CERN Neutrino Platform and the ProtoDUNEs detectors

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on behalf of the Neutrino Platform team

10th Symposium on Large TPCs for low-energy rare event detection - 16th December 2021

Overview

Introduction to the Neutrino Platform Facility

Installation and operations of the two ProtoDUNEs

Sample of results and lessons learned

Ongoing activities

Outlook and plans for the ProtoDUNEs

2013 European Strategy

High-priority large-scale scientific activities

> “Rapid progress in neutrino oscillation physics, with significant European involvement, has established a strong scientific case for a long-baseline neutrino programme exploring CP violation and the mass hierarchy in the neutrino sector. ***CERN*** *should develop a* ***neutrino programme to pave the way*** *for a* ***substantial European role*** *in future* ***long-baseline experiments****. Europe should explore the possibility of major participation in leading long-baseline neutrino projects* ***in the US and Japan****.”*

2013 European Strategy

In other words:

- No neutrino beam from CERN

- Neutrino beam in US and Japan

- A structure at CERN to foster an active involvement of Europe and CERN in the US and Japanese new programs

This led to the establishment of the CERN Neutrino Platform part of the CERN Medium Term Plan since 2015

NP mandate

- **Assist** the various groups in their R&D phase in the short and medium term and give **coherence** to a fragmented European Neutrino Community

- Provide a charged particle test beam **infrastructure** for tests and R&D

- Bring R&D programs to the level of **technology demonstrators** in view of major construction activities

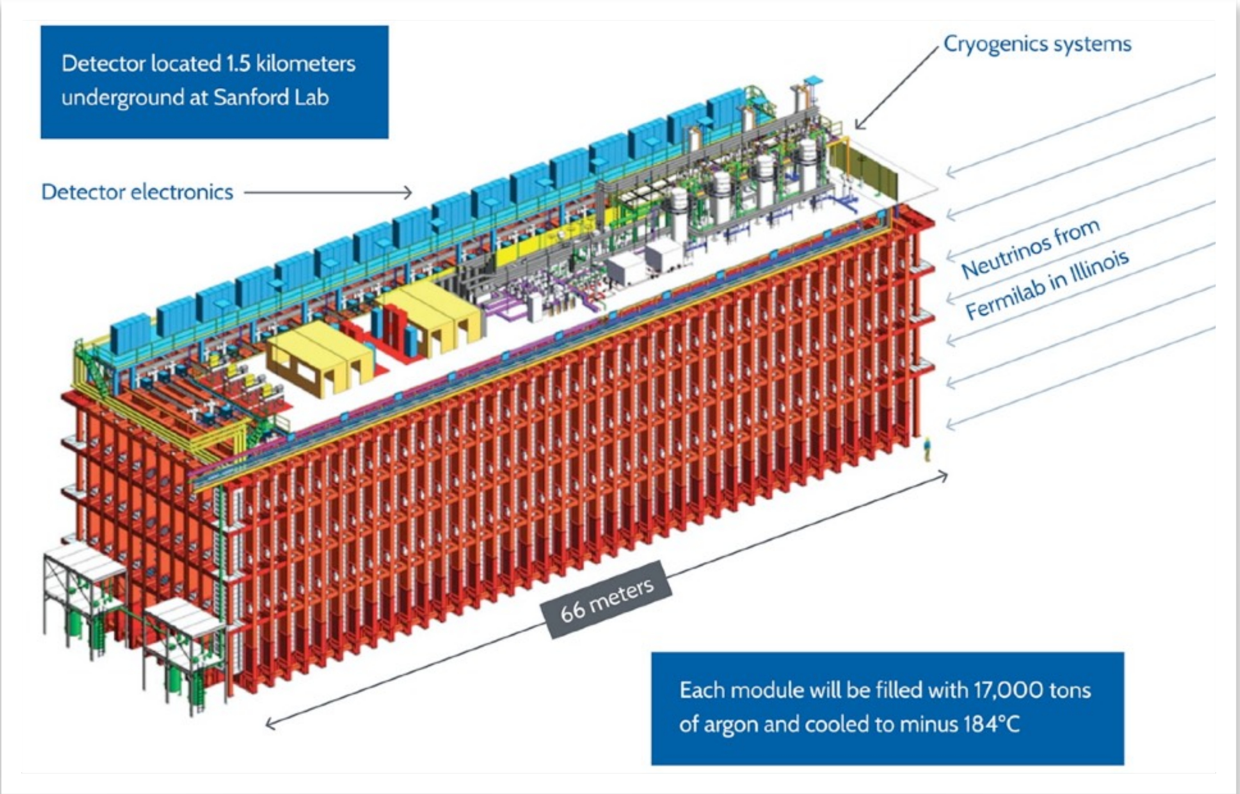
- Support **neutrino beam** R&D, as possible basis for further collaborations

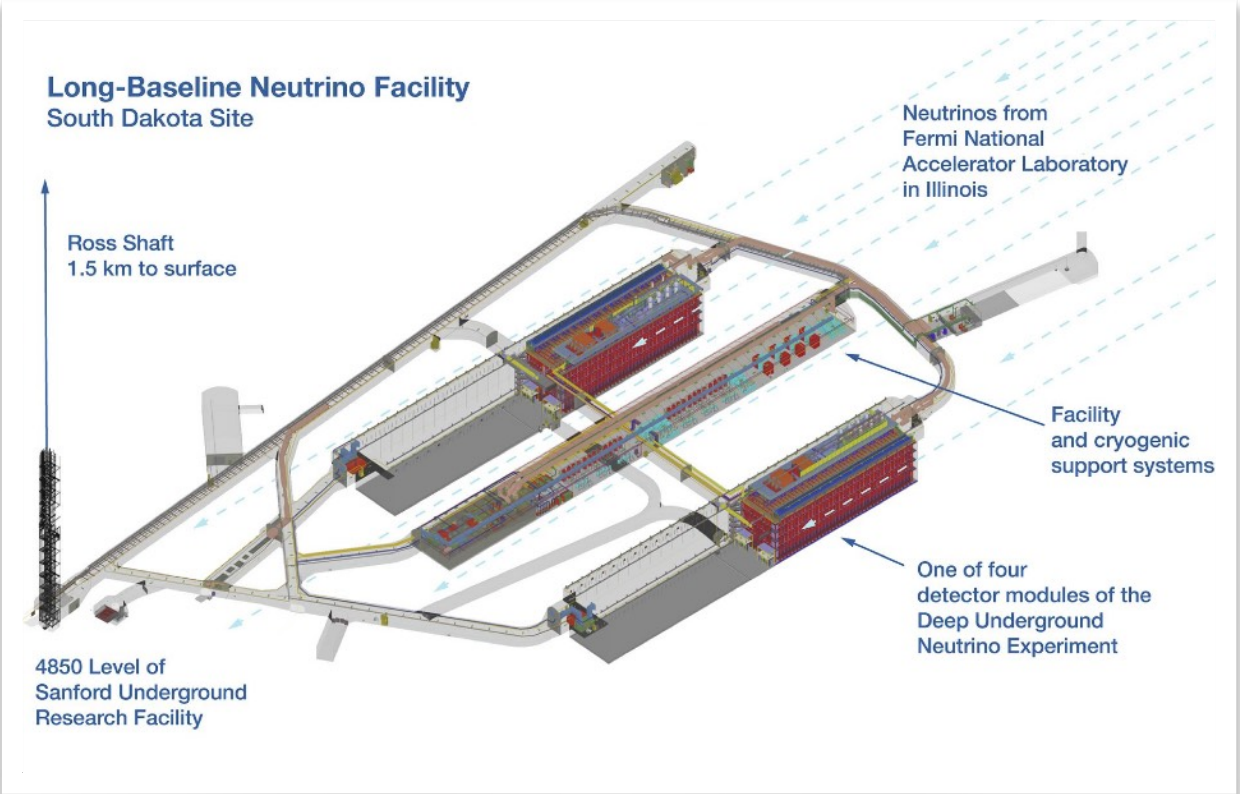
- Support the **short baseline** activities (infrastructure & detectors)

- Support the **long baselines** activities (infrastructure & detectors)

- Be a partner in the **physics exploitation**

DUNE Far Detectors





4 independent detector modules 1.5 km underground at Homestake Mine (South Dakota):
Present baseline:
* 3x ~17 kTon total mass LAr TPCs
 - 1st module Single Phase LAr TPC Vertical Drift (~2028) - cryostat funded
 - 2nd module Single Phase LAr TPC Horizontal Drift (~2029) - cryostat funded
 - 3rd module LAr TPC technology TBD (> 2030)
* 1x “open technology” module (> 2030)

Why ProtoDUNEs

ICARUS: the largest LAr TPC (~760 ton) ever operated underground.
Several **new challenges** to scale from ICARUS to DUNE.
Need **prototypes** to develop solutions **scalable** for DUNE:

- R&D on critical aspects, like cryostat, LAr purity, VHV, cold electronics, detector ground isolation, …
- Test full scale detector elements that will be used in DUNE
- Consolidate installation sequence and test procedures
- Validate long term operation stability
- Perform hadrons argon cross section measurements
- Benchmark reconstruction performance
- Study space charge effects, dQ/dx recombination, low energy calibrations with Michel electrons, …

Why ProtoDUNEs

Needs of two prototypes to test the two LAr TPC *types*
- **Single Phase:** active components in the liquid, primary charge readout à la ICARUS (planes of sensing wires sensing), ~free choice of drift direction and length
- **Dual Phase:** sensing element in the vapour (extraction of electrons from LAr to GAr), LEM (Thick GEM) amplifies the signal, drift must be vertical and upwards. From ~2020 evolved in Single Phase Vertical Drift.

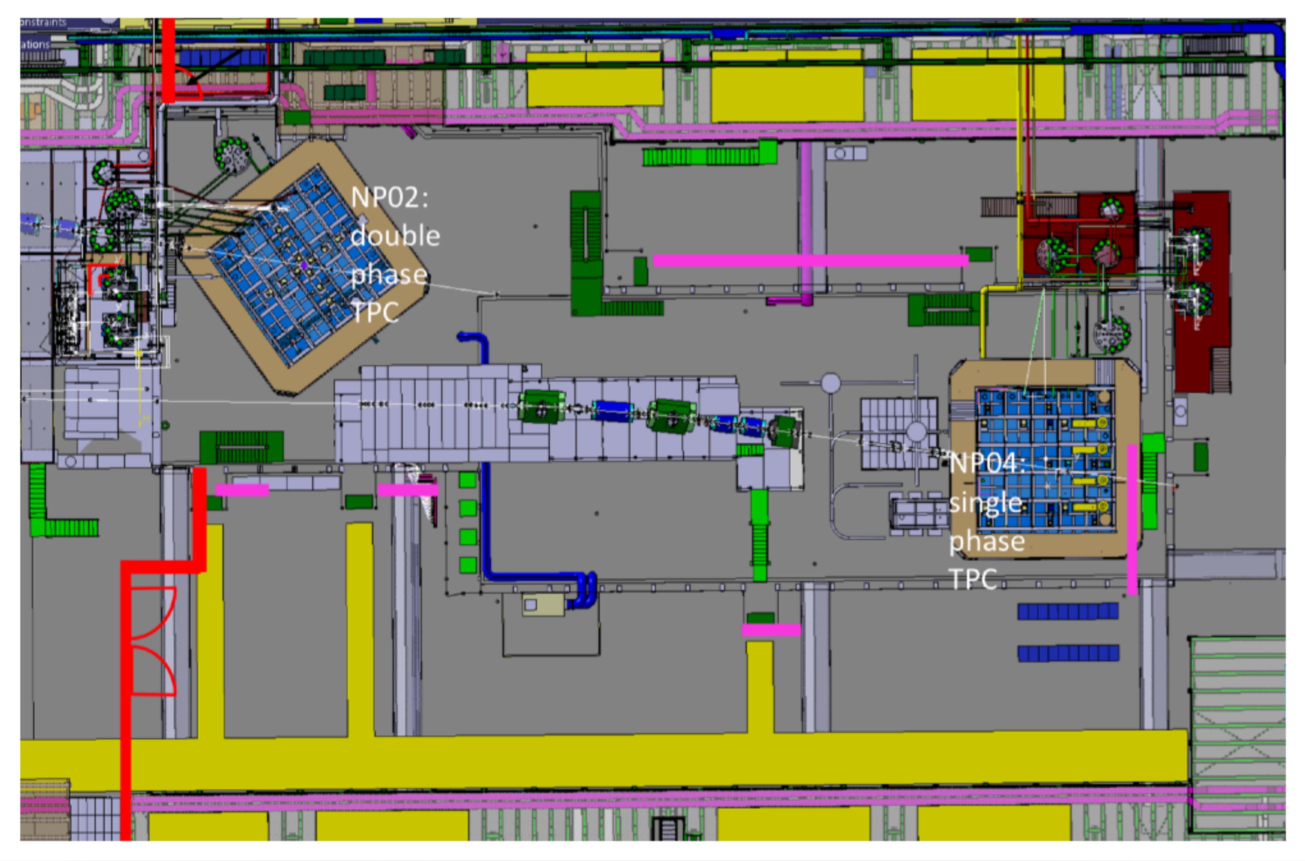
At the Neutrino Platform two cryostats and two beam lines to develop and demonstrate the two technologies.

EHN1 extension

Extension of the EHN1 building in the CERN North Area to host the two ProtoDUNEs.

887 building

Building completed in September 2016



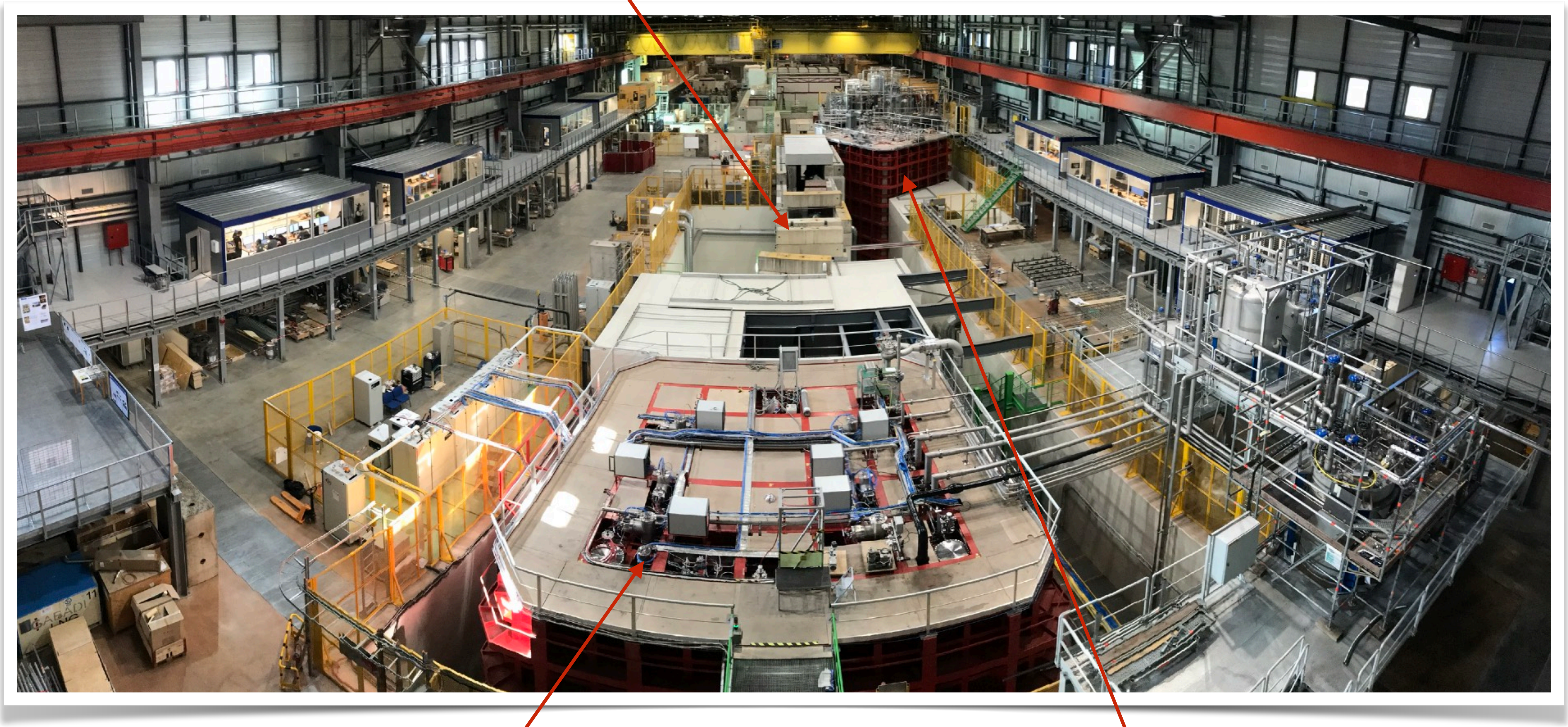
Summer 2016

Extension of EHN1
building 887 at CERN Prévessin site

Summer 2018

H4 extension

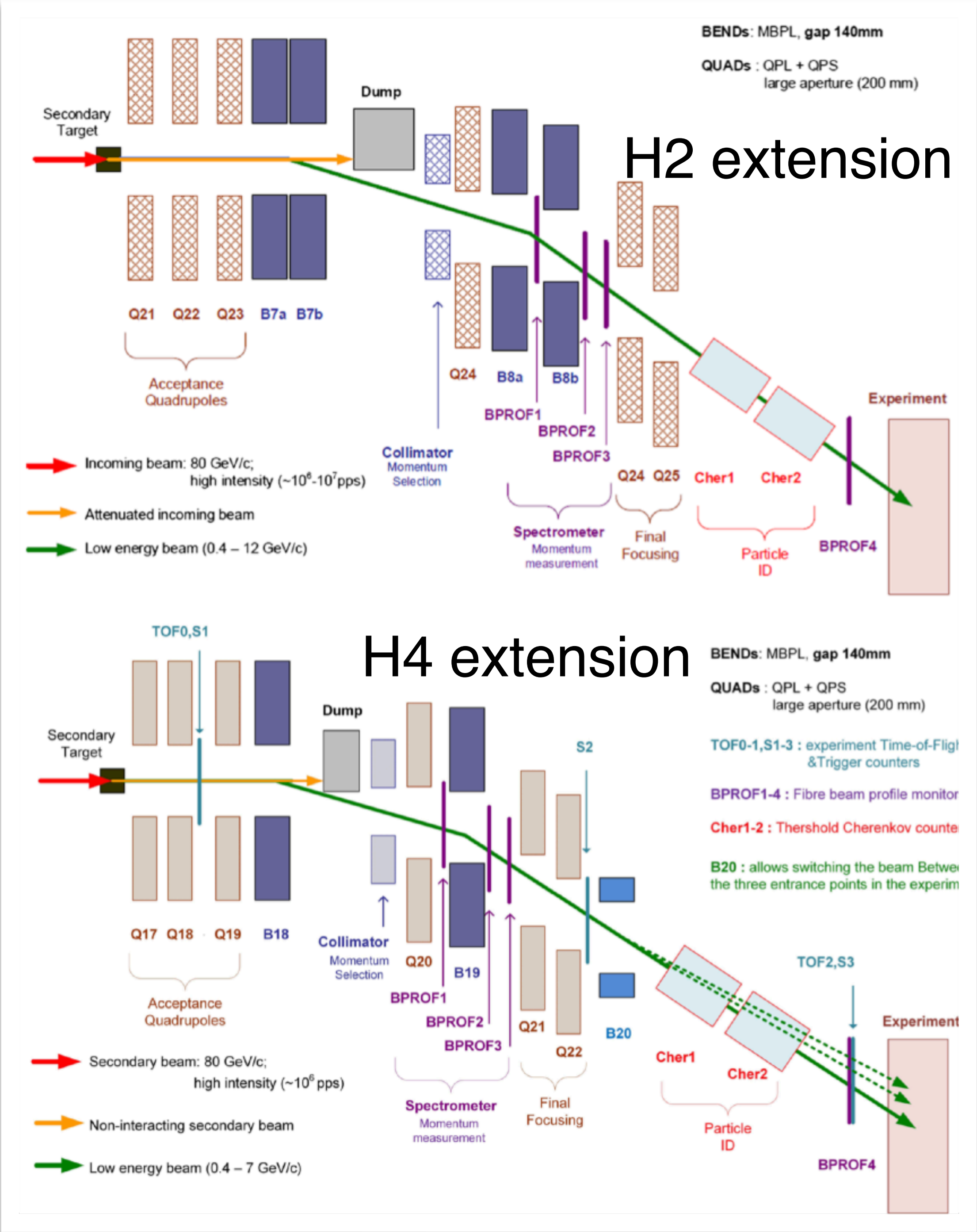
Extension of EHN1
building 887 at CERN Prévessin site



Single phase NP04 ~750 ton total LAr
Operated for two years from September 2018
Installation of the Module-0 from March 2022

Dual phase NP02 ~750 ton total LAr
Operated for 1.5 years from summer 2019
Upgraded in 2021 and in operation now

Beam lines extension

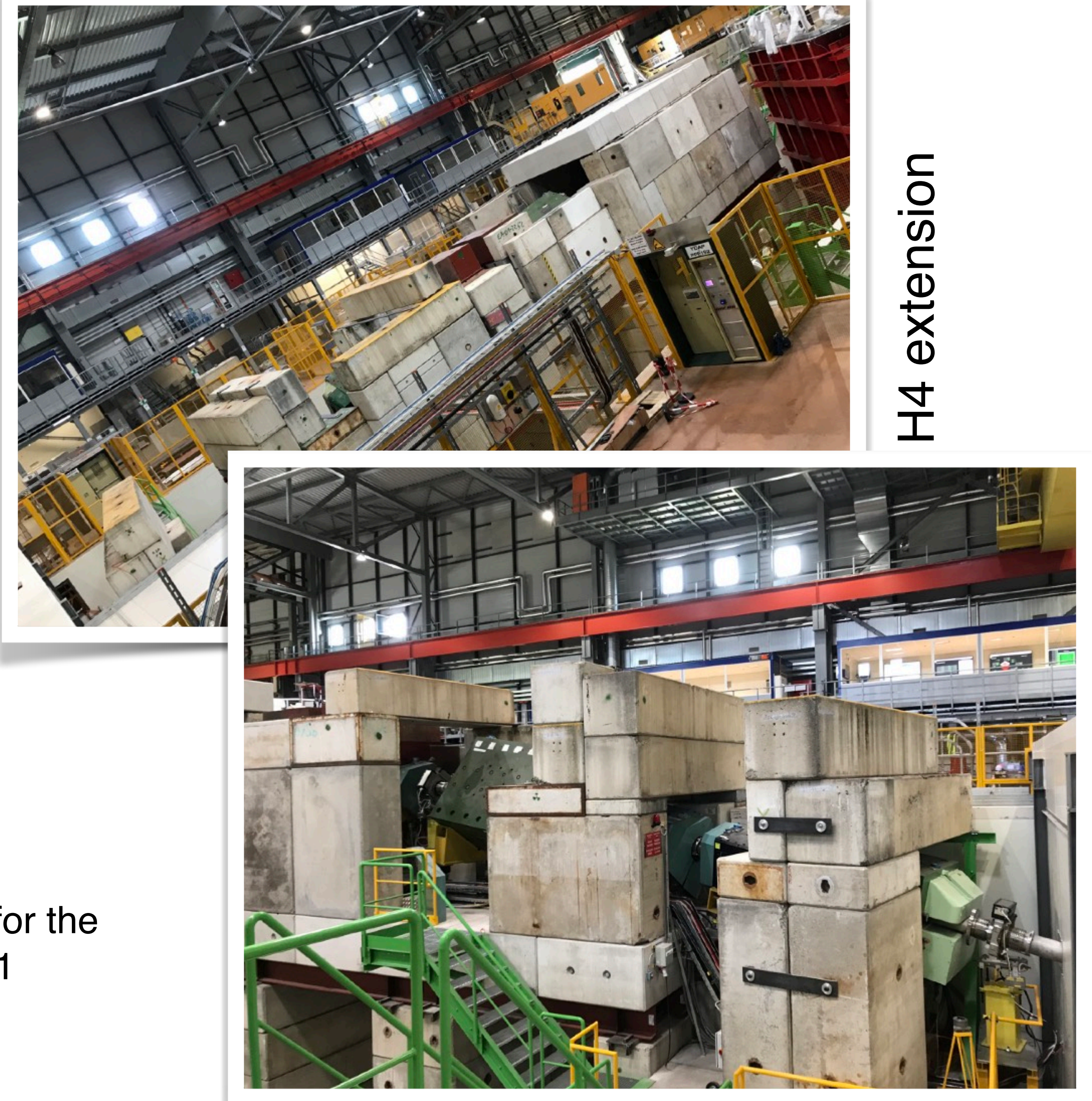


H2 extension

H4 extension

N Charitonidis et al., “Low energy tertiary beam line design for the CERN neutrino platform project,” Phys. Rev. Acc. 20, 111001

New extension of the H2 and H4 beam lines in the North Area. Tertiary low energy beam: p, pi, K, mu, e ~1 GeV/c -> 7 GeV/c



H4 extension

Cryostat: LAr purity

Electronegative contaminants spoil the LAr TPC signals
O_2 molecules attach to drifting electrons slowing them down

UHV to clean the TPCs is the classical solution:
- remove the air at the beginning
- improve the outgassing of the material
- simple to find leaks towards the atmosphere

Building large cryostat that can be put under vacuum not realistic.
The same is valid for the vacuum insulation (safety concerns too).

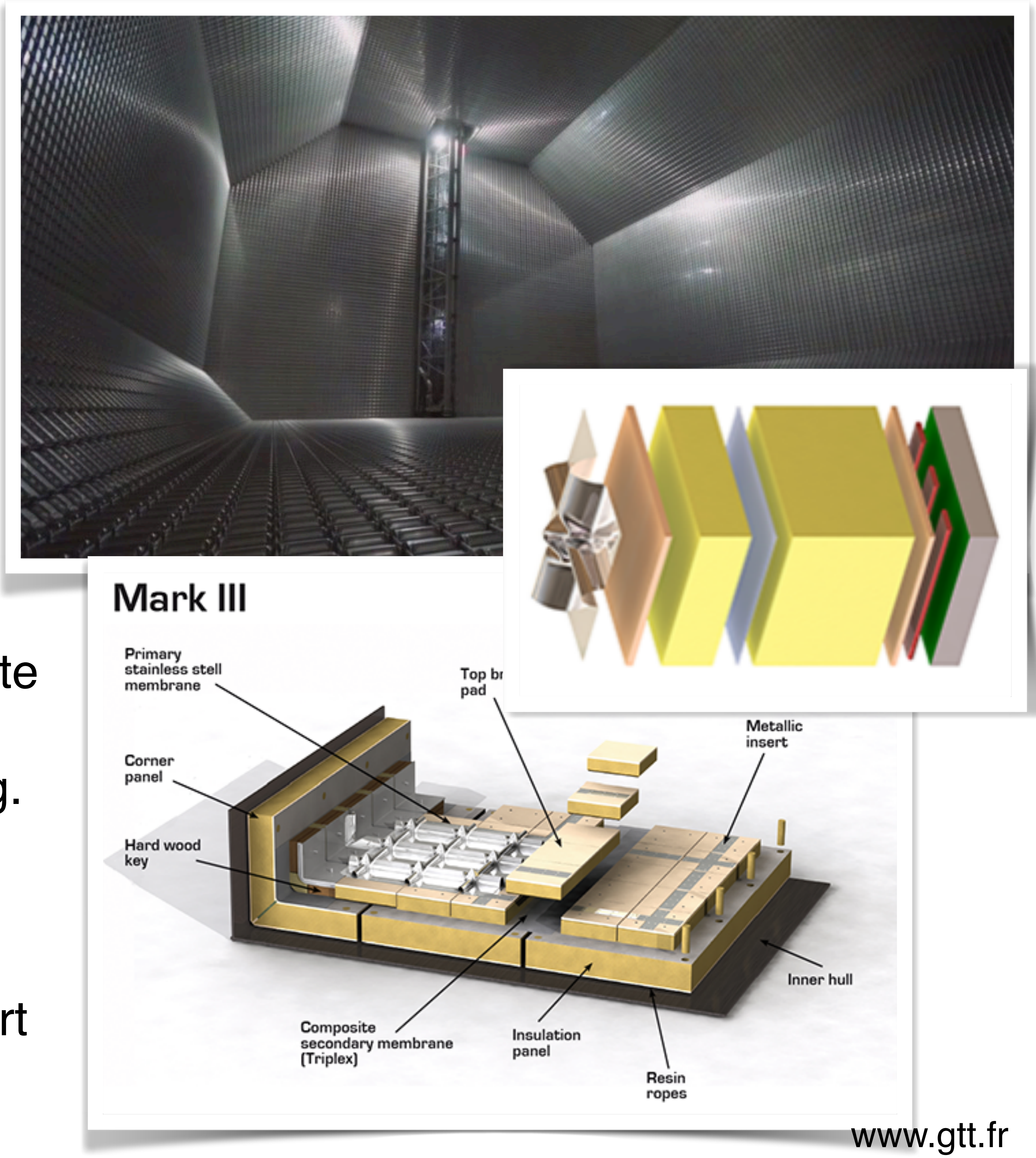
Adapt what is available: membrane cryostat technology used in LNG carriers.
Focus on: installation underground, heat input, passive insulation, penetrations, …

Approach:
- Air is evacuated at the beginning gently flowing pure gas argon from the bottom
- Argon gas is recirculated through getters to maintain the purity in warm and cold
- Leaks must be found in another way

Cryostat: the technology

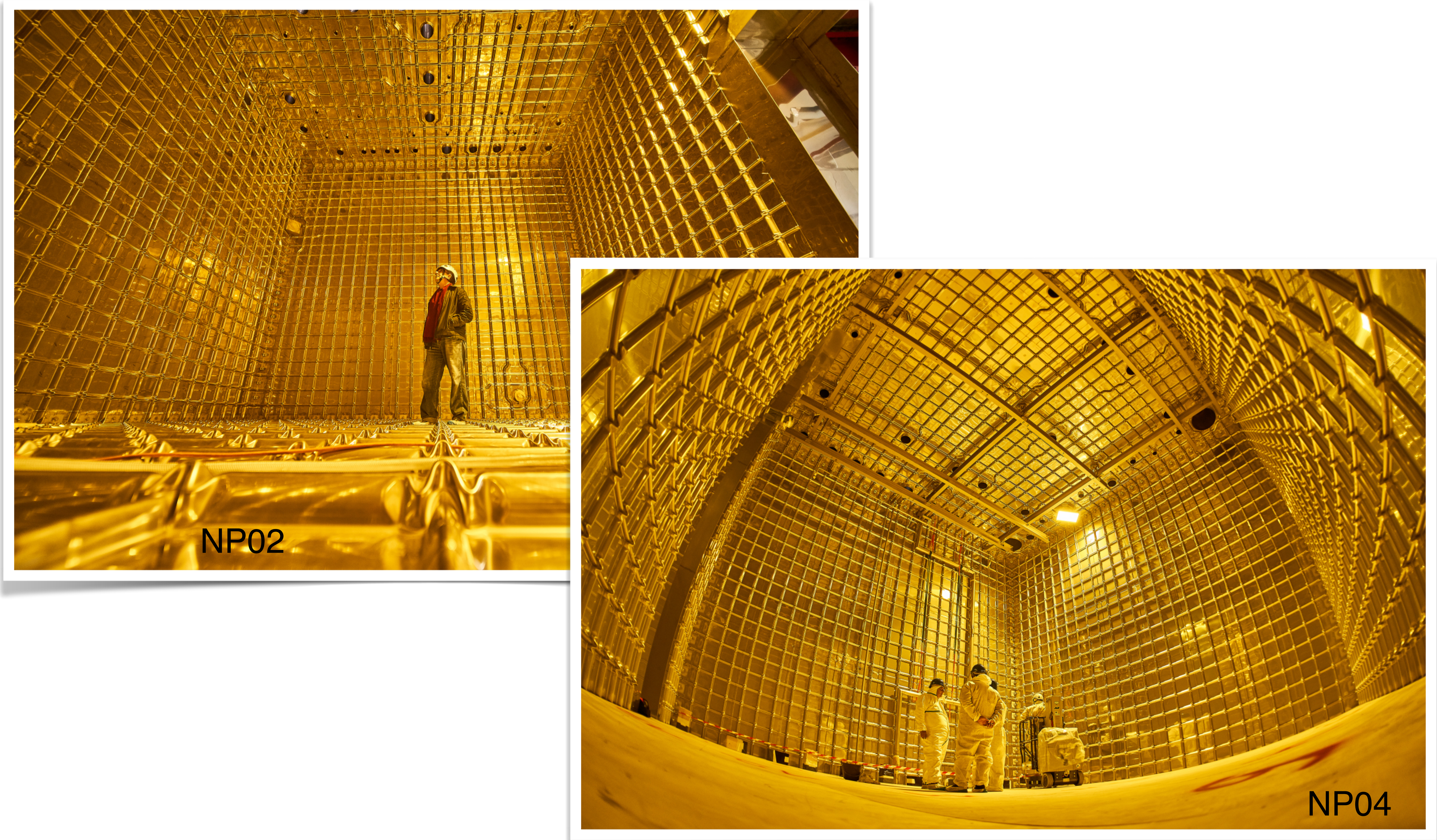
Royalties owner: GTT (France)
Licensee: Gabadi (Spain) among several
Applications:
- LNG carriers (>200000 m^3 in 5 sub-tanks)
- Floating storages and re-gasification vessels
- Land storage tanks
- Fuel tank for vessels
- Cryostats for LAr TPCs

- Primary membrane: in contact with the liquified gas. Flexible and elastic to accomodate wave impacts, vessel deformation, thermal expansion and contraction. Not self supporting.
- Thermal insulation: passive, in between and directly connected to the primary membrane and the hull.
- Hull: the warm structure, sustains and support the entire system.



www.gtt.fr

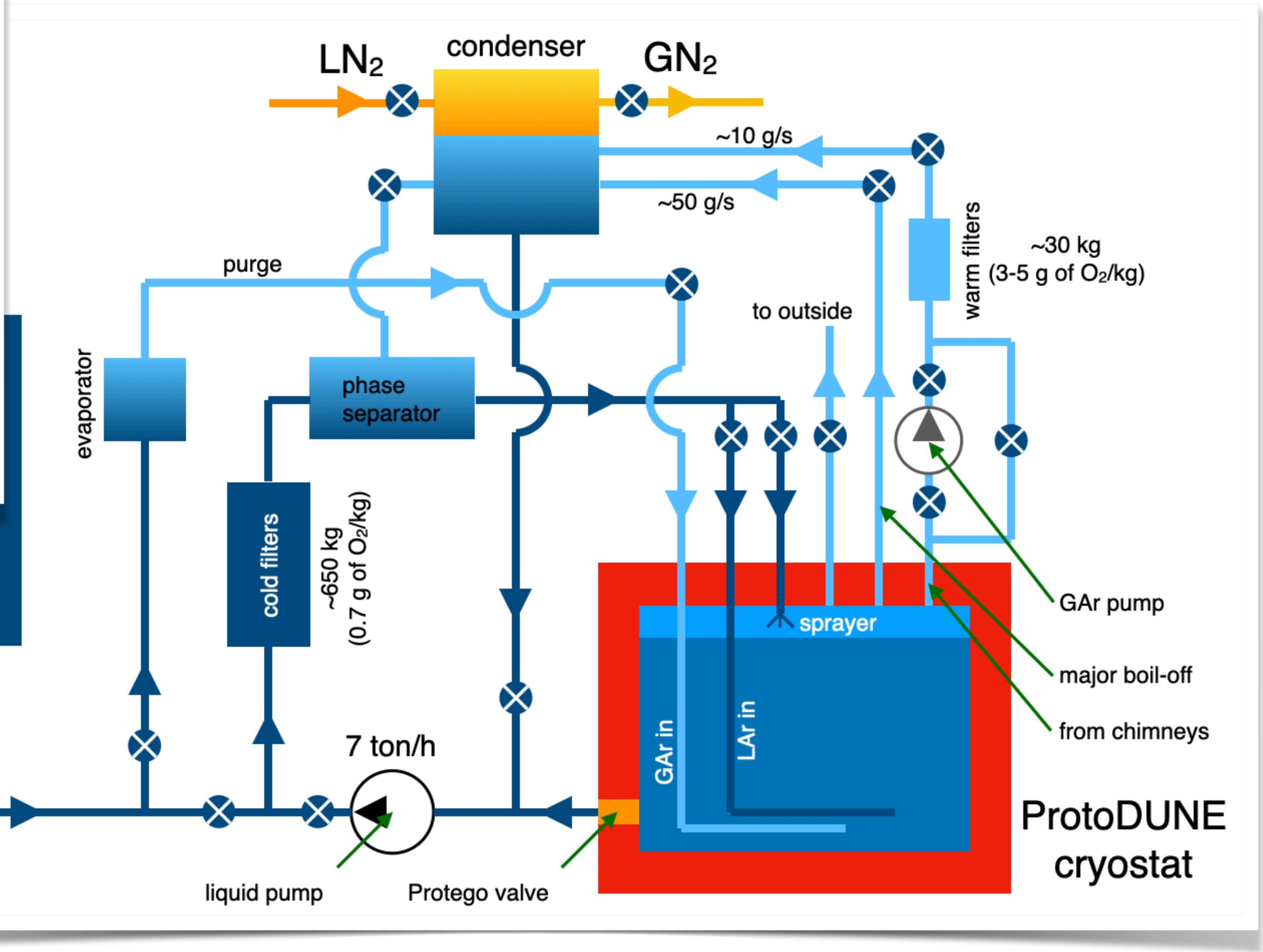
ProtoDUNEs membrane



Cryogenic system

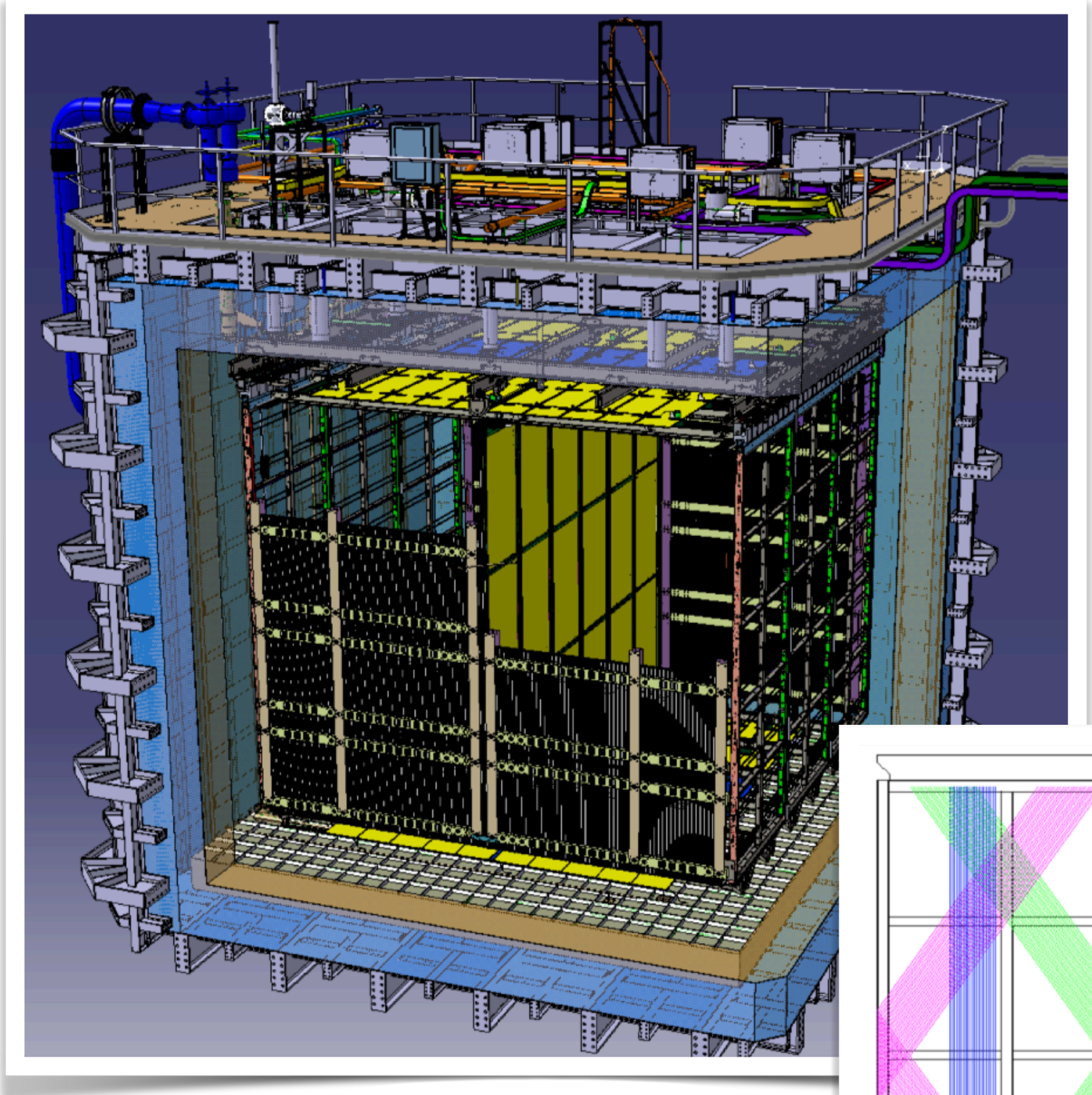
- Maintain the liquid argon level stable by re-condensing the boil-off
- Keep stable thermodynamic condition inside the cryostat (pressure and temperature)
- Purify and keep clean the liquid argon

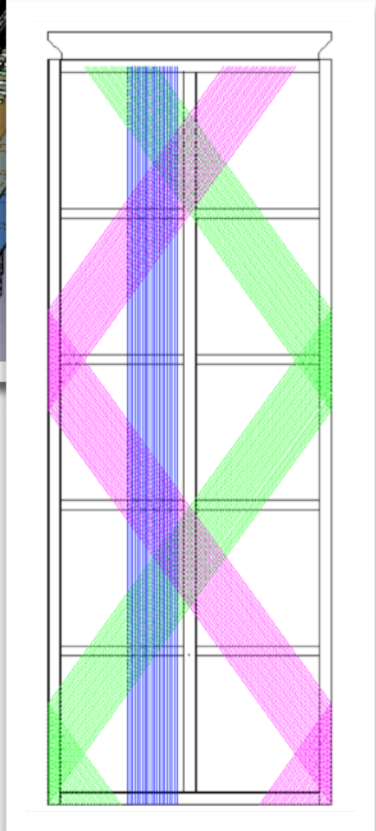
Simplified cryo scheme



NP04 detector components

- **Cryostat and cryogenics:** scalability and cost effectiveness imply non-evacuable and passive insulated tanks. Technology developed for the LNG carriers. Impact on purity and stability.
- **VHV system:** PS, feedthrough, cathode, field cage and ground planes. TPC with highest voltage ever operated.
- **Anode Plane Assembly:** 2x(3+1) sets of wires winded around a frame forming three independent views for each of the 6 APA.
- **Cold Electronics:** preamplifier and digitiser in cold. Low electronic noise is fundamental. Electronics must survive the entire detector lifetime.
- **Photon Detectors:** scintillating bars installed within the APA wire planes. They provide low energy trigger and the t0.
- **Beam Plug:** Filled with GN2, it reduces the interactions of the beam particles in the in non-active region between the cryostat and the TPC.
- **Instrumentation:** Fundamental diagnostic for commissioning and operation (Purity monitors, Temperature profilers, cameras, strain gauges).



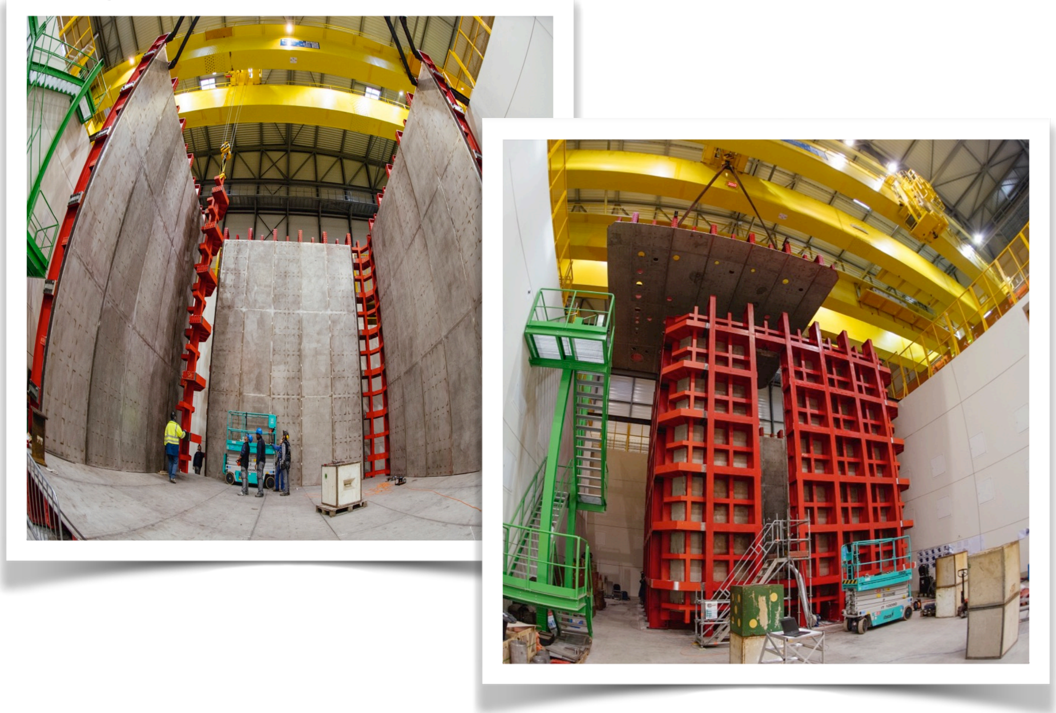


APA

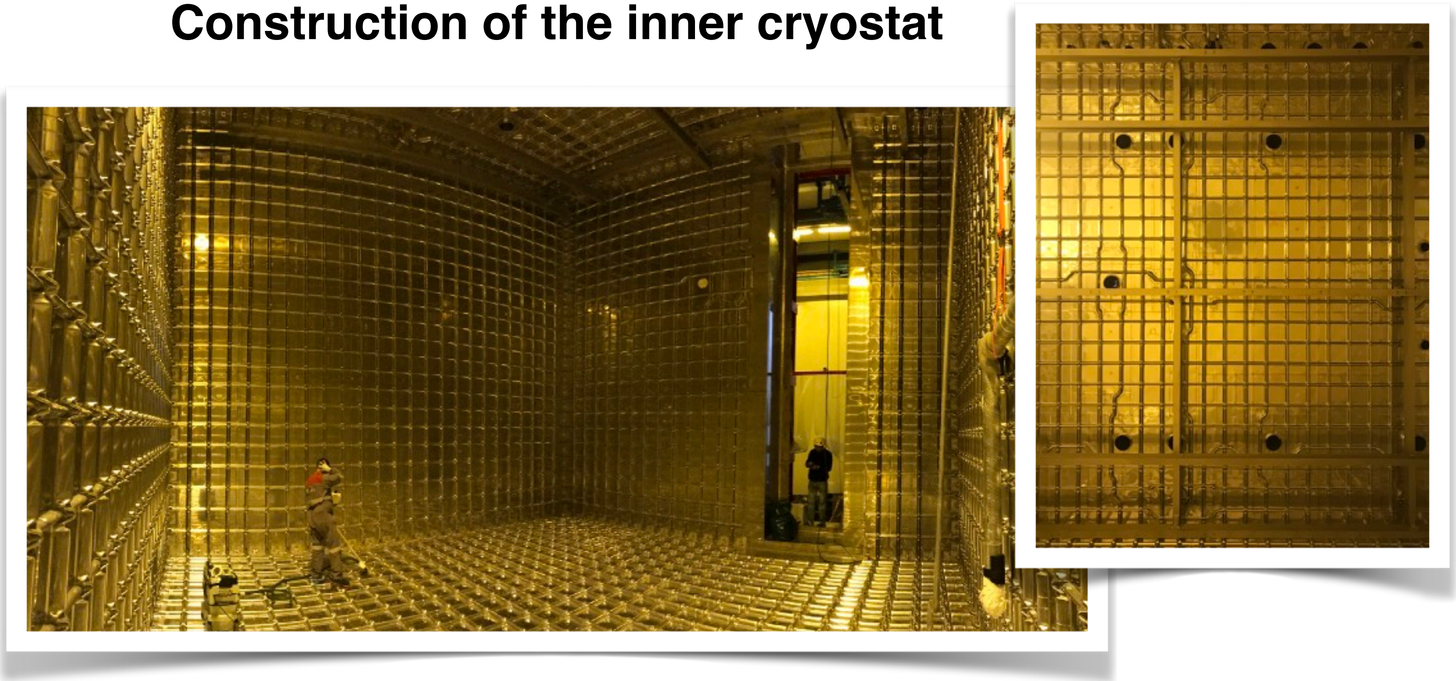
NP04 timeline

Sep. 2016 — Jan 2017 — May 2017 — Sep. 2017

Construction of the outer structure

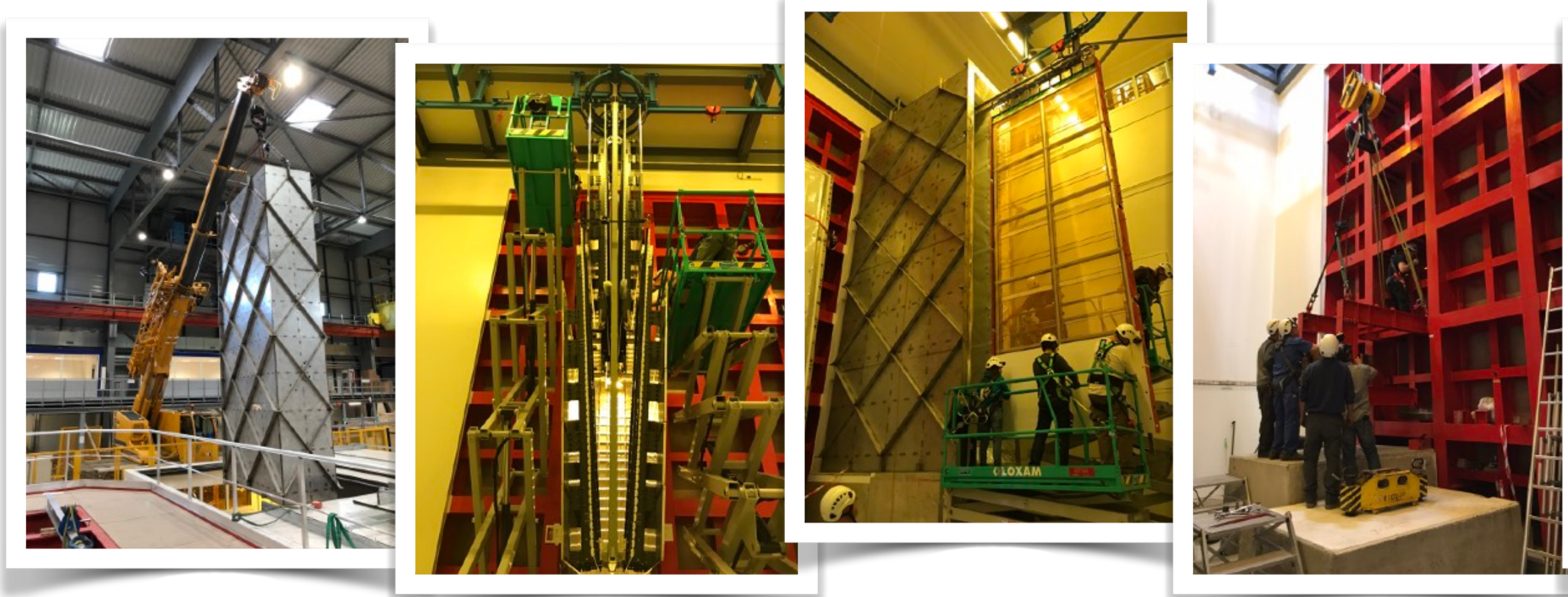


Construction of the inner cryostat



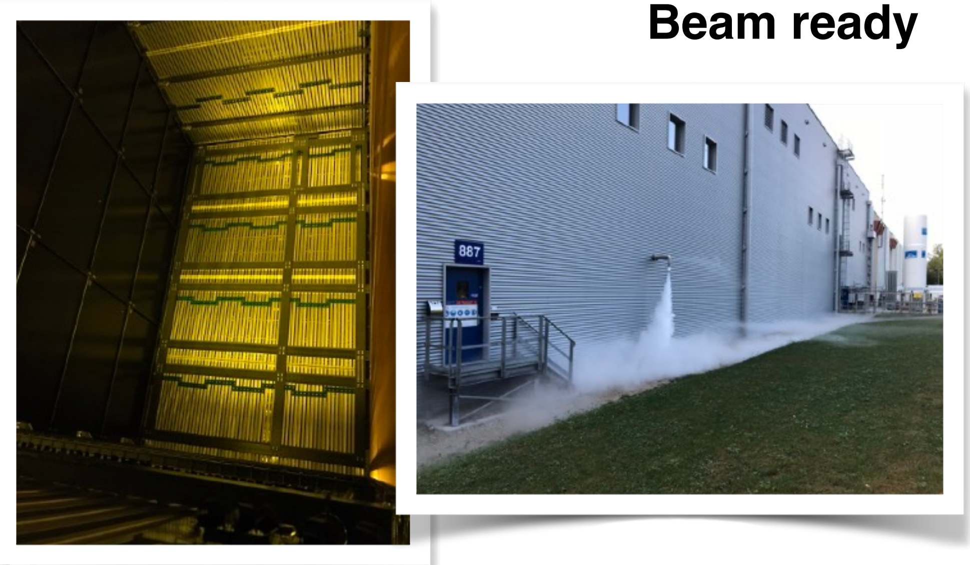
Sep. 2017 — Jan 2018 — May 2018 — Sep. 2018

Test and installation of the TPC



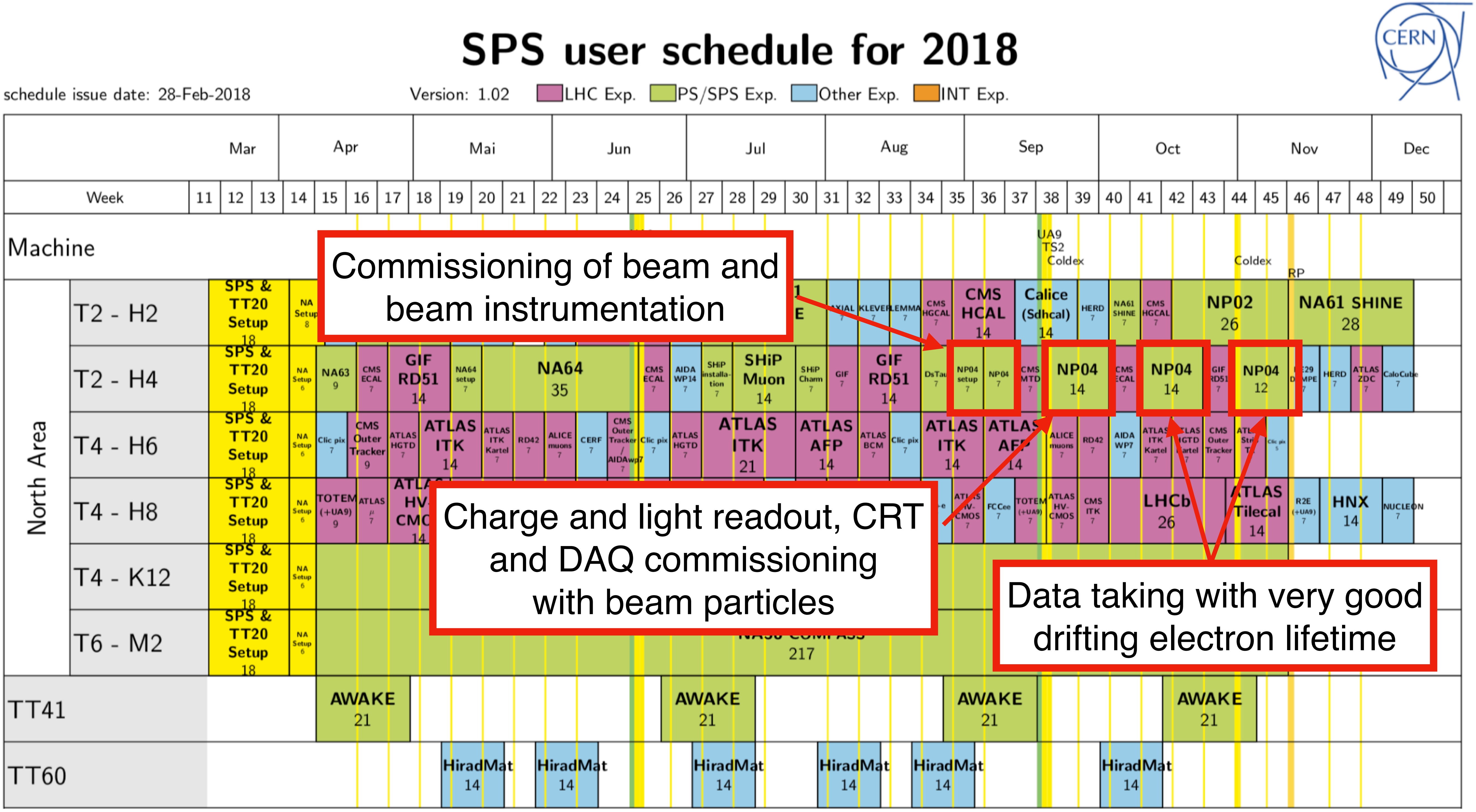
Purging cooling and filling

Beam ready



Time as H4 main users

Fruitful collaboration with CMS, GIF++ and RD51 colleagues during the entire beam run



SPS user schedule for 2018

schedule issue date: 28-Feb-2018

Version: 1.02

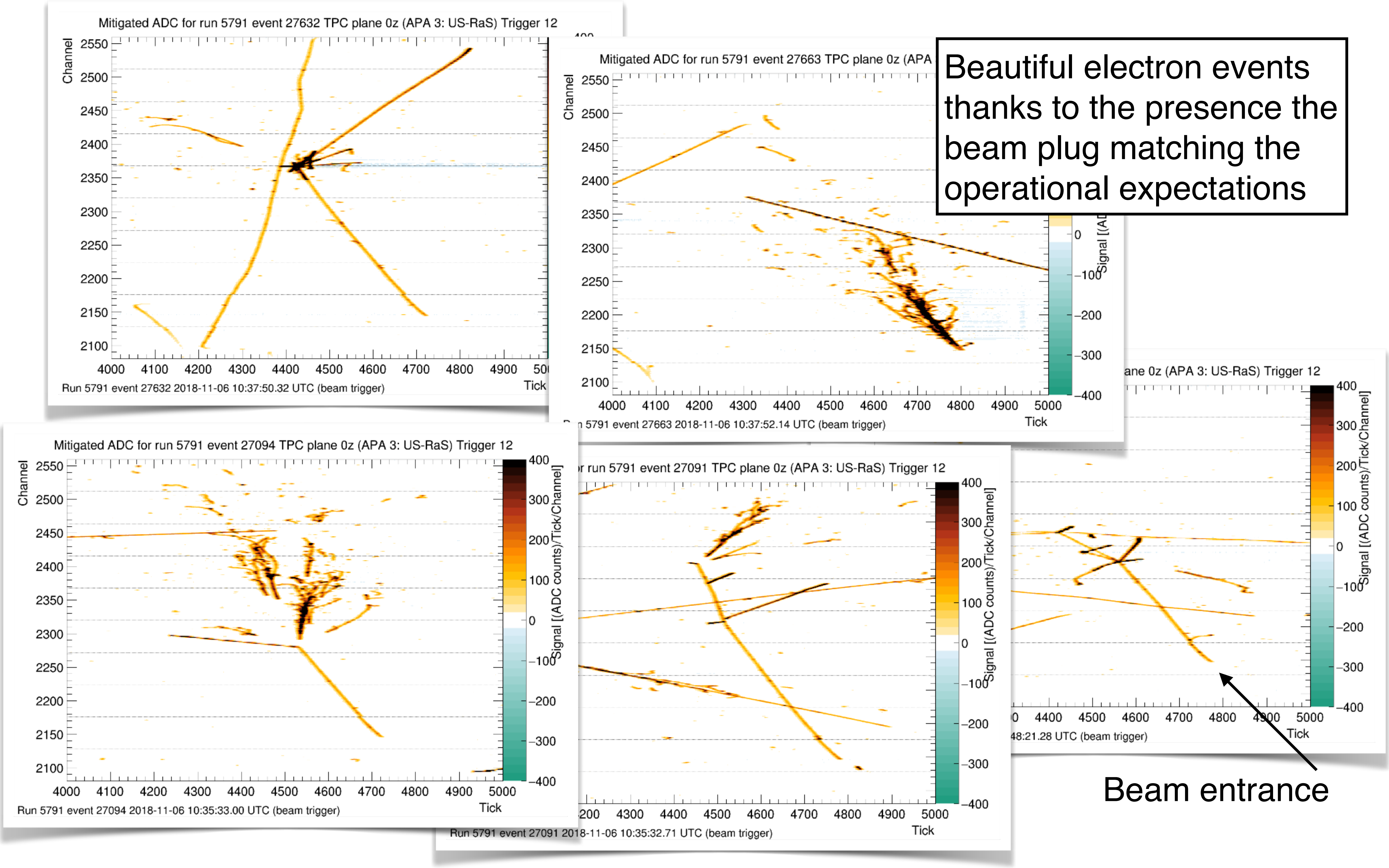
🟪 LHC Exp. 🟩 PS/SPS Exp. 🟦 Other Exp. 🟧 INT Exp.

Commissioning of beam and beam instrumentation

Charge and light readout, CRT and DAQ commissioning with beam particles

Data taking with very good drifting electron lifetime

Some raw beam events



Beautiful electron events thanks to the presence the beam plug matching the operational expectations

Beam entrance

Detector response

DUNE Collaboration, “First results on ProtoDUNE-SP liquid argon time projection chamber performance from a beam test at the CERN Neutrino Platform,” https://arxiv.org/pdf/2007.06722.pdf

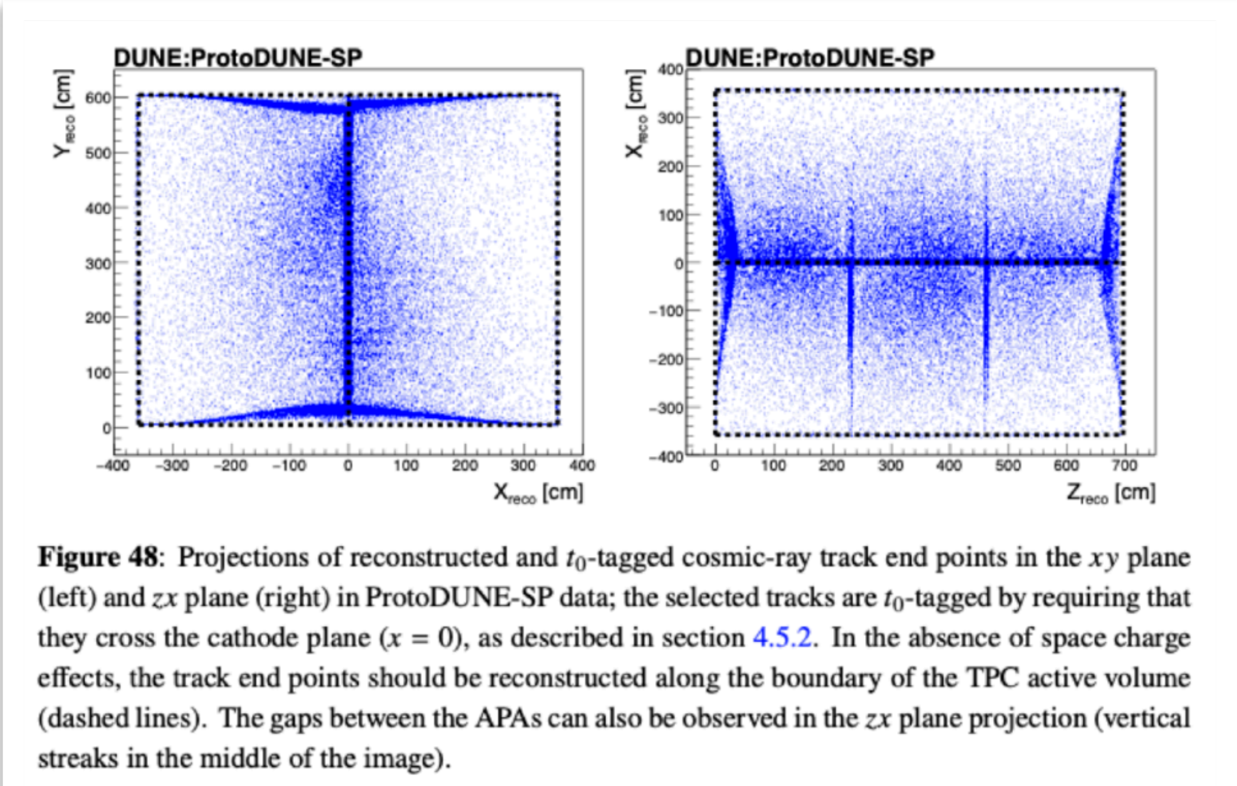


Figure 48: Projections of reconstructed and t_0-tagged cosmic-ray track end points in the xy plane (left) and zx plane (right) in ProtoDUNE-SP data; the selected tracks are t_0-tagged by requiring that they cross the cathode plane ($x = 0$), as described in section 4.5.2. In the absence of space charge effects, the track end points should be reconstructed along the boundary of the TPC active volume (dashed lines). The gaps between the APAs can also be observed in the zx plane projection (vertical streaks in the middle of the image).

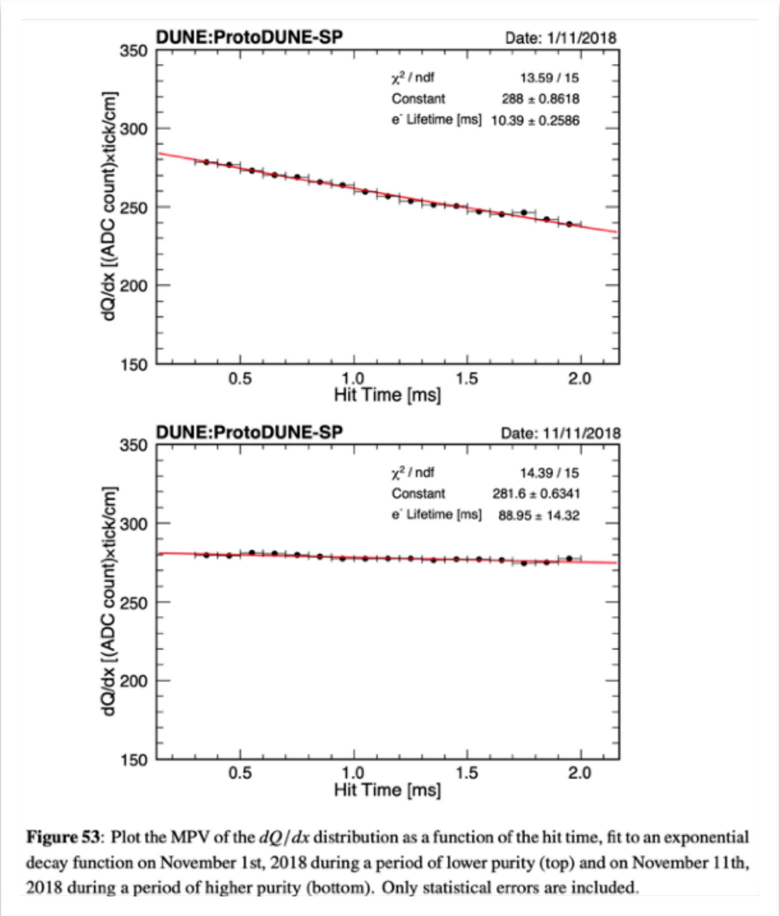


Figure 53: Plot the MPV of the dQ/dx distribution as a function of the hit time, fit to an exponential decay function on November 1st, 2018 during a period of lower purity (top) and on November 11th, 2018 during a period of higher purity (bottom). Only statistical errors are included.

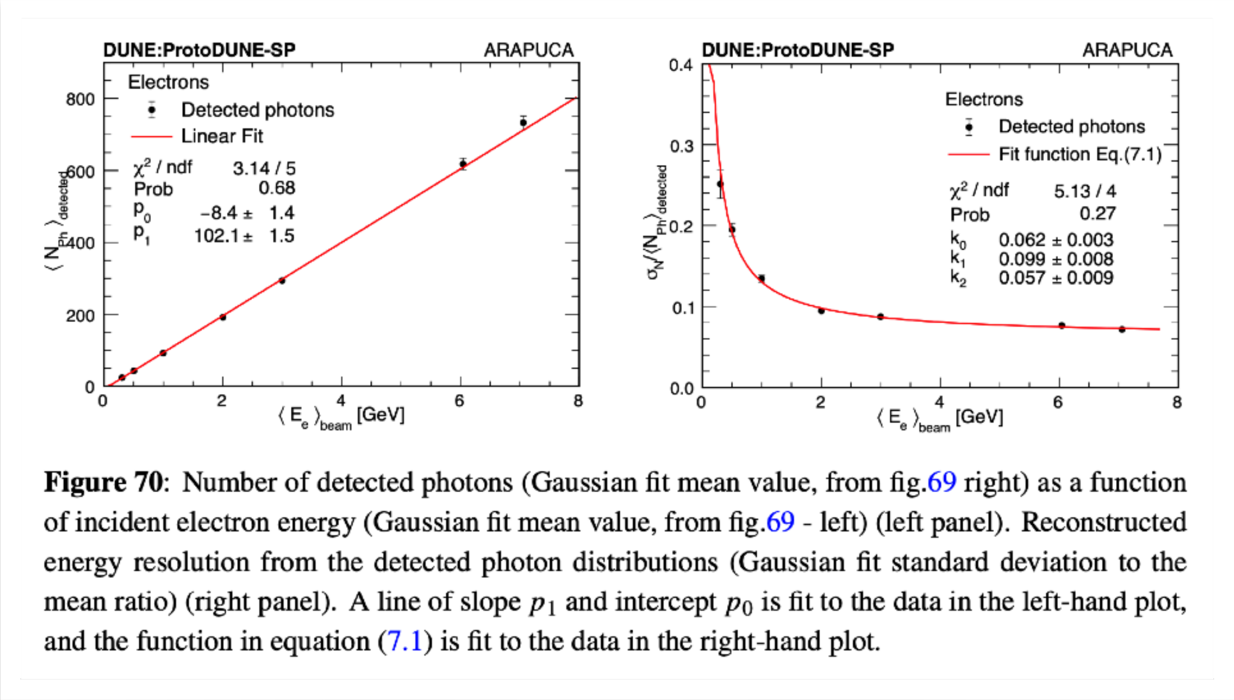
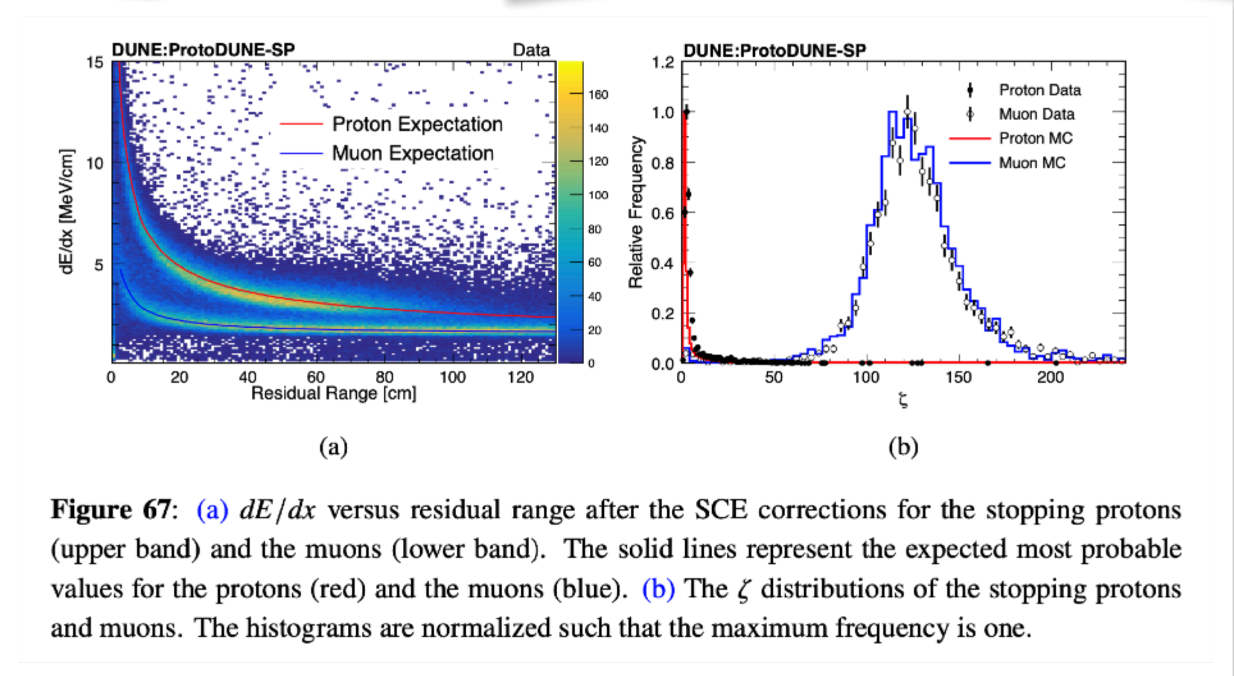


Figure 70: Number of detected photons (Gaussian fit mean value, from fig.69 right) as a function of incident electron energy (Gaussian fit mean value, from fig.69 - left) (left panel). Reconstructed energy resolution from the detected photon distributions (Gaussian fit standard deviation to the mean ratio) (right panel). A line of slope p_1 and intercept p_0 is fit to the data in the left-hand plot, and the function in equation (7.1) is fit to the data in the right-hand plot.

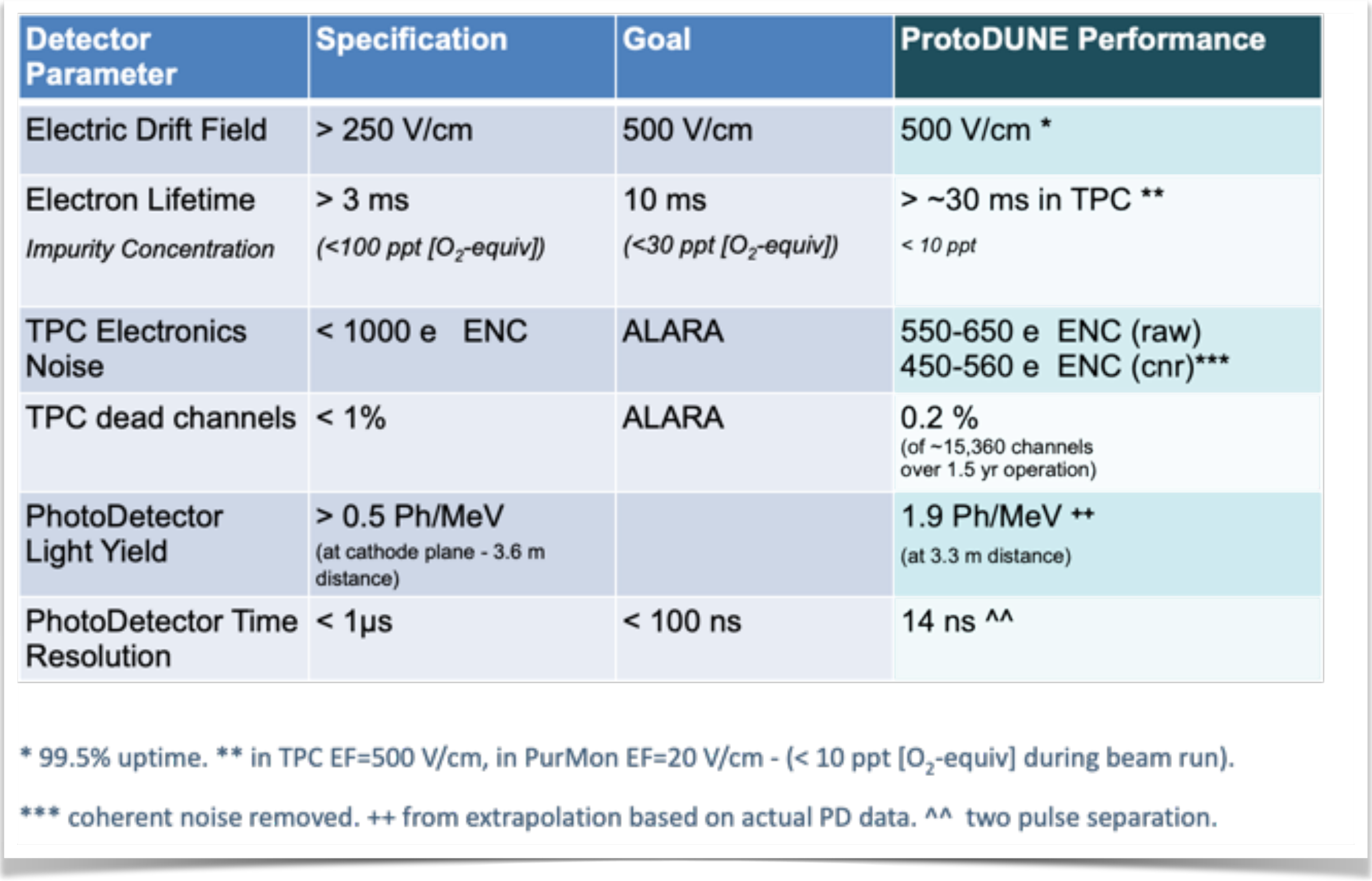


(a) (b)

Figure 67: (a) dE/dx versus residual range after the SCE corrections for the stopping protons (upper band) and the muons (lower band). The solid lines represent the expected most probable values for the protons (red) and the muons (blue). (b) The ζ distributions of the stopping protons and muons. The histograms are normalized such that the maximum frequency is one.

Long term performance

DUNE Collaboration, “Deep Underground Neutrino Experiment (DUNE), Far Detector Technical Design Report, Volume IV: Far Detector Single-phase Technology,” https://arxiv.org/pdf/2002.03010.pdf



Detector Parameter	**Specification**	**Goal**	**ProtoDUNE Performance**
Electric Drift Field	> 250 V/cm	500 V/cm	500 V/cm *
Electron Lifetime *Impurity Concentration*	> 3 ms *(<100 ppt [O$_2$-equiv])*	10 ms *(<30 ppt [O$_2$-equiv])*	> ~30 ms in TPC ** *< 10 ppt*
TPC Electronics Noise	< 1000 e ENC	ALARA	550-650 e ENC (raw) 450-560 e ENC (cnr)***
TPC dead channels	< 1%	ALARA	0.2 % (of ~15,360 channels over 1.5 yr operation)
PhotoDetector Light Yield	> 0.5 Ph/MeV (at cathode plane - 3.6 m distance)		1.9 Ph/MeV ++ (at 3.3 m distance)
PhotoDetector Time Resolution	< 1µs	< 100 ns	14 ns ^^

* 99.5% uptime. ** in TPC EF=500 V/cm, in PurMon EF=20 V/cm - (< 10 ppt [O$_2$-equiv] during beam run).

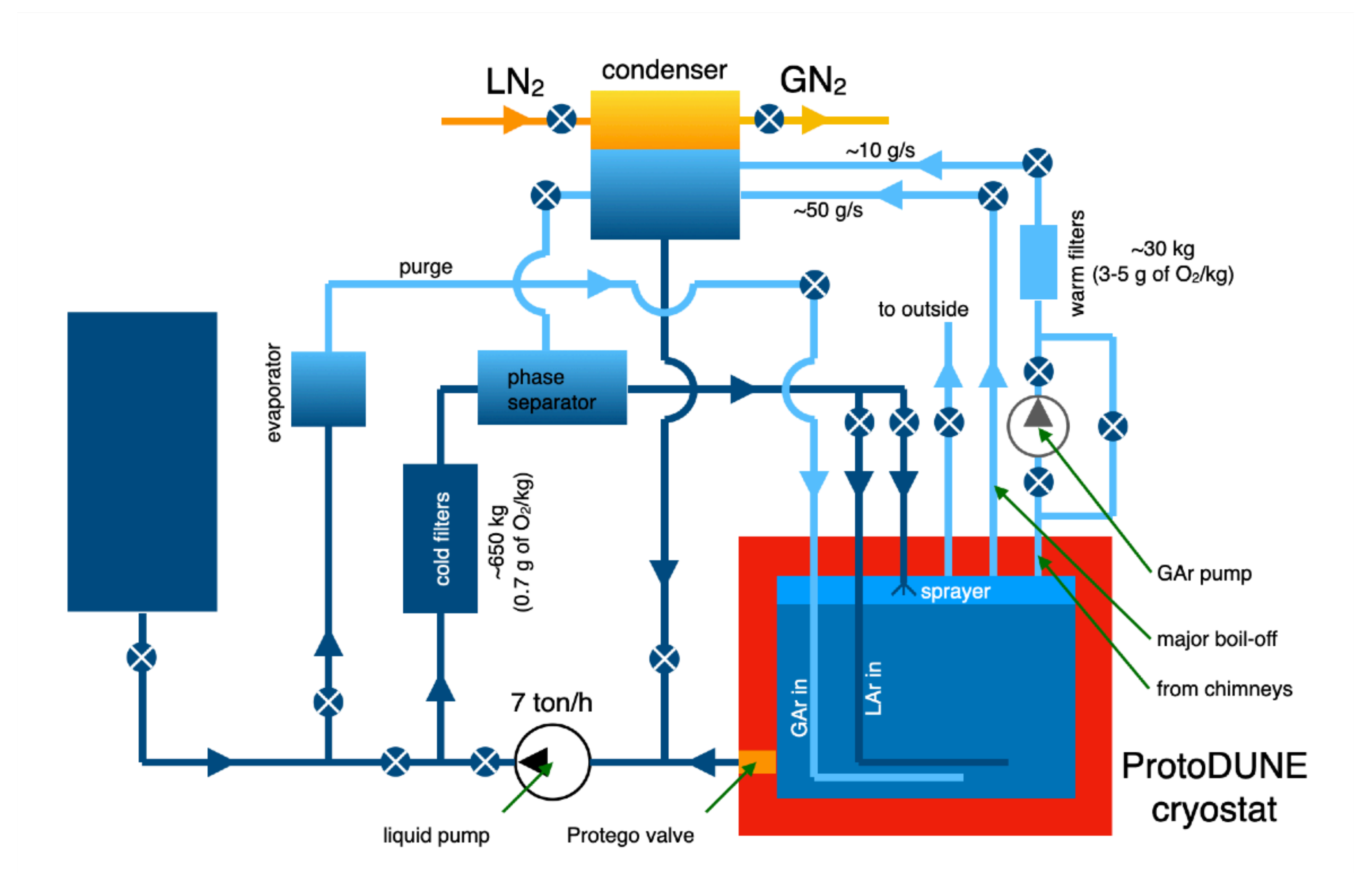
*** coherent noise removed. ++ from extrapolation based on actual PD data. ^^ two pulse separation.

Not only fun and games

Issue with liquid argon purity found on Monday 22nd of July 2019.
The pump that pushes the warm gas argon from the chimneys through the purification cartridge developed a leak to the atmosphere that resulted in injecting air in the system:

- Oxygen was filtered by warm and cold filters up to saturation (*O(*100 ppb) injected).
- Nitrogen was directly diluted in the liquid argon (~5 ppm).

The use of the pump is avoided increasing 10-20 mbar the operation pressure of the cryostat and optimising the gas flow and the pressures in the various stages of the cryogenics



Every cloud has a silver lining

DUNE Collaboration, “Design, construction and operation of the ProtoDUNE-SP Liquid Argon TPC ,” https://arxiv.org/pdf/2108.01902.pdf

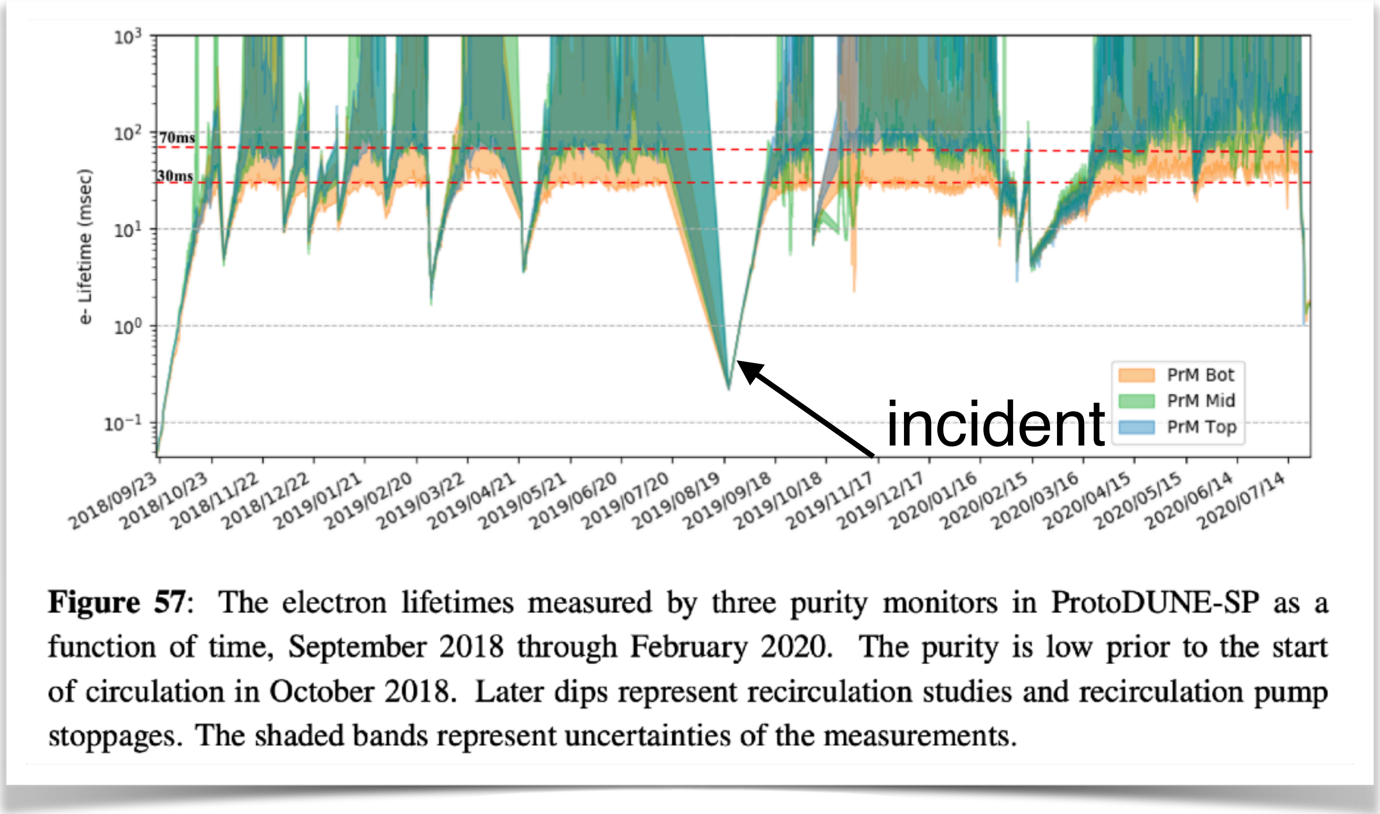


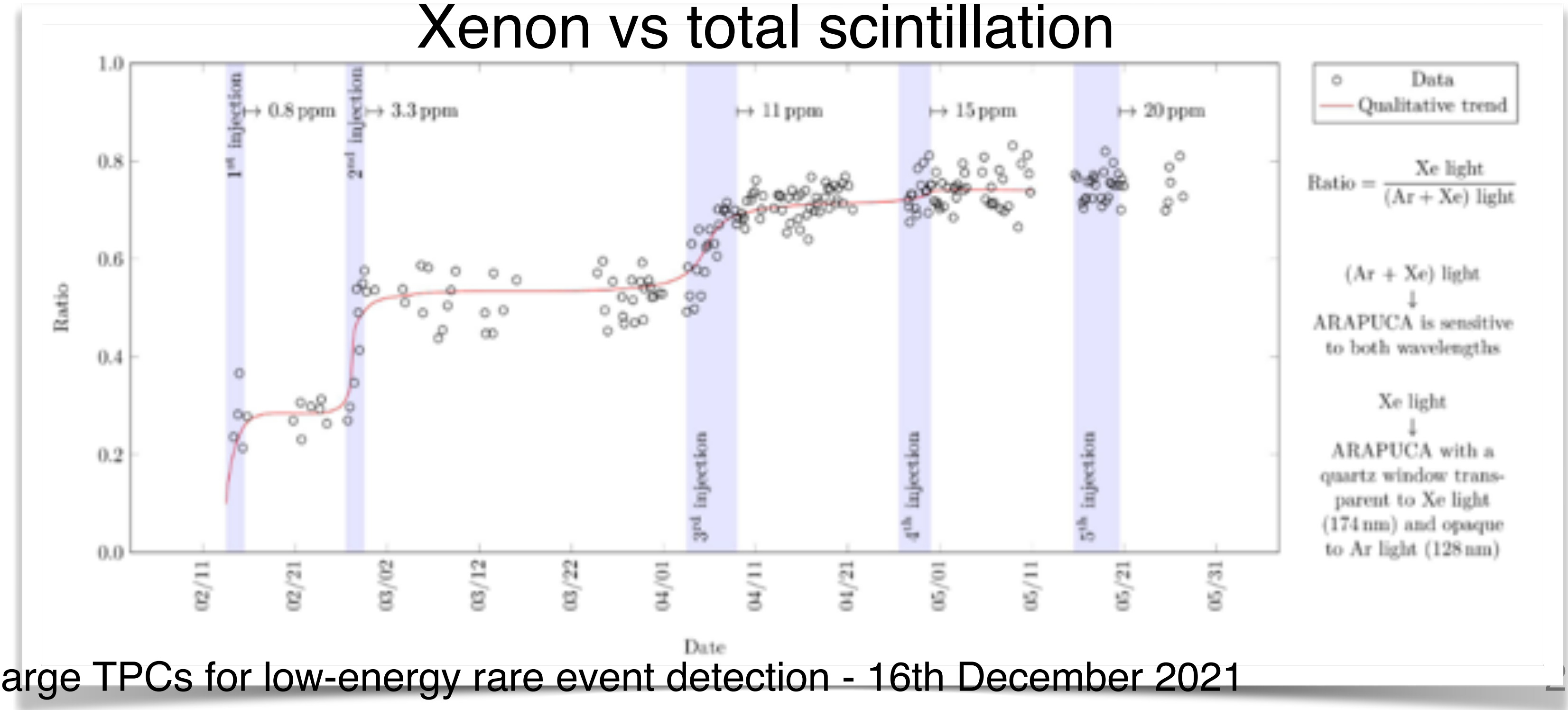
Figure 57: The electron lifetimes measured by three purity monitors in ProtoDUNE-SP as a function of time, September 2018 through February 2020. The purity is low prior to the start of circulation in October 2018. Later dips represent recirculation studies and recirculation pump stoppages. The shaded bands represent uncertainties of the measurements.

Drifting electron lifetime recovered by circulating and purifying LAr from O_2 (electronegative) impurities.

N_2 contamination affects the scintillation
$Ar_2^* + N_2$ -> non radiative
N_2 not filtered by purification

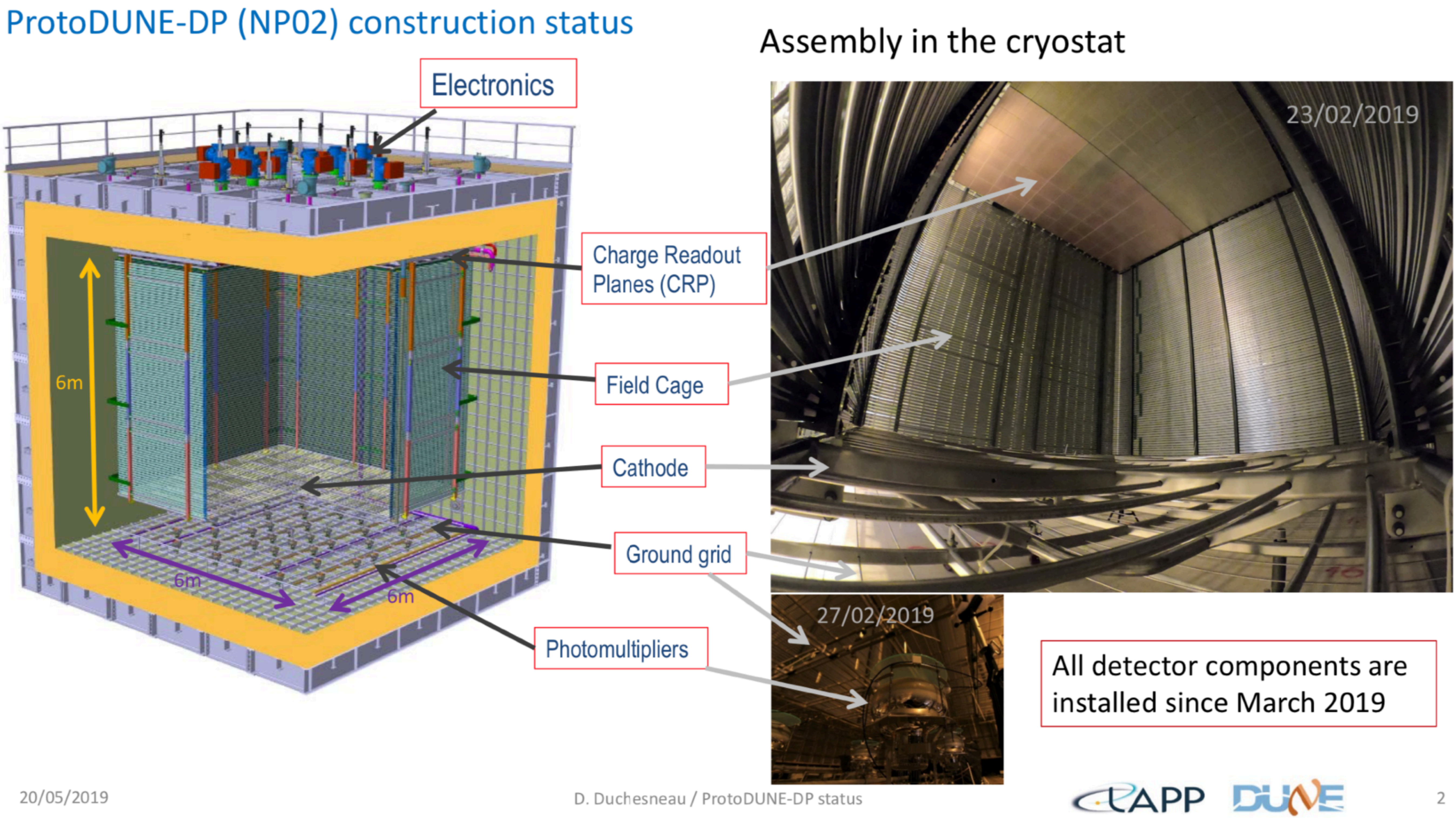
Argon scintillation blind PDs installed while cryostat full.

Xenon vs total scintillation



Xenon doping to recover light yield and increase uniformity
- $Ar_2^* + Xe$ -> radiative (175 nm)
- Rayleigh scattering reduced for 175 nm vs 128 nm
- Up to 20 ppm Xe dopants stable for months

ProtoDUNE-DP



ProtoDUNE-DP (NP02) construction status

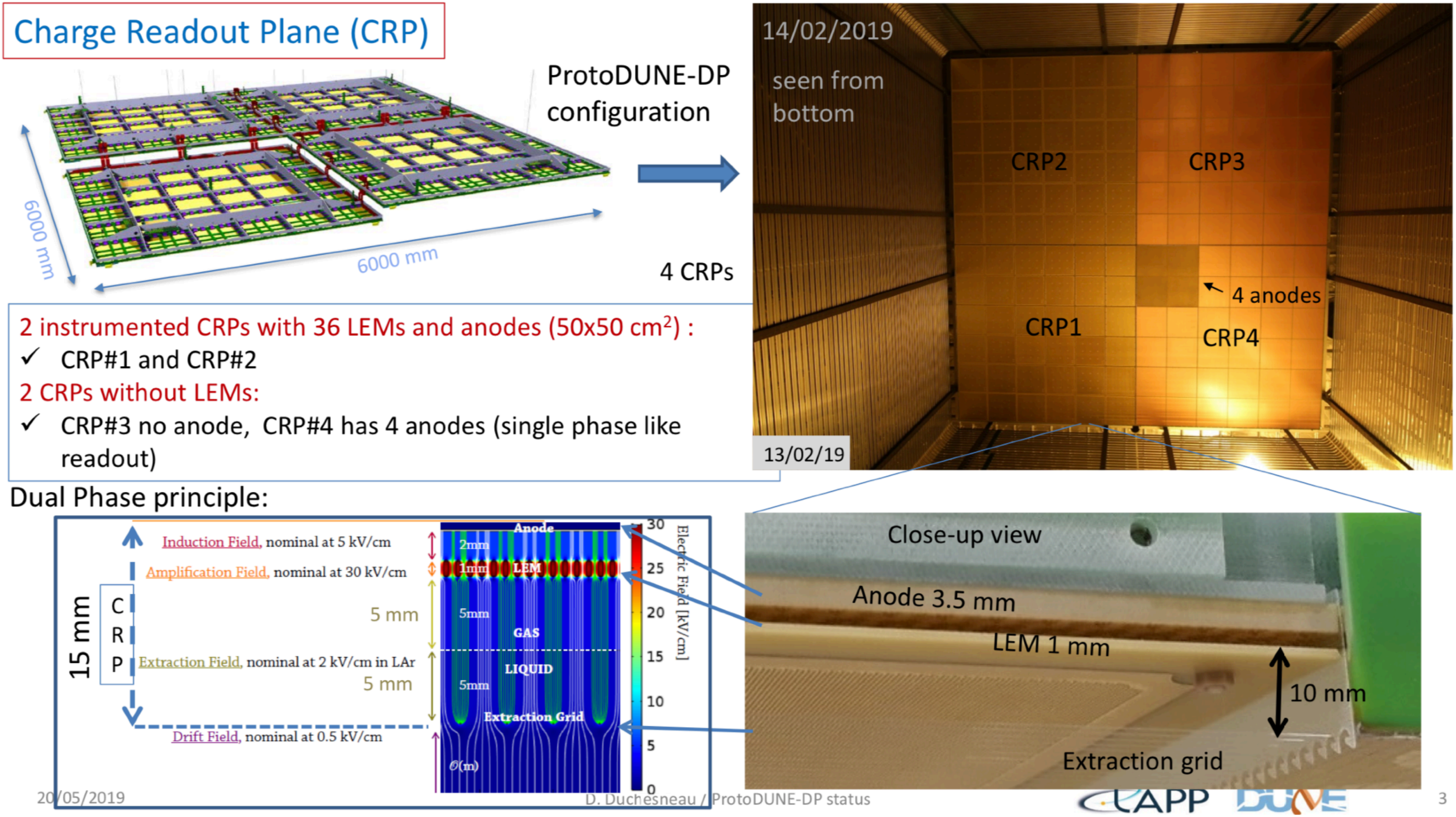
Assembly in the cryostat

All detector components are installed since March 2019

20/05/2019 D. Duchesneau / ProtoDUNE-DP status 2

D. Duchesneau, “ProtoDUNE-DP status ,” DUNE Collaboration May 2019

Charge Readout Plane



Charge Readout Plane (CRP)

ProtoDUNE-DP configuration

4 CRPs

2 instrumented CRPs with 36 LEMs and anodes (50x50 cm^2) :

- ✓ CRP#1 and CRP#2

2 CRPs without LEMs:

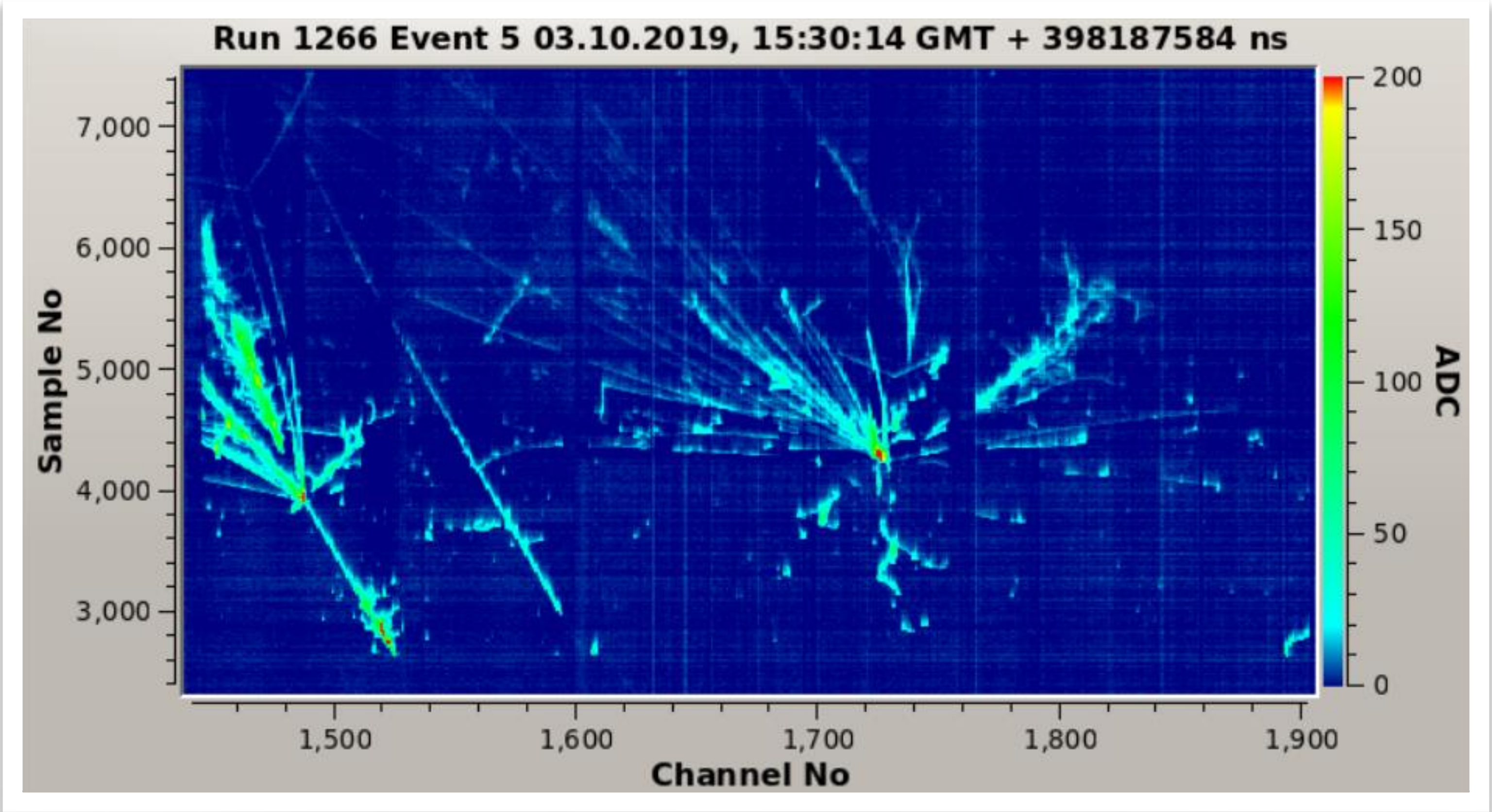
- ✓ CRP#3 no anode, CRP#4 has 4 anodes (single phase like readout)

Dual Phase principle:

20/05/2019 D. Duchesneau / ProtoDUNE-DP status LAPP DUNE 3

D. Duchesneau, “ProtoDUNE-DP status ,” DUNE Collaboration May 2019

Lessons learned



Demonstrated/understood:

- Overall detector design easy to assemble. CRP cheaper than APA.
- Field cage/Cathode hanging from the cryostat roof (independently from other components)
- CRP support structure (3x3 m^2) allows precise alignment and mm planarity of anode
- Scintillation light detection over 6 m demonstrated and understood (also with Xenon doping)
- Cold FE Electronic performance: good S/N with moderate amplification (Noise ~ 600 el.)

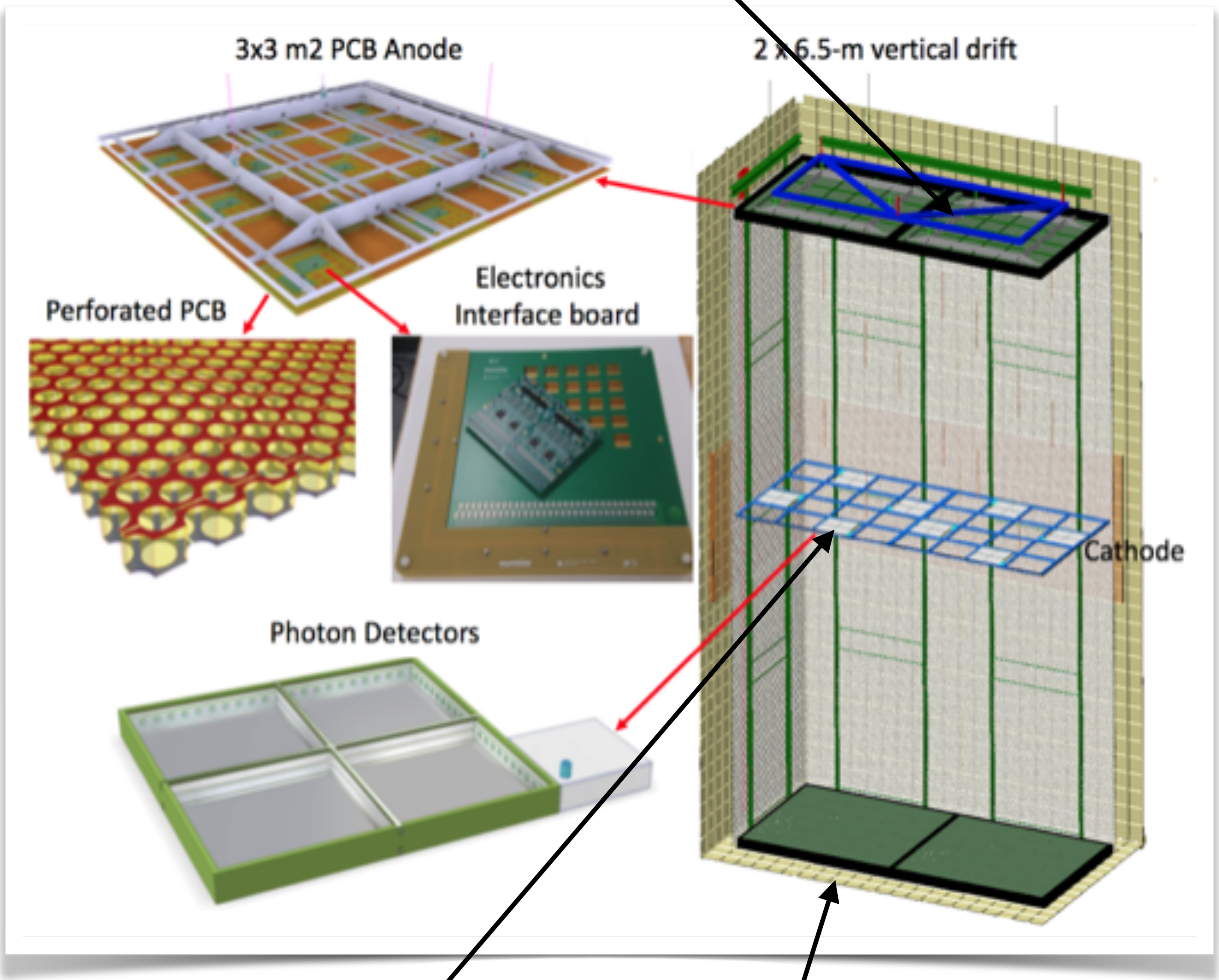
Not demonstrated:

- 6 m drift with 300 kV on Cathode (damage of HV delivery). Extrapolation to 600 kV for DUNE.
- Long term stability at high gains of the multiplication stage.
- CRP performance very sensitive to LAr-GAr interface (bubble formation, LAr level flatness).

Single Phase Vertical Drift

Capitalising on the important developments and lessons learned of the last years on both ProtoDUNEs, new solutions emerged in late 2019 for the DUNE Far Detector 2:

- Outstanding LAr purity allows for drifts anger than 3.6 m (aim for 6-7m).
- Charge readout electronics in NP04/NP02 demonstrated excellent S/N (>30). No need of high signal amplification in gas phase.
- The Vertical Drift layout is simpler and cheaper to construct, it uses the drift space in a more efficient way, it will reduce schedule and financial risks by increasing the level of modularity.
- Lightweight PCB support developed for DP well suited for immersed PCB anode (SP)
- Xe-doping improves the light yield and opens the possibility to optimise the photon detector in its physics performance.
- Investments & know-how from institutions on DP moving to SP-VD



signals readout with DP electronics

PDs operated at HV (PoF and SoF)

signals readout with SP electronics

Perforated anode readout

Working principle

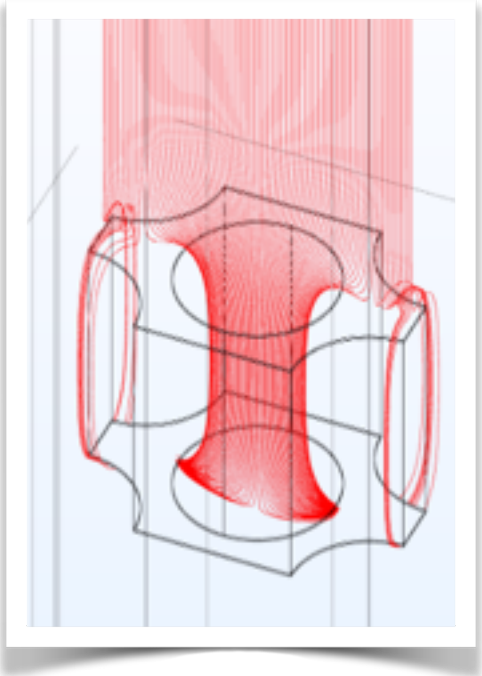
- Electron trajectories are focused into 2D holes not in a “slice” like for wires. Focusing can be repeated on stacked PCBs for multiple readout views.

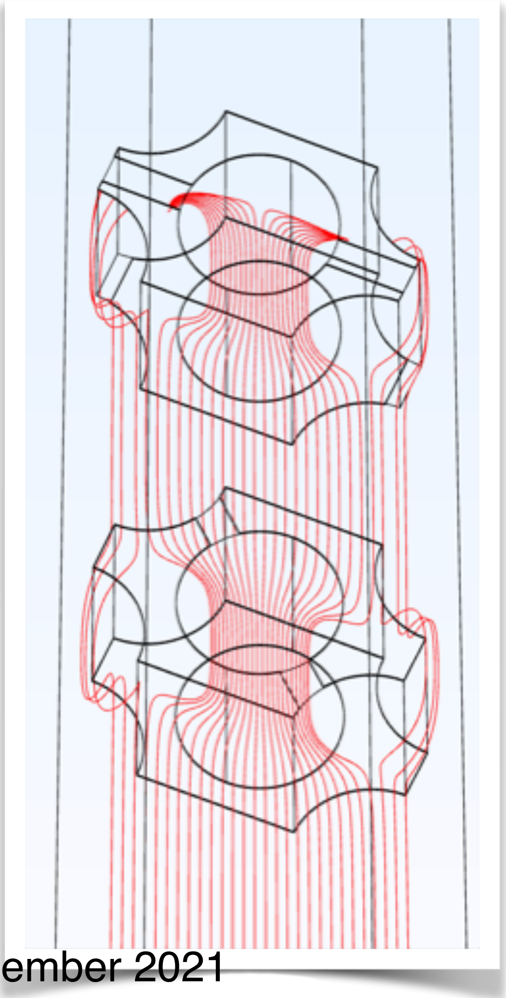
PRO:

- Electric and weighting field in the hole is more uniform than for the wires.
- Bipolar shape of induction signal is asymmetric with benefit for visibility of large dip angle tracks because “cancellation effects” are reduced
- Induction signal is intrinsically larger than with wires and less blurred because the weighting field is confined to a single strip and not distributed on several wires
-3 views possible: PCB stack (preferred), multilayer, charge sharing

CONS:

- focusing EF ratio is high kV voltage differences
-Capacitance of strips ~5x higher than wires at the same pitch: higher noise for same length

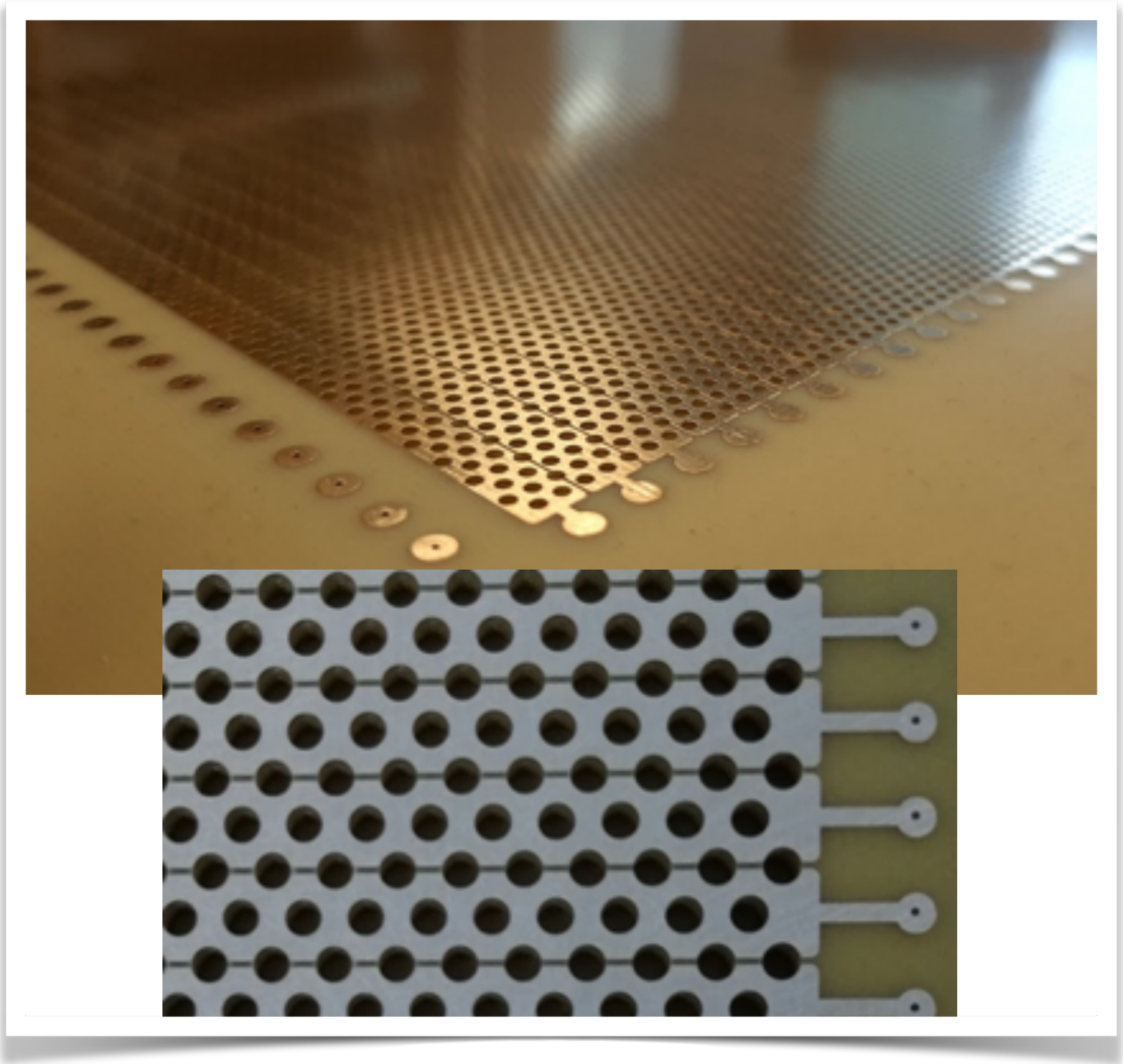




F. Pietropaolo, CERN Detector Seminar, December 10th, 2021 https://indico.cern.ch/event/1103484/

Perforated anode readout

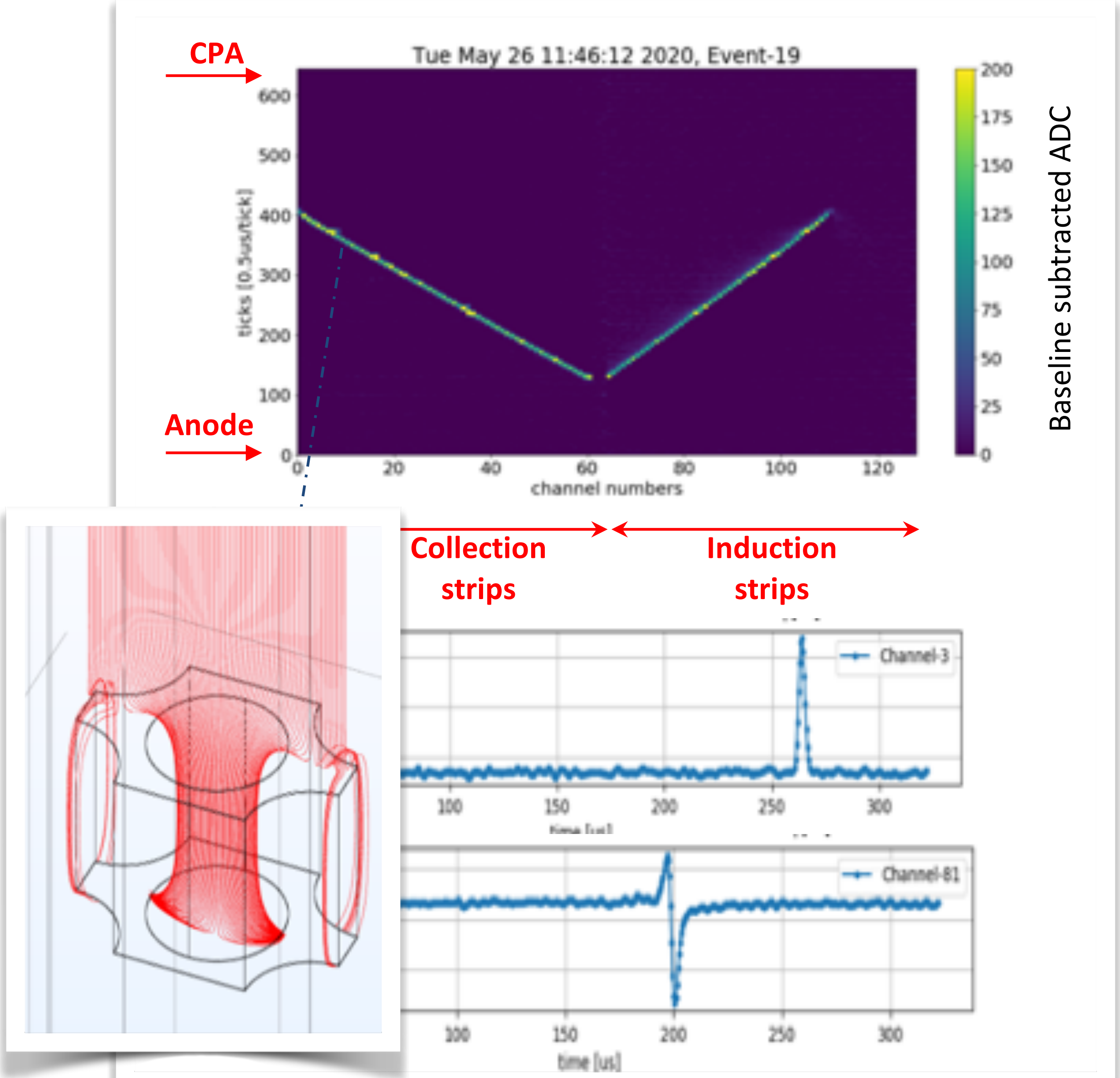
Advantages:
Most components can be mass produced commercially
The anode plane is robust, without risk of broken wires, has simpler support structure
Integrating the FE electronics / cable connectors on interface PCB's
The design took advantage of the technological development of wide area Thick-GEMs

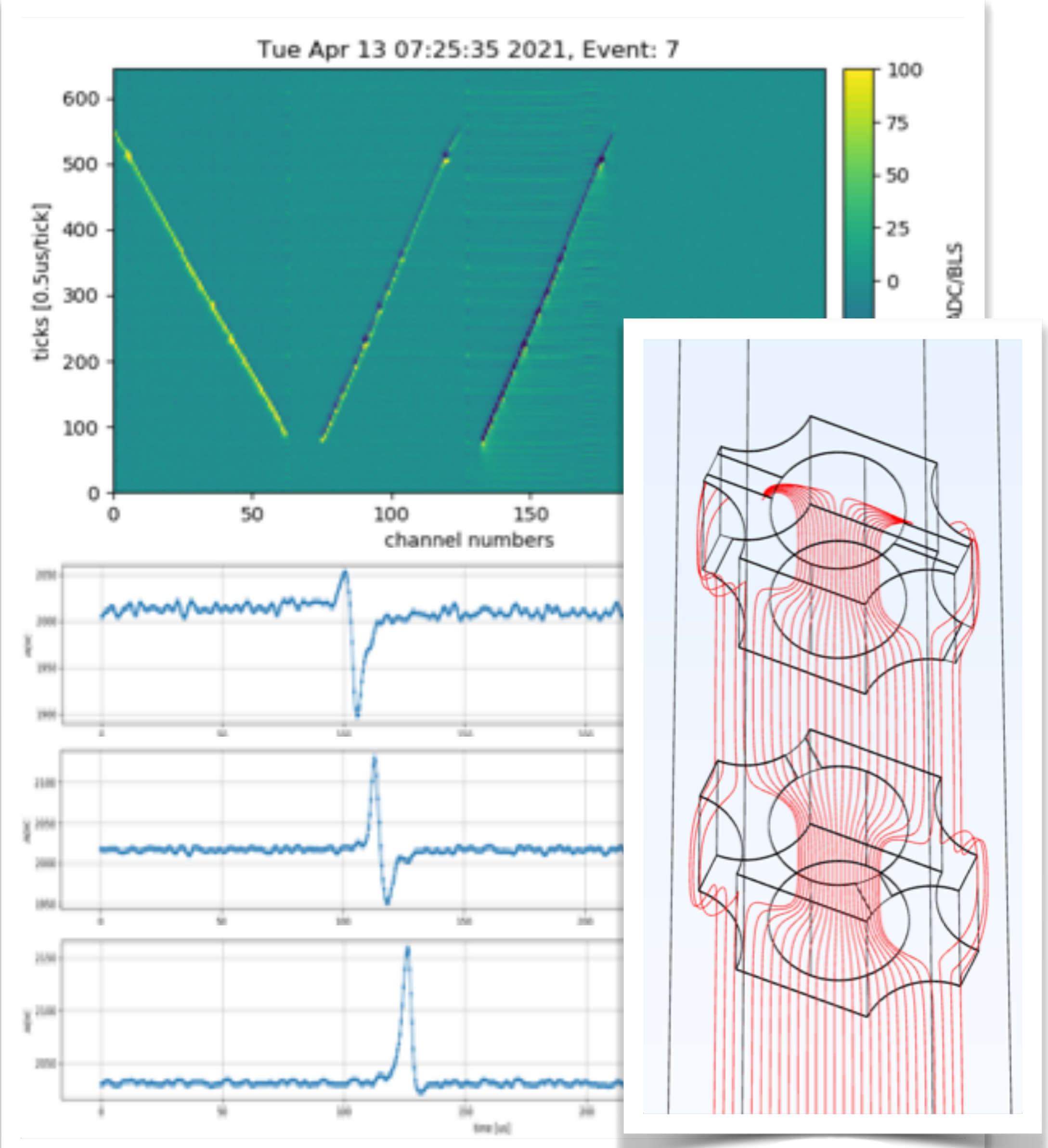


F. Pietropaolo, CERN Detector Seminar, December 10th, 2021 https://indico.cern.ch/event/1103484/

Small scale development

Extensive developments on ~30 x 30 cm^2 readouts in 2020.
Two view: signal vs hole size/pitch, transparency vs bias V, signal shapes and localisation, energy resolution (comparison with wire chamber)
Three view: feasibility of stacked PCB layout, layer connection concepts, signal shapes and noise studies, strips orientation, feedback to signal simulations.

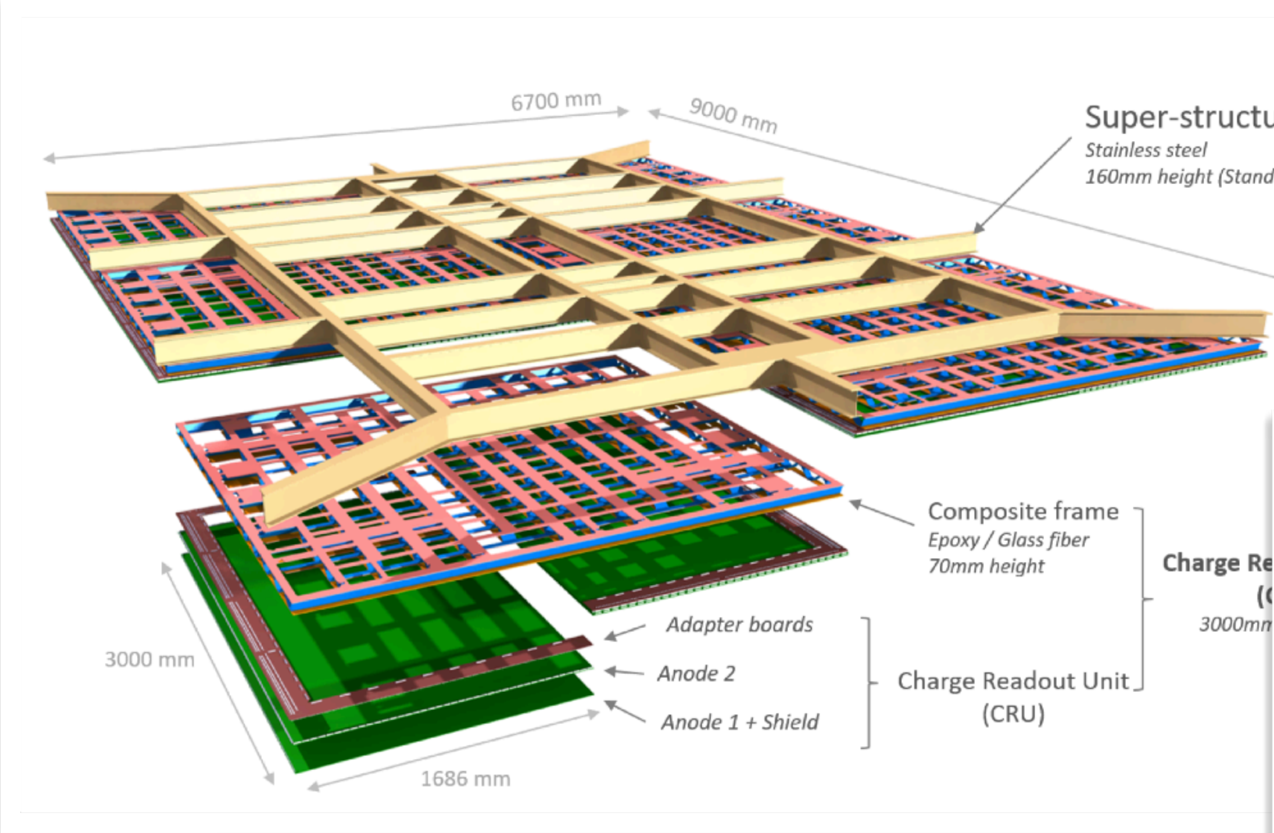


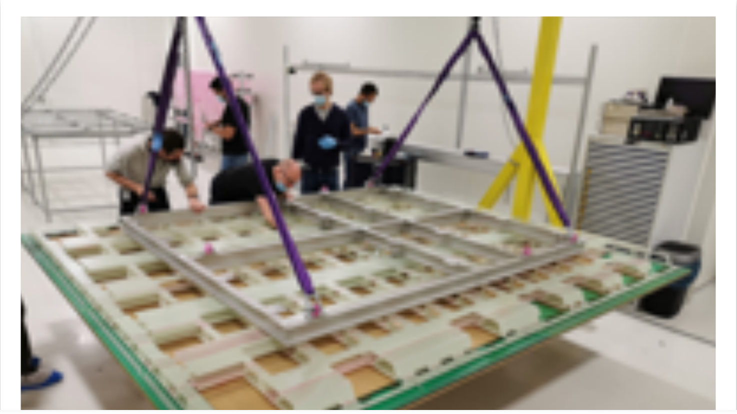


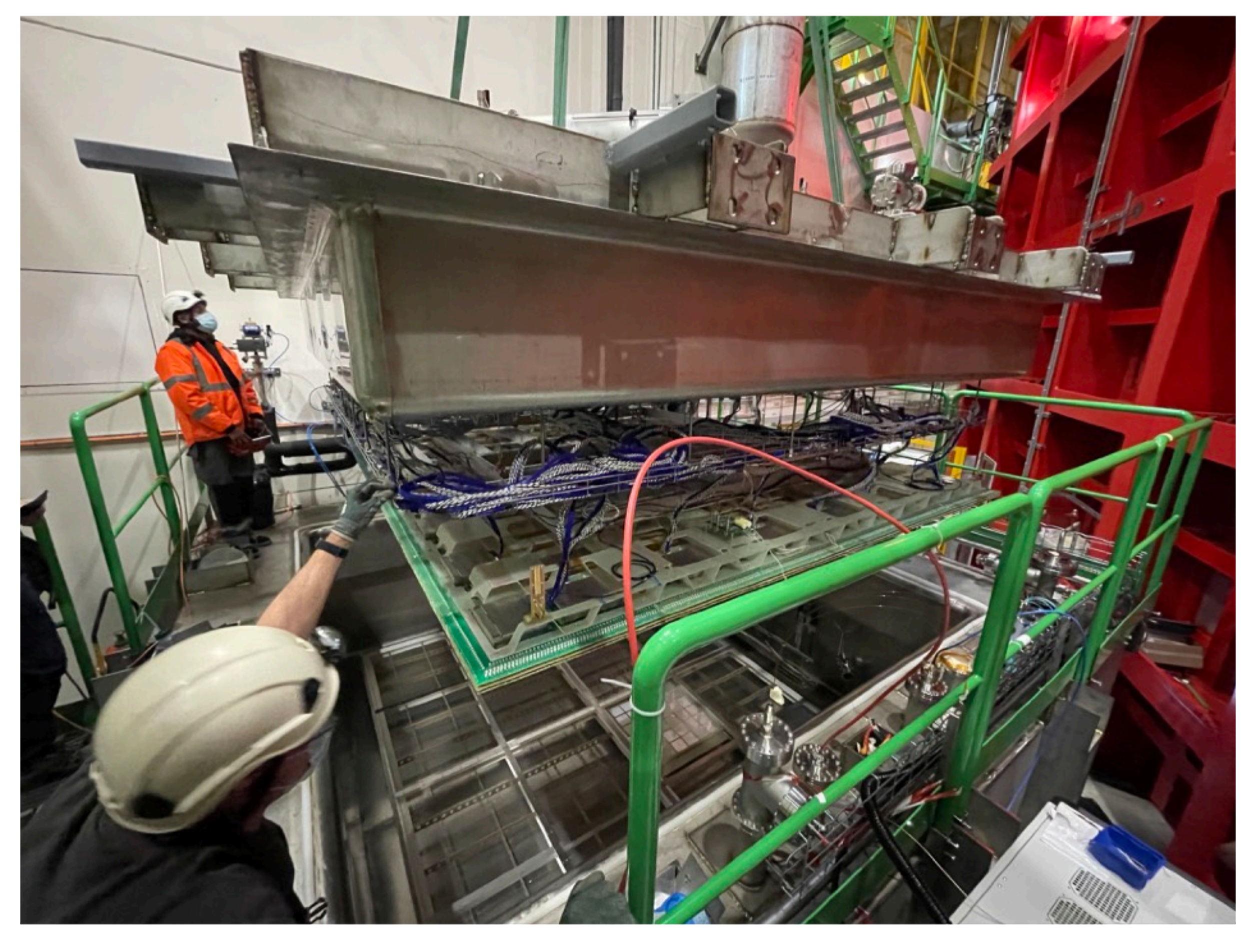
Full size CRP demonstrator

Full size (~3 x 3.4 m^2) CRP module being tested in a TPC with 25 cm drift

Engineering, construction, installation and operation in 2021





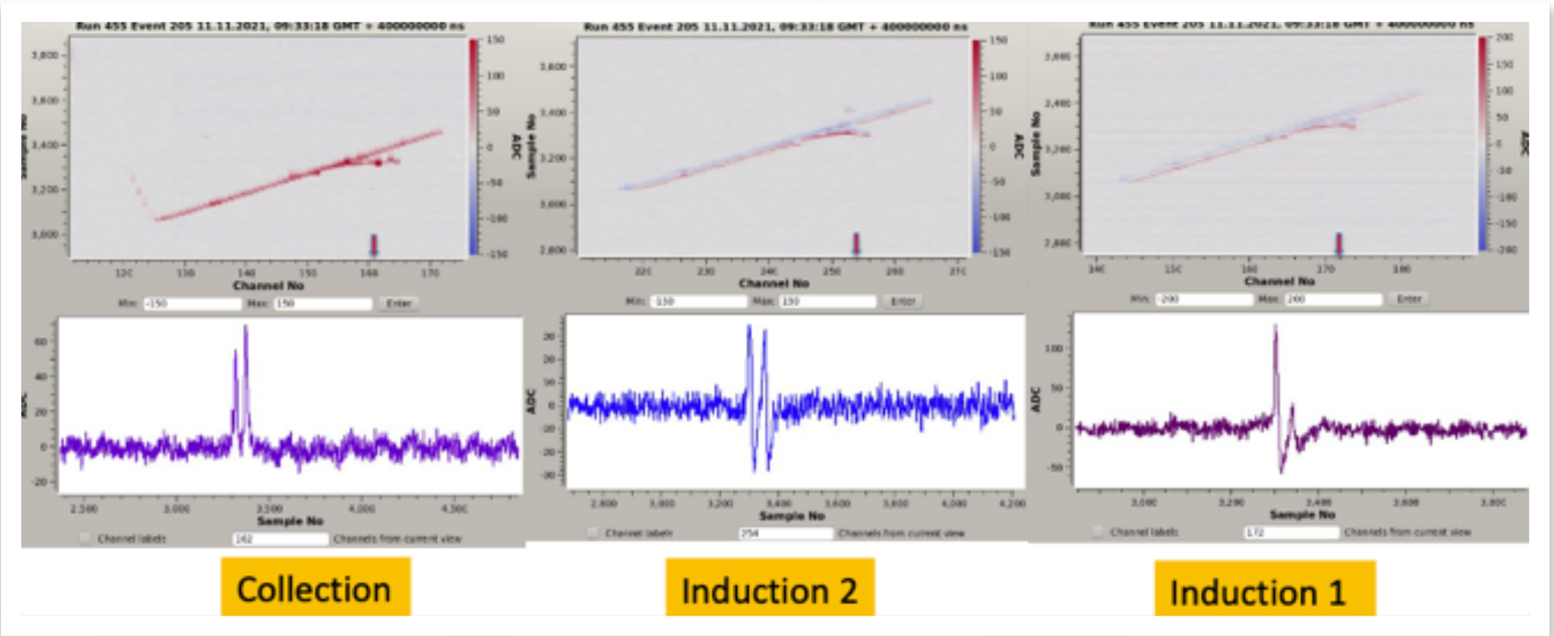


Half CRP readout with top electronics (DP) and half with bottom electronics (SP)

Tests includes operation of the PDs at HV

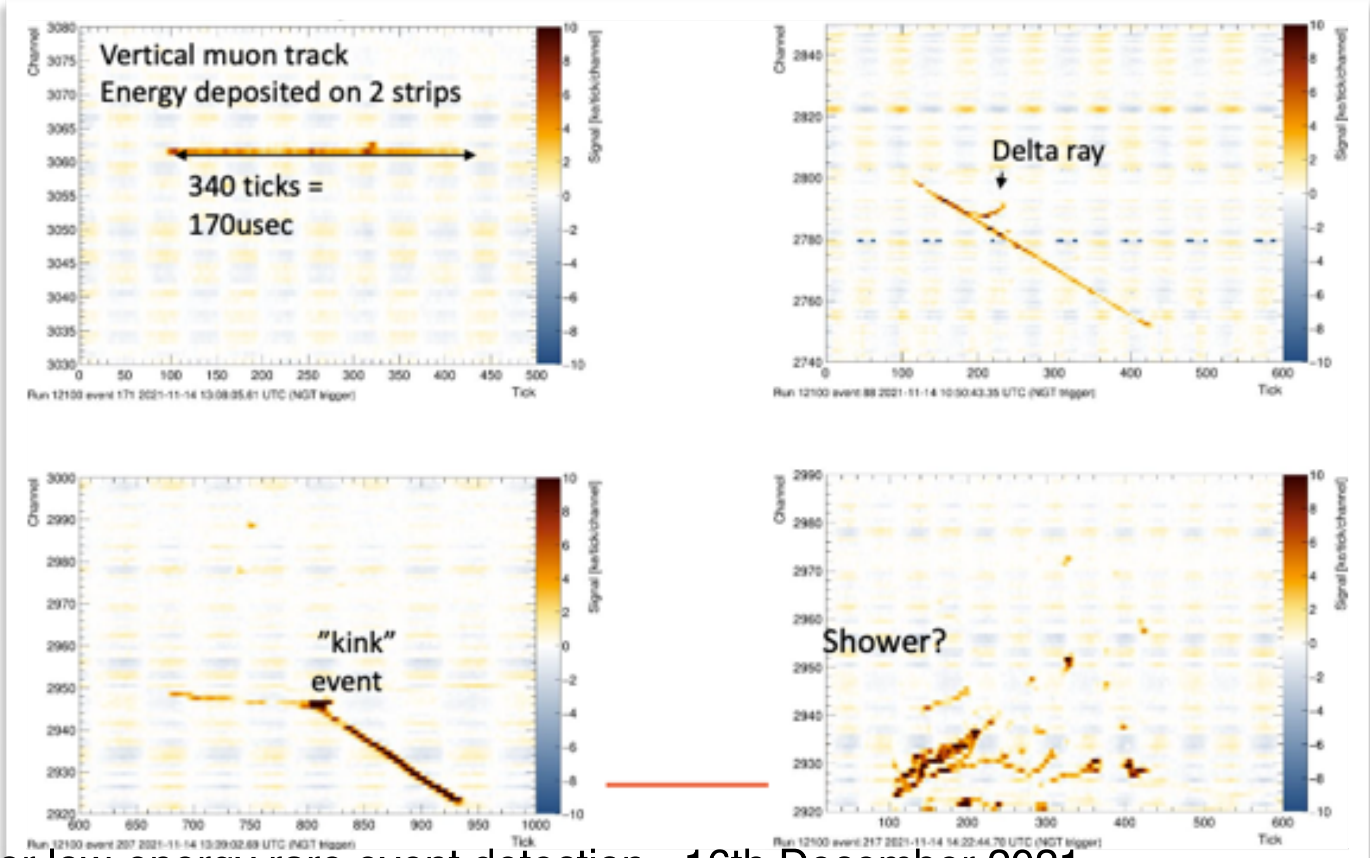
First tracks

- All channels online soon after LAr filling
- Cosmic ray tracks observed right away after turning on cathode and CRP bias voltages



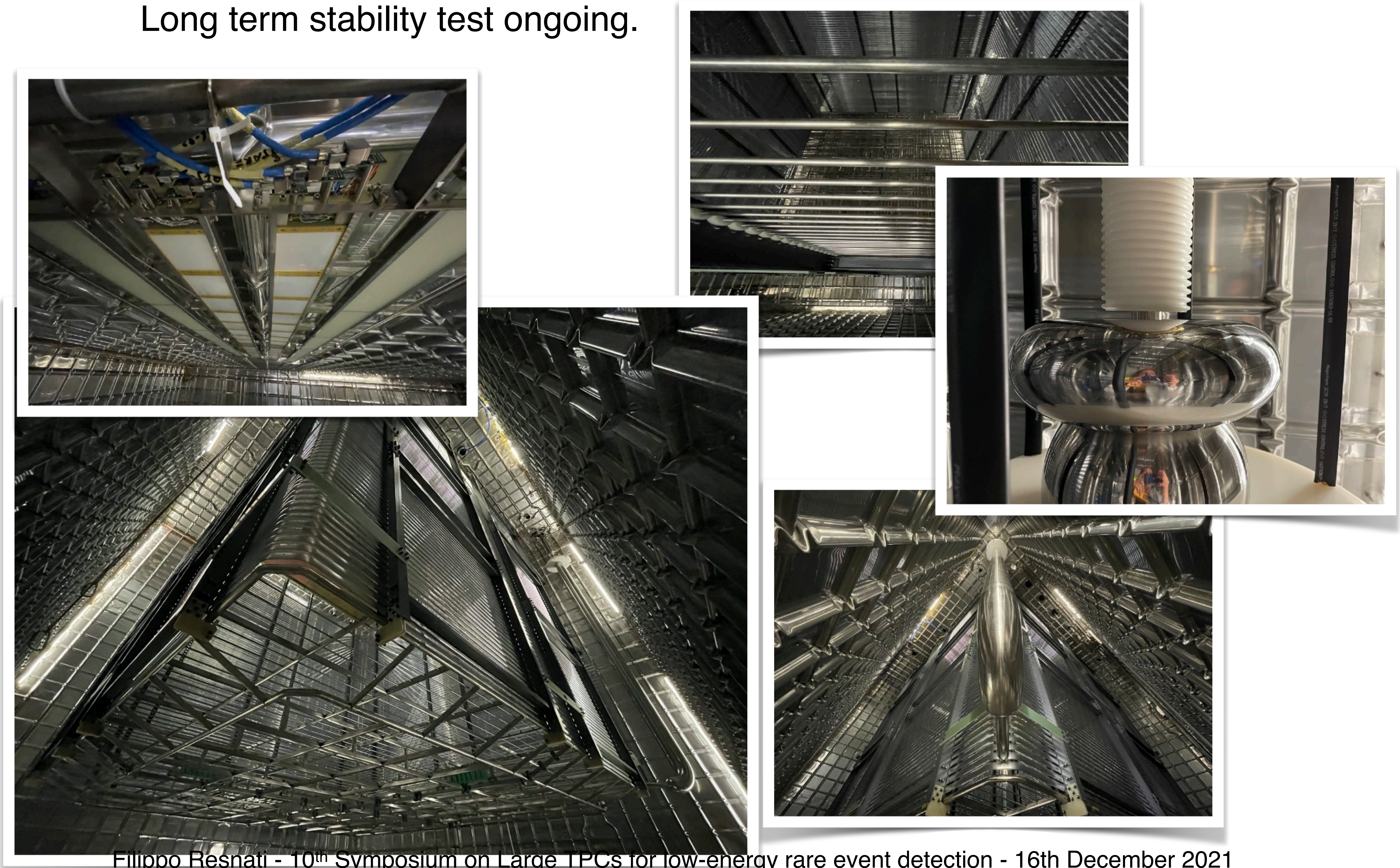
Top electronics (DP):
Very good S/N ratio already from raw waveforms

Bottom electronics (SP):
Origin of coherent noise understood.
New run in progress.



300 kV demonstrator

HV distribution in NP02 modified in early 2021. NP02 filled in summer.
In October 2021 reached the nominal 300 kV.
Long term stability test ongoing.



Next steps

Both ProtoDUNEs will be used to operate the so called Module0 detectors:

Single Phase Horizontal Drift:
- 2x 2 APA (test also the bottom APA of the duplets)
- Nominal 3.5 m drift and voltage
- Optimised field cage
- Upgraded electronics
- Nominal installation sequence
- First APA tested in fall 2021 in cold box
- detector component installation in cryostat staring April 2022
- Operation with beam from fall 2022

Single Phase Vertical Drift:
- Produce and test the final upgraded versions of full scale CRPs (before summer 2022)
- Engineering of the the Module0 and integrate it in NP02
- Continue developments of the Photon detector modules (Power and signal over fibre)
- 2022 procurements of the components
- Installation and operation in 2023