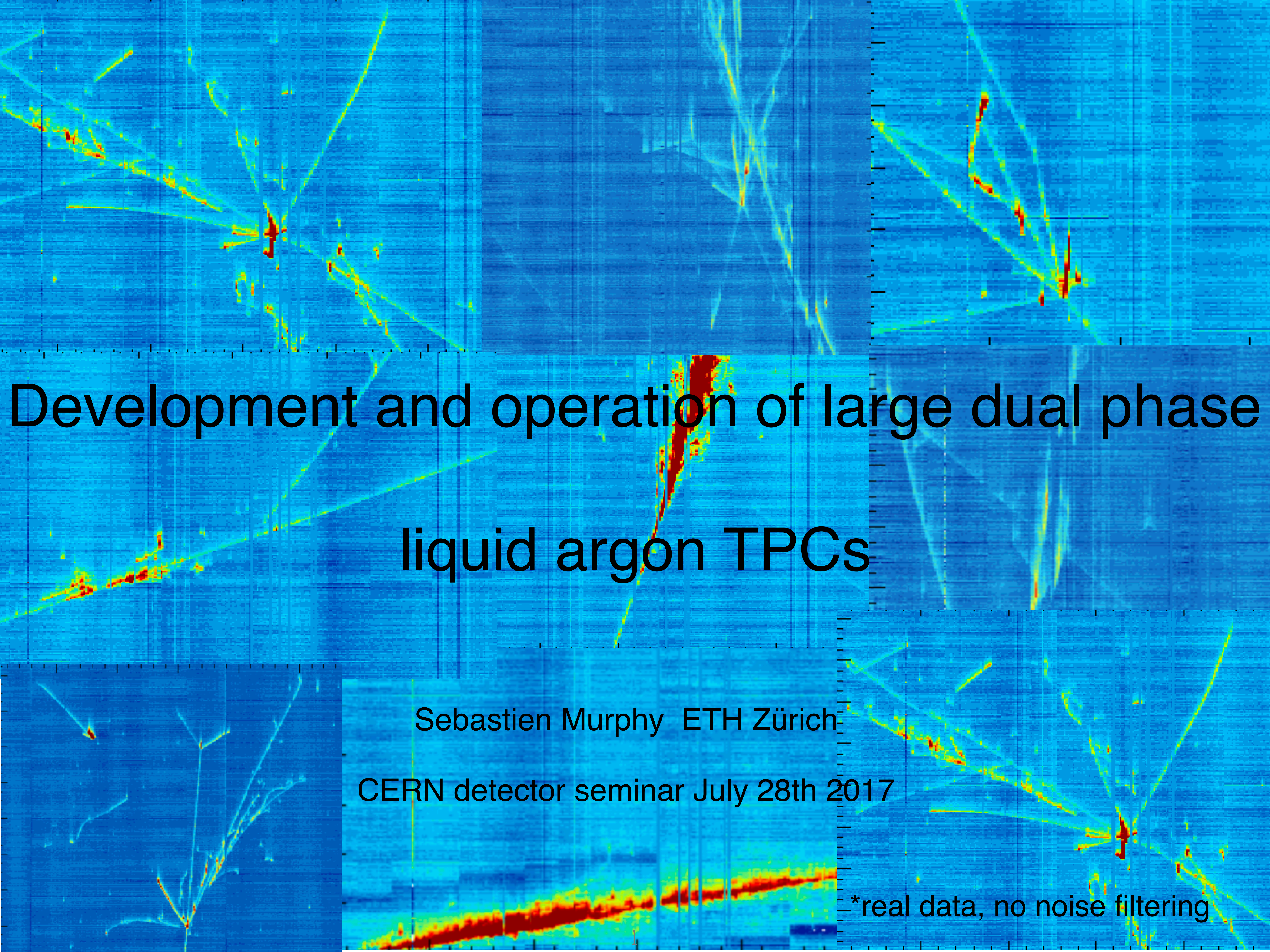


Development and operation of large dual phase liquid argon TPCs

Sebastien Murphy ETH Zürich

CERN detector seminar July 28th 2017

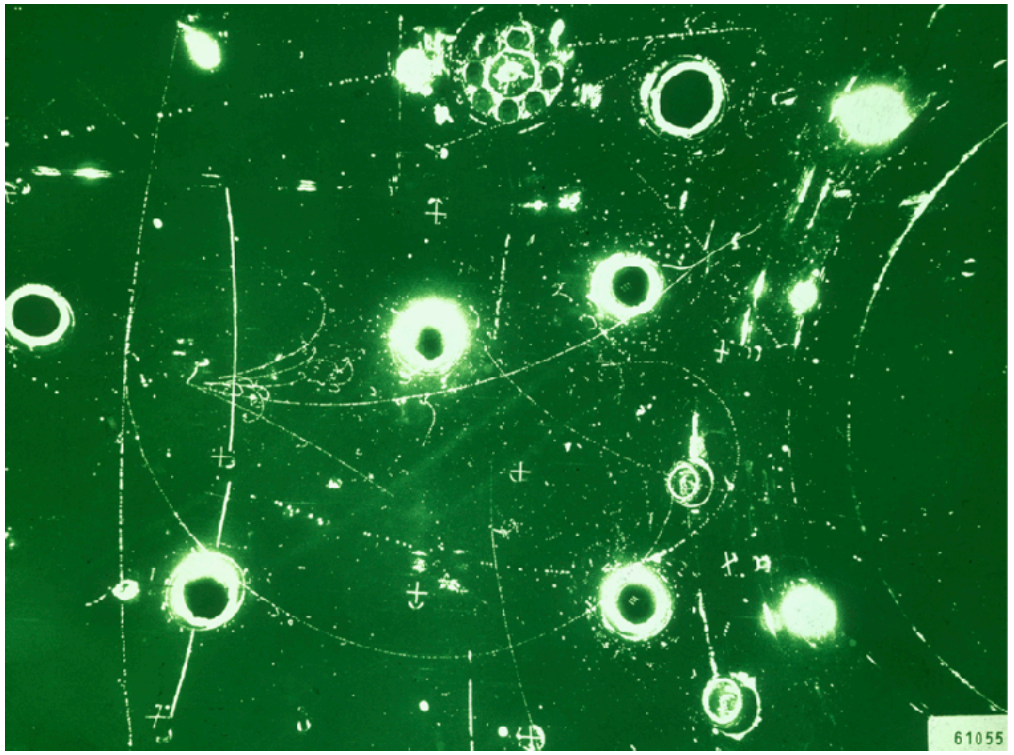
*real data, no noise filtering

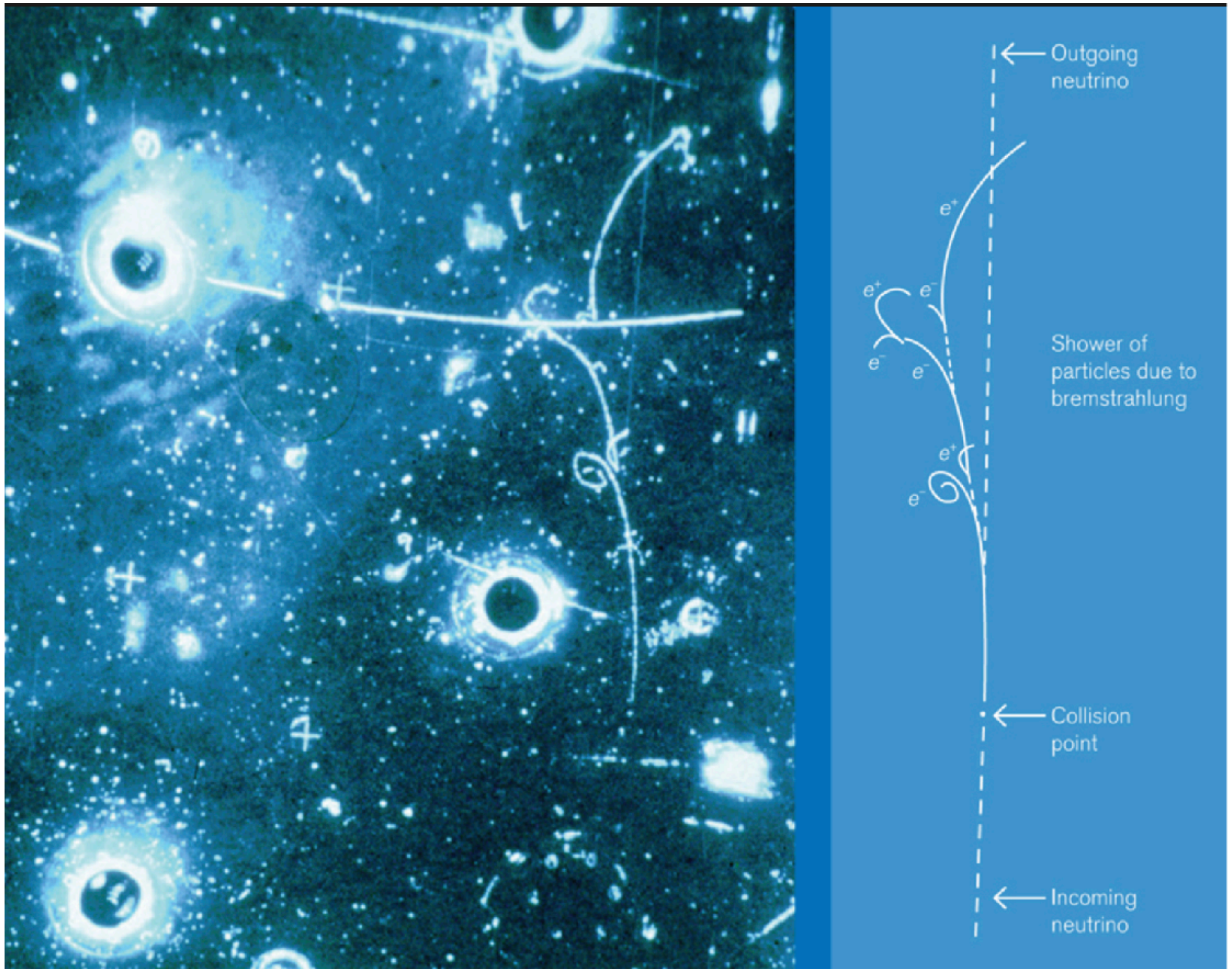
The electronic bubble chamber

Key for neutrino detection: large mass and full imaging of the interaction

Gargamelle bubble chamber at CERN 1970-1978.12 m^3 CF_3Br

1973: 1st experimental observation of weak neutral current

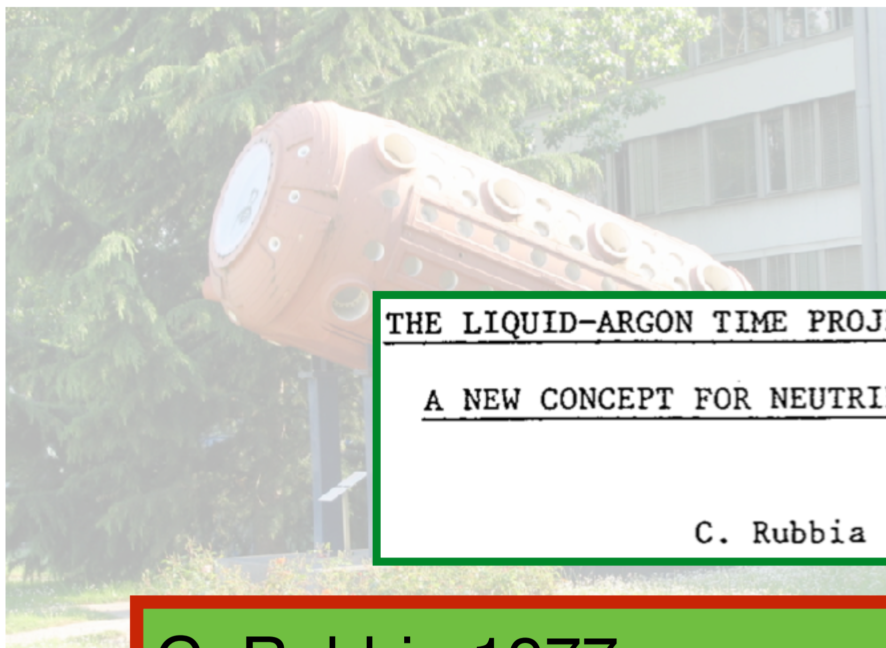


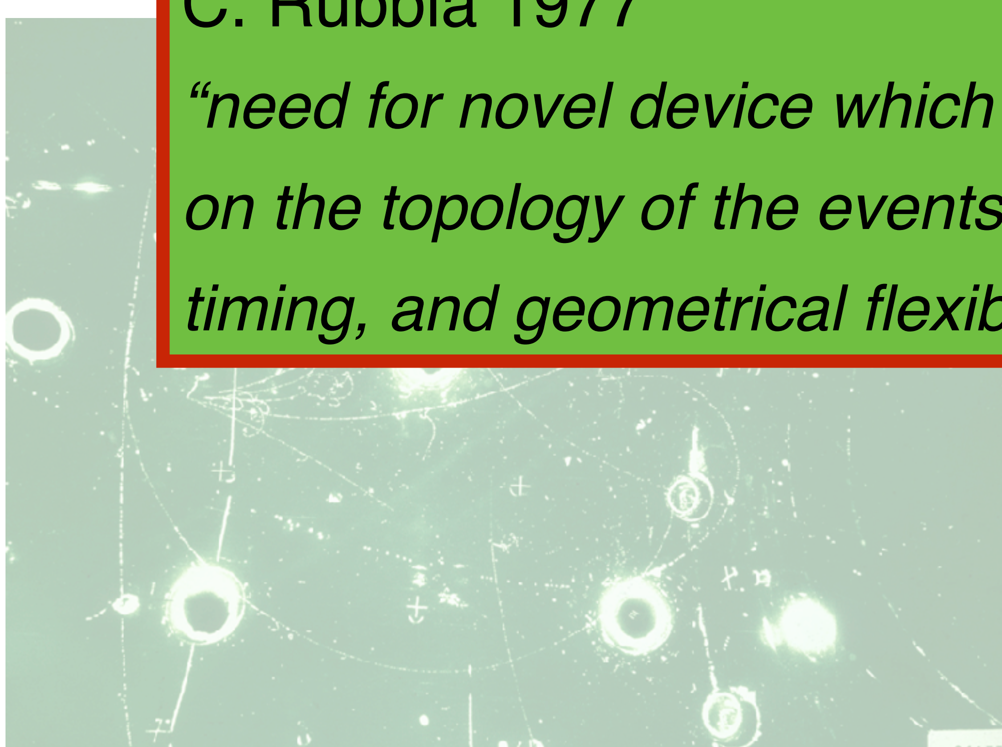


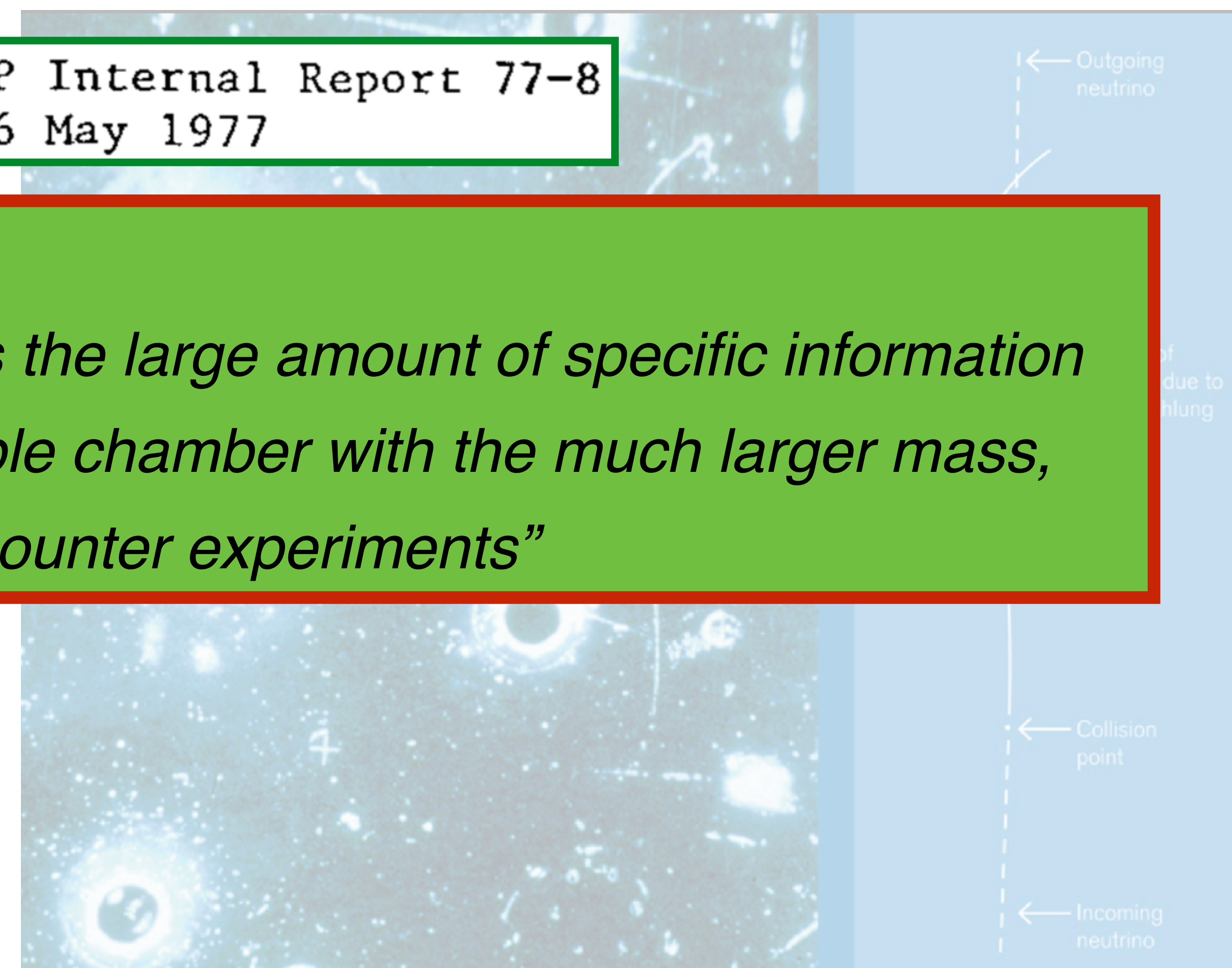
The electronic bubble chamber

Key for neutrino detection: large mass and full imaging of the interaction

Liquid Argon Time Projection Chamber







THE LIQUID-ARGON TIME PROJECTION CHAMBER:

A NEW CONCEPT FOR NEUTRINO DETECTORS

C. Rubbia

EP Internal Report 77-8
16 May 1977

C. Rubbia 1977

"need for novel device which combines the large amount of specific information on the topology of the events of a bubble chamber with the much larger mass, timing, and geometrical flexibility of a counter experiments"

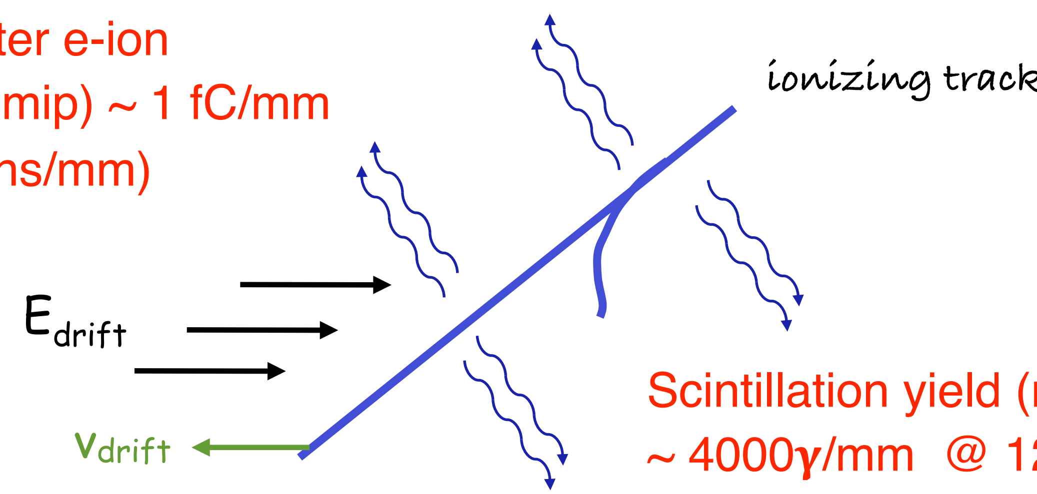
The electronic bubble chamber

Liquid Argon:

- High density, cheap medium
- Quasi free electrons from ionising tracks are drifted by E_{drift} ~500 V/cm
- Electron drift velocity ≈ 2mm/μs @ 1 kV/cm
- Electron cloud diffusion is small
  ($\sigma \approx \sqrt{2Dx/v_{drift}} \approx$ mm after several meters of drift)
- High scintillation yield (@ 128 nm) can be used for T_0, trigger, ...

Property	Liquid Argon
Density (g/cm3)	1.4
Radiation length (cm)	14
Interaction length (cm)	83.6
dE/dx mip (MeV/cm)	2.1
We (eV) @ E=∞	23.6
Wγ (eV) @ E=0	20
Refractive index (visible)	1.24
Cerenkov angle	36°
Cerenkov $d^2N/dEdx$ (β=1)	≈ 130 eV^{-1} cm^{-1}
Muon Cerenkov threshold	140 MeV/c
Boiling point @ 1 bar	87 K

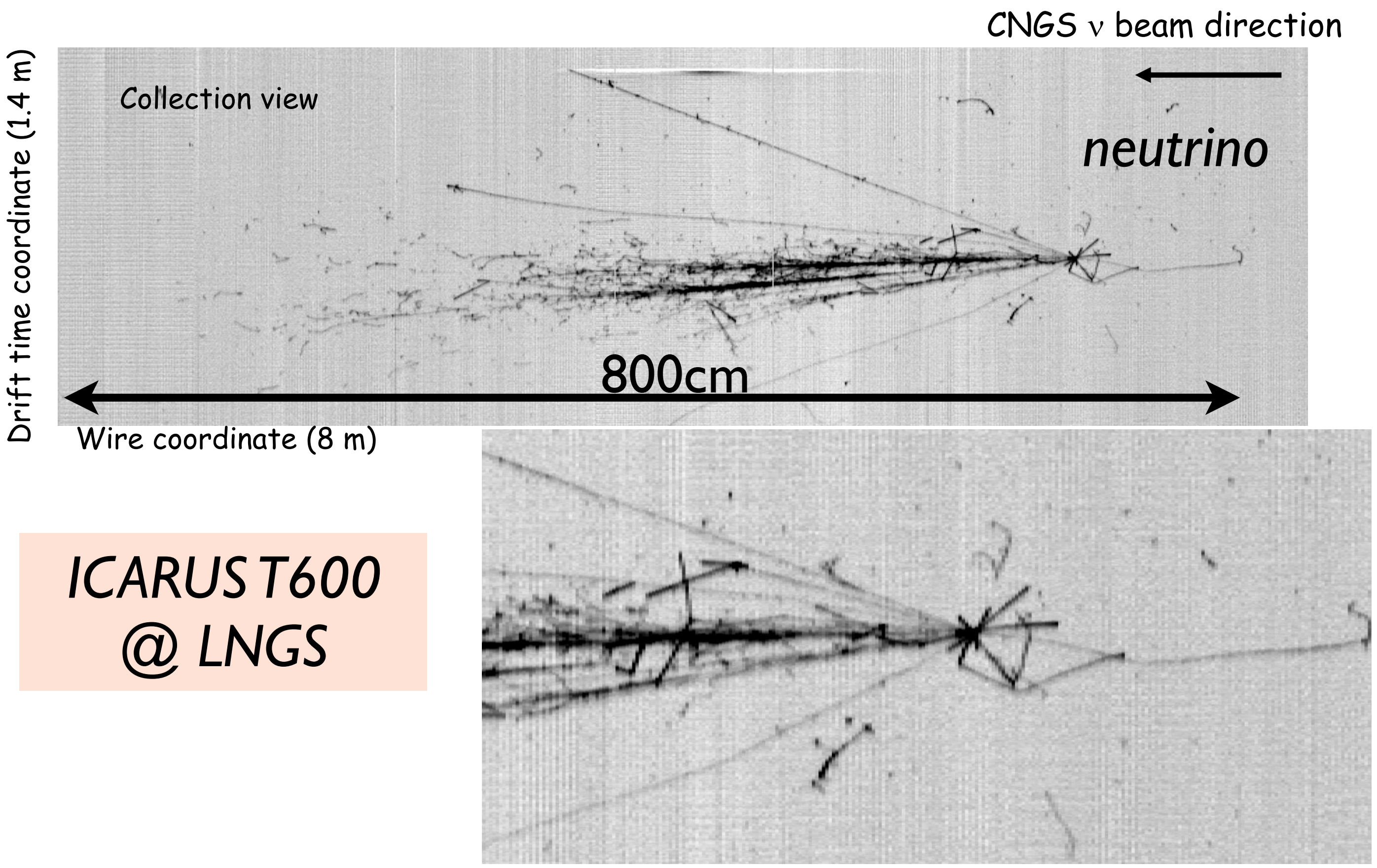
Charge yield after e-ion recombination (mip) ~ 1 fC/mm (~ 6000 electrons/mm)

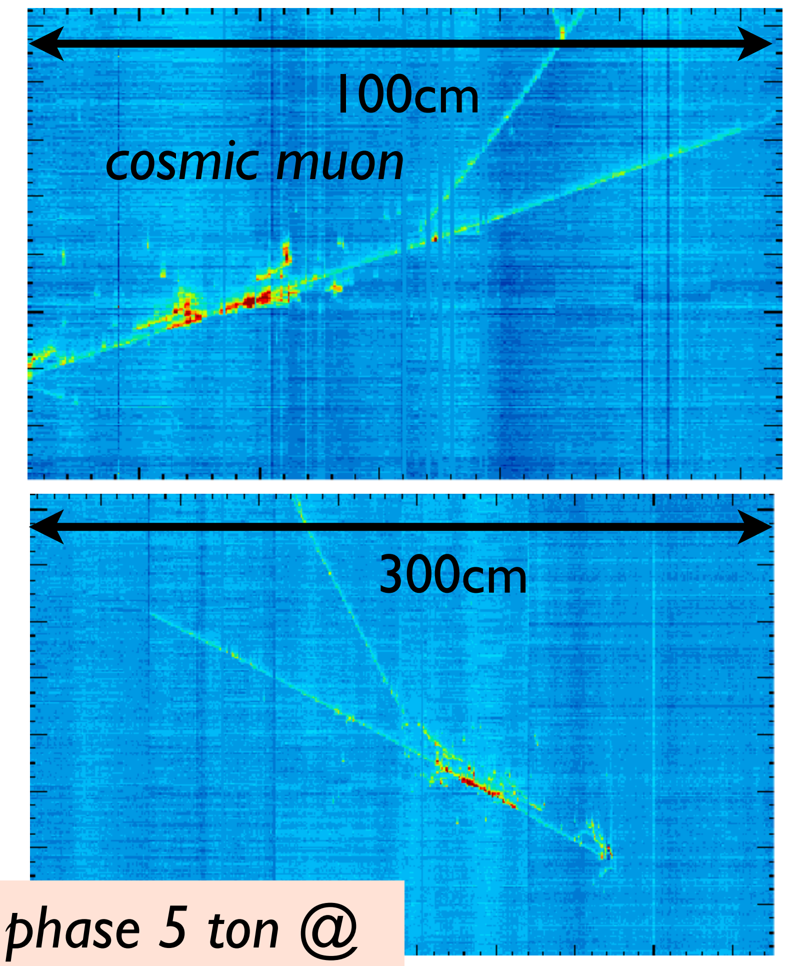


Scintillation yield (mip) ~ 4000γ/mm @ 128nm

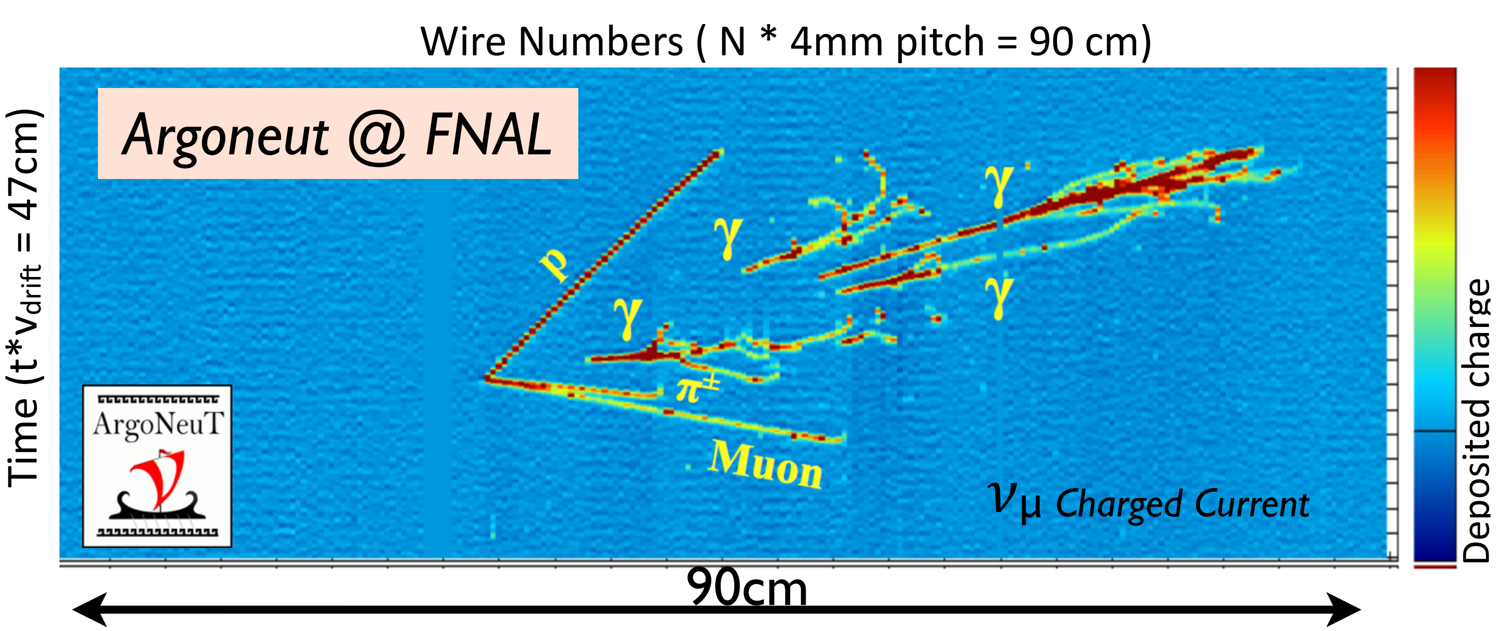
(Electron-ion recombination ≈ 30% for m.i.p. @ 1 kV/cm)

The electronic bubble chamber

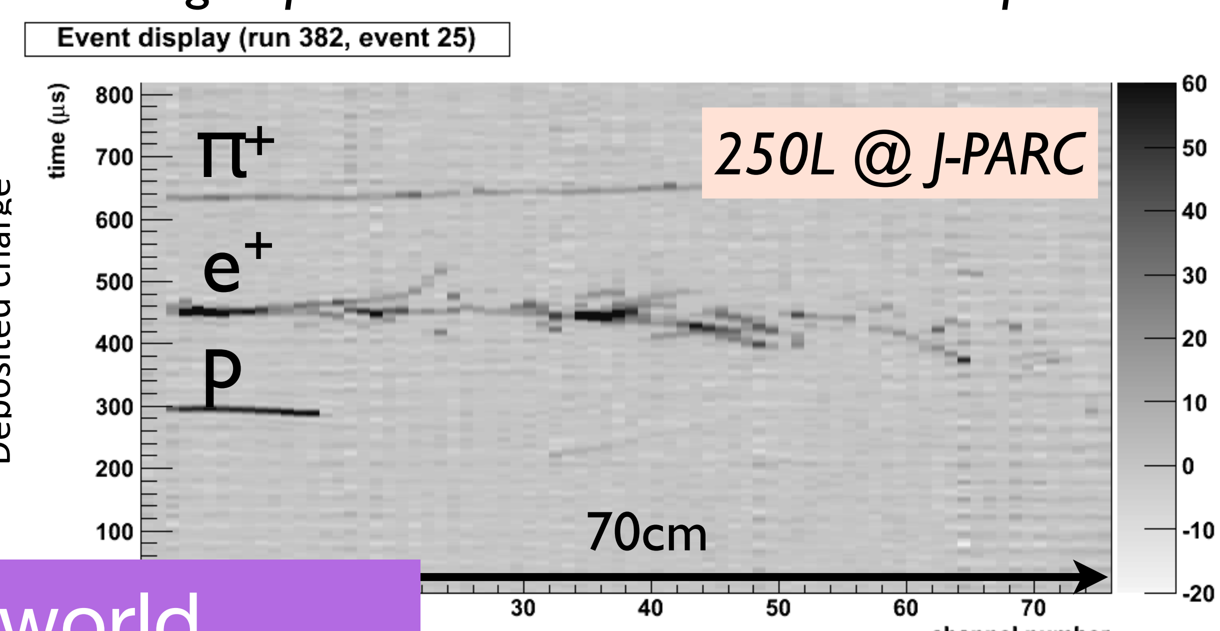




Dual phase 5 ton @ CERN (WA105)



Charged particle beam ≈800 MeV/c exposure



Features reproducible around the world

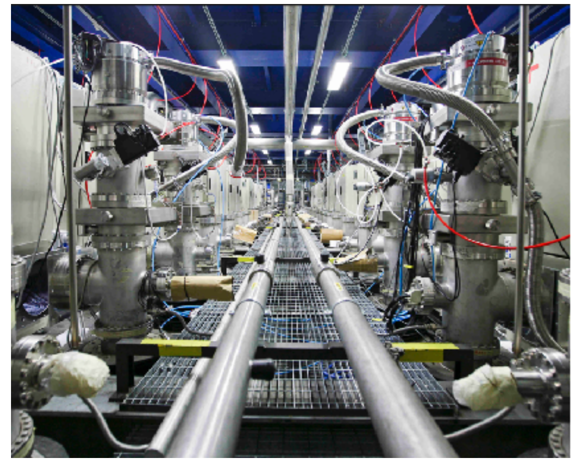
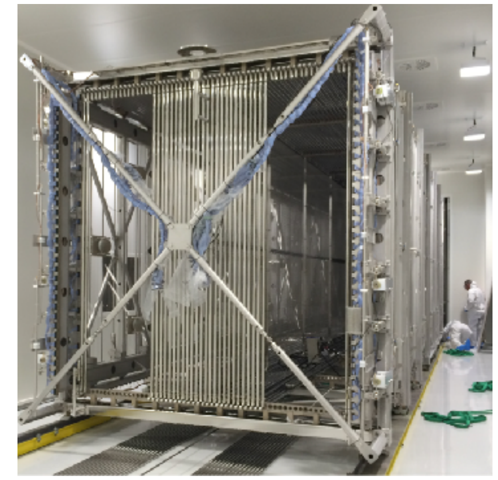
Liquid Argon TPCs for neutrino physics

- The Liquid Argon Time Projection Chamber is the successful marriage between the "gaseous TPC" and "the liquid argon calorimeter" to obtain a dense and very fine grained 3D tracking device (mm-scale resolution) with local dE/dx information and a homogenous full sampling calorimeter (e.g. ≈2%X_0 sampling rate for 3mm pitch). It can be operated in trigger-less mode, hence is continuously active.

- After many decades of pioneering R&D, the technology has matured into a fundamental and necessary technique to address the particle physics challenges of the 21st century. It has the potential to be the tool to discover new phenomena, such as:
  - the convincing case for the existence of sterile neutrinos;
  - the discovery of CP-violation in the lepton sector;
  - the measurement of the neutrino mass states ordering
  - the unambiguous observation of nucleon decay;
  - the possible observation of unpredicted rare events.

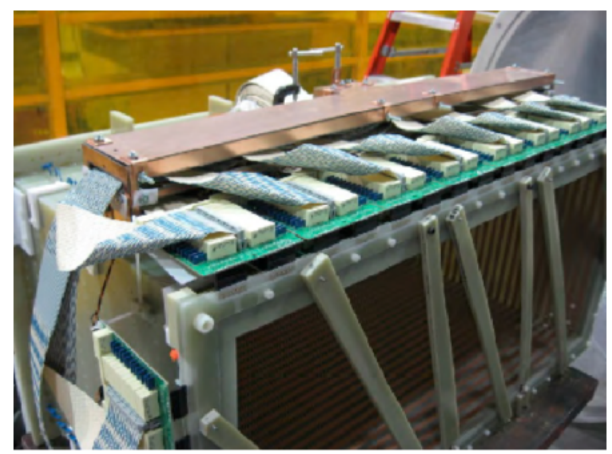
Liquid Argon TPCs exposed to neutrinos

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

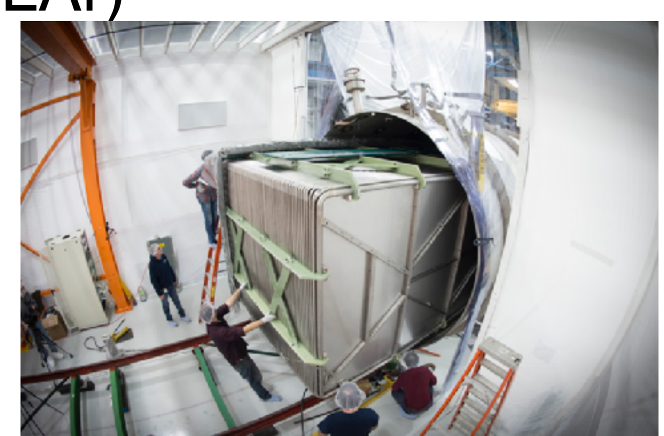
Argoneut @ FNAL (2009-2010, 240 kg LAr)





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





Liquid Argon TPCs exposed to neutrinos

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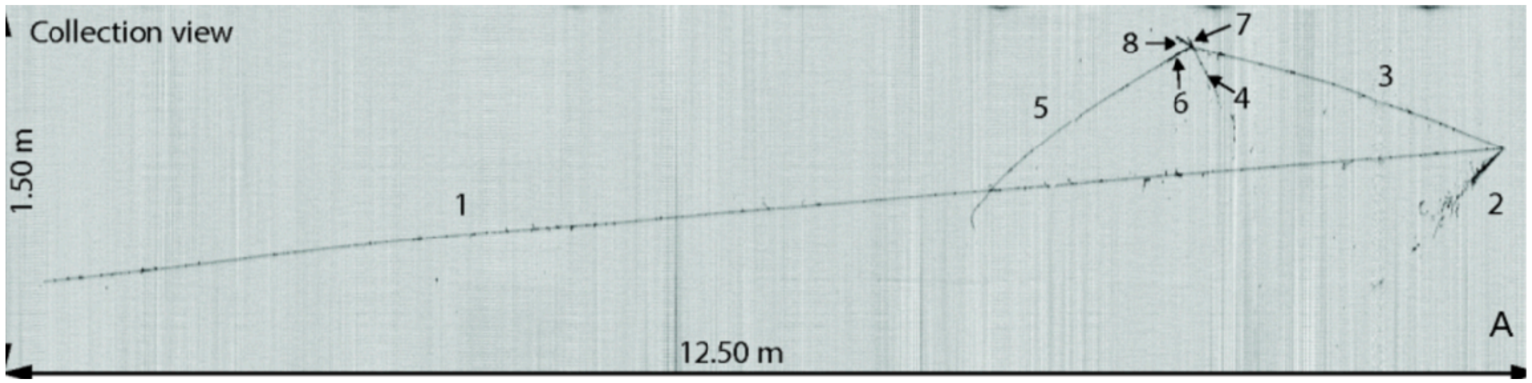

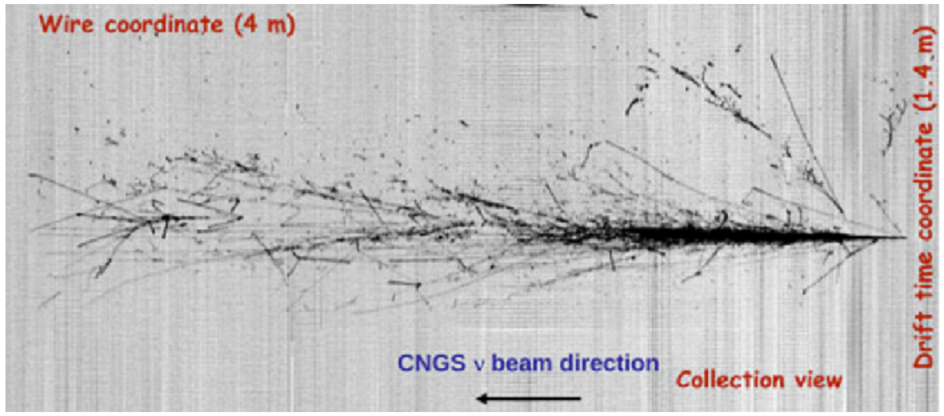

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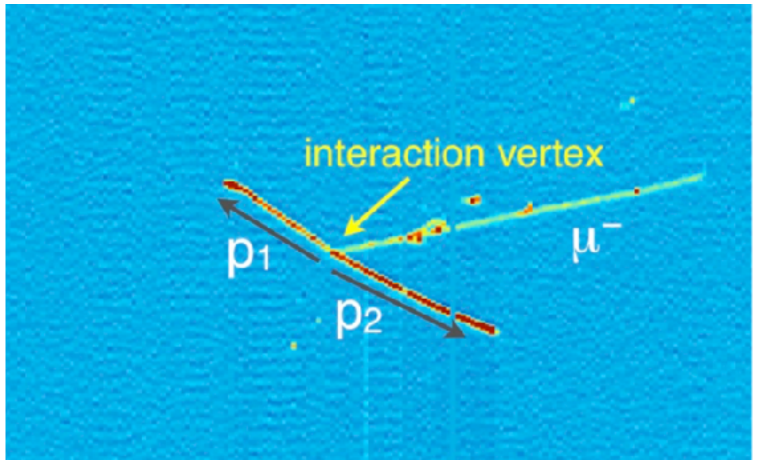

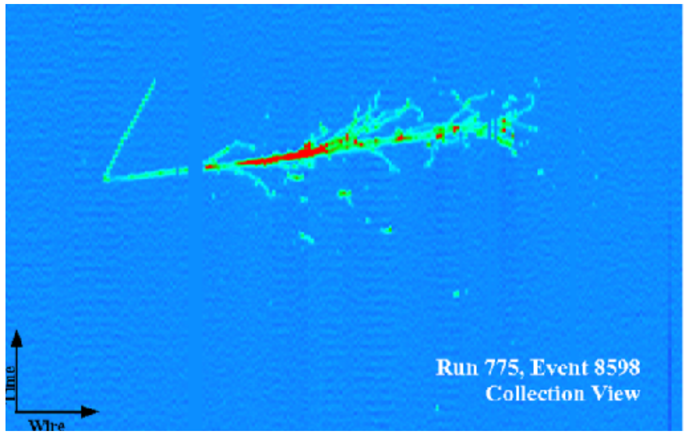

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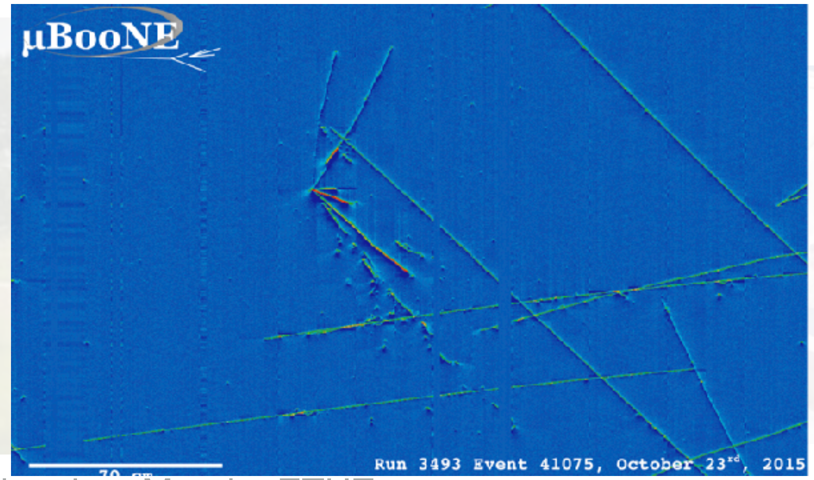
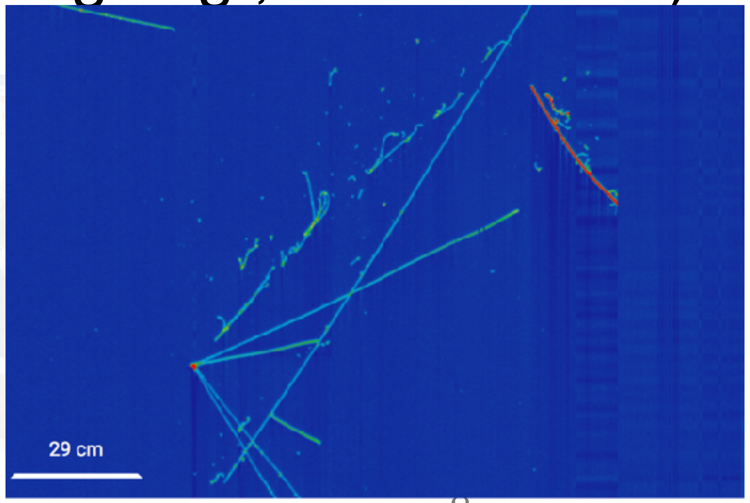
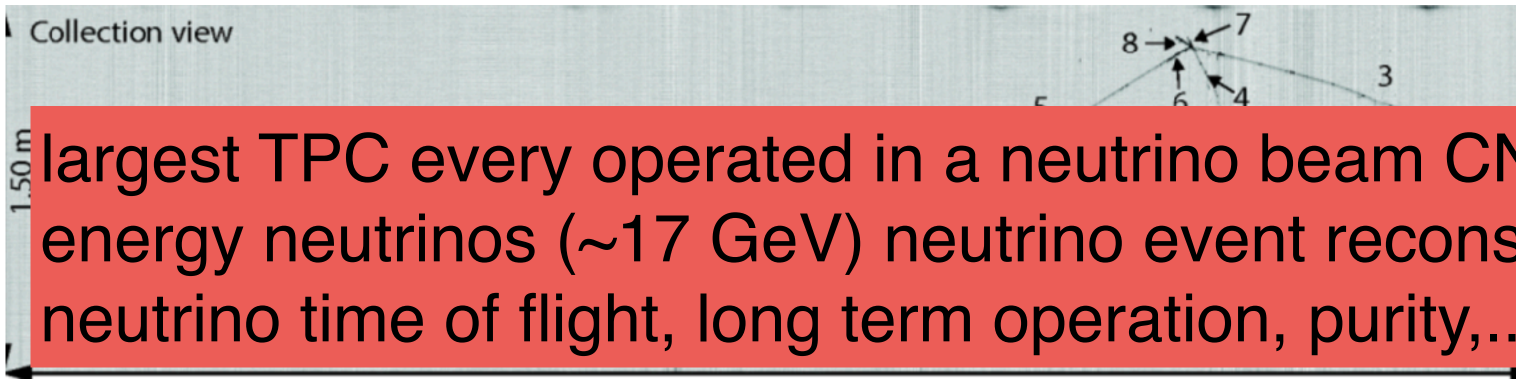


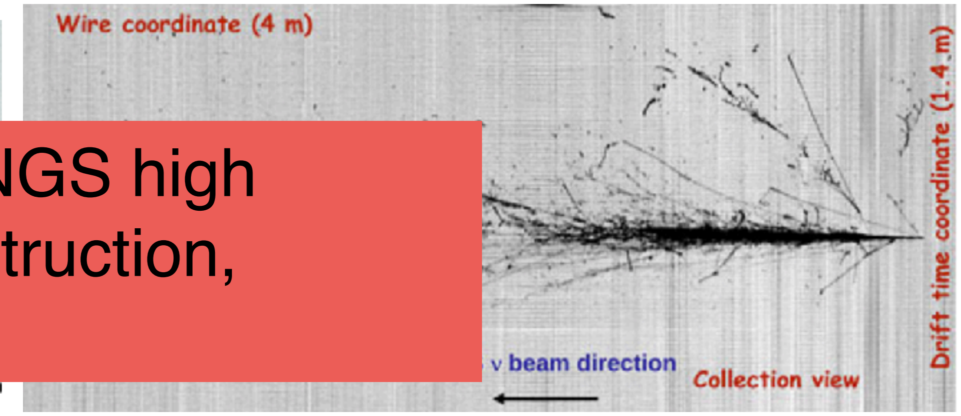


LAr- TPCs exposed to neutrinos - past & present

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

AHEP Volume 2013(2013), Article ID 260820,
Phys.Lett. B713 (2012) 17-22
…

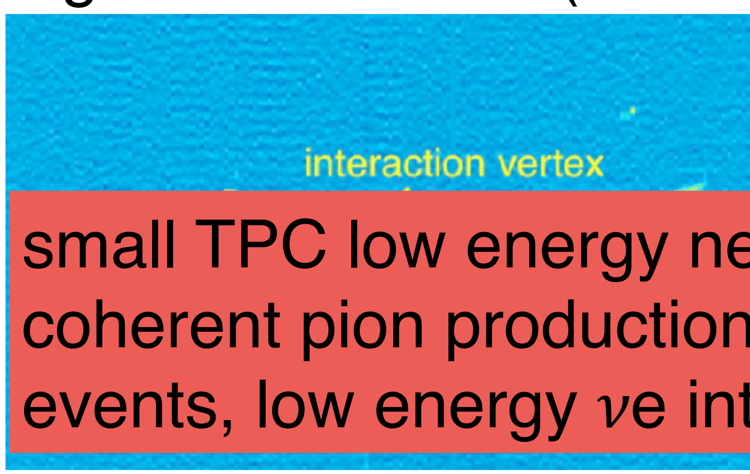


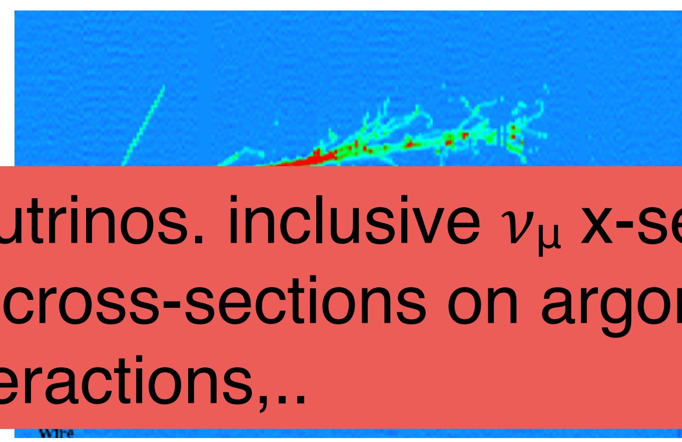


largest TPC every operated in a neutrino beam CNGS high energy neutrinos (~17 GeV) neutrino event reconstruction, neutrino time of flight, long term operation, purity,..

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

Phys. Rev. Lett., 108:161802, (2012)
Phys. Rev. D95, 072005(2017)
Phys.Rev.D90(2014)012008.
…

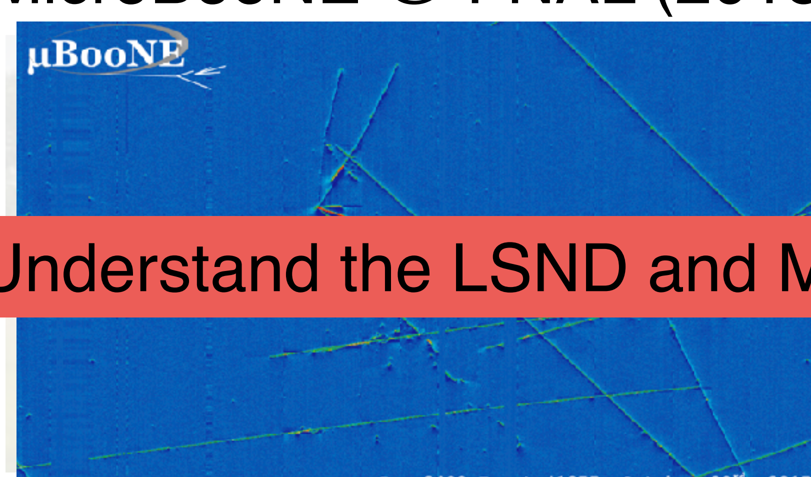


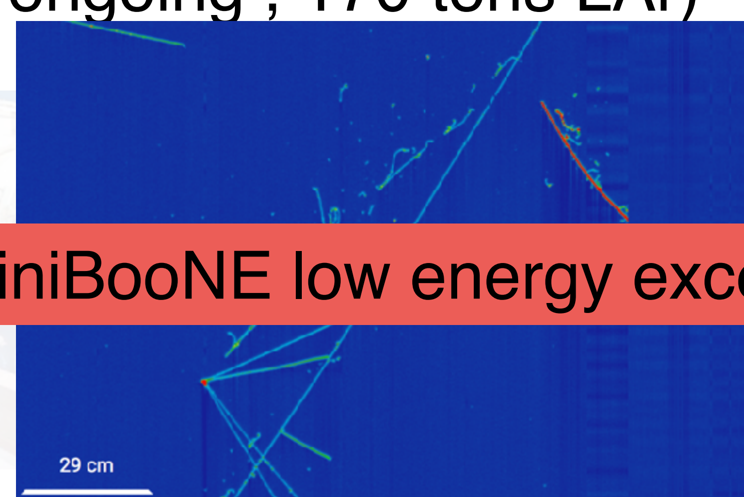


small TPC low energy neutrinos. inclusive ν_μ x-section, ν_μ and ν_μ coherent pion production cross-sections on argon, study of two-proton events, low energy νe interactions,..

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

arXiv:1705.07341,
arXiv:1704.02927,
JINST 12, P03011 (2017)
…





Understand the LSND and MiniBooNE low energy excess of ve, ve.

LAr- TPCs exposed to neutrinos - past & present

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AHEP Volume 2013(2013), Article ID 260820,
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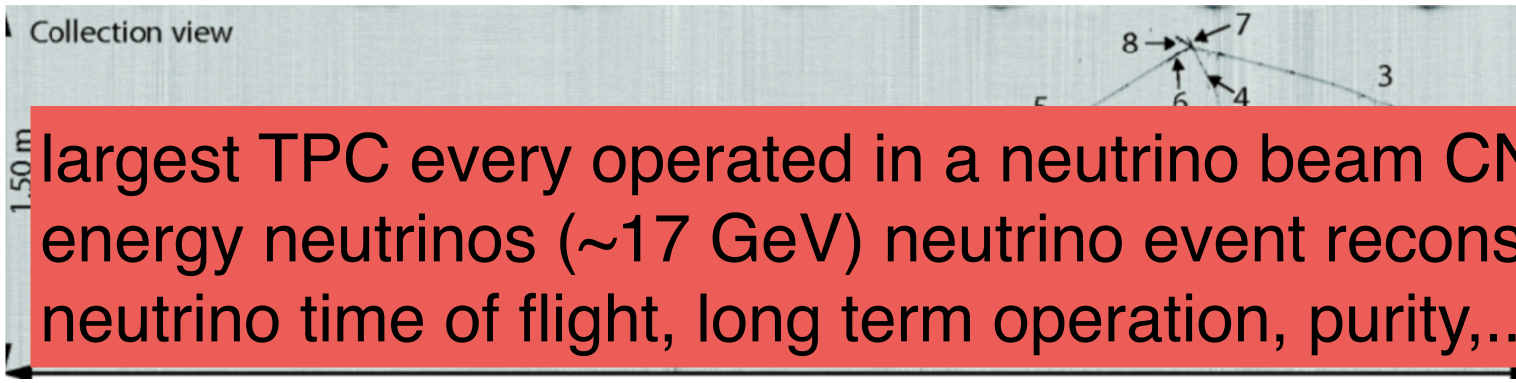

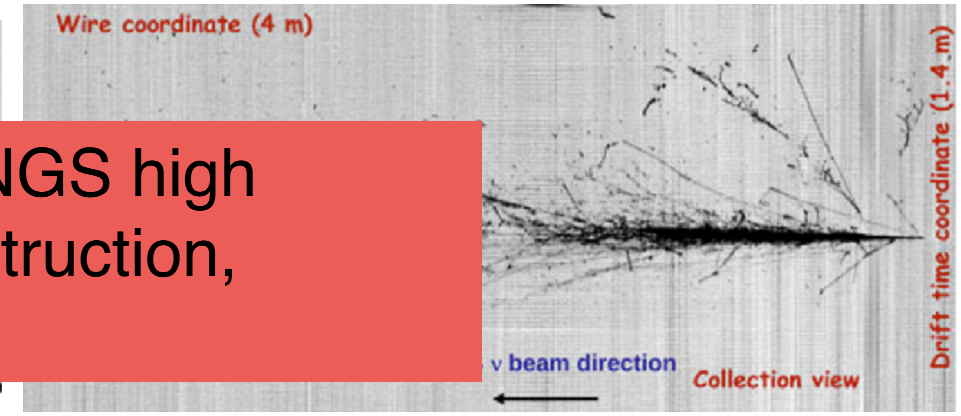

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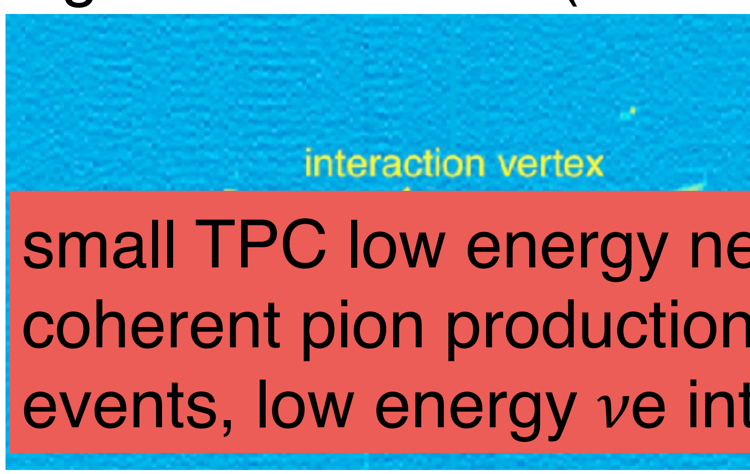
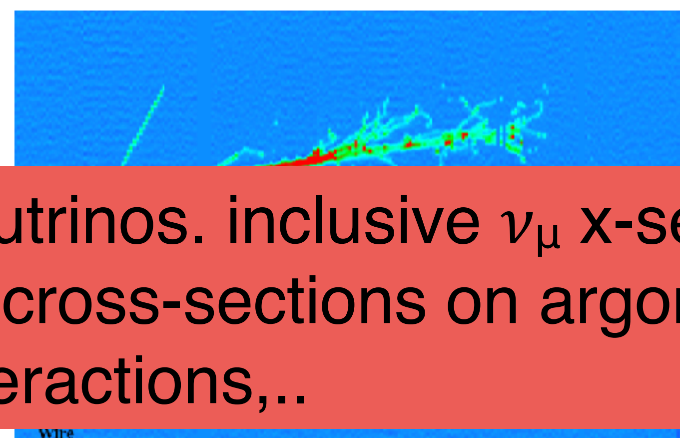


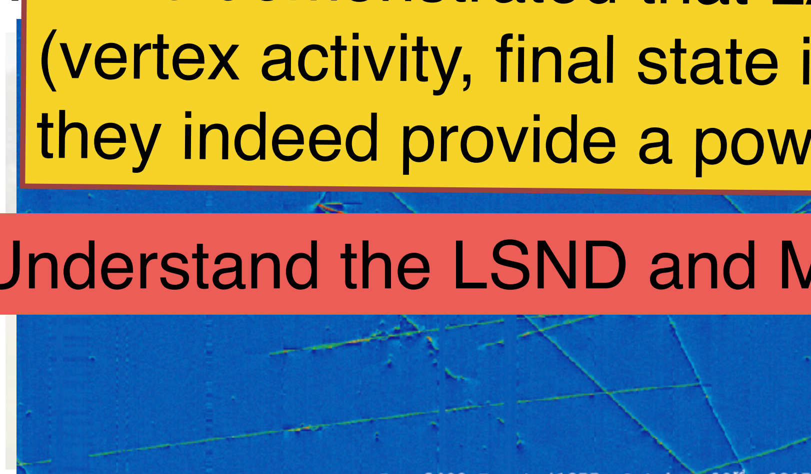


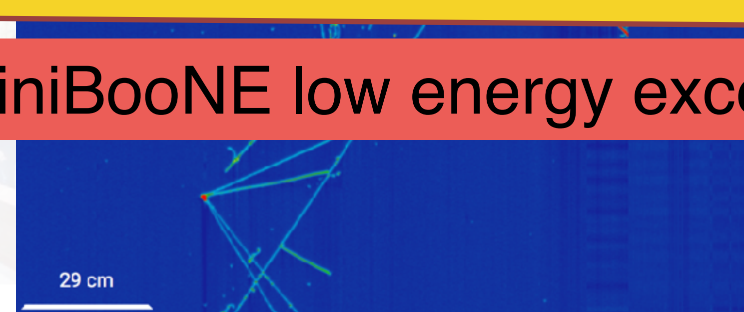
small TPC low energy neutrinos. inclusive ν_μ x-section, ν_μ and $\nu_{\bar{\mu}}$ coherent pion production cross-sections on argon, study of two-proton events, low energy νe interactions,..

M

Have demonstrated that LAr TPCs offer unprecedented imaging of neutrino interactions (vertex activity, final state interactions, good sig/background discrimination,..) and that they indeed provide a powerful tool for future neutrino experiment.

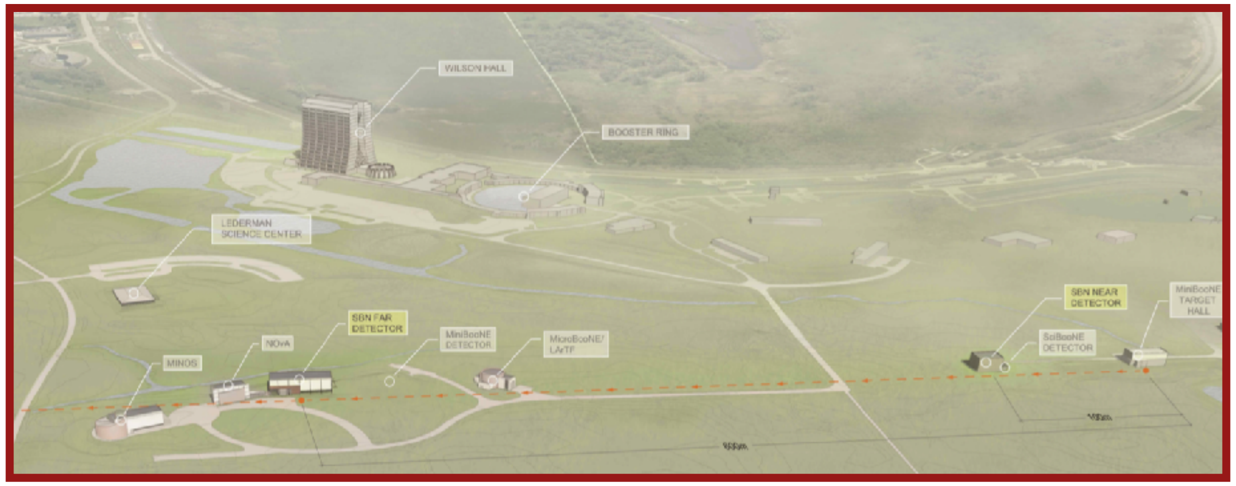
Understand the LSND and MiniBooNE low energy excess of ν_e, $\bar{\nu}_e$.

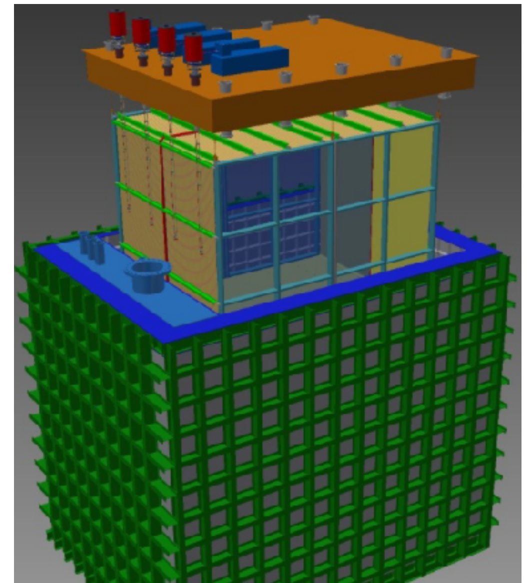




Liquid Argon TPCs for neutrino physics - planned

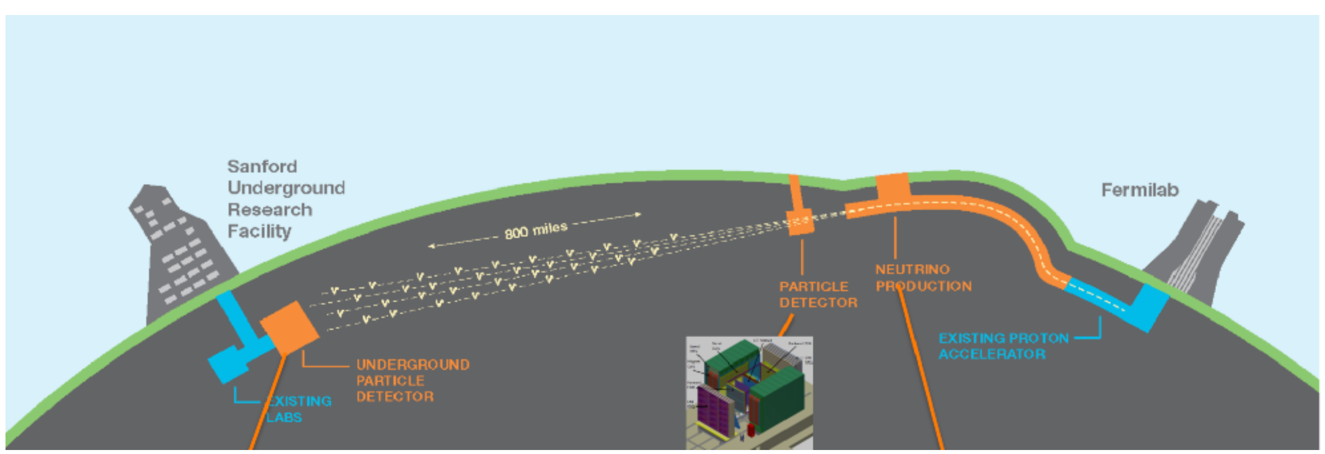
Planned @FNAL short baseline 2020+ SBND 112 ton + ICARUS 760 tons

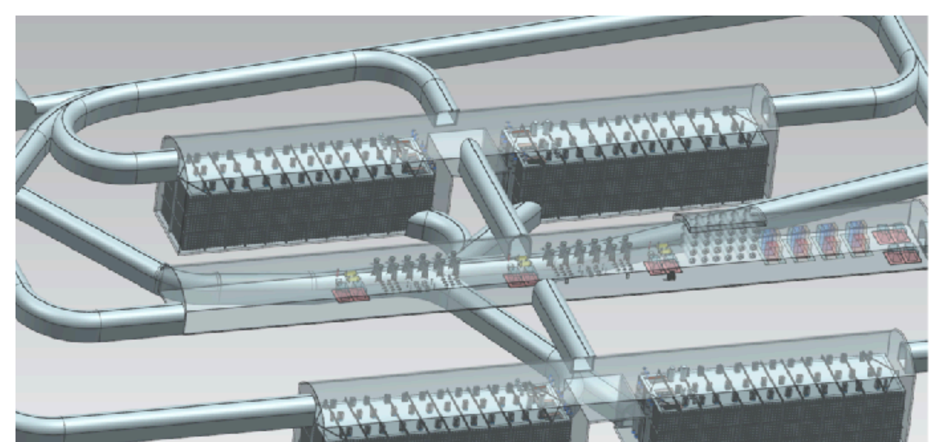




convincing cases for the existence (or not) of sterile neutrinos

Planned DUNE: FNAL to SURF 2025+. 4x10 ktons underground





The ordering of the neutrino masses, CP-violation in the lepton sector bound nucleon decay, atmospheric and supernovae neutrinos,
the possible observation of unpredicted rare events.

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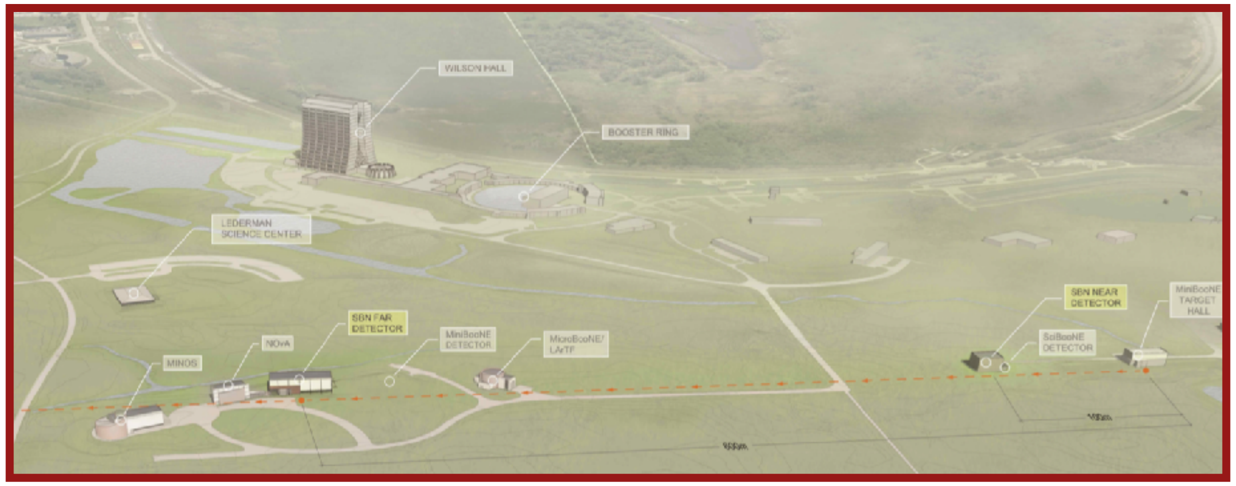

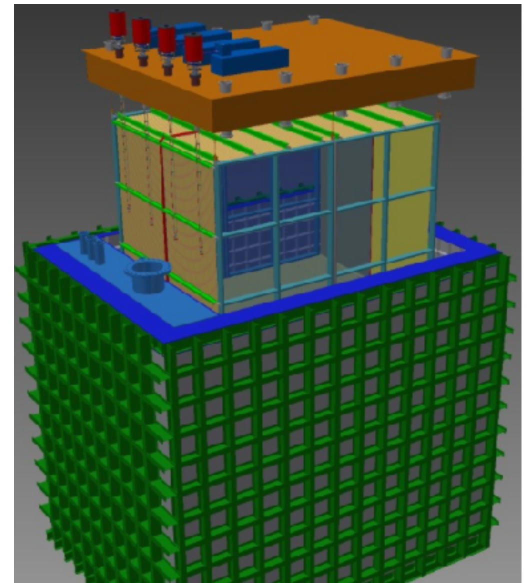

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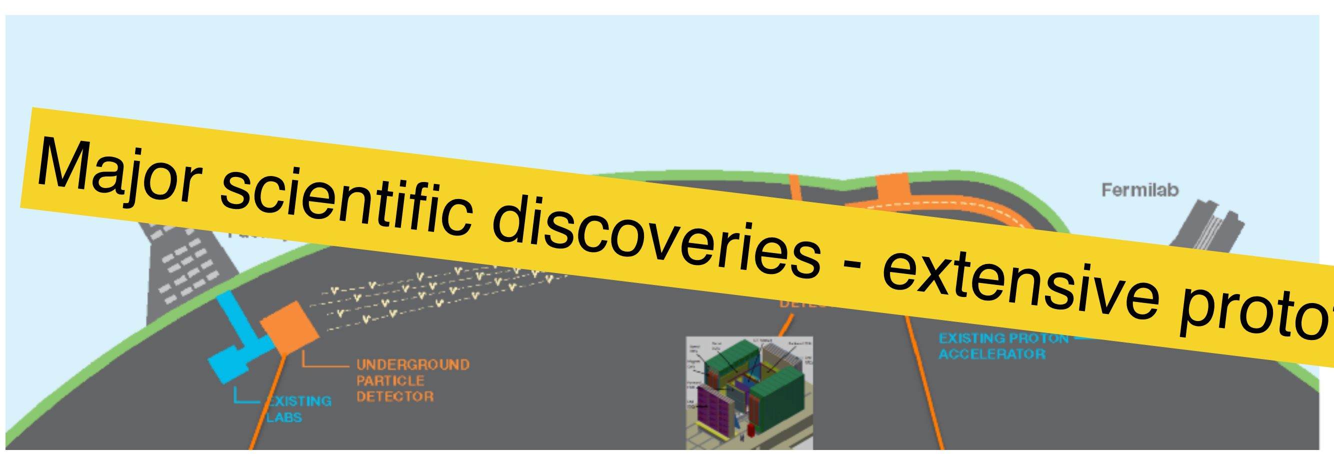
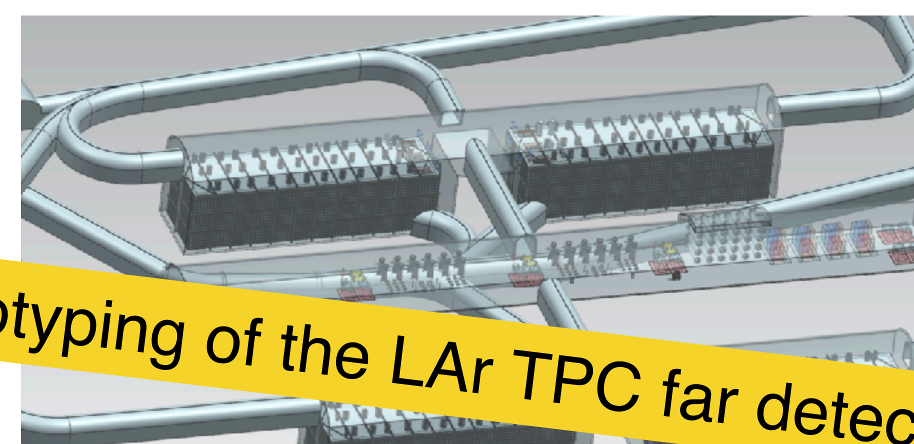




Major scientific discoveries - extensive prototyping of the LAr TPC far detectors required

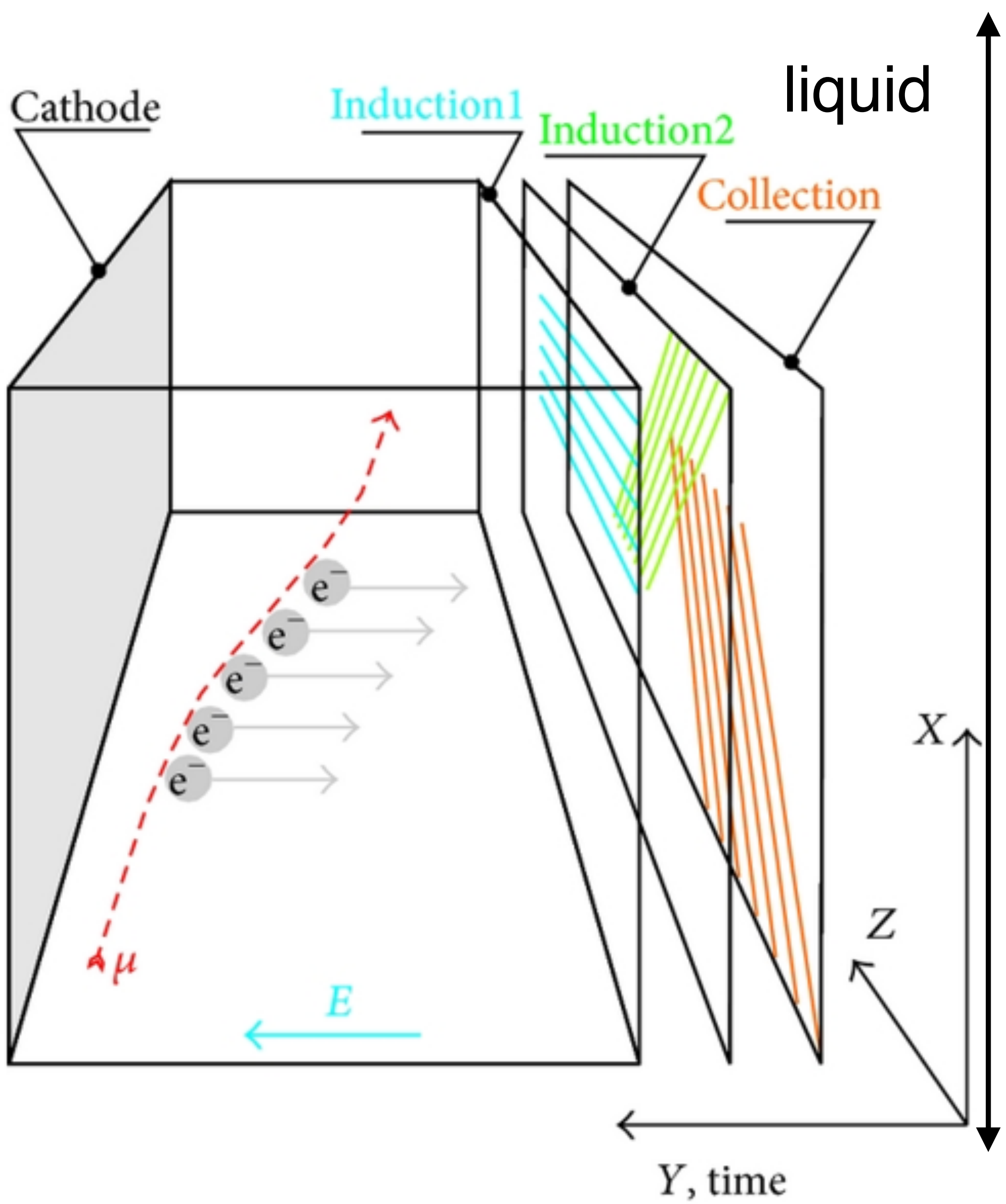
The ordering of the neutrino masses, CP-violation in the lepton sector bound nucleon decay, atmospheric and supernovae neutrinos,
the possible observation of unpredicted rare events.

Liquid argon TPC-single and dual phase

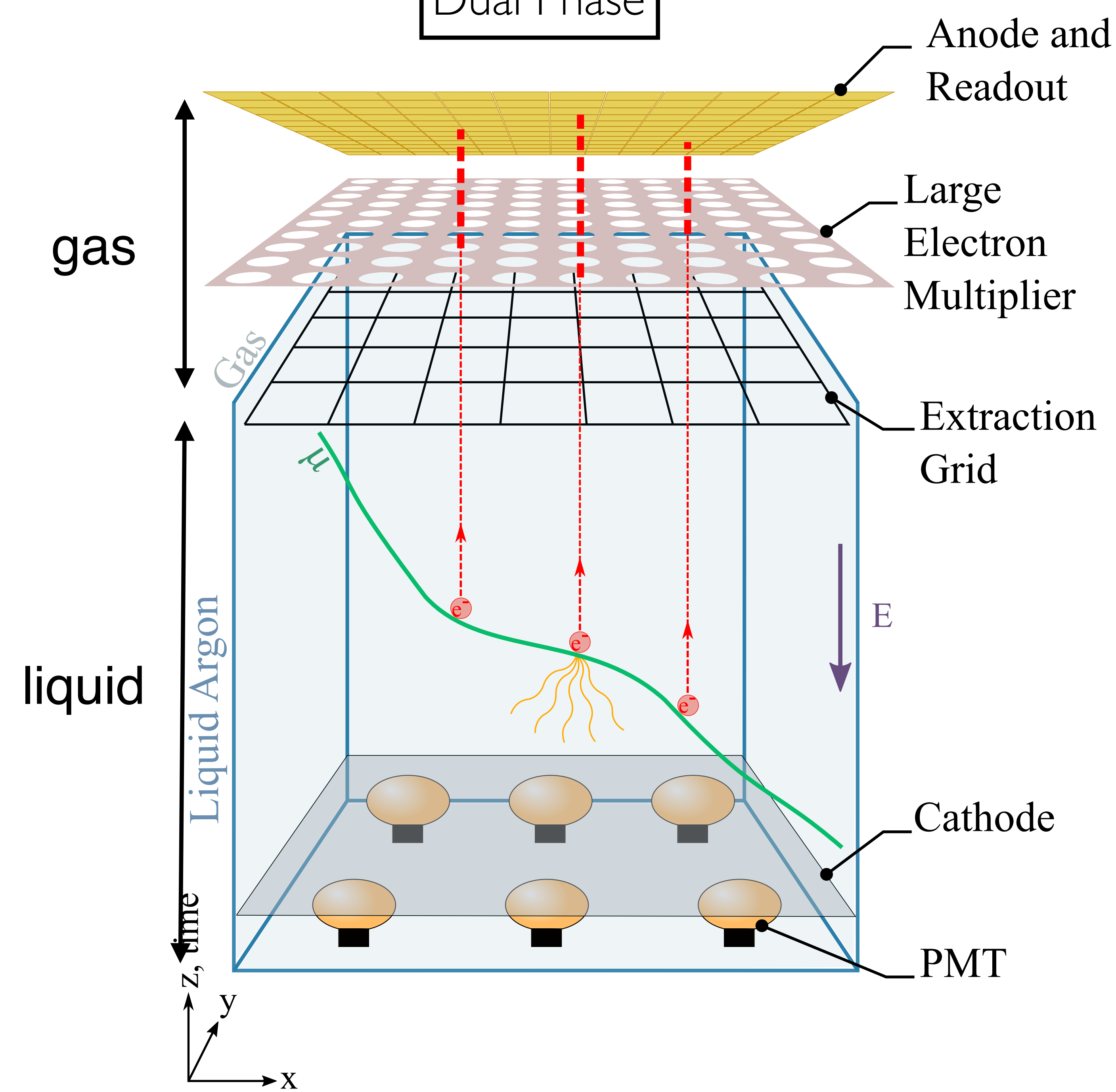
- ionisation charges are drifted horizontally and readout by wires.
- No amplification of the signal.

- ionisation charges are drifted vertical and readout by PCB anodes.
- amplification of the signal in LEMs

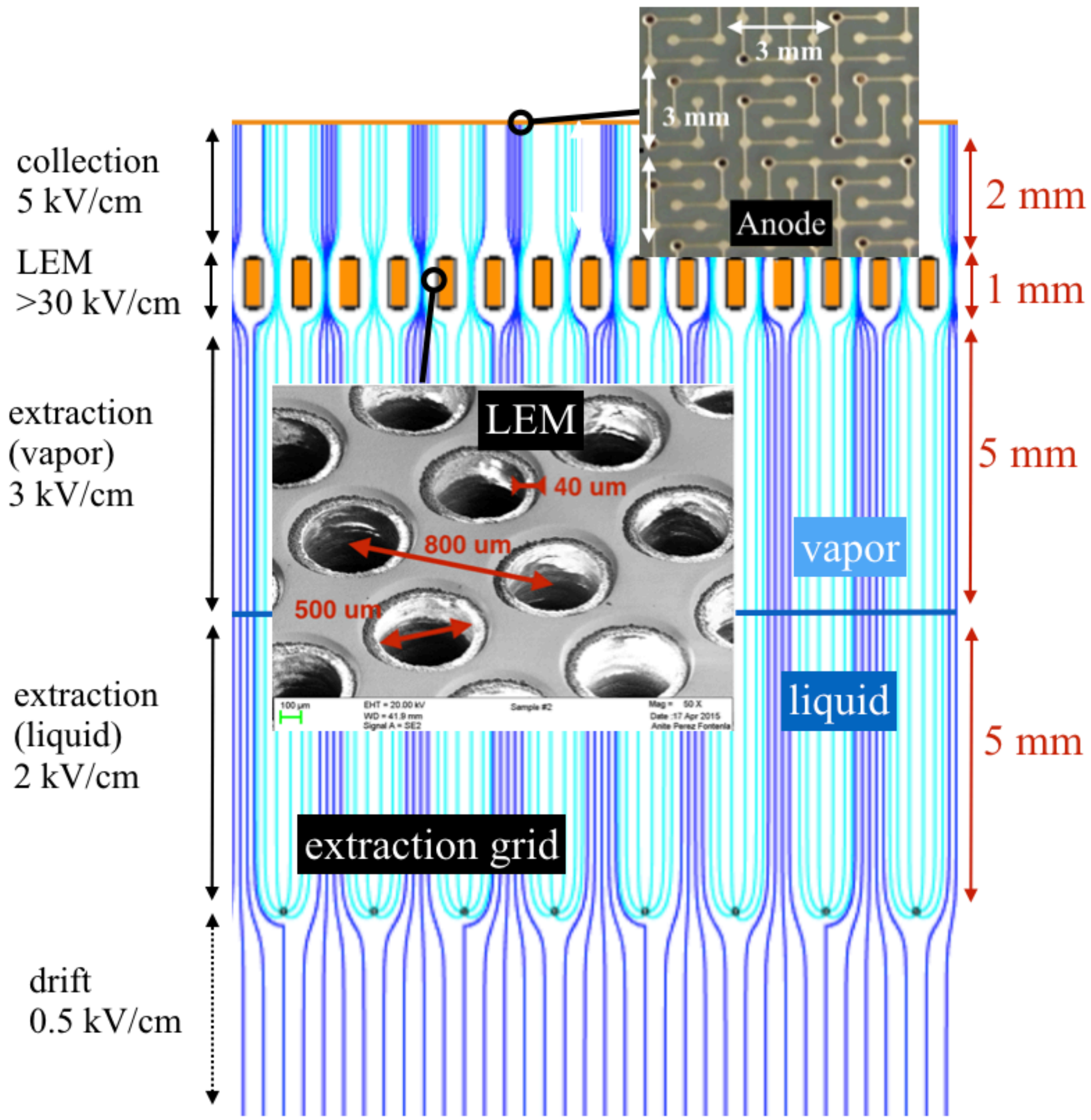
Single Phase

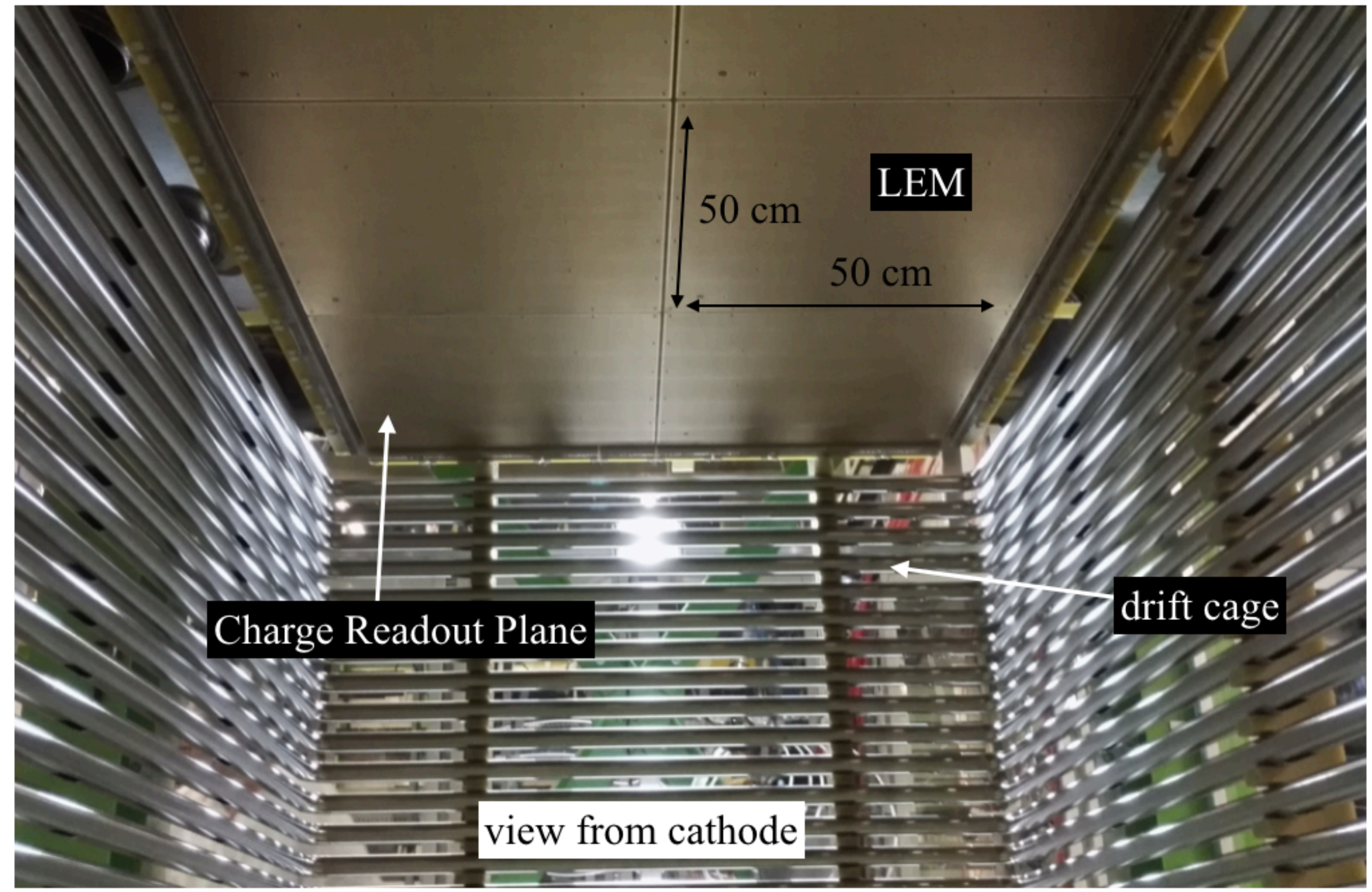


Dual Phase



Dual phase LAr TPCs

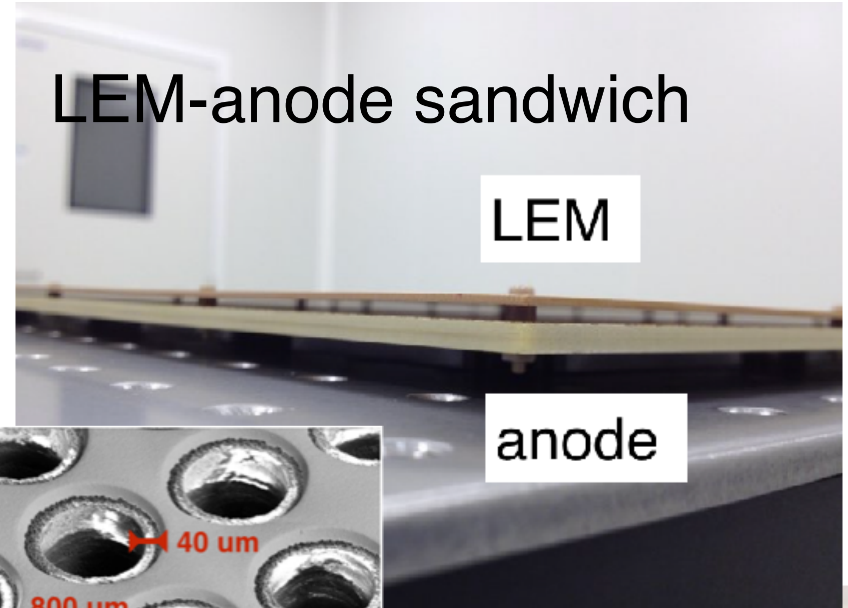




- drifting charges are extracted from the liquid to the vapour phase by an electric field in the liquid of around 2 kV/cm
- the charges once in pure argon vapour are multiplied inside LEMs (Large Electron Multipliers)
- the amplified charges are collected on a 2D segmented anode

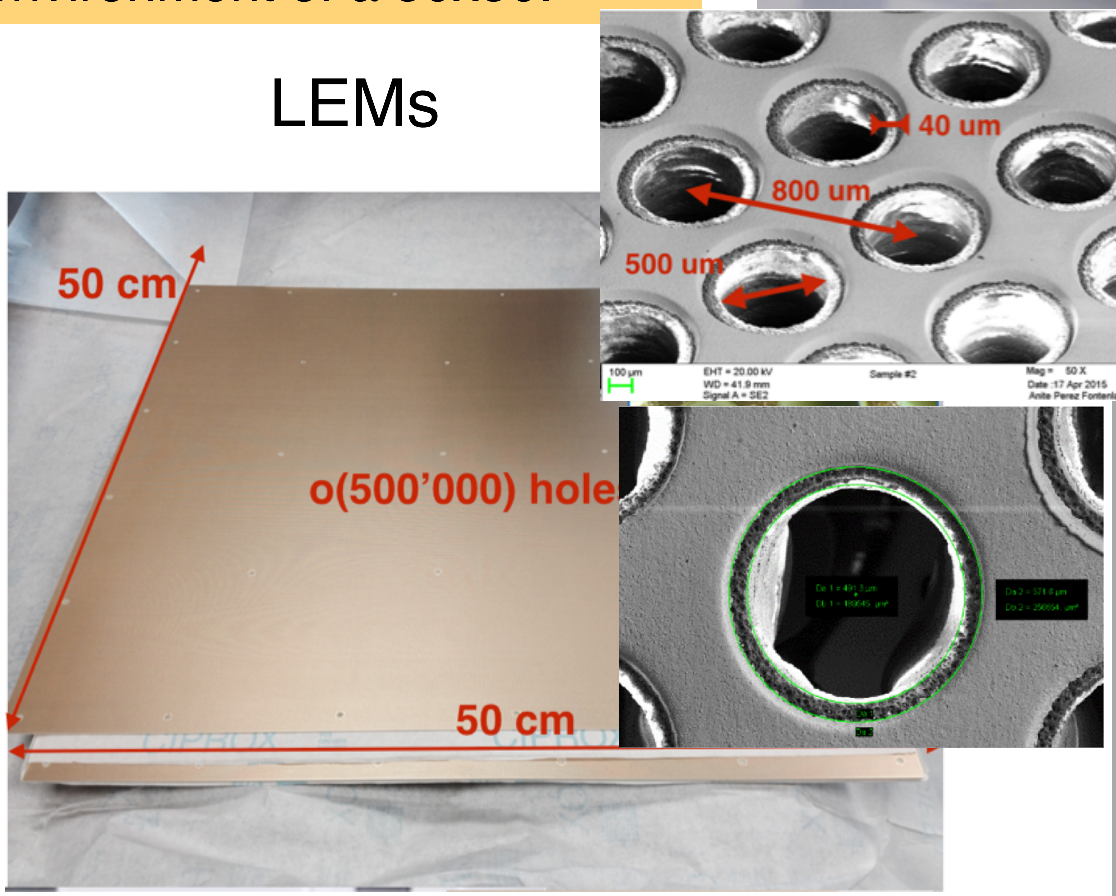
LEMs and anode

design has matured from many year of R&D on small prototypes and from dedicated tests in cryogenic environment of a 50x50.

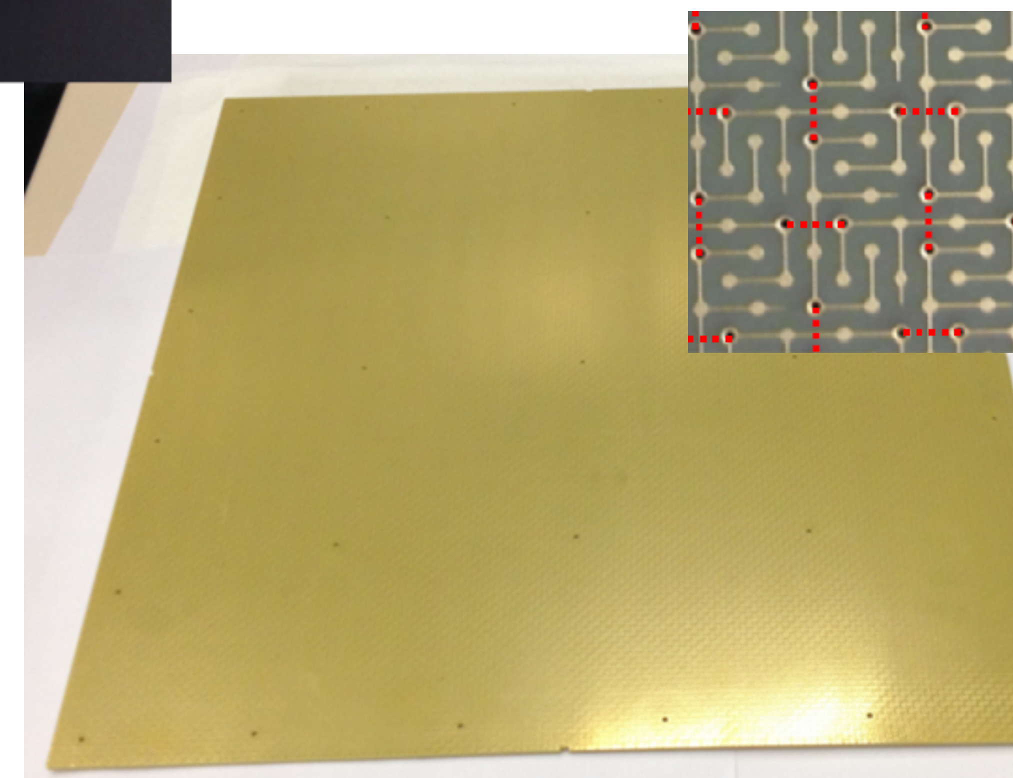


dC/dl 140 pF/m. about 450-500 pF before preamp on 3m readout. ENC of ~ 1500 electrons at 110 K

LEMs



Anodes



- ✓ PCB CNC drilled with o(150) holes per cm^2. 1 mm thick.
- ✓ 500 um hole diameter 800 um pitch.

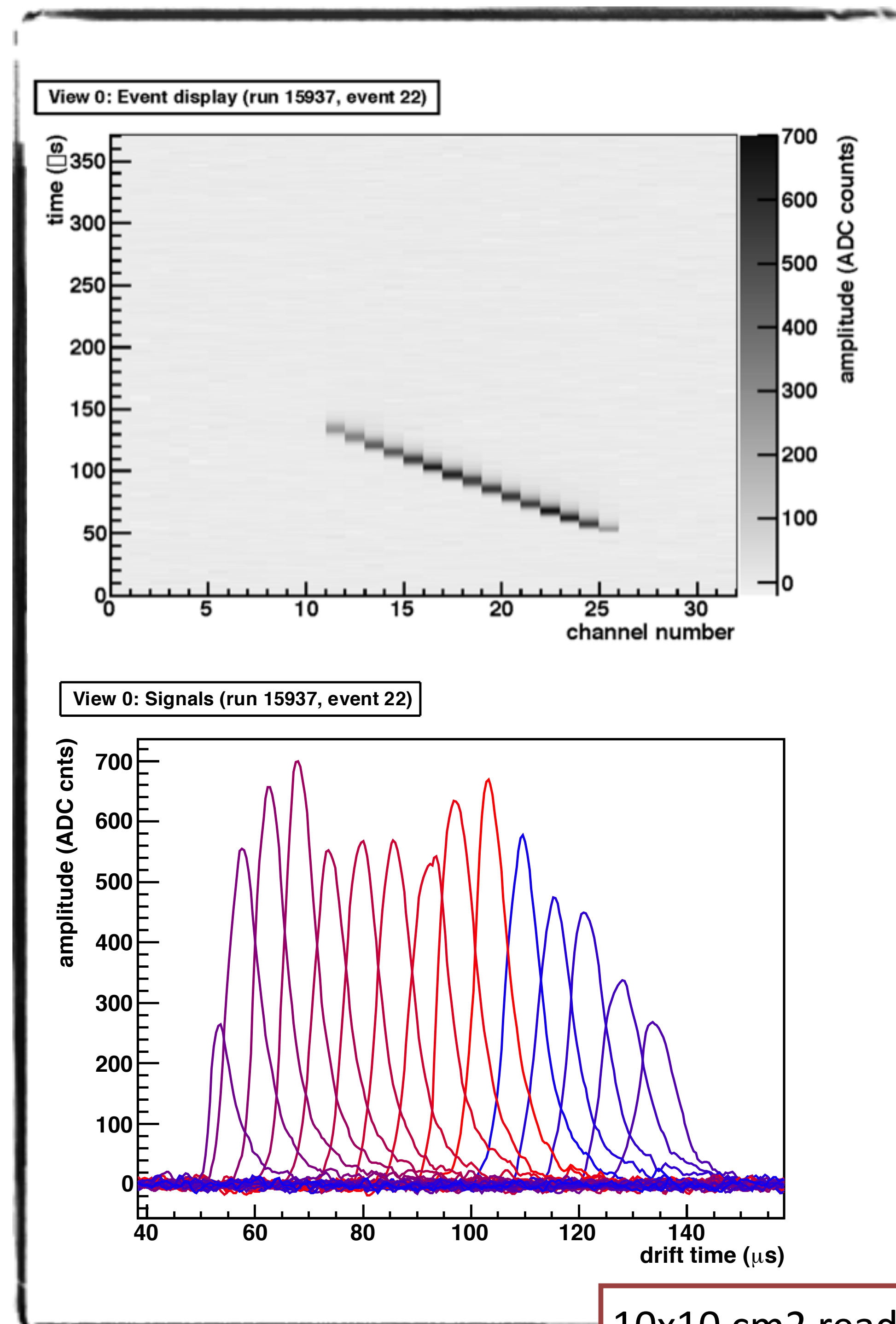
- 4-layer 3.4 mm thick PCB
- Rather standard to manufacture
- electrical continuity tested by company
- Minimal QC needed on our side.

JINST 8 (2013) P04012   JINST 9 (2014) P03017   JINST 10 (2015) P03017

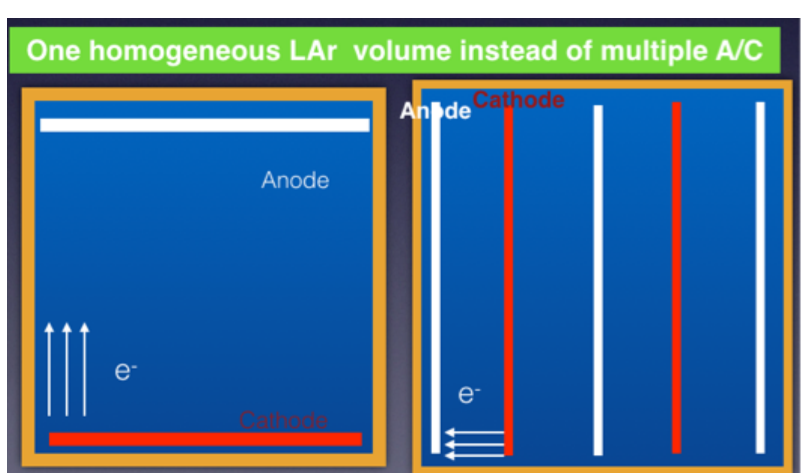
Dual phase LAr TPCs

Double-phase for charge readout with amplification:

- Long drift distances (>10 meters)
- More robust S/N ratio with tuneable gain
- Low energy detection thresholds
- Gain demonstrated up to 90 on small prototypes
- readouts with only collection views on PCBs (avoid wire-planes and induction views)
- One fully homogeneous active LAr volume with reduced number of channels.
- rigid structure insensitive to microphonic noise



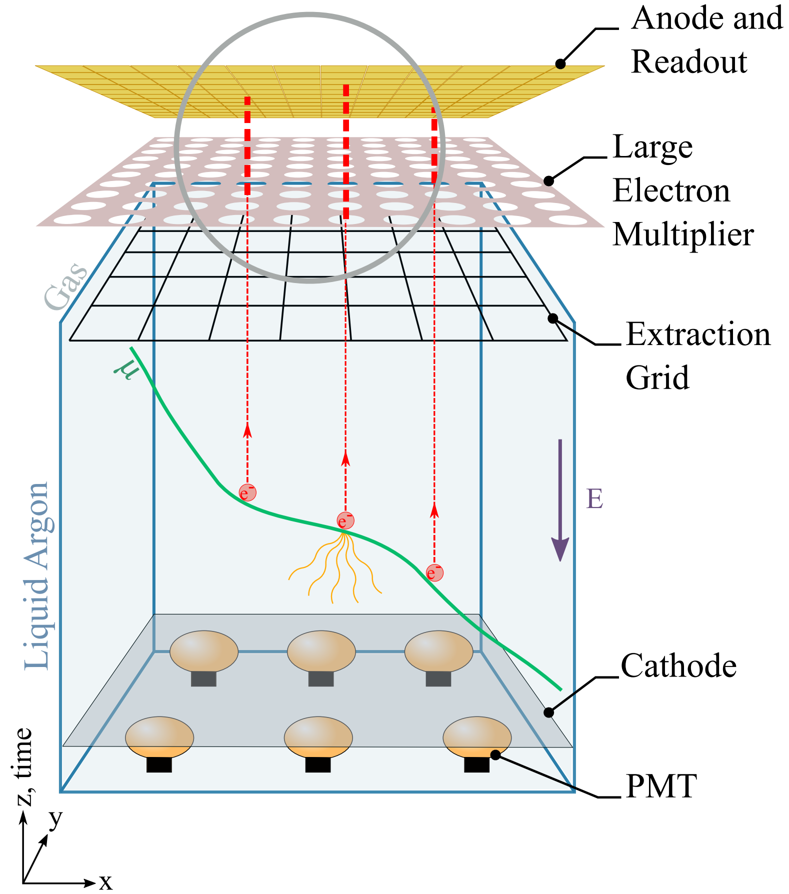
10x10 cm2 readout
Raw waveform no software filtering



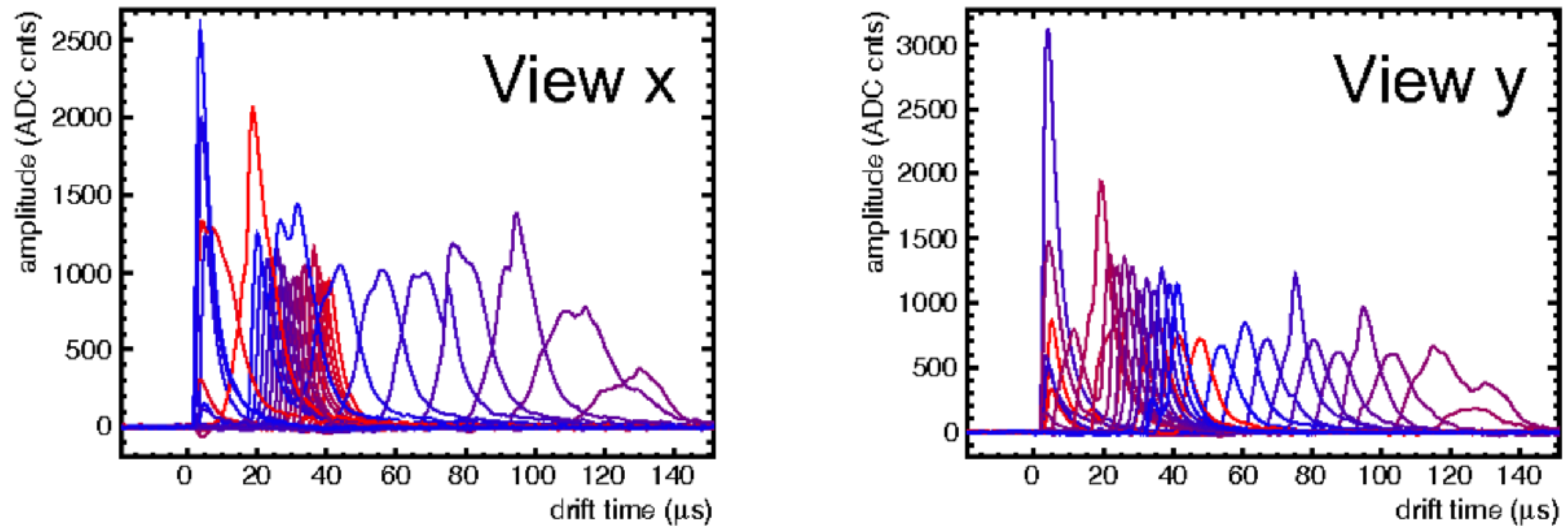
2 Symmetric collection planes/views

ETH

Dual phase 2 collection planes

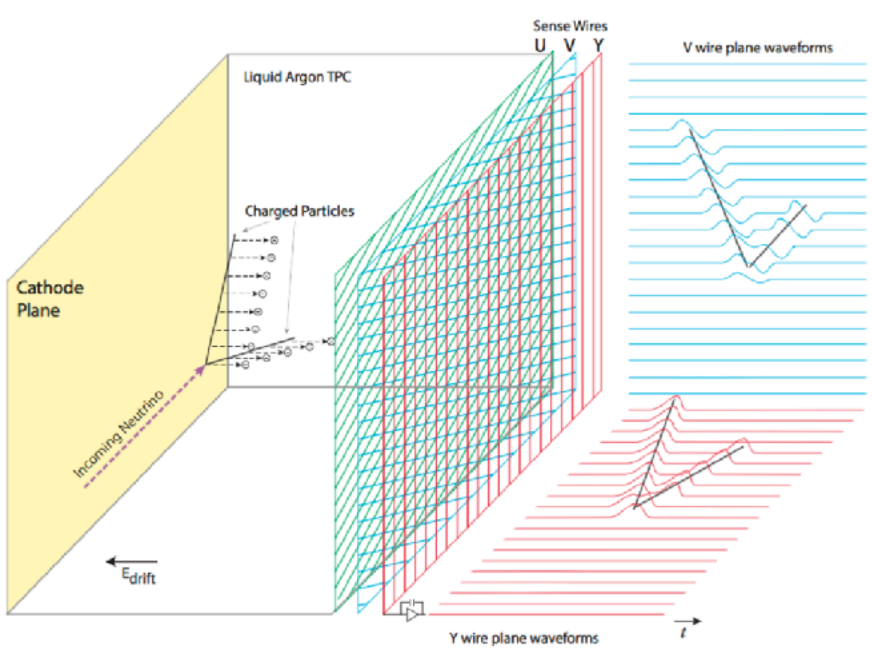


electrons are collected on both planes (each plane sees half of the signal)



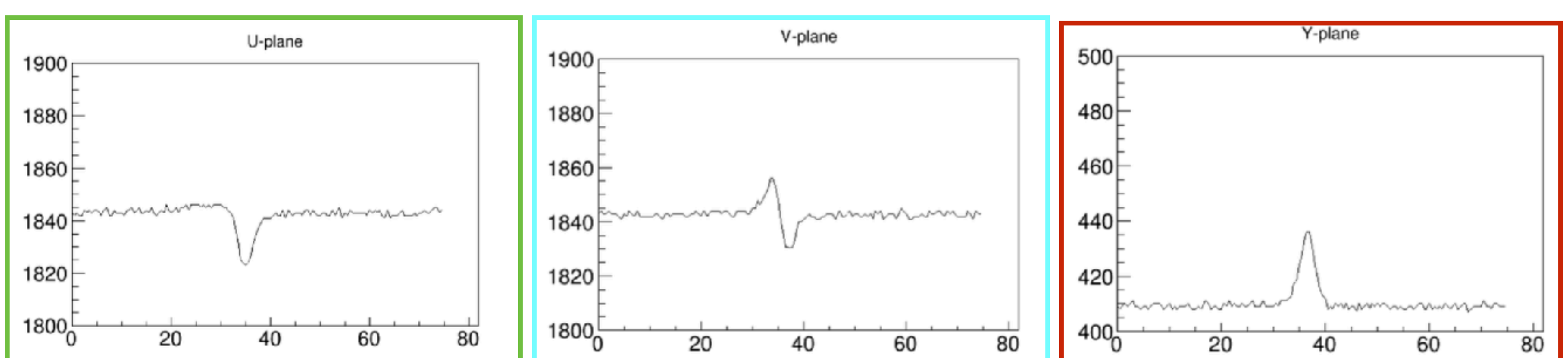
arXiv:1304.0127

single phase: 1 collection and 2 induction planes



JINST 12 (2017) no.03, T03003

electrons induce a bipolar signal on two induction wire planes (=views) and are collected on the last one

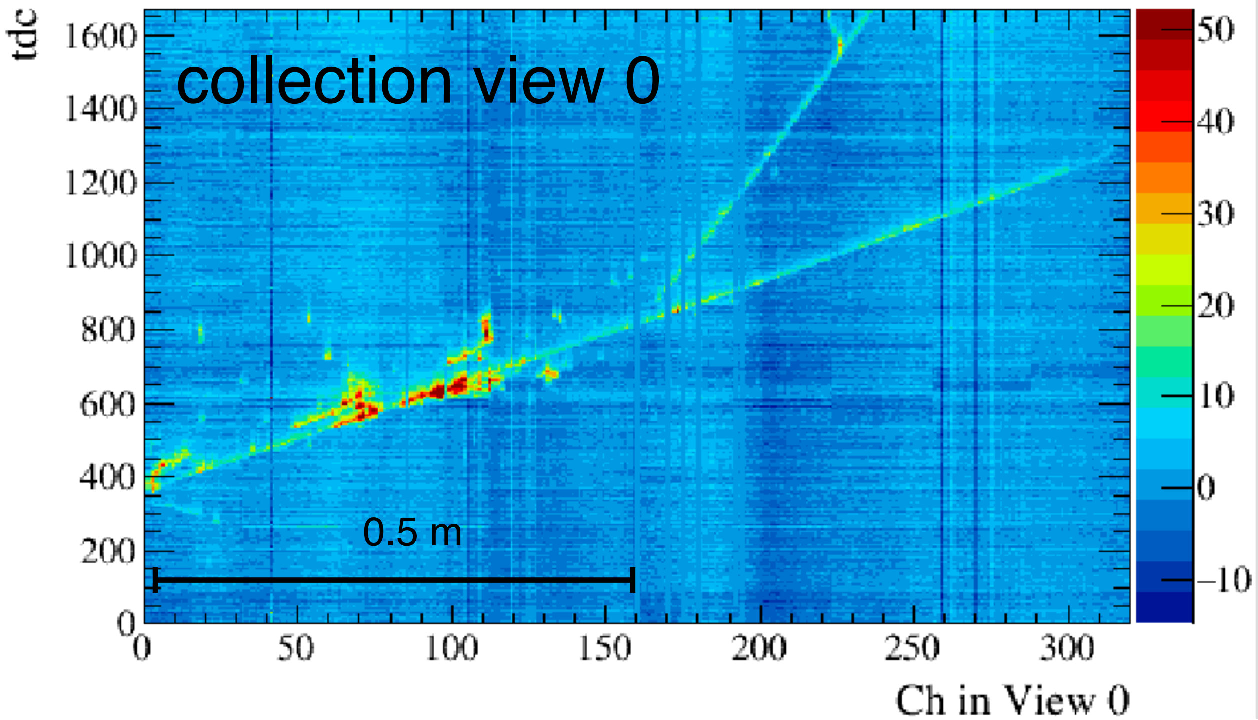


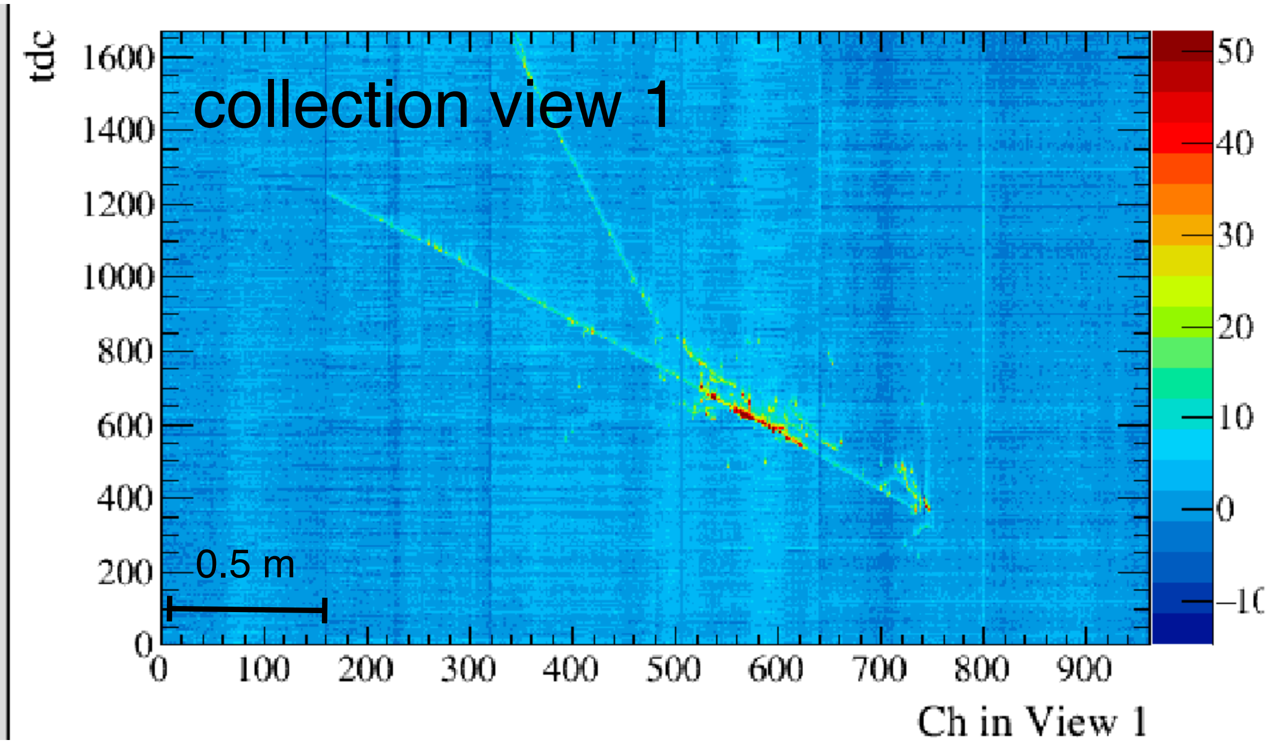
arXiv:1511.00317

2 Symmetric collection planes

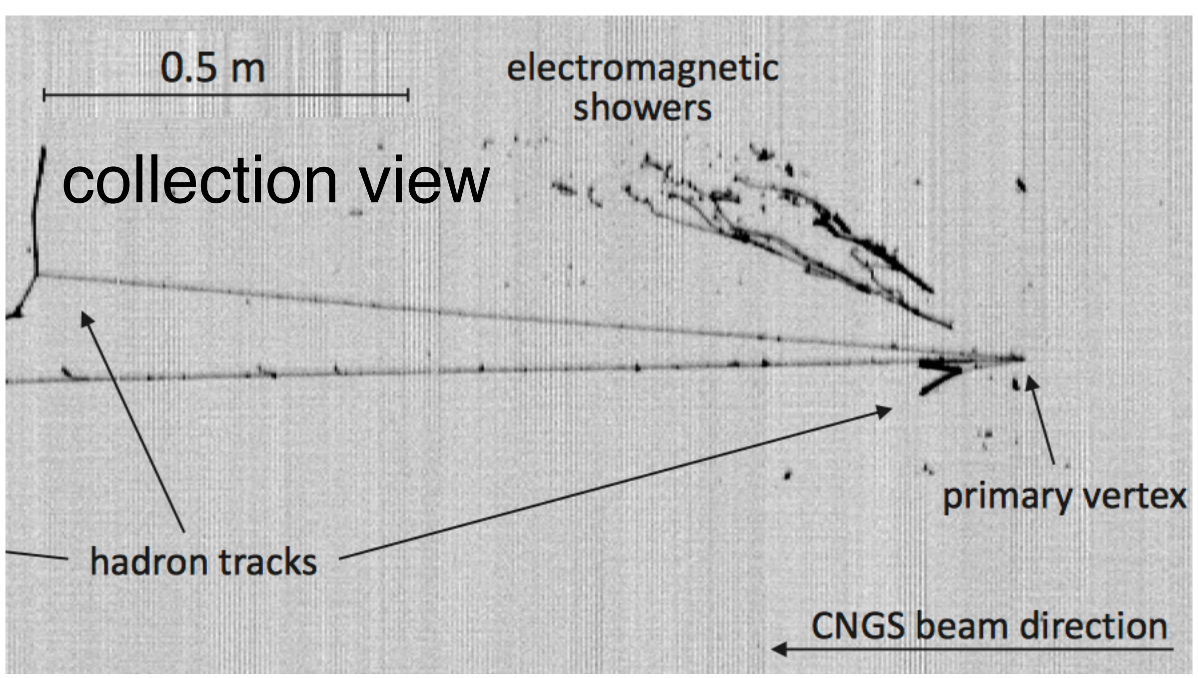
Dual phase 2 collection views

cosmic event dual phase 3x1x1 m3 TPC

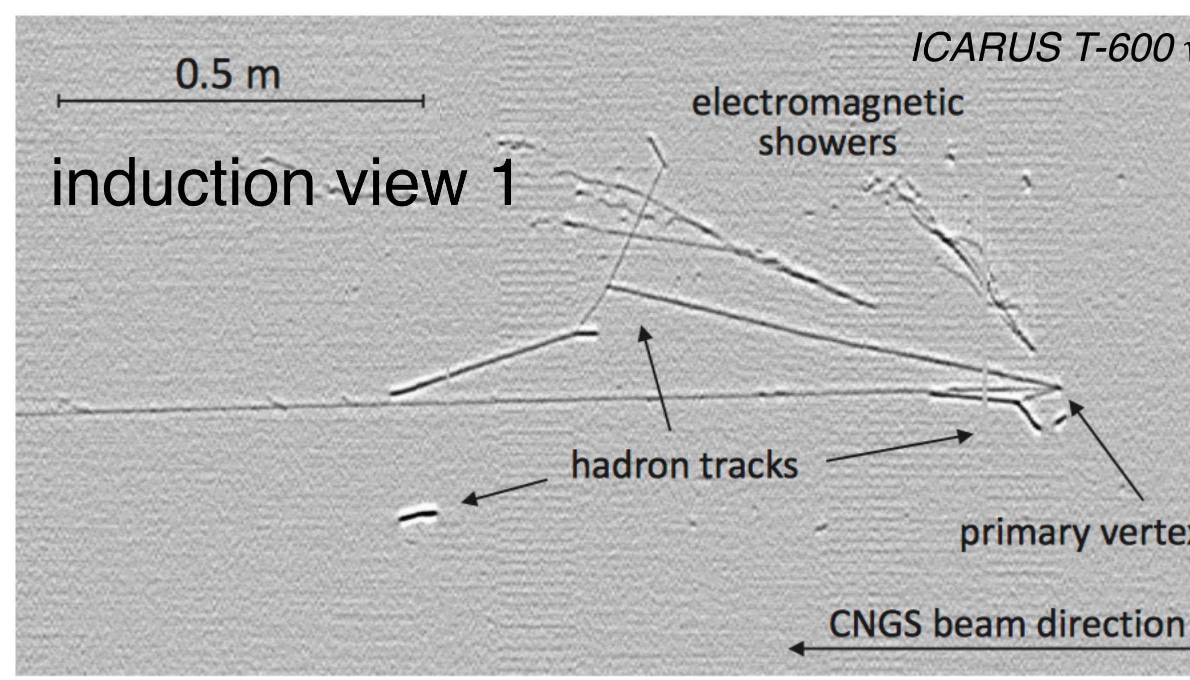




single phase: 1 collection and 2 induction views (only one induction view shown)



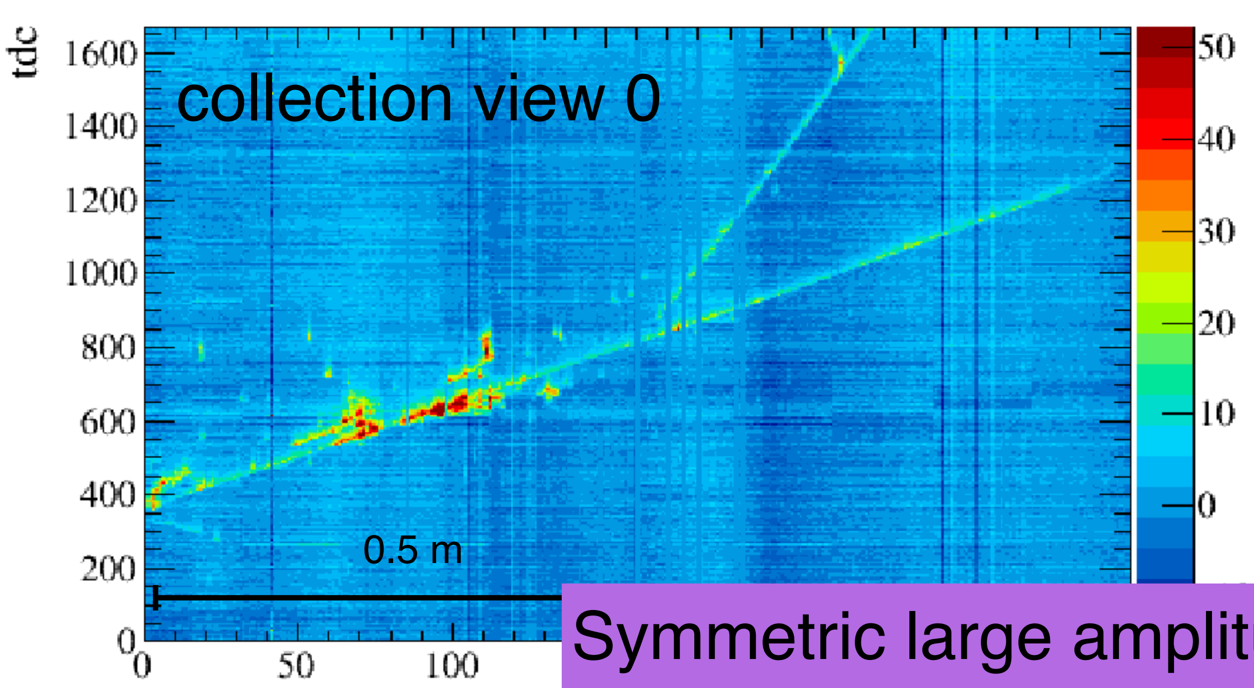
ICARUS T-600 ν_μ event

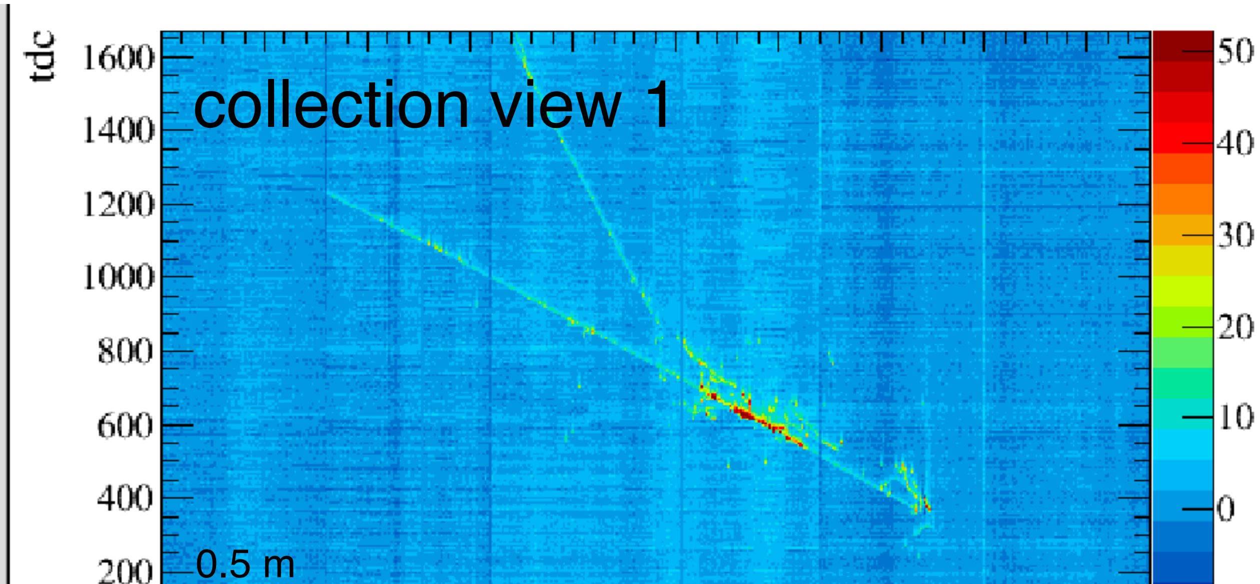


2 Symmetric collection planes

ETH

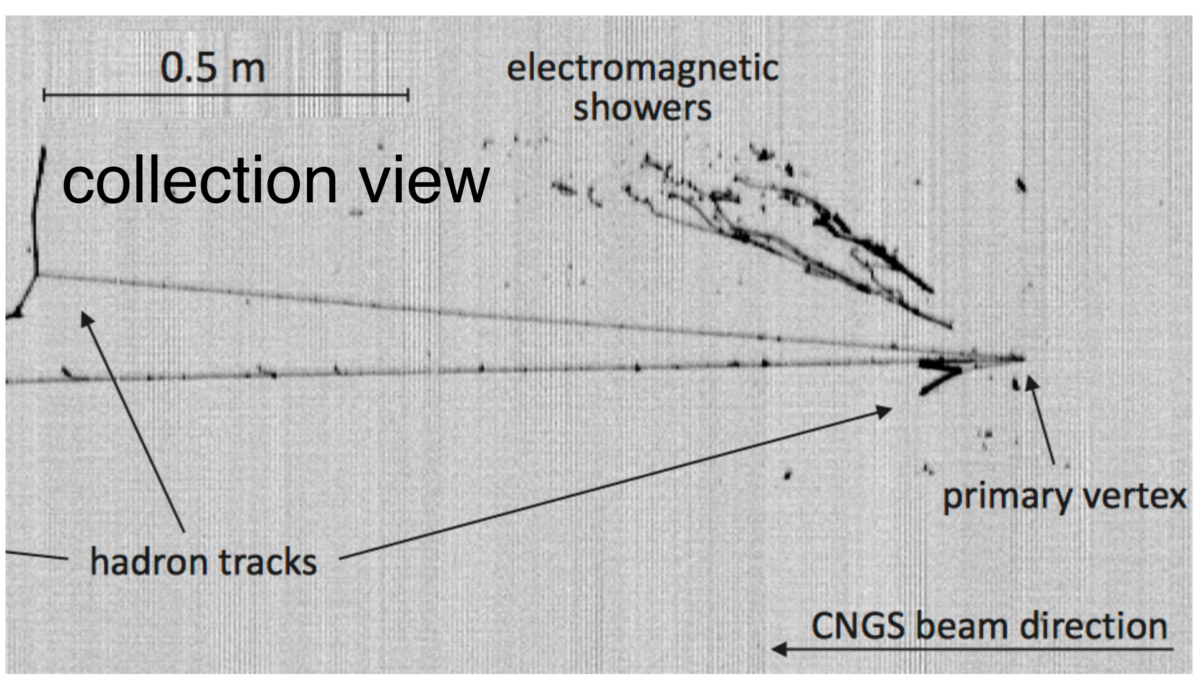
Dual phase 2 collection views

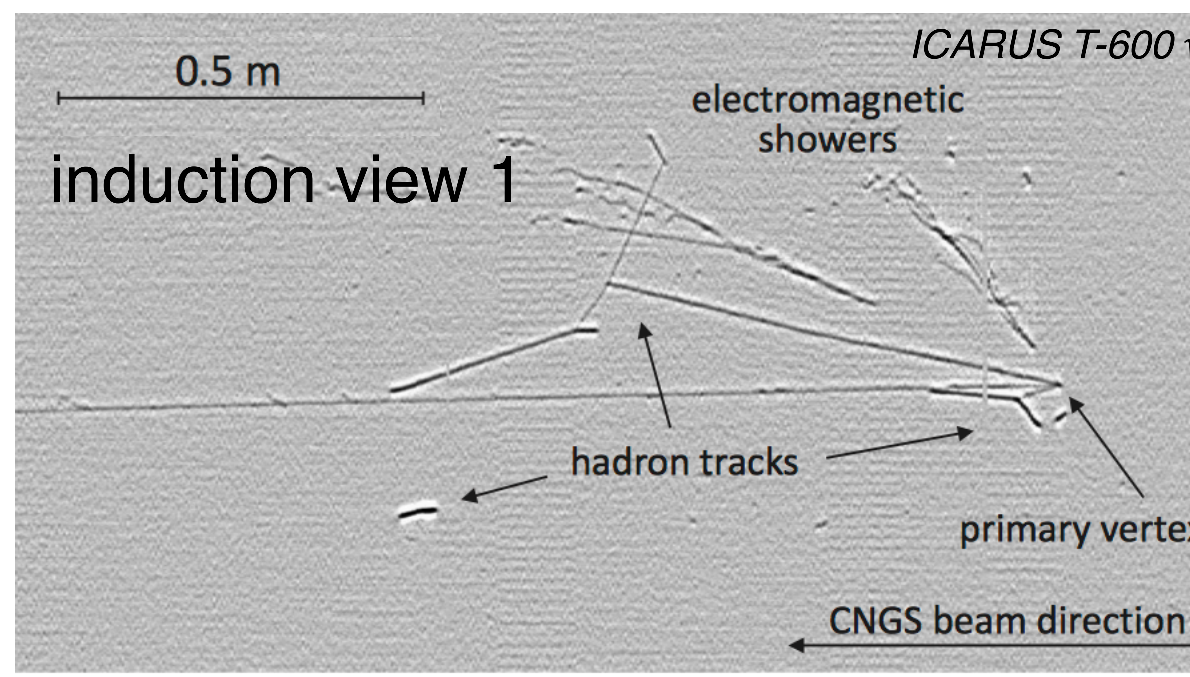




Symmetric large amplitude and clear signal on all views, significantly easier to reconstruct no need for complex deconvolution algorithms.

single phase: 1 collection and 2 induction views (only one induction view shown)

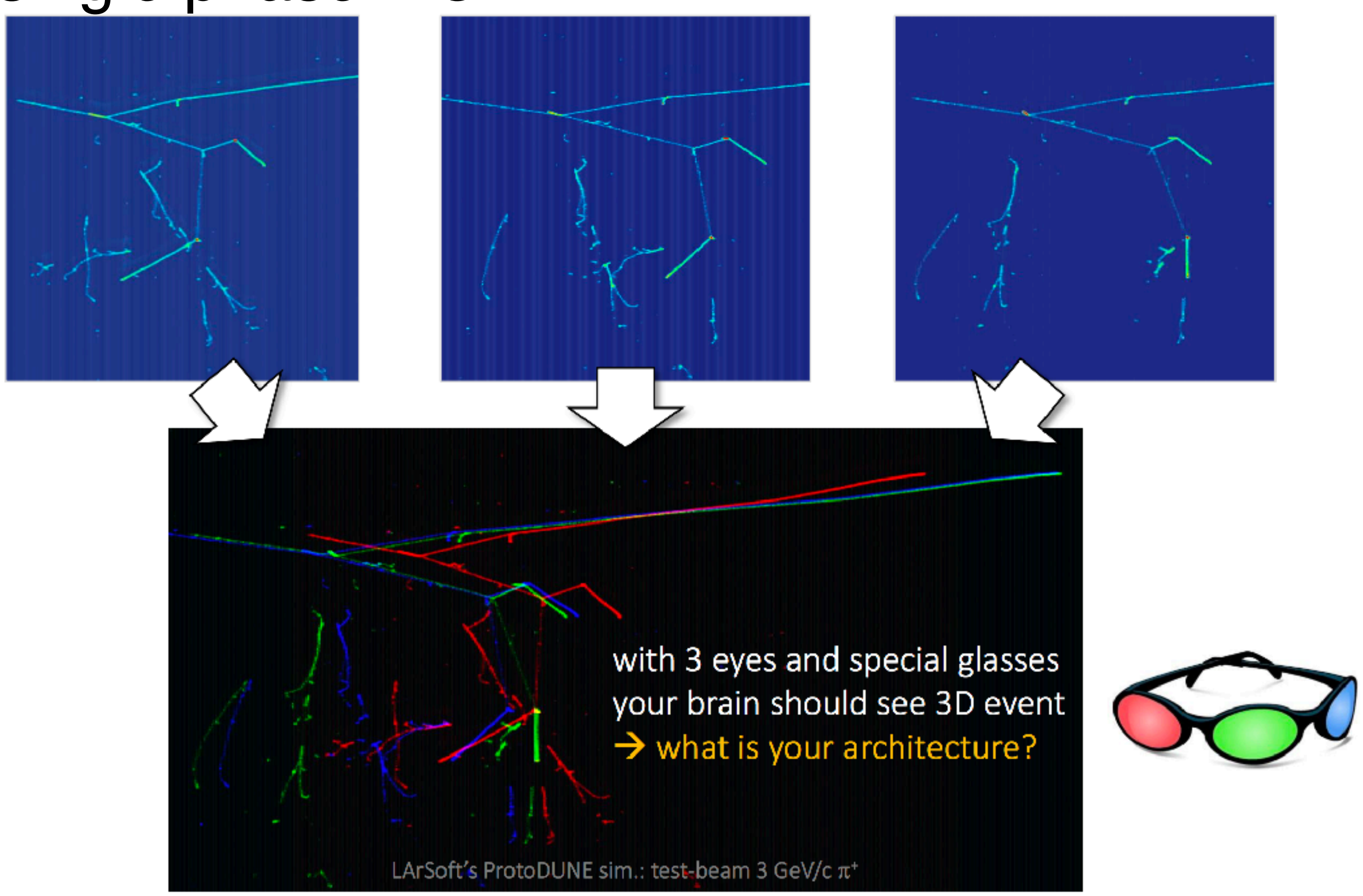




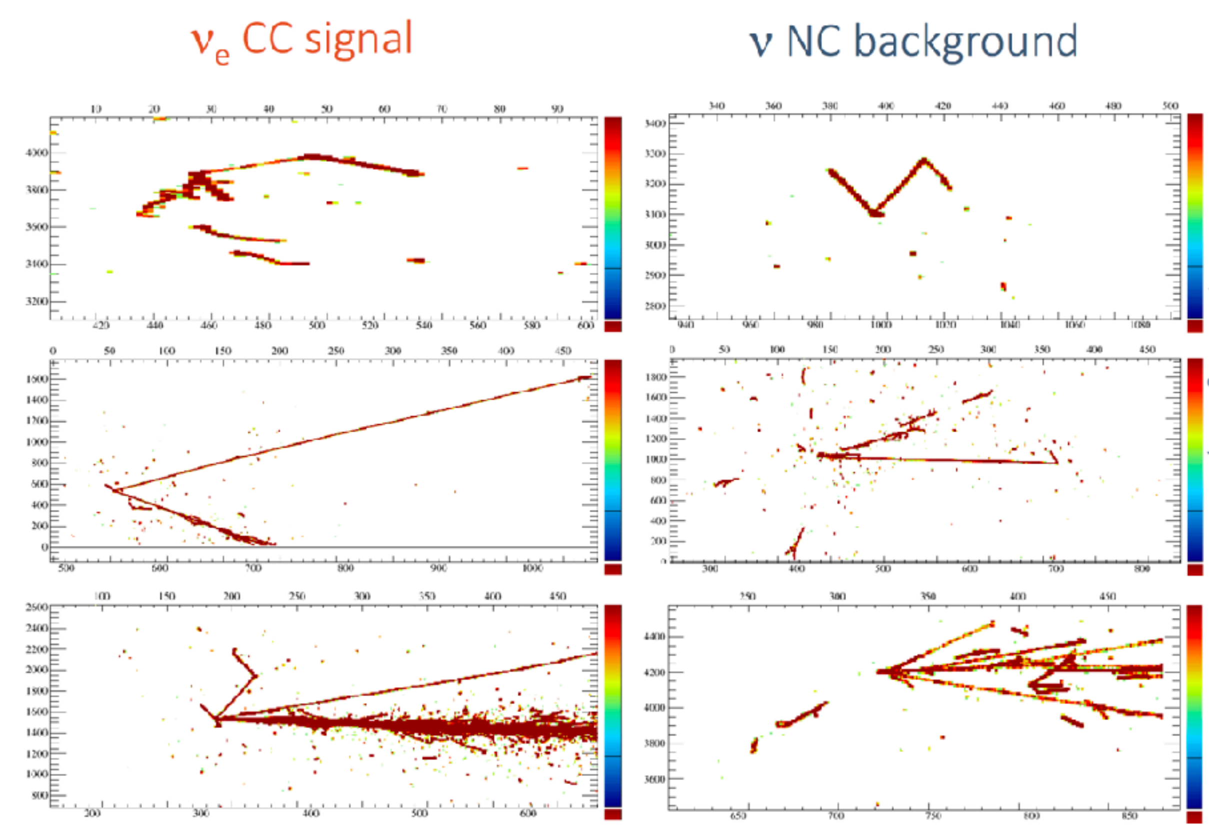
Automatic reconstruction of LAr events

- views in 2D projections are independent, need to figure out object associations to have 3D view of the event.
- <u>Having similar signals(=hits) with large amplitude on all views is an essential precondition to be able to perform reconstruction of the event</u>
- => advantage of dual phase (large amplitudes, no induction views)

single phase MC



single phase MC



huge effort for reconstruction of LAr event in the community

[R.Sulej, How Machine Learning conquers reconstruction in neutrino experiments, CERN EP/IT Data Science seminar, 26.07.2017]

Automatic reconstruction of LAr events

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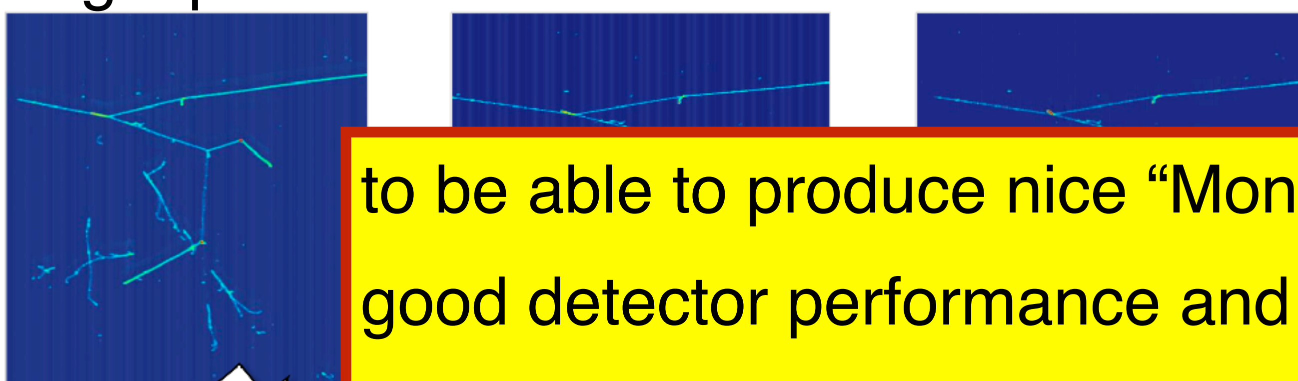
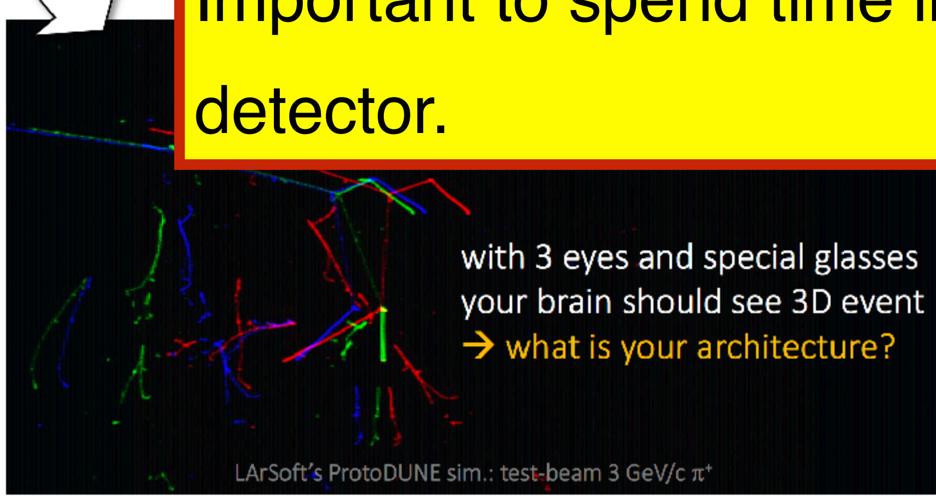
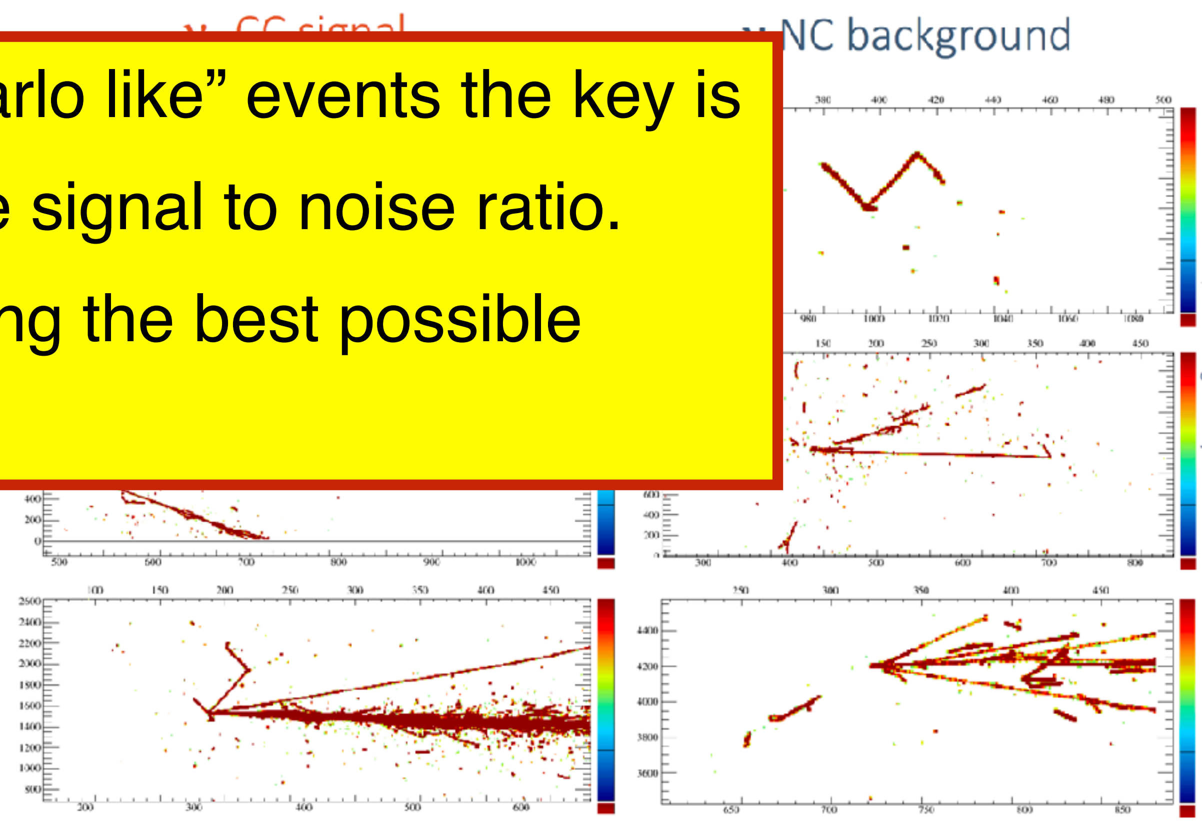




single phase MC



to be able to produce nice "Monte Carlo like" events the key is good detector performance and large signal to noise ratio. Important to spend time in constructing the best possible detector.

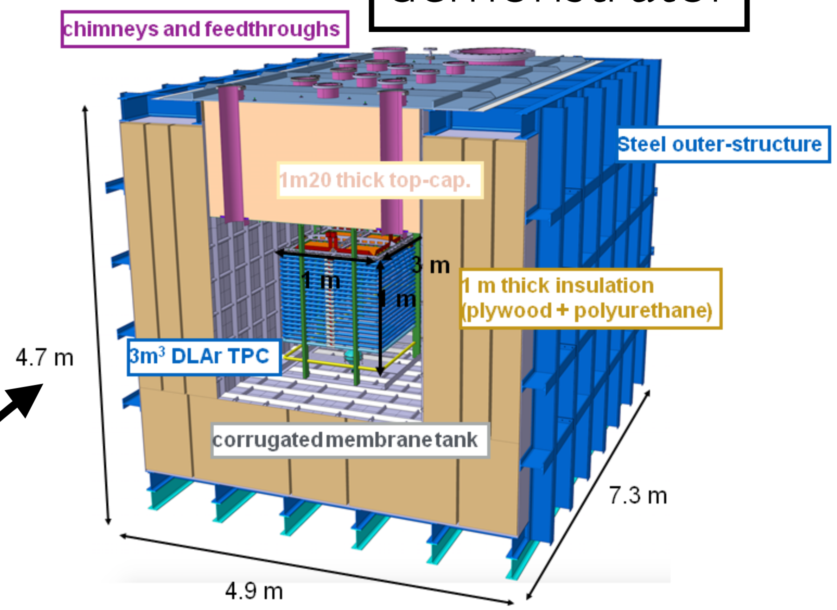
huge effort for reconstruction of LAr event in the community

[R.Sulej, How Machine Learning conquers reconstruction in neutrino experiments, CERN EP/IT Data Science seminar, 26.07.2017]

The path towards 10 kt dual phase TPCs

2014 ~ 2017

3x1x1 m^3 demonstrator

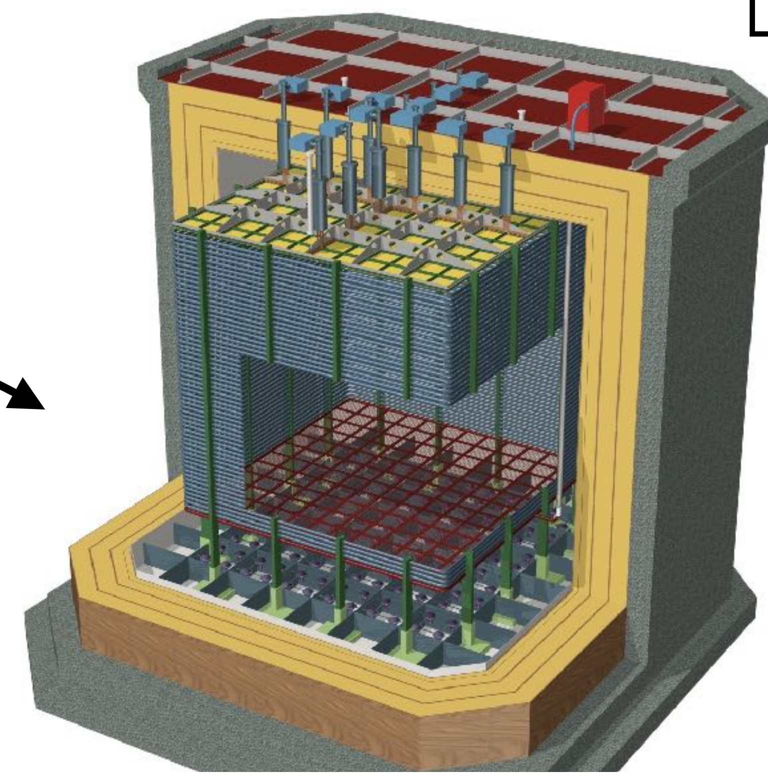


@ CERN BLDG. 182

@ CERN IN NORTH AREA

6x6x6 m^3 prototype

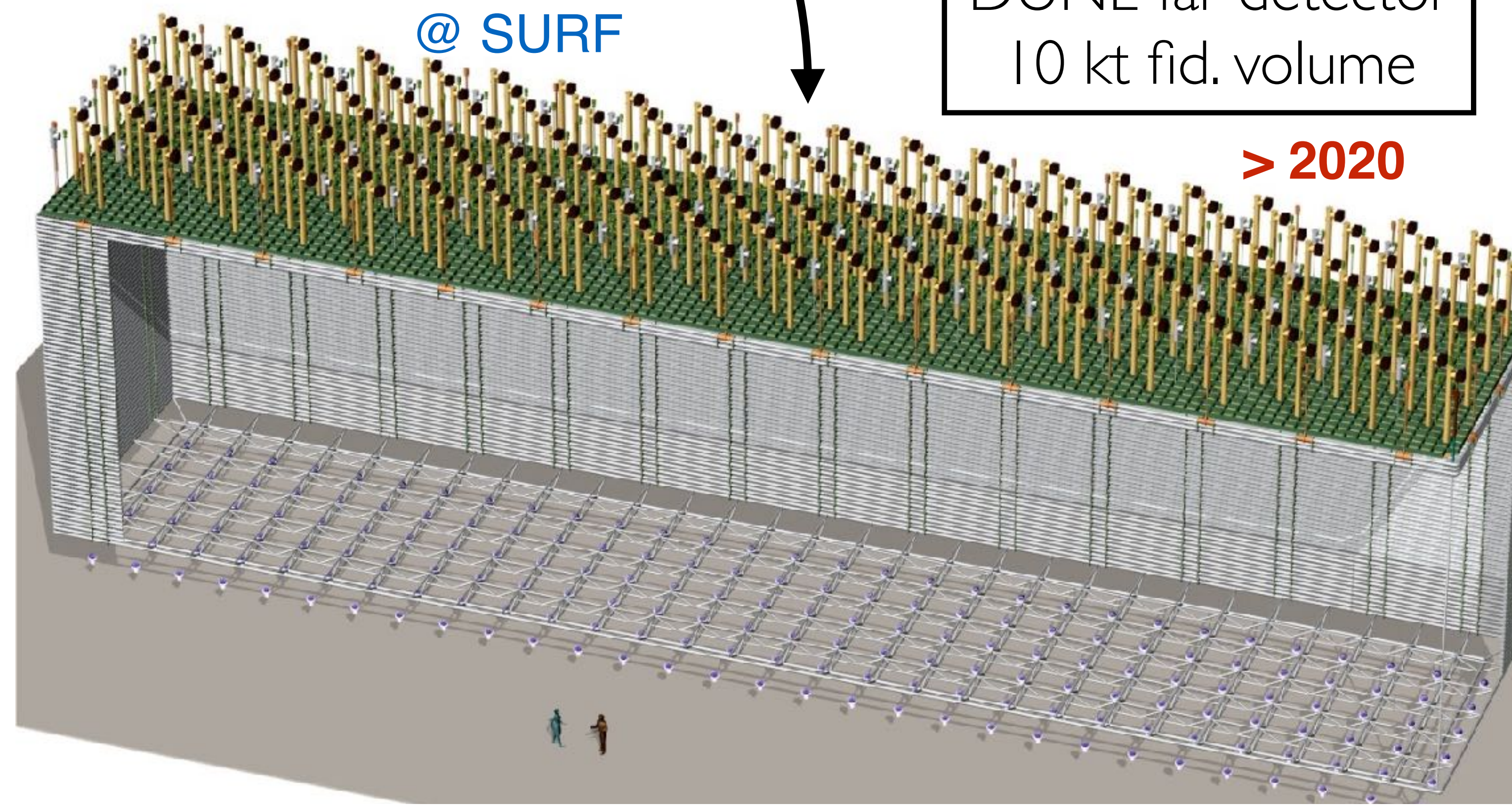
2016 ~ 2019



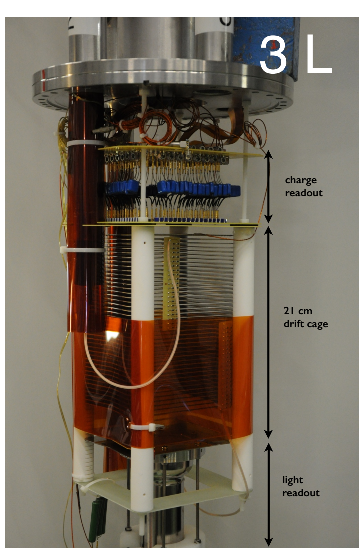
@ SURF

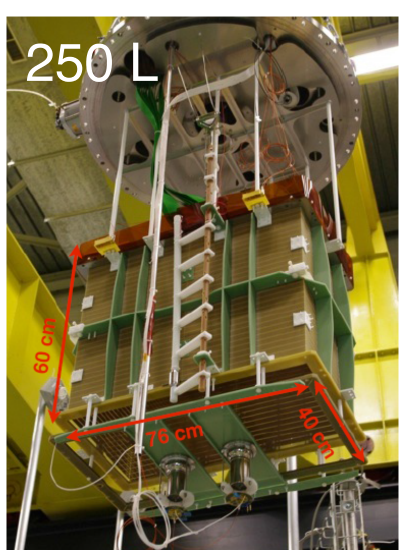
DUNE far detector 10 kt fid. volume

> 2020



Small TPCs for R&D



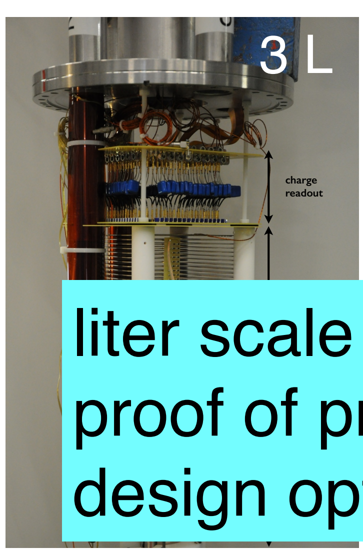


2007 ~ 2014

The path towards 10 kt dual phase TPCs

ETH

Small TPCs for R&D

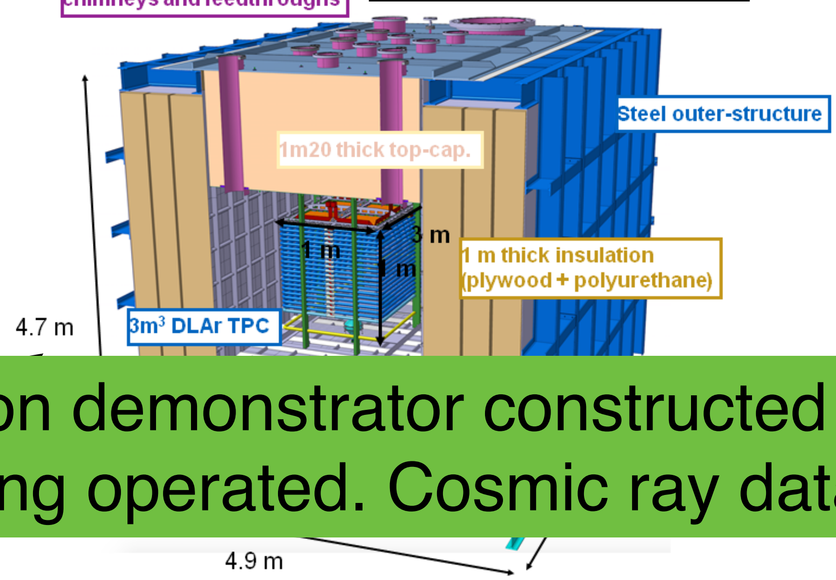


liter scale TPCs. A decade proof of principle and design optimisation.

2007 ~ 2014

3x1x1 m^3 demonstrator

2014 ~ 2017



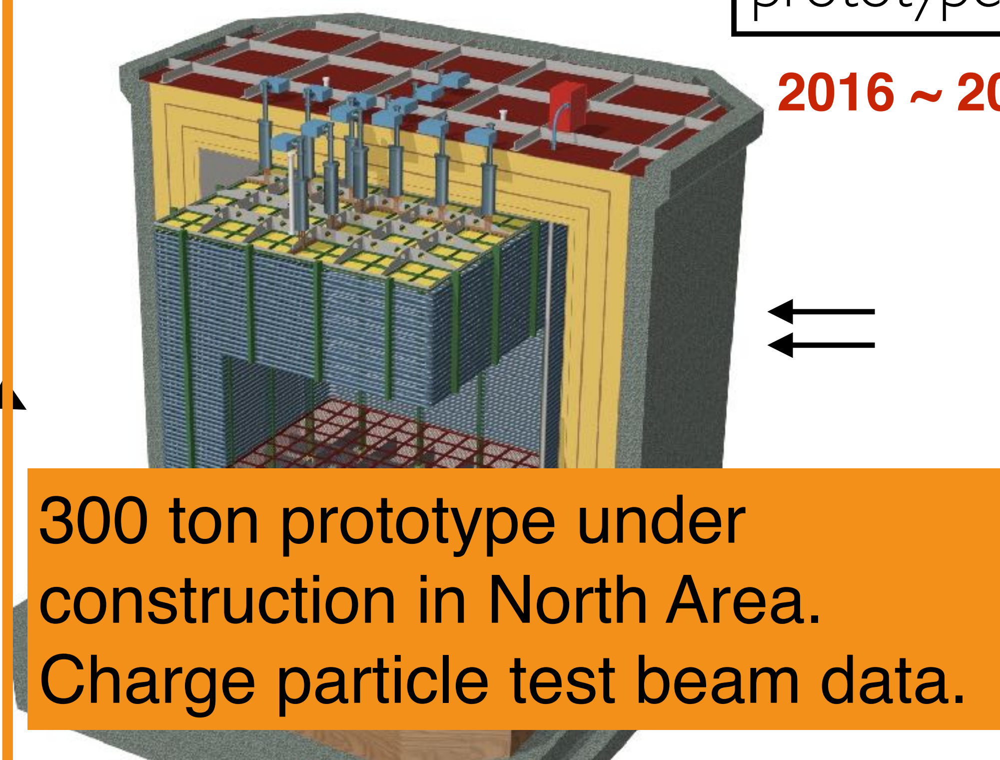
5 ton demonstrator constructed - being operated. Cosmic ray data

@ CERN BLDG. 182

6x6x6 m^3 prototype

@ CERN IN NORTH AREA

2016 ~ 2019

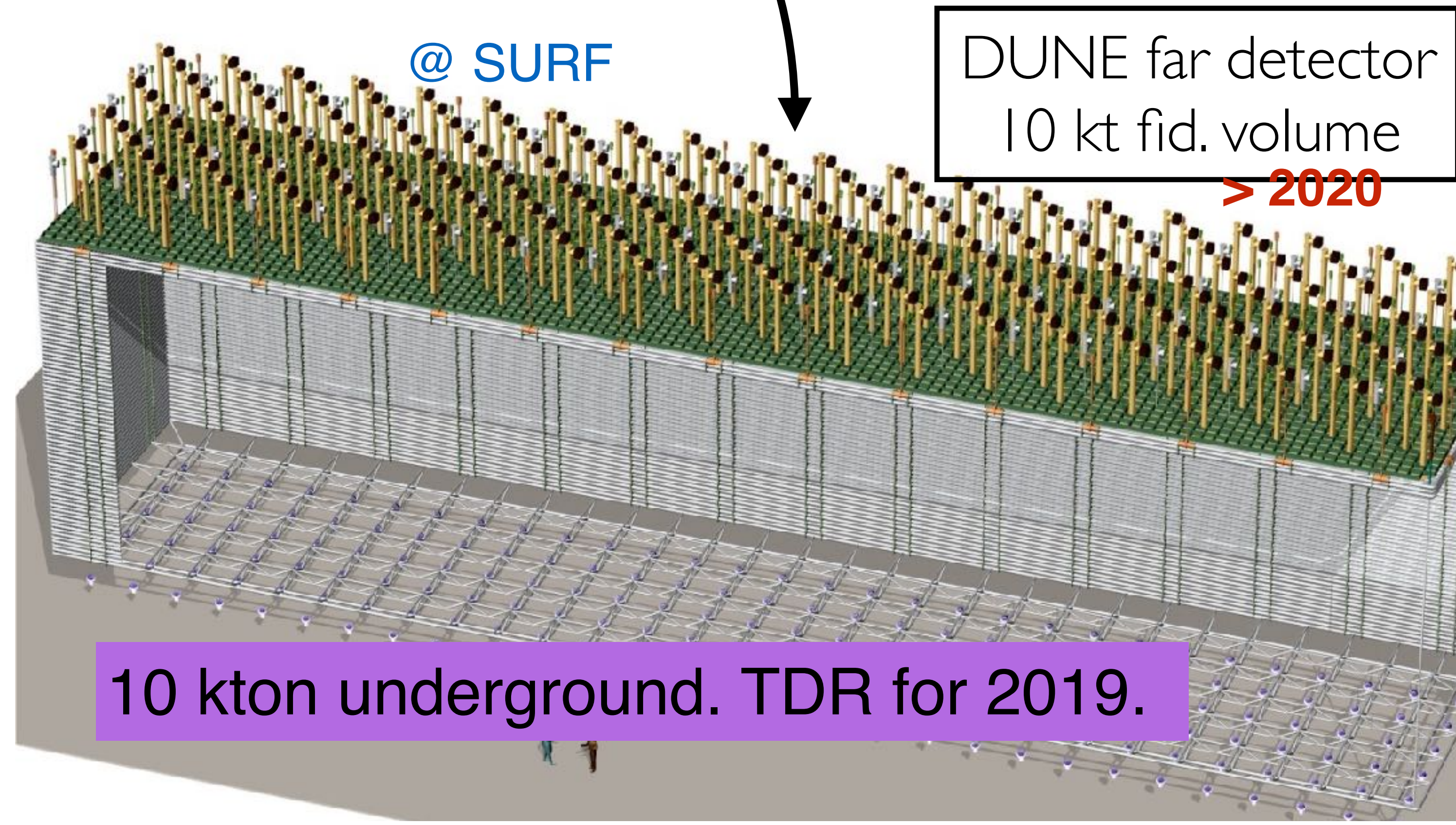


300 ton prototype under construction in North Area. Charge particle test beam data.

DUNE far detector 10 kt fid. volume

@ SURF

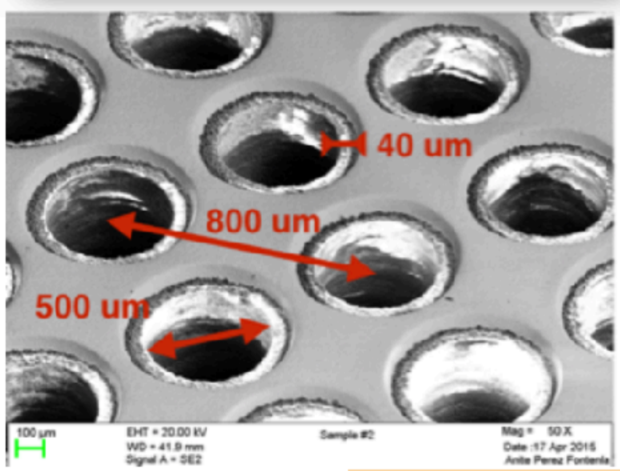
> 2020

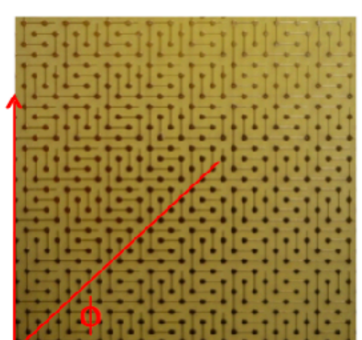


10 kton underground. TDR for 2019.

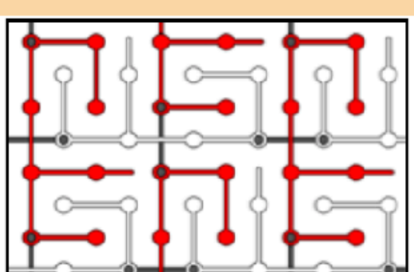
Dual phase: a decade of test and optimisation

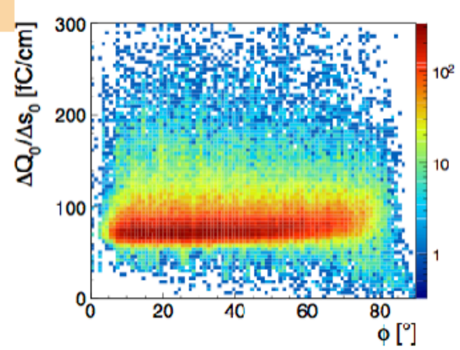
10x10cm²: LEM/anode R&D



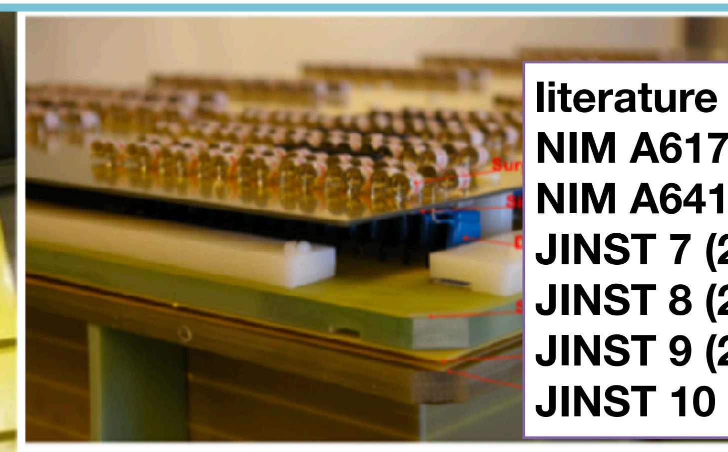


dC/dl ~ 120 pF/m



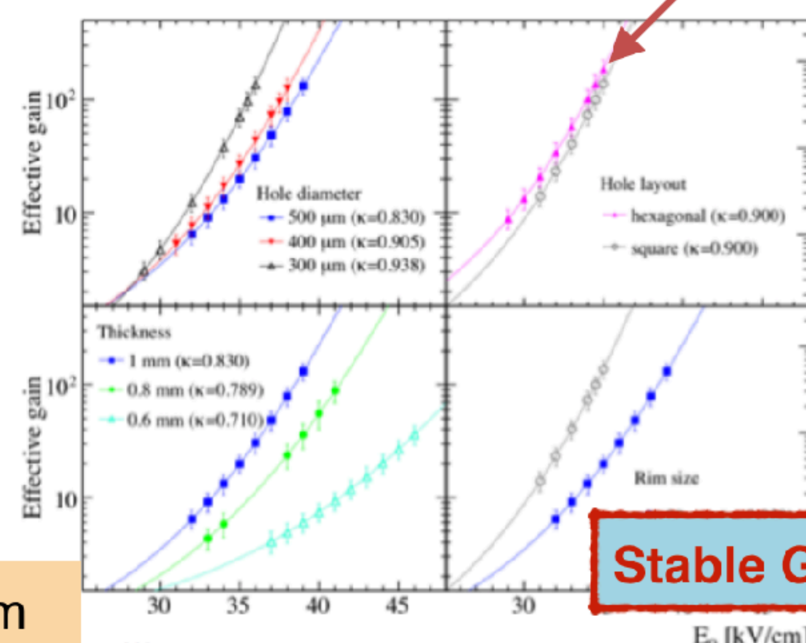


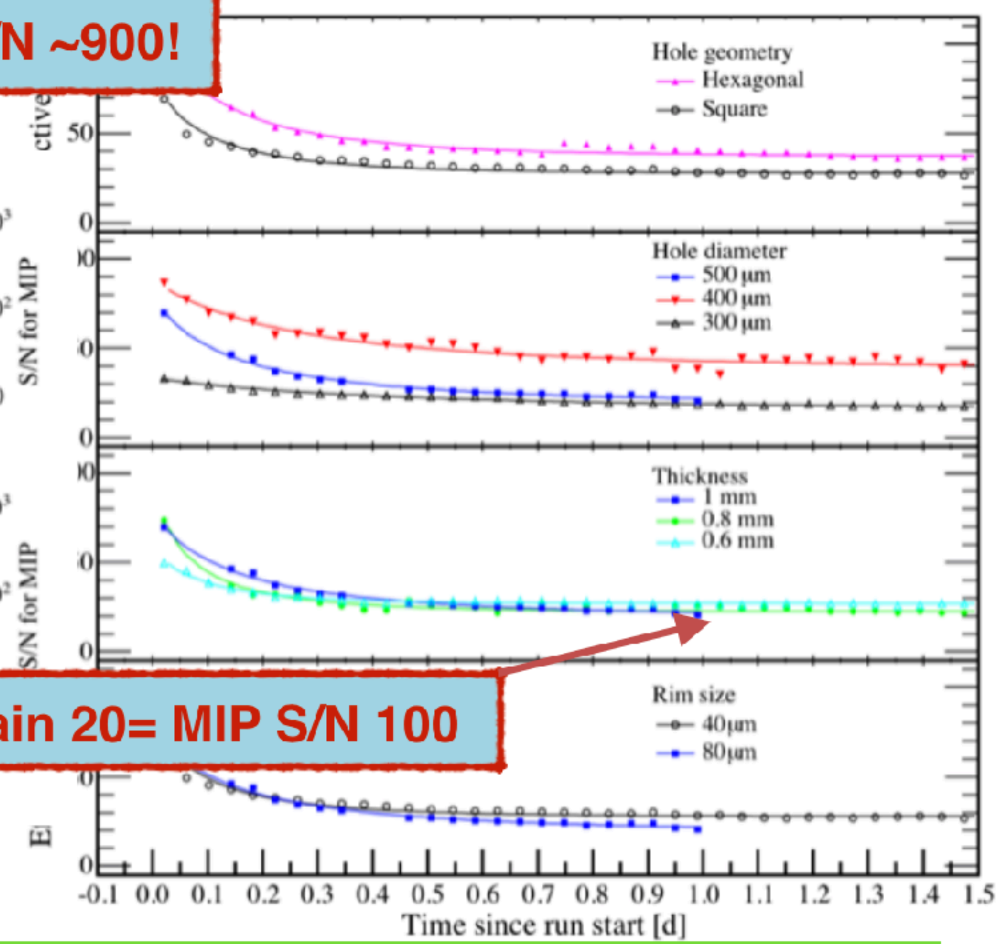
40x80cm²: stable operation of large area readouts



literature
NIM A617 (2010) p188-192
NIM A641 (2011) p 48-57
JINST 7 (2012) P08026
JINST 8 (2013) P04012
JINST 9 (2014) P03017
JINST 10 (2015) P03017

Max Gain 180 = MIP S/N ~900!





Stable Gain 20= MIP S/N 100

Operating with amplification of about a factor 20

WA105 collaboration

demonstrate the capabilities of the dual phase technology at the kton scale

DUNE

Ciemat
Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

UNIVERSITY OF JYVÄSKYLÄ

UCL

APC

Fermilab

LPNHE PARIS

IPNL

lapp

CERN

KEK
HIGH ENERGY ACCELERATOR RESEARCH ORGANIZATION

LABORATORIUM FÜR HOCHENERGIEPHYSIK
LHEP
UNIVERSITÄT BERN

Institut de Física d'Altes Energies IFAE

IN2P3
Institut National de Physique Nucléaire et de Physique des Particules

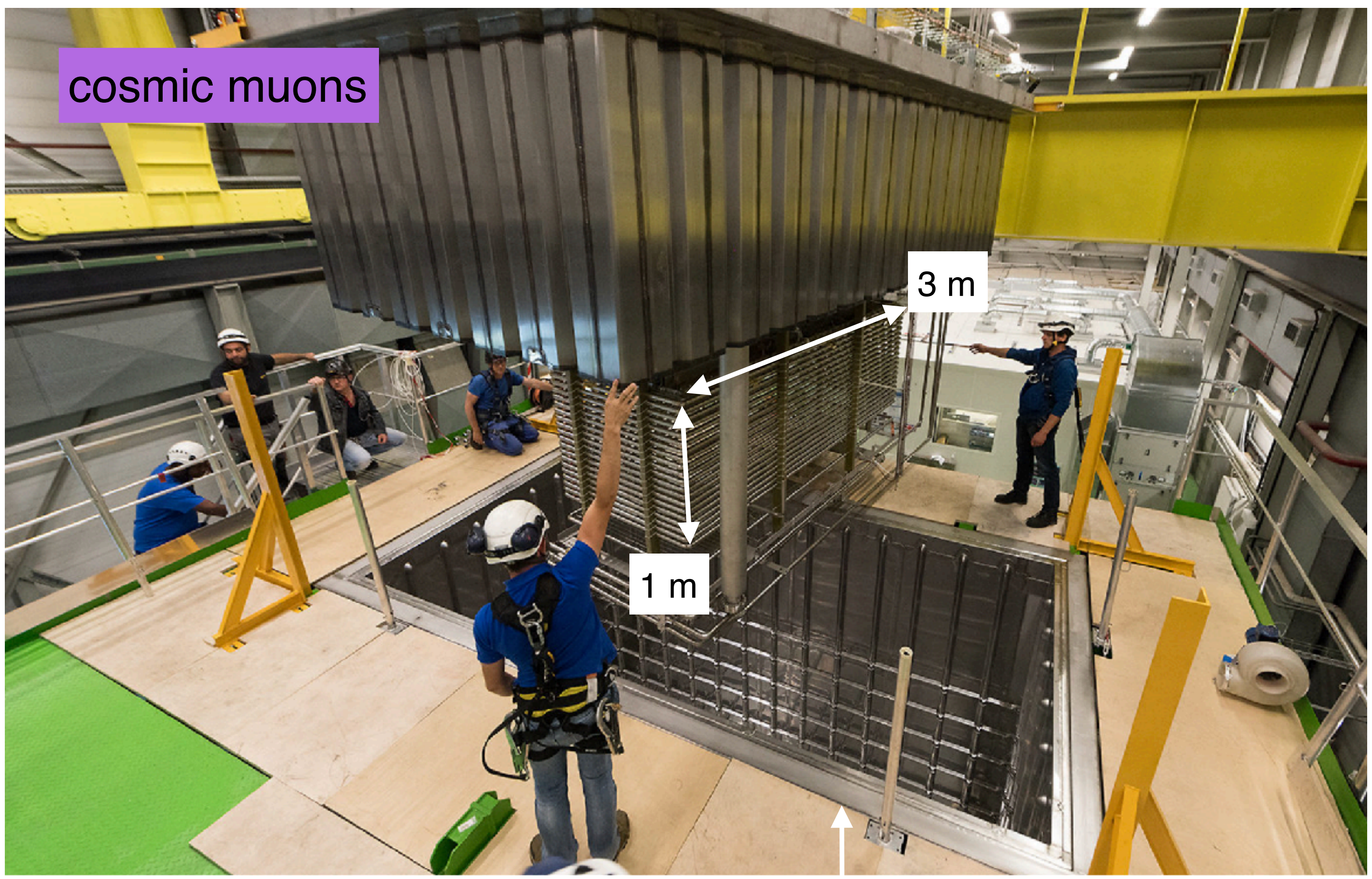
cea SACLAY

IFIN-HH

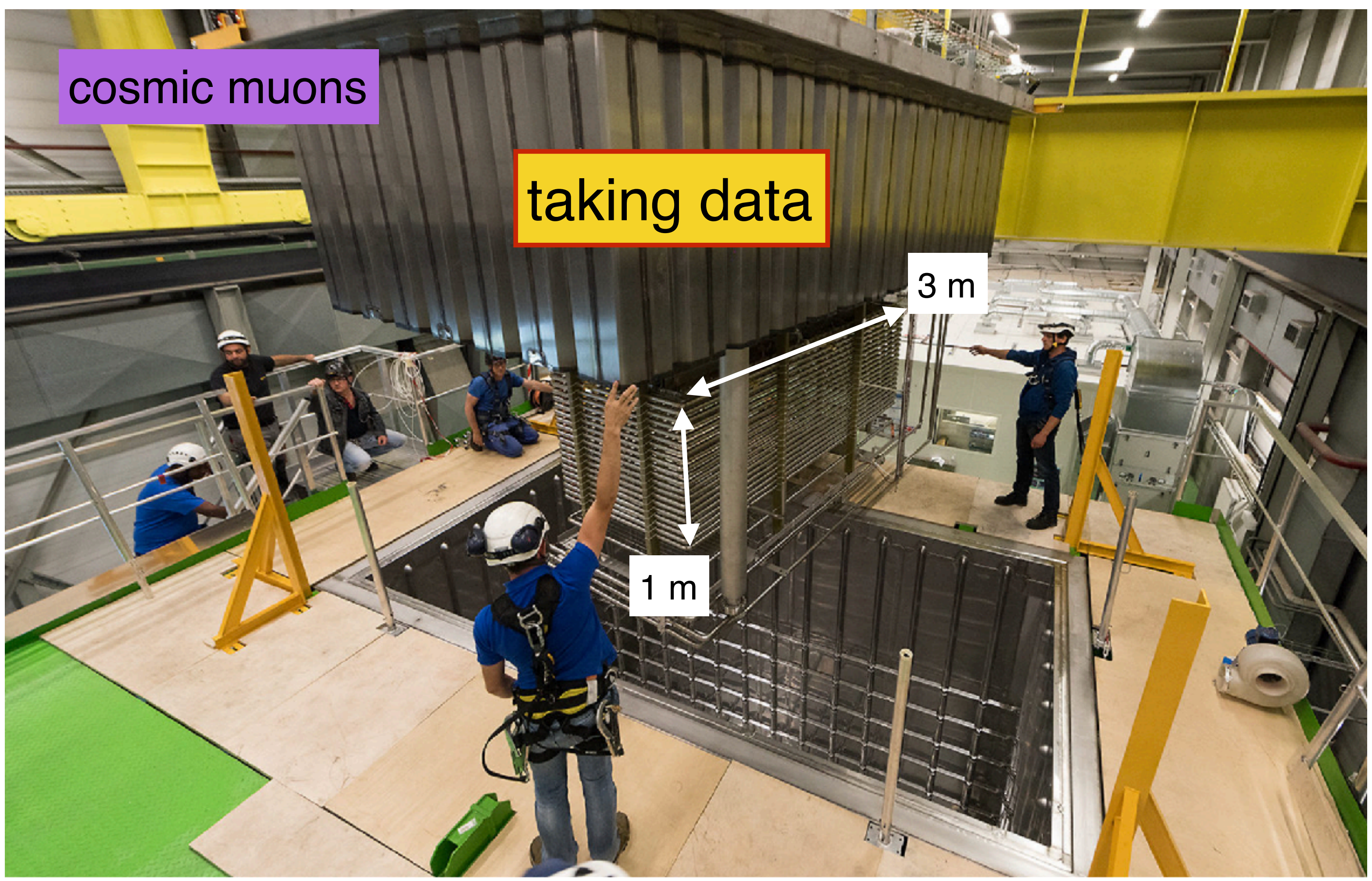
UBR

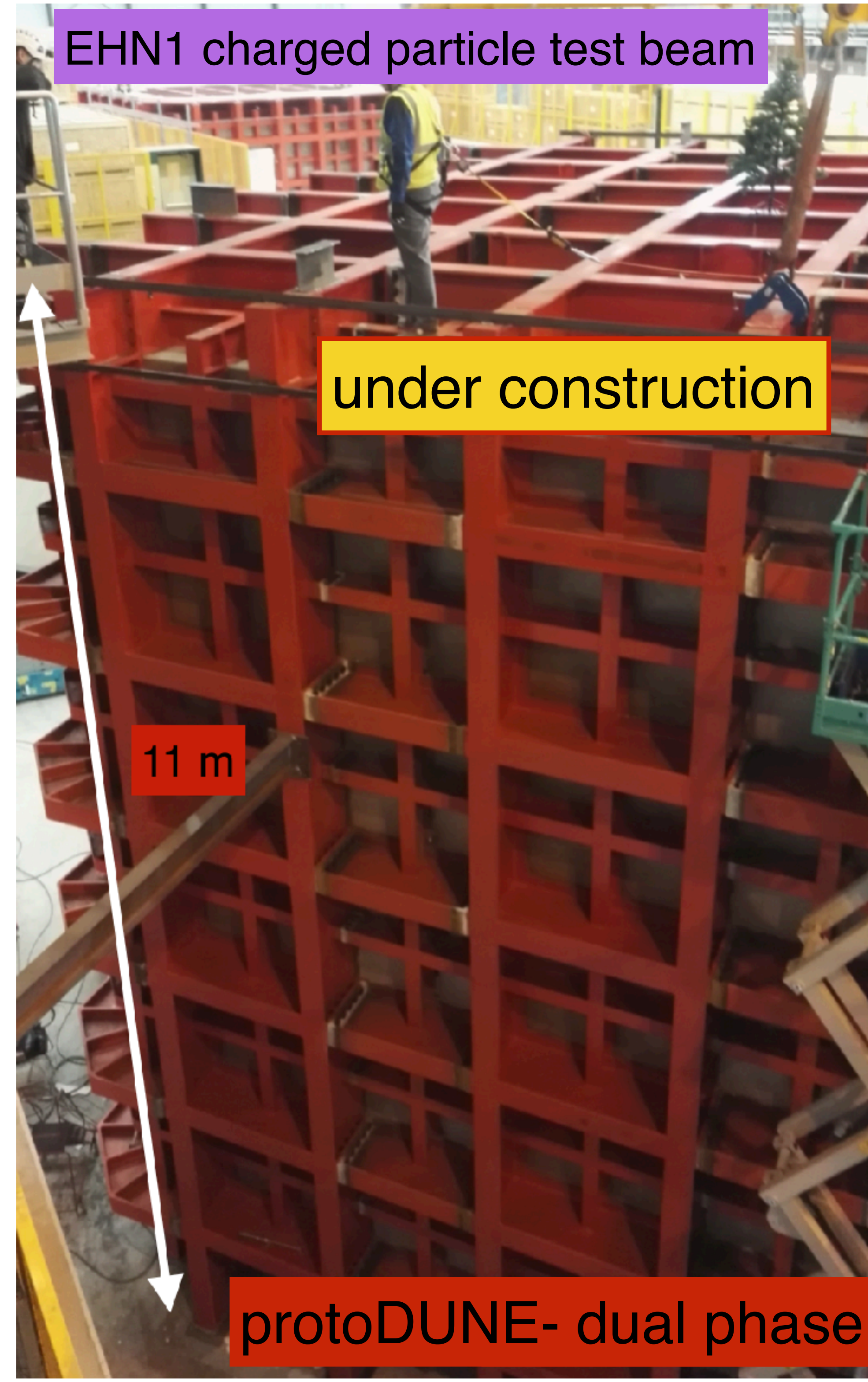
LAr-TPC prototyping at CERN for DUNE

same technology, two scales, different goals



LAr-TPC prototyping at CERN for DUNE

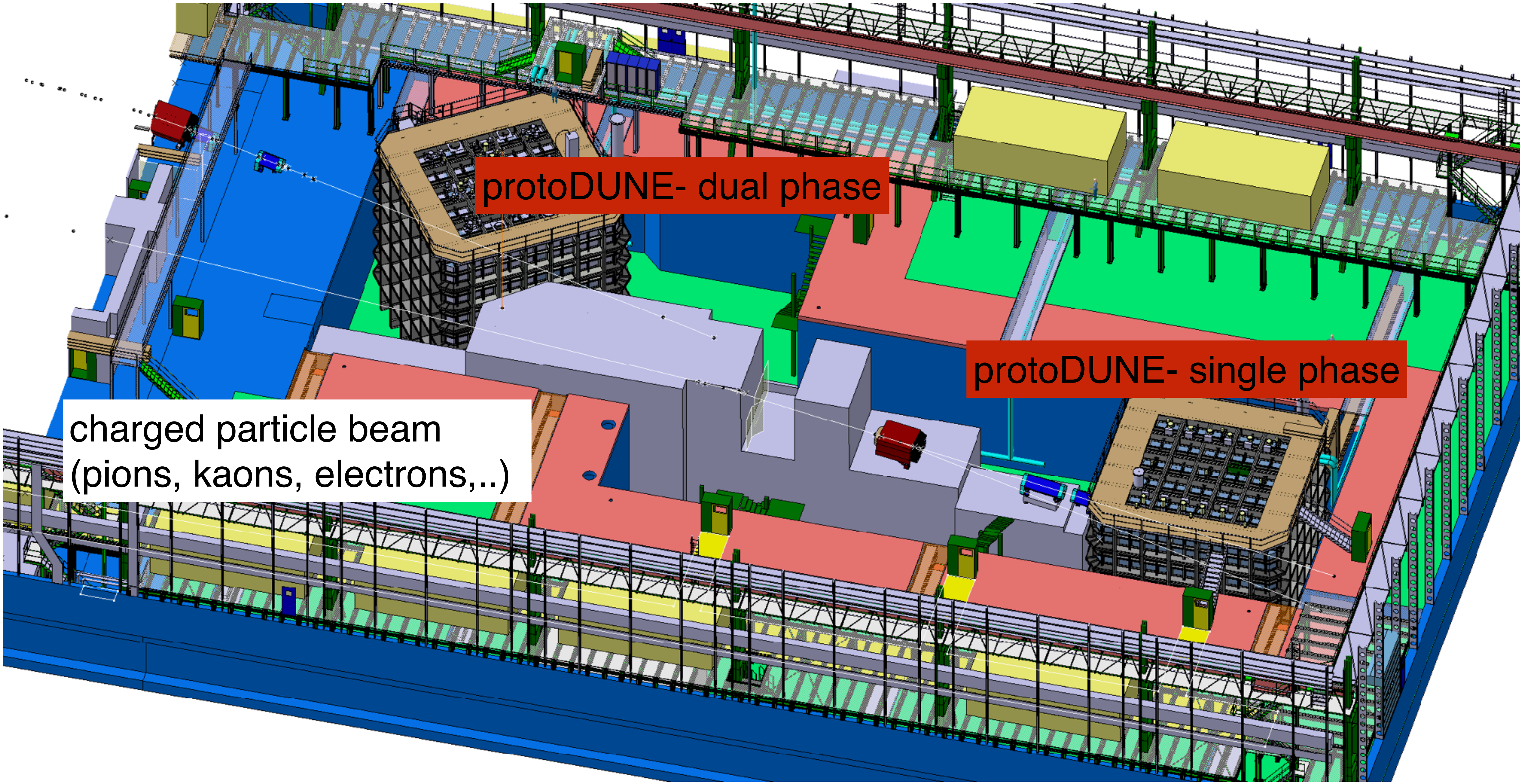




Since 2014 and the creation of the Neutrino platform. CERN has been significantly involved in the developments of large LAr TPCs prototypes.

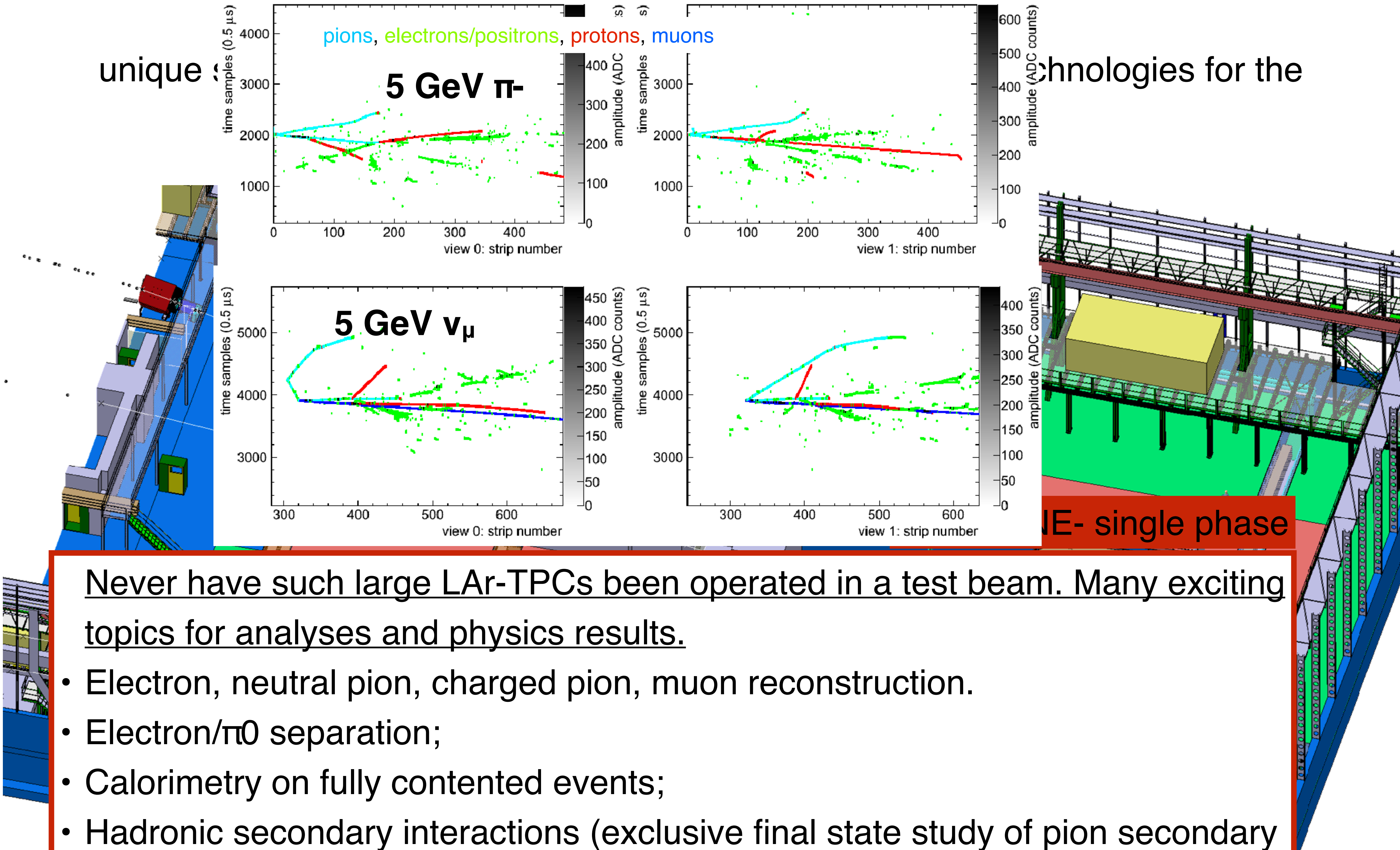
protoDUNE in EHN1 extension

unique setup to test and compare the performance of both technologies for the DUNE far detector



protoDUNE in EHN1 extension

unique s… chnologies for the



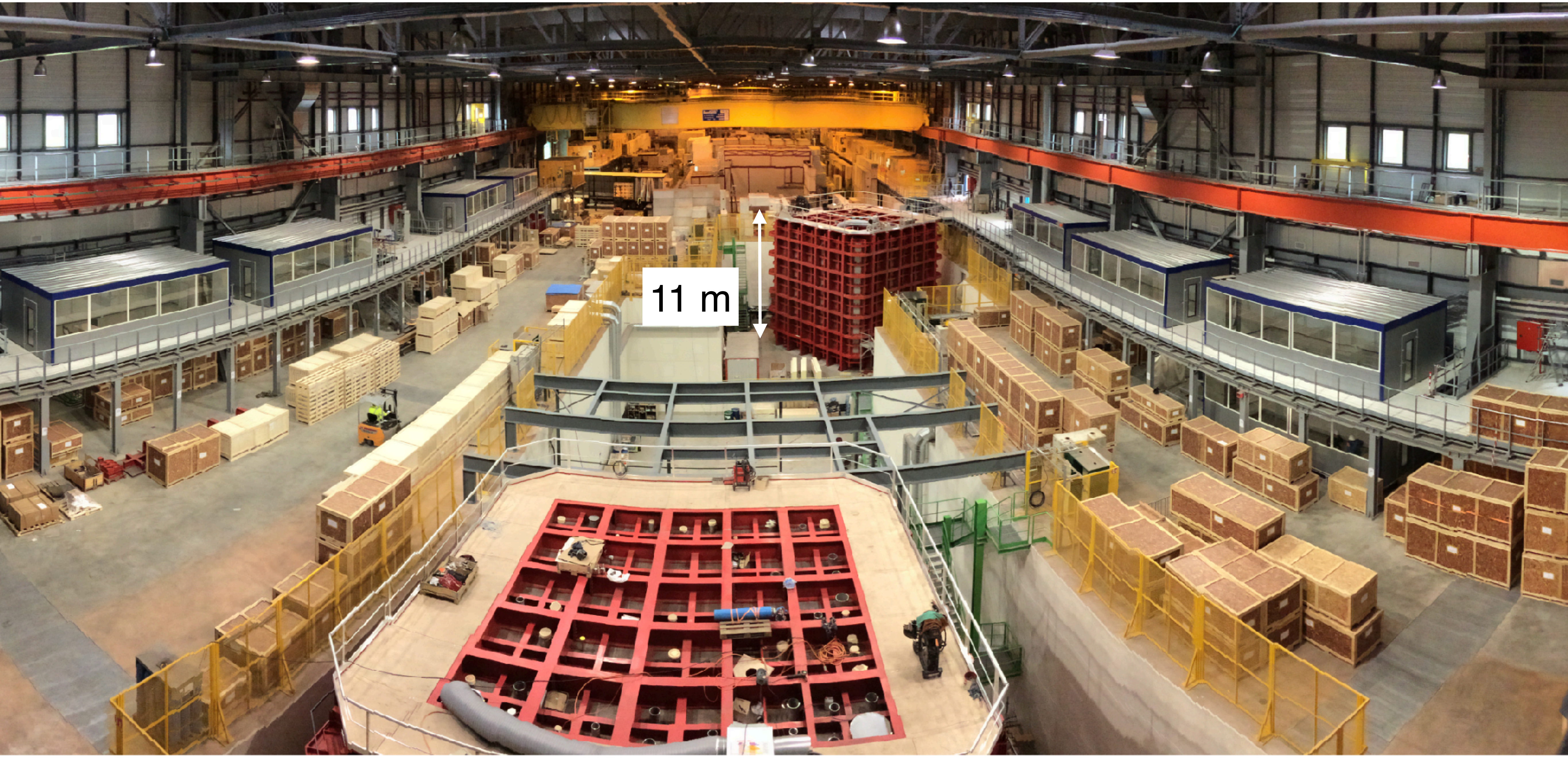
…NE- single phase

Never have such large LAr-TPCs been operated in a test beam. Many exciting topics for analyses and physics results.

- Electron, neutral pion, charged pion, muon reconstruction.
- Electron/π0 separation;
- Calorimetry on fully contented events;
- Hadronic secondary interactions (exclusive final state study of pion secondary interactions);
- …

Test beam area (EHN1 extension)

during construction of the cryostats (~April 2017)



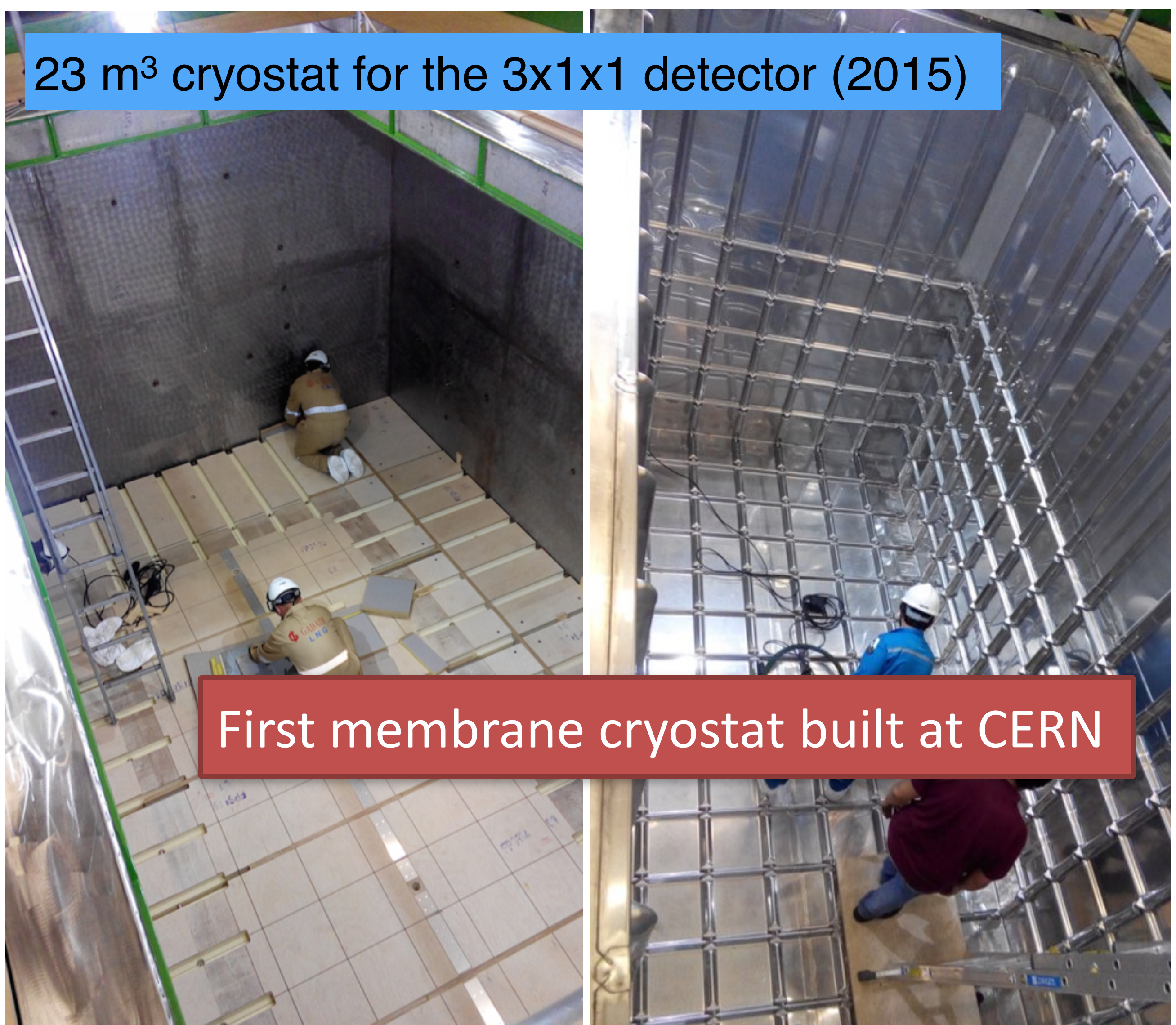
https://twitter.com/cern_fr/status/888415925397049344?refsrc=email&s=11

The cryostats

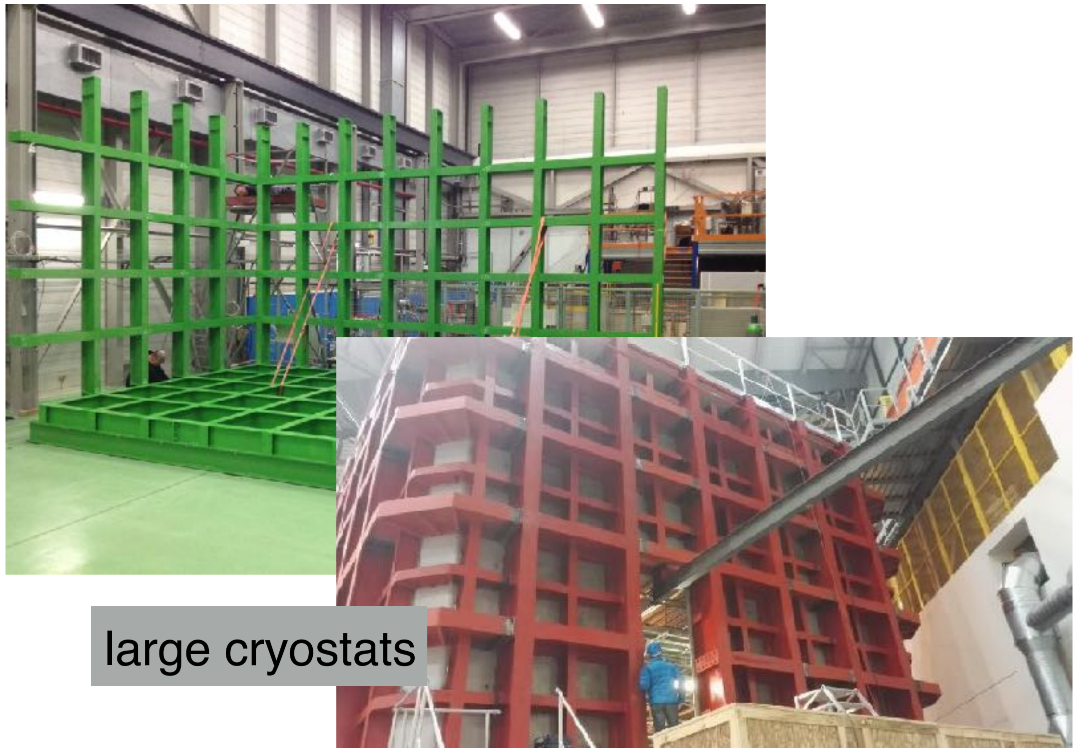
<u>Insulation:</u>

- passive insulation <1 meter thick made from blocks of Polyurethane+plywood. <u>designed for 5 W/m² heat input.</u>
- inner surface made from corrugated "membrane"steel panels welded together.
- Tightness of welds tested to 1e-9 mbar l/s.

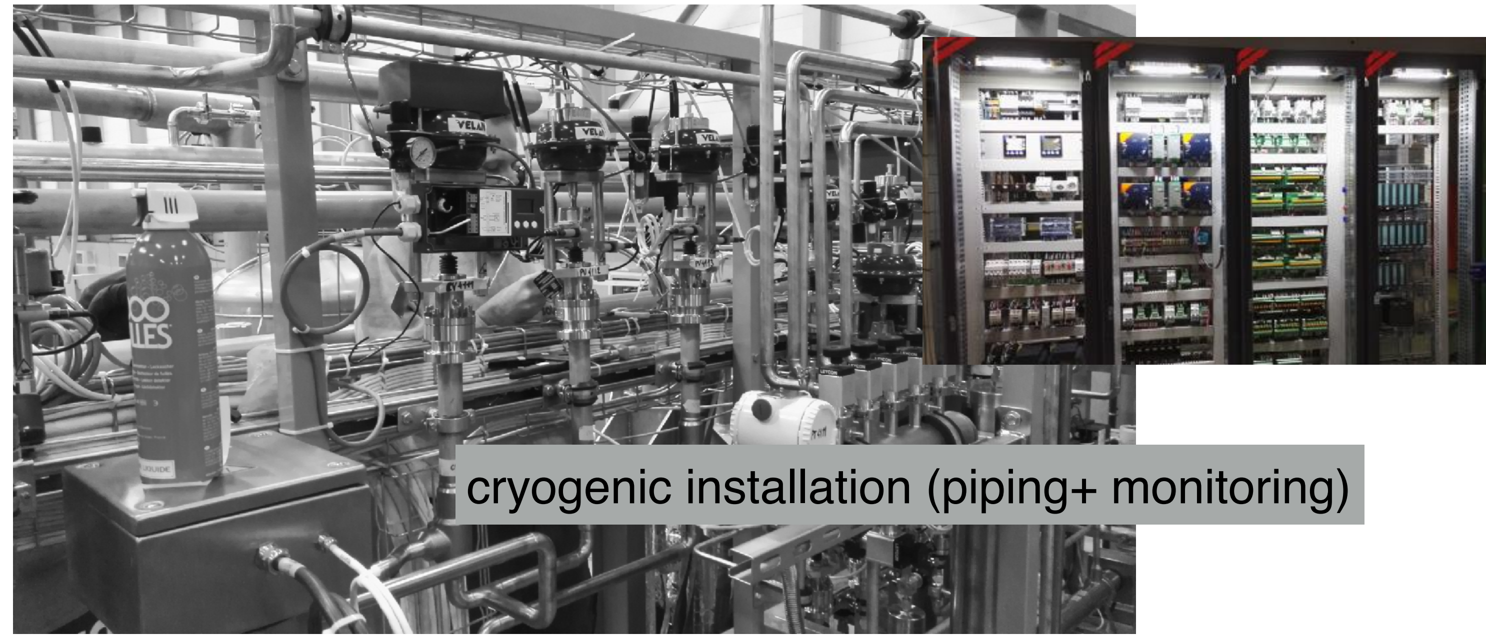
The cryostat itself is an important part of the R&D.
GTT (France) licence. Corrugated membrane steel panels used for storage and transport of Liquified Natural Gas.



The role of CERN and Neutrino platform

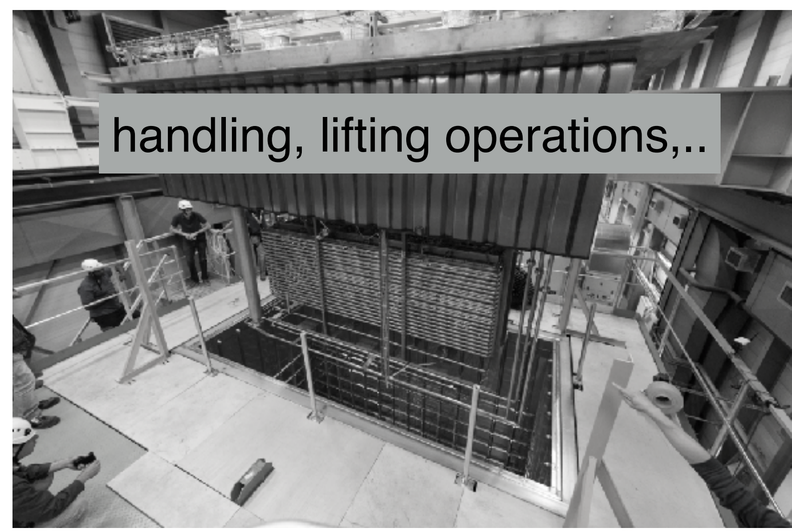


large cryostats



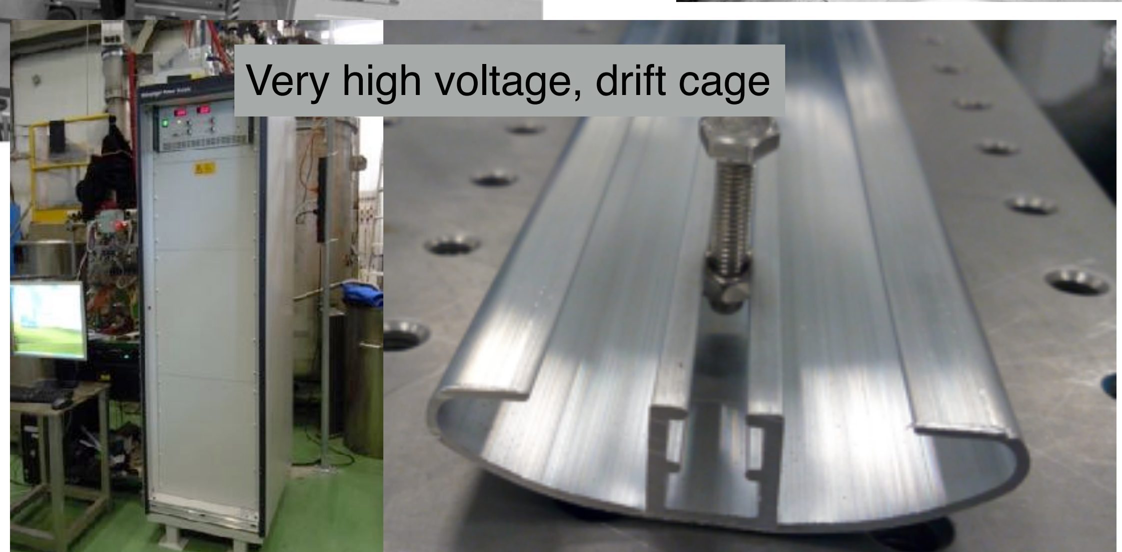
cryogenic installation (piping+ monitoring)

infrastructure (clean room, structures,..) & safety



handling, lifting operations,..

Detector slow control and monitoring

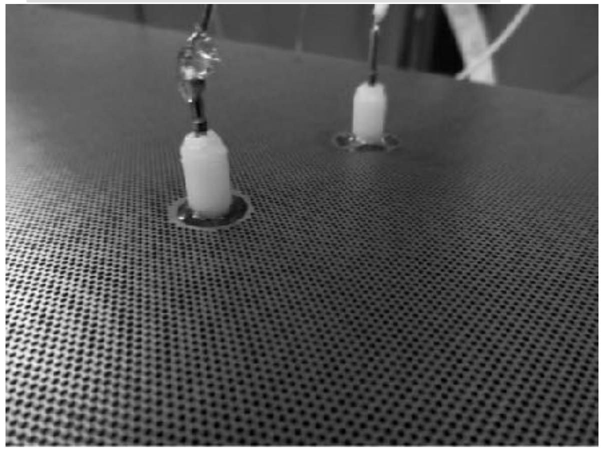


Very high voltage, drift cage

The role of CERN

in addition to the support from Neutrino Platform, important assistance from many CERN groups and labs

anode+LEM: EP-DT-EF

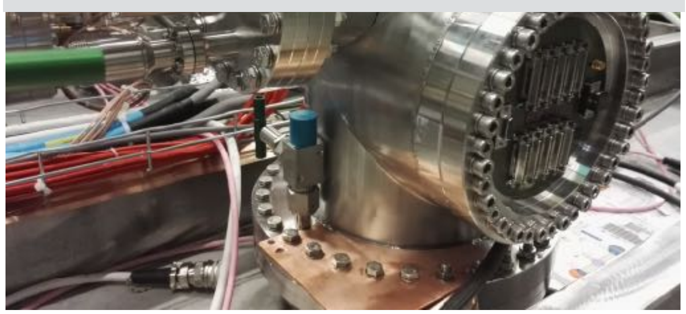


photogrammetry + survey EN-ACE-SU

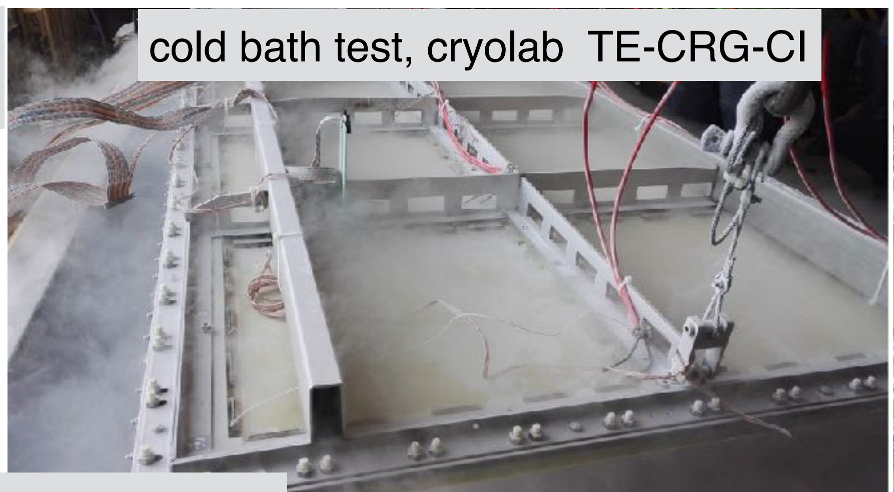
polymers: TE-MSC-MDT

PMT coating and qualification EP-DT-EF

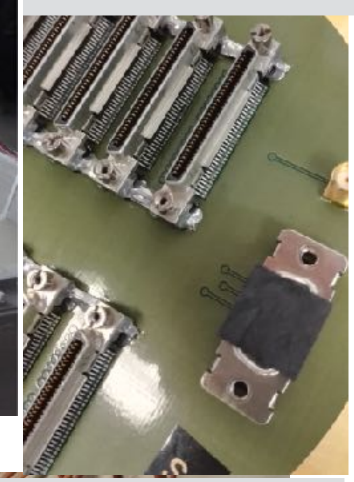
cabling and grounding installation EP-DT-DI



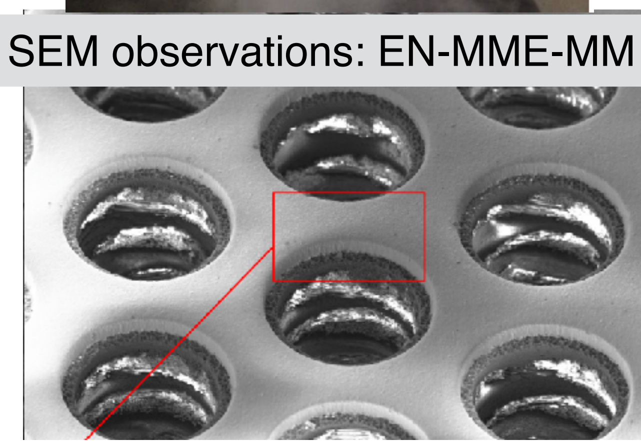
cold bath test, cryolab TE-CRG-CI



SMD soldering TE-MPE-EM

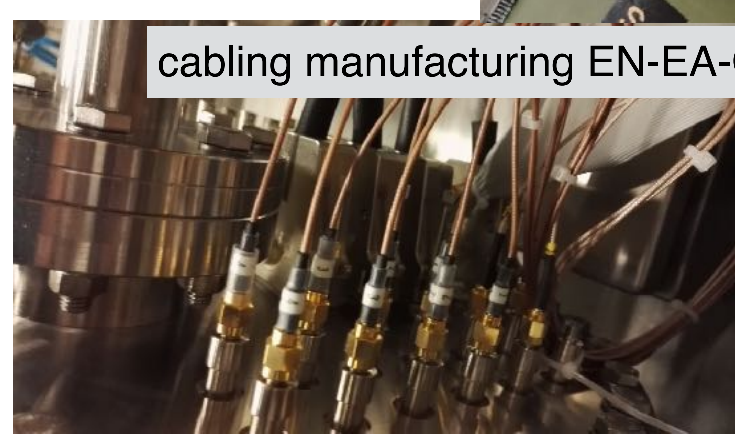


SEM observations: EN-MME-MM

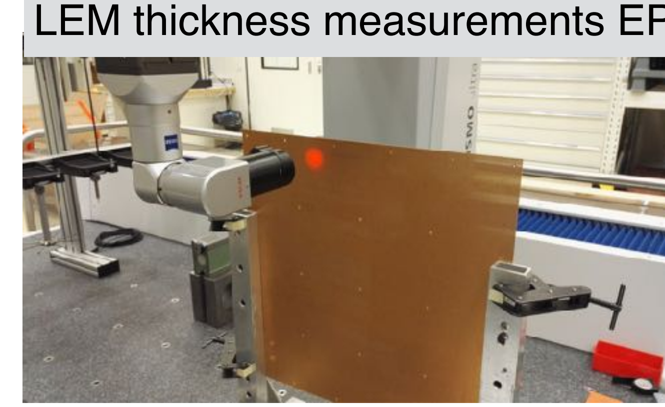


drift cage profile bending: EN-MME-FW main workshop

cabling manufacturing EN-EA-CT

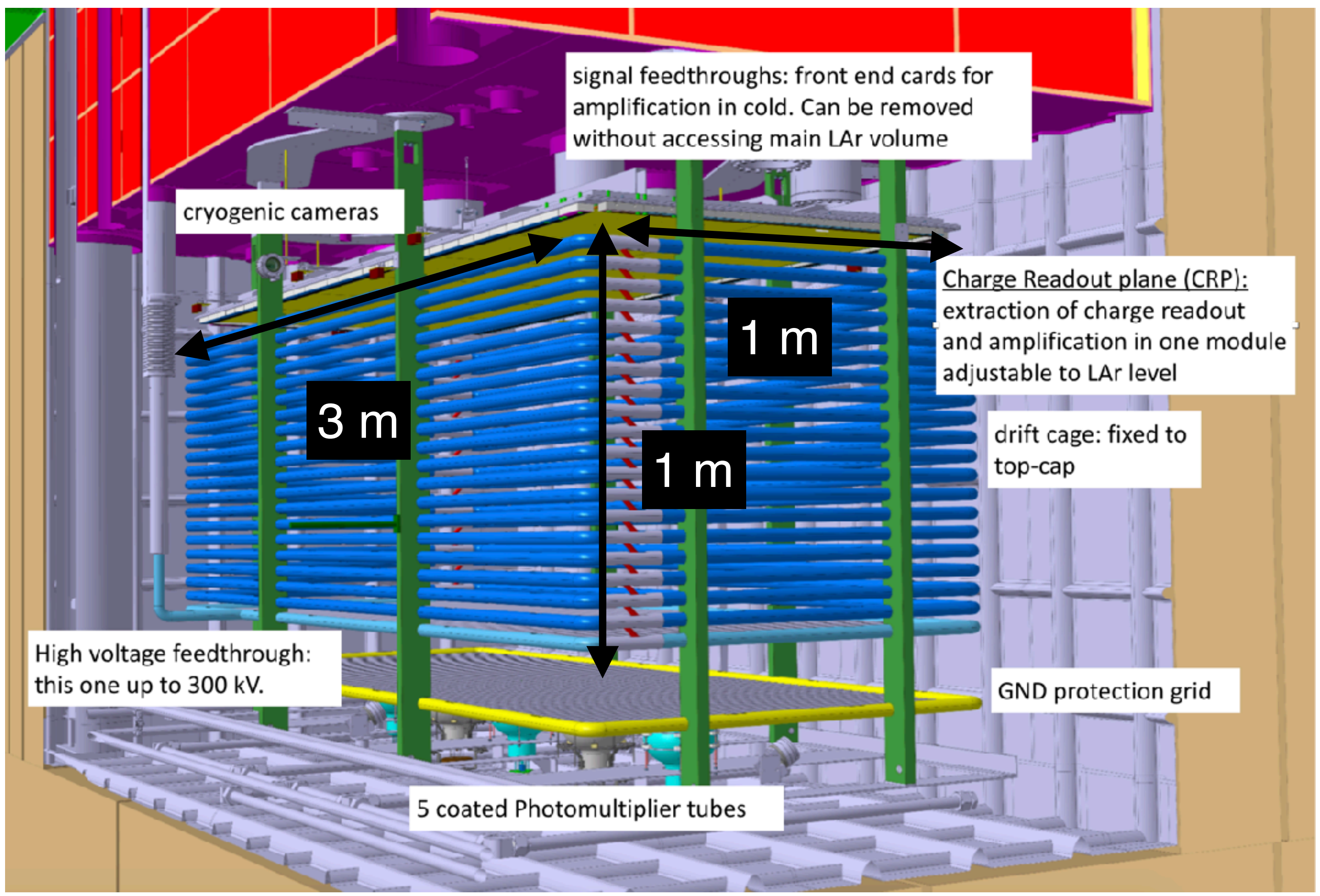


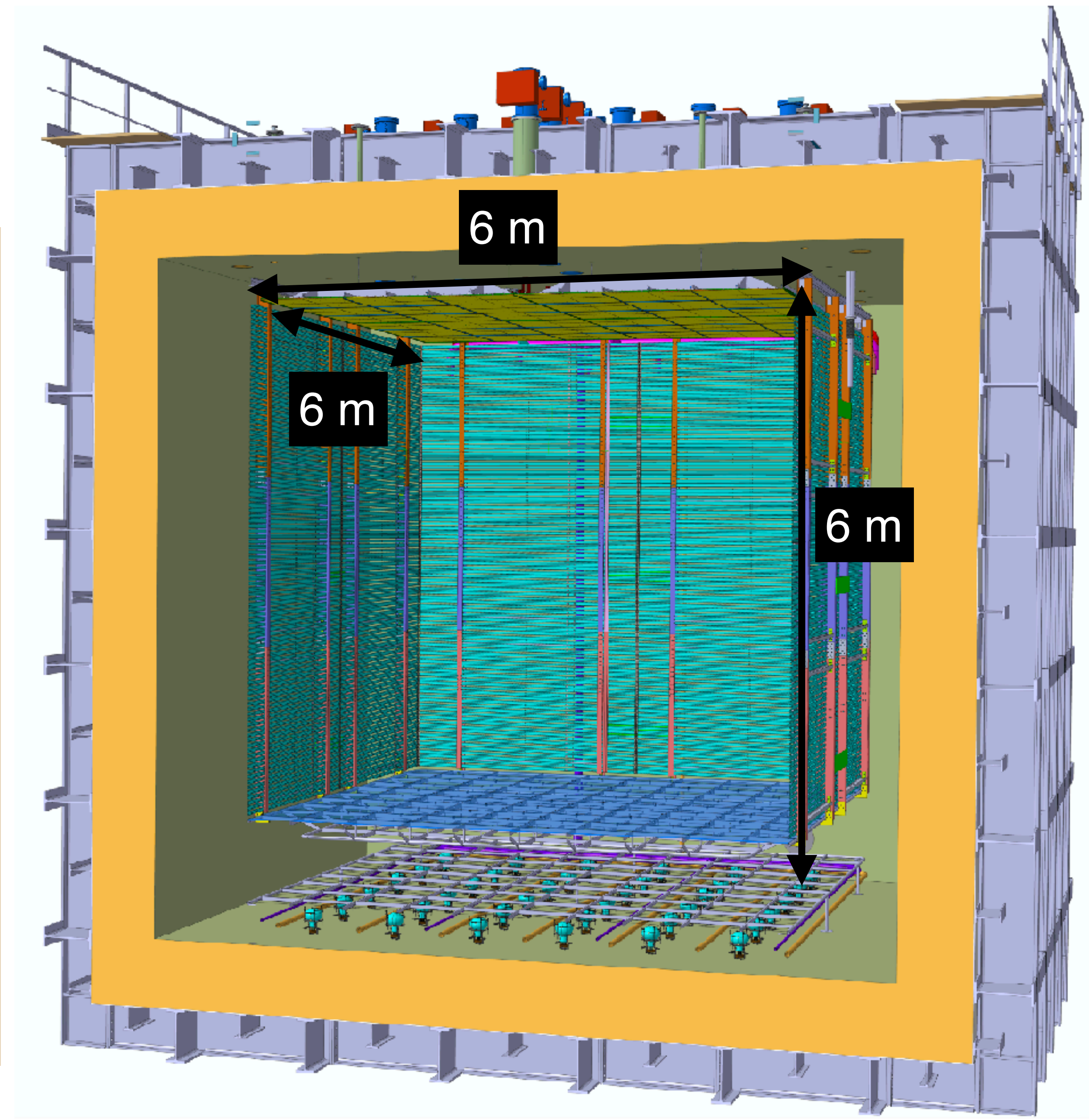
LEM thickness measurements EP-UAT



The WA105 TPCs

1. TBP coated photomultipliers at the bottom
2. large monolithic drift cage meter long drift.
3. independent frames (CRPs) at the top performing the Charge extraction, amplification and readout.
4. Feedthroughs for signal, high voltage,..





The WA105 TPCs

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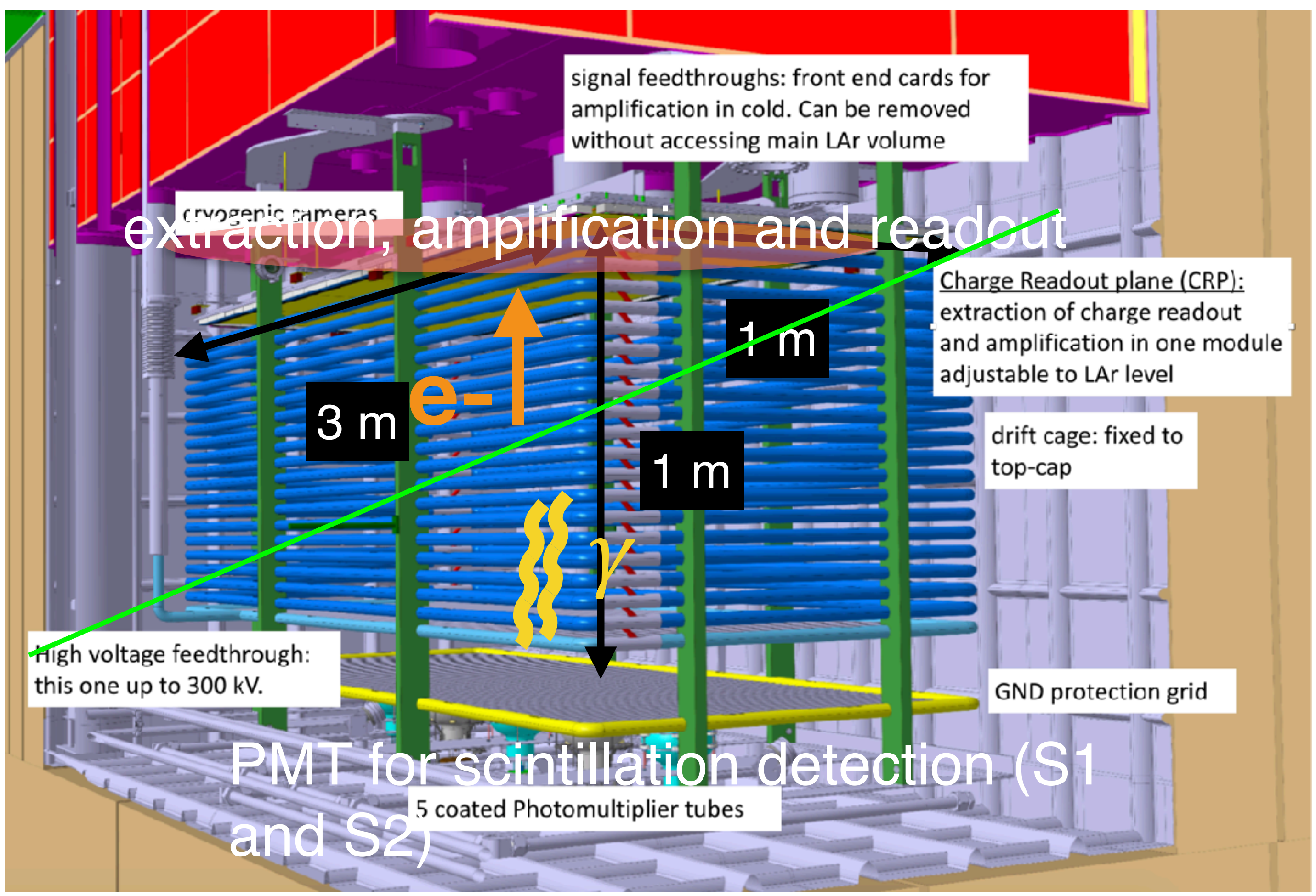

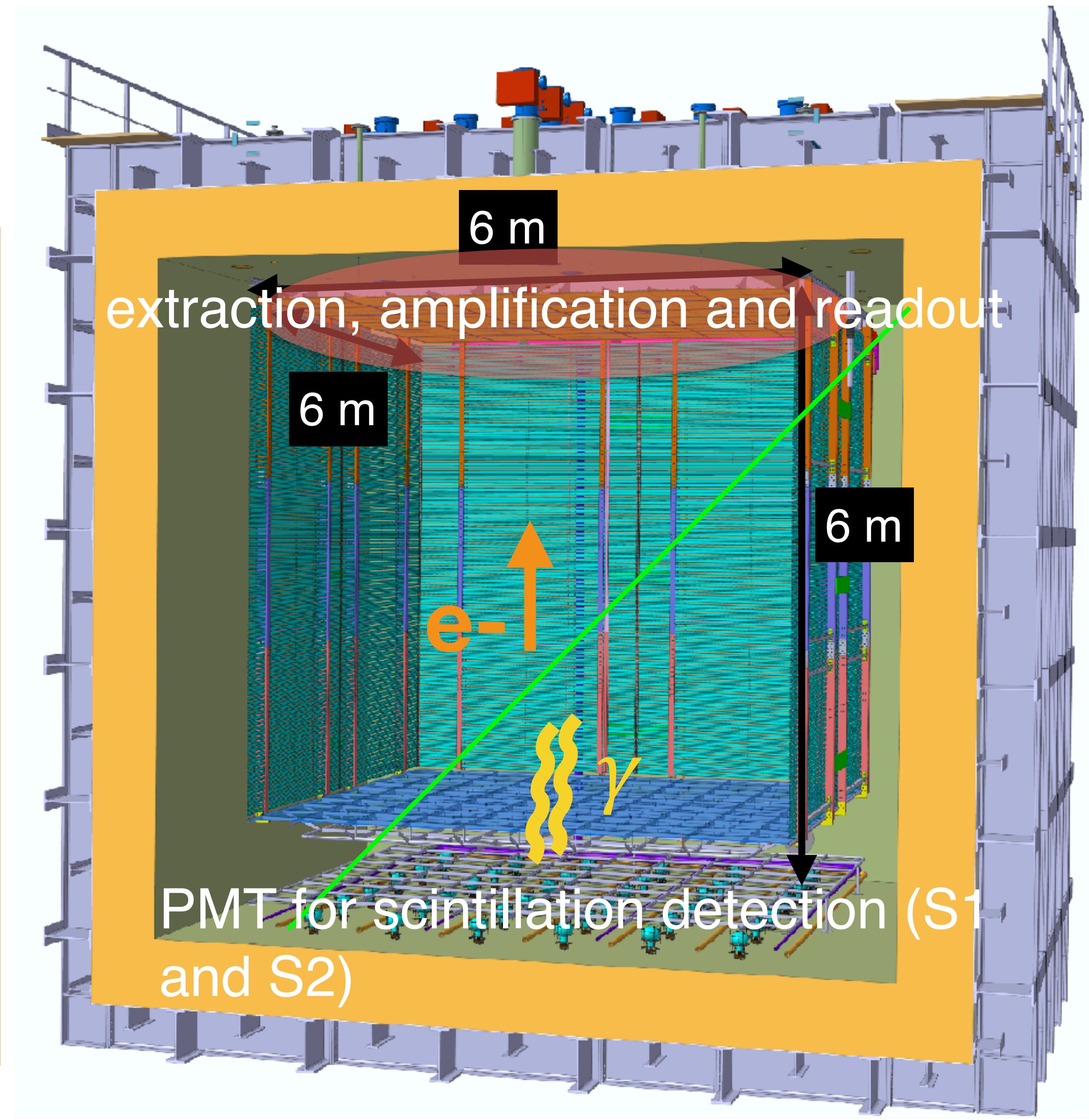

The WA105 TPCs

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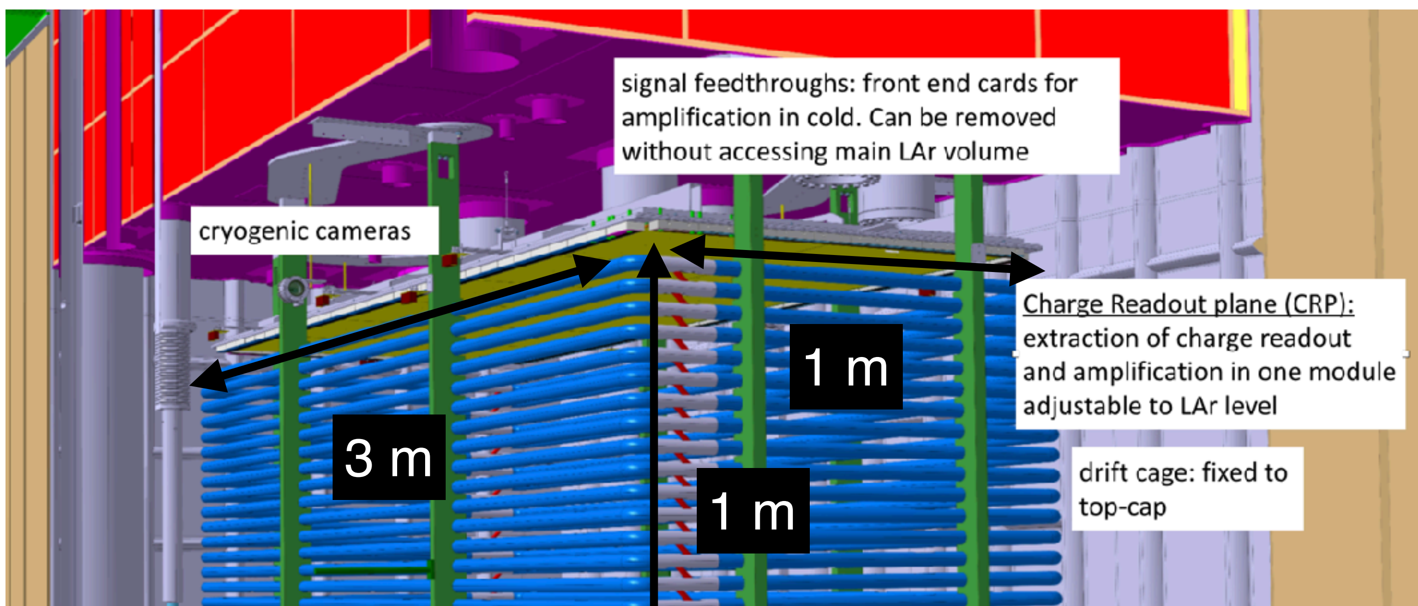
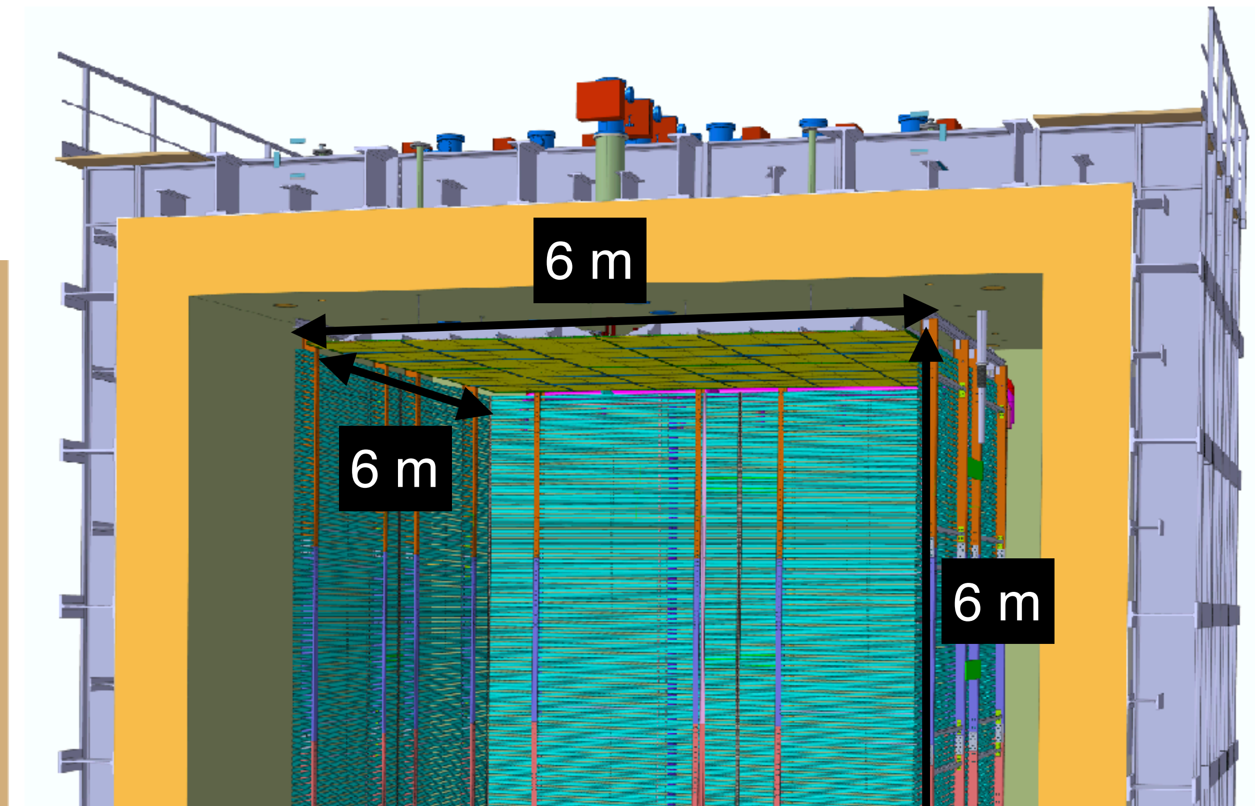


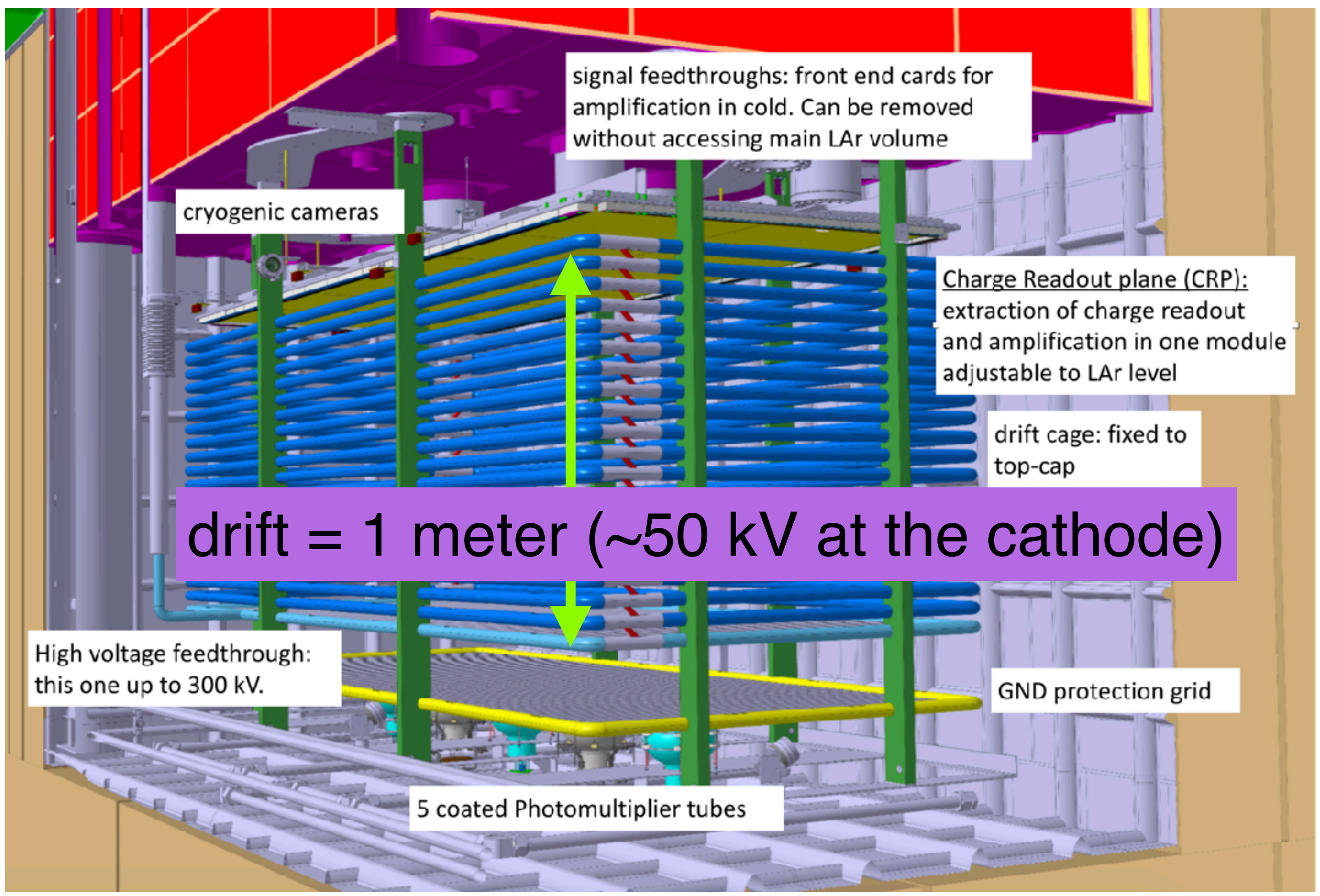
- test of extraction amplification and readout on square meter areas
- all instrumentation and feedthroughs
- QA/QC aspects
- light readout
- purity in non evacuable cryostat

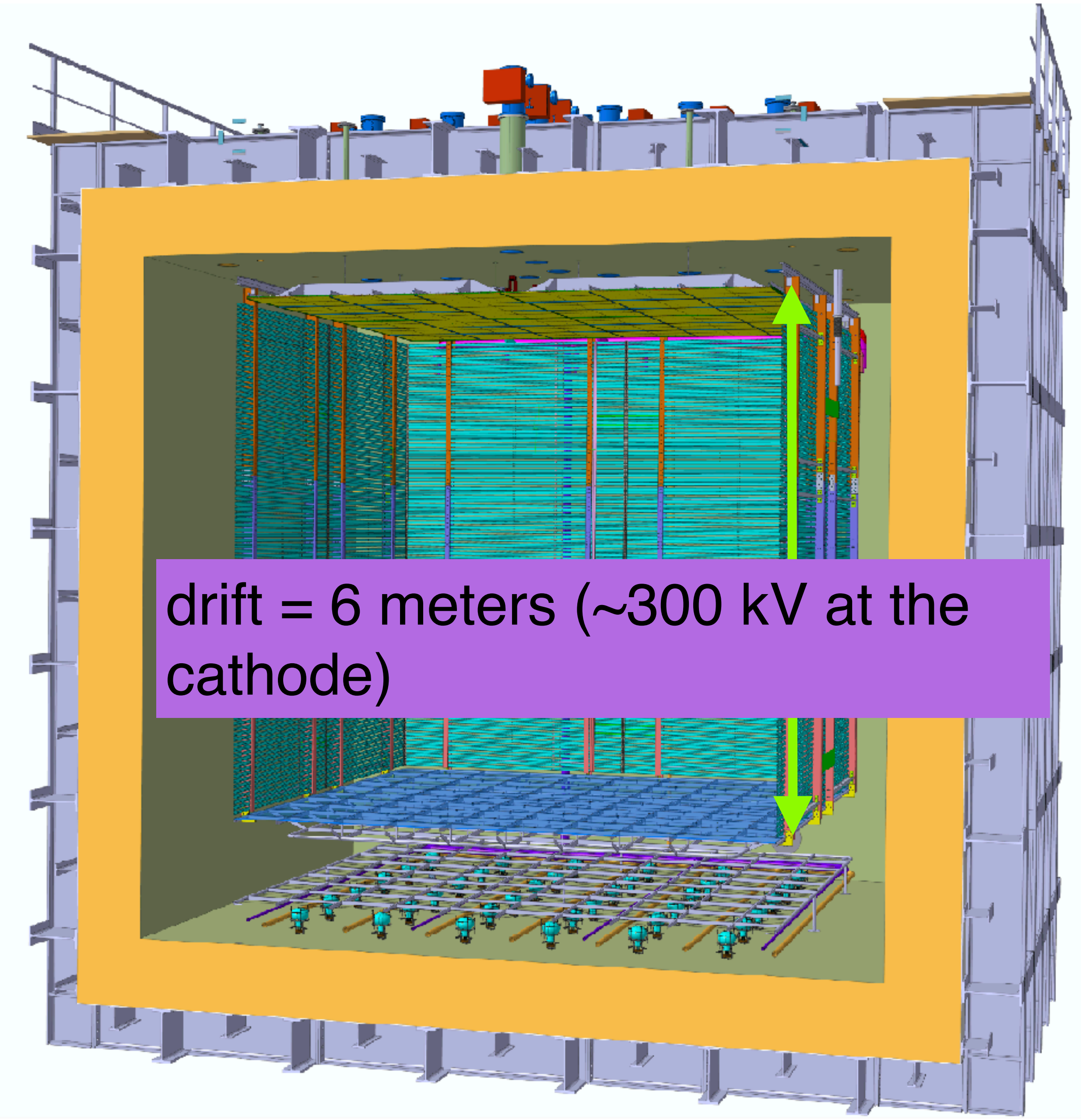


- long drift and very high voltage
- almost all detector aspects are identical to those foreseen for the 10 kt
- The installation sequence is also similar to the underground deployment of the 10 kt

The WA105 TPCs

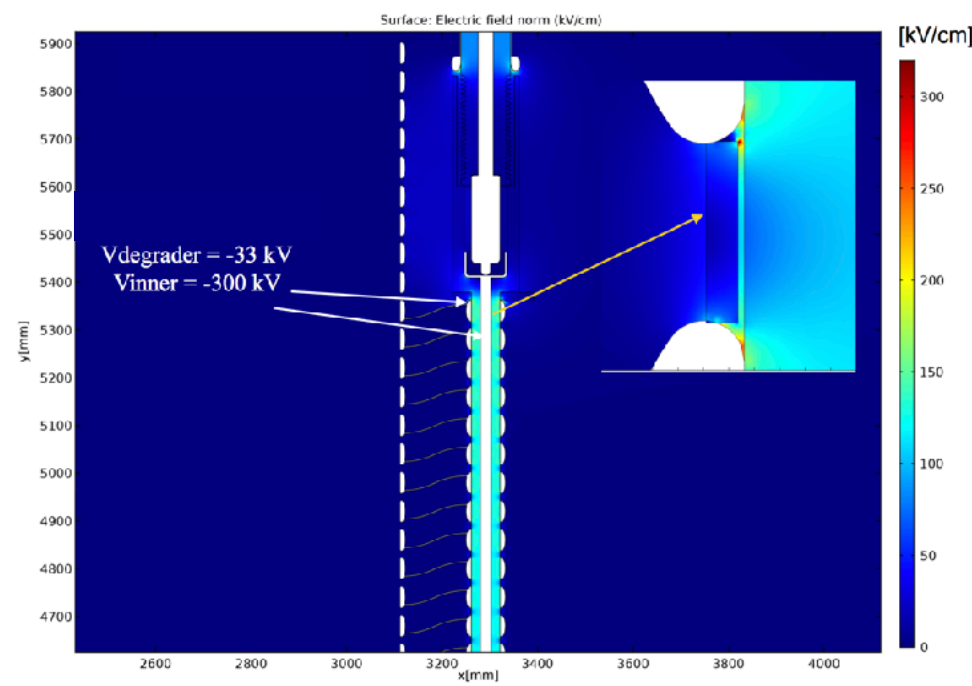
- TBP coated photomultipliers at the bottom
- large monolithic drift cage meter long drift.
- independent frames (CRPs) at the top performing the Charge extraction, amplification and readout.
- Feedthroughs for signal, high voltage,..



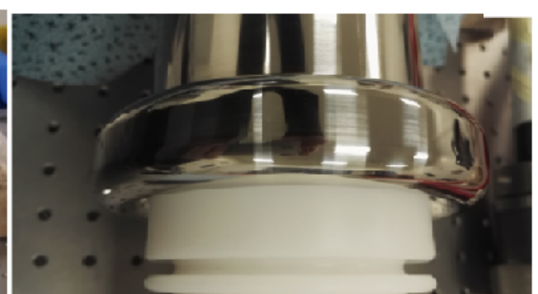


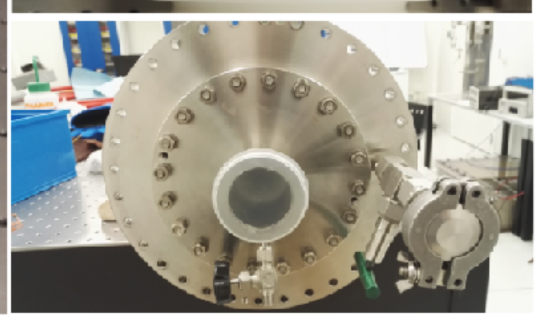
Very high voltage

Tested, installed and are operating a 300 kV capable feedthrough inside the 3x1x1



Heinzinger 300 kV PSU

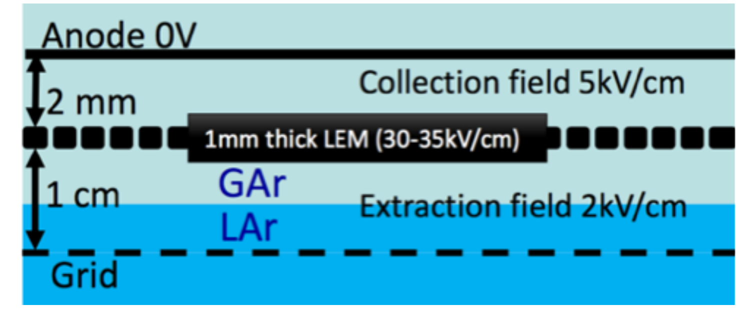


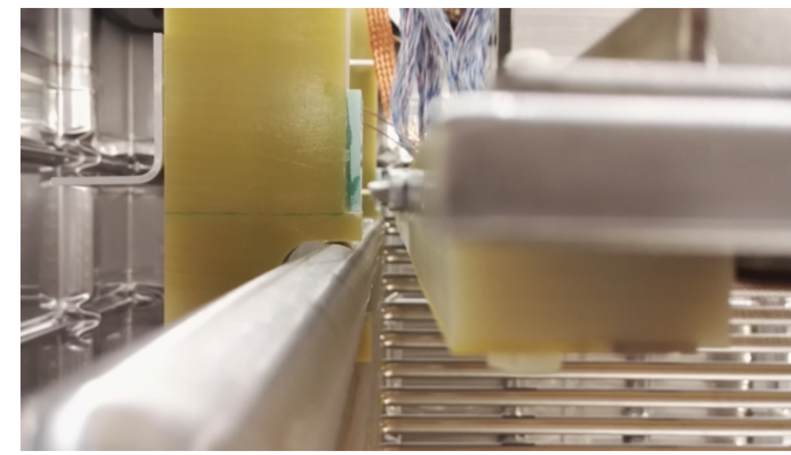


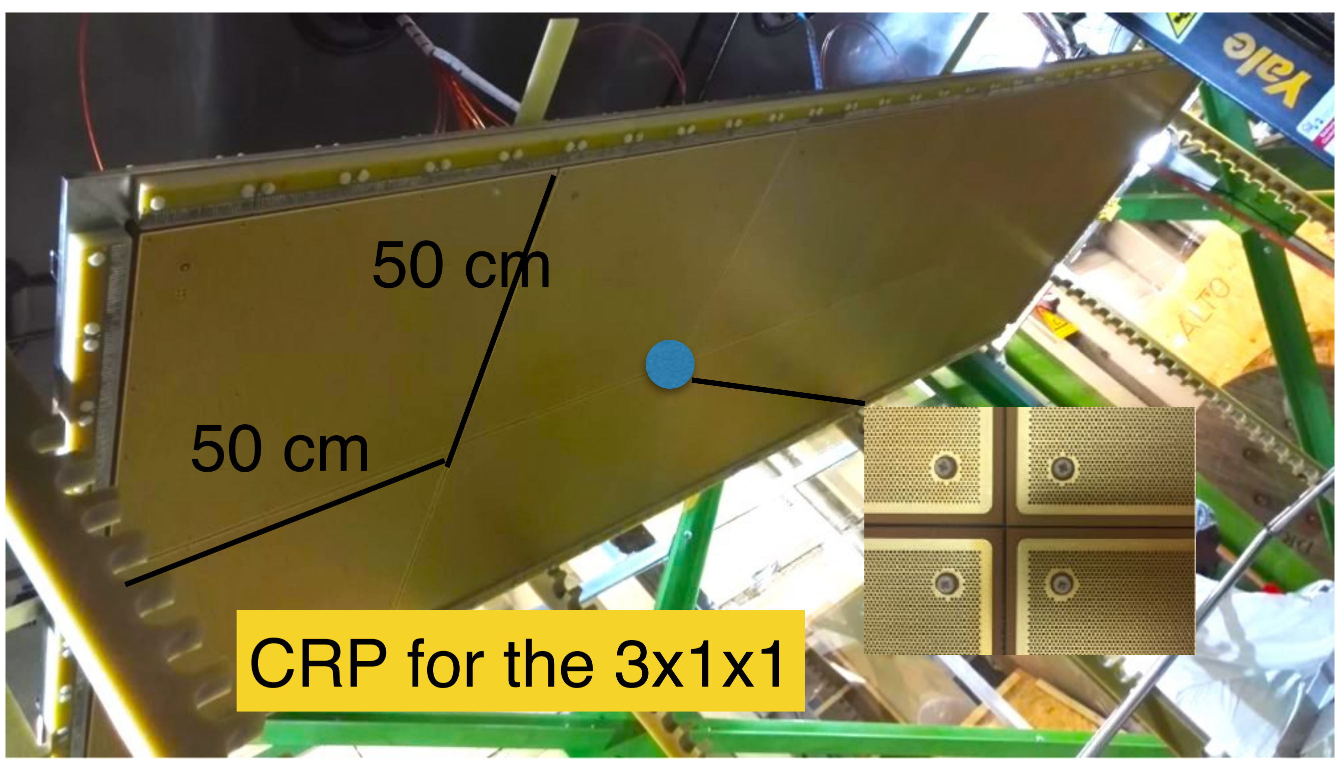
Design successfully tested in dedicated setup up to the end of the scale of the Heinzinger PSU. About 295 kV. JINST 12 P03021 arXiv:1611.02085

Dual phase LAr TPC Charge Readout Section

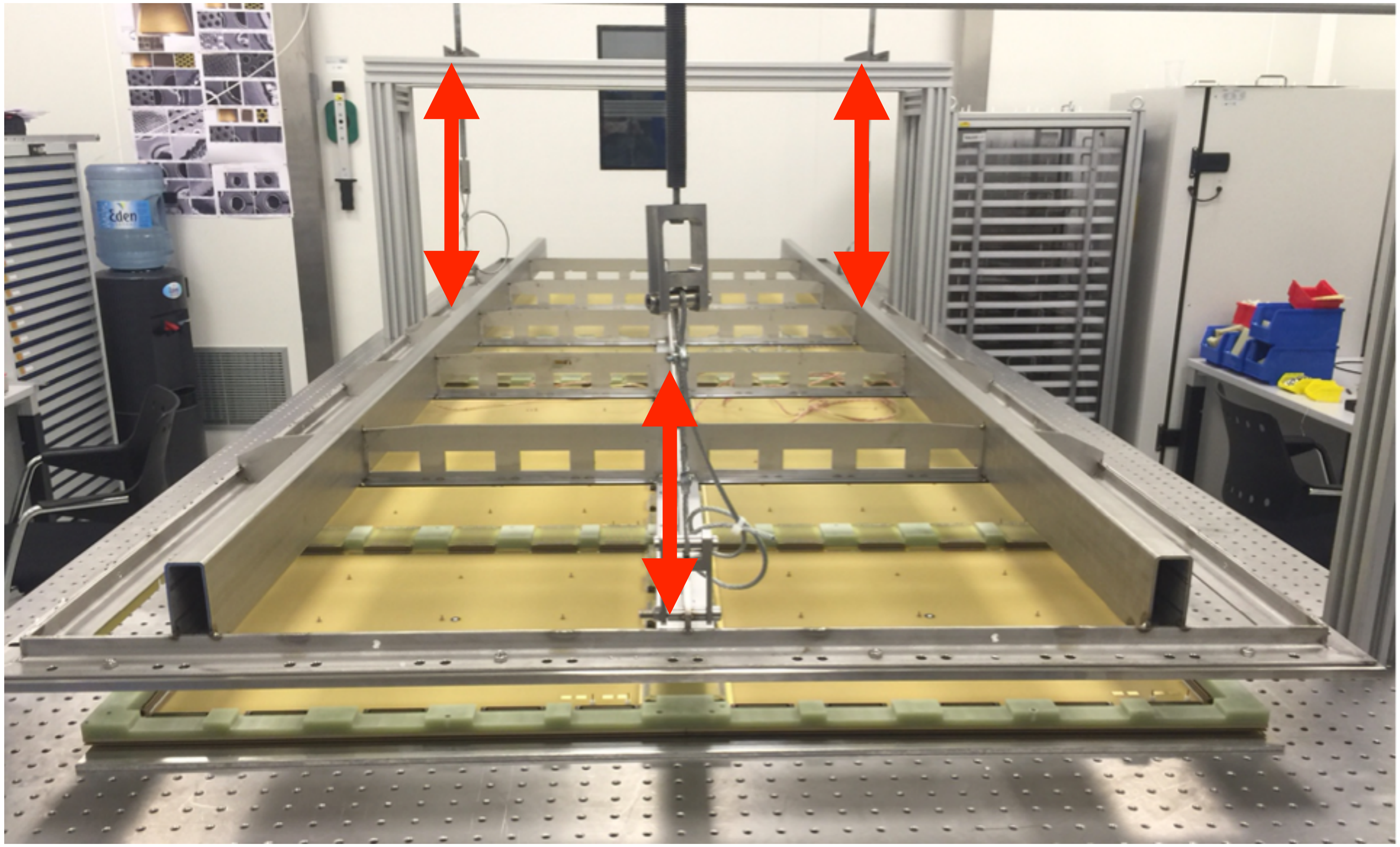
- The grid that provides the charge extraction from liquid to gas, the LEM amplification devices and the anodes are all mounted on a specifically designed frame called **Charge Readout Plane (CRP)**.
- The CRP is designed to precisely maintaining the interstage distances between the grid, LEM and anodes **at warm and cold.**
- The CRP is **modular and independent** from the drift cage, it can be **remotely adjusted** to the liquid argon level in order to align the LEMs and extraction grid with the LAr level

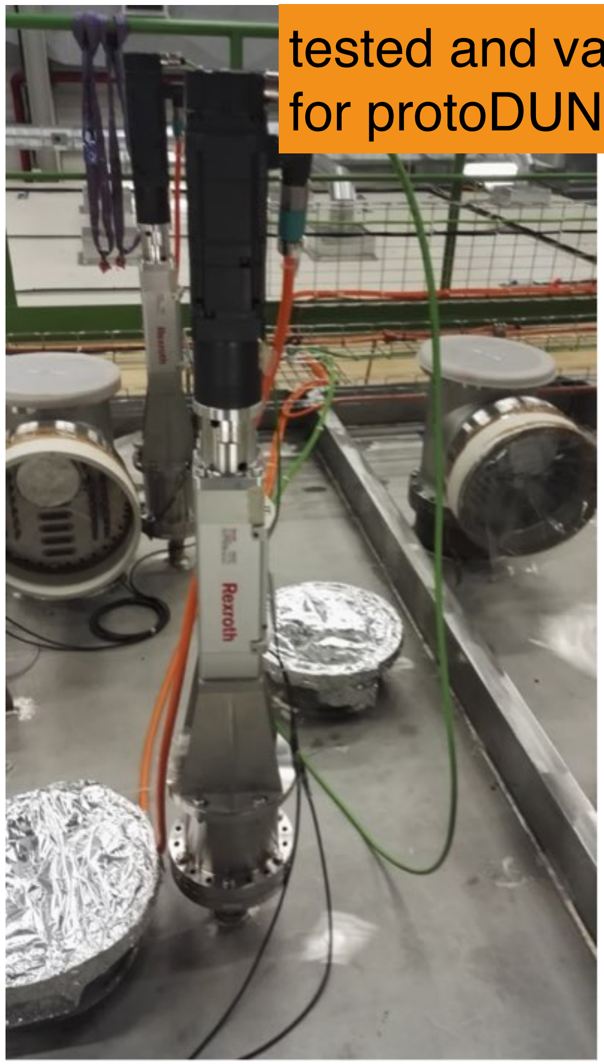




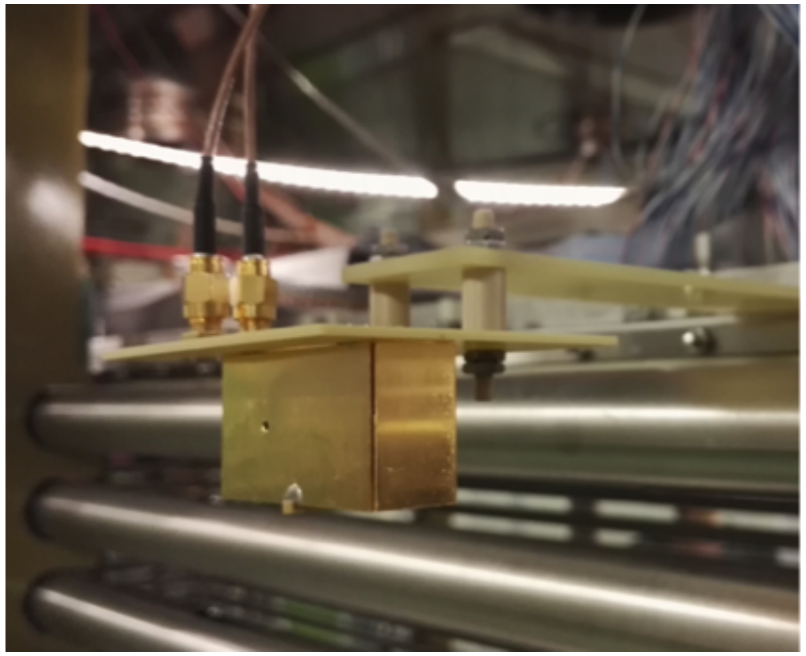


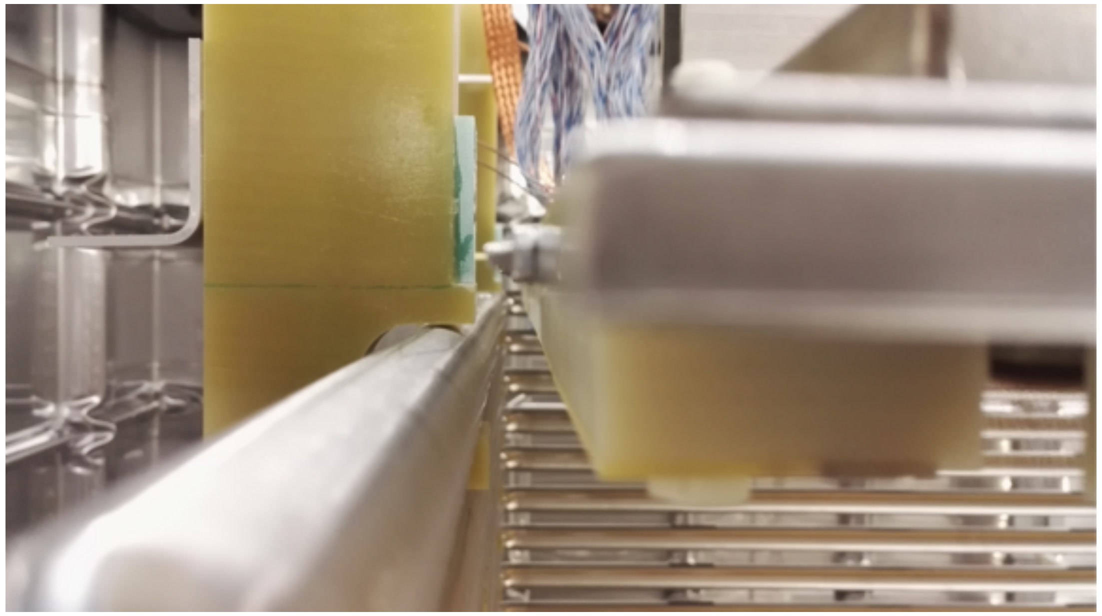
CRP suspension





tested and validated for protoDUNE-DP





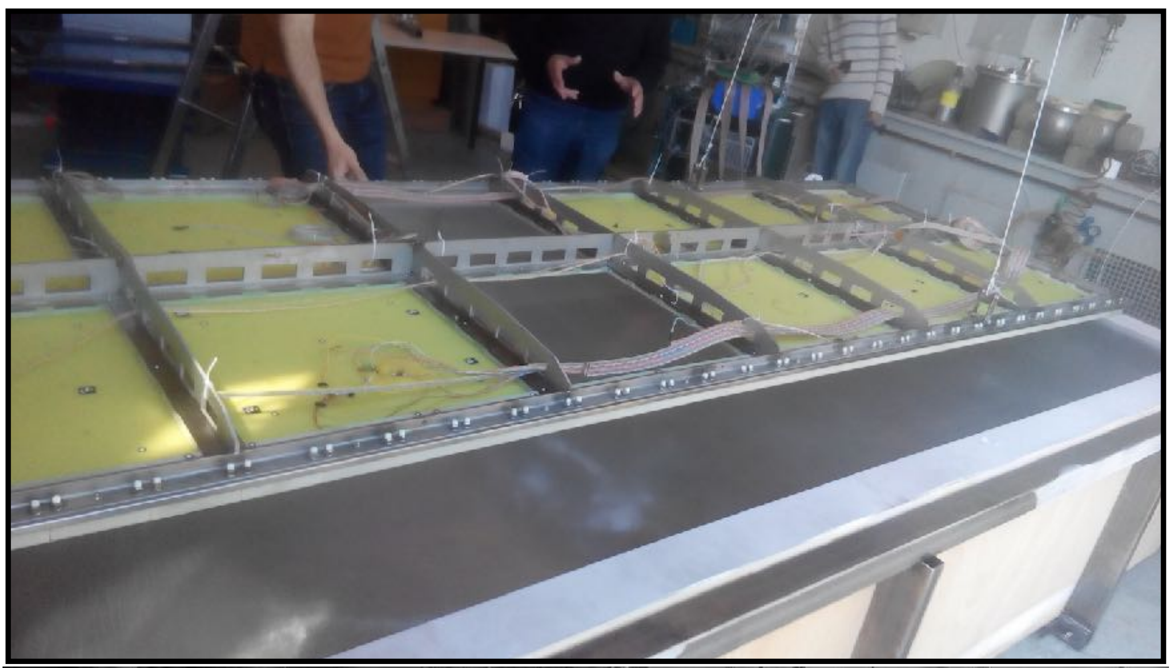
suspended by 3 ropes coupled to motors on top-cap. Precision of motors <u>100 um over 4 cm</u>.
8 capacitive level meters readout the LAr level with similar precision

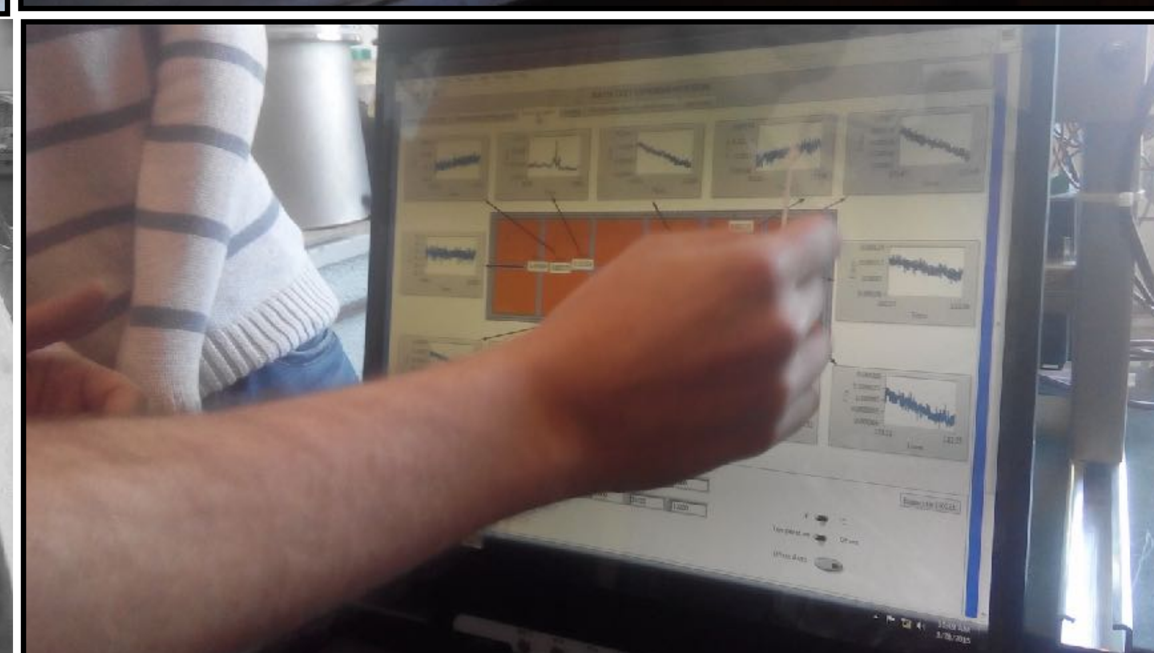
3x1 m2 CRP: resistance to thermal shock

The horizontal geometry of the CRP allows to perform **cryogenic test in open baths**. Already demonstrated for the 3x1x1.

What we checked:

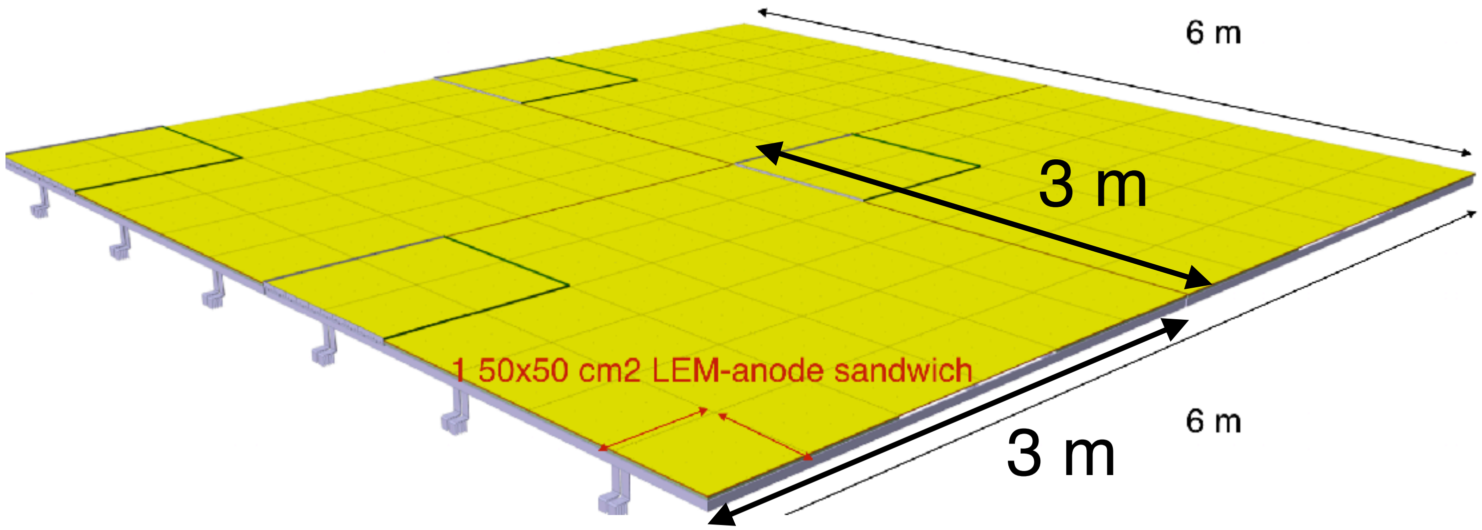
- monitor expected shrinkage with photogrammetric measurements.
- extraction grid robustness.





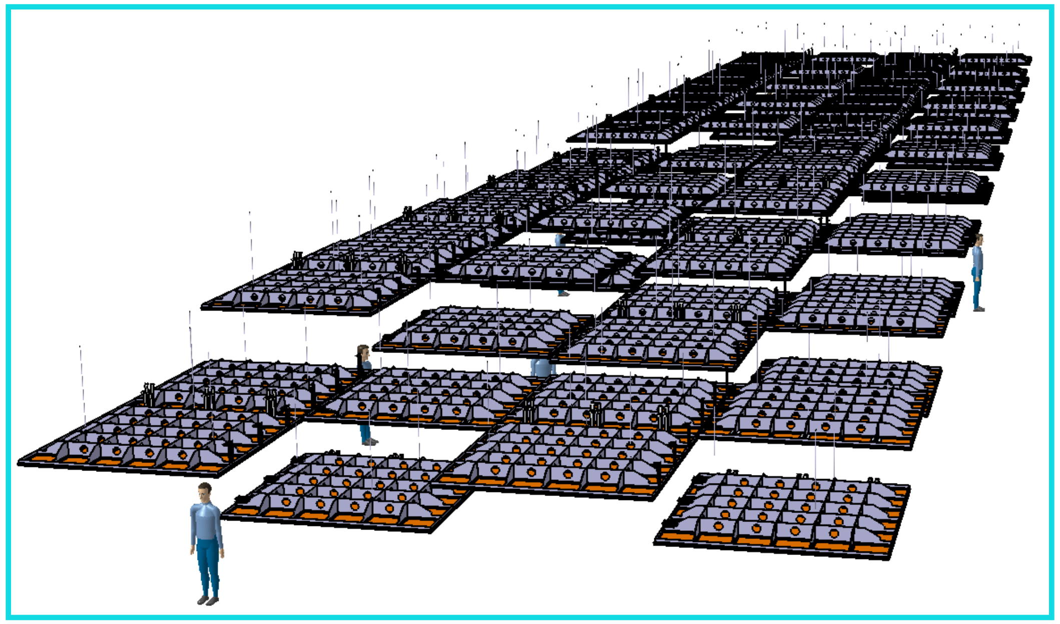
Modularity of the detector

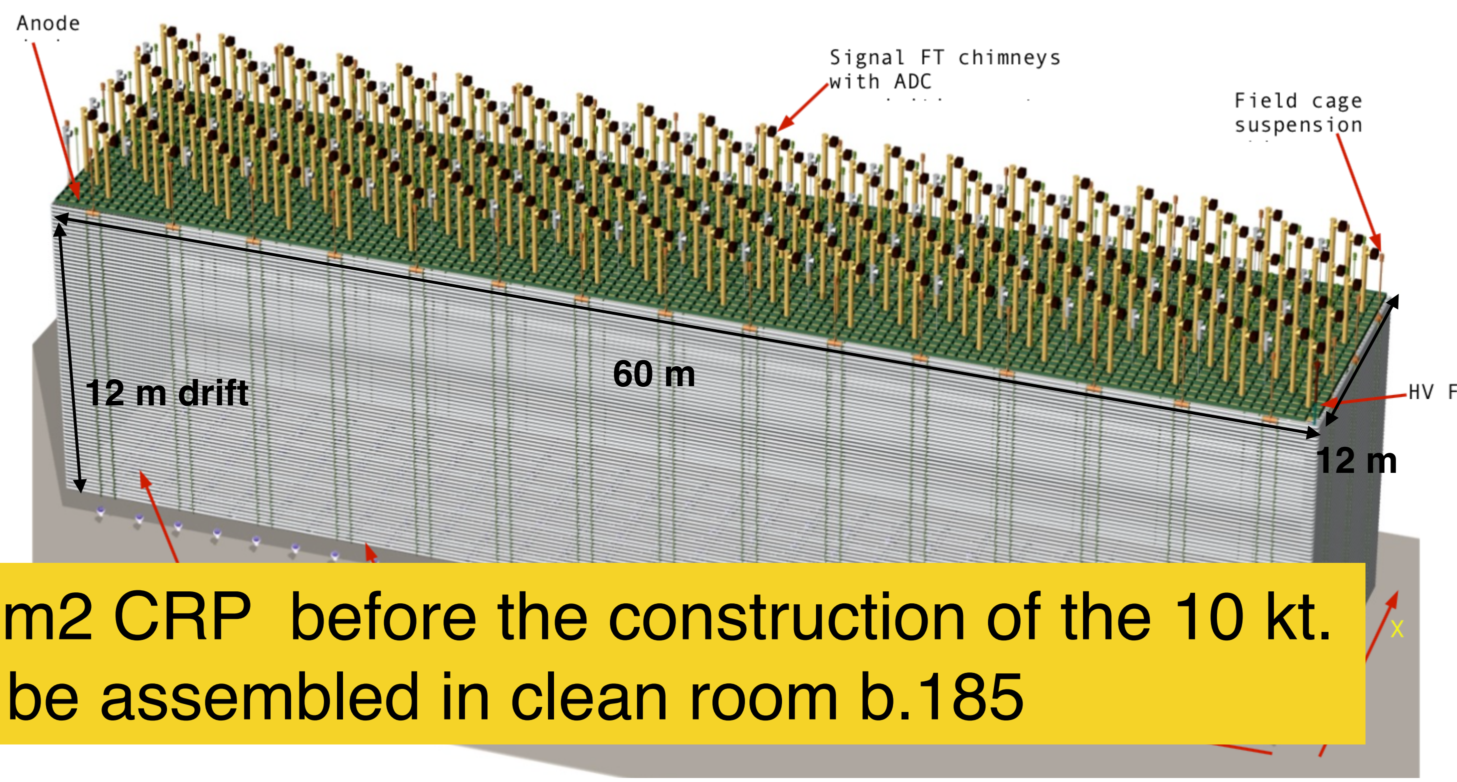
protoDUNE-DP and DUNE-10kt: each CRP functions as an independent detector of 3x3 m2 unit



Four 3x3 m2 CRPs for protoDUNE-DP

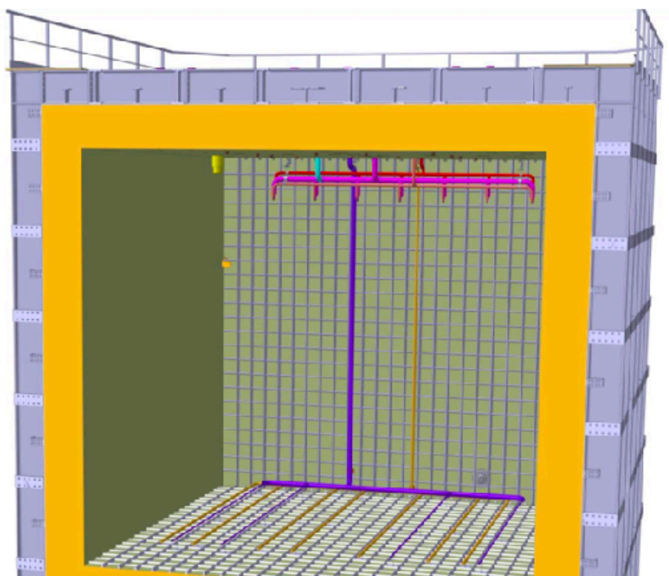
eighty 3x3 m2 CRPs for DUNE 10kt



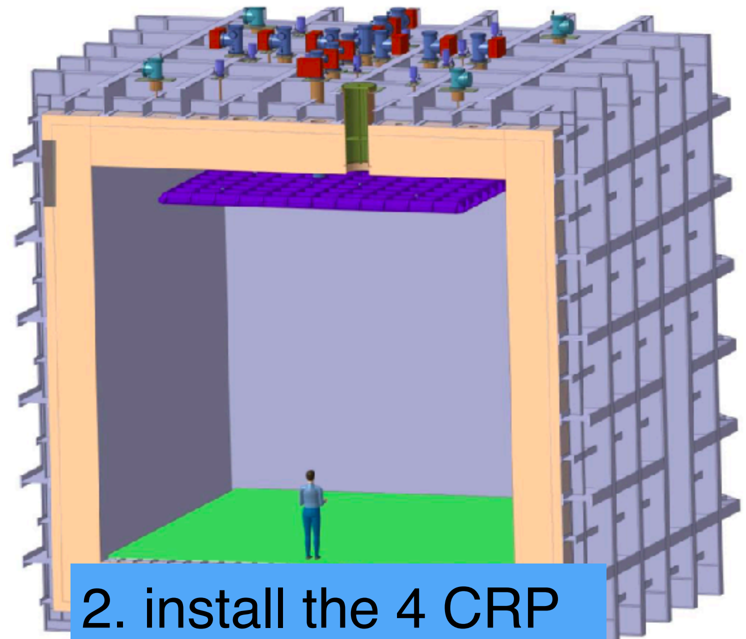


protoDUNE-DP: ultimate test of the 3x3 m2 CRP before the construction of the 10 kt.
First 3x3 m2 CRP for protoDUNE-DP to be assembled in clean room b.185

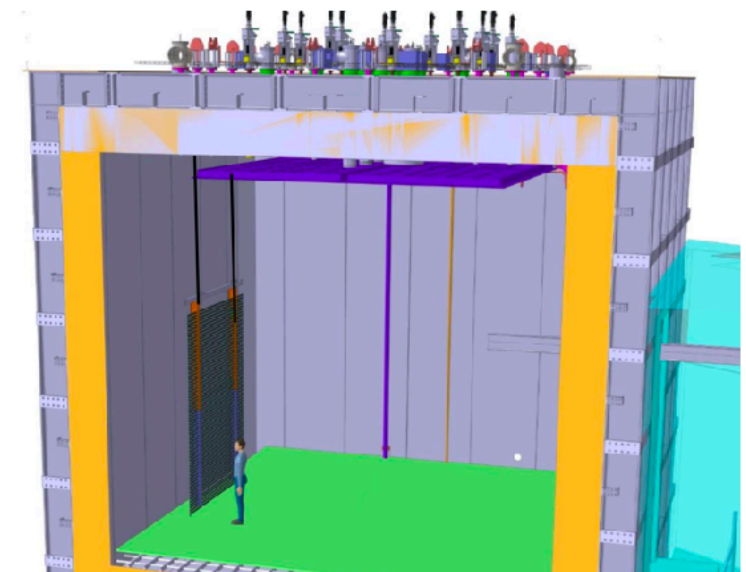
protoDUNE-DP installation sequence



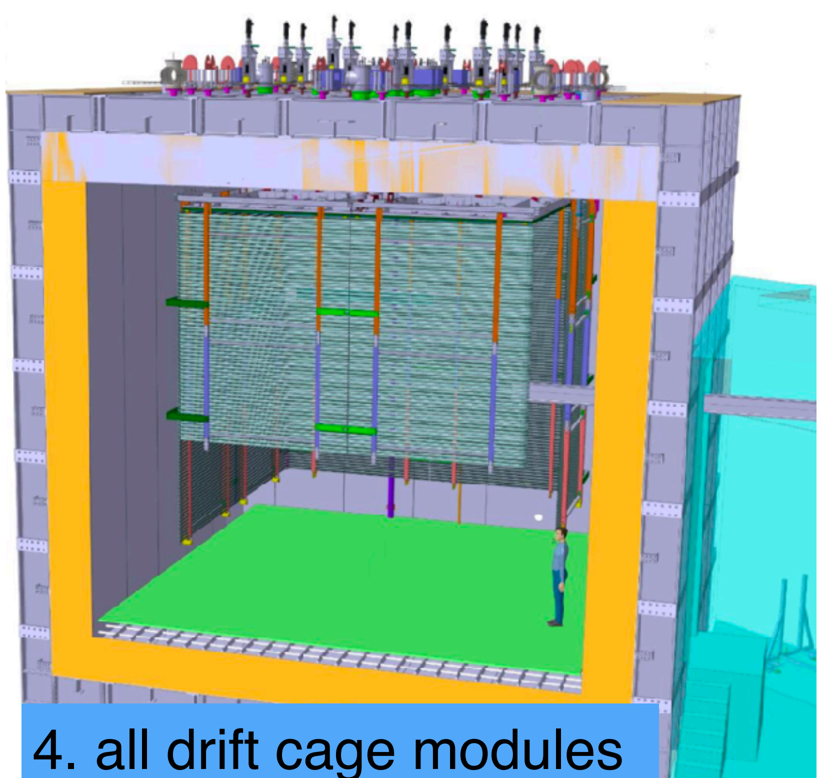
1. install internal piping & temporary floor



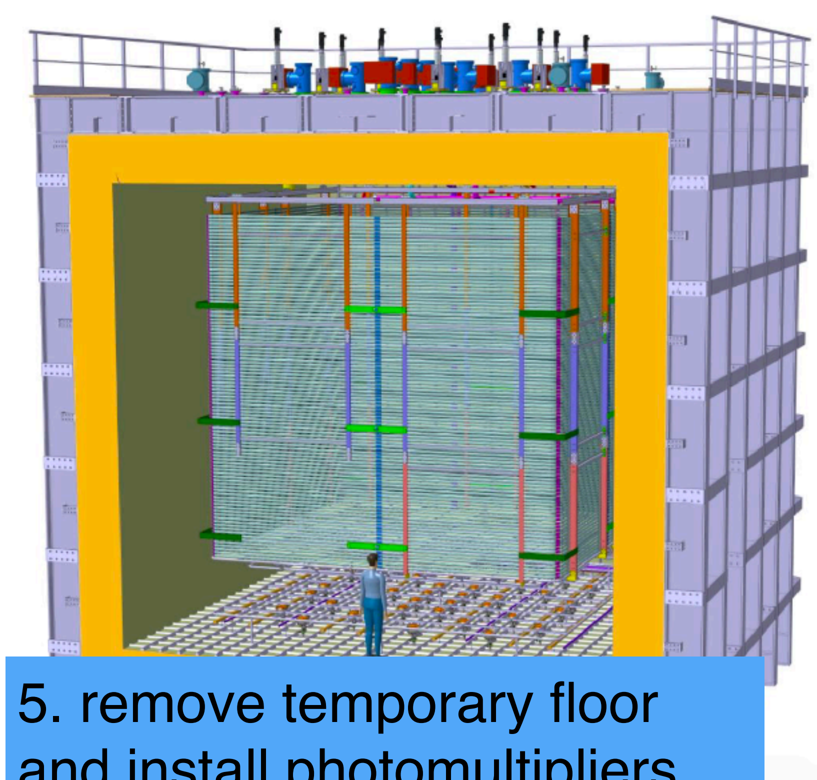
2. install the 4 CRP frames



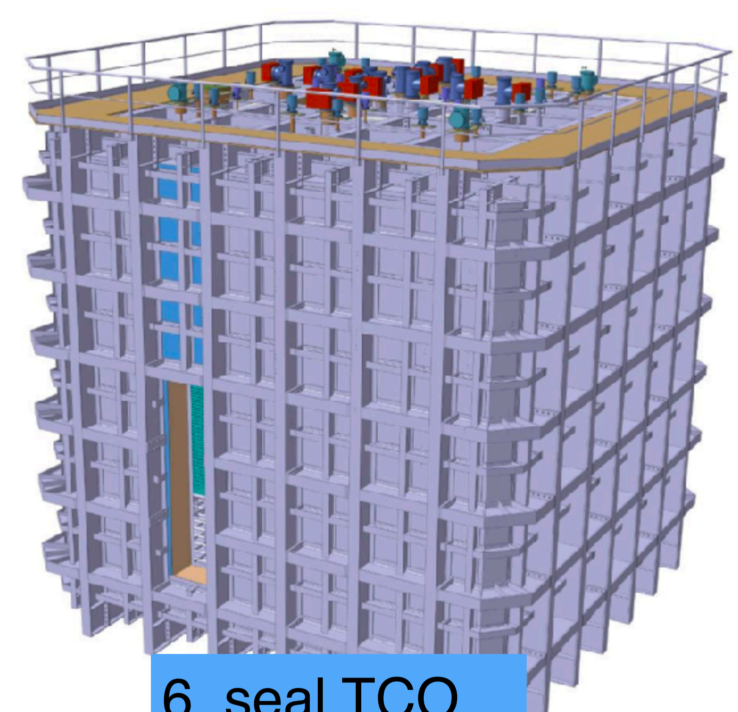
3. install the first drift cage modules



4. all drift cage modules installed



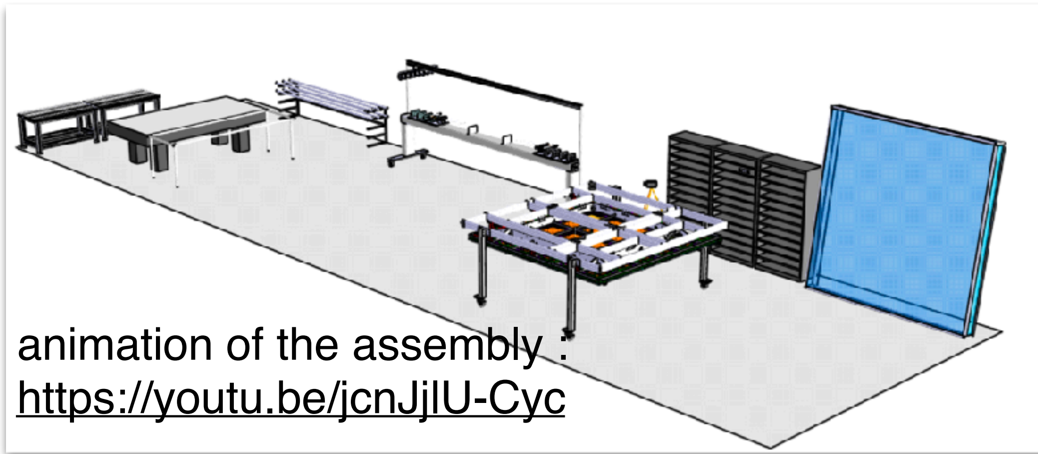
5. remove temporary floor and install photomultipliers



6. seal TCO

Construction of detector parts has started

The individual CRPs are assembled in the clean room of building 182 and shipped one by one to the cryostat via the clean room buffer.

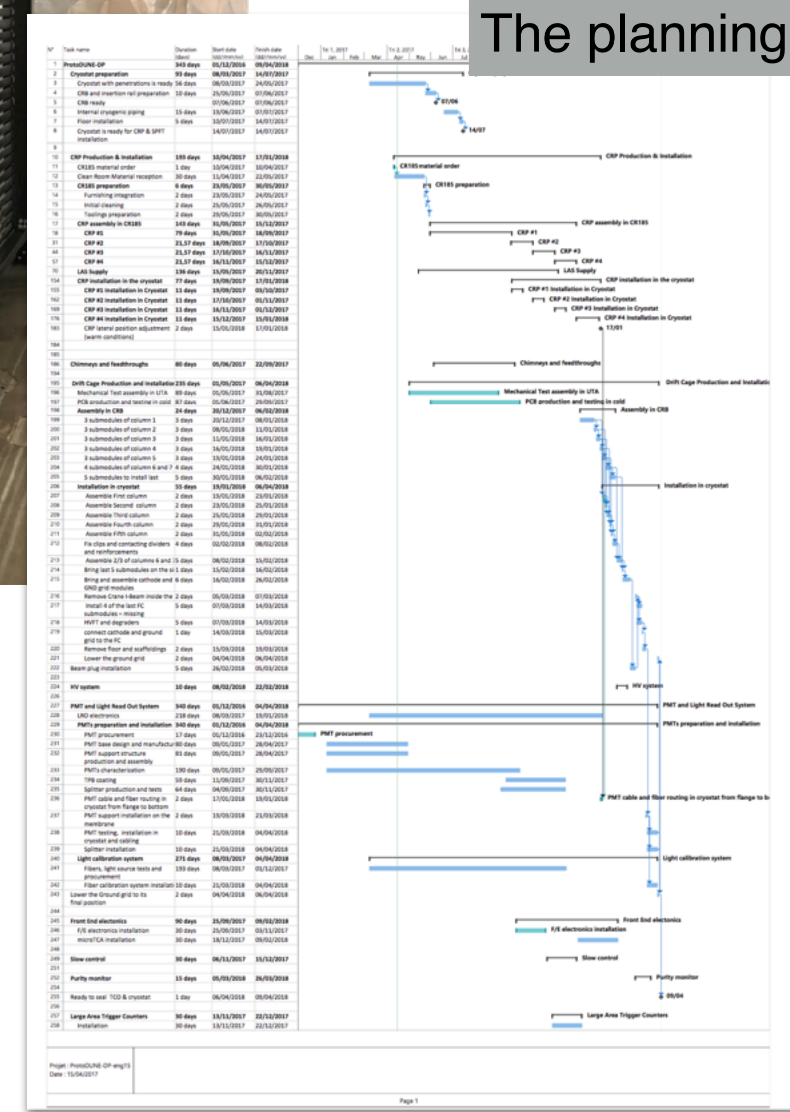


animation of the assembly : https://youtu.be/jcnJjlU-Cyc

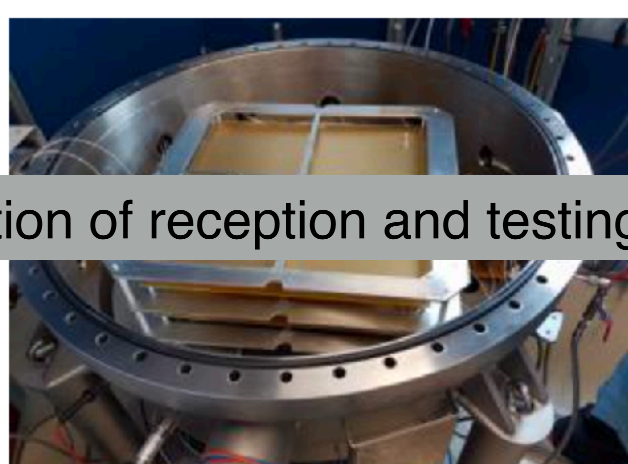
drift cage mockup assembly (Texas)

CRP assembly preparation in clean room b. 185

The planning!



preparation of reception and testing of 144 LEMs (Saclay)



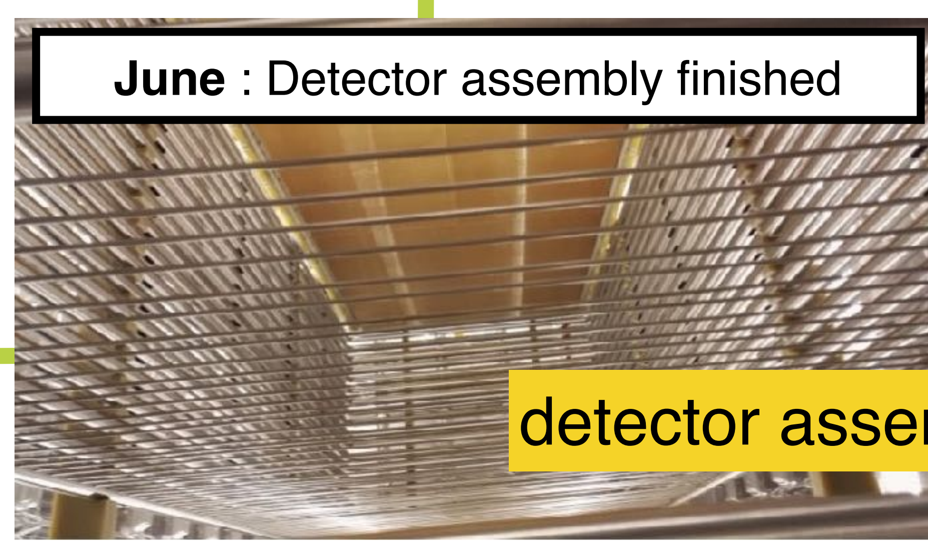
Construction of the 3x1x1 in 2016

Feb : Top Cap delivered

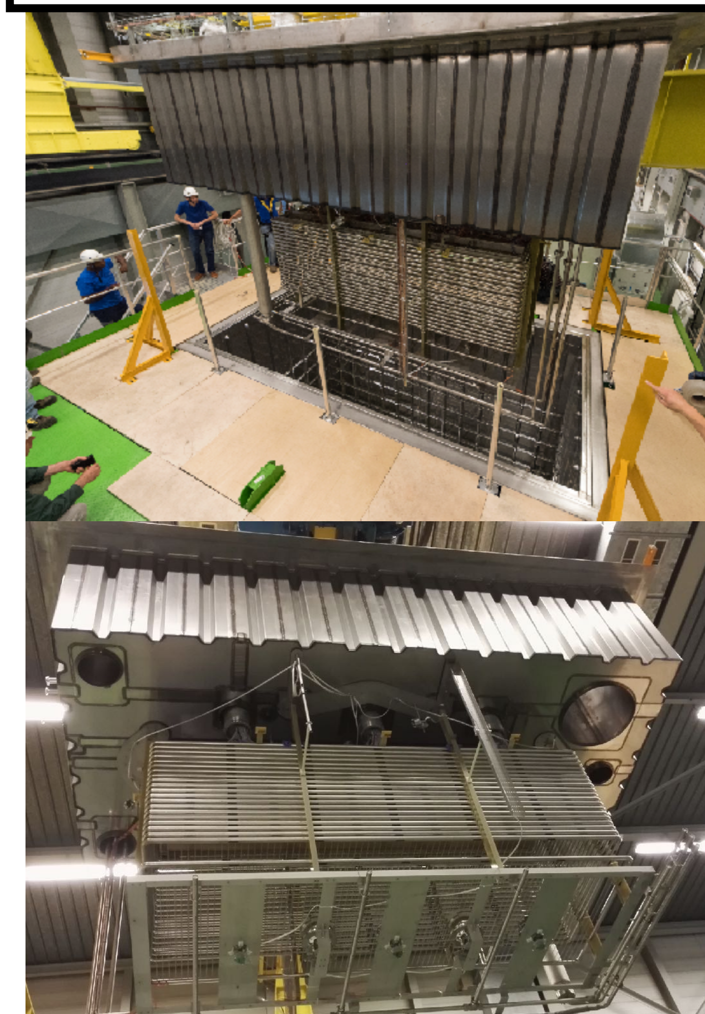
March : CRP installed under top cap

April : CRP cryogenic bath test

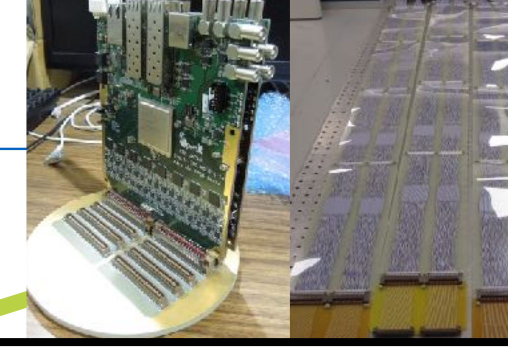
June : Detector assembly finished

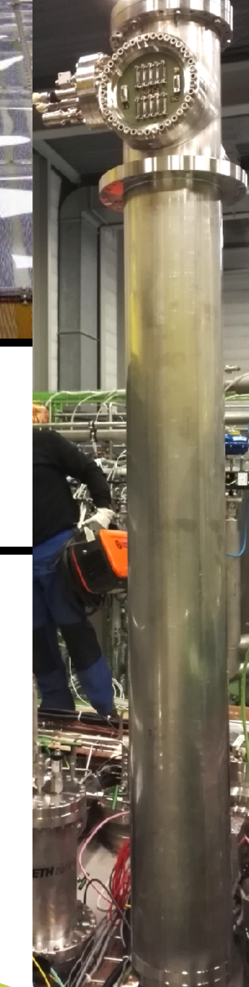


July : Top Cap lifted inside the cryostat



Aug : FE electronics + cables installed inside feedthroughs





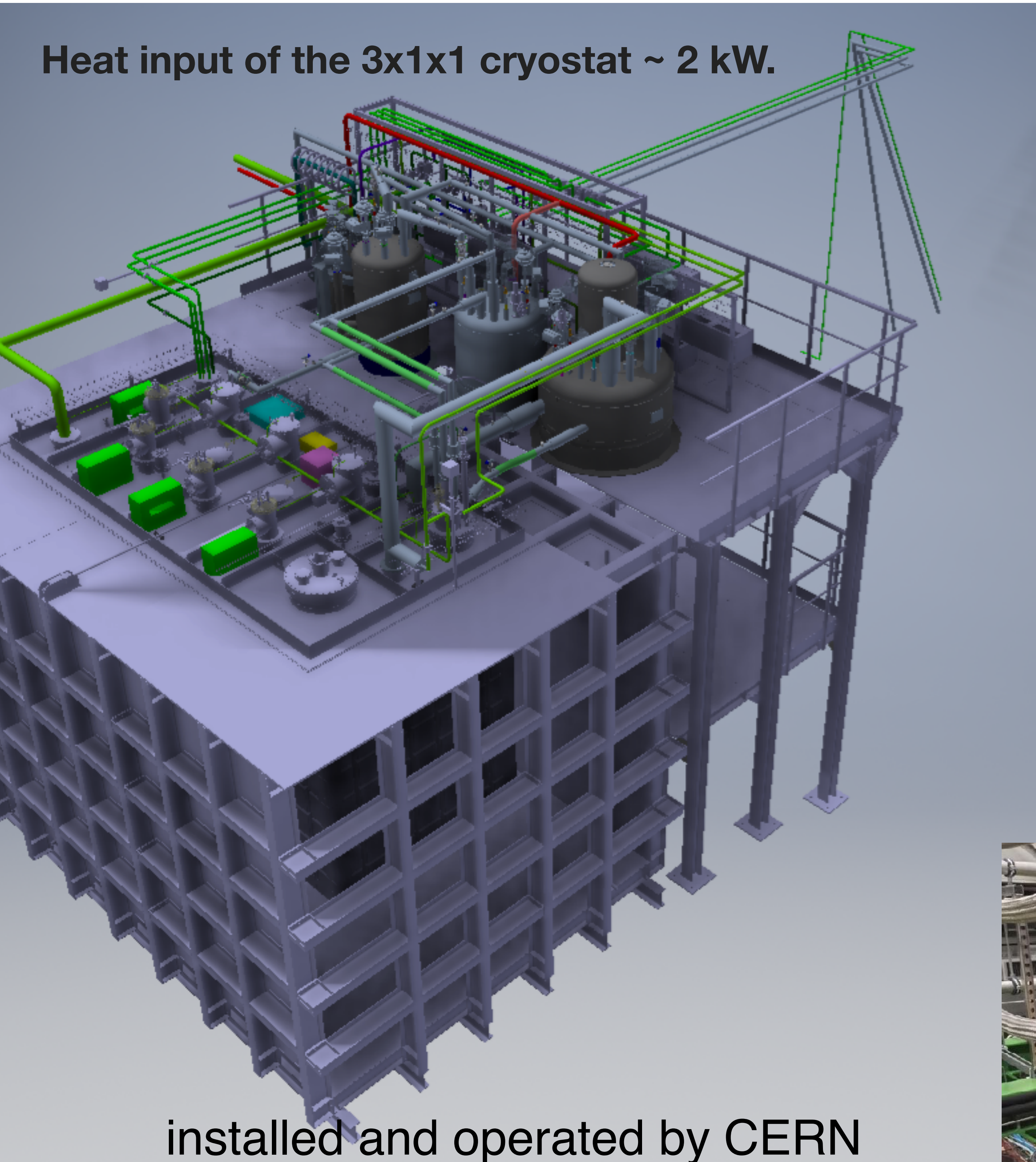
Sept : Test & insertion of 300 kV HV feedthrough

JINST 12 P03021 arXiv:1611.02085

Nov : control racks, DAQ and cryogenics installed, cabled and tested

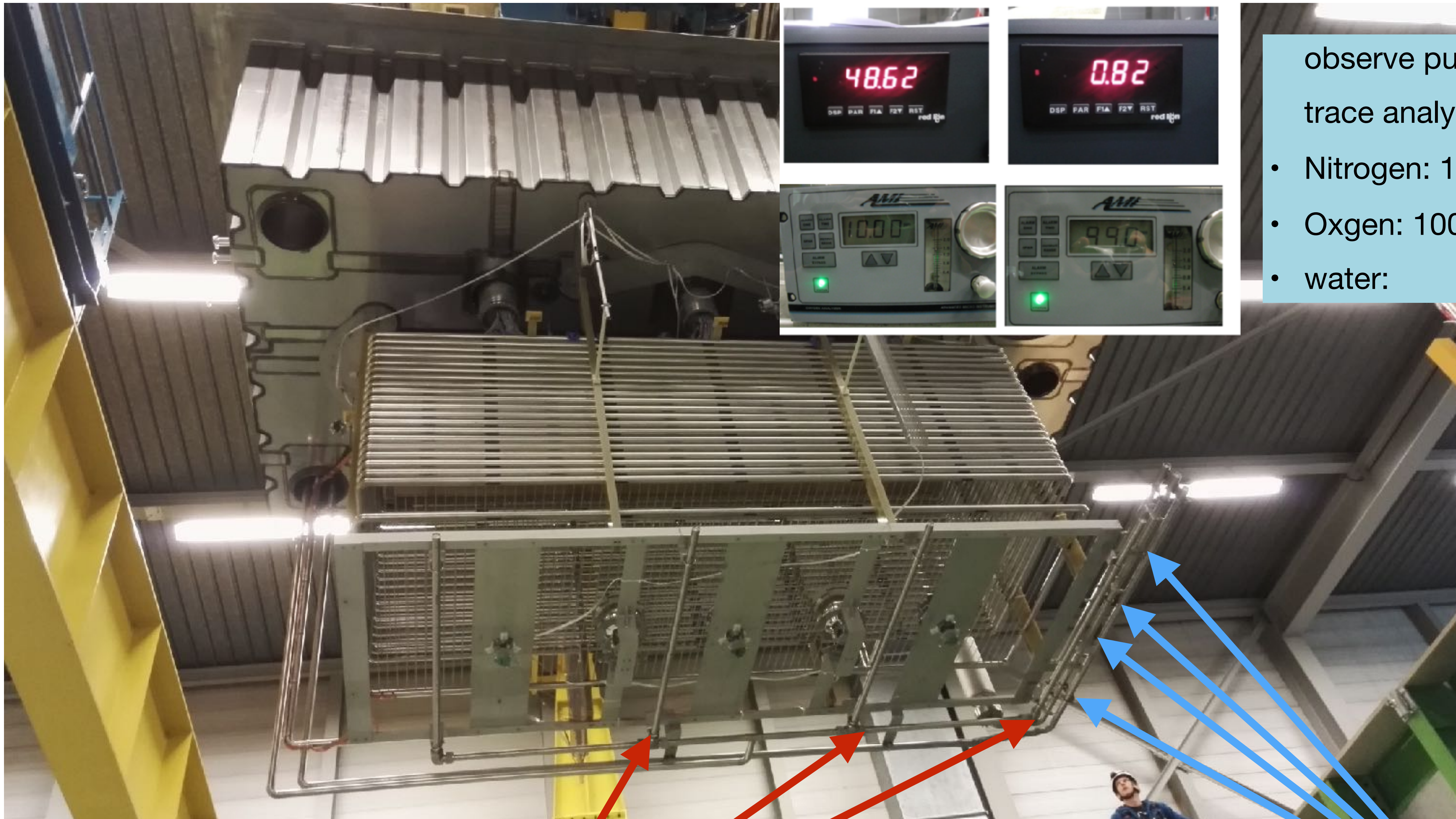
detector assembled in 6 months

Cryogenics and purity



- prior to operation: evacuation of air and cool down.
- during detector operation: safely condense the boiling-off gas and purify liquid+gas.
- Condensation of the boiling-off gas performed using liquid nitrogen heat exchangers.
- Purification with custom made cartridges filled with copper pellets to remove the oxygen and molecular sieve to remove the water by physical absorption.

piston purge - evacuation of air



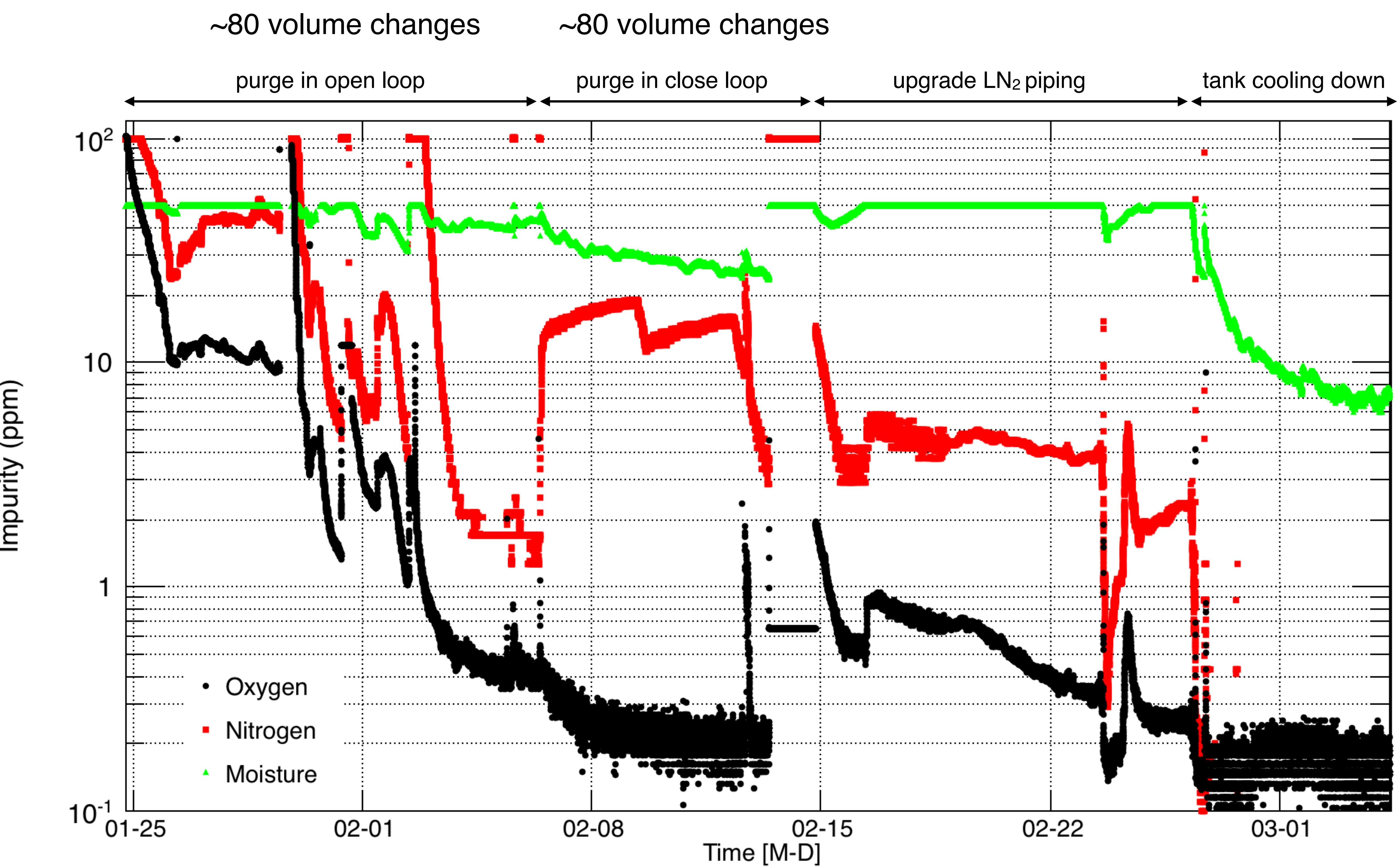
observe purity evolution with 3 gas trace analysers

- Nitrogen: 100 ppb precision
- Oxgen: 100 ppb precision
- water:

Piston purge
4 warm gas lines each with 3 openings of 12 mm ø.
total flow rate during piston purge ~4 l/s

Cool down: 4 sprays mixture of LAr and GAr for slow and uniform cool down. Nominal flows:
300 K GAr 500 l/m
87 K LAr 21 l/h

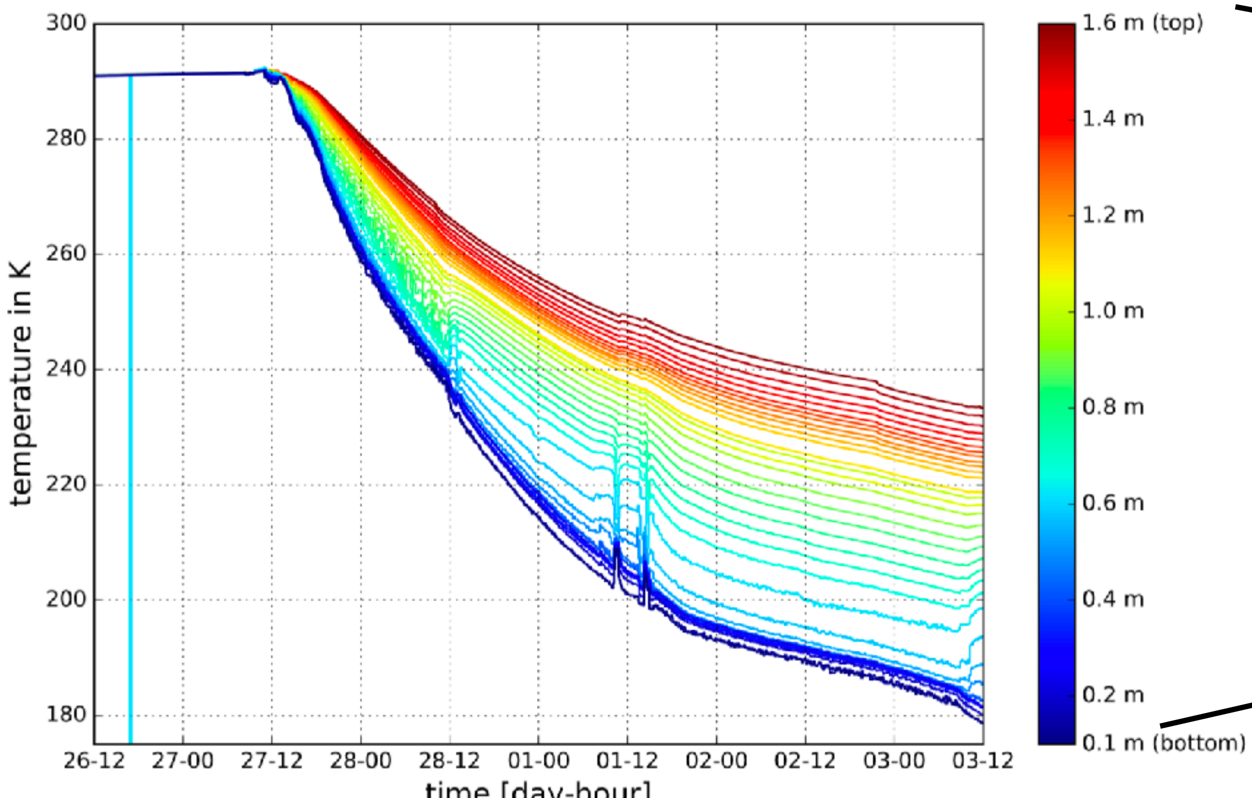
Piston purge



Cool down and filling

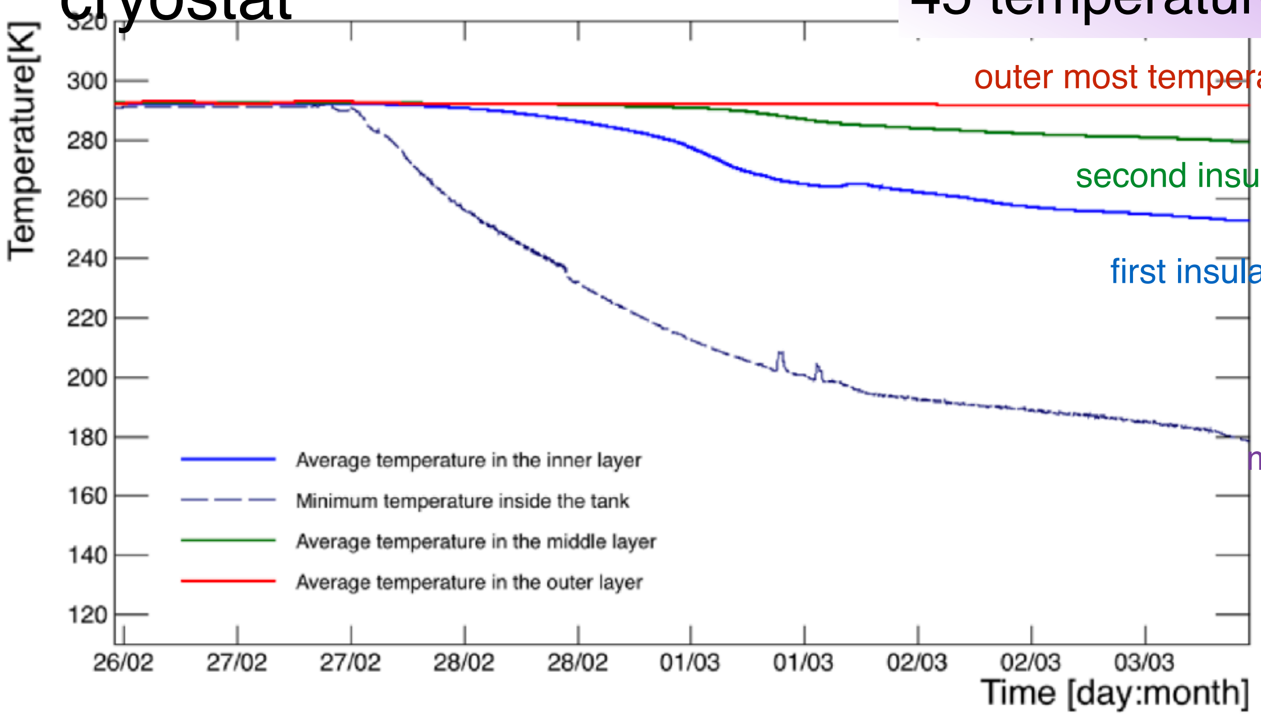
detector

chain of temperature probes along drift cage



cryostat

45 temperature probes inside insulation

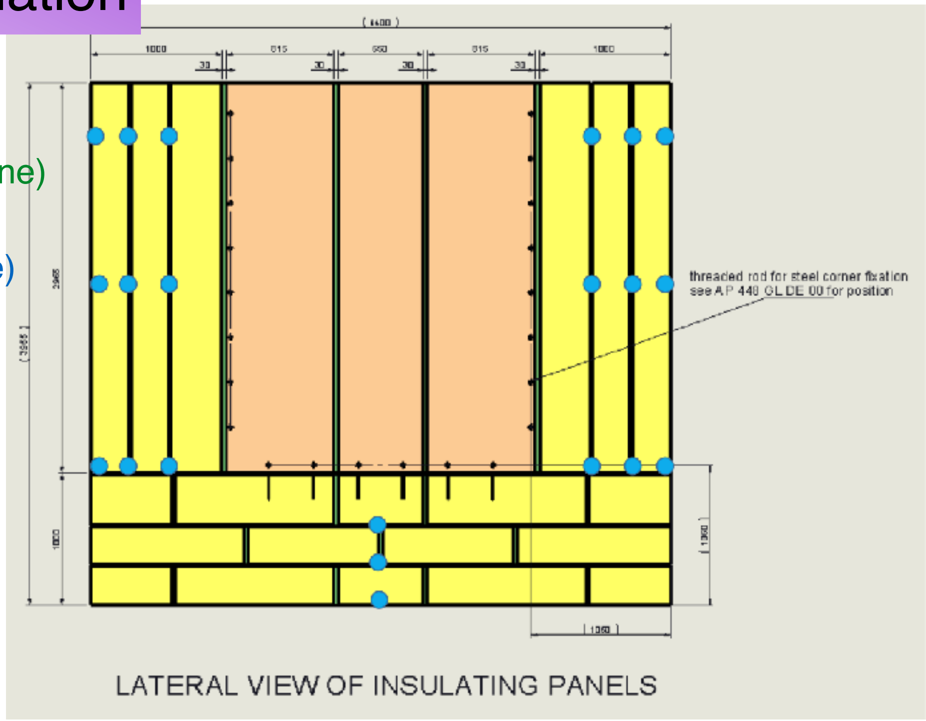


outer most temperature (cryostat outer structure)

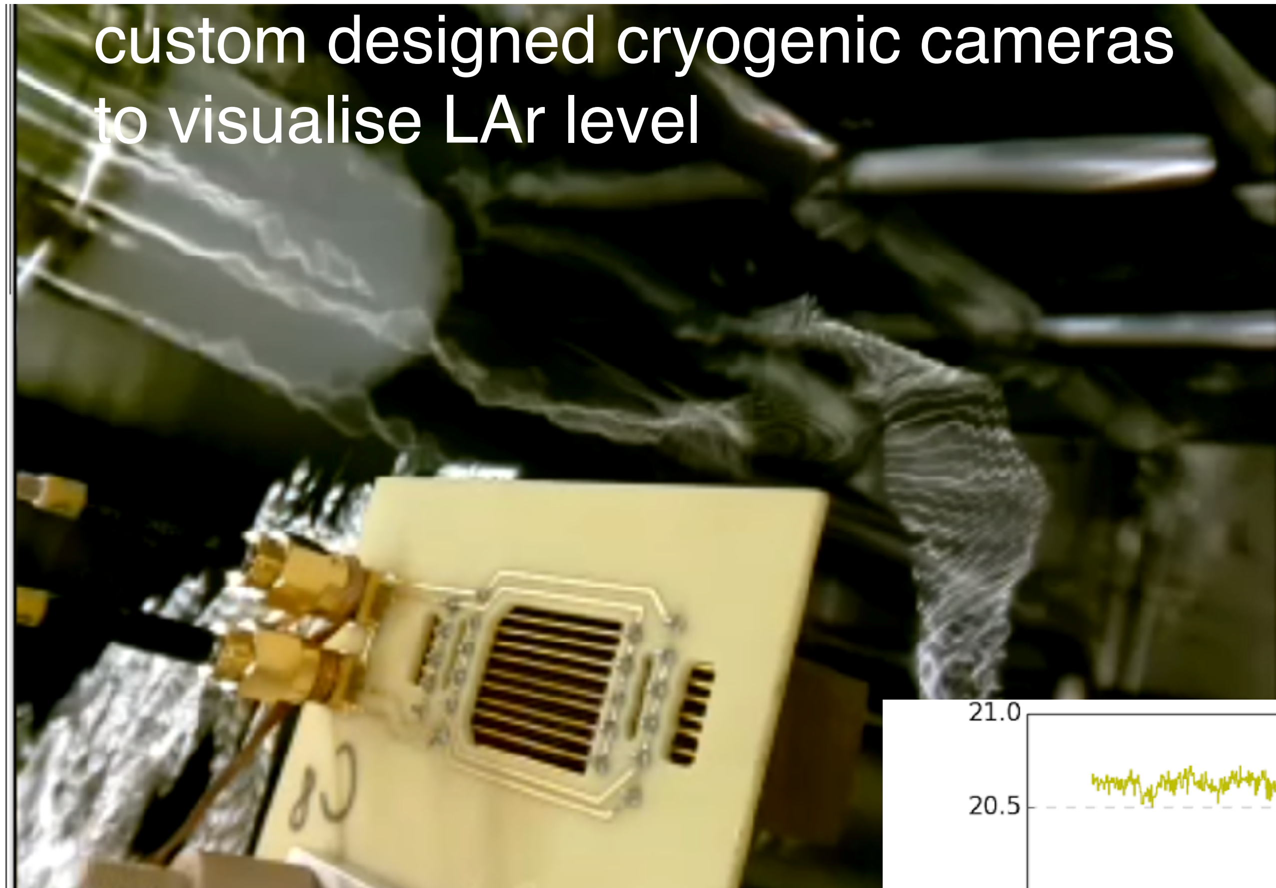
second insulation layer (70 cm from membrane)

first insulation layer (40cm from membrane)

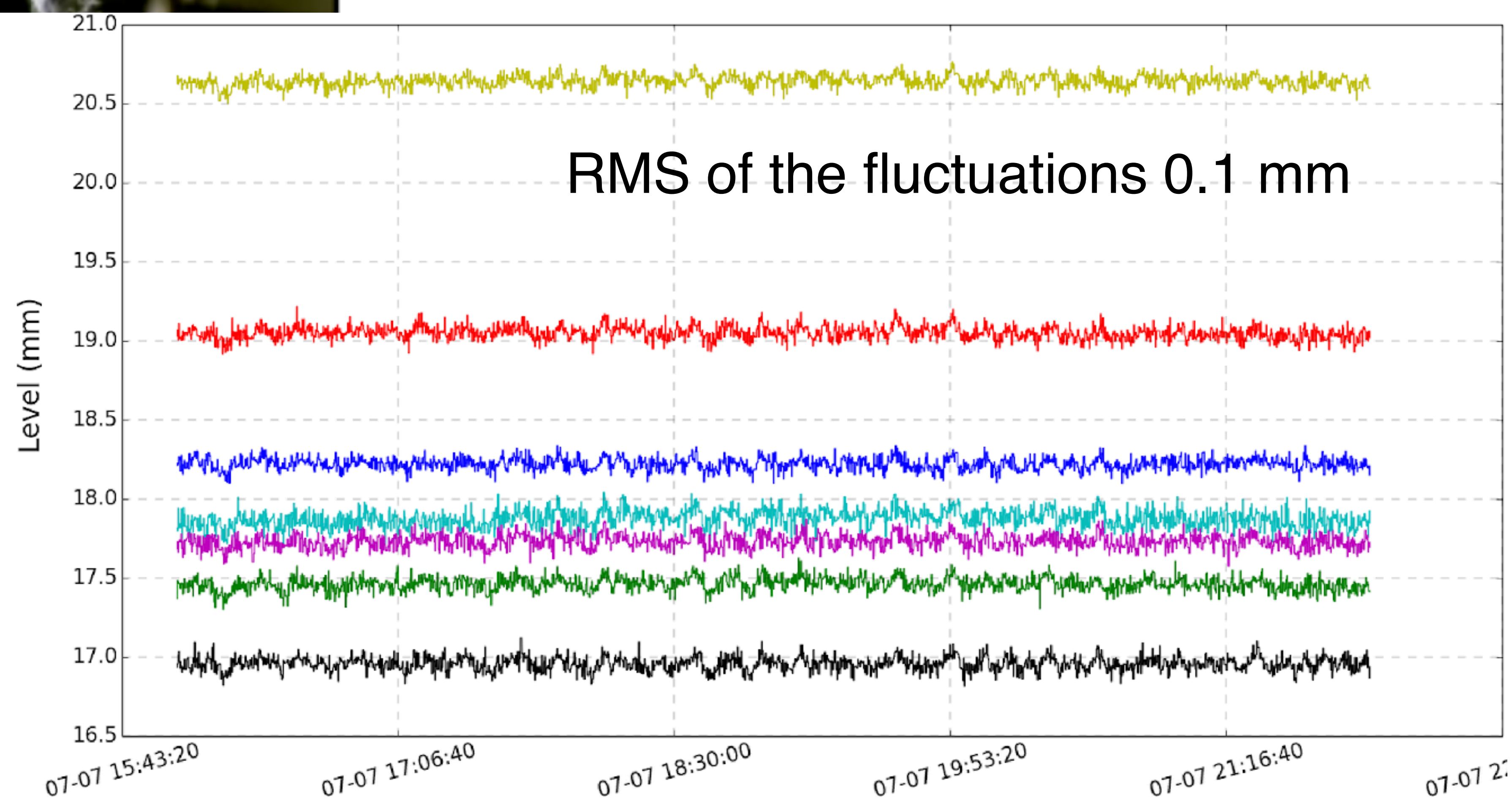
minimum temperature in cryostat



Monitoring of liquid level during operation

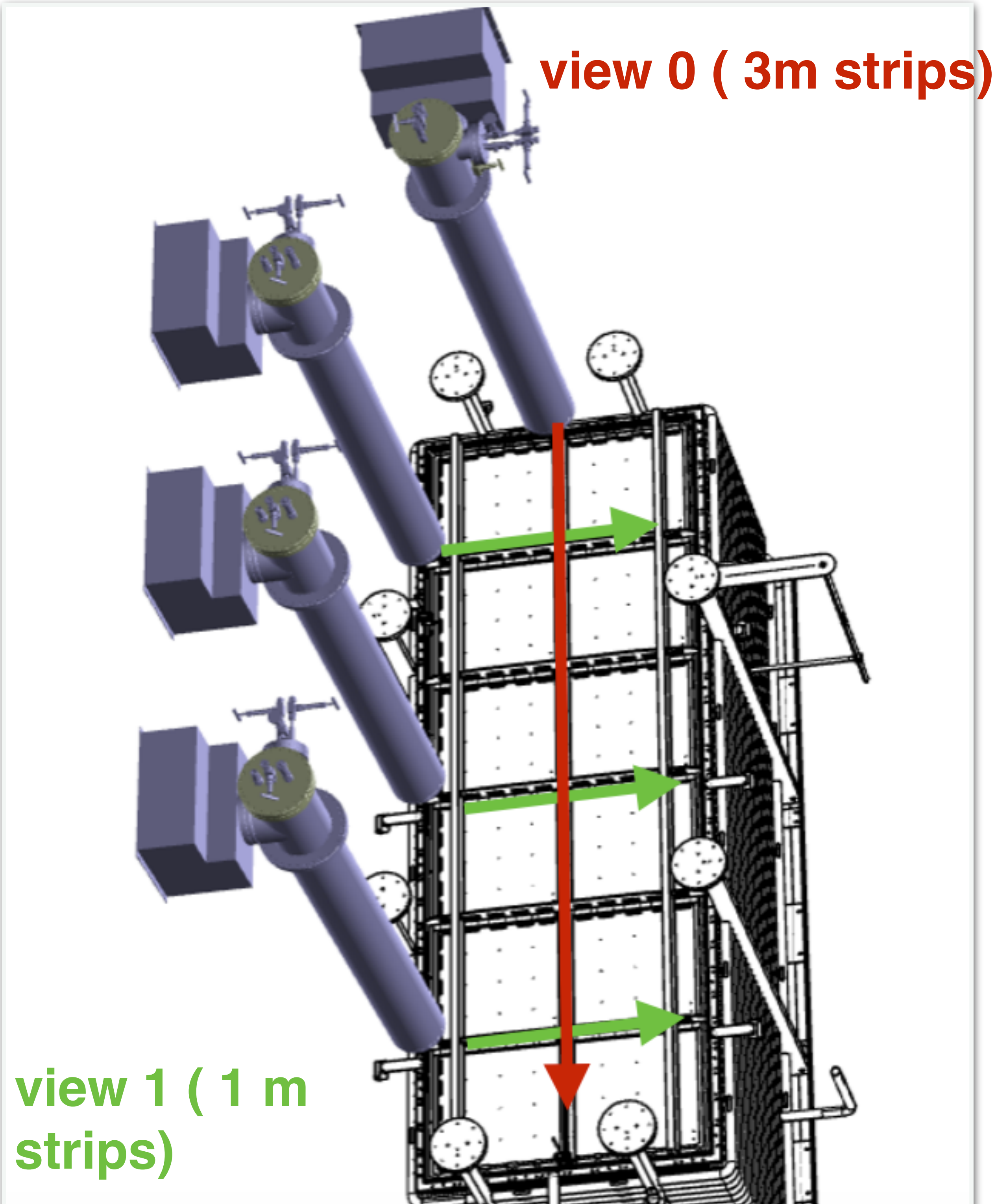


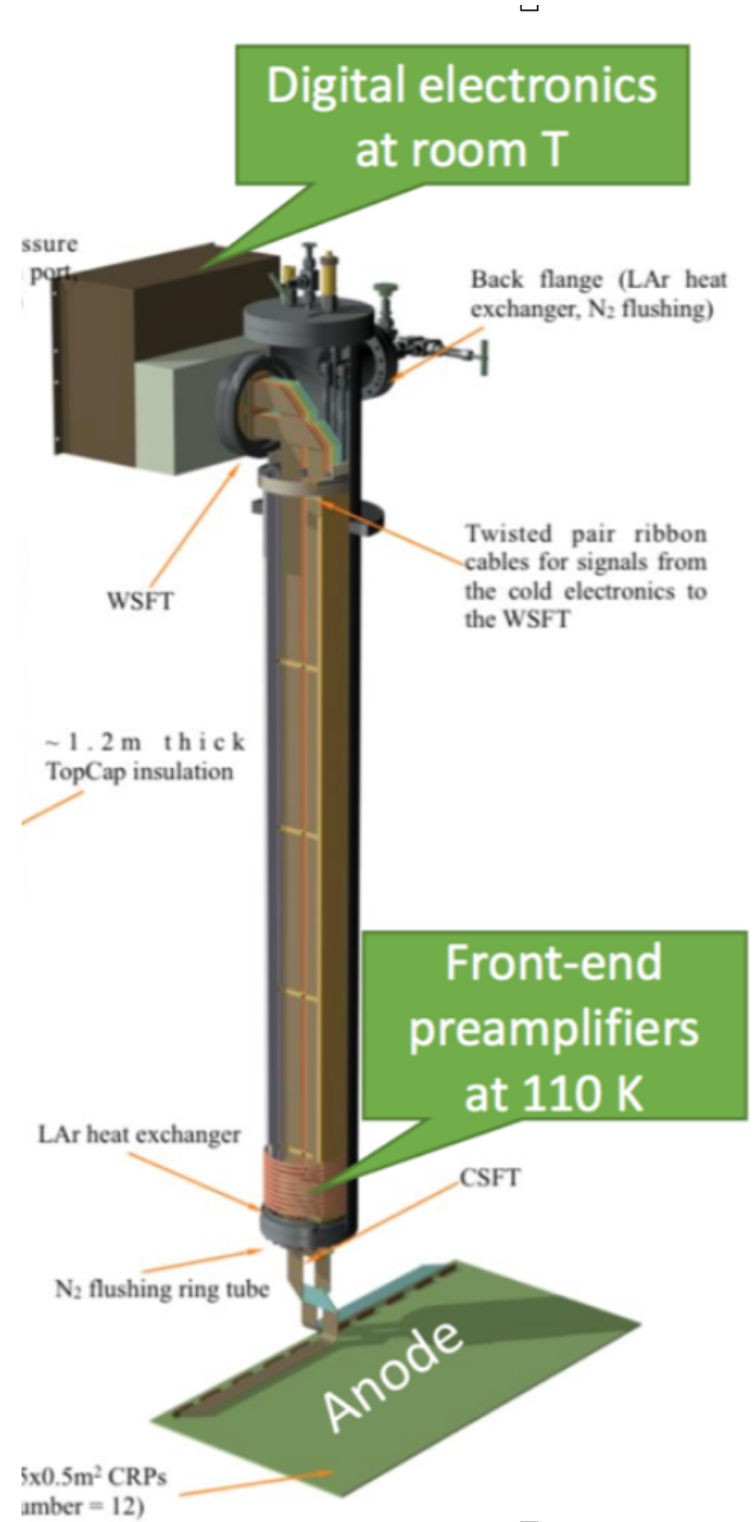
- The level is adjusted and constantly monitored using **7 capacitive level meters on the CRP**, and **5 along the drift cage**. **This information is also sent to the cryogenic system to constantly regulate the system to keep the level stable**.
- **4 cryogenic cameras** are recording pictures continuously.



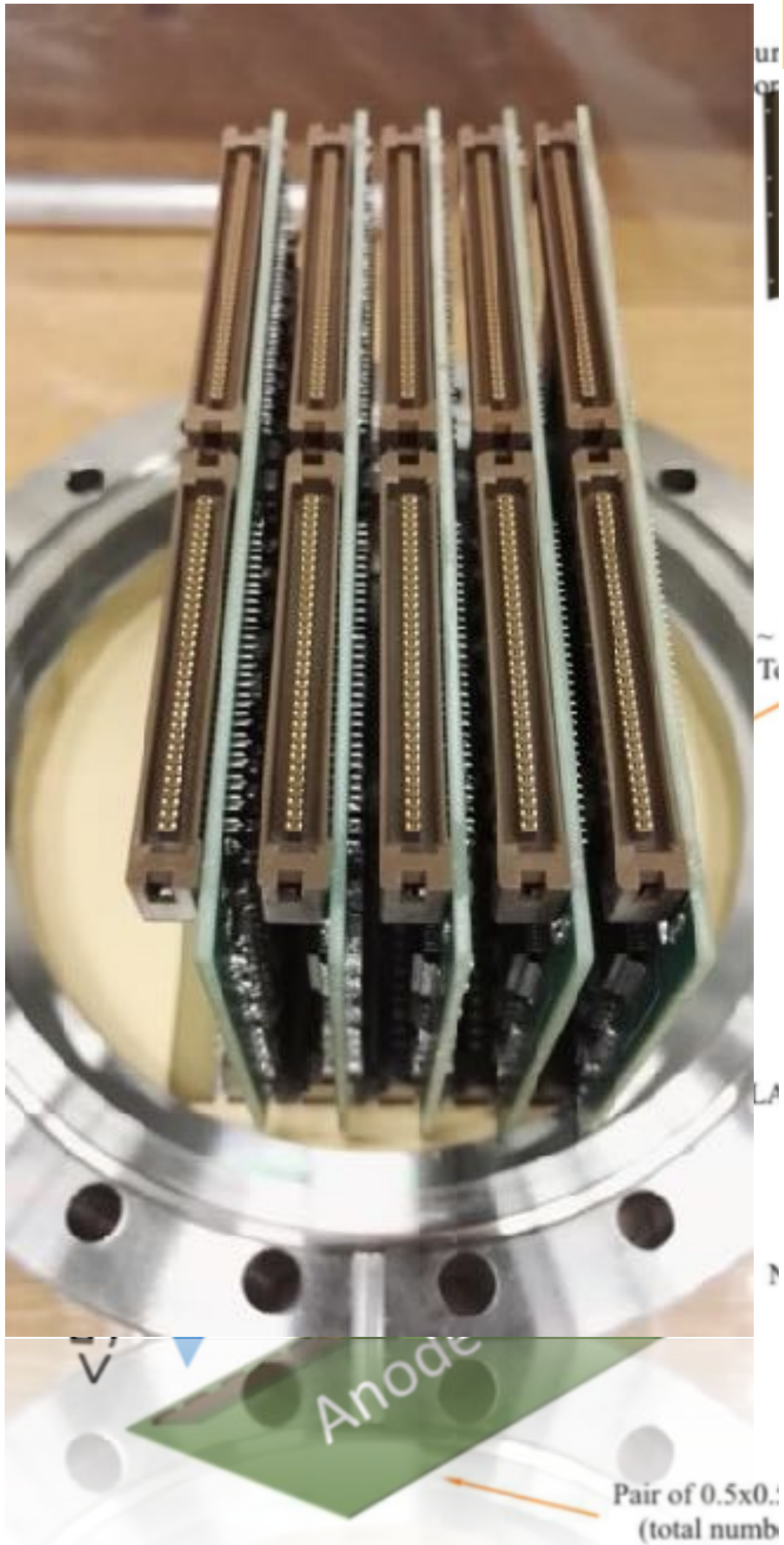
liquid level is flat, the cryogenic system and pressure inside the cryostat is very stable at 1000 mbar.

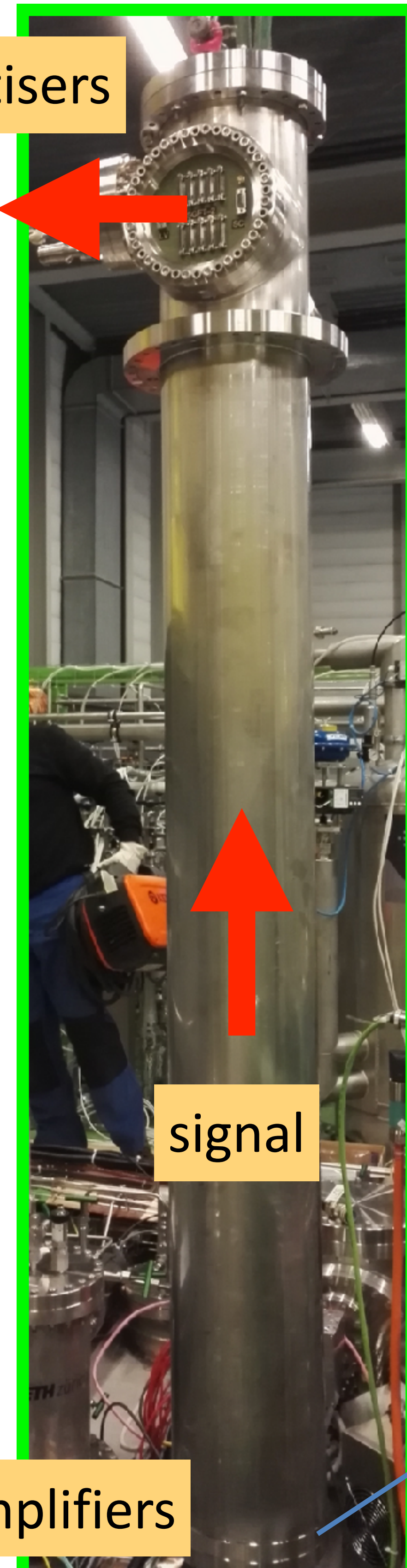
Charge Readout



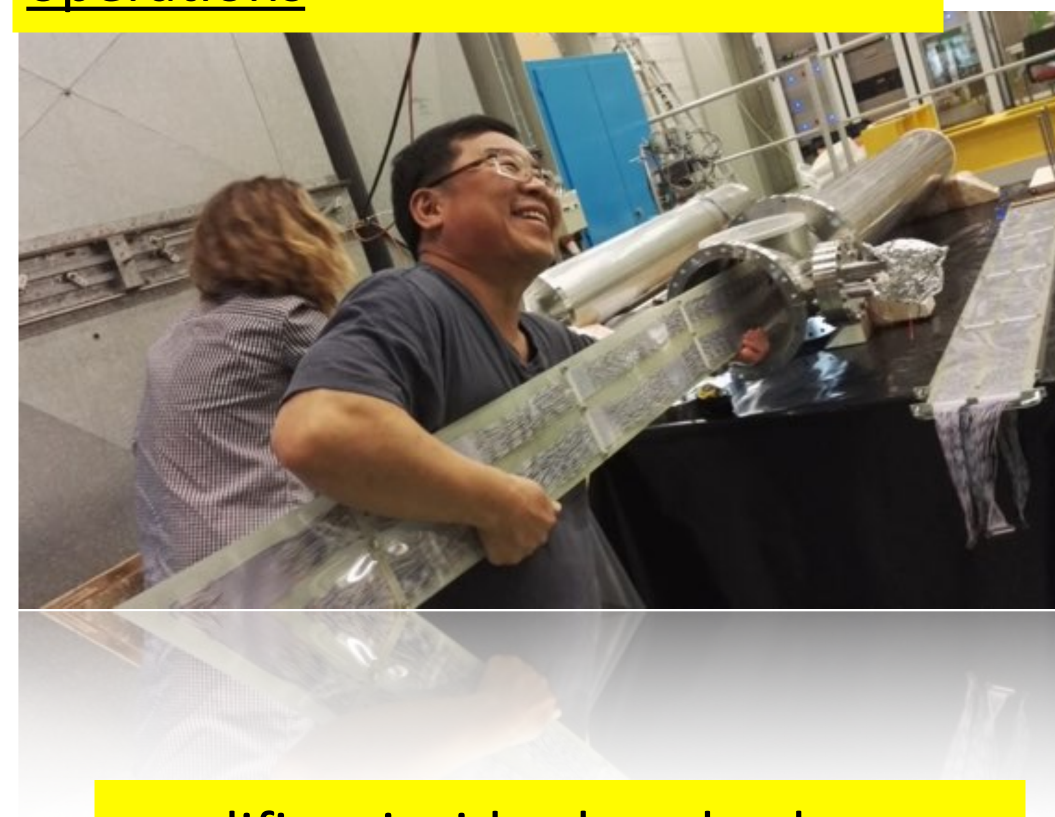


Charge Readout





amplifiers accessible during operations



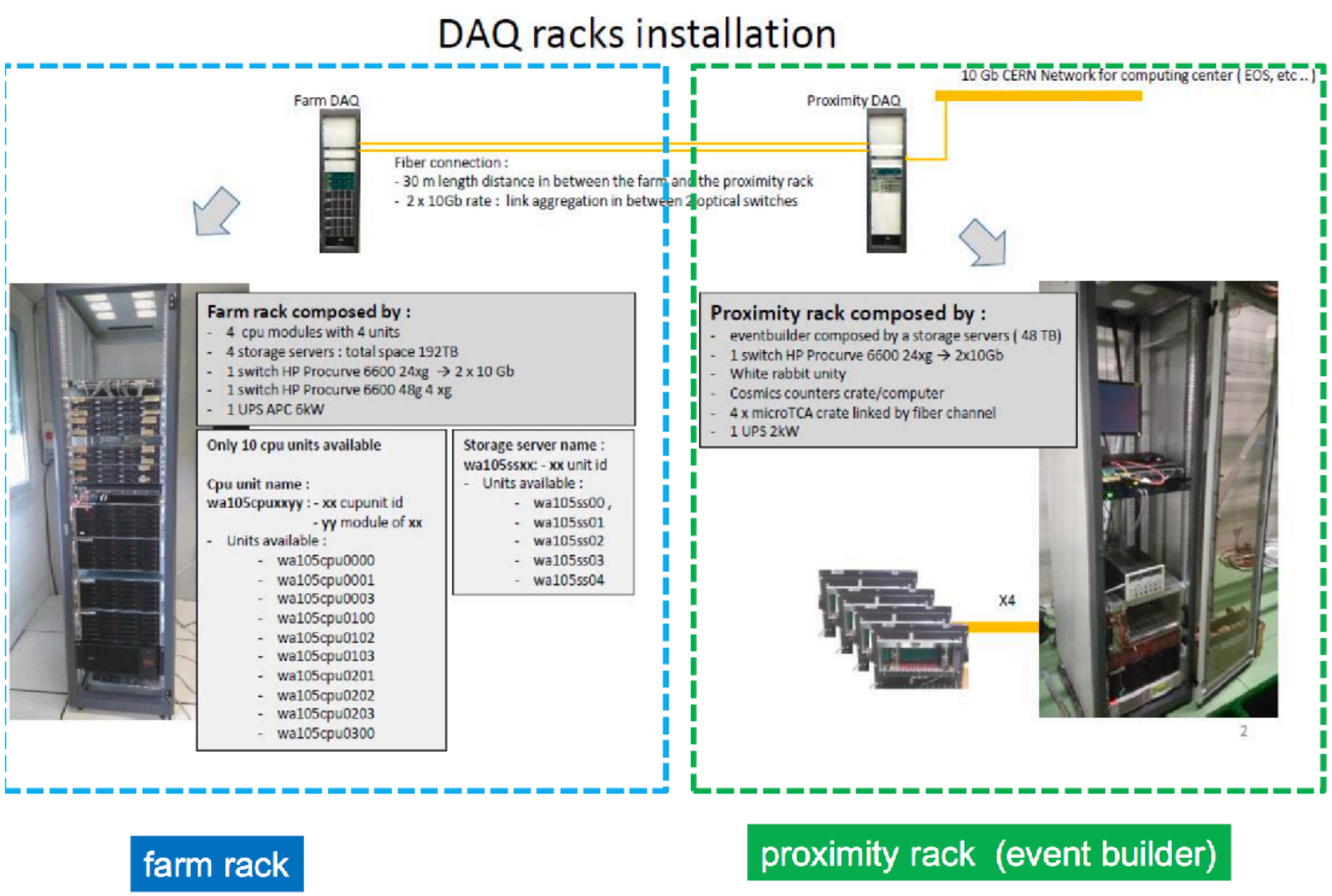
amplifiers inside closed volume. Close to anodes, ~110 K

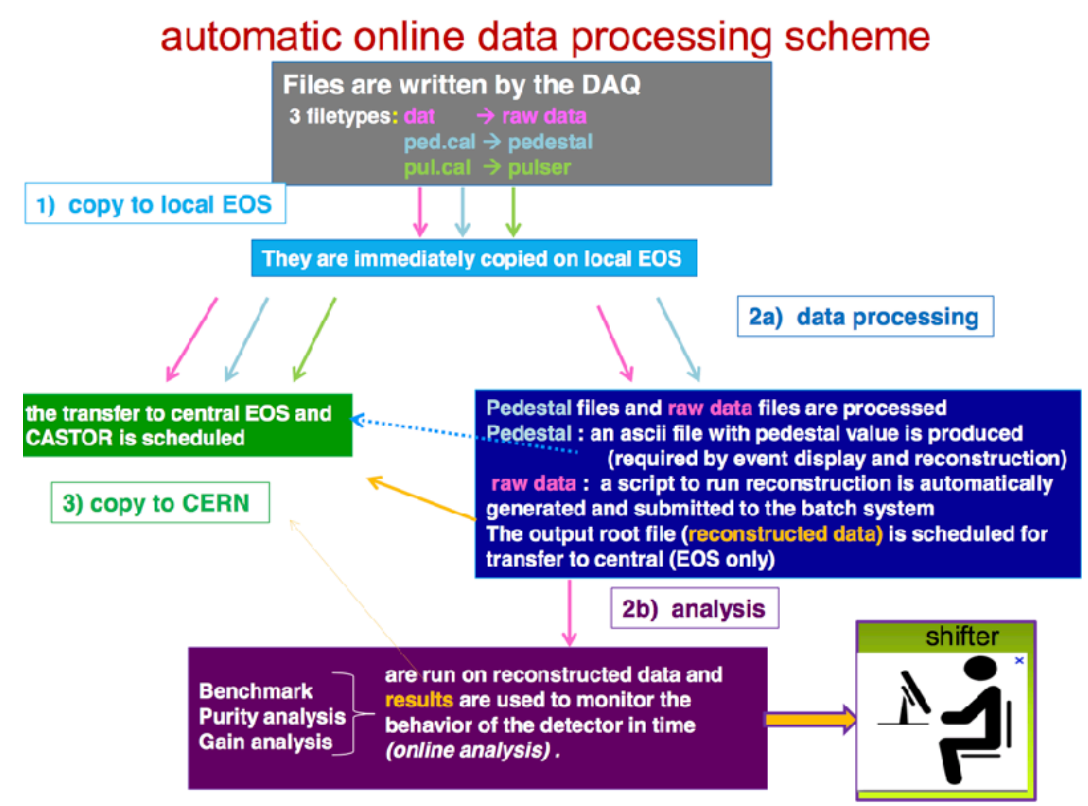
4 ASICs per board

3x1x1 online storage and processing: test for protoDUNE-DP.

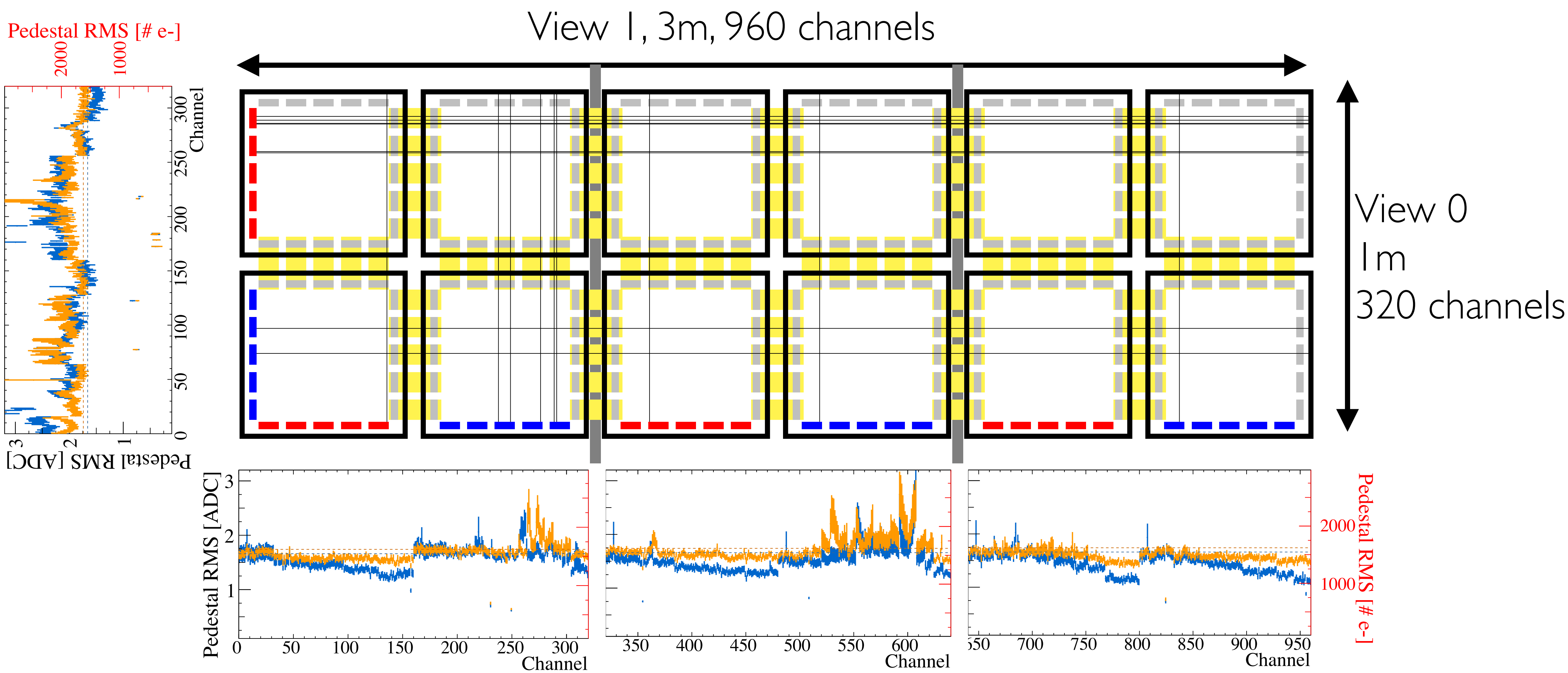
The online processing has been tested during the different campaigns of noise and data measurements in the 3x1x1: files transferred to a local EOS and then moved to the CERN computing center.

- All the necessary codes for 3x1x1 operation including online monitoring processes are functioning well and has been tested.





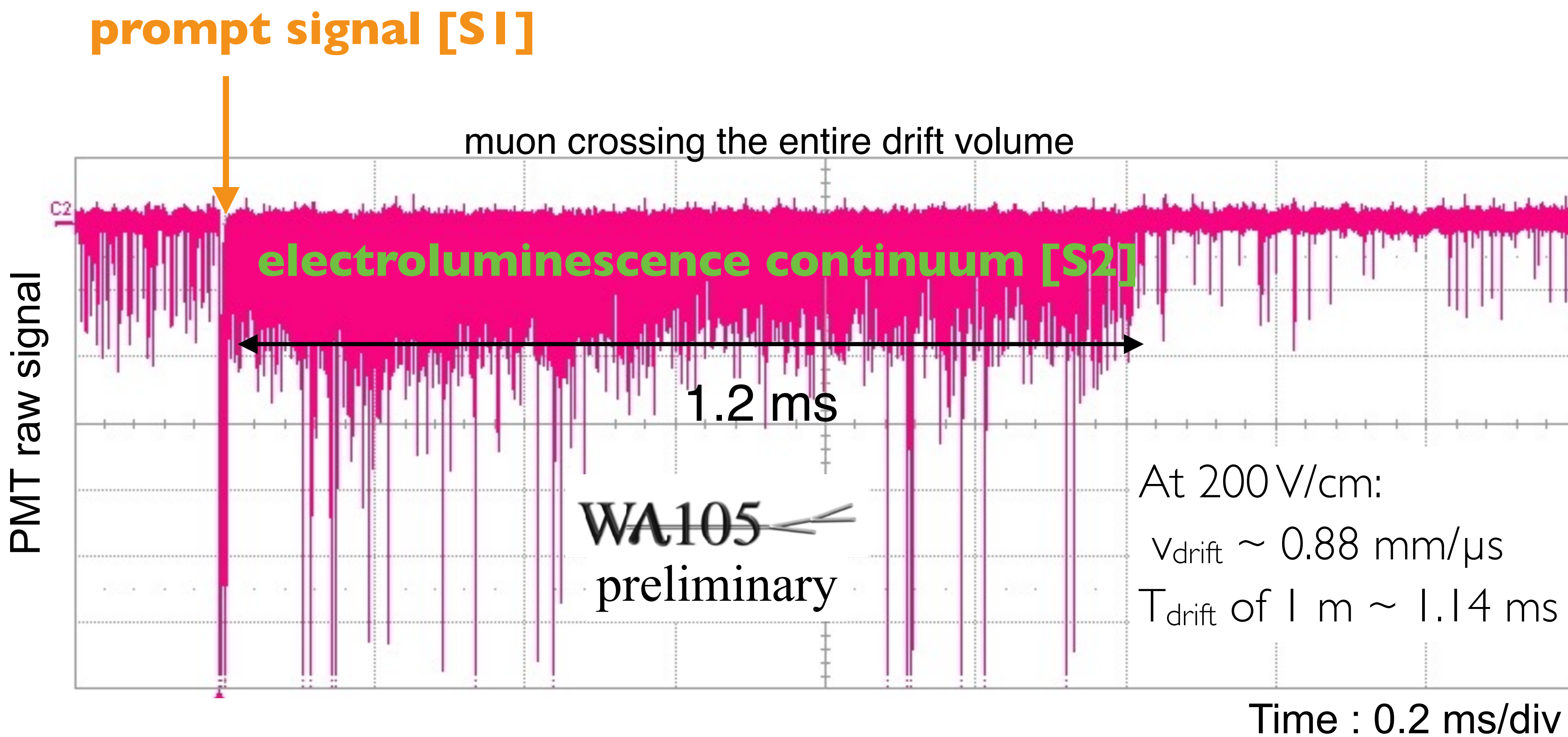
Electronic noise

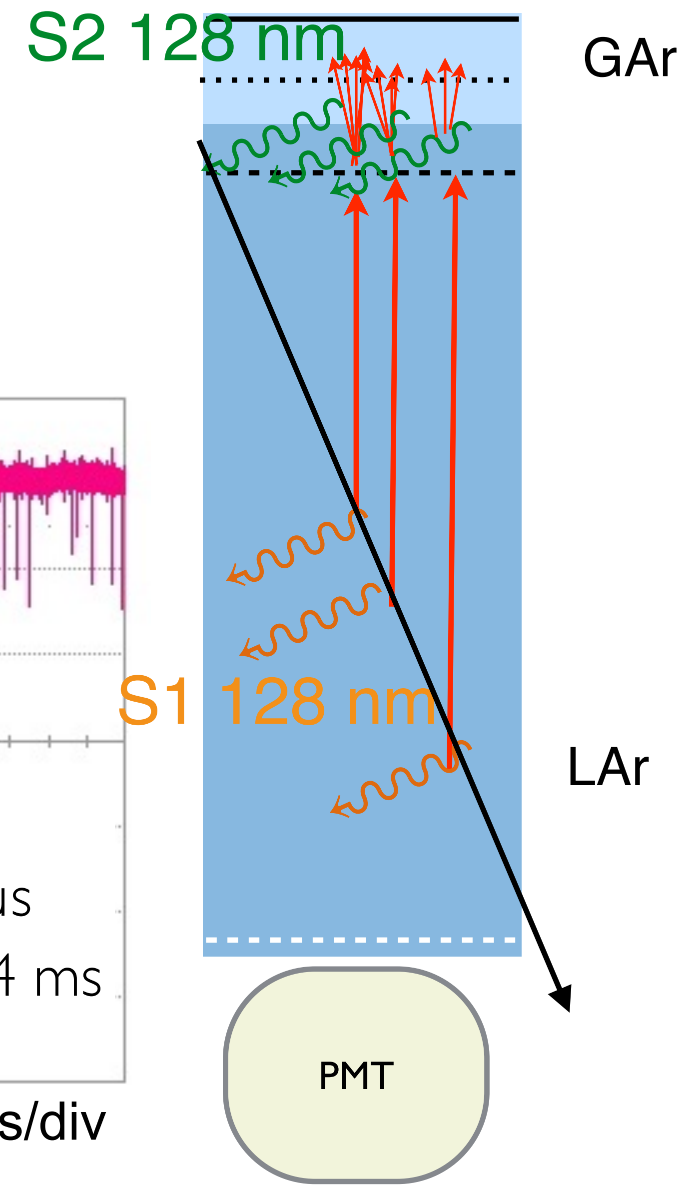


- Out of 1280 channels, 17 found problematic or dead (1.3%)
- Noise at room temperature stable at around 1600 e^-
- Noise at cryogenic temperature stable at around 1550 e^-
- Calibration runs with pulsed injected charge runs have shown ~ 4% of crosstalk

June 15th First evidence of charge extraction

First check with PMTs that ionisation charge is drifted and extracted to the gas phase.





Detector configuration :

Drift field at 200 V/cm

Extraction field at 1600 V/cm

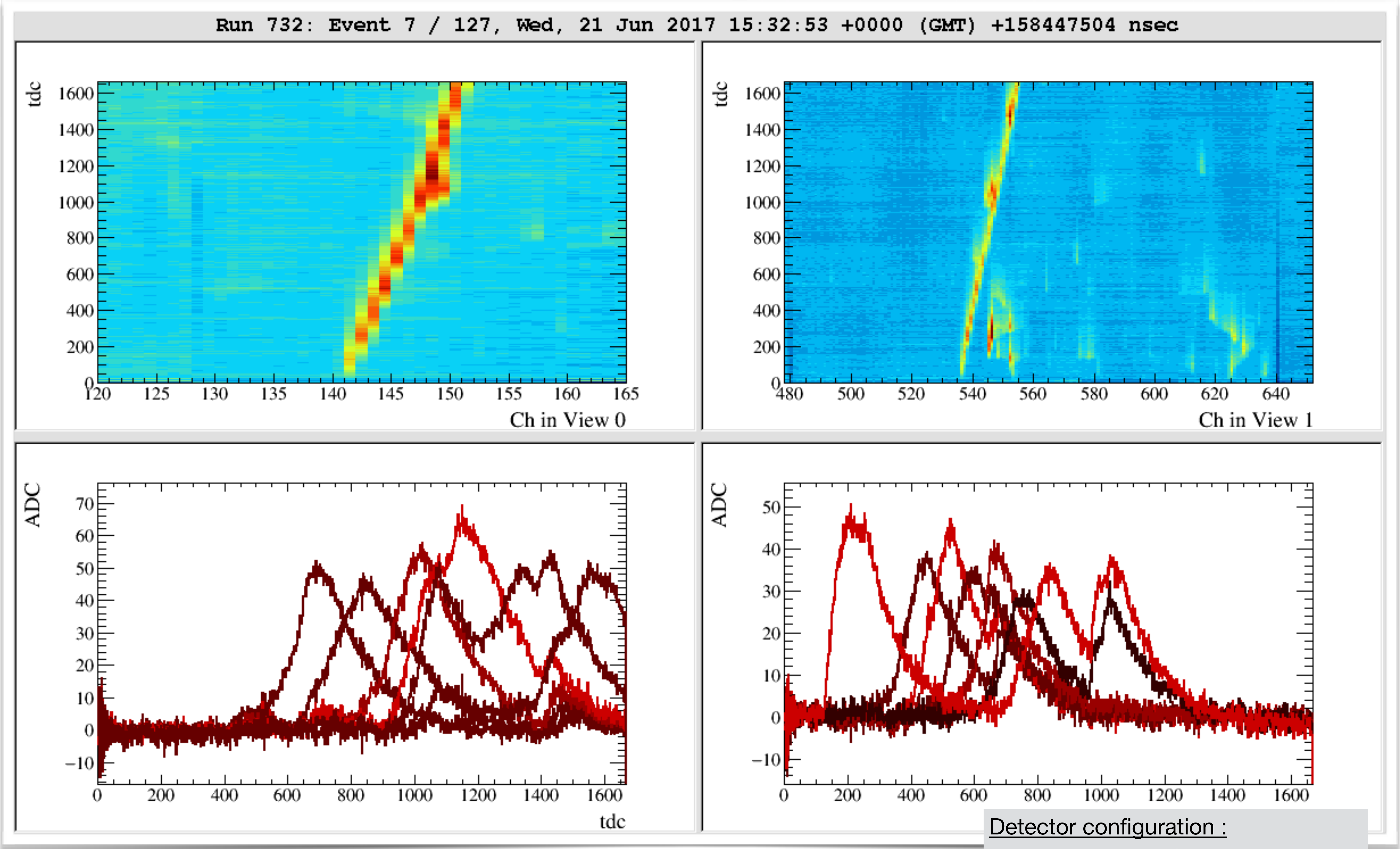
Amplification field at 10 kV/cm

Long PMT runs (~10 k triggers/run) are being analysed.

From this event acquired on the scope :

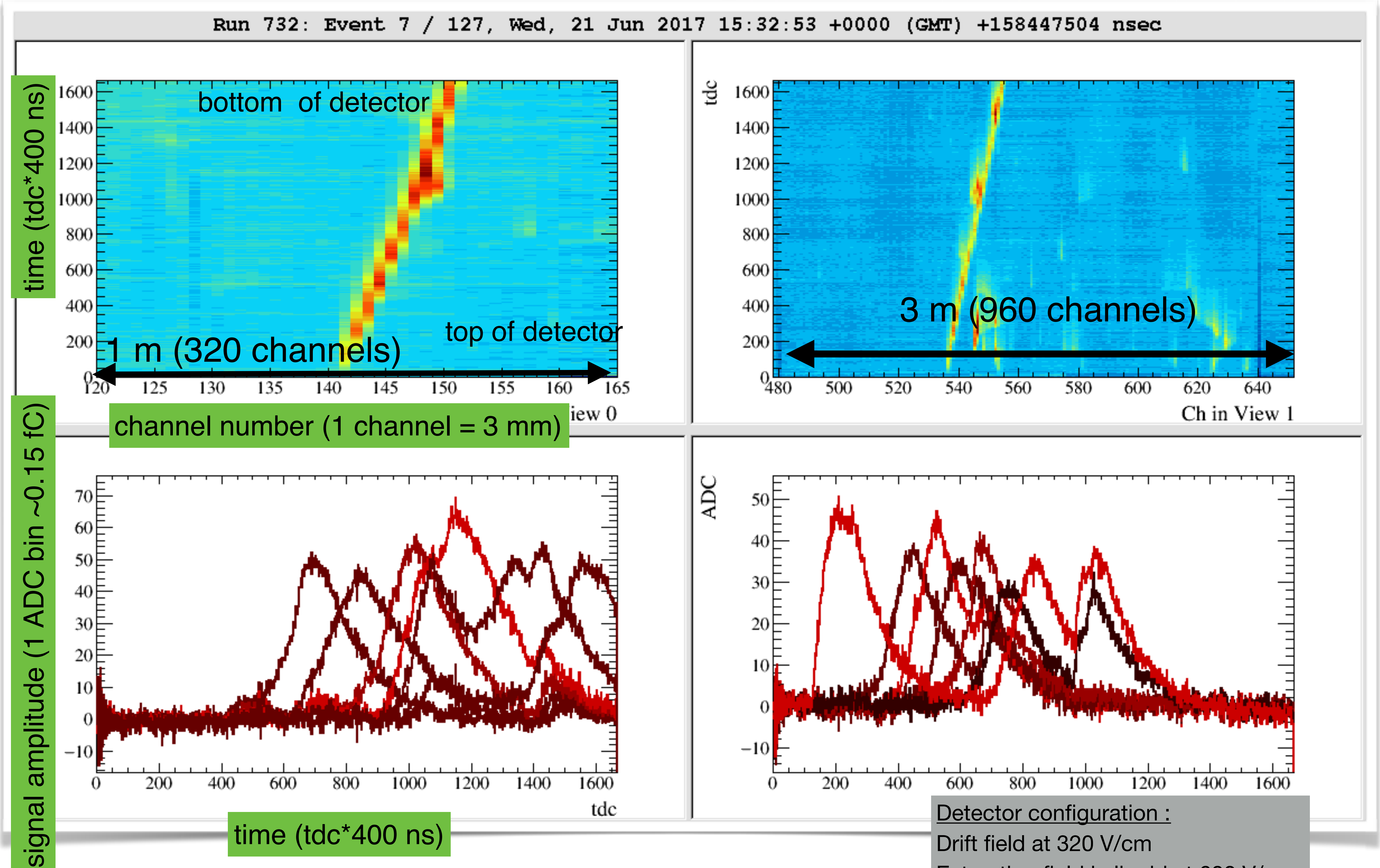
- Evidence electron extraction and amplification in the LEM
- Evidence of good liquid argon purity through ms drift observe

June 21st first cosmic track!



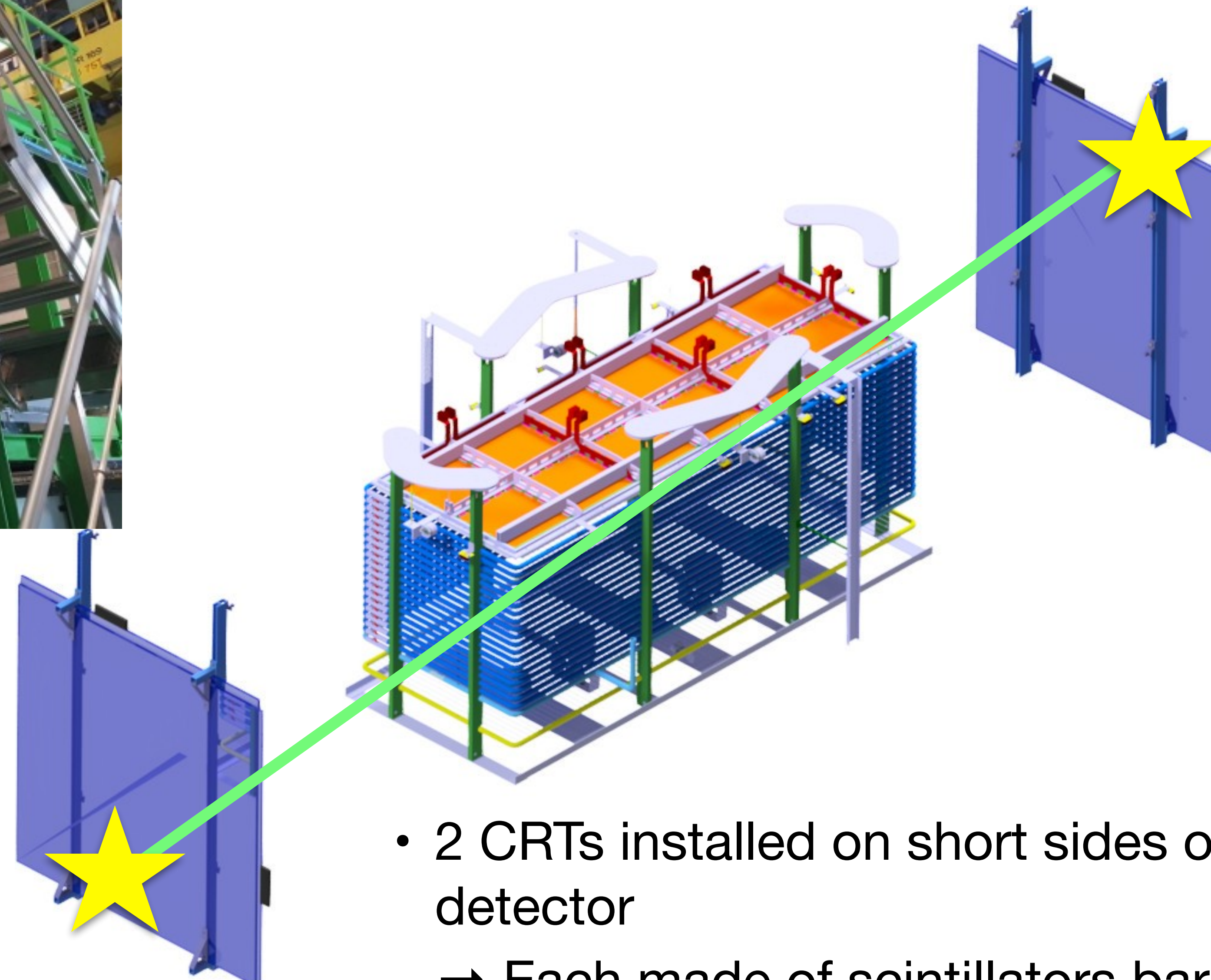
Detector configuration :
Drift field at 320 V/cm
Extraction field in liquid at 600 V/cm
Amplification field at 29 kV/cm
Induction field at 1 kV/cm

June 21st first cosmic track!

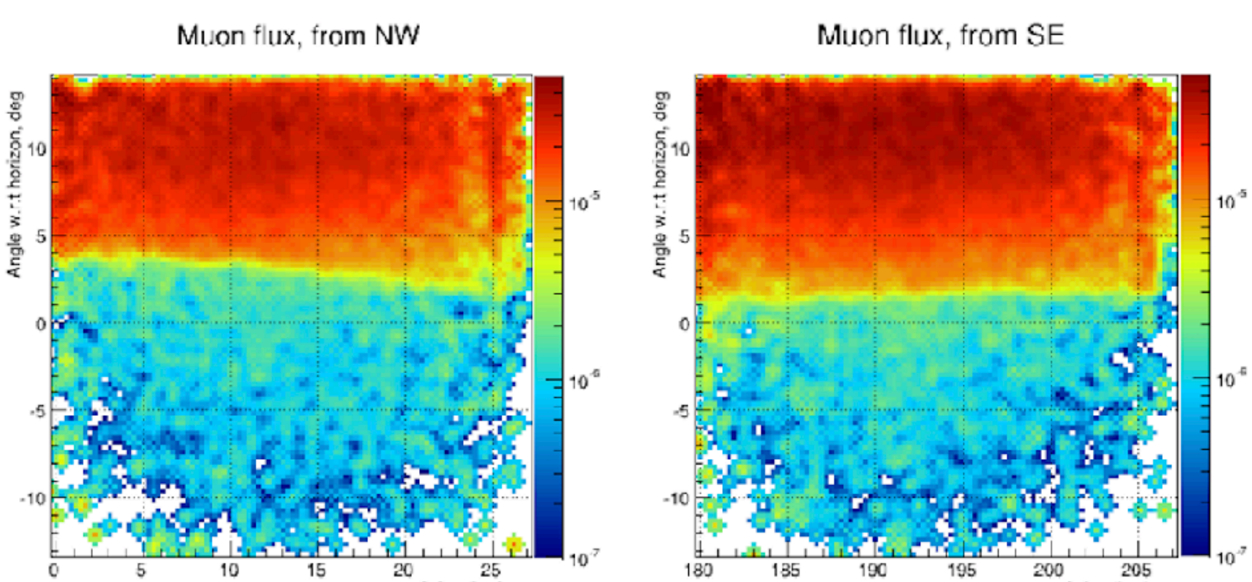


Detector configuration :
Drift field at 320 V/cm
Extraction field in liquid at 600 V/cm
Amplification field at 29 kV/cm
Induction field at 1 kV/cm

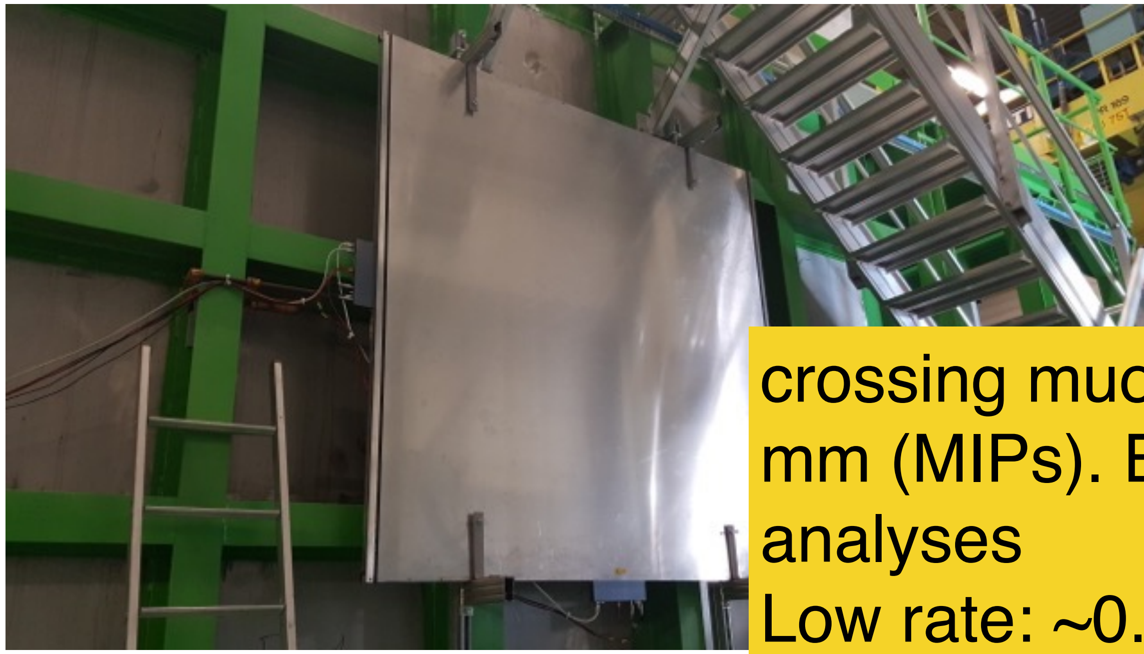
2 type of triggers: Cosmic ray tagger

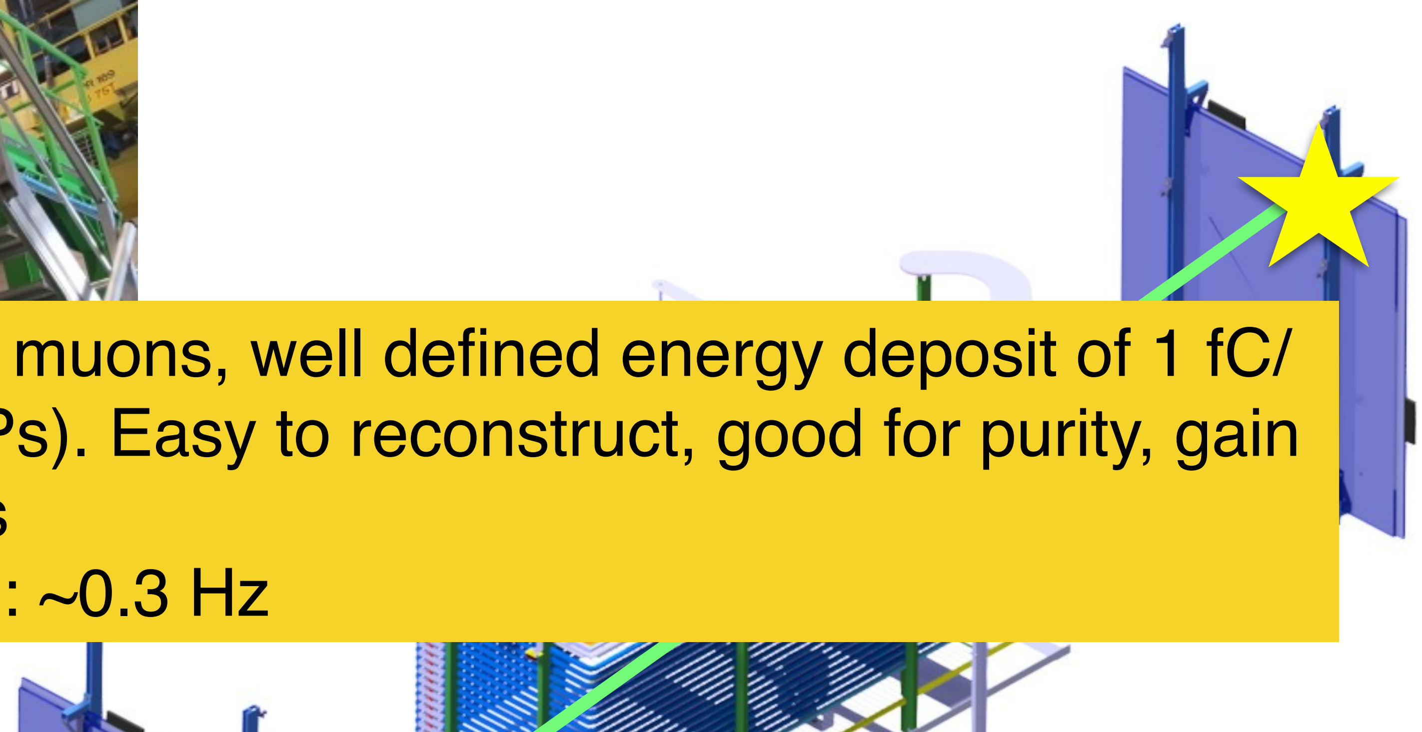


- 2 CRTs installed on short sides of the detector
  → Each made of scintillators bars in x-y to provide 2D coordinates
- Provide trigger for selecting crossing tracks along the detector, and inputs for μ tracking
- Trigger rate at ~ 0.3 Hz
- Can see the effect of Jura mountain shape on the cosmic ray flux !

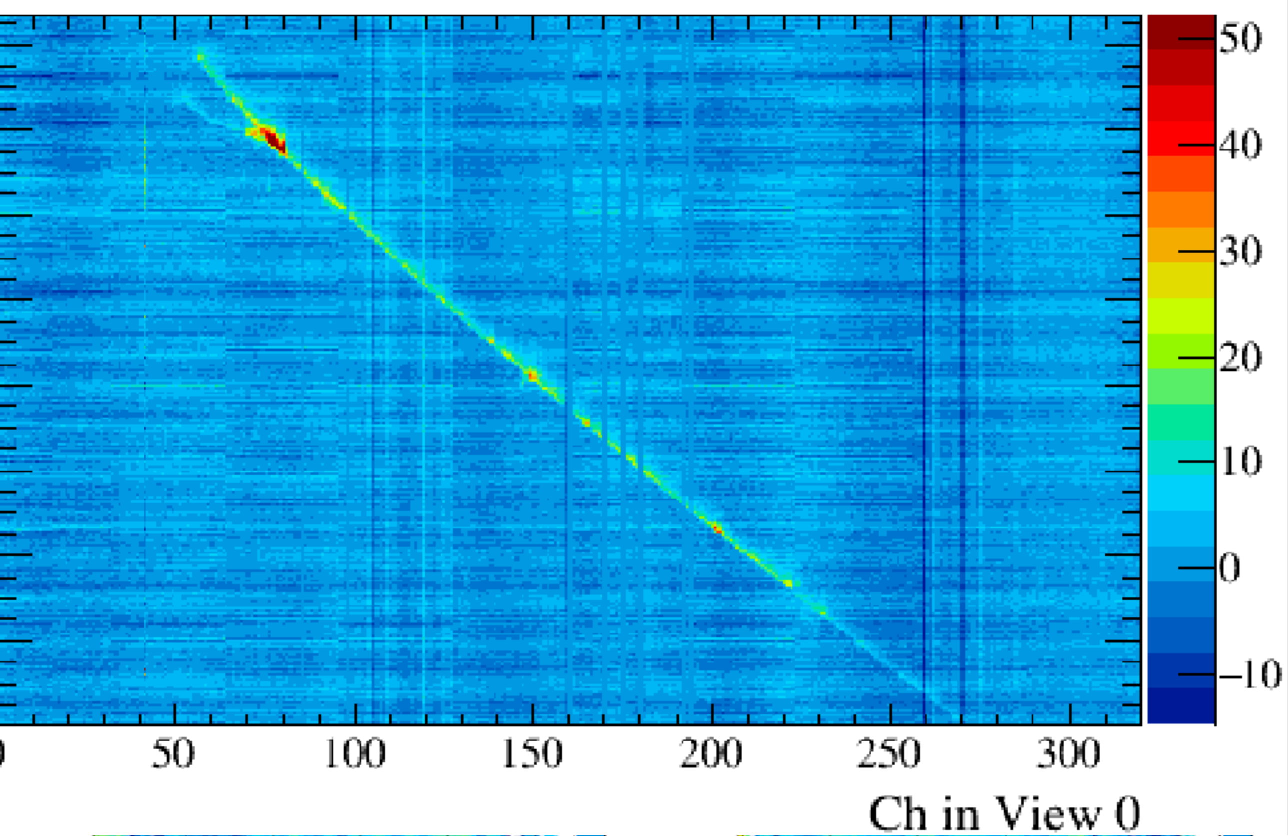


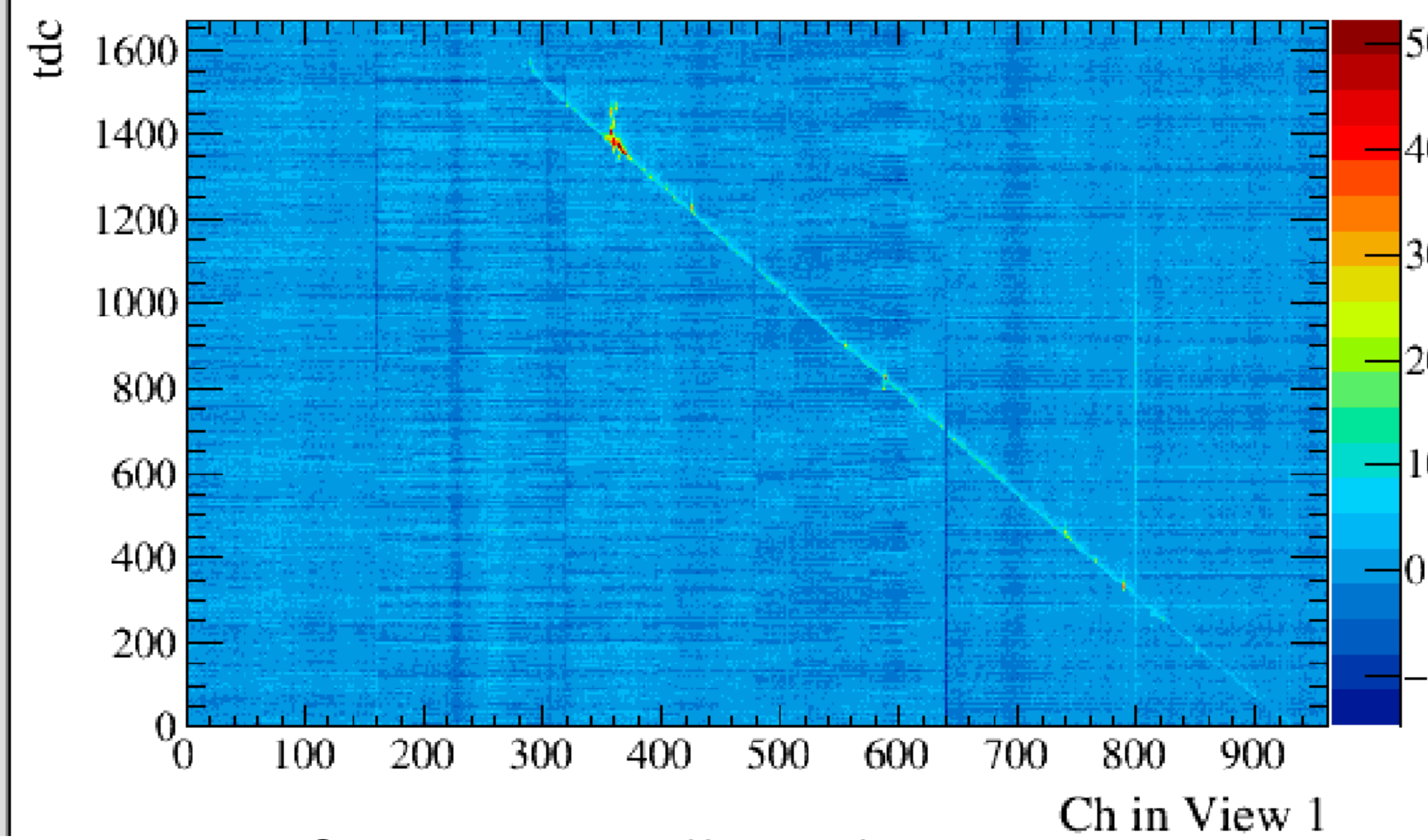
2 type of triggers: Cosmic ray tagger

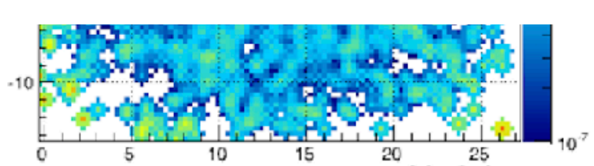


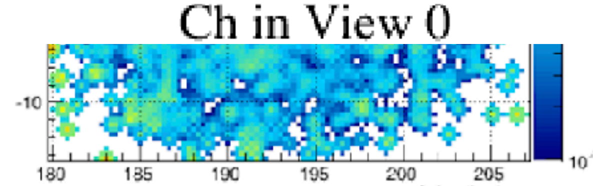


crossing muons, well defined energy deposit of 1 fC/mm (MIPs). Easy to reconstruct, good for purity, gain analyses
Low rate: ~0.3 Hz



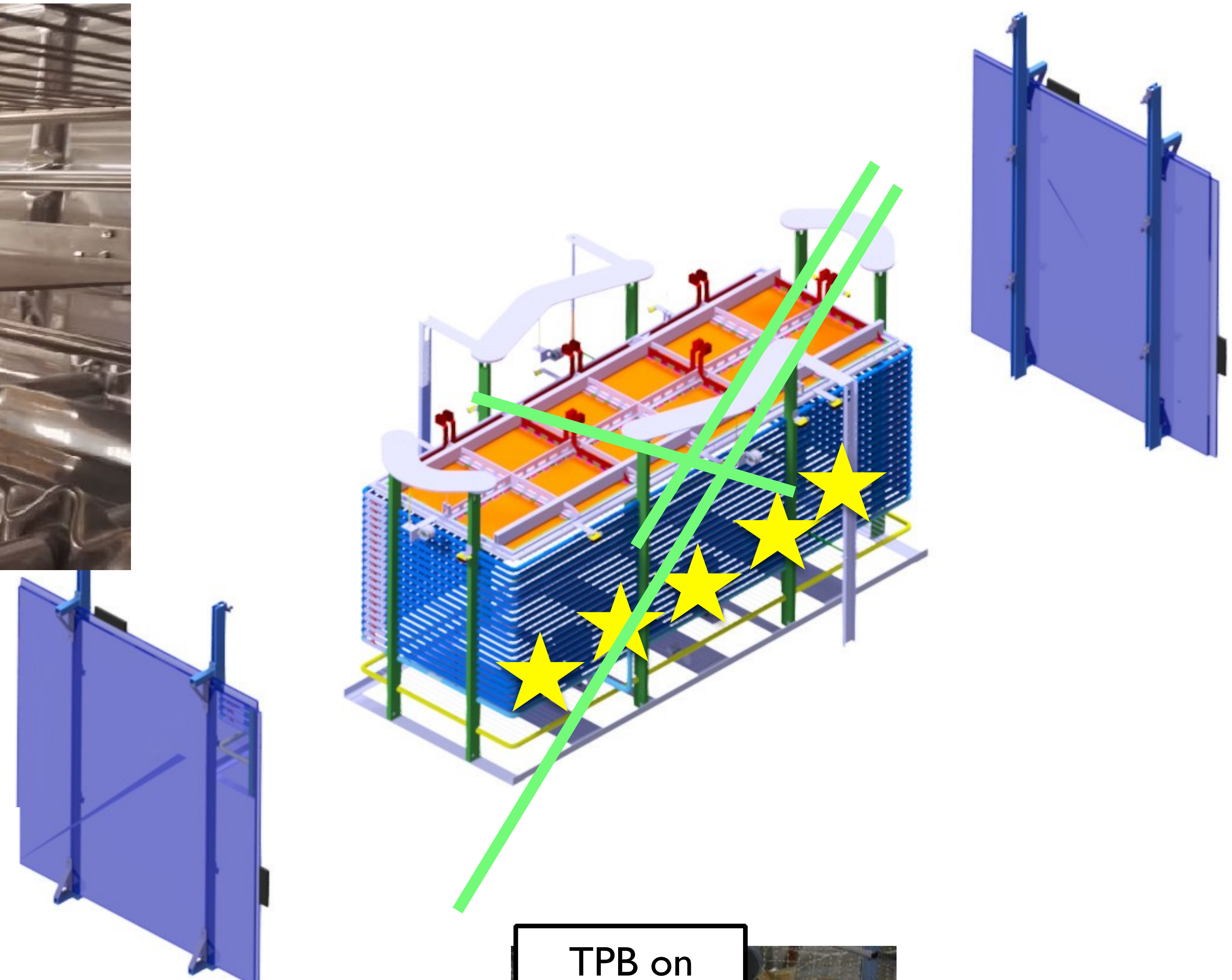


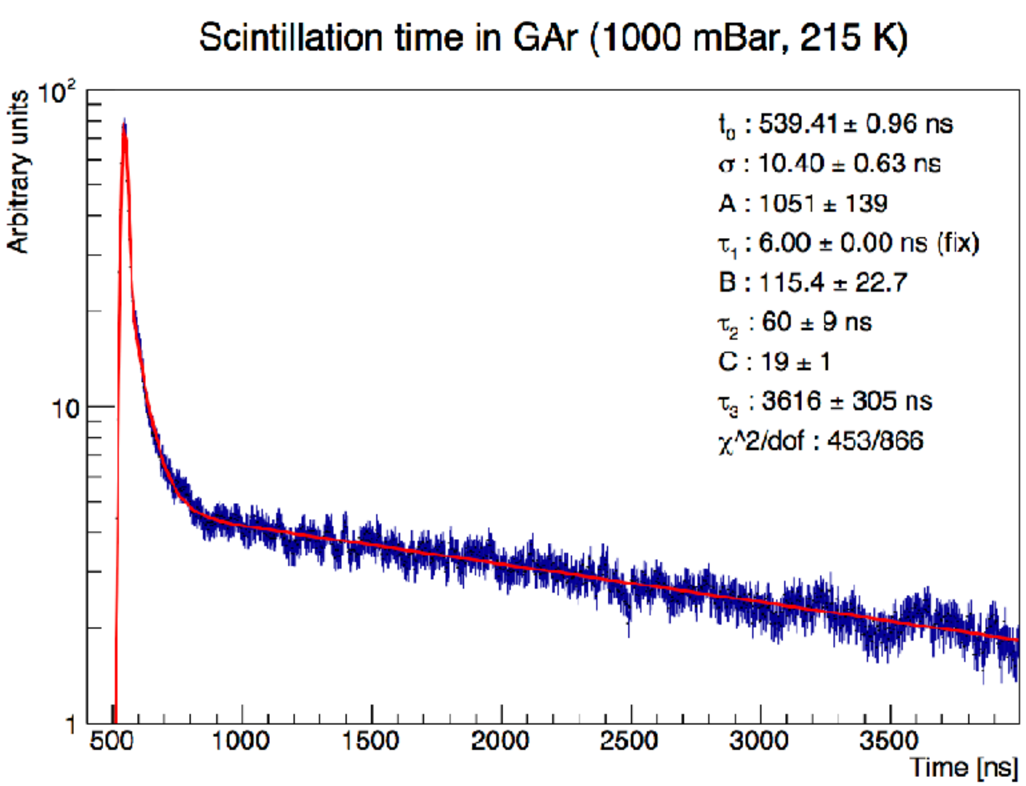


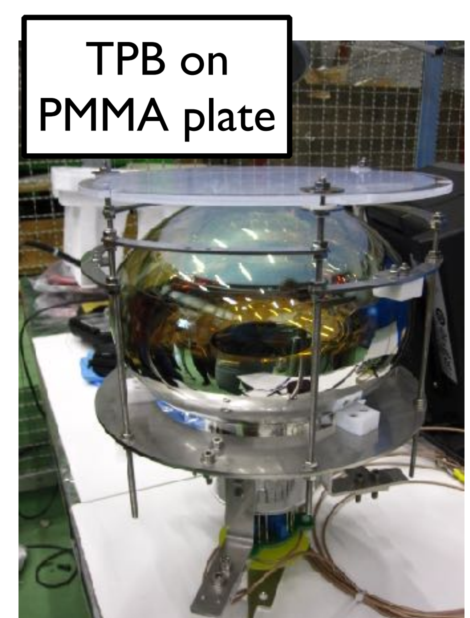


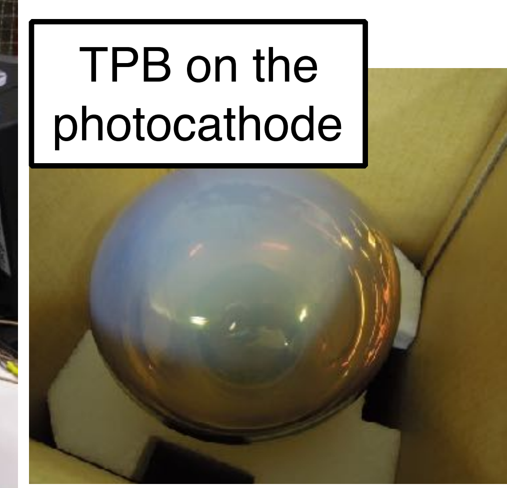
- Can see the effect of Jura mountain shape on the cosmic ray flux !

2 type of triggers: scintillation light



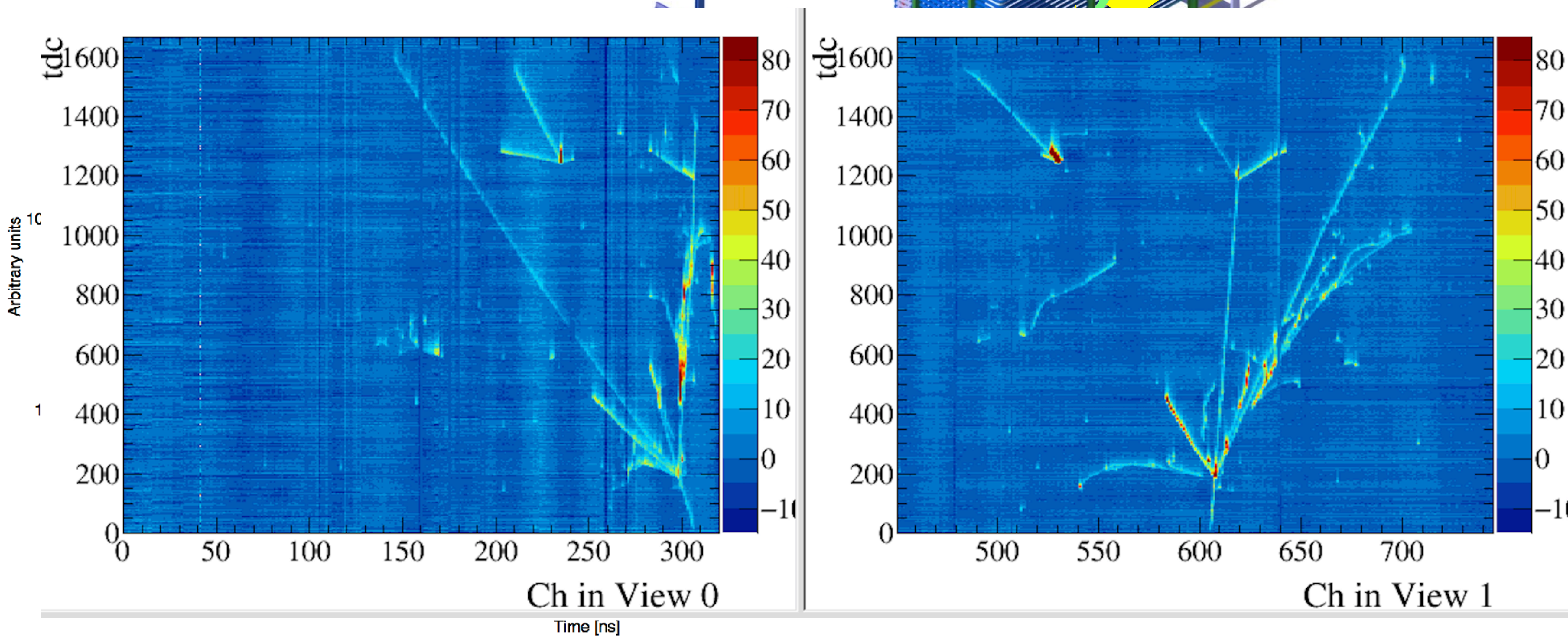




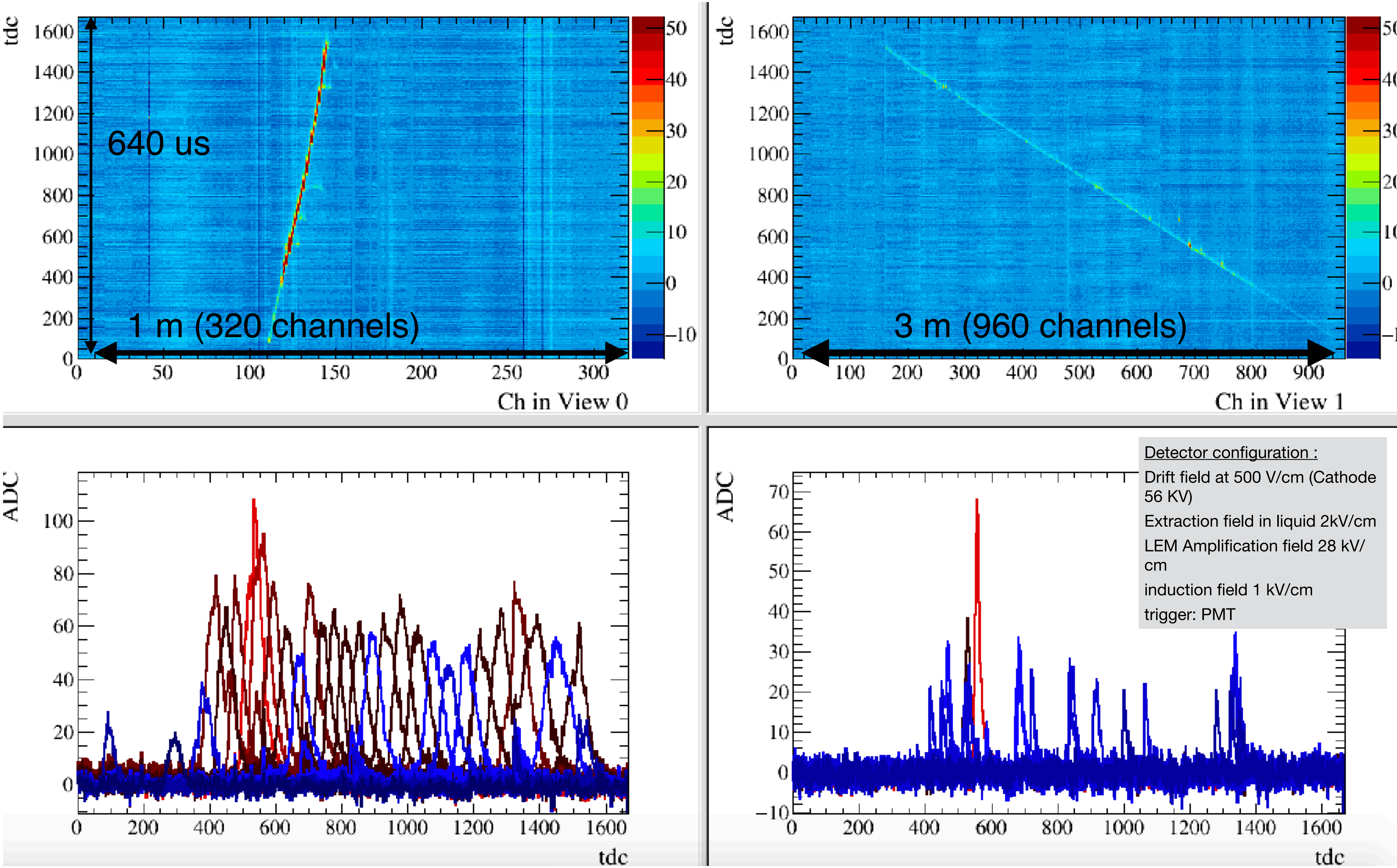


2 type of triggers

crossing muons + showering events. Many topologically interesting events, => test neutrino reconstruction algorithms.
Rate: ~3 Hz



Event library



Detector configuration :

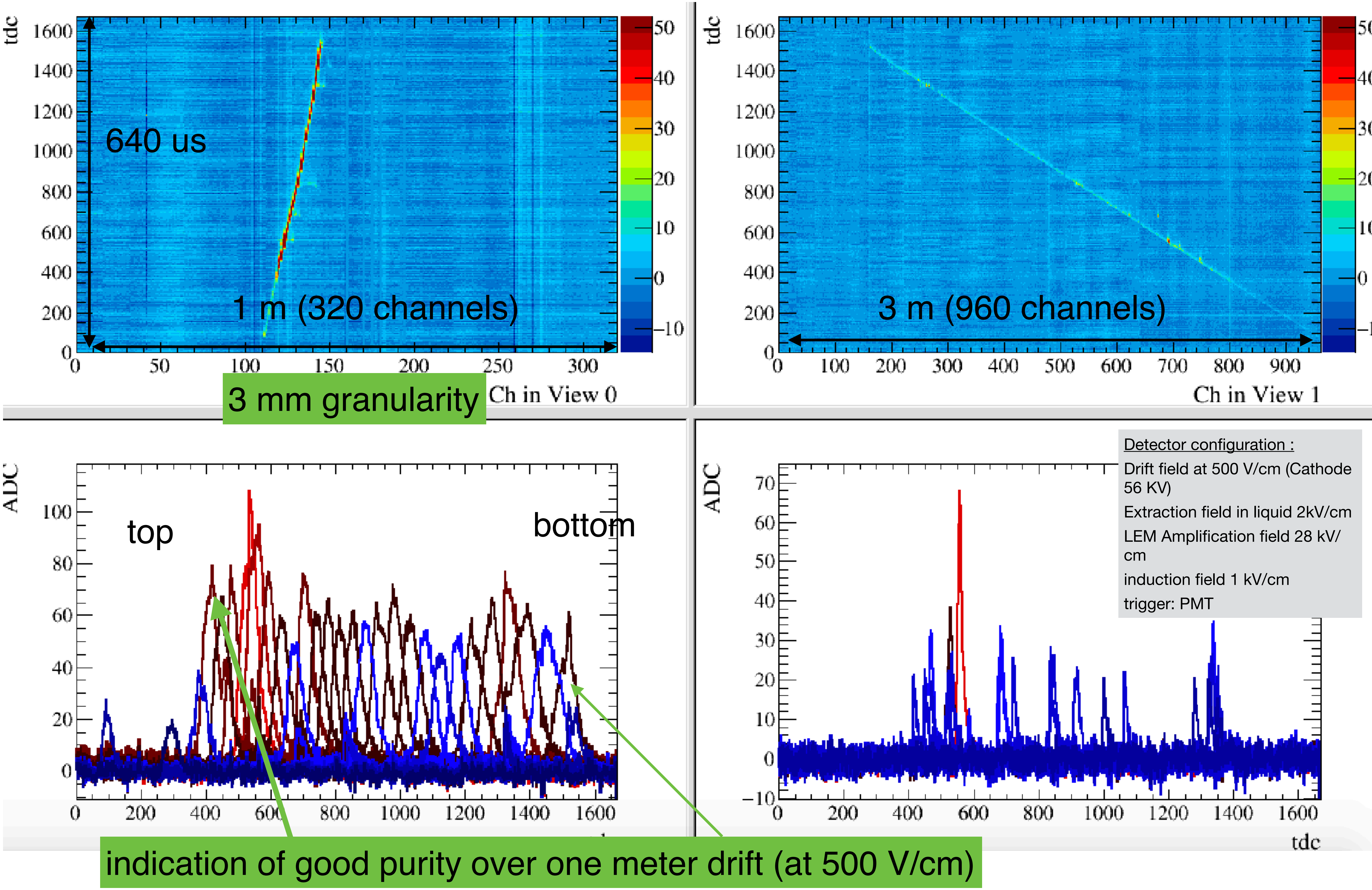
Drift field at 500 V/cm (Cathode 56 KV)

Extraction field in liquid 2kV/cm

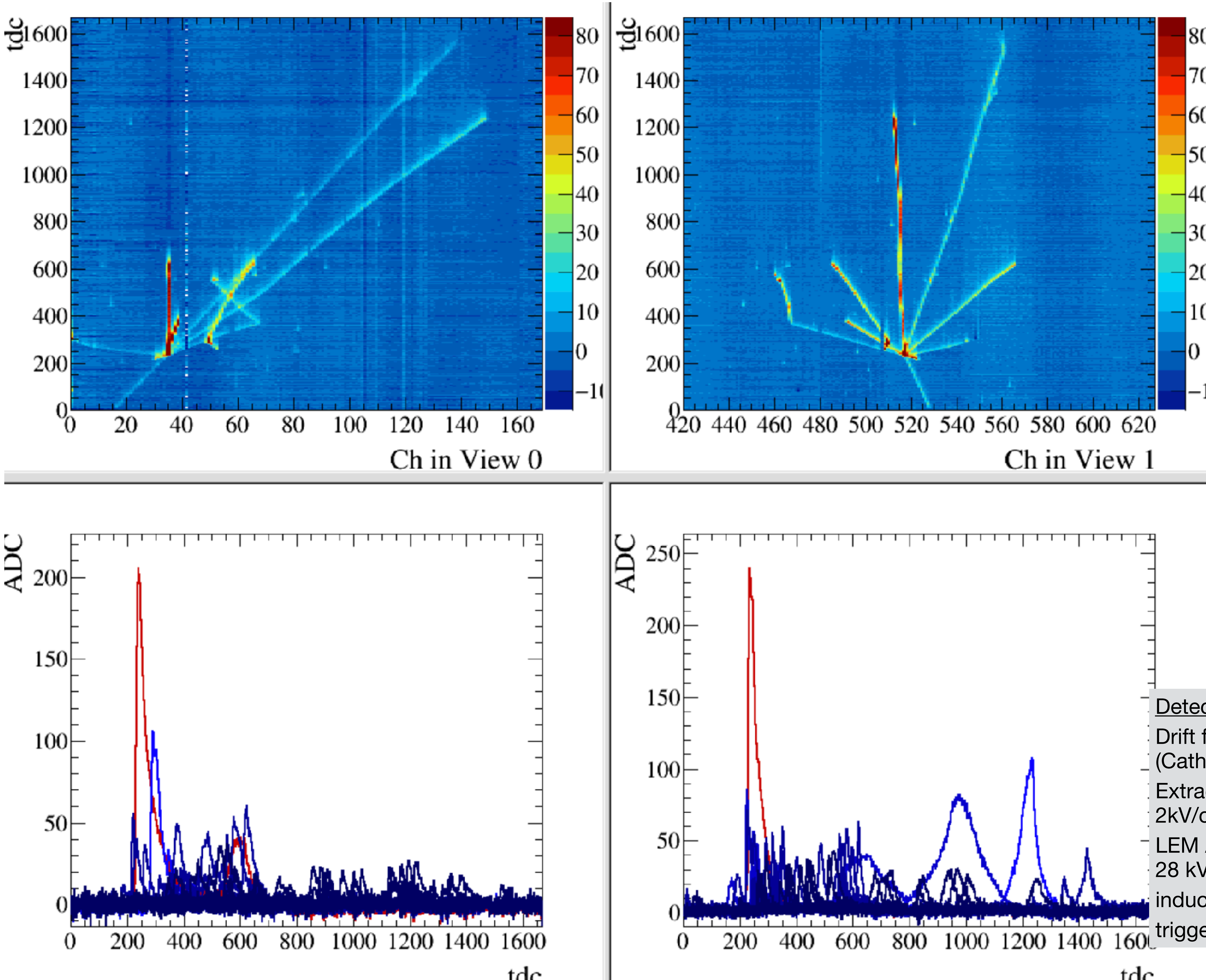
LEM Amplification field 28 kV/cm

induction field 1 kV/cm

trigger: PMT


640 us
1 m (320 channels)
3 mm granularity
Ch in View 0
tdc
3 m (960 channels)
Ch in View 1
ADC
top
bottom
indication of good purity over one meter drift (at 500 V/cm)
Detector configuration :
Drift field at 500 V/cm (Cathode 56 KV)
Extraction field in liquid 2kV/cm
LEM Amplification field 28 kV/cm
induction field 1 kV/cm
trigger: PMT

Event library



Detector configuration :

Drift field at 500 V/cm (Cathode 56 KV)

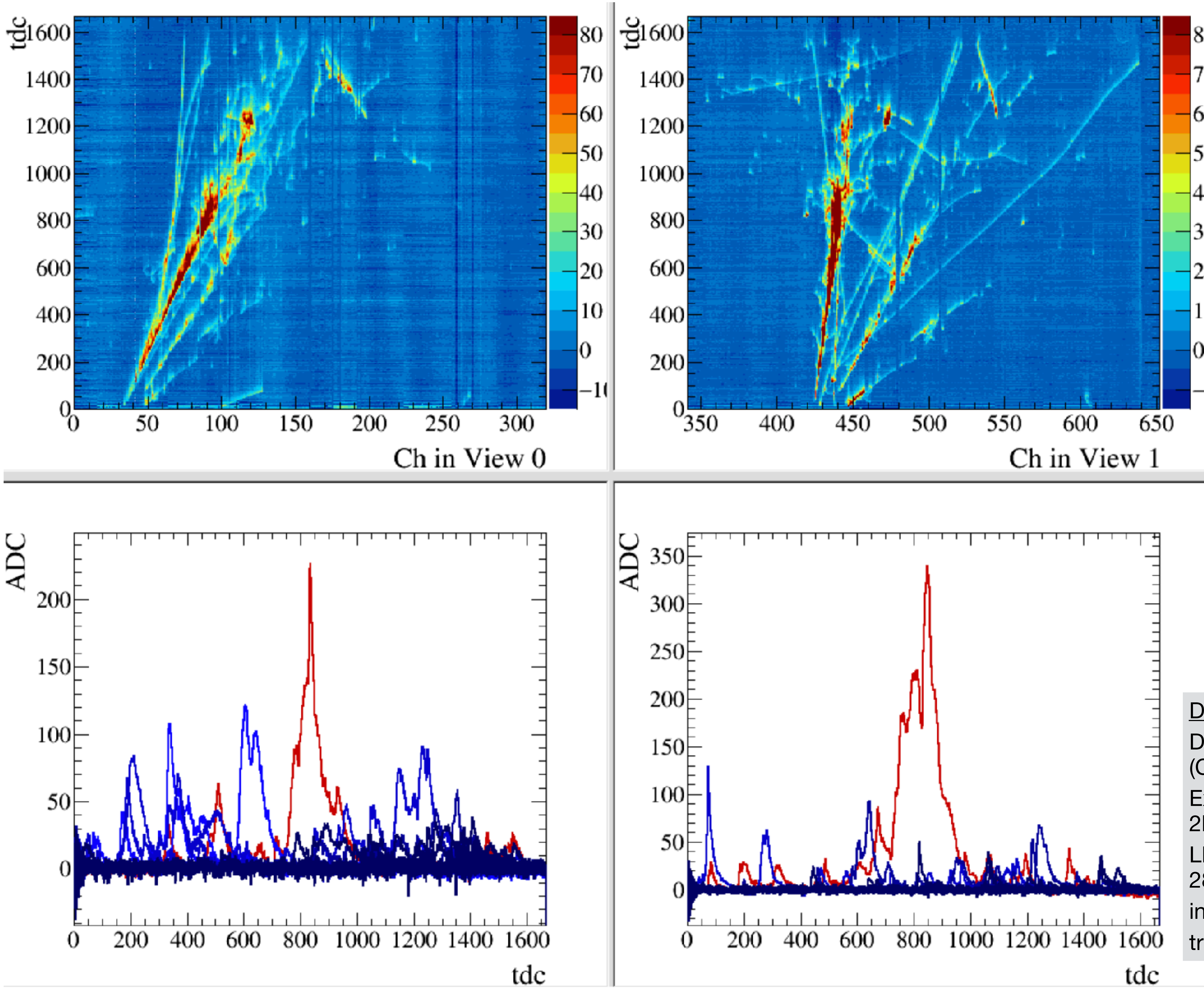
Extraction field in liquid 2kV/cm

LEM Amplification field 28 kV/cm

induction field 1 kV/cm

trigger: PMT

Event library



Detector configuration :

Drift field at 500 V/cm (Cathode 56 KV)

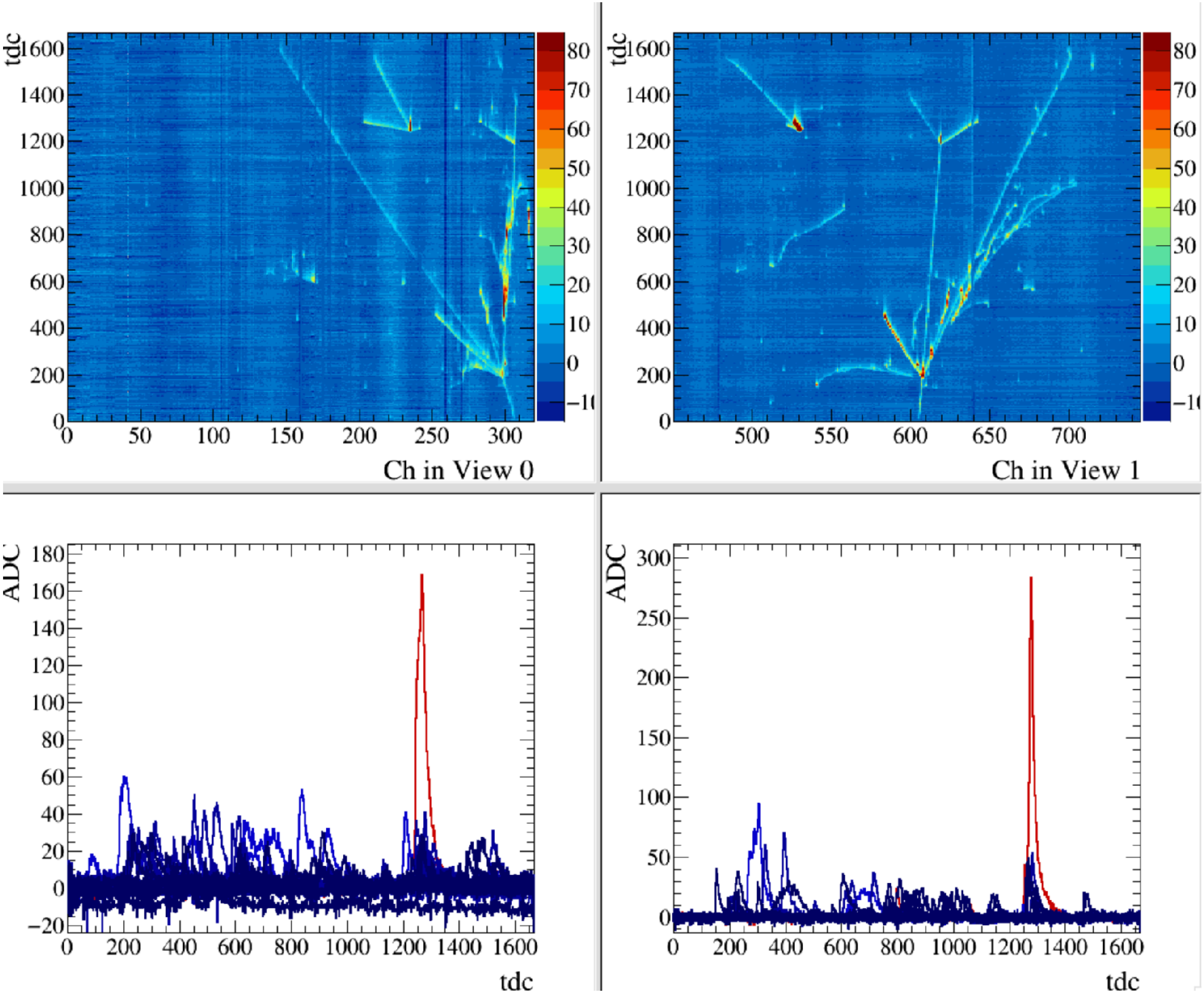
Extraction field in liquid 2kV/cm

LEM Amplification field 28 kV/cm

induction field 1 kV/cm

trigger: PMT

Event library



<u>Detector configuration :</u>

Drift field at 500 V/cm (Cathode 56 KV)

Extraction field in liquid 2kV/cm

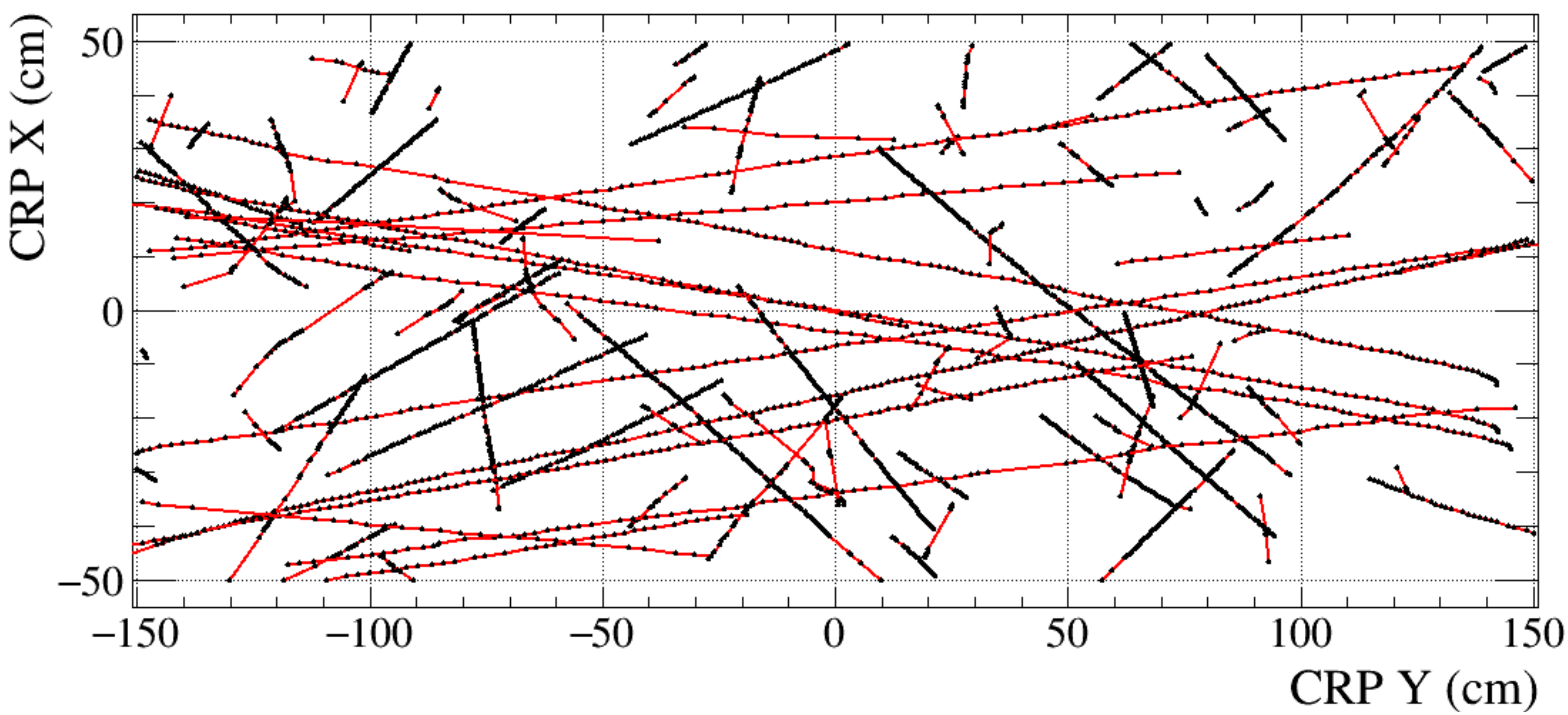
LEM Amplification field 28 kV/cm

induction field 1 kV/cm

trigger: PMT

Preliminary track reconstruction

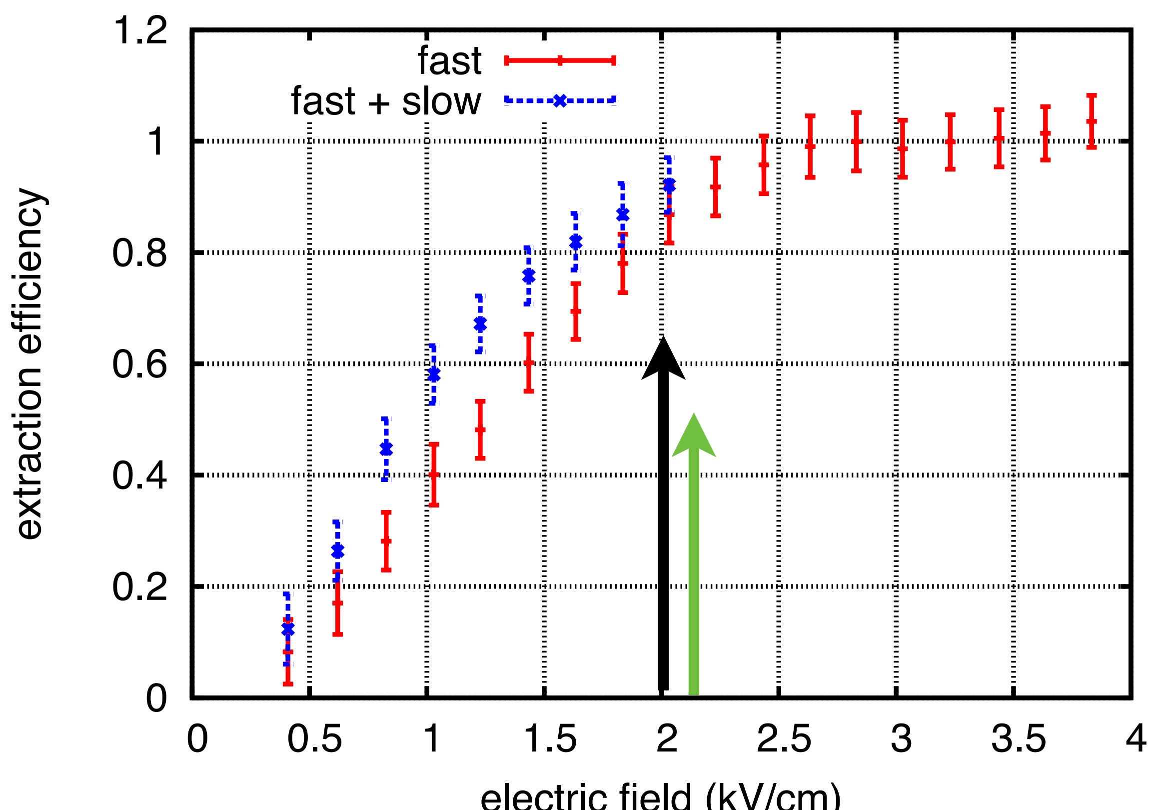
- Projection on the x-y plane of 3D tracks reconstructed in one run
- Points are the hits on view 0 associated to the reconstructed tracks (red line)
- Long tracks are the one triggered by the CRT, short tracks are cosmics crossing the detector during the readout window



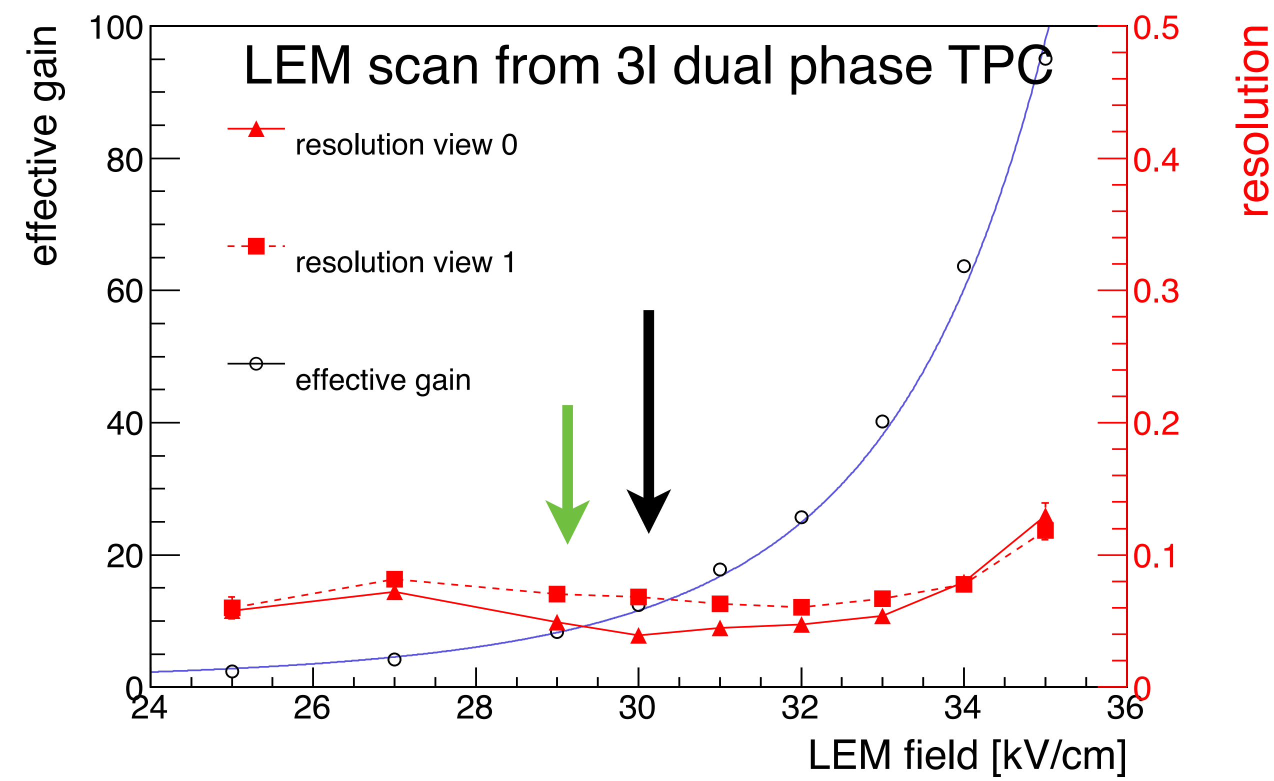
Data taking - ongoing

- Detector is under commissioning we have collected about 150 k “good” events with both trigger configurations.
- Currently trying to scan the different fields to optimise the gain and signal to noise ratio

Extraction Field



Amplification Field



LBNO TDR, CERN-SPSC-2014-013, 1409.4405

Best configuration achieved in the 3x1x1 so far

Nominal configuration

Conclusion

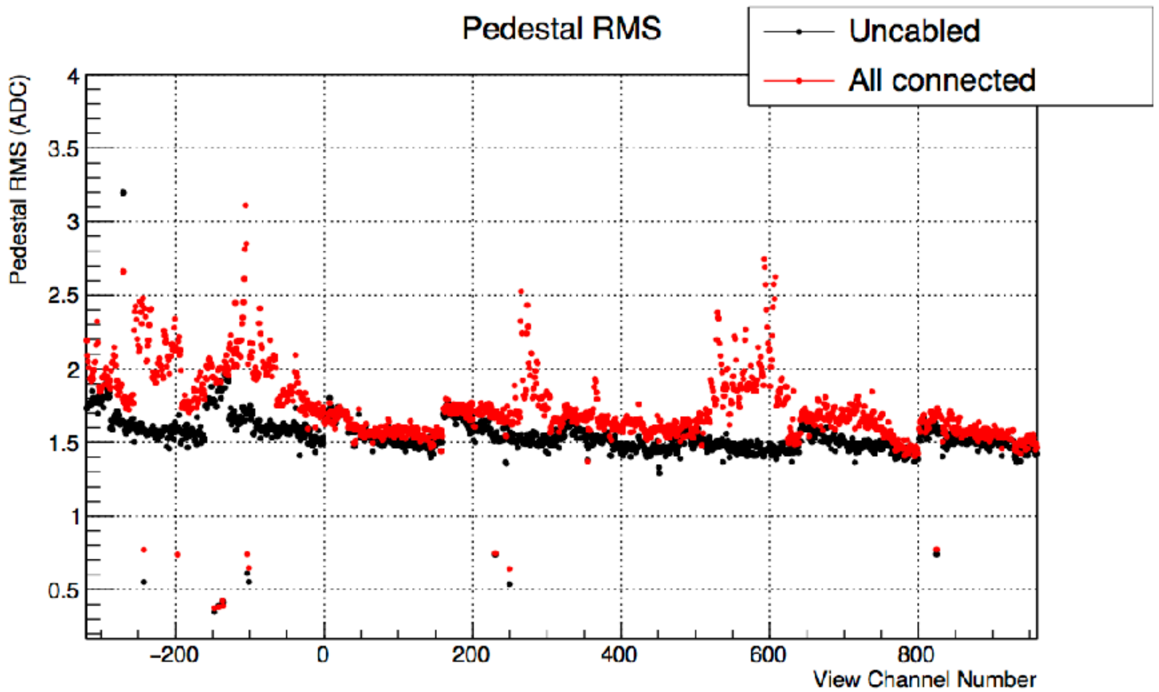
- Liquid argon TPCs have been under developments for a few decades. They have proven to provide unprecedented images of neutrino interactions and are clearly recognised as a unique tool to address the particle physics challenges of the 21st century.
- The dual phase TPC represents a major technological advancement for the field by amplifying the drifting electrons.
- The first data from the WA105 3x1x1 m3 TPC is encouraging for the future of the technology and the construction of protoDUNE-DP.
- Still major challenges ahead with data analyses of the 3x1x1 and the construction and operation of protoDUNE-DP.
- CERN is playing a very important role with the developments or prototypes and the associated infrastructure (cryostats, cryogenics,..).


THANK YOU

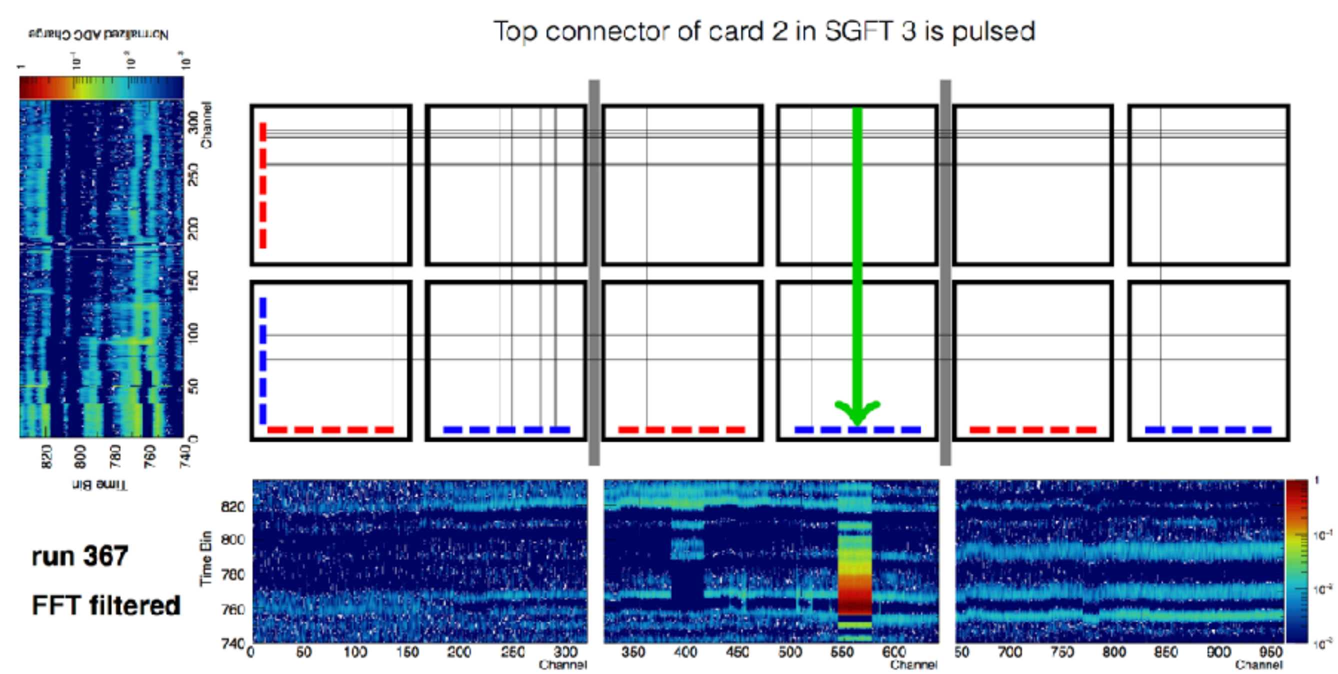
BACKUP

Software tools

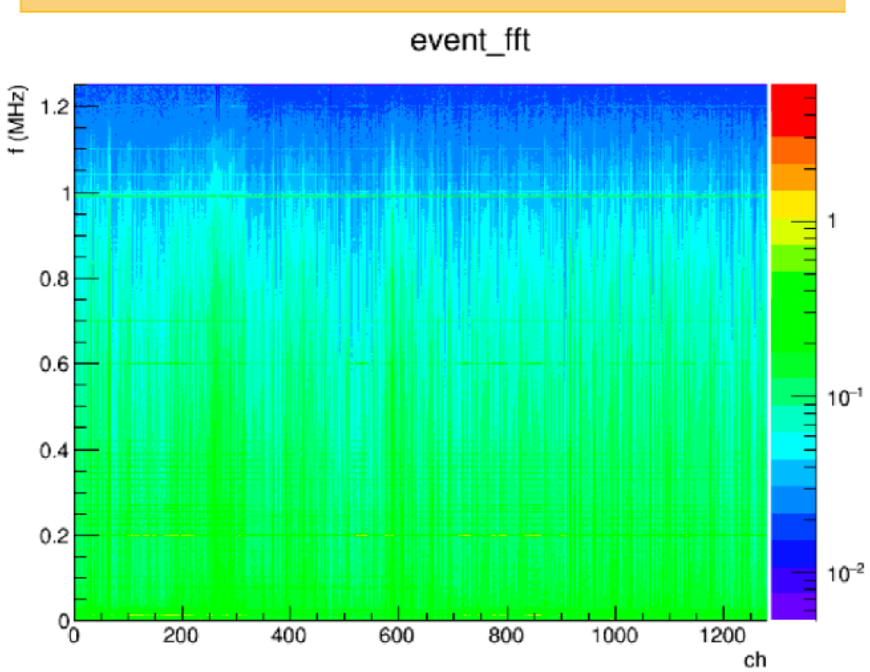
systematic check of noise

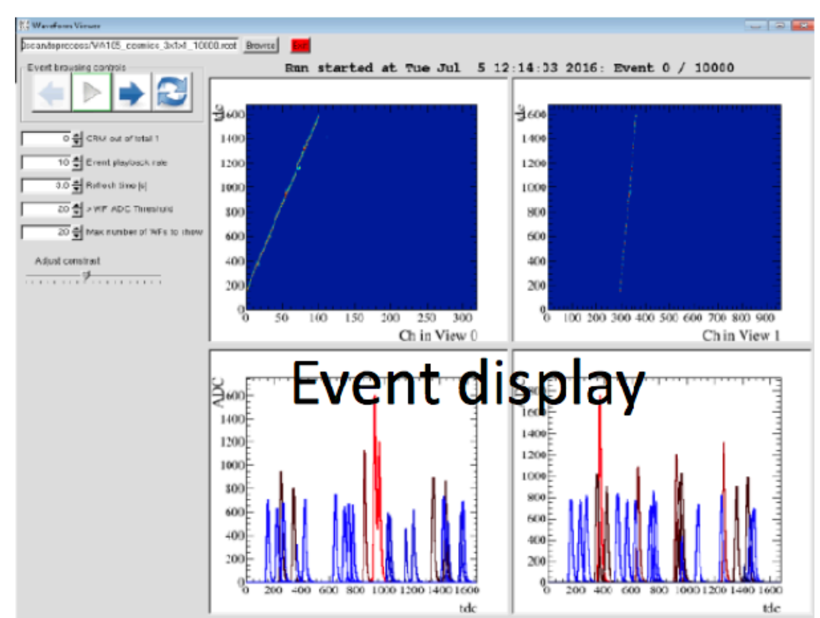


pulsing to check detector response



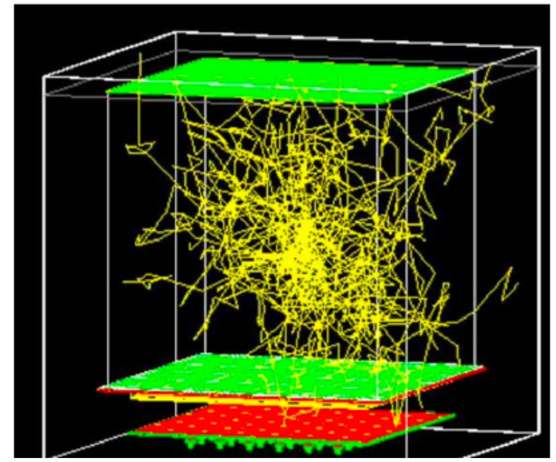
src/dofft.cc performs FFT on the raw data



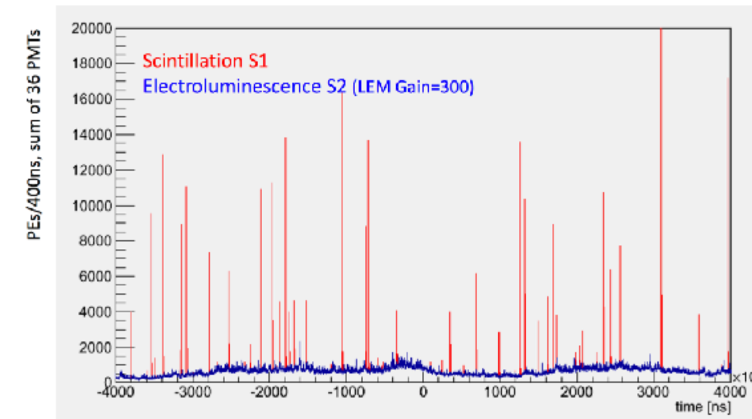


Software tools protoDUNE-DP

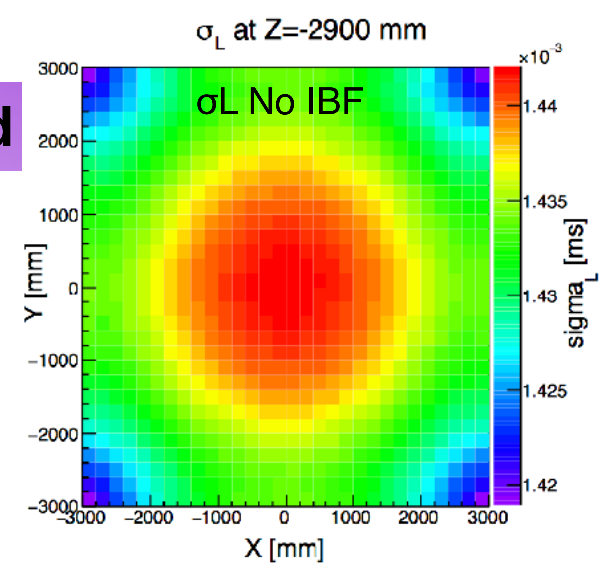
Light simulation:
-light yield and accurate positioning of PMT
-impact of electroluminescence (S2)
-cosmic ray tagging
-Absorption in LAr

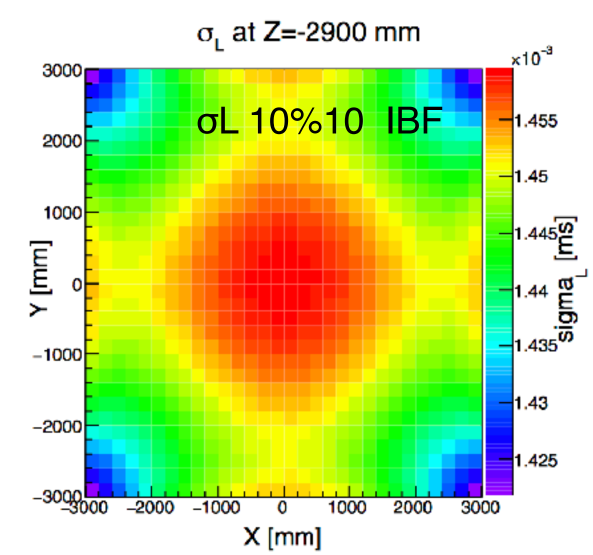


Cosmic muons' light signal in 8 ms window



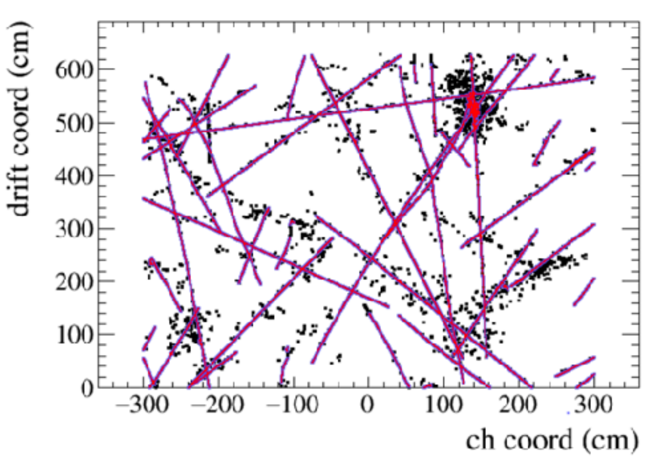
Study of space charge and effect on electric field

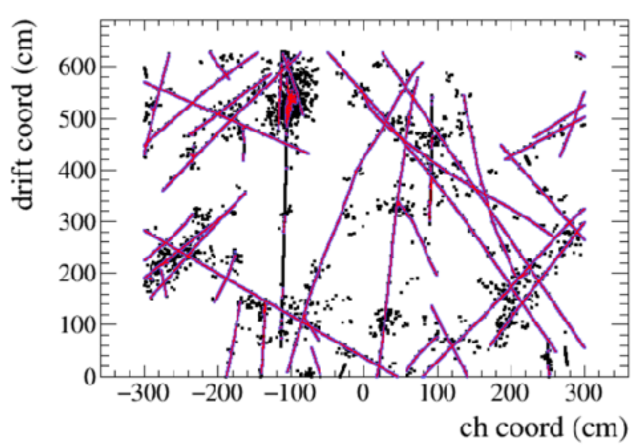




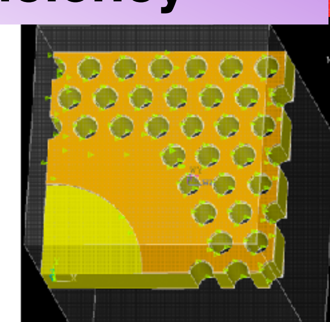
cosmic muon reconstruction

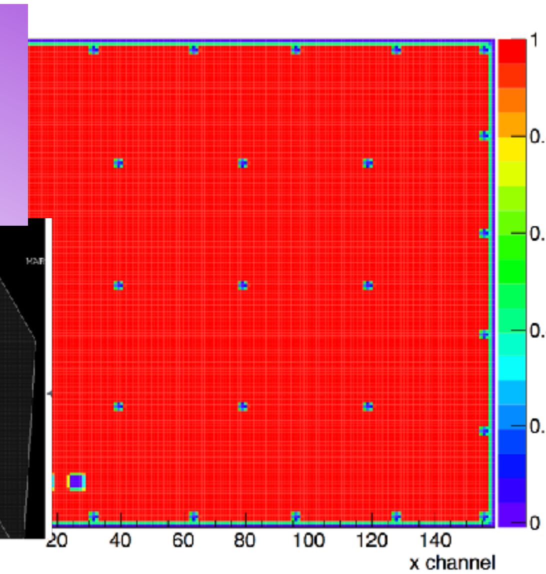
Black points show the reconstructed hits
Magenta points show hits associated to some track
Red lines indicate track paths





Study of LEM borders, effect on charge collection efficiency



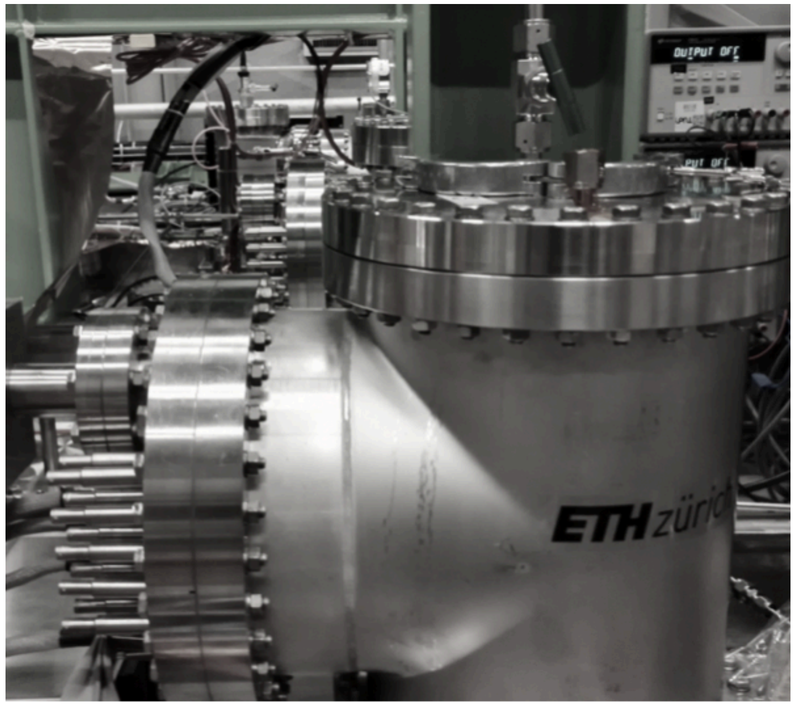


Feedthroughs installed on the 3x1x1 m3 TPC

All feedthroughs operational and tested over the past year. Same to be installed in pDUNE-DP

<u>4 signal chimneys</u>

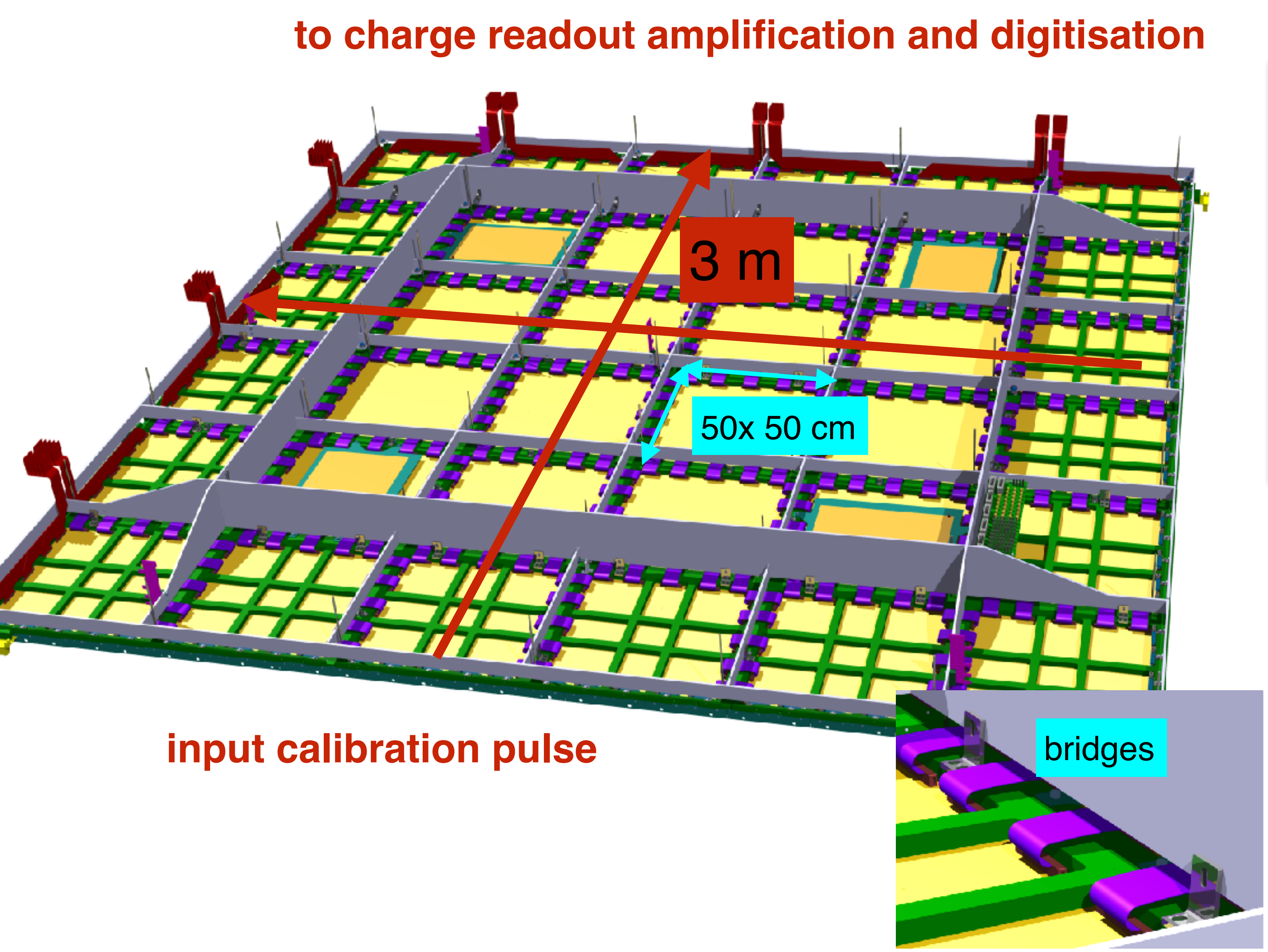
<u>3 slow control and medium voltage</u>

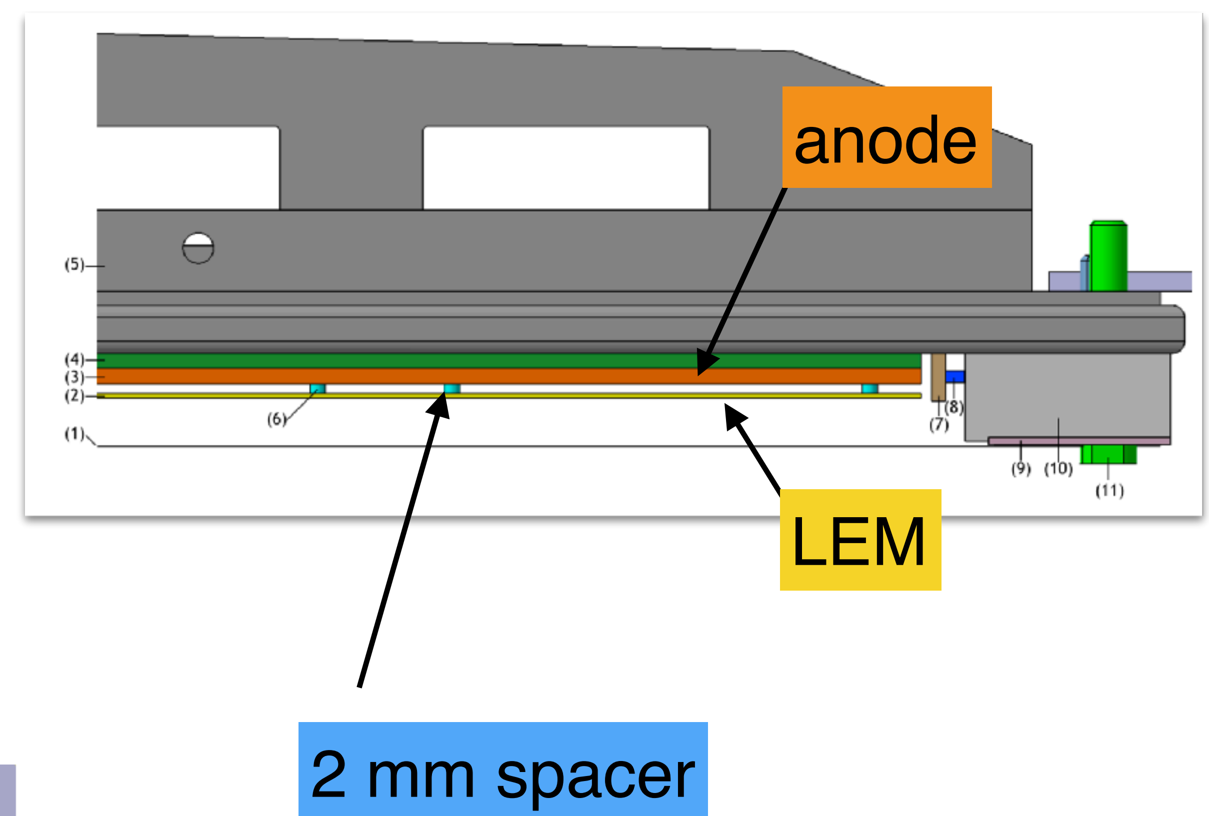


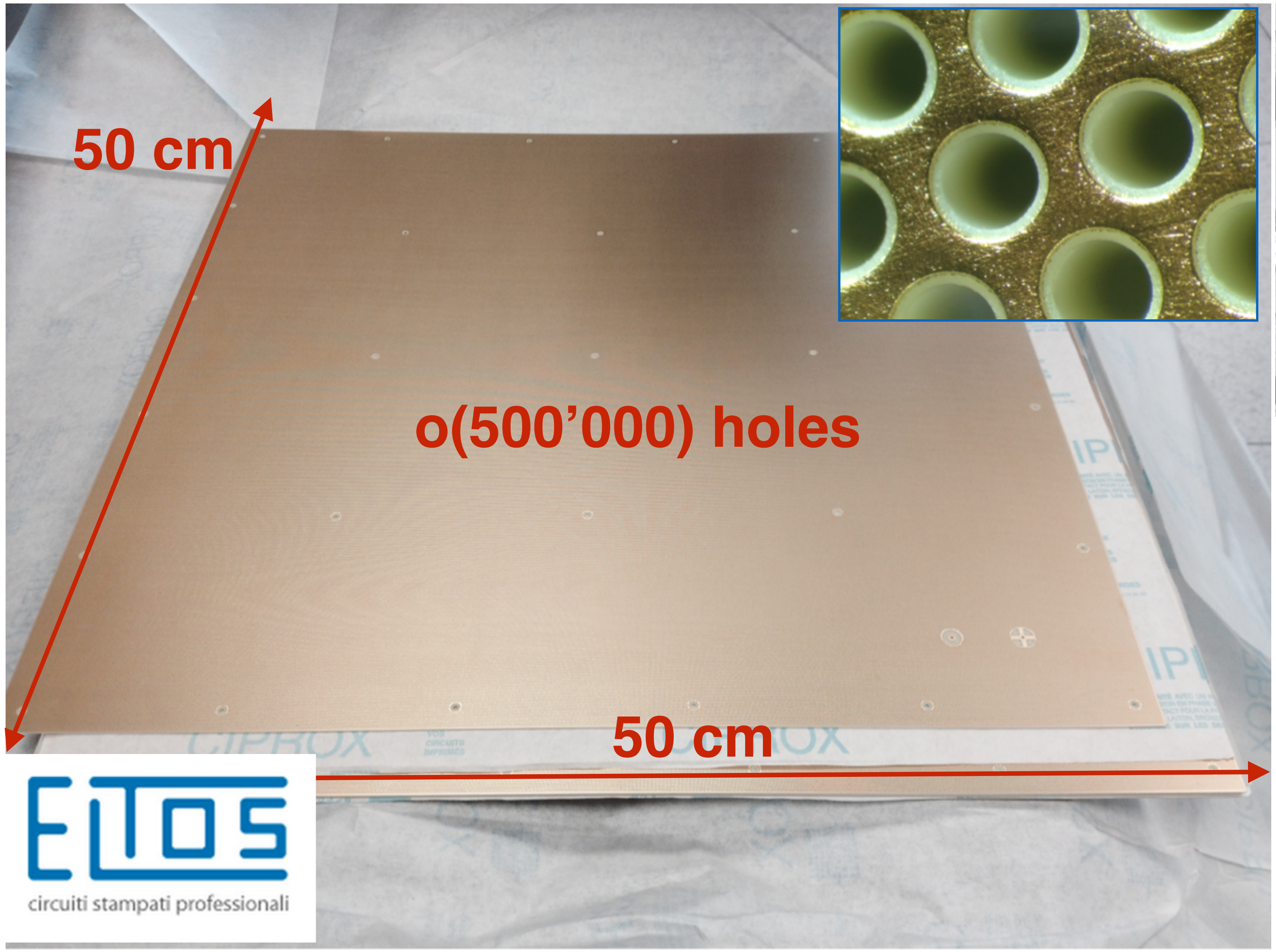
<u>3 CRP suspension</u>

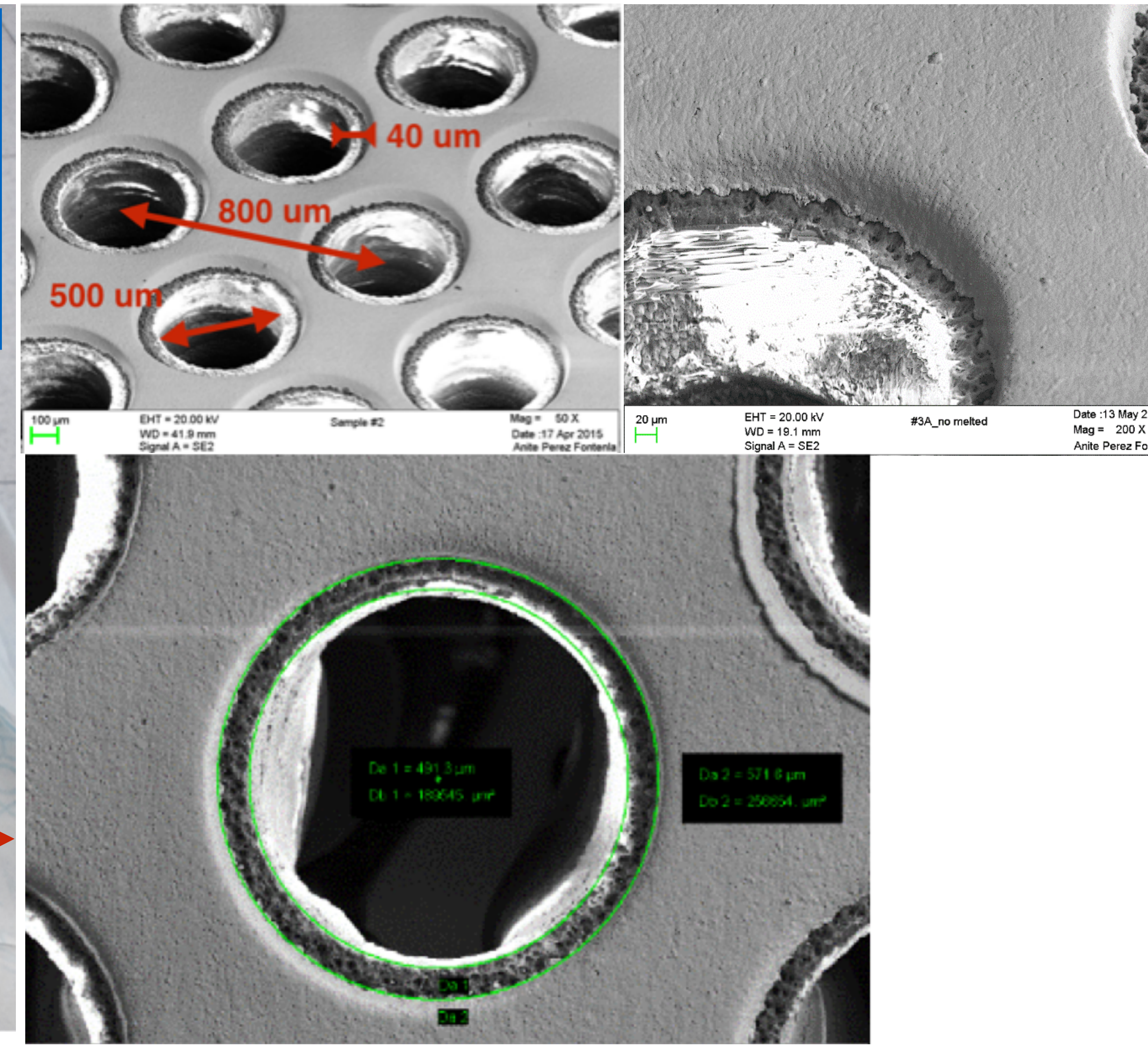
<u>1 High voltage</u>
tested at 300 kV, operated at ~50 kV

- Tiled arrangement of independent 50x50 cm2 LEM and Anode Sandwiches (LAS).
- Provide fully active amplification area and 3 mm granularity *x-y* strip readout
- The LEMs are independently powered to provide o(30 kV/cm) accros the electrodes
- The anodes are bridged together to provide 3 meter long readout strips
- Both LEM and anodes are made from PCBs. They are produced industrially using standard techniques







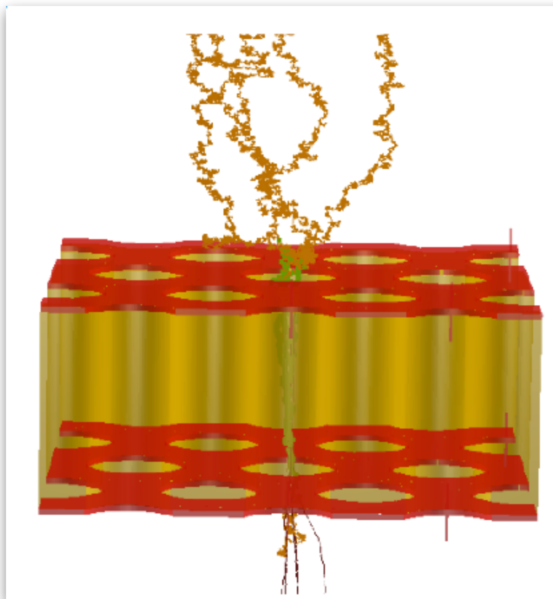


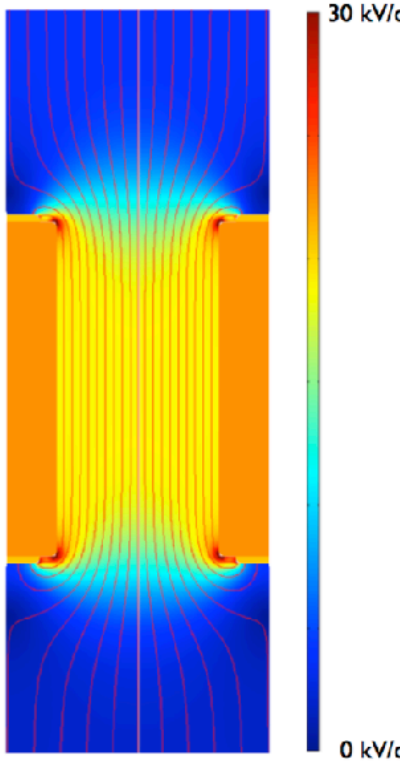
- ✓ PCB CNC drilled with o(150) holes per cm^2. 1 mm thick.
- ✓ 500 um hole diameter 800 um pitch.
- ✓ 40 um dielectric rim around the holes to avoid edge-induced discharges
- ✓ powered at around 30 kV/cm
- ✓ design is the result of many years of R&D on smaller scale prototypes.

Multiply number electrons by creating large electric field (>30 kV/cm) inside the holes.

$$G_{eff} = Te^{\alpha x} = Te^{A\rho x e^{-B\rho/E}}$$

- gas density
- amplification length
- electrical transparency of the LEM-anode system
- electric field inside the LEM hole



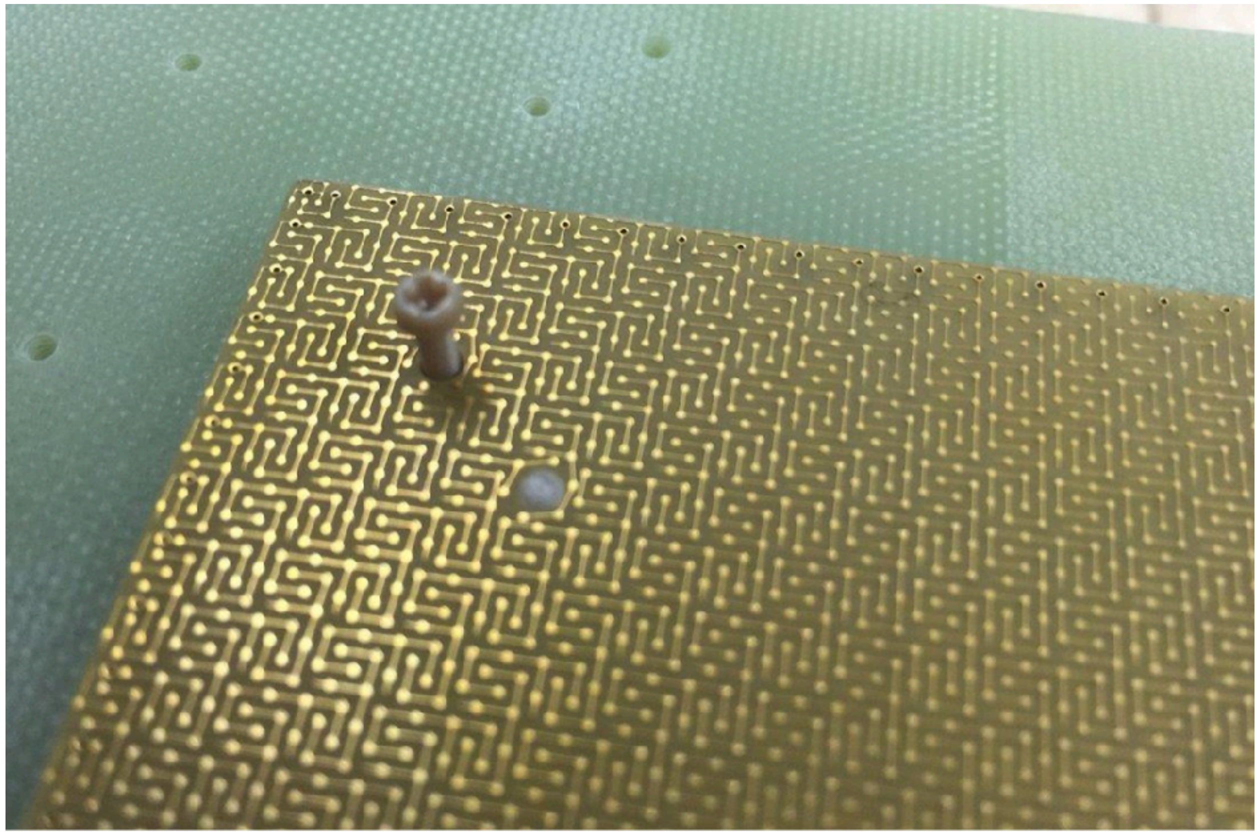


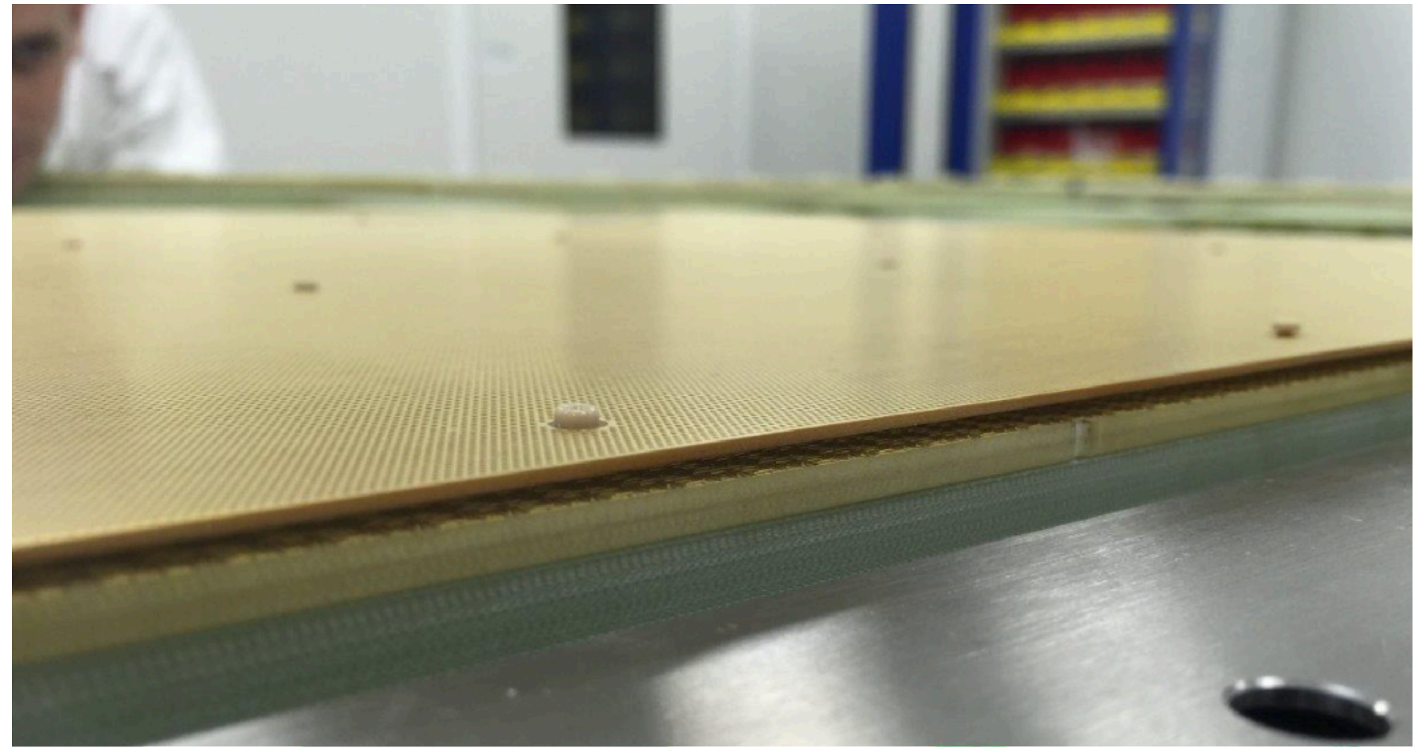
- Robust (1 mm thick), economic, high-gain electron multipliers for large area detectors. Well suited for cryogenic detectors and use in pure noble gas without quencher. Avalanche confinement preventing photon-feedback.

NIM A (2005) 10.102 NIM A598 p121-125 JINST 3 P07001 JINST 8 P02008 NIM A423 (1999) p119-125

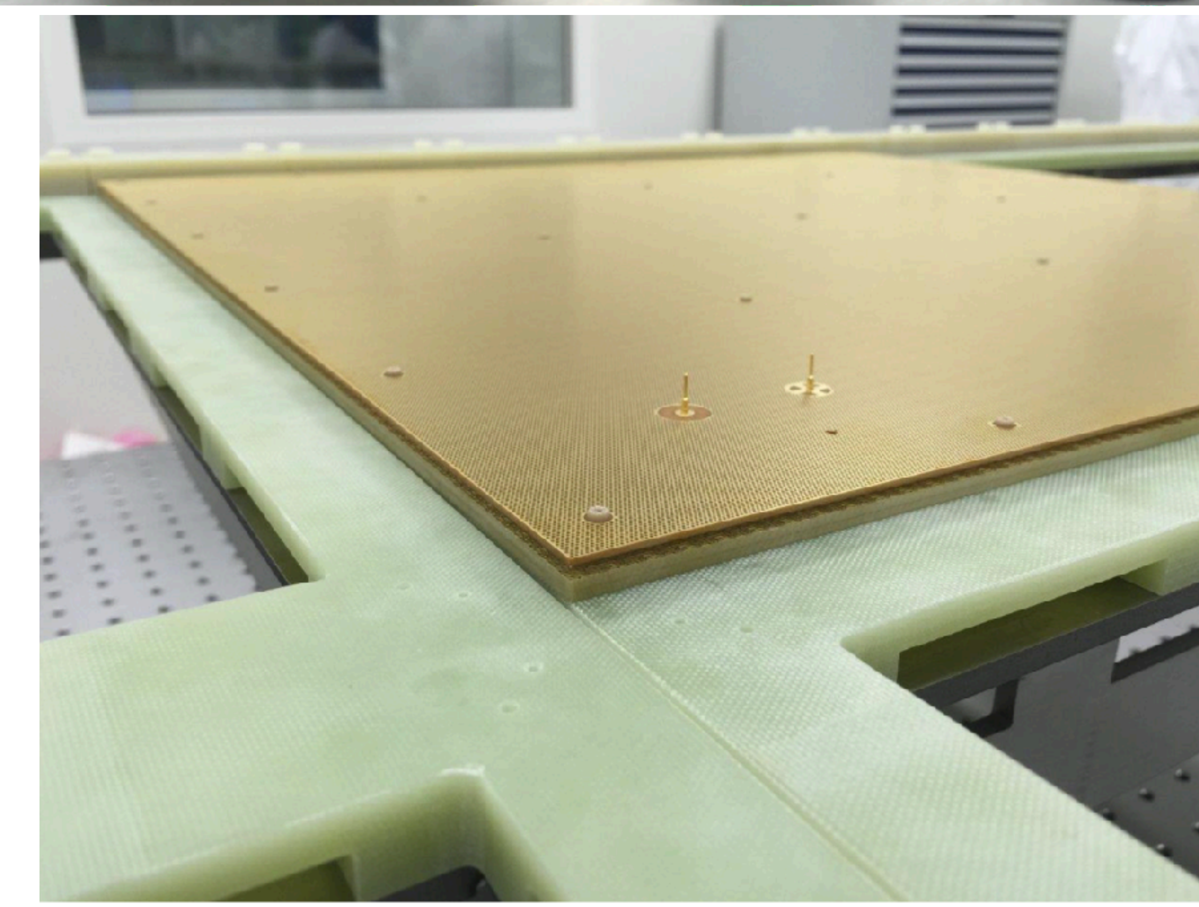
- Large expertise and almost a decade of developments by ETHZ group concerning operation in pure cryogenic argon gas of multiple 10x10 cm2 and a 40x80 cm2 LEM.

NIM A617 (2010) p188-192 NIM A641 (2011) p 48-57 JINST 7 (2012) P08026 JINST 8 (2013) P04012 JINST 9 (2014) P03017 JINST 10 (2015) P03017

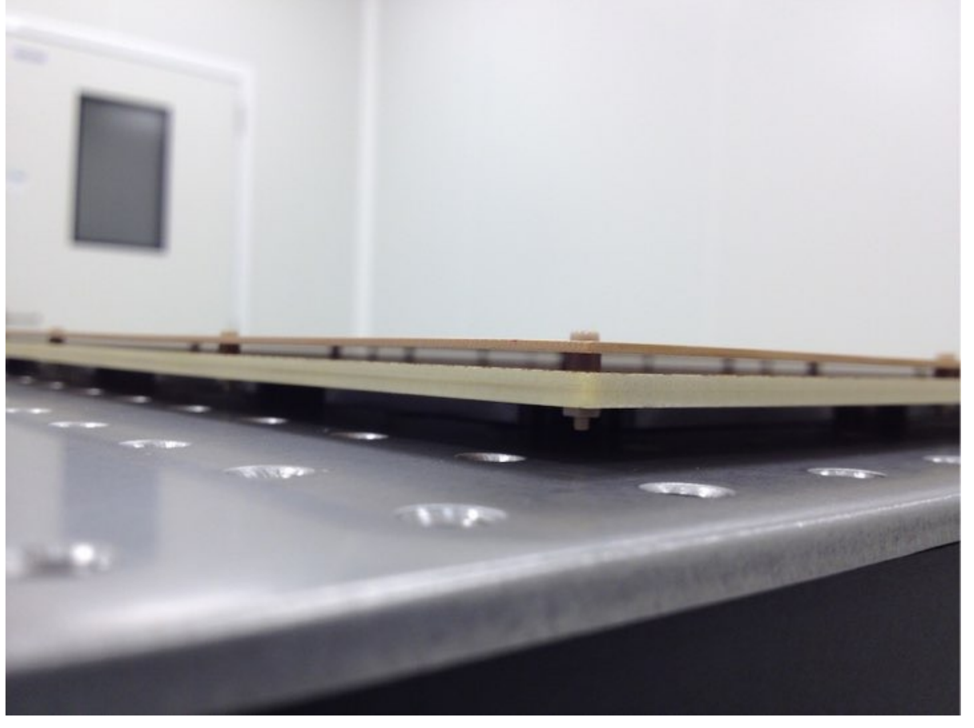


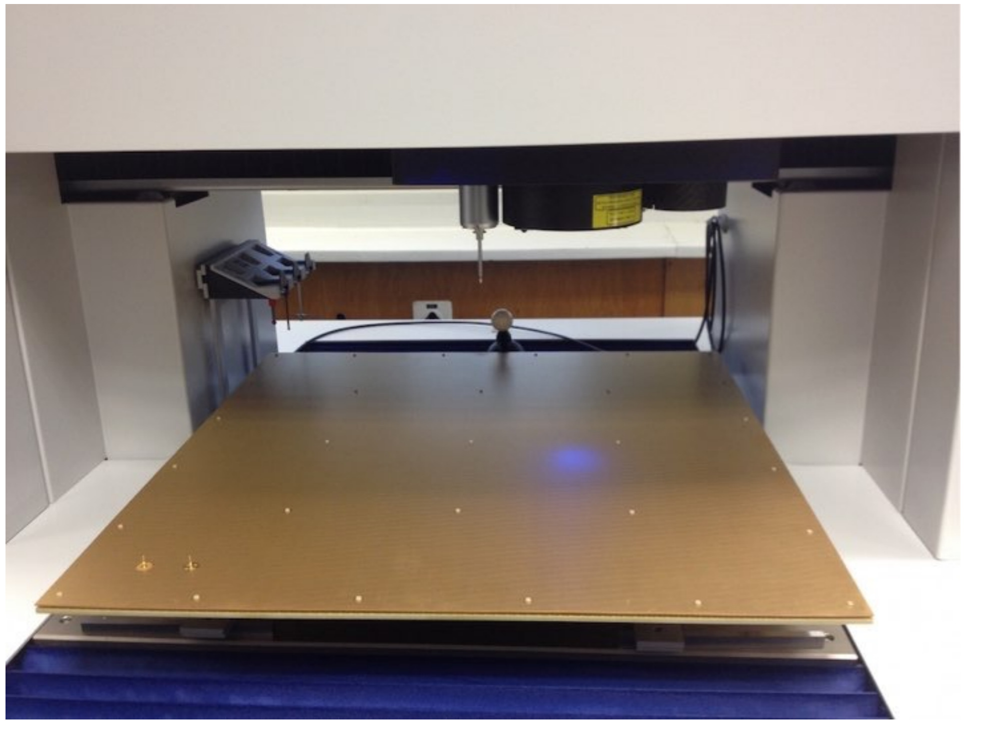


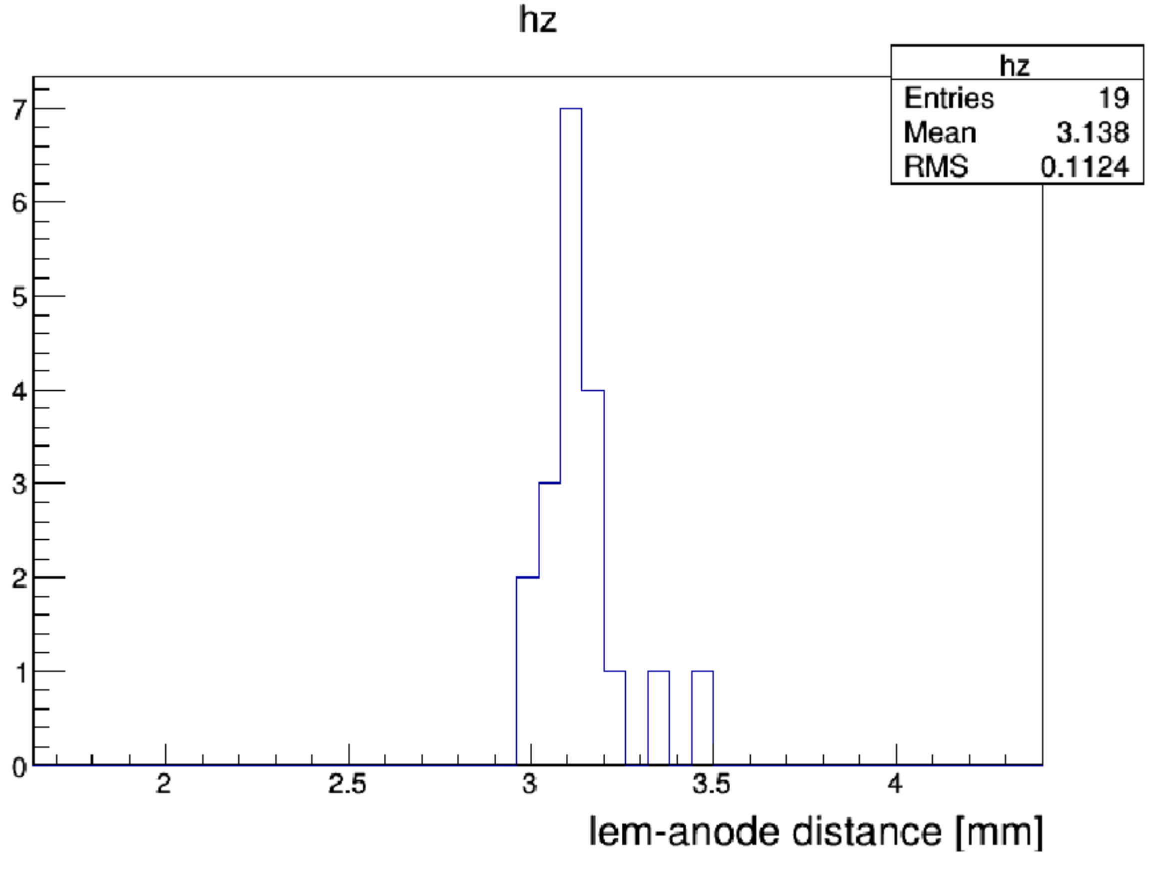
item	material	amount
M2 screw	peek	4176
LAS spacers	PE	4176
centering pins	G10	288



surveyed a 50x50 cm² LEM + anode with a camera through LEM holes

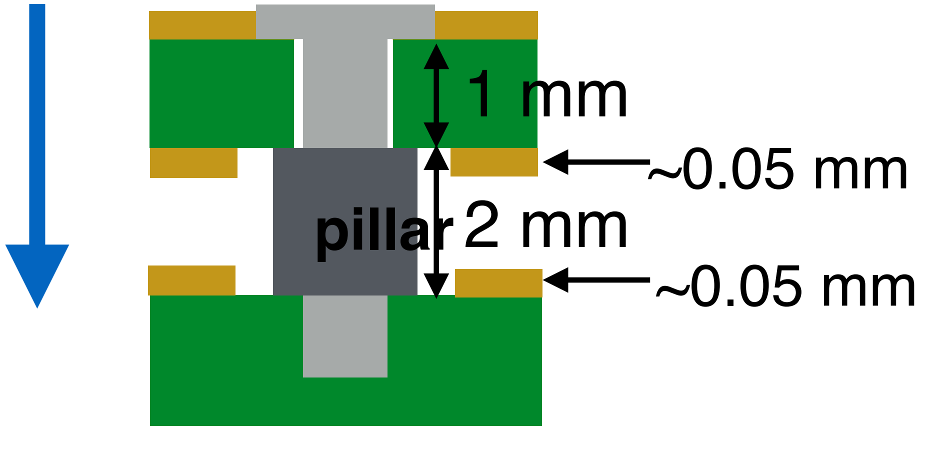






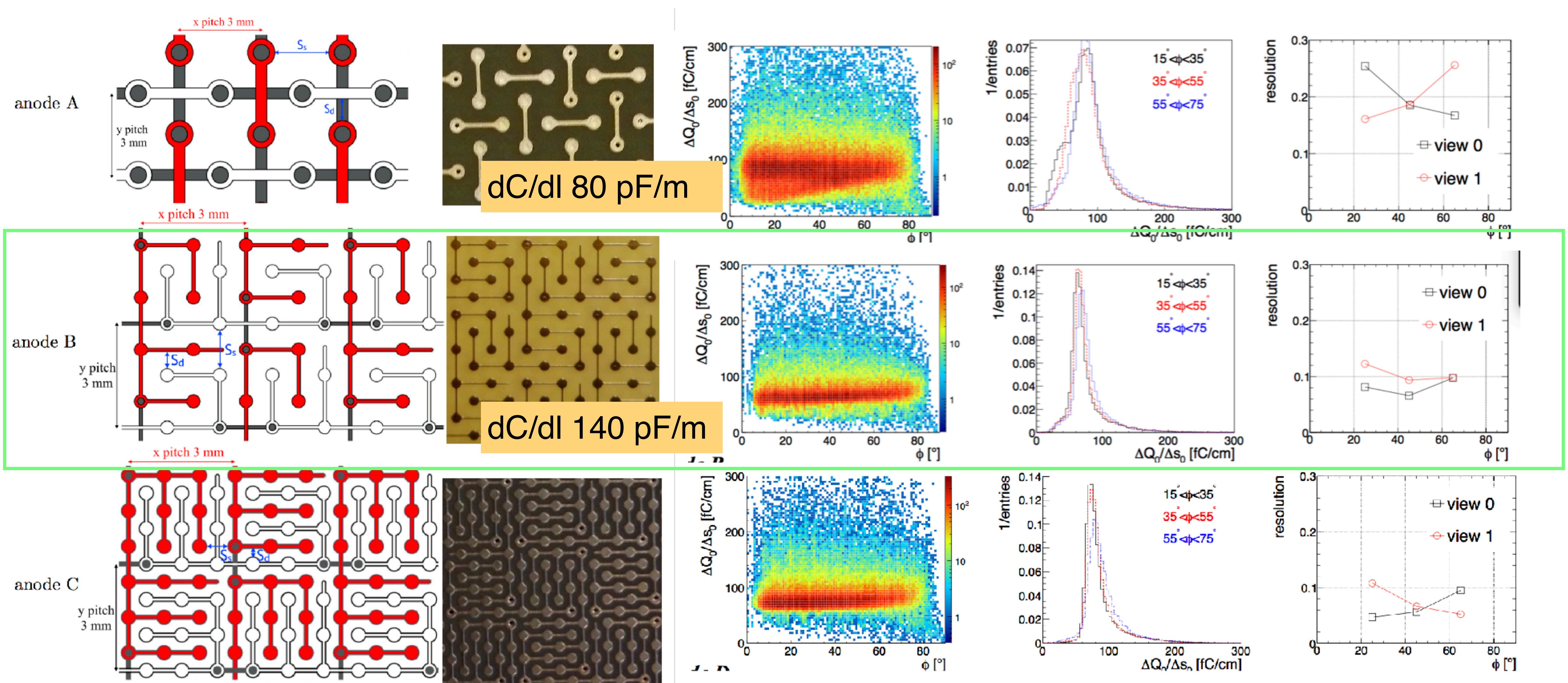
nominal ~ 2 (LEM-anode) + 1 (LEM thickness) + ~.05 mm ≈ **3.05 mm**

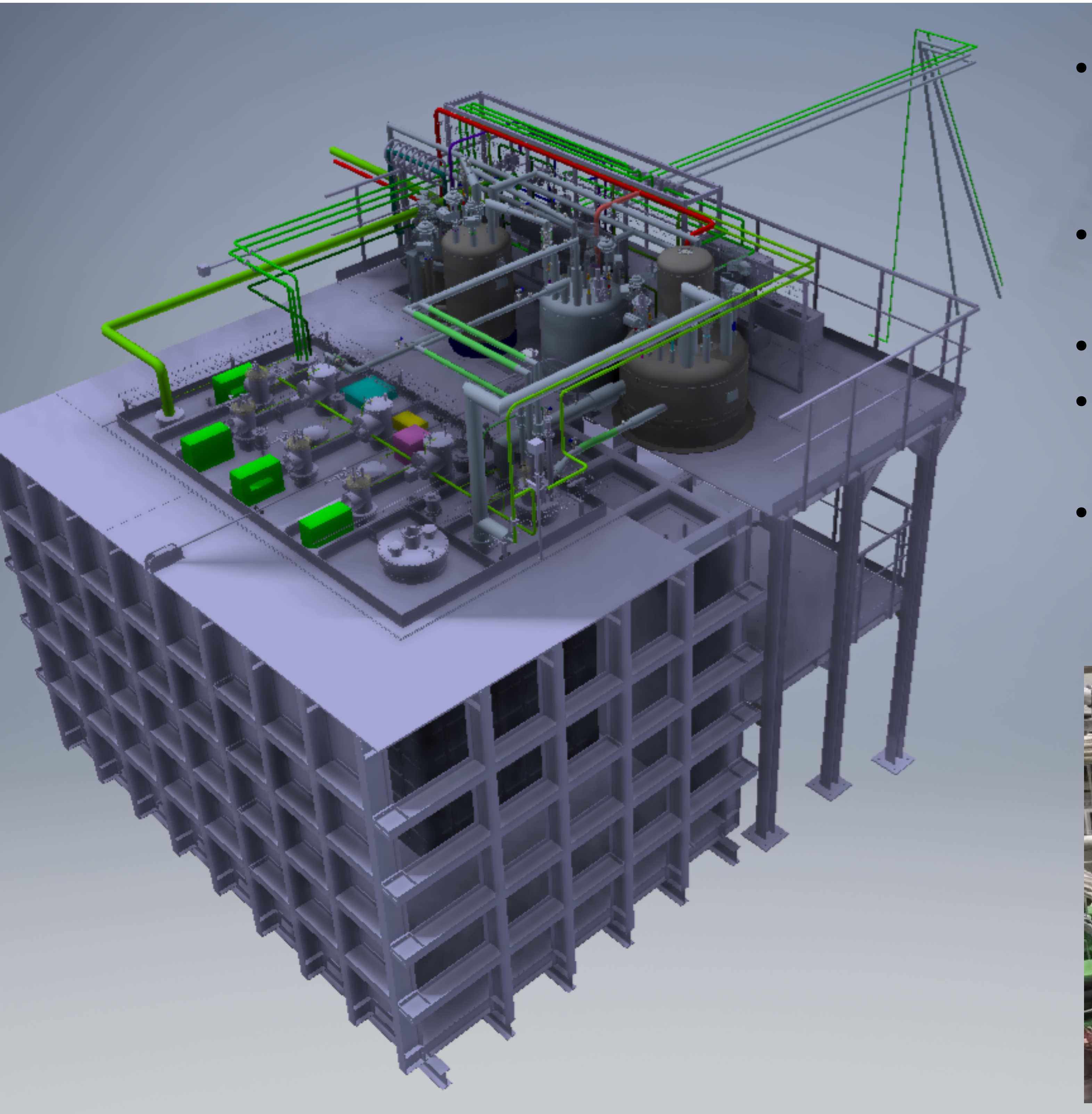
camera through LEM hole



Obtain best charge sharing and minimal capacitance per unit length. Tests on 10x10 cm2 readouts.

dC/dl 140 pF/m. about 450-500 pF before preamp on 3m readout. ENC of ~ 1500 electrons at 110 K





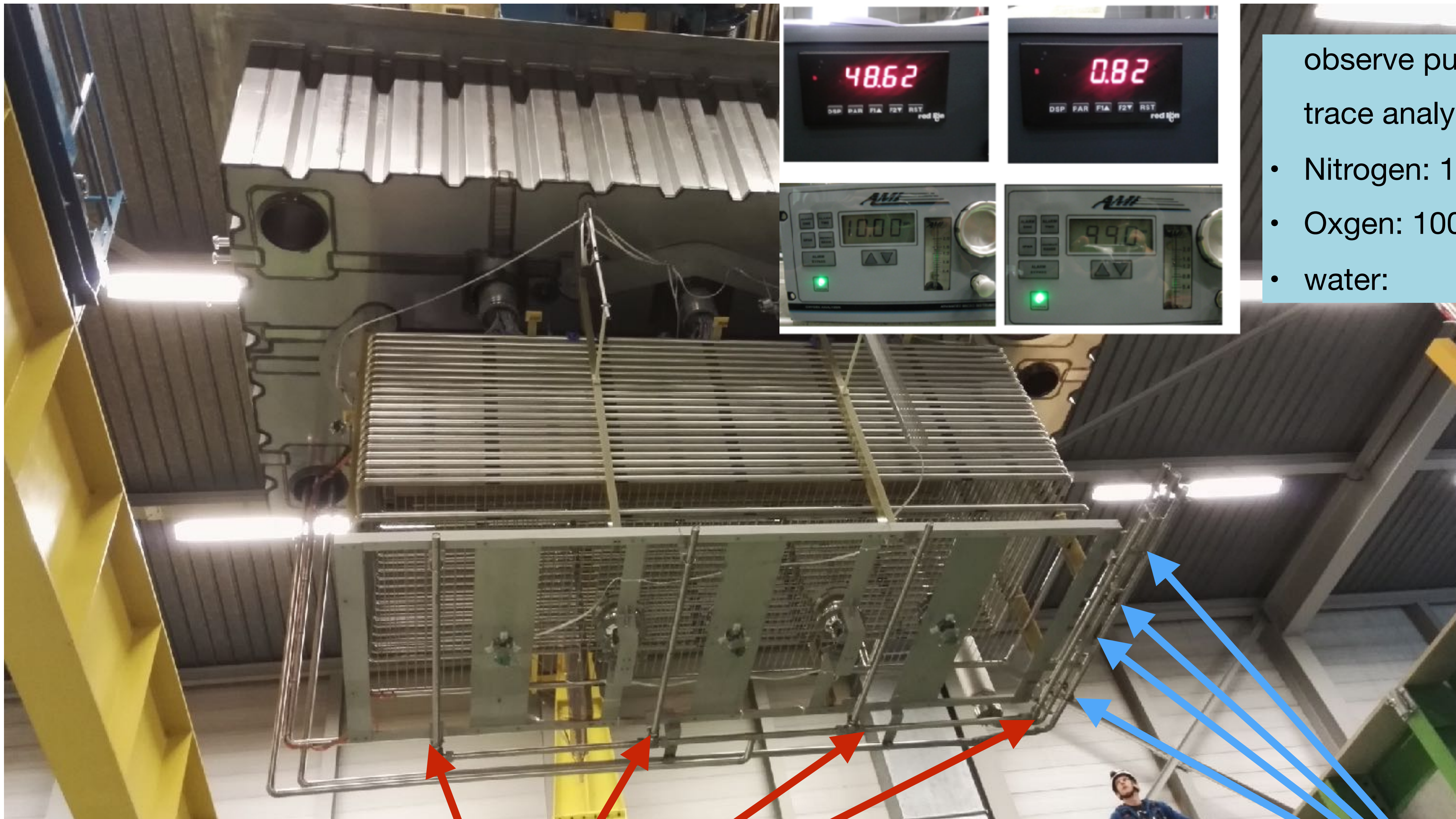
- Cold piping (LAr+ LN2 lines, valve boxes, liquid purification,..) Sept 19th- Oct 13th
- Warm piping (gas argon purification system, chimney purges, ..) Oct-Nov
- Control system Sept-Nov
- Start of gas argon piston purge Jan 24th
- Start of cool down Feb 27th

Remove contaminants by flushing gas argon and recirculating and filtering in closed loop.

observe purity evolution with 3 gas trace analysers

- Nitrogen: 100 ppb precision
- Oxgen: 100 ppb precision
- water:

all pre-tested and operated beforehand

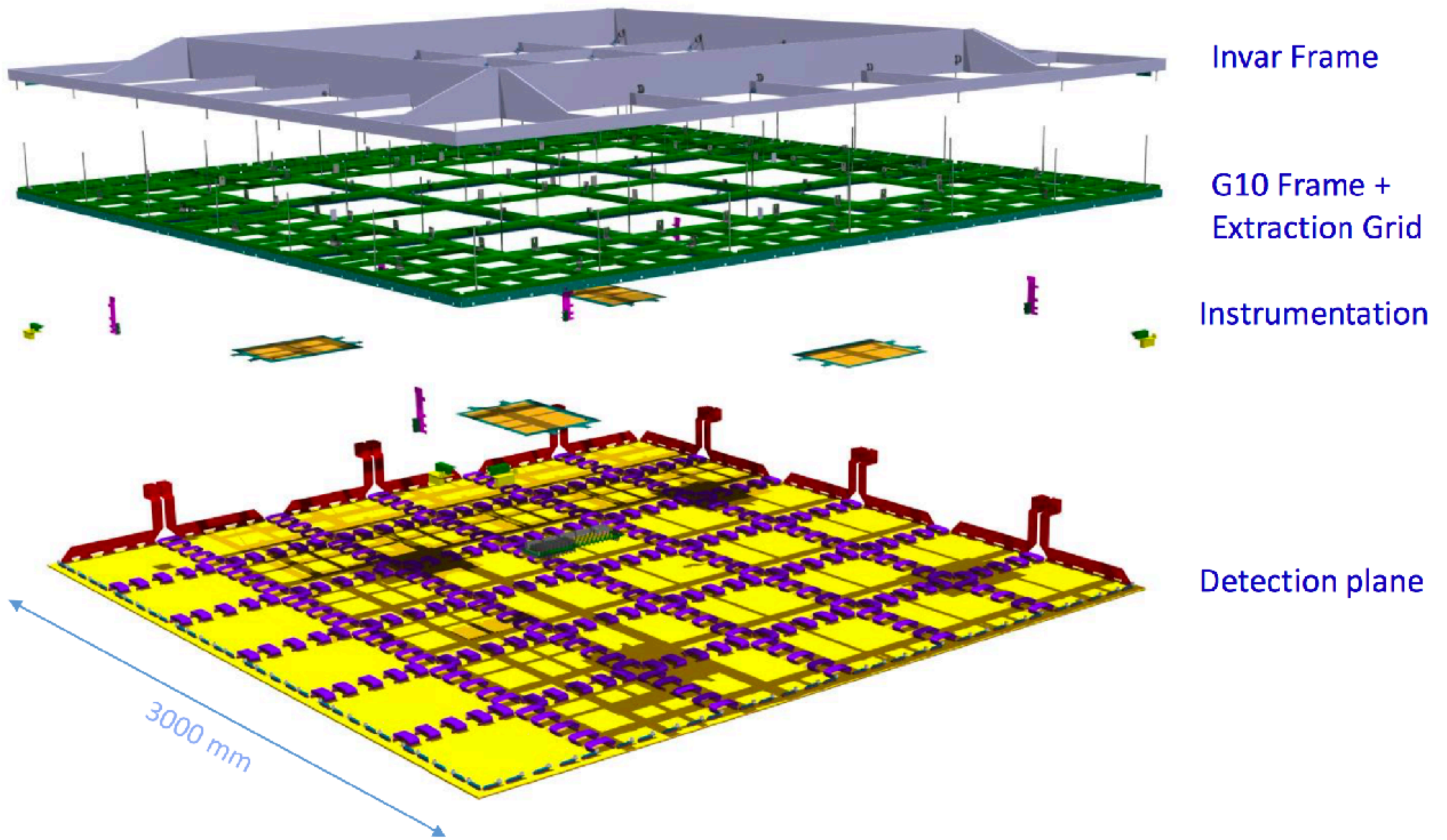


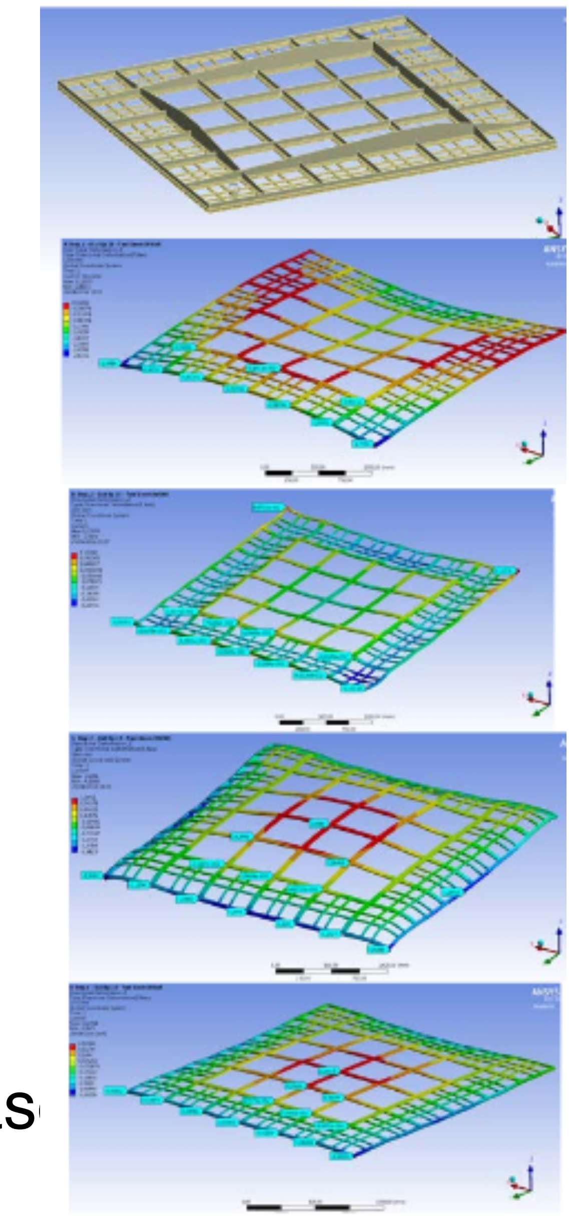
observe purity evolution with 3 gas trace analysers

- Nitrogen: 100 ppb precision
- Oxgen: 100 ppb precision
- water:

Piston purge
4 warm gas lines each with 3 openings of 12 mm ø.
total flow rate during piston purge ~4 l/s

Cool down: 4 sprays mixture of LAr and GAr for slow and uniform cool down. Nominal flows:
300 K GAr 500 l/m
87 K LAr 21 l/h





- Four 3x3 m2 CRPs integrating the LEM-anode sandwiches (50x50 cm2) and their suspension feedthroughs (CRP specific to dual-phas technology: critical item)
- Invar frame + decoupling mechanisms in assembly in order to ensure planarity conditions +-0.5 mm (gravity, temperature gradient) over the 3x3 m2 surface which incorporates composite materials and ensure minimal dead space in between CRPs

- During cool down, a formation of ice appeared on the side of the tank
- Holes were drilled around the cold spots in the membrane, and sheets of fiberglass appeared missing. It was replaced by polyurethane foam.
- Now the problem has been fixed by GTT experts.
- The protoDUNE-DP cryostat will be constructed in a different manner and this problem should not appear.