# ProtoDUNE-SP Physics Analysis

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LBNC Review

March 4, 2020

# Outline

- Status of the ProtoDUNE-SP performance paper
- What can we learn from ProtoDUNE-SP data beyond the performance paper
  - Better understanding of the LArTPC technology
  - Physics measurements: hadron-argon cross sections
  - Push the limit on reconstruction capabilities
  - Provide critical information on DUNE far detector

PREPARED FOR SUBMISSION TO JINST

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

- Aug. 16, 2019: Overleaf document created
- Dec. 13, 2019: Group review started
- **Feb. 28, 2020: ARC review started**

……

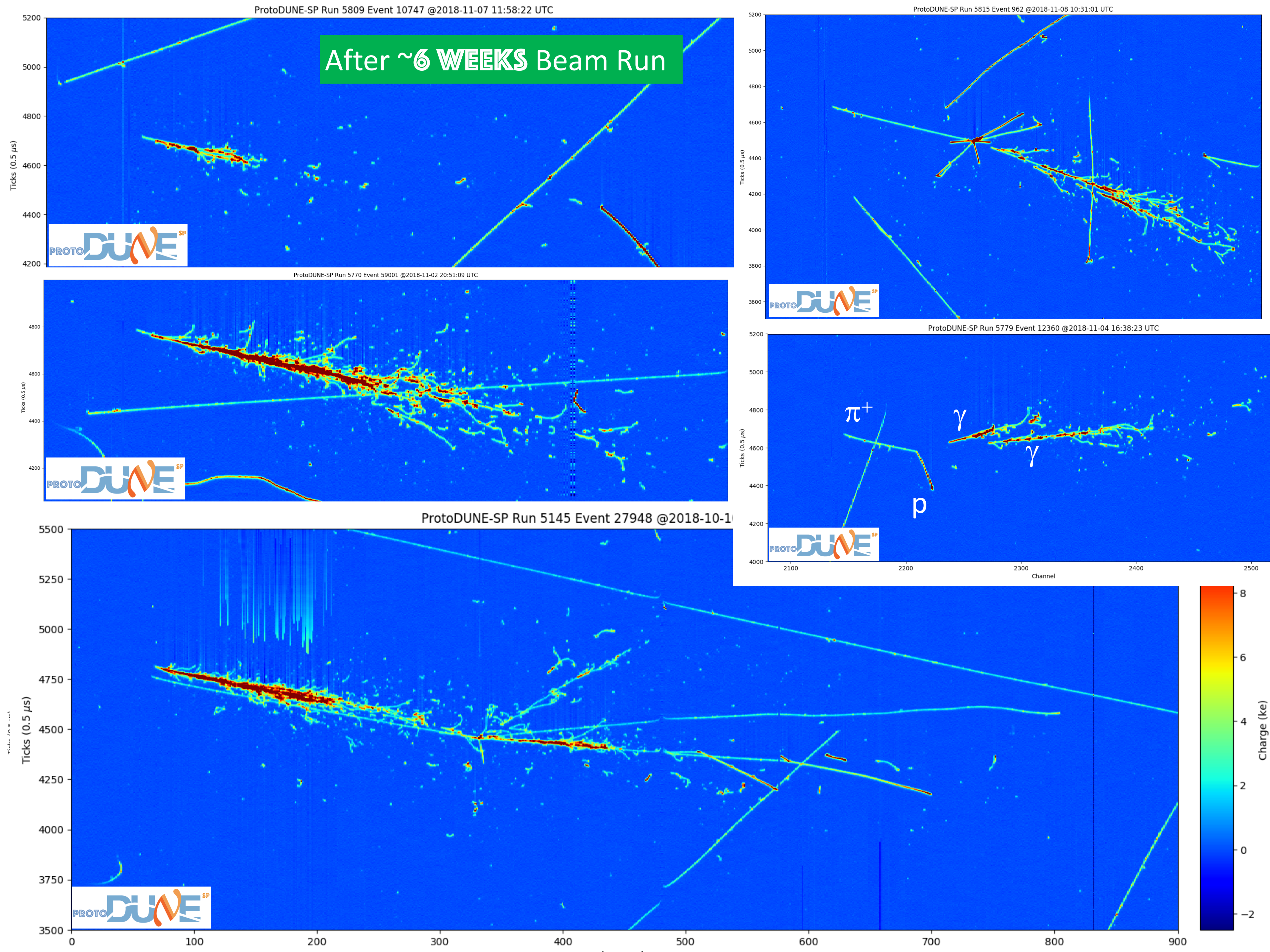
- Expected future path:
  - Collaboration review starts in middle March
  - Paper will be submitted by the end of March or early April

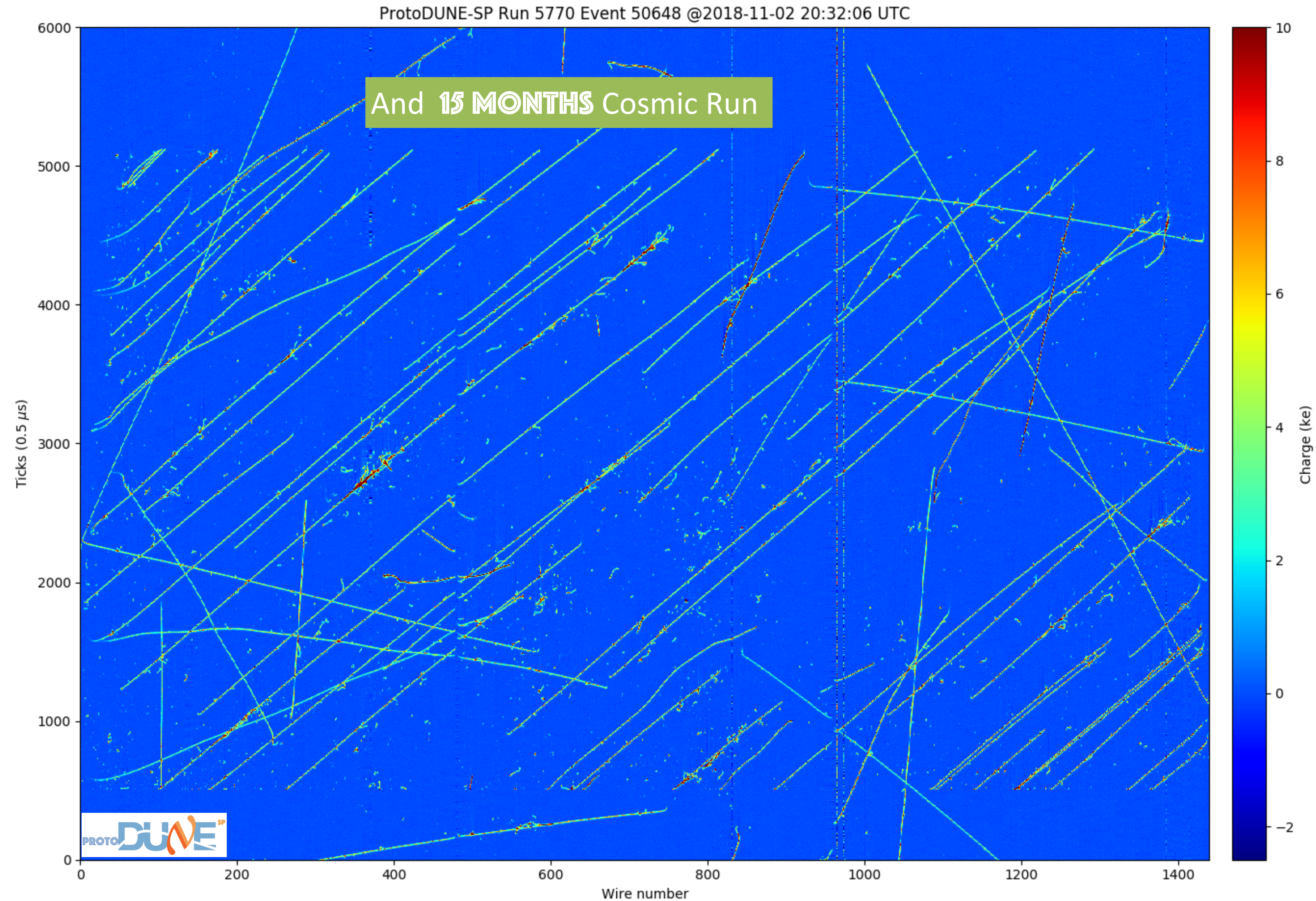
Work on the technical paper has started:
"**Design, construction and operation of the ProtoDUNE-SP liquid argon TPC**"
Gina Rameika is leading the work. A technical team is formed with four people.

# Outline of the paper

1. Introduction
2. The ProtoDUNE-SP detector
3. CERN beam line instrumentation
4. TPC characterization
5. Photon detector characterization
6. TPC response
7. Photon detector response
8. Conclusions

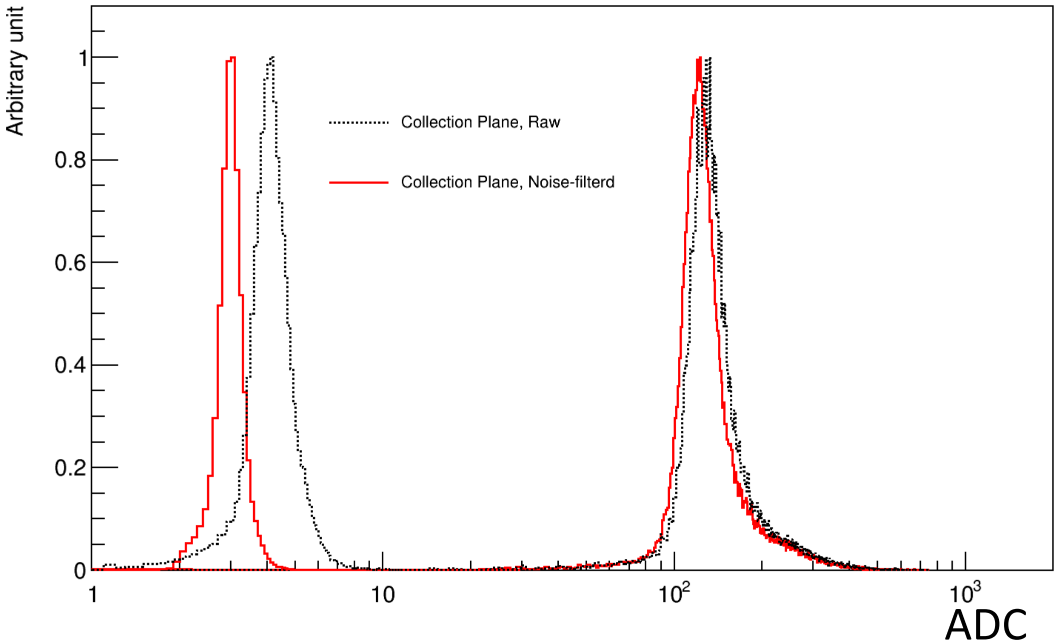
85 pages, 64 figures, 4 tables.


ProtoDUNE-SP Run 5809 Event 10747 @2018-11-07 11:58:22 UTC
After ~6 WEEKS Beam Run
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
$\pi^+$
$\gamma$
$\gamma$
p
Channel
ProtoDUNE-SP Run 5145 Event 27948 @2018-10-1
Ticks (0.5 μs)
Charge (ke)

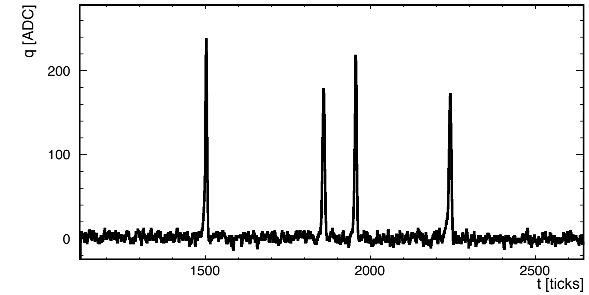



A muon bundle event.

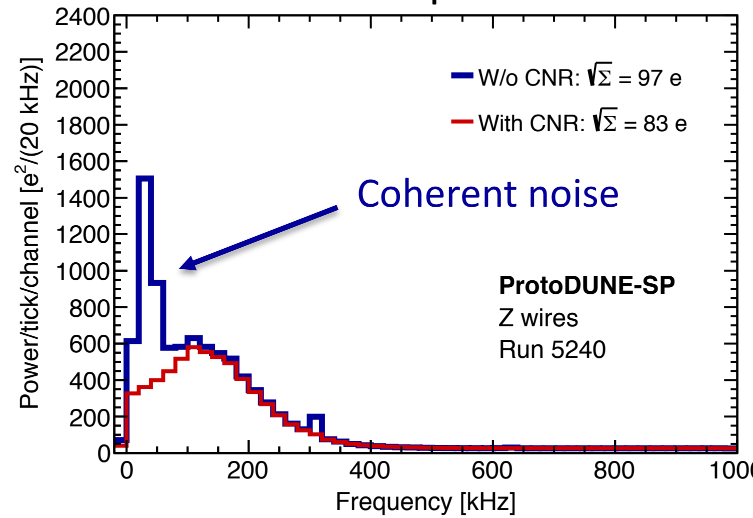
# TPC characterization




A typical waveform




Noise spectrum

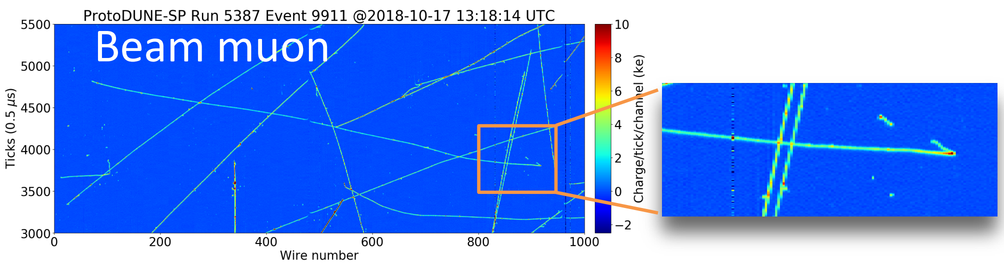


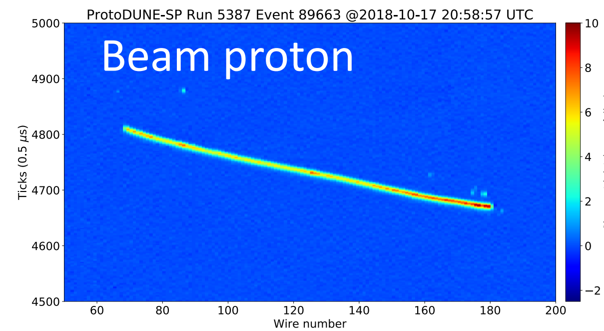

- **Low noise level**
  - *Coherent noise can be removed*
- **Excellent signal-to-noise ratio**
- **Robust reconstruction**
  - *WireCell, Pandora*

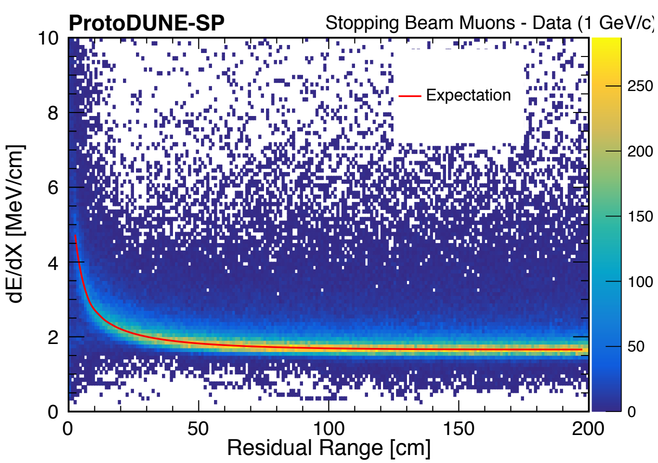
| Plane | Peak signal-to-noise ratio | | | |
|---|---|---|---|---|
| | Raw Data | | After Noise Filtering | |
| | MPV | Average | MPV | Average |
| Collection | 30.9 | 38.3 | 40.3 | 48.7 |
| U | 12.1 | 15.6 | 15.1 | 18.2 |
| V | 14.9 | 18.7 | 18.6 | 21.2 |

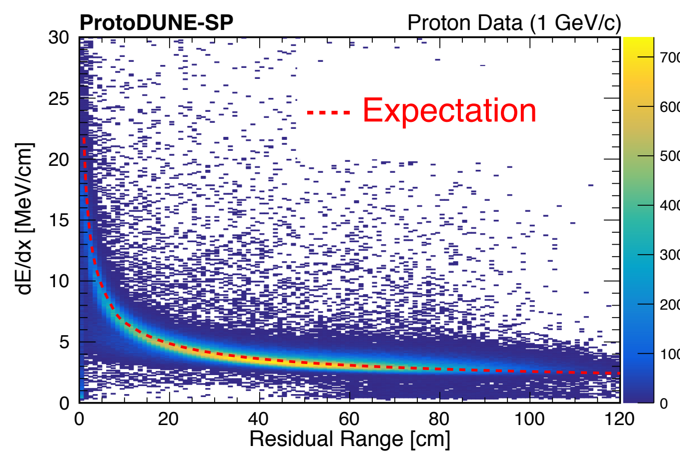
# TPC response

- Detector response is calibrated using cosmic ray muons.
- The calibration constants work well on beam particles (muons, pion, protons, positrons).



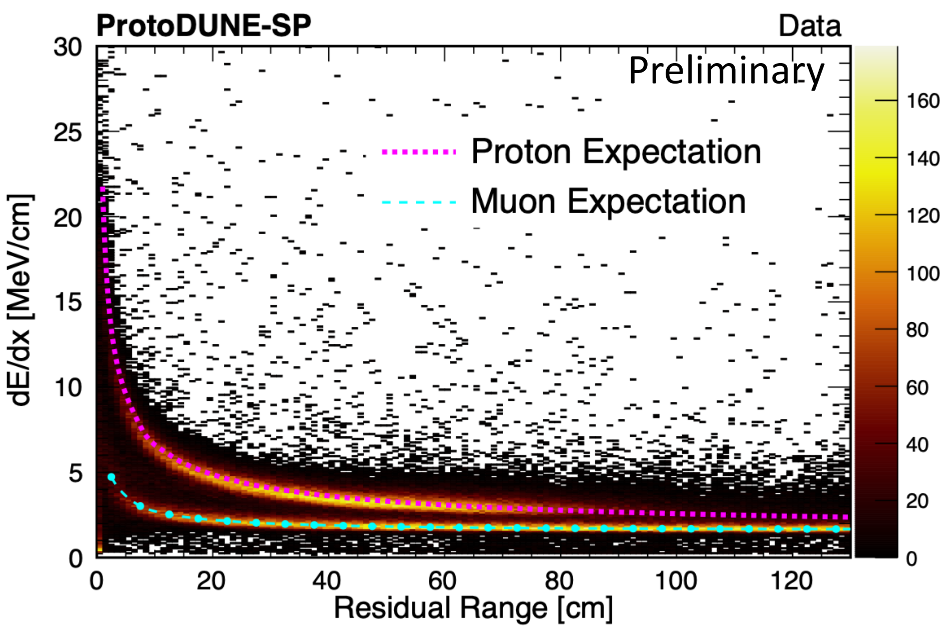



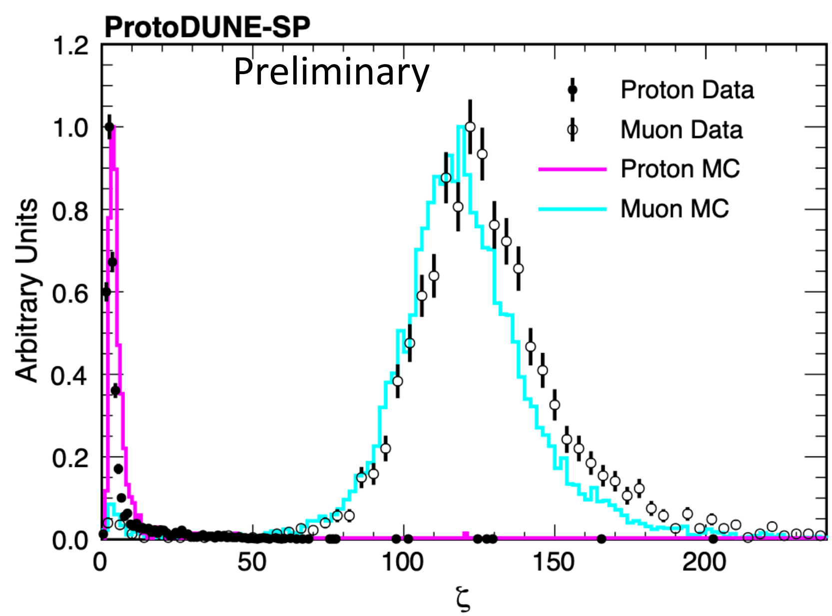




- **Developing alterative calibration scheme based on pulser measurements.**
  **- Import for DUNE because of low cosmic-ray rate.**

# dE/dx - Ptcl Id

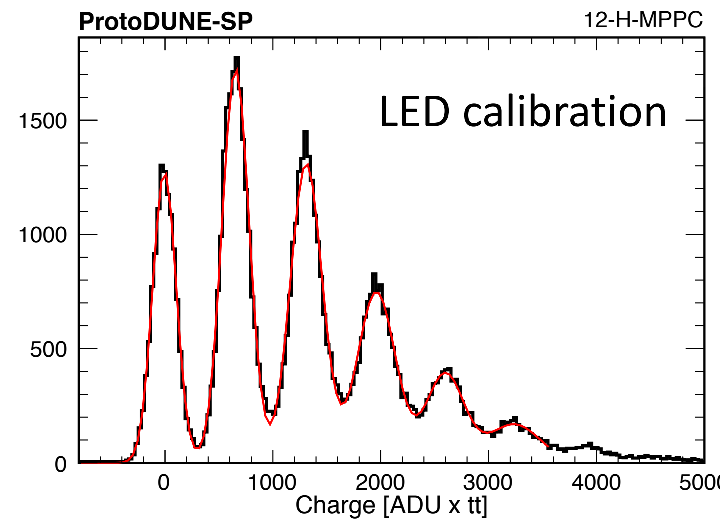


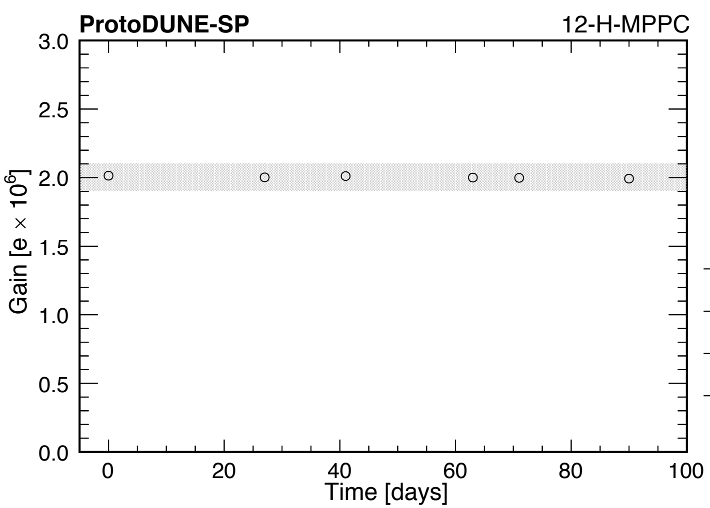




- Very well understood detector response to particles of different species.
- Excellent separation of muons/pions and protons using calorimetric information.

# Photon detector characterization

- **3 light collectors:**
  - *ARAPUCA, double-shift light guide, dip-coated light guide*
- **3 photosensors**
  - *SensL SiPM, two types of Hamamatsu MPPC*
- Stable gain
- High signal-to-noise ratio (6-12)
- Efficiencies measured using electron and muon data.

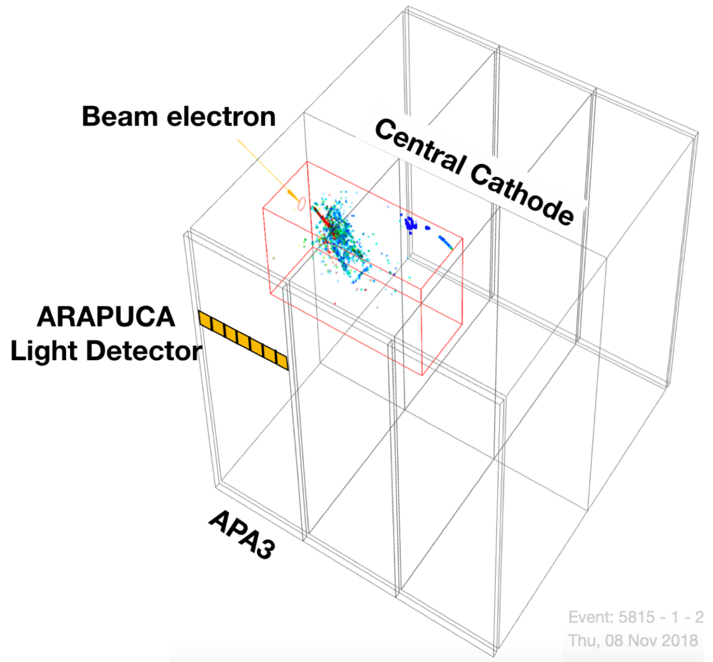


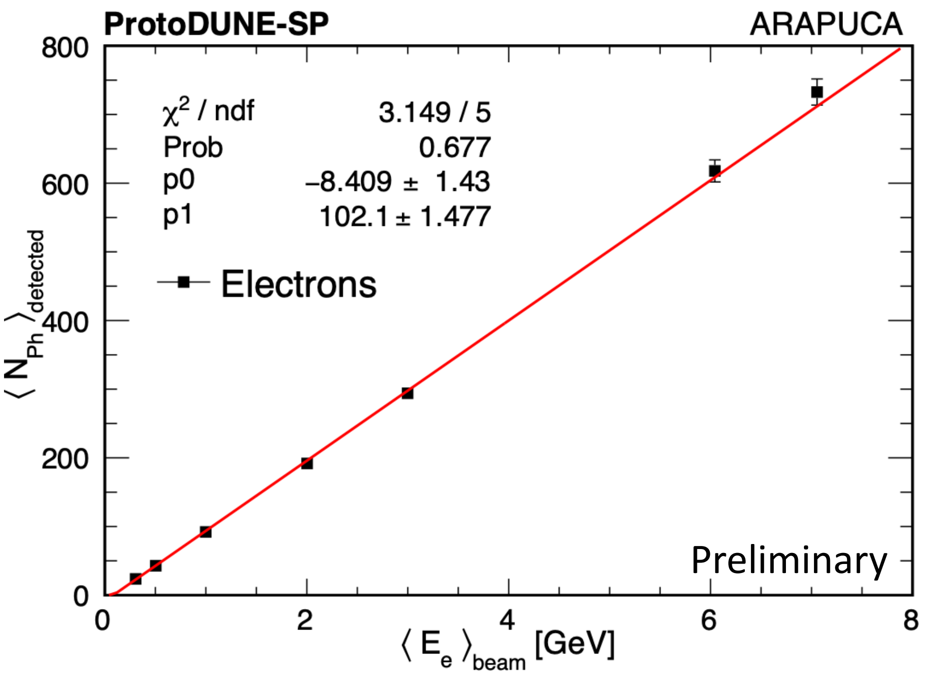




| Detector Type | # of elements in PDS | Efficiency |
|---|---|---|
| ARAPUCA cell | 8 | $\tilde{\epsilon}_A = (2.00 \pm 0.005_{\text{stat}} \pm 0.25_{\text{syst}})$ % |
| ARAPUCA cell (double area) | 4 | $\tilde{\epsilon}_{A2} = (1.06 \pm 0.005_{\text{stat}} \pm 0.09_{\text{syst}})$ % |
| Double-shift module | 15 | $\tilde{\epsilon}_{DS} = (0.21 \pm 0.000_{\text{stat}} \pm 0.03_{\text{syst}})$ % |
| Dip-coated module | 14 | $\tilde{\epsilon}_{DC} = (0.08 \pm 0.000_{\text{stat}} \pm 0.02_{\text{syst}})$ % |

# PHOTO-DETECTOR PERFORMANCE :

## calorimetric response to EM showers from *LIGHT Signal*




single ARAPUCA module
(~0.5‰ photo-sensitive area coverage)
Resolution: 10% @ 2 GeV

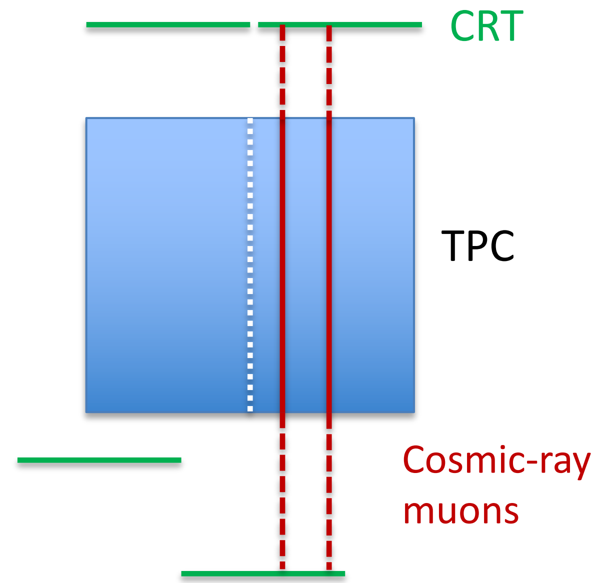
## LINEARITY

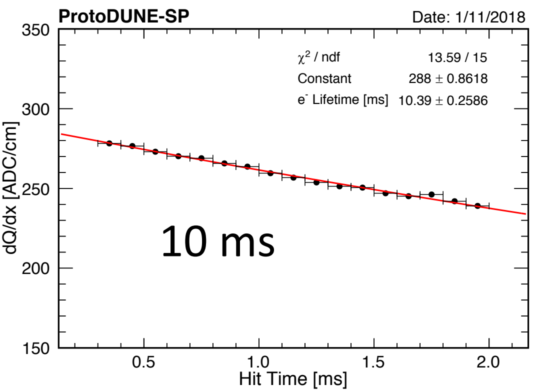
Observed (first approx) linear response over the entire range of energies.

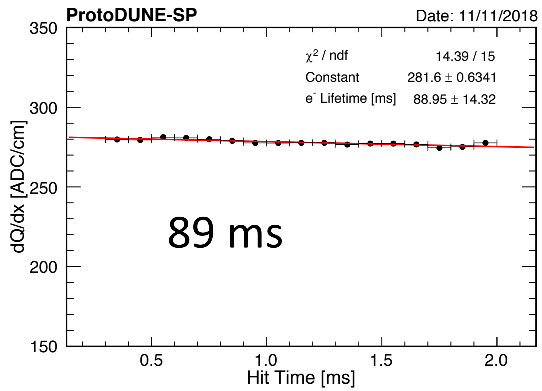
The slope gives the light yield $LY = 102 Ph/GeV$

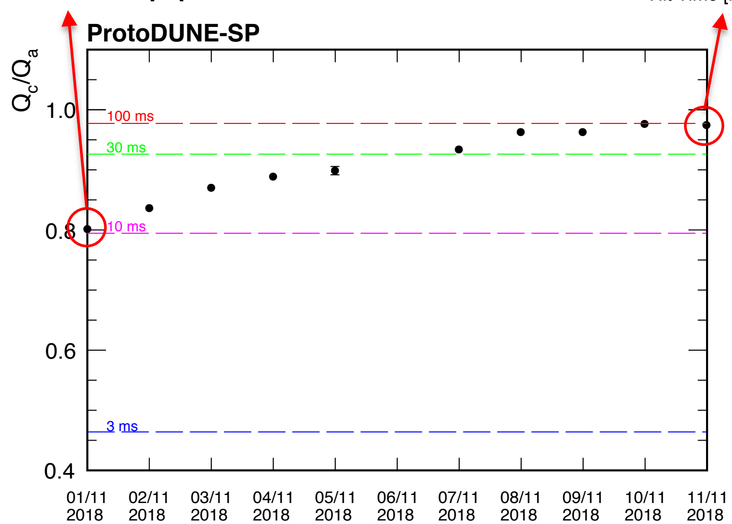
from (only) one ARAPUCA PhDet module, relative to a diffused light source (EM shower) at a distance of about 3 m

# Electron lifetime



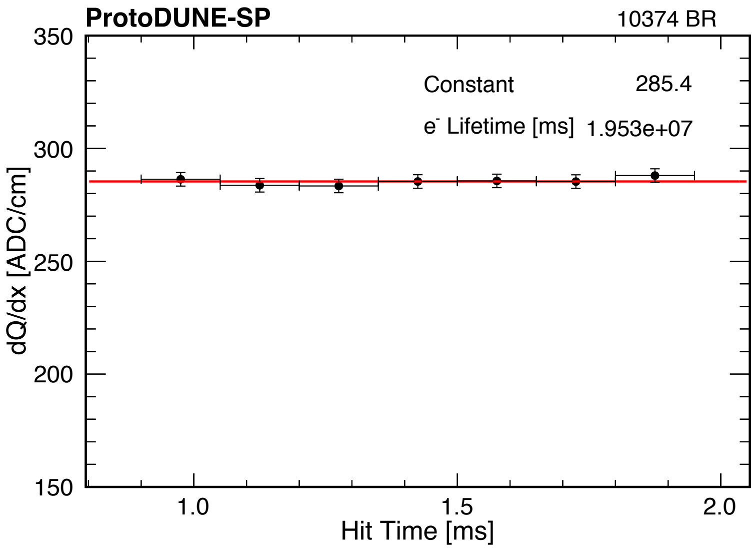




- Use CRT coincidences to select tracks parallel to the wire planes.
- dQ/dx vs drift time -> e lifetime
- This method is not sensitive to the space charge effects.
- Lifetime increases from 10 ms to 89 ms in the last 11 days of beam run.
- Can use this measurement to “calibrate” the purity monitor measurement.

# New CRT data

- CRT was actively used during the beam runs.
- CRT was reactivated in Nov 2019.
  - Stability of CRT readout was much improved.
- Three weeks (Nov 6 – Dec 6) of dedicated data taking with CRT triggers:
  - Detector calibration and stability studies



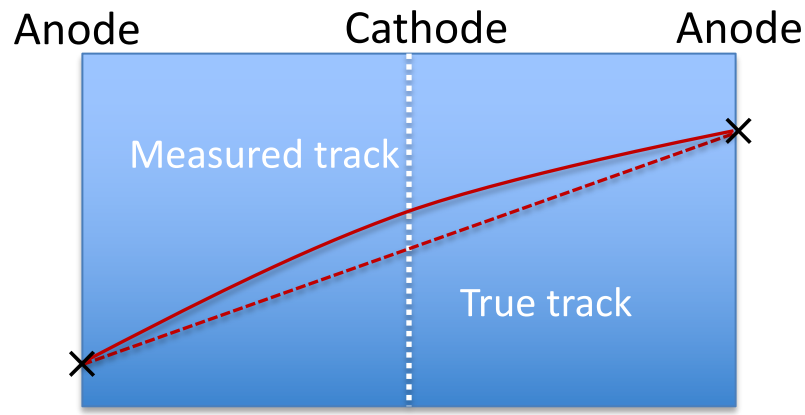

Excellent LAr purity.
No electron lifetime correction needed.

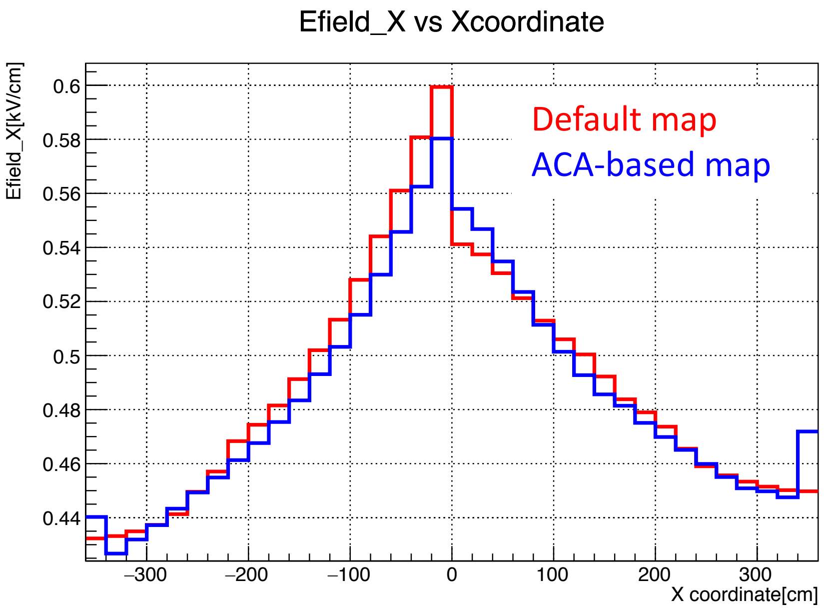
# On-going analyses

- **Detector responses**
  - Improve space charge measurements
  - Electron energy resolution
  - Electron/photon response
  - Michel electron spectrum
- **Hadron-argon cross sections**
  - Inclusive pion- and proton-argon cross sections
  - Exclusive channels: pion absorption, pion charge exchange
- Testing new simulation and reconstruction tools
- Focusing on the connection to the DUNE far detector.

# Space charge effects

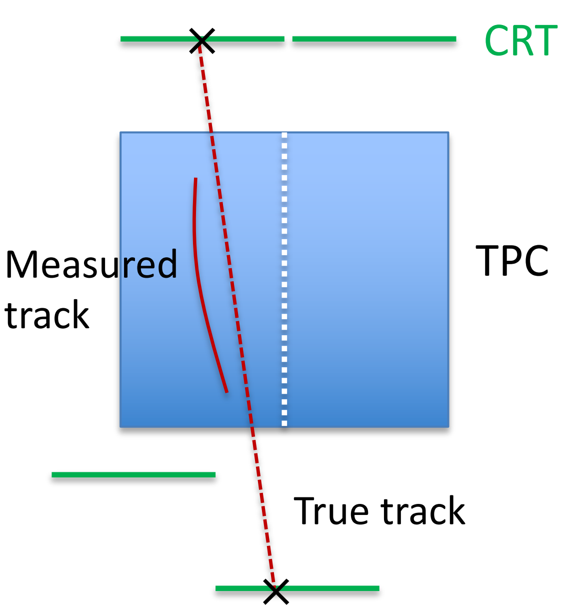
- Current method measures spatial distortion at TPC faces and calculates distortion in the bulk through interpolation.
- A novel method is developed to measure spatial distortion using anode-cathode-anode tracks.
- Spatial distortion is negligible at anode
  - *Reference points to measure distortion*
- Direct measurement of distortion.

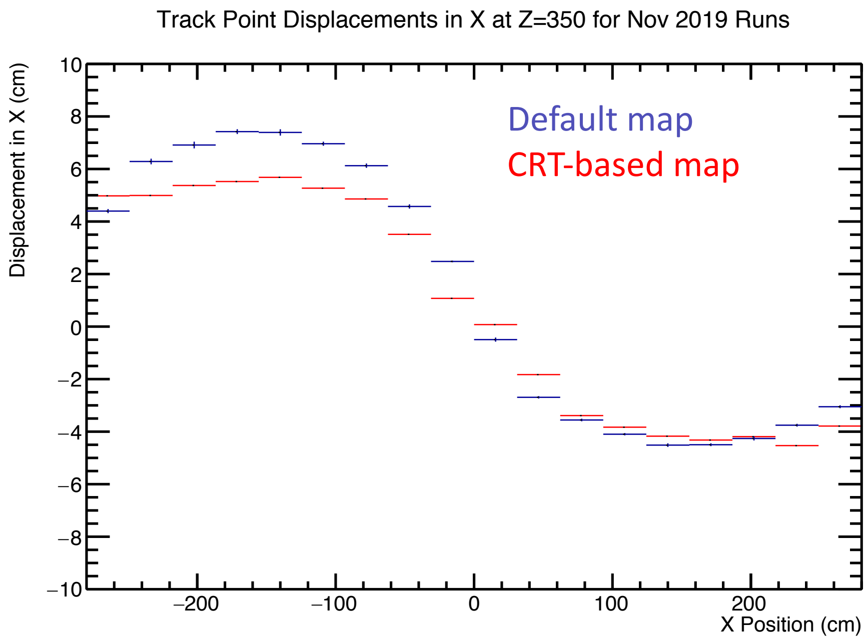


# More space charge measurements

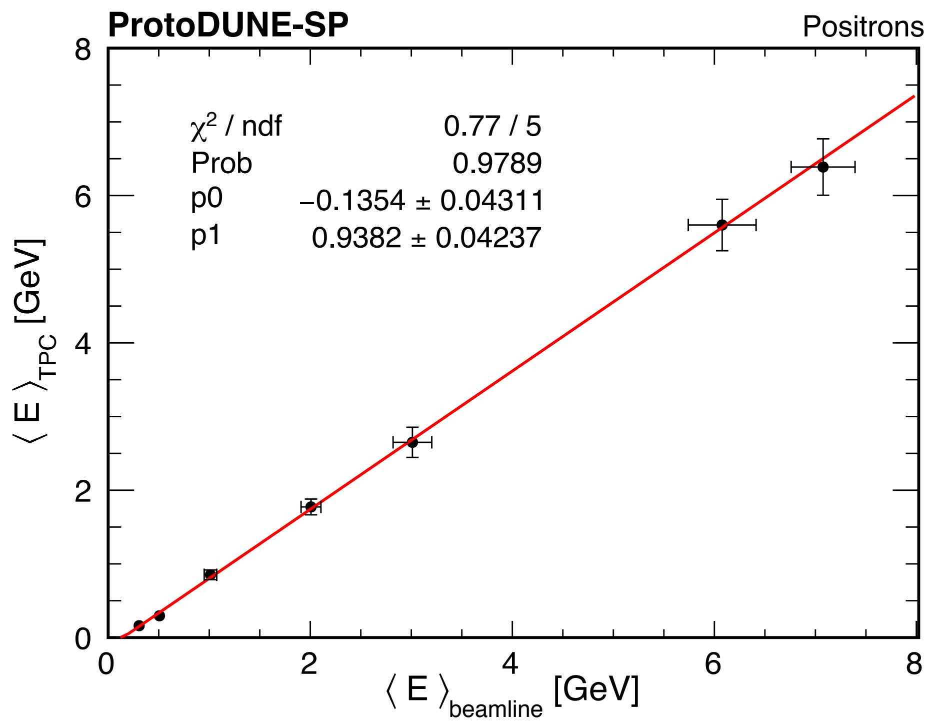
- Another approach is to use CRT tagged tracks to measure spatial distortion.
- CRT strips provide information on the track muon trajectory.
- Compare the measured distortion in drift direction between this method and the standard method.



# Electron energy measurement in TPC

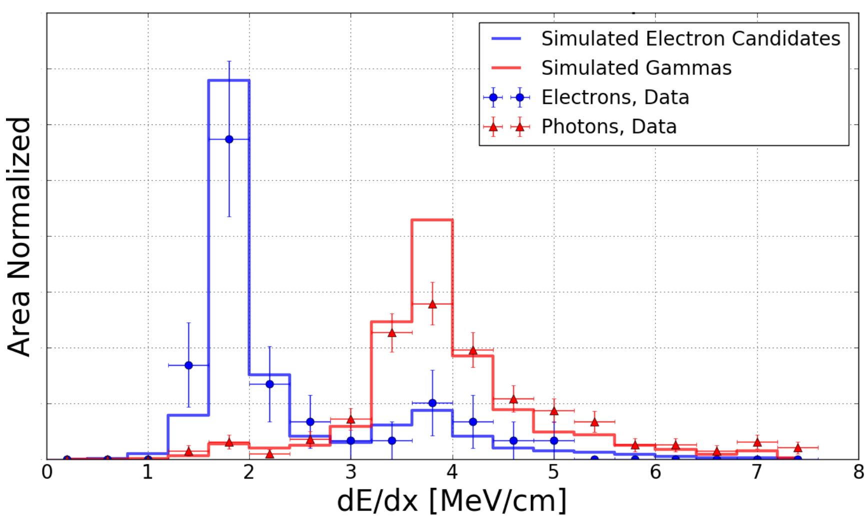
- Calorimetric measurement of electron energy in TPC
- Bias in energy measurement is well understood:
  - *Upstream energy loss*
  - *Threshold in hit finding*
  - *Bias from Gaussian fit in hit reconstruction*
  - *Pandora reconstruction inefficiency*
  - *Recombination*
- **Bias and resolution in electron energy measurement is critical information for DUNE.**



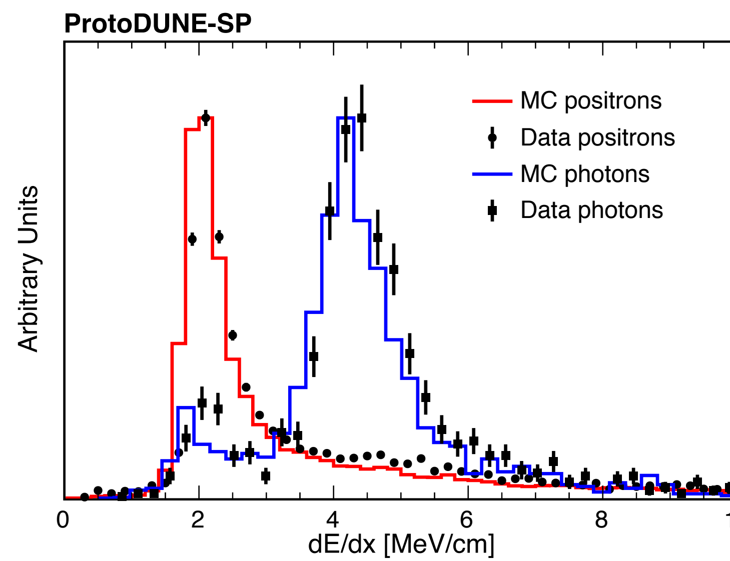
# Electron/photon dE/dx

- Measure dE/dx at the beginning of electron or photon.
- 1 GeV beam electrons.
- Photons from 6 GeV pion interactions.
- Clear e/γ separation in dE/dx distributions.

ArgoNeuT, PRD 95, 072005 (2017)



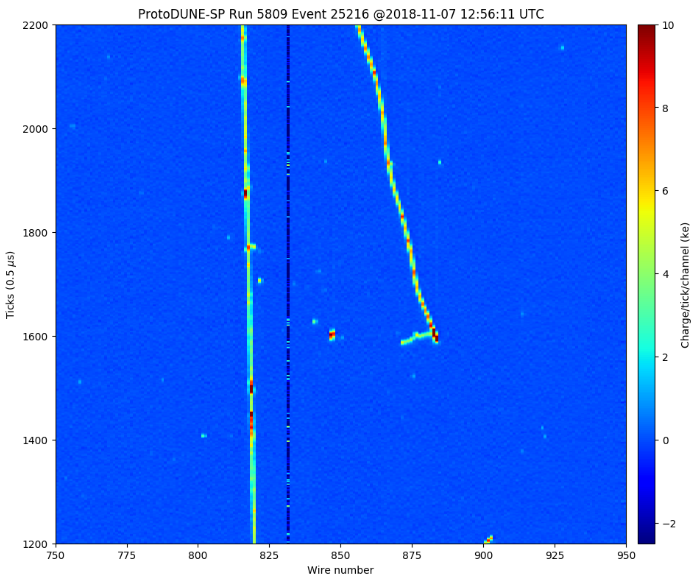

Hand picked events, limited statistics

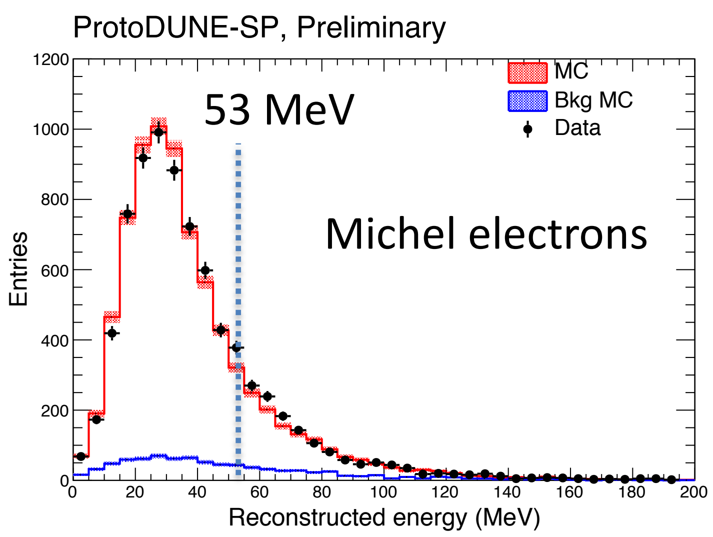



Fully automated reconstruction and event selection, large statistics.

# Michel electron spectrum

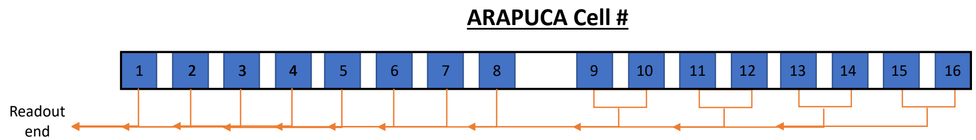
- Look for Michel electron hits near the stopping cosmic-ray muons.
- Excellent data and MC Michel energy spectra.
- Goal is to improve the selection and energy reconstruction so we can see the shape edge at 53 MeV – reference energy for calibration.

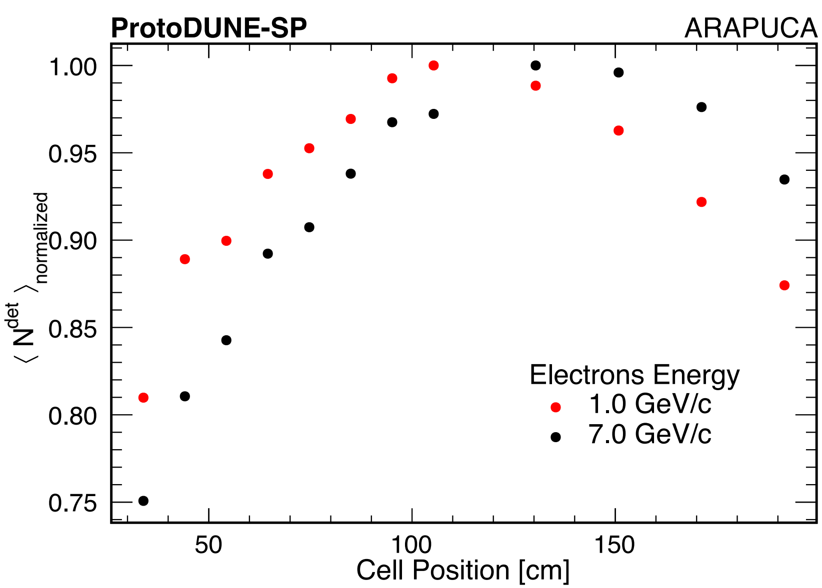


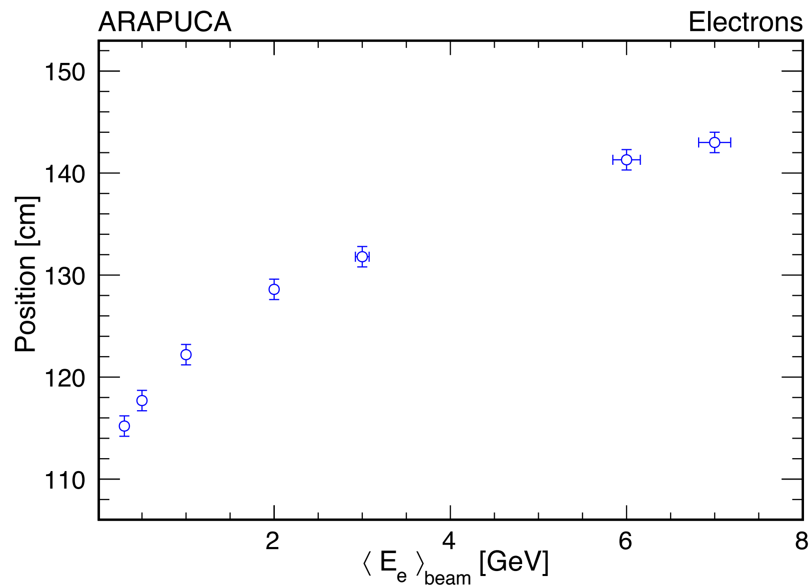



# Electron energy loss profile

- Measure light signal in each of the ARAPUCA cell for electrons of different energies.



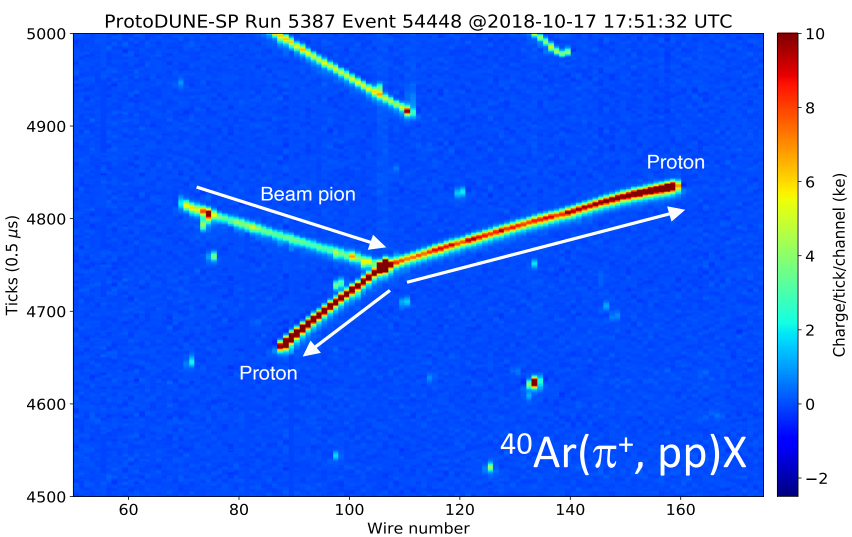




Shower max as a function of electron energy can be used to determine critical energy and radiation length in liquid argon.

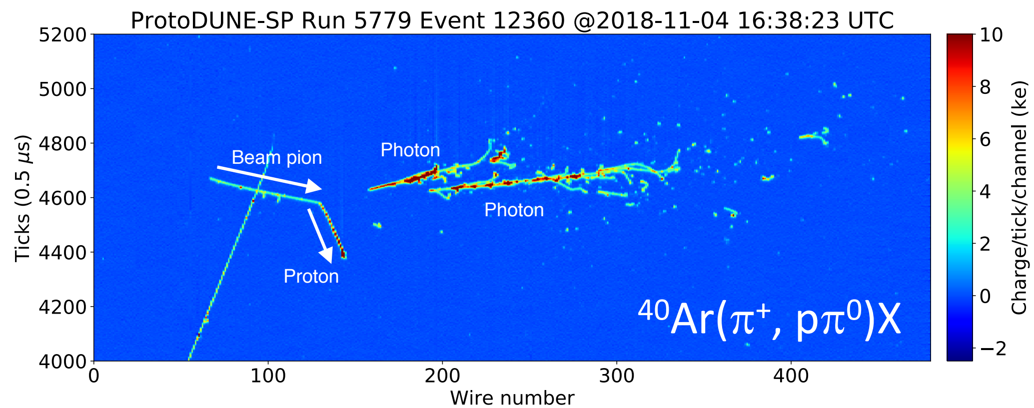
More details in *FERMILAB-CONF-20-008-ND.*

# Hadron-argon cross sections

- Hadron-argon cross sections provide critical information to **final state interaction (FSI)** in neutrino-argon interactions.
  - Collaboration with neutrino generator experts has started.
- Inclusive pion-argon and proton-argon cross sections
  - **Elastic scattering** and **inelastic scattering**
- Exclusive channels




Pion absorption candidate.

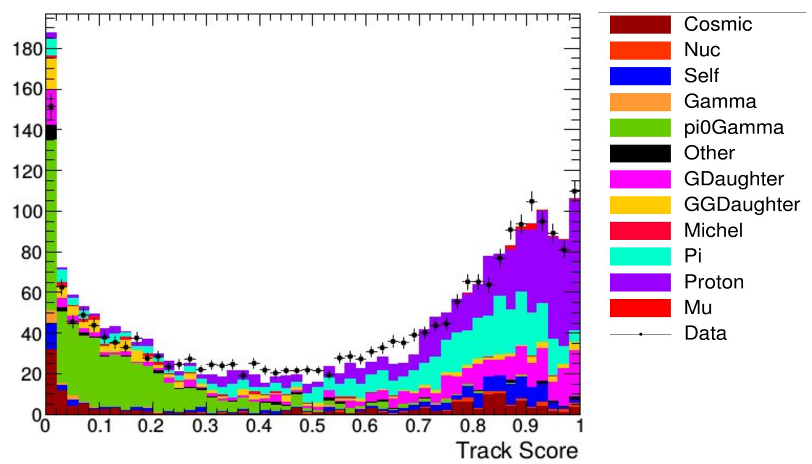


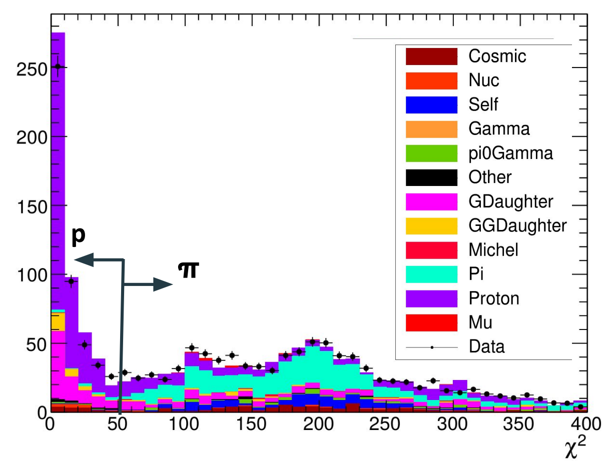

Pion charge exchange candidate.

# Pion absorption

- The primary process for pion absorption on heavy nuclei is thought to be the absorption on two nucleons
  - $\pi^+ nn \rightarrow pn$, $\pi^+ pn \rightarrow pp$
  - Final state interaction will change the number of nucleons seen in the TPC
- Event selection: only protons in the final state (no charged or neutral pions)
  - CNN track/shower ID to remove $\gamma$, $\chi^2$ PID to remove charged pions

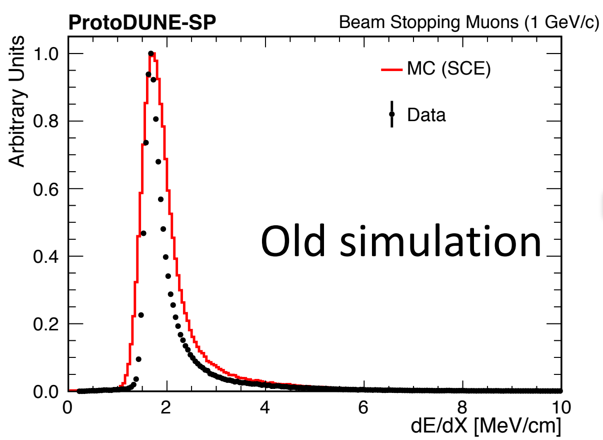
CNN on Collection plane



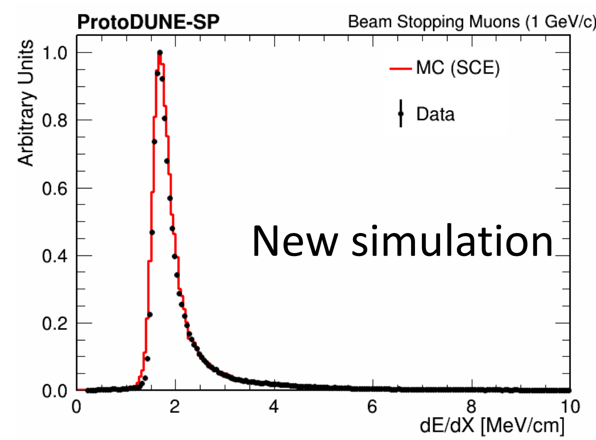



# Improvement on simulation

- A simulation task force was formed
  - Improved interface to Geant4 through refactorization of code.
    - A connection with the Geant4 community is established
  - Wire-Cell detector simulation
    - Improved detector response simulation: realistic response functions, induced charge on neighboring wires
- The simulation tuned with ProtoDUNE data will be used in DUNE far detector simulation.

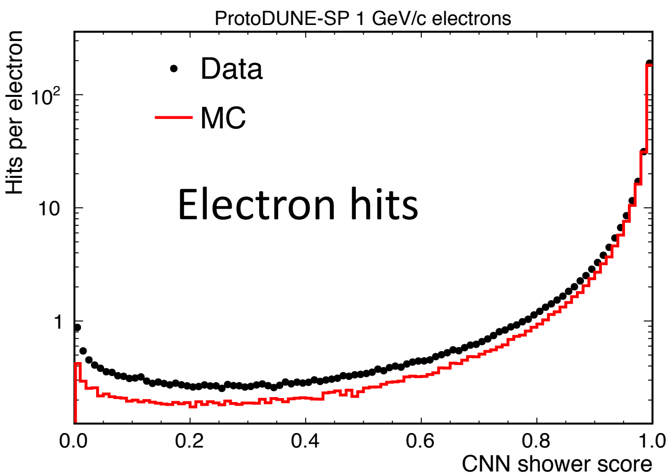


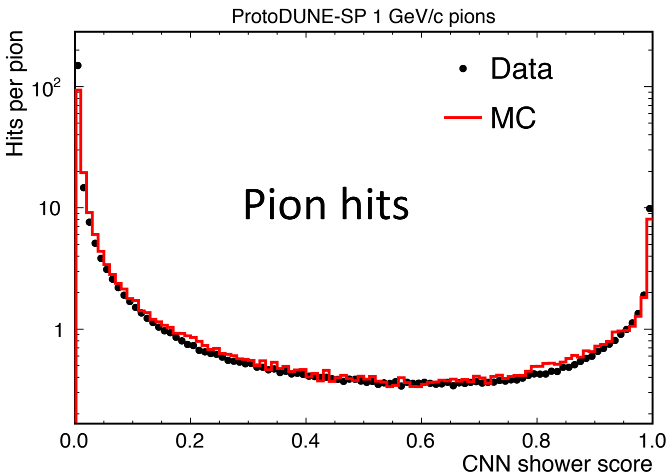

MC resolution is worse than data



# Testing reconstruction tools

- The high-quality of ProtoDUNE-SP data are ideal to test reconstruction tools that will be used in DUNE.
- One powerful tool is to use convolutional neural network (CNN) to separate track and shower hits.




- Also in collaboration with ML experts to develop new tools
  - Using TensorRT improves CNN speed by a factor of 14!

# Conclusions

- ProtoDUNE-SP performance paper is currently under review and will be submitted soon.
- ProtoDUNE-SP have a very strong and effective analysis team that will deliver many more results:
  - Improving the understanding of LArTPC technology
  - Physics measurements: hadron-argon cross sections
  - Valuable information for the future DUNE reconstruction and data analysis.