Long-Baseline Neutrino Experiments and the enabling role of the CERN Neutrino Platform: DUNE and ProtoDUNE

Gargamelle, 1970s

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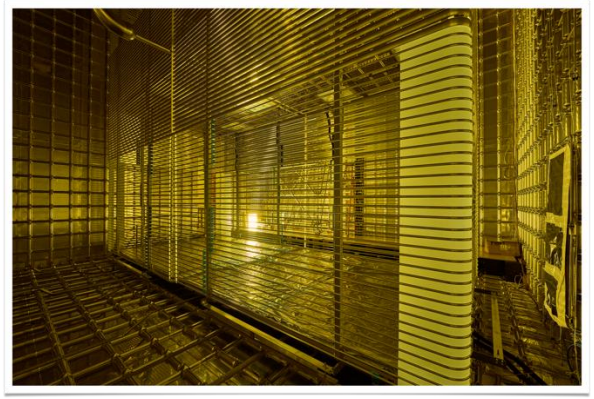
January 2025



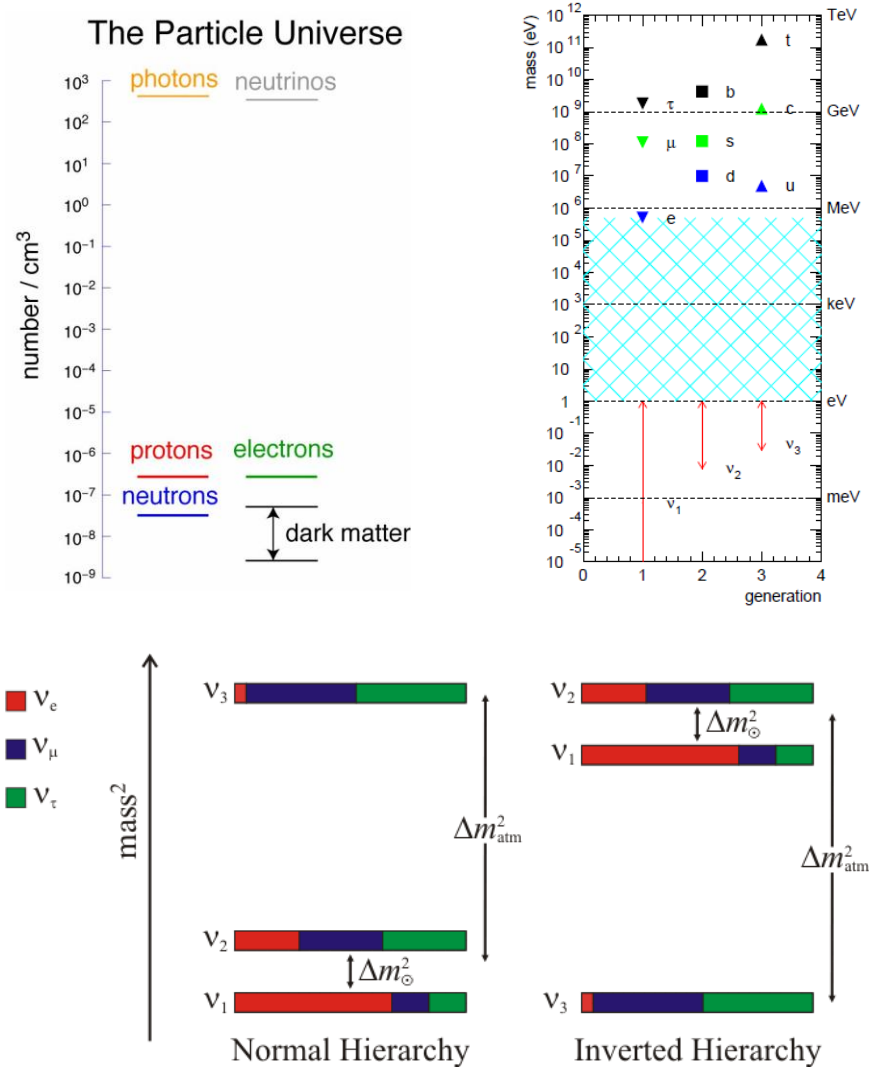
ProtoDUNE VD, 2020s

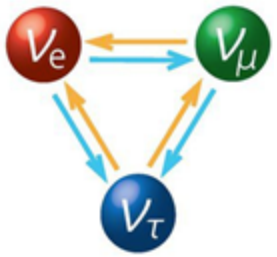
UNIVERSITY OF LIVERPOOL

CERN

Science context: the mysteries of neutrinos

- Abundant, light, elusive.
- Mass origin mechanism unknown
  - Dirac or Majorana?
- Mass ordering, mass values unknown.
- Do neutrino oscillations violate CP?
  - If yes, is this related to the development of our matter-dominated universe?
- Is three-flavour mixing a complete description of all neutrino flavour oscillations?
  - Unitarity test of PMNS mixing matrix.





Neutrino mixing

$$c_{ij} = \cos(\theta_{ij})$$
$$s_{ij} = \sin(\theta_{ij})$$

2-neutrino oscillation

$$P_{\alpha\beta} = \delta_{\alpha\beta} - (2\delta_{\alpha\beta} - 1)\sin^2(2\theta)\sin^2\left(1.27 \bullet \Delta m^2 \bullet \frac{L}{E}\right)$$

Weak eigenstates — PMNS mixing matrix — Mass eigenstates

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

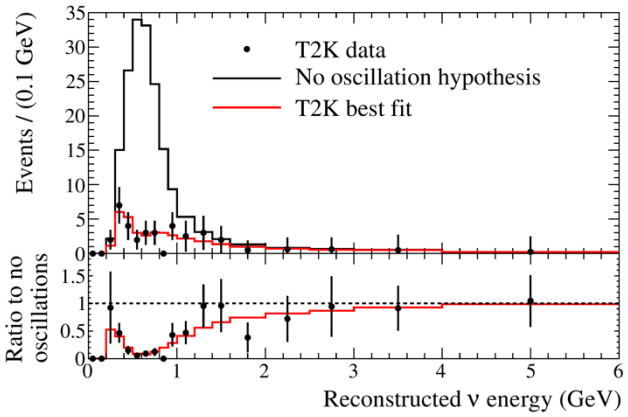
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} c_{21} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

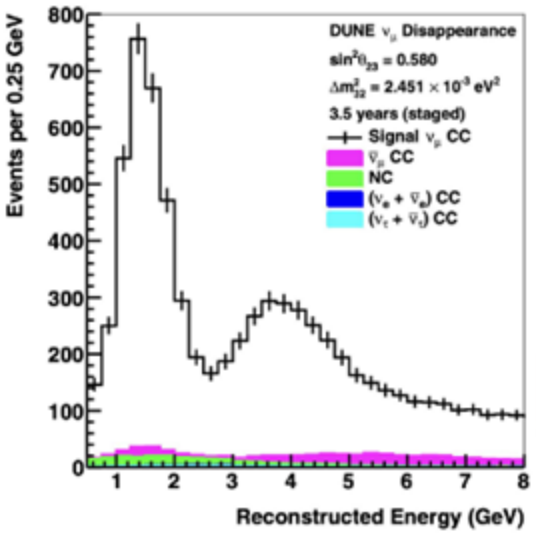
Atmospheric (+ ν_μ Long BL)

ν_μ Long BL reactor Short BL

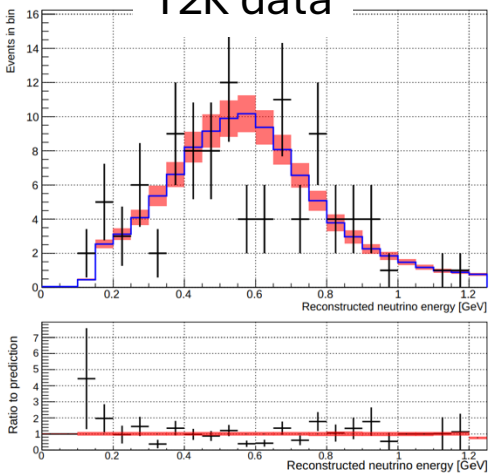
Solar (+ reactor Long BL)

ν_μ to ν_μ disappearance

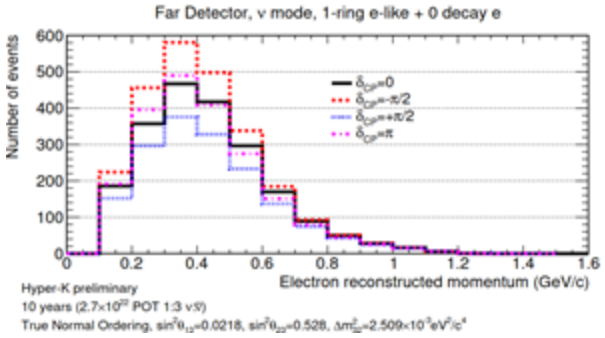




T2K data

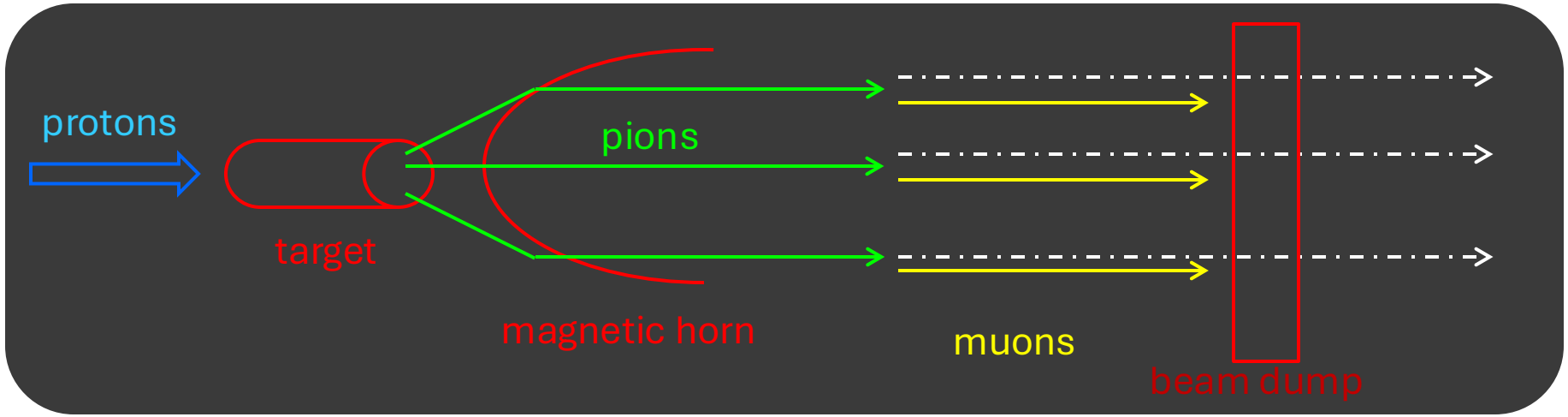


ν_μ to ν_e appearance



Outline of a Long-Baseline neutrino oscillation experiment

- High intensity proton beam (30-120 GeV, 1-2 MW) on target, focusing (2-3 horns), pion decay tunnel, dump: ~99% ν_μ beam production.



- Near Detector (few 100 m from target) to characterize neutrino beam.
- Huge Far Detector (50-500 kton) 300-1300 km away, underground (0.5 – 1.5 km).
- Adjust **L/E** for FD to be at maximum of ν_μ disappearance: maximum sensitivity.

International Context: strategies

USA P5 2014

- Physics drivers: Higgs, Neutrinos, Dark Matter, Cosmic Acceleration, New Physics.
- Recommended Large Projects:
  - LHC, HL-LHC: *highest-priority near-term* large project,
  - LBNF and experiment (DUNE): *highest-priority* large project *in its timeframe*.

USA P5 2023

- Physics drivers: Neutrinos, Higgs, New Particles, Quantum Imprints, Dark Matter, Cosmic Evolution.
- Highest priorities, not ranked: HL-LHC, DUNE phase I, Rubin Observatory.
- Highest priority new large projects, ranked: CMB-S4, DUNE phase II, off-shore Higgs Factory, G3 Dark Matter, IceCube Gen-2.

Japan 2022

- ILC realization, while continuing physics at LHC and HL-LHC.
- Hyper-Kamiokande completion, while continuing T2K.

European Strategy for Particle Physics

2013 "Large-scale priorities":

- LHC, HL-LHC;
- design studies and R&D towards an ambitious post-LHC accelerator project at CERN;
- discuss a possible participation at ILC in Japan;
- develop a neutrino programme to pave the way for a substantial European role in future long-baseline experiments. Explore the possibility of major participation in leading long-baseline neutrino projects in the US and Japan.

2020 "Major developments from the 2013 Strategy":

- The full physics potential of the LHC and the HL-LHC, including the study of flavour physics and the quark-gluon plasma, should be exploited.
- Europe, and CERN through the Neutrino Platform, should continue to support long baseline experiments in Japan and the USA. In particular, they should continue to collaborate with the USA and other international partners towards the successful implementation of LBNF and DUNE.

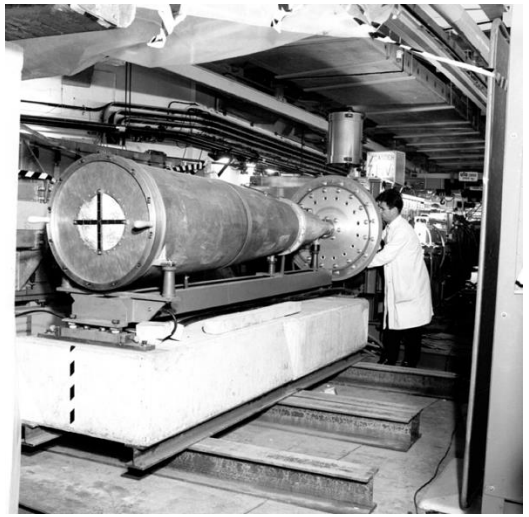
CERN actions

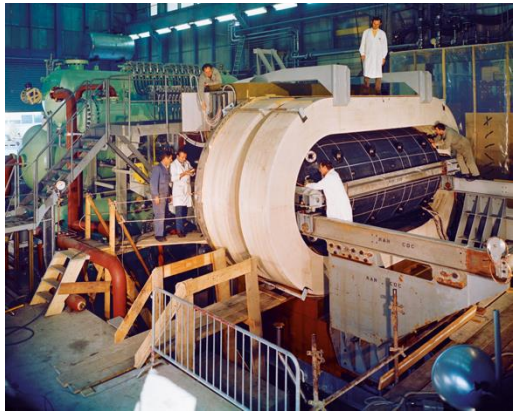
- 2013: Neutrino Platform Project created.
- 2015: Resource allocation to the NP; CERN-DOE Neutrino Protocol.
- 2017: Addendum to CERN-DOE agreement: ProtoDUNEs, first DUNE FD cryostat.
- 2022: Amendment to the agreement: second DUNE FD cryostat.

A first for CERN: contributions to both detector and facility for an off-laboratory experiment.

Neutrinos at CERN: a long history

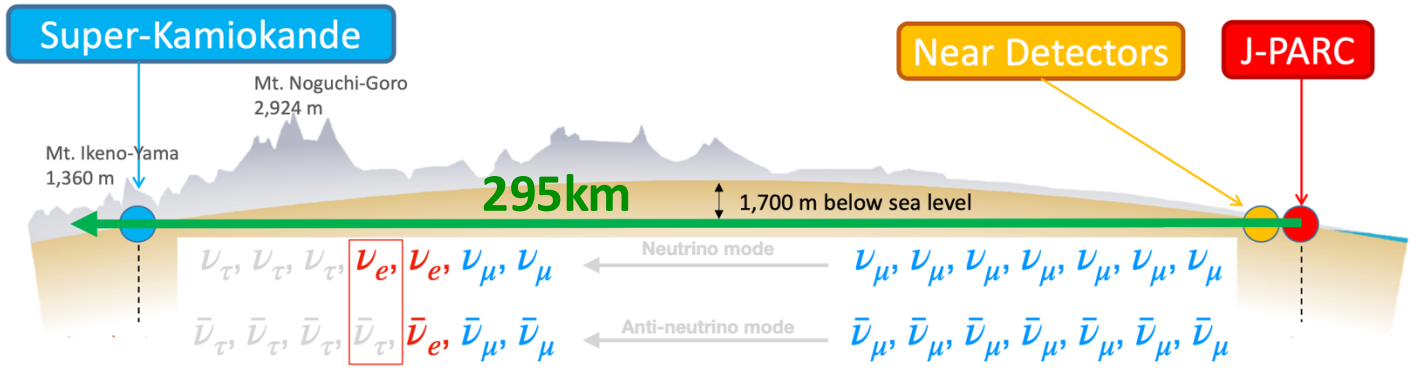
- 1958: observation of the (π to $e\nu_e$) decay (Fidecaro, Fazzini et.al.)
- 1961: invention of magnetic horn, a focusing device for intense neutrino beams (S. Van der Meer)
- 1973: discovery of neutral currents in neutrino scattering (Gargamelle)
- 1977-91: CDHS, CHARM, CHARM II
- 1994-98: CHORUS, NOMAD
- 2006-12, CNGS: OPERA (observation of ν_μ to ν_τ appearance), ICARUS (demonstration of large LAr TPC, neutrino oscillation program).





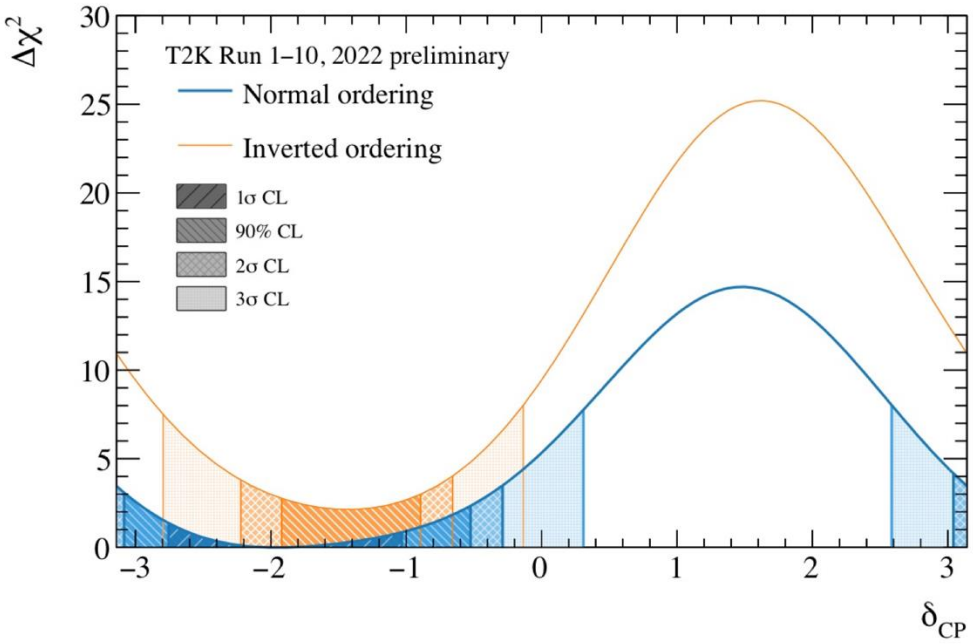
Ongoing experiments: T2K, NOvA

T2K experiment

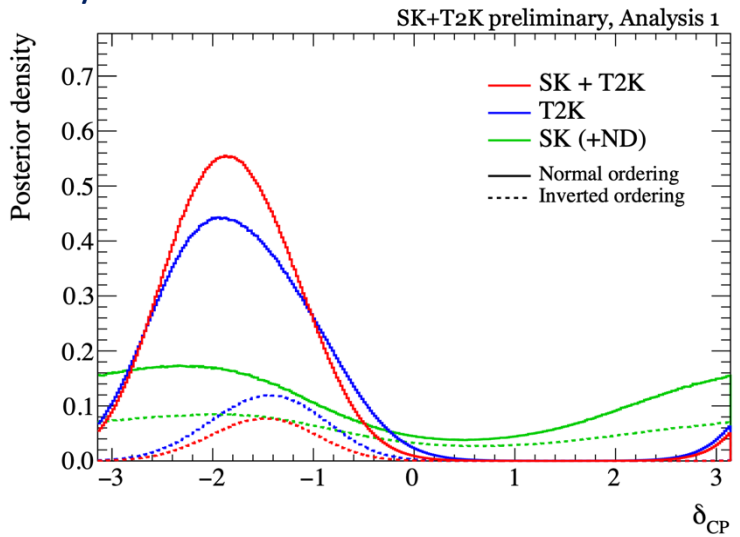


~560 members, 74 institutes, 15 countries(incl. CERN)

- Latest status of CPV search in T2K



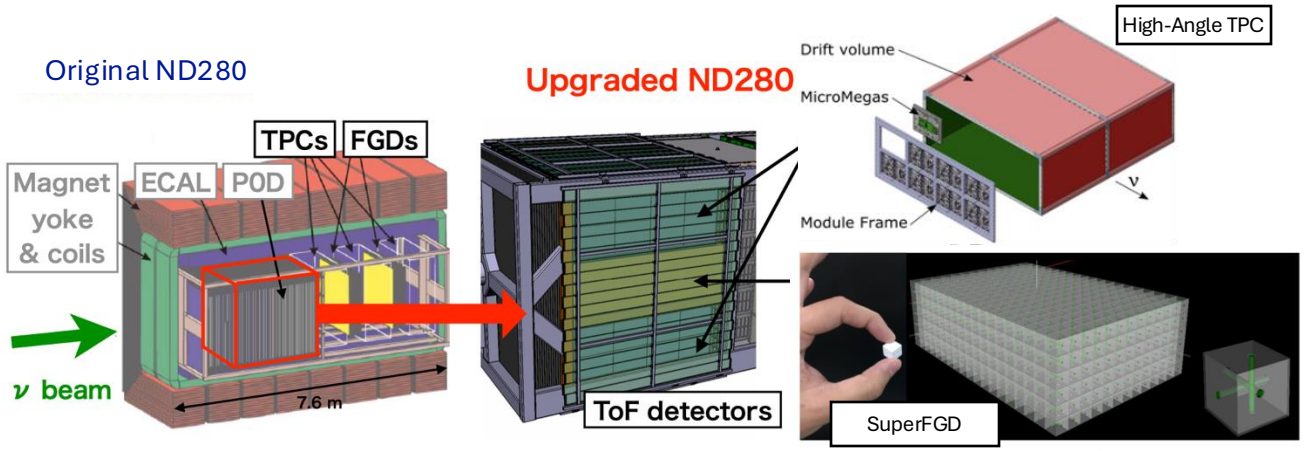
Joint oscillation analysis SK+T2K:



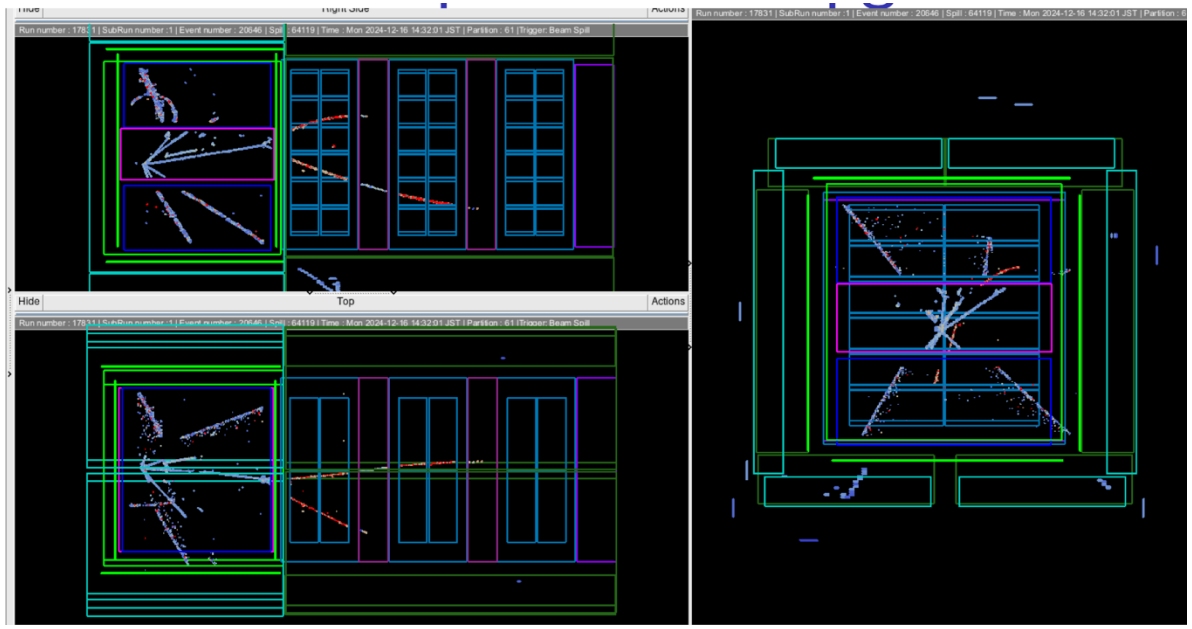
CP conservation excluded at 90% C.L.

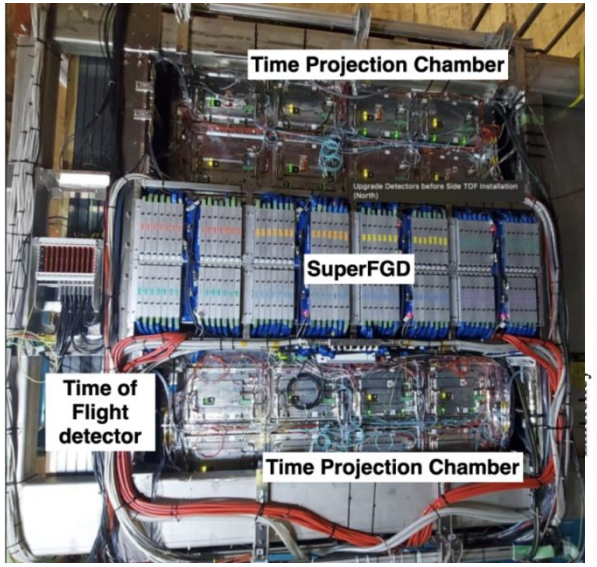
T2K ND280 upgrade (CERN-NP07)

CERN has been playing key roles in the ND280 upgrade project



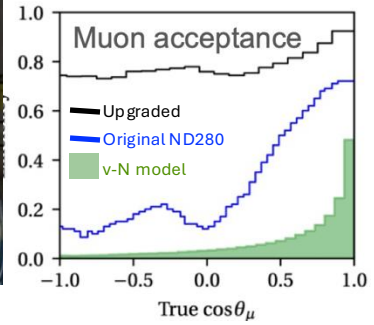
Event display (data)

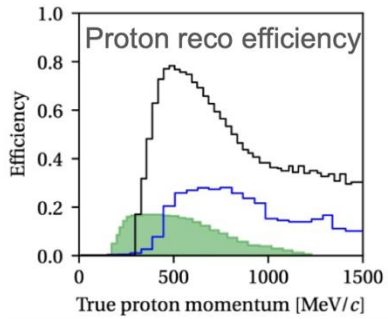




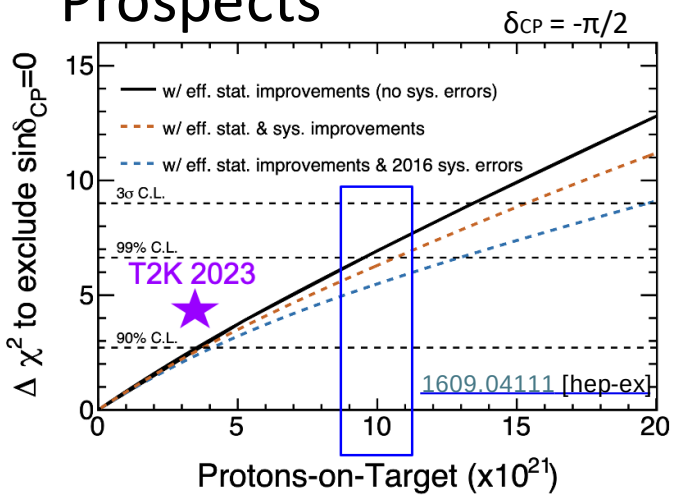
2×10^6 of 1cm^3 scintillator cubes

New capability to deeply understand neutrino interactions





Prospects

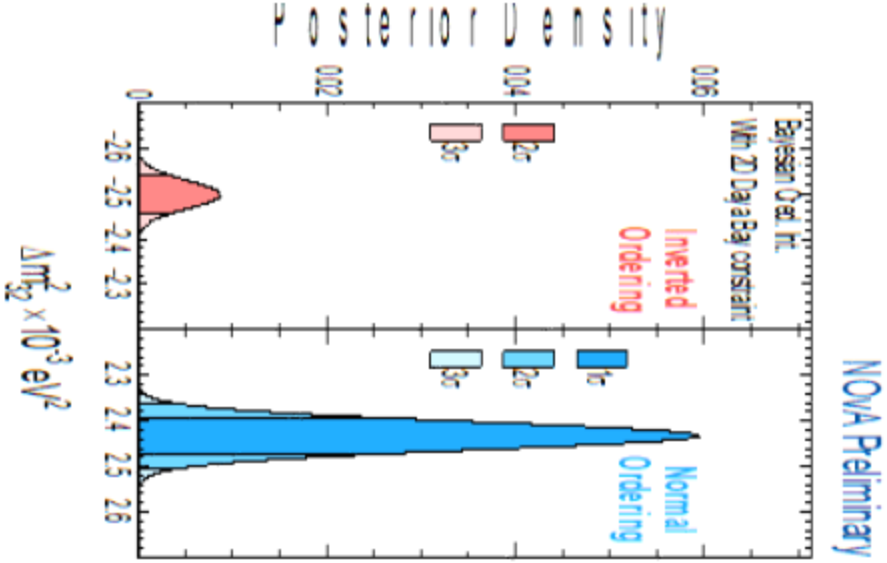


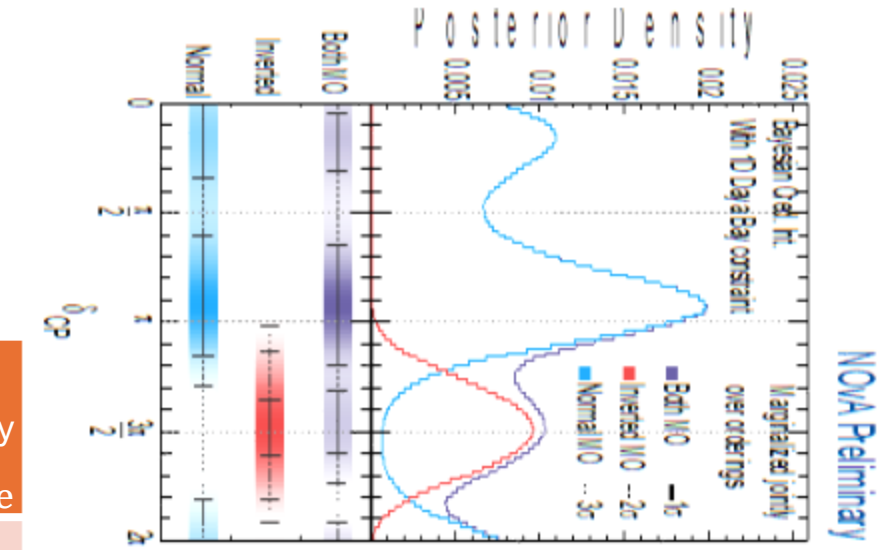
- T2K aims to double data sample by increasing beam power up to 1.3MW (currently 0.8MW)
- With 10 x 10^{21} POT, T2K will have world leading CPV sensitivity

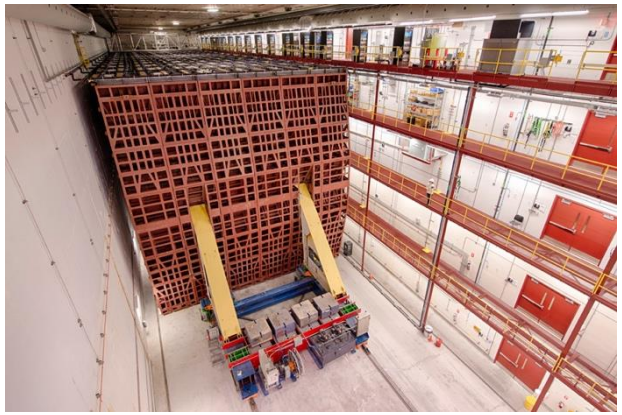
Installation of the upgraded detectors completed !
Physics data taking since June 2024

NOvA

- 800 km baseline from Fermilab to Ash River, Minnesota
- 14,000 ton segmented liquid scintillator Far Detector
- Exposure: (26.6, 12.5)x10^{20} POT (neutrinos, antineutrinos)
- New (2024) low energy electron neutrino sample enhances mass ordering sensitivity, among other analysis updates.
- Incorporates reactor (DayaBay) data in NOvA analysis to either constrain θ_{13} (1D) or both θ_{13} and Δm^2 (2D)
- Bayesian and Frequentist techniques give similar results



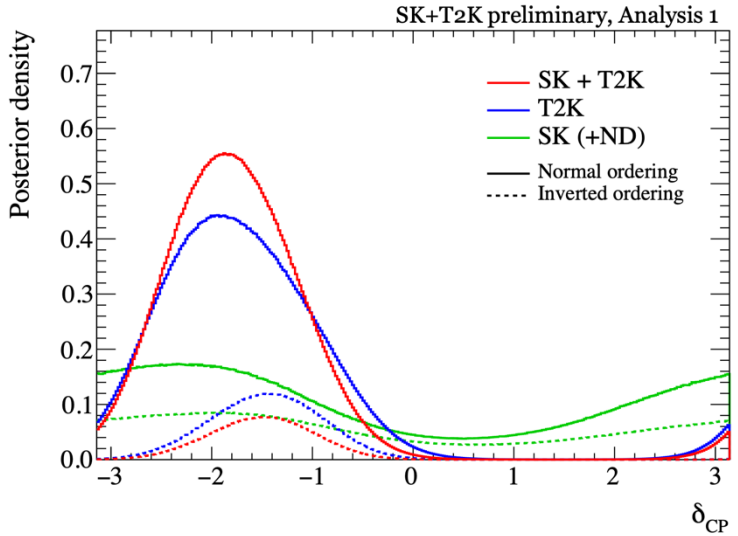


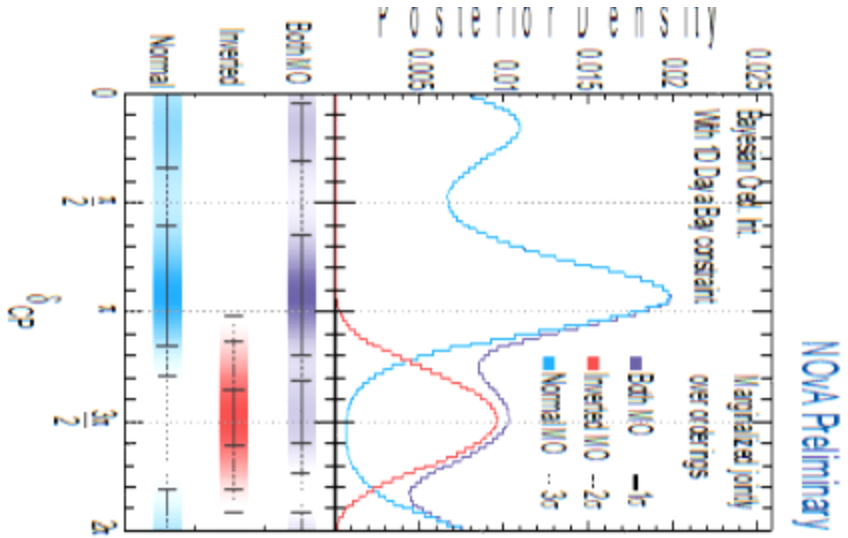


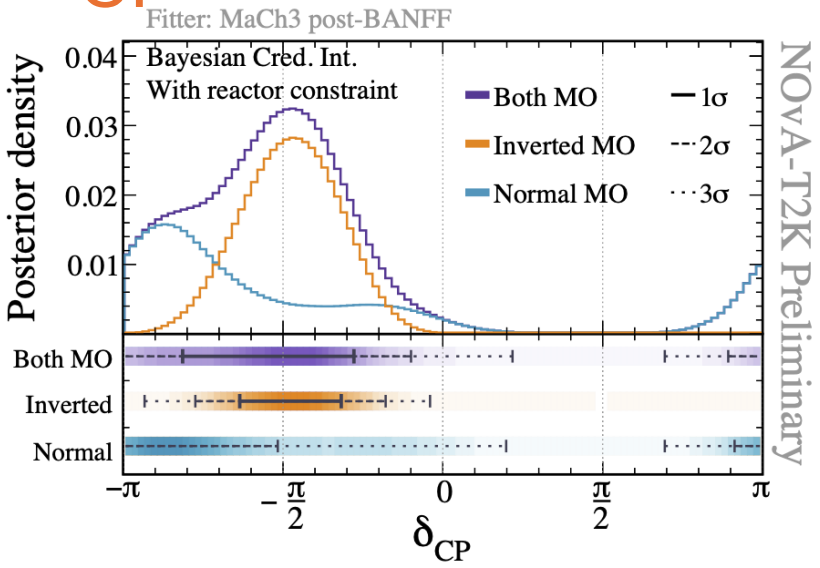
10 years of NOvA FD Data

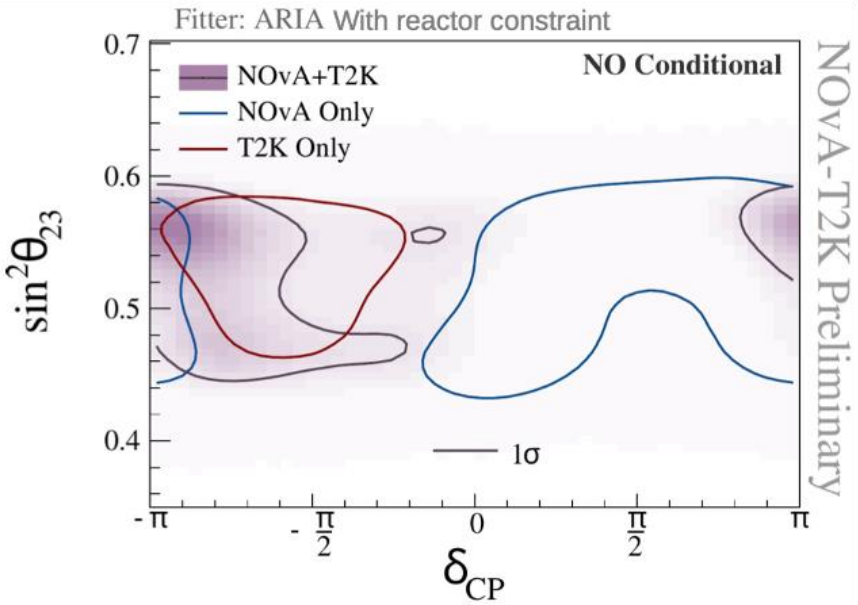
	ν_μ	$\overline{\nu_\mu}$	ν_e	$\overline{\nu_e}$	Low Energy ν_e
Observed	384	106	169	32	12
Pred. BG	11.3	1.7	54.9	12.2	6.8

T2K-NOvA joint analysis: δ_{CP}







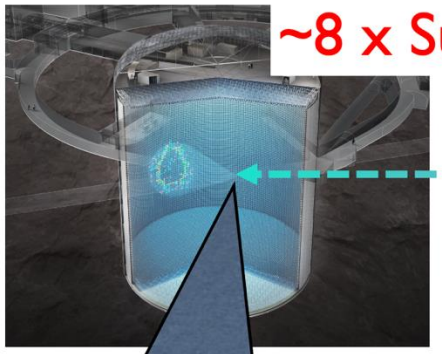


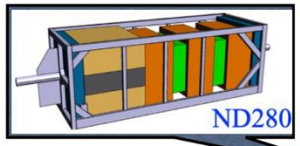
The next generation: Experiments under construction

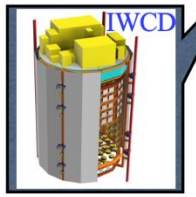
Experiment	Baseline	Far Detector fiducial mass	Far Detector type	Location
DUNE	1,300 km	40 kton	Liquid Argon TPC	USA
Hyper-Kamiokande	300 km	190 kton	Water Čerenkov	Japan

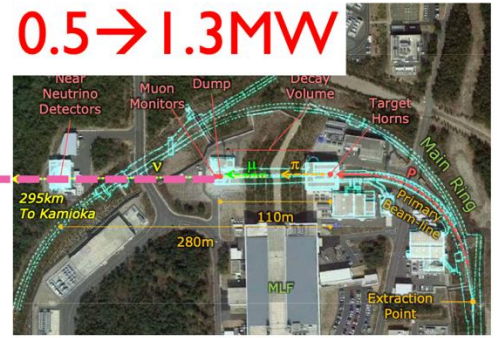
Hyper-K snapshot

J-PARC off-axis ν_μ & $\overline{\nu}_\mu$ beam (~0.6 GeV, ~295 km)



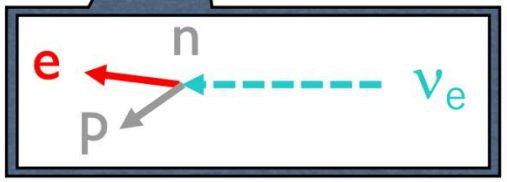






$\nu_e / \overline{\nu}_e$ The Japanese Alps $\nu_\mu / \overline{\nu}_\mu$

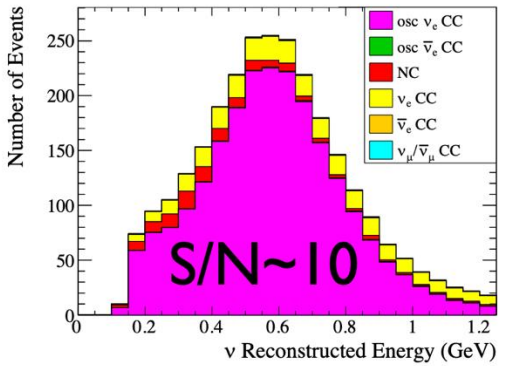
2.5 deg. off-axis

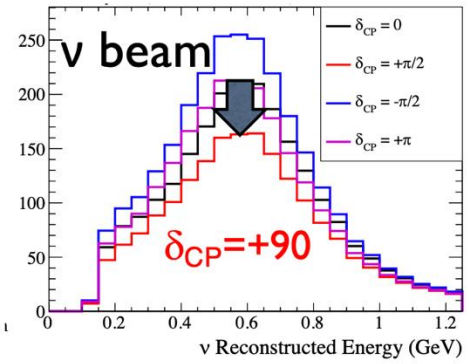


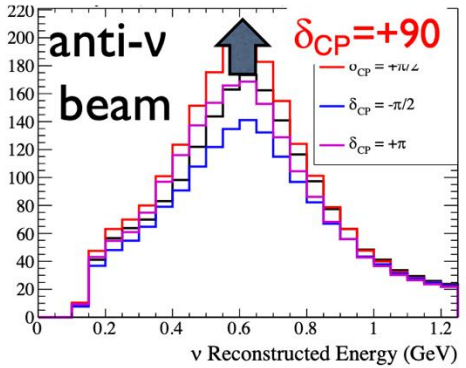
ν_e appearance signal = single e event

CCQE : $\nu_e + n \rightarrow e + p$

(dominant process at J-PARC beam energy)







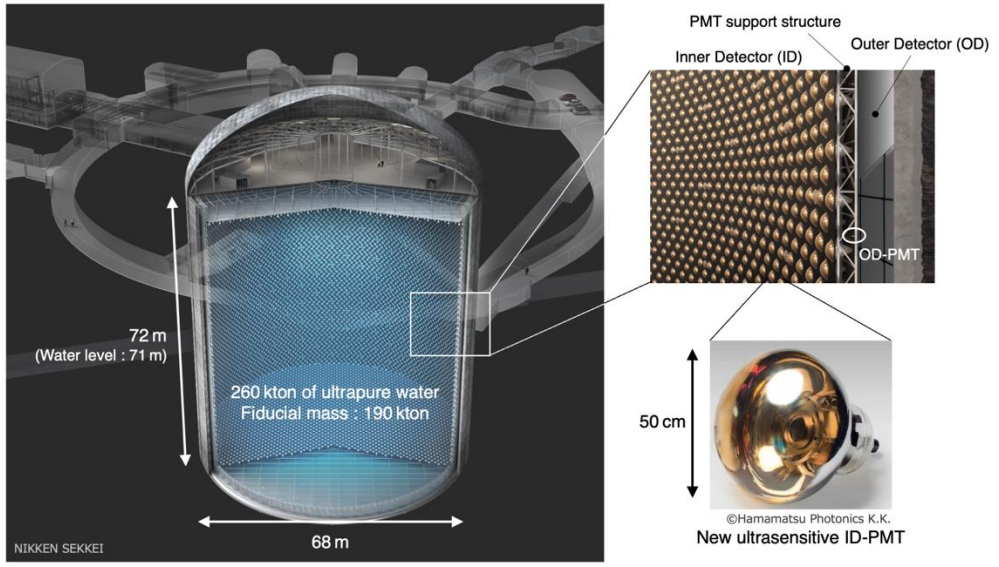
Relatively Small matter Effect & Large CPV Effect

HK 10 yr, 2.7×10^{22} POT 1:3 ν:$\overline{\nu}$, 1-ring e-like + 0 decay e, > 1000 events each

Hyper-K highlights

- ~ 600 members, ~300 Europeans
- Main cavern to be completed in the next few months
- 20,000 50cm-diameter PMTs, >10,000 delivered. Efficiency SK x2.
- Underwater electronics to be assembled and tested at the CERN NP.

- ND280 upgraded (T2K).
- IWCD intermediate detector, prototype at CERN (T9).



DUNE

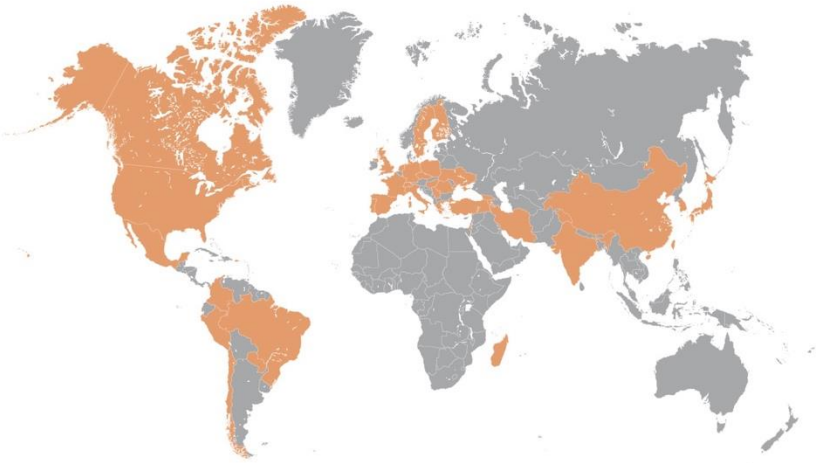
Deep Underground Neutrino Experiment

P5 2023 Report:

“the centerpiece of a decades-long program to reveal the mysteries of elusive neutrinos”

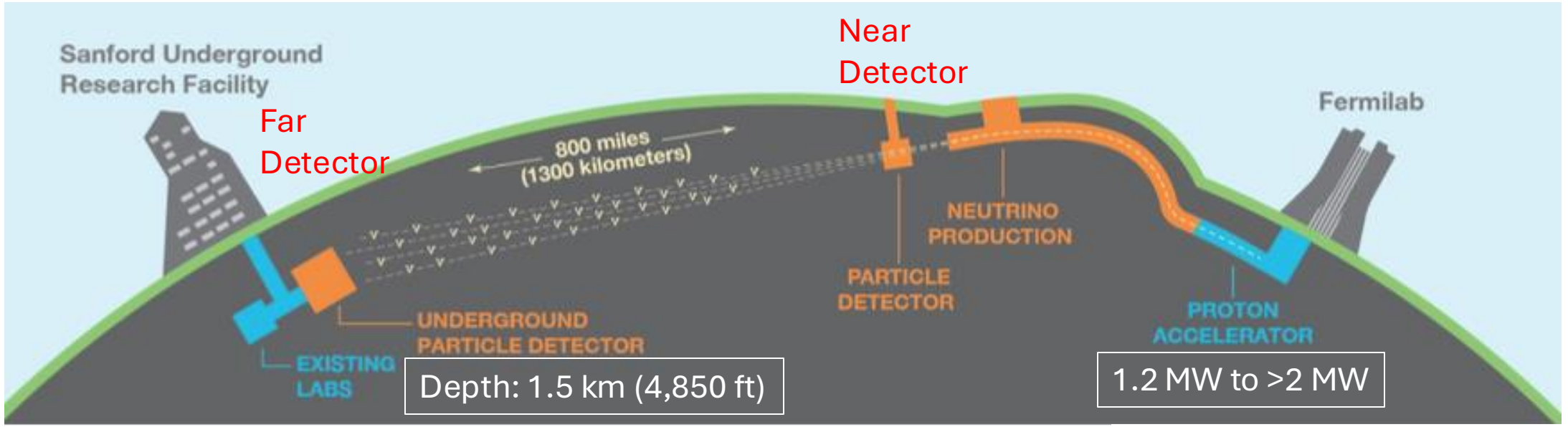
“the definitive long-baseline neutrino oscillation experiment of its kind”

DUNE: the Collaboration

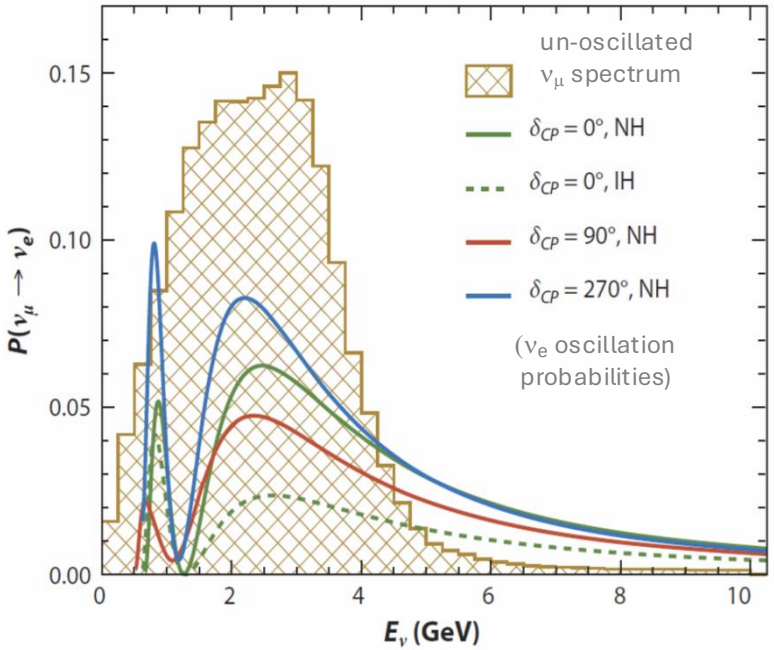


- >1,500 collaborators: >600 European
- ~220 Institutes, including CERN
- 35 countries

DUNE

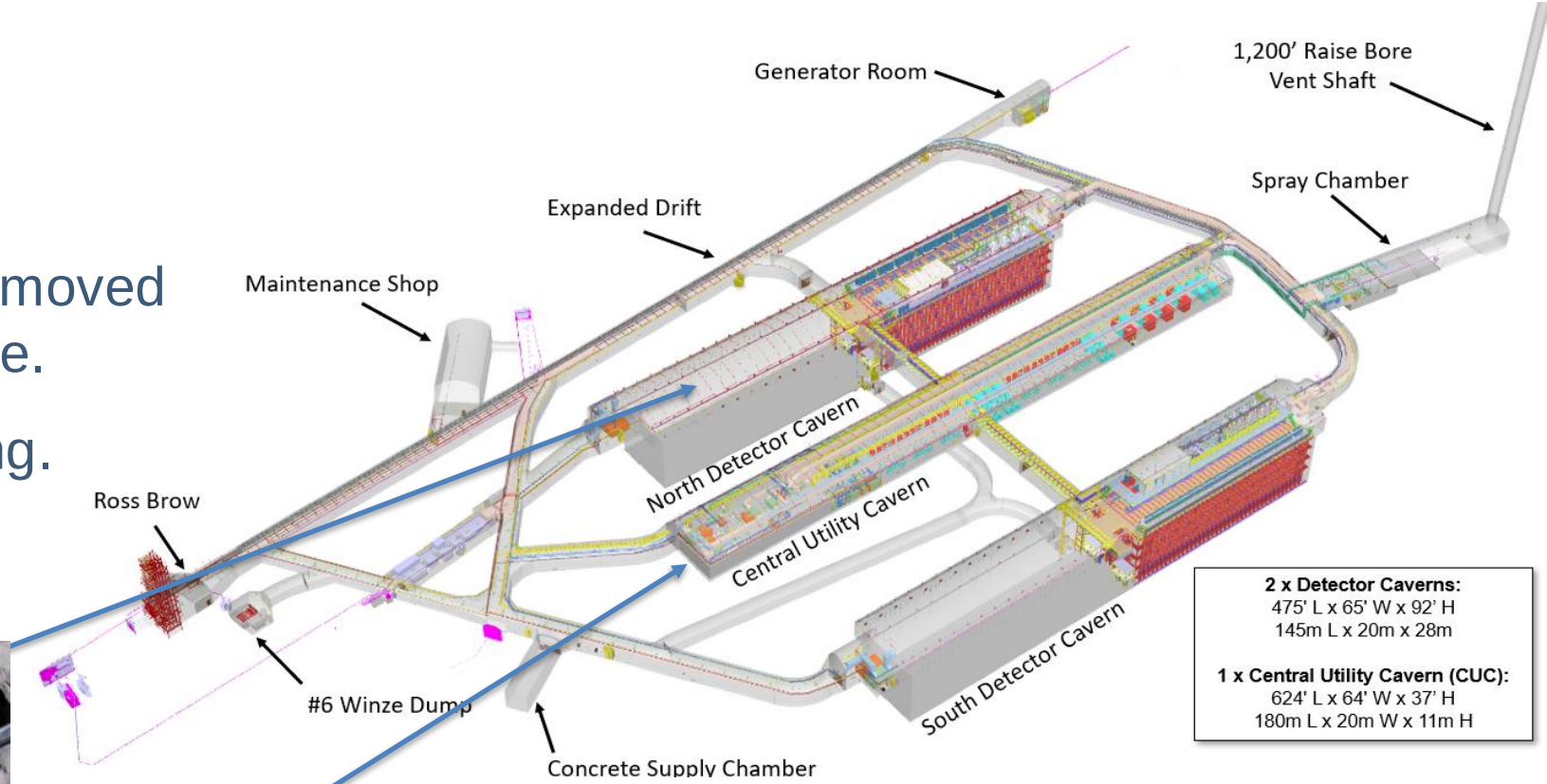


- *High precision measurements of neutrino mixing in a single experiment*
- Determination of the neutrino Mass Ordering in the first few years.
- Observation and measurement of CP Violation in the neutrino sector.
- Stress the 3-neutrino paradigm (PMNS unitarity).
- Solar, Atmospheric, Supernova neutrinos
- Search for New Physics.



LBNF Far Site

- 1,500 meters underground.
- 800,000 tons of rock blasted, removed to the surface. Shotcreet in place.
- Infrastructure installation ongoing.
- Cryostat assembly next!

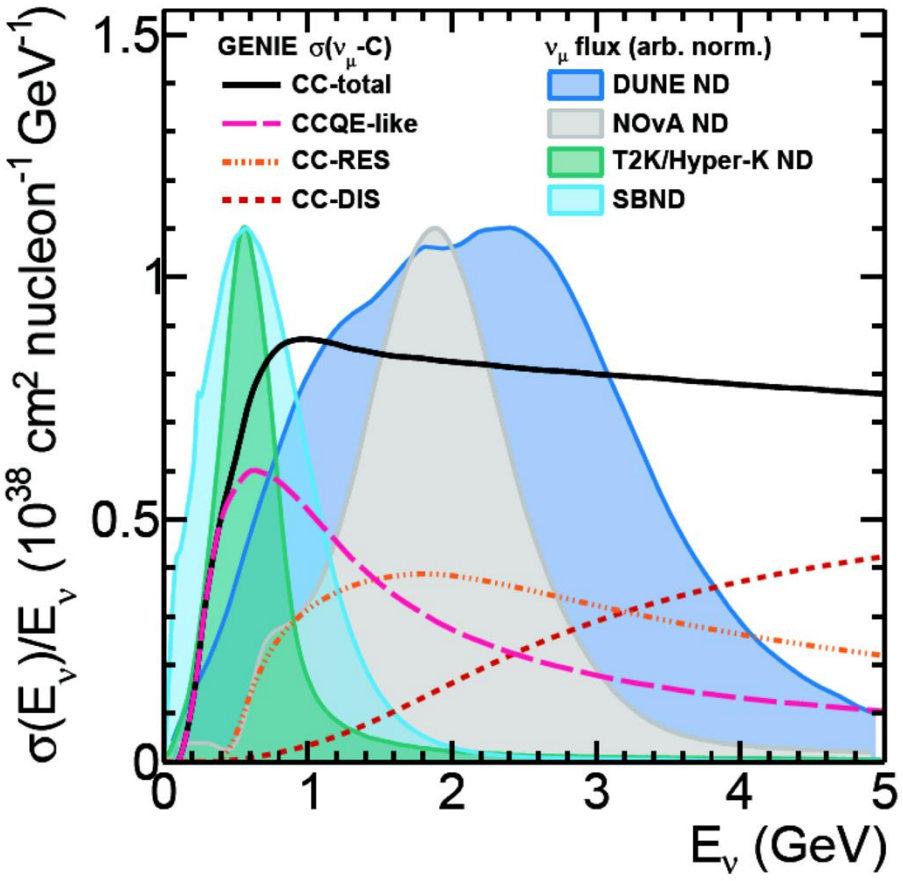


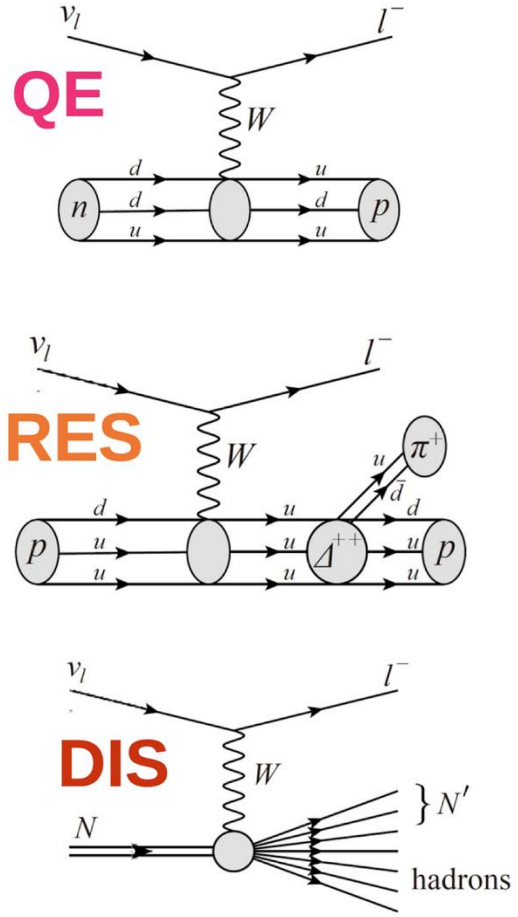
Cryostats steel at Lead, South Dakota

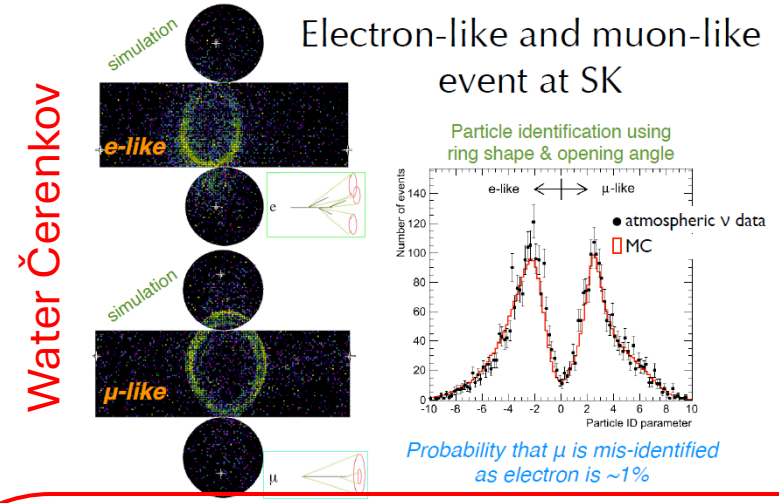
- The steel for two cryostats (CERN contribution) has been produced (Spain) and is now in the USA.
- Steel has arrived at Leeds, SD.
- Cryostat cold structure ordered.
- Ready for underground assembly (CERN).

Lead, SD

On energy, interactions, complexity & detectors

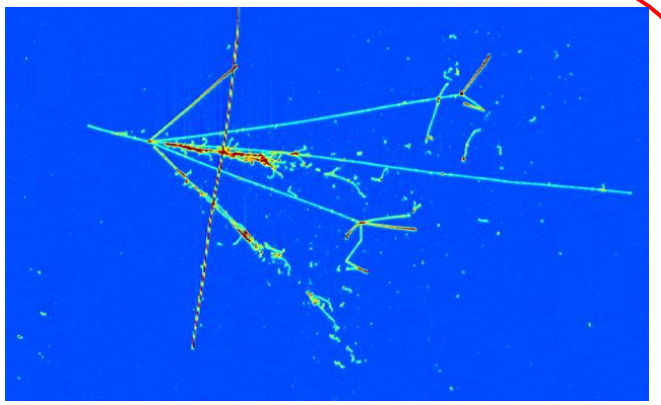


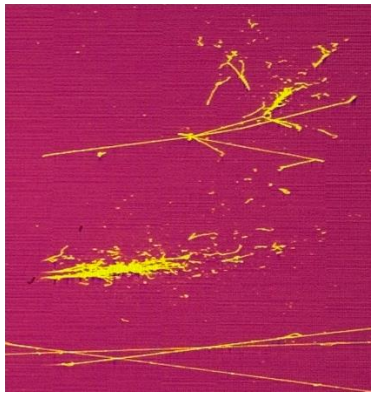


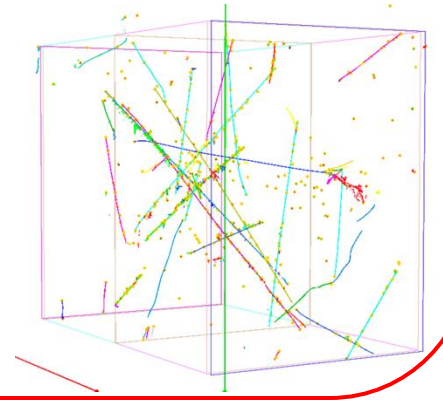


LAr TPC

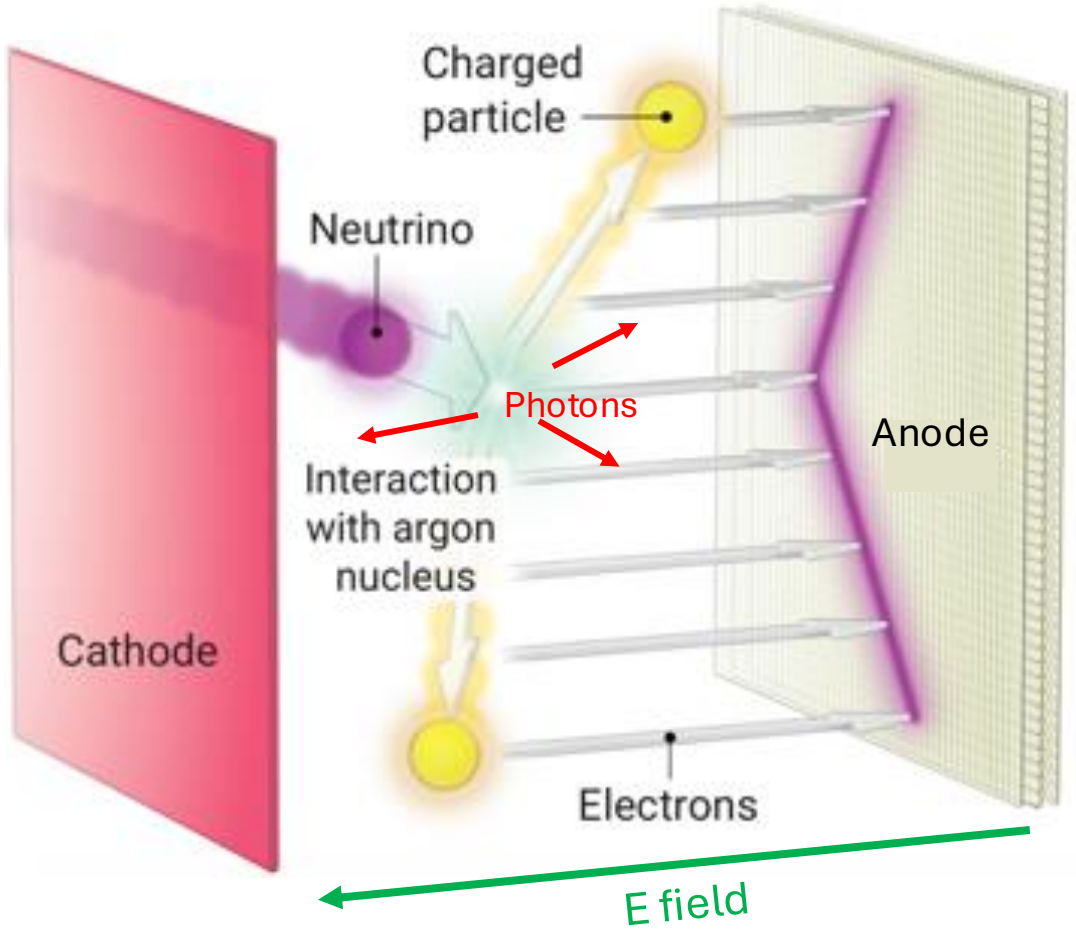
ProtoDUNE real data







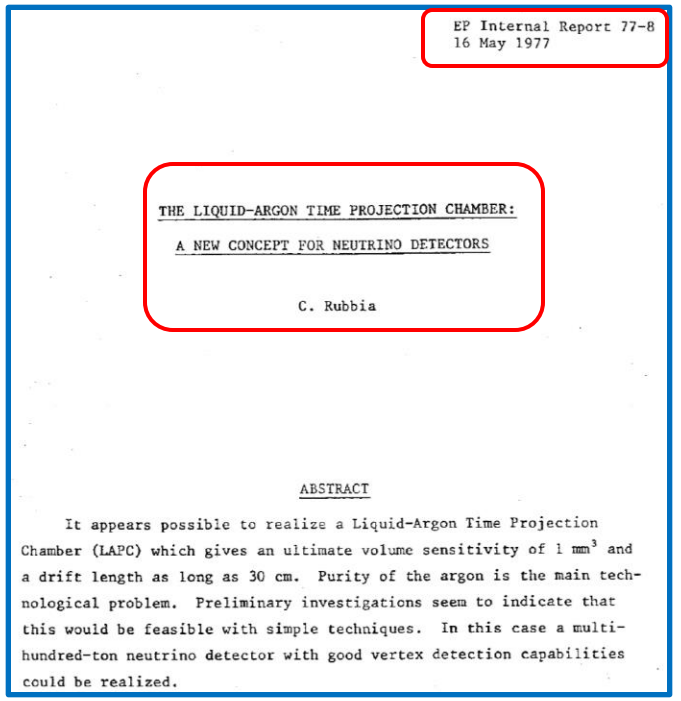
Liquid Argon Time Projection Chamber



"Electronic Bubble Chamber",
"3D camera"

- Fully active tracking calorimeter
- Homogeneity, no amplification:
  - easy to calibrate, stable in time
- Transparent to its own scintillation (128 nm)

Requires:
- High LAr purity
- E field ~500V/m



EP Internal Report 77-8
16 May 1977

THE LIQUID-ARGON TIME PROJECTION CHAMBER:
A NEW CONCEPT FOR NEUTRINO DETECTORS

C. Rubbia

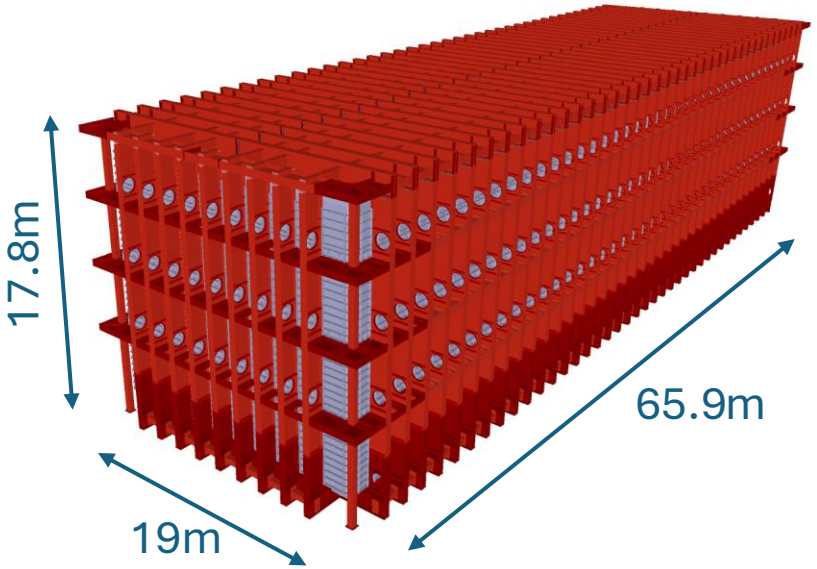
ABSTRACT

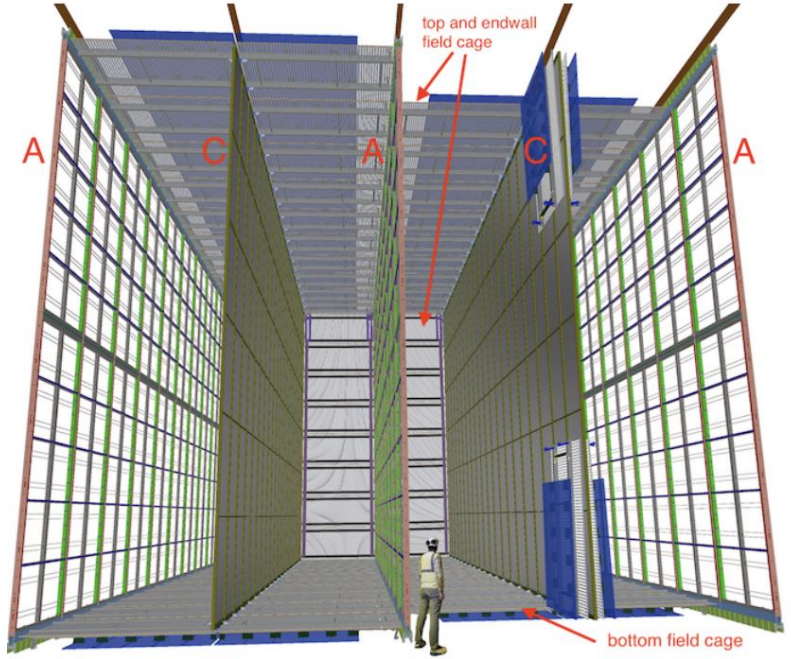
It appears possible to realize a Liquid-Argon Time Projection Chamber (LAPC) which gives an ultimate volume sensitivity of 1 mm^3 and a drift length as long as 30 cm. Purity of the argon is the main technological problem. Preliminary investigations seem to indicate that this would be feasible with simple techniques. In this case a multi-hundred-ton neutrino detector with good vertex detection capabilities could be realized.

One detector principle, two realizations: HD, VD

First 2 modules, each one holds 17 kt Argon total :

- Horizontal (charge) Drift
- Vertical (charge) Drift



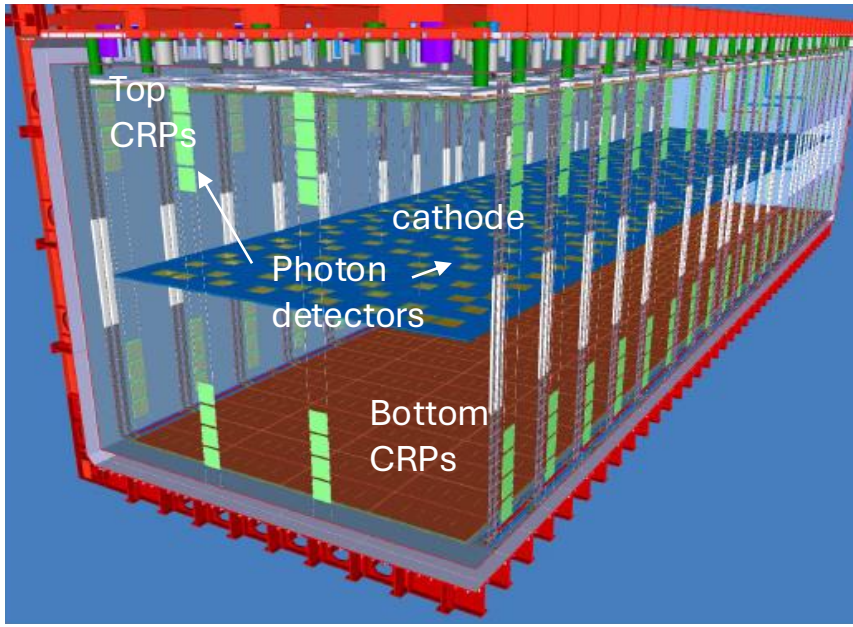


HD

Anode Plane Assemblies : wire chamber technology

Drift length 350 cm -> ~ 180 KV

9800 m^3 = 13.2 ktons active LAr



VD

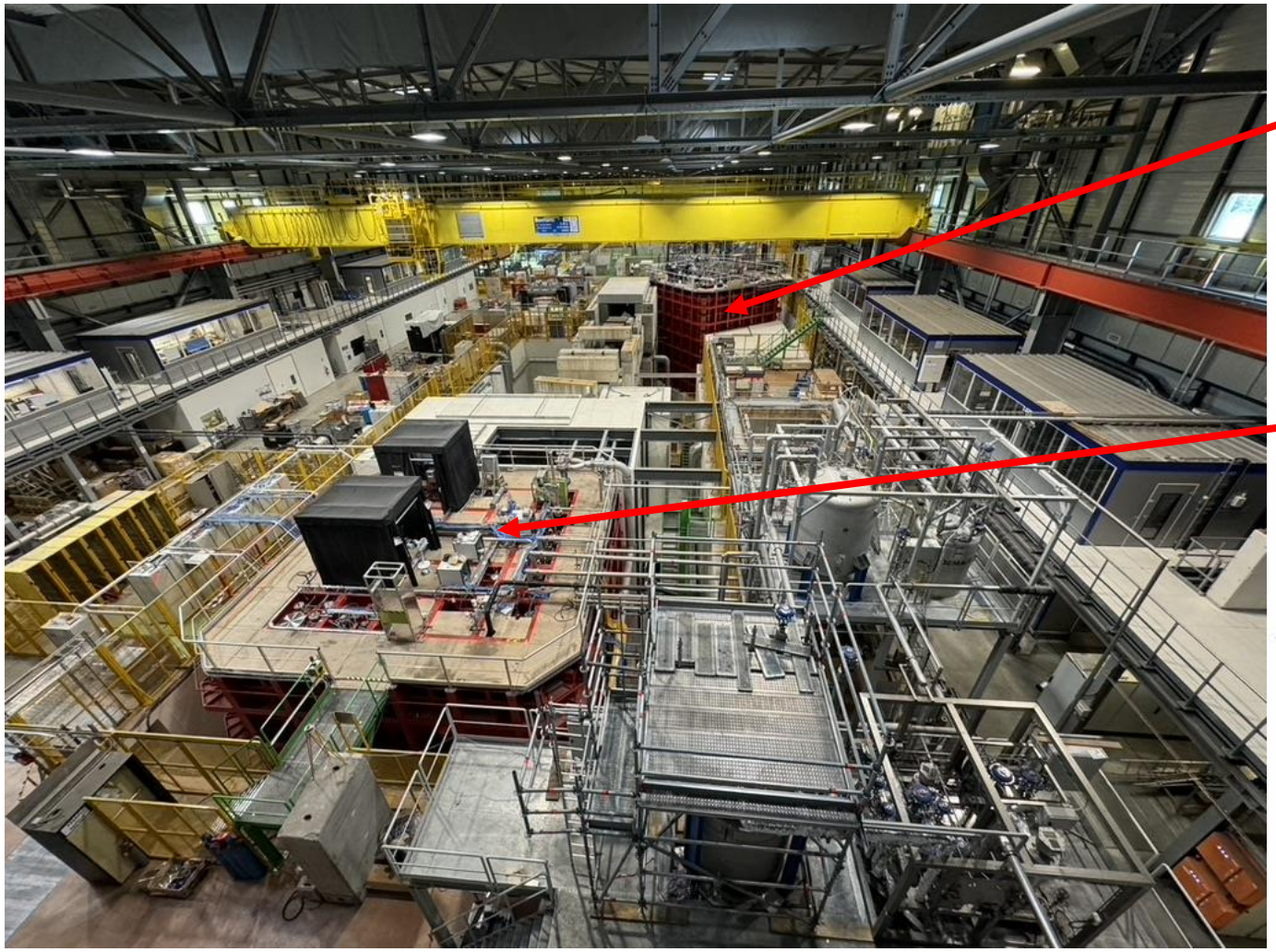
Charge Readout Planes : perforated PCB technology

Drift length ~ 640 cm -> ~ 300 KV

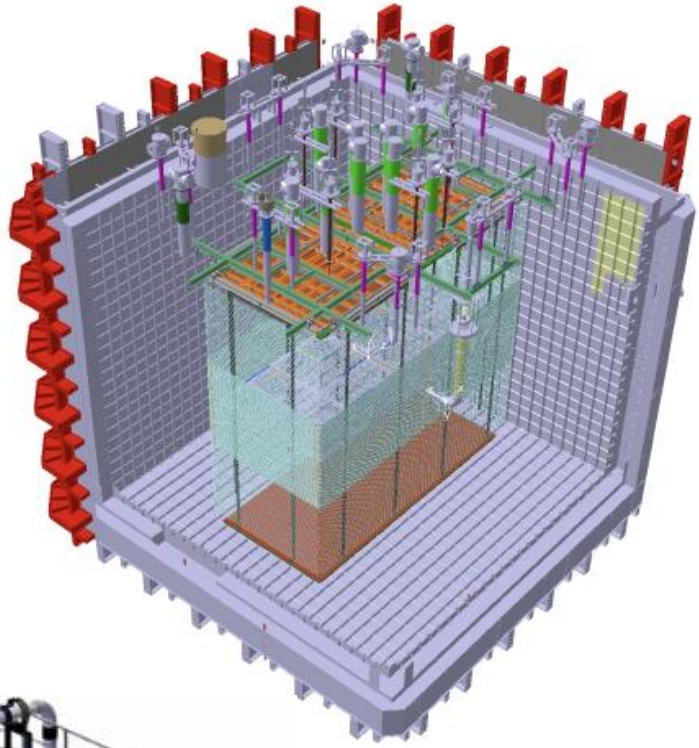
10180 m^3 = 14.2 ktons active LAr

Photon detectors on the cathode at 300 KV

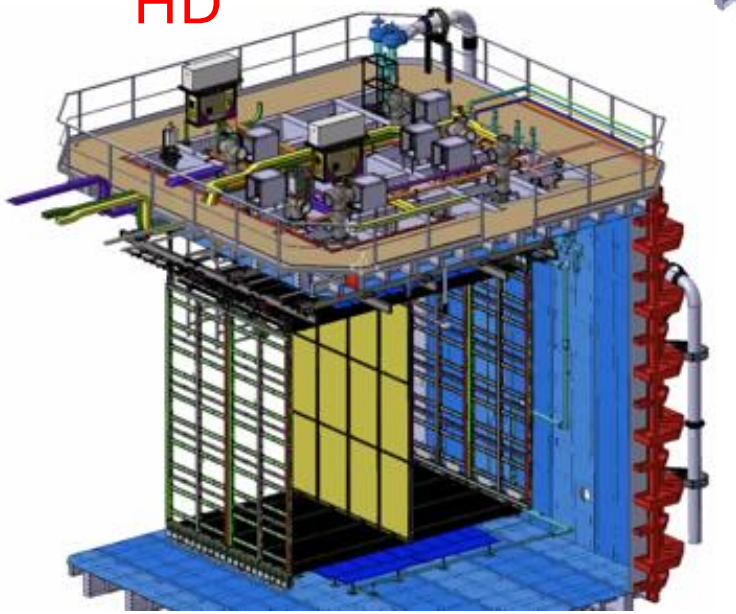
ProtoDUNEs at the CERN NP



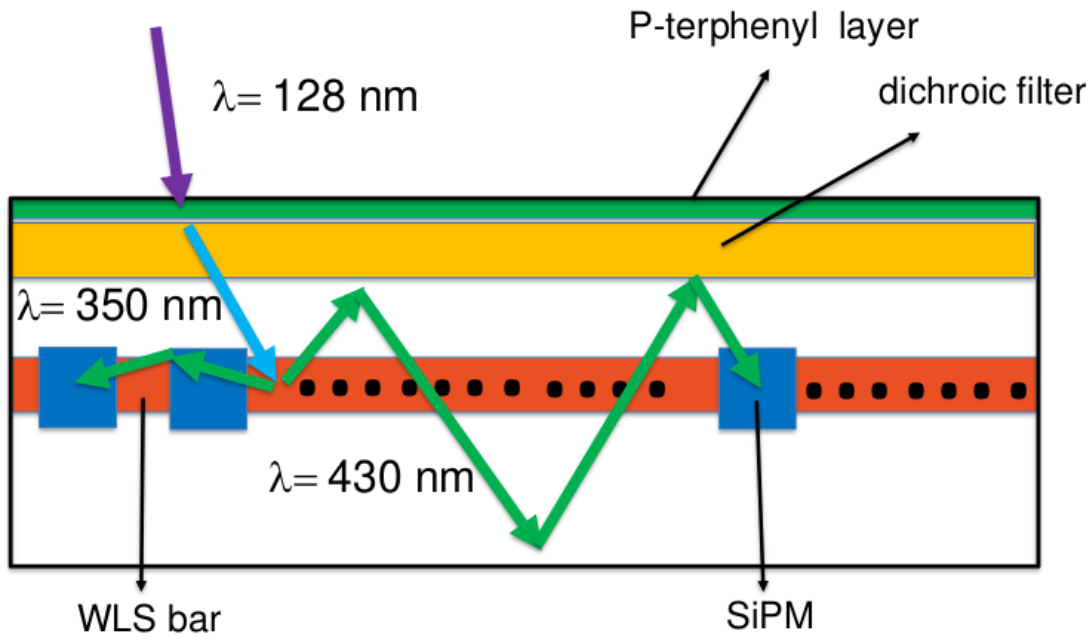
NP02
VD

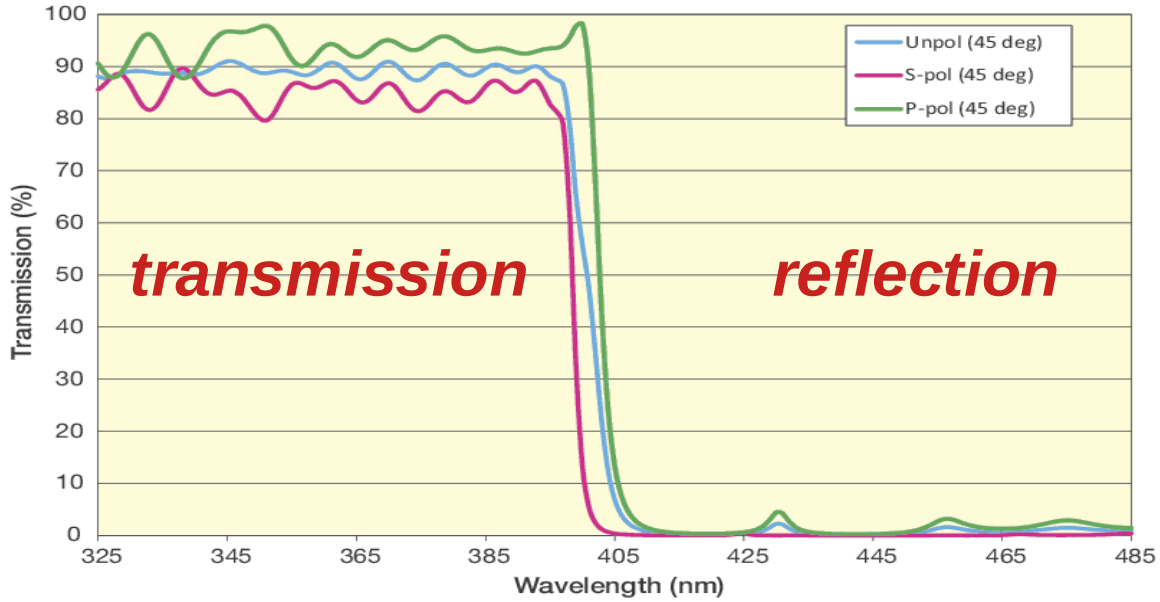


NP04
HD



DUNE Photon Detection System: X-ARAPUCA

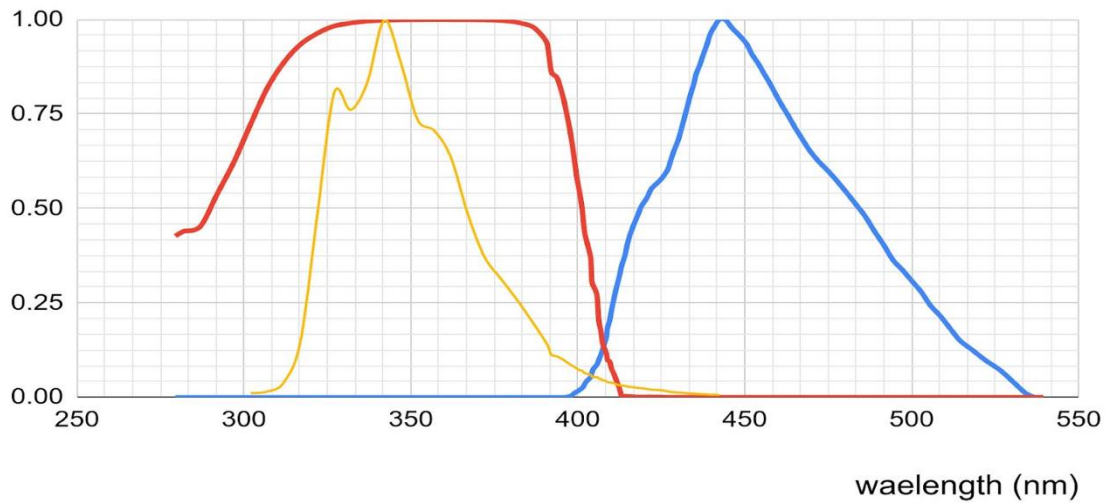




Large area photon collector coupled to an array of SiPMs

Photon trapping through:

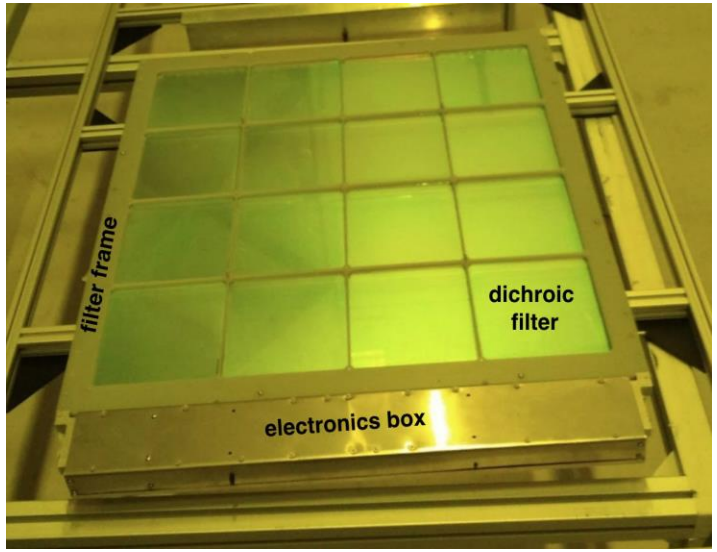
- ✓ ***Total internal reflection in the WLS***
- ✓ ***Trapping through dichroic filter***



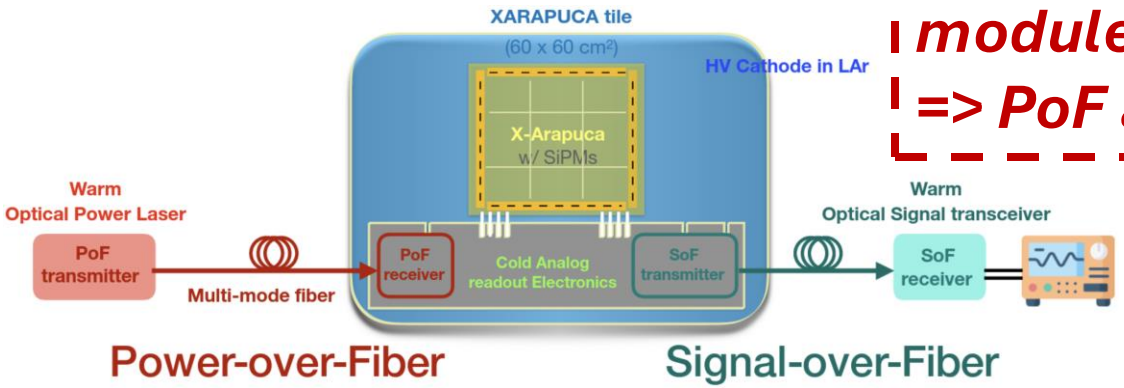
X-ARAPUCAs in DUNE

- ✓ Bar shaped modules
- ✓ 200 x 10 cm^2
- ✓ 4 independent read-out channels
- ✓ 4 x 48 SiPMs ganged together

- ✓ Square modules
- ✓ 60 x 60 cm^2
- ✓ 2 independent read-out channels
- ✓ 2 x 80 SiPMs ganged together



Efficiencies between 2% - 4%



Half of the modules at 300 kV => PoF and SoF

Main aims of ProtoDUNEs Run II (2024-25)

FD(1,2) Module 0:

- TPC integration test, performance & stability evaluation before mass production.
- Validation of pre-production, shipping, and installation procedures.
- Validation of tools, confirmation of personnel and time required for FDs.

Photon Detector System:

- First X-ARAPUCA tests at kton scale deployment. POF, SOF validation.

Cold Electronics:

- CE redesigned from ProtoDUNE I, three new chips. Used in HD (APAs) and VD (bottom CRPs).

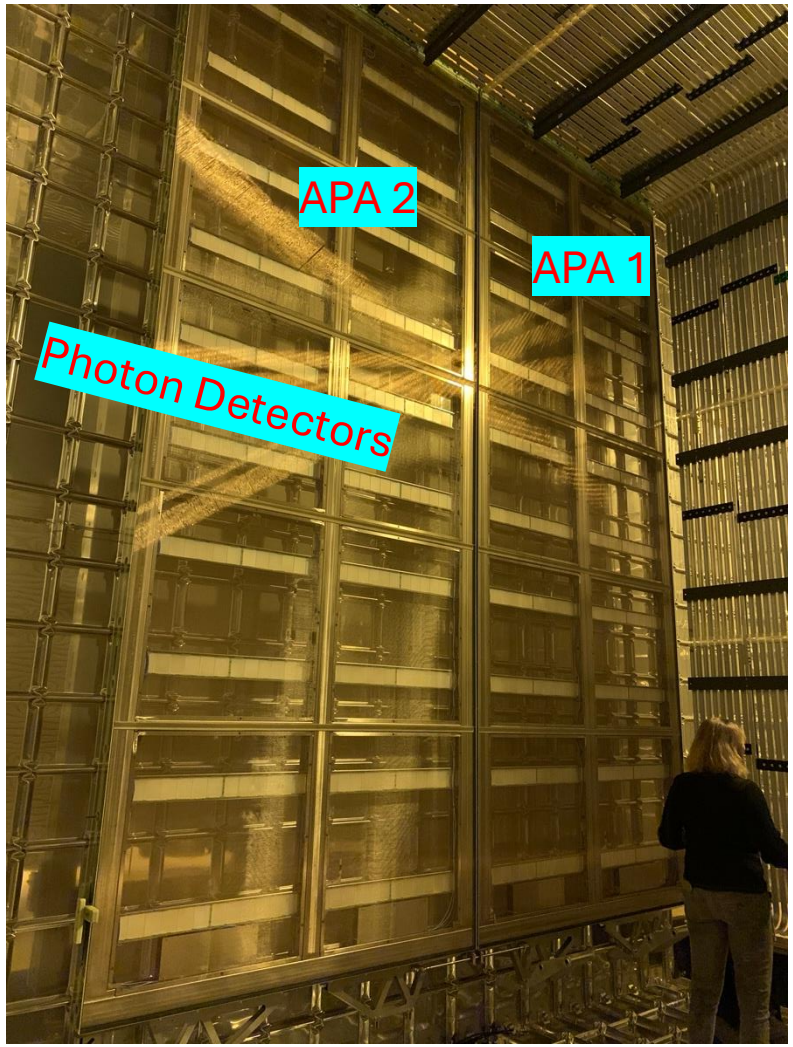
TDAQ:

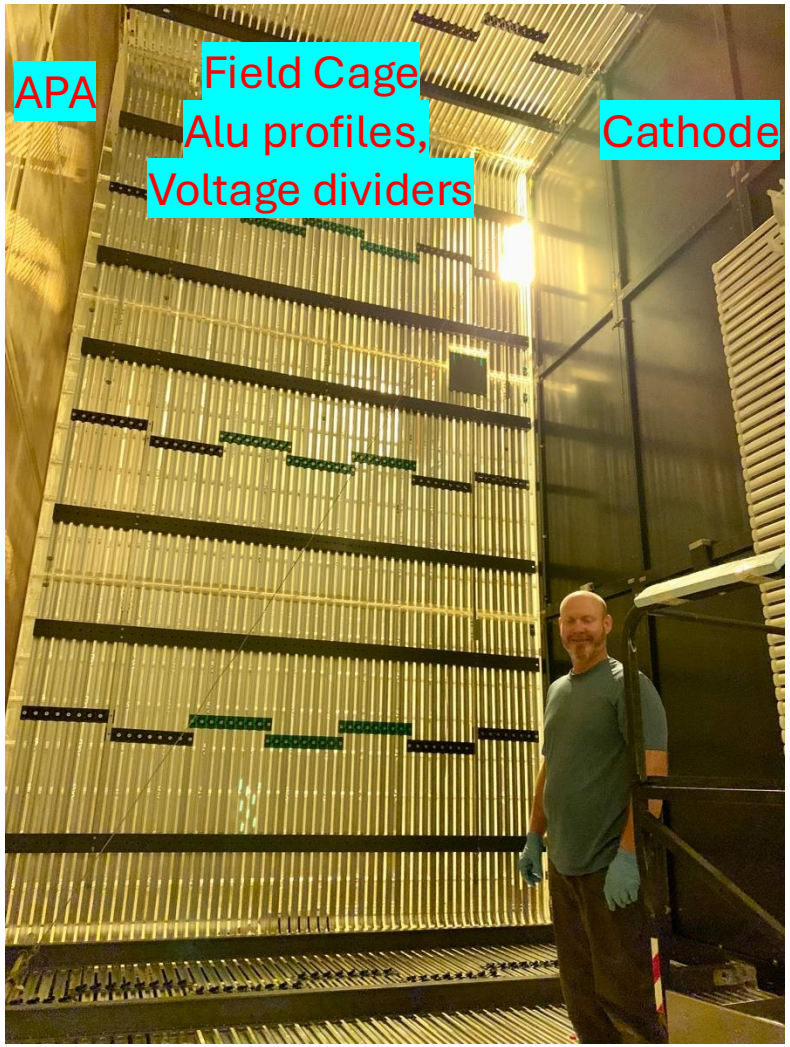
- Final DUNE readout scheme implemented; new ethernet readout; integration of final electronics, new PDS readout, Ionization Laser; implementation of trigger schemes; performance tests.
- Charged particle data for cross-section measurements; BSM search capabilities.

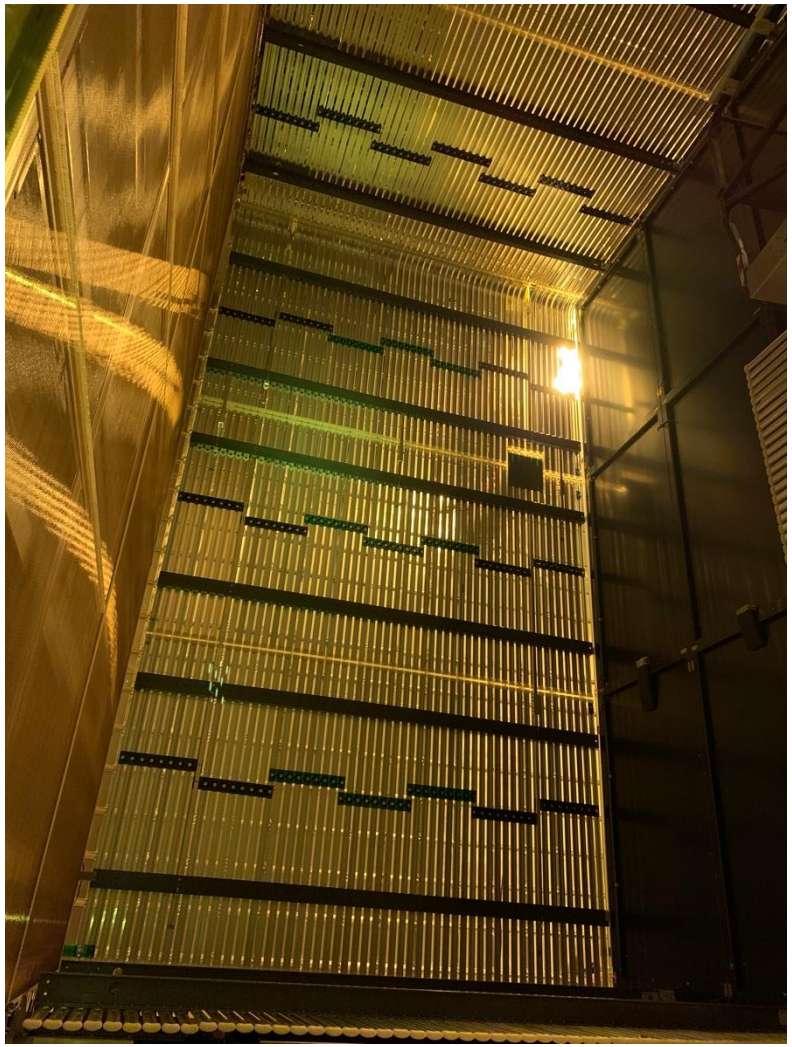
NP04 II – ProtoDUNE HD

NP04 TPC – ProtoDUNE HD

Beam (Saleve) side TPC completed



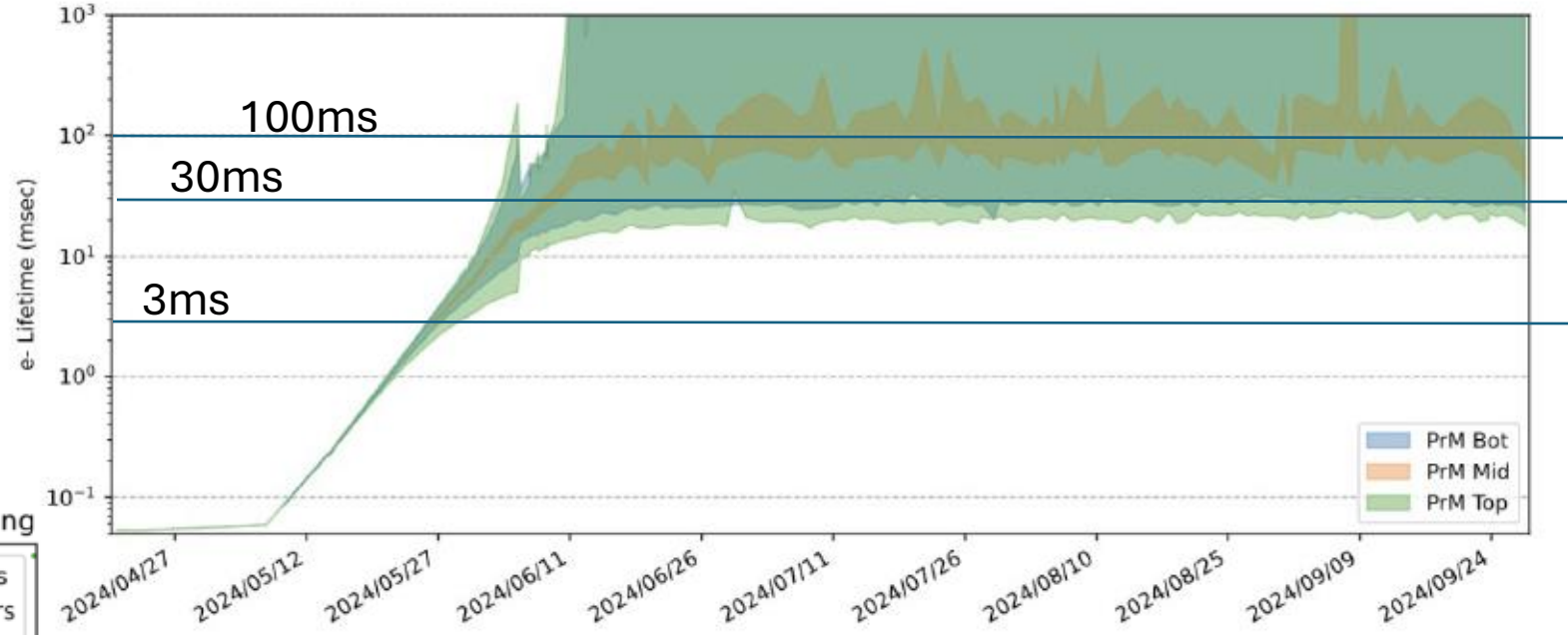


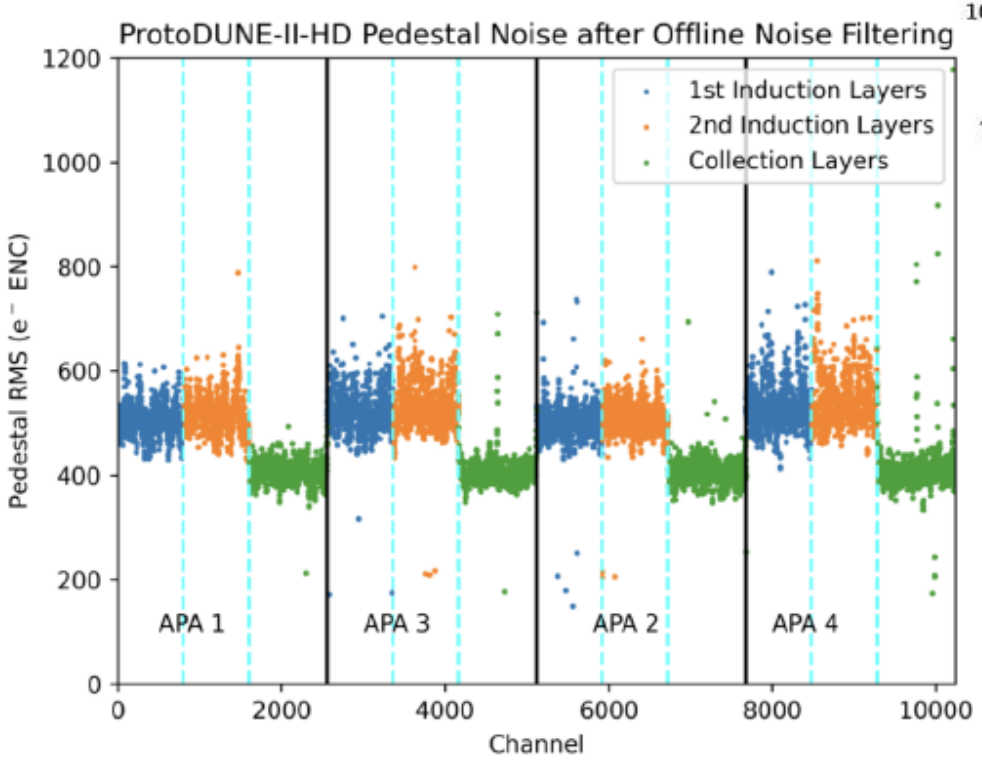


NP04 run in 2024

Purity levels of LAr x10 higher than required

No purity loss in 6 months





Excellent overall noise performance (comparable or better than ProtoDUNE I)

Approximately 1 ‰ channels dead or problematic

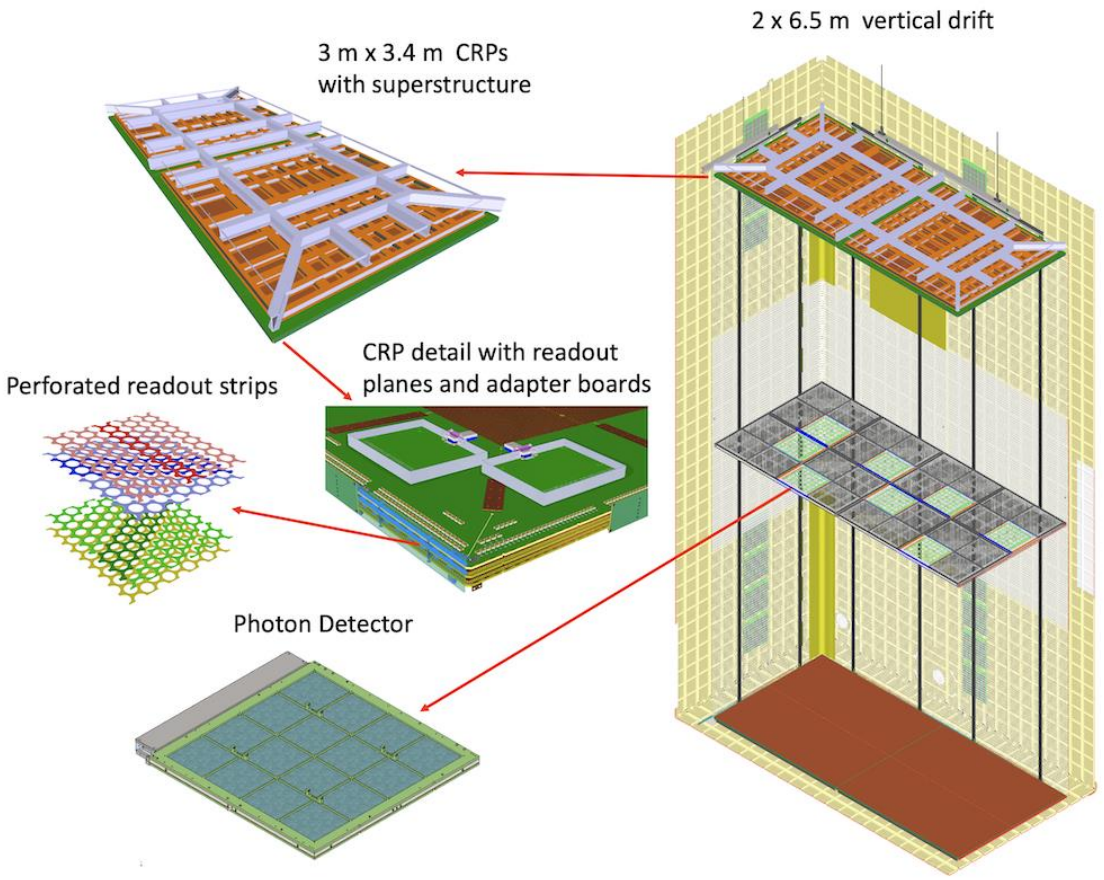
Dynamic range increase compared thanks to better S/N and 14 bit ADC

2024 highlights

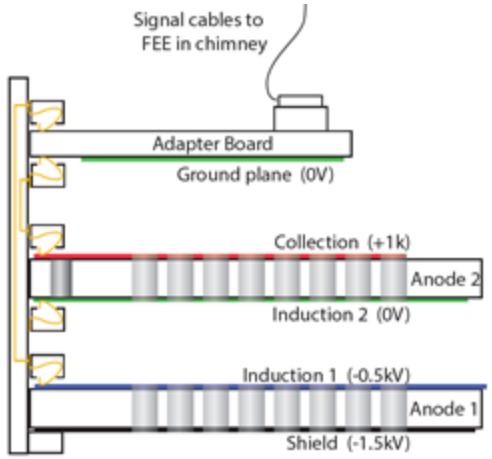
- Six months of stable TPC (Argon purity, nominal HV at 500 V/m, no trips)
- Stable HV up to 275 kV, ~800 V/m.
- 10 weeks of charged particle beams (pions, electrons, kaons, protons), both polarities for the first time: Argon cross-sections. >30M events recorded.
- Stable DAQ: 100% uptime.
- Ionization lasers integrated with TDAQ and Slow Control: volume scans.
- Trigger primitives generated, different TPC trigger conditions implemented.
  - Including high-energy deposition in TPC used for BSM background studies without charged beam but with / without beams in the North Area, leading to neutrino candidates detection.
  - TDAQ performance reached DUNE FD requirements for throughput.
  - 5 PB of data collected and transferred to FNAL via CERN EOS.
- Data processing, reconstruction ongoing.

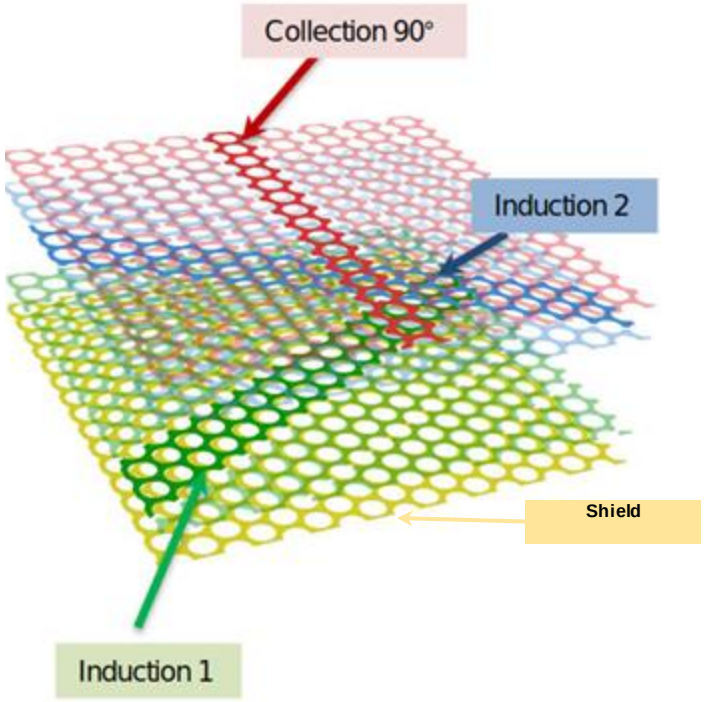
NP02 II – ProtoDUNE VD

Vertical Drift TPC



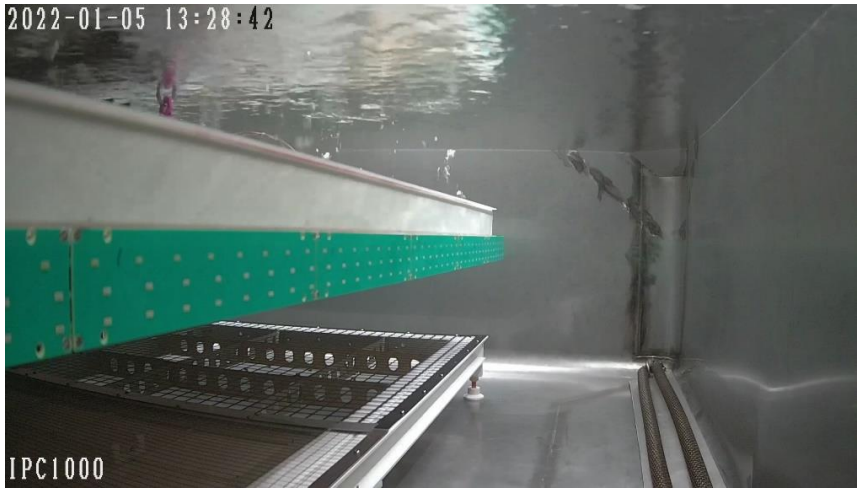
- Three view anode layout with perforated PCBs
  - +30º, -30º, 90º strip orientation with 5.1mm collection, 7.65mm induction strip pitches
  - 3072 readout channels for each CRP



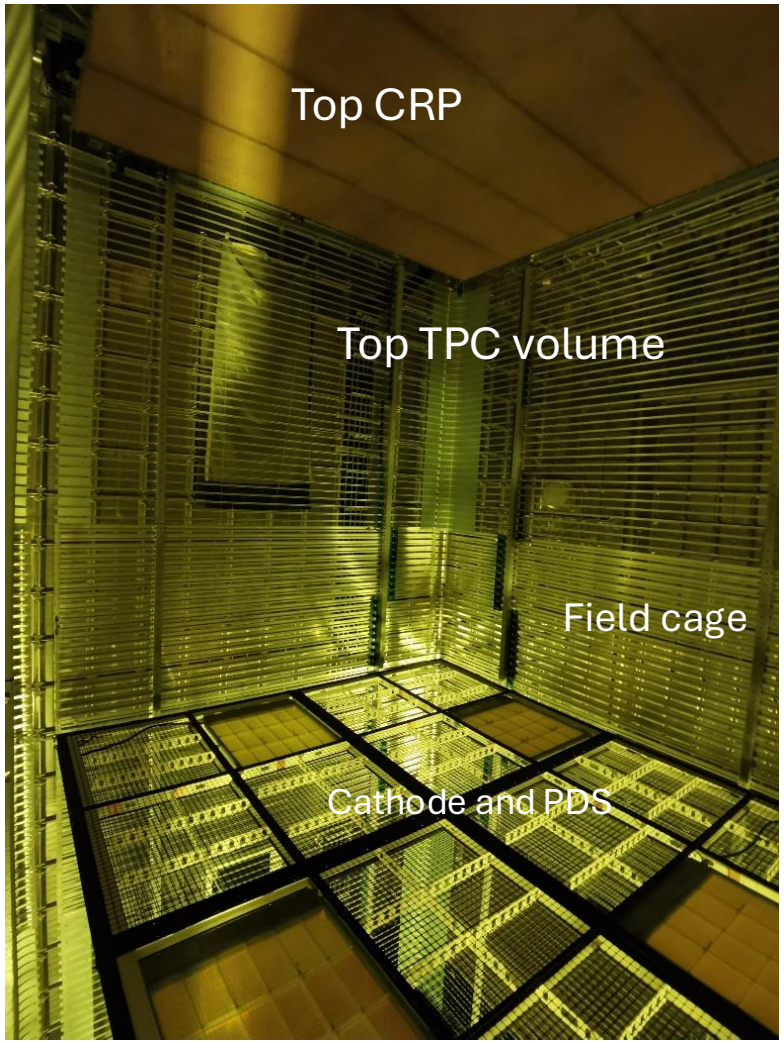


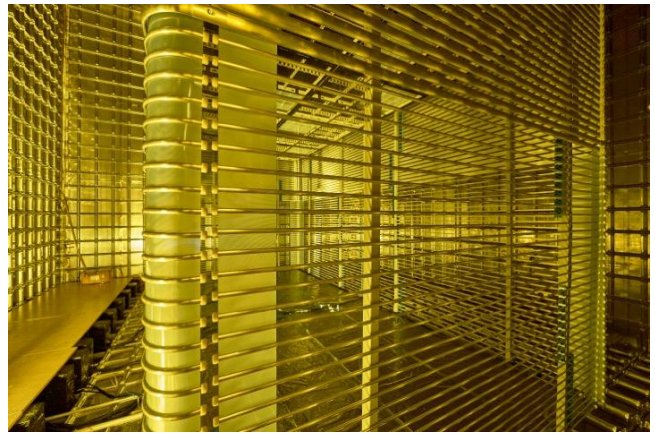
Cold Box tests (>12 cycles so far)

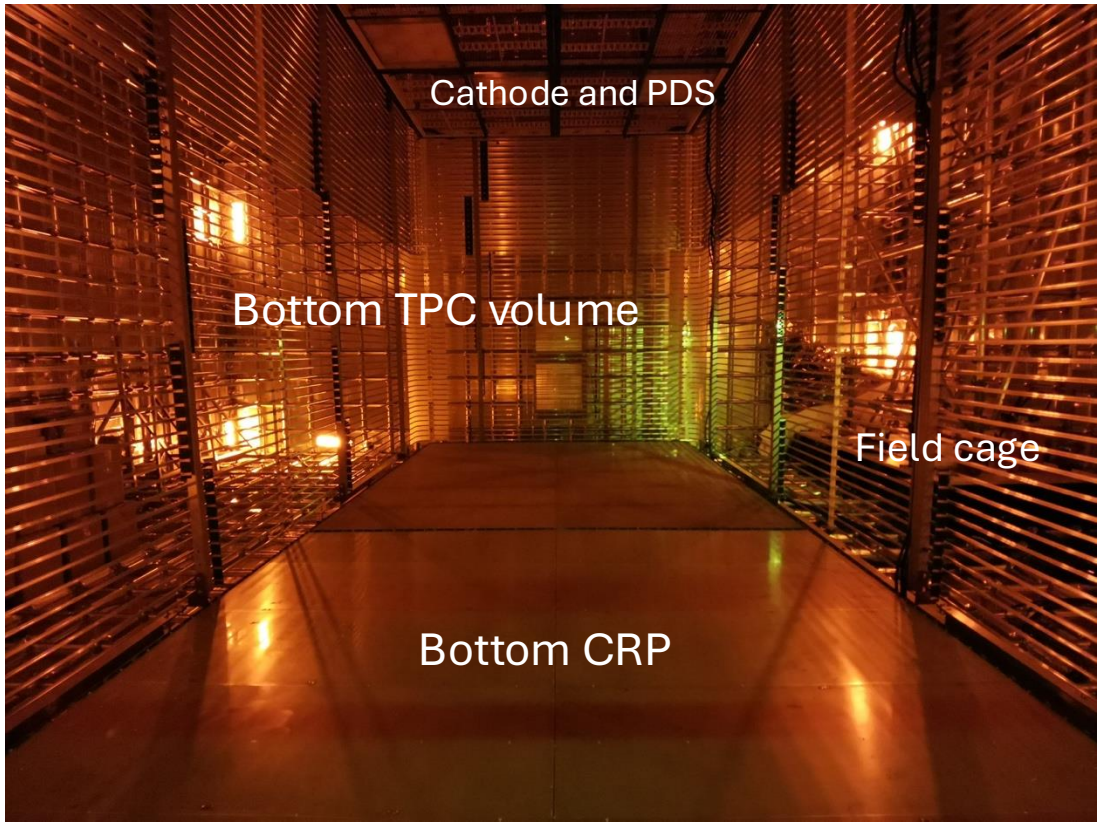
- Evolution of CRPs using cold box lessons
- PDS demonstrated too
- 300 kV over 6m drift already demonstrated in NP02 - DP



NP02 TPC assembly

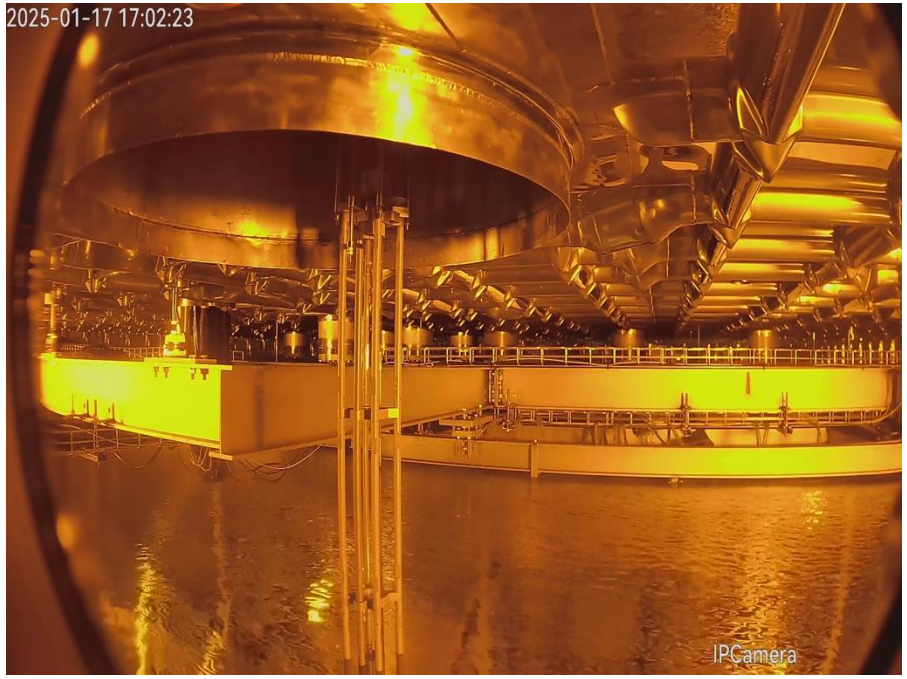






NP02 filling and plan

- Detector filled and ready for commissioning.
- Beam run in summer 2025.



CERN NP experiments / projects

8 Experiments approved by the SPS Committee and by the Research Board:

- **NP01**: ICARUS for the US/FNAL SBN (completed 2017), SBND

LAr TPC developments for LBNF/DUNE

- **NP02**: demonstrator/engineering prototype initially for a double phase TPC - now Vertical Drift (ongoing)
- **NP03**: PLAFOND, a generic detector R&D framework for accelerator-based neutrino experiments (ongoing)
- **NP04**: ProtoDUNE for single phase (Horizontal Drift) engineering prototype (ongoing)
- **NP05**: Baby Mind, a muon spectrometer for the WAGASCI experiment at T2K (delivered 2017)
- **NP06**: Enhanced Neutrino Beam via kaon tagging (ENUBET)
- **NP07**: Contributions to the T2K Near Detector
- **NP08**: Procurement, assembly and testing of electronics components for the Hyper-K experiment

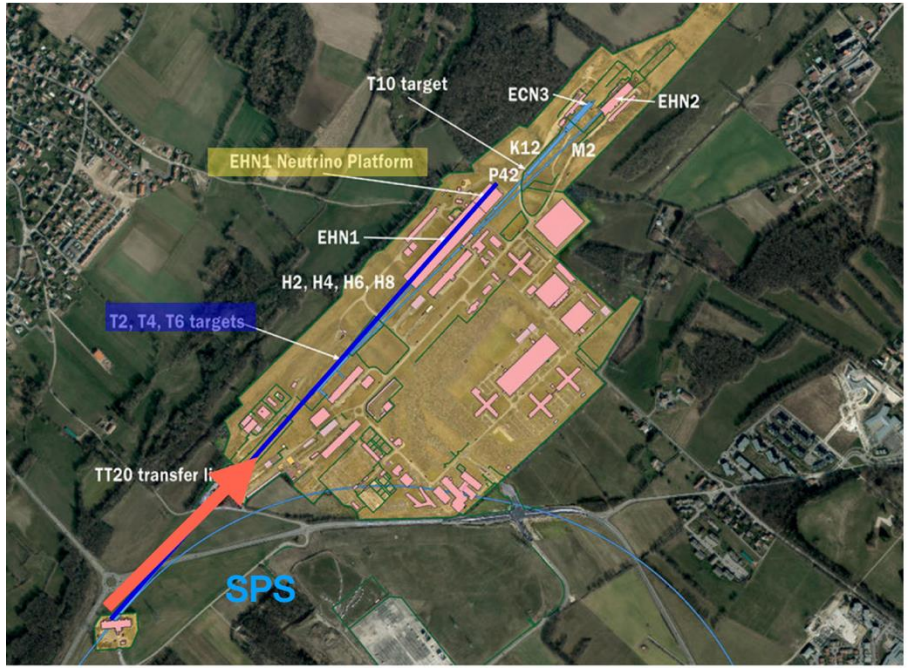
LBNF/DUNE: FD1,2 cryostats; Cryo; Compliance Office; HV; TDAQ; Andes; Electronics.

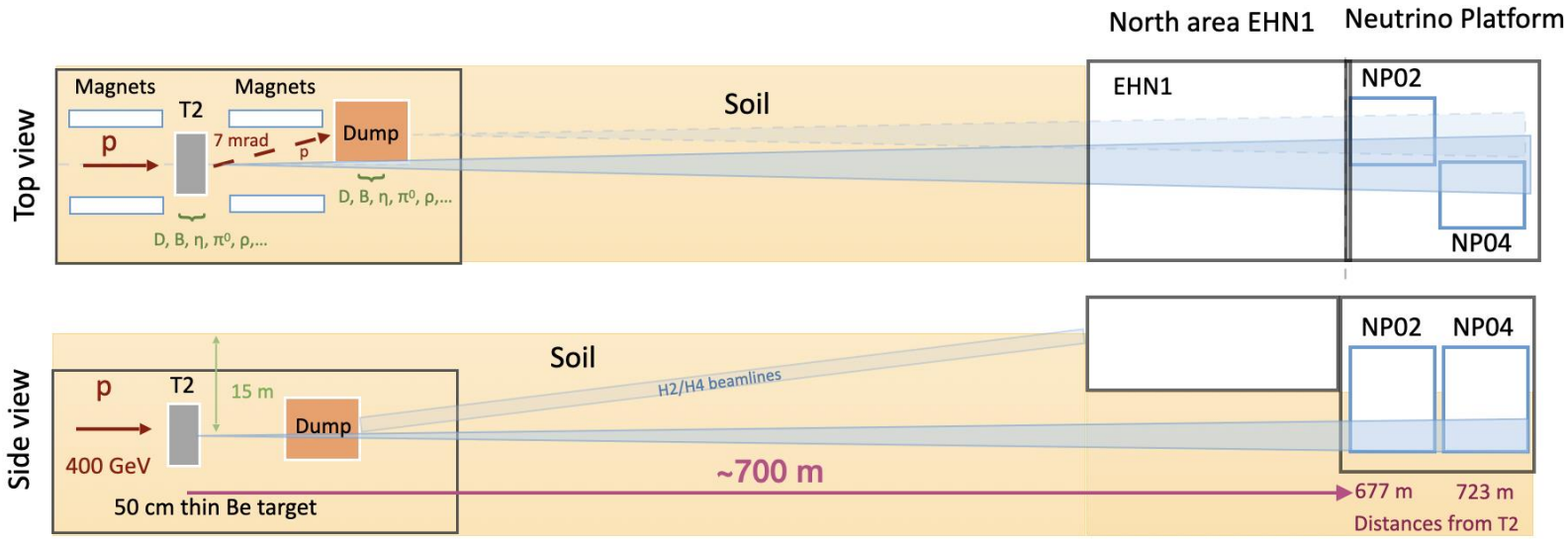
Darkside-20k cryostat (DM experiment at INFN LNGS)

A case of serendipity

ProtoDUNE capabilities, opportunity: BSM & neutrinos

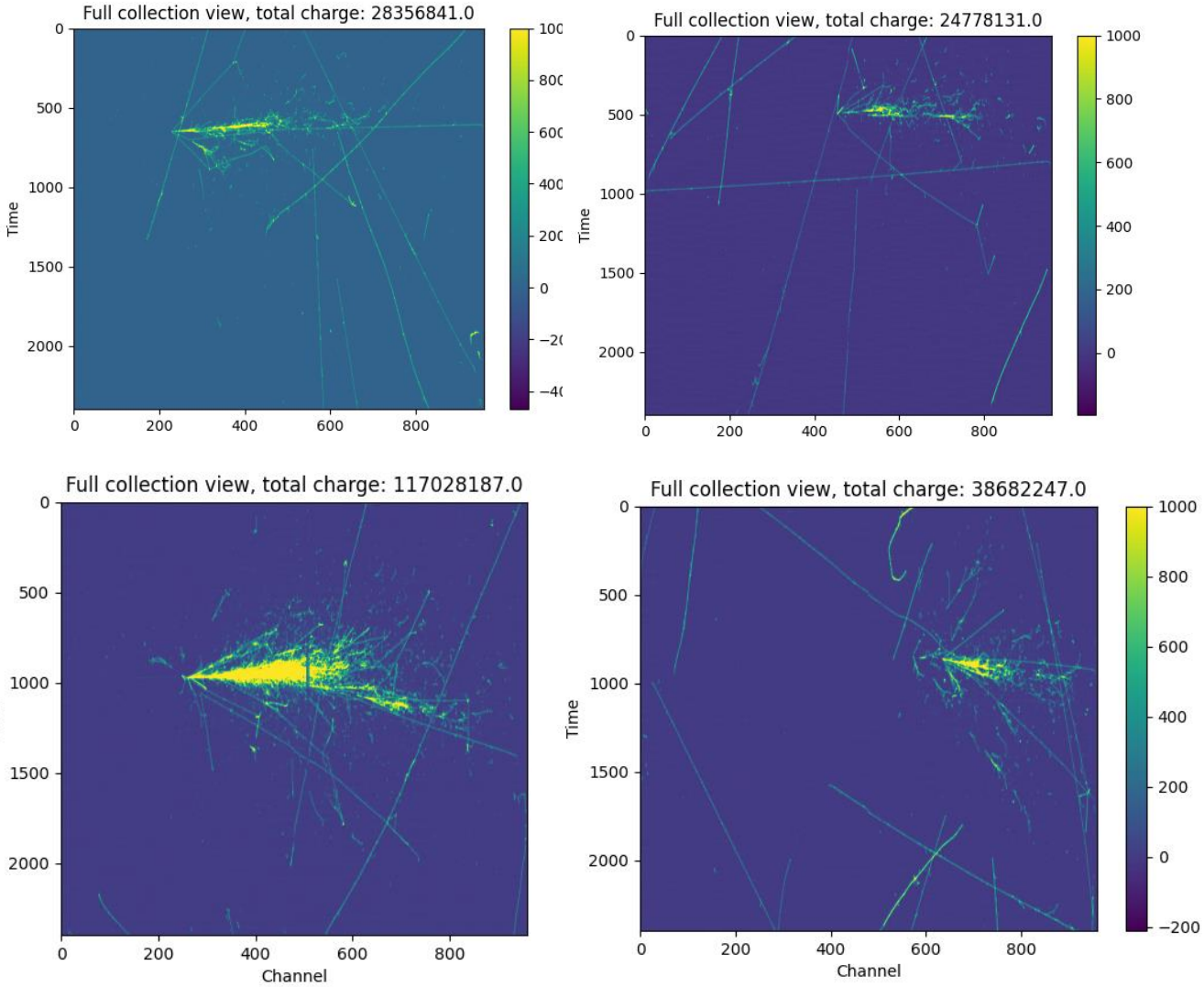
- Increasing interest in BSM scenarios involving long-lived, weakly-interacting particles (Dark Sectors, HNL, Axions).
- Explored in most experiments: consider as beam dump, search for BSM signatures. T2K, NOvA, MicroBooNE, SBND, ICARUS, DUNE.
  - Opportunistic "no cost" scope extension; complementary to dedicated experiments (SHIP).
- Excellent ProtoDUNE HD performance, TPC trigger implementation, detector tests with no test beam to the detector but SPS 400 GeV protons on T2 target: opportunity to validate background modeling for an ongoing BSM search study.

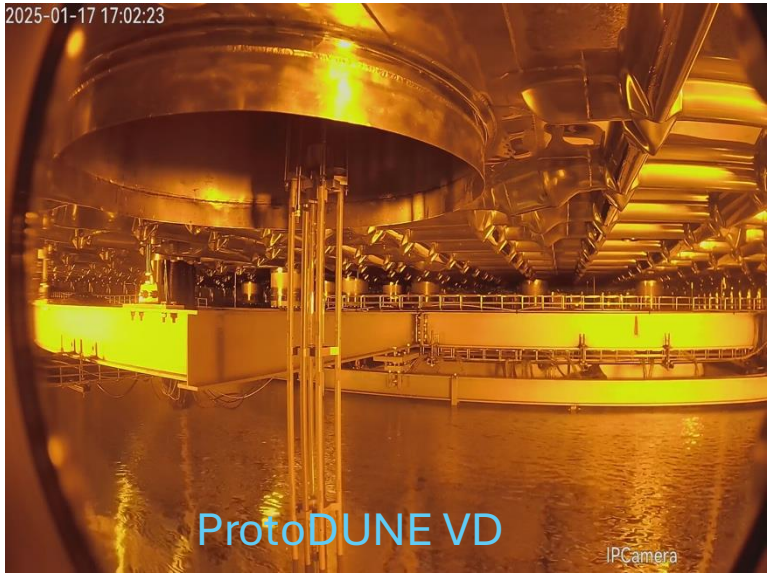




Neutrino candidate events in ProtoDUNE HD

- Main background to BSM: neutrinos.
- A considerable neutrino flux illuminates the ProtoDUNEs while the North Area gets beam.
- Event rate very small to see in continuous cosmic “rain”.
- TPC (BSM-inspired) trigger with adjustable E_{min} requirement was investigated after our beam run.
- Neutrino candidates identified.
- Very early stage, ongoing work. No statement to make. Enjoy the events (52 years after neutral currents at Gargamele).





2018

2024

THANK YOU