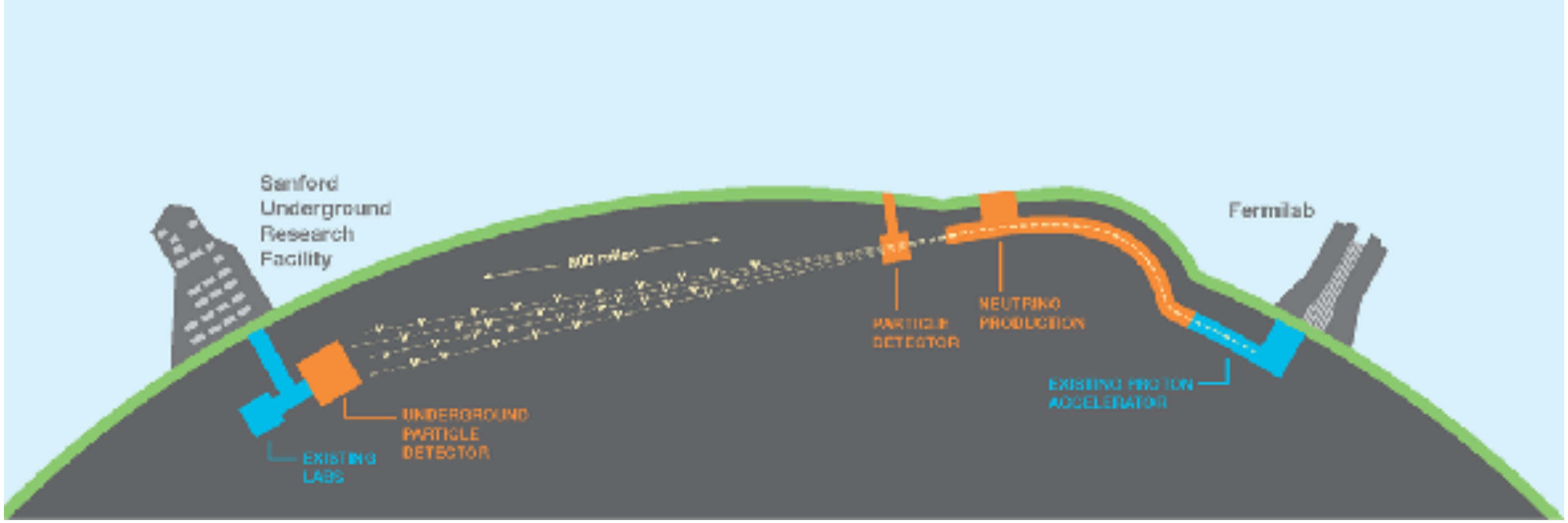
DUNE
Precision Neutrino Physics of the Future



Alfons Weber

University of Oxford, UKRI/STFC Rutherford Appleton Lab

Warwick, 10-Oct-2019

Neutrino Mixing: The PMNS Matrix

- Assume that neutrinos do have mass:
  - mass eigenstates ≠ weak interaction eigenstates
  - Analogue to CKM-Matrix in quark sector!

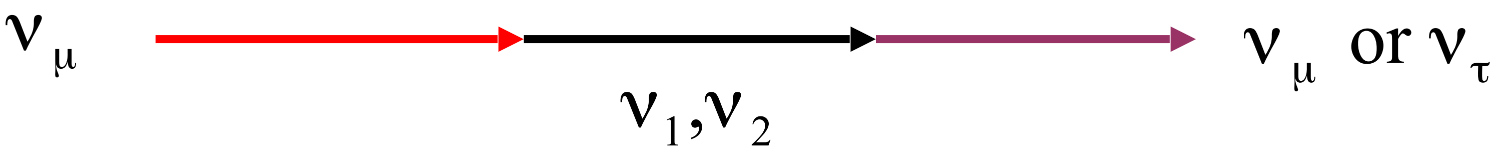
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Pontecorvo-Maki-Nakagawa-Sakata

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\delta_2} & 0 \\ 0 & 0 & e^{i\delta_3} \end{pmatrix}$$

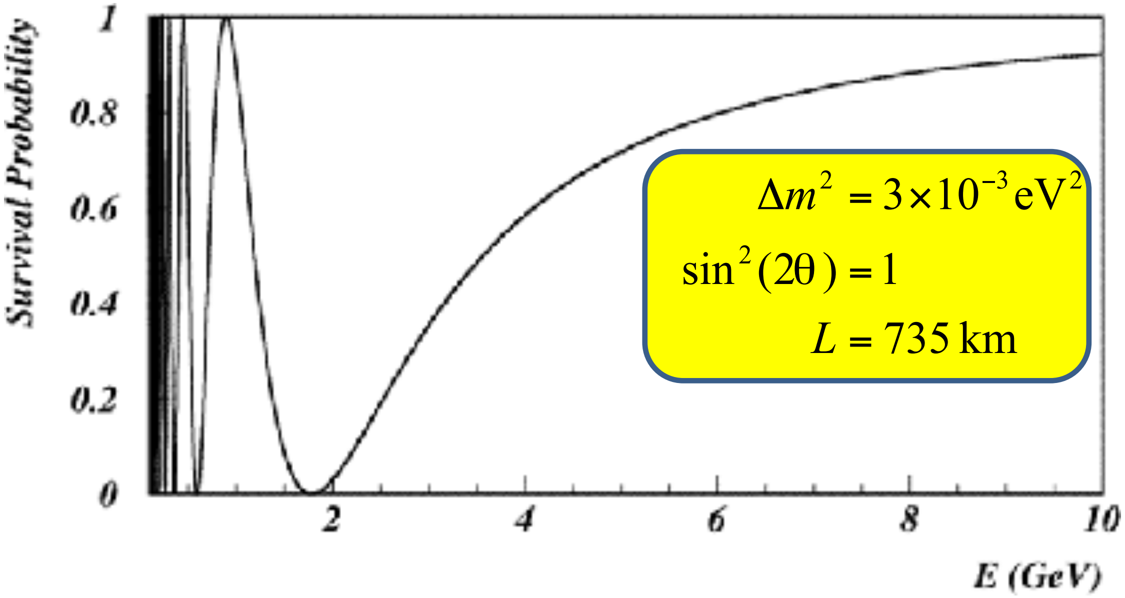
with $c_{ij} = \cos(\theta_{ij})$, $s_{ij} = \sin(\theta_{ij})$, θ_{ij} = mixing angle and Δm^2_{ij} = mass^2 difference

Oscillations for Dummies


ν_μ ν_1,ν_2 ν_μ or ν_τ

$$\begin{pmatrix}\nu_\mu\\ \nu_\tau\end{pmatrix}=\begin{pmatrix}\cos\theta & \sin\theta\\ -\sin\theta & \cos\theta\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\end{pmatrix} \qquad P(\nu_\mu\rightarrow\nu_\tau)=\sin^2(2\theta)\sin^2\left(\frac{1.27\Delta m^2 L}{E_\nu}\right)$$

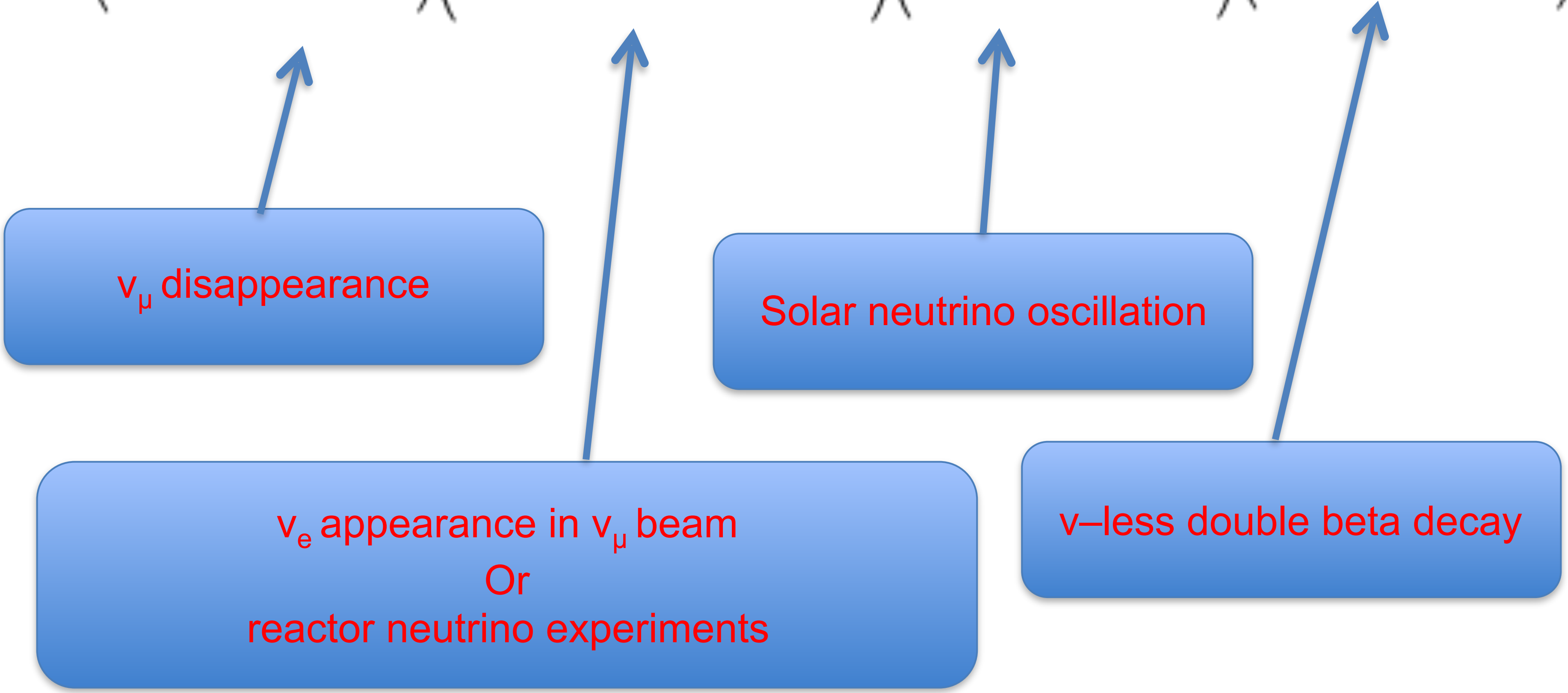
- Measure prob.
  - Survival
  - Appearance
- Result
  - Mixing angle
  - Mass differences



$$\Delta m^2 = 3\times10^{-3}\,\mathrm{eV}^2$$
$$\sin^2(2\theta)=1$$
$$L = 735\ \mathrm{km}$$

The Who-is-Who

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\delta_2} & 0 \\ 0 & 0 & e^{i\delta_3} \end{pmatrix}$$



ν_μ disappearance

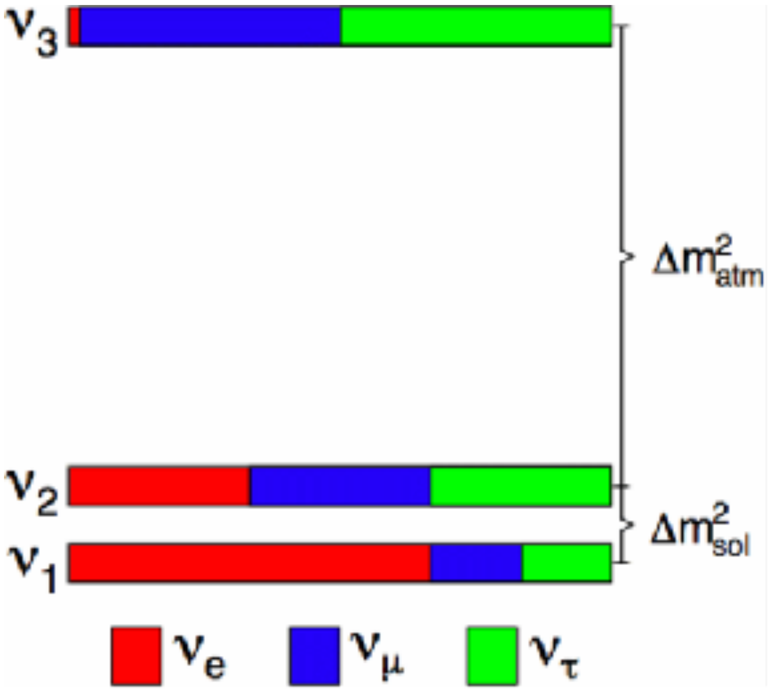
Solar neutrino oscillation

ν_e appearance in ν_μ beam
Or
reactor neutrino experiments

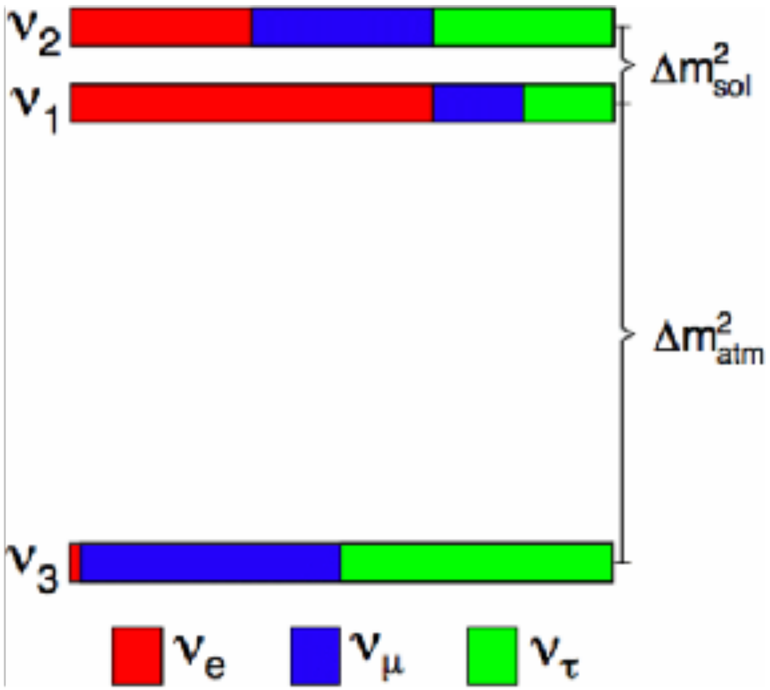
ν–less double beta decay

Mass Ordering (Hierarchy)

Normal



Inverted



Matter Effects

- Simplified treatment: two neutrinos only

In vacuum

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

in matter

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2(2\theta_m)\sin^2\left(\frac{\Delta m_m^2 L}{4E}\right)$$

$$\text{with } \sin(2\theta_m) = \frac{\sin(2\theta)}{\sqrt{(\cos 2\theta - A)^2 - \sin^2(2\theta)}}$$

$$\Delta m_m^2 = \Delta m^2\sqrt{(\cos 2\theta - A)^2 - \sin^2(2\theta)}$$

$$A = \pm\frac{2\sqrt{2}G_F N_e E}{\Delta m^2}$$

- Matter modifies oscillation probability
  - Sign of mass difference matters (opposite for anti-ν)
  - Larger effect at higher energies

The Full Monty

- Life isn't that easy
  - 3 Flavour oscillations
  - Matter effects
- The full formula

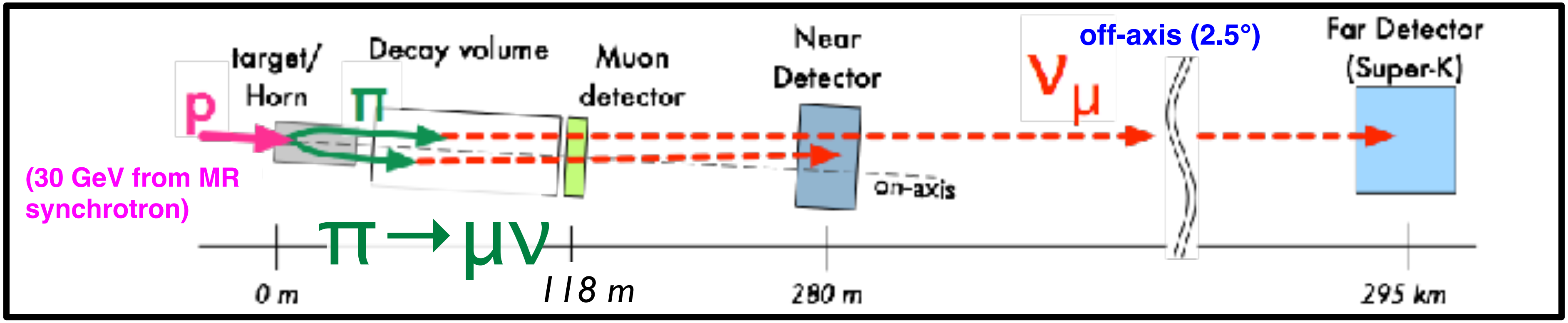
$$P(\nu_\mu \rightarrow \nu_e) = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

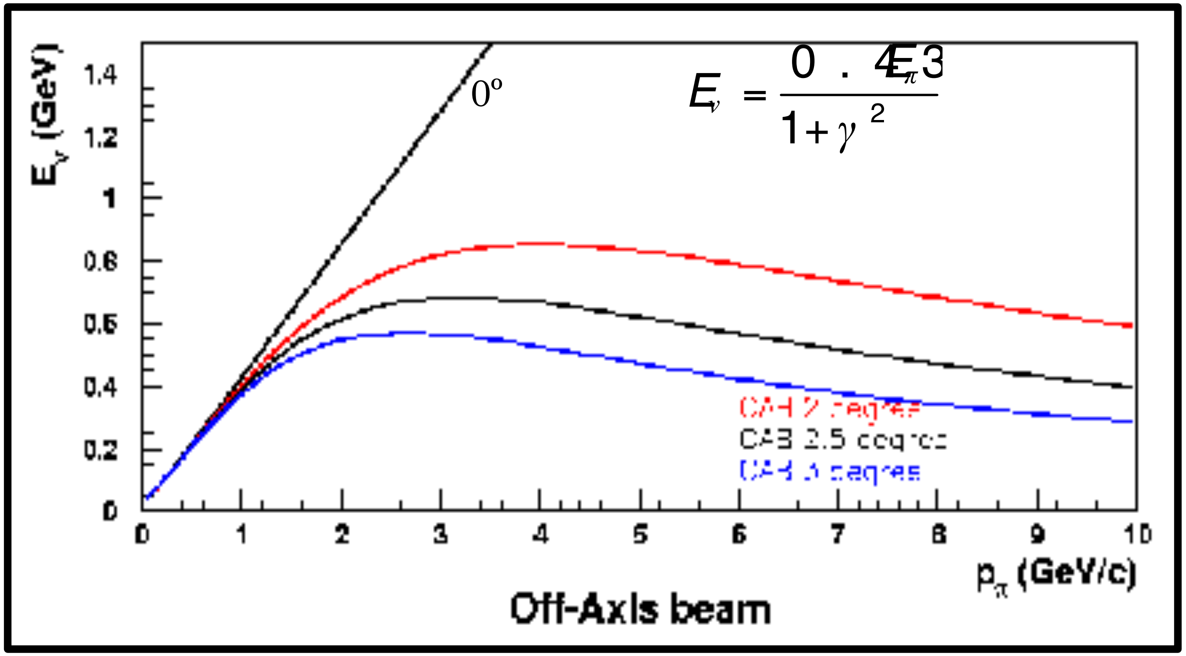
$$\begin{aligned}
P(\nu_\mu \rightarrow \nu_e) = {} & 4C_{13}^2 S_{13}^2 S_{23}^2 \sin^2 \frac{\Delta m_{31}^2 L}{4E} \times \left(1 + \frac{2a}{\Delta m_{31}^2}\left(1 - 2S_{13}^2\right)\right) \\
& + 8C_{13}^2 S_{12} S_{13} S_{23} (C_{12} C_{23} \cos\delta - S_{12} S_{13} S_{23}) \cos \frac{\Delta m_{32}^2 L}{4E} \sin \frac{\Delta m_{31}^2 L}{4E} \sin \frac{\Delta m_{21}^2 L}{4E} \\
& - 8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin\delta \sin \frac{\Delta m_{32}^2 L}{4E} \sin \frac{\Delta m_{31}^2 L}{4E} \sin \frac{\Delta m_{21}^2 L}{4E} \\
& + 4S_{12}^2 C_{13}^2 \left\{C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12} C_{23} S_{12} S_{23} S_{13} \cos\delta\right\} \sin^2 \frac{\Delta m_{21}^2 L}{4E} \\
& - 8C_{13}^2 S_{13}^2 S_{23}^2 \cos \frac{\Delta m_{32}^2 L}{4E} \sin \frac{\Delta m_{31}^2 L}{4E} \frac{aL}{4E} \left(1 - 2S_{13}^2\right)
\end{aligned}$$

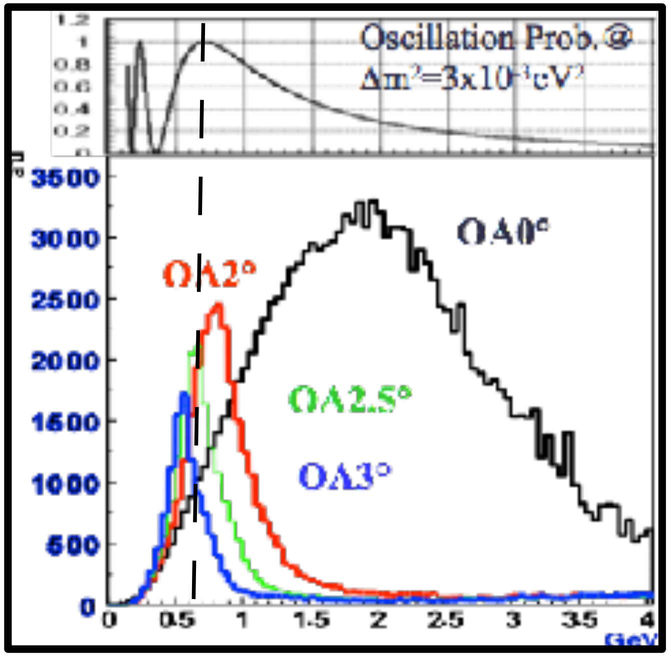
The T2K Experiment

- Neutrino Beam from J-PARC
  - Beam power 50 – 480 kW
- Far Detector
  - SuperKamiokande
  - 40 kton water Cherenkov

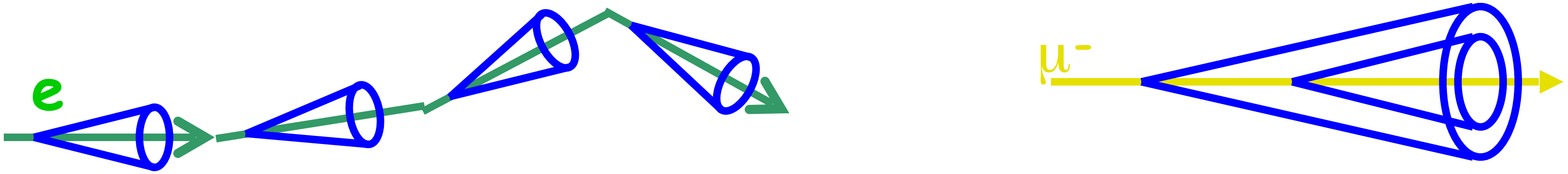
Producing Neutrinos

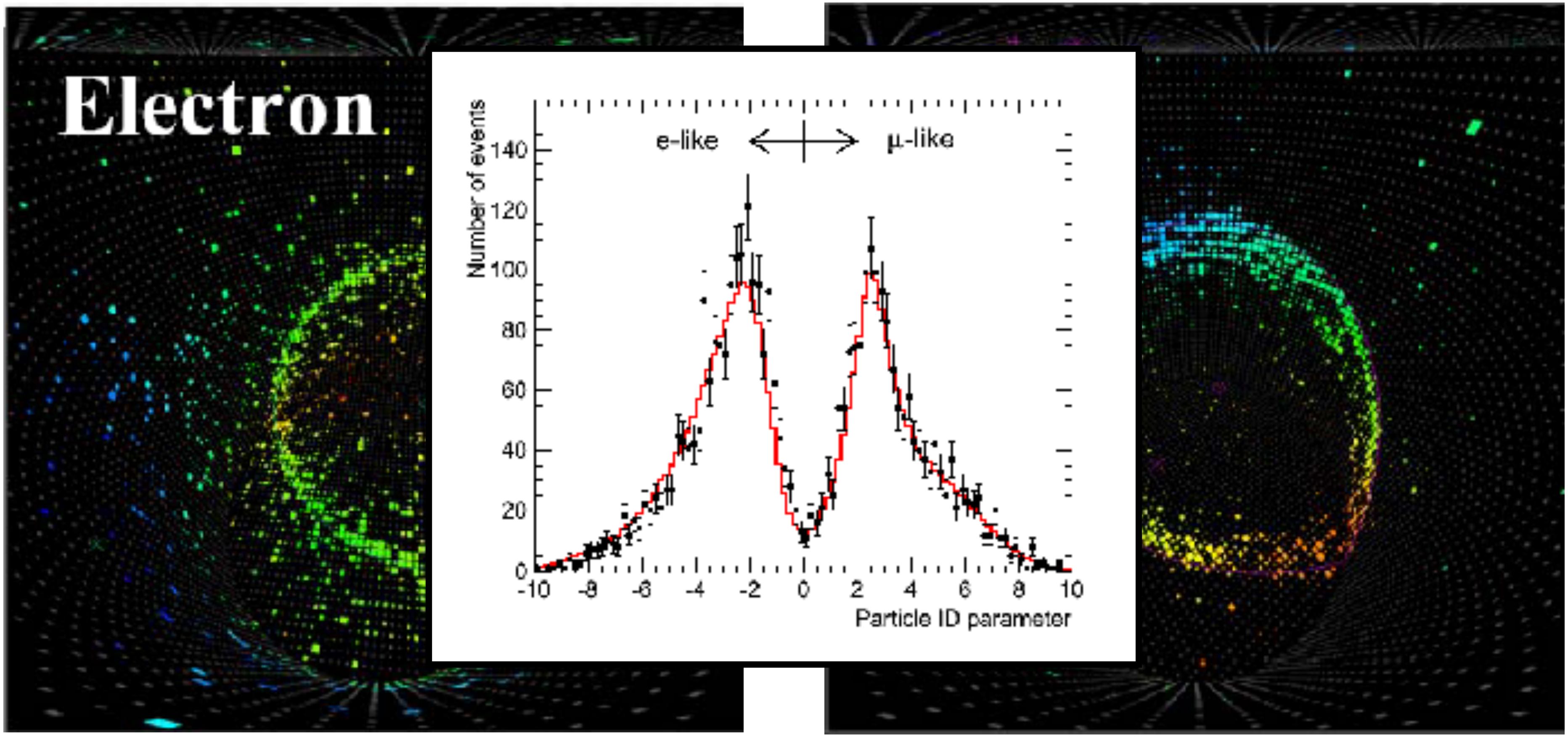




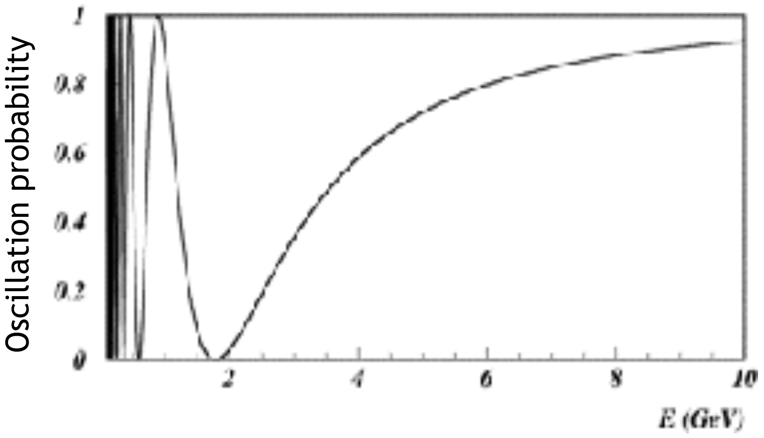


Super-Kamiokande PID

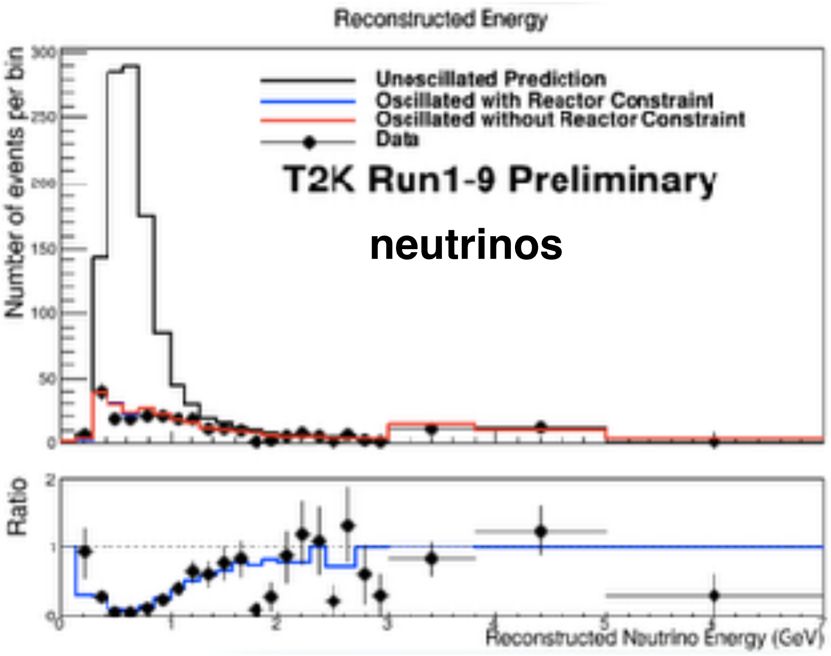


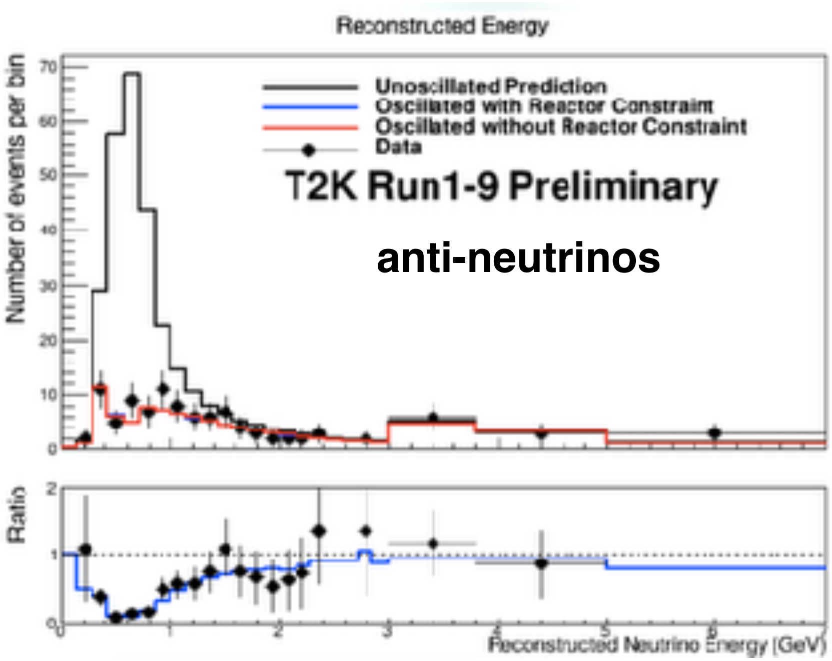


Muon Neutrino Disappearance



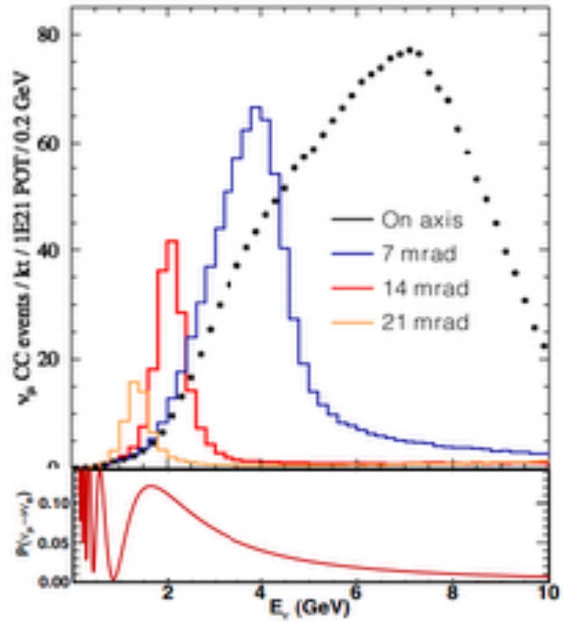
$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2(2\theta)\sin^2\left(1.27\Delta m^2 \frac{L}{E_\nu}\right)$$

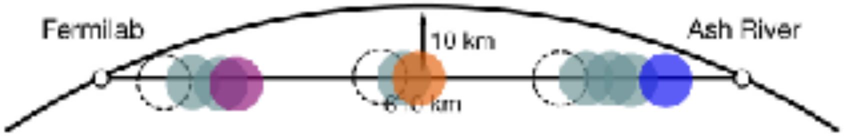




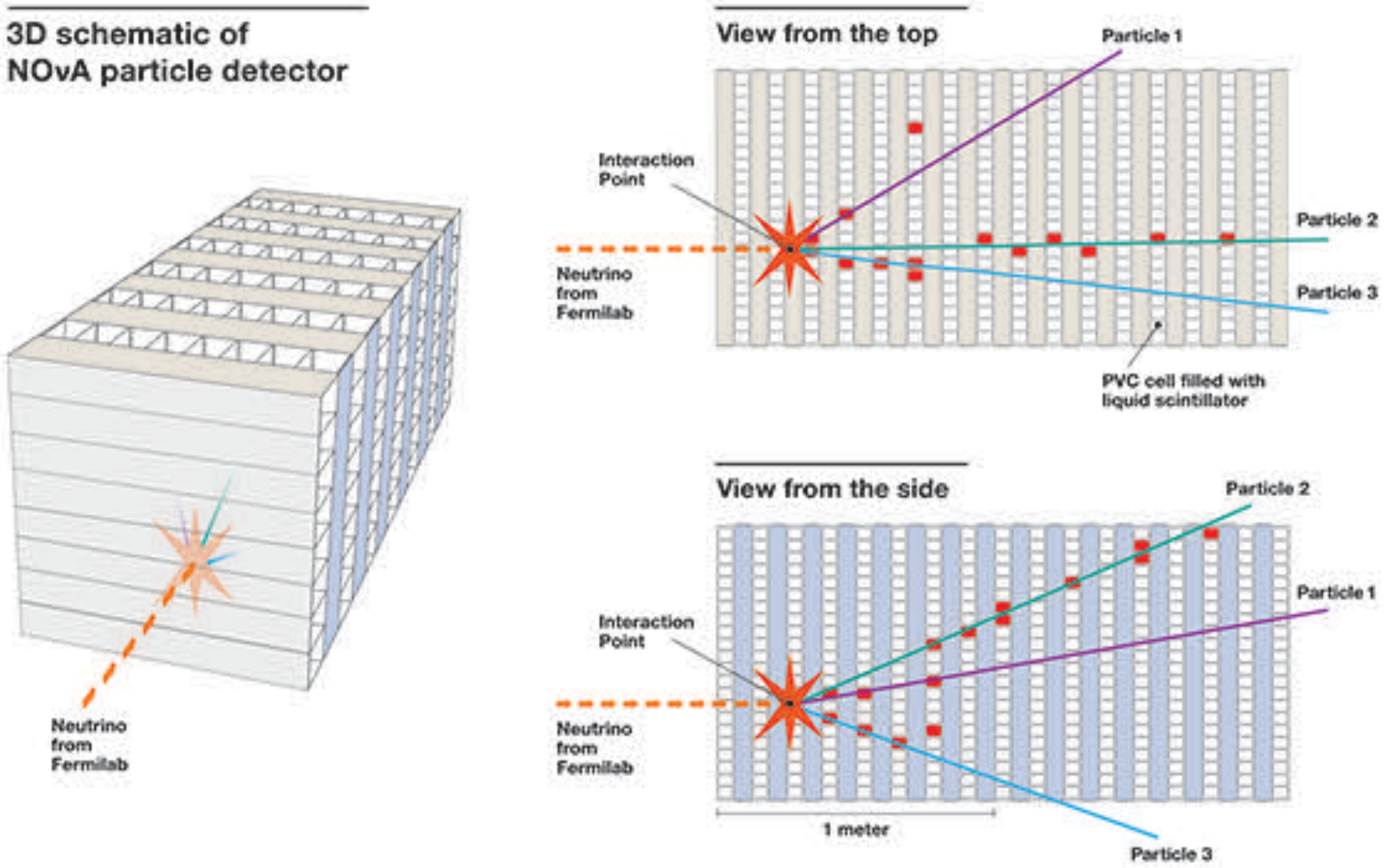
NOvA


NOvA
Ash River
International Falls
Duluth
MN
Minneapolis
WI
Fermilab
IL

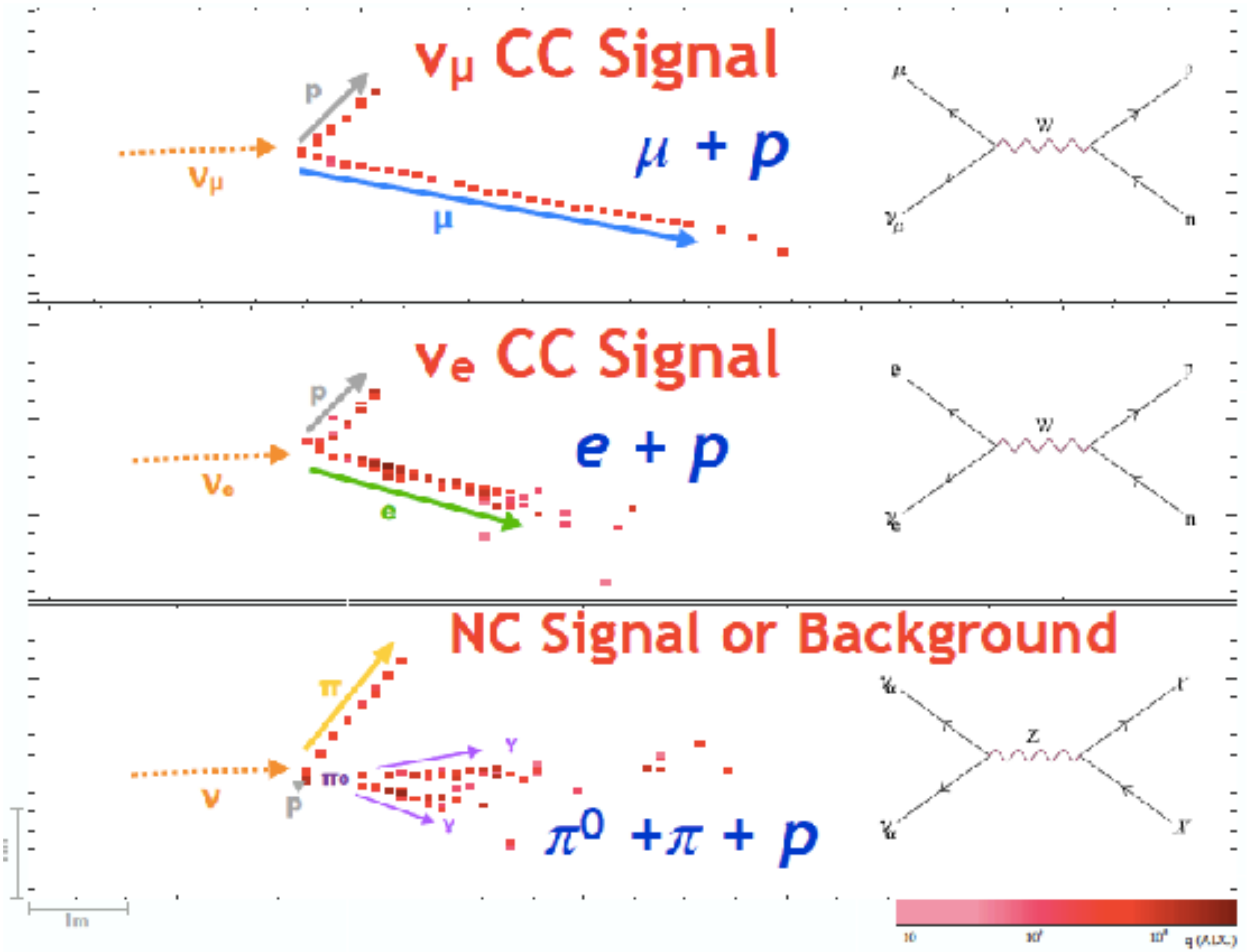

ν_μ CC events / kt / 1E21 POT / 0.2 GeV
80
60
40
20
0
On axis
7 mrad
14 mrad
21 mrad
$P(\nu_\mu \rightarrow \nu_e)$
0.10
0.05
0.00
2
4
6
8
10
E_ν (GeV)


Fermilab
10 km
810 km
Ash River

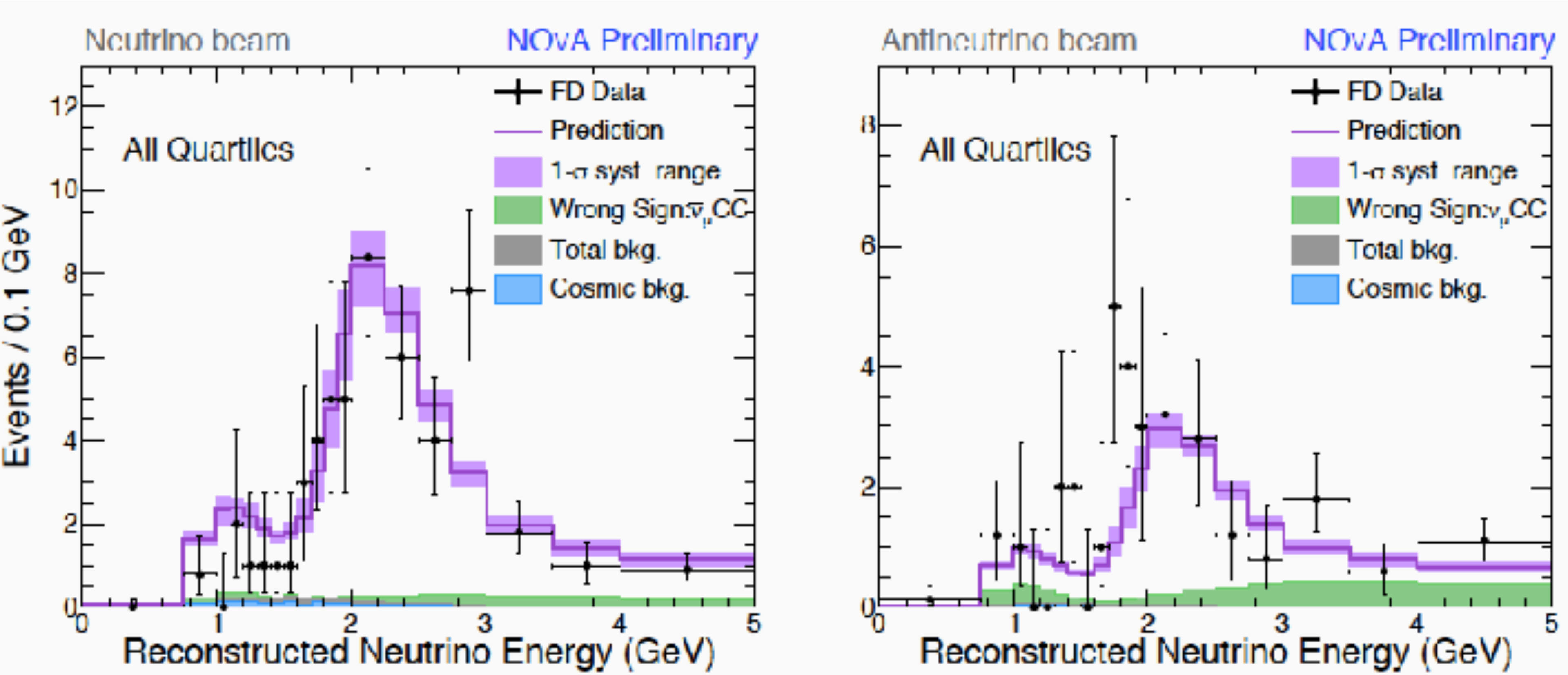
NOvA Detector Concept



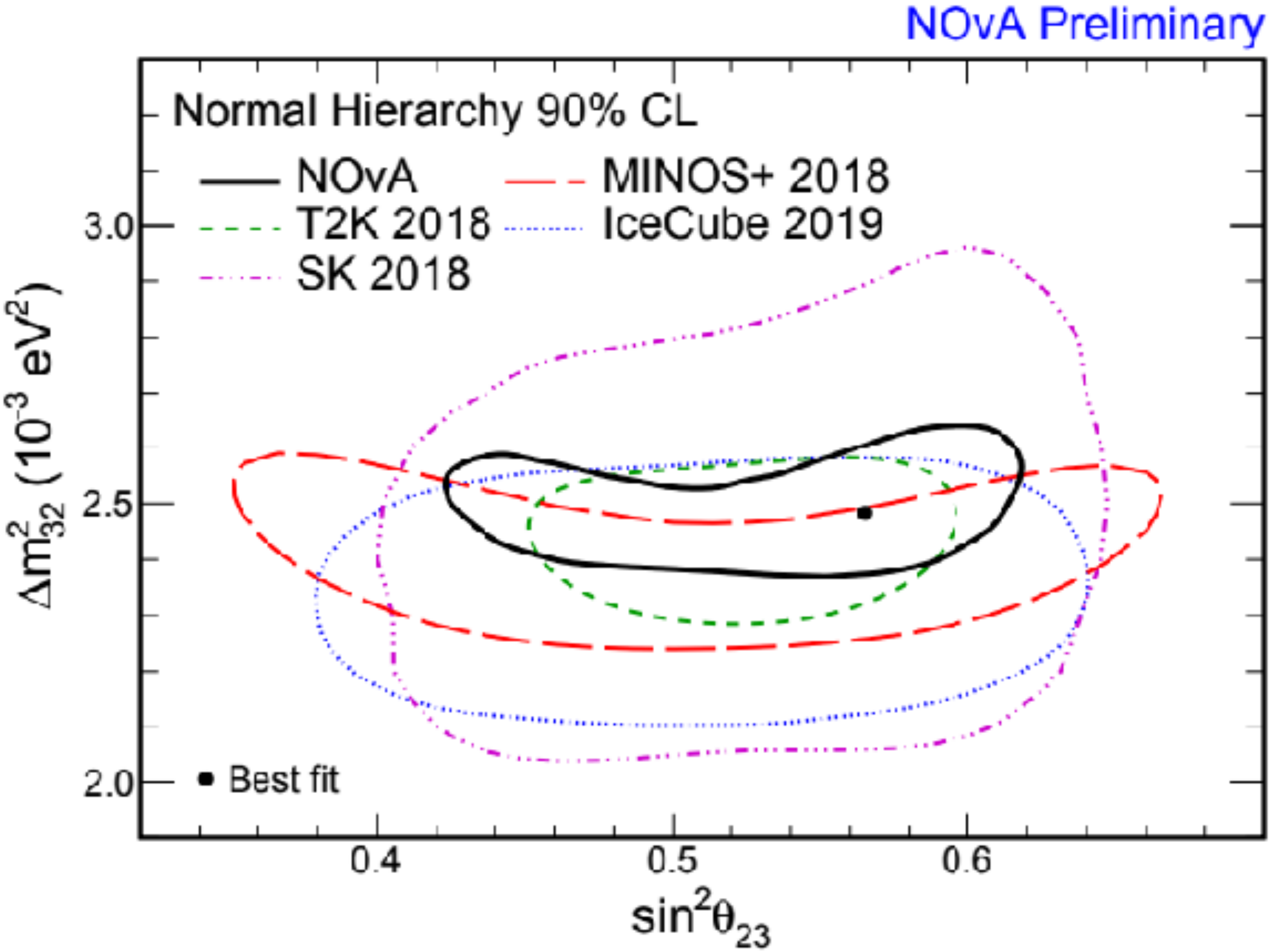
NOvA Events


νμ CC Signal
p
νμ
μ
μ + p
W
νe CC Signal
p
νe
e
e + p
W
NC Signal or Background
π
ν
p
π0
γ
γ
π0 + π + p
Z
1m
q (A.U.)

NOvA Disappearance

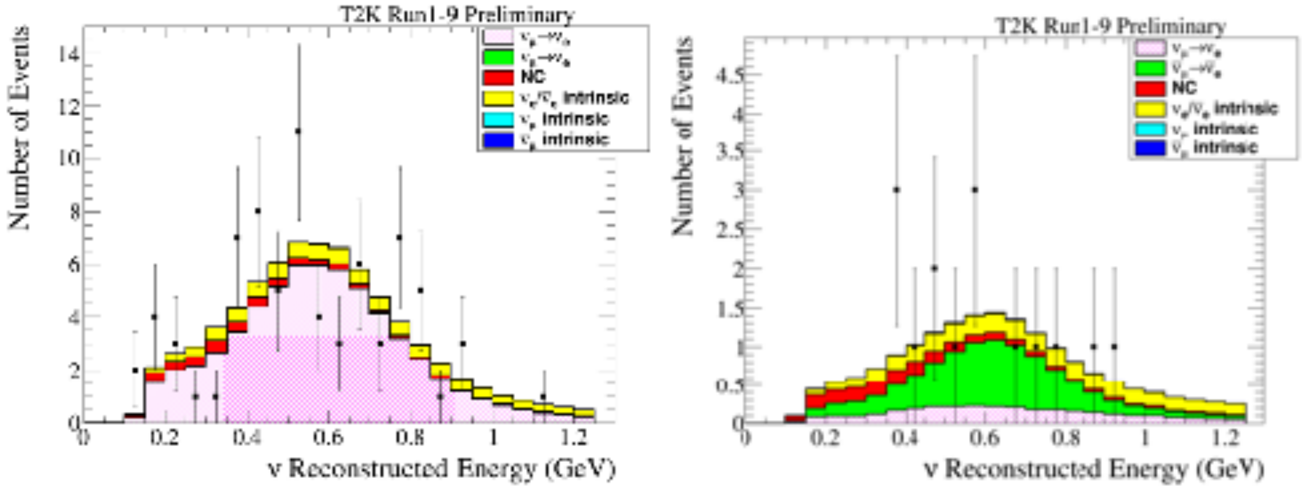


Global Picture

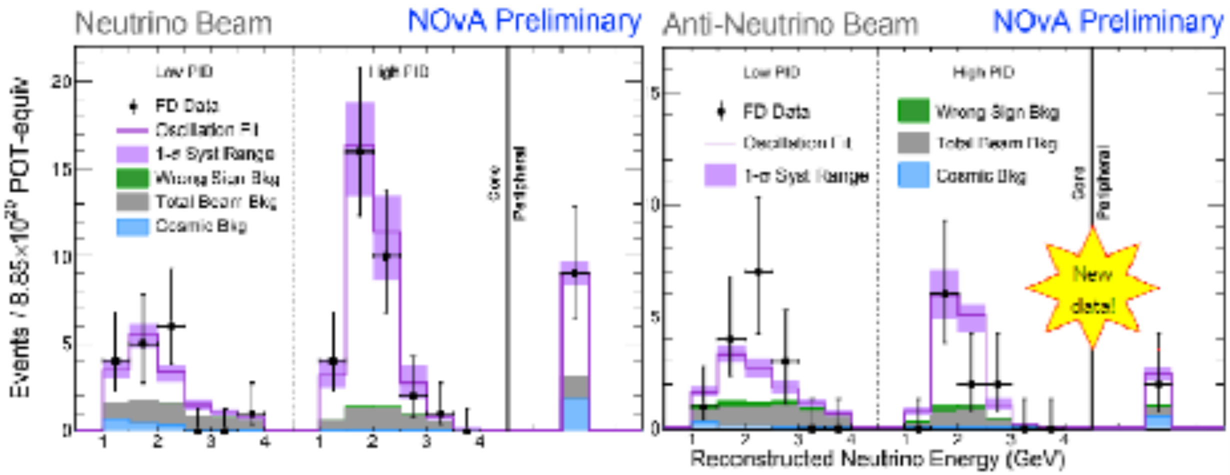


Electron Neutrino Appearance

T2K



NOvA



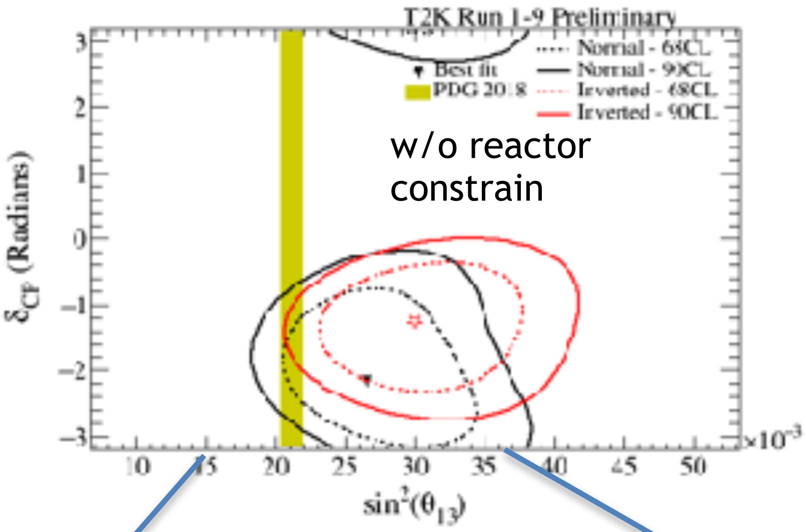
The Full Monty

$$
\begin{aligned}
P(\nu_\mu \to \nu_e) = {} & 4C_{13}^2 S_{13}^2 S_{23}^2 \sin^2\frac{\Delta m_{31}^2 L}{4E} \times \left(1 + \frac{2a}{\Delta m_{31}^2}\left(1 - 2S_{13}^2\right)\right) \\
& +8C_{13}^2 S_{12} S_{13} S_{23} (C_{12} C_{23} \cos\delta - S_{12} S_{13} S_{23}) \cos\frac{\Delta m_{32}^2 L}{4E} \sin\frac{\Delta m_{31}^2 L}{4E} \sin\frac{\Delta m_{21}^2 L}{4E} \\
& \boxed{-8C_{13}^2 C_{12} C_{23} S_{12} S_{13} S_{23} \sin\delta \sin\frac{\Delta m_{32}^2 L}{4E} \sin\frac{\Delta m_{31}^2 L}{4E} \sin\frac{\Delta m_{21}^2 L}{4E}} \\
& +4S_{12}^2 C_{13}^2 \left\{C_{12}^2 C_{23}^2 + S_{12}^2 S_{23}^2 S_{13}^2 - 2C_{12} C_{23} S_{12} S_{23} S_{13} \cos\delta\right\} \sin^2\frac{\Delta m_{21}^2 L}{4E} \\
& -8C_{13}^2 S_{13}^2 S_{23}^2 \cos\frac{\Delta m_{32}^2 L}{4E} \sin\frac{\Delta m_{31}^2 L}{4E} \frac{aL}{4E} \left(1 - 2S_{13}^2\right)
\end{aligned}
$$

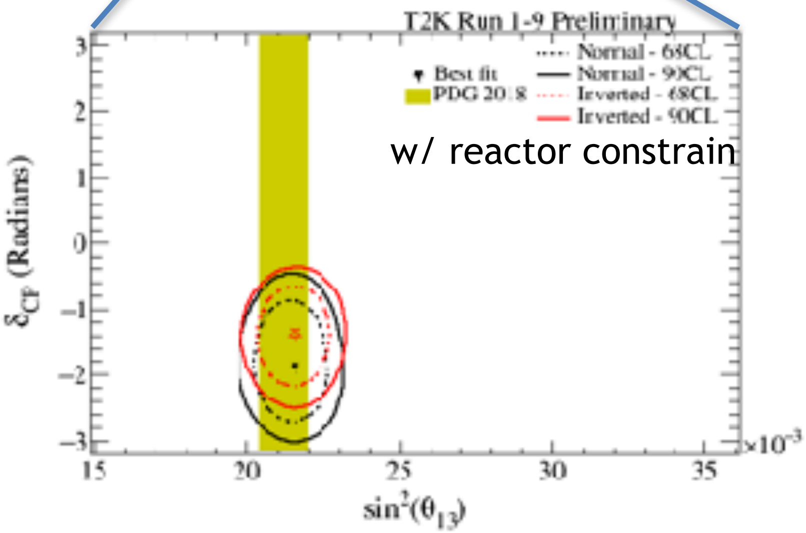
sin(δ) changes sign for anti-neutrinos

- δ is CP-violating phase
- Matter ⇔ anti-matter difference

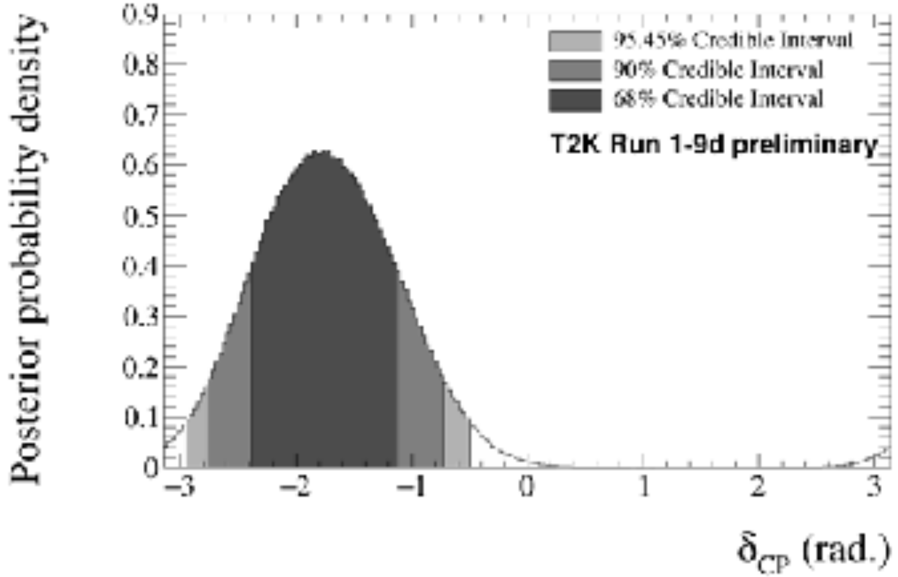
T2K Results



w/o reactor constrain



w/ reactor constrain

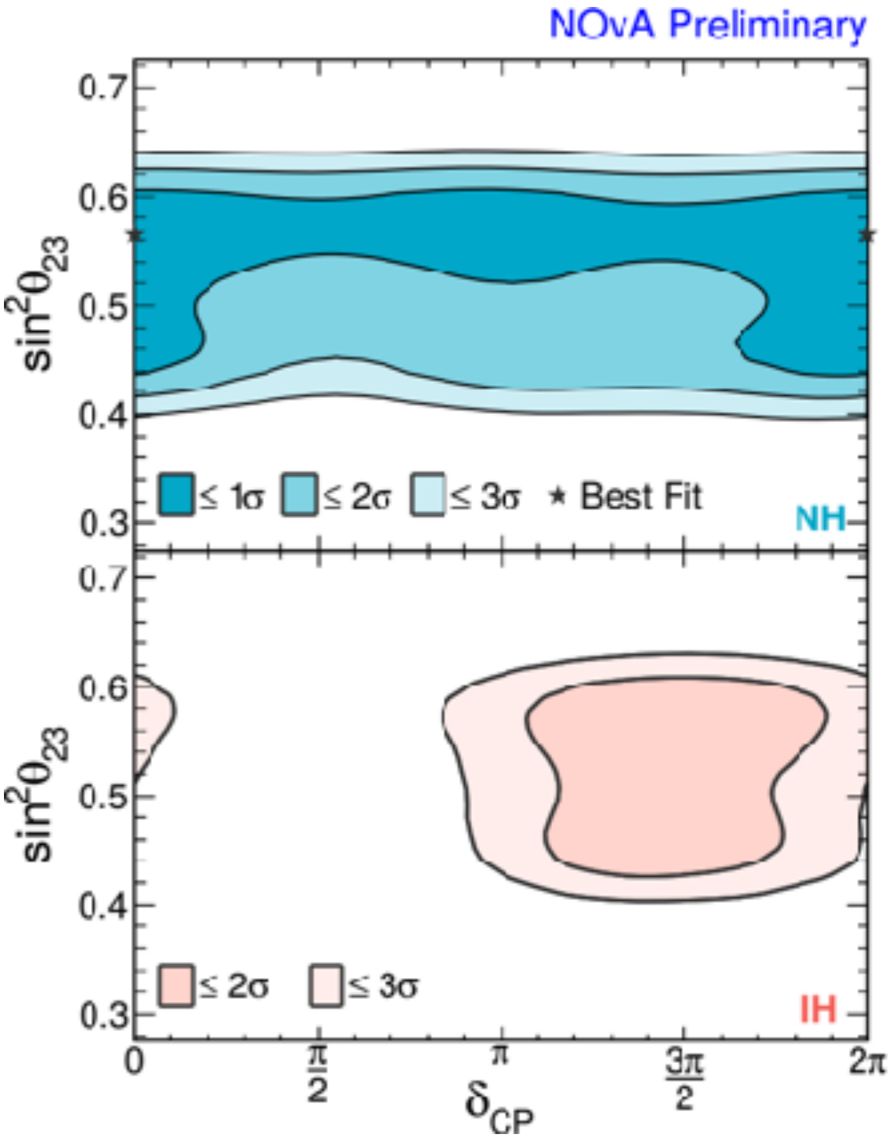


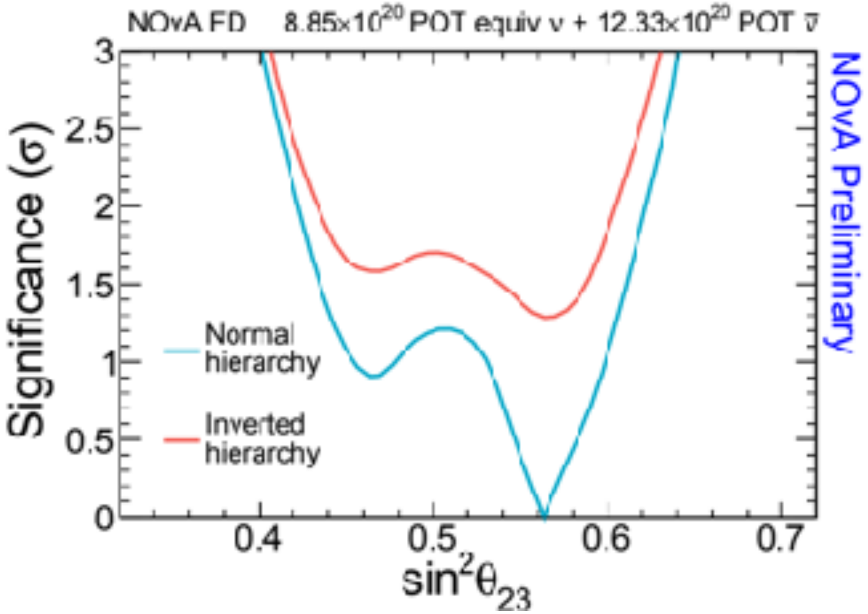
Bayesian Posterior Probabilities

	$\sin^2\theta_{23} \leq 0.5$	$\sin^2\theta_{23} > 0.5$	SUM
NH ($\Delta m^2_{32} > 0$)	0.184	0.705	0.889
IH ($\Delta m^2_{31} < 0$)	0.021	0.090	0.111
SUM	0.205	0.795	1

Bayes factor NH/IH=8: moderate evidence

NOvA Results





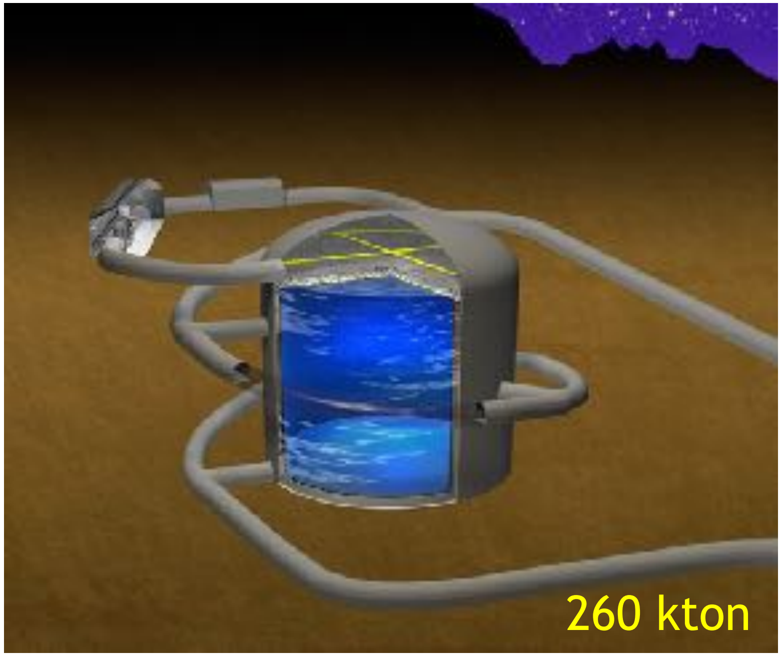
Best fit:

- $\sin^2\theta_{23} = 0.56^{+0.04}_{-0.03}$
- $\Delta m^2_{32} = +2.48^{+0.11}_{-0.06} \times 10^{-3}\,\mathrm{eV}^2/c^4$ (NH)
- $\delta_{CP} = 0.0^{+1.3}_{-0.4}\,\pi$

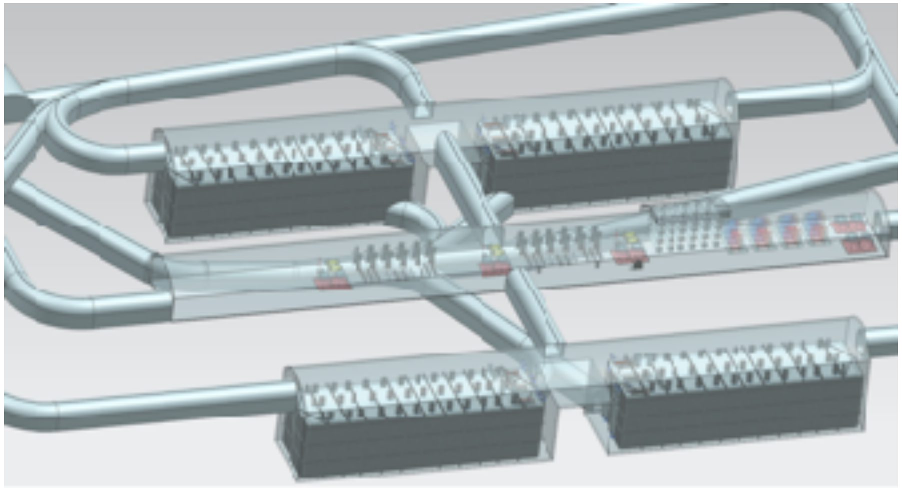
Quo Vadis?

- Bigger Detectors
- Mega-Watt Beams

HyperK

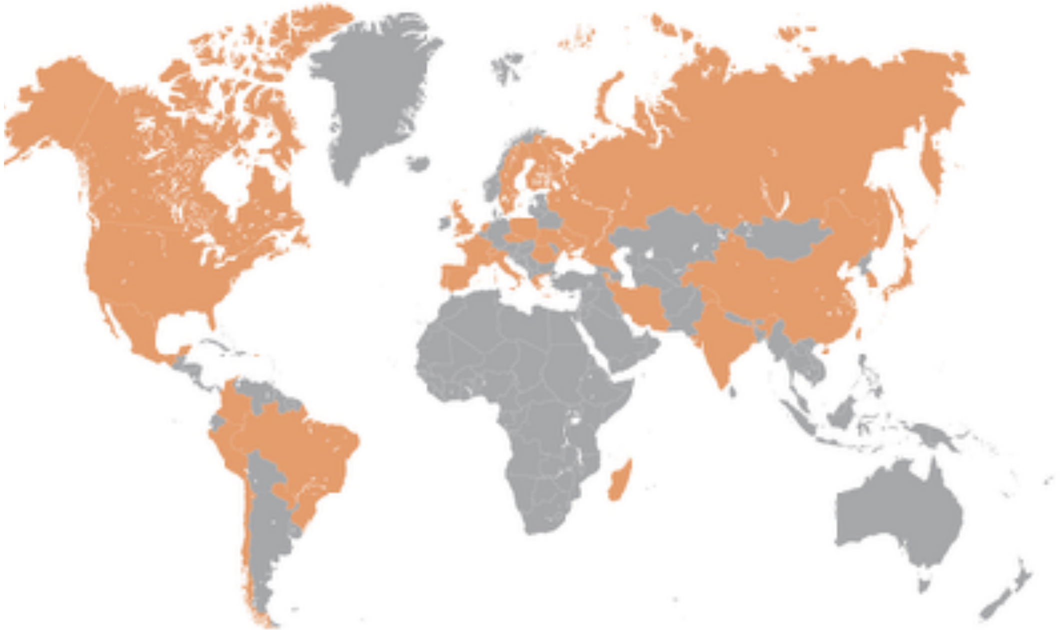


DUNE



4x ~10 kton

DEEP UNDERGROUND NEUTRINO EXPERIMENT

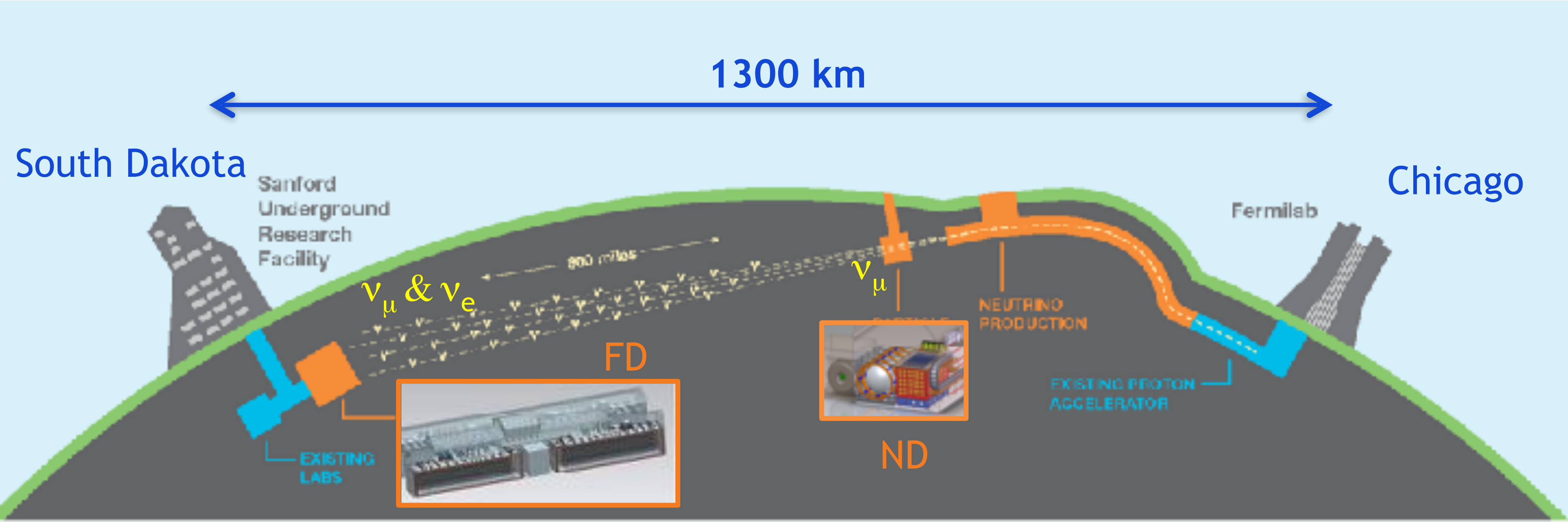


An international science collaboration

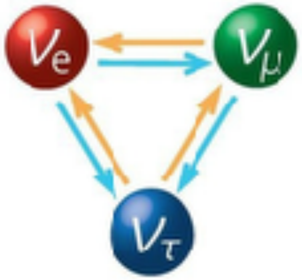
1106 collaborators from **184 institutions** in **31 countries**

General Setup

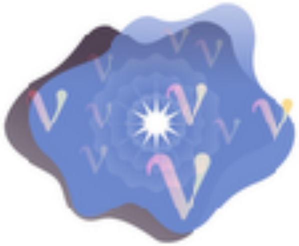
- LBNF/DUNE will consist of
  - An intense 1.2 MW upgradeable ν-beam fired from Fermilab
  - A massive 68 kt (40kt instrumented) deep underground LAr detector in South Dakota and a large Near Detector at Fermilab
  - A large international collaboration



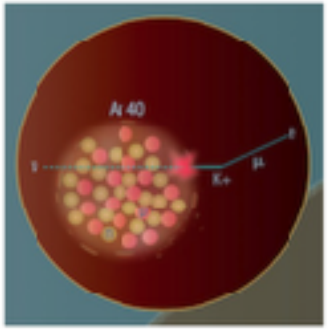
Physics Program



- Neutrino Oscillations
  - Search for leptonic CP violation
  - Determine neutrino mass ordering
  - Precision PMNS measurements



- Supernova Physics
  - Observation of time and flavour profile provides insight into collapse and evolution of supernova
  - Unique sensitivity to electron neutrinos

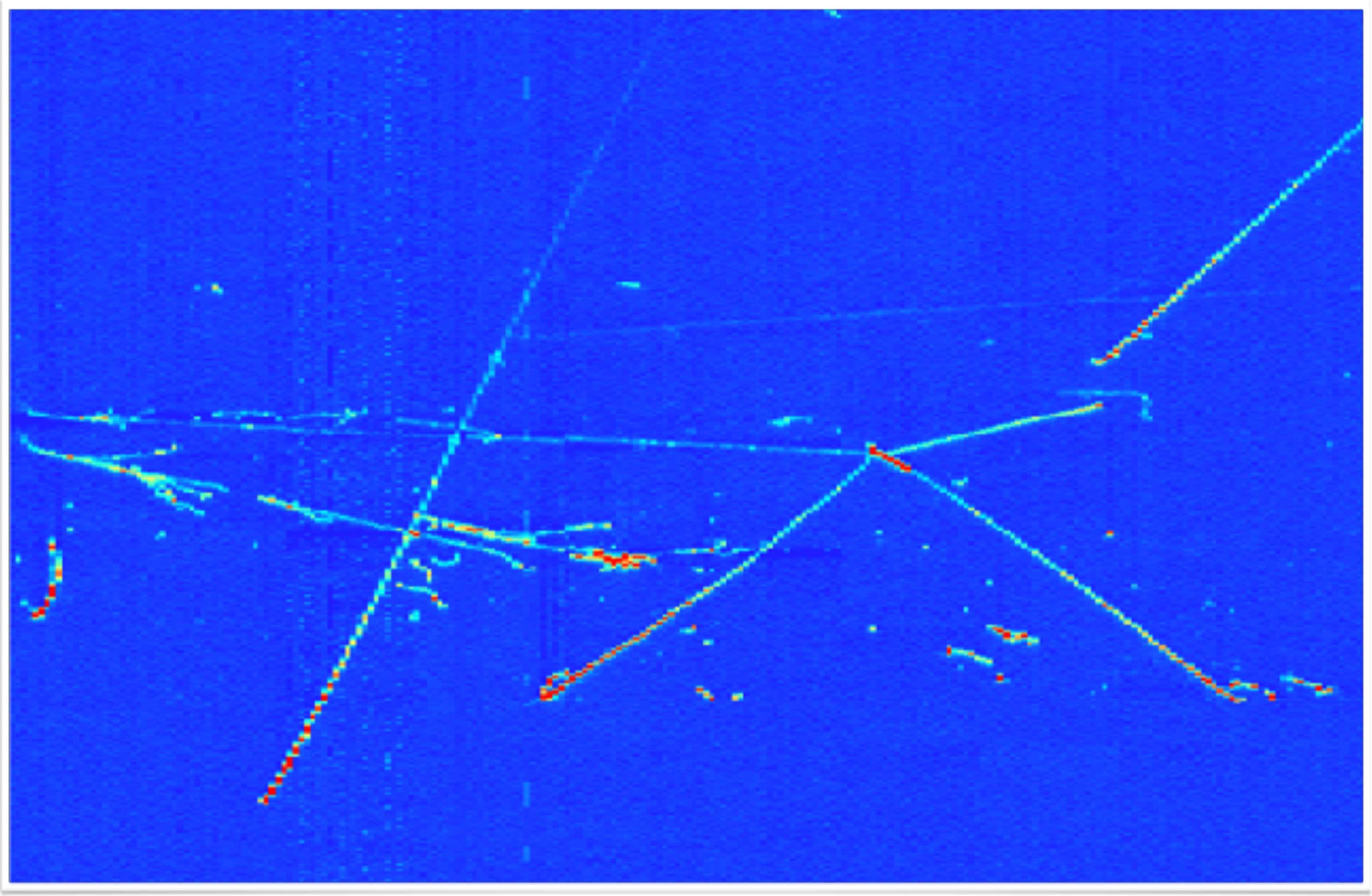


- Baryon number violation
  - Predicted by many BSM theories
  - LAr TPC technology well-suited to certain proton decay channels (*e.g.*, p→K+ν) –
  - Δ(B-L) ≠ 0 channels accessible (*e.g.*, n→n̄)

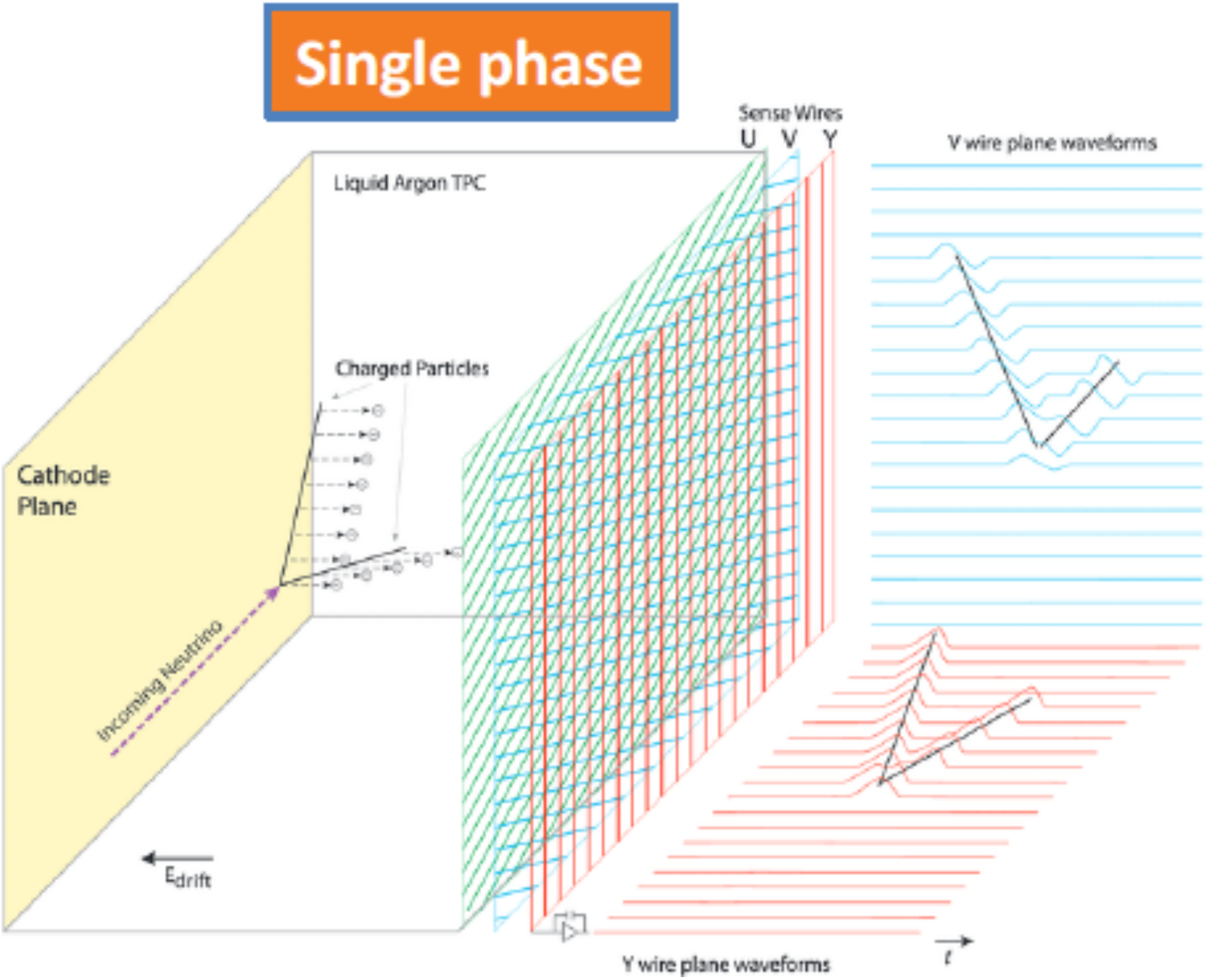
Liquid Argon Detectors (TPC)

- **Dense**:
  40% denser than water
- **Cheap**:
  abundant (1% of atmos.)
- **Ionizes easily**:
  55,000 electrons/cm
- **Excellent scintillation**:
  20,000 photons/MeV
  (@ 500 V/cm)

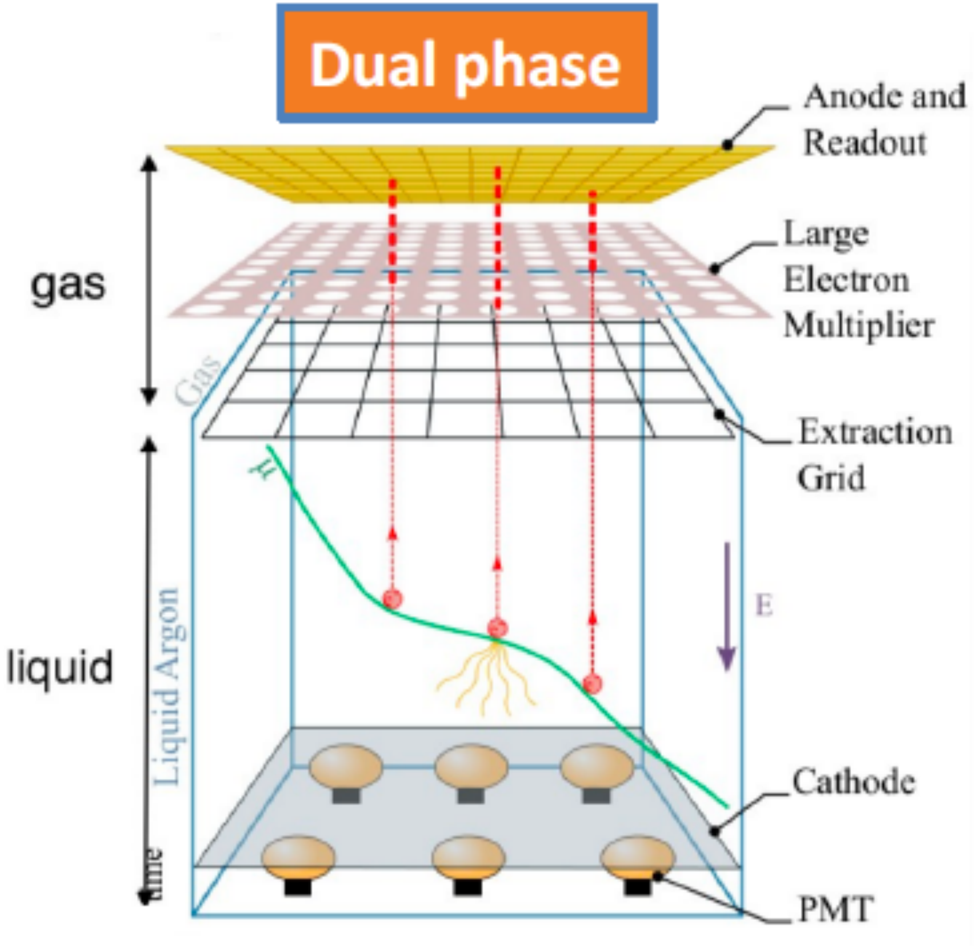
Unmatched Imaging Details



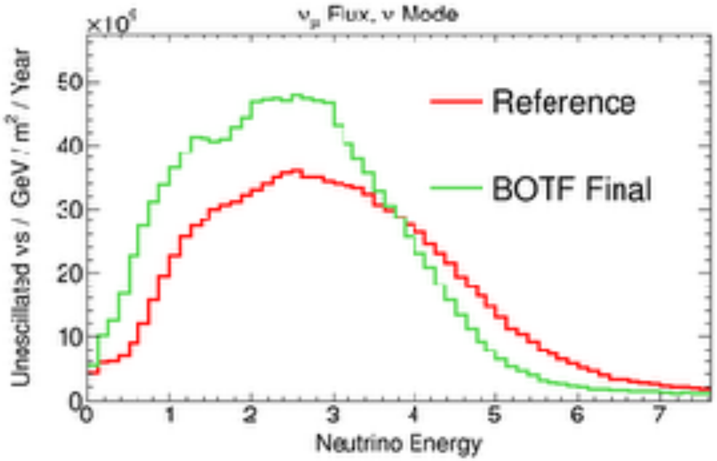
Single Phase Technology

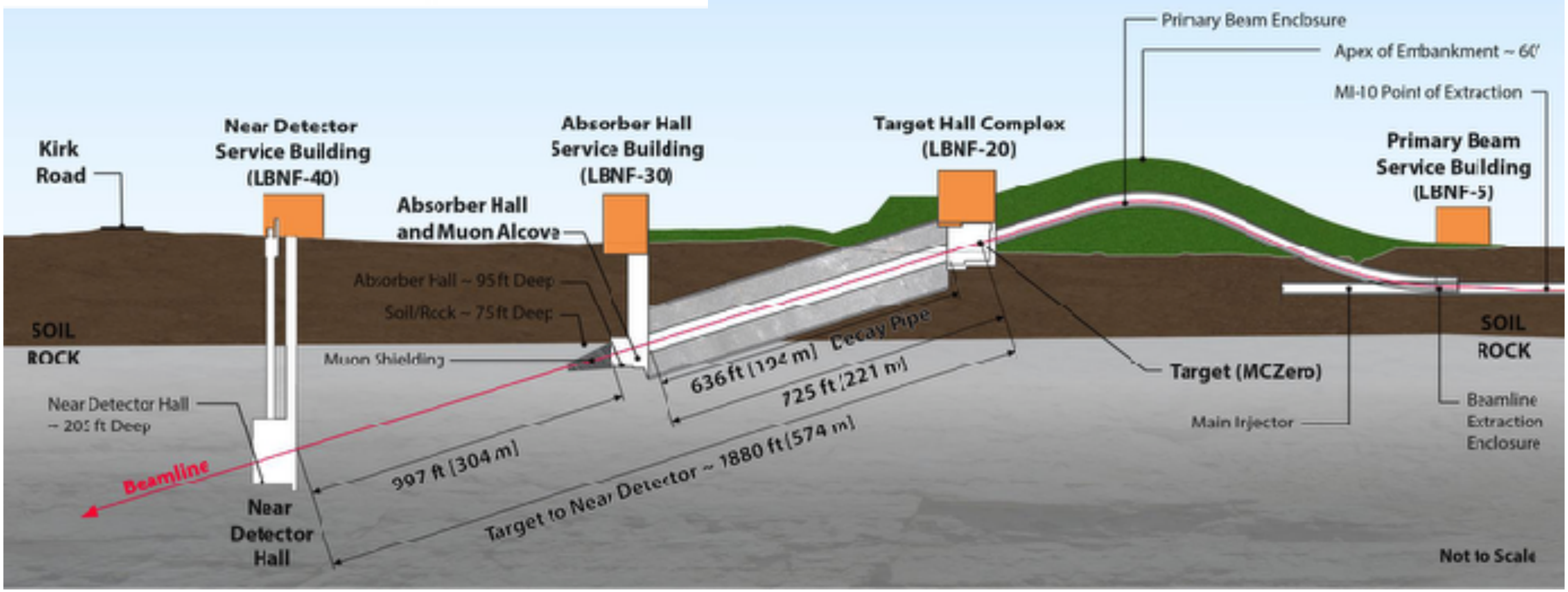


Dual Phase Technology



Beam


ν_μ Flux, ν Mode
$\times10^6$
Unoscillated vs / GeV / m^2 / Year
0
10
20
30
40
50
0
1
2
3
4
5
6
7
Neutrino Energy
Reference
BOTF Final


Primary Beam Enclosure
Apex of Embankment ~ 60'
MI-10 Point of Extraction
Kirk Road
Near Detector Service Building (LBNF-40)
Absorber Hall Service Building (LBNF-30)
Target Hall Complex (LBNF-20)
Primary Beam Service Building (LBNF-5)
Absorber Hall and Muon Alcove
Absorber Hall ~ 95ft Deep
Soil/Rock ~ 75ft Deep
Muon Shielding
SOIL
ROCK
Near Detector Hall ~ 205 ft Deep
Decay Pipe
636 ft (194 m)
725 ft (221 m)
997 ft (304 m)
Target to Near Detector ~ 1880 ft (574 m)
Target (MCZero)
Main Injector
Beamline Extraction Enclosure
SOIL
ROCK
Beamline
Near Detector Hall
Not to Scale

How to Measure Oscillations

- Oscillation probabilities

$$P_{\nu_\mu \to \nu_e}(E_\nu) = \frac{\phi_{\nu_e}^{far}(E_\nu)}{\phi_{\nu_\mu}^{far,no-osc}(E_\nu)} = \frac{\phi_{\nu_e}^{far}(E_\nu)}{\phi_{\nu_\mu}^{near}(E_\nu) * F_{far/near}(E_\nu)}$$

Well known (1-2%)

- Number of events/energy spectrum

$$\frac{dN_\nu^{det}}{dE_\nu} = \phi_{\nu_\mu}^{det}(E_\nu) * \sigma_{\nu_\mu}^{Ar}(E_\nu)$$

- In reality

$$\frac{dN_\nu^{det}}{dE_{rec}} = \int \phi_\nu^{det}(E_\nu) * \sigma_\nu^{target}(E_\nu) * T_{\nu_\mu}^{det}(E_\upsilon, E_{rec}) \; dE_\nu$$

- Folding of detector effects
  - Prevents (easy) cancellations of many systematic effects
  - Needs unfolding

Are there cancellations?

- Oscillation signal

$$\frac{\dfrac{dN^{far}_{\nu_e}}{dE_\upsilon}}{\dfrac{dN^{near}_{\nu_\mu}}{dE_\upsilon}} = P_{\nu_\mu\to\nu_e}(E_\nu) * \frac{\sigma^{Ar}_{\nu_e}(E_\nu)}{\sigma^{Ar}_{\nu_\mu}(E_\nu)} * F_{far/near}(E_\nu)$$

Small theo. uncertainty or measurement

1-2% uncertainty

- Near muon/electron ratio

$$\frac{\dfrac{dN^{near}_{\nu_e}}{dE_\upsilon}}{\dfrac{dN^{near}_{\nu_\mu}}{dE_\upsilon}} = \frac{\sigma^{Ar}_{\nu_e}(E_\nu)}{\sigma^{Ar}_{\nu_\mu}(E_\nu)} * \frac{\phi^{near}_{\nu_e}(E_\nu)}{\phi^{near}_{\nu_\mu}(E_\nu)}$$

Not so small uncertainty

- Need to know
  - Flux & cross section ratios
  - Far/near extrapolation

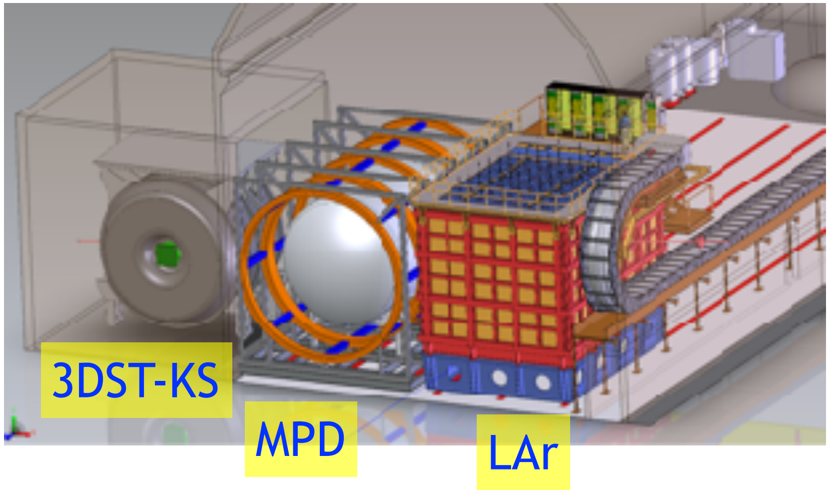
But in Reality

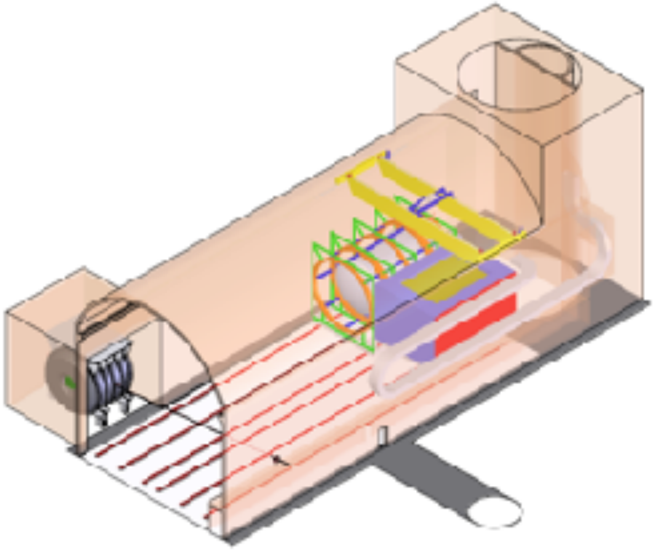
$$\frac{\frac{dN^{far}_{\nu_e}}{dE_{rec}}}{\frac{dN^{near}_{\nu_\mu}}{dE_{rec}}} = \frac{\int P_{\nu_\mu\to\nu_e}\left(E_\nu\right) * \phi^{near}_{\nu_\mu}\left(E_\nu\right) * F_{far/near}(E_\nu) * \sigma^{Ar}_{\nu_e}\left(E_\nu\right) * T^{far}_{\nu_e}\left(E_v, E_{rec}\right)\ dE_\nu}{\int \phi^{near}_{\nu_\mu}\left(E_\nu\right) * \sigma^{Ar}_{\nu_\mu}\left(E_\nu\right) * T^{near}_{\nu_\mu}\left(E_v, E_{rec}\right)\ dE_\nu}$$

- No cancellations
  - Unless you unfold
- Need to understand especially
  - Detector effects in near and far detector
  - Relation of visible to neutrino energy
  - Cross section ratios
  - Near to far flux extrapolation
- Flux normalisation cancels
  - Shape is more important

Near Detector Complex

- Four main components, working together:
  1. Liquid argon detector (ArgonCube)
  2. Downstream tracker with gaseous argon target (MPD)
  3. LAr and GAr systems can move to off-axis fluxes (DUNE PRISM)
  4. On-axis flux monitor with neutron detection capability (3DST-KS)
- High statistics constrains
  - Cross section & Flux





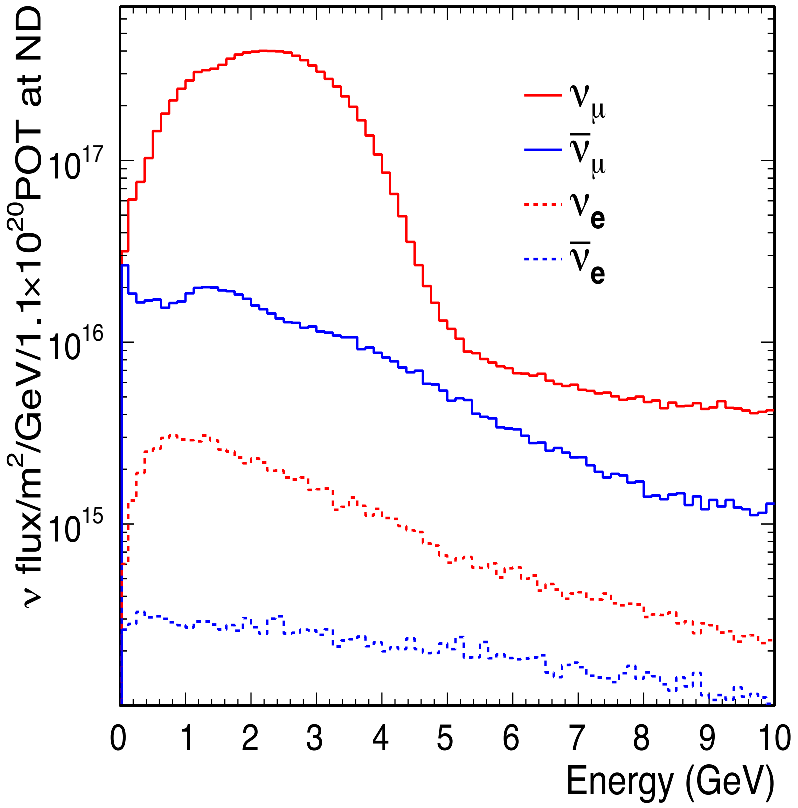
Detector Functionality

Multi-pronged approach

- ν interactions on Ar
  - LAr provides ν-Ar interaction as seen by FD
  - MPD provides ν-Ar interactions with sign selection, very low thresholds, and minimal secondary interactions
- Integration
  - MPD is necessary to complete reconstruction of events in LAr detector
    - μ spectrometer
  - ECAL necessary to complete reconstruction of interactions in the HPgTPC
- Beyond interactions on Ar
  - 3DST-KS provides detailed fixed, on-axis beam monitoring
  - 3DST-KS provides look at ν-CH interactions with novel neutron detection capabilities

Flux & Event Rates @ ND570

Optimized CPV tune
FHC On-axis
1.25 MW

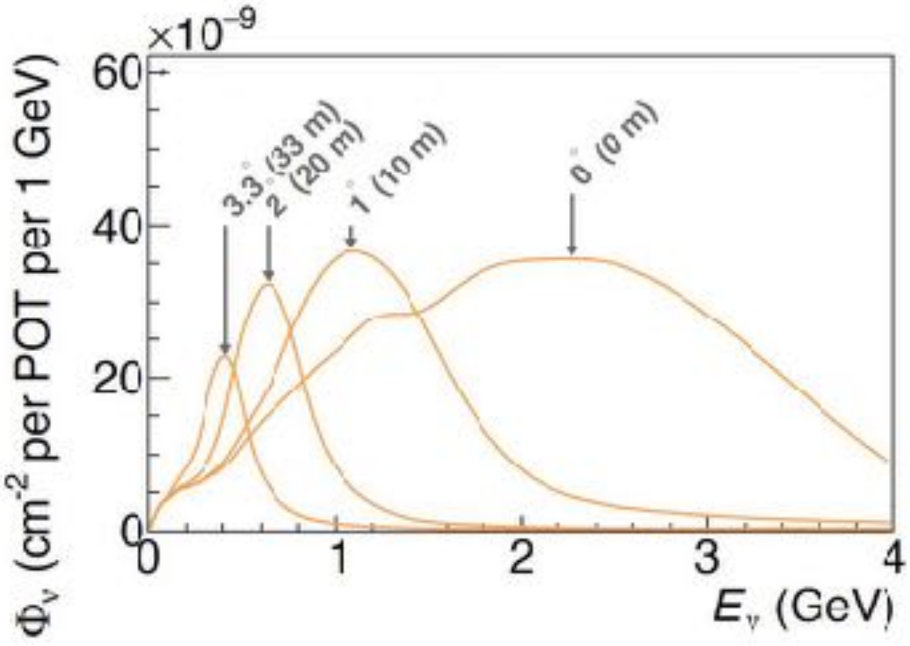


Events/year in Fiducial volume

Detector	Target (Fid. mass t)	# ν_μ CC (X10^6)
LAr	Ar (50)	80
HPgTPC	Ar (1)	1.5
3DST-KS	CH (8)	12

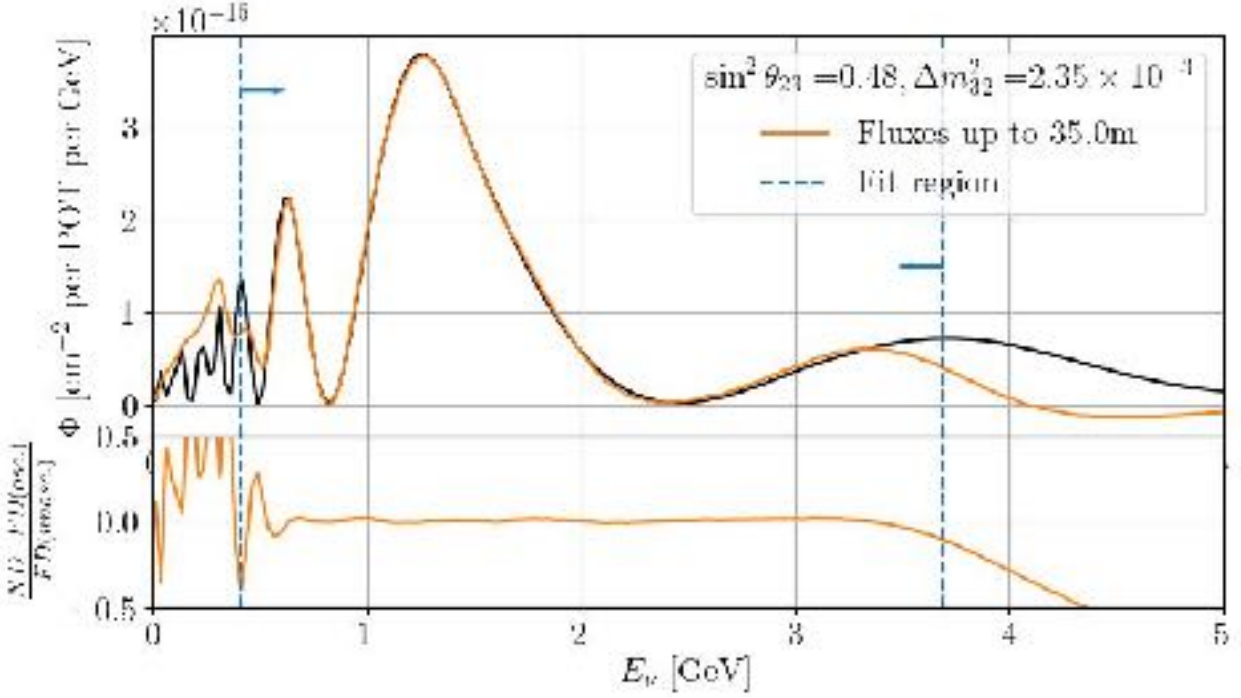
Taking Data Off-axis

- The DUNE near detector complex will allow for off-axis running in order to accommodate the PRISM concept
  - Precision Reaction Independent Spectrum Measurement
- Flux varies as a function of detector transverse position
  - Pseudo-monochromatic beams can be formed by taking linear combinations of beam data at different off-axis positions
  - These can help in understanding of relationship between E_ν and E_{reco} and thus help deconvolve the flux and cross section uncertainties
  - Can predict oscillated neutrino event spectra at FD with reduced model dependence

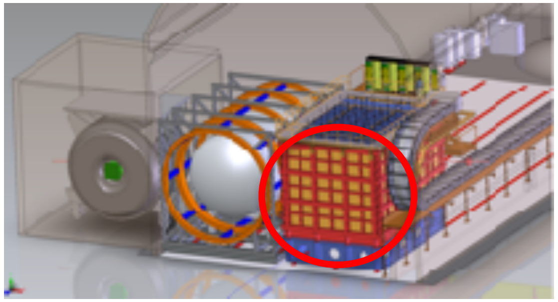


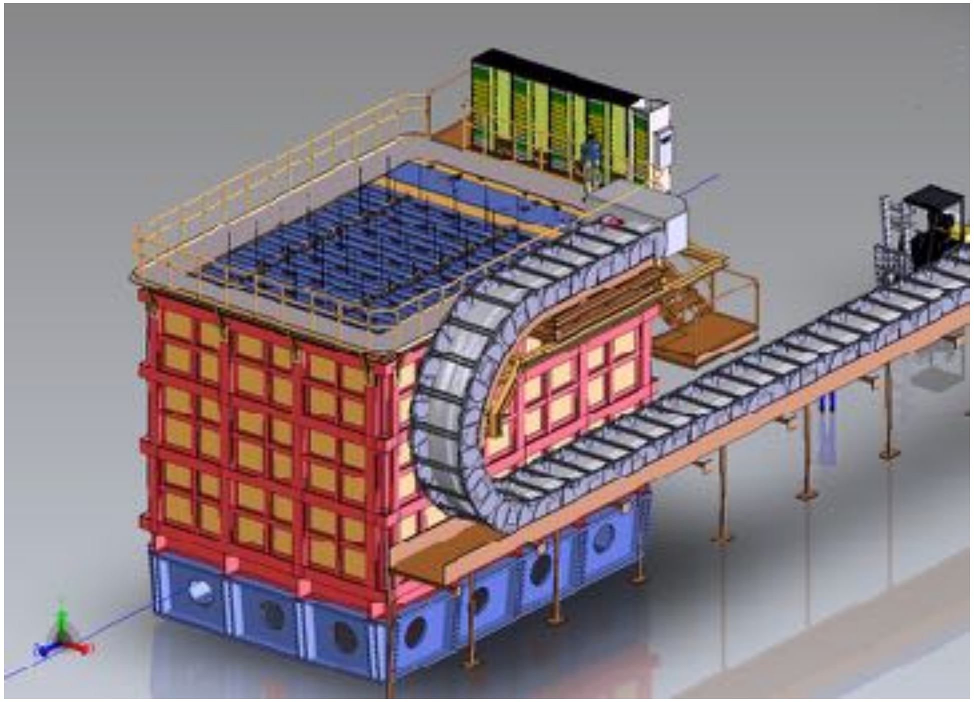
PRISM

- Predict oscillated neutrino event spectra at FD with reduced model dependence
  - Form “oscillated” flux at near detector with linear combinations of off-axis data
  - Extrapolate to Far detector
  - Interaction model independent



LAr Overview

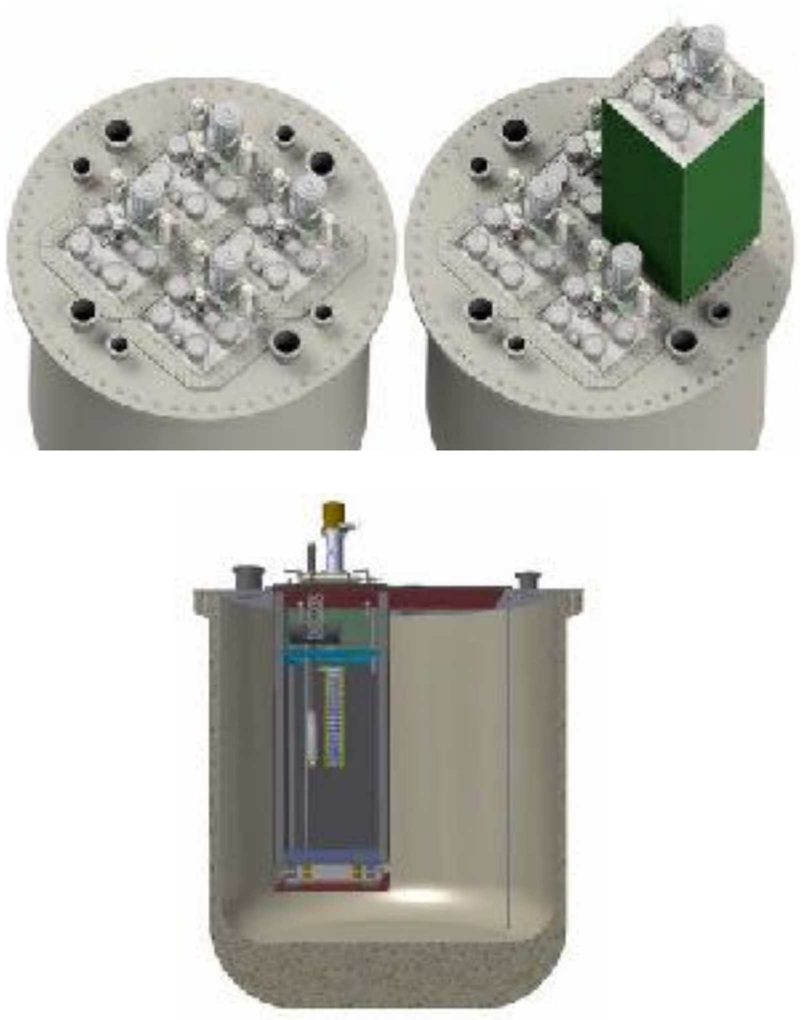




- ArgonCube concept
- Pixelated readout to accommodate high rate (>5 evts/spill)
  - 12 million pads
  - ~2 billion voxels
- Active volume:
  - 5 m deep in beam direction and 3 m tall for hadronic shower containment.
  - 7 m transverse to mitigate side muon spectrometer.
- Active mass ~ 150 t
  - 50t fiducial (3 m x 2 m x 6 m)
    - Hadronic containment
- Divided into 35 modules:
  - 1 m x 1 m x 3.5 m
  - 50 cm drift, 50 kV max
- Can move off axis

ArgonCube 2X2 prototype (ProtoDUNE-ND)

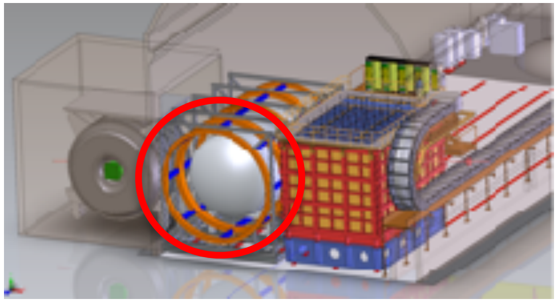
Engineering concept

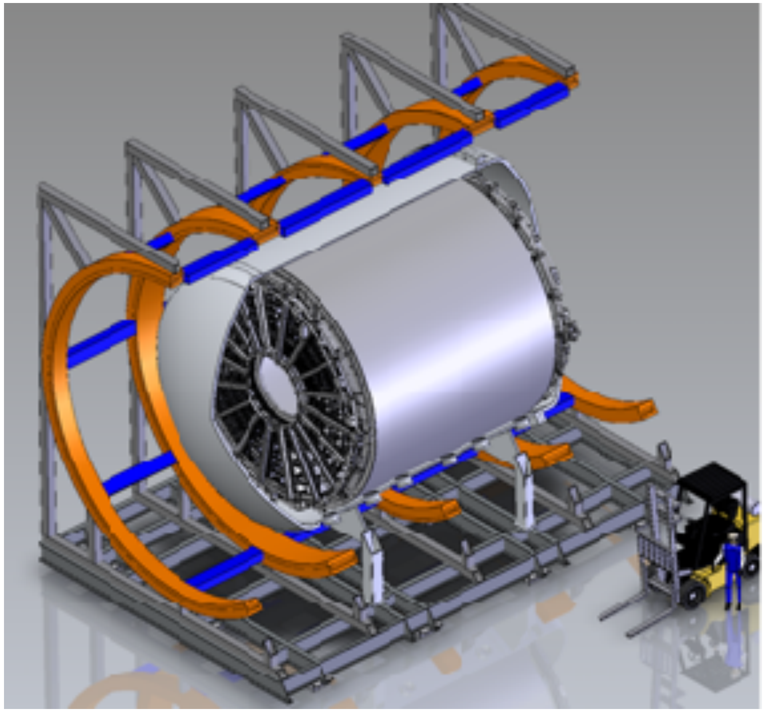


In the laboratory in Bern

Will be brought to Fermilab after testing at Ber
To be placed in the NuMI beam MINOS ND Hall

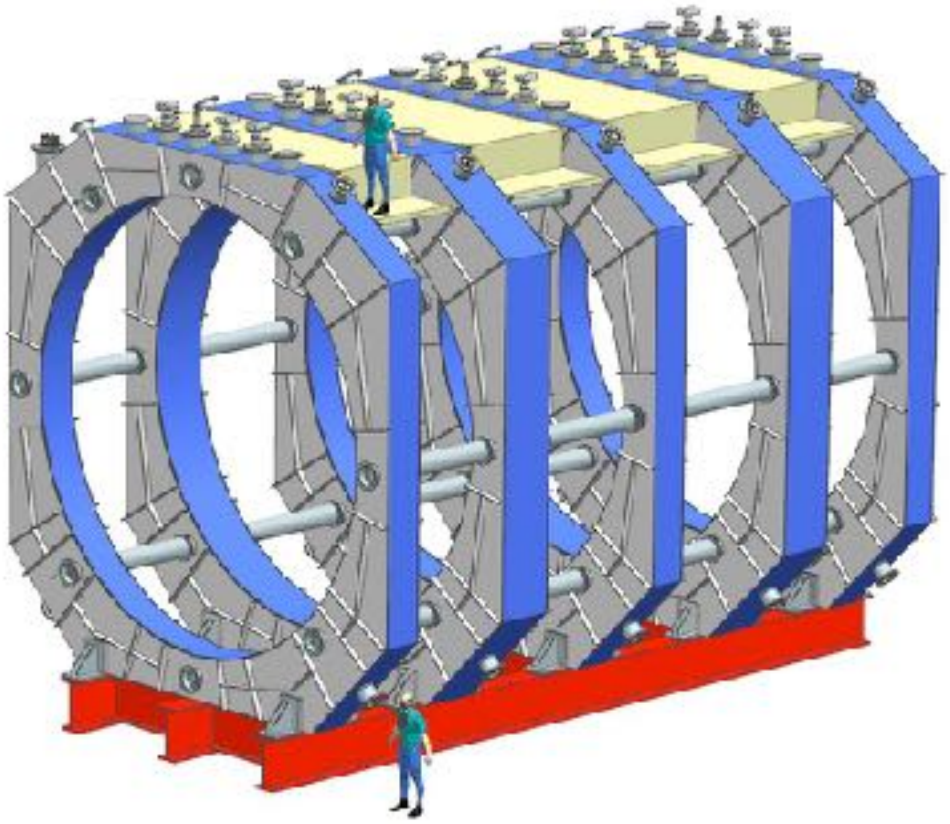
Multi-Purpose Detector





- High pressure (10bar) gas TPC + ECAL + SC magnet + μ tag
- Provides muon spectrometry for muons leaving LAr
  - LAr event containment
- Provides an independent, statistically significant event sample on Ar gas
  - Sign selection
  - Full 4π coverage
  - Very-low tracking threshold
  - Essentially no secondary interactions
    - Low density
- Can move off axis

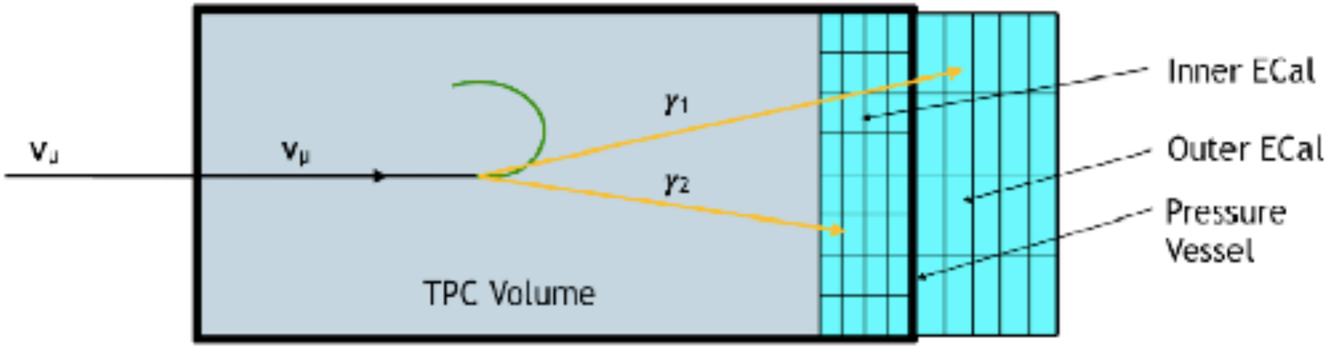
Magnet: Superconducting 3-coil Helmholtz System with 2 Superconducting Bucking Coils

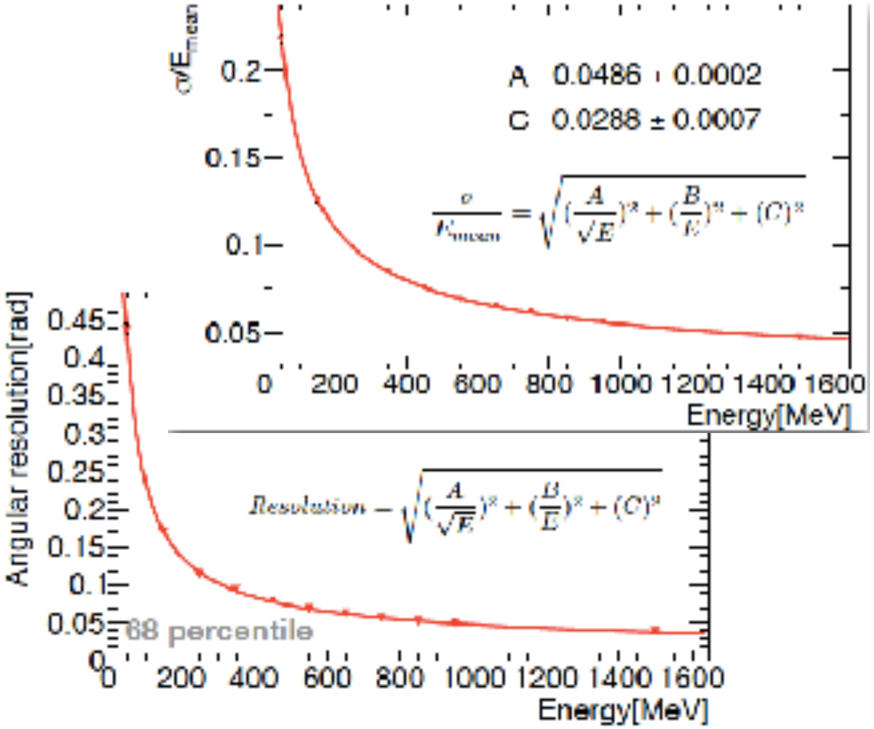


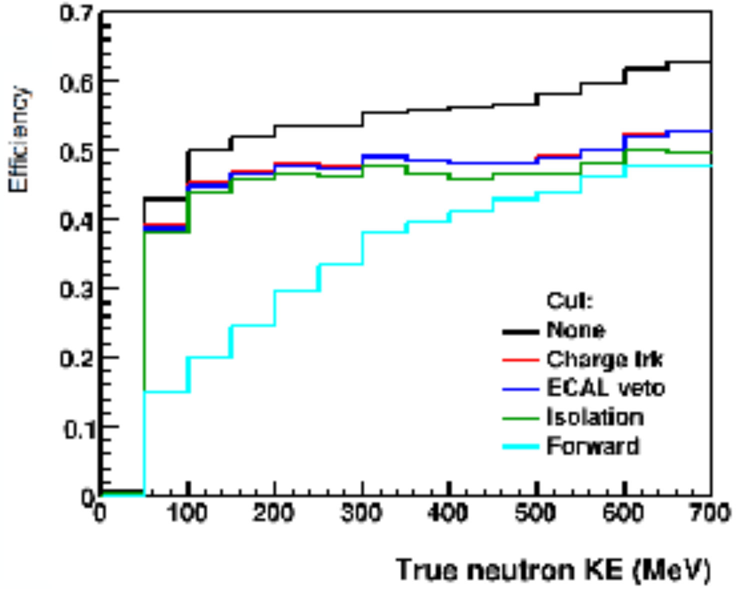
Magnet design concept

- Overarching requirements
  - Large acceptance for particles leaving LAr
  - Present minimal mass
- Central field = 0.5T
- Side coils at 2.5 m, shielding coils placed at 5 m from the magnet center in Z.
  - All coils have the same inner radius (3.5m)
  - Center and shielding coils are identical.
- Basic magnetic, cryostat and structural designs complete

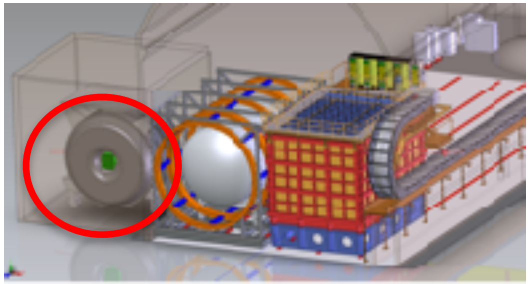
ECAL Concept

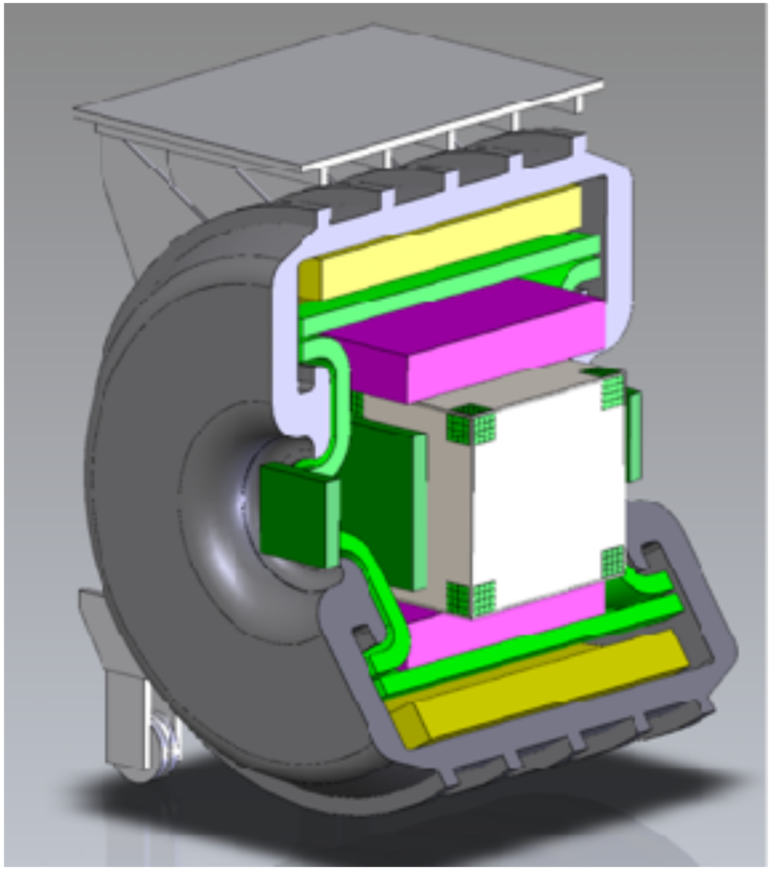




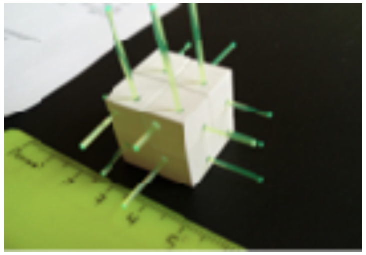


3DST-KS



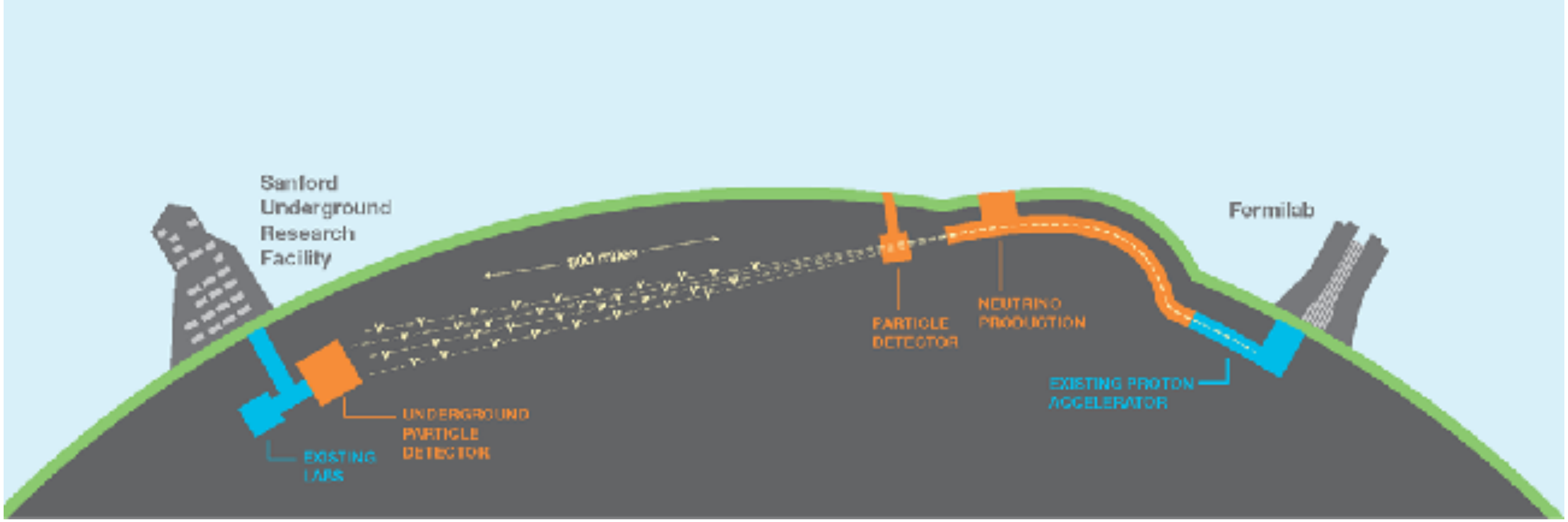


- Provides precision on-axis monitoring of neutrino beam through rate, profile, and spectrum measurements
- Consists of
  - 3D scintillator tracker active target (8t)



  - Tracking
    - 1 atm TPCs or
    - Straw tube tracker
  - KLOE EM calorimeter
    - Scintillator fiber + Pb
  - KLOE magnet system
    - 0.6T central field (SC magnet)
    - Return Fe
- **Fixed on-axis position**

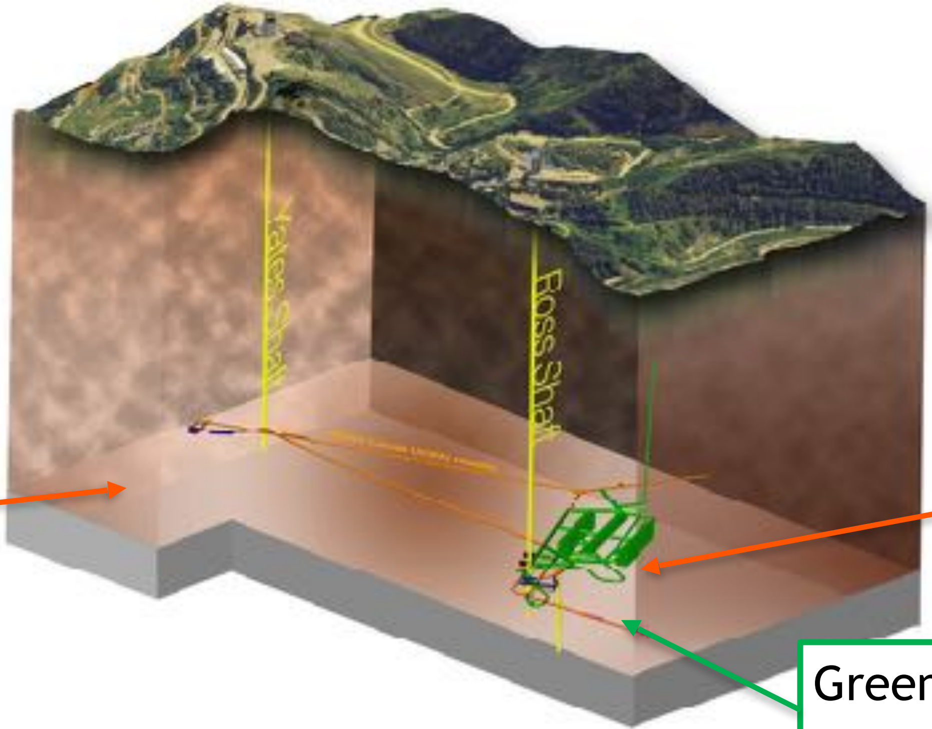
Far Detector



Underground Laboratory SURF

DUNE Far Detector site

- Sanford Underground Research Facility (SURF), South Dakota
- Four caverns on 4850 level (~ 1 mile underground)



Davis Campus:
- LUX
- Majorana
- …
- LZ

Ross Campus:
- CASPAR
- …
- DUNE

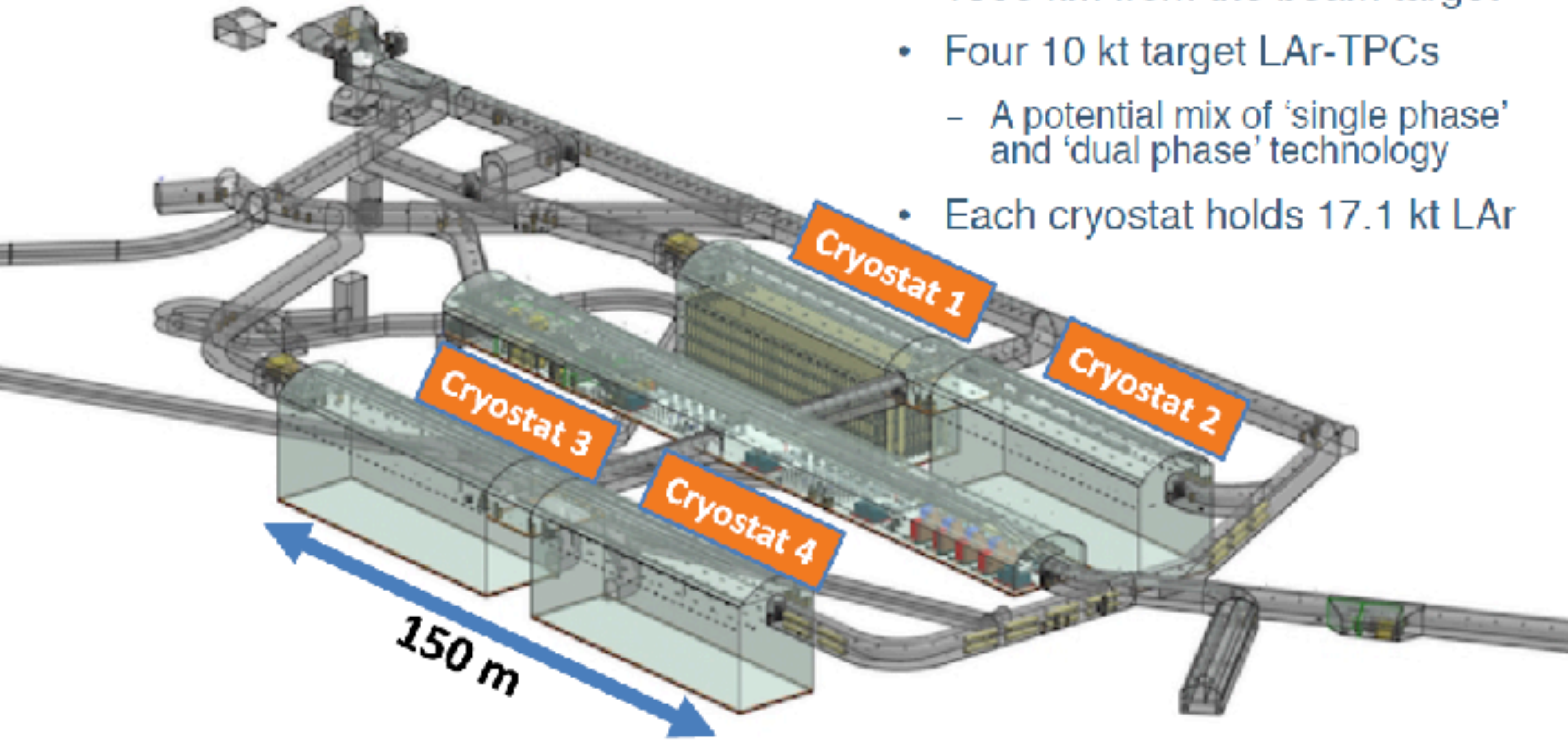
Green = new excavation commenced in 2017

It’s real!

21st July 2017: Ground breaking at SURF

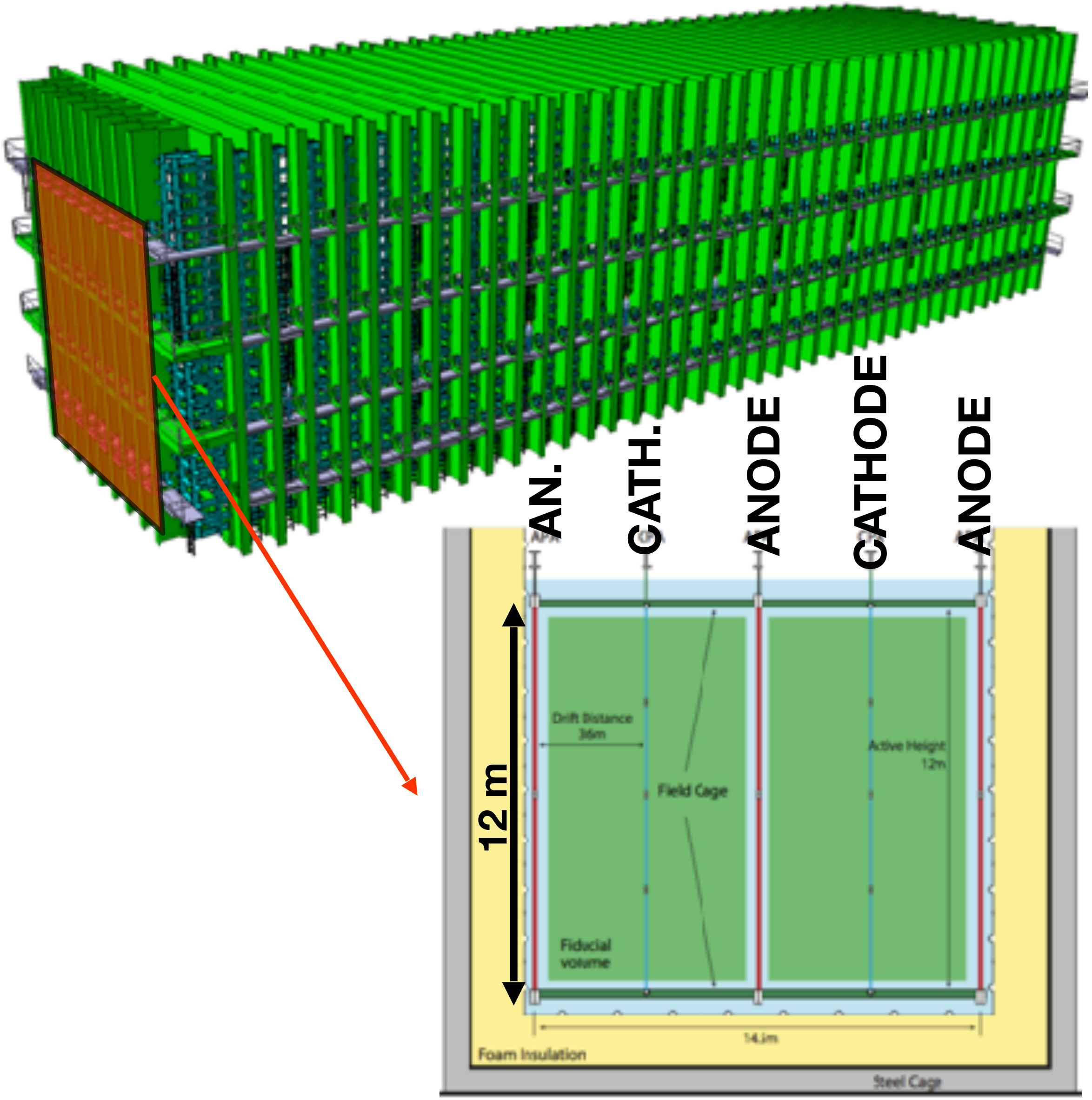
DUNE Far Detector

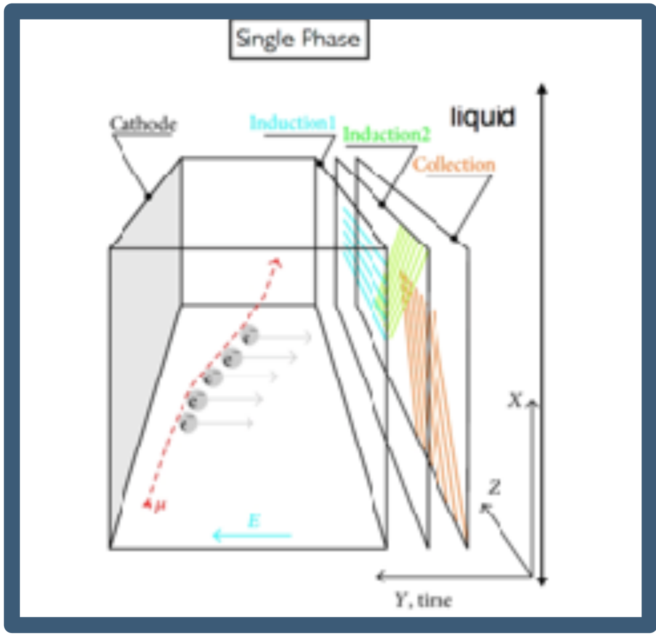
- 1478 m underground
- 1300 km from the beam target
- Four 10 kt target LAr-TPCs
  - A potential mix of 'single phase' and 'dual phase' technology
- Each cryostat holds 17.1 kt LAr



Far detectors: 1st module

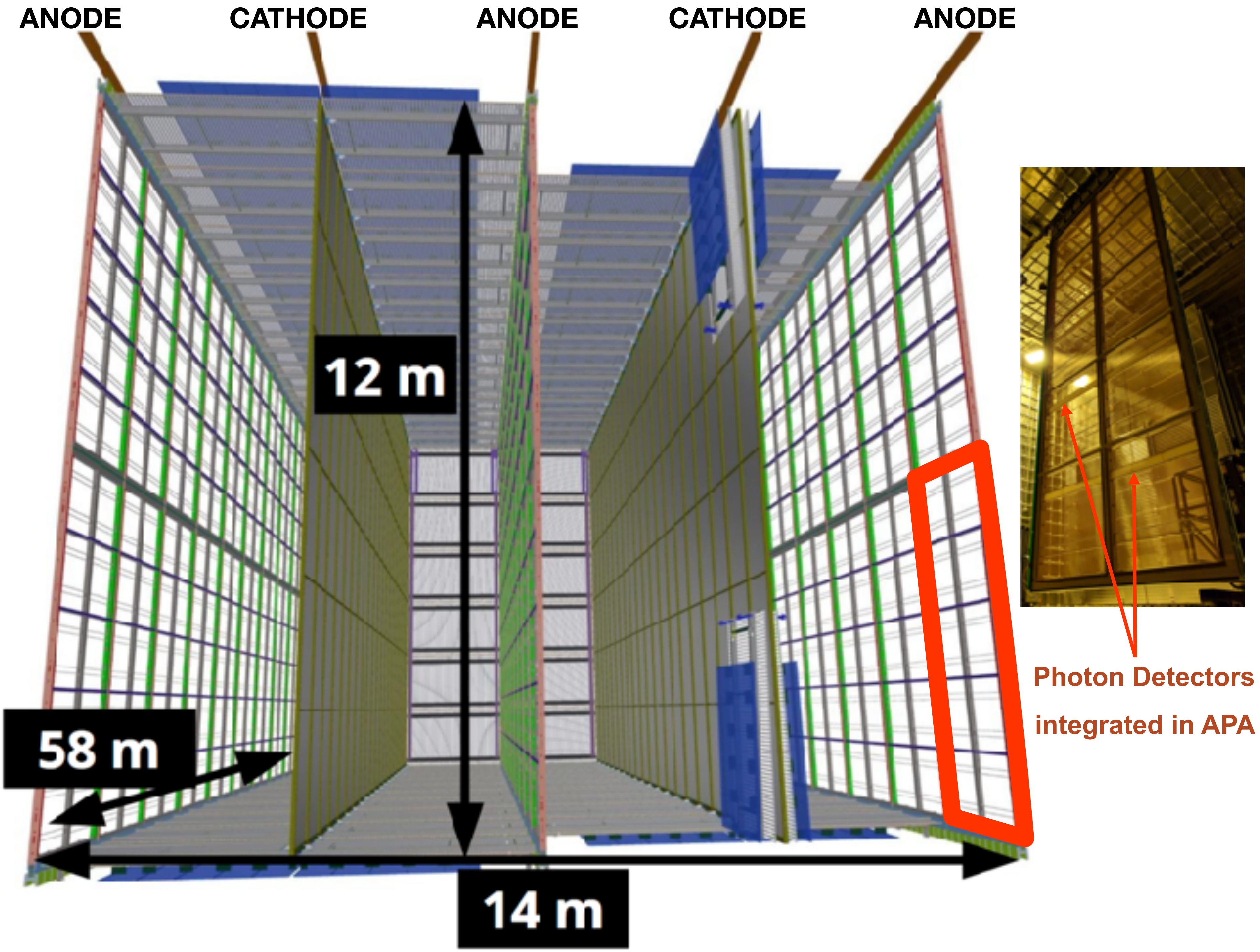
Single-Phase



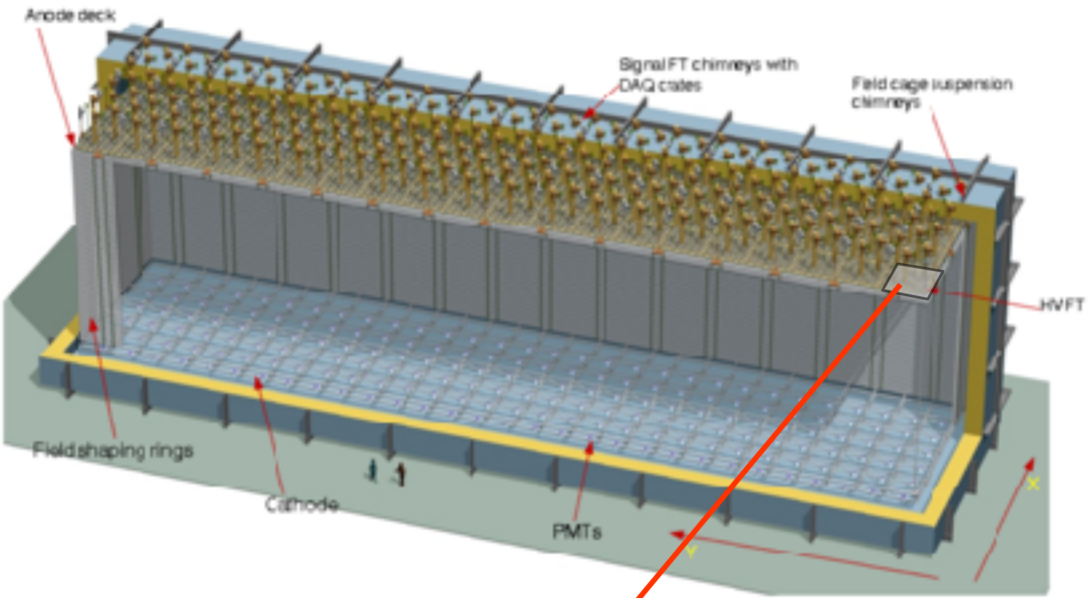


180,000 volts between

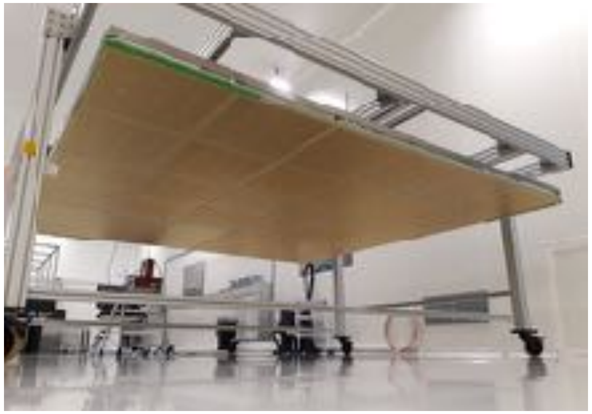
cathode and anode


ANODE
CATHODE
ANODE
CATHODE
ANODE
12 m
58 m
14 m
Photon Detectors
integrated in APA

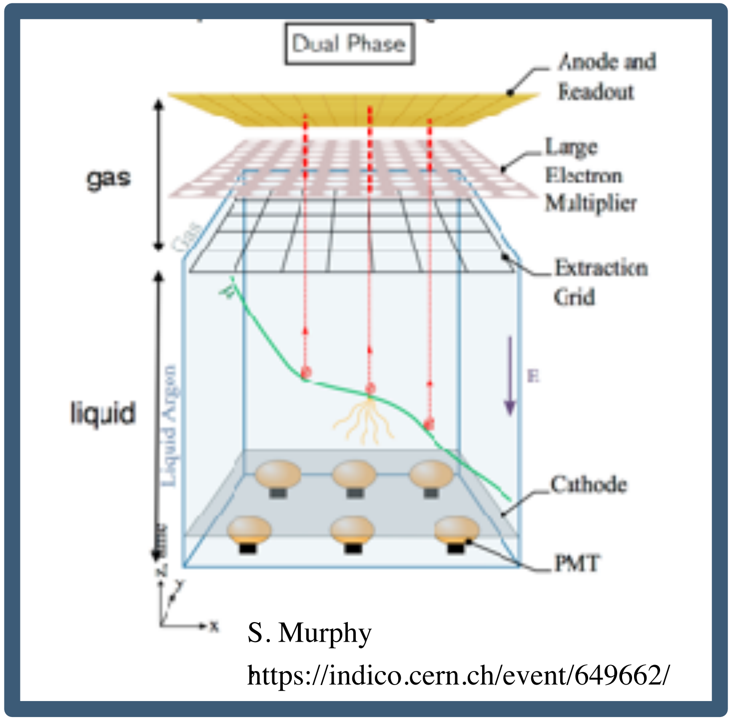
2-Phase Technology



Charge Readout Plane (Anode)



signal amplification in the gas phase

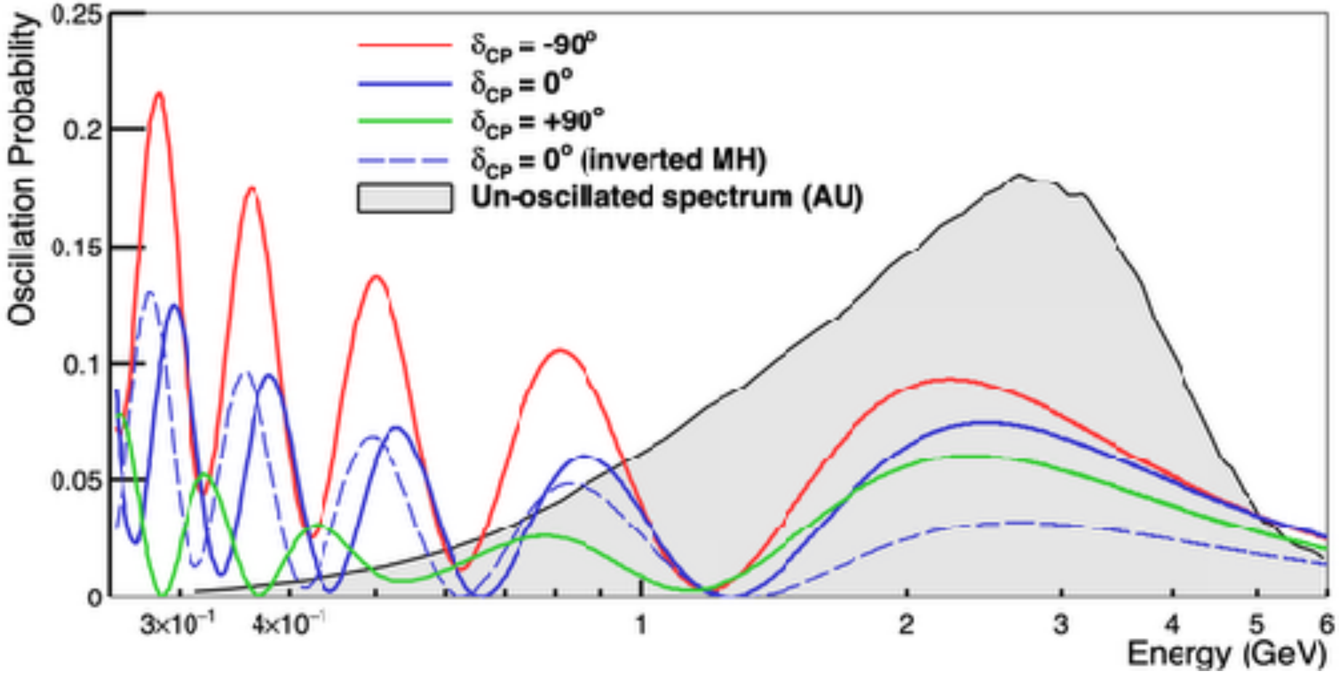


S. Murphy
https://indico.cern.ch/event/649662/

Photon detectors below cathode

600,000 volts between cathode and anode

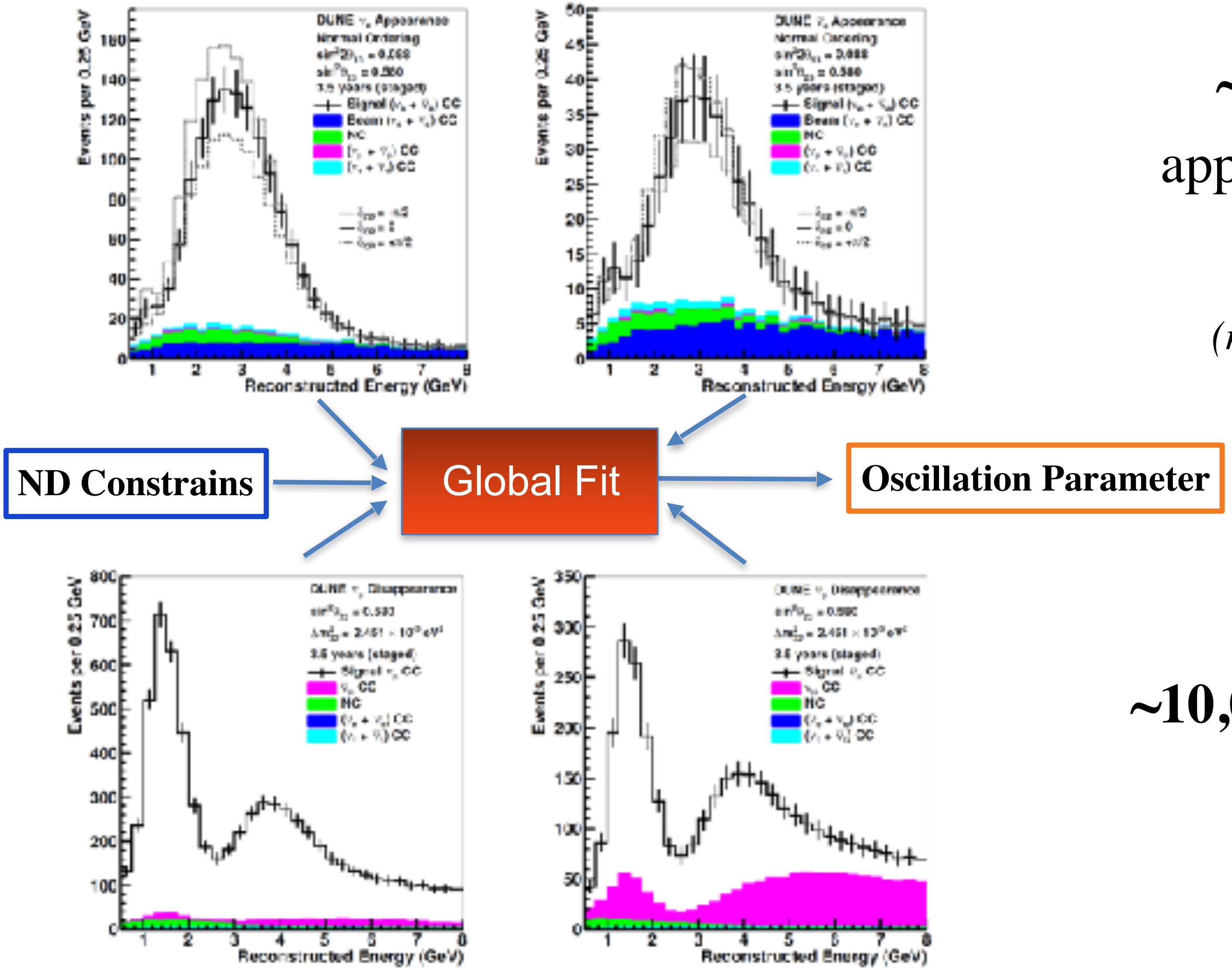
Experimental Technique



- Produce wide-band pure ν_μ beam
  - Cover 1st and 2nd oscillation maximum
- Constrain models and systematics with near detector
- Measure spectrum of ν_μ and ν_e at a far detector
  - Combined analysis

Measurement Strategy

DUNE simulation



ND Constrains

Global Fit

Oscillation Parameter

~1,000 $\nu_e / \overline{\nu_e}$

appearance events

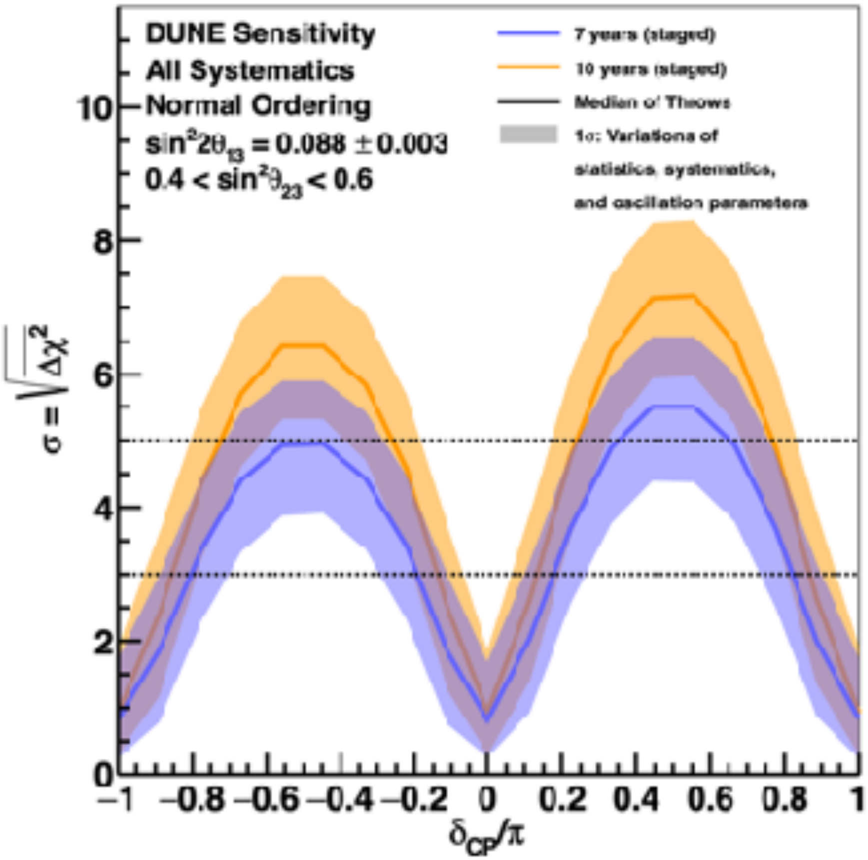
in 7 years!

(normal ordering)

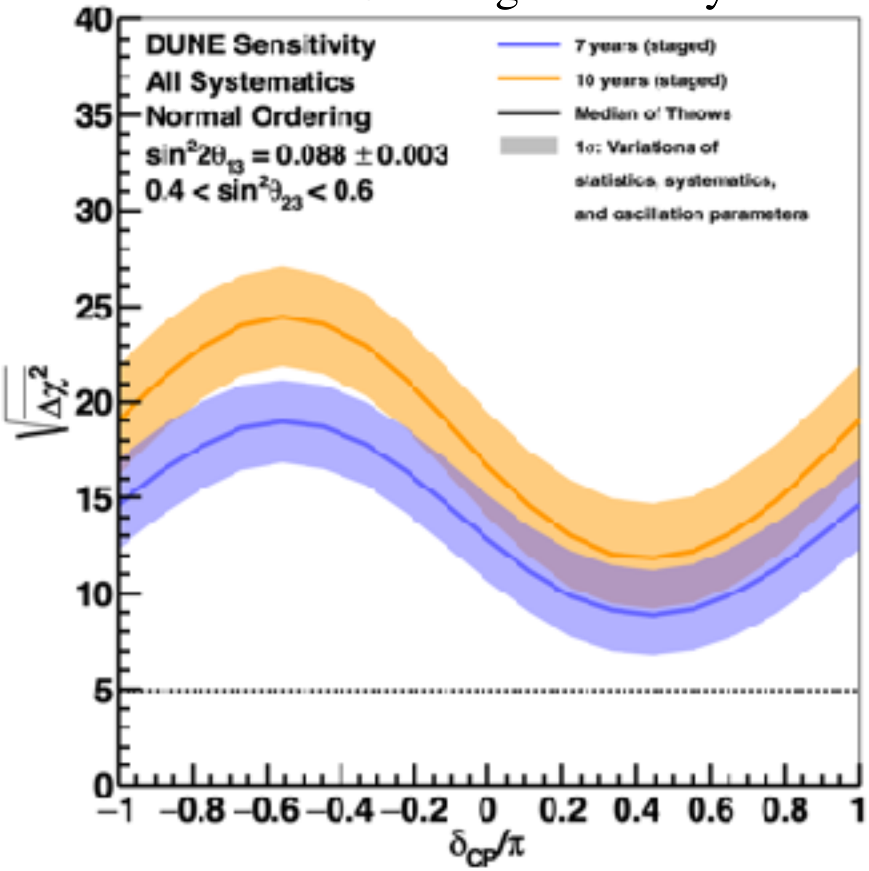
~10,000 $\nu_\mu / \overline{\nu_\mu}$ events

CP Violation and Mass Ordering

*CP*v sensitivity



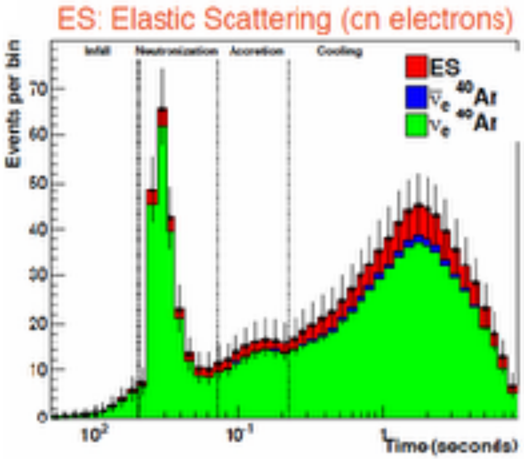
Mass ordering sensitivity



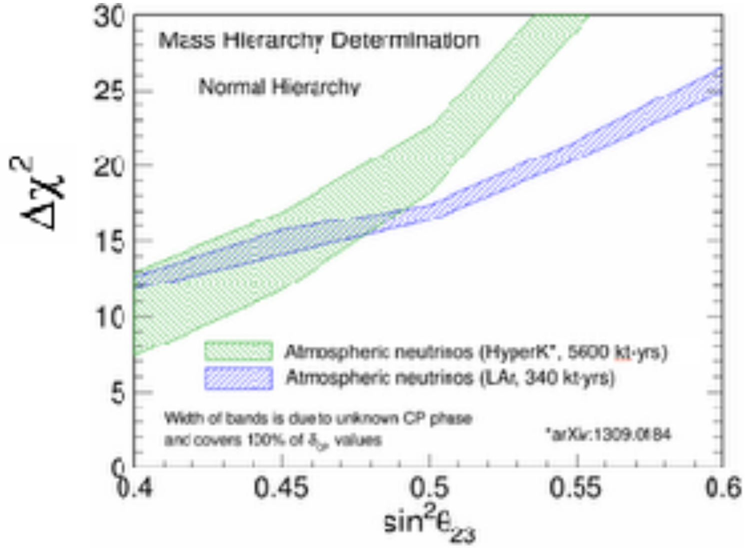
- Updated Sensitivity with realistic systematics and reconstruction
  - Move quickly to potential ***CP* violation discovery**
  - Rapid, definitive **mass ordering determination** (>5σ)

Other Physics

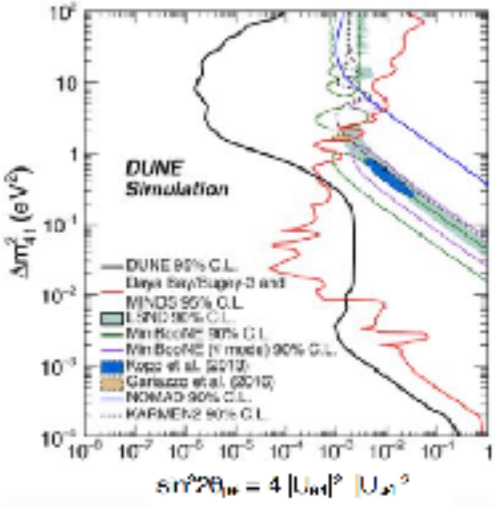
supernova



atmospherics



atmospherics

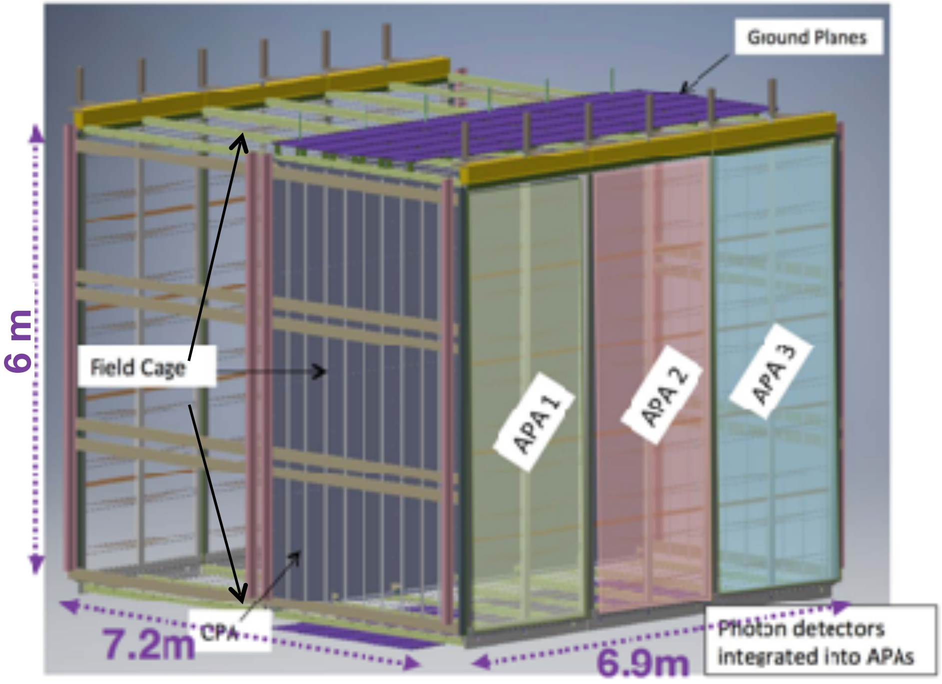


- Dark matter
- Large extra dimensions
- Dark photons
- NS interactions

Two Technologies

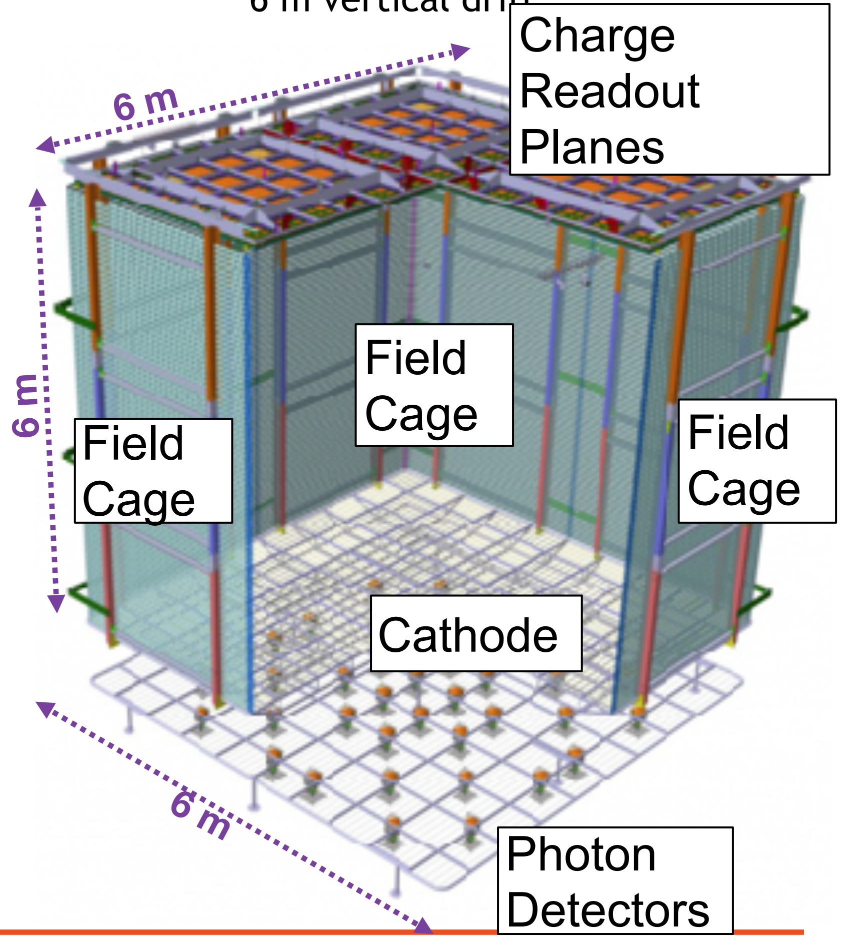
Single-Phase

3.6 m horizontal drift



Dual-Phase

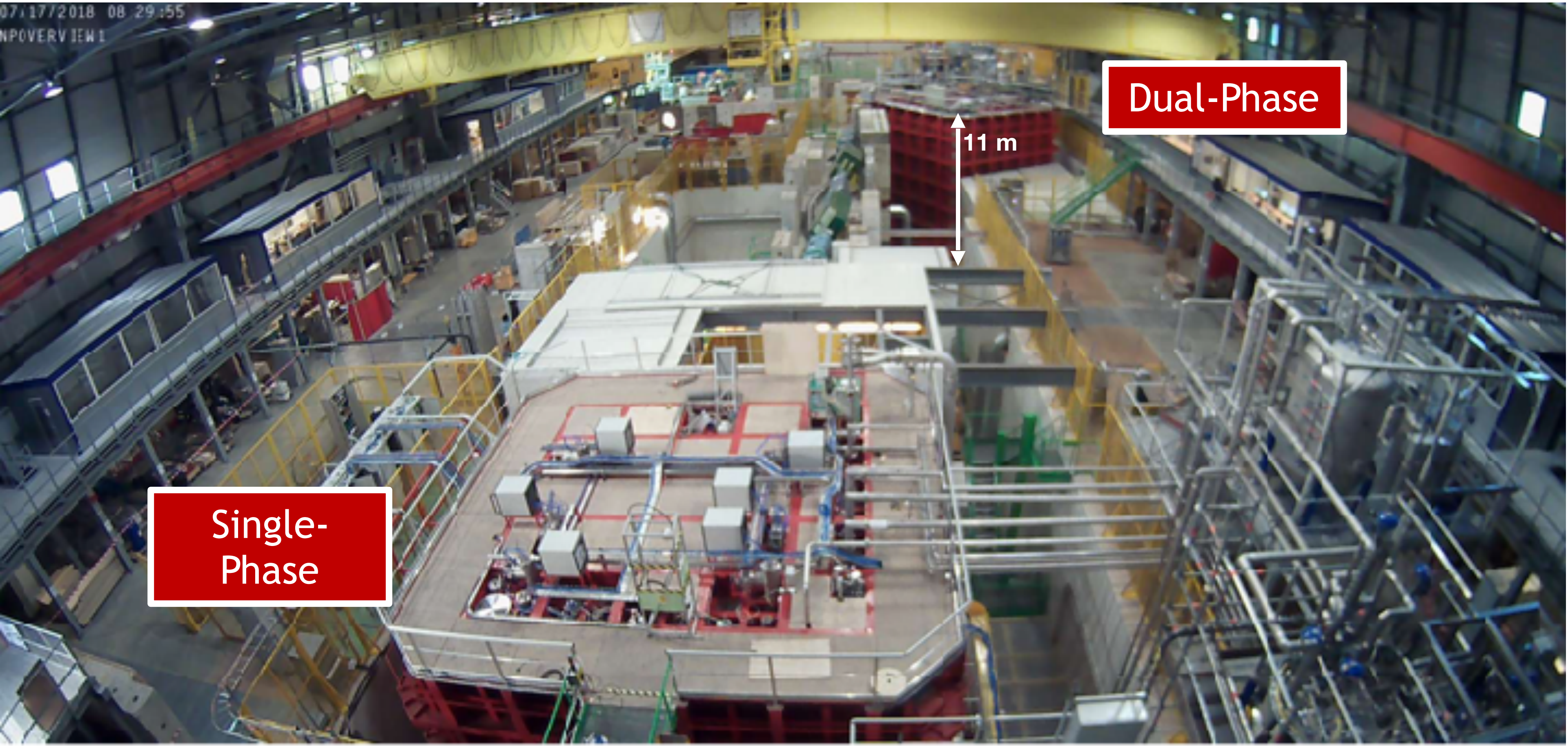
6 m vertical drift



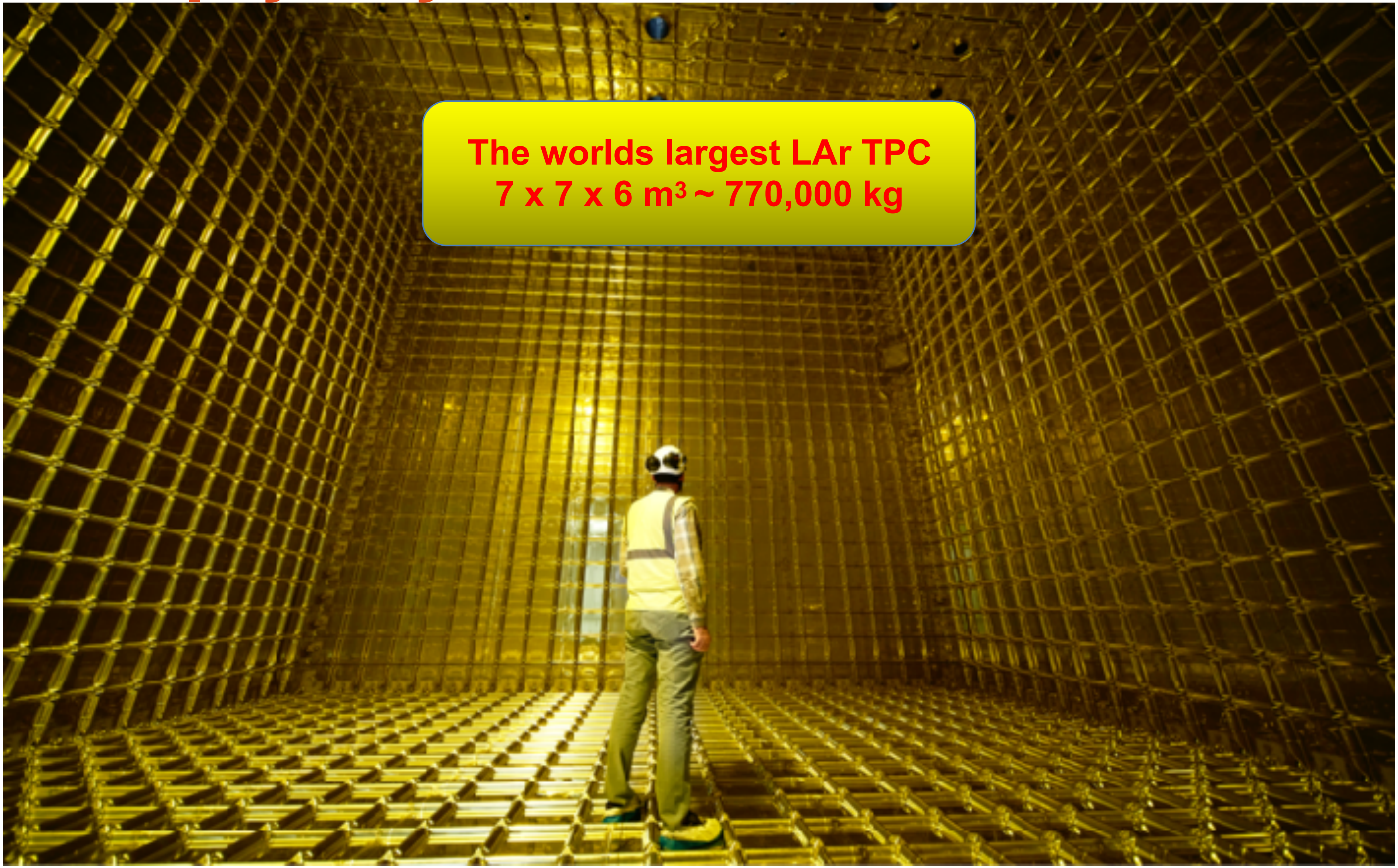
March 2016

CERN EHN1 extension

July 2018

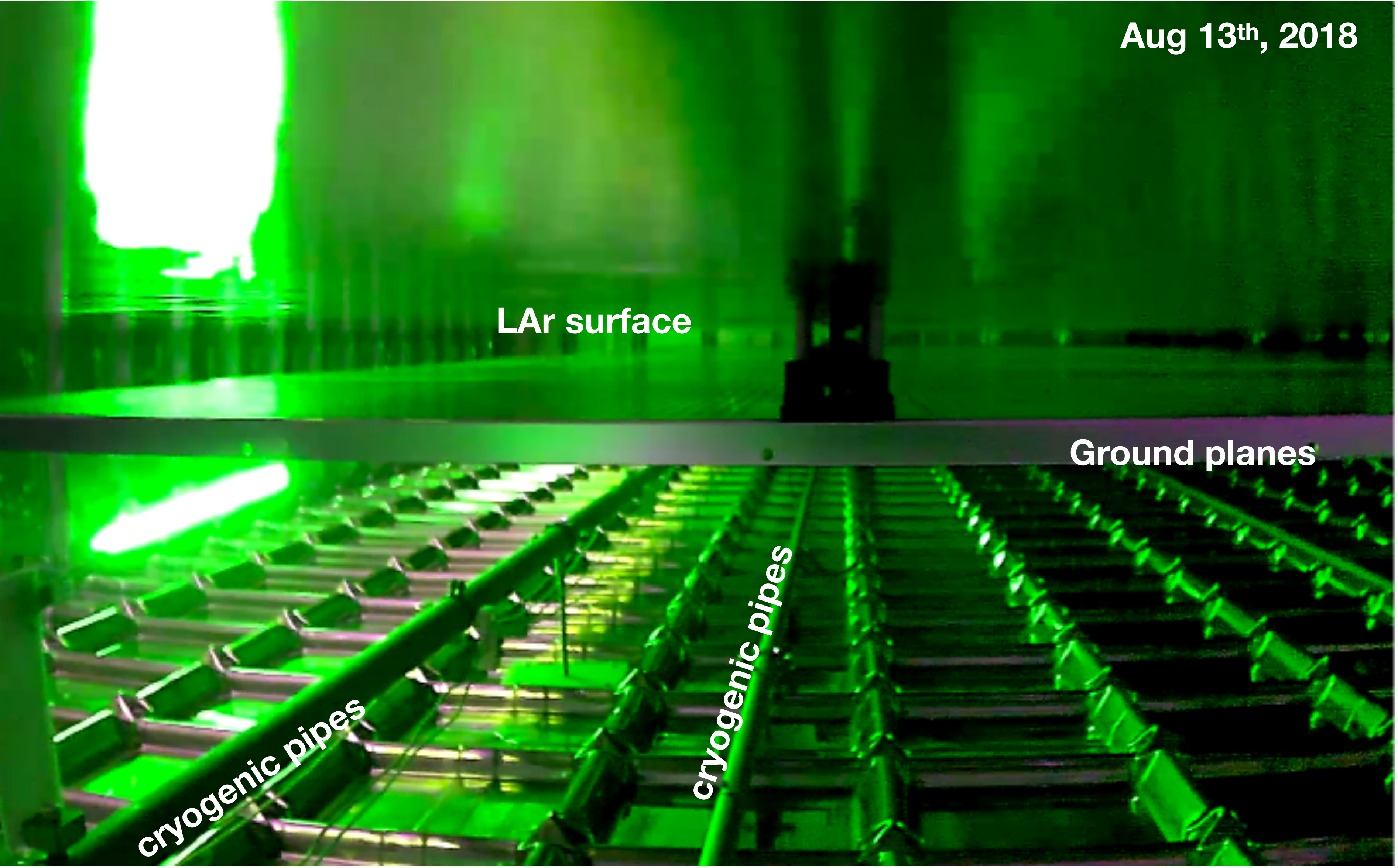


Empty Cryostat

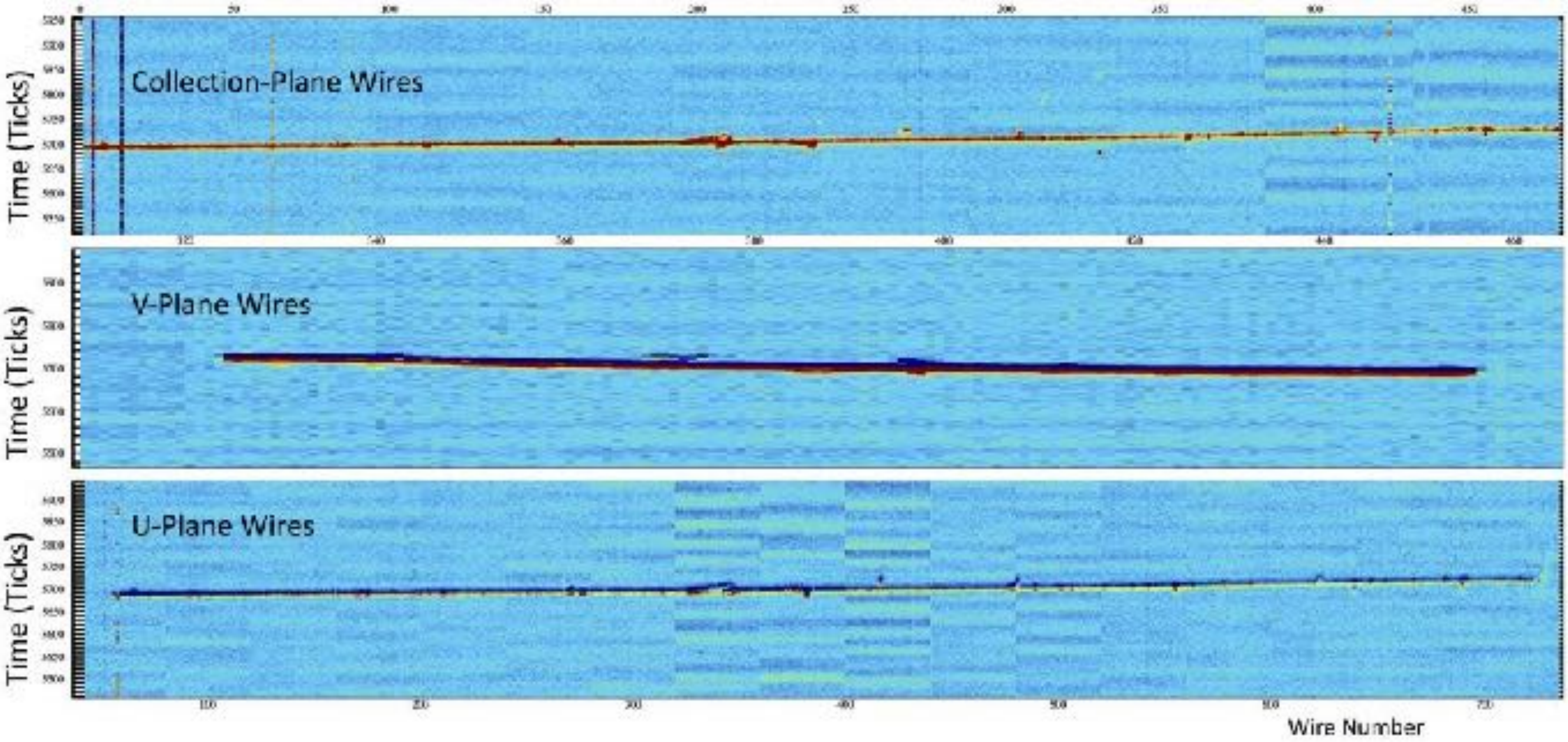


The worlds largest LAr TPC
7 x 7 x 6 m^3 ~ 770,000 kg

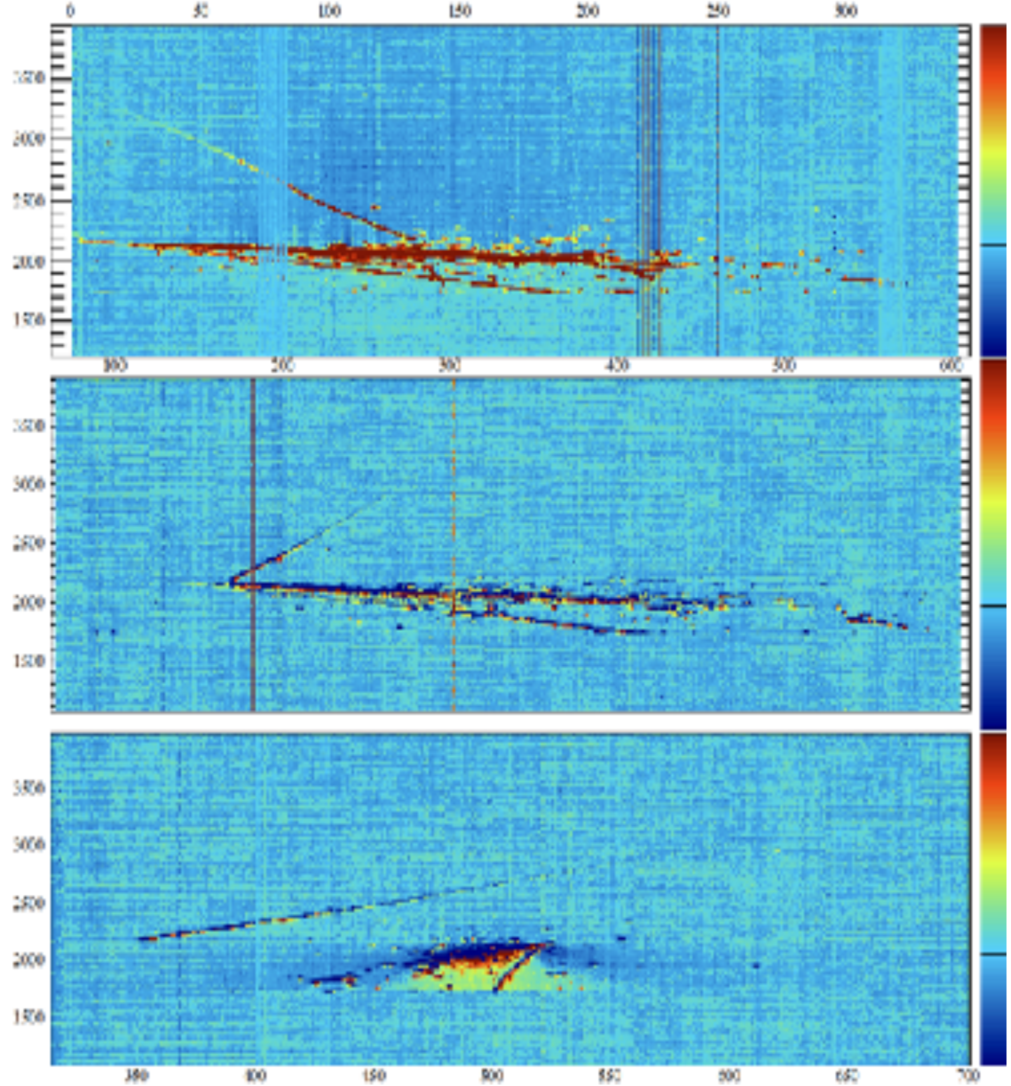
Filling the Cryostats

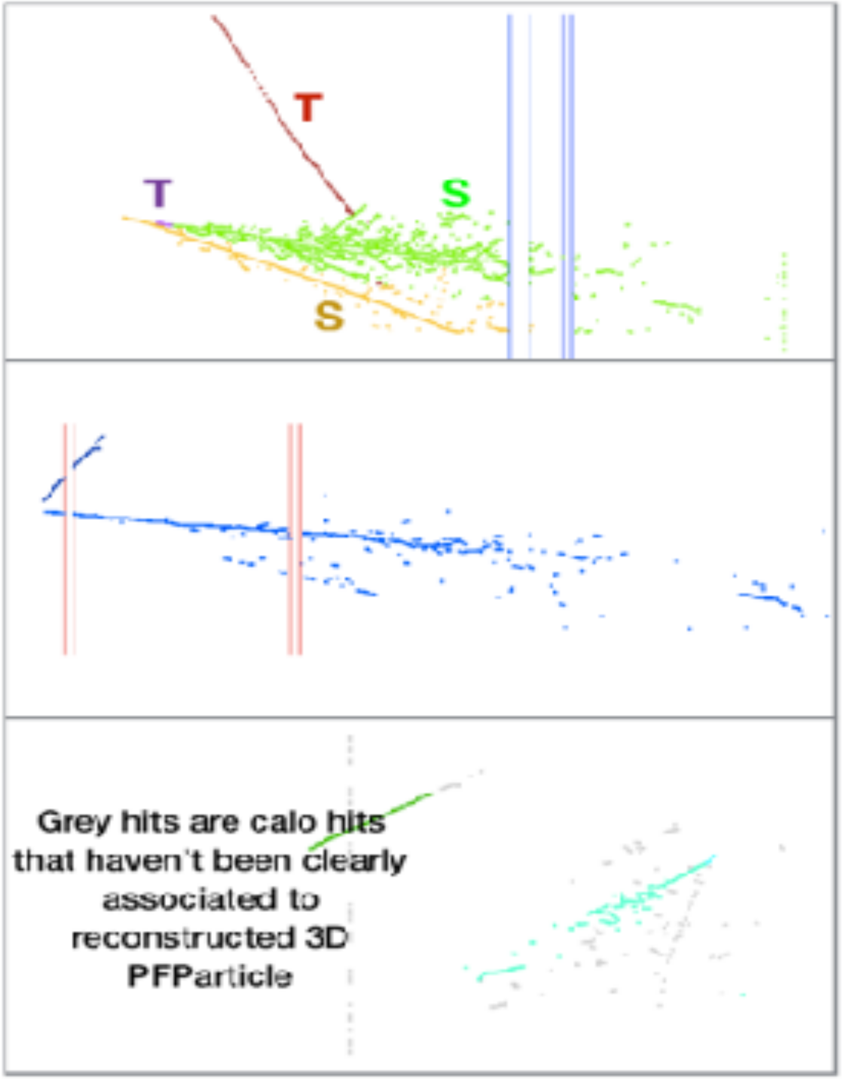


The First Event



Automatic Reconstruction

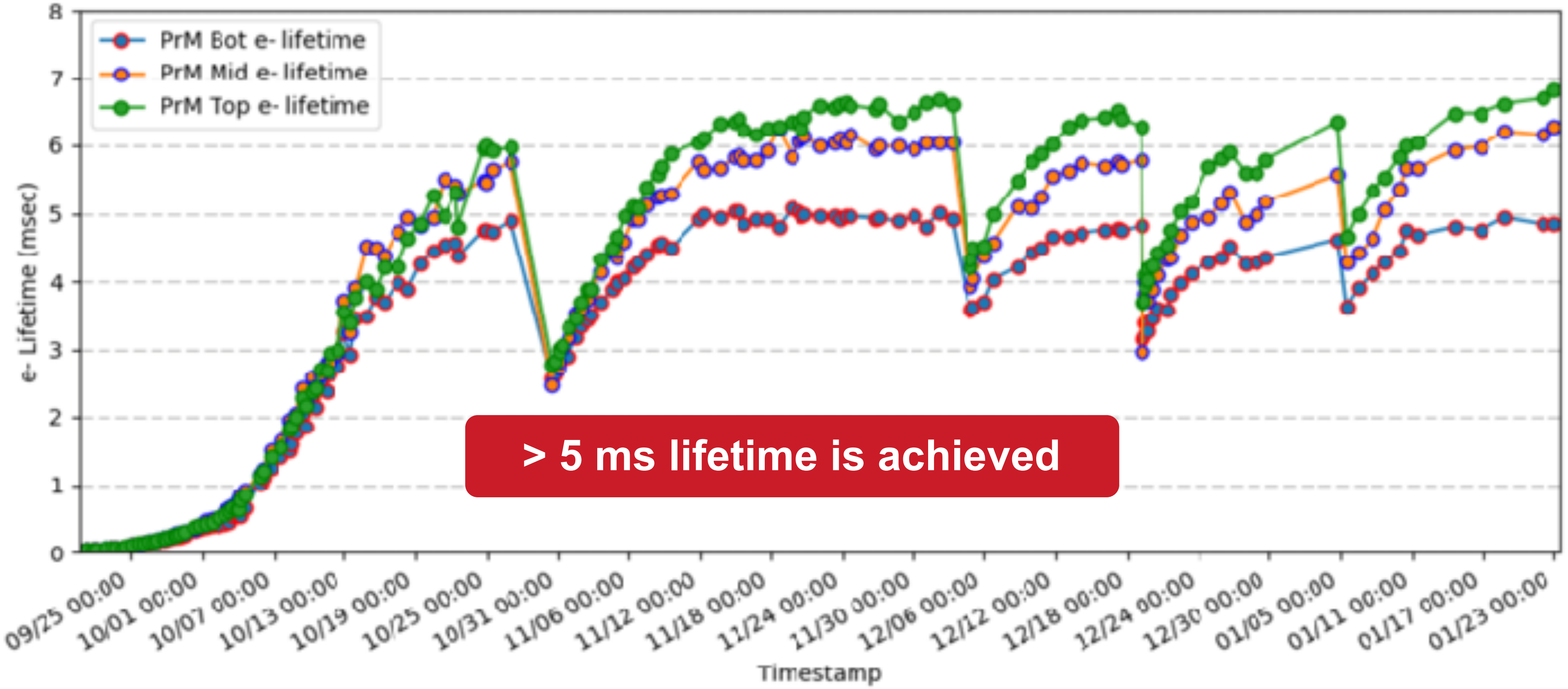




Grey hits are calo hits that haven't been clearly associated to reconstructed 3D PFParticle

Liquid Argon Purity

The purity is measured as the electron lifetime



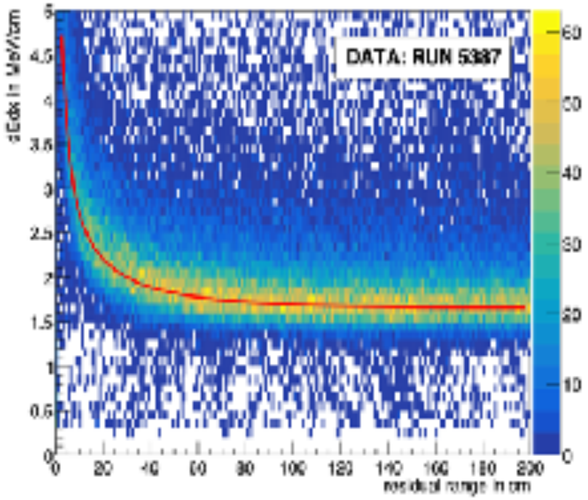
> 5 ms lifetime is achieved

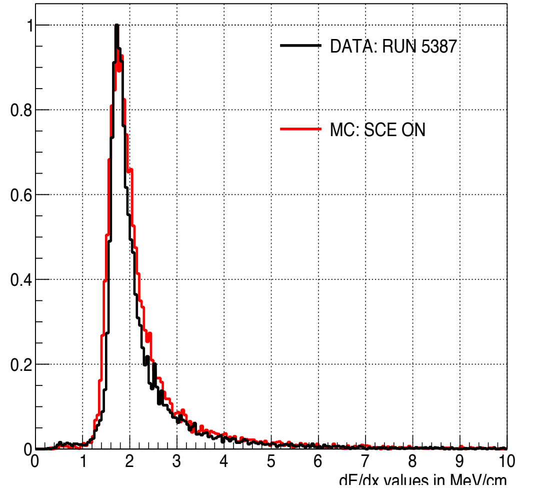
Electrons need 3 ms to cross the drift volume

ProtoDUNE Performance (prelim.)

dE/dx

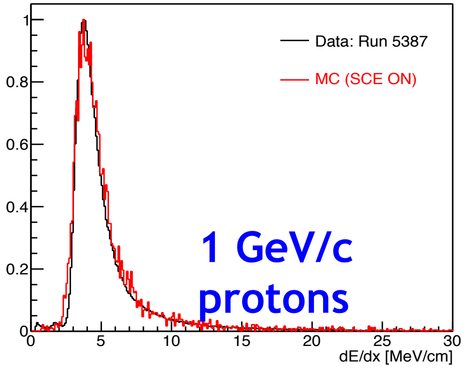
Calibrated with muons



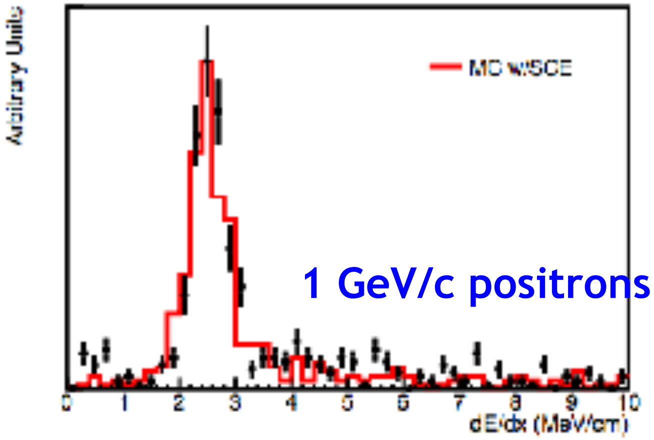


dE/dx at the beginning of the shower

Applied to other particles



1 GeV/c protons



1 GeV/c positrons

Very good agreement between data and simulation!

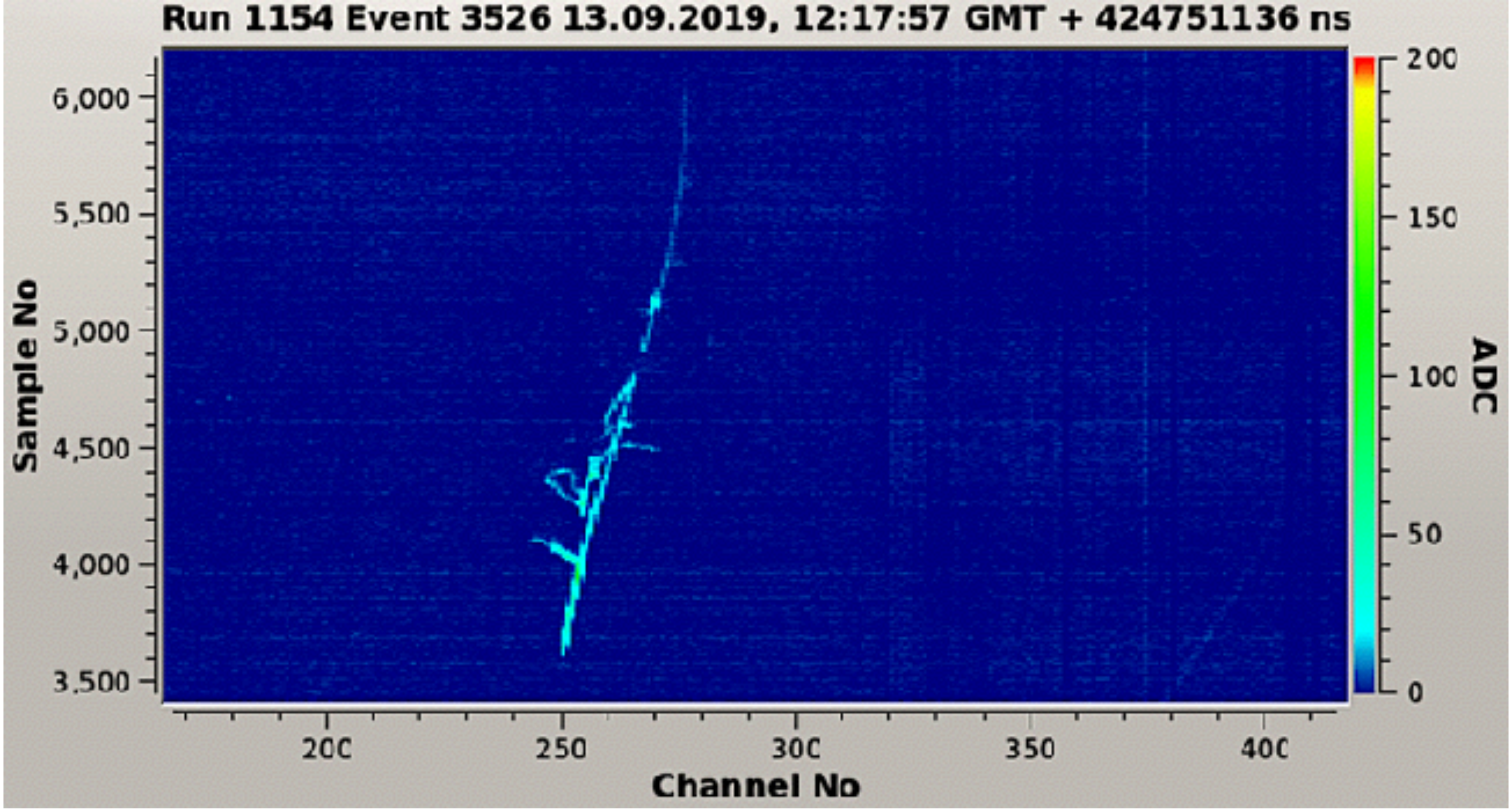
Additional calibration work and **particle-Ar cross section measurements** are underway

ProtoDUNE Status

- **ProtoDUNE-SP** detector was completed at the end of June 2018, filling of the cryostat completed on September 13th, TPC activated and on data taking since September 21st, 2018.
- **ProtoDUNE-SP** took beam data until November 11th, followed by an endurance run with cosmics to assess the stability and performances of the detector.
- ***ProtoDUNE-DP*** installation finished, and commissioning ongoing. First tracks seen
- ***ProtoDUNE-DP*** will go for an extended cosmic run to assess the stability and performances of the detector

ProtoDUNEs have submitted a proposal to the SPSC for taking data with beam after Long Shutdown 2

First ProtoDUNE-DP Event



Summary and Conclusion

- DUNE has an ambitious physics program
  - Precision oscillation parameter measurements
  - CP Violation, mass ordering
  - Nucleon decay, SN
- Truly international project with strong support
  - US & internationally
  - UK is in strongest non-US contributer (DAQ, FD, Software)
- Technology is well understood
  - Prototyping and verifications are well underway
- DUNE is the neutrino physics of the future