The ProtoDUNEs: Successes, lesson learned, and more to come

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Neutrino Oscillations

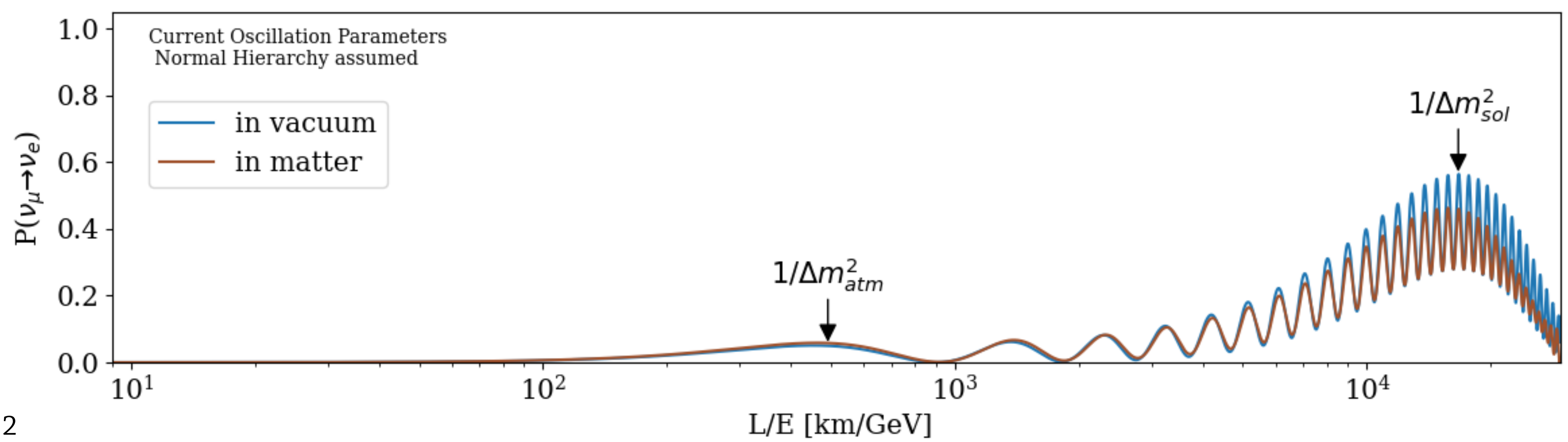
Neutrino Oscillation formalism introduced to explain the solar & atmospheric neutrino anomalies

Neutrino mass (i=1,2,3) and flavor (α=e,μ,τ) eigenstates are linked by the PMNS unitary matrix.

$$|\nu_\alpha\rangle = \sum_{i=1}^{3} U^*_{\alpha i} |\nu_i\rangle$$

The oscillation phenomena is described by:

- 3 mixing angles: θ_{12}, θ_{23} and θ_{13}
- 2 mass splittings: Δm^2_{sol}, Δm^2_{atm}
- 1 CP violation phase δ



History of LBL experiments

<u>The first generation of LBL experiment</u> [~2000, NOMAD, CHORUS, K2K,…]
Couldn't assess the oscillation phenomena due to limited statistics

<u>The second generation of LBL experiment</u> [~2010, T2K, NOνA, MINOS, OPERA]
Observed the ν_μ disappearance and ν_e and ν_τ appearance
-> Discovery of θ_{13} mixing angle being ≠ 0
-> Open the door to the measurement of CP violation in the leptonic sector

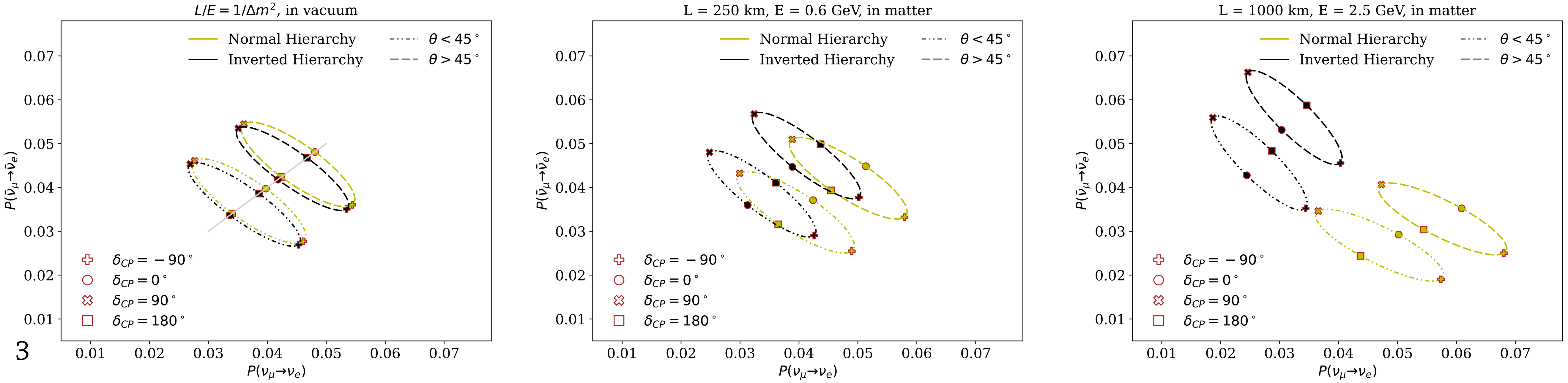
$$\Delta P_{\alpha\beta} = P(\nu_\alpha \to \nu_\beta) - P(\bar{\nu}_\alpha \to \bar{\nu}_\beta) = \pm 16 \mathcal{J} \ell_{12}\ell_{23}\ell_{31}$$

$$\mathcal{J} = \frac{1}{8}\cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}\sin\delta_{\mathrm{CP}}$$

$$\ell_{ij} = \sin\left(\Delta m^2_{ij}\frac{L}{E}\right)$$

$$\mathcal{J} = \mathrm{Im}(U^*_{\alpha i}U_{\beta j}U_{\alpha i}U^*_{\beta j})$$

+ for even permutation of (α,β,γ) = (e,μ,τ)
- for odd permutation of (α,β,γ) = (e,μ,τ)



History of LBL experiments

The third generation of LBL experiment

High precision ν_μ —> ν_x measurements

-> Very intense ν_μ source : beams at the MW scale

-> Very large/massive detectors

Planning these experiments started shortly after the discovery of $\theta_{13} \neq 0$

-> Three proposals

T2HK

In Japan, L = 300 km
Tokai->Kamioka
Off-axis beam at E~650MeV
1.3 MW beam

260 kt new Water Cherenkov detector

-> Potential upgrade with a water Cherenkov in Korea on the 2nd oscillation maximum

Hyper-Kamiokande TDR

LBNE

In US, L = 1300 km
Fermilab->Homestake/SURF
On-axis wide-band beam
1.2->2.4 MW beam

34k LArTPC following ICARUS concept

LBNE CDR

LBNO

In Europe, L = 2300 km
CERN->Pyhäsalmi
On-axis wide-band beam
700 kW beam

20kt Dual Phase LArTPC + 35kt magnetized muon detector

-> Potential upgrade with a beam from Protvino

LBNO sensitivity

History of LBL experiments

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-> ~~Three~~ Two proposals

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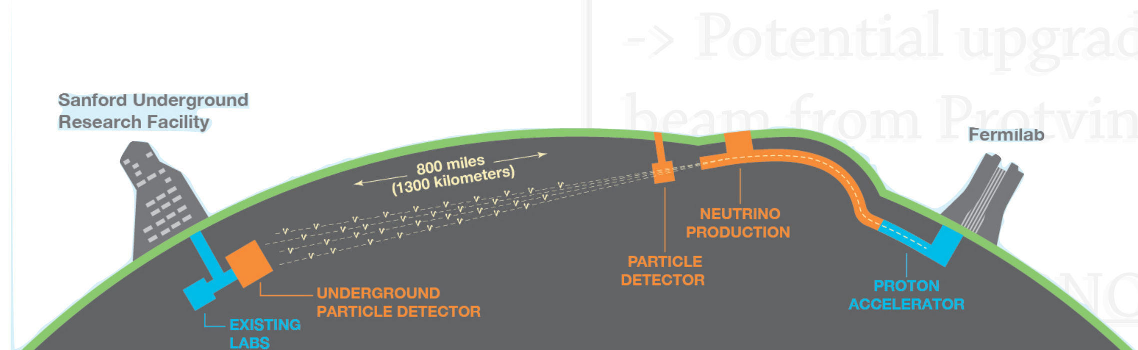
Hyper-Kamiokande TDR

LBNF / DUNE

In US, L = 1300 km
Fermilab -> SURF
On-axis wide band beam
1.2->2.4 MW beam

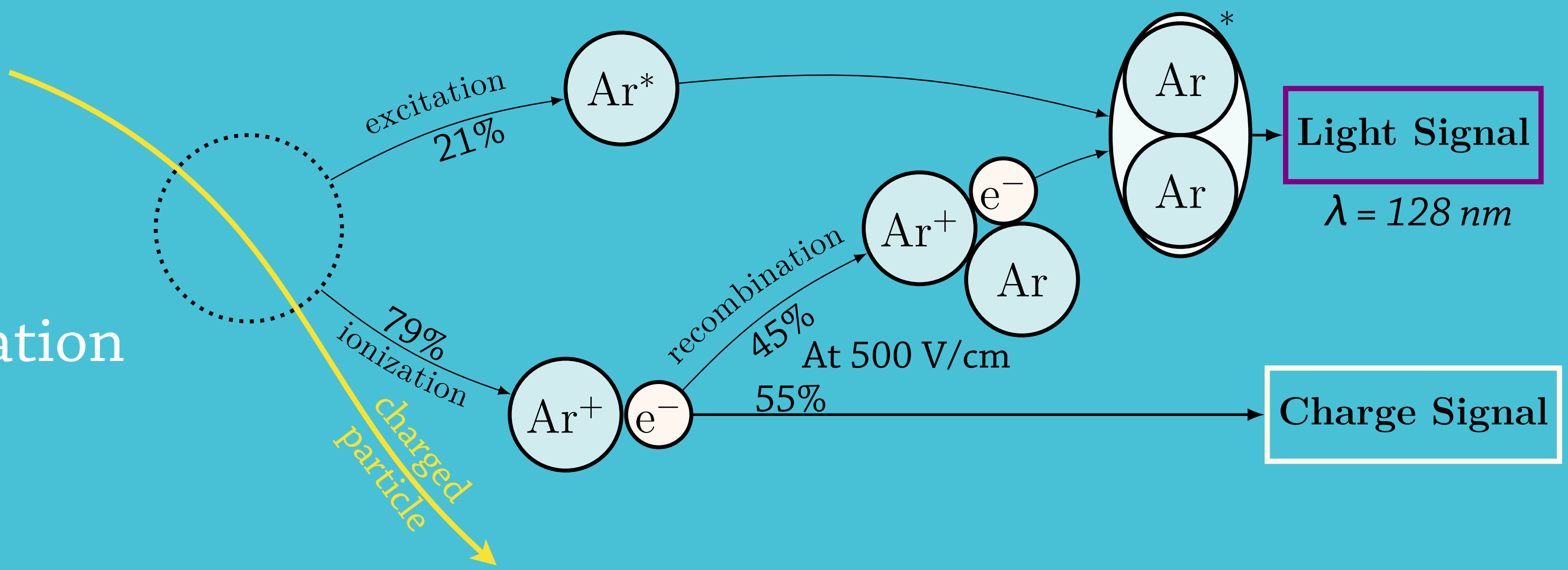
4×17 kt LArTPC modules:
- 1.5 km underground
- Active volume ≃ 12 m × 12 m × 60 m per module
- Different LArTPC technologies



DUNE CDR

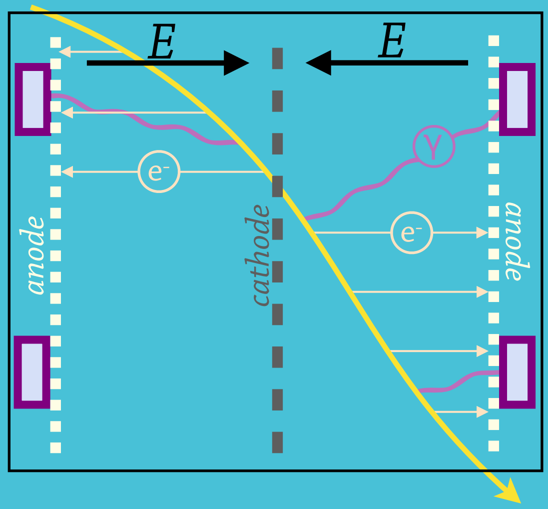
Liquid Argon TPC

Charge particles excite and ionize LAr
-> Produces a charge & light signal
An electric field suppresses the recombination and allow to collect the e⁻ at the anode



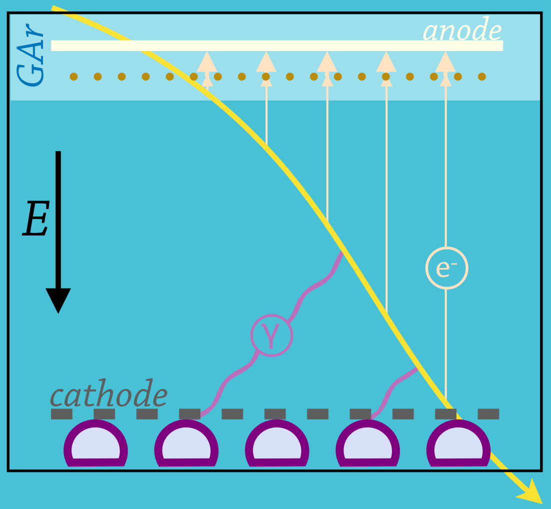
Different TPC designs to collect both signals :

Single-Phase Horizontal drift



- Two drift volumes
- Anode made of wires
- Light collected with X-ARAPUCAs behind the anodes

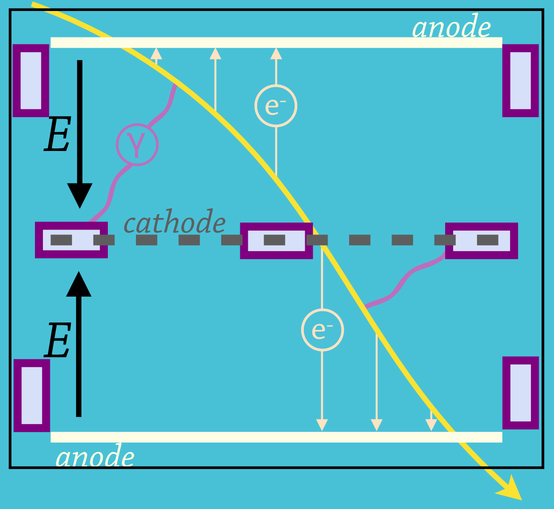
Dual-Phase



- Single drift volume
- Electron cloud amplified in gas argon layer with thick GEM
- Anode made of PCBs
- Light collected with PMTs below the cathode

⚠SPOILER ALERT ⚠

Vertical drift



- Two drift volumes
- Anode made of drilled PCBs
- Light collected with X-ARAPUCAs on the cathode and behind the field cage

DUNE Prototypes

Building such large detectors deep underground is a huge engineering challenge

credit : SURF

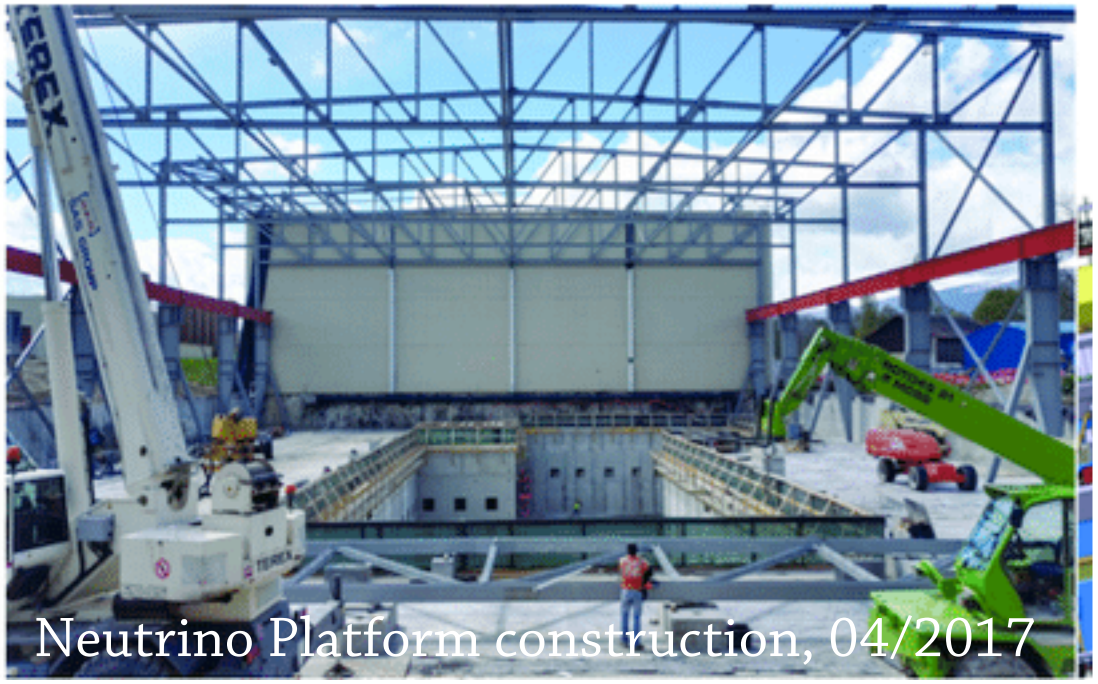
The elements of the detector (cryostat, field cage, anode, cathode, …) are modular such that they can fit in the SURF Ross shaft, and assembled together in the underground cryostat.

Large scale prototypes are mandatory for :

- Integration test with 1:1 components
- Validate the procurement and installation sequence
- Estimate future ressources needed
- Approve the detector design
- Assess the LArTPC performances

These prototypes should be built *as if* we were in deep undergoing in the SURF mine

The CERN Neutrino Platform

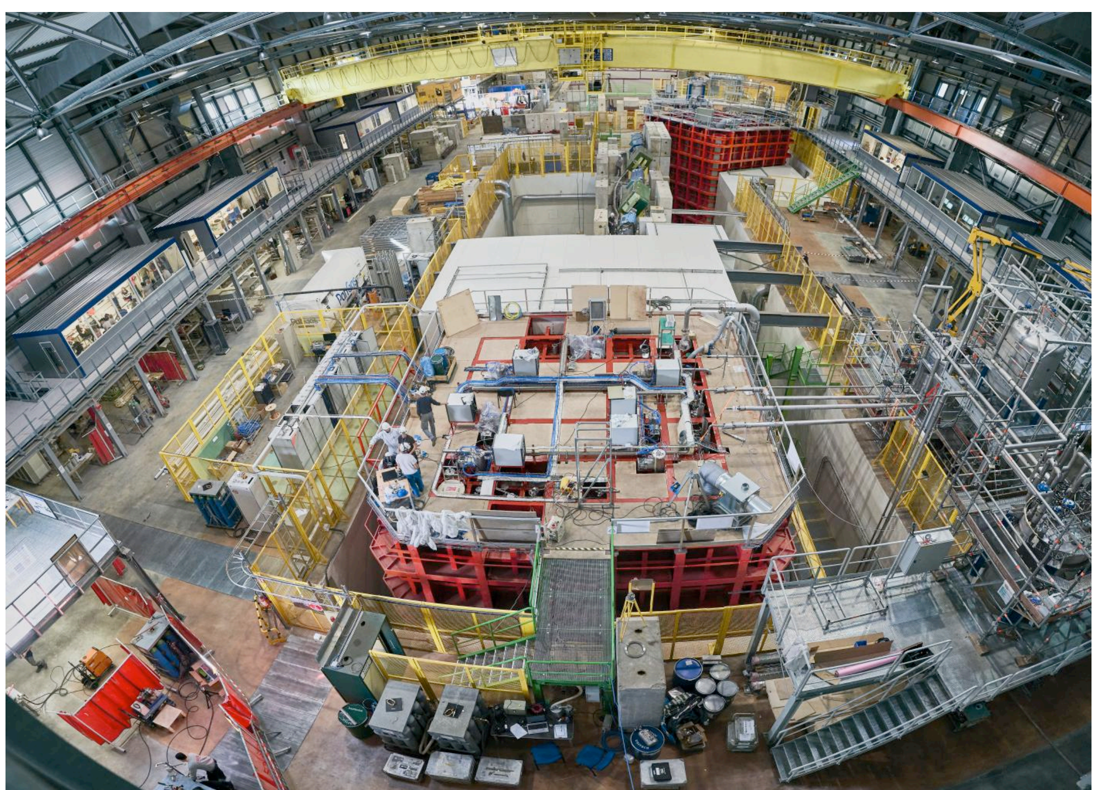

Neutrino Platform construction, 04/2017

Starting 2016, the North Hall of CERN was extended to held the Neutrino Platform

Two large cryostats were built for the DUNE LArTPC prototypes, together with two new secondary low energy beamlines.

Both cryostat have an opening access matching the DUNE shaft dimension

NP04 cryostat: Single-Phase technology
NP02 cryostat : Dual-Phase technology

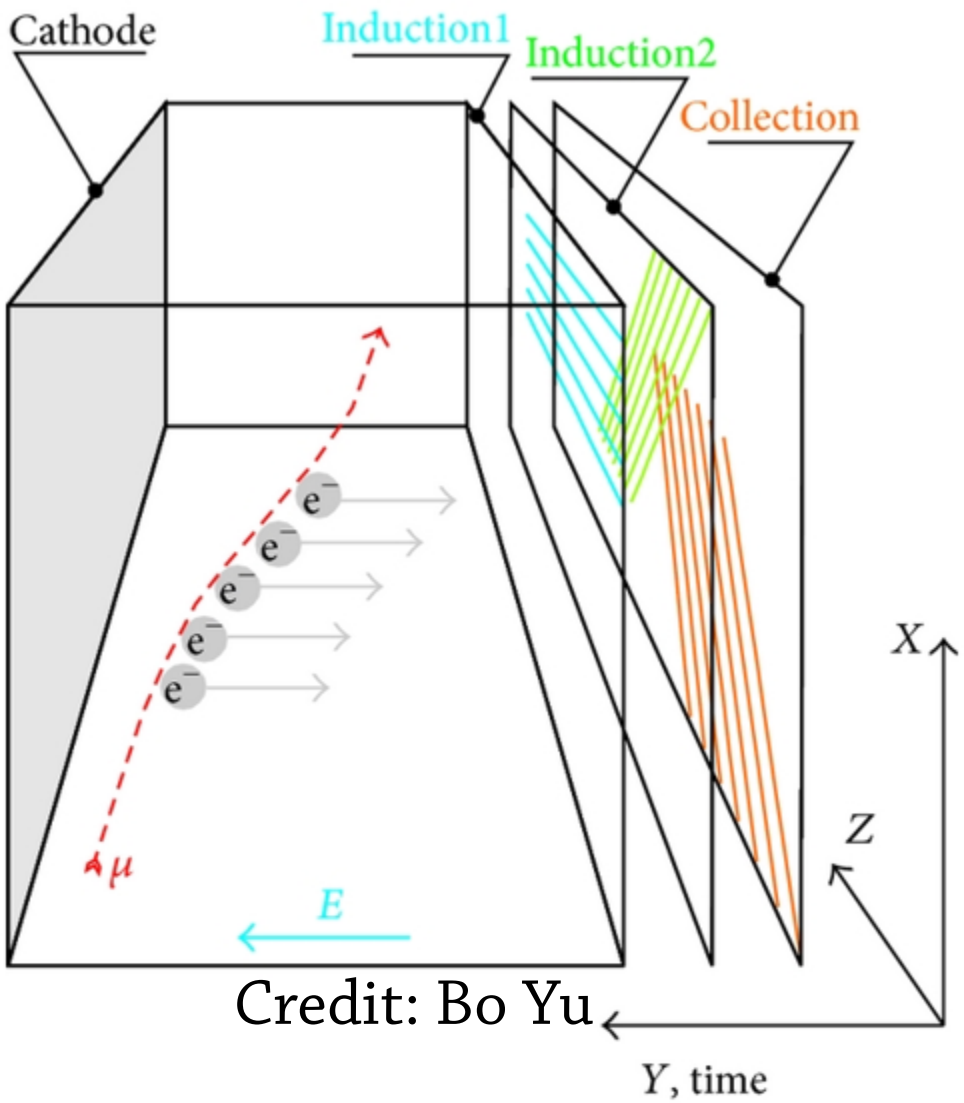


credit : CERN, Fermilab

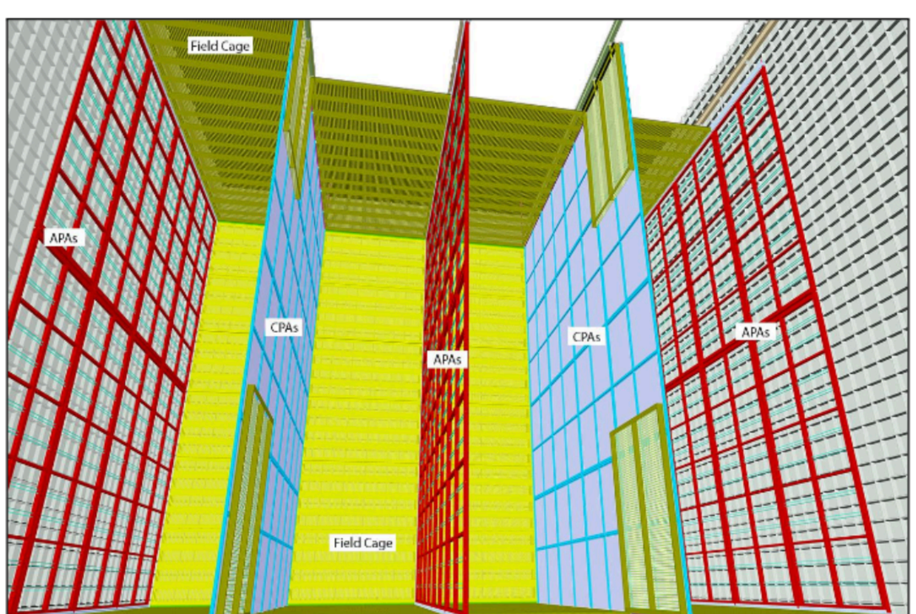
— ProtoDUNE-I —

The Single Phase
or
'The Wire-Based'

ProtoDUNE Single Phase



Credit: Bo Yu



In the Single Phase design, the electron cloud drift horizontally to an anode made of 3 wires planes:

- First two plane will see the electron cloud by induction (bipolar signal)
- Last plane collects the electrons (unipolar signal)
- wire pitch is 4.7 mm for all planes

Anode modules are called APA:

- ‘Anode Plane Assembly’
- 6×2.3 m^2

Cathode modules are called CPA

- ‘Cathode Plane Assembly’
- Same size as the APA

Light detector system can be embedded in the APA

At the DUNE far detector, 4 drift volumes are foreseen with interleaved APA and CPA walls

-> Represents 150 APAs and 100 CPAs modules

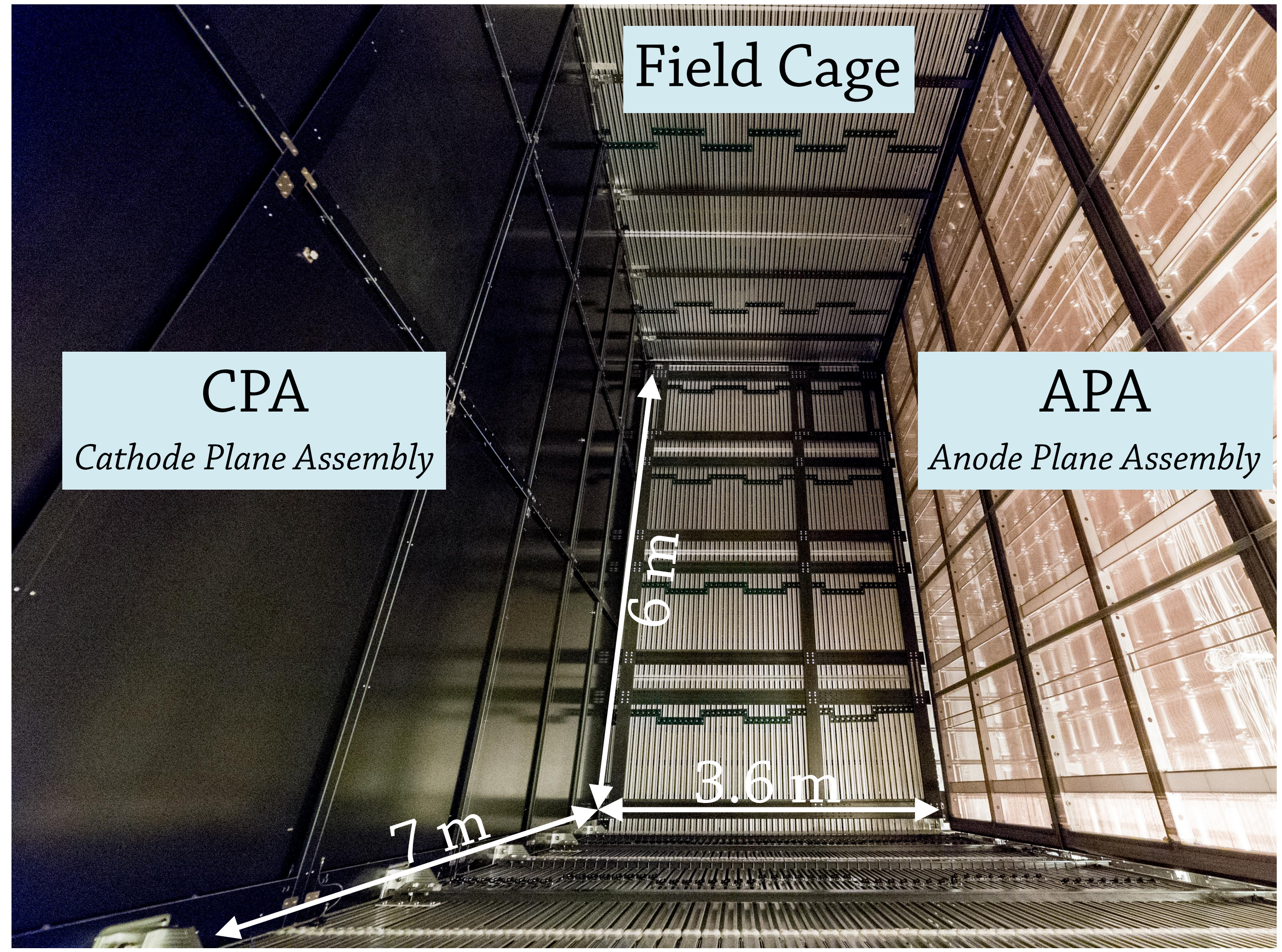
ProtoDUNE Single Phase

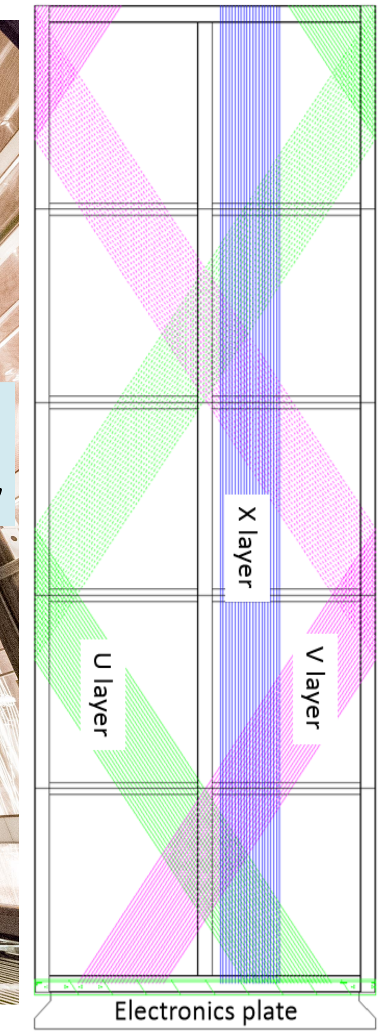
Assembly of 2 drift volumes
  -> 3.6 m drift each

One CPA and two APA walls
  -> 6 APA and 6 CPA modules

Nominal drift field of 500 V/cm
  -> V_{cath} = -180 kV

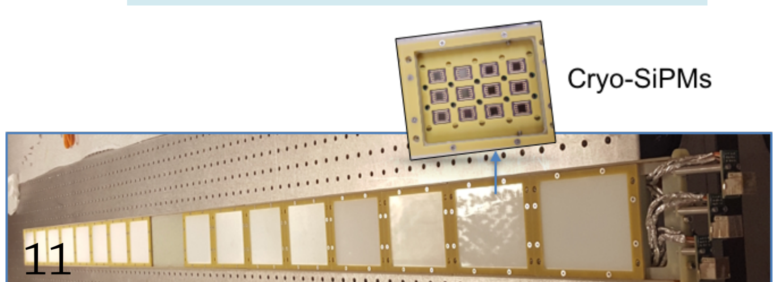
Charge readout by 3 wires plane:
  - U & V layers sees induced signal
  - X layer collects the e^- cloud



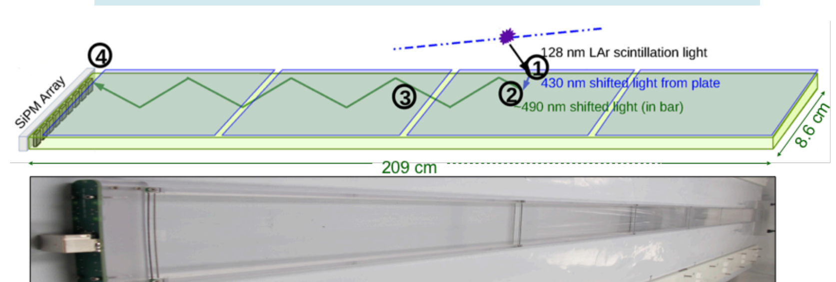


Light collection system embedded in the APA
 -> 3 designs tested

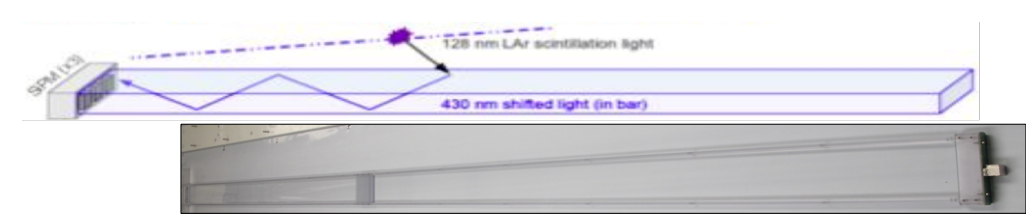
ARAPUCA light trap



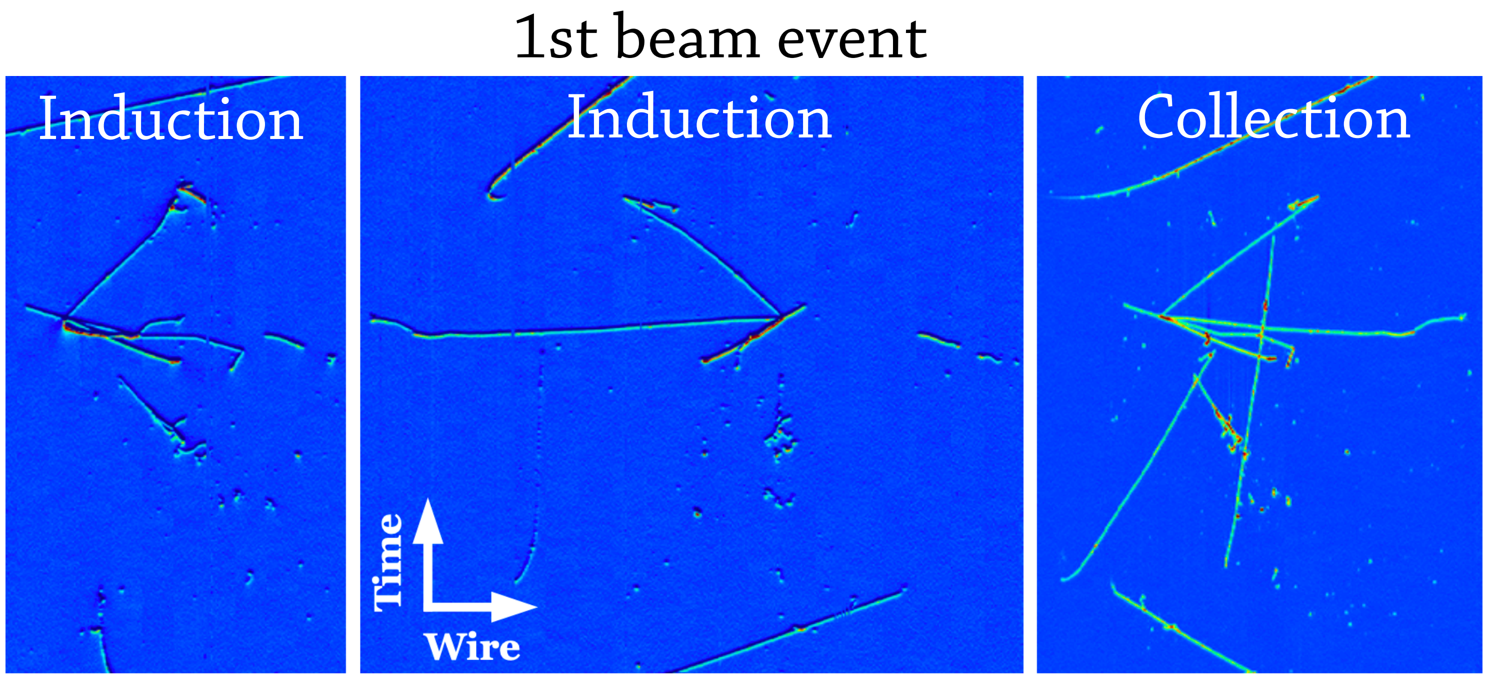
Double shift light guide

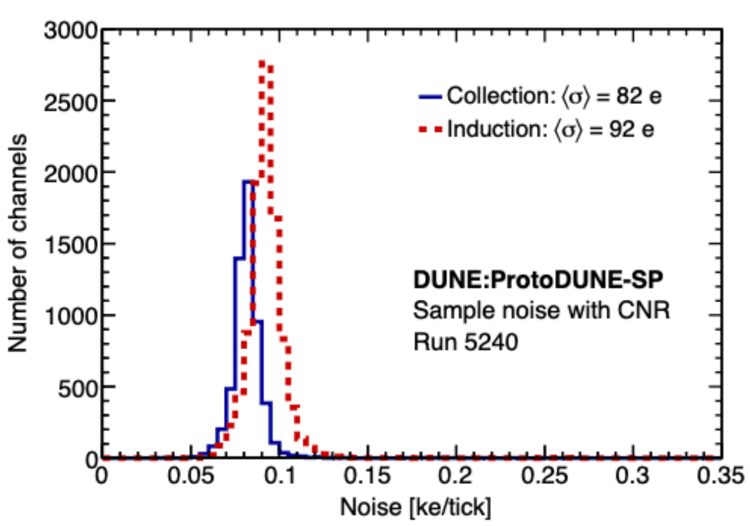


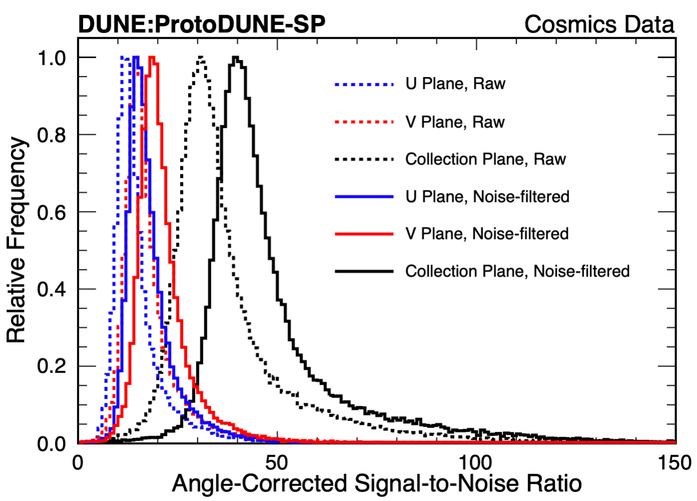
Dip coated light guide



ProtoDUNE Single Phase : Data







- Less than 0.5% of defective channels
- Filtered noise at the level of ~90 e^-
- S/N ratio up to 15-30

Oct.~Nov. 18: Beam data

- h^+ with momenta 0.3 ~ 7 GeV/c
- 4×10^6 triggered events
- H4-VLE beamline instrumented with ToF and Cherenkov counters for PID

Phys. Rev. Accel. Beams 22, 061003 (2019)

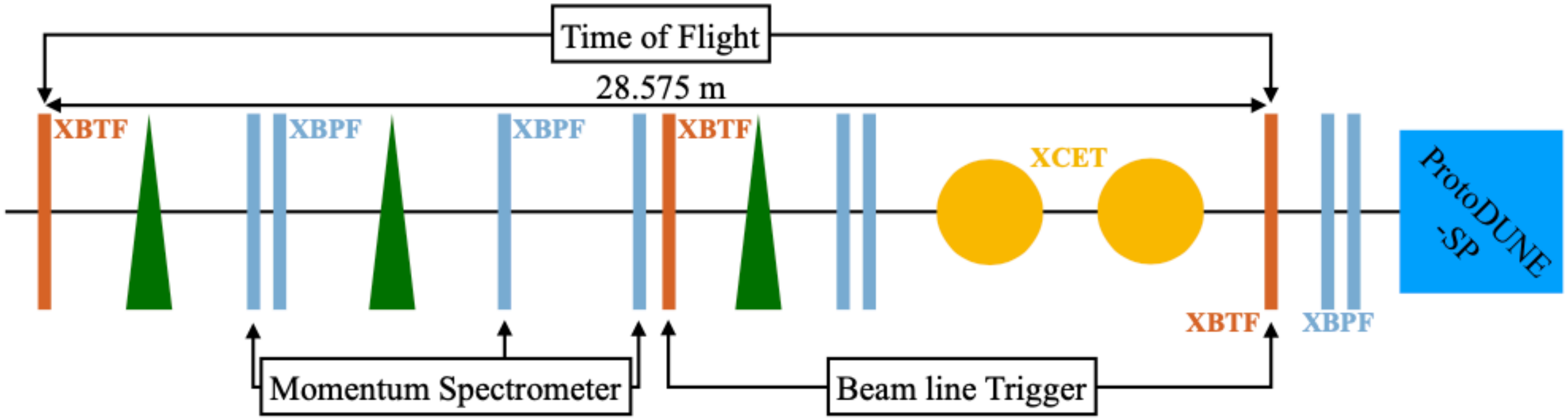
Nov. 18 ~ Jan. 20: Cosmic data

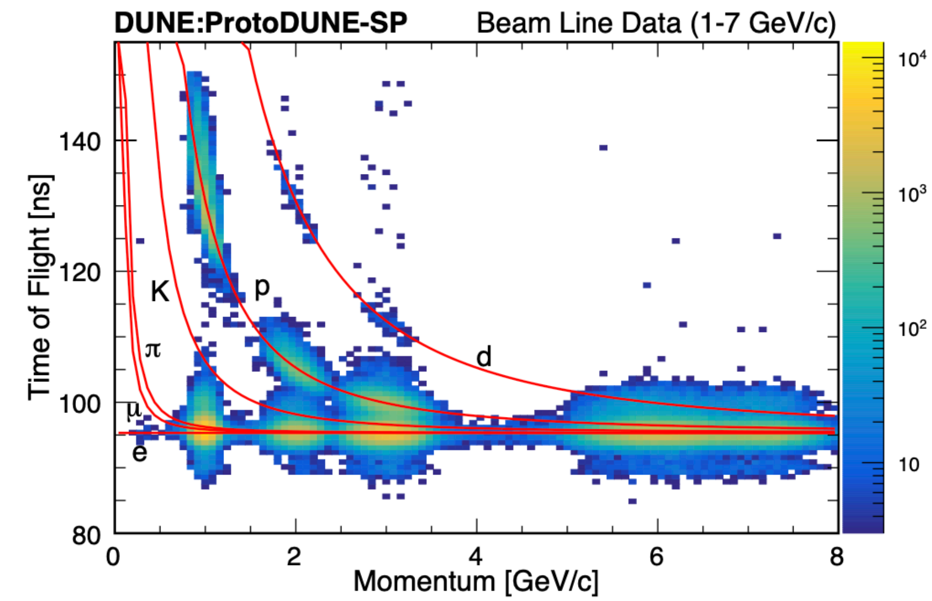
- Random and CRT trigger
- Tests of detector performances & stability

Feb. 20 ~ Jul 20:

- LAr doped with 20 ppm Xe
- Test of light yield increase

ProtoDUNE-SP Beam





The beamline is instrumented with :

8 profile monitors (XBPF) to compute the beam momentum and trajectory

3 trigger counters (XBTF) to set the general trigger and compute beam time of flight

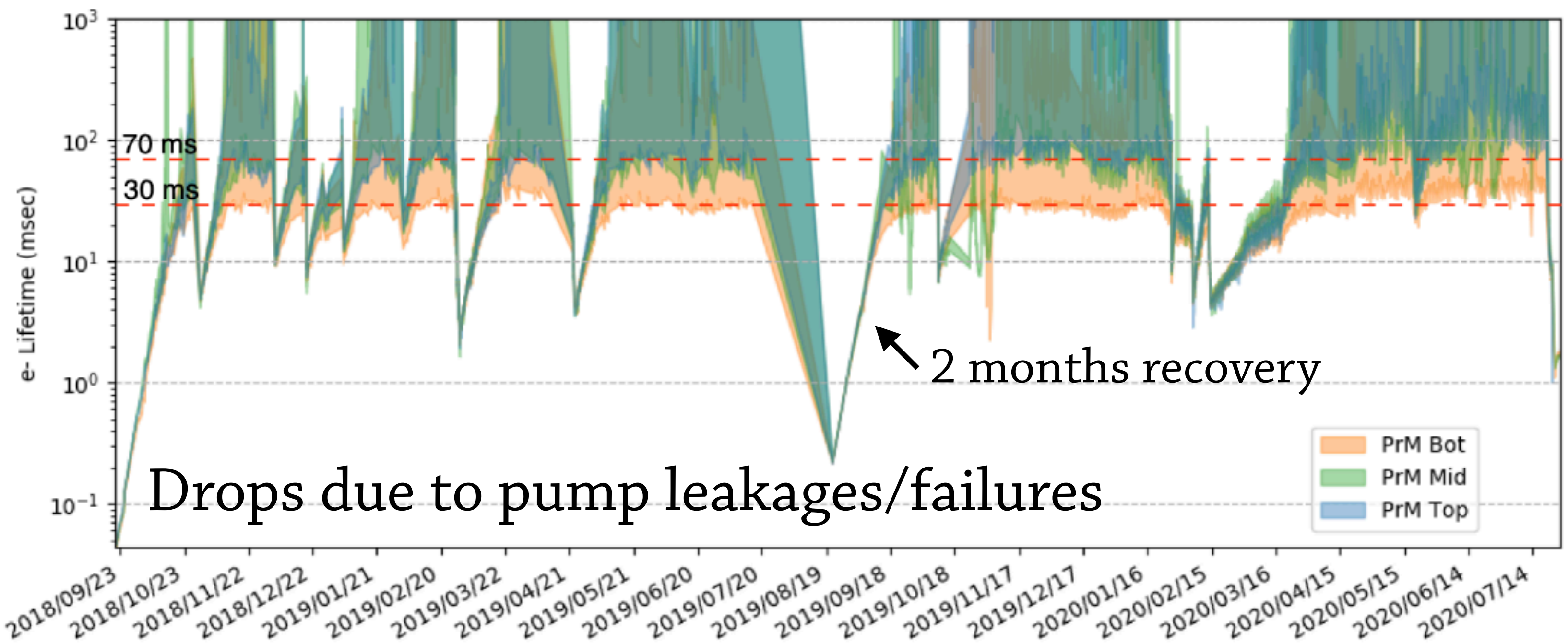
2 Cherenkov counters(XCET) to tag particle species

Momentum (GeV/c)	Total Triggers Recorded (K)	Total Triggers Expected (K)	Expected Pi trig. (K)	Expected Proton Trig. (K)	Expected Electron Trig. (K)	Expected Kaon Trig. (K)
0.3	269	242	0	0	242	0
0.5	340	299	1.5	1.5	296	0
1	1089	1064	382	420	262	0
2	728	639	333	128	173	5
3	568	519	284	107	113	15
6	702	689	394	70	197	28
7	477	472	299	51	98	24
All momenta	4173	3924	1693.5	777.5	1381	72

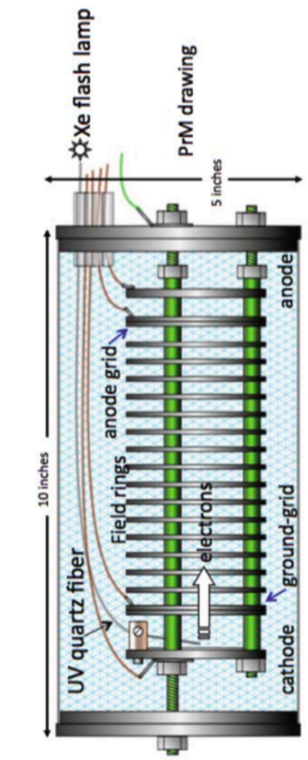
PDSP performances

ProtoDUNE-SP Purity

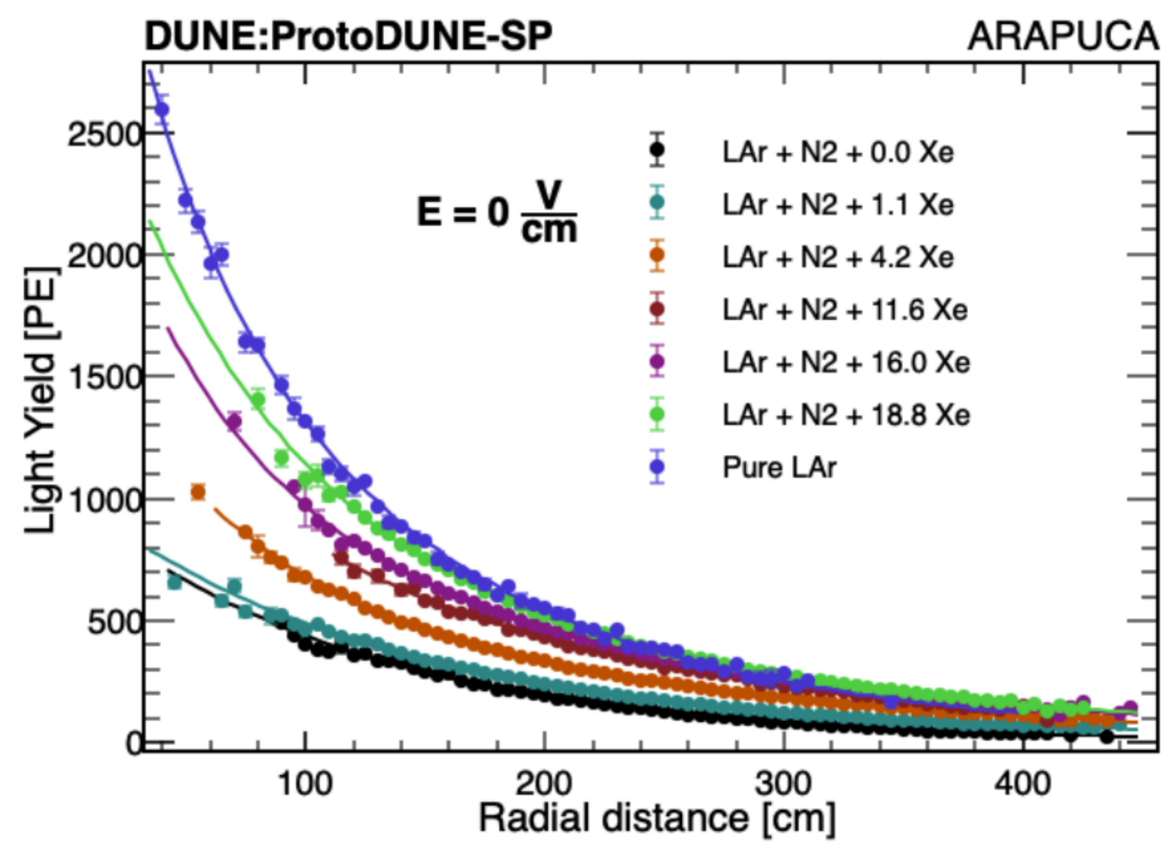
Impurities (e.g O_2, H_2O) in LAr will catch the electrons on their drift :
$Q(t_{\mathrm{drift}}) = Q_0 \exp(-t_{\mathrm{drift}}/\tau_e)$, and τ_e [ms] $= 300/\rho_{O_2}$ [ppt]



- Pumped boiling Ar goes through filters, condensed and re-injected
- LAr purity is monitored daily with 3 purity monitors at different height



- Excellent purity achieved in ProtoDUNE-SP, far beyond the 10ms requirement for DUNE
- Most data collected with electron lifetime ≥ 30 ms ↔ 7% charge loss over 2.25 ms of drift
- July 2019 gas pump leakage introduced about 5.4ppm of N_2 in the detector
  - Cannot be filtered out
  - N_2 quenches the light, recovered with Xe doping in 2020



PDSP performances

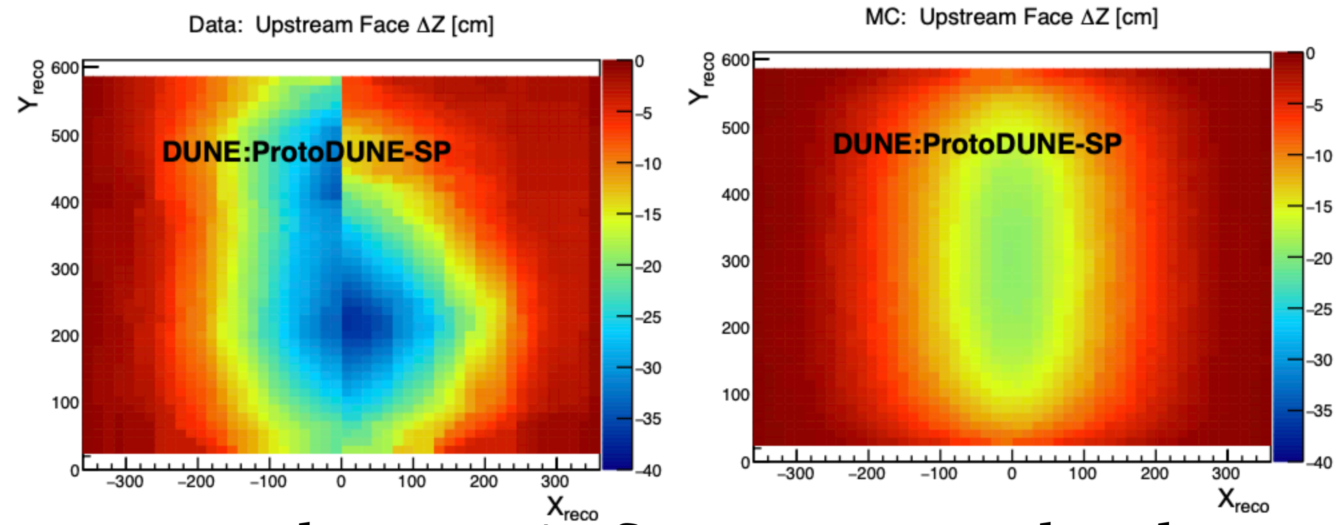
ProtoDUNE-SP Calibration

The collected charge is affected by many factors that are individually assessed and corrected for:

Electronic gain: regularly calibrated with a charge injection system

Purity: estimated with the purity monitors

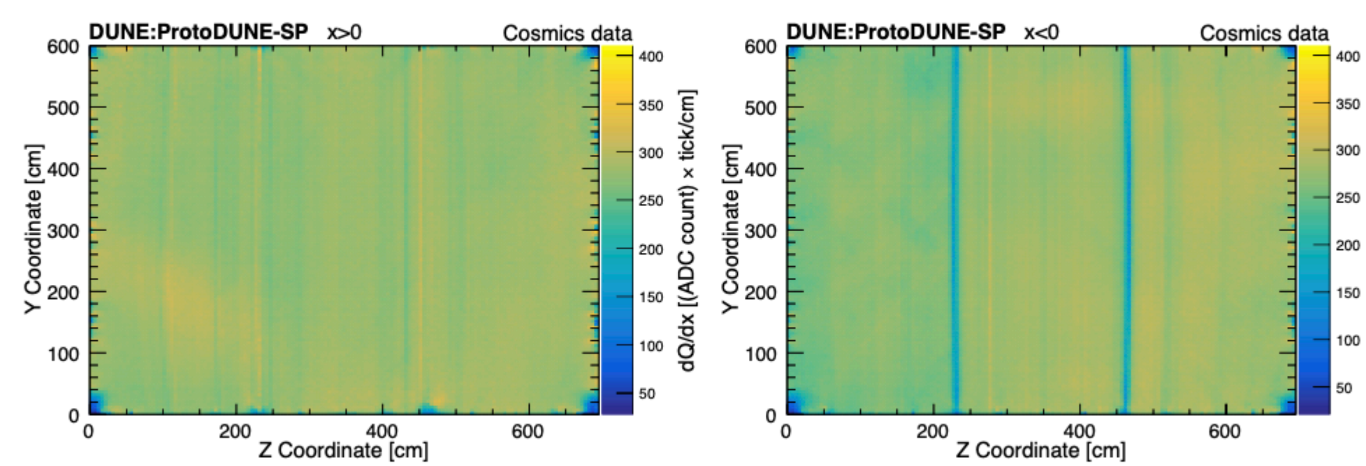
Space Charge Effect: Slow drift of Ar^{+} cloud to the cathode screens the drift field, charge recombination is position dependent, field lines have a transverse component



Displacement maps estimated using tracks with known topologies, LAr flow is not simulated

Hardware effects: dQ/dx uniformity affected by the electron diverters in x<0 volume

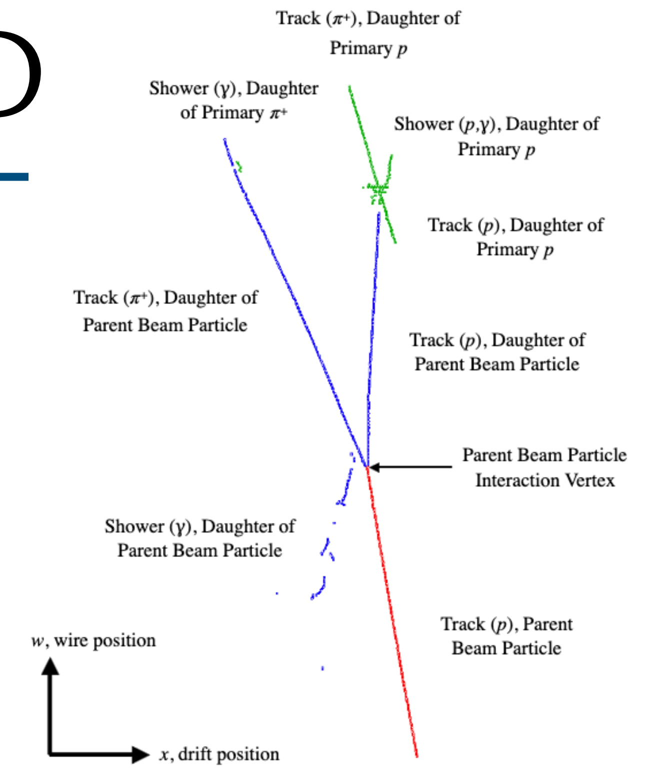
Diffusion: spread of electron cloud in time and space with the drift



PDSP performances

Once corrected, the detector response is uniform in space and time after the corrections

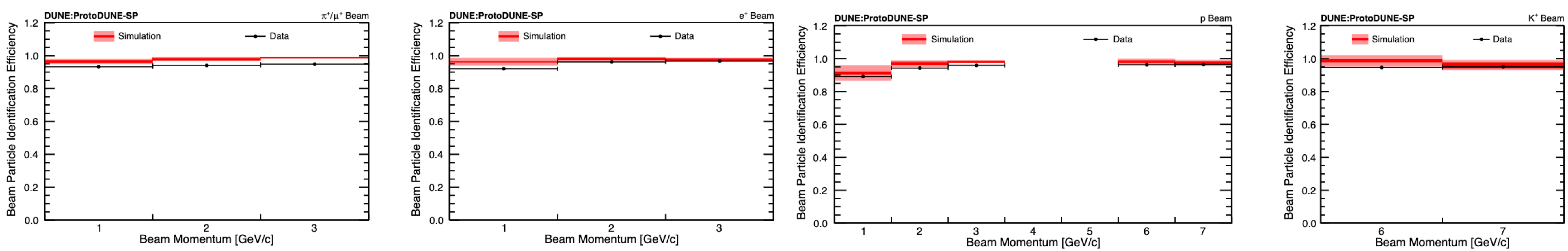
ProtoDUNE-SP Reconstruction & PID

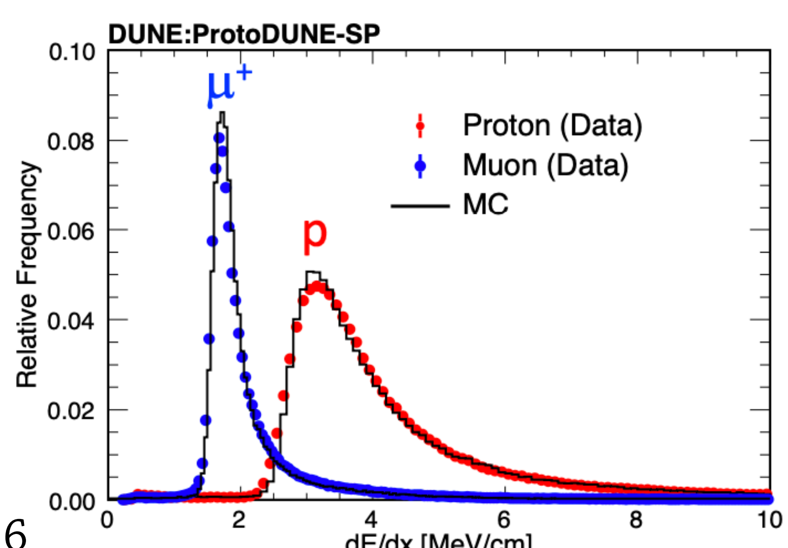


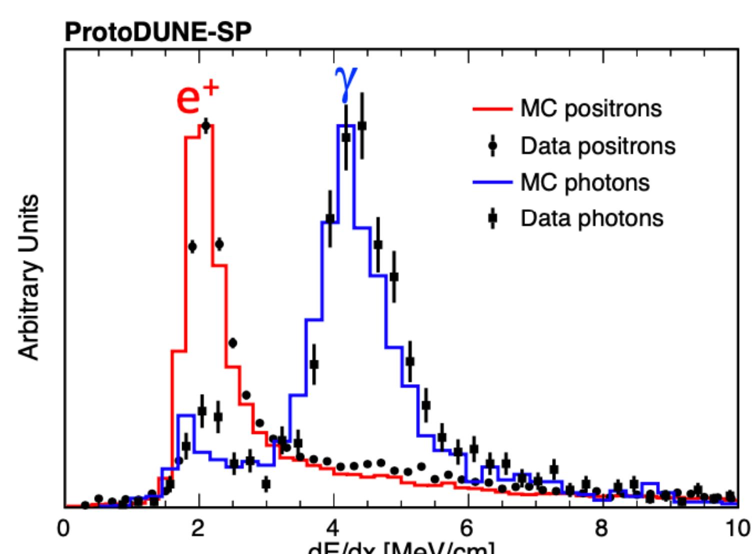
The 3D reconstruction is handled by PANDORA: a multi-algorithm approach with pattern recognition:

- Separation of cosmic tracks from beam tracks
- Hierarchical reconstruction
- Reconstruction efficiency close to 100%
- Beam particle identification efficiency well above 80%

PDSP reconstruction with Pandora







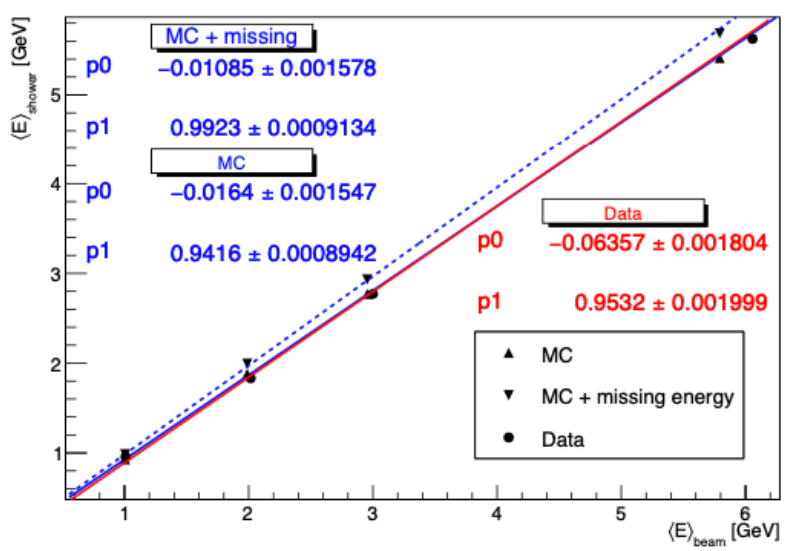
With the corrected dE/dx, an excellent e/γ and μ/p separation power is obtained, which is crucial for DUNE neutrino oscillation analysis

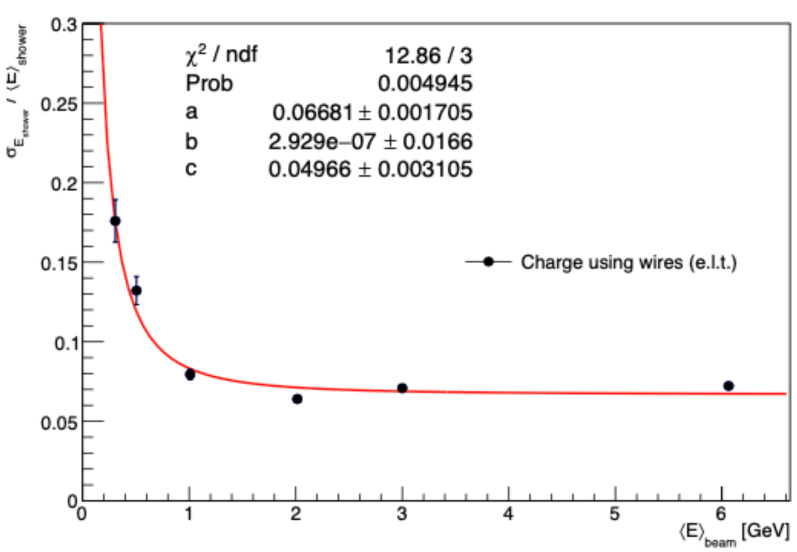
PDSP performances

ProtoDUNE-SP Positron Reconstruction

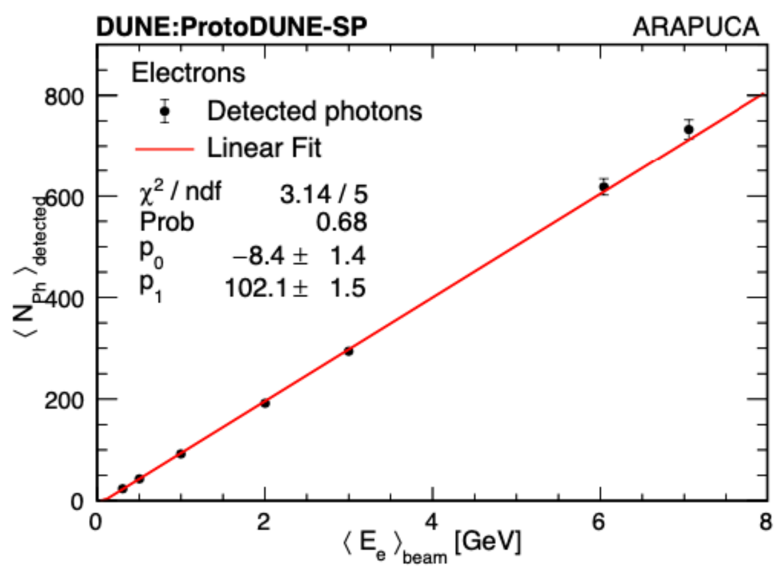
ProtoDUNE-SP got a positively charged particles beam scan in momentum [0.3 ~ 7 GeV]
-> Study the detector response and its linearity with energy
-> Very important measurement for DUNE oscillation analyses

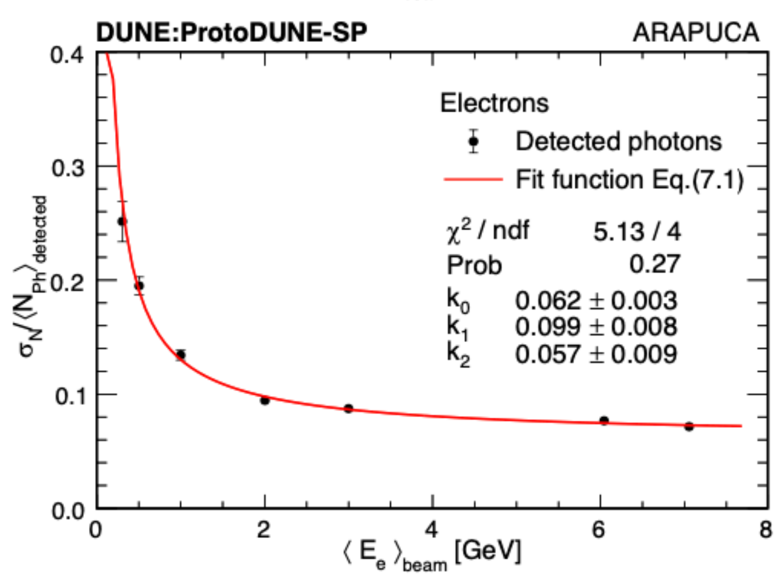
Charge Reconstruction





Light Reconstruction





- Very good linearity observed in both systems
- Resolution fitted with:

$$\sigma_E / \langle E \rangle = \sqrt{a^2 + (b/\sqrt{\langle E \rangle})^2 + (c/\langle E \rangle)^2}$$

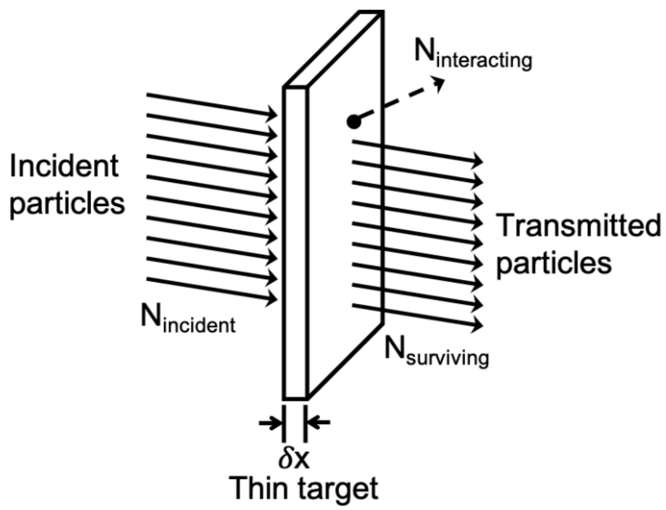
Constant (a) and Noise terms (c) are related to the beam (spread in momentum and energy loss)

Stochastic term (b) represents the intrinsic detector resolution
-> 2% for the charge
-> 9% for the light

PDSP performances

Hadron Cross Section measurements

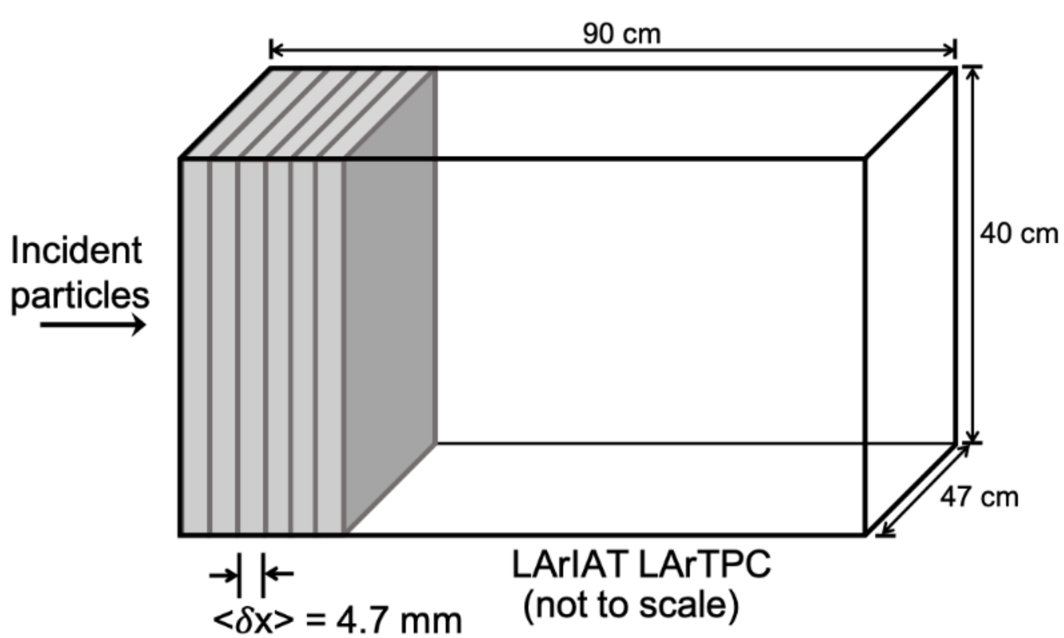
Understanding the neutrino Final State Interaction is a crucial input for the future DUNE analyses



In a thin target experiment, the cross section is:

$$\sigma = \frac{m_A}{\rho N_A} \frac{1}{\delta X} \frac{N_{\text{interacting}}}{N_{\text{incident}}}$$

The *thin slice method* considers that the LArTPC volume is a collection of stacked thin slices



Drawings from LARIAT cross section

○ In each slice, count the number of incident and interacting particles

○ The kinetic energy of the interacting particles in a given slice *j* is given by:

$$E_{\text{kin},j} = \sqrt{p_{\text{beam}}^2 + m^2} - m - E_{\text{loss}} - \sum_{n<j} E_{\text{dep},n}$$

Where:

p_{beam} is given by the beamline instrumentation

E_{loss} accounts for the lost energy up to the 1st slice

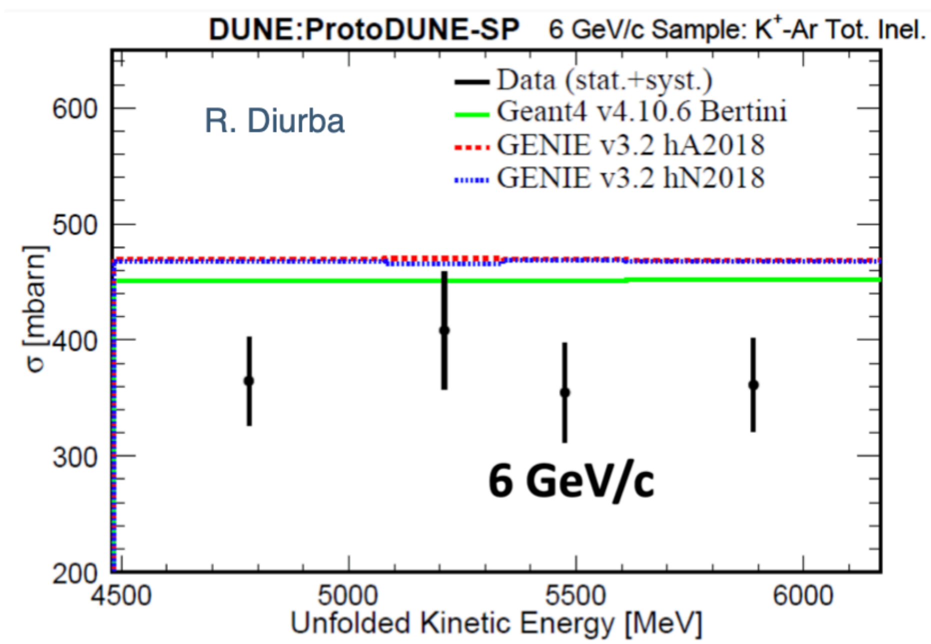
$E_{dep,n}$ is the amount of energy lost in each slice

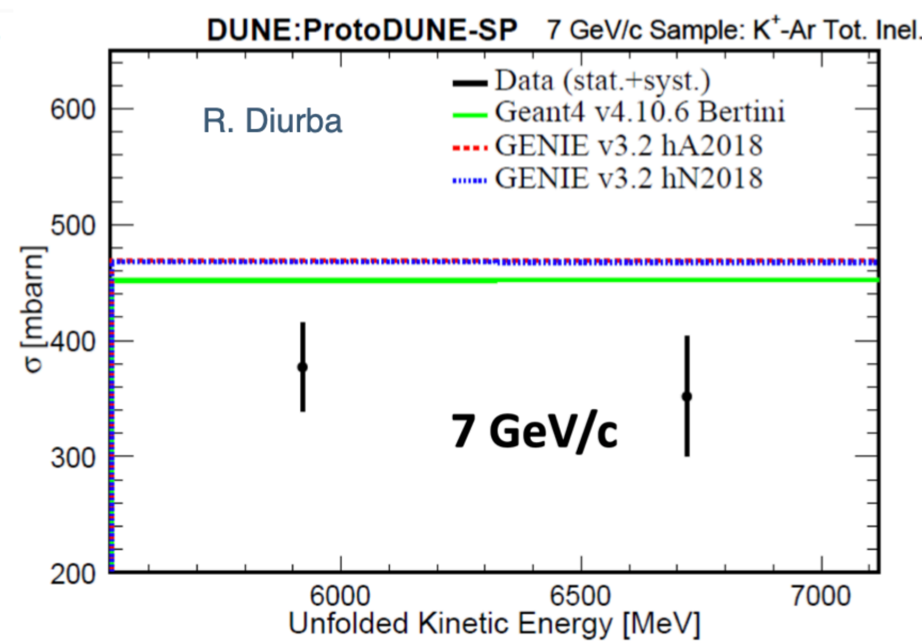
NB: In protoDUNE-SP, the method was changed to slices in energy (instead of distance) due to the spread of beam momenta

ProtoDUNE-SP inclusive inelastic XS results

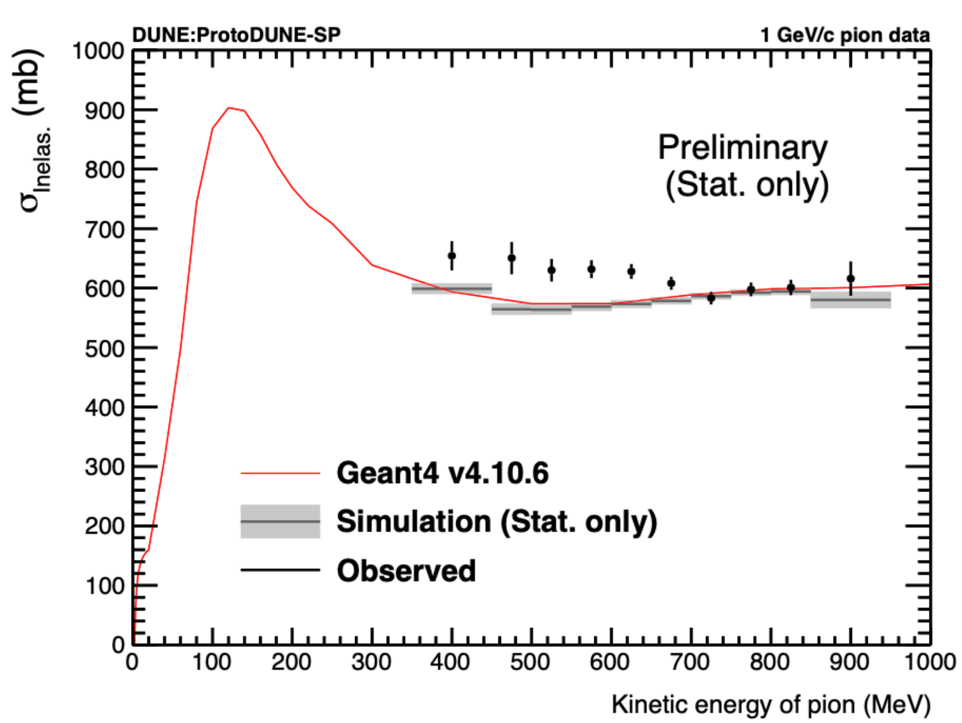
-> All results are about to be published

Kaon-Argon inelastic cross section

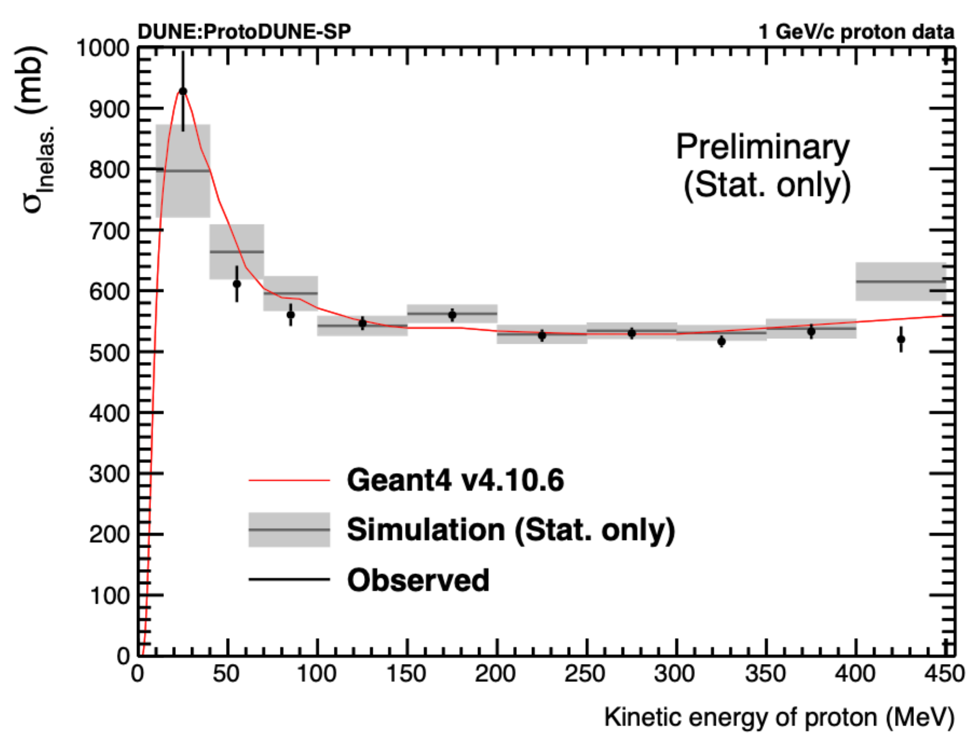




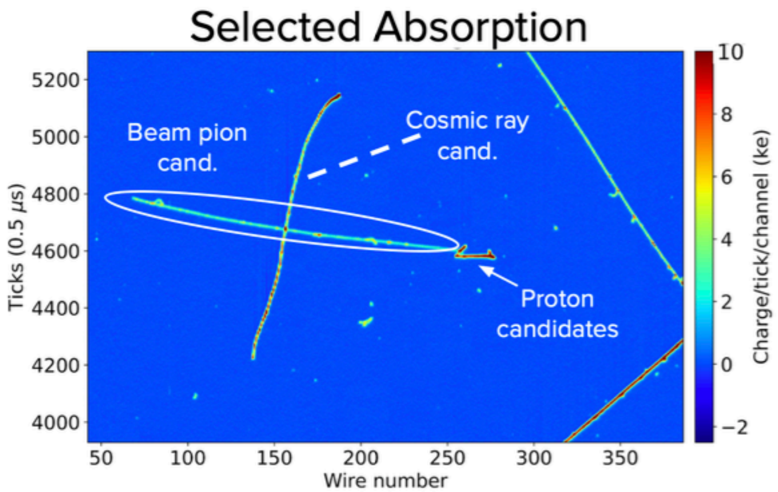
pion-Argon inelastic cross section

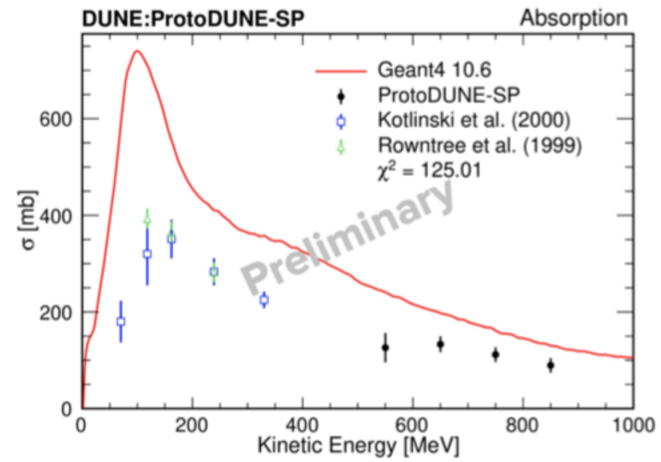


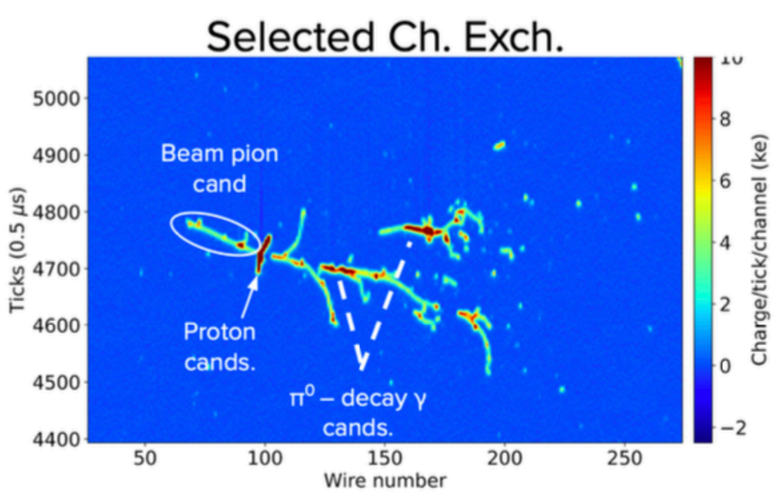
proton-Argon inelastic cross section

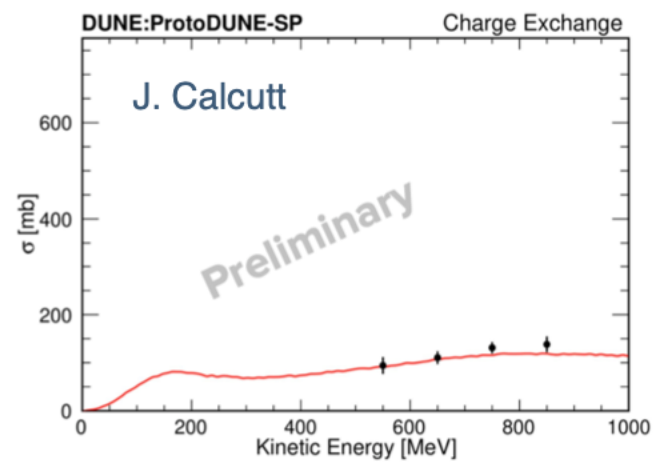


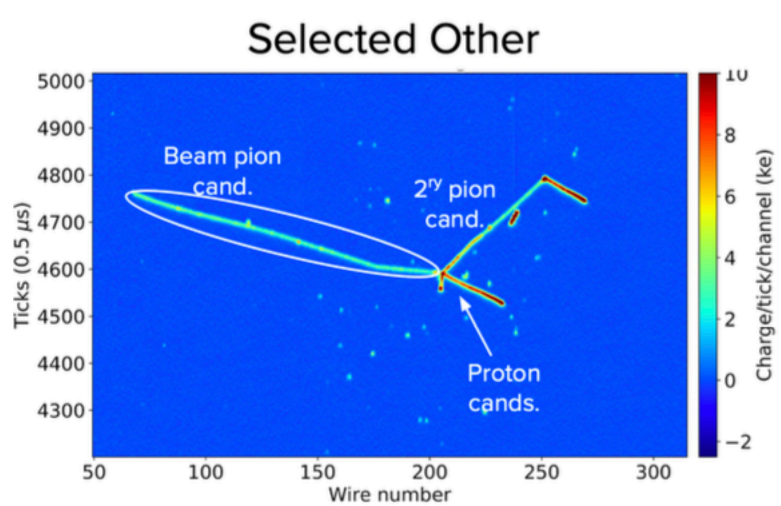
ProtoDUNE-SP exclusive XS results

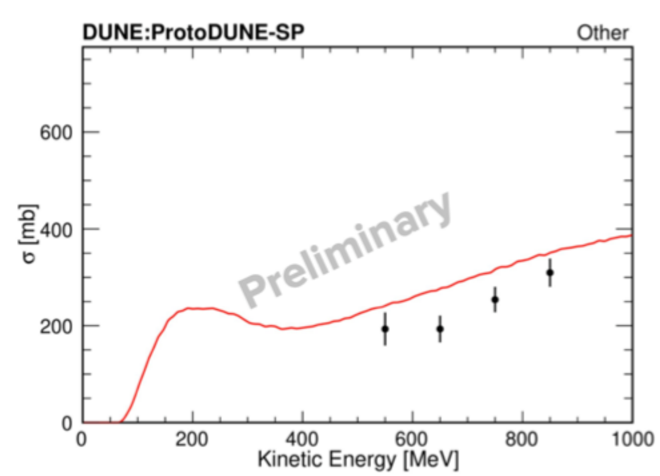












With the beam pion data, a first analysis of exclusive cross section could be done

Selection of π interaction channel:
Pion absorption : π^+ + Ar -> p, n
Pion charge exchange : π^+ + Ar -> π^0
Others includes quasi-elastic, pion production, …
The analysis is limited by the statistics, and about to be published

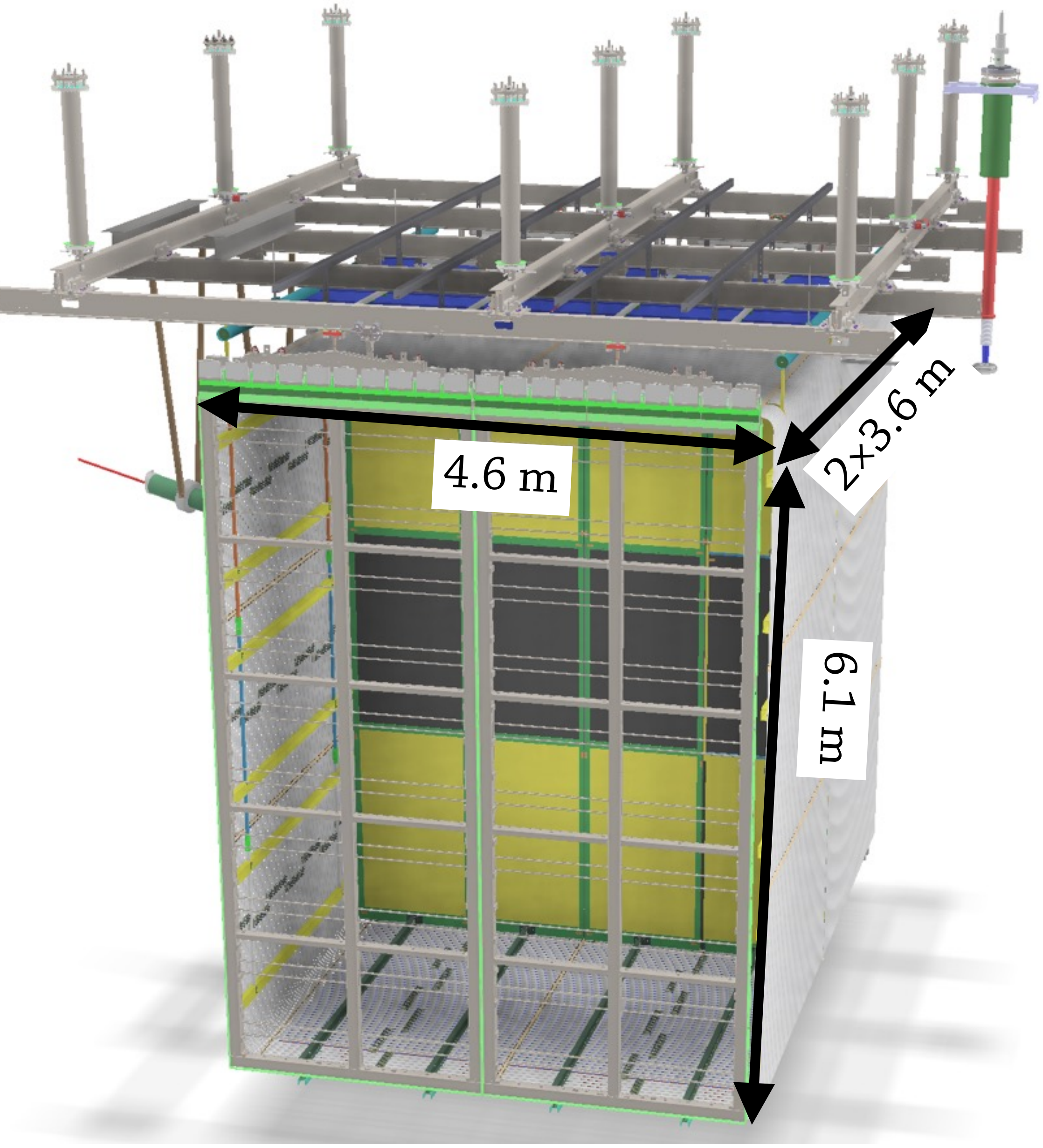
As for the inclusive pion-inelastic analysis, because of statistics and hardware issues (electron diverters), the delta resonance peak could not be probed

Jacob Calcutt thesis

— ProtoDUNE-II —

The Horizontal Drift

ProtoDUNE-HD : motivations

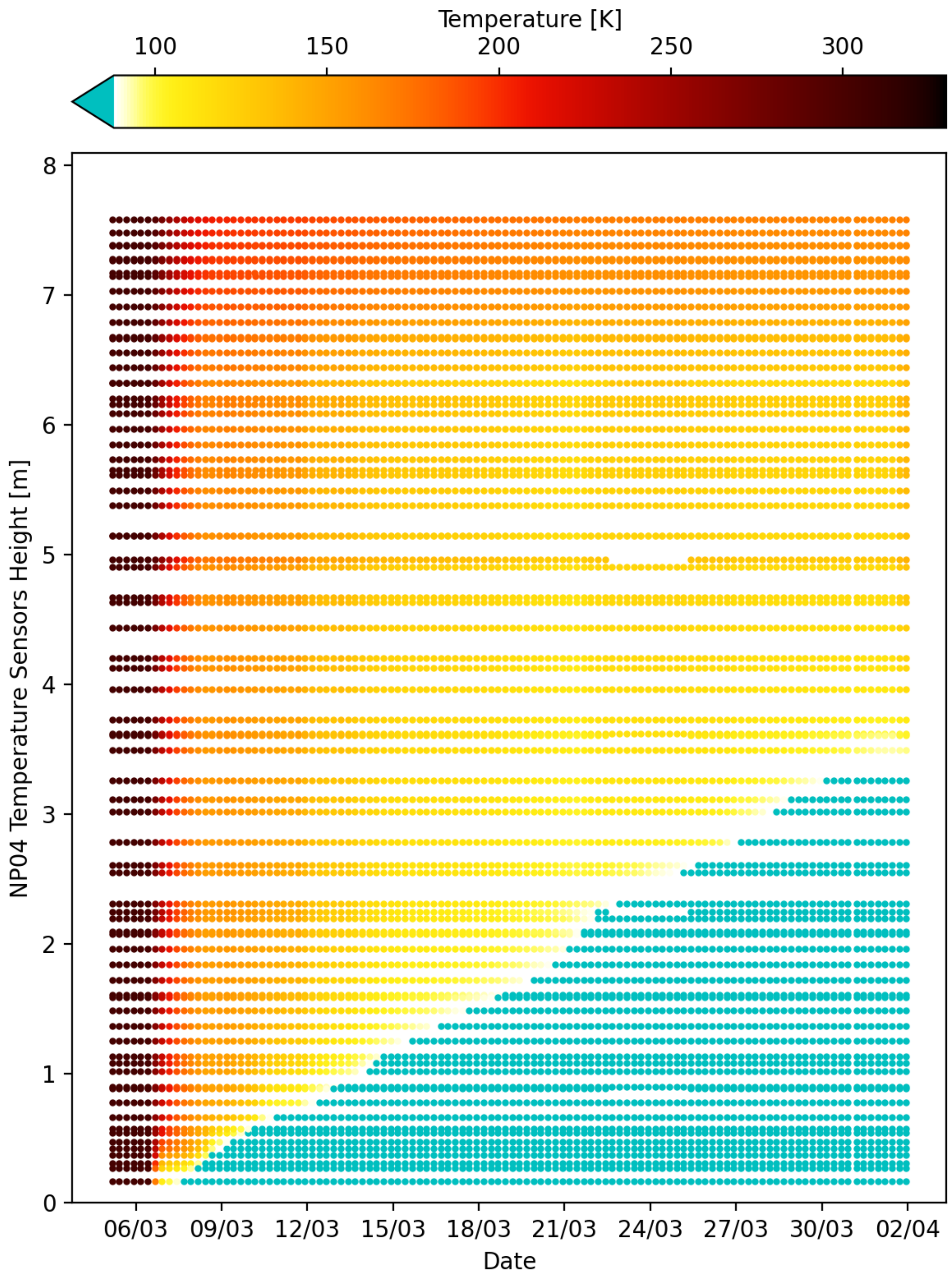


NB : The name changed in opposition to the second DUNE FD technology

The detector design has been improved based on protoDUNE-SP experience. A new ProtoDUNE (named 'Horizontal Drift') has been constructed to:

- Test the final detector layout & components:
  - Updated APA, CPA and cold electronics designs
  - No electron diverters between the APAs
  - 4 APAs to match the field cage-cryostat distance of the FD module
  - 2 APAs upside down with the electronics at the bottom
  - 160 ×-ARAPUCAs with 4 WLS configurations
- Tune mass production, installation procedures, manpower needs and final costs
- Test new calibration systems:
  - Neutron source, laser, ^{207}Bi sources, temperature sensors along the APAs

ProtoDUNE-HD : plans



The filling of ProtoDUNE-HD started in March 5th
-> As of Monday, about 3.5m of LAr !
Filling should end in late April, foreseen to have good LAr purity around the end of May.

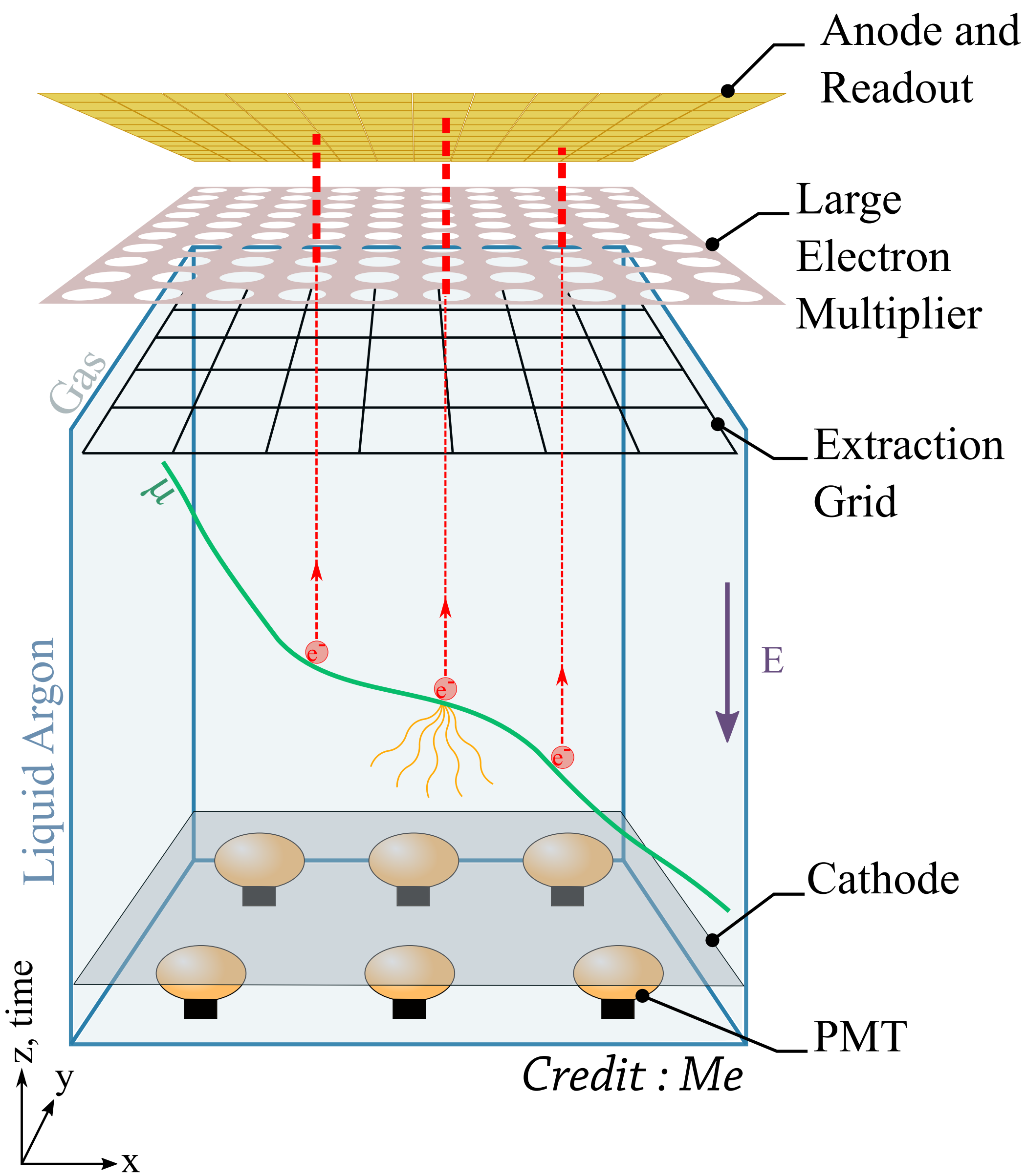
Six weeks of beam data have been approved by CERN:

- Momentum scan at negative polarity (1 week in mid-June)
- ± 1 GeV beam (5 weeks in July-August) to further study pion-argon and proton-argon cross section

— ProtoDUNE-I —

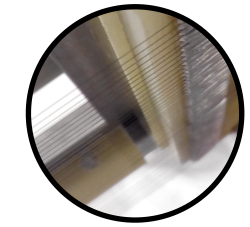
The Dual Phase
or
The 'PCB-Based'

Dual-Phase LArTPC design

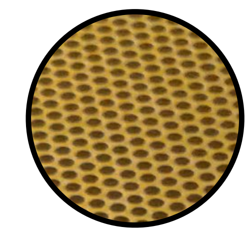


In the Dual phase design, electrons are:

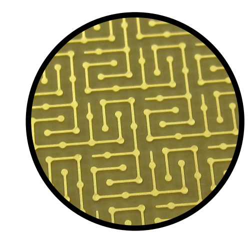
1. ***extracted*** to the gaseous phase,
   -> extraction grid in LAr below the surface



2. ***amplified*** in the LEM,
   -> Townsend avalanche in a drilled PCB with high ΔV

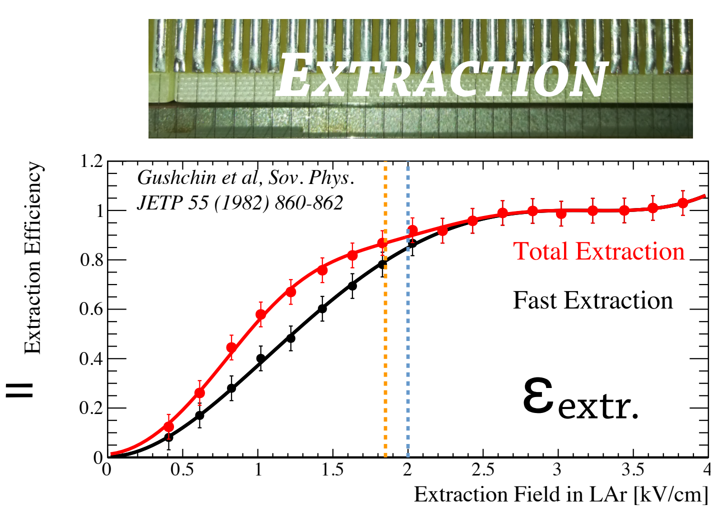


3. ***collected*** to the anode
   -> made of 2 orthogonal views with 3.125mm pitch



The effective gain depends on:

$G_{eff} =$



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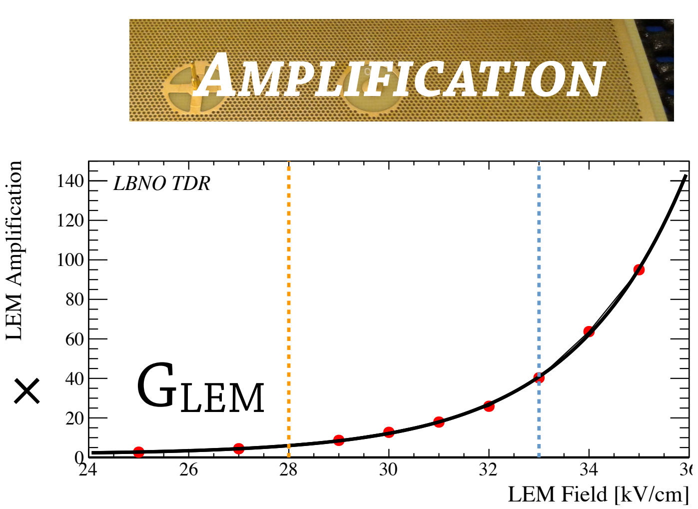

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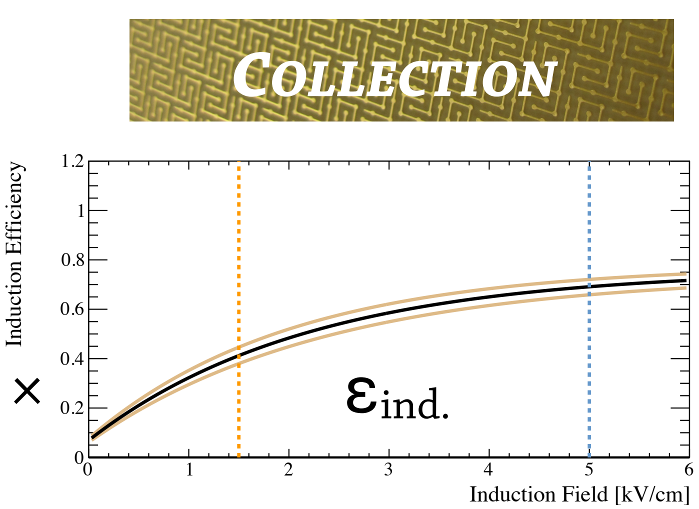
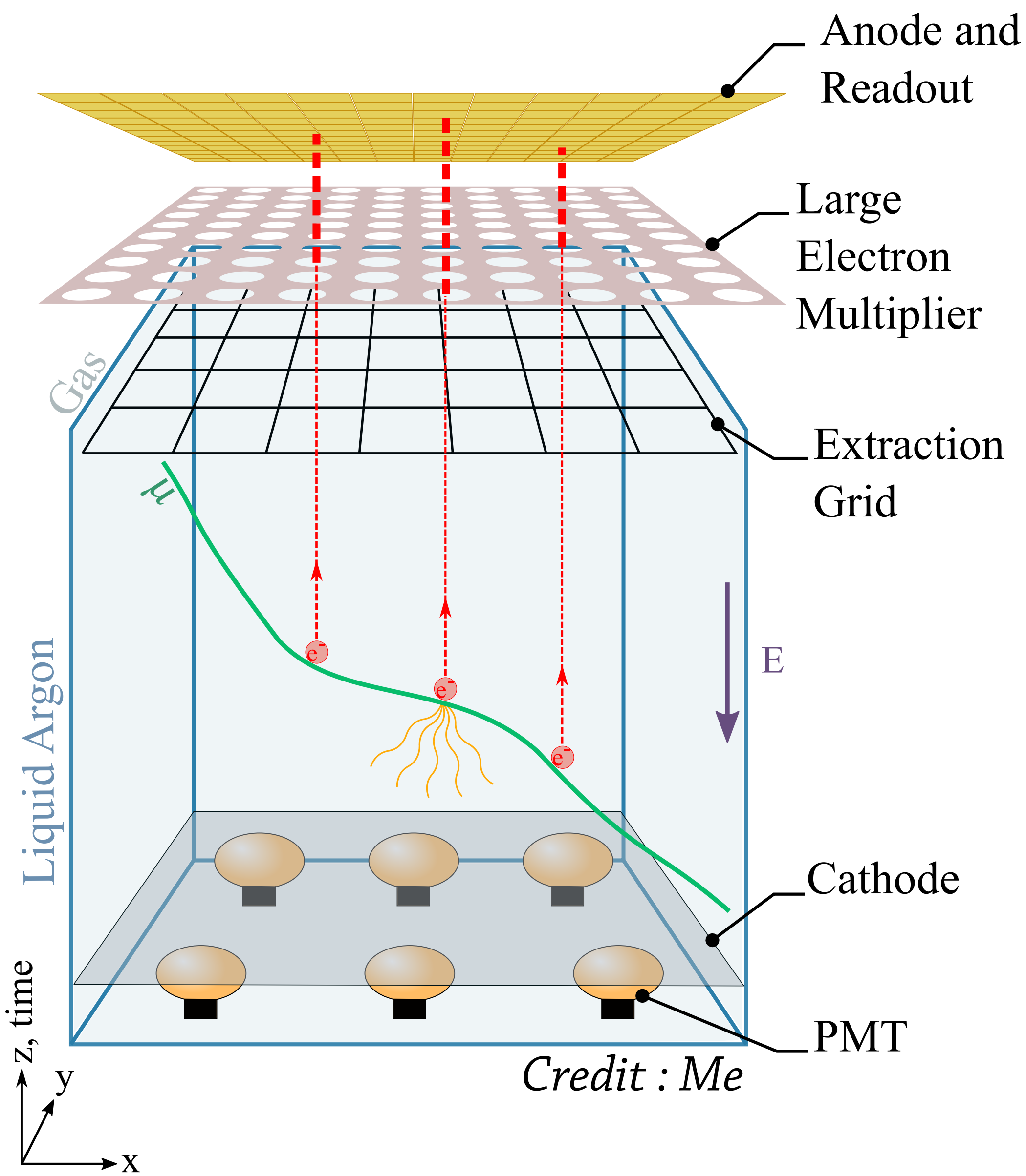
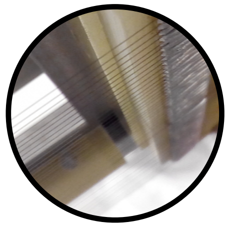


Dual-Phase LArTPC design

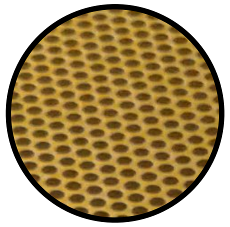


In the Dual phase design, electrons are:

1. ***extracted*** to the gaseous phase,
   -> extraction grid in LAr below the surface



2. ***amplified*** in the LEM,
   -> Townsend avalanche in a drilled PCB with high ΔV



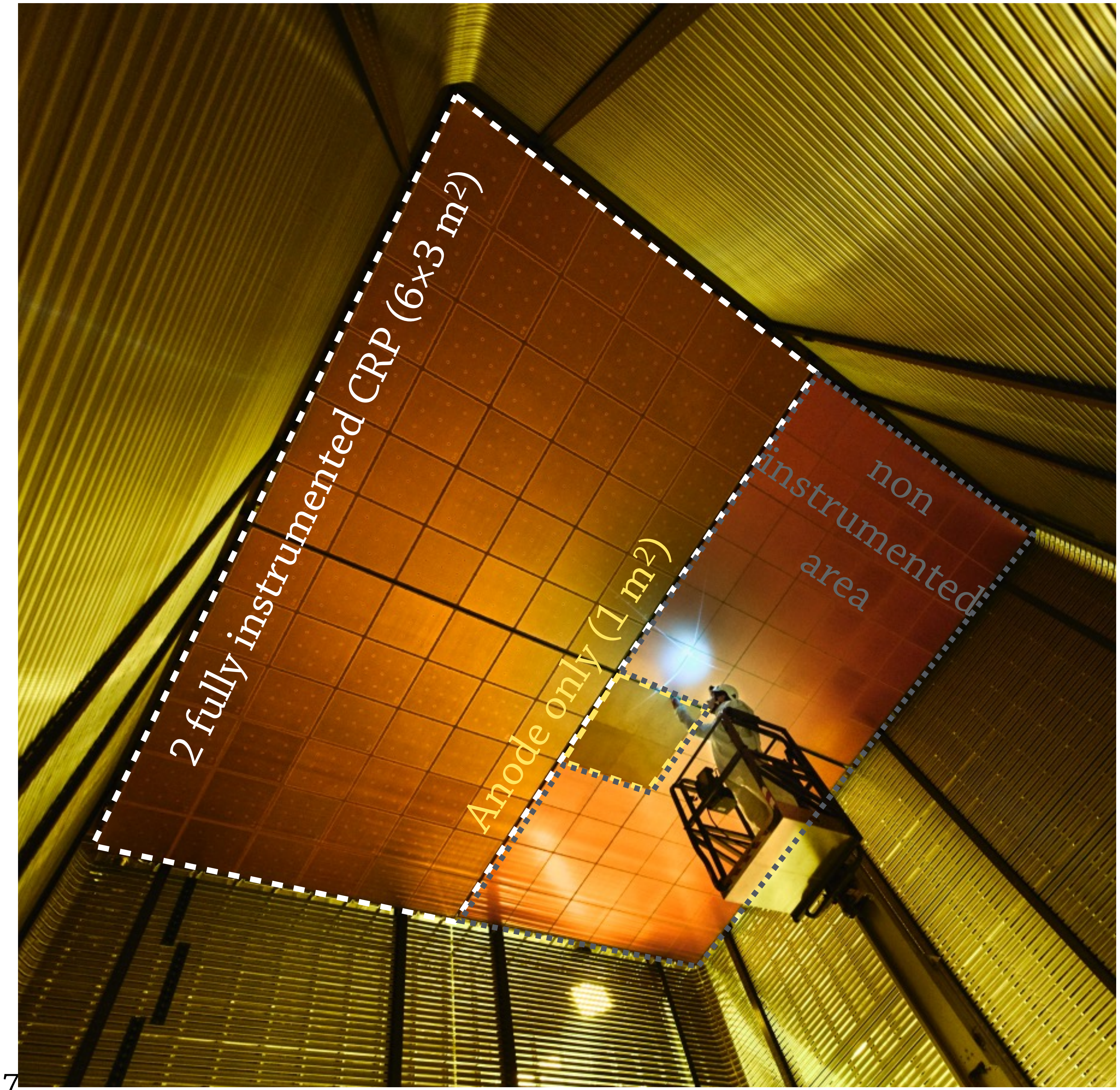
3. ***collected*** to the anode
   -> made of 2 orthogonal views with 3.125mm pitch

The signal being amplified, longer drift are possible:
-> 6m drift in ProtoDUNE-DP (V_{cath} = -300 kV)
-> 12m drift in DUNE-FD (V_{cath} = -600 kV)

Compared to the Single-Phase design:
⊕ Accessible electronics, better resolution, larger S/N
⊖ Stability of LAr level, Operation of a large area of amplification & readout

ProtoDUNE Dual-Phase

The ‘extraction - amplification - collection’ system are held in a CRP [Charge Readout Plane] 3×3 m² modules.



Credit : CERN

The LEMs and the anodes are 50×50 cm² units
-> A CRP is made of 36 LEM & Anodes

In ProtoDUNE-DP, 4 CRPs was planned to be installed
Due to many constrains, only 2 fully instrumented could be installed (LEM+Anode)
-> Surface detection of 6×3 m²

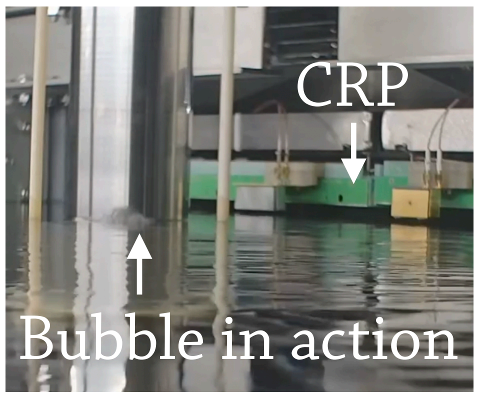
4 spare anode units was installed
-> Surface of 1 m² without amplification

ProtoDUNE Dual-Phase

ProtoDUNE-DP operated from August 2019 to January 2020 (run 1) and in August 2020 (run 2)

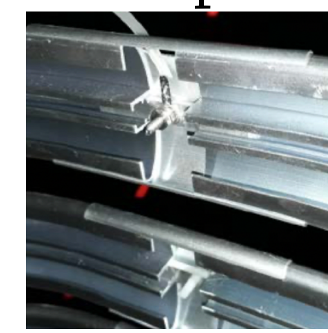
Couples of issues during the run :

- ***Non flat liquid argon surface***



High pressure →

#1 suspect :



Ar gas trapped in field cage clip

A non-flat LAr surface is a major problem for the Dual Phase:

- ○ If the extraction grid is in the gas, it will discharge ; the detector can be damaged
- ○ If the LEM is in liquid, there is no amplification ; by capillarity, LEM holes can be obstructed if splashed

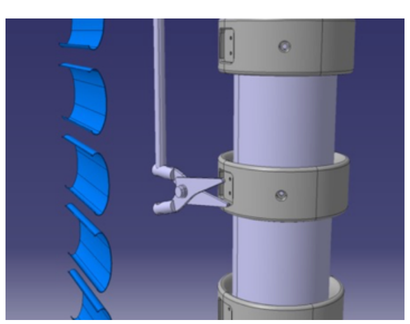
To disable the bubbles, the detector was temporarily over-pressured ; long runs was not possible

ProtoDUNE Dual-Phase

ProtoDUNE-DP operated from August 2019 to January 2020 (run 1) and in August 2020 (run 2)

Couples of issues during the run :

- Non flat liquid argon surface
- ***Short between the VHV extender and the field cage***



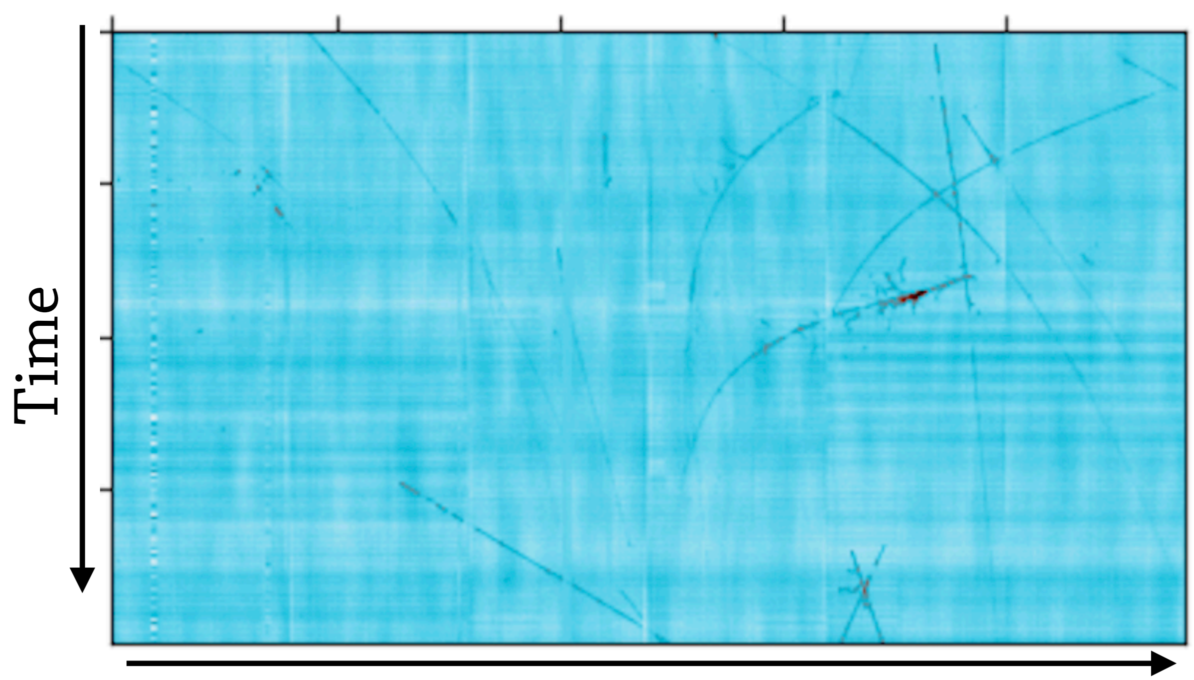
A short occurred during the HV ramping-up, at 1.2m depth

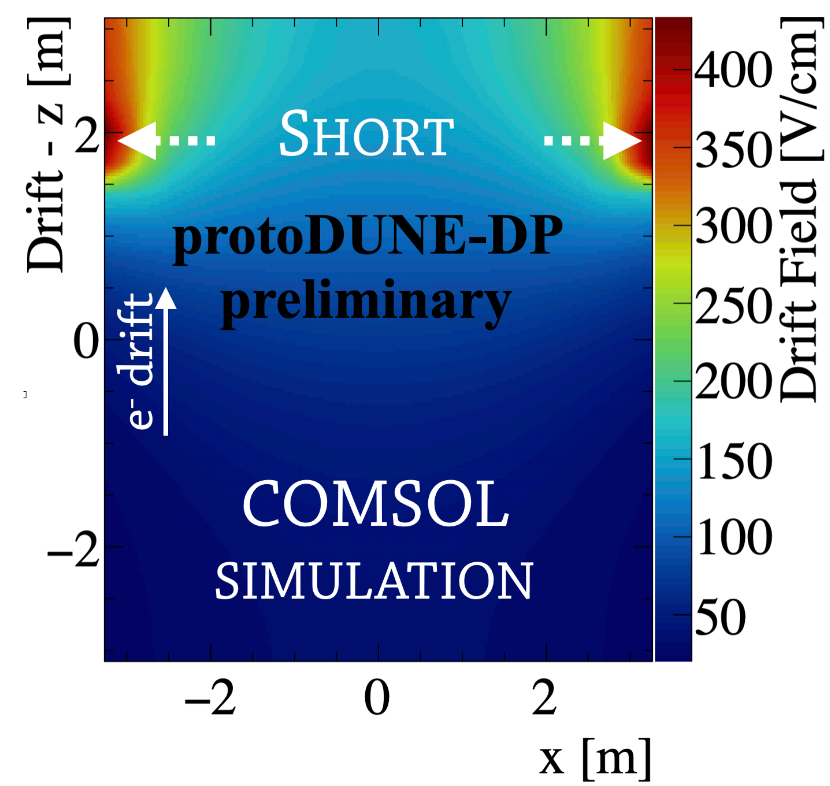
-> The drift field was not uniform

-> The active volume reduced to ~1.2m of drift

-> Tracks are very bended

-> Safe operating voltage was V_{cath} = -50 kV : E_{drift} ~ 160 V/cm



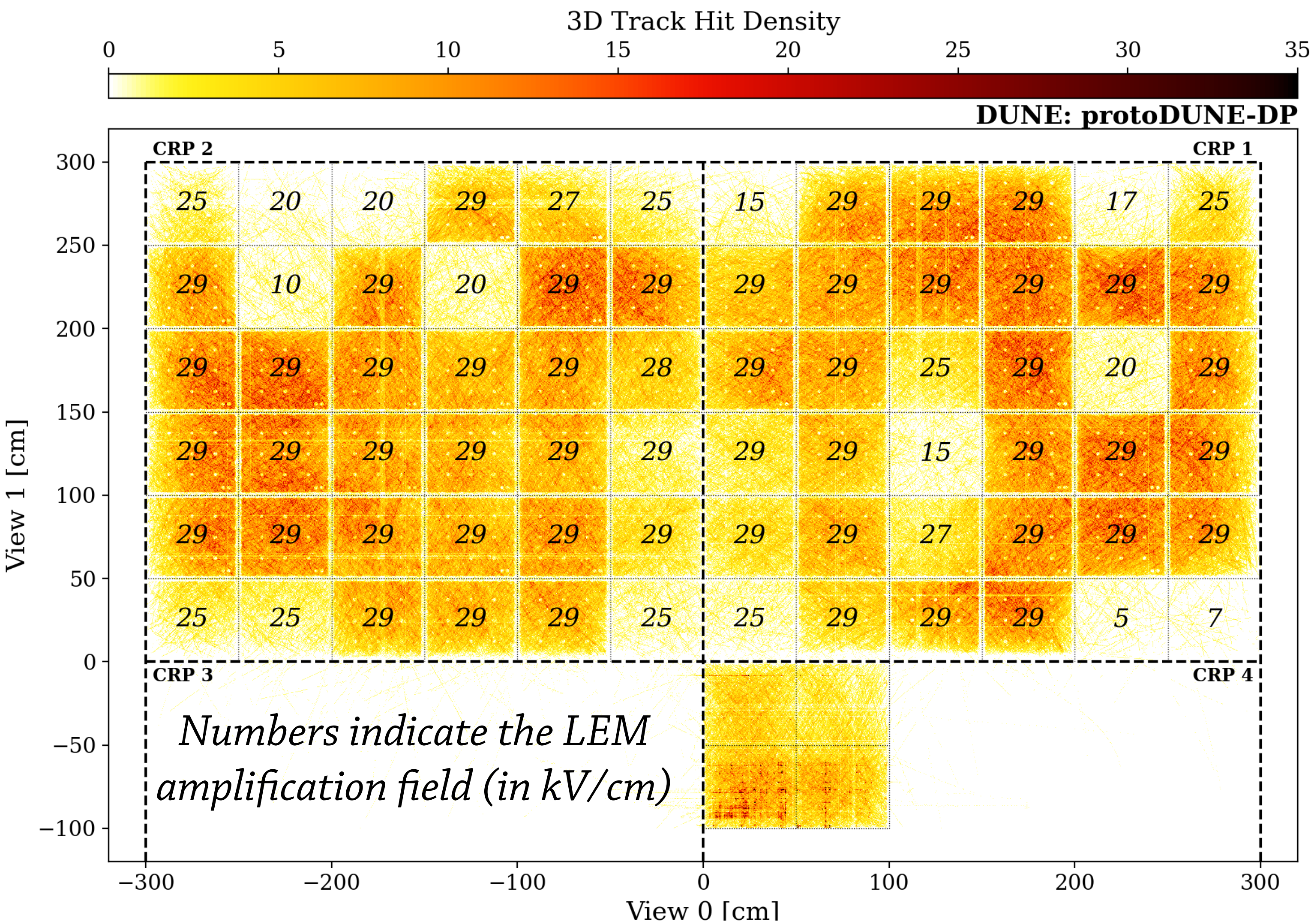


-> A surgery was performed in July 2020 to cut the extender-Field Cage faulty connection, but it was not successful

ProtoDUNE Dual-Phase : Data Reconstruction

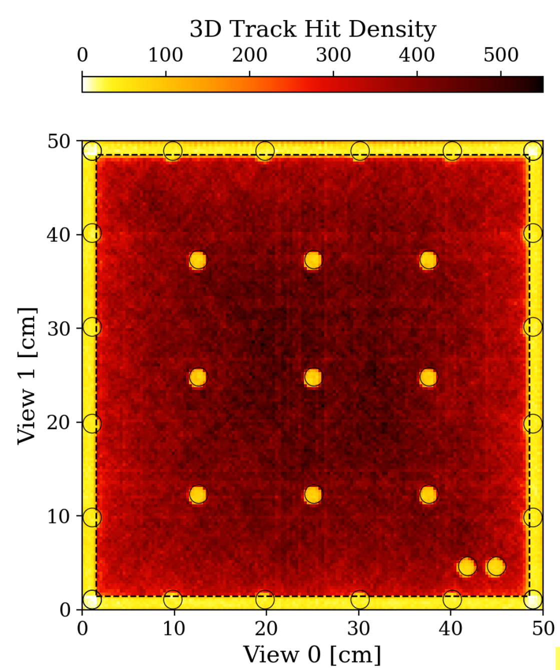
From simulated electric field maps, the measured dQ/dx could be corrected from the field distortions induced by the HV short ; only hits up to 50cm depth was considered in the analyses

Two reconstruction chain was used to study the ProtoDUNE-DP data : LArSoft and LARDON

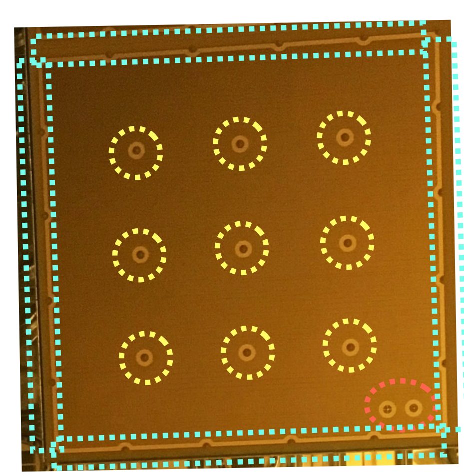


<- All tracks reconstructed in one run (Not all the LEMs were operated at the same voltage)

↓ All hits summed as one LEM :



Picture of a LEM installed :



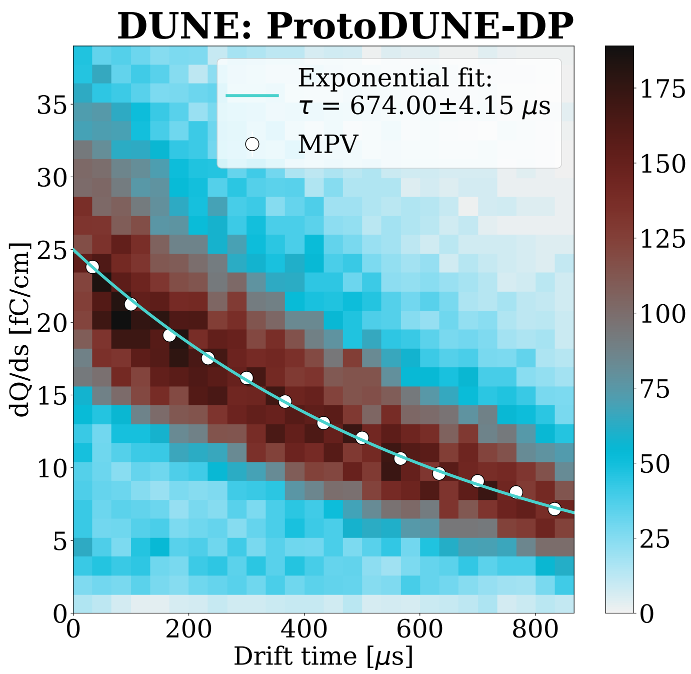
Supporting screws

Protective borders

HV connectors

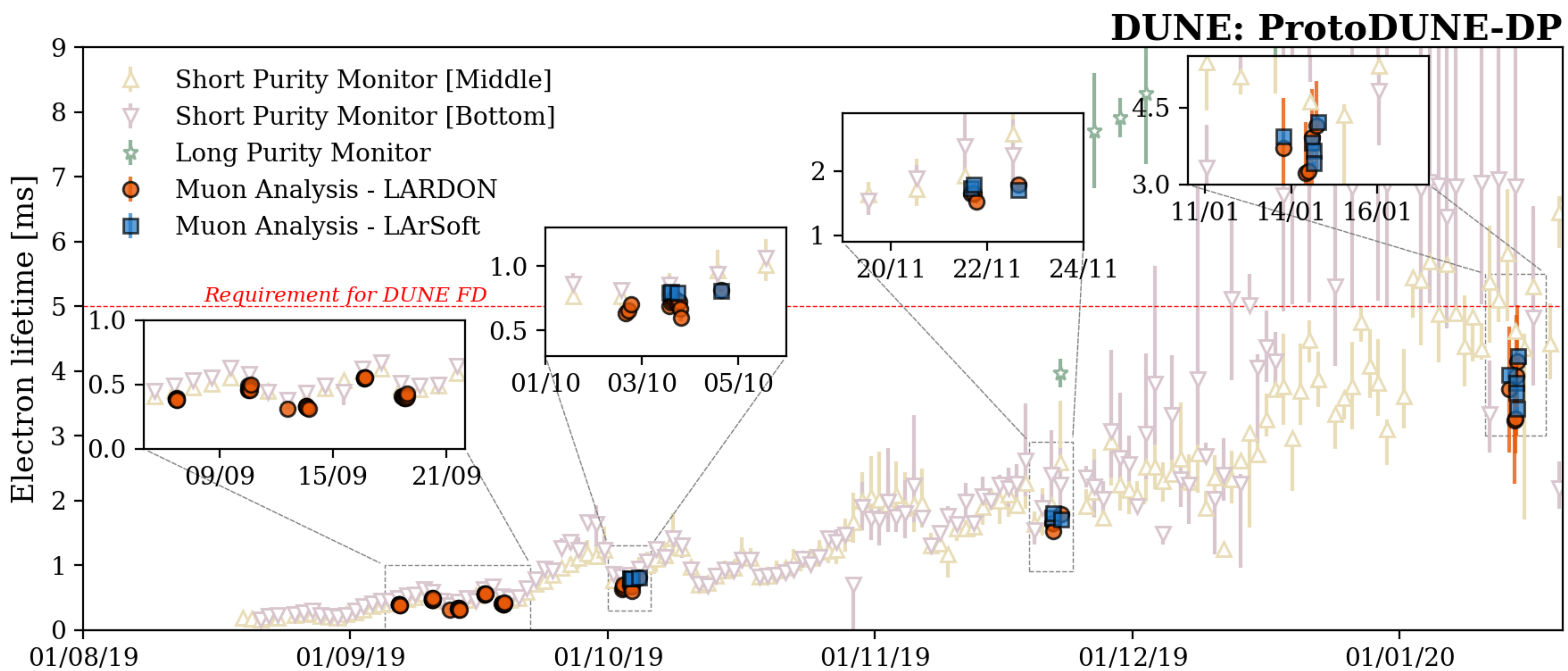
Paper in preparation

ProtoDUNE Dual-Phase : Purity



During protoDUNE-DP operation, four cosmic data taking periods was taken.

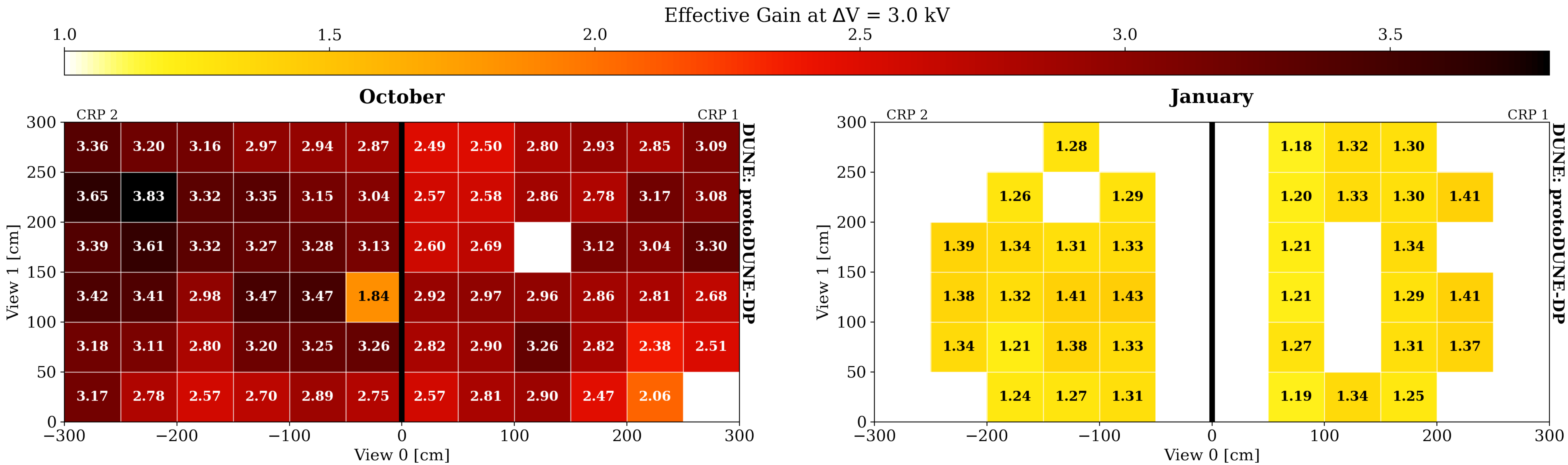
The electron lifetime measured using the cosmic muon data was in good agreement with the purity monitors
  -> In the latest run, the electron lifetime was ≥ 4ms
  -> It corresponds to less than 75 ppt impurities



Paper in preparation

ProtoDUNE Dual-Phase : Effective gain

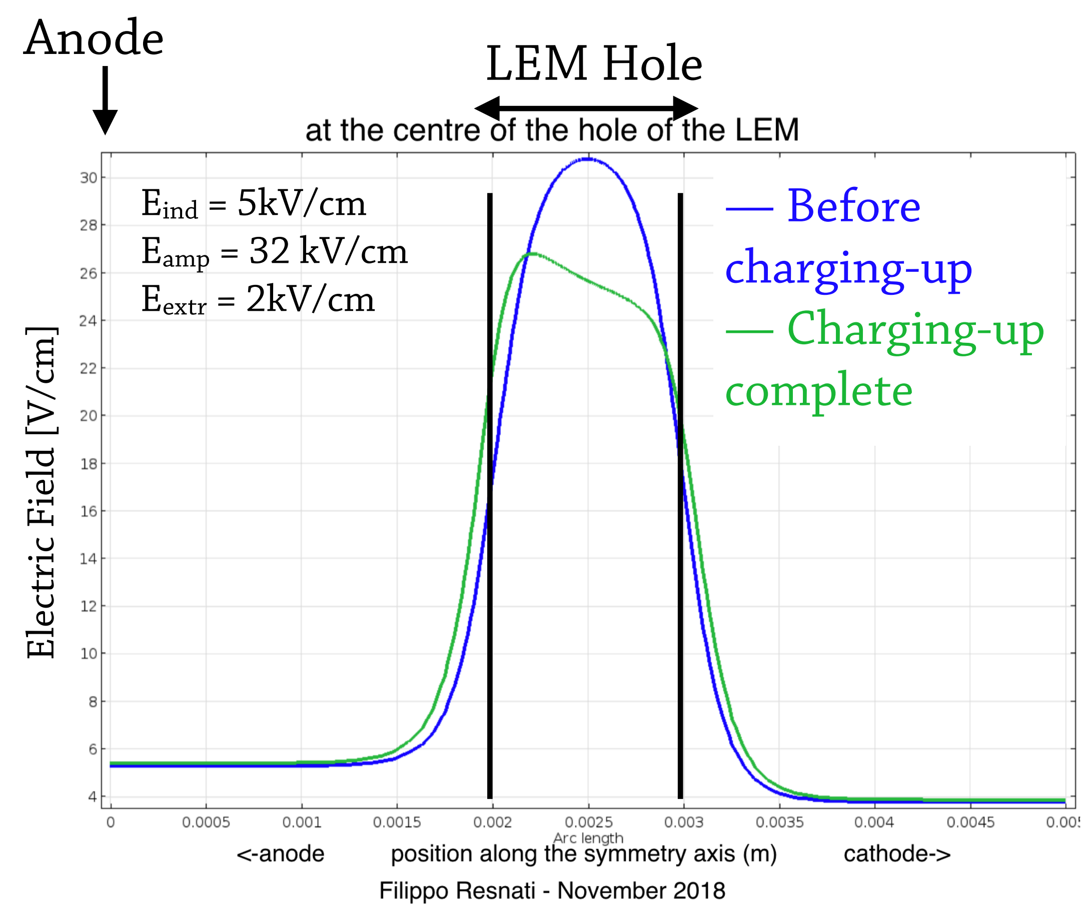
Effective gains measured in same conditions in two periods, $G_{eff} = dQ/dx_{meas} / dQ/dx_{expected}$



- The effective gain decreases with time due to the charging-up effect

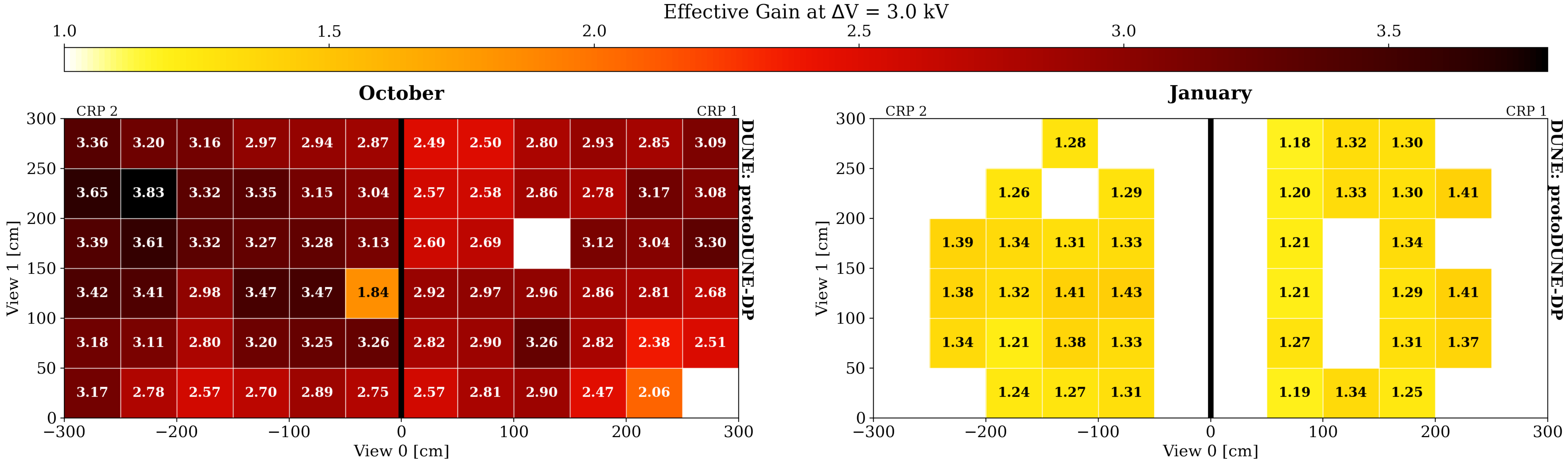
During the Townsend avalanches in the LEM, some electrons and ions are stuck in the insulated surface.

These buildup charges affects the field inside the LEM, and decrease its amplification power until a plateau is reached.



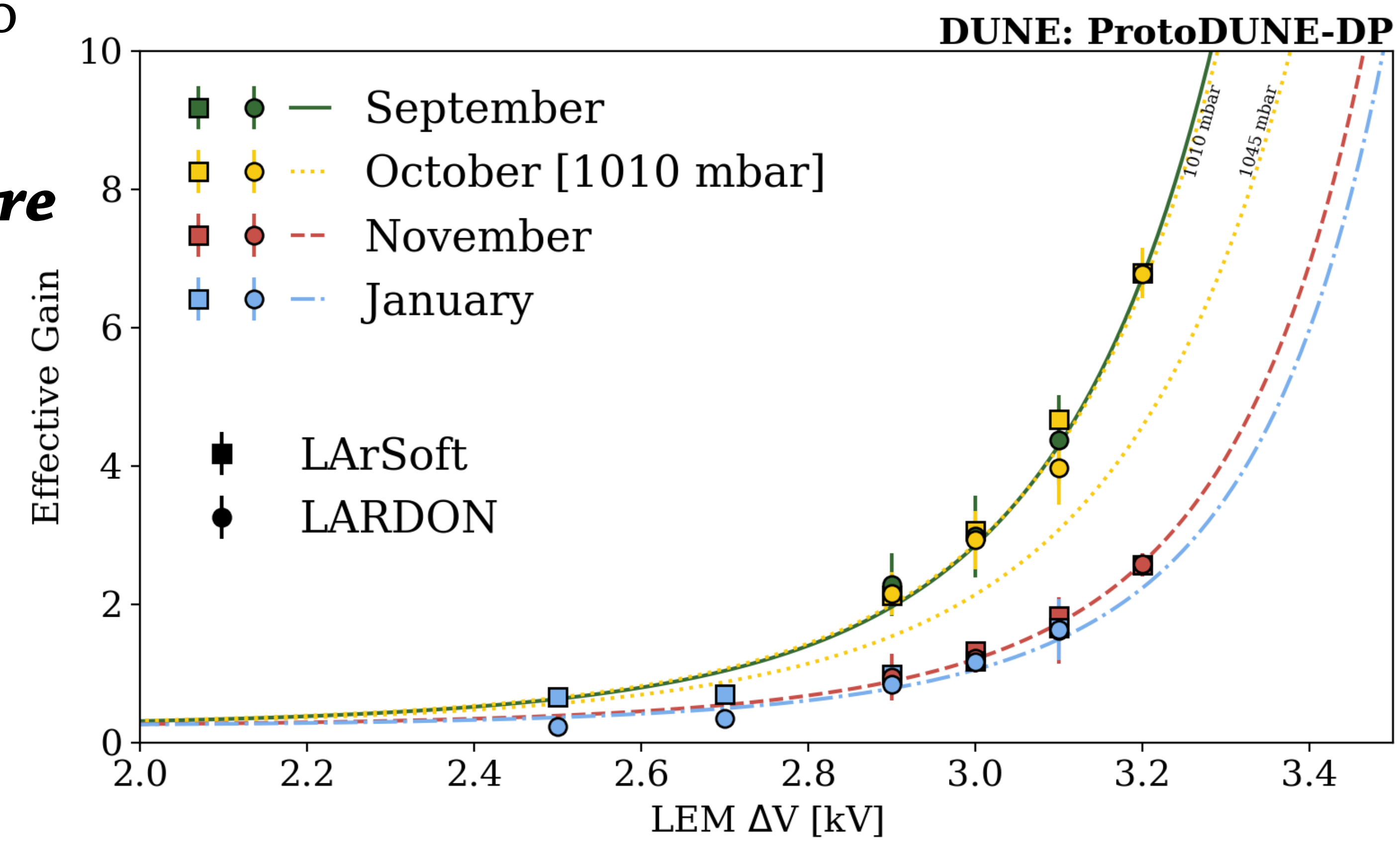
ProtoDUNE Dual-Phase : Effective gain

Effective gains measured in same conditions in two periods, $G_{eff} = dQ/dx_{meas} / dQ/dx_{expected}$



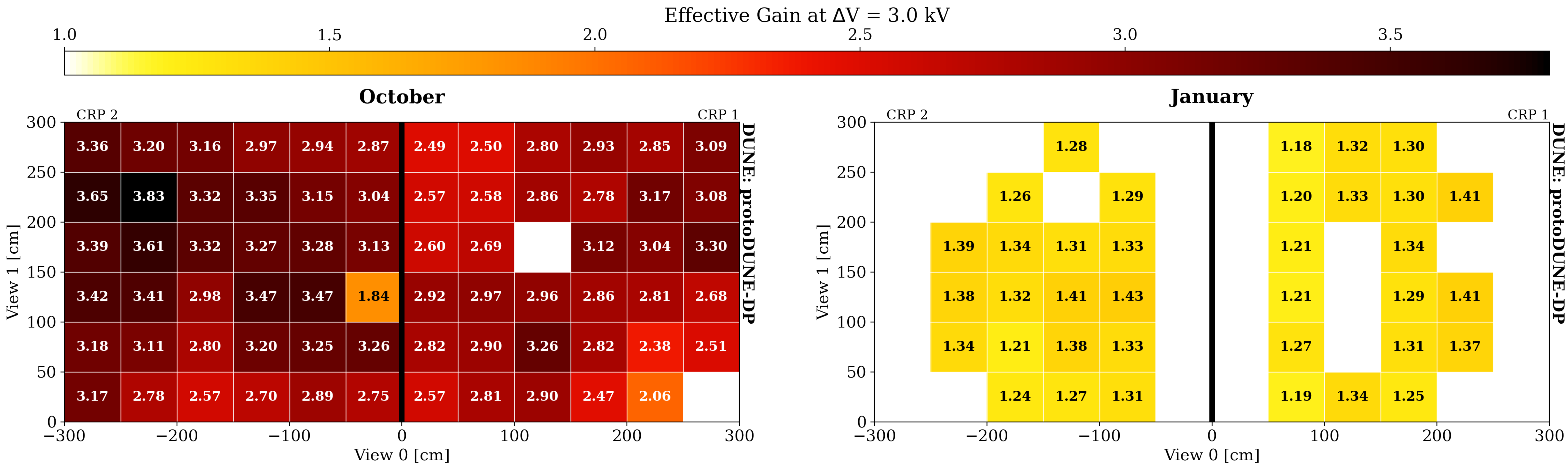
- The effective gain decrease with time due to the charging-up effect

- Highest gain achieved was G_{eff} = 6.8 before charging-up, G_{eff} = 1.5 after completion



ProtoDUNE Dual-Phase : Effective gain

Effective gains measured in same conditions in two periods, $G_{eff} = dQ/dx_{meas} / dQ/dx_{expected}$

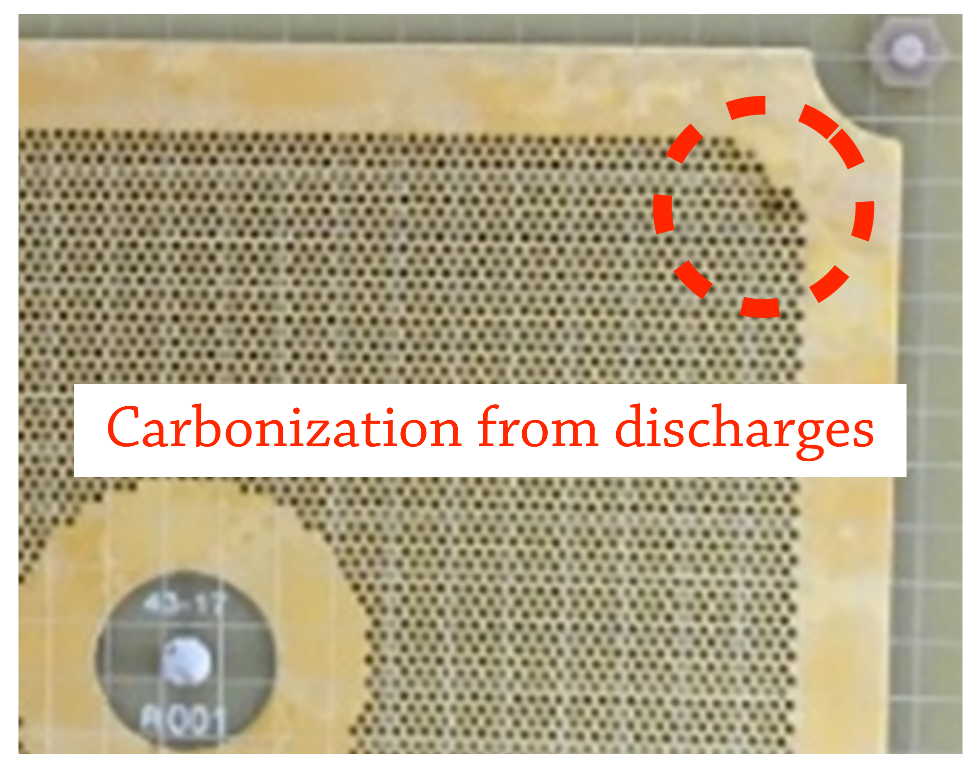


- The effective gain decrease with time due to the charging-up effect

- Highest gain achieved was G_{eff} = 6.8 before charging-up, G_{eff} = 1.5 after completion

- LEM could not be operated higher than ΔV = 3.2 kV

At higher ΔV, the LEMs discharged which could have damaged the detector and/or electronics



ProtoDUNE Dual-Phase : Effective gain

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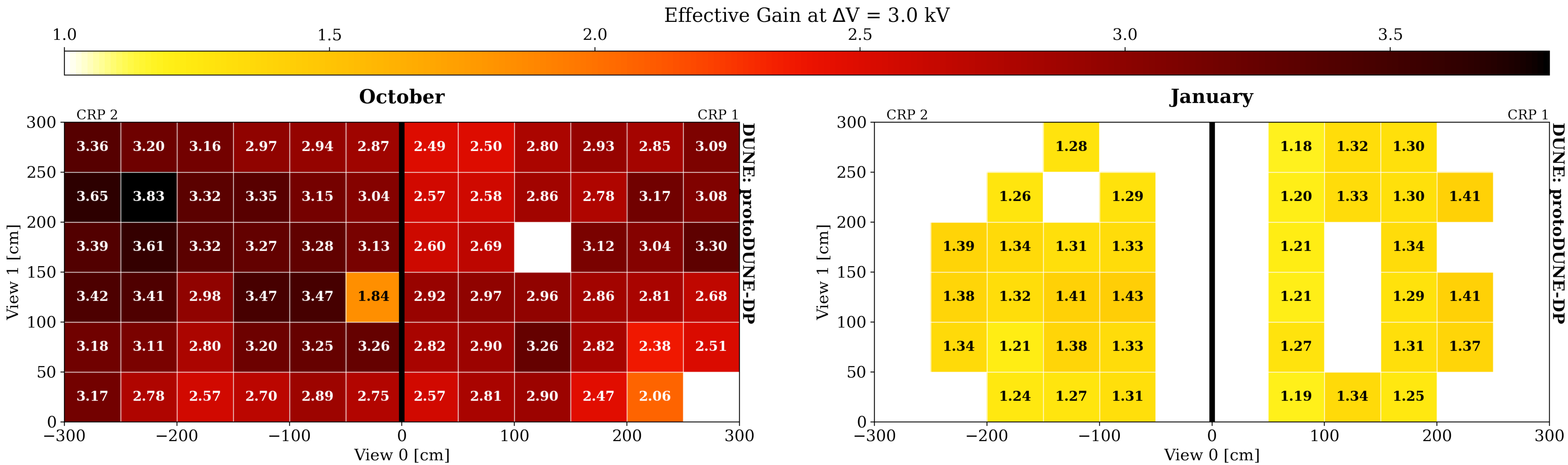

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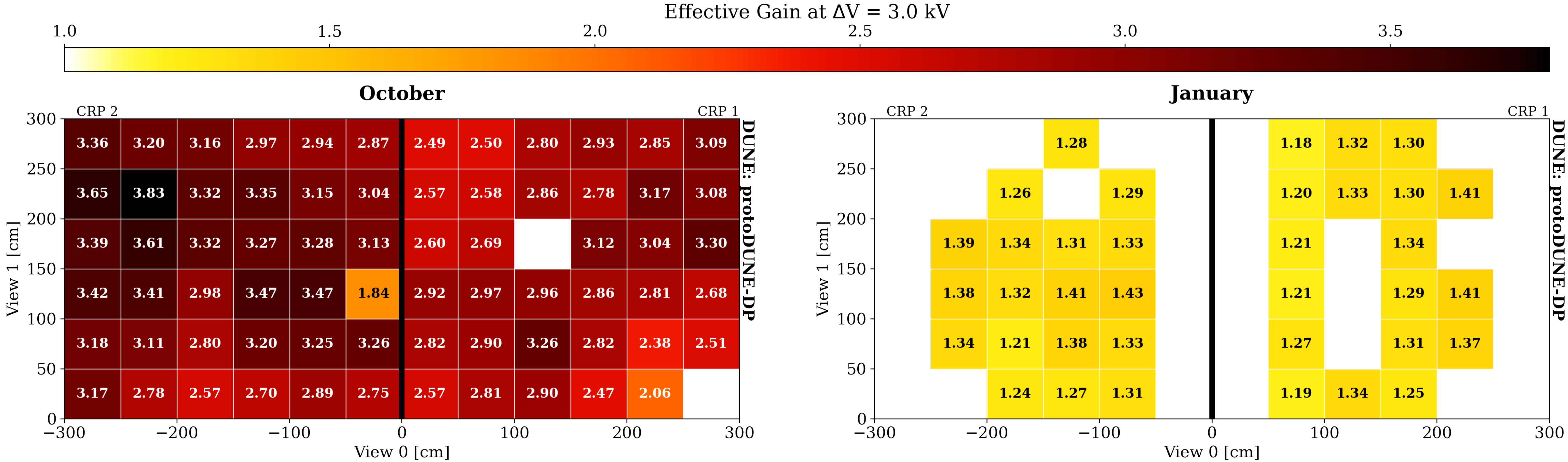
- Highest gain achieved was $G_{eff} = 6.8$ before charging-up, $G_{eff} = 1.5$ after completion

- LEM could not be operated higher than $\Delta V = 3.2$ kV

- At the end of data taking, 36 LEMs (out of 72) could no longer be operated at high ΔV

ProtoDUNE Dual-Phase : Effective gain

Effective gains measured in same conditions in two periods, $G_{eff} = dQ/dx_{meas} / dQ/dx_{expected}$

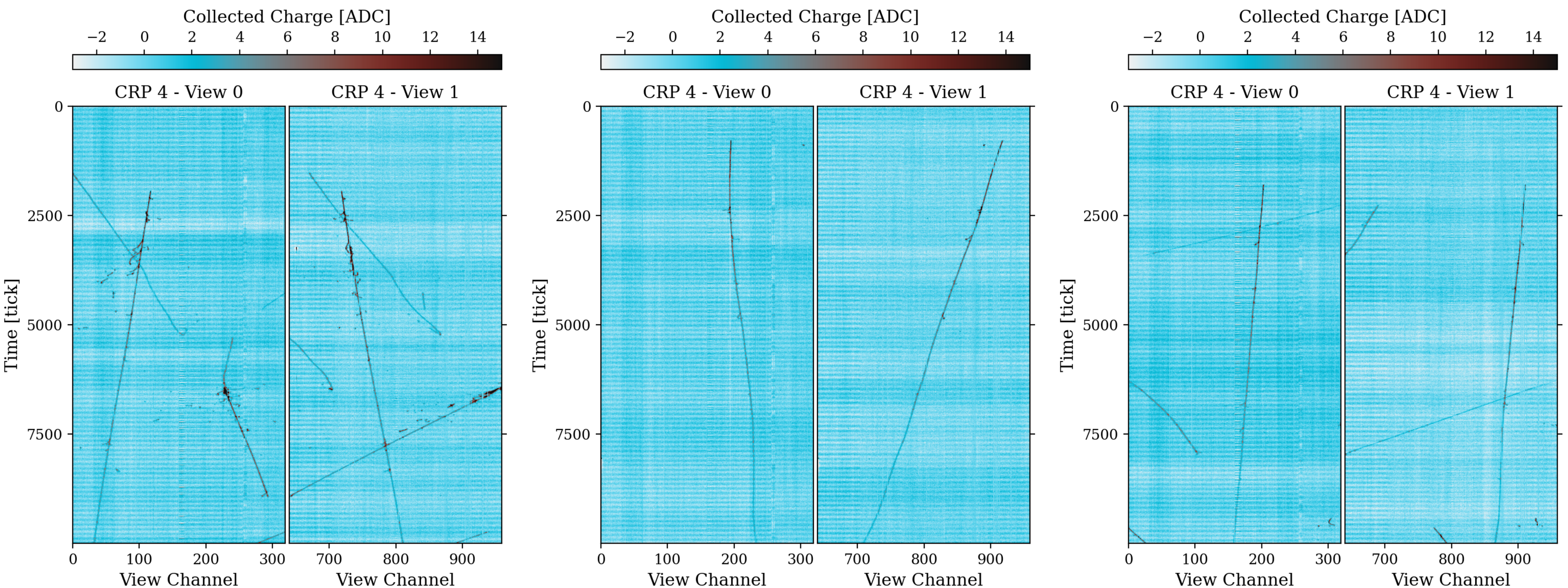


- The effective gain decrease with time due to the charging-up effect
- Highest gain achieved was $G_{eff} = 6.8$ before charging-up, $G_{eff} = 1.5$ after completion
- LEM could not be operated higher than $\Delta V = 3.2$ kV
- At the end of data taking, 36 LEMs (out of 72) could no longer be operated at high ΔV

A huge R&D effort would be needed to revise the design of the LEMs, which would conflicts with DUNE calendar

6m long tracks recorded in 'single-phase'-mode

In September 2020, the detector was emptied.
The HV extender has been dismantled and replaced with a new design and the top 3 rings of the Field cage was removed.
In summer 2021, the detector was filled with LAr and HV has been ramped up safely to -300kV



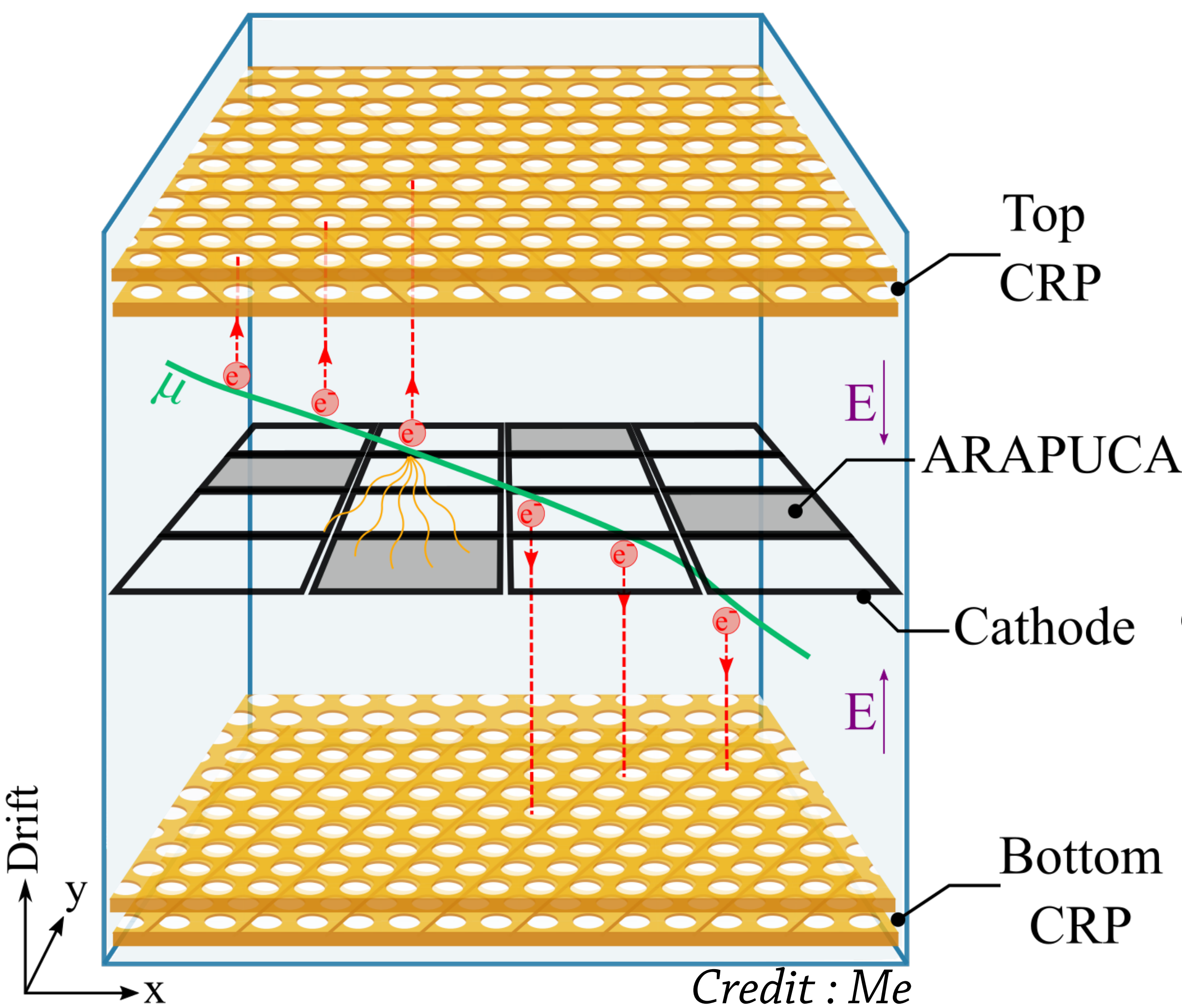
The two CRPs fully instrumented could not operated ; only the 1 m^2-anode collected data for a couple of days

-> First observation of 6m long tracks in a LArTPC without amplification !

ProtoDUNE-II: Vertical Drift

The Vertical Drift concept

At the end of 2020, a new concept combining the strengths of the single and dual-phase designs was proposed :
the vertical drift



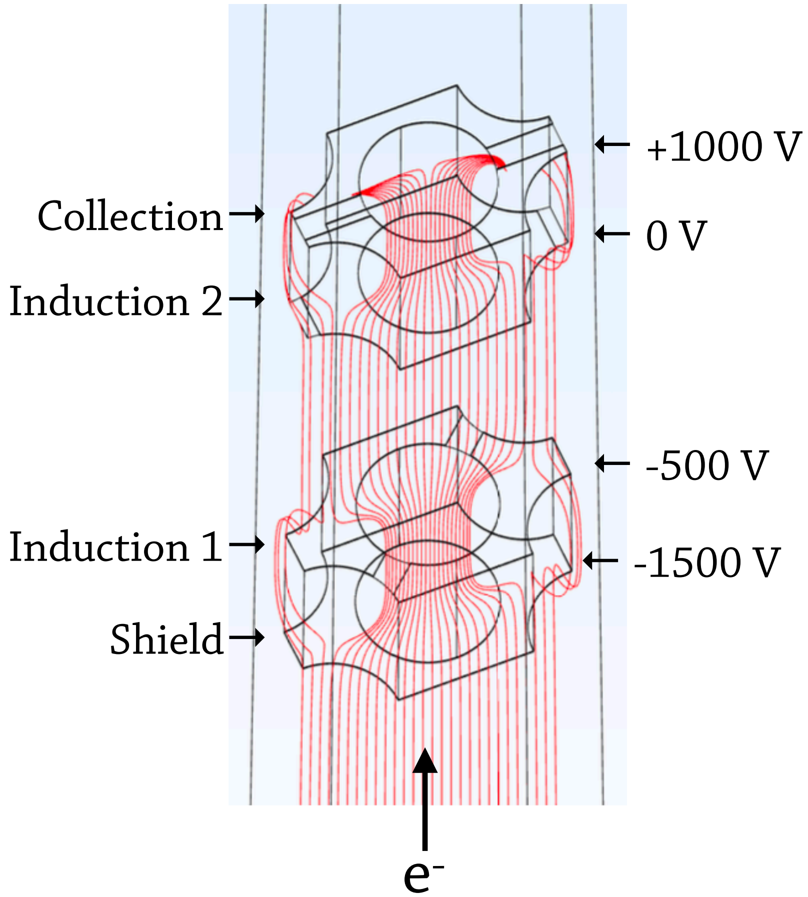
○ No more gaseous phase nor amplification
- Very low electronic noise
- can see 6m-deep depositions without amplification
- clear light signal and less space-charge effects

○ Anode made of drilled PCB with etched strips
- Can have 3 views to resolve ambiguities
- First two views see the signal through induction, as in single-phase
- More robust than wires

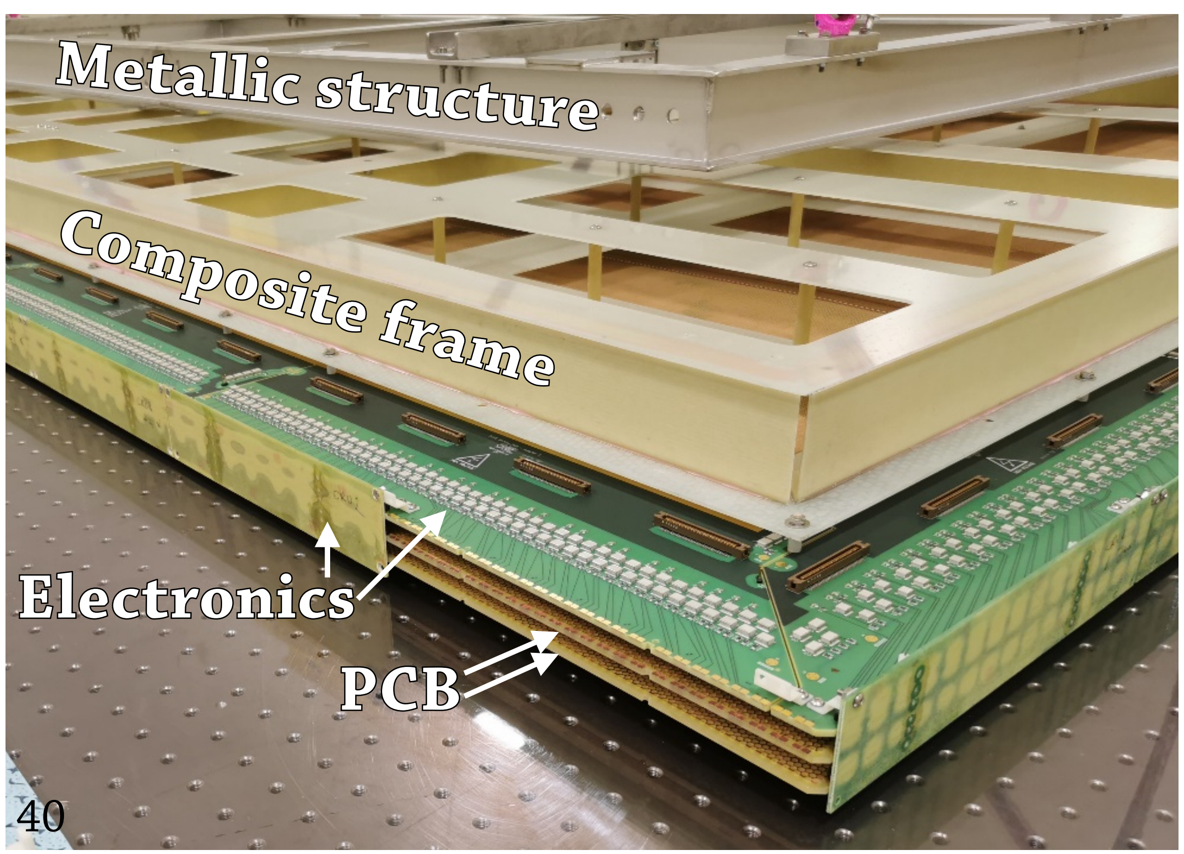
○ Two drift volumes separated by a suspended cathode
- Upper anode can use the accessible electronics developed for the dual-phase
- Bottom anode uses embedded electronics as in single-phase
- In FD: 2×6m of drift ↔ V_{cath} = -300kV

○ Light detection system made of ×-ARAPUCAs embedded in the cathode

Vertical Drift Anodes

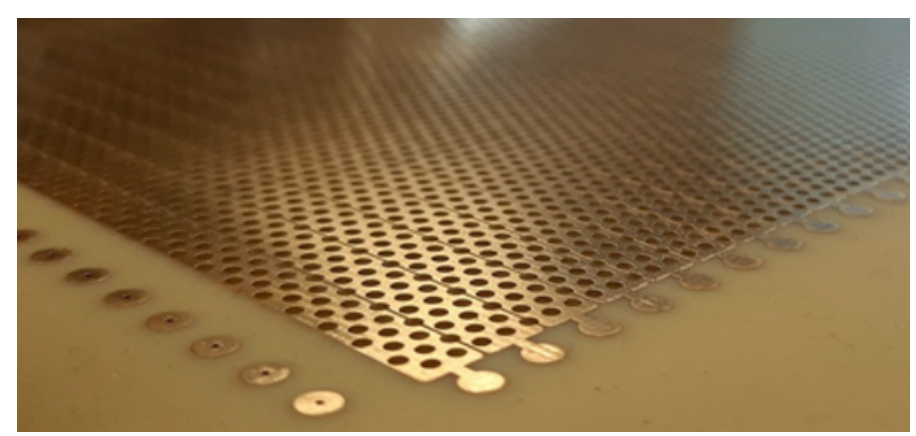


- Each PCB face has a bias to attract the electrons through the holes towards the collection (last) plane
  -> ongoing HV studies to ensure transparency
- The 3 instrumented planes have {-30°, +30°, +90°} strip orientation w.r.t. the ν beam
- Induction strips are 7.65 mm wide, collection strips are 5.1 mm



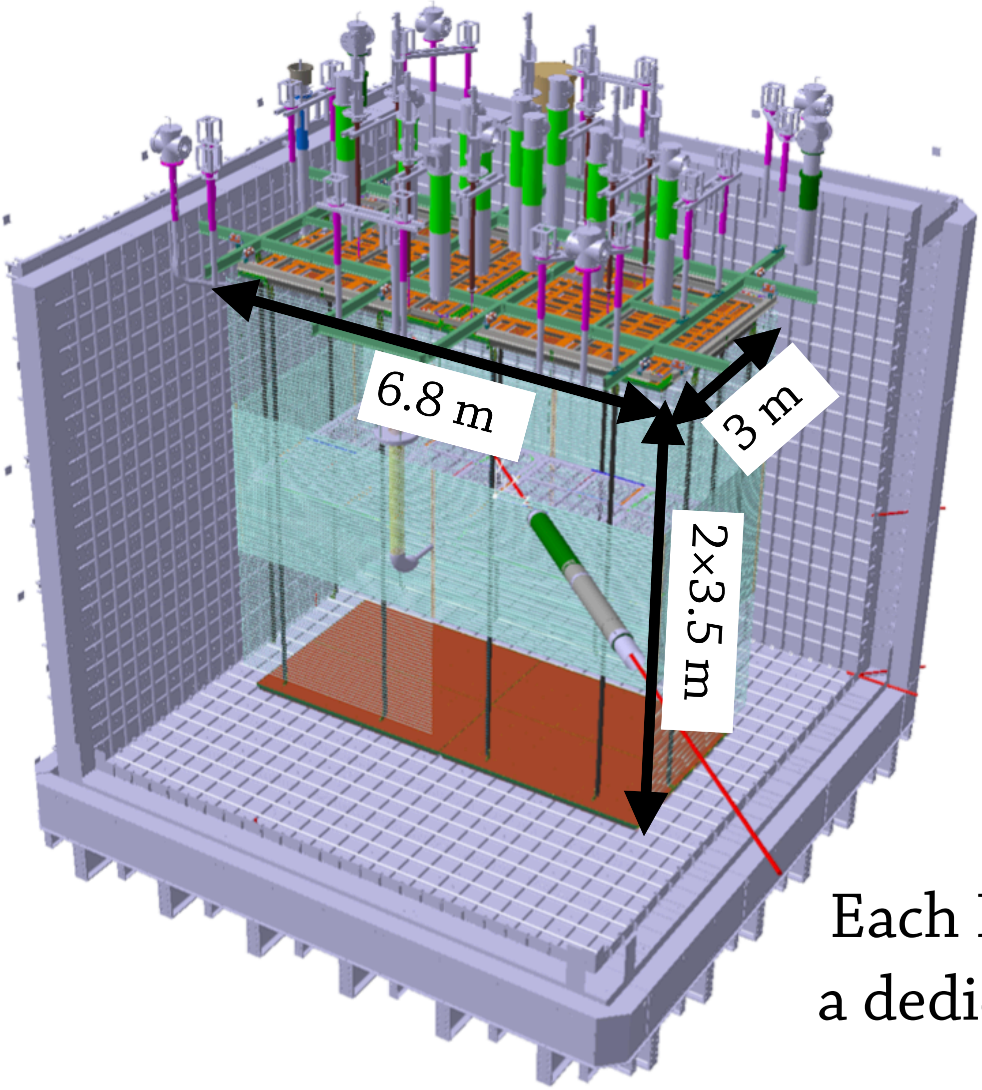
The PCBs and their electronics are held in Charge Readout Plane (CRP) modules:

- One CRP is 3 × 3.4 m^2
- DUNE-FD will be made of 2×80 CRPs



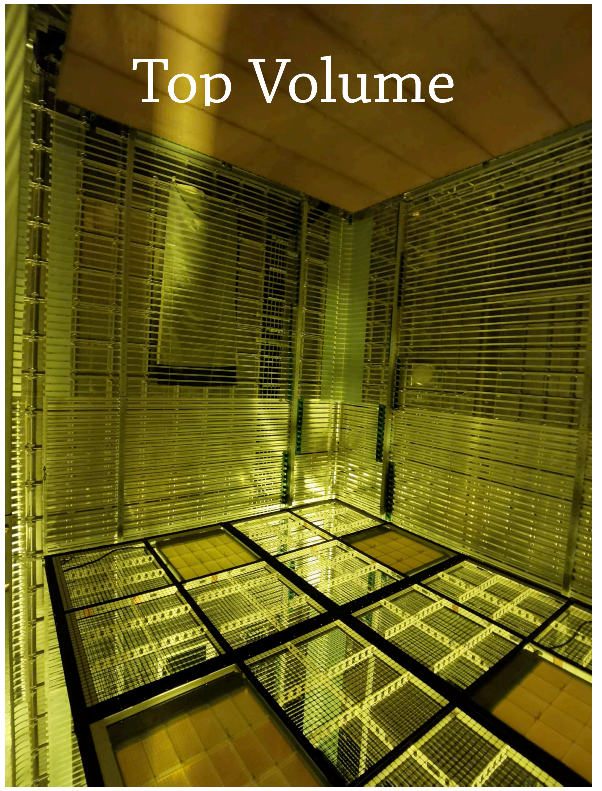
ProtoDUNE Vertical Drift

Large-scale test of the Vertical Drift design in the NP02 cryostat in the Neutrino Platform at CERN
-> cosmic and test-beam data foreseen in 2024/25, LAr from protoDUNE-HD



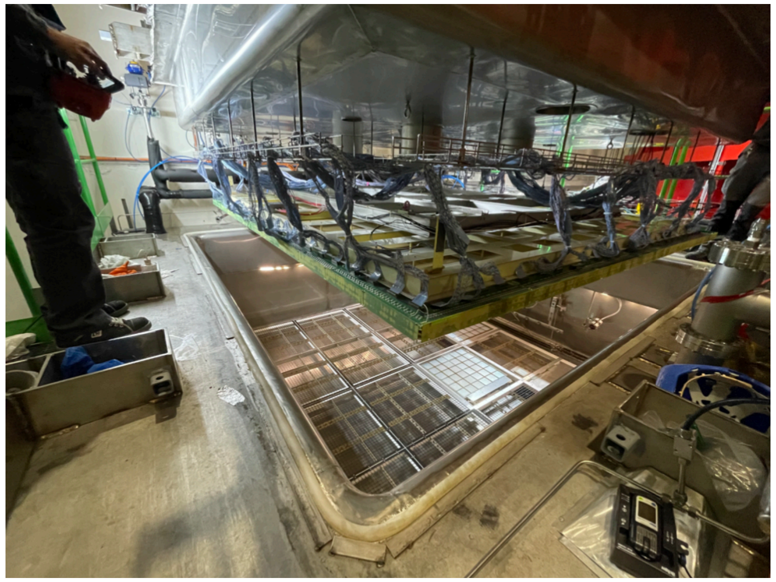
Characteristics of ProtoDUNE-VD:

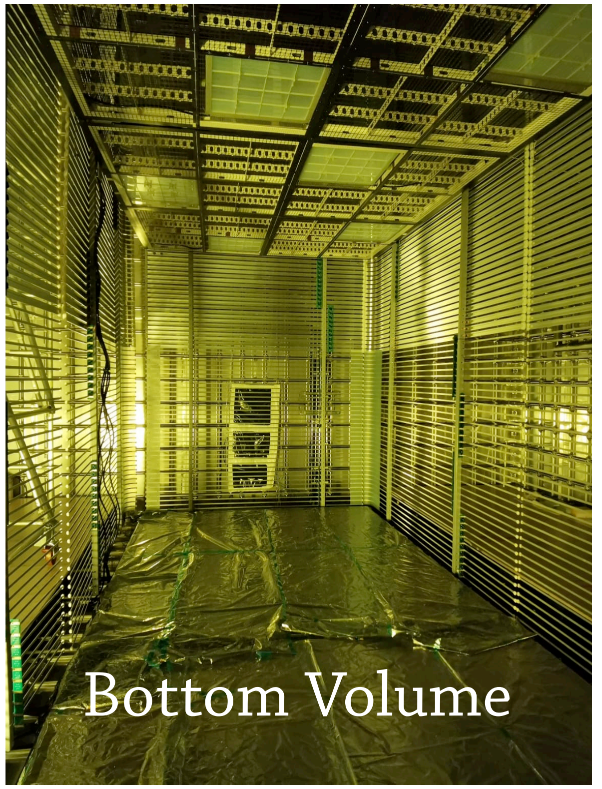
- 4 CRPs : 2 top + 2 bottom
- Cathode hanged in the center, V_{cath} = 175 kV
- ×-ARAPUCAs on the cathode (8) and on the field cage (2×4)



Each ProtoDUNE-VD CRPs have been tested in a dedicated instrumented cryostat: the ColdBox

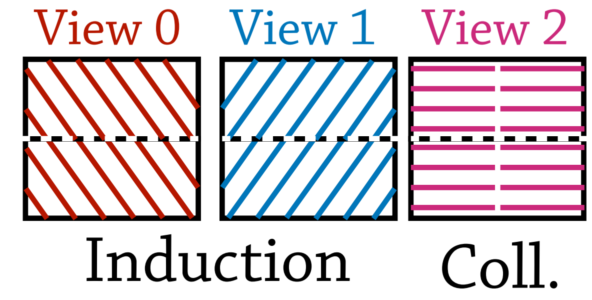
The ColdBox is a small TPC collecting cosmic data with 23 cm of drift



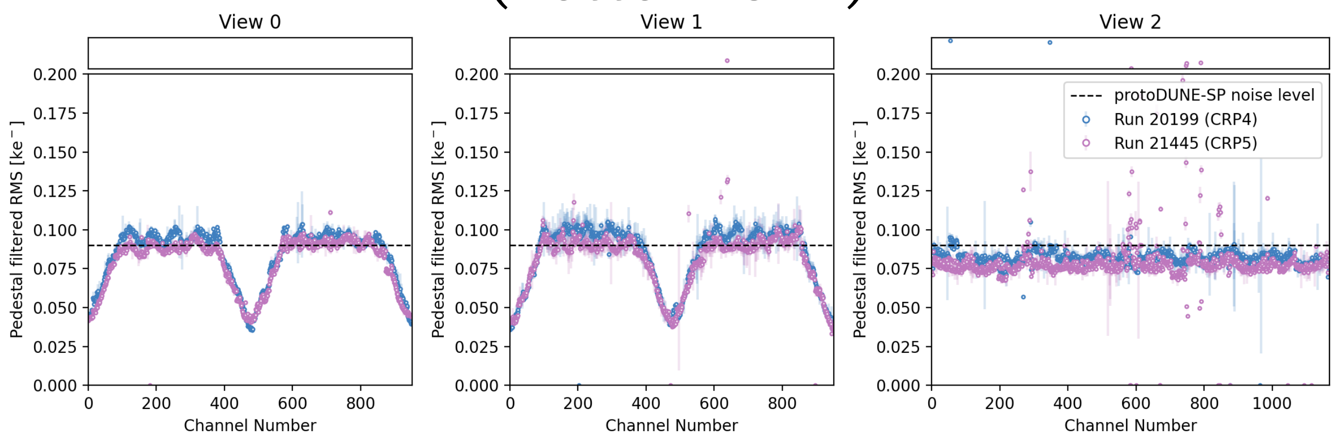


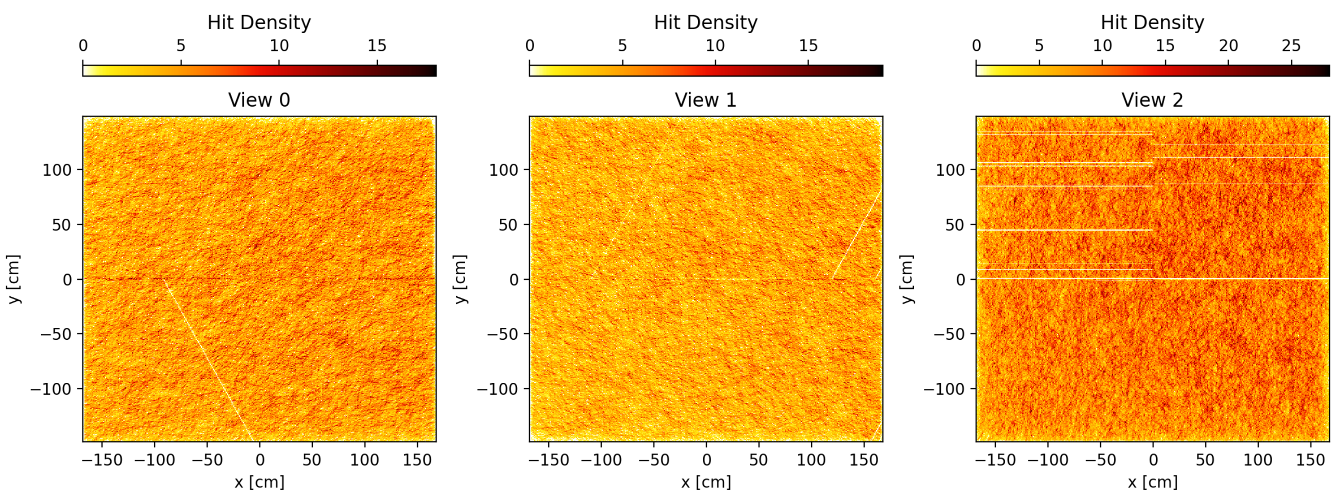
Credit : CERN

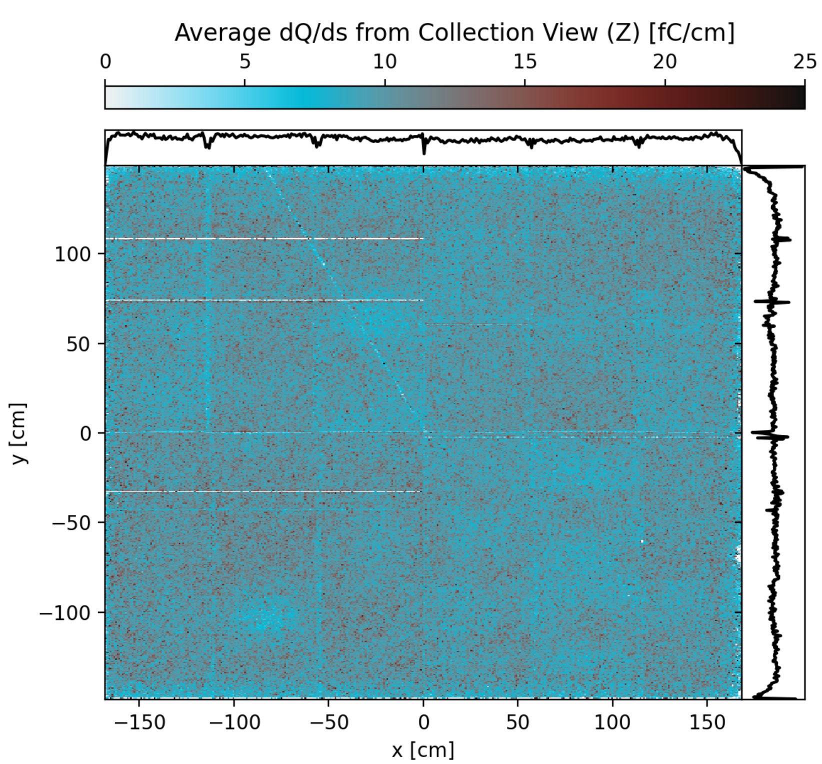
VD-Coldbox: noise & uniformity



(Bottom CRP)







In terms of noise:

○ Coherent noise filtered

○ Bridge-shape due to the noise being proportional to the strip length

-> Equivalent amount of noise for Top and Bottom CRP, at the same level of protoDUNE-SP

In terms of uniformity:

○ Less than 1% of channels either unresponsive or very noisy

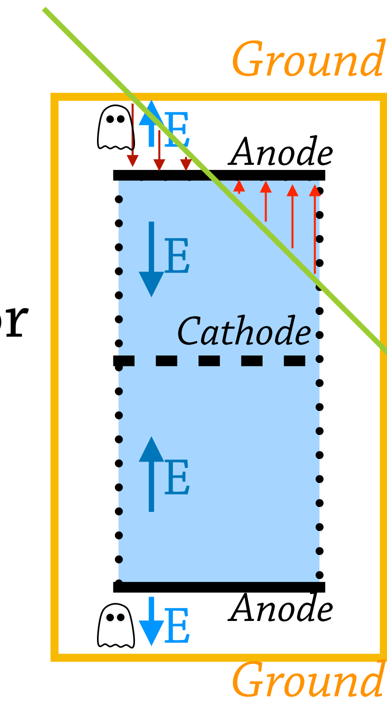
○ Very uniform dQ/dx across the CRP

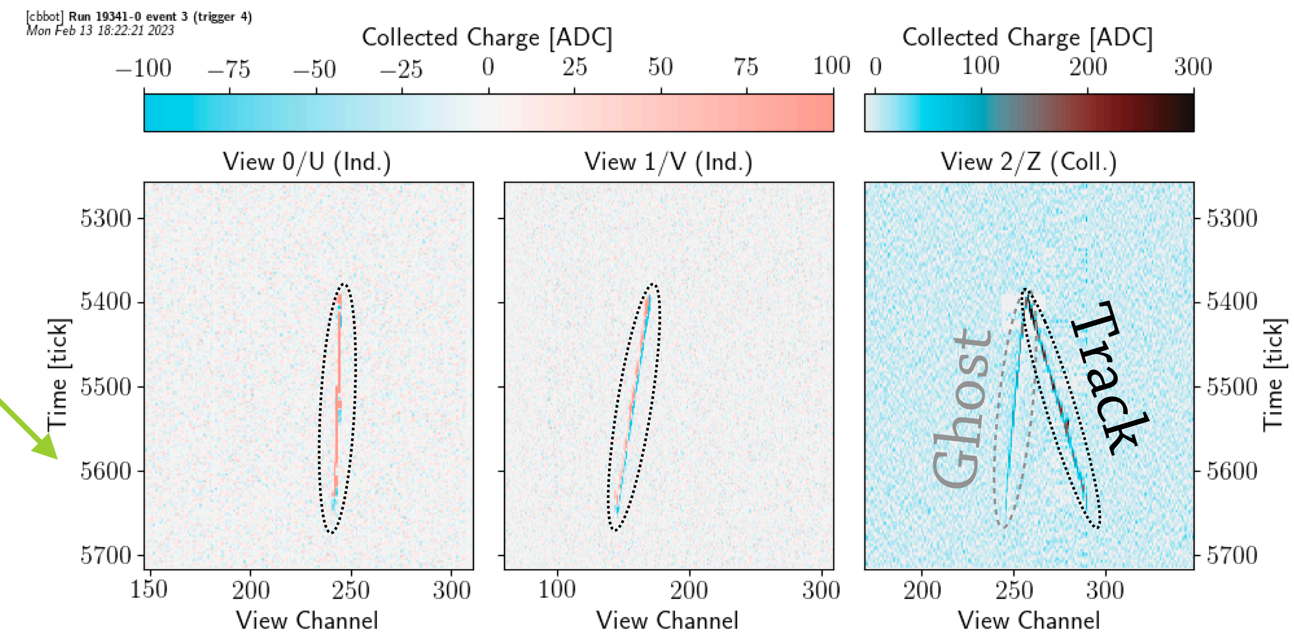
- small loss of charges at the PCB panels junction (vertical lines)
- 'low spots' of dQ/dx follows CRP waviness

-> A new, simpler, faster, PCB assembly procedure is currently being tested in the Coldbox has shown a drastic dependance on the transparency of the CRP to the hole geometry -> Discussions with the manufacturers to have stringent specifications on the drilled PCB design

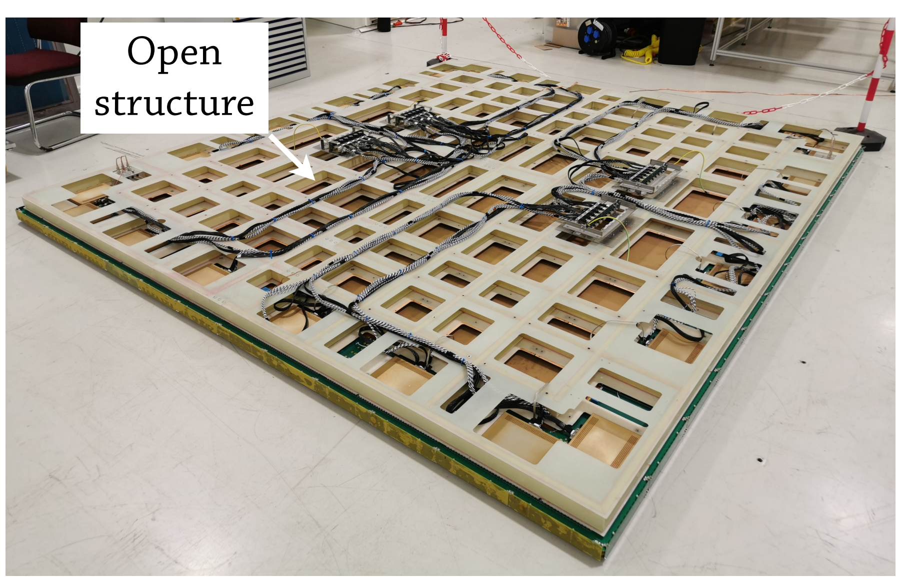
VD-Coldbox: ghost muons

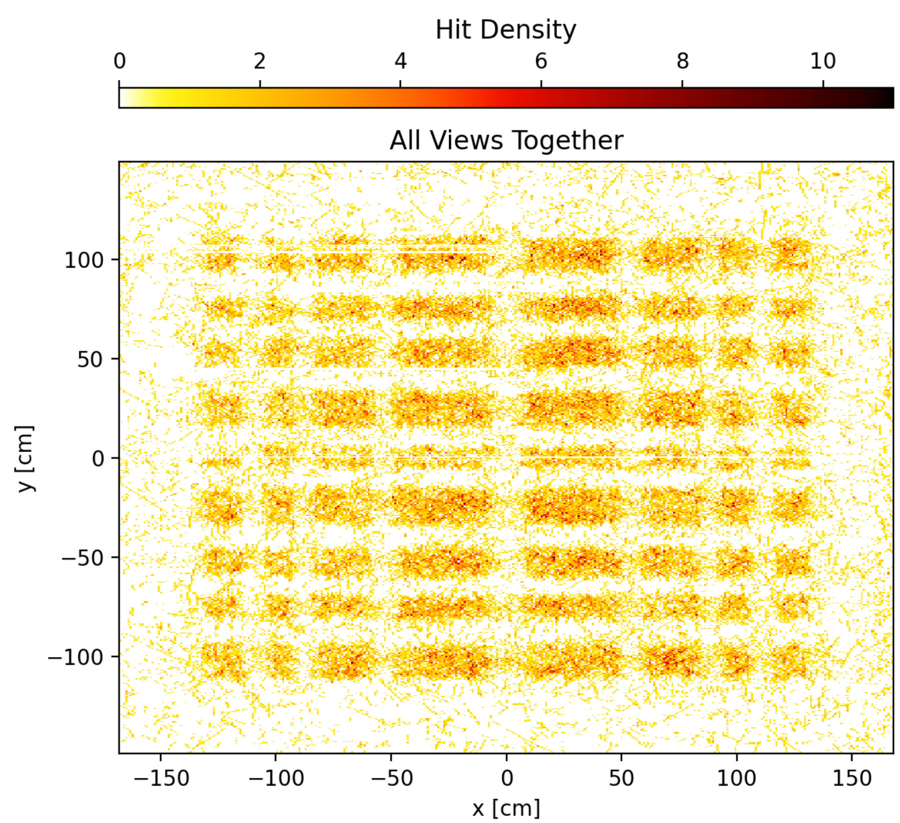
There is a dummy or 'ghost' field between the anodes and the closest ground (on the cryostat or on the composite frame)
-> This field creates a ghost track only seen in the collection view



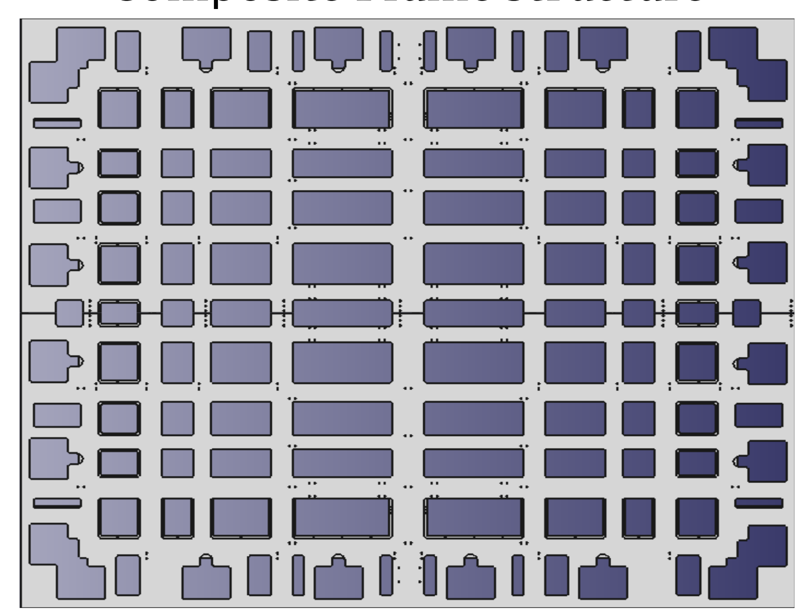


A 3D reconstruction of these tracks allow to muon-scan of the composite frame



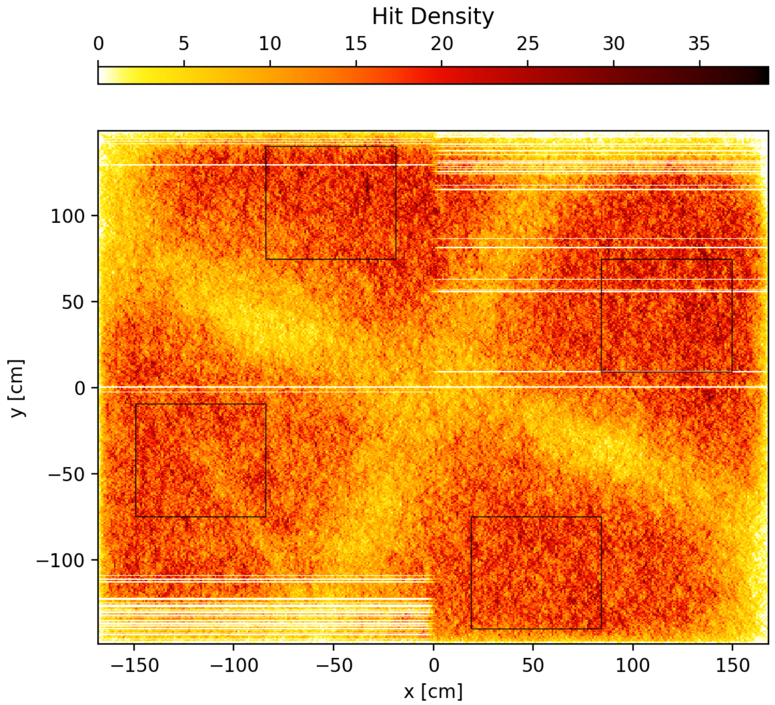


Engineering drawing of the Composite Frame structure

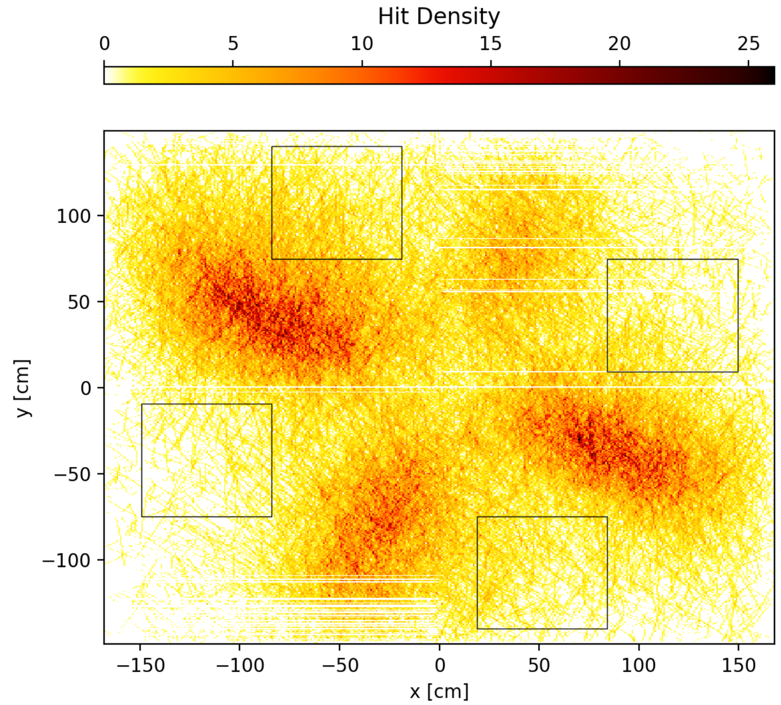


VD-Coldbox: charge and light

3D tracks seen by 1 ×-ARAPUCA



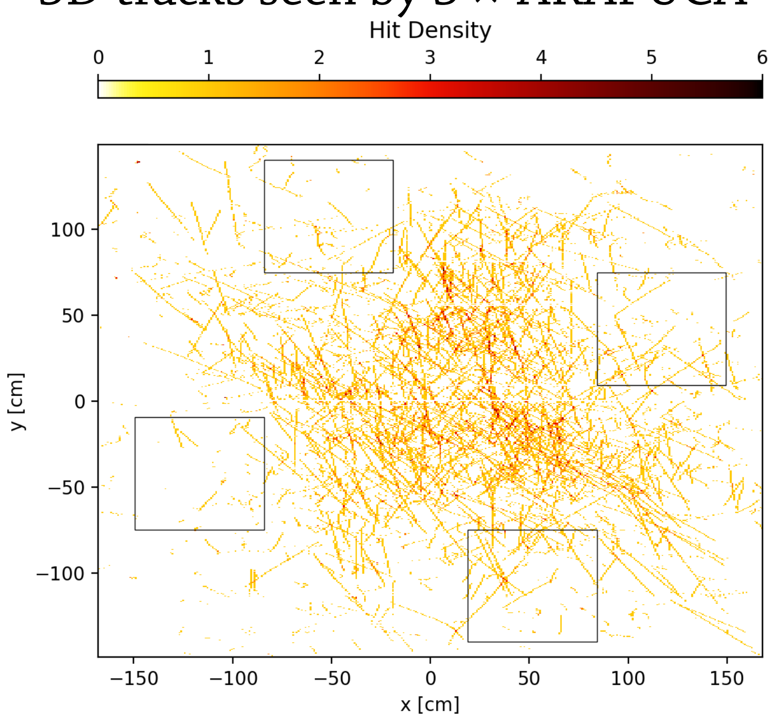
3D tracks seen by 2 ×-ARAPUCA



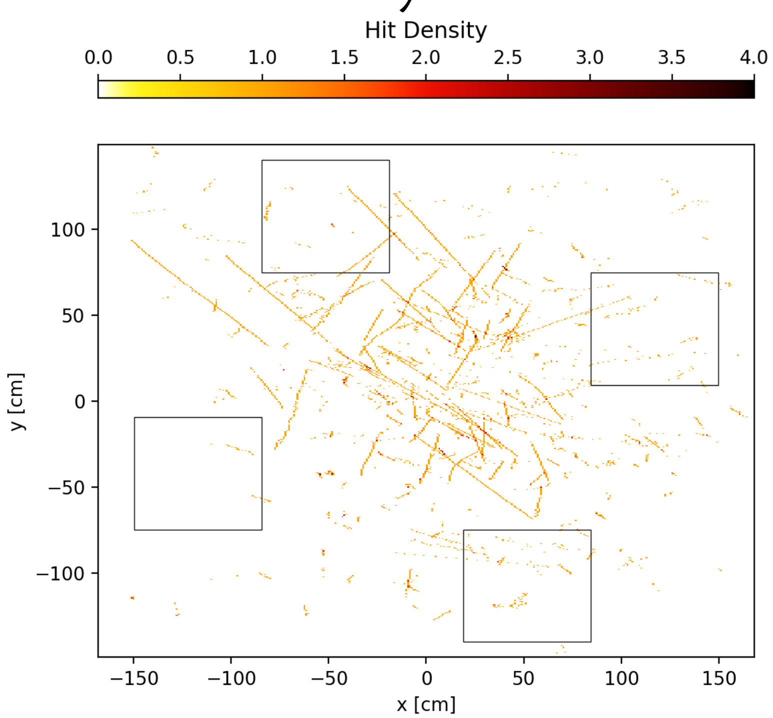
In the last CRP Coldbox test, the charge and the light readout was synchronized at the DAQ level

- 4 ×-ARAPUCAs installed
- tracks & light flashes could be matched offline

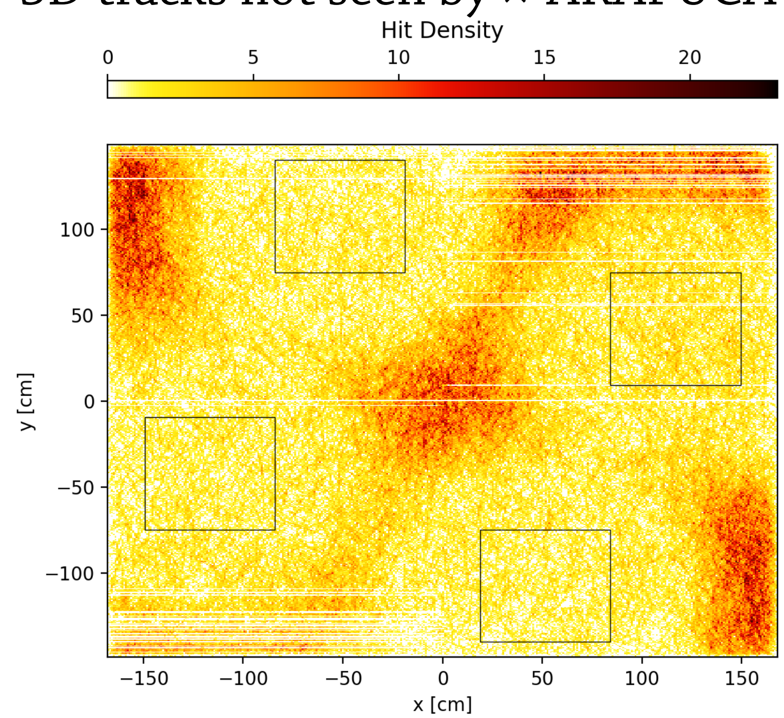
3D tracks seen by 3 ×-ARAPUCA



3D tracks seen by all ×-ARAPUCA



3D tracks not seen by ×-ARAPUCA



Perspectives

DUNE is expected to start its data taking with a neutrino beam and 2 modules in ~2032

-> One HD and one VD LArTPC module

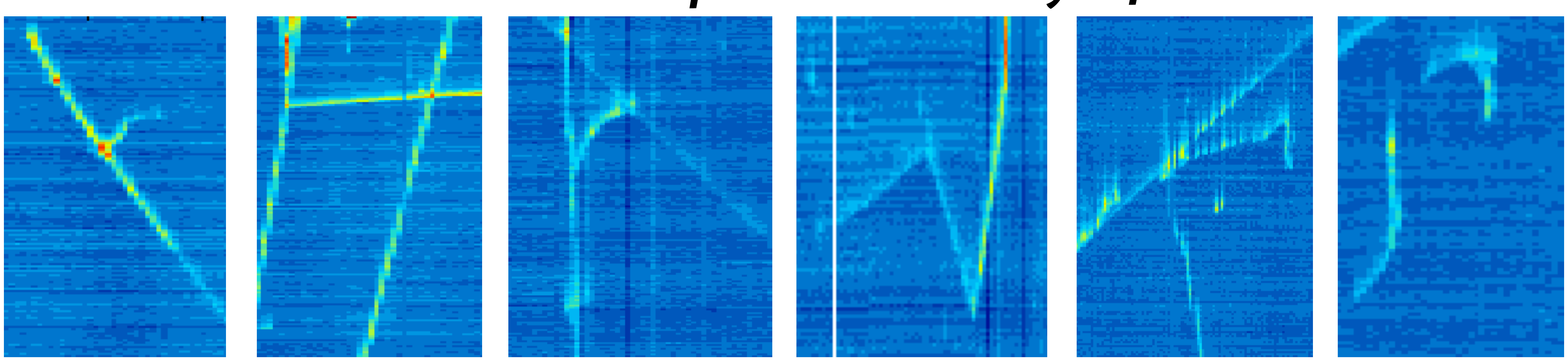
-> Both technologies are thoroughly being tested at CERN with the protoDUNEs:

- Engineering
- Performances
- Reconstruction algorithms
- Energy scale, Resolution
- LAr physics
- Hadron-Argon cross sections

-> Gave crucial inputs for the success of DUNE (construction, operation, physics)

-> A new round of data is about to start, stay tuned!

From the dual-phase data and myself :



SP/HD signal Formation