Prototyping DUNE

The first run of ProtoDUNE-SP detector and plans for a second run

Andrea Zani, *INFN Milano*

Weekly DPNC seminars - Université de Genève

13 October 2021

Why ProtoDUNE ?

- ProtoDUNE is the moniker for two prototype facilities built at CERN Prevessin, aiming at… well, prototyping new detector solutions to be later deployed in the DUNE far detector.

- Usually a prototype fits in a lab, or in a large room with a crane… the two DUNE protoypes are as big as the largest LArTPC ever operated before them (ICARUS)!

- On the other hand, Liquid Argon TPC technology (LArTPC), on which DUNE far detectors are built, is nowadays pretty well known and tested (ICARUS, MicroBoone, …). Why the need for such large test-beds?

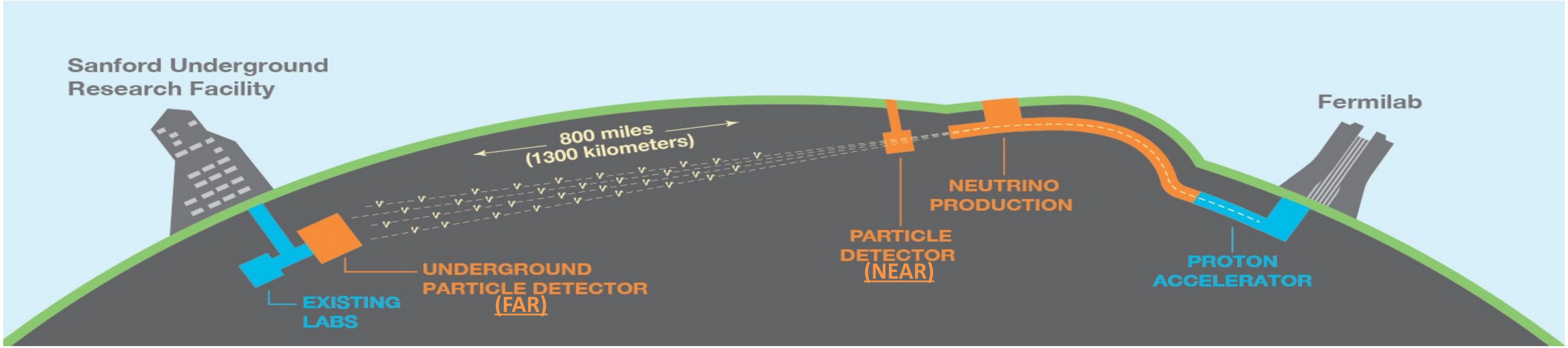
Introducing DUNE

DUNE

Deep Underground Neutrino Experiment

- Long-baseline (LB - 1300 km) experiment:
  - Neutrino and antineutrino beams
- ~ 70 kton volume far detector, 1.5 km underground, divided in 4 modules
- Multi-technology Near Detector, focused on beam characterization and physics
- > 20 years foreseen life span

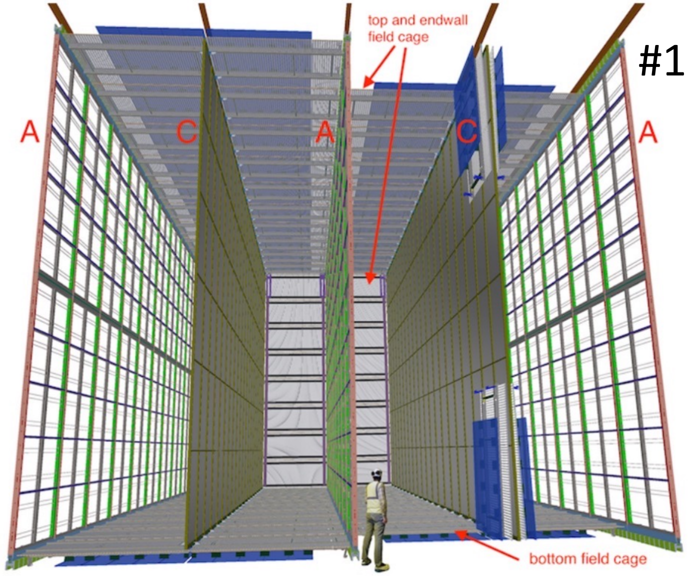
- **Primary physics goals**:
  - 3-neutrino oscillations parameters: $\nu_\mu/\overline{\nu_\mu}$ disappearance, $\nu_e/\overline{\nu_e}$ appearance
  - δ_{CP} ; mass hierarchy
- **SuperNova** burst neutrinos
- **Beyond-Standard-Model physics**: baryon number violation, sterile neutrinos, non-standard interactions, etc.



Deep Underground Neutrino Experiment

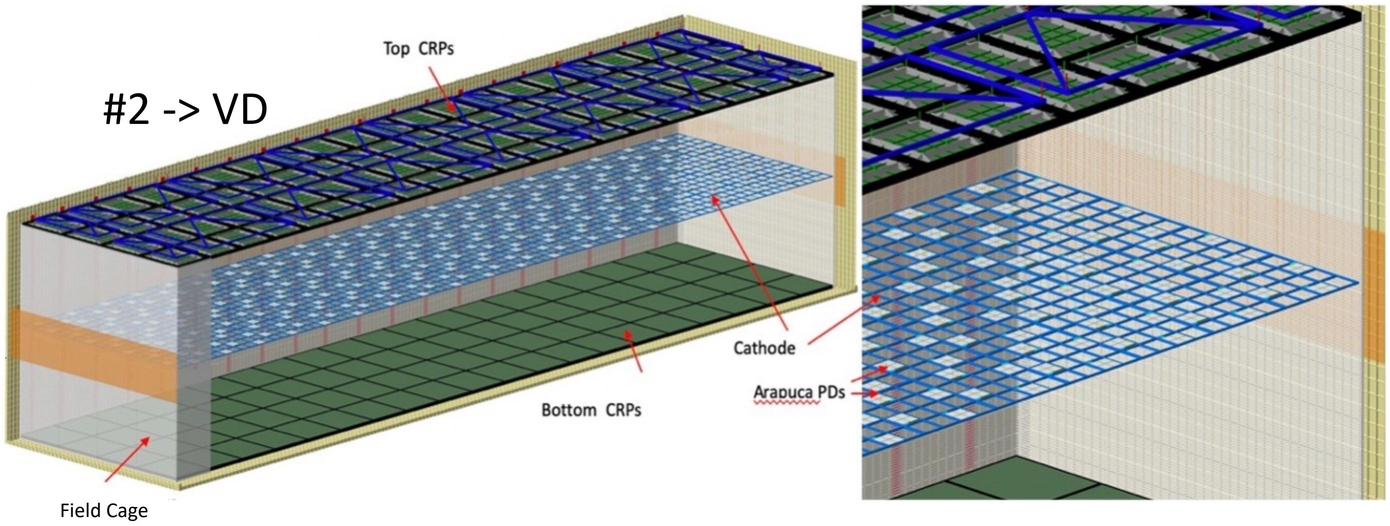
- Long-baseline (LB - 1300 km) experiment:
  - Neutrino and antineutrino beams
- **~ 70 kton volume far detector, 1.5 km underground, divided in 4 modules**
- Multi-technology Near Detector, focused on beam characterization and physics
- > 20 years foreseen life span

- **Highly modular design,** for cryostat and detectors, required by access to SURF caverns through shafts.
- Based on **Liquid Argon Time Projection Chamber (LAr-TPC) technology**, in different flavours
- First module will be a single-phase, Horizontal Drift LAr-TPC; second module a single-phase, Vertical Drift LAr-TPC
- **Different solutions** for charge read-out (wires, pixels, PCBs) foreseen within the program; same for light readout.

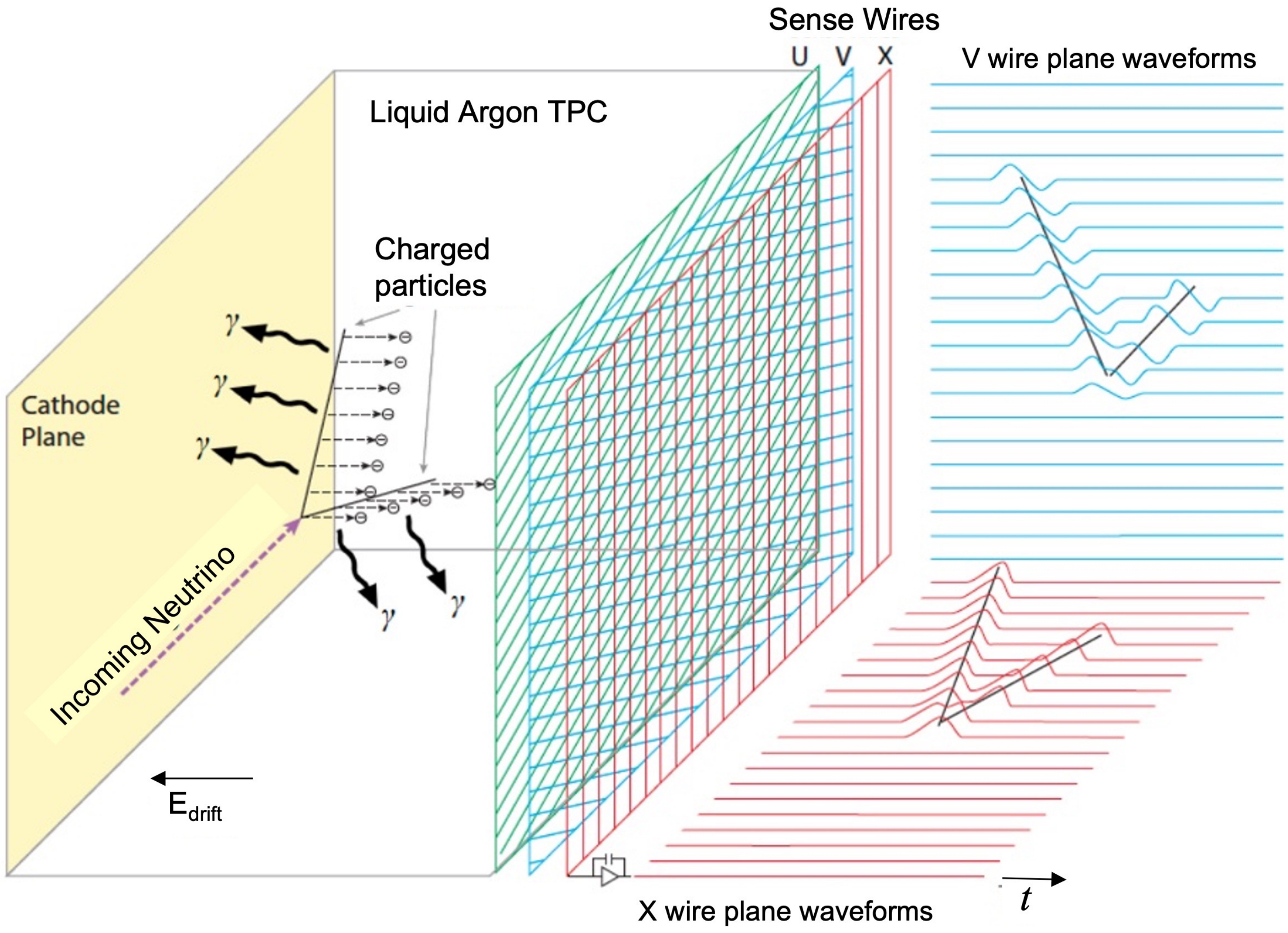


#1 -> HD

#2 -> VD



LAr-TPC technology



Original concept

Particle interaction in argon produces ionization and excitation -> scintillation light

- With electric field, ionization charge can be collected with multiple wire-plane read-out
  - Two/three 2D images of events -> redundant and precise 2D imaging
- "Non-destructive read-out" ; e^- cross induction planes and are collected on the last plane
  - Precise calorimetric reconstruction
- Scintillation light (4π, λ=128 nm) allows obtaining the absolute time of the event (trigger)
- Combination of light and charge information provide the 3rd space coordinate
- Uniform, stable electric field required, to have uniform drift velocity and derive drift time.
- Complete 3D reco of each event. (1 mm precision)
- **High-purity argon fundamental for charge/ light transport through large distances**

ProtoDUNE because…

- The present knowledge in LArTPC technology allows building and operating a ton-scale detector for neutrino physics in a reasonable amount of time (2 years!)
- The needs of the physics require a push on the technology towards, new solutions, new materials, even larger scales (kton to 10s of kton)
- It would be unwise to jump that distance in mass, implying yet-unmentioned challenges in many LArTPC aspects, without any in-between step

- **In ProtoDUNE one can**:
  - test new solutions of materials/technology on many aspects;
  - DUNE is highly modular: build full scale elements of DUNE – exercize all aspects: handling, assembly, operation, problem-finding, dismounting, issue-investigation… and then again!
  - characterize detector performance on charged-particle beams;
  - train and develop reconstruction and ID algorithms on different event topologies;
  - perform in-depth studies of hadron-Argon cross-section -> physics results and feedback to Monte Carlo.

*I will indeed change name according to the time of the activity described

Ah, before we dive into it…

- Some due clarifications on acronyms
  - As the protoDUNE program started at CERN, two technologies were being developed, Single-Phase and Dual-Phase LArTPCs -> the two detectors were identified as ProtoDUNE SP (NP04) and ProtoDUNE DP (NP02). The alternate nomenclature refers to the CERN identifier of the experiment (Neutrino Platform 4 and 2)
  - Recent developments demonstrated that the Dual-Phase technology, while having large potential, requires more R&D, and in parallel an alternate version of the Single Phase LArTPC was developed
  - Historically, physics detectors have had Horizontal Drift, however the new proposal featuring perforated PCBs for charge readout, will feature a Vertical Drift design. Therefore names change
  - When looking to the next stage of the protoDUNE project at CERN, it goes like*:
    - ProtoDUNE SP (PDSP, NP04) –> ProtoDUNE HD (for second Beam Run)
    - ProtoDUNE DP (PDDP, NP02) –> ProtoDUNE VD (for present and near future R&D)

ProtoDUNE SP

The past and the future – ProtoDUNEs

The ProtoDUNEs – in a nutshell

- Two ~1 kton prototypes
- Exposed to Very Low Energy (VLE) charged particle beams at CERN
- Validation of DUNE components design & installation, commissioning, performance and stability studies on **FULL-SCALE** prototypes
- **ProtoDUNE-Single Phase** operated 2018–2020
  - **1 detector, 2 TPCs**: 2x 3.6m drift volumes, sharing a common cathode
  - 3-month beam run in late 2018, then cosmics
  - Event reconstruction/identification training
  - **R&D site**: low-energy calibration (neutron gun), Xenon doping, Higher Voltage tests, …
  - Upcoming **Phase-II** on beam with HD updated design
- **ProtoDUNE-Dual Phase** operated 2019–2020
  - Development of charge signal amplification, as well as Very High Voltage / large drift (6-12 m) studies
  - Evolved into Vertical Drift -> Phase II
  - New run presently to test some developments toward VD.

The ProtoDUNEs – in a nutshell

- Two ~1 kton prototypes
- Exposed to Very Low Energy (VLE) charged particle beams at CERN
- Validation of DUNE components design & installation, commissioning, performance and stability studies on **FULL-SCALE** prototypes
- **ProtoDUNE-Single Phase** operated 2018–2020
  - **1 detector, 2 TPCs**: 2x 3.6m drift volumes, sharing a common cathode
  - 3-month beam run in late 2018, then cosmics
  - Event reconstruction/identification training
  - **R&D site**: low-energy calibration (neutron gun), Xenon doping, Higher Voltage tests, …
  - Upcoming **Phase-II** on beam with HD updated design
- **ProtoDUNE-Dual Phase** operated 2019–2020
  - Development of charge signal amplification, as well as Very High Voltage / large drift (6-12 m) studies
  - Evolved into Vertical Drift -> Phase II
  - New run presently to test some developments toward VD.

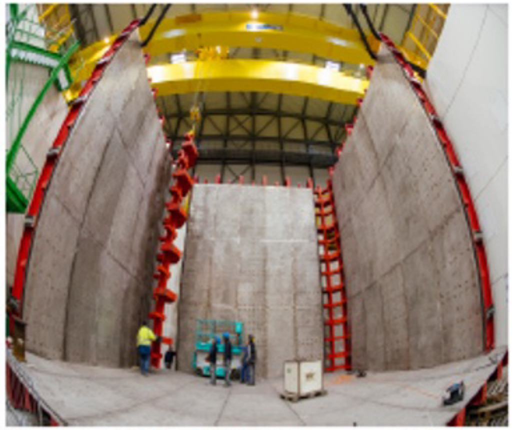
Today we will concentrate on ProtoDUNE Single Phase

PD-SP 1-slide Timeline

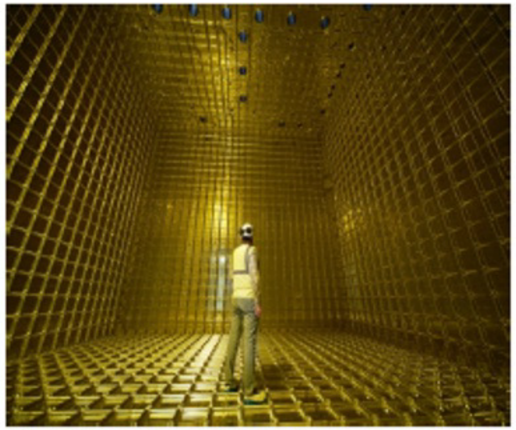
Physics run timeline
- ***Beam run: September-November 2018***
- ***Continuous data taking with cosmic rays until July 2020***

From building construction to detector commissioning in roughly 3 years

March 2016, construction of EHN1 extension

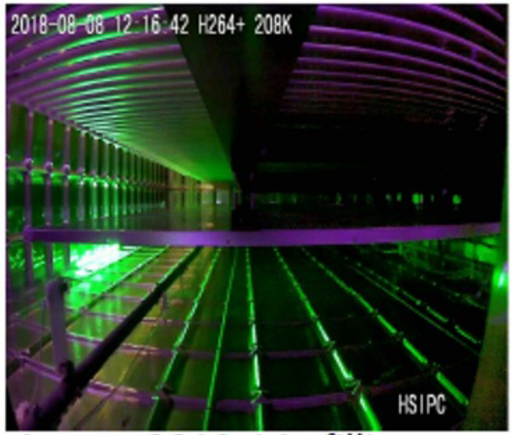


November 2016, cryostat structure assembly



September 2017, cryostat completion

February 2018, detector assembly and installation

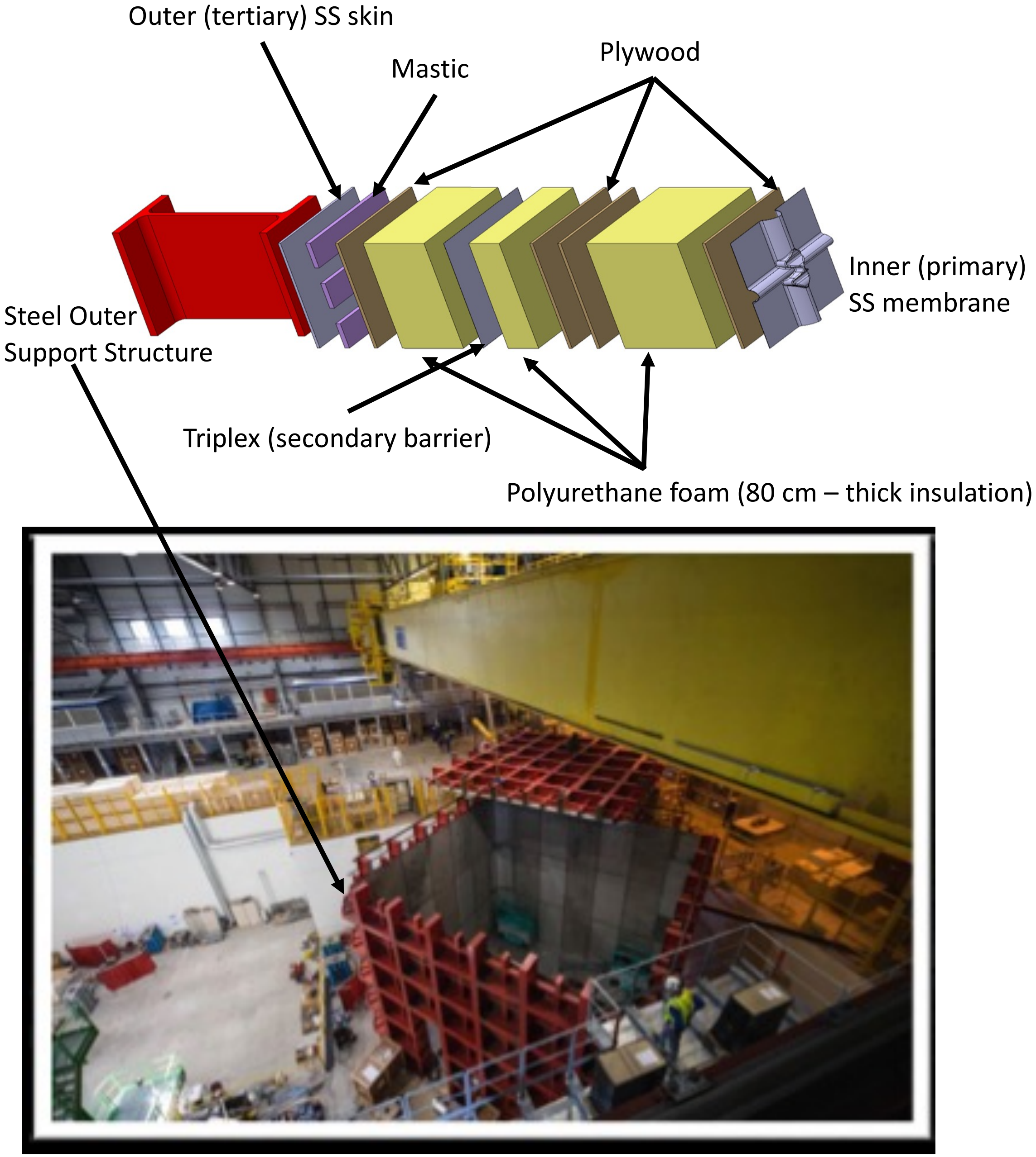


August 2018, LAr filling and purification

September 2018, beam ready & detector ready for beam!

Membrane cryostat

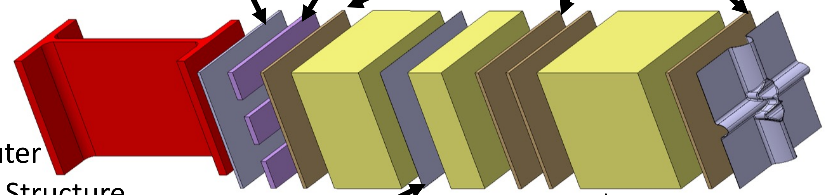
- **Modular design** for transport into DUNE cavern
  - Scalability / Exact prototyping (ProtoDUNEs)
- **Membrane cryostats**
  - elastic, 1.2 mm thick stainless steel (SS) inner skin, accommodates cryogenic shrinking
  - used on LNG* transport ships – mature technology; commercial partners (GTT)
  - No need for vacuum -> argon purge
  - Leak tightness tested intensively on ProtoDUNEs
  - Exported concept to wider Physics panorama (DarkSide 20k)
  - 21 (9) weeks to build NP04 (NP02) external structure (learning fast!)

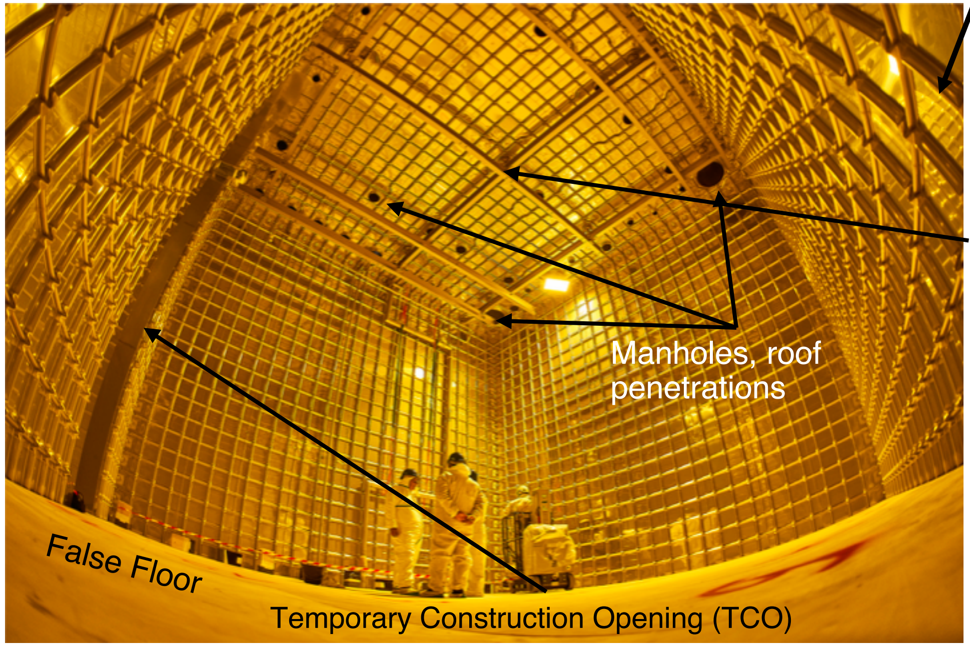


**Liquid Natural Gas*

Membrane cryostat

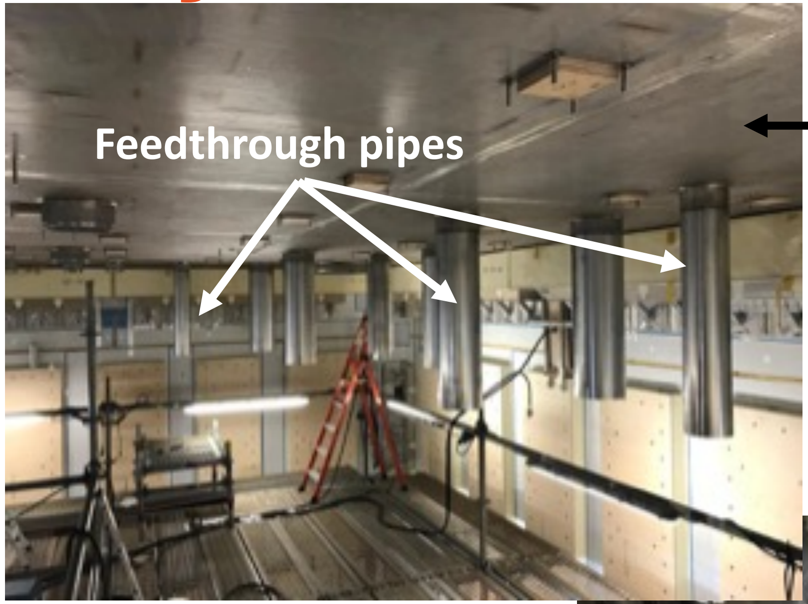
- **Modular design** for transport into cavern
  - Scalability / Exact prototyping (ProtoDUNEs)
- **Membrane cryostats**
  - elastic, 1.2 mm thick stainless steel (SS) inner skin, accommodates cryogenic shrinking
  - used on LNG* transport ships – mature technology; commercial partners (GTT)
  - No need for vacuum -> argon purge
  - Leak tightness tested intensively on ProtoDUNEs
  - Exported concept to wider Physics panorama (DarkSide 20k)
  - 21 (9) weeks to build NP04 (NP02) external structure (learning fast!)





*Liquid Natural Gas

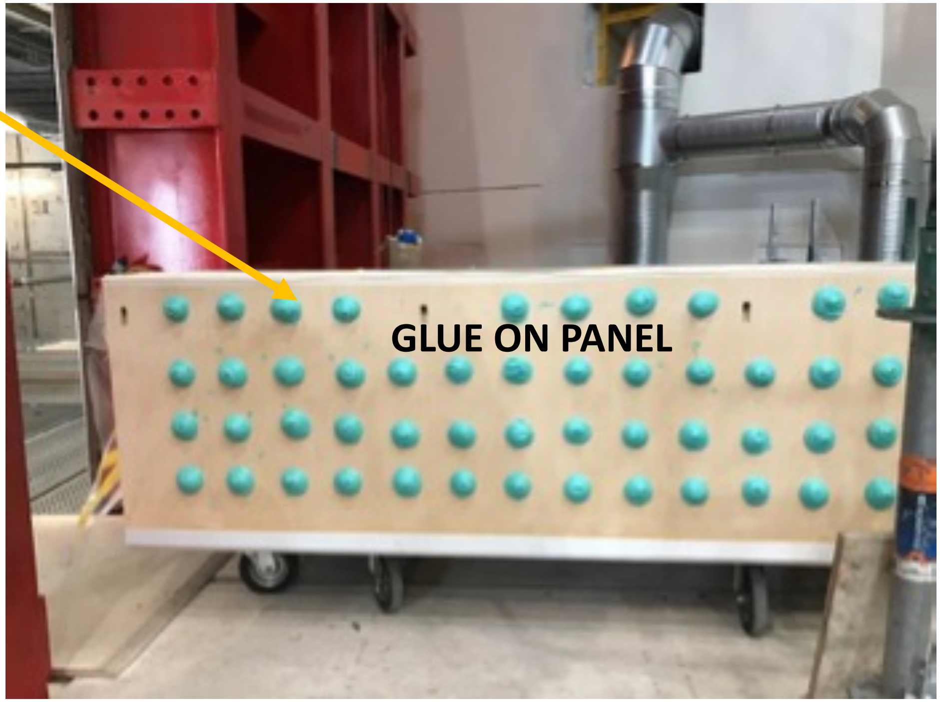
Cryostat installation



Outer SS skin
inner side

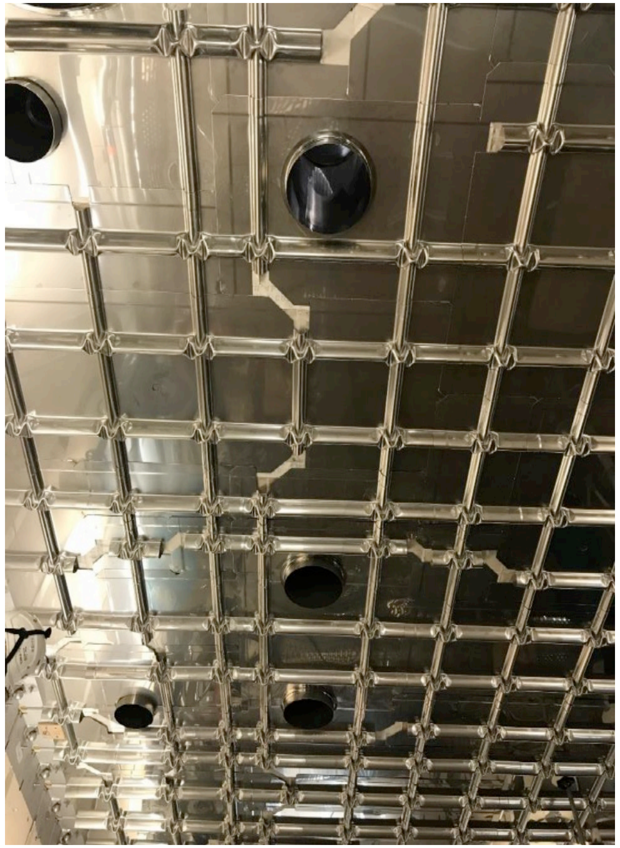
Secondary
barrier

Insulation panels
(foam+plywood)



Start in February 2017

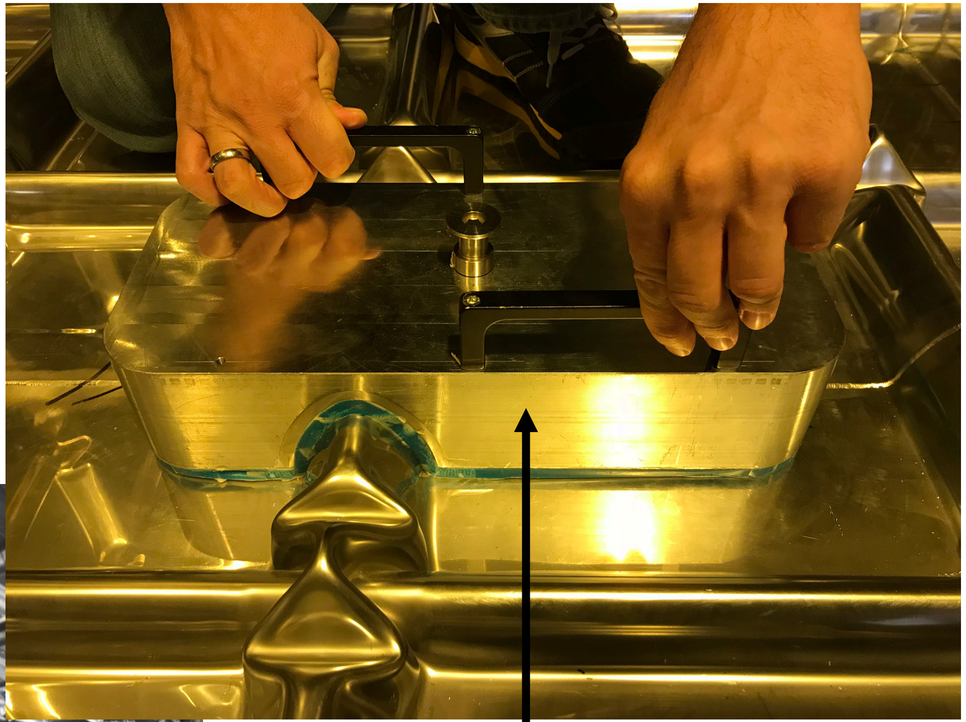
Membrane Installation



Custom pieces on roof, around penetrations

Most panels are 2x3 m wide, but many small patches are needed, especially on the roof

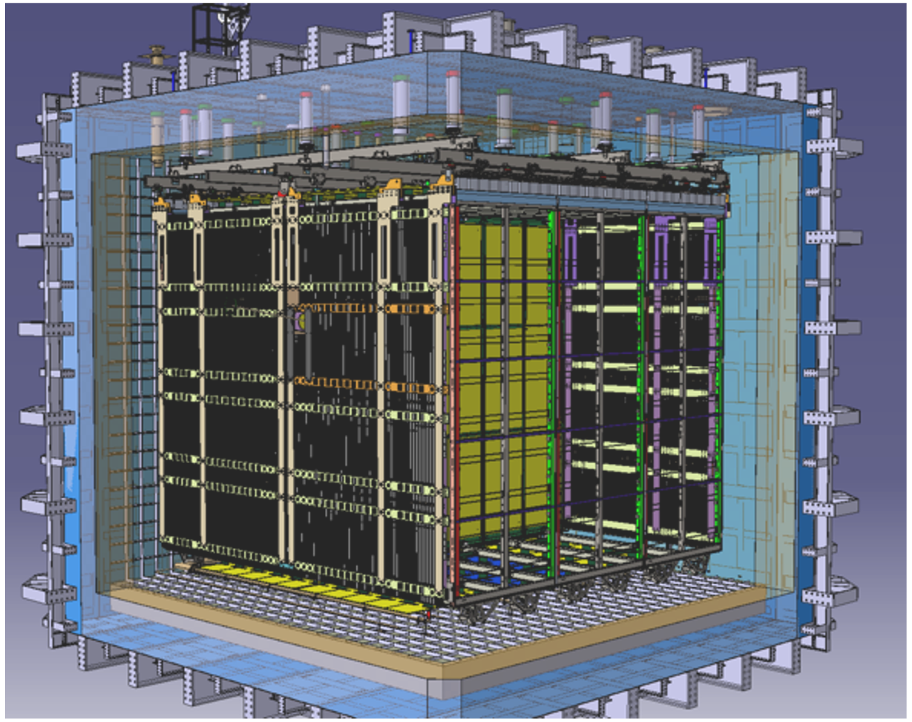
Standard “square” is 34x34 cm

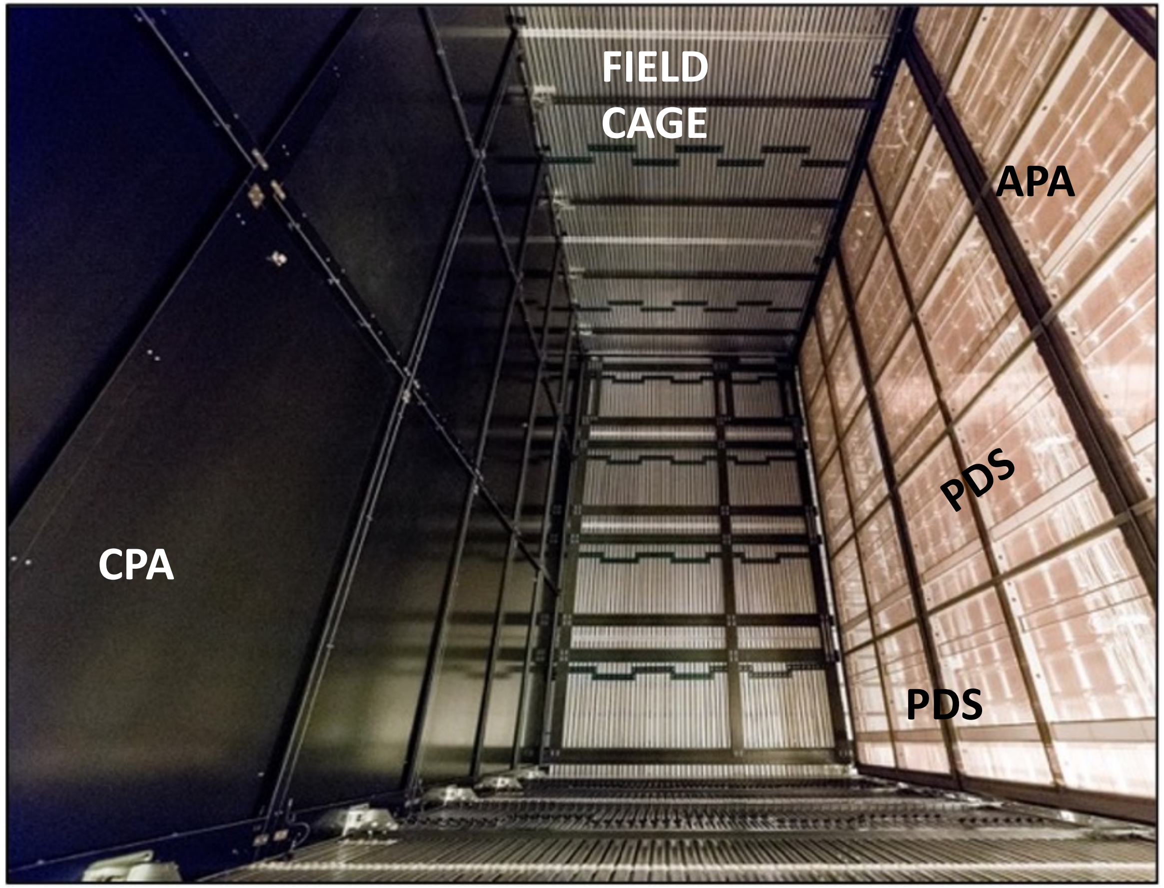


Welds Helium-leak tested globally (in sniffing mode) and locally with “vacuum boxes”.

He injected in insulation volume

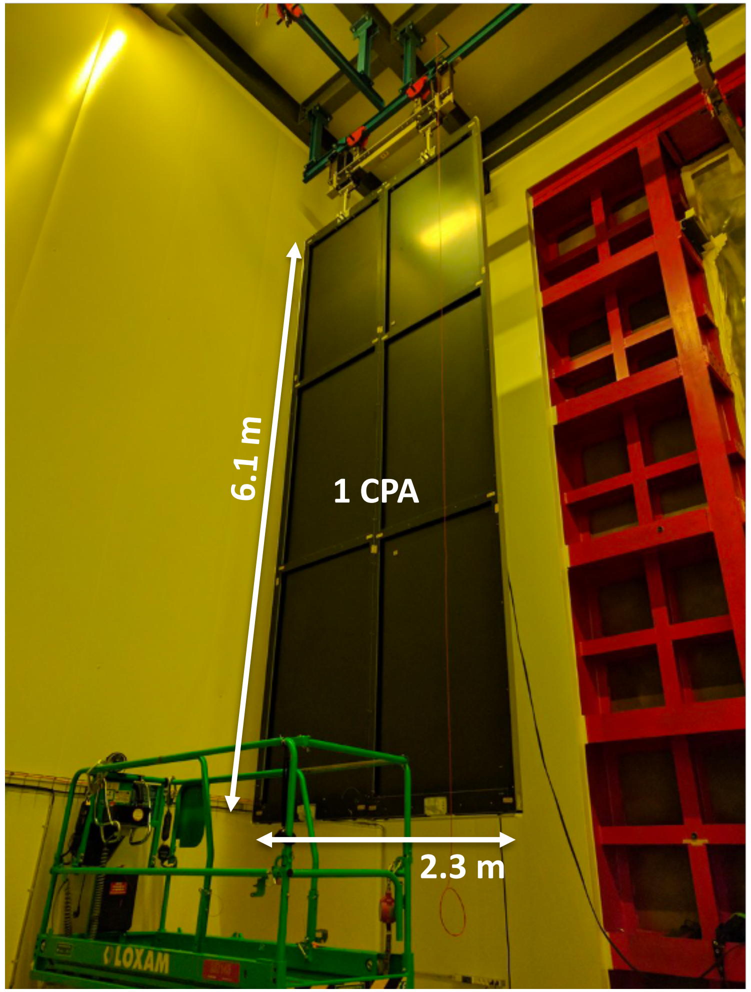
Detector Overview



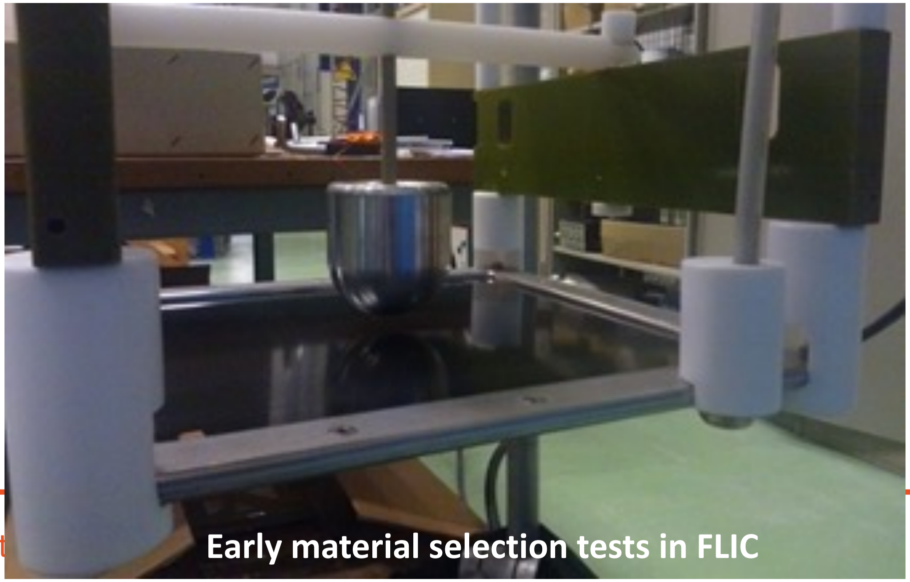


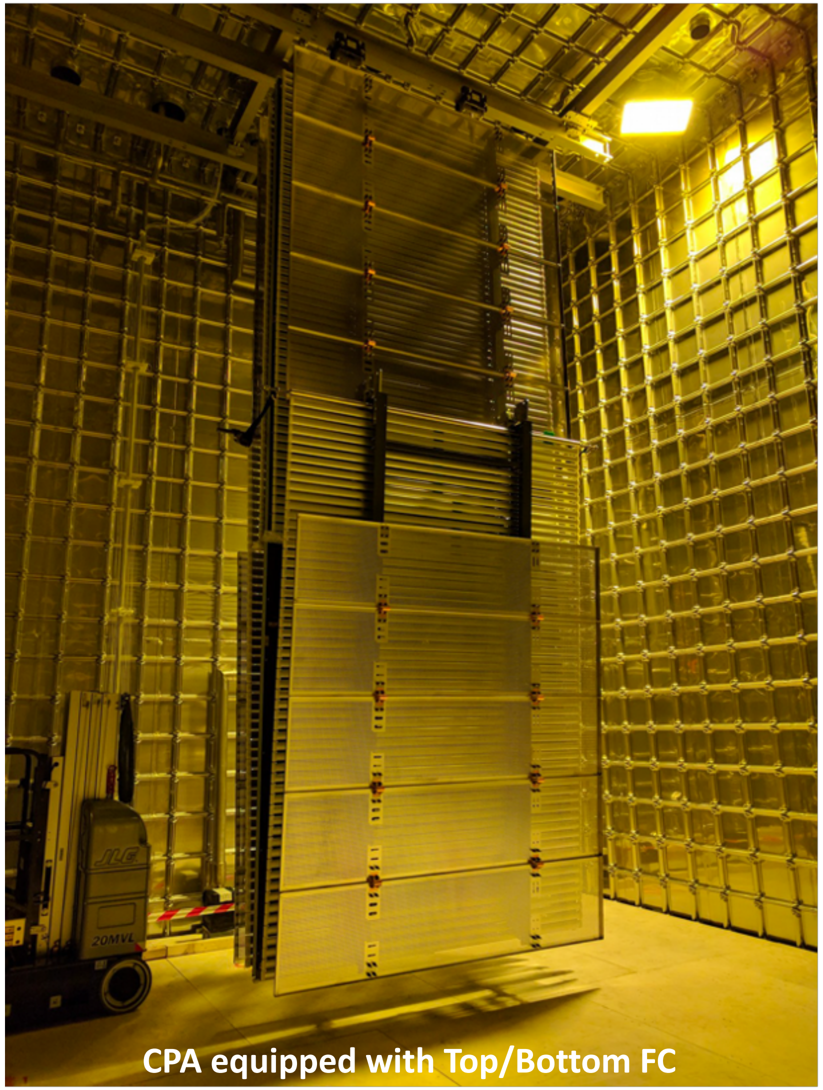
ProtoDUNE SP (HD) : 3.6 m drift (Half detector)

Cathode Plane Assembly (CPA)



- 3 mm thick FR4* panels laminated with high-resistivity Kapton to better control energy release in case of discharge
- 6 columns -> 3 CPAs -> one cathode plane, defining (with APAs) two 3.6 m drift volumes
- HV @ 180 kV, same as DUNE (E = 500 V/cm)
- Protruding CPA edges equipped with field shaping strips to maintain a uniform E field
- Top/Bottom Field Cages panels attached to CPA and deployed from hinges


Early material selection tests in FLIC

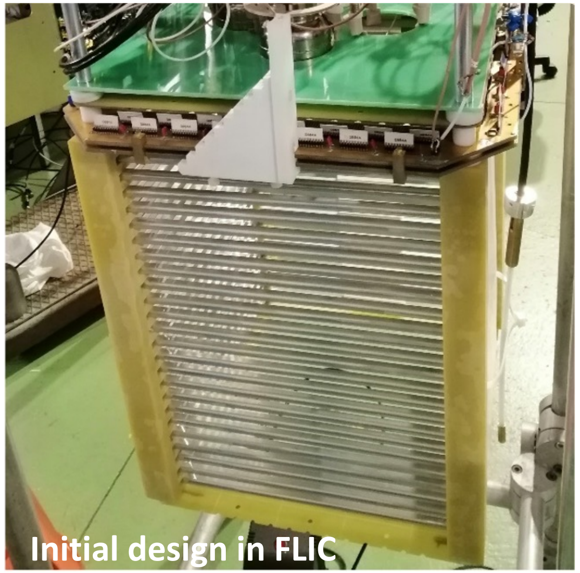

CPA equipped with Top/Bottom FC

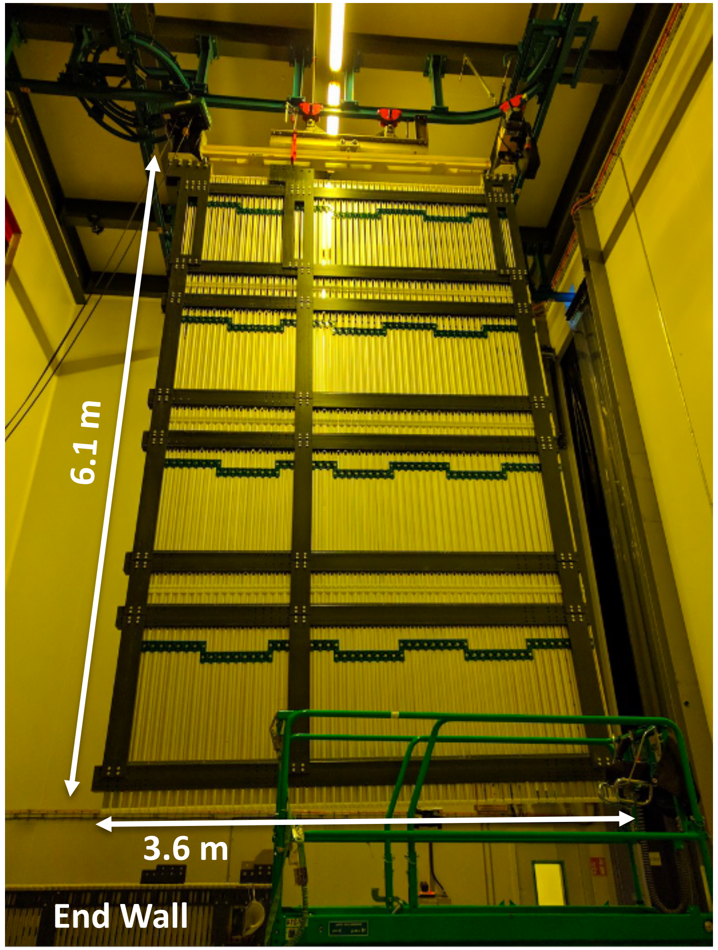
*A kind of Flame-Retardant glass-reinforced epoxy laminate material.

TPC – Field Cage

- 12 total Field Cages modules close top and bottom part of active volumes
- End Walls (4 assemblies, 4 modules each) close active volumes sides
- Resistive divider chains equipped with varistors provide constant electric field of 500 V/cm
- Made from parallel rounded aluminum profiles supported by FR4 frame

- SS ground planes with holes for LAr circulation ensures null field outside active volume

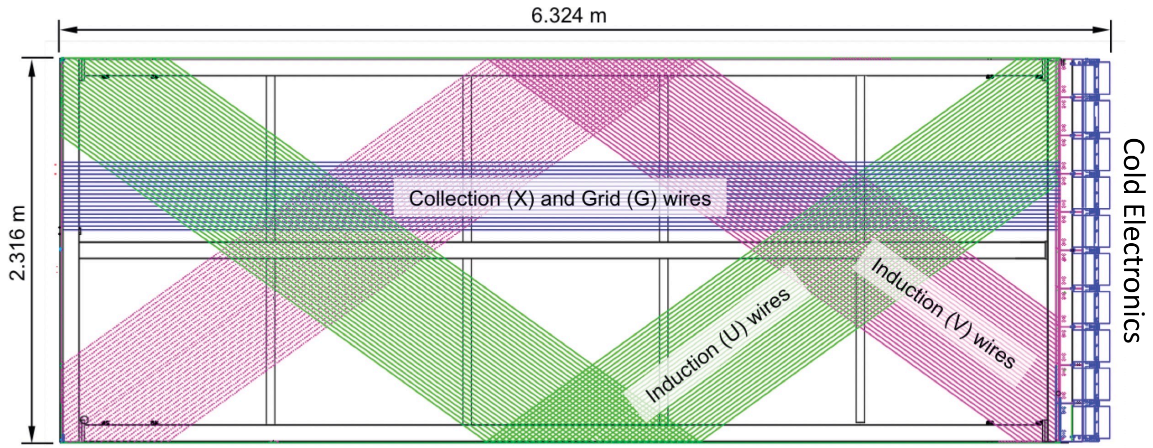


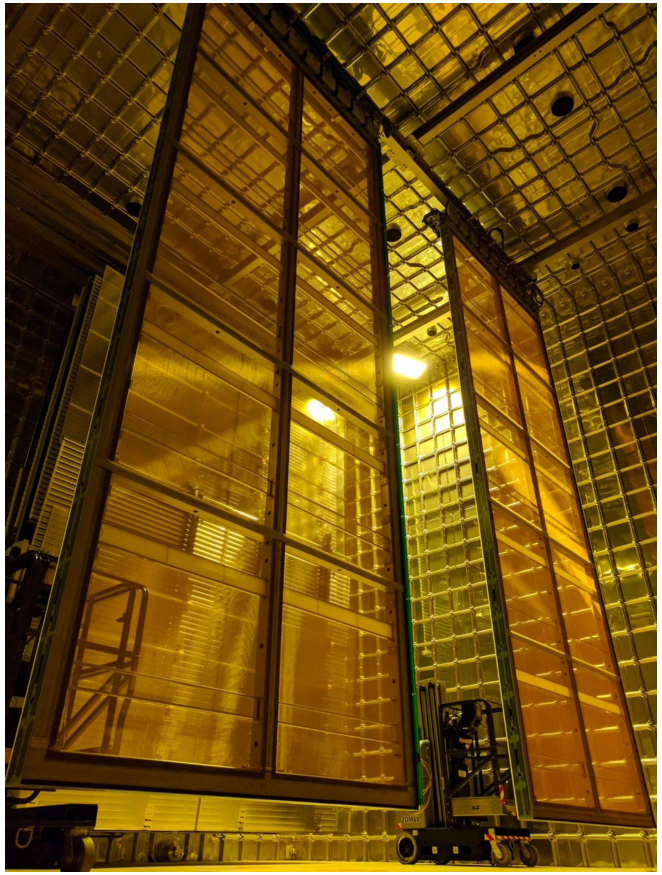


TPC – Anode Plane Assemblies

Charge-Readout plane:

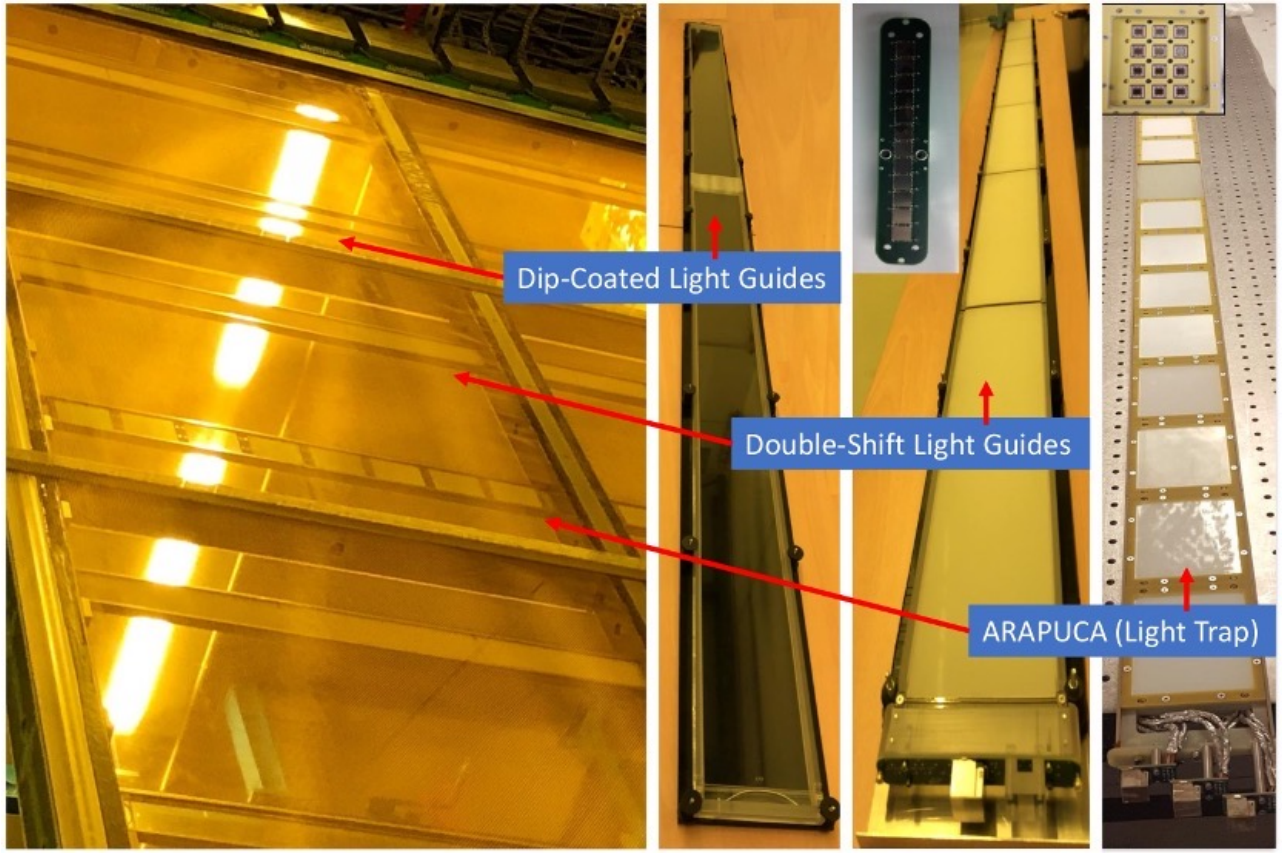
- 6 independent Anode Plane Assemblies (APA) with three active wire planes (15360 channels)
- 1 Grid; <u>2x Induction planes</u> (U,V, wrapped wires); <u>1x Collection plane</u> (X) + mesh to isolate Photon Detectors inside the frame
- Read-out on both sides – one side used in PDSP
- Cold Front-End electronics installed on top of the frames (in LAr) to minimise the noise



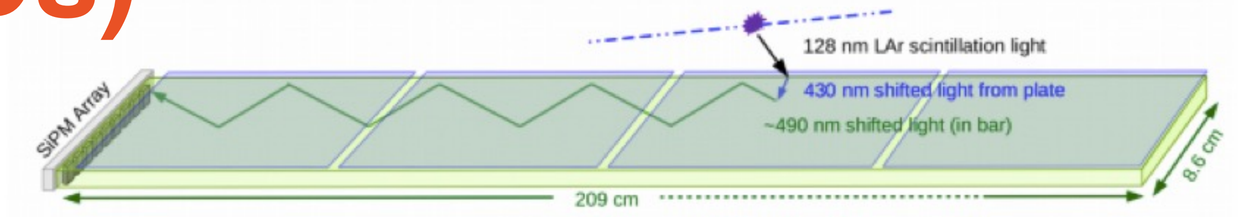


Photon Detectors (PDs)

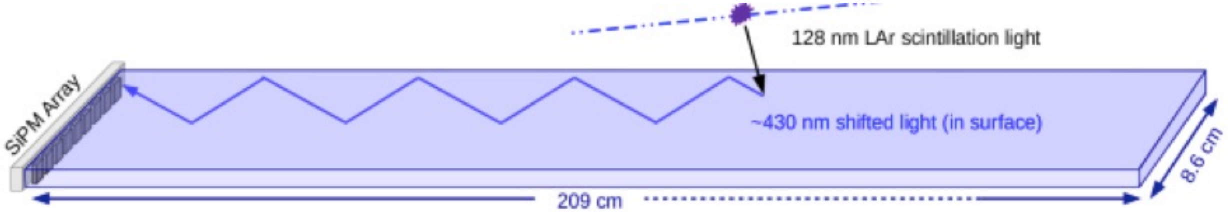
- 3 different technologies read by arrays of 3 or 12 Silicon PhotoMultipliers (SiPMs) from SensL or Hamamatsu
- 10 bars per APA, inside the frame: 207 x 8.6 cm view area into the TPC, per bar
- Metallic mesh to decouple electrically PDs and wire planes
- Characterization and comparison of the three different solutions, to select one/more for deployment in DUNE



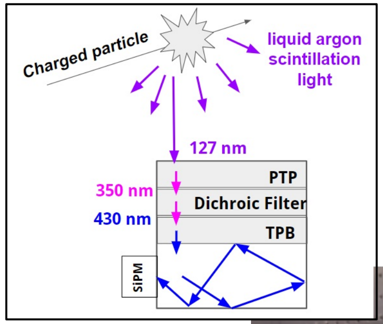
Photon Detectors (PDs)

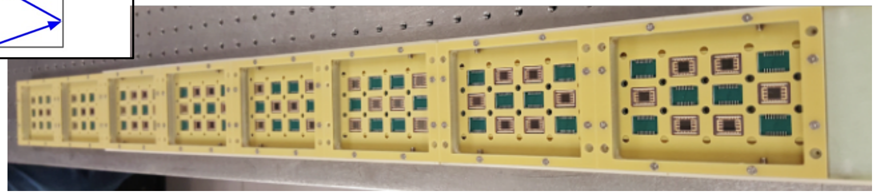


Double-shift light guide
B. Howard et al. 10.1016/j.nima.2018.06.050
128nm → 430nm → 490nm
Wavelength-shifting (WLS) plates + WLS light guide
Shifted light travels, via total internal reflection, to the readout on one side (four 3-SiPM arrays <-> four read-out channels)



Dip-coated light guide
L.Bugel, et al 10.1016/j.nima.2011.03.003
128 nm → 430 nm
Acrylic dip-coated with TPB+acrylic+toluene solution
Shifted light travels, via total internal reflection, to the readout on one side (four 3-SiPM arrays <-> four read-out channels)





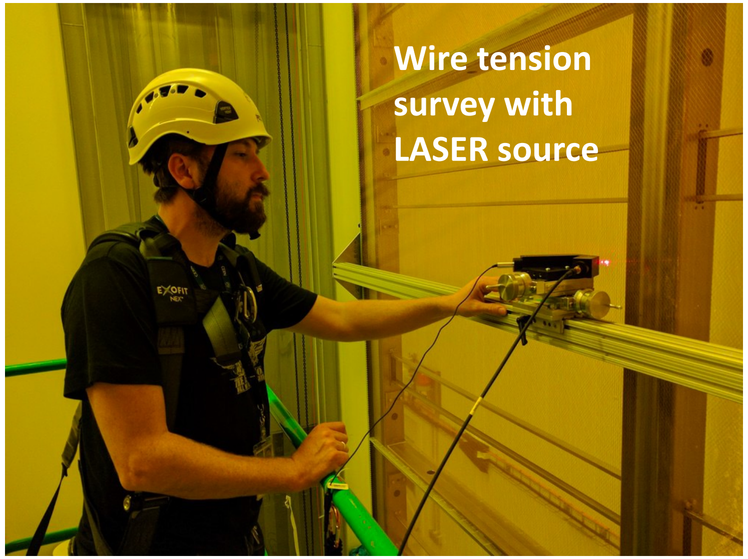
Arapuca
E. Segreto, et al 2018 JINST 13 P08021
128 nm → 350nm → 430nm
Light shifted a first time (pTP) crosses a dichroic filter, opaque to higher λ, then meets TPB -> second shift.
Photons collected promptly or trapped and reflected till they hit one SiPMs (12 cells – read-out channels, each read by 12 SiPM)

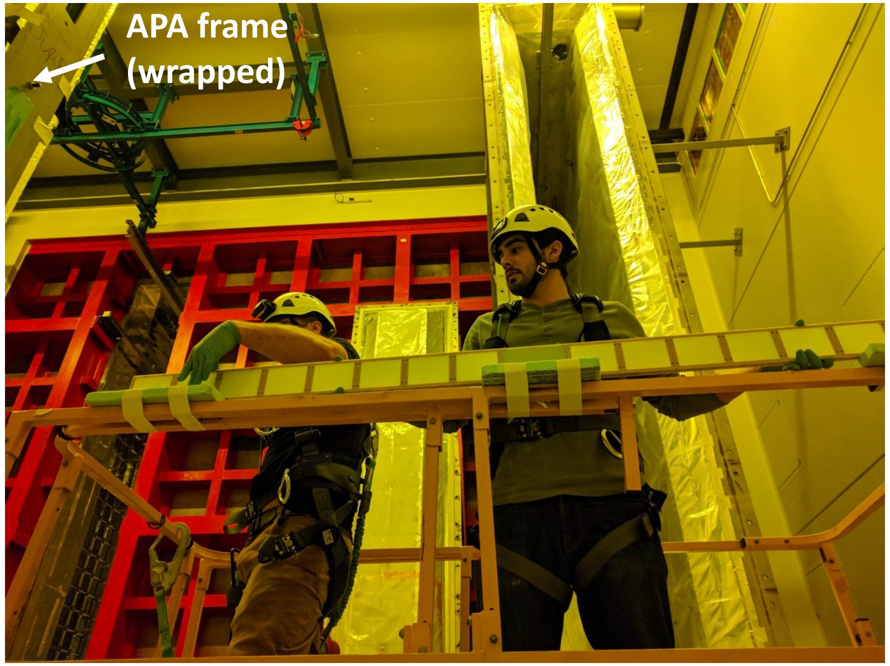
TPC – APA integration

Clean room monorail

APAs slide through clean room and cryostat (DSS) hanging from I-beams

Installation of Cold Electronics (CE) boxes on top of APA frame





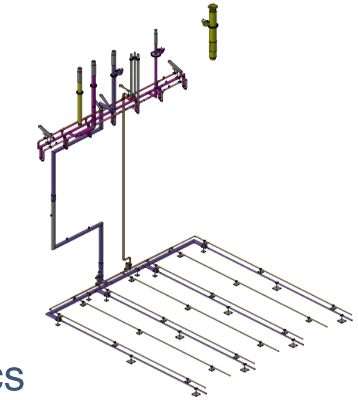
Photon Detector (PD) bars installation: sliding in from frame side (here: ARAPUCA)

NP04 Cold Box

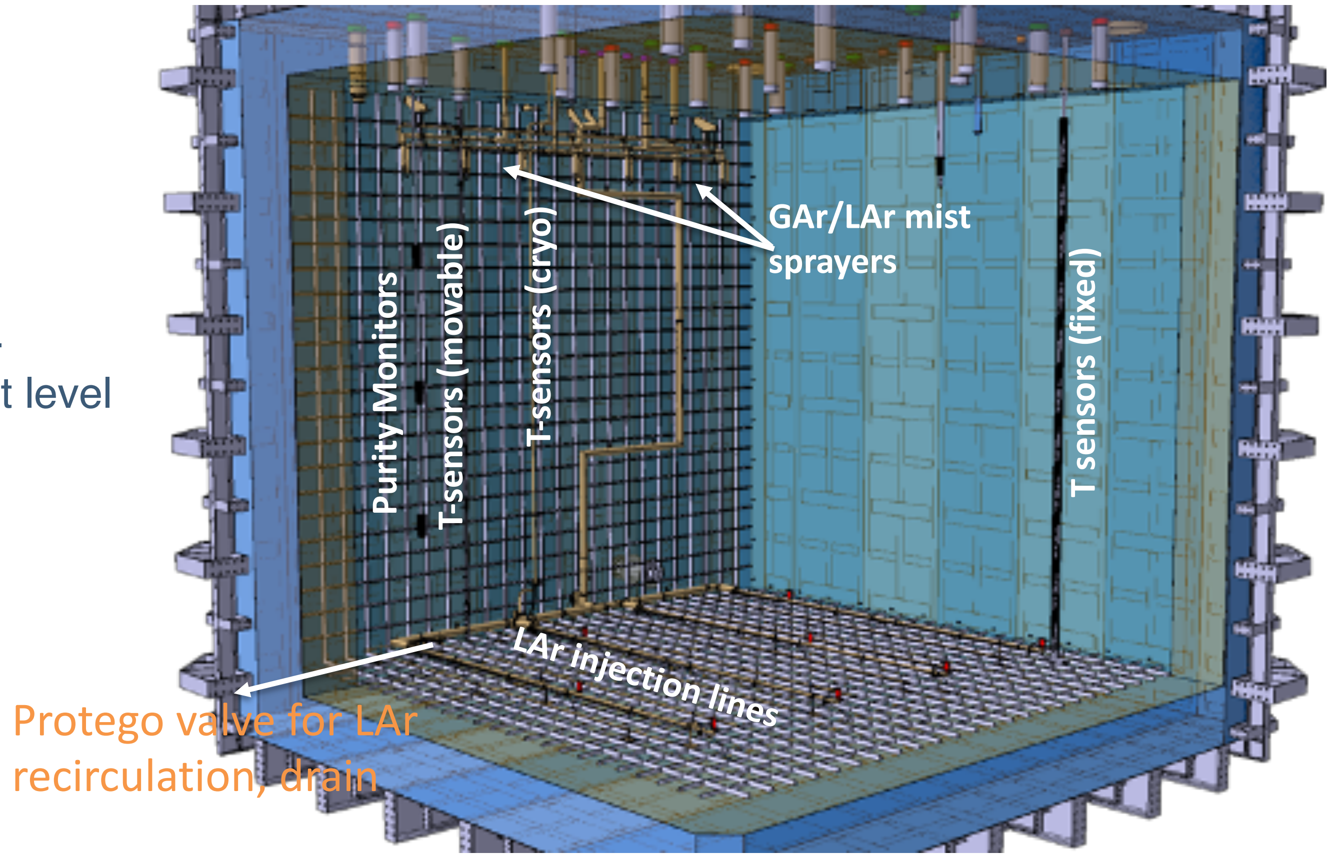
- Deployed to **cold-cycle integrated APAs before insertion in cryostat**
- It features exact copies of TPC/Photon Detector feedthroughs and electronics; dedicated Pressure and Temp probes
- 300 mm foam insulation, inner polyethylene skin, external steel structure. Operated with GN_2
- Dual input line
  - → "warm" line, with passive vaporizer, for preliminary purge and warm-up
  - → "cold" line with in-line heater to produce cold gas
- Commissioning run in October 2017
- First APA cold test in November 2017
- **150 K minimum temp reached on Cold Electronics**
- Refitted for tests of ProtoDUNE Run-II APAs

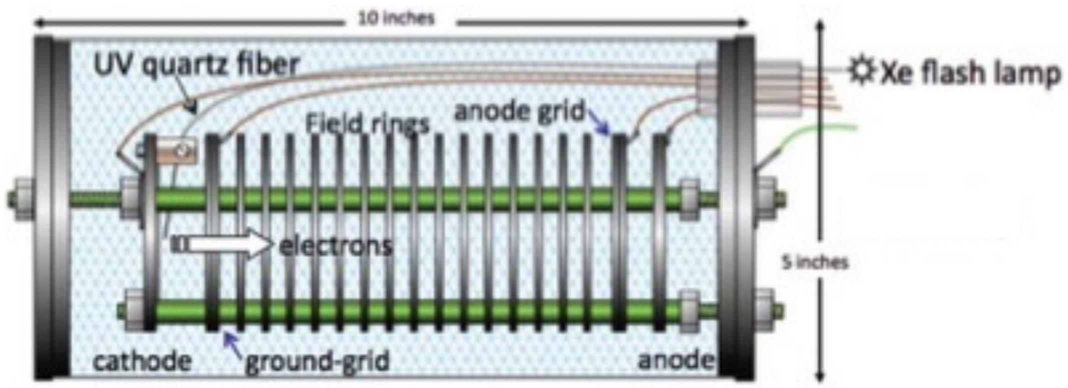
Cryogenic instrumentation

- Distribution system featuring liquid lines distributed on the floor and GAr/LAr sprayers close to the roof
- Temperature arrays (one static, one dynamic)
- Three LAr purity monitors from ICARUS, refurbished
- Cryogenic cameras and LEDs to follow live the filling
- Normal operations: LAr recirculation rate of 7 t / hour corresponding to a full volume purification in 4.6 days
- Purification filters for LAr and GAr, to remove electron-attaching impurities (O_2, H_2O, CO_2, …) down to the ppt level



- CFD to study flow dynamics

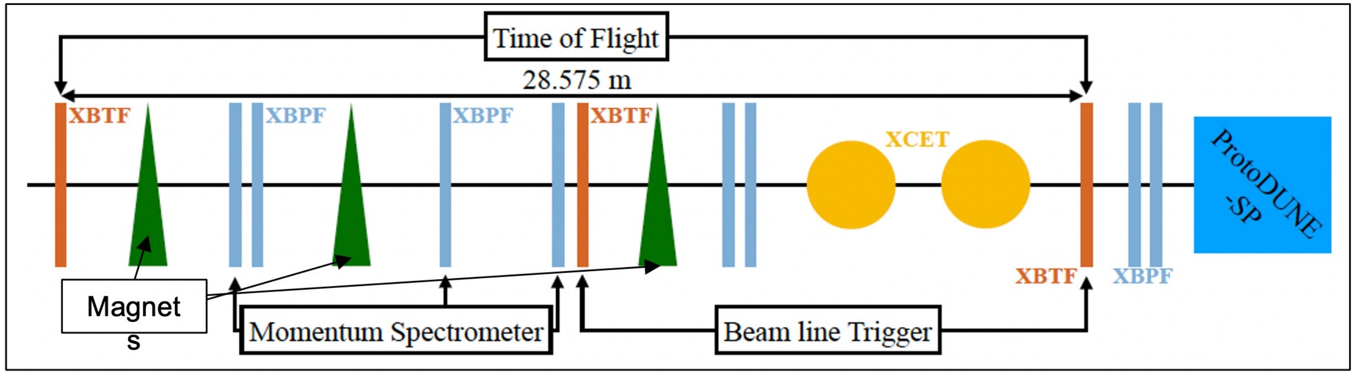




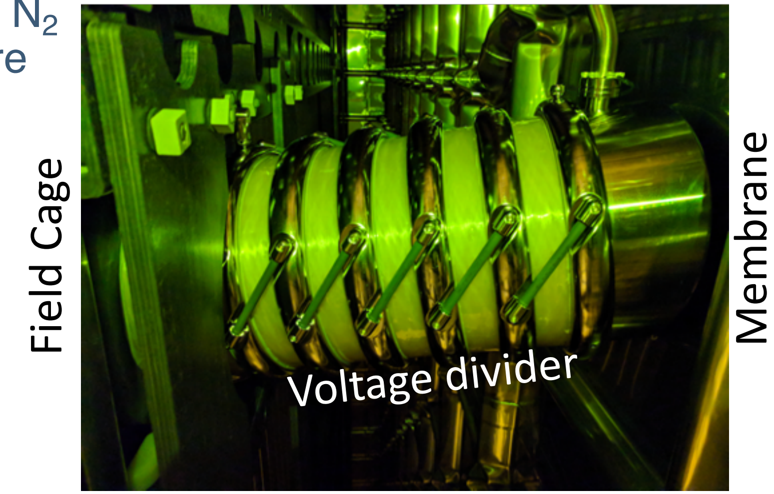
Purity Monitor working principle

Beam Line Instrumentation

- ProtoDUNE SP exposed to the H4 Very Low Energy tertiary beam from SPS in CERN Prevessin
- Particles of both polarities can be produced, in the 0.3 – 7 GeV momentum range.
- ProtoDUNE-SP collected more than 4M events with *e* and hadrons, with momentum from 1 to 7 GeV/c – positive polarity. Very low momenta (0.3, 0.5 GeV/c) for *e* only
- Beamline instrumented with ToF (XBTF), Cherenkov detectors (XCET) to tag the particle types entering the detector, wire chambers to measure position (XBPF) and momentum (XBPF-magnet)
- **Beam Plug** installed in PDSP between membrane and Field Cage: filled with gas N_2 and voltage divider to membrane ground, allows minimal particle interaction before entrance into main LAr volume

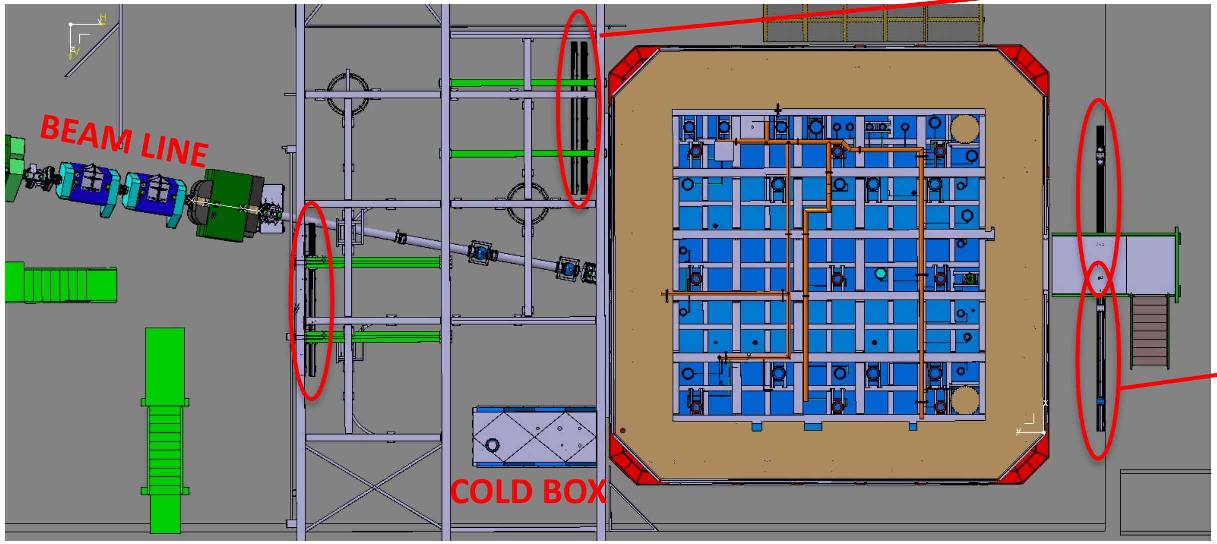


Beam Plug



Cosmic Ray Tagger (CRT)

- Installed on the upstream and downstream faces of the detector
- Intercepts and tags muons from cosmic rays and from beam halo
- Four (6.8 x 3.65) m assemblies made of scintillating strips, (365 x 5) cm (L x W)
  - supplied by Double Chooz



PDSP Performance

ProtoDUNE SP performance

Excellent detector stability over the entire data taking period (TPC signal strength, PDS response)

Detector Parameter	Specification	Goal	ProtoDUNE Performance
Electric Drift Field	> 250 V/cm	500 V/cm	500 V/cm (99.5% up-time)
Electron Lifetime *Impurity Concentration*	> 3 ms *(<100 ppt [O_2-equiv])*	10 ms *(<30 ppt [O_2-equiv])*	> ~30 ms in TPC * *(< 10 ppt [O_2-equiv])*
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 ^

* in TPC E=500 V/cm, in PurMon E=20 V/cm – measured as high as 85 ms.

** after coherent noise removal.

§ extrapolation to full ARAPUCA deployment, based on actual PD data.

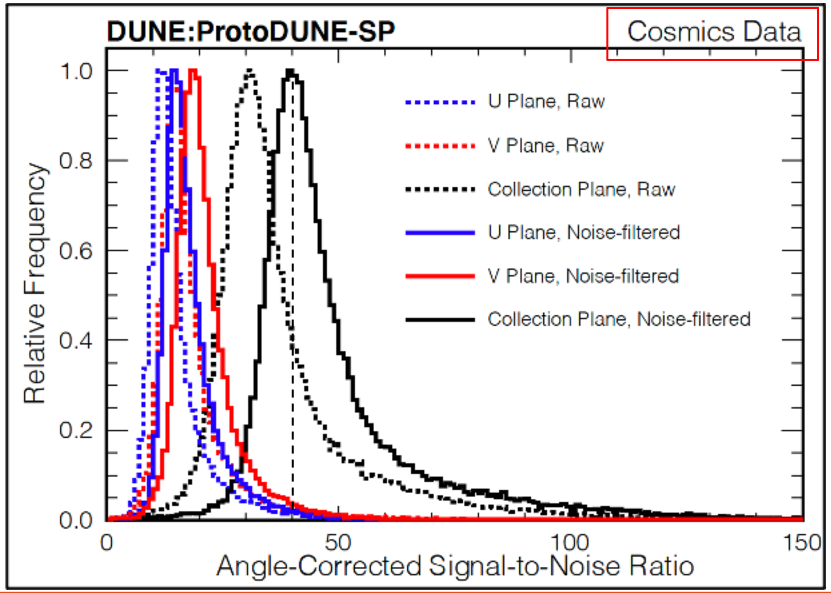
^ two consecutive LED-flashes separation.

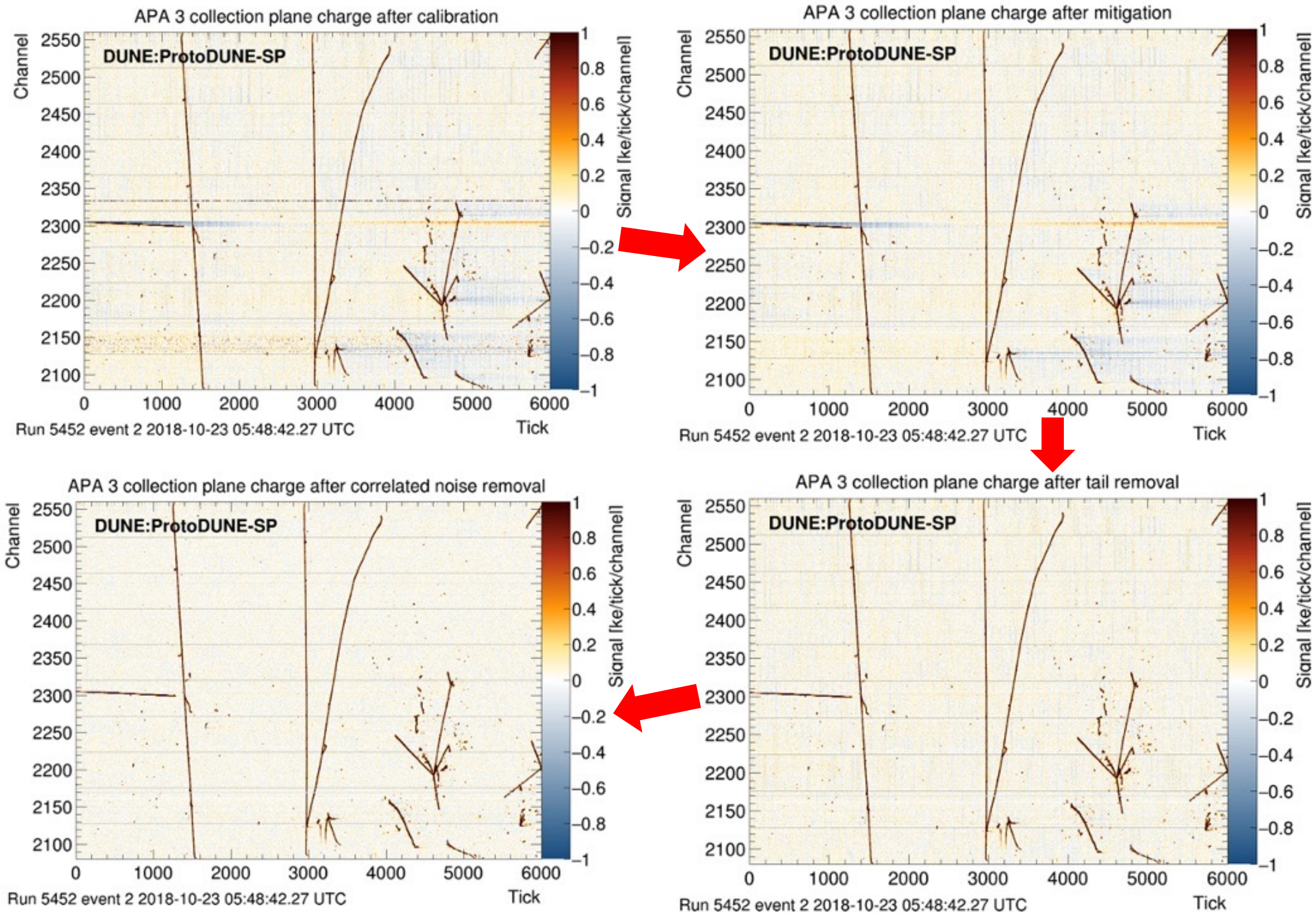
JINST 15 (2020) 12, P12004

TPC – Data preparation

Careful TPC data pre-processing and calibration to extract the ionising signal

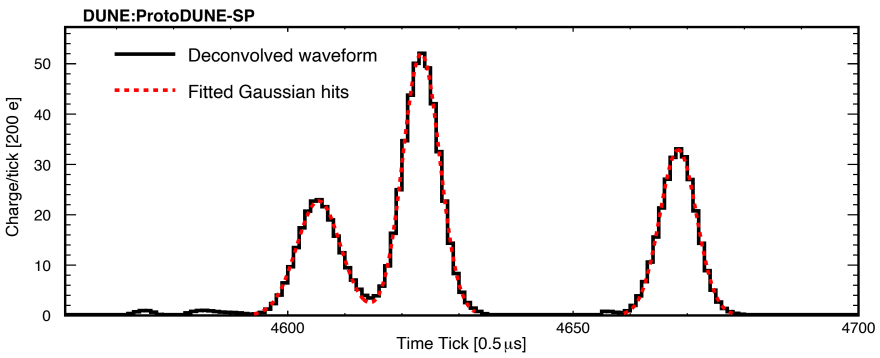
- Charge calibration: using known pulses with variable amplitude
- Data preparation: Pedestal subtraction, noisy/bad channel flagging, timing mitigation, tail removal
- Noise level estimation: for single and 50 contiguous samples –> far lower than specs -> high S/N

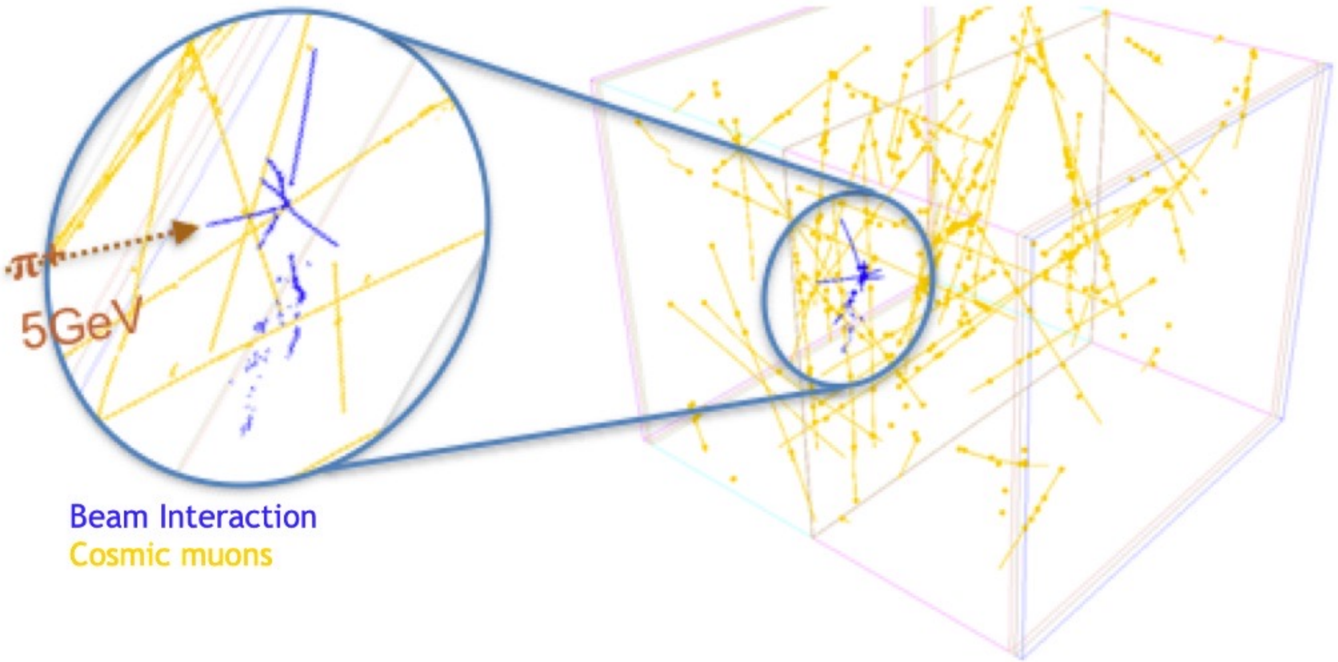


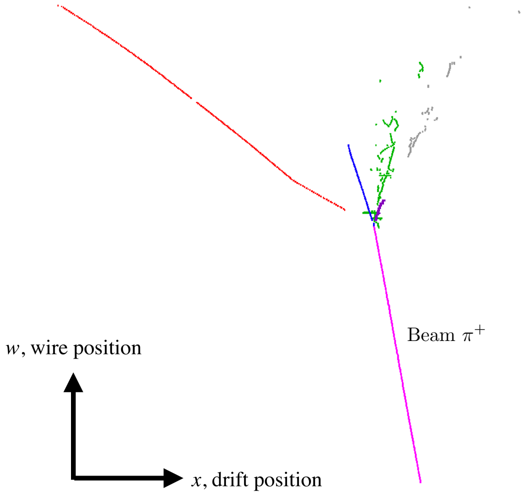


JINST 15 (2020) 12, P12004

TPC – Event reco







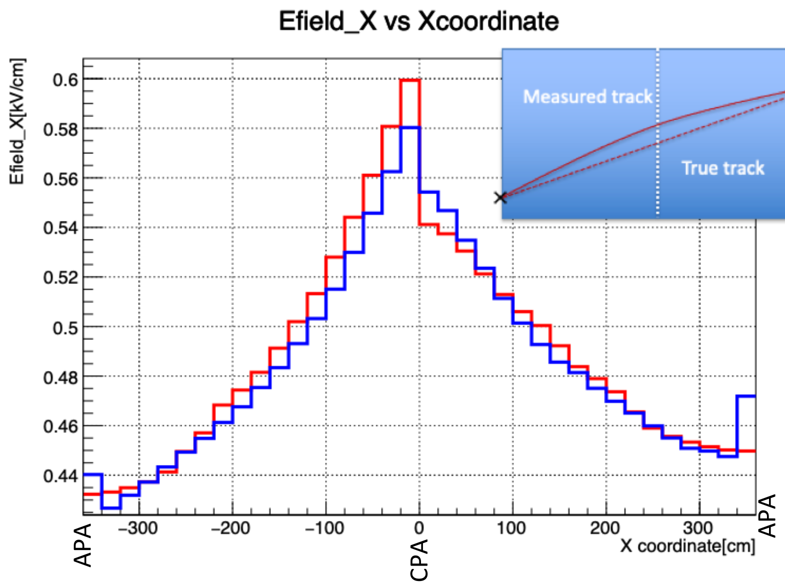
- Event reconstruction:
  - hit finding: gaussian fit of waveform peak
  - pattern recognition with Pandora: from 2D to 3D hit clustering, 3D detector slicing, determination of cosmic vs beam particle, particle hierarchy
- Very busy environment due to the large rate of cosmic recorded (≈70/beam event)

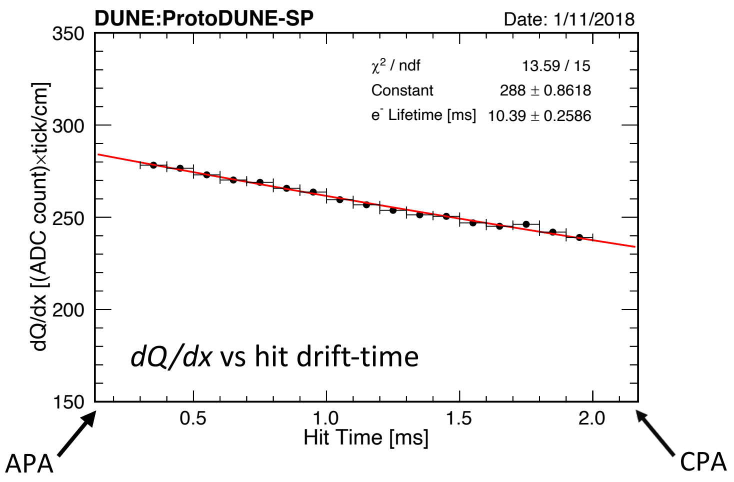
JINST 15 (2020) 12, P12004

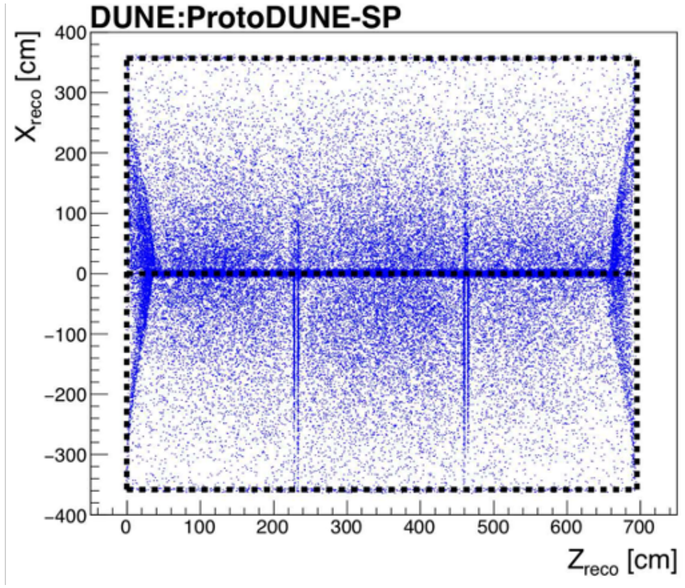
JINST 15 (2020) 12, P12004

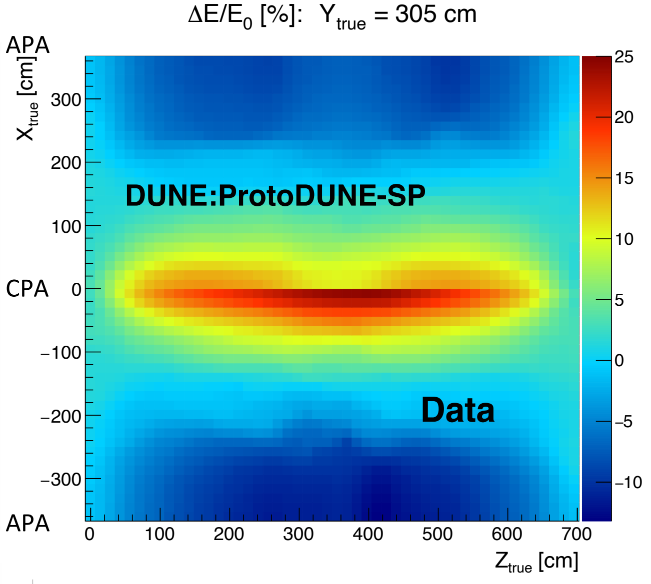
TPC – Event reco

- Detector calorimetric response affected by several effects: free electron attenuation from impurities, electron recombination, longitudinal diffusion and space charge effects
- Lifetime correction estimated using CRT-TPC tracks.
- Large effort to understand and correct for the space charge effect due to the large rate of cosmic rays crossing the detector:
  - spatial distortions : stretching/squeezing of the tracks
  - E-field distortions : impact on electron-ion recombination





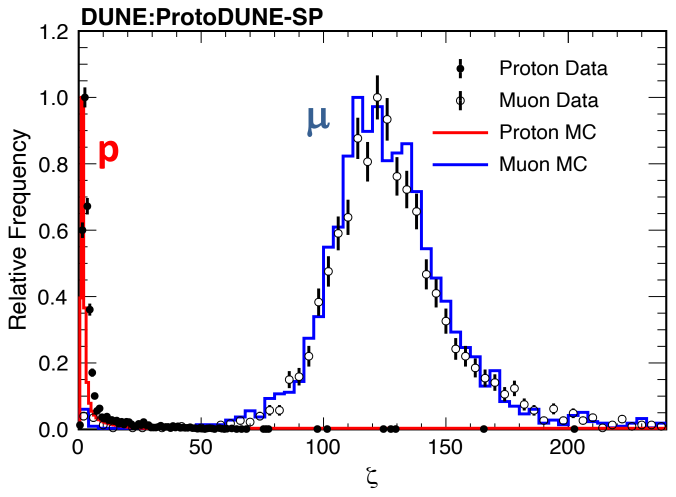


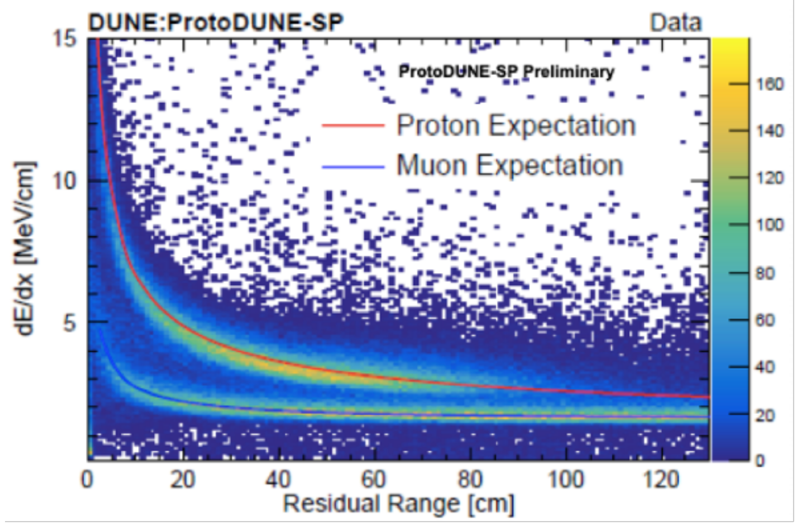


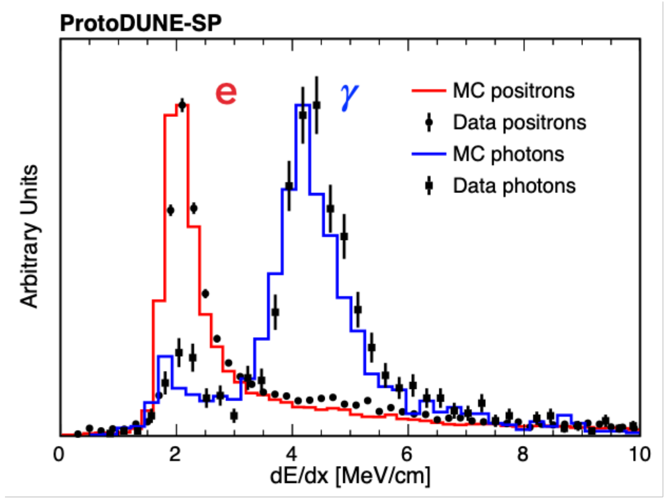
- Use of data-driven 2D maps at the faces of the detector, propagated to the bulk via interpolation. 3D displacement maps are inverted to correct the effect.
- Alternative method developed using anode-cathode-anode (ACA) crossing tracks

TPC – Calorimetry

- Cosmic ray muons crossing the detector are used to equalise the detector response
  - dQ/dx calibration to uniform detector response in (y,z and x)
  - dE/dx calibration factor from the Landau-Vavilov theoretical value
- Stopping muons are used as standard candle for the the energy scale calibration
- dE/dx offers a high discriminating power between particle types
  - Good μ/p and e/γ separation crucial for neutrino oscillation measurements and cross-section studies (in pDUNE)



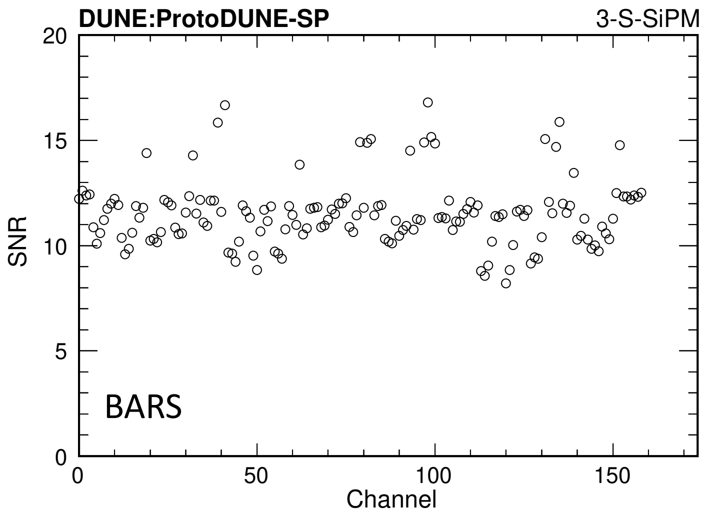


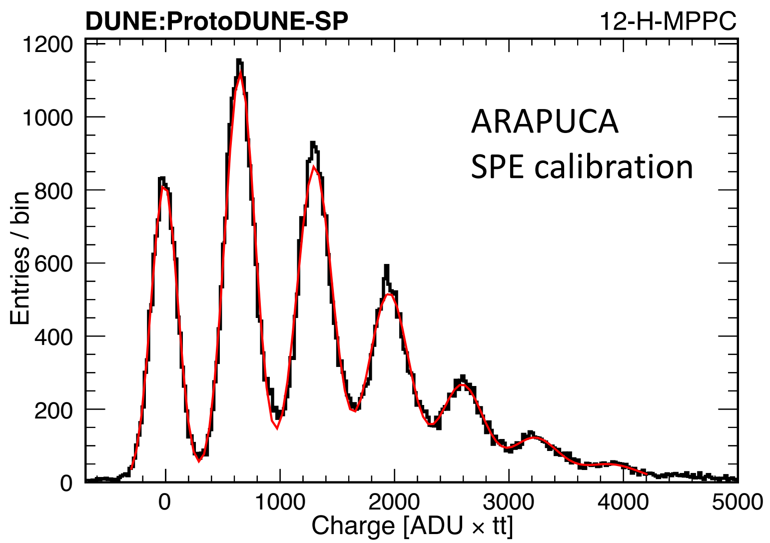


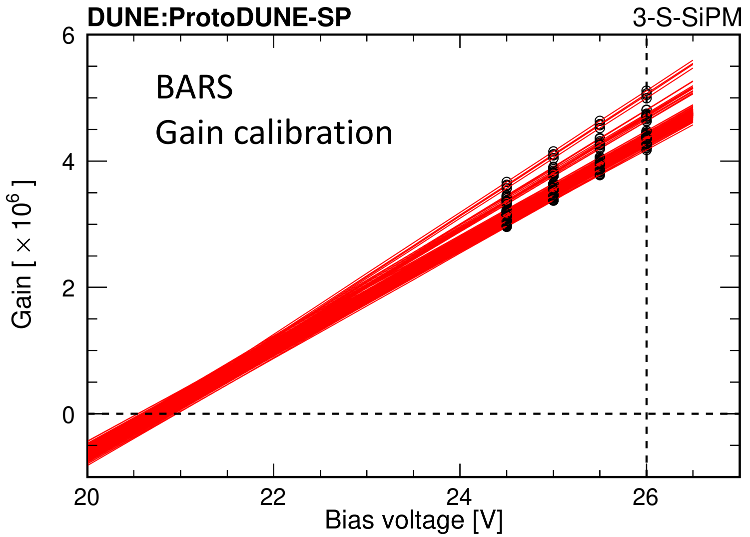
JINST 15 (2020) 12, P12004

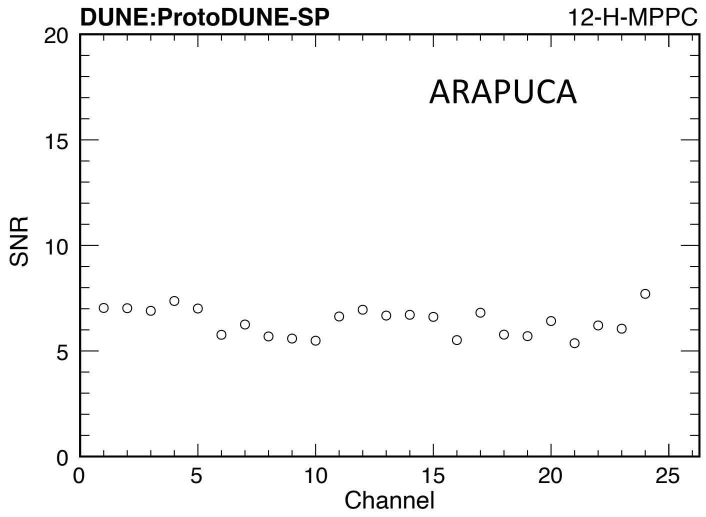
PDS Calibration

- Calibration and characterization using a dedicated LED system installed on the CPA
  - Linearity in gain vs bias voltage -> high gain stability across run
  - SNR, higher for bars (double-shift; dip-coated)





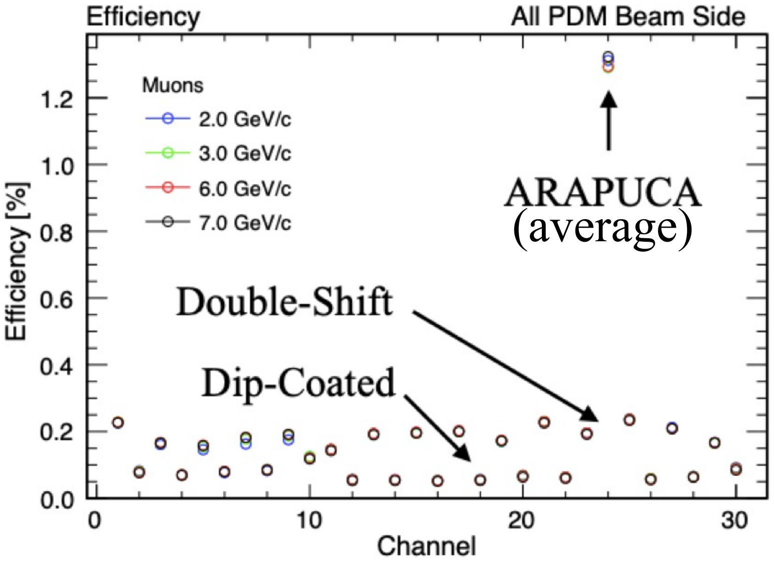


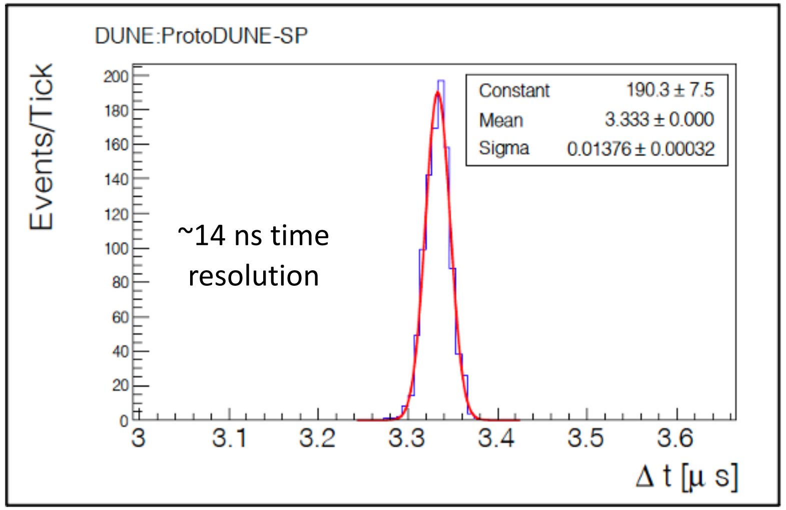


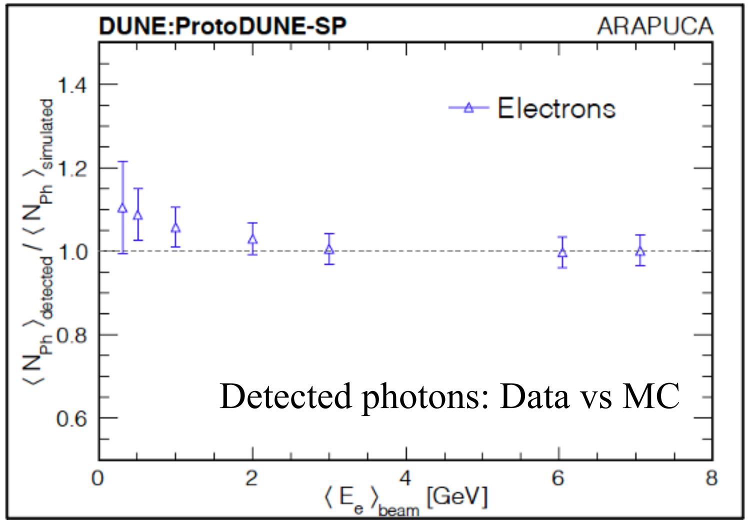
[JINST 15 (2020) 12, P12004](#)

PDS Performance

- Detector efficiency estimated against ProtoDUNE-SP MonteCarlo simulation
  - ARAPUCA technology shows best results with ~2% efficiency
  - 1.9 phe/MeV light yield extrapolated, in case PDSP were fully instrumented with ARAPUCAs
- Time resolution for two consecutive signals (using LED pulses): important for correlated events (stopping μ + Michel electron, kaon decay, nucleus de-excitation)
- Time matching with TPC signal: determination of the t_0 of the event

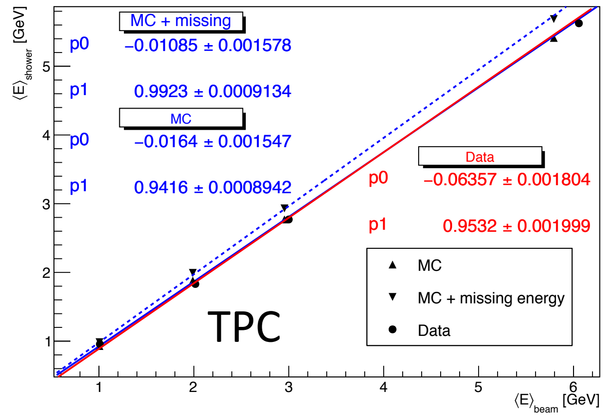


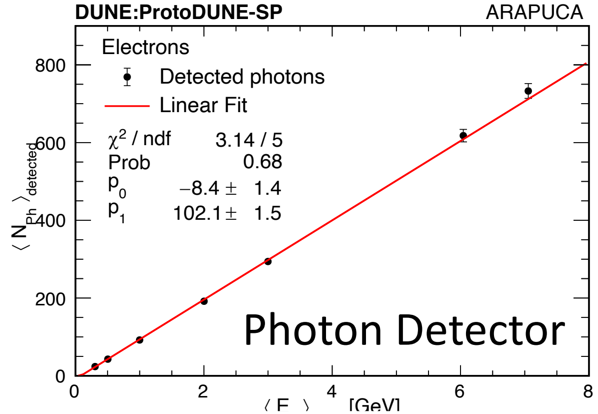


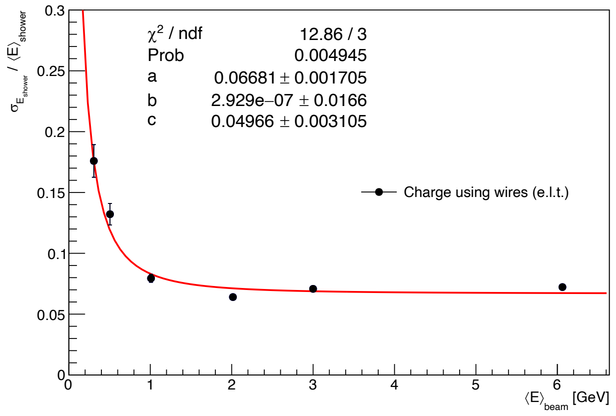


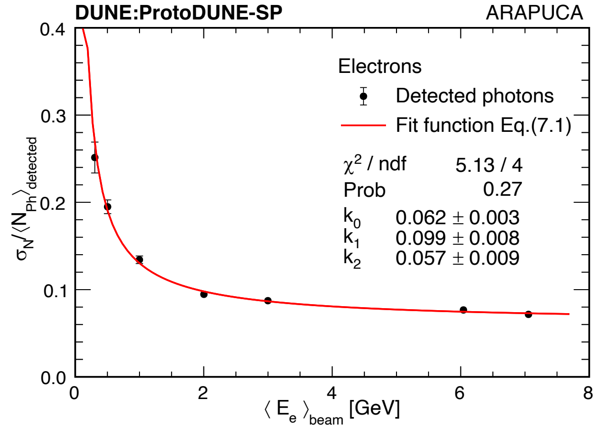
JINST 15 (2020) 12, P12004

Energy Resolution to beam electrons









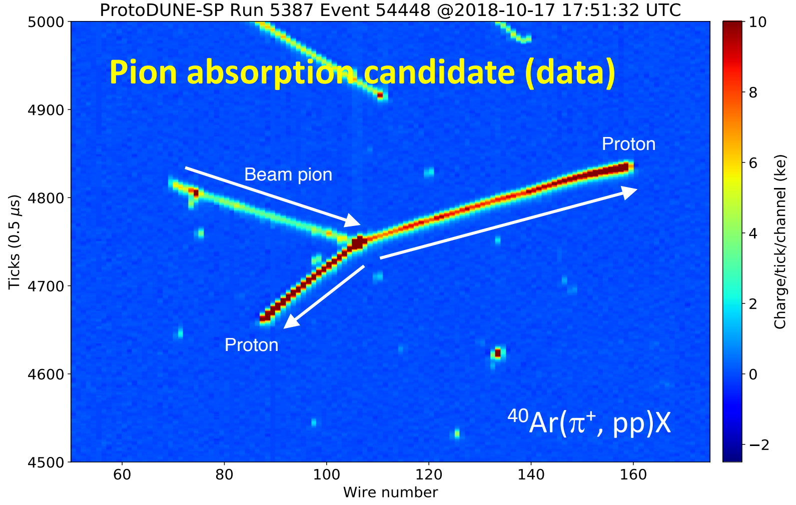
$$\sigma_E/\langle E\rangle = \sqrt{a^2 + (b/\sqrt{\langle E\rangle})^2 + (c/\langle E\rangle)^2}$$

- **Good linearity** seen in both analyses
- **Constant term (a)** dominated by spread of beam momenta.
- **Noise term (c)** dominated by fluctuation in the energy loss upstream.
  - Electronic noise has a negligible impact on the energy resolution
- **Stochastic term (b)** characterizes the intrinsic detector resolution.
  - ~2% for TPC and 9.9% for PD
  - Better than the design requirements

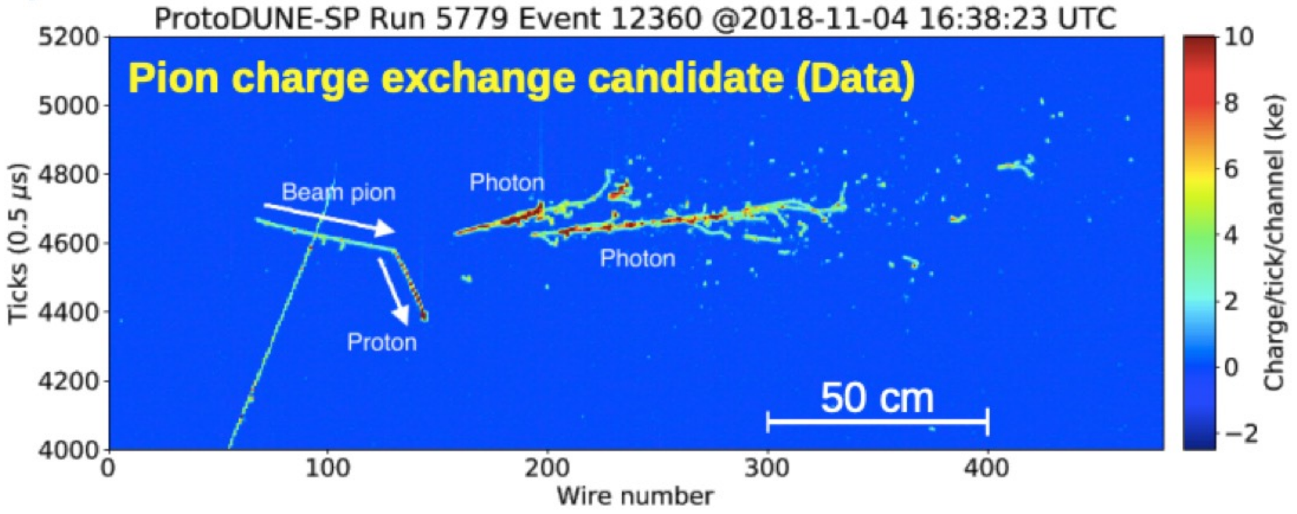
	TPC	PD
Constant term	6.7%	6.2%
Stochastic term	~2%	9.9%
Noise term	50 MeV	57 MeV

Hadron-Argon cross sections

- Main physics goal for ProtoDUNE-SP: hadron - LAr cross sections
  - Charged pions (at 1GeV/c) -> Inclusive, absorption, and charge exchange cross sections
  - Protons (at 1GeV/c) -> Inclusive cross section
  - Charged kaons (at 6GeV/c) -> Inclusive cross section
  - Neutrons -> Cross section using protons produced by secondary neutrons



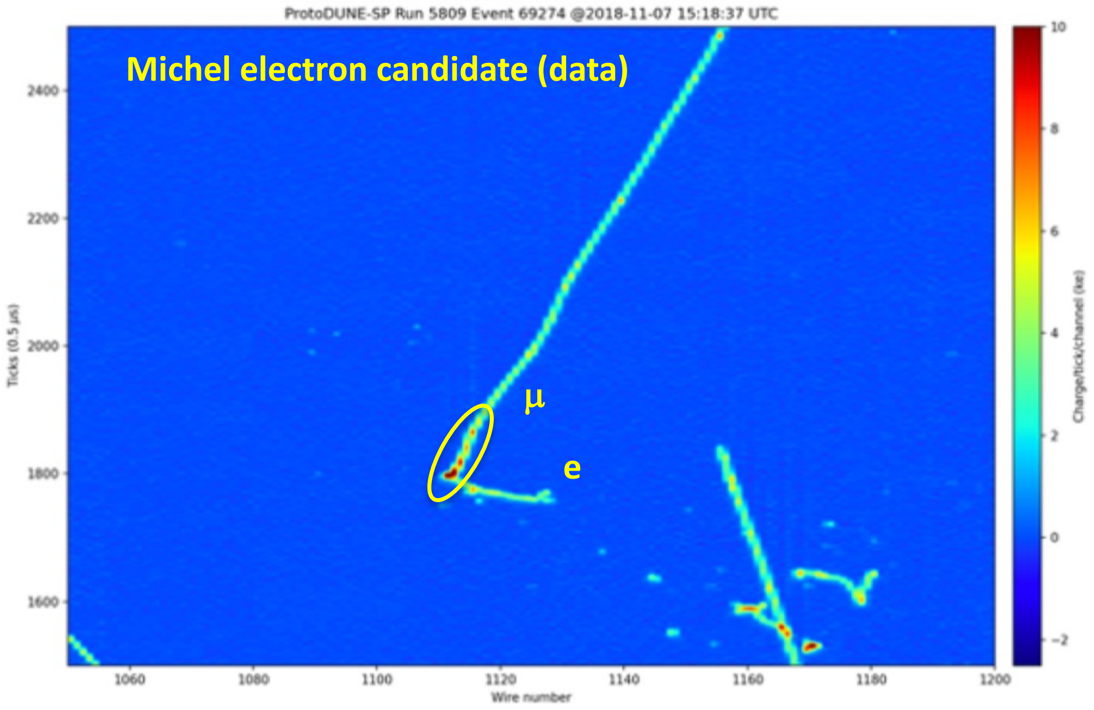
- Almost no measurement existing in LAr
- Provide constraints to reduce Final-State Interactions systematics for DUNE



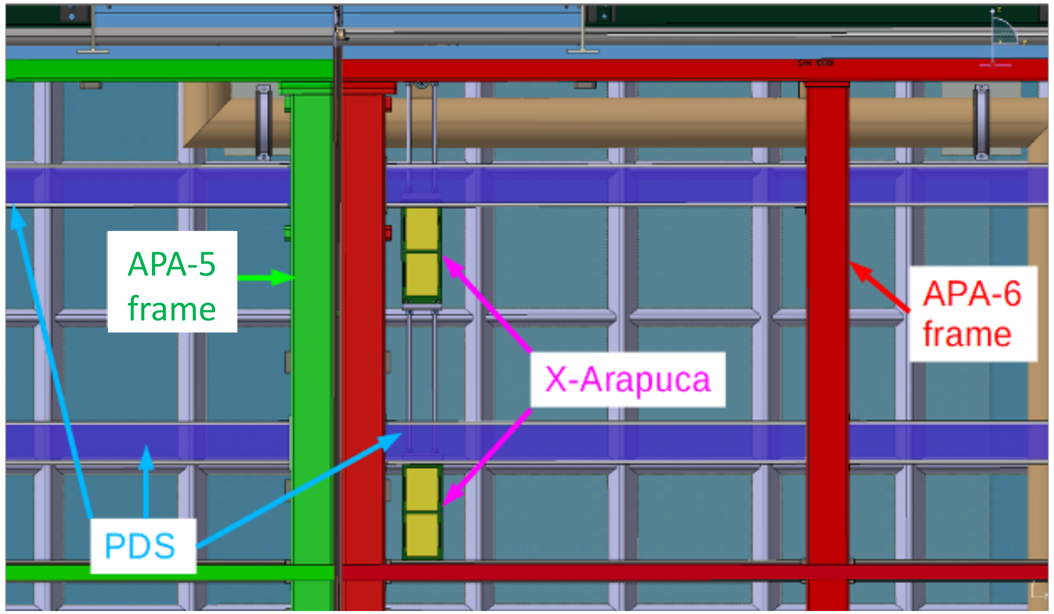
Other analyses

- Michel electron identification:
  - Muon decay provides a well understood sample of low energy electrons
  - Important for DUNE low energy analyses (Supernova neutrinos, solar neutrinos, etc)
  - Selected from stopping cosmic ray muons

- π_0 identification: possible background for ν_e CC events
- Muons seasonality : comparison with existing measurements



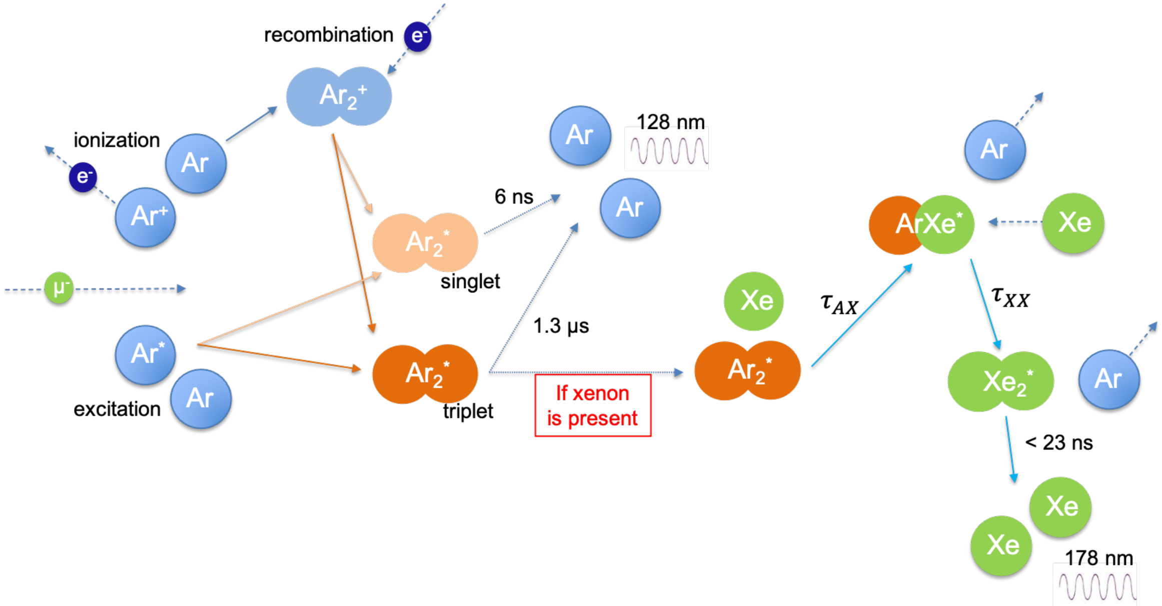
ProtoDUNE SP R&D – Xenon Doping



Location of custom X-ARAPUCAs behind APAs for Xe-doping run

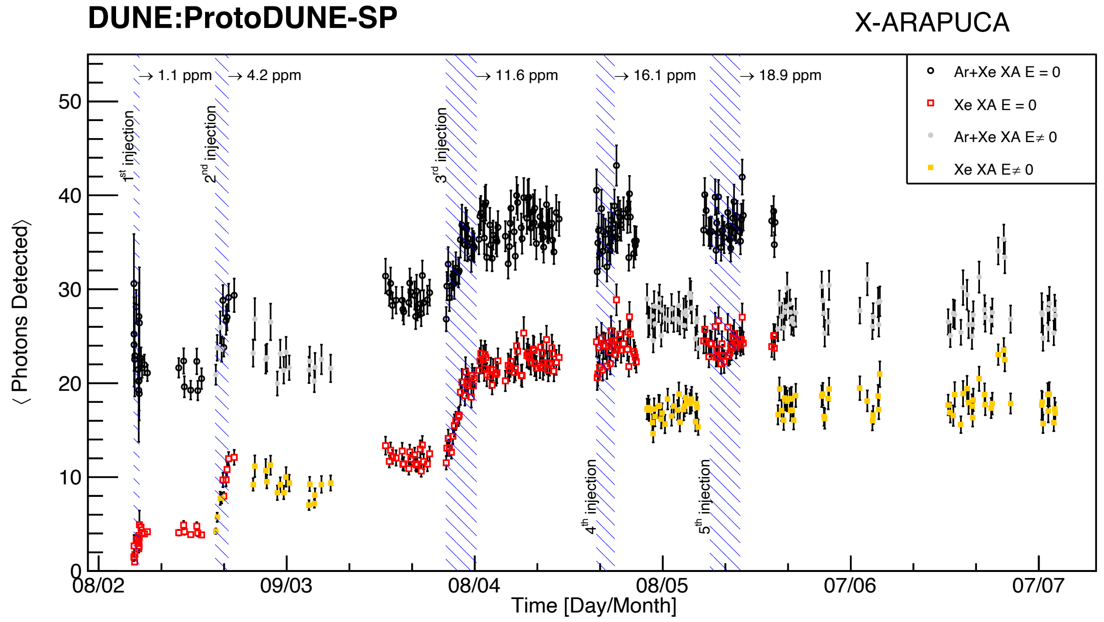
- Dedicated studies with PDS and custom dedicated X-ARAPUCA detectors
  - No effect on TPC response
  - First test of X-ARAPUCA in a large-scale detector
- In ProtoDUNE SP, doping also helped recovering light loss due to N_2 pollution (issue with recirculation pump)

- Doping considered for DUNE, to enhance PDS response
- Scintillation light shifted from 128 nm (Ar) to 178 nm (Xe)
  - Photon detectors have higher detection efficiency
  - Shorter pulses -> faster detector response
  - Larger Rayleigh Scattering length -> more uniform response in space (recovering light far from sensors)

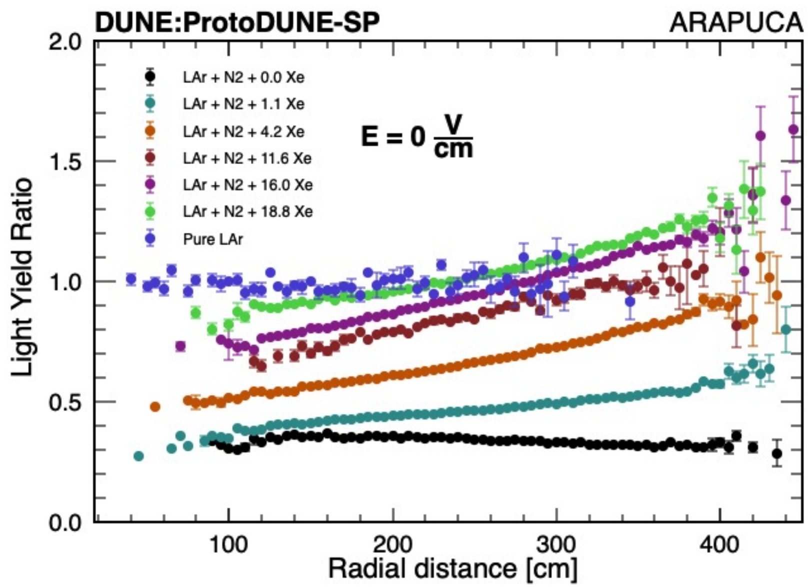


ProtoDUNE SP R&D – Xenon Doping

- ~ 19 ppm of Xenon introduced in steps in LAr (~13.5 kg)
- Demonstrated efficient energy transfer from Ar^*_2 to Xe^*_2
- Fraction of Xe light increases with each doping (w.r.t. N_2-polluted LAr) and stabilizes around 0.65 after 16.1 ppm Xe
- Fraction of converted light is not affected by recirculation or by E-field presence.



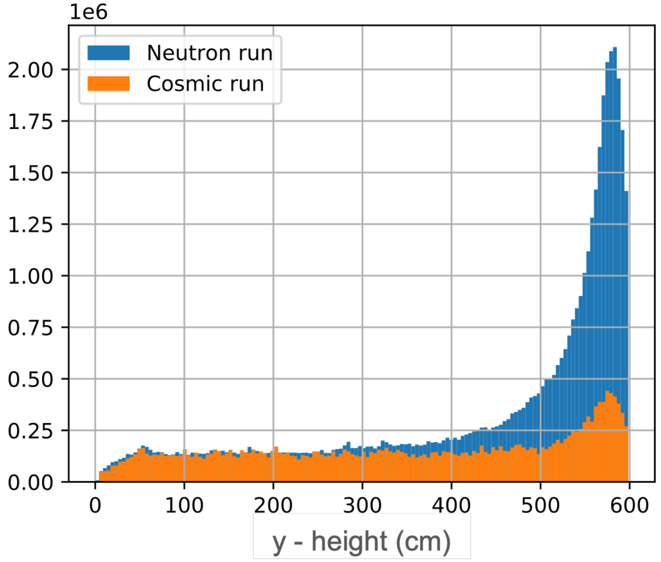
[Paper in preparation]()

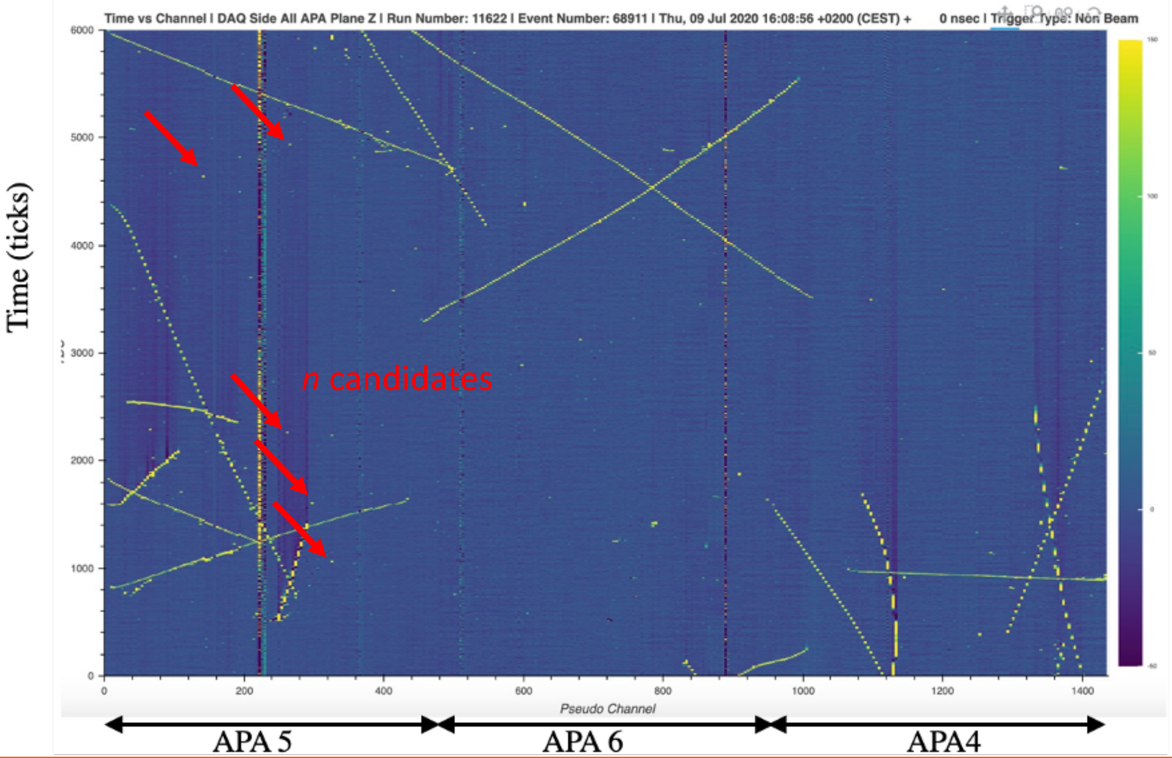


- Xe doping recovers 95% of light before N_2 contamination.
- Enhanced uniformity in collected light, due to Rayleigh scattering
  - Rayleigh length ~6 m for Xe light, ~1 m for Ar light
- Initial drop in fast component (Xe absorption), overall increase in slow component
- First demonstration of Xe-doping in a 770-ton LArTPC!

ProtoDUNE SP R&D – Neutron Gun

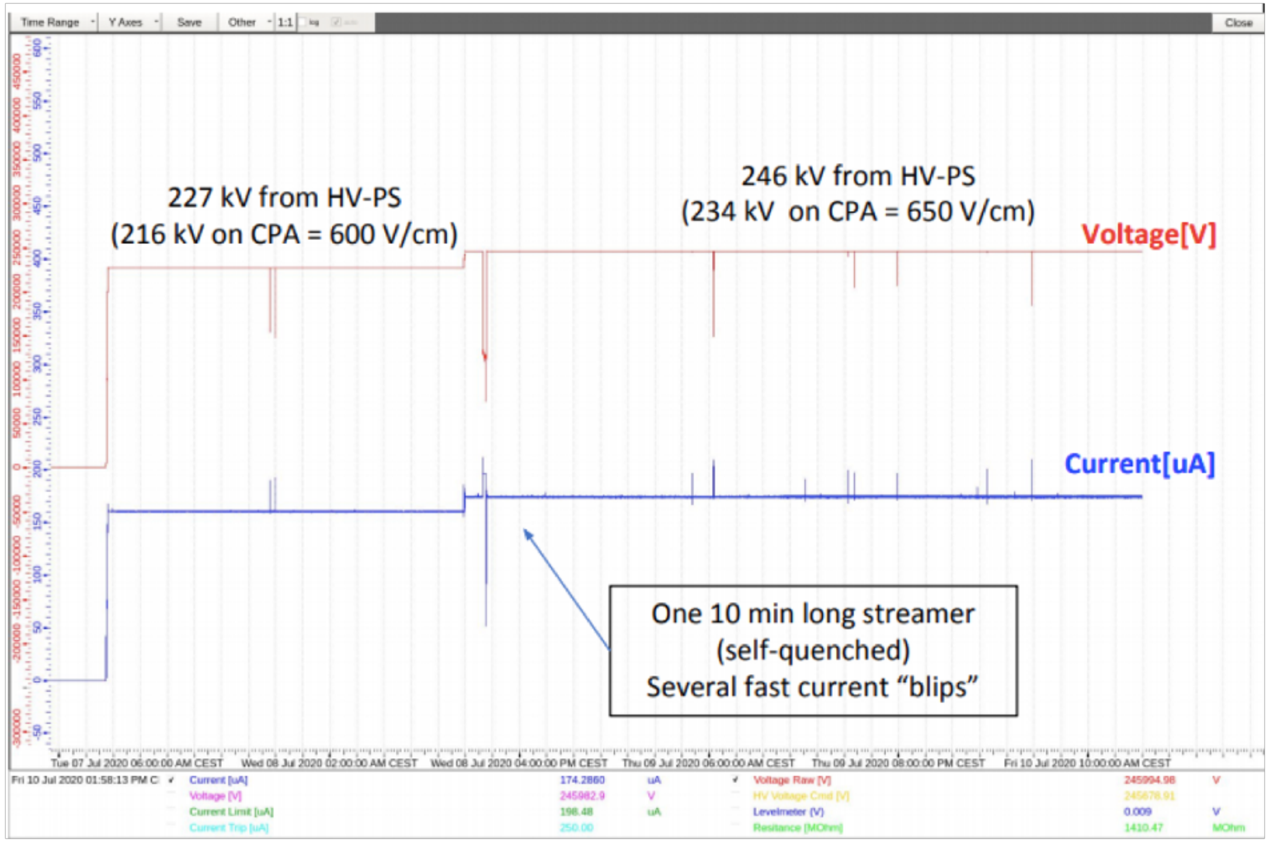
- To test the neutron-based calibration method for DUNE, a DD neutron generator was installed on top of APA 5 in July 2020.
  - Up to 10^6 neutrons per second with energy peaked at 2.5 MeV
- Low energy photons produced by neutron capture or elastic scattering in APA5





ProtoDUNE SP R&D – HV stress tests

- Last two weeks of operation devoted to **stress HV above nominal** to identify possible weak points:
  - HV first ramped up to 216 kV (600 V/cm): stable operation, no increase of noise on CE.
  - HV then ramped up to 234 kV (**650 V/cm**): stable for 3 days until sudden HV trip occurred.
- Analysis of HV feedthrough led to updating the design, to be deployed in the next beam rum.
- Visual and electrical inspections of FC components have not identified any other damages



ProtoDUNE SP decommissioning

- Decommissioning started in November 2020 with the removal of the Temporary Construction Opening (TCO) red structure, followed by the TCO primary membrane cut in February 2021
- The detector removal was done partially using new procedures and partially doing the exact time reversal of the installation procedures
- No major problems were encountered during the decommissioning (apart from the limited manpower due to COVID-19 restrictions)
- Decommissioning ended in September 2021

TCO opening starts

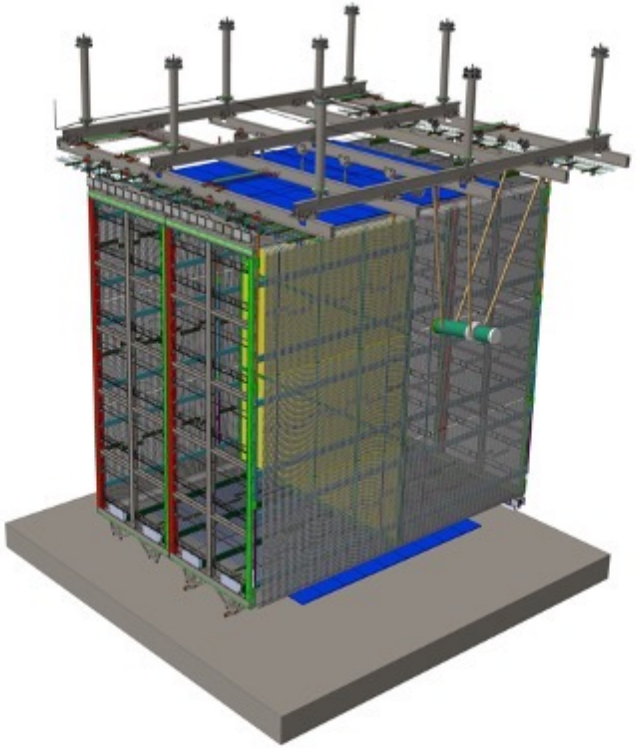
APAs "out of the box"

Towards Run-II

ProtoDUNE SP -> HD : Goals

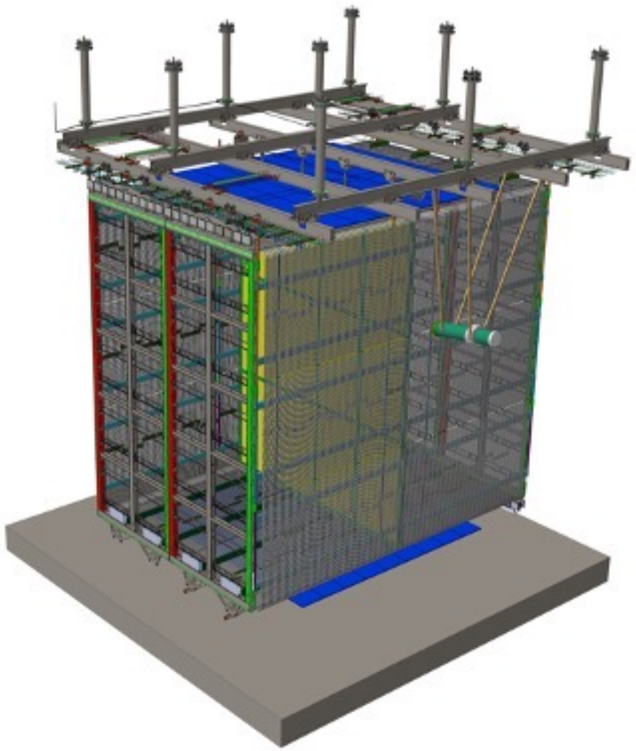
- Improve detector with lesson learned from ProtoDUNE-SP
- Implement final detector layout for DUNE (Module-0) & final components
- Tune mass production, installation procedures & manpower needs

- Full characterization of “Module 0”s for DUNE Far Detector: improved APAs, HV system components, cold electronics, photon detectors, DAQ.
- Increase beam data statistics (cross section measurements, particle identification, calibration, reconstruction)
- Complete data sets with negative polarity for electrons, muons, pions, kaons in momentum range 0.3-7 GeV, with special attention to lower momenta
- Develop, implement, and demonstrate new calibration techniques, not implemented in ProtoDUNE SP, including a laser calibration system and a pulsed neutron source



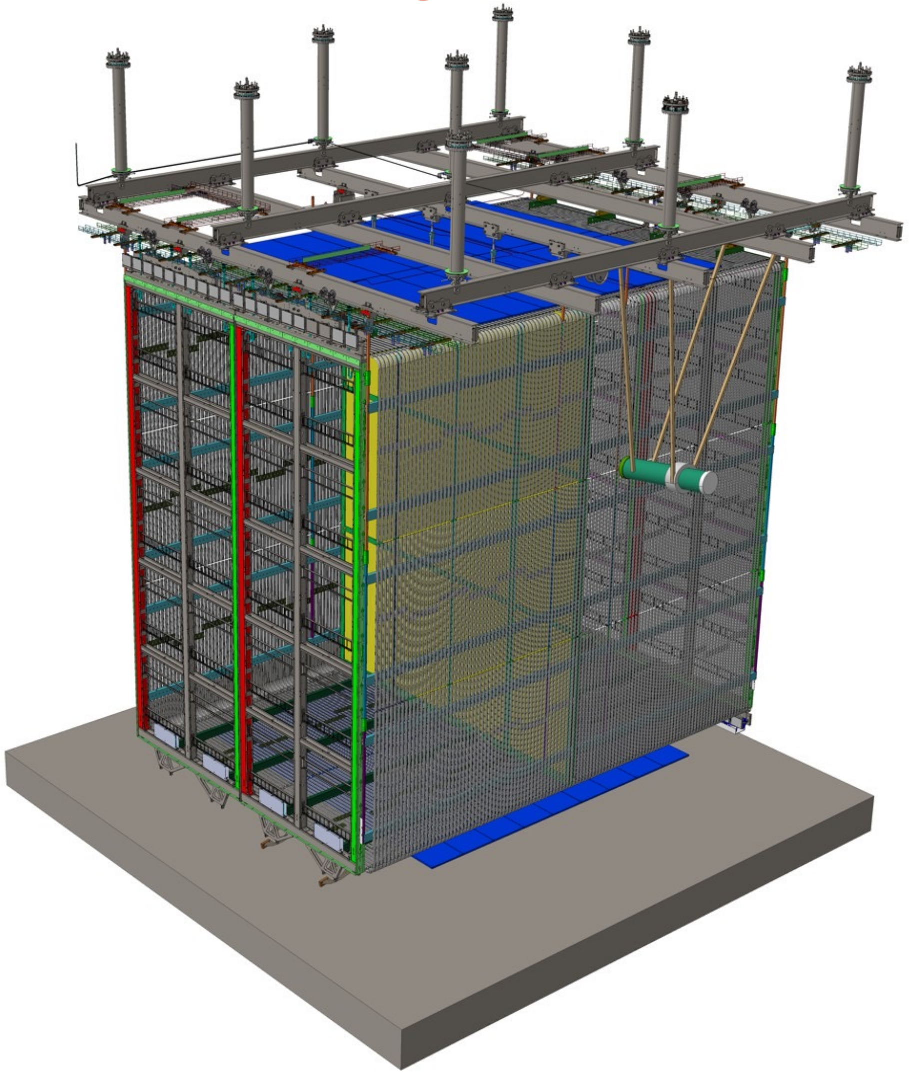
ProtoDUNE SP -> HD

- 4 APAs instead of 6 to allow the DUNE Far Detector distances between cryostat and end-wall field cages
- 2 Flipped APAs on one-side (electronics on bottom) to mimic the DUNE bottom APAs
- New, longer beam plug
- Photon Detectors upgraded to full X-ARAPUCAs
- Improved cryogenics systems (based on ProtoDUNE-SP experience)
- New calibration and cryogenic instrumentation (laser, neutron source, temperature sensors on APAs, etc.)
- As much as possible, final Far Detector components. Full long cables will be used for the CE.
  - Full-scale mechanical prototyping of ProtoDUNE-HD TPC being carried out at the Ash River facility



ProtoDUNE HD – Commissioning plan

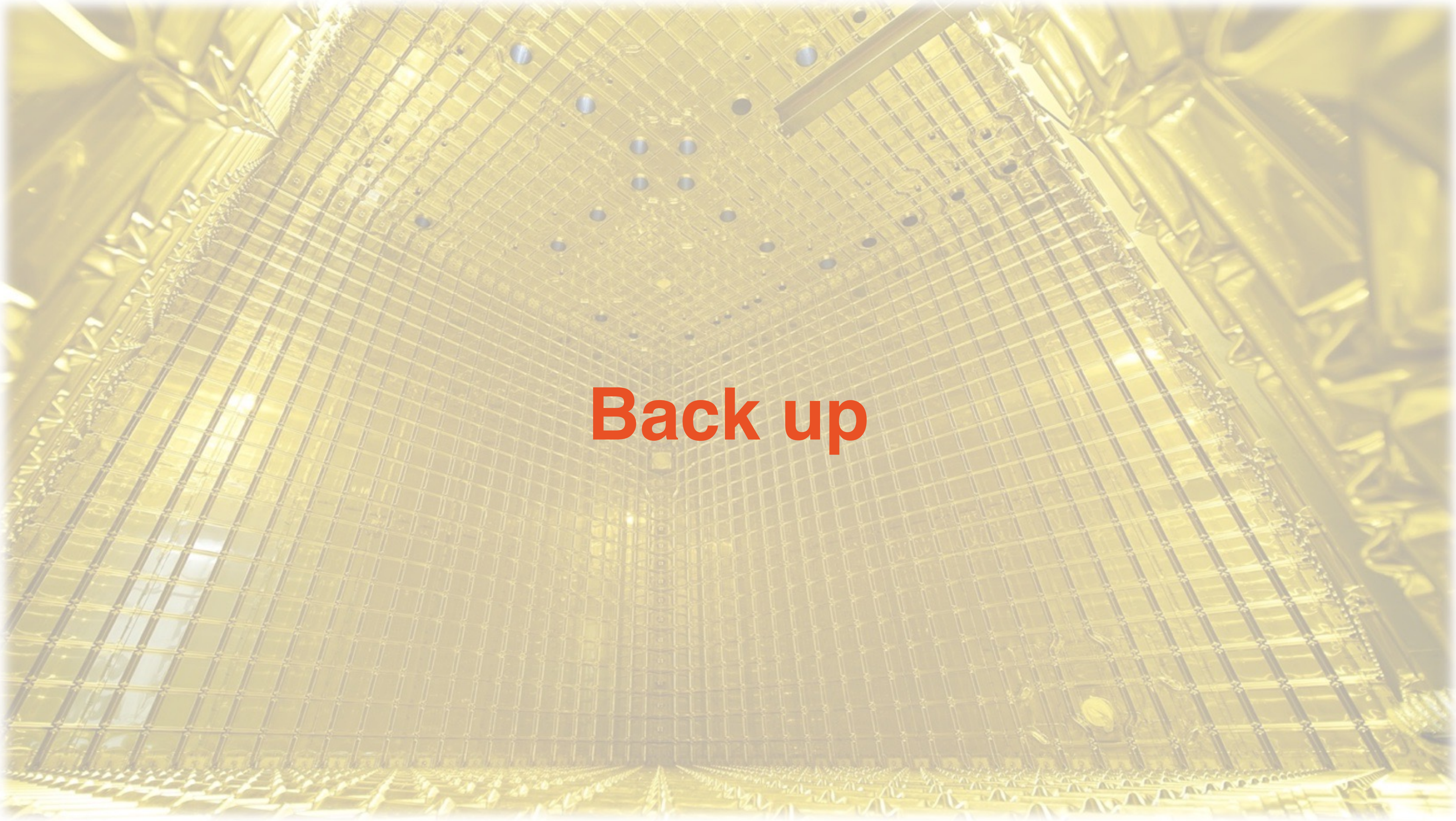
- First APA for ProtoDUNE-HD already at CERN
  - Cold test foreseen to start in upcoming weeks.
- All APAs cold tested by April 2022
- Installation complete in July 2022
- Cryostat close and filled by October 2022
- Beam operation from October 2022
- Module-0 operation continuing in 2023



Summary

- ProtoDUNE SP is a kton size prototype for the DUNE far detector module
  - engineering prototype for the cryostat design and cryogenic system;
  - test bed for the TPC assembly procedure and operation;
  - validation ground for newly developed detector solutions towards DUNE.
- ProtoDUNE-SP has been switched OFF on July 2020, after two years of data taking (three months of charged particle beam)
- Excellent detector performance. Analysis of data collected with cosmic and tagged beam particles (hadrons, electrons) are ongoing, with papers in preparation
- All lessons learnt were implemented in an upgraded detector, closely resembling a fraction of DUNE FD1
  - **ProtoDUNE Run-II**: installation will take place in 2022, along with start of beam data taking
  - The new beam run will allow increasing statistics for the analyses and collect data with negatively charged particles.
  - Looking forward to the new upcoming challenges!

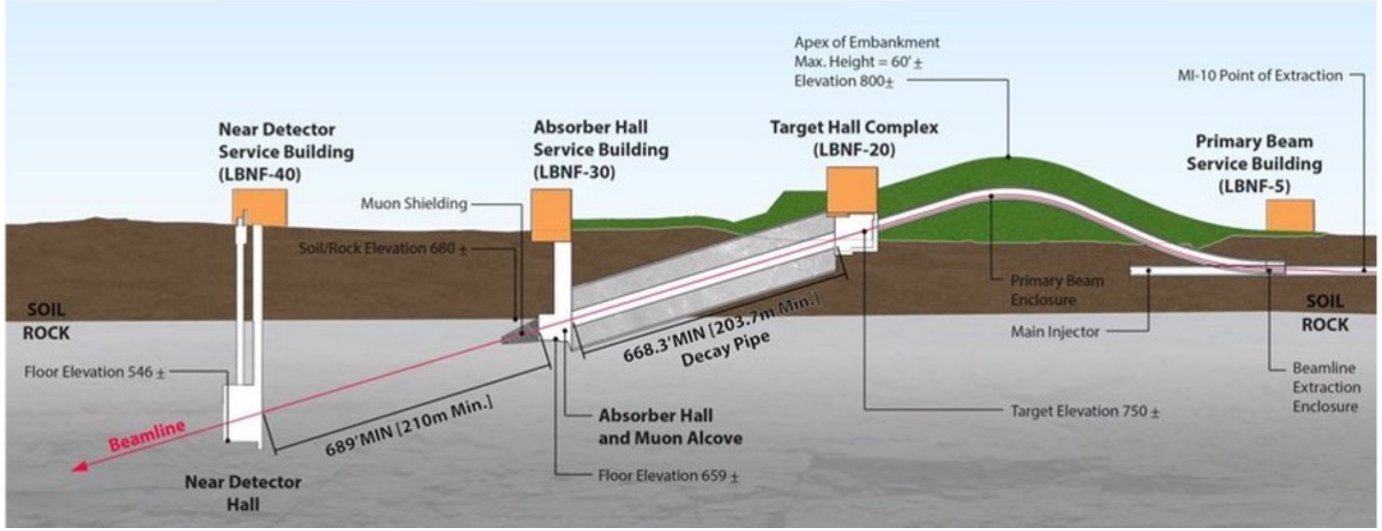
Thank you!



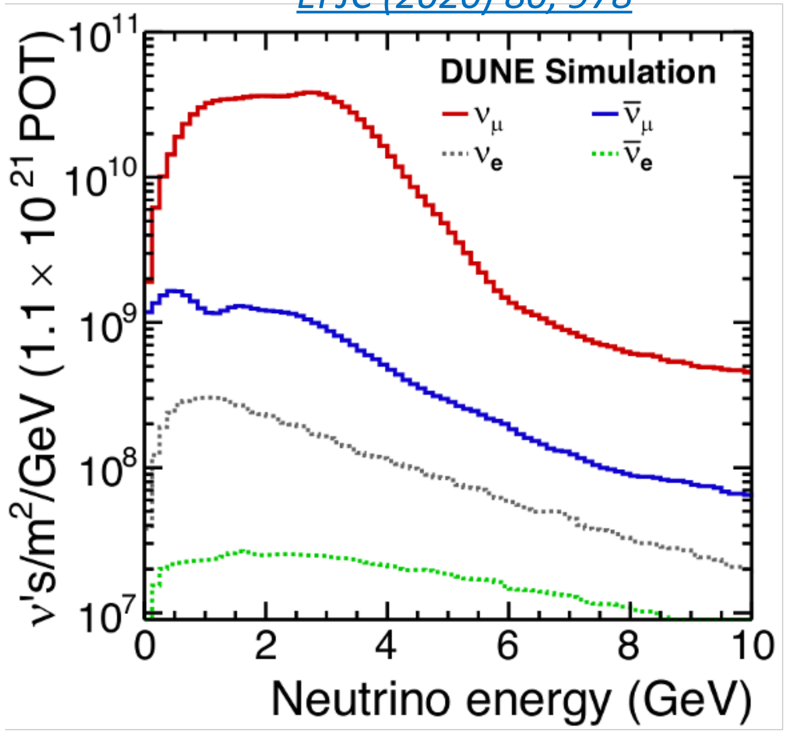
Back up

Long Baseline Neutrino Facilities

- **Beam line** design under way
  - 60-120 GeV proton beam
  - 5.8 degree vertical bend, to reach SURF
  - 1.2 MW by late 2020's, upgradable to 2.4 MW
  - Assumed minimum uptime of 55%



EPJC (2020) 80, 978

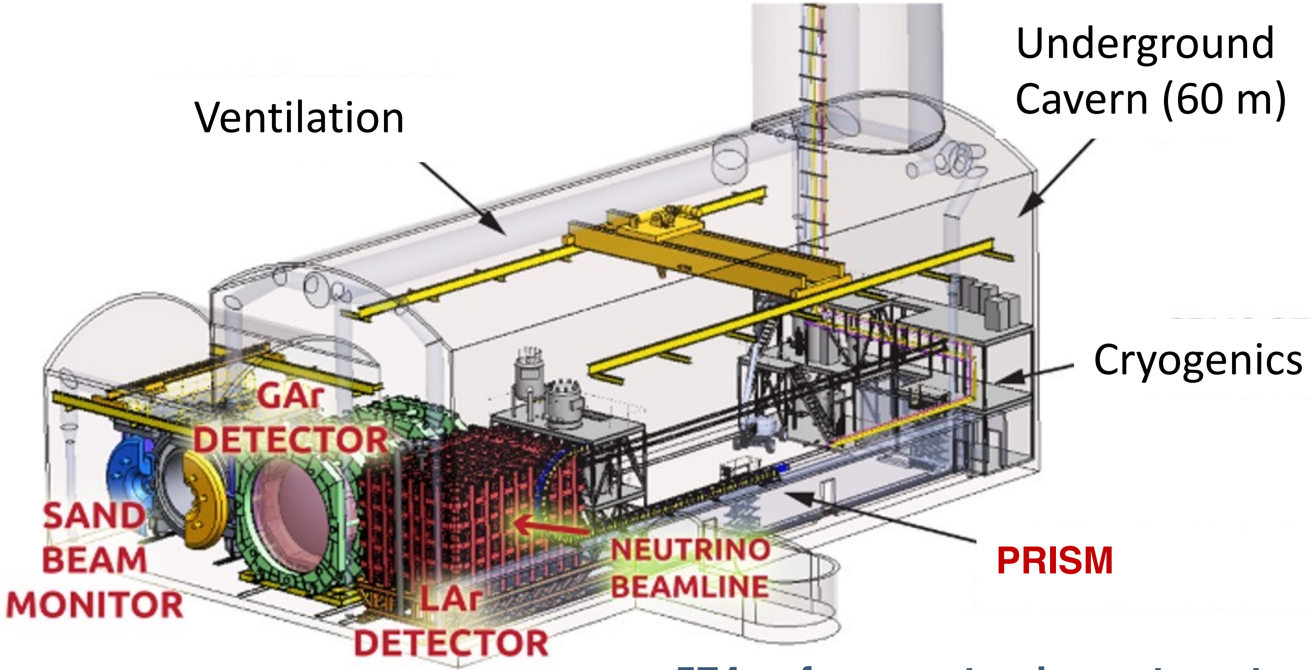


(1.1-1.9) x 10^{21} POT*/y @ 1.2 MW
10 μs pulse duration
*Protons On Target

The Near Detector Station

- Precise characterization of neutrino beam
- Limitation of cross-section uncertainties for LB neutrino oscillation measurements

- Multiple complementary systems:
  - **ND-LAr** primary target, modular, pixelated charge read-out LAr-TPC (300 ton)
    - Module 0 successfully tested at Univ. Bern
  - **ND-GAr**: high-pressure GAr-TPC, surrounded by ECAL and magnet
    - intercepts muons escaping LAr-TPC
    - Muon spectrometer; nuclear interaction model constraints
    - Will come at a later stage. A Temporary Muon Spectrometer (**TMS**) will be installed at Day 1
  - **SAND**: inner tracker surrounded by 100 ton ECal and SC magnet (0.6 T)
    - On-axis beam monitor (spectrum/stability)

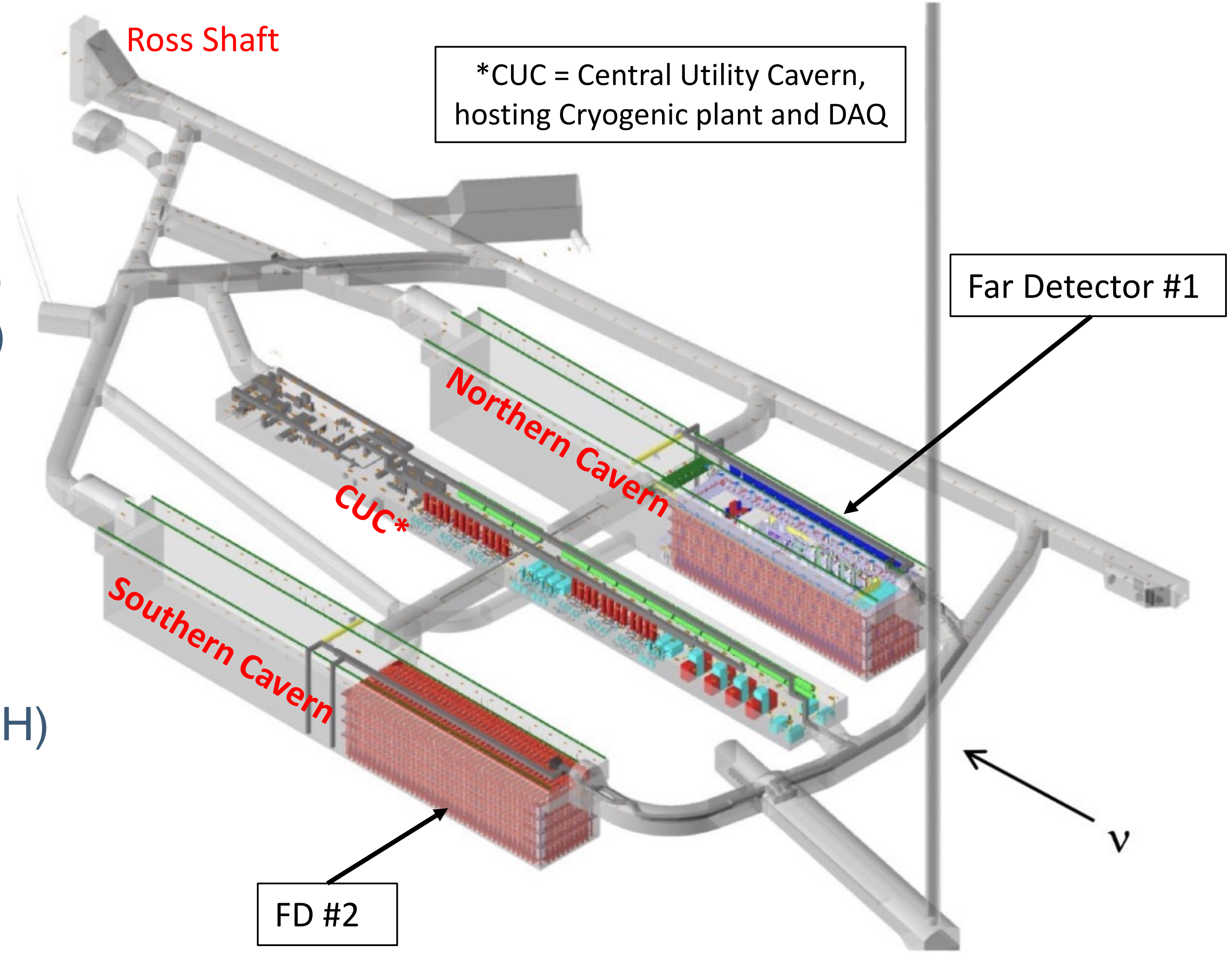


574 m from proton beam target

PRISM: ND-LAr and TMS/ND-GAr can move up to 30 m Off-Axis for beam characterization and lower-energy ν detection

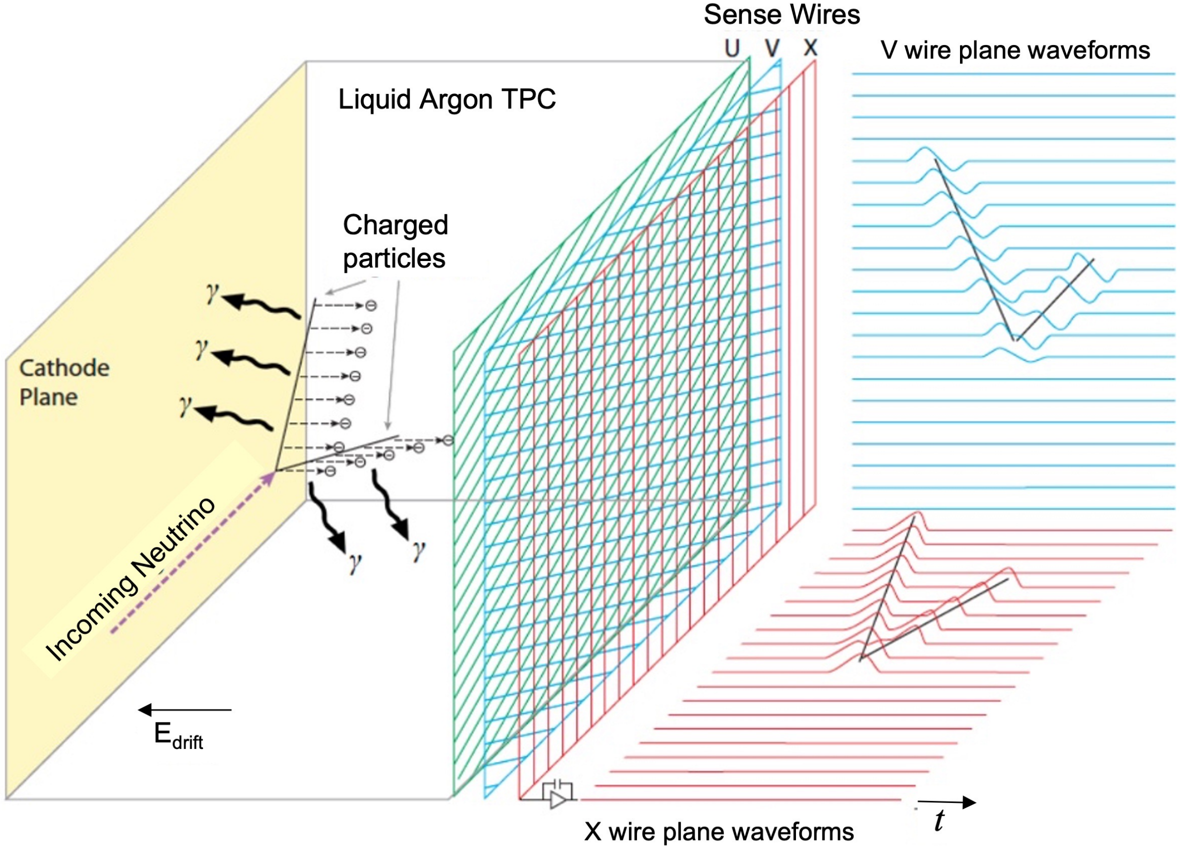
Far Detector Site - SURF

- 4 Detector modules, ~17 kton total volume each
  - Construction in stages
- **FD #1, #2** will be **single-phase (SP) LAr-TPCs,** with Horizontal Drift (HD) and Vertical Drift (VD), respectively
- FD #1 construction starts in mid Twenties
- Maximal cryostat external dimensions: ~ 66 x 19 x 18 m (LxWxH)

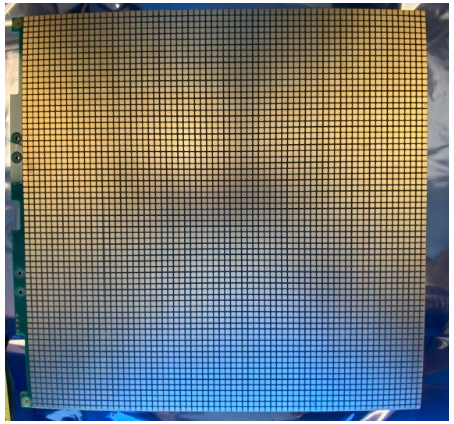


LAr-TPC technology

- Advancements in material science and bigger detector require new ideas
  - Mature, reliable technology (ICARUS, MicroBooNE)
  - Fully compatible with very-long expected life span of the detectors

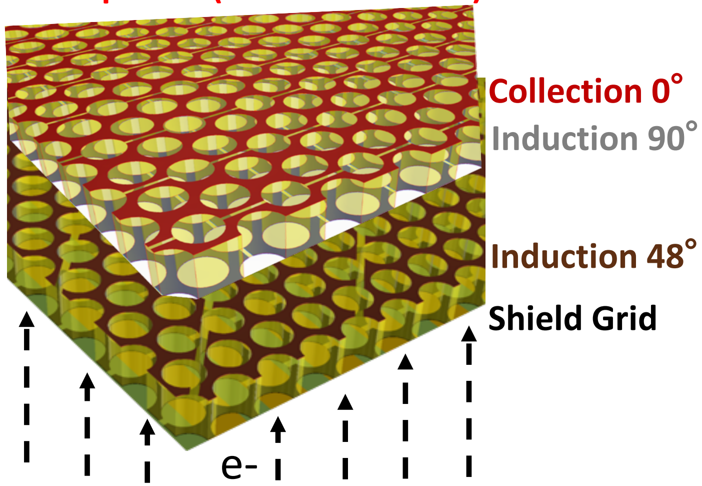


- New charge-readout solutions gaining momentum:
  - Pixels
  - Perforated PCBs

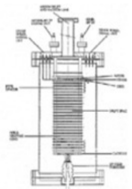


LArPix anode
32 x 32 cm
4.9k pixels

Three planes (3D corner detail)



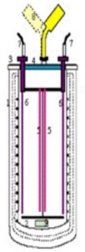
The "electronic bubble chamber" history



24 cm drift wires chamber ①

1987: First LAr TPC. Proof of principle. Measurements of TPC performances.

② 3 ton prototype

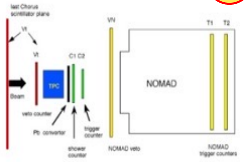


1991-1995: First demonstration of the LAr TPC on large masses. Measurement of the TPC performances. TMG doping.

CERN

CERN

③ 50 litres prototype 1.4 m drift chamber



1997-1999: Neutrino beam events measurements. Readout electronics optimization. MLPB development and study. 1.4 m drift test.

④

Pavia

10 m3 industrial prototype

1999-2000: Test of final industrial solutions for the wire chamber mechanics and readout electronics.

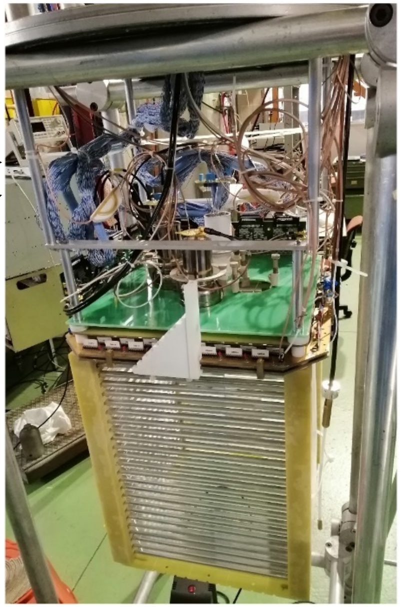
⑤ Cooperation with industries

LNGS Hall-B

ICARUS 600tons 2010-13

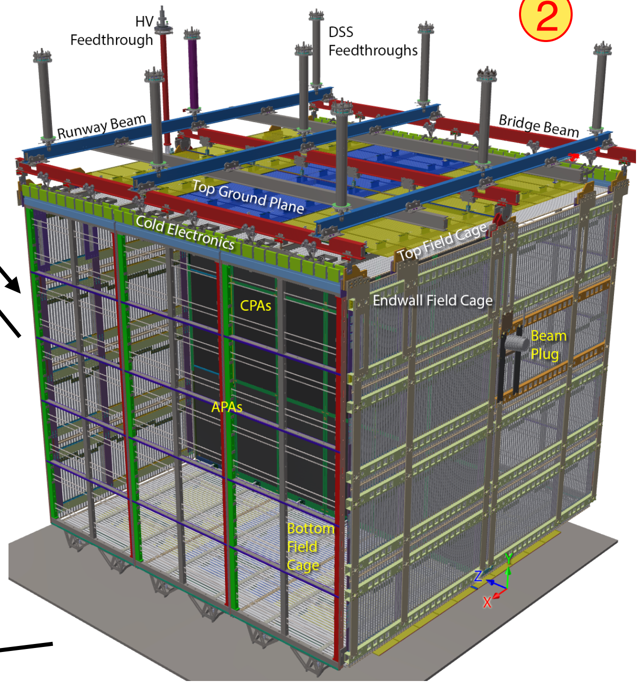
⑥

Evolved into…



① FLIC – 50liters, 50 cm drift
Main R&D set-up @ Meyrin

②



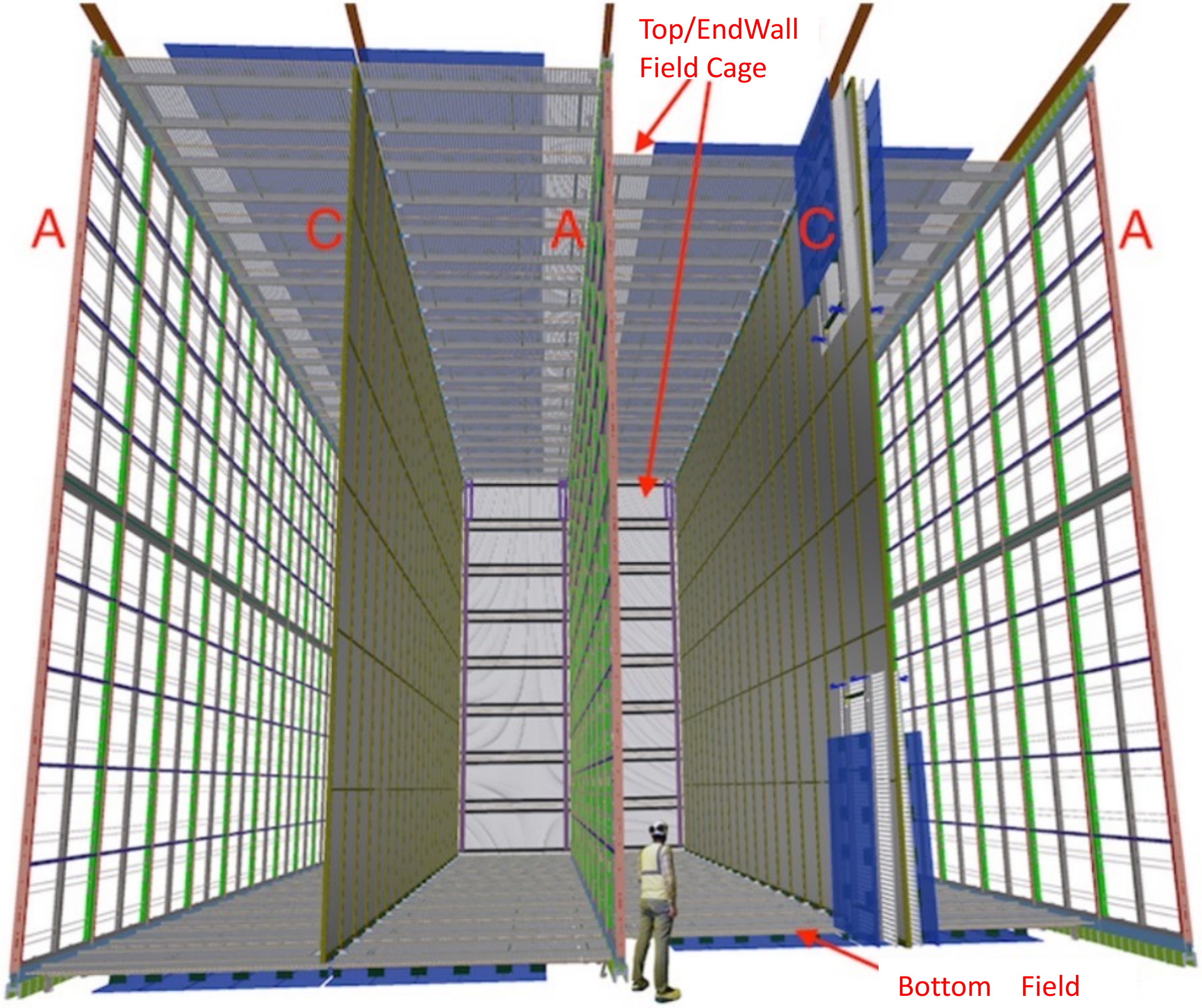
ProtoDUNE SP
8.5x8.5x7.9 m^3 inner
Around 700 tons of LAr

③ … DUNE ← *

*Cheating a bit: ICEBERG, 35ton, …

The evolution of prototyping steps, as scale evolves

DUNE Far Detector #1 (Horizontal Drift)



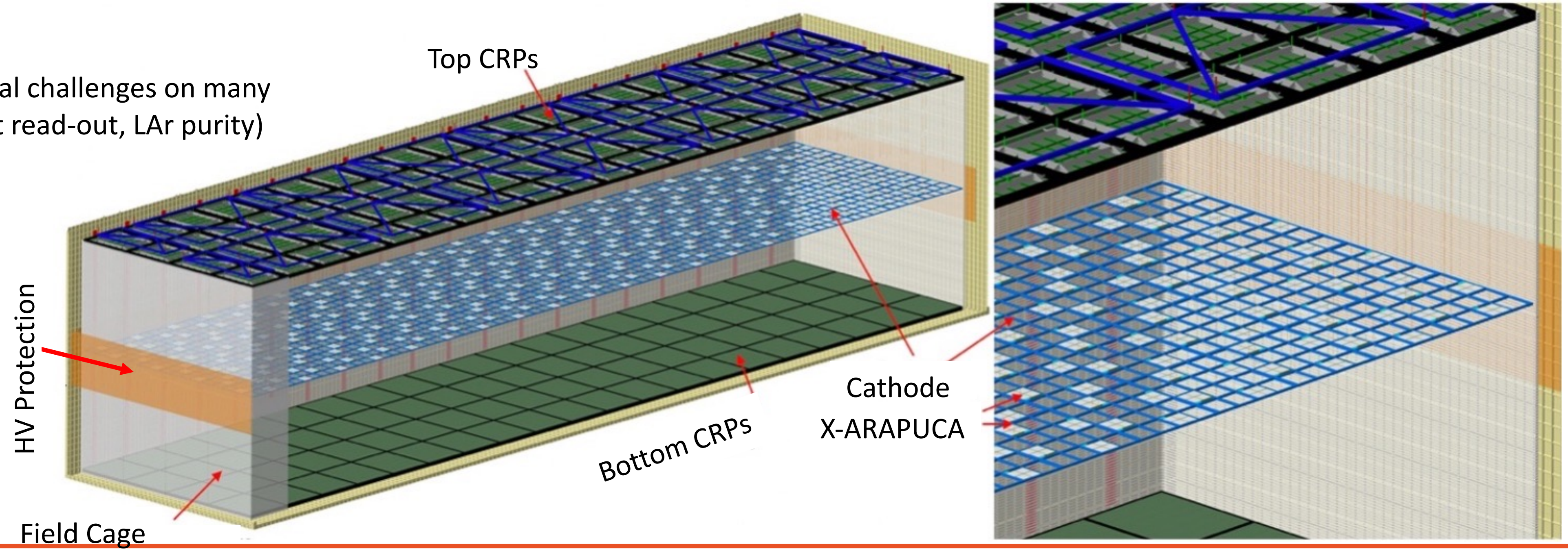
- Structure wholly suspended on roof
- Alternating Anode and Cathode Plane Assemblies (APA – CPA)
  - 4 drift volumes, 3.6 m drift / Electric field = 500 V/cm (HV = -180 kV)
  - High-resistivity CPA for fast discharge prevention
- Anode: 150 APAs, each with 4 wire planes (Grid, 2 x Induction, Collection)
  - Wrapped induction wires
- Photon Detectors: X-ARAPUCA light traps
  - 10 modules / APA
  - Timing
  - Cosmic / SN / BSM event triggering

DUNE Far Detector #2 (Vertical Drift)

- Single-phase, read-out on cryostat top and bottom
- 2 x 6 m drift ⇔ 300 kV HV on (central) cathode
- Charge Readout via perforated PCB anode, fully immersed in LAr
- Reference: 3-view design plus shield (2 anodes)

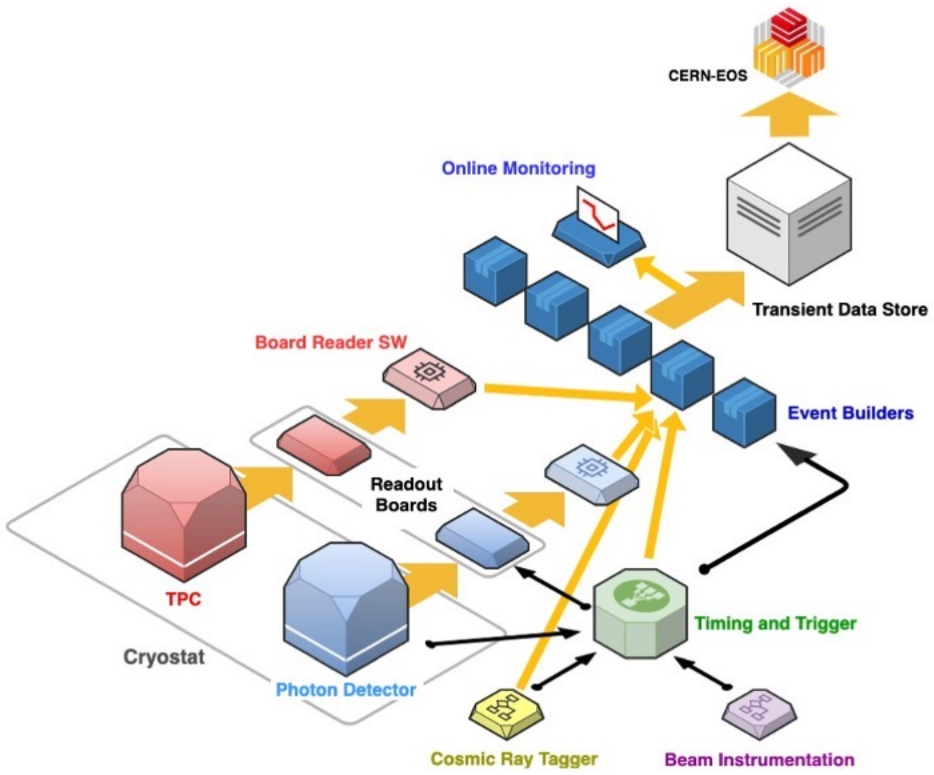
- Photon Detection Based on X-ARAPUCA tech. – on membrane and on Cathode @ 300 kV
- R&D towards Power-over Fiber and Signal-over-Fiber for SIPMs
- Enhanced scintillation yield by doping with Xenon (tested in ProtoDUNE SP)

New technological challenges on many aspects (HV, light read-out, LAr purity)



PDSP DAQ

- Two TPC readouts implemented (RCE and FELIX)
  - 430 Gb/s, continuous digitisation at 2 MHz
  - 15.360 channels (30 Warm Interface Boards, WIB)
- PDS custom design readout (SSP)
  - 3 Gb/s, continuous digitisation at 150 MHz
  - 240 channels (24 SSP)
- Trigger/Timing system
  - Phase-aligned master clock to all DAQ components
  - CTB* to aggregate trigger inputs from PDS, CRT and Beam line
  - Nominal trigger rate at 25Hz with readout window of 3ms
  - Achieved trigger rates peaking at 40Hz during data taking with beam
- DAQ farm with 20 high performance severs for data flow, monitoring and control
  - 700 TB on-site storage
  - maximum 20Gb/s data rate toward EOS



* Central Trigger Board

Cryogenic plant

Phases of Commissioning

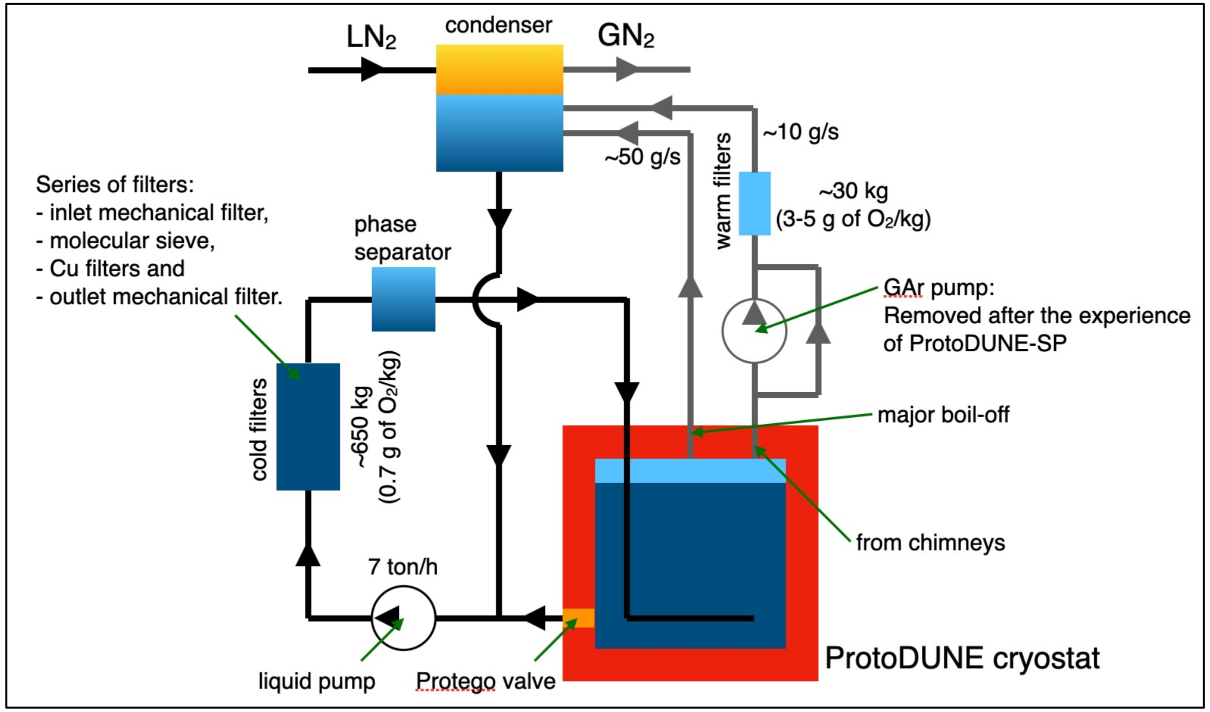
- "Piston purge": GAr flushing from the bottom to push air out (gas wave vertical velocity 1.2m/h). Air contamination reduced to few ppm.
- Open loop purging continued for 44 h corresponding to 7 volume changes to reduce O_2 and H_2O level
- Cool-down with GAr and LAr via sprayers from the top and LAr filling via the liquid purification system from lines at the bottom of the cryostat

Continuous recirculation

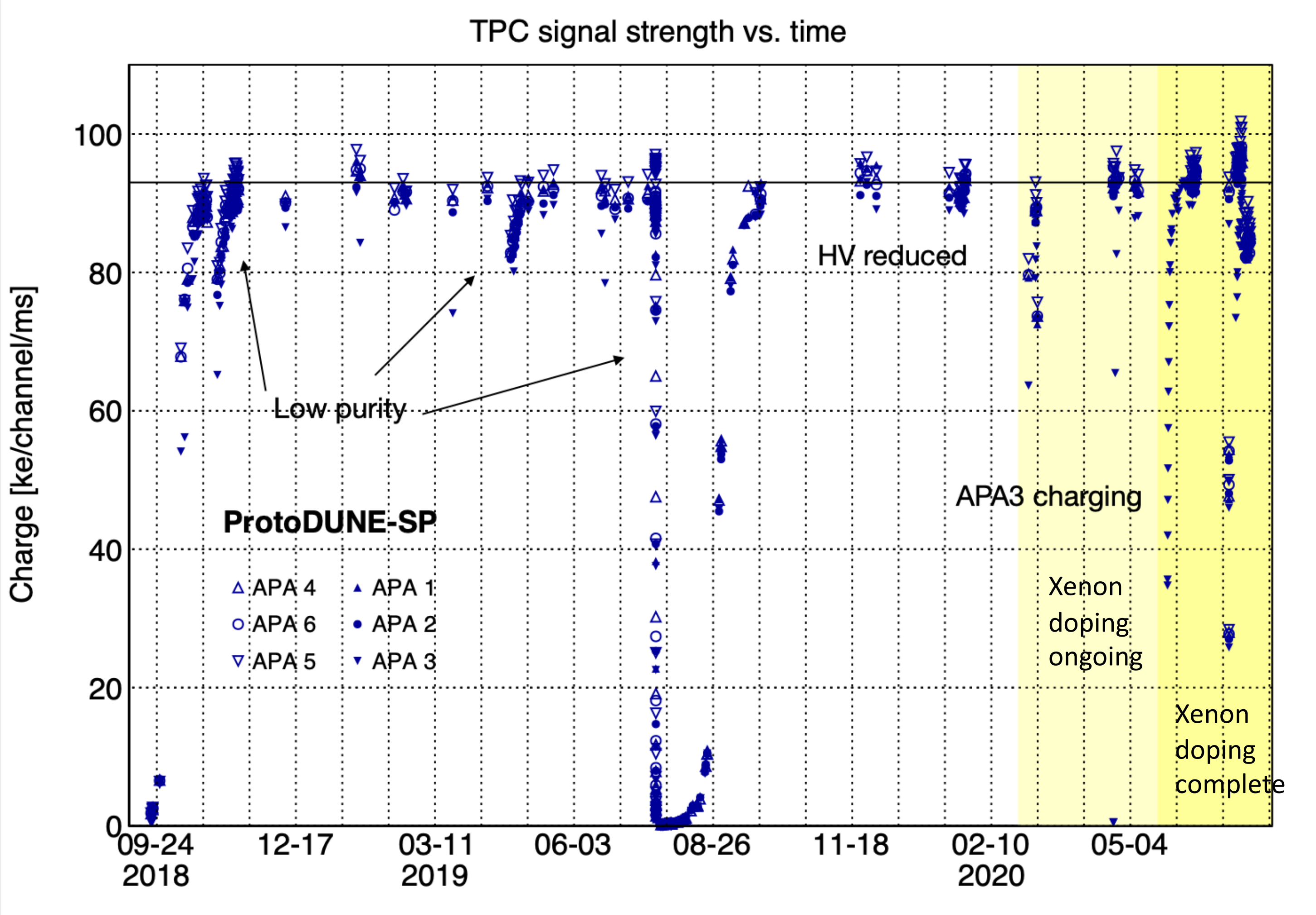
- Mechanical and chemical filters to remove polar molecules like H_2O (molecular sieve) and O_2 (Cu oxidation)
- LAr extracted via Protego valve and pumped through liquid purification
- GAr boil-off extracted from the top (from dedicated port and feedthrough exhausts): partially purified in gas phase, liquified, then purified in liquid phase.

Plant sections

- **External** cryogenics: Storage dewars for LAr (filling), LN_2 (cooling) and H_2 (filters regeneration)
- **Proximity** cryogenics: Purification/re-circulation circuits for LAr and Gar (impurity concentration < 100 ppt required)
- **Internal** cryogenics: pipes and manifolds for LAr and GAr distribution

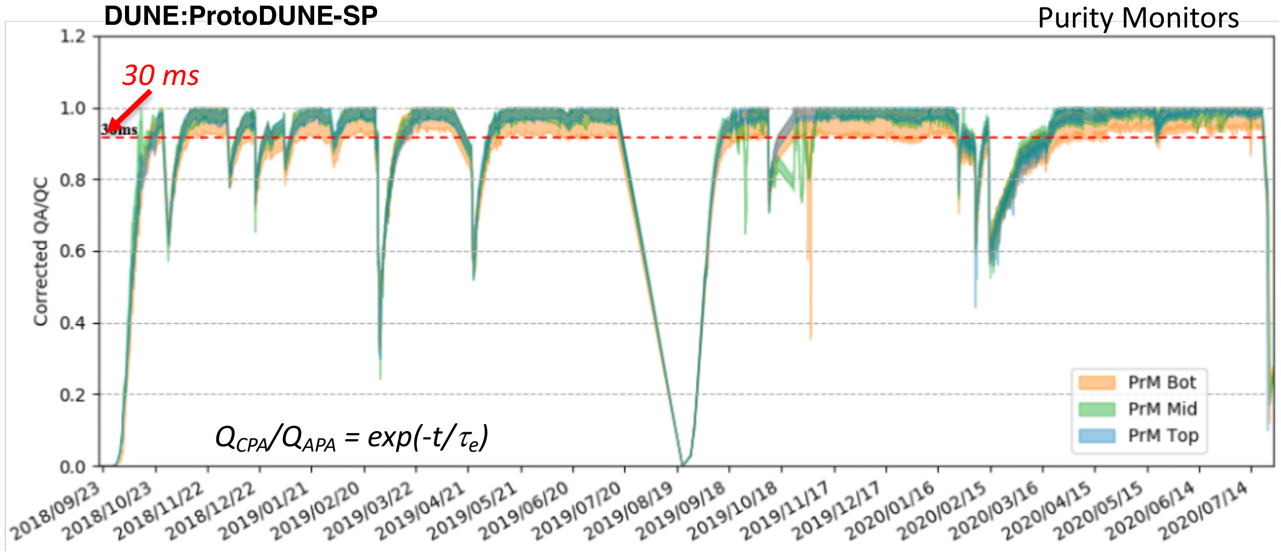


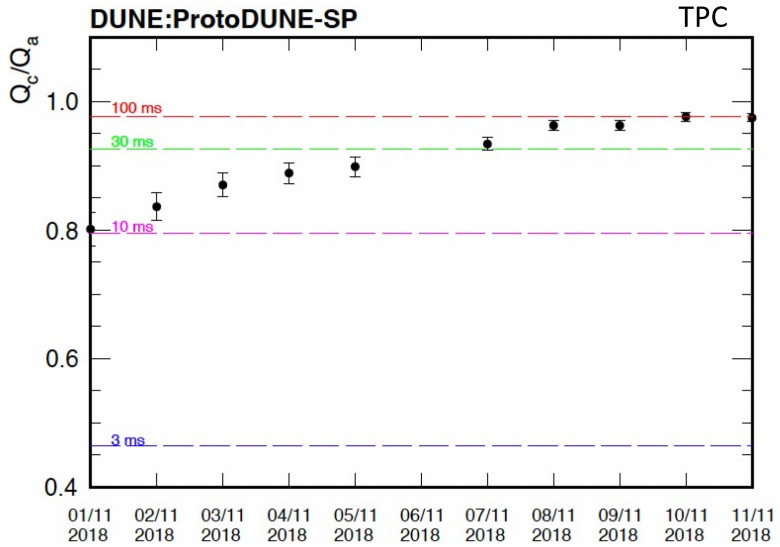
Detector stability – collected charge



PDSP Performance – LAr purity

- LAr purity measured through electron life-time (τ_e): an estimate of the survival rate of electrons while traveling through Argon and electronegative impurities (O_2, N_2, H_2O, CO_2, etc.)
- Purity monitors used during the entire data-taking. Fast, real-time feedback about the local LAr impurity concentration and possible sudden faults of the cryogenic system
- Purity monitor limited due to low field – alternative is to study crossing muons with the TPC. Results are corrected to take into account the different nominal E-field
- Sustained lifetimes >30 ms corresponding to 10 ppt O_2 equivalent. Achieved lifetimes >85 ms or 3.5 ppt.





Xenon doping – X-ARAPUCA

New Photon Detectors deployed for the test

- Array of SiPM with and without TPB
- Green-fibres with PEN foil readout by SiPM
- X-Arapuca : sensitive to LAr and Xe light
- X-Arapuca with Quartz window : sensitive to only Xe light
  - X-ARAPUCA evolution of the ARAPUCA detector
  - SiPMs on the side of the cells, instead of bottom
  - Possible double-sided sensitivity to light
  - Wavelength-shifting bar common to multiple cells -> enhanced light collection w.r.t. ARAPUCA