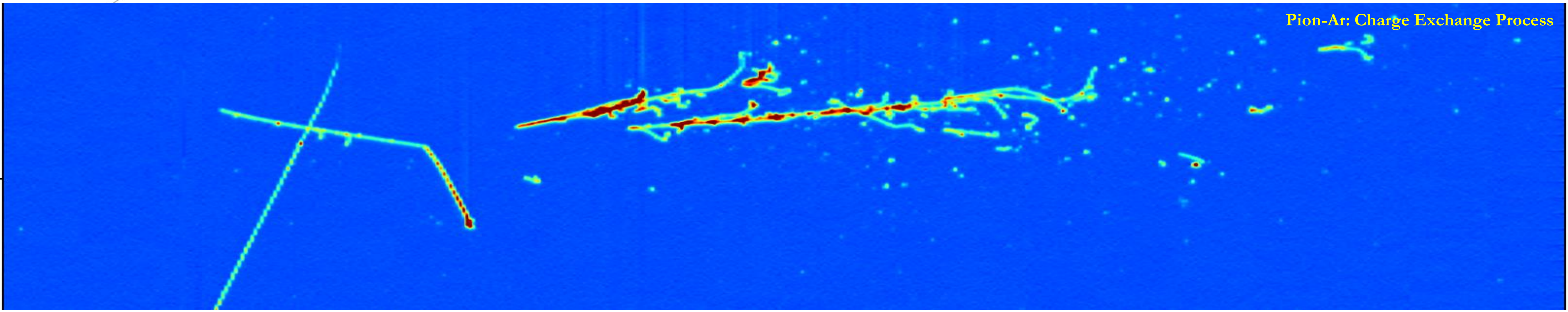



# First results on ProtoDUNE single-phase LArTPC performance

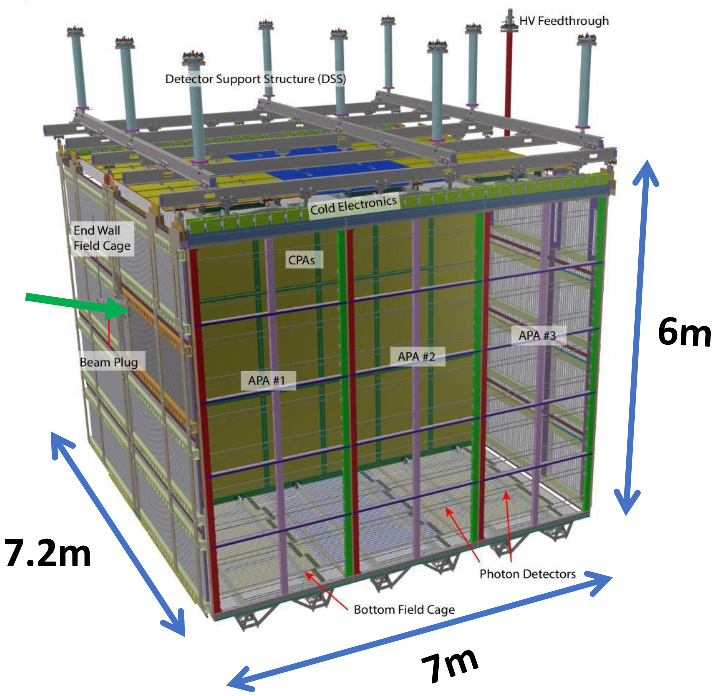
Wenqiang Gu

Brookhaven National Laboratory

arXiv:2007.06722 [physics.ins-det]

# Outline

- Deep Underground Neutrino Experiment (DUNE)
- Liquid Argon Time Projection Chamber (LArTPC)
  - History for LArTPC
  - Why Liquid Argon for DUNE?
  - Challenges for building multiple 10-kton detectors
- **ProtoDUNE-SP: single-phase prototype for DUNE**
  - Construction and operation
  - First results on the performance
  - Other ongoing analyses



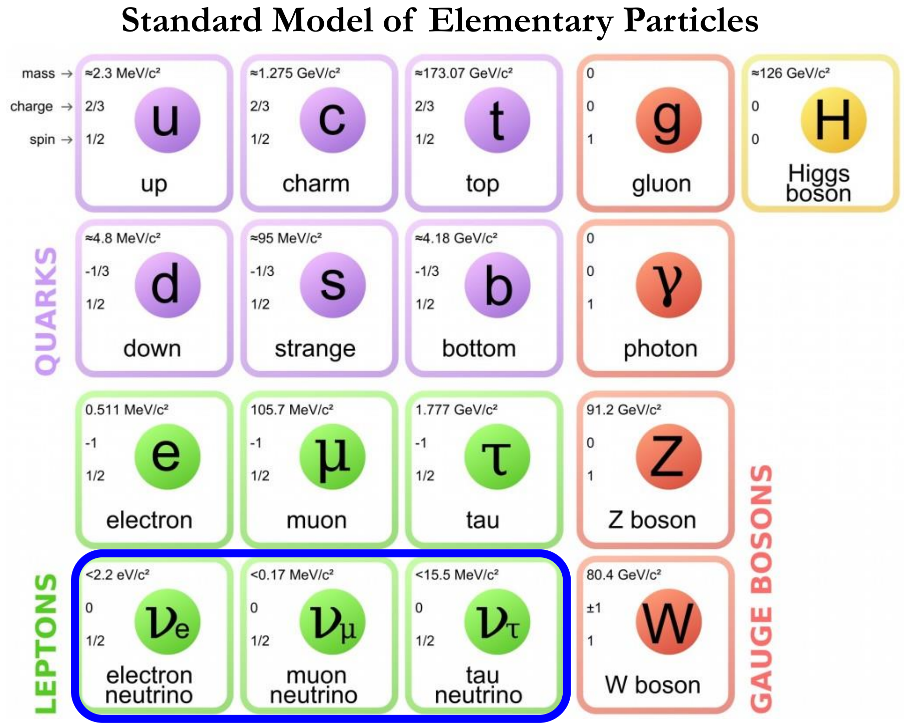
# Neutrino Oscillation

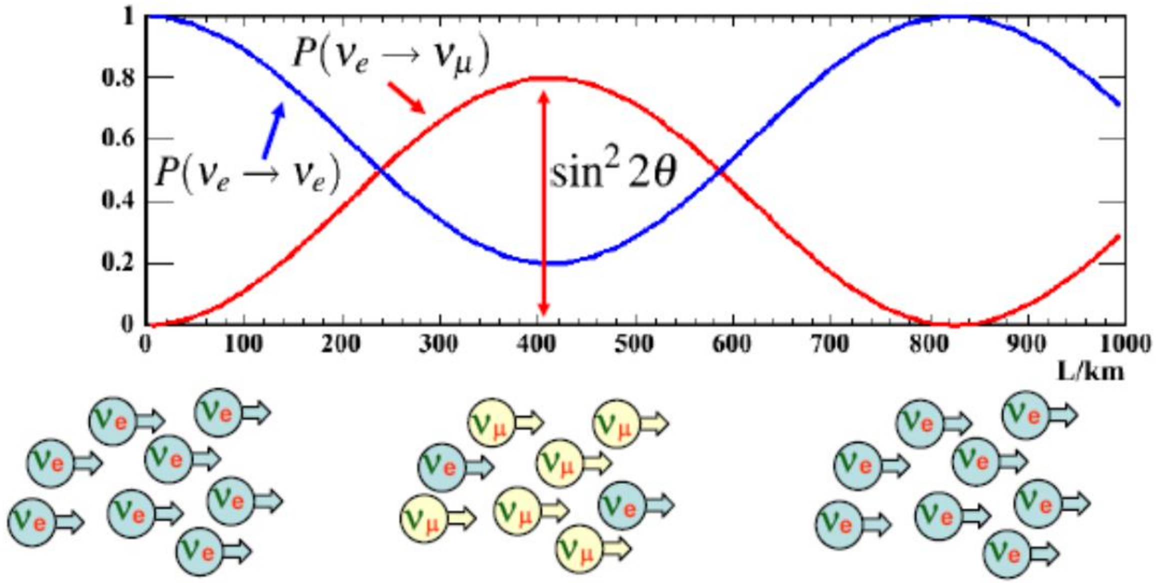
- Neutrinos can change one flavor to another because of lepton mixing

  ⇒ neutrinos have mass!

Mass splitting

$$P(\nu_\alpha \to \nu_\beta) = sin^2(2\theta) sin^2(1.27\Delta m^2 \frac{L}{E_\nu})$$

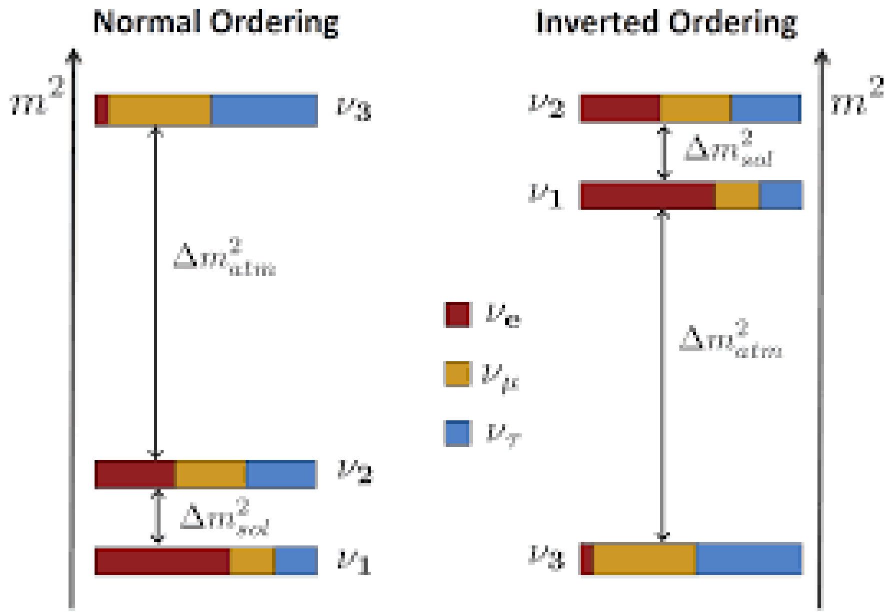


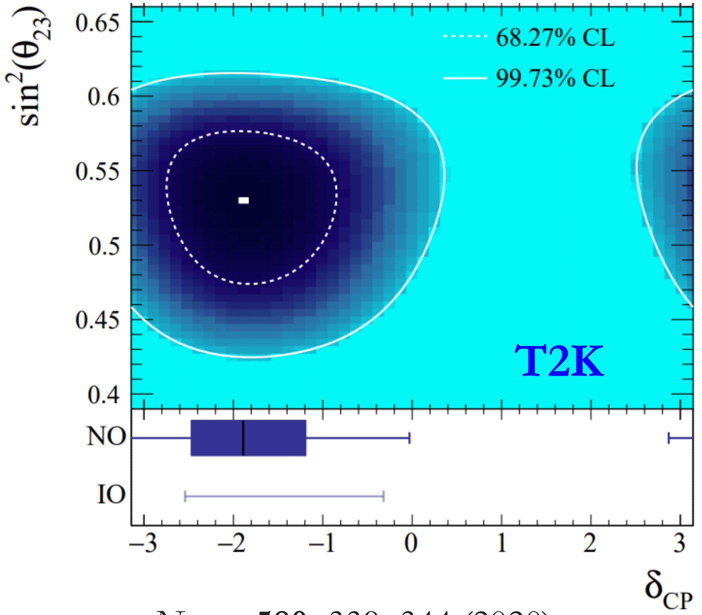



# Open Questions

- Is the neutrino mass ordering “normal” or “inverted”?
- Do neutrinos violate CP (charge-parity) ?

  ⇒ a non-zero $\delta_{\mathrm{CP}}$ could explain the matter anti-matter asymmetry in the universe

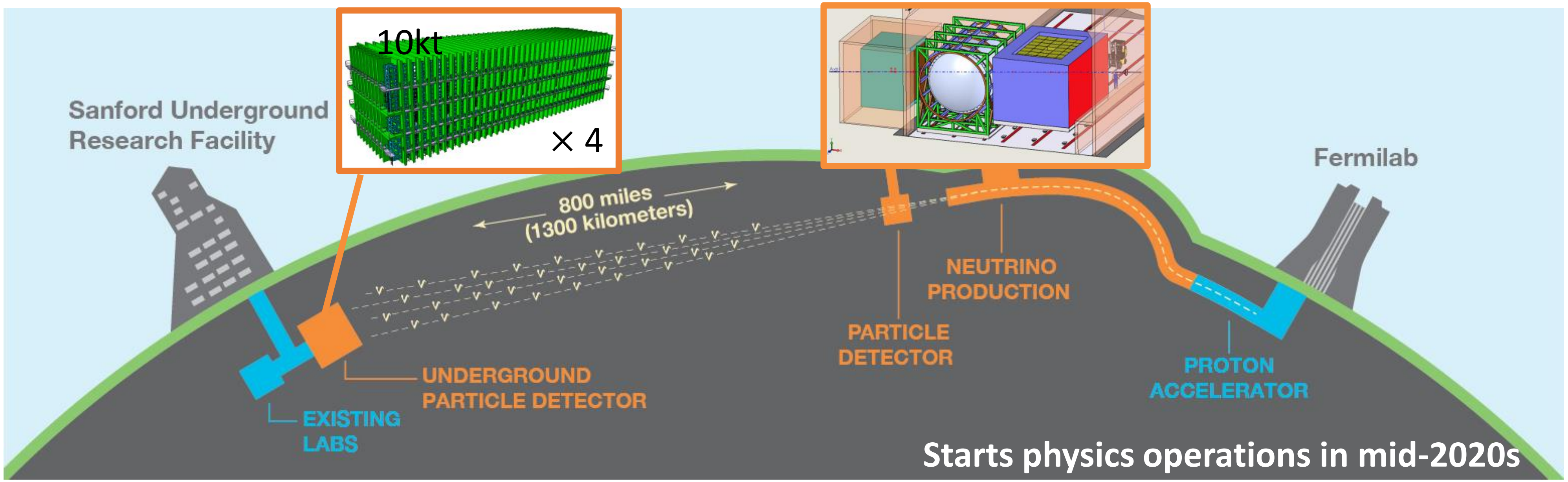



*Nature* **580,** 339–344 (2020)

# Introducing DUNE

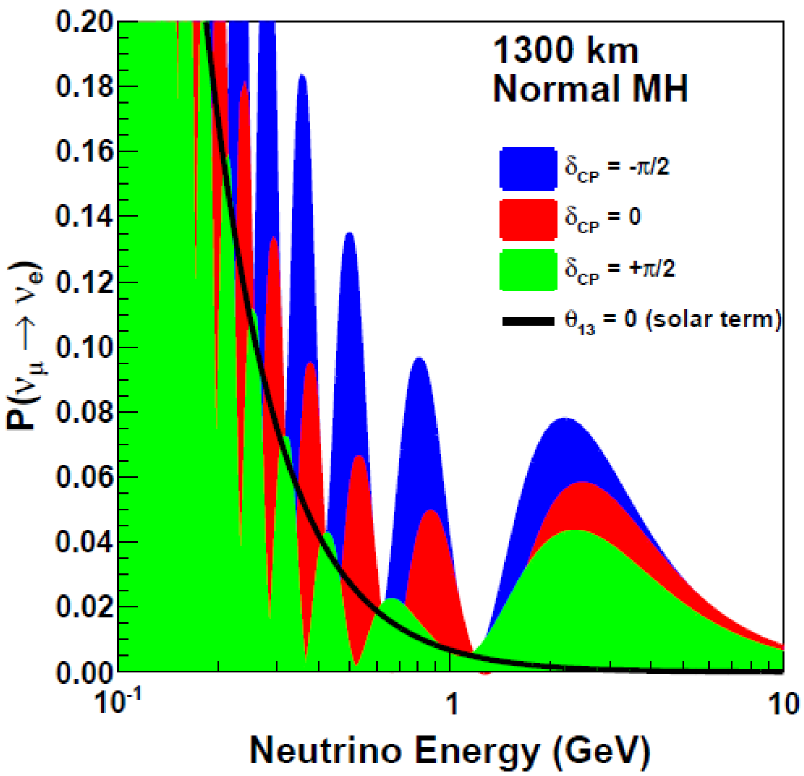
Technical Design Report on arXiv
Vol I: 2002.02967 | Vol II: 2002.03005
Vol III: 2002.03008 | Vol IV: 2002.03010

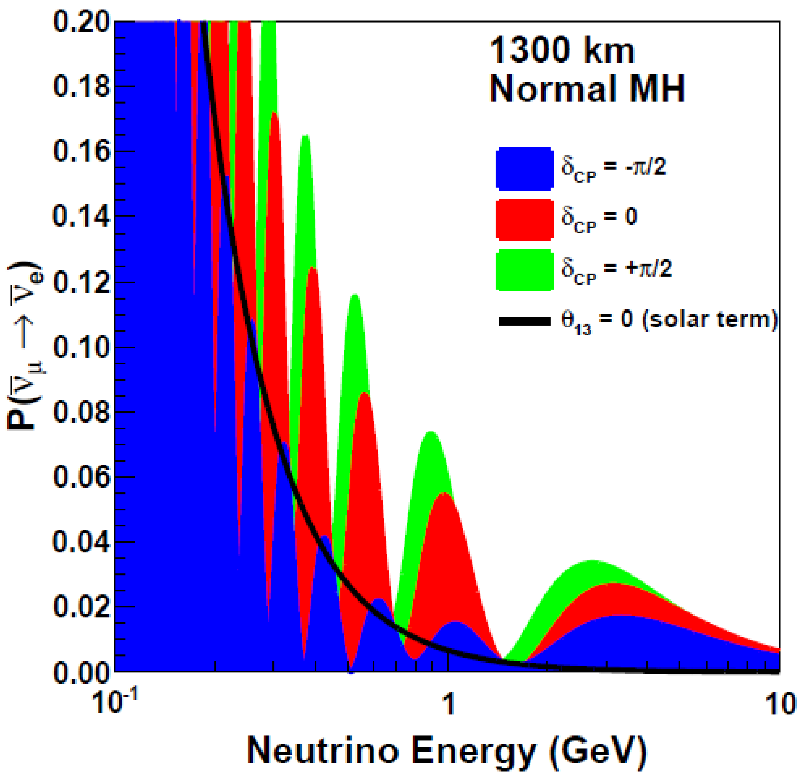



- "**D**eep **U**nderground **N**eutrino **E**xperiment"
  - 1300 km baseline, far detector 1.5 km underground
  - Large (4x10kt) **far detector** and near detector
  - Wide-band, on-axis neutrino beam
- Primary physics goals
  - $\nu$ oscillations ($\nu_e/\bar{\nu}_e$ appearance, $\nu_\mu/\bar{\nu}_\mu$ disappearance,)
    - $\boldsymbol{\delta_{\mathrm{CP}}}$ **,** $\boldsymbol{\nu}$ **mass ordering**, $\theta_{13}$, $\theta_{23}$
  - Nucleon decay
  - Supernova burst neutrinos
  - Solar neutrinos

# Oscillation Patterns of $\nu_\mu, \bar{\nu}_\mu$ Beams over 1300km

arXiv: 2002.03005




- DUNE is sensitive to CP violation and mass ordering
- 1300km baseline: large matter effect to solve mass ordering

$$
\begin{aligned}
P(\nu_\mu \to \nu_e) \simeq\ & \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2(\Delta_{31}-aL)}{(\Delta_{31}-aL)^2}\Delta_{31}^2 \\
& + \sin 2\theta_{23}\sin 2\theta_{13}\sin 2\theta_{12}\frac{\sin(\Delta_{31}-aL)}{(\Delta_{31}-aL)}\Delta_{31}\frac{\sin(aL)}{(aL)}\Delta_{21}\cos(\Delta_{31}+\delta_{CP}) \\
& + \cos^2\theta_{23}\sin^2 2\theta_{12}\frac{\sin^2(aL)}{(aL)^2}\Delta_{21}^2,
\end{aligned}
$$

$\boxed{a = G_F N_e/\sqrt{2}}$ → "Matter effect"

$\Delta_{ij} = \Delta m_{ij}^2 L/4E$

# DUNE Collaboration


- Over 1000 collaborators from 180+ institutions and 30+ countries (w/ CERN)!

# Liquid Argon TPC

# Early History of the Development of LArTPC

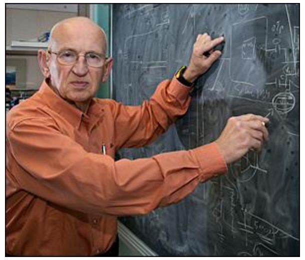
- **W. Willis and V. Radeka**, Liquid argon ionization chambers as total absorption detector, NIMA 120:221 (1974)

- **D. R. Nygren**, The Time Projection Chamber: A New 4π Detector for Charged Particles. eConf. C740805:58 (1974)

- **H. H. Chen** et al. A Neutrino detector sensitive to rare process. I. A study of neutrino electron reactions. FNAL-Proposal-0496 (1976)

- **C. Rubbia**, The liquid argon time projection chamber: a new concept for neutrino detector, CERN-EP/77-08 (1977)

William Willis



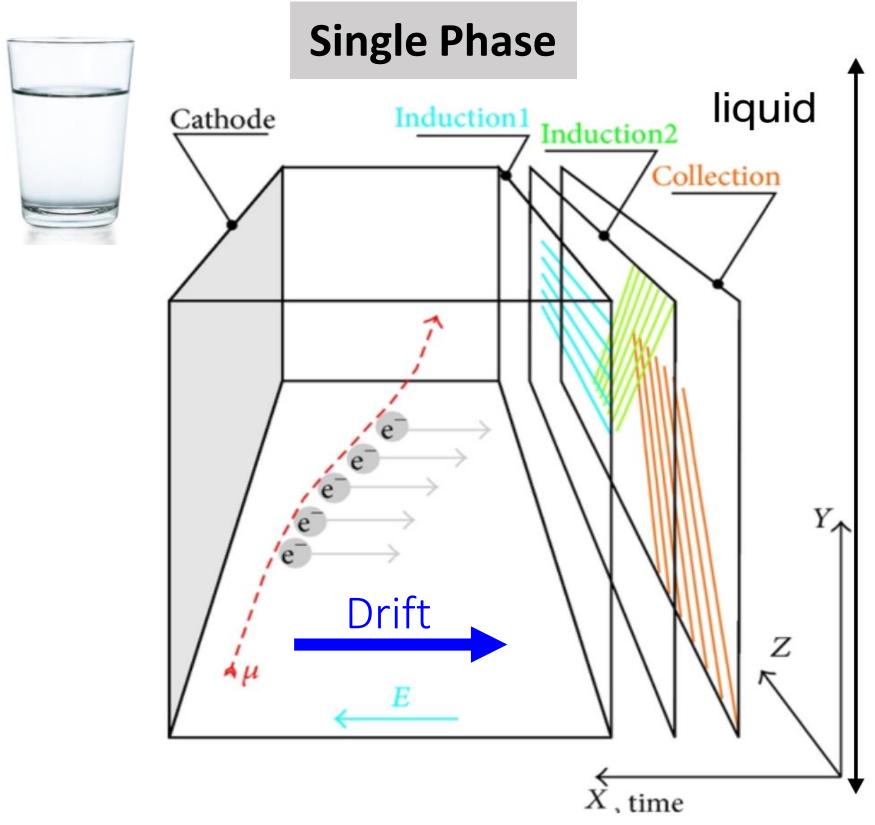
V. Radeka (BNL)

D. R. Nygren

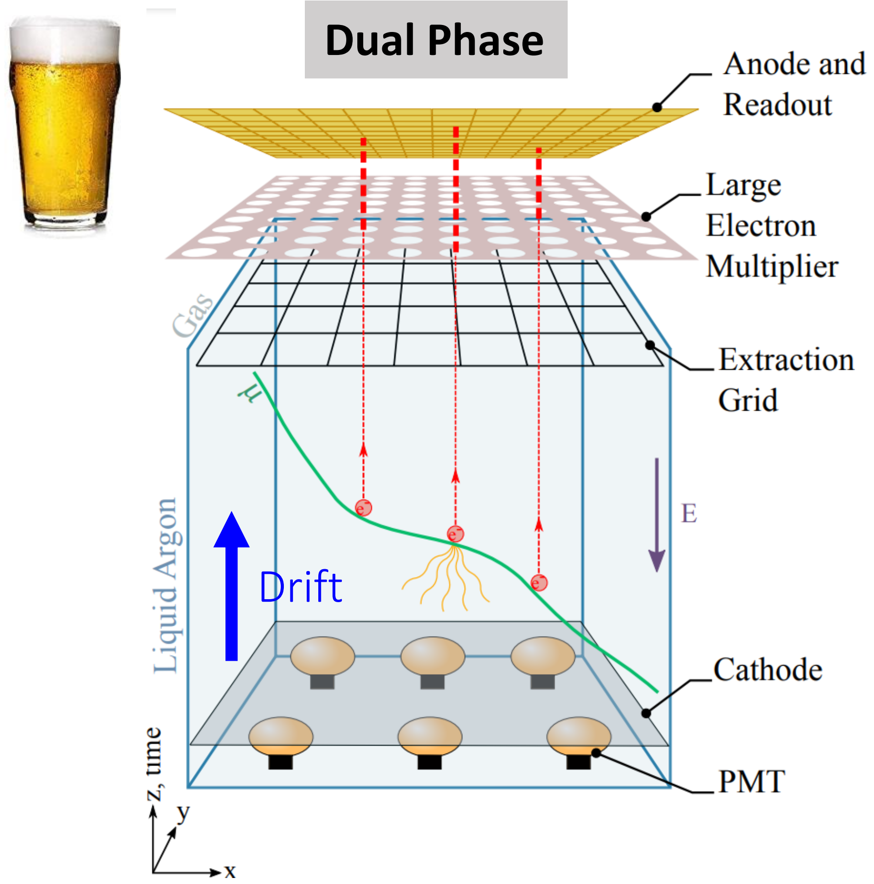
H. H. Chen

C. Rubbia

# LArTPC: Concepts



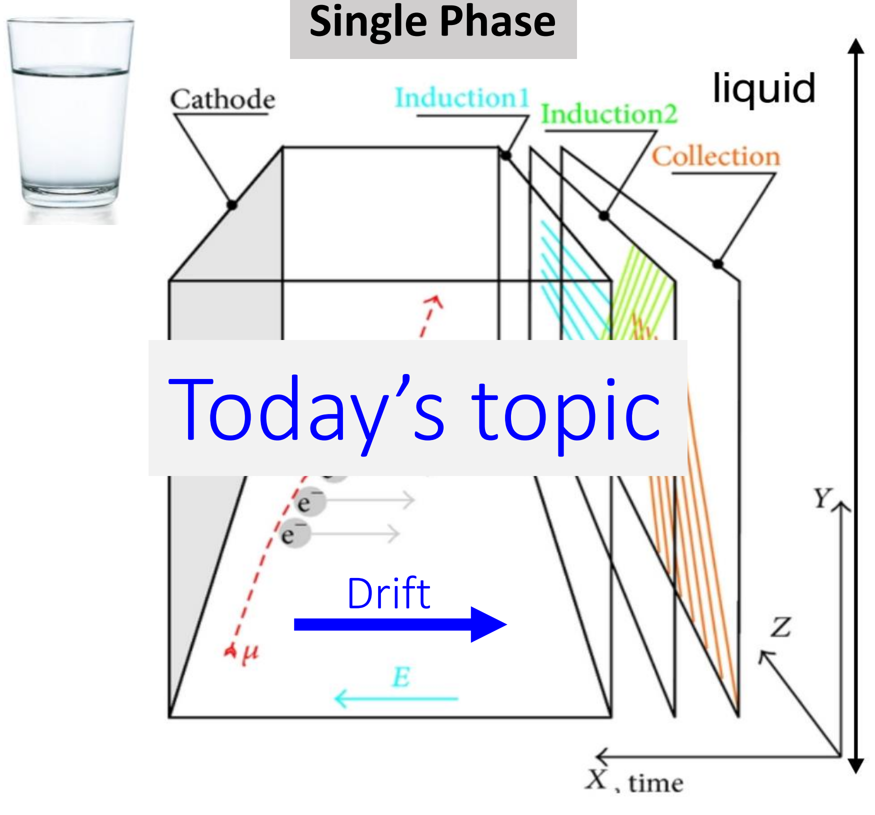

- Traditional design
- Horizontal drift in liquid Ar
- Three 1-D wire readout planes (two induction, one collection)




- Vertical drift in liquid Ar
- Amplification in gaseous Ar
- 2-D segmented readout

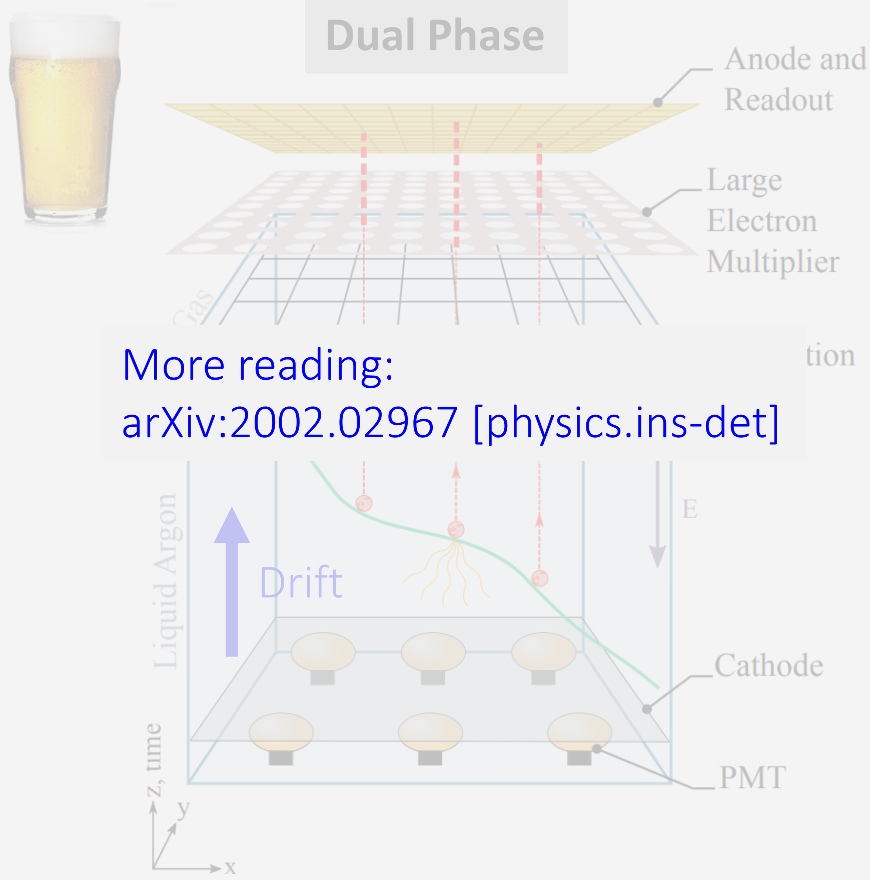
# LArTPC: Concepts

## Single Phase



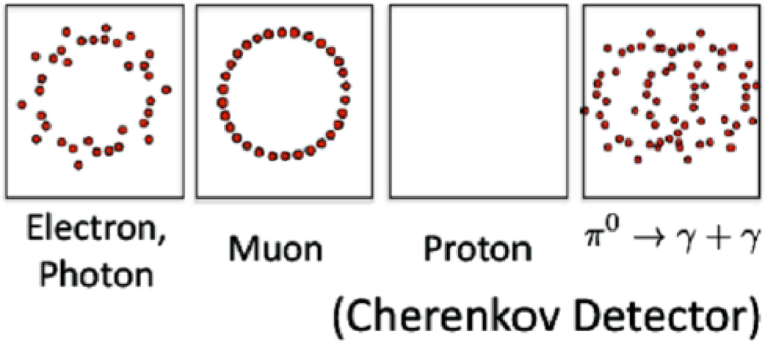

- Traditional design
- Horizontal drift in liquid Ar
- Three 1-D wire readout planes (two induction, one collection)

## Dual Phase



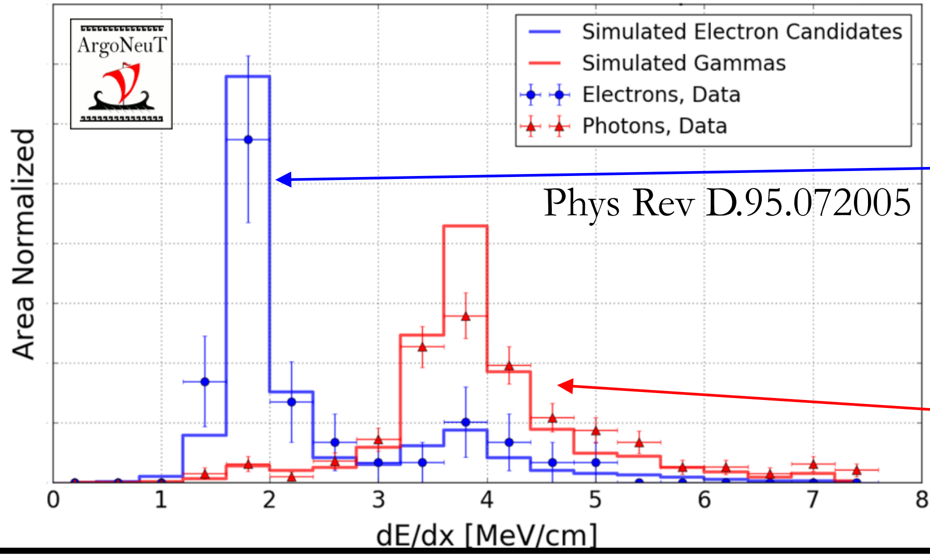

- Vertical drift in liquid Ar
- Amplification in gaseous Ar
- 2-D segmented readout

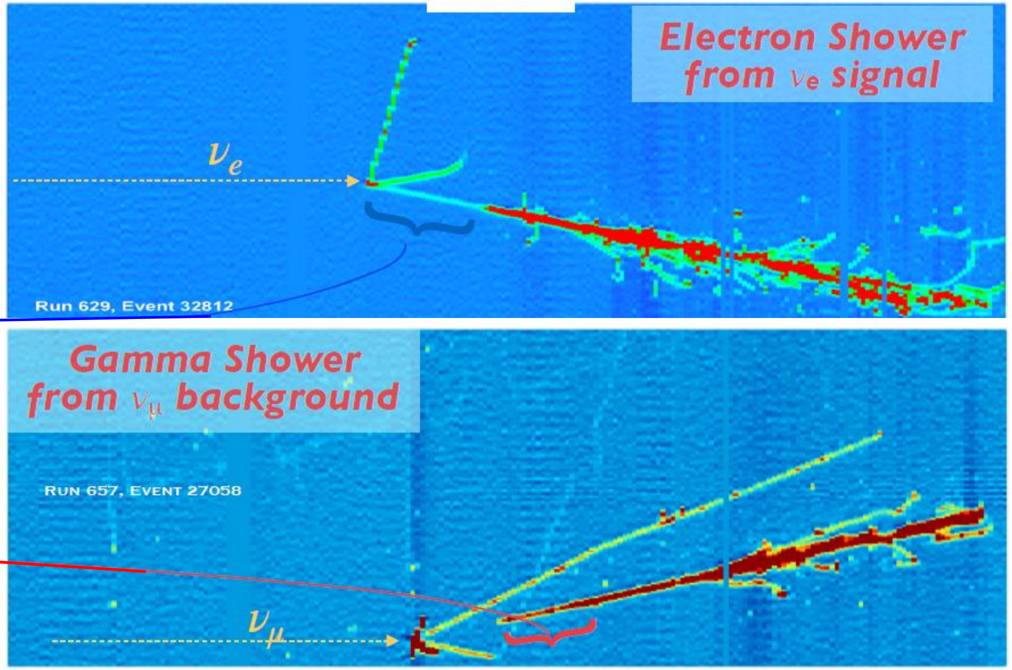
# Unique electron ID capability in LArTPC




- Bubble chamber: sacrifice mass & calorimetry for topology
- Cherenkov: sacrifice topology for mass & calorimetry
- Large sampling calorimeters: middle ground solution, coarse resolution, not fully active

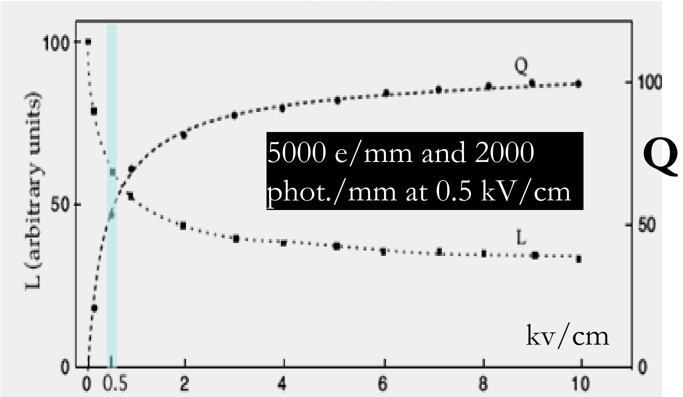
- LArTPC: powerful e/γ separation for $\nu_e$CC interaction via gap identification + dE/dx



# Why Liquid Argon?

- Most abundant noble element on earth
- Relatively dense target (more $\nu$-N interactions)
- High scintillation light yield
- Relatively small radiation length for shower containment



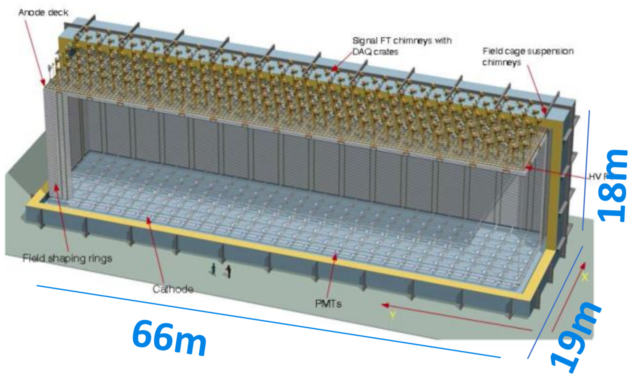

| | He | Ne | Ar | Kr | Xe | Water |
|---|---|---|---|---|---|---|
| Atomic Number | 2 | 10 | 18 | 36 | 54 | |
| Boiling Point [K] @ 1atm | 4.2 | 27.1 | 87.3 | 120 | 165 | 373 |
| Density [g/cm$^3$] | 0.125 | 1.2 | 1.4 | 2.4 | 3 | 1 |
| Radiation Length [cm] | 755.2 | 24 | 14 | 4.9 | 2.8 | 36.1 |
| dE/dx [MeV/cm] | 0.24 | 1.4 | 2.1 | 3 | 3.8 | 1.9 |
| Scintillation [$\gamma$/MeV] | 19,000 | 30,000 | 40,000 | 25,000 | 42,000 | |
| Scintillation $\lambda$ [nm] | 80 | 78 | 128 | 150 | 175 | |
| Cost ($/kg) | 52 | 330 | 5 | 330 | 1200 | |

# Liquid Argon TPC for DUNE?

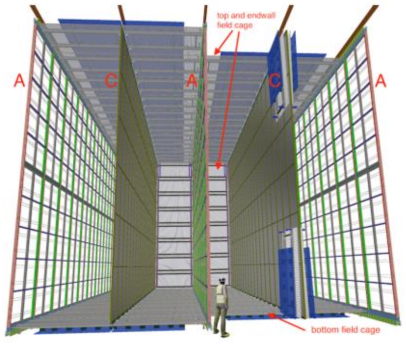
- DUNE physics program requires detector technology with:
  - **Excellent Calorimetry**
    - Important for precise estimation of neutrino energy, particle ID with dE/dx
  - **High Spatial Resolution**
    - Allows for e/γ separation and background rejection
  - **Low Threshold**
    - Important for detecting low-energy particles
    - e.g., supernova/solar neutrino detection
  - **Scalability**
    - Large detectors yielding high event rate for precision physics measurements
- These are all traits of the Liquid Argon Time Projection Chamber (LArTPC)

# DUNE Far Detector Module

- Four 10-kton modules deployed in stages
- Two designs being considered: single-phase and dual-phase LArTPC
  - Single phase will be the first module
  - $4^{th}$ module: module of opportunity
- Single phase design uses modular drift cells (scalable)
  - Suspended Anode and Cathode Plane Assemblies (APAs and CPAs)
  - 3.6 m drift, 500 V/cm E-field; **photon detectors** for triggering non-beam events

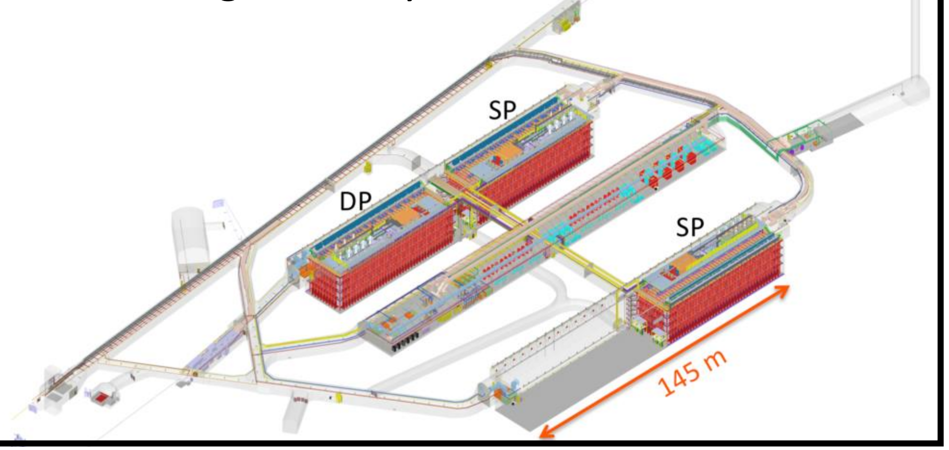


Dual-phase LArTPC

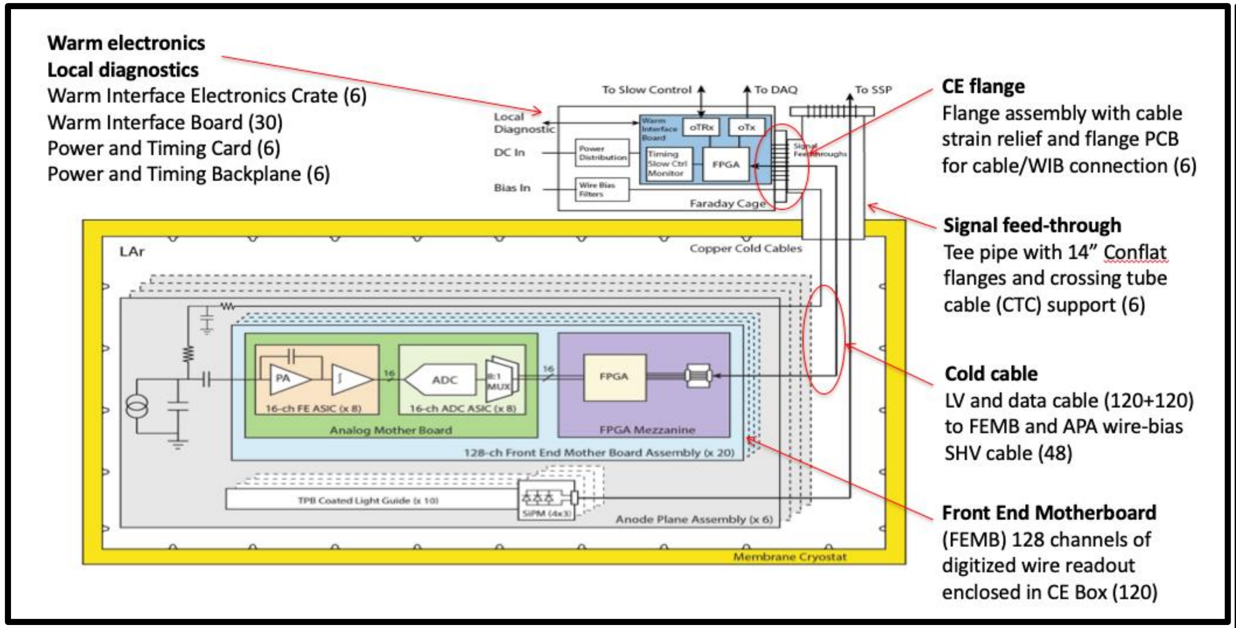


Single-phase LArTPC

Underground layout: four 10-kt modules



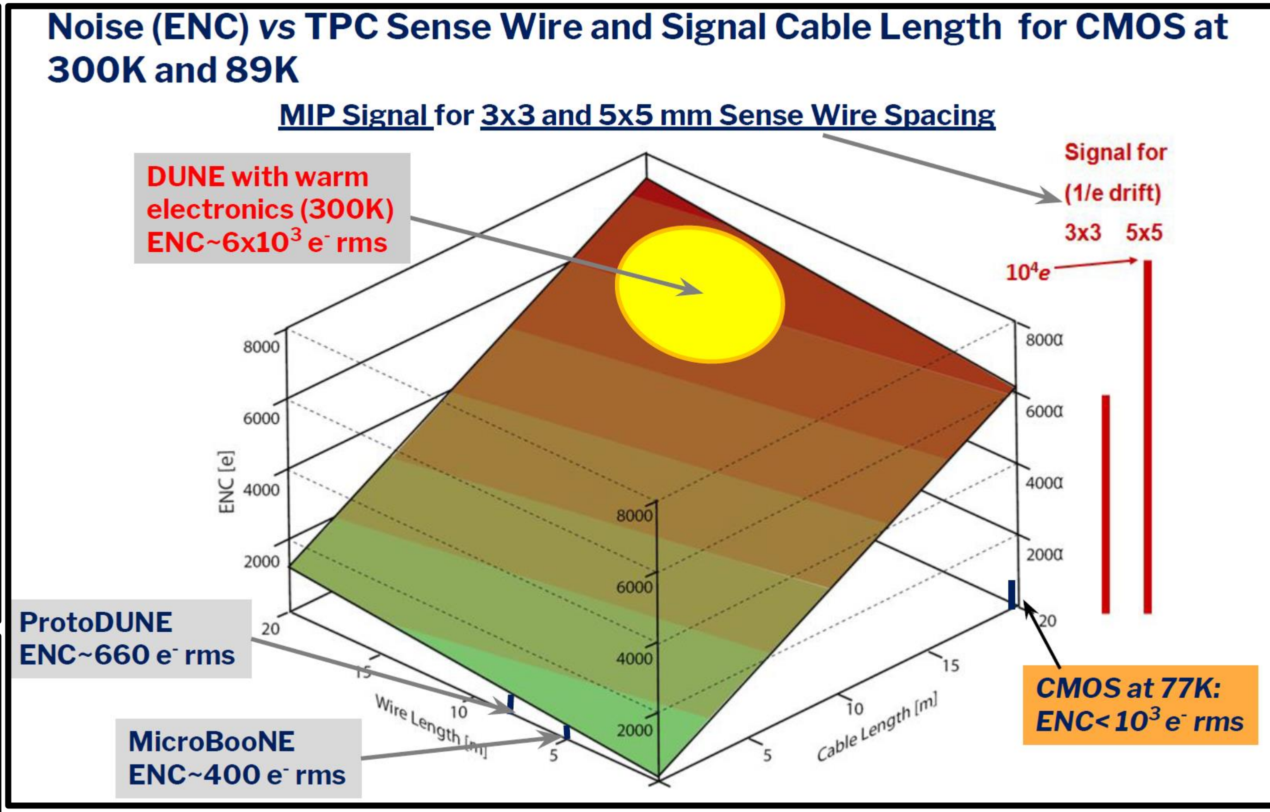
# Enabling technology: Cold Readout Electronics




**Cold electronics for "Giant" Liquid Argon Time Projection Chambers**

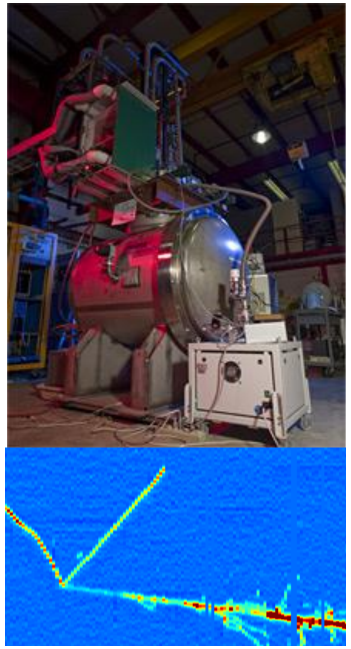
Veljko Radeka[1*], Hucheng Chen[1], Grzegorz Deptuch[2], Gianluigi De Geronimo[1], Francesco Lanni[1], Shaorui Li[1], Neena Nambiar[1], Sergio Rescia[1], Craig Thorn[1], Ray Yarema[2], Bo Yu[1]

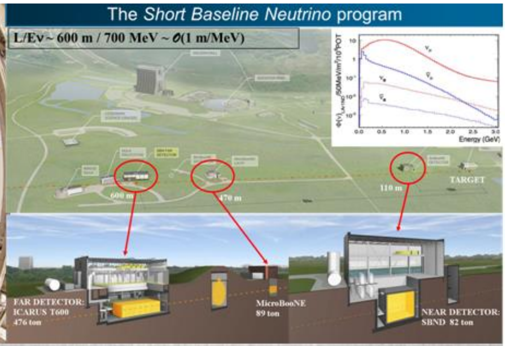
1st International Workshop towards the Giant Liquid Argon Charge Imaging Experiment (2011)

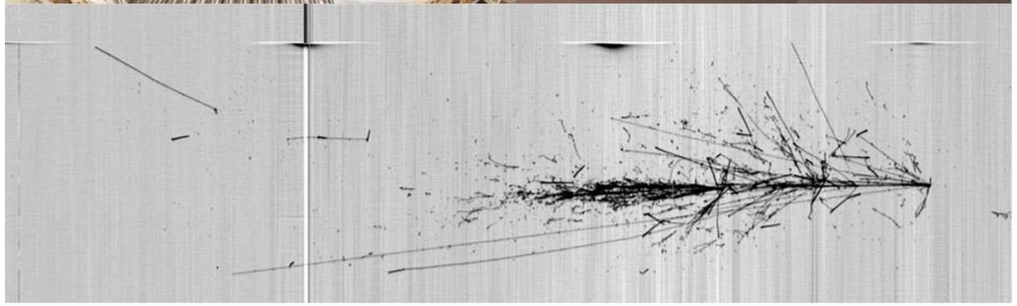


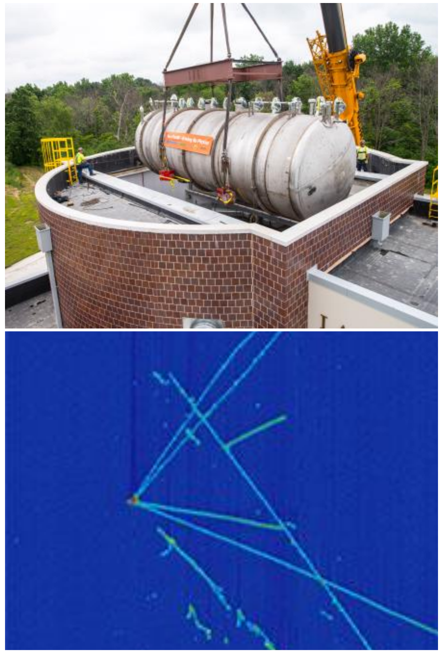

- Place the cold electronics inside of the LAr cryostat ⇒ reduce electronics noise to ~ 660 ENC
- Cold electronics developed at BNL is an **enabling technology** to make giant LAr TPC realizable

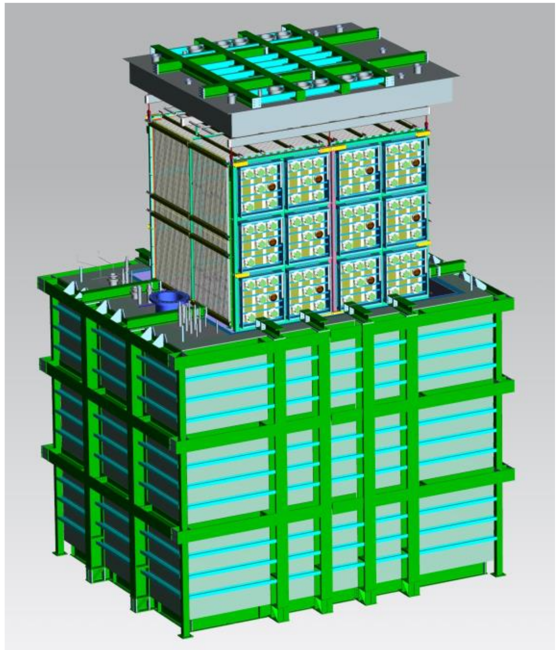
# LArTPC Development for Neutrino Physics









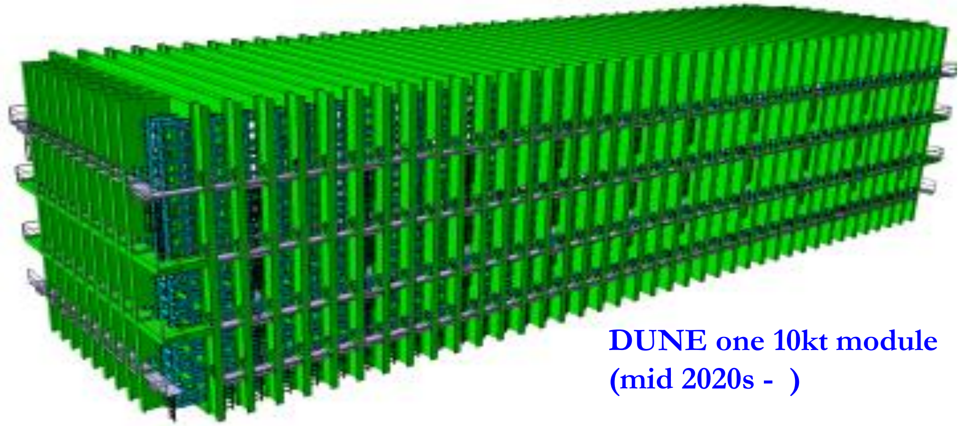
ArgoNeuT 0.5t
FNAL NUMI (2009-2010)

ICARUS 300t x2
- CERN CNGS (2010-13)
- FNAL BNB (commissioning)

MicroBooNE 100t
FNAL BNB (2015 - present)

SBND 200t
FNAL BNB (under construction)

- Despite many earlier developments, there is still a large gap in target mass
- Are we ready for building multiple 10-kt modules ?



DUNE one 10kt module
(mid 2020s - )

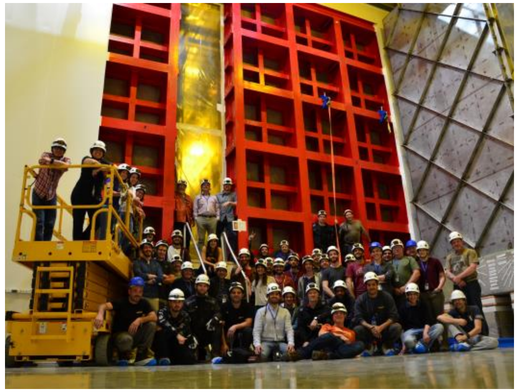
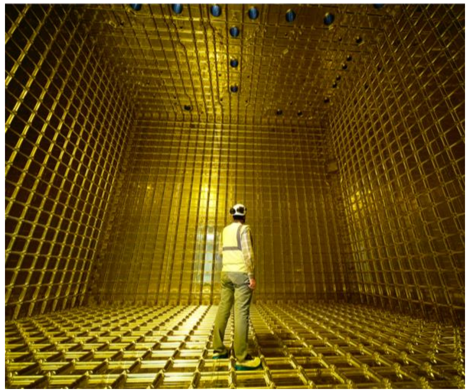
# DUNE’s Challenges

- Scale up in size
  - Cryostat for 10-kton fiducial, a huge step up from ICARUS & MicroBooNE’s O(100t)
- Underground location & expected duration of the experiment
  - Assembly in underground and no access (no maintenance/repair for ~20yrs) – somehow similar constraints as for HEP experiments in space
- Technical challenges
  - Longer drift and more stringent requirements on:
    - HV system: higher voltage than all the existing LArTPCs
    - LAr purity
  - Detector stability over time: cold electronics/TPC, photon sensors
  - Overall mechanical engineering
  - …
- Solution to prove the Far Detector design: build a large-scale 1-kton prototype

# The single-phase prototype

# ProtoDUNE Single Phase (SP)

- A **0.42-kt** (fiducial mass) LArTPC at the CERN Neutrino Platform
  - World largest monolithic single-phase LArTPC
- Prototypes DUNE far detector (FD) components design at **1: 1 scale**
- Started operation in late 2018
- Exposed to cosmic ray & a charged particle beam (0.3 - 7 GeV)
  - Demonstrate capability of particle identification
  - Control over DUNE systematics on Hadron-Ar cross section


# ProtoDUNE-SP Overview

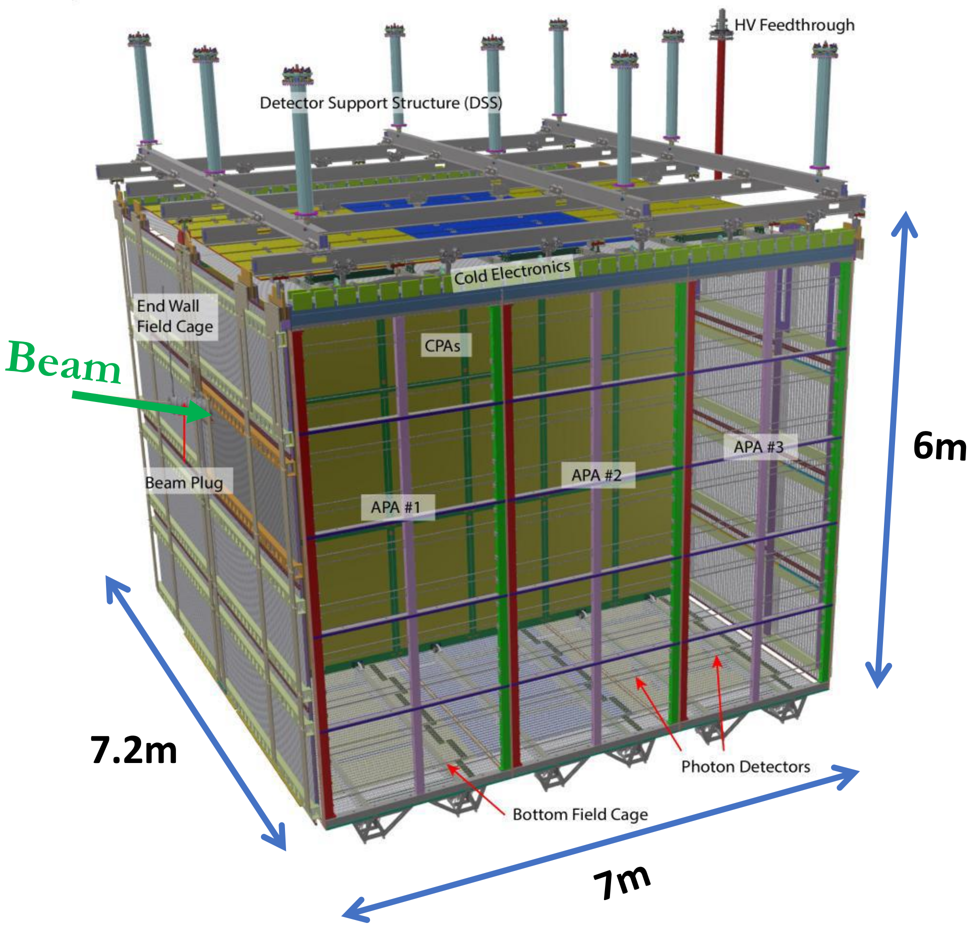
- **6 Anode Plane Assemblies (APAs)**
  - Total **15,360** TPC sense wires/channels with ~ 5mm pitch

  *99.74%: active channels*

- **3 Cathode Plane Assemblies (CPA)**
  - Resistive Kapton laminated on dielectric panels
  - 180 kV nominal (2 x 3.6 m drift @ 500 V/cm)

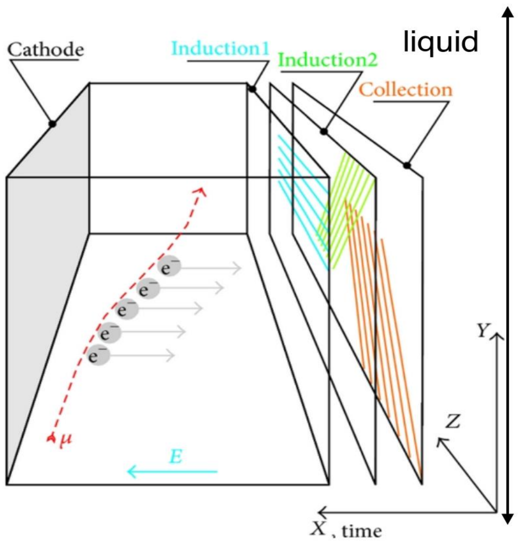
  *Highest voltage in all LArTPCs to date*

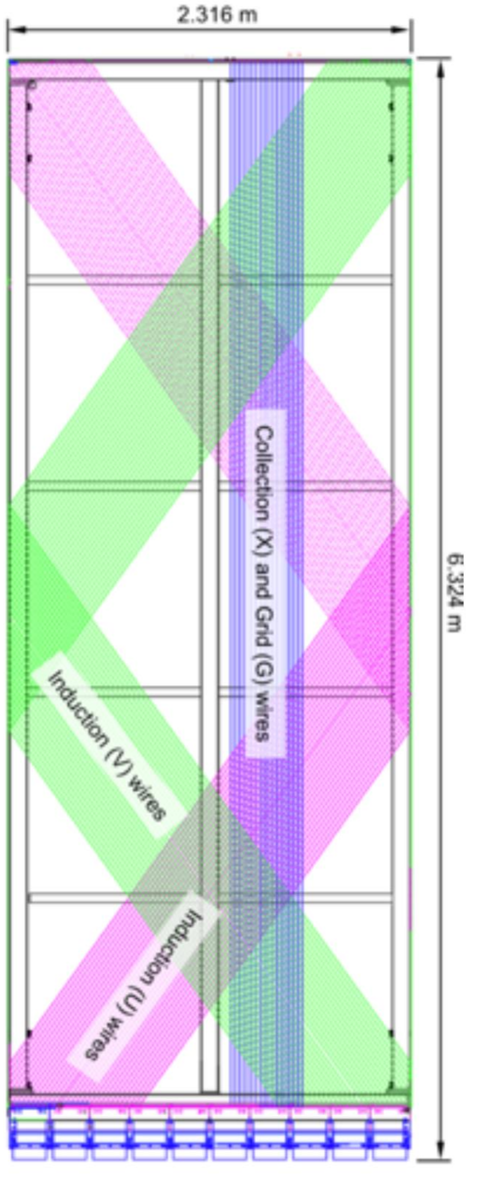
- **3 Types of Photon Detectors**
  - Light collecting bars read out by SiPMs installed in the APA frame (10 detectors/APA)



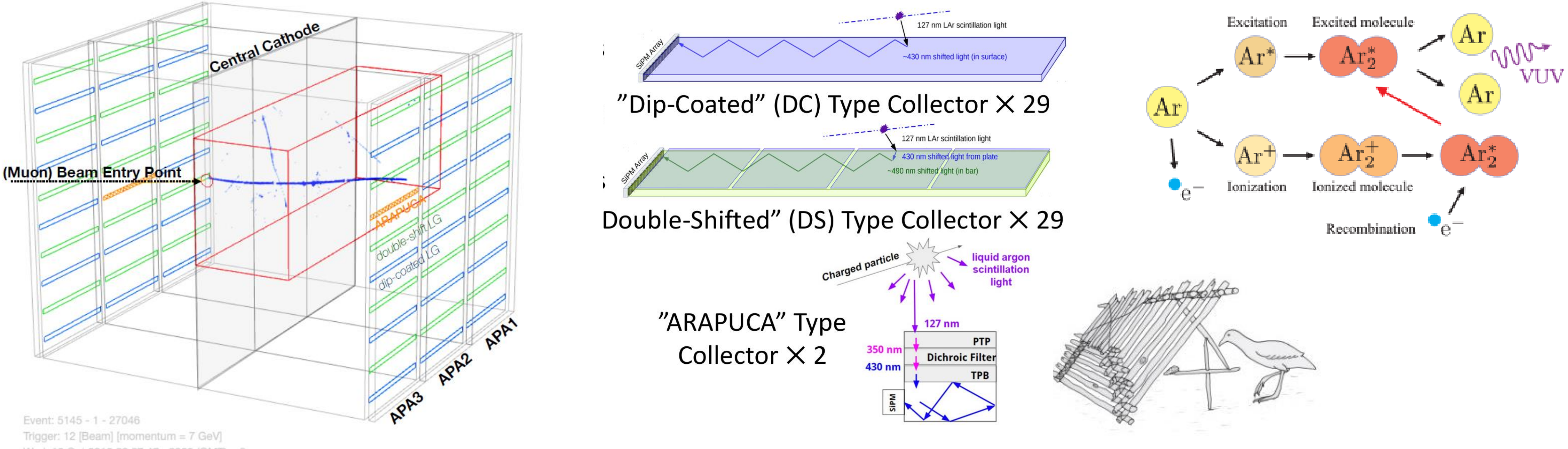
# Anode Plane Assembly (APA)

- Wrapped wires: reduce number of readout channels, cabling complexity
- For a 2560-channel anode (5mm pitch), 2D pixel readout requires half million channels
- Saves cost and power consumption of electronics inside LAr



# Photon Detection System (PDS)




- Three types of photon detection units (60 in total, 10 per APA)
  - Detect prompt ($\tau \approx 6$ ms) and late ($\tau \approx 1500$ ns) scintillation light
- Provide timing information ($t_0$) for non-beam triggered particle
  - Key for proton decay, supernova/solar neutrino physics

# The CERN Neutrino Platform

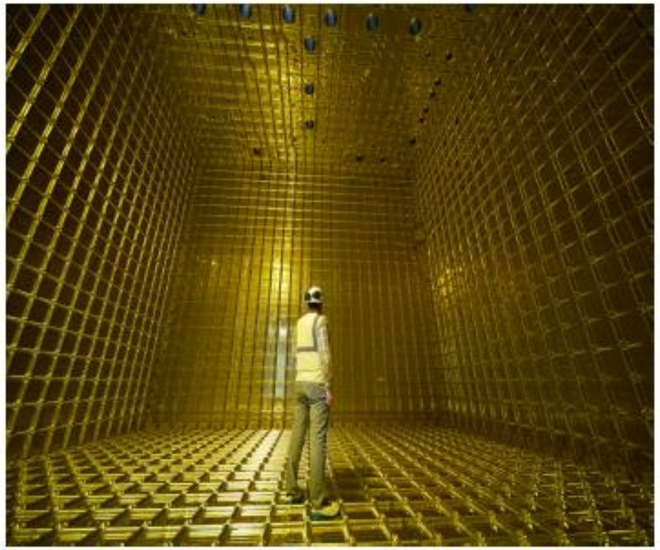
- A new dedicated experimental facility

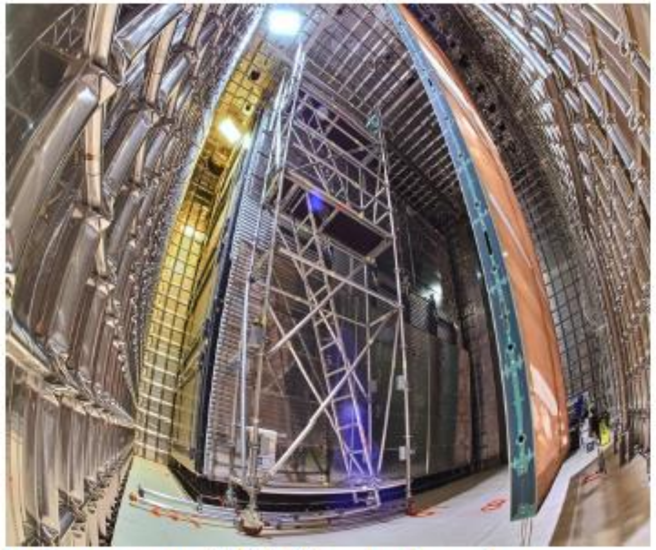
**Dec. 12, 2015**

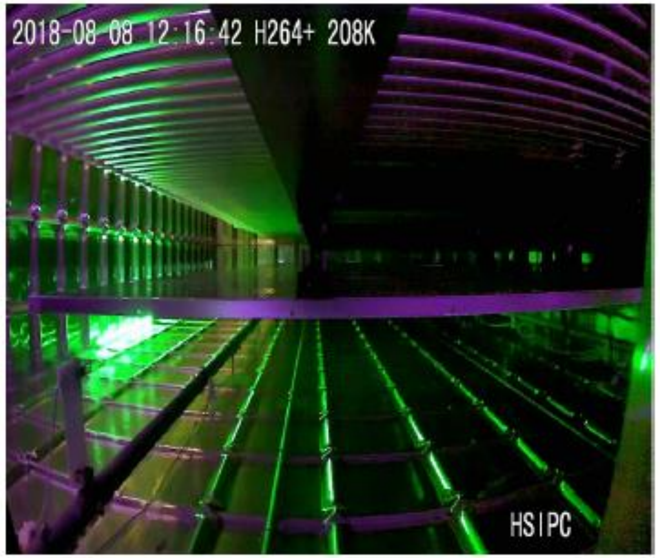
**Sept. 21, 2018**

March 2016, construction of EHN1 extension


November 2016, cryostat structure assembly


September 2017, cryostat completion


February 2018, detector assembly

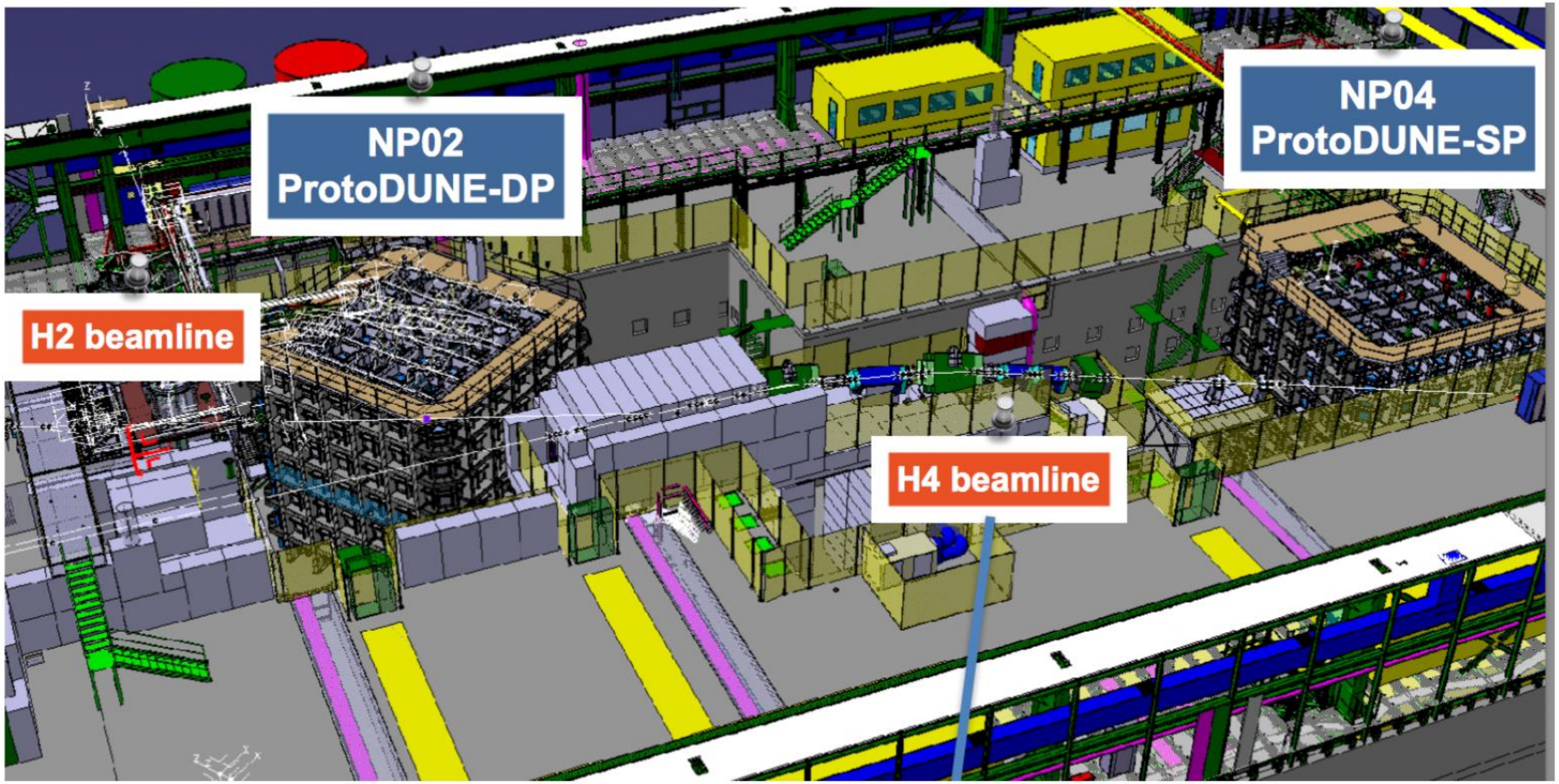


August 2018, LAr filling


September 19, 2018 - ready for beam!

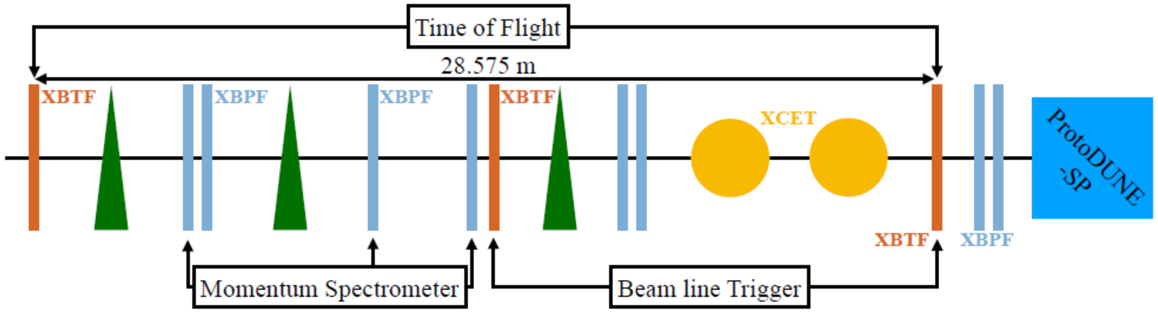
# ProtoDUNE at CERN Neutrino Platform

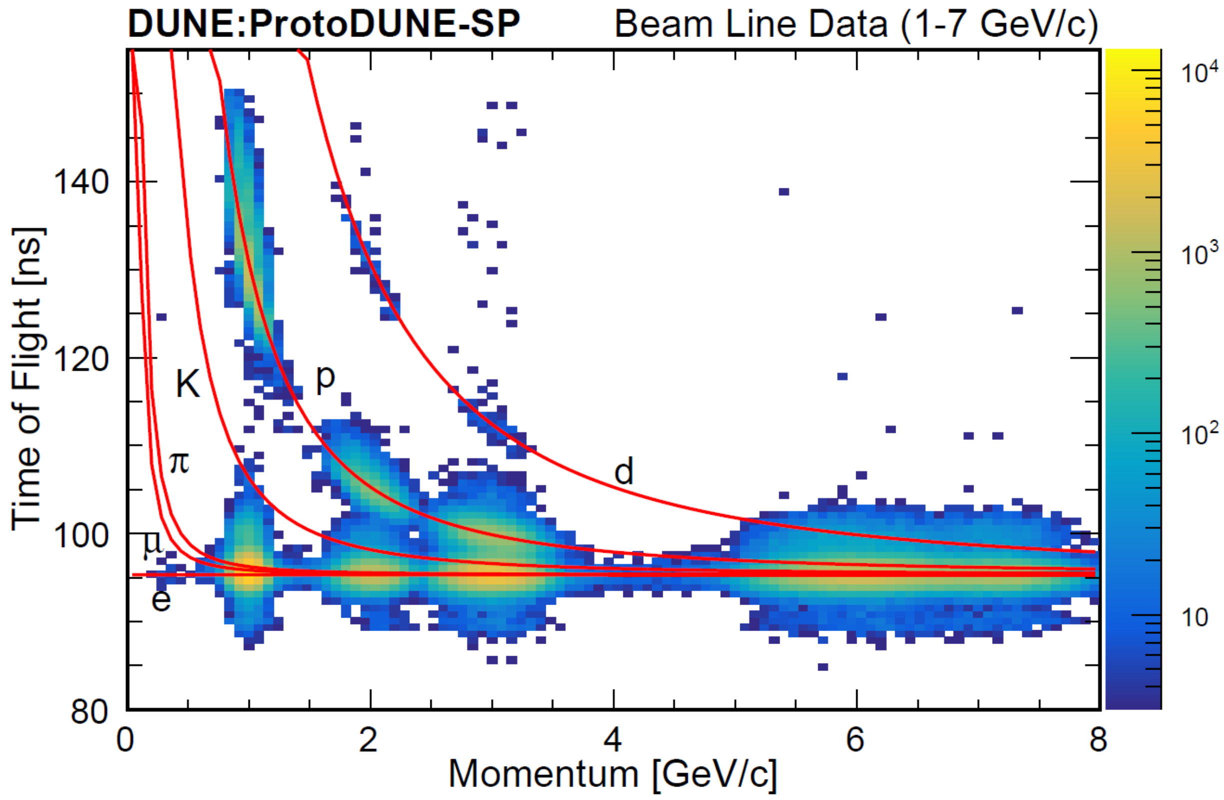
- The ProtoDUNE-SP is in a tertiary extension branch of the H4 beamline in the CERN EH1N extension



# ProtoDUNE-SP on the Beamline

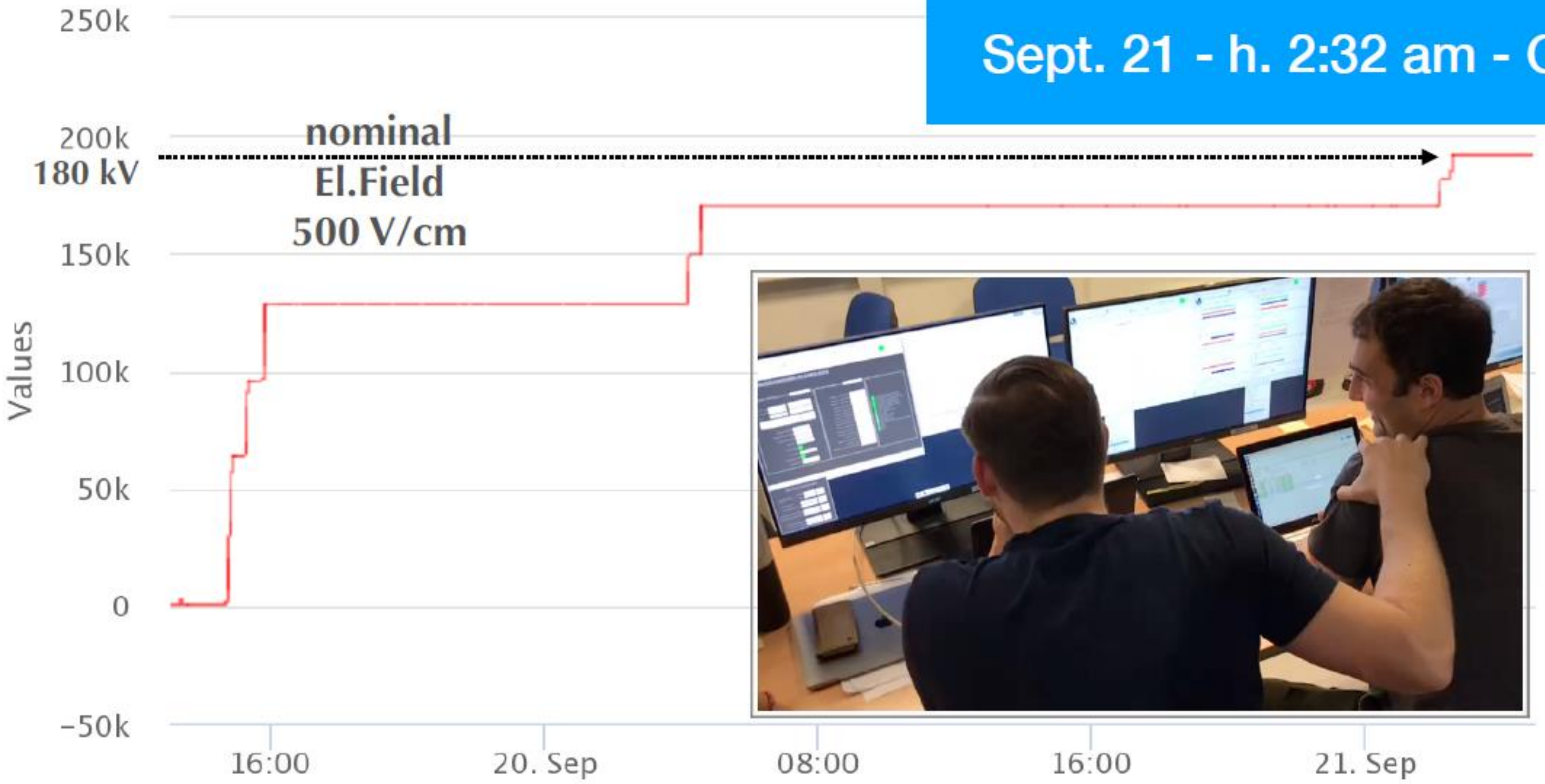
- Tertiary beam with momentum range: 0.3~7 GeV/c
- Spectrometer to measure the particle momenta
- Particle ID from time of flight and two Cherenkov detectors
- Over 4 million beam triggers of charged particles



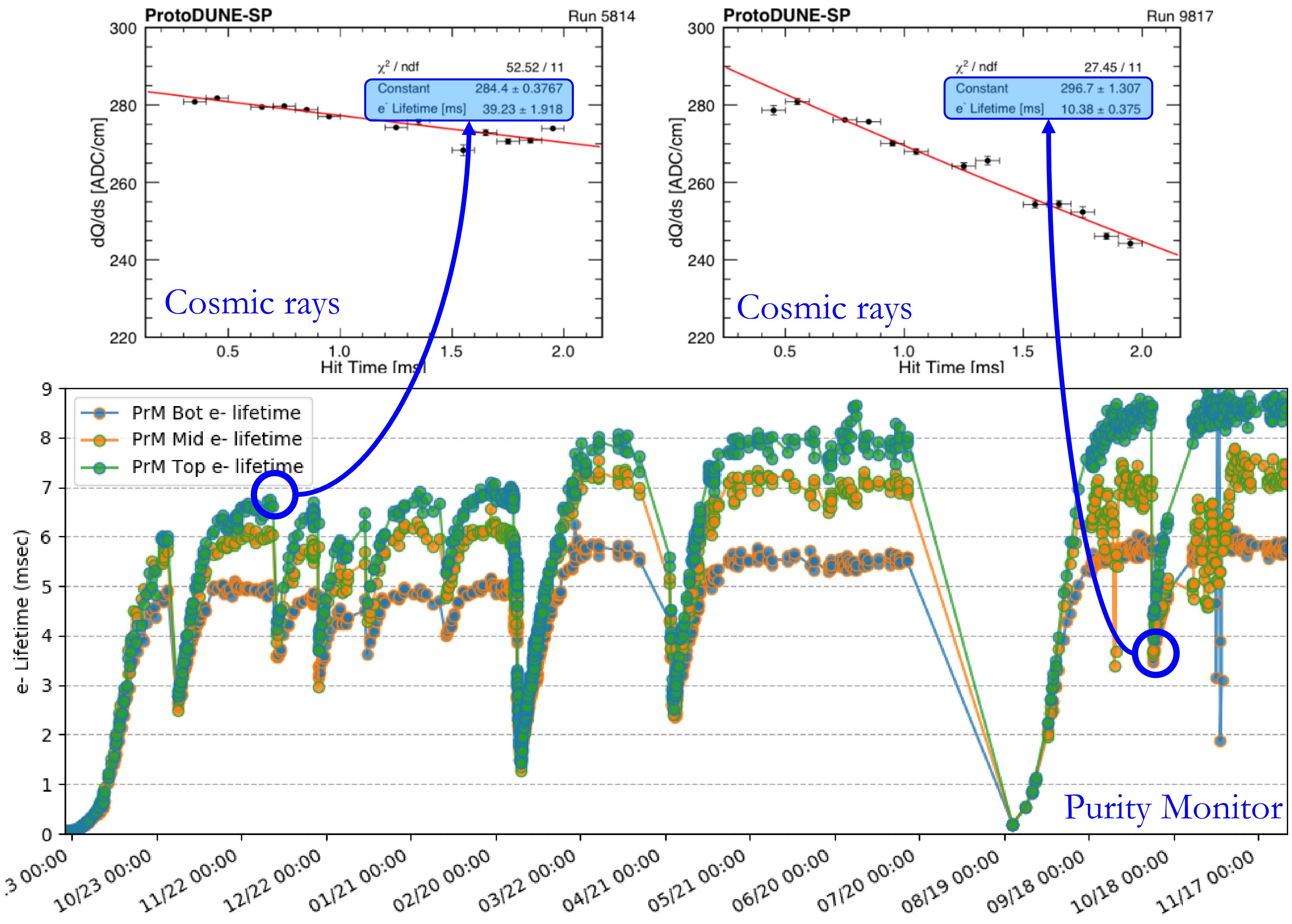
# Successful High Voltage System

**Sept. 21 - h. 2:32 am - CDT**

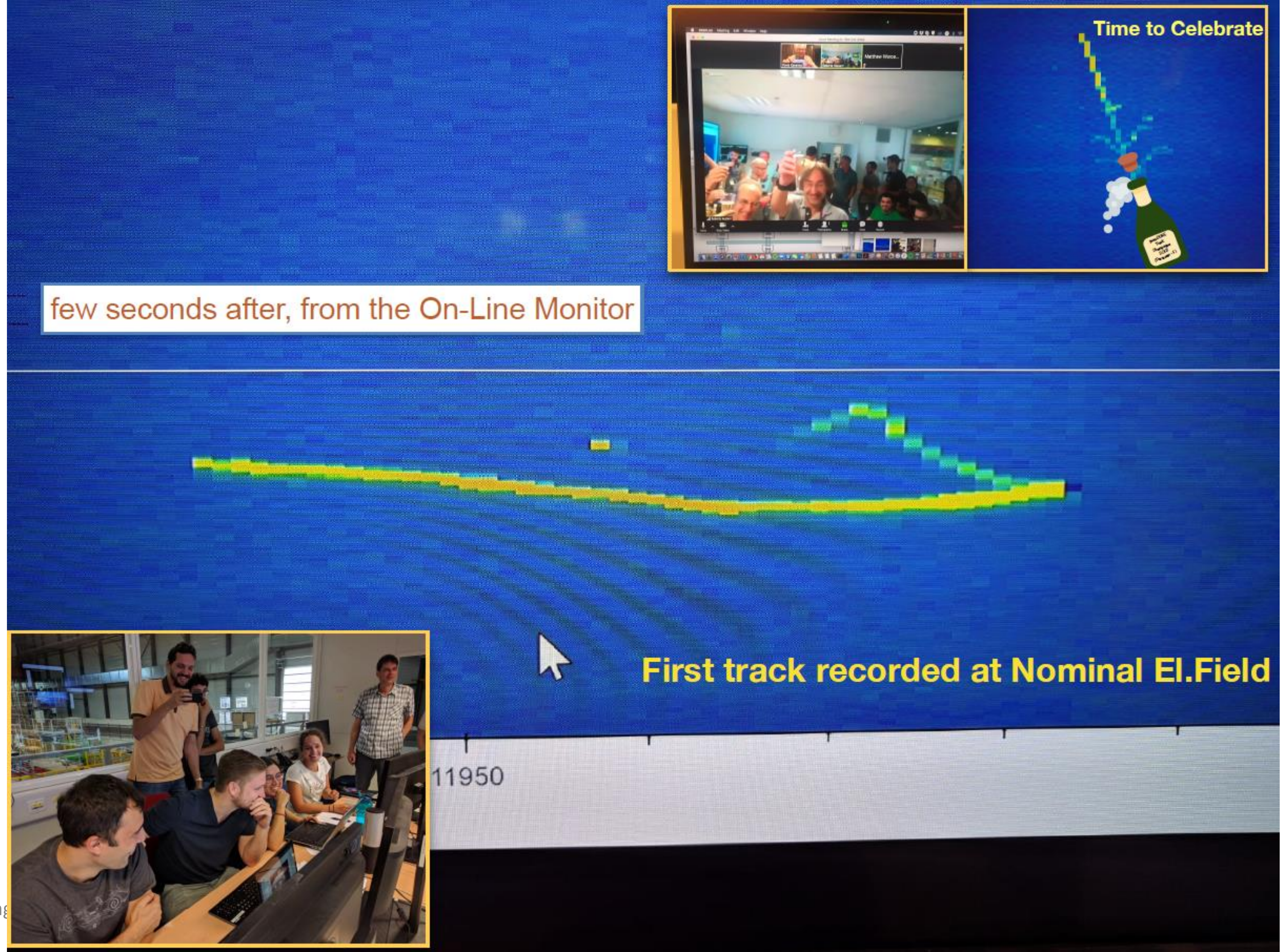



**HV Ramp from 0 to 180 kV (Nominal)**

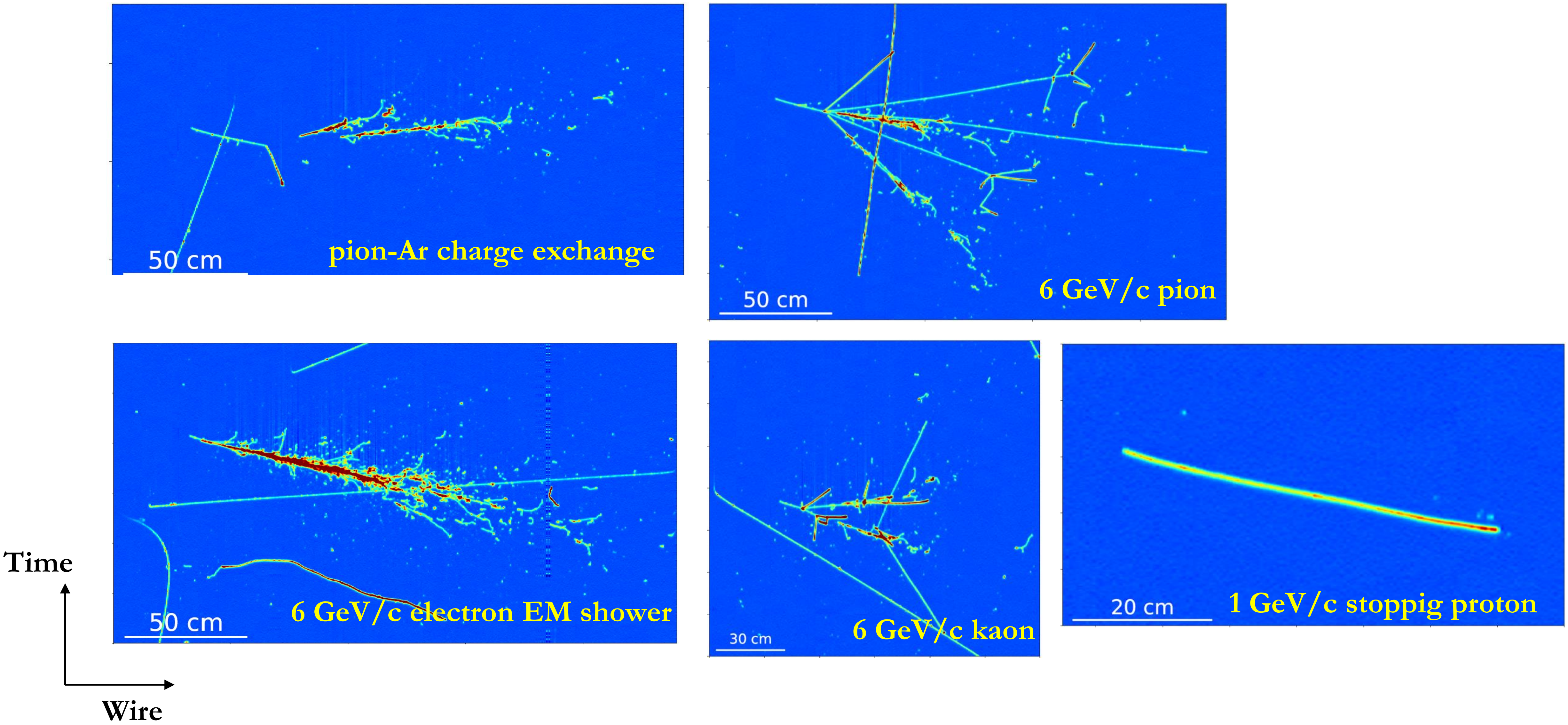
# e-Lifetime and LAr Purity

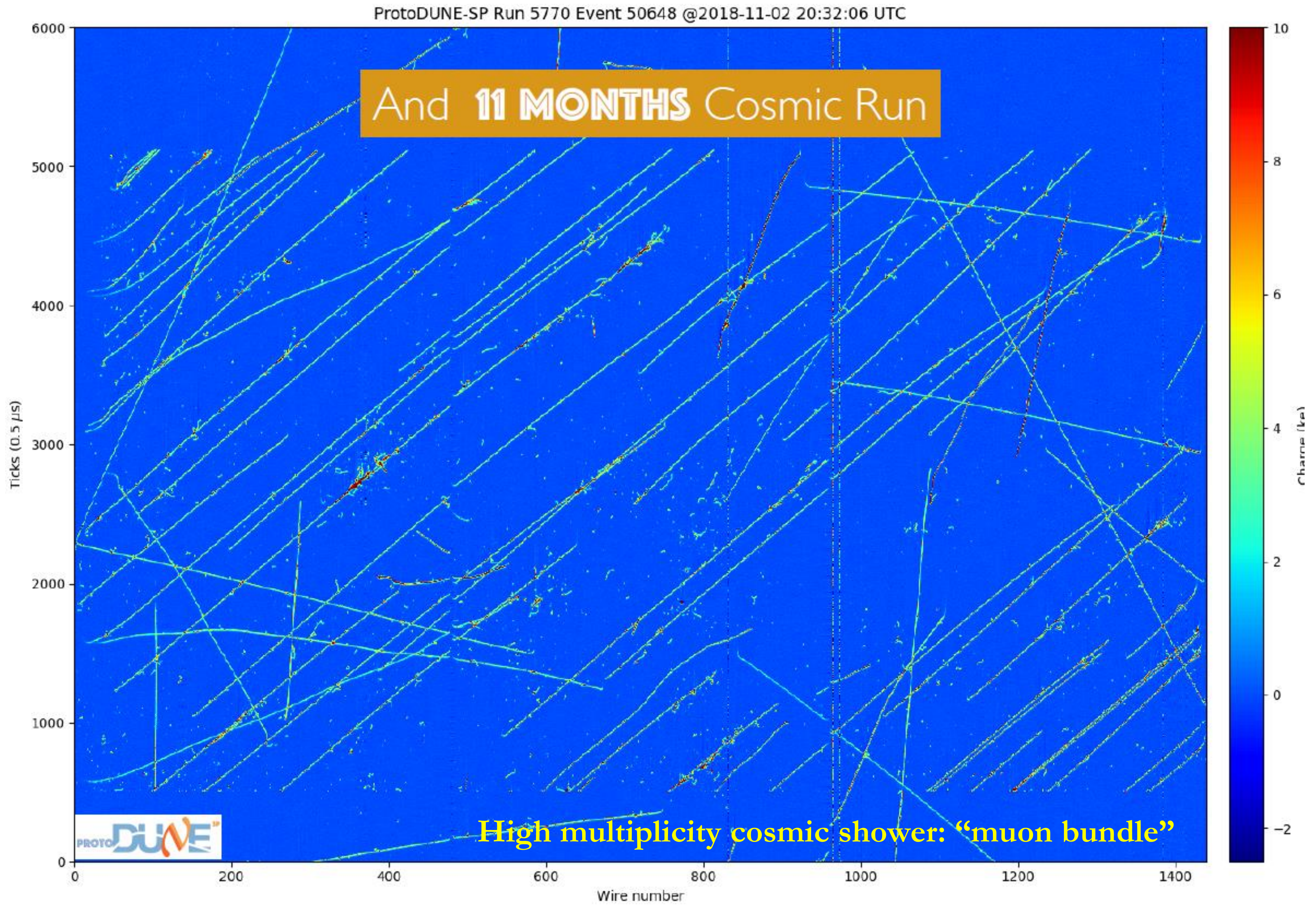



- Electron lifetime measures the LAr purity
- Two independent monitoring are highly correlated and crosschecked
  - Purity Monitors outside of TPC, 20 V/cm E-field
  - In situ measurement inside TPC ($dQ/dx$ vs. $t$) with cosmic rays, 500 V/cm E-field
- Three Purity Monitors at 1.8 m, 3.7 m and 5.6 m from bottom of the cryostat


Time to Celebrate
few seconds after, from the On-Line Monitor
First track recorded at Nominal El.Field
11950

# After ~6 WEEKS Beam Run

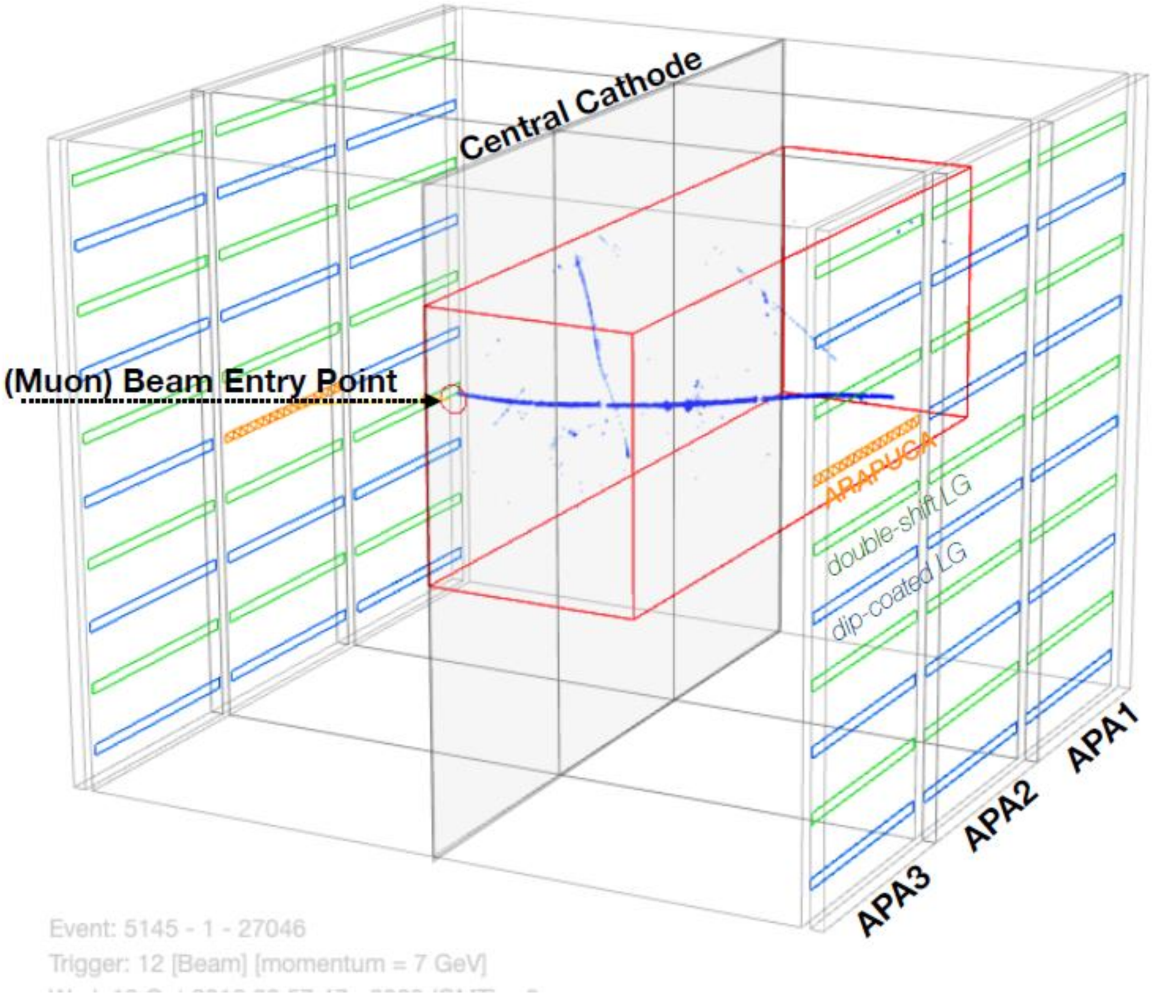



ProtoDUNE-SP Run 5770 Event 50648 @2018-11-02 20:32:06 UTC
And 11 MONTHS Cosmic Run
High multiplicity cosmic shower: “muon bundle”
Ticks (0.5 μs)
Wire number
Charge (ke)
PROTODUNE SP

# Detector Performance

- TPC
  - Noise Level and Charge Extraction
  - Calorimetry: dE/dx
  - Particle Identification

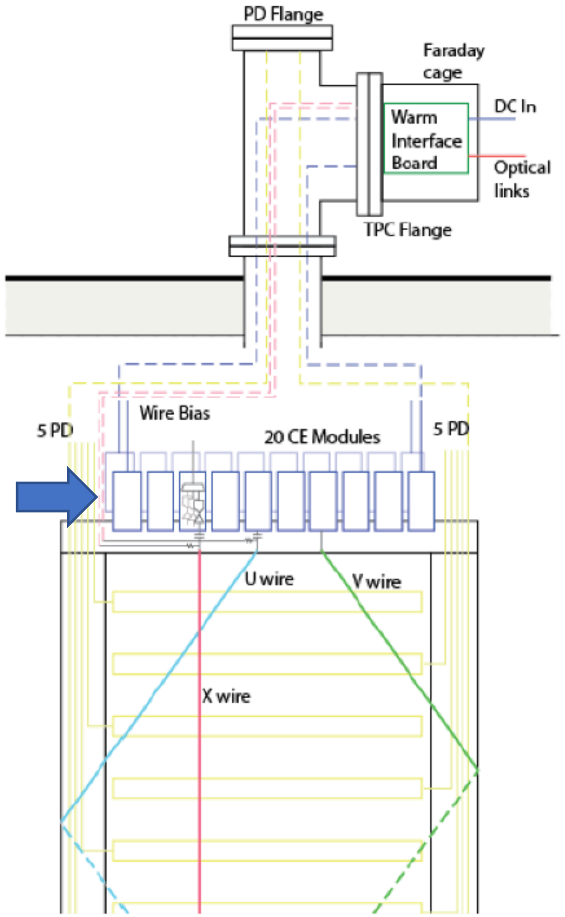
- PDS
  - Light Yield
  - Calorimetric Energy from Light

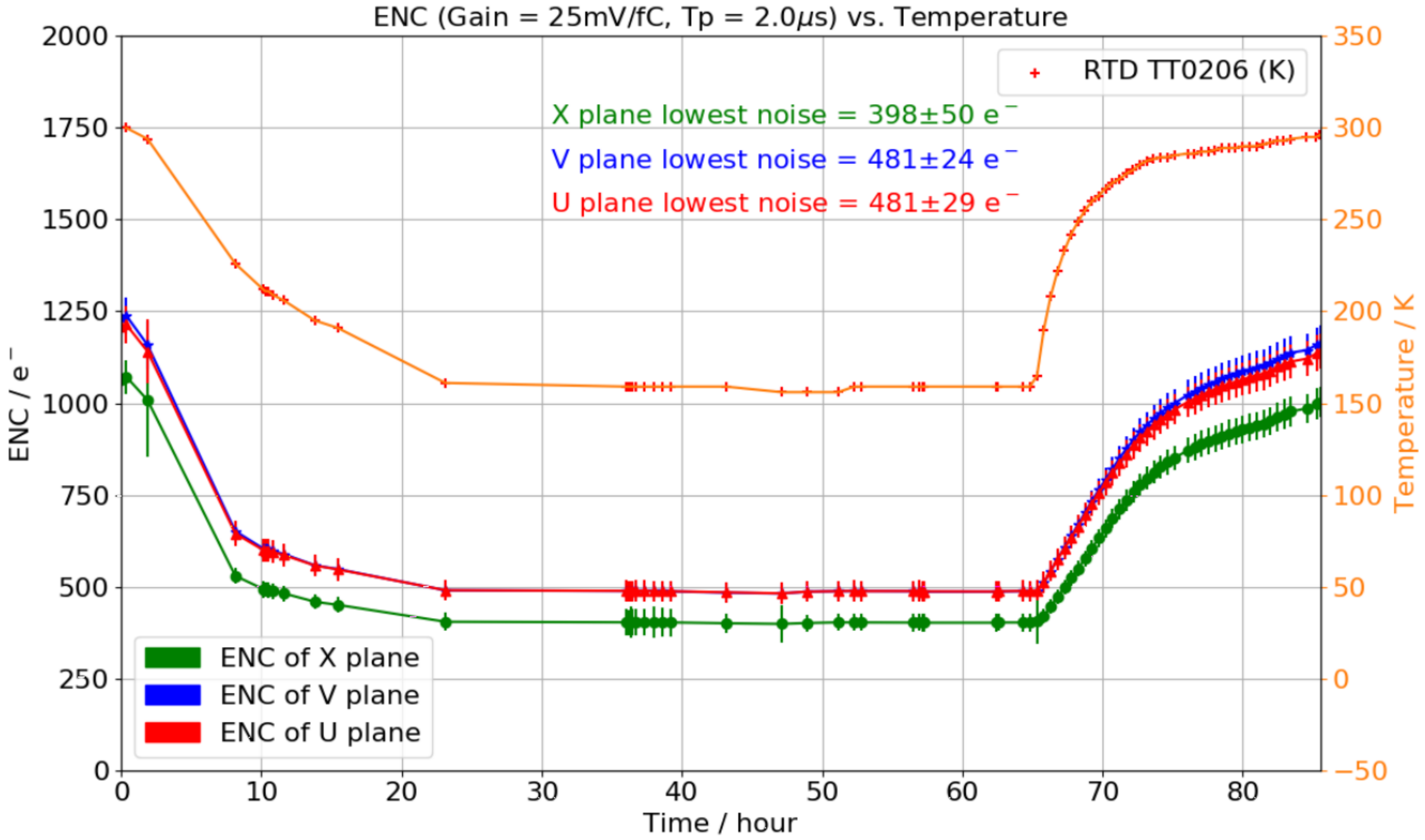


# Cold Electronics Performance

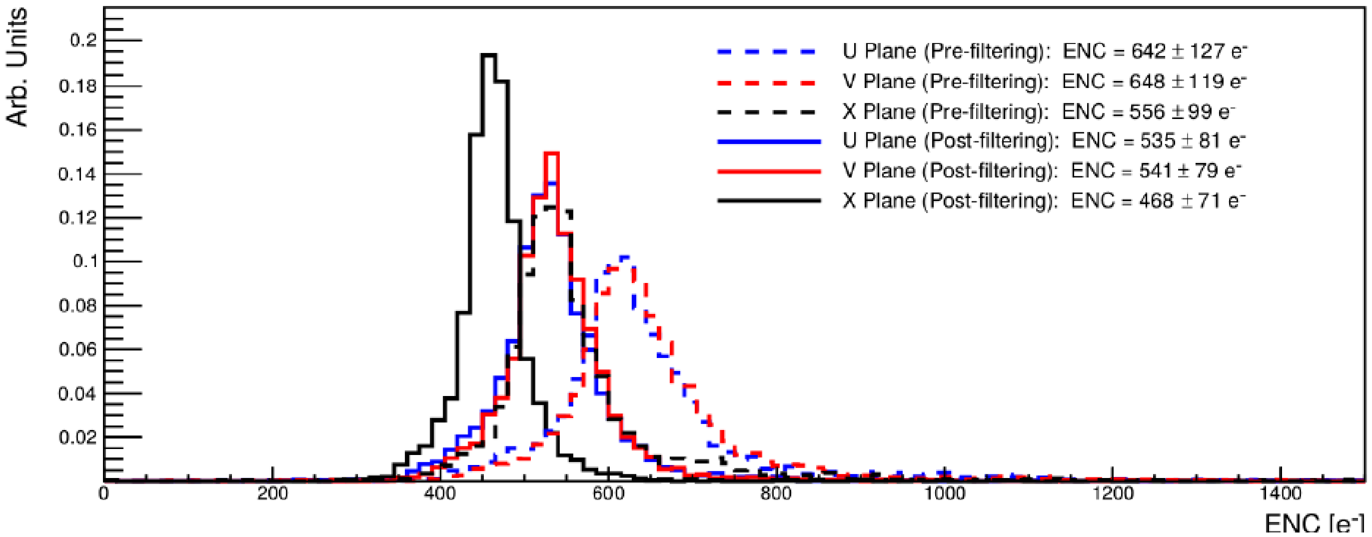
*JINST* 15 (2020) 06, P06017

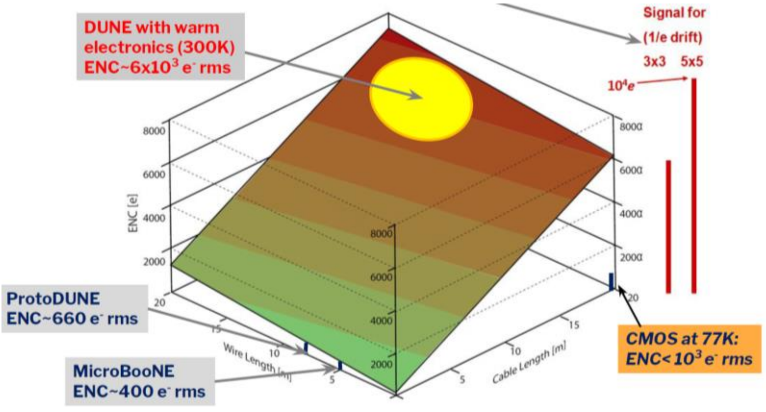
Cold electronics installed on APA



# Noise Level

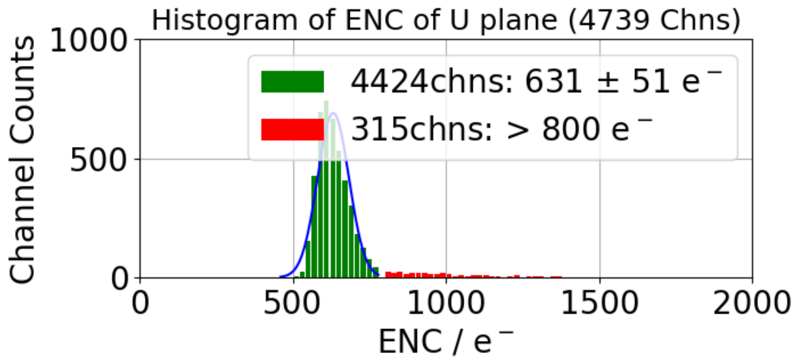


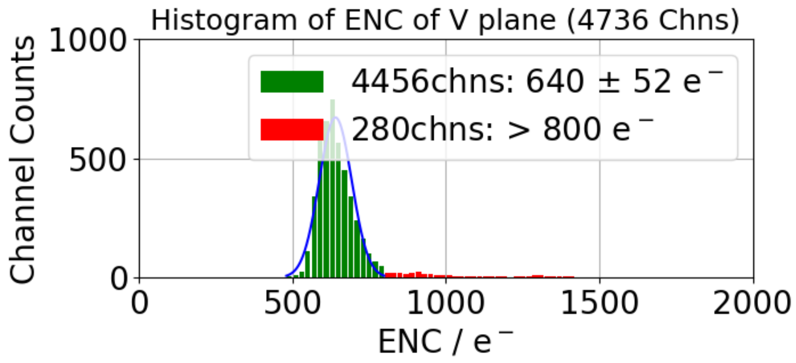



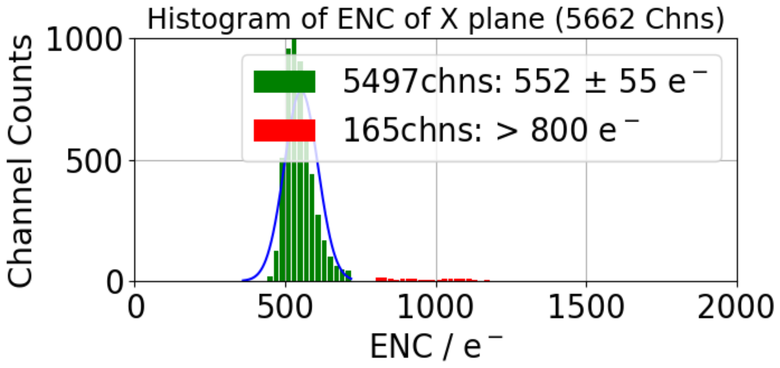

- The noise level well agrees the expectation from the cold electronics design
- Software filter further reduce the noise

# TPC Channels and Electronics Noise

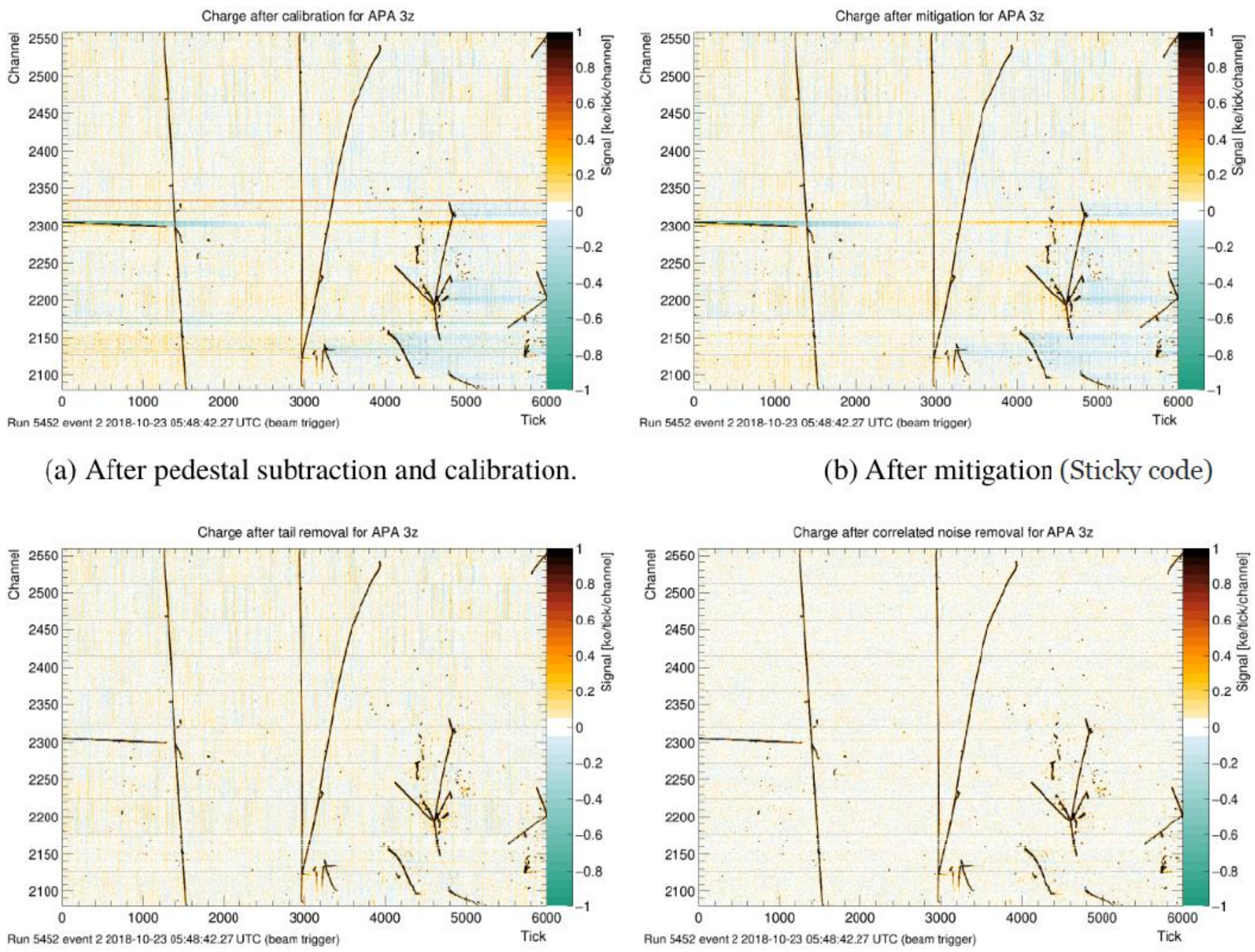
- Total TPC channels: 15360
  - 99.74% (15320 of 15360) TPC channels are active
  - 92.83% (14259 of 15360) TPC channels are working with excellent noise performance (ENC < 800e-)



# 2-D Images from One Wire Plane

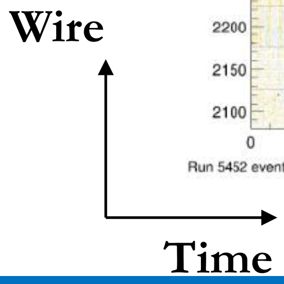



(a) After pedestal subtraction and calibration.

(b) After mitigation (Sticky code)

(c) After tail removal.

(d) After correlated noise removal.



# 2-D Deconvolution Technique

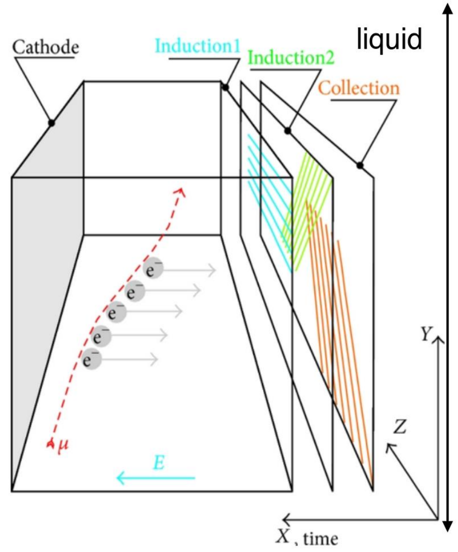
*JINST* 13 P07006 (2018)

- A novel signal processing technique developed at BNL for MicroBooNE
- Consider the **long-range induction** effect in a 2D deconvolution kernel (time + wire)

$$\mathrm{M}_i(t_0) = \int_t (R_0(t_0 - t) \cdot S_i(t) + \mathrm{R}_1(\mathrm{t}_0 - \mathrm{t}) \cdot S_{i+1}(t) + \ldots) \cdot dt$$

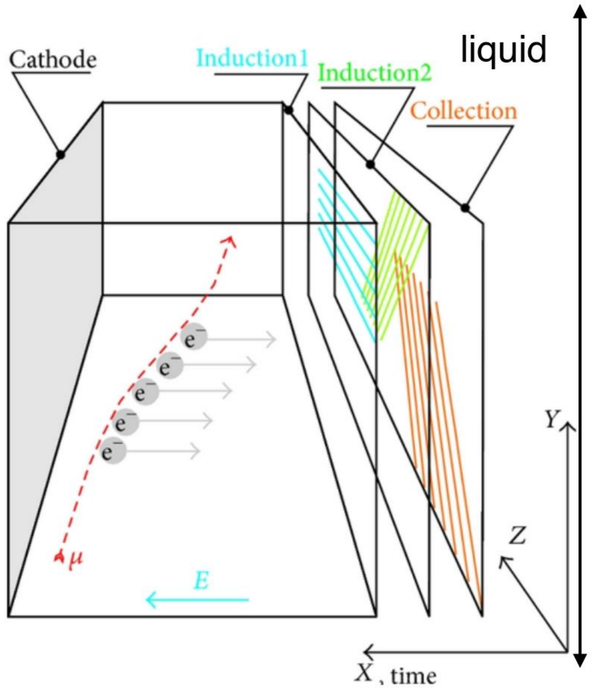
***t: time, α: wire***

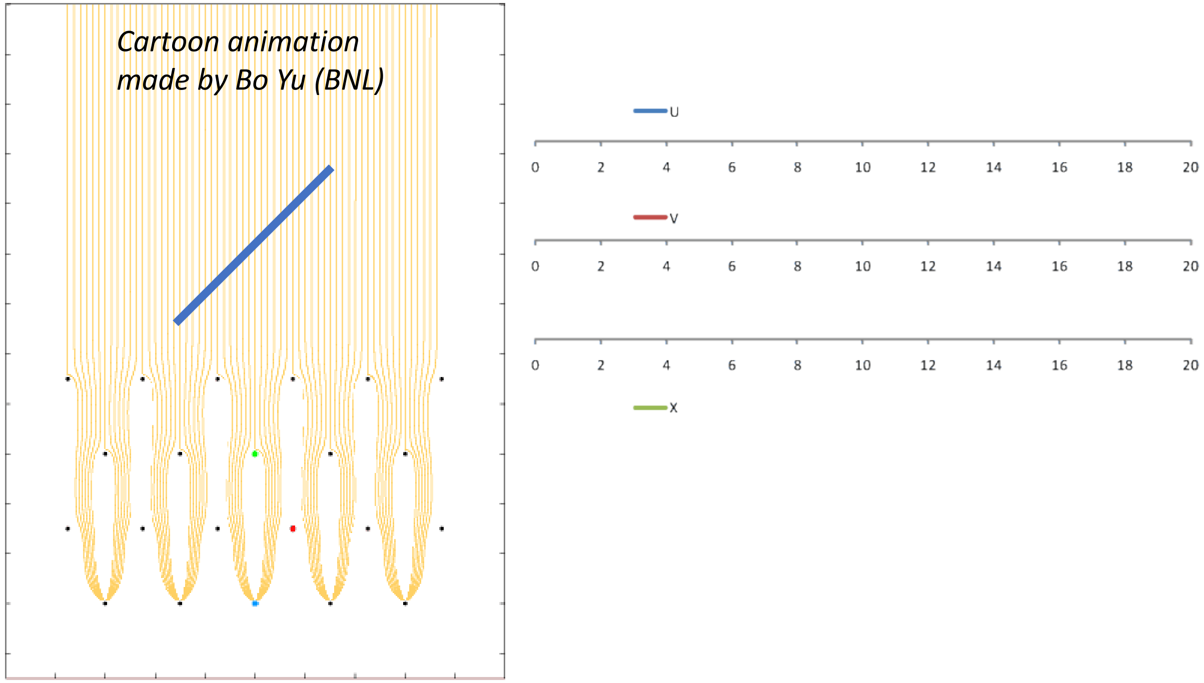
$$\mathrm{M}_i(t_0) = \iint_{t,\alpha} \boldsymbol{R}(t_0 - t, i - \alpha) \cdot \boldsymbol{S}(t, \alpha) \cdot dt\, d\alpha$$




- Equivalently, recover ionization charges from induced current from all adjacent wires

# Revisit the Concept




- Ionization electrons drifted and induced current read out by three (1D) wire planes

# 2-D Deconvolution Technique

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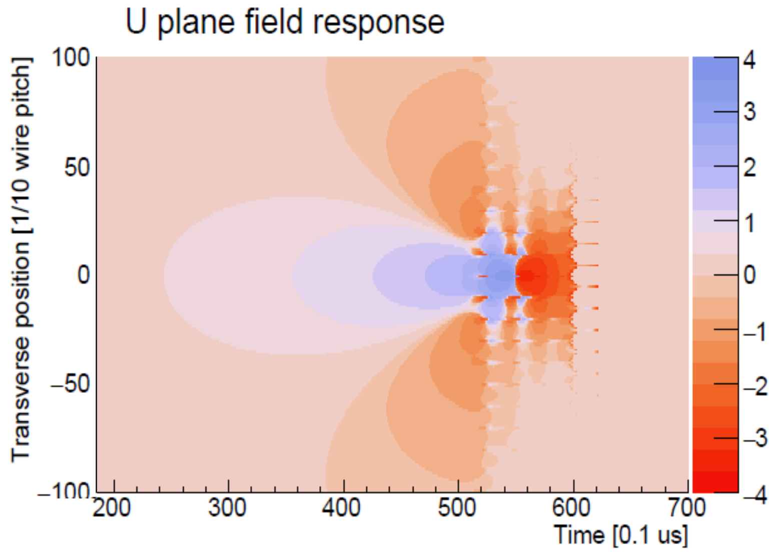
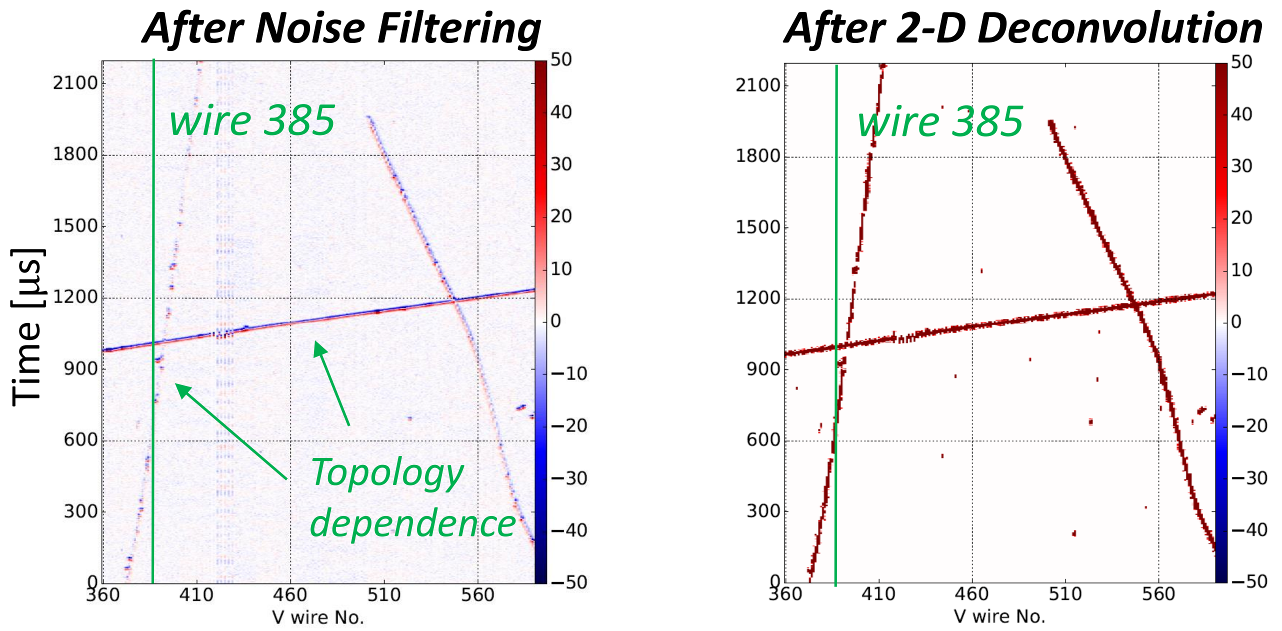
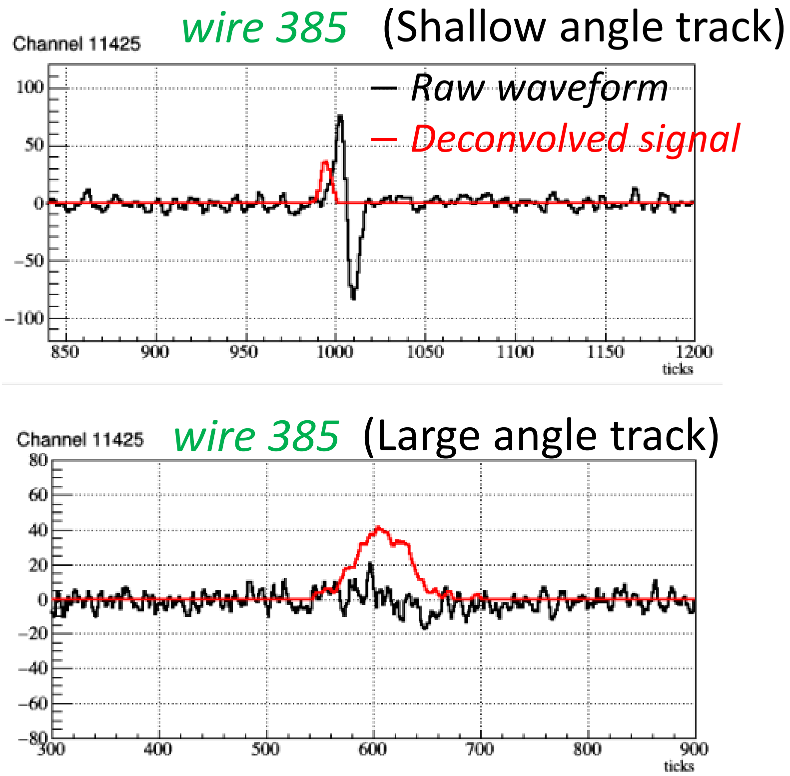



- Equivalently, recover ionization charges from induced current from all adjacent wires

# Signal Processing Example

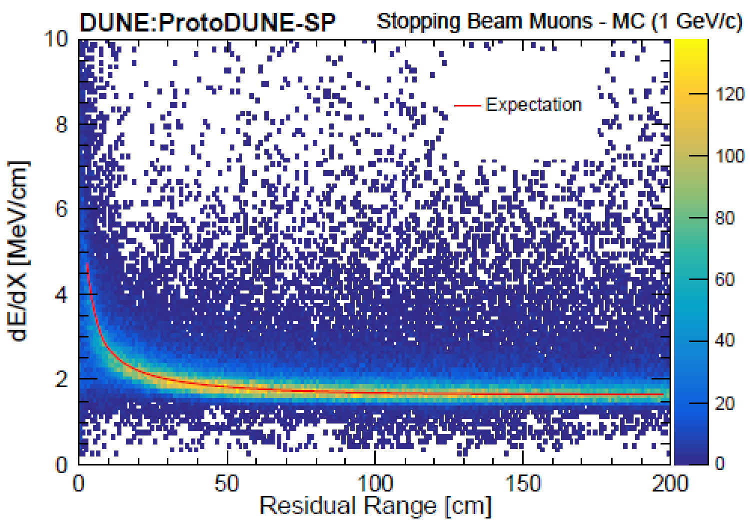


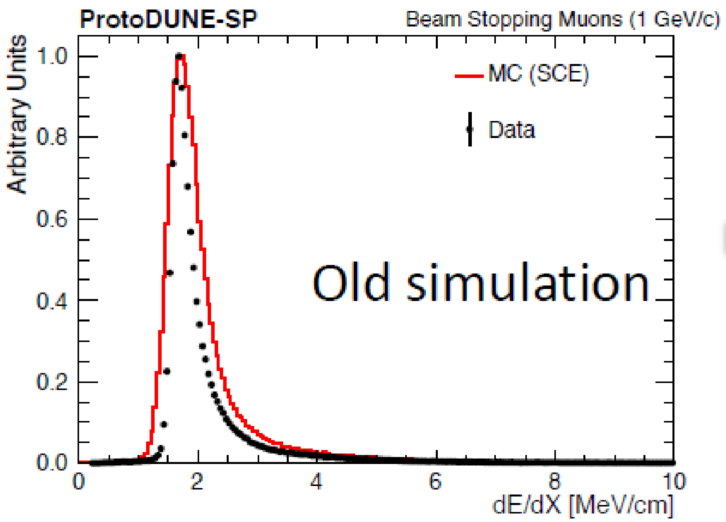



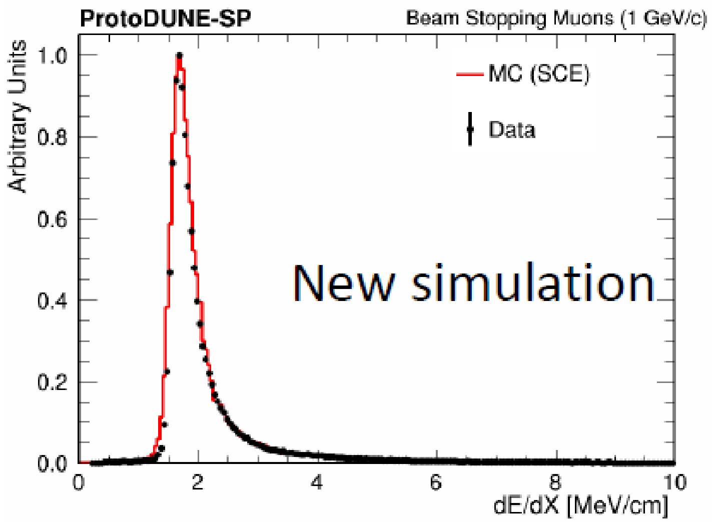

- Bipolar signal deconvolved into a unipolar charge distribution
- Long tracks in drift direction are obscure in the induction waveform
  - cancellation of successive bipolar signals ⇒ **recovered via the 2D deconvolution**

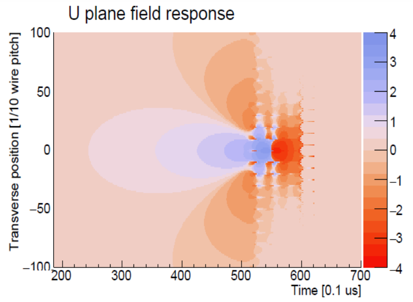
# TPC Performance: dEdx - Calorimetry

- Use stopping muon to determine the absolute dE/dx energy scale
- A good understanding of the long-range induction effect improves the data-MC agreement

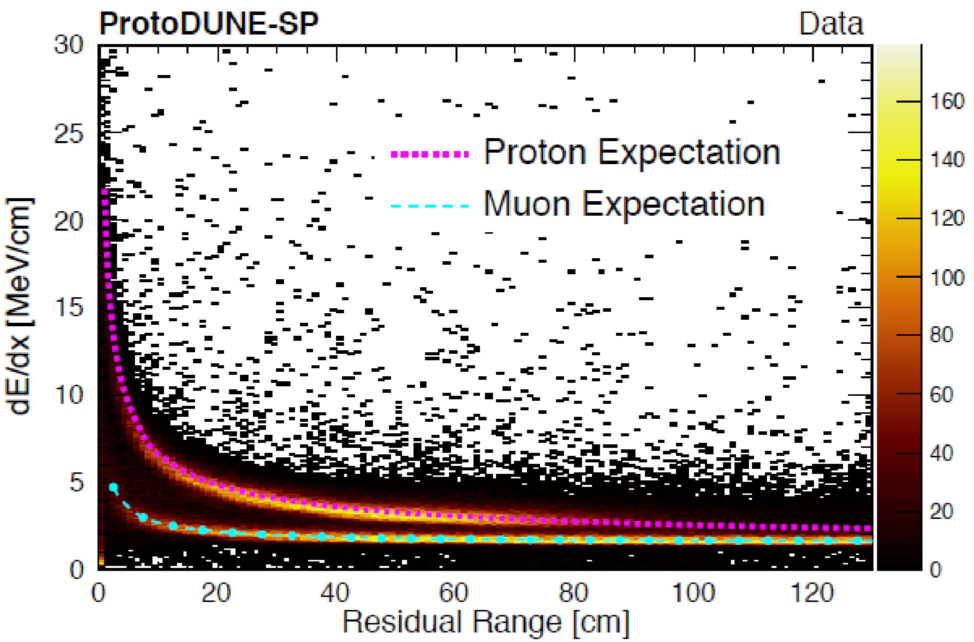


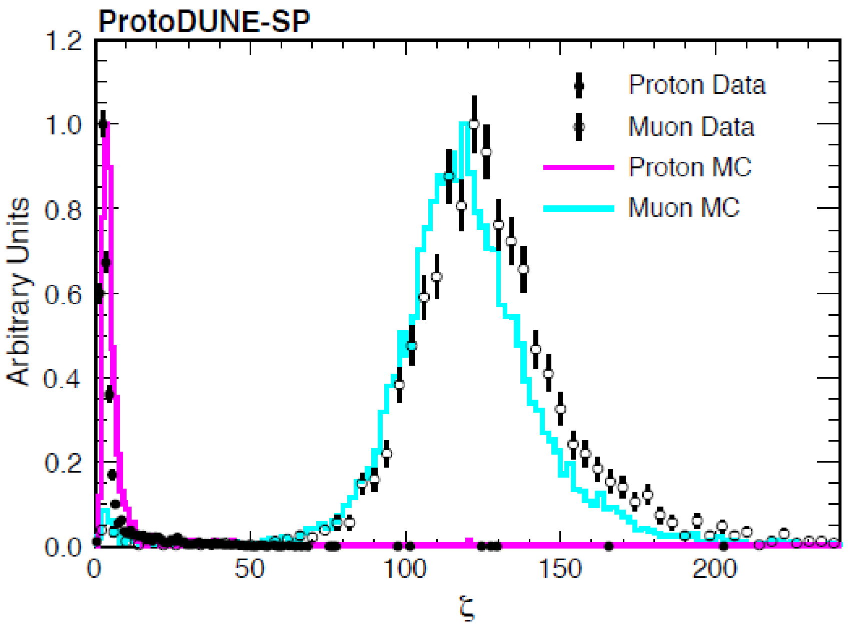



# TPC Performance: Particle ID



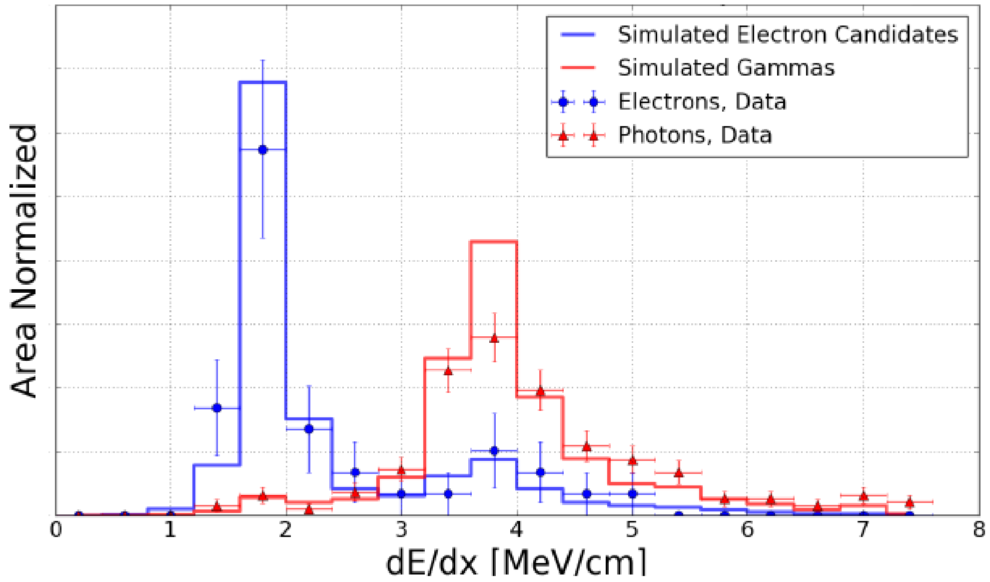



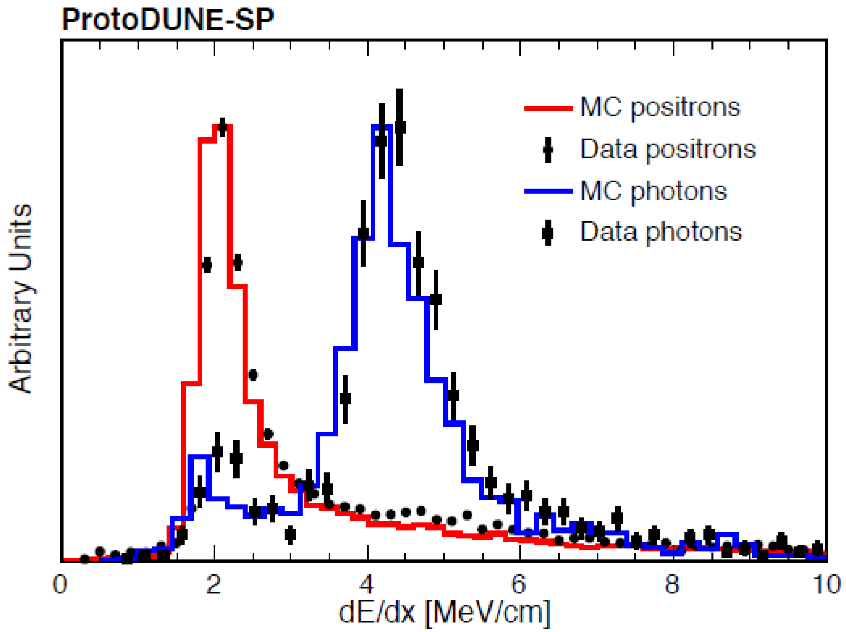

- Well understood detector response to particles of different types
- Excellent separation of muons and protons using calorimetric information

# TPC Performance: Electron/photon dE/dx

- Measure dE/dx at the beginning of electrons and photons
- 1 GeV beam electrons
- Photons from 6 GeV pion interactions
- Clear e/$\gamma$ separation in dE/dx distributions

ArgoNeuT, PRD 95, 072005 (2017)

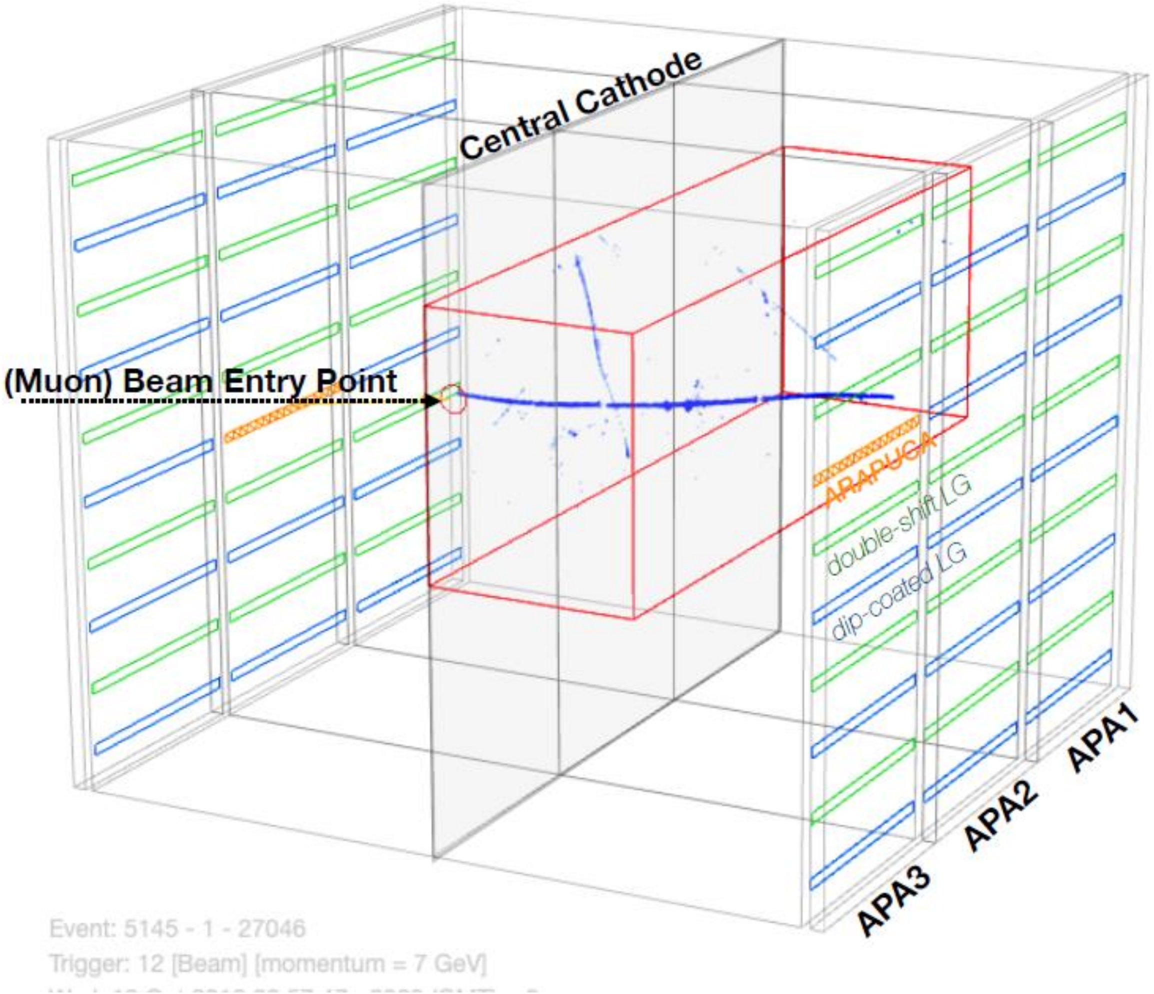


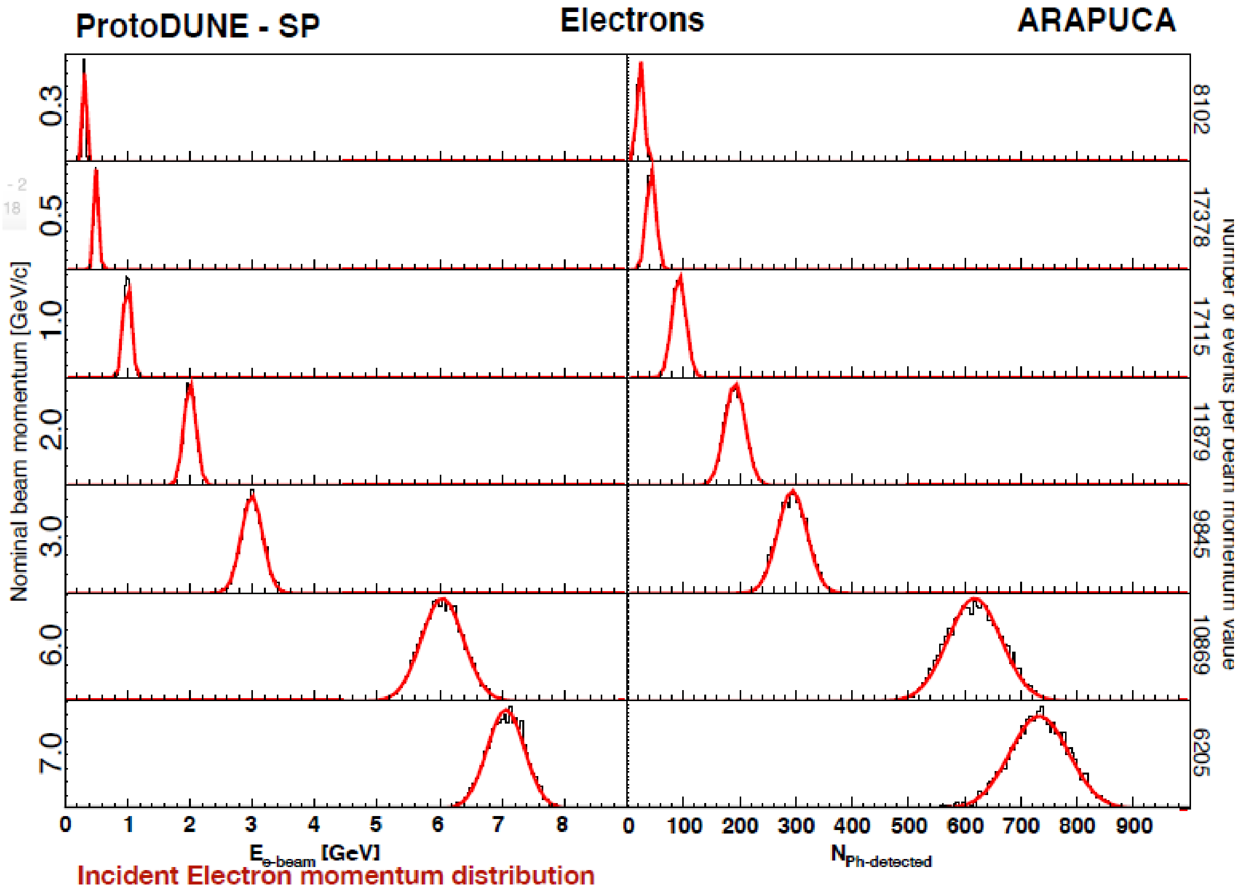
# Detector Performance

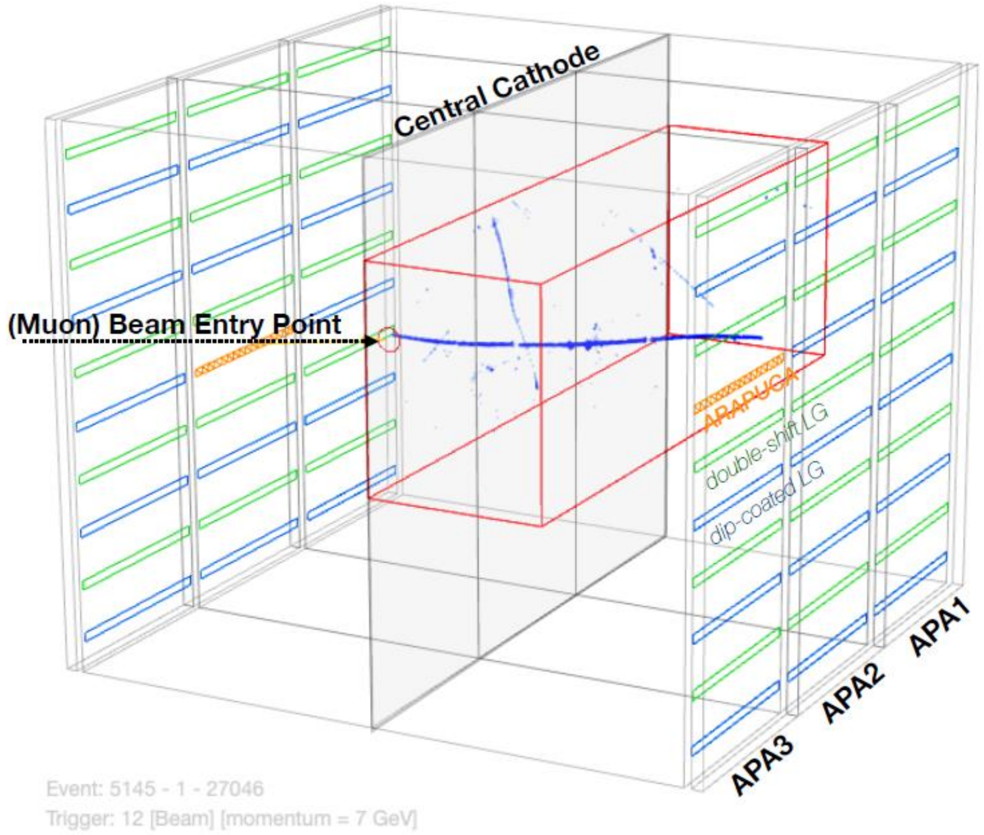
- TPC
  - Noise Level and Charge Extraction
  - Calorimetry: dE/dx
  - Particle Identification

- PDS
  - Light Yield
  - Calorimetric Energy from Light

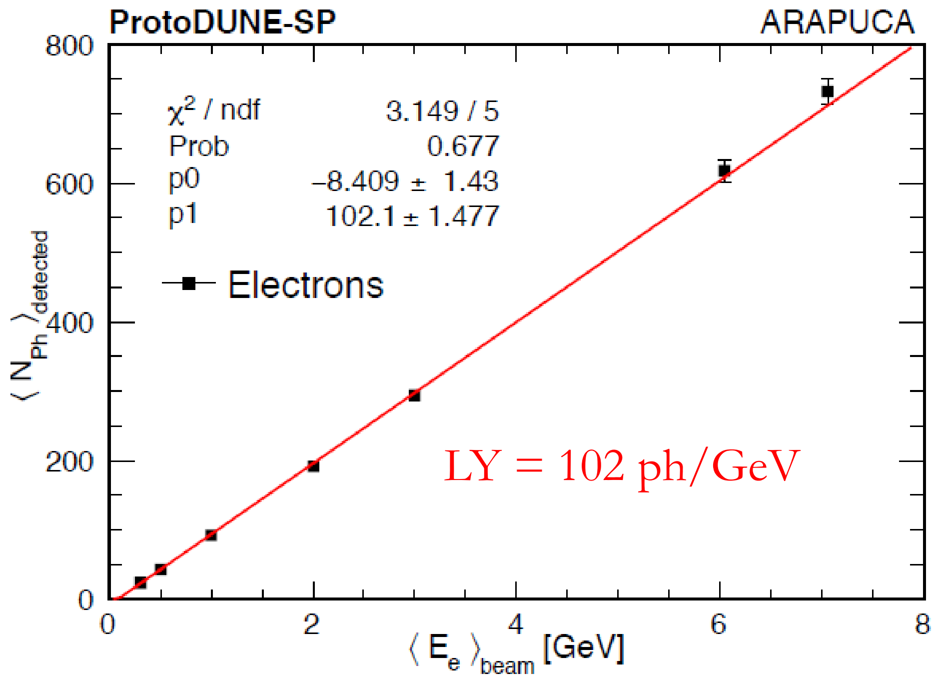


# Photon Detector Performance

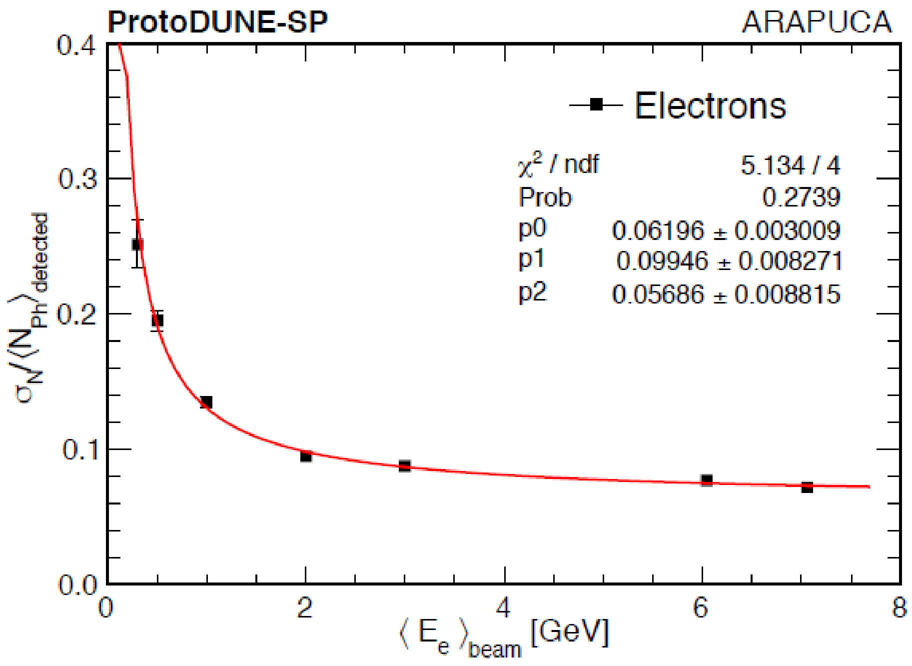


# Photon Detector Performance




**Light Yield**




**Energy Resolution from Light**

$$\frac{\sigma_E}{E} = p_0 \oplus \frac{p_1}{\sqrt{E}} \oplus \frac{p_2}{E}$$

- **Stochastic term:** $p_1 = 10\,\%$
  *from limited photo-sensitive area coverage*
- **Noise term:** $p_2 = 57\ MeV$
  *from excellent SiPM readout S/N ratio*
- **Constant term:** $p_0 = 6.2\,\%$

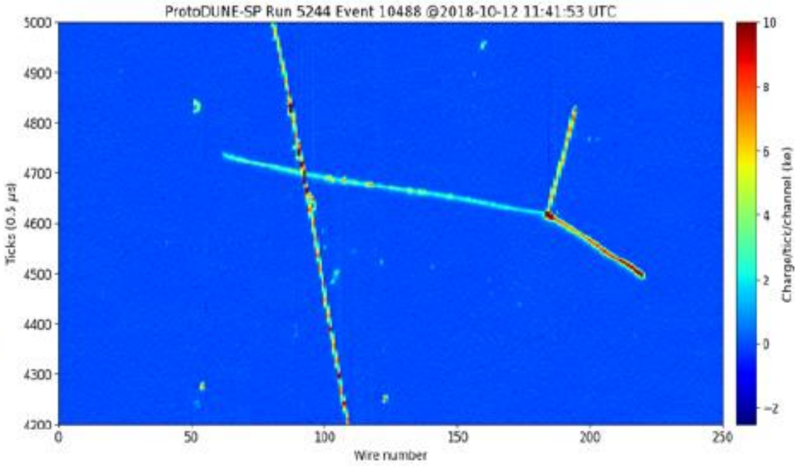
# Summary of the Performance

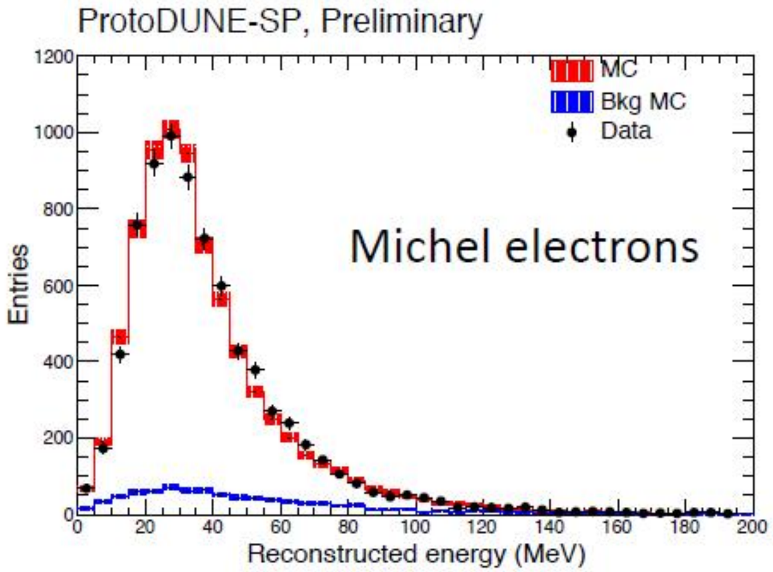
| Detector parameter | ProtoDUNE-SP performance | DUNE specification |
|---|---|---|
| Average drift electric field | 500 V/cm | 250 V/cm (min)<br>500 V/cm (nominal) |
| LAr e-lifetime | > 20 ms | > 3 ms |
| TPC+CE<br>Noise<br>Signal-to-noise ⟨SNR⟩ | (C) 550 e, (I) 650 e ENC (raw)<br>(C) 48.7, (I) 21.2 (w/CNR) | < 1000 e ENC |
| CE dead channels | 0.2% | < 1% |
| PDS light yield | 1.9 photons/MeV<br>(@ 3.3 m distance) | > 0.5 photons/MeV<br>(@ cathode distance - 3.6 m) |
| PDS time resolution | 14 ns | < 100 ns |

- The performance meets or exceeds the DUNE specification
- Successfully demonstrates the effectiveness of the single-phase design

# Other Ongoing Development

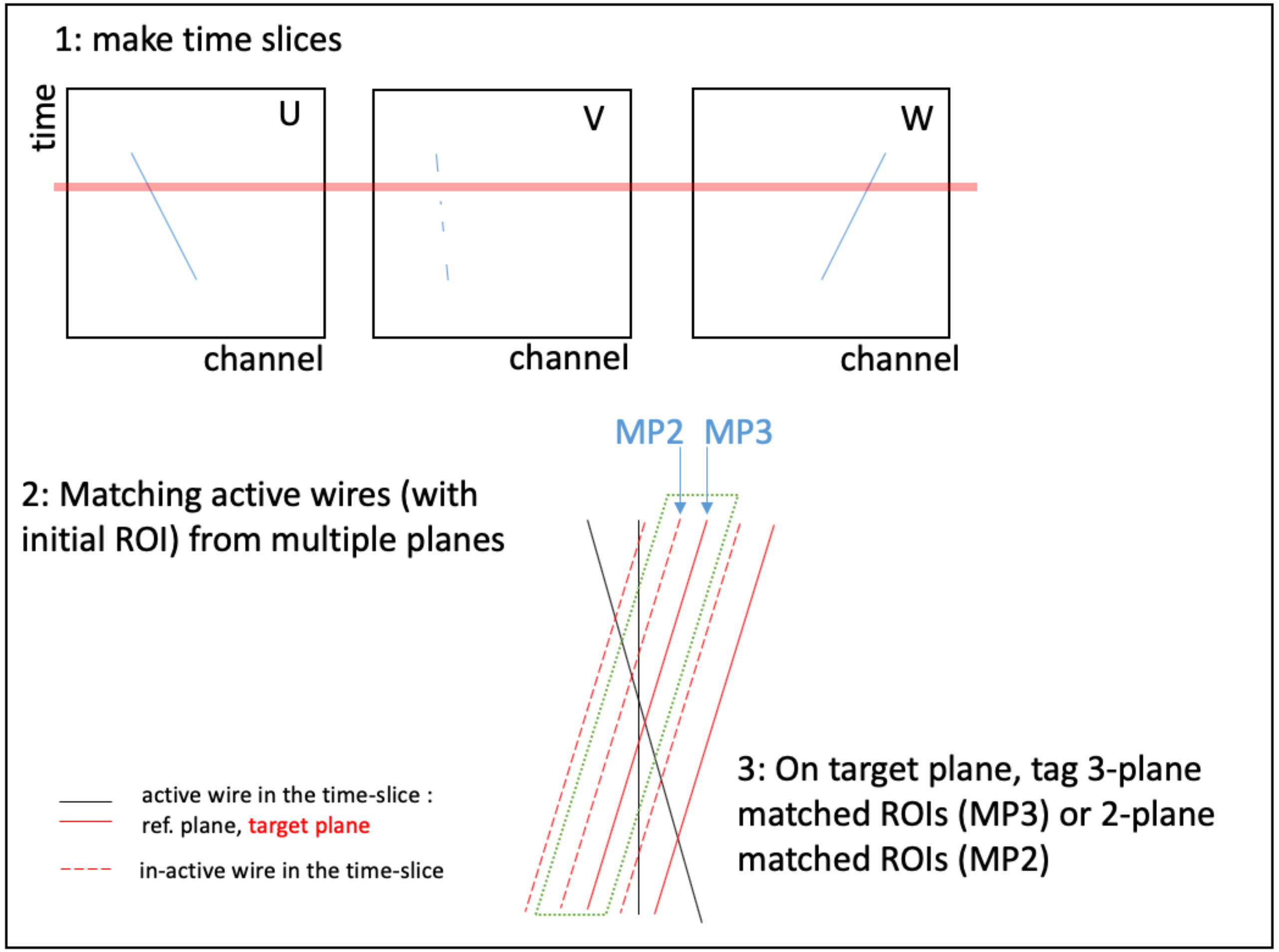
- Hadron-argon cross sections
  - Inclusive cross sections: $\pi^+$+Ar, p+Ar
  - Exclusive channels
    - Pion absorption: $\pi^+$+Ar -> 2p, 2p1n, 2p2n, etc.
    - Charge exchange: $\pi^+$+Ar->Ar*+p+$\pi^0$
- Low energy activities
  - $^{39}$Ar
  - Neutron captures
  - Michel electrons



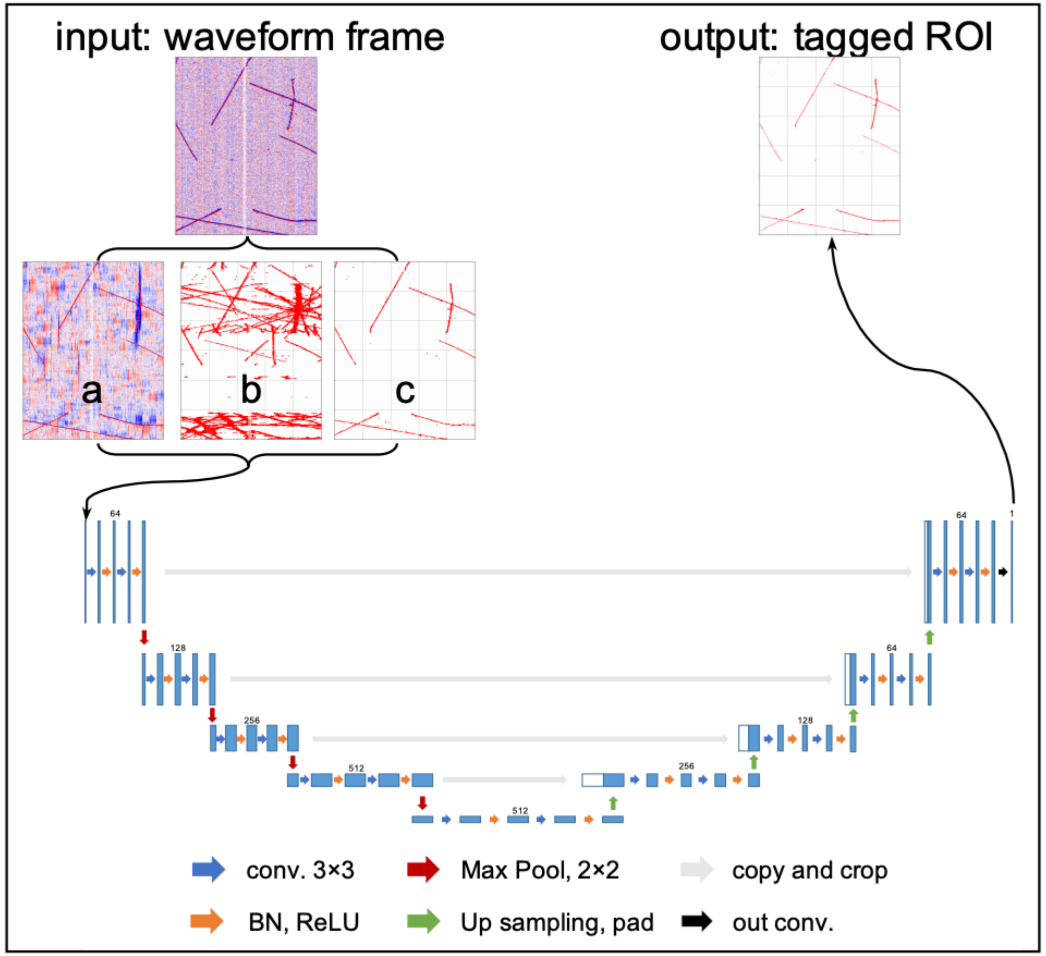



# Deep Neural Network (DNN) for ROI Finding

## Obtain multi-plane (MP) information

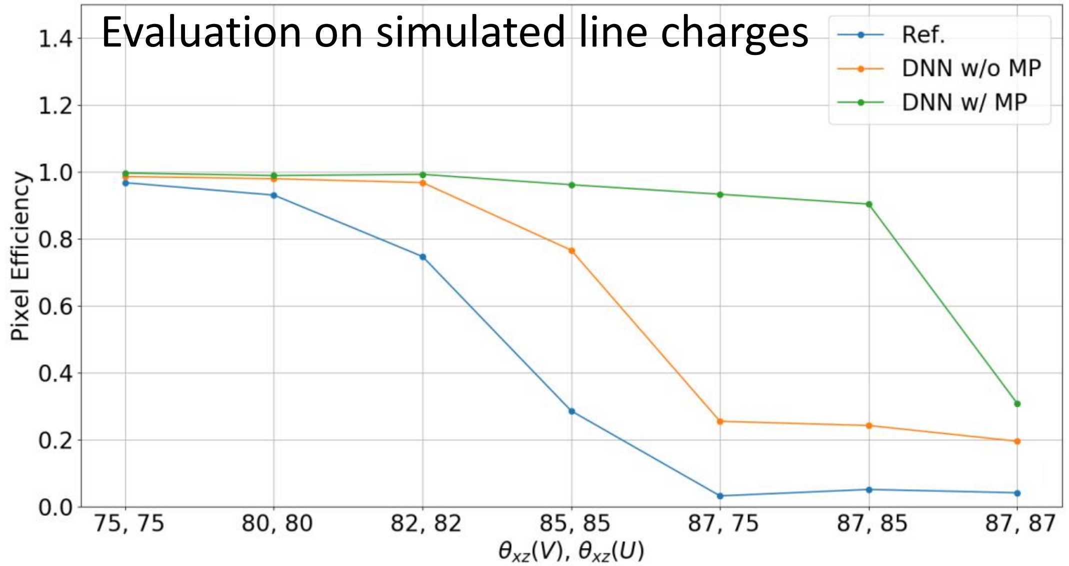


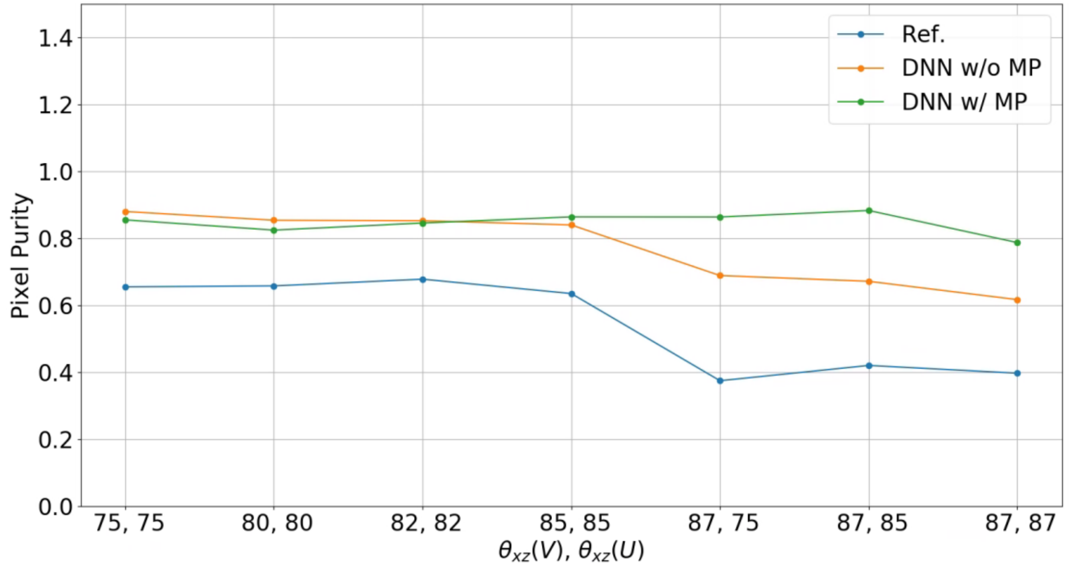

## Network structure




Haiwang Yu et al. , arxiv: 2007.12743 (submitted to *JINST*)

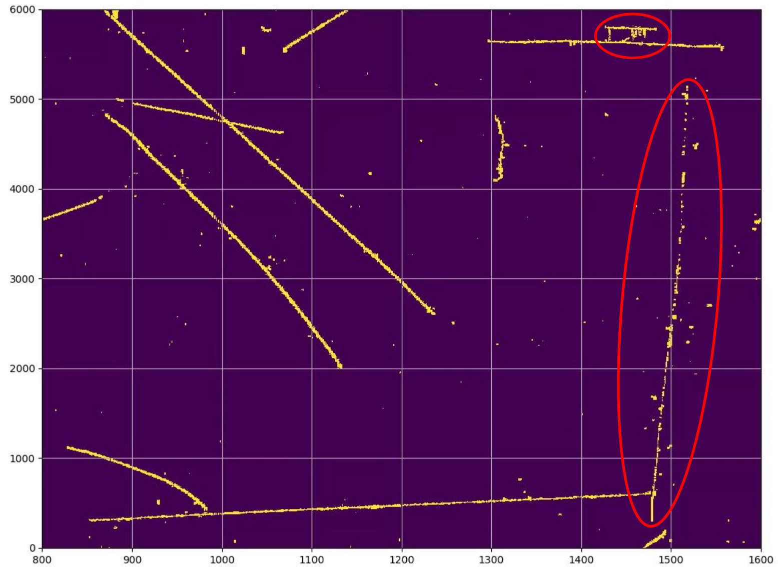
# Boosting Performance for the ROI Finding



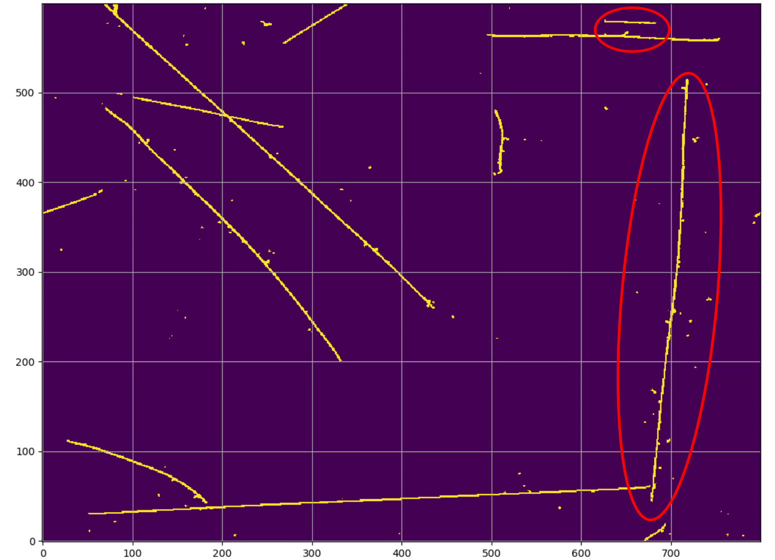




Evaluation on ProtoDUNE data

Reference



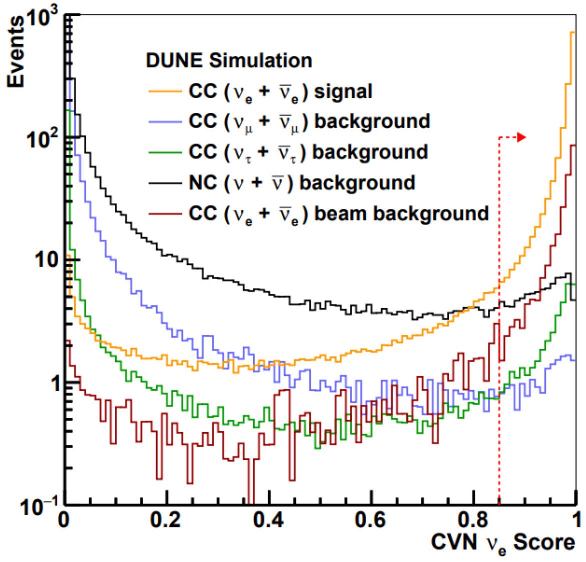
DNN w/ MP



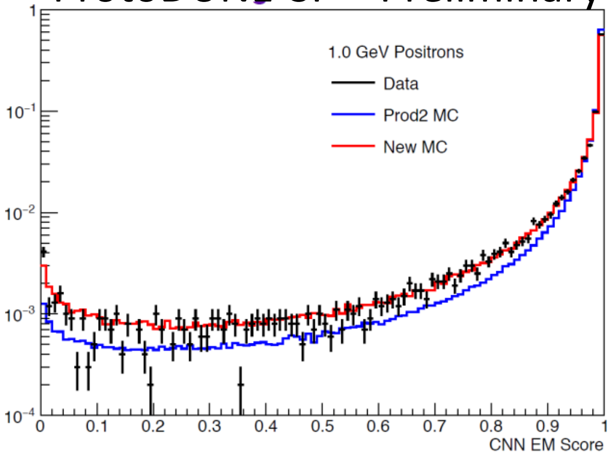
# Event Reconstruction and Classification

arXiv:2006.15052

- “Neutrino interaction classification with a convolutional neural network in the DUNE far detector”
- Use convolutional neural network (CNN) to classify events (images)
- Results: 80-90% efficiency for both $\nu_\mu$ and $\nu_e$ selections
- ProtoDUNE provides an excellent opportunity to test the technique using single particles to mimic simple neutrino interactions




ProtoDUNE-SP Preliminary



# Final Remarks

## ProtoDUNE-SP accomplished the mission

☑ Prototyping production and installation procedures for DUNE Far Detector

☑ Validating design from perspective of basic detector performance

Meets or exceeds the DUNE specification

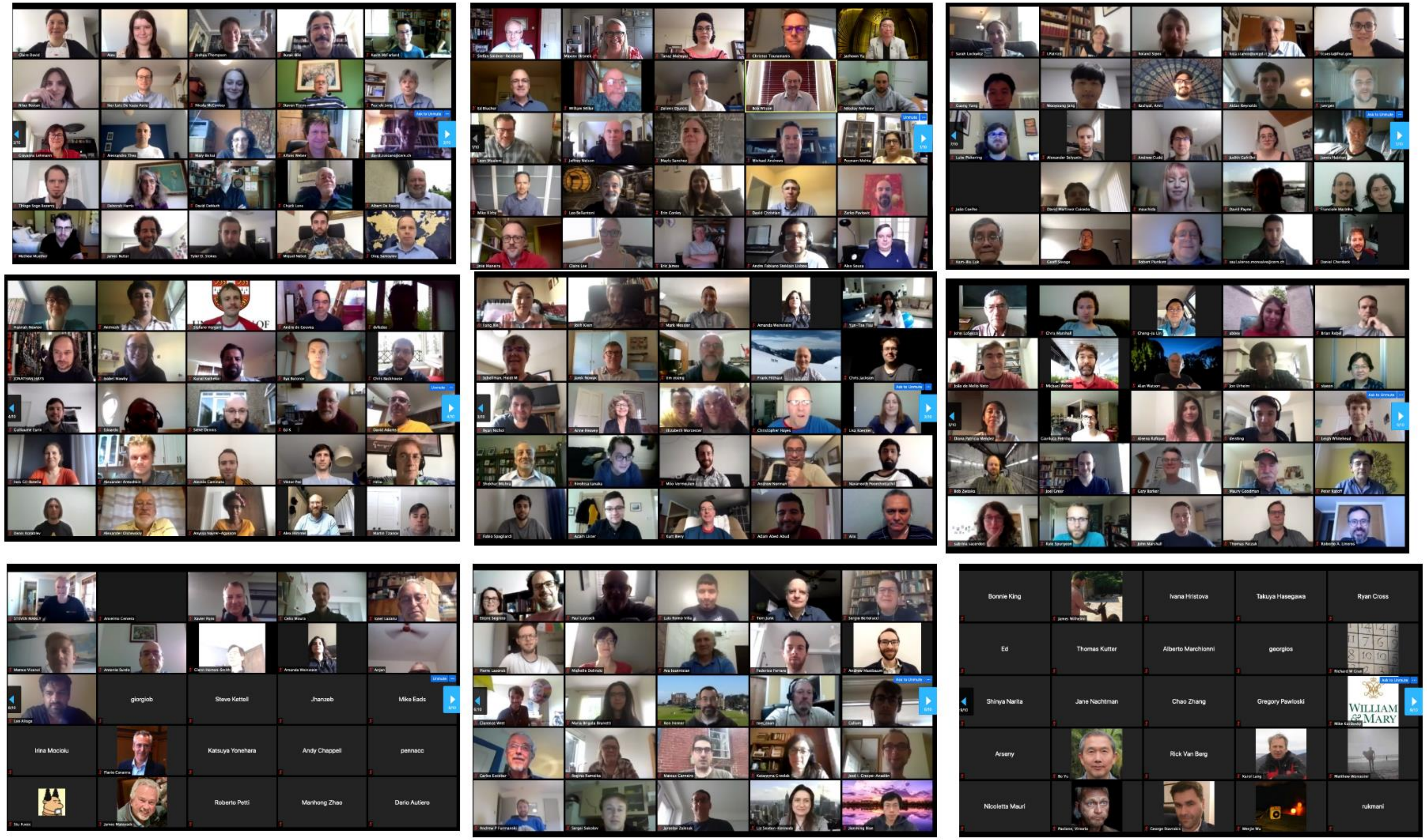
☑ Accumulating test-beam data to understand/calibrate response of detector to different particle species

~ 3M beam triggers accumulated and analyzed

☑ Demonstrating long term operational stability of the detector

~ 500 days of operation

# Thanks!



May 2020 Collaboration Photo