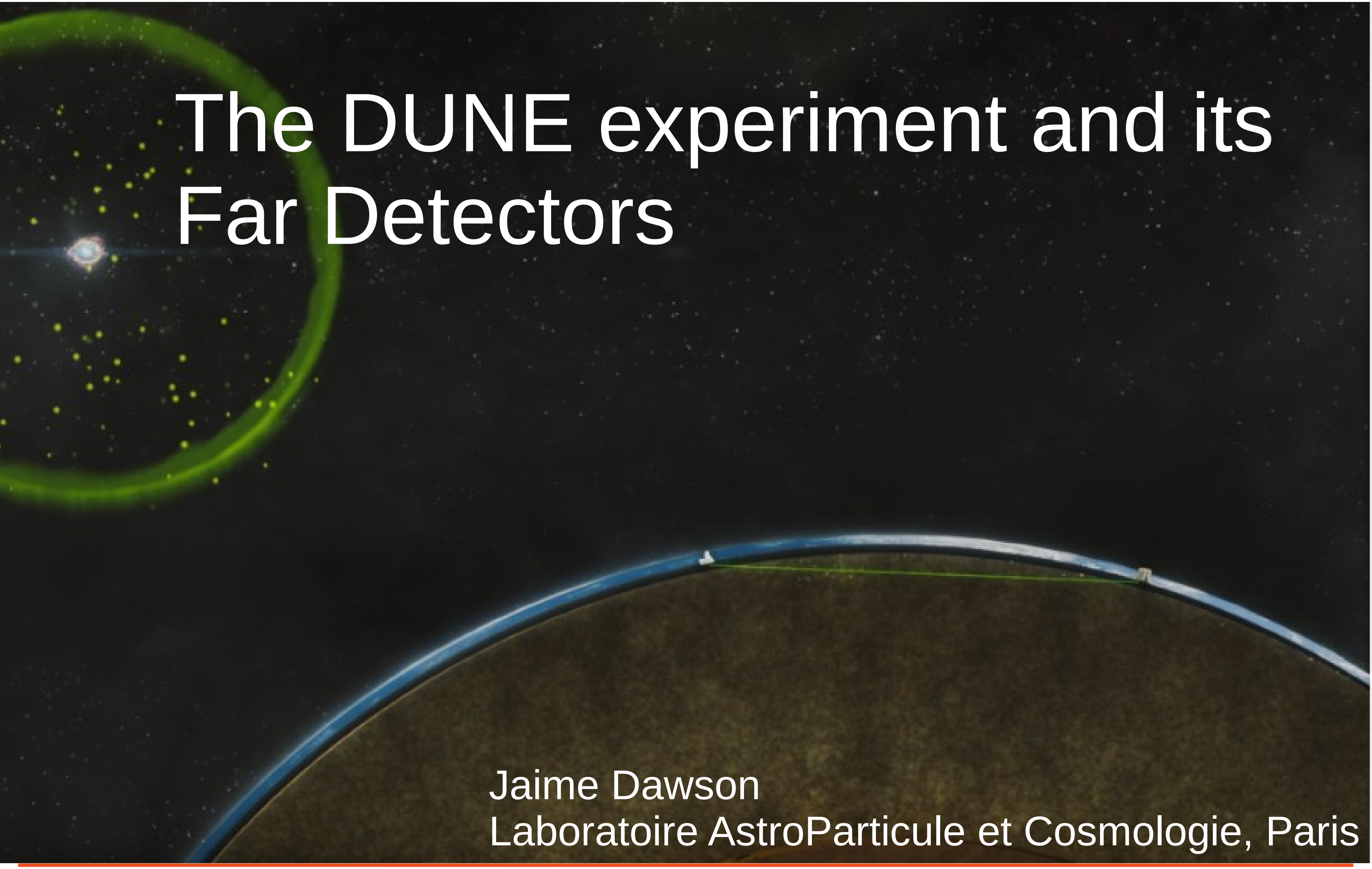
The DUNE experiment and its Far Detectors



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- Neutrino Oscillation
  - A brief Reminder
- Long Baseline Oscillation Experiments
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- DUNE Far Detector – Vertical Drift
  - Photon Detector System

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

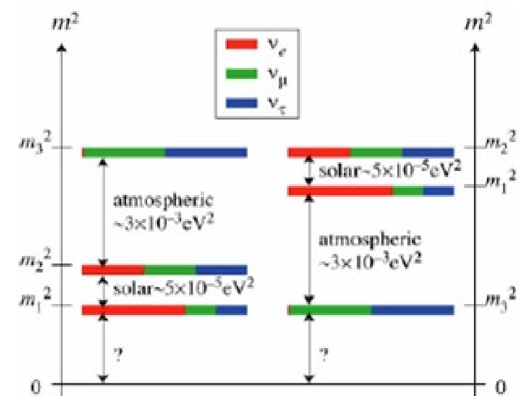
- 3 mixing angles
- 1 CP phase

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

solar atmospheric

θ_{12}~33° θ_{13}~9° θ_{23}~45°

- 2 mass splittings Δm^2_{ij}
- We don't know: octant θ_{23}, δ_{cp} and sign of Δm^2_{31}



Normal $\Delta m^2_{31}>0$ Inverted $\Delta m^2_{31}>0$

Global Fits

Solar

Reactor

Atmospheric

Accelerator

IC19 without SK atmospheric data

	Normal Ordering ($\Delta\chi^2 = 0.6$)		Inverted Ordering (best fit)	
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
$\sin^2\theta_{12}$	$0.307^{+0.012}_{-0.011}$	$0.275 \to 0.345$	$0.308^{+0.012}_{-0.011}$	$0.275 \to 0.345$
$\theta_{12}/^\circ$	$33.68^{+0.73}_{-0.70}$	$31.63 \to 35.95$	$33.68^{+0.73}_{-0.70}$	$31.63 \to 35.95$
$\sin^2\theta_{23}$	$0.561^{+0.012}_{-0.015}$	$0.430 \to 0.596$	$0.562^{+0.012}_{-0.015}$	$0.437 \to 0.597$
$\theta_{23}/^\circ$	$48.5^{+0.7}_{-0.9}$	$41.0 \to 50.5$	$48.6^{+0.7}_{-0.9}$	$41.4 \to 50.6$
$\sin^2\theta_{13}$	$0.02195^{+0.00054}_{-0.00058}$	$0.02023 \to 0.02376$	$0.02224^{+0.00056}_{-0.00057}$	$0.02053 \to 0.02397$
$\theta_{13}/^\circ$	$8.52^{+0.11}_{-0.11}$	$8.18 \to 8.87$	$8.58^{+0.11}_{-0.11}$	$8.24 \to 8.91$
$\delta_{CP}/^\circ$	177^{+19}_{-20}	$96 \to 422$	285^{+25}_{-28}	$201 \to 348$
$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.49^{+0.19}_{-0.19}$	$6.92 \to 8.05$	$7.49^{+0.19}_{-0.19}$	$6.92 \to 8.05$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$+2.534^{+0.025}_{-0.023}$	$+2.463 \to +2.606$	$-2.510^{+0.024}_{-0.025}$	$-2.584 \to -2.438$

NuFIT 6.0 (2024), www.nu-fit.org

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 ($\bar{\nu}_e$)

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

From T. Patzak

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 ($\bar{\nu}_e$)

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

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

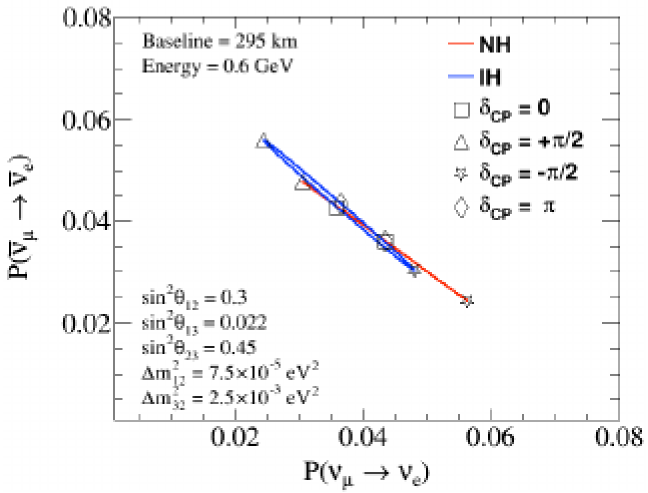
Beam of ν_μ
or $\bar{\nu}_\mu$

hundreds of km through
the Earth

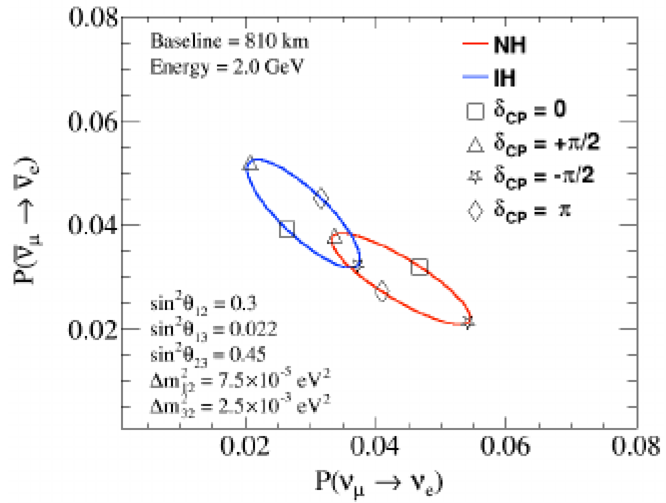
Detect ν_μ ($\bar{\nu}_\mu$)
ν_e ($\bar{\nu}_e$)

If the baseline is long enough, the matter effect dominates, and δ_{CP} and neutrino mass ordering disentangle.

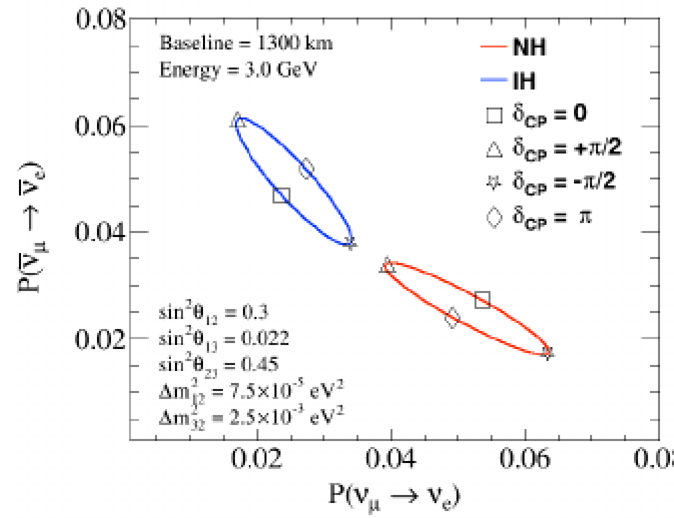
Baseline 295 km
Energy 0.6 GeV



Baseline 810 km
Energy 2.0 GeV

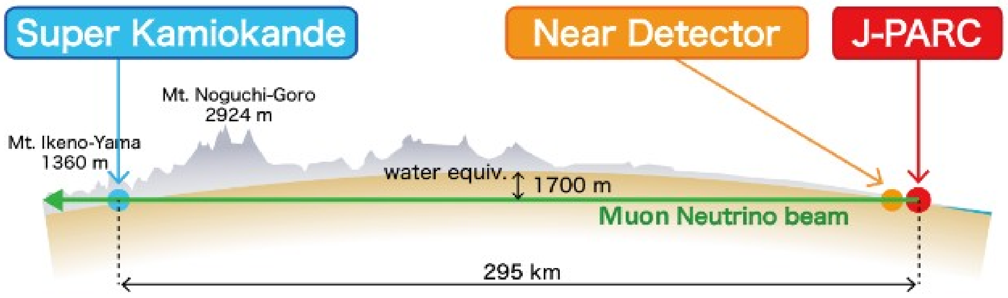


Baseline 1300 km
Energy 3.0 GeV



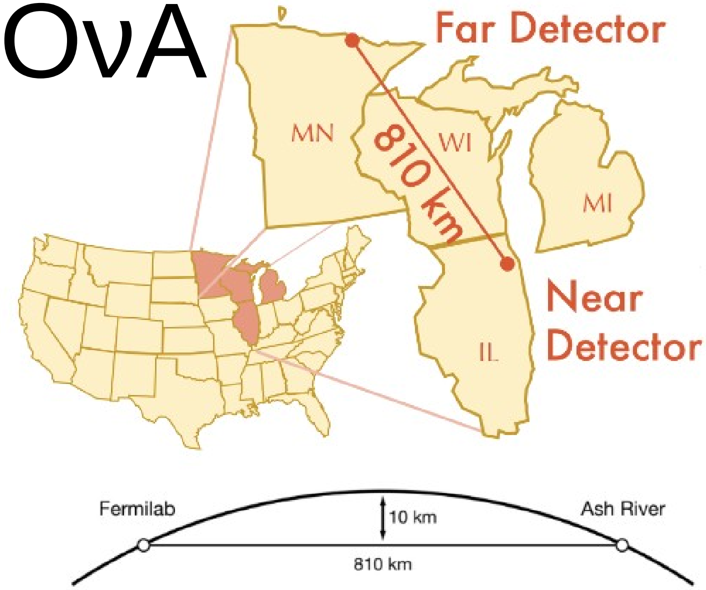
Long Baseline Experiments – State of the Art

T2K



- 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

NOνA



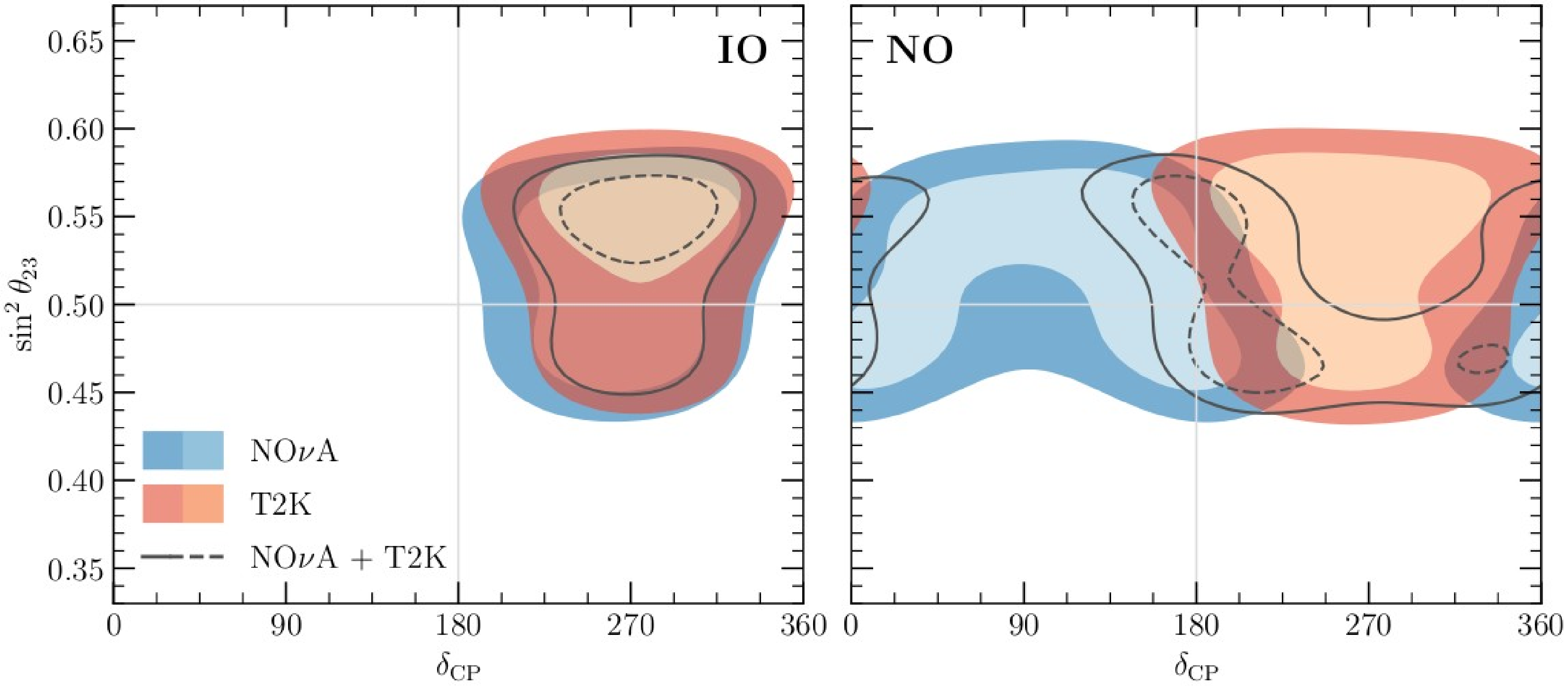
- NOVA has functionally identical Near and Far detectors (finely grained liquid scintillator; 14kton far)
- Baseline is 810km
- Higher neutrino energy
  - DIS occurs

Long Baseline Experiments – State of the Art

As of Neutrino 2024

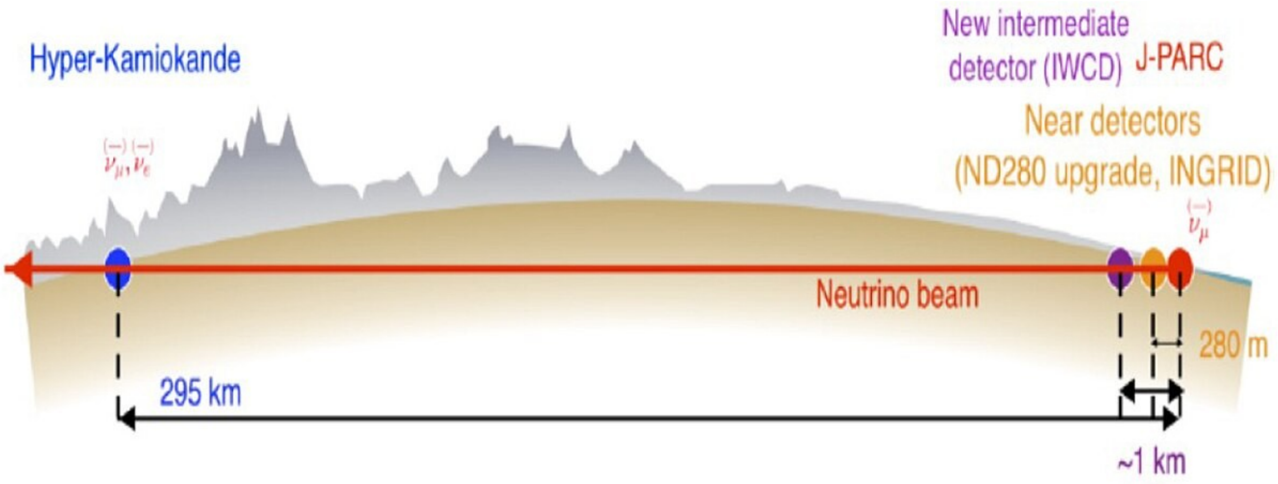
NOνA see maximal degeneracy between mass ordering and δ_{CP}

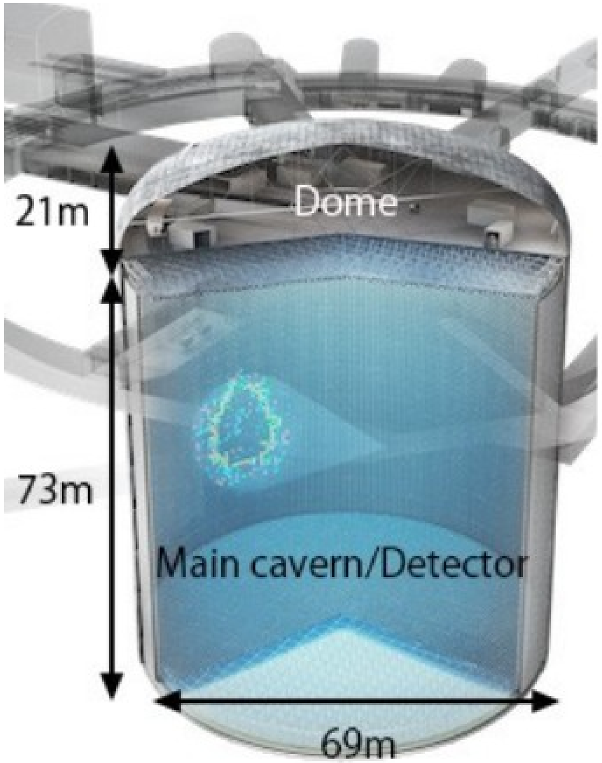
NOνA and T2K overlap better if Inverted Ordering



arXiv: 2410.0538
NuFIT 6.0 (2024), www.nu-fit.org

To go further – HyperK and DUNE



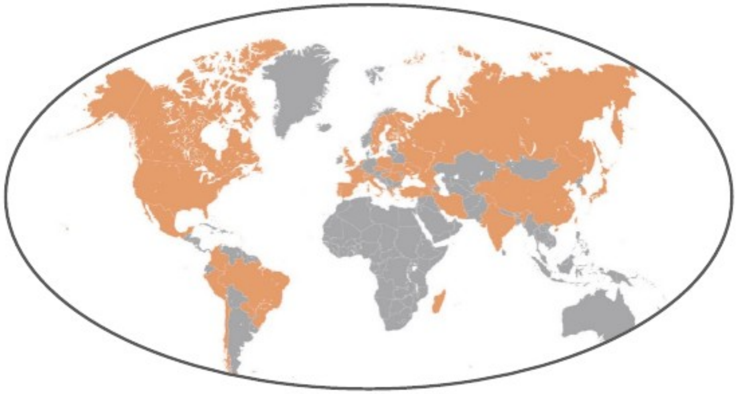


Same baseline (295km) and off-axis (2.5^0)as T2K
Increased beam power (1.3 MW)
8.4 times larger than SK (187 kton fiducial volume) – Water Cherenkov
T2K Near Detectors (ND280 upgrade, INGRID) New intermediate detector IWCD (spans 1.5-4^0 off-axis)

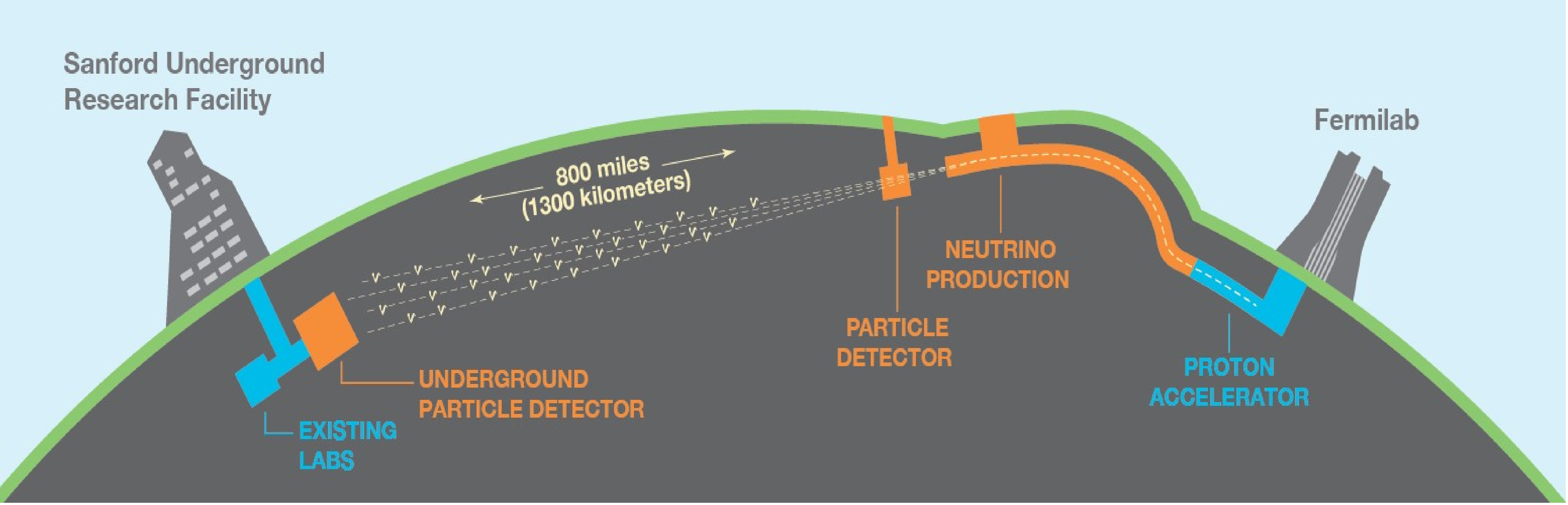
DUNE: international collaboration

DUNE Collaboration Meeting, Fermilab, May 2023

1400+ collaborators
200+ institutions
37 countries (including CERN)



DUNE is next generation neutrino oscillation experiment



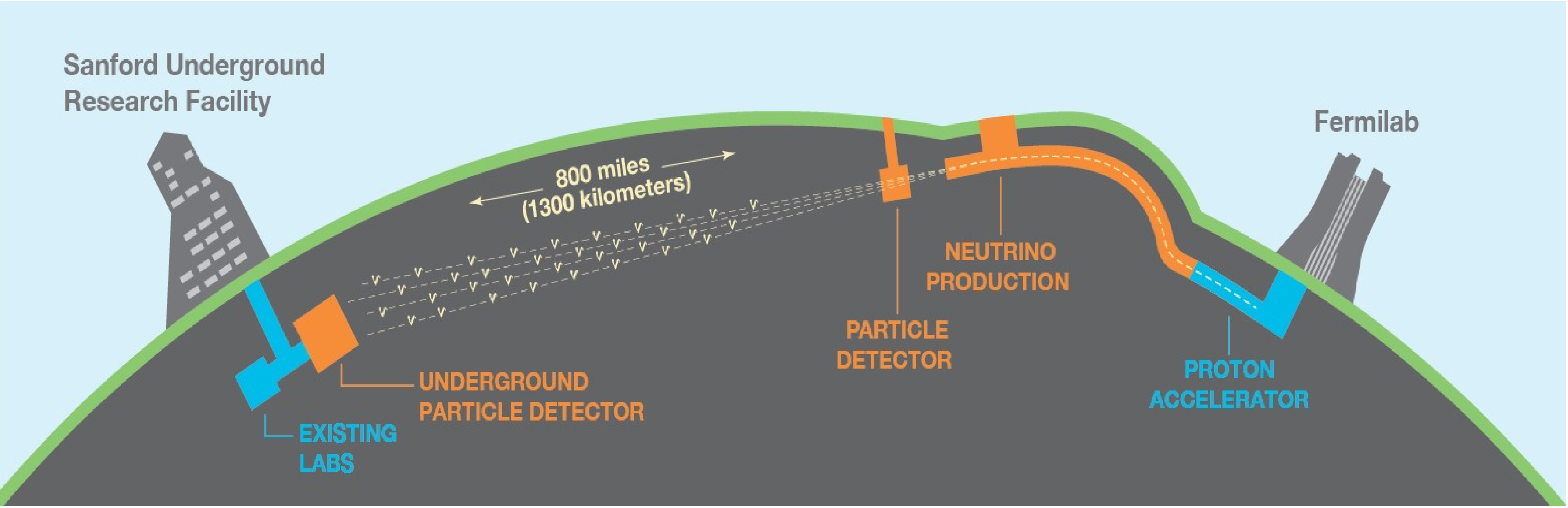
Physics goals :

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

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

DUNE is next generation neutrino oscillation experiment



Far detectors at SURF:
4 x 17 kt 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

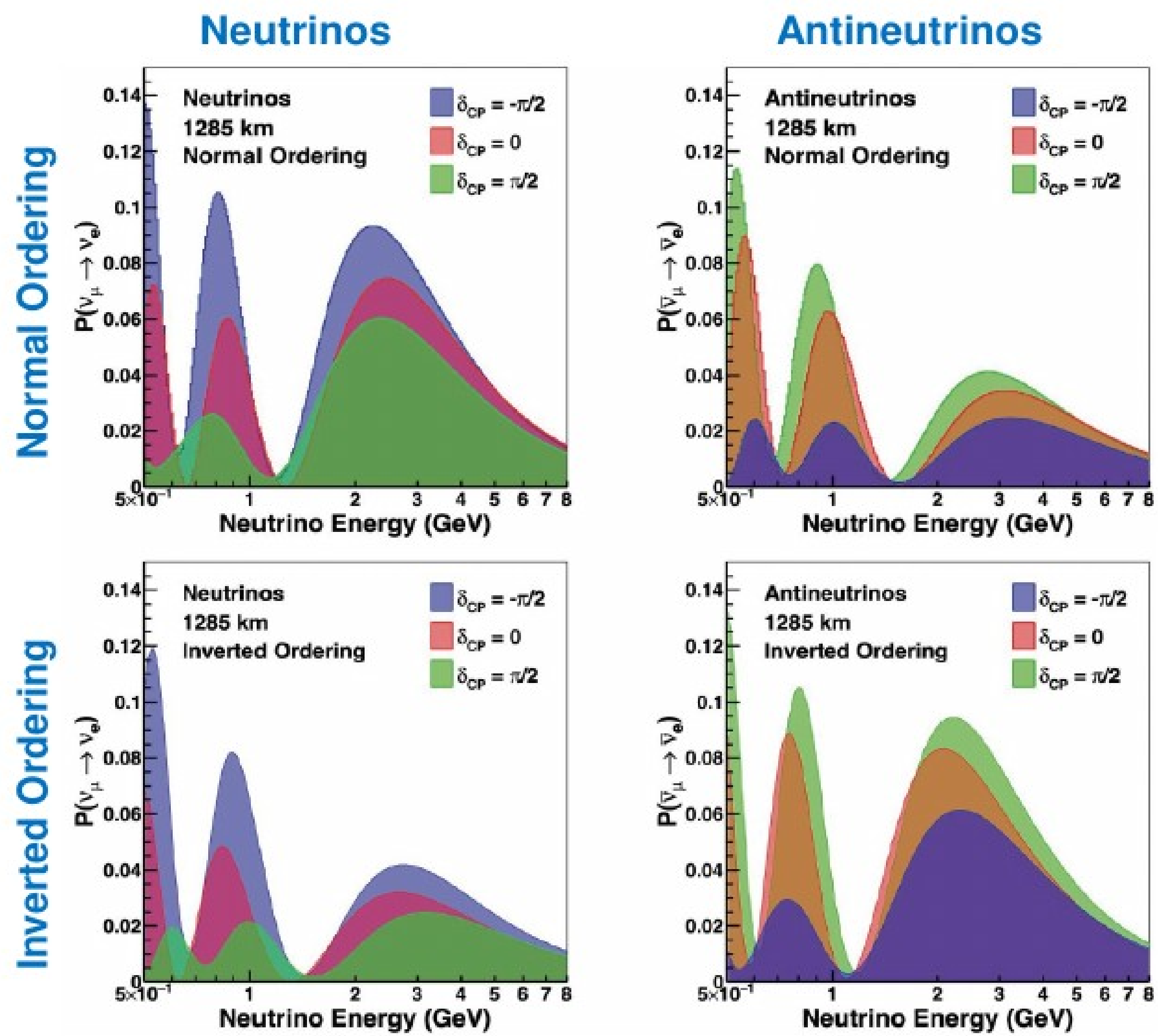
DUNE

Long baseline (completely disentangle mass ordering and CP violation)
High power beam and gigantic far detectors (more stats)

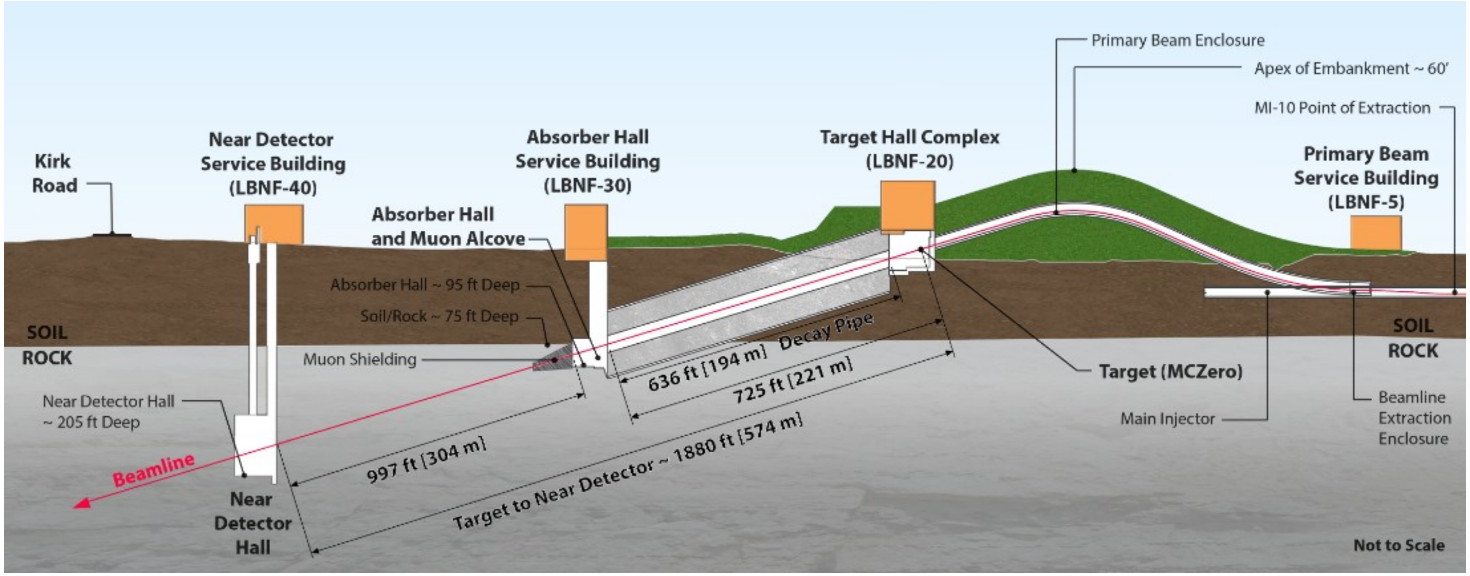
Make a spectral measurement
use a wide band beam (neutrino/anti-neutrino mode)

Measurement range spans 2 oscillation peaks

Gain additional power on deltaCP



Neutrino Beam

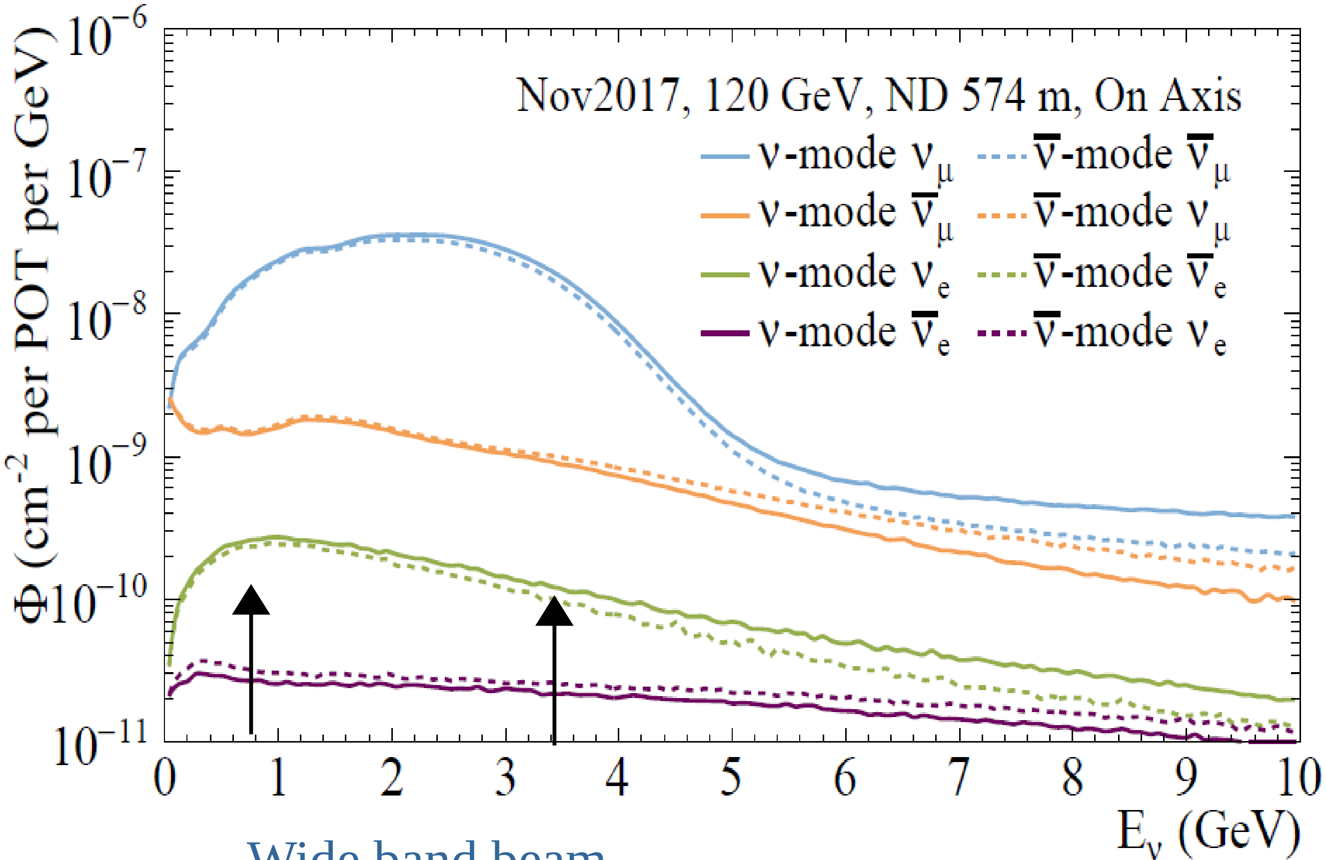


World's most intense neutrino (anti-neutrino) beam

PIP-II construction
- first beam 2031
- reach 1.2 MW end of 2032

Phase-2
- upgrade to deliver 2.1 MW

LBNF beam

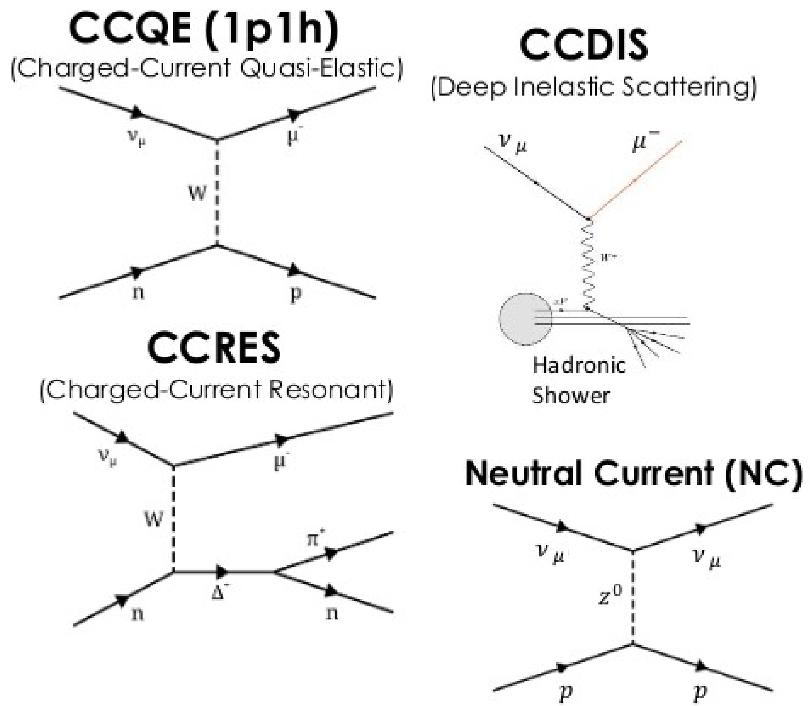


Wide band beam
2 oscillation maxima

- 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

Neutrino Signal

Neutrino interactions can be quite complex (multiple products and showers)

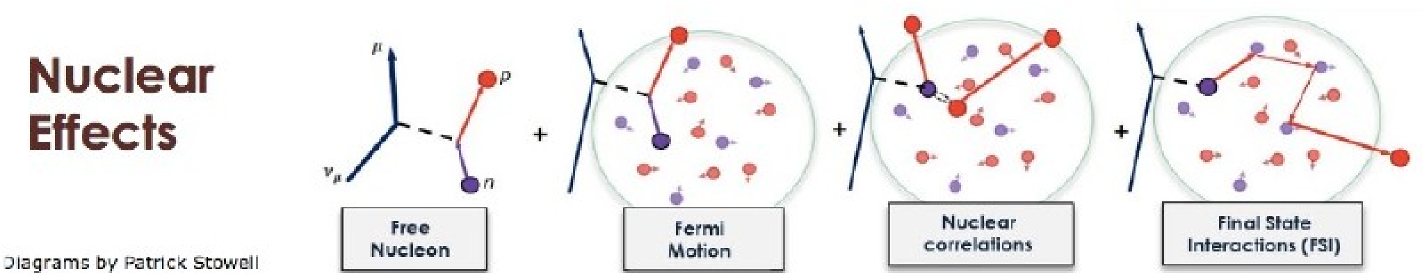


Neutrino flavour determined by outgoing lepton

Neutrino Energy Reconstruction dependent on Interaction Model

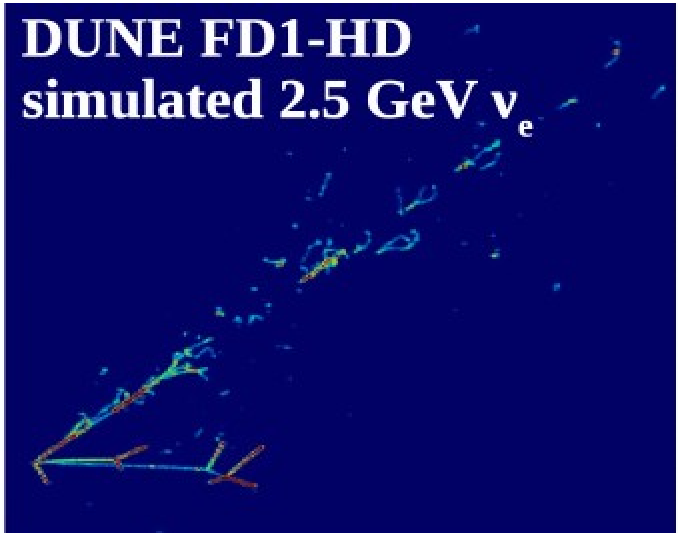
Not all products may be visible (neutrons)

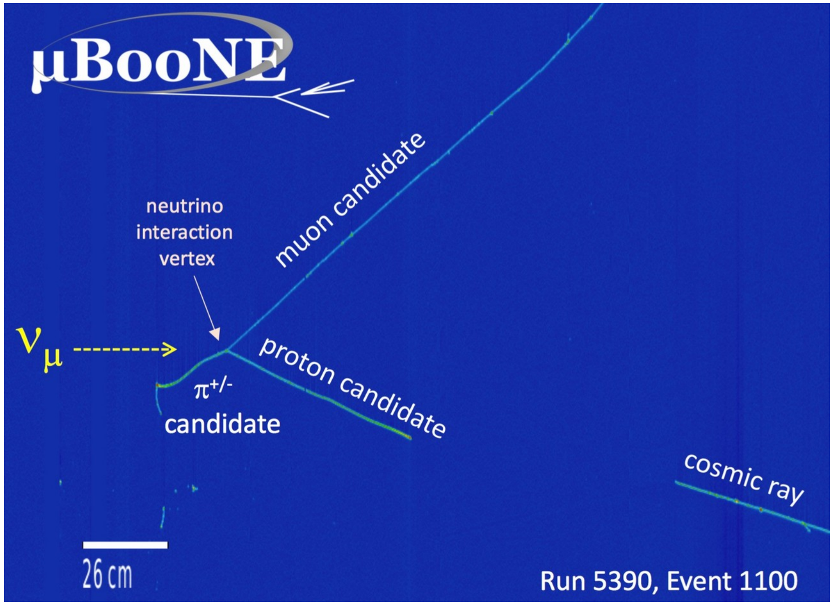
Need highly performing Near and Far detectors!

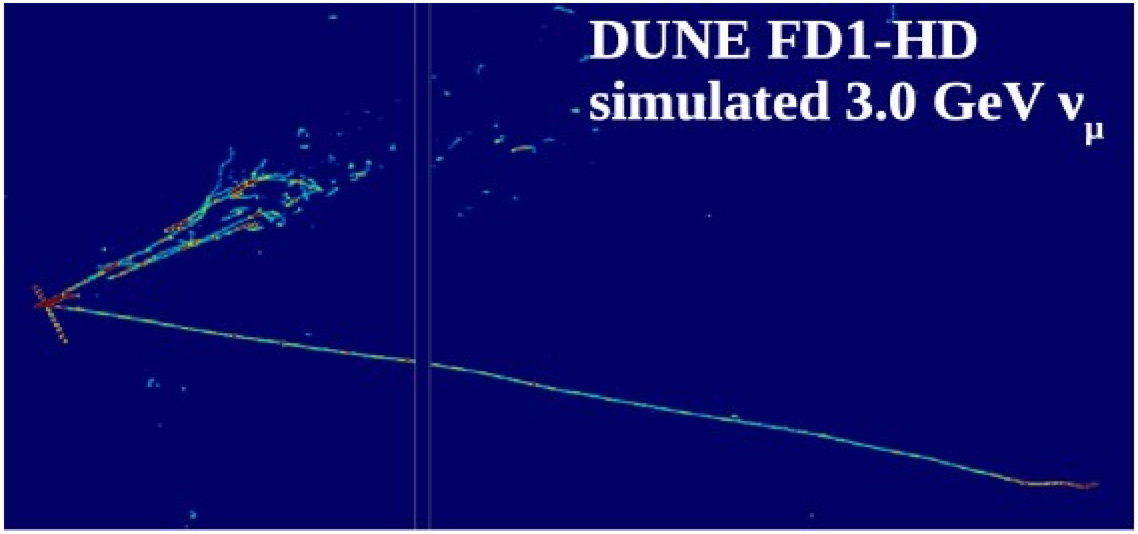


LAr TPCs

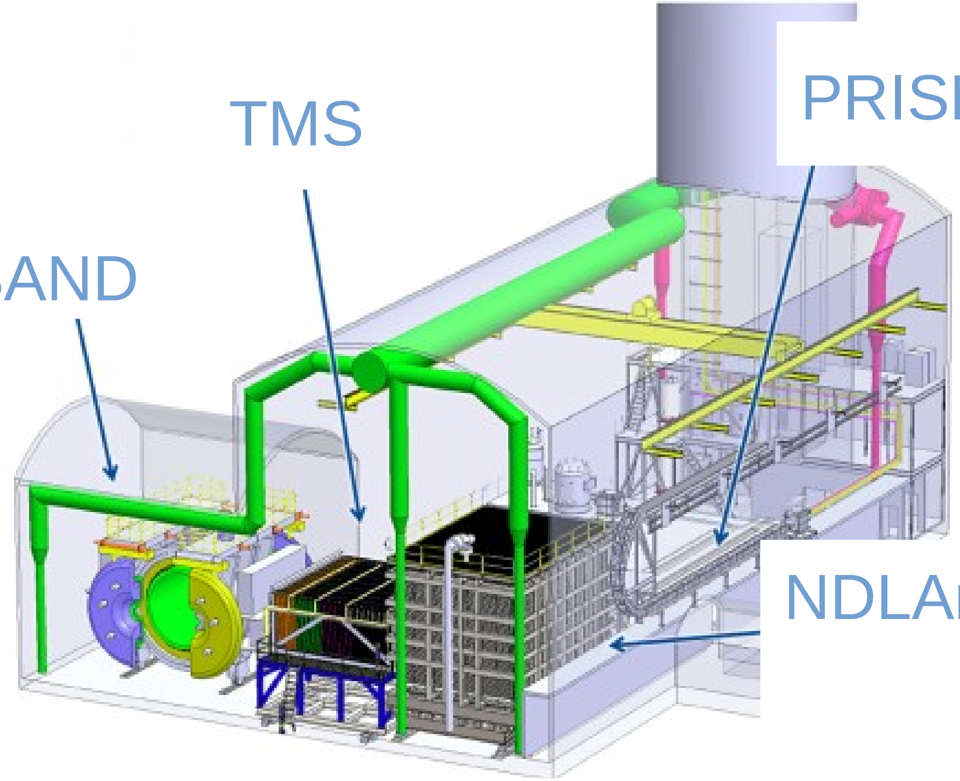
- Massive detectors (17 ktons Far Detectors)
- Fine-grain ‘images’ of neutrino interactions
- Separation ν_μ/ν_e
- Good energy reconstruction
- Low energy threshold







Near detector system



Phase-2
- Upgrade TMS with Gas-Ar TPC (NDGar)

Suite of high performance detectors

NDLAr – 150t liquid argon TPC

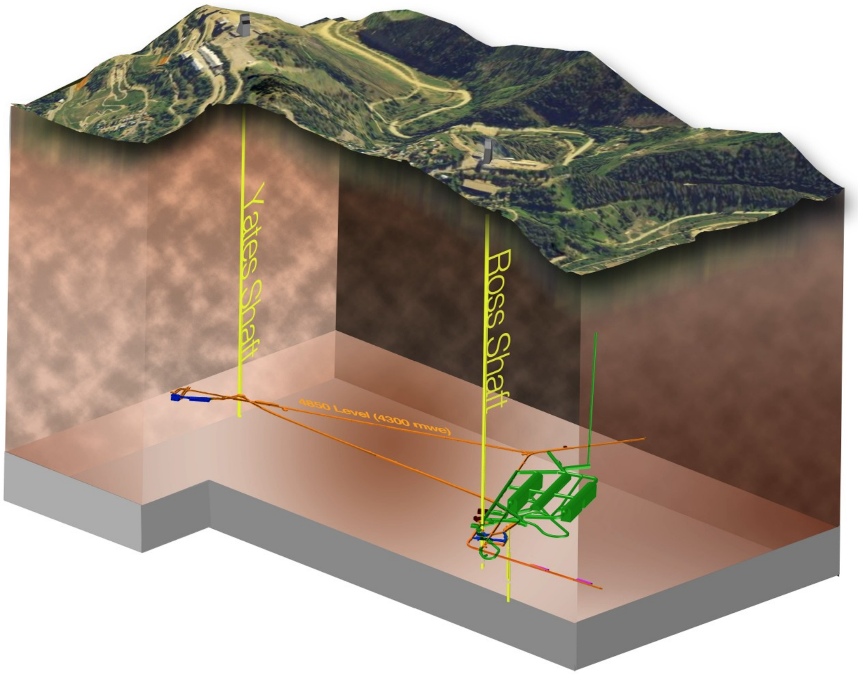
The Muon Spectrometer – magnetised steel range stack
measures sign and momenta of escaping ν_μ

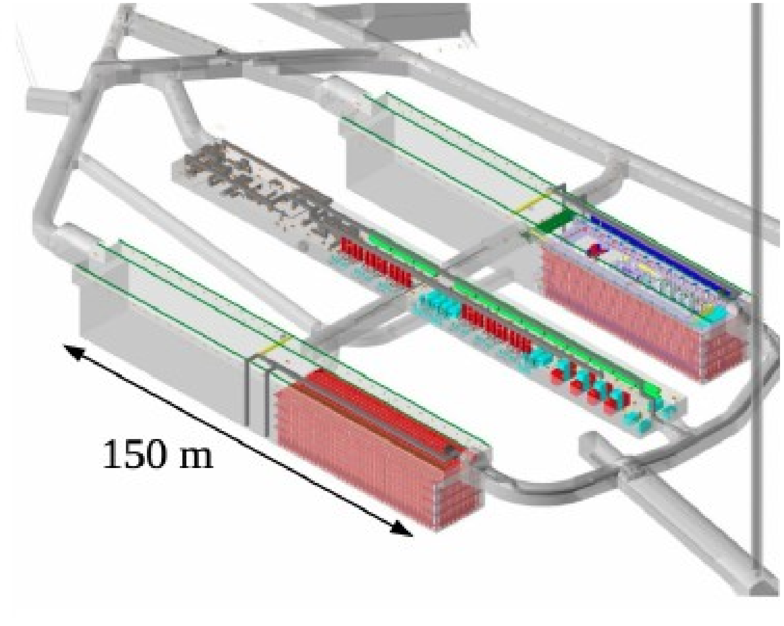
SAND – magnetized LAr Target (GRAIN), tracking (STT) and calorimeter (ECAL)
Fixed On-axis beam monitor

PRISM – Moveable component - NDLAr + TMS

Construction of Near site facilities starts 2025

Far detector at SURF

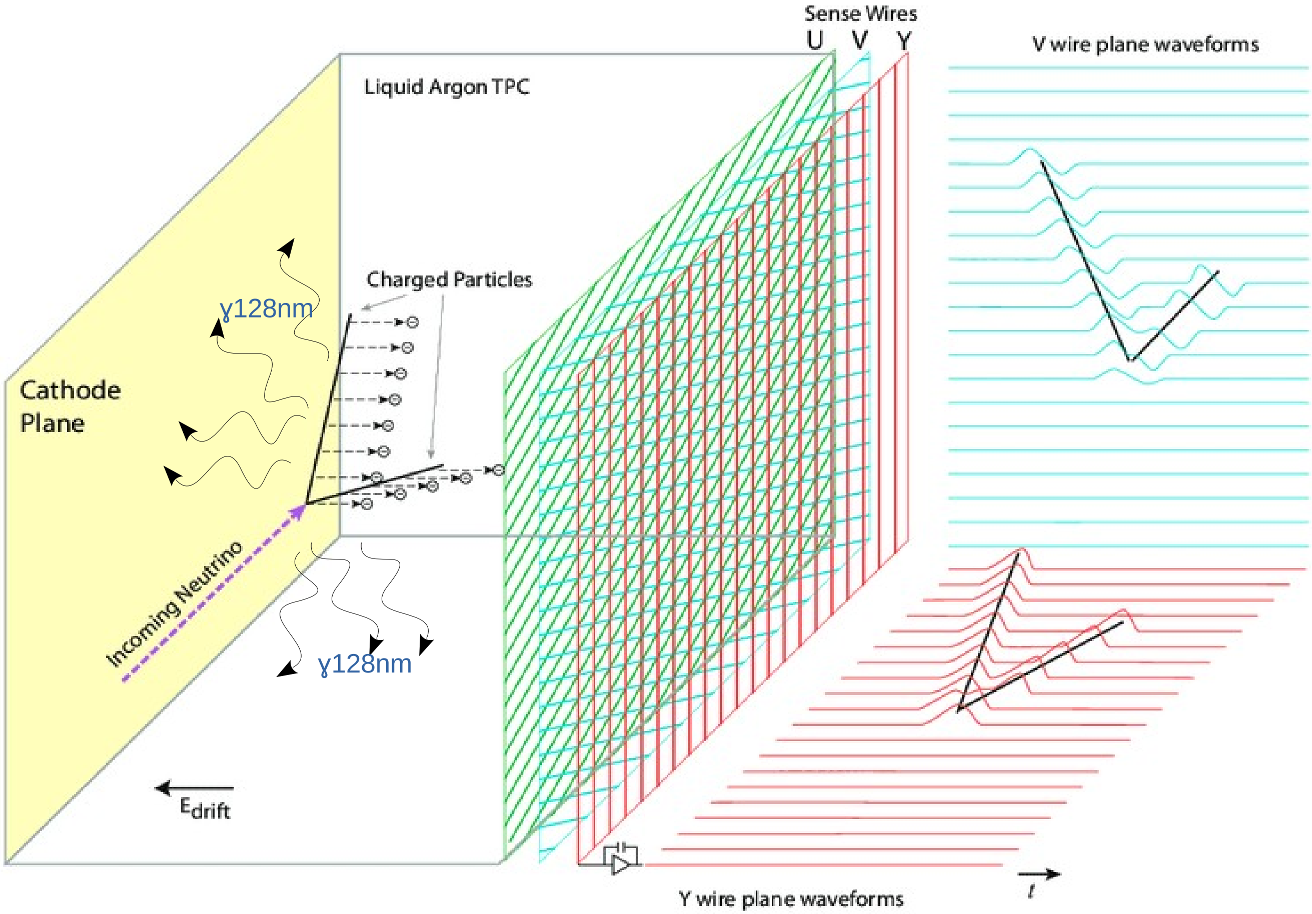




- Sanford Underground Research Facility in Lead, South Dakota
- Four 17-kt LAr TPC modules, located 1.48 km underground
- Excavation complete 2024
- Phase 1 – 2 Detectors (FD1 and FD2)
- FD1 – Horizontal Drift
- **FD2 – Vertical Drift**

Phase-2
- FD3 (decision 2027)
- FD4 module of opportunity (decision 2028)

LAr TPC



- Prompt Scintillation signal (LAr 128nm)
  - Detected with PMTs/SiPMs (wavelength shifting)
  - Gives time-stamp of interaction (T0)
- Electric Field ~0.5kV/cm
- Drifts electrons towards anodes (mm/us)
  - Induces signals on wires
  - Proportion of drifting electrons reduced by electronegative contaminants (liquid purity)
- Read out wires (strips)
- 3D Interaction Position
  - Drift time = Δ Arrival time (Charge - Light)

Needed for off-beam physics

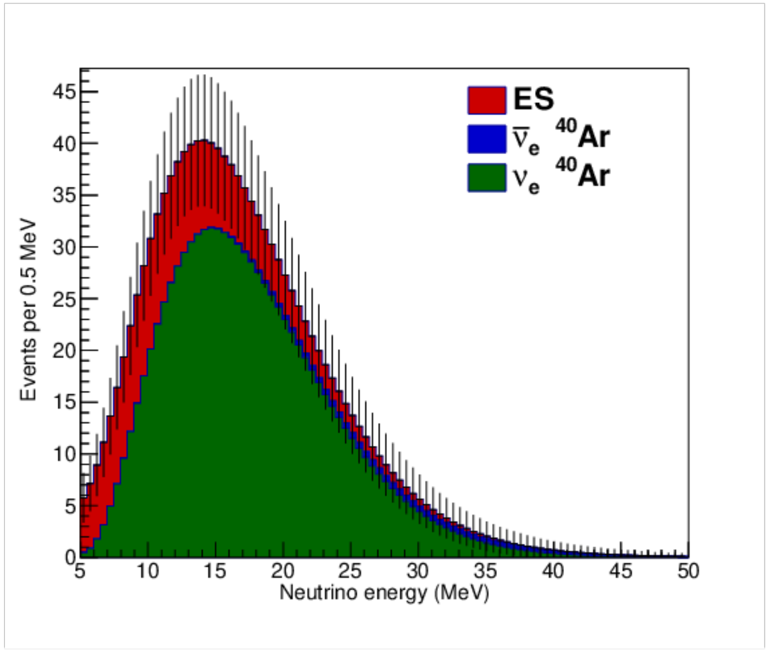
Off beam searches - Galactic SuperNova

Uniquely DUNE is sensitive to ν_e

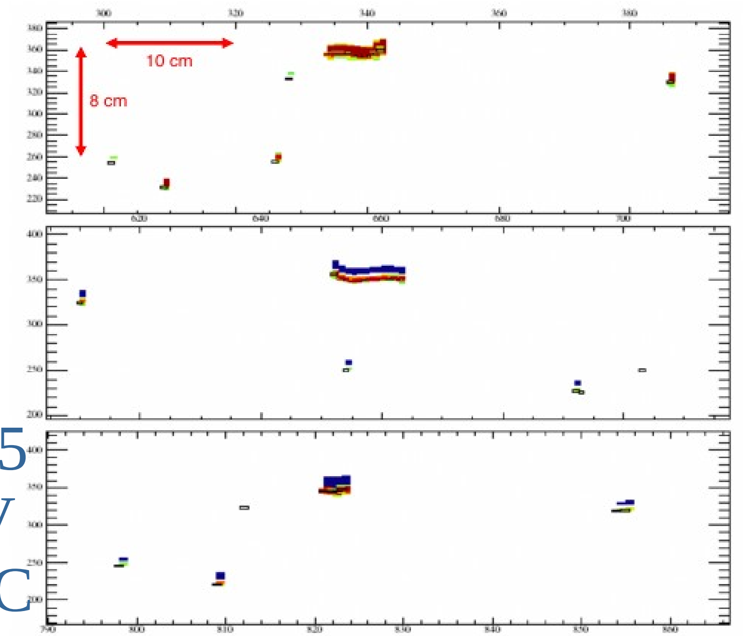
ve + ^{40}Ar $\rightarrow$ e^- + $^{40}K^*$

Also elastic-scattering

5-50 MeV signals



'Garching' model SN as seen by 40 ktons DUNE (inc detector response)



20.25 MeV ν_eCC

2008.06647

22

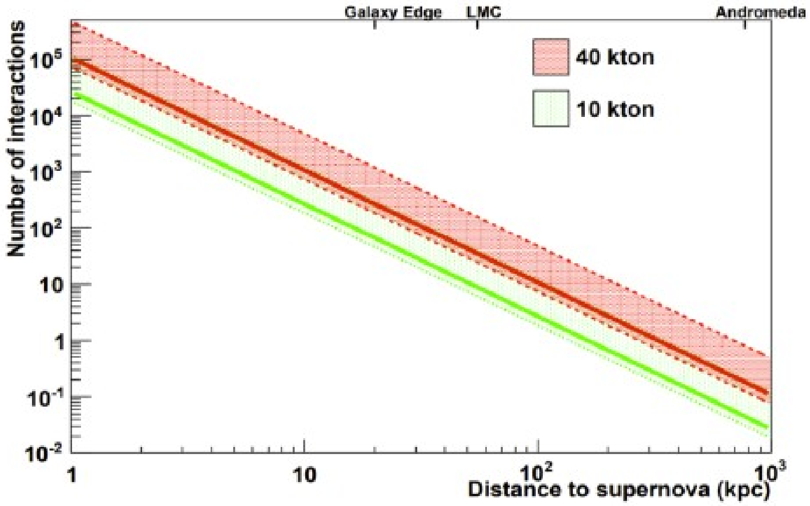
Galactic SuperNova

SN trigger – (Light and Charge signals)
Continuous data-taking, all waveforms stored for 100s (with 10s pre-trigger)

Light signal provides:

- SN signal arrival times
  - Global triangulation (SuperNova Early Warning System)
- Position in drift direction needed to correct of electron drift loss (Energy estimate)

ES short tracks – forward scattering allows direction estimate



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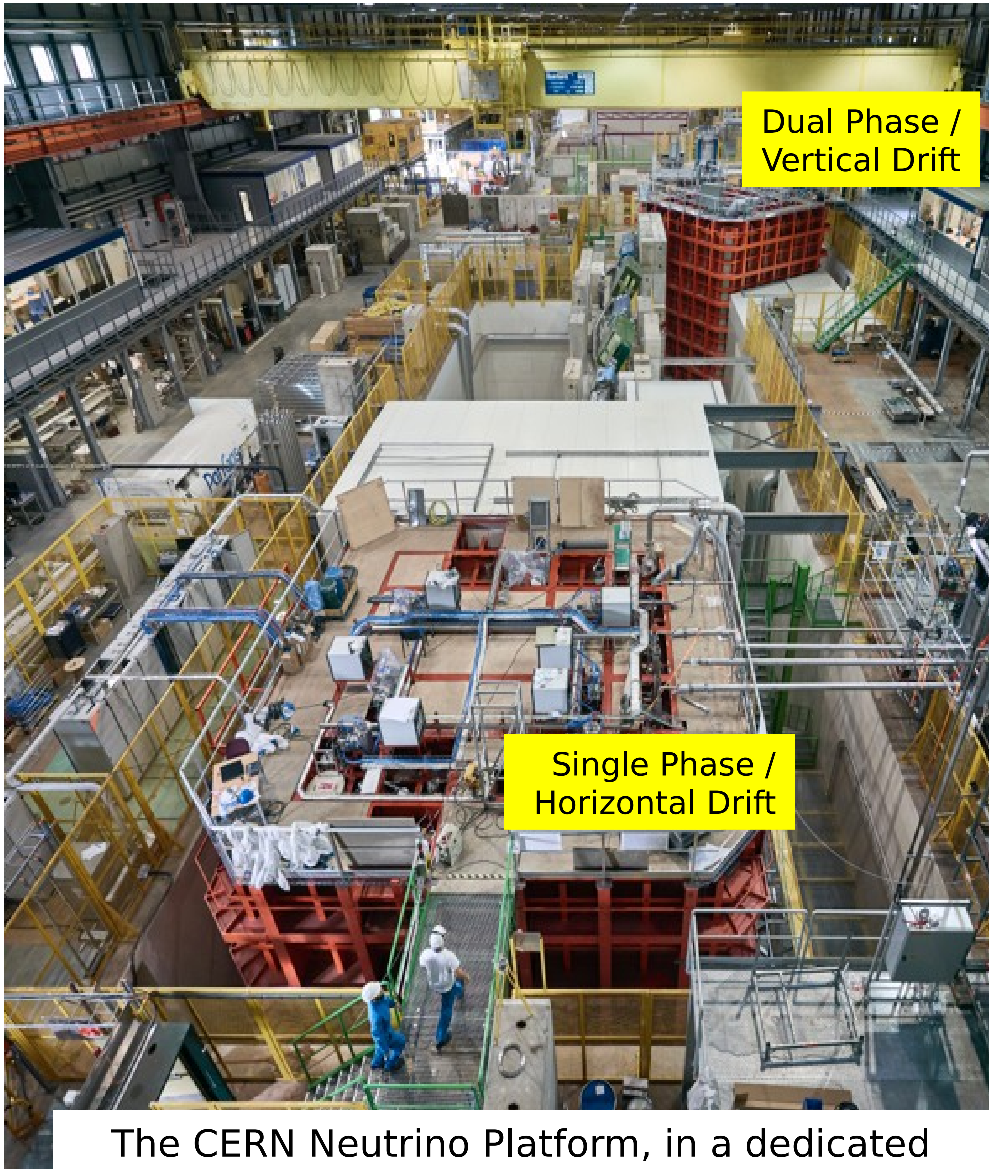
protoDUNEs

- Two LAr cryostats hosting the protoDUNEs – Giant Liquid Argon TPCs
  - Single Phase / Horizontal Drift
  - Dual Phase / Vertical Drift
- 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)

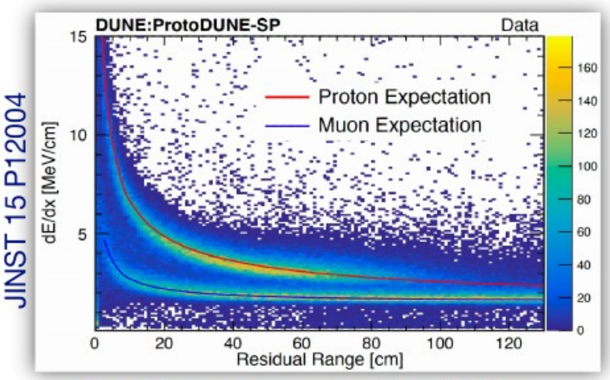


The CERN Neutrino Platform, in a dedicated extension of the North Area

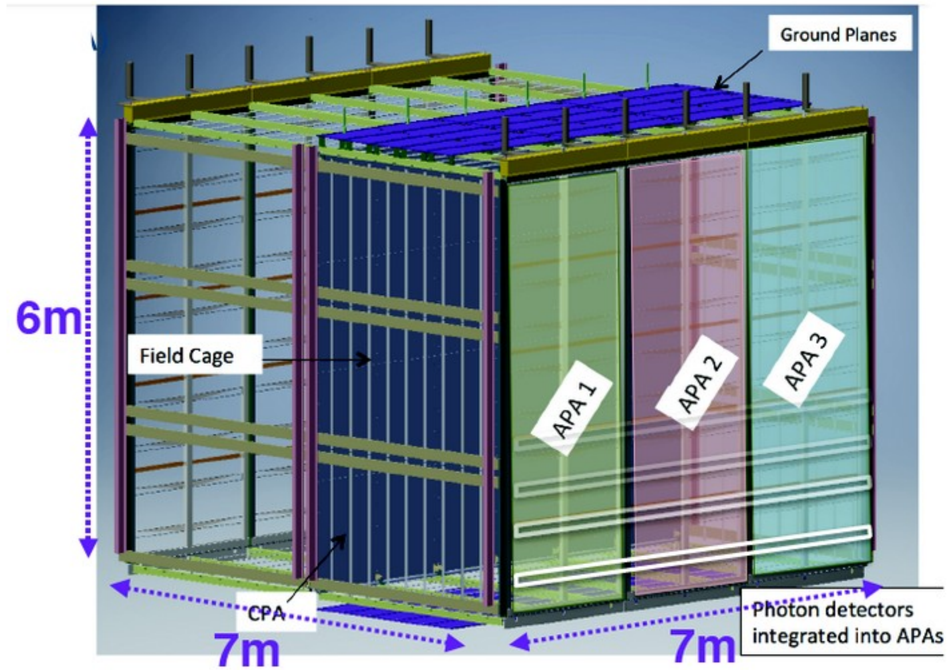
ProtoDUNE-Single Phase

- LArTPC (770 tons) in a charged-particle test beam
- 2 drift volumes (3.6m drift)
- Operated from August 2018 – July 2020
- Instrumented Beamline
- Known incident particle momentum - 300 MeV/c to 7 GeV/c

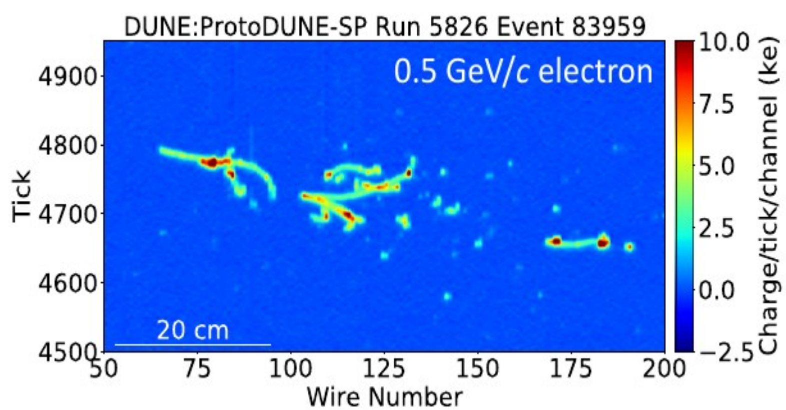
First results paper: JINST 15 P12004

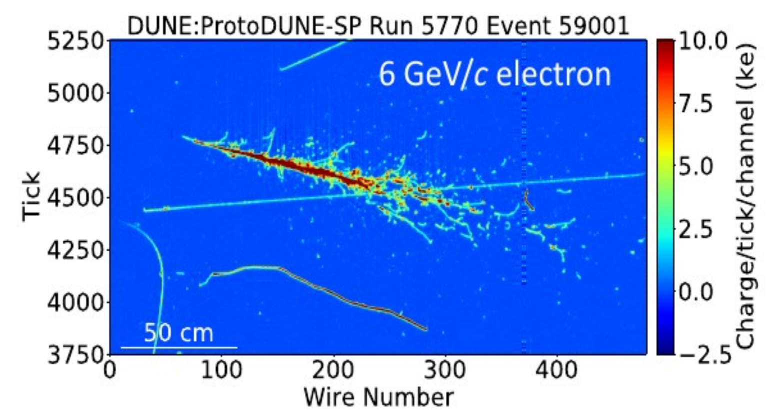


Stopping muon and proton dE/dx vs. residual range in ProtoDUNE-SP.

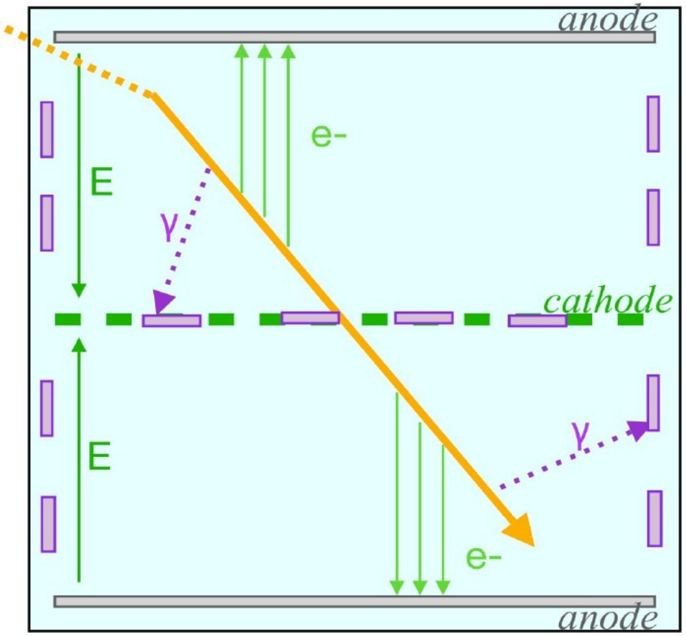


6 anode plane assemblies (APAs) (one far detector module has 150 APAs)





Vertical Drift



Base on experience with Dual Phase
New concept merging positive features of Dual Phase with successful Single Phase LArTPC

Single Phase LArTPC

HV delivery allows large drift volumes
– Top and Bottom

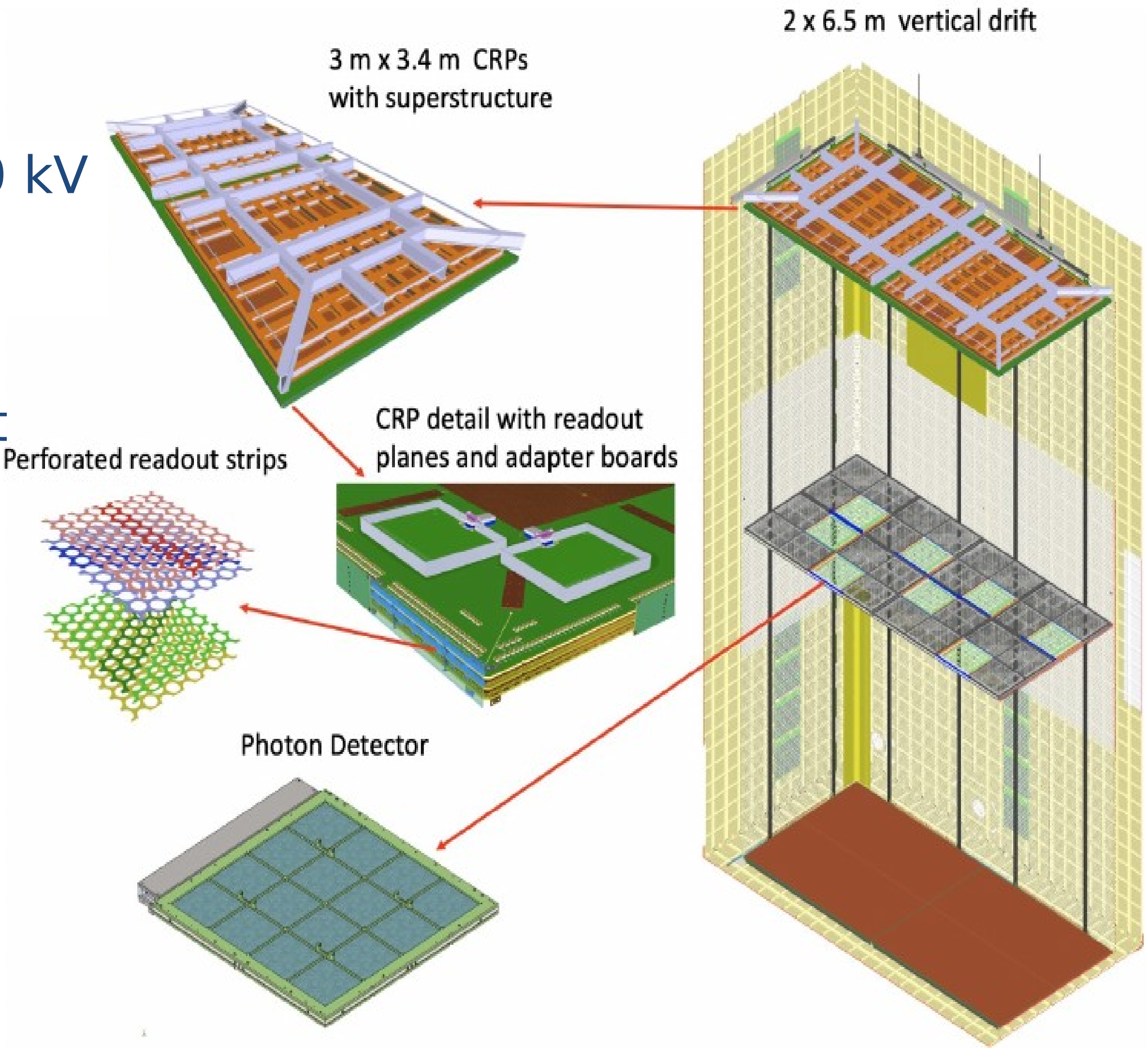
Top volume electronics is accessible

PCB-based charge read-out (3-views)

Advantageous for manufacturing and installation

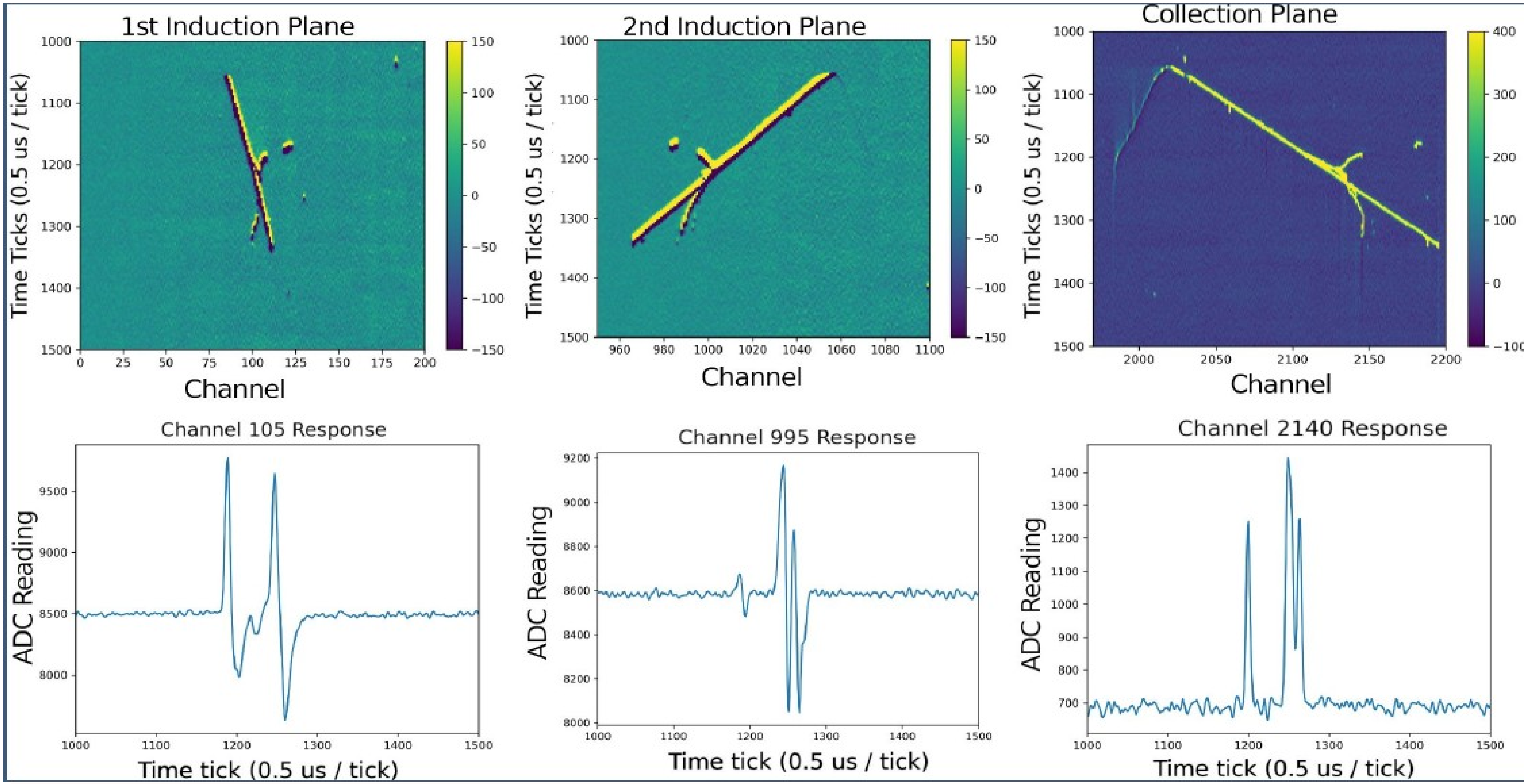
Vertical Drift

- Charge-readout planes (CRP) (anode) on top and bottom.
- Cathode in the middle at -300 kV
- 6,5 m drift distance
- Photon detectors
  - X-Arapuca
  - Behind field cage (on cryostat walls)
  - Embedded in cathode !!



Charge Read-Out

- Charge Read-Out Planes testing
- Successfully operated
- Less than 1% channel failure

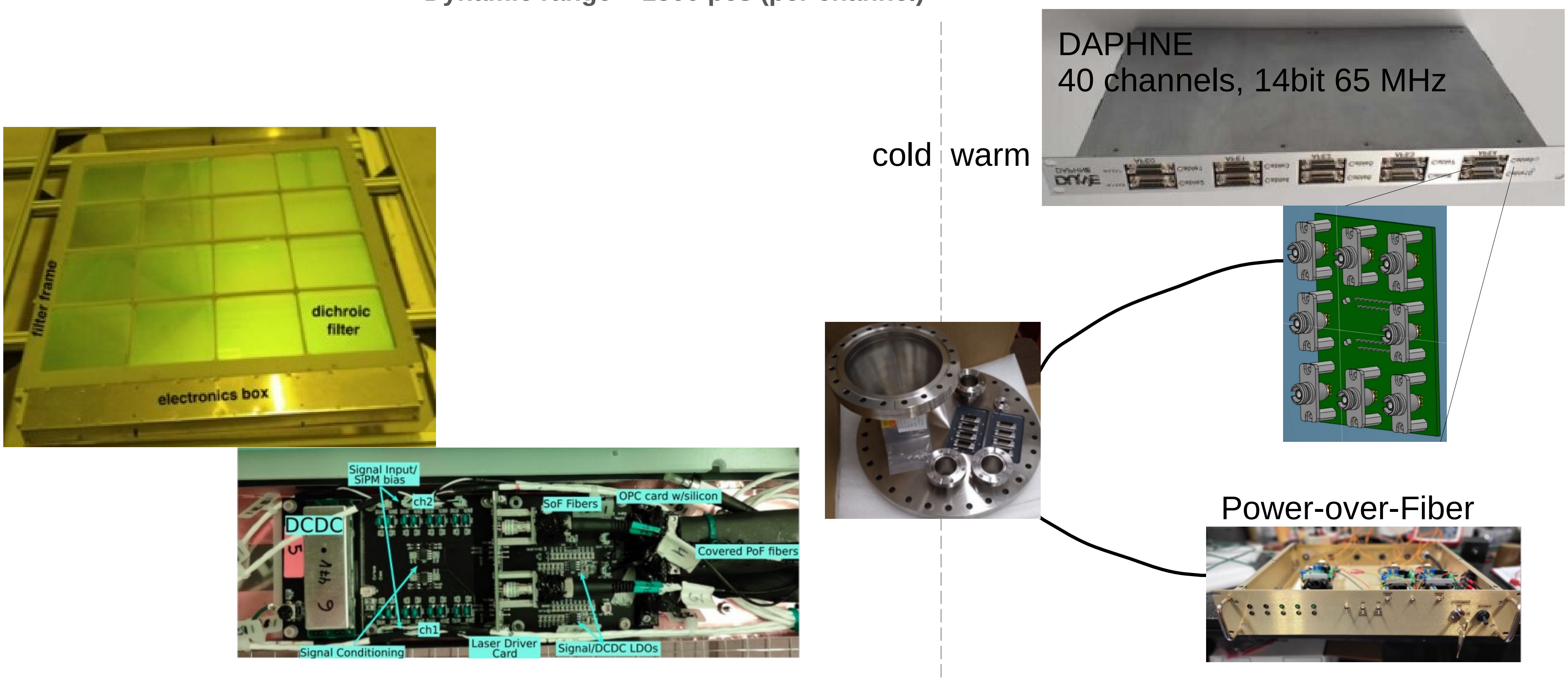


Photon Detection System

Challenge – SiPMs embedded in cathode (at -300 kV)
Power and Signal Read-out via optical fiber
- **Signal-over-Fiber**

Objective: S/N (single photoelectron) > 4

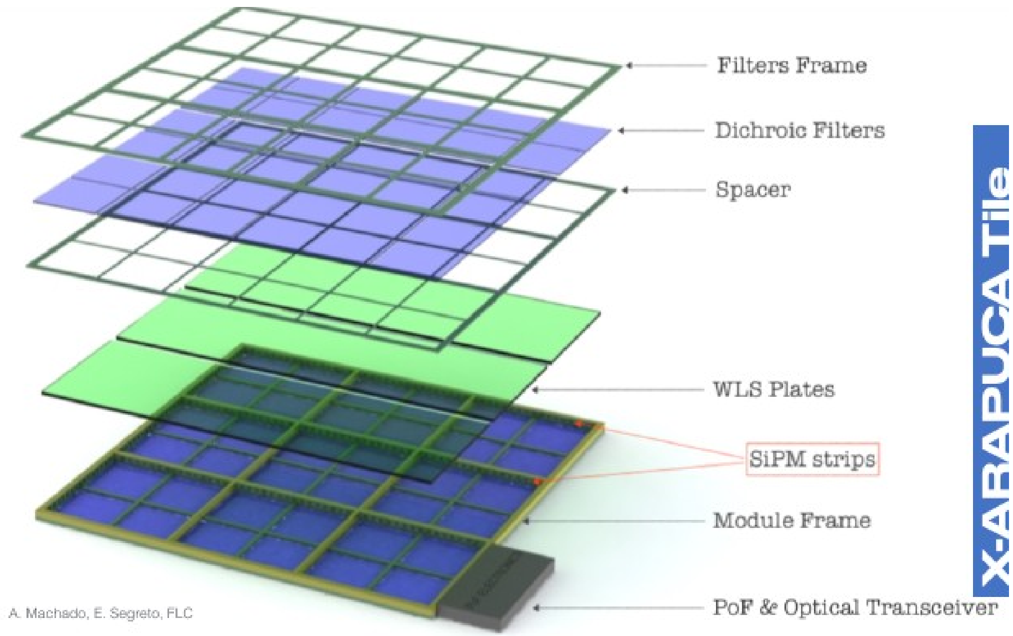
Dynamic range > 1500 pes (per channel)

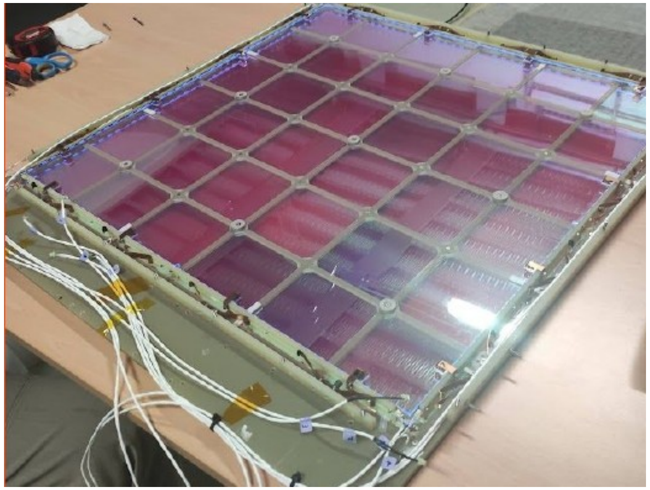


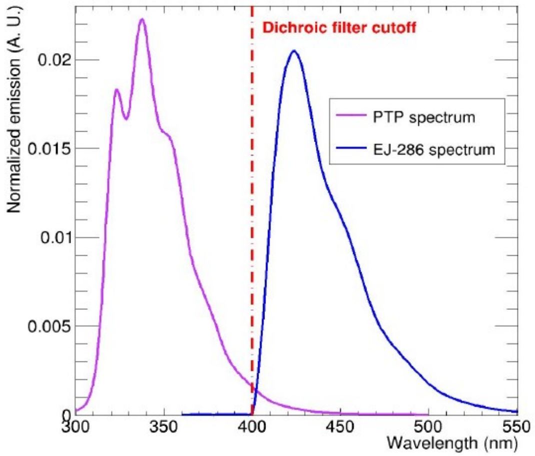
Photon Detectors

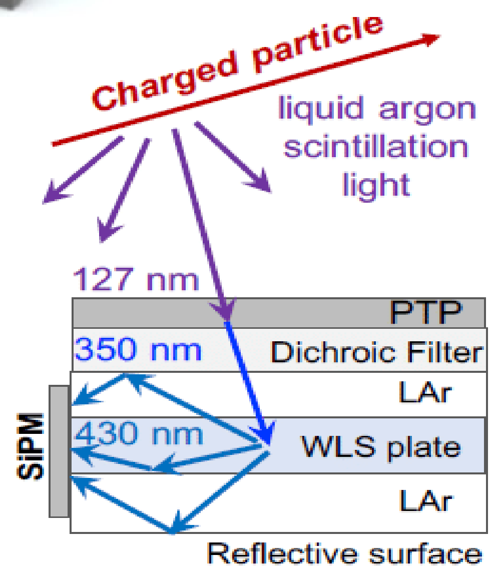
X-ARAPUCA

- Light-trapping device
  - Photons trapped inside due to combination of two wavelength filters and one dichroic filter
- 65 x 65 cm^2
- 2 x 80 Silicon Photomultipliers (SiPMs)

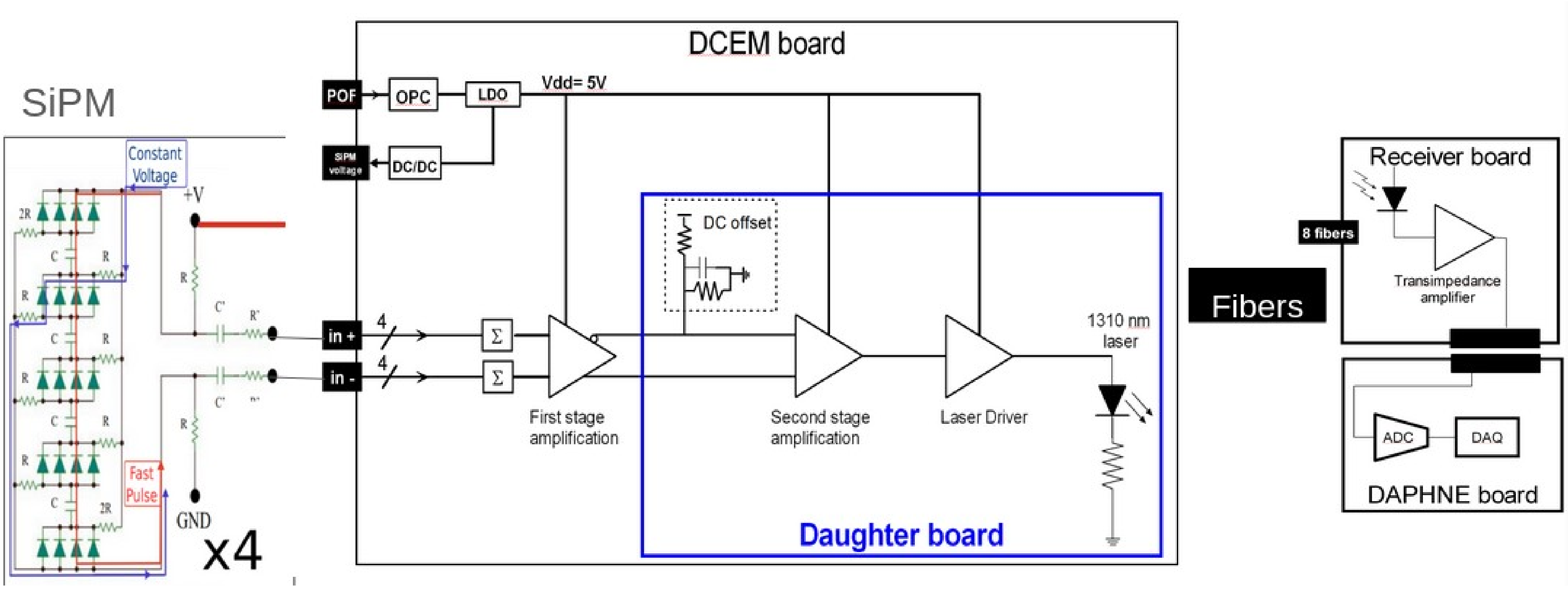


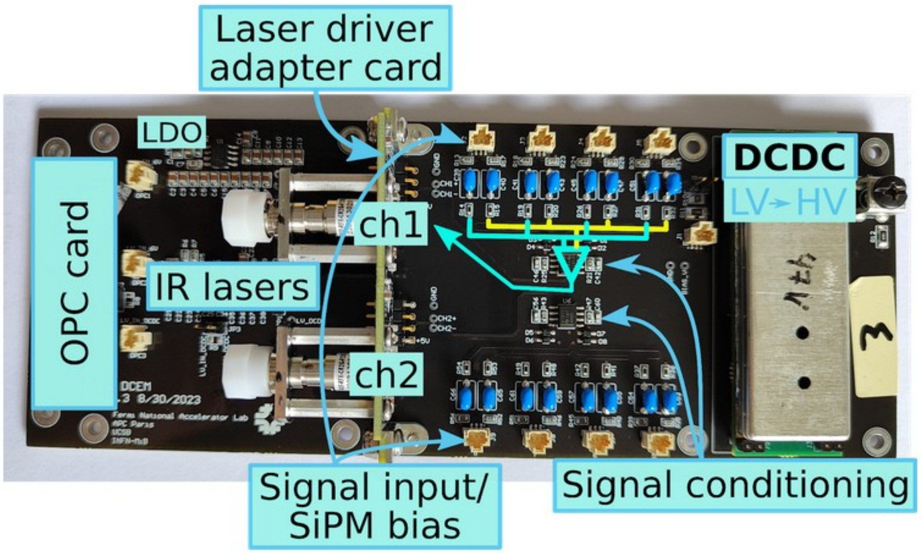






PDS Electronics

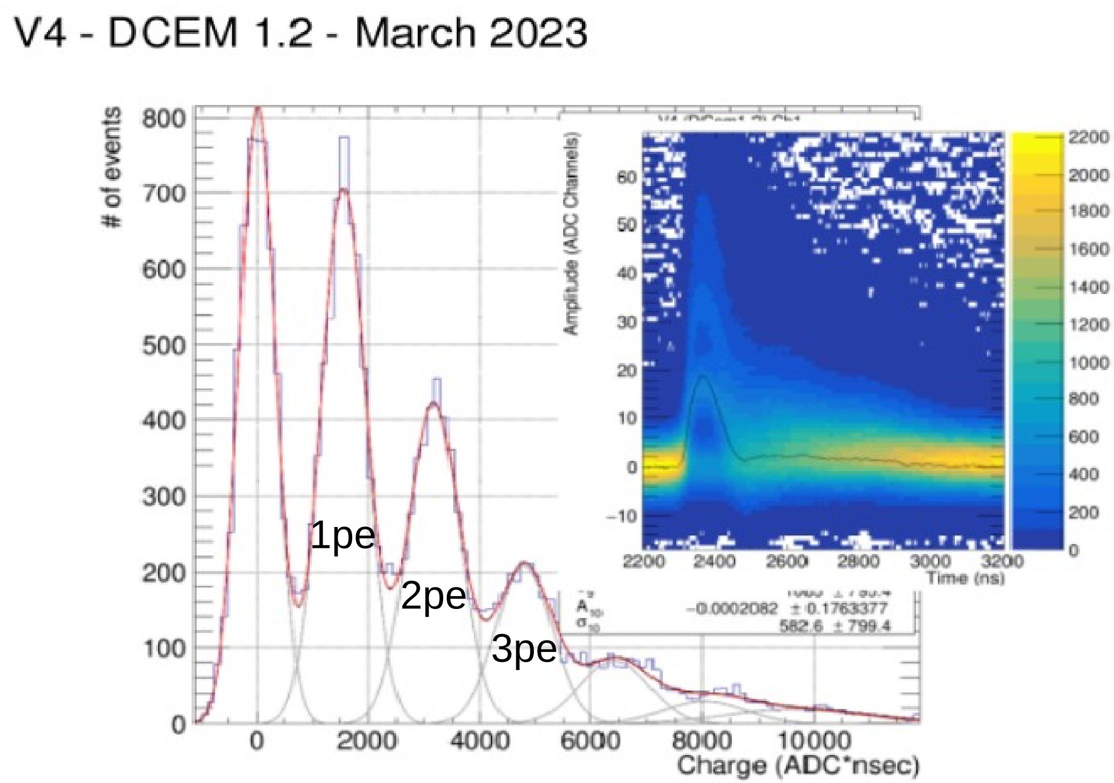


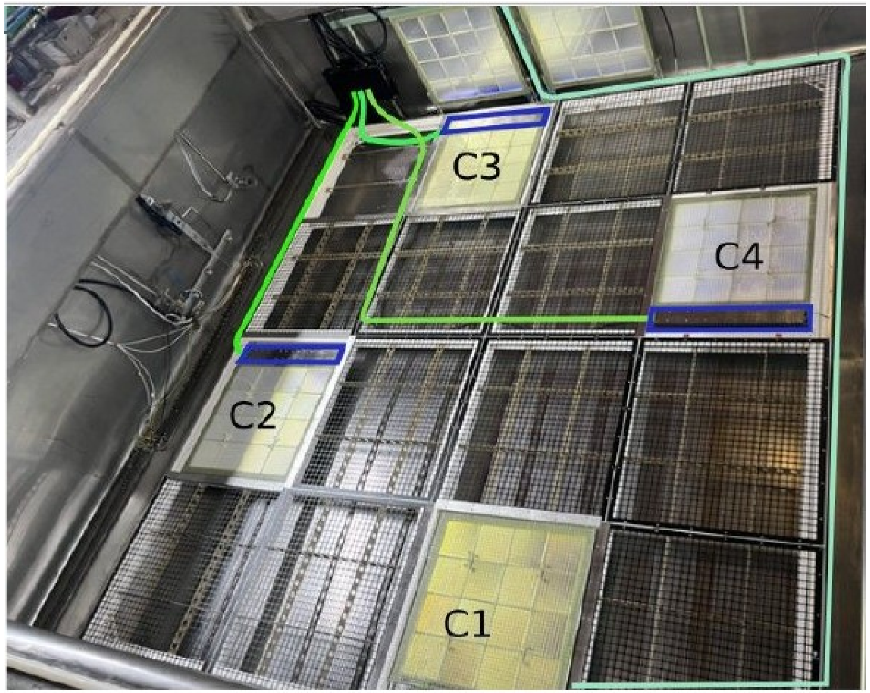


Cold Box – Performance March 2023

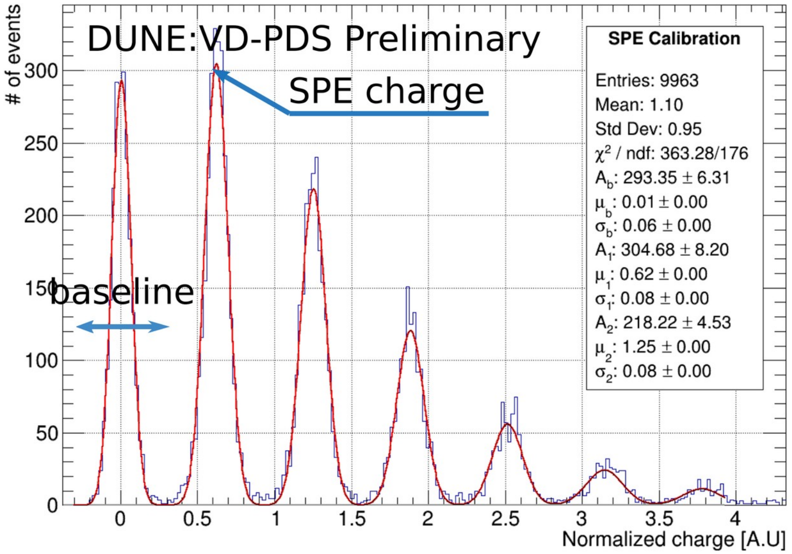
Tests made at CERN Neutrino Platform cold-box (3×3×1 m^3)
First demonstration of transmitter achieving DUNE goals

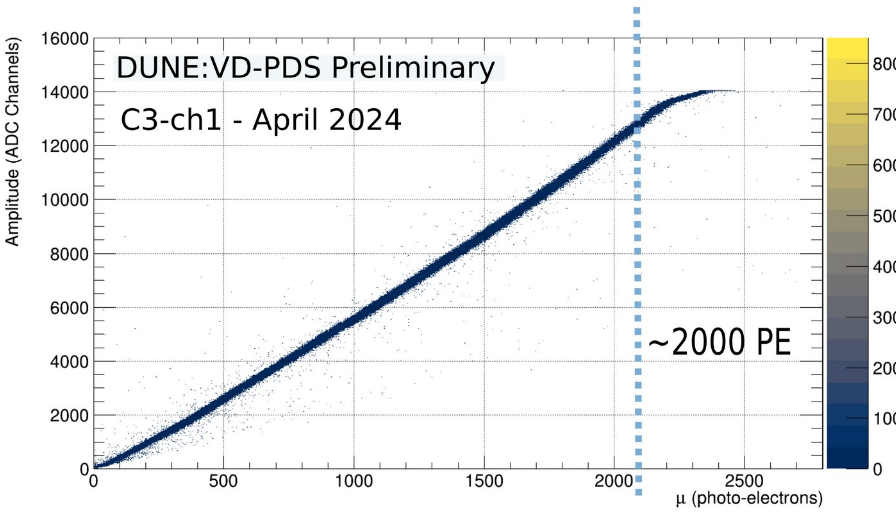
- S/N ~5 , dynamic ~1700 Pes

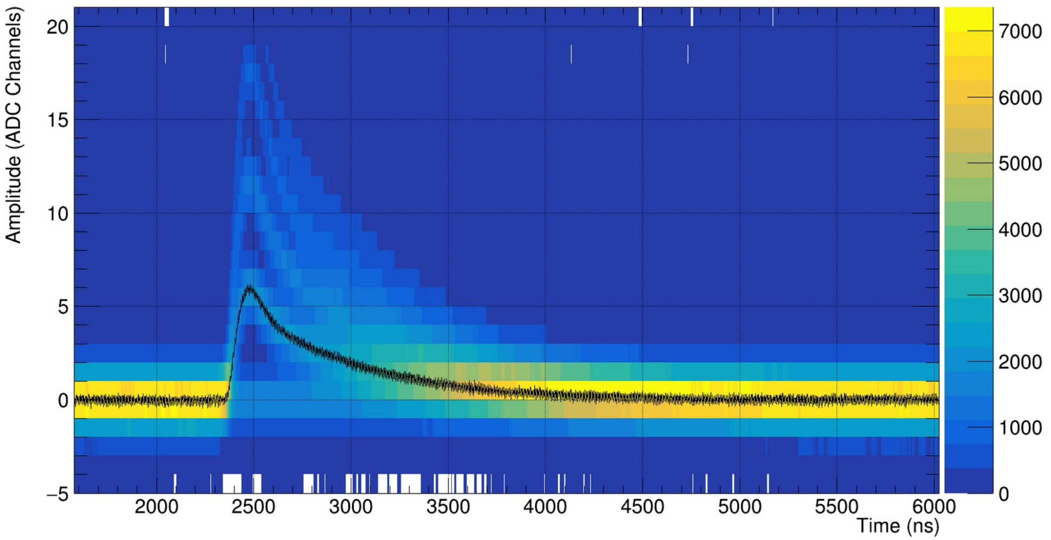




Performance – April 2024





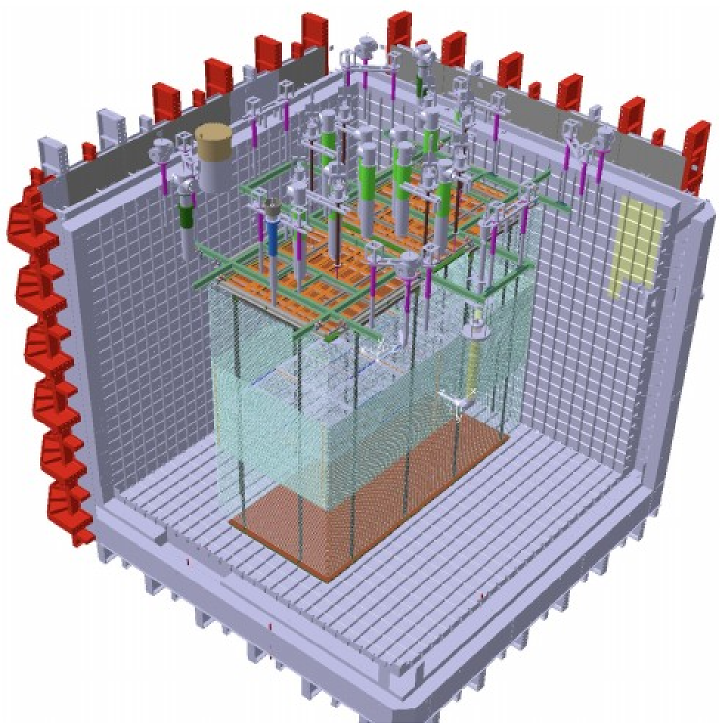


ProtoDUNE-Vertical Drift

Large-scale test of the Vertical Drift design in the NP02 cryostat in the Neutrino Platform at CERN
Active volume: $3 \times 6.8 \times 7$ m^3

- 2 CRPs top
- 2 CRPs bottom
- 2 Cathode modules

 Operated at -175 kV
Filling soon!

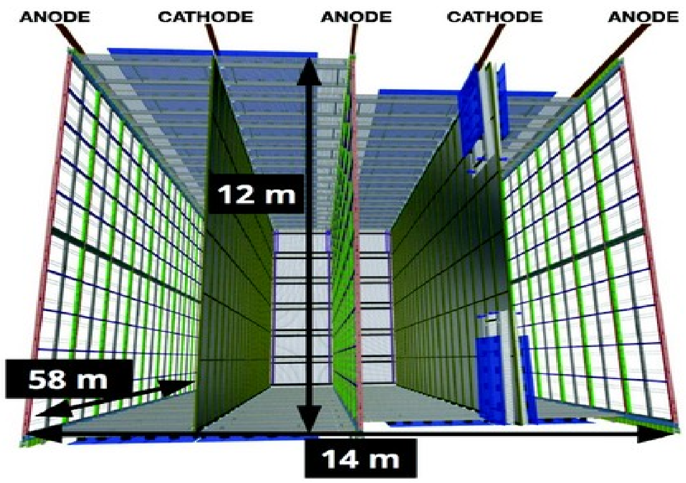


Top volume

Bottom volume

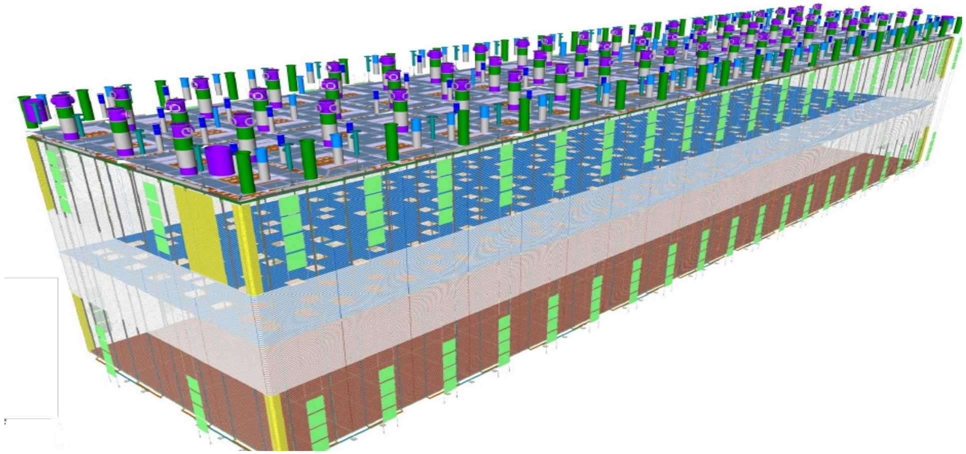
DUNE Far Detectors (FD1 and 2)

Horizontal Drift



- Modular design
  - 500 V/cm horizontal-drift (HD) field
  - 3.5-meter drift length
- Wire plane charge read-out
- Photodetectors (Arapuca) embedded in Anode Plane Assemblies

Vertical Drift



- Two volumes
  - 500 V/cm vertical-drift (VD) field
  - 6-meter drift length
- PCB charge read-out
- Top electronics replaceable
- Xe-doping
- Photodetectors (Arapuca) embedded in Cathode and on membrane

Neutrino Oscillations

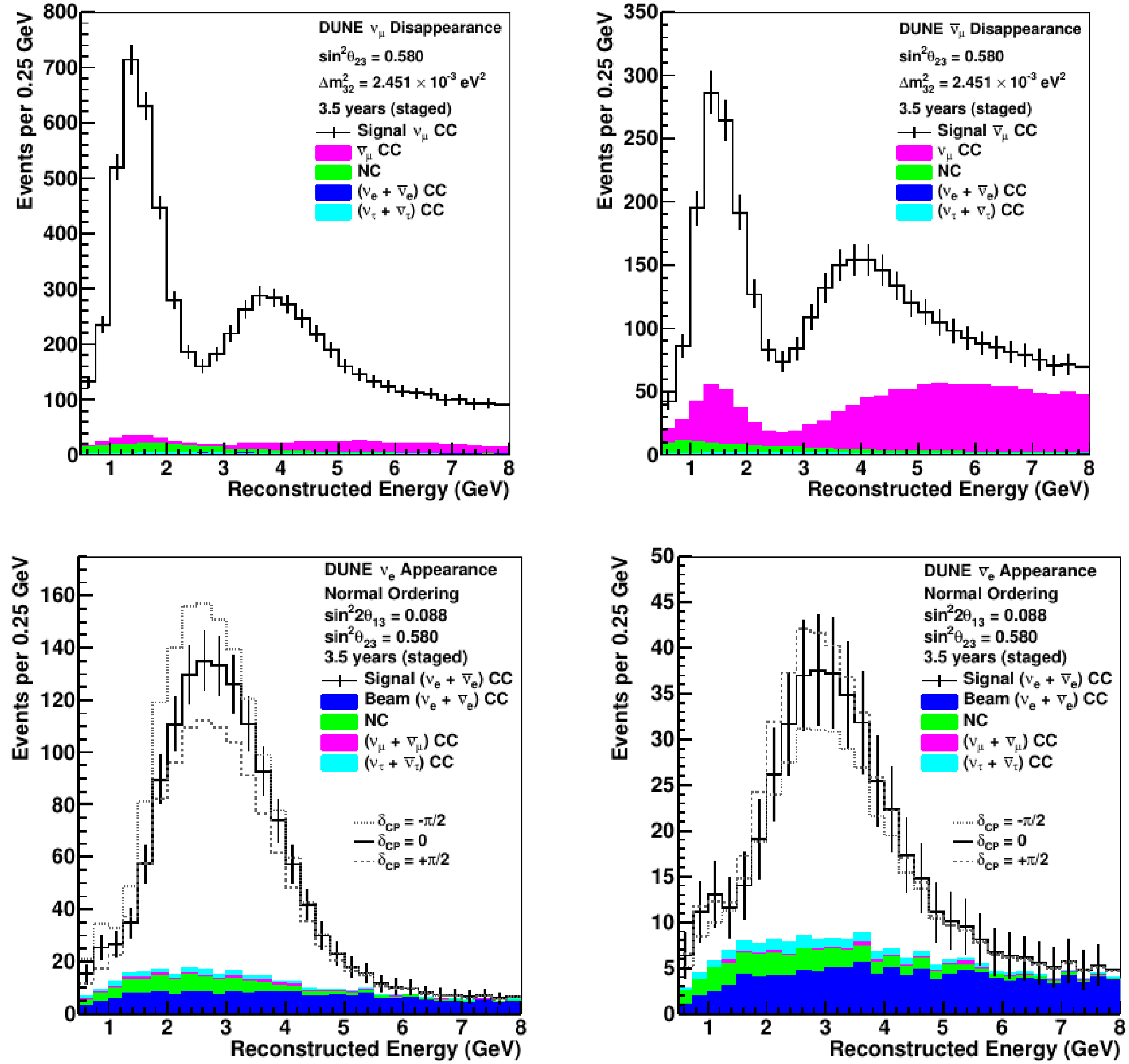
Measure appearance and disappearance for both neutrino and anti-neutrinos

disentangle Mass Ordering and CP effects

Spectral measurement - 1st and 2nd maxima

~7 years running

Order of 10,000 ν_μ and 1,000 ν_e

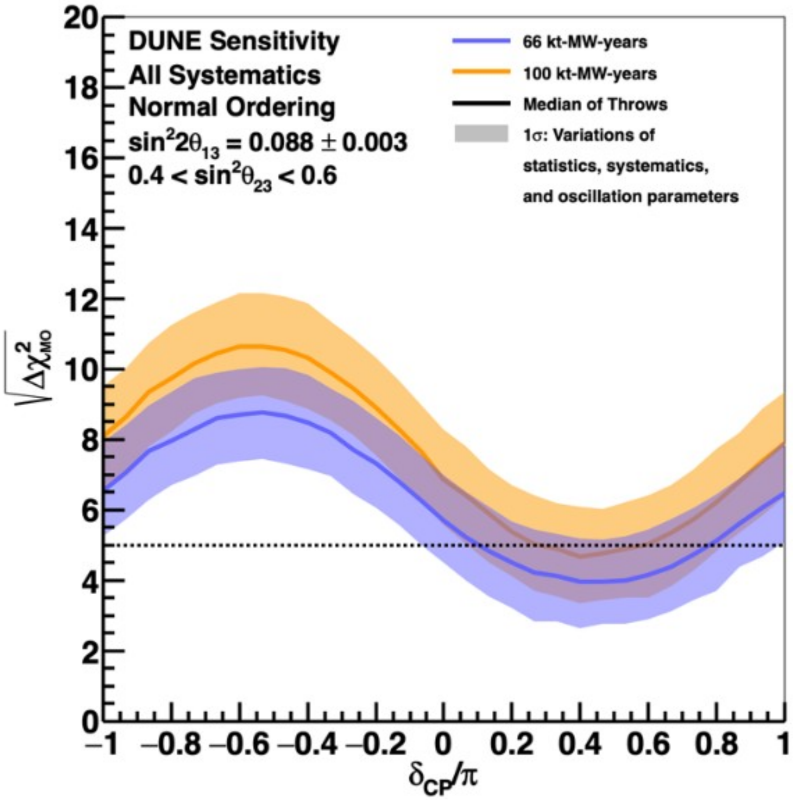


DUNE Technical Design Report (TDR) arXiv:2002.03005 EPJC (2020) 10, 97

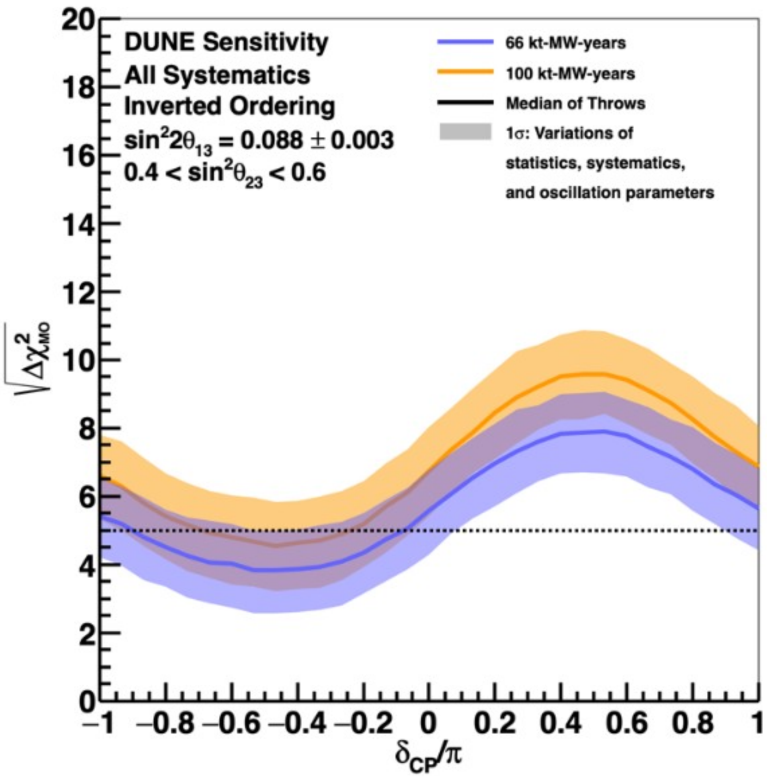
Sensitivity – Phase 1

Determine neutrino mass ordering at 3σ (5σ) with 66 (100) kt-MW-yr exposure

Normal ordering



Inverted ordering



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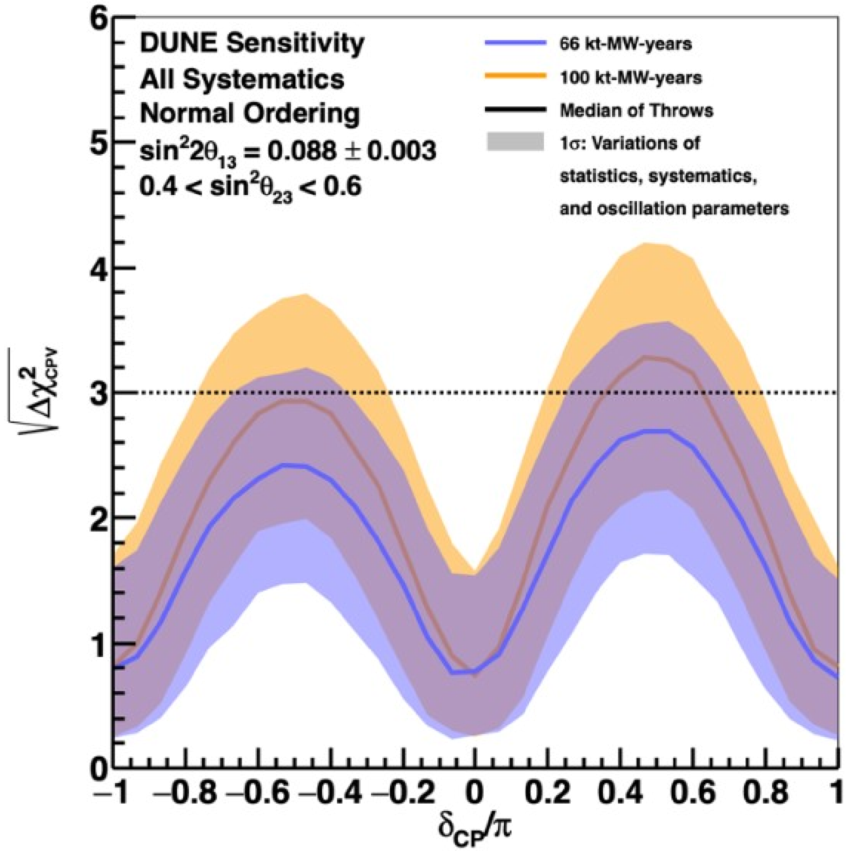
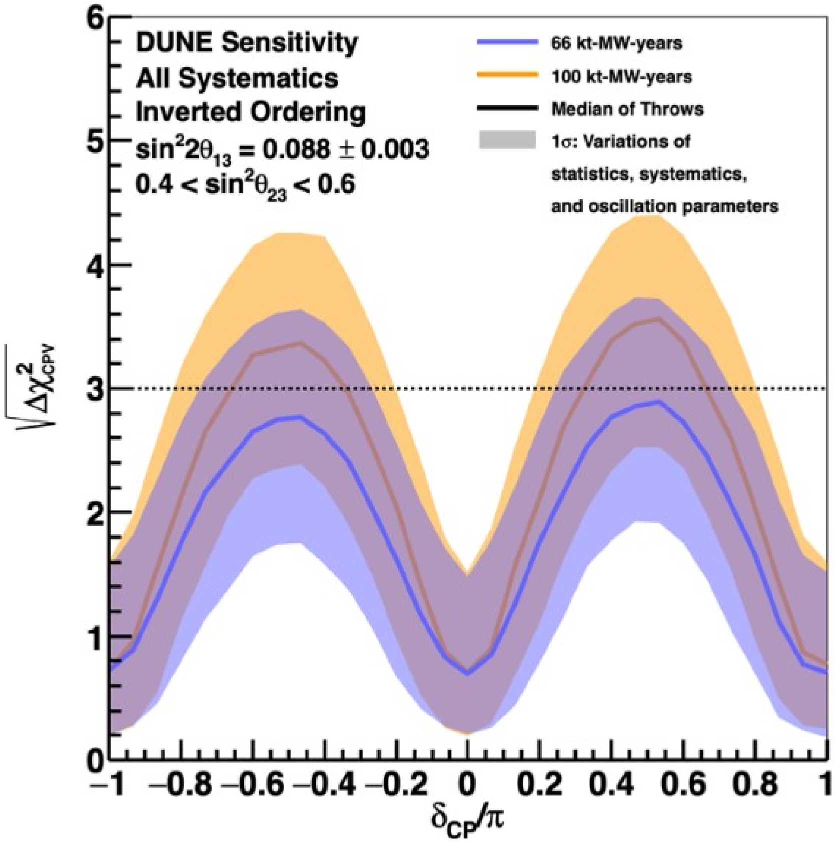
Sensitivity – Phase 1

$\delta_{CP} = \pm 90°$, CPV at 3σ

Normal ordering



Inverted ordering



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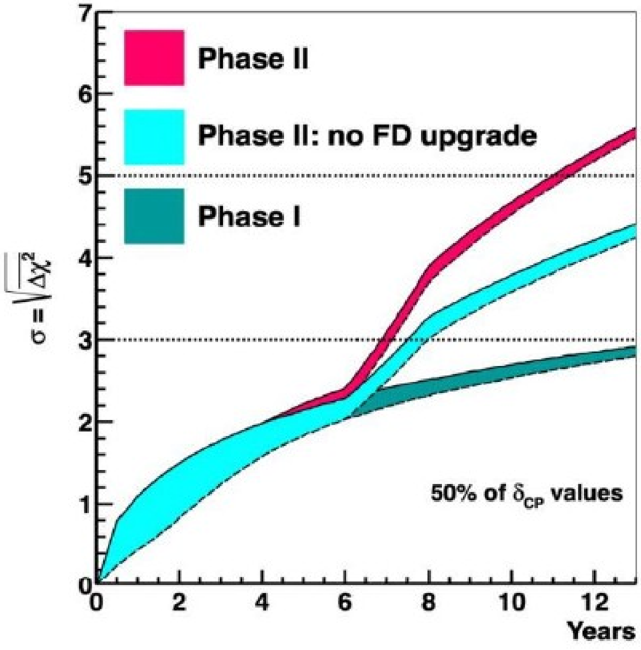
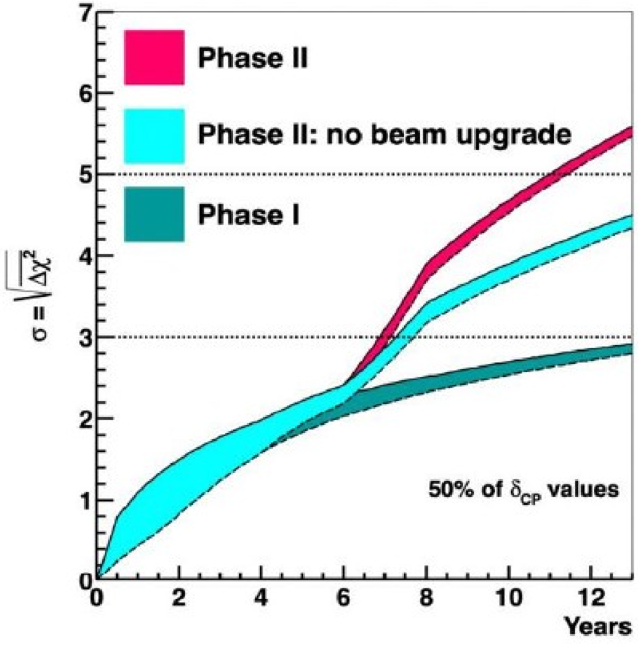
Sensitivity – Phase 2

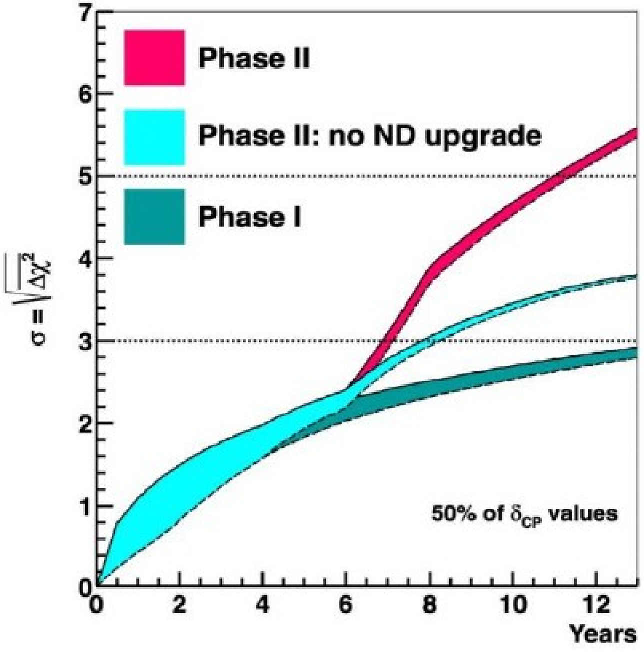
- 4 FD
- ND upgrade
- 2.4 MW beam

If δ_{CP} = ±90°, 5σ in 7 years

For 50% of δ_{CP} values 5σ CPV in 12 years







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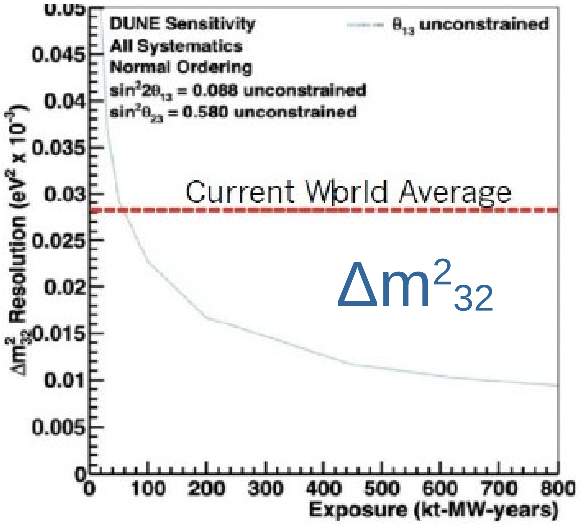
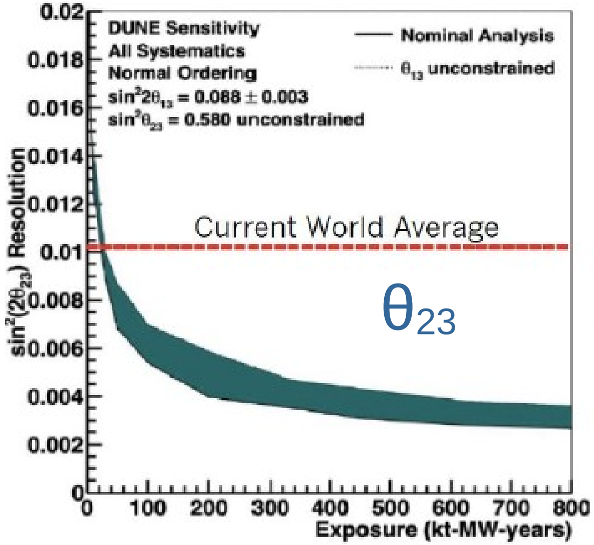
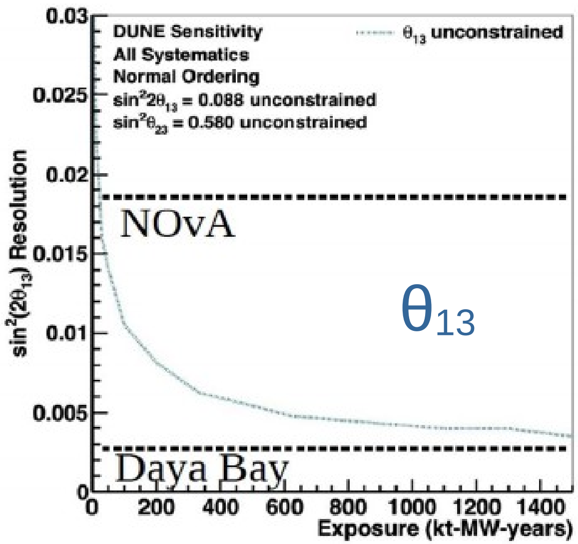
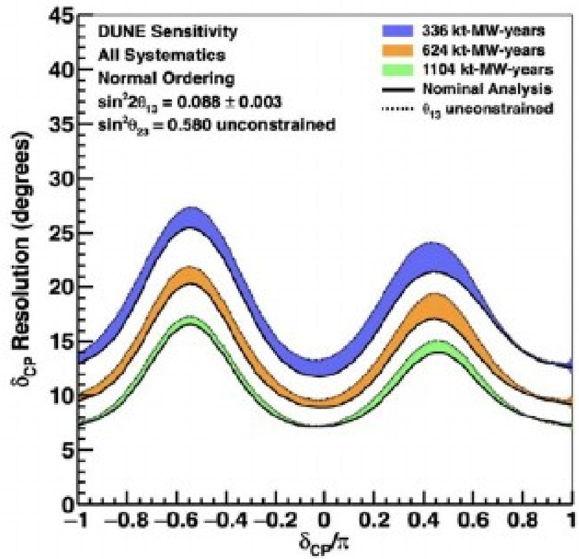
Precision Measurements





Oscillation parameters:
Δm^2_{32}, δ_{CP}, θ_{23}, θ_{13}





Precision δ_{CP} : 6 – 16°

Conclusion

- DUNE is under construction!
- At CERN neutrino platform
  - Testing of Vertical Drift in the cold-box continues
  - ProtoDUNE Vertical Drift – filling soon (to run with beam test 2025)
- R&D continues preparing for Phase 2
- Running FDs expected from 2028
- Beam and ND from 2031