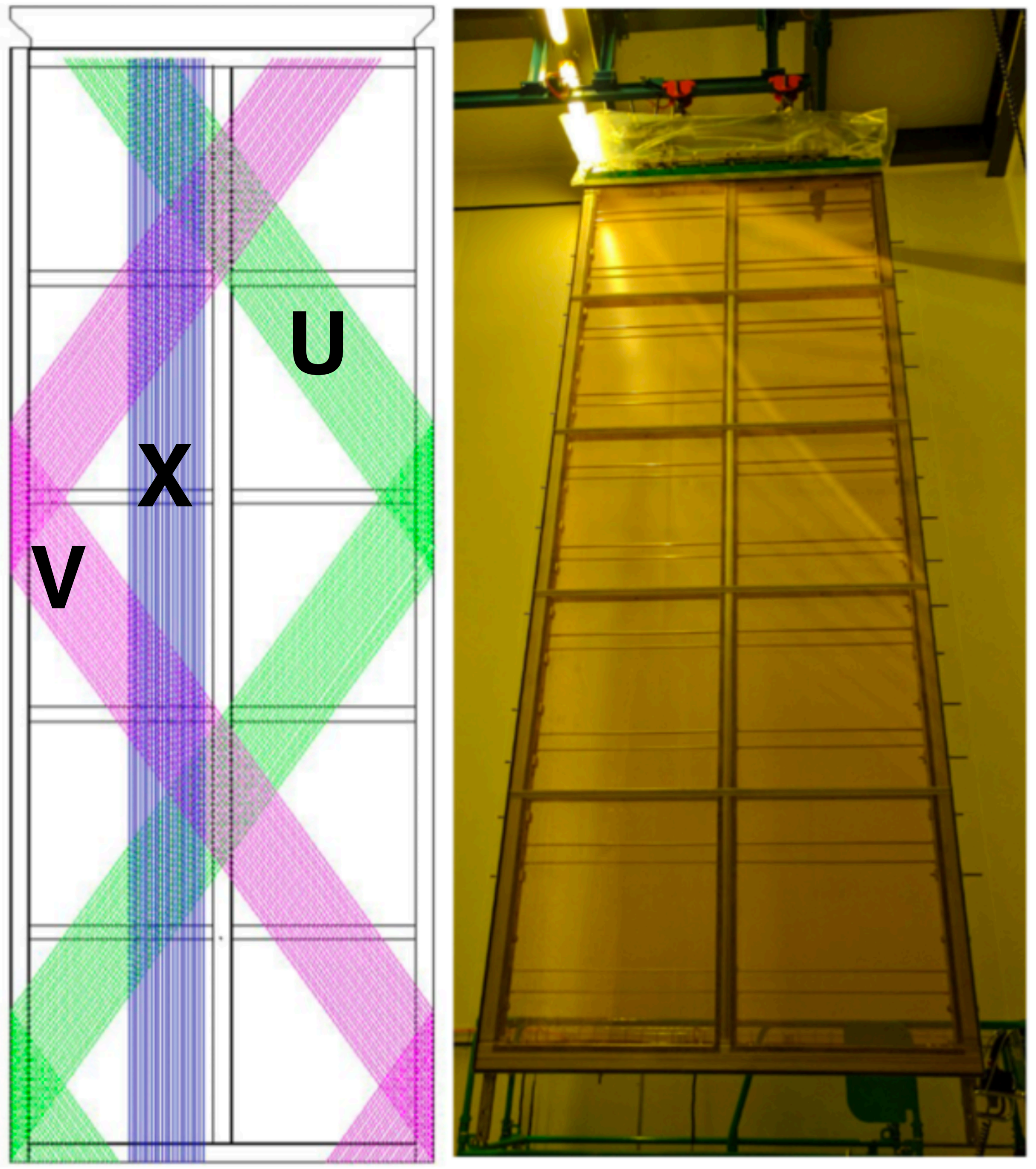
ProtoDUNE-SP's Performance, Physics status, and Future Plans

Sungbin Oh, on behalf of the DUNE collaboration
Fermi National Accelerator Laboratory

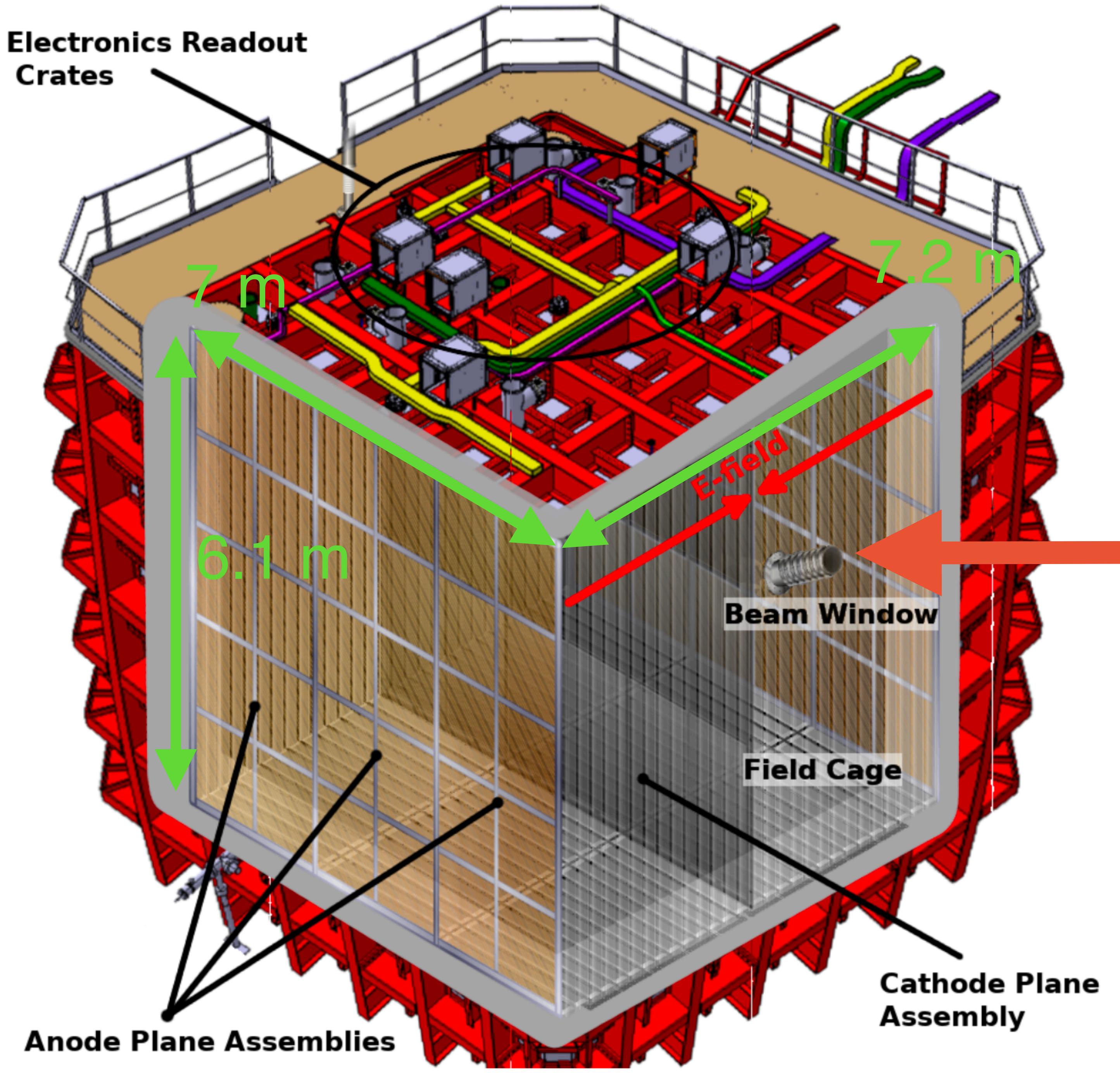
NuFACT 2023, Seoul, Korea

ProtoDUNE-SP : Overview

- A single-phase liquid argon (LAr) time projection chamber (TPC)
- A prototype for full-scale elements of the first far detector module of the DUNE
- Total LAr mass of 0.77 kt on surface at the CERN neutrino platform



An anode plane assembly



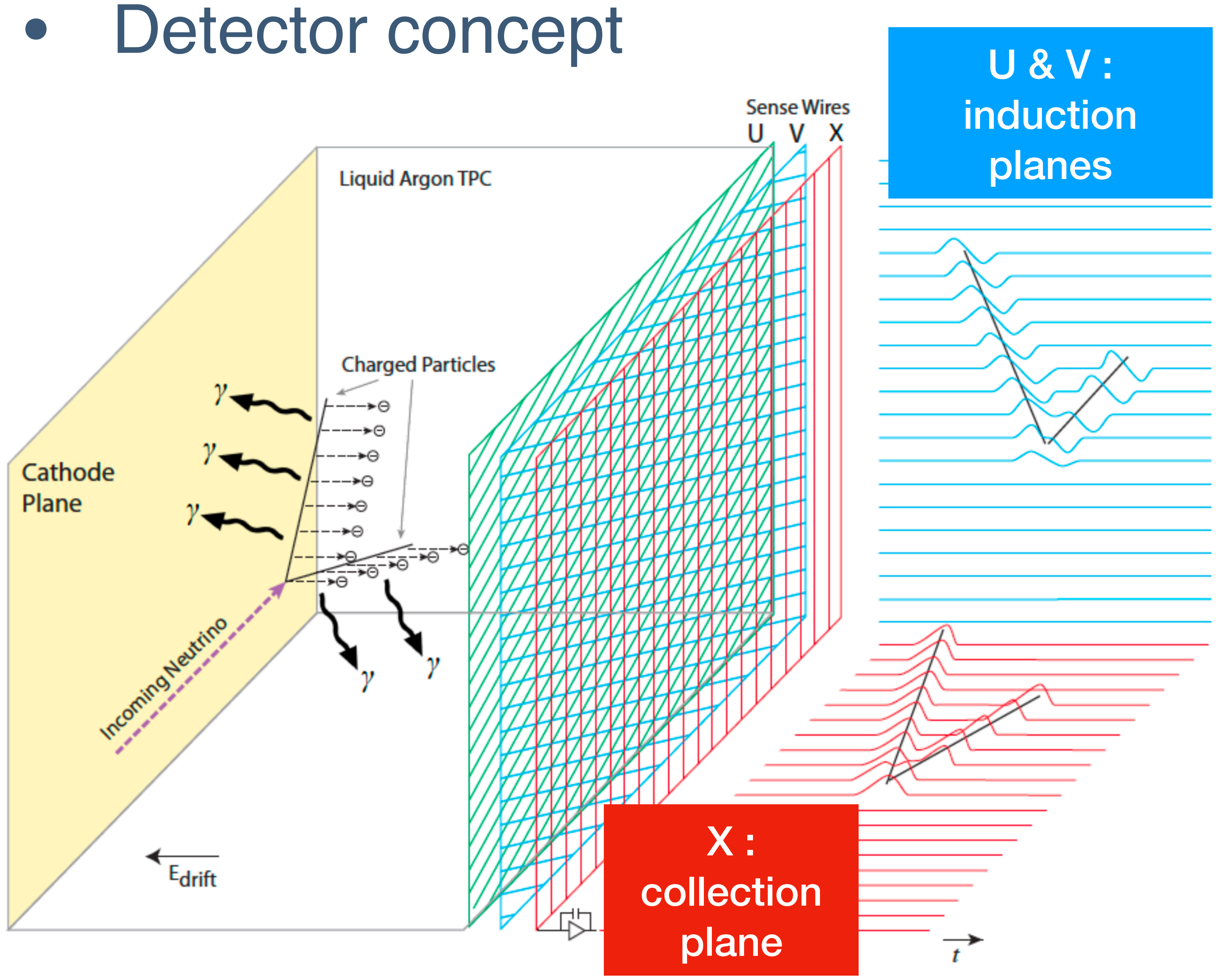
ProtoDUNE-SP

Tagged and Momentum analyzed particle beam
e^+, μ^+, π^+,K^+ and p^+
with momentum from 0.3 to 7 GeV/c

ProtoDUNE-SP : Operation

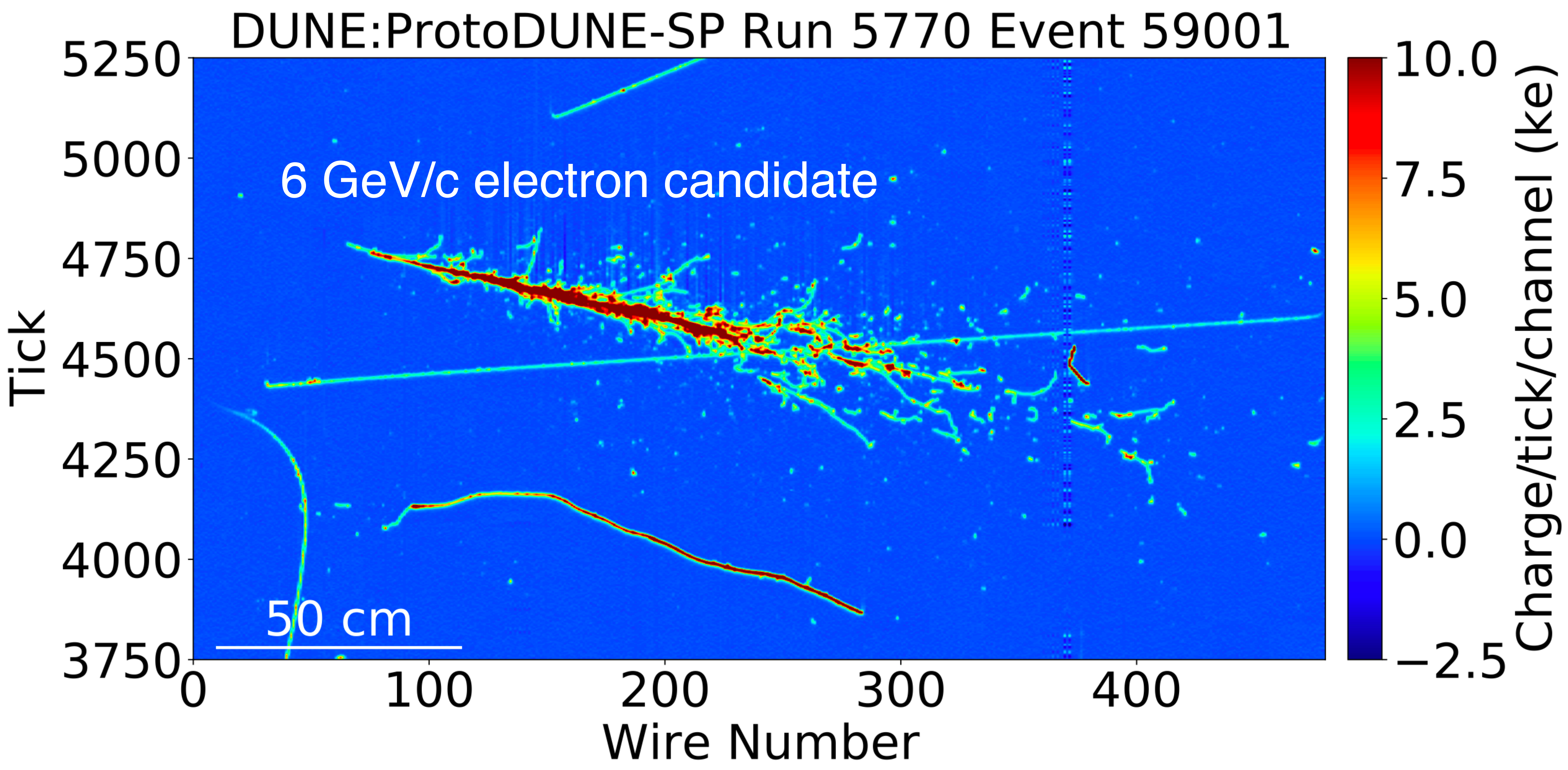
- Construction and installation was completed : early July 2018
- Filling LAr and commissioning : July - Aug. 2018
- Beam run : Aug. 29 - Nov. 11 2018
- Cosmic run : continued through July 19, 2020

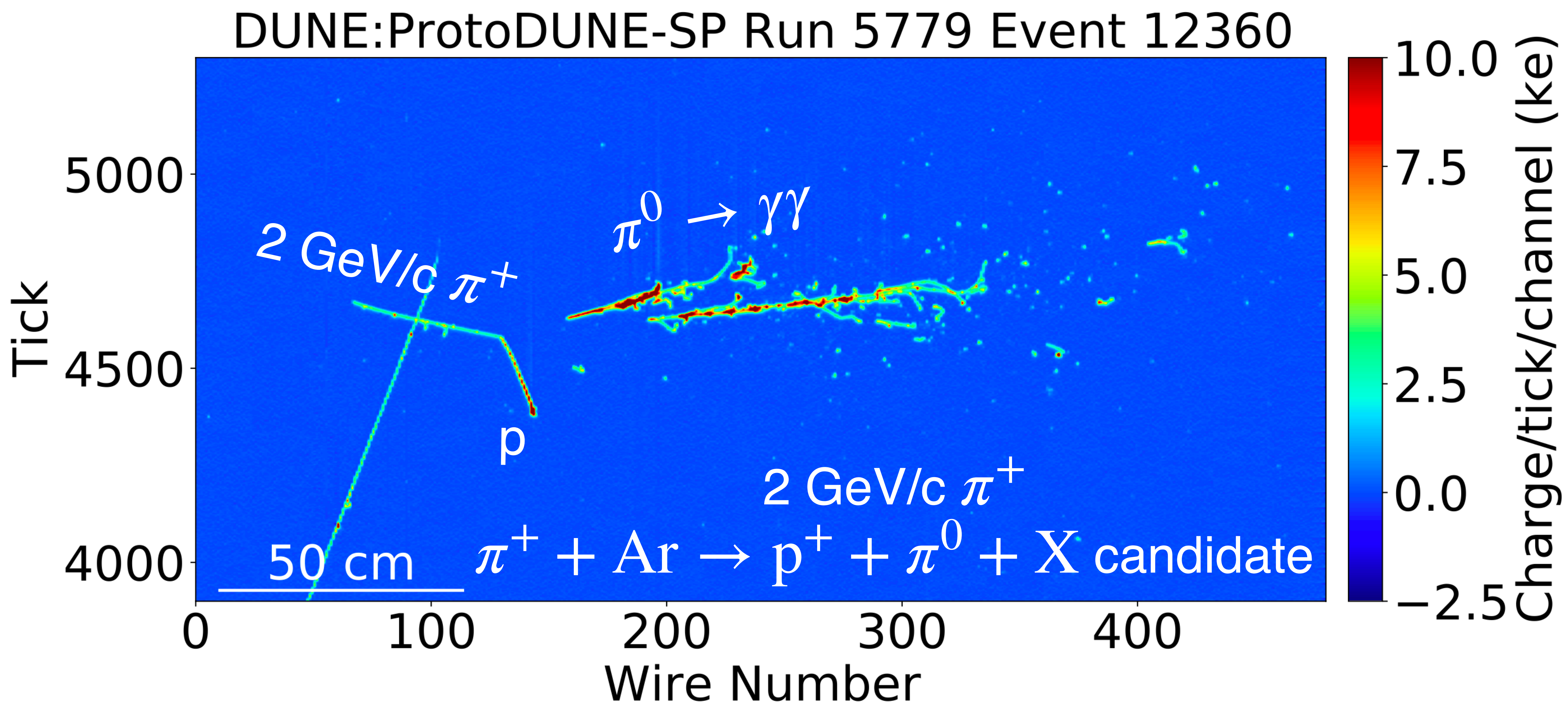
- Detector concept

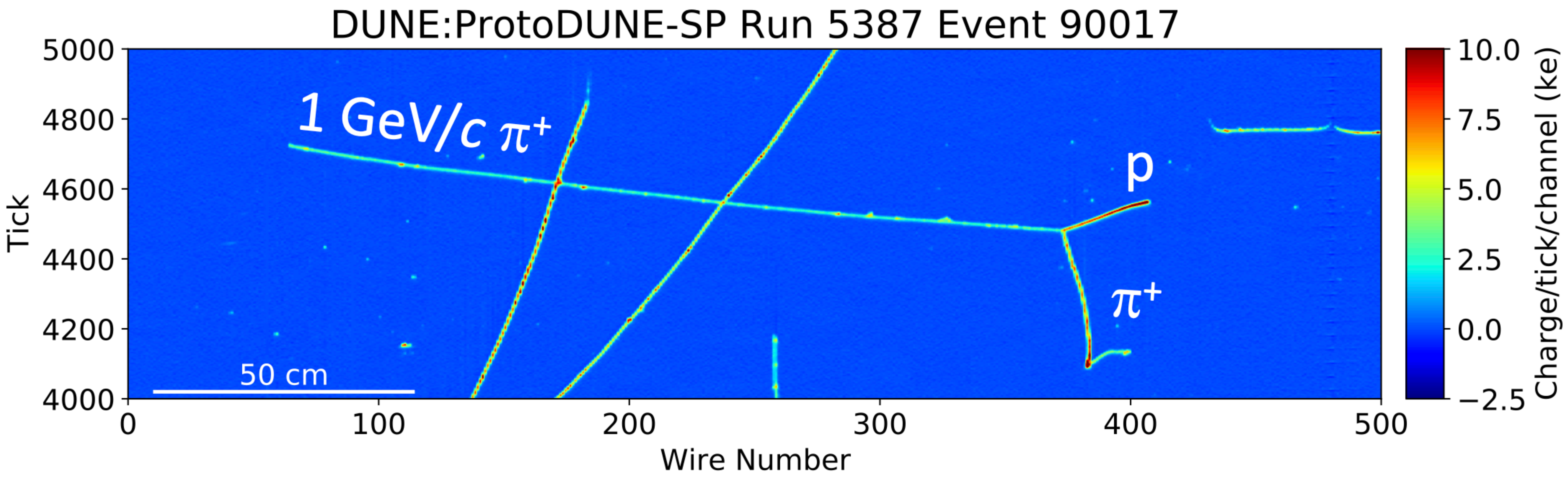


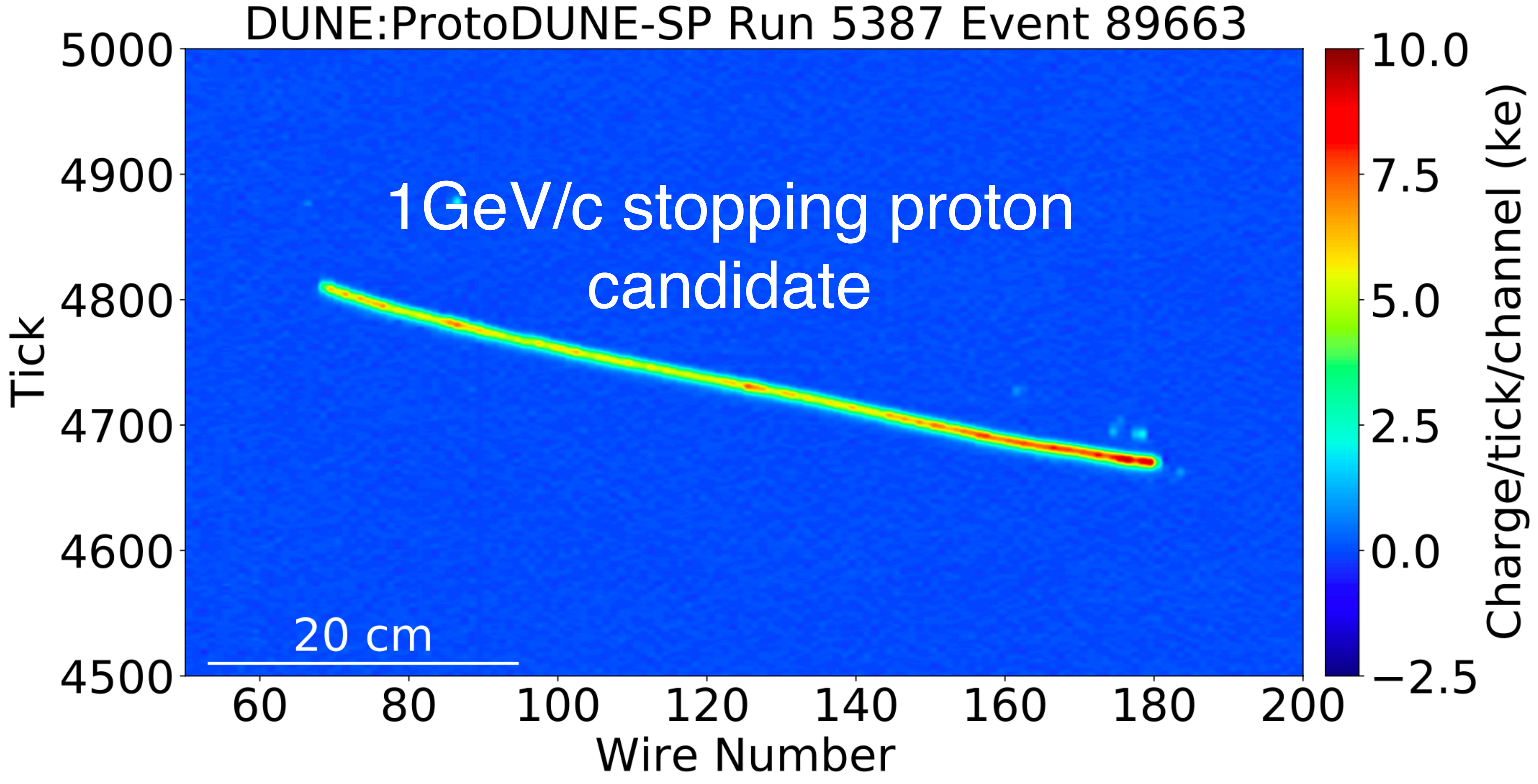
- Charged particles ionize argon atoms
  - Electrons are drifted by an electric field to anode wires
    - Maximum drift time is about 2.2 ms
    - Impurities such as O_2 and H_2O absorb drifting electrons
  - Photons are emitted through recombination between Ar^+ and e^-
    - Detected by photon sensors
    - Impurities such as N_2 absorb such photons
    - Used to define the T_0 of an event

ProtoDUNE-SP : Event Displays







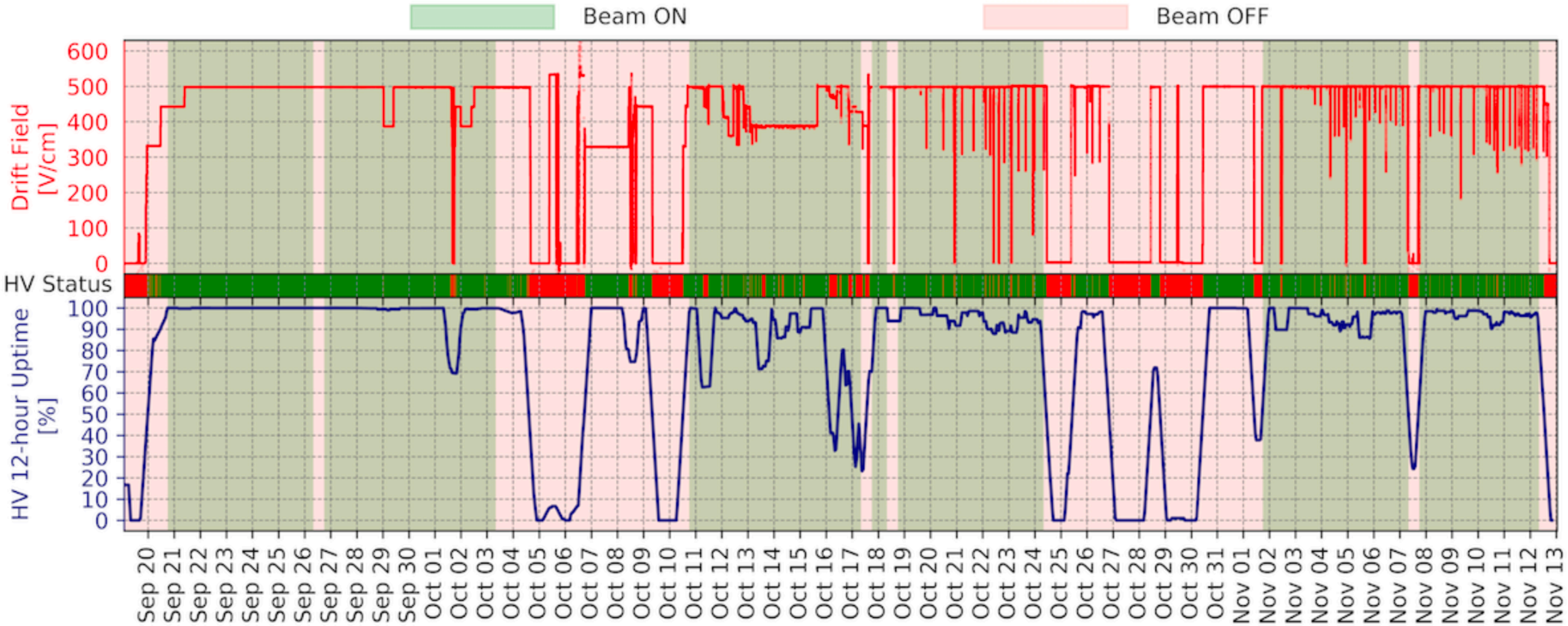


Performance - Drift Electric Field

- During the beam run
  - Stably worked at nominal level of 500 V/cm
  - Recovery from trips took an average of 4 minutes during beam-on periods
- For total data taking periods including cosmics, > 99.5% of uptime

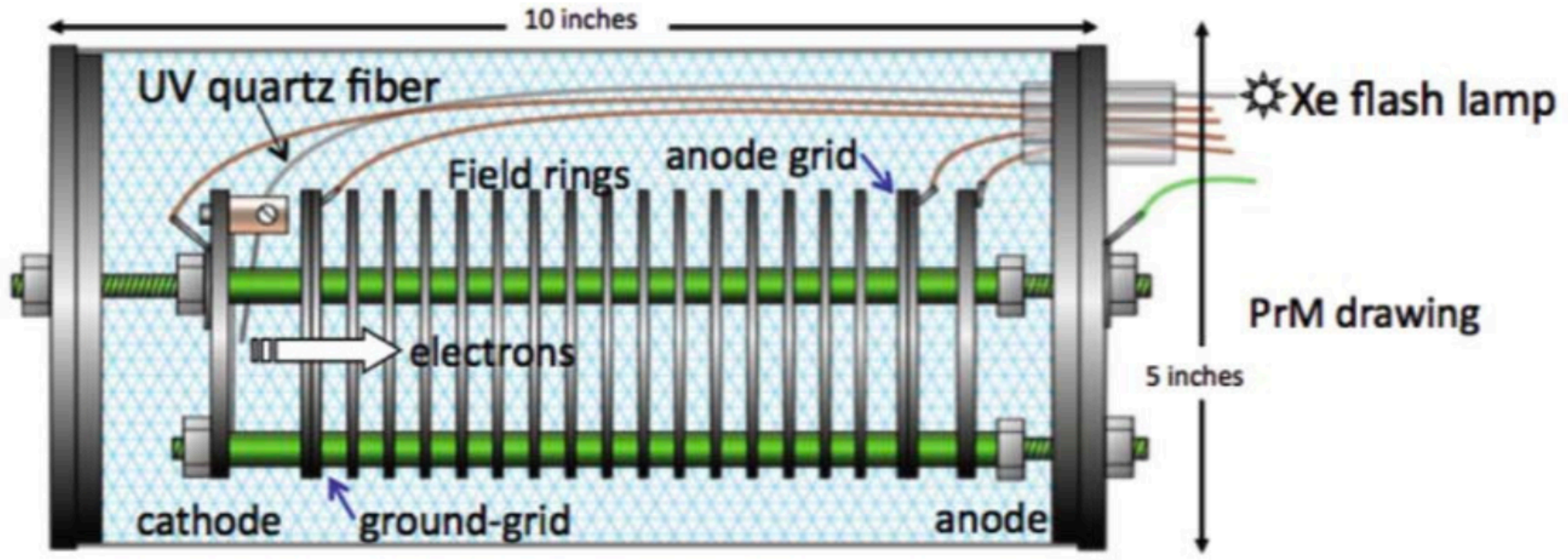
Drift Field [V/cm]

HV 12-hour uptime [%]

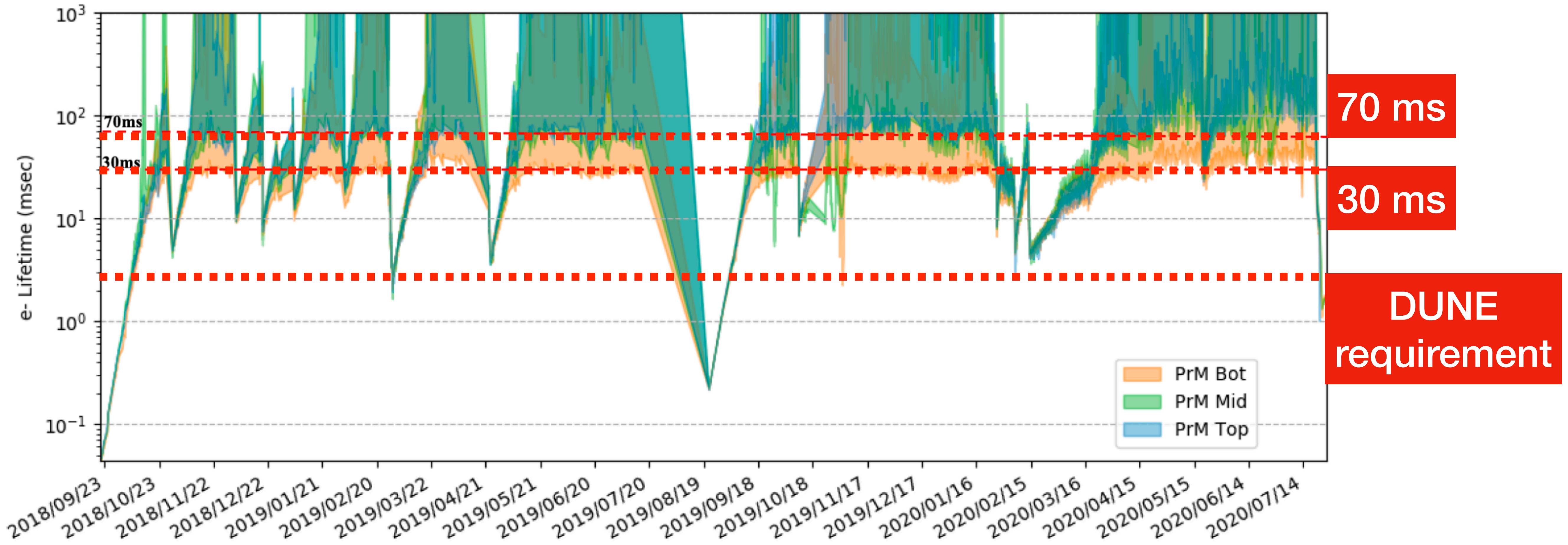


Drift field values and uptime percentage during beam data taking period

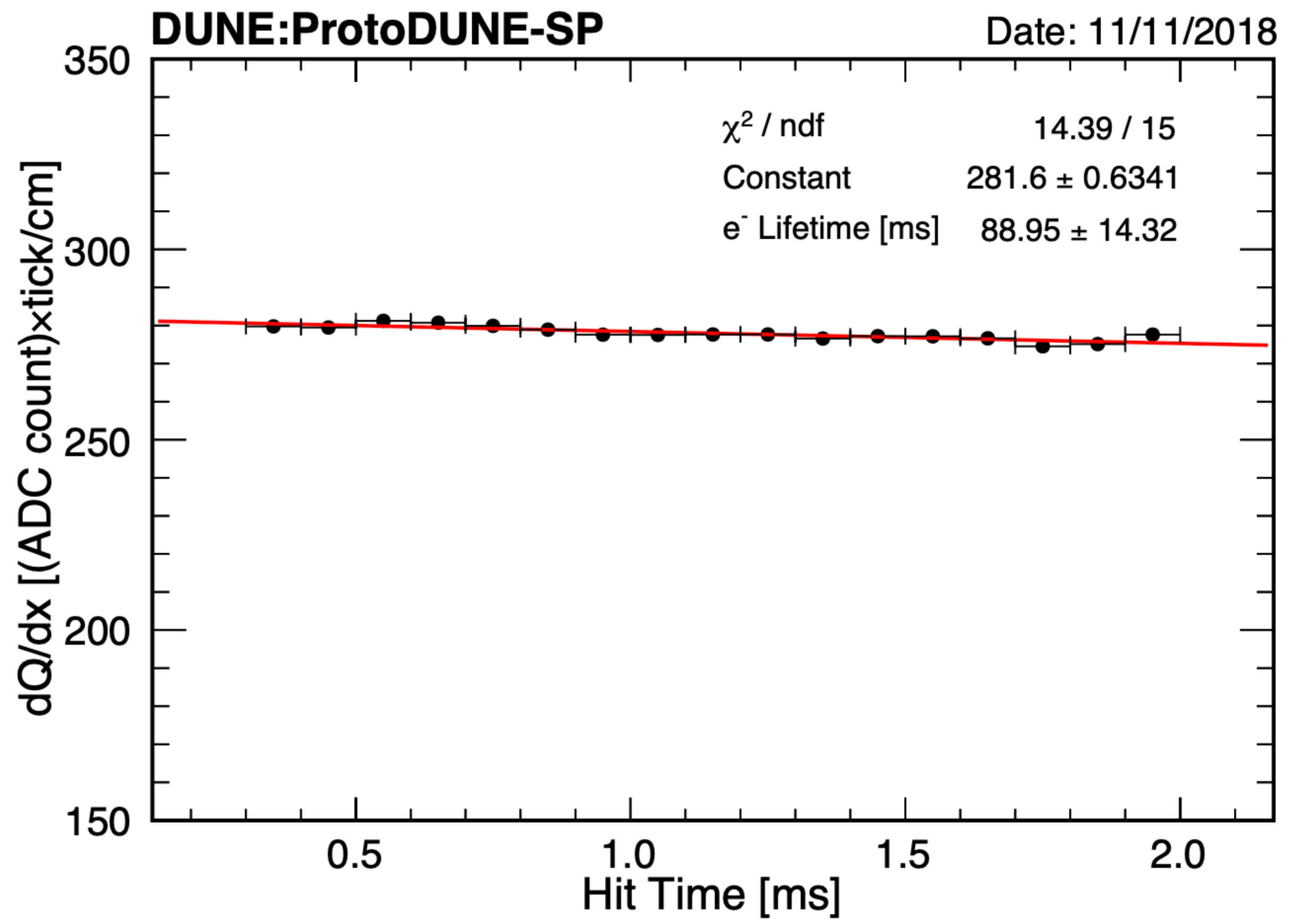
Performance - Electron Lifetime



- Purity monitors : outside field cage
  - Use fraction of photoelectrons generated at the cathode (Q_C) that arrive at the anode (Q_A) after time t
    - $Q_A/Q_C = exp(-t/\tau)$, where τ is the electron lifetime
- Cosmic muon sample : data from the TPC
  - Through going muons which pass cathode plane of the TPC : almost uniform dE/dx (MIP) and good T_0
  - Distribution of dQ/dx as a function of hit time provides electron lifetime

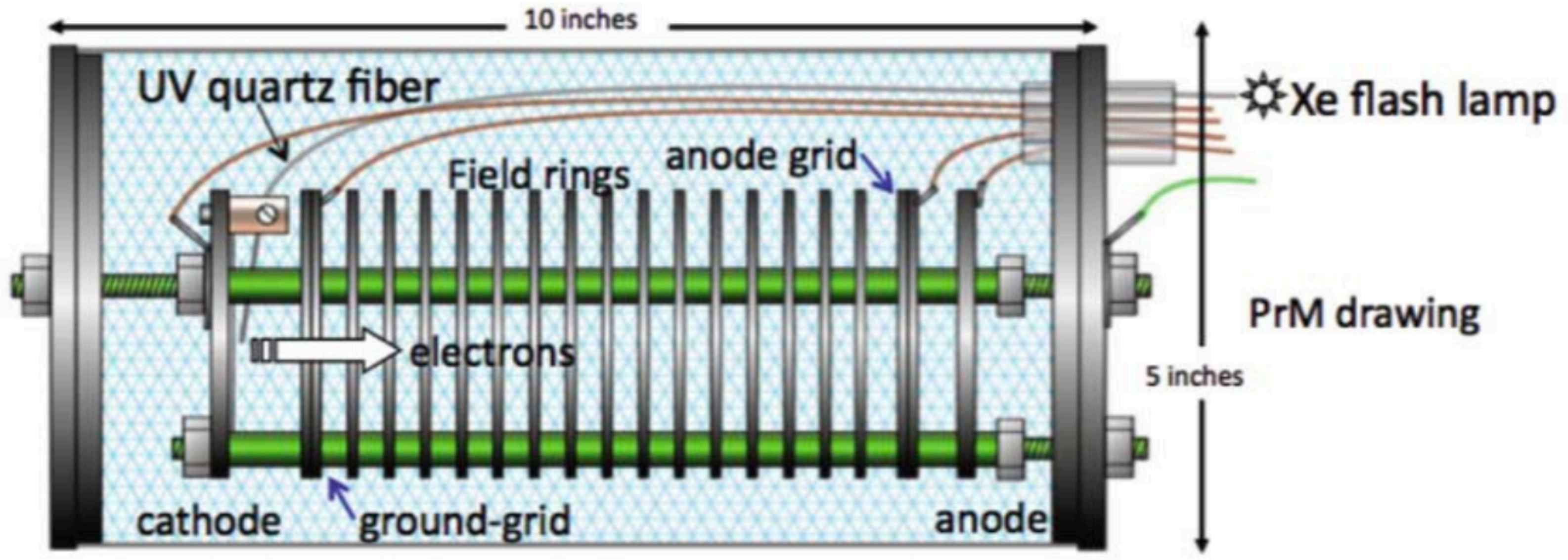


Purity monitor results

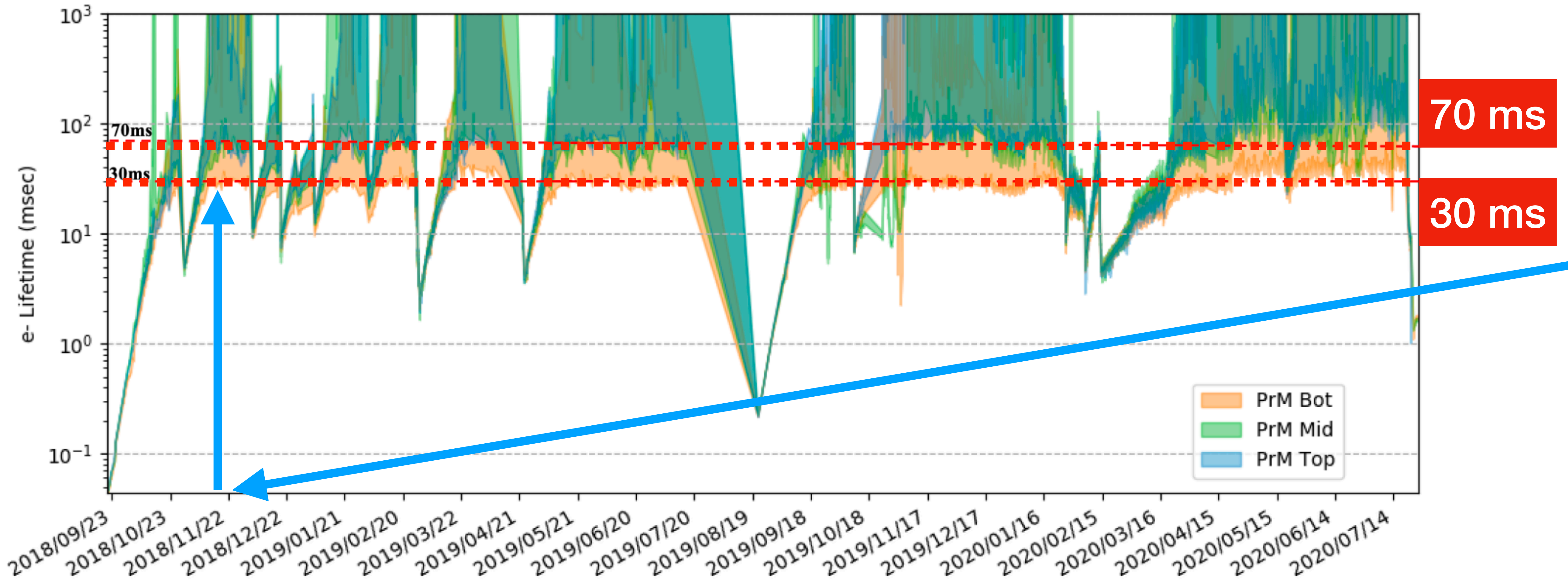


Cosmic muon result (2018/11/11)

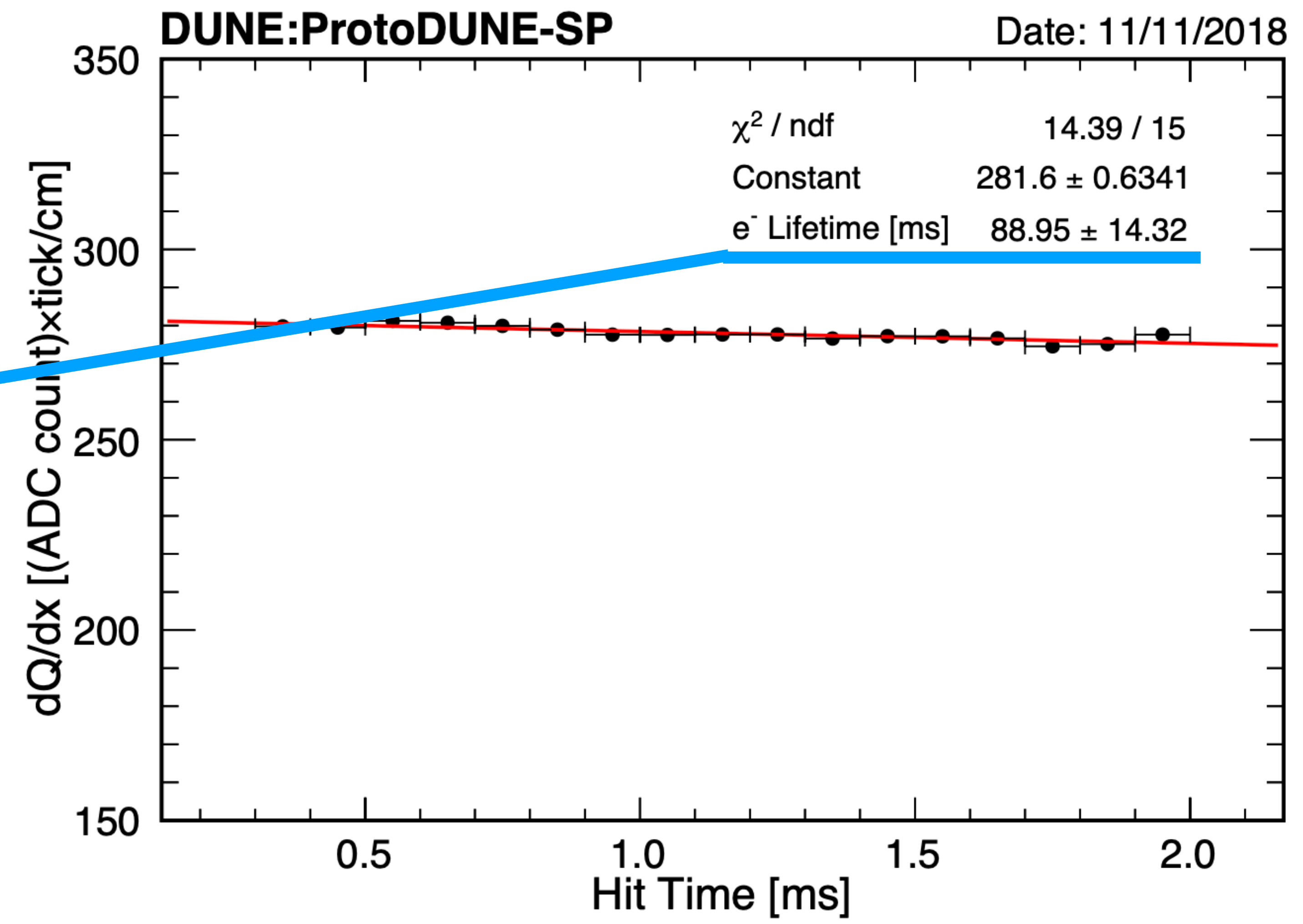
Performance - Electron Lifetime



- Purity monitors : outside field cage
  - Use fraction of photoelectrons generated at the cathode (Q_C) that arrive at the anode (Q_A) after time t
    - $Q_A/Q_C = exp(-t/\tau)$, where τ is the electron lifetime
- Cosmic muon sample : data from the TPC
  - Through going muons which pass cathode plane of the TPC : almost uniform dE/dx (MIP) and good T_0
  - Distribution of dQ/dx as a function of hit time provides electron lifetime



Purity monitor results

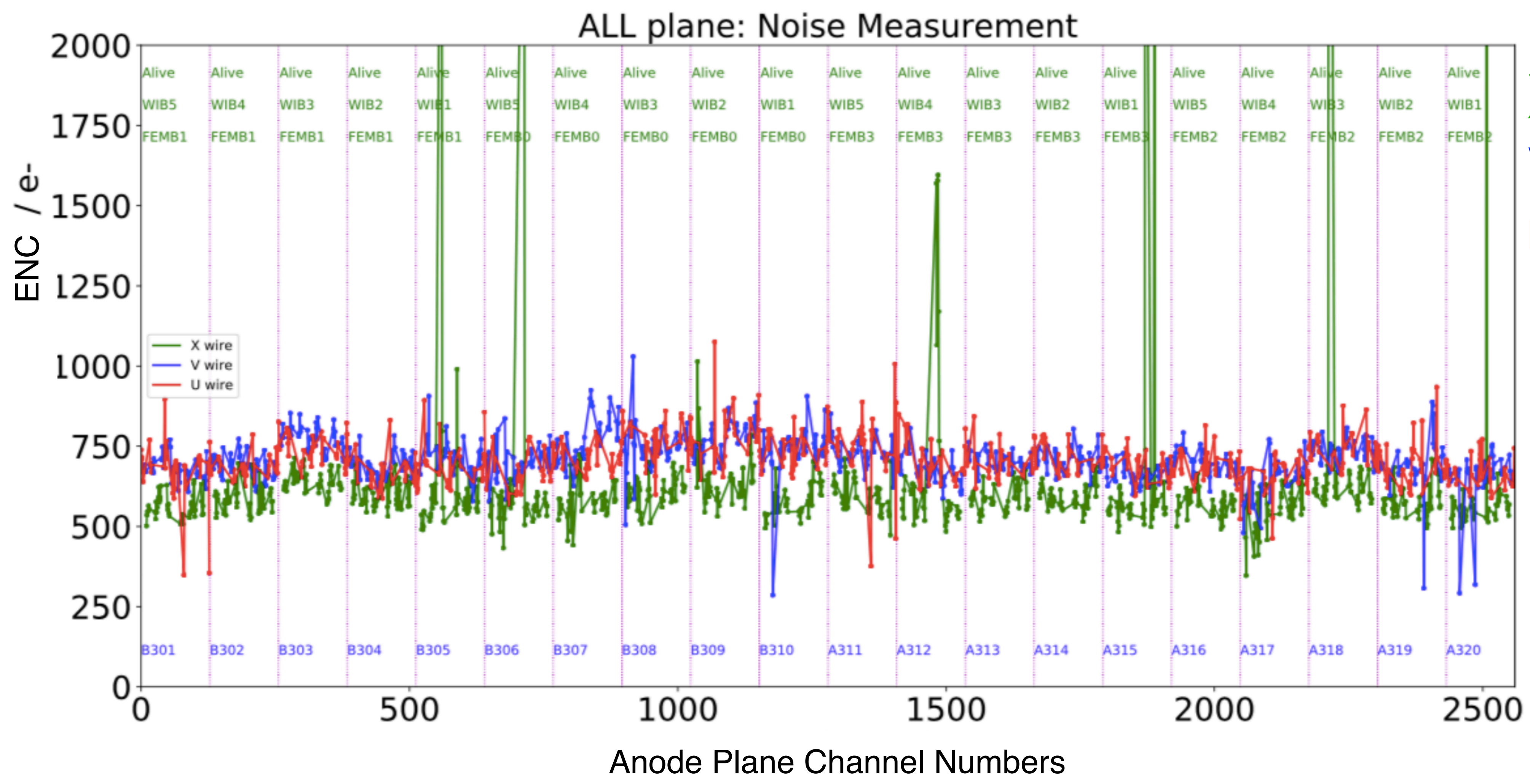


Cosmic muon result (2018/11/11)

Fermilab DUNE

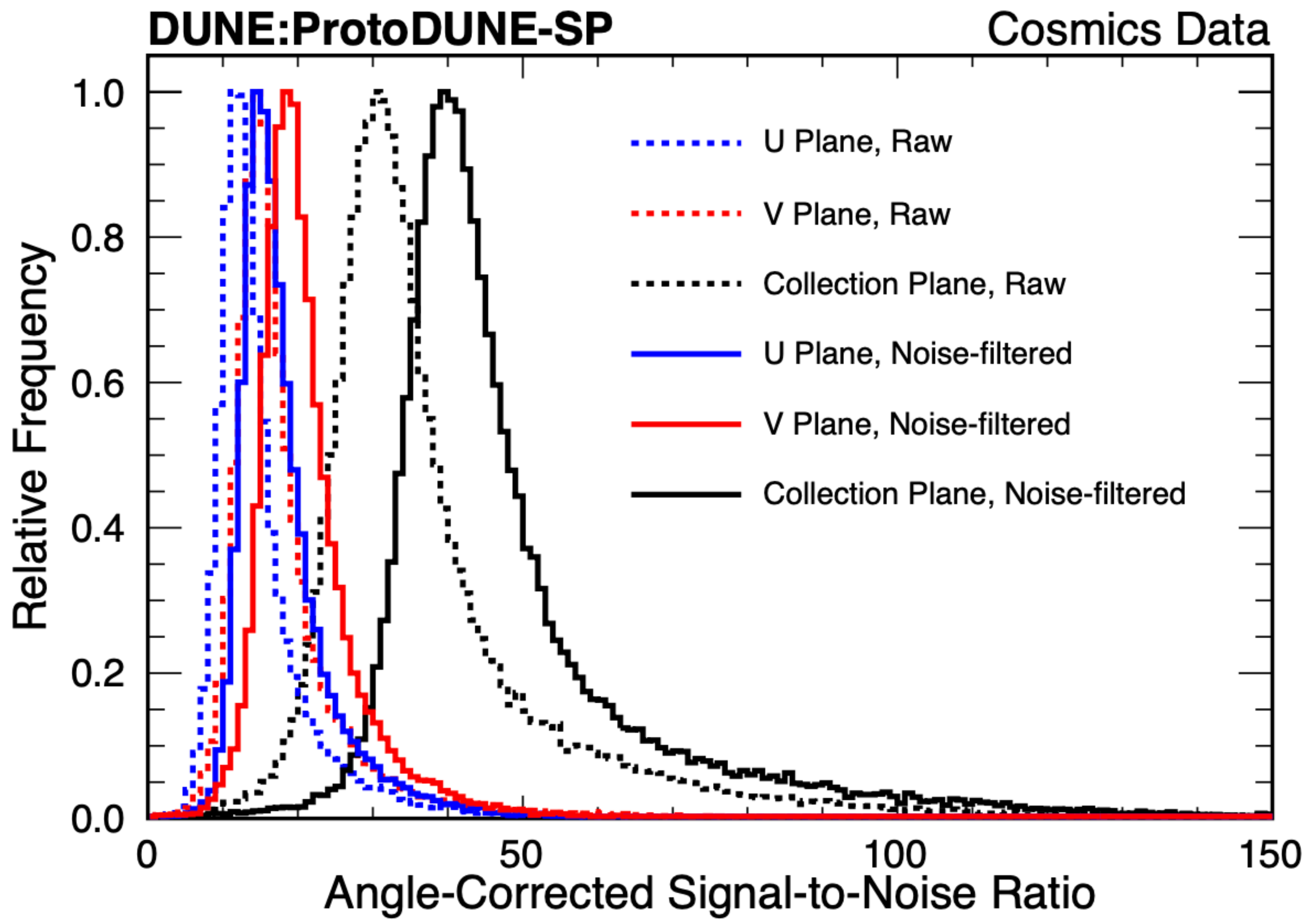
Performance - Electronic Noise

- There is no electron multiplication upstream of sense wires
  - Signals on wires induced by drifting electrons are very small : thousands of electrons
  - Noise level much lower than such signals is essential for hit reconstruction
- Electronic noise of all channels in anode planes : in the unit of equivalent noise charge (ENC) - more in backup
  - Averaged over all operational channels : $\sim 550\ e^{-}$ for the collection plane, $\sim 650\ e^{-}$ for the induction planes



X plane
V plane
U plane

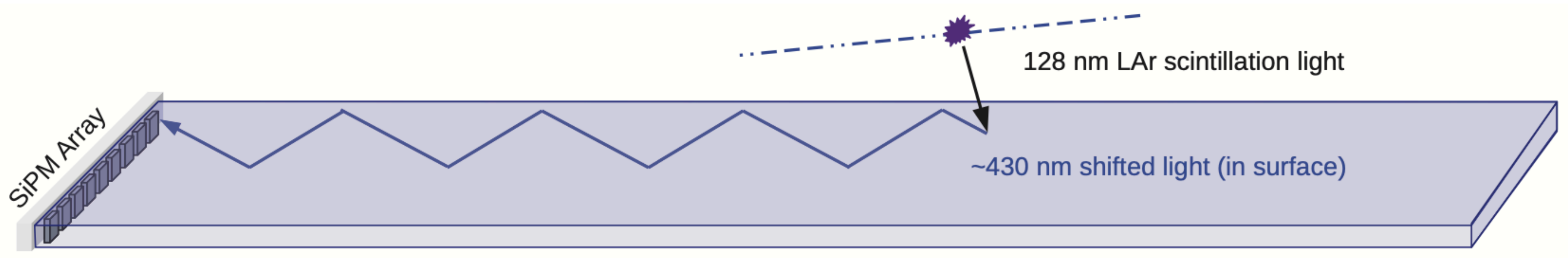
ENC of all channels of an anode plane assembly

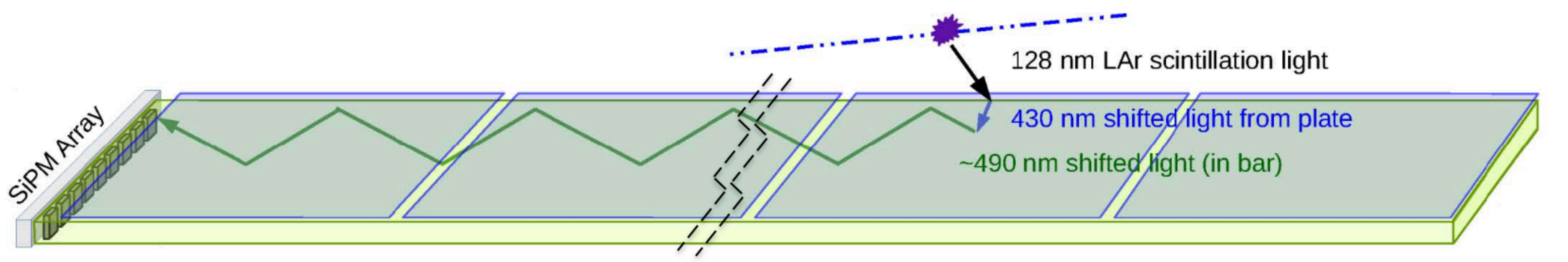


Plane	Peak signal-to-noise ratio			
	Raw Data		After noise filtering	
	MPV	Average	MPV	Average
Collection	30.9	38.3	40.3	48.7
U	12.1	15.6	15.1	18.2
V	14.9	18.7	18.6	21.2

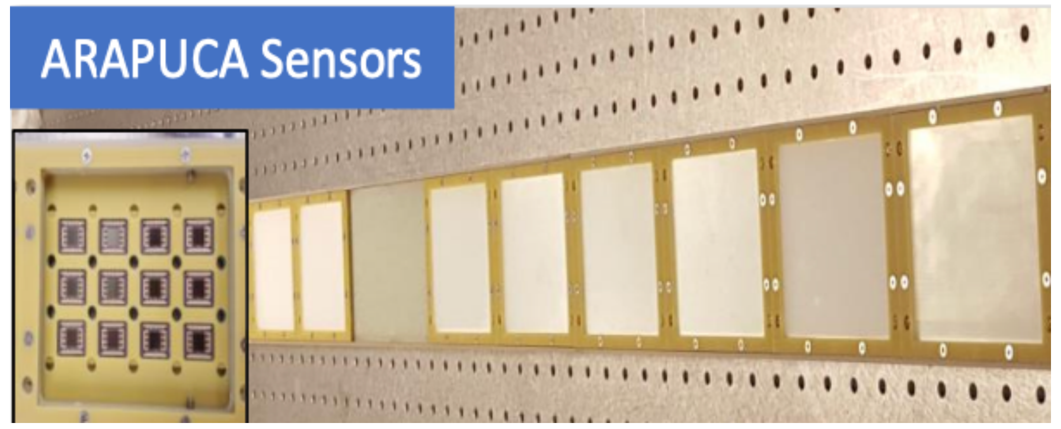
Signal-to-Noise Ratio

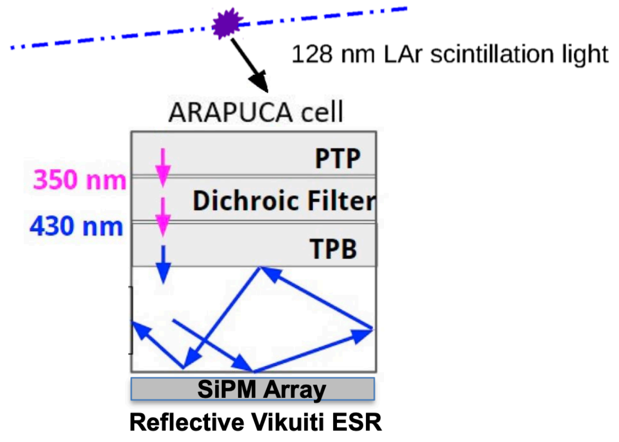
Performance - Photon Detector System

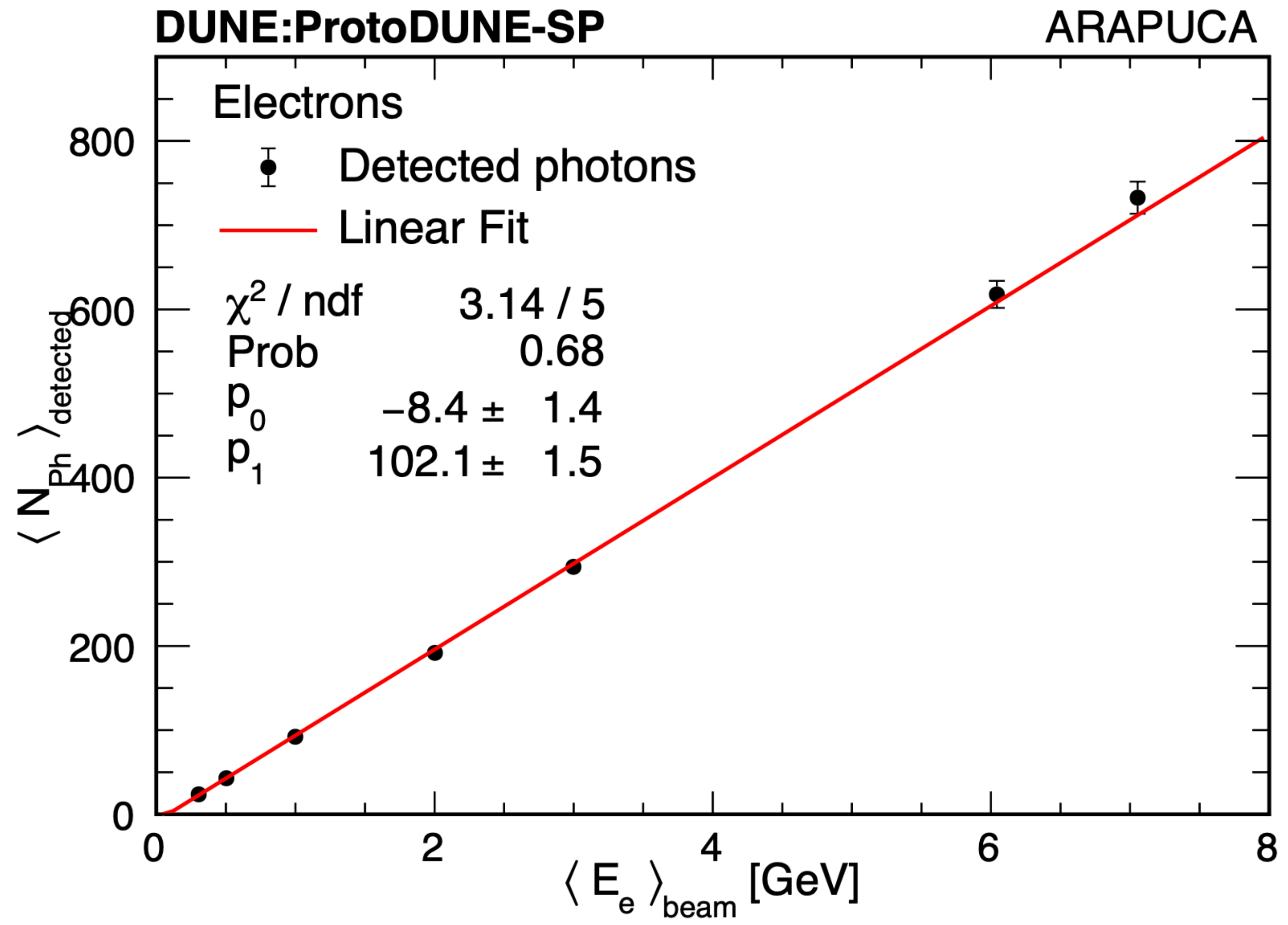


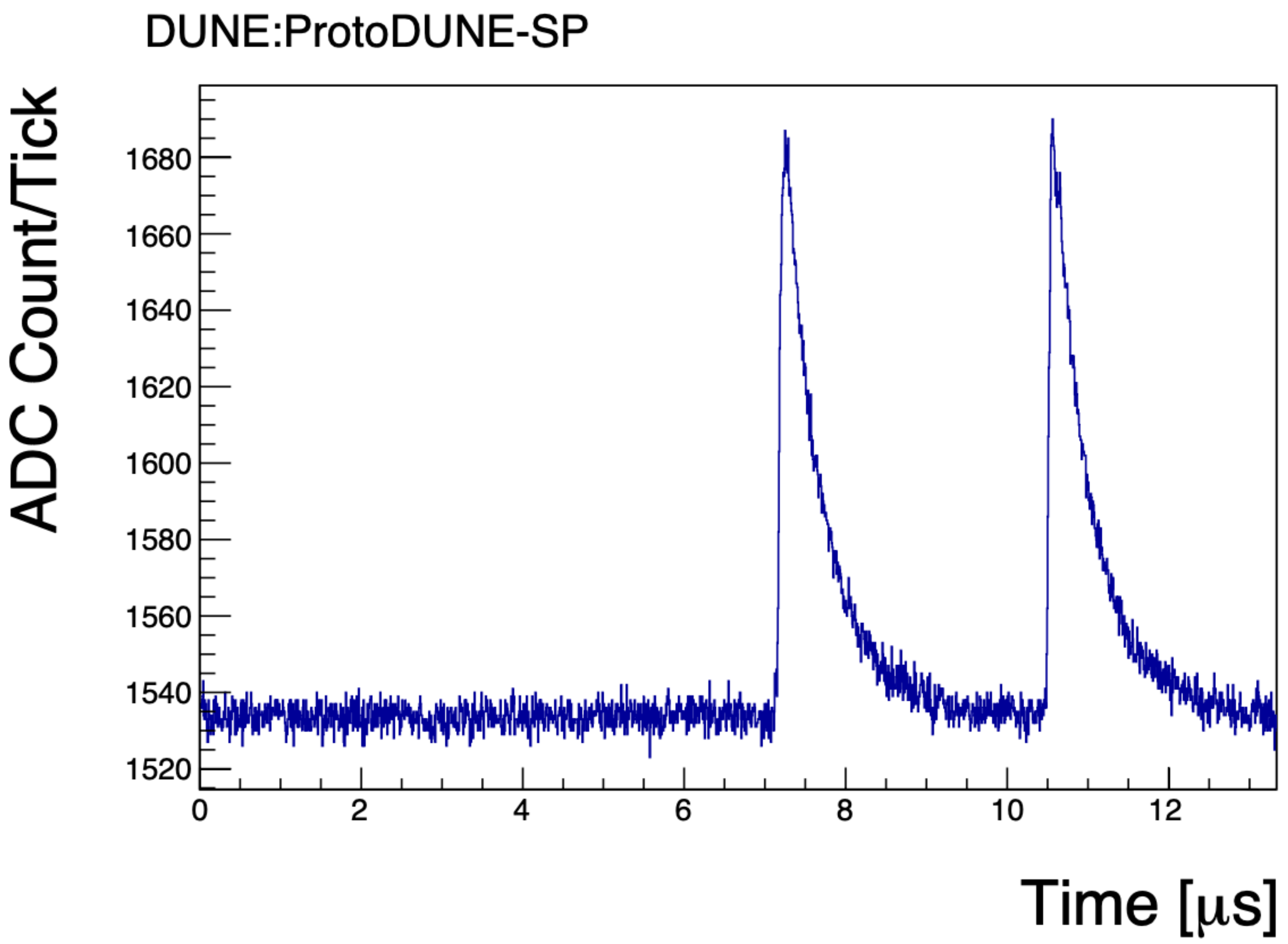


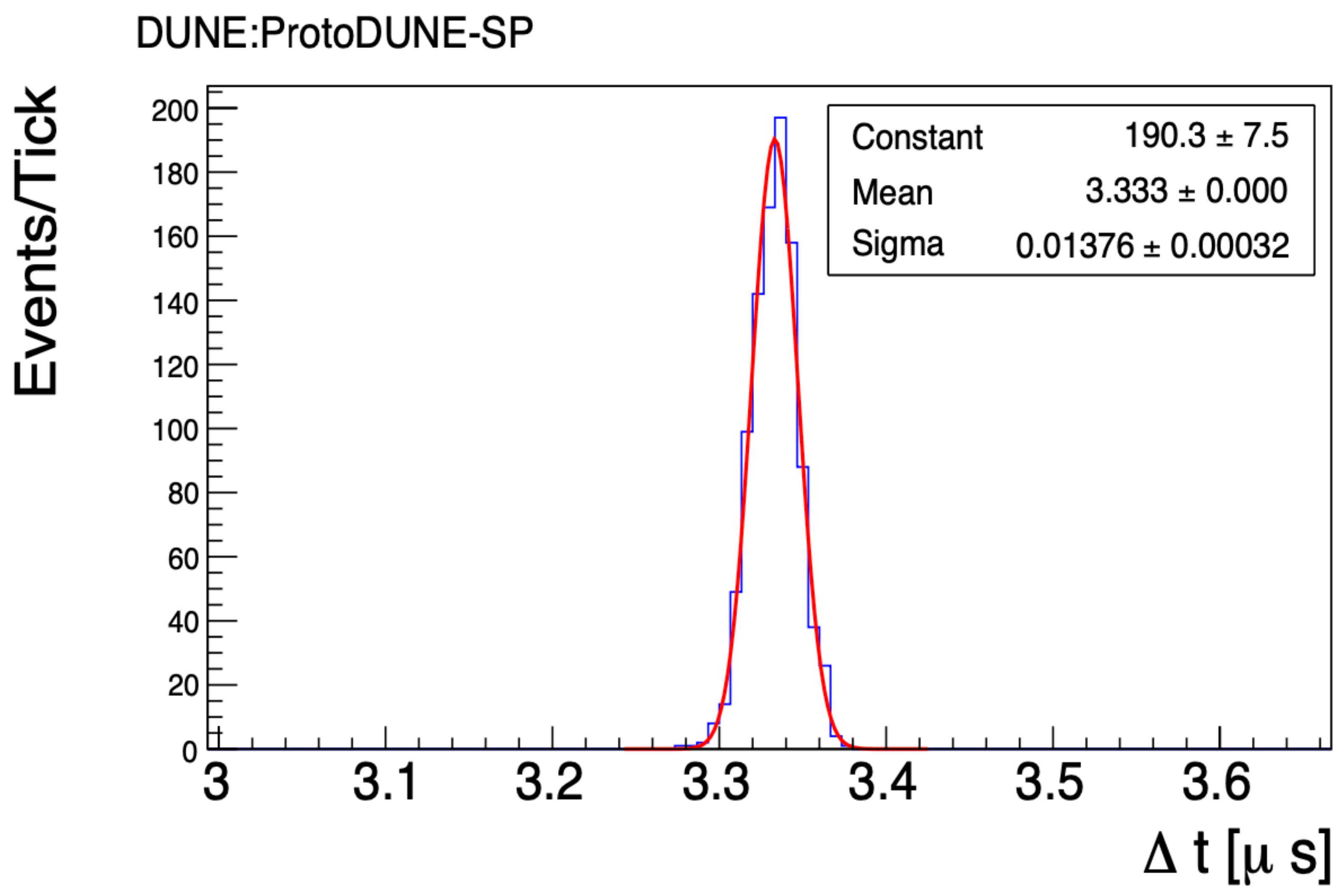
- The photon detector system (PDS) consists of three types
  - Wave guiding to SiPMs with two coating schemes
  - Light trap - "ARAPUCA"
- Light yield : 1.9 photons / MeV
- Timing resolution
  - Resolution on time difference between two pulses : ~ 14 ns











Electron beam energy vs. ARAPUCA light yield

Timing resolution measurement using the calibration system provided pulses

Performance - Summary

- ProtoDUNE-SP meets or surpasses the specifications set for the DUNE far detector
  - Effectiveness of the single-phase DUNE far detector design
  - Execution of the fabrication, assembly, installation, commissioning, and operations phases

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

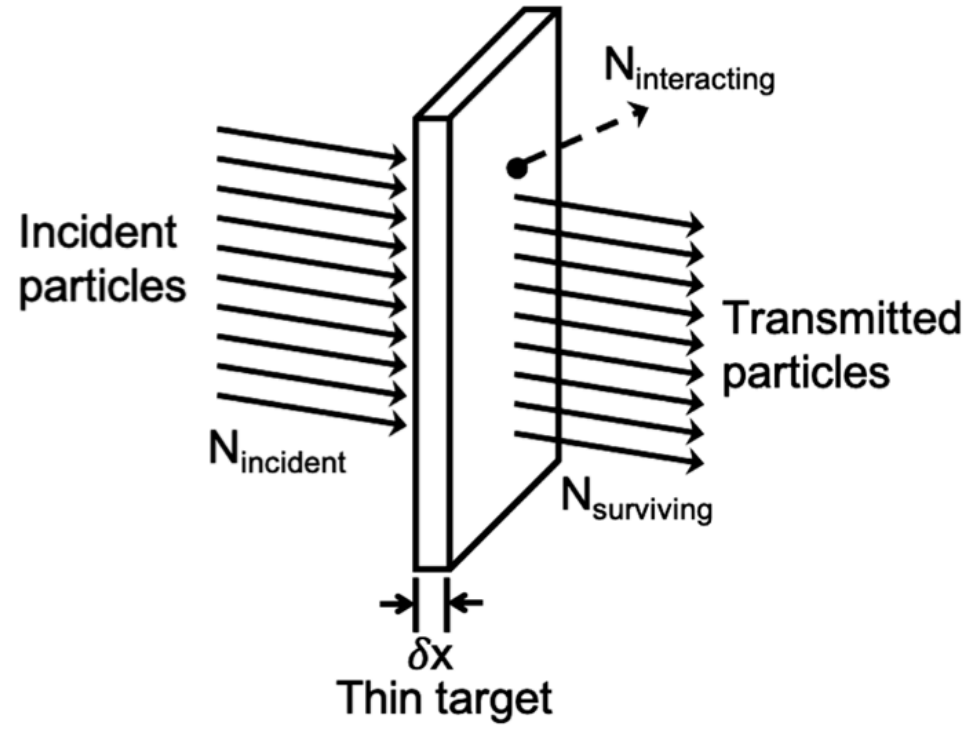
JINST 15 (2020) 12, P12004

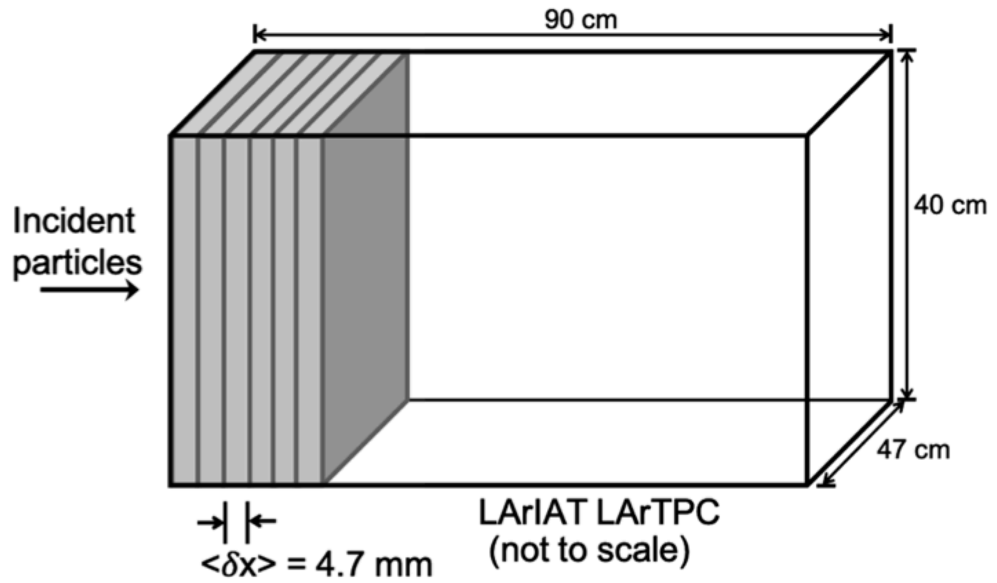
Hadron - Argon Cross Section Measurements

- Motivations
  - Nuclear effects in argon will be one of the most dominant sources of systematic uncertainties of the DUNE
  - Hadron - Ar cross section results are essential inputs to model such effect
    - Final-state interactions of knocking out nucleons and resonantly produced particles before leaving the interacting nucleus
    - Multi-nucleon correlations for neutrino - Ar interactions
    - Secondary interactions of knocked out nucleons or resonantly produced particles with other argon atoms in the detector

  - Not enough experimental results for hadron - Ar scatterings in kinetic energy ~ 100 MeV to 1 GeV region
    - We are interpolating experimental results of nuclides with similar atomic masses to model hadron - Ar cross sections
    - ProtoDUNE analyses can provide unique results that have never been measured

Cross Section Measurement Principle



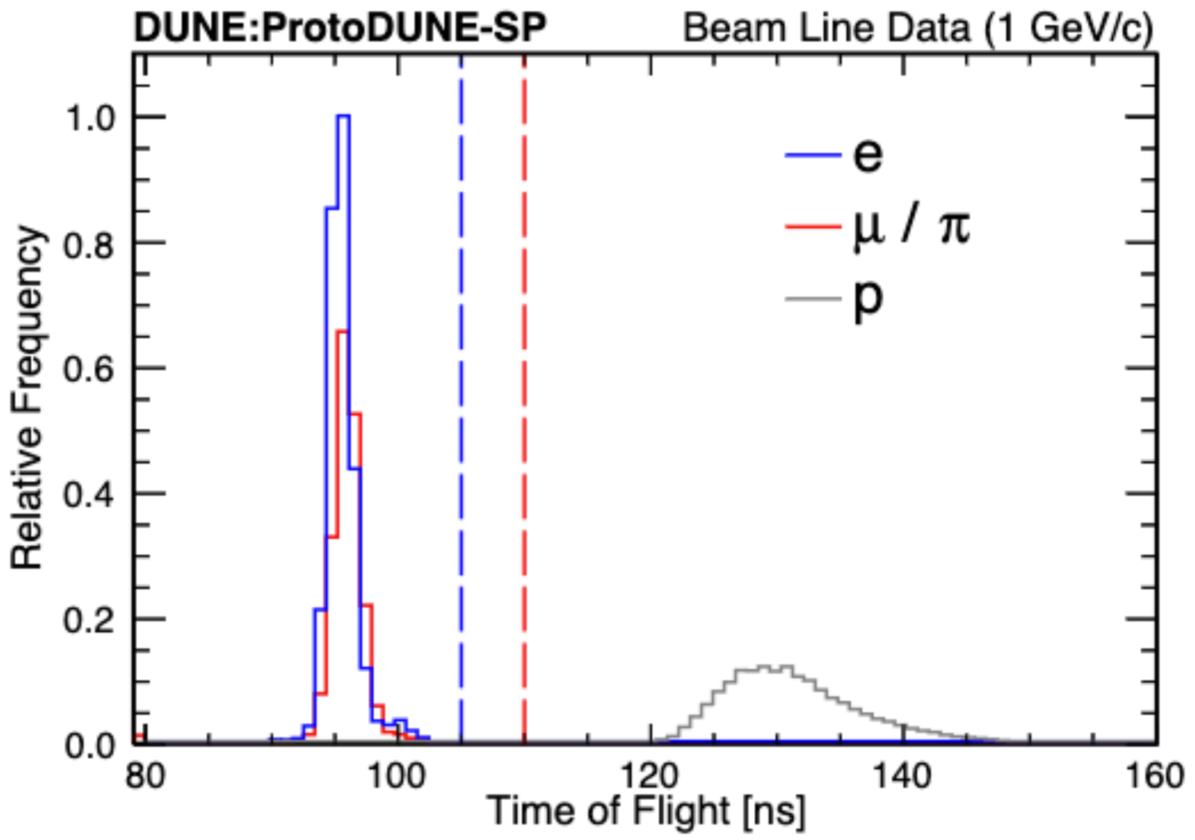


- Interactions inside a continuous medium
  - Consider propagation of beam particle as **series of thin-target experiments**
  - The LArIAT collaboration introduced the "thin slice method" **Phys. Rev. D 106, 052009**
    - ProtoDUNE expands this pioneering work
- The formula measuring cross sections
  - Cross section (σ) in a thin slice with a width δx
    - Count number of beam particles enter the slice : $N_{Incident}$
    - Count number of beam particles that interact inside the slice : $N_{Interact}$
  - Interaction probability $= \frac{N_{Interact}}{N_{Incident}} = 1 - \exp(-\sigma n \delta x) = 1 - \exp\left(-\sigma n \Delta E \frac{1}{dE/dx}\right)$,

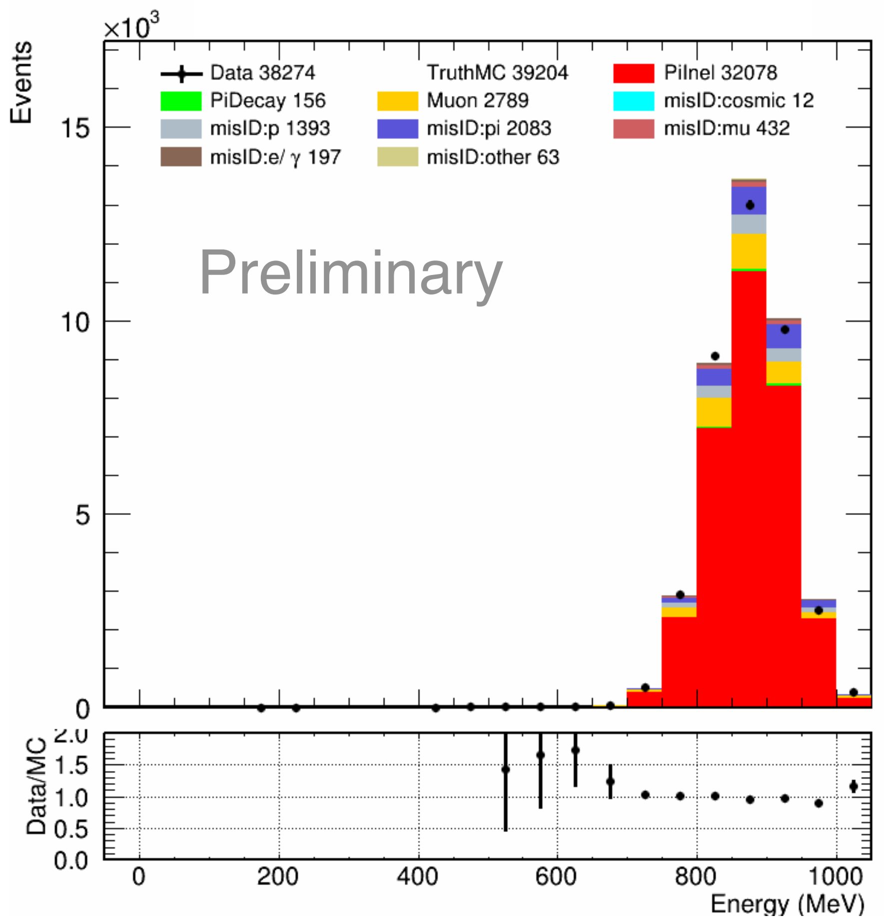
    where n is argon number density ($= \frac{\rho N_A}{M_{Ar}}$)
  - $\sigma(E_i, E_i + \Delta E) = \frac{M_{Ar}}{\rho N_A \Delta x} \ln\left(\frac{N_{Incident}}{N_{Incident} - N_{Interact}}\right) = \frac{M_{Ar}}{\rho N_A \Delta E} \frac{dE}{dx}\Big|_{E_i + \frac{\Delta E}{2}} \ln\left(\frac{N_{Incident}}{N_{Incident} - N_{Interact}}\right)$

Total Inelastic Scattering Cross Section : 1 GeV/c π^+ Beam

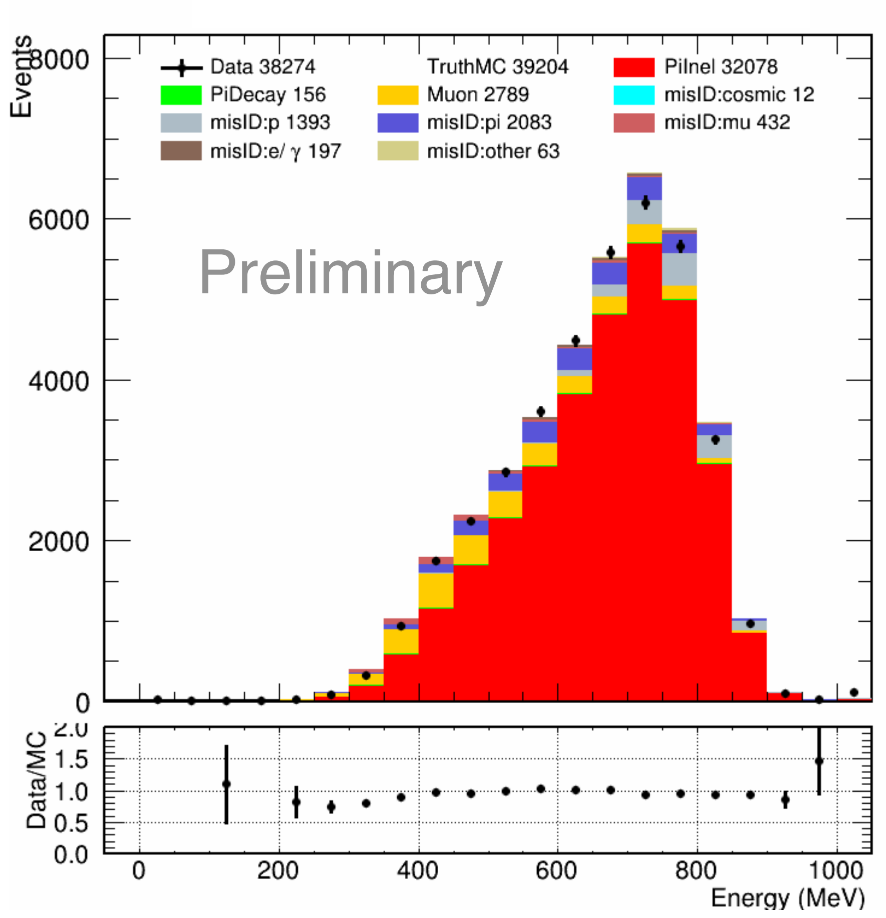
- Important event selection requirements
  - Beam instrumentation TOF < 110 ns : to remove beam proton background
  - Proton veto using energy loss profile
    - To reduce background coming from events in which secondary protons are reconstructed as beam tracks
  - Stopping muon veto cut : to reduce muon beam background
- Results



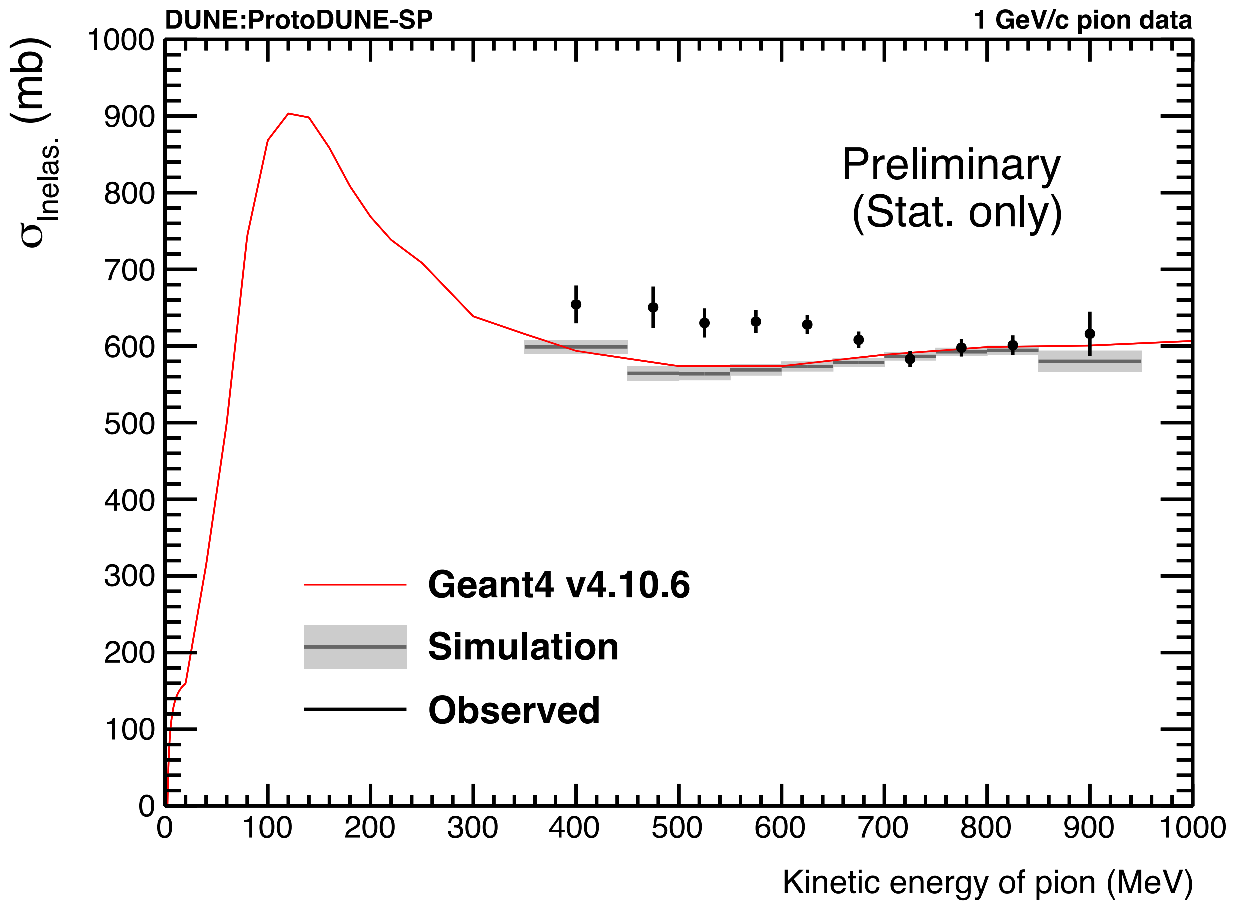
Beam TOF (1GeV/c)



Beam π^+ kinetic energy (KE) at the front face of the TPC



Beam π^+ KE at the last hit

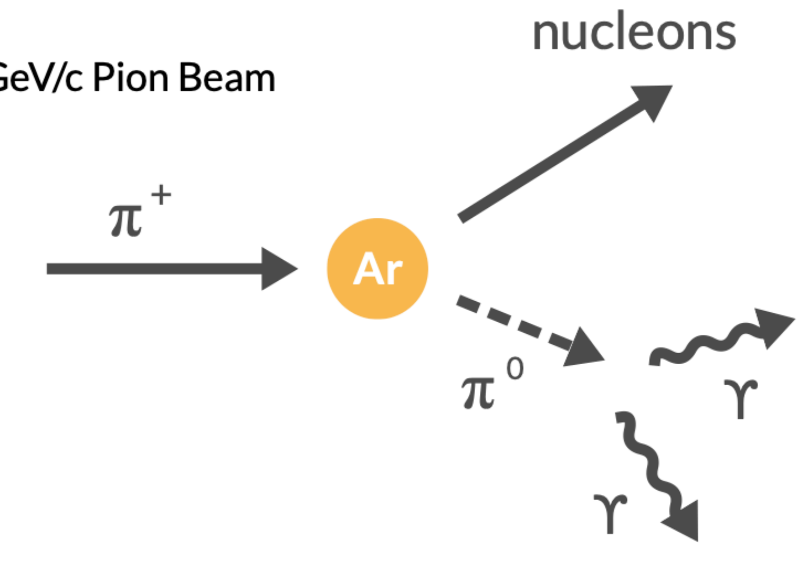


Total inelastic scattering cross section as a function of beam π^+ KE

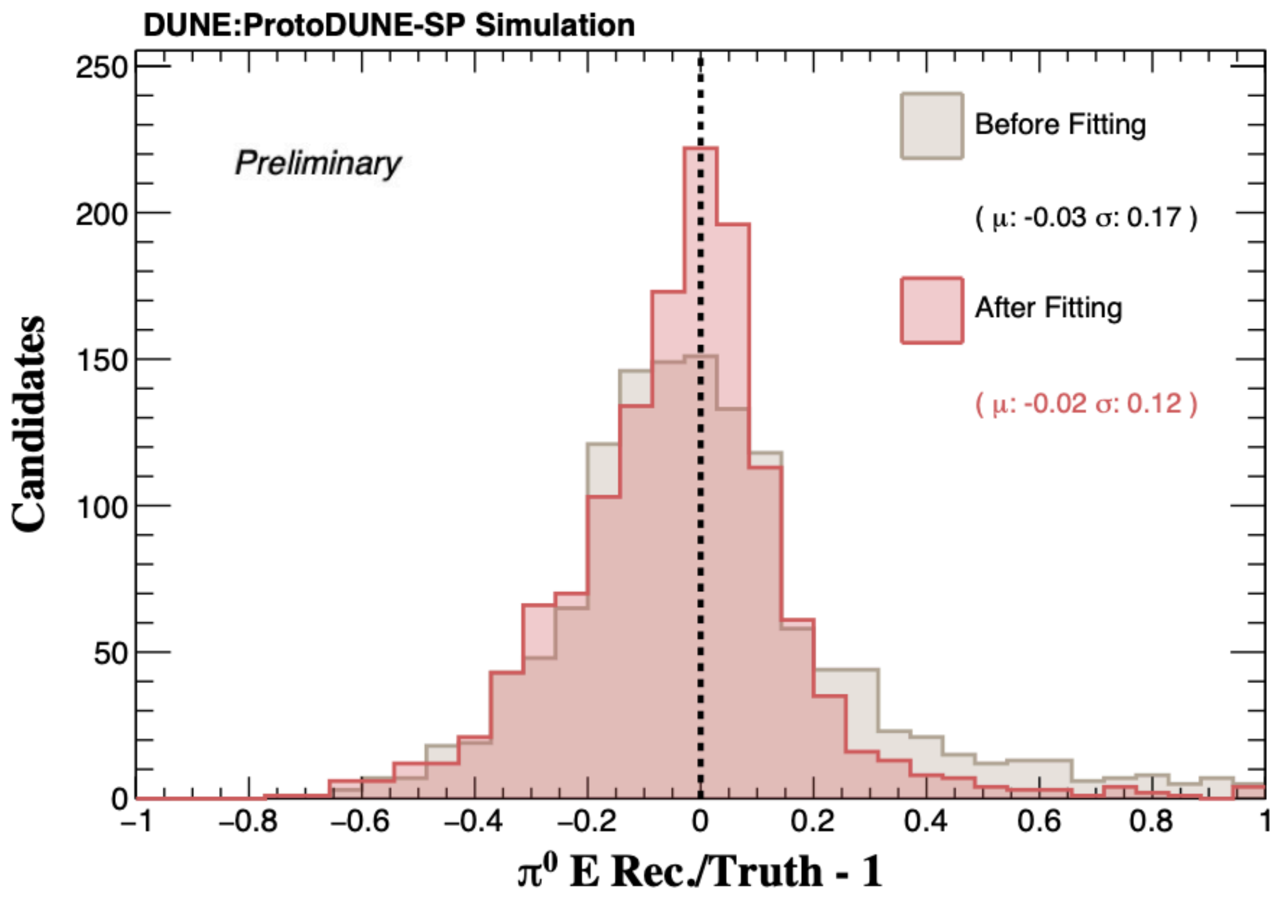
Fermilab DUNE

Charge Exchange Cross Section : 1 GeV/c π^+ Beam

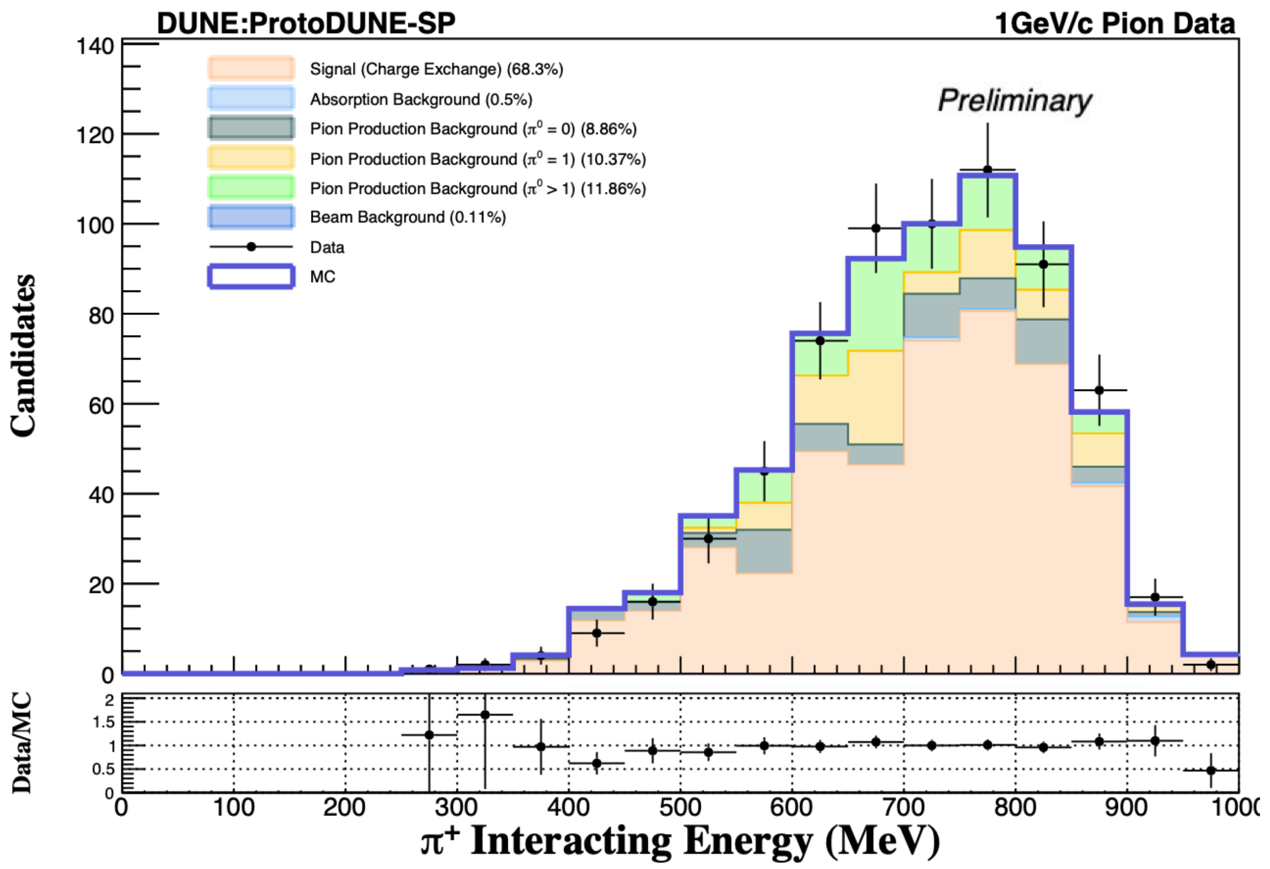
- Important event selection requirements
  - Beam instrumentation TOF < 110 ns
  - Reconstruct secondary $\pi^{\pm}$ and π^0
    - Kinematic fitting for $\pi^0 \to \gamma\gamma$ using known mass
    - Signal region : no $\pi^{\pm}$ and at least one π^0
    - Background tuning in sideband regions defined by $\pi^{\pm}$ and π^0 multiplicities
- Results



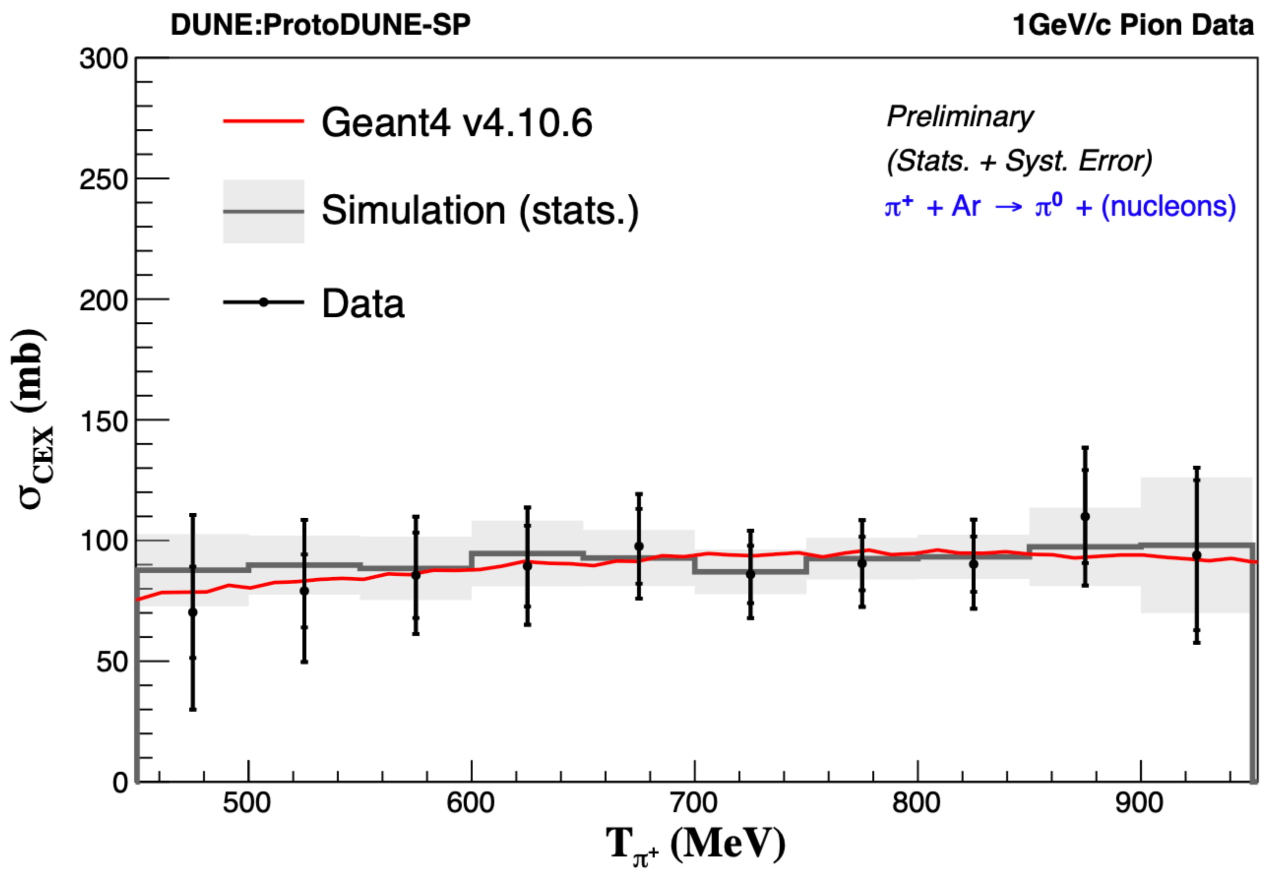
Signal process



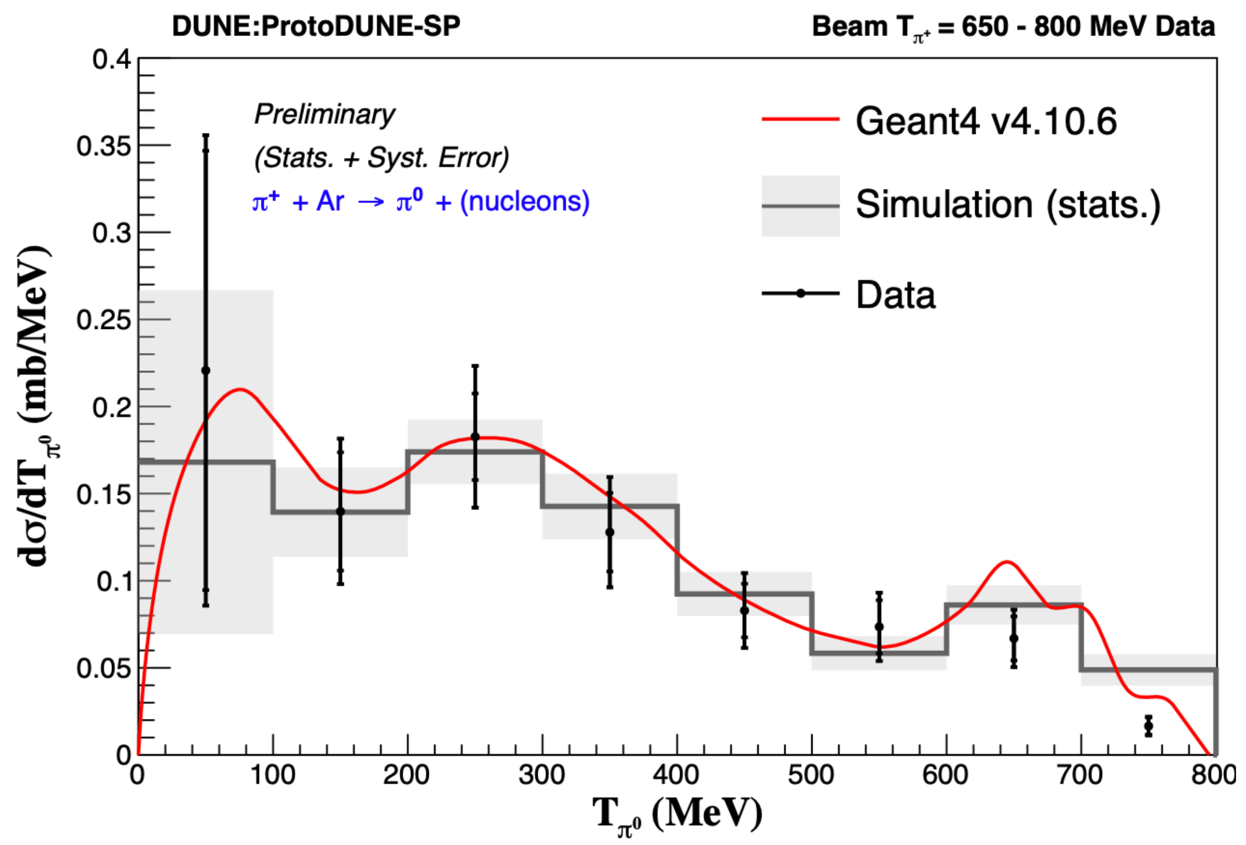
π^0 energy resolution before/after kinematic fitting

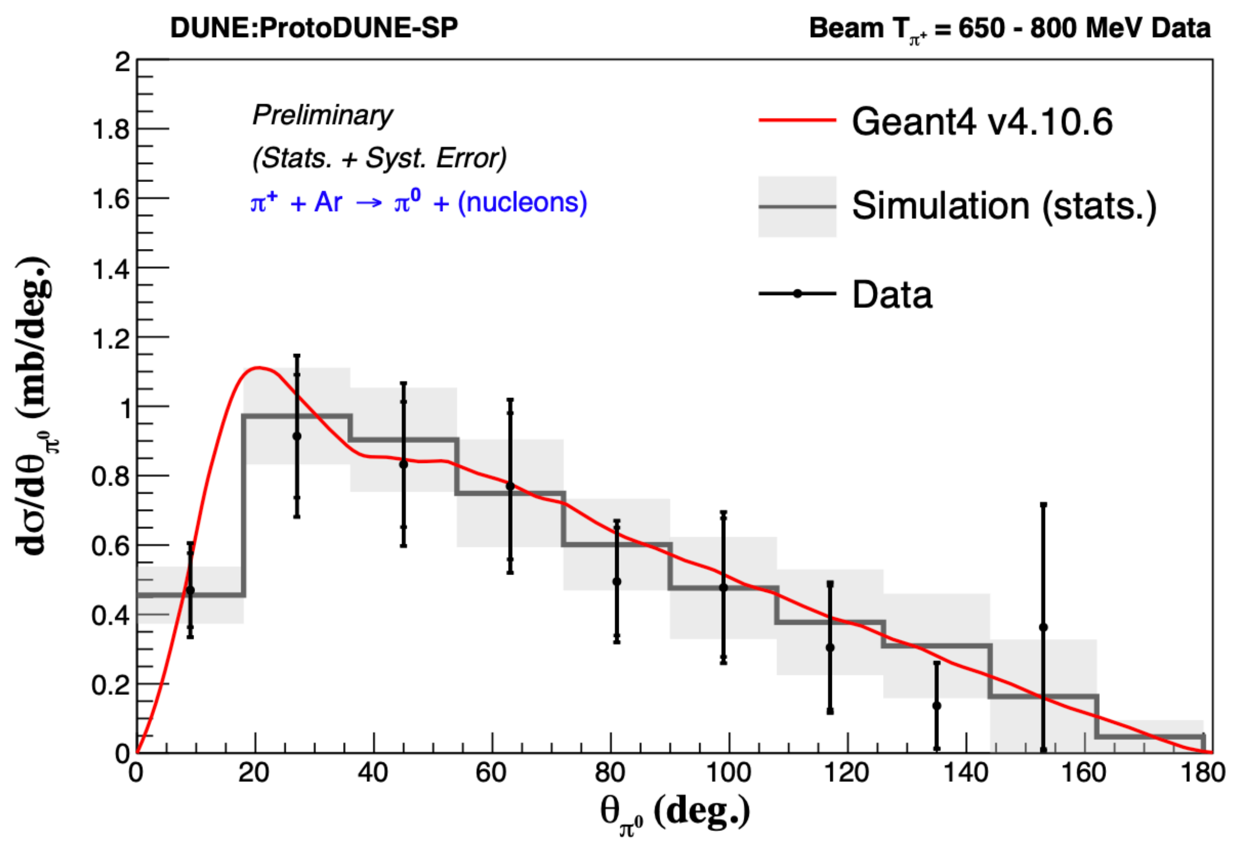


Beam π^+ KE at the last hit



Cross section as a function of beam π^+ KE

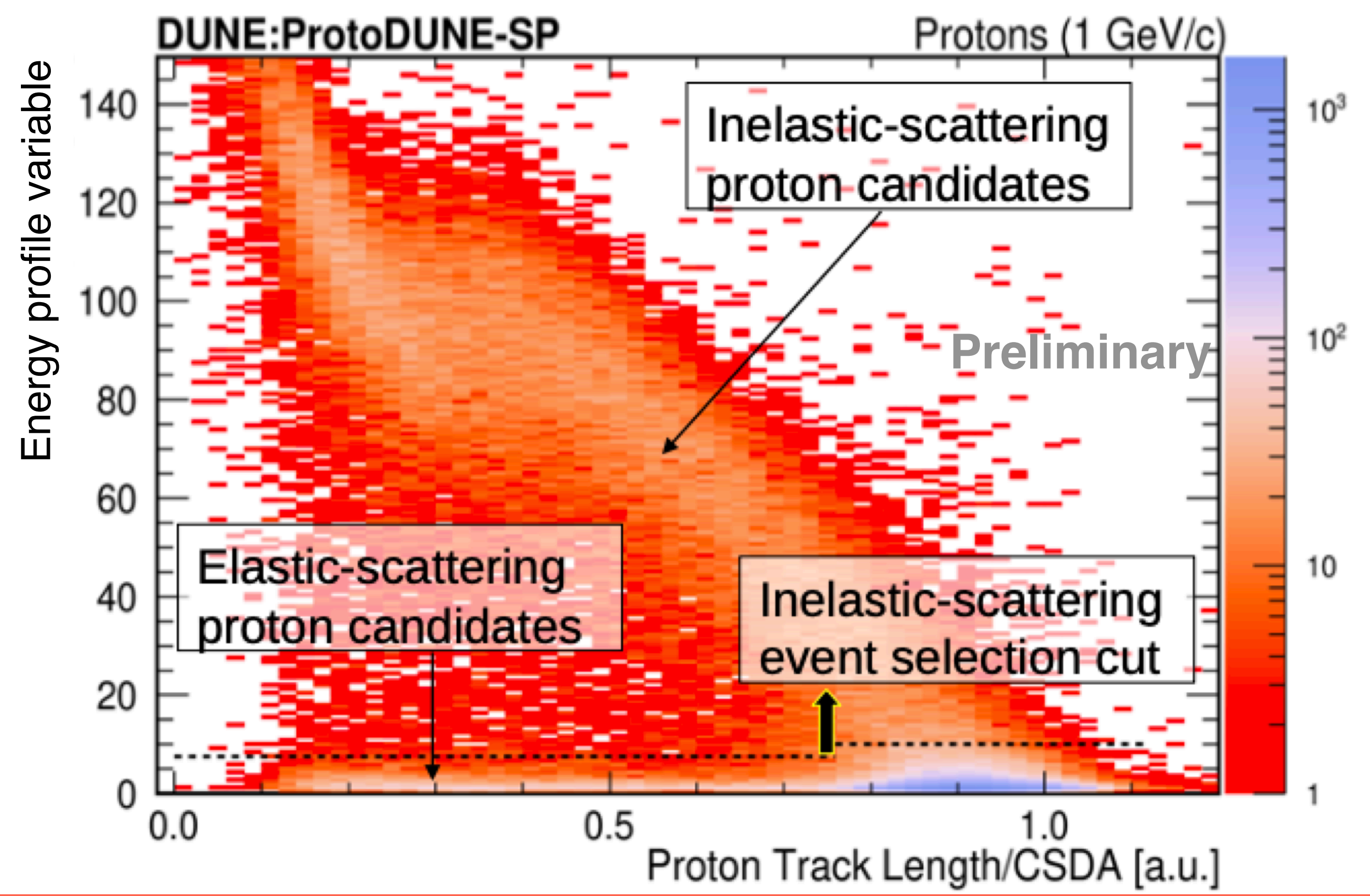




Piece of double differential cross sections as a function of beam π^+ KE and secondary π^0 KE/angle

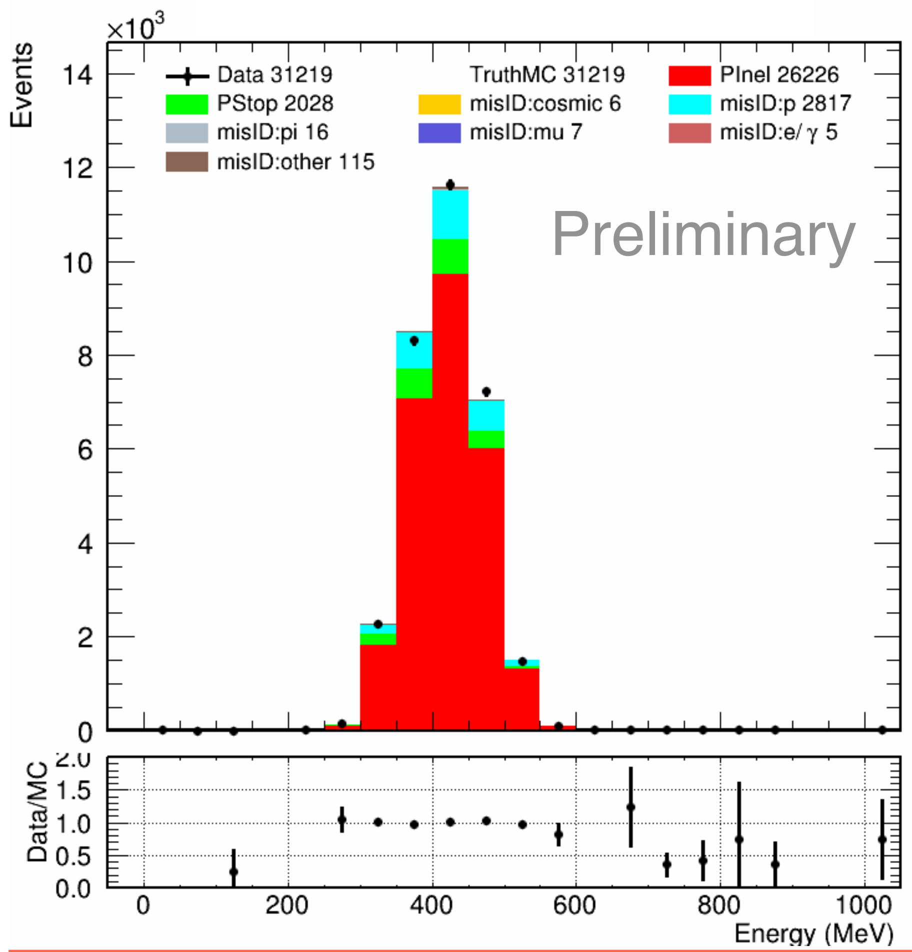
Total Inelastic Scattering Cross Section : 1 GeV/c p^+ Beam

- Important event selection requirements
  - Beam instrumentation 110 ns < TOF < 160 ns
  - Stopping proton veto using energy loss profile
    - To reduce background coming from events that beam proton with no inelastic scattering

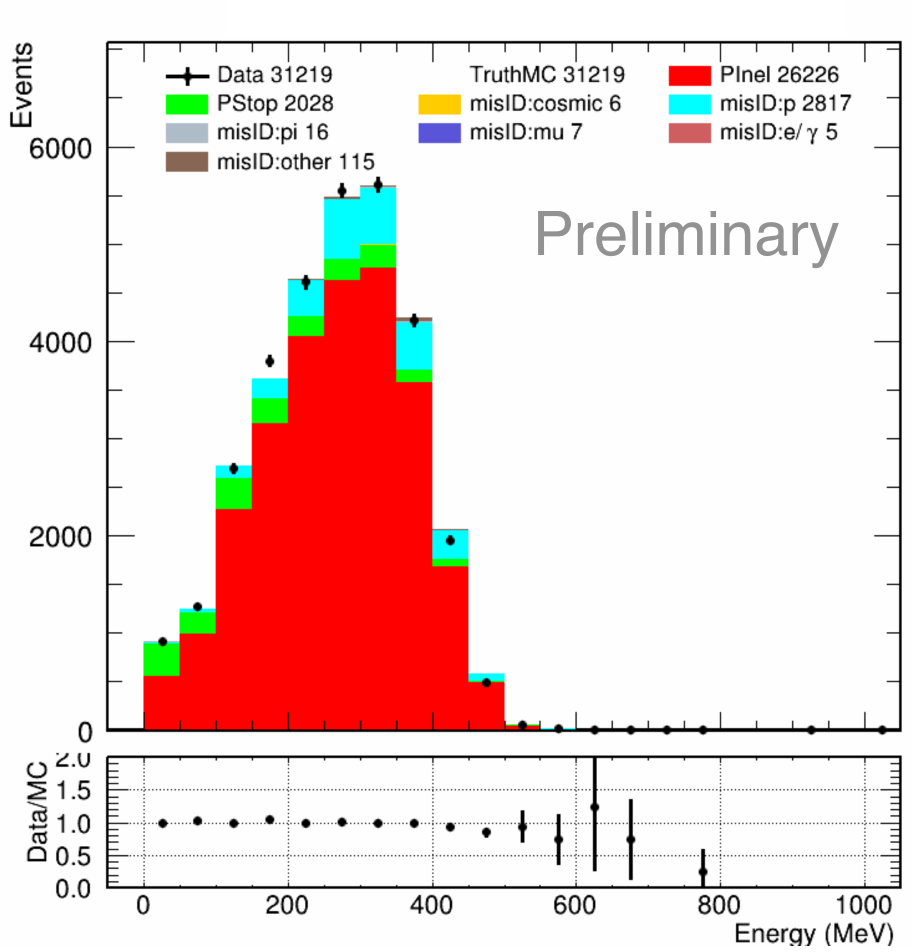


Proton beam energy loss profile variable
vs.
Reco. track length / Track length if stopped

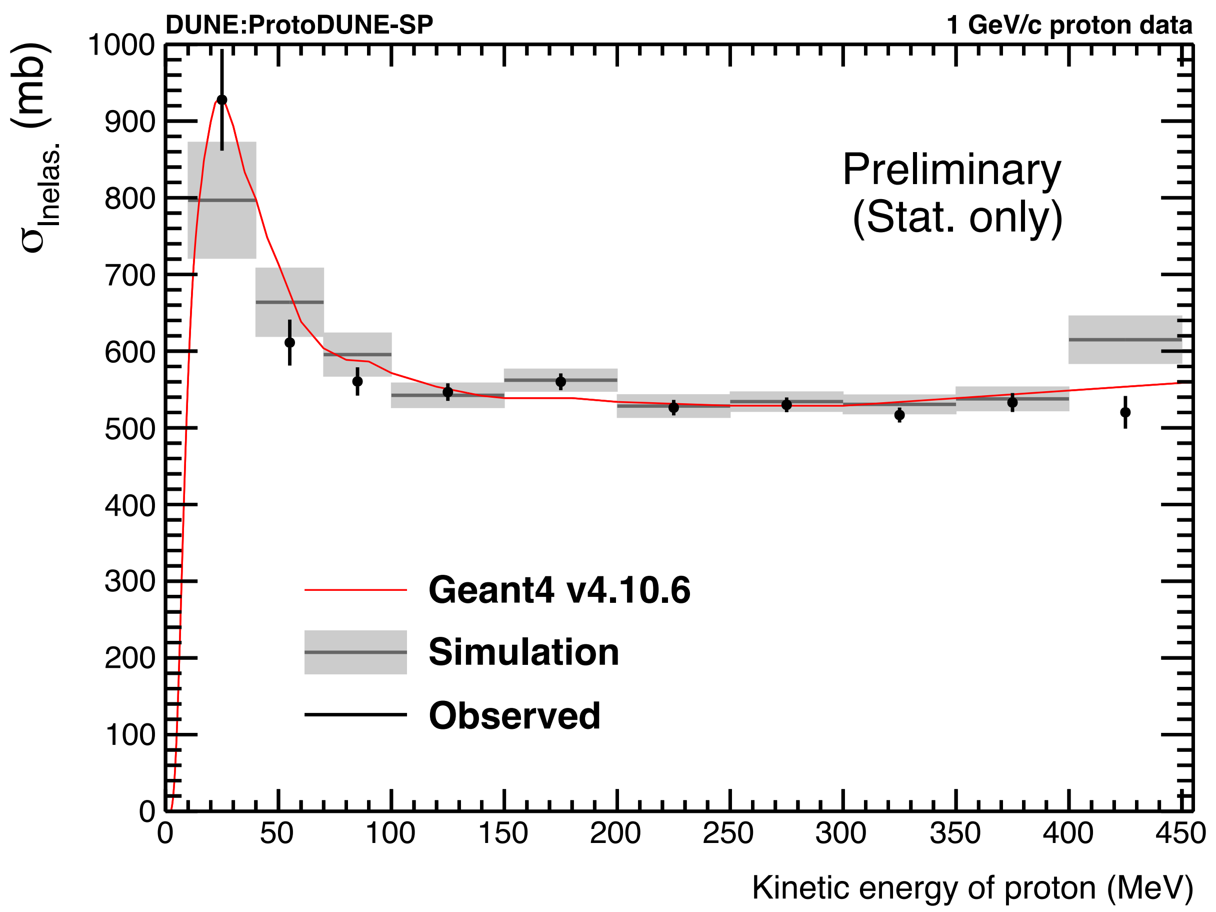
- Results



Beam p^+ KE
at the front face of the TPC



Beam p^+ KE at the last hit



Total inelastic scattering cross section
as a function of beam p^+ KE

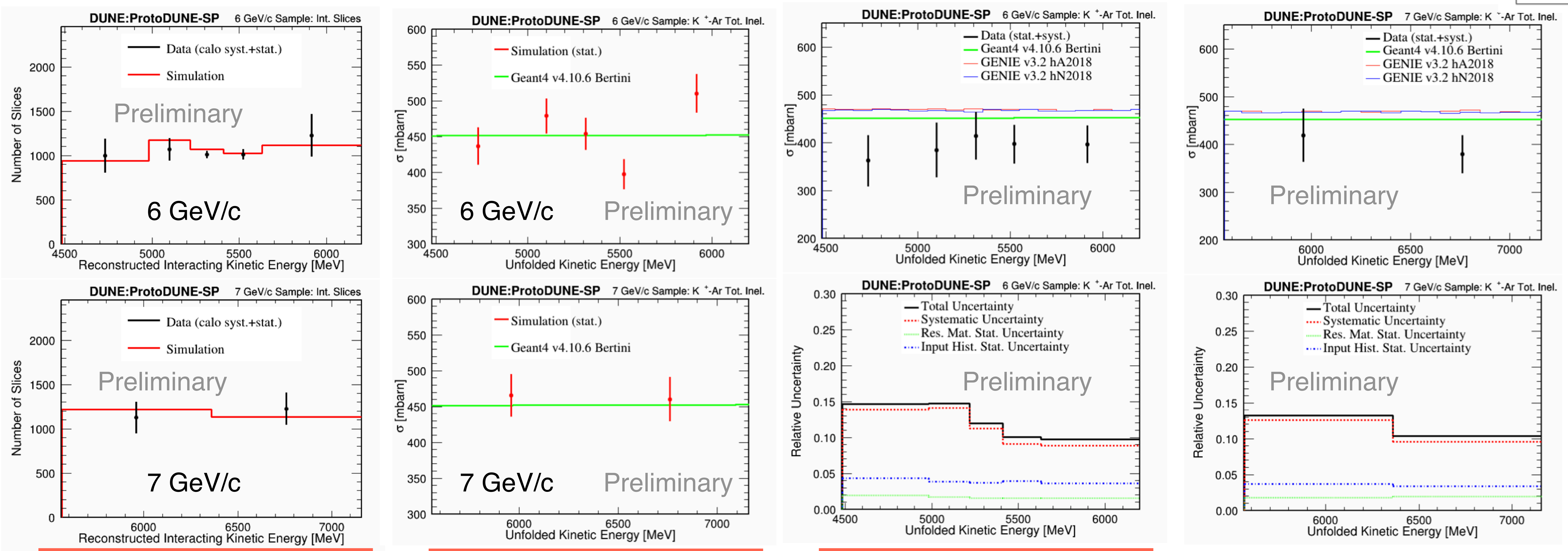
Total Inelastic Scattering Cross Section : 6 and 7 GeV/c K+ Beam

- Important event selection requirements
  - High energy beam sample : enough number of events with beam K^+
  - Beam instrumentation Cherenkov detectors
    - Signal in high-pressure Cherenkov and no signal in low-pressure Cherenkov
- Results

		Momentum (GeV/c)			
		1	2	3	6–7
e	TOF (ns)	0, 105	0, 105	—	—
	Low P Che.	1	1	1	1
	High P Che.	—	—	1	1
μ / π	TOF (ns)	0, 110	0, 103	—	—
	Low P Che.	0	0	0	1
	High P Che.	—	—	1	1
K	TOF (ns)	—	—	—	—
	Low P Che.	—	—	0	0
	High P Che.	—	—	0	1
p	TOF (ns)	110, 160	103, 160	—	—
	Low P Che.	0	0	0	0
	High P Che.	—	—	0	0

Phys. Rev. Accel. Beams **22**, 061003

Beam instrumentation particle ID logic



Beam K^+ KE at the last hit | X-sec reproduction test | X-sec result : 6 GeV/c data | X-sec result : 7 GeV/c data

Fermilab DUNE

LAr Properties : Electron - Ar^+ Recombination

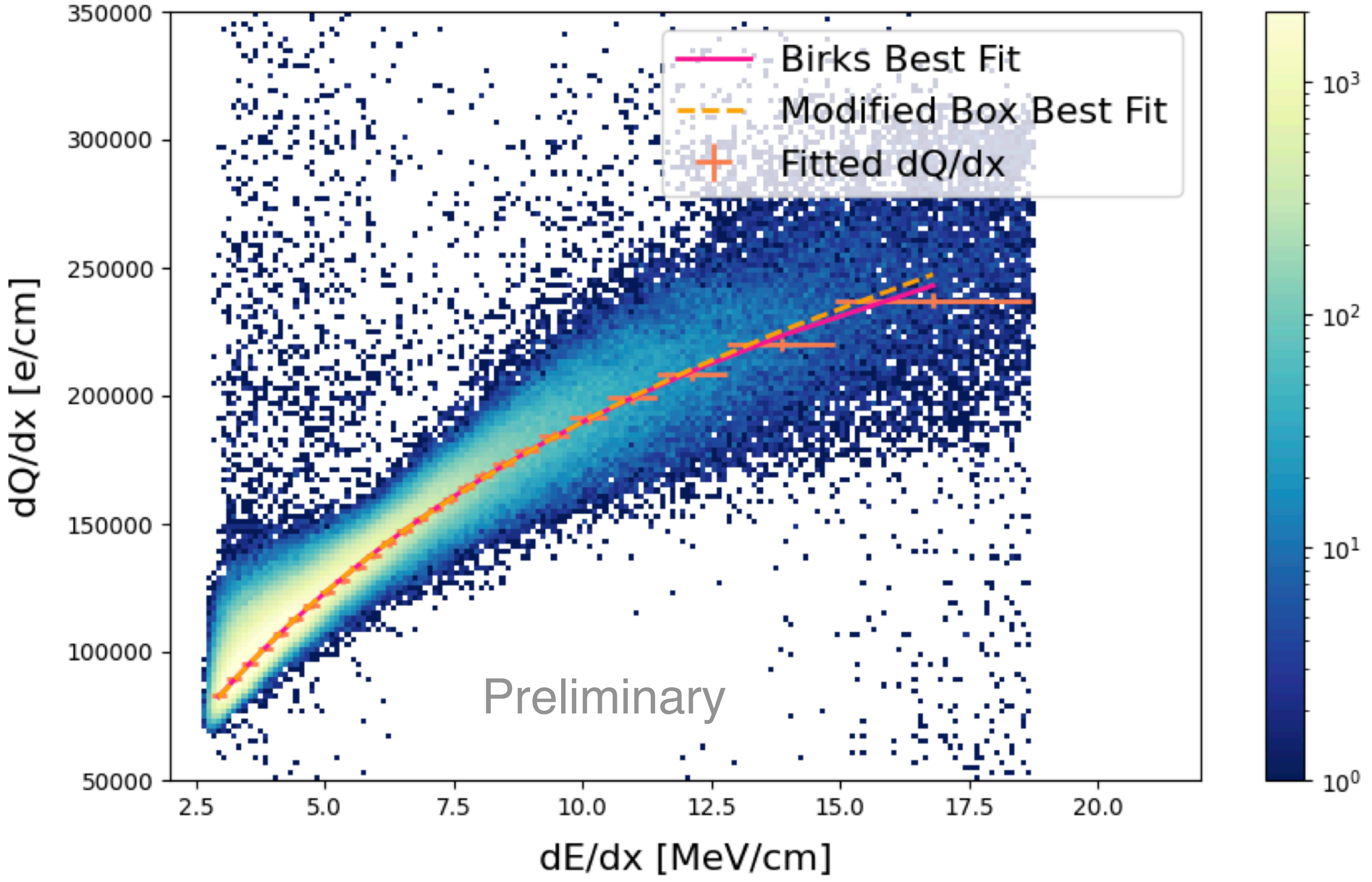
- Recombinations between Ar^+ ions and electrons
  - Non-linear relation between deposited energy (dE/dx) by passing particle via ionization and observed number of electrons from ionizations (dQ/dx)

- Leading models
  - Birks model
    - $$\frac{dQ}{dx} = \frac{A_B}{W} \frac{\frac{dE}{dx}}{1 + \frac{k_B}{\rho\epsilon}\frac{dE}{dx}}$$
  - Modified box model
    - $$\frac{dQ}{dx} = \frac{1}{\rho\epsilon\beta' W}\log\left(\rho\epsilon\beta'\frac{dE}{dx} + \alpha\right)$$

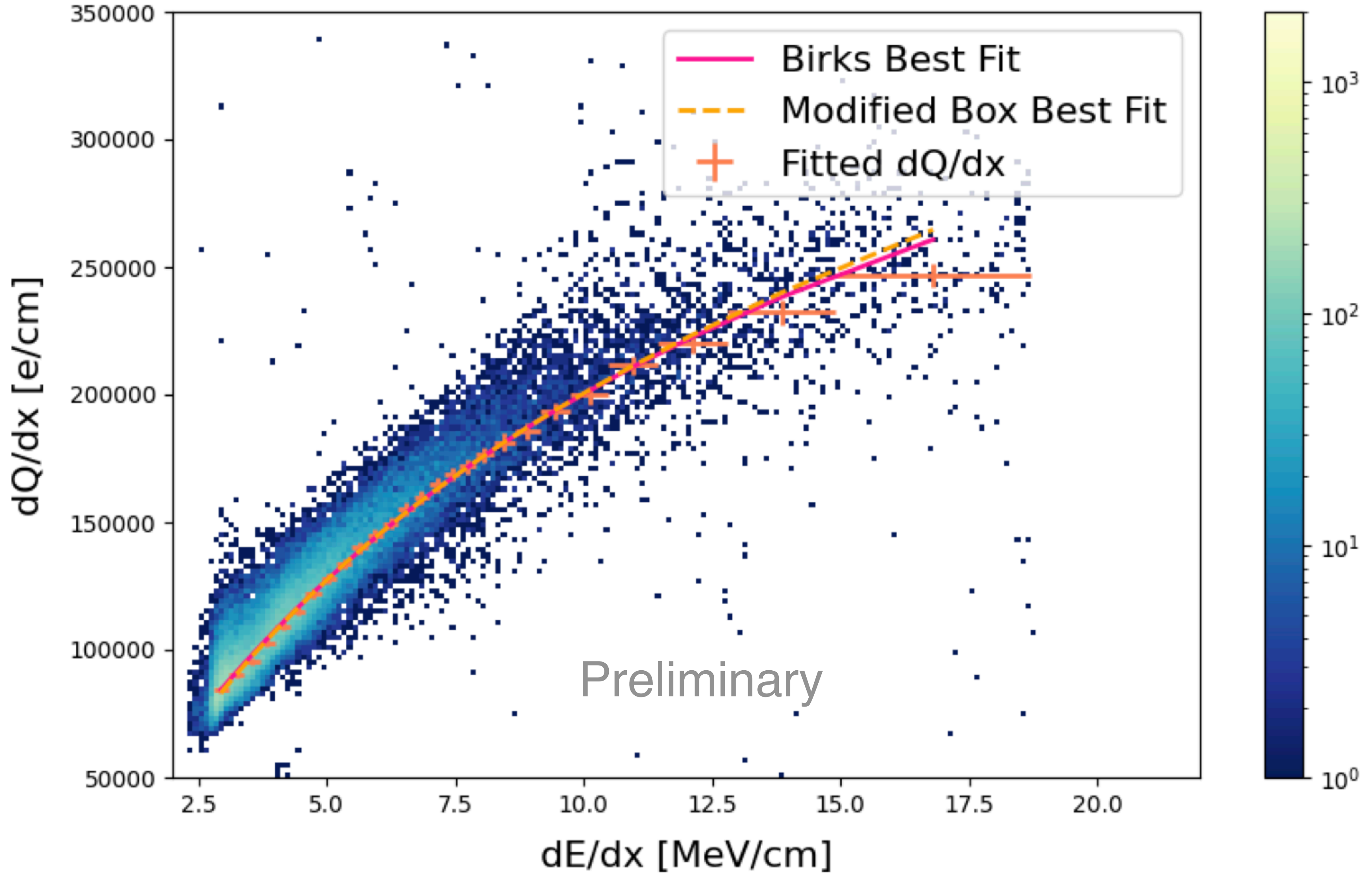
  - W = 23.6 eV/electron (average energy to ionize argon atom), ϵ = electric field strength (kV/cm), and ρ = density of liquid argon (g/cm^3)
  - A_B, k_B, α, and β' are fitted parameters

LAr Properties : Electron - Ar^+ Recombination

- Perform fitting on dQ/dx distributions as function of residual range of stopping beam protons
  - Use Landau-Vavilov function to convert residual range into expected most probable value of dE/dx
- MC sample : recombination was simulated using the modified box model
  - Parameters from Acciarri, R. et al (ArgoNeuT Collab.), *JINST* 8 (2013) P08005



Fitting on MC sample



Fitting on data sample

Preliminary	Mod. box α	Mod. box β' (kV/cm)(g/cm²)/MeV	Birks A_B	Birks k_B (kV/cm)(g/cm²)/MeV
MC input param.	0.93	0.212		
MC fitting result	0.911 ± 0.022	0.209 ± 0.004	0.825 ± 0.019	0.057 ± 0.004
Data fitting result	0.904 ± 0.020	0.208 ± 0.006		

Fitted parameters

Future Plans

- ProtoDUNE-SP physics analyses
  - Secondary K^+ analysis
    - Secondary K^+ particle identification development
    - Understanding energy deposition of K^+ inside the ProtoDUNE-SP
    - Secondary K^+ production cross section measurement
  - Neutron argon cross section measurement
    - Using displaced proton signature from π^+ beam events with various beam momenta

- New DUNE prototype detectors at the CERN neutrino platform
  - ProtoDUNE-HD (horizontal drift) and ProtoDUNE-VD (vertical drift)
  - Will be online in 1-year time window
  - More data with low energy beam ($<$ 0.5 GeV/c) will provide physical constraints for Ar nuclear properties and hadron - Ar interactions in phase spaces of the DUNE's neutrino interactions

Summary

- Detector performance
  - ProtoDUNE-SP prototypes most of the components of a DUNE single-phase far detector module at 1:1 scale
  - By meeting or surpassing the DUNE requirements, the ProtoDUNE-SP proved
    - Effectiveness of the single-phase DUNE far detector design
    - Execution of the fabrication, assembly, installation, commissioning, and operations phases
- Physics
  - Hadron - Ar scattering cross section measurements
    - Three 1D inelastic cross section and one 2D π^+- Ar charge exchange cross section measurements will be published soon
    - Secondary K^+ analysis and neutron - Ar cross section measurement are in progress
  - Liquid argon properties
    - Recombination result will be published soon
    - Electron diffusion study is on the way
  - For more details, please check the annual report to the CERN-SPSC : CERN-SPSC-2023-017
- Future runs with ProtoDUNE-VD and ProtoDUNE-HD will start in one year - stay tuned!

Back Up

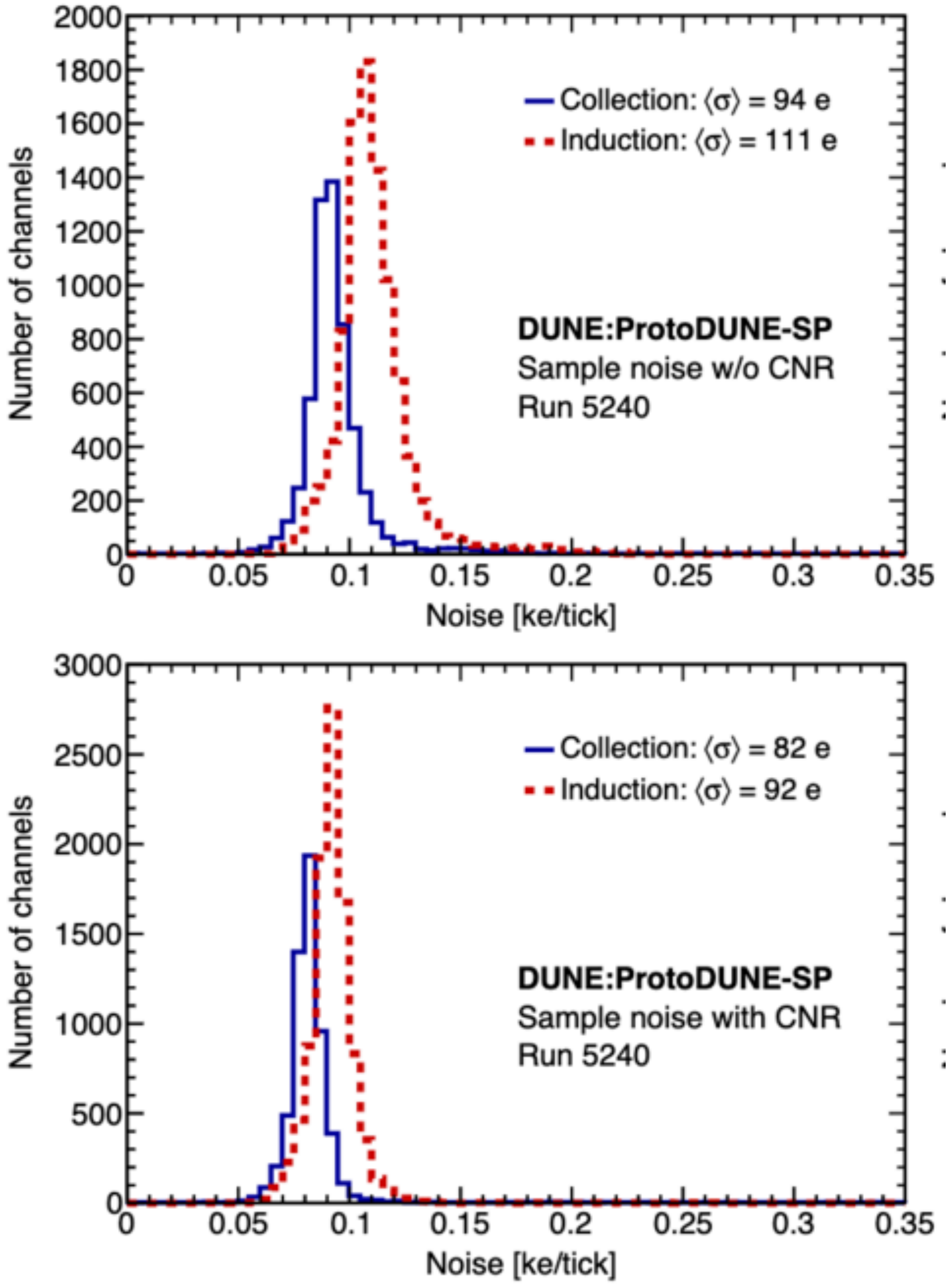
ENC

JINST 15 (2020) 12, P12004

For charge deposits much faster than the nominal 2 μs shaping time of the amplifier, the area A of the resulting signal pulse is proportional to the height h and shaping time τ: $A = Kh\tau$. The shape is well understood [39] and has been verified with fits of the ProtoDUNE-SP pulser signals. Numerical integration gives $K = 1.269/\text{tick} = 2.538/\mu\text{s}$. For such fast signals, the charge may be deduced directly from the pulse height and its standard deviation is called the ENC (equivalent noise charge) [39]. The ProtoDUNE-SP signals are slower than this but the ENC is a standard metric and is presented here to allow comparison with results from other detectors.

The ratio of ENC to sample noise defined here is $A/h = K\tau$. The actual shaping time varies from channel to channel but has central value around 2.2 μs which gives a ratio of ENC to sample noise of 5.58. With this factor and the above values for the sampling noise, the mean ENC for the collection channels is 530 e before correlated noise removal and 430 e after. The corresponding numbers for the induction channels are 620 e and 500 e. These noise values are similar to the 500-600 e values obtained from bench measurements with a prototype FEMB at LN2 temperature [3].

- Raw (without correlated noise removal)
  - Collection plane : $94 \text{ e} \times 5.58 = 524.5 \text{ e}$
  - Induction plane : $111 \text{ e} \times 5.58 = 619.4 \text{ e}$



H4 VLE

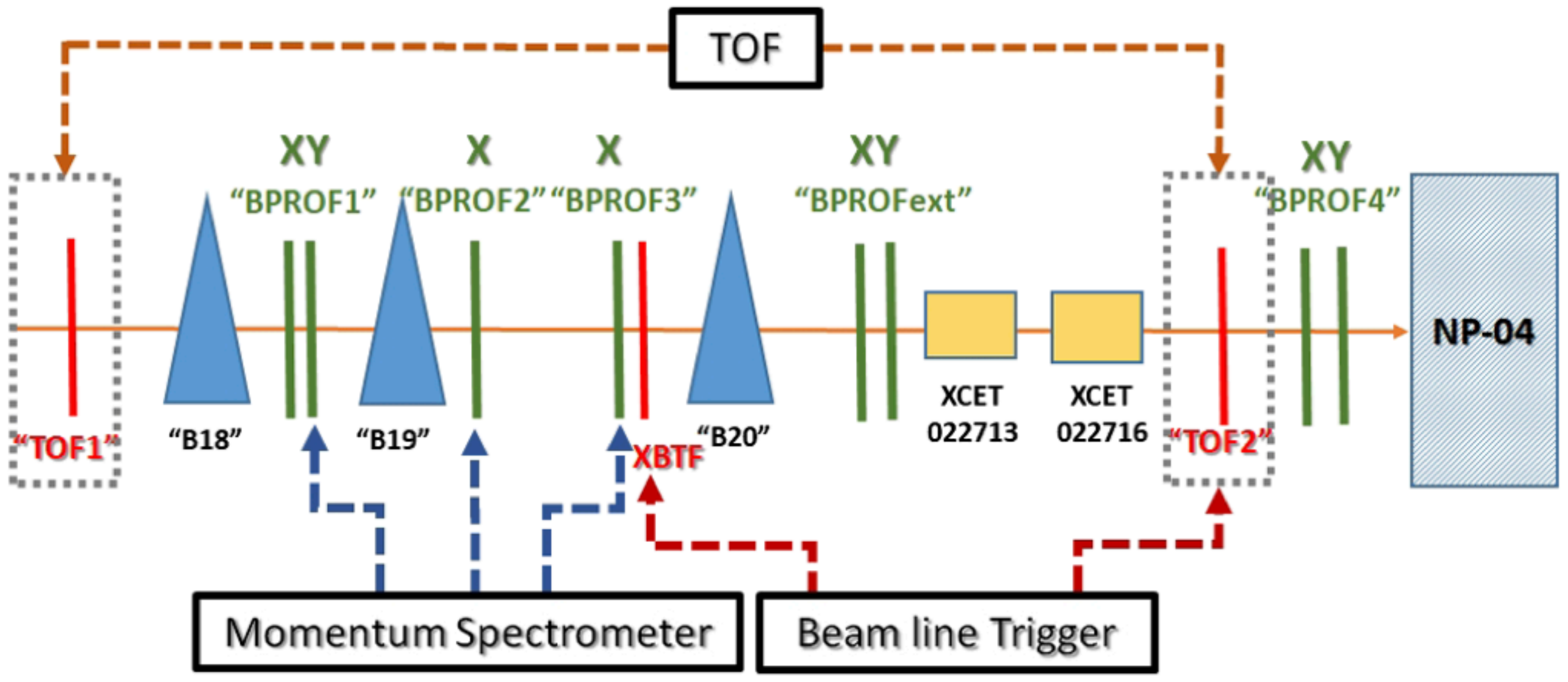


FIG. 10. An overview of the H4-VLE instrumentation, as discussed in the text.

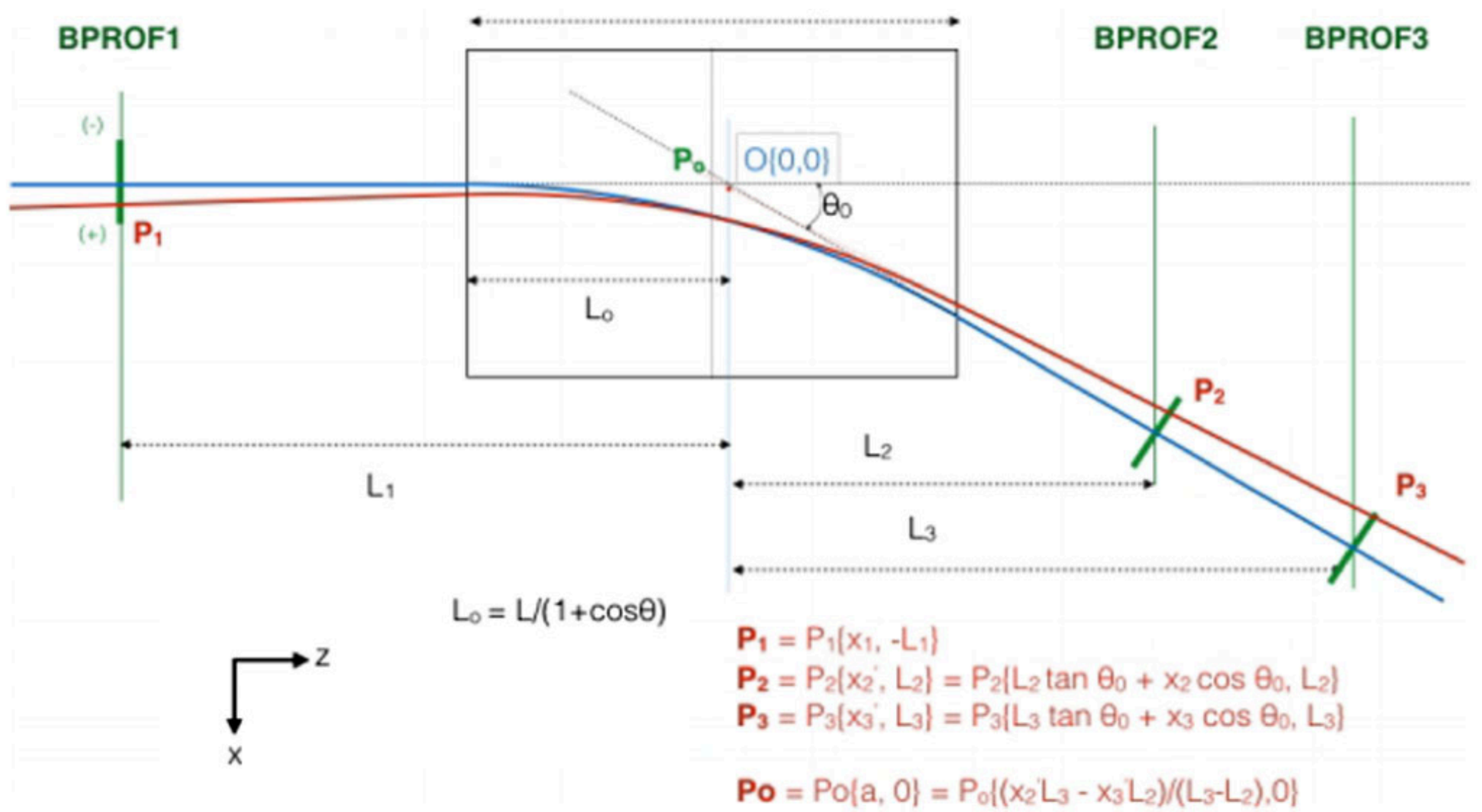
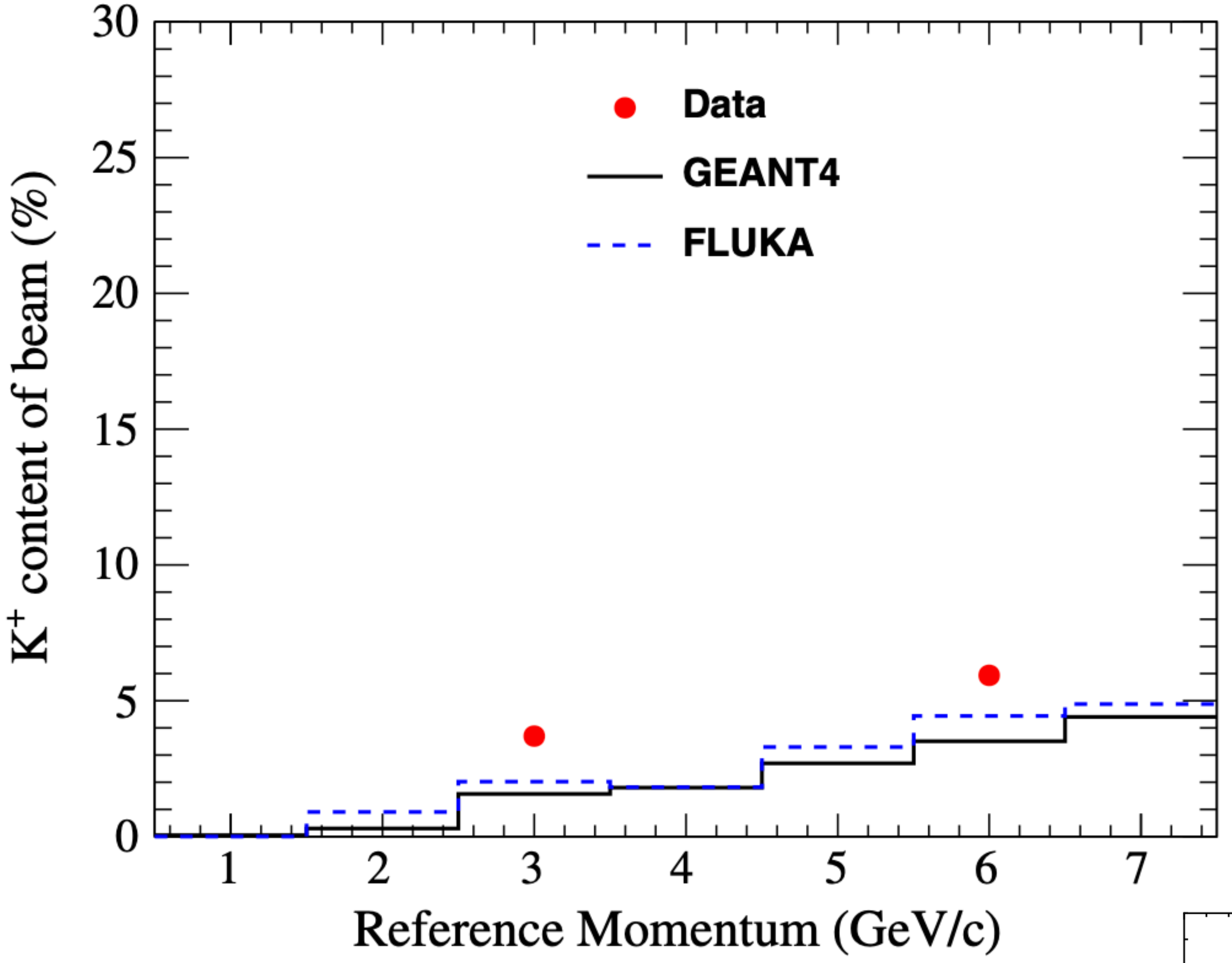
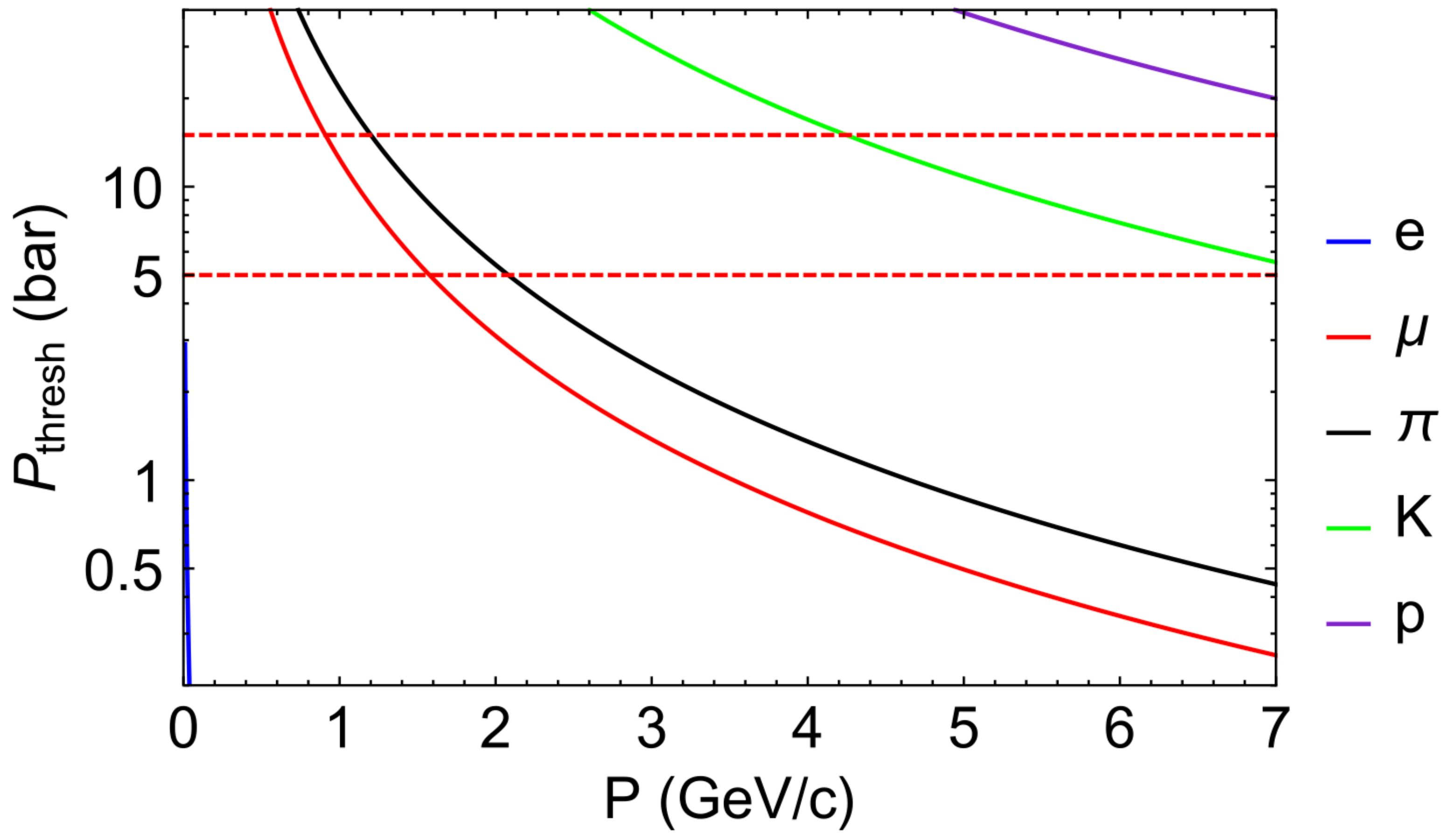


FIG. 17. Schematic of the spectrometer principle, taken from [26].

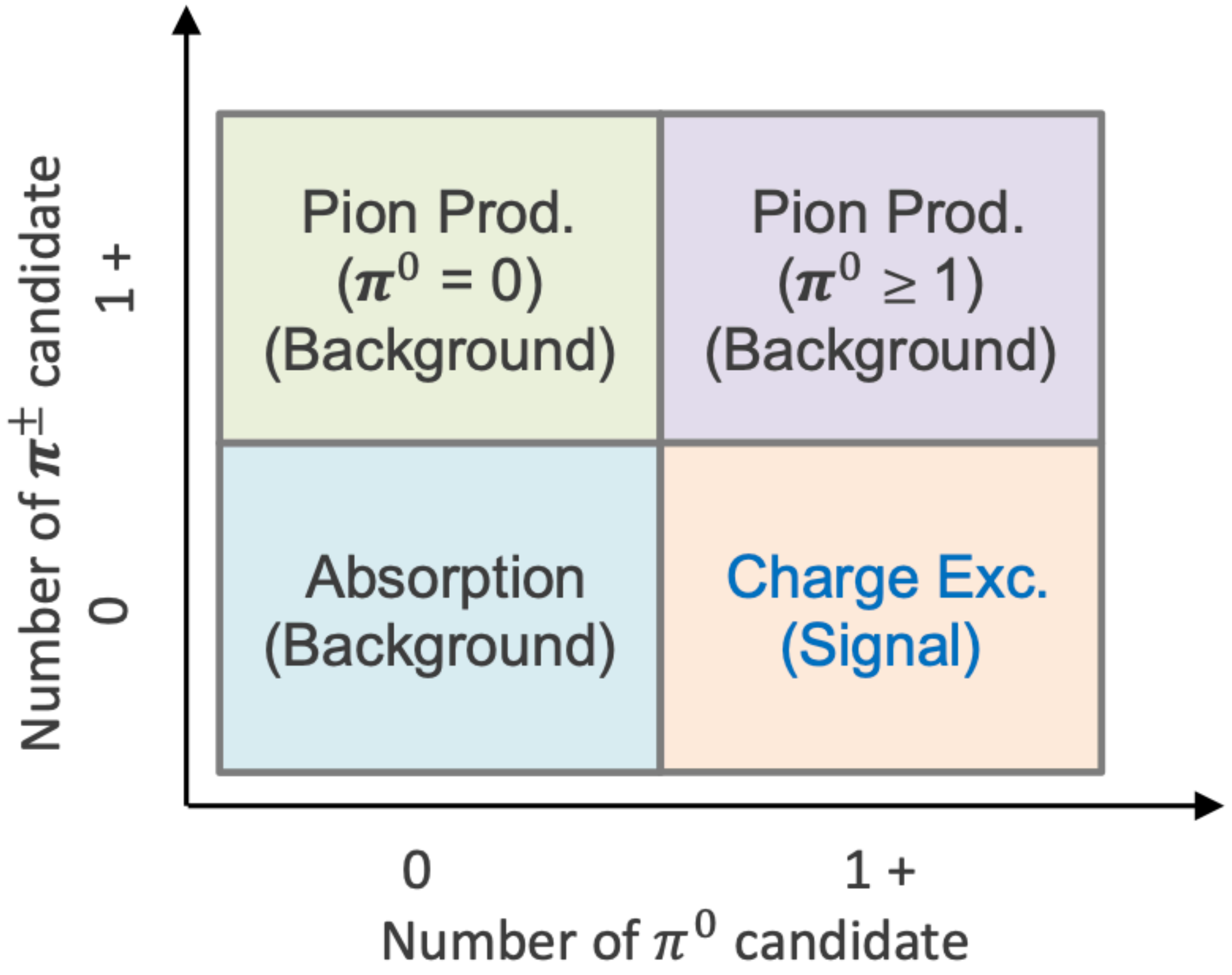


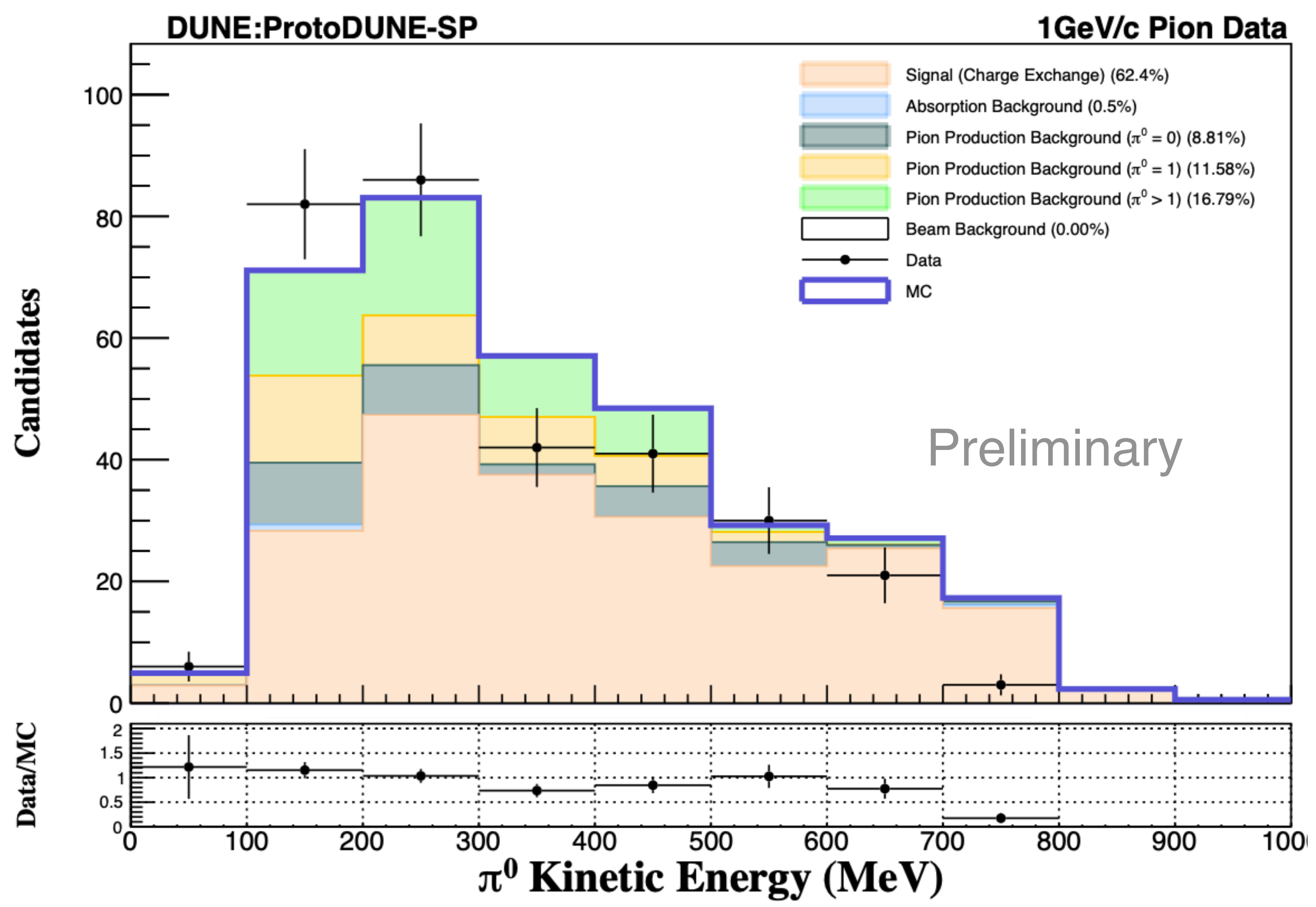
$$\cos\theta = \frac{M \cdot [\Delta L \cdot \tan\theta_0 + \Delta\chi \cdot \cos\theta_0] + L_1 \cdot \Delta L}{\sqrt{[M^2 + L_1^2][(\Delta L \cdot \tan\theta_0 + \Delta\chi \cdot \cos\theta_0)^2 + \Delta L^2]}} \quad (3)$$

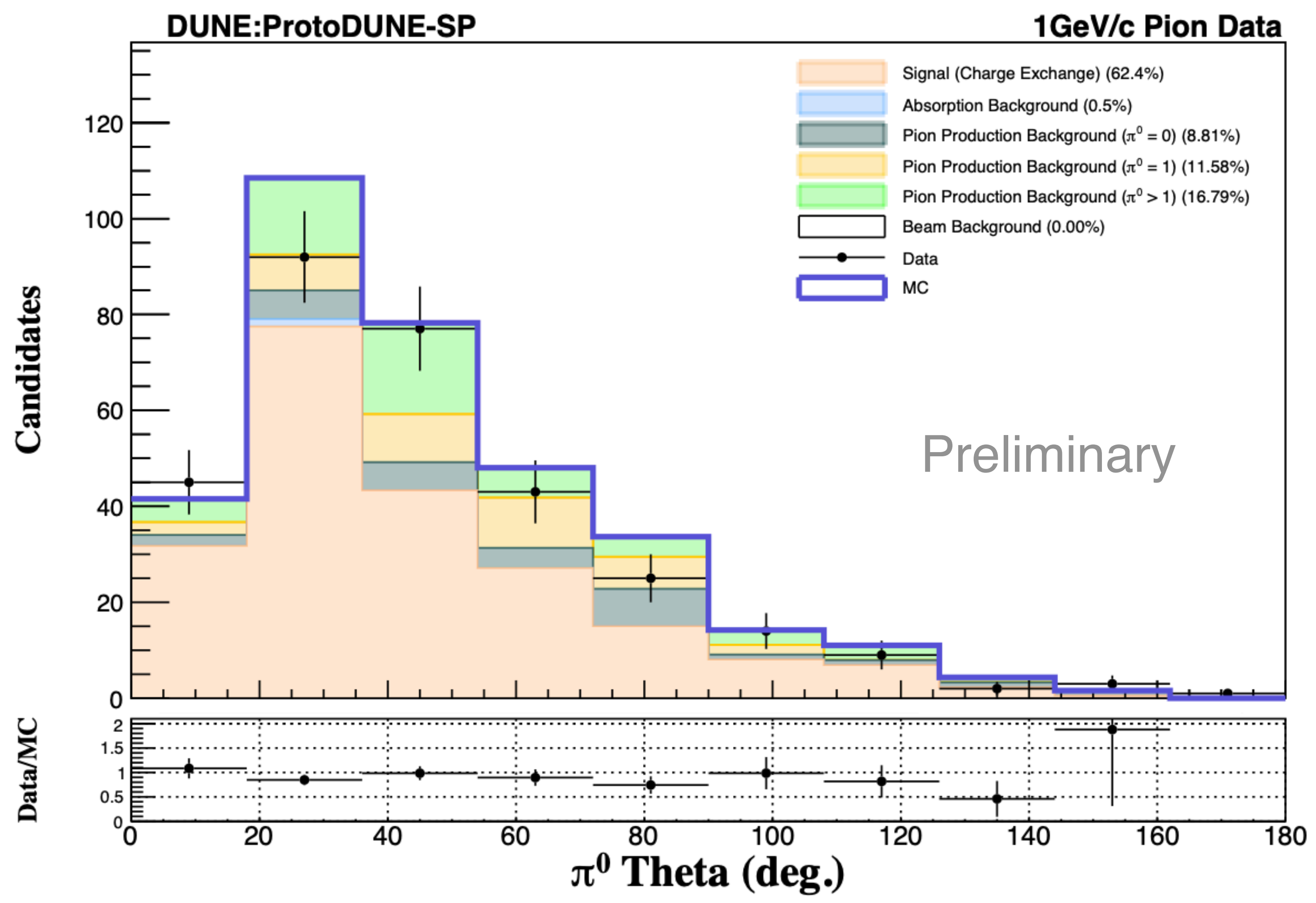
$$p = \frac{299.7924}{\theta} \times \int_0^{L_{mag}} (B \cdot dl) \quad (4)$$

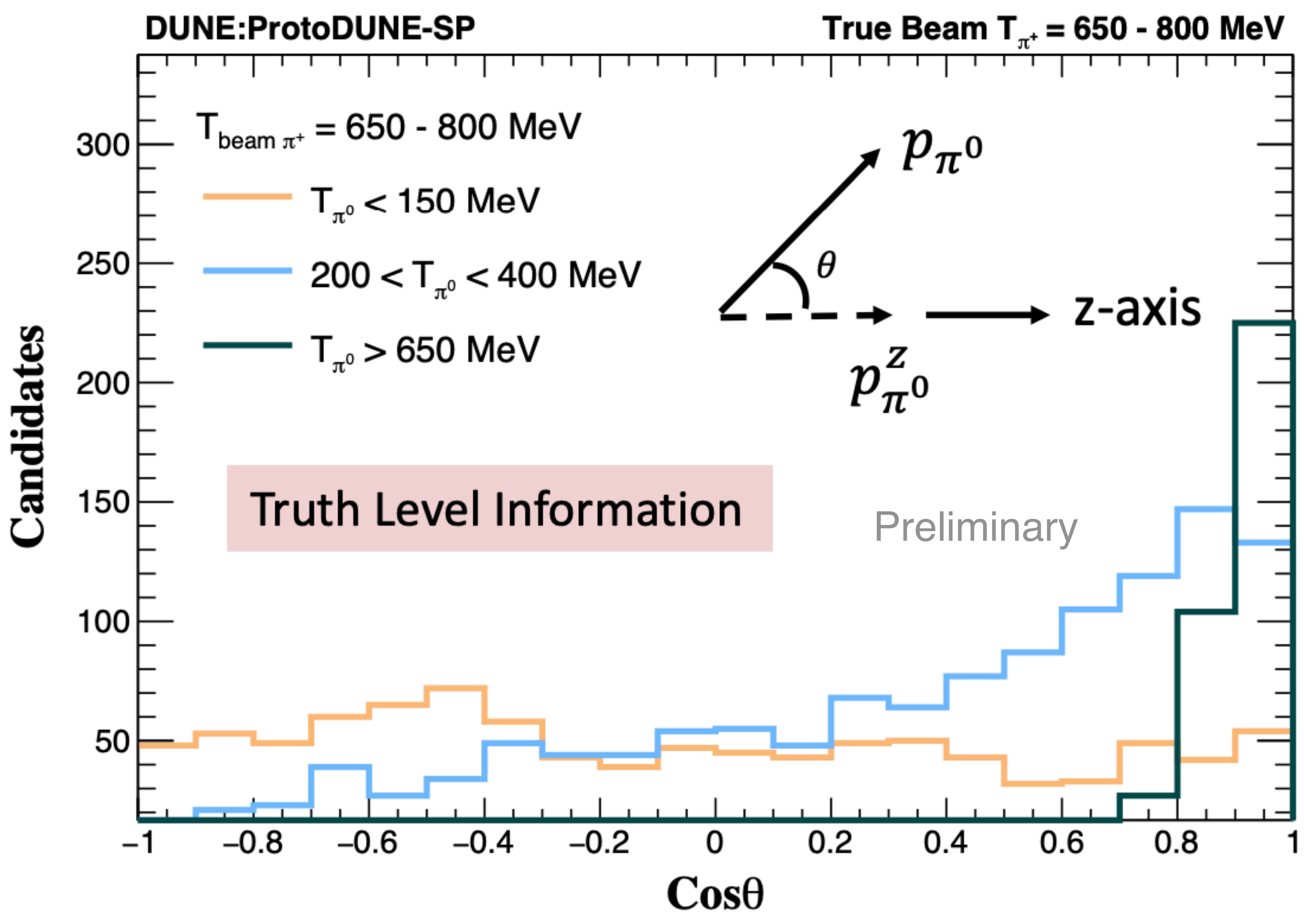


Charge Exchange







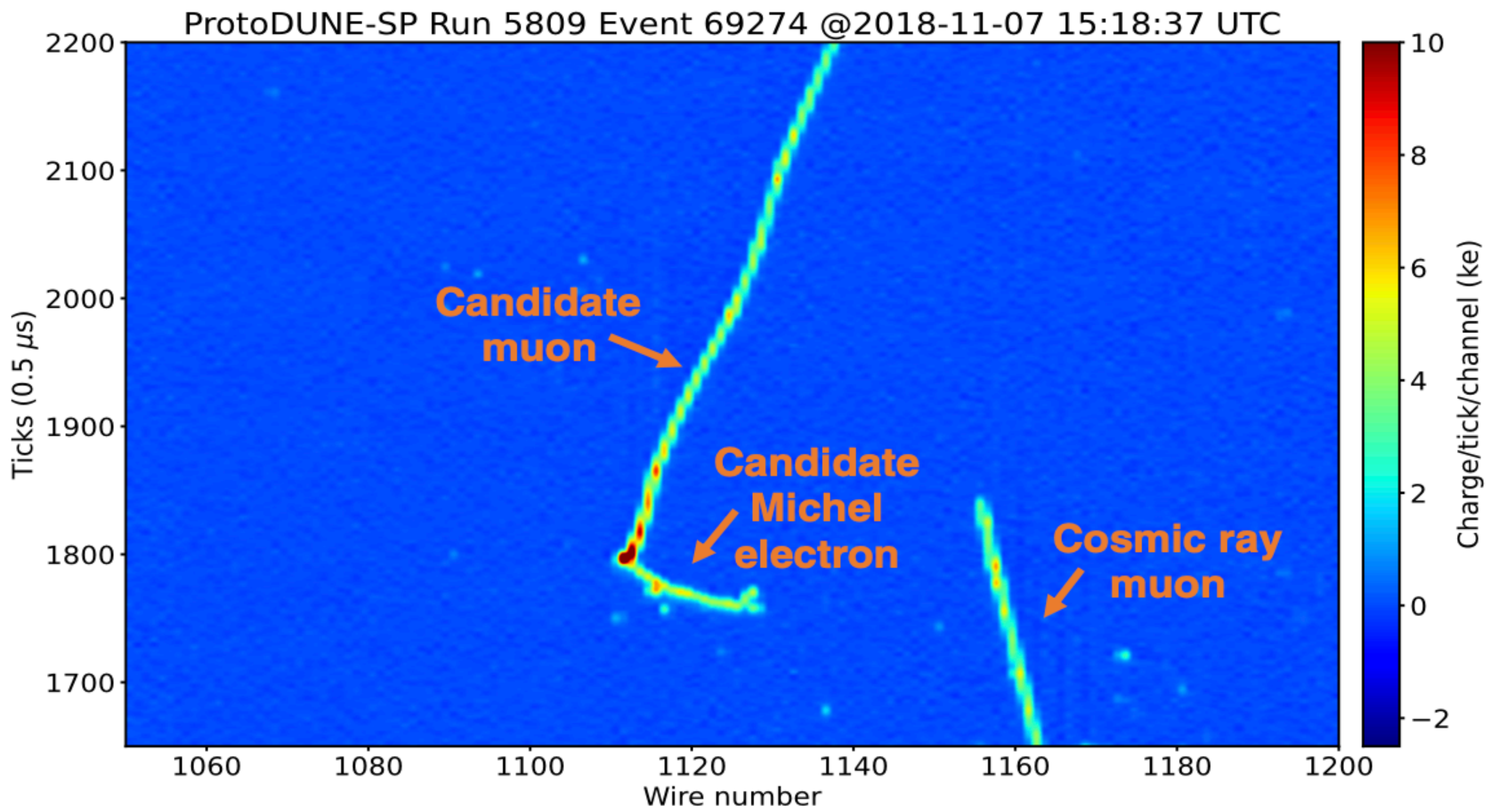


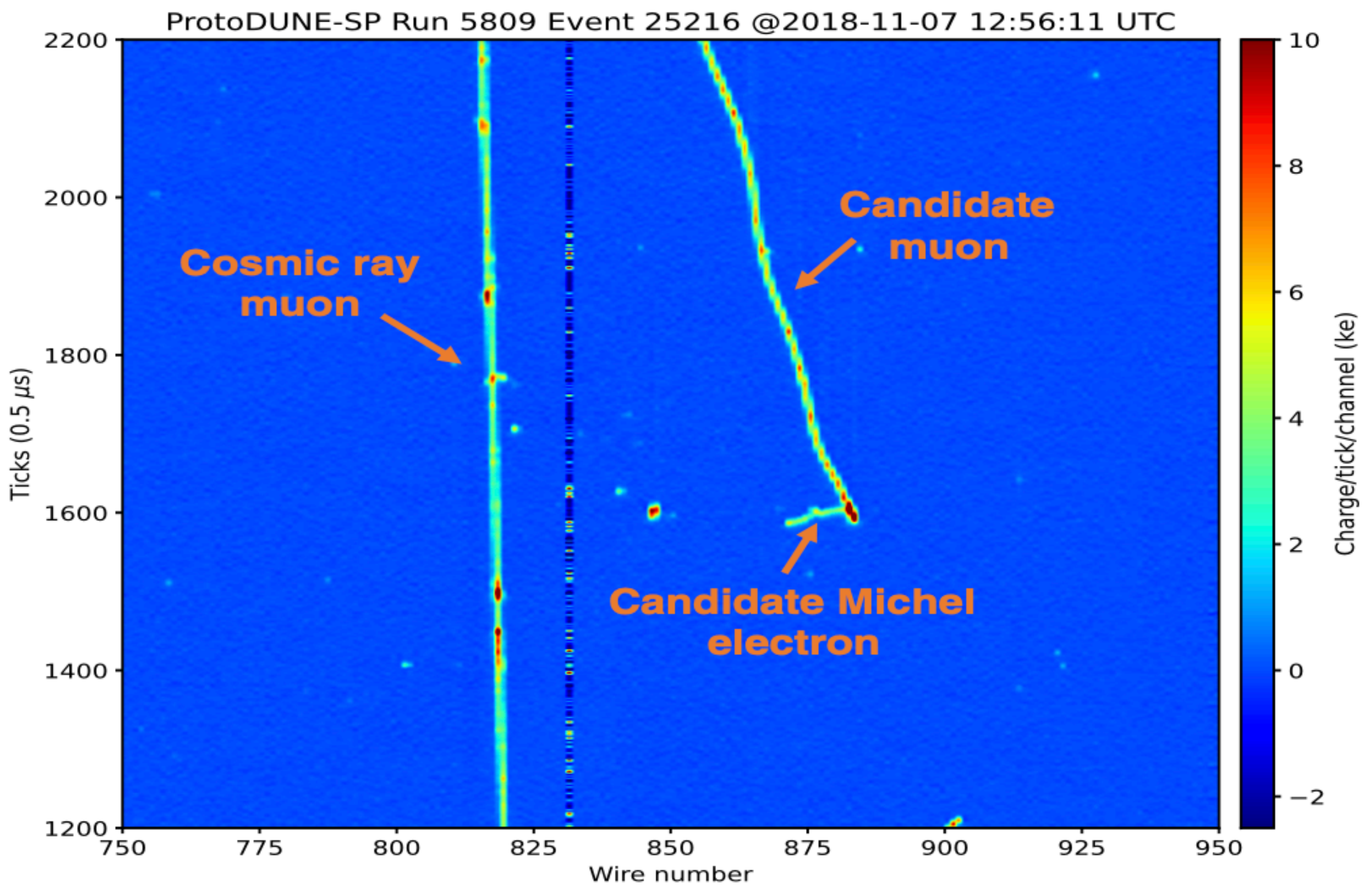
Fermilab DUNE

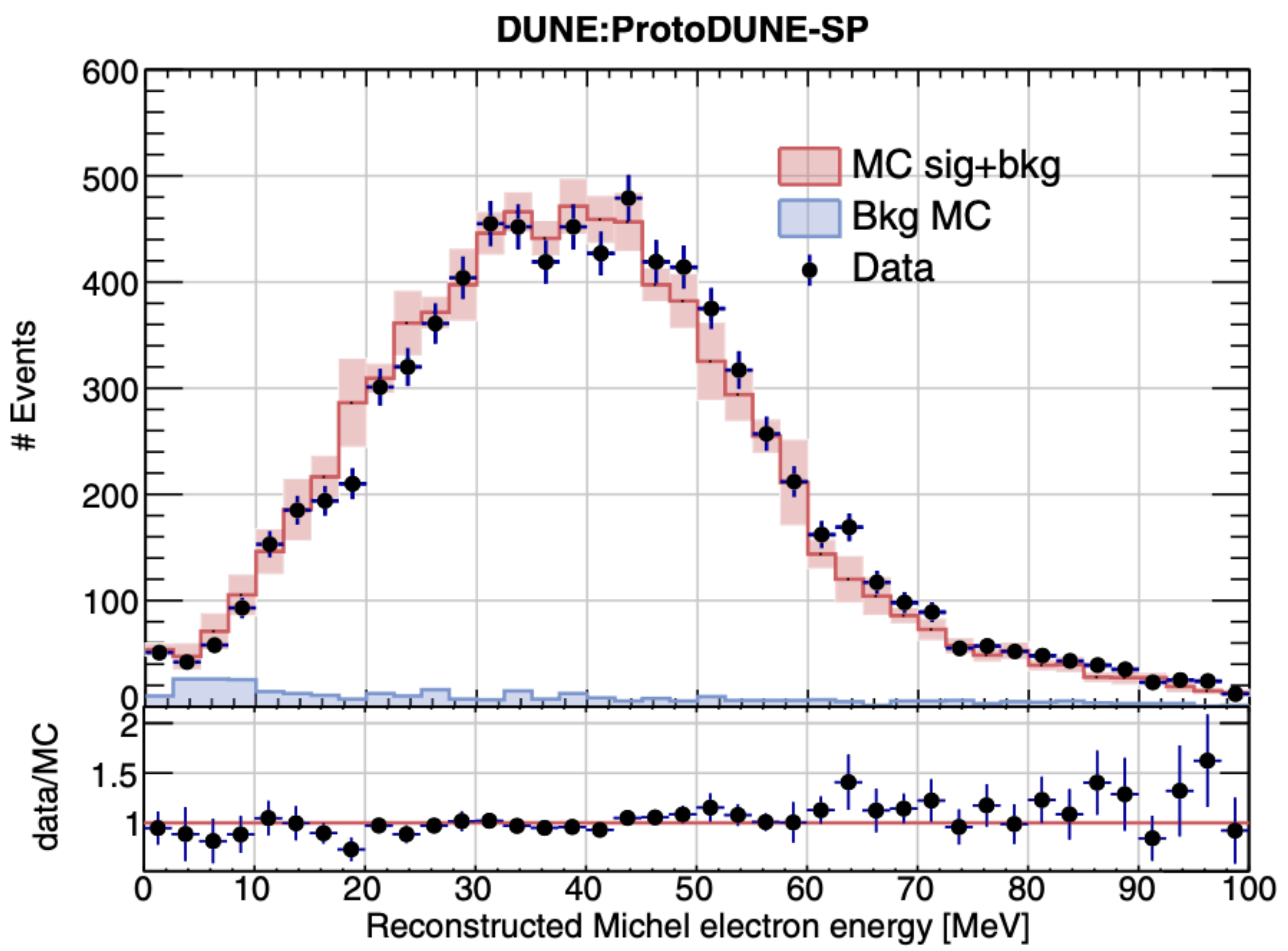
Low Energy Electron ID and Reco.

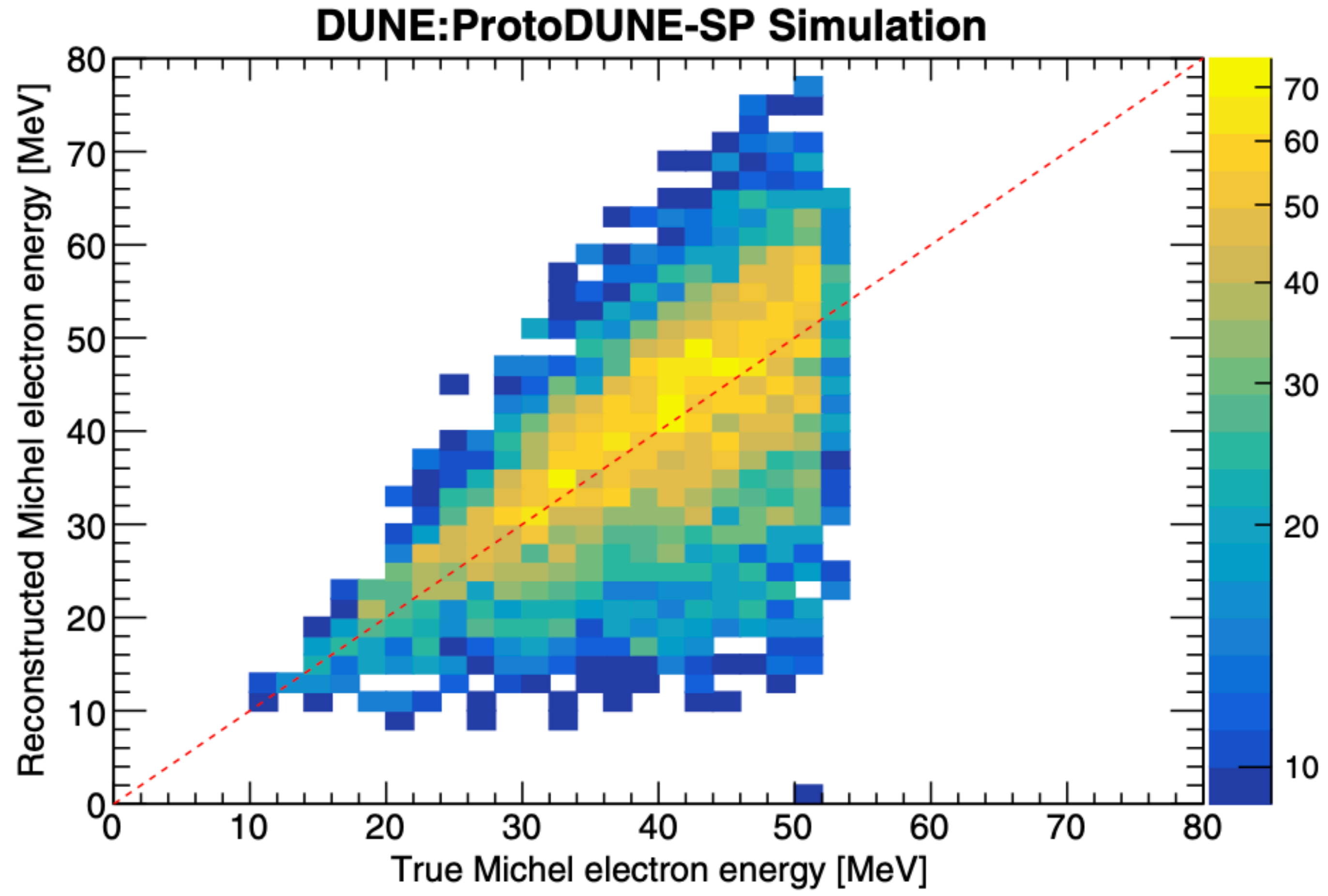
- Study using Michel electrons from muon decays

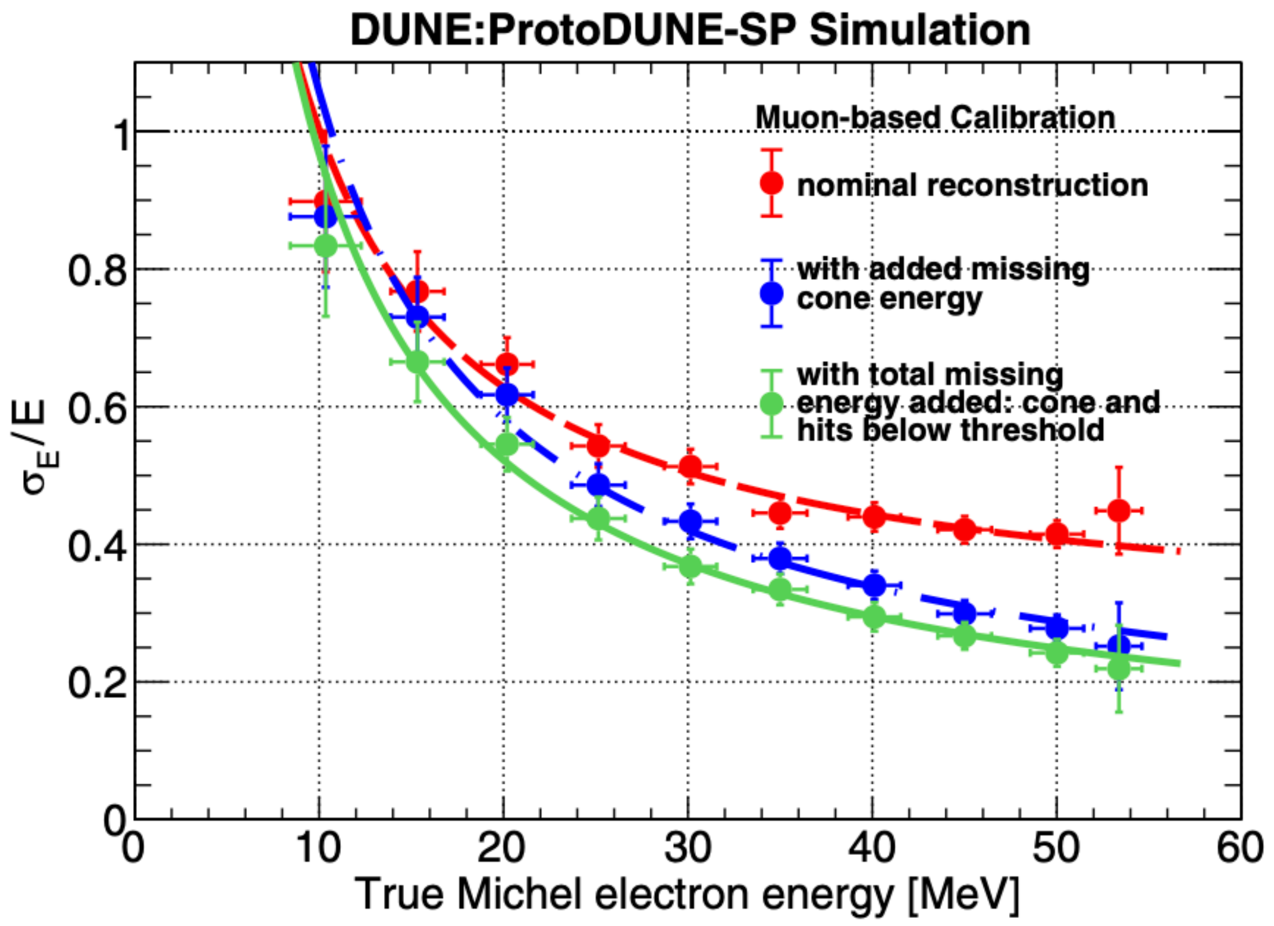
Phys.Rev.D 107 (2023) 9, 092012

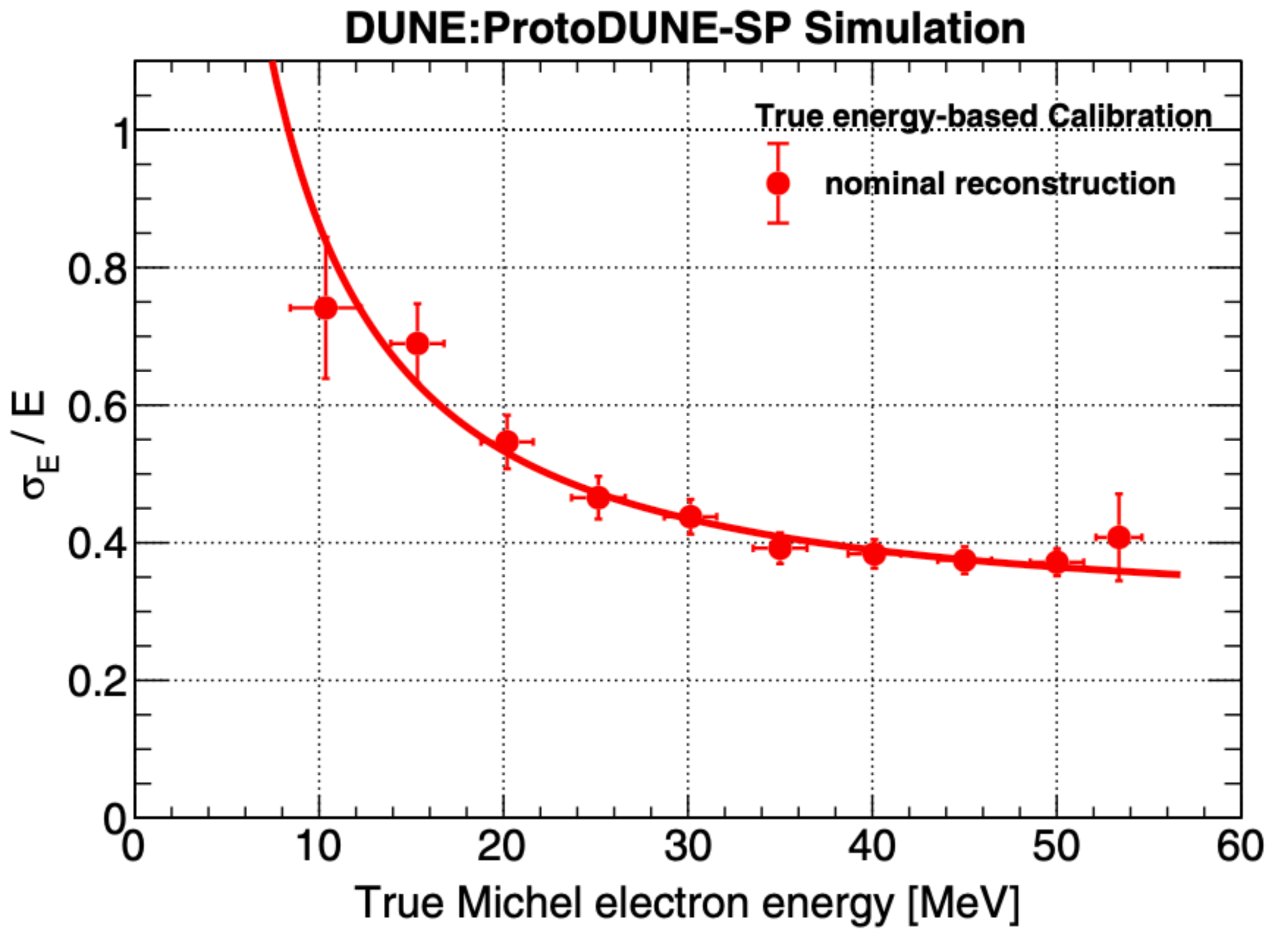






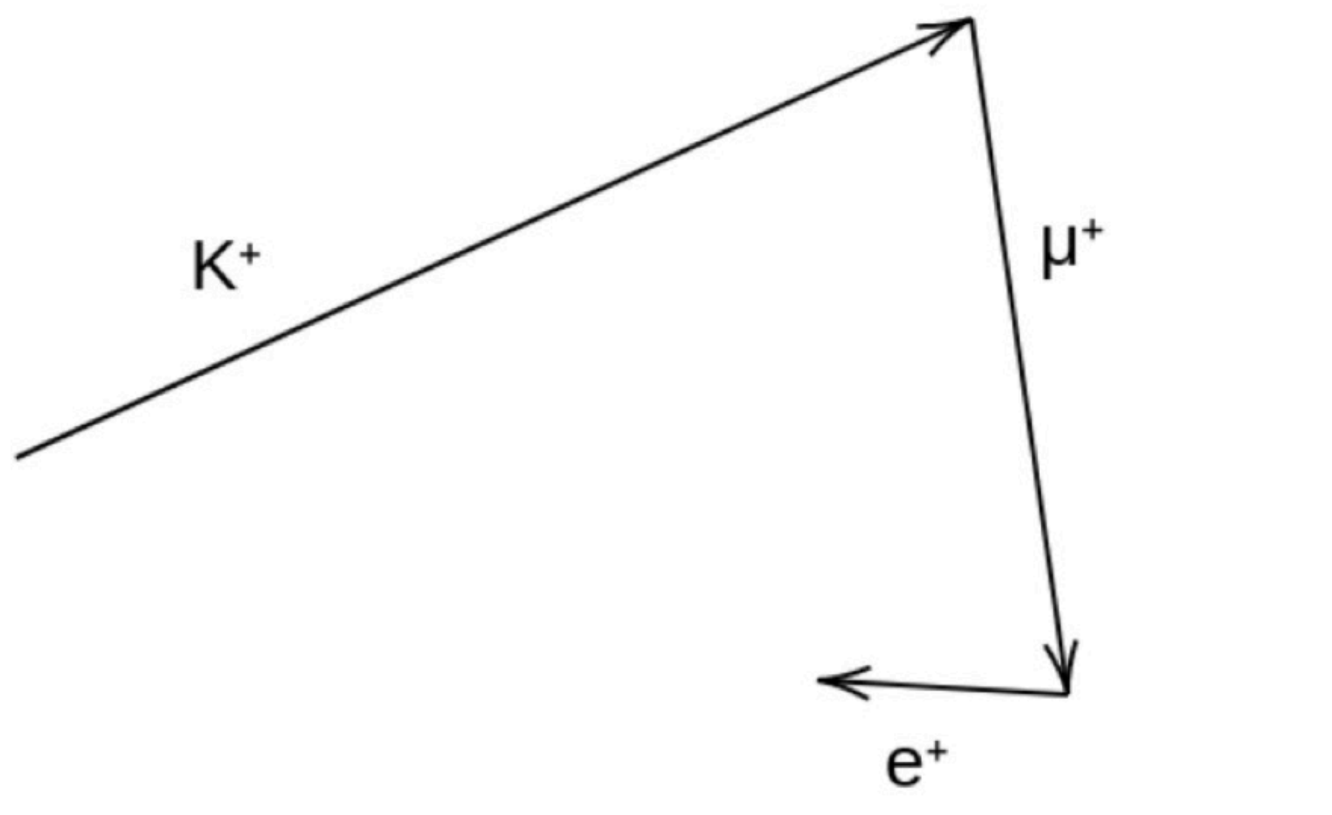


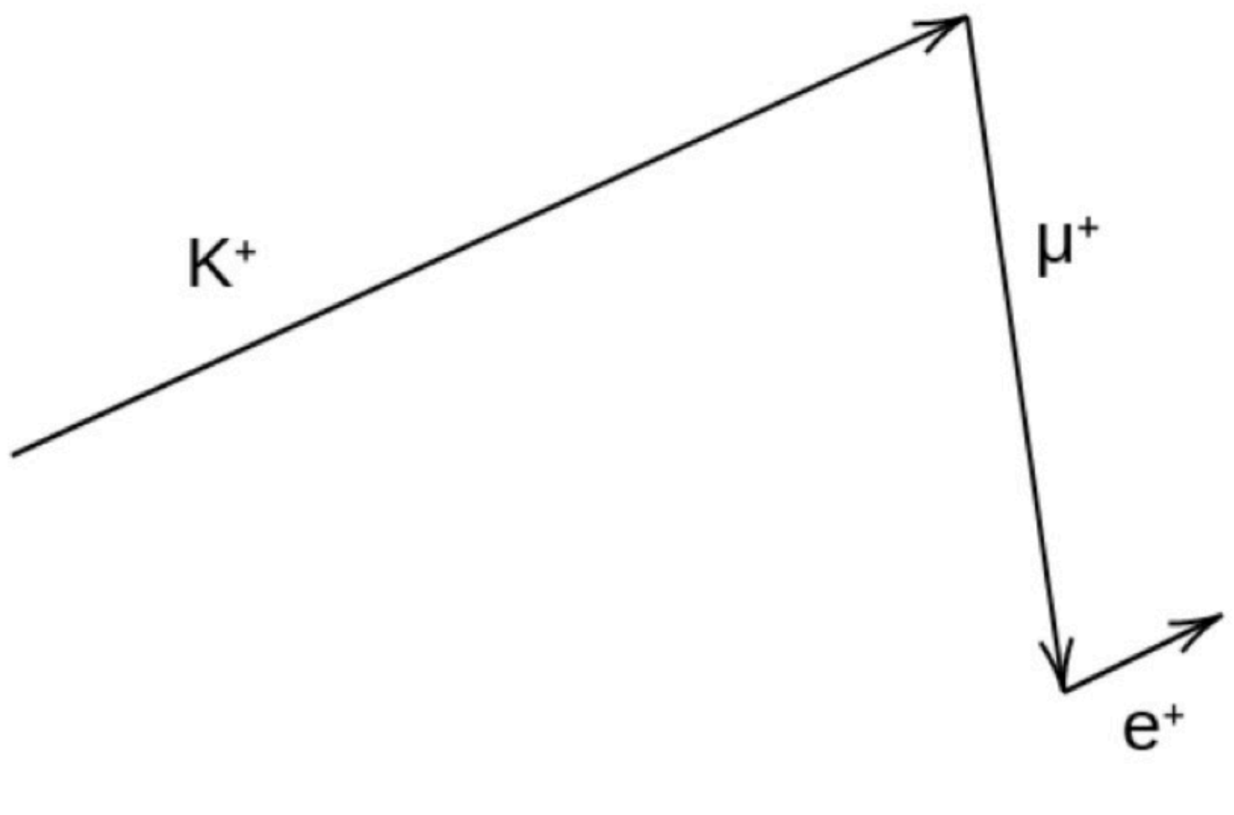


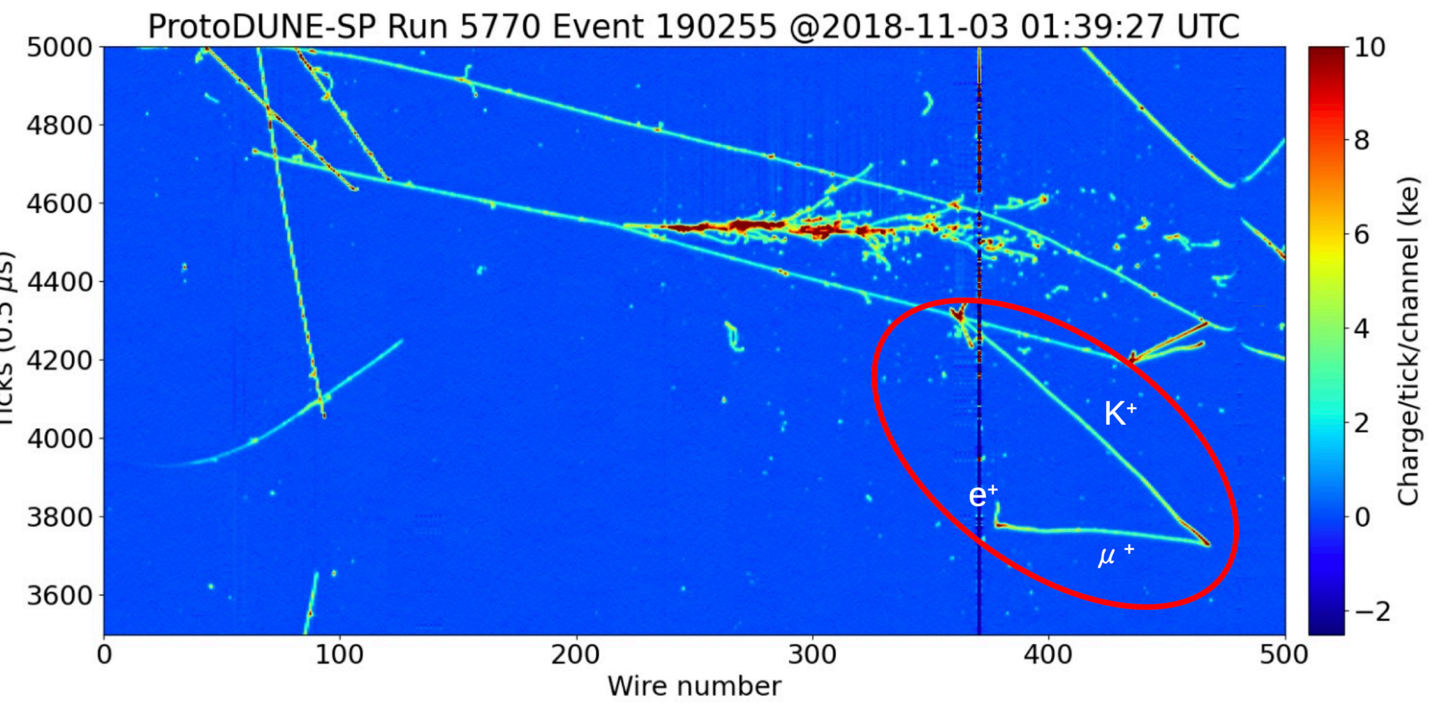


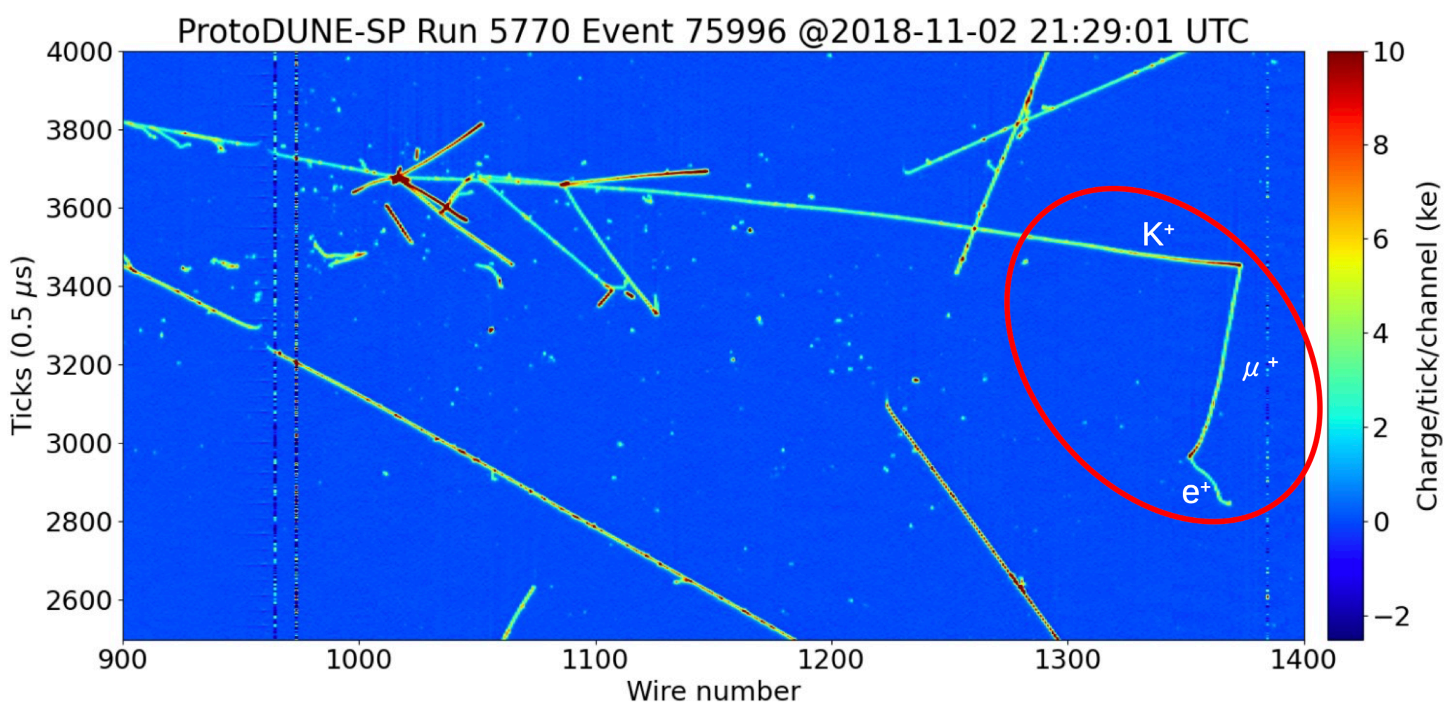
Secondary Charged Kaon Study

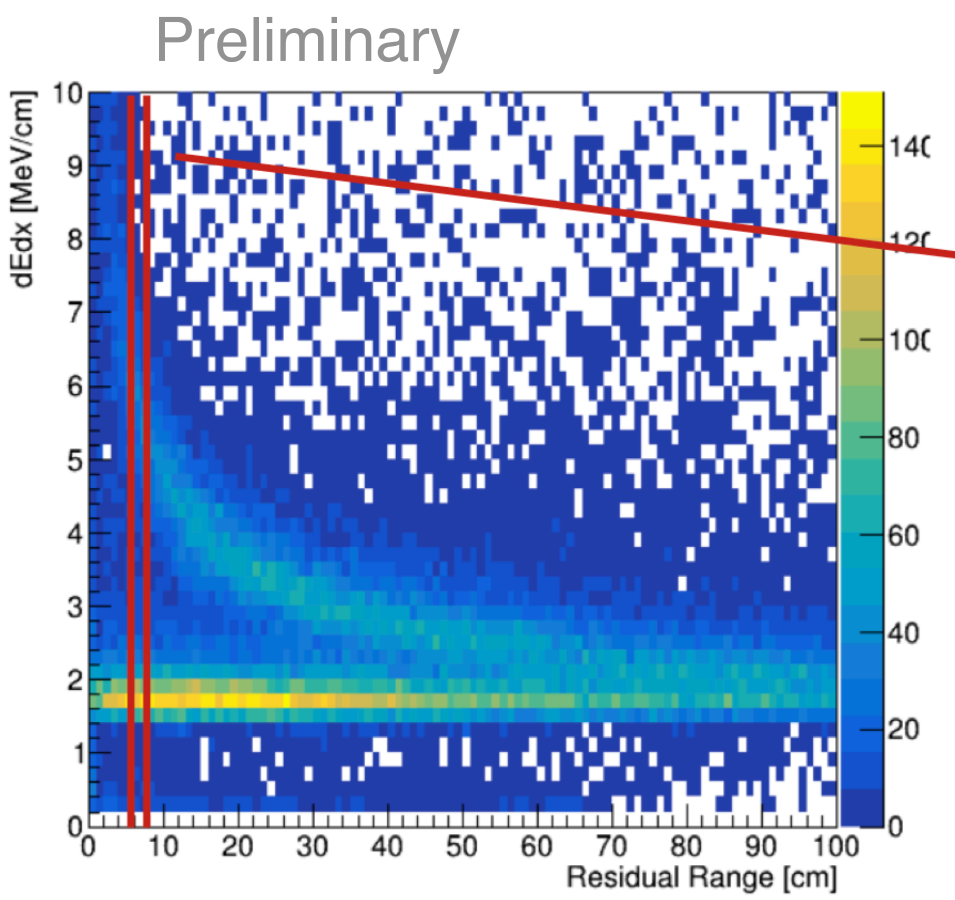
- Using 'hook' signature of stopping secondary charged kaons

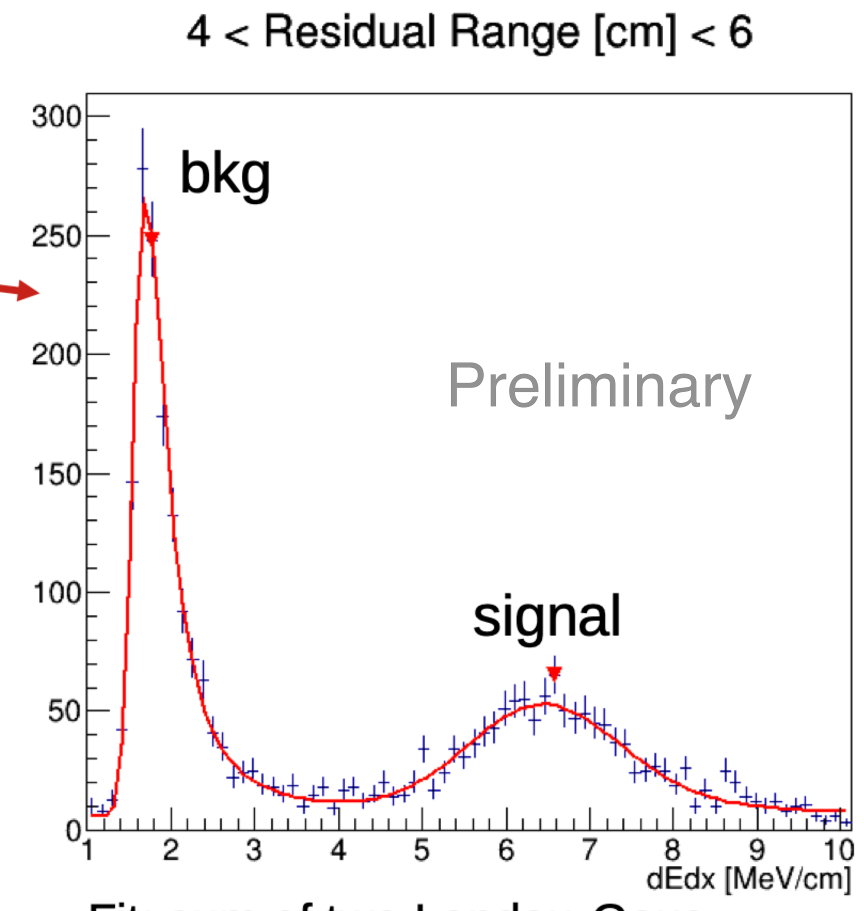










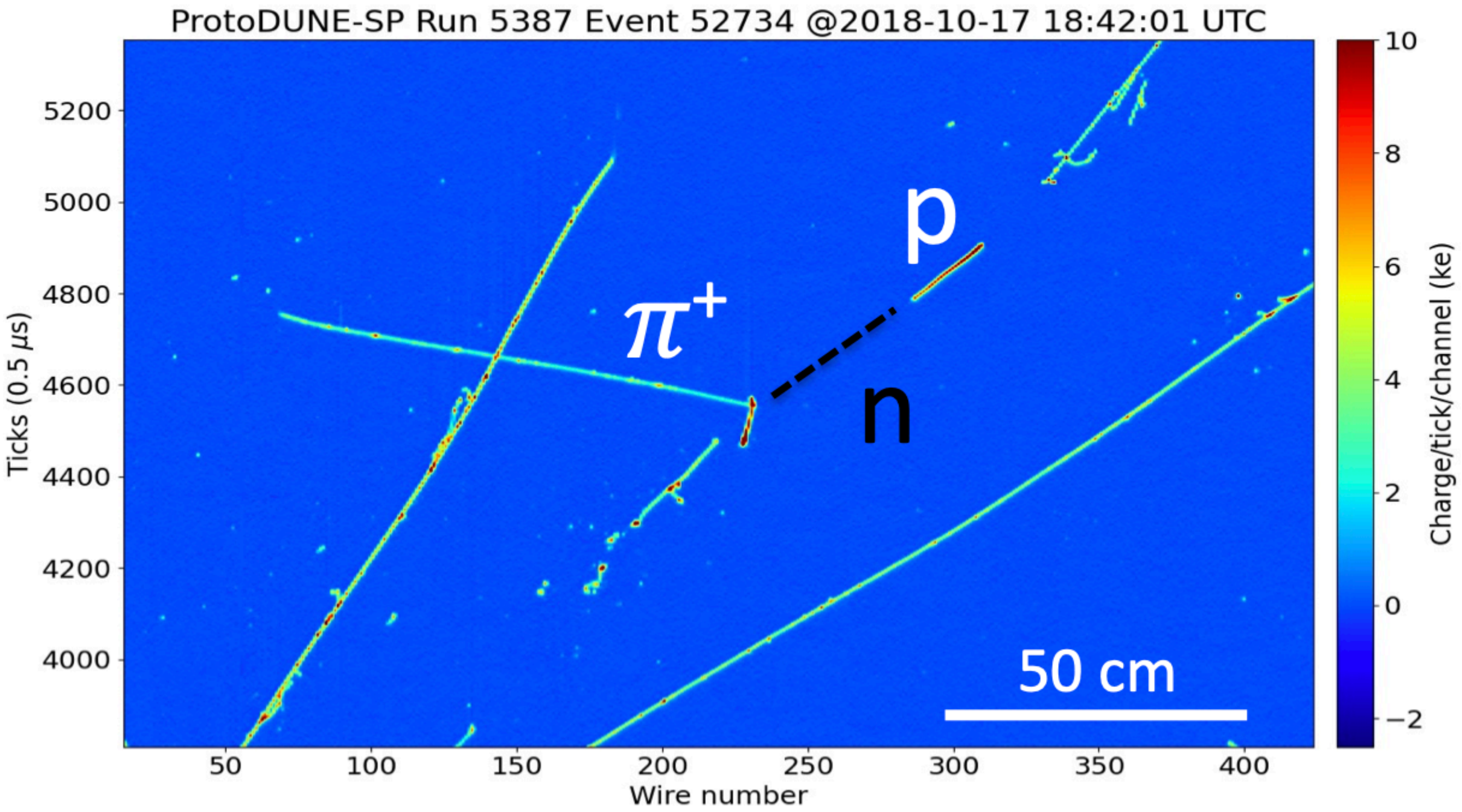


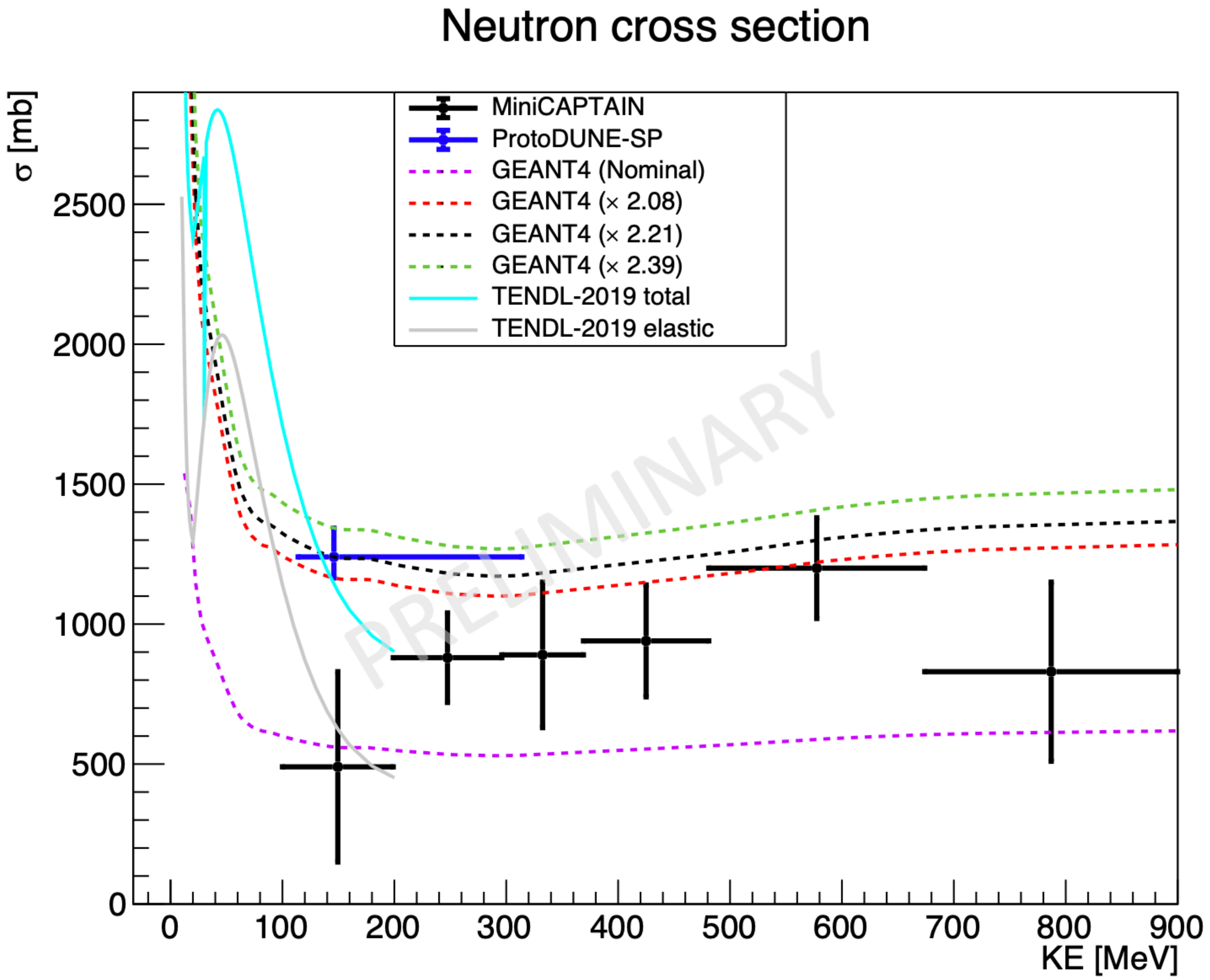
Fit: sum of two Landau-Gaus

- Understand energy deposition of secondary charged kaons

Neutron Inelastic Cross Section Measurements

- Using displaced proton signature in charged pion beam events





- Disjoint proton candidates (r>5cm) from reco π vertex
- Signal : Particles that result from ≥ 1 true neutron inelastic collision(s)
- Background : particles having no neutron ancestors that underwent any inelastic collisions

Fermilab DUNE