Long-Baseline Oscillations at DUNE

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On behalf of the DUNE Collaboration

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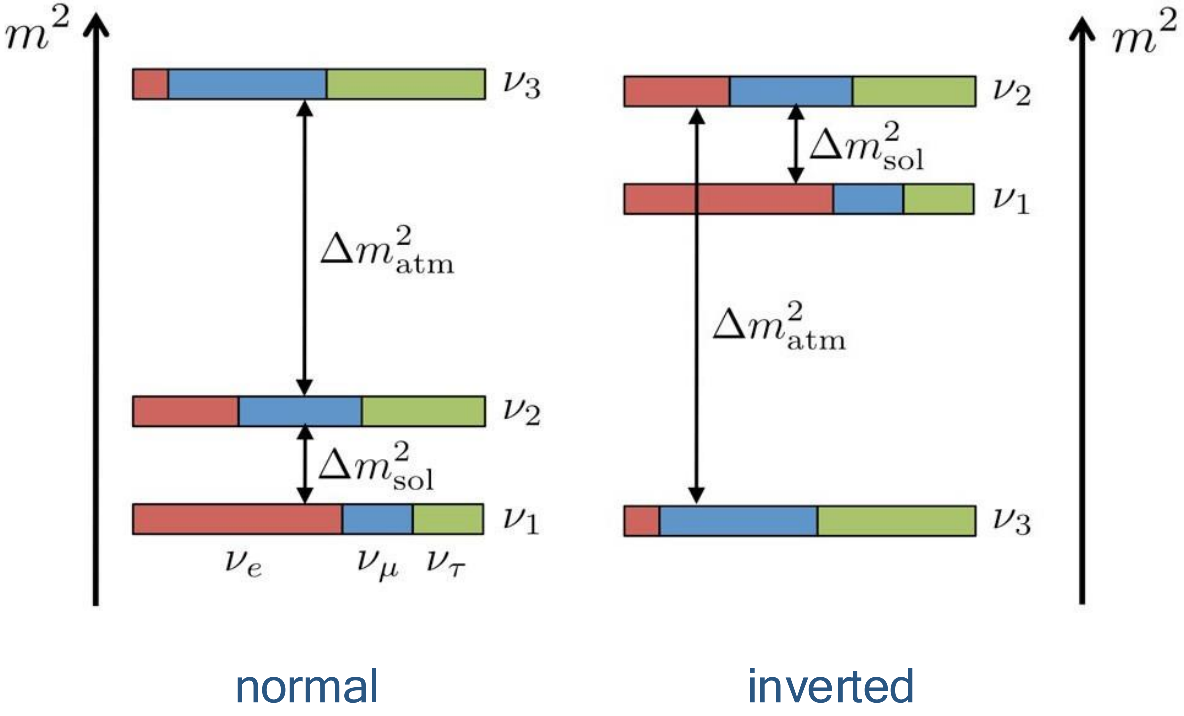
Lake Louise Winter Institution 2025

Big Questions in Neutrino Oscillation Physics

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

- What is the neutrino mass ordering? Is it normal ordering (NO) or inverted ordering (IO)?
- Is there CP violation? What is the value of δ_{CP}?
- Are there symmetries in neutrino mixing (PMNS matrix)? What is the octant of θ_{23}?



DUNE Physics Goals

DUNE has a **rich** physics program which includes:

1. Make precise measurements of the oscillation parameters θ_{23}, θ_{13} and Δm_{32}^2
2. Resolve the neutrino mass hierarchy, i.e. whether $m_3^2 > m_2^2$ or $m_3^2 < m_2^2$
3. Determine the octant of θ_{23}
4. Determine whether CP is violated in neutrinos and make a measurement of δ_{CP}
5. Search for τ appearance
6. Check the unitarity of the PMNS matrix
7. Search for nucleon decay
8. Be ready to detect low-energy neutrinos from a supernova
9. Search for Beyond Standard Model physics, e.g. sterile neutrinos, heavy neutral leptons etc .

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This talk will focus on **(1-4)**

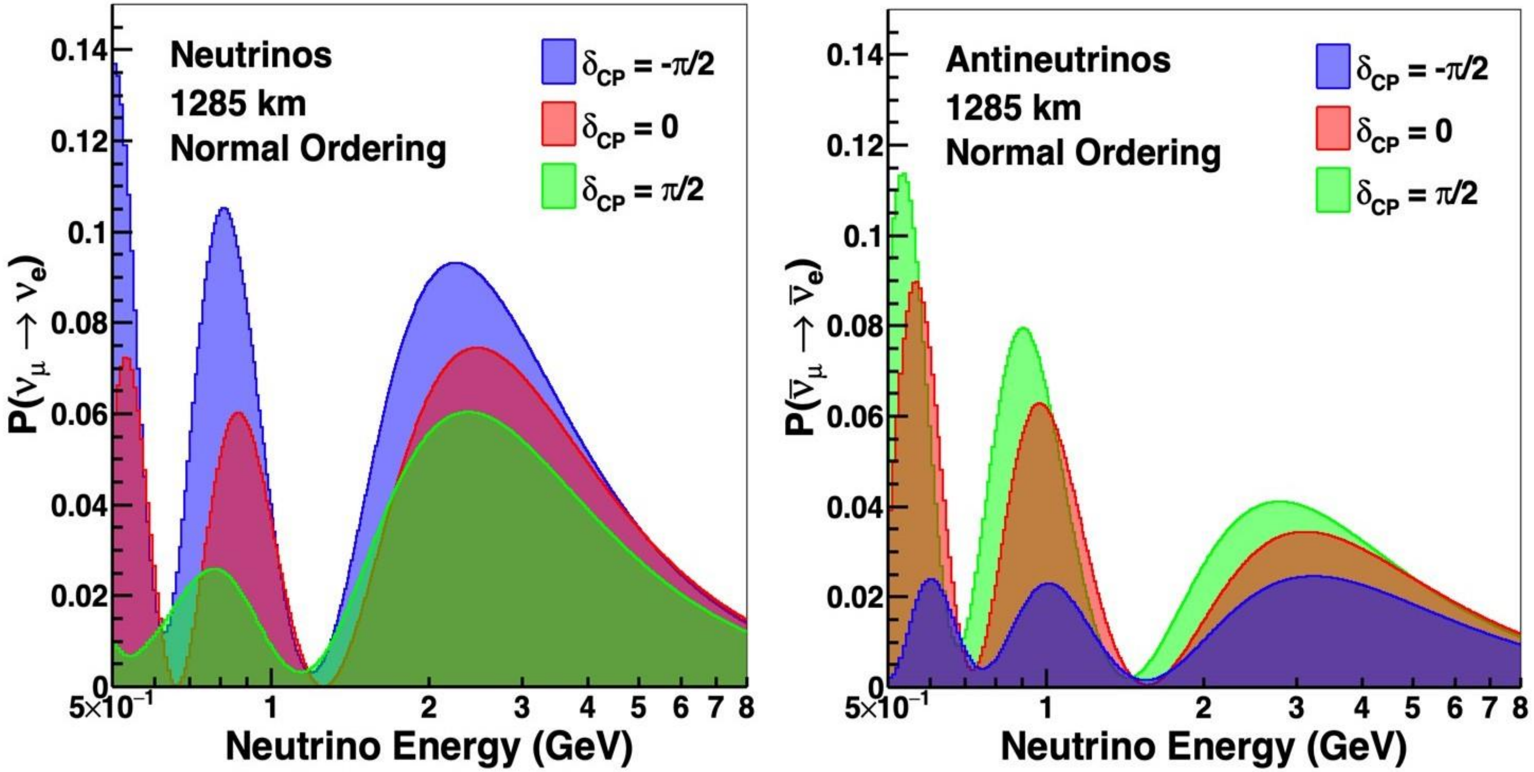
Long-Baseline Neutrino Oscillation

Measure neutrino and antineutrino oscillation as a function of L/E

Does the three-flavor model describe the data?

- If yes: measure the mixing angles, mass splittings, and CP phase
- If no: characterize the new physics

Need for a global program: different energies, matter effects, systematic uncertainties, etc.



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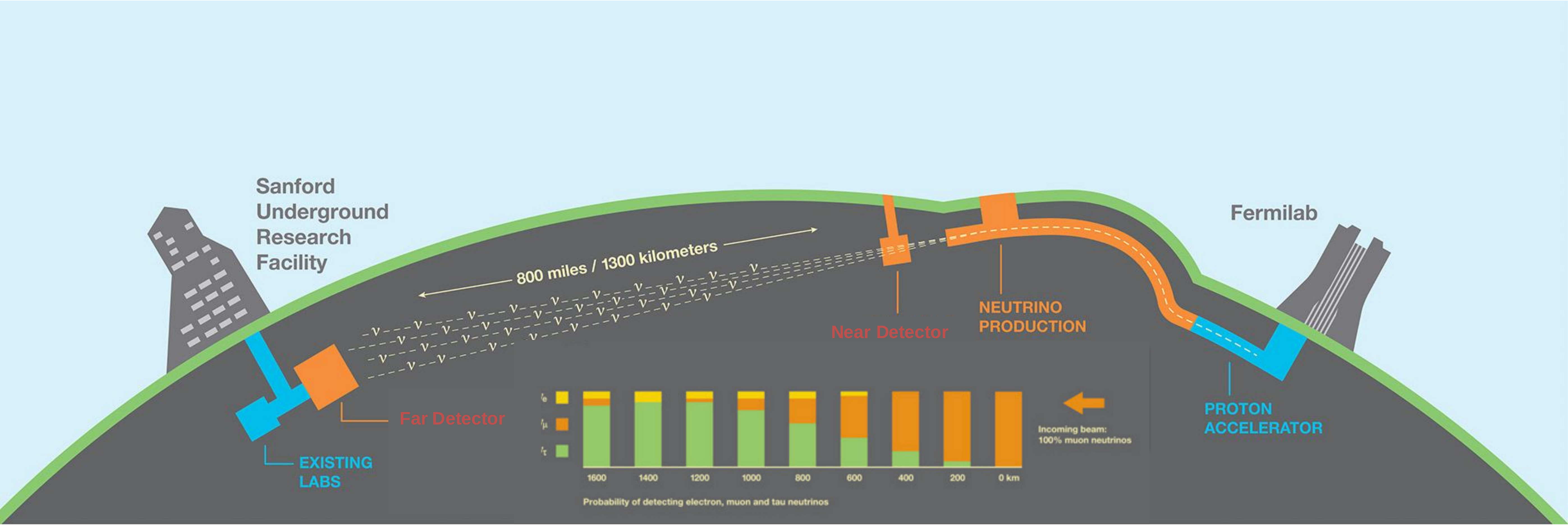
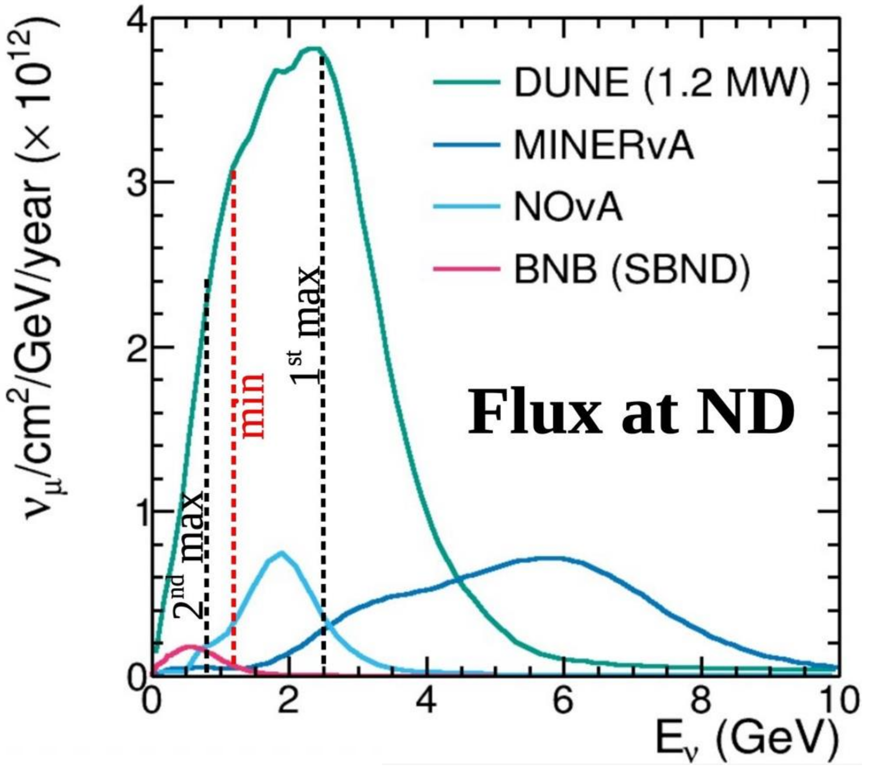
Deep Underground Neutrino Experiment (DUNE)

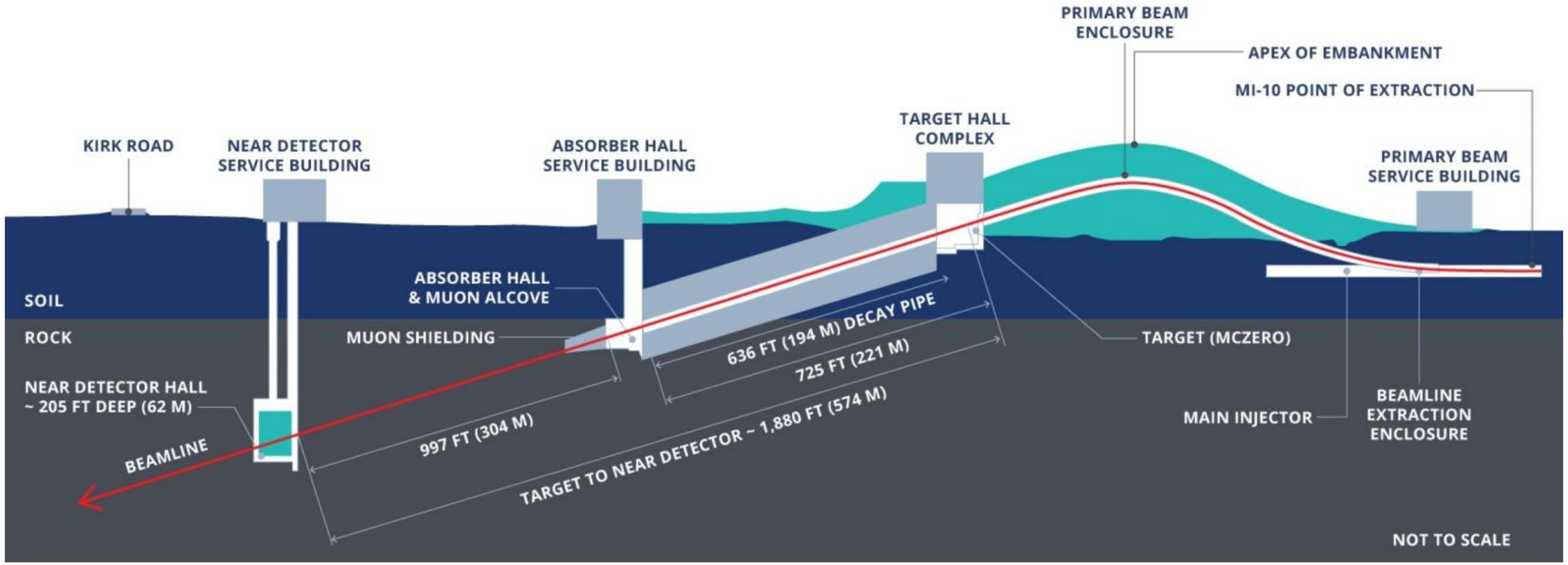


Neutrino Beam

- LBNF beamline will produce **world-leading intensity**
  - Phase 1: **1.2 MW**
  - Phase 2: Upgrade to → **2 MW**

- On-axis beam —> broad range of energies
  - Covers **1st & 2nd oscillation maxima**

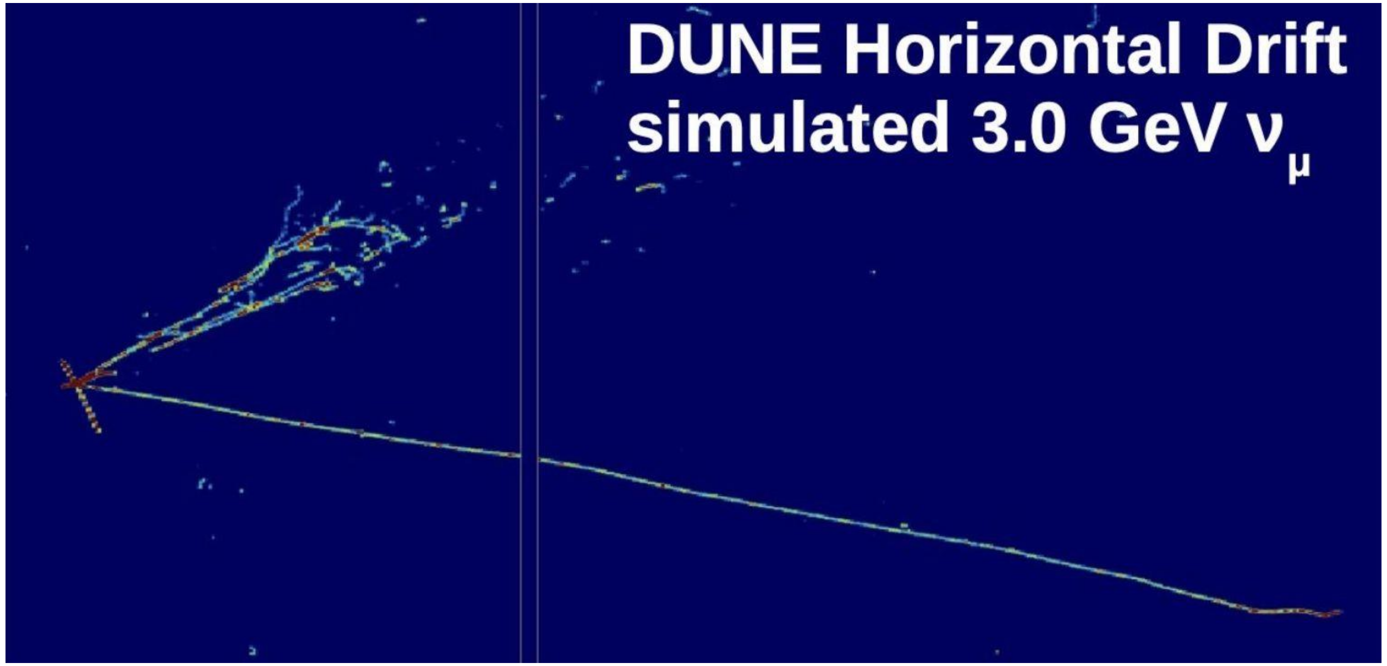


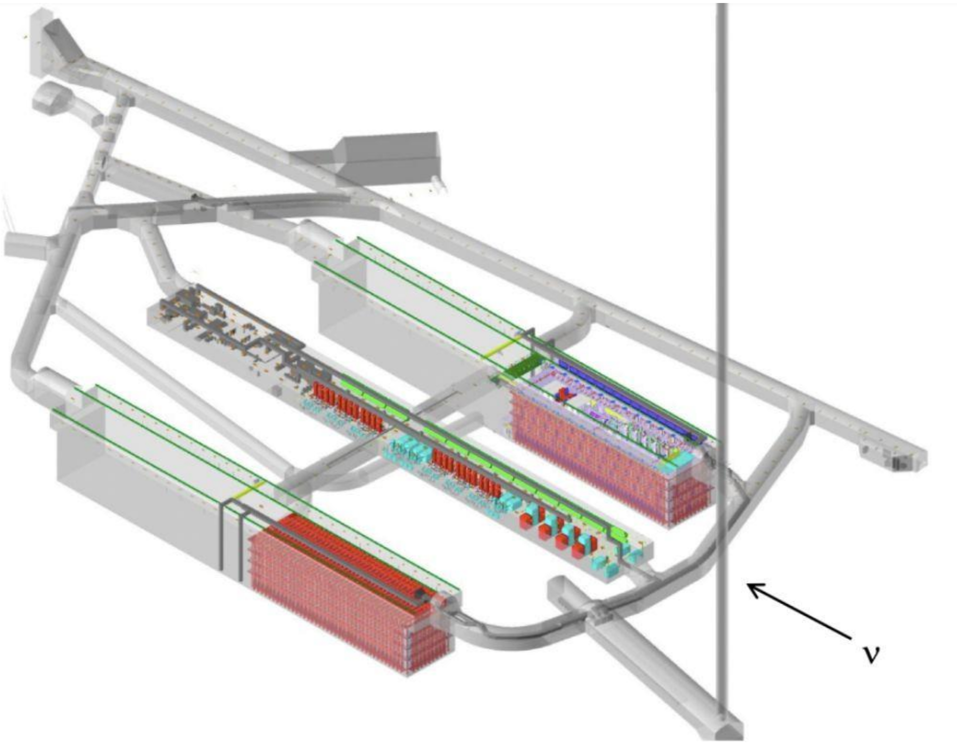


Far Detector (FD)

- Liquid argon provides **precise reconstruction** of lepton and hadronic energy over **a broad energy range**

- Will consist of **4 x 10kt fiducial mass LArTPC modules**



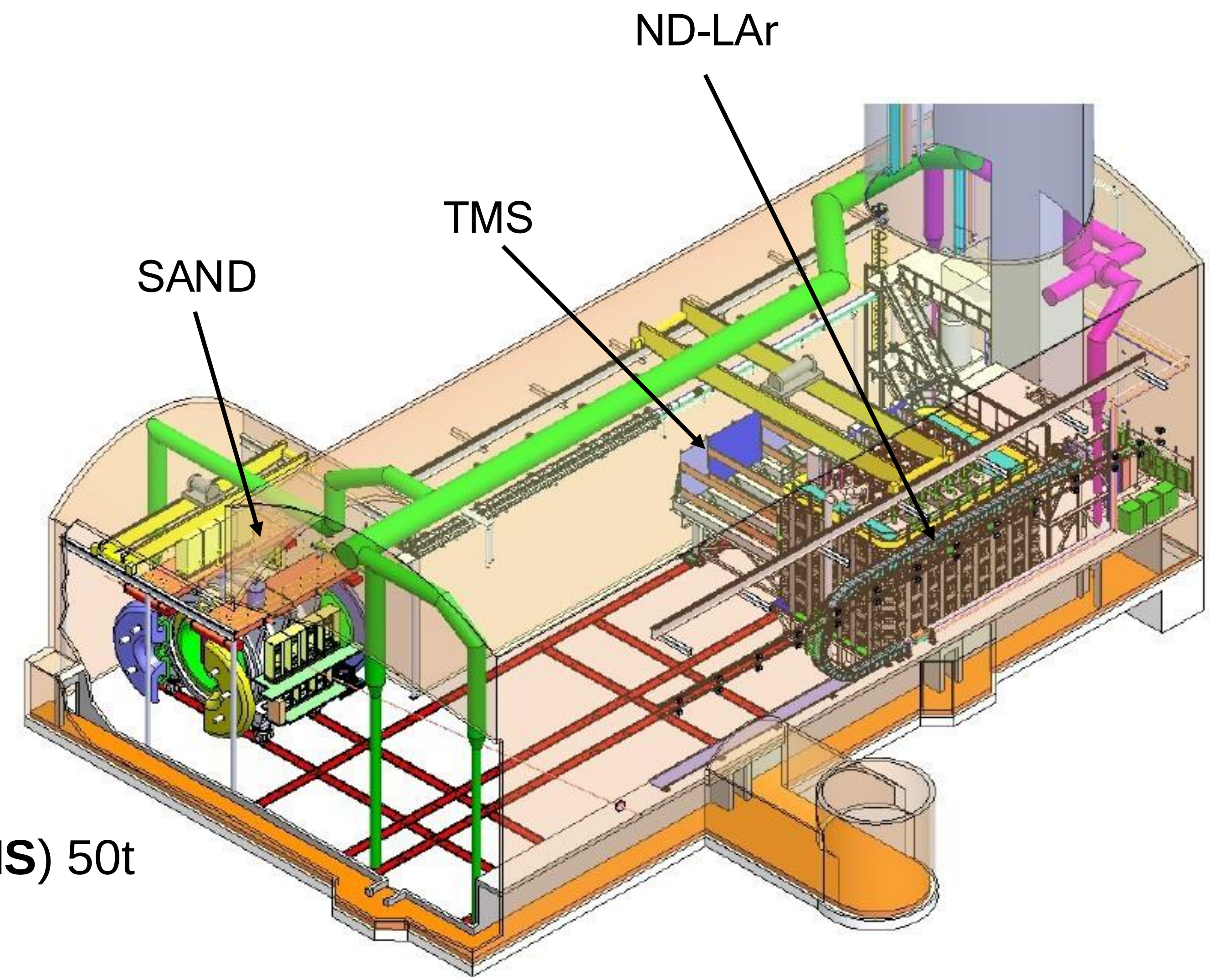


Near Detector (ND)

Main purpose: enable prediction of Far Detector reconstructed spectra

Movable detector system: LArTPC with muon spectrometer (PRISM)

Same target, same technology → inform predictions of reconstructed E_{ν} in Far Detector



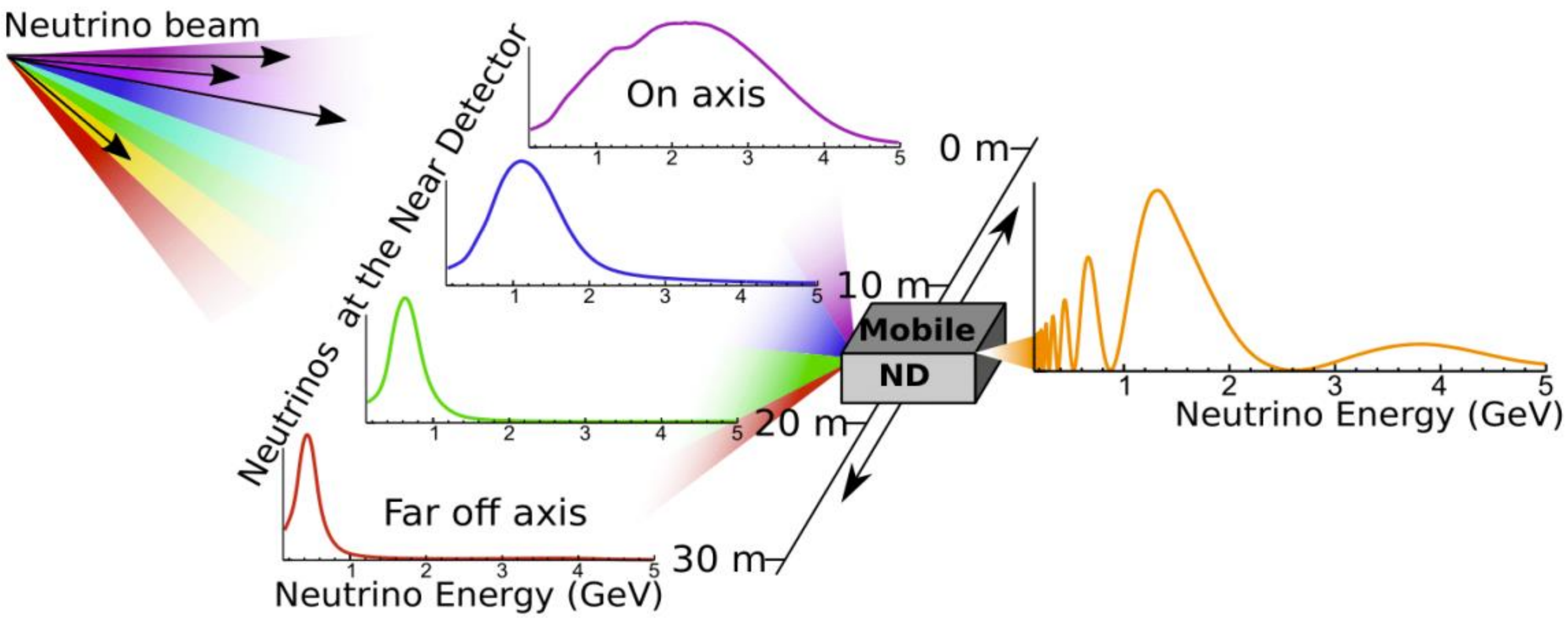
ND-LAR: liquid argon TPC with muon spectrometer (**TMS**) 50t detector with pixel readout to reduce pileup

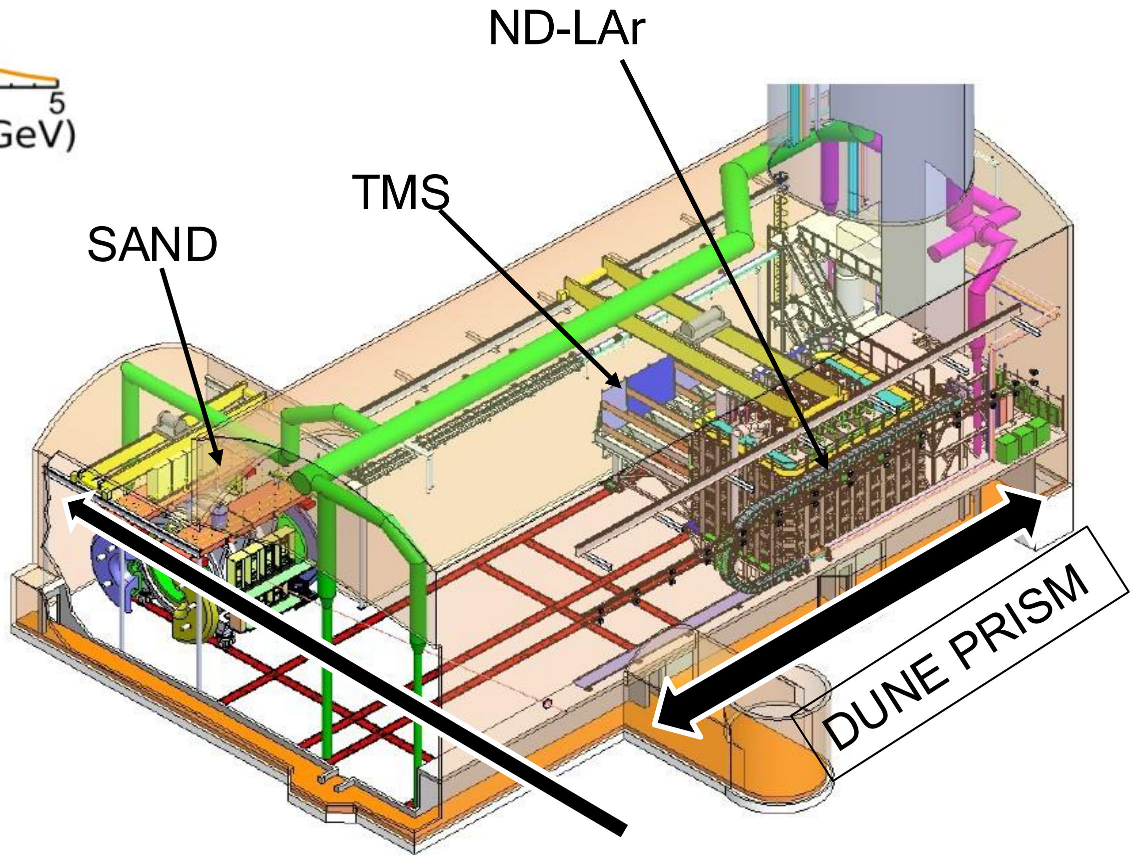
- Characterize beam flux and neutrino interactions

SAND: System for on-Axis Neutrino Detection

- Inner tracker & ECAL in magnetic field serve as beam monitor

ND – PRISM



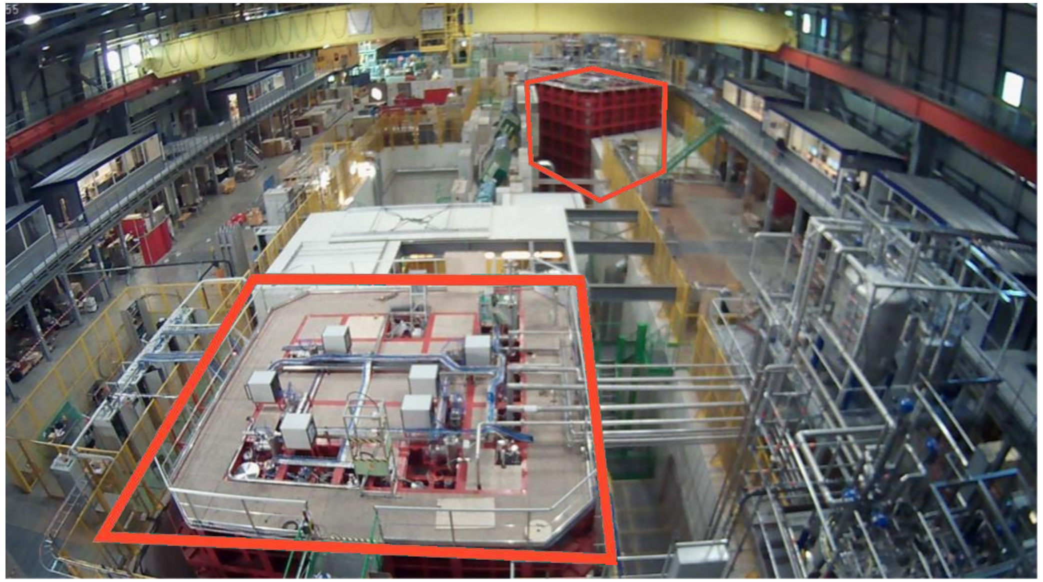


Precision Reaction-Independent Spectrum Measurement (PRISM)

Off-axis data in different neutrino fluxes constrains energy dependence of neutrino cross sections, independent of interaction model

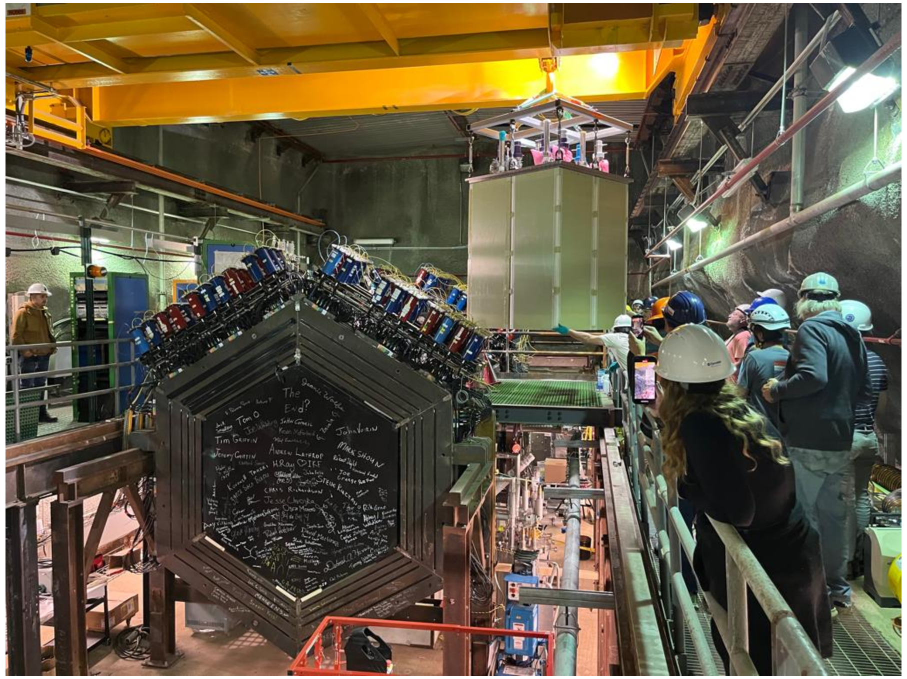
Current Canadian contributions

DAQ development at ProtoDUNE
- **ProtoDUNE**: FD prototypes at CERN
- Readout system tests & developments
- ProtoDUNE second run with SPS hadron beam



ND-LAr prototyping with 2x2 modules
- On cosmics and with Fermilab NuMI beamline
- Reusing MINERvA detector planes for “fast tracker”

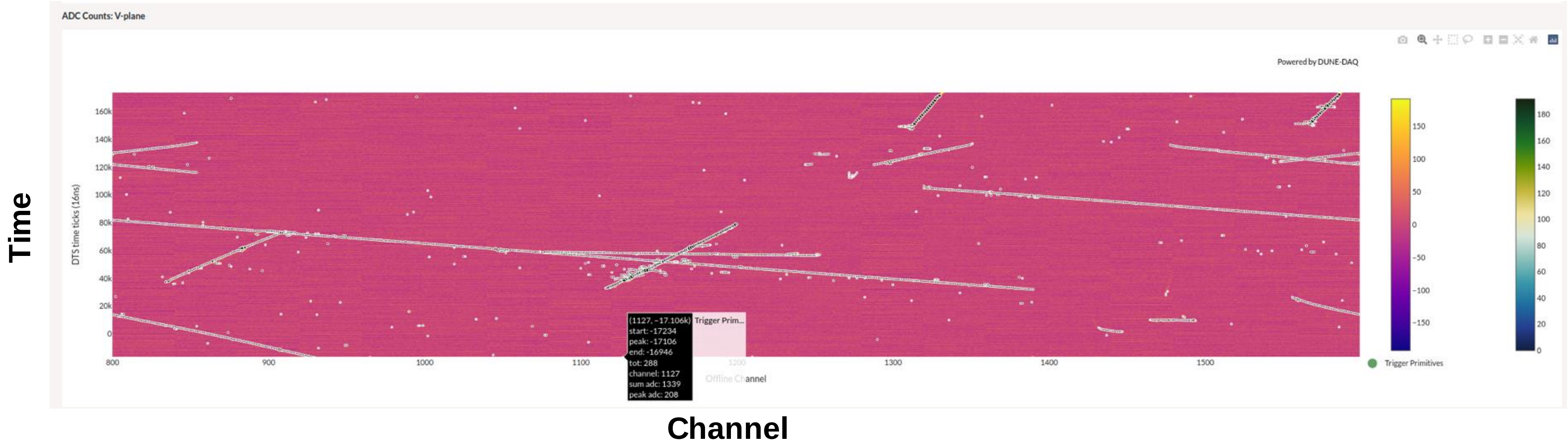
ND-LAr event reconstruction



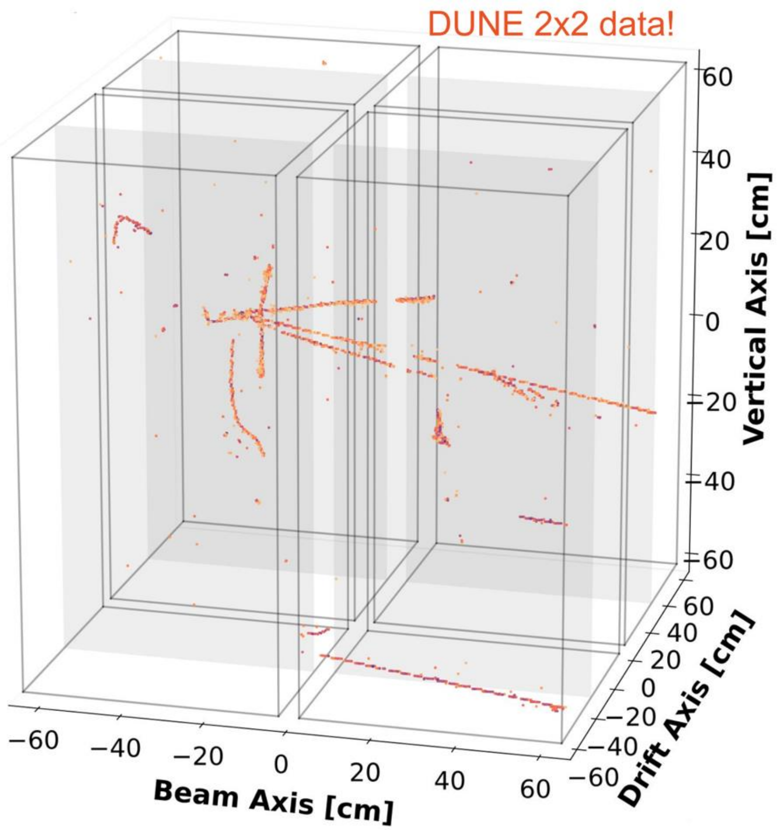
Latest developments

Far detector cavern excavation complete!

ProtoDUNE run 2 event display



ND-LAr prototype event display



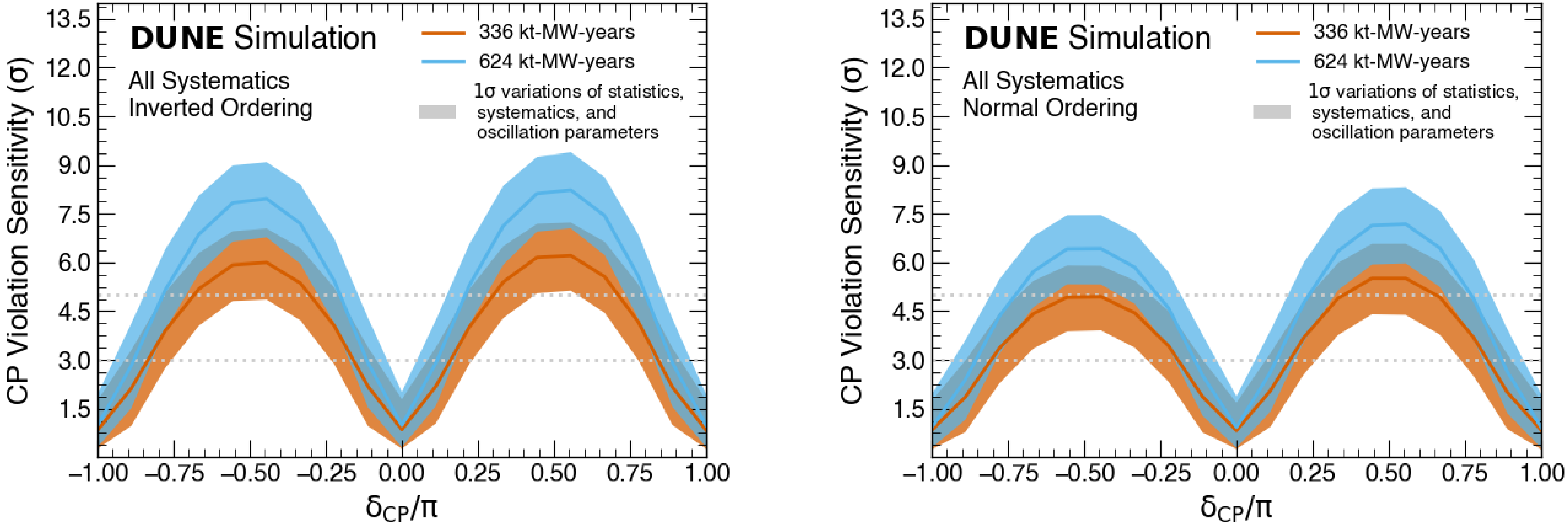
DUNE's Sensitivities

Long-baseline analysis

$$N(\text{Observables}) = \int \text{Flux}(E_\nu, \text{time}) \times \text{Interaction prob}(E_\nu, \text{final state}) \times \text{Detector Efficiency}(\text{final state}) \times \text{Osc}(E_\nu)$$

- Measure event rates → product of **oscillations** and **flux/interaction/detector models**
- Near detector has lots of events and assumed to have **no oscillations** → **constrain the systematics**
- Far detector has oscillations → **apply systematic constraints** → **infer oscillation parameter values**

CP Sensitivity



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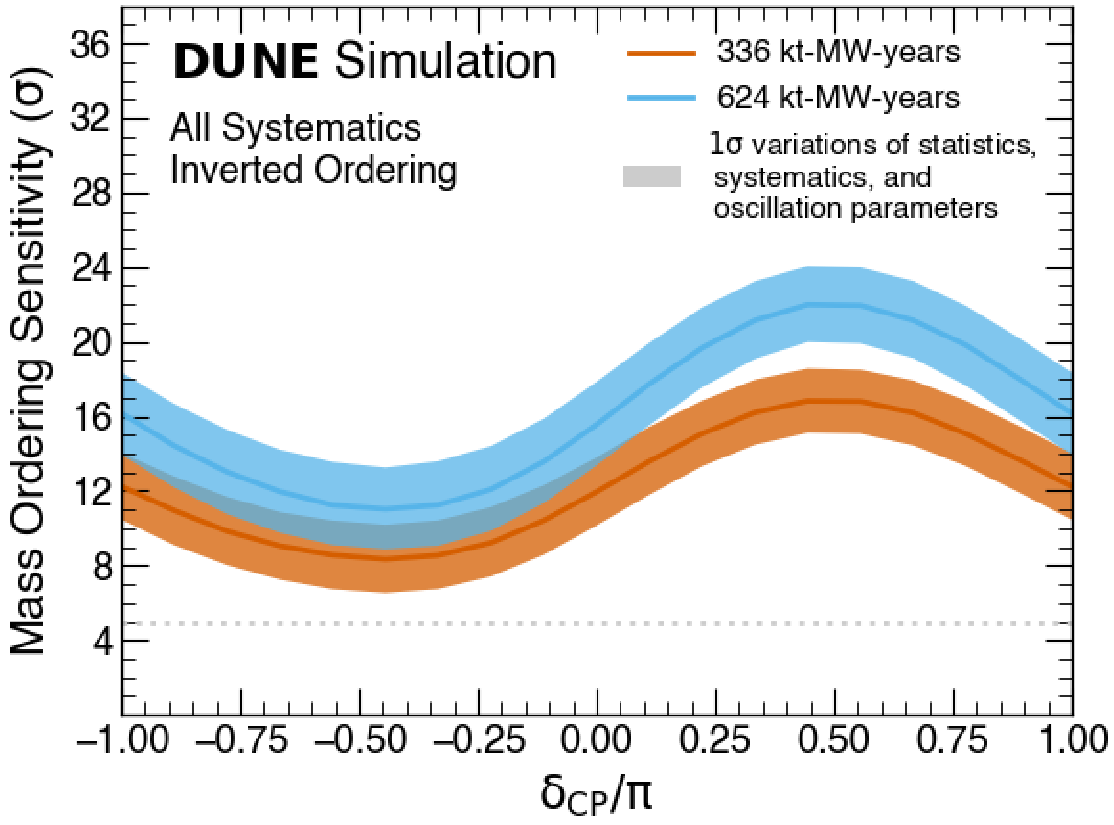
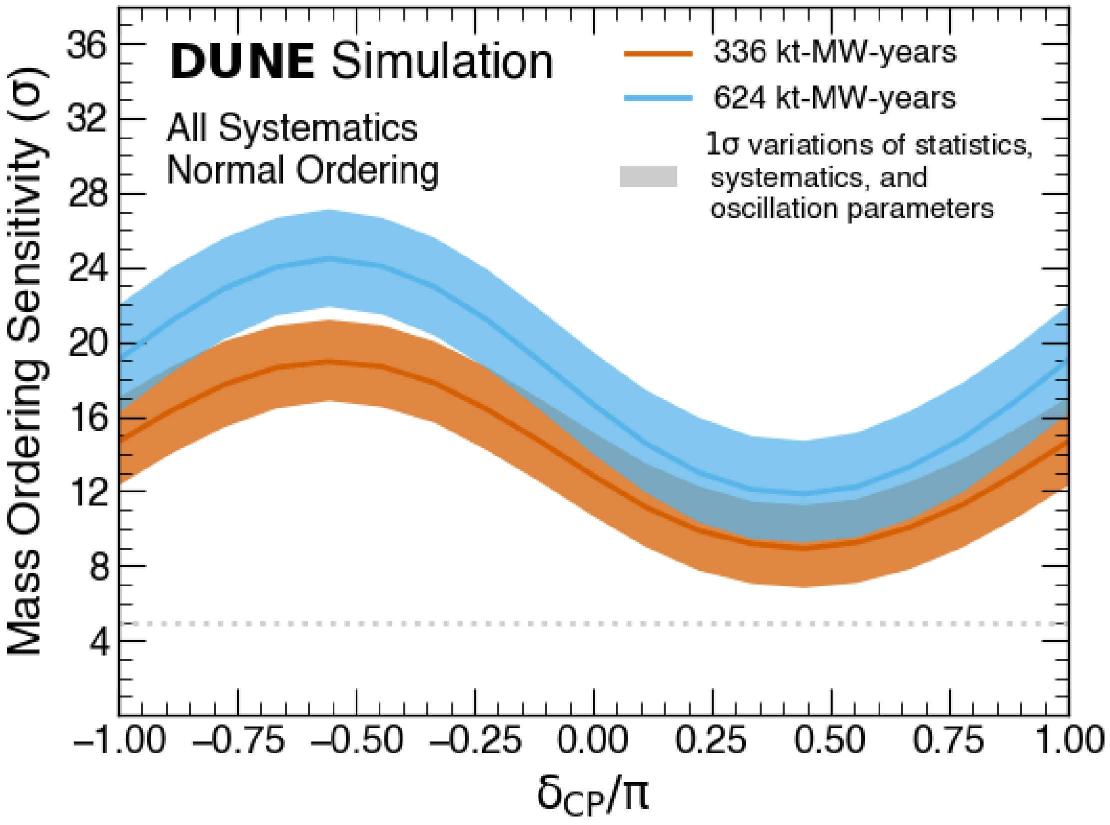
- After 10 years exposure there is significant CP violation (**$\delta_{CP} \neq 0, \pi$**) discovery potential across true values of **δ_{CP}** and for both hierarchies
- DUNE can establish CPV over 75% of **δ_{CP}** values at >3σ

Mass Ordering Sensitivity





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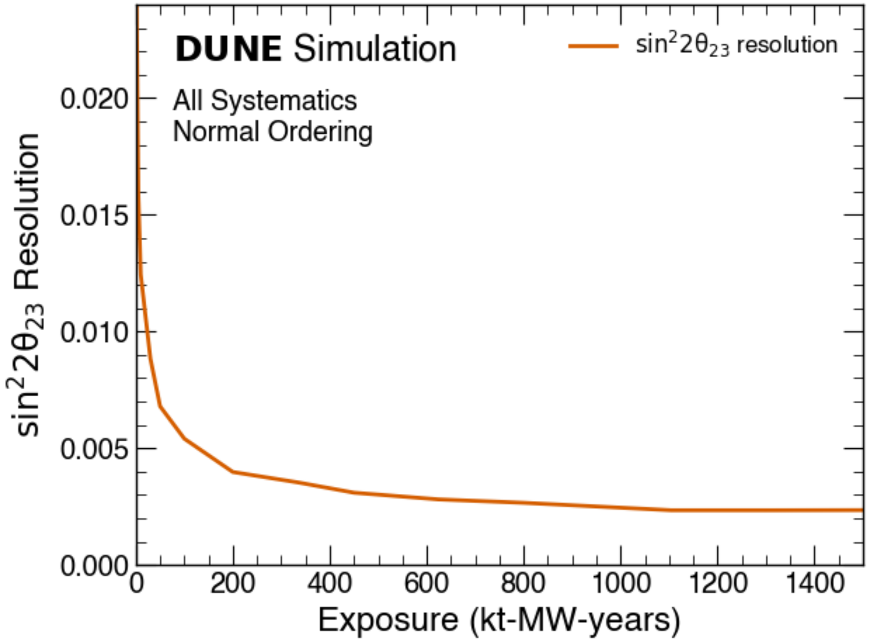
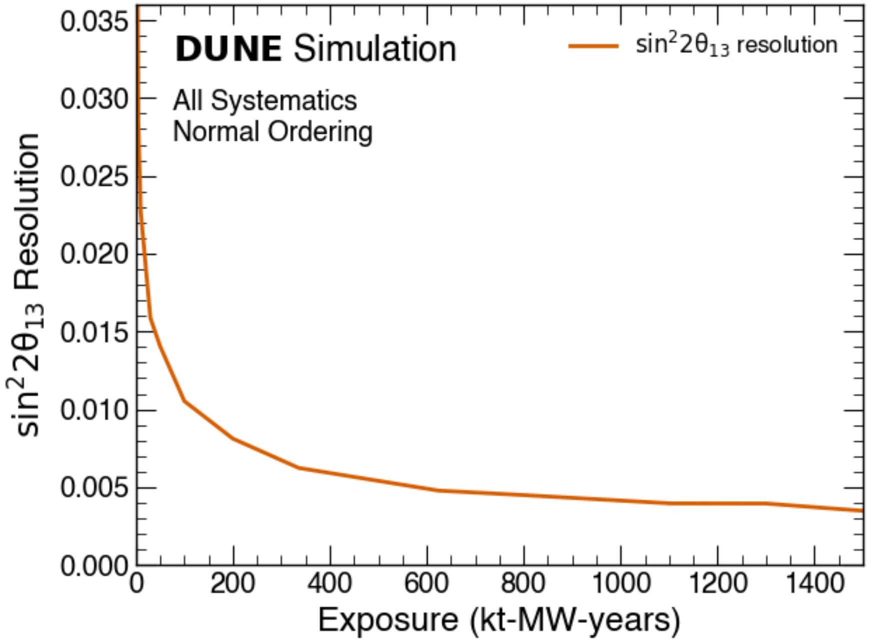
- Obtain a definitive answer for the mass hierarchy within 7 years, regardless of the values of the other oscillation parameters

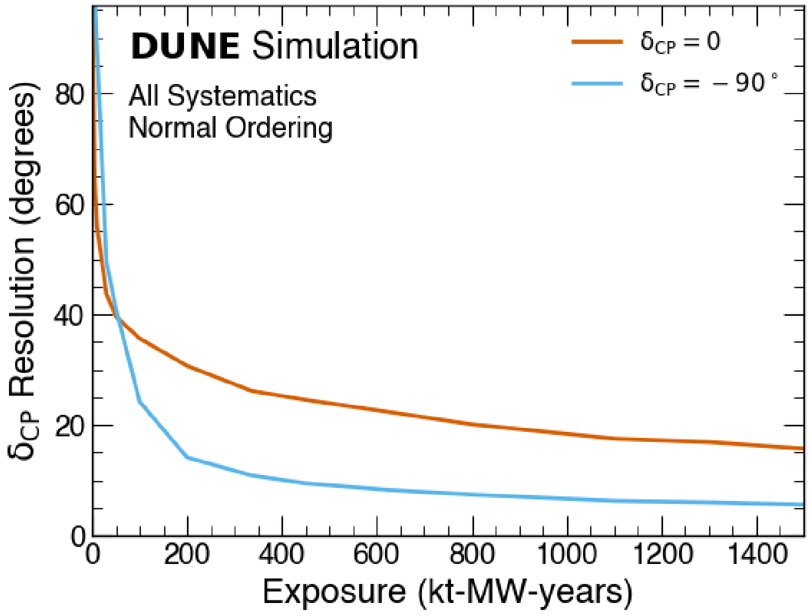
Resolution to oscillation parameters

Ultimate precision 6-16° in δ_{CP}

World-leading precision (for long-baseline experiment) in θ_{13} and Δm^2 → comparisons with reactor measurements are sensitive to new physics







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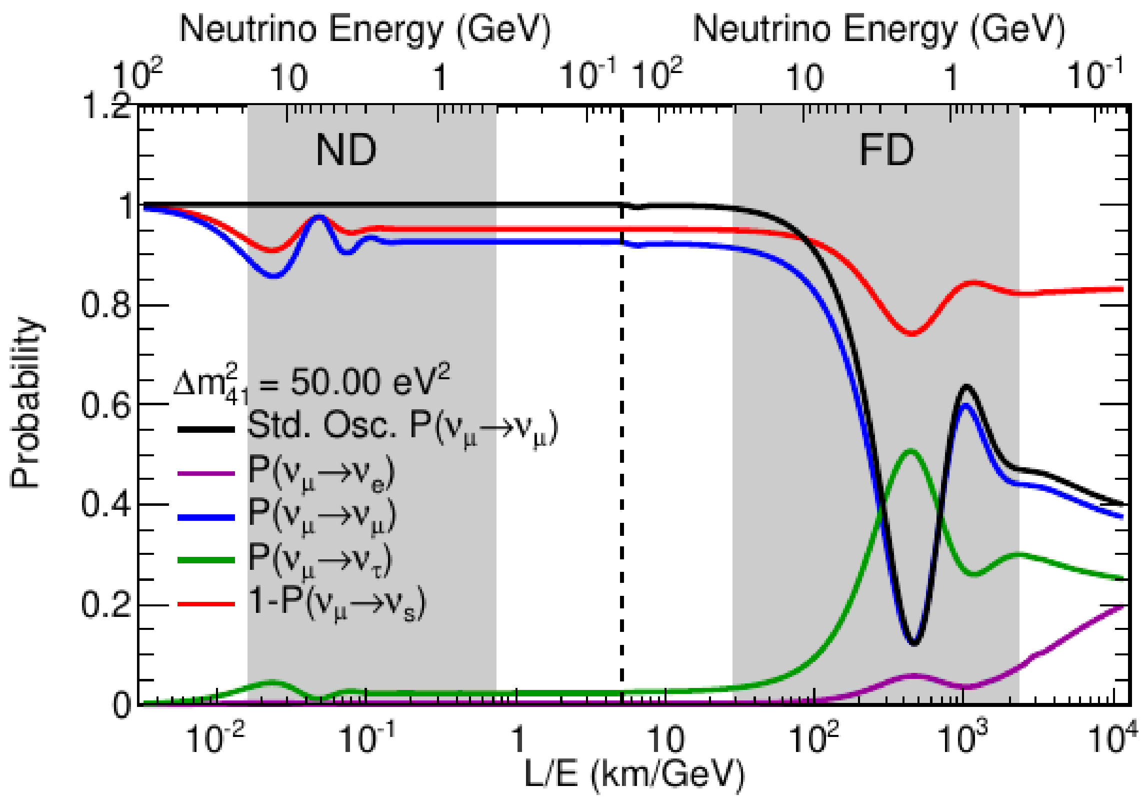
Beyond the 3-flavour paradigm



See Sergio's talk next for more!

Broad range of L/E at ND and FD → search for non-SM oscillations

Sterile neutrino mixing can be probed by comparing 3-flavour and 3+1-flavour neutrino disappearance and appearance probabilities

Summary

- DUNE will enable an exciting physics program and aims to make precise measurements of the oscillation parameters:
  - Definitively measure the **MO** regardless of other oscillation parameters
  - Sensitivity to **CPV** and **θ_{23} octant**

DEEP UNDERGROUND NEUTRINO EXPERIMENT

END

Thanks for your time!!!

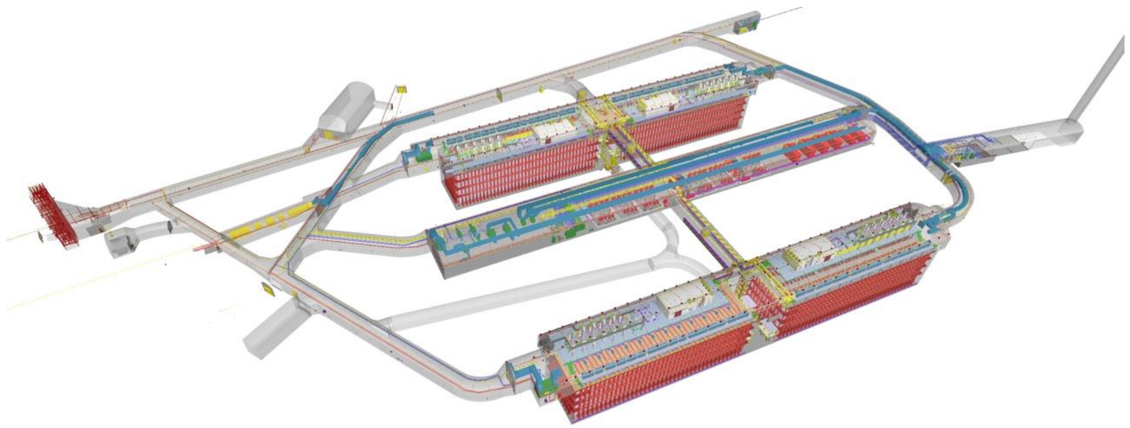
References

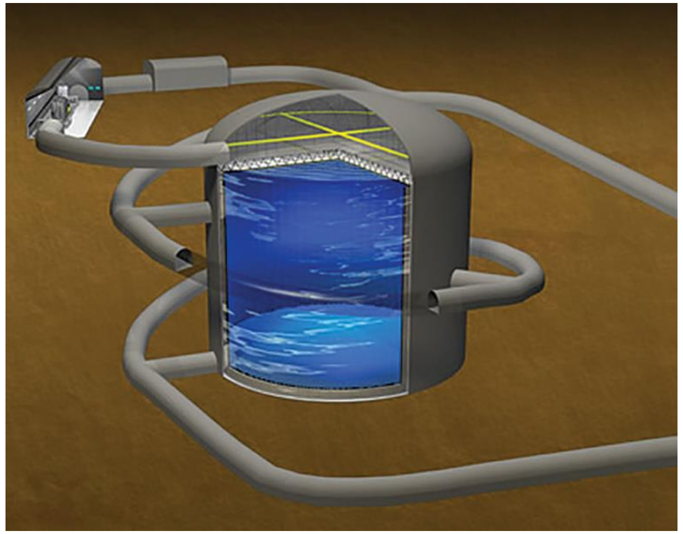
- DUNE TDR II arXiv:2002.03005
- Long-baseline neutrino oscillation physics potential of the DUNE experiment Eur. Phys. J. C 80, 978 (2020)

Inside ProtoDUNE!

Backup slides

DUNE & Hyper-K Complementarity





- Very long baseline → large matter effect
- On-axis location & broad energy spectrum
- Reconstruct ν energy over broad range → LArTPC technology
- Highly-capable near detectors to constrain systematic uncertainties

- Shorter baseline → small matter effect
- Off-axis location & narrow energy spectrum
- Lower energy and mostly quasi-elastic interactions → very large water Cherenkov detector
- Highly-capable near detectors to constrain systematic uncertainties

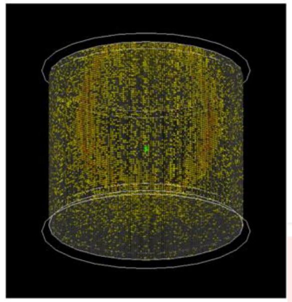
Together we'll have resolved parameter degeneracy, better precision, better parameter sensitivity irrespective of true δ_{CP} value, and increased sensitivity to new physics.

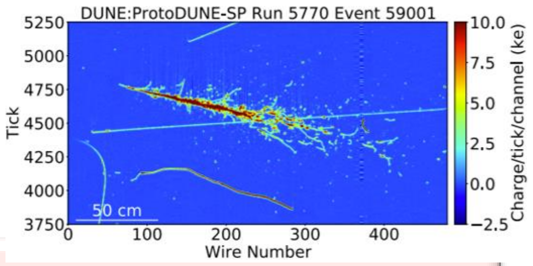
Why both DUNE & Hyper-K?

Effect on matter on neutrino oscillations complicates some measurements

Matter does not have same effect on neutrino and anti-neutrino oscillations – complicates CPV measurement

Possible strategies:





Small oscillations length (~300 km) = insignificant matter effects
Off axis beam gives high flux at oscillation maximum, narrow energy range

Hyper-Kamiokande

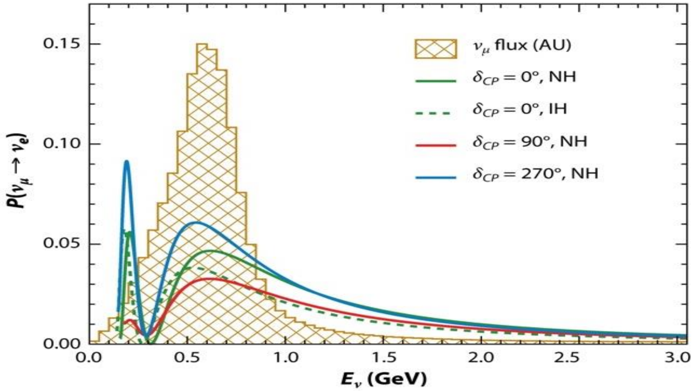
Large oscillations length (~1000 km) = significant matter effects
On axis beam gives wide range of neutrino energy – differentiate CPV effects from matter effects through energy dependence

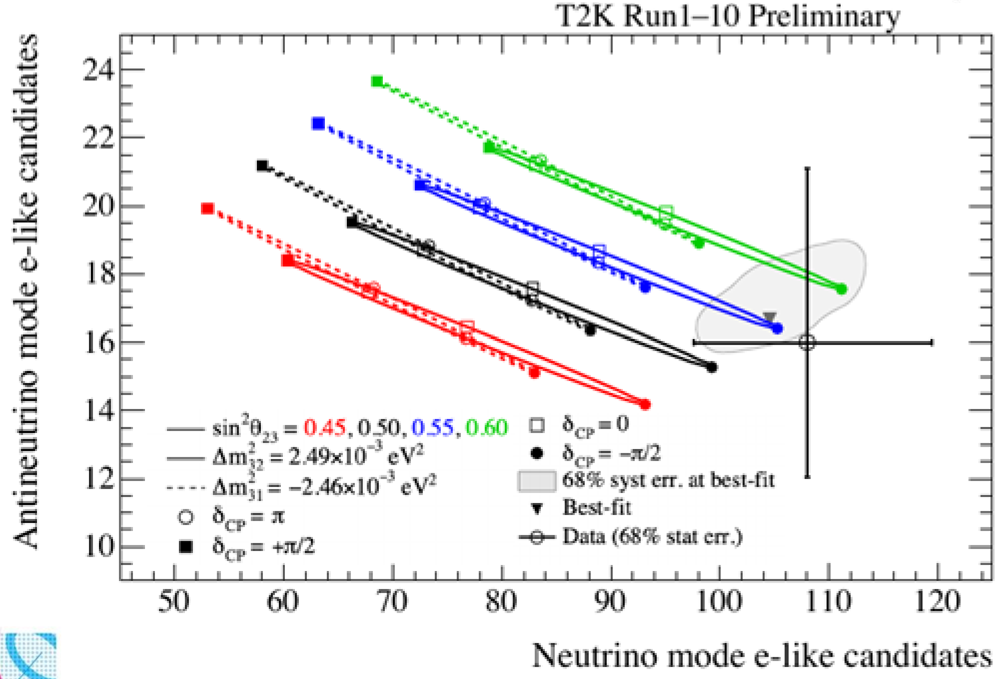
DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT

Why both DUNE & Hyper-K?

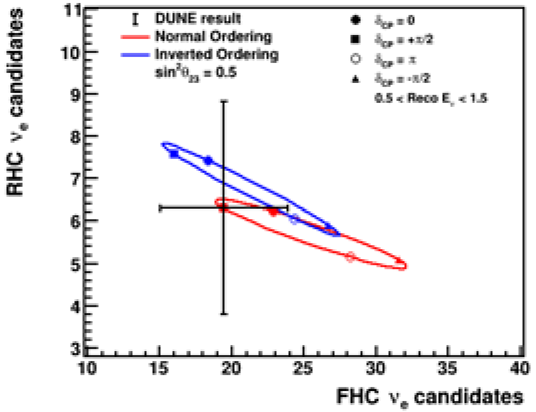
- Count ν_e events in neutrino mode (x axis), and count ν_e in antineutrino mode (y axis)
- Ellipses represent effect of $\delta_{CP,}$ Matter effect splits the NH and IH ellipses about y=x, $\sin^2\theta_{23}$ moves ellipses along y=x

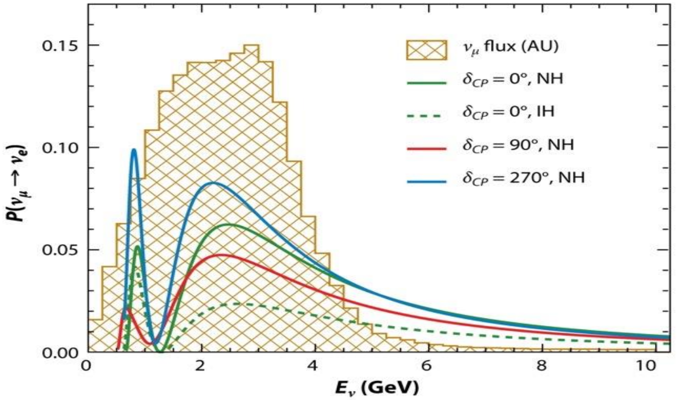
Getting as many neutrinos at one energy at possible to maximize event rate

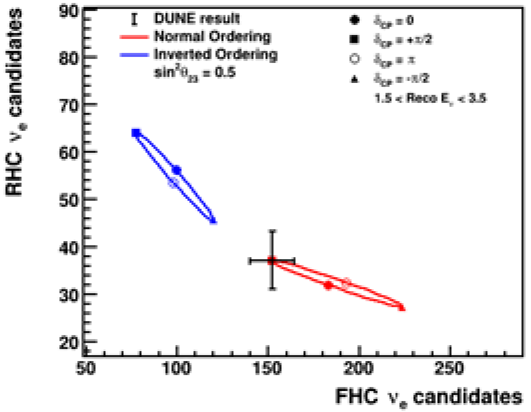


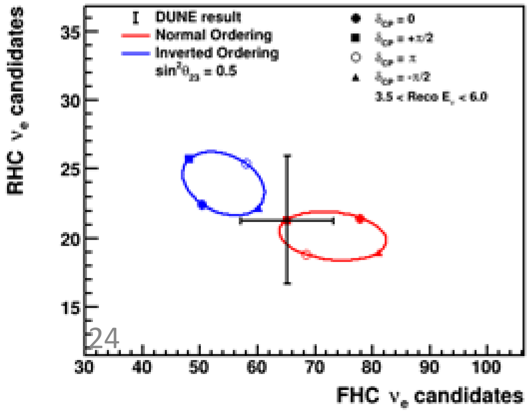


Detector optimized for higher energies









ProtoDUNE

Prototypes of 2 DUNE far detector (FD) modules, located at CERN

Two LArTPC designs:

- Horizontal drift (HD) technology
- Vertical drift (VD) technology

- ProtoDUNE Horizontal drift is an 800t active mass TPC, making it the largest LArTPC constructed.
- ProtoDUNE successfully operated in 2018 and is preparing for its second run now

Figure: CERN Neutrino Platform.

Figure: CERN.

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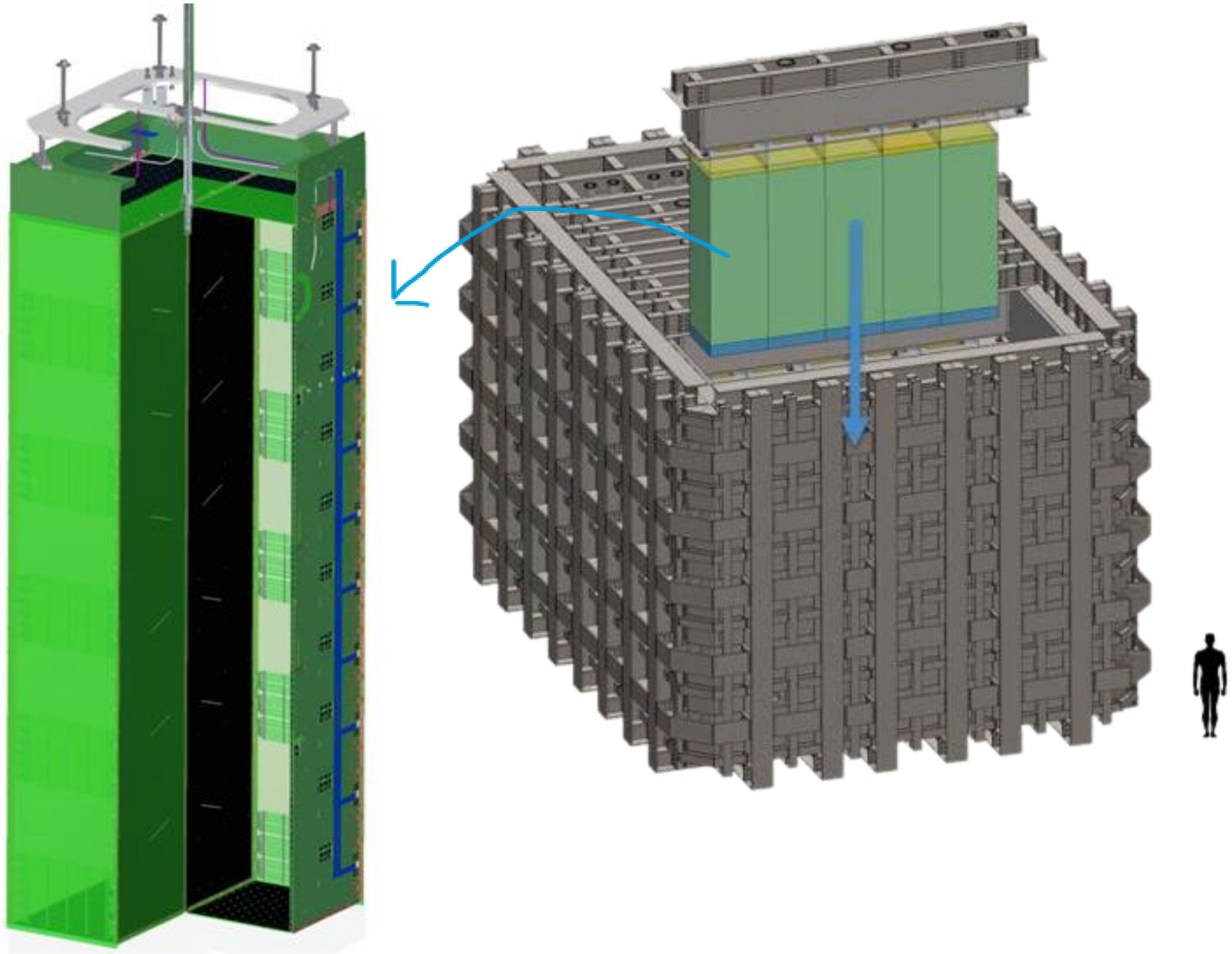
Segmented Pixelated ND LArTPC

- 130t of active Argon
- ~20 **ν** events (energy from ~50 events)/ **10 μs spill (**with a 1.2 MW beam)
- (FD sees 3.4 **ν** events/**hr**)

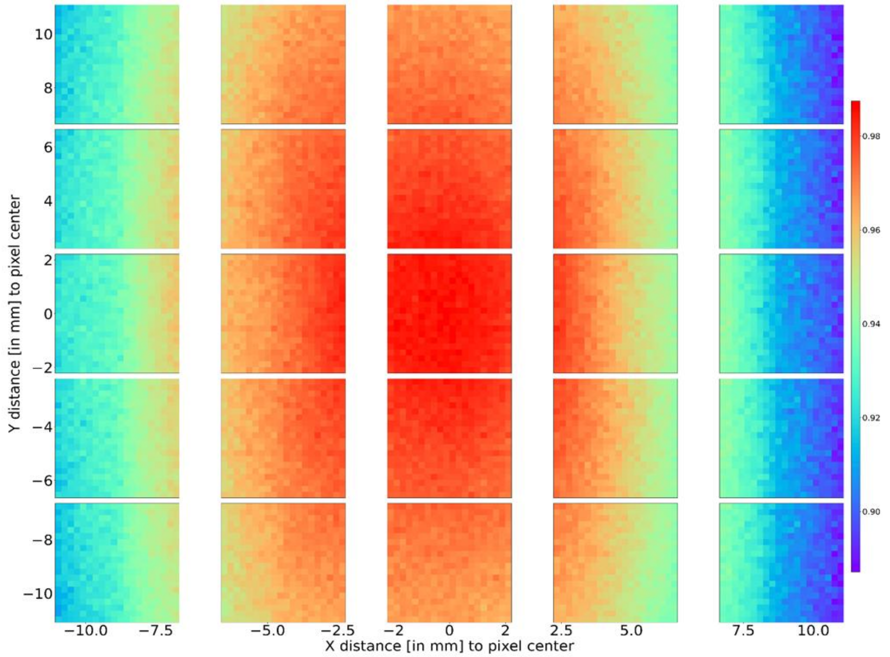


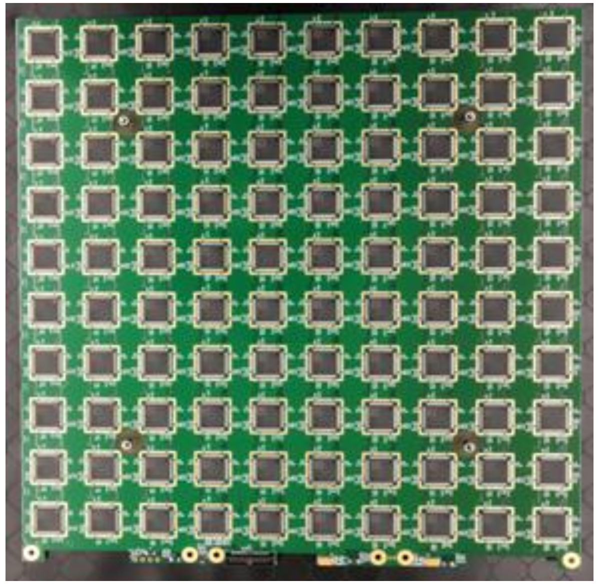
Necessary to reduce pileup

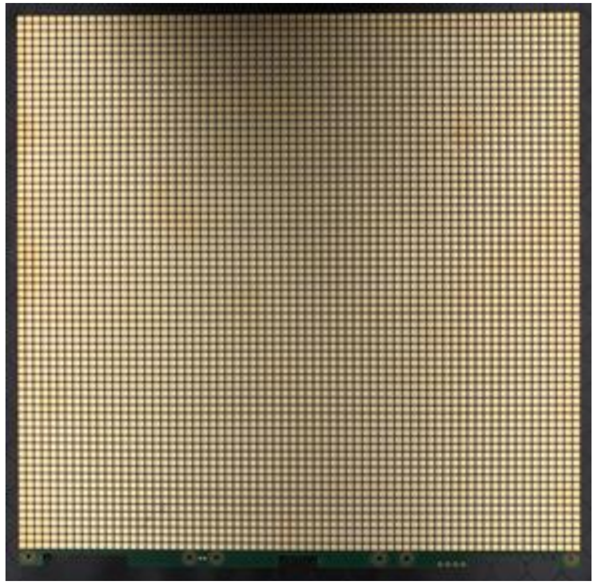
- Optical: the detector is sliced up int 7x5 modules to contain prompt scintillation light
- Charge: pixelated charge readout

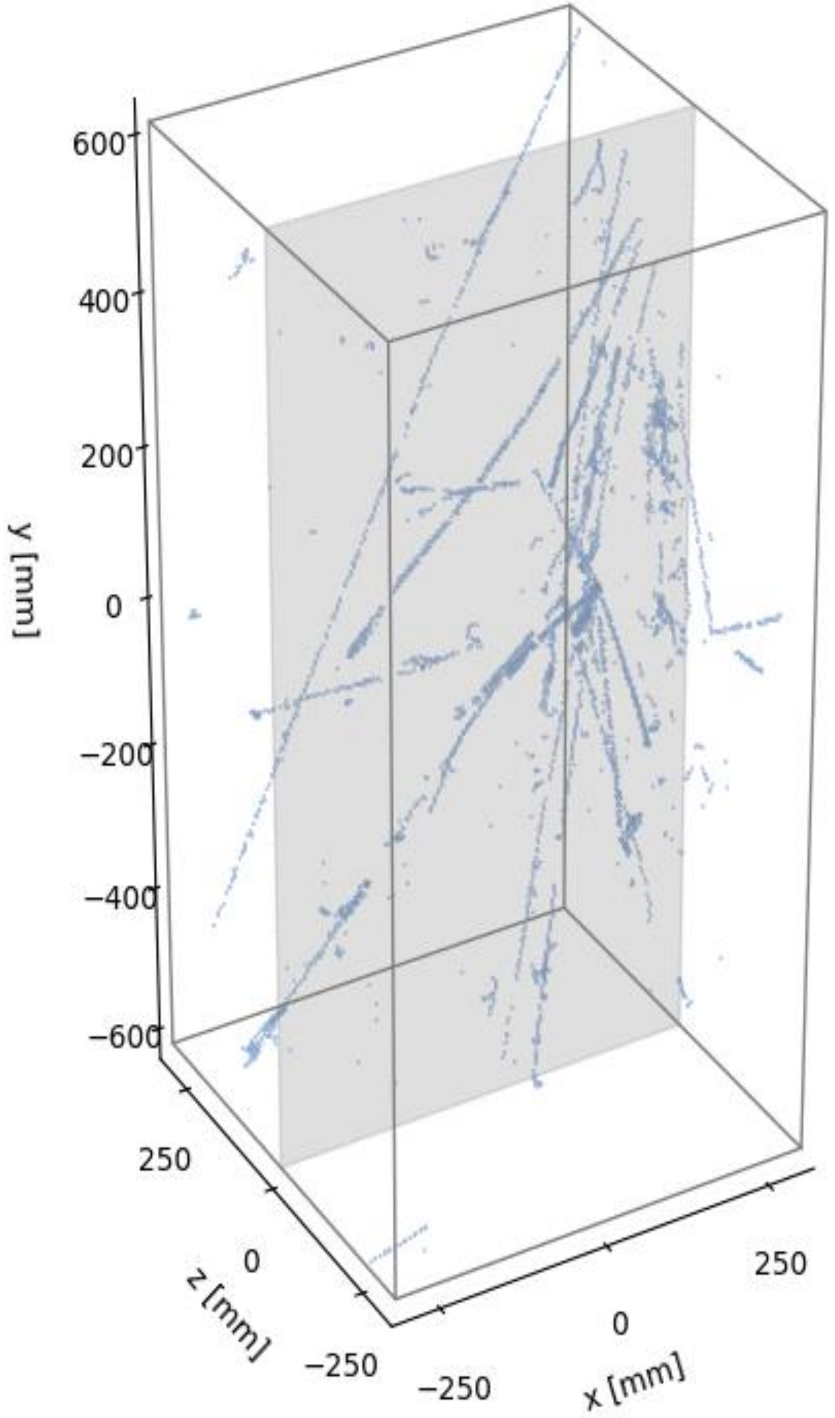
Beyond the Engineering Drawings

- Have built four 14% scale modules for Near Detector, tested their performance with cosmic rays @ Bern
- Mapping out pixel response: 4mmx4mm pixels, checking our ability to simulate this new detection technique



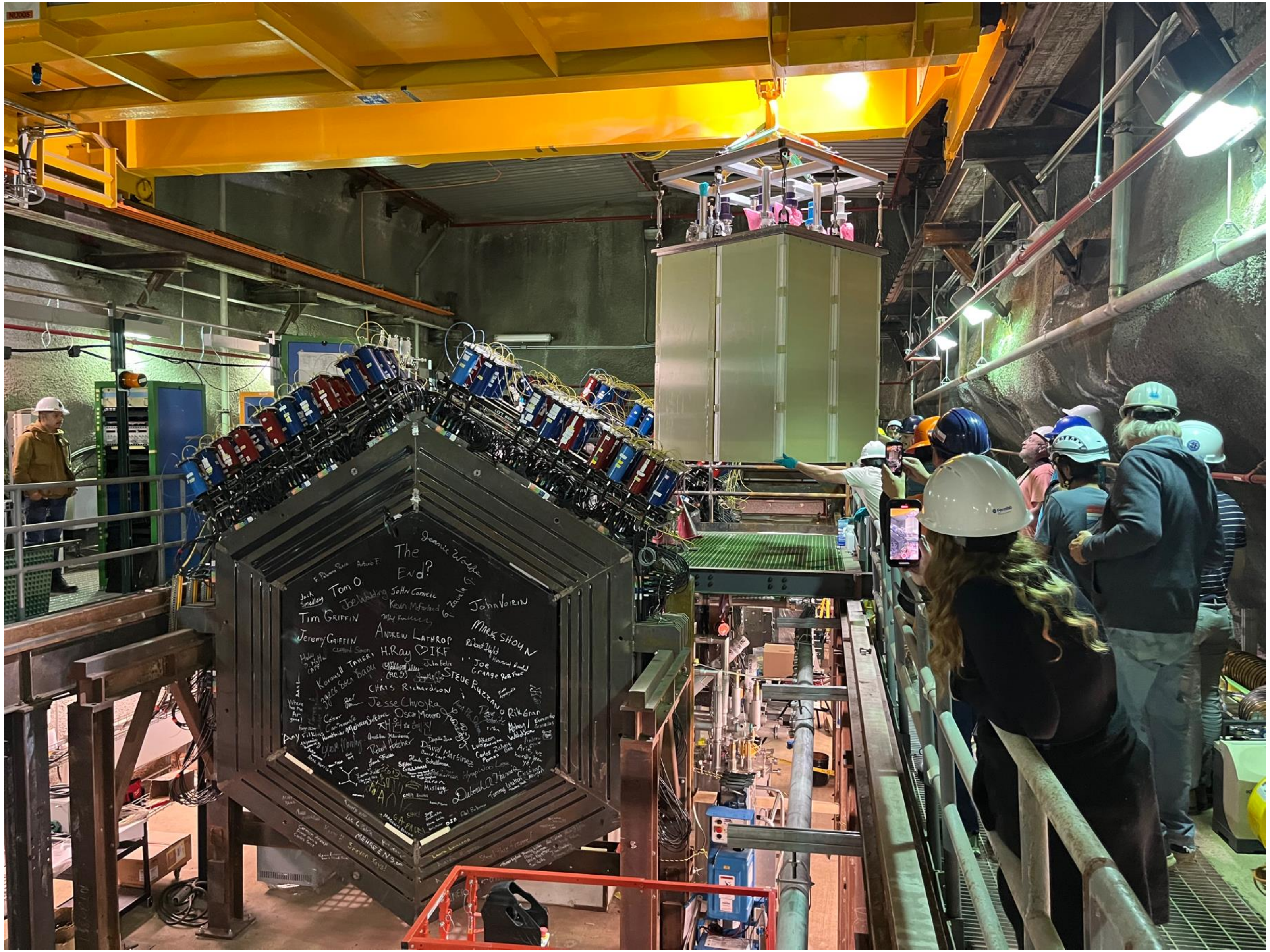




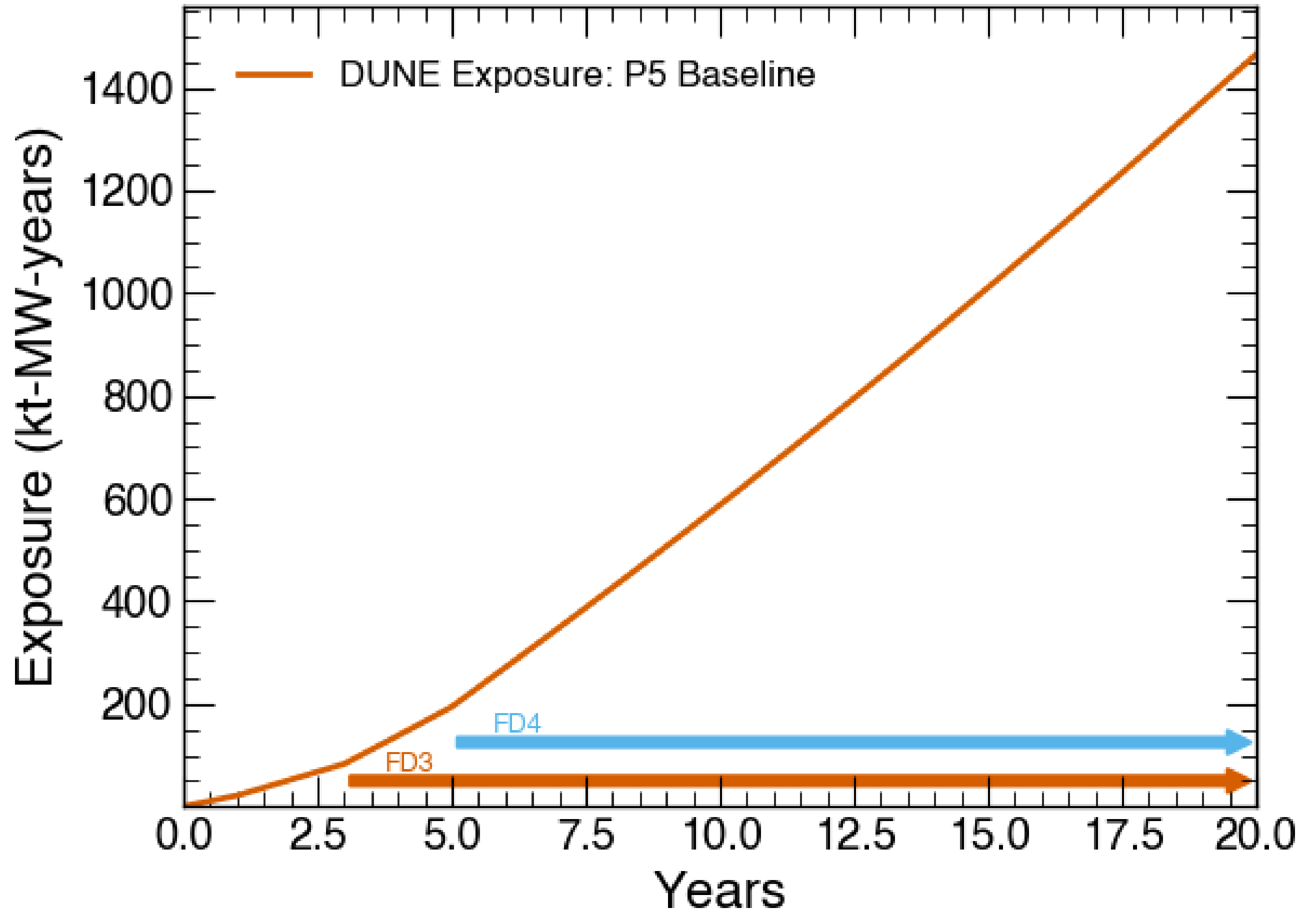


Neutrino Test of Near Detector Strategy

- Moving beyond tests of cosmic rays
- Want to test strategy in operating neutrino beam
- Fermilab is already home to most intense neutrino beam in the world
- Also reusing MINERvA | detector planes for “fast tracker”
- ~4 days of NuMI antineutrino data was taken in July 2024
- Plan to take data in Spring 2024!
- 4 modules
- 2.4 instrumented tons of Aron



Exposure

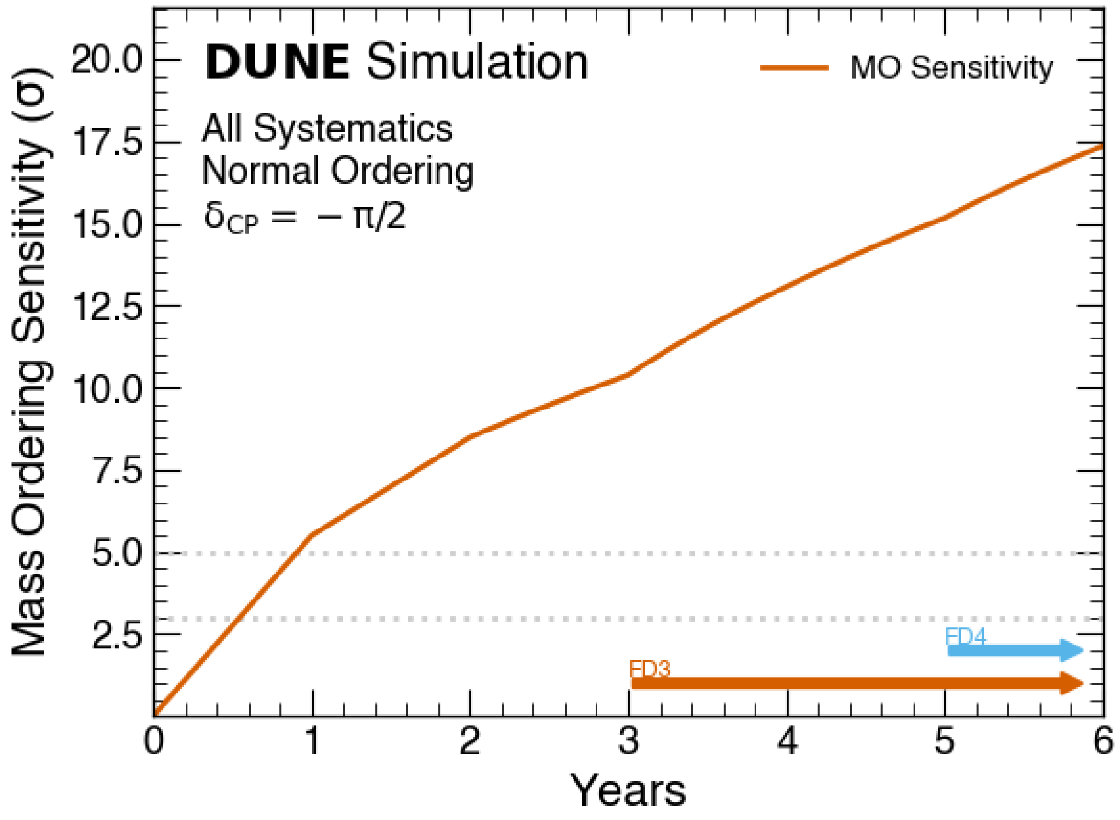


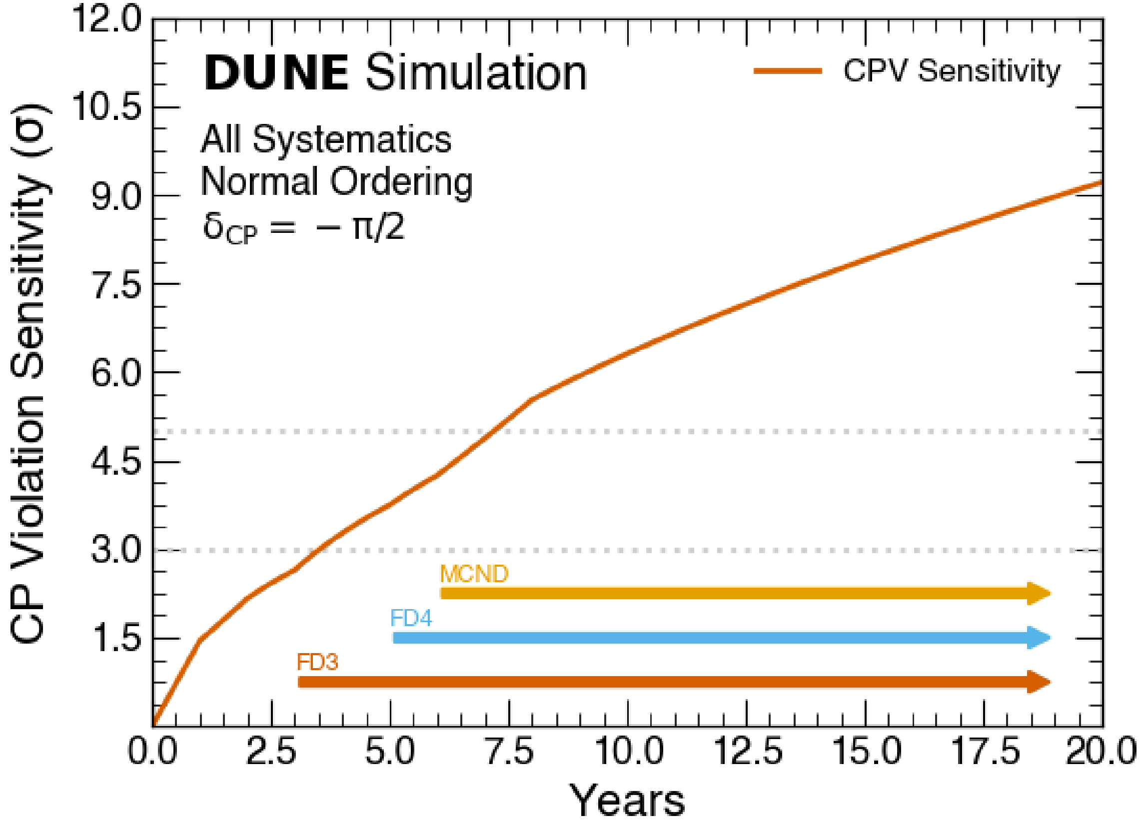
Staging scenario is FD3 after 3 years, FD4 after 5 years

Mass ordering and CP sensitivity – best case

For best-case oscillation scenarios, DUNE has

- >5σ mass ordering sensitivity in 1 year
- >3σ CPV sensitivity in 3.5 years





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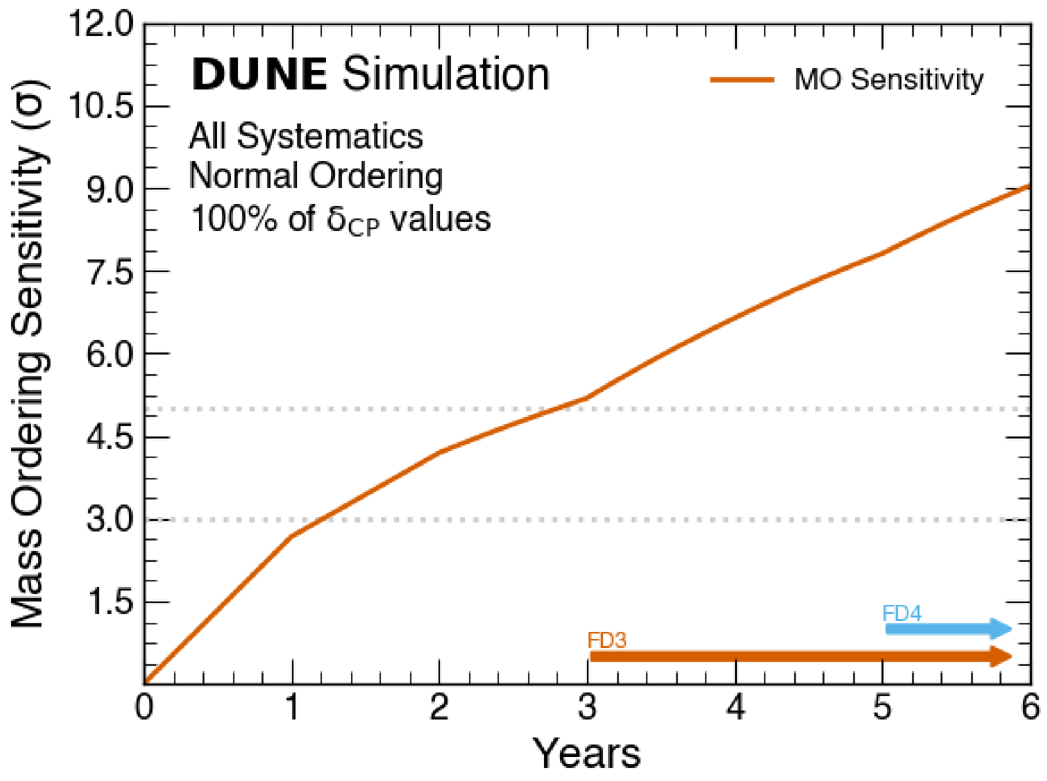
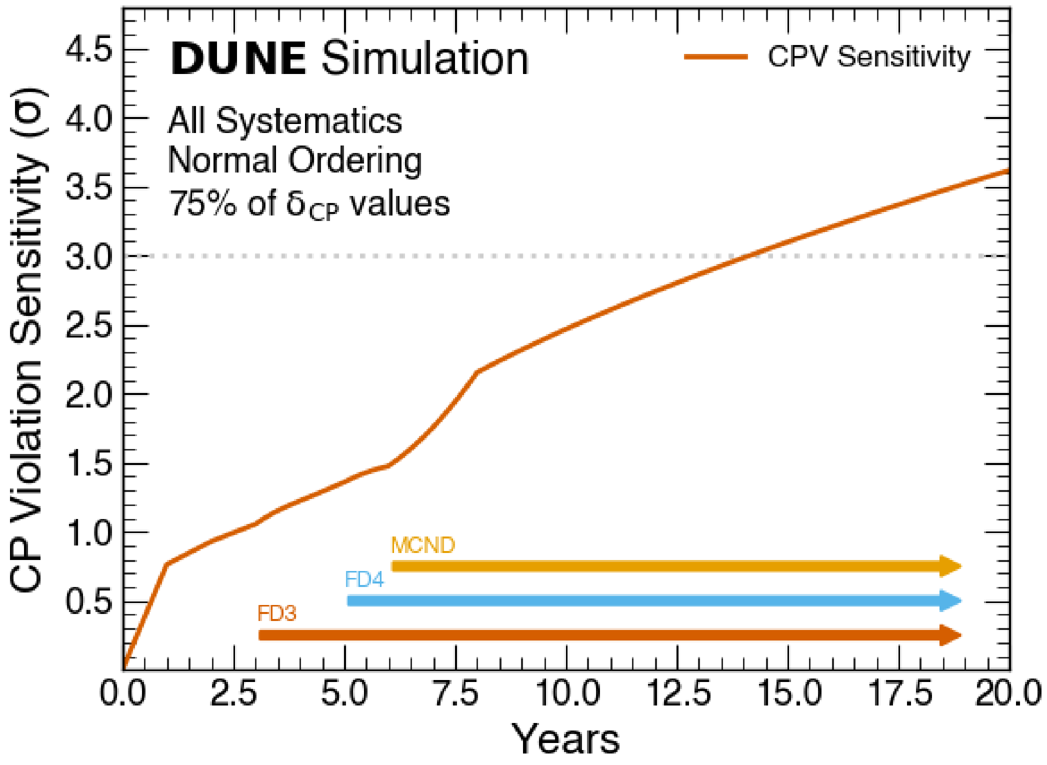
Mass ordering and CP sensitivity – otherwise

For worst-case oscillation scenarios, DUNE has >5σ mass ordering sensitivity in 3 years

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





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