ProtoDUNE SP:
from 500 days of continuing operation

PAC Meeting Jan. 15, 2020 - FERMILAB

Outline

- Status of the experiment
- Plans for Run 2
- Status of Recommendations from last PAC meeting

[Charge of the PAC Mtg (Jan. 15, 2020 - FNAL)]

⇓

[PAC meeting Report - Jan. 2019]

- *Collect data with cosmic rays for Long-term stability and further study of detector performance*
- *Collect data on fluid and space-charge dynamics*

  - *Explore on Limiting factors on electron lifetime*
  - *Explore on Origin of observed high voltage instabilities*

    - *Report on Improvements in Space Charge model*
    - *Report on Tracking and dE/dx measurements after Space Charge calibration*
    - *Report on Performance of the three light detection systems and comparison*

      - *Study Calorimetric response to positrons, pions, and protons*
      - *Study Exclusive reactions for pions and protons*

- Fermilab's involvement in the Dual Phase LArTPC development

PROTO DUNE SP MISSION (ACCOMPLISHED)

- ☑ Prototyping production and installation procedures for DUNE Far Detector Design
- ☑ Validating design from perspective of basic detector performance → inform TDR
- ☑ **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

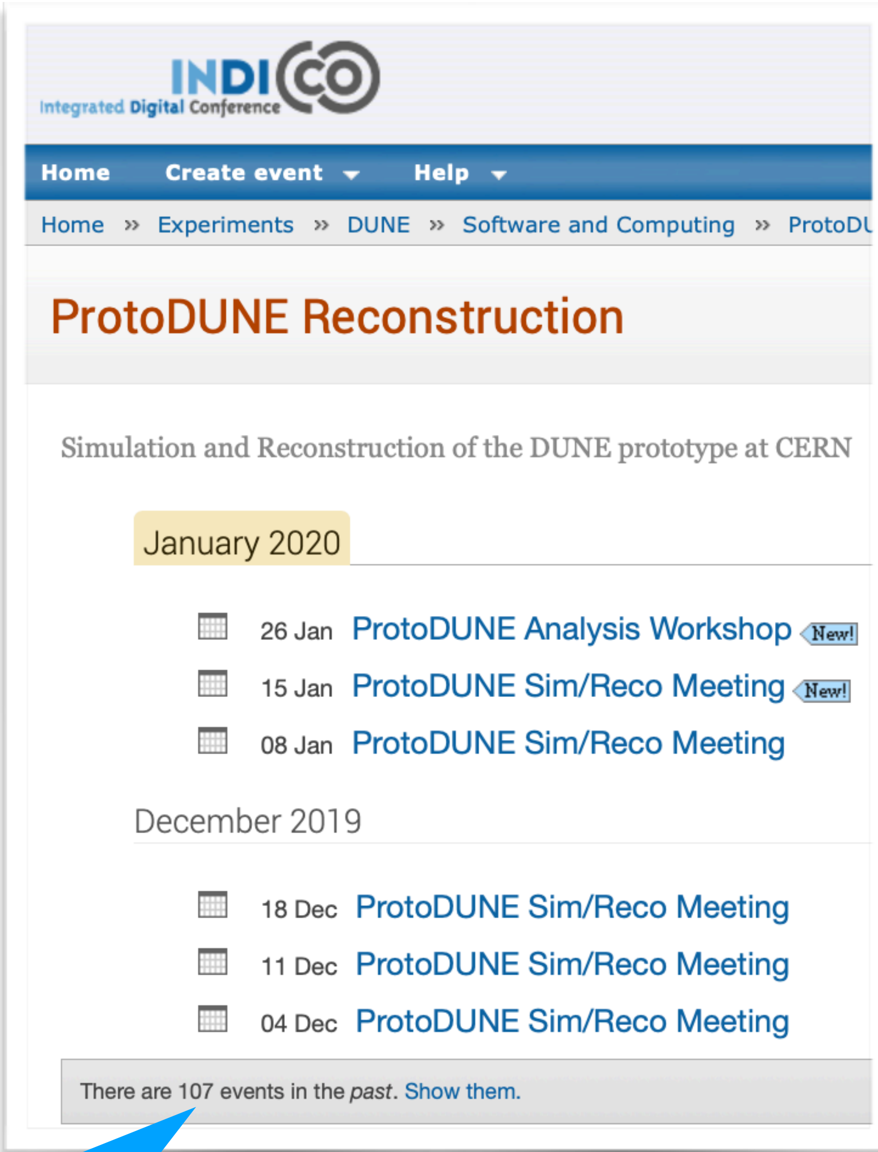
Here *announced*:

1ST PAPER COMPLETED BY DEC. 15, 2019

PREPARED FOR SUBMISSION TO JINST

First results on ProtoDUNE-SP LArTPC performance from a test beam run at the CERN Neutrino Platform

ABSTRACT: The ProtoDUNE-SP detector is a single-phase liquid argon time projection chamber (TPC) with an active volume of $7.0 \times 6.0 \times 3.6\ m^3$. It is installed in a specially-constructed calibration beam that provides samples of incident particles with well-measured momenta and high-purity particle identification. The ProtoDUNE-SP detector is a prototype for the first far detector module of the Deep Underground Neutrino Experiment, and it incorporates full-size components as designed for that module. ProtoDUNE-SP's successful operation during 2018 and 2019 and its production of large samples of high-quality data demonstrate the effectiveness of the single-phase far detector design. This paper describes the beam line, the TPC, the photon detectors, the signal processing and particle reconstruction. It presents the first results on ProtoDUNE-SP's performance. These results include TPC noise and gain measurements, dE/dx calibration for muons, protons, pions and electrons, drift electron lifetime measurements, and photon detector noise, signal sensitivity and time resolution measurements.



$\langle N.\ of\ Attendees \rangle \geq 50$

1ST PROTODUNE-SP PAPER CURRENTLY UNDER DUNE INTERNAL REVIEW

Contents

Some highlights are shown in this talk

Assessments on LONG TERM STABILITY

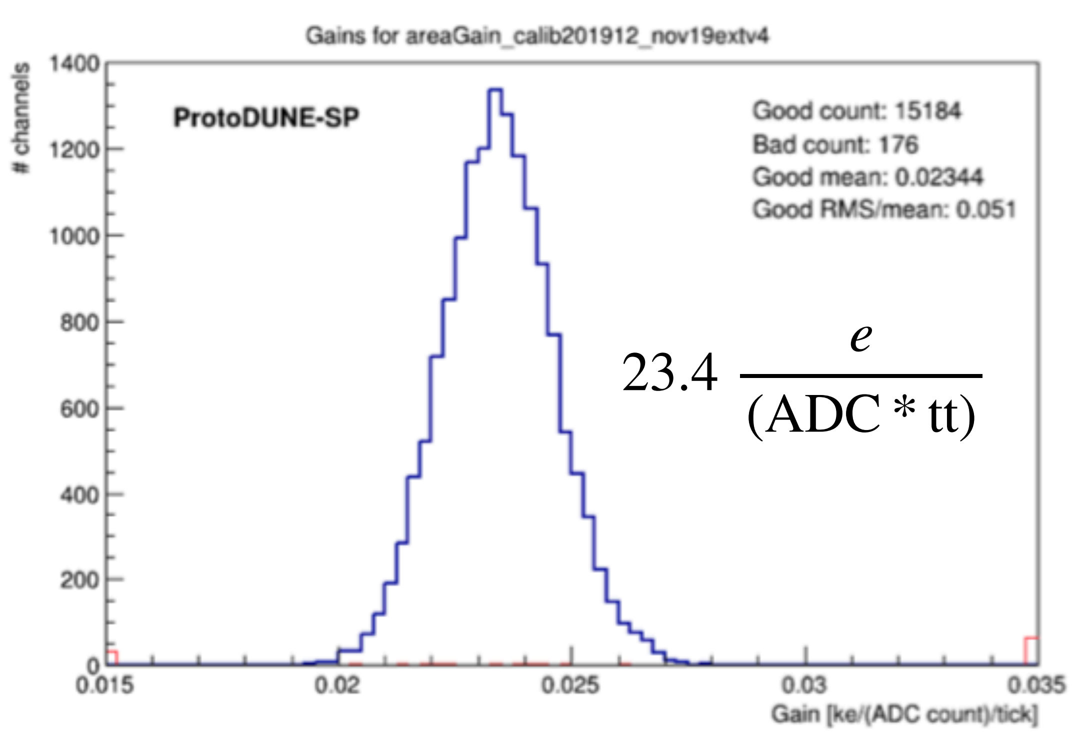
from 500 days Detector Operation

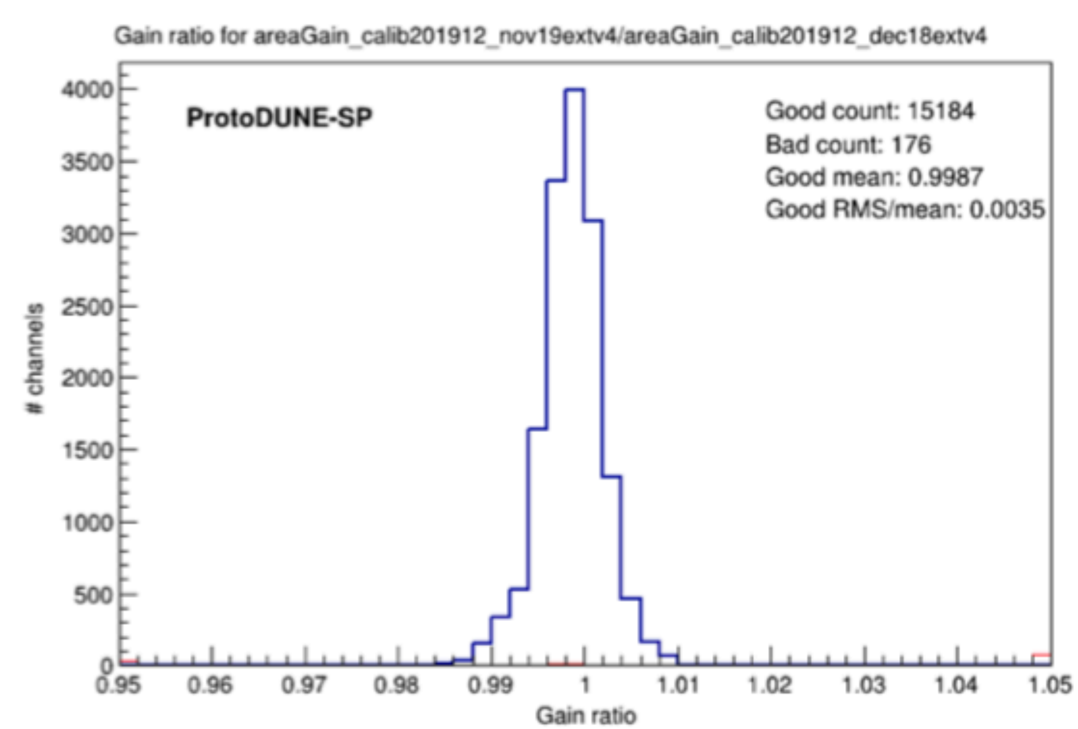
- CE response & PhotoSensors response stable to test pulse calibration
- TPC response stable (for stable LAr purity)
- PhotoDetector response stable (for stable LAr purity)
- LAr Purity stable with a slight increase (e-lifetime vs time)
  Occasional minor drops (cryo/recirculation tests) and an accidental major drop due to a hw failure in the GAr recirculation system [Purity fully recovered after the accident].
- HV stable at the nominal setting (EF 500 V/cm vs time).
  Minimal current instabilities detected and attributed to charge up of some insulating material in a high field region.
- Cryogenics parameters stable (P, T, heat load/LN2 consumption)

TPC - Cold Electronics Gain:

Nov 2018 pulser data *vs*. Dec 2019 pulser data

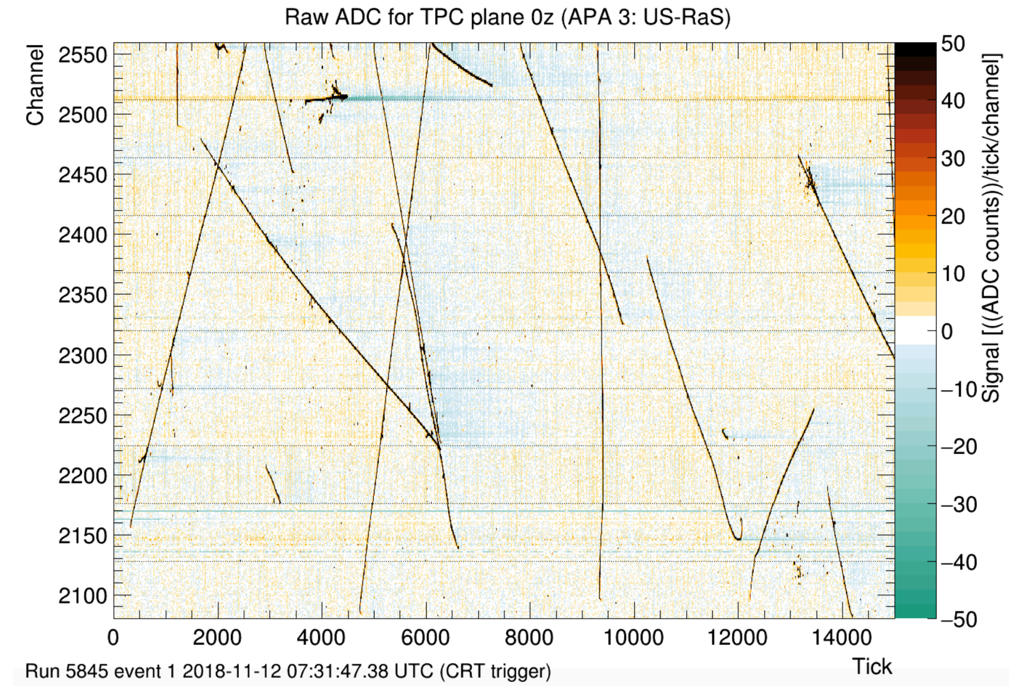
- Plot on left is the gain distribution
- Plot on right is the ratio to the same calibration using Dec 2018 data
  - Shift is 0.13 %
  - RMS is 0.4 %

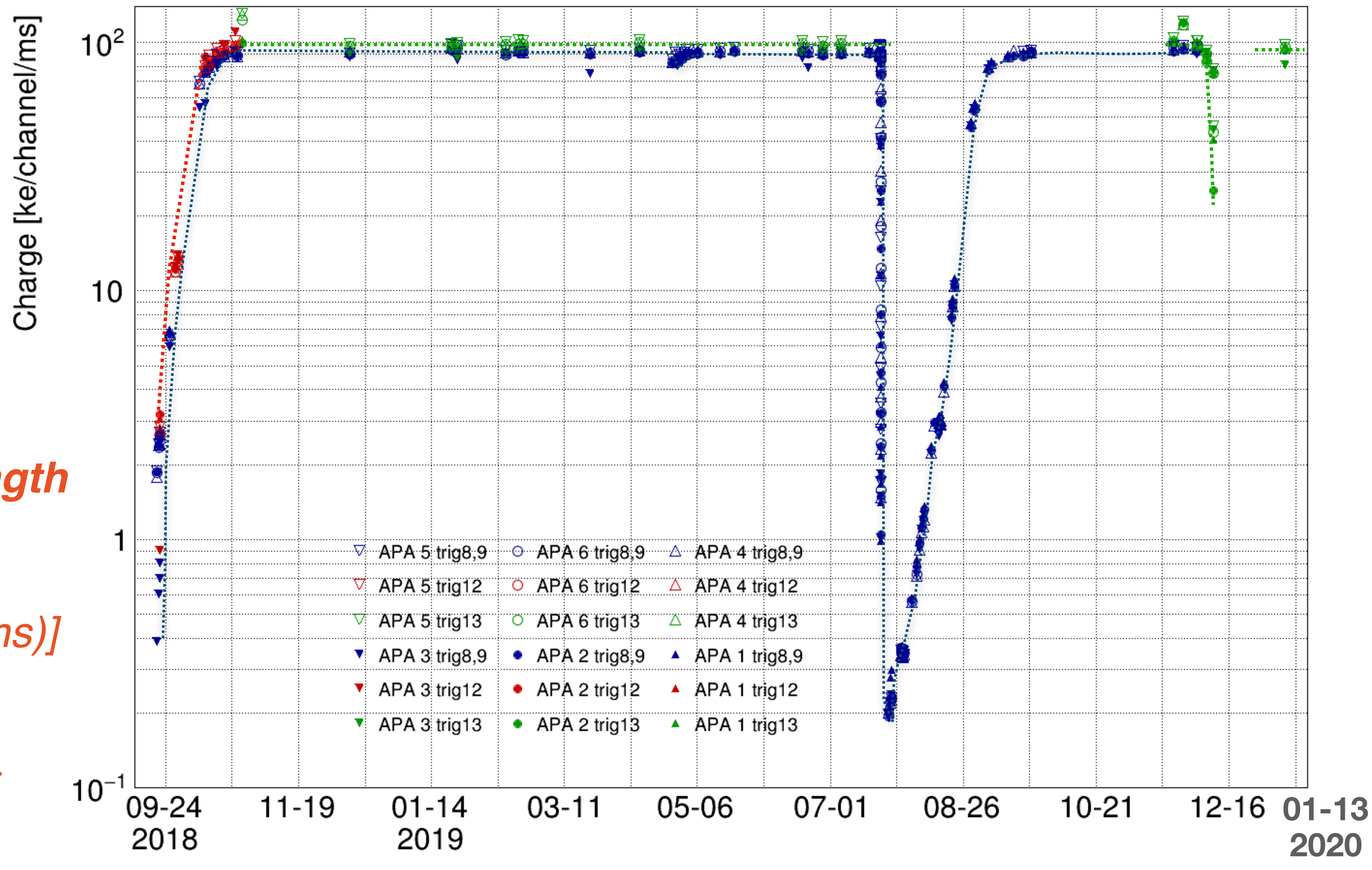




LONG TERM STABILITY

-TPC Response:



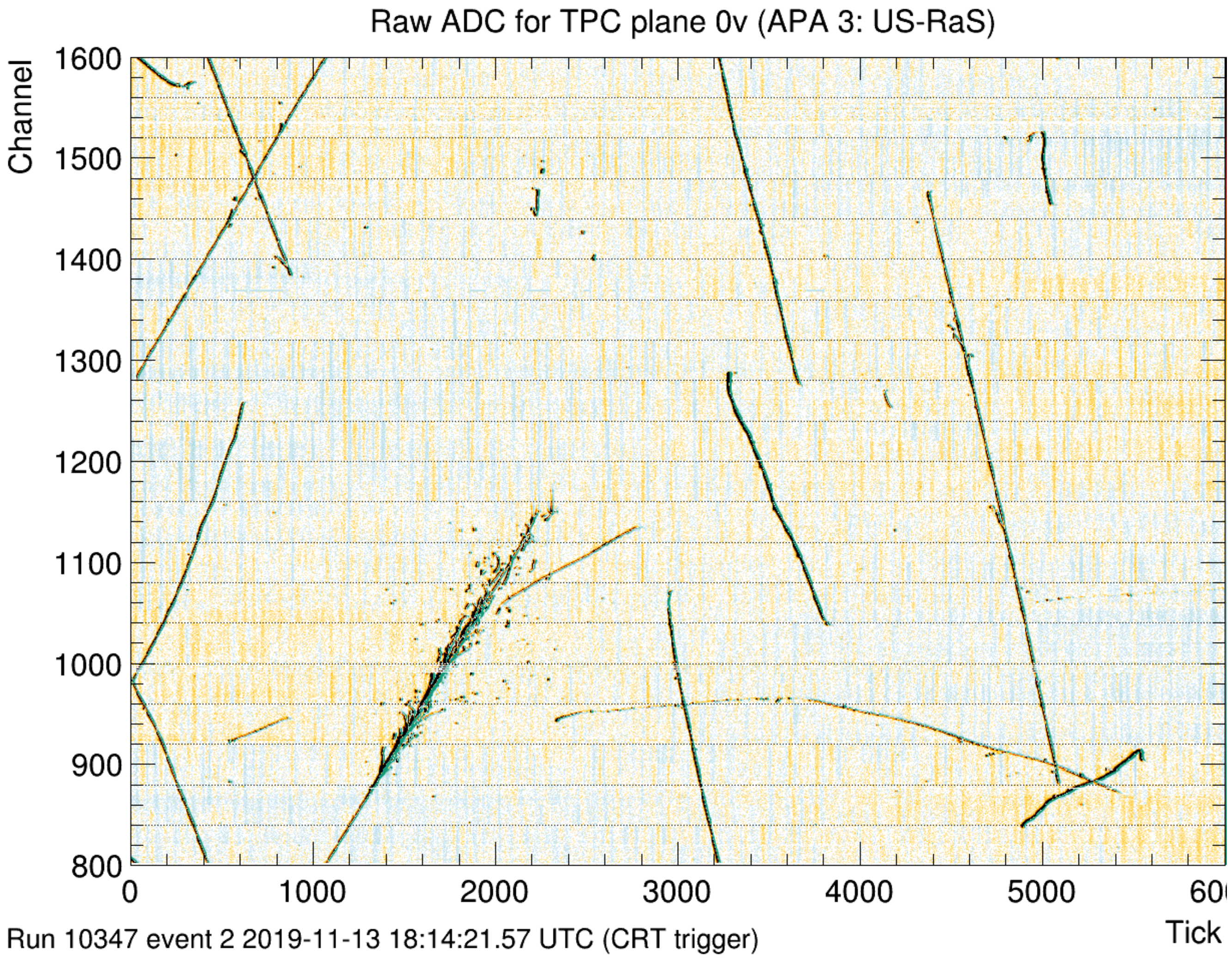


TPC Signal Strength
[Average Charge per Channel per Time unit (1 ms)]

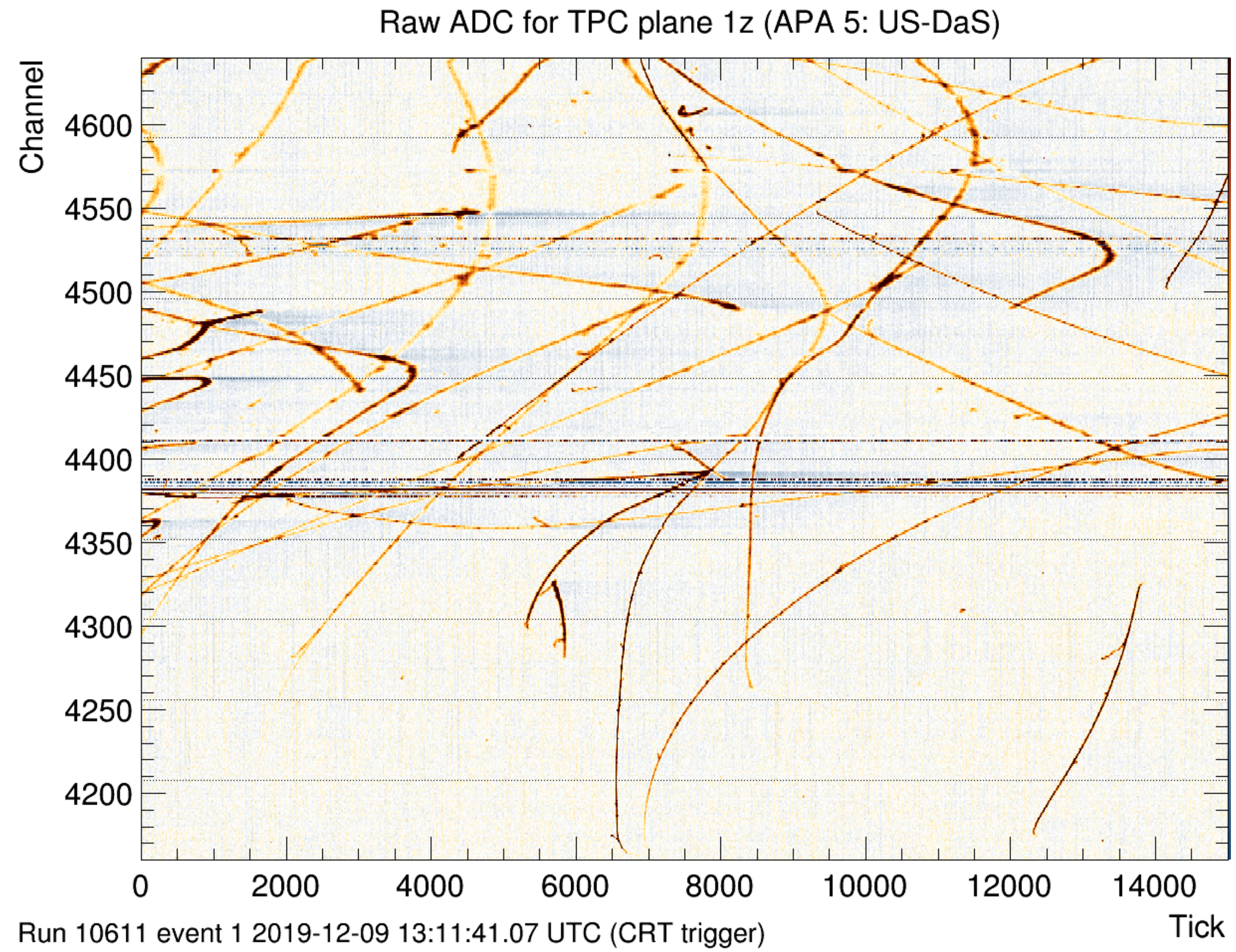
SPACE CHARGE & FLUID FLOW

Distortion due to Sp.Charge evident when TPC operated at low(er) El. Field

180 kV at the Cathode (nominal)
[during beam run and operation w/ cosmics]



72 kV at the Cathode
[during SpCharge dedicated tests]

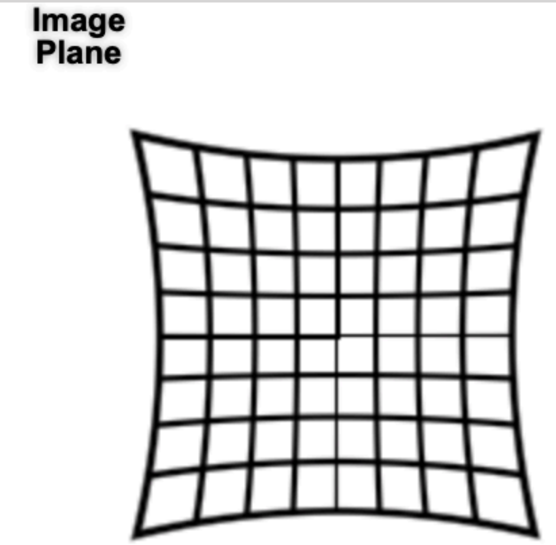


Space Charge & Fluid Flow

180 kV at the Cathode (nominal)

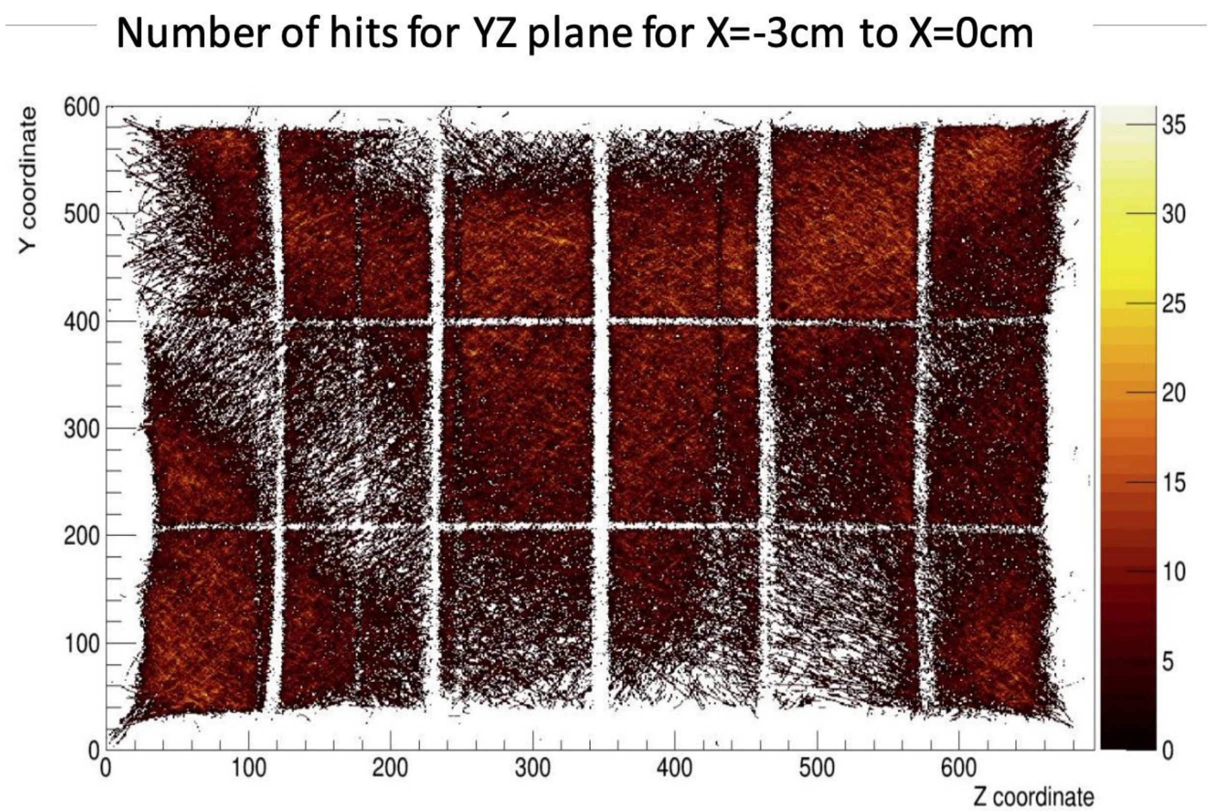
Space Charge in Drift Volume:
local deviations from nominal (uniform) EF
⇒ Geometric Distortion Aberration

⇒ Variation of charge recombination

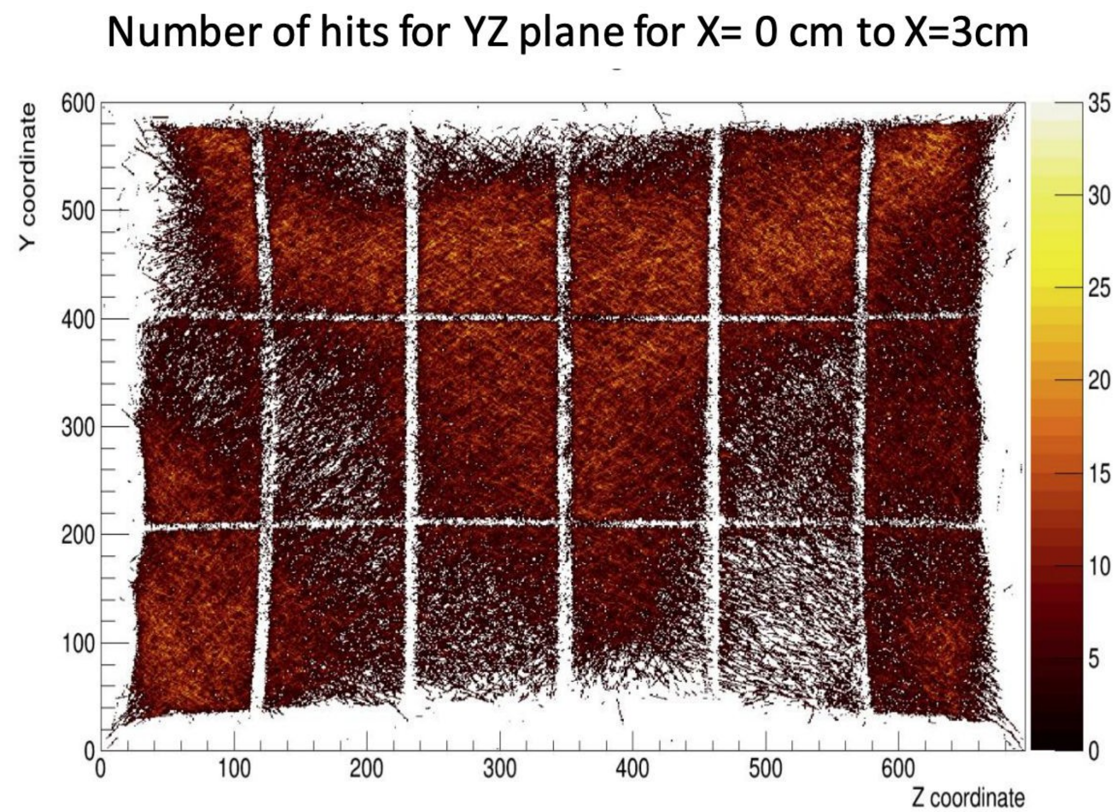


15 % Positive

tomographic imaging



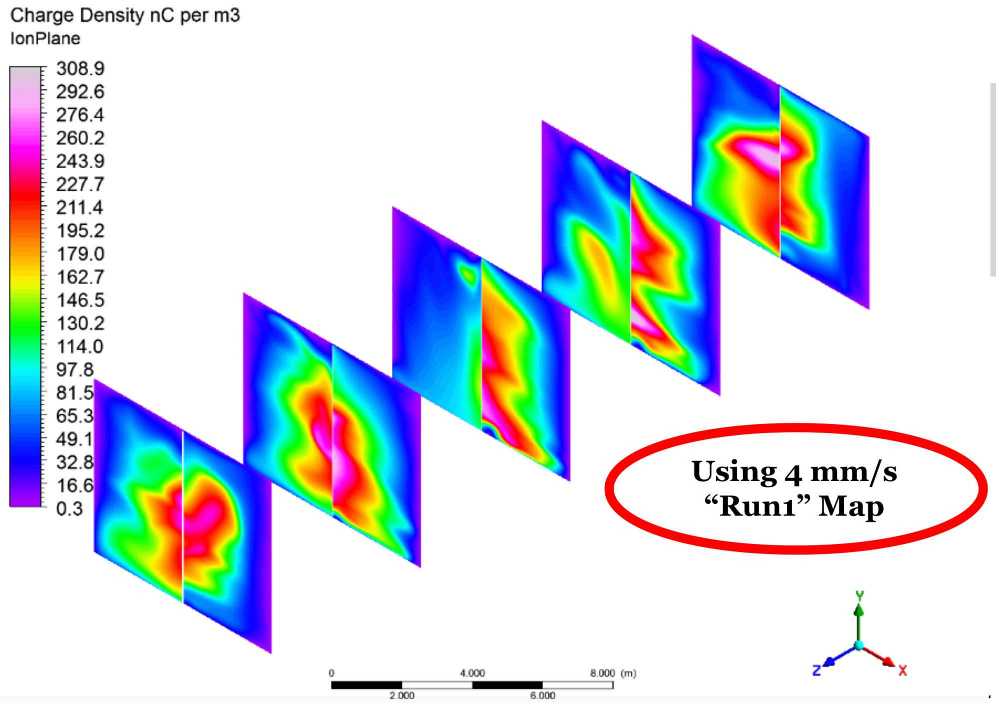
Beam right



Beam left

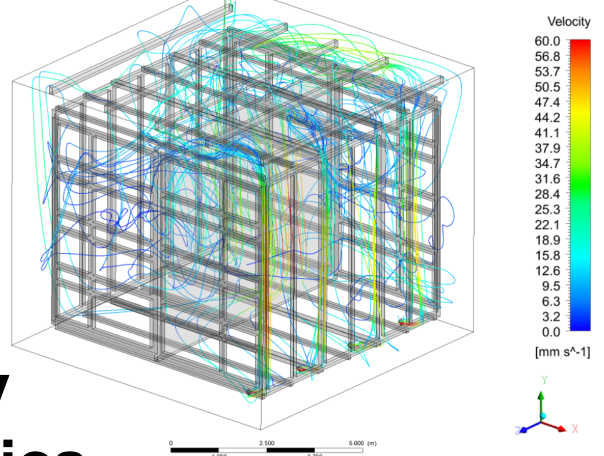
Track selection for e-lifetime measurement inside TPC volume:
Tracks contained within the central part of the TPC, where distortion along y and z axes are negligible

15

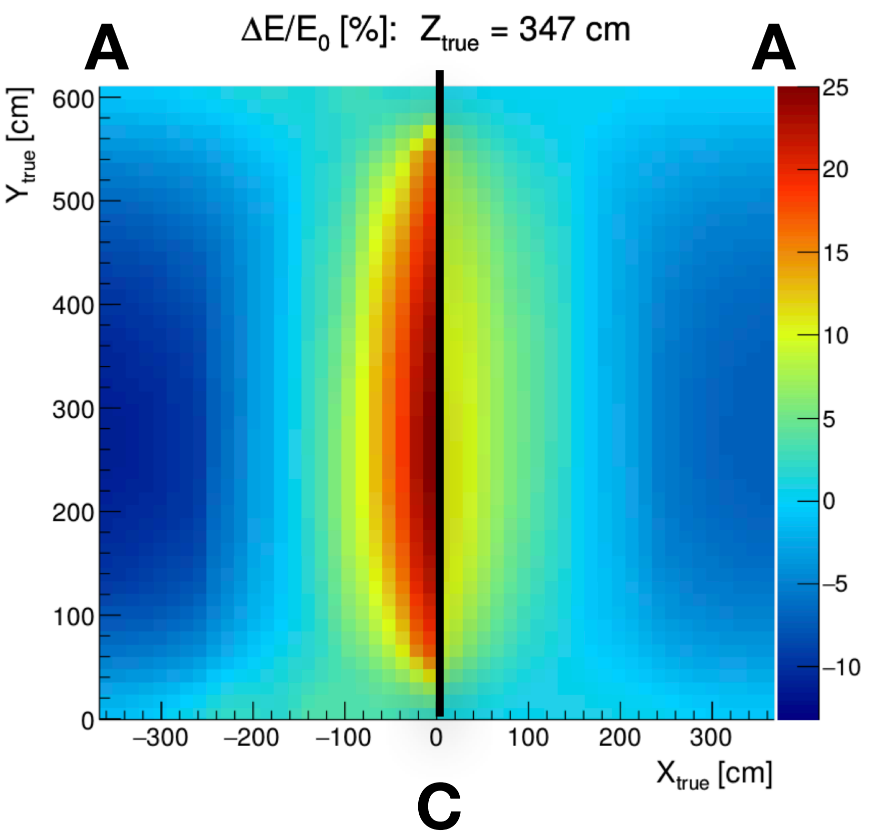


FLUID FLOW

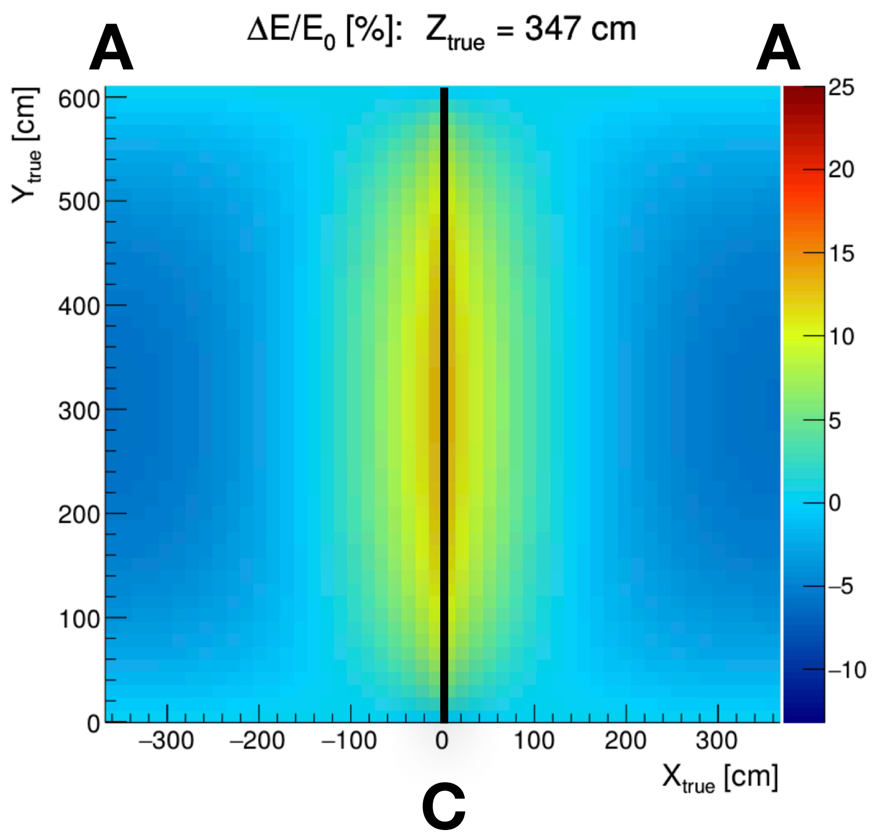
Calculation/Simulation by Computational Fluid Dynamics Methods



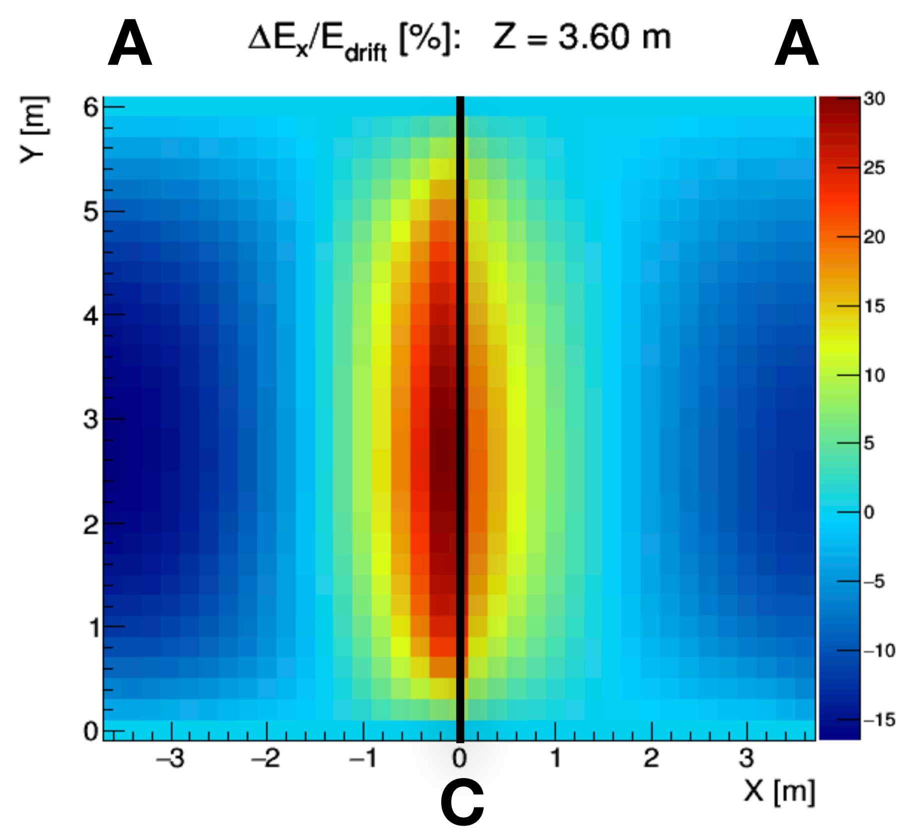
DATA



MC (no Fluid Flow)

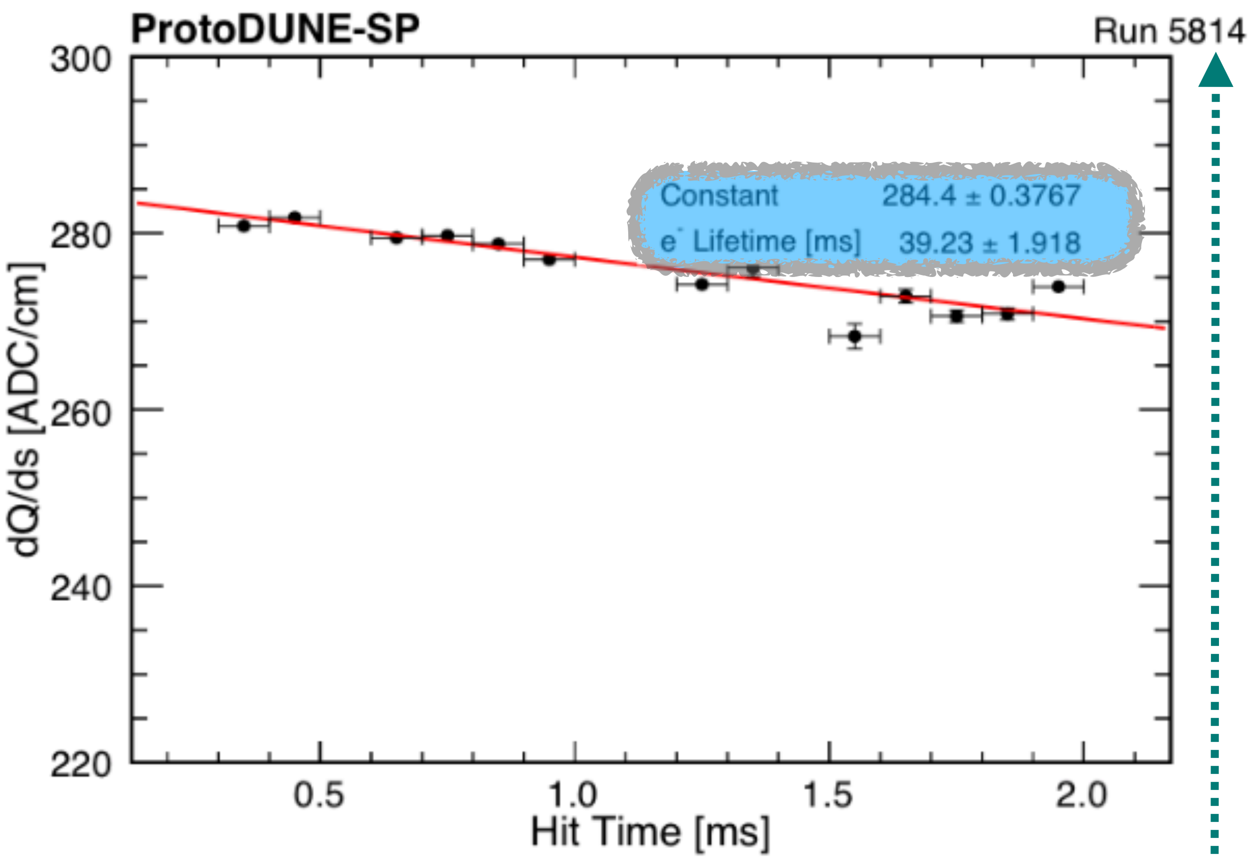


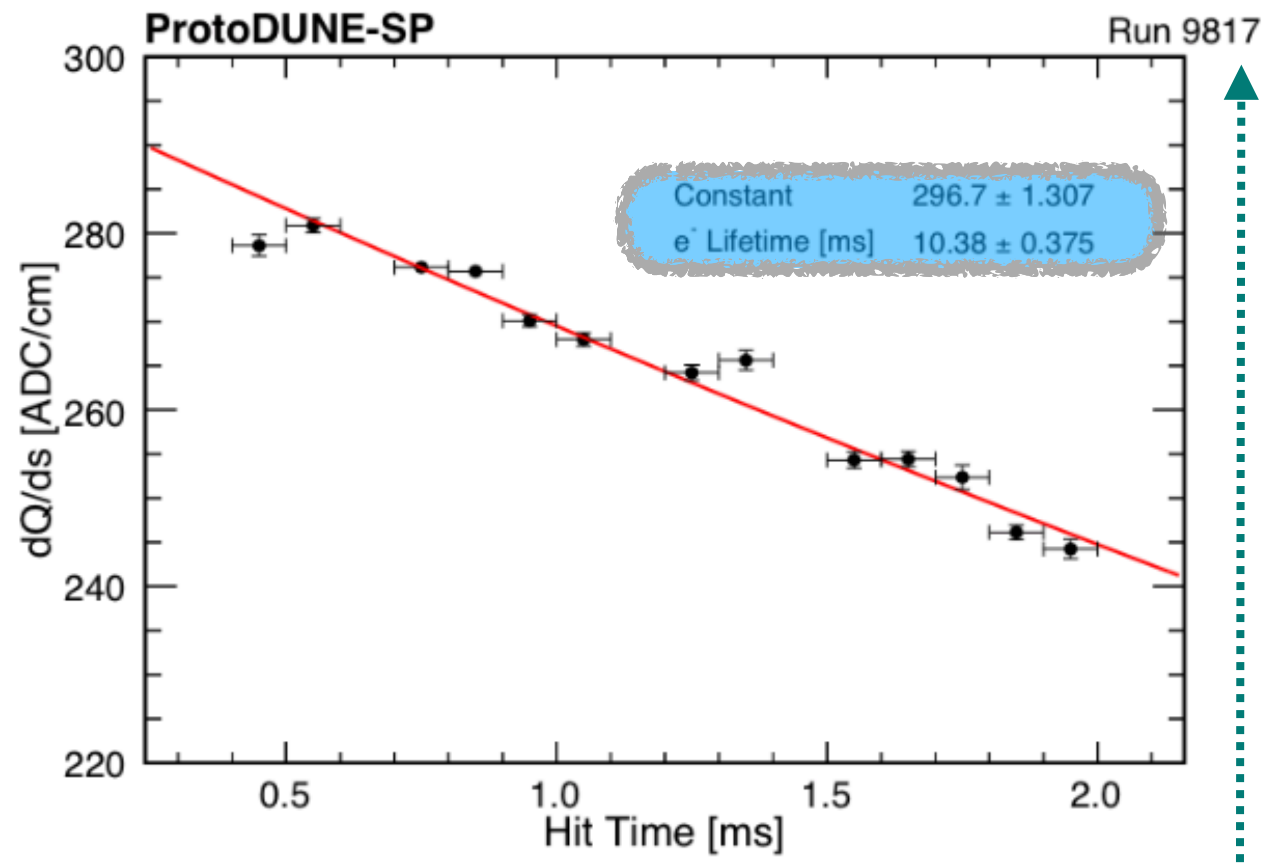
MC (w/ Fluid Flow)



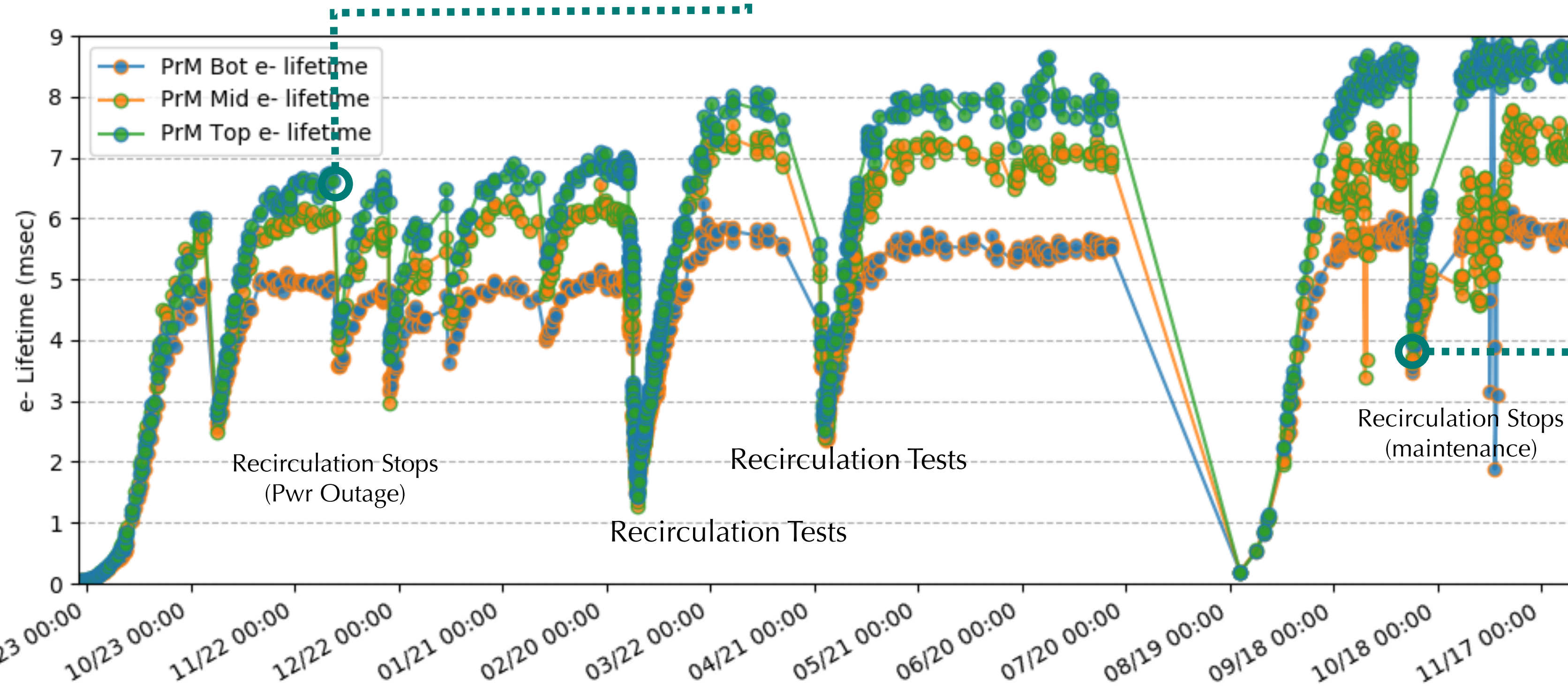
- Better agreement between data and MC for model w/ fluid flow – larger on side where beam comes in ("beam right")

LONG TERM STABILITY e-Lifetime (and LAr Purity)



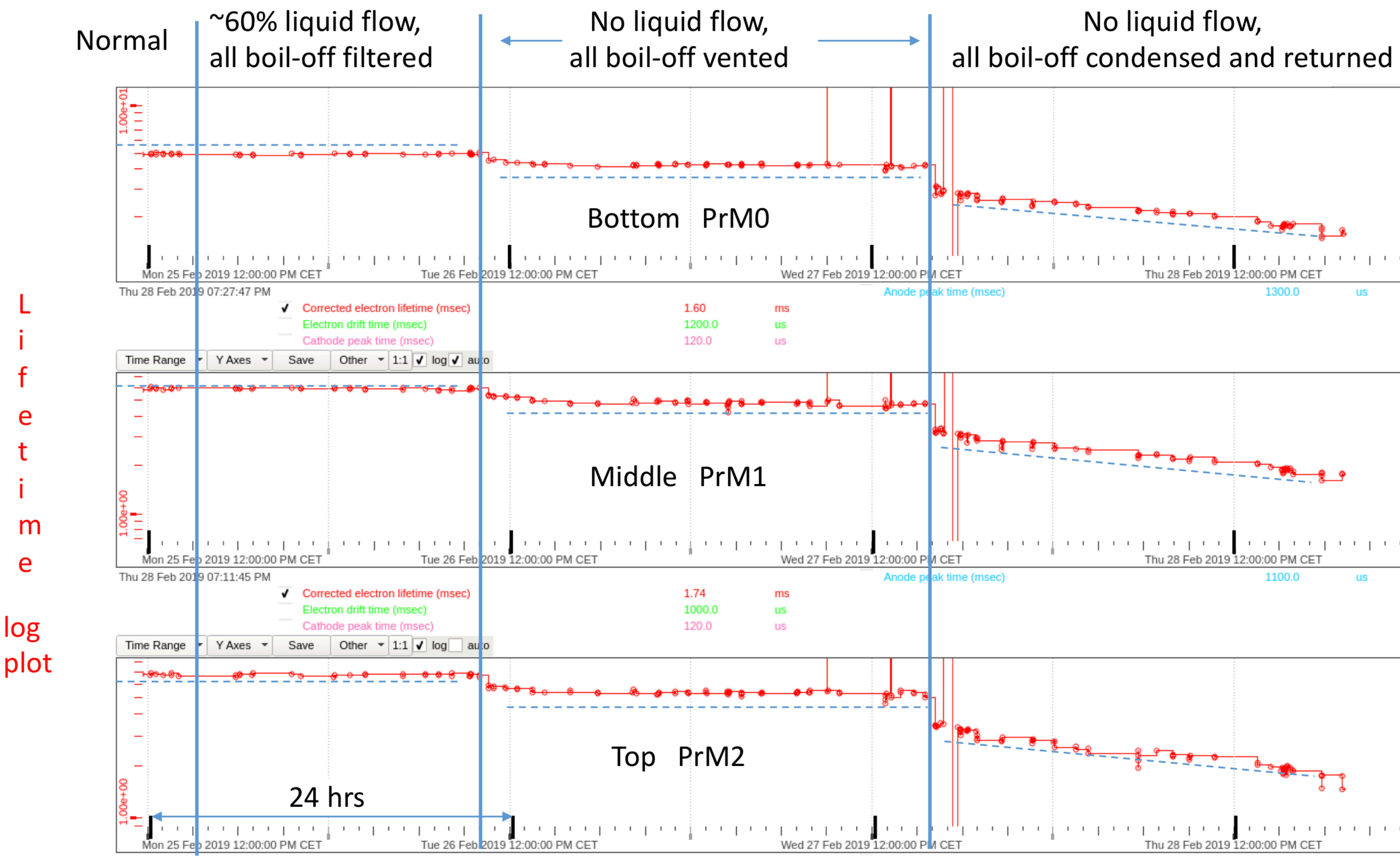


Stratification *(if any in TPC)* **will make little effect on lifetime correction factor**



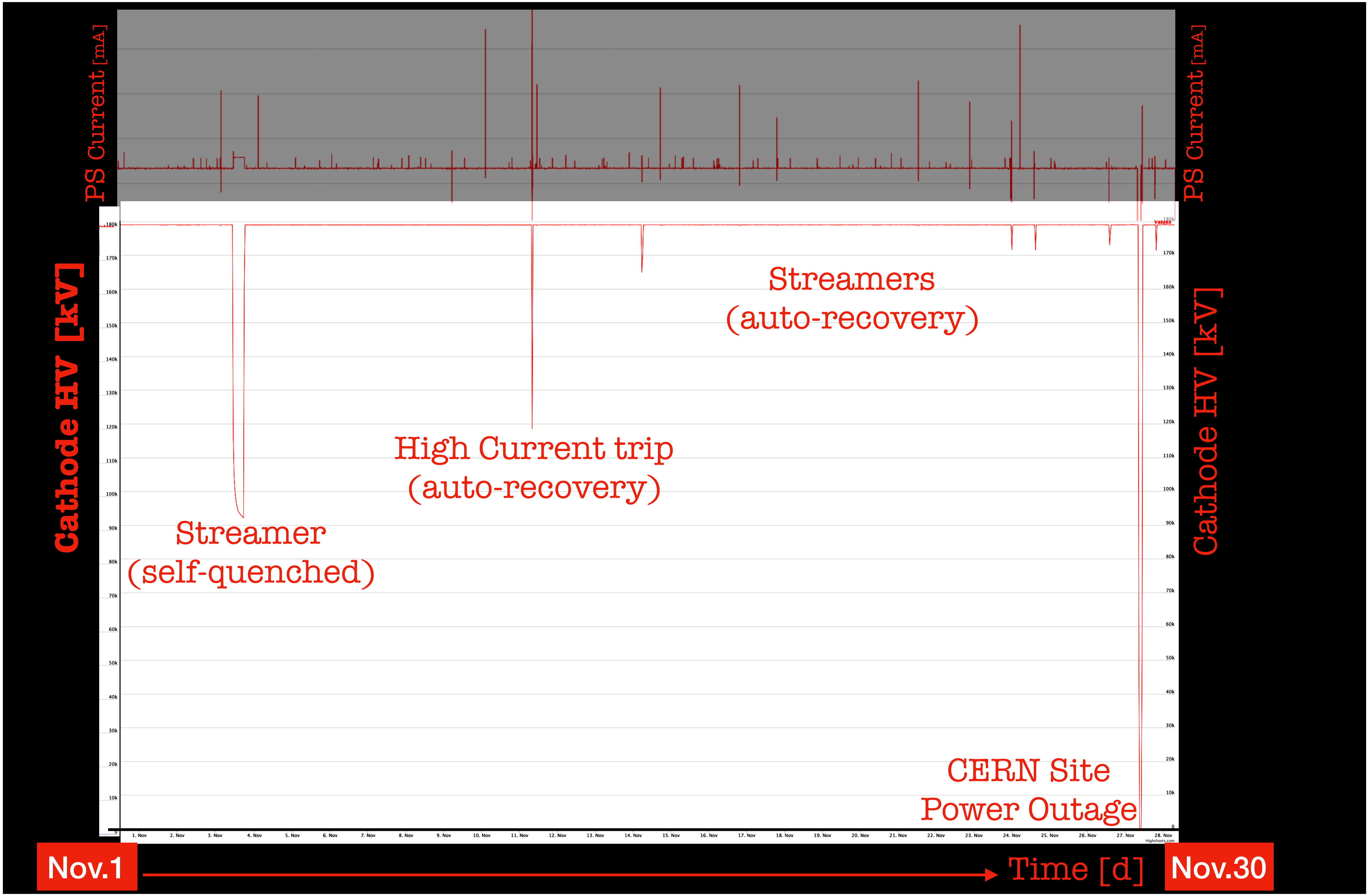
PurMon - Service Apparent Stratification *visible in low lifetime measurement w/ PurMon*

LIMITING FACTORS ON ELECTRON LIFETIME/LAR PURITY



Cryogenic Circulation Studies

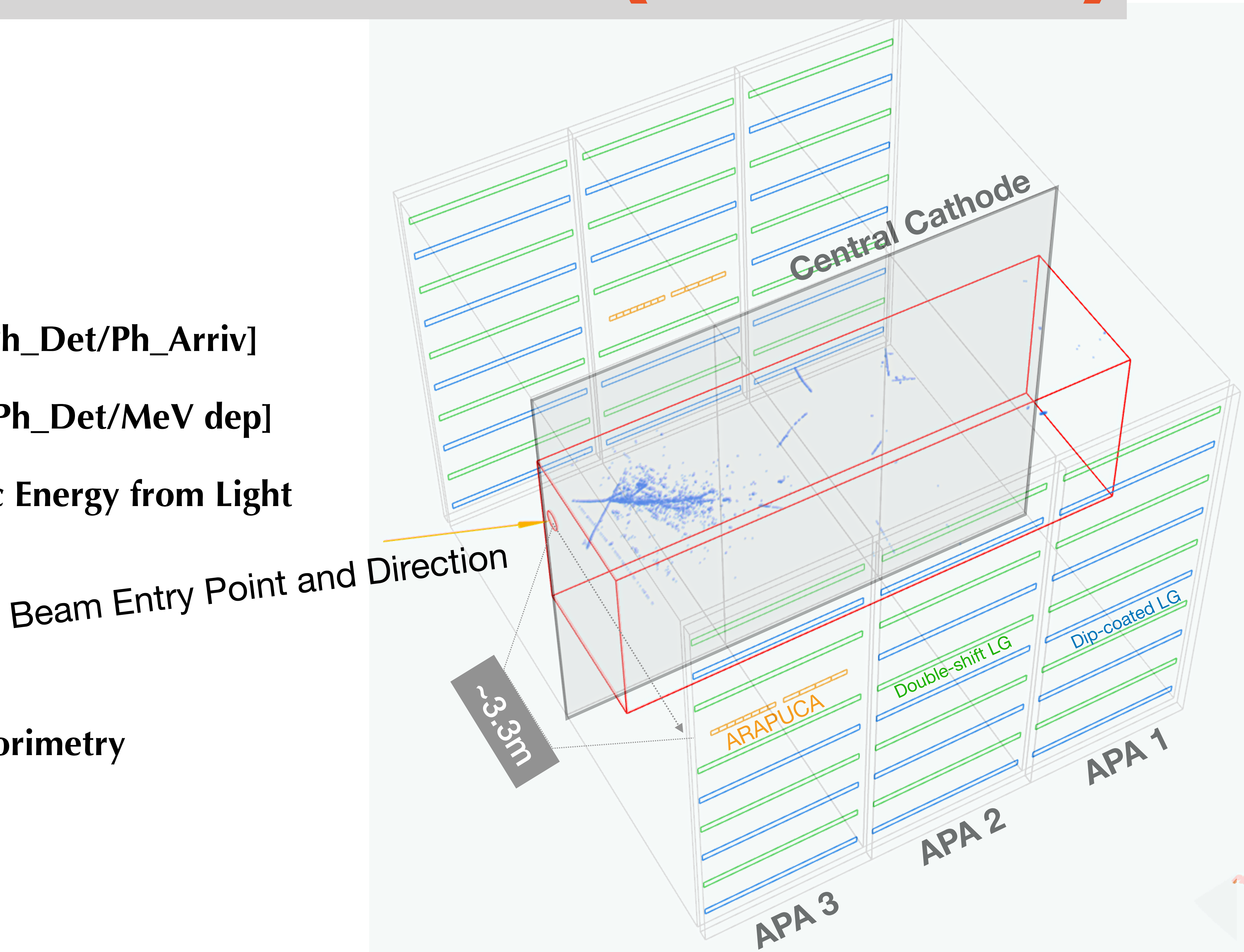
LONG TERM STABILITY - HV / E-field



DETECTOR RESPONSE (BEAM DATA)

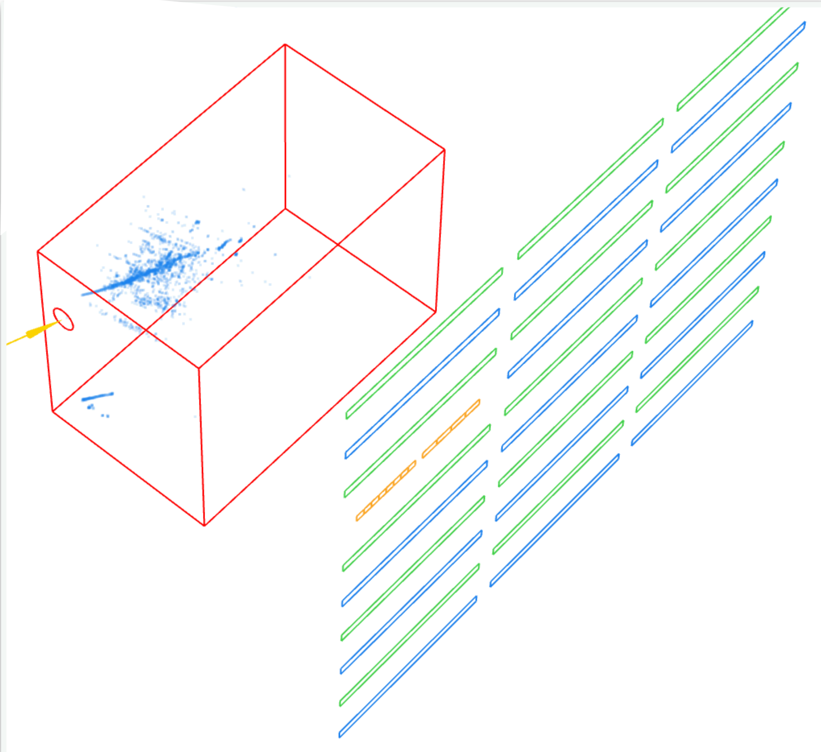
PDS

- Efficiency [Ph_Det/Ph_Arriv]
- Light Yield [Ph_Det/MeV dep]
- Calorimetric Energy from Light



TPC

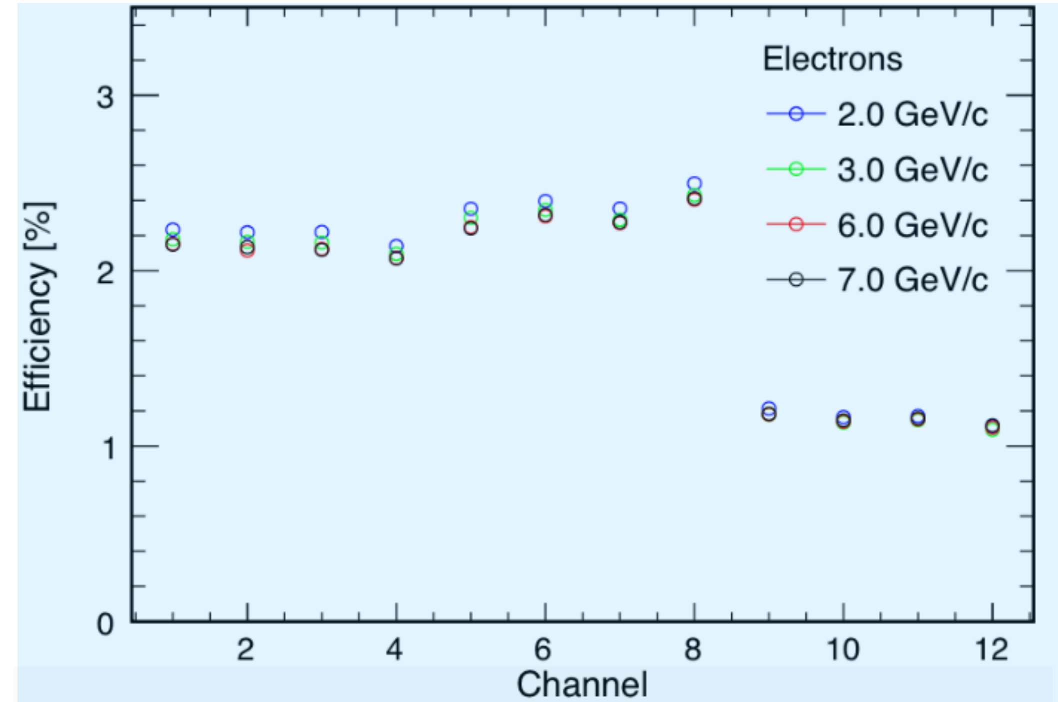
- dE/dx - Calorimetry
- SNR & PID



ARAPUCA

$$\tilde{\epsilon}_{A1} = (2.00 \pm 0.25)\,\%$$

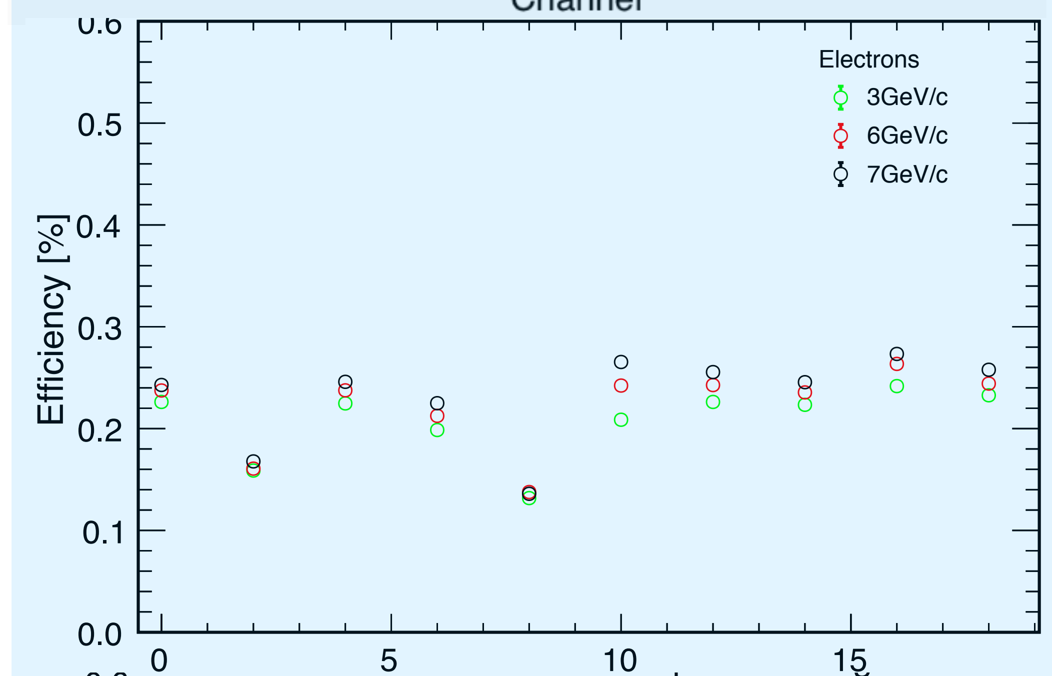
$$\tilde{\epsilon}_{A2} = (1.09 \pm 0.09)\,\%$$

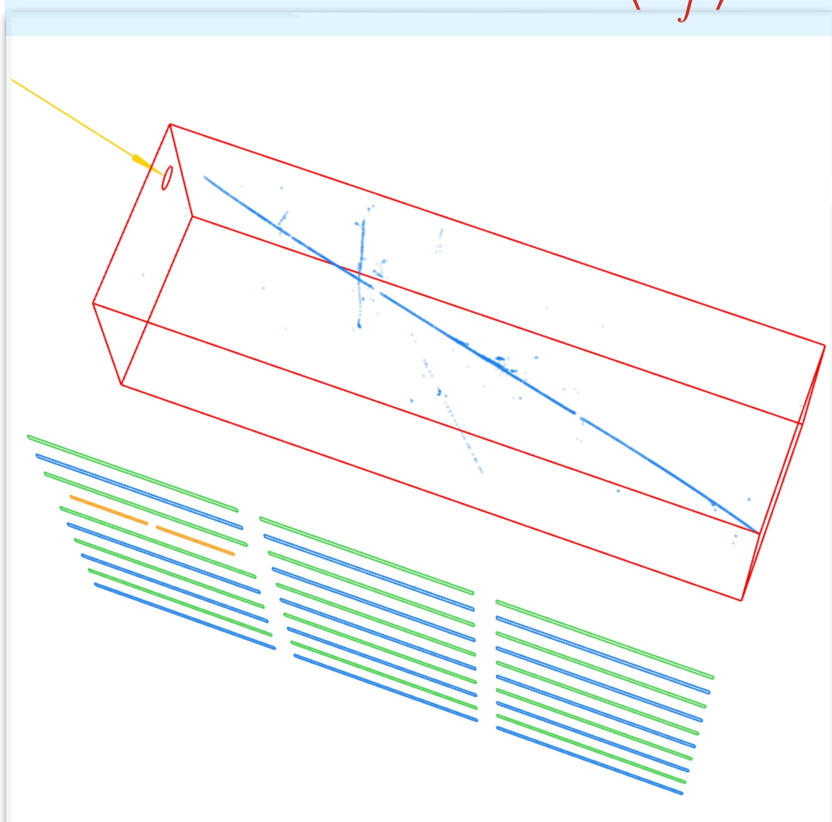


EFFICIENCY $\epsilon_j = \frac{\langle N_j^D \rangle}{\langle N_j^L \rangle}$

DOUBLE-SHIFT LIGHT GUIDE

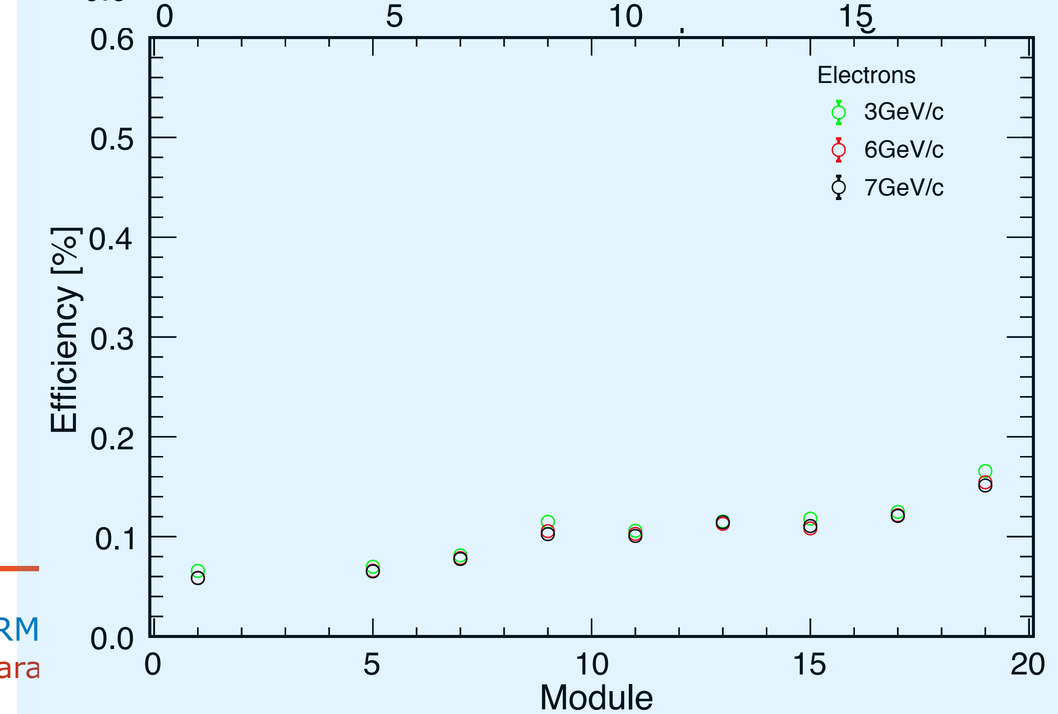
$$\tilde{\epsilon}_{DS} = (0.21 \pm 0.04)\,\%$$

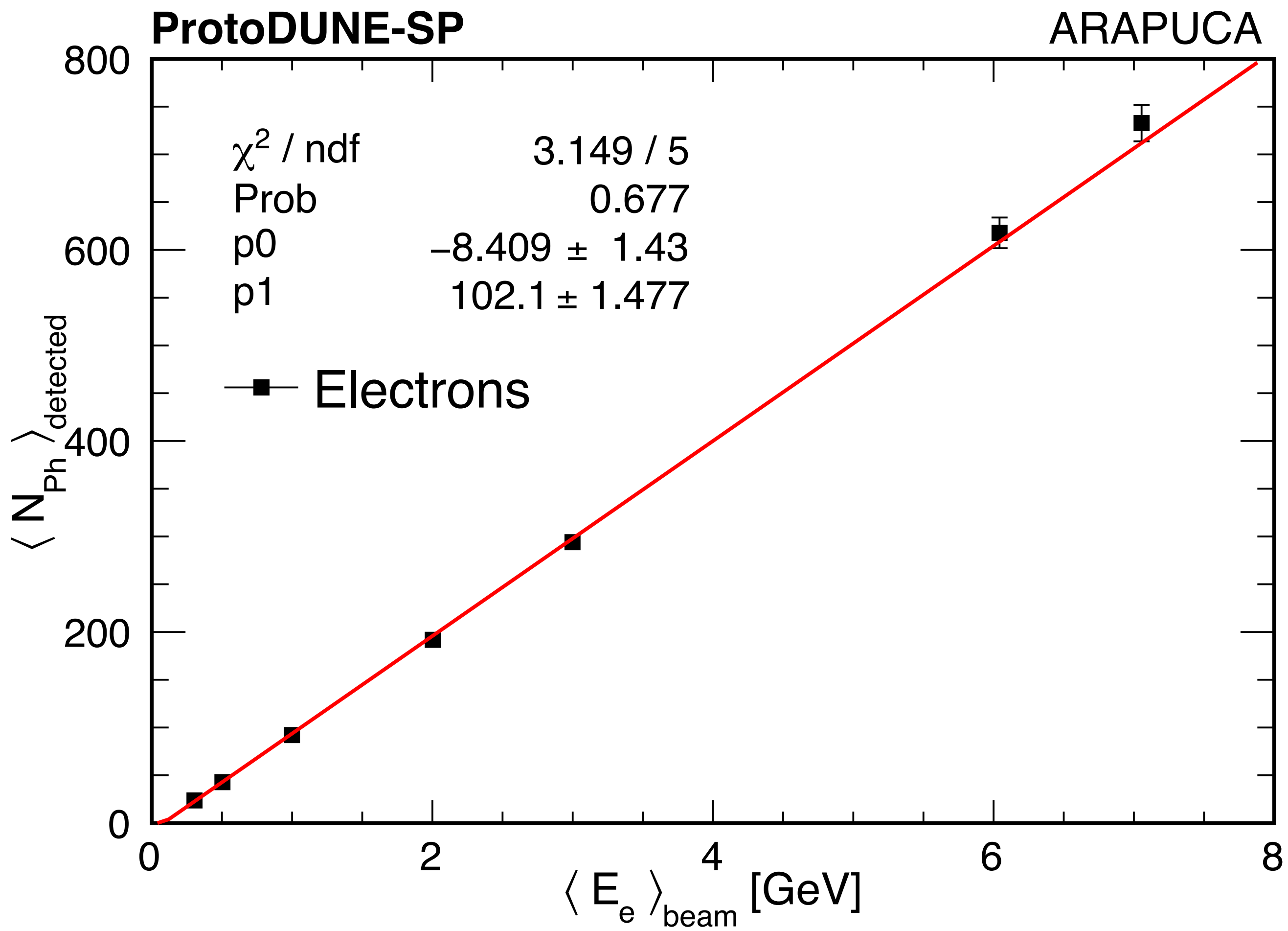


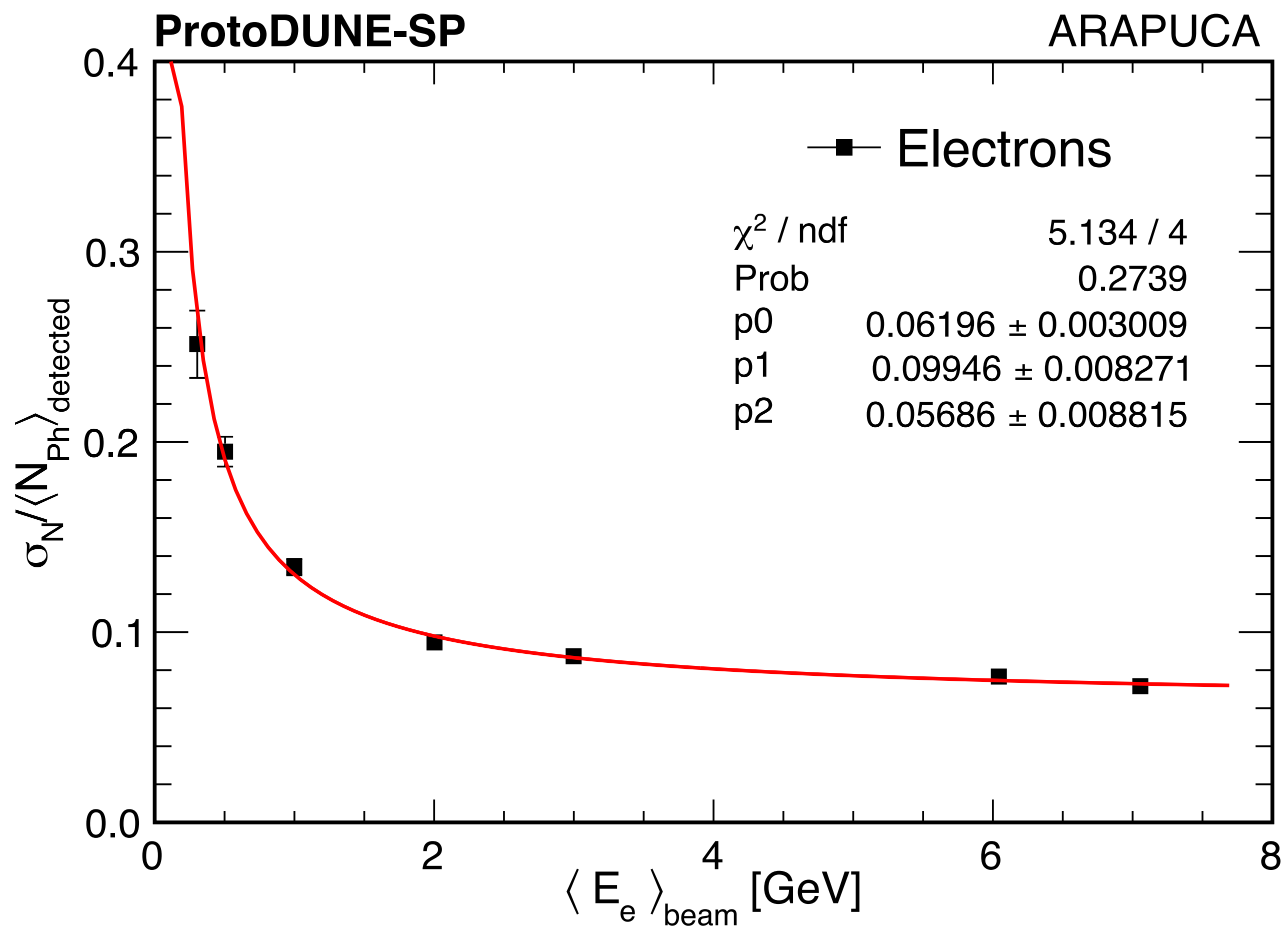


DIP-COATED LIGHT GUIDE

$$\tilde{\epsilon}_{DC} = (0.10 \pm 0.02)\,\%$$







LINEARITY

Observed (first approx) over the entire range of energies.

The slope gives the light yield $LY = 102\ Ph/GeV$ **from (only) one ARAPUCA module, relative to a diffused light source (EM shower) at a distance of about 3 m**

The non-zero (negative) y-intercept (p0 from the fit) corresponds to an incident energy offset

$$E_o = 82 \pm 14\ MeV$$

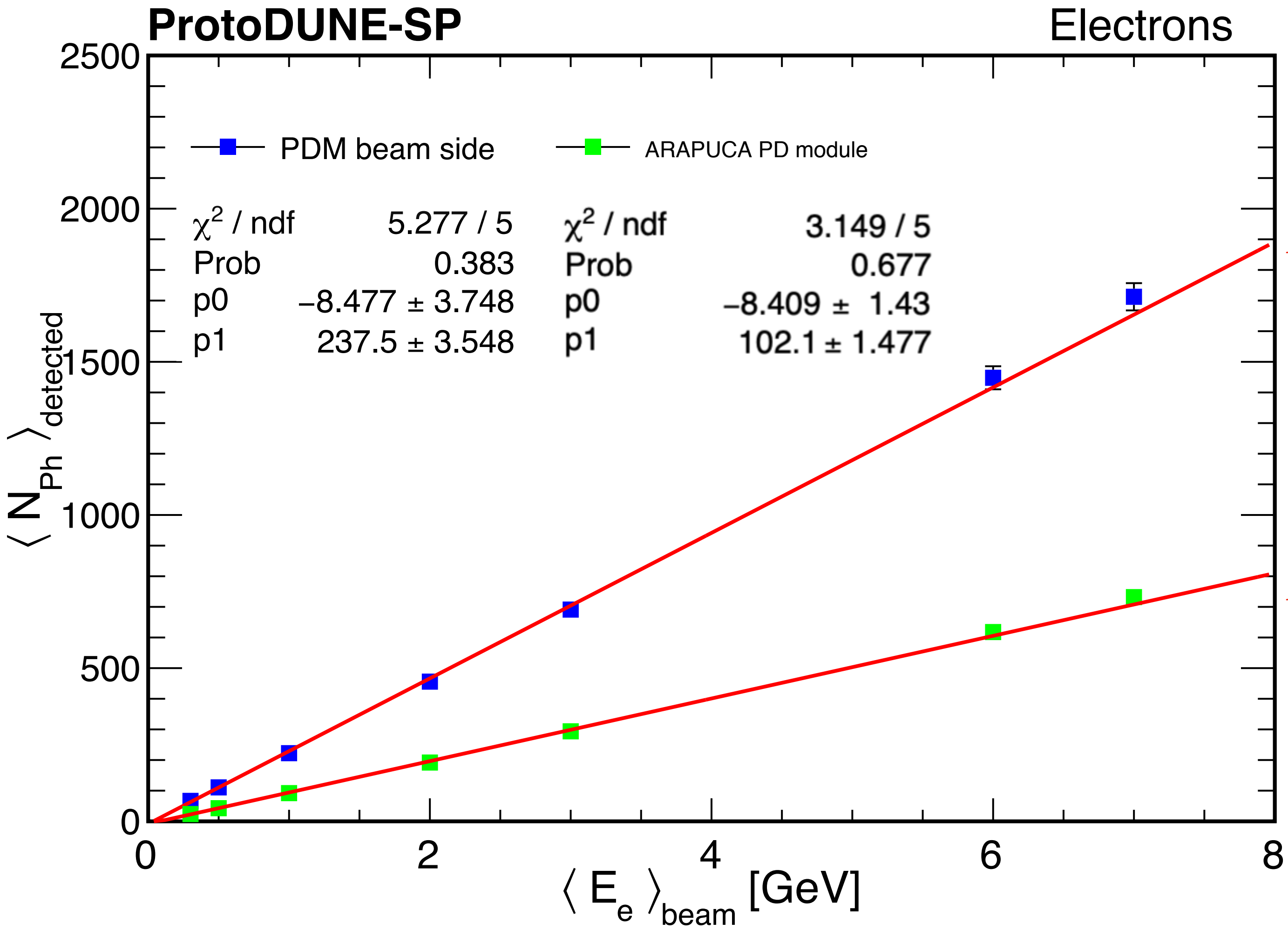
compatible with expected energy loss in material upstream TPC

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:** $p_0 = 6.2\ \%$
  from beam momentum spread & uncertainty and non-uniformities in light collection (non linearity)



$LY = 237\ Ph/GeV$

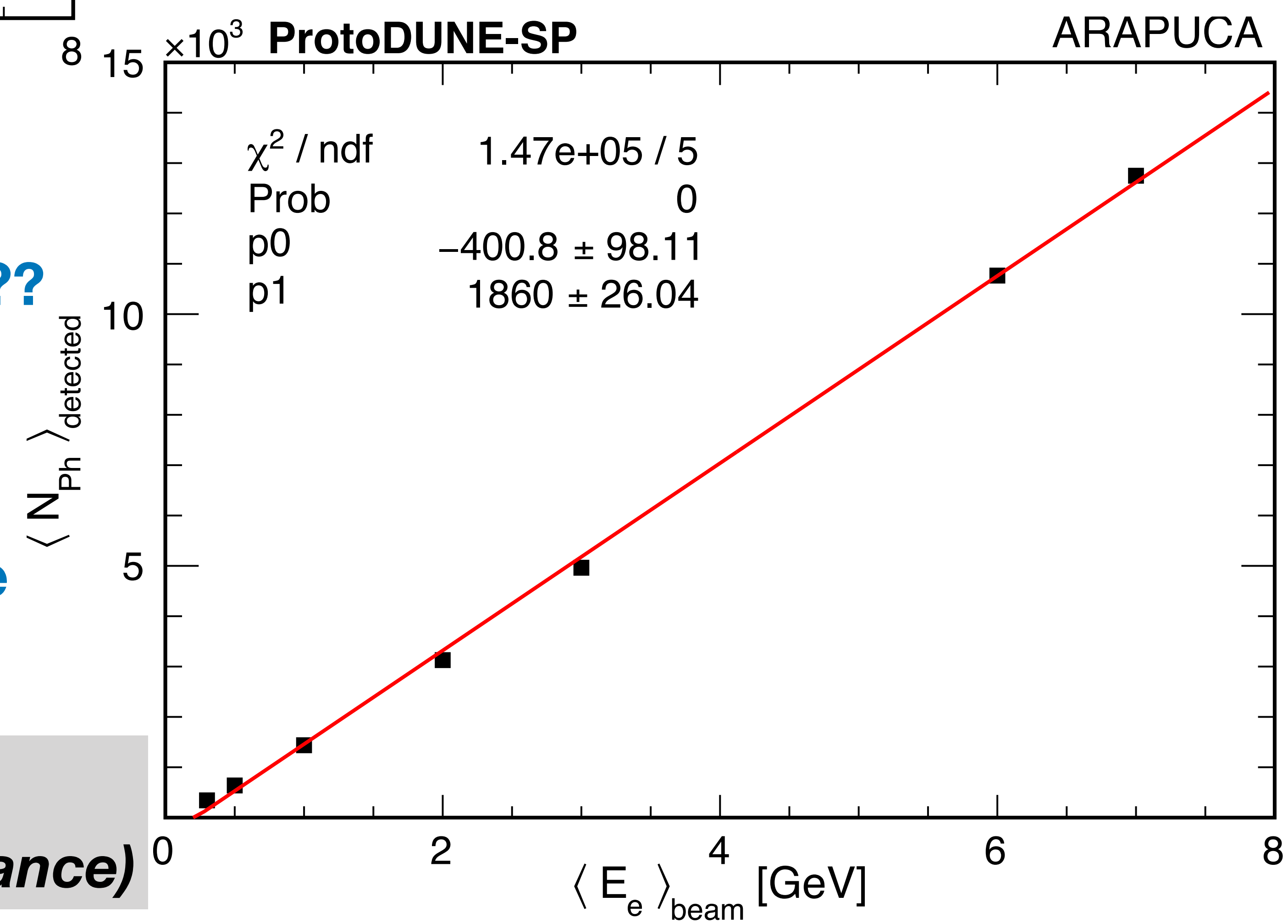
All PDS (beam side):
1 ARAPUCA +
15 Double-shift LG's +
14 Dip-coated LG's

$LY = 102\ Ph/GeV$ **1 ARAPUCA (only)**

What if
PDS made all by (30) ARAPUCA modules ??

by extrapolation from current data: $N_{ph} \cdot \frac{\epsilon_{Arapuca}}{\epsilon_{LightGuide}}$

$LY \simeq 1.9\ Ph/MeV$ **@ 3.3 m distance**

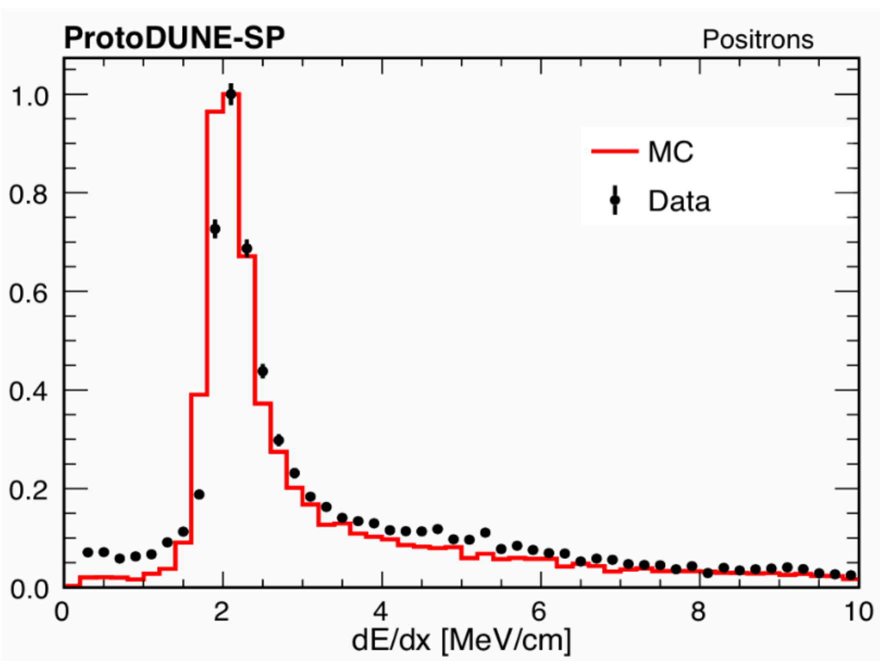


Note: DUNE FD Requirement:
> 0.5 Ph/MeV (at anode plane - 3.6 m distance)

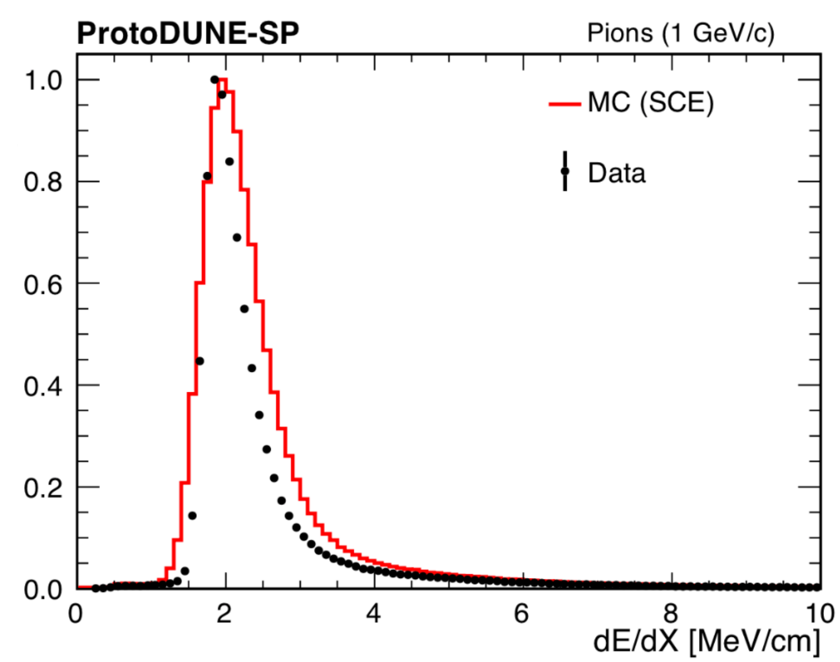
BEAM DATA - dE/dx

(after Space Charge Calibration)

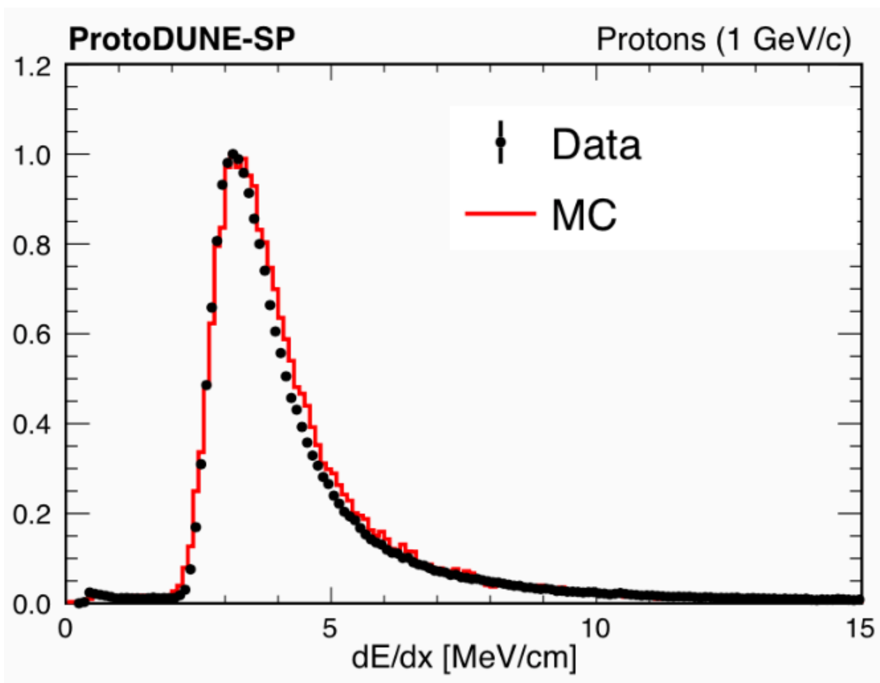
1 GEV ELECTRONS



1 GEV PIONS



1 GEV PROTONS



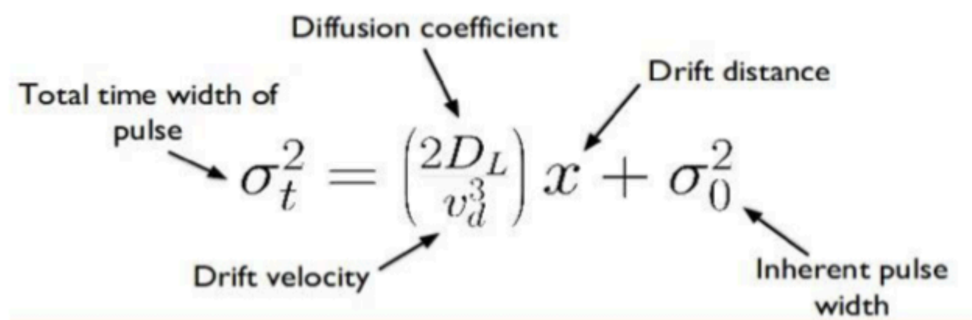
Resolution appears better in DATA than in MonteCarlo !

dE/dx width is found to depend on diffusion constants

Diffusion Coefficient(s)

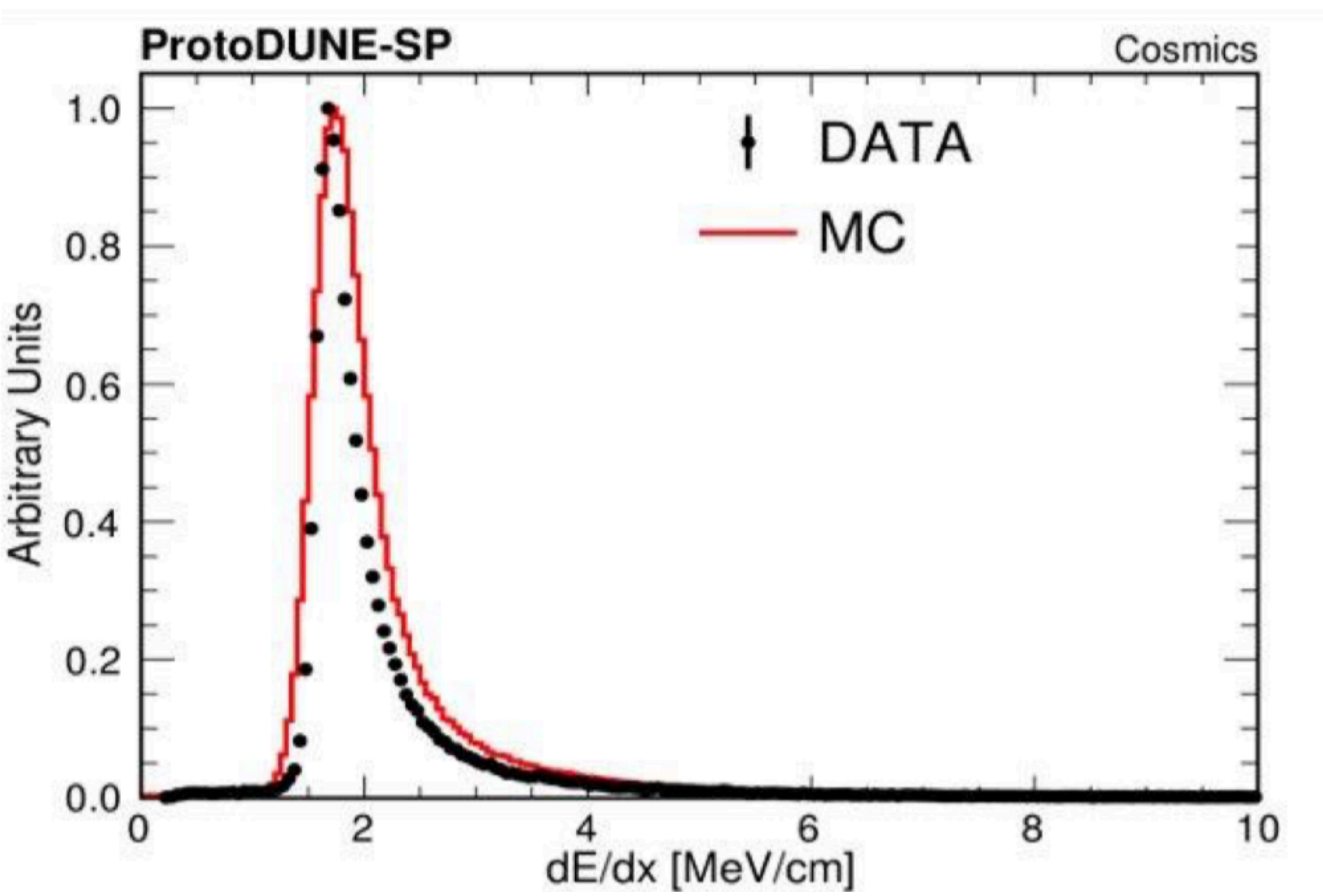
Stopping muon dE/dx distributions for the ProtoDUNE-SP cosmic data and MC.

Diffusion in data appears to be less than in simulation

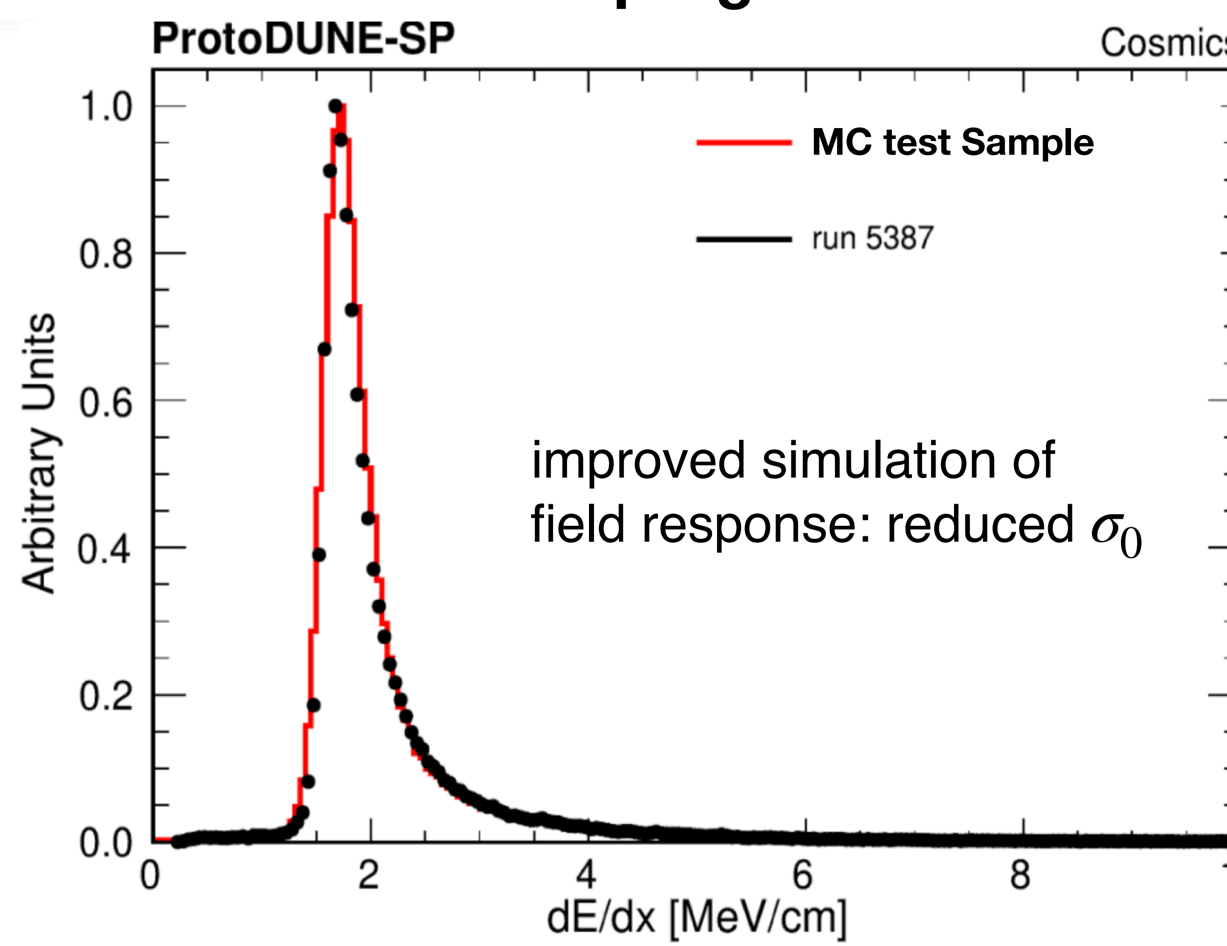


$$\sigma_t^2 = \left(\frac{2D_L}{v_d^3}\right) x + \sigma_0^2$$

Width of dE/dx for Data and MC doesn't agree



MC Tuning of longitudinal diffusion in progress



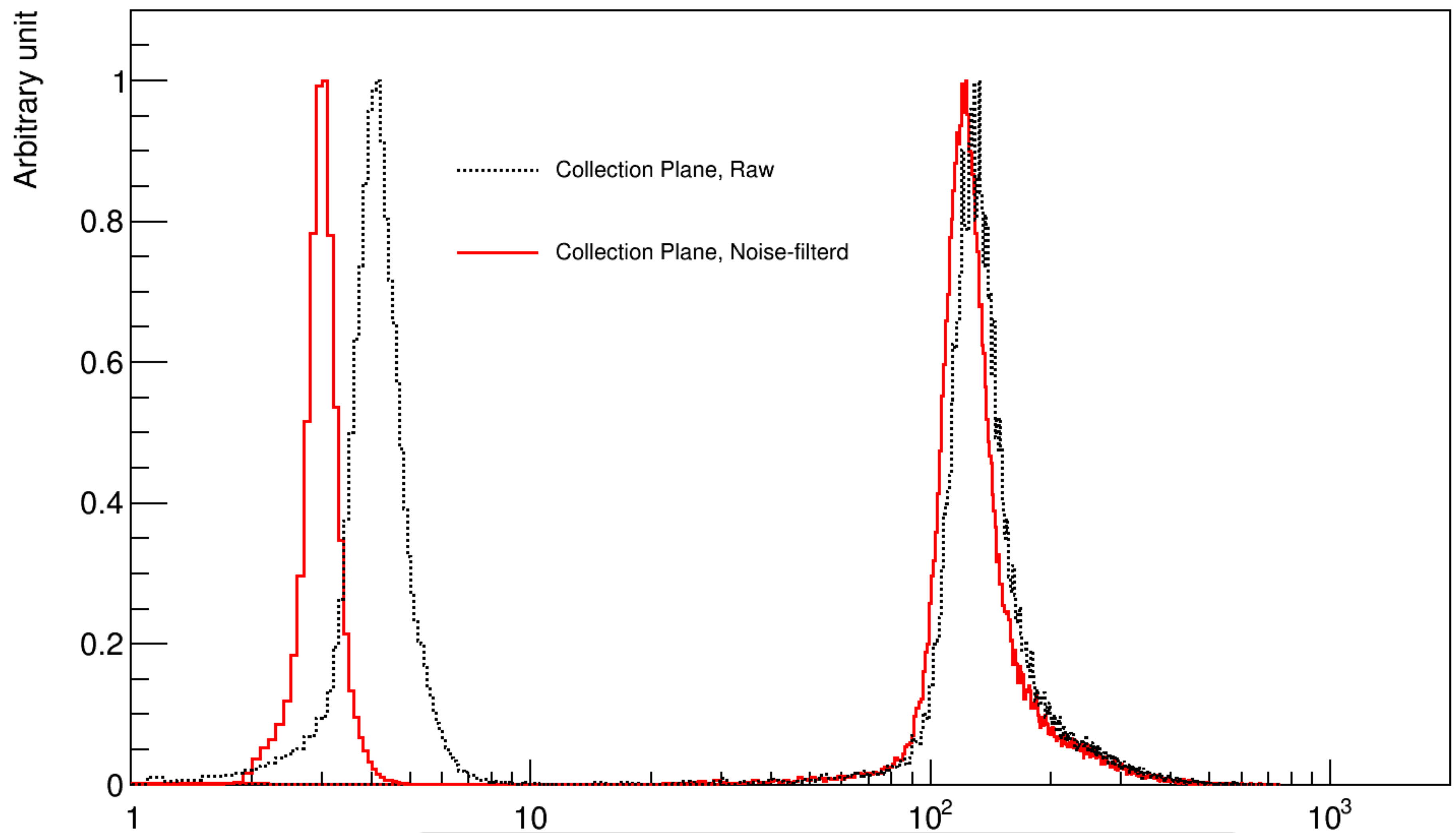
TPC + CE Performance (1):

Signal to Noise Ratio

where

Signal: detected Charge (*hit Peak-amplitude)* in individual channel waveform (from U,V,C wire-plane) from mip tracks corrected by angle of incidence

Noise: σ of baseline fluctuation in corresponding channel waveform

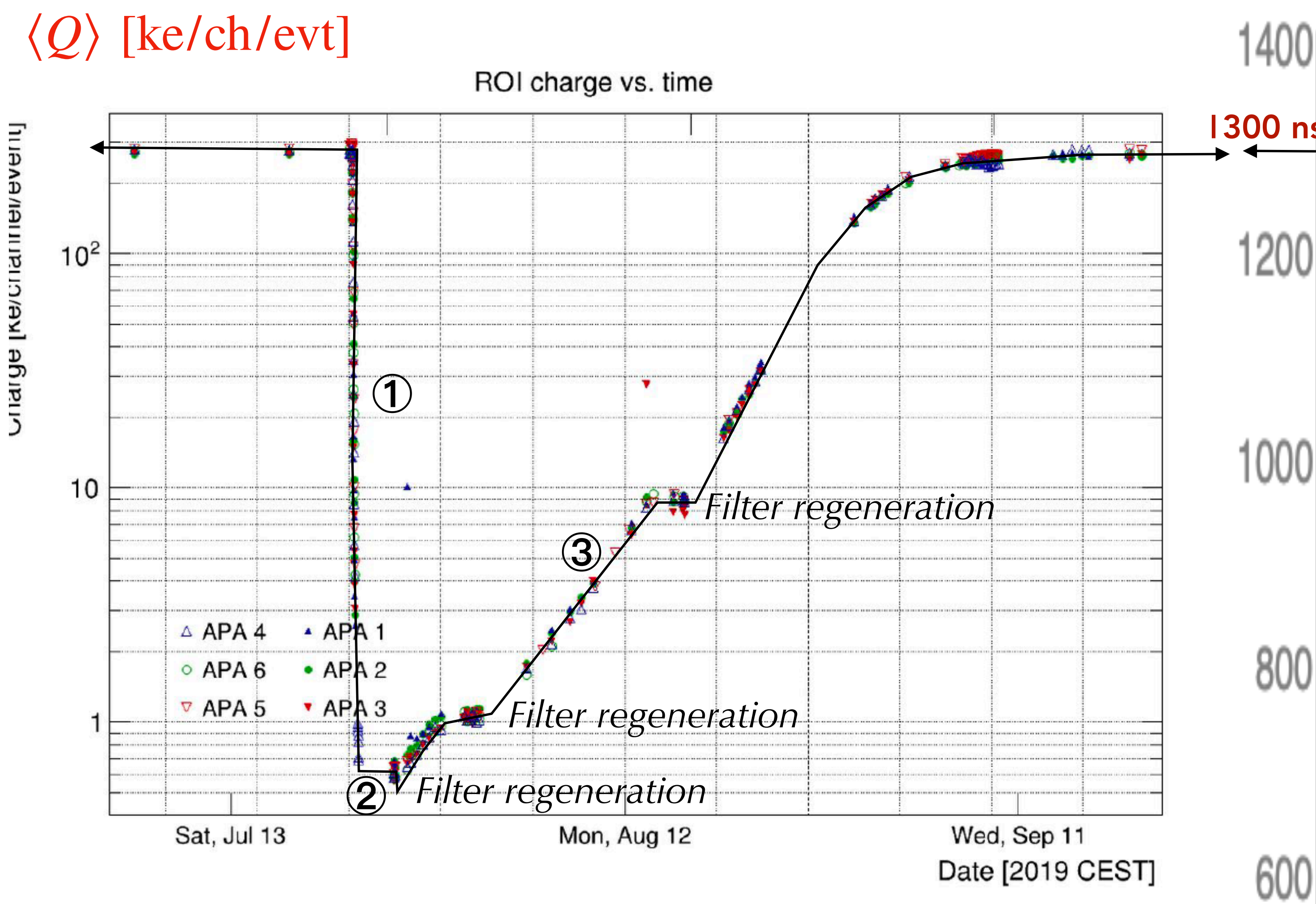


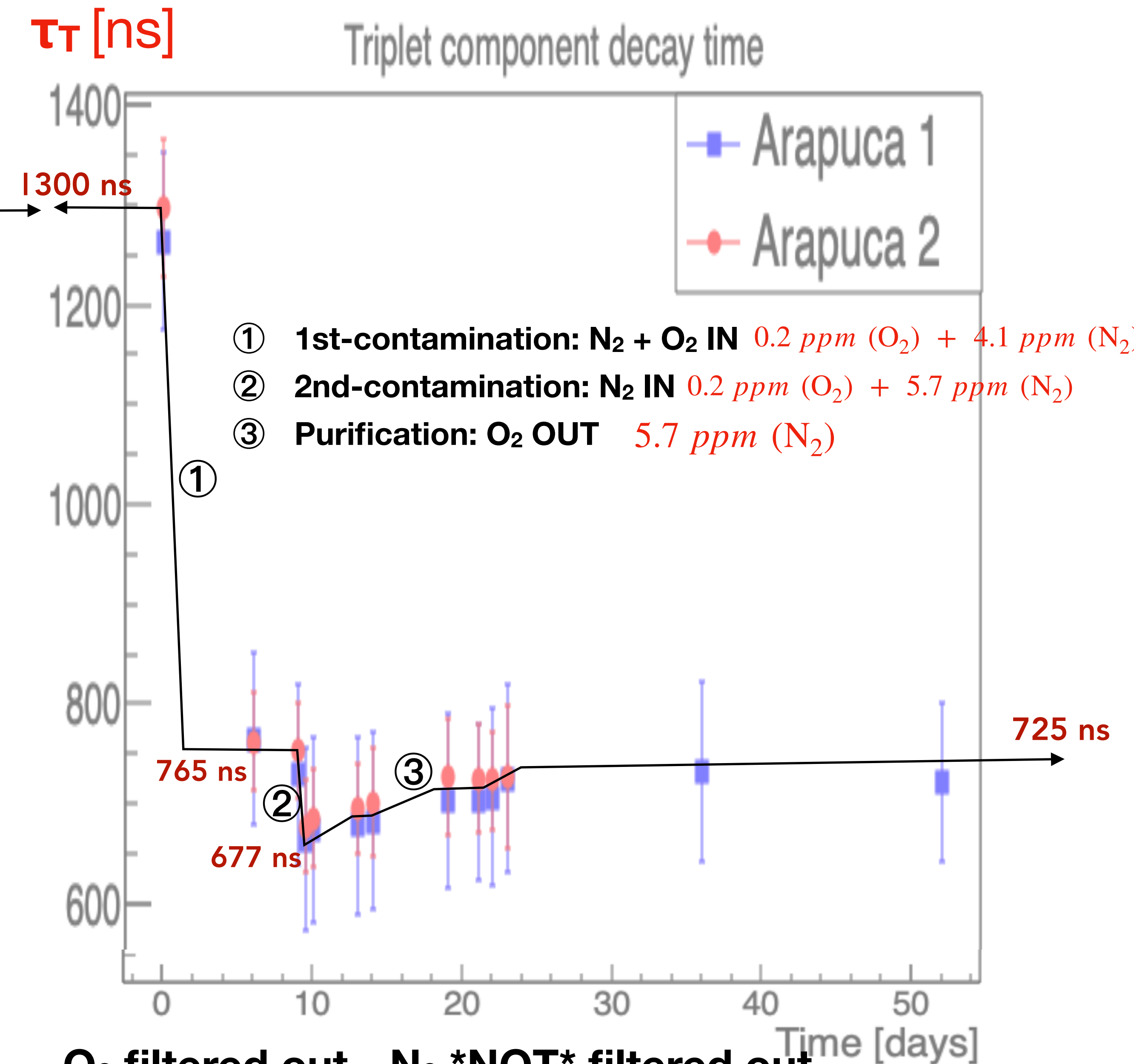
Plane	Peak signal-to-noise ratio			
	Raw Data		After Noise Filtering	
	MPV	Average	MPV	Average
Collection	30.9	38.3	40.3	48.7
U	12.1	15.6	15.1	18.2
V	14.9	18.7	18.6	21.2

138 e/ADC

FALL AND RESURRECTION

History of the event fully analyzed:
- TPC Charge Response (Signal Strength)
- PDS Light Response (Time constant Slow Component)





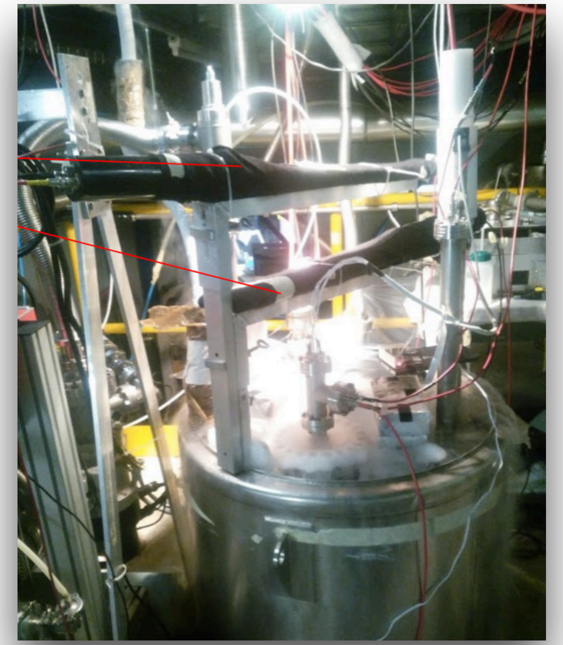
O_2 filtered out -
Full recovery of Charge Signal

O_2 filtered out - N_2 *NOT* filtered out -
Partial recovery of Light Signal
(~30% Triplet Component quenched)

XE DOPING

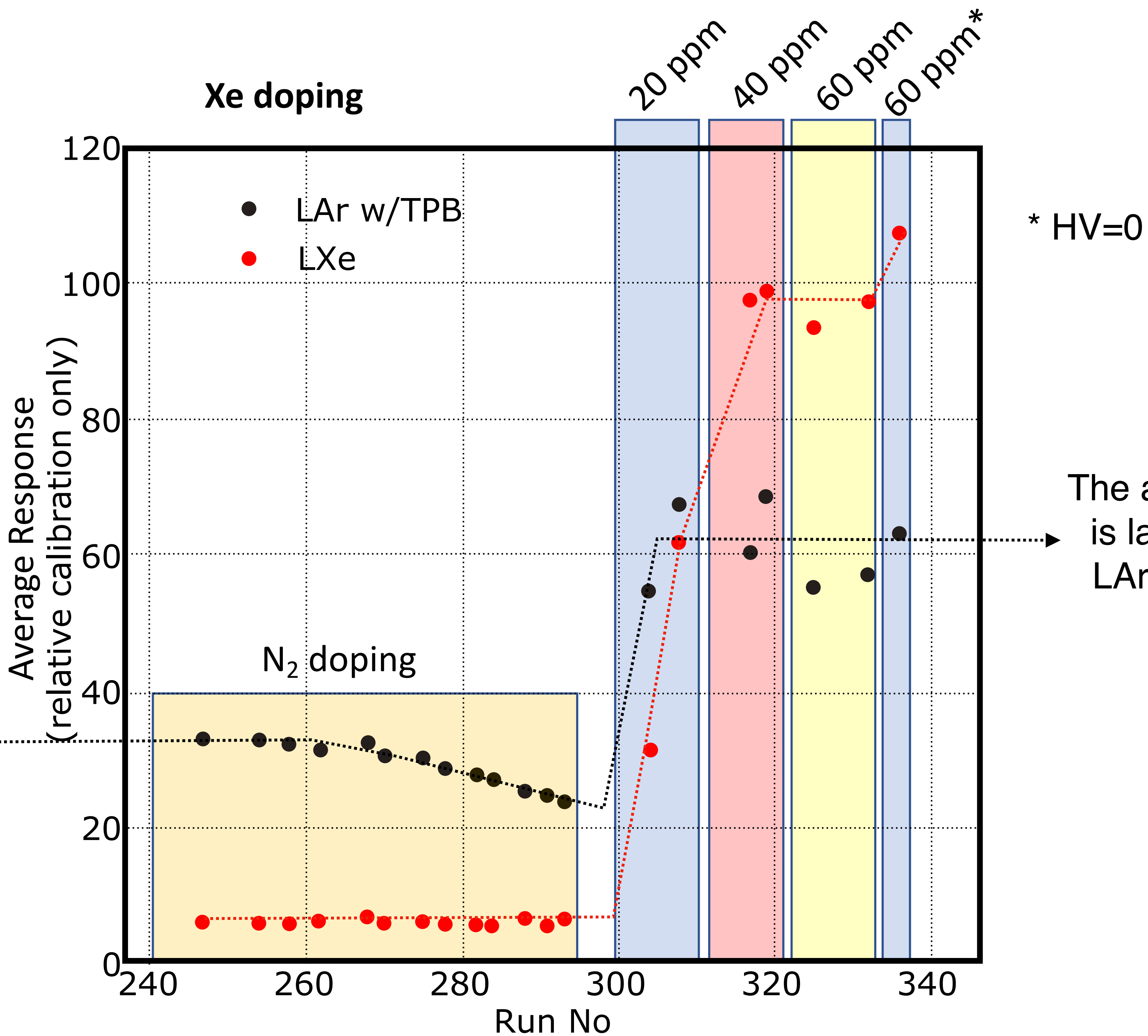
.. a strong medication against N_2 Contamination in LAr

En Transfer of Ar2* to Xe wins over N_2 quenching: recovering light (from Xe_2*) otherwise lost by N_2 quenching.



Small scale Tests at CERN

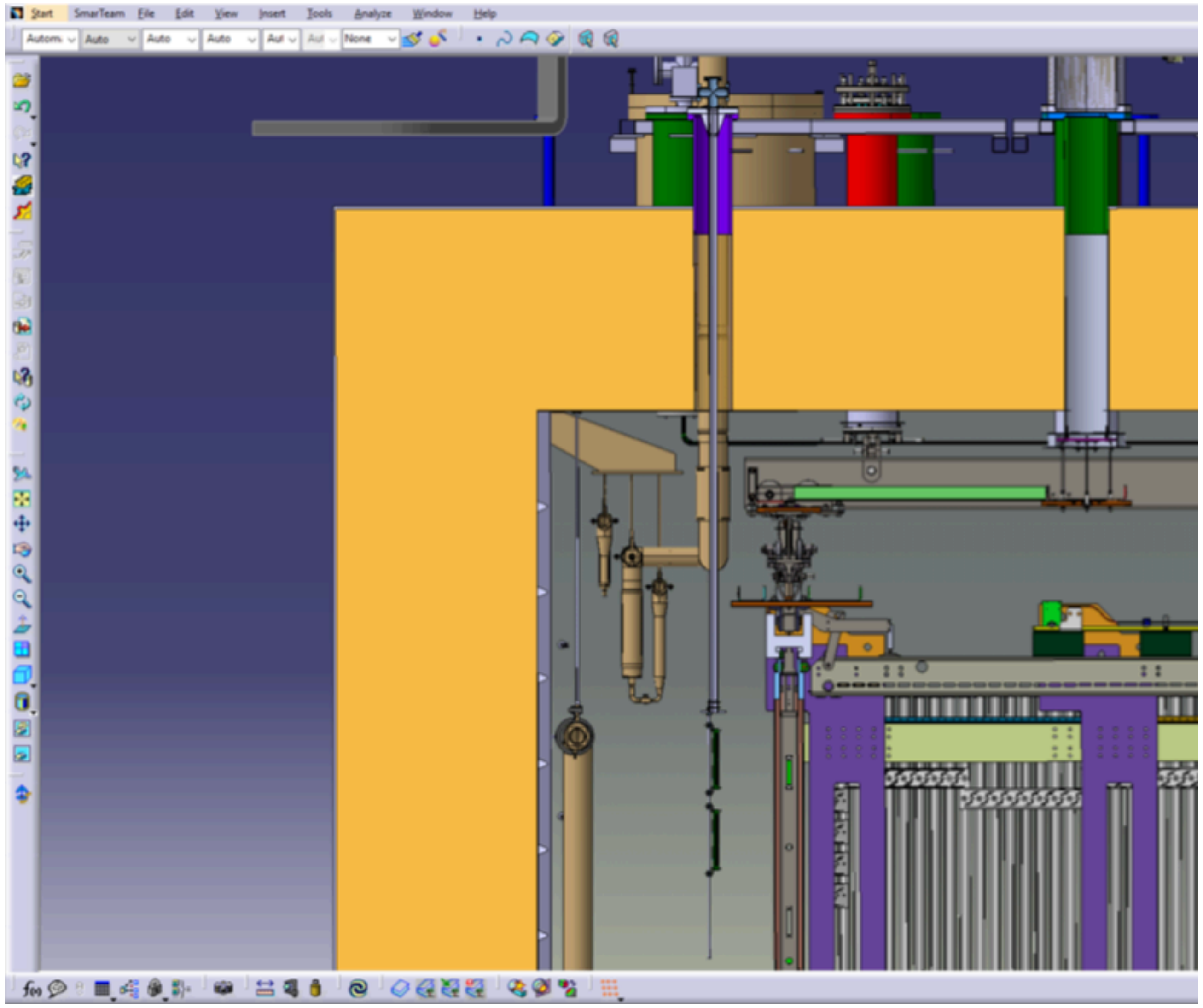
LAr w/TPB response drops (-30 %) with N_2 doping to 5.2 ppm

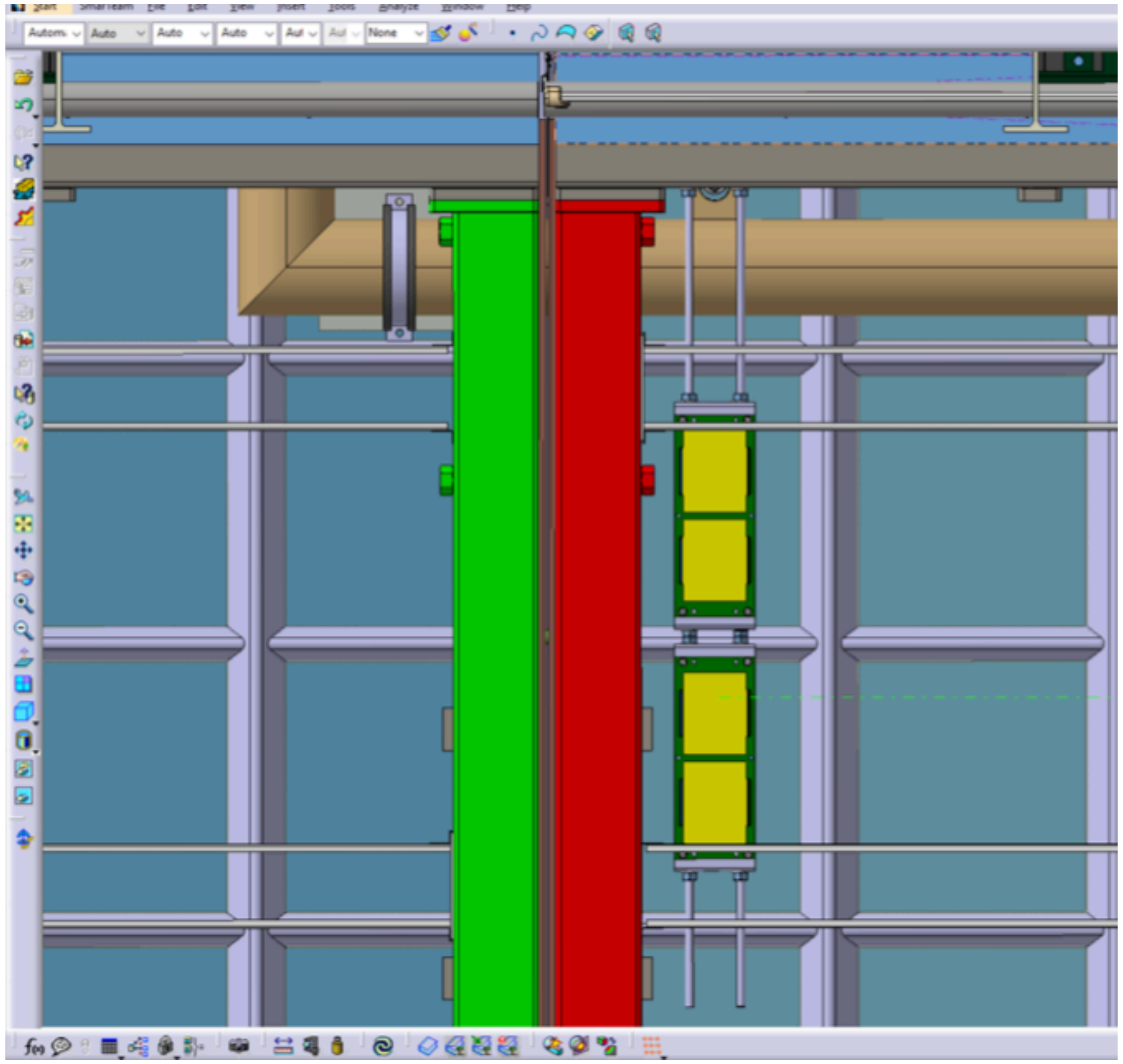


The amount of light seen is larger than the pure LAr response with the first Xe doping

XE DOPING TEST IN PROTODUNE-SP

(next and last protoDUNE-SP test effort before operation shut-down - April 2020)





X-ARAPUCA PHOTO-DETECTORS READY TO BE DEPLOYED INTO LAR FOR THIS SPECIFIC XE DOPING TEST

FERMILAB INVOLVEMENT IN THE DUAL PHASE LARTPC

R&D on the 600 kV - HV system

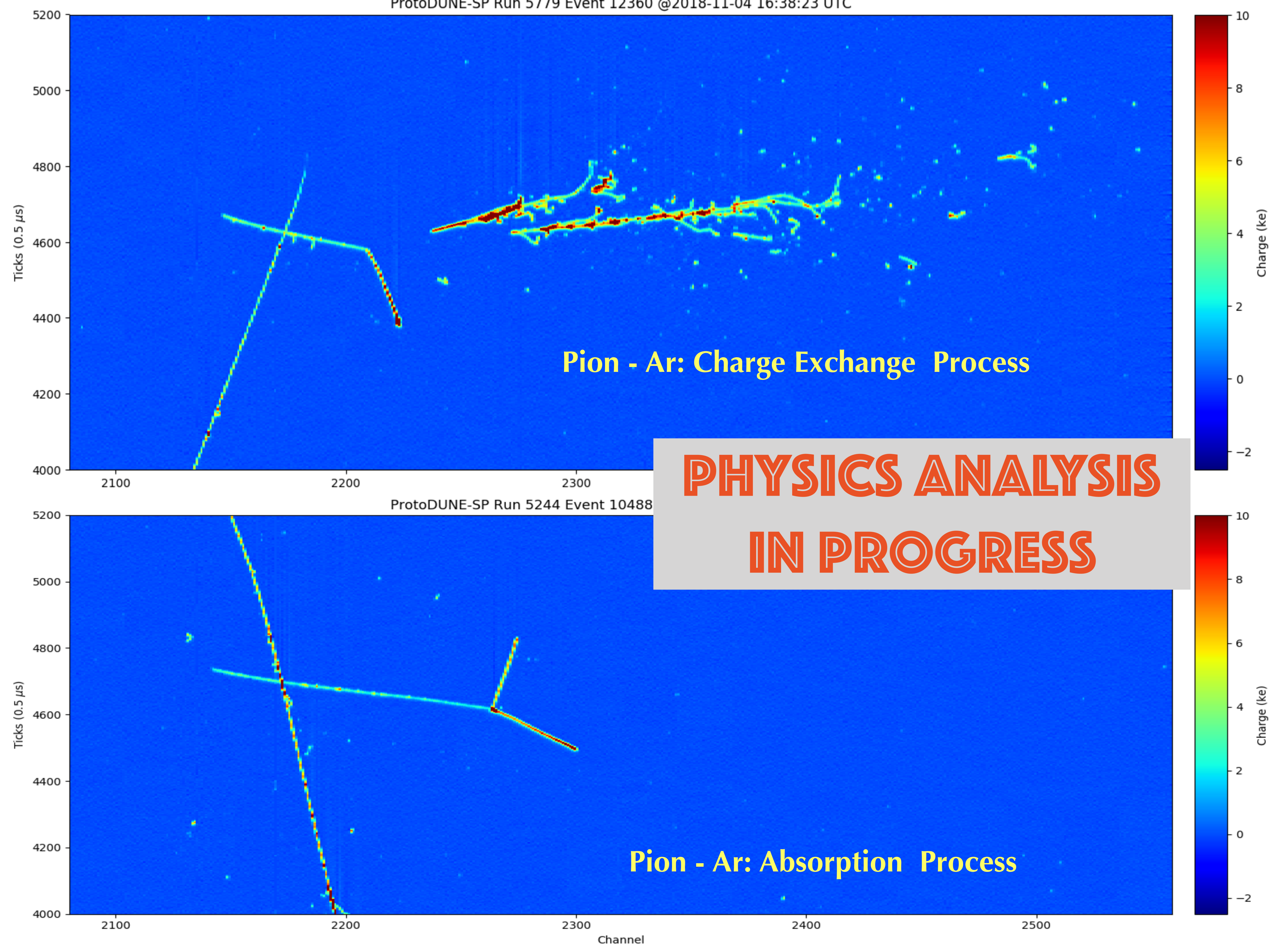
- **600 kV Power Supply** with LArTPC grade specs: custom modification of existing commercial 500 kV - *Glassman Power Supply unit* (in the picture) - with additional dedicated filter for ultra-low ripple

- Design, realization and test of a C**old HV Feed-Through** and flange for Membrane Cryostat side penetration - possibly integrated with the HV filter & 600 kV Power Supply Unit

- Use of **Resistive HV Cable**, instead of discrete resistive components, as part of the HV ripple filter. Commercially available, coextruded PE with graphite doped inner core and outer layer (LZ detector)

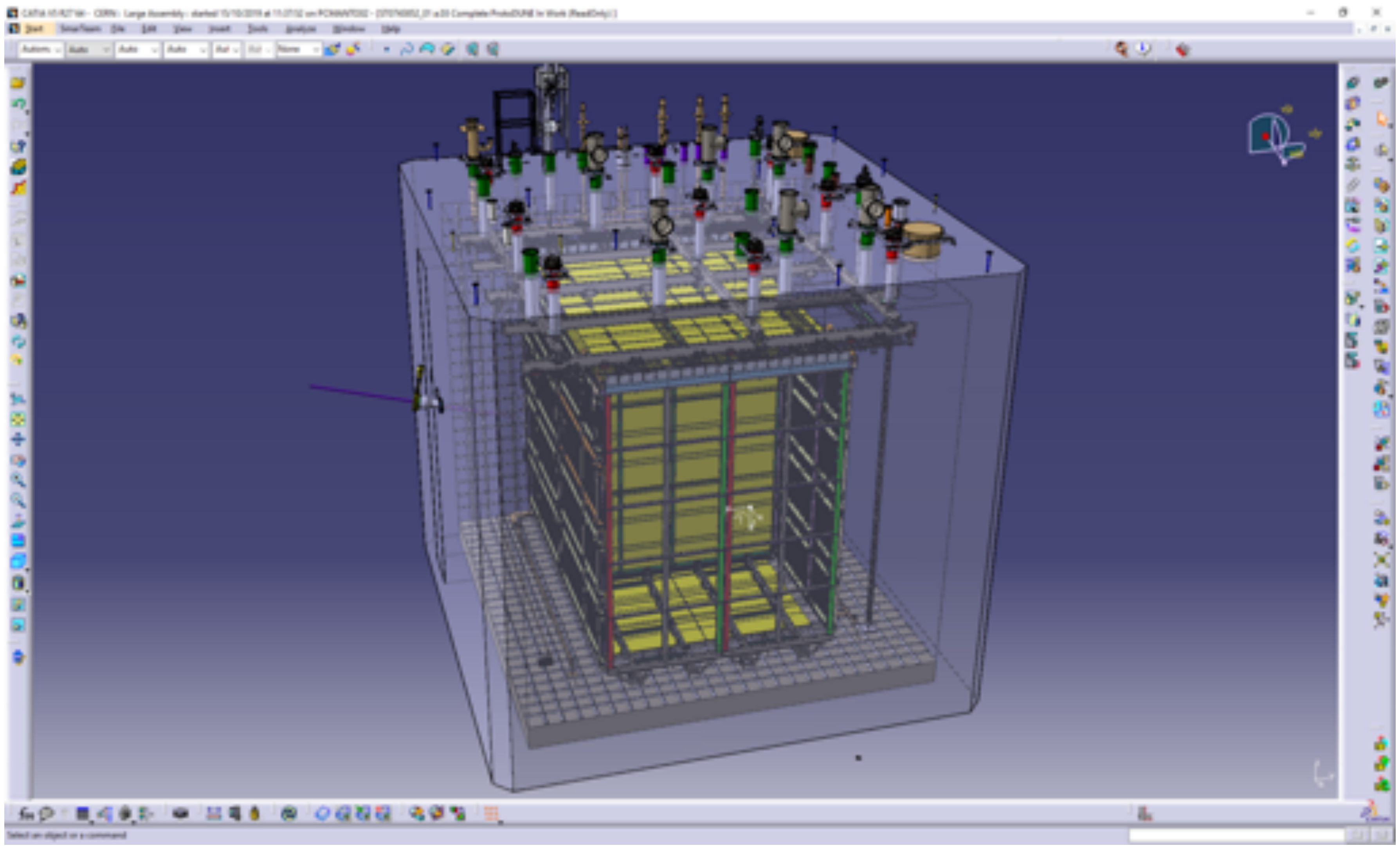
- **12 m drift / 600 kV Demonstrator** *(as already proposed at FNAL- PACMtg in January 2019)*

Proposal for $20k grant submitted to FACCTS
(France & Chicago Collaborating in the Sciences)
currently out for review



ProtoDUNE-SP Run 5779 Event 12360 @2018-11-04 16:38:23 UTC
Pion - Ar: Charge Exchange Process
ProtoDUNE-SP Run 5244 Event 10488
Pion - Ar: Absorption Process
PHYSICS ANALYSIS
IN PROGRESS
Ticks (0.5 μs)
Channel
Charge (ke)

PROTODUNE PHASE II



All detector elements from DUNE FD production line:

4 APAs + CE
40 X-ARAPUCA modules
Felix DAQ readout

+

calibration tools
(laser, neutron generator)

+

improvement on the internal cryogenics

+

Improvement on HV system

Expect to start Beam Run in Mar. 2022
(negative polarity, improved H4-VLE beam line for < 1GeV/c)

BACK UP

1) lessons learned - HV System / E-field

- *[after PS and dry HV-filters replacement]* **All the HVS components are operating reliably and stably at the TPC nominal Electric field (500 V/cm)**
- (Residual) Current draws/HV instabilities observed - whose origin is not identified
- However, after one year of HVS operation, **no degradations** of the HVS performance due to instabilities have been observed:
  - On the contrary **Current streamer rate has decreased** from *3 to 4 per day* during beam exposure to *< 1 per day* in the last month(s) (during current Cosmic Run)
- Behavior of current streamers indicates that they follow **charge-up of insulators in high field regions,** localized in a specific region inside the cryostat *[Upstream, Top, Center/BeamLeft]* - recently spotted also by light signals
- In the last few months, **HV uptime** (with auto-recovery ON) has reached a value of more than **99.5%**

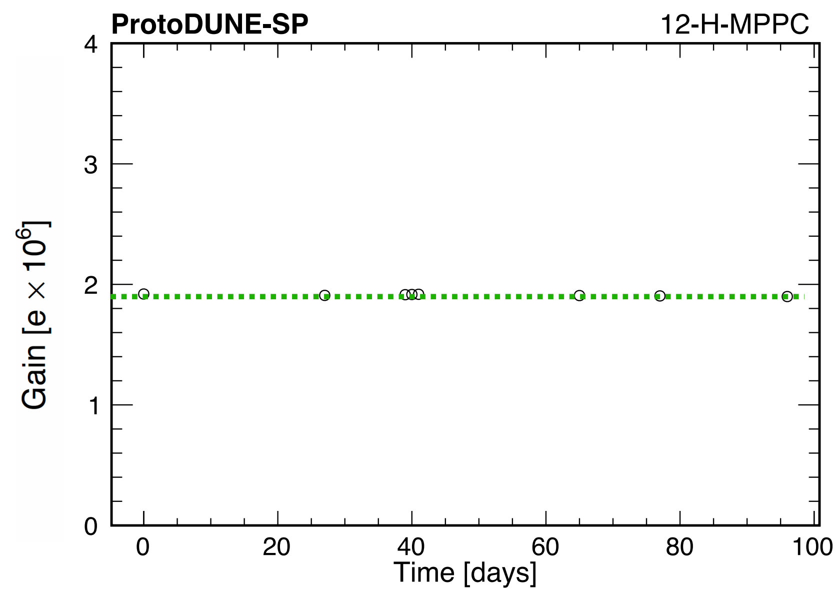
- **Test at higher HV/EF (max 300 kV - PS limit/800 V/cm) to be performed at the end of Run (last topic in agenda for protoDUNE-SP Phase-1)**

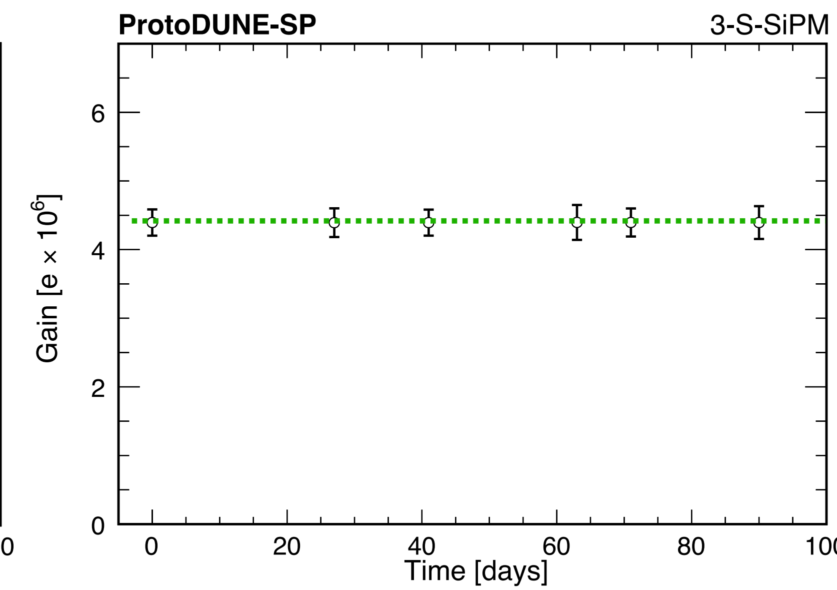
2) lessons learned - e-Lifetime and LAr Purity

- **e-Lifetime dependance on El.Field** (Measurement in TPC necessary for Charge correction).
- Developed method (CRT track selection) for lifetime measurement in TPC volume in presence of Sp.Charge distortion - **Ultra-high e-lifetime observed in TPC volume** ($\tau_e \simeq 40$ ms)
- **LAr Purity stable -** with a slight increase (PurMon e-lifetime vs time) from minor air leakage fixes.
- LAr (and GAr) **recirculation system very effective** - Filter regeneration in situ very efficient
- **Apparent Stratification in height** seen by PurMon: to be confirmed [systematic or real] - small effect for high e-lifetime in TPC volume
- Accidental major drop due to a hw failure in the GAr recirculation system: Purity fully recovered after the accident [next slides]

LONG TERM STABILITY

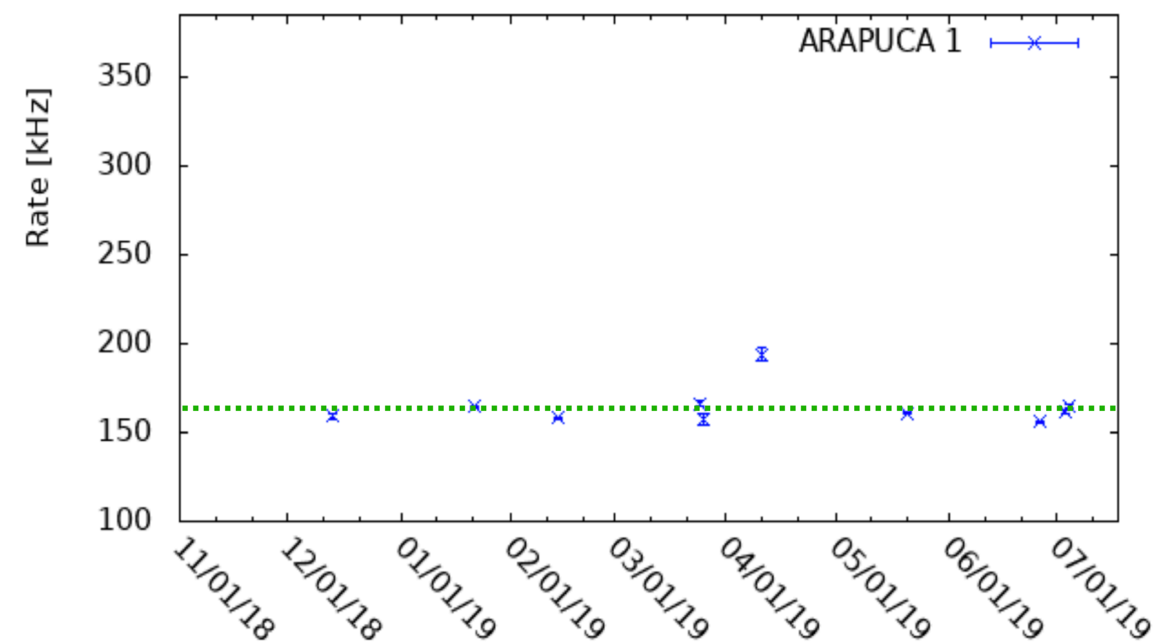
- **PDS - PhotoSensors gain:**





- **PDS Response:**

Single Photon Rate



How to measure e-Lifetime inside TPC

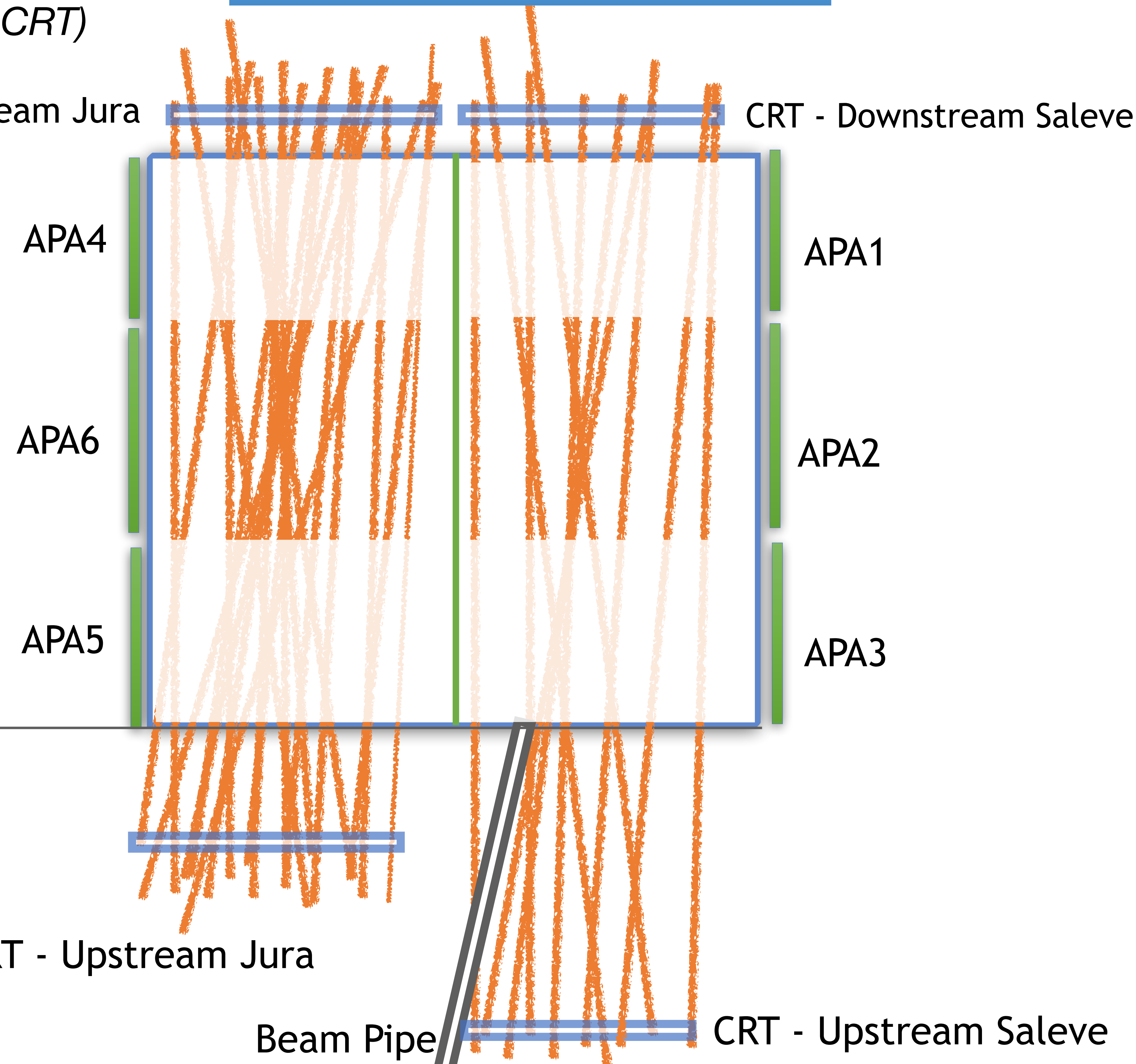
(the importance of the CRT)

ProtoDUNE-SP View from the TOP

CRT Triggered ~Hor. Muons parallel to APA & Tracks in TPC central region:

No/minimal Space Charge Spacial Distortion

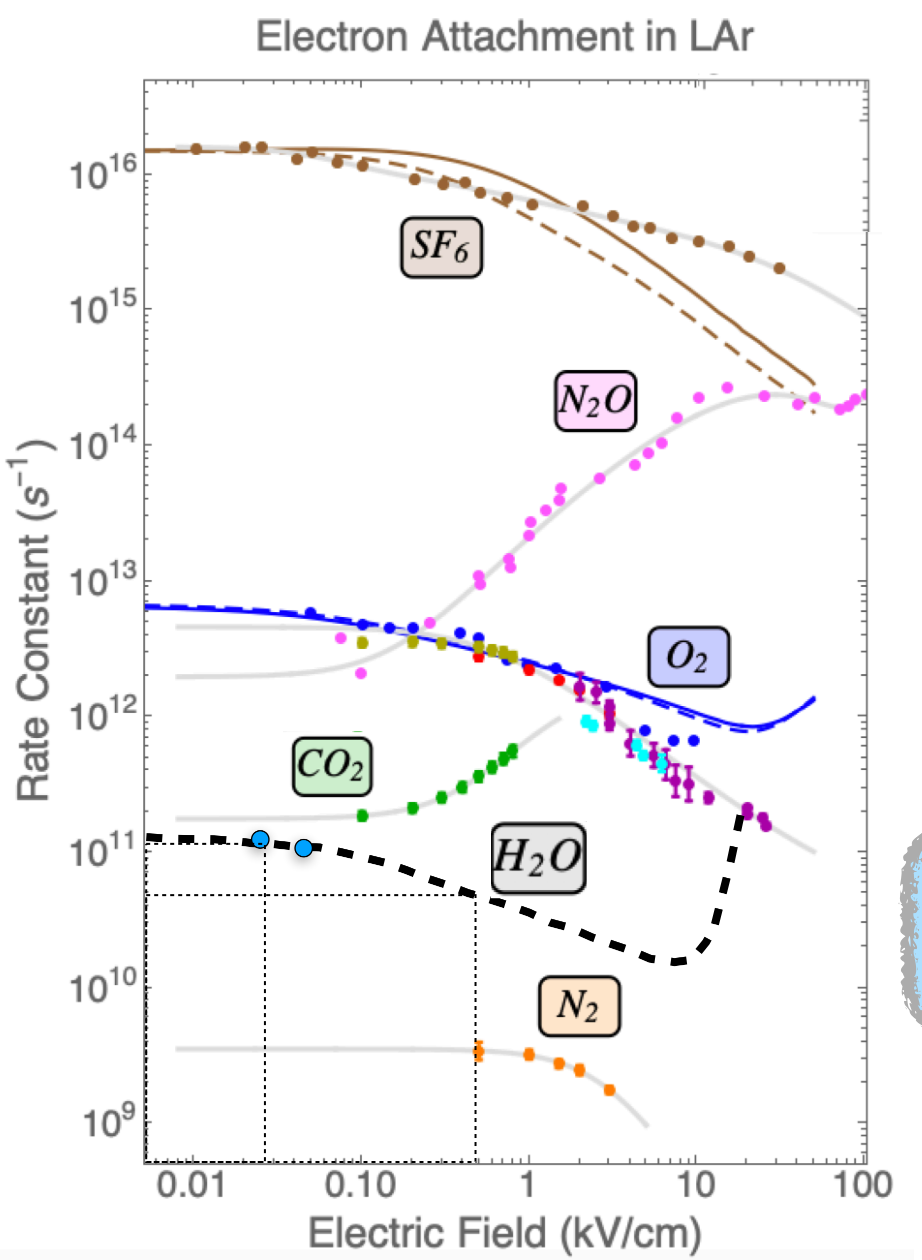
[in drift x-coord Correction for EF distortion on recombination



e-Lifetime vs Purity

$$\tau_e = \frac{1}{k_A\ [X]}$$

$$Q_{corr} = \frac{Q_{det}}{exp[-t_d/\tau_e]}$$



- **Purity of LAr corresponds to** $[X]$ (ppt) **-** ***concentration of el.neg. impurity*** X **- with** $X = H_2O, O_2$

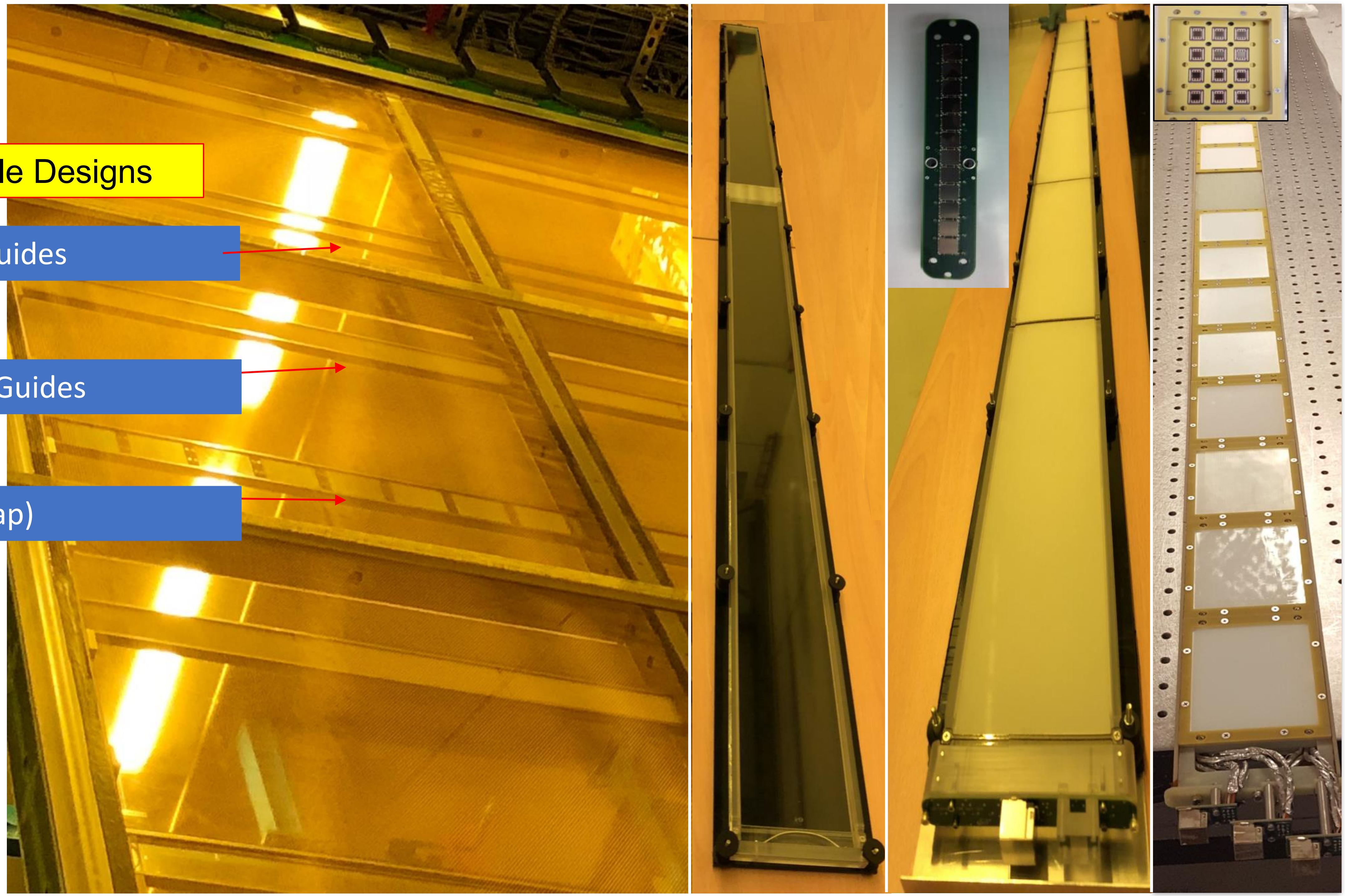
- $k_A = k_A(EF)$ **-** ***Attachment Rate constant*** **(for** X**) depends on EF in the drift volume**

- τ_e **measures the LAr Purity, but its value depends on the EF where is measured**

- **TPC vs PurMon:** $\tau_e(500\ V/cm) > \tau_e(20\ V/cm)$

- **Lifetime measurement in TPC with tracks** (dQ/ds vs t_d) **difficult on surface due to SpCh track distortion**

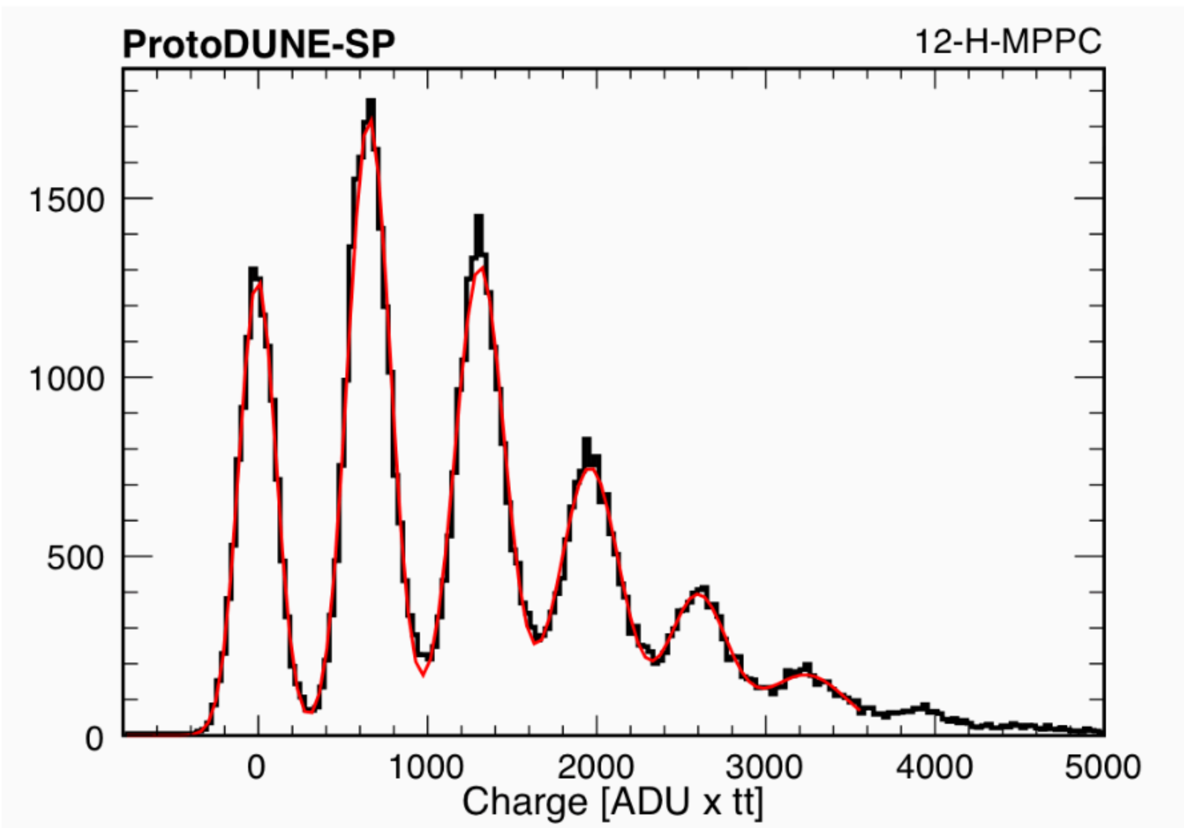
N.-*Type* of Sensor per Channel	N. of Channels	N.Channels per Module	N.Dip Coated Modules	N.DoubleShift Modules	N.ARAPUCA Modules
3 SensL SiPM (parallel passive ganging)	172	4	21	22	-
3 Hamamatsu MPPC (parallel passive ganging)	60	4	8	7	-
12 Hamamatsu MPPC (parallel passive ganging)	24	12	-	-	2



Single photon Sensitivity

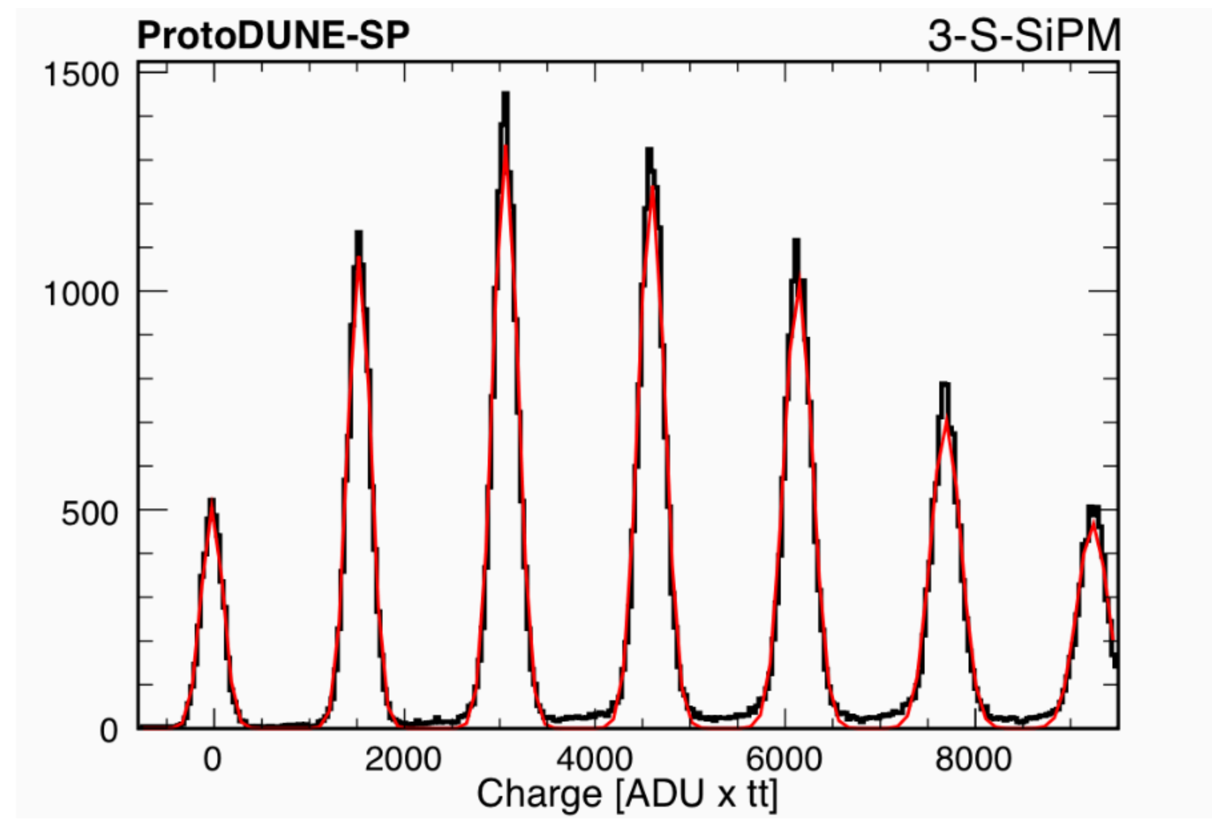
ARAPUCA photoSensors response

12 Hamamatsu MPPC (parallel passive ganging)



LightGuide photoSensors response

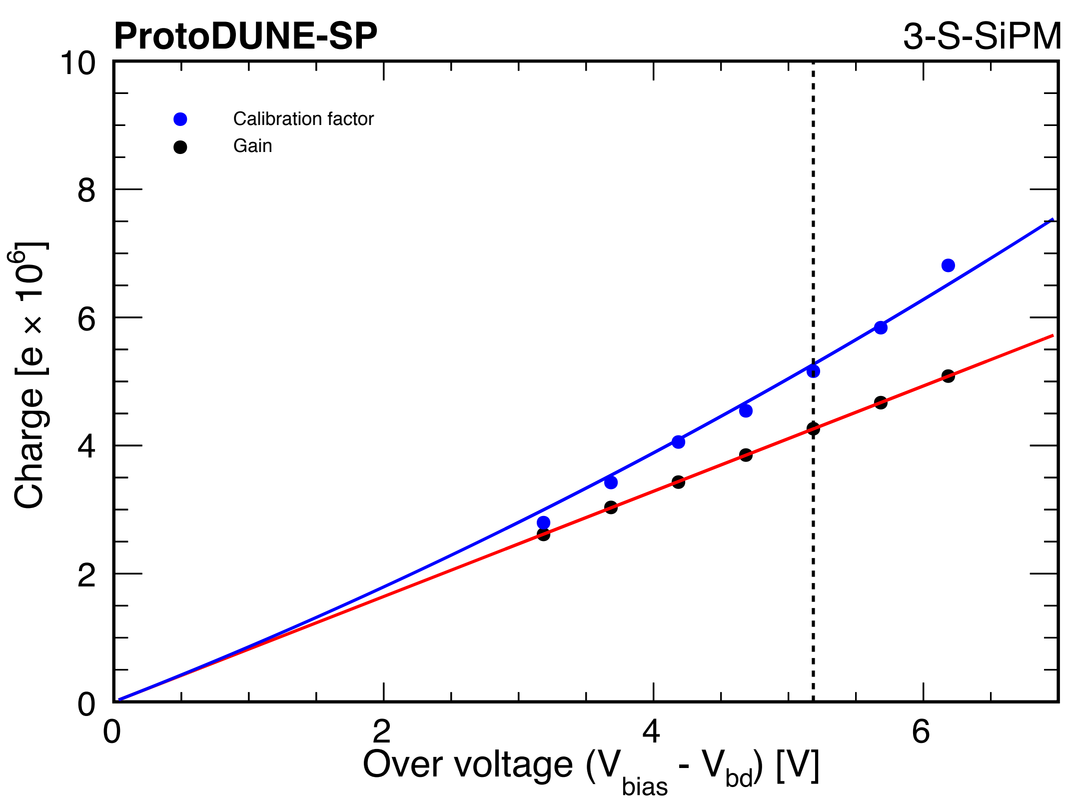
3 SensL SiPM (parallel passive ganging)

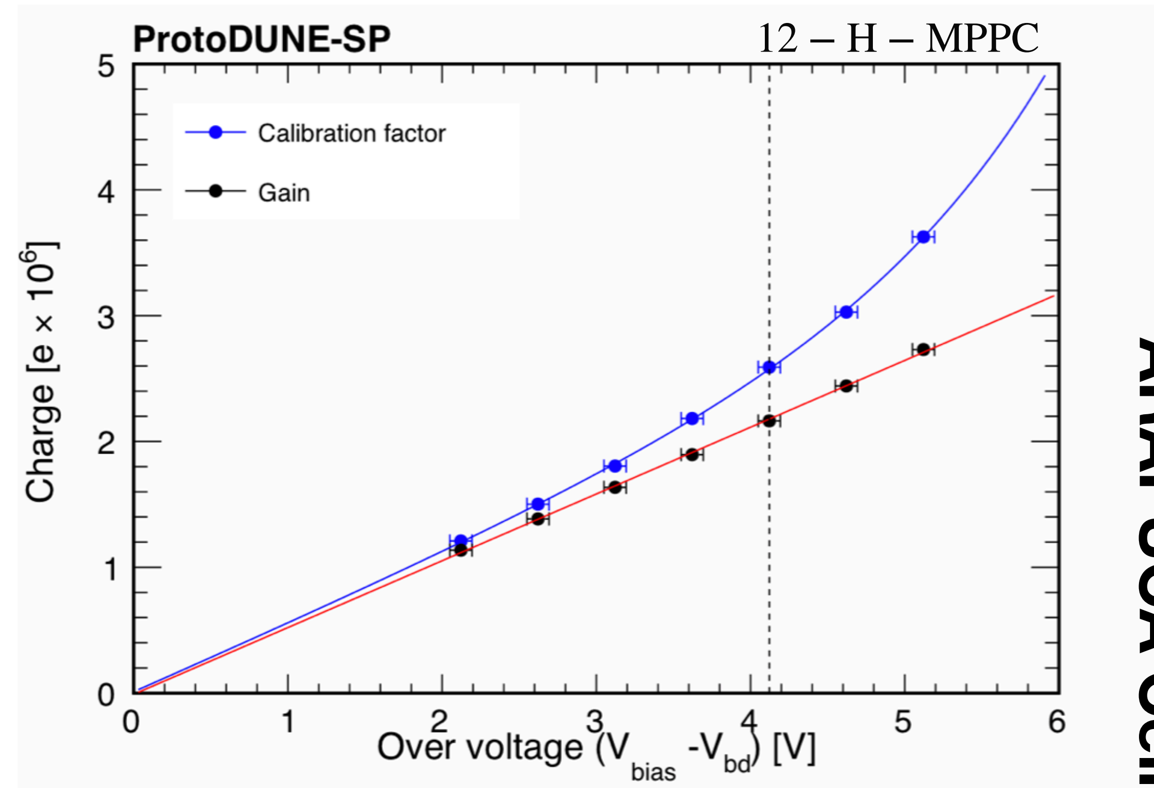


Demonstration of operability of large array of Si photo-sensors into one channel (passive parallel ganging)

PD Calibration

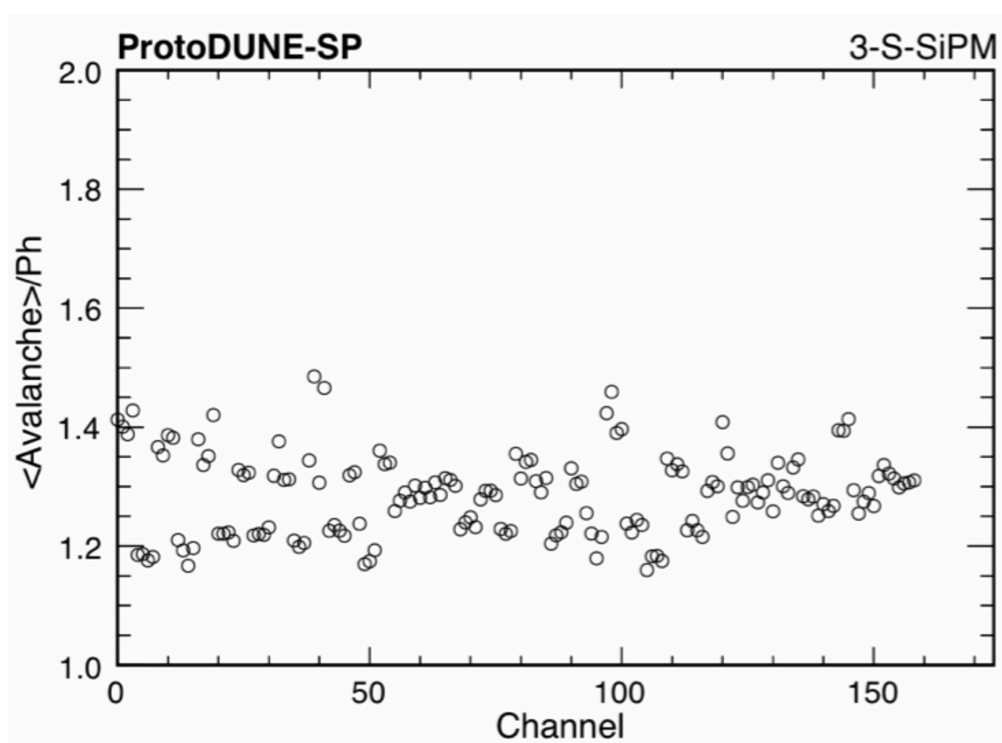
LightGuide Bar photoSensors

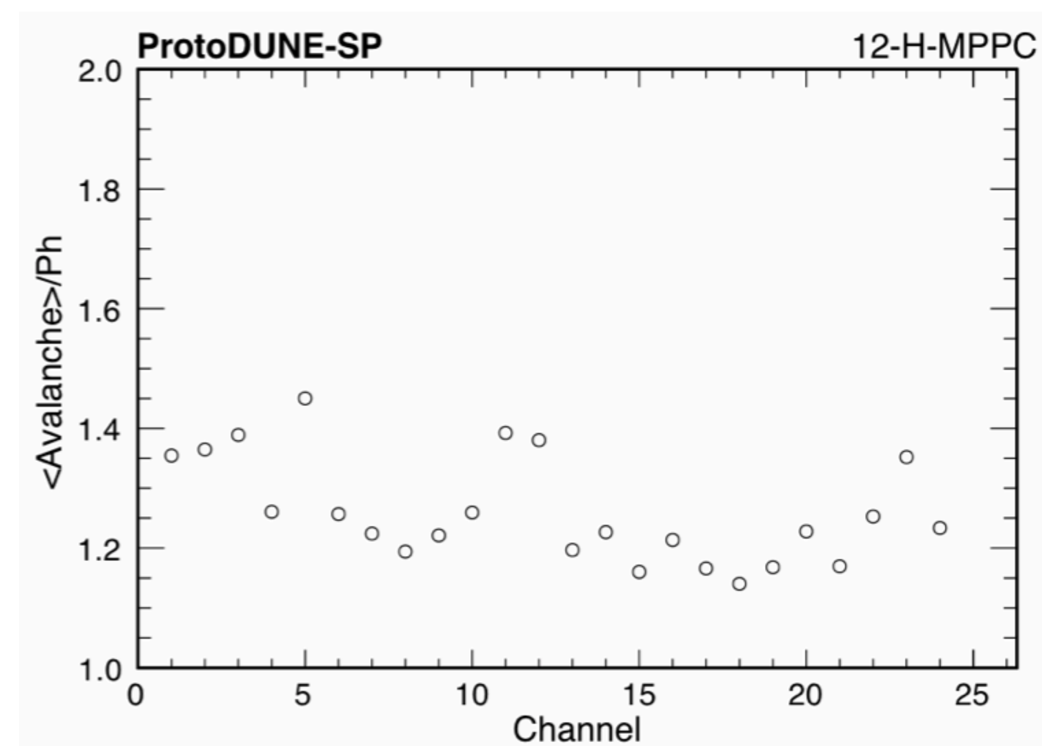




ARAPUCA Cell photoSensors

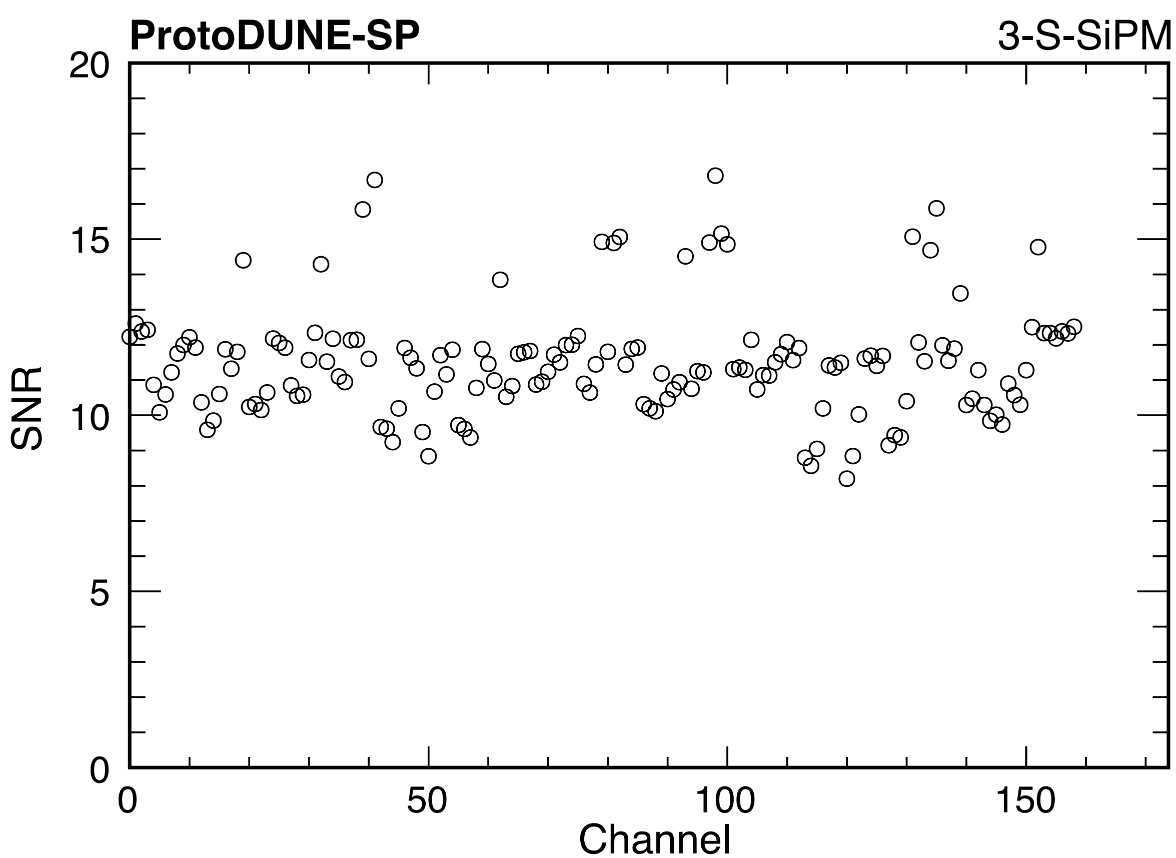
After Pulses and Cross Talk



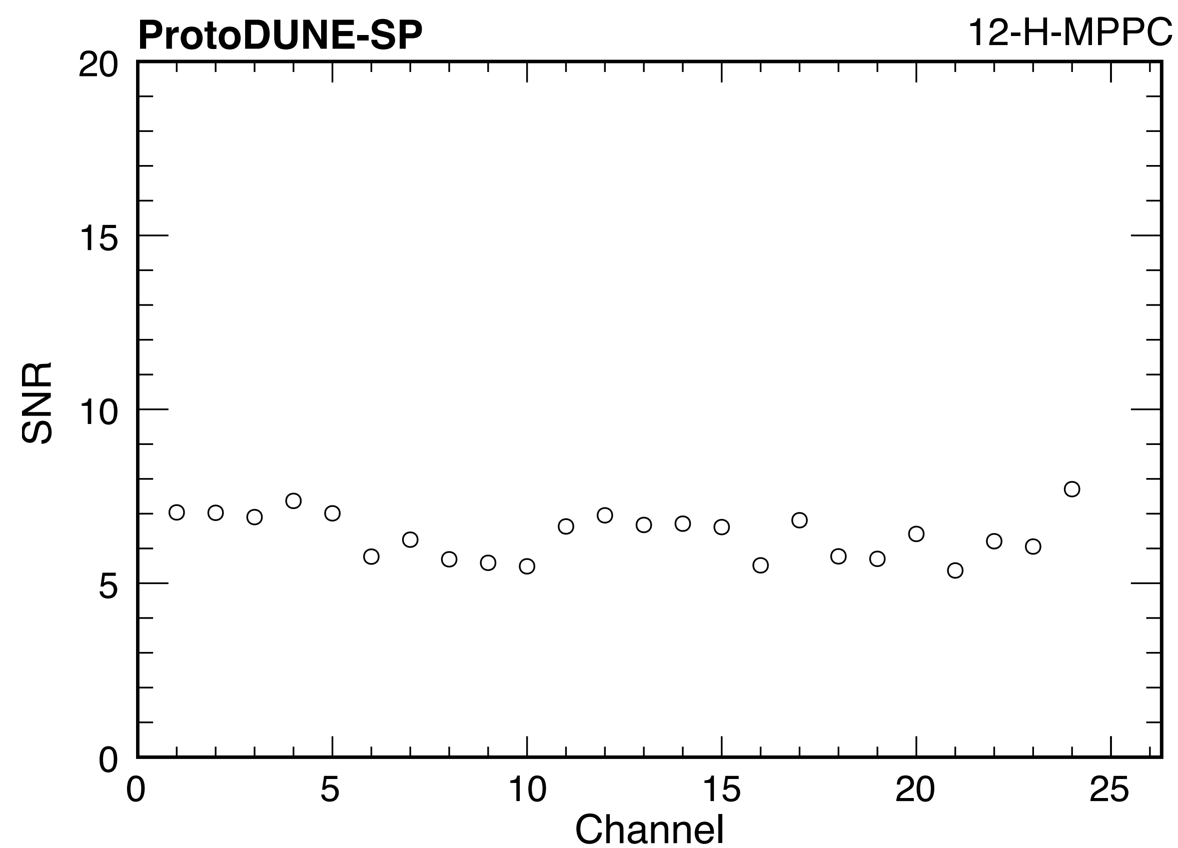


S/N ratio - photoSensor read/out

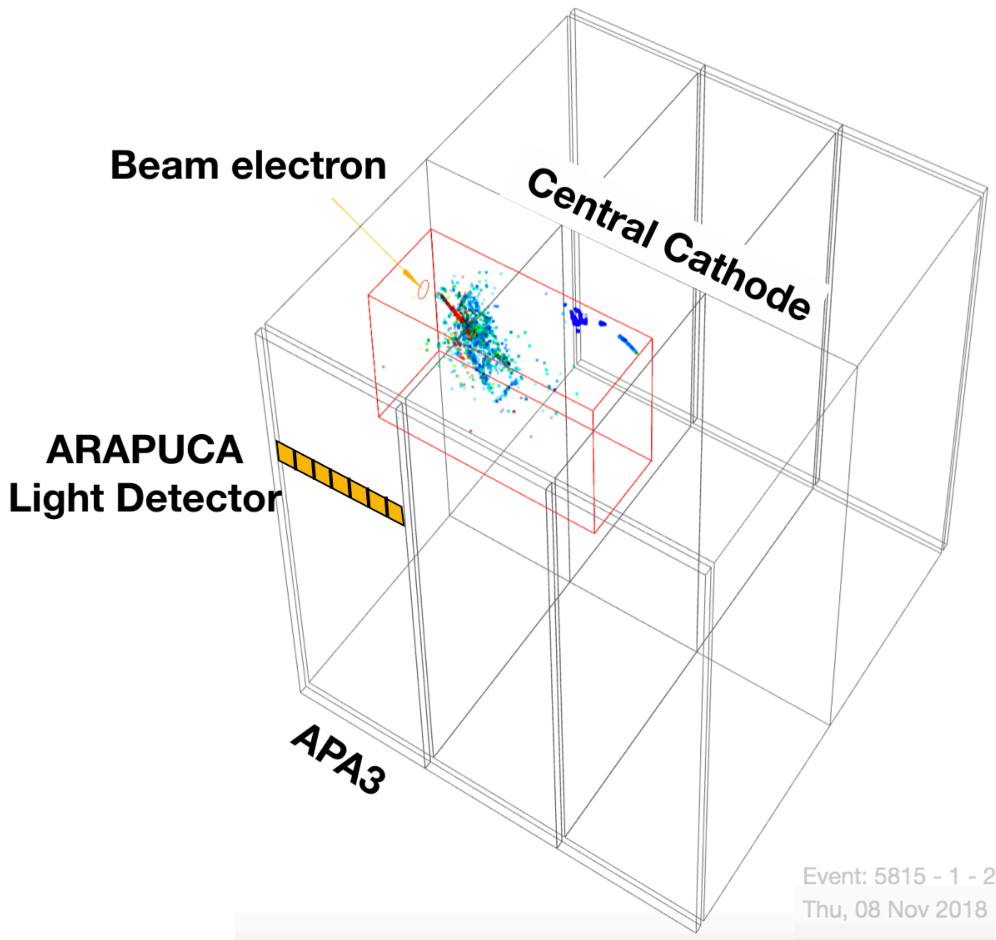
LightGuide Bar photoSensors



ARAPUCA Cell photoSensors



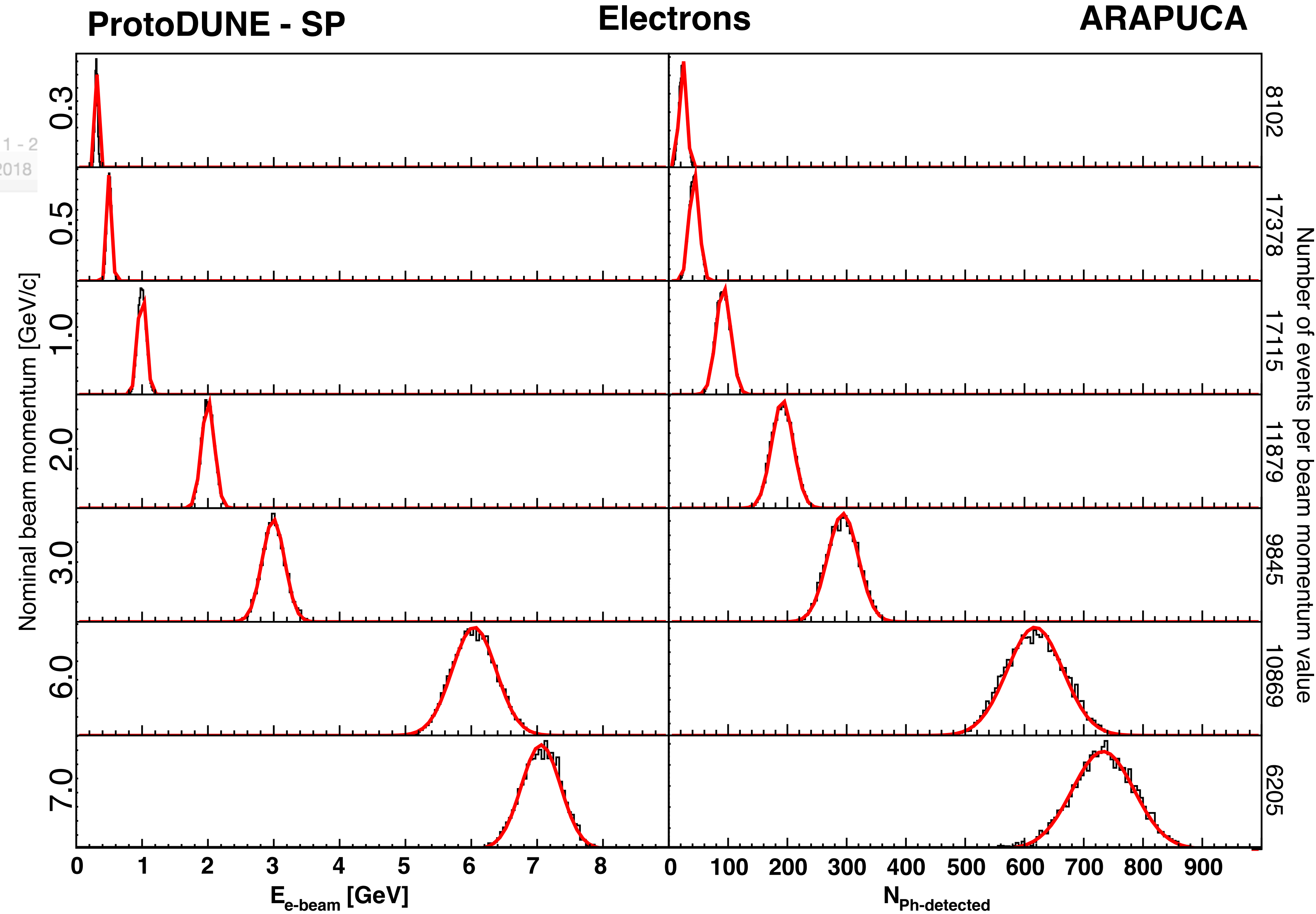
Large LAr detector operating at
the CERN Neutrino Platform



calorimetric response to EM showers from *light signal*

single ARAPUCA module
(~0.5‰ photo-sensitive area coverage)

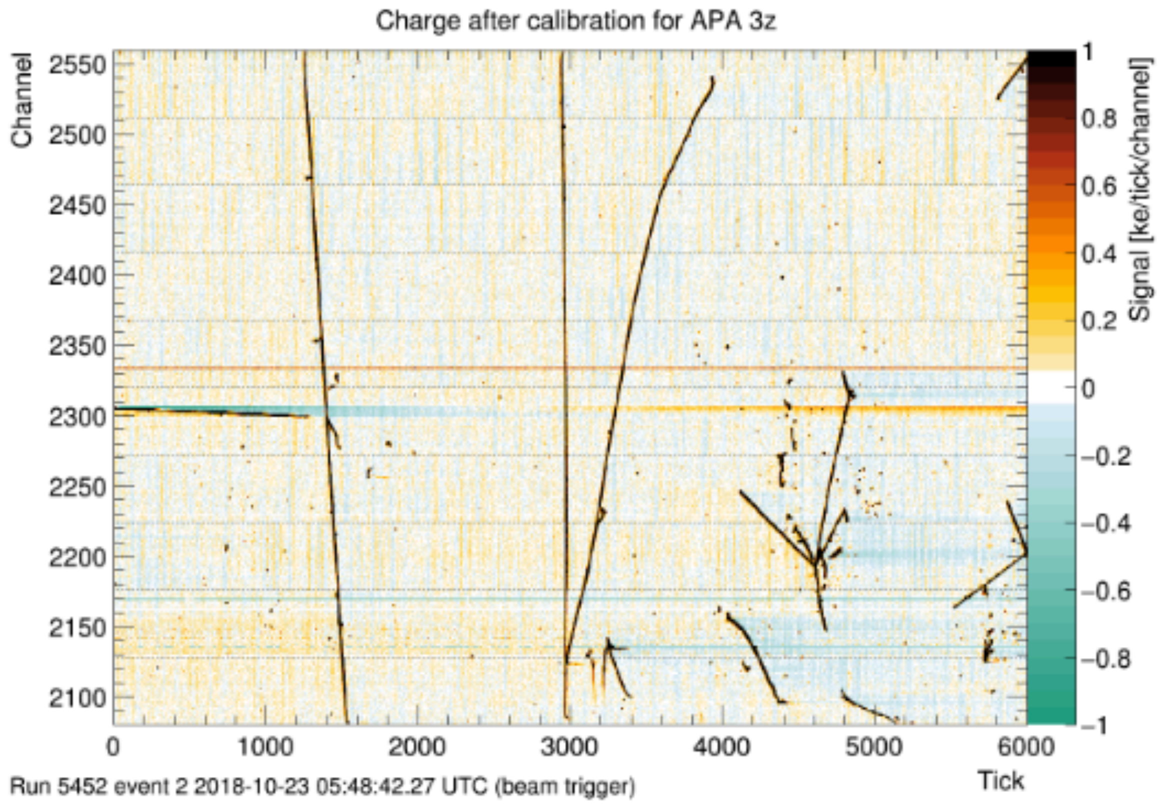
EM shower at ~3 m distance in the x (drift) direction



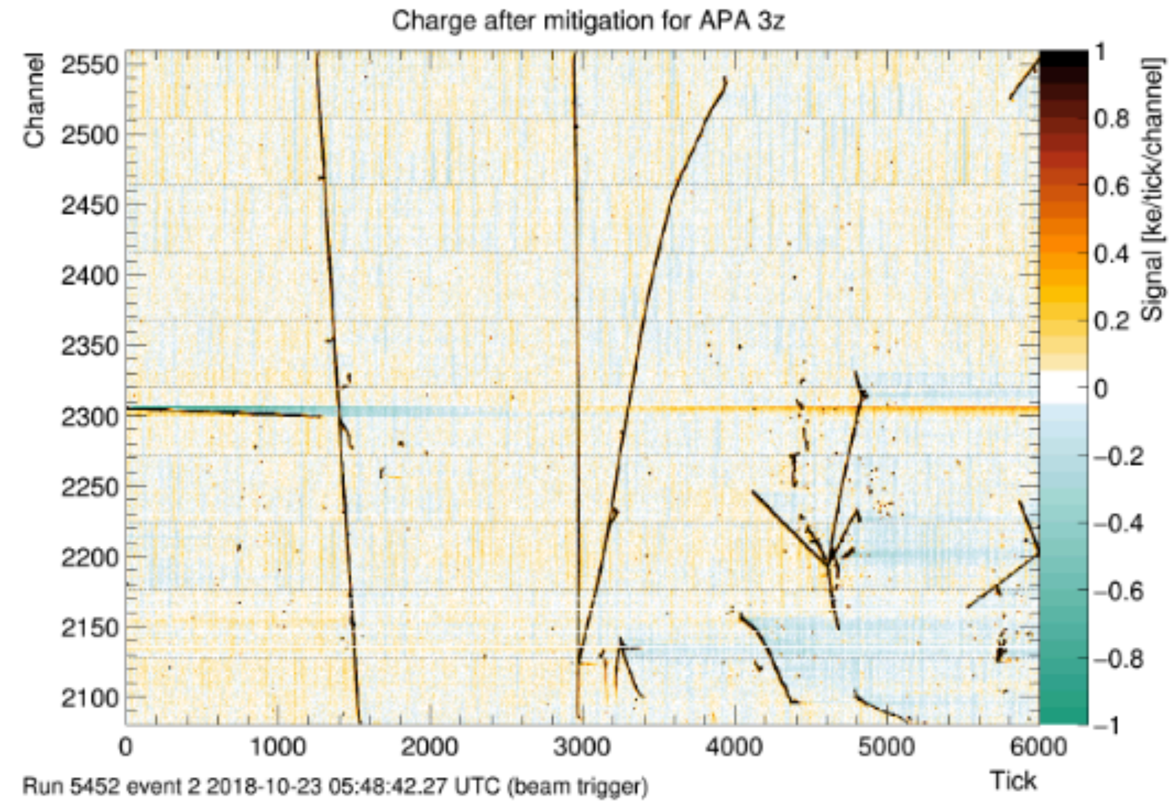
Incident Electron momentum distribution

detected photons spectra

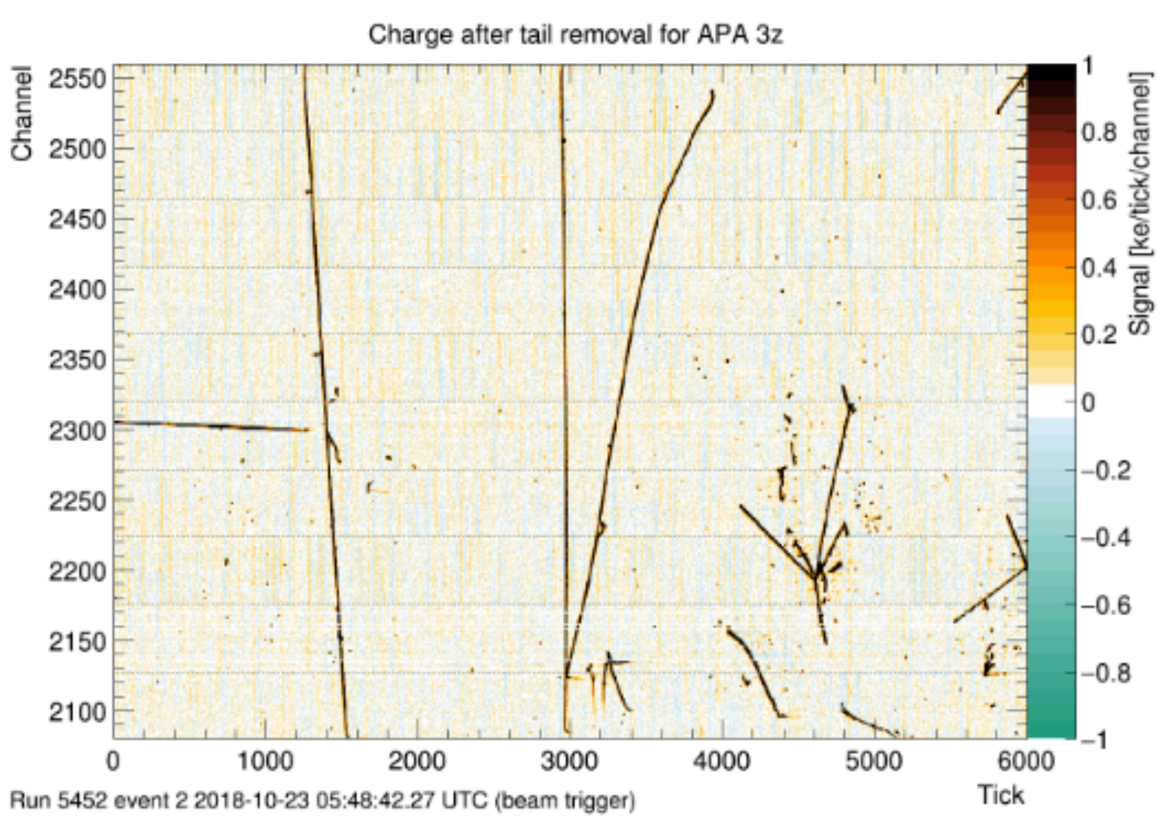
stages of data processing and noise mitigation



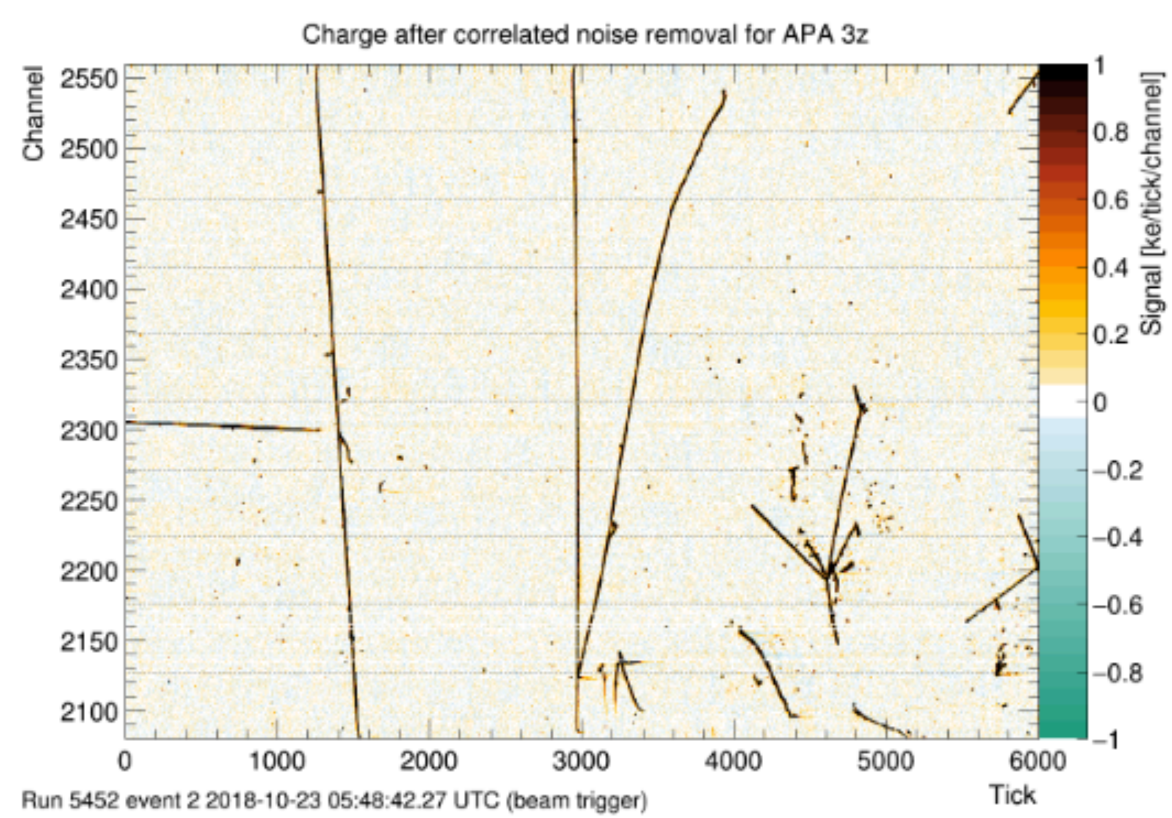
(a) After pedestal subtraction and calibration.



(b) After mitigation (Sticky code)



(c) After tail removal.



(d) After correlated noise removal.

Fall and Resurrection

Large Air-Contamination accident [July 21-26, 2019]

- Alarm: Major loss of LAr purity
- Analysis of the effects on Charge Signal (TPC and Purity Monitors)
- Analysis of the effects on Light Signal (PhDetector System - PDS)
- Analysis of Data log from Cryogenic/Purification Plant

⇩⇩⇩⇩

- Hardware failure identified
- Actions taken (Recirculation stopped, Filter regeneration, alarm/interlock implemented, recirculation restarted)
- Full recovery of Charge Signal (by O_2 contamination removal - 0.2 ppm)
- Some degradation of Light Signal (O_2 removed but 5.7 ppm N_2 non-removable by filtration)
- Method for Light Recovery identified (by Xe doping) and tested:
  - first small scale demonstration test - successful
  - second small scale assessment test - *in progress NOW (w/ X-ARAPUCA)*
  - Xe doping in protoDUNE-SP considered for Jan.2020 - before end of Run

FALL AND RESURRECTION

History of the event fully analyzed and understood

July 21 — **Gas pump injects air into the system and GAs filter exhausts**

GAr filter starts to saturate and exhaust around midnight

July 22 — **LAr filter exhausts and the problem appears**

LAr filter saturates ~7am and electron lifetime starts to drop. Around the lunch time, all lifetime is lost. LAr re-circulation stopped.

July 23 — **Checks for possible leaks**

Inspect the system and perform regular purity monitor measurements to monitor the system.

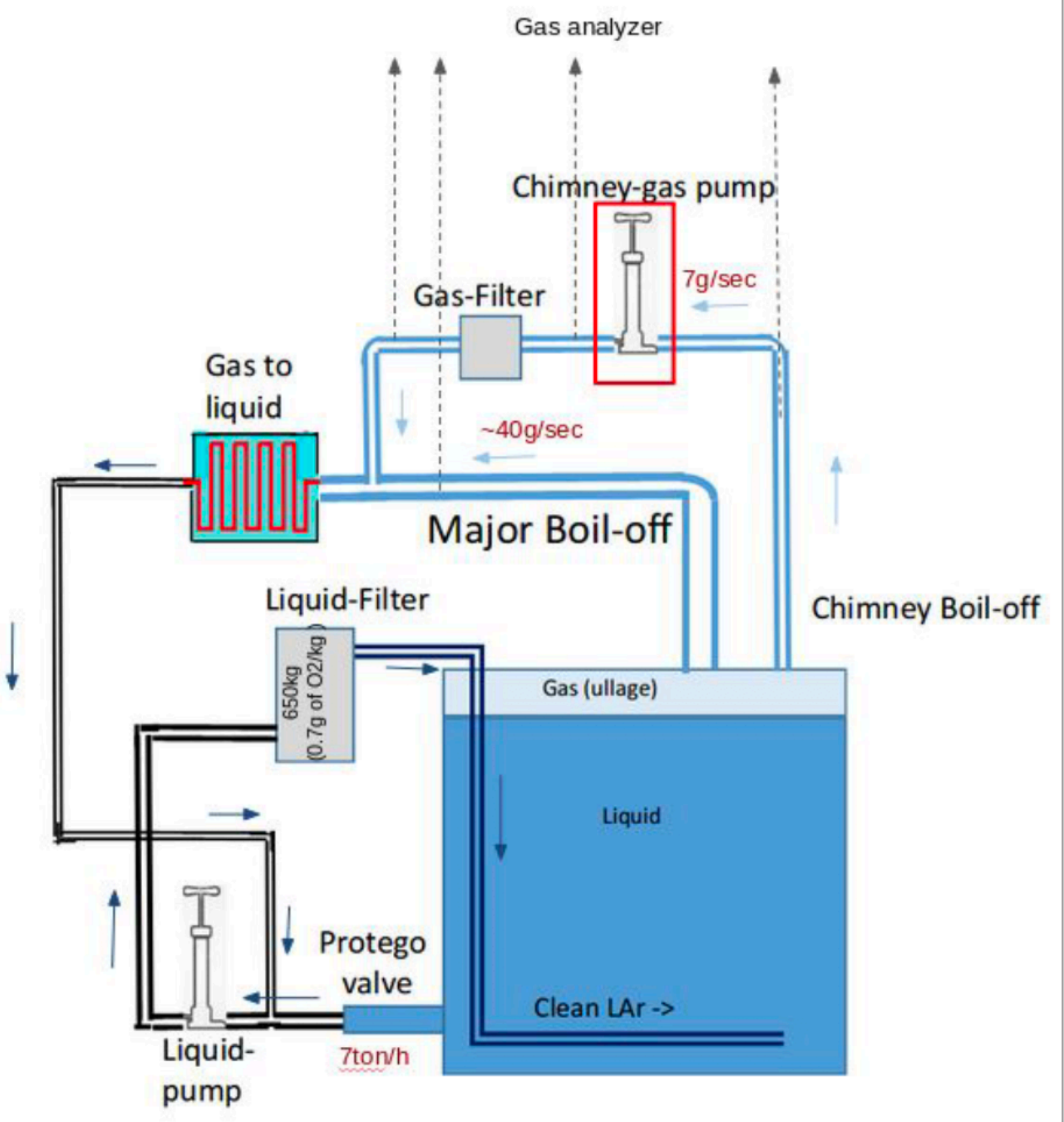
July 24 — **LAr filter regeneration**

July 25 — **GAr filter regeneration and smoking gun**

With LAr and GAr filters re-generated, impurities are trapped.

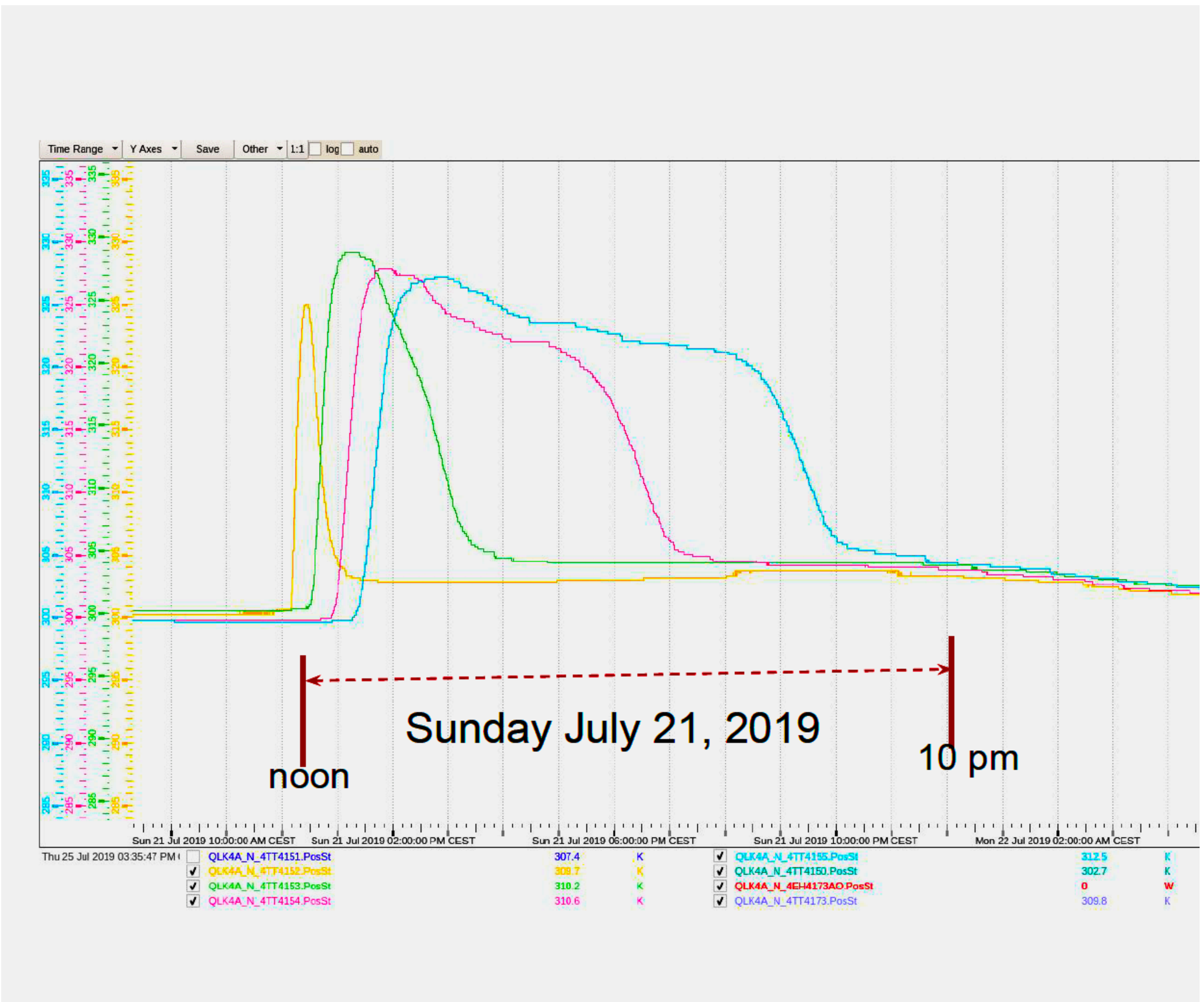
July 26 — **GAr filter saturated. Source of problem understood**

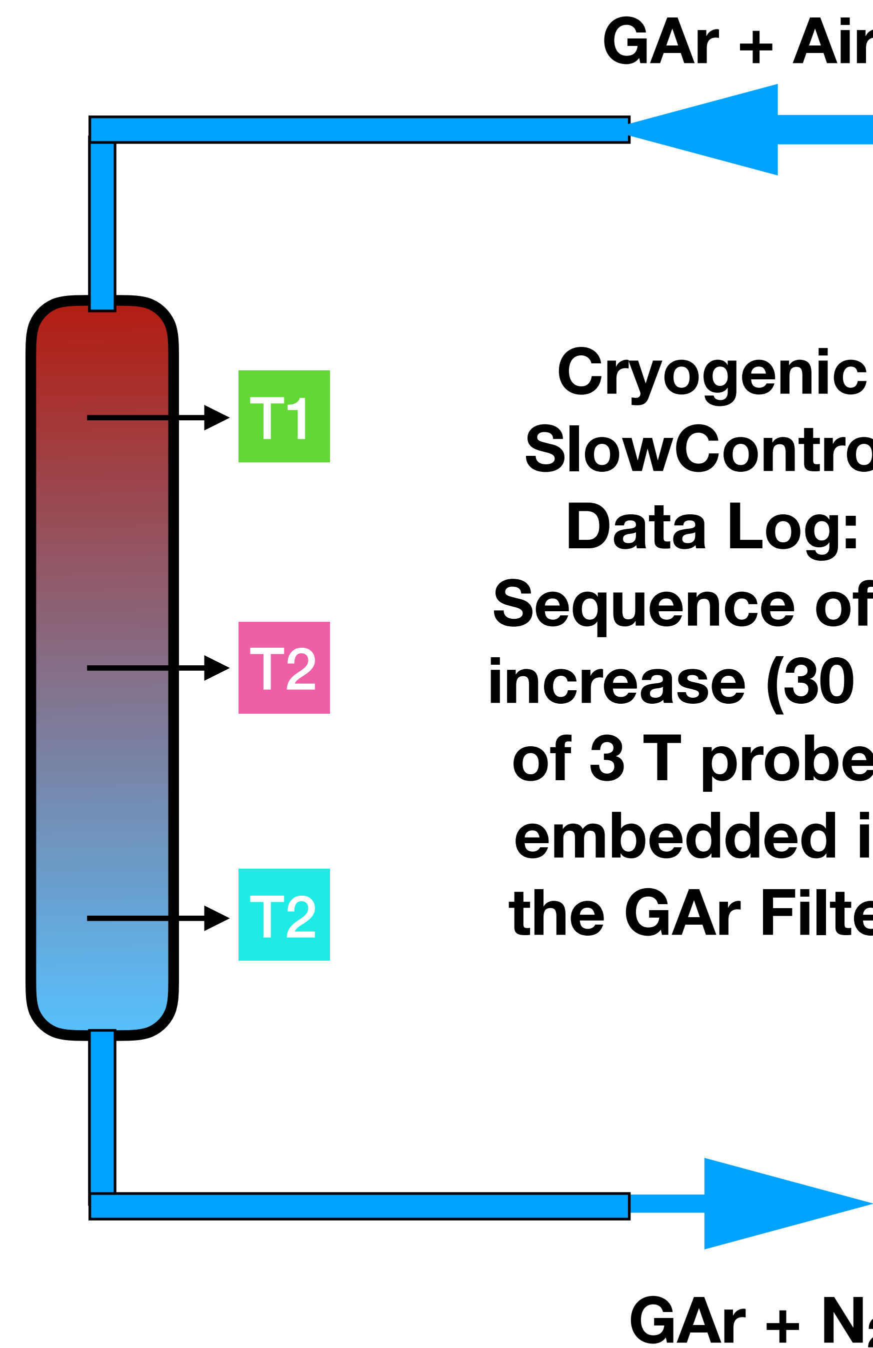
Gas analyzer overflowed at the pump output. Gas circulation pump stopped and excluded from the cryogenic circuit.



FALL AND RESURRECTION

Origin of the issue FOUND: GAr warm pump failure (membrane crack)





Cryogenic SlowControl Data Log: Sequence of T increase (30 K) of 3 T probes embedded in the GAr Filter

Time to react (12 hrs) - filter sustains air(O_2) leakage - good alarm (for the next time) already implemented

Any possibility to recover Light loss by quenching from N_2 Contamination ??

Yes, by Xe Doping

When doping LAr with **Xe** the **Energy Transfer** process occurs: $Ar_2^* + Xe \rightarrow (ArXe)^* + Ar$ eventually leading to wavelength shifting from 128 nm (Ar) to 174 nm (Xe) light emission

In mixture of N_2 and Xe in liquid Ar, since rate constants $k_{EnT}(Xe) > \simeq k_Q(N_2)$, for equal concentrations of N_2 and Xe in LAr the N_2 Quenching process and the Xe Energy Transfer process compete.

When Xe doping is at concentrations higher than the N_2 contamination, the En Transfer of Ar2* to Xe will largely win over N_2 quenching, recovering light (from Xe_2^*) otherwise lost by N_2 quenching.

e.g. for [N2] = 5 ppm and [Xe]=20 ppm:

$f_{EnT} \simeq$ 70% - Ar_2^* Triplet **fraction converted by Xe (174 nm photon emission)**

$f_Q \simeq$ 10% - Ar_2^* Triplet **fraction lost by N_2 quenching**

f_T= 20% - Ar_2^* Triplet **fraction surviving** (128 nm **photon emission)**

Small scale test demonstrated theory above - Xe doping in protoDUNE-SP in January (for N_2 contamination recovery and Xe doping stability in time and uniformity in the LAr Volume)

ProtoDUNE Measurement Plan & Goals

- **Short-term goals** – ***Detector Performance***
  - ☑ (noisy or dead channels map) *- update*
  - ☑ Noise level, signal to noise ratio *- update*
  - ☑ Electron lifetime *(LAr purity)* *- update*
- **Medium-term goals** – ***Detector Response***
  - ☑ dE/dx of ✔muons, ✔pions, ✔protons, ✔electrons - *update - new*
  - Energy and momentum resolutions - *in progress*
- **Long-term goals** – ***Physics Measurements***
  e.g. ***π-Ar cross sections***
  - ☐ *(started)* Total pion cross section in [1-7] GeV range
  - Exclusive channels Cross Section - *in progress*:
    - π *absorption:* $\pi^{\pm} \rightarrow$ *2p, 3p, 2p1n,..*
    - $\pi^{\pm} \rightarrow \pi^{0}$ *charge exchange*, etc.

(NEVER MEASURED)

Information for DUNE physics TDR

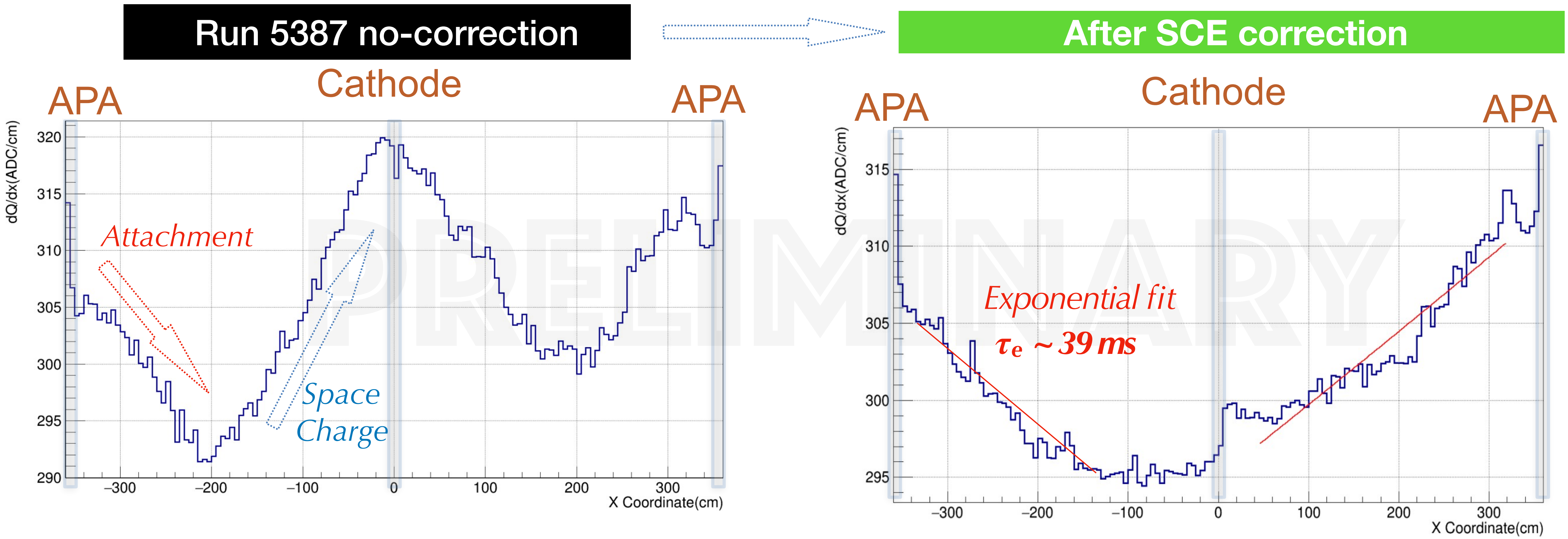
Physics publications

ProtoDUNE-SP Performance

Detector Parameter	Specification	Goal	ProtoDUNE Performance
Electric Drift Field	> 250 V/cm	500 V/cm	500 V/cm *
Electron Lifetime	> 3 ms	10 ms	> 15 ms **
Electronics Noise	< 1000 enc	ALARA	550-650 enc (raw) 450-560 enc***

*99.5% uptime
** inside TPC (500 V/cm)
*** coherent noise removed

Ionization e-Charge in the TPC Volume from cosmic tracks as fcn. of distance from Cathode: Attenuation by impurity attachment opposed by Space Charge effect due to accumulation of slowly moving Ions in LAr Volume (EF=500 V/cm).



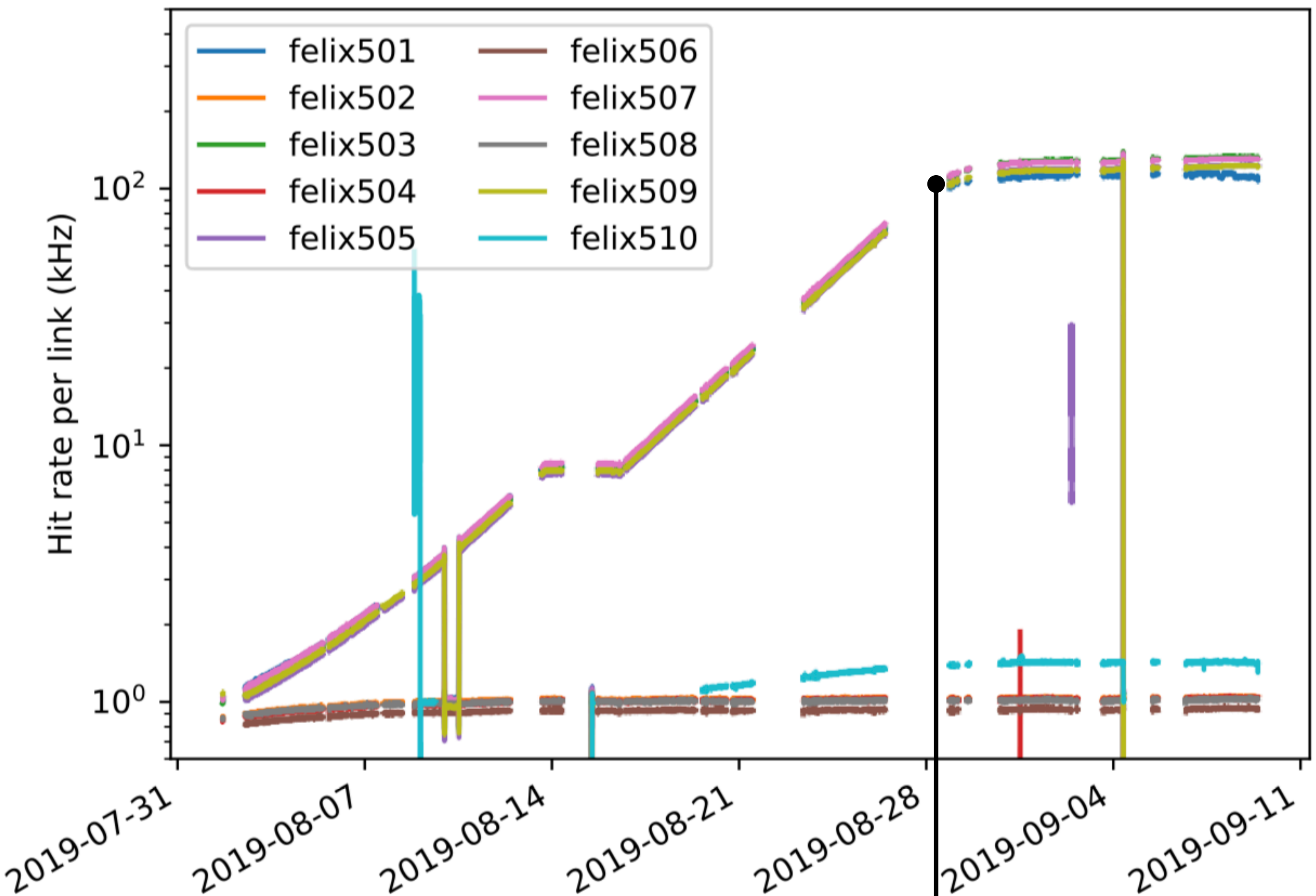
e-Lifetime, Attachment Rate Constant and Impurity Concentration

$$\tau_e = \frac{1}{k_A\ [X]}$$

The rate constant of the attachment process k_A depends on the EF. Measurements from Pur. Mon. at low EF, measurements from TPC at much higher EF: at the same impurity concentration level $[X]$ ppt, τ_e from PurMon expected ~3 times shorter than from τ_e from TPC

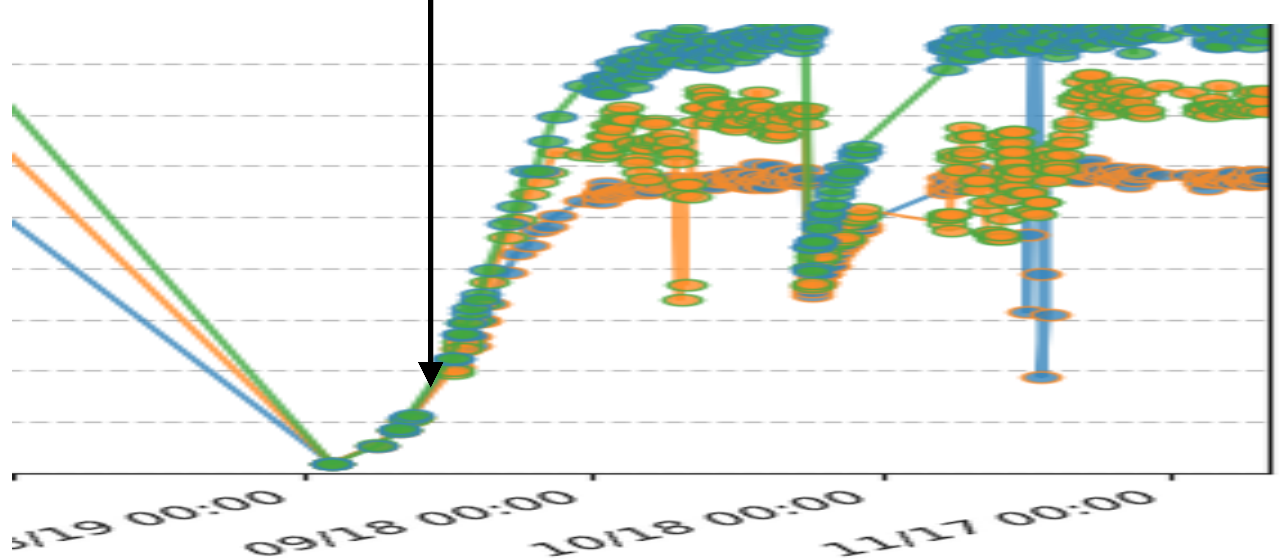
Impurity Concentration in the range of 50 ppt [O2 equivalent] compatible with both Pur Mon and TPC measurements

Detected hit count during Resurrection Period



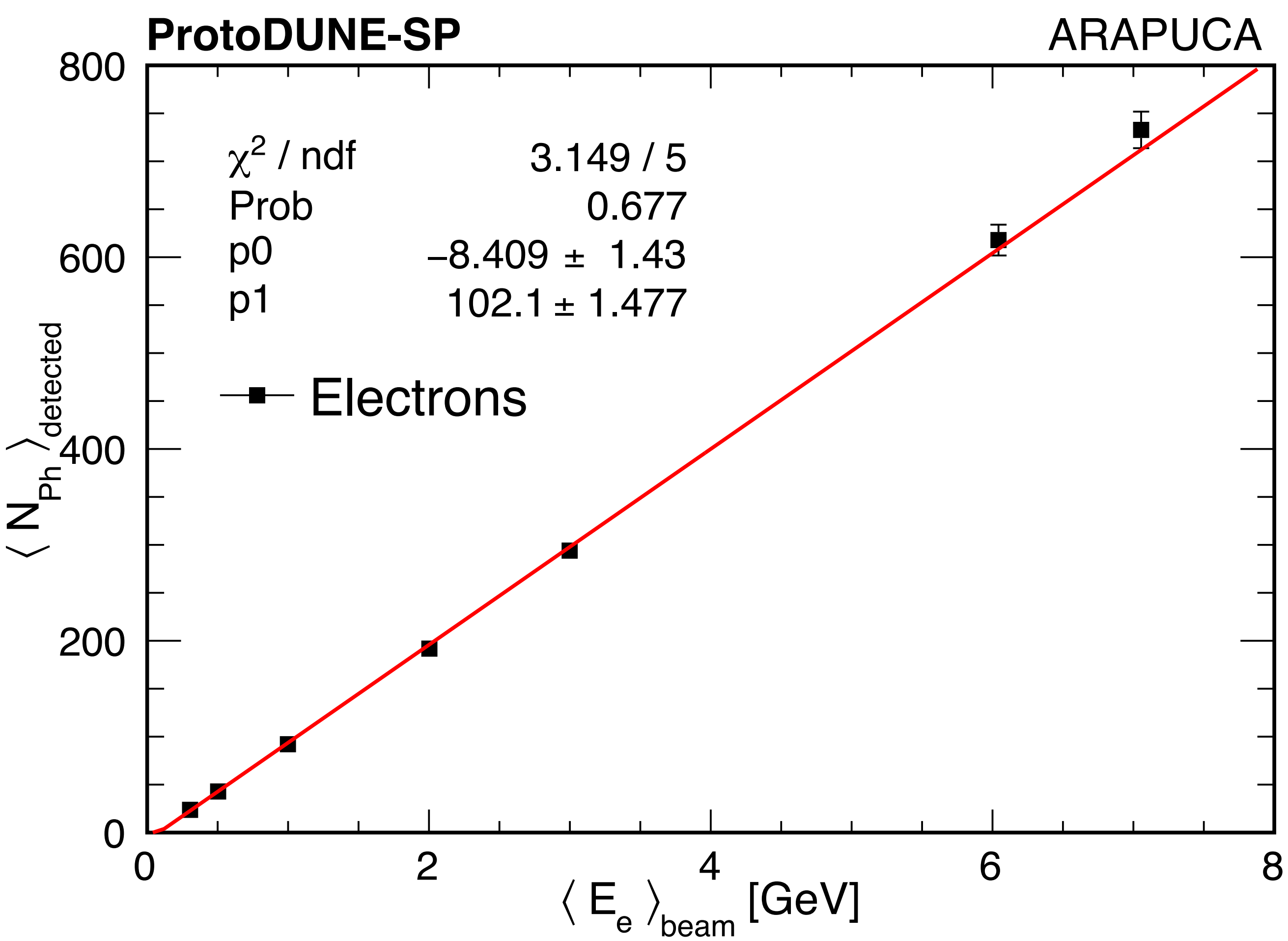
Validation of existing DUNE specification

100% TPC wire hit detected when LAr purity from Pur Mon showed a Lifetime $\tau_e \leq 2$ ms



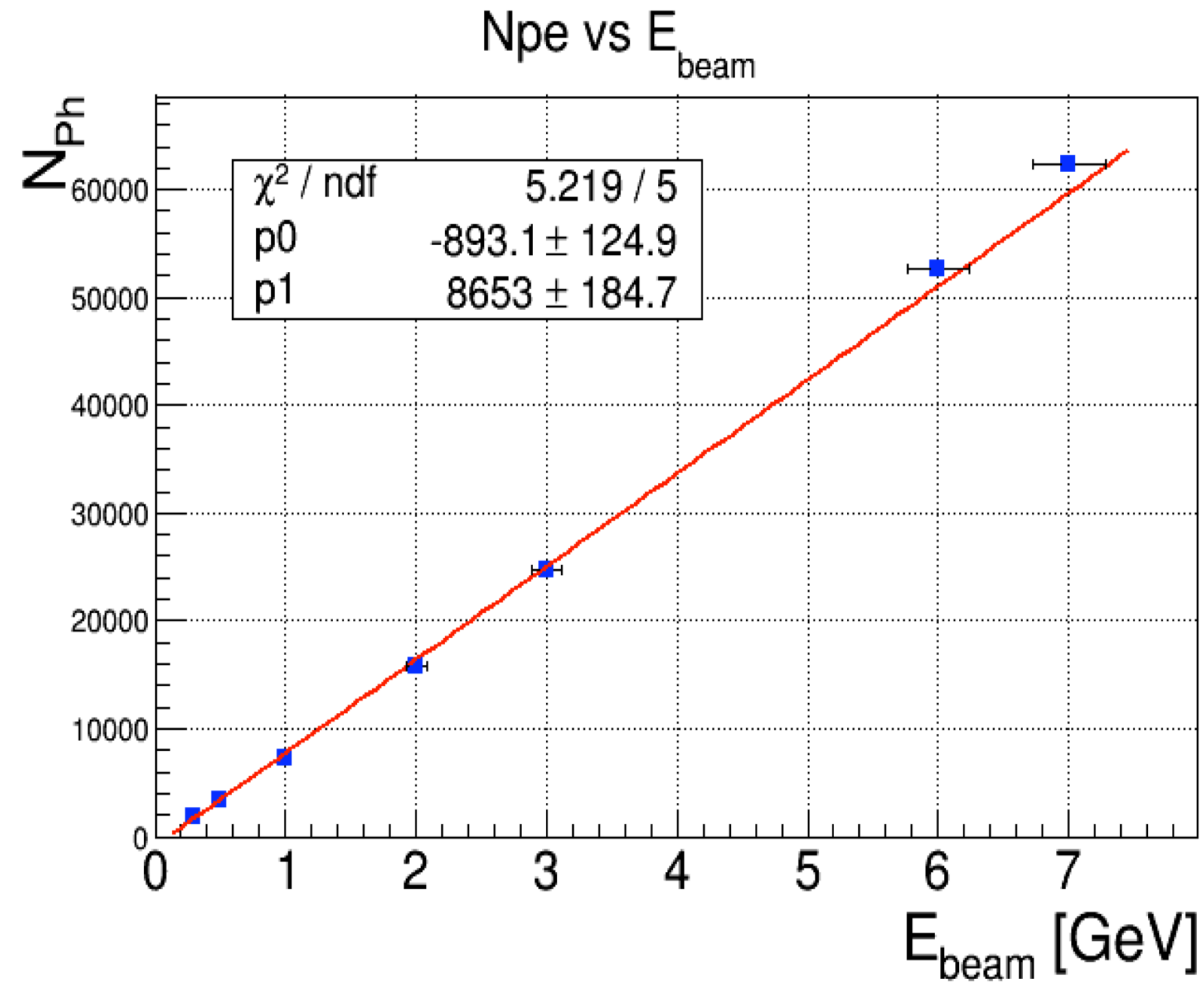
Light Response “linearity”

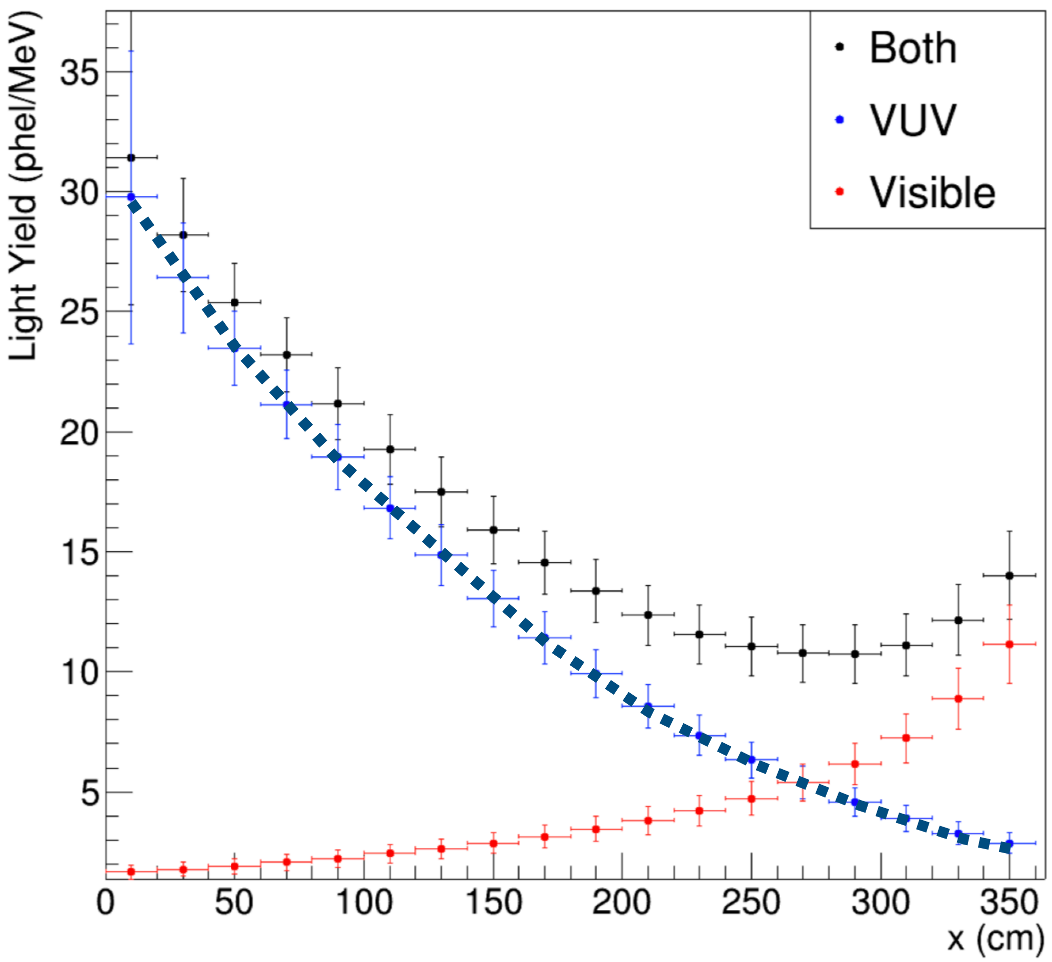
DATA



MONTECARLO

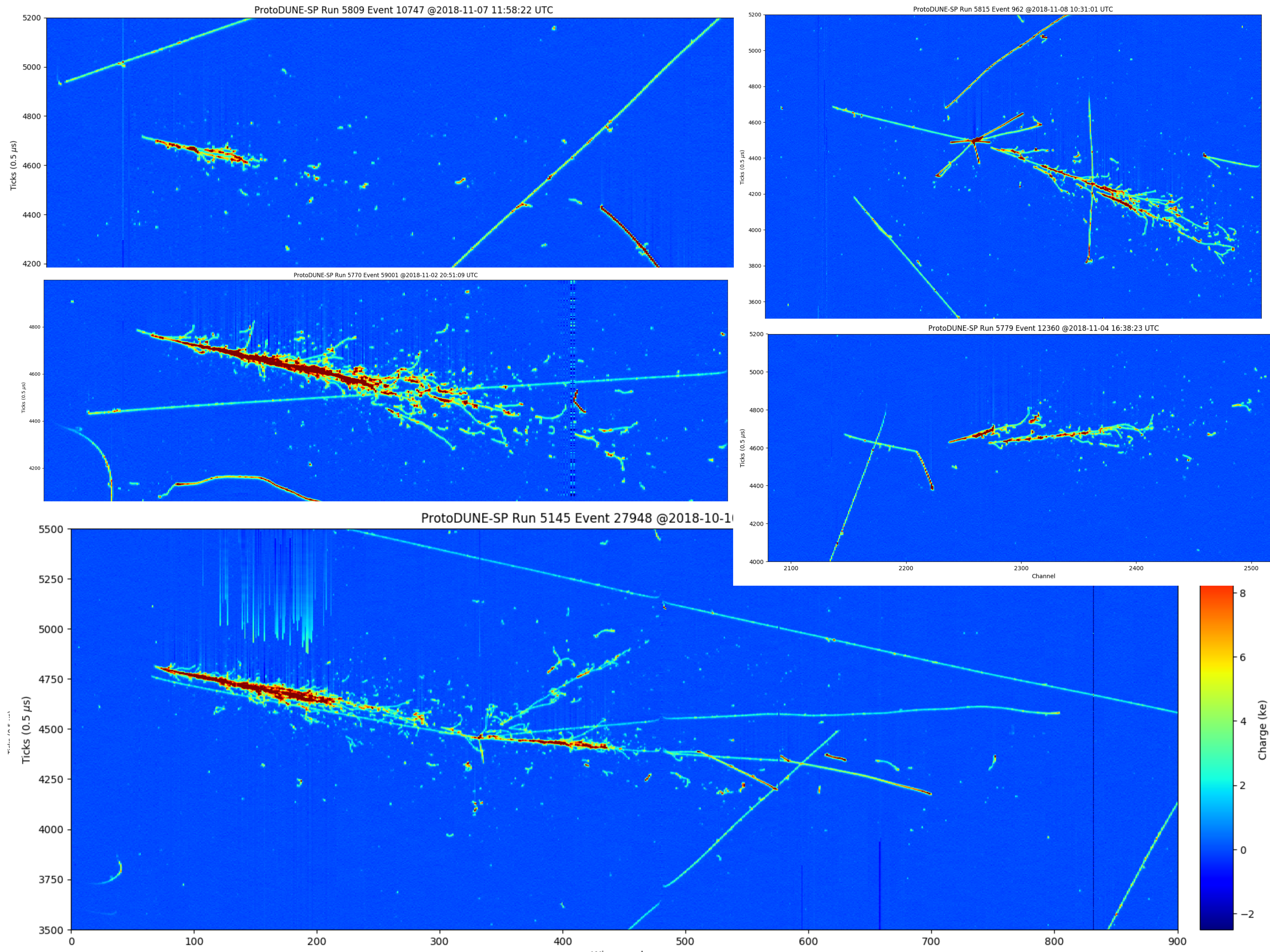
-note: MC not “scaled” by efficiency

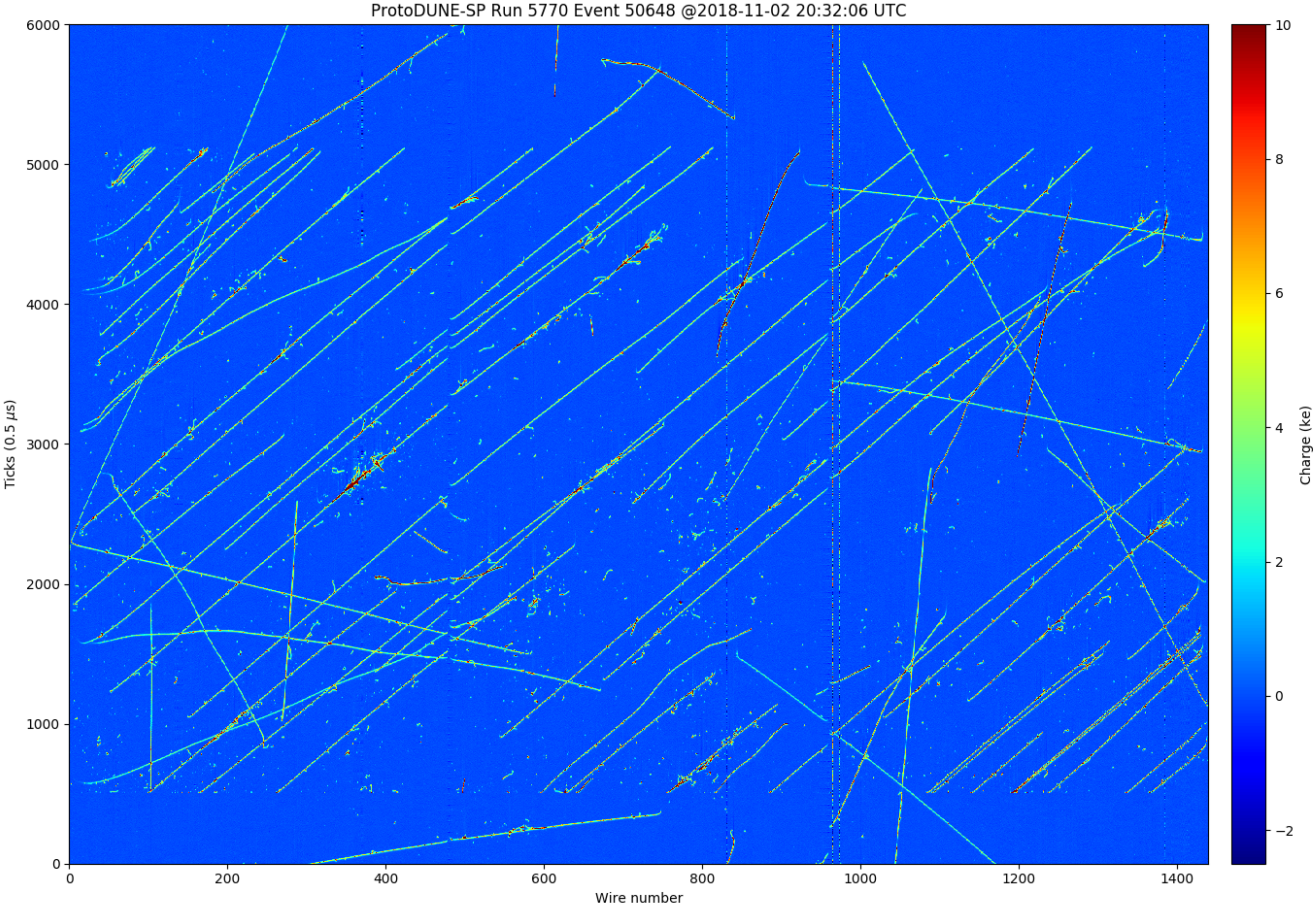




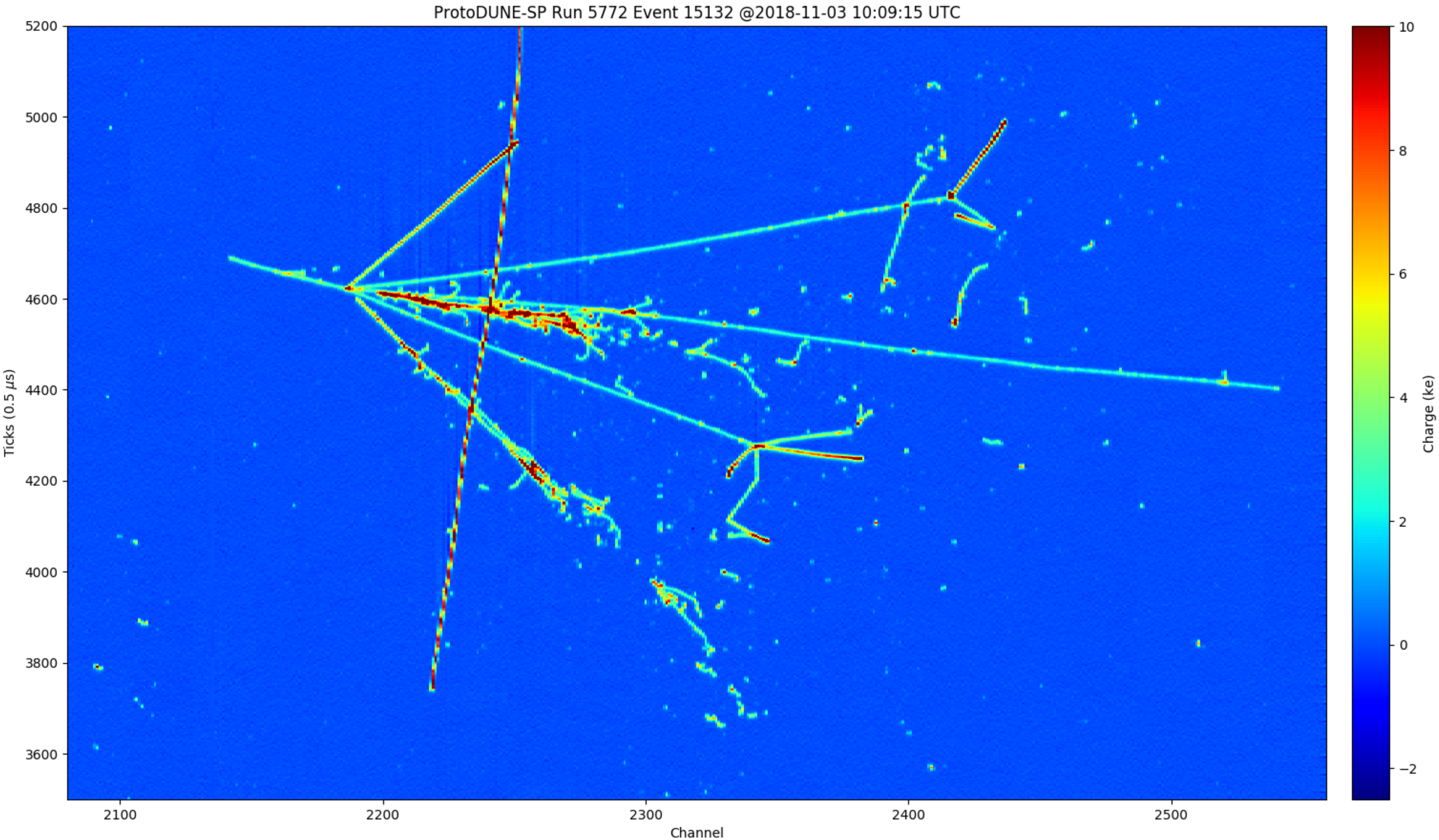
QE = 3.5%; 80% cathode foil coverage; 80% optical detectors TPB coated; 60% visible light transmittance through TPB coating

LY as a function of distance


ProtoDUNE-SP Run 5809 Event 10747 @2018-11-07 11:58:22 UTC
ProtoDUNE-SP Run 5815 Event 962 @2018-11-08 10:31:01 UTC
ProtoDUNE-SP Run 5770 Event 59001 @2018-11-02 20:51:09 UTC
ProtoDUNE-SP Run 5779 Event 12360 @2018-11-04 16:38:23 UTC
ProtoDUNE-SP Run 5145 Event 27948 @2018-10-1
Ticks (0.5 μs)
Channel
Charge (ke)

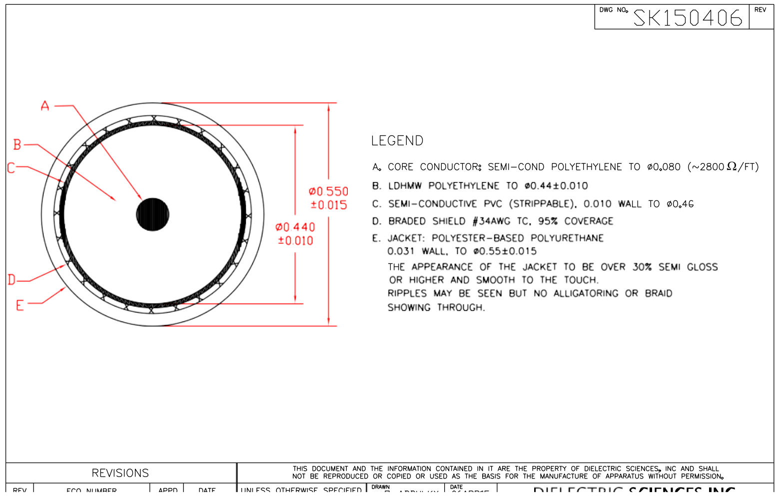


ProtoDUNE-SP Run 5770 Event 50648 @2018-11-02 20:32:06 UTC
Ticks (0.5 μs)
Wire number
Charge (ke)
6000
5000
4000
3000
2000
1000
0
0
200
400
600
800
1000
1200
1400
10
8
6
4
2
0
−2


ProtoDUNE-SP Run 5772 Event 15132 @2018-11-03 10:09:15 UTC
Ticks (0.5 μs)
Channel
Charge (ke)
5200
5000
4800
4600
4400
4200
4000
3800
3600
2100
2200
2300
2400
2500
10
8
6
4
2
0
−2

R&D on resistive cables

- HV Resistive cables are commercially available, coextruded PE with graphite doped inner core and outer layer
  - It allows avoiding the use of external discrete resistive filters to reduce HV ripple
  - The LZ detector is successfully using a 150 kV cable with 10 kOhm/m inner conductor
- We are investigating the possibility to scale this concept to 300 kV and higher with Dielectric Science (on the basis of their commercial solutions)
- The cable is vacuum tight and cryogenically compatible:
  - a new HV extender designed on this concept is under examination



All-plastic HV cable