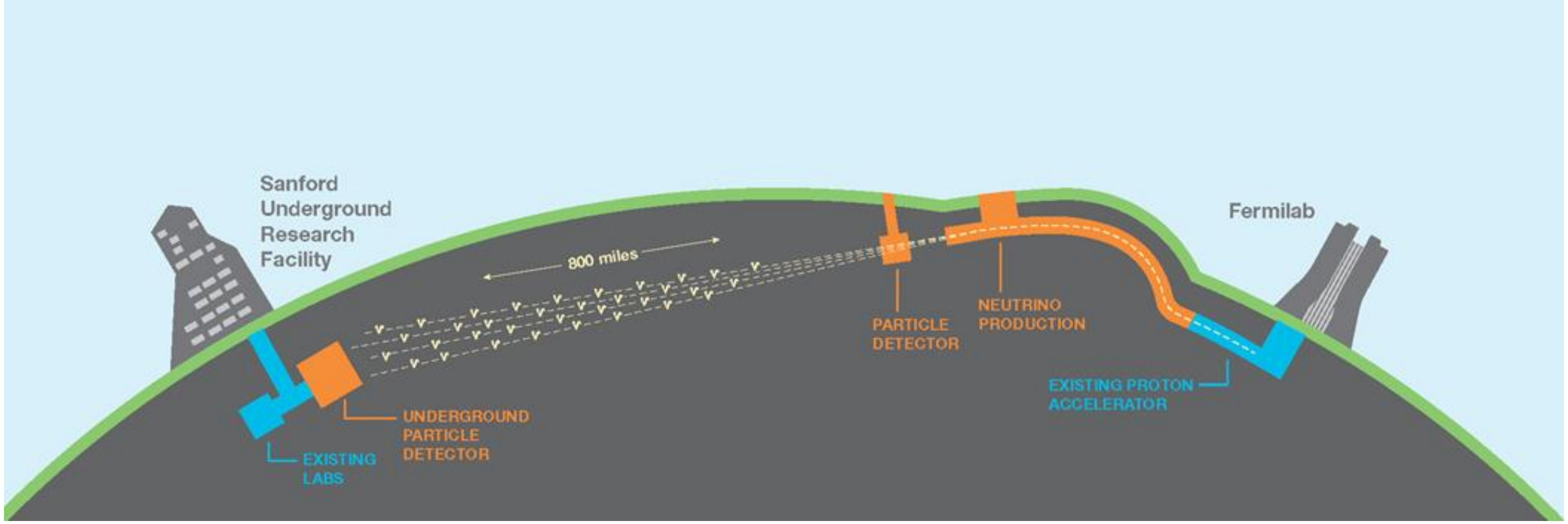
DUNE
Precision Neutrino Physics of the Future



Alfons Weber

University of Oxford, UKRI/STFC Rutherford Appleton Lab

Birmingham, 27-February-2019

Neutrino Mixing The PMNS Matrix

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

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

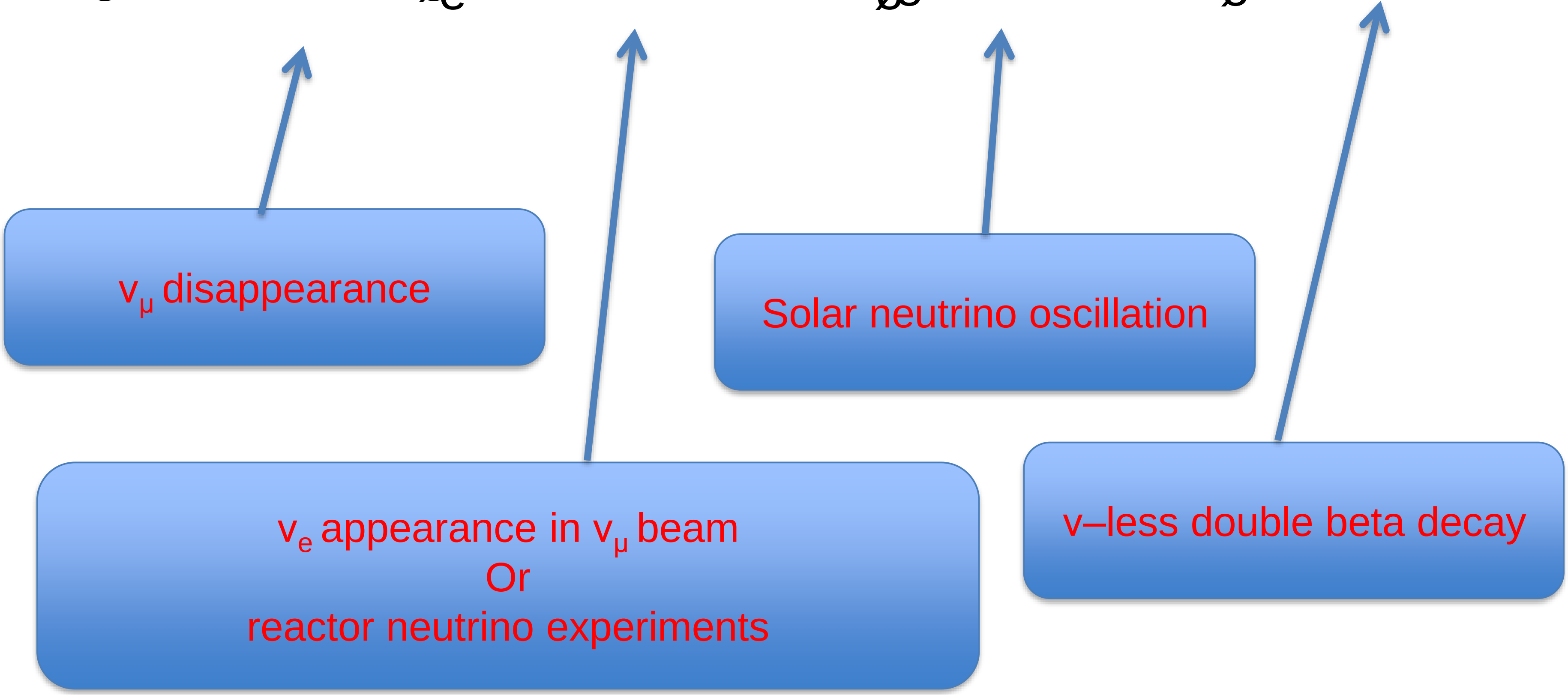
Pontecorvo-Maki-Nakagawa-Sakata

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

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

The Who-is-Who

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



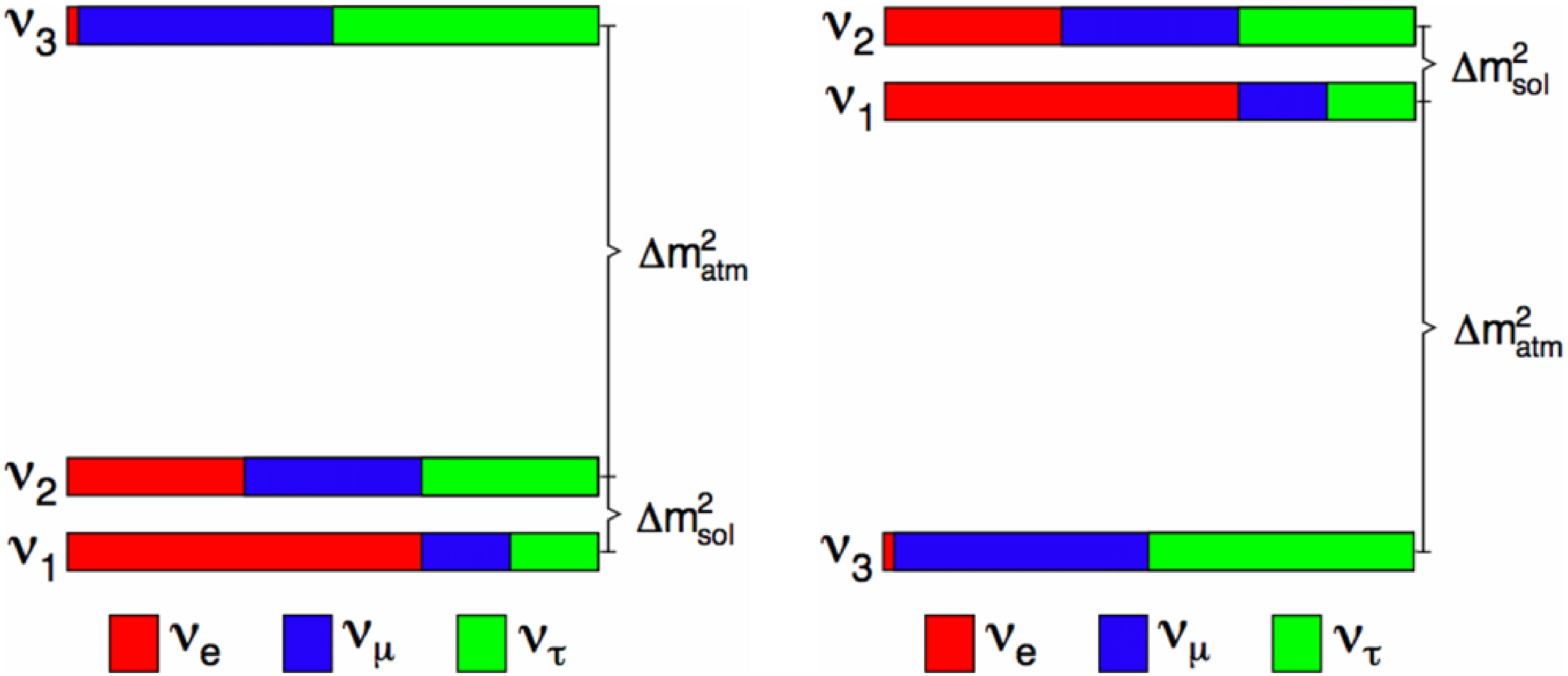
v_μ disappearance

Solar neutrino oscillation

v_e appearance in v_μ beam
Or
reactor neutrino experiments

v–less double beta decay

Mass Ordering



Normal

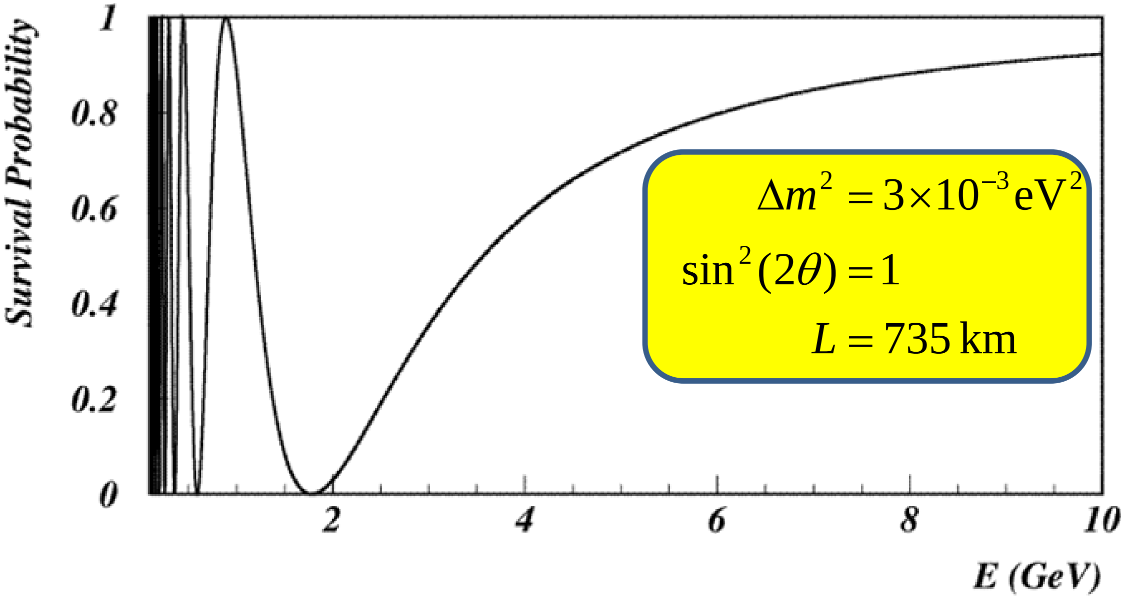
Inverted

Oscillations for Dummies

$$\nu_\mu \longrightarrow \underset{\nu_1,\nu_2}{\longrightarrow} \longrightarrow \nu_\mu \text{ or } \nu_\tau$$

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

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



Matter Effects

- Simplified treatment: two neutrinos only

In vacuum

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

in matter

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

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

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

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

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

The Full Monty

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

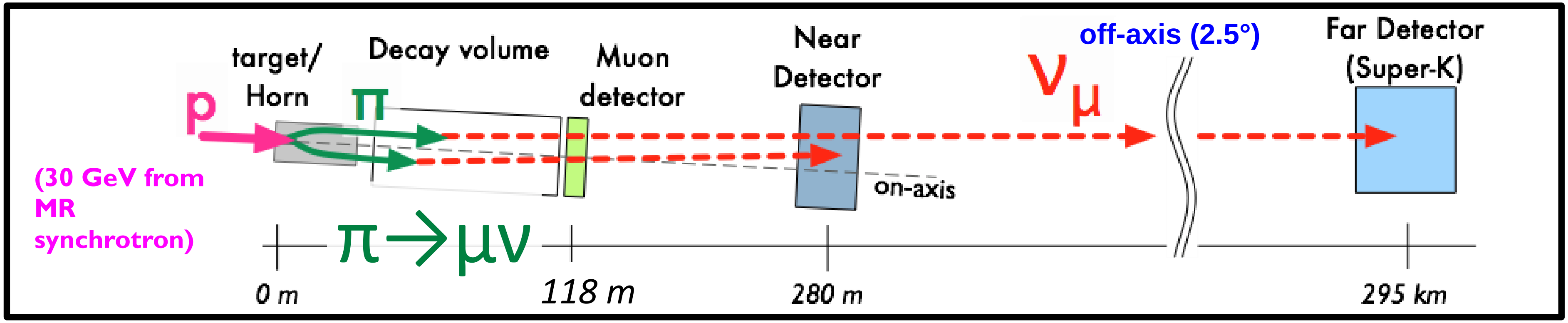
$$P(\nu_\mu \to \nu_e) = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

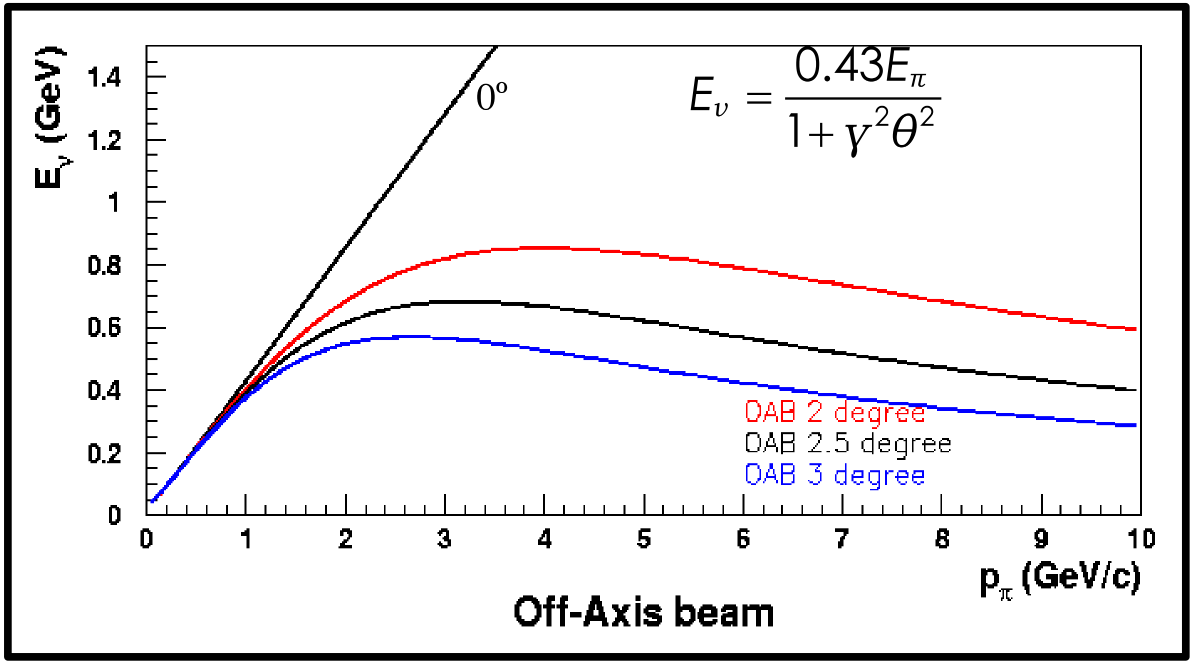
$$\begin{aligned}
P(\nu_\mu \to \nu_e) = {}& 4C_{13}^2 S_{13}^2 S_{23}^2 \sin^2 \frac{\Delta m_{31}^2 L}{4E} \times \left(1 + \frac{2a}{\Delta m_{31}^2} \left(1 - 2S_{13}^2\right)\right) \\
&+8C_{13}^2 S_{12} S_{13} S_{23} (C_{12} C_{23} \cos\delta - S_{12} S_{13} S_{23}) \cos\frac{\Delta m_{32}^2 L}{4E}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

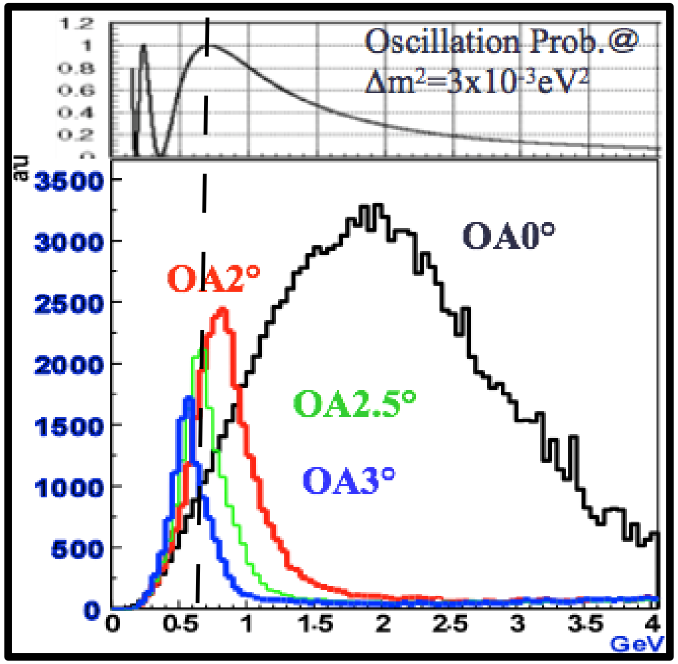
The T2K Experiment

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

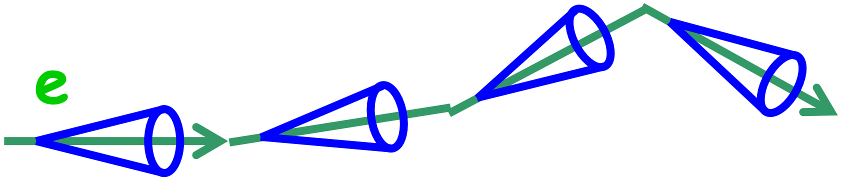
Producing Neutrinos

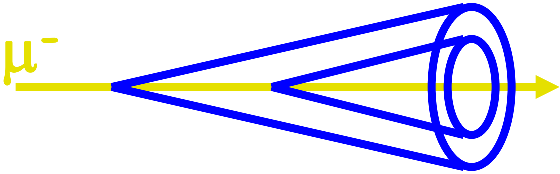


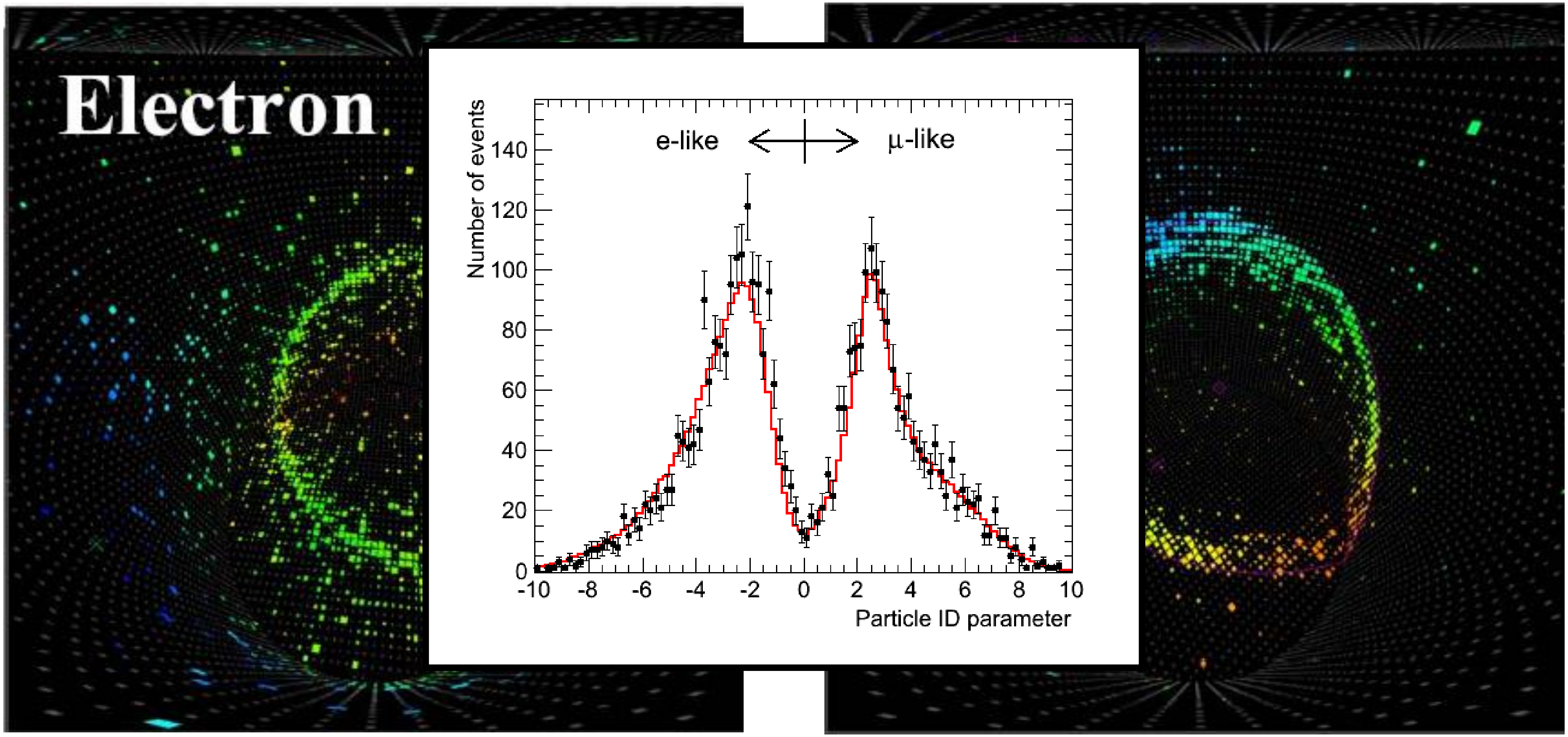




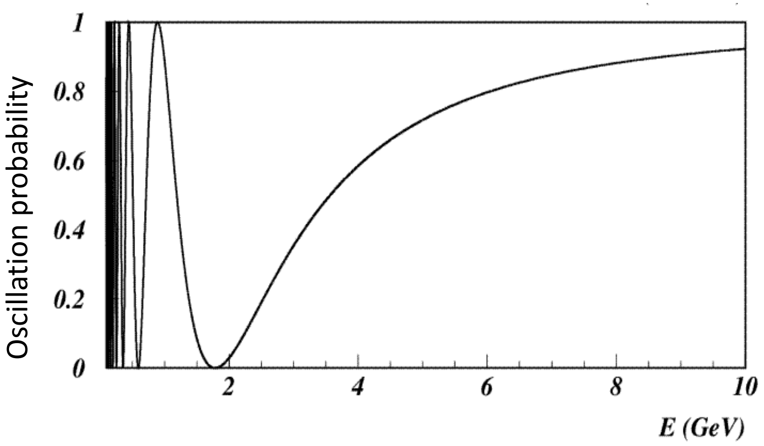
Super-Kamiokande PID



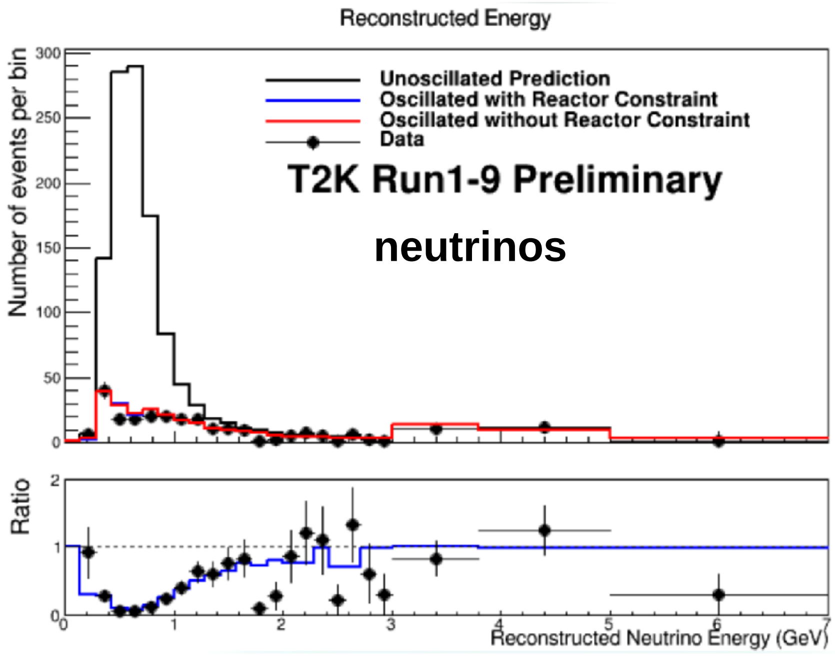


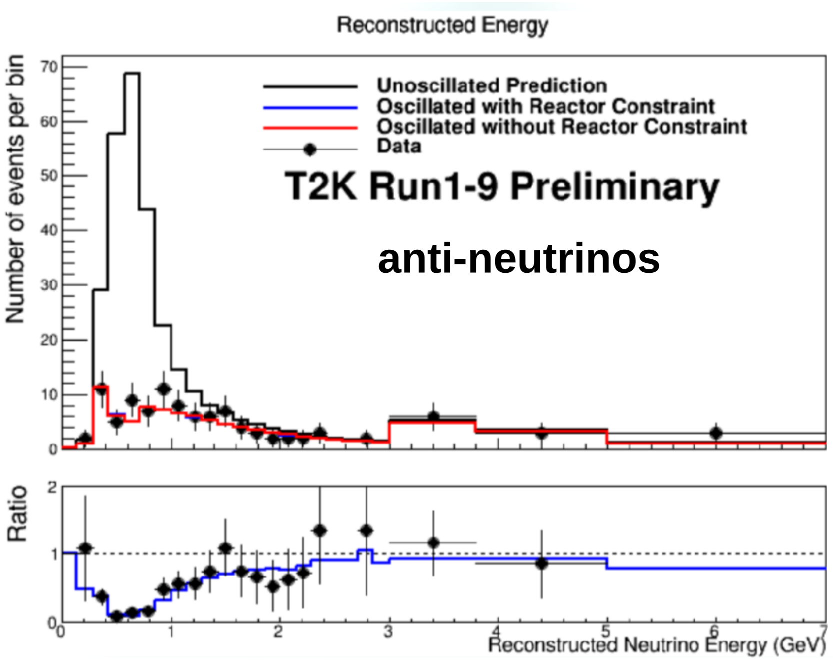


Muon Neutrino Disappearance



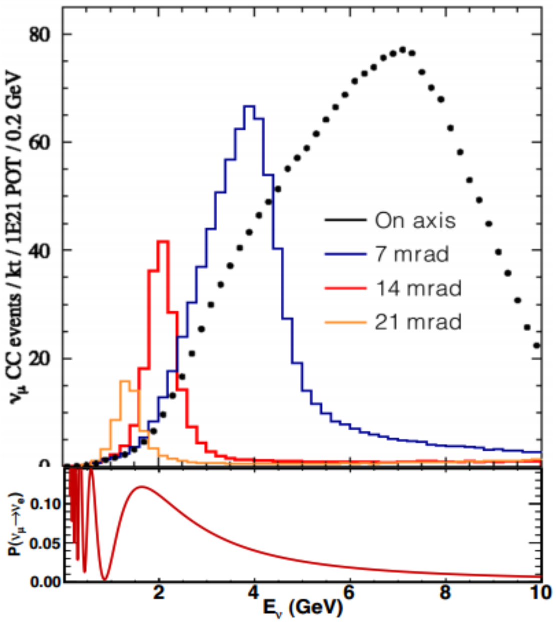
$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2(2\theta)\sin^2\left(1.27\Delta m^2 \frac{L}{E_\nu}\right)$$

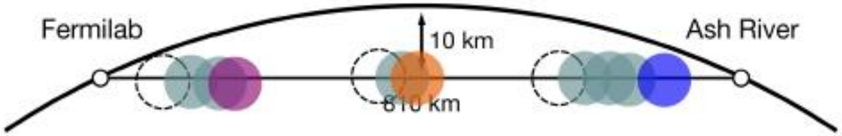




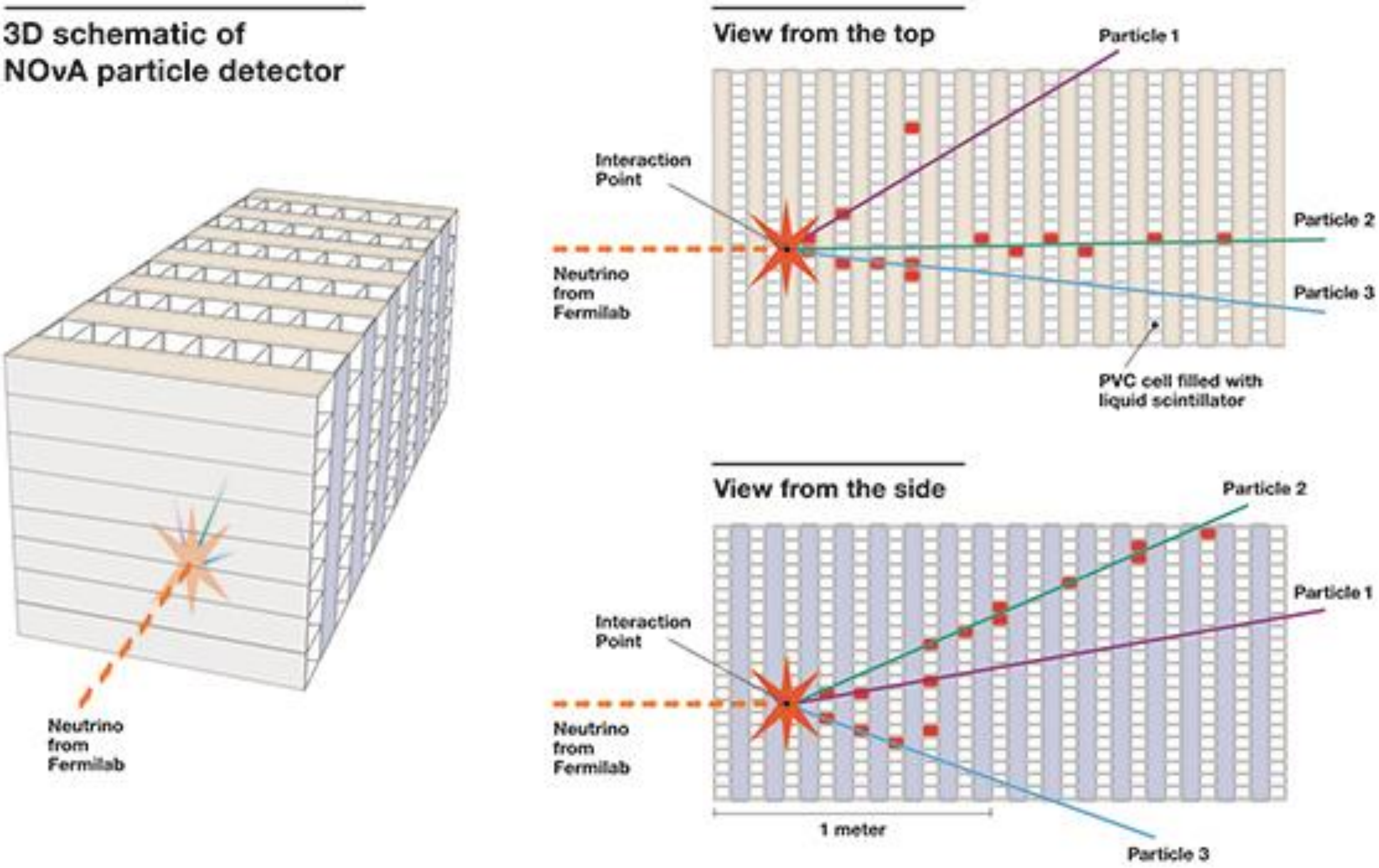
NOvA


NOvA
Ash River
International Falls
Duluth
MN
Minneapolis
WI
Fermilab
IL

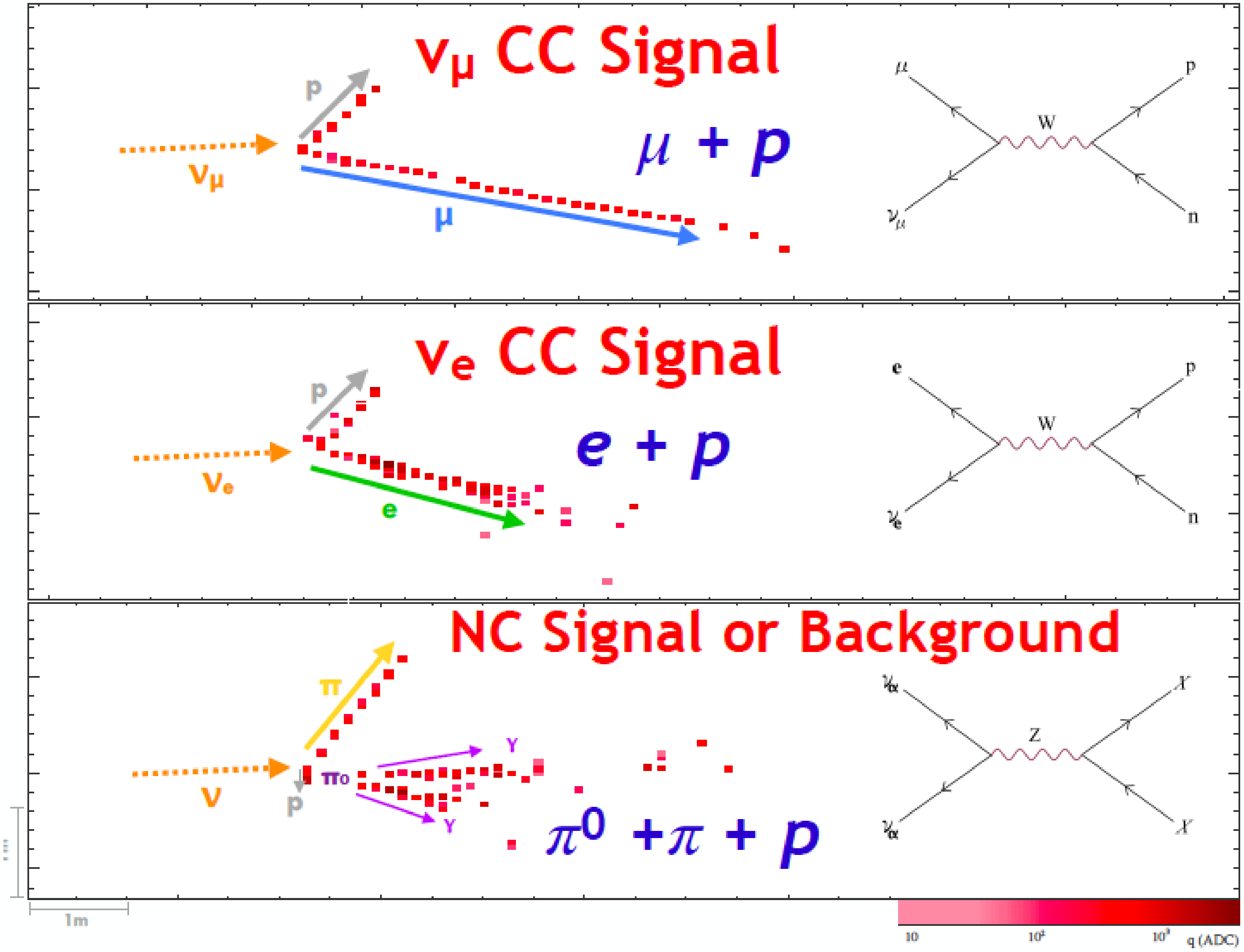

80
60
40
20
0
ν_μ CC events / kt / 1E21 POT / 0.2 GeV
On axis
7 mrad
14 mrad
21 mrad
0.10
0.05
0.00
$P(\nu_\mu \rightarrow \nu_e)$
2
4
6
8
10
E_ν (GeV)


Fermilab
Ash River
10 km
810 km

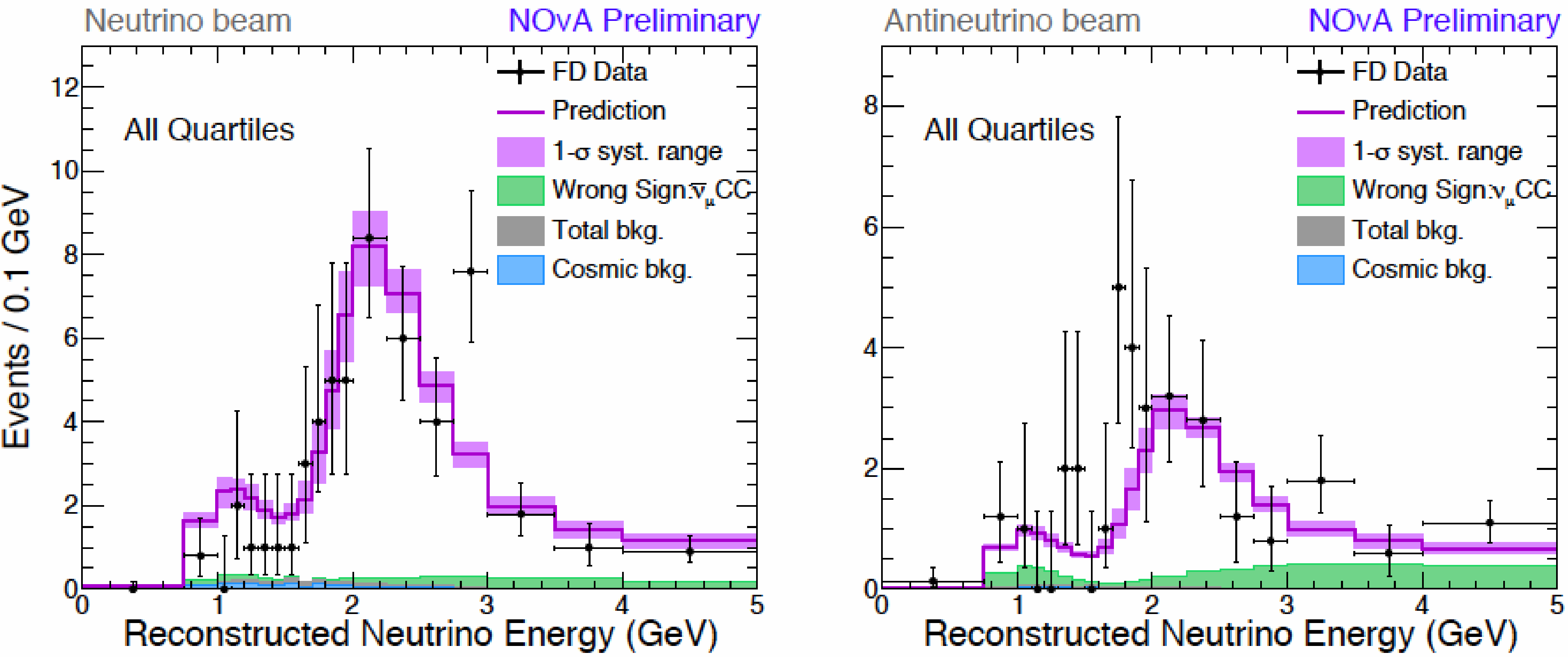
NOvA Detector Concept



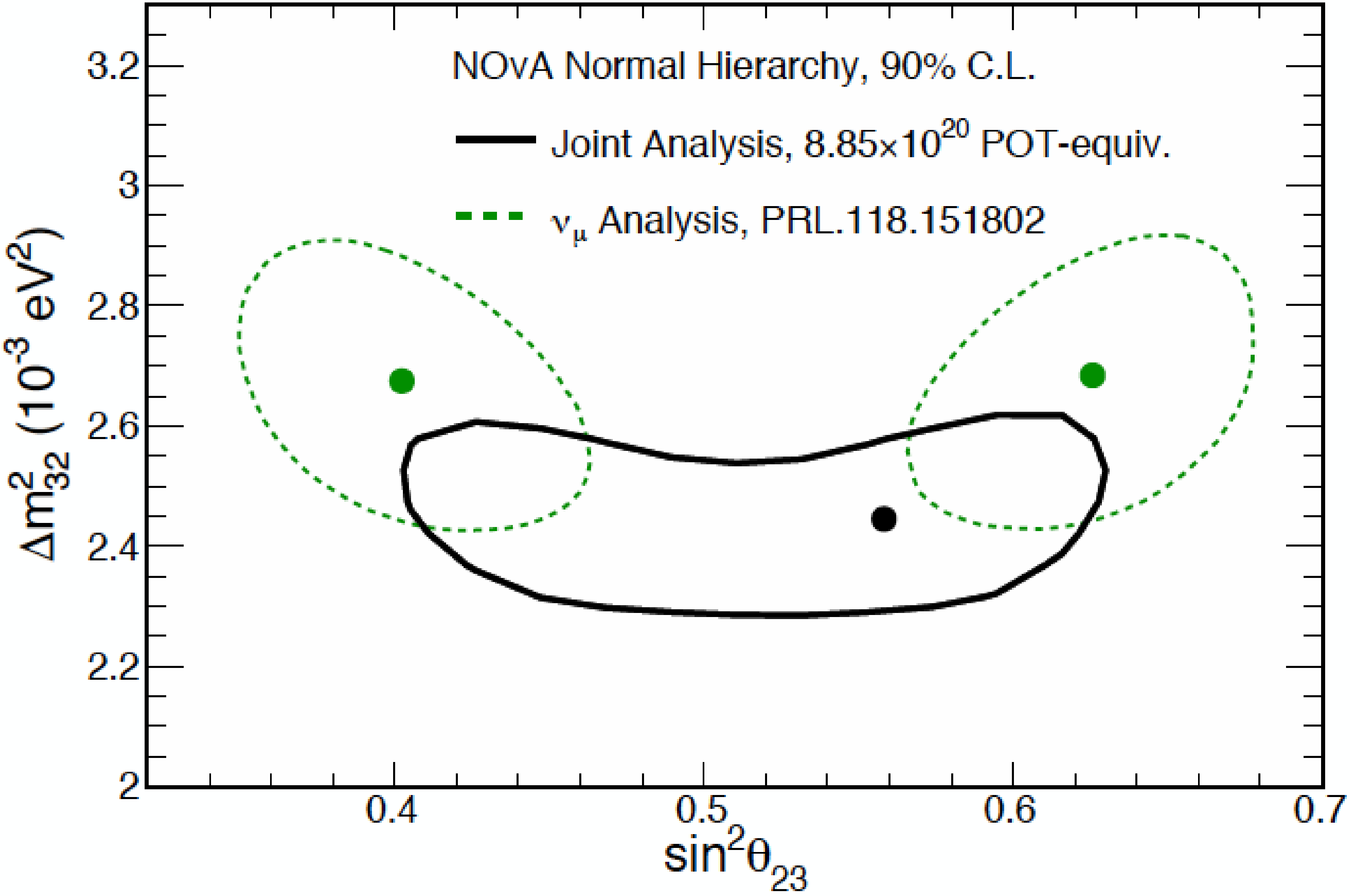
NOvA Events


ν_μ CC Signal
$\mu + p$
p
ν_μ
μ
μ
p
W
ν_μ
n
ν_e CC Signal
$e + p$
p
ν_e
e
e
p
W
ν_e
n
NC Signal or Background
$\pi^0 + \pi + p$
π
ν
p
π0
γ
γ
ν_α
X
Z
ν_α
X
1m
10
10^2
10^3
q (ADC)

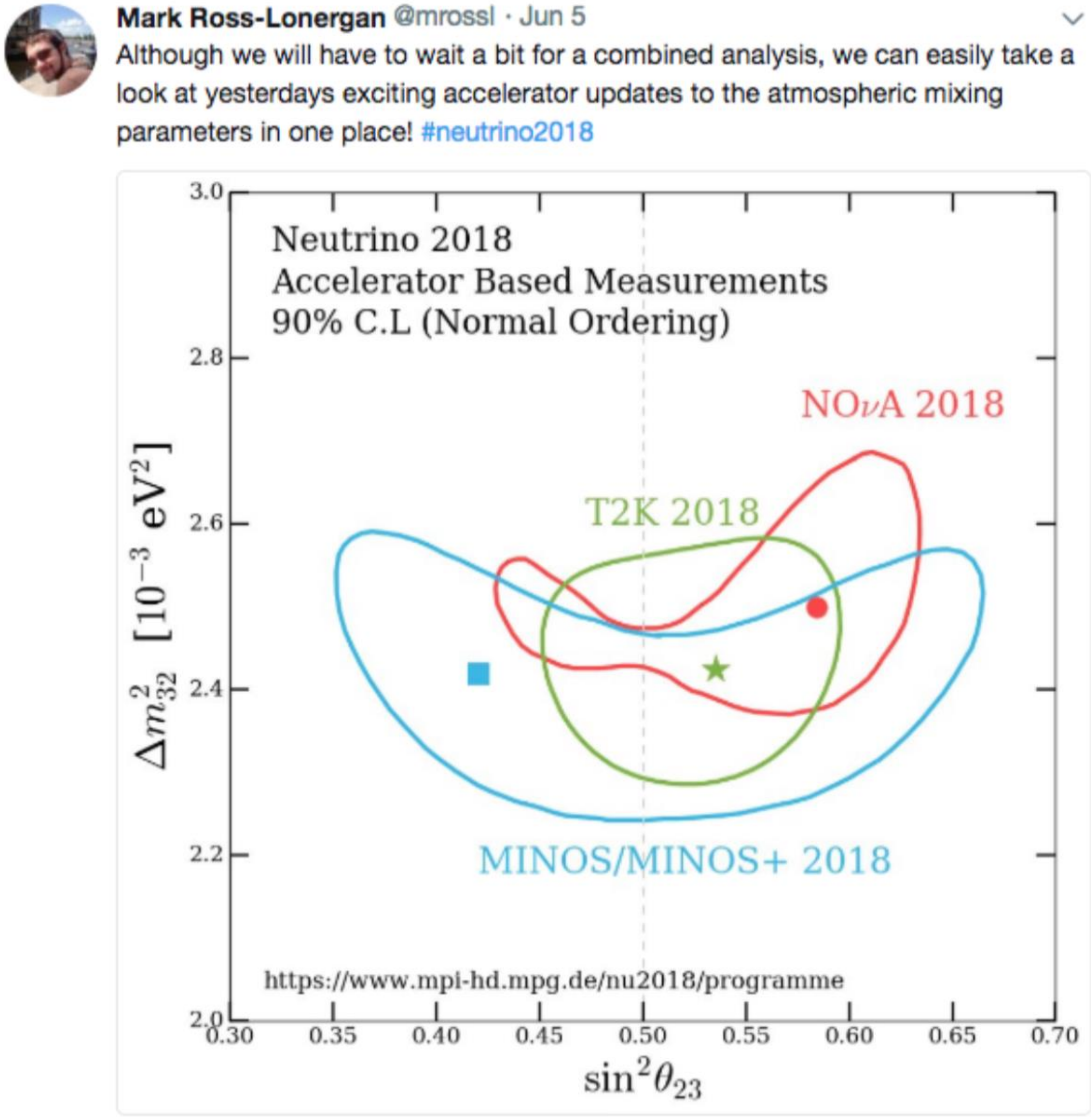
NOvA Disappearance



A word of caution



The Happy Family



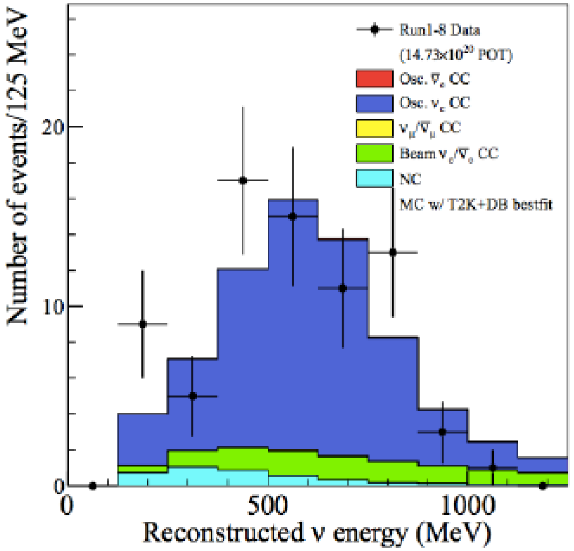
Mark Ross-Lonergan @mrossl · Jun 5

Although we will have to wait a bit for a combined analysis, we can easily take a look at yesterdays exciting accelerator updates to the atmospheric mixing parameters in one place! #neutrino2018

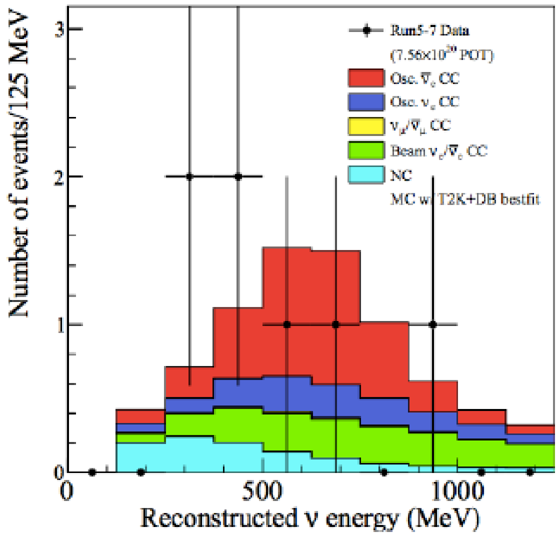
Electron Neutrino Appearance

T2K

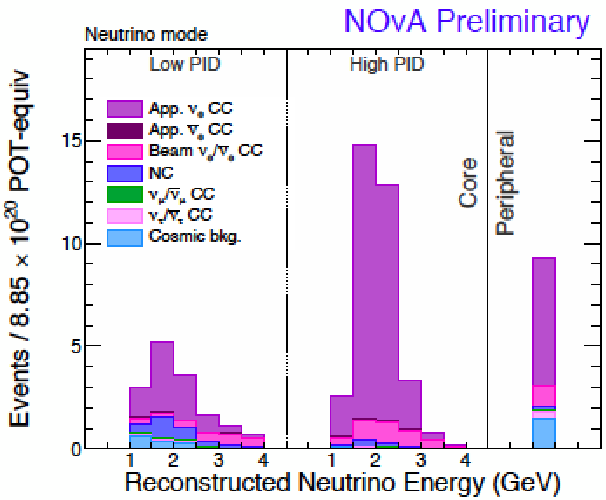
Neutrino CCQE 1 e-like ring

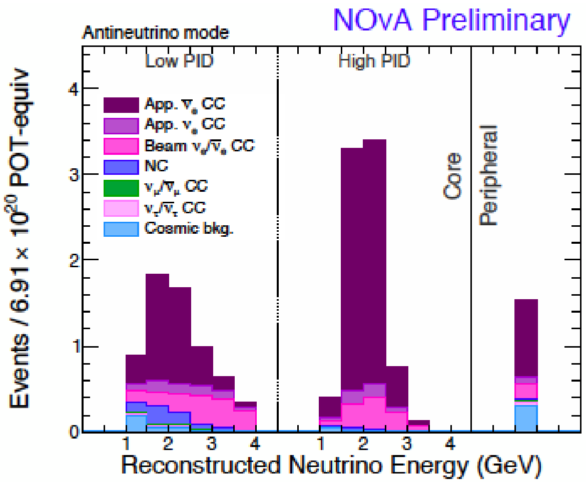


Antineutrino CCQE 1e-like ring



NOvA





The Full Monty

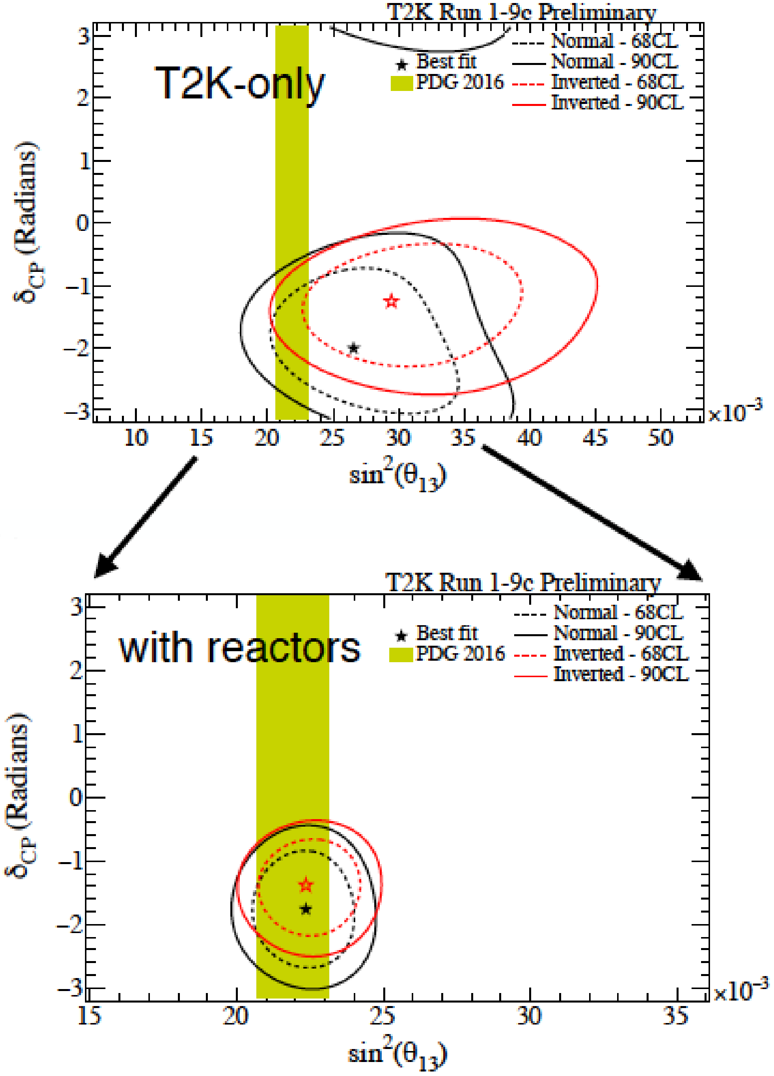
$$
\begin{aligned}
P(\nu_\mu \to \nu_e) = {} & 4C_{13}^2 S_{13}^2 S_{23}^2 \sin^2 \frac{\Delta m_{31}^2 L}{4E} \times \left(1 + \frac{2a}{\Delta m_{31}^2} \left(1 - 2S_{13}^2\right)\right) \\
& + 8C_{13}^2 S_{12} S_{13} S_{23} (C_{12} C_{23} \cos\delta - S_{12} S_{13} S_{23}) \cos \frac{\Delta m_{32}^2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

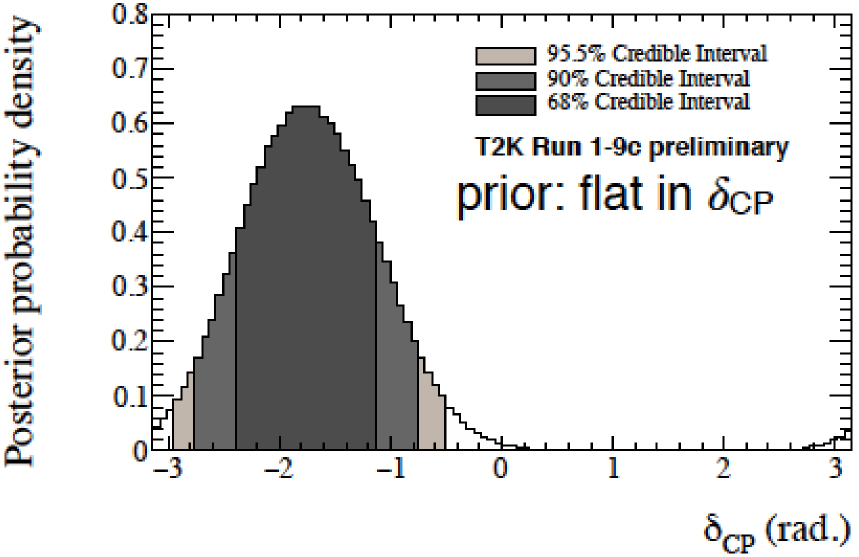
sin(δ) changes sign for anti-neutrinos

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

T2K Results

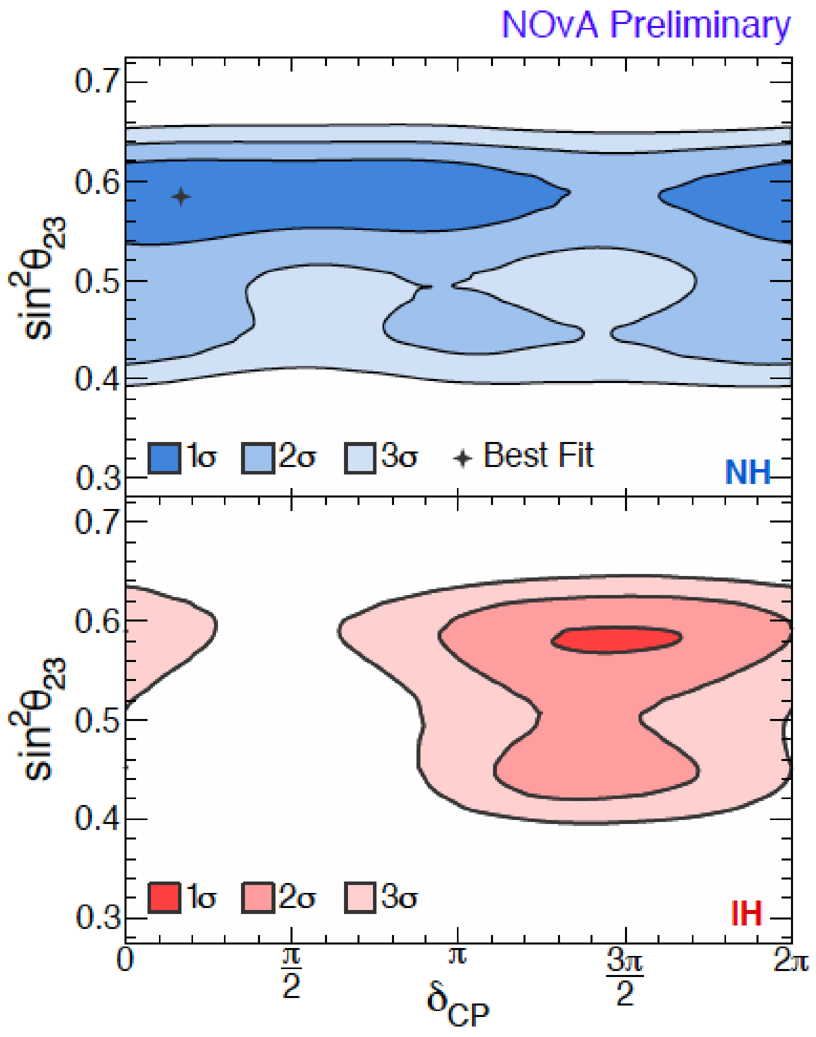
DATA FIT

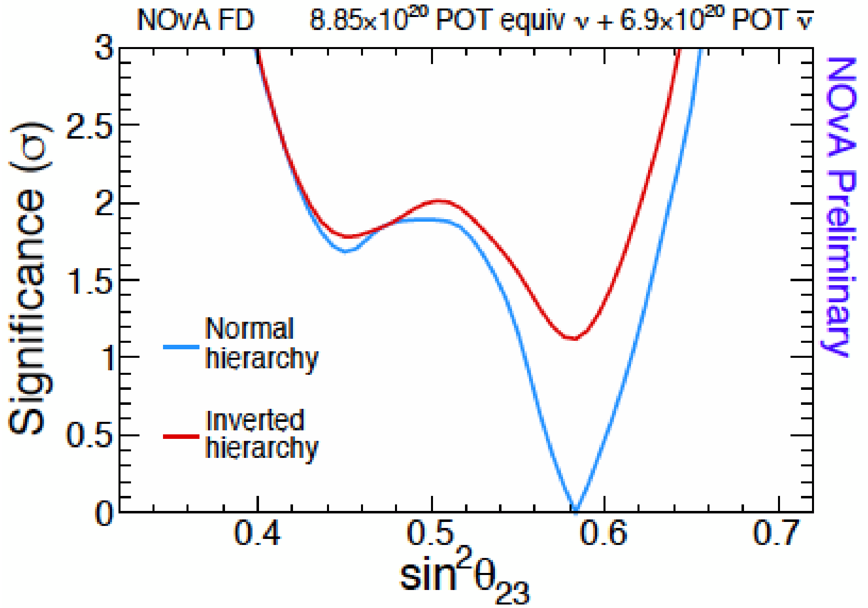




	$\sin^2\theta_{23} \leq 0.5$	$\sin^2\theta_{23} > 0.5$	SUM
NH ($\Delta m^2_{32} > 0$)	0.204	0.684	0.888
IH ($\Delta m^2_{31} < 0$)	0.023	0.089	0.112
SUM	0.227	0.773	1

NOvA Results





Best fit: Normal Hierarchy

δ_{CP}= 0.17π

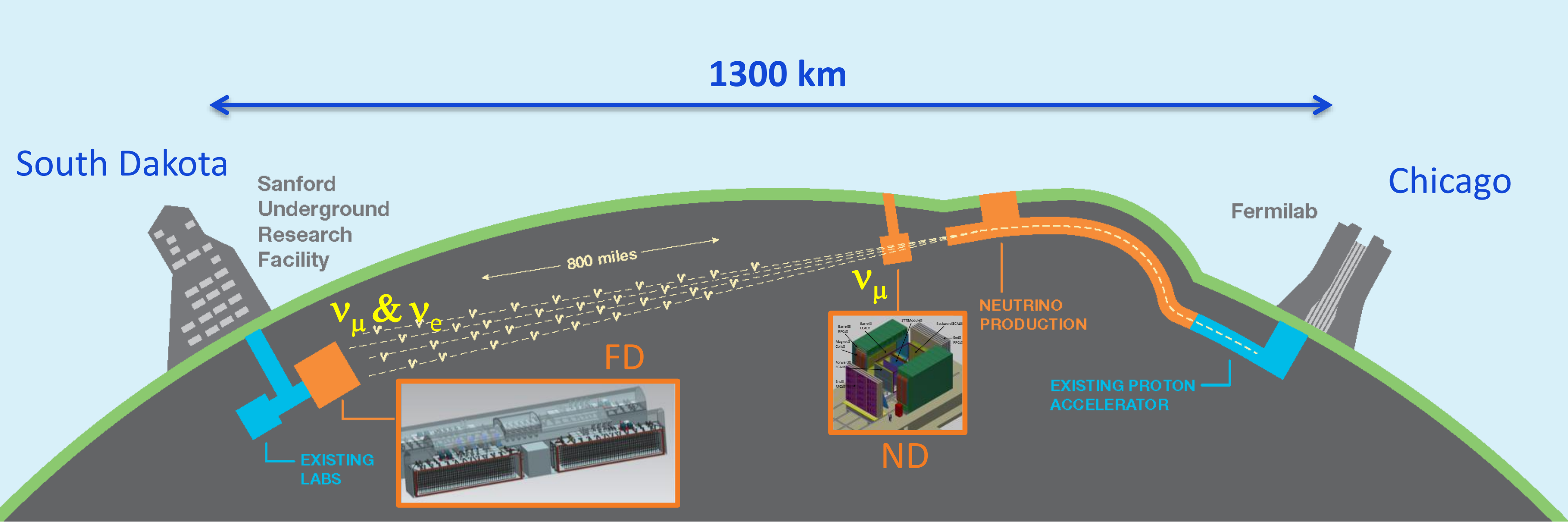
$\sin^2\theta_{23}$ = 0.58±0.03 (UO)

$\Delta m^2_{32} = (2.51^{+0.12}_{-0.08}) \cdot 10^{-3}$ eV^2

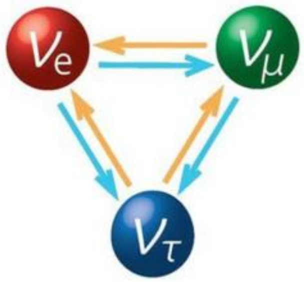
DEEP UNDERGROUND
NEUTRINO EXPERIMENT

General Setup

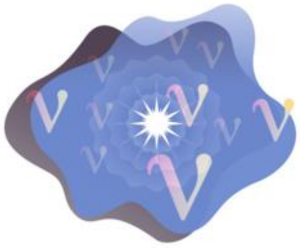
- LBNF/DUNE will consist of
  - An intense 1.2 MW upgradeable ν-beam fired from Fermilab
  - A massive 68 kt (40kt instrumented) deep underground LAr detector in South Dakota and a large Near Detector at Fermilab
  - A large international collaboration



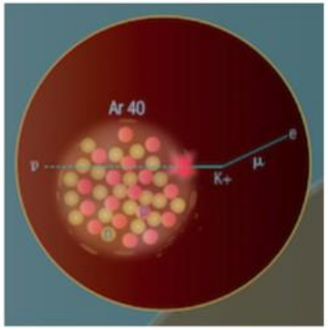
Physics Program



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



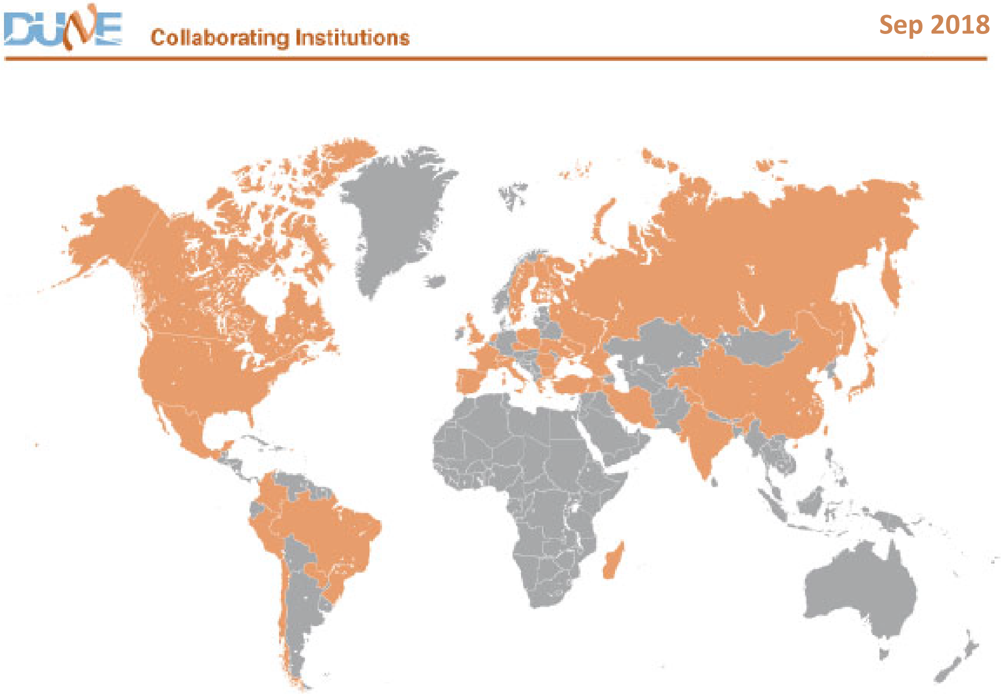
- Supernova Physics
  - Observation of time and flavour profile provides insight into collapse and evolution of supernova
  - Unique sensitivity to electron neutrinos



- Baryon number violation
  - Predicted by many BSM theories
  - LAr TPC technology well-suited to certain proton decay channels (*e.g.*, $p \to K+\bar{\nu}$)
  - $\Delta(B\text{-}L) \neq 0$ channels accessible (*e.g.*, $n \to \bar{n}$)

The DUNE Collaboration

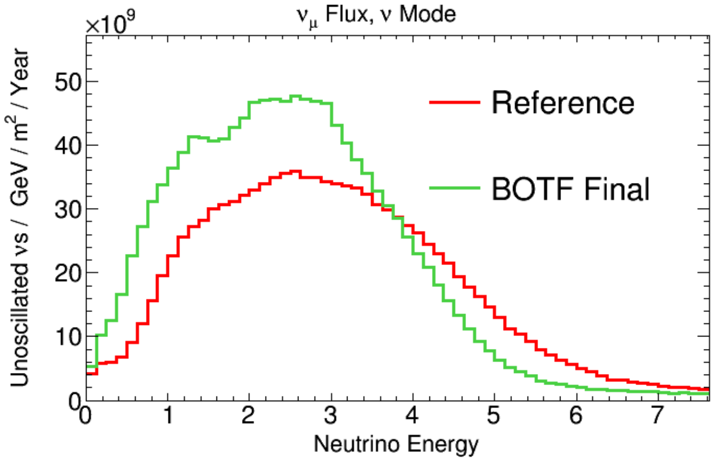
- 1144 collaborators from 178 institutions in 32 countries
- 622 faculty/scientists, 191 postdocs, 106 engineers, 5 computing professionals, 220 PhD students
- Growing at a rate of about 100 collaborators/year



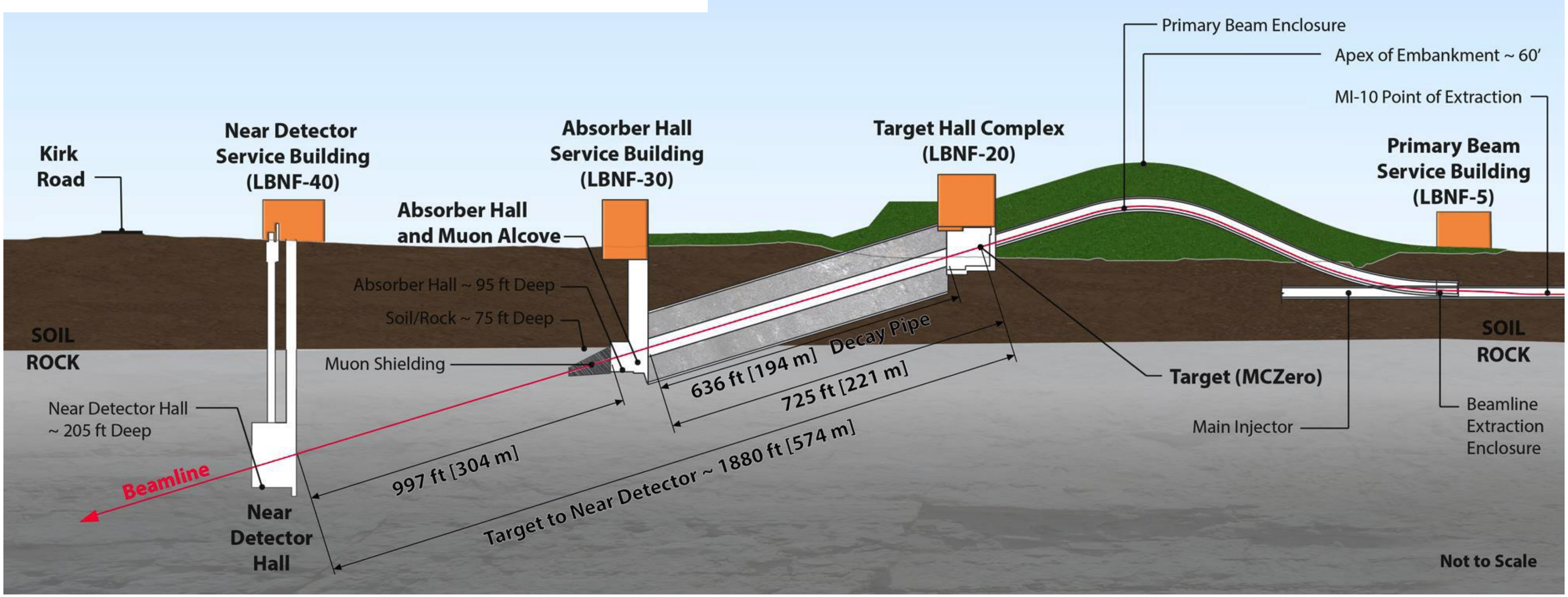
Armenia (3), Brazil (29), Bulgaria (1), Canada (1), CERN (32), Chile (3), China (5), Colombia (13), Czech Republic (11), Spain (34), Finland (4), France (23), Greece (4), India (45), Iran (2), Italy (63), Japan (7), Madagascar (8), Mexico (8), The Netherlands (4), Paraguay (4), Peru (8), Poland (6), Portugal (7), Romania (7), Russia (10), South Korea (4), Sweden (1), Switzerland (35), Turkey (2), UK (136), Ukraine (4), USA (621)

The DUNE Collaboration

Beam



- Proton beam energy
  60-120 GeV
- Power
  1.2 MW ➔ 2.4 MW
- Neutrinos and anti-neutrinos



How to Measure Oscillations

- Oscillation probabilities

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

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

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

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

Are there cancellations?

- Oscillation signal

Small theo. uncertainty or measurement

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

1-2% uncertainty

- Near muon/electron ratio

$$\left.\frac{dN^{near}_{\nu_e}}{dE_\nu}\right/\frac{dN^{near}_{\nu_\mu}}{dE_\nu} = \frac{\sigma^{Ar}_{\nu_e}(E_\nu)}{\sigma^{Ar}_{\nu_\mu}(E_\nu)} * \frac{\phi^{near}_{\nu_e}(E_\nu)}{\phi^{near}_{\nu_\mu}(E_\nu)}$$

Not so small uncertainty

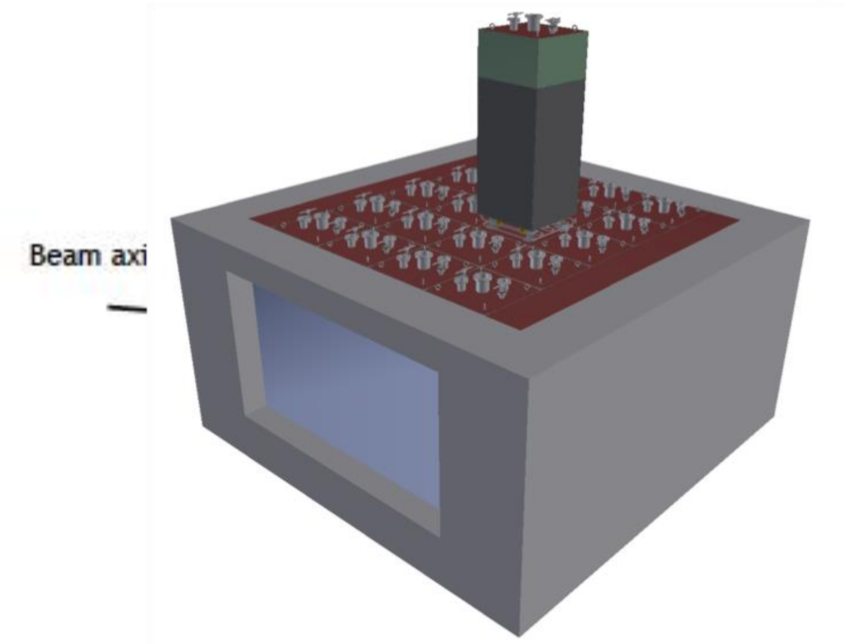
- Need to know
  - Flux & cross section ratios
  - Far/near extrapolation

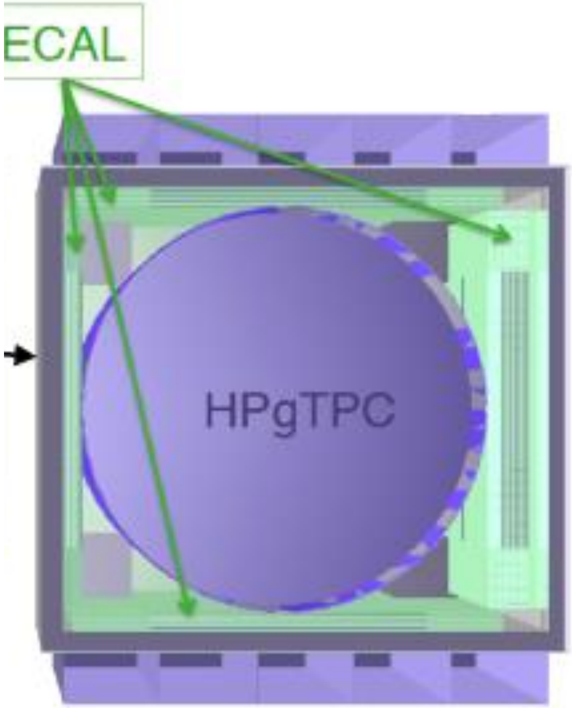
But in Reality

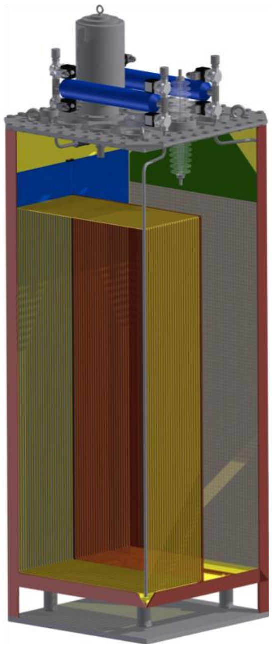
$$\frac{\frac{dN^{far}_{\nu_e}}{dE_{rec}}}{\frac{dN^{near}_{\nu_\mu}}{dE_{rec}}} = \frac{\int P_{\nu_\mu \to \nu_e}(E_\nu) * \phi^{near}_{\nu_\mu}(E_\nu) * F_{far/near}\,(E_\nu) * \sigma^{Ar}_{\nu_e}\,(E_\nu) * T^{far}_{\nu_e}(E_\nu, E_{rec})\; dE_\nu}{\int \phi^{near}_{\nu_\mu}(E_\nu) * \sigma^{Ar}_{\nu_\mu}\,(E_\nu)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

- 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



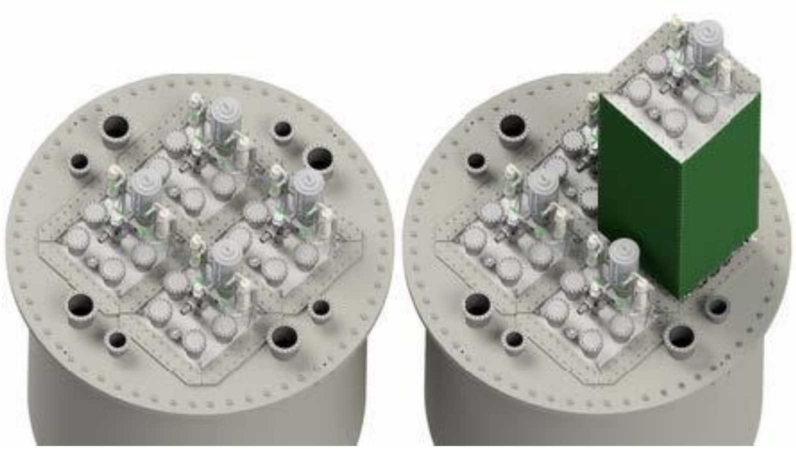


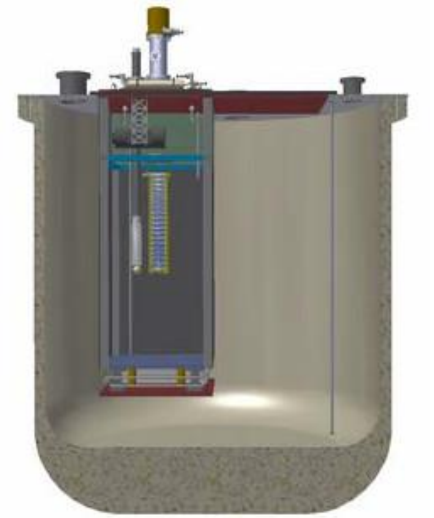


- Multiple Near Detectors
  - characterise beam & neutrino interactions & detector response
  - LAr TPC (similar to FD)
  - High pressure gaseous argon TPC tracker
  - Calorimeter and muon systems

ArgonCube 2X2 prototype (proto-DUNE-ND)

Engineering concept





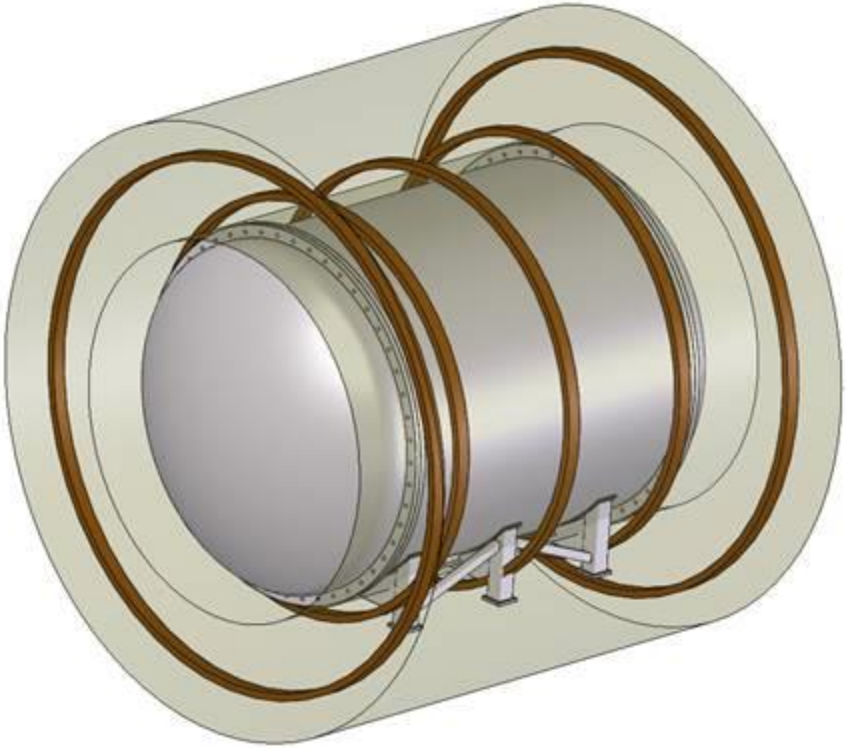
In the laboratory in Bern

First cool down starts next week

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

Multi-purpose detector

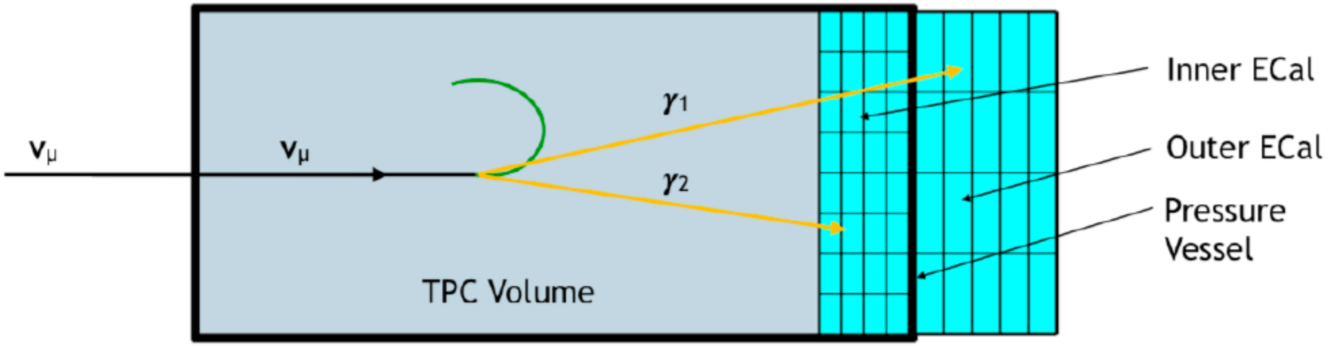
Raaf, Junk, Mohayai, Bellantoni



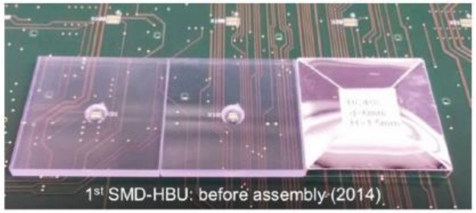
HPgTPC pressure vessel surrounded by the 5 coils comprising the Helmholtz coil system.
Not shown: ECAL and μ tagger.

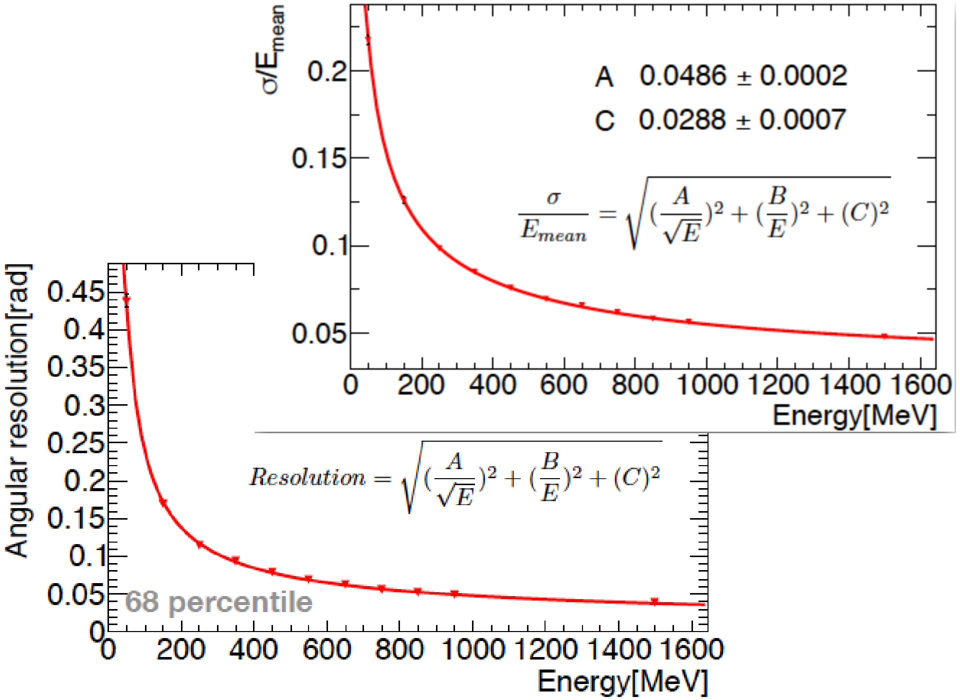
- 10 ATM Ar-CH_4 TPC inside cylindrical pressure vessel
- ECAL
  - Scintillator-Pb or Scintillator Cu
  - ½ inside pressure vessel, ½ outside
- SC Helmhotz coil magnet system
  - 3 coils for central field
  - 2 bucking coils
  - Note: continuing optimization study for NC magnet (BARC, Mumbai)
- μ tagging system

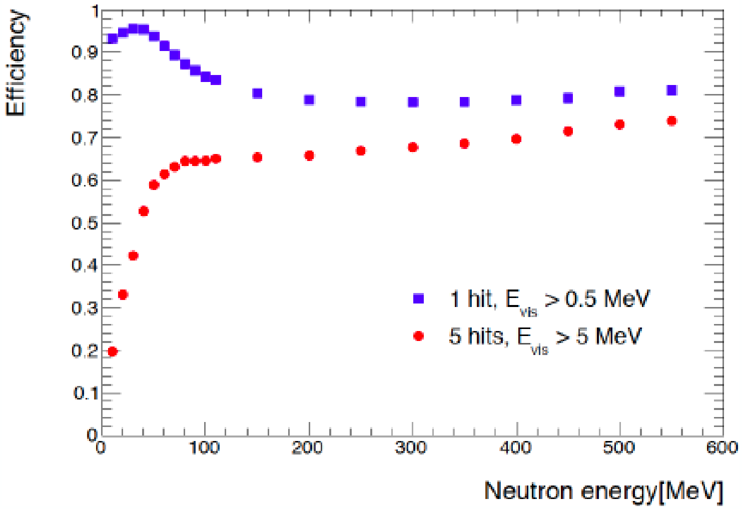
ECAL Concept



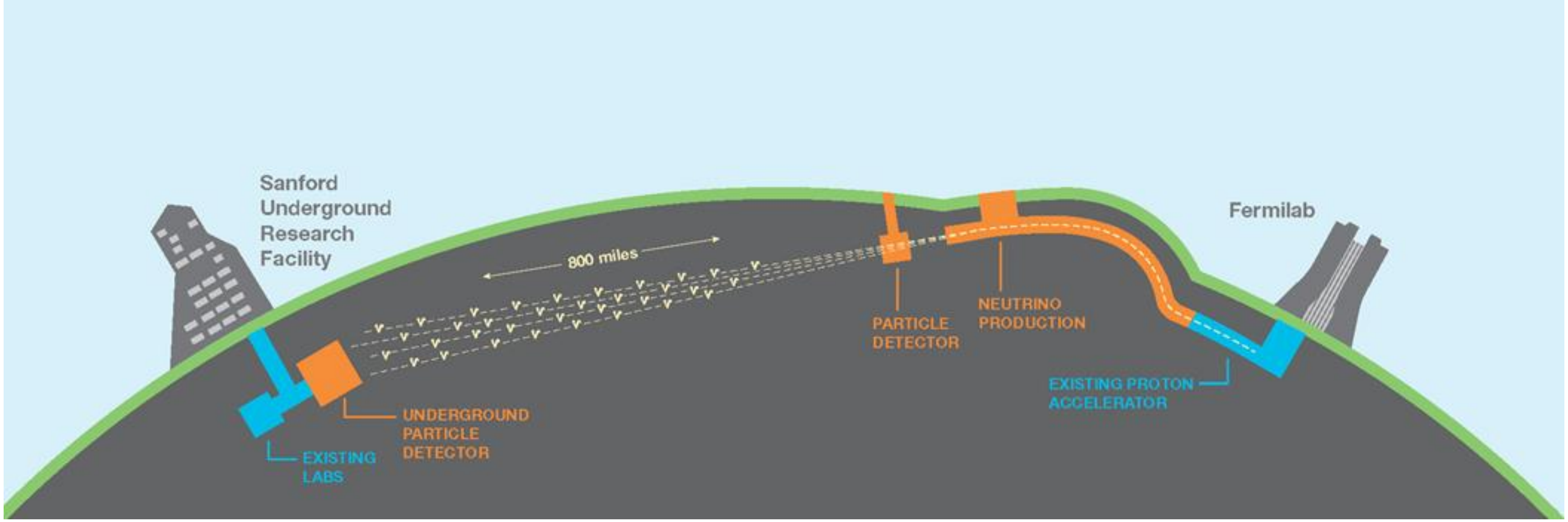
CALICE AHCAL concept







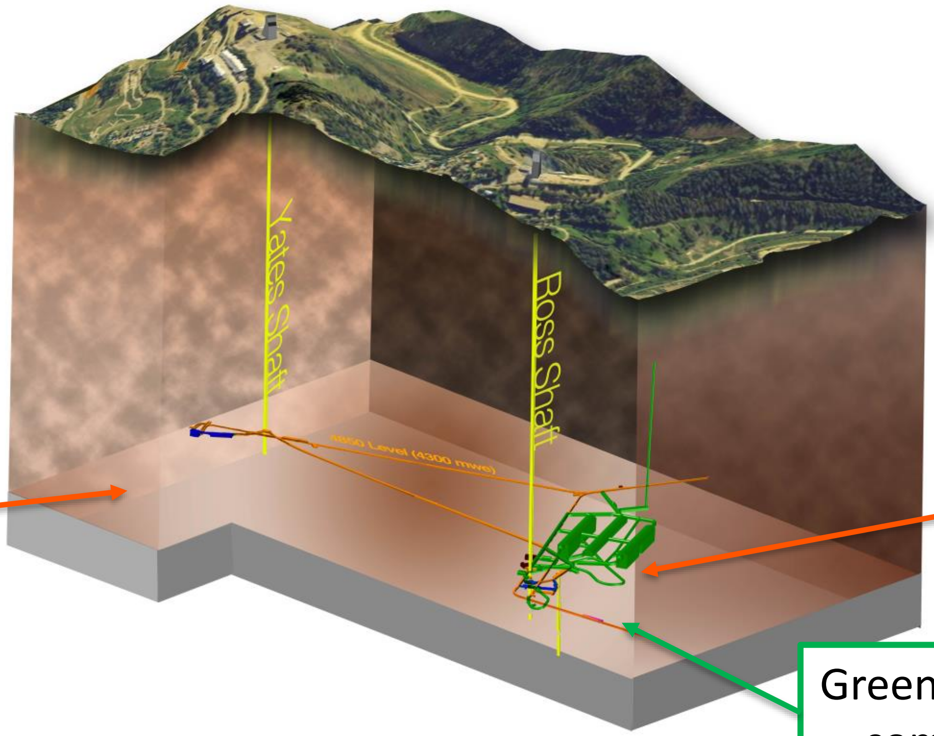
Far Detector



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**

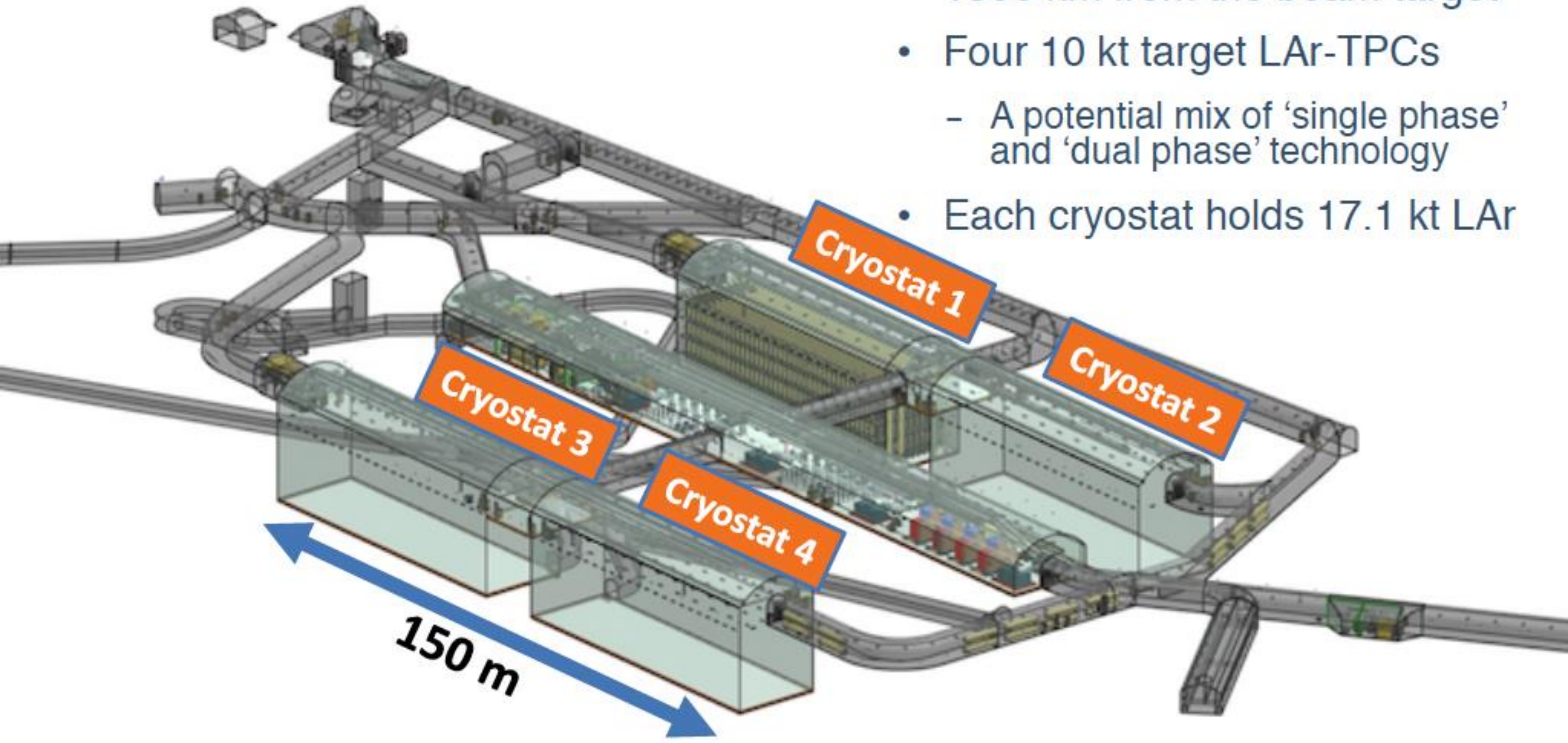
Green = new excavation commenced in 2017

It’s real!

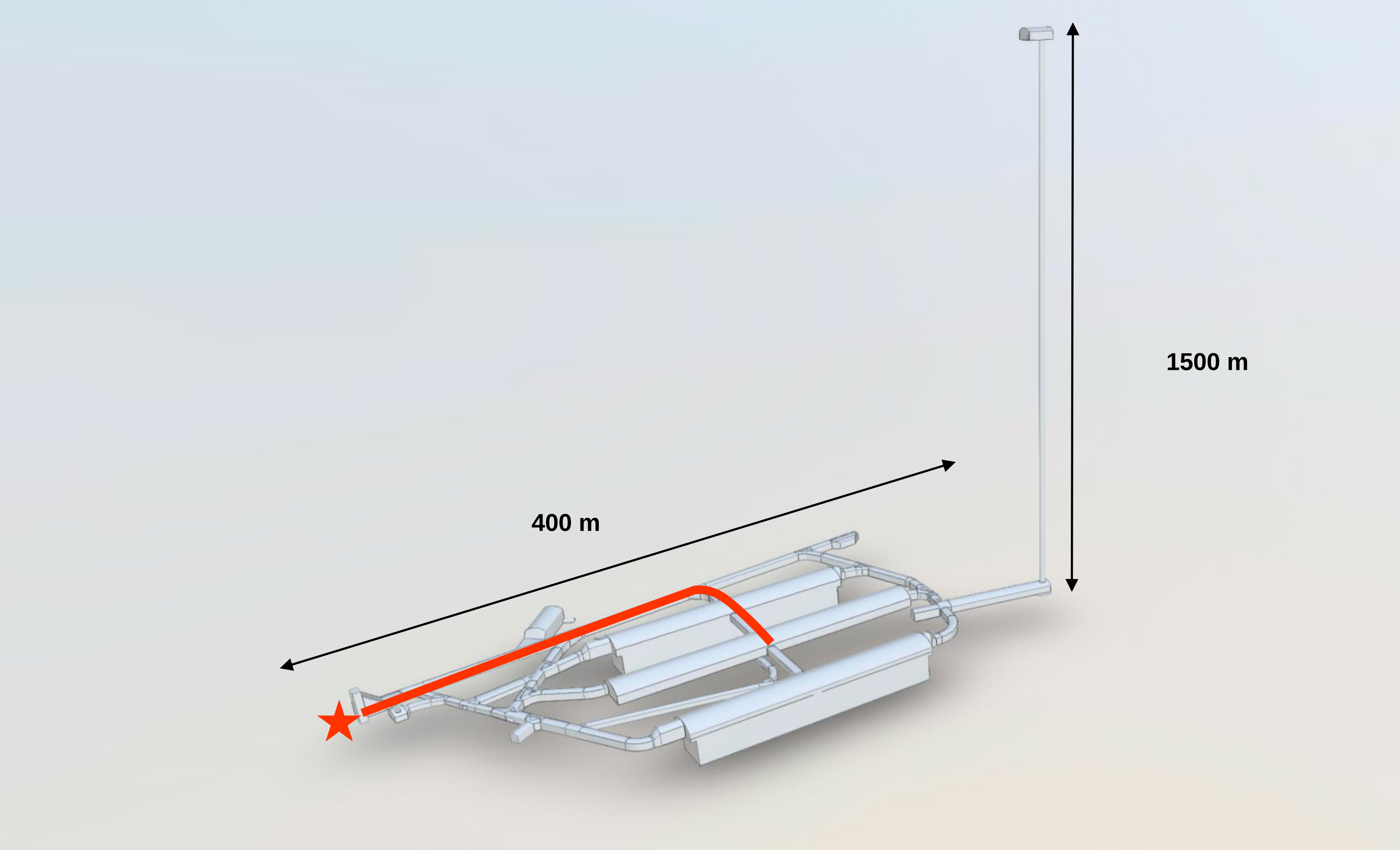
21st July 2017: Ground breaking at SURF

DUNE Far Detector

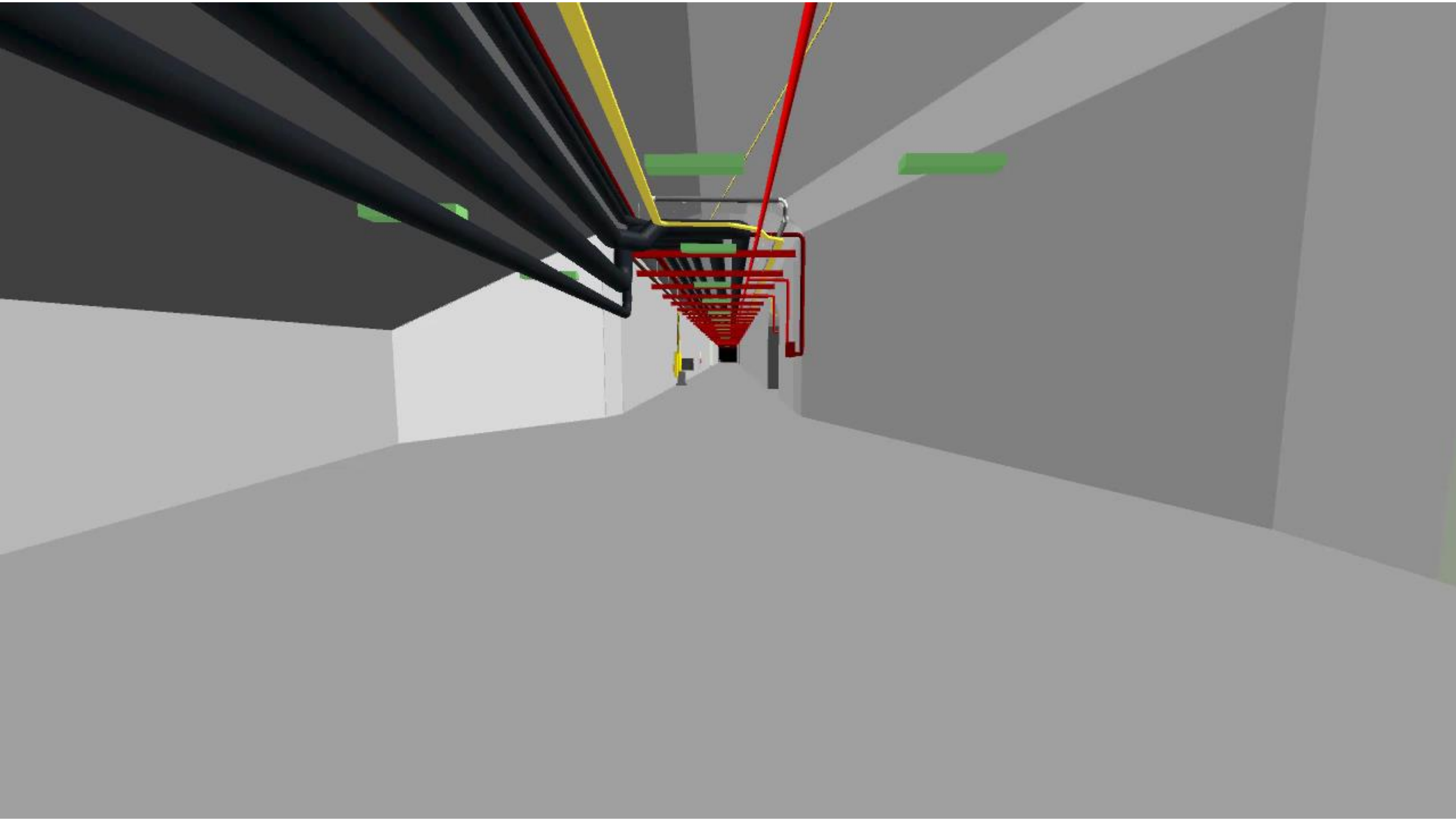
- 1478 m underground
- 1300 km from the beam target
- Four 10 kt target LAr-TPCs
  - A potential mix of ‘single phase’ and ‘dual phase’ technology
- Each cryostat holds 17.1 kt LAr

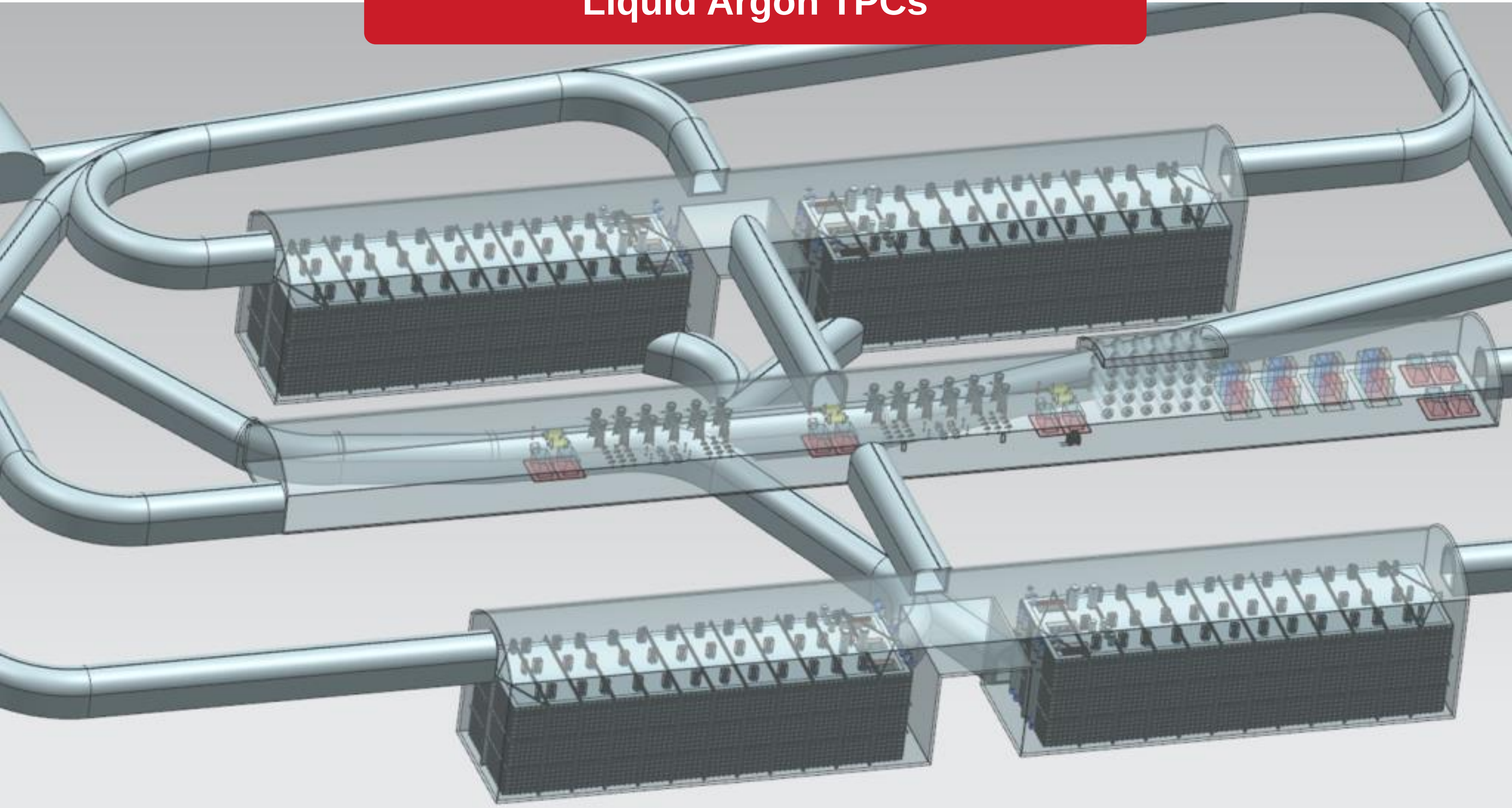


Far Detector



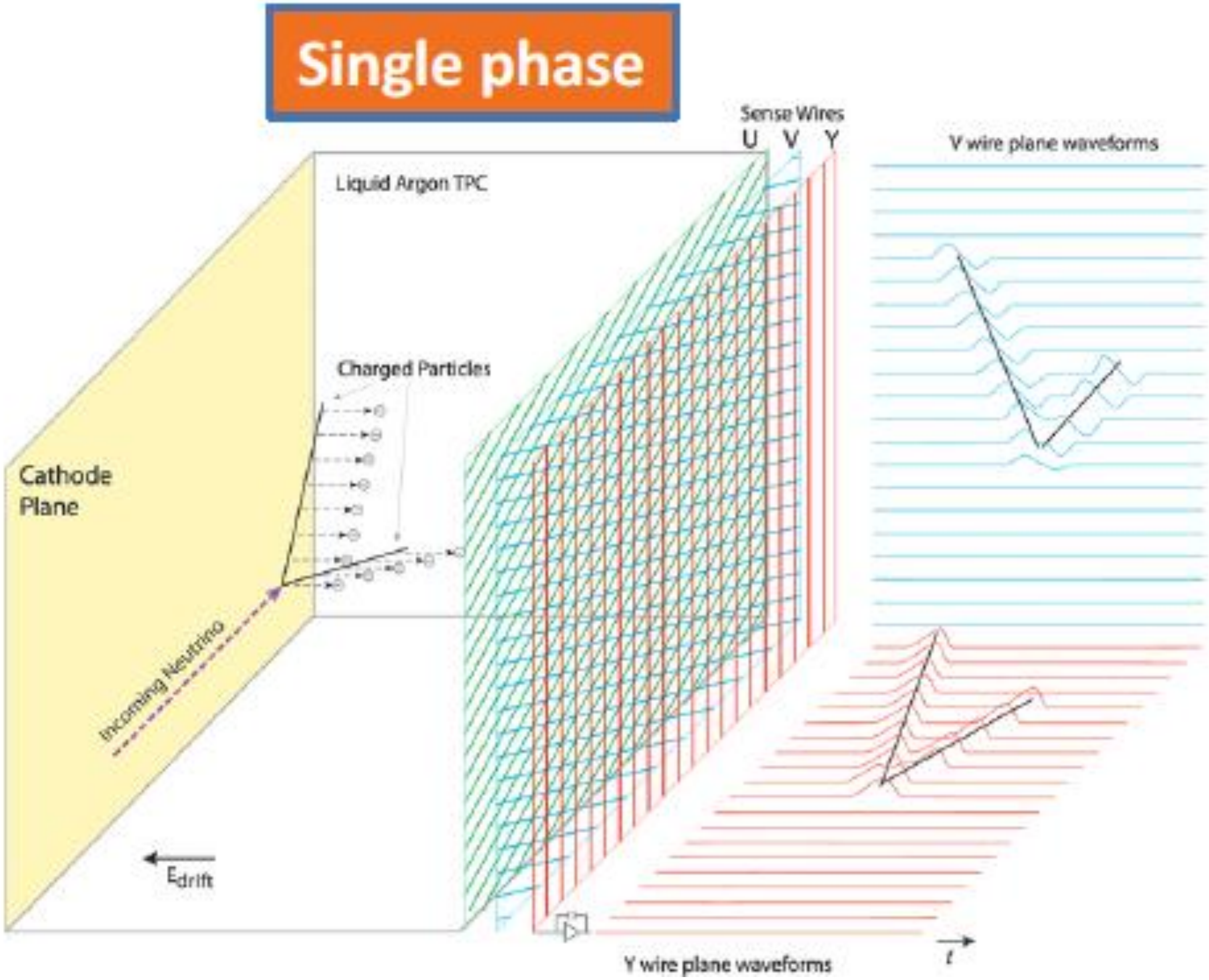
A Walk Through the Tunnels



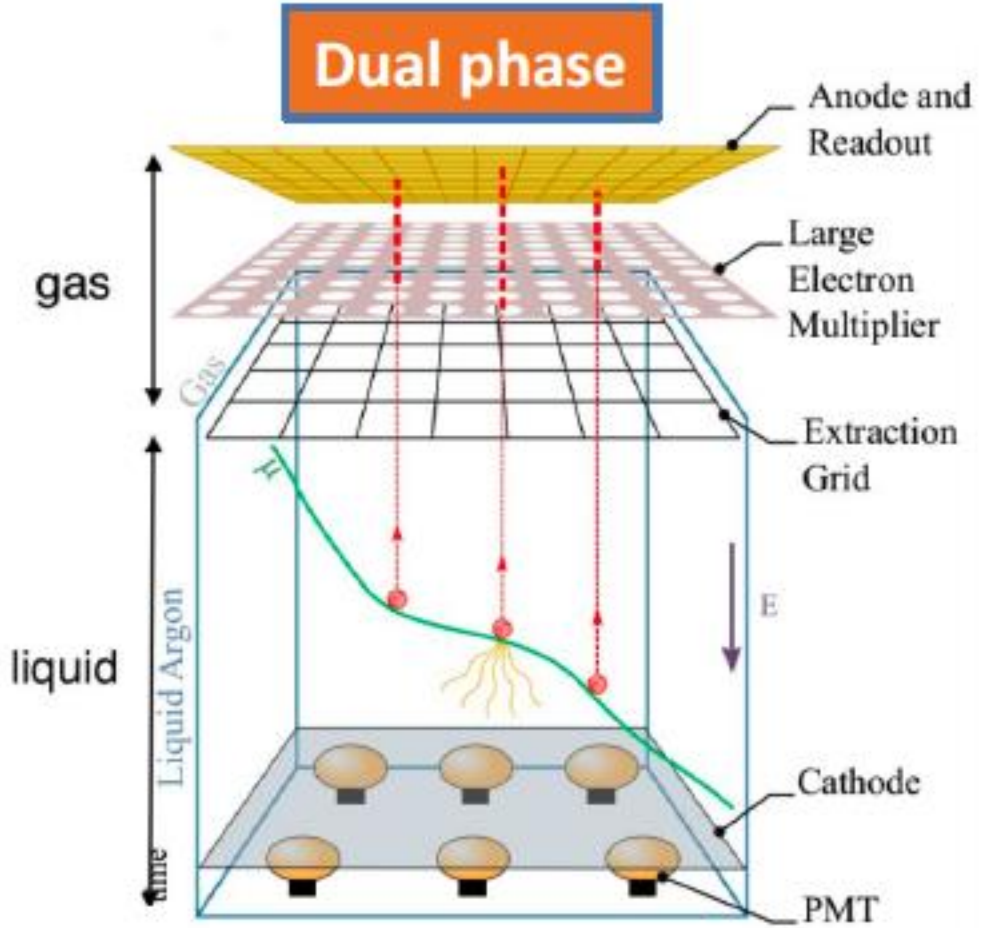


Four 10 Kton fiducial mass (17 Kton total) Liquid Argon TPCs

Single Phase Technology



Dual Phase Technology

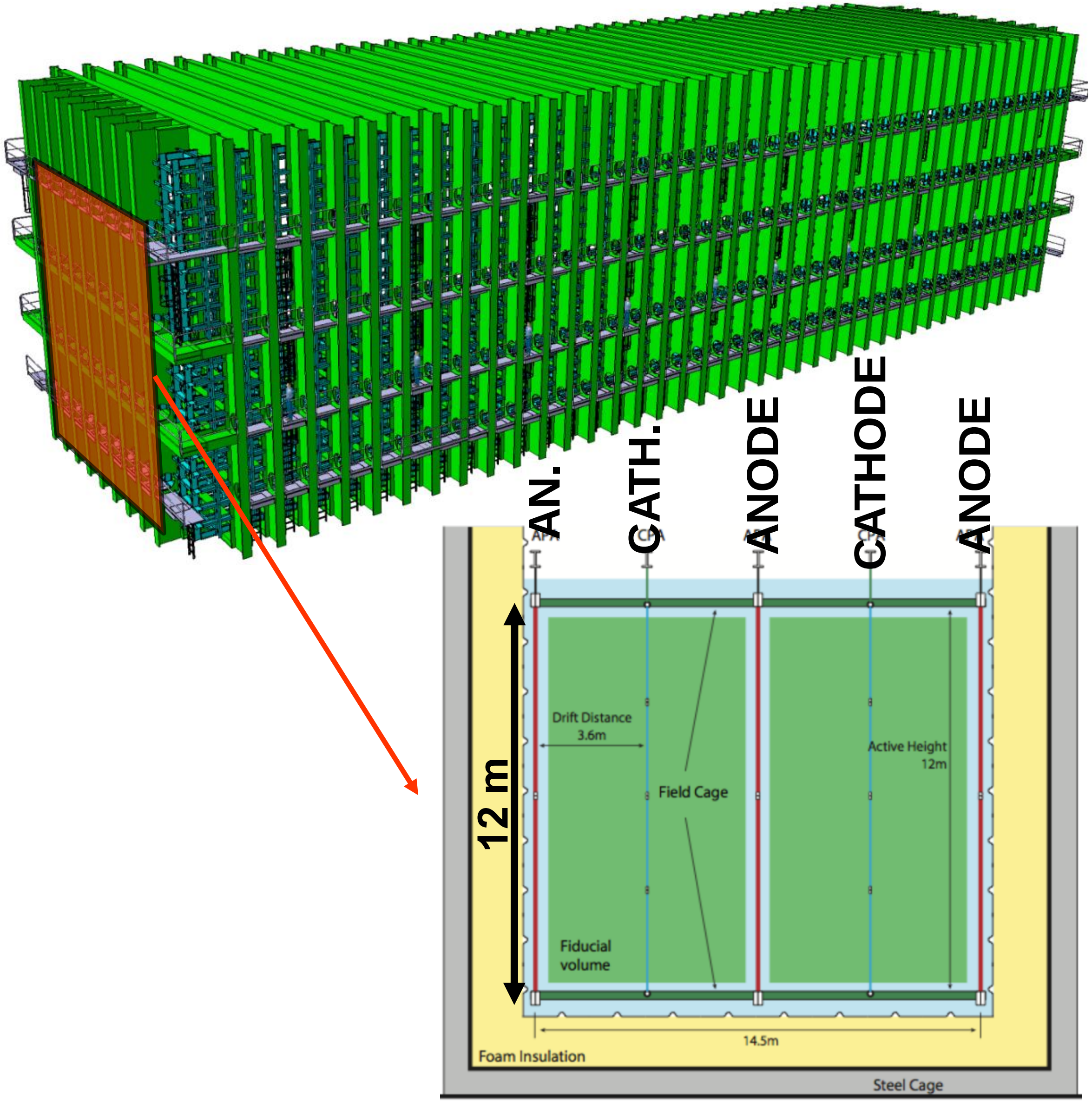


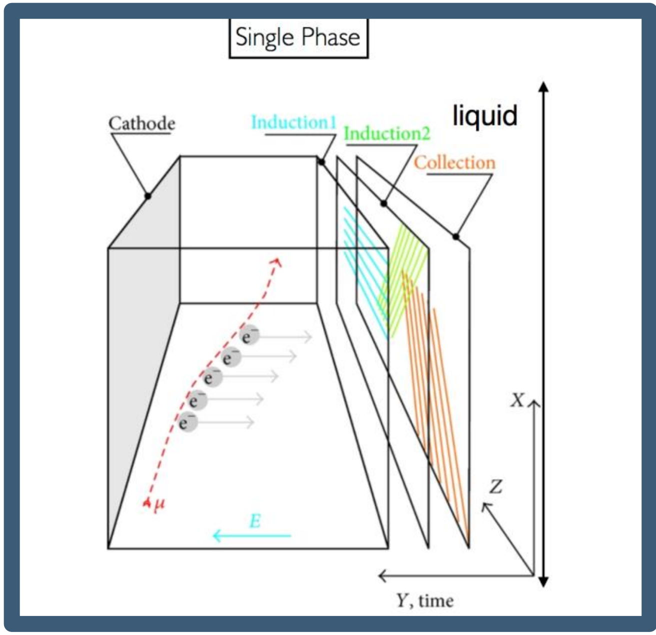
Why Liquid Argon ?

- **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)

Far detectors: 1st module

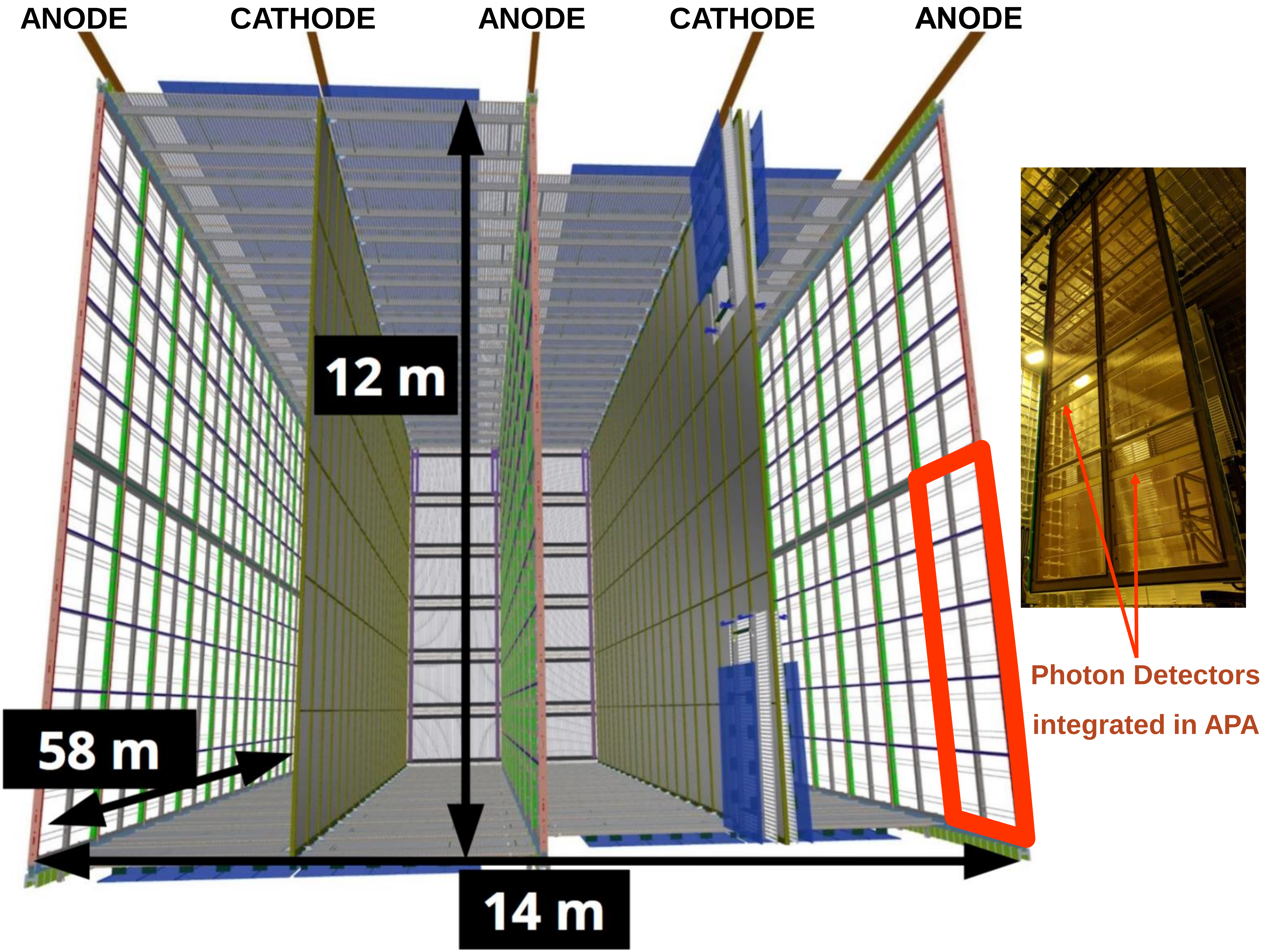
Single-Phase





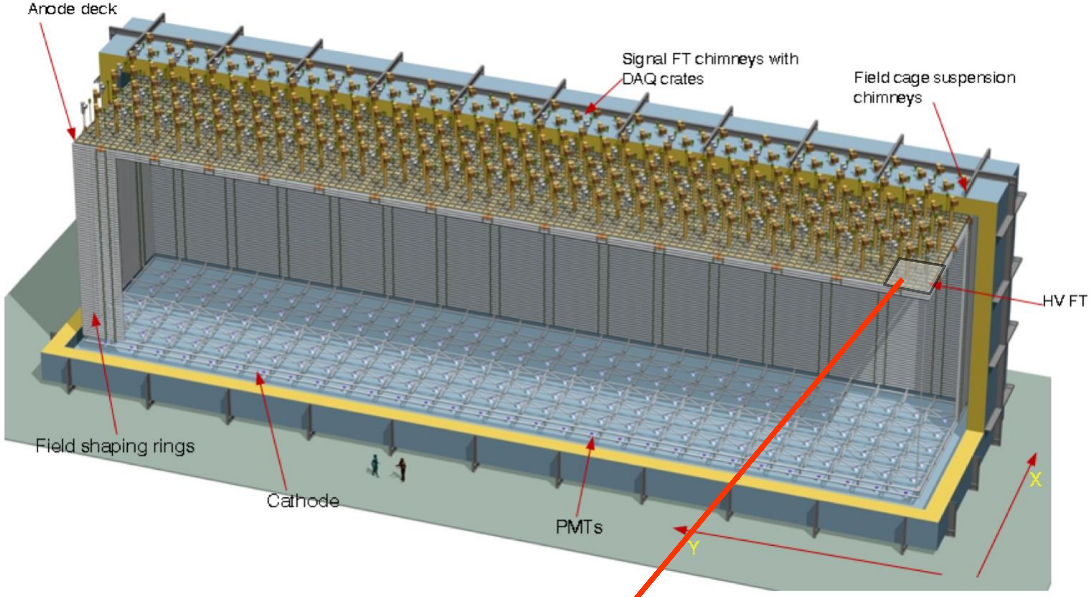
180,000 volts between

cathode and anode

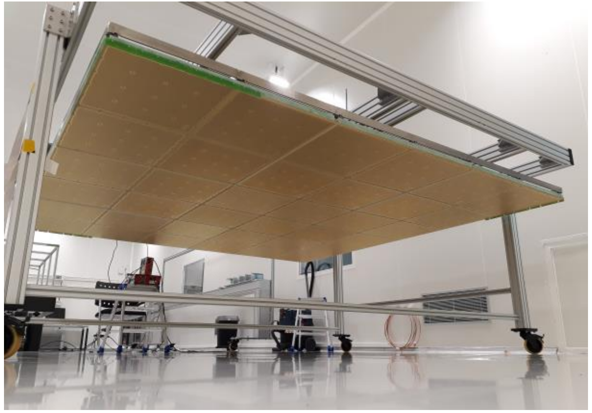

ANODE
CATHODE
ANODE
CATHODE
ANODE
12 m
58 m
14 m
Photon Detectors
integrated in APA

Far detectors: 2nd module

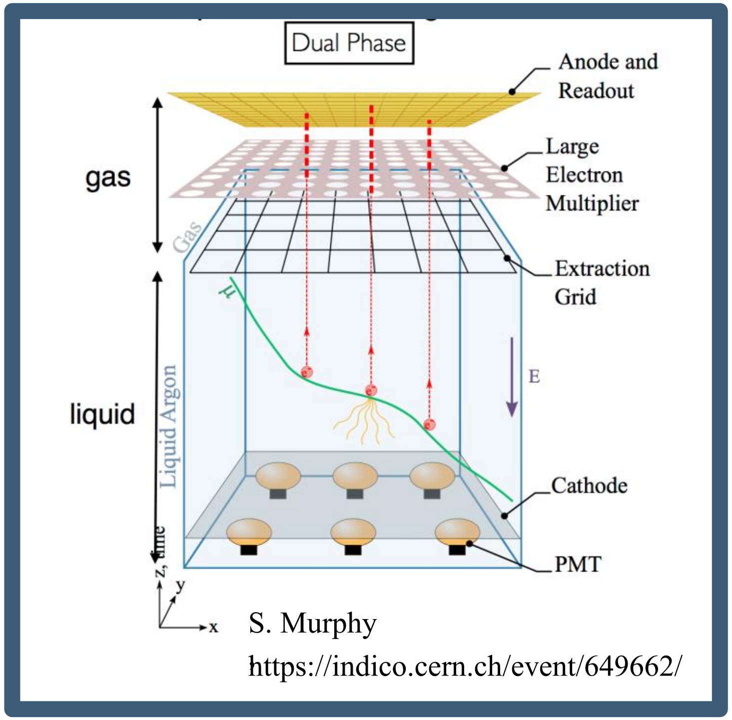
Dual-Phase



Charge Readout Plane (Anode)



signal amplification in the gas phase

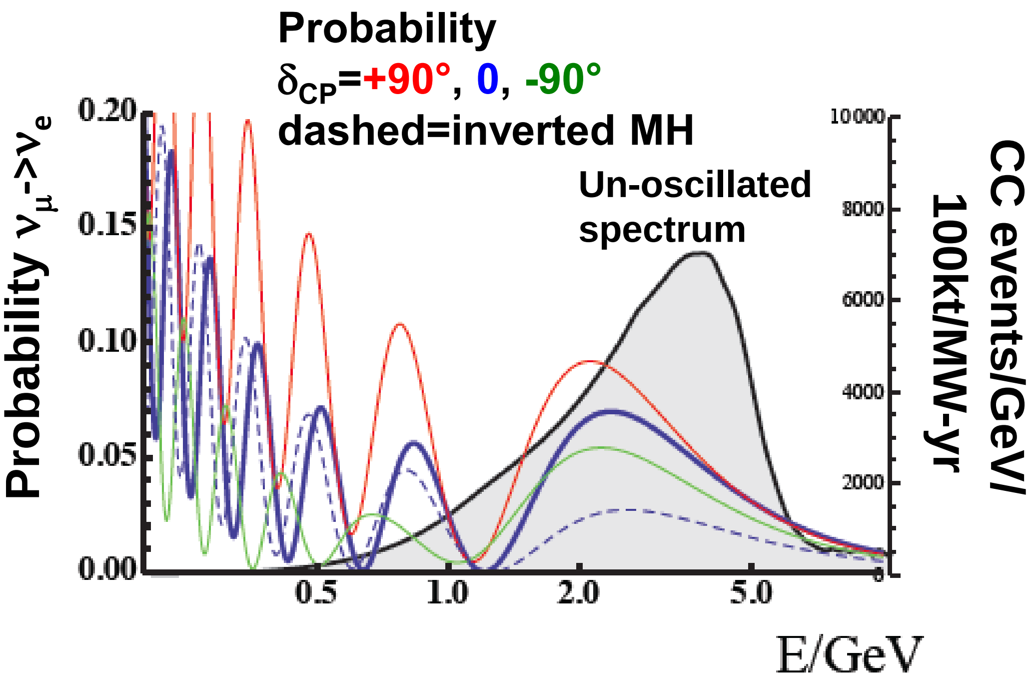


S. Murphy
https://indico.cern.ch/event/649662/

Photon detectors below cathode

600,000 volts between cathode and anode

Experimental Technique



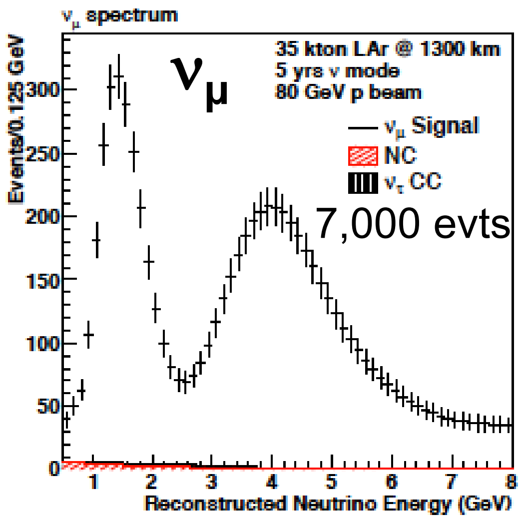
Probability
δ_{CP}=+90°, 0, -90°
dashed=inverted MH

Un-oscillated spectrum

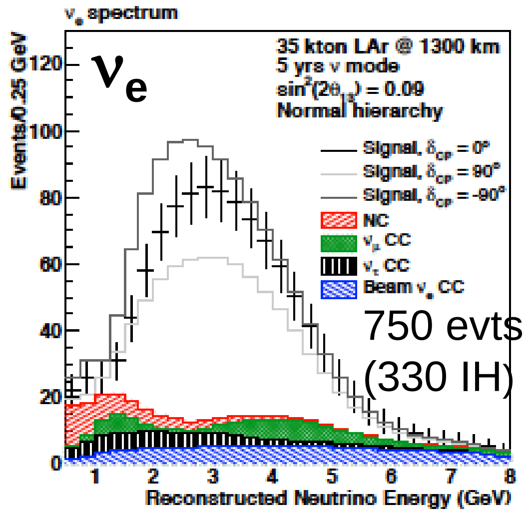
disappearance

appearance

700 kW beam



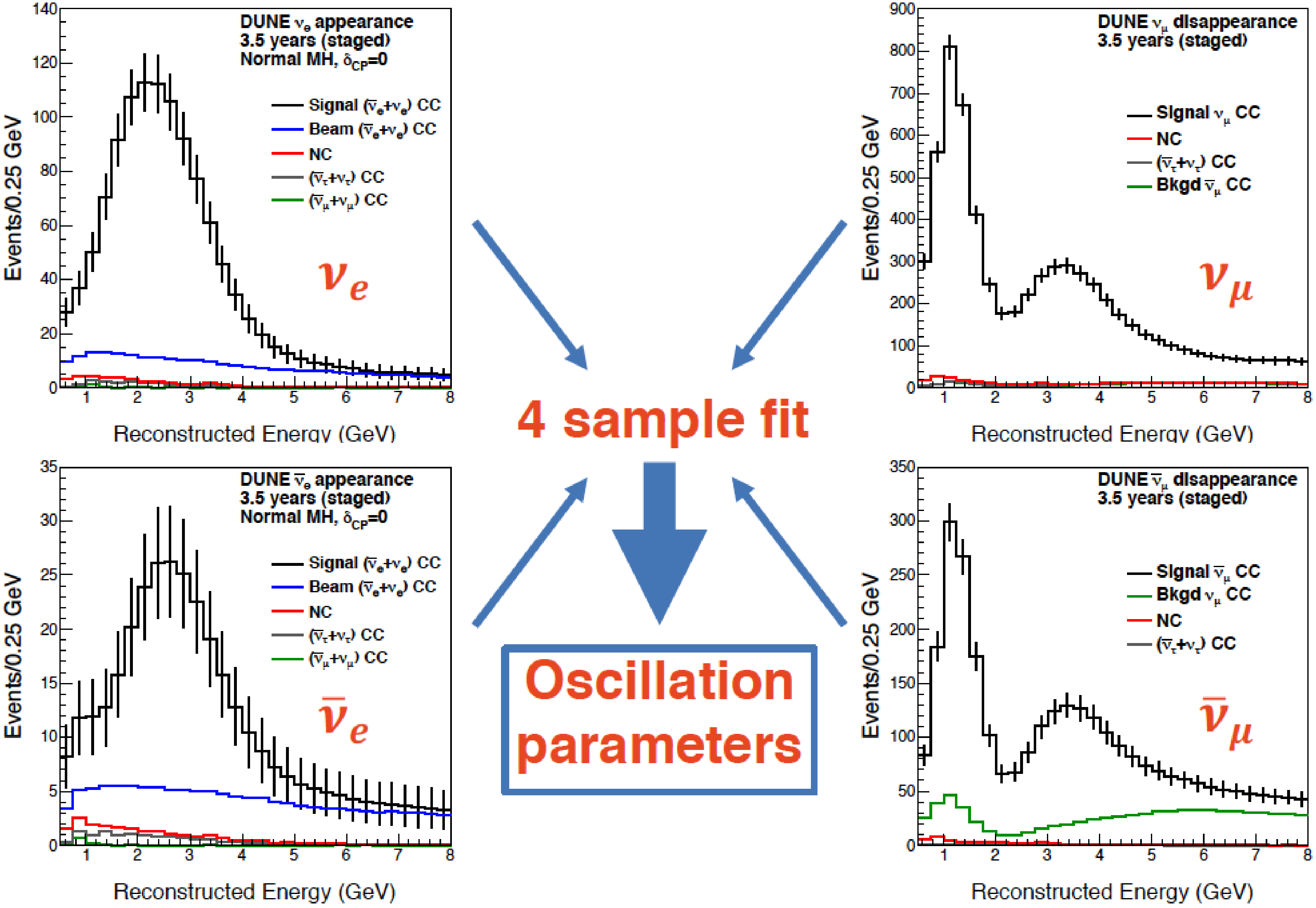
7,000 evts



750 evts
(330 IH)

- **Produce a pure wide band ν_μ muon-neutrino beam with energy spectrum matched to the 1st and 2nd oscillation maximum**
- **Measure spectrum of ν_μ and ν_e at a distant detector**

Measurement Strategy

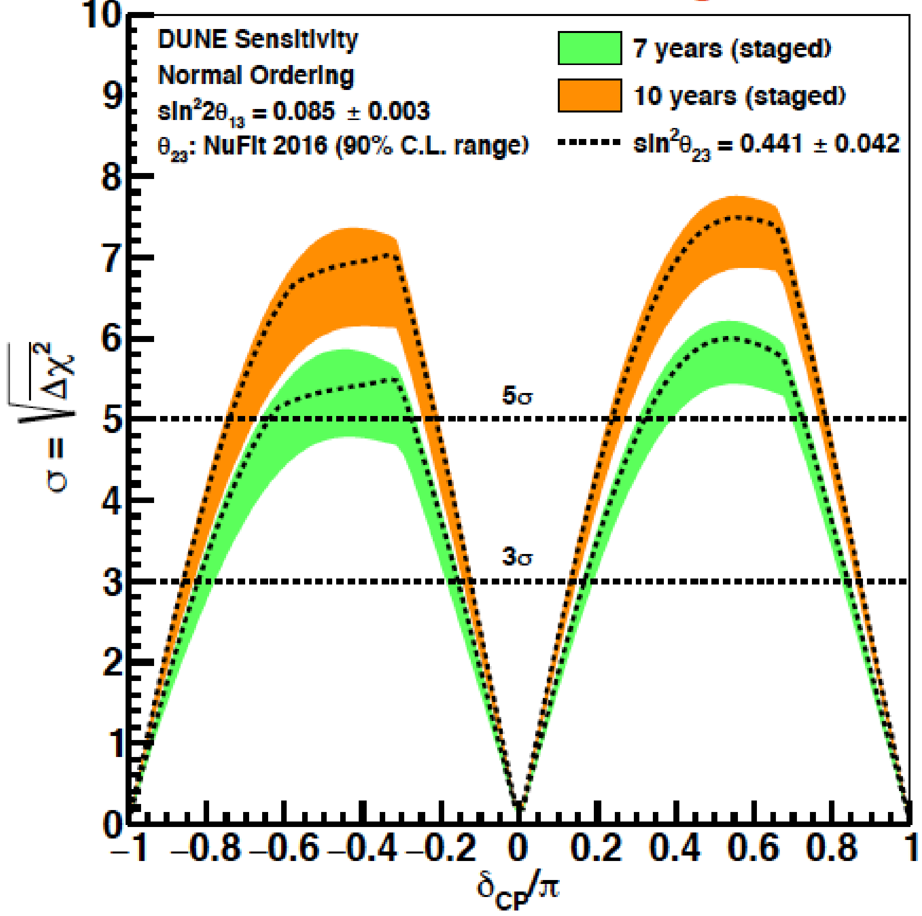


4 sample fit

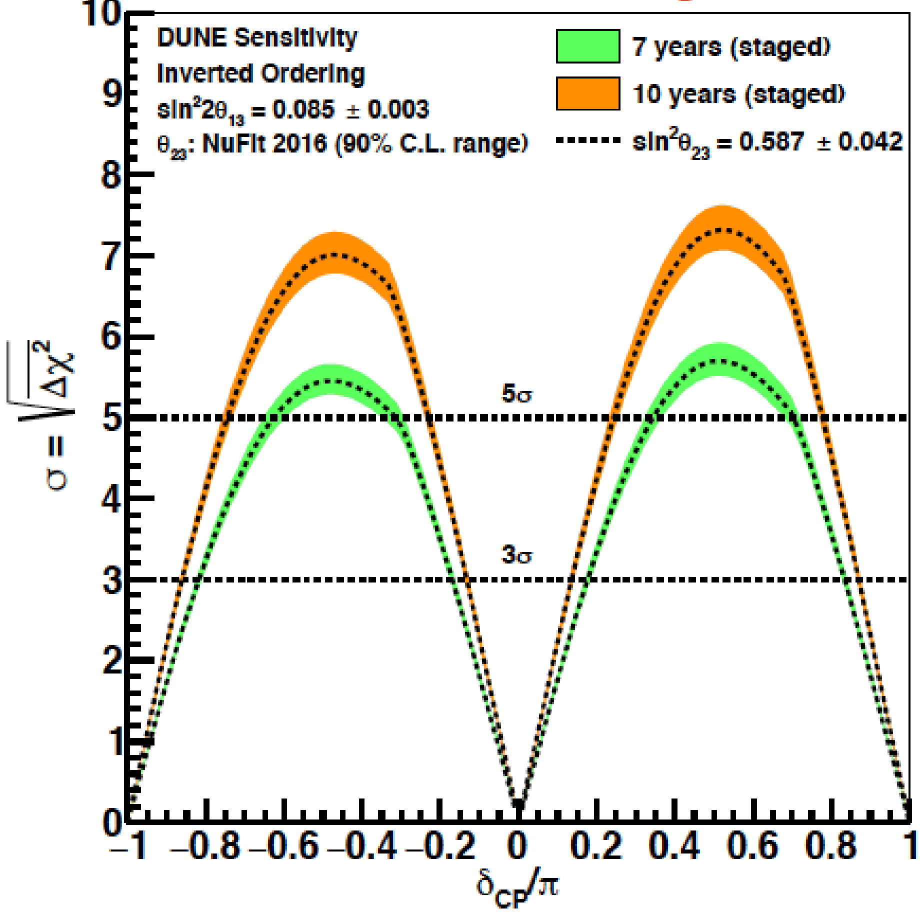
Oscillation parameters

CP Sensitivity

Normal ordering



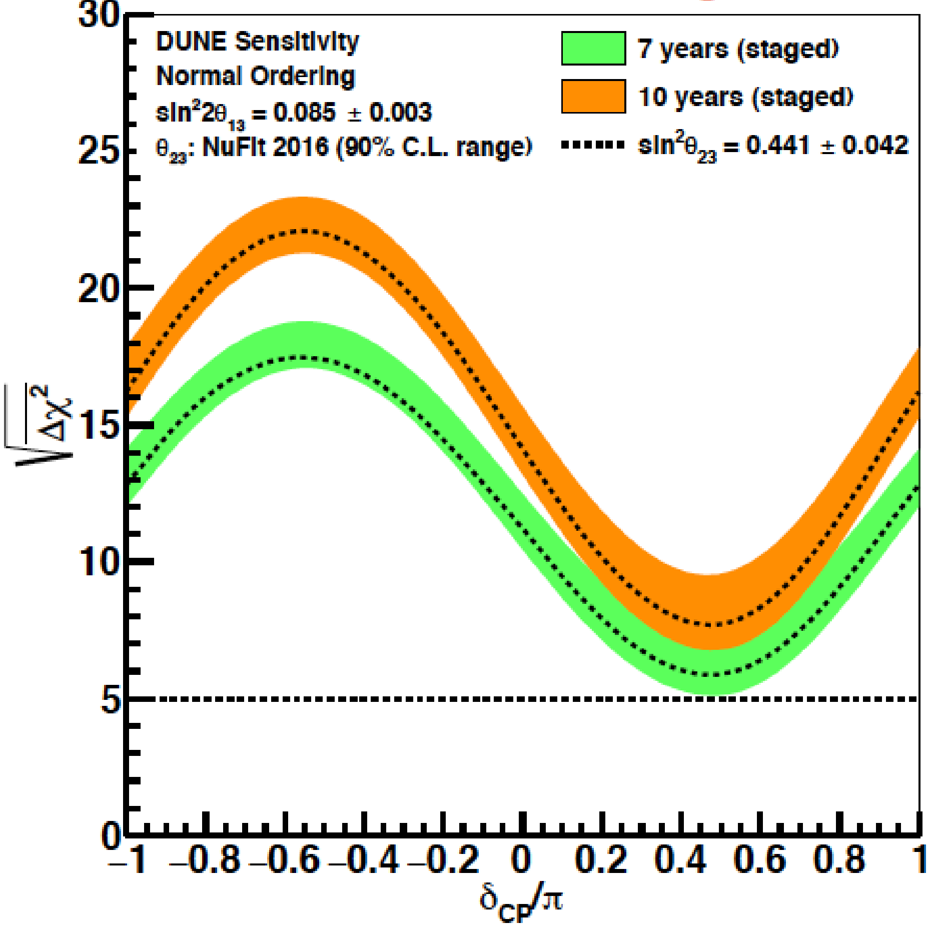
Inverted ordering



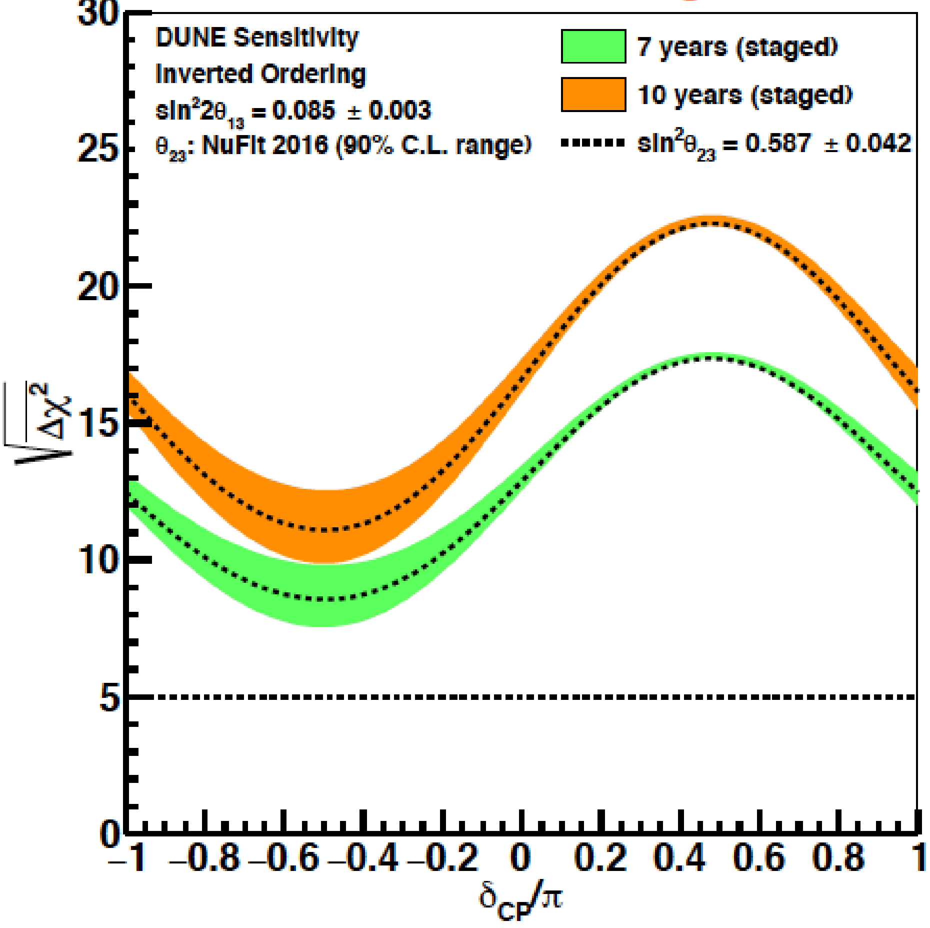
The upper and lower boundary of each band refers to the the input θ_{23} maximum and minimum respectively

Mass Ordering

Normal ordering



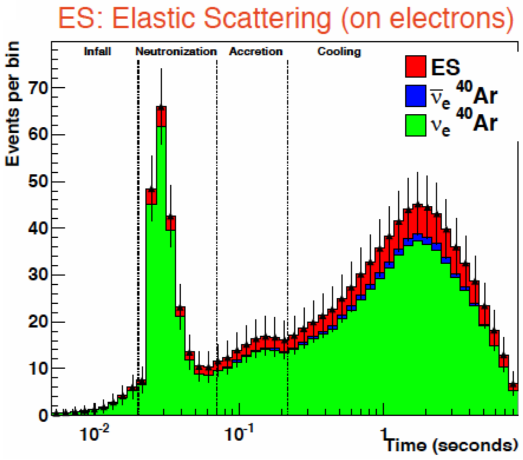
Inverted ordering



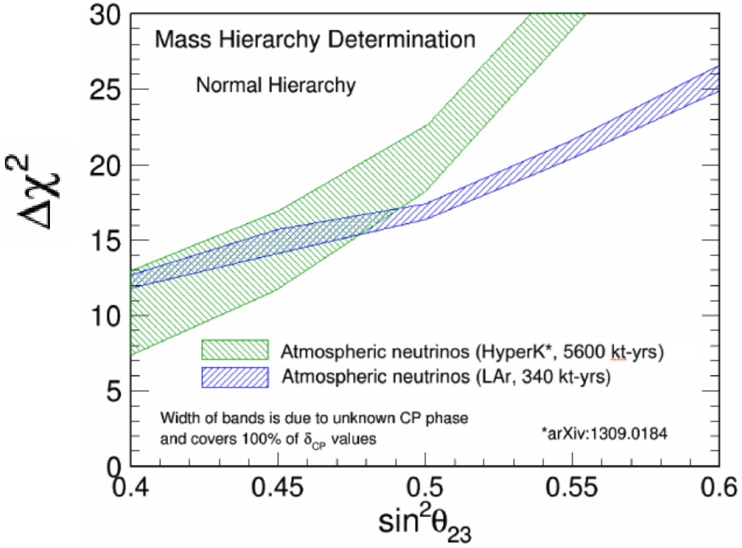
The upper and lower boundary of each band refers to the the input θ_{23} maximum and minimum respectively

Other Physics

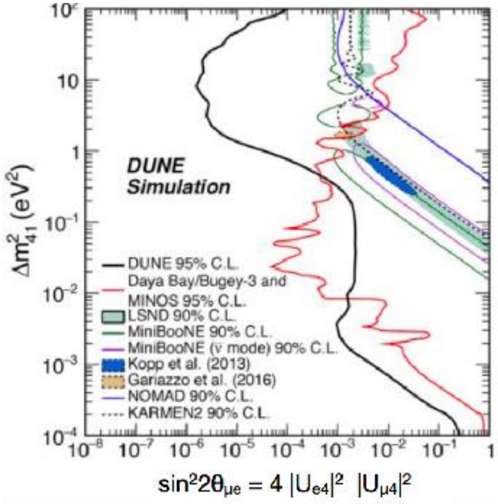
supernova



atmospherics



atmospherics

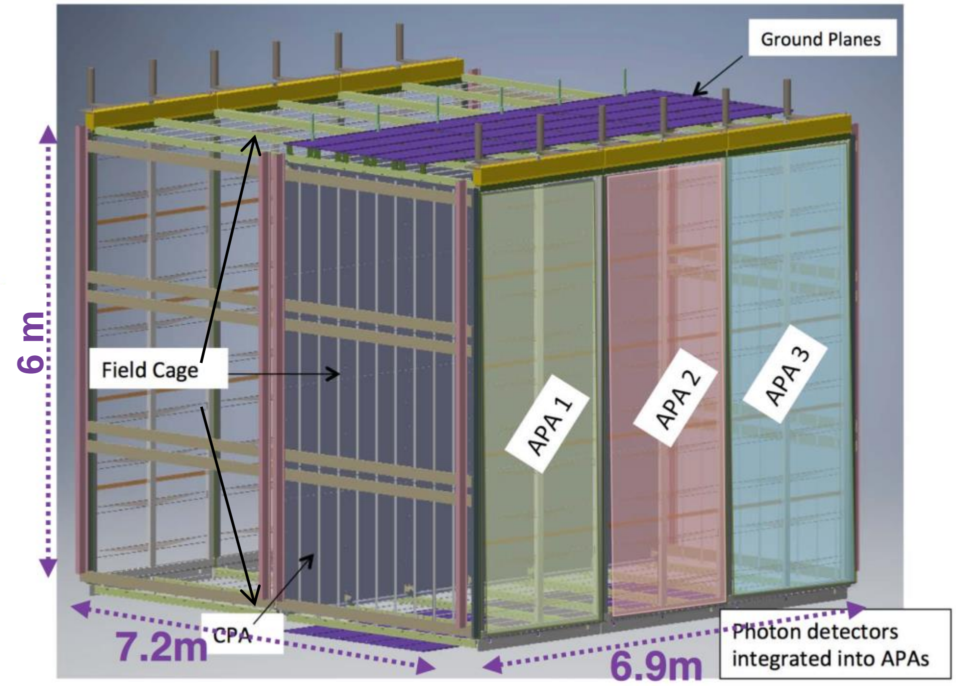


- Dark matter
- Large extra dimensions
- Dark photons
- NS interactions

Two Technologies

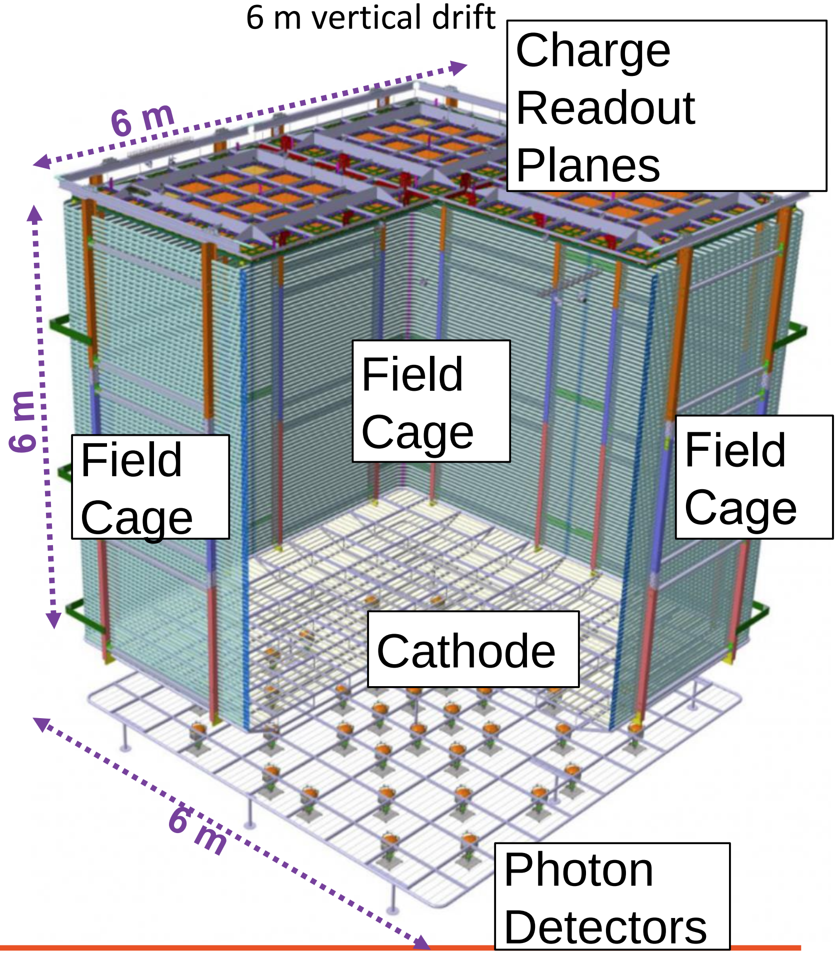
Single-Phase

3.6 m horizontal drift



Dual-Phase

6 m vertical drift

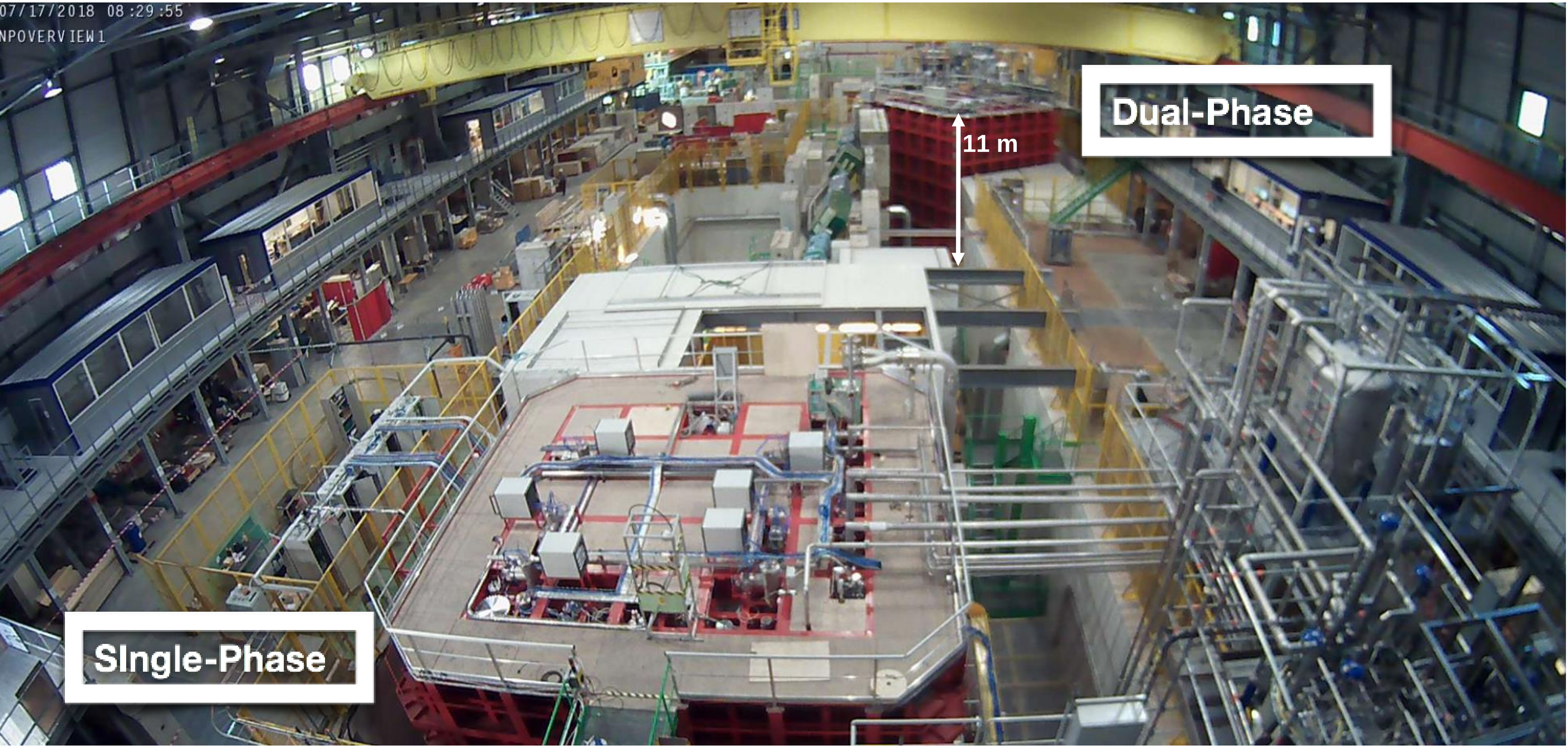


March 2016

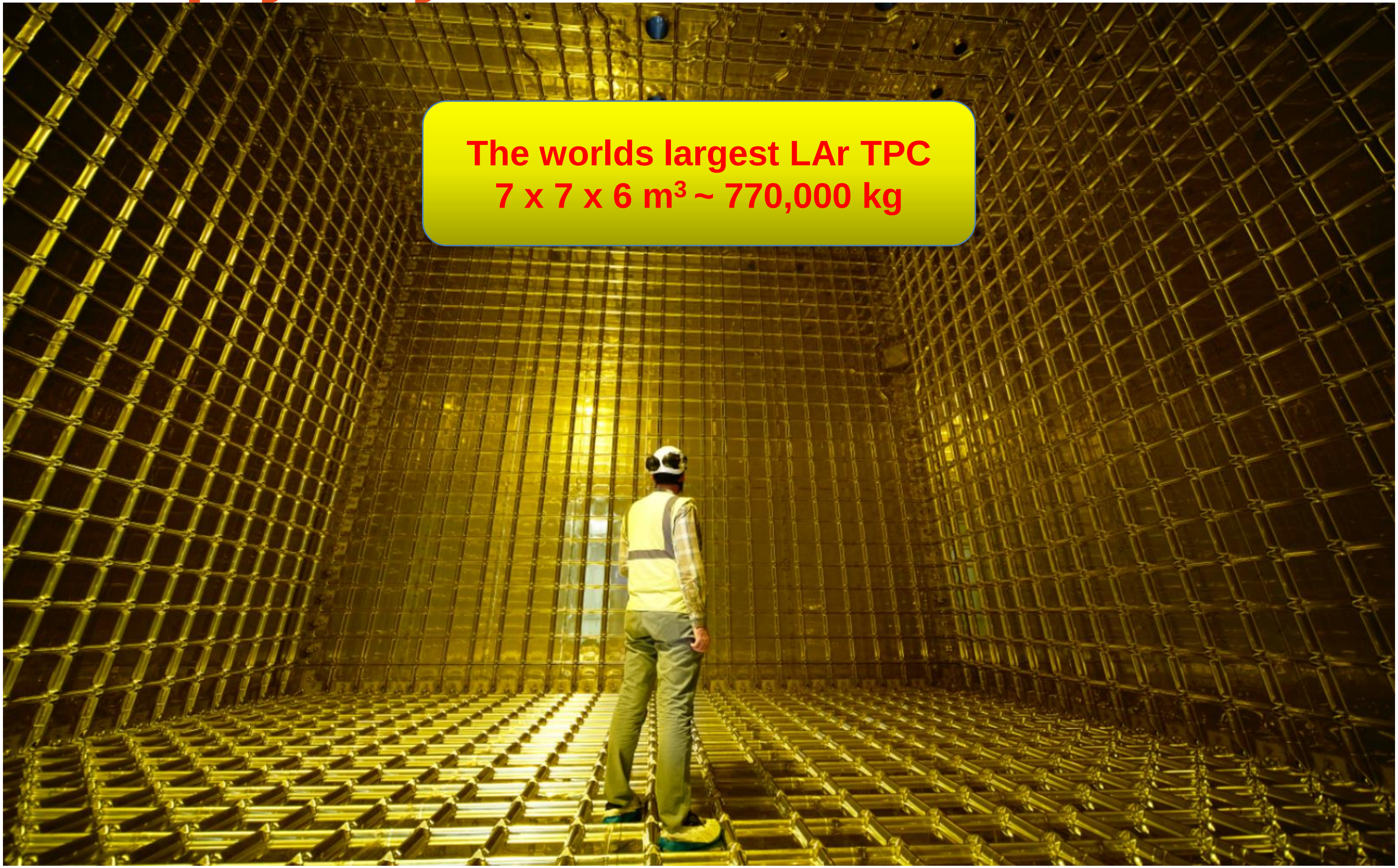
CERN EHN1 extension

October 2016

July 2018

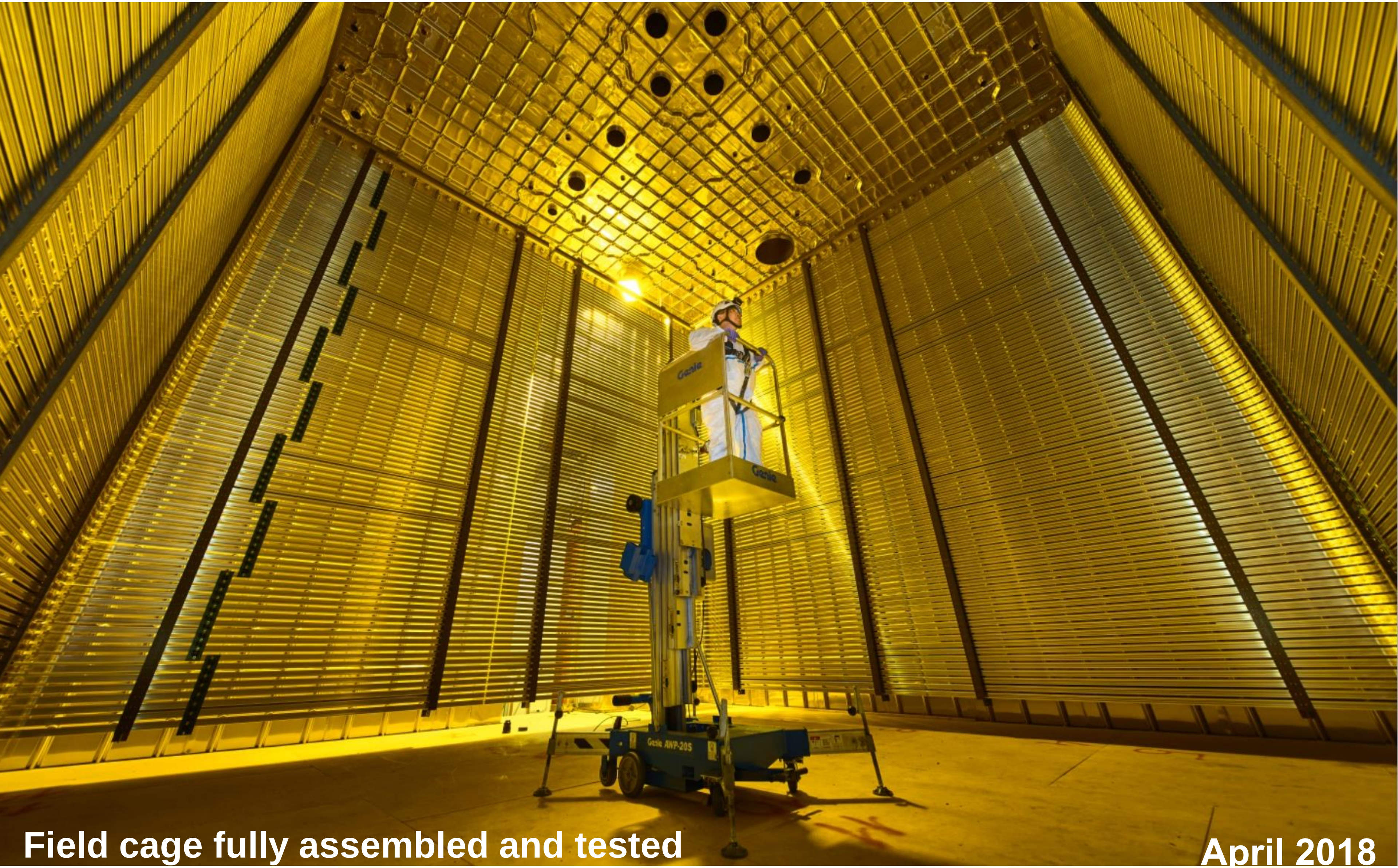


Empty Cryostat



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

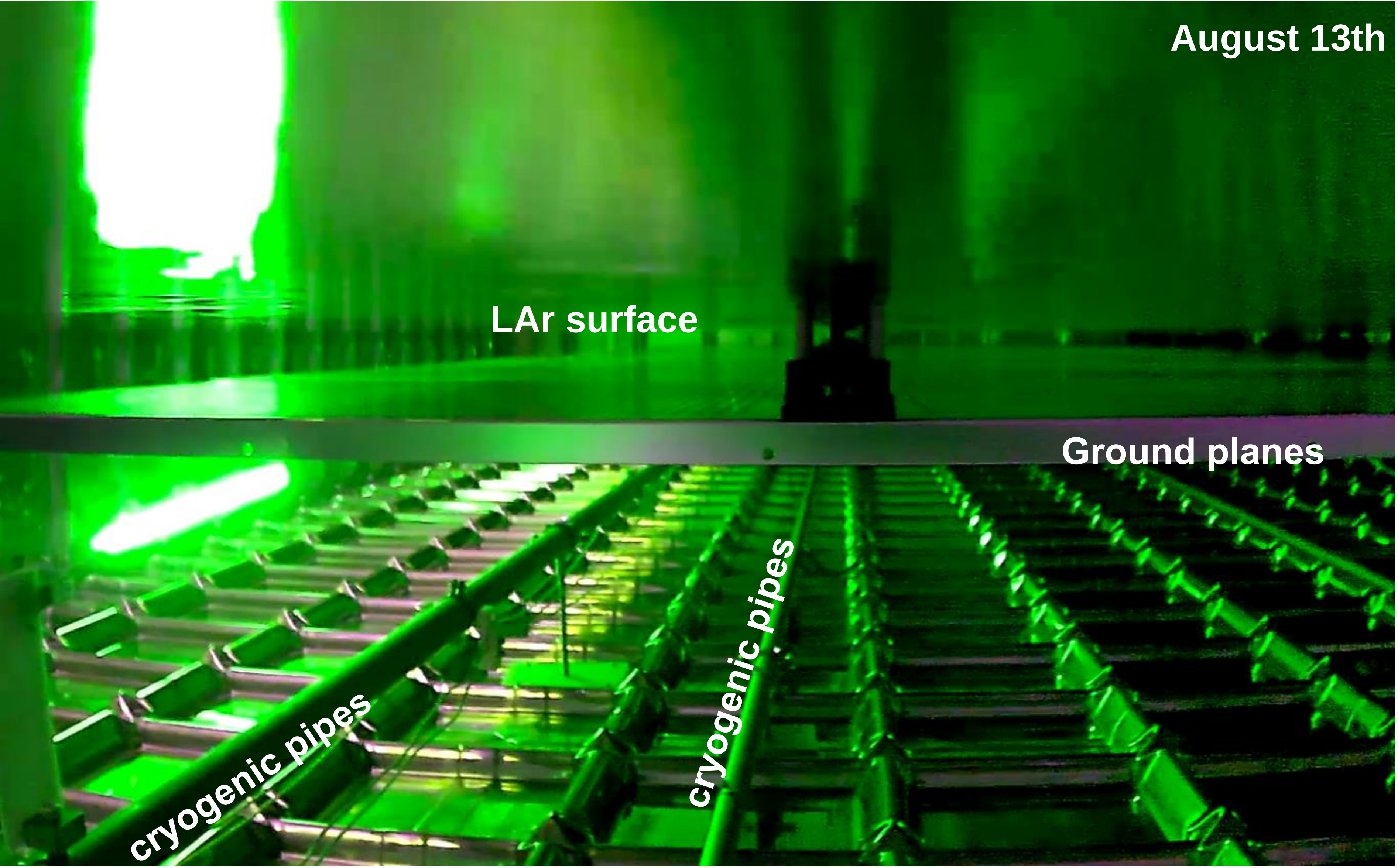
ProtoDUNE-DP



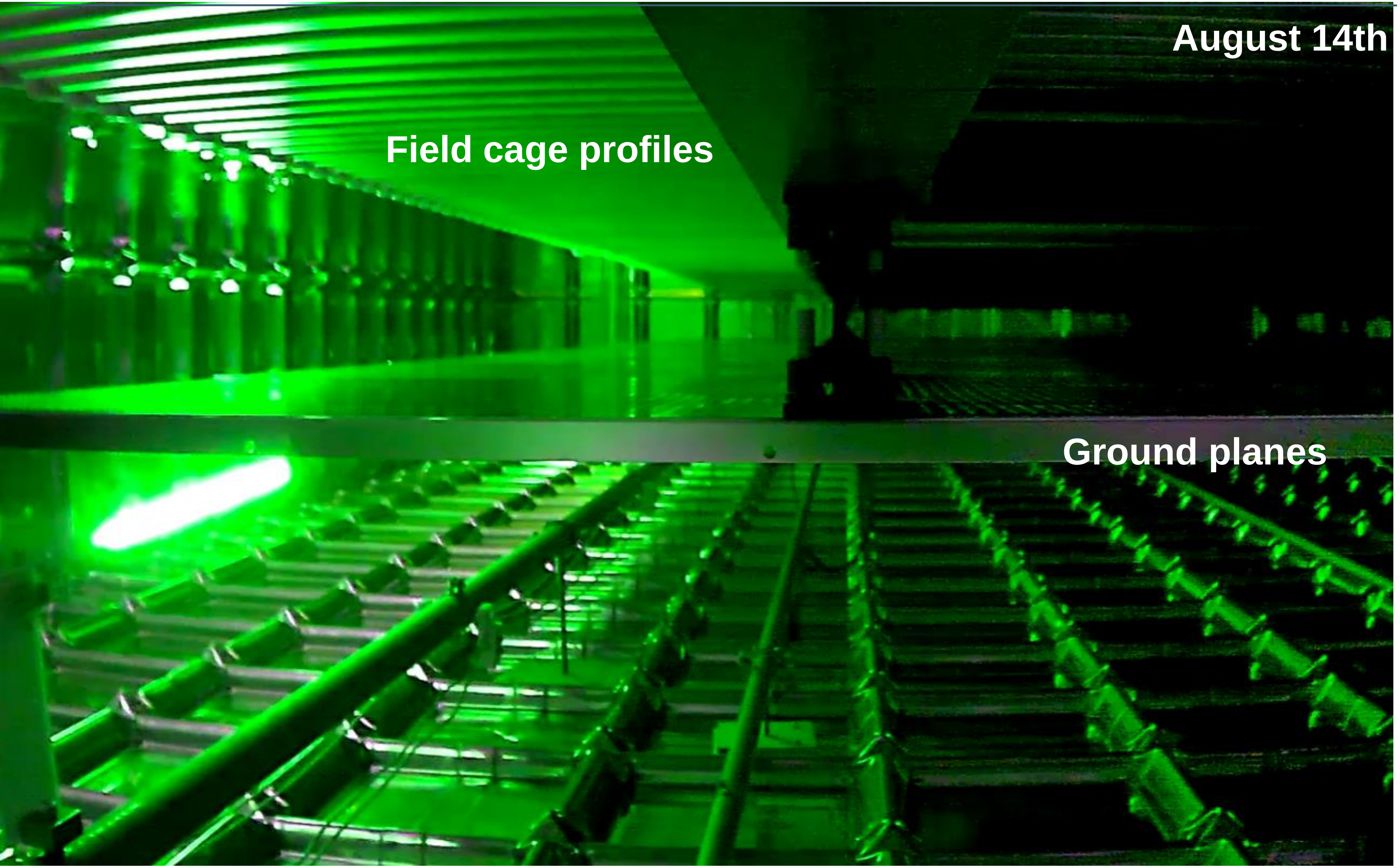
Field cage fully assembled and tested

April 2018

Yellow light becomes green

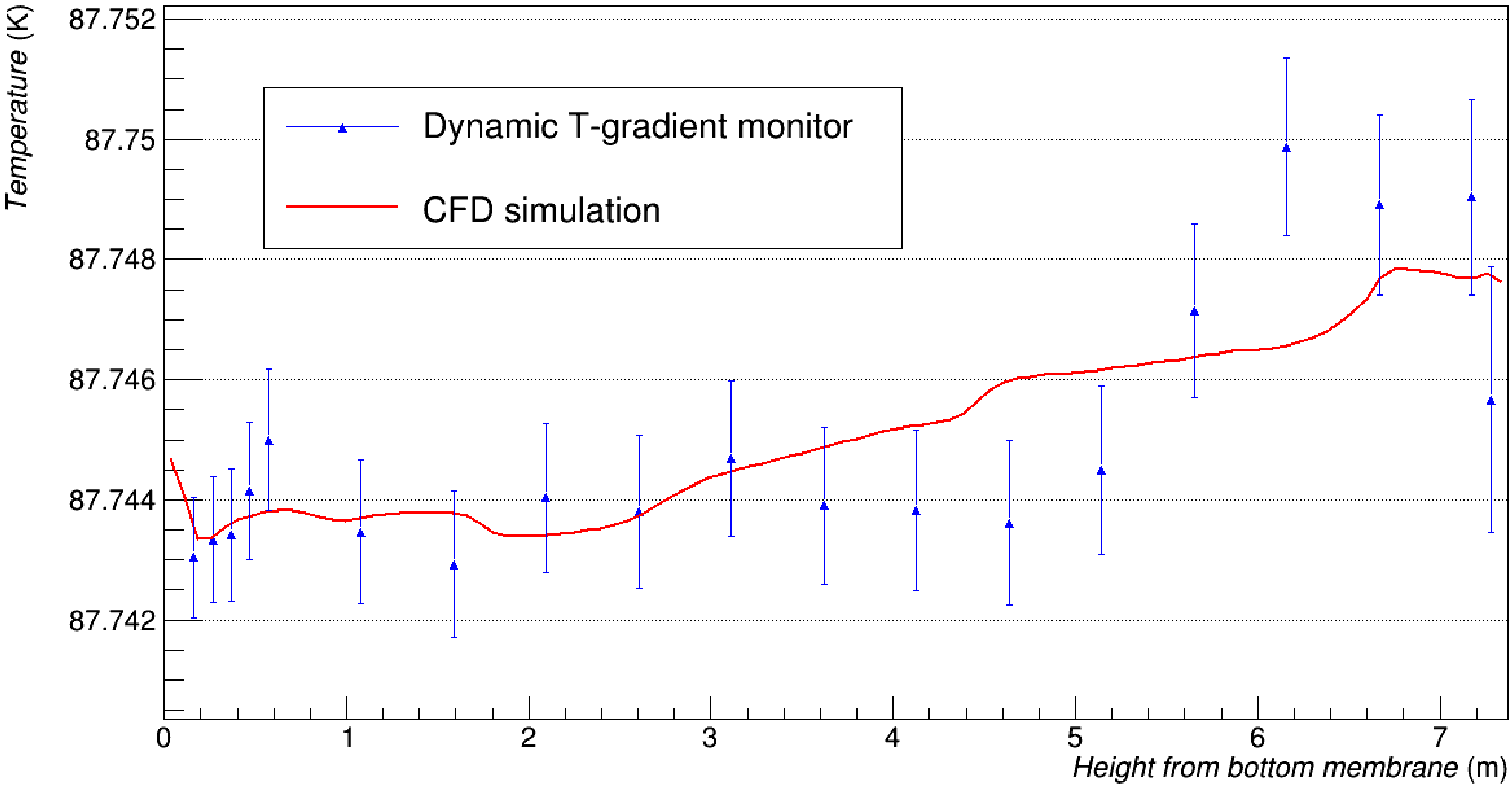


Yellow light becomes green

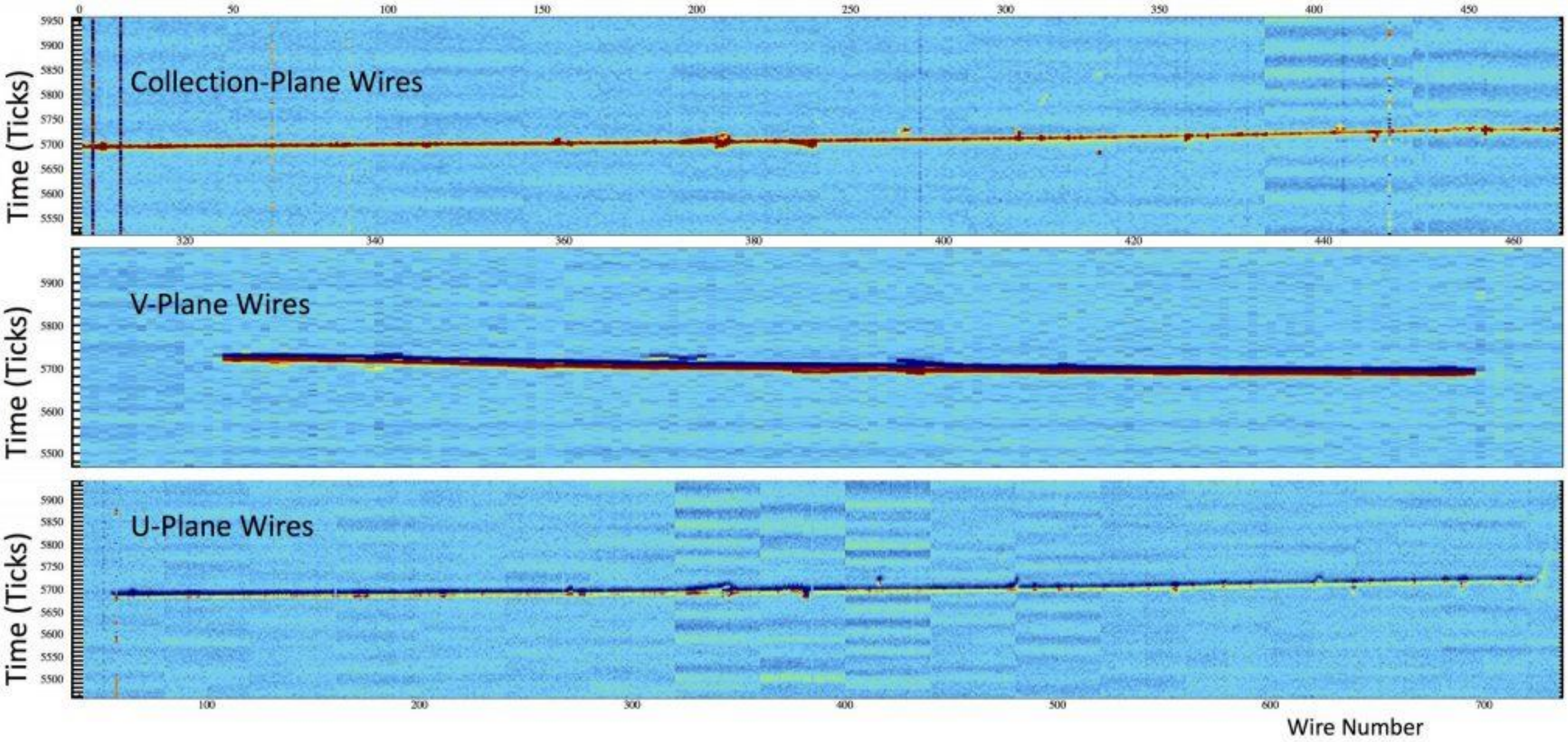


Liquid Argon temperature

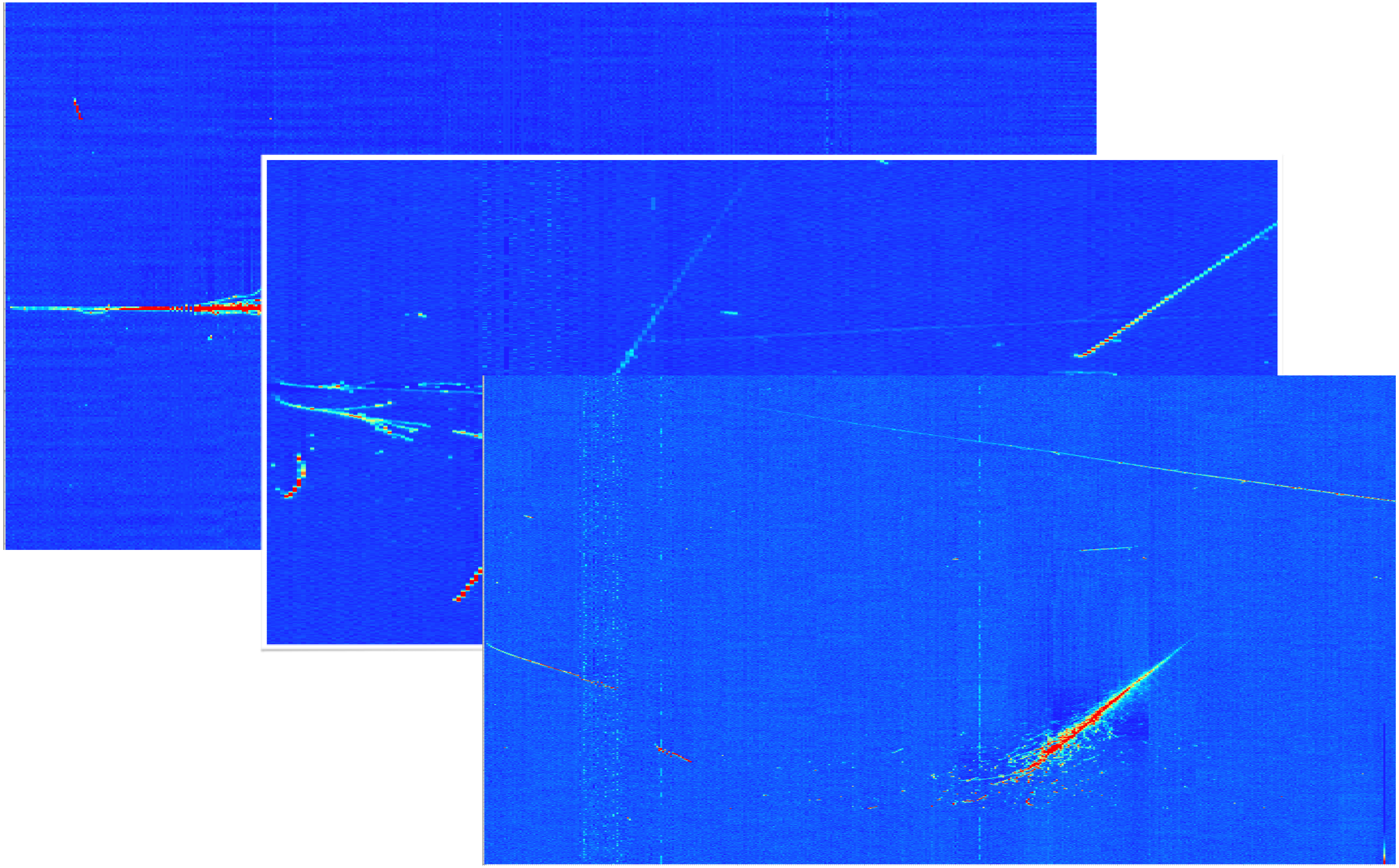
Temperature varies < 0.01 K across the cryostat



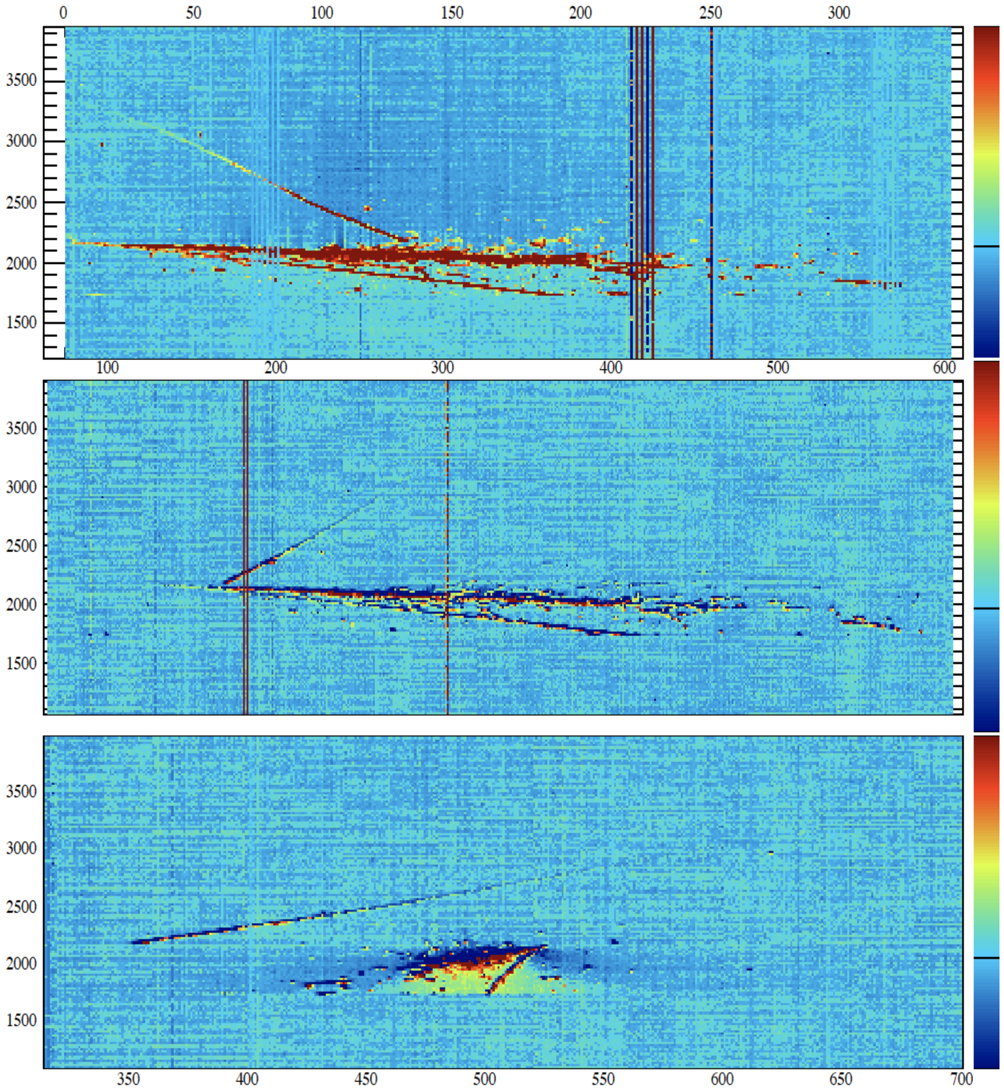
The First Event

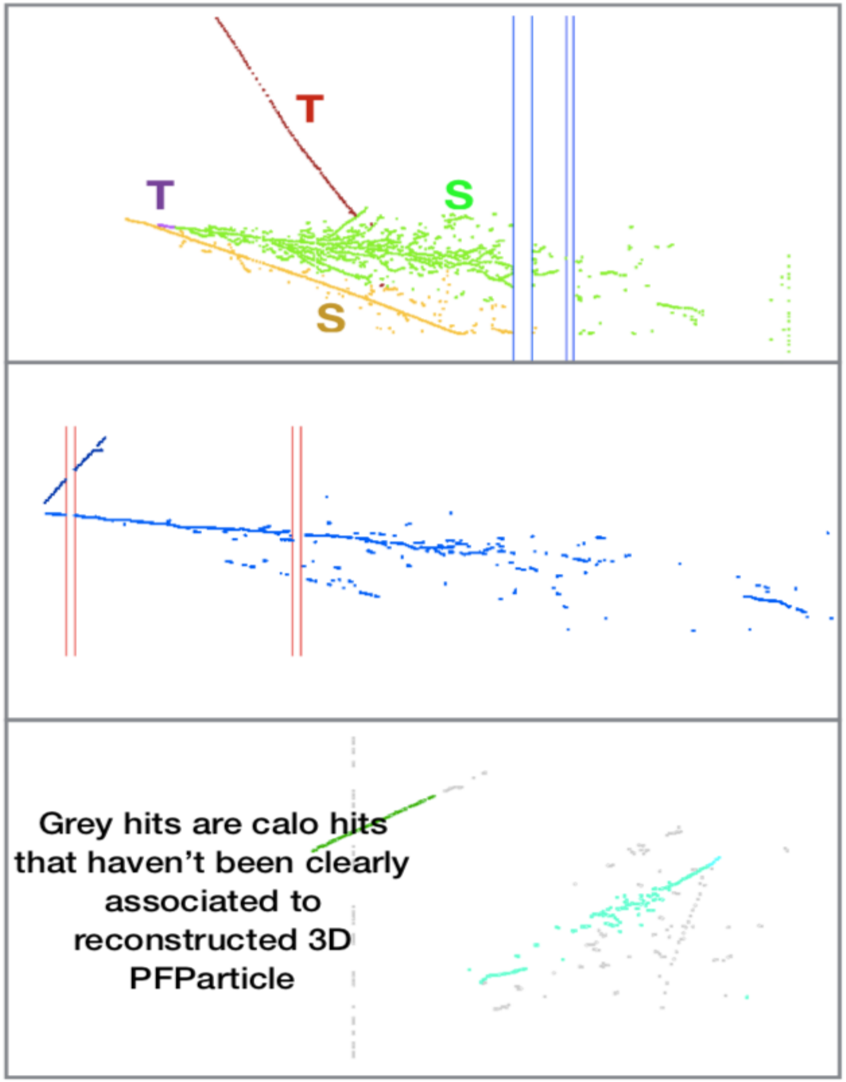


Real Events



Automatic Reconstruction

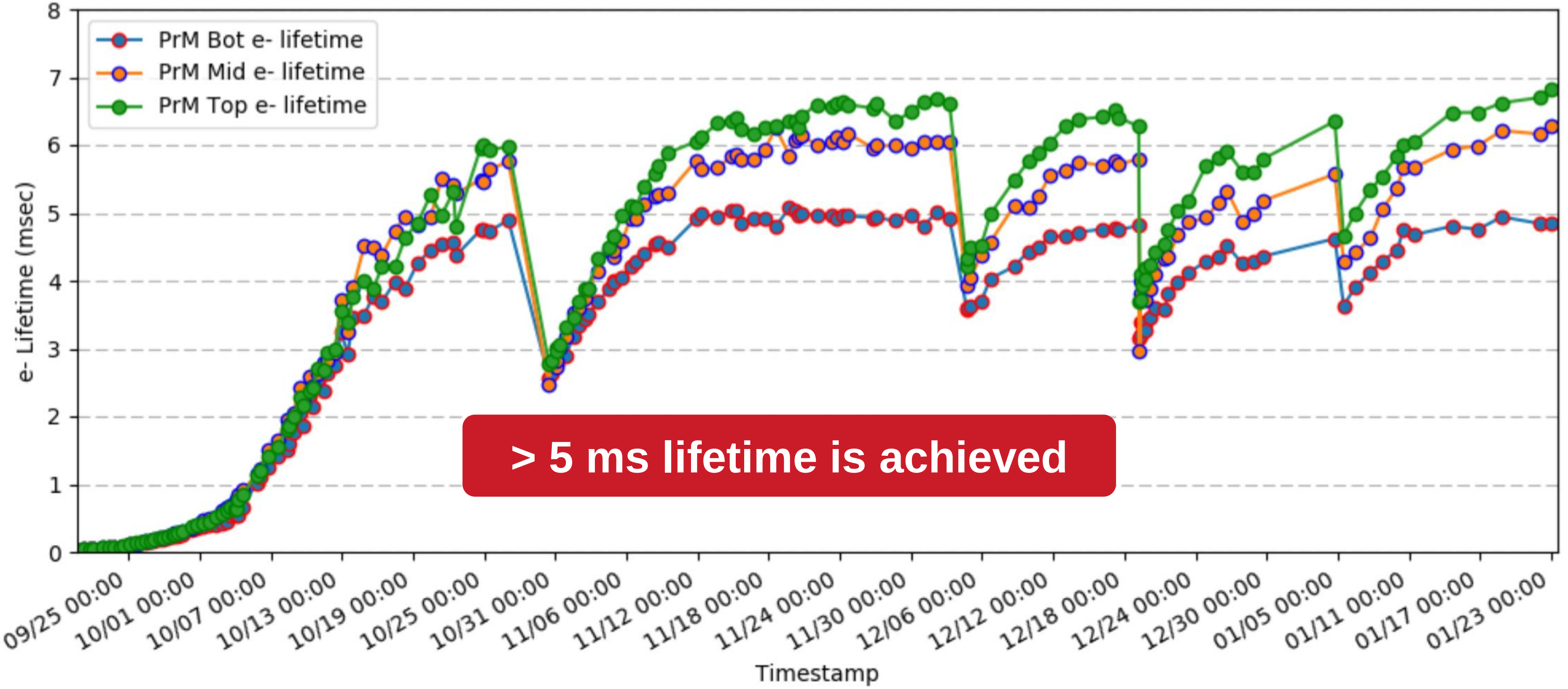




Grey hits are calo hits that haven't been clearly associated to reconstructed 3D PFParticle

Liquid Argon Purity

The purity is measured as the electron lifetime



> 5 ms lifetime is achieved

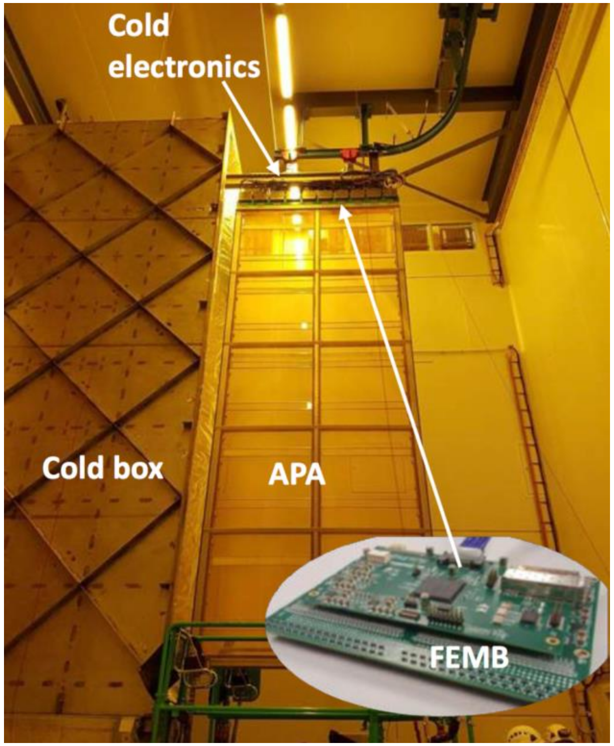
Electrons need 3 ms to cross the drift volume

APAs and Cold Electronics

Exceptionally low noise operation and scalable cryostat design

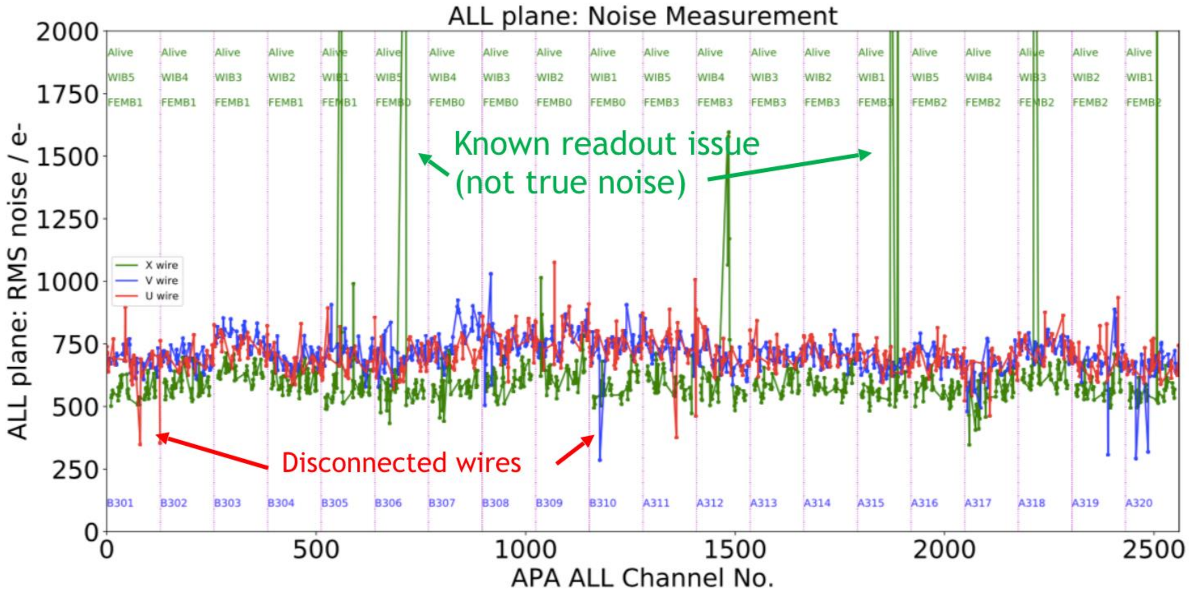
~ 15000 wires, only 4 channels dead (0.03%)

Electronics on top of APAs submerged in LAr at 87 K



ENC < 750 e⁻ ⟶ S/N ~ 20

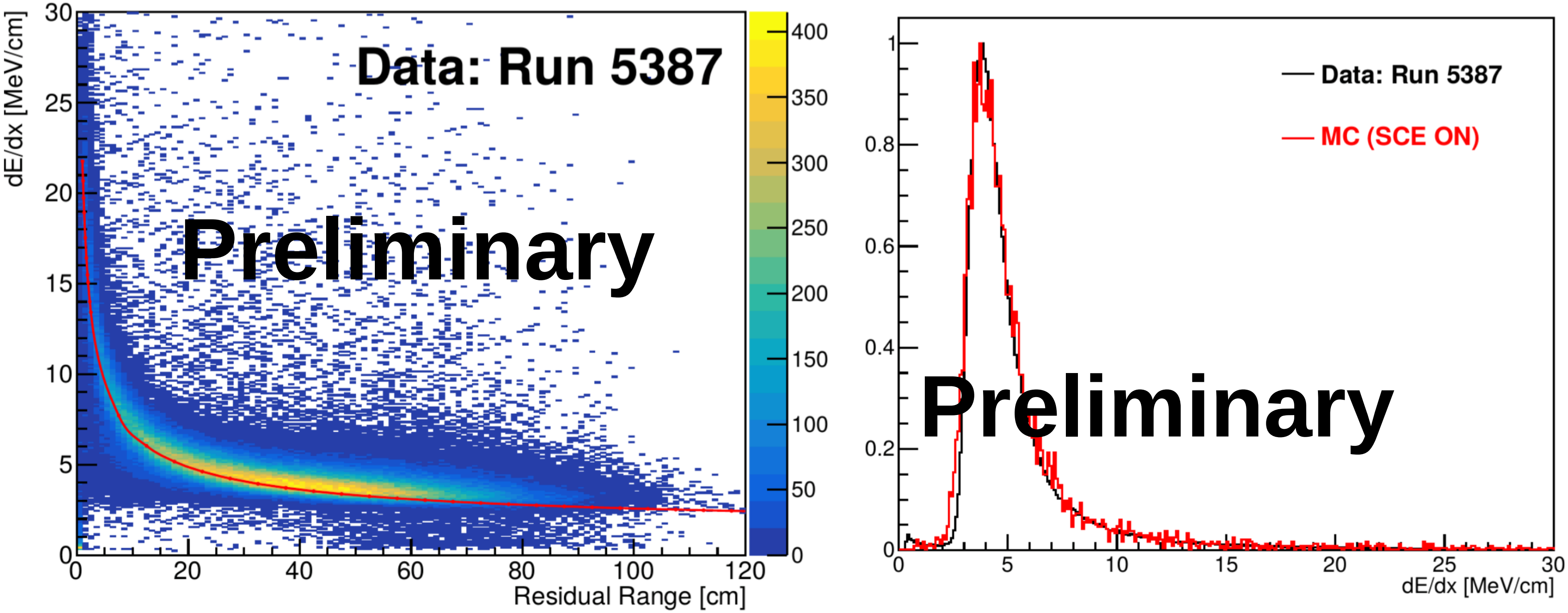
meets DUNE requirements (S/N>10)



dE/dx

Very preliminary !!!

dE/dx for 1 GeV/c beam protons



ProtoDUNE status

- **ProtoDUNE-SP** detector was completed at the end of June, filling of the cryostat completed on September 13th, TPC activated and on data taking since September 21st
- **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 ongoing, with cryostat closure foreseen for March 2019 and physics run for July 2019
- Once filled, ***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

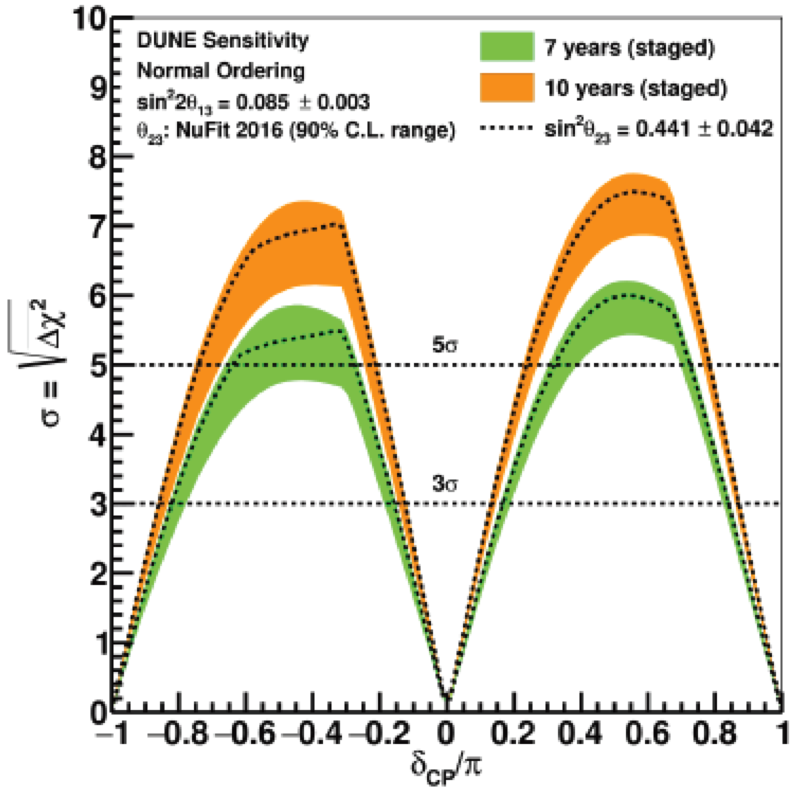
Summary and Conclusion

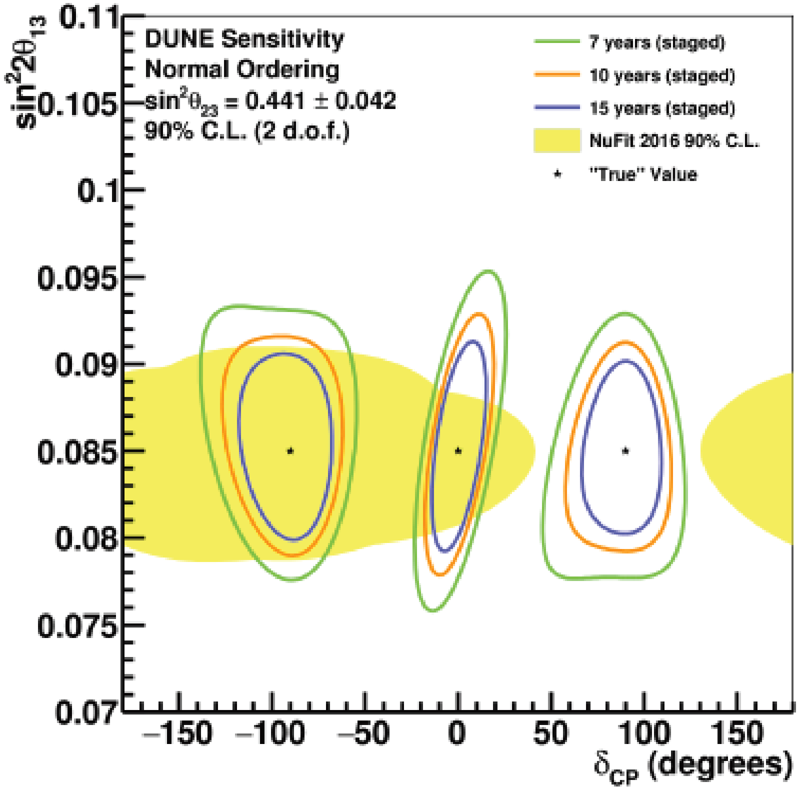
- DUNE has an ambitious physics program
  - Precision oscillation parameter measurements
  - CPV, mass ordering
  - Nucleon decay, SN
- Truly international project with strong support
  - US & internationally
  - UK and RAL are leading
- Technology is well understood
  - Prototyping and verifications are well underway
- DUNE is the neutrino physics of the future

Backup

Oscillation Highlights (I)

CP Violation



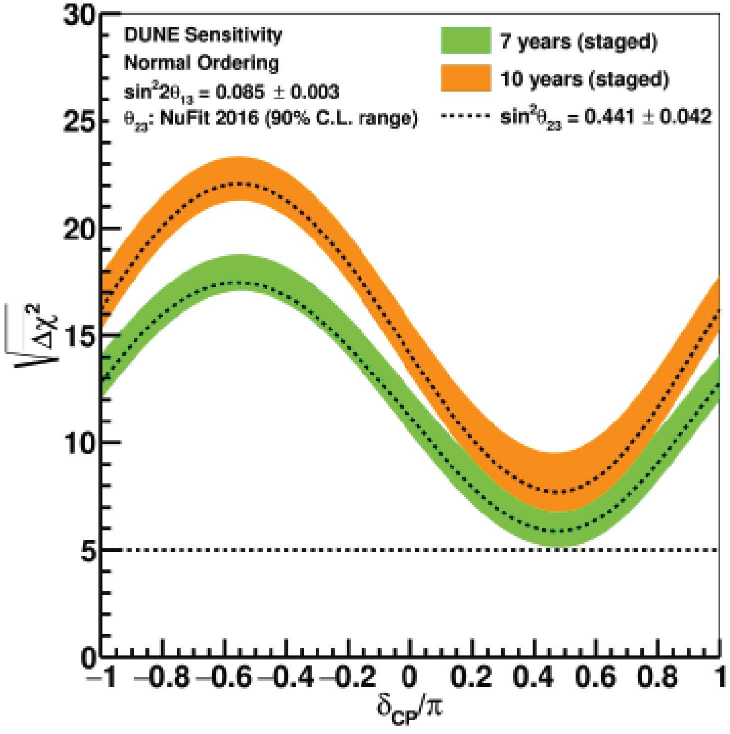


Width of band indicates variation in possible central values of θ_{23}

Simultaneous measurement of neutrino mixing angles and δ_{CP}

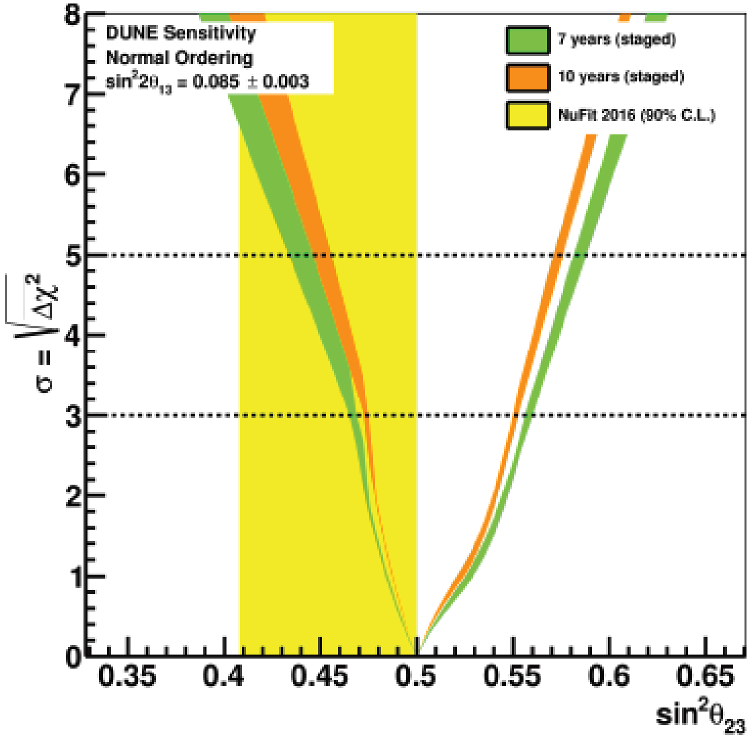
Oscillation Highlights (II)

Mass Ordering



Width of band indicates variation in possible central values of θ_{23}

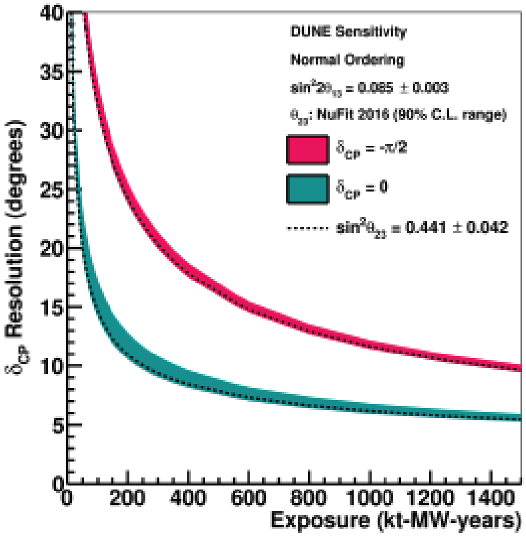
Octant



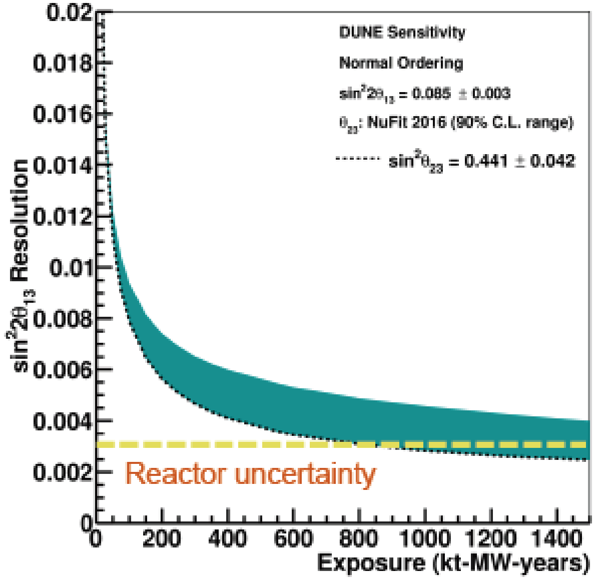
Width of band indicates variation in possible true value of δ_{CP}

Oscillation Highlights (III)

δ_{CP} Resolution

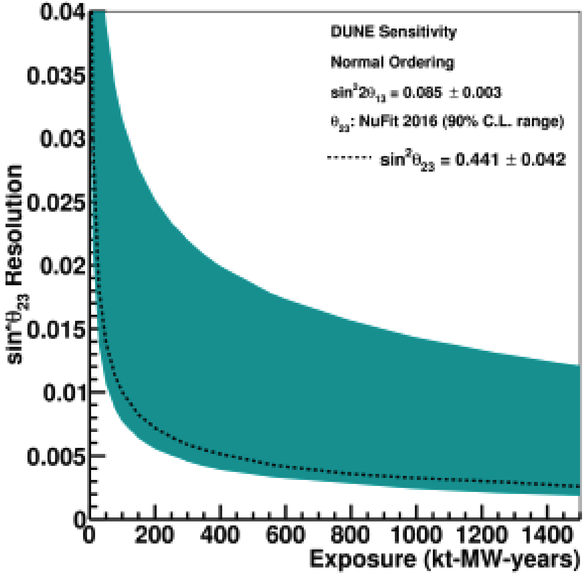


$\sin^2 2\theta_{13}$ Resolution



Reactor uncertainty

$\sin^2\theta_{23}$ Resolution



Schedule/Timeline

★ Costs and technical schedule are understood

- Multiple independent reviews
- FD excavation started

★ Schedule based on a realistic funding profile

- DOE planning line (including large contingency)
- Planned CERN contributions
- Anticipated international contributions

★ International Key Milestones:

- **2017:** start of construction at SURF
- **2018:** operation of two large-scale prototypes at CERN
- **2019**: International approval of DUNE funding matrix
- **2021:** start of installation of first 17-kt far detector module
- **2024:** start of operation of 17-kt far detector module
- **2026:** start of beam operation (1.2 MW) with two 17-kt FD modules