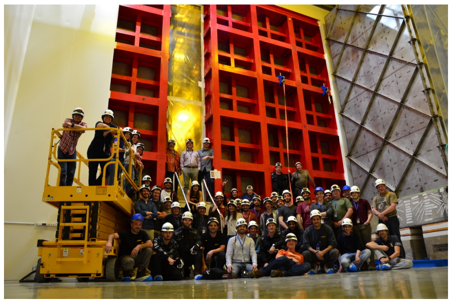
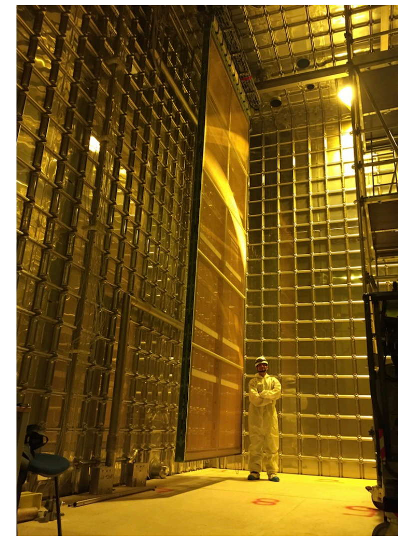
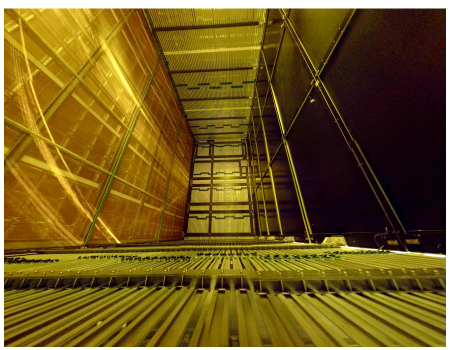
Large Liquid Argon TPCs and the search for CP Violation in the lepton sector with Long Baseline neutrino experiments







Christos Touramanis, VCI 2019

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Outline

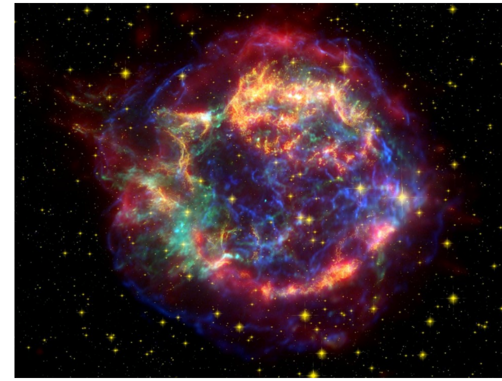
- Neutrinos: what is it all about?
  - Why we care about them
  - What we know
  - Long Baseline experiments now and in the next ~10 years
  - The next generation

- LAr TPCs
  - DUNE and the DUNE Far Detectors
  - Single Phase ProtoDUNE (NP04) at CERN

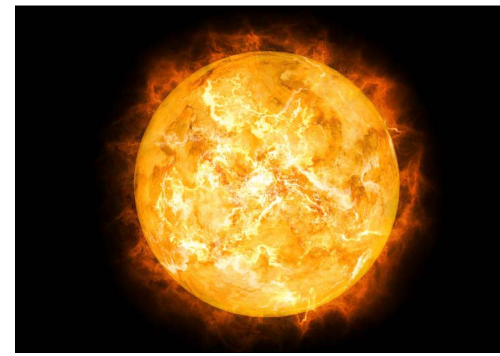
- Conclusions

Neutrinos are everywhere

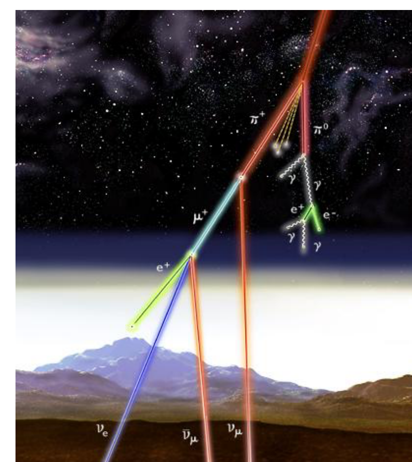
- Most abundant matter particles in the universe: 10^9 for every proton/neutron/ electron



- 99% of the energy of a supernova carried by neutrinos



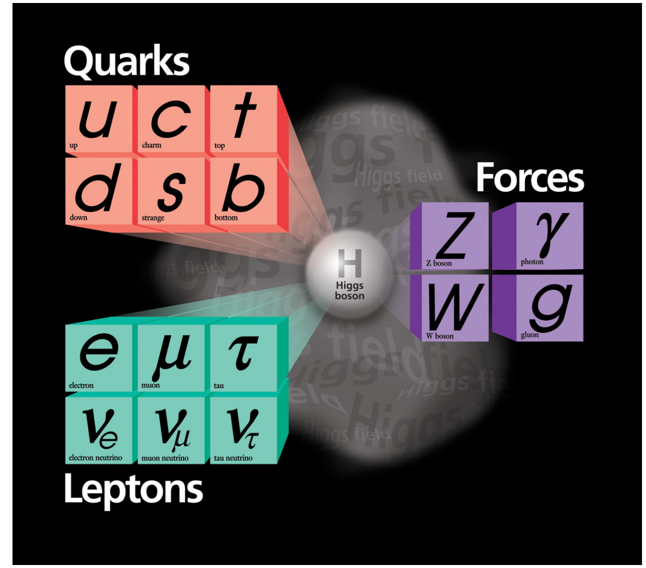
- 10^{38} per second produced in the sun
- Also produced in the atmosphere

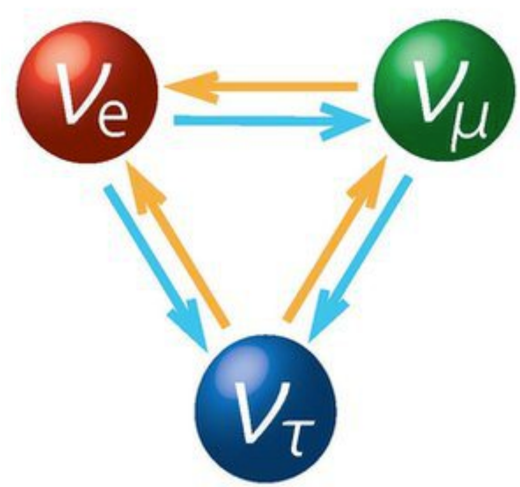


- Man-made neutrinos from:
  - Accelerators
  - Nuclear Reactors

Neutrinos in and beyond the Standard Model

- Neutrinos assumed massless in the SM: no mixing allowed
- Neutrino mixing established 20 years ago (Super-K, SNO)
- Third mixing observed earlier in this decade
  - θ_{13} in ν_e disappearance (reactors)
  - ν_e appearance in pure ν_μ beam (T2K)
- Large θ_{13} (c.f. expectations) opened up the search for leptonic CP Violation





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Knowns, unknowns and possible connections

- No neutrino mass term (mechanism) in SM
- Mixing: 3 mass eigenstates (ν_1,ν_2,ν_3), 3 WI eigenstates (ν_e,ν_μ,ν_τ)

- CP Violation
- Mass Hierarchy (MH)
- θ_{23} exactly 45°; octant
- Unitarity of mixing matrix – extra states (steriles)

- Baryon Asymmetry: Leptogenesis?
- Inflation and Unification (coincidences?):
  - Seesaw, heavy neutrinos ~10^{14}GeV
  - Inflation field ~10^{13}GeV
  - Interaction unification ~10^{16}GeV

3-neutrino mixing 2018 (http://www.nu-fit.org)

T2K: 1.5×10^{21} ν, 1.1×10^{21} anti-ν
NOvA: 0.9×10^{21} ν, 0.7×10^{21} anti-ν

NuFIT 4.0 (2018)

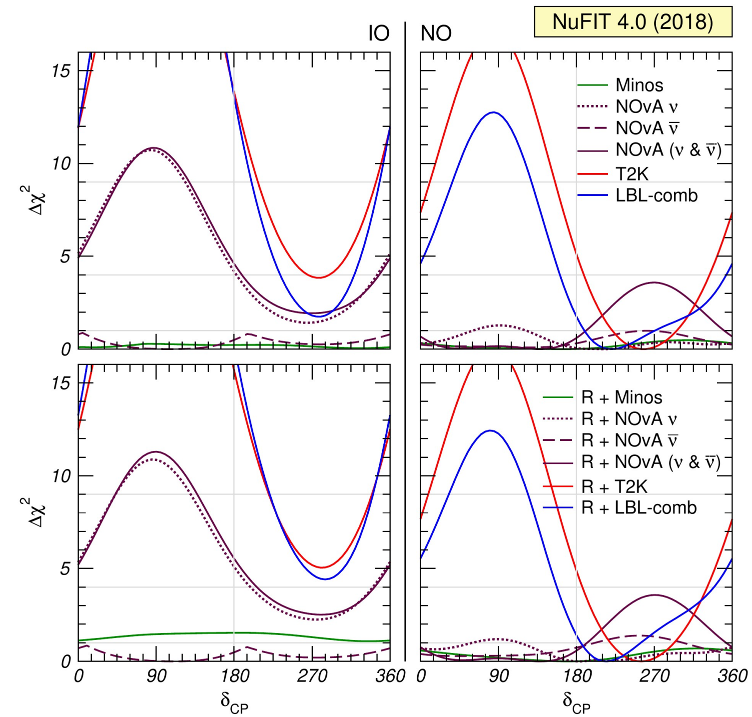
without SK atmospheric data

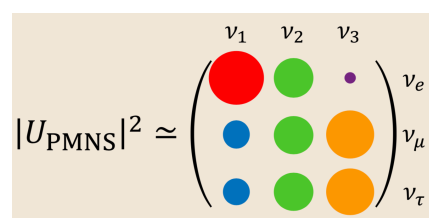
	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 4.7$)	
	bfp $\pm1\sigma$	3σ range	bfp $\pm1\sigma$	3σ range
$\sin^2\theta_{12}$	$0.310^{+0.013}_{-0.012}$	$0.275 \to 0.350$	$0.310^{+0.013}_{-0.012}$	$0.275 \to 0.350$
$\theta_{12}/^\circ$	$33.82^{+0.78}_{-0.76}$	$31.61 \to 36.27$	$33.82^{+0.78}_{-0.76}$	$31.61 \to 36.27$
$\sin^2\theta_{23}$	$0.580^{+0.017}_{-0.021}$	$0.418 \to 0.627$	$0.584^{+0.016}_{-0.020}$	$0.423 \to 0.629$
$\theta_{23}/^\circ$	$49.6^{+1.0}_{-1.2}$	$40.3 \to 52.4$	$49.8^{+1.0}_{-1.1}$	$40.6 \to 52.5$
$\sin^2\theta_{13}$	$0.02241^{+0.00065}_{-0.00065}$	$0.02045 \to 0.02439$	$0.02264^{+0.00066}_{-0.00066}$	$0.02068 \to 0.02463$
$\theta_{13}/^\circ$	$8.61^{+0.13}_{-0.13}$	$8.22 \to 8.99$	$8.65^{+0.13}_{-0.13}$	$8.27 \to 9.03$
$\delta_{CP}/^\circ$	215^{+40}_{-29}	$125 \to 392$	284^{+27}_{-29}	$196 \to 360$
$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.39^{+0.21}_{-0.20}$	$6.79 \to 8.01$	$7.39^{+0.21}_{-0.20}$	$6.79 \to 8.01$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$+2.525^{+0.033}_{-0.032}$	$+2.427 \to +2.625$	$-2.512^{+0.034}_{-0.032}$	$-2.611 \to -2.412$

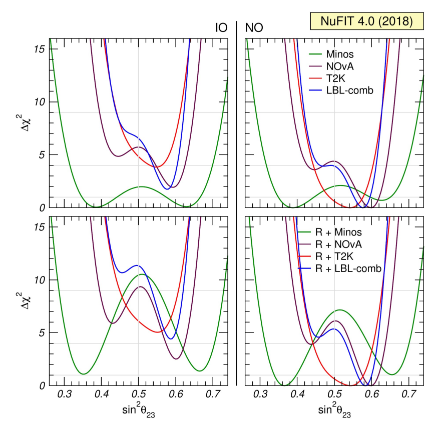
with SK atmospheric data

	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 9.3$)	
	bfp $\pm1\sigma$	3σ range	bfp $\pm1\sigma$	3σ range
$\sin^2\theta_{12}$	$0.310^{+0.013}_{-0.012}$	$0.275 \to 0.350$	$0.310^{+0.013}_{-0.012}$	$0.275 \to 0.350$
$\theta_{12}/^\circ$	$33.82^{+0.78}_{-0.76}$	$31.61 \to 36.27$	$33.82^{+0.78}_{-0.75}$	$31.62 \to 36.27$
$\sin^2\theta_{23}$	$0.582^{+0.015}_{-0.019}$	$0.428 \to 0.624$	$0.582^{+0.015}_{-0.018}$	$0.433 \to 0.623$
$\theta_{23}/^\circ$	$49.7^{+0.9}_{-1.1}$	$40.9 \to 52.2$	$49.7^{+0.9}_{-1.0}$	$41.2 \to 52.1$
$\sin^2\theta_{13}$	$0.02240^{+0.00065}_{-0.00066}$	$0.02044 \to 0.02437$	$0.02263^{+0.00065}_{-0.00066}$	$0.02067 \to 0.02461$
$\theta_{13}/^\circ$	$8.61^{+0.12}_{-0.13}$	$8.22 \to 8.98$	$8.65^{+0.12}_{-0.13}$	$8.27 \to 9.03$
$\delta_{CP}/^\circ$	217^{+40}_{-28}	$135 \to 366$	280^{+25}_{-28}	$196 \to 351$
$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.39^{+0.21}_{-0.20}$	$6.79 \to 8.01$	$7.39^{+0.21}_{-0.20}$	$6.79 \to 8.01$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$+2.525^{+0.033}_{-0.031}$	$+2.431 \to +2.622$	$-2.512^{+0.034}_{-0.031}$	$-2.606 \to -2.413$

$$|U|^{\text{with SK-atm}}_{3\sigma} = \begin{pmatrix} 0.797 \to 0.842 & 0.518 \to 0.585 & 0.143 \to 0.156 \\ 0.235 \to 0.484 & 0.458 \to 0.671 & 0.647 \to 0.781 \\ 0.304 \to 0.531 & 0.497 \to 0.699 & 0.607 \to 0.747 \end{pmatrix}$$







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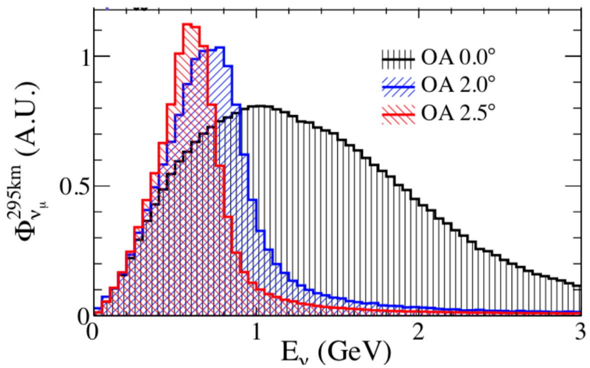
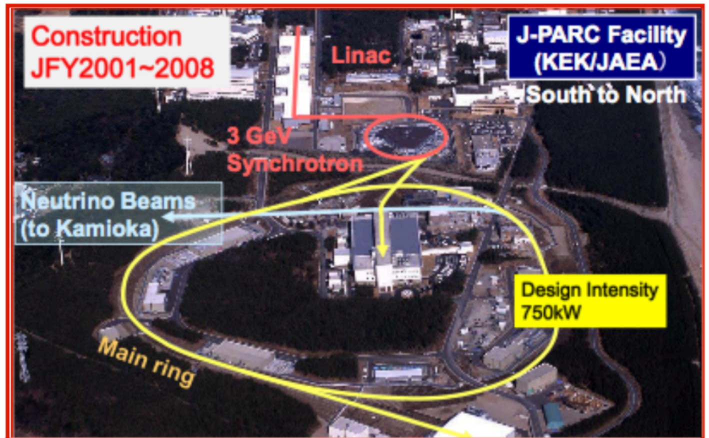
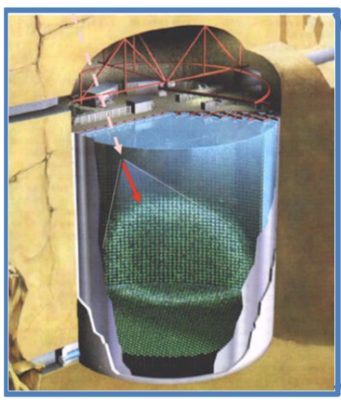
T2K

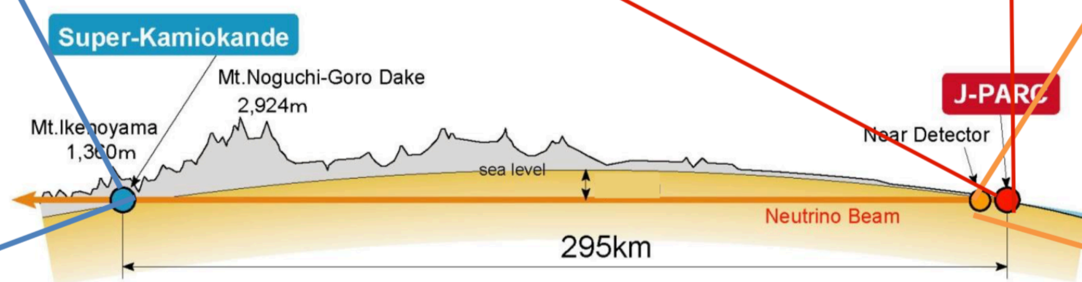
12 countries
66 institutions
~500 people

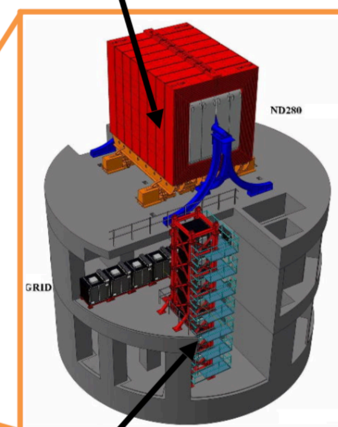




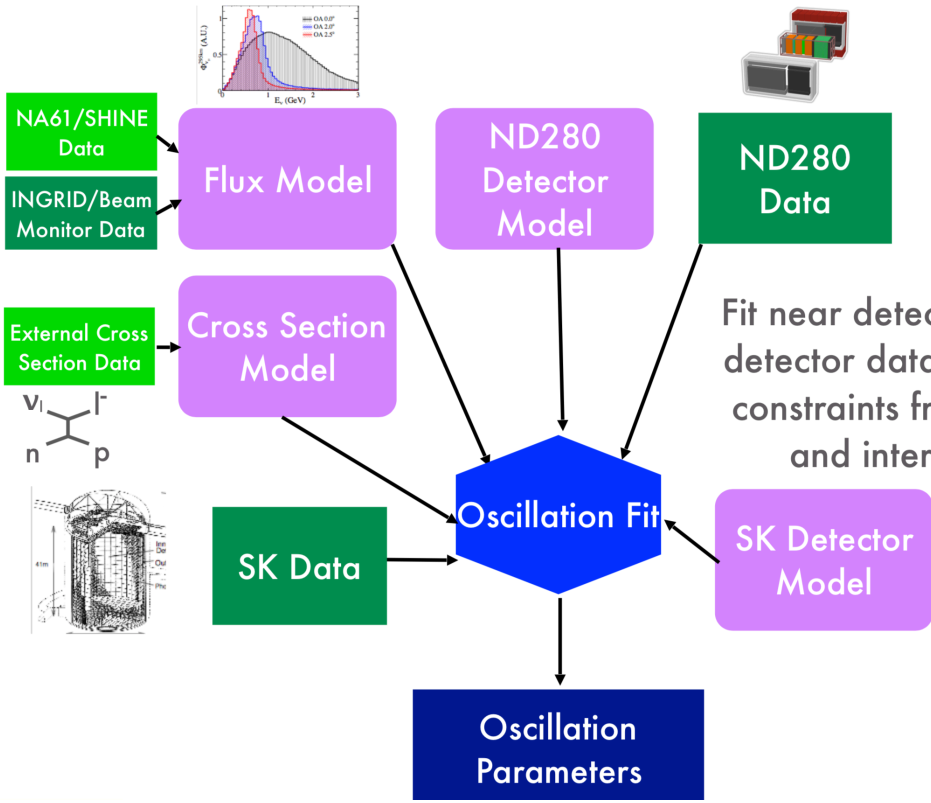
ND280



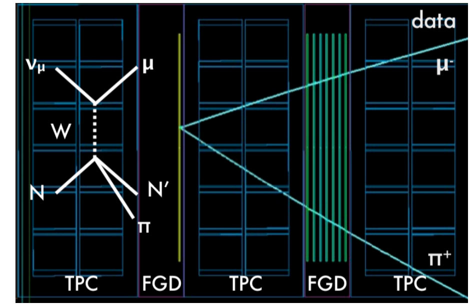


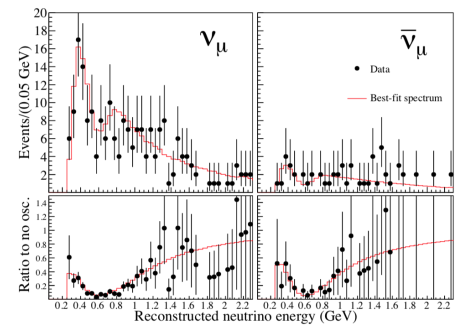


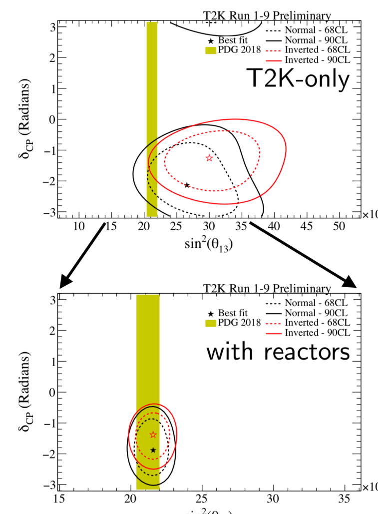
T2K Analysis & Results



Fit near detector data, far detector data, and model constraints from external and internal data







$$\sim 1.49 \times 10^{21}\ \nu + \sim 1.63 \times 10^{21}\ \bar{\nu}\ \mathrm{POT}$$

fit with reactor constraint on $\sin^2\theta_{13}$:

Best fit point : $\delta_{CP} = -1.885$ radians in Normal Hierarchy

δ_{CP} 2σ CL confidence interval :

- Normal mass hierarchy : [-2.966, -0.628] radians
- Inverted mass hierarchy : [-1.799, -0.979] radians

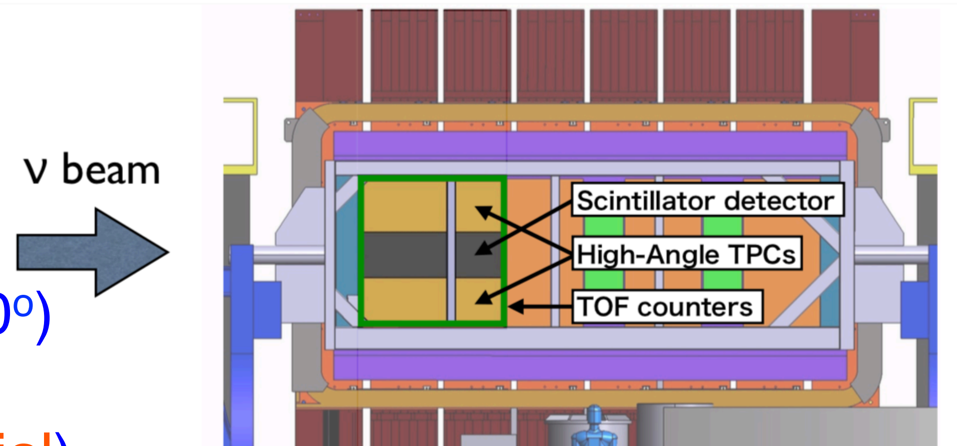
CP conserving values (0, π) fall outside of the 2σ CL intervals !

T2K future

- Beam power: currently stable at 490kW
- Upgrade to 750kW: 2.48s to 1.16s rep rate & more ppp; by 2022
- Expect 1.3MW by 2028 (H-K)

- ND280 upgrade: TDR submitted, test beams ongoing
- Replace P0D by active scintillator target, TPCs, TOF
- 4π acceptance, short track resolution, direction from timing

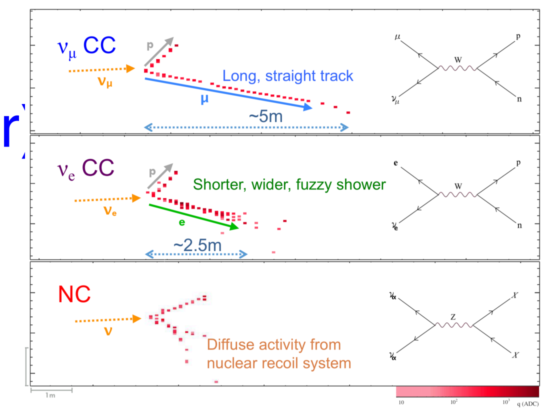
- T2K-II:
- 20×10^{21} POT by 2028
- Reduce systematics ~9% to 4%
- Reach 3σ CP sensitivity (for -90°)



- Hyper-K: 260kt WC (190kt fiducial)
- 40,000 PMTs
- Option for second detector in Korea in future

NOvA

- Fermilab NuMI beam at 700kW
- Off-axis, 810km baseline to Ash River, MI
- Identical Near / Far detectors
- 0.3 kt / 14 kt respectively
- Extruded PVC cells filled with liquid scintillator
- WLS fibers and APDs
- CVN event classification



- Neutrino mode: observe 58 ν_e events (15 bgr)
- Antineutrino: observe 18 anti-ν_e events (5.3 bgr
- $>4\sigma$ antineutrino appearance
- Data prefer NH at 1.8σ

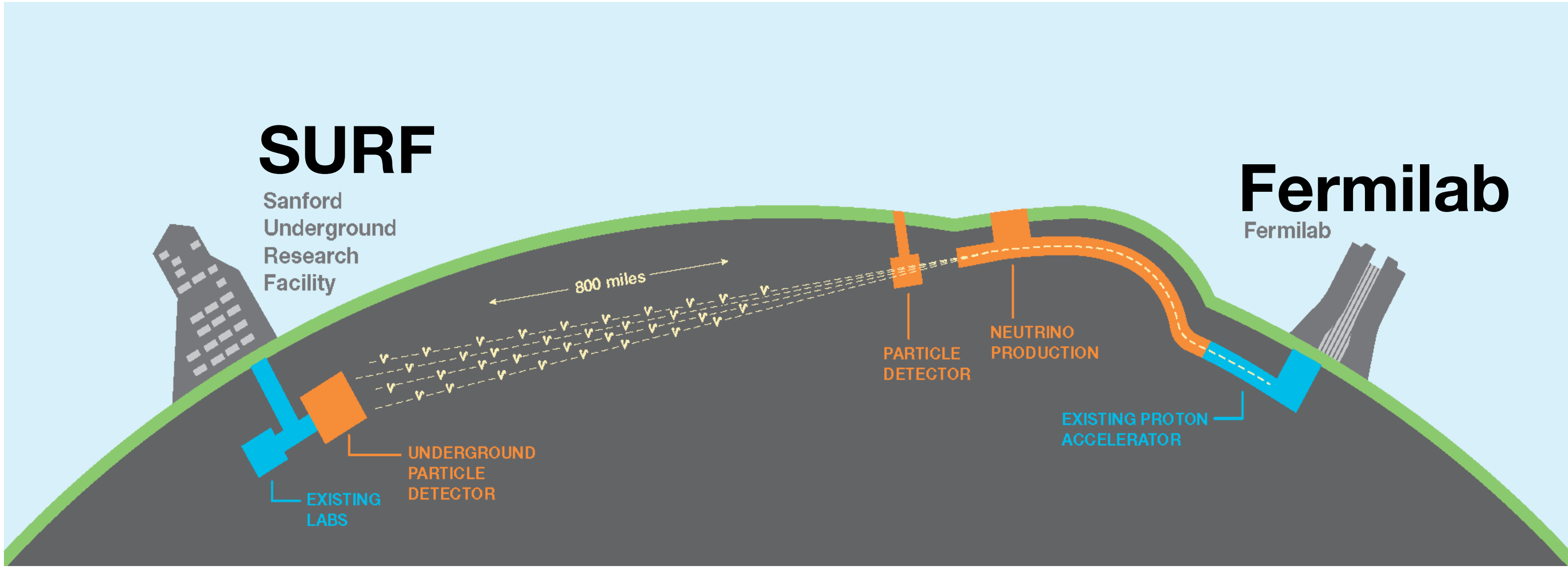
- Extended running to 2024
- Expect 2σ CP Violation sensitivity for -90^o

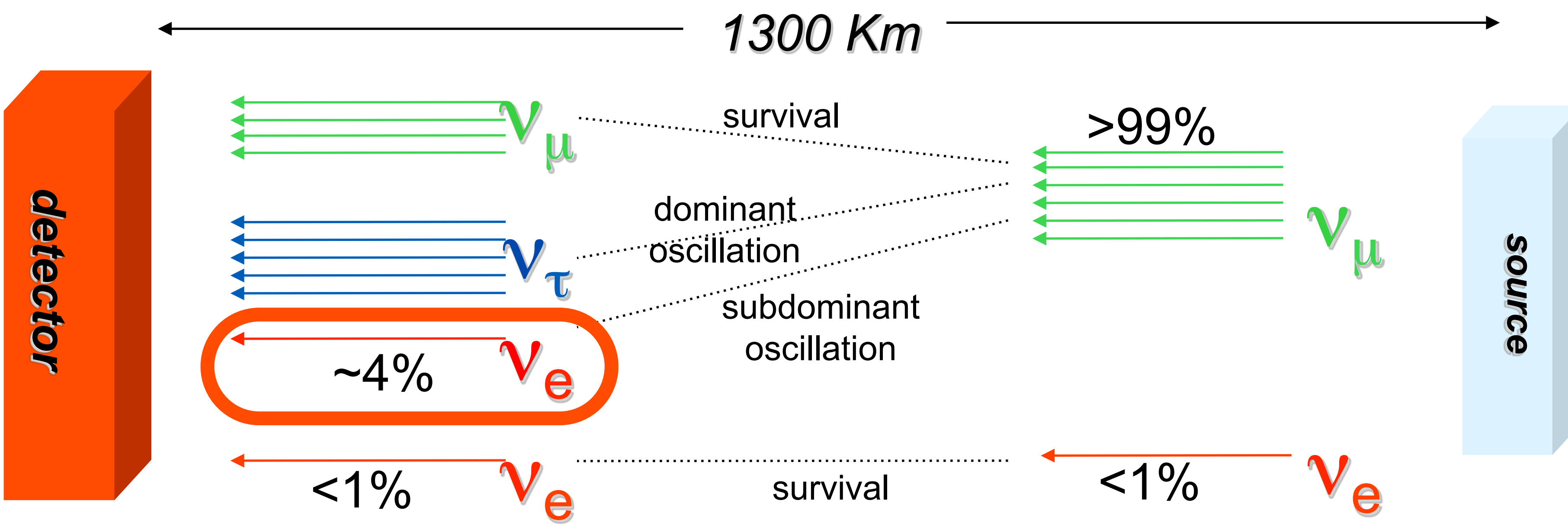
DUNE

DEEP UNDERGROUND
NEUTRINO EXPERIMENT

1180 collaborators, 177 institutions, 31 countries

Neutrino oscillations in DUNE

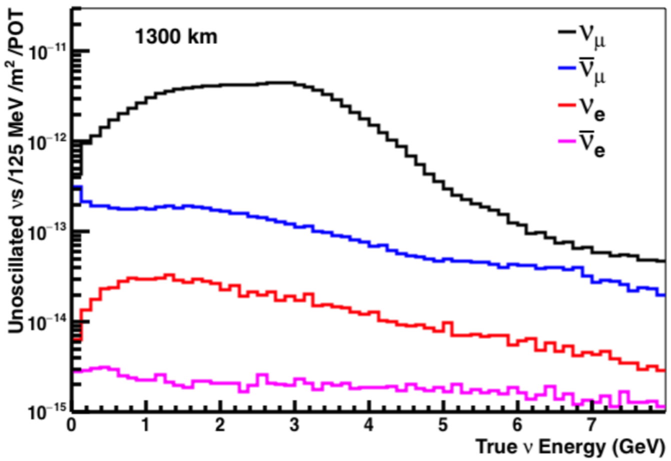


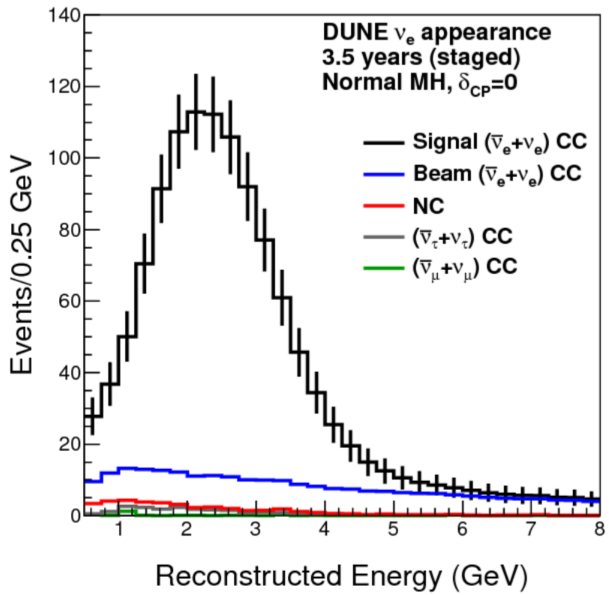


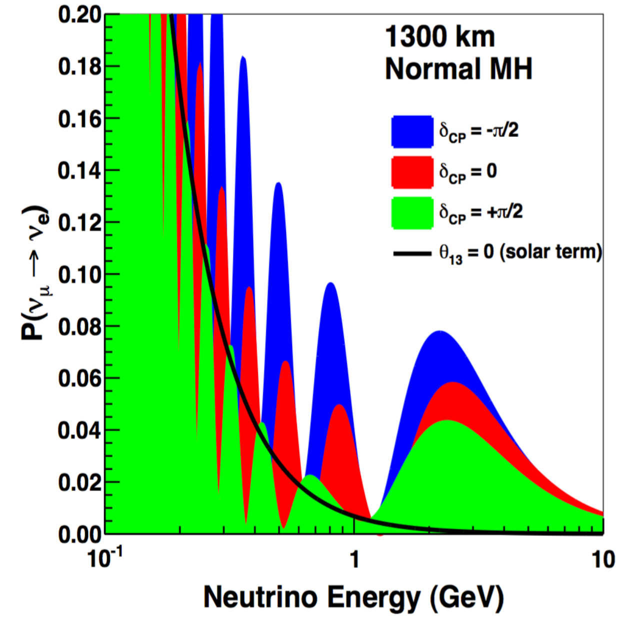
DUNE oscillation physics in a snapshot
arXiv:1512.06148

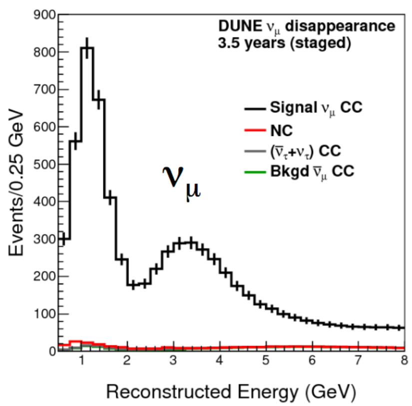
Oscillation probability for different values of δ_{CP}

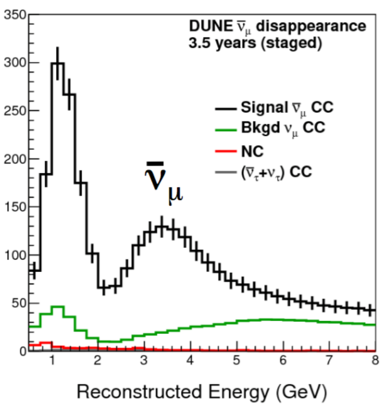
Neutrino Flux at 1300 km
(CDR Optimized Beam)

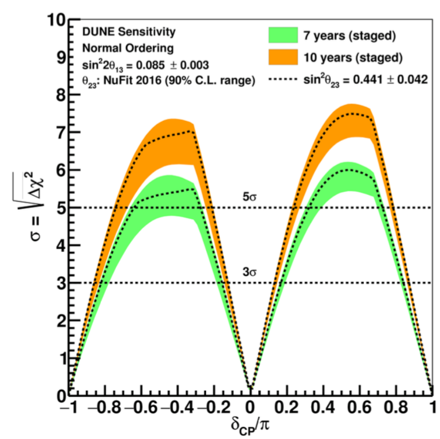












CP VIOLATION

- Full reconstruction MC improves performance over CDR
- TDR in preparation for summer 2019

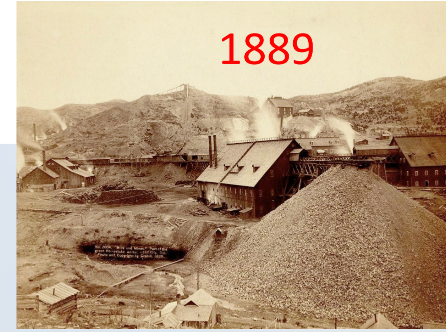
DUNE physics programme

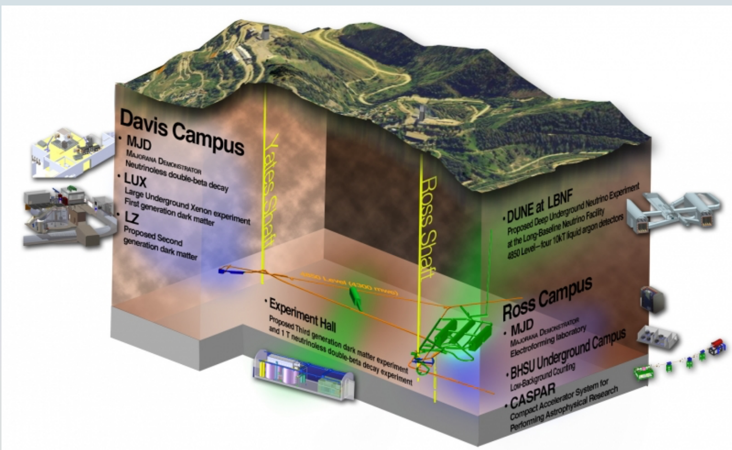
- Neutrino oscillations
  - CP Violation discovery, measurement of δ_{CP}
  - Determination of Mass Hierarchy
  - Test PMNS unitarity (3-neutrino mixing paradigm)
- Neutrino cross sections (Near Detector)

- Proton decay (Far Detector)
- Supernova & Low energy neutrinos (Far Detector)
- BSM (ND, FD)
  - Light DM; Boosted DM; Steriles; NSI; CPT violation; neutrino tridents; Large Extra Dimensions; neutrinos from DM annihilation in the sun, …

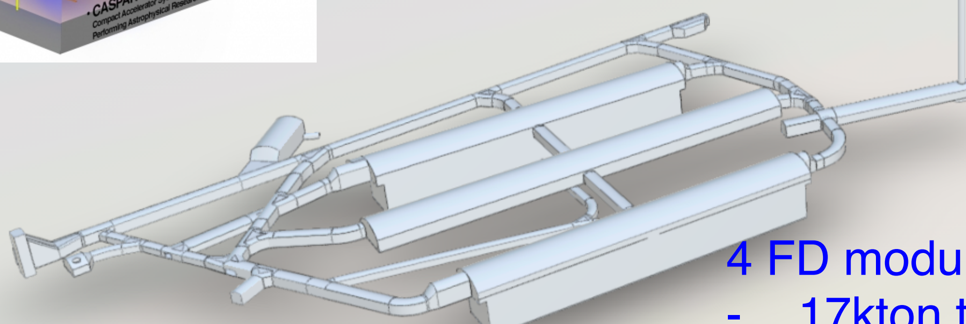
DUNE Far Detector (FD)

Sanford **U**nderground **R**esearch **F**acility (Lead, SD)
Homestake Mine, new caverns: 800,000 tons of rock
1,300 km from Fermilab
1,500 m underground





Ray Davis's experiment



4 FD modules, each one:
- 17kton total
- 10kton fiducial
- Infrastructure in middle tunnel

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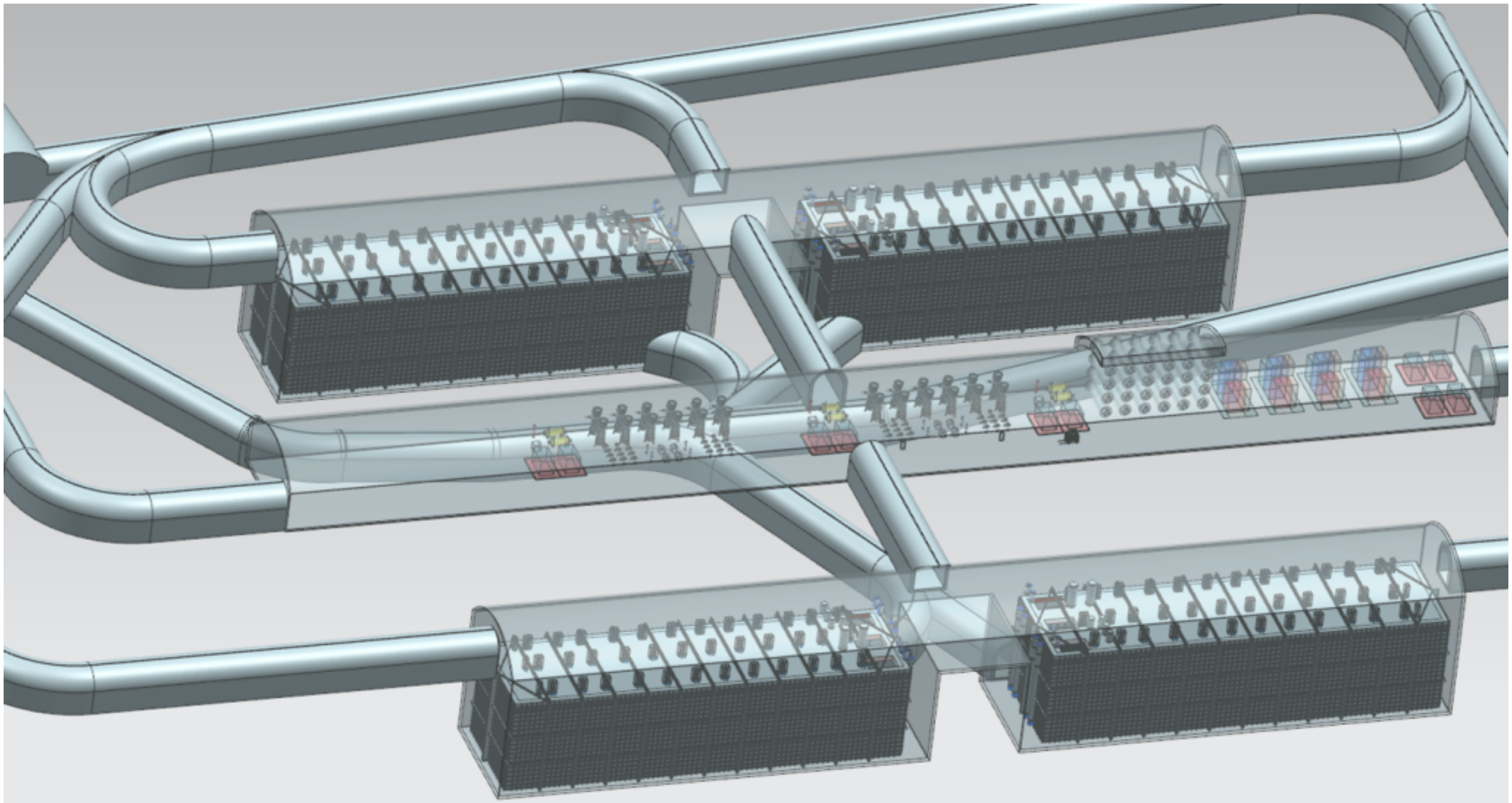
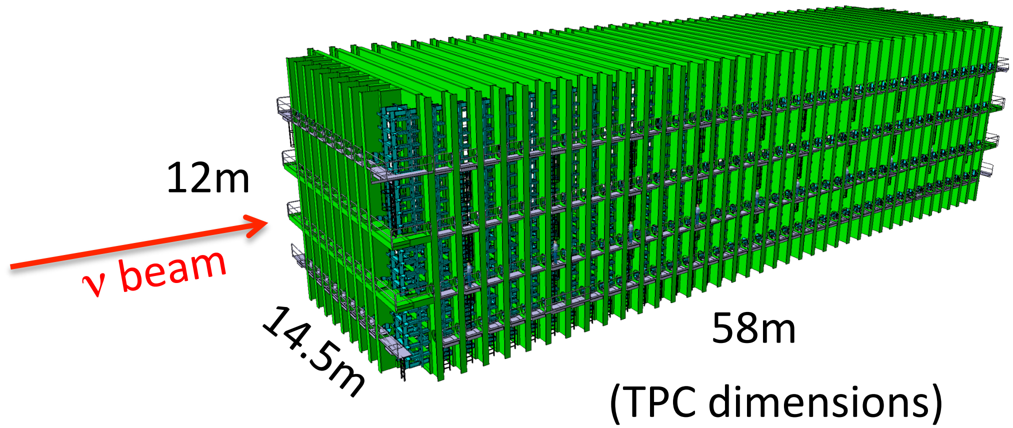
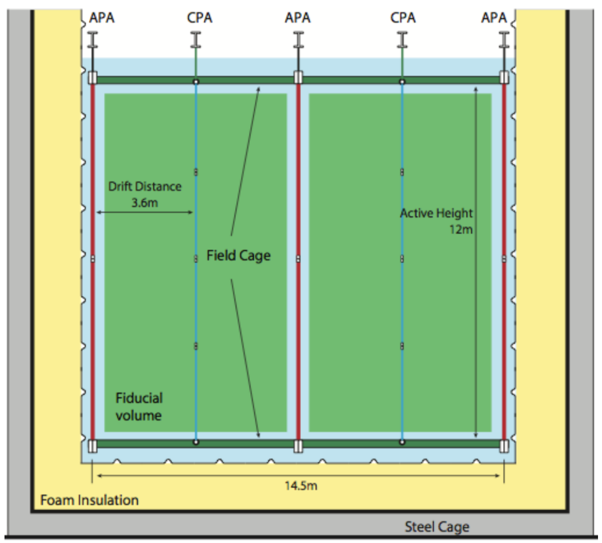
Four 17 kton LAr TPCs, single-phase and dual-phase in some combination TBD



Single Phase FD module





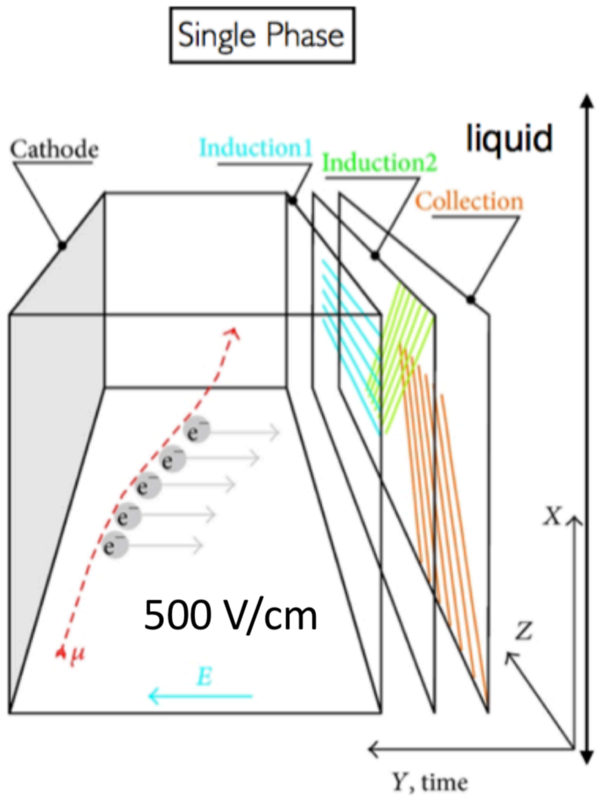
Maximum drift: 3.6m
500v/cm
Cathode HV: -180kV
Demonstrated in protoDUNE

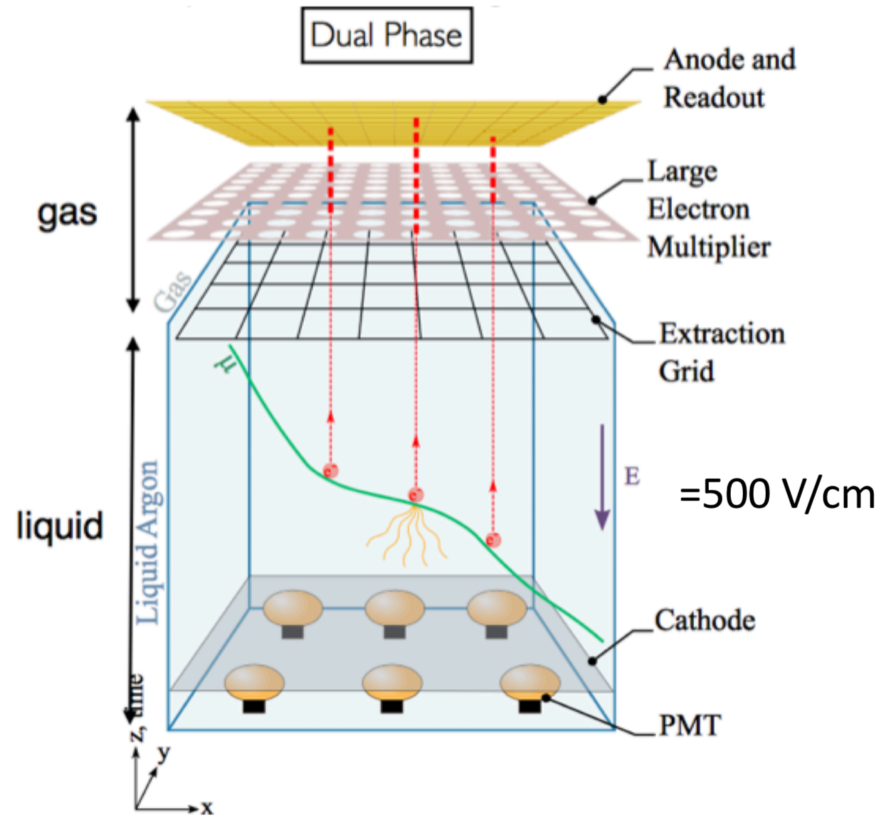
The ProtoDUNE programme at the CERN Neutrino Platform

A validation and evaluation programme for the DUNE FDs

- Hardware design and construction of full-size elements
- Integration, QA and installation procedures
- Long term operational stability
- Test beam data: performance evaluation
  - Evaluation of detector response and demonstrate calibration
  - Exercise pattern recognition, track, cluster and vertex reconstruction
  - Characterize energy and spatial resolution, dE/dx, PID
  - Perform haron cross-section measurements on Argon
- Cosmics data
  - 3D map of detector response, space charge, E field distortions
  - Vary E field, recirculation etc

The two technology options



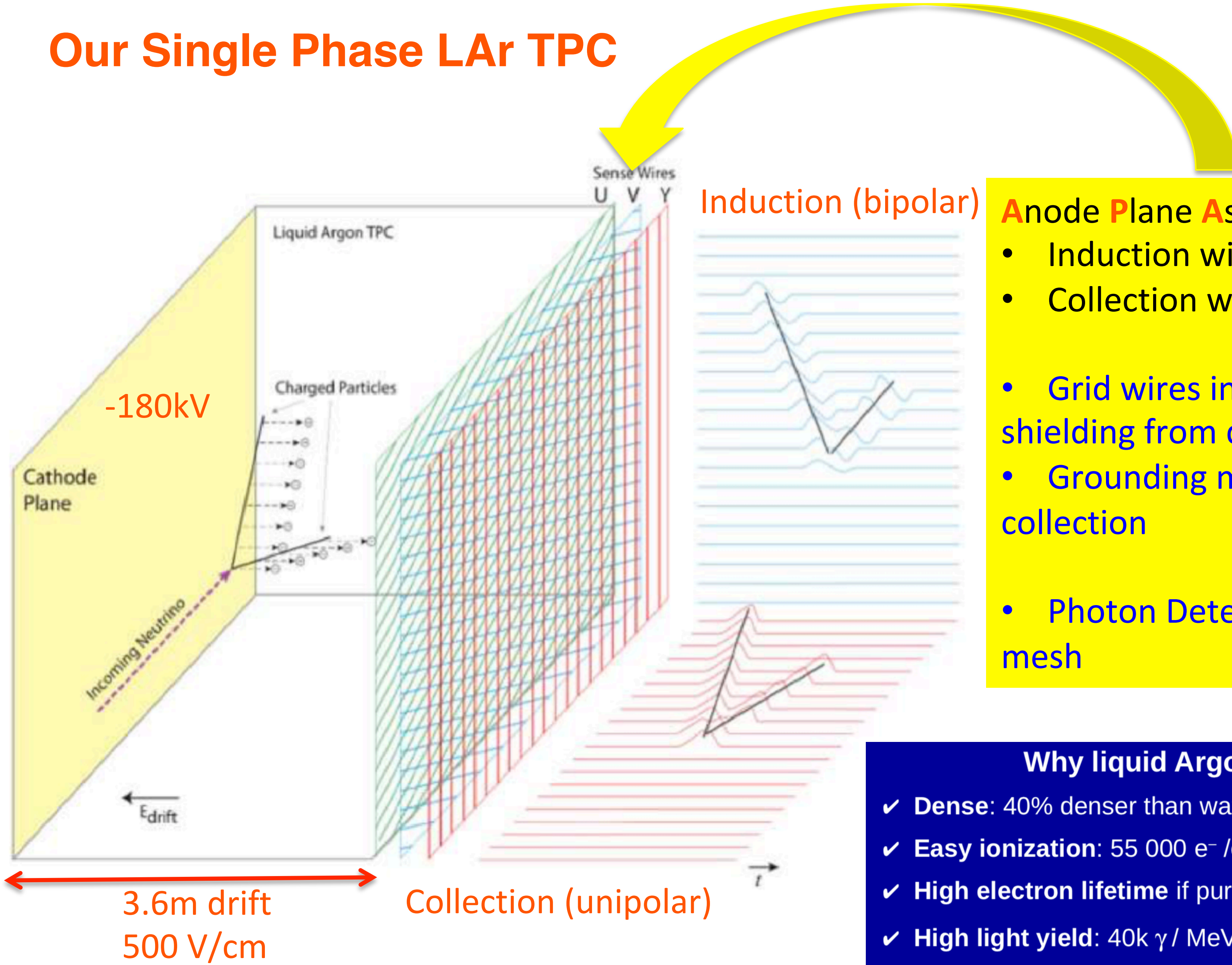


- Ionization charges drift horizontally and are read out with wires
- No signal amplification in liquid
- 3.6 m maximum drift
- Read out by APAs

- Ionization charges drift vertically and are read out on PCB anode
- Amplification of signal in gas phase by LEM
- 12 m maximum drift
- Access through chimneys on top

DUNE is committed to deploying both technologies – staging depends on funding and ProtoDUNE results

Our Single Phase LAr TPC



Anode Plane Assembly

- Induction wires +/-35.7°
- Collection wires vertical

- Grid wires in front shielding from drift region
- Grounding mesh behind collection

- Photon Detectors behind mesh

Why liquid Argon?

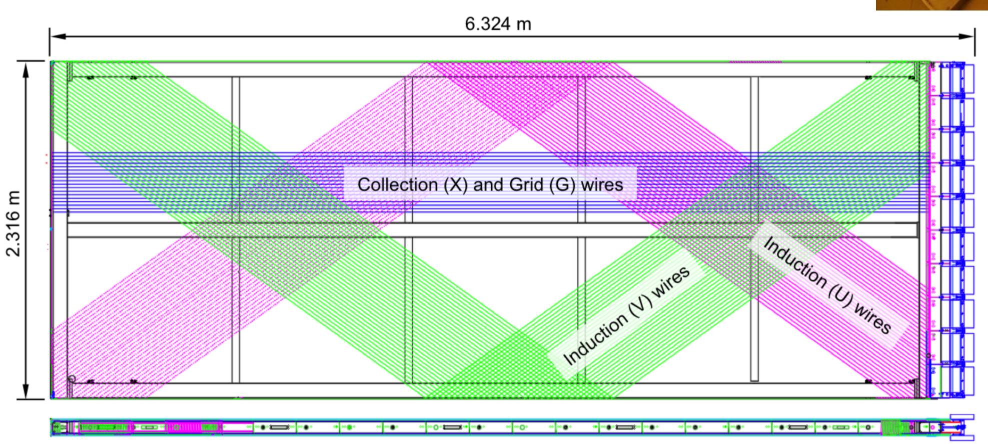
- ✔ **Dense**: 40% denser than water
- ✔ **Easy ionization**: 55 000 e^- /cm
- ✔ **High electron lifetime** if purified → long drifts
- ✔ **High light yield**: 40k γ / MeV
- ✔ **Abundant**: ~1% of the atmosphere
- ✔ **Cheap**: $ 2/L ($ 3000/L for Xe, $ 500/L for Ne)

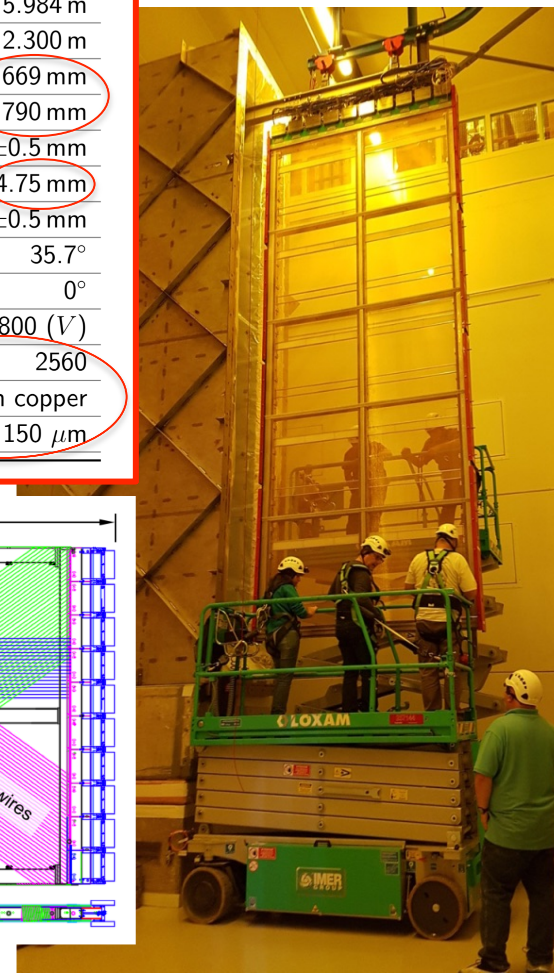
The APA

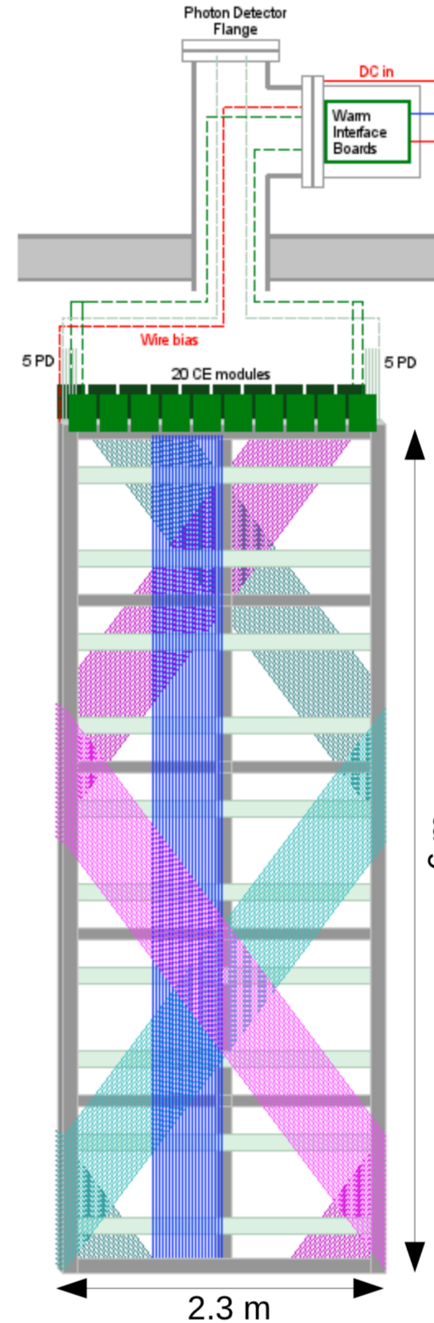
- Wrap-around wires
  - Charge collections from both sides
  - Keep readout channel number low
  - All electronics on one side (tiling)

Table 2.2: APA design parameters

Parameter	Value
Active height	5.984 m
Active width	2.300 m
Wire pitch (U, V)	4.669 mm
Wire pitch (X, G)	4.790 mm
Wire pitch tolerance	$\pm$0.5 mm
Wire plane spacing	4.75 mm
Wire plane spacing tolerance	$\pm$0.5 mm
Wire Angle (w.r.t. vertical) (U, V)	35.7°
Wire Angle (w.r.t. vertical) (X, G)	0°
Number of wires / APA	960 (X), 960 (G), 800 (U), 800 (V)
Number of electronic channels / APA	2560
Wire material	beryllium copper
Wire diameter	150 μm







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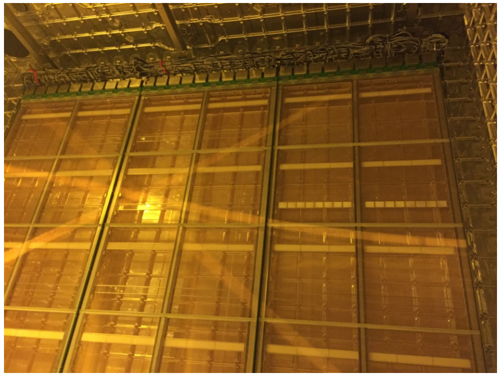
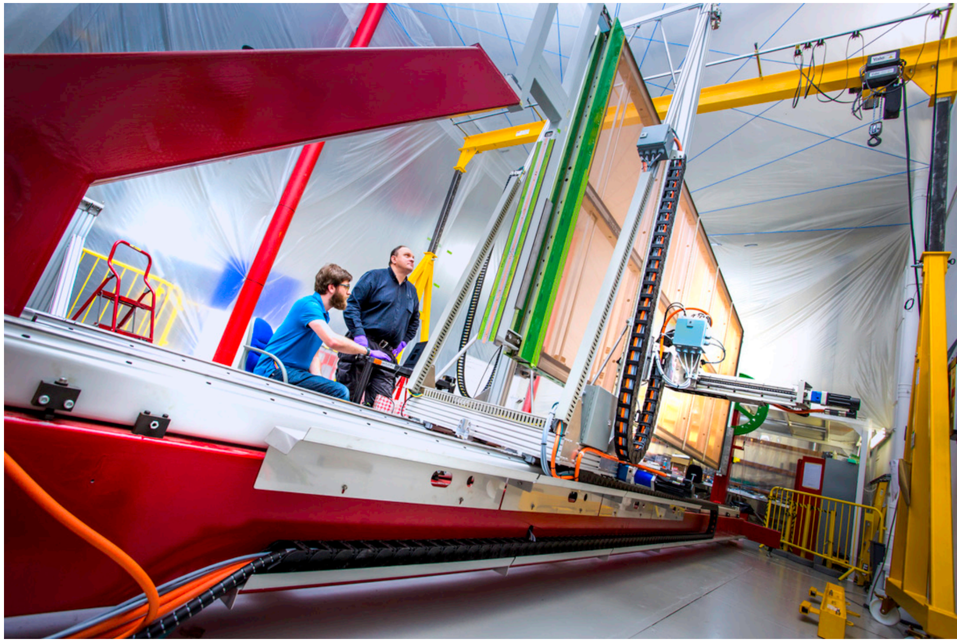
ProtoDUNE APAs

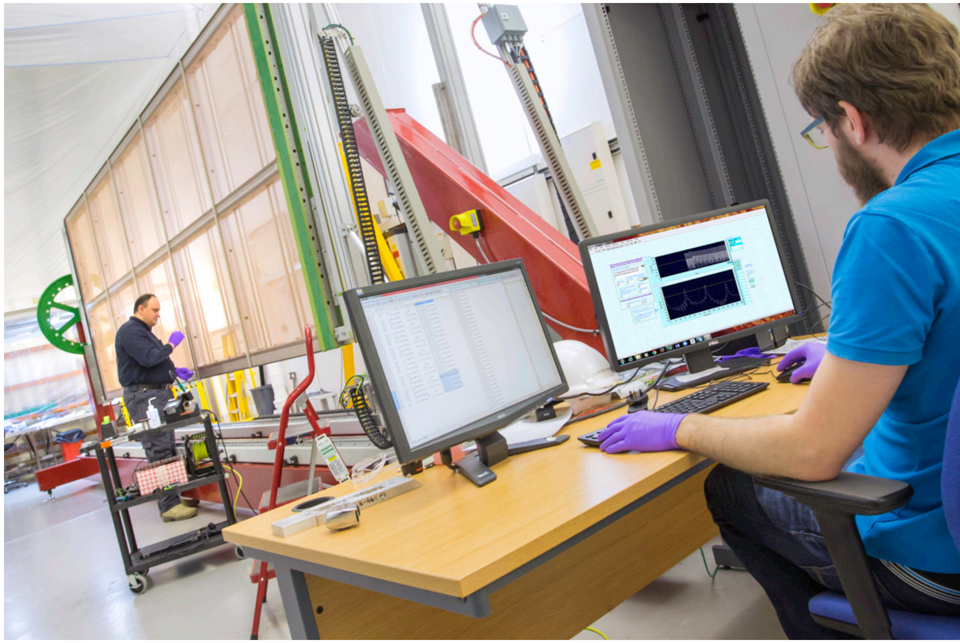


Anode Plane	Bias Voltage
Grid (G)	-665 V
Induction (U)	-370 V
Induction (V)	0 V
Collection (X)	820 V
Mesh (M)	0 V

At CERN



Wiring machine (Daresbury Lab, UKRI/STFC)

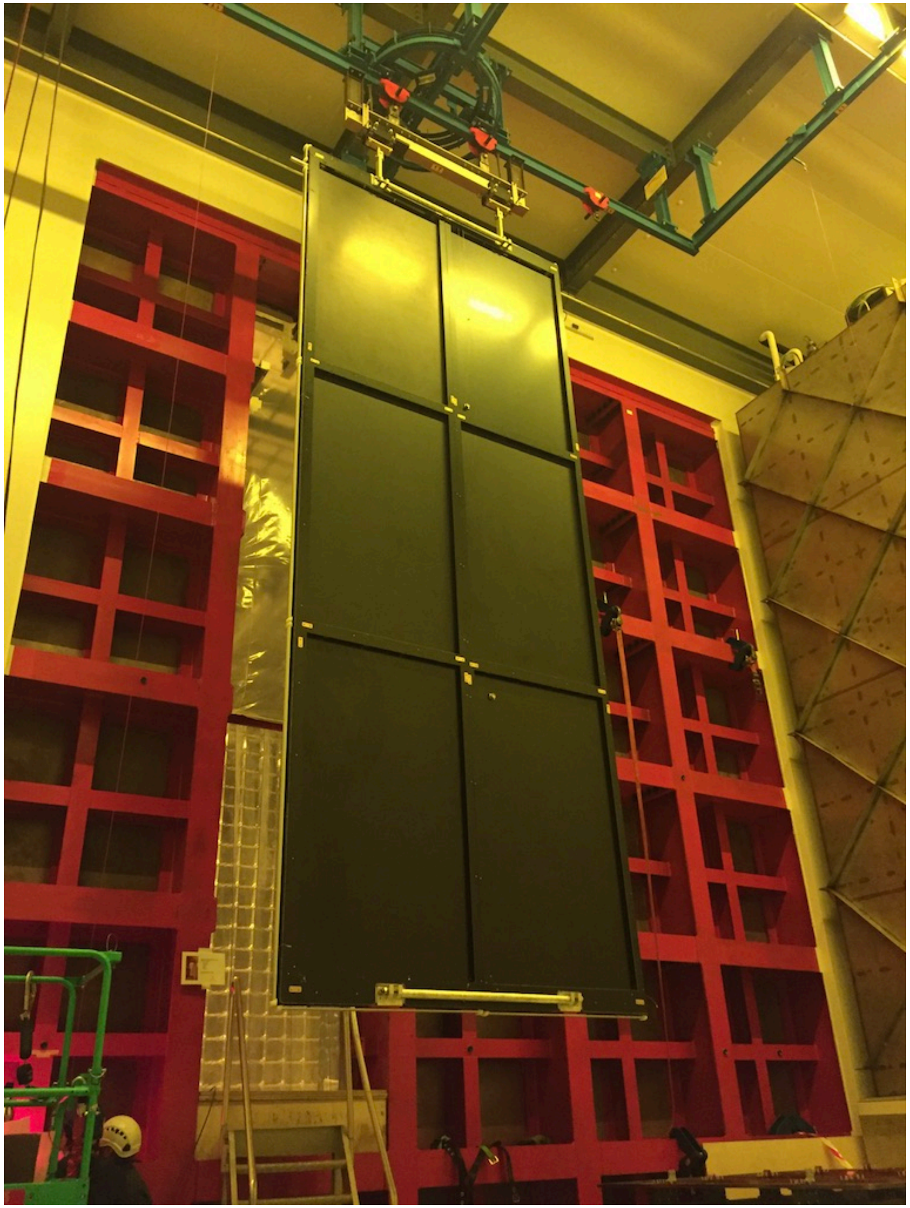


The CPA (Cathode Plane Assembly)

- Large ($700m^2$) equipotential surface at -180kV
- Resistive to slow down the release of >100J from a discharge, that could damage the CE

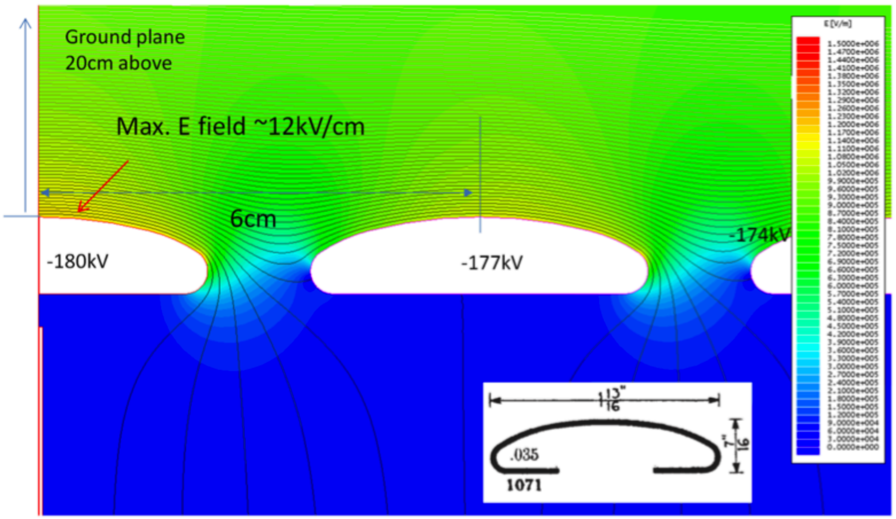
- Flat to <1cm in LAr
- CTE match to steel

- 3mm thick FR4 panels laminated with commercial resistive Kapton film

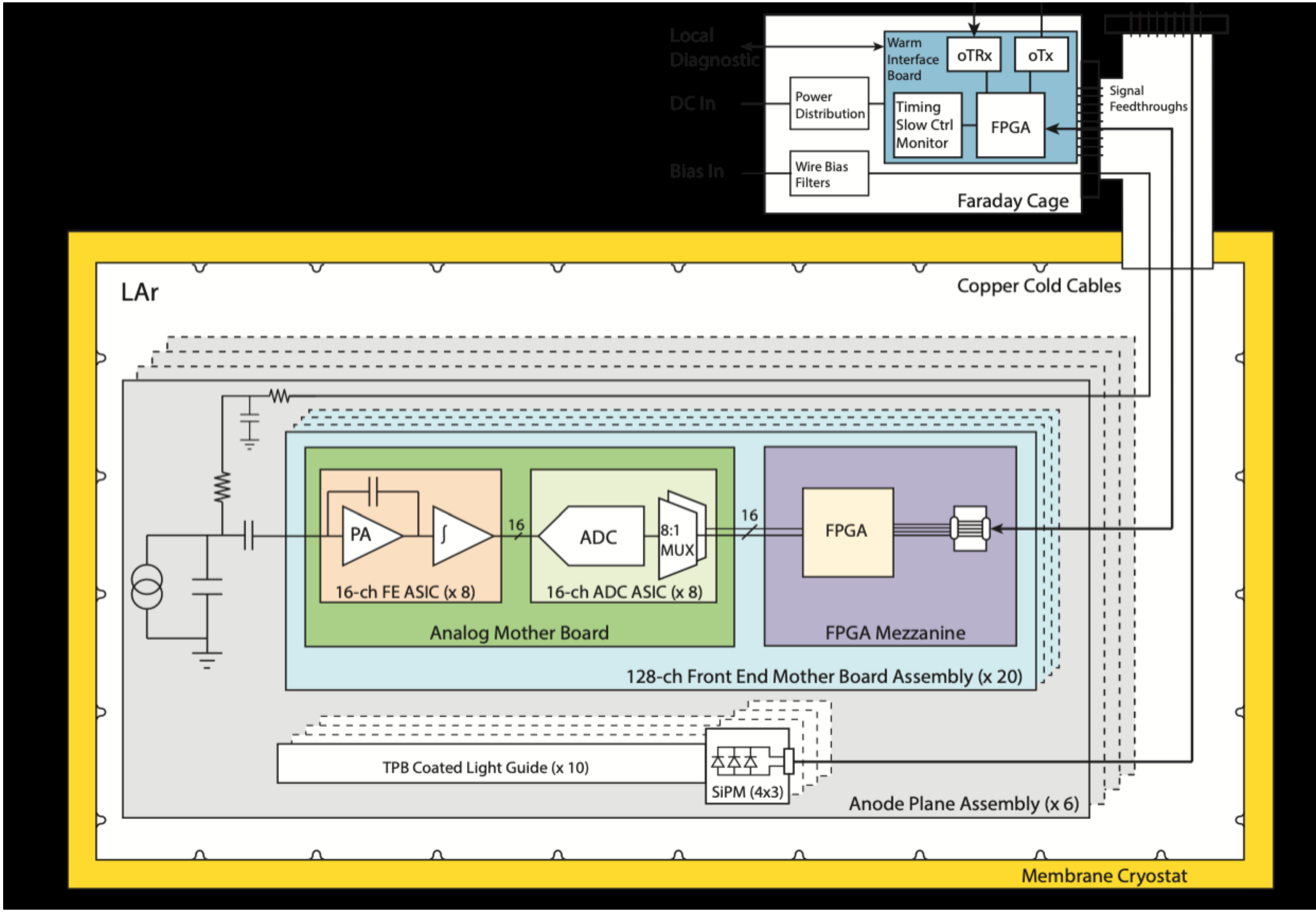


The Field Cage

- To ensure a uniform E field in the drift volume
- Consecutive electrodes, extruded Alu profiles
- Biased using divider chain (resistors and varistors)

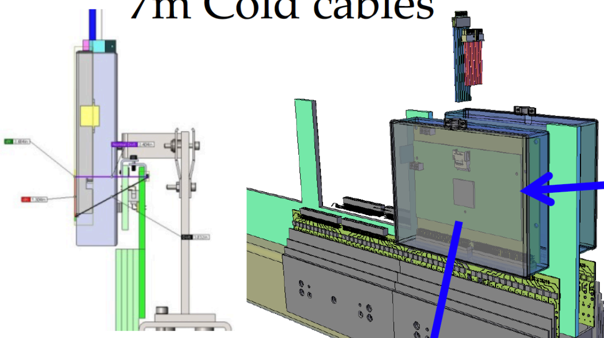


Charge Readout Electronics

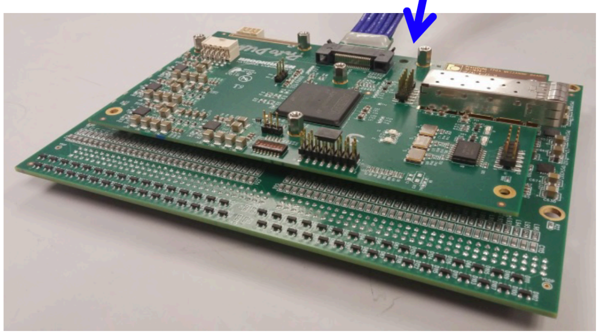


Charge Readout Electronics

7m Cold cables

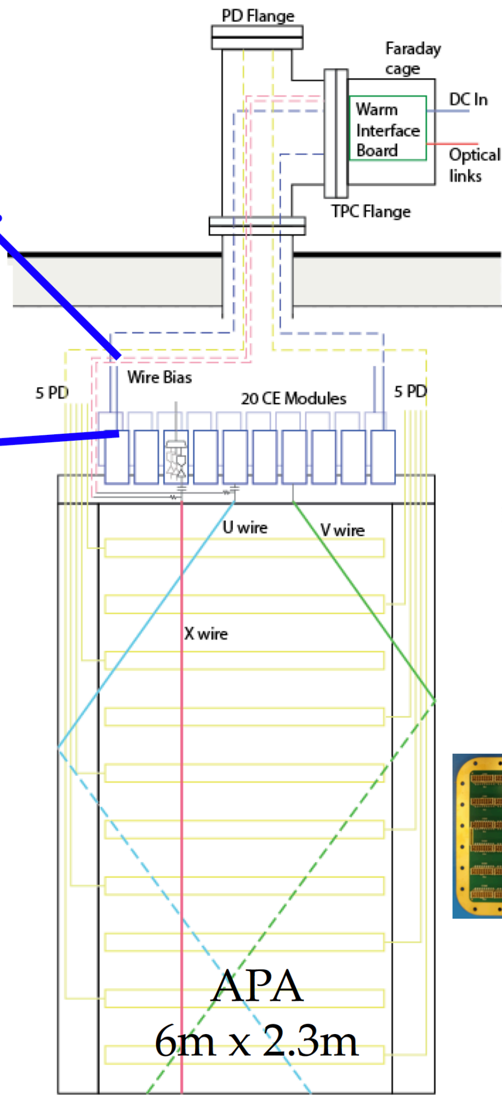


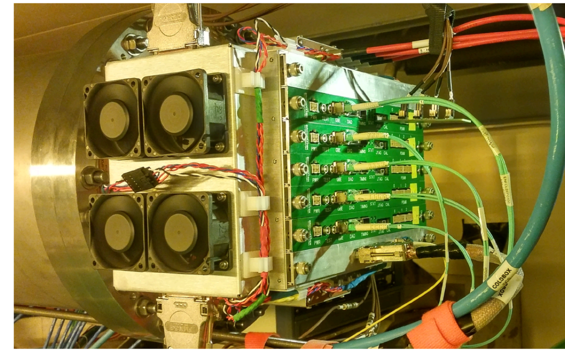
20 CE boxes on APA



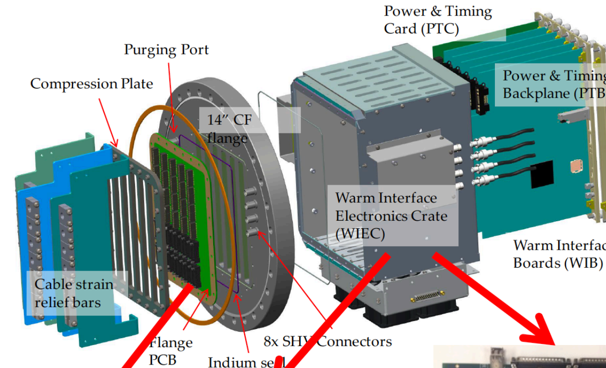
FEMB (inside CE box)

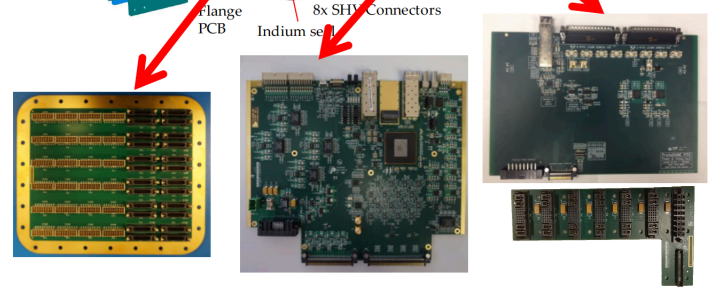
Cold Side





Signal Feed-through Assembly

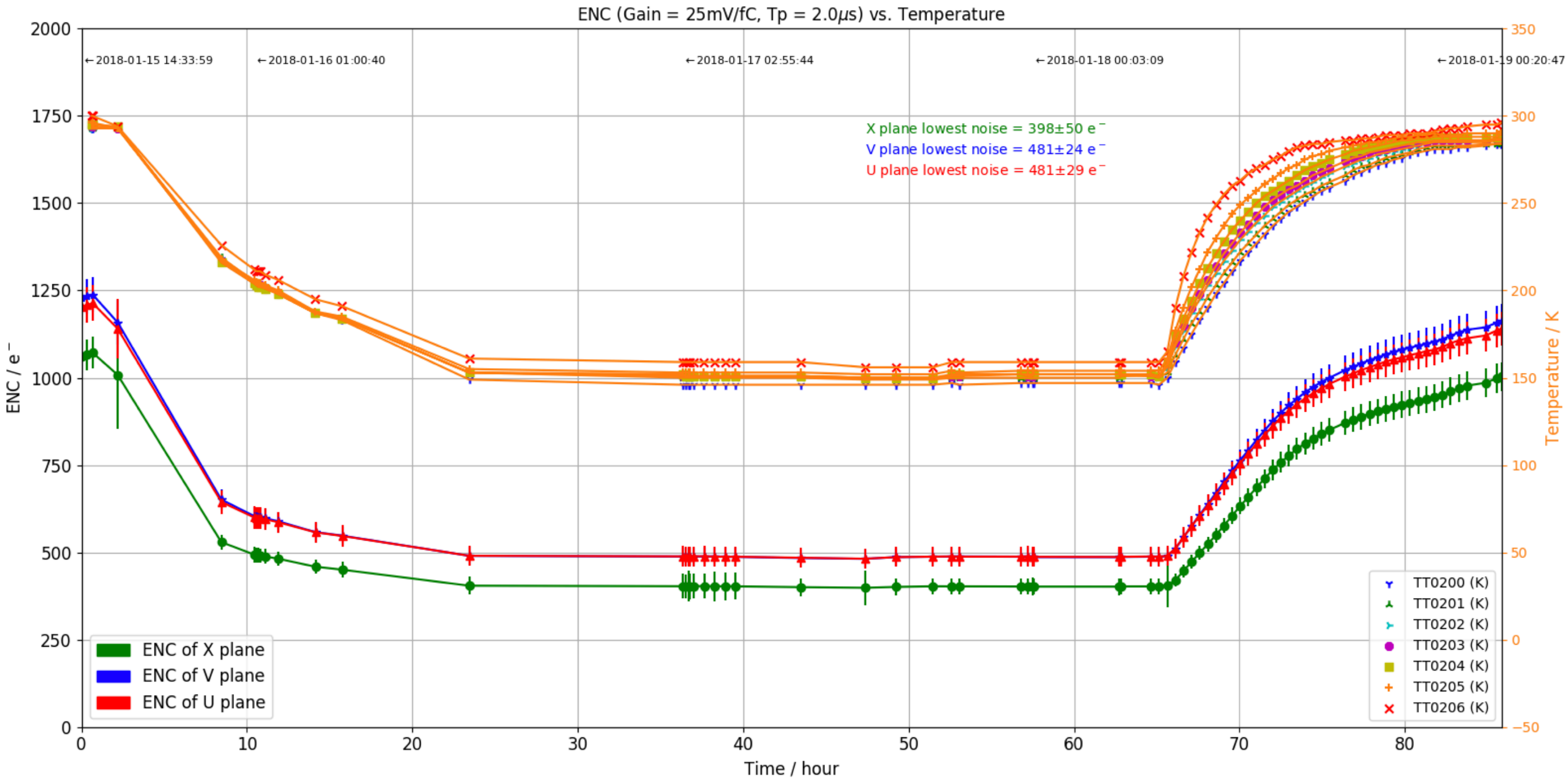




Flange Board, WIB, PTC, PTB

Warm Side

Charge Readout Electronics: Cold Box test results



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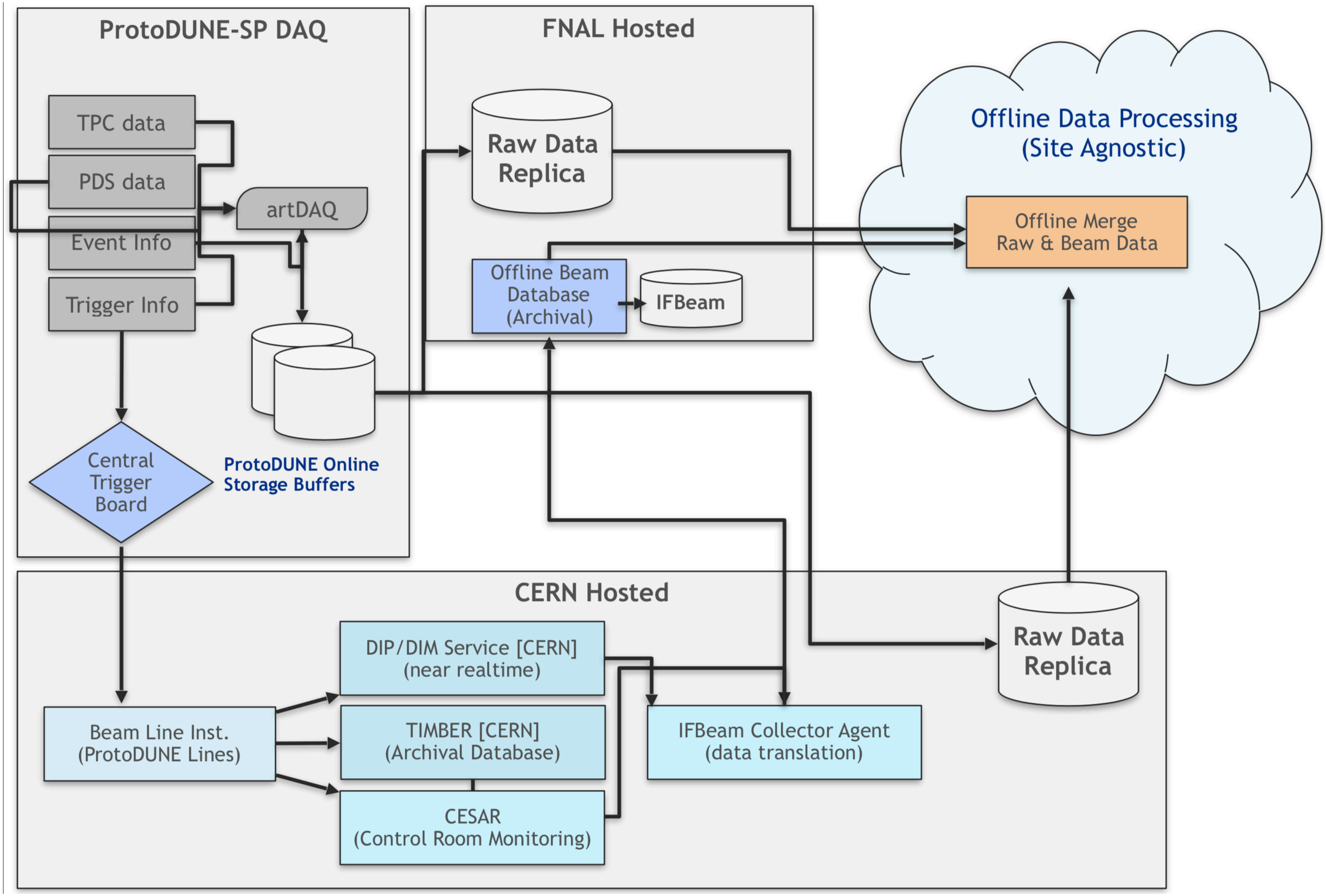
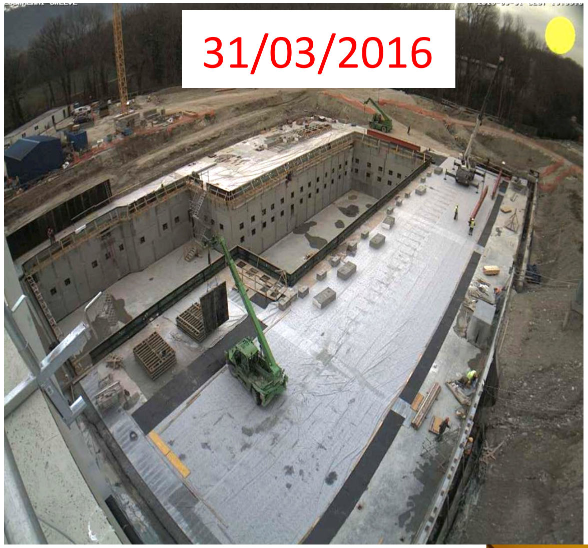
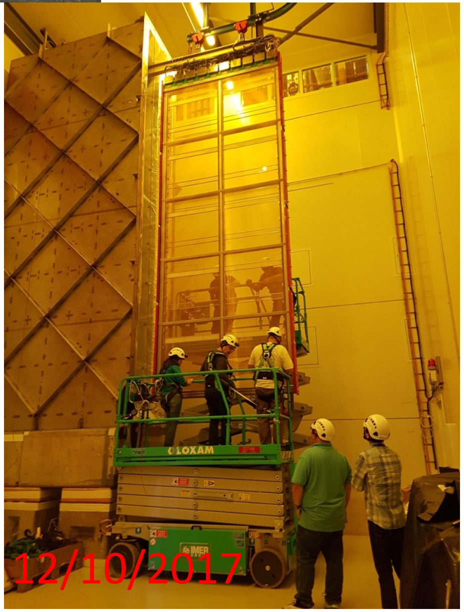
Data handling model



The CERN NP at the EHN1 extension & ProtoDUNE-SP



16/03/2017



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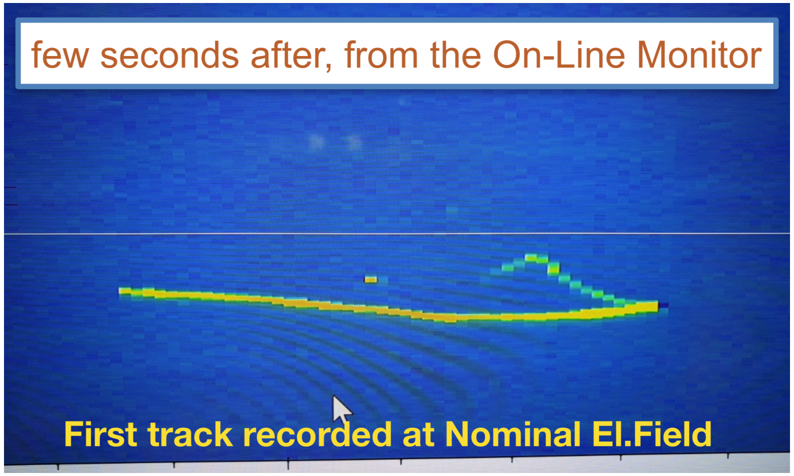
ProtoDUNE-SP in June 2018

The last man out of the cryostat

Purging, Cool down, LAr filling, activation

- 15 July – 13 September
  - Use "piston effect" with room temperature Argon to get air out
  - Spray cold Argon from top for cooling
  - Keep LAr level below the APAs until temp. gradient between its ends reached 50 degrees
  - 13 August – 13 September fill to nominal level with higher fill rate
- HV ramp up: 130kV, 160kV, 180kV in 2 days



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DAQ

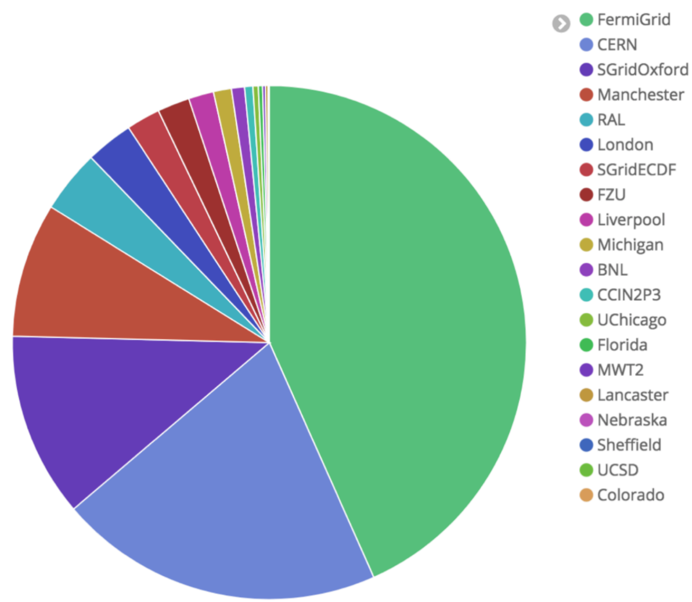
- Achieved required 25Hz, max 60Hz
- Excellent uptime, some runs up to 7hrs

- RCE baseline option & data compression
- FELIX solution for DUNE demonstrated, including real time compression with Intel QAT

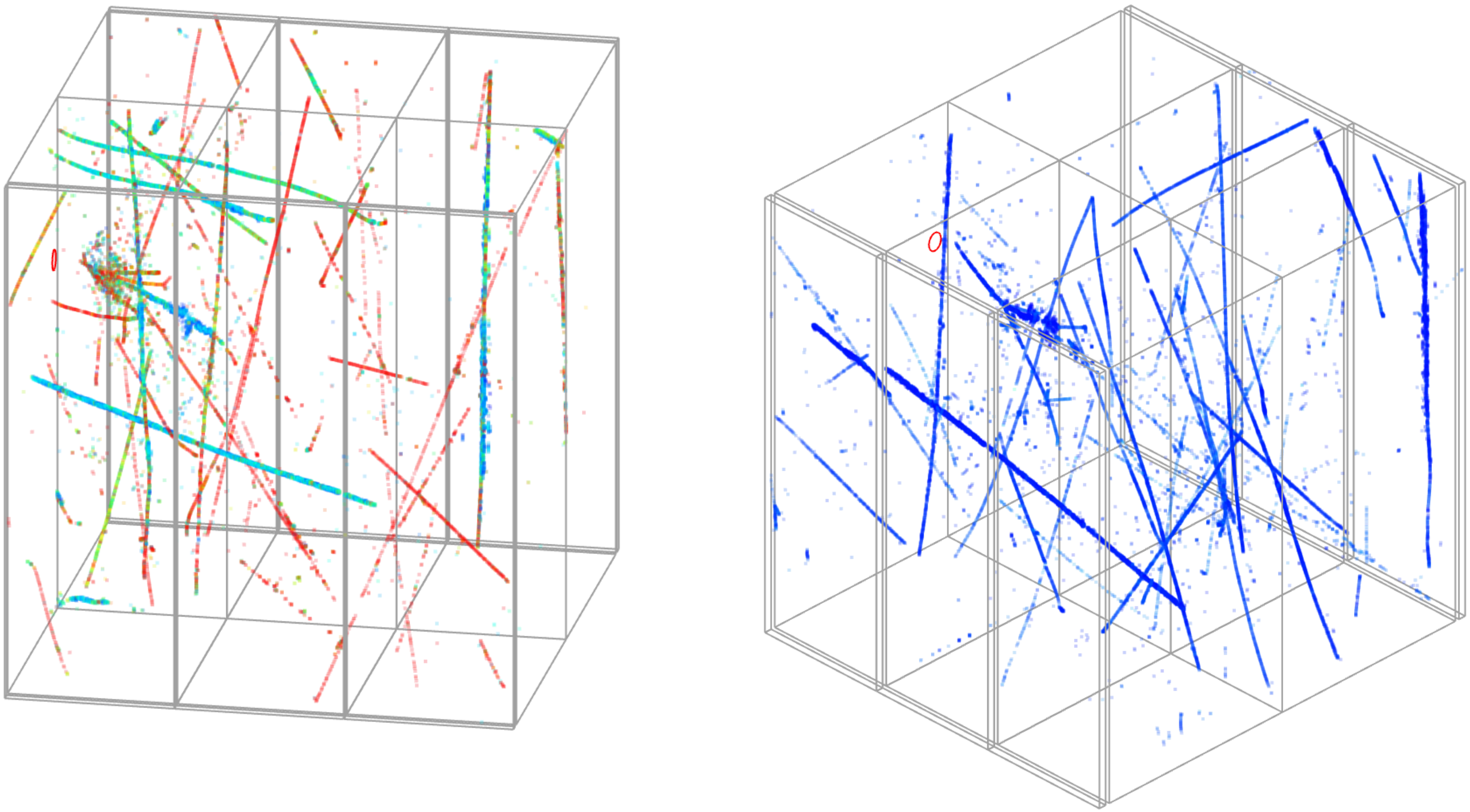
- HW trigger allowed beam, cosmics, random and calibration triggers
- Demonstrated WinCC/JCOP Run Control
- Parallel write performance with artdaq dataflow reading data from disk buffer to offline at 20Gb/s
- Timing, online monitoring, event display, resource monitoring etc

Offline

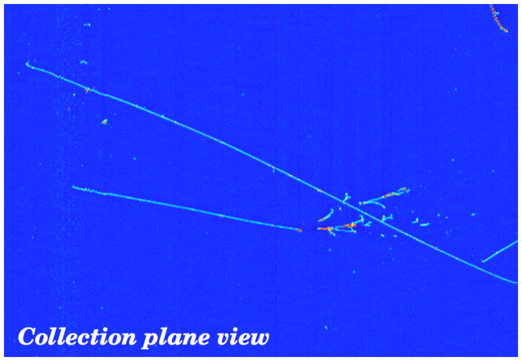
- 15,360 wires read out
- 3msec electron drift time
- 12-bit ADC per wire, read out every 500nsec
- At 25Hz the detector produced 2.5GB/sec, <1GB/sec compressed
- Total data collected 1.8PB
- 7.9M events in good physics runs (beam and cosmics) for analysis (509TB)
- 14M MC events also (full reco)
- Jobs on the GRID



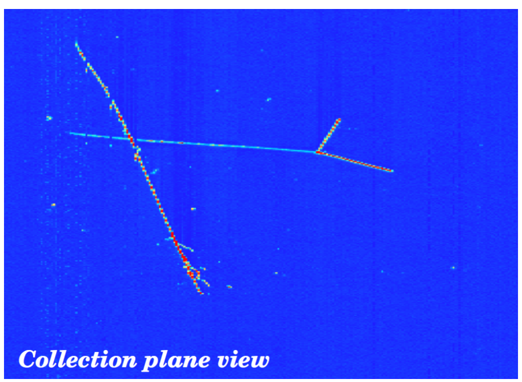
Events from 7 GeV beam

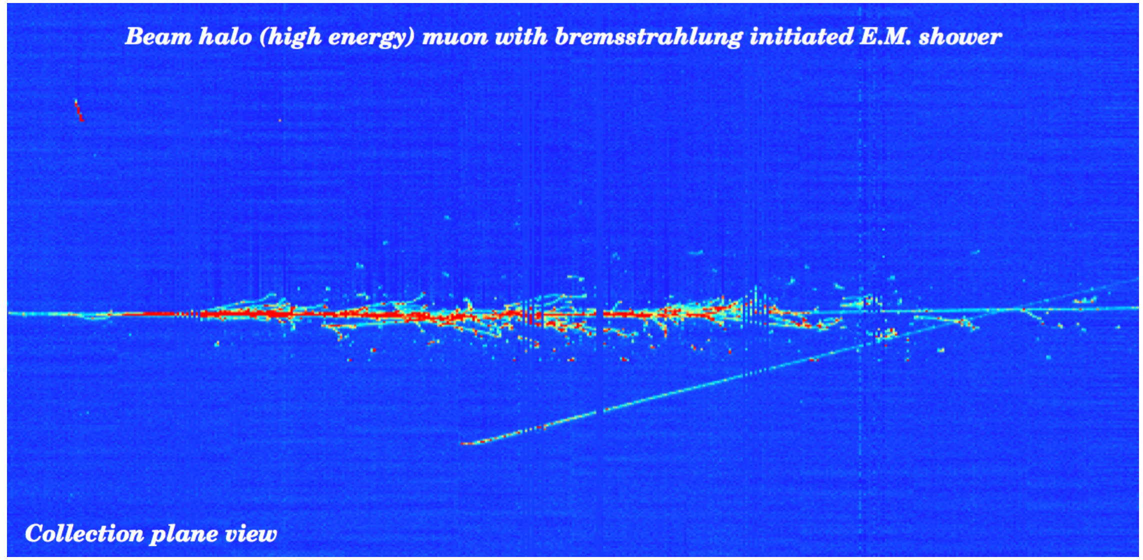


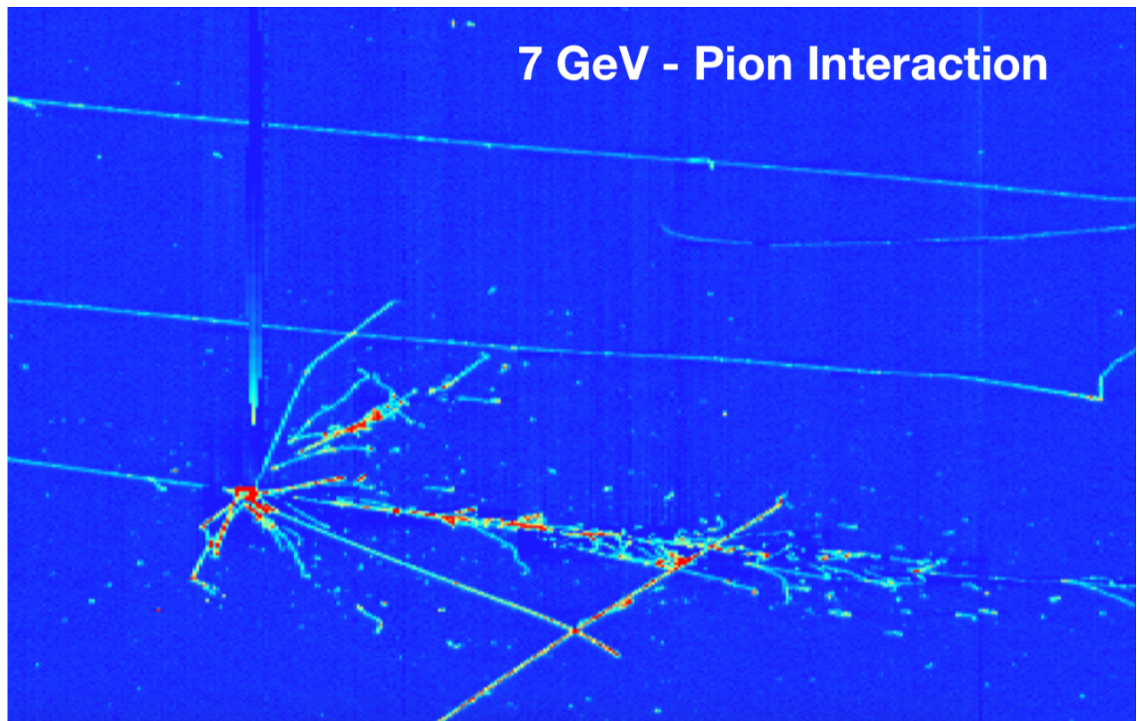
More events



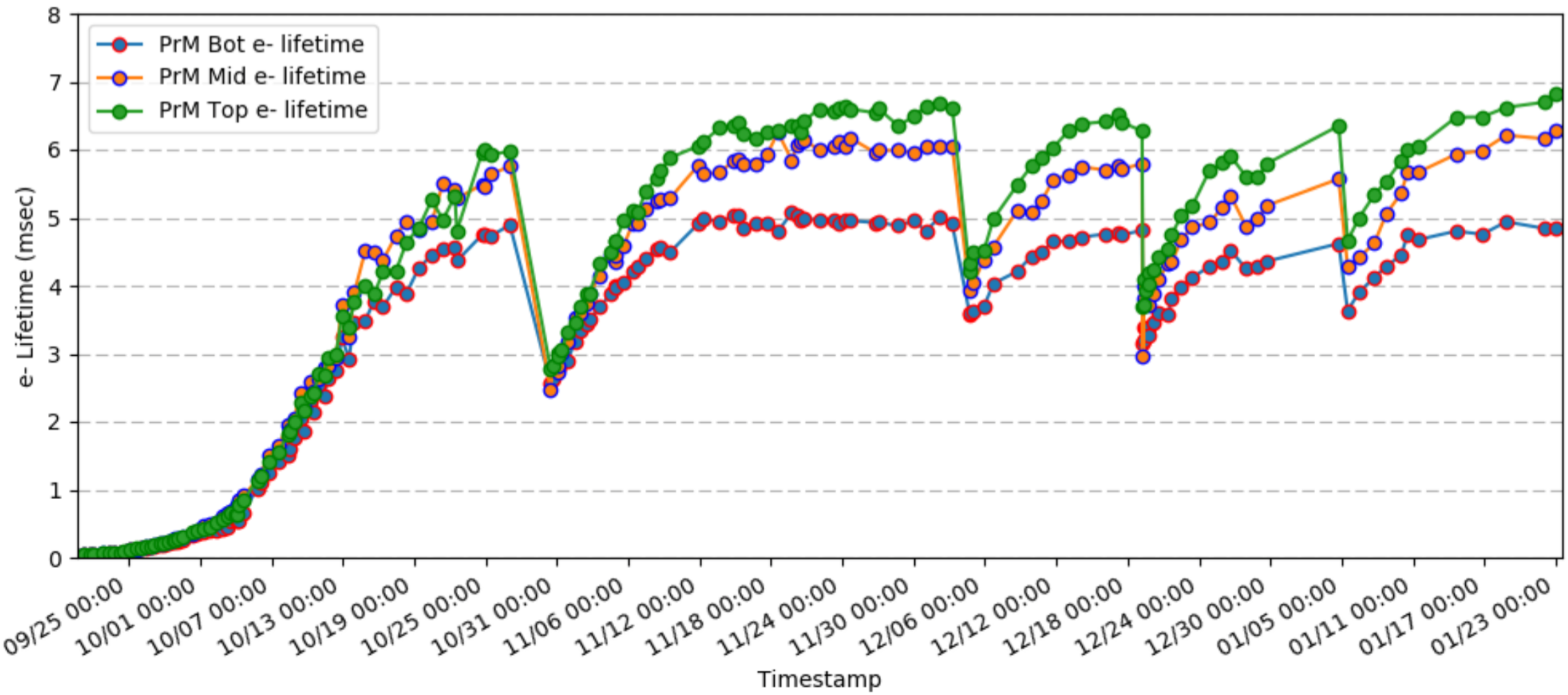
1 GeV pions







Detector stability



- Argon purity (electron lifetime): above 5msec, exceeding DUNE requirements
- HV: stable running at 180kV (500V/cm)
  - short (< 1s) current glitches, not visible on data, no intervention required
  - Sustained events (one or a few / day), quenched by automatic procedure controlling the HV

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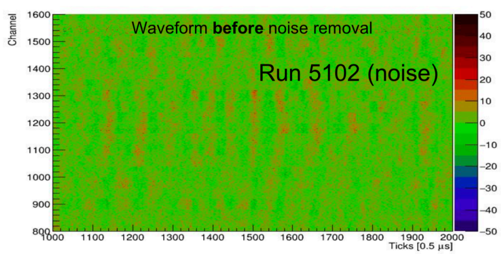
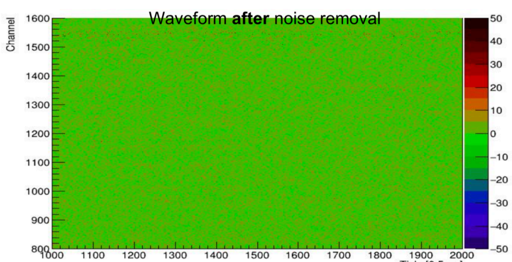
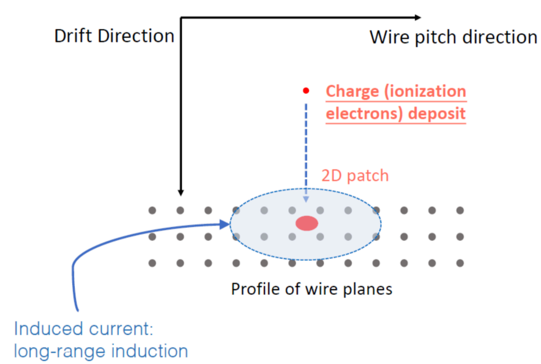
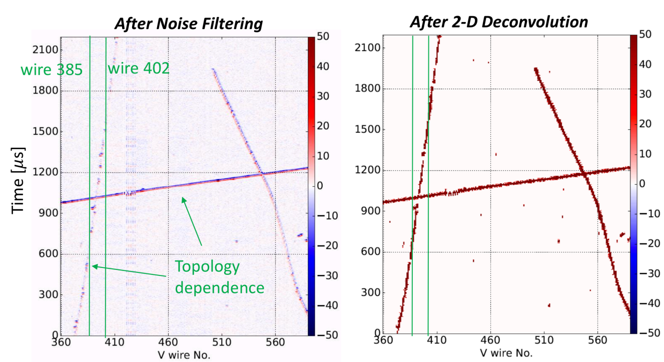
Offline highlights

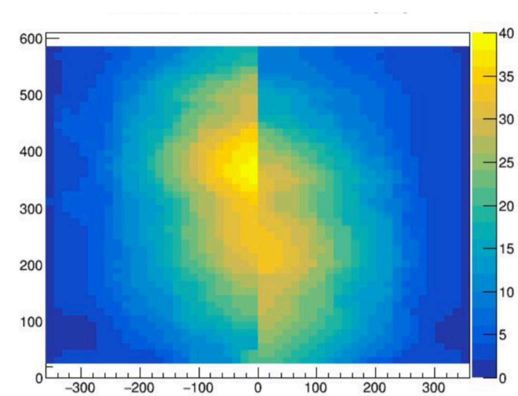
- Noise filtering
- Variety of pattern recognition methods implemented
- 2D deconvolution
- PANDORA (track / cluster formation including track “stitching”)
- PID, NNs, ….
- Looking at space charge effect







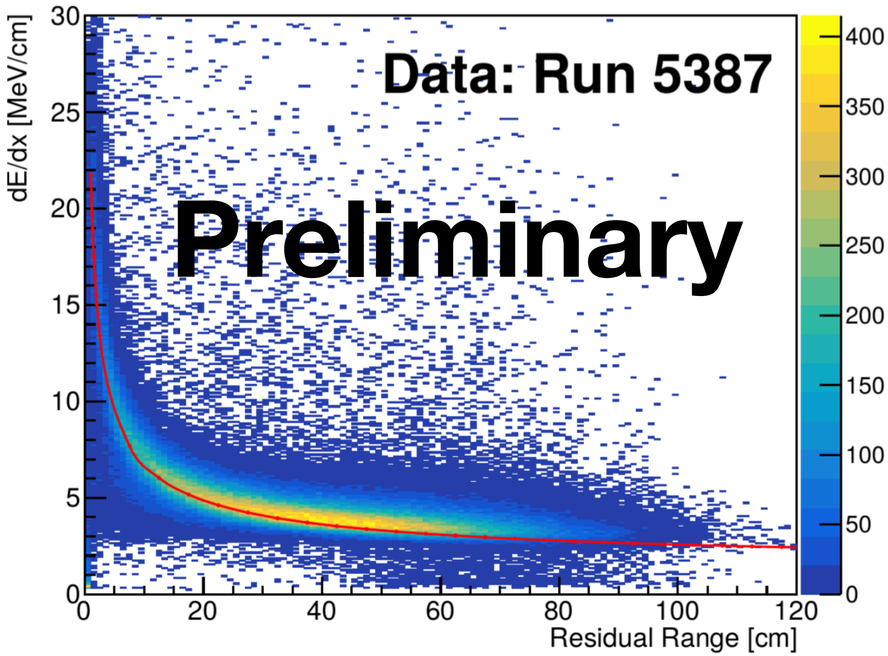


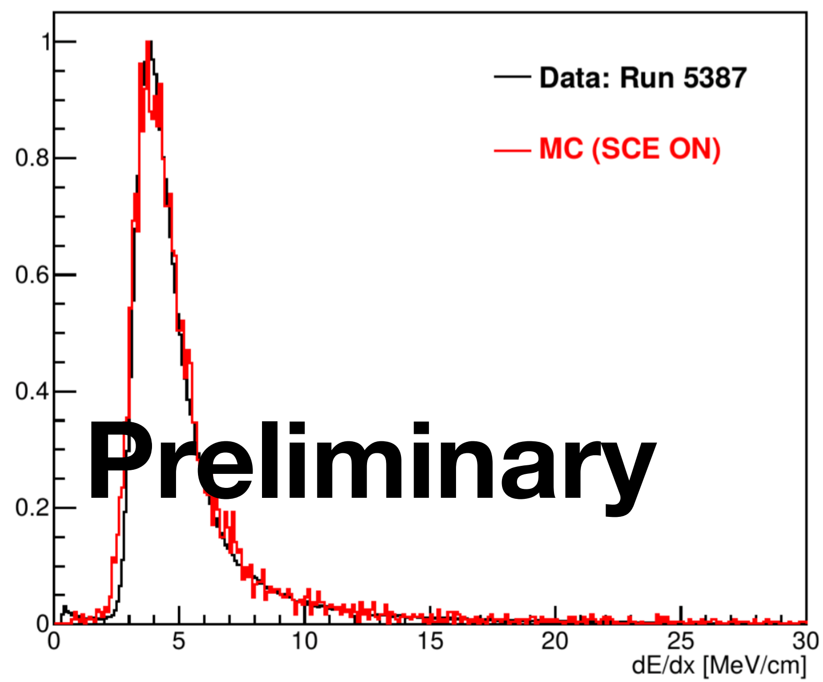


dE/dx

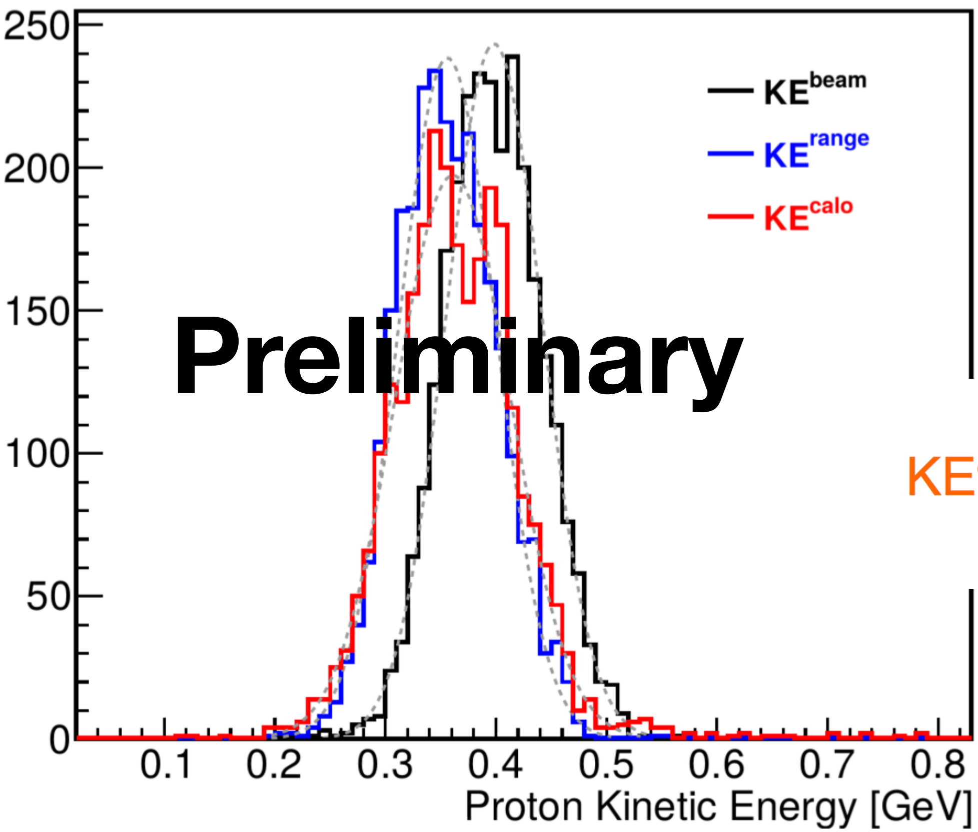
--- VERY PRELIMINARY ---

dE/dx for 1 GeV/c beam protons





Calorimetry --- VERY PRELIMINARY ---



$$KE^{calo} = \sum_j \frac{dE_j}{dx_j} dX_j \quad \text{(sum over all hits)}$$

Benchmark Quantity	Mean	Sigma
KE^{range}/KE^{calo}	0.974	0.043
KE^{calo}/KE^{beam}	0.928	0.045
KE^{range}/KE^{beam}	0.896	0.055

Conclusions

- ProtoDUNE-SP has demonstrated that we can:
  - Build a kton-scale TPC from scratch in < 2 years
  - One that performs to full specification and exceeds it in many ways
  - That can be commissioned and run without problems worth mentioning
  - Readout, DAQ, offline reconstruction and analysis are solved problems
- ProtoDUNE-SP will run in 2019 for detector studies with cosmics
- Will then open it, replace part / all of the TPC with final DUNE designs
- Take beam and cosmics data post LS2

Many thanks to the VCI organizers for the invitation

Many thanks to CERN for the investment and support for the neutrino Platform and ProtoDUNE