
  - Slow emission from argon triplets light is emitted with a lifetime 1.3 us
  - Different light collections exploited in DUNE: PMTs coated with wavelength shifter, flatter photon detectors (ARAPUCA), etc. JINST **17** P01005 (2022)
- Low threshold for ionization: 23.6 eV/e- and transparent to its own scintillation

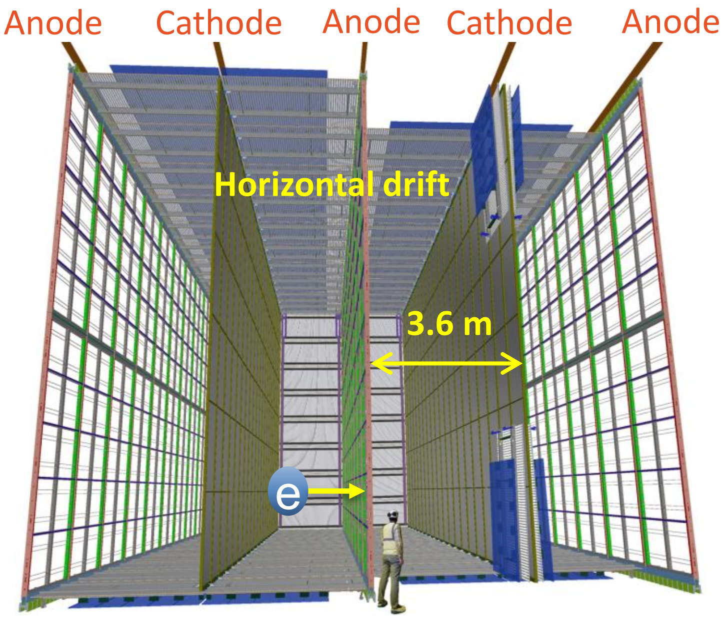


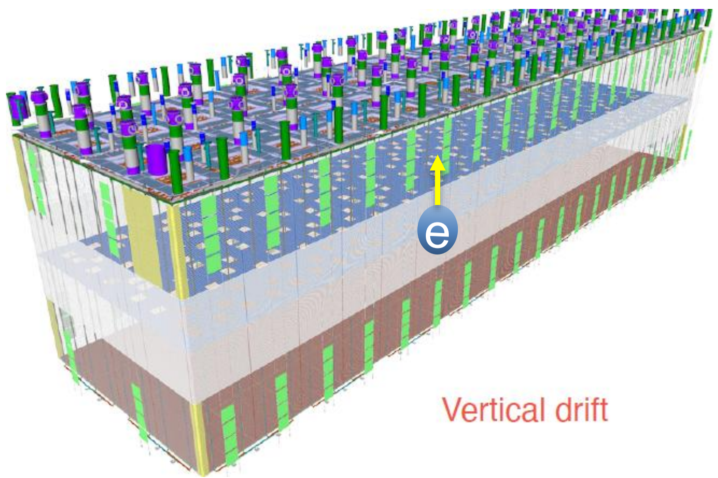


LArTPC module of DUNE Far Detector (17 kton)

DUNE's design – Far Detector

- DUNE will start with 2 Far Detector modules, each 17 kt total volume about 1 mile underground
- There are two different configurations planed: electric field is
  - **Horizontal**: 3.5 m drift, 500 V/cm, 180 kV cathode plane assembly, 5 mm wire spacing, fine-grained info
  - **Vertical**: 6.5 m drift, 450 V/cm, 294 kV cathode plane. Instead of planes of wires, the sensitive elements conducting strips printed on 3.2 mm thick printed circuit boards
- Low threshold for ionization: 23.6 eV/e-
- High granularity → substantial data volume → DUNE Data Acquisition System, to which the Canadian group is heavily contributing





Low energy background model

- LAr internal backgrounds
  - ^{39}Ar, ^{42}Ar, ^{85}Kr
  - ^{222}Rn and daughters
- Detector materials (FD-HD)
  - CPA: ^{42}K, ^{40}K, ^{238}U, ^{232}Th chains
  - APA boards: ^{40}K, ^{238}U, ^{232}Th chains
  - APA: ^{60}Co, ^{238}U, ^{232}Th chains
  - PDS: ^{222}Rn daughters emanations
- External backgrounds
  - Cavern neutrons from $(\alpha$,n) and fission
  - Cavern γ from ^{40}K, ^{238}U, ^{232}Th chains
  - Cavern γ from *n*-capture
  - Cryostat foam: γ from ^{40}K, ^{238}U, ^{232}Th chains

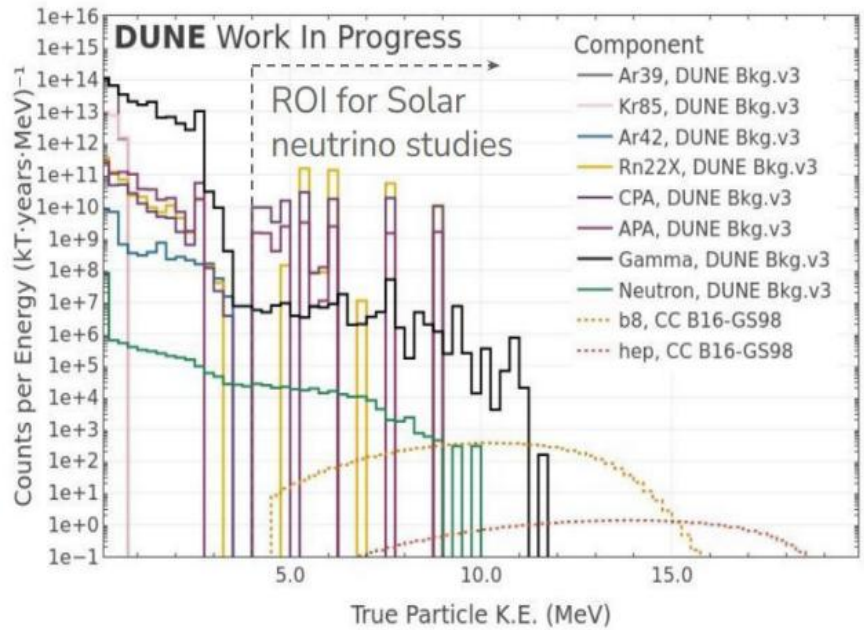
Background model v3

Exhaustive work to develop a background model with external backgrounds (omitted in FD-HD TDR) using Decayo.

Effort lead by SDSMT (J. Reichenbauer) and validated by the review committee (DUNE-doc-33958) formed by D. Guffanti, V. Kudryavstev, C. Palomares, S. Peeters, and S.Westerdale.

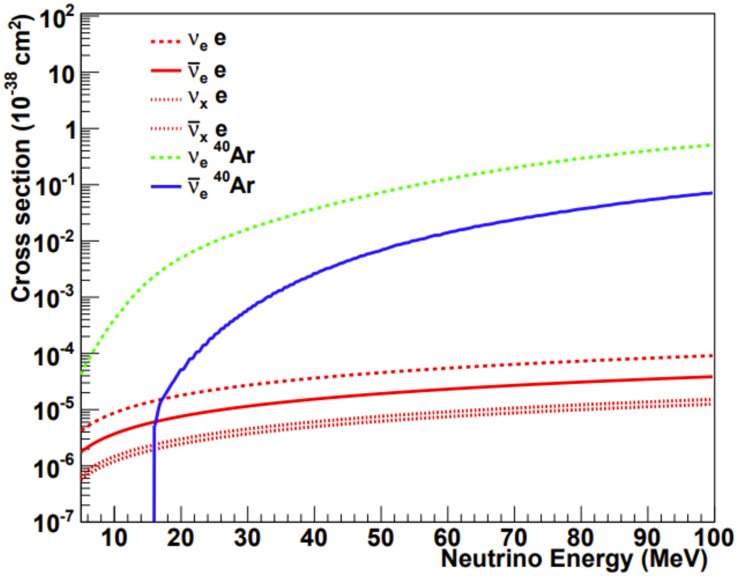
- **LAr bulk contributions** (^{39}Ar, ^{85}Kr, ^{42}Ar) and isotopes with ion drifting towards cathode.
- **Internal contributions** inside FD-HD and FD-VD cryostats: cathode, anode, and photon detection system
- **External contributions** from cavern neutrons, cavern gammas, cavern gammas from neutron capture in the cavern and cryostat, and cryostat foam gammas considering 3 scenarios:
    - **Nominal**: based on shotcrete assay results from DUNE manufacturer:
        - Neutrons from SF of U/Th: 2.2·10-6 n/cm2/s
        - Gammas fromU/Th/K/captures: 9.2 γ/cm2/s
    - **Optimistic**: average-activity shotcrete which would reduce 3x gamma flux and 2x neutron flux.
    - **Shielded:** x13 bkg reduction.

Tech note and paper in preparation



15:00 Wed LEP session devoted to backgrounds

Low Energy physics in DUNE FD



Event counts for **40 kton** detector, **10 kpc** core collapse

Channel	Events "Livermore" model	Events "GKVM" model
$\nu_e + ^{40}\mathrm{Ar} \to e^- + ^{40}\mathrm{K}^*$	2720	3350
$\overline{\nu}_e + ^{40}\mathrm{Ar} \to e^+ + ^{40}\mathrm{Cl}^*$	230	160
$\nu_x + e^- \to \nu_x + e^-$	350	260
Total	3300	3770

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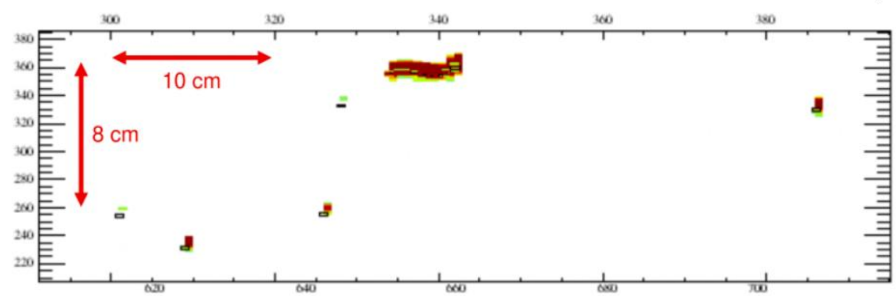
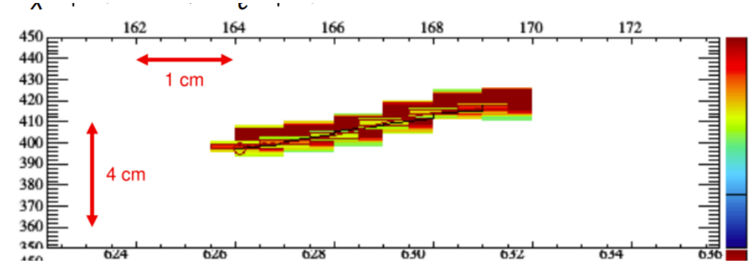
- $\nu_e + ^{40}Ar \to e^- + ^{40}K^* \to e^- + ^{40}K + N\gamma$

Signature: **short electron track** + gamma ejected from nucleons observable via energy deposition from Compton scattering, showing up as **small charge blips**

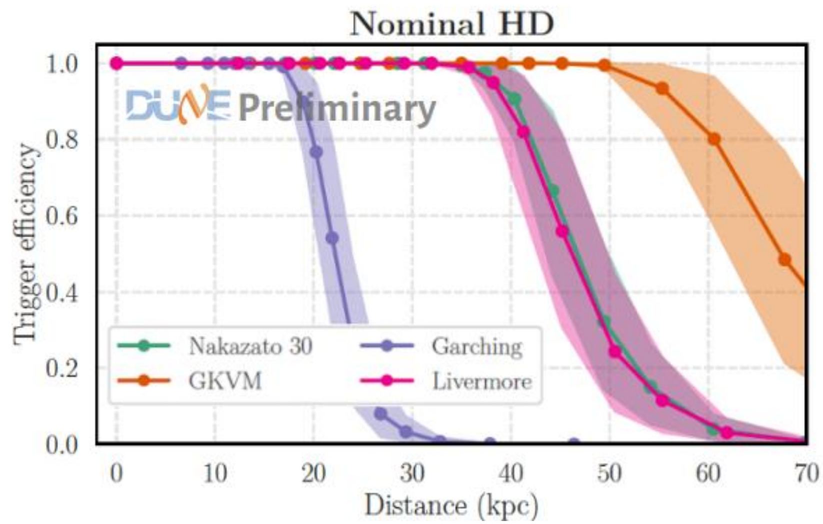


- Elastic scattering $\nu_x + e^- \to \nu_x + e^-$



Supernova trigger efficiency

- The general strategy will be to record data from all channels over a **30-100 second** period around every trigger
- A real-time algorithm should provide **trigger primitives** by searching for photomultiplier hits and **optical clusters**, where the latter combines several hits together based on their time/spatial information
- 1/month false trigger rate
- During the first 50 ms of a 10-kpc-distant supernova, the mean interval between successive neutrino interactions is 0.5−1.7 ms depending on the model. The TPC alone provides a time resolution of 0.6 ms



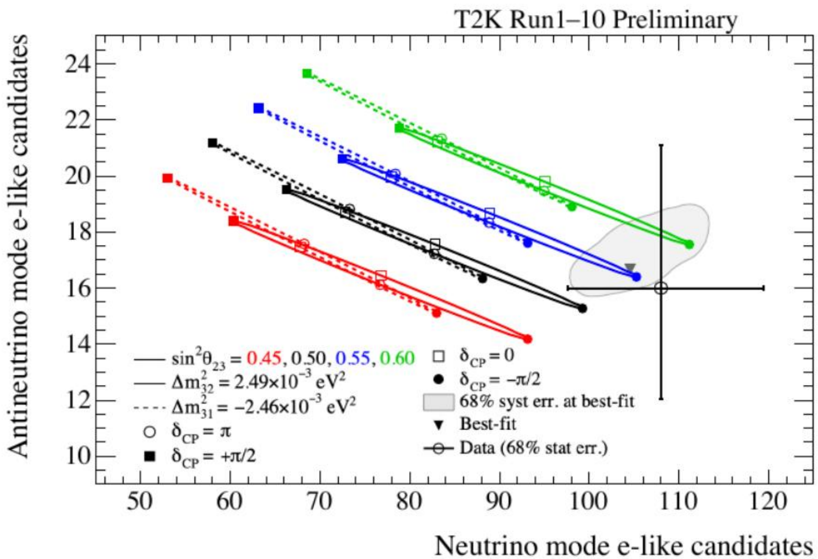
Trigger system:

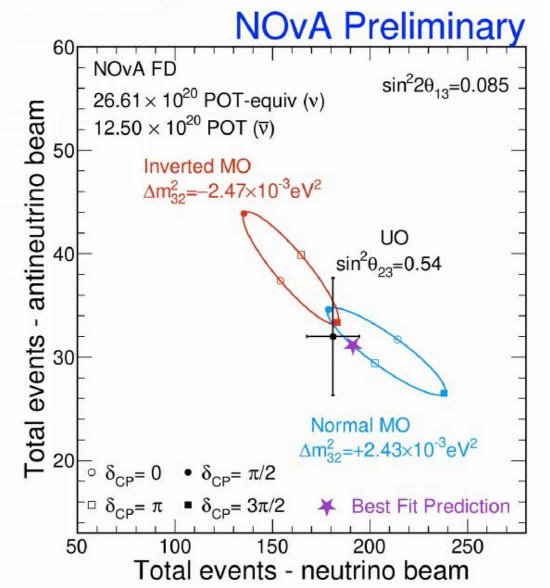
- Trigger can use both TPC and PDS information, exploiting signal coincidences over the SNB timescale
- Aims at 95% efficiency @ 20 kpc
- 1/month false trigger rate

Preliminary results for PDS-only trigger:

- Trigger primitives made of PDS hits + clusters based on space-time information
- >90% efficiency on a SNB at $\lesssim$ 20 kpc (Milky Way edge)

Limitation of existing data

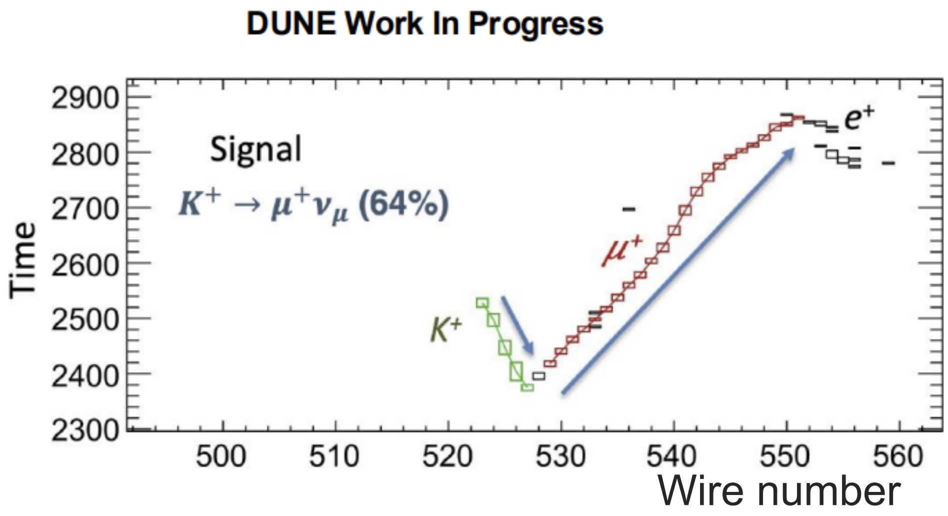




- Matter effect and CP violation are degenerate
- Statistical uncertainty is large compared to allowed parameter space
  - There will always be a combination of standard parameters that agrees with the data
  - There will likely be many allowed combinations → degeneracies

BSM in DUNE- proton decay

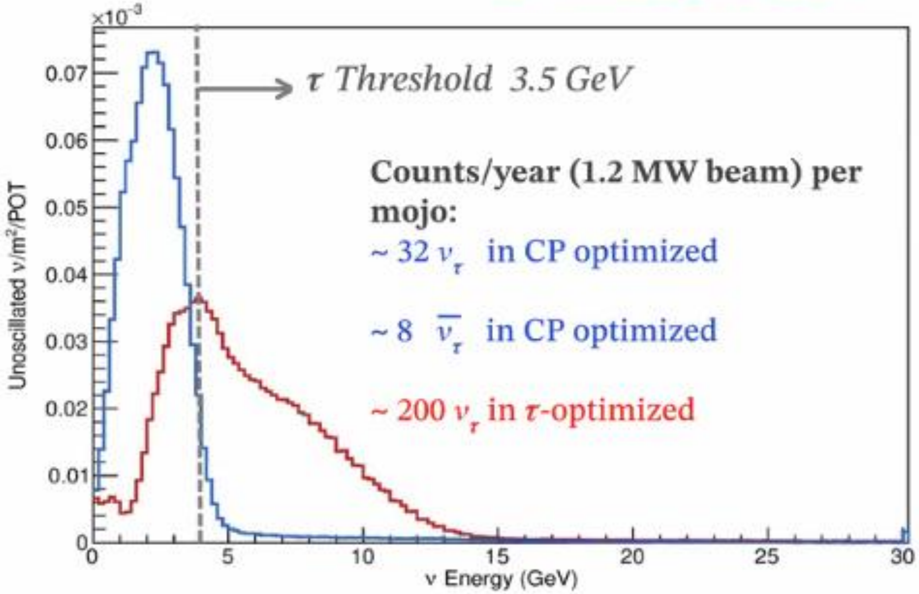
- DUNE will be an excellent detector to perform nucleon decay searches: Underground location, Very large fiducial mass; Millimeter size imaging capabilities
- Golden channel in DUNE: $p \rightarrow \overline{\nu} + K^+$

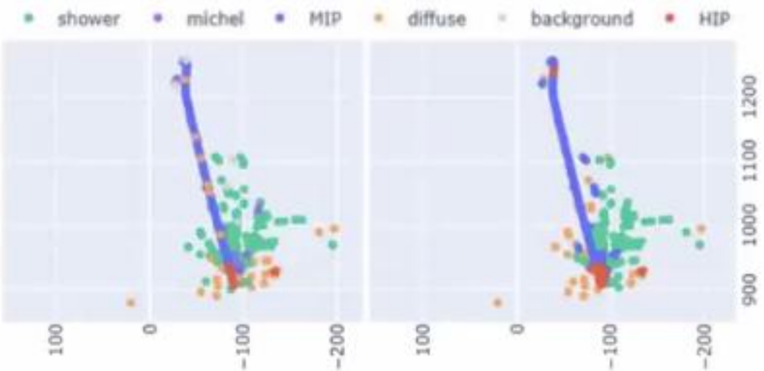


ν_τ appearance in DUNE beam

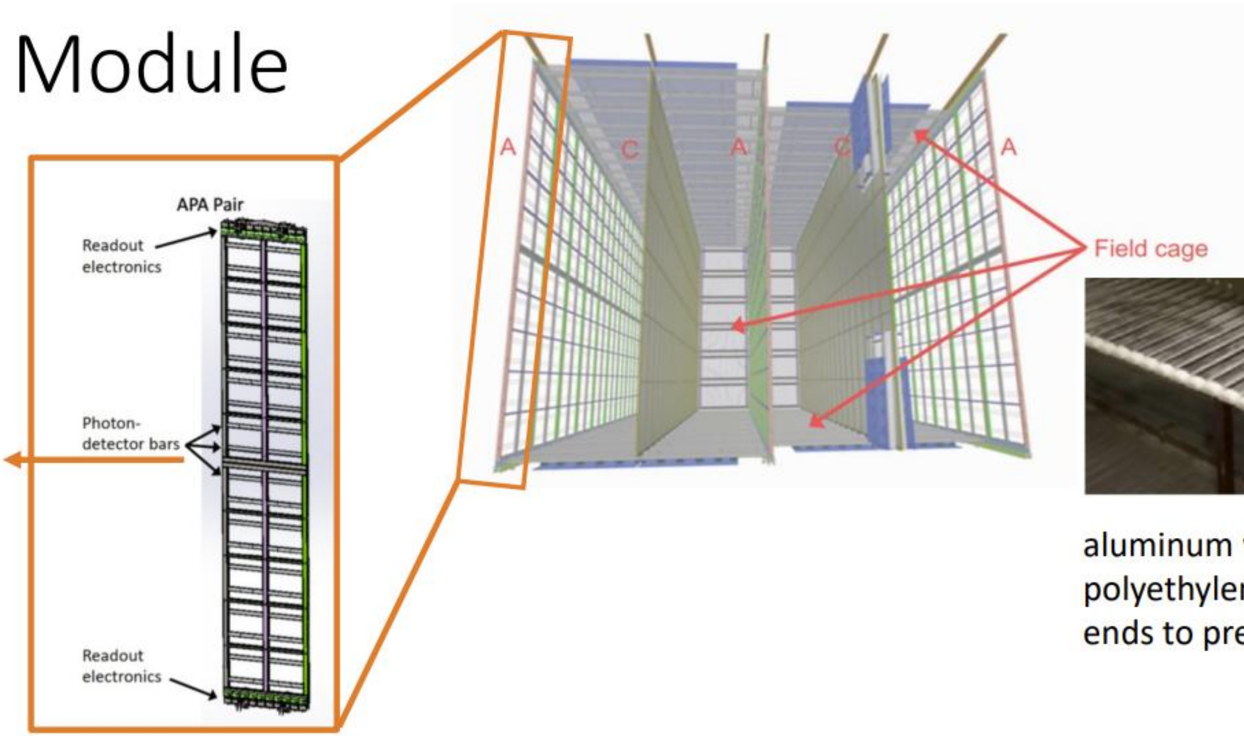
arXiv:2203.05591

- DUNE has a substantial flux above 3.5 GeV CC threshold → possibility to measure ν_τ appearance
- Imaging capabilities of DUNE's LArTPCs makes it possible to reconstruct complex τ final states kinematically
- ML-driven reconstruction based on hierarchical graph neutral network (GNN) being pursued
- Opportunity to directly measure 3-flavor oscillations and test unitarity





DUNE 1st Module

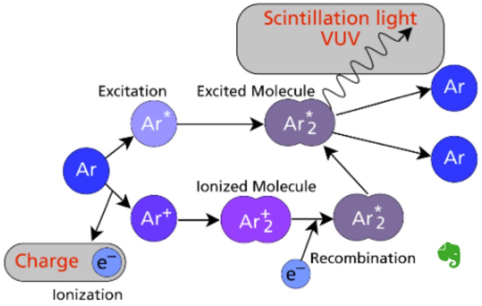


aluminum with white polyethylene caps on the ends to prevent discharges

- Photon detection provides time of interaction, and can serve to identify backgrounds, non-beam physics trigger (Supernova, proton decay, etc.)
- Photons collected by X-ARAPUCAs
  - layers of dichroic filter and wavelength-shifter
- Signals sent to feedthroughs in roof of cryostat, merged with APA data at DAQ

Light Production in Liquid Argon

Quality	Scintillation Light
Intensity (for a MIP)	~40,000 photons/MeV
Direction	Isotropic
Timing	Fast component (nsec) and slow component (usec) measured by DEAP collaboration
Photon Wavelength	Spectrum peaks at 128 nm



Light Production in Liquid Argon

Quality	Scintillation Light	Cherenkov Light
Intensity (for a MIP)	~40,000 photons/MeV	~ 700 photons/MeV (wavelength > 100nm)
Direction	Isotropic	Directional
Timing	Fast component (nsec) and slow component (usec) measured by DEAP collaboration	Prompt (psec start)
Photon Wavelength	Spectrum peaks at 128 nm	$dN/d\lambda \propto \lambda^{-2}$