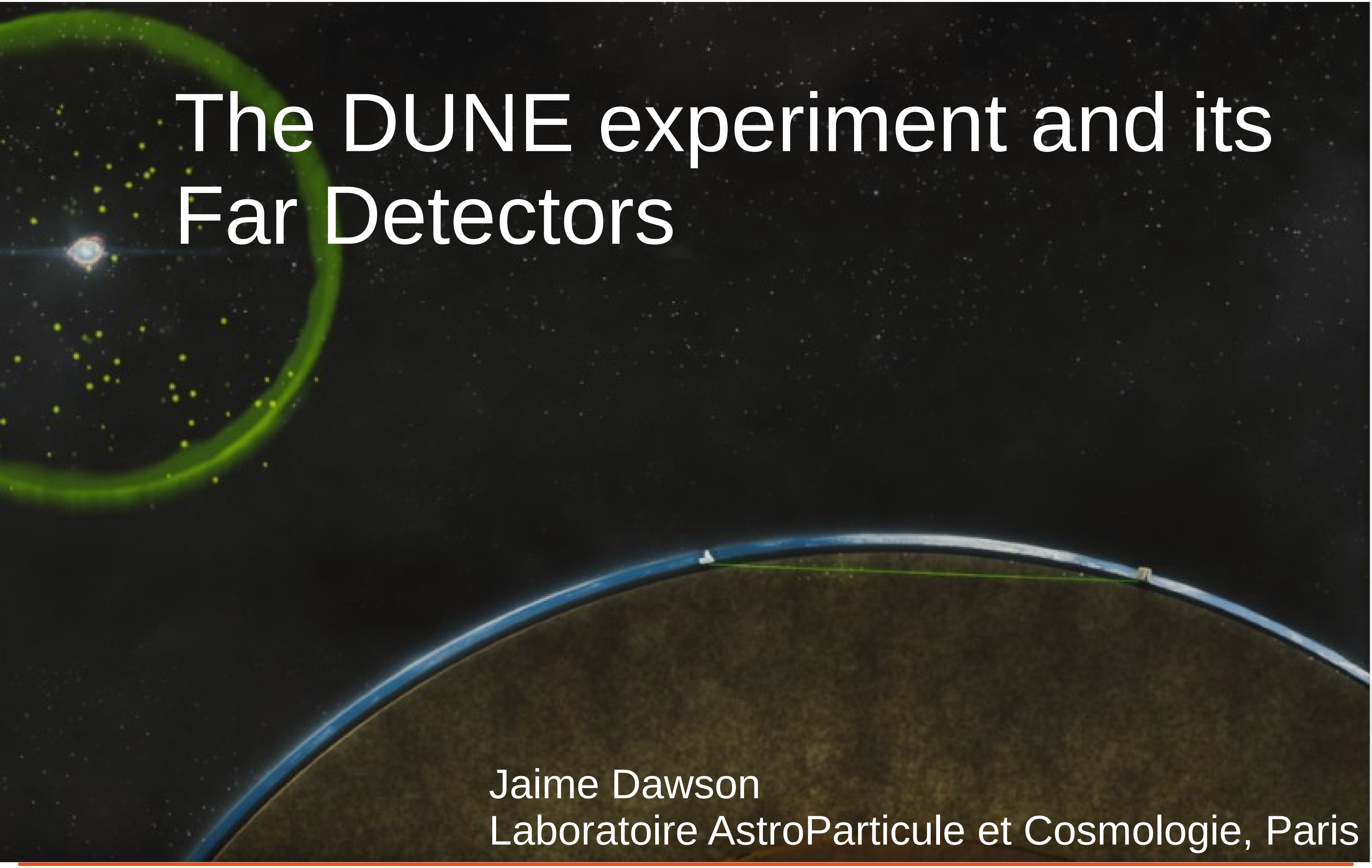


The DUNE experiment and its Far Detectors

Jaime Dawson
Laboratoire AstroParticule et Cosmologie, Paris

Contents

- Neutrino Oscillation
  - A brief Reminder
- Long Baseline Oscillation Experiments
  - The Signal
  - The State of the Art
- DUNE experiment
- DUNE detectors
  - Dual Phase 3x1x1
  - ProtoDUNE Dual-Phase

Illustration by Sandbox Studio/Symmetry Magazine

Neutrino Oscillation

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

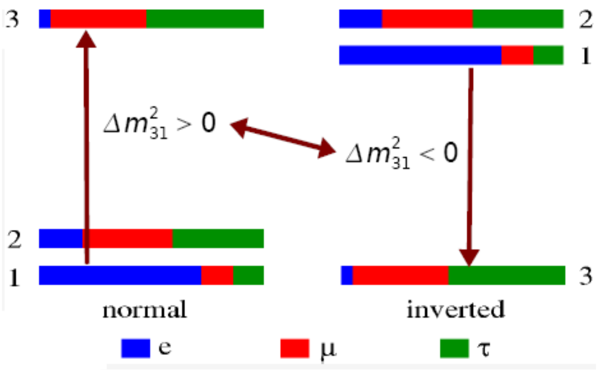
Pontecorvo – Maki – Nakagawa – Sakata (PMNS) matrix

- 3 mixing angles
- 1 CP phase

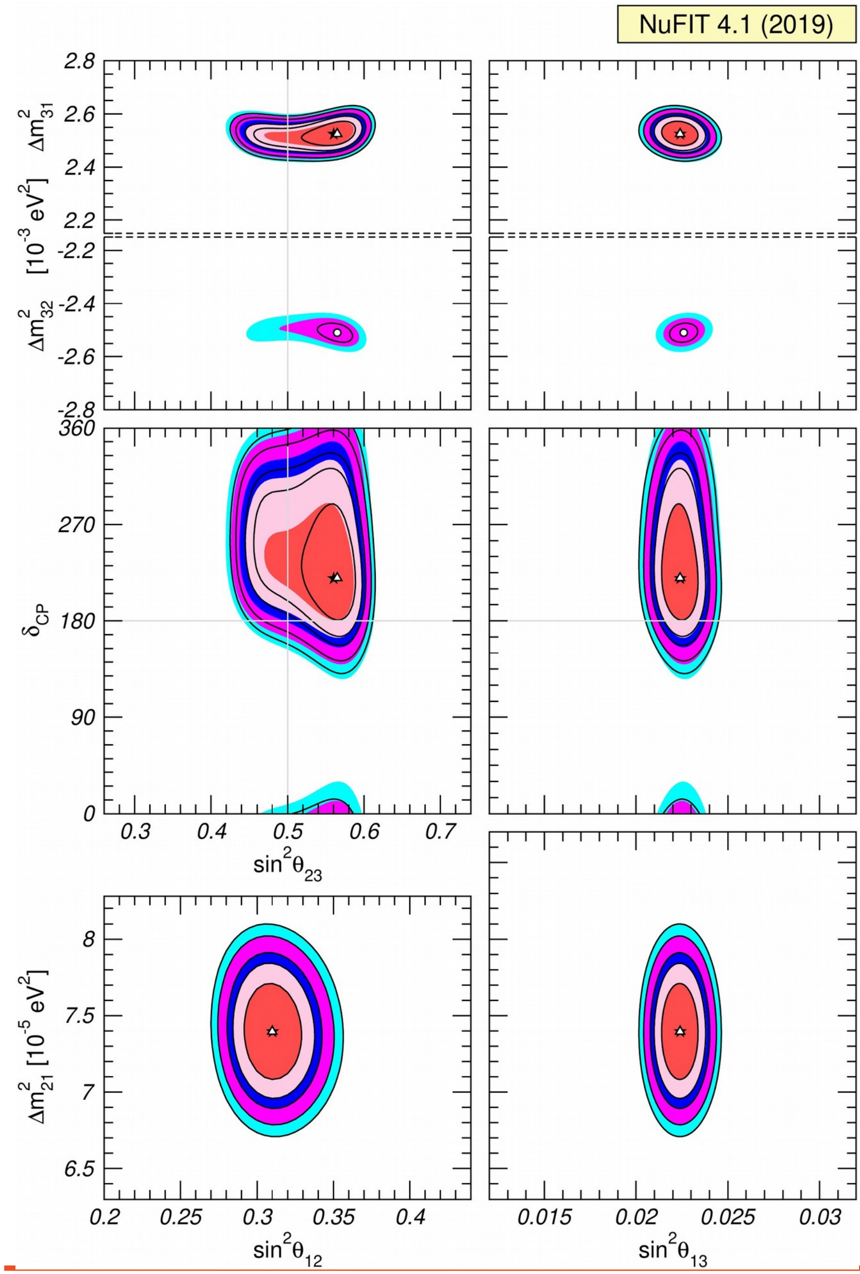
$$U = \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13} e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}$$

solar atmospheric

- 2 mass splittings Δm^2_{ij}
- θ_{13} → δ_{cp} and sign of Δm^2_{31}



Global Fits



with SK atmospheric data		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 10.4$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
	$\sin^2\theta_{12}$	$0.310^{+0.013}_{-0.012}$	$0.275 \to 0.350$	$0.310^{+0.013}_{-0.012}$	$0.275 \to 0.350$
	$\theta_{12}/^\circ$	$33.82^{+0.78}_{-0.76}$	$31.61 \to 36.27$	$33.82^{+0.78}_{-0.75}$	$31.61 \to 36.27$
	$\sin^2\theta_{23}$	$0.563^{+0.018}_{-0.024}$	$0.433 \to 0.609$	$0.565^{+0.017}_{-0.022}$	$0.436 \to 0.610$
	$\theta_{23}/^\circ$	$48.6^{+1.0}_{-1.4}$	$41.1 \to 51.3$	$48.8^{+1.0}_{-1.2}$	$41.4 \to 51.3$
	$\sin^2\theta_{13}$	$0.02237^{+0.00066}_{-0.00065}$	$0.02044 \to 0.02435$	$0.02259^{+0.00065}_{-0.00065}$	$0.02064 \to 0.02457$
	$\theta_{13}/^\circ$	$8.60^{+0.13}_{-0.13}$	$8.22 \to 8.98$	$8.64^{+0.12}_{-0.13}$	$8.26 \to 9.02$
	$\delta_{CP}/^\circ$	221^{+39}_{-28}	$144 \to 357$	282^{+23}_{-25}	$205 \to 348$
	$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.39^{+0.21}_{-0.20}$	$6.79 \to 8.01$	$7.39^{+0.21}_{-0.20}$	$6.79 \to 8.01$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.528^{+0.029}_{-0.031}$	$+2.436 \to +2.618$	$-2.510^{+0.030}_{-0.031}$	$-2.601 \to -2.419$

JHEP 01 (2019) 106 arXiv:1811.05487

NuFIT 4.1 (2019), www.nu-fit.org

$$|U_{\text{PMNS}}| \sim \begin{pmatrix} 0.8 & 0.5 & 0.1 \\ 0.5 & 0.6 & 0.7 \\ 0.3 & 0.6 & 0.7 \end{pmatrix}$$

Long Baseline Experiments

Beam of ν_μ or $\bar{\nu}_\mu$

hundreds of km through the Earth

Detect ν_μ ($\bar{\nu}_\mu$)
ν_e ($\bar{\nu}_e$)
and if you can
ν_τ ($\bar{\nu}_\tau$)

ν_e appearance

$$P(\nu_\mu \to \nu_e) \approx \sin^2 2\theta_{13} \sin^2\theta_{23} \frac{\sin^2(A-1)\Delta}{(A-1)^2}$$

$$+\ 2\alpha \sin\theta_{13} \cos\delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{(A-1)} \cos\Delta$$

$$-\ 2\alpha \sin\theta_{13} \sin\delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{(A-1)} \sin\Delta$$

$$\alpha = \frac{\Delta m^2_{21}}{\Delta m^2_{31}} \qquad \Delta = \frac{\Delta m^2_{31} L}{4E} \qquad A = +G_f N_e \frac{L}{\sqrt{2}\Delta}$$

- ν_e appearance: mass hierarchy, δ_{CP} and octant of θ_{23}
- ν_μ disappearance: high precision $|\Delta m_{32}|$ and $\sin^2 2\theta_{23}$, constrain octant

Long Baseline Experiments

Beam of ν_μ

or $\bar{\nu}_\mu$

hundreds of km through the Earth

Detect ν_μ ($\bar{\nu}_\mu$)

ν_e ($\bar{\nu}_e$)

and if you can

ν_τ ($\bar{\nu}_\tau$)

Compare oscillation probabilities $P(\nu_\mu \to \nu_e)$ to $P(\bar{\nu}_\mu \to \bar{\nu}_e)$

They are not the same due to:

1) $\delta CP \neq 0$ or π (CP violation!!)
2) asymmetry due to matter effects (the Earth is made of matter)

- ν_e appearance: mass hierarchy, δ_{CP} and octant of θ_{23}
- ν_μ disappearance: high precision $|\Delta m_{32}|$ and $\sin^2 2\theta_{23}$, constrain octant

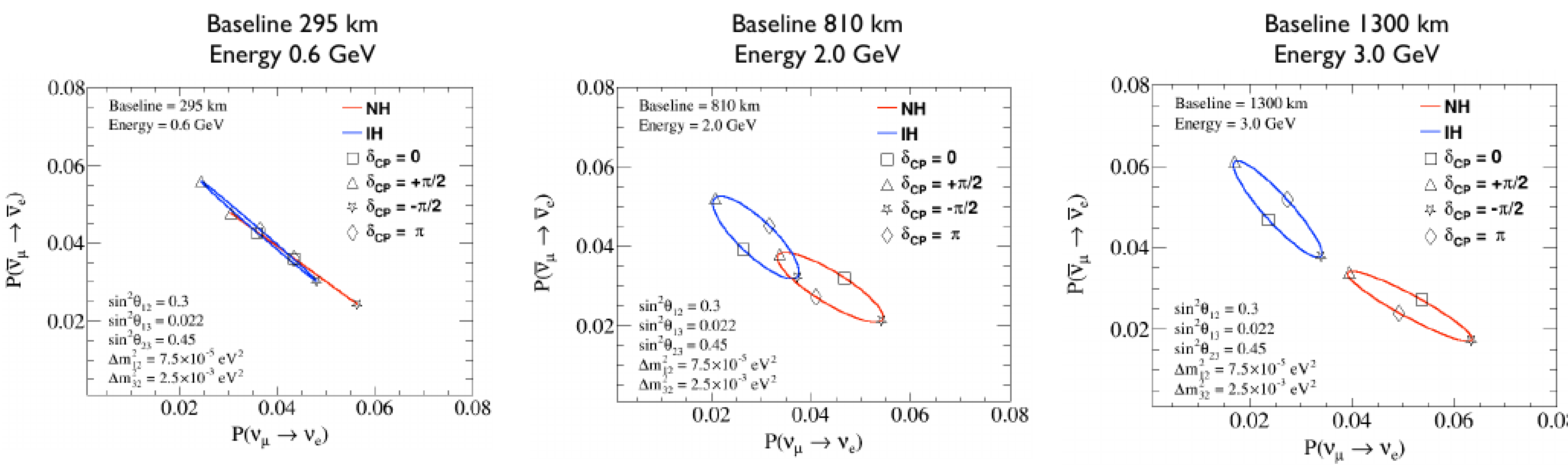
Long Baseline Experiments

Beam of ν_μ or $\bar{\nu}_\mu$

hundreds of km through the Earth

Detect ν_μ ($\bar{\nu}_\mu$)
ν_e ($\bar{\nu}_e$)
and if you can
ν_τ ($\bar{\nu}_\tau$)

If the baseline is long enough, the matter effect dominates, and δCP and neutrino mass ordering disentangle.

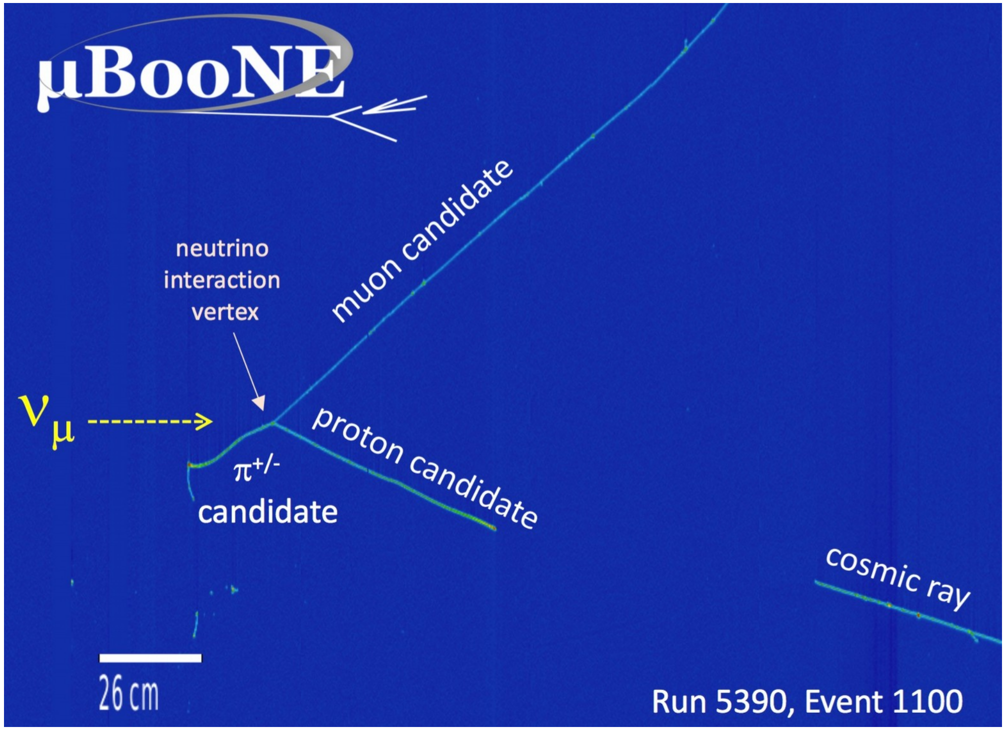


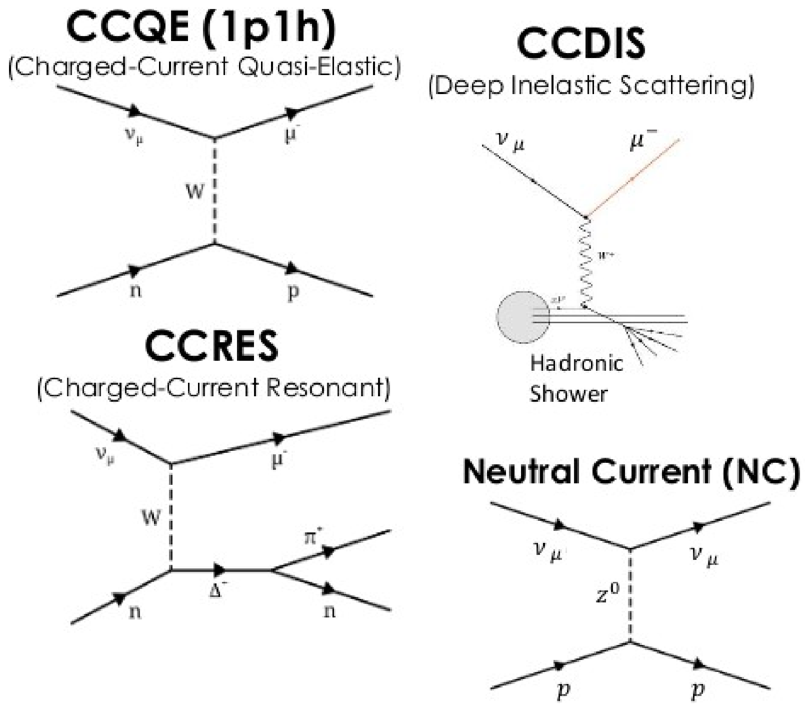
Long Baseline Experiments – Neutrino Signal

Real ν_μ as seen by µBooNE

Neutrino flavour determined by outgoing lepton

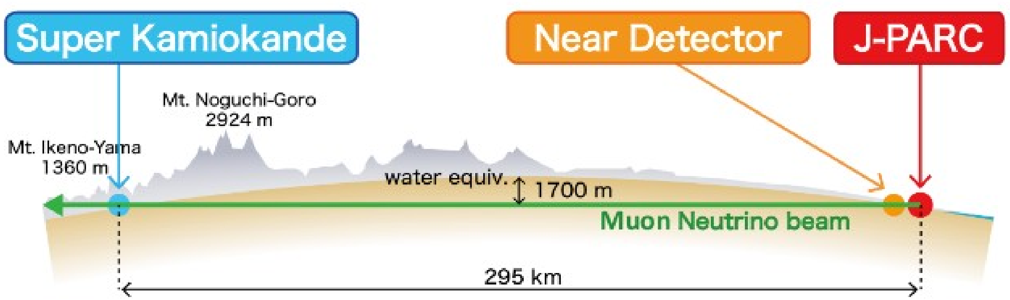
Depending on neutrino energy, interactions can be quite complex (multiple products and showers)



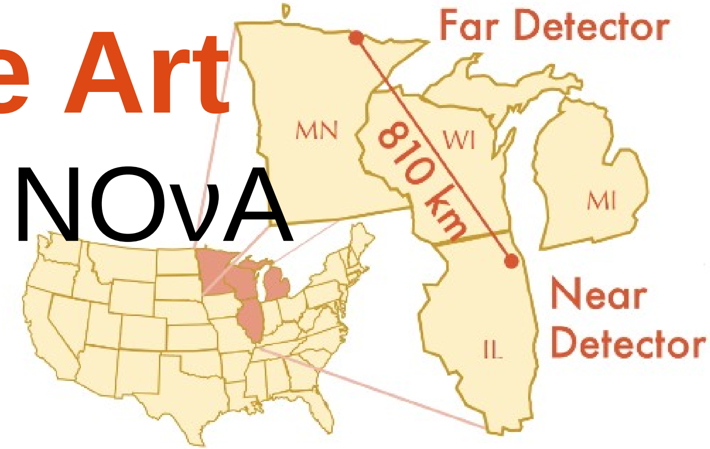


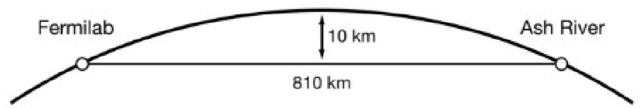
Long Baseline Experiments – State of the Art

T2K



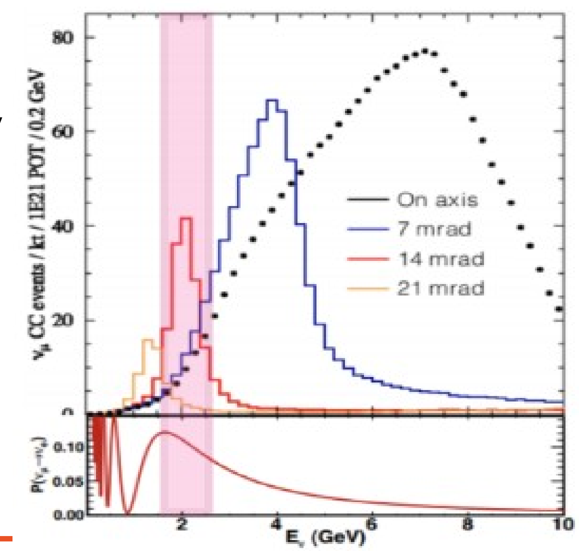
NOνA





- T2K Far Detector is Water Cherenkov (SuperK 50 ktons)
- Baseline is 295 km
- Both have narrow-band beams (off-axis) peaked at 0.6 GeV (T2K) and 1.9 GeV (NOVA)
- Most events are CCQE

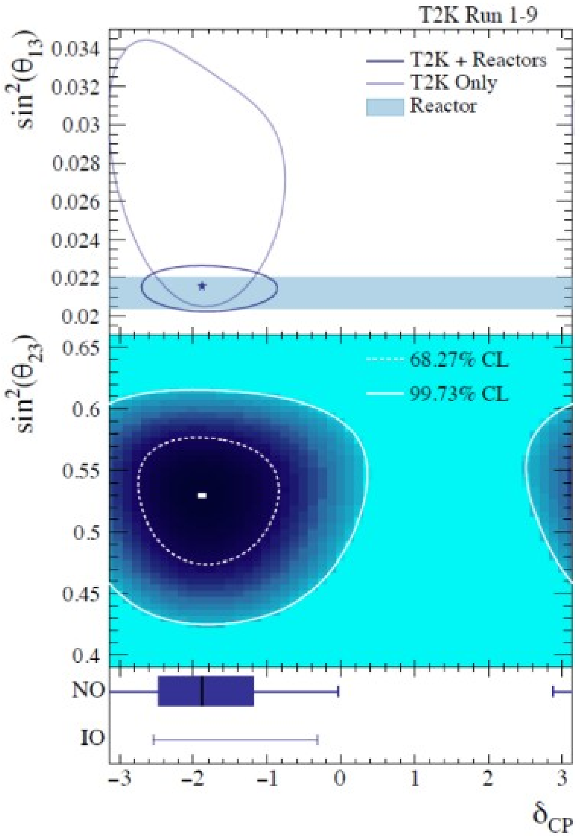
- NOVA has functionally identical Near and Far detectors (finely grained liquid scintillator; 14kton far)
- Baseline is 810km
- Higher neutrino energy
  - DIS occurs



Long Baseline Experiments – State of the Art

T2K

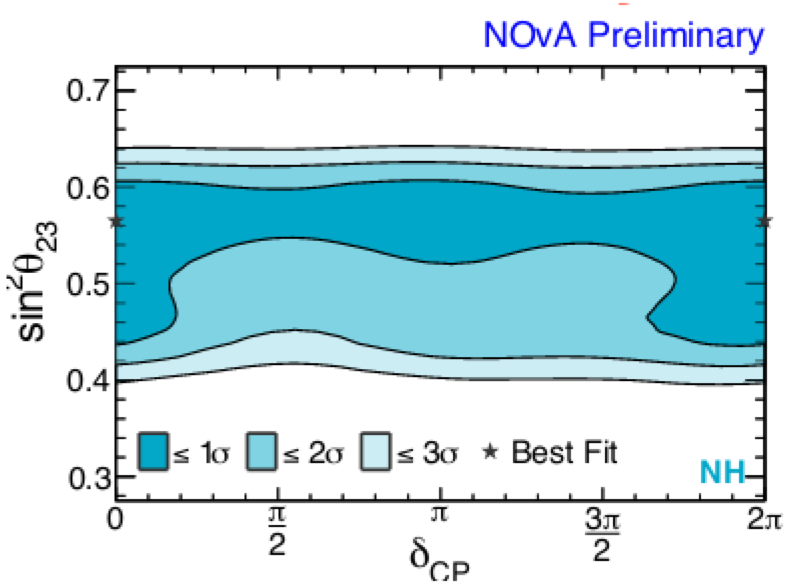
- Preference for maximal CP violation (confidence intervals at 3σ) and Normal Ordering



arXiv:1910.03887

NOνA

- Disfavours Inverted Ordering (at 1.9σ)

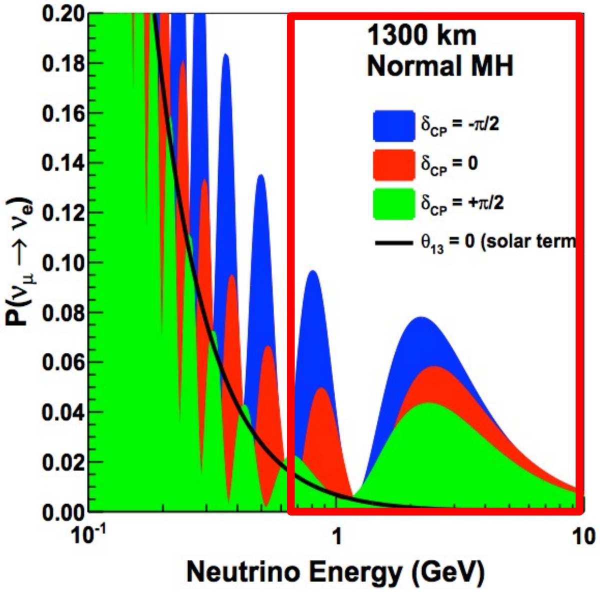


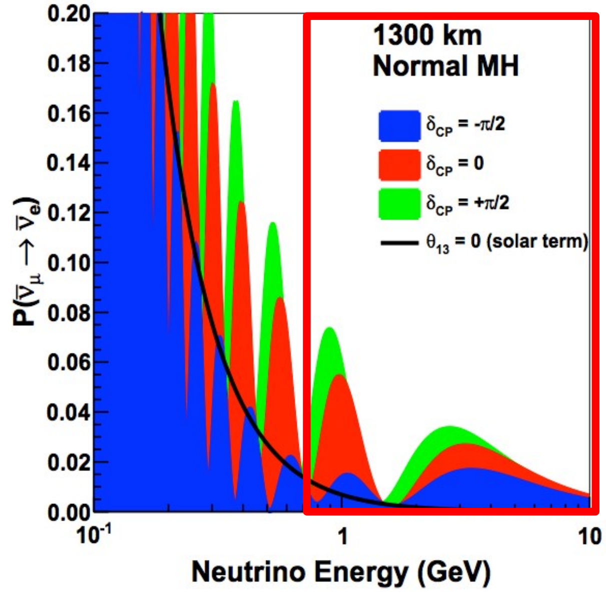
L Kolupaeva epshep2019

Collaborations are working towards a joint analysis → 2021

Long Baseline Experiments – Future

Higher power beam (more stats)
Make a spectral measurement – use a wide band beam
And a longer baseline (completely disentangle mass ordering and CP violation)
Make a spectral measurement
- use a wide band beam
- highly performing detectors



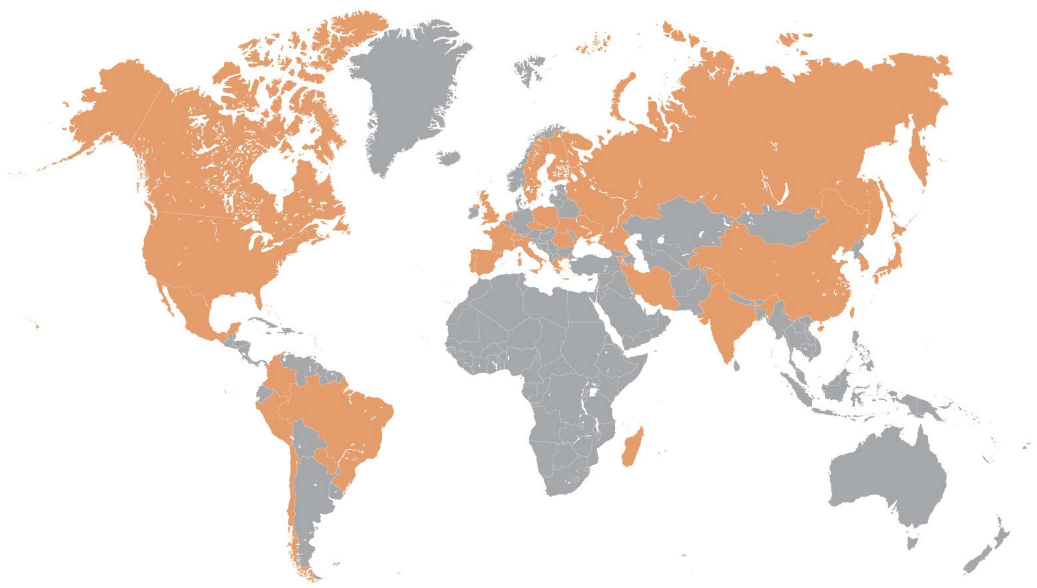


Measurement range spans 2 oscillation peaks
Gain additional power on deltaCP

Downside – hit all forms of neutrino interactions.
Need highly performing Near Detectors...

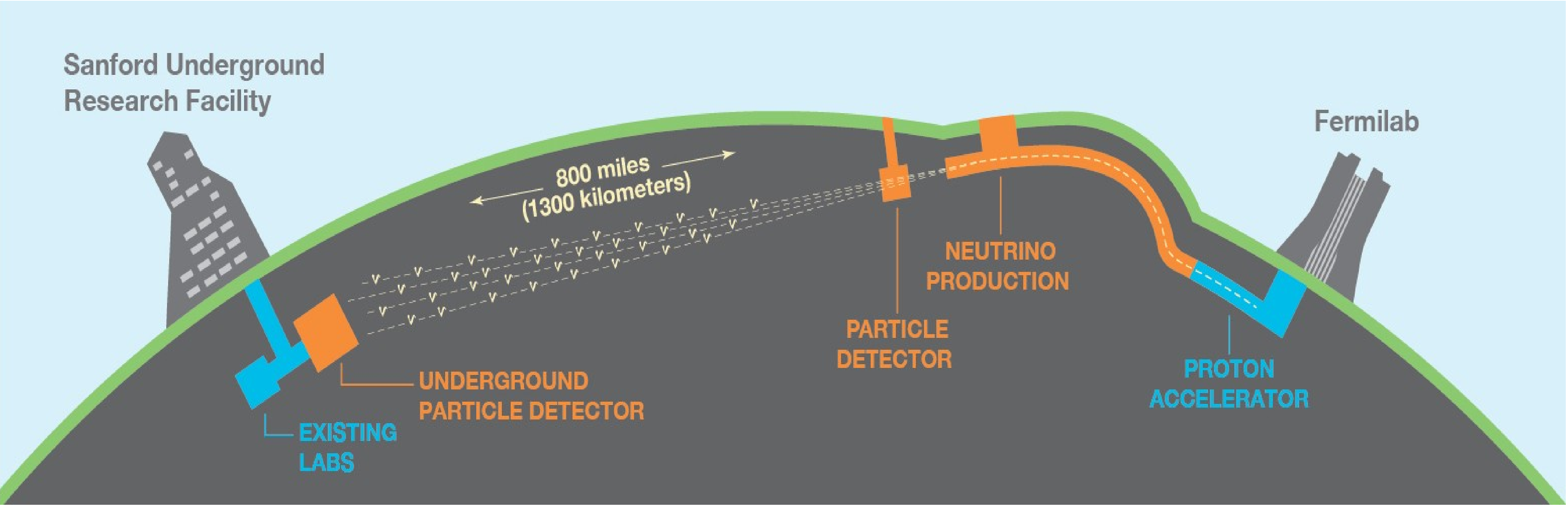
DUNE: international collaboration

- 1069 collaborators from 177 institutions in 31 countries
- 578 faculty, 184 postdocs, 109 engineers, 198 Ph.D. students



Armenia (3), Brazil (31), Canada (1), CERN (37), Chile (3), China (2), Colombia (8), Czech Republic (11), Spain (35), Finland (4), France (38), Greece (5), India (44), Iran (2), Italy (66), Japan (7), Madagascar (4), Mexico (10), The Netherlands (6), Paraguay (4), Peru (7), Poland (6), Portugal (6), Romania (7), Russia (10), South Korea (5), Sweden (1), Switzerland (30), UK (146), Ukraine (4), USA (528)

DUNE is next generation neutrino oscillation experiment



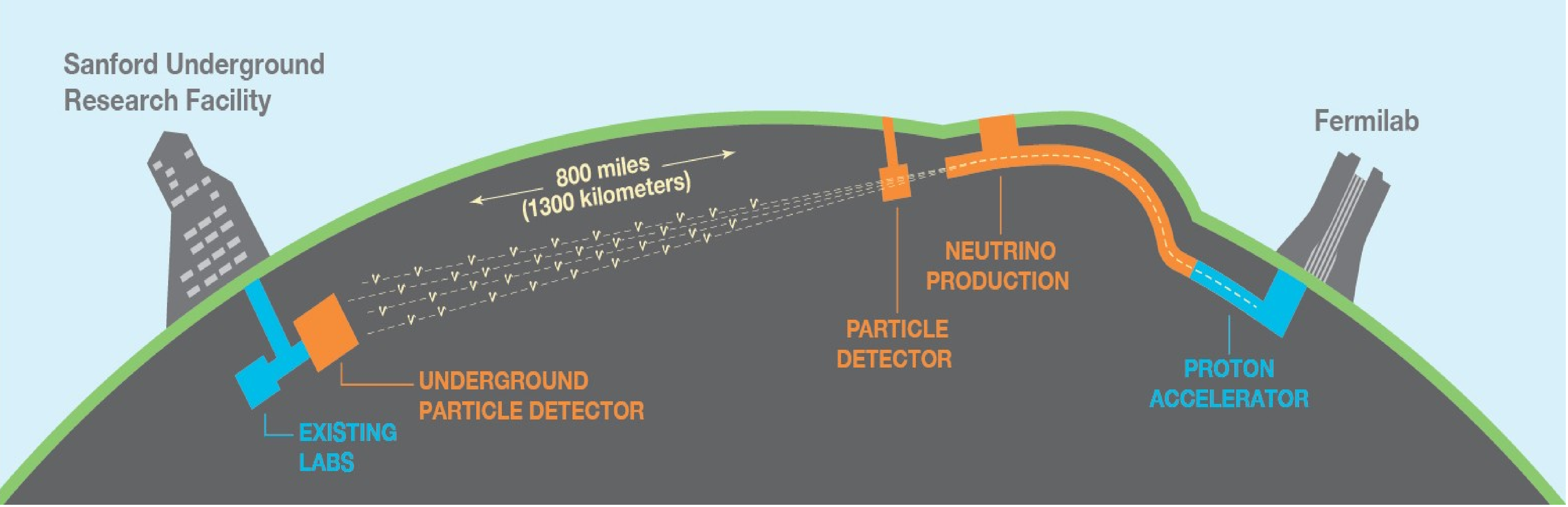
Physics goals :

Neutrino oscillations : measure ν_μ disappearance + ν_e and ν_τ appearance (both neutrino and anti-neutrino modes)

Mass Ordering, leptonic CP Violation discovery, θ_{23} octant and more in a single experiment + physics beyond the Standard Model

Large underground detectors : Nucleon Decay searches, SuperNovae core collapse etc

DUNE is next generation neutrino oscillation experiment

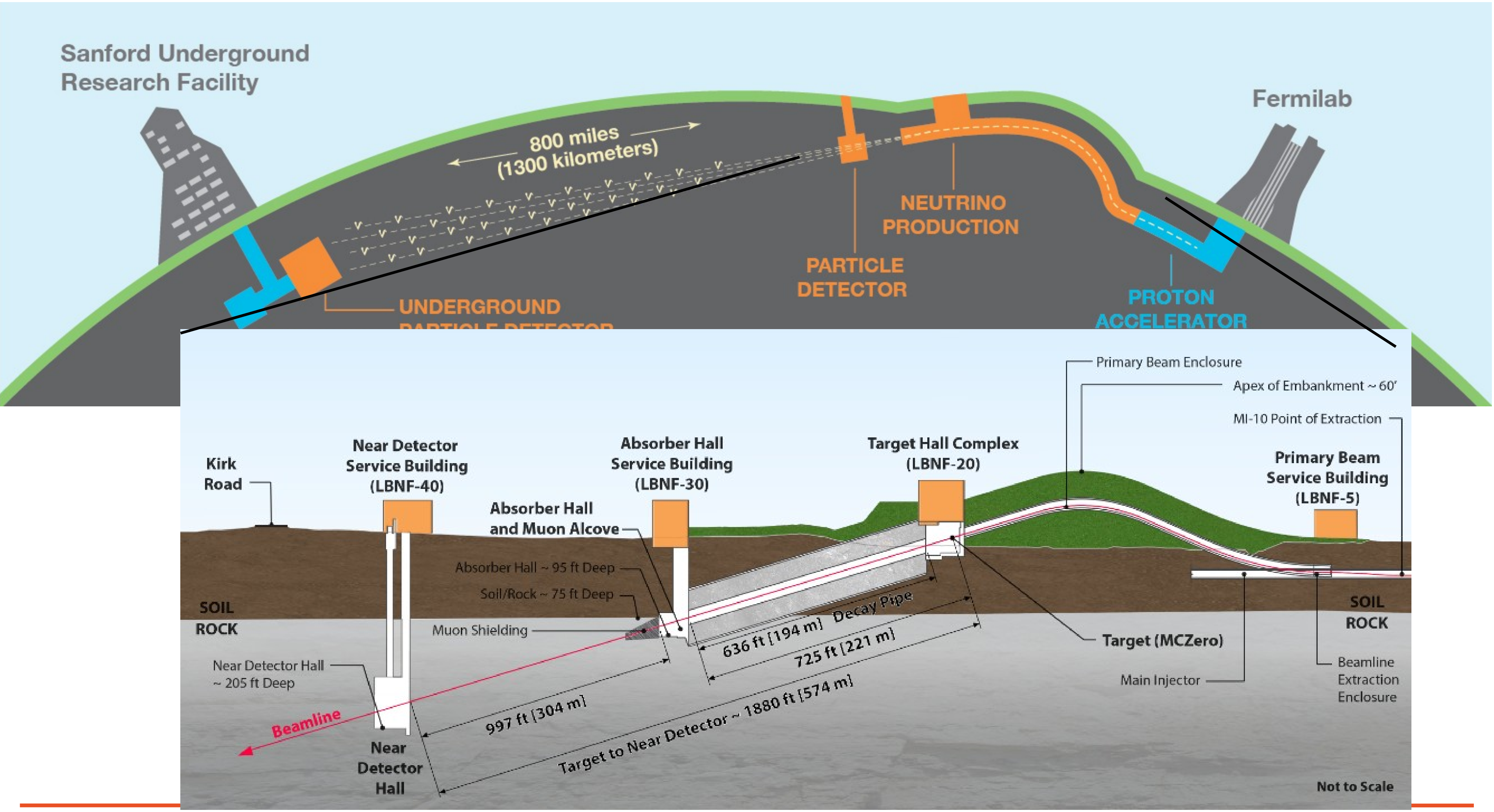


Far detectors at SURF:
4 x 10 kt (fiducial) Liquid Argon TPCs
1.5 km underground

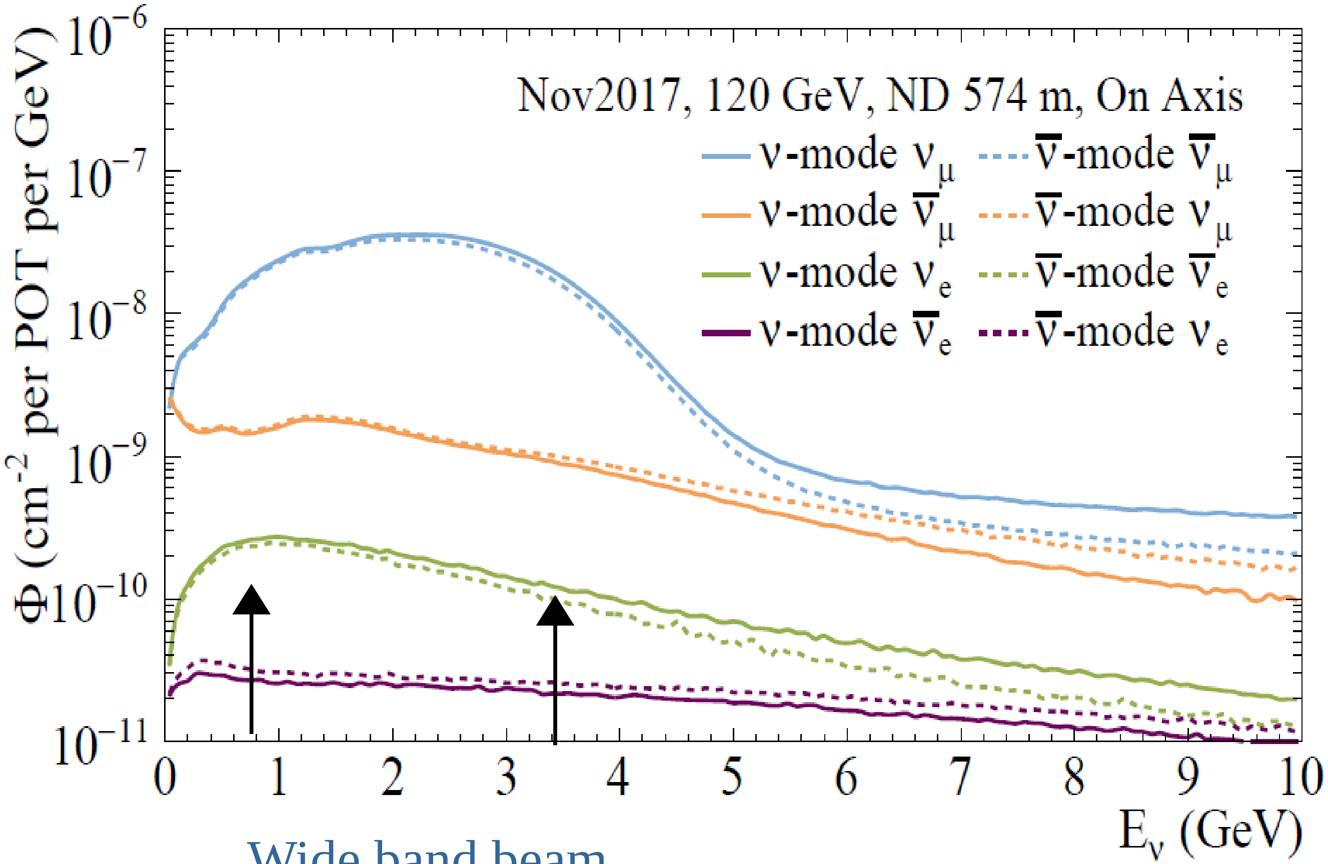
1.2 MW wide-band beam from Fermilab (upgradable to 2.4 MW)

Near Detector to measure initial composition

Long Baseline Neutrino Facility



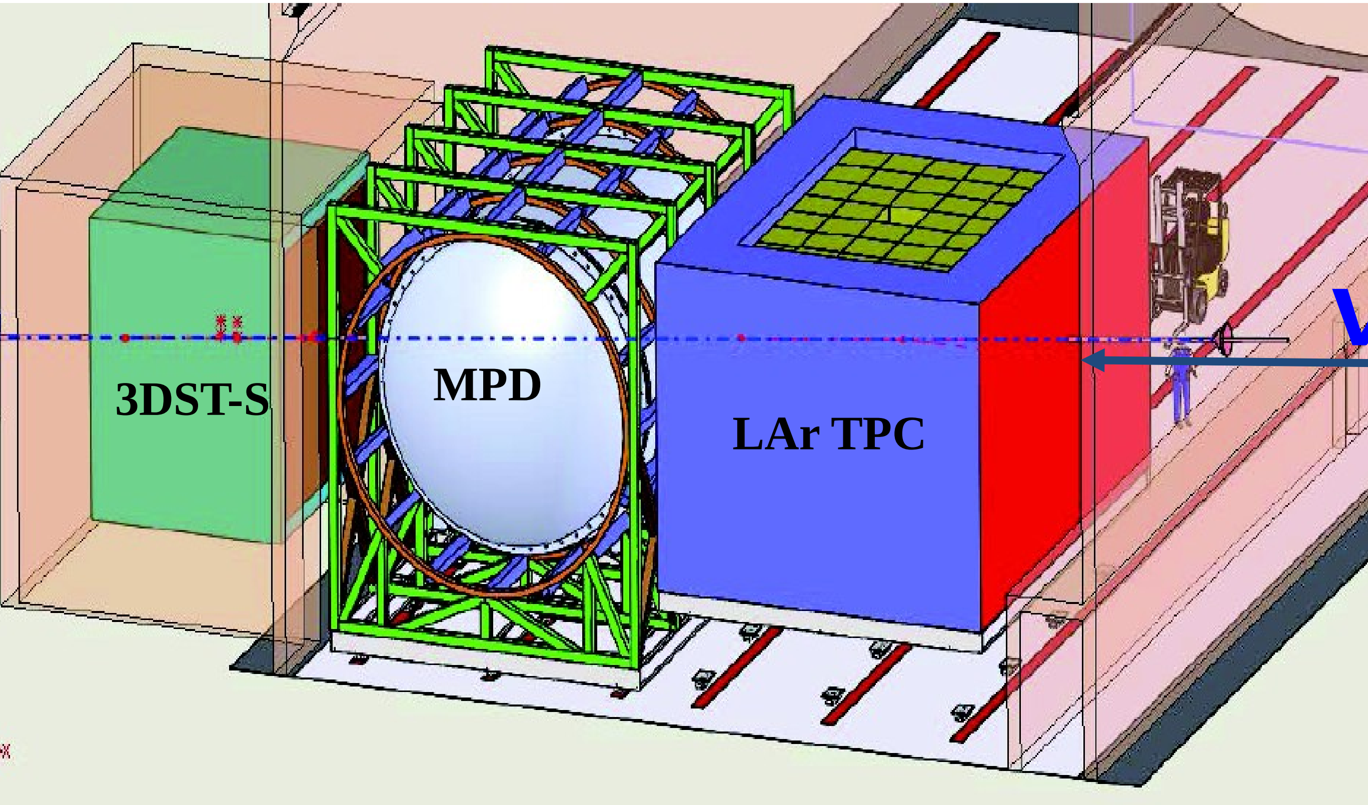
LBNF beam



Wide band beam
2 oscillation maxima

- 120 GeV Main Injector proton beam
- 1.2 MW initial beam power, upgradeable to 2.4 MW
- Beamline and focusing system optimized for CP violation sensitivity

Near detector system at Fermilab



Predict the neutrino spectrum at the FD

Measure interactions on Ar

Measure neutrino energy

Constrain x-section model

Measure neutrino flux

Obtain data with different fluxes

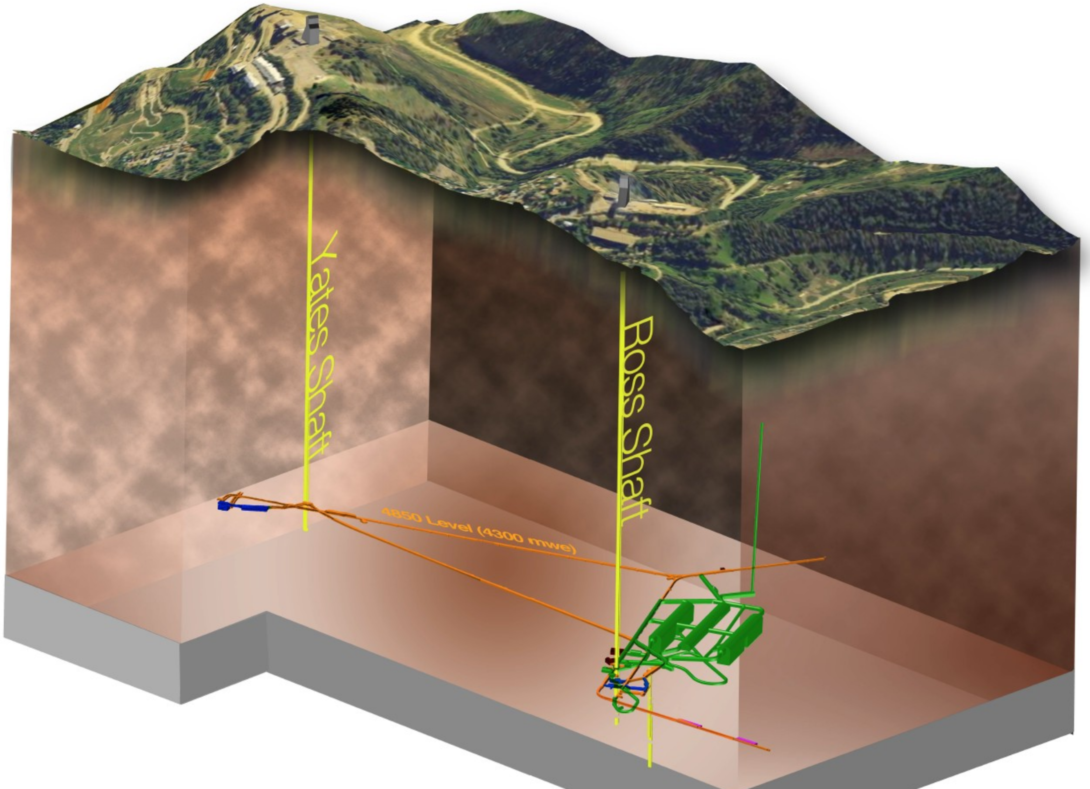
Monitor the neutrino beam

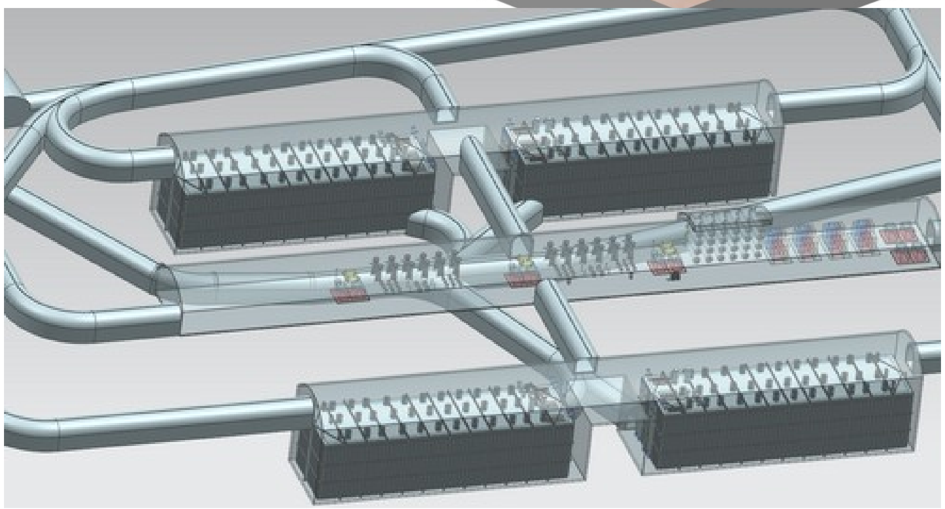
Liquid Argon TPC

Multi-Purpose Detector - HP gaseous Argon TPC + ECAL + Magnet

3D Scintillating Tracking Spectrometer

Far detector at SURF





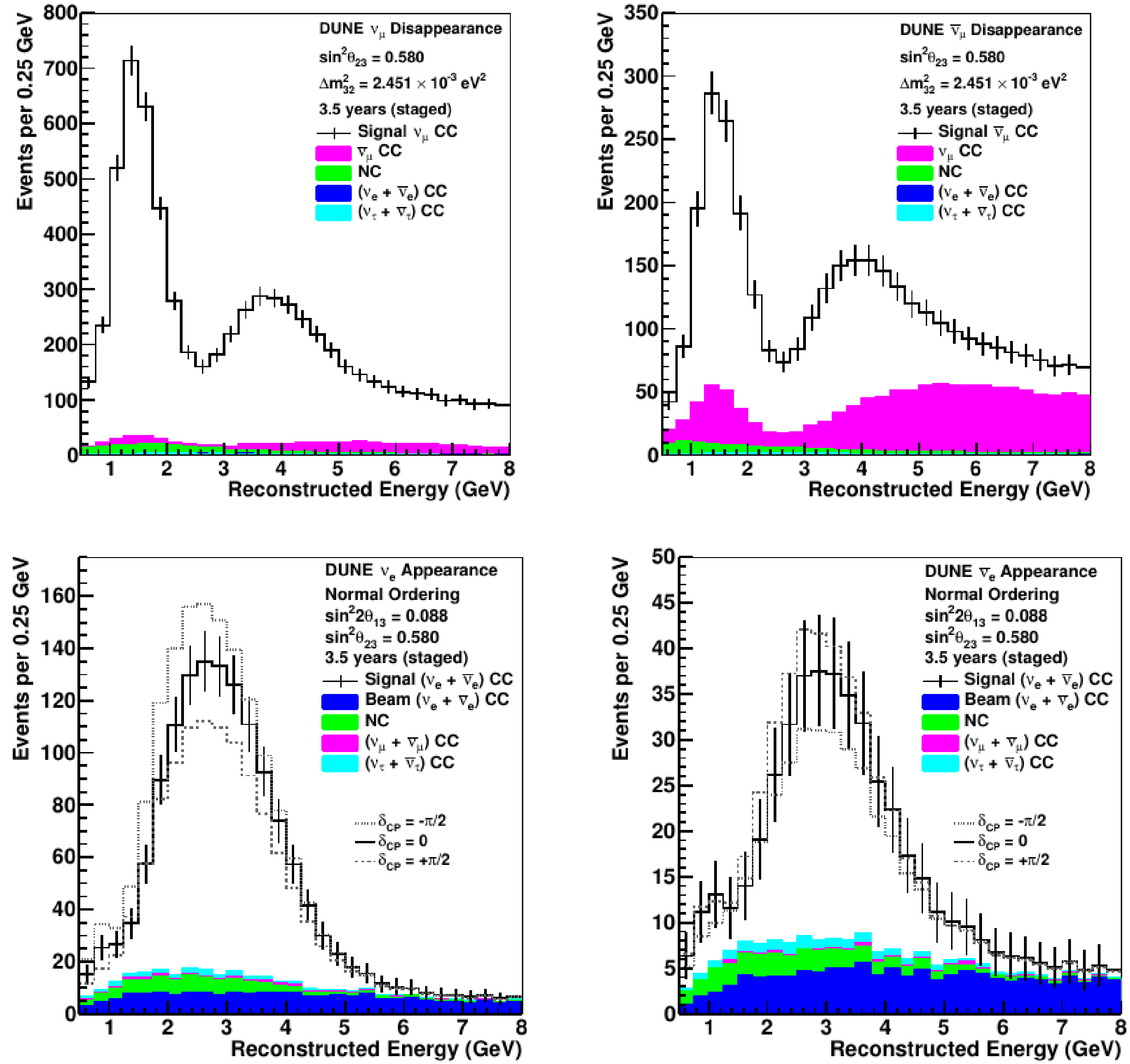
- Sanford Underground Research Facility in Lead, South Dakota
- Four 10-kt Fiducial LAr TPC modules, located 1.48 km underground
- Excavation
- first module operational in 2024
- Start of run: 2 FD modules (20 kt), 1.2 MW beam power, with ND
- +1 year: 3 FD modules (30 kt)
- +3 years: 4 FD modules (40 kt)
- +6 years: upgrade to 2.4 MW beam

Neutrino Oscillations

Measure appearance and disappearance for both neutrino and anti-neutrinos

disentangle Mass Ordering and CP effects

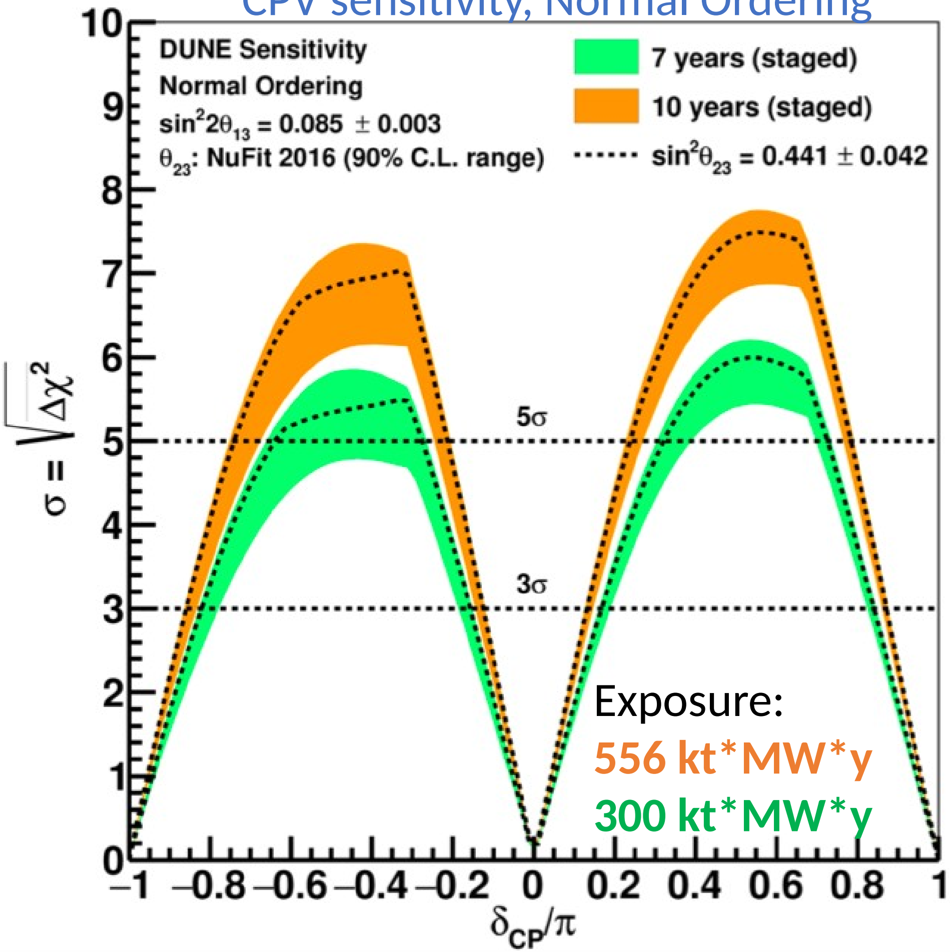
Spectral measurement - 1st and 2nd maxima



DUNE Technical Design Report (TDR) arXiv:2002.03005

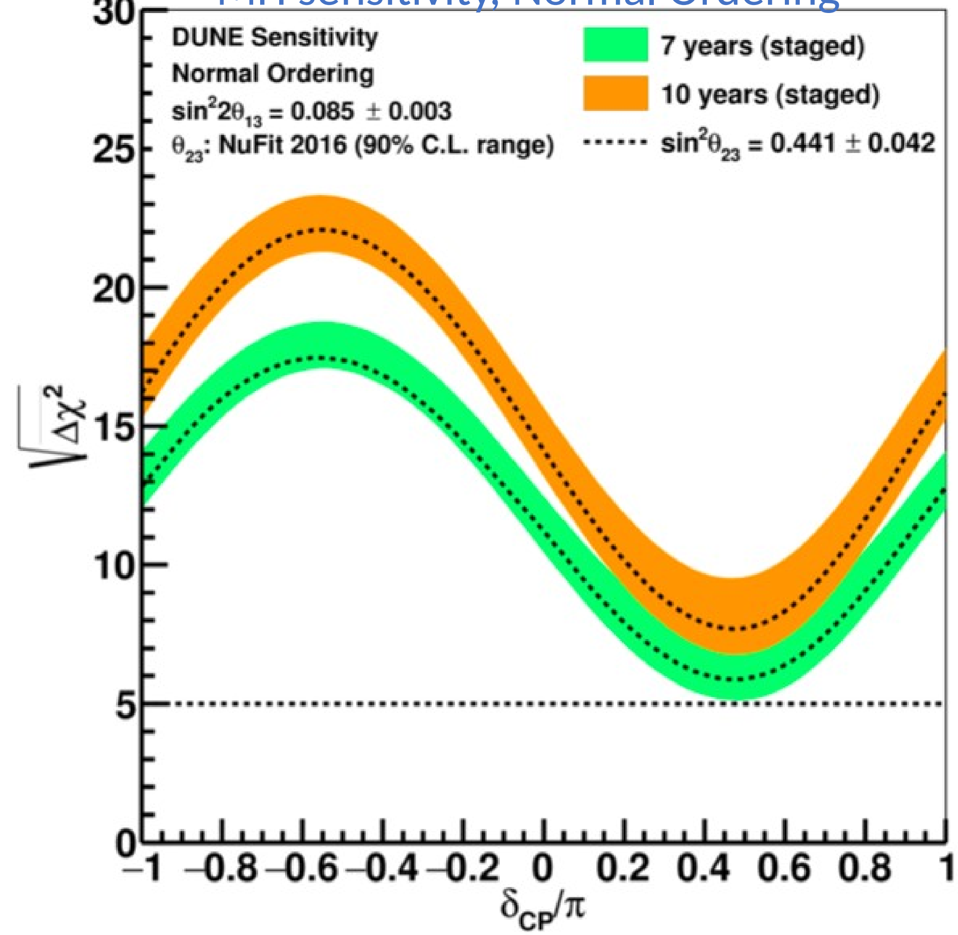
sensitivity to CPV and Mass Ordering

CPV sensitivity, Normal Ordering



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

MH sensitivity, Normal Ordering



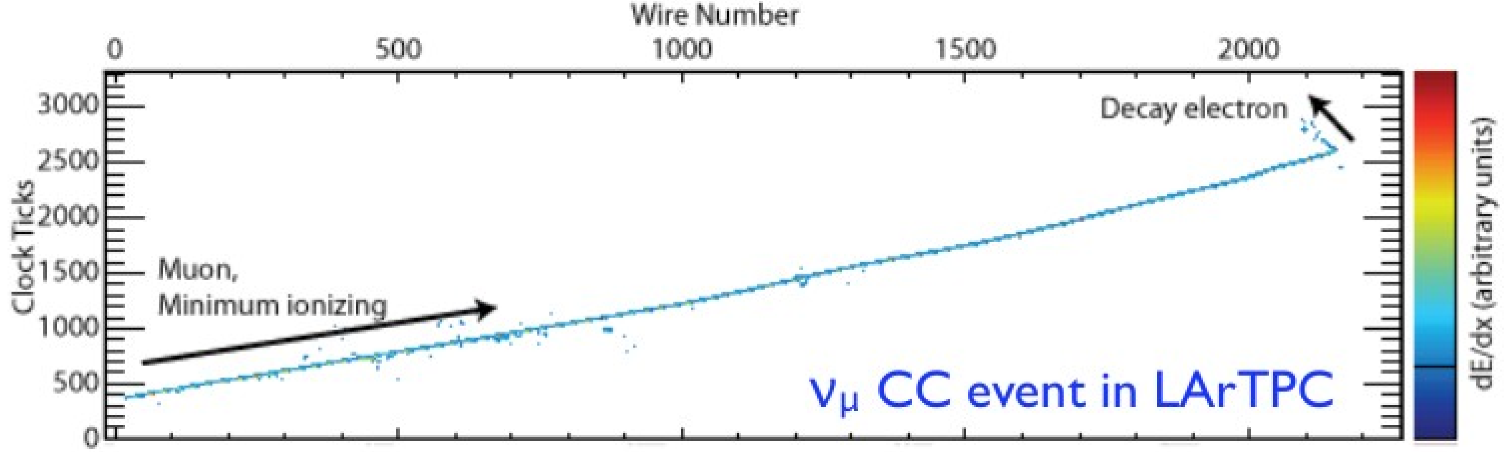
>5σ sensitivity for both orderings and the full range of δ_{CP}

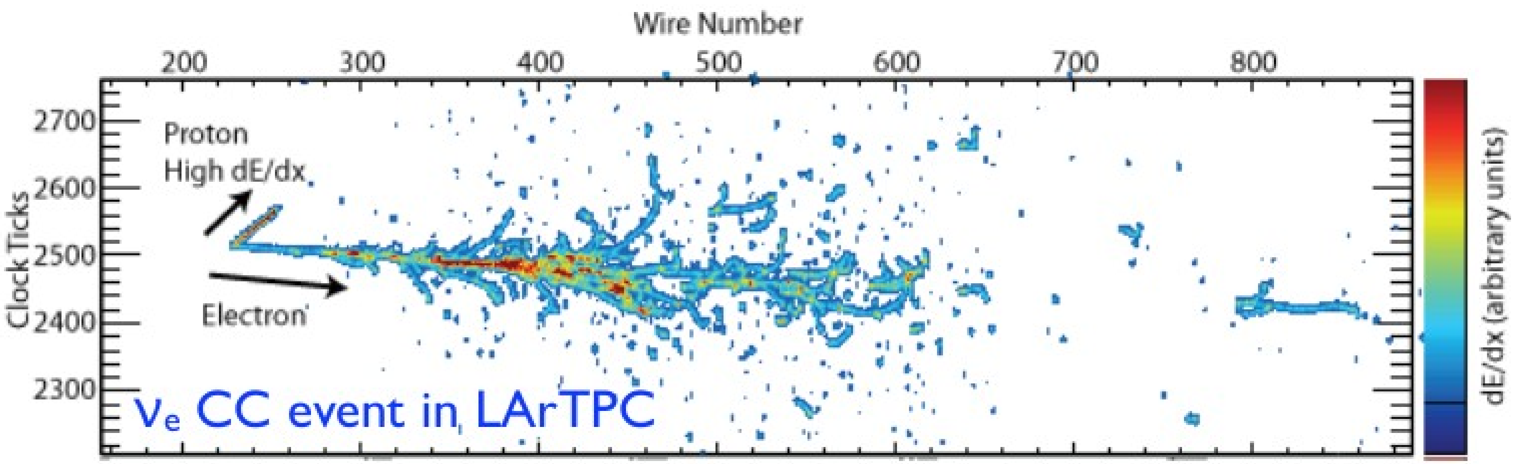
Updated analysis with full FD simulation & reconstruction, detailed systematic uncertainties, and ND, in TDR

LAr TPCs

- Gigantic detectors deep underground with Excellent calorimetric and spatial resolution
- Wide off-beam physics program

Simulation



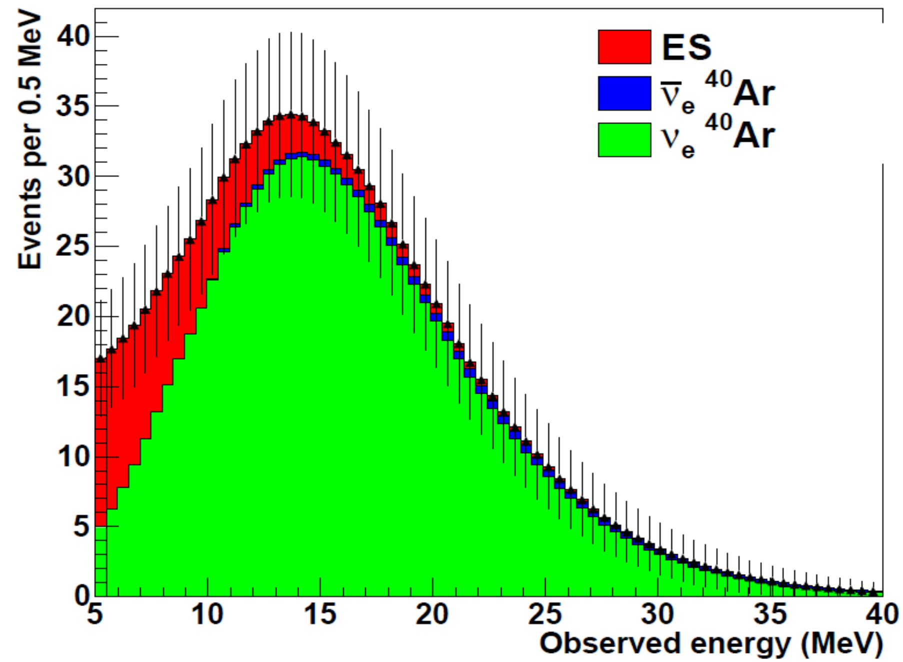


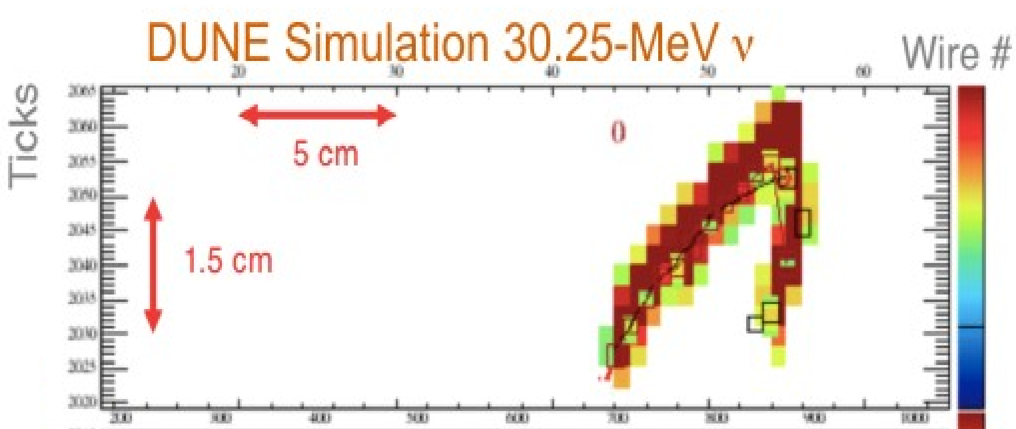
non-beam physics: SuperNova burst

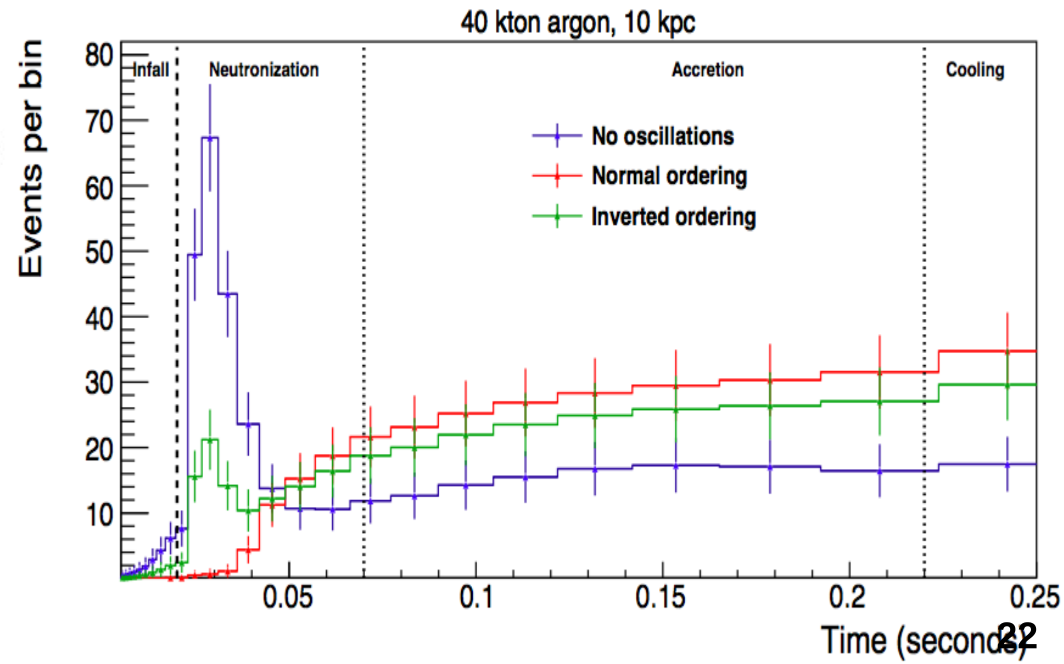
Uniquely DUNE is sensitive to ve
ve + ^{40}Ar → e$^-$ + ^{40}K*

5-50 MeV signals: efficient triggering + continuous data collection

Monte Carlo studies ongoing with Marley generator and full simulation

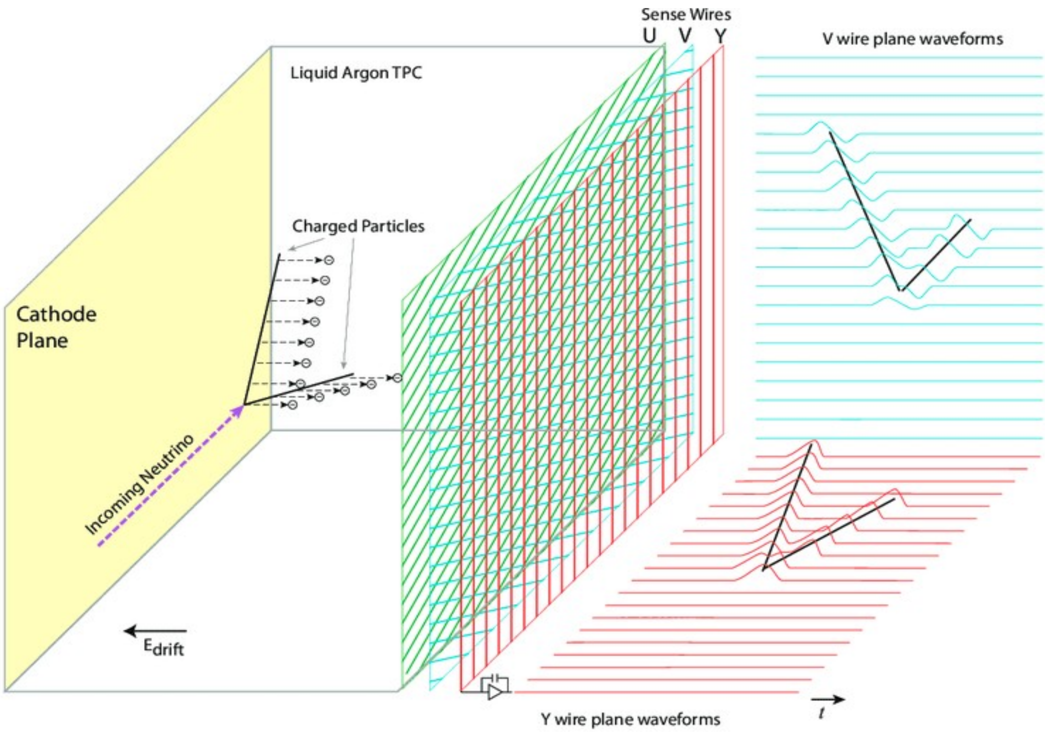






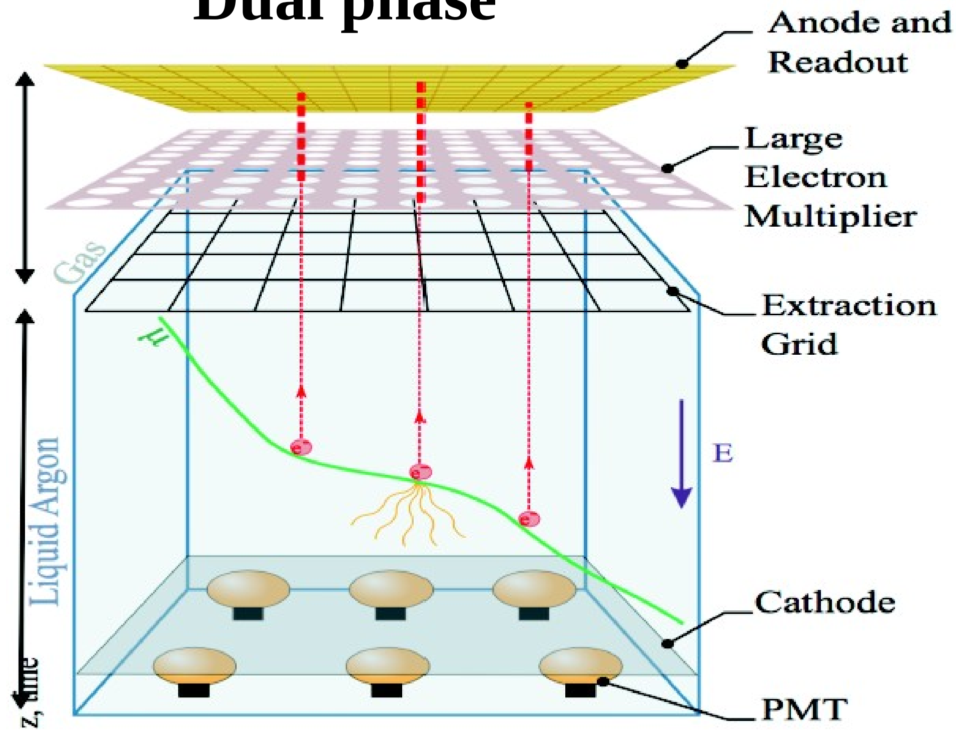
Two detector technologies

Single phase



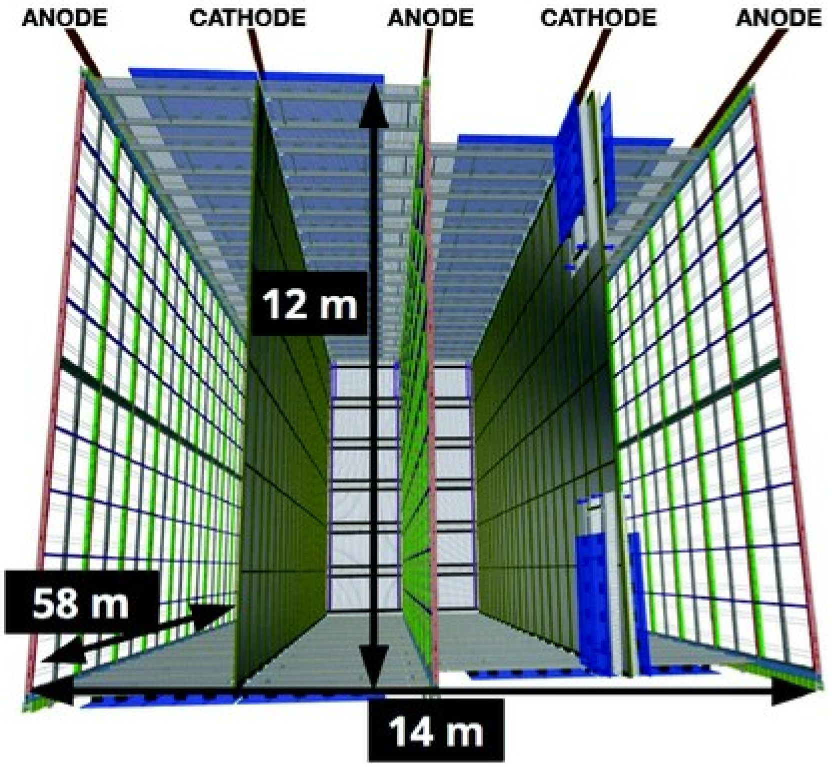
Horizontal drift, distance 3.6 m
Anode wires immersed in LAr
Vertical Anode and Cathode Plane Assemblies (APA,CPA)
1 collection, 2 induction wires at 37.7^{o}, wire pitch 5 mm
Photon detectors: light guides + SiPM,embedded in APAs

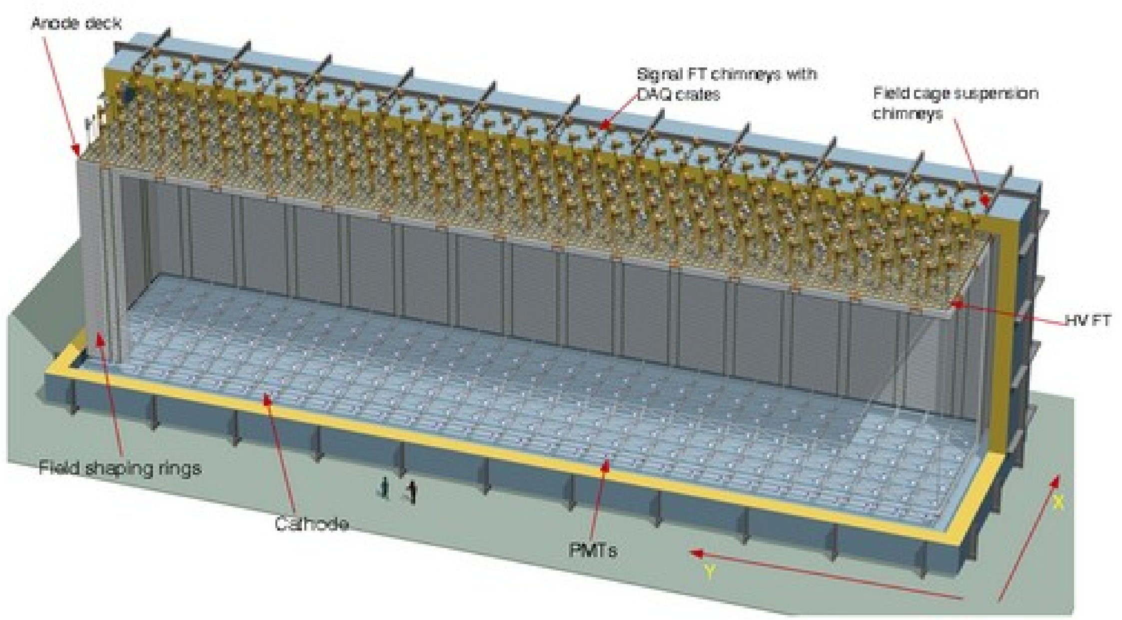
Dual phase



Vertical drift, distance 12 m
Ionization electrons extracted from LAr to gas
Signal amplified in GAr by Large Electron Multiplier (LEM)
Charge collected on 2 orthogonal views, 3mm pitch
Photon detectors: PMTs below the cathode

Far Detectors



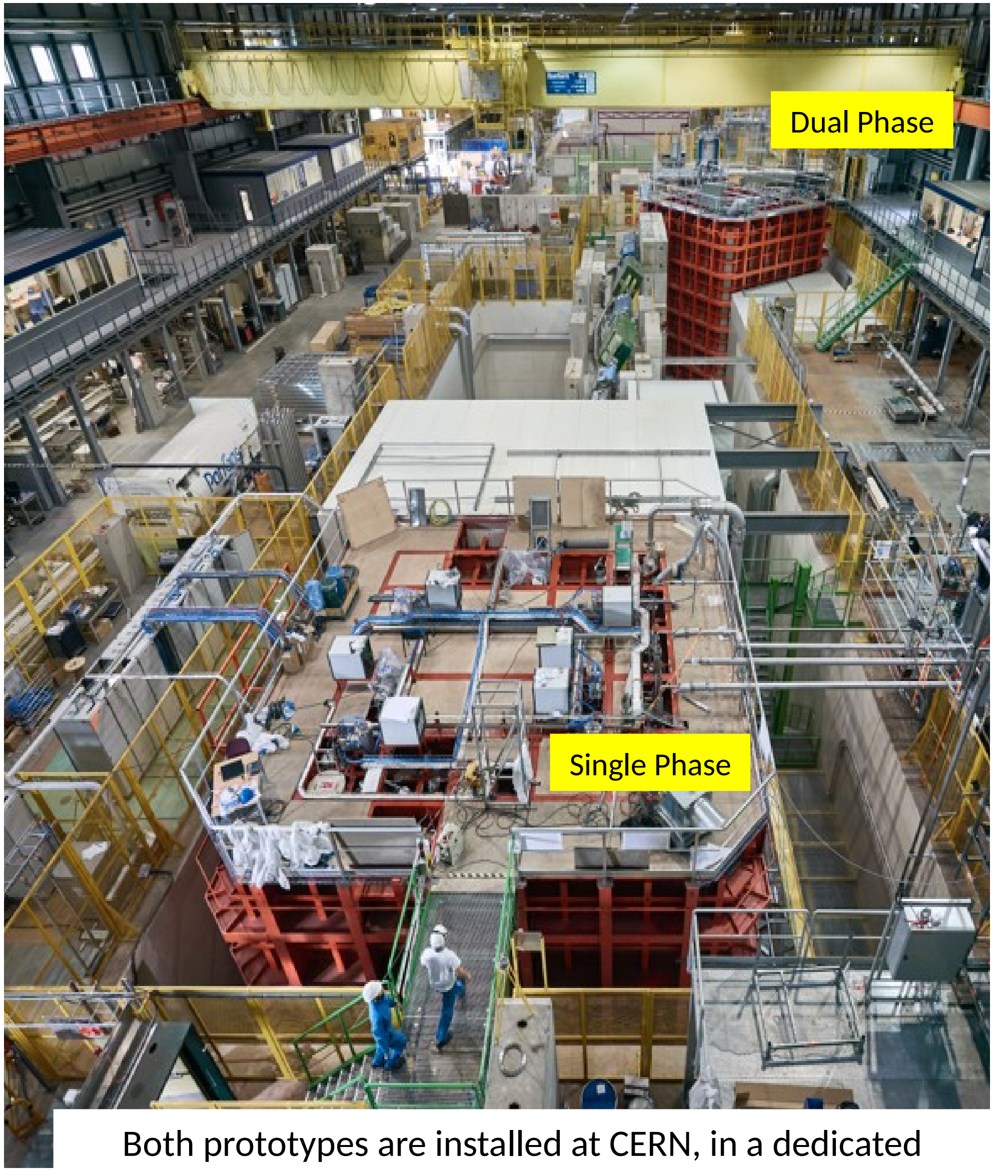


- Single Phase is modular
- Shorter drift lengths (and distance to photodetectors)
- Immersed cold electronics (inaccessible)

- Dual Phase is homogenous
- Drift is longer (12m) (and distance to photodetectors)
- Cold Electronics at the top of the detector (accessible)

protoDUNEs

- Giant Liquid Argon TPCs (LArTPC) – one Single-Phase, one Dual-Phase hosted at the CERN neutrino platform
- Necessary R&D step towards the DUNE Far Detectors
  - Tests of all engineering solutions and installation procedures
  - Use full-size components identical to those planned for DUNE FD
- 300t fiducial mass of LAr
  - Technology demonstrators
  - Demonstrate long term performance and stability
- Charged particle test beams to characterise detector response over the energy range of interest for DUNE (~0.5 GeV to 8 GeV)



Both prototypes are installed at CERN, in a dedicated extension of the North Area

A history of Single Phase LAr TPCs

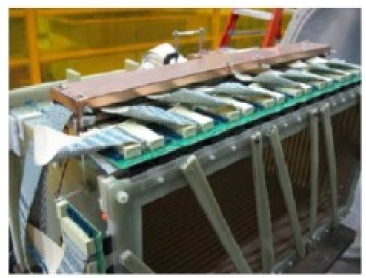
ICARUS T-600 @ CNGS (2010-2012, 760 tons LAr)



Successfully reconstructed neutrino events from CNGS beam (~17 GeV)

Argoneut @ FNAL (2009-2010, 240 kg LAr)





Small TPC, precise measurements of cross-sections and neutrino interactions

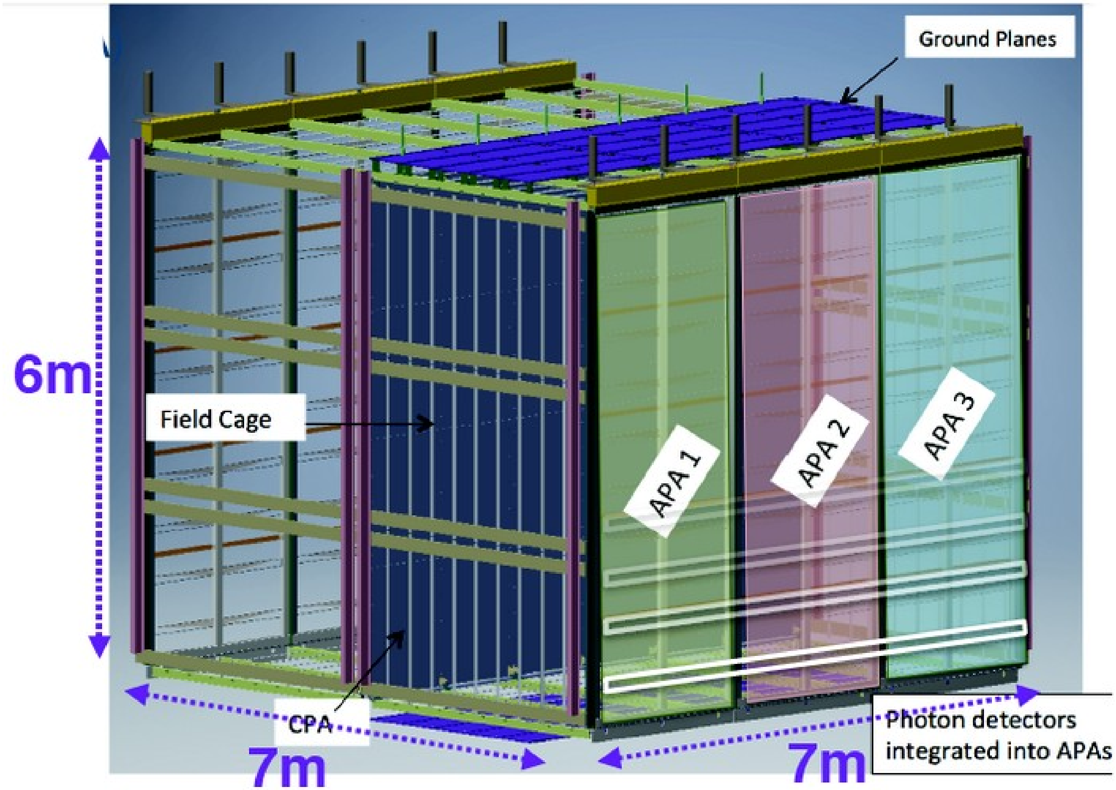
MicroBooNE @ FNAL (2015-ongoing , 170 tons LAr)

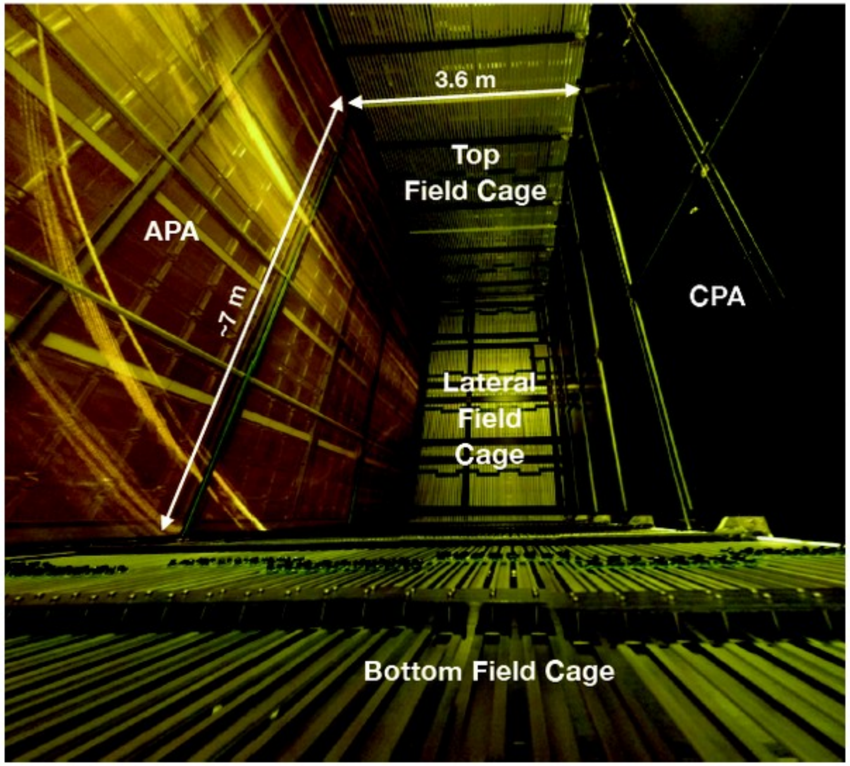


Sterile neutrino search. Neutrino event selection and reconstruction. Leads to protoDUNE Single Phase

taken from A. Chatterjee

Single Phase protoDUNE

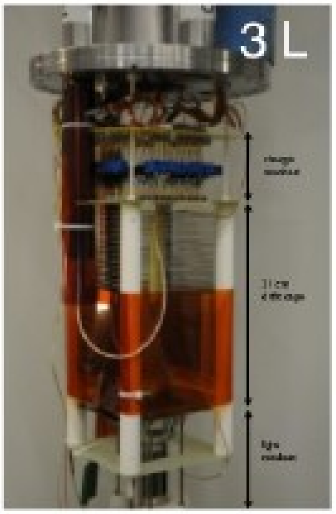




Successful Beam test in 2018 (Sept-Nov) – pions, protons, kaons from 0.3-7GeV (~4M triggers)
Achieved stable running, >5ms electron lifetime,S/N > 20

A history of Dual Phase LAr TPCs

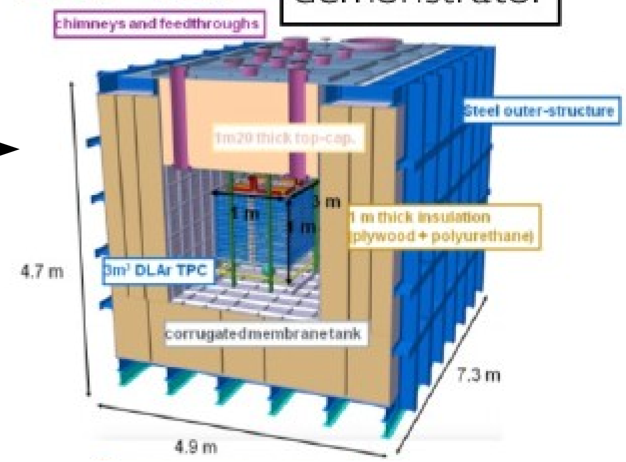
Small R&D TPCs



2007 ~ 2014

2014 ~ 2017

3x1x1 m^3 demonstrator

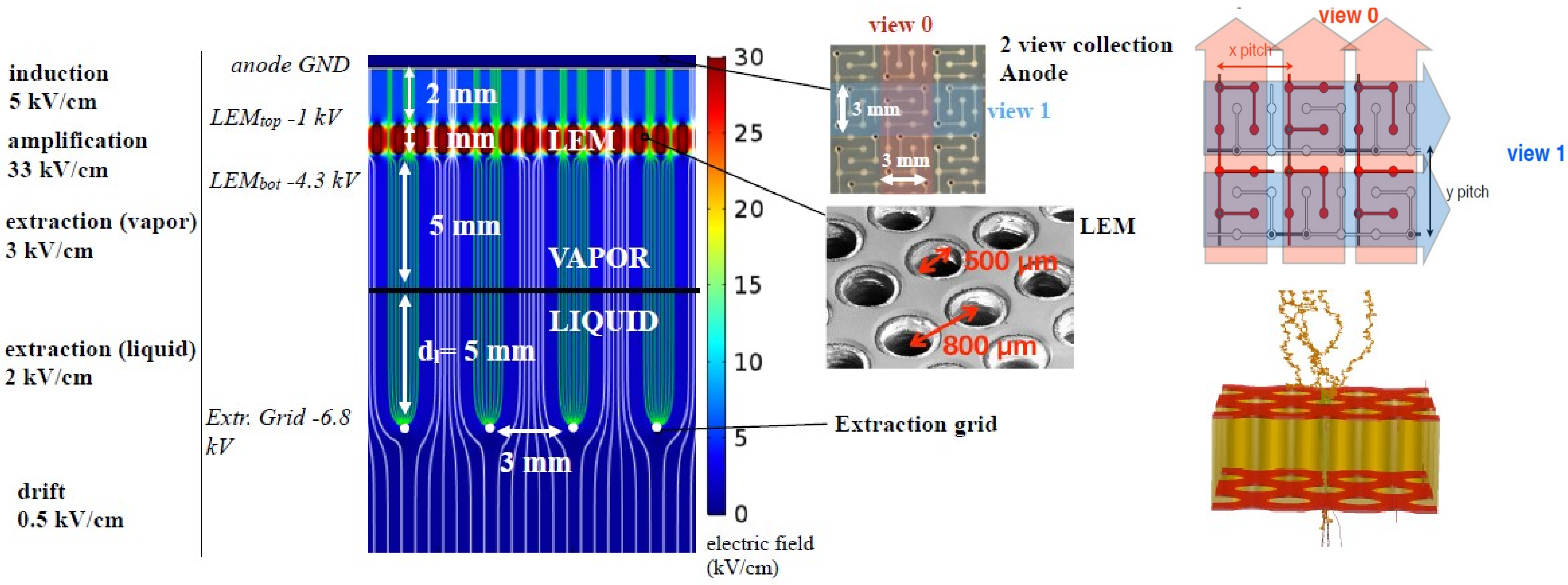


ProtoDUNE DP
6m x 6m x 6m

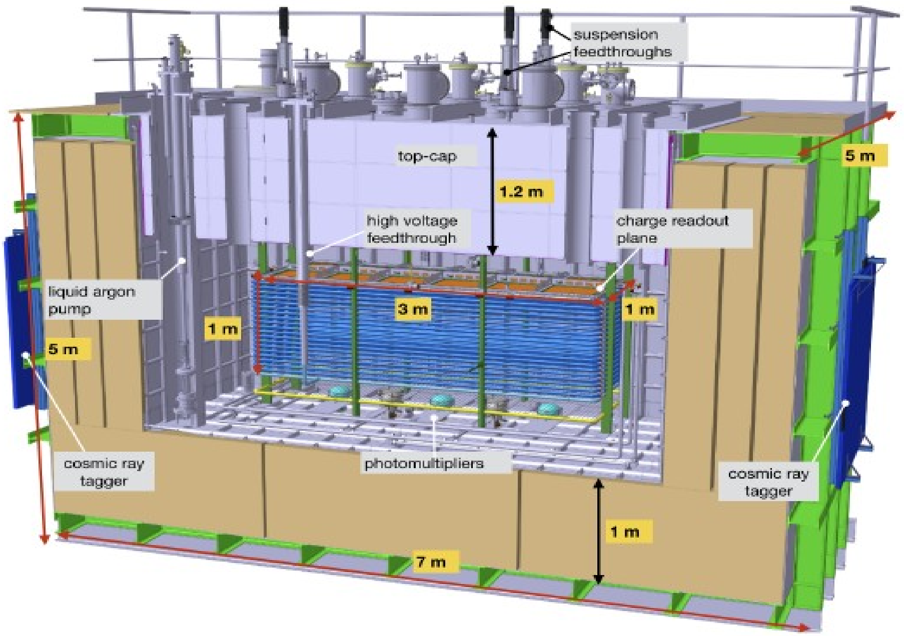
Charge Read Out Planes

Each CRP is 3m x 3m and contains:

1 x Extraction Grid
36 x Large Electron Multipliers (0.5m x 0.5m)
36 x Anodes



Dual-Phase 4t demonstrator



3x1x1 m^3 (4t) fiducial volume,
installed at CERN
500k cosmic events in summer-fall 2017

First results on

- charge amplification
- light detection
- LAr purity

arXiv:1806.03317 [ins-det]
B. Aimard et al, 2018, JINST 13, P11003

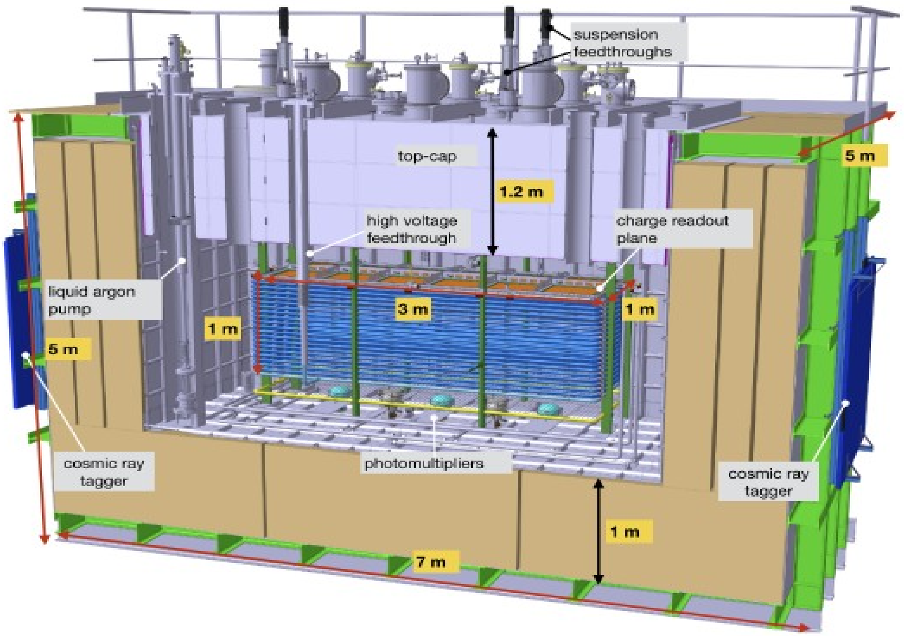
Technical problems encountered with

- Extraction Grid
- LEM HV

Gain needed for DUNE could not be demonstrated

Issues addressed for protoDUNE

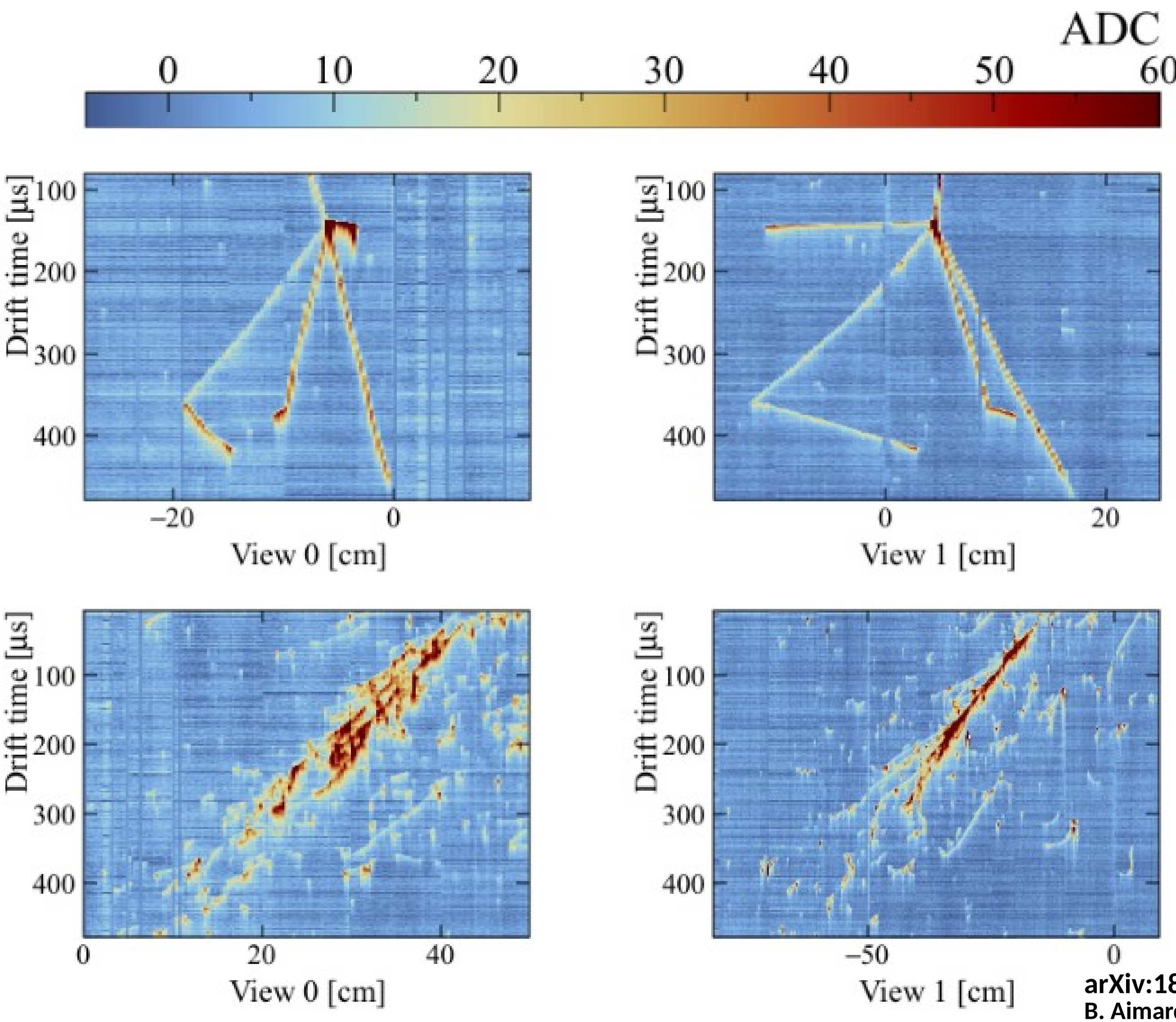
Dual-Phase 4t demonstrator



Several milestones achieved

- LAr level stability over time
- Stable drift field for entire operation
- Equal charge splitting at the anode
- Purity compatible with a 4ms electron lifetime

Dual-Phase 4t demonstrator

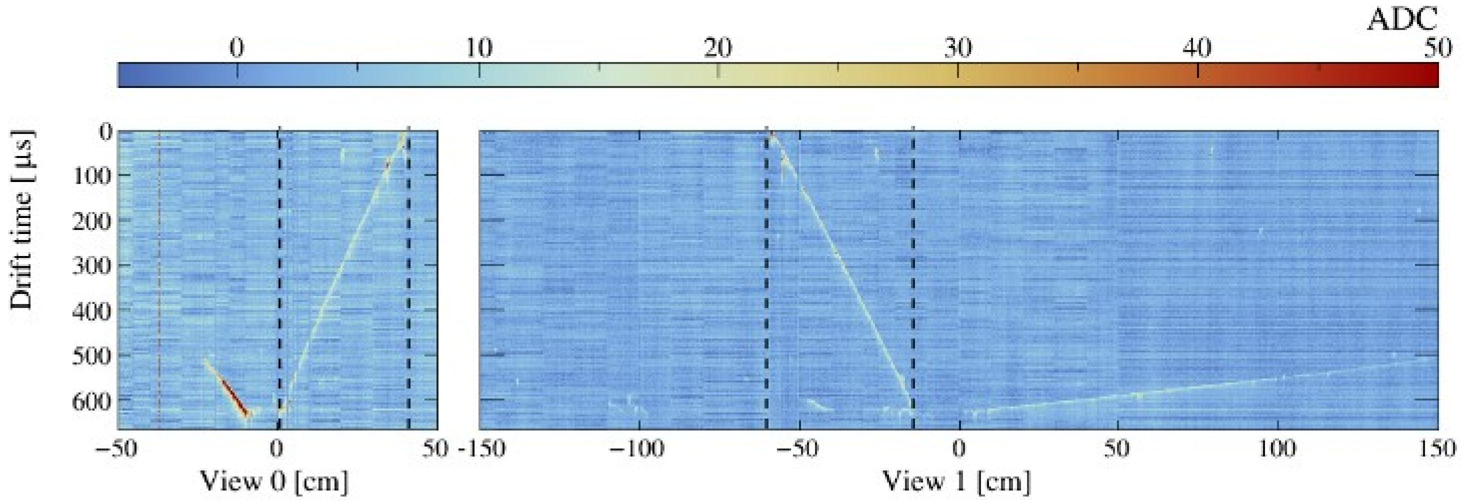


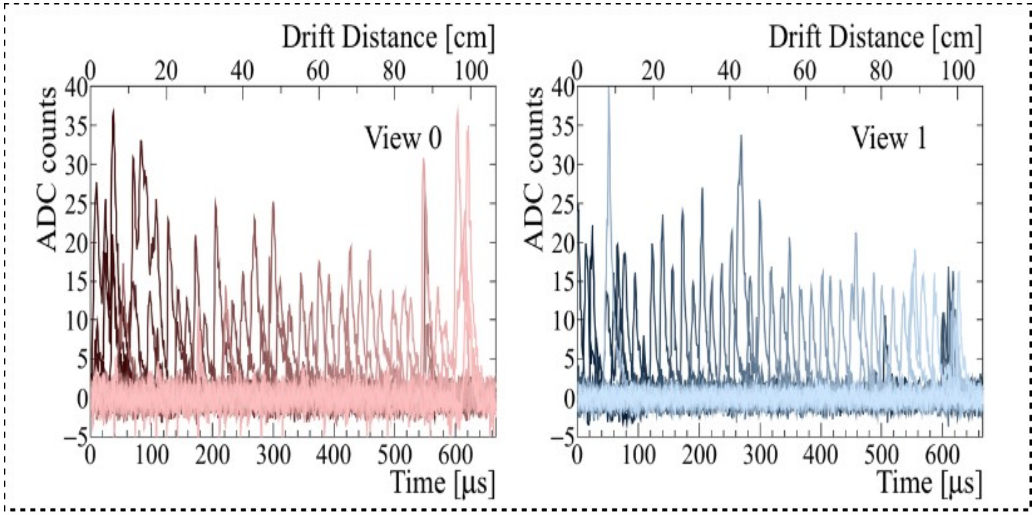
Hadronic shower

Electronic shower

arXiv:1806.03317 [ins-det]
B. Aimard et al, 2018, JINST 13, P11003

Dual-Phase 4t demonstrator



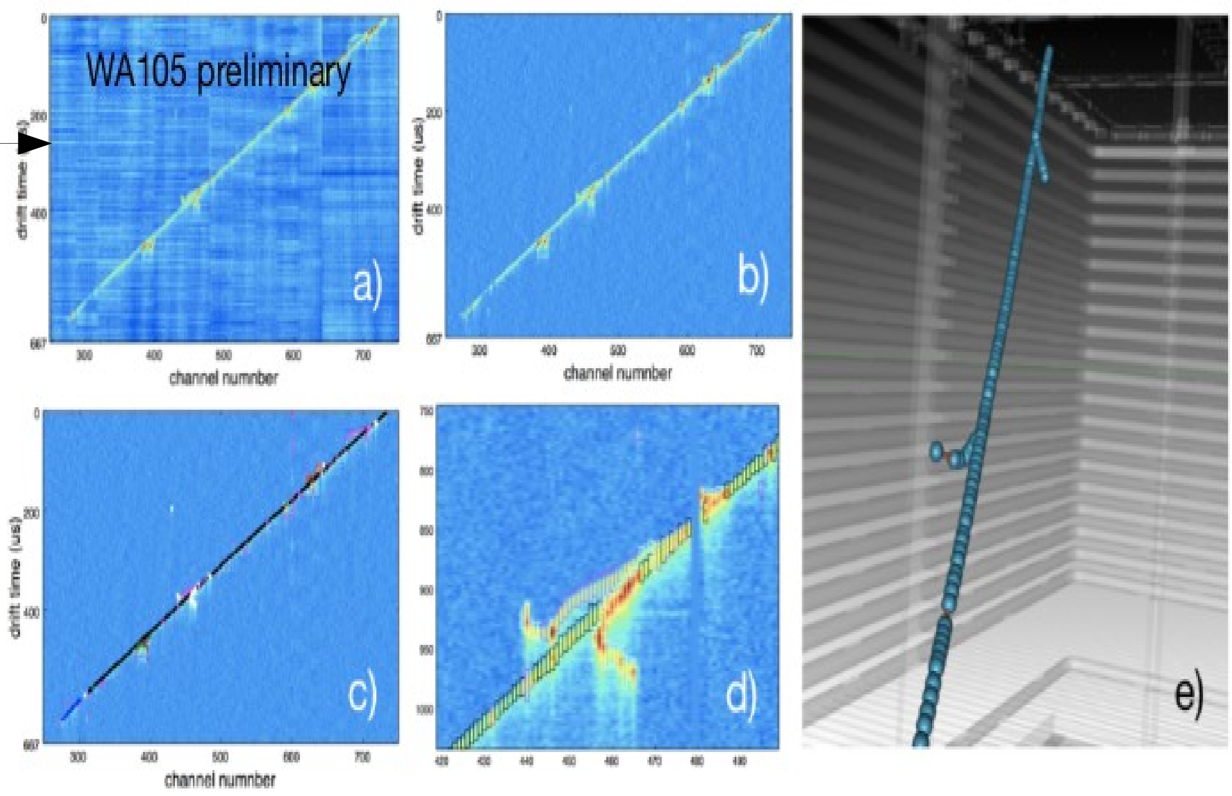


Through-going muon

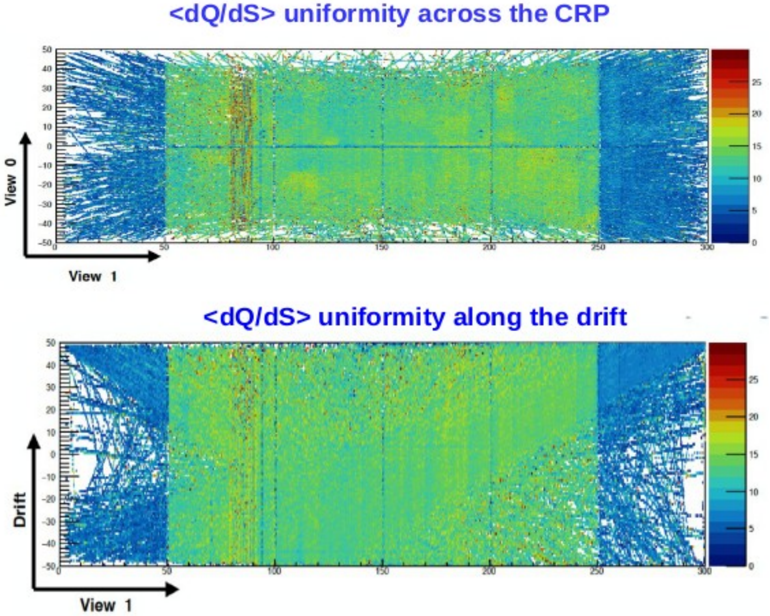
arXiv:1806.03317 [ins-det]
B. Aimard et al, 2018, JINST 13, P11003

Dual-Phase 4t demonstrator

Noise filtering
3D reconstruction
Track selection



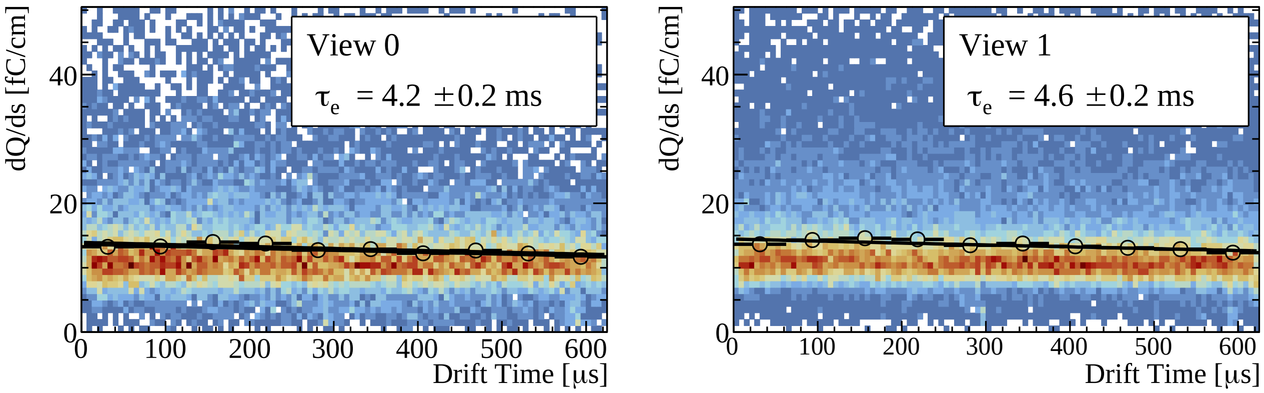
Dual-Phase 4t demonstrator



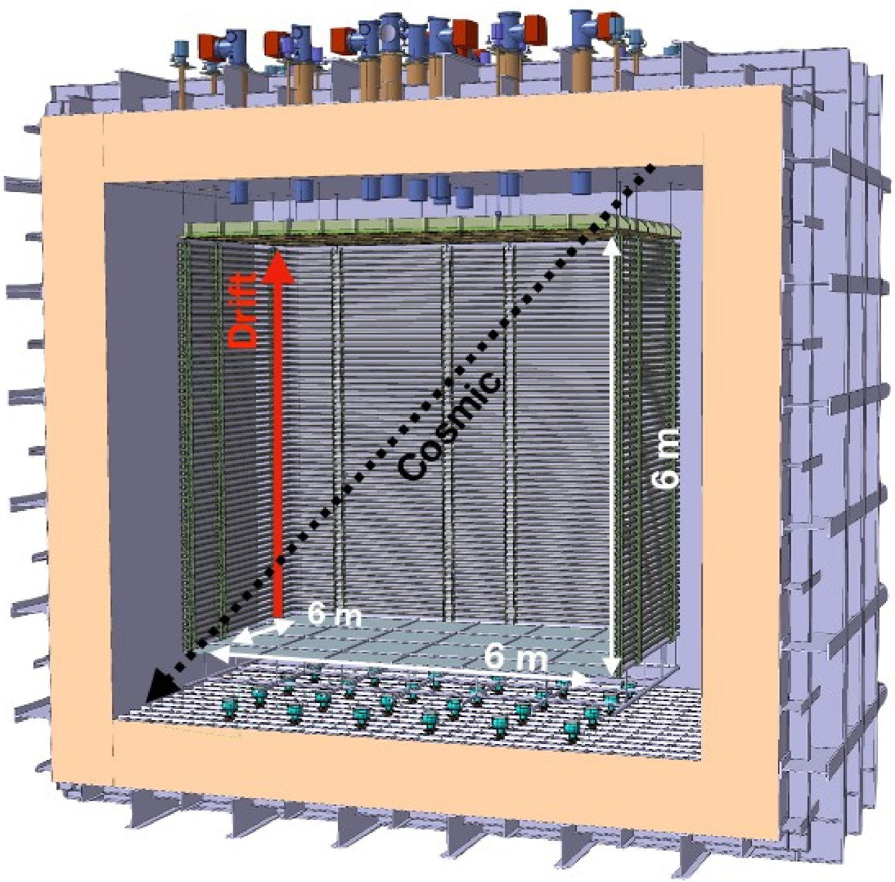
500k cosmic events in summer-fall 2017
example crossing muons

Using through-going muon tracks (top to bottom)
And 3D reconstruction
Calculate dQ/dS for each hit of track

Indicates electron lifetime



ProtoDUNE Dual-Phase



Fiducial mass is 300t

Half the drift length of DUNE FD
Drift field 0.5 kV/cm → -300 kV on cathode

Expected S/N > 20

36 photomultipliers

DUNE Interim Design Report
Dual Phase - arXiv:1807.10340

Drift Field

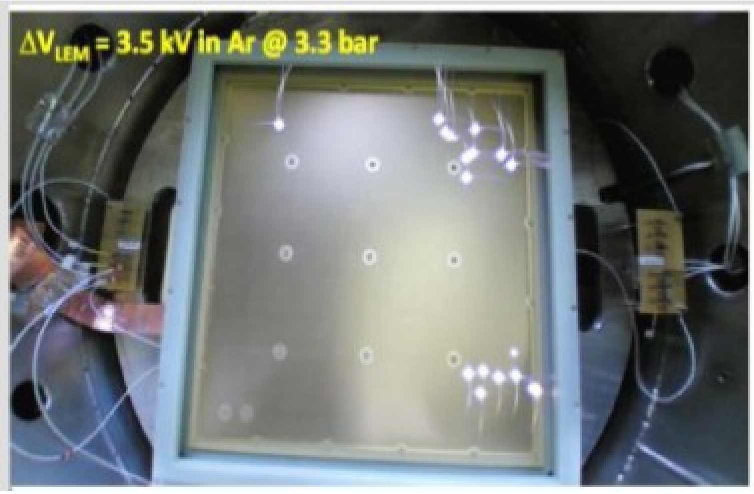
Drift field objective is 0.5 kV/cm
-300 kV on Dual-Phase cathode
Cathode design is modular (3m x 3m)
60% optical transparency
Maximum local field requirement
<30kV/cm

High Voltage feedthrough based on ICARUS design same from Single/Dual-phase

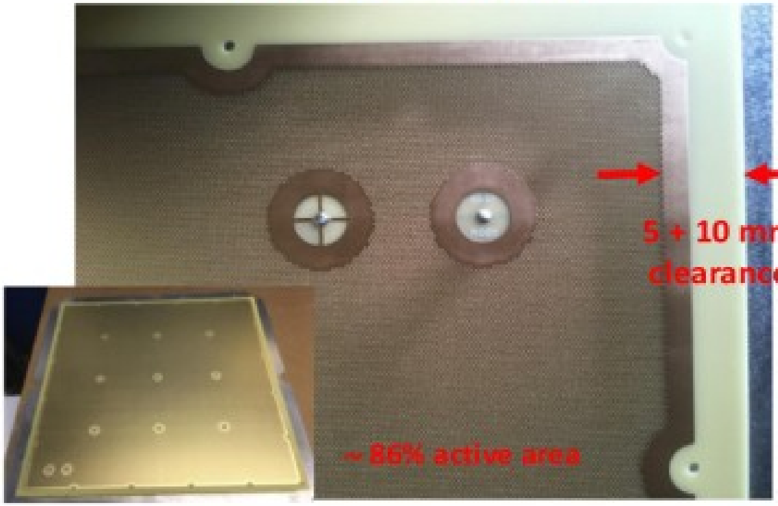
HV extender-degrader delivers HV to field rings and cathode

- April 2018 : field cage completed, stable operation at 150 kV in middle of cathode, ground on top and bottom
- Demonstrated OK for 0.5 kV/cm

Large Electron Multiplier



CFR-35 – NP02



LEMs are tested in gaseous argon
3 types have been tested (CFR-34, 35, 36)

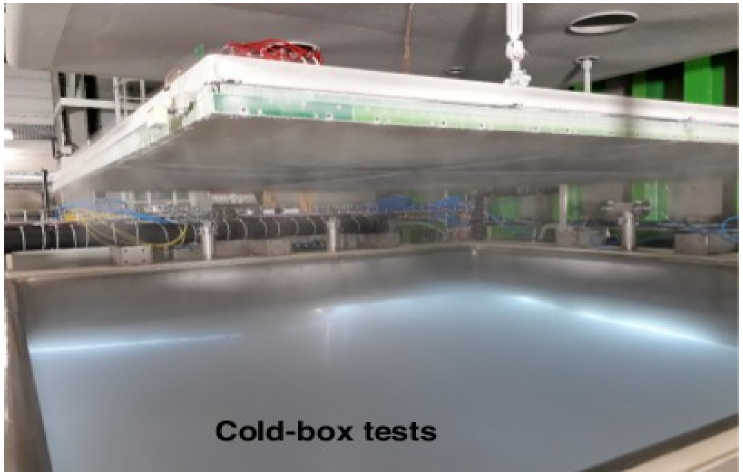
Arrived at a LEM design:
No trips > 64h
No sparks
Effective gain > 20

Further optimisation of active area

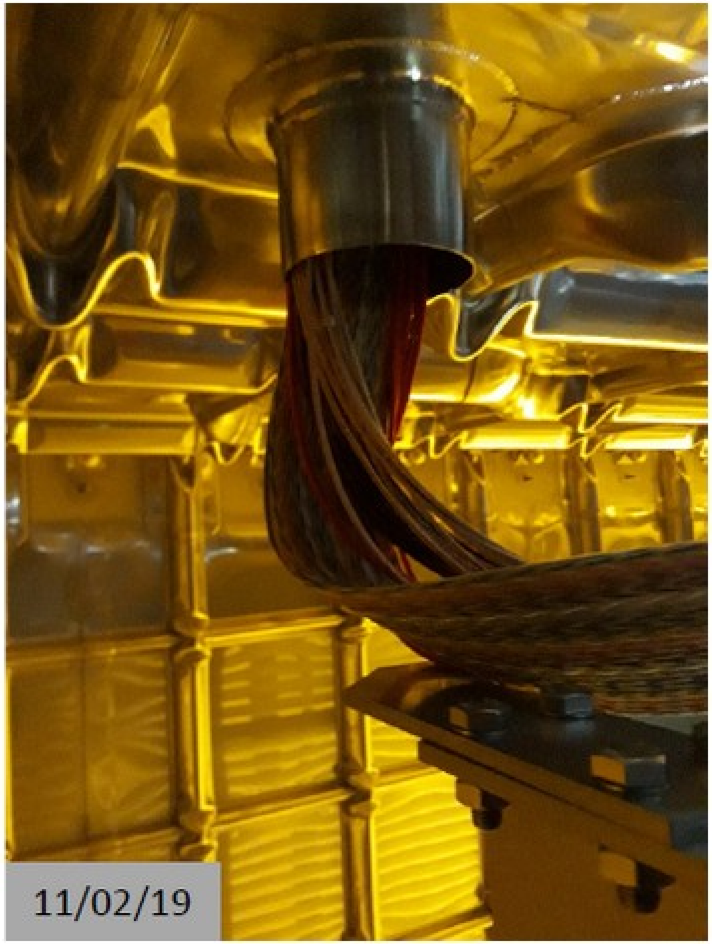
Charge Readout Planes

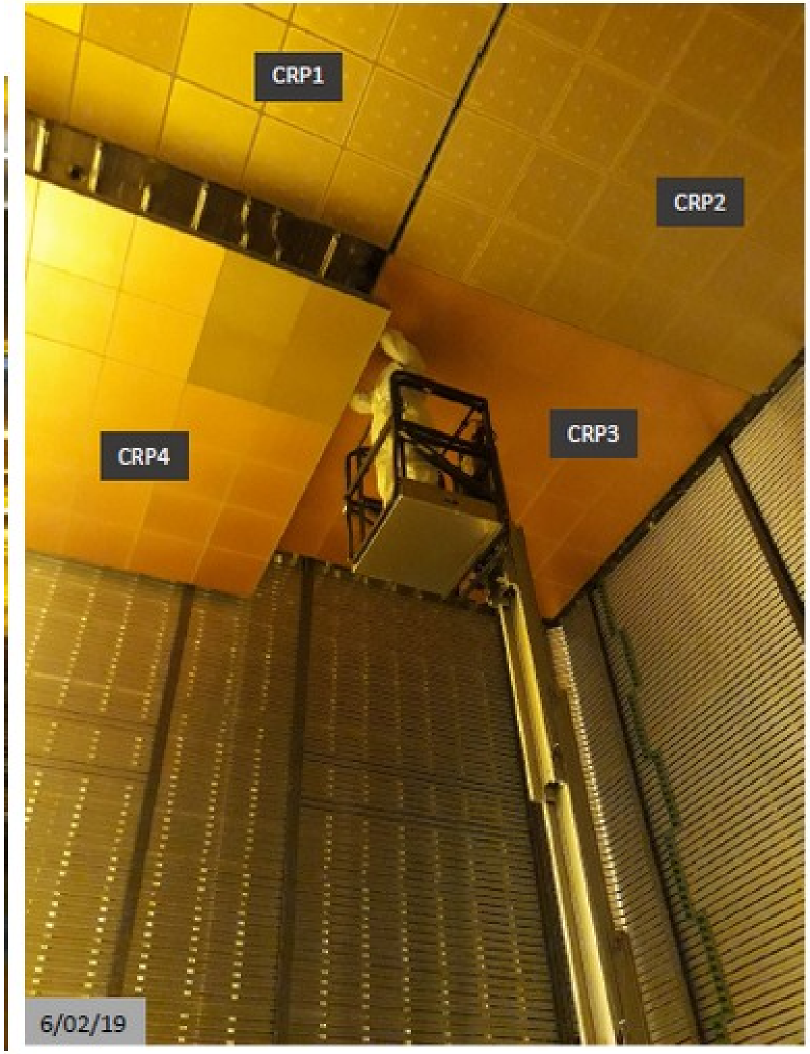
CRP assembly in clean room

- June 2018 : first Charge Readout Plane (CRP) assembly completed
- August 2018 : first CRP cold-box test completed



Cold-box tests





Assembly completed March 2019
Purging, cooling, filling completed August 2019

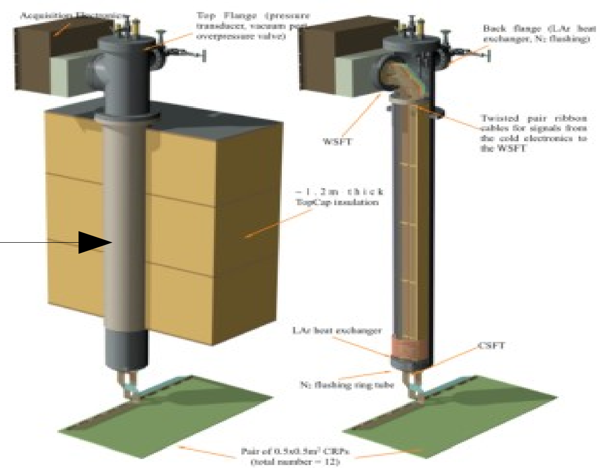
Accessible Cold Electronics

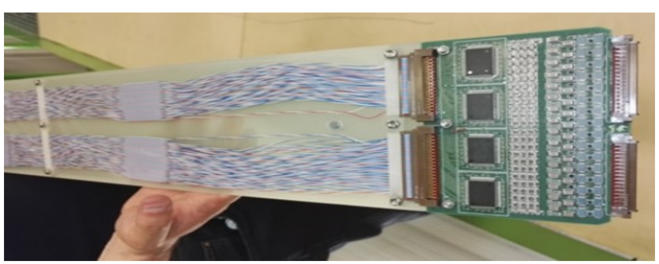
Specially developed signal chimneys

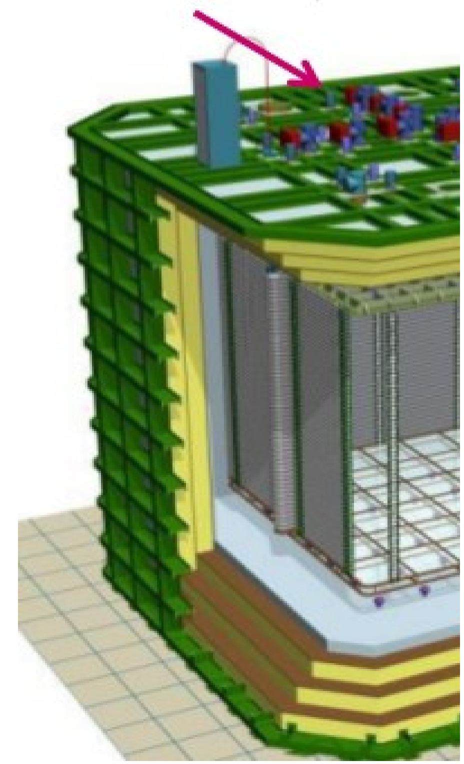
- 16-channel Cryogenic ASIC amplifiers close to the anodes but are also externally accessible!

On the tank deck (warm): digital electronics

- Based on uTCA standard
- 1 uTCA crate/ signal chimney
- AMC card – 64 channels, 12 bit ADC, 2.5 MHz
- 10 AMC cards (64 channels/card)
- Total of 12 uTCA crates (7,680 channels)





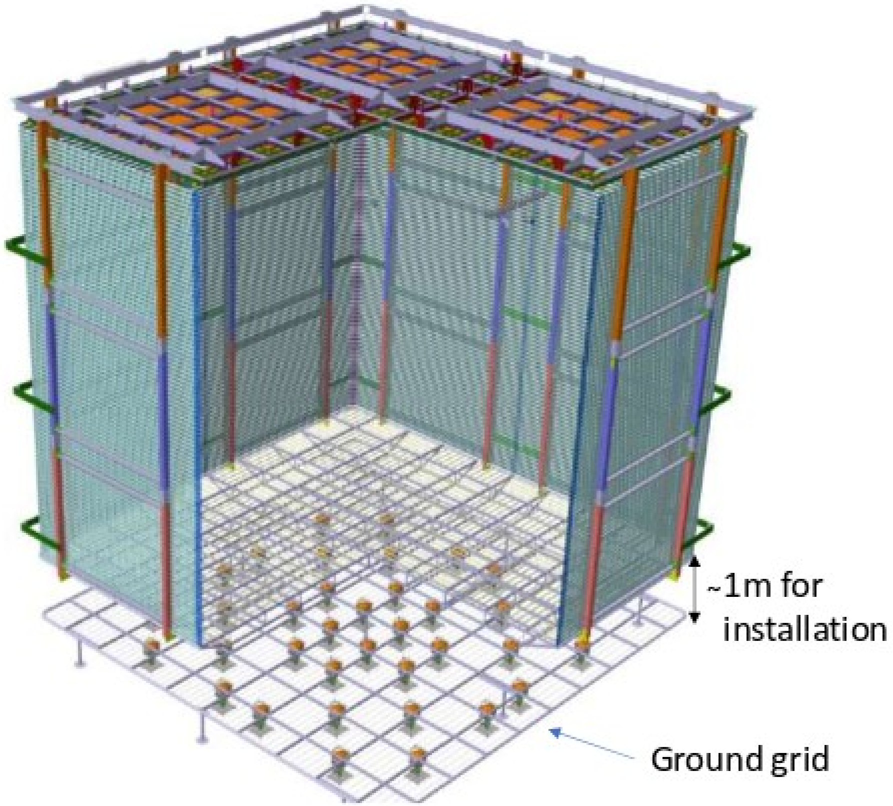


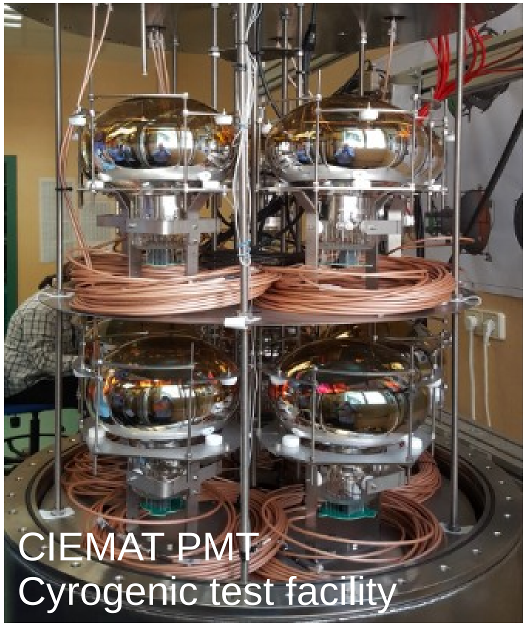
Successfully tested on the 4t demonstrator

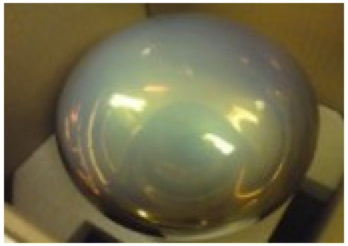
Light Read Out

Light signal gives the t0 of an event
→ determines the z co-ordinate

36 PMTs (Hamamatsu R5912-02 MOD 8 inch) coated with TPB – as used in 4t demonstrator

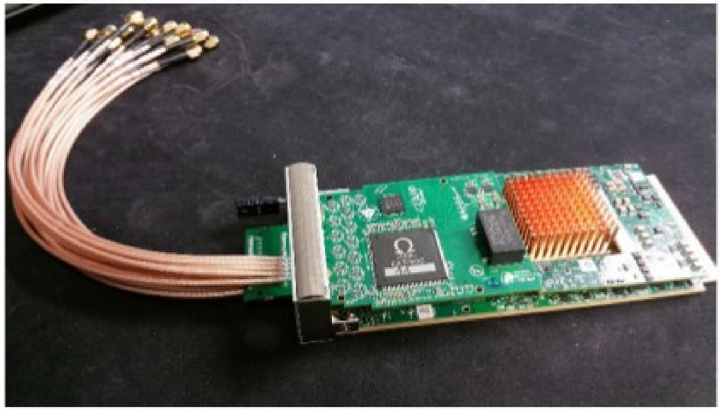






Light Read Out

1uTCA crate for Light Read-Out electronics
Designed to integrate into Global DAQ



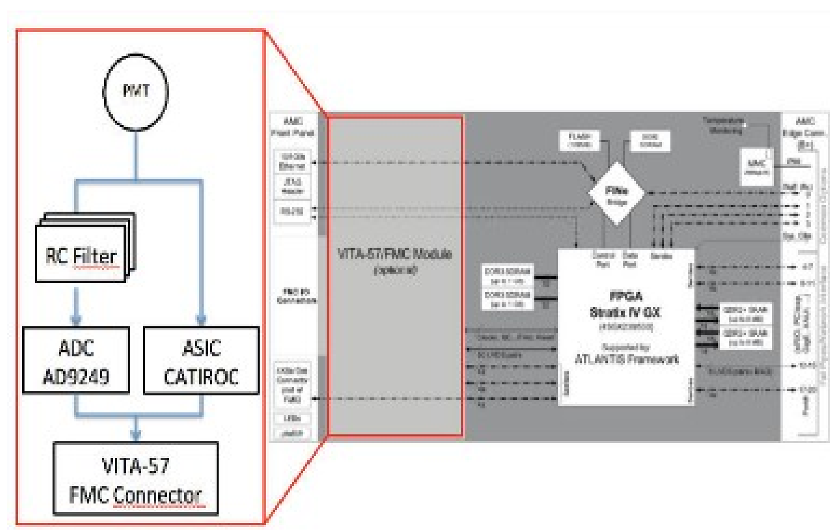
Under-development
16 channels
Anti-aliasing low pass filter

ADC: AD9249 65 MHz (max), 14 bits
provides waveform with a window of ± 4ms around the external trigger down-sampled to 400 ns

ASIC: CATIROC
Provides auto-triggered channel-wise Q, t

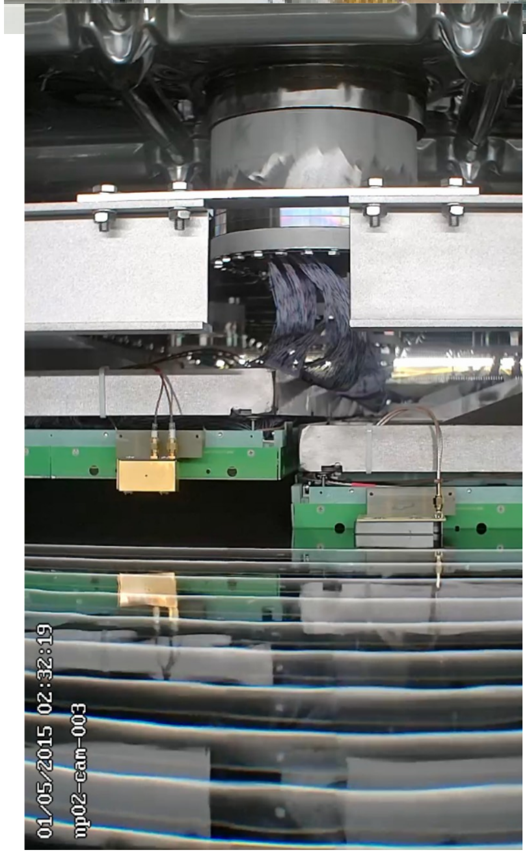
Readout time of Dual Phase is <=4ms
Light Read Out needs to timestamp cosmic ray muons occurring before and after trigger

ASIC – measurements at single ph.e. level (calibration, low energy signals)



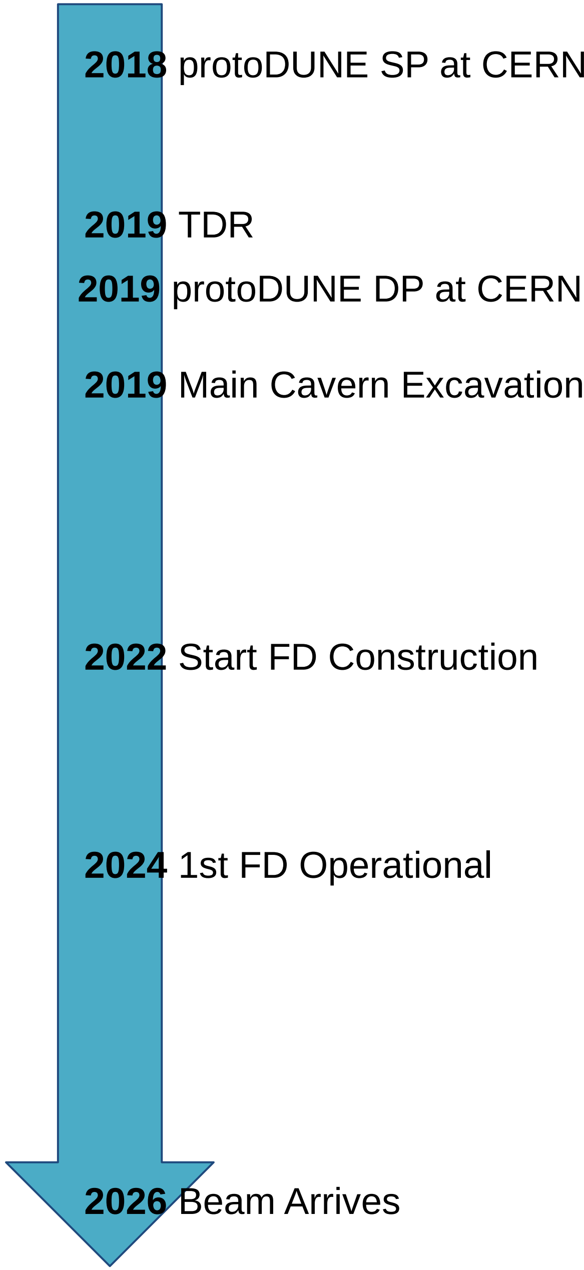
Dual Phase Status

- ProtoDUNE Dual Phase has been operated from September 2019
  - Experiencing some technical issues
- Runs of Cosmic Ray muon data (~7 kHz muon rate)
- With CR muons
  - We can explore 3D response of detector
  - Determine operational parameters such as gain, purity etc
  - Demonstrate track reconstruction
  - Search for Michel electrons (low energy signal)
  - And more..



Summary

- DUNE will measure neutrino and anti-neutrino oscillations over a 1300 km baseline with gigantic (4x10kt fiducial) LAr TPCs
- Large underground detectors will provide other interesting physics (Nucleon decay, neutron-antineutron oscillations, SN etc)
- Large-scale detector prototypes, ProtoDUNE, are being tested at CERN
- DUNE TDR is on the archive
  arXiv:2002.03010 arXiv:2002.03008
  arXiv:2002.02967 arXiv:2002.03005
  volume 5 (Dual Phase) to come



Backups

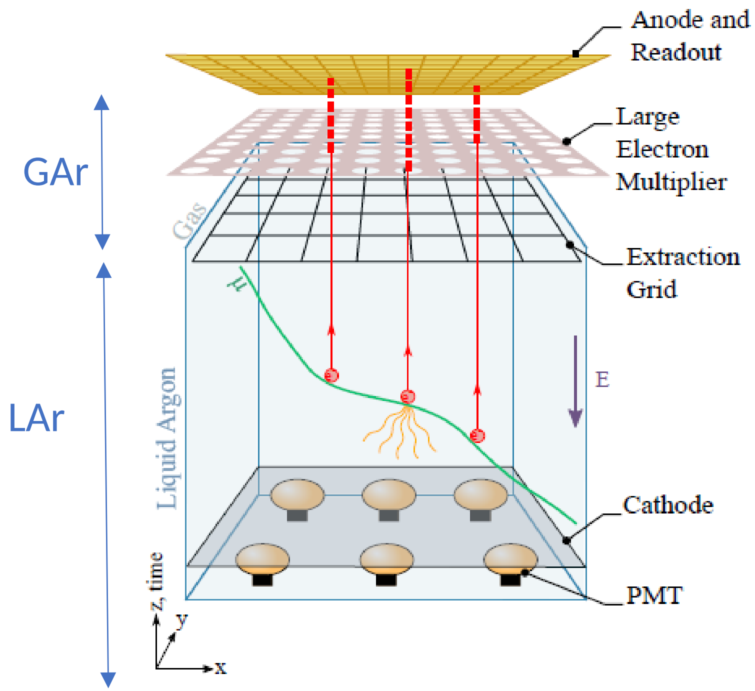
Dual Phase

In Liquid

Ionization: ~8k electrons/mm from a mip

Recombination: electrons captured by their parent ions

Lifetime: electrons captured by impurities during drift



In Gas

Extraction: probability of extraction > 90%

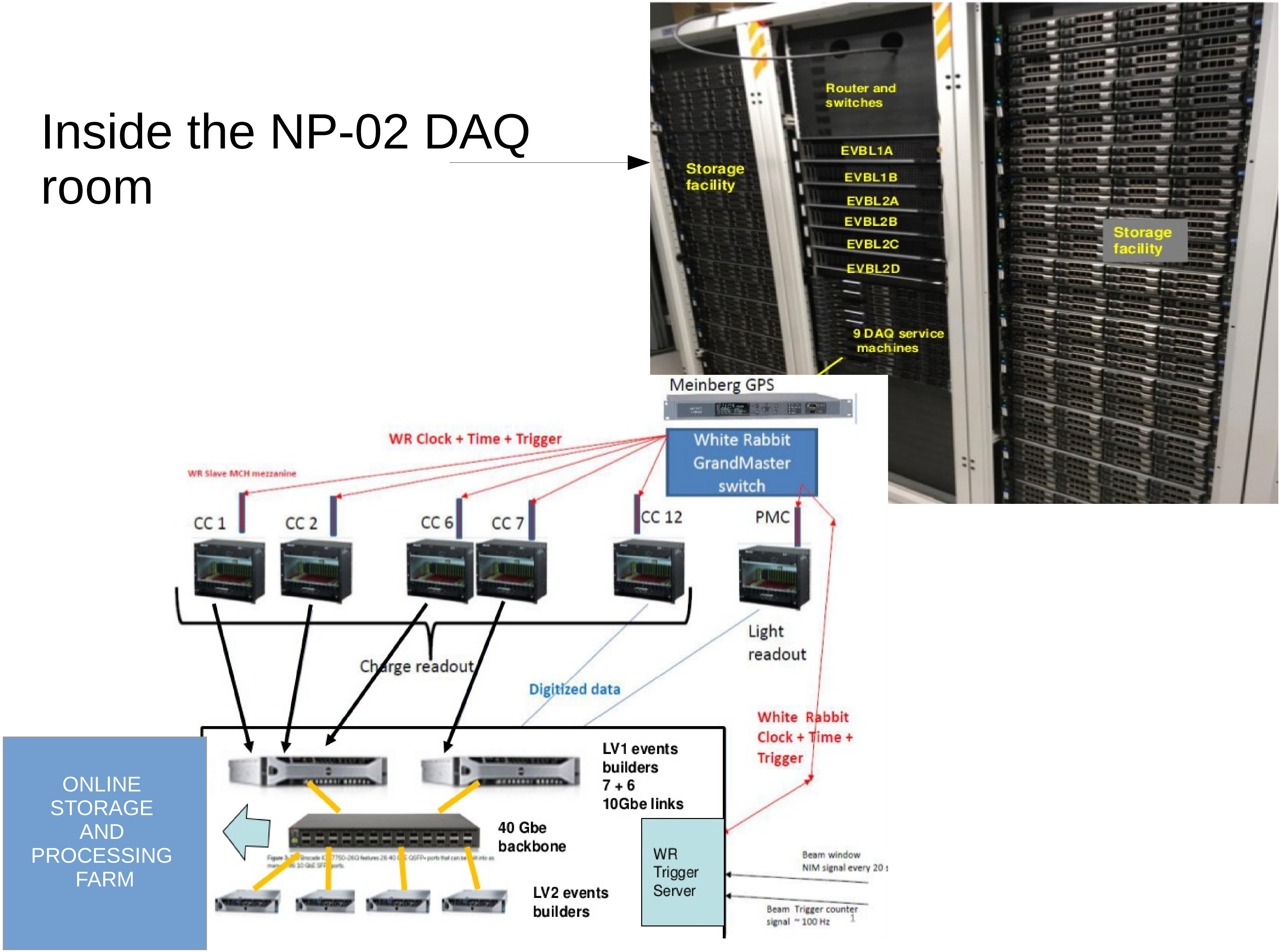
Amplification: Townsend avalanches of electrons

Nominal Eamp is 33 kV/cm and ENC is 1500 electrons

S/N > 10 for a mip on both views

Single Phase measures >4ms lifetime!

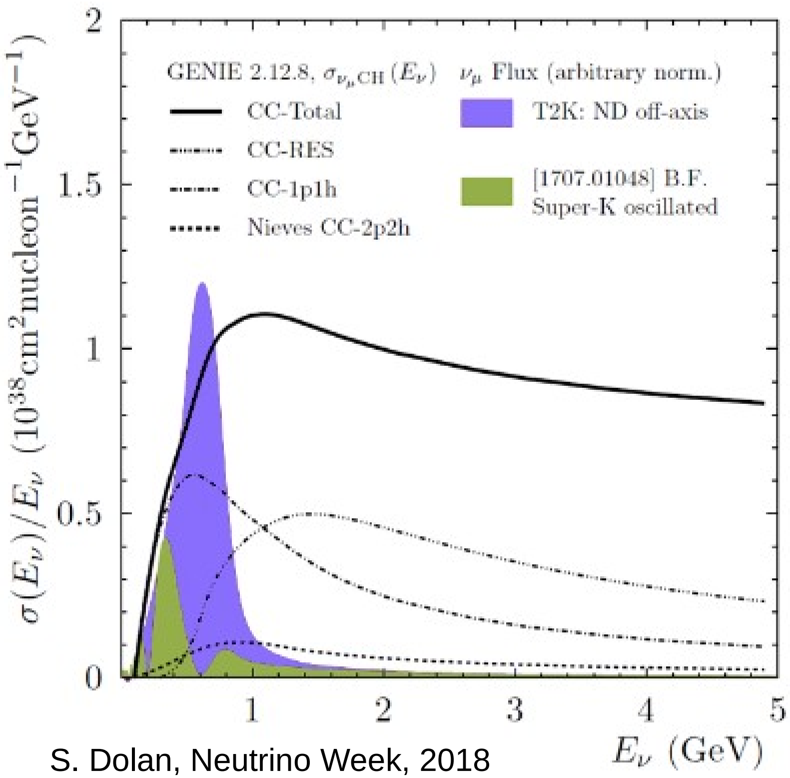
Inside the NP-02 DAQ room



Long Baseline Experiments – State of the Art

T2K

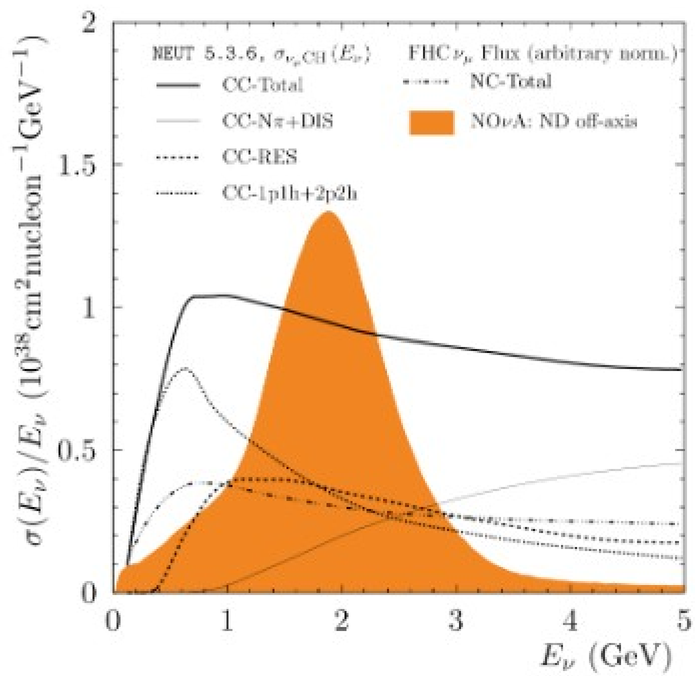
- Interactions are CCQE or CCRES



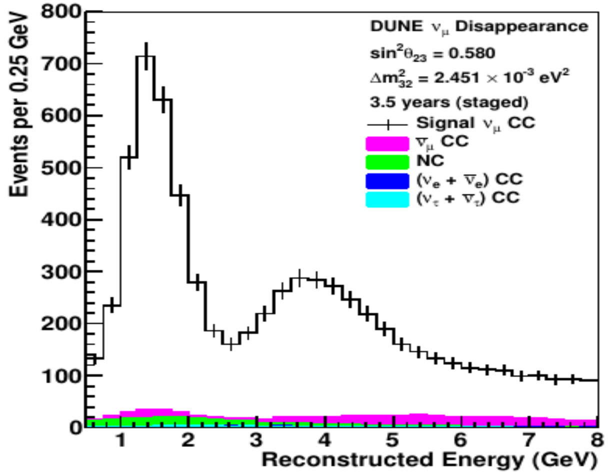
S. Dolan, Neutrino Week, 2018

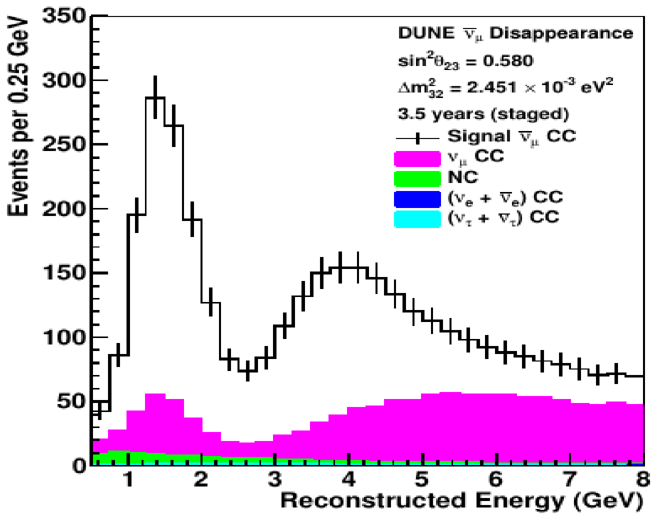
NOνA

- Higher energy neutrinos means most interactions are not CCQE
- Deep Inelastic Scattering occurs



ν_μ Appearance



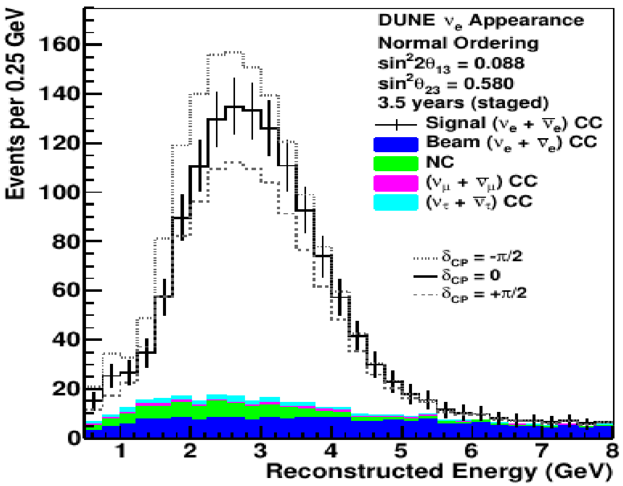


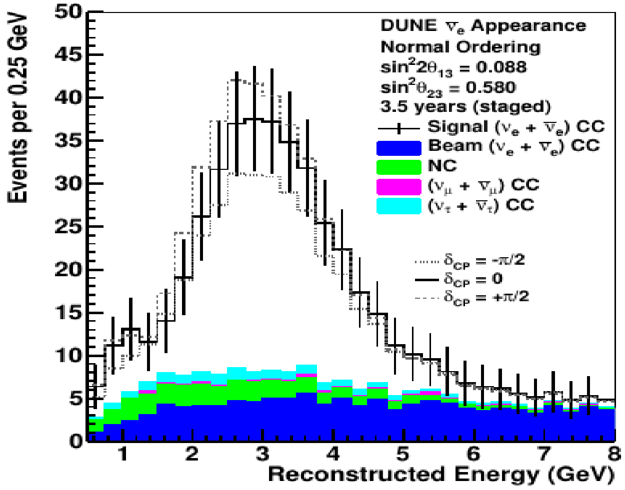
	Expected Events (3.5 years staged)
ν mode	
ν_μ Signal	6200
$\bar{\nu}_\mu$ CC background	389
NC background	200
$\nu_\tau + \bar{\nu}_\tau$ CC background	46
$\nu_e + \bar{\nu}_e$ CC background	8
$\bar{\nu}$ mode	
$\bar{\nu}_\mu$ Signal	2303
ν_μ CC background	1129
NC background	101
$\nu_\tau + \bar{\nu}_\tau$ CC background	27
$\nu_e + \bar{\nu}_e$ CC background	2

DUNE Technical Design Report (TDR) arXiv:2002.03005

νe Appearance

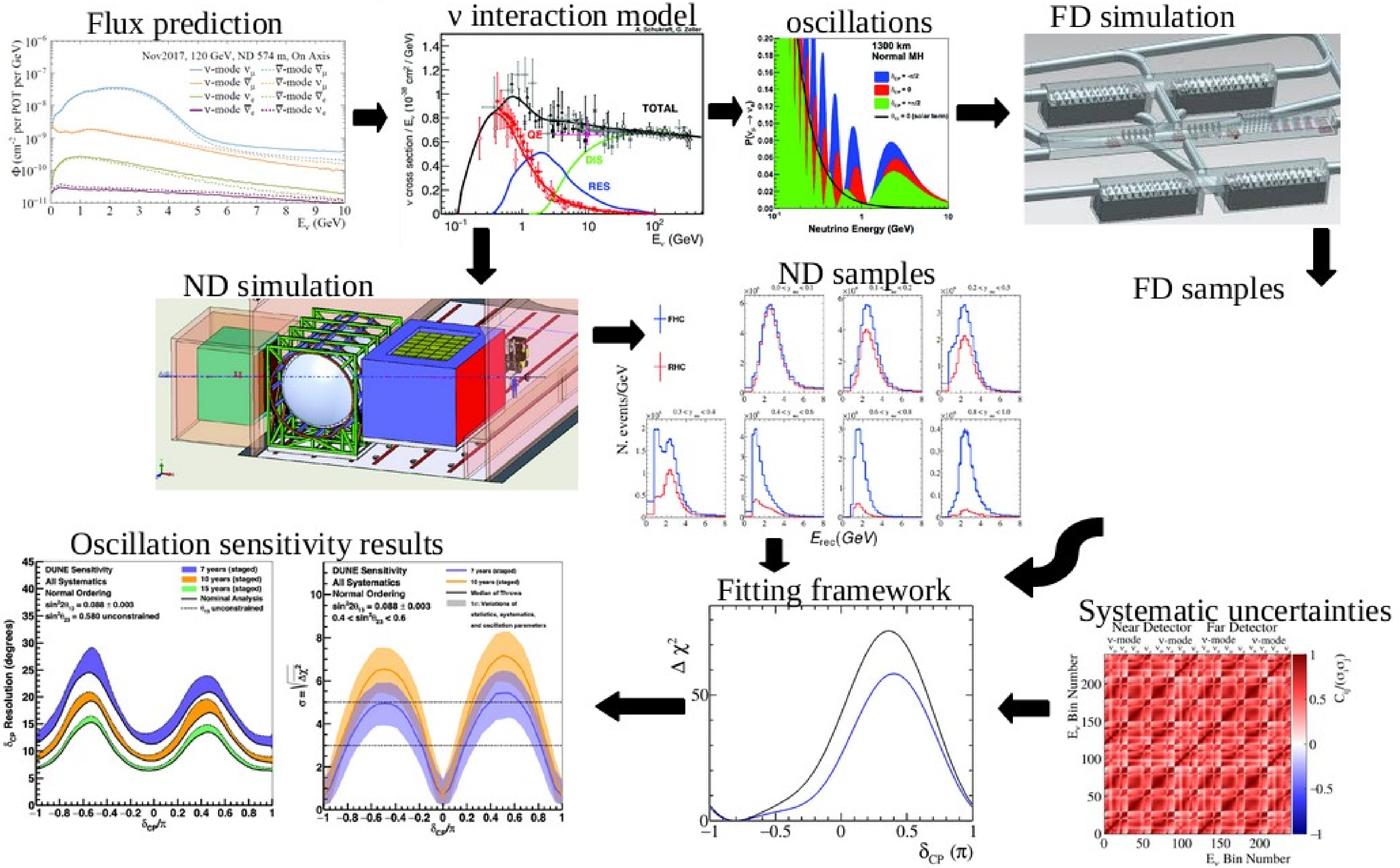
	Expected Events (3.5 years staged)
ν mode	
ν_e Signal NO (IO)	1092 (497)
$\bar{\nu}_e$ Signal NO (IO)	18 (31)
Total Signal NO (IO)	1110 (528)
Beam $\nu_e + \bar{\nu}_e$ CC background	190
NC background	81
$\nu_\tau + \bar{\nu}_\tau$ CC background	32
$\nu_\mu + \bar{\nu}_\mu$ CC background	14
Total background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



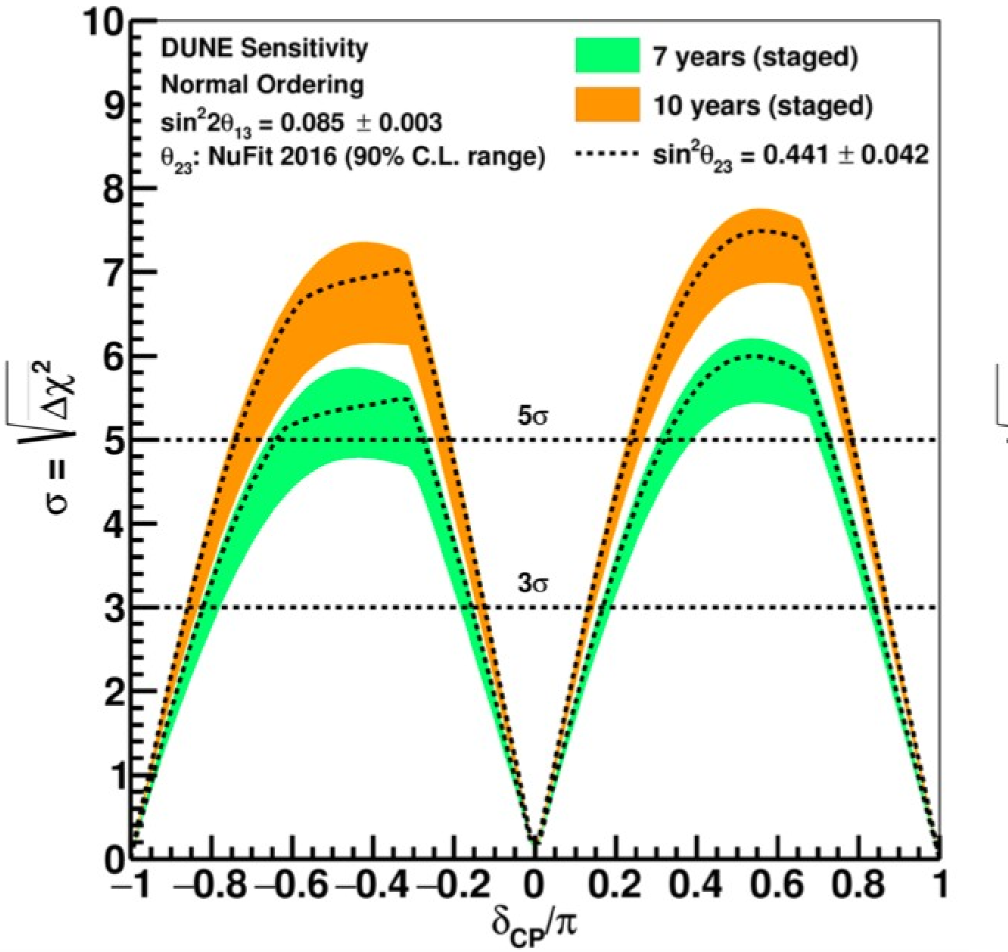


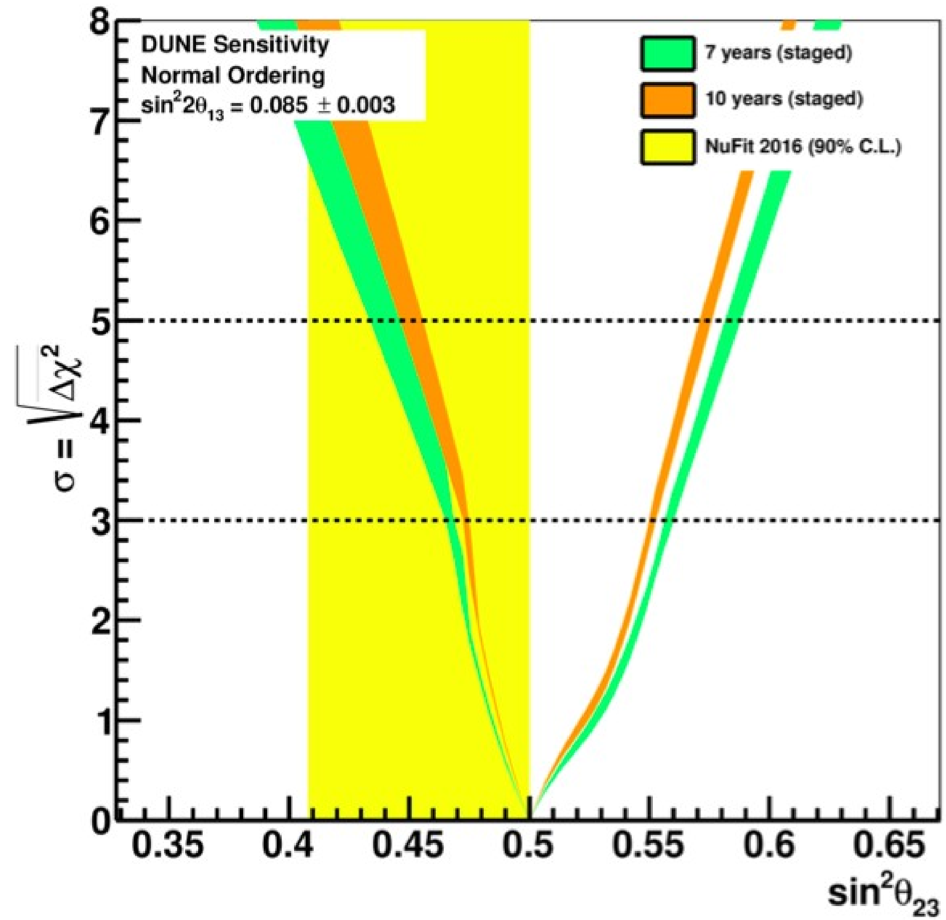
DUNE Technical Design Report (TDR) arXiv:2002.03005

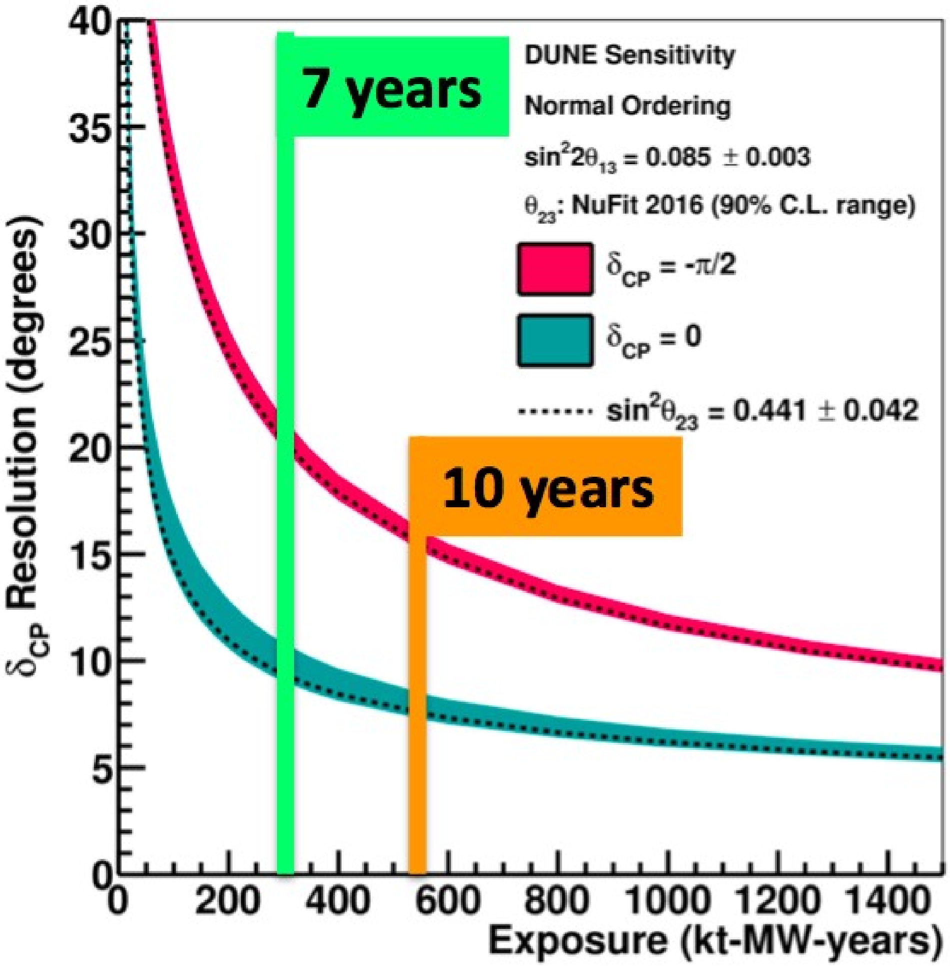
DUNE long-baseline oscillation analysis

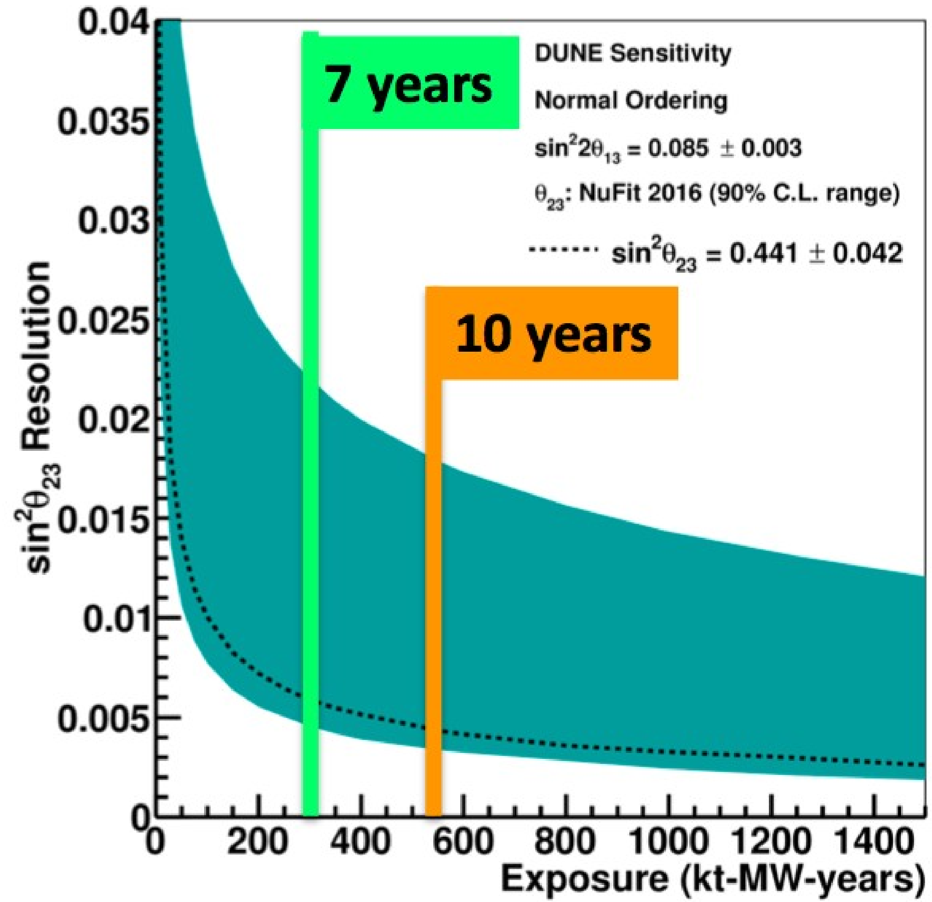


CP violation and theta_23






7 years
10 years
DUNE Sensitivity
Normal Ordering
$\sin^2 2\theta_{13} = 0.085 \pm 0.003$
θ_{23}: NuFit 2016 (90% C.L. range)
$\delta_{CP} = -\pi/2$
$\delta_{CP} = 0$
$\sin^2\theta_{23} = 0.441 \pm 0.042$
δ_{CP} Resolution (degrees)
Exposure (kt-MW-years)
0
5
10
15
20
25
30
35
40
200
400
600
800
1000
1200
1400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DUNE Sensitivity
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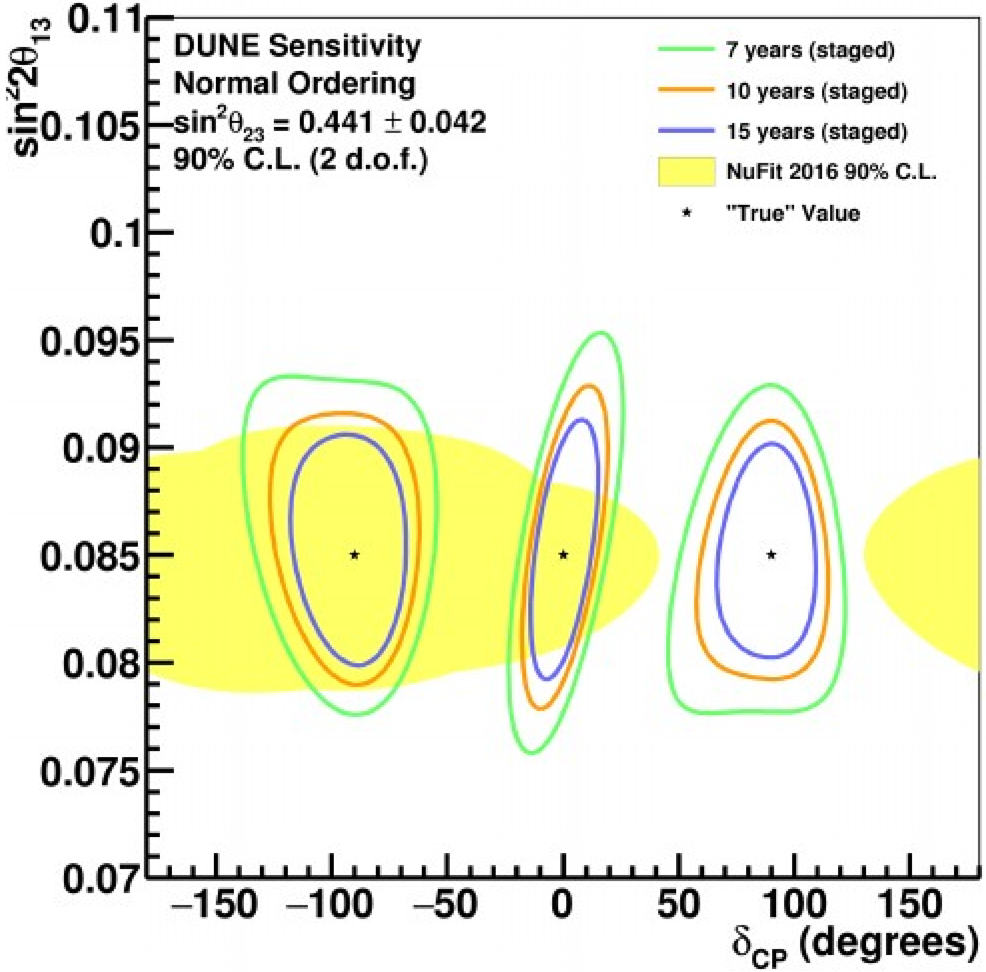
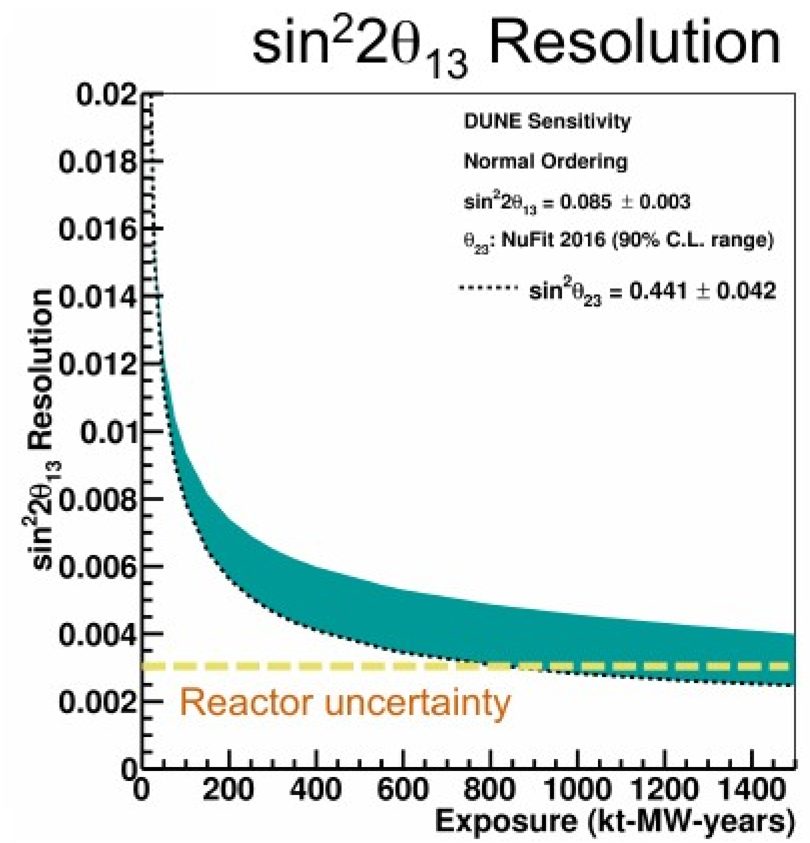
θ_{23}: NuFit 2016 (90% C.L. range)
$\sin^2\theta_{23} = 0.441 \pm 0.042$
$\sin^2\theta_{23}$ Resolution
Exposure (kt-MW-years)
0
0.005
0.01
0.015
0.02
0.025
0.03
0.035
0.04
200
400
600
800
1000
1200
1400





Simultaneous measurement of neutrino mixing angles and δ_{CP}

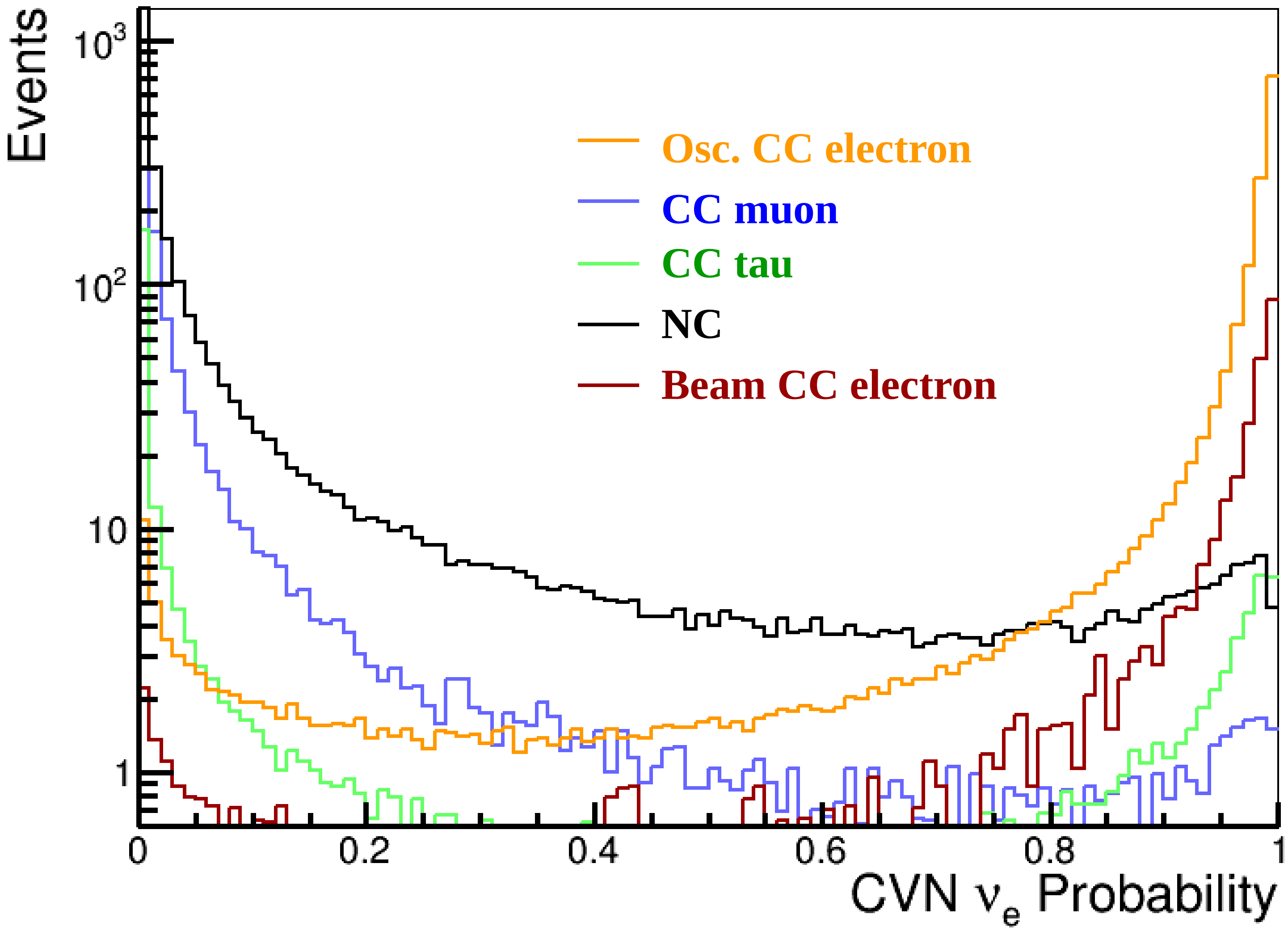
Systematic Uncertainties (CDR/IDR)

Source of Uncertainty	MINOS ν_e	T2K ν_e	DUNE ν_e
Beam Flux after N/F extrapolation	0.3%	3.2%	2%
Interaction Model	2.7%	5.3%	$\sim 2\%$
Energy scale (ν_μ)	3.5%	included above	(2%)
Energy scale (ν_e)	2.7%	2.5% includes all FD effects	2%
Fiducial volume	2.4%	1%	1%
Total	5.7%	6.8%	3.6 %
Used in DUNE Sensitivity Calculations			$5\% \oplus 2\%$

DUNE Conceptual Design Report (CDR)
arXiv:1512.06148

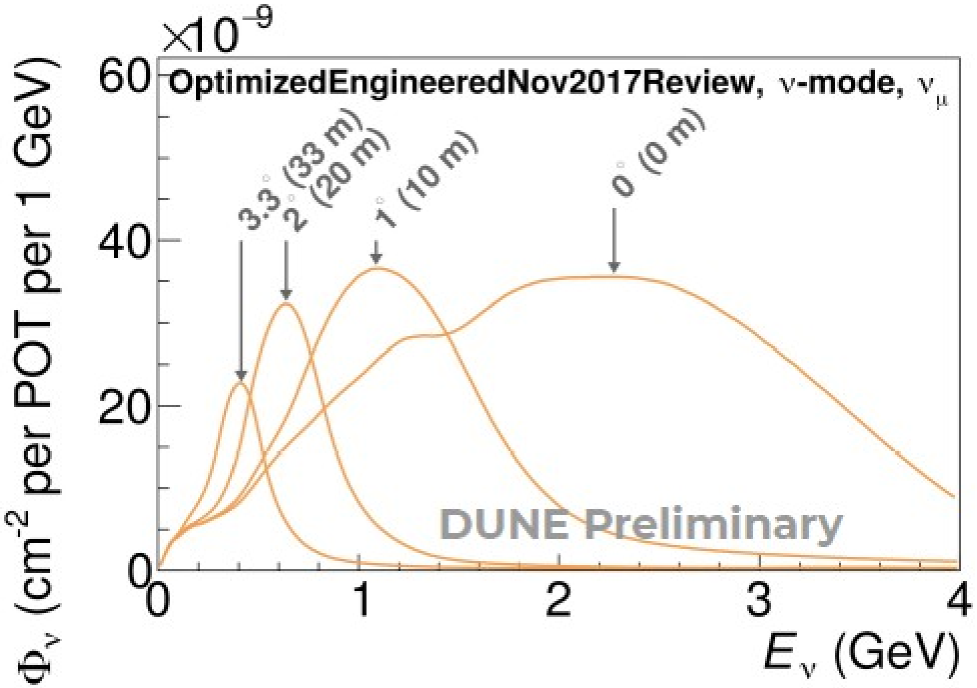
DUNE Conceptual Design Report (CDR) arXiv:1512.06148, the DUNE signal normalization uncertainty is taken to Be 5% ⊕ 2% in both neutrino and antineutrino mode, where 5% is the normalization uncertainty on the FD νμ sample and 2% is the effective uncorrelated uncertainty on the FD νe sample after fits to both near and far detector data and all external constraints

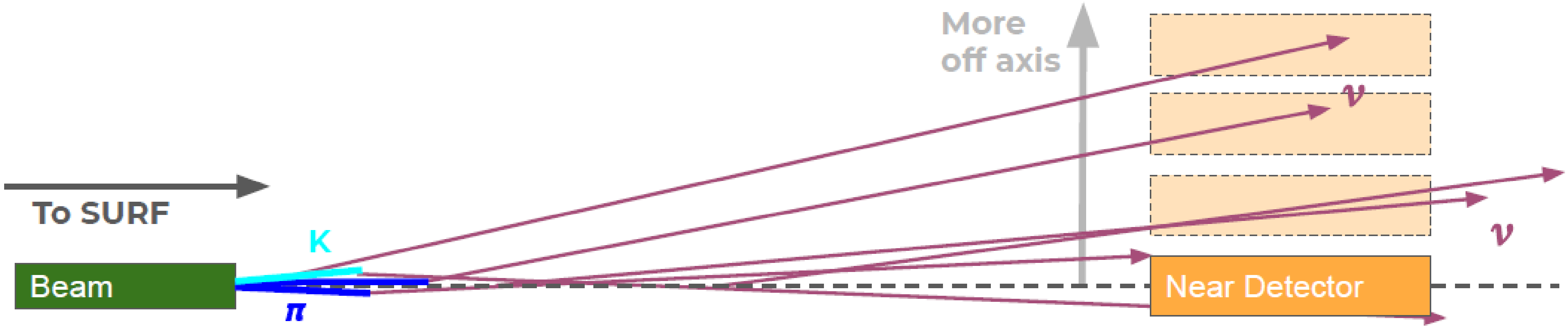
ν_e charged-current selection



- Selects both oscillated and intrinsic ν_e
- Backgrounds include $\pi^0 \rightarrow \gamma\gamma$, $\tau \rightarrow e$

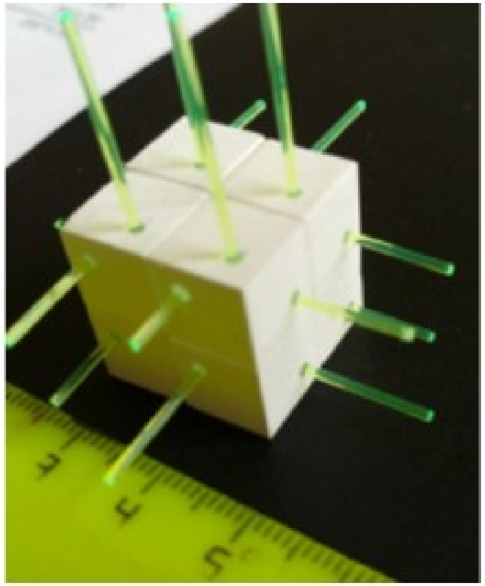
DUNE-PRISM: off-axis ND



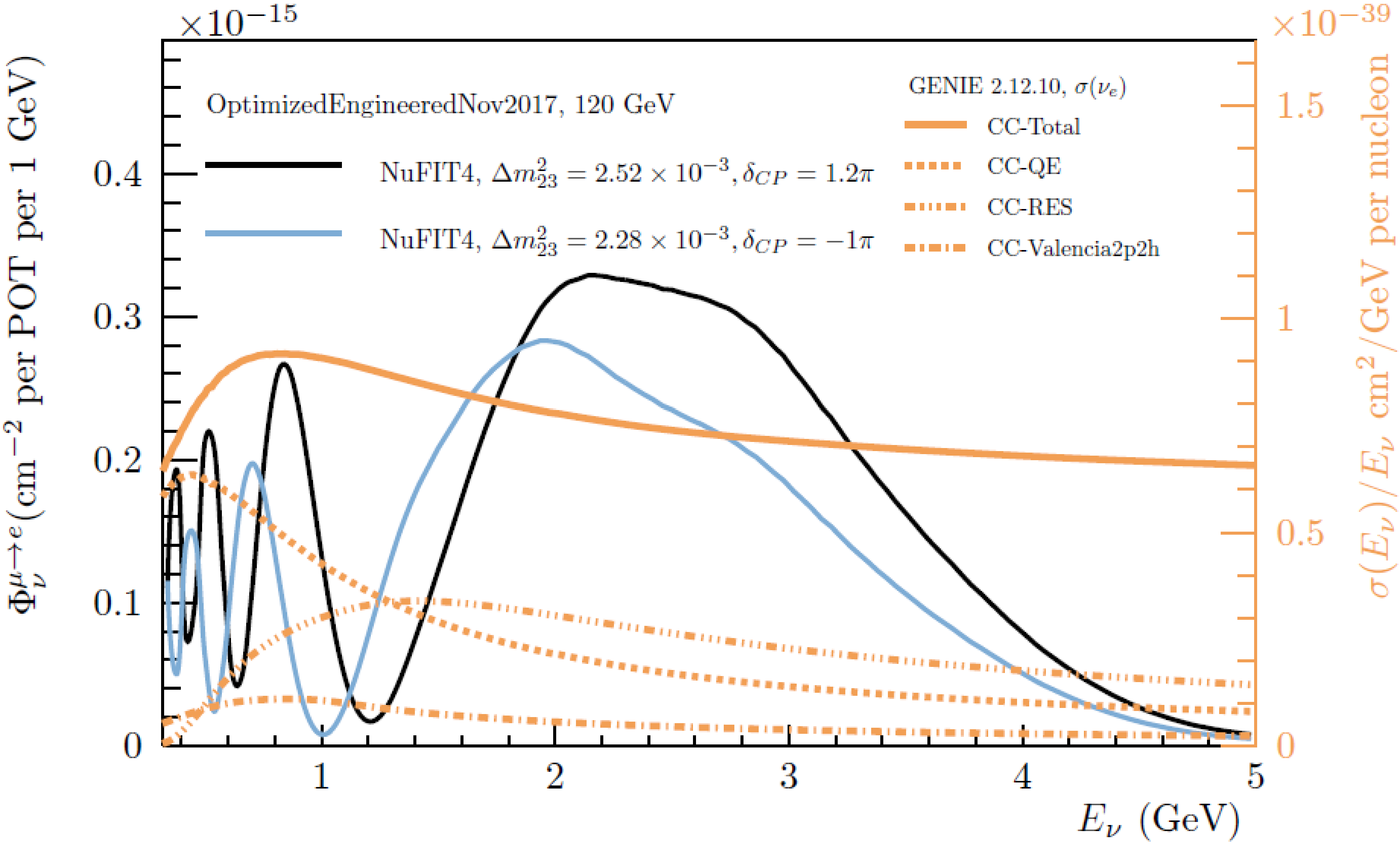


3D scintillator tracker (3DST)

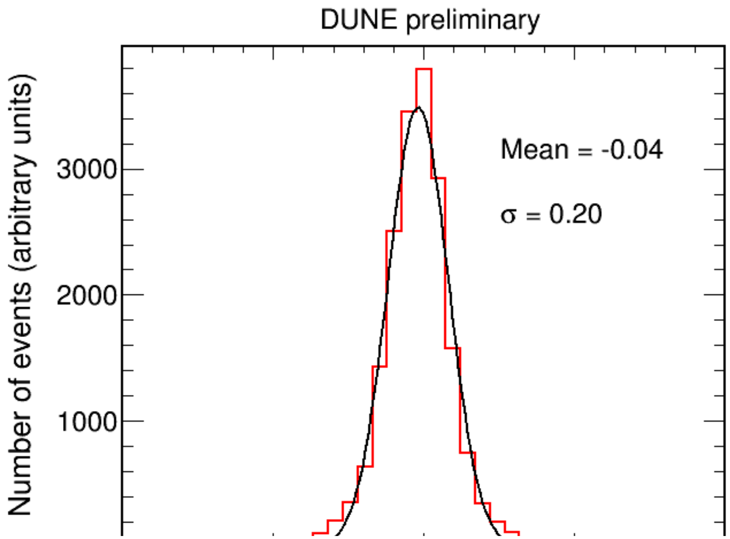
- 1 cm^3 scintillator cubes in a large array, read out with orthogonal optical fibers in three dimensions
- Same concept being pursued by T2K ND280 upgrade, called "Super-FGD"
- Excellent 4π acceptance – no hole at 90°
- Very fast timing: capable of tagging neutrons from recoils, and measuring energy from time-of-flight
- Could be placed in front of (or inside?) gas TPC, or operated in its own magnet with muon spectrometer

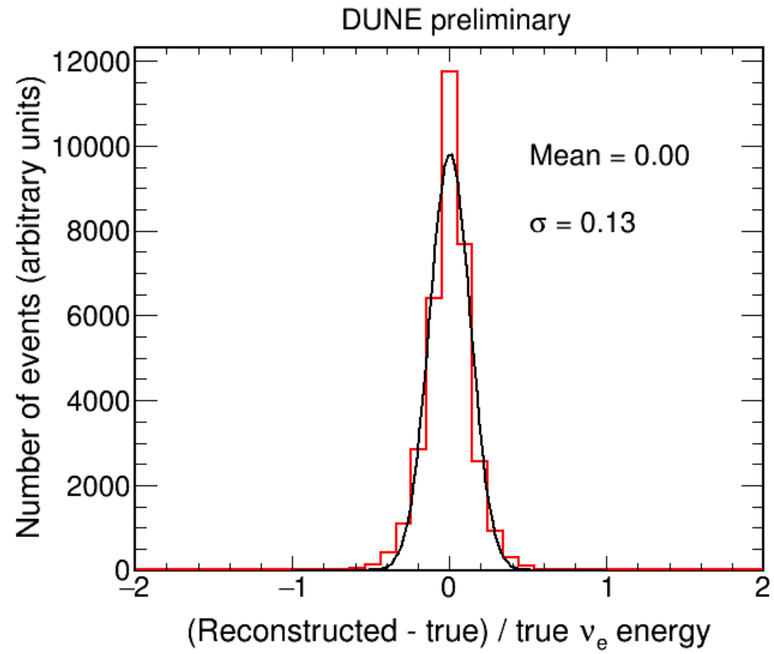


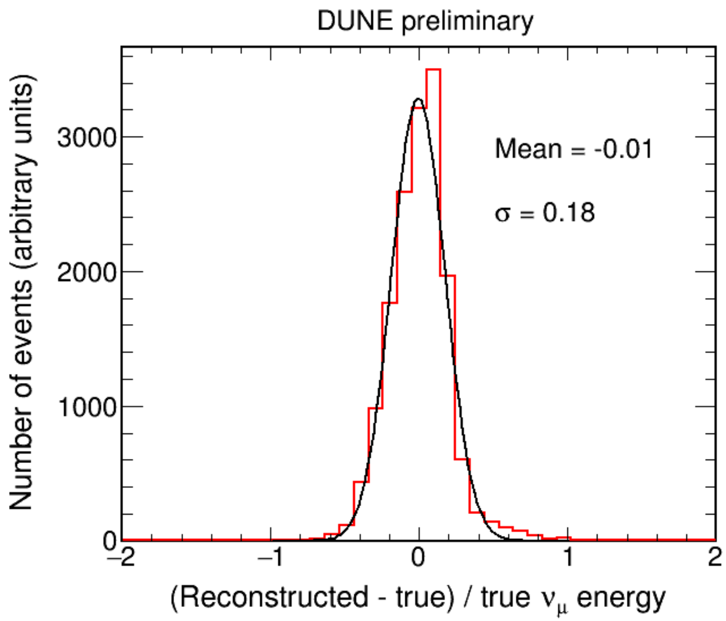
Far detector spectra, with cross section predictions vs. energy



Neutrino energy resolution



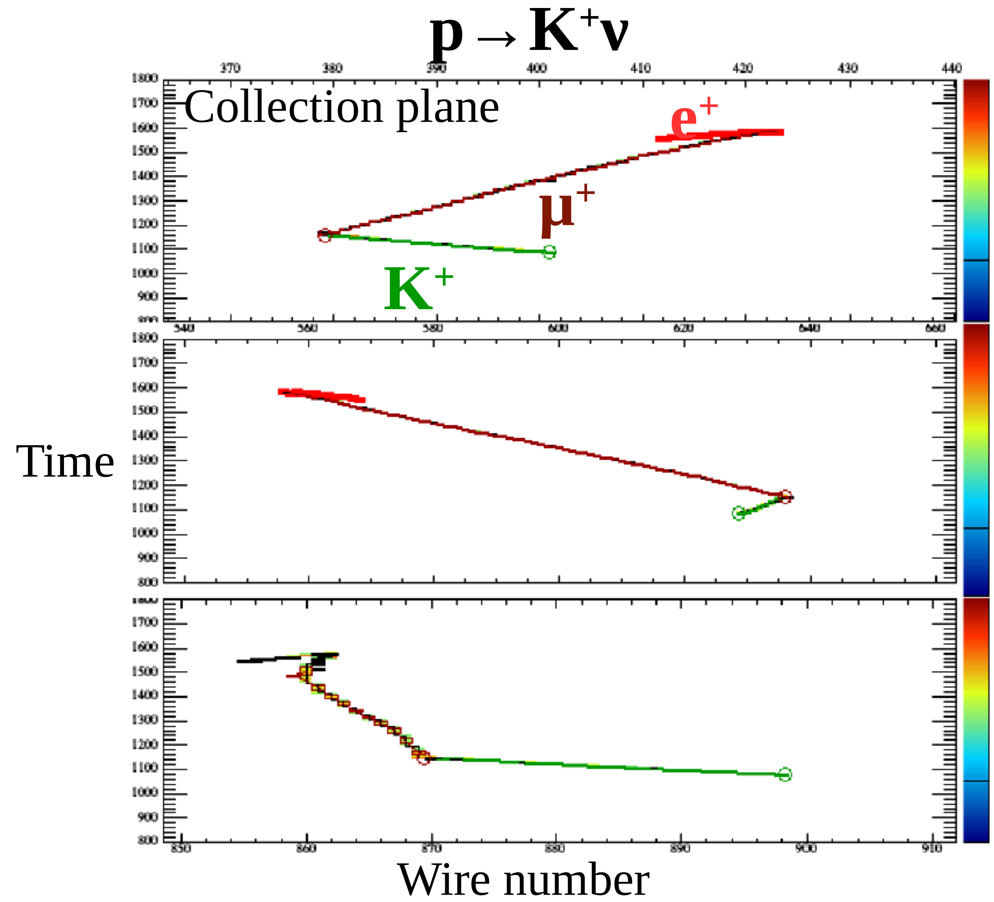




- Muons ~ 18% for contained tracks, 20% for exiting
- Electrons ~ 13%

Nucleon decay

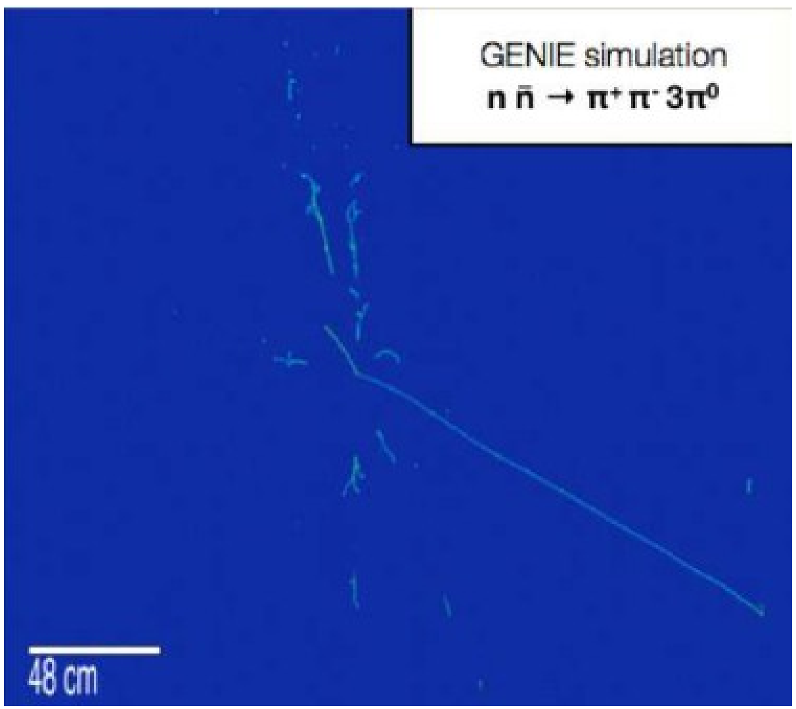
- DUNE sensitive to:
  - $p \rightarrow K^{+} \nu$
- and other channels:
  - $n \rightarrow K^{+} e^{-}$
  - $p \rightarrow l^{+} K^{0}$
  - $p \rightarrow \pi^{0} e^{+}$

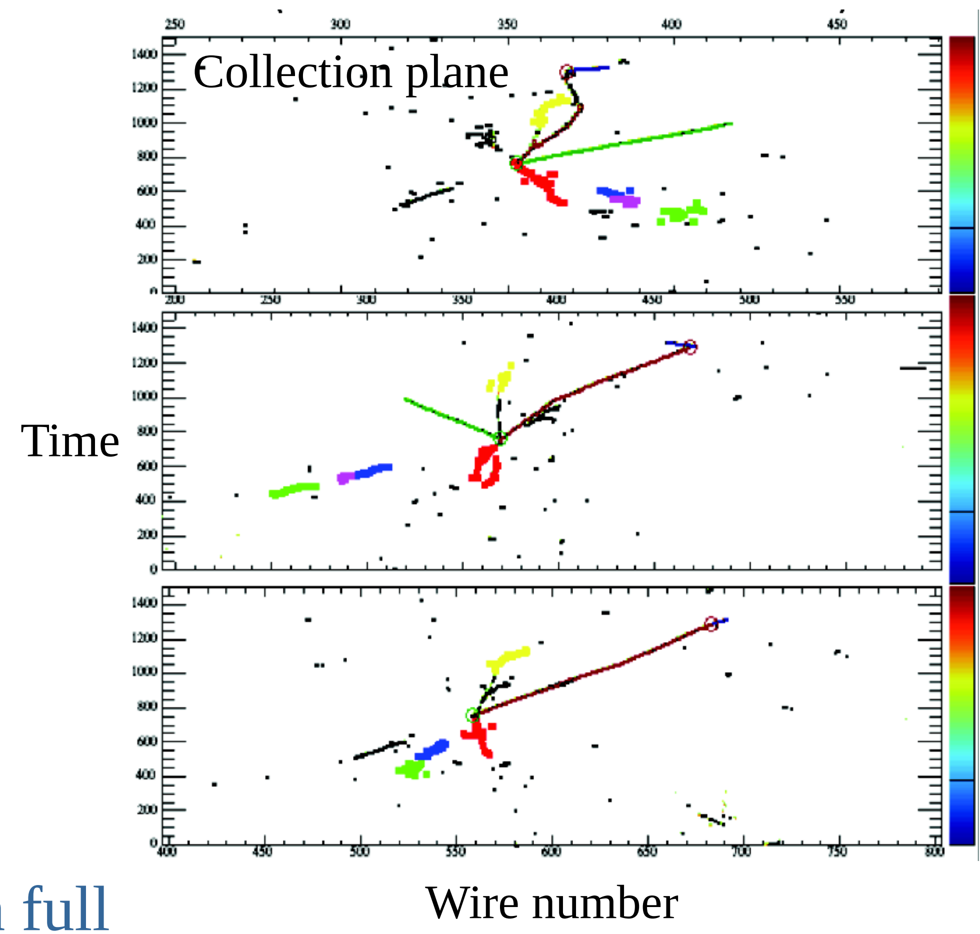


upcoming TDR contains analyses with full simulation & reconstruction

neutron-antineutron oscillations

Baryon number violating BSM process
Signature is a 'star' of charged and neutral pions





upcoming TDR contains analyses with full simulation & reconstruction

and other BSM physics

New particles:

light dark matter, boosted dark matter, heavy neutral leptons

Deviations from PNMS ν mixing paradigm:

non-standard ν interactions, non-unitarity, CPT or Lorentz violation, large extra dimensions, ν-trident production

Sterile neutrino searches
(ν_e appearance at ND)