ProtoDUNE SP - Status, Analysis and Operations parameters

LBNC Meeting December 5-7, 2019 - CERN

Outline

From the Charge of the LBNC Mtg (Dec 5-7, 2019 - CERN):

The LBNC would like to hear about the **progress with ProtoDUNE SP**, addressing both the analyses, including **results from the photo-detection and progress towards defining the operating parameters**, which was seen as a primary goal for 2019.

From last LBNC meeting Report [July 31-Aug 2, 2019]

Comments

- At the next meeting the LBNC would like to hear an update on **what has been learned from the ProtoDUNE-SP running thus far in 2019**, with emphasis on studies to establish the operational safety margin and **long-term stability of the system**.

- It is important that **lessons learned from the pump seal failure** inform monitoring, instrumentation and inhibit systems for DUNE-SP. The LBNC encourages the collaboration to continue developing a full fault analysis to estimate situations such as the pump membrane failure rate in the FD-SP system based on the observations in ProtoDUNE-SP.

- The LBNC would like to see the **comparison in the measured number of photons/MeV from the ARAPUCA photo-sensor system vs. the other two Photon Detector designs** in the array of deployed PDS units in ProtoDUNE-SP.

- At the April 2019 meeting, the LBNC encouraged the collaboration to pursue the following studies. The LBNC reiterates the value of these studies for establishing the technical baseline for the FD-SP TDR, and would like to see these presented in future meetings.

  - ***Noise mitigation, S/N, ADC calibration, etc.***
  - ***Suggest to study resolution impact by masking of few ADC bits.***
  - ***dE/dx of beam protons and electrons data vs. MC (after all corrections).***
  - ***Would be more useful to see lower level data/MC comparison before the corrections.***
  - ***Fine tune and explore current technological limits, with three main objectives:***
    - ***Investigate limiting factors toward higher LAr purity level***
    - ***Collect data to study fluid and space charge dynamics***
    - *LAr Purity + Cryogenics (Fluid Dynamics)*
  - ***Investigate how different cryogenic conditions affects the electron lifetime***.

Recommendations

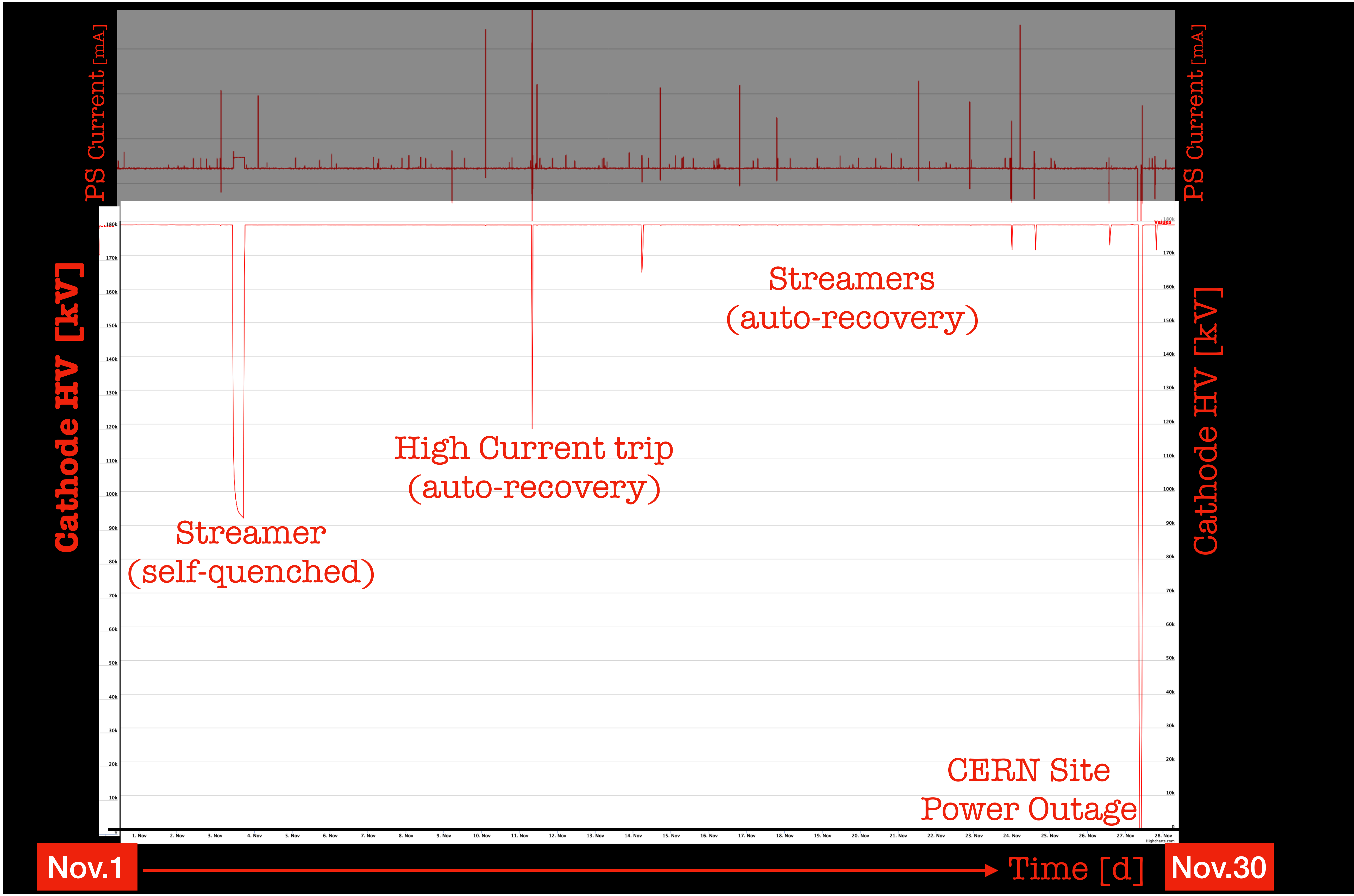
- While recovering from contamination, **take cosmic ray data with 3ms electron lifetime to validate existing DUNE specification**, explore operational parameter space.

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)**

Long Term Stability - HV System / E-field

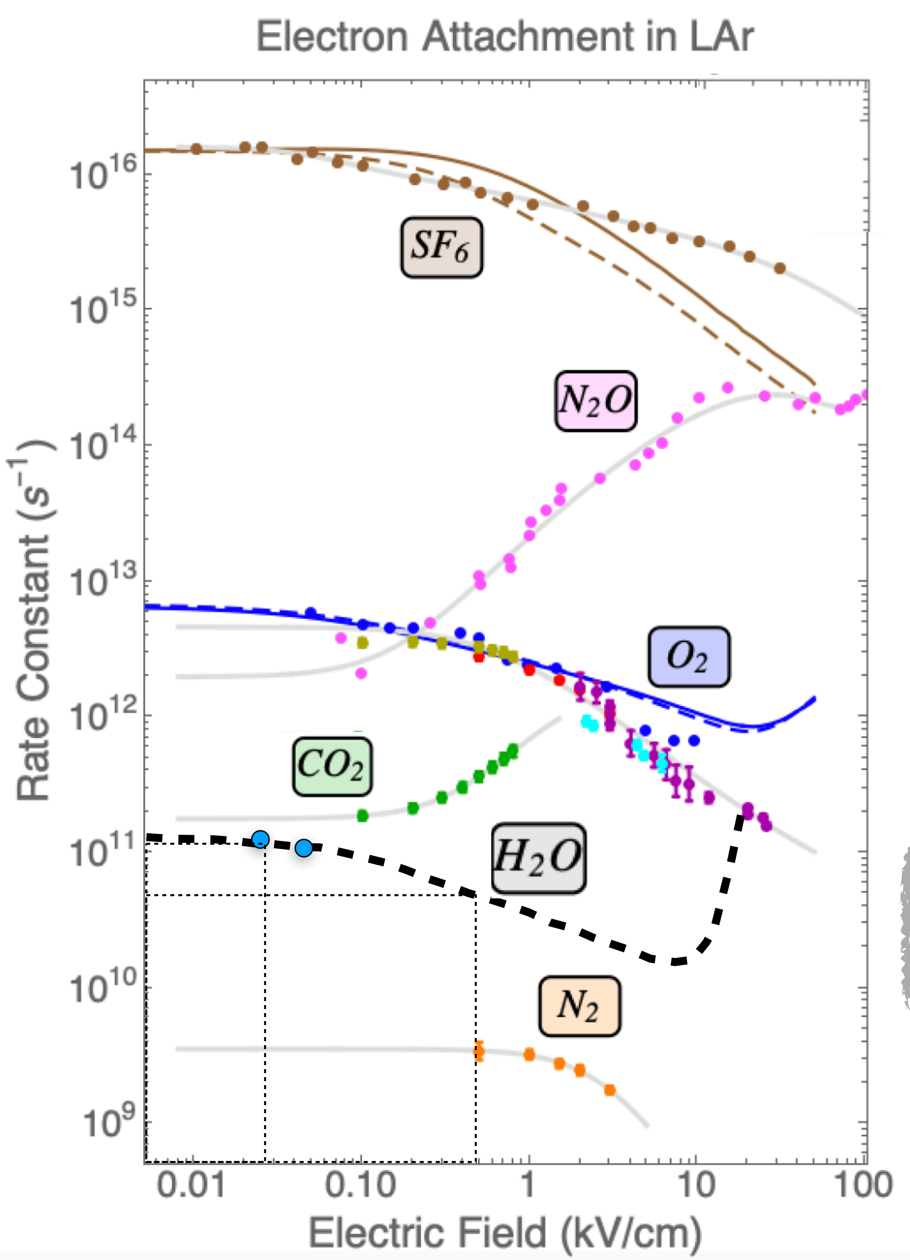


2) lessons learned - e-Lifetime and LAr Purity

- **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]

e-Lifetime vs Purity

$$\tau_e = \frac{1}{k_A\ [X]} \qquad Q_{corr} = \frac{Q_{det}}{exp[-t_d/\tau_e]}$$



- **Purity of LAr depends on** $[X]$ (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**

How to measure e-Lifetime inside TPC

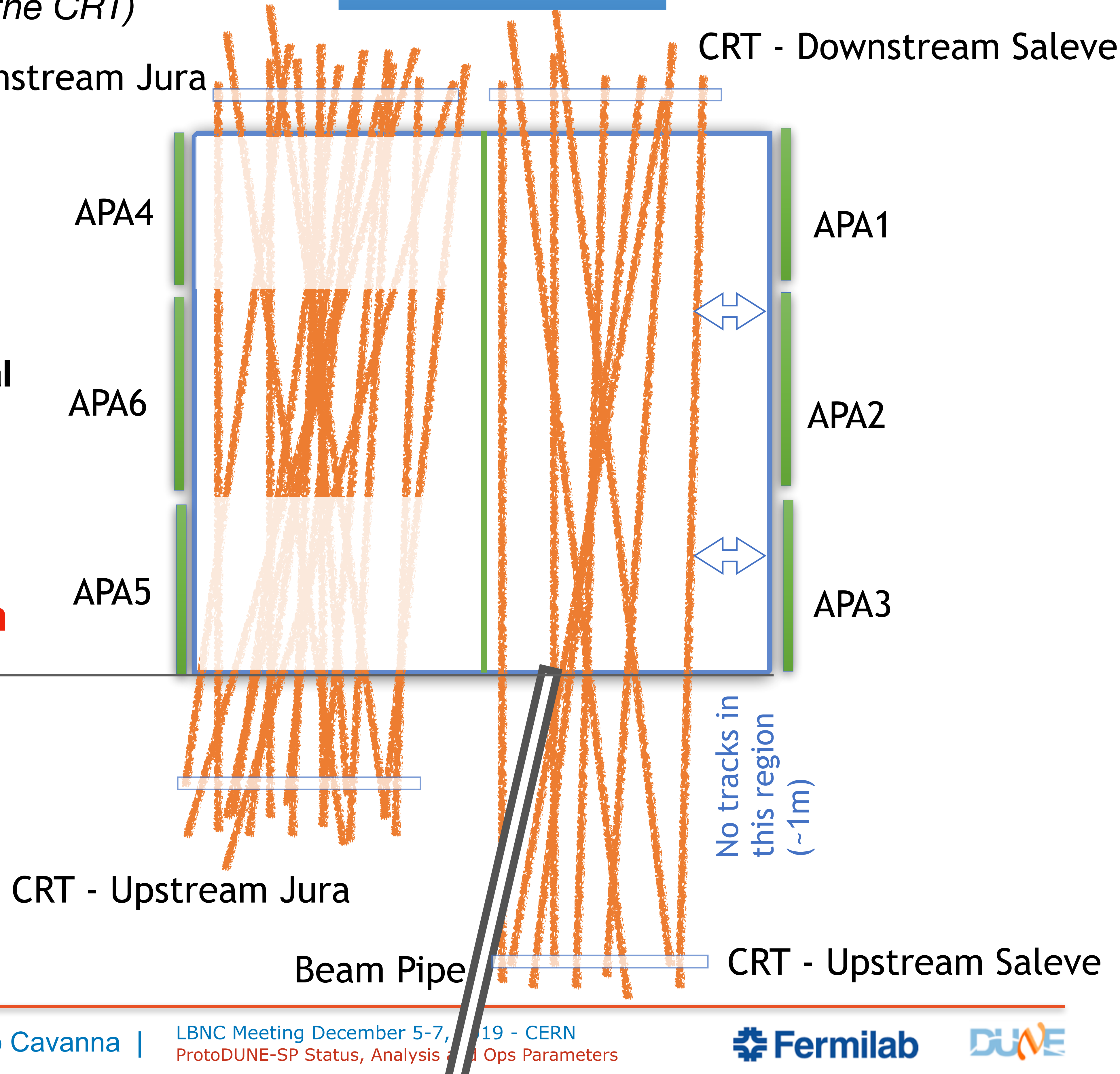
(the importance of the CRT)

ProtoDUNE-SP View from the TOP

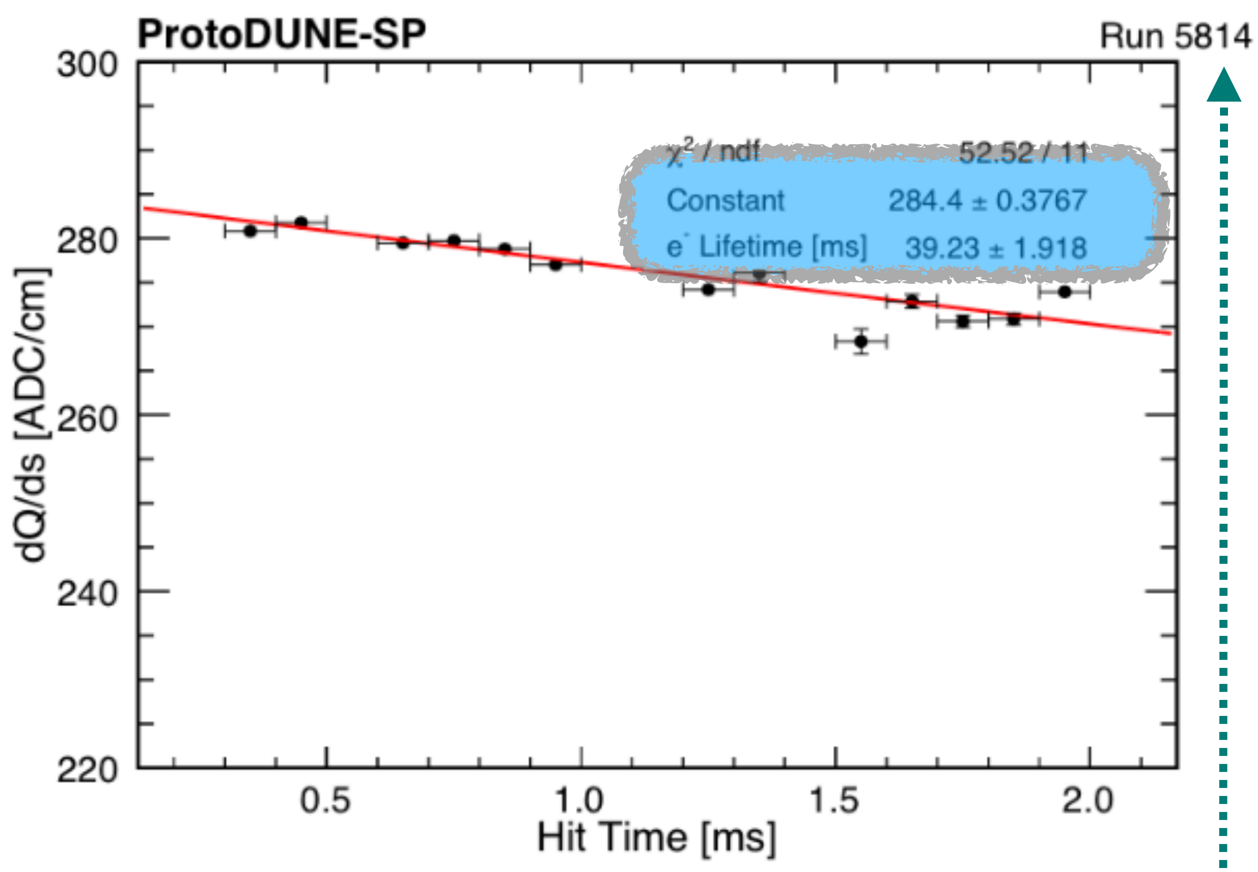
CRT Triggered ~Hor. Muons parallel to APA & Tracks in TPC central region:

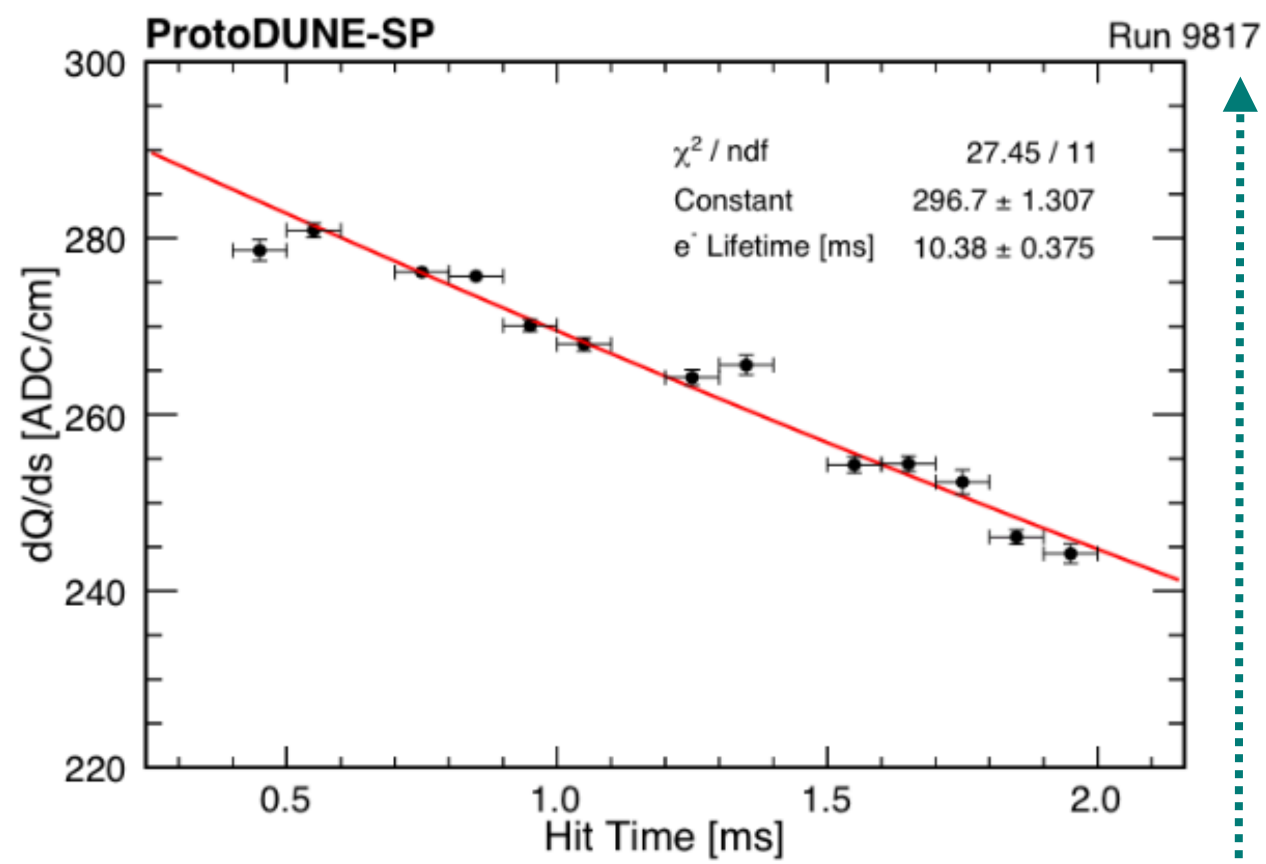
No/minimal Space Charge Spacial Distortion

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

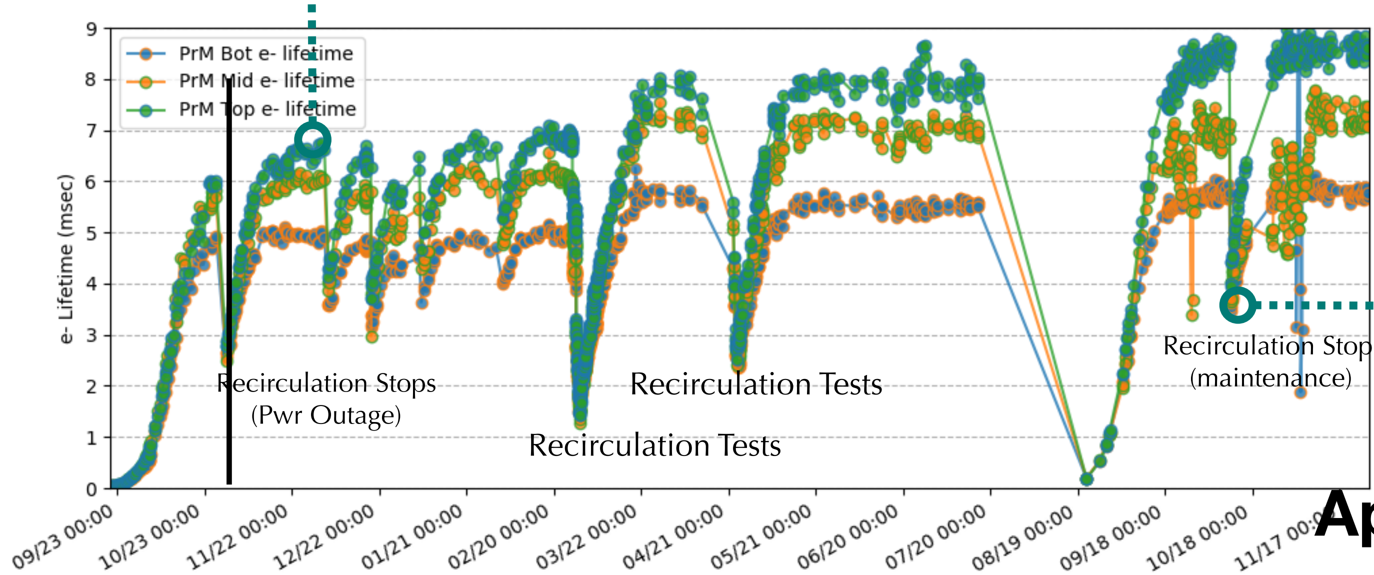


Long Term Stability - LAr e-Lifetime (vs Purity)





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



PurMon - Service

Apparent Stratification visible in low lifetime measurement w/ PurMon

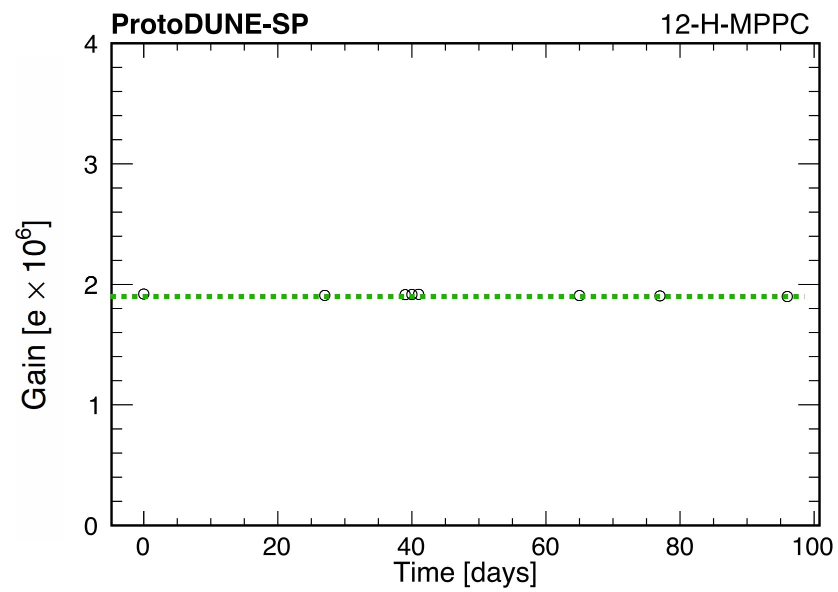
3) lessons learned - Detector(s) Operation

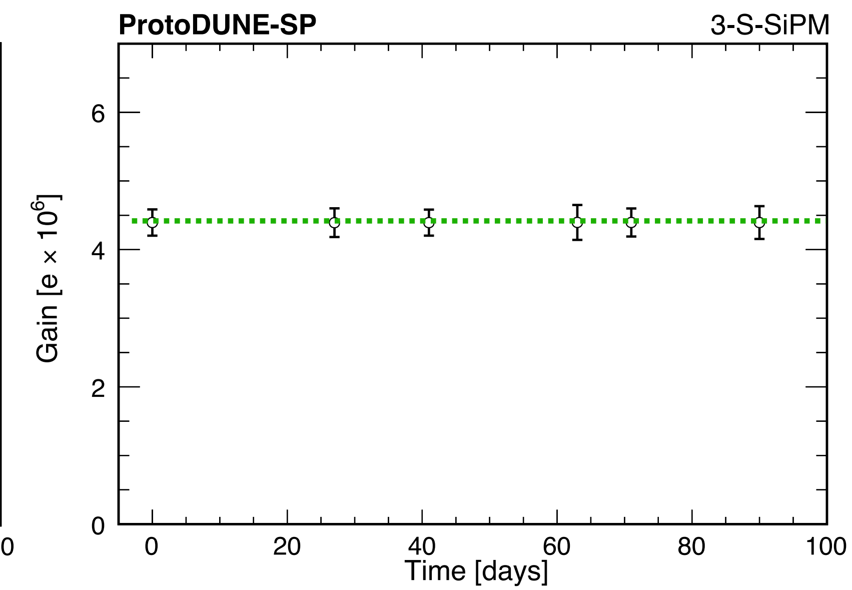
- CE calibration stable (**gain)**
  - TPC response stable (***charge signal strength vs time***) for stable LAr purity condition

- PhotoSensors calibration stable (**gain)**
  - PhotoDetector response stable (***single photon rate vs time***) for stable LAr purity condition

Long Term Stability - Detector(s) Operation

- **PDS - PhotoSensors gain:**





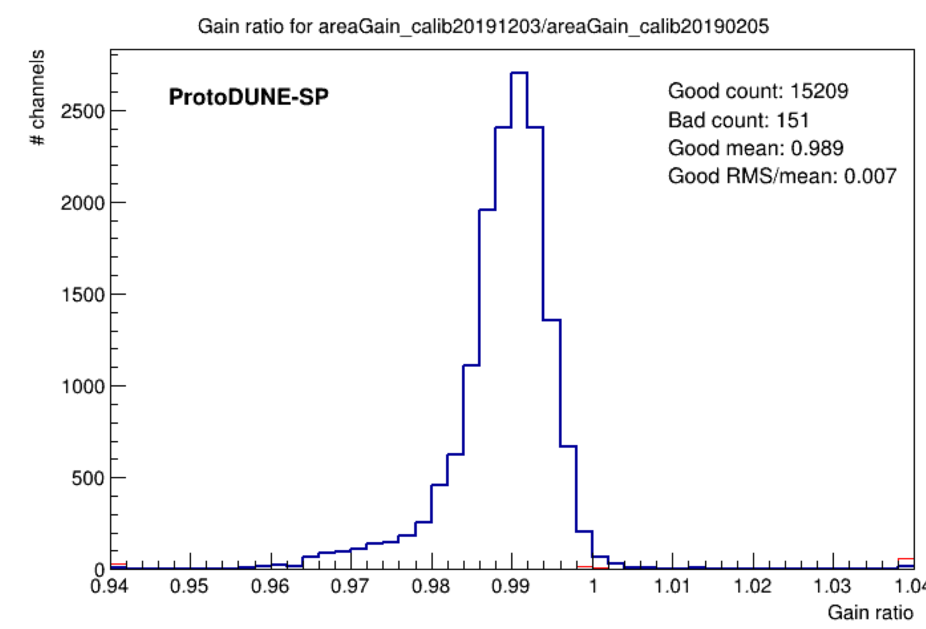
- **TPC - Cold Electronics gain:**

Dec.19 **Dec.18**
Ratio (new gain)/(old gain) - for all 15,209 CE r/o channels

Jan, Feb data confirm the December calibration

Calibration scale scale stable within < 1% [over 1 yr period]

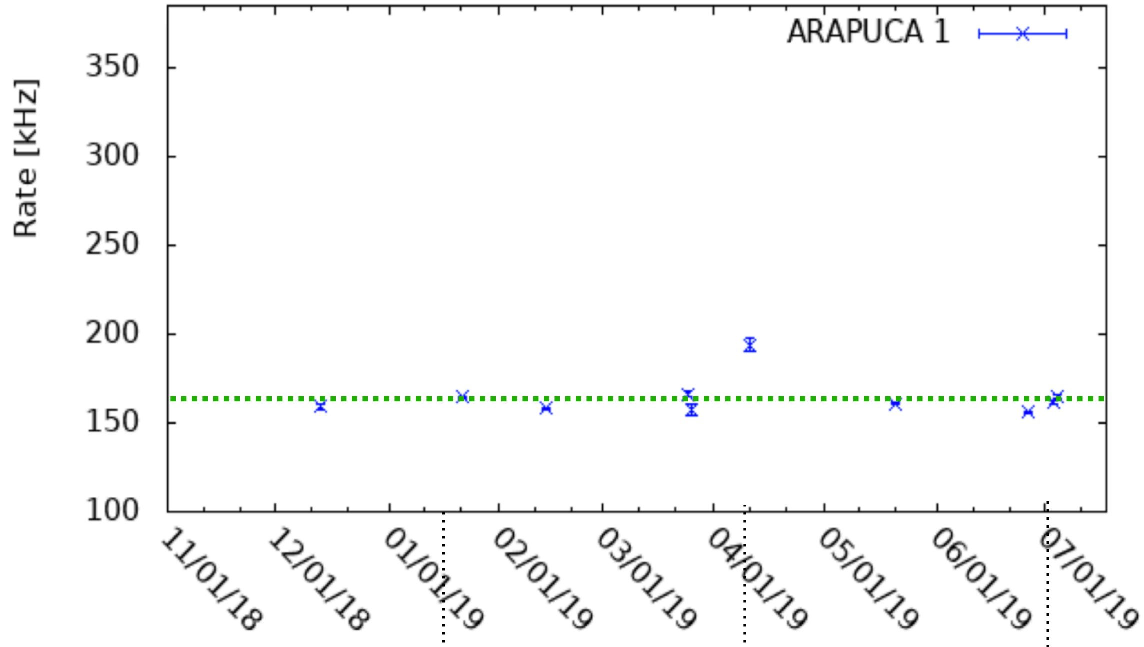
The RMS of the ratio distribution is less than 1%



Long Term Stability

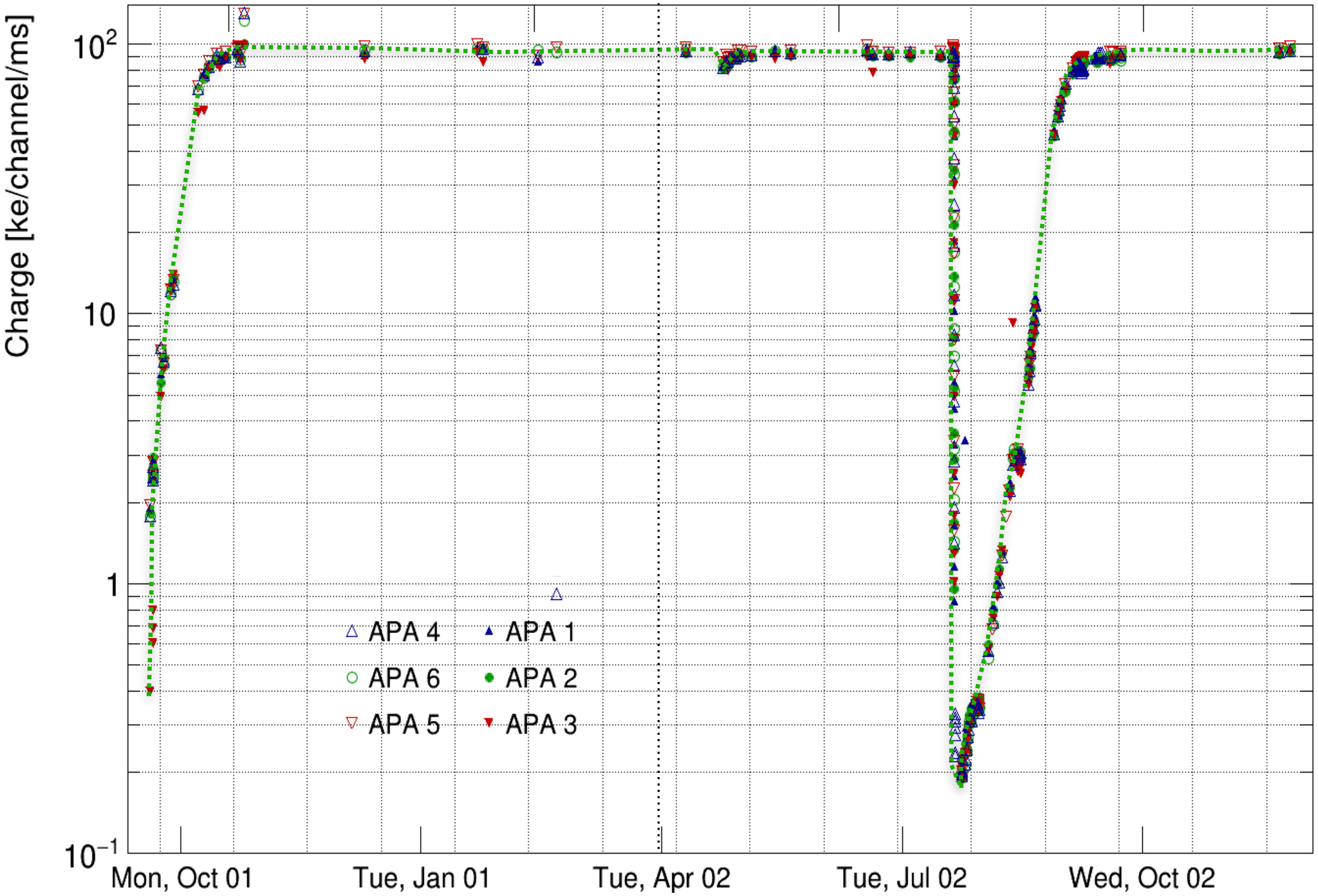
- PhotoDetector Response:

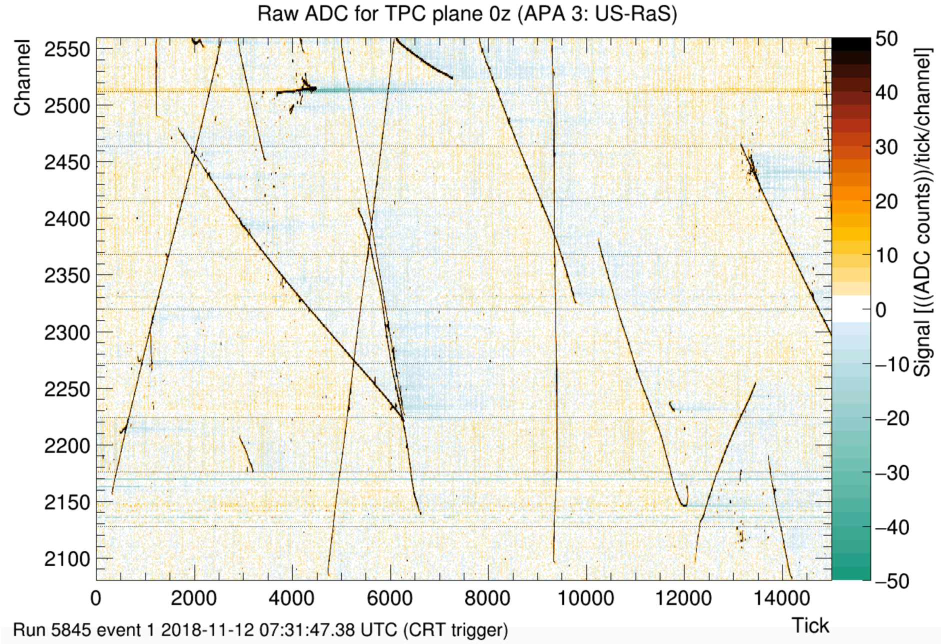
Single Photon Rate



-TPC Response:

Signal Strength
[Average Charge per Channel per Event]





lessons learned - SUMMARY

- Cryogenics parameters stable (P, T, heat load/LN2 consumption)
- HV stable at 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. *In protoDUNE-SP Phase2 design changed, removing insulating materials from high EF regions*
- LAr Purity stable with a slight increase (e-lifetime vs time), except for 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.*
- CE response stable
- PhotoSensors response stable
- TPC response stable (for stable LAr purity)
- PhotoDetector response stable (for stable LAr purity)

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.

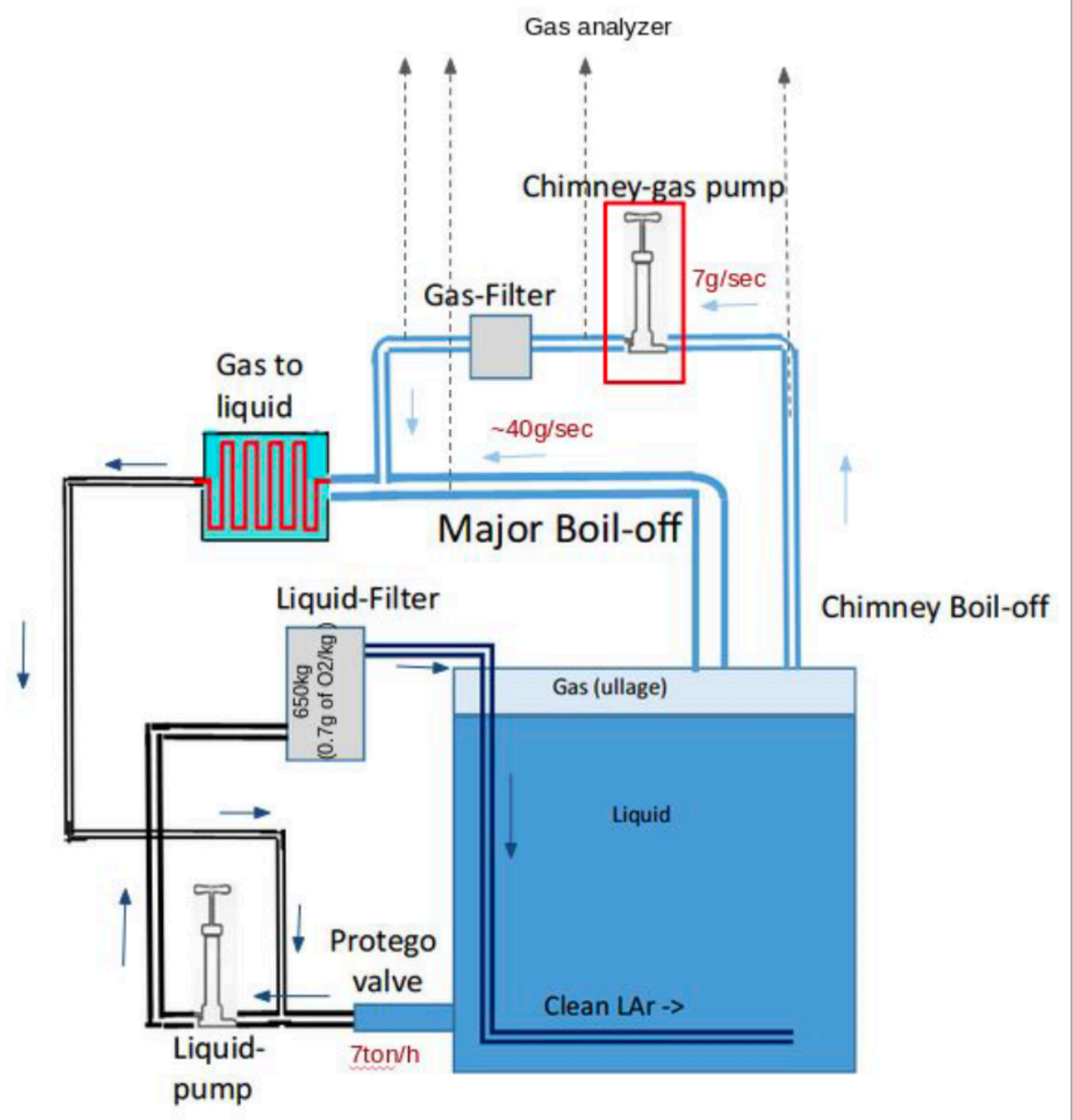
July 24 — **LAr filter regeneration**

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

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

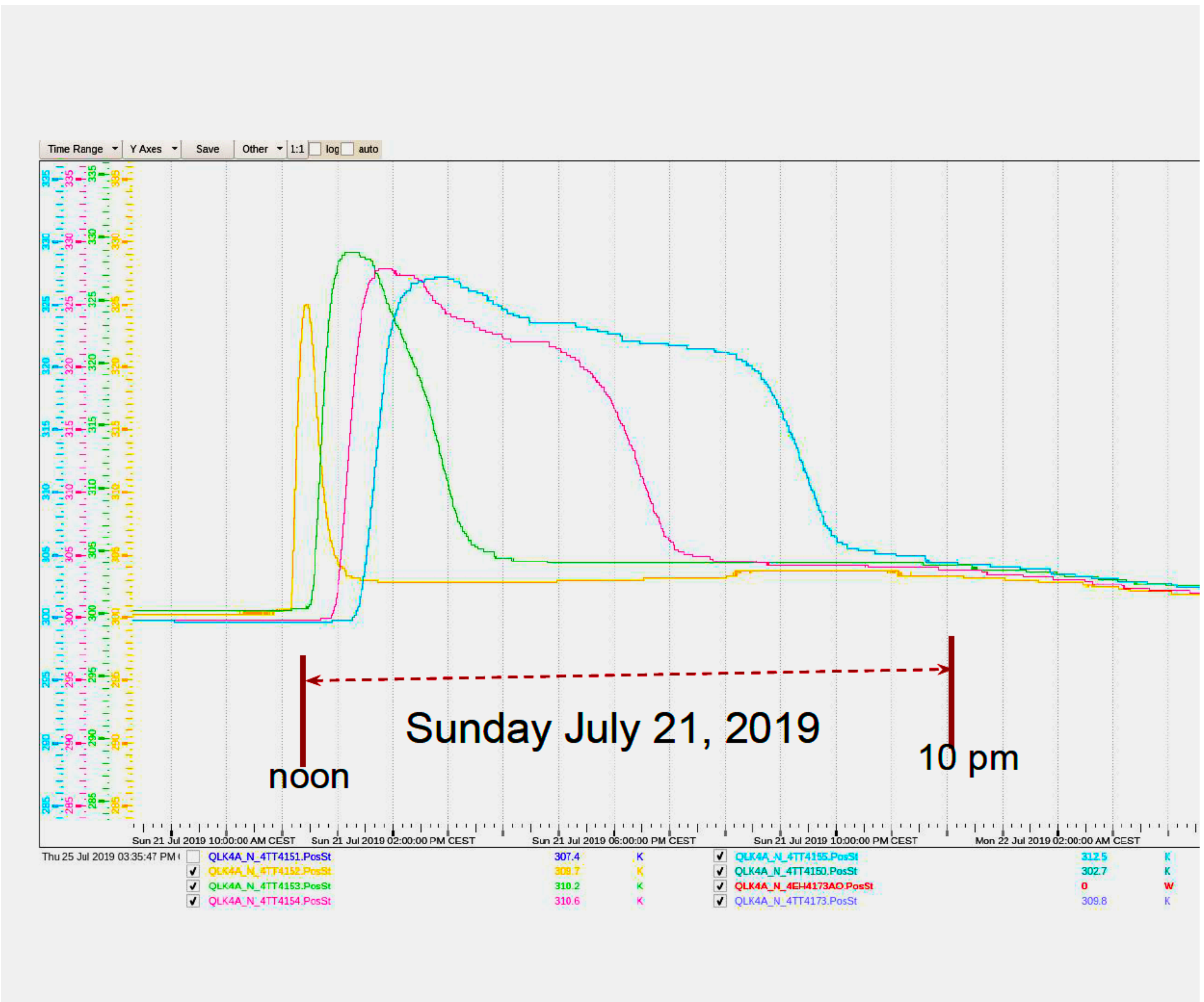
July 26 — **GAr filter saturated. Source of problem understood**

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

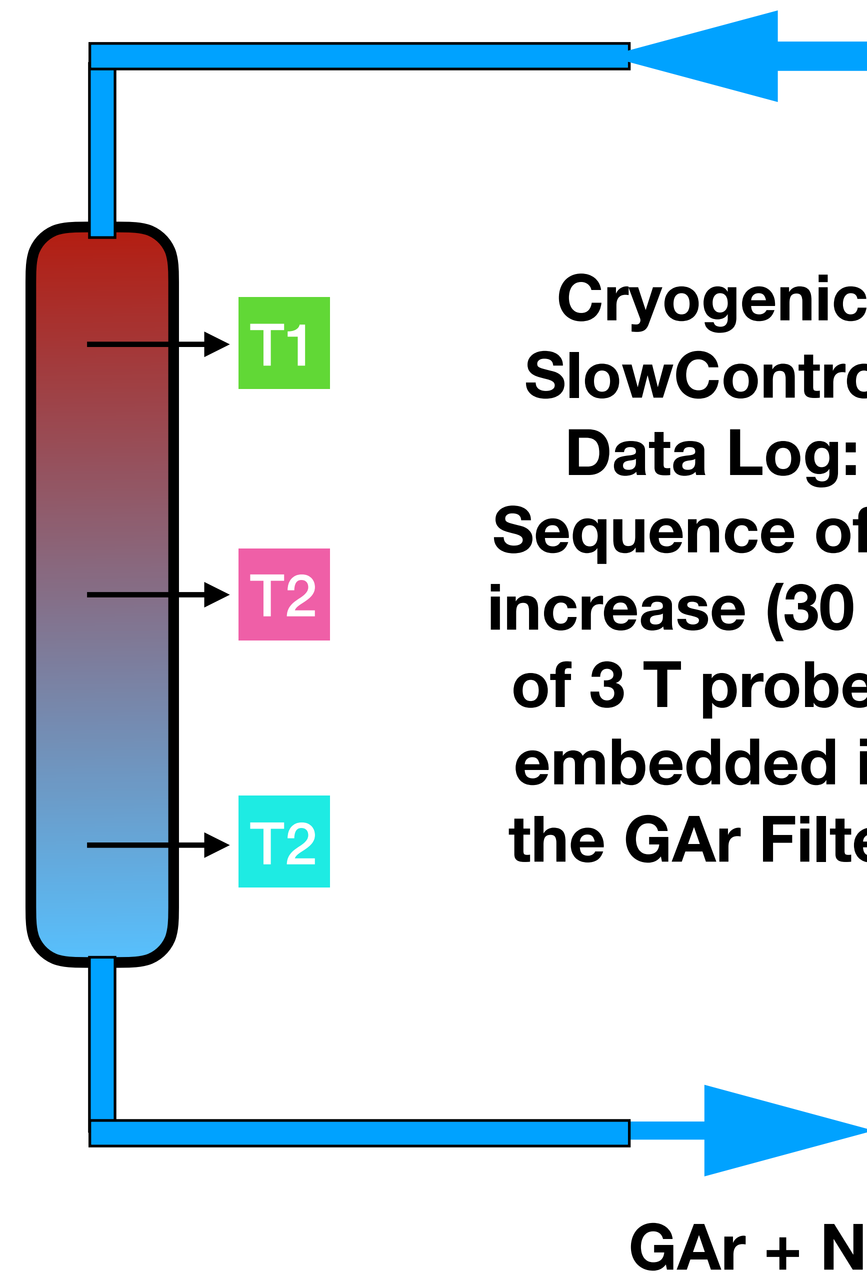


FALL AND RESURRECTION

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



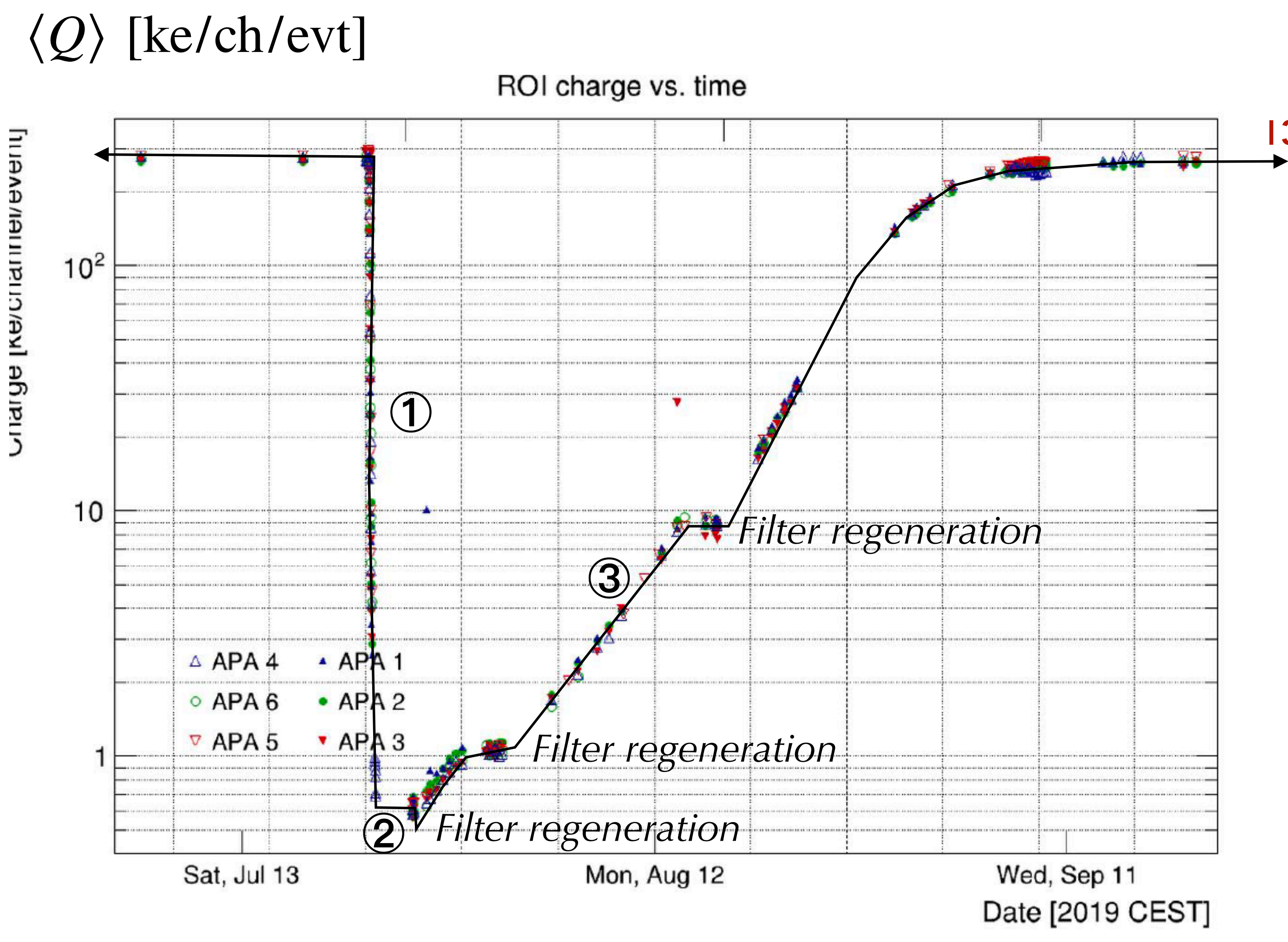
Time to react (12 hrs) - filter sustains air(O_2) leakage - good alarm (for the next time) already implemented

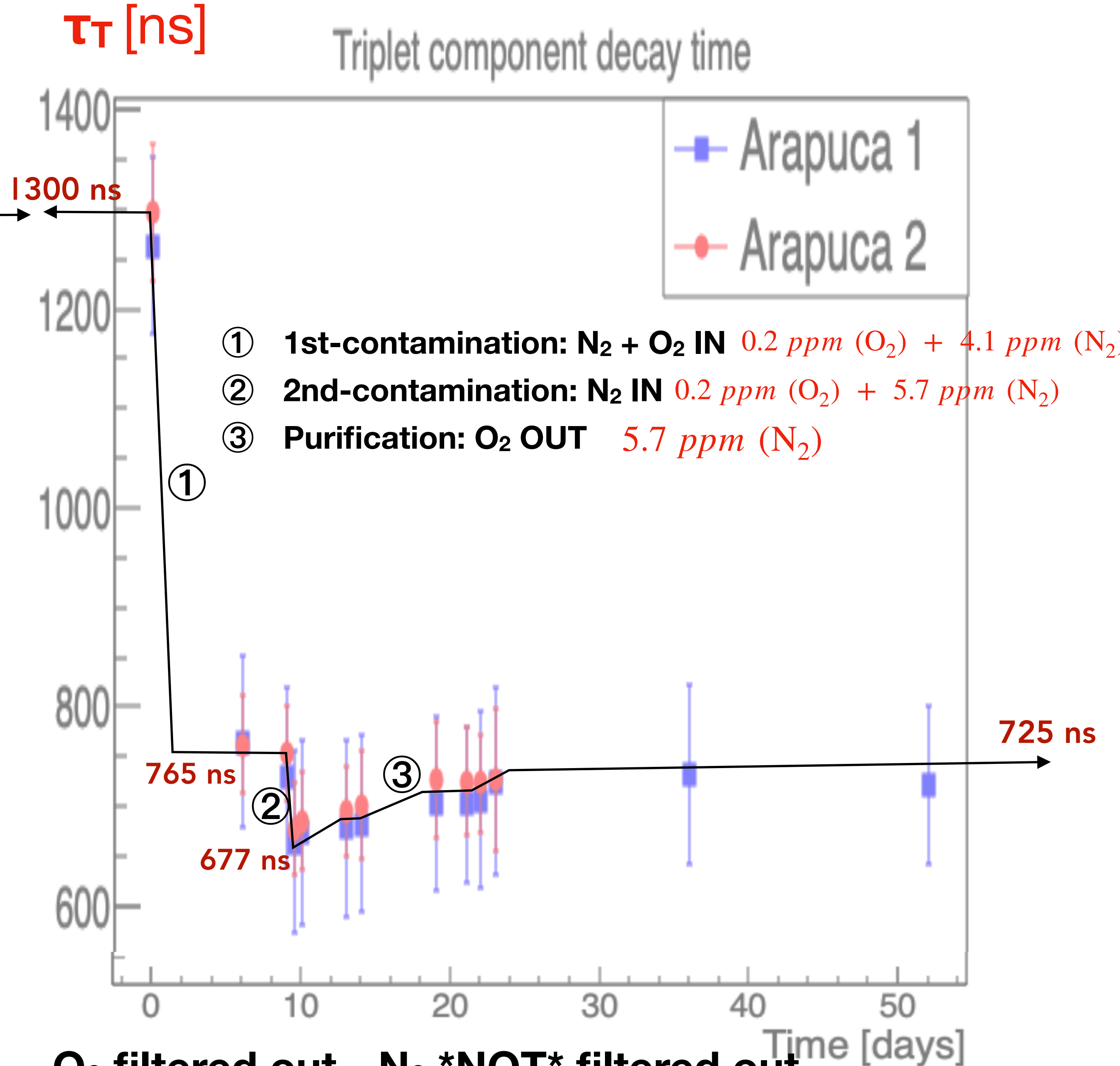


Cryogenic SlowControl Data Log: Sequence of T increase (30 K) of 3 T probes embedded in the GAr Filter

FALL AND RESURRECTION

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

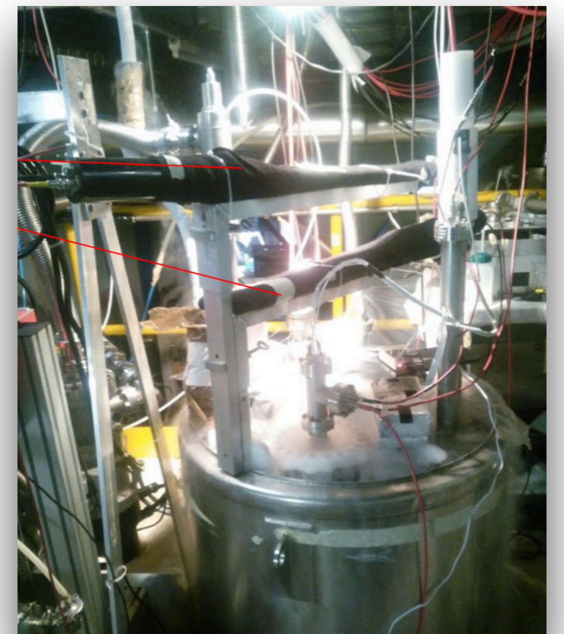




O_2 filtered out -
Full recovery of Charge Signal

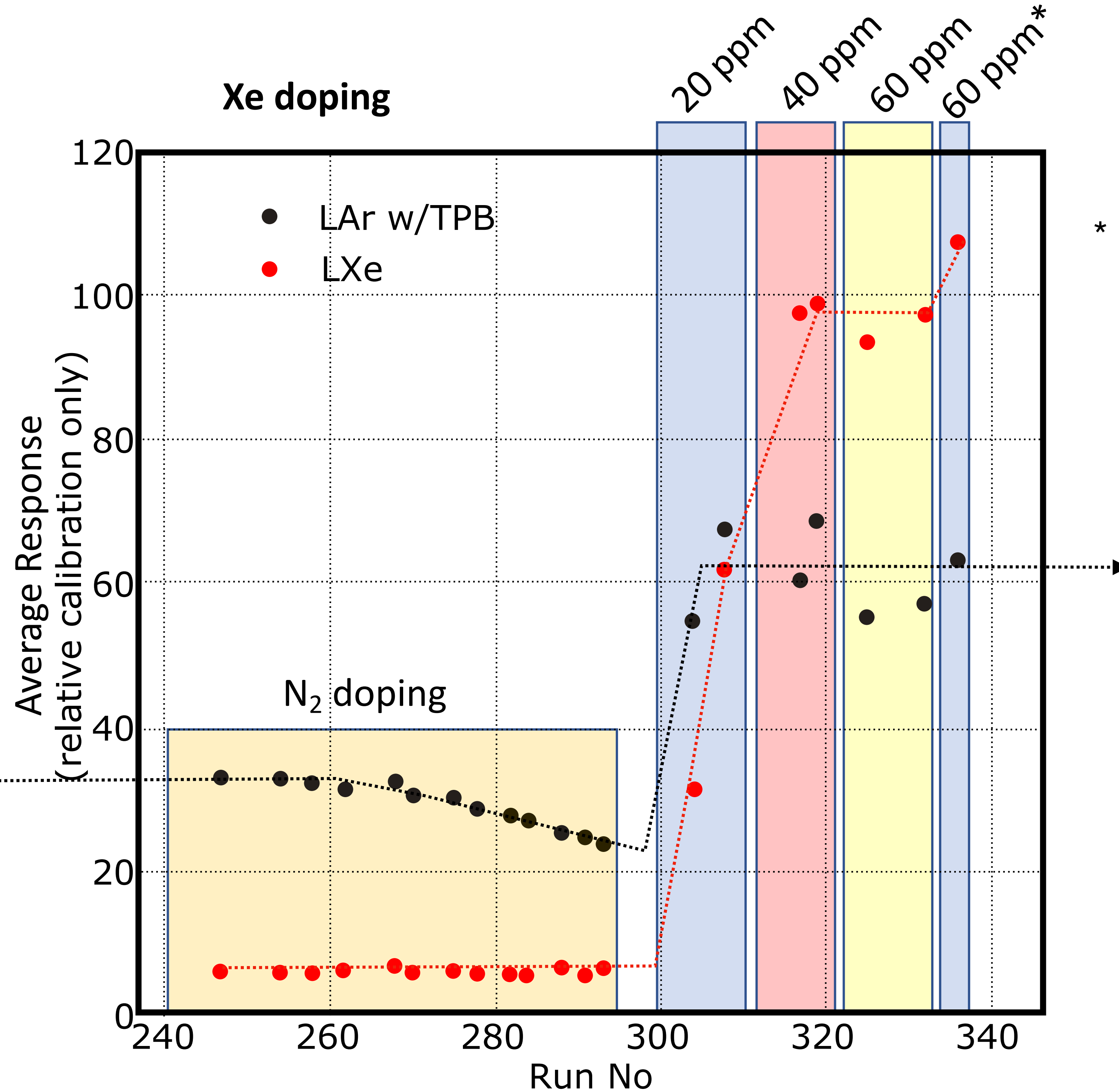
O_2 filtered out - N_2 *NOT* filtered out -
Partial recovery of Light Signal
(~30% Triplet Component quenched)

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.



Small scale Tests at CERN

All PMTs see an increase in the level of light when Xe is added

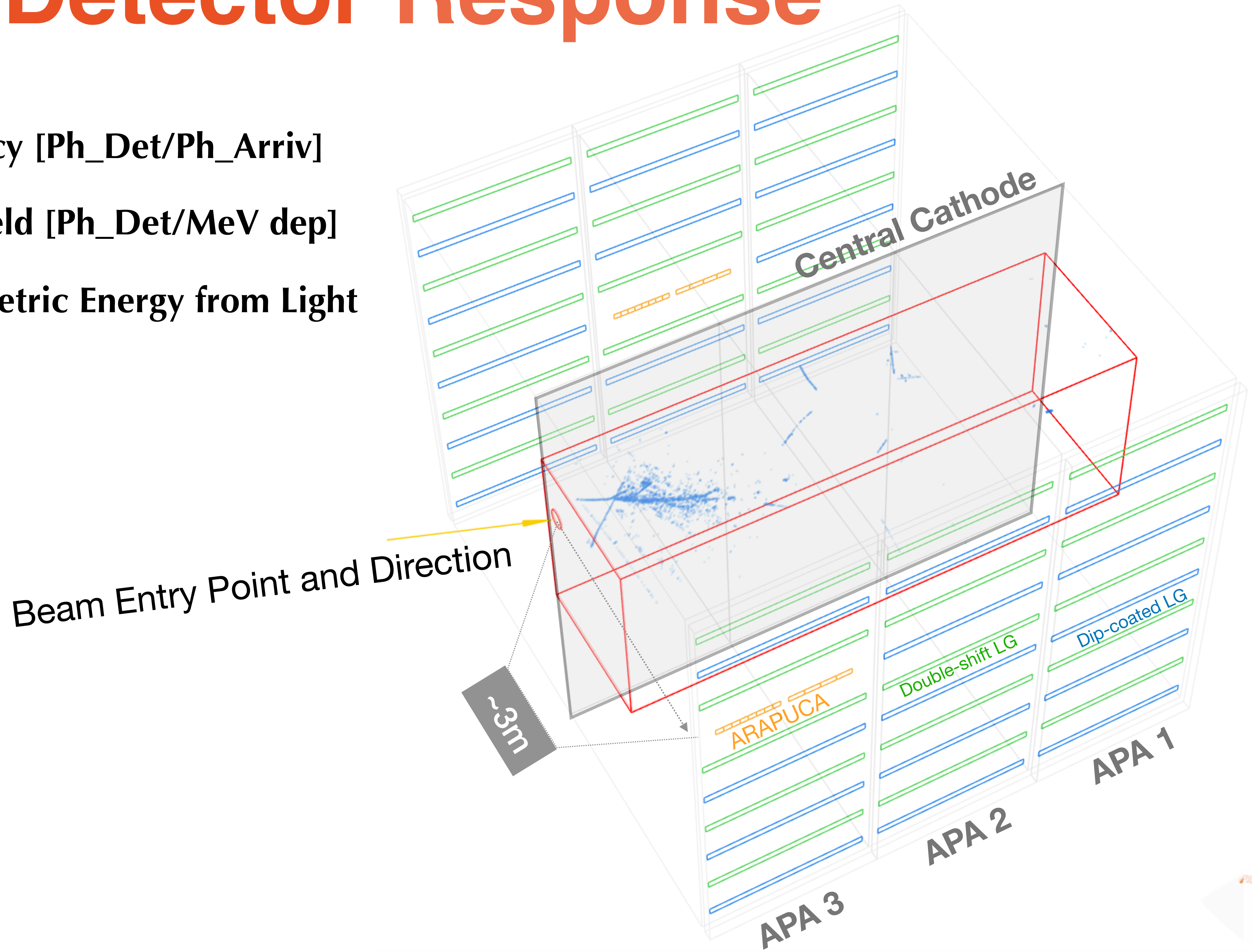


The amount of light seen is larger than the pure LAr response with the first Xe doping

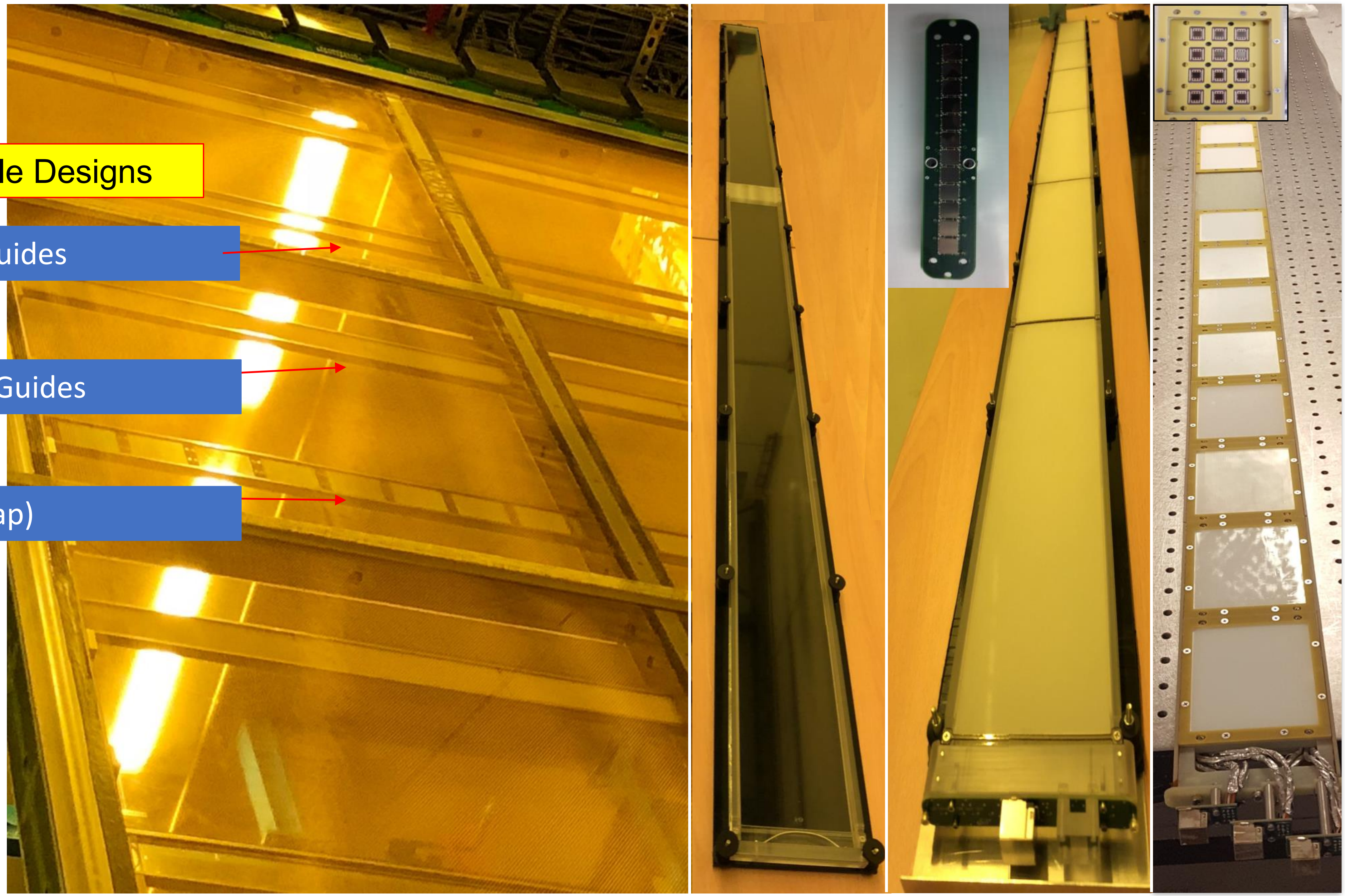
LAr w/TPB response drops (-30 %) with N_2 doping to 5.2 ppm

Ph.Detector Response

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



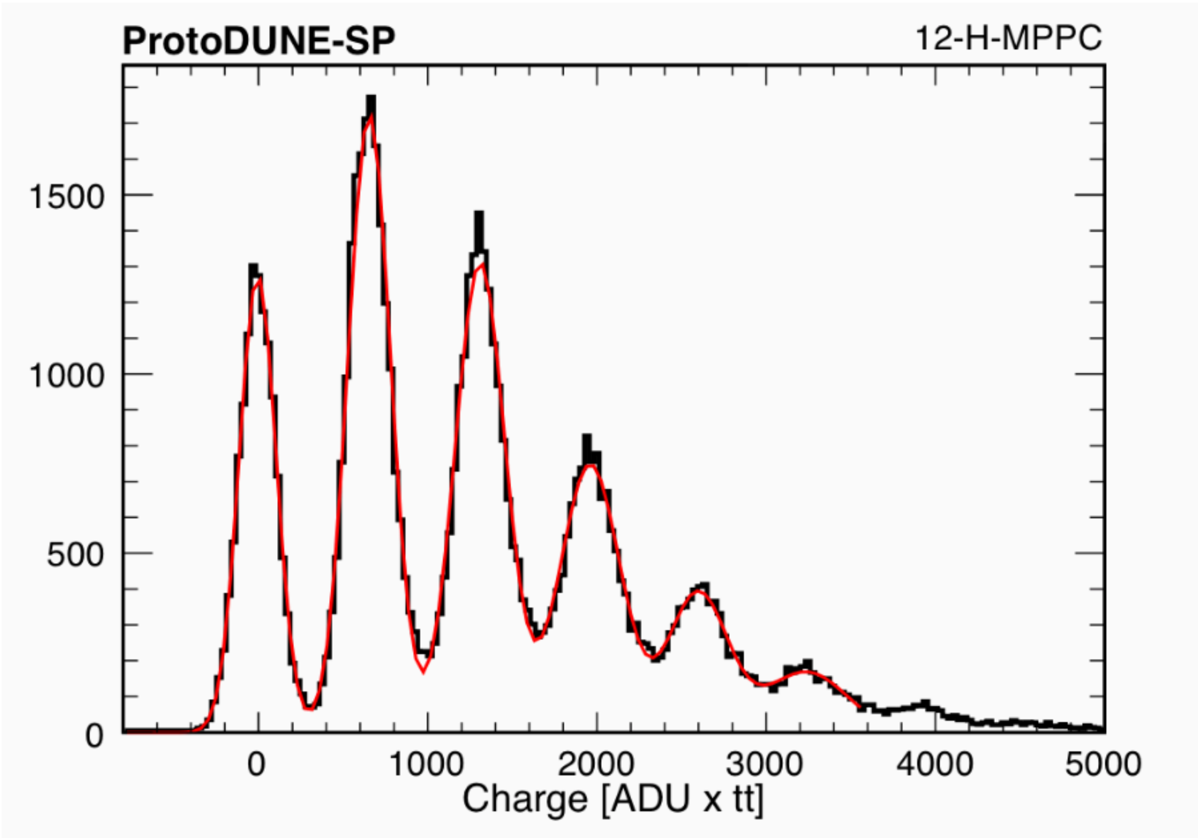
N.-*Type* of Sensor per Channel	N. of Channels	N.Channels per Module	N.Dip Coated Modules	N.DoubleShift Modules	N.ARAPUCA Modules
3 SensL SiPM (parallel passive ganging)	172	4	21	22	-
3 Hamamatsu MPPC (parallel passive ganging)	60	4	8	7	-
12 Hamamatsu MPPC (parallel passive ganging)	24	12	-	-	2



Single photon Sensitivity

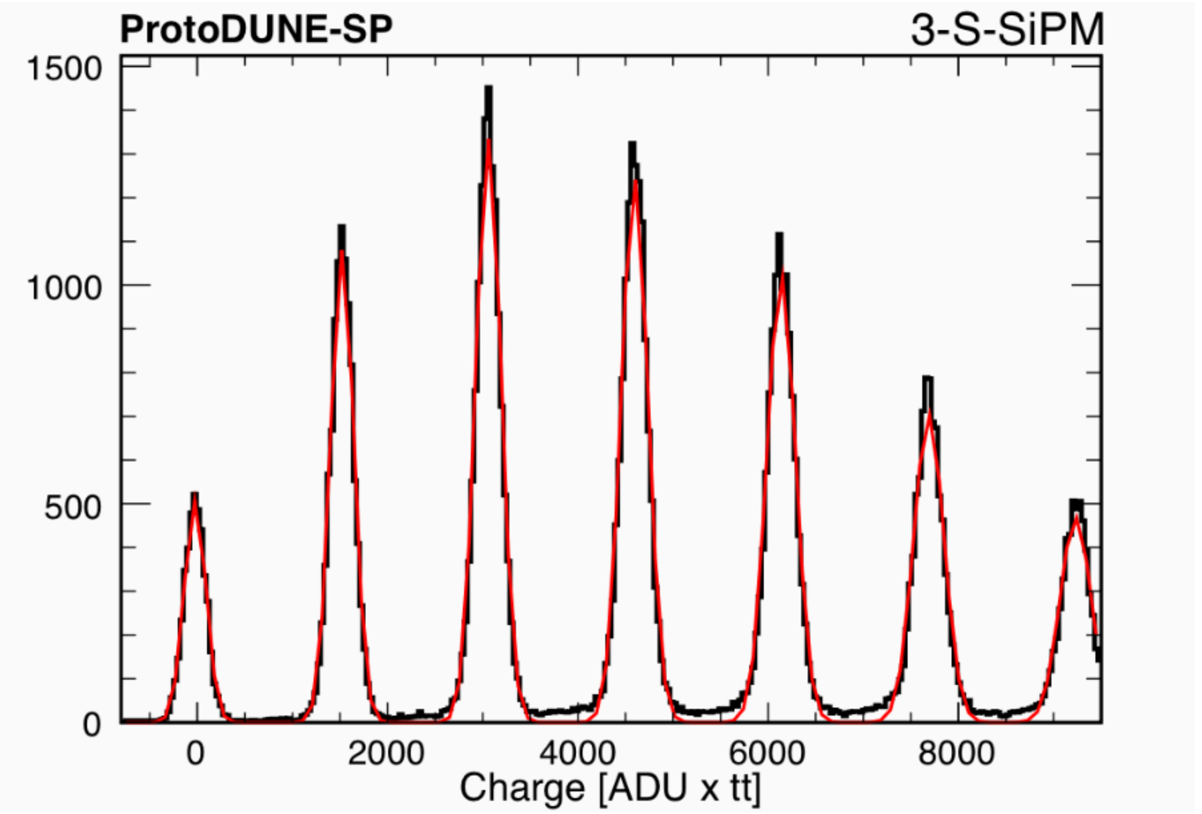
ARAPUCA photoSensors response

12 Hamamatsu MPPC (parallel passive ganging)



LightGuide photoSensors response

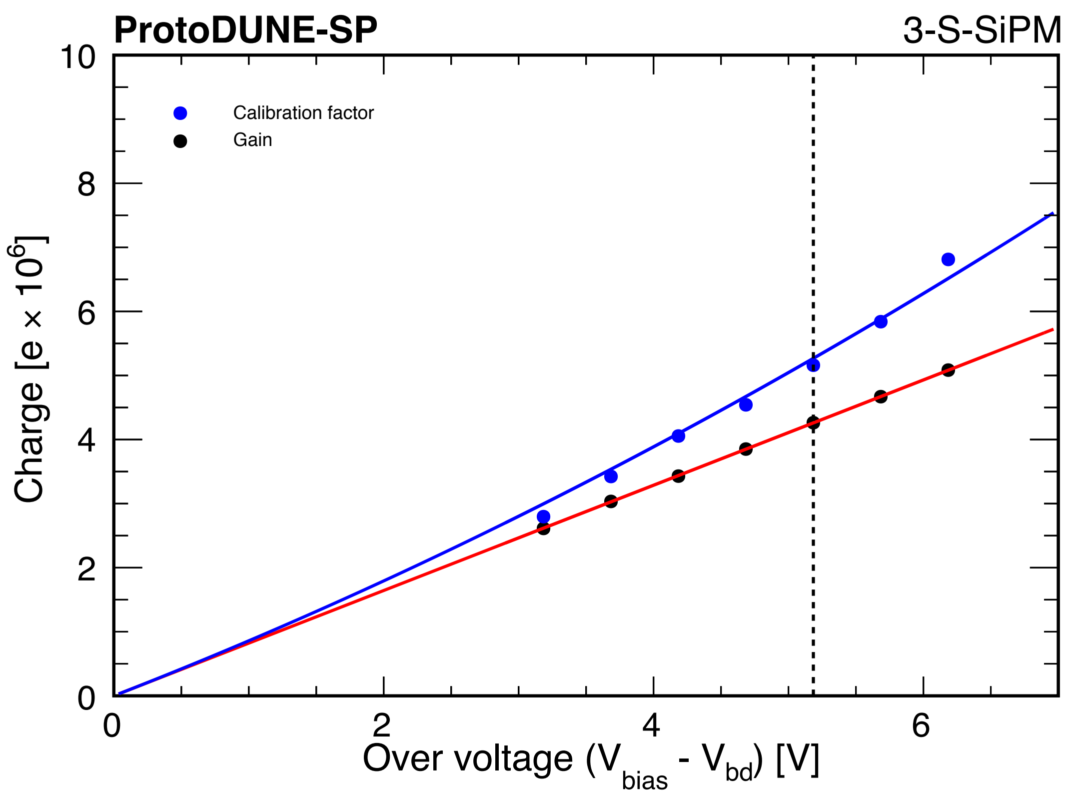
3 SensL SiPM (parallel passive ganging)

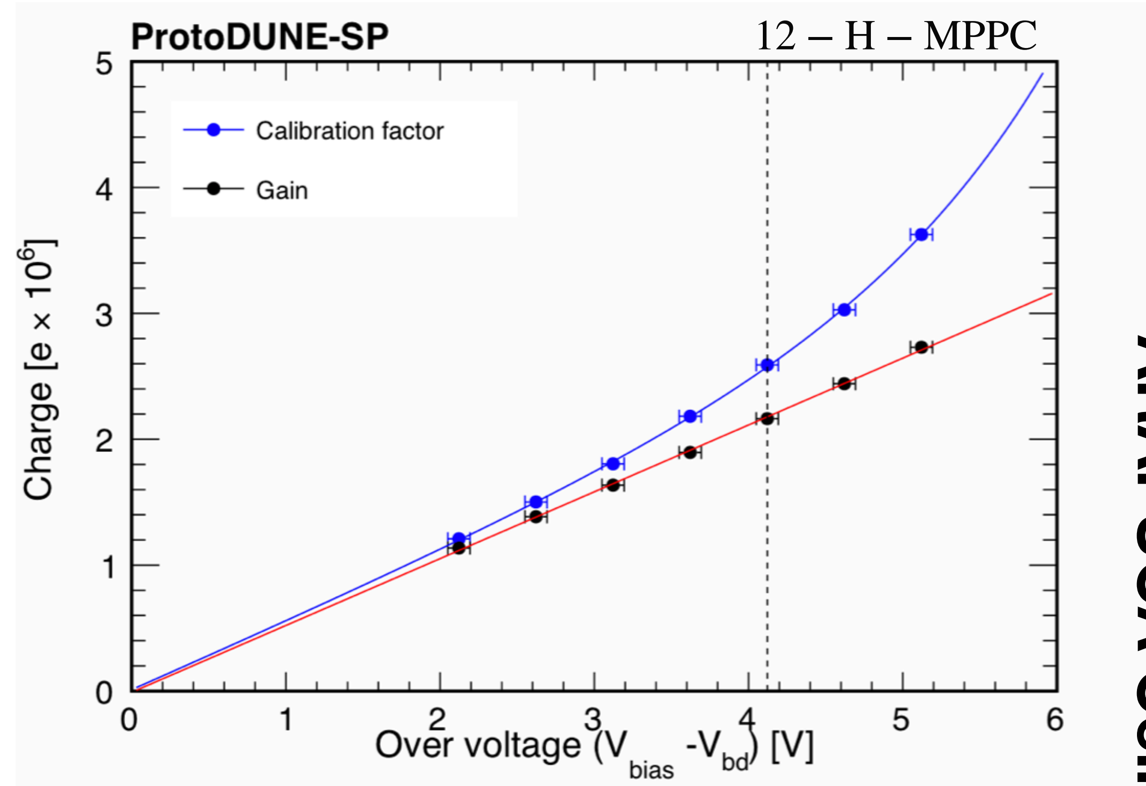


Demonstration of operability of large array of Si photo-sensors into one channel (passive parallel ganging)

PD Calibration

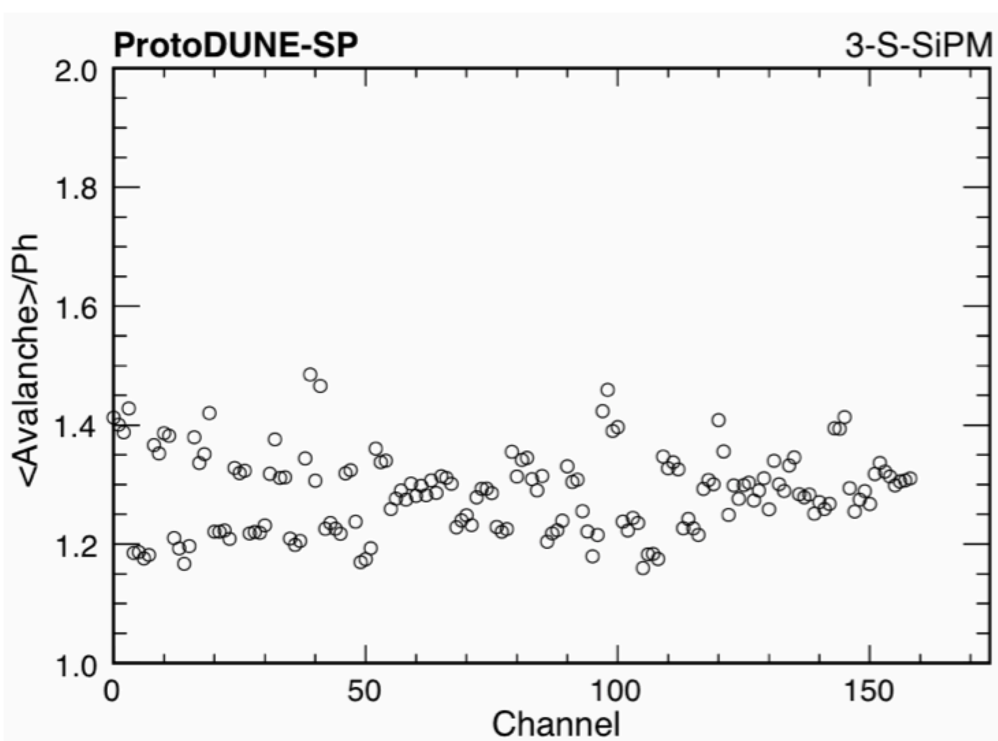
LightGuide Bar photoSensors

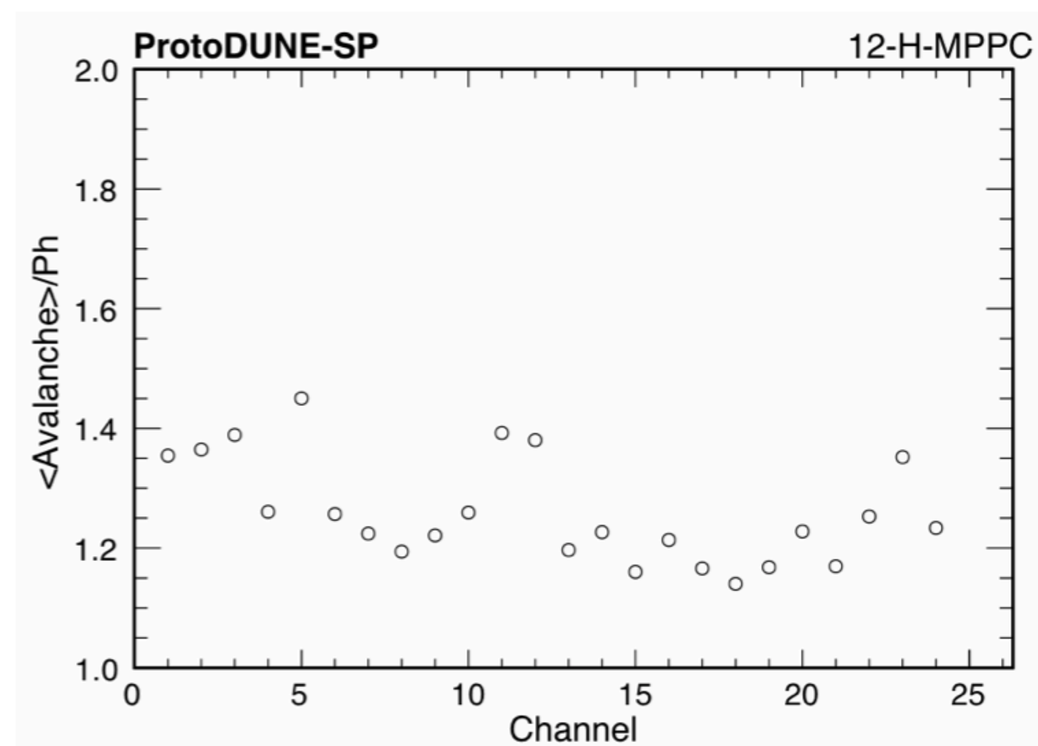


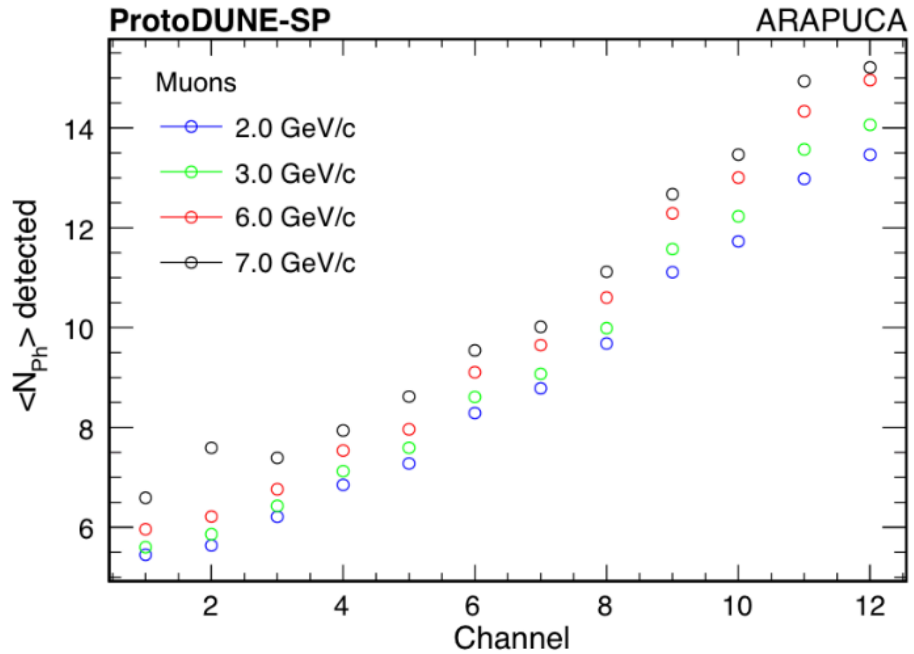


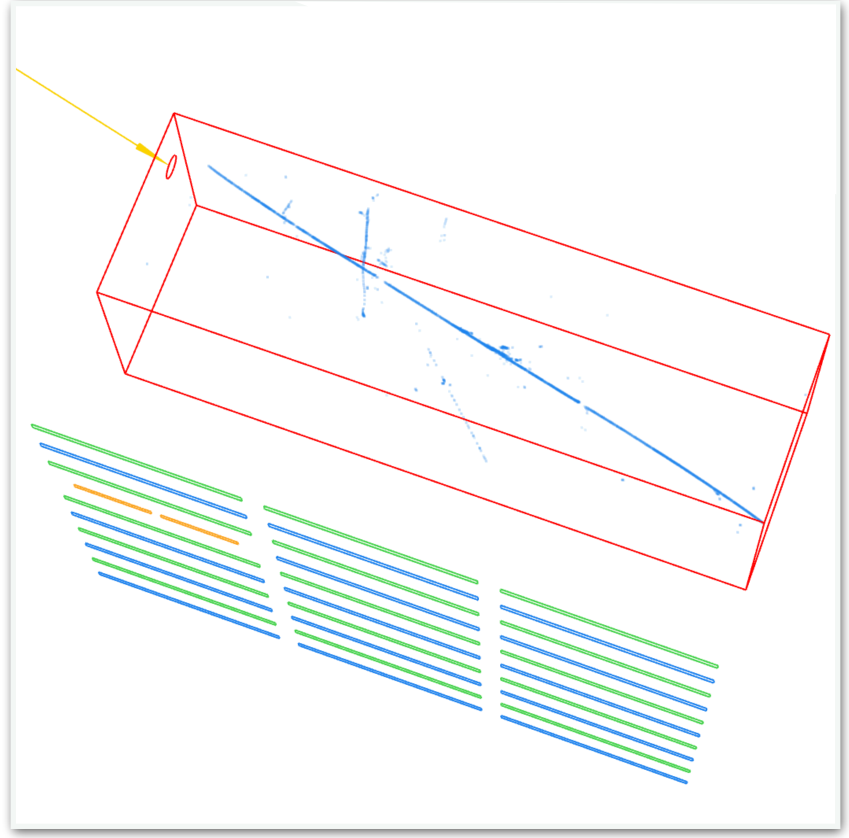
ARAPUCA Cell photoSensors

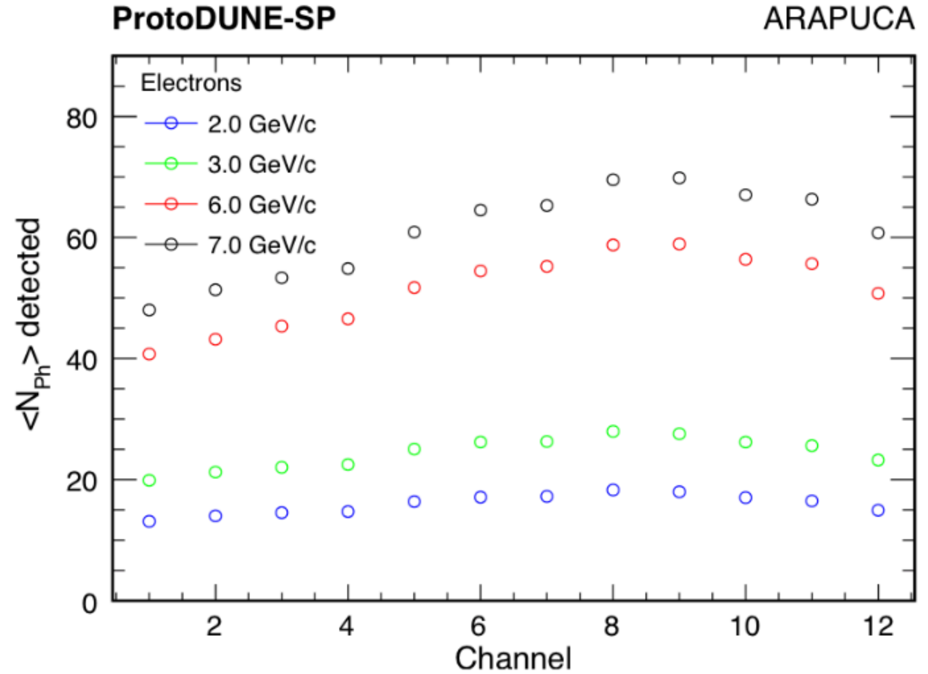
After Pulses and Cross Talk

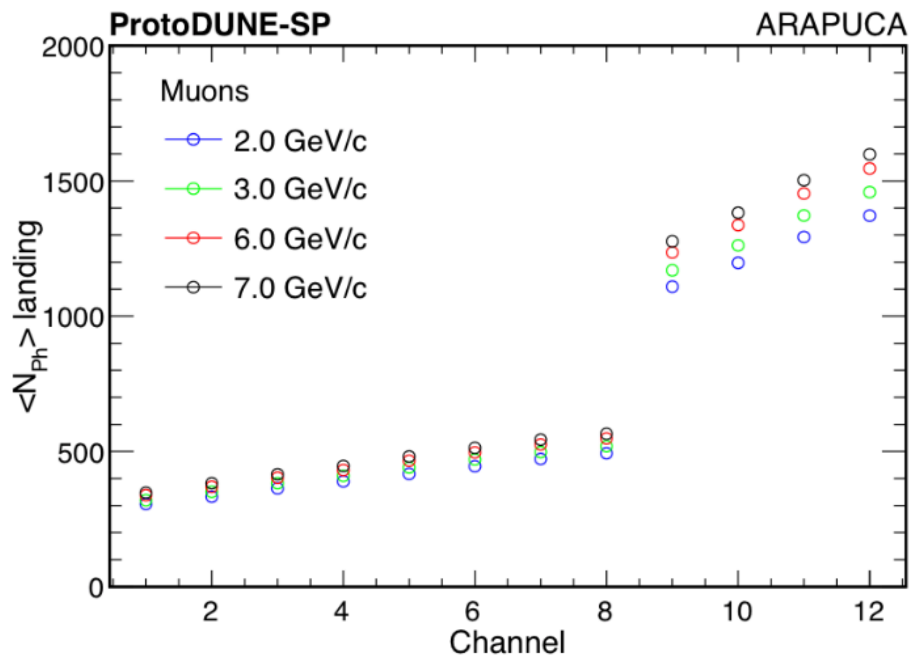




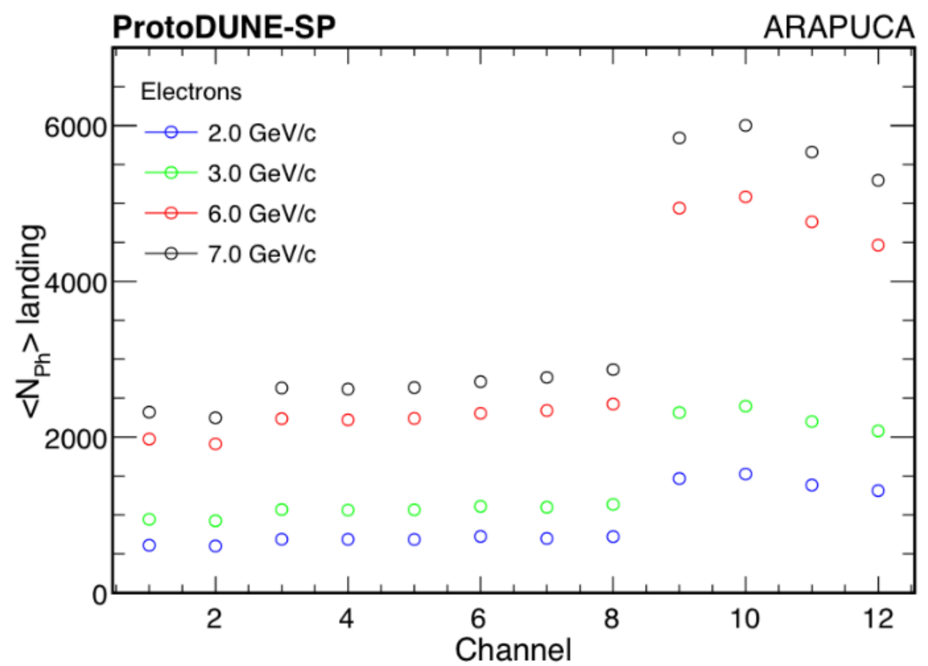


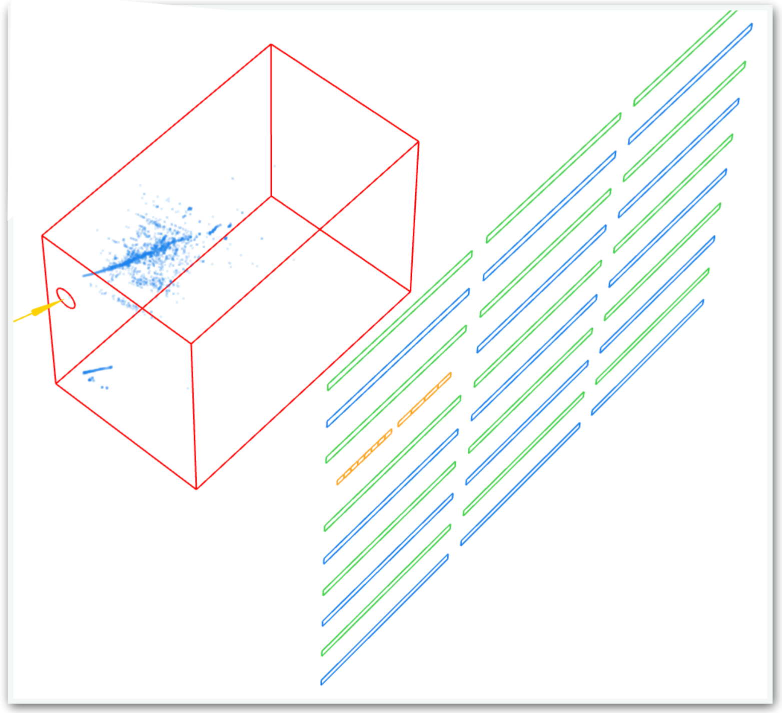


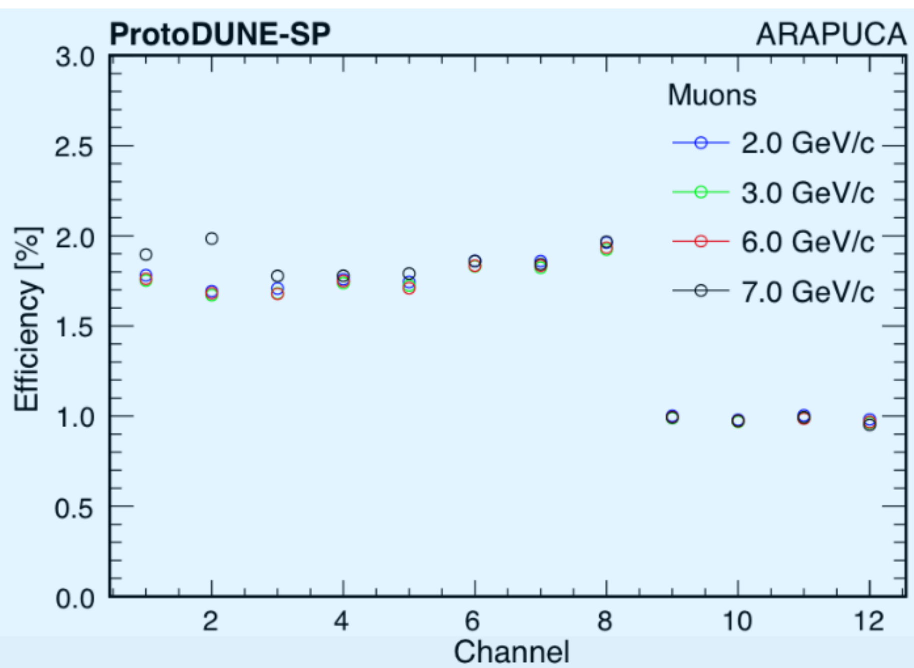




ARAPUCA





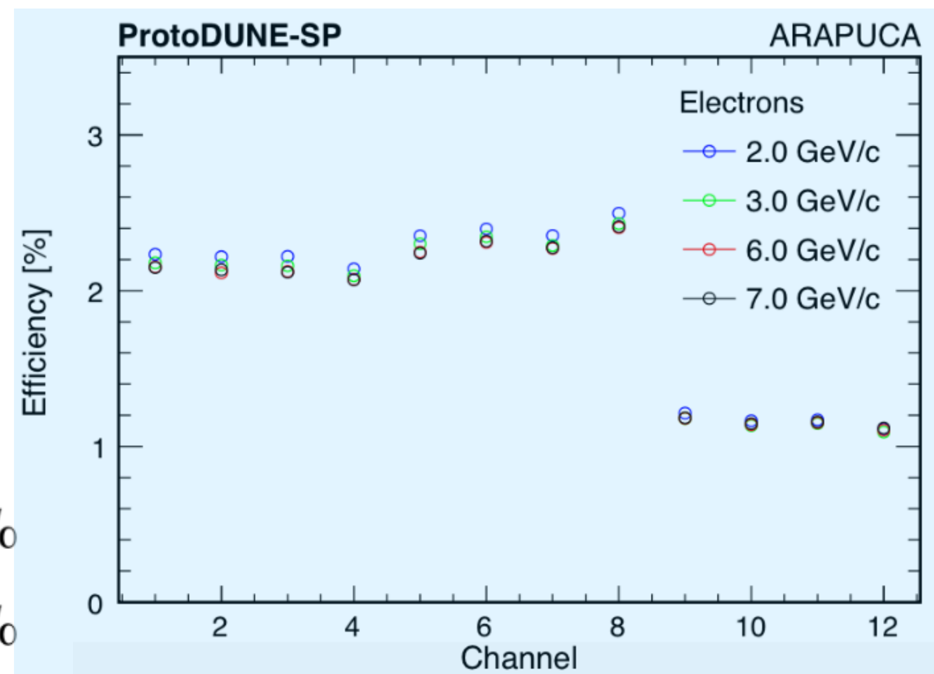


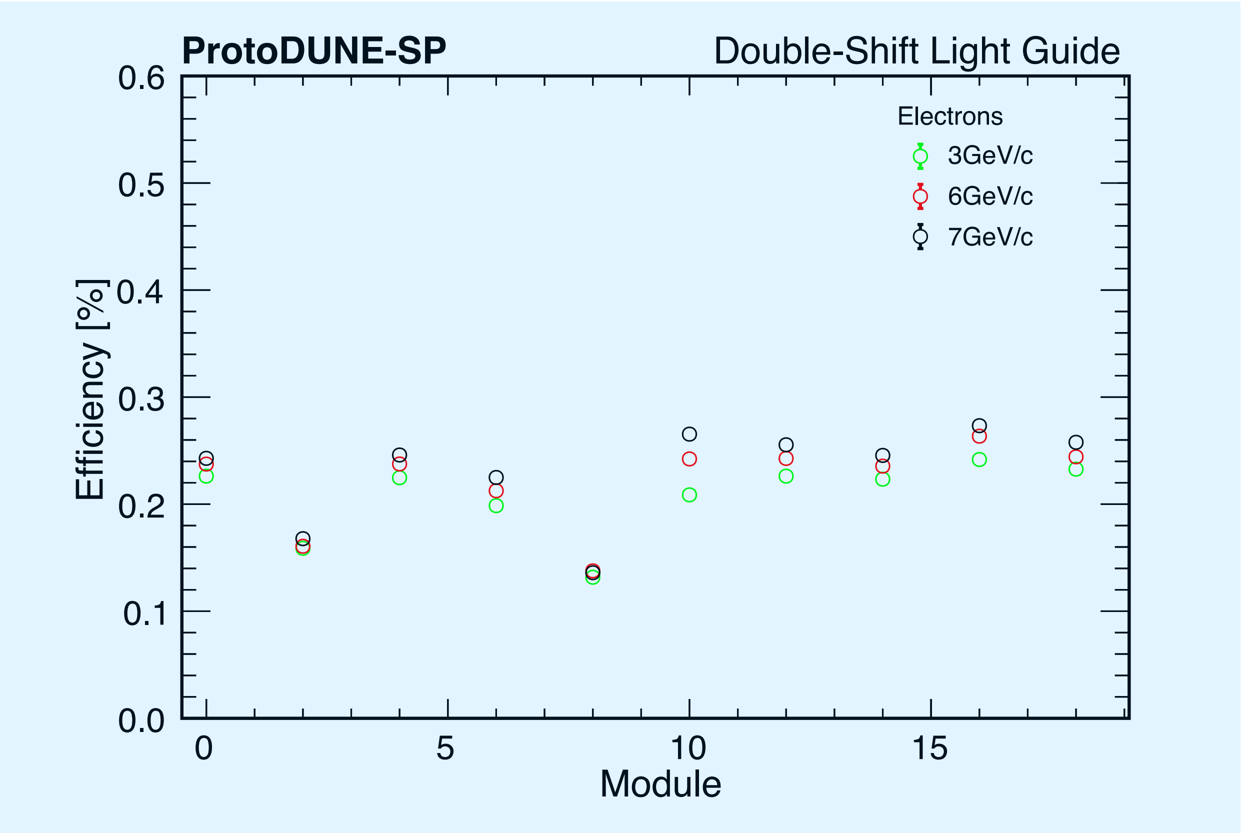
EFFICIENCY

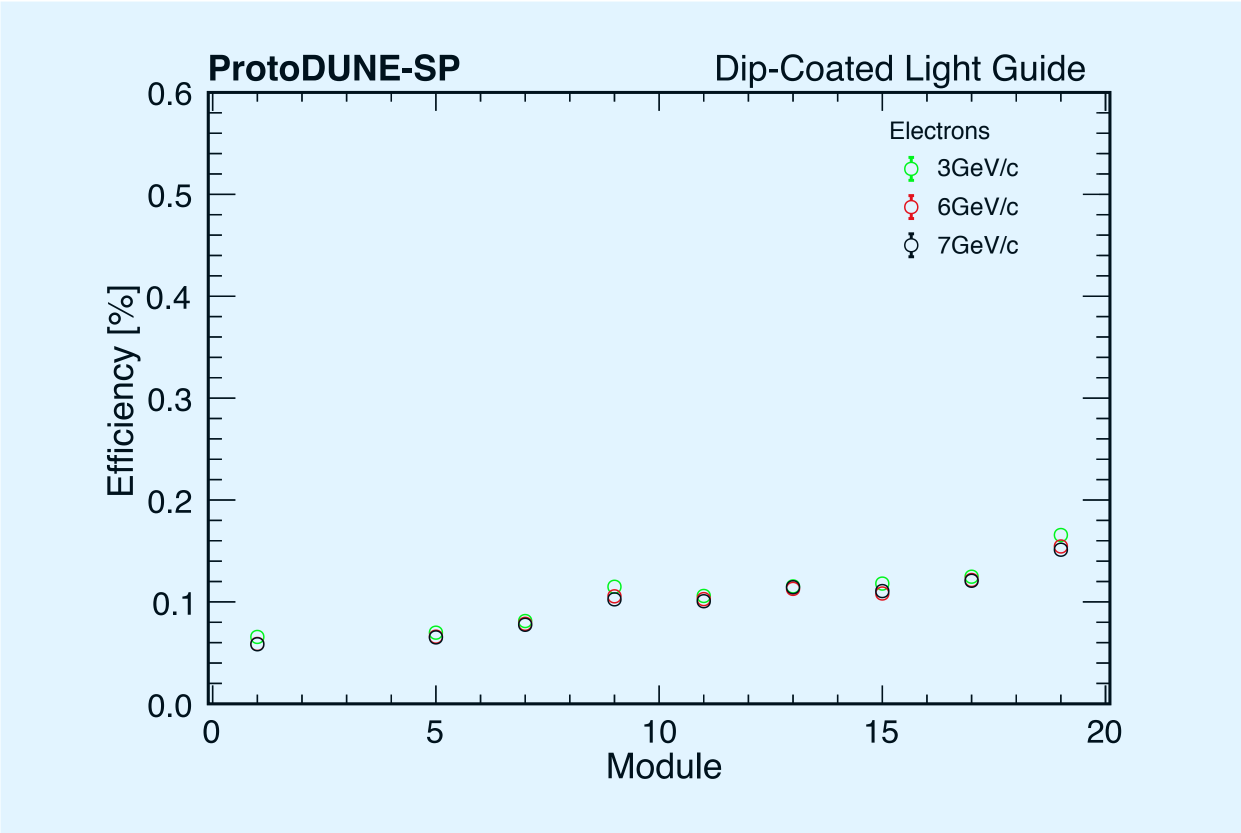
$$\epsilon_j = \frac{\langle N_j^D \rangle}{\langle N_j^L \rangle}$$

cell type−1 ; $\tilde{\epsilon}_1 = (2.00 \pm 0.25)\%$

cell type−2 ; $\tilde{\epsilon}_2 = (1.06 \pm 0.09)\%$







DOUBLE-SHIFT LIGHT GUIDE

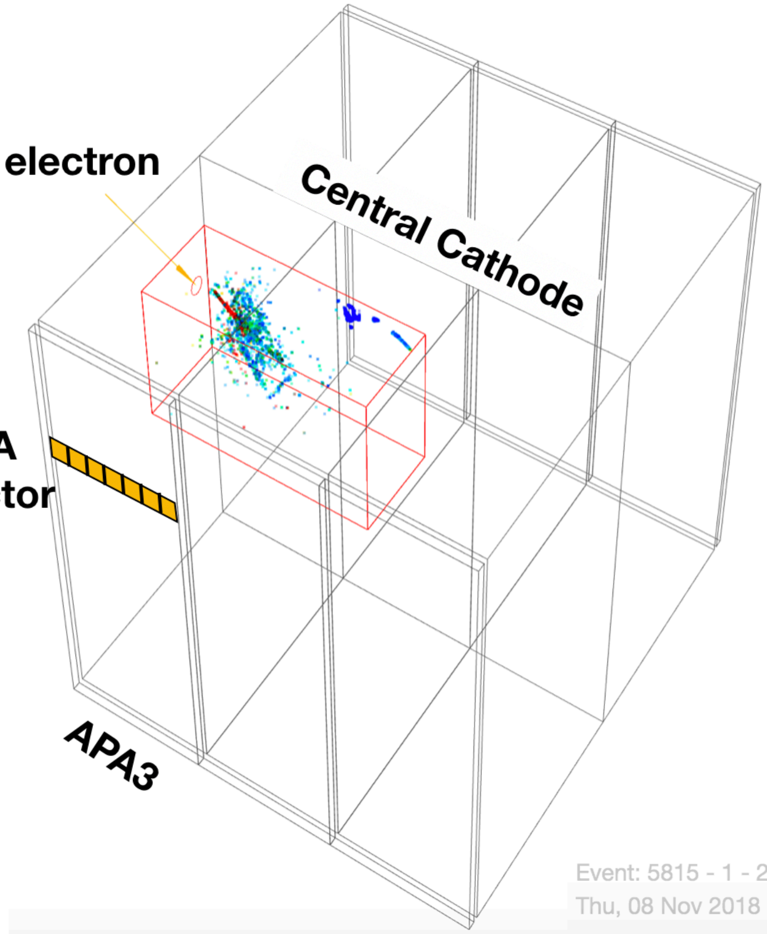
DIP-COATED LIGHT GUIDE

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

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

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

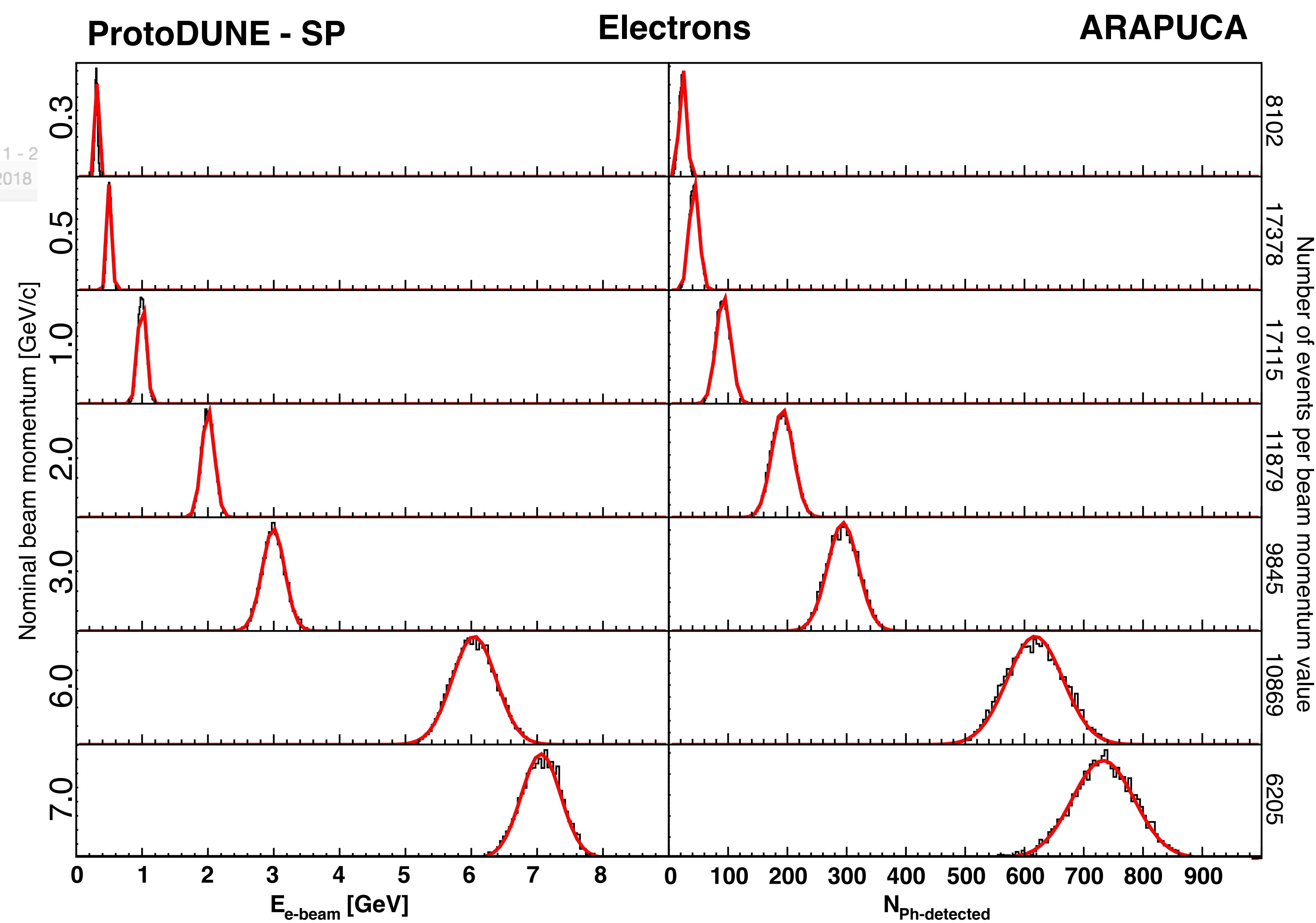
Large LAr detector operating at
the CERN Neutrino Platform



Operating on the H4-VLE charged particle test beam offers a first ever opportunity to directly probe the calorimetric response to EM and hadronic showers in the sub- to few-GeV momentum range from *light signal*

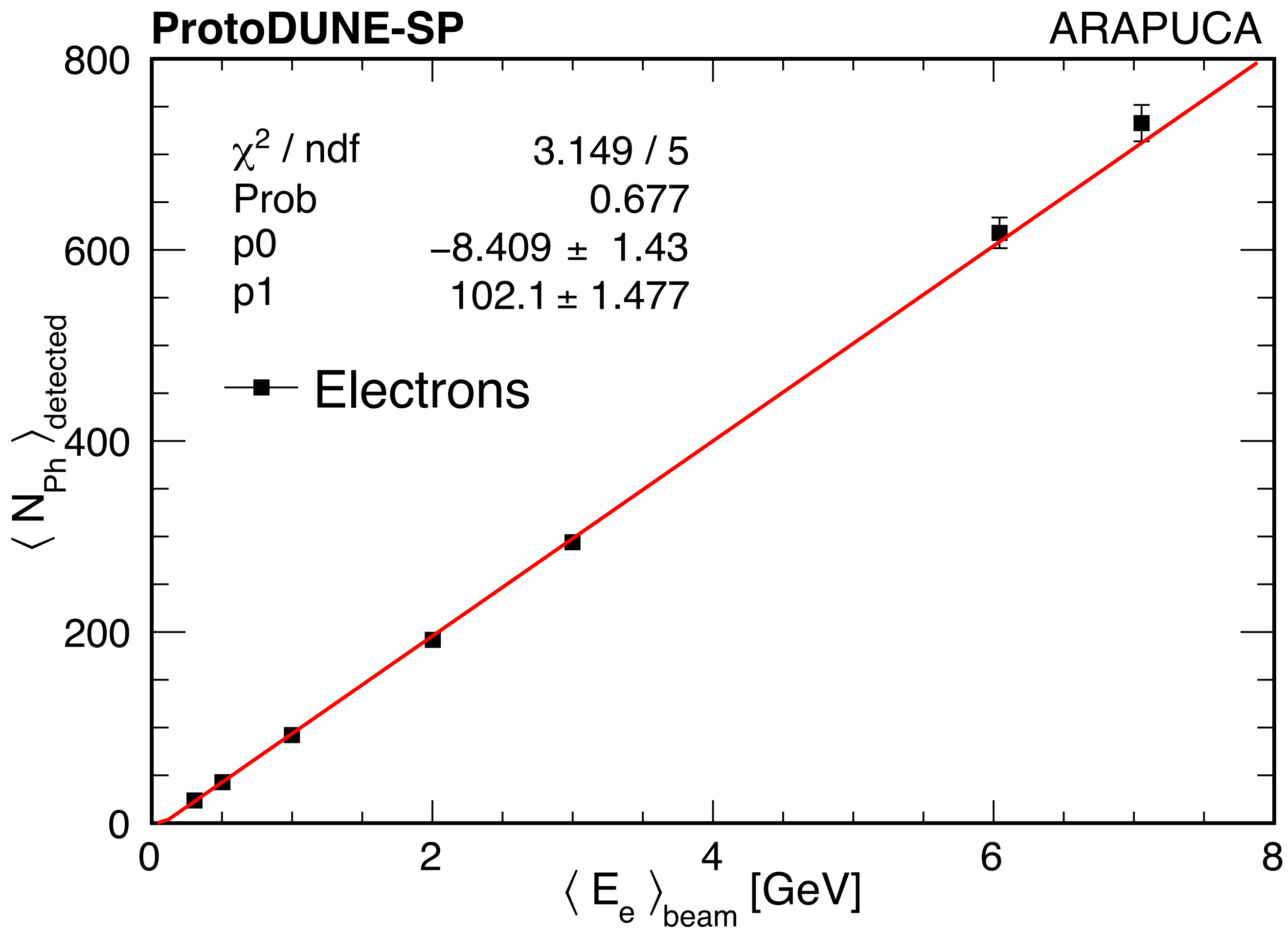
calorimetric response from Light signal from a single ARAPUCA module (~0.5‰ photo-sensitive area coverage)

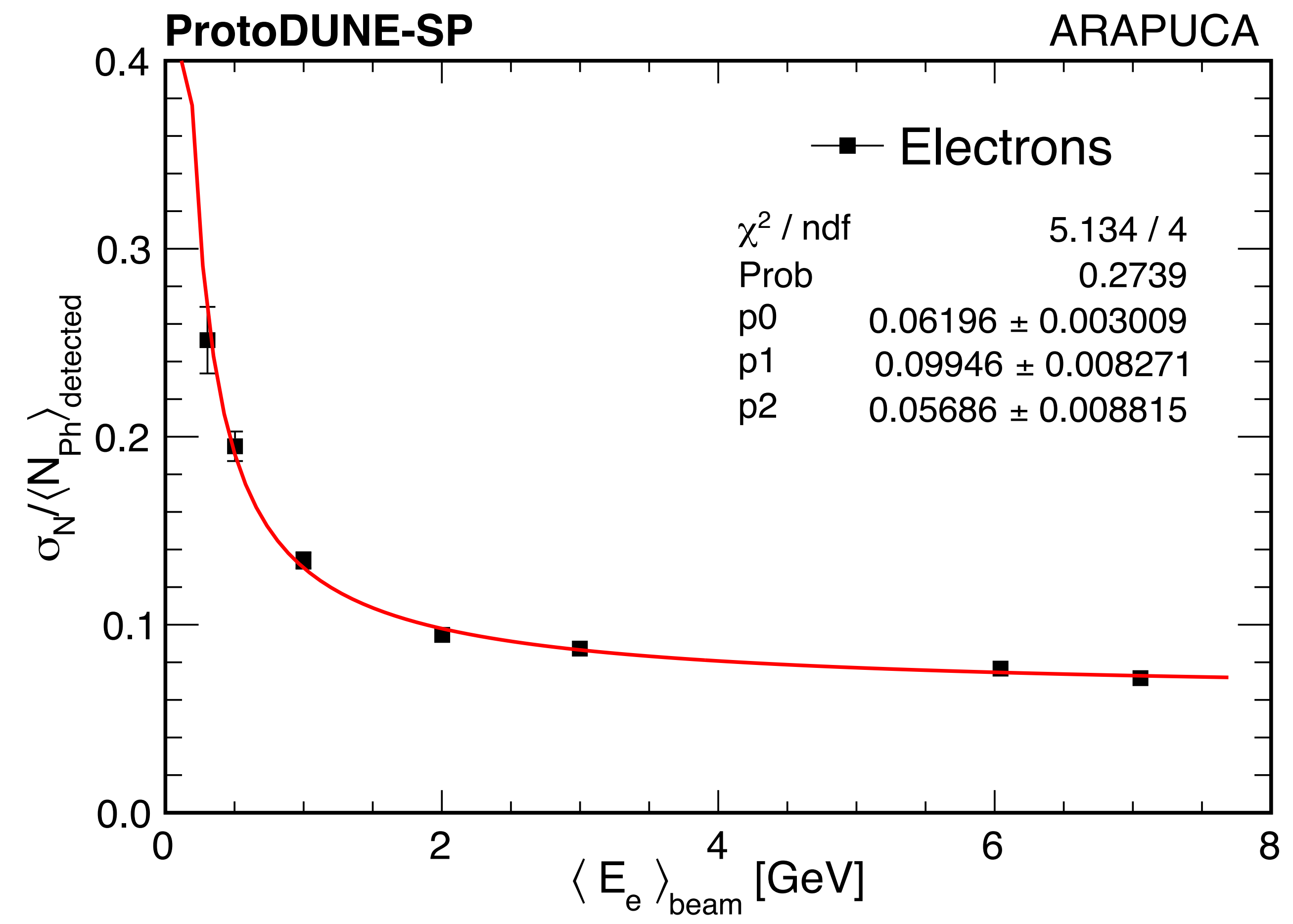
EM shower at ~3 m distance in the x (drift) direction



Incident Electron momentum distribution

detected photons spectra





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

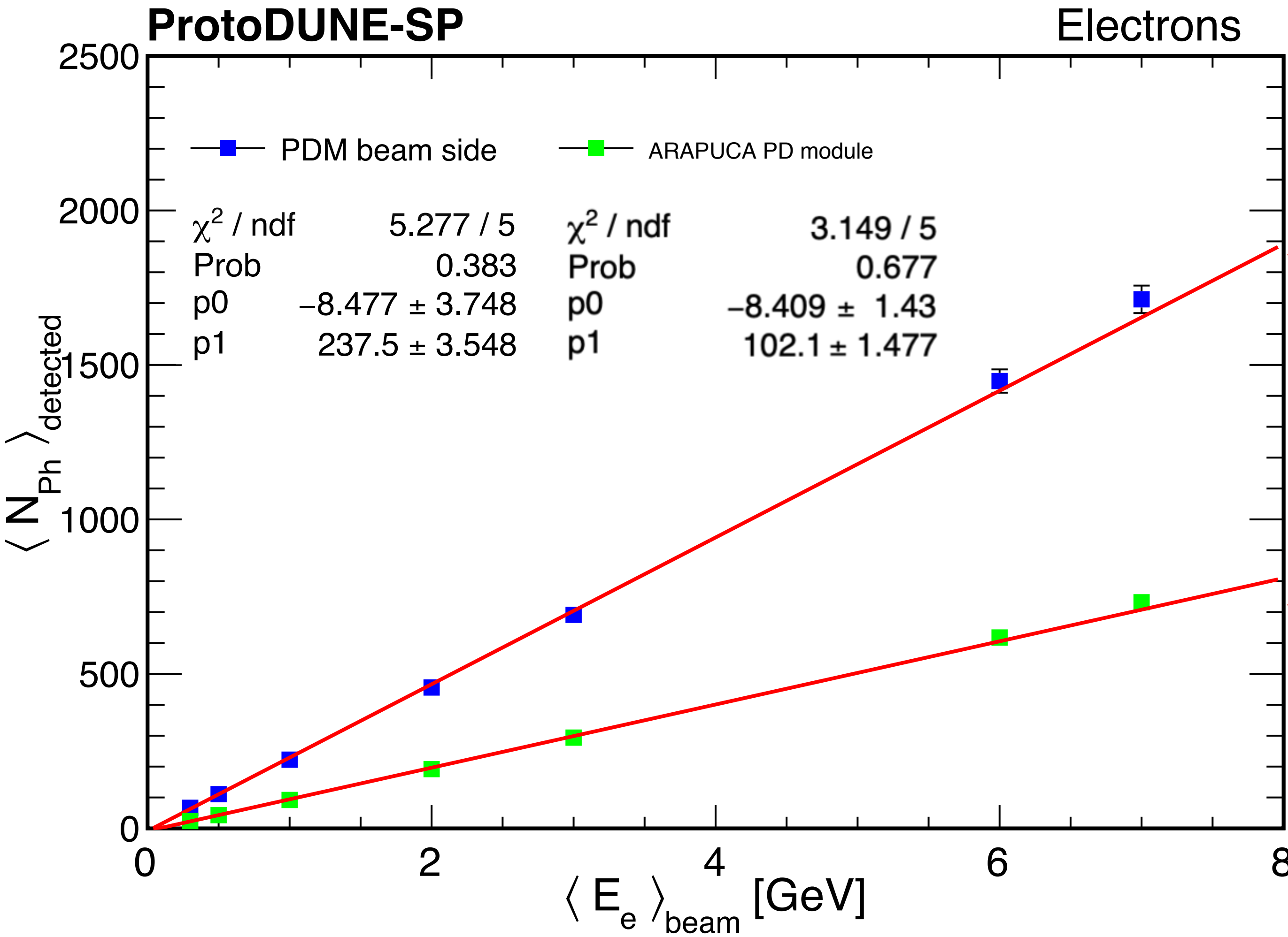
$$E_o = 82 \pm 14\ MeV$$

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:** $p_2 = 55\ MeV$
  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)



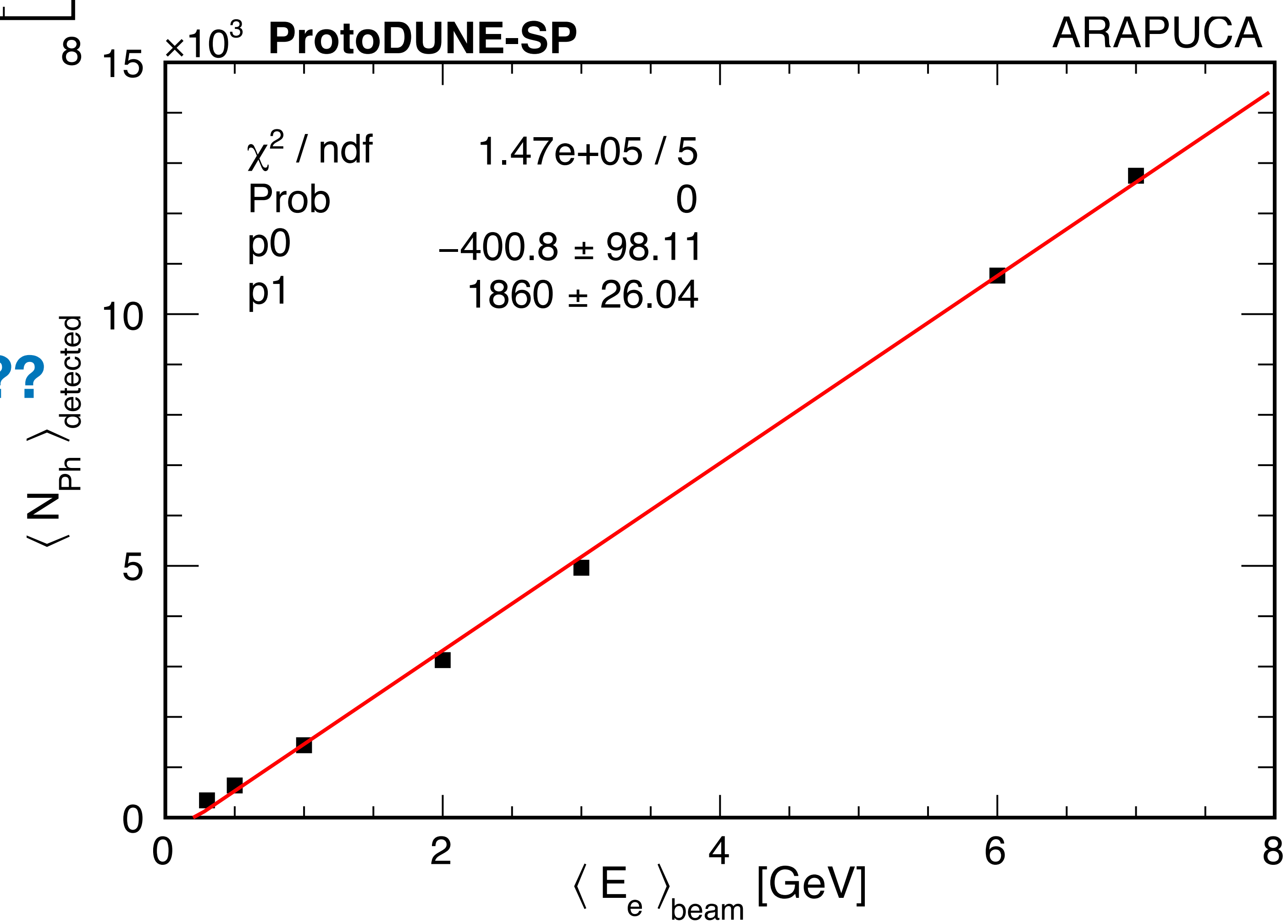
$LY = 237\ Ph/GeV$

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: $N_{ph} \cdot \dfrac{\epsilon_{Arapuca}}{\epsilon_{LightGuide}}$



$LY = 1.9\ Ph/MeV$ **@ 3m distance**

(LY ~7-8 ph/MeV at centre of TPC)

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*

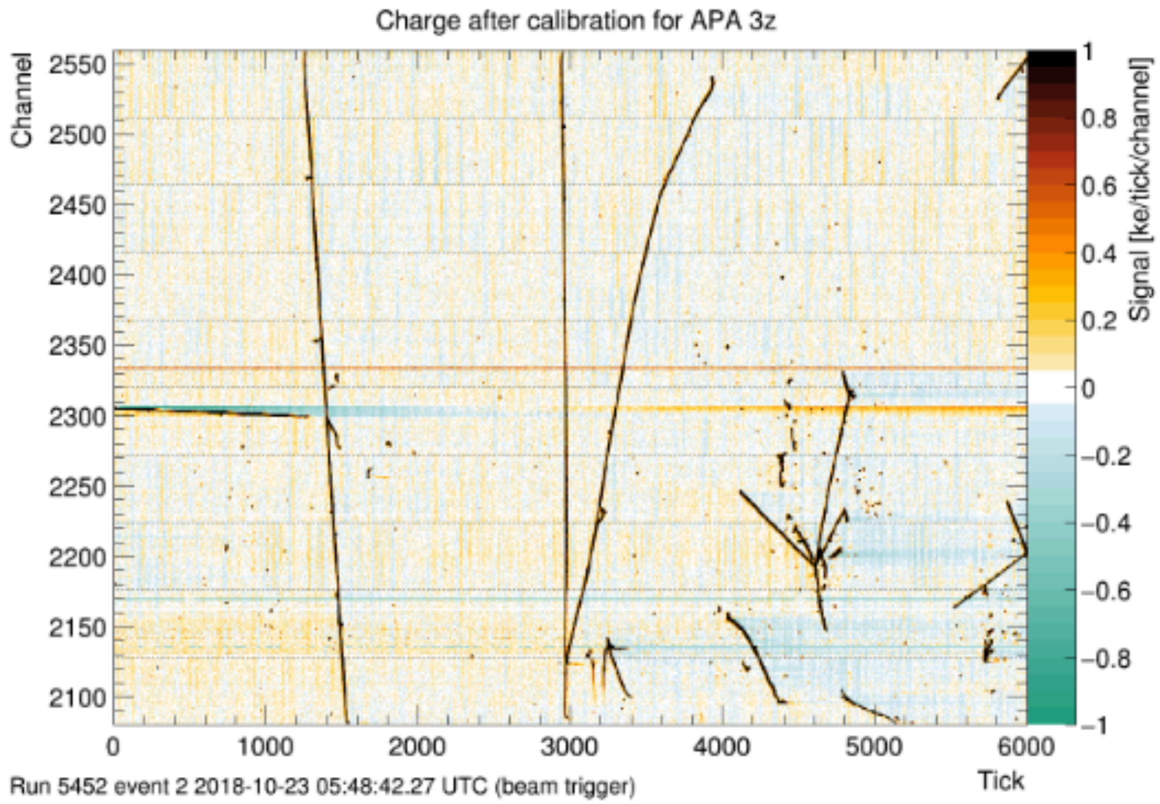
Information for DUNE physics TDR

- **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.

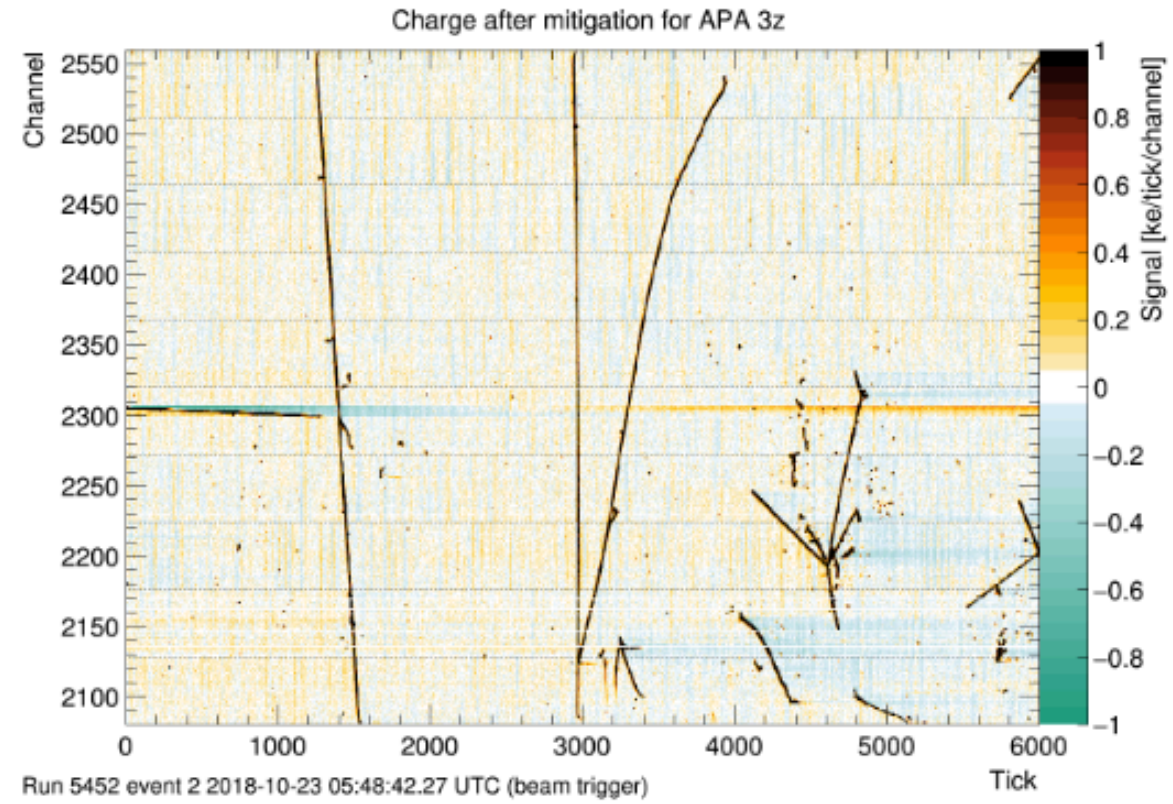
(NEVER MEASURED)

Physics publications

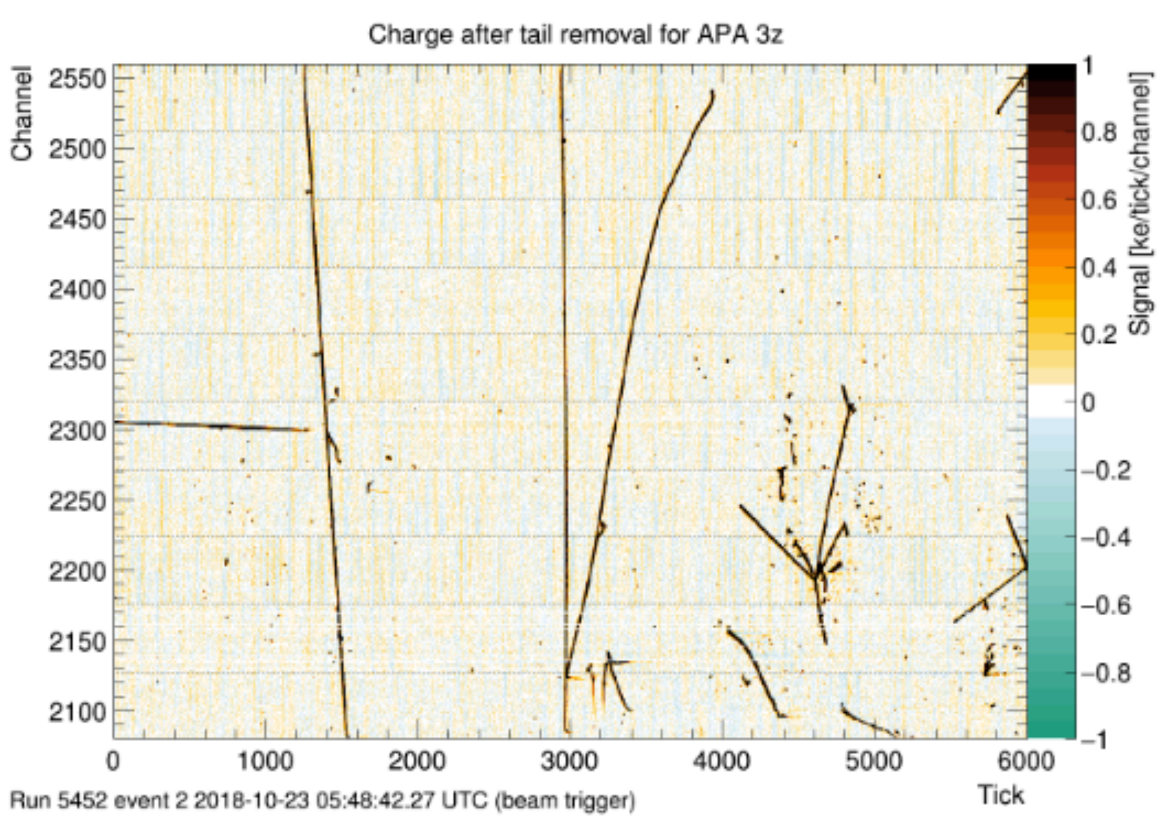
stages of data processing and noise mitigation



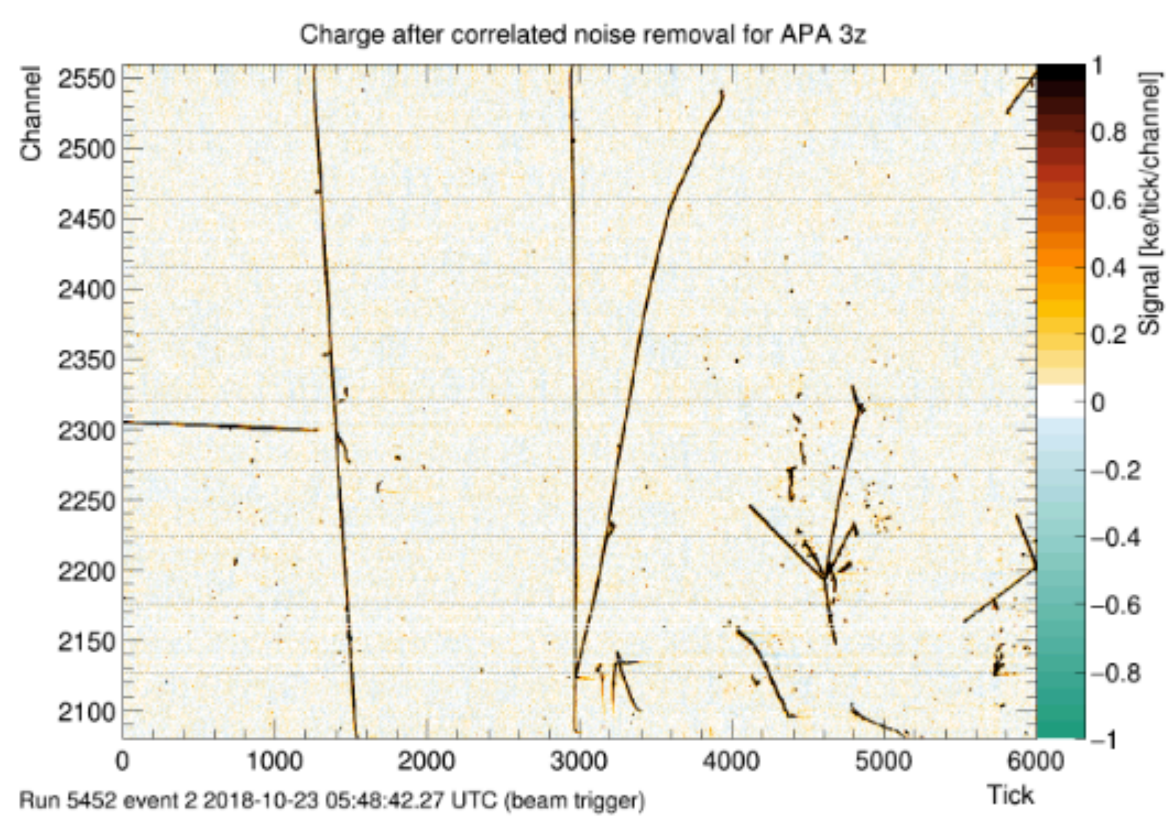
(a) After pedestal subtraction and calibration.



(b) After mitigation (Sticky code)



(c) After tail removal.



(d) After correlated noise removal.

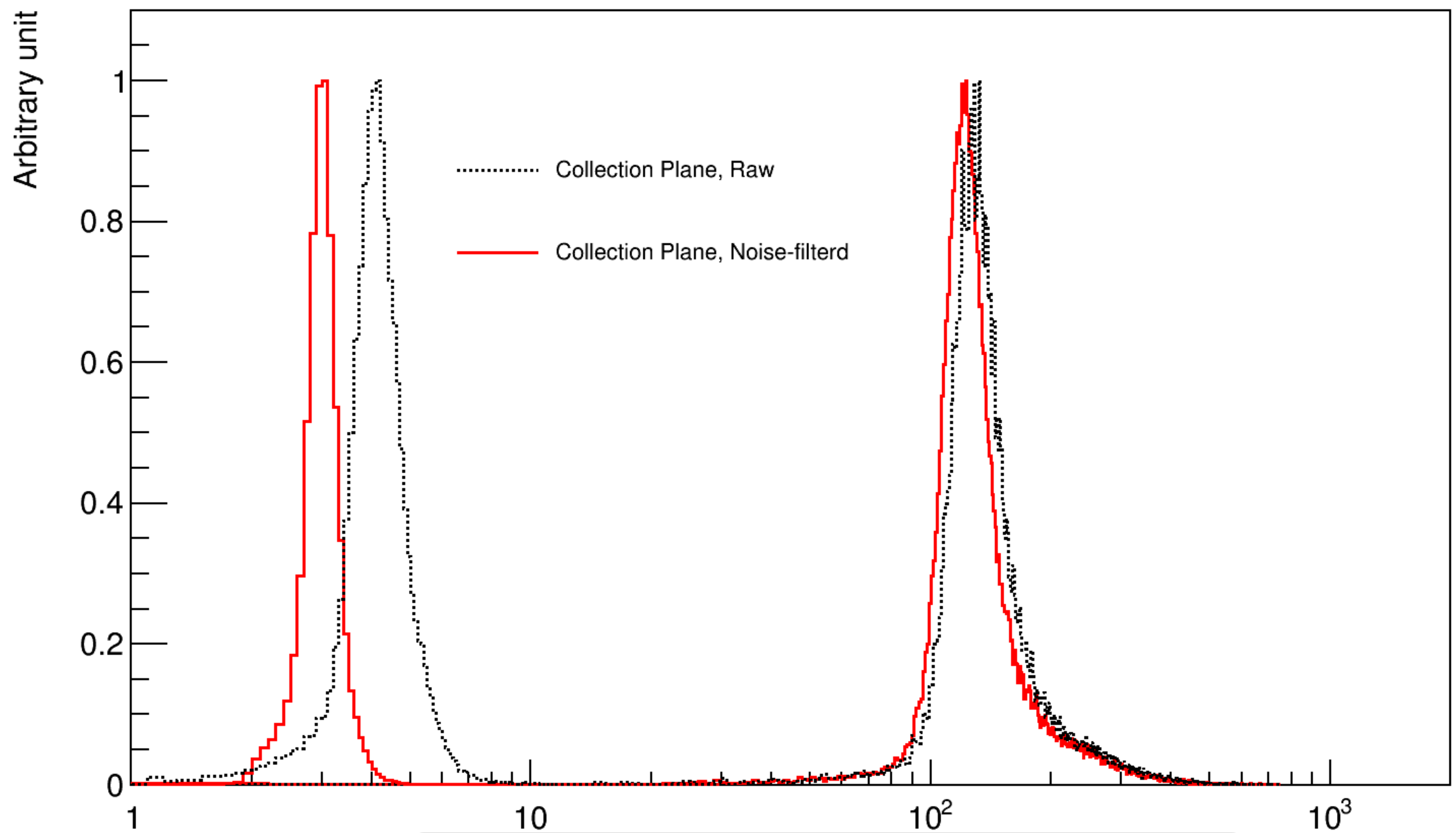
TPC + CE Performance (1):

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

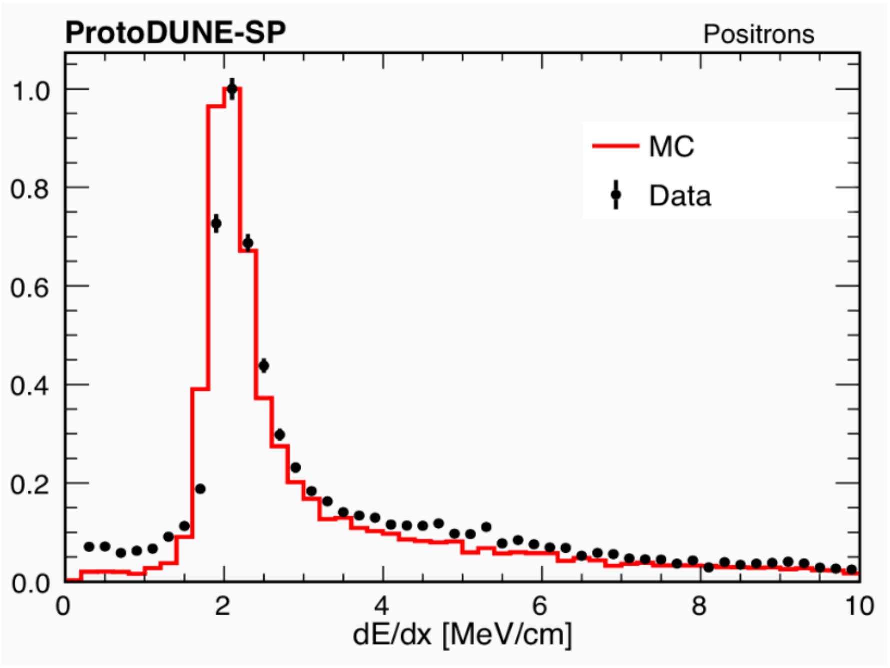
Noise: σ of baseline fluctuation in corresponding channel waveform

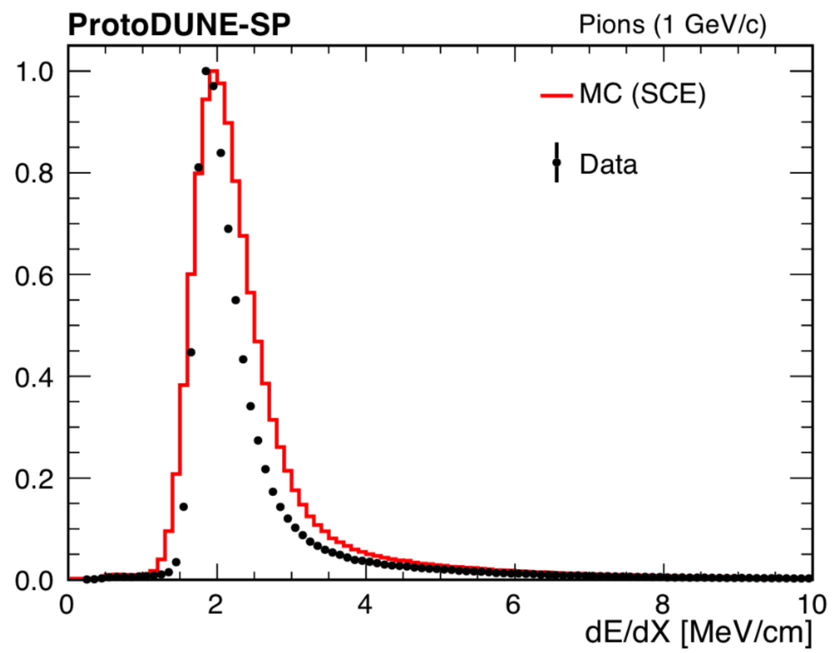


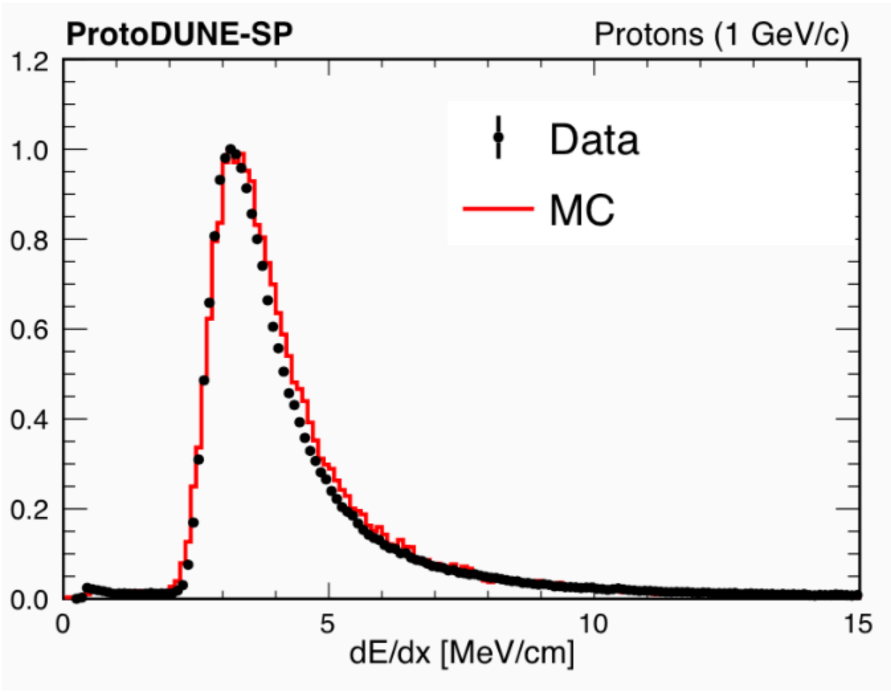
Plane	Peak signal-to-noise ratio			
	Raw Data		After Noise Filtering	
	MPV	Average	MPV	Average
Collection	30.9	38.3	40.3	48.7
U	12.1	15.6	15.1	18.2
V	14.9	18.7	18.6	21.2

160e/ADC

Beam Data - Calibration







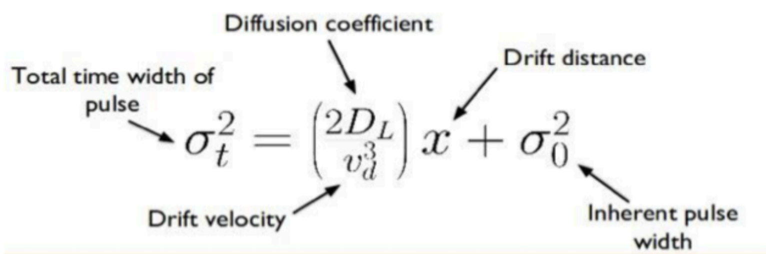
Resolution in DATA appears better than in MC

dE/dx width is found to depend on diffusion constants

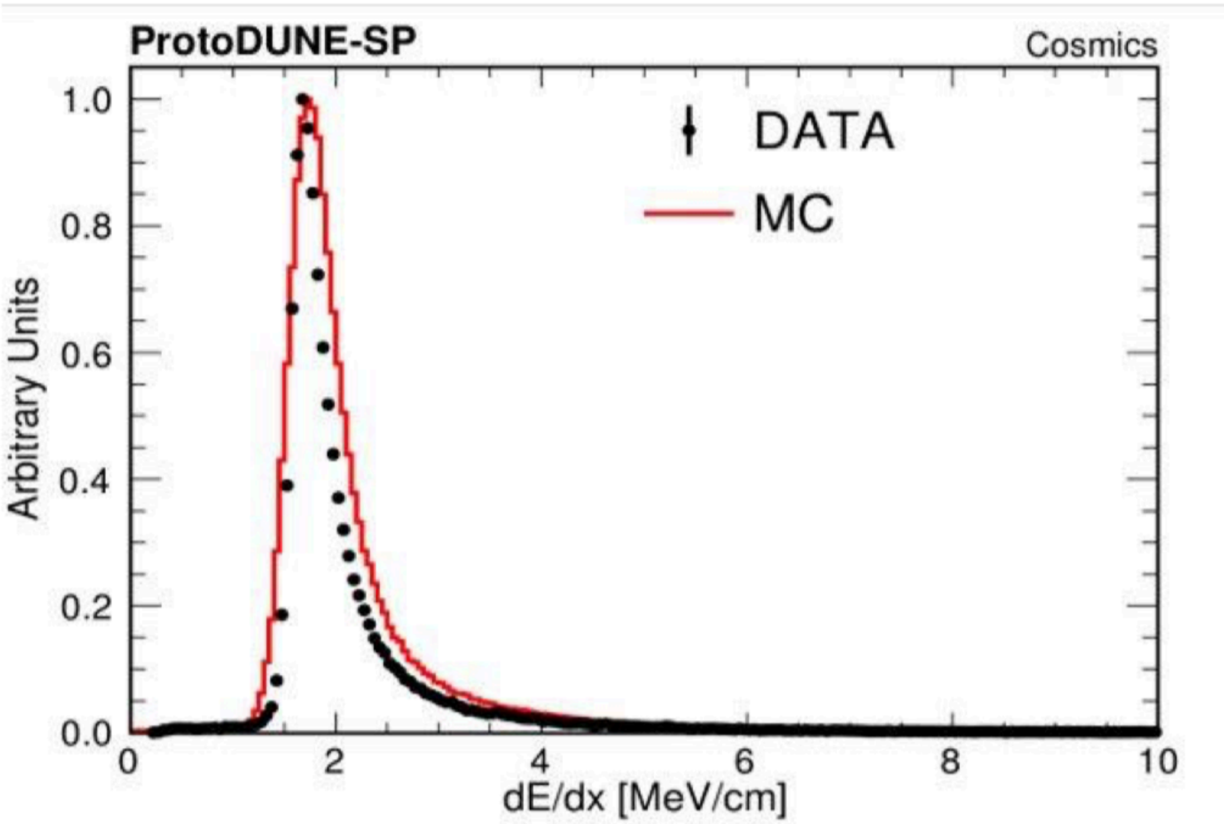
Diffusion Coefficient(s)

dE/dx width is found to depend on diffusion constants

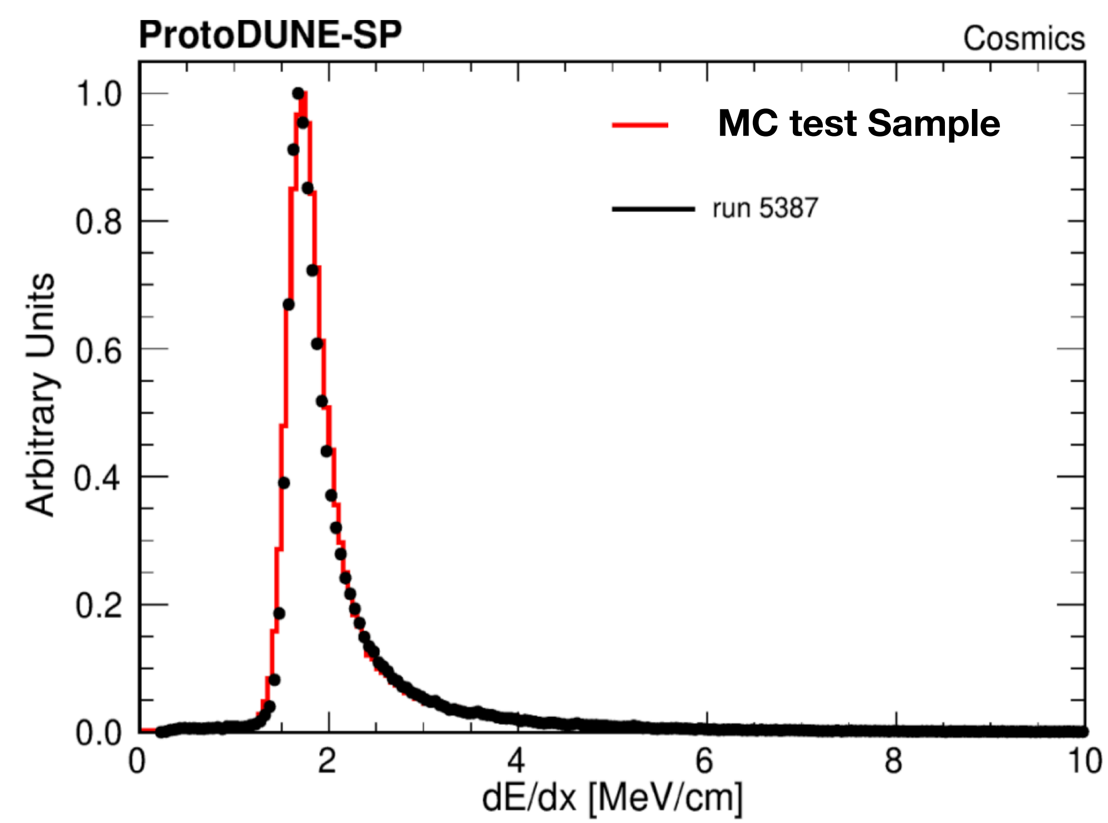
Stopping muon dE/dx distributions for the ProtoDUNE-SP cosmic data and MC.



longitudinal diffusion of 6.2cm^2/sec



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

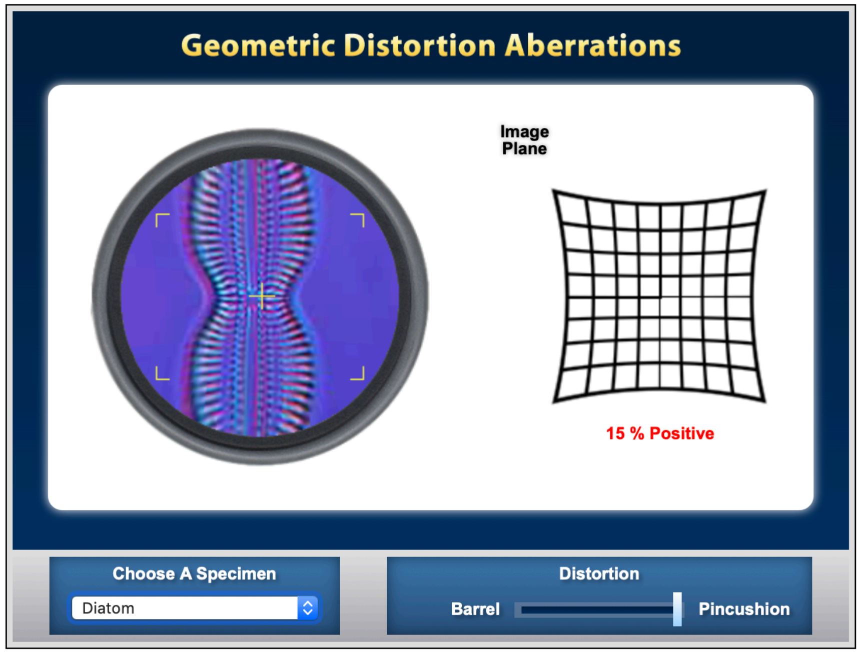


Diffusion in data appears to be less than in simulation

Space Charge & Fluid Flow

Effect of Space Charge accumulation in Drift Volume:

Geometric Distortion Aberration

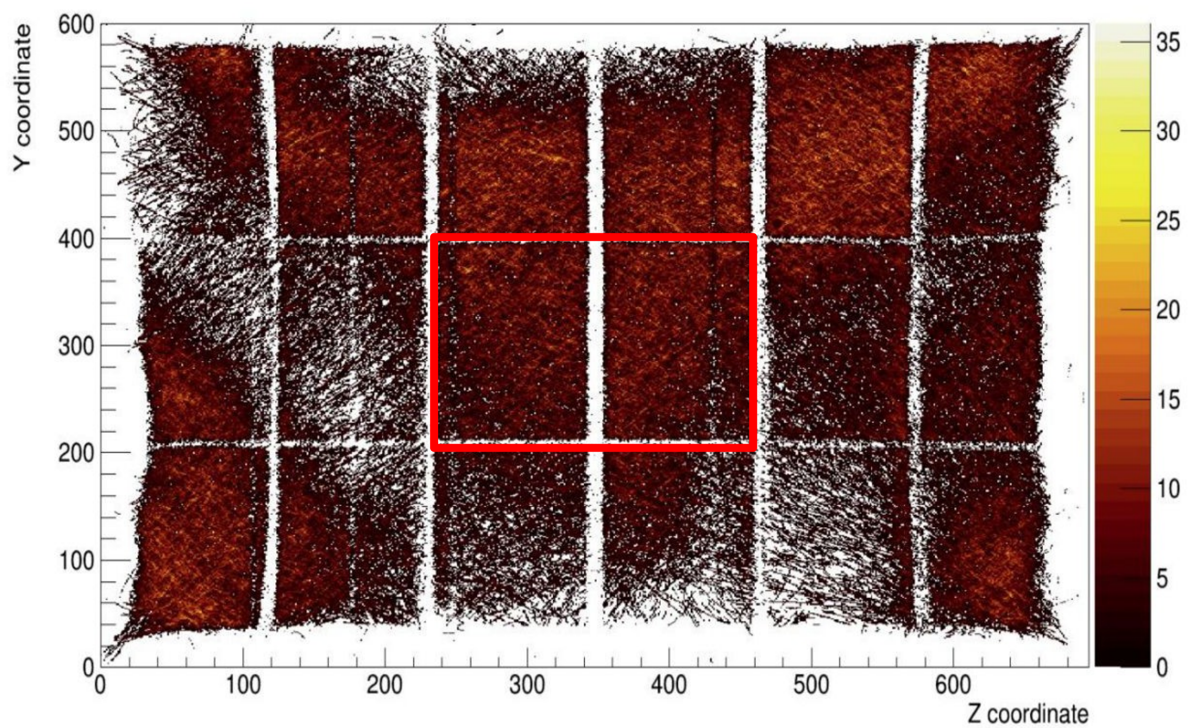


Track selection

Select tracks that are contained within the central part of the TPC, where distortion along y and z axes are negligible

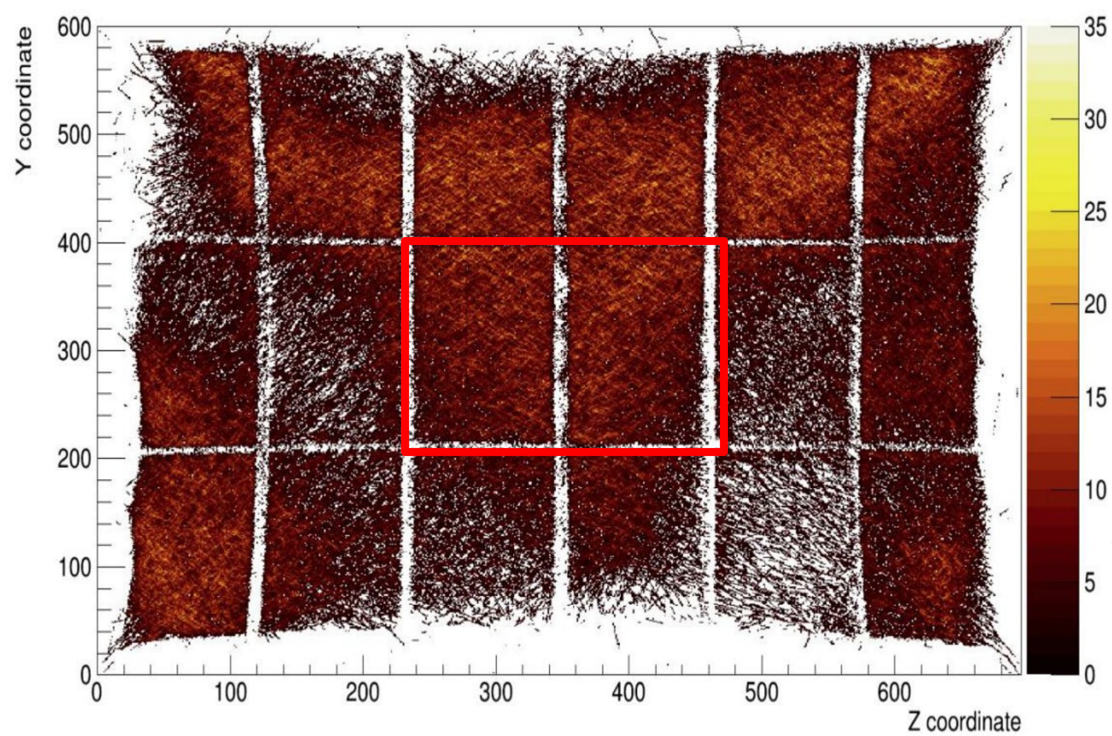
tomographic imaging

Number of hits for YZ plane for X=-3cm to X=0cm

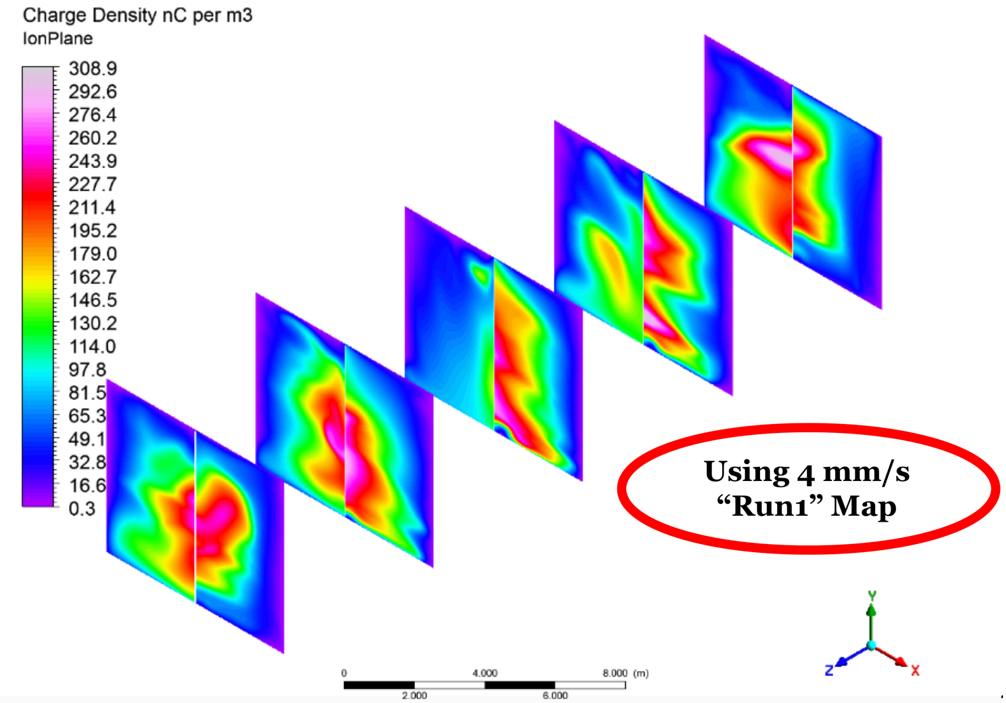


Beam right

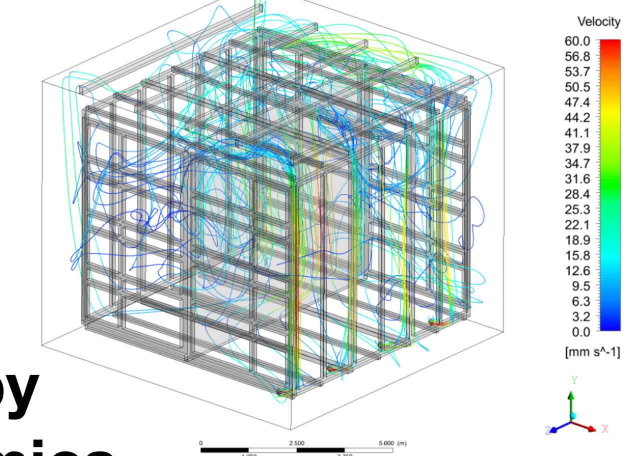
Number of hits for YZ plane for X= 0 cm to X=3cm



Beam left

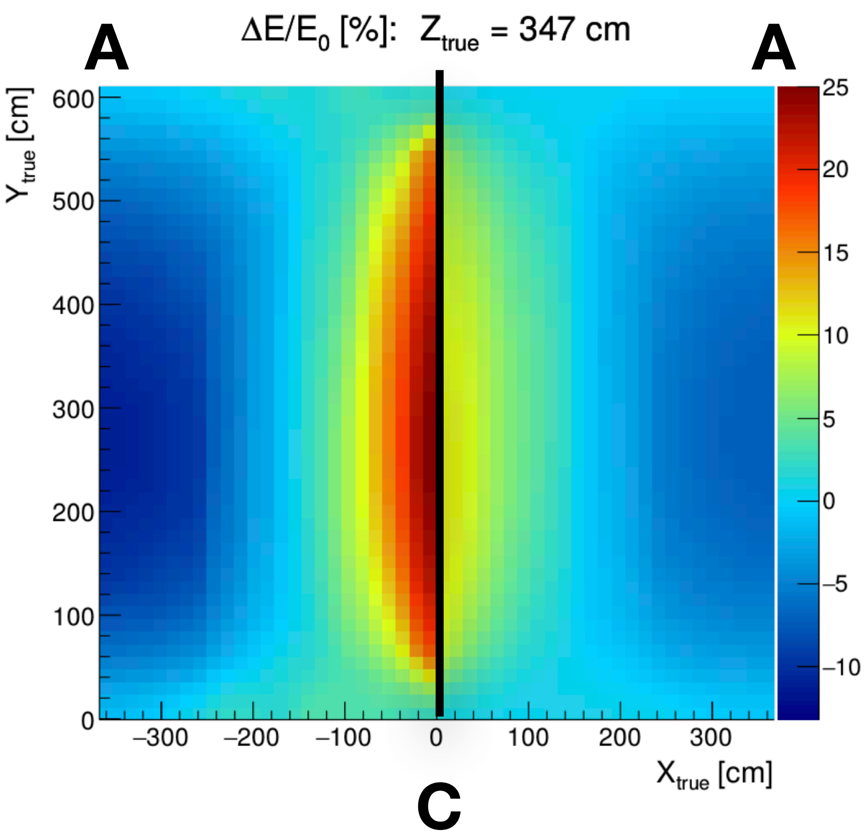


Fluid Flow

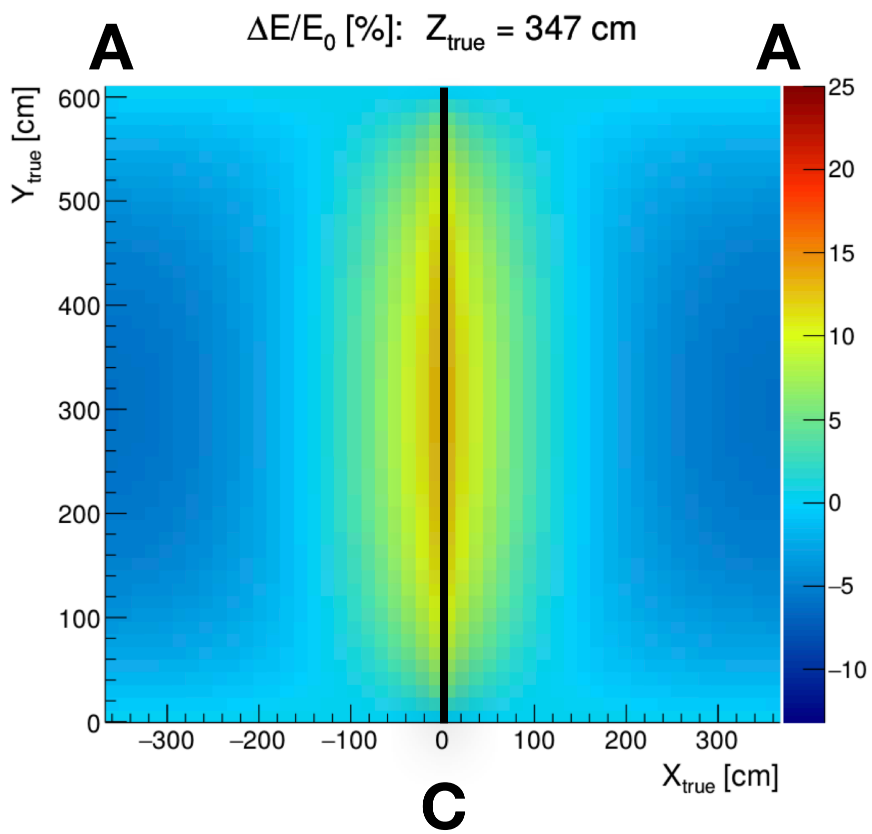


Calculation/Simulation by Computational Fluid Dynamics Methods

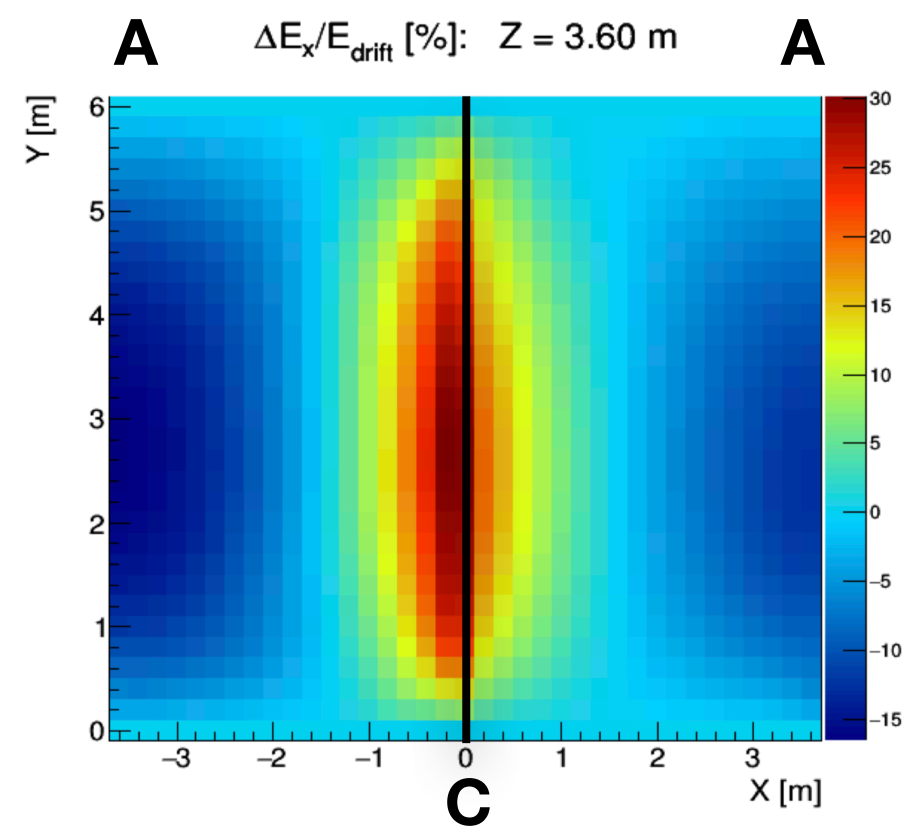
DATA



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")

ProtoDUNE-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**
- ☑ **Demonstrating long term operational stability of the detector**

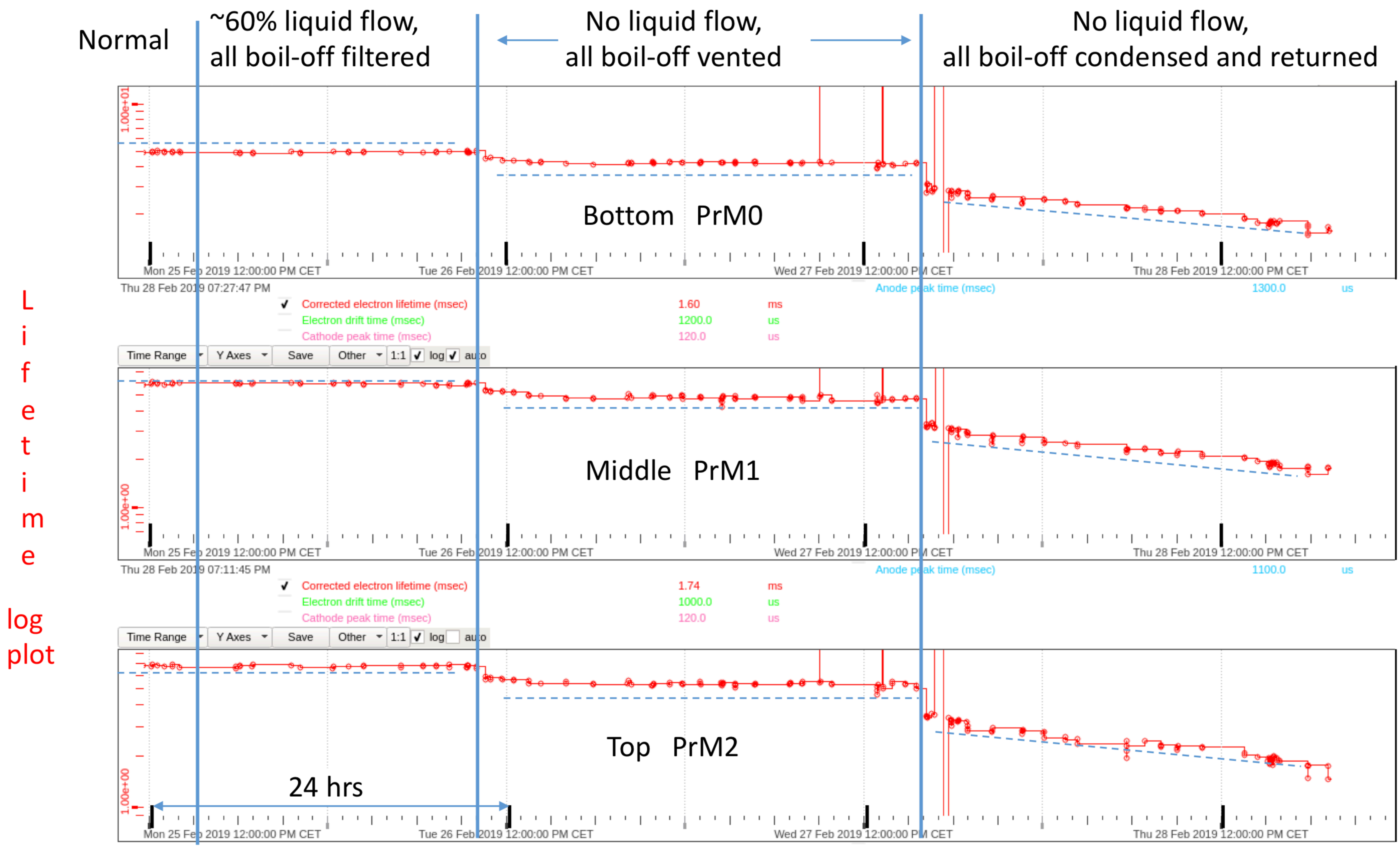
BACK UP

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***

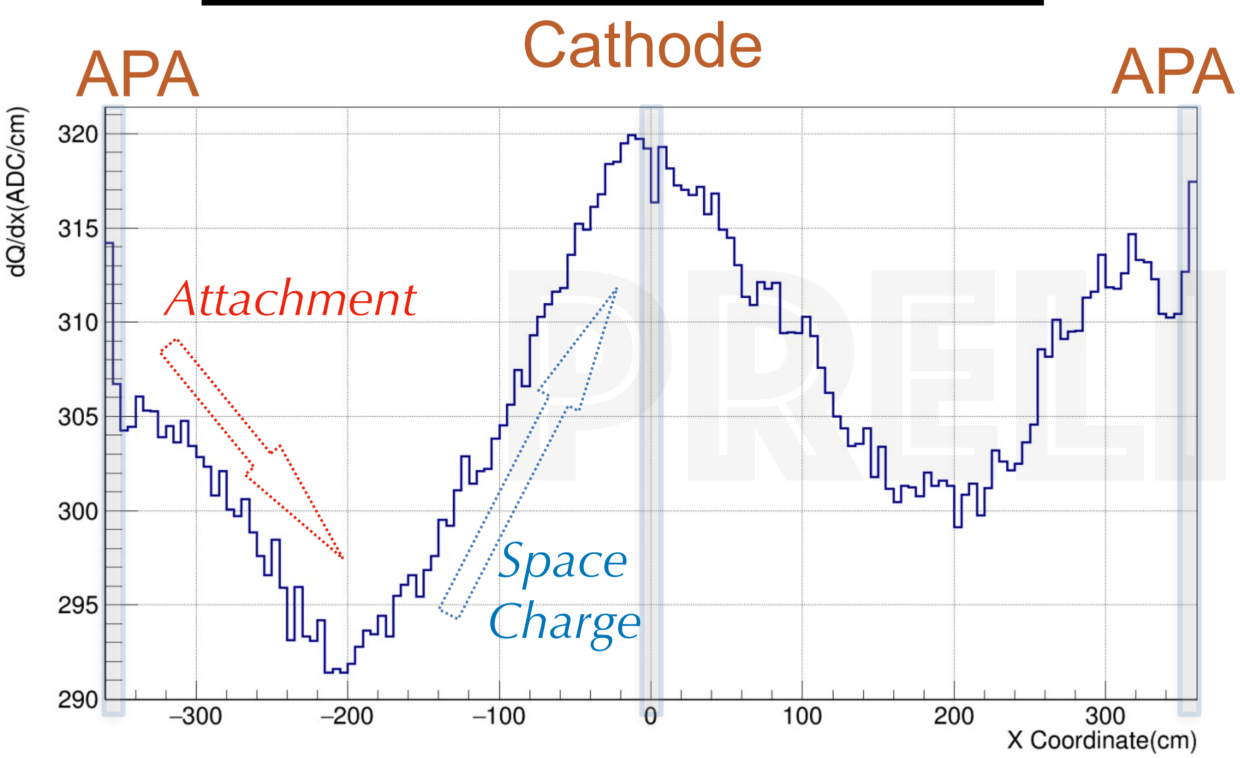
*99.5% uptime
** inside TPC (500 V/cm)
*** coherent noise removed

Cryogenic Circulation Studies

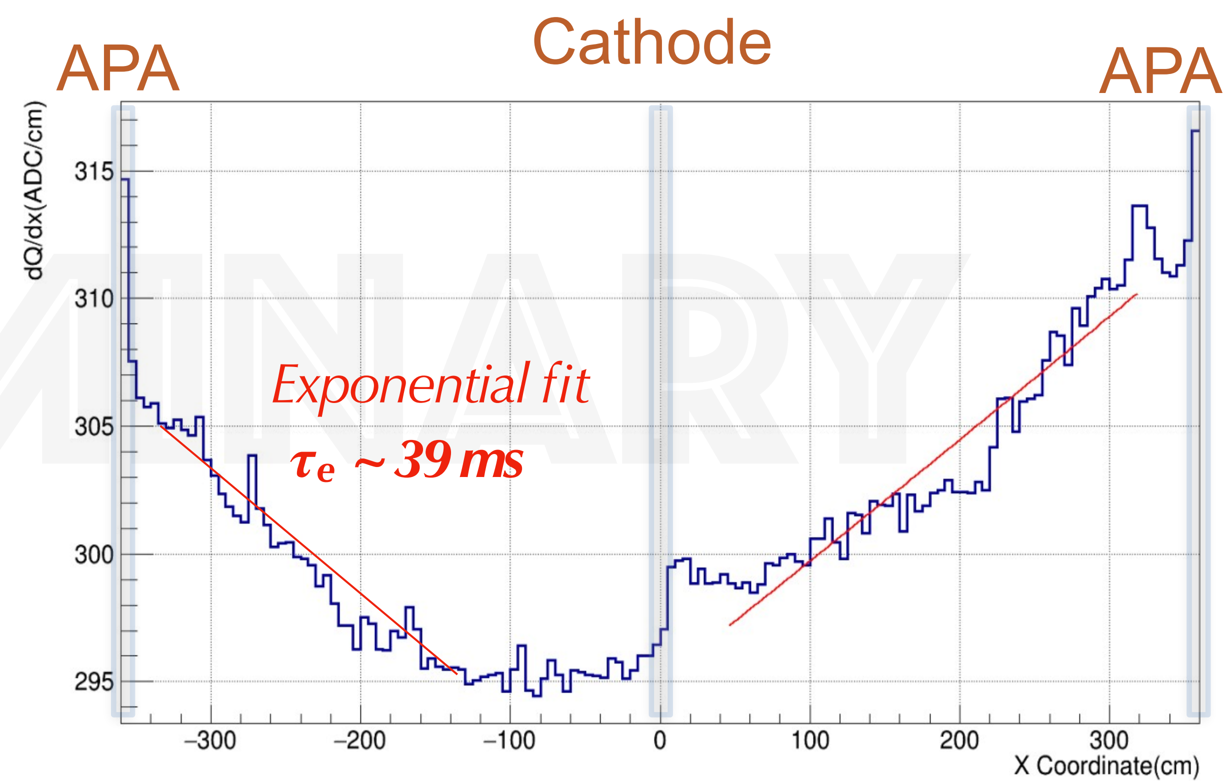


Ionization e-Charge in the TPC Volume from cosmic tracks as fcn. of distance from Cathode: Attenuation by impurity attachment opposed by Space Charge effect due to accumulation of slowly moving Ions in LAr Volume (EF=500 V/cm).

Run 5387 no-correction



After SCE correction



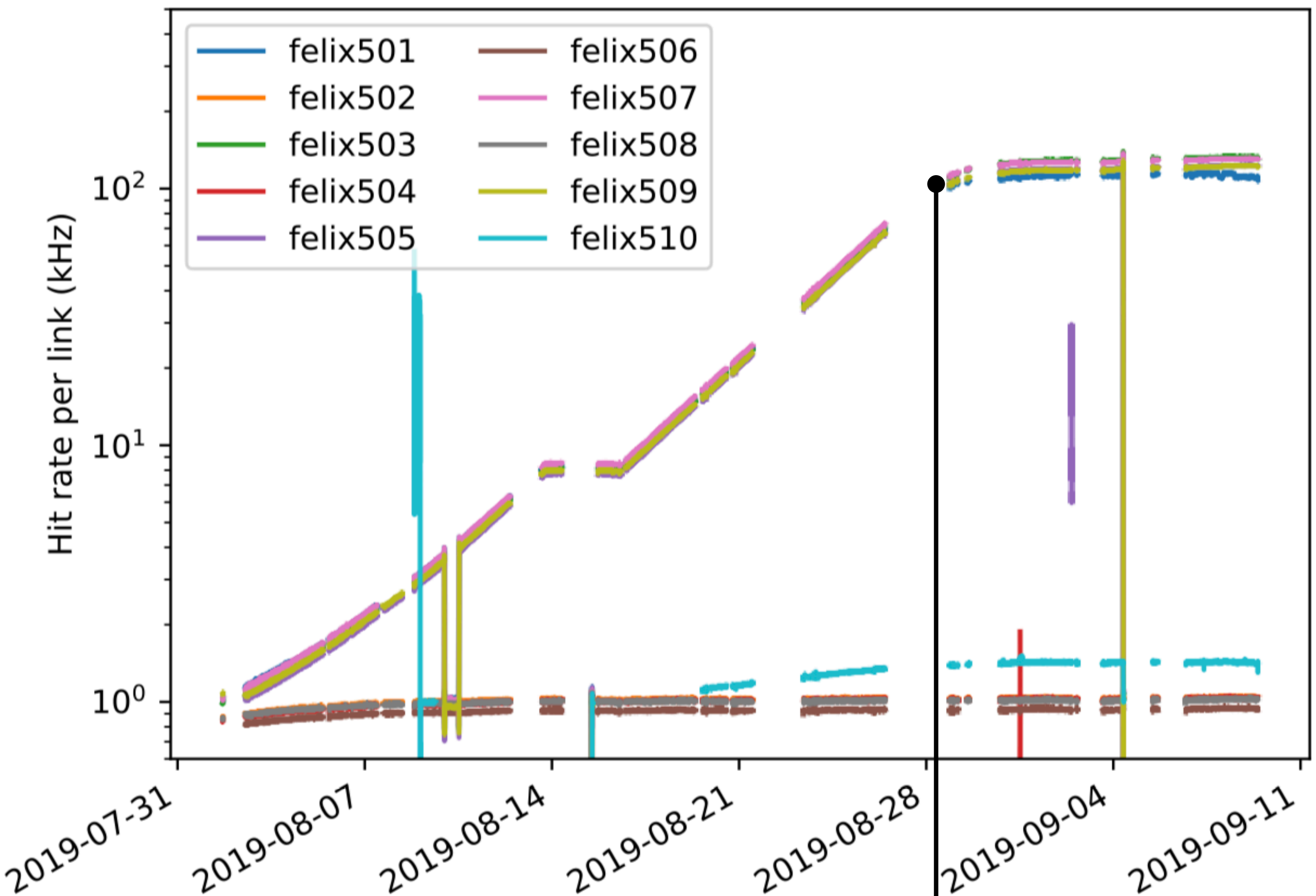
e-Lifetime, Attachment Rate Constant and Impurity Concentration

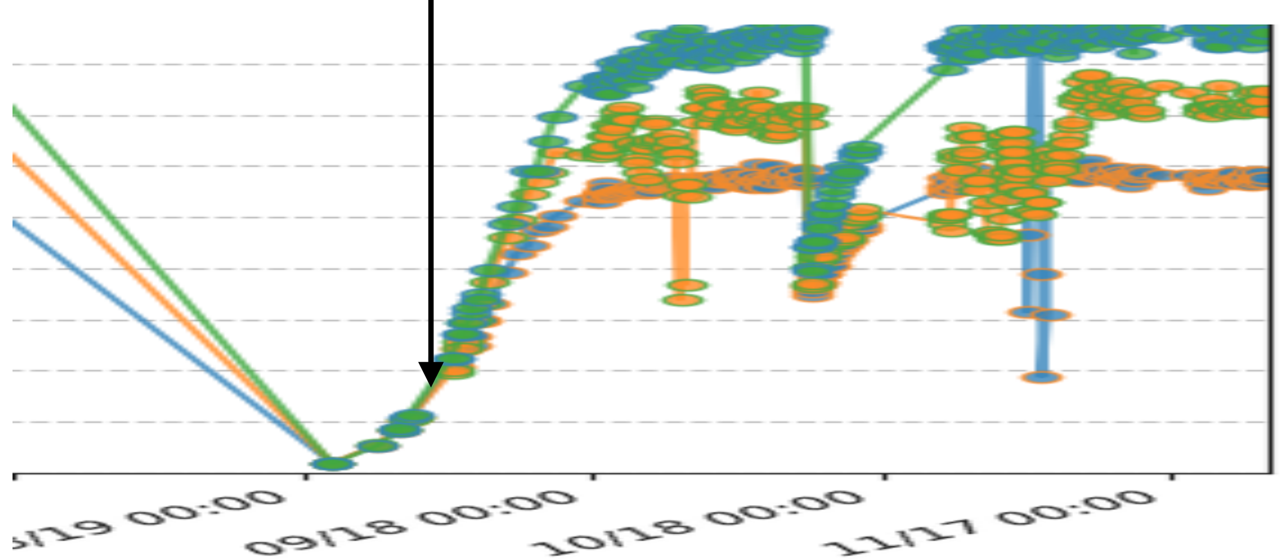
$$\tau_e = \frac{1}{k_A\ [X]}$$

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

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)**

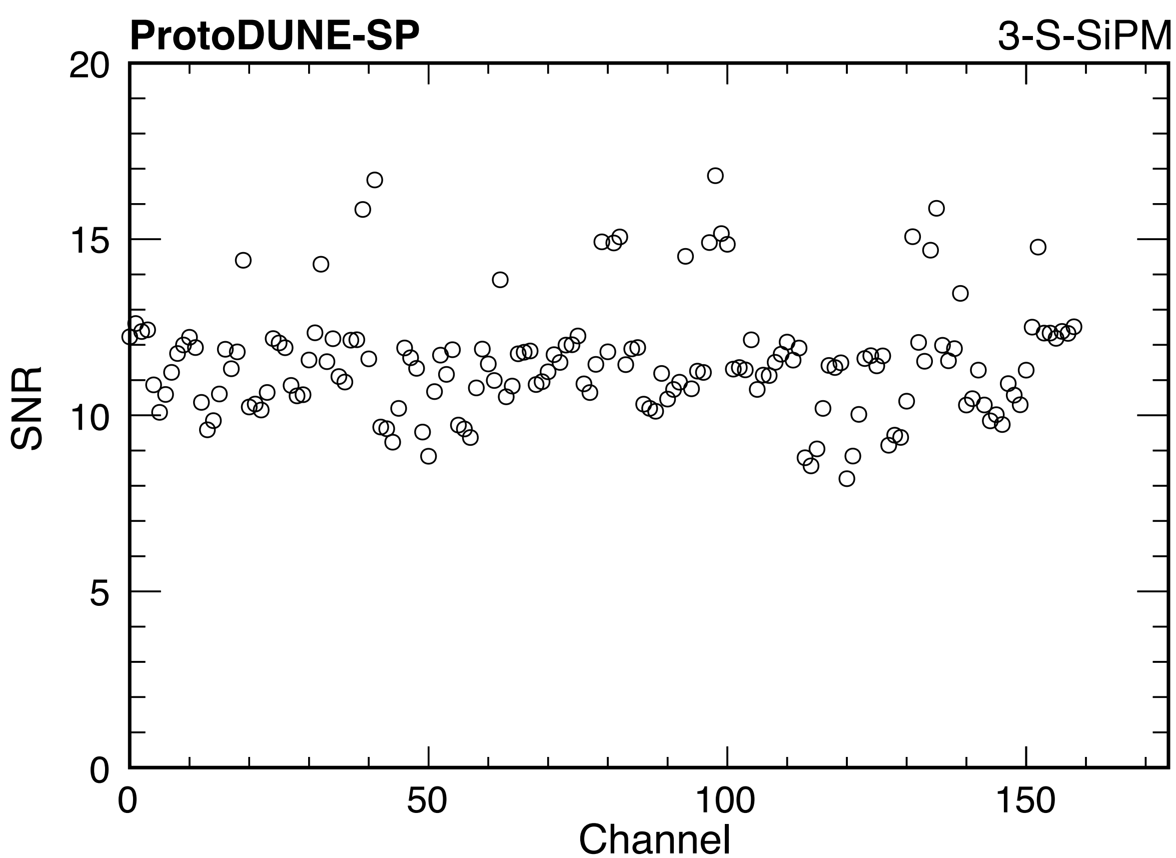
$f_Q \simeq$ 10% - Ar_2* Triplet **fraction lost by N_2 quenching**

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

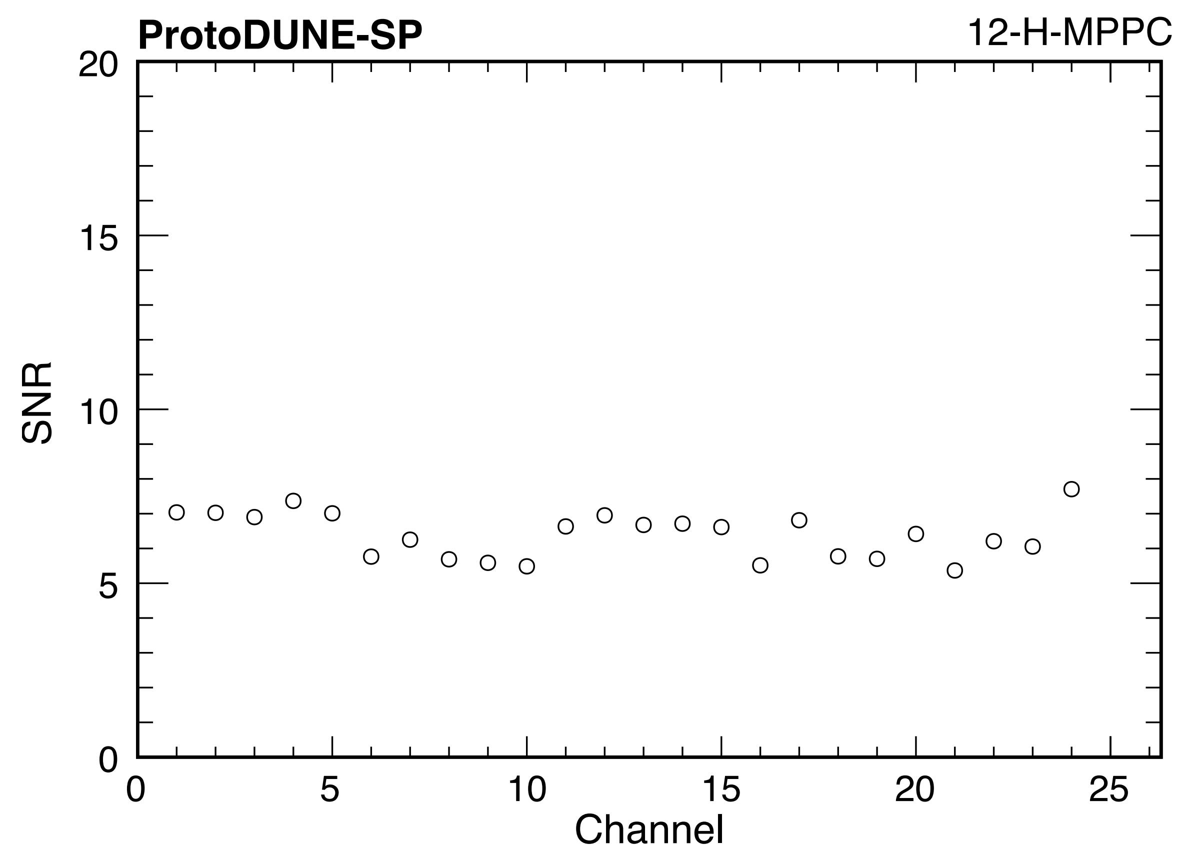
Small scale test demonstrated theory above - Xe doping in protoDUNE-SP in January (for N_2 contamination recovery and Xe doping stability in time and uniformity in the LAr Volume)

S/N ratio - photoSensor read/out

LightGuide Bar photoSensors

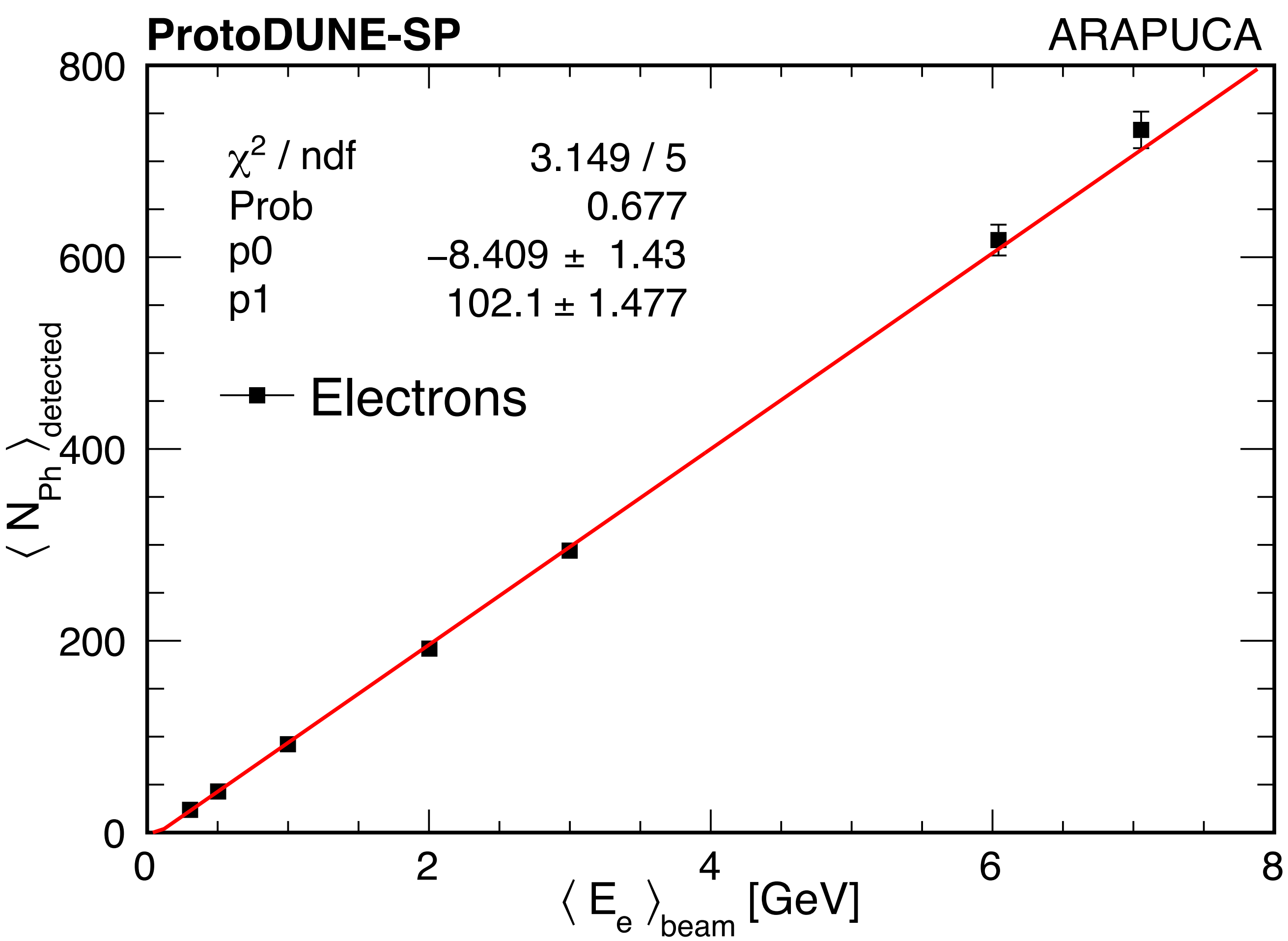


ARAPUCA Cell photoSensors



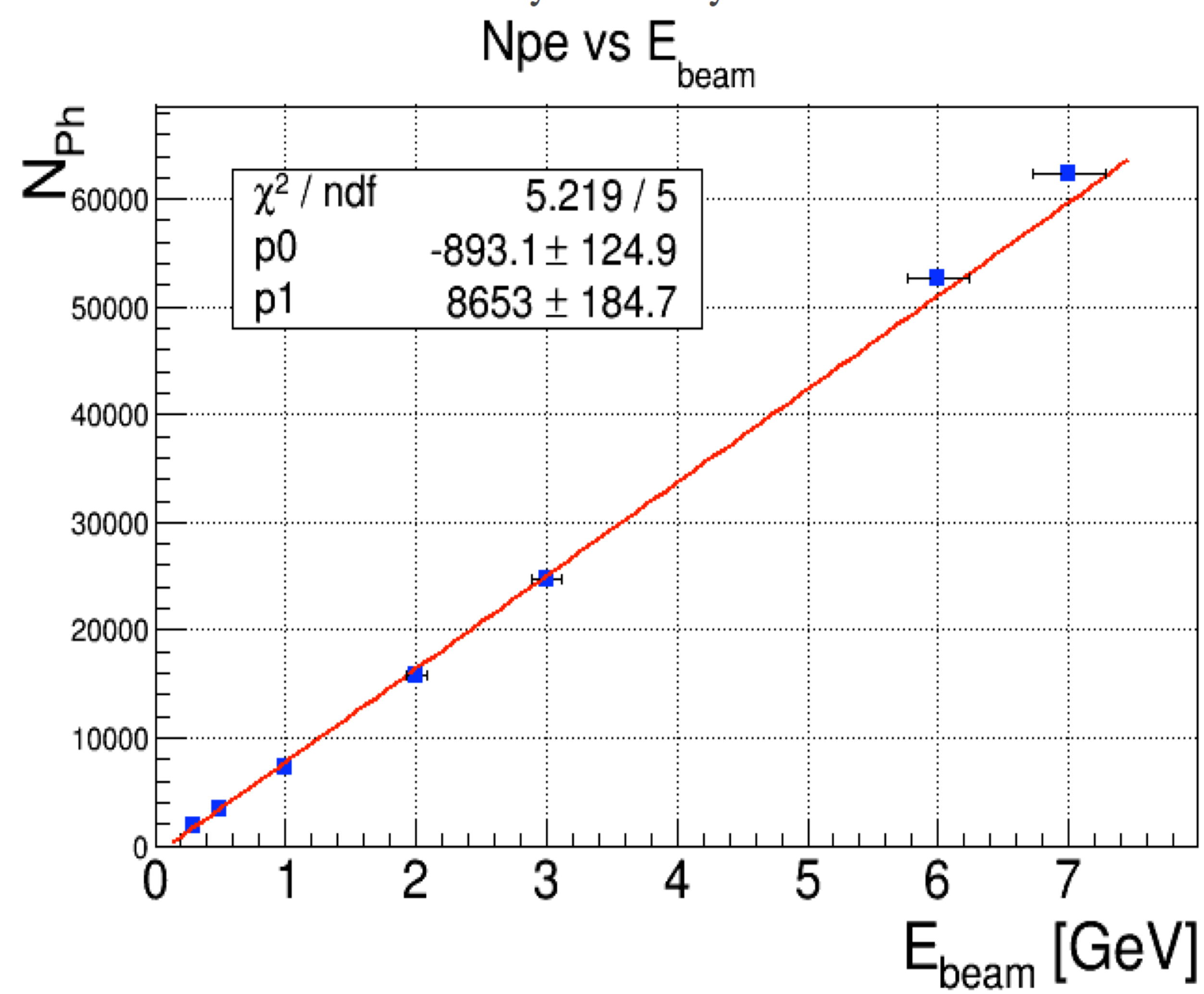
Light Response “linearity”

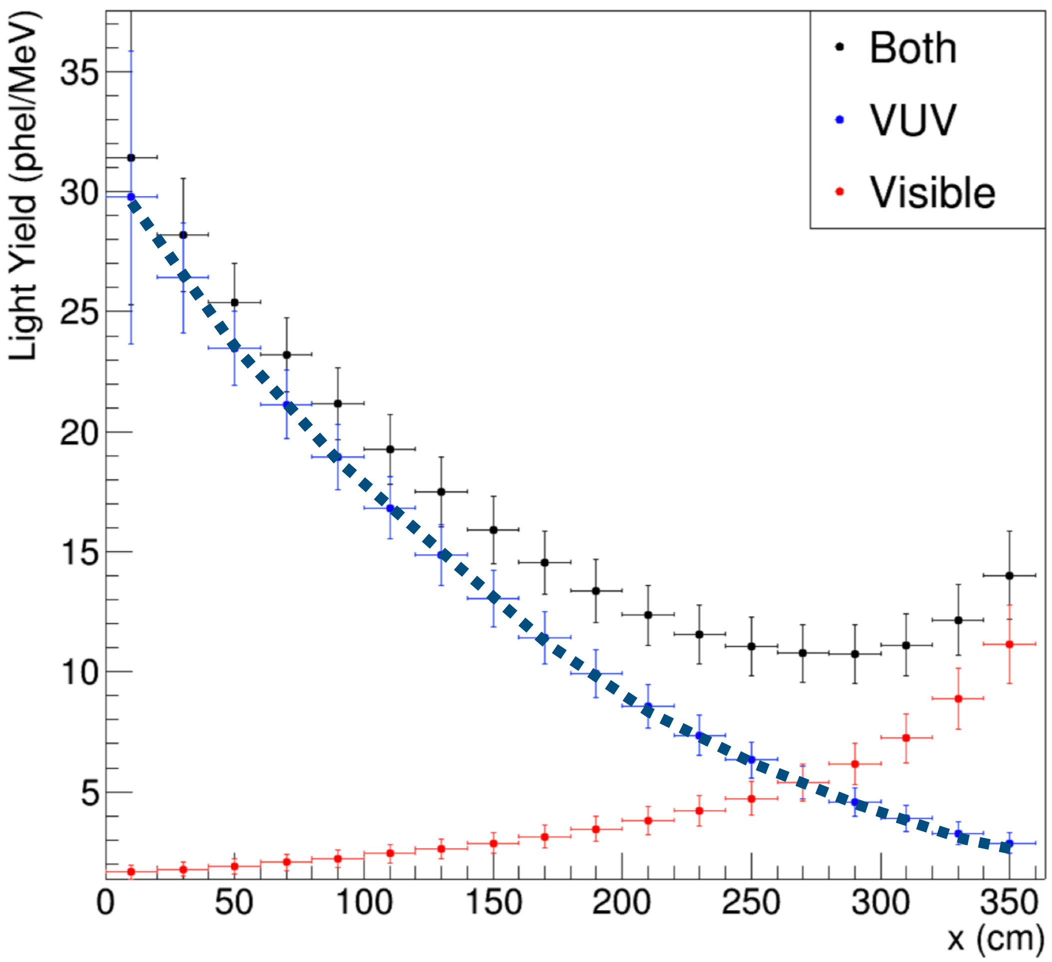
DATA



MONTECARLO

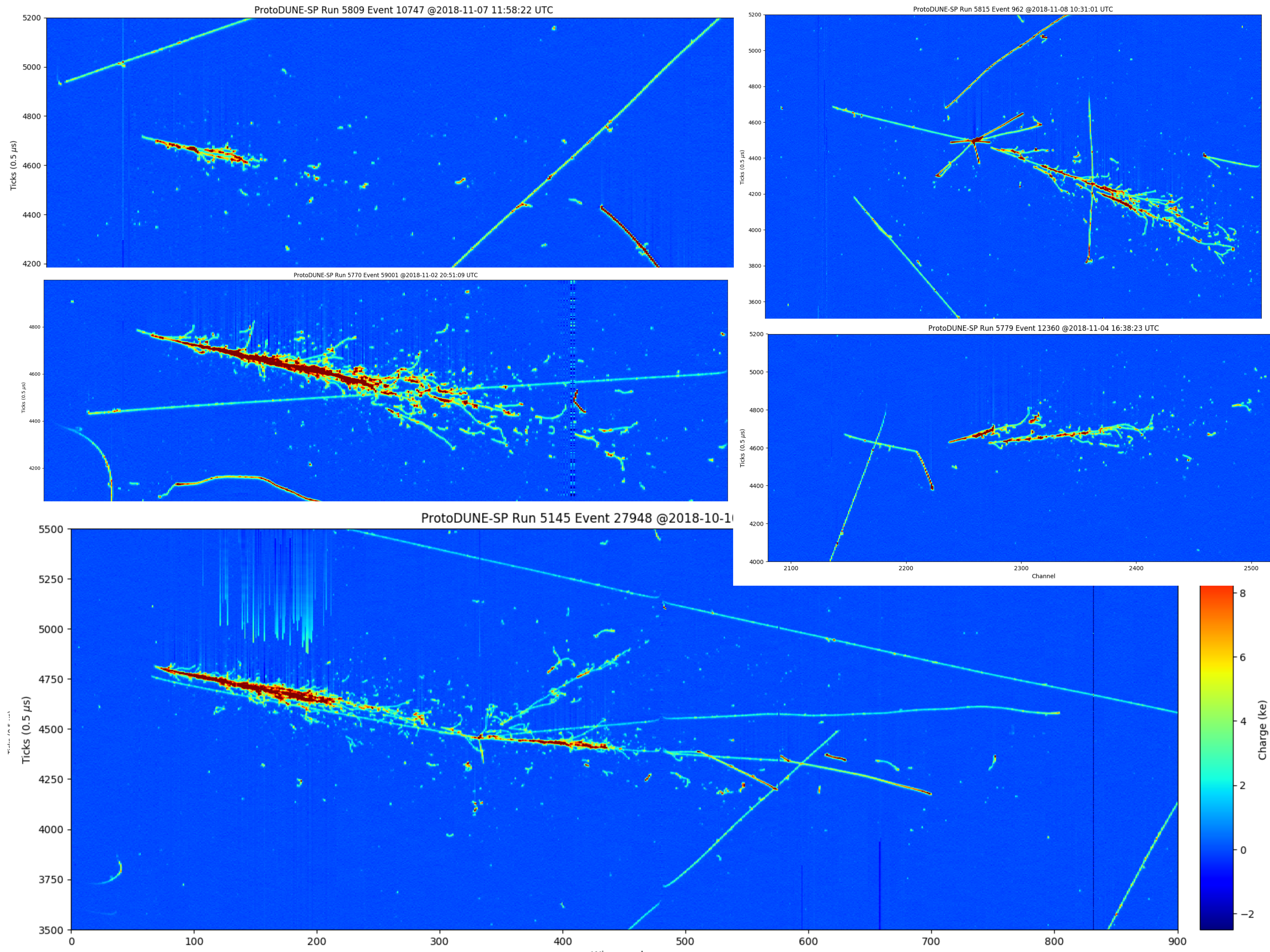
-note: MC not “scaled” by efficiency

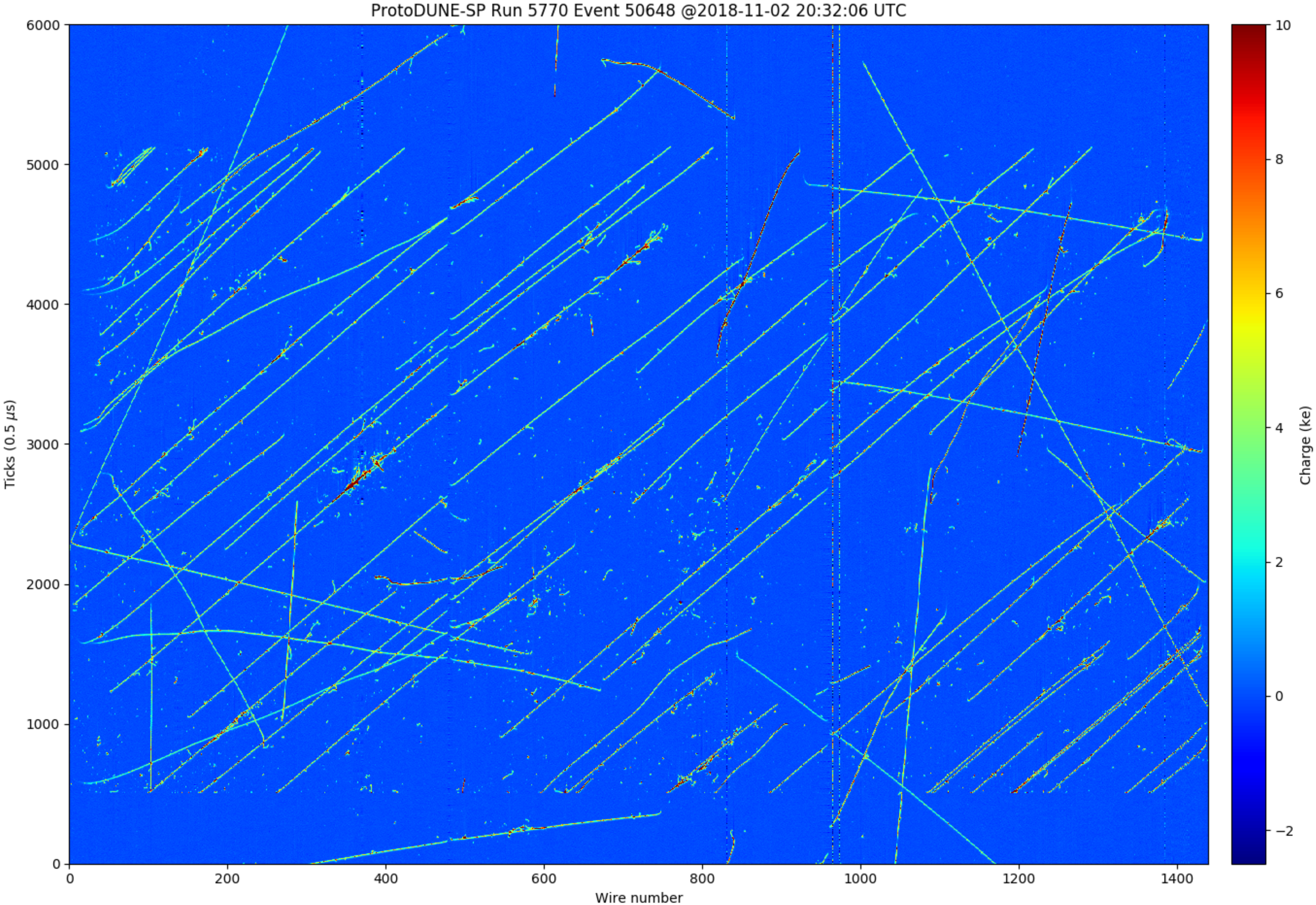


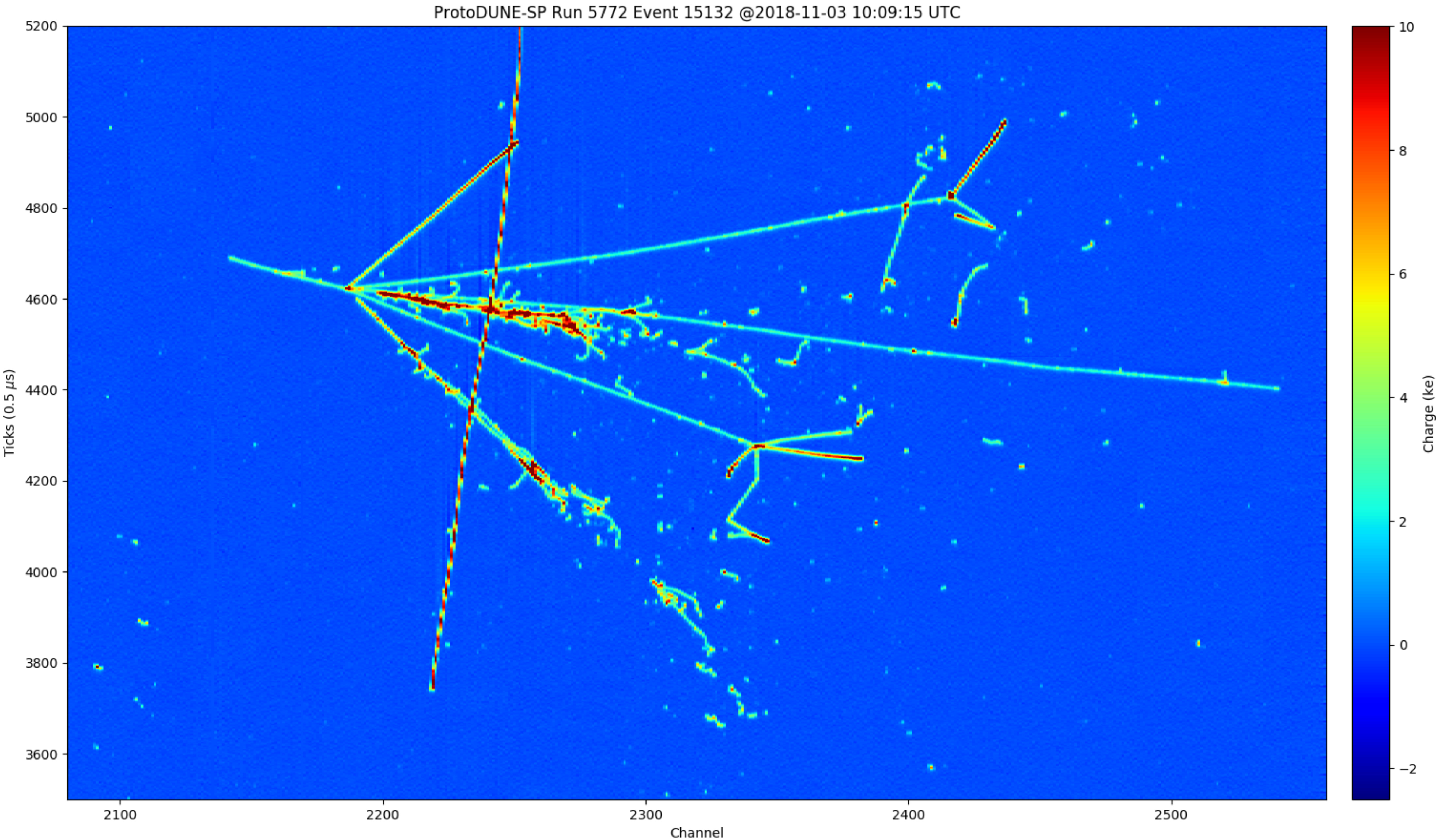


QE = 3.5%; 80% cathode foil coverage; 80% optical detectors TPB coated; 60% visible light transmittance through TPB coating

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)
0
1000
2000
3000
4000
5000
6000
200
400
600
800
1000
1200
1400
10
8
6
4
2
−2


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