Neutrino Detectors for the DUNE Experiment

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On behalf of the DUNE Collaboration

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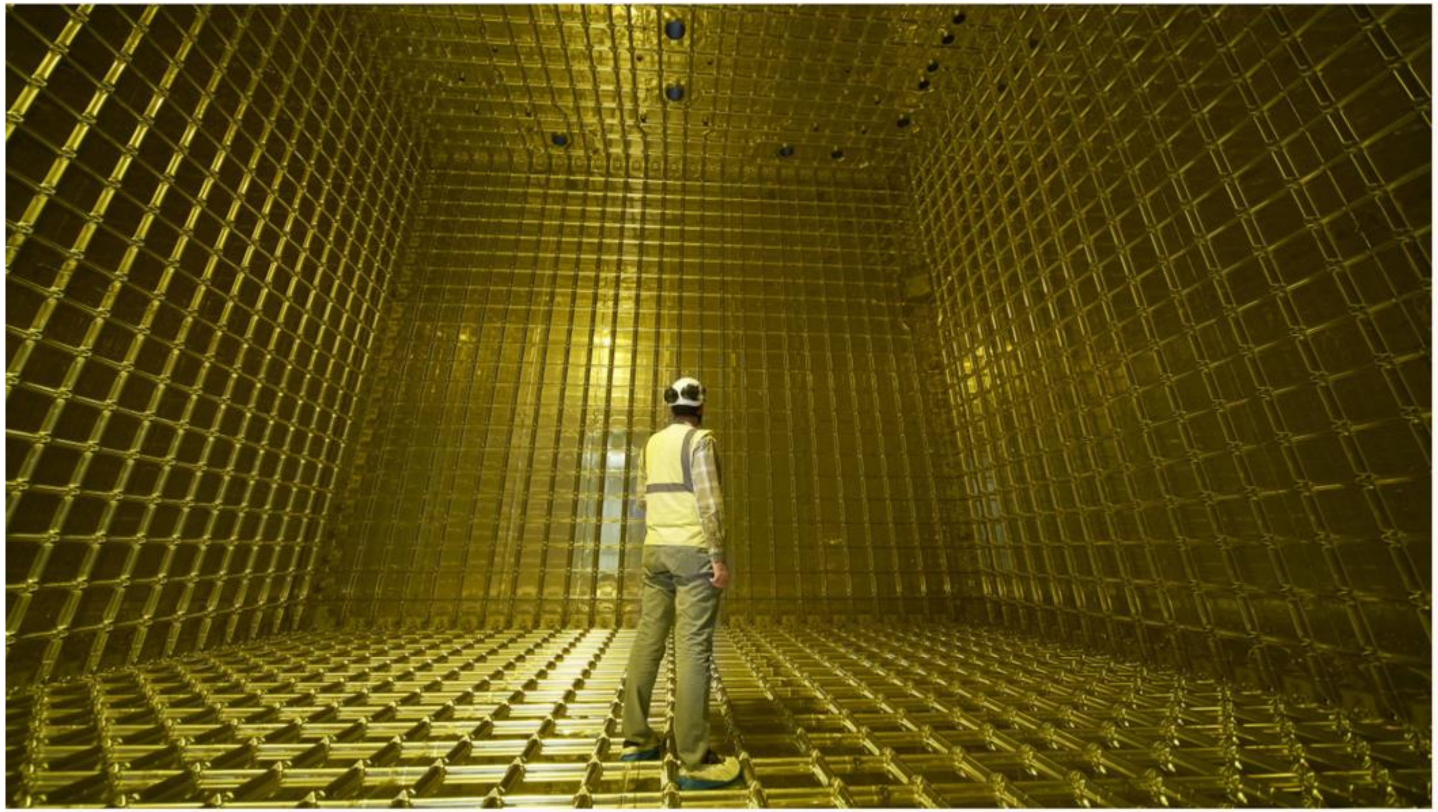


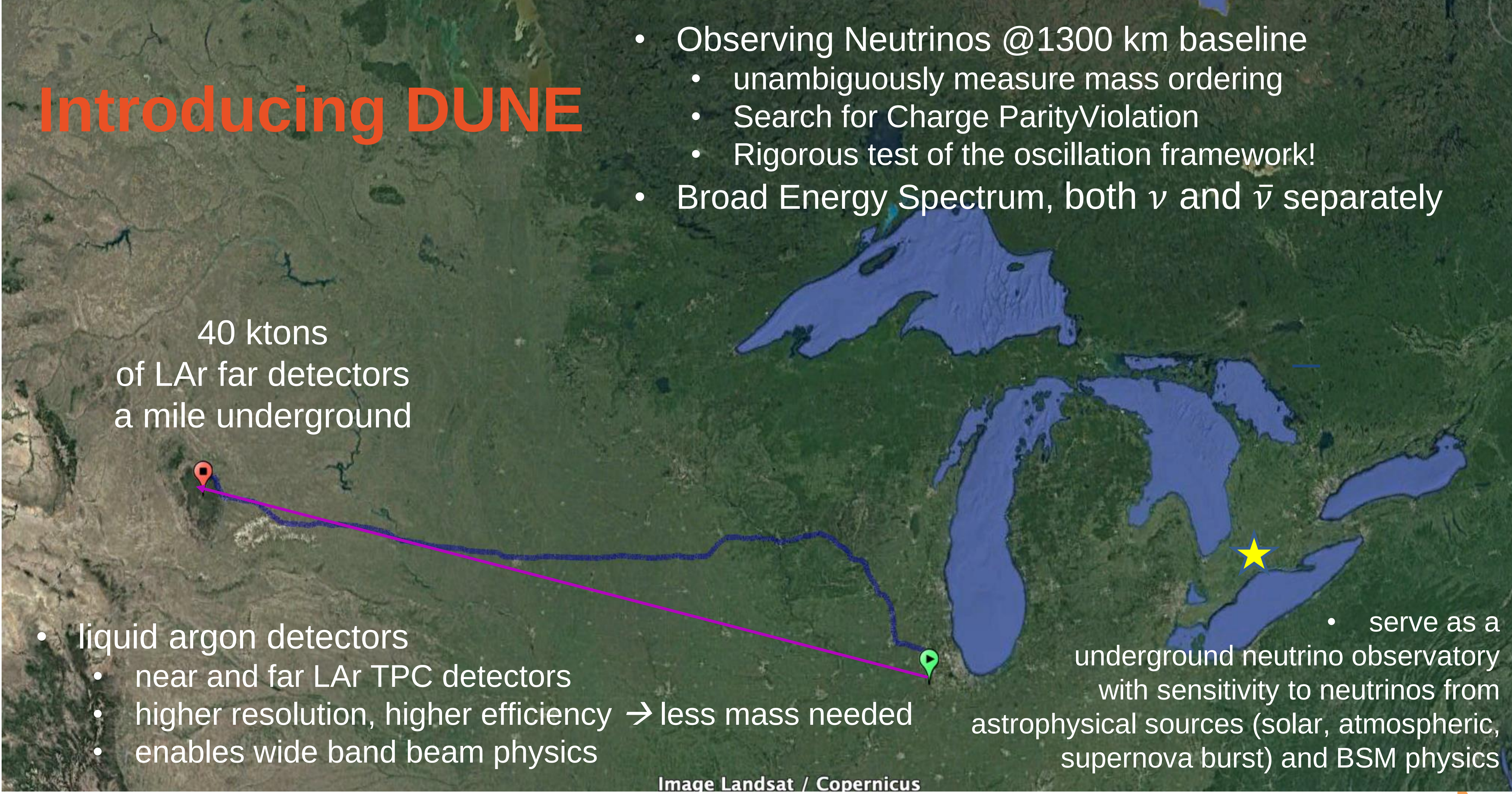
Photo by CERN

CAP Congress 2024, London, Ontario

Introducing DUNE

- Observing Neutrinos @1300 km baseline
  - unambiguously measure mass ordering
  - Search for Charge ParityViolation
  - Rigorous test of the oscillation framework!
- Broad Energy Spectrum, both ν and $\bar{\nu}$ separately

40 ktons
of LAr far detectors
a mile underground



- liquid argon detectors
  - near and far LAr TPC detectors
  - higher resolution, higher efficiency → less mass needed
  - enables wide band beam physics

- serve as a underground neutrino observatory with sensitivity to neutrinos from astrophysical sources (solar, atmospheric, supernova burst) and BSM physics

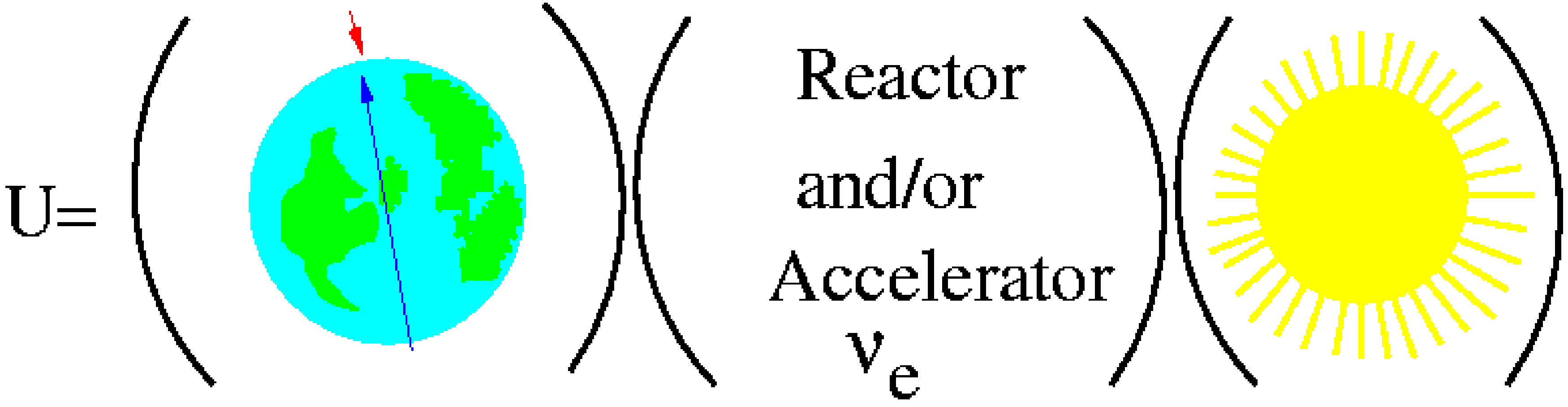
Why study neutrinos over 1300km?
To study three Generation Mixing w/leptons

- Matrix described by 3 mixing angles
- Featuring a CP-violating phase δ!
- This phase would imply neutrinos and antineutrinos oscillate differently
- Similar to quarks but WAY LESS diagonal, CP-violating effects may be large

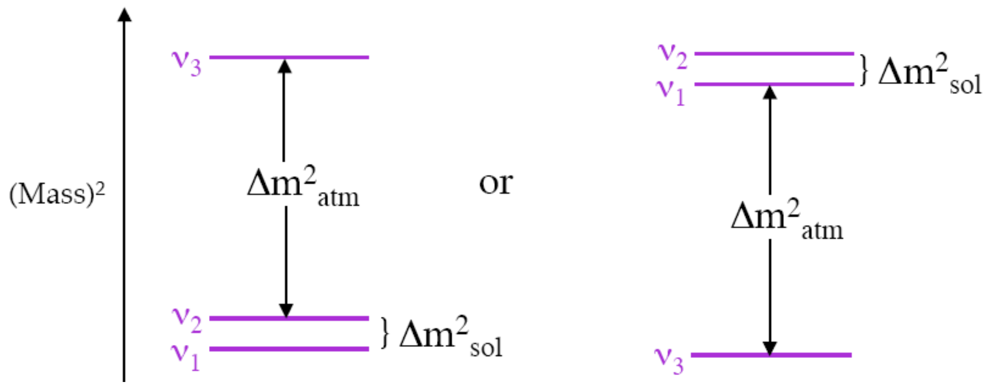
Weak Eigenstates are NOT the same as Mass Eigenstates!

$$s_{ij} = \sin\theta_{ij}, \text{ and } c_{ij} = \cos\theta_{ij}$$

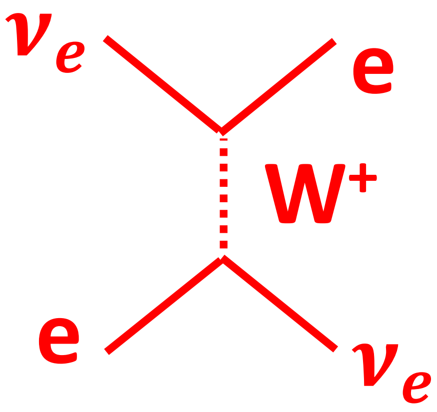
$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

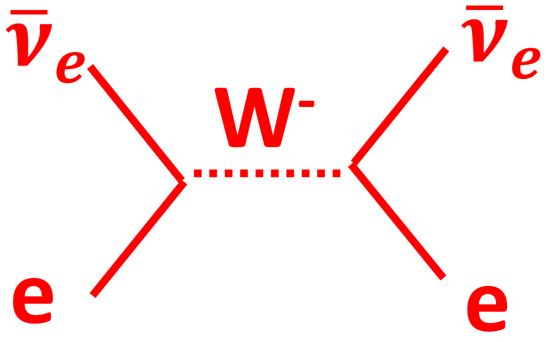


What is in 1300km of Earth?



- Electrons in the earth act on ν_e and $\bar{\nu}_e$'s differently from each other, and from ν_μ or ν_τ





Wolfenstein, PRD (1978)

$$x = \frac{2\sqrt{2} G_F n_e E_\upsilon}{\Delta m^2}$$

$n =$ e$^-$ density

- For 2 generations…
  - Oscillations in vacuum: $$P(\nu_\mu \rightarrow \nu_\tau) = \sin^2 2\theta \sin^2\left(\frac{(m_2^2 - m_1^2)L}{4E}\right)$$
  - Oscillations in Matter: $$\sin^2 2\Theta_M = \frac{\sin^2 2\Theta}{\sin^2 2\Theta + (\pm x - \cos 2\Theta)^2} \qquad L_M = L \times \sqrt{\sin^2 2\Theta + (\pm x - \cos 2\Theta)^2}$$

Bad news: this complicates search for CP violation,
Good news: it means you can measure the mass ordering

Fermilab YORK UNIVERSITÉ UNIVERSITY DUNE

3-generation $\nu_\mu \rightarrow \nu_e$ Probabilities

- $P(\nu_\mu \rightarrow \nu_e) = P_1 + P_2 + P_3 + P_4$

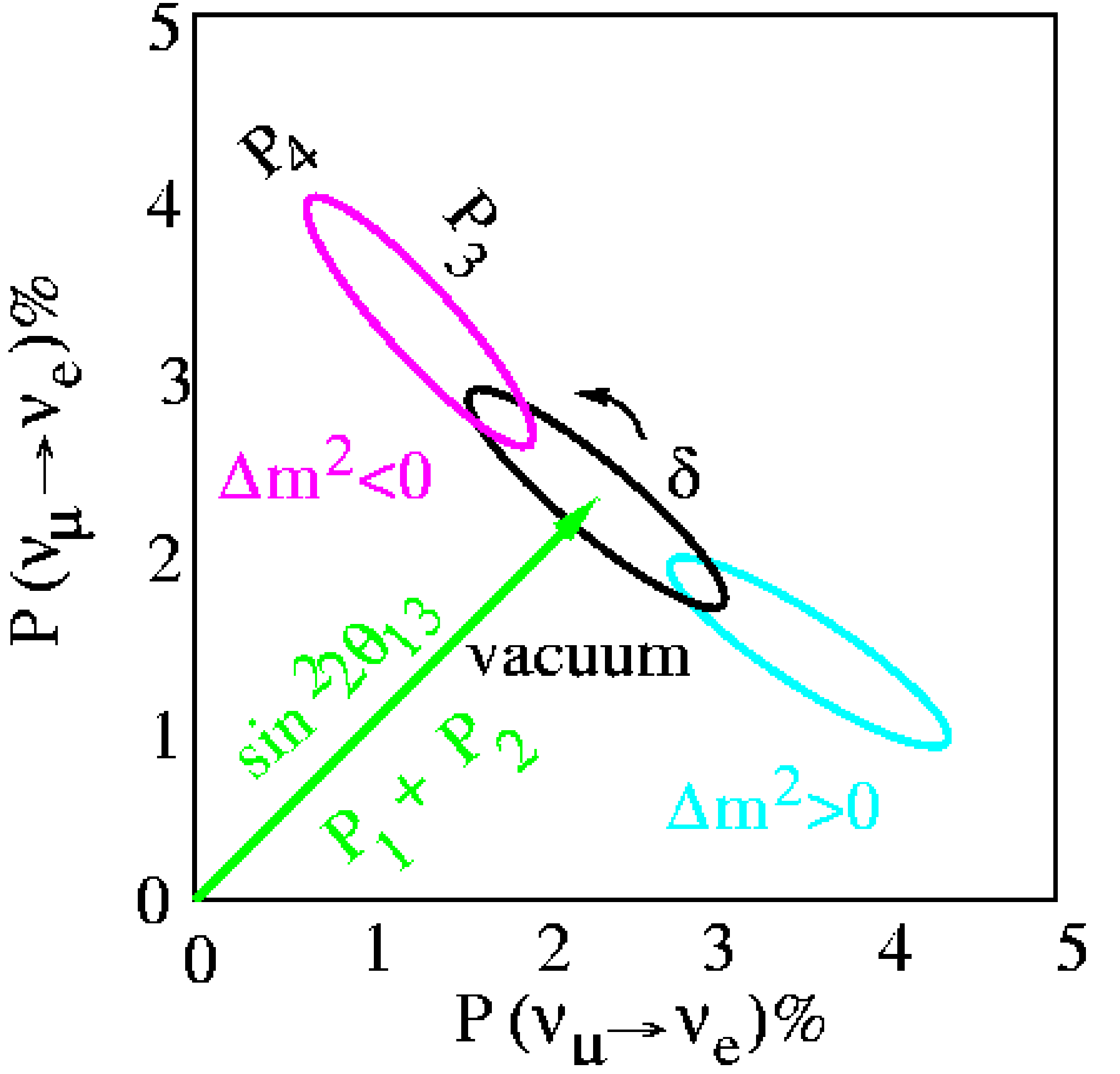
$$P_1 = \sin^2\theta_{23} \sin^2 2\theta_{13} \left(\frac{\Delta_{13}}{B_\pm}\right)^2 \sin^2 \frac{B_\pm L}{2}$$

$$P_2 = \cos^2\theta_{23} \sin^2 2\theta_{12} \left(\frac{\Delta_{12}}{A}\right)^2 \sin^2 \frac{AL}{2}$$

$$P_3 = J \cos\delta \left(\frac{\Delta_{12}}{A}\right) \left(\frac{\Delta_{13}}{B_\pm}\right) \cos\frac{\Delta_{13} L}{2} \sin\frac{AL}{2} \sin\frac{B_\pm L}{2}$$

$$P_4 = \mp J \sin\delta \left(\frac{\Delta_{12}}{A}\right) \left(\frac{\Delta_{13}}{B_\pm}\right) \sin\frac{\Delta_{13} L}{2} \sin\frac{AL}{2} \sin\frac{B_\pm L}{2}$$

- Much more complicated than 2-generation mixing
- Interference between atmospheric and solar terms is where CP violation arises
- Size of that interference is function of all angles
- Measurement at one L and E is not enough!

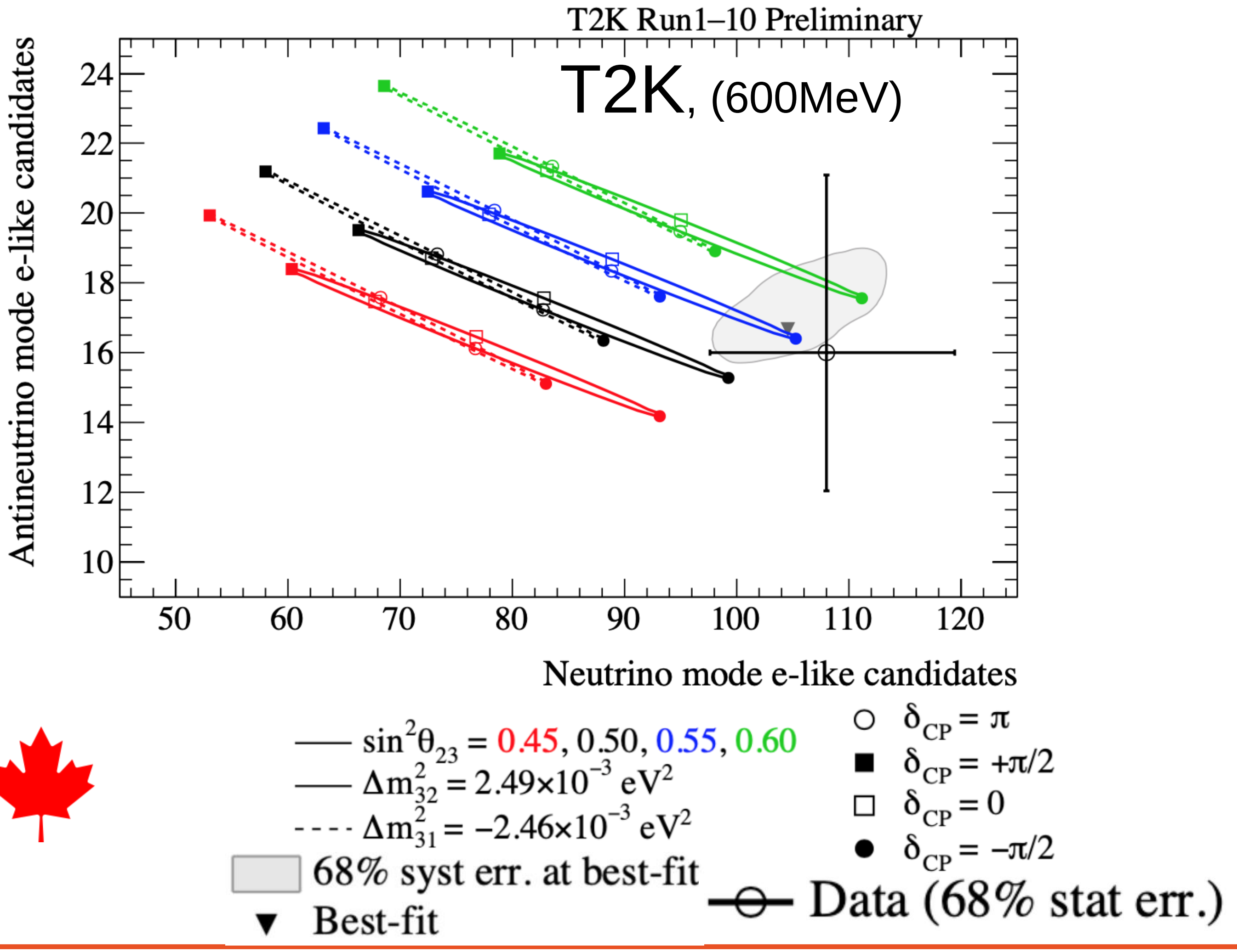


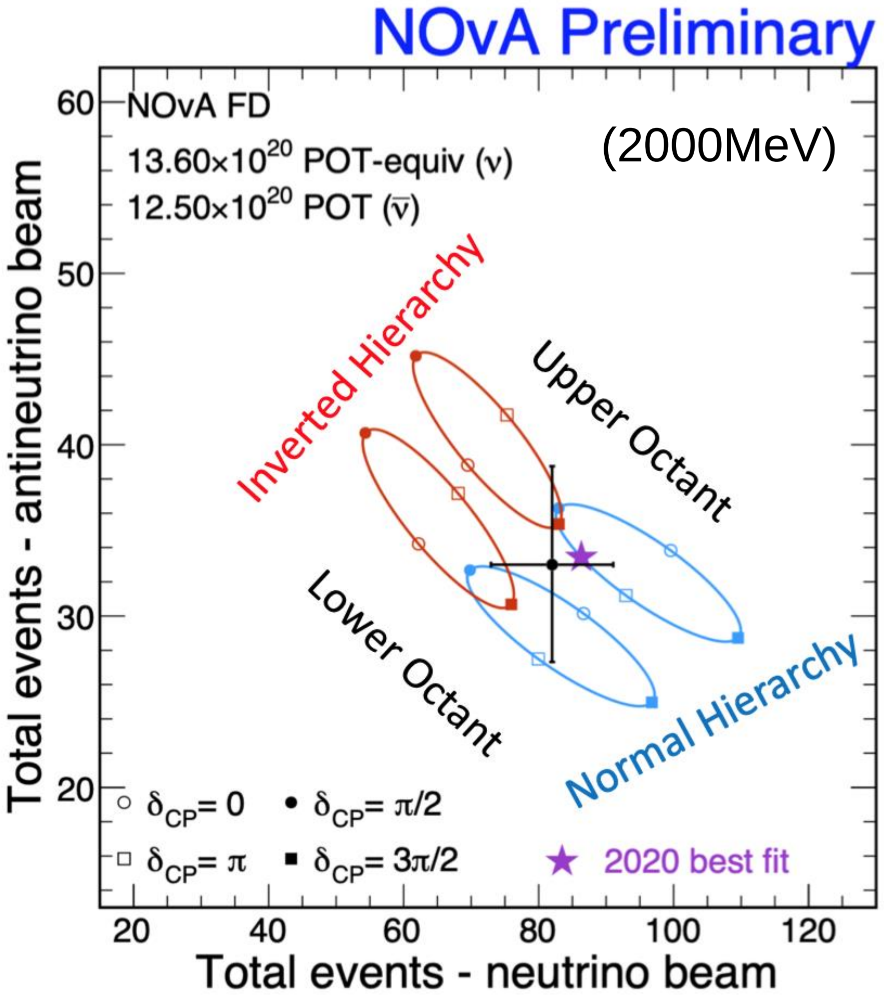
Minakata & Nunokawa JHEP 2001

Appearance of ν_e in a ν_μ beam: circa 2020

Two currently-running experiments have most of their ν_e and $\bar{\nu}_e$ statistics in narrow range of energy

P. Dunne, Neutrino 2020

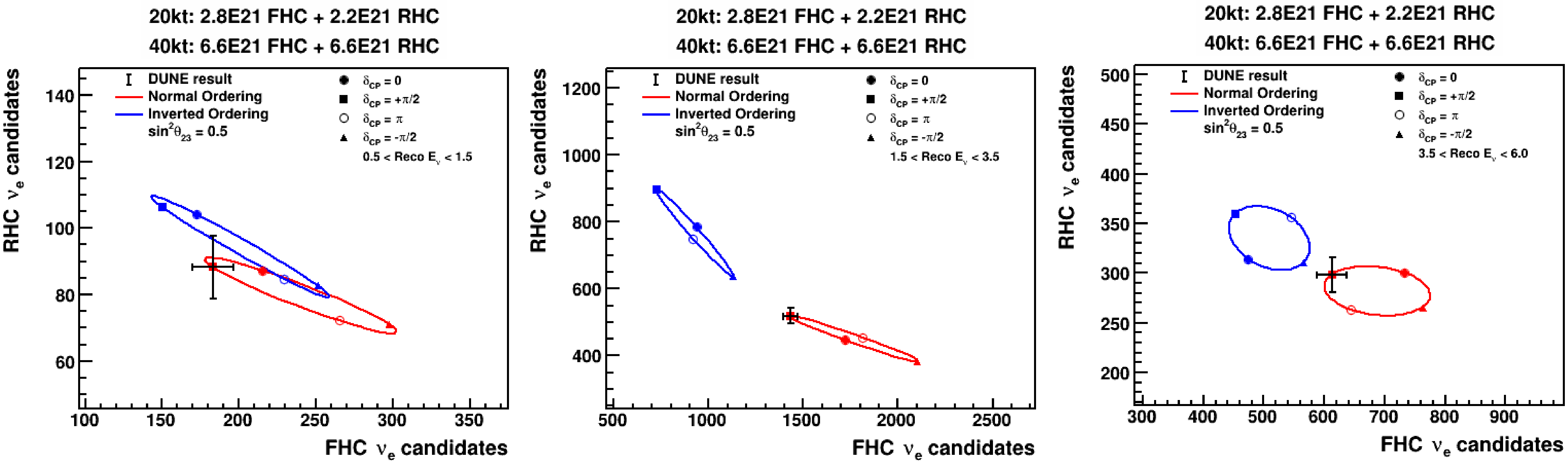




A. Himmel, Neutrino 2020

Neutrino vs Antineutrino Appearance @ DUNE

Statistics after staged running, nearly equal protons on target in both ν and $\bar{\nu}$ mode

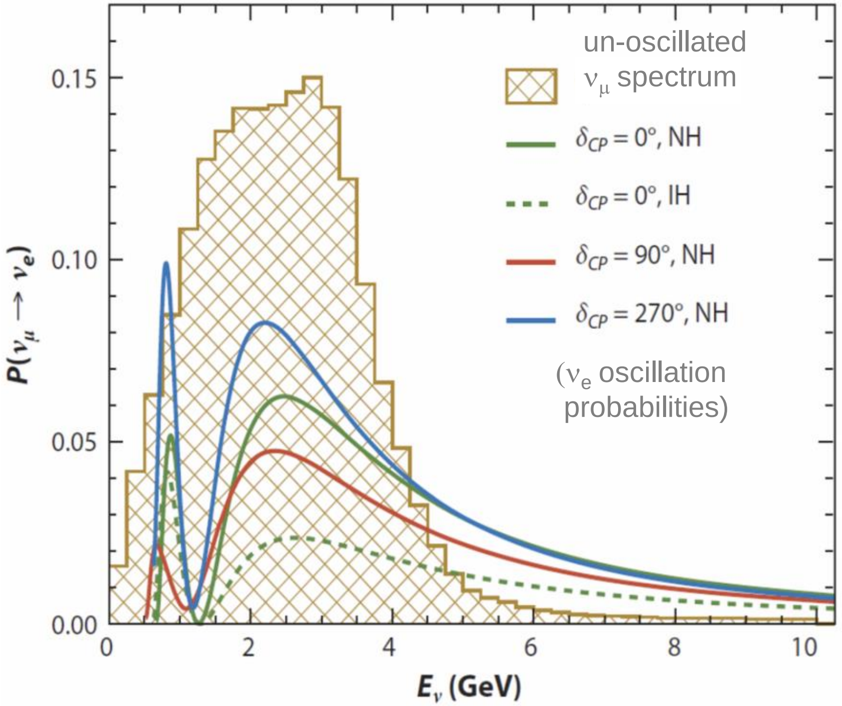


0.5GeV<E_ν<1.5GeV   1.5GeV<E_ν<3.5GeV   3.5GeV<E_ν<6.0GeV

What's the catch? Have to detect neutrinos at several GeV   C. Marshall, NuFact 2023

DUNE Collaboration,
Eur. J. Phys. C80, 978 (2020)

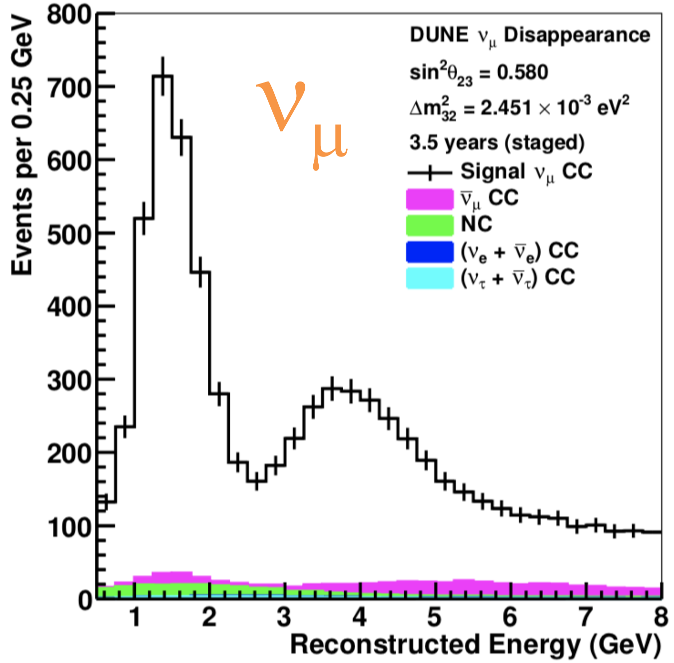
DUNE Neutrino Energy Spectra

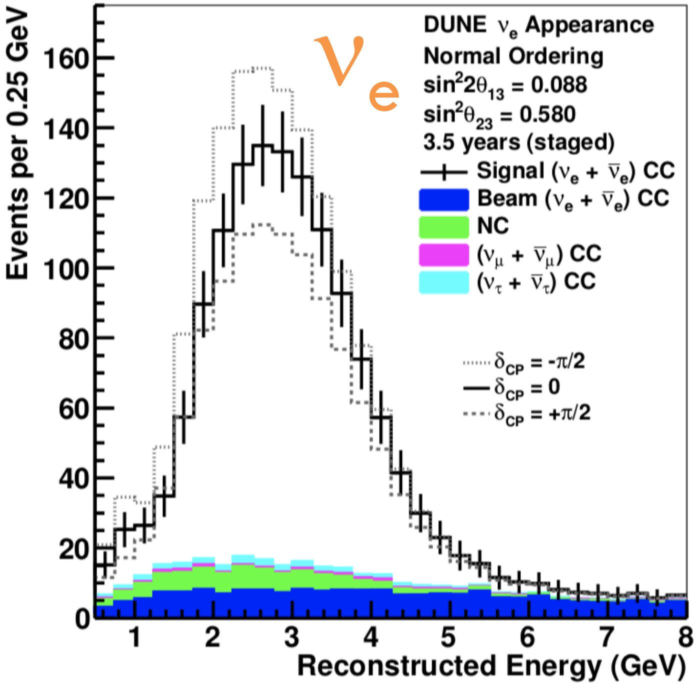


disappearance

$\nu_\mu \rightarrow \nu_e$

appearance



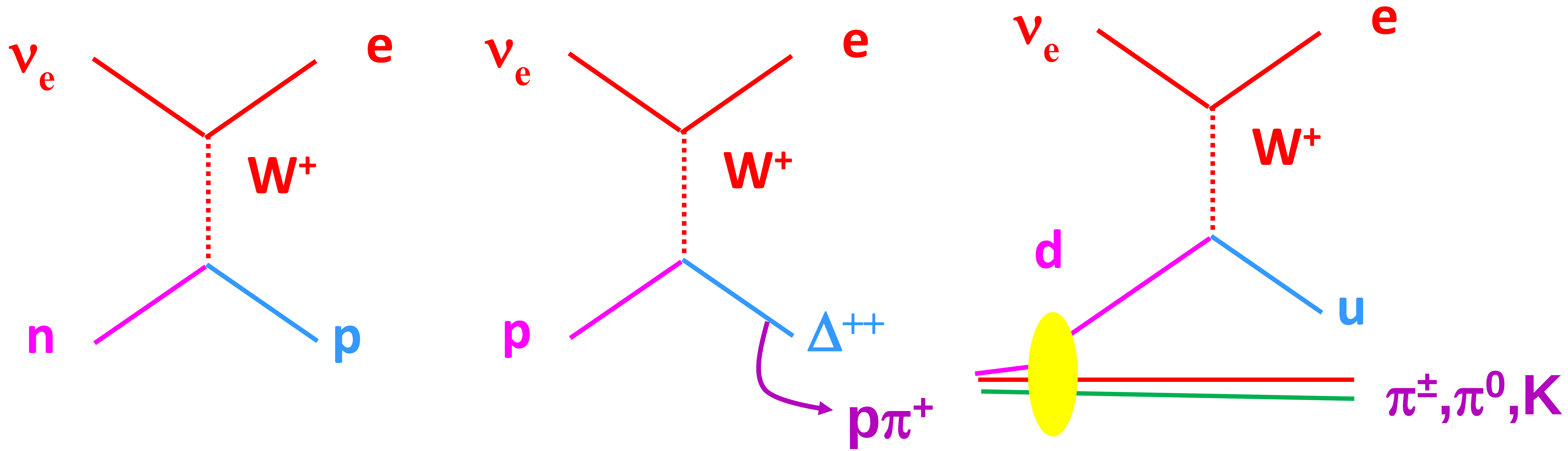


- DUNE will be able to unambiguously and simultaneously measure Mass Ordering, CP given baseline and on-axis beam

- In the 1st year, DUNE will collect ~150 oscillated ν_e events
    - assuming a beam ramp-up to 1.2 MW, 2 FDs, normal ordering, δ_{CP}=0
    - expected range is 70-180 ν_e events in ν mode, depending on true MO, CP

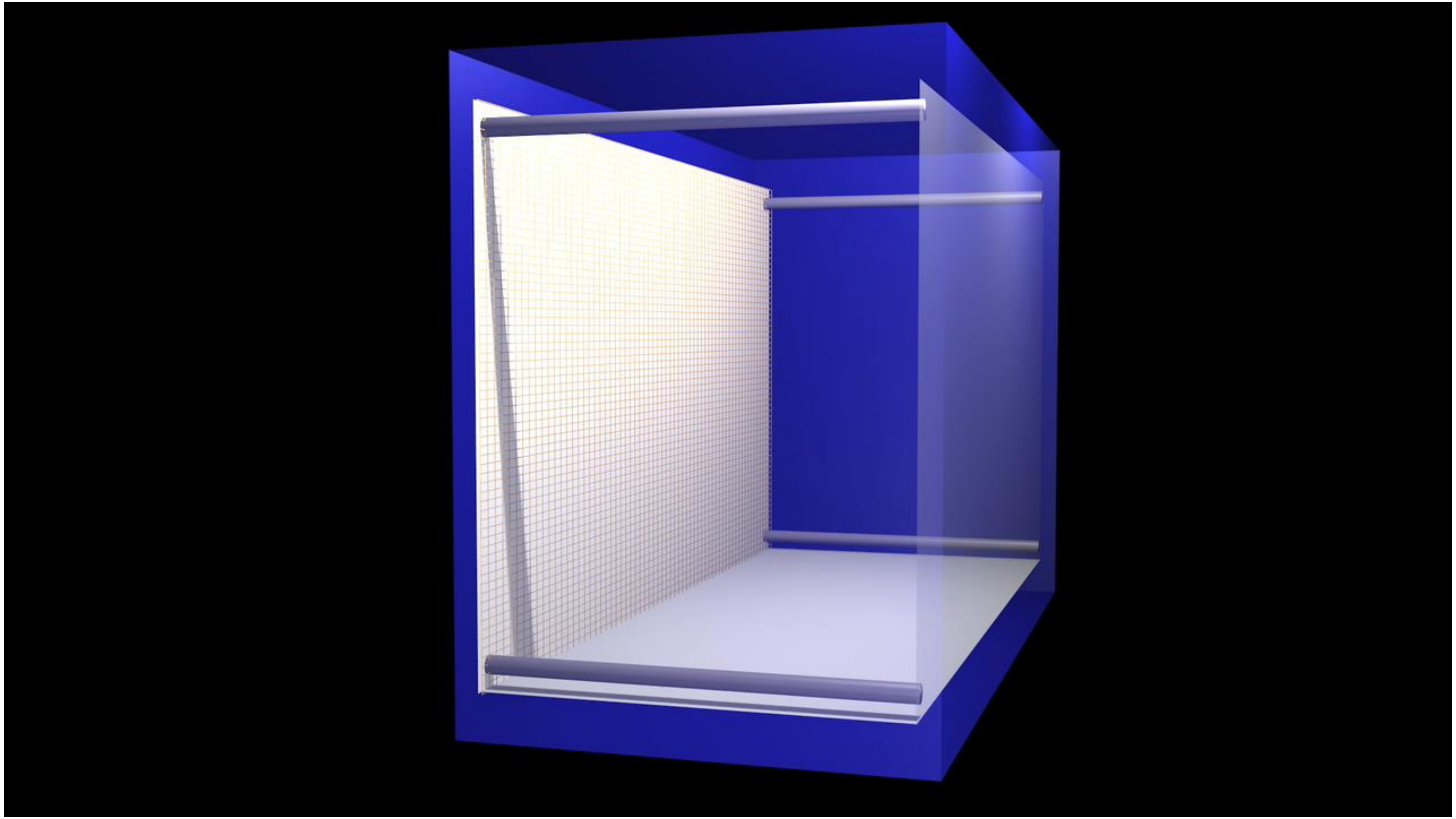
Neutrino Interactions, 20 words or less

- Optics analogy: the wavelength of your probe determines what you can see
- High energy neutrinos can transfer more momentum, which means they can see smaller structure (quarks), and make more particles



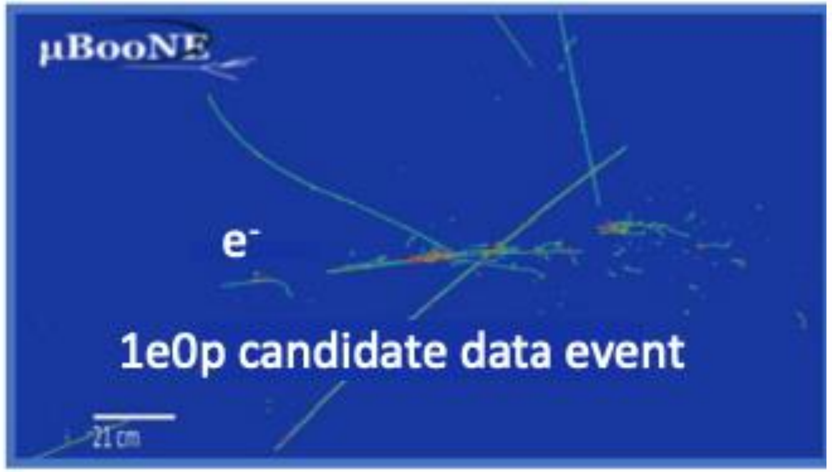
"QuasiElastic" "Pion Production" "Deep Inelastic Scattering"

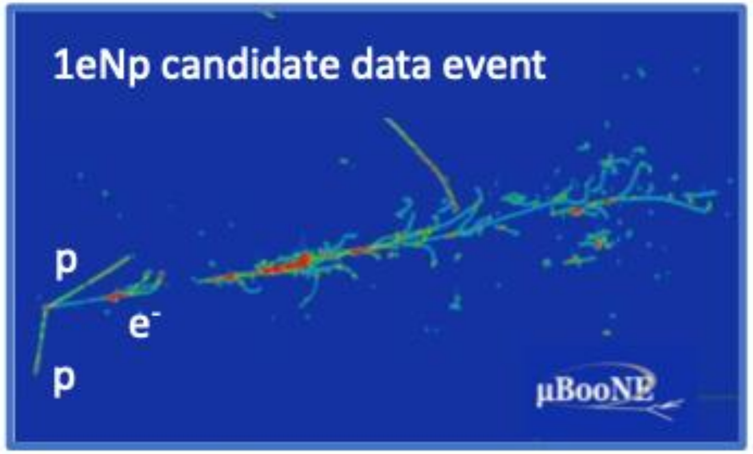
Liquid Argon Time Projection Chamber

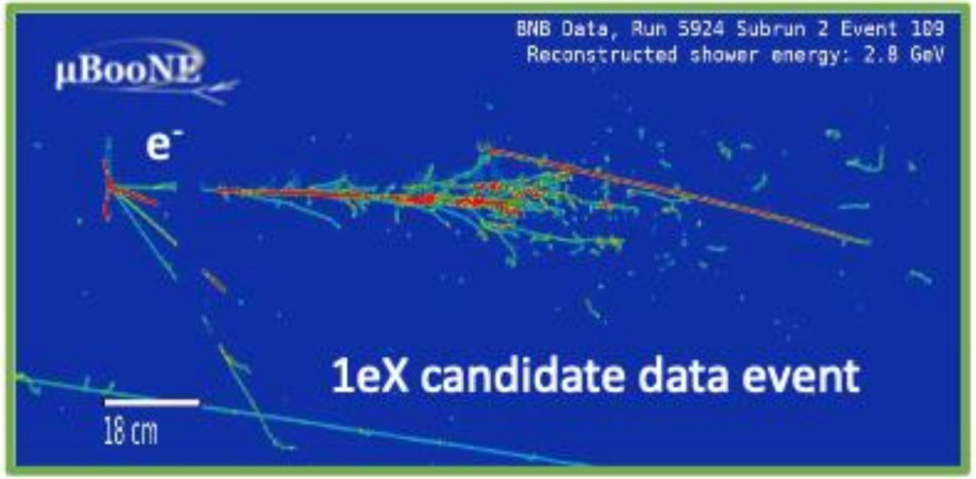


Liquid Argon Time Project Chambers in Practice…

- Proof of principle from MicroBooNE …
  - Sitting in a 1GeV neutrino beam @ Fermilab
  - Several new processes studied on Argon
  - Particle ID available from looking at energy deposits along tracks
  - Fine granularity allows for low tracking thresholds
- More to come!
  - SBND, ICARUS





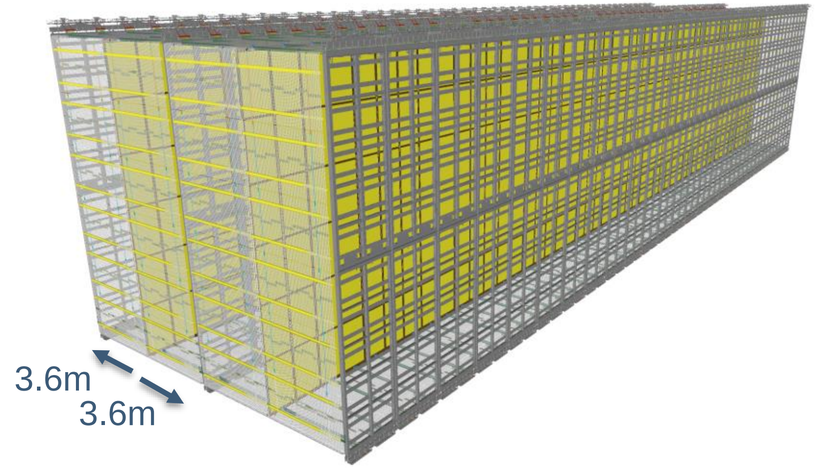


S. Zeller, Fermilab JETP seminar

DUNE Far Detectors (Phase I)

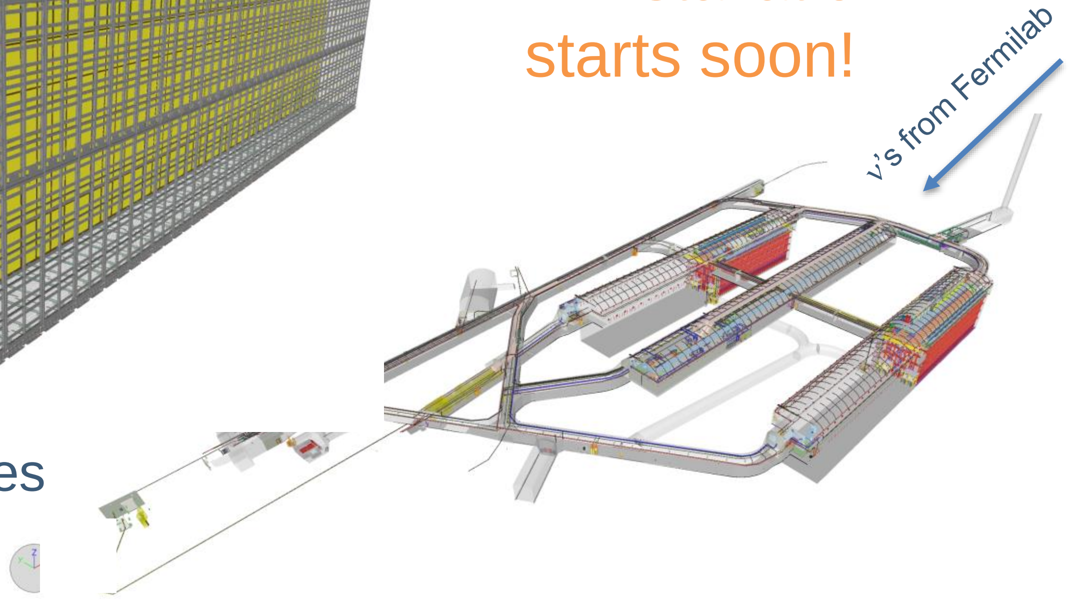
- We have excavated caverns for 4 detector modules in South Dakota and are now building 2 far detector modules, each 17 kton of liquid argon (10 kton fiducial mass)
  - Horizontal Drift (like ICARUS, MicroBooNE)
  - Vertical Drift (capitalizing on dual phase development)

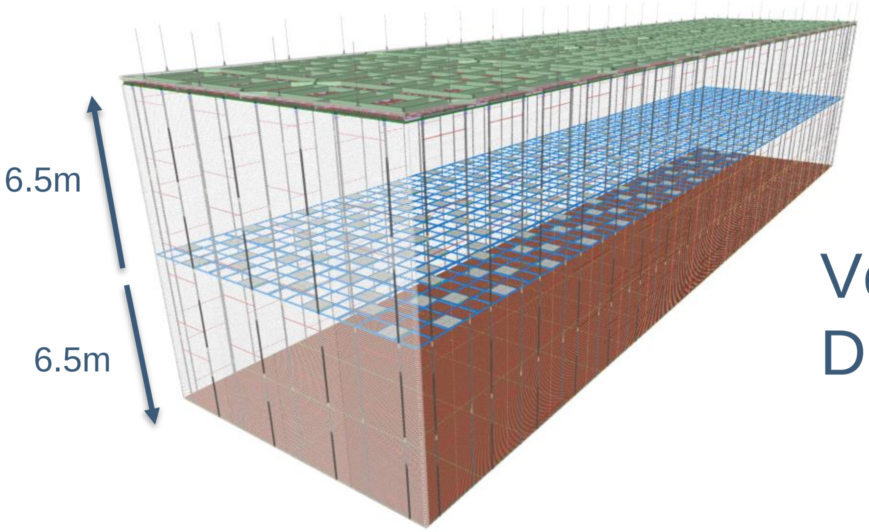
Horizontal Drift



Anode Plane Assemblies

FD installation starts soon!





Vertical Drift

Charge Readout Planes

- Order of magnitude more mass than has been deployed up to now from all LAr detectors

Beam test of Far Detector Technologies: ProtoDUNE

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

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

- ProtoDUNE HD is an 800t active mass TPC
- ProtoDUNE HD successfully operated in 2018 and is preparing for its second run now (ProtoDUNE-II)

Figure: CERN Neutrino Platform.

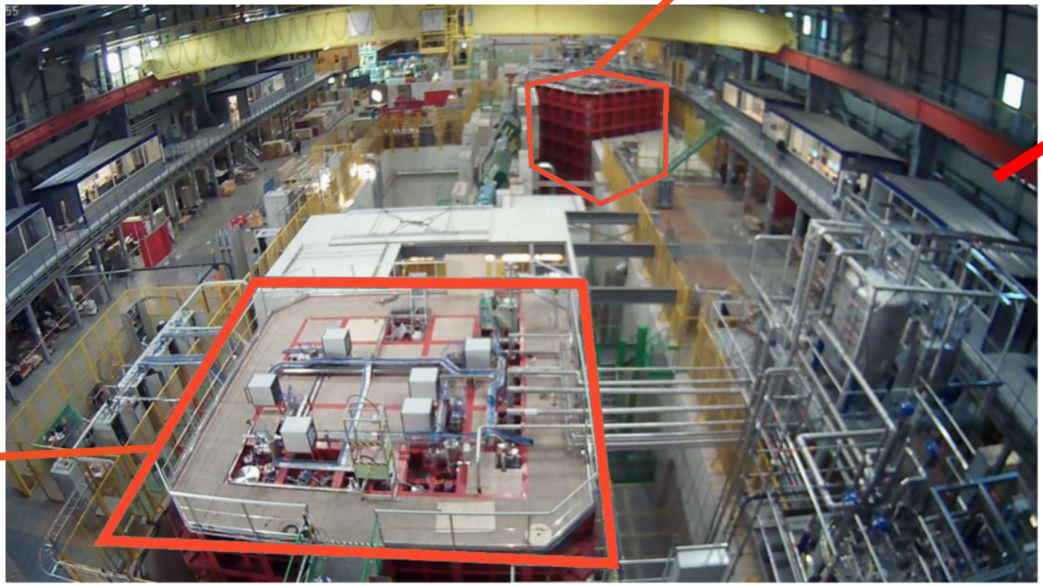
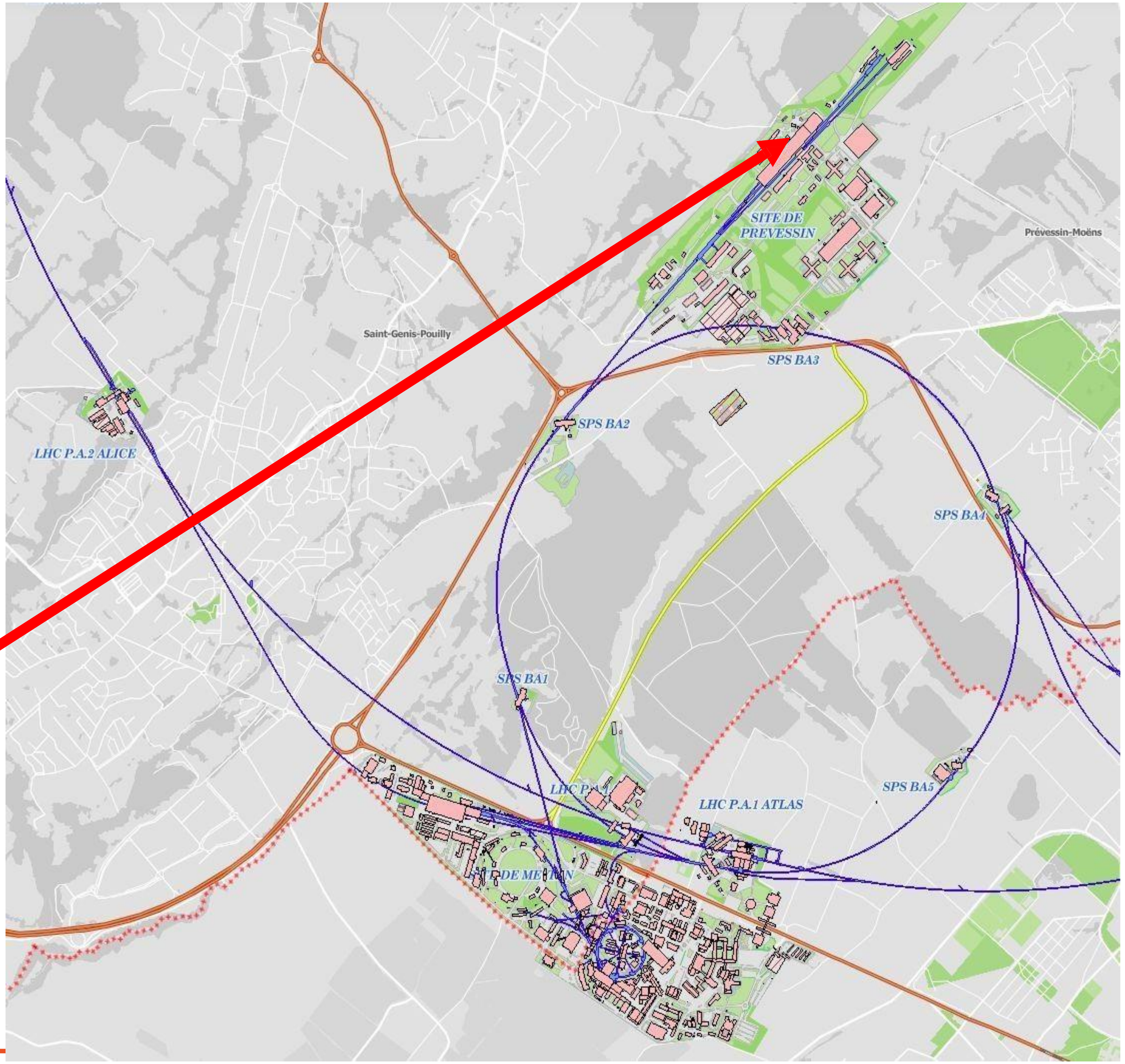


Figure: CERN.

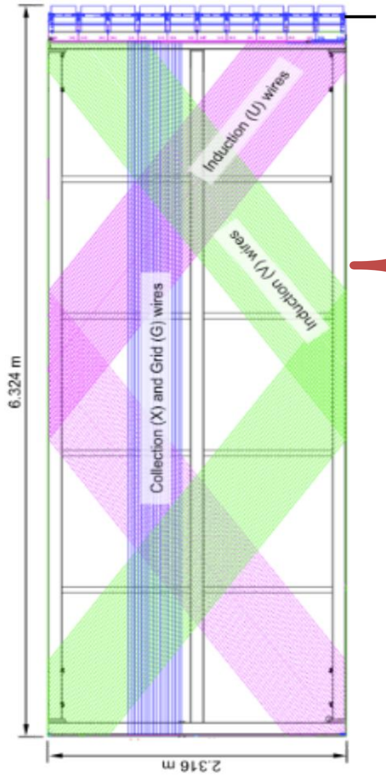


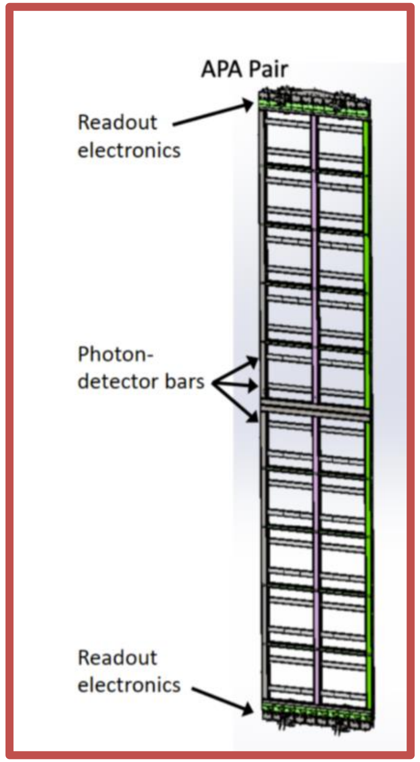
ProtoDUNE Horizontal Drift detector

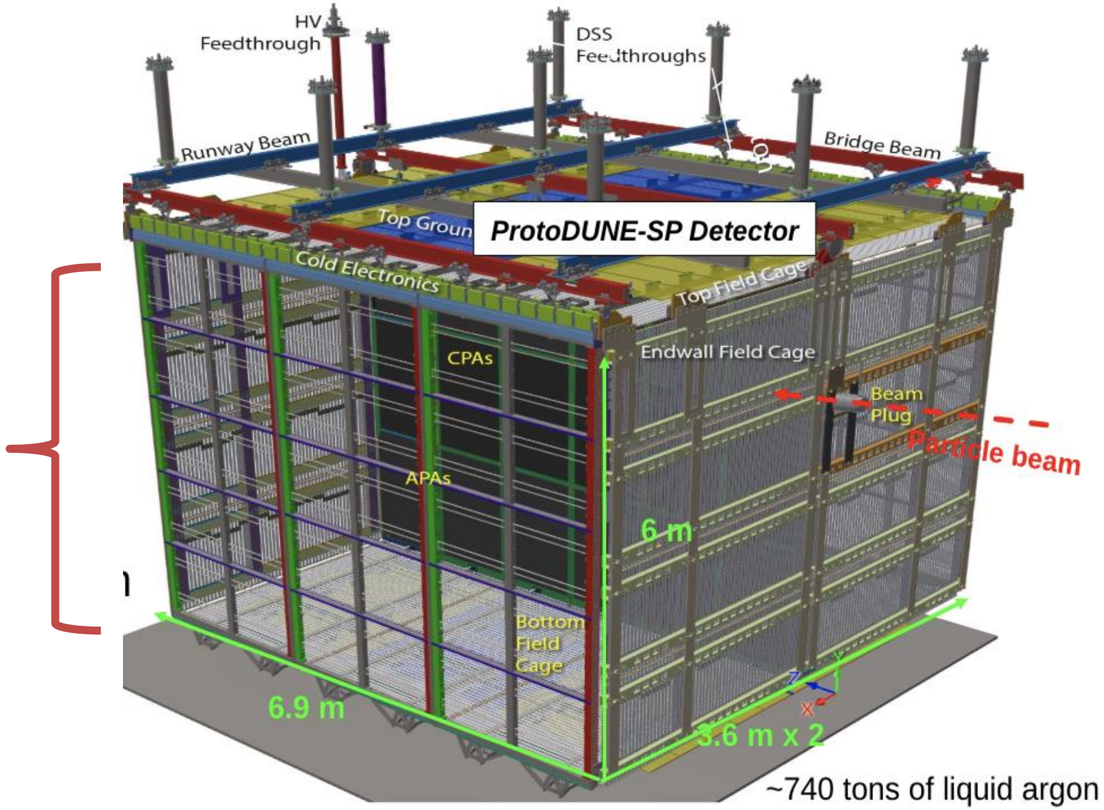
Anode module called APAs:
- Anode Plane Assembly
- Anode wire planes, electronics, and frame
- Light collection modules embedded behind anode
  - Several technologies tested in ProtoDUNE-I

Cathode module called CPAs:
- Cathode Plane Assembly
- Vcathode = -180 kV

APA





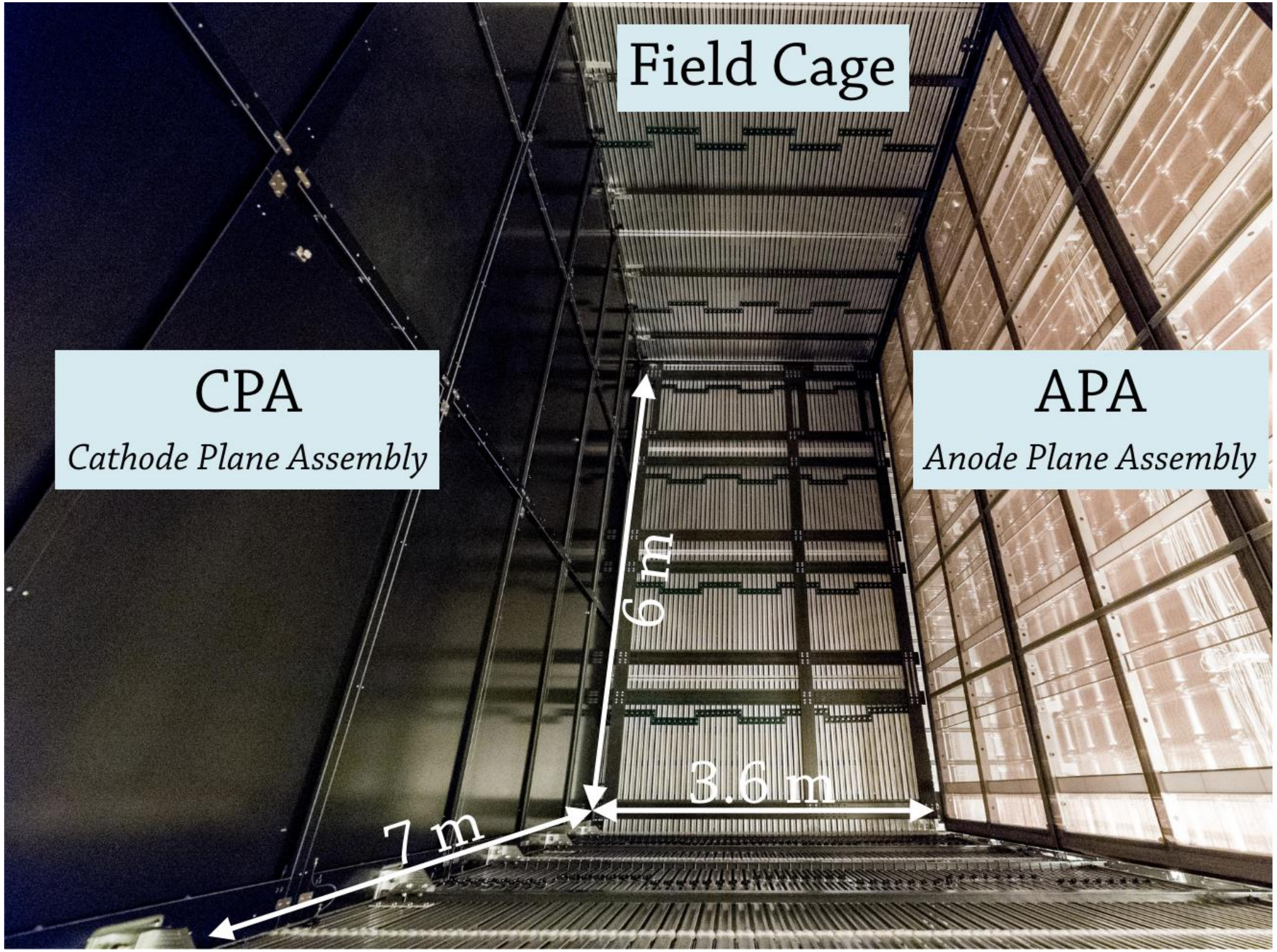


2 active volumes,
3.6 m drift each

APA – CPA – APA
6 APA and 6 CPA modules
(FD will have 150 APAs!)

Nominal drift field: 500 V/cm

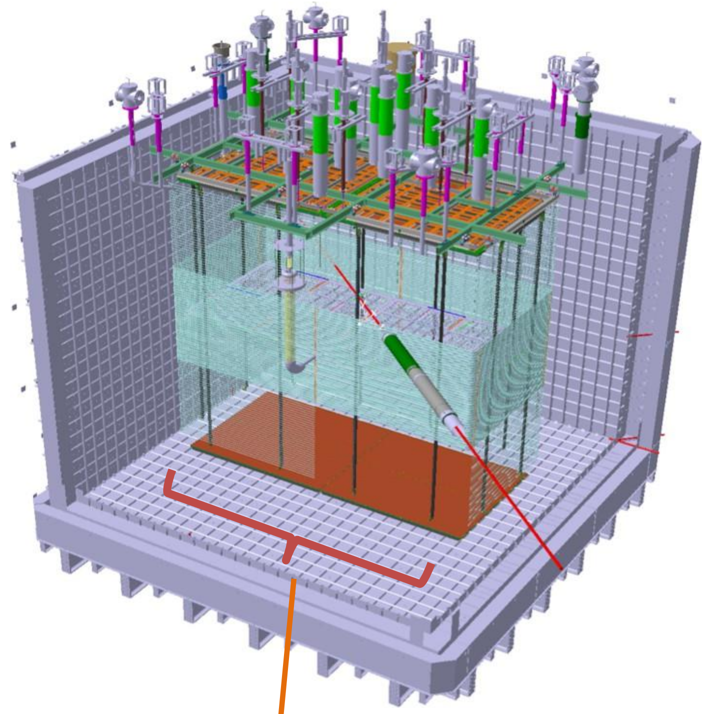
ProtoDUNE Horizontal Drift

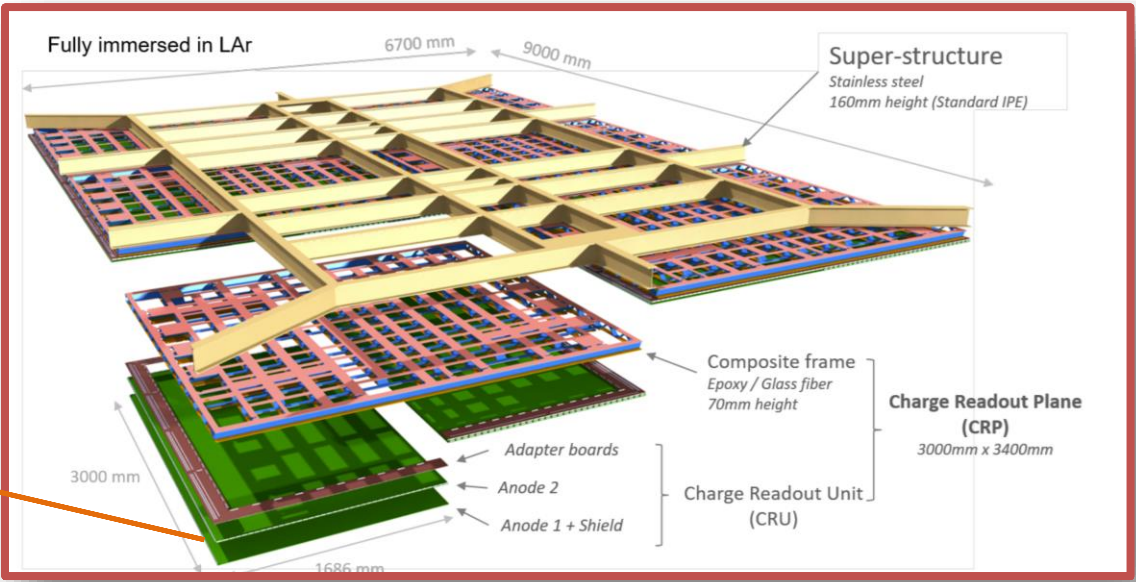


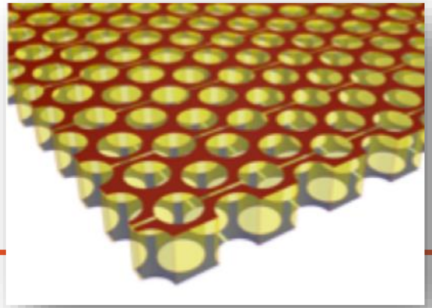
ProtoDUNE Vertical Drift

Vertical drift technology:

- Charge readout plane (CRP) houses the anode planes, electronics, and frame.
- Dimensions 3 x 3.4 m^2
- Anode of drilled PCBs with etched strips
  - More robust than wires
- 3 anode planes at varying angles {-30˚,+30˚, +90˚} wrt. beam
- X-ARAPUCA embedded in cathode

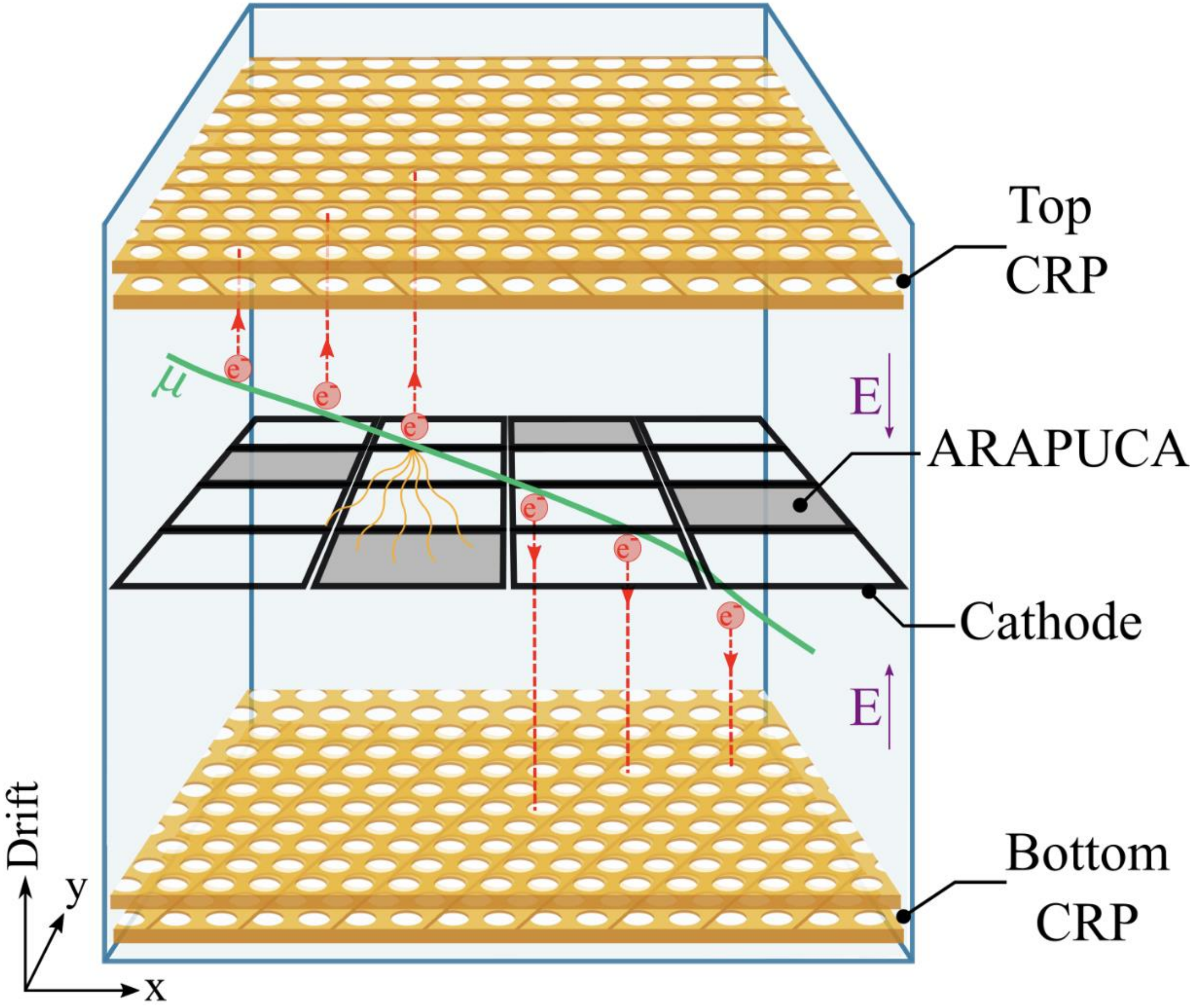






ProtoDUNE Vertical Drift

- Very low electronic noise
- 2 top Charge Readout Planes +
  2 bottom CRPs
  (Far Detector will have 2 x 80 CRPs)
- 2x3m drift distance
  (Far Detector will have
  2x6m drift distance)



ProtoDUNE Measurement Program

Large scale prototypes are mandatory for:

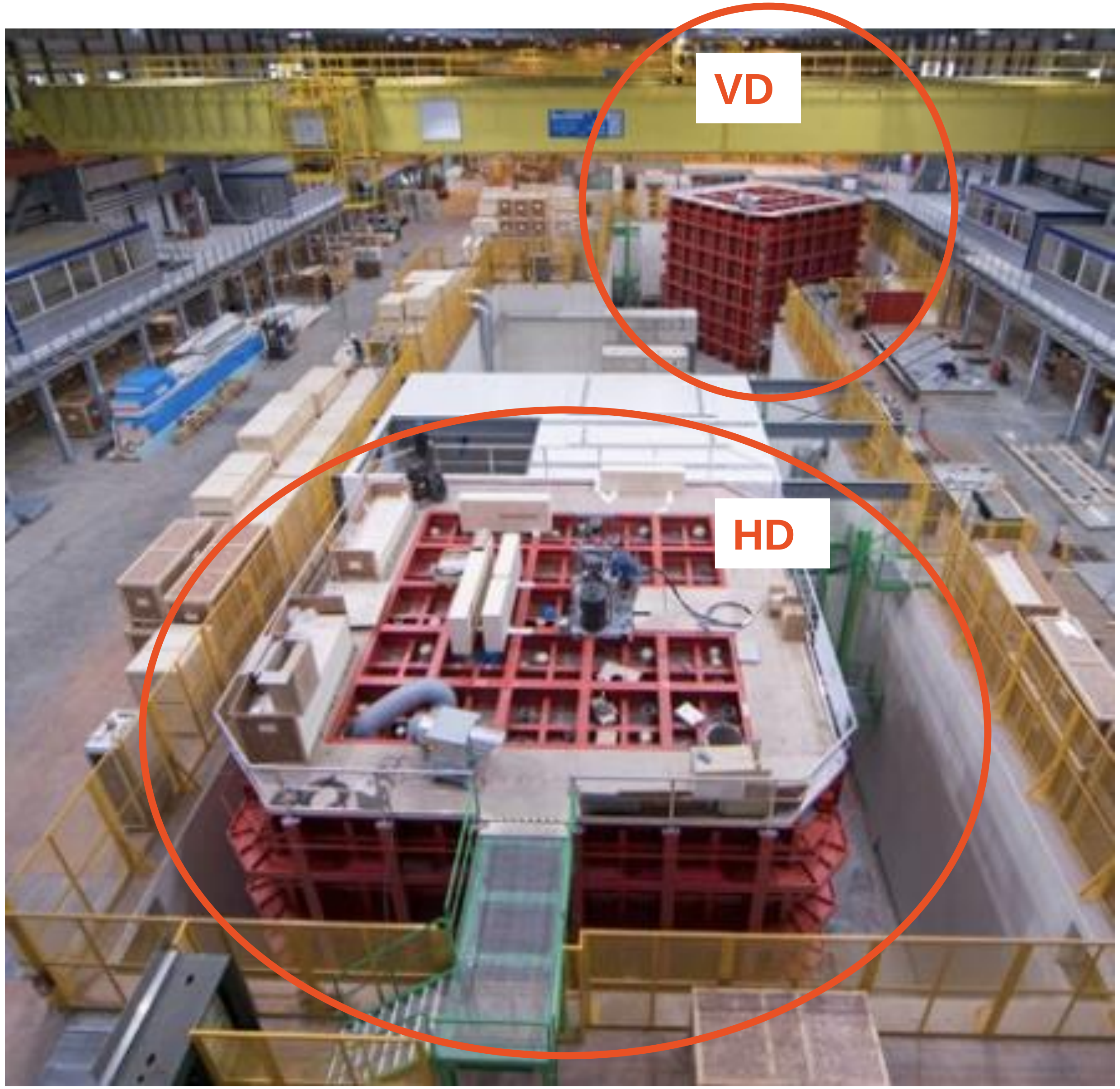
- Integration test with 1:1 components
- Assess the LArTPC technology performance

Detector physics:

- LArTPC detector physics
- Calorimetry with charged particles
- Evaluations of photon detectors in liquid argon

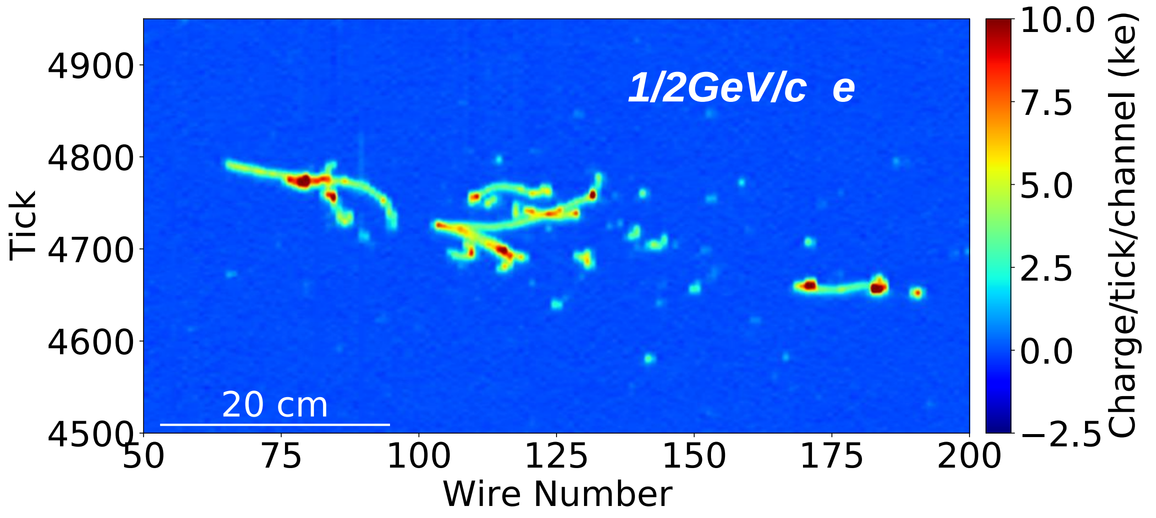
Ar-hadron interactions, Electromagnetic showers, and Cosmic physics:

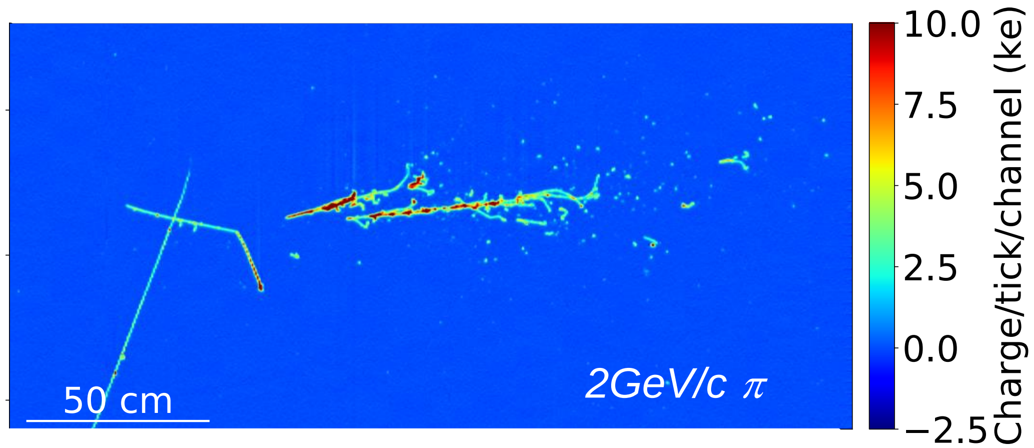
- Hadron-argon interactions with pions, protons, and kaons.
- Including total and exclusive cross sections
- dE/dx with charged particles, including electromagnetic showers.
- Michel electron energy reconstruction
- Seasonal variations of cosmic-ray muons

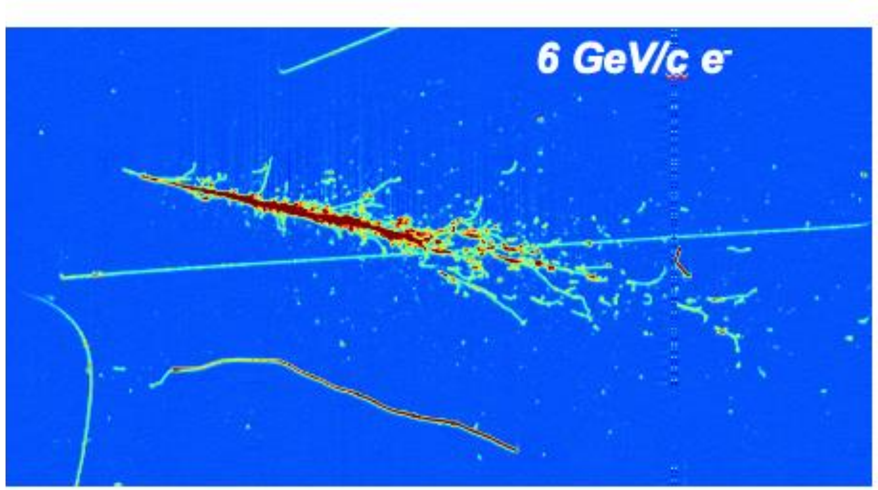


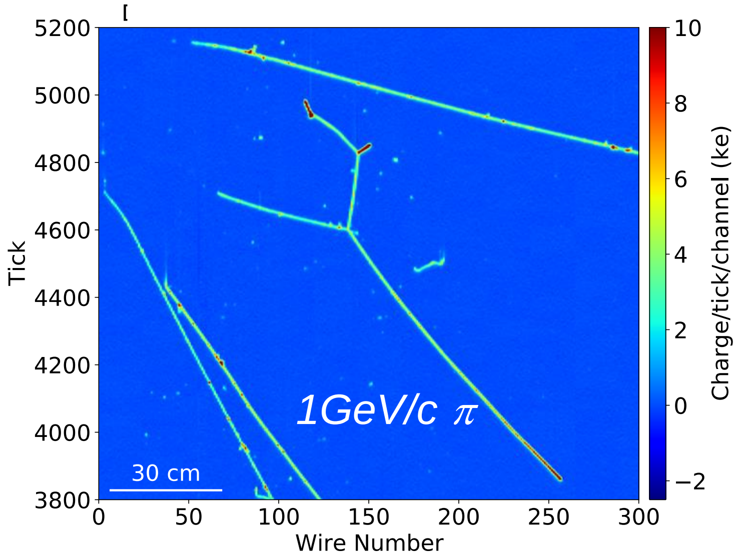
Far Detector Prototyping Tests

- Getting physics out of these prototypes through their exposure to the CERN testbeam
- Not only testing the technology but also providing vital calibration measurements + important e,π,K re-scattering data on argon
- Stringent test of DAQ in beam and cosmic rays









Eur. Phys. J. C82, 903 (2022)

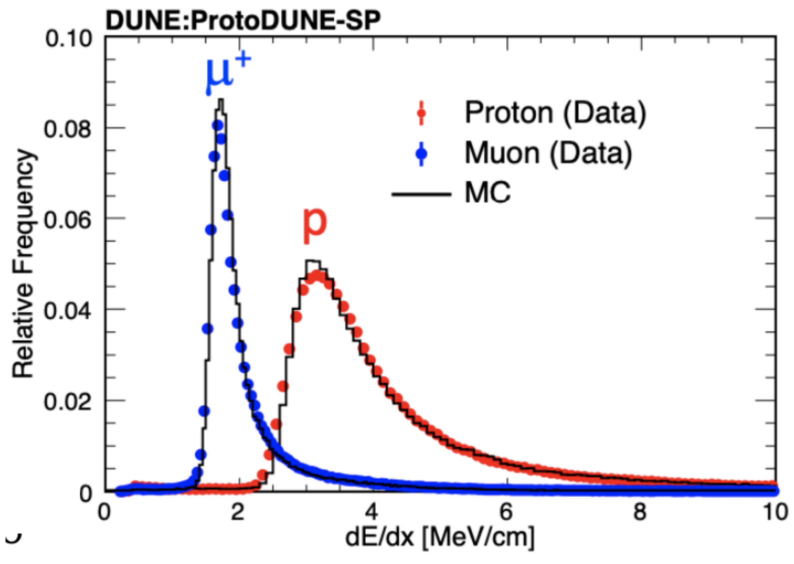
ProtoDUNE Horizontal Drift: Results!

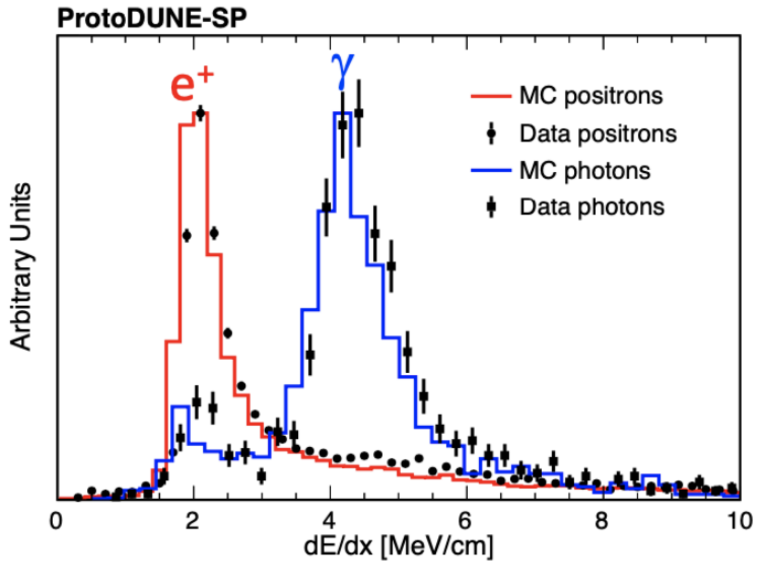
Oct.~Nov. 2018: Beam data
- hadrons with momenta 0.3 ~ 7 GeV/c
- 4×10^{6} triggered events
- H4-VLE beamline instrumented with Time of Flight and Cherenkov counters for Particle Identification

Nov. 2018 ~ Jan. 2020: Cosmic data
- Random and cosmic ray trigger
- Tests of detector performances & stability

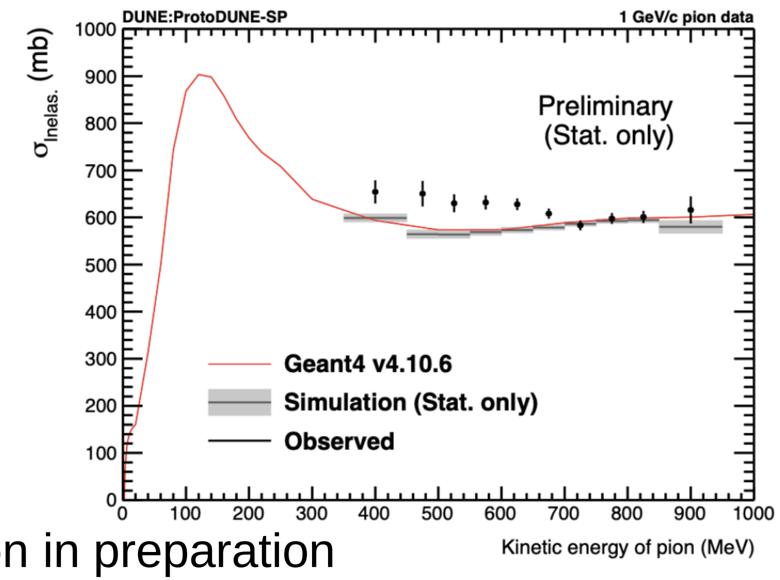
Feb. 2020 ~ Jul 2020:
- LAr doped with 20 ppm Xe
- Test of light yield increase

Stay tuned: New Beam time approved by CERN for both Horizontal and Vertical Drift technologies

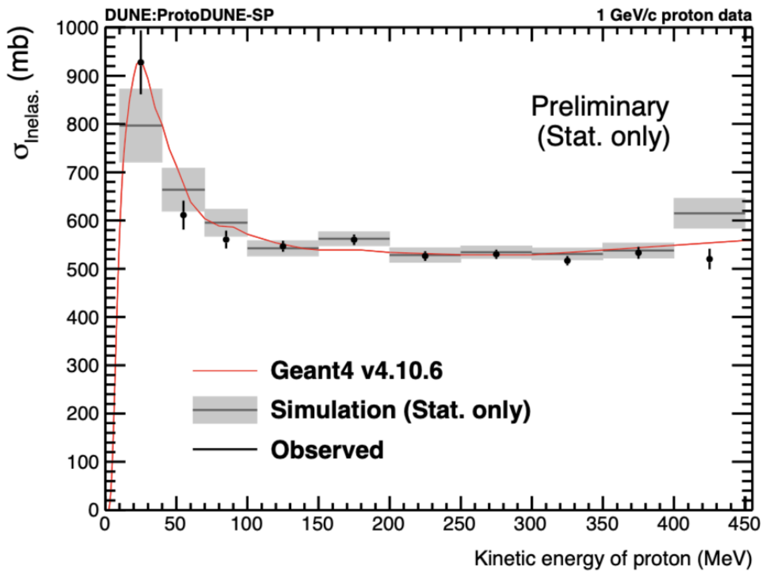




pion-Argon inelastic cross section



proton-Argon inelastic cross section



Publication in preparation

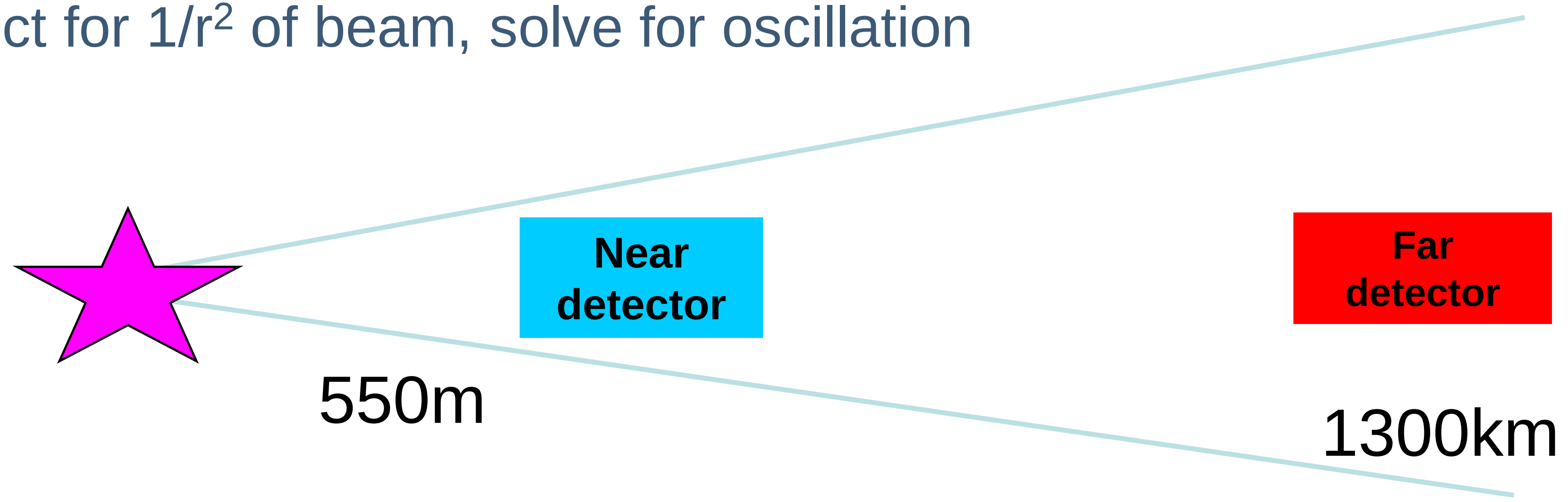
Expected Event Rates @ DUNE

- From Far Detector Technical Design Report: if there is no CP violation other than the electrons in the earth…two options: normal or inverted mass ordering. (NO or IO)
- Staged increase in detector mass and proton power

	Expected events (3.5 years staged per mode)	
	ν mode	$\bar{\nu}$ mode
ν_e Signal NO (IO)	1092 (497)	76 (36)
$\bar{\nu}_e$ NO (IO)	18(31)	224 (470)
Total Signal NO (IO)	1110 (528)	300 (506)
Beam $\nu_e + \bar{\nu}_e$ background	190	117
NC background	81	38
$\nu_\tau + \bar{\nu}_\tau$ CC background	32	20
$\nu_\mu + \bar{\nu}_\mu$ CC background	14	5
Total background	317	180

With hundreds of appearance events in each mode, systematics will matter!

- Using two detectors to measure oscillations precisely:
  - Near detector sees beam before oscillations
  - Far detector measures beam after oscillations
  - Ideally, near and far detectors made of same material (Ar)
  - Correct for $1/r^2$ of beam, solve for oscillation



Current collections of ν_e and $\bar{\nu}_e$ appearance?

- T2K: Eur.Phys.J.C 83 (2023) 9, 782: **94+14 $\boldsymbol{\nu_e}$** QE-like+π production candidates in neutrino mode, and **16 $\boldsymbol{\bar{\nu}_e}$** QE-like candidates
- NOVA: *Phys.Rev.D* 106 (2022) 3, 032004, **82 $\boldsymbol{\nu_e}$** candidates in neutrino mode, and **33 $\boldsymbol{\bar{\nu}_e}$** candidates

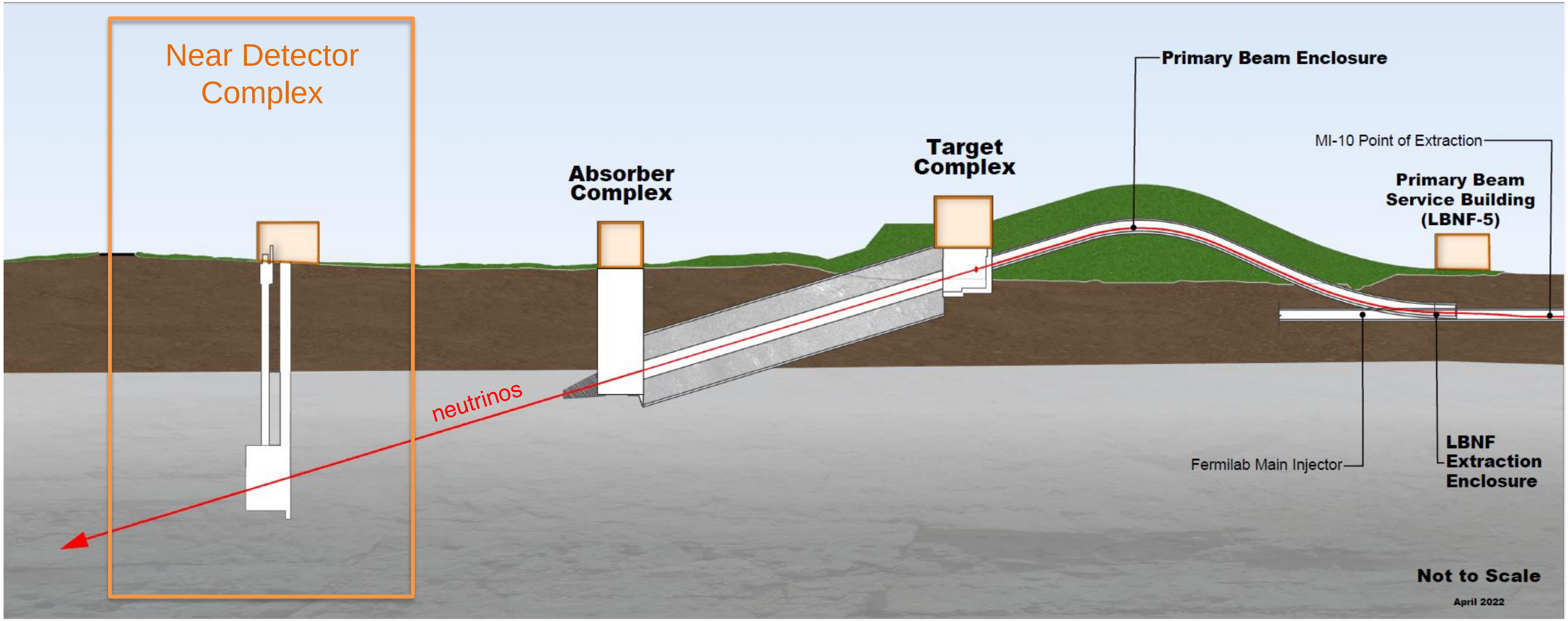
T2K, Eur. Phys. J. C (2023) 83:782

DUNE will need 3x lower systematic uncertainties to be as statistics dominated as T2K is now

Sample		Uncertainty source (%) Flux	Interaction	FD + SI + PN	Flux⊗Interaction (%)	Total (%)
1Rμ	ν	2.9 (5.0)	3.1 (11.7)	2.1 (2.7)	2.2 (12.7)	3.0 (13.0)
	$\bar{\nu}$	2.8 (4.7)	3.0 (10.8)	1.9 (2.3)	3.4 (11.8)	4.0 (12.0)
1Re	ν	2.8 (4.8)	3.2 (12.6)	3.1 (3.2)	3.6 (13.5)	4.7 (13.8)
	$\bar{\nu}$	2.9 (4.7)	3.1 (11.1)	3.9 (4.2)	4.3 (12.1)	5.9 (12.7)
1Re1de	ν	2.8 (4.9)	4.2 (12.1)	13.4 (13.4)	5.0 (13.1)	14.3 (18.7)

Current T2K uncertainty on integrated event rates with (without) the near detector constraints

Near Detector Complex

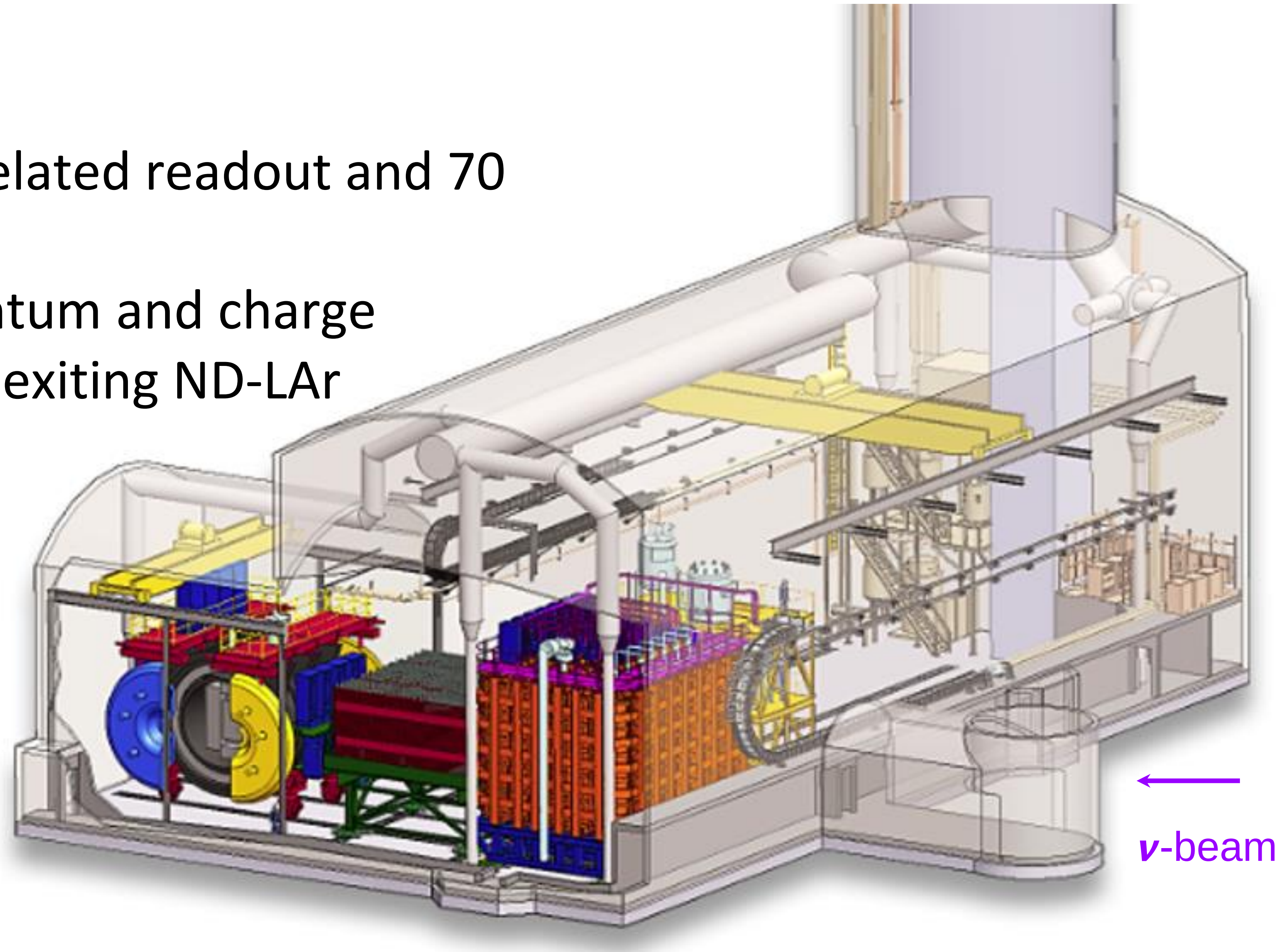


- **Where?** ND hall is located 550m from proton target, 65m deep, on-site at Fermilab
- **Why?** measure the rate & spectrum of ν's before oscillations, check beam stability.

DUNE Near Detector Complex

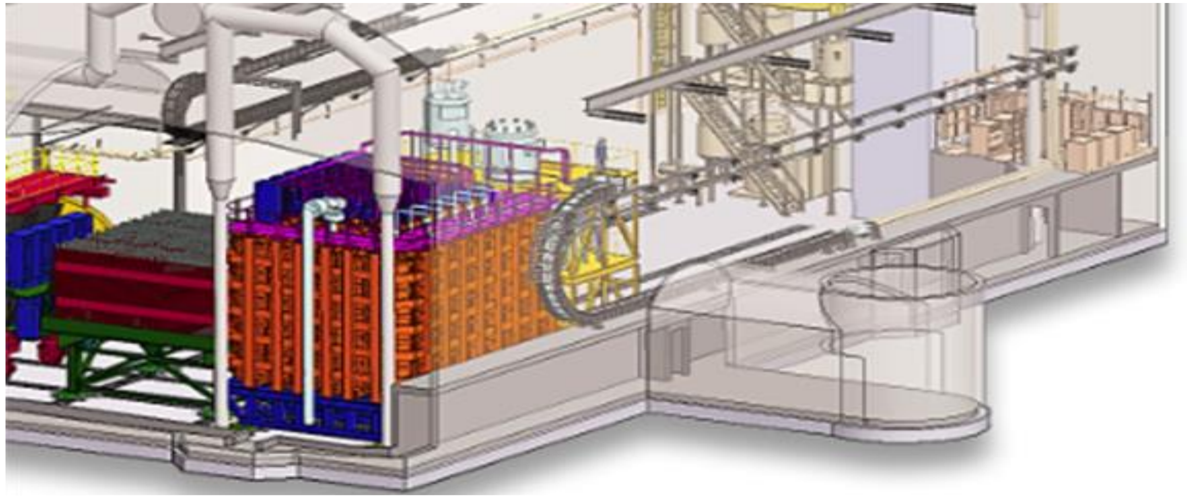
- ***Moveable LArTPC system***
  - ND-LAr: novel LArTPC with pixelated readout and 70 optically isolated TPC volumes
  - TMS: spectrometer for momentum and charge measurement of $\boldsymbol{\nu}_{\mu}$-CC muons exiting ND-LAr
  - PRISM: ND-LAr + TMS system moves up to 28.5m (2.8°) off-axis

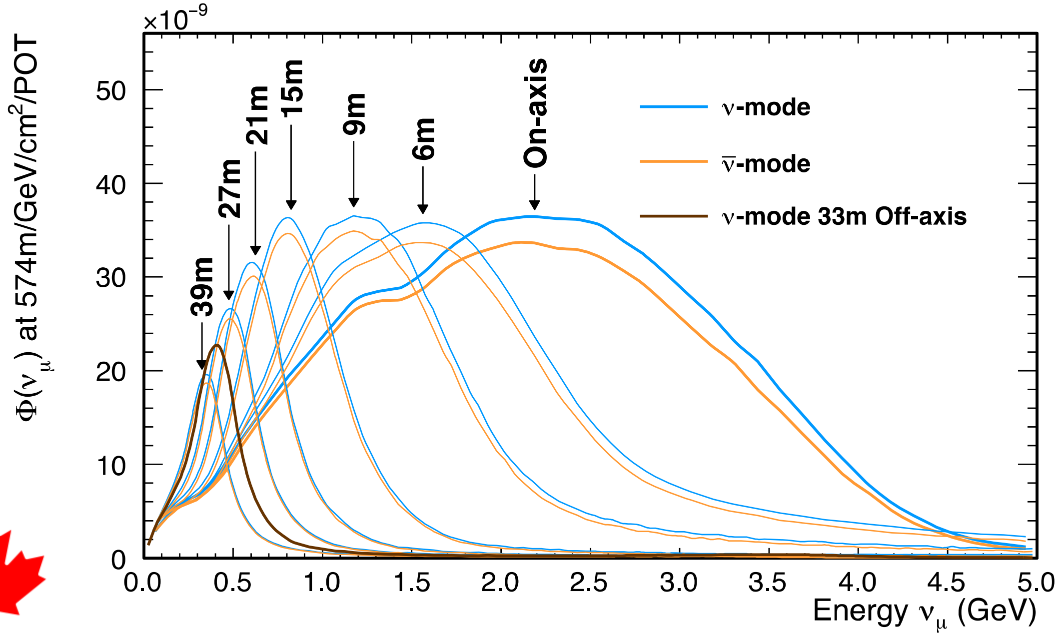
- ***Multi-purpose on-axis magnetized detector***
  - SAND: Straw tube tracker with Argon target inside KLOE superconducting solenoid



Why Move a Near Detector?

- Because pion decays to ν_μ are 2-body decays, neutrino energy determined by angle between pion direction and ν_μ direction, and pion energy.
- Different off axis angles give you different incoming neutrino spectra
- One angle is “sweet spot” which is what T2K, HyperK, and NOvA use
- But sampling at many angles gives you many different near fluxes
- This will help inform the relationship between true neutrino energy and visible energy
- You can make “whatever incoming spectrum you want” by linear superpositions of data taken at different angles

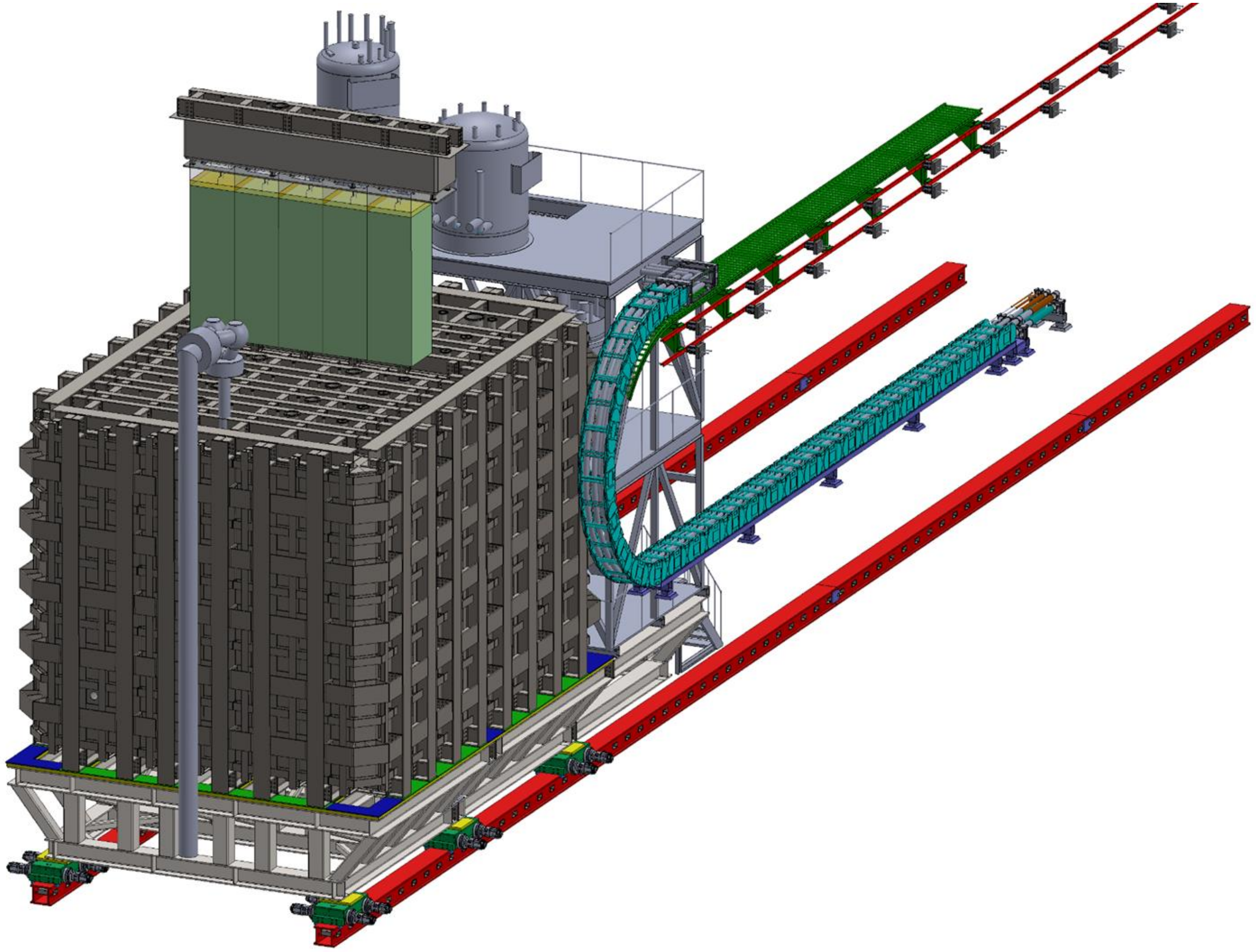




arXiv:2002.03005v1 [hep-ex]

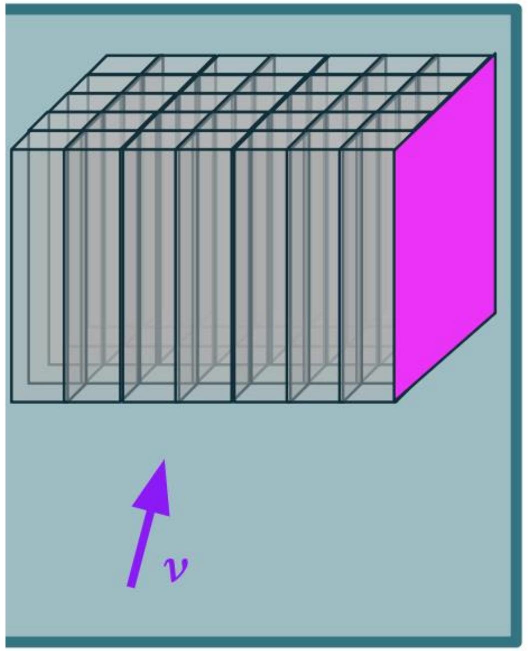
Liquid Argon TPC Near Detector

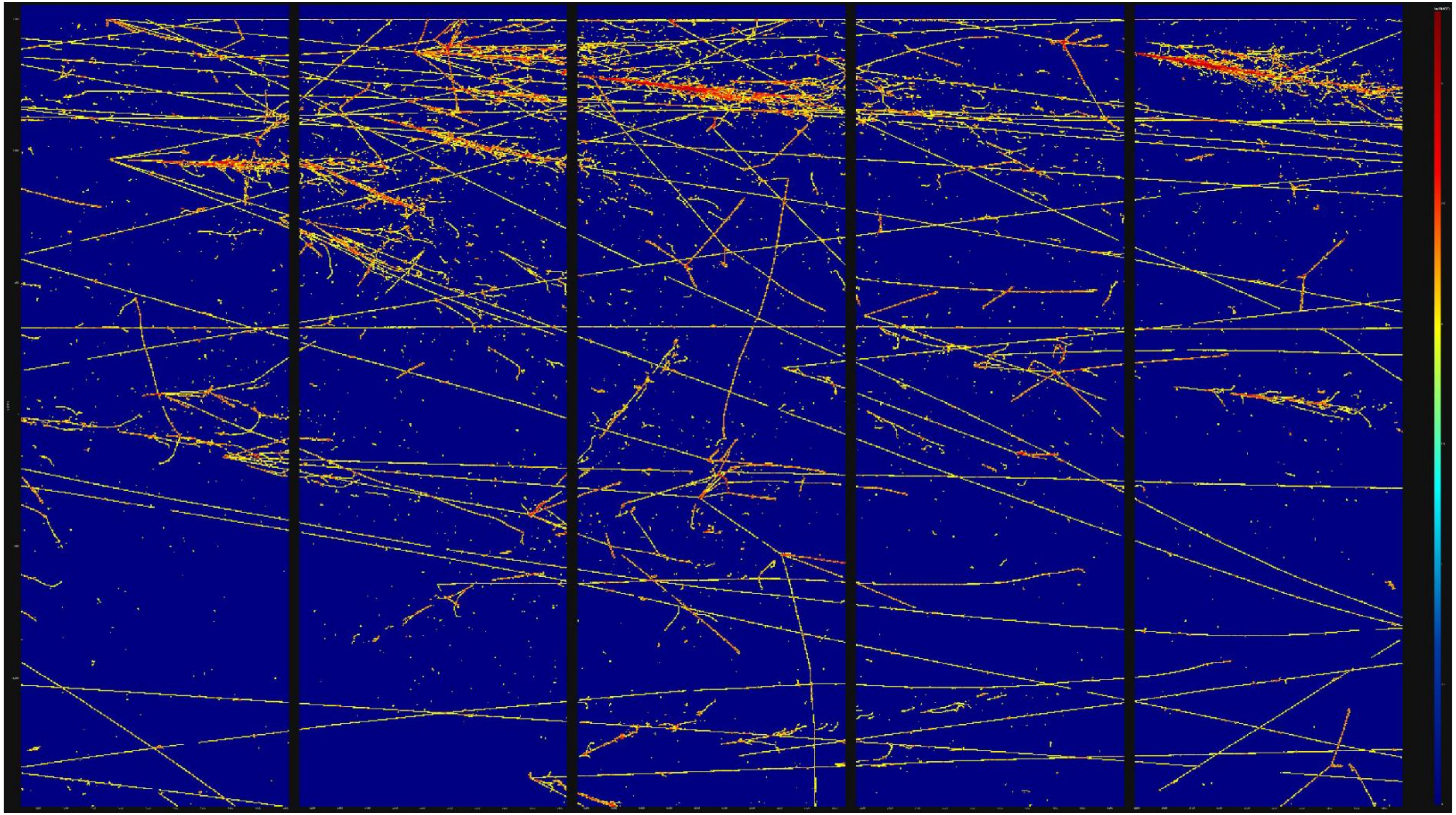
- 7x5 grid of 1x1x3 m^3 LArTPC modules
  - 7x5x3 m^3 active volume
- Designed to cope with high-pileup environment
  - ~60 interactions / 1.2 MW spill
- Optical segmentation provides interaction-level timing information
- Native 3D readout from pixelated charge readout mitigates hit ambiguity
  - >14M pixel channels!



1.2MW Proton power: welcome to Neutrino Pileup!

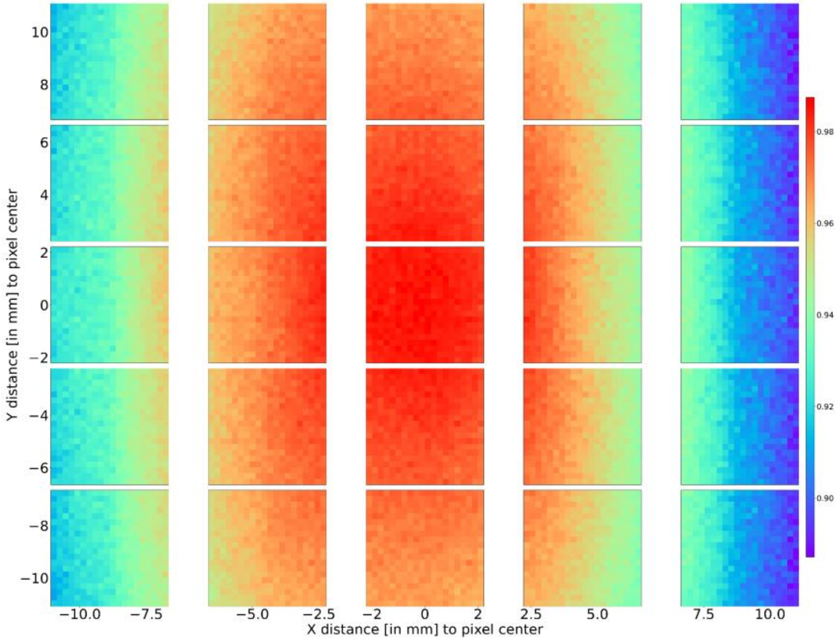
~60 neutrino interactions per beam spill in Liquid Argon TPC

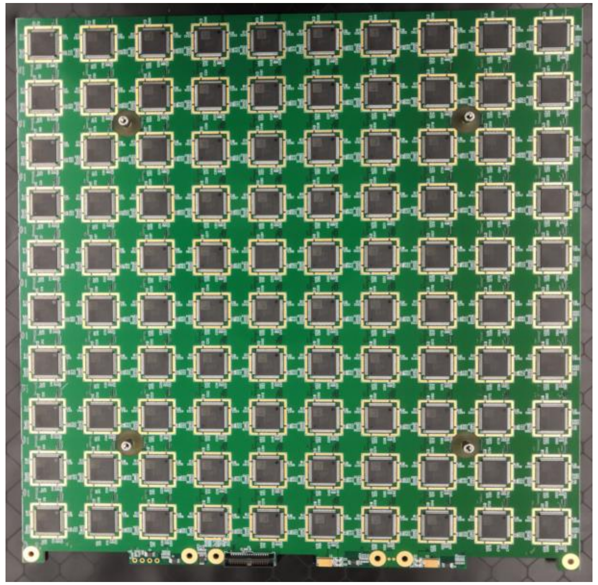


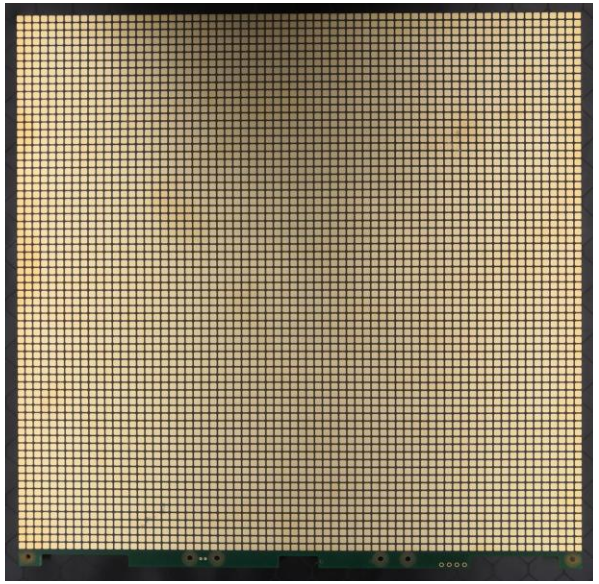


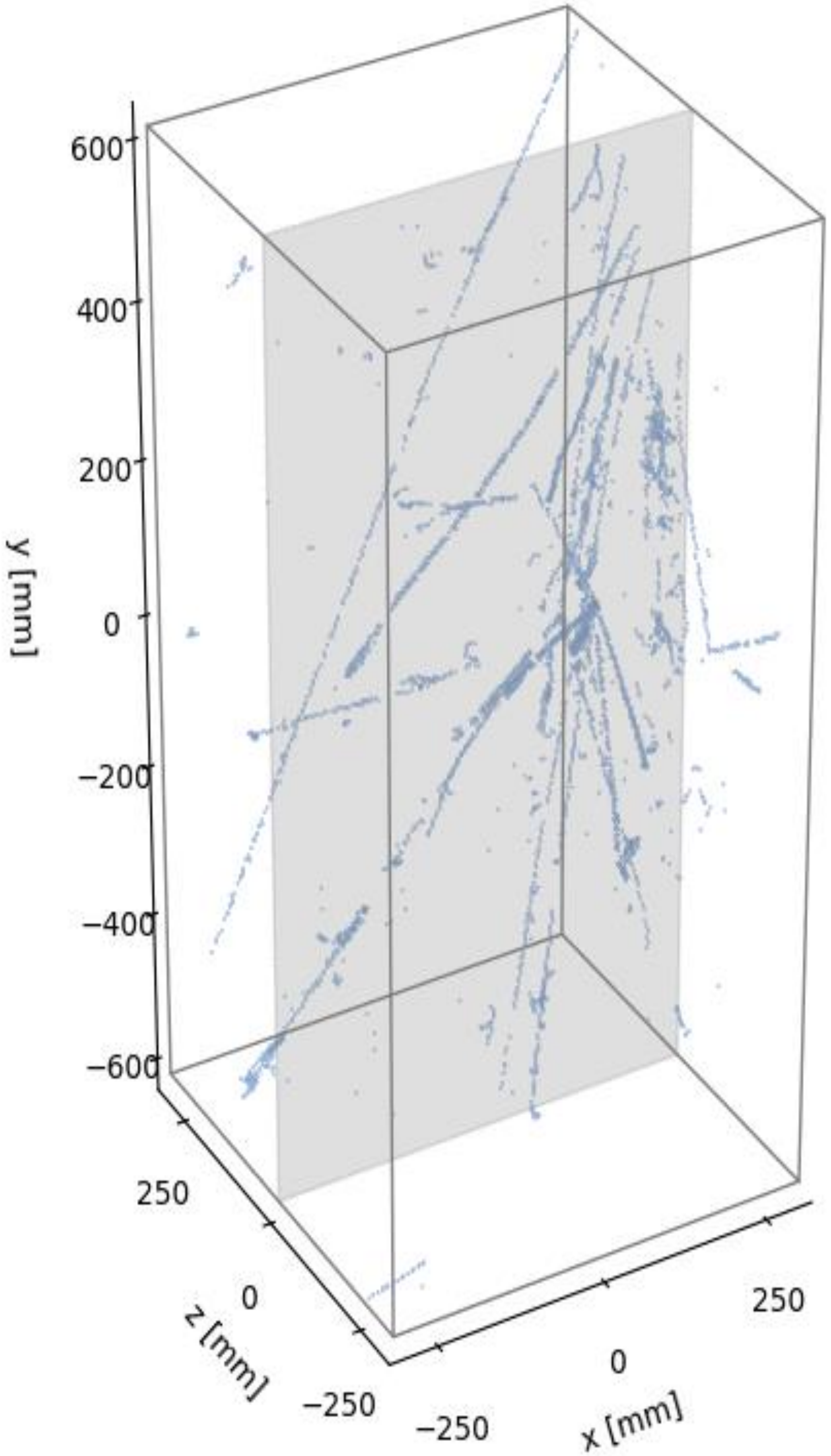
From Wires to Pixels: in practice

- Have built four 20% scale modules for Liquid Argon TPC Near Detector, tested their performance with cosmic rays @ Bern
- Mapping out pixel response: 4mmx4mm pixels, checking our ability to simulate this new detection technique







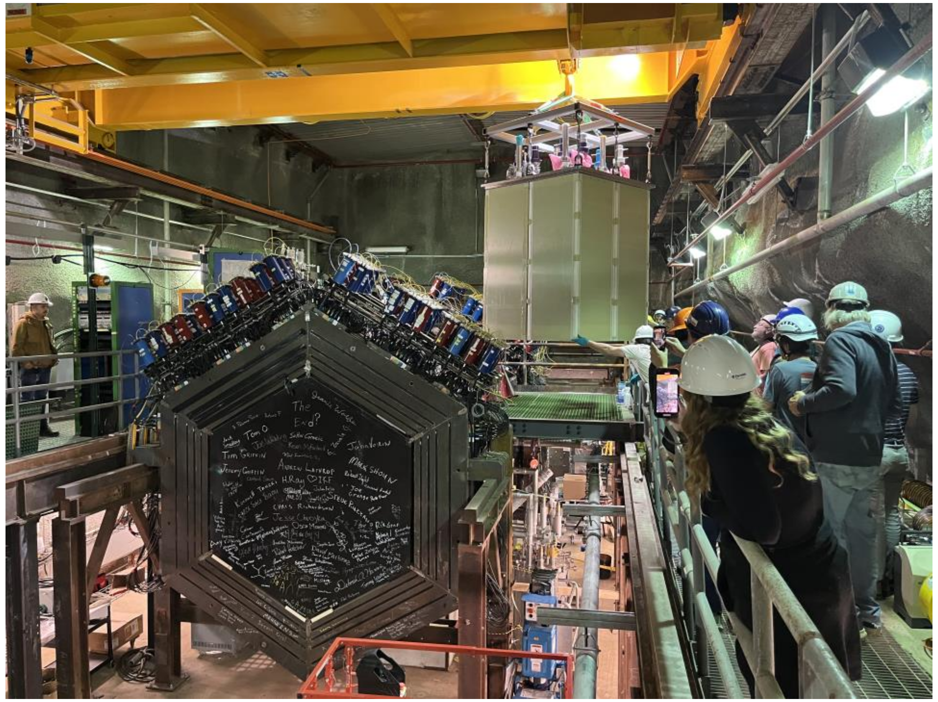


Neutrino Test of Near Detector Strategy

- 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”
- Plan to take data this month!
- 4 modules
- 2.6 tons of “active” Argon

Summary

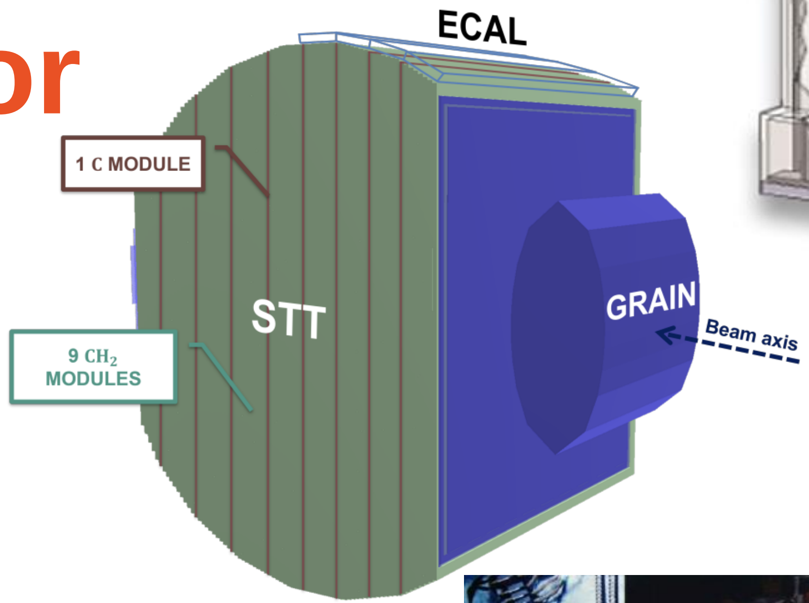
- DUNE has an ambitious program to measure neutrino oscillations across broad range of energies
- Use fully active Liquid Argon TPC detector
- Expected statistics means we need to reduce systematics below current generation of experiments
- Near Detector Suite at Fermilab:
  - Moveable Liquid Argon TPC with pixels not wire planes
  - On Axis Neutrino Beam Monitor (SAND)
  - Lots of exciting data on prototypes:
    - CERN test beam on Prototypes of Horizontal and Vertical drift
    - Neutrino Beam on Prototype of Liquid Argon Near Detector

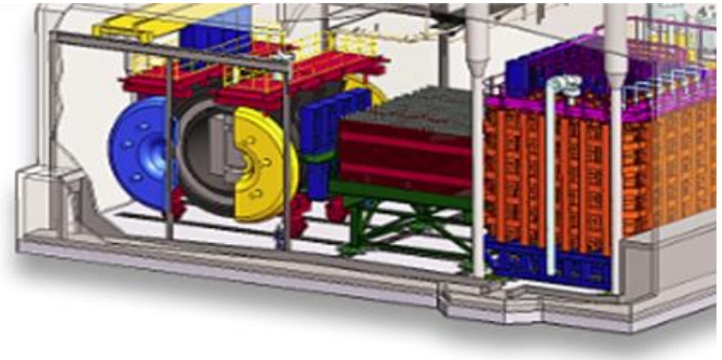


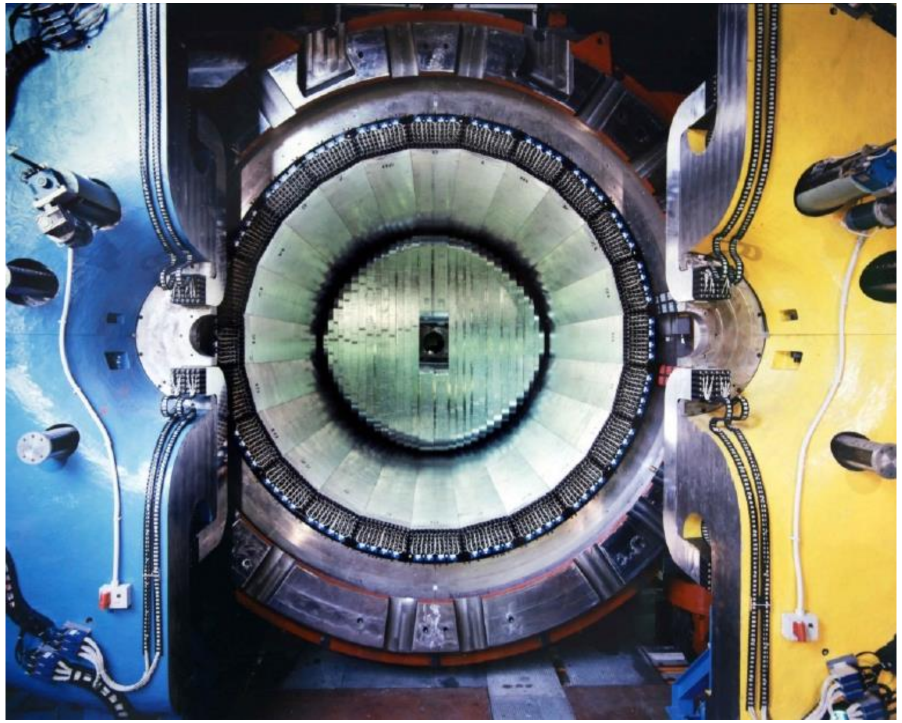
Merci
Thank you

On Axis Near Detector

- Need to make sure that the beamline is producing neutrinos with the same spectrum for 7+ years!
- Liquid Argon TPC will not always see the same flux if it's moving, that's the point
- Need detector with well-known technology to stay in one place for the entire run
- SAND: straw tube tracker with passive targets for mass for neutrino detection: bonus of cross section measurements
- Repurposed KLOE Detector
- All in a magnetic field so we can get on axis mix of ν and $\bar{\nu}$

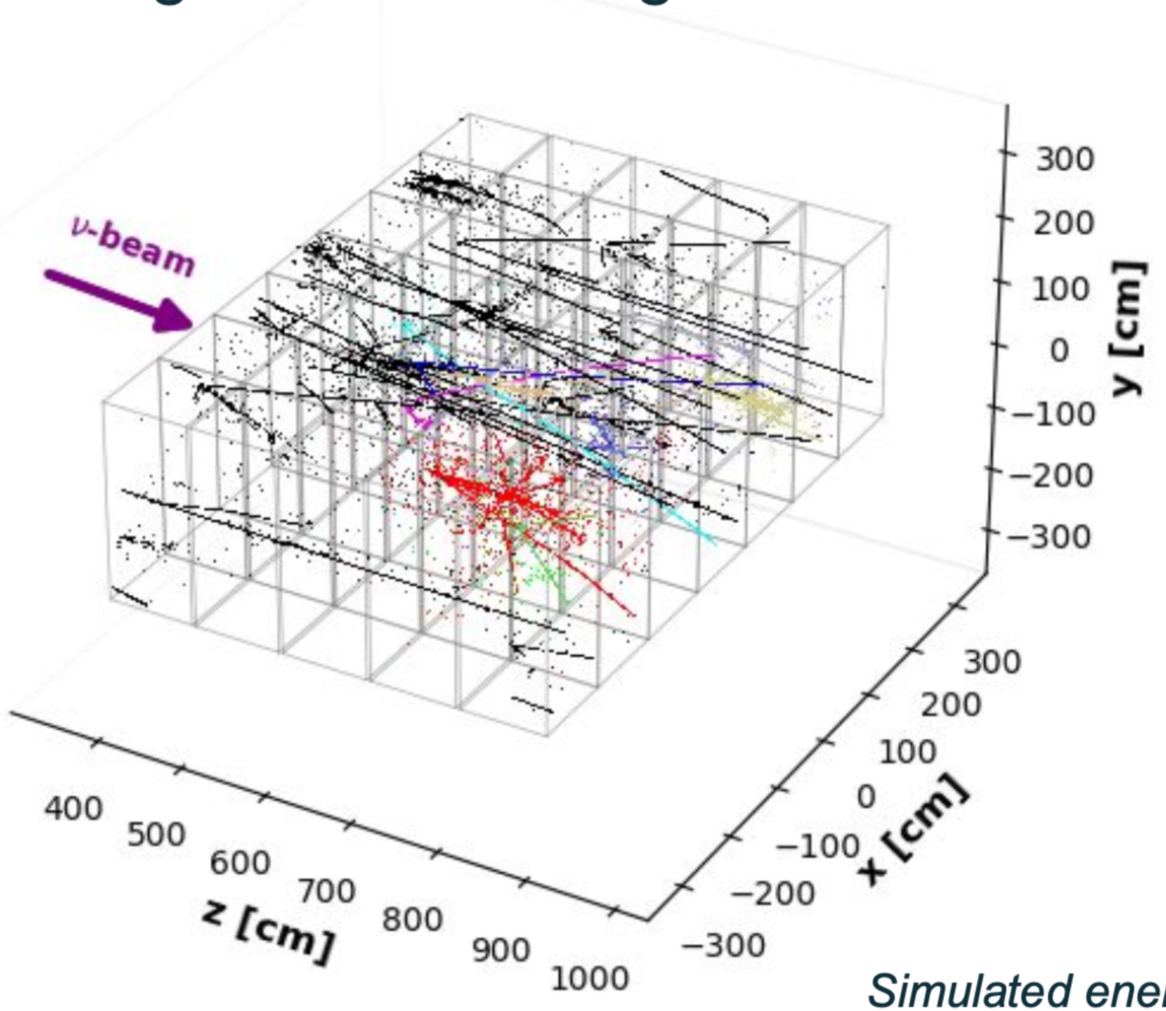


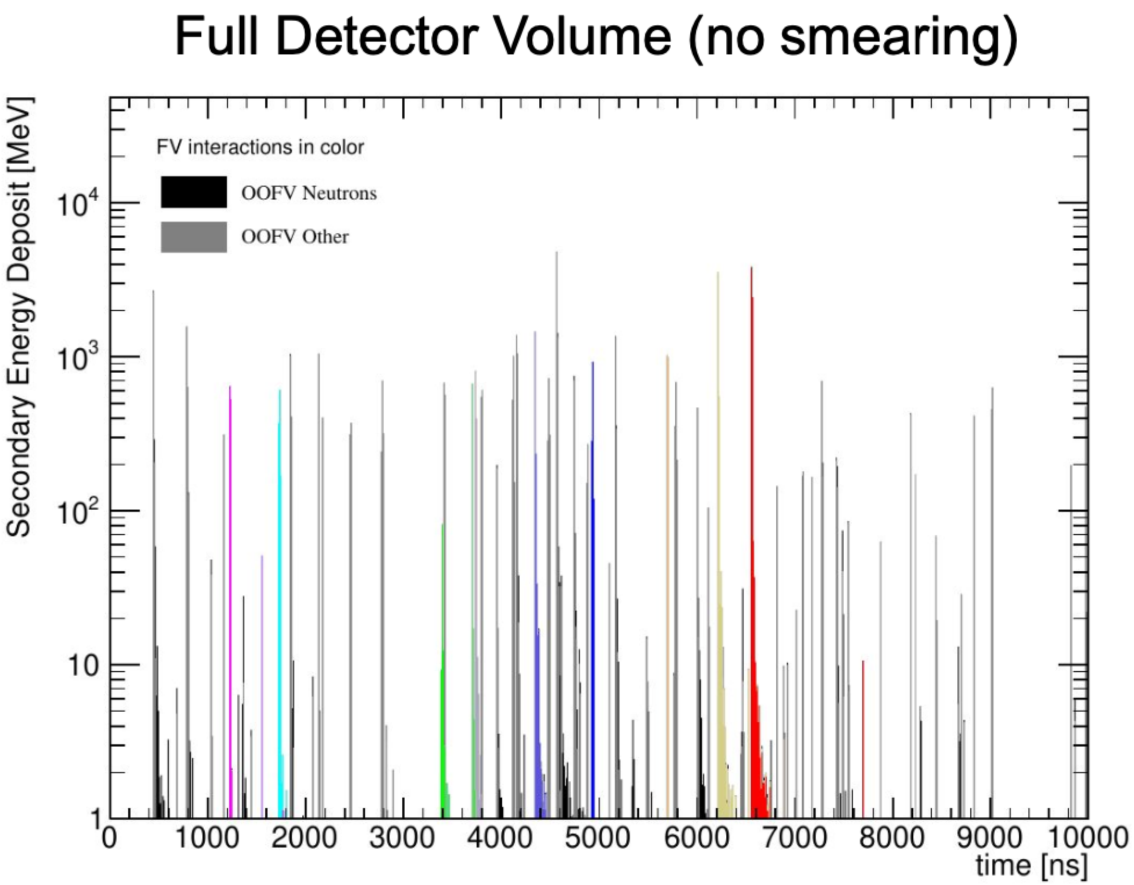




Modularity also reduces pileup…

- LArTPC charge readout very slow compared to beam microstructure
- Leverage scintillation light readout for timing information: must match charge to light





Simulated energy deposits from 1.2 MW LBNF Beam Spill in ND-LAr

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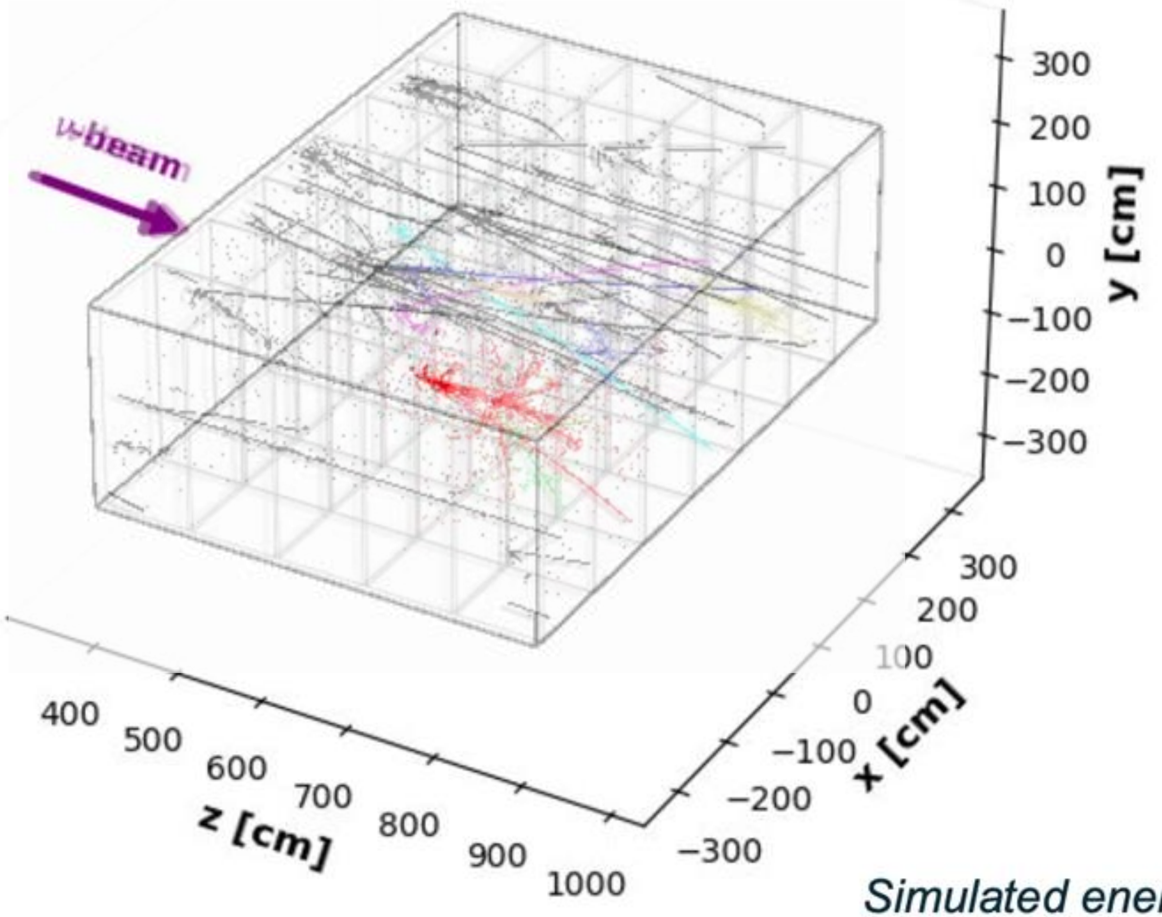
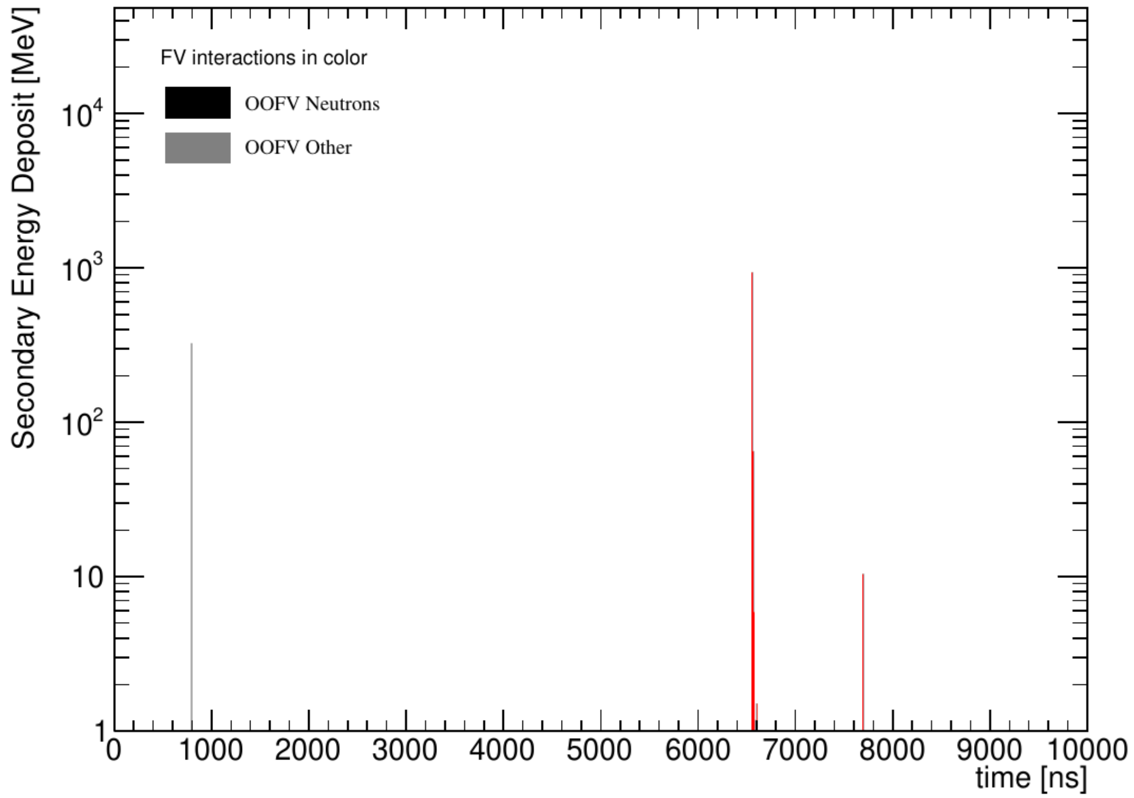


1/70th Detector Volume (no smearing)



Simulated energy deposits from 1.2 MW LBNF Beam Spill in ND-LAr

DUNE ν_e and $\bar{\nu}_e$ spectra

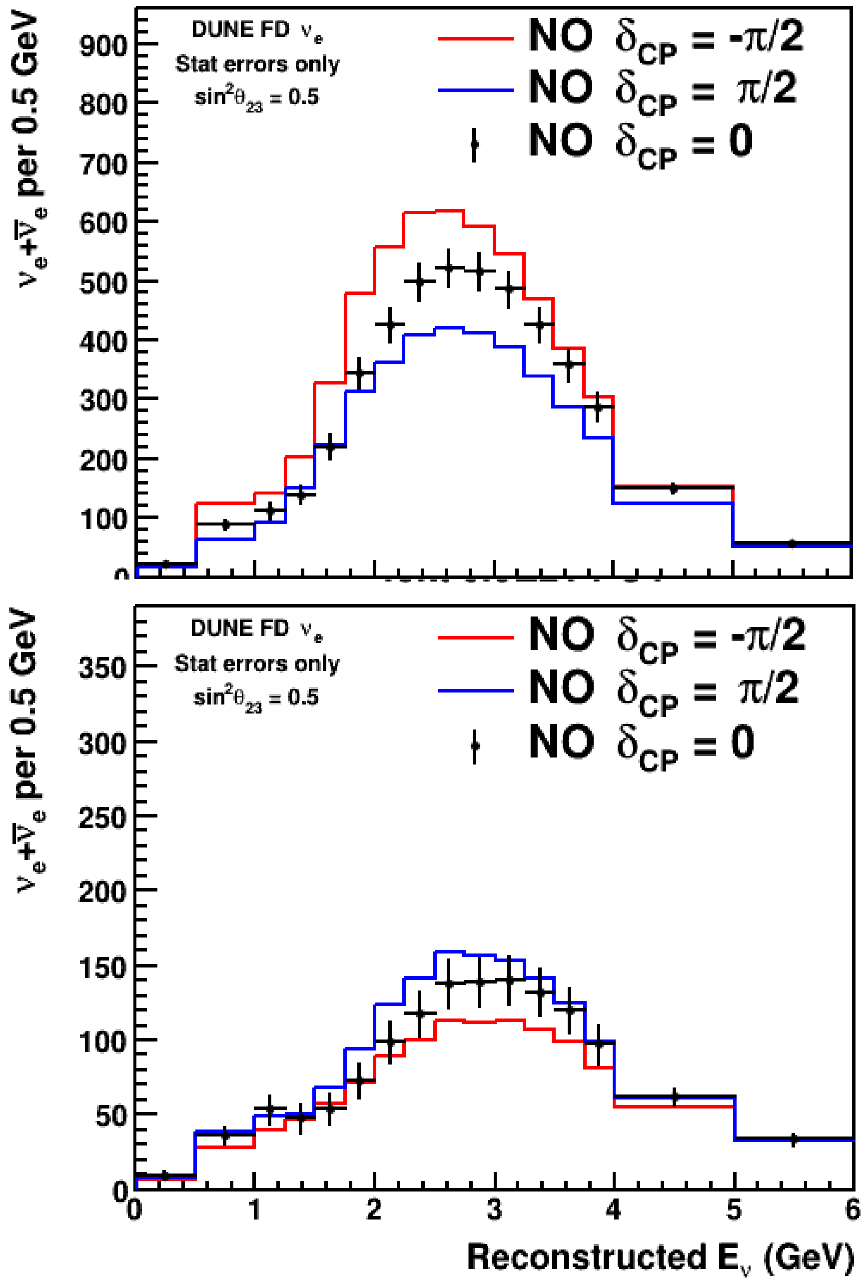
"Data" is
Normal Ordering,
$\delta_{CP} = 0$,
$\sin^2\theta_{23} = 0.5$

Neutrino mode

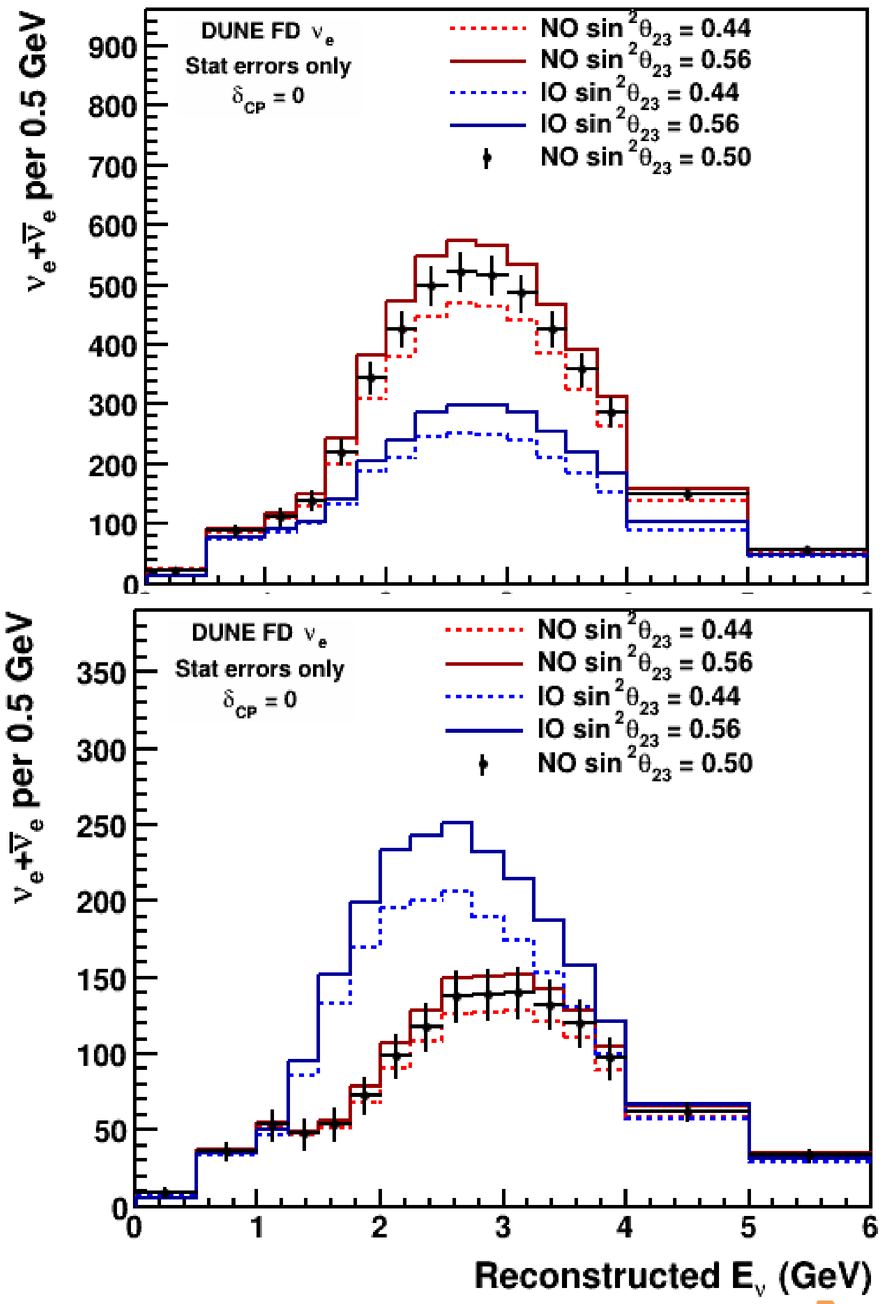
Antineutrino mode

20kT 2.8E21POT
+40kt 6.6E21 POT
In each mode

Vary δ_{CP}



Vary Mass Ordering and $\sin^2\theta_{23}$



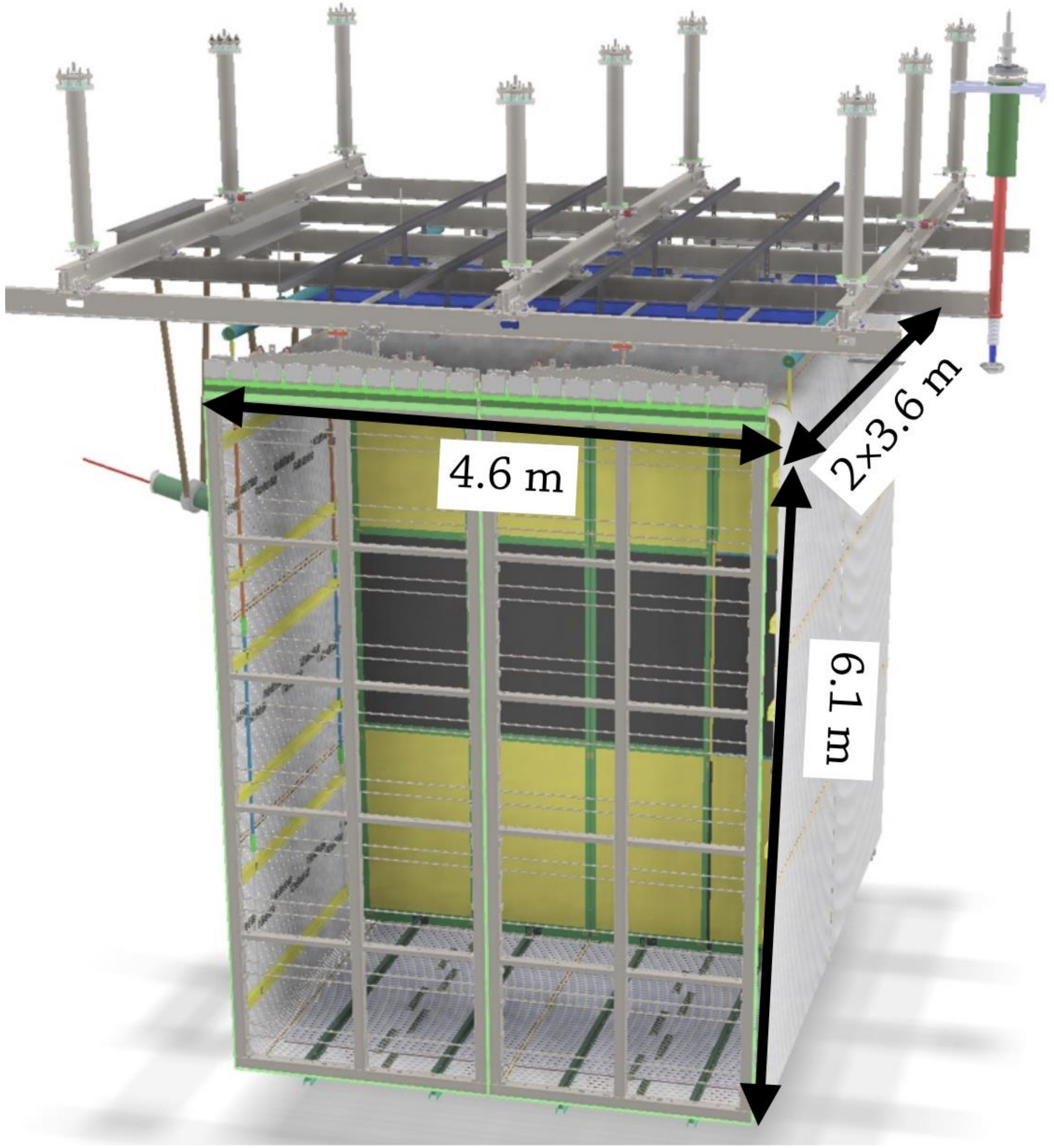
ProtoDUNE Upgraded Horizontal Drift Plans

Improved HD design:

- Updated APA, CPA and cold electronics designs
- 4 APAs to match the field cage-cryostat distance of the FD module
- 2 APAs upside down with the electronics at the bottom
- Light collection modules: X-ARAPUCA technology chosen
- Test new calibration systems
    - Neutron source, laser, 207Bi sources, temperature sensors along the APAs

Beam time approved by CERN
Running at $\pm$1 GeV:

- **Negative polarity -1 GeV** for π^- studies that weren't taken with protoDUNE-I (1 week in mid June)
- 1 GeV beam, best match of energy of hadrons produced in DUNE neutrino interactions
- More data for **differential XS measurements** and **improved inclusive XS** results (5 weeks in July-Aug)
    - Proton, π^-, π^+ differential XS with different final states



DUNE Plan for Phased Construction

- LBNF/DUNE Phase I:
  - Full near + far site facility and infrastructure
  - Upgradeable 1.2 MW beam
  - Two 17kt LArTPC modules
  - Movable LArTPC near detector (ND-LAr) with muon catcher (TMS)
  - On-axis near detector (SAND)
- DUNE Phase II:
  - Two additional Far Detector modules
  - Beam upgrade to >2MW
  - More capable Near Detector