ProtoDUNE-SP: Past, Present and Future

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UNIVERSITY OF CAMBRIDGE

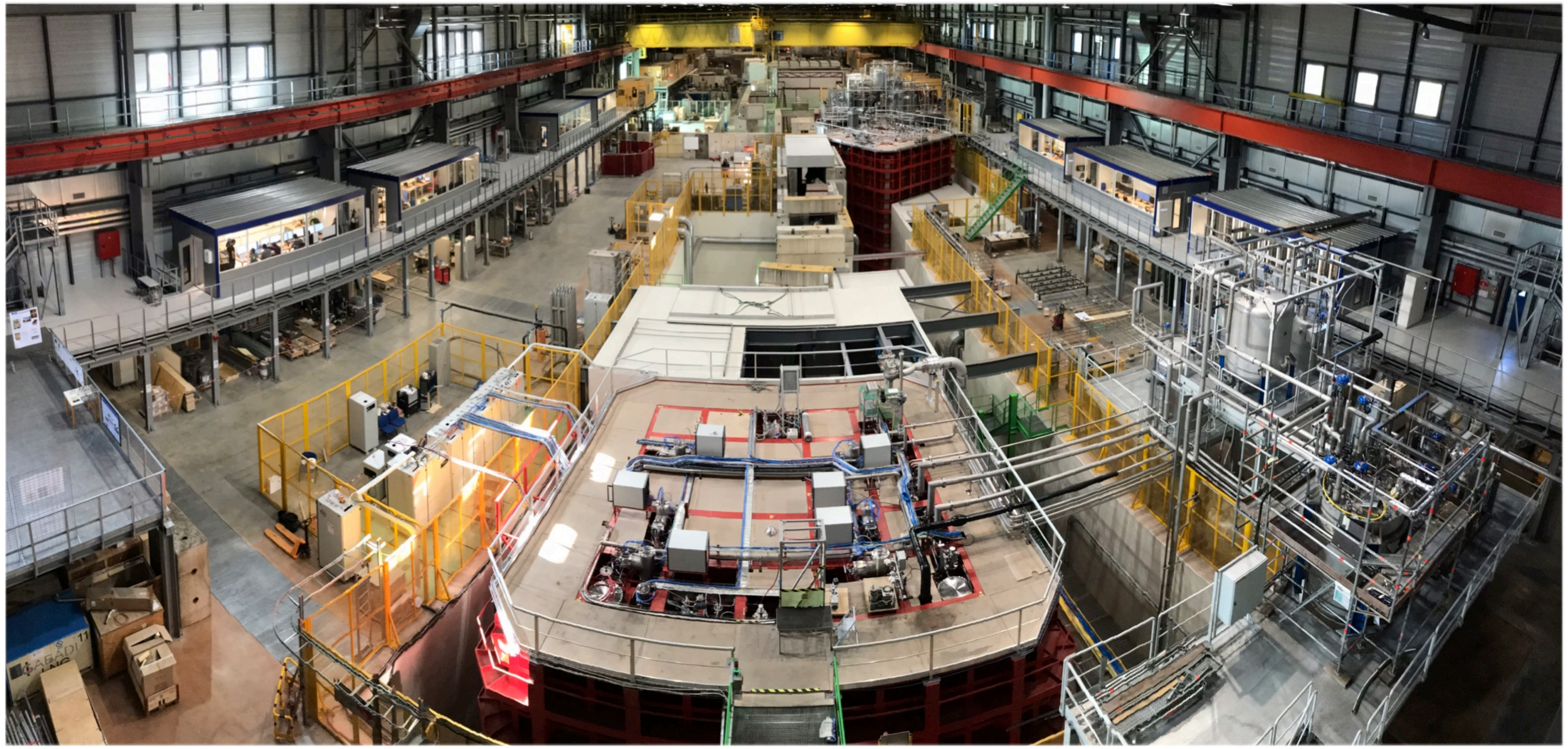
Overview

This talk will provide a summary of some DUNE prototype detectors

- ProtoDUNE-SP
  - Introduction
  - Detector performance
  - Physics analyses

Introduction

- ProtoDUNE-SP was a prototype of the DUNE Far Detector (FD) located at CERN
  - It used full-size components as an engineering prototype
  - It is still the largest liquid argon TPC built to date
  - It has a wide and strong physics programme in its own right



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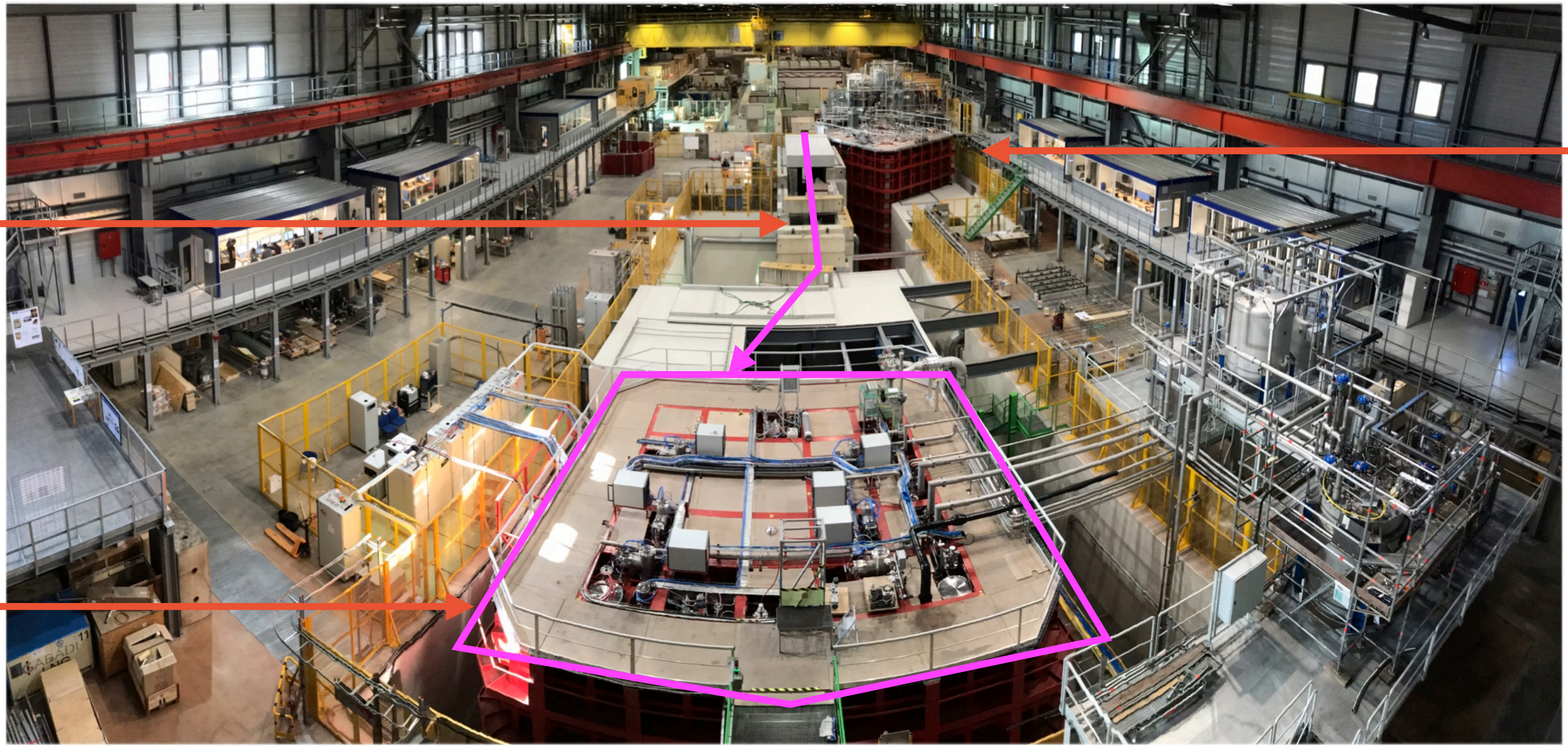
H4 VLE beamline



ProtoDUNE-DP
(won't discuss here)

ProtoDUNE-SP

CERN Neutrino Platform
Prévessin site

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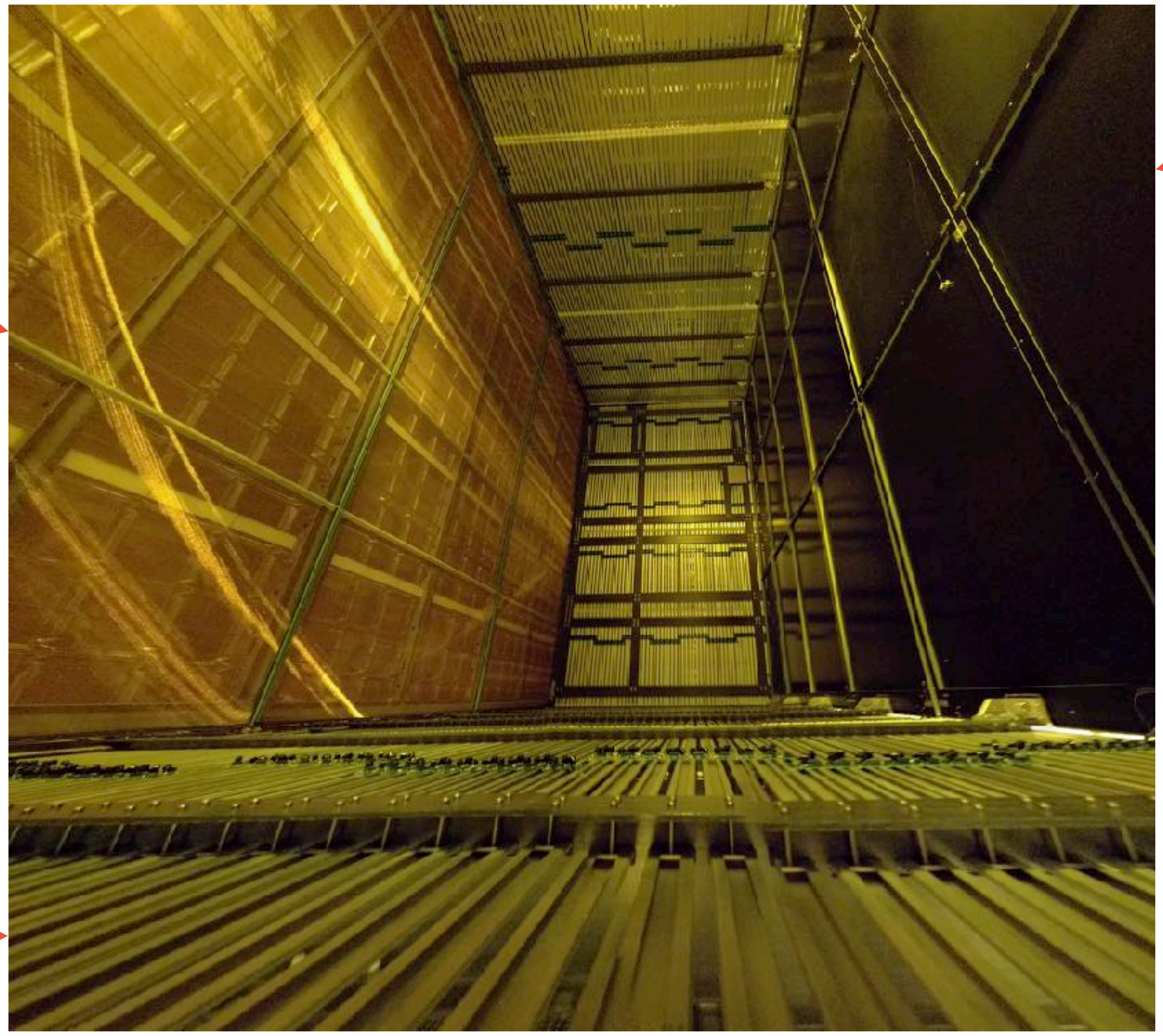
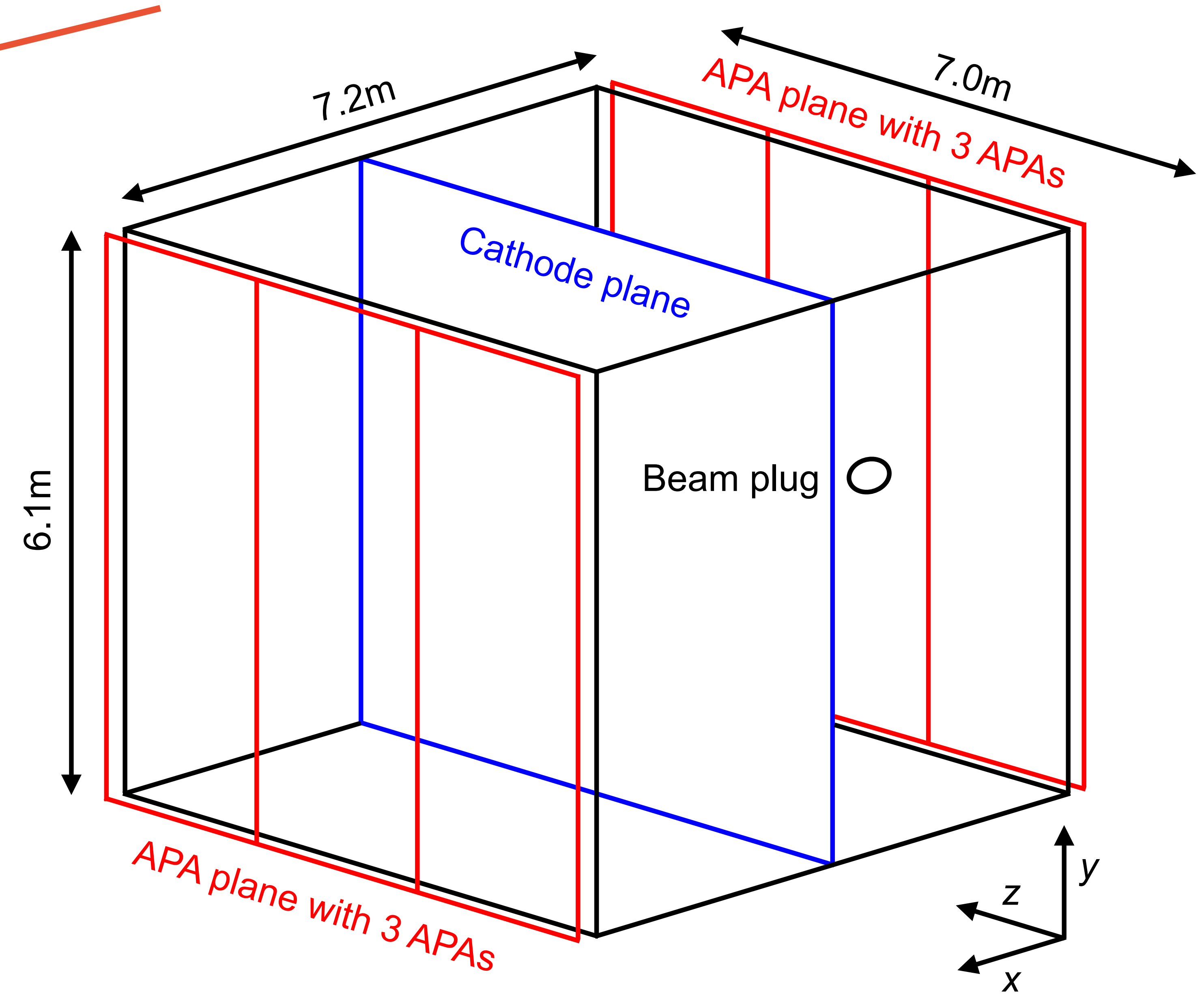
Anode with three wire planes

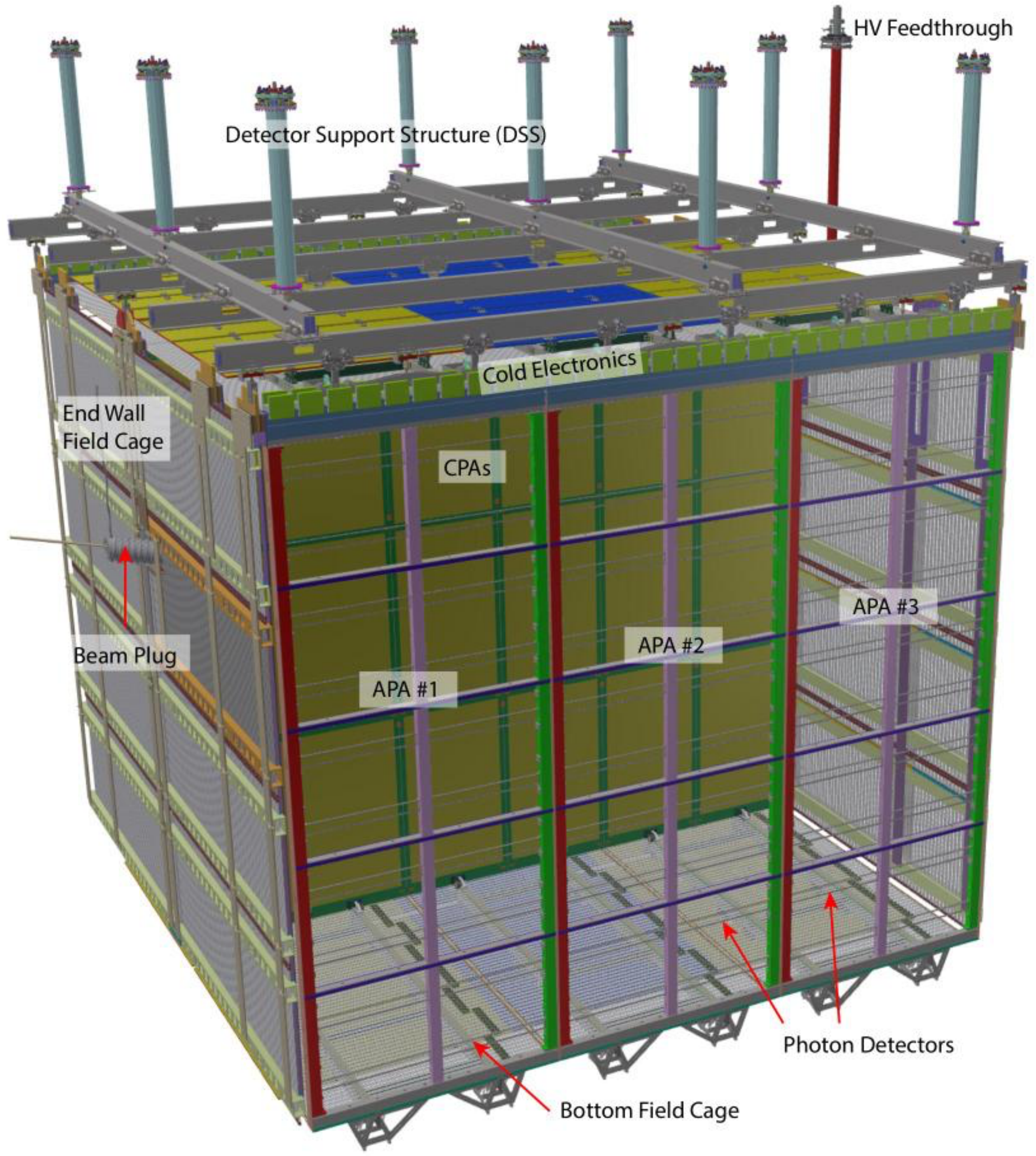
Cathode

Field cage



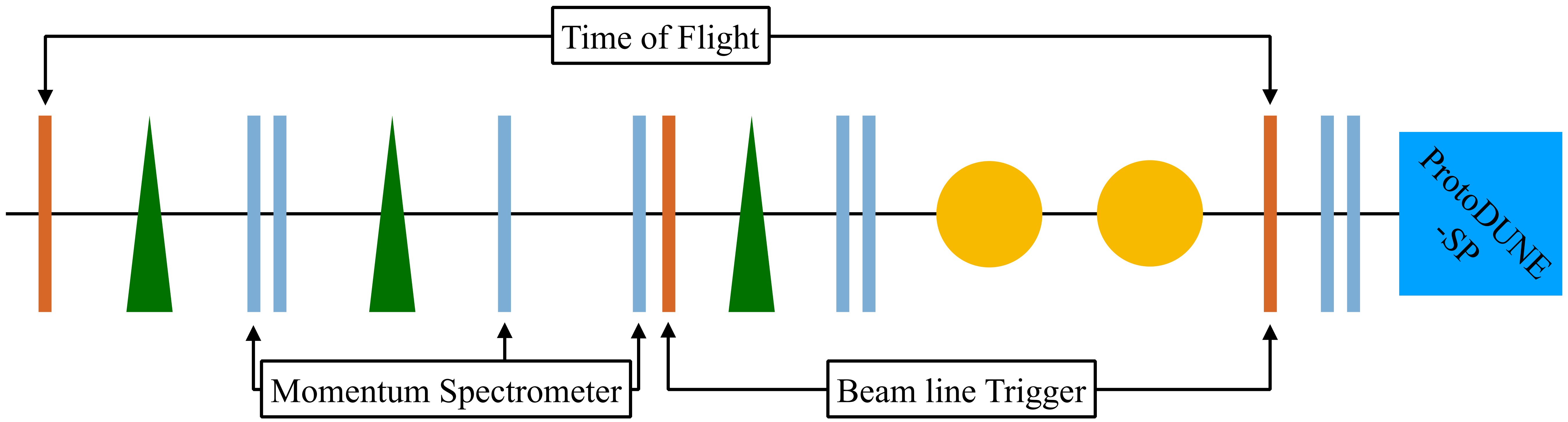
One of ProtoDUNE-SP's two drift volumes

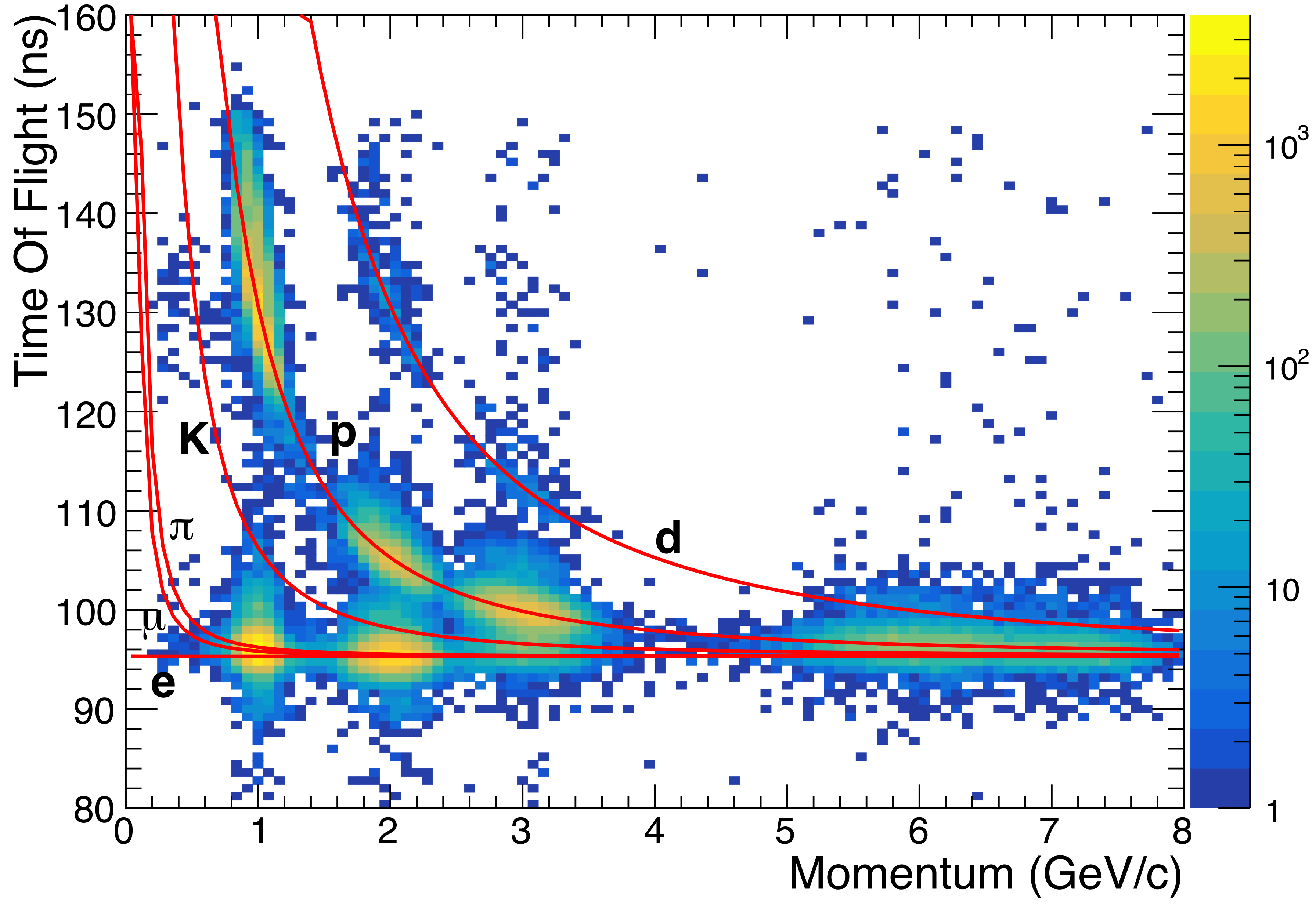




H4 VLE beam line

- A new beam line extension was built at CERN for ProtoDUNE-SP
  - Mixed hadron and electron beam
  - Particle momenta tuneable in the range 0.3 - 7 GeV/c in positive and negative polarity
    - Collected over 4 million triggers in positive polarity: e^+, μ^+, p, π^+, K^+





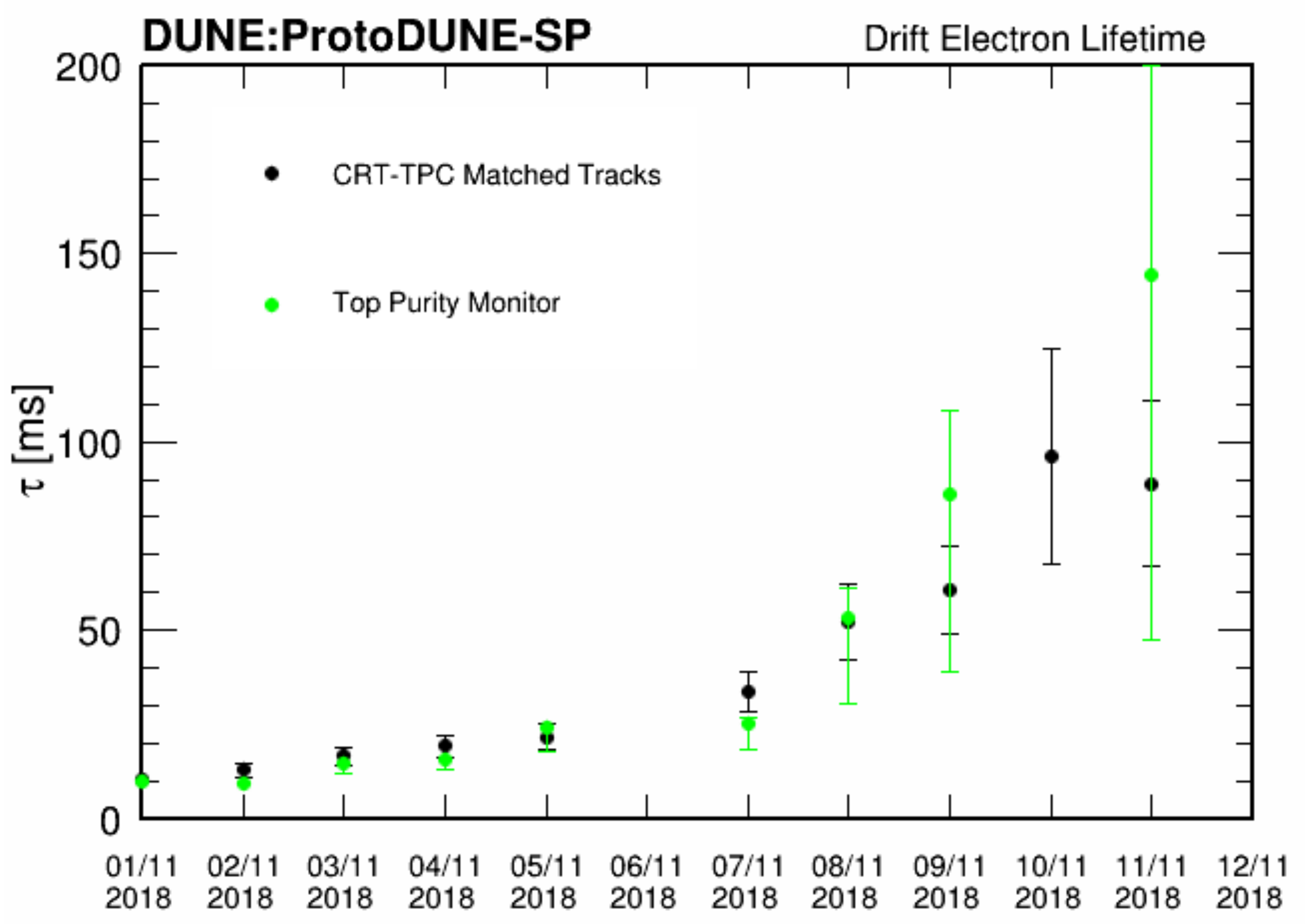
ProtoDUNE-SP: Detector Performance

Electron lifetime

- An important goal for ProtoDUNE-SP was to show that the DUNE FD will meet certain performance criteria as defined in the TDR

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

- Argon purity is defined in terms of the electron lifetime
  - Time taken for a drifting electron to be captured by an impurity
  - Measured in two complementary ways
    - Dedicated purity monitors
    - Cosmic-ray muons



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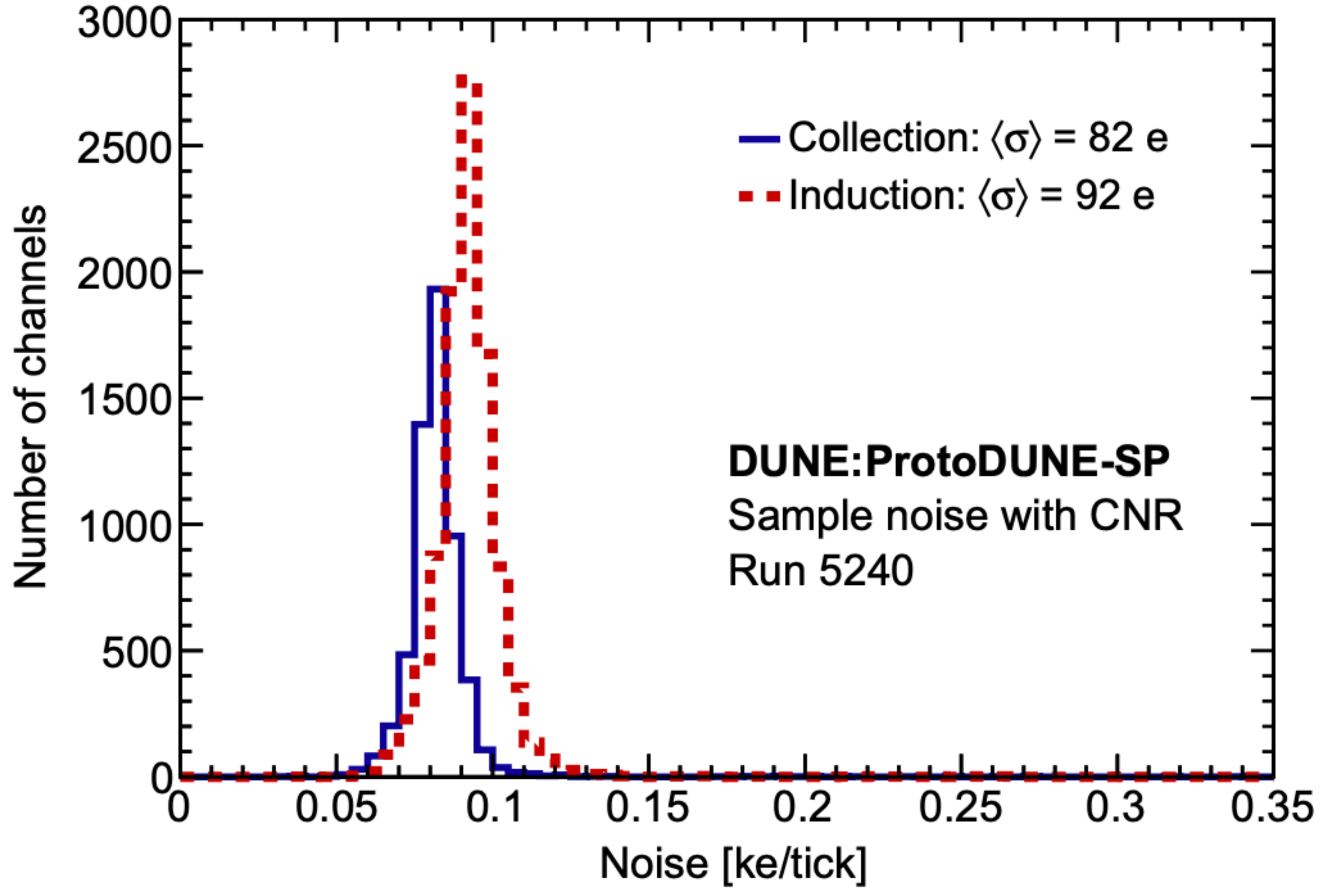
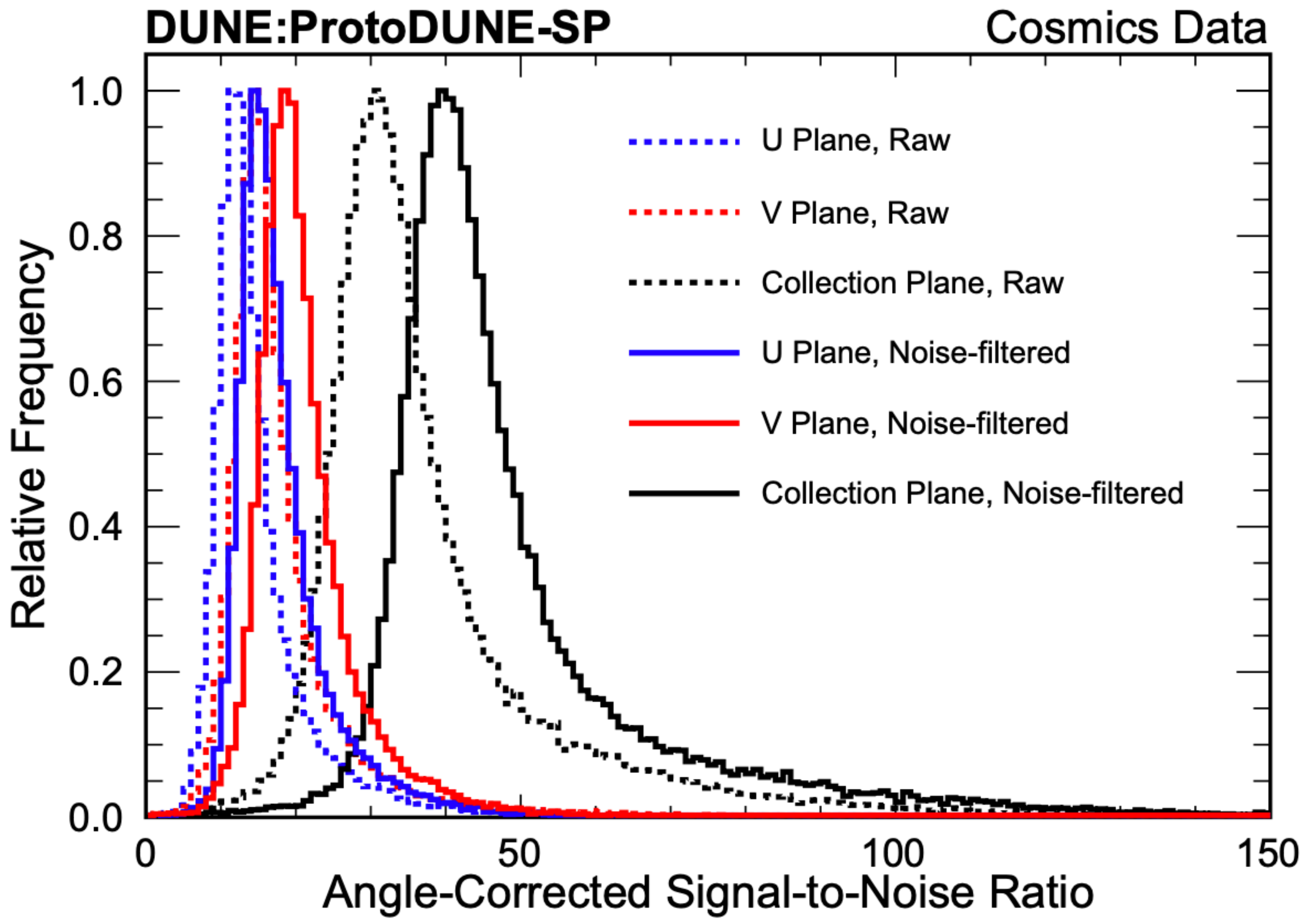
- Channel noise measured to be low
  - Includes coherent noise removal
  - Good signal to noise ratio for cosmic-ray muons





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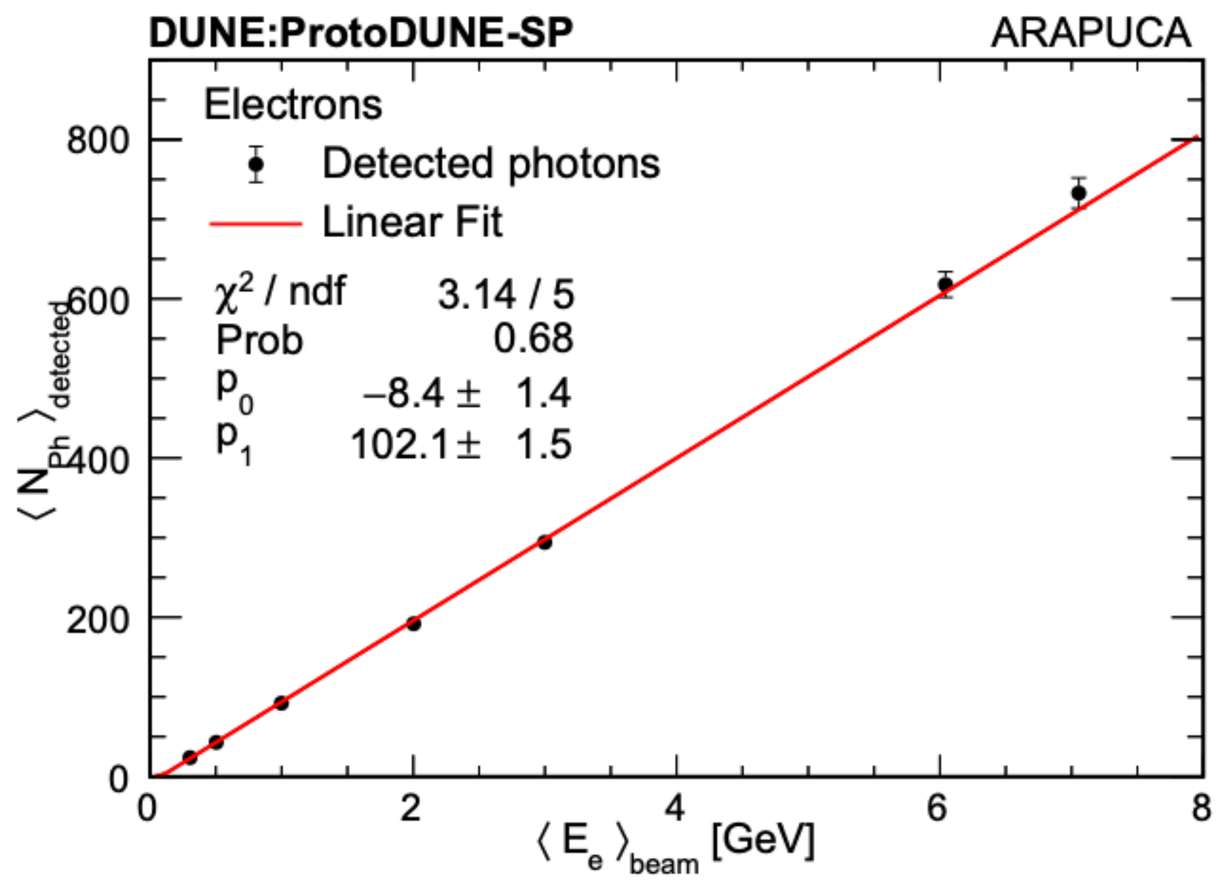
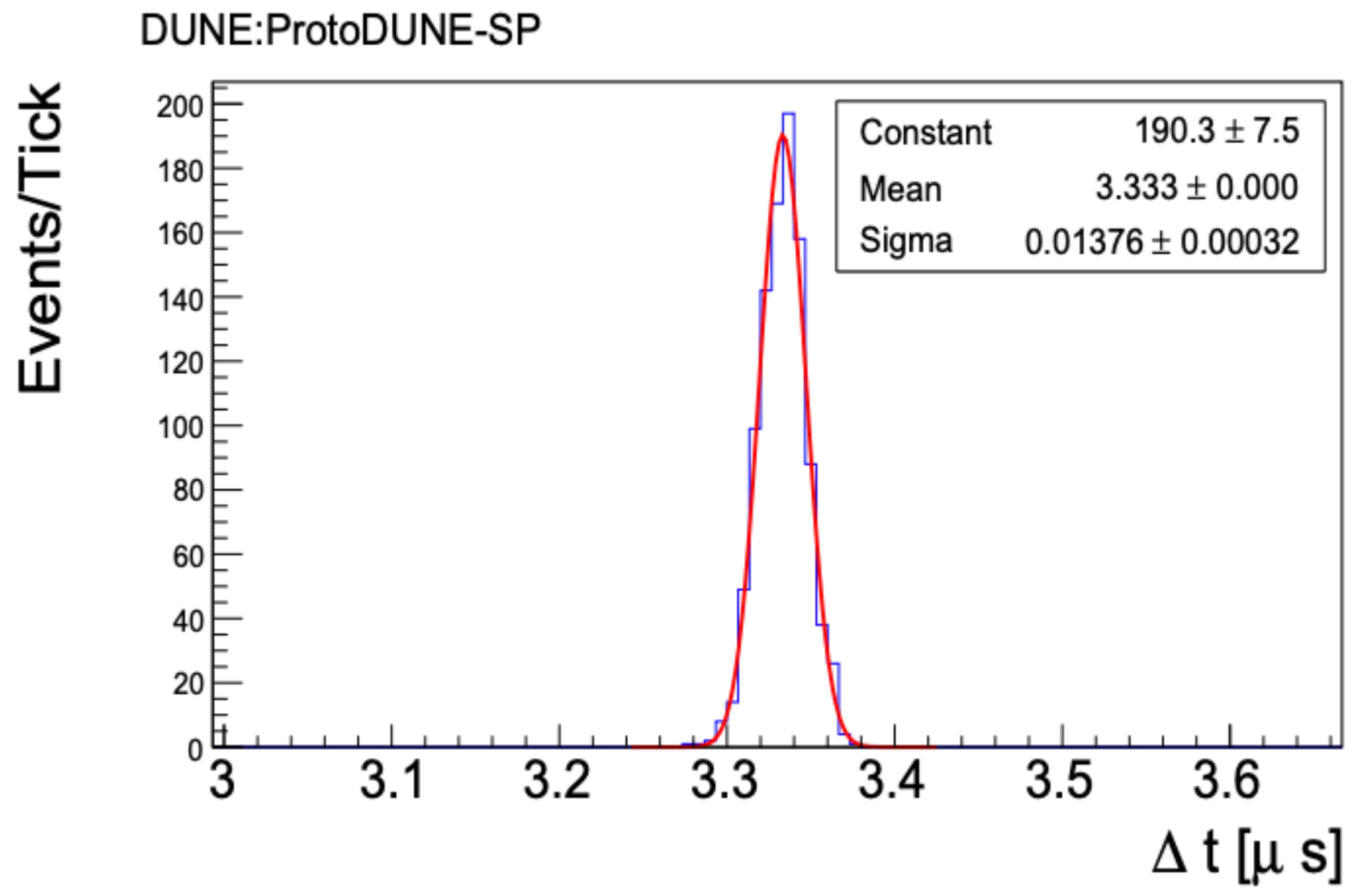
- ARAPUCA performance
  - Measured number of photons observed from beam positrons
  - Measured using the time between two calibration pulses

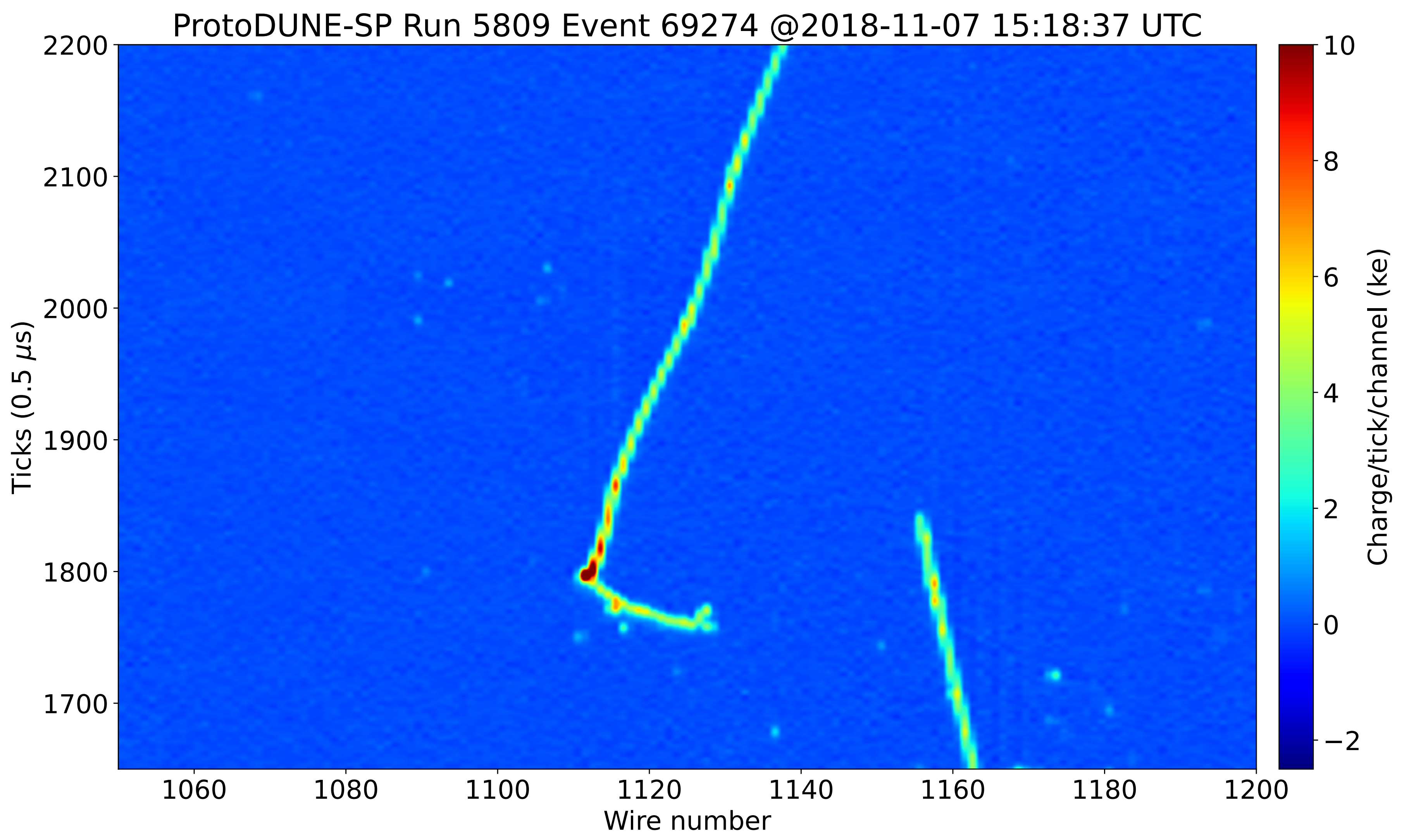


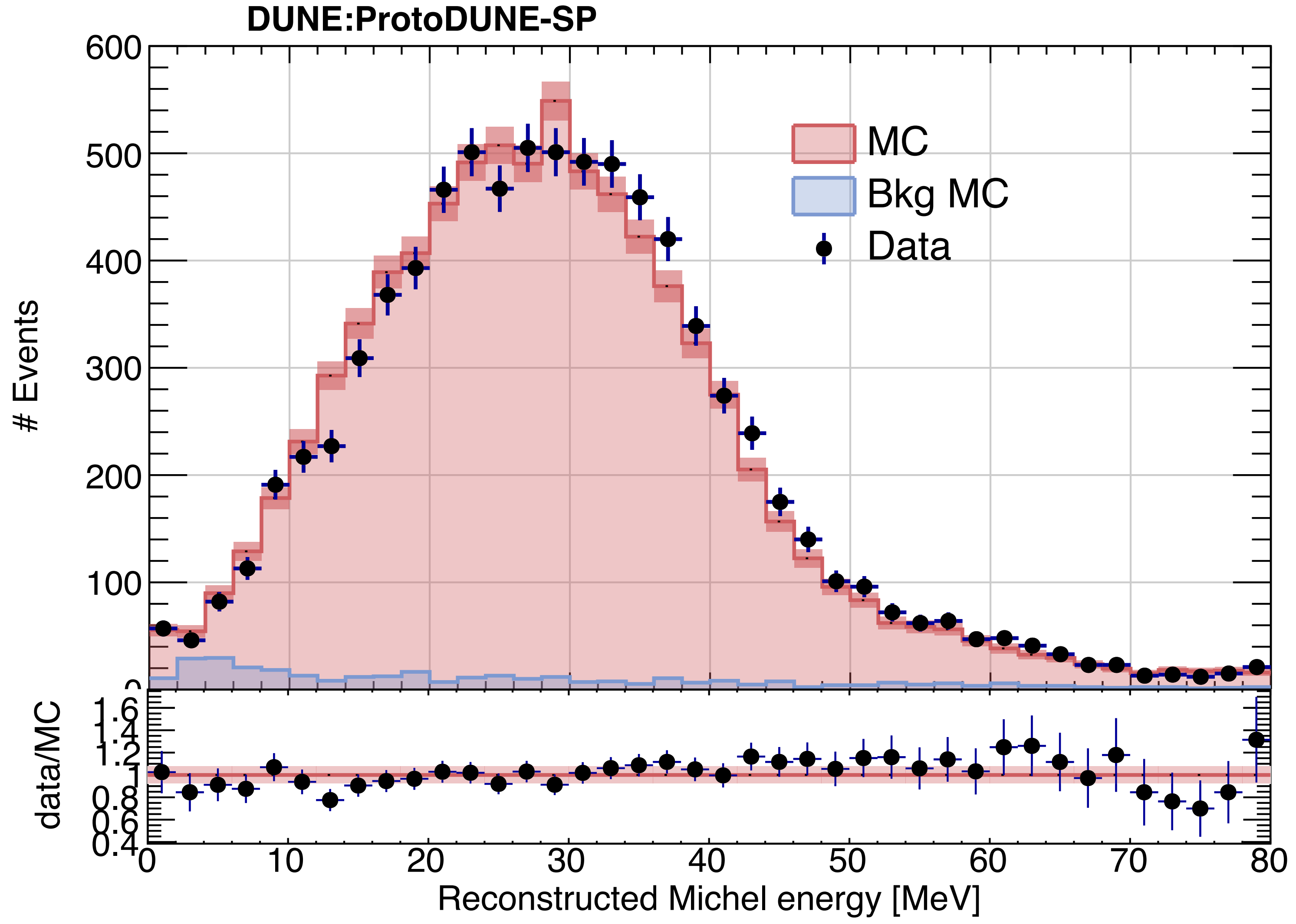


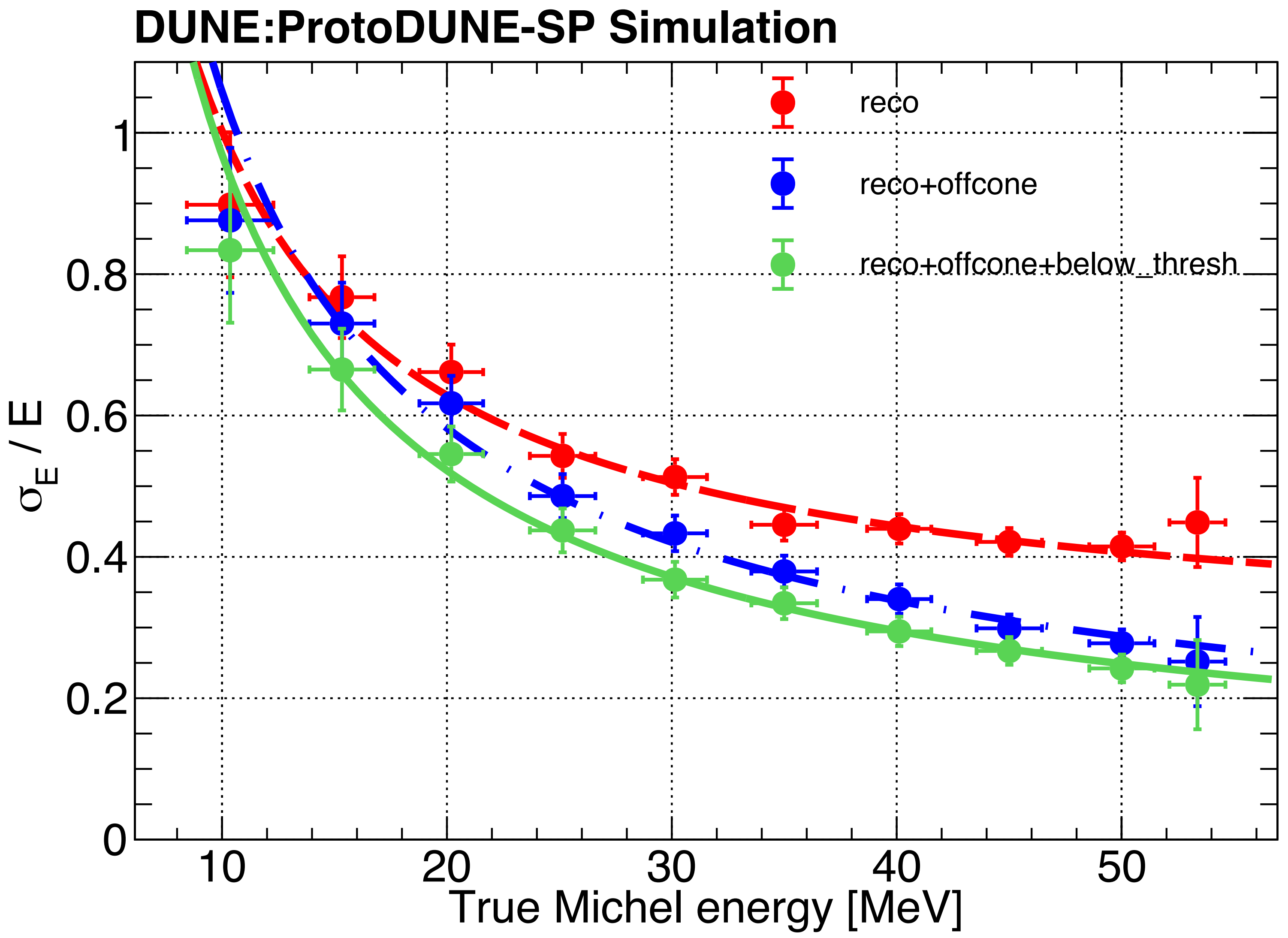
ProtoDUNE-SP: Physics

Michel Electrons

- Michel electrons (and positrons) selected from stopping cosmic rays
- Measured energy resolution after correcting for hits below threshold and missed hits
- Good agreement between data and simulation
- Provides evidence of successful reconstruction of low energy electrons
  - Important for DUNE's low-energy physics programme
- Paper draft in ProtoDUNE review

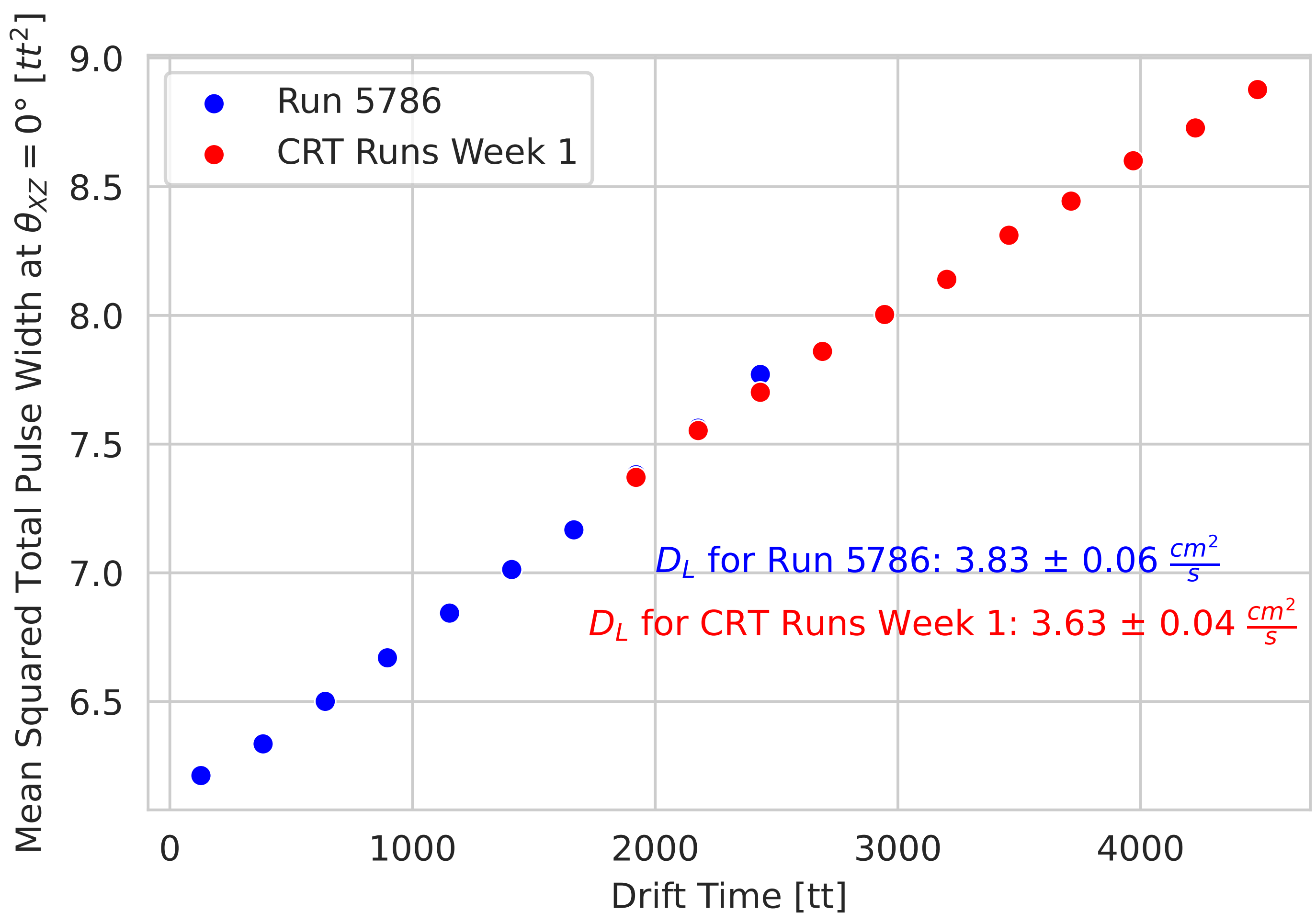


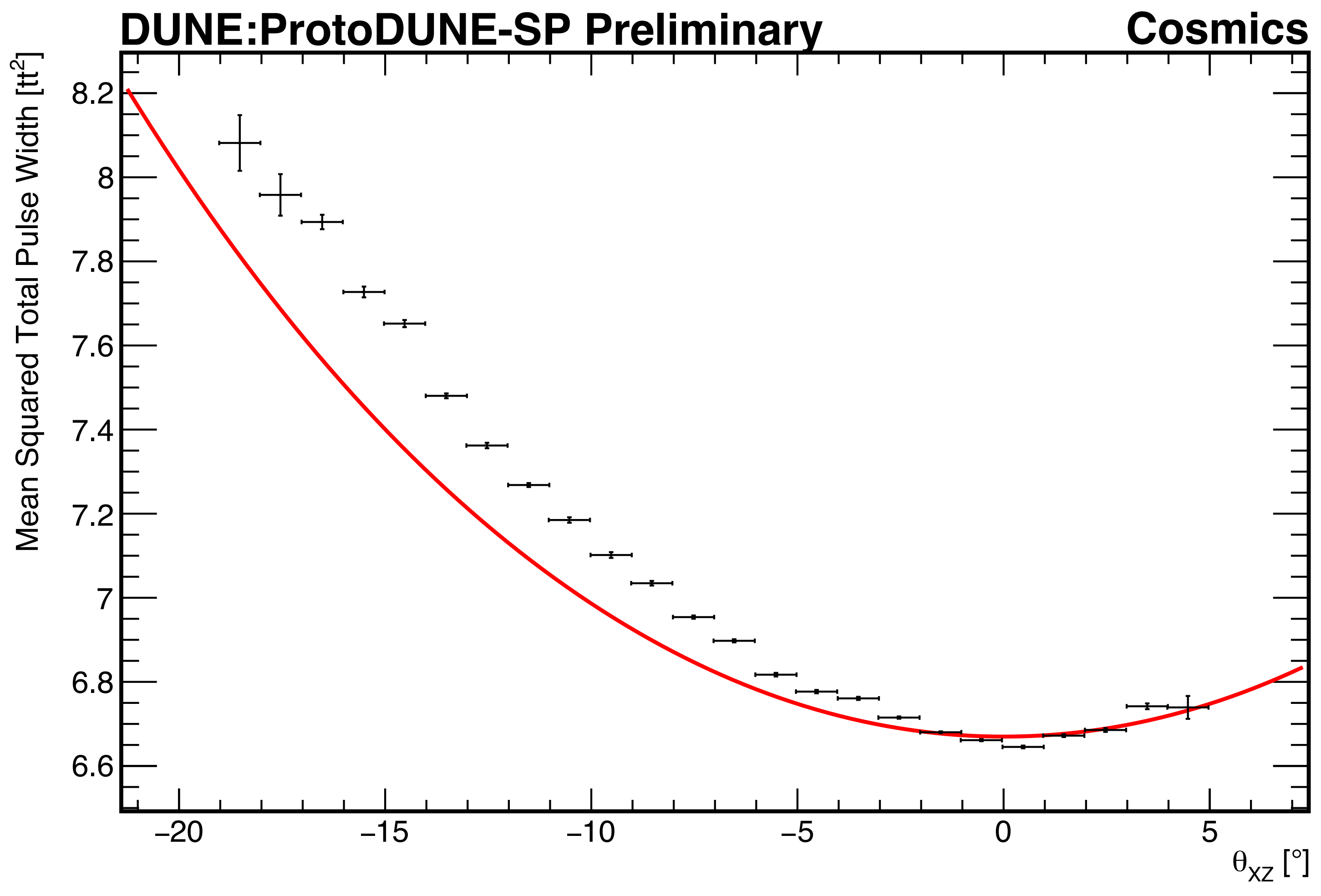




Diffusion

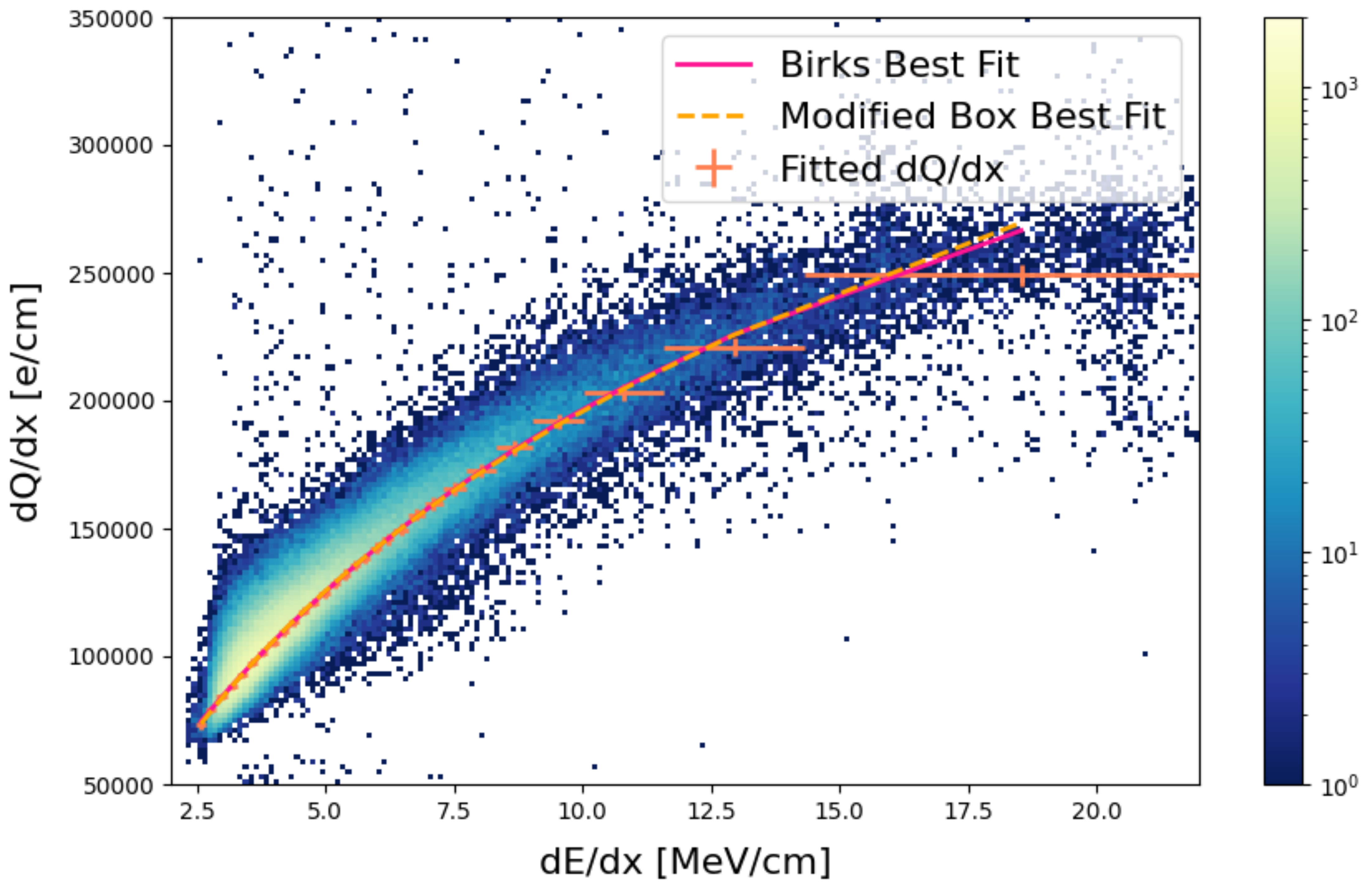
- Electron diffusion is a source systematic uncertainty
  - Electrons diffuse along (longitudinal) and perpendicular (transverse) to the E-field
- Diffusion can be probed through the width of hits in time
  - Longitudinal diffusion (D_L) smears the distribution
  - Transverse diffusion (D_T) adds an angular dependence
- Aim to simultaneously extract both diffusion terms





Recombination

- Recombination of electrons with argon ions causes non-linearity between the deposited energy and the charge response of the detector
- Use stopping 1 GeV/c beam protons to probe the effect
  - Modified box model
  - Birks' model
- Preliminary results consistent with previous experiments
  - ArgoNeuT and ICARUS
- Finalising potential space charge effect systematic uncertainty
- Run on full data sample

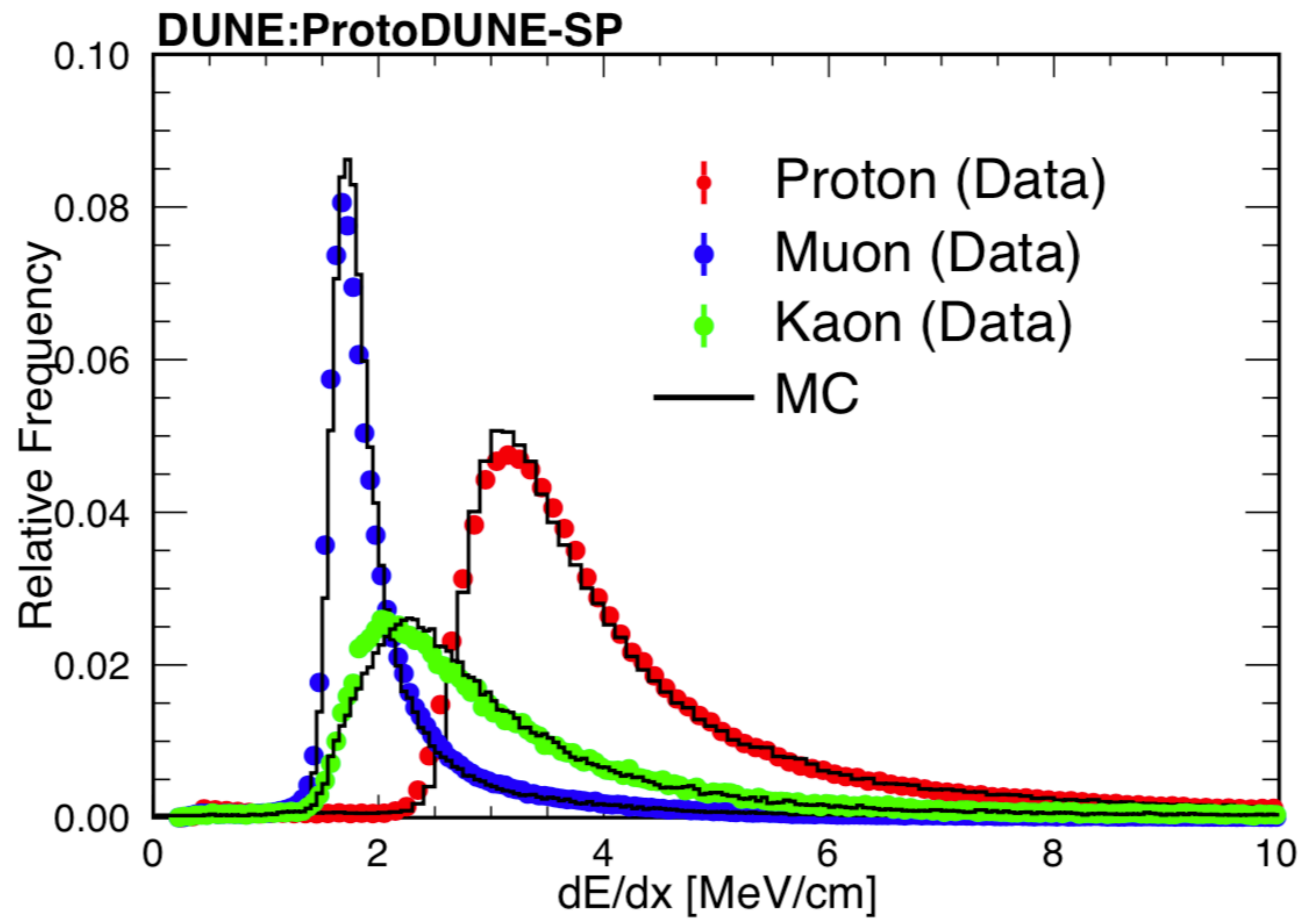


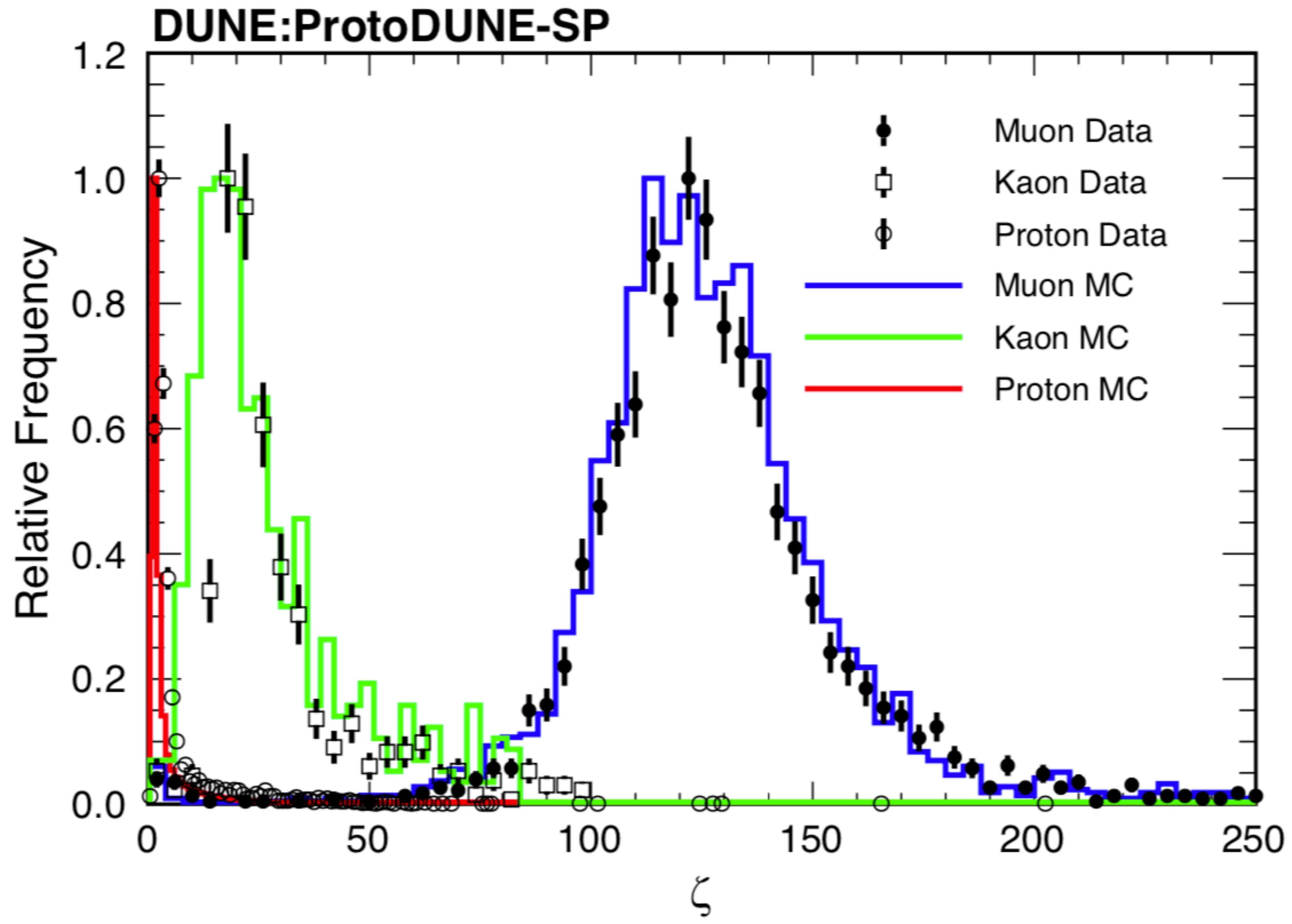
dE/dx Modelling

- Use stopping particles to characterise dE/dx
  - Cosmic ray muons
  - 1 GeV/c beam protons
  - Secondary kaons produced in 6 and 7 GeV/c kaon beam interaction

- Secondary kaons selected by characteristic muon decay channel
  - 90% pure sample of stopping kaons obtained

- Good dE/dx agreement between data and MC



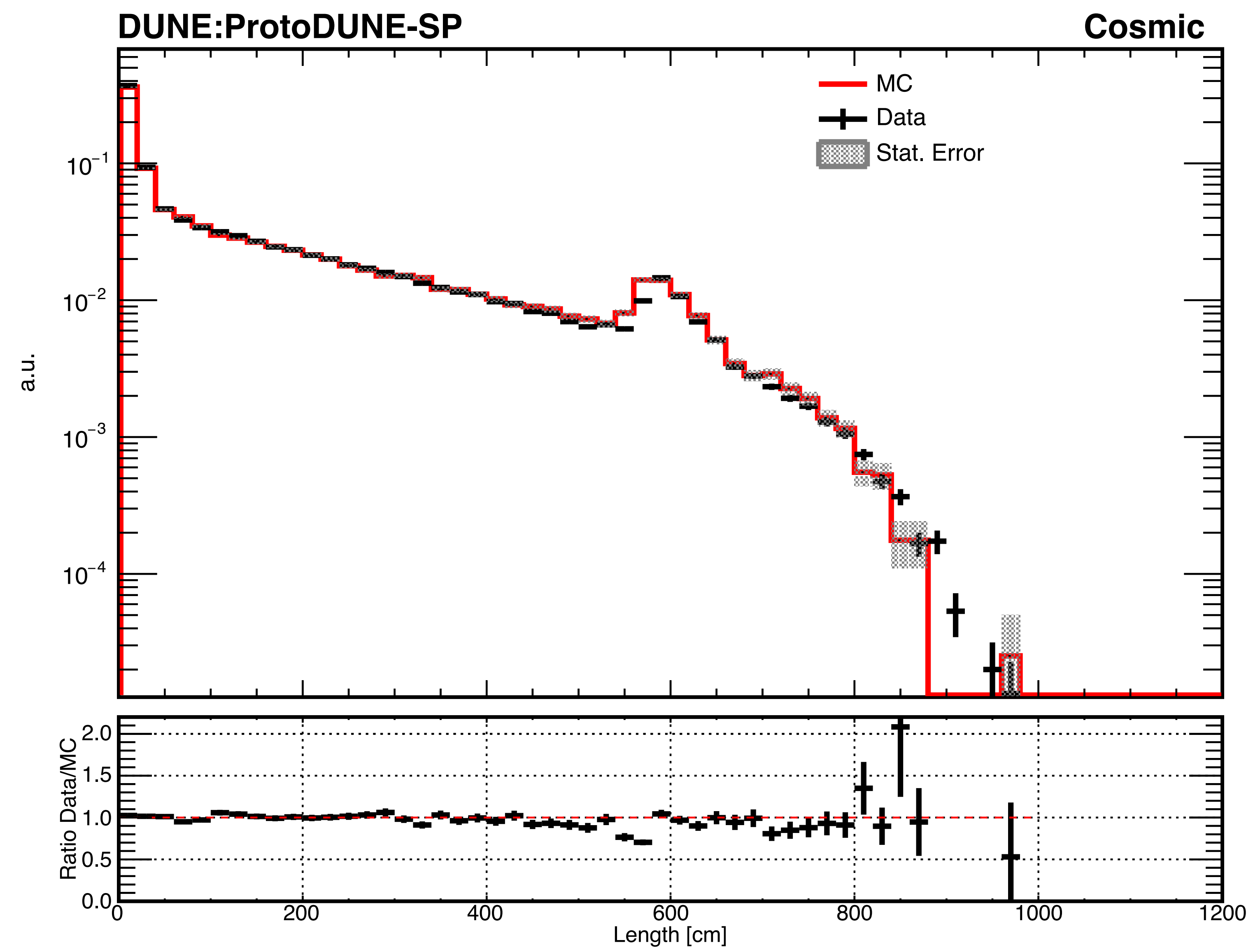


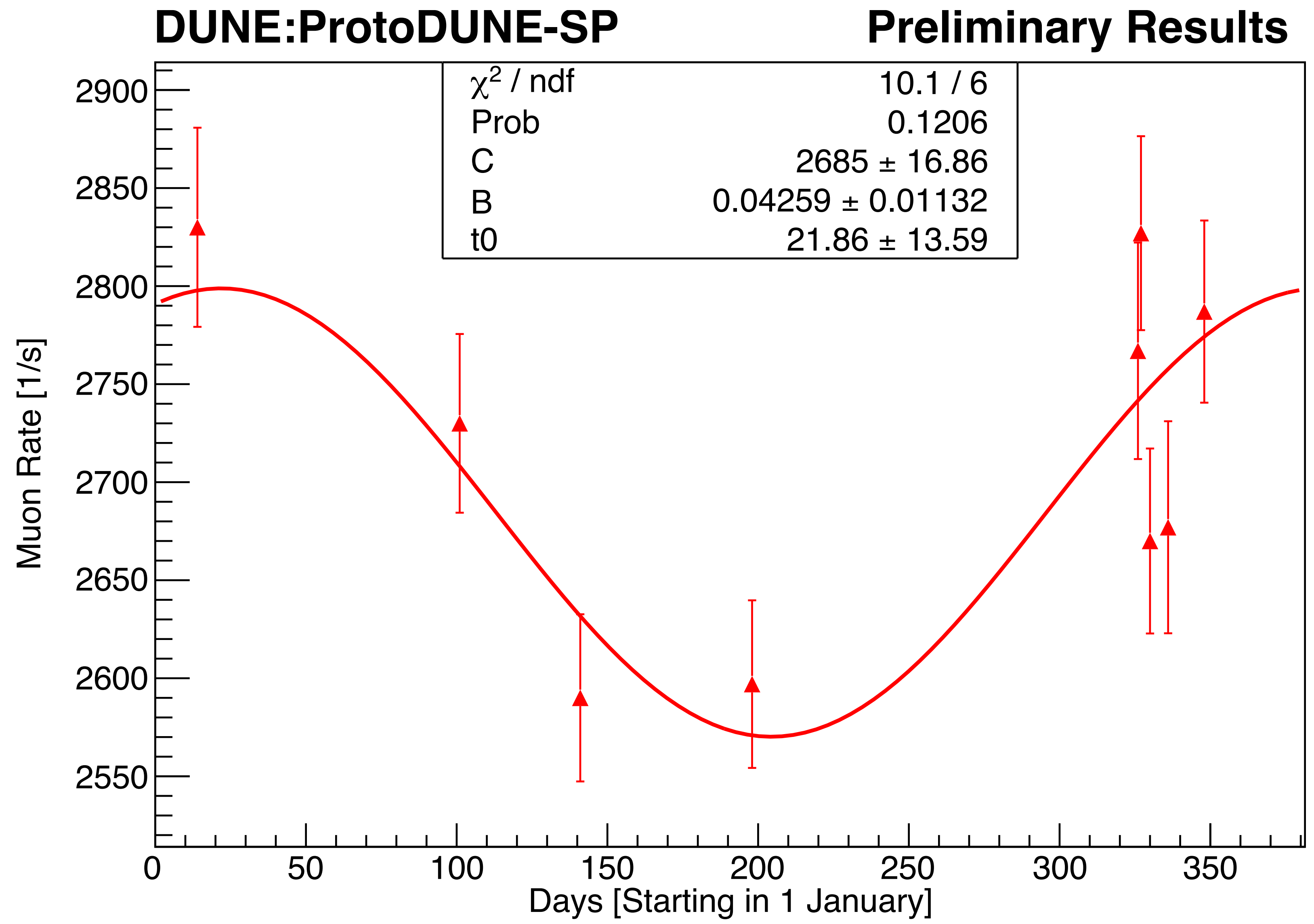
Cosmic muon seasonal variations

- Expect to see seasonal variations in cosmic ray rates due to changes in atmospheric temperature
- Good agreement for the selected cosmic ray muon sample between data and MC
- Measure the rate in data for a number of different runs and fit the distribution:

$$g(t) = C * \left(1 + B * \cos\left[\frac{2\pi}{P}(t - t_0)\right]\right)$$

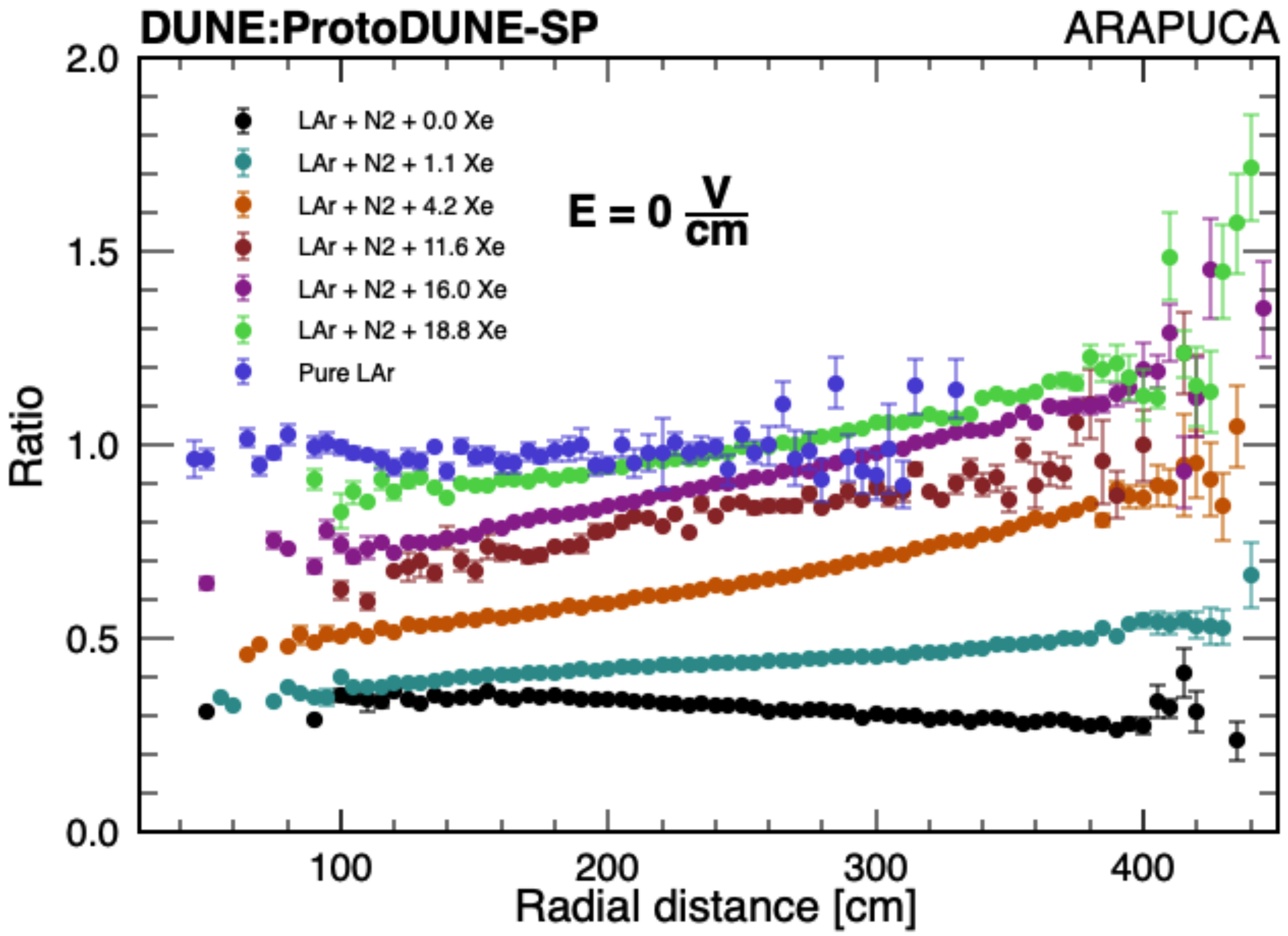
  - See a clear signal at 3.8σ
  - Amplitude = 4.3 ± 1.1%
  - Maximum rate on day 21.9 ± 13.6 days
- In agreement with other surface experiments

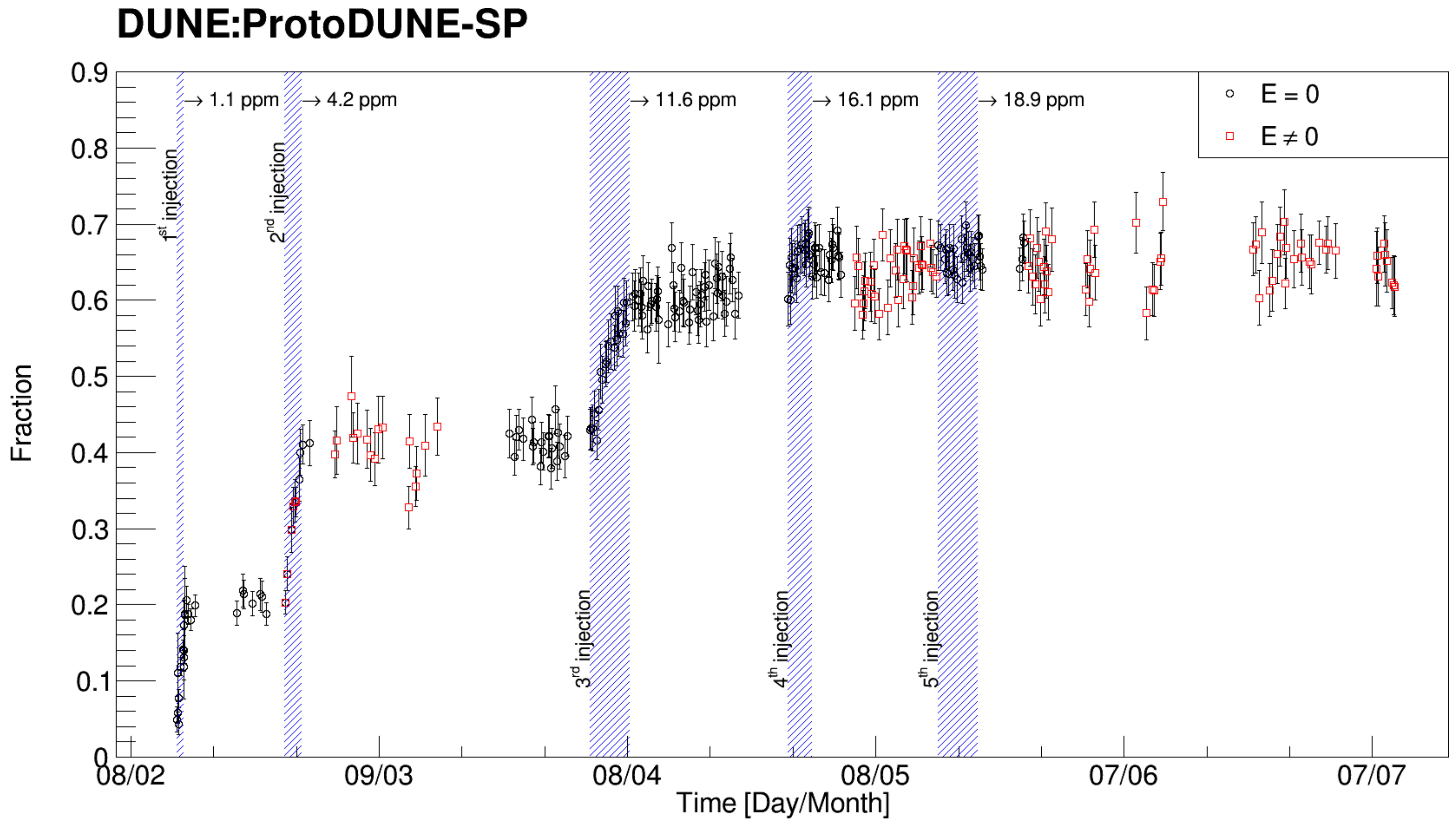




Photon Detector Analysis

- Xenon added in 2020 after N2 contamination
  - 18.8ppm enough to recover the 70% light drop
- Light increases with Xe concentration and then saturates above ~16ppm
- Similar results from PDS and two additional X-ARAPUCA detectors suggest uniform Xe distribution in the detector
- Results stable over a time scale of months
- No detectable interference between TPC operation and light level from Xe
- Paper in internal review





ProtoDUNE-SP: Hadronic Cross Sections

Hadron - argon cross sections

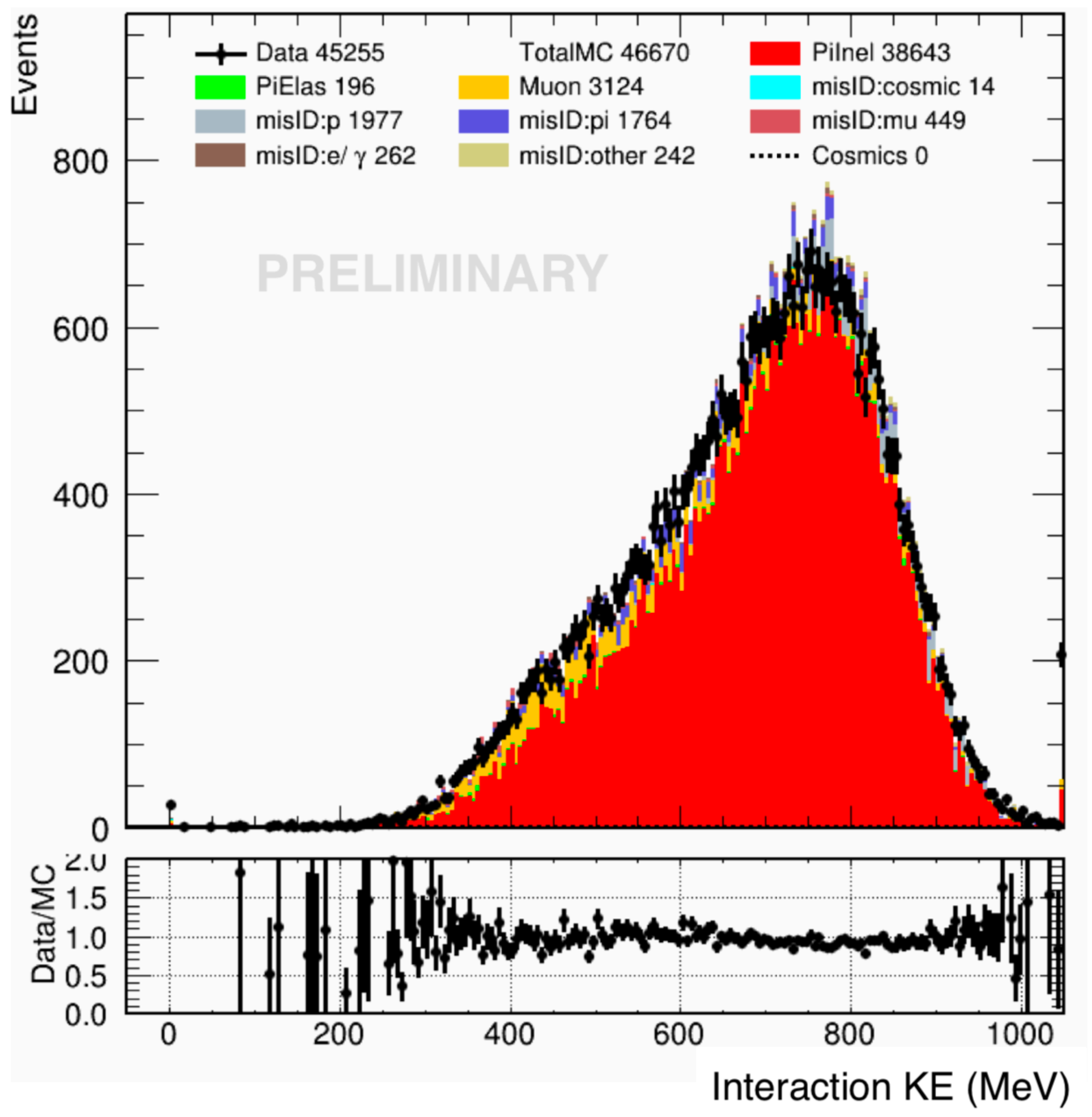
- Very few measurements of hadron interactions on liquid argon
- Important for neutrino interaction modelling:
  - Interactions of primary pions and protons within the argon nucleus
  - Interactions of primary hadrons as they propagate from the neutrino interaction

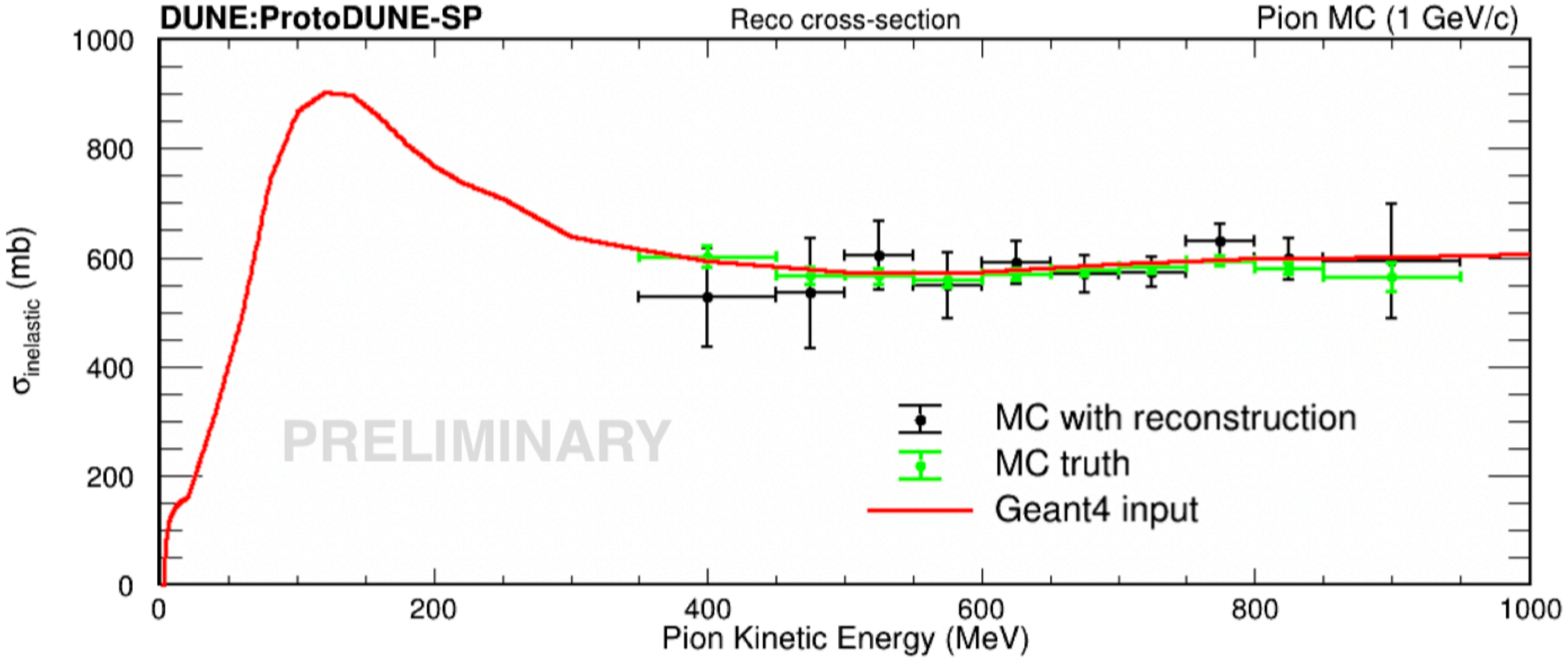
- Make use of the thin-slice method from LArIAT
  - Effectively divide the TPC into separate detectors in the beam direction
  - Modified to divide based on energy instead of distance
  - Cross section is proportional to the ratio of incident and interacting pions per slice

$$\sigma = \frac{M_{\mathrm{Ar}}}{\rho N_A \Delta E}\frac{dE}{dx}(E)\ln\left(\frac{N_{\mathrm{inc}}(E)}{N_{\mathrm{inc}}(E) - N_{\mathrm{int}}(E)}\right)$$

Pion Inelastic Cross Section

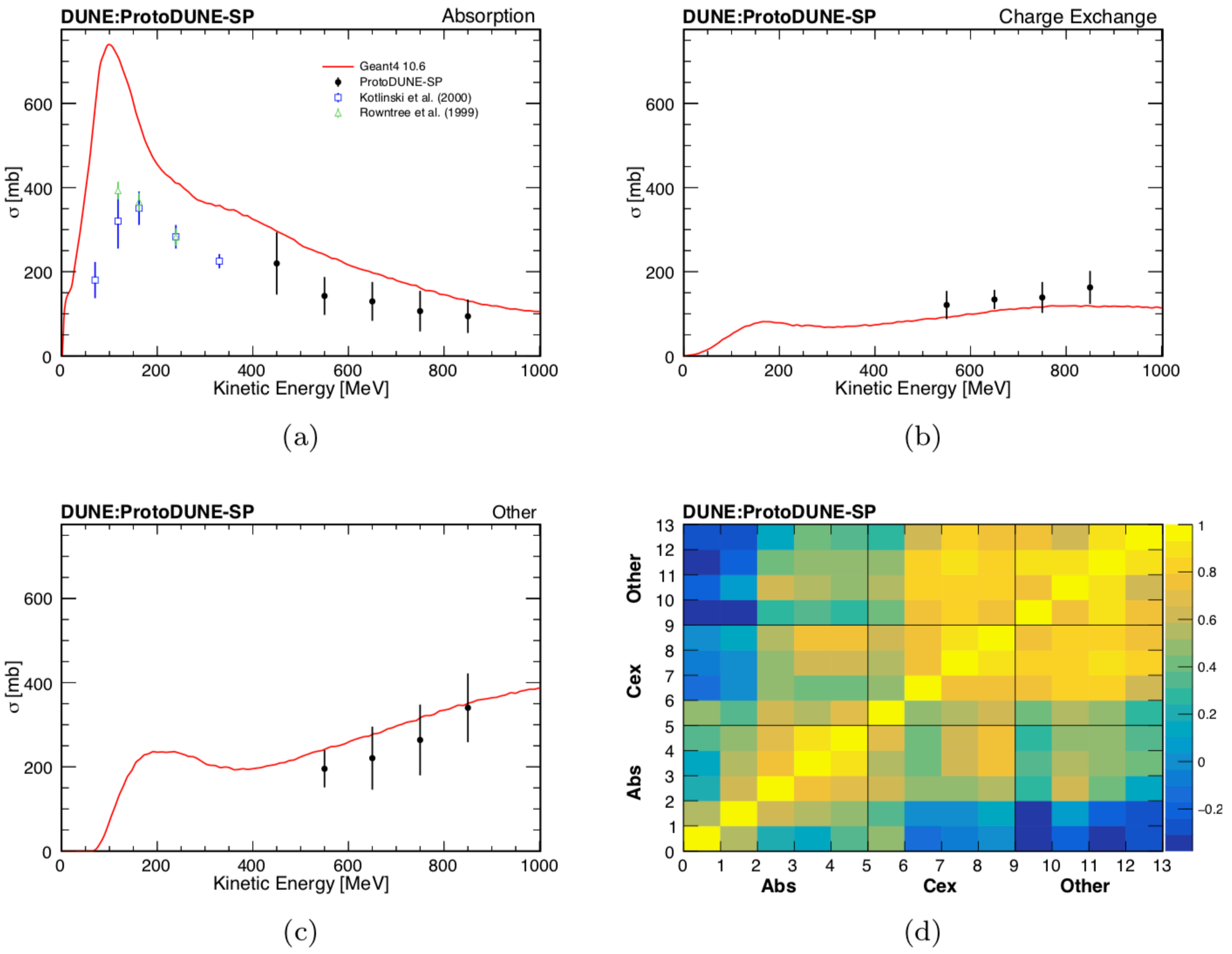
- Analysis of the inelastic cross section
  - Includes all possible final states
- Data-driven background estimation
  - Beam-line muons and mis-id of beam protons
- Cross-section extraction on MC works well
- Aim to open the box on 1 GeV/c data very soon
- Will then work towards a paper draft and publication





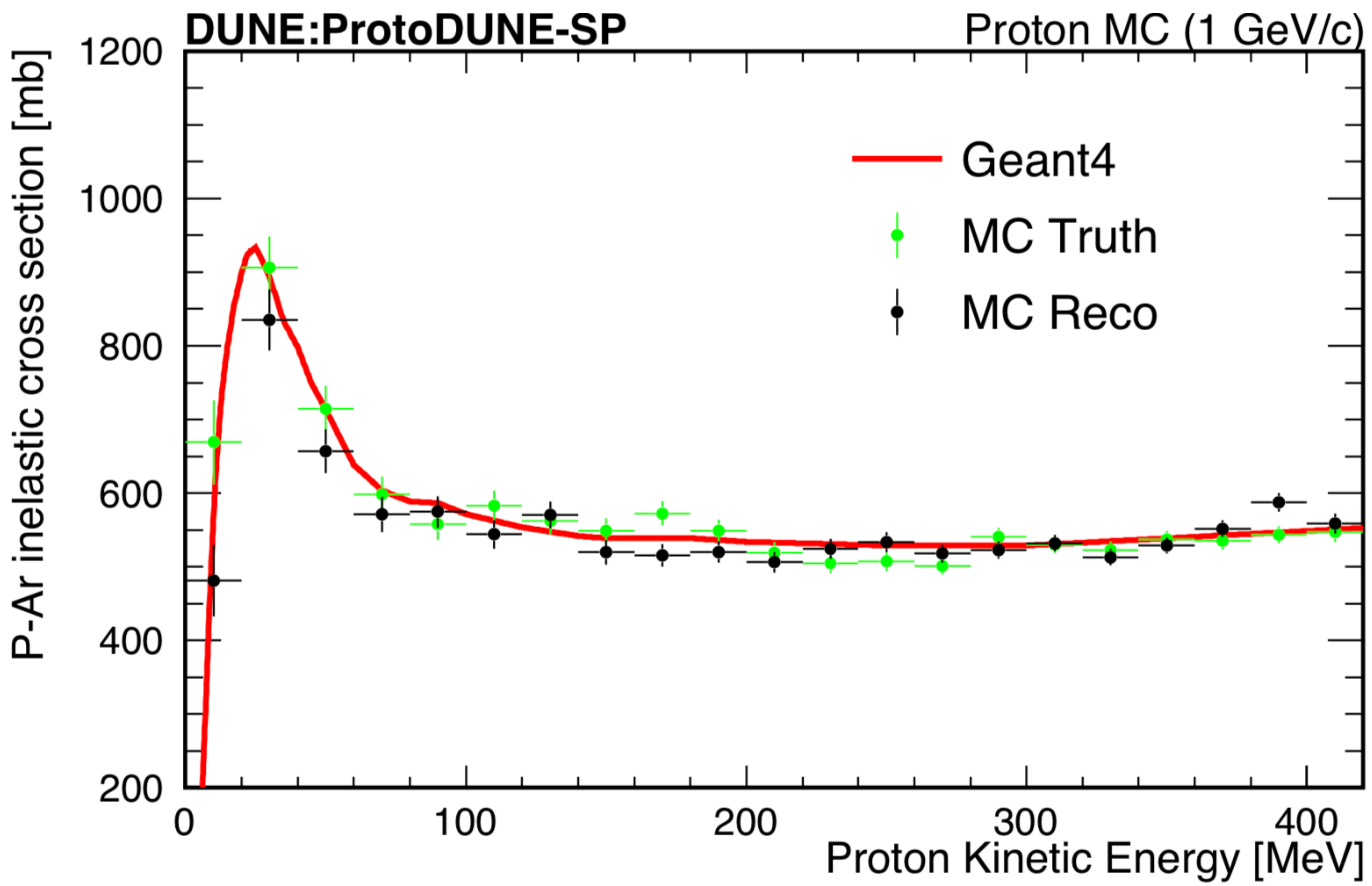
Pion absorption and charge exchange xsec

- Look at three channels
  - Absorption: no pions in final state
  - Charge exchange: pi-zero(s) but no charged pions in final state
  - Other: events that are neither of the above
- Two different methods used for absorption measurement
  - Presented in two thesis
- Analysis in working group review
- Paper draft is being written



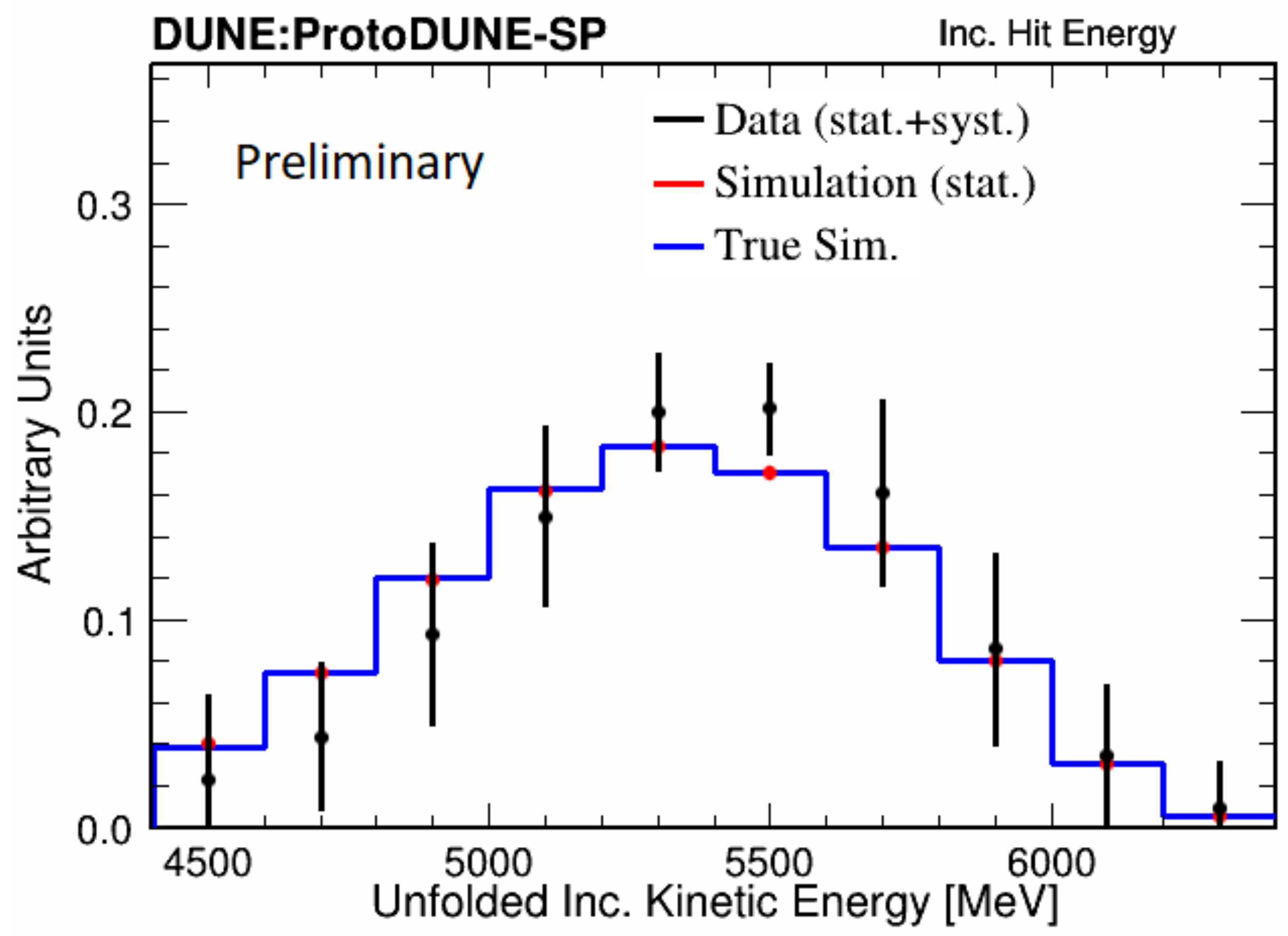
Proton Inelastic Cross Section

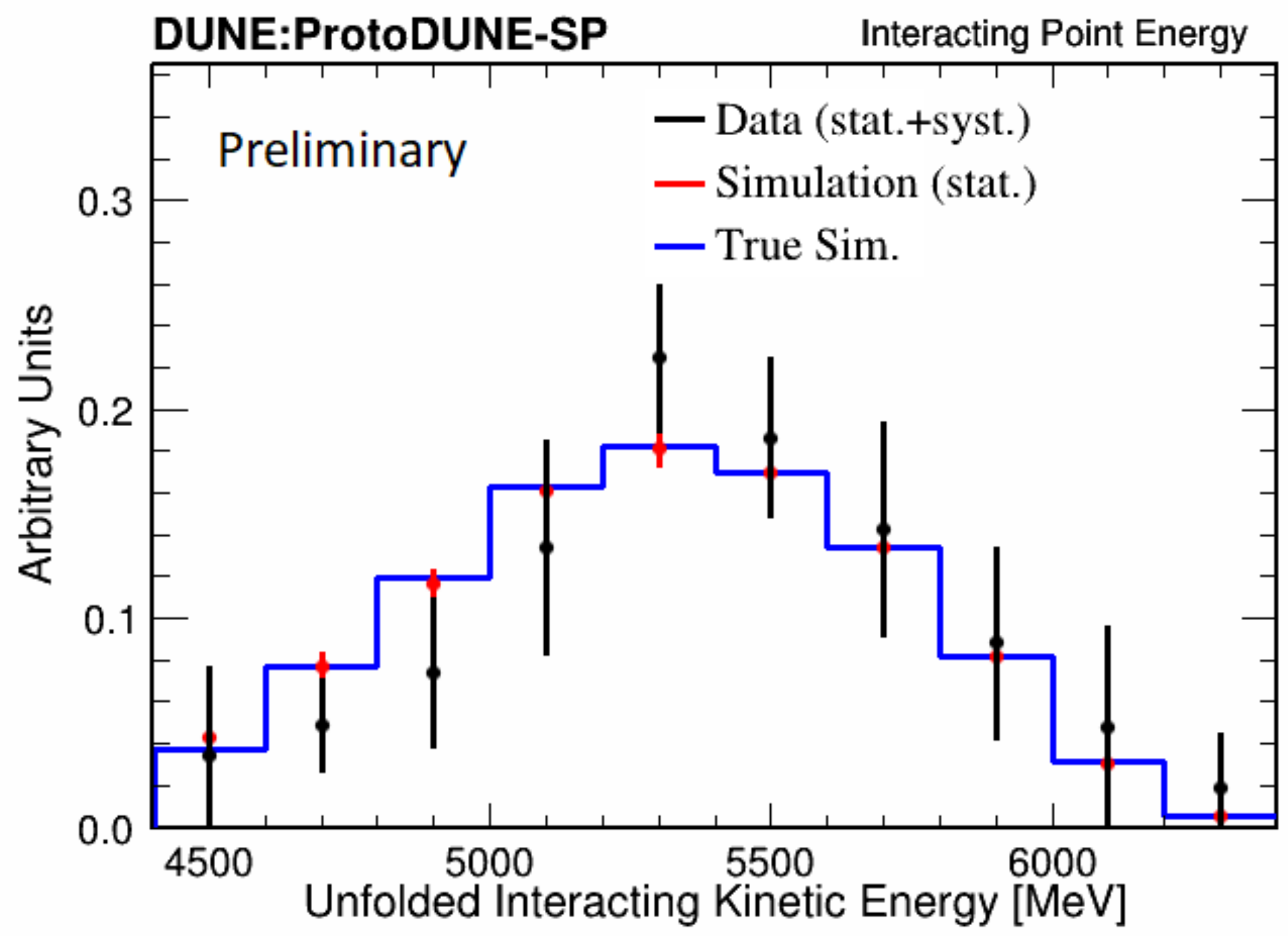
- Analysis similar to pion inelastic cross section
- Select inelastically interacting 1 GeV/c beam protons
- Main backgrounds from elastically scattering protons and mis-id of secondary protons
- Comparison of thin slicing by length and energy
  - E-slicing allows a wider energy range
- Aim to unblind soon
- Goal to publish by the end of 2022

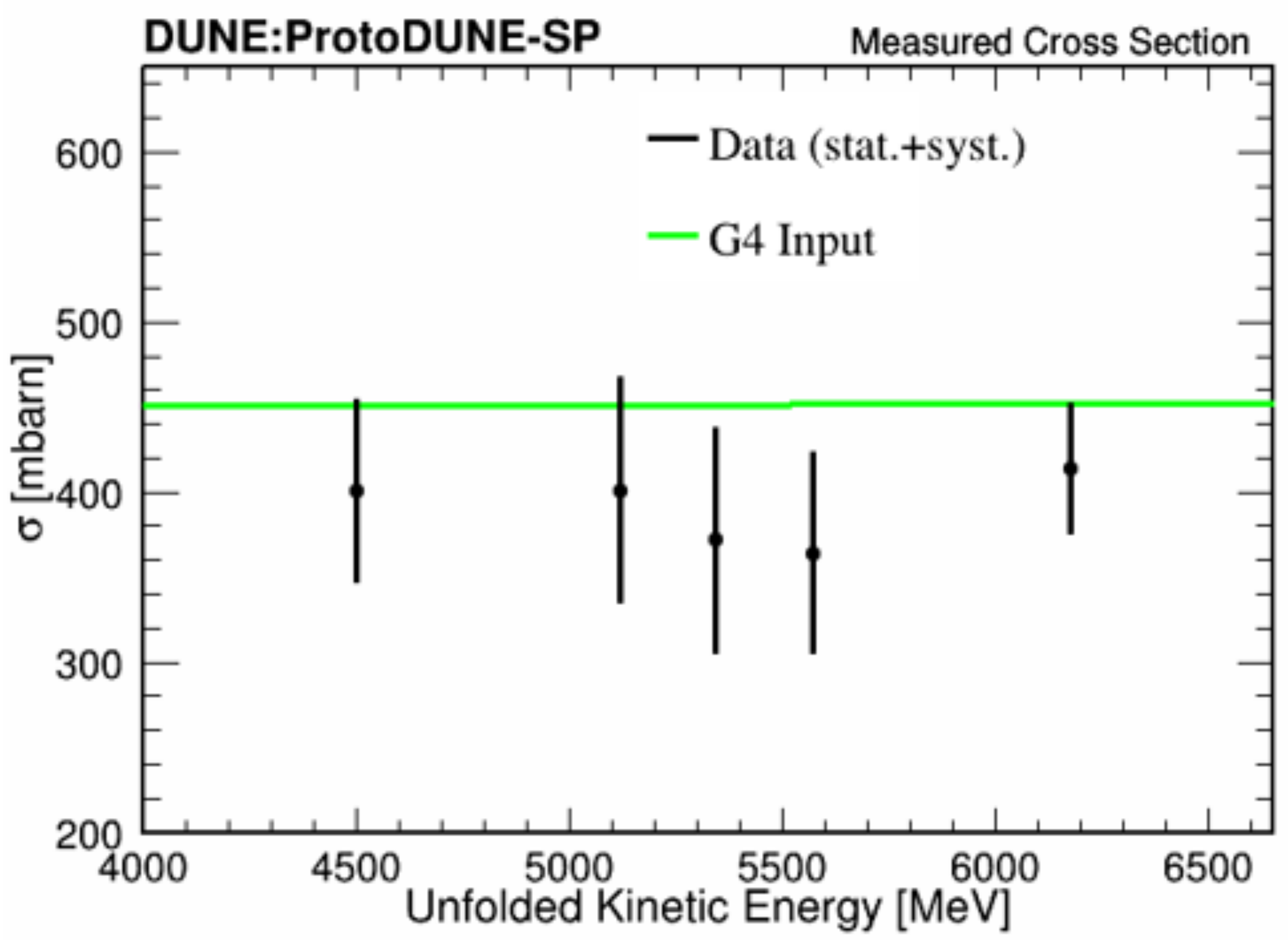


Kaon Inelastic Cross Section

- High energy inelastic cross section measurement
  - 6 GeV/c K^+ beam
- Preliminary result suggests G4 overestimates the measured cross section
- Now finalising the systematic uncertainties
  - Backgrounds from secondary particles etc
- Will add the 7 GeV/x beam sample to the analysis
- Aim for journal submission by the end of the year

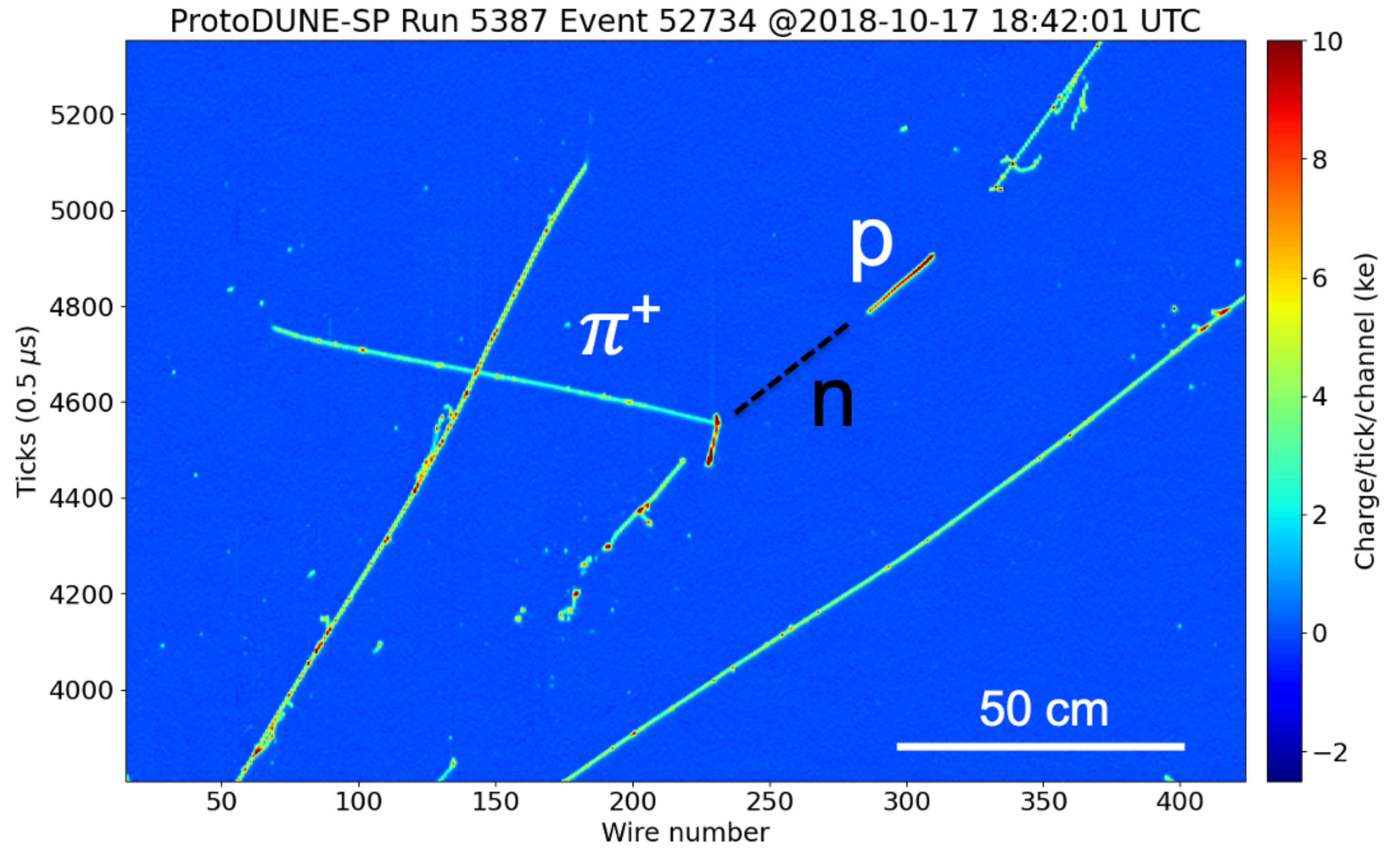


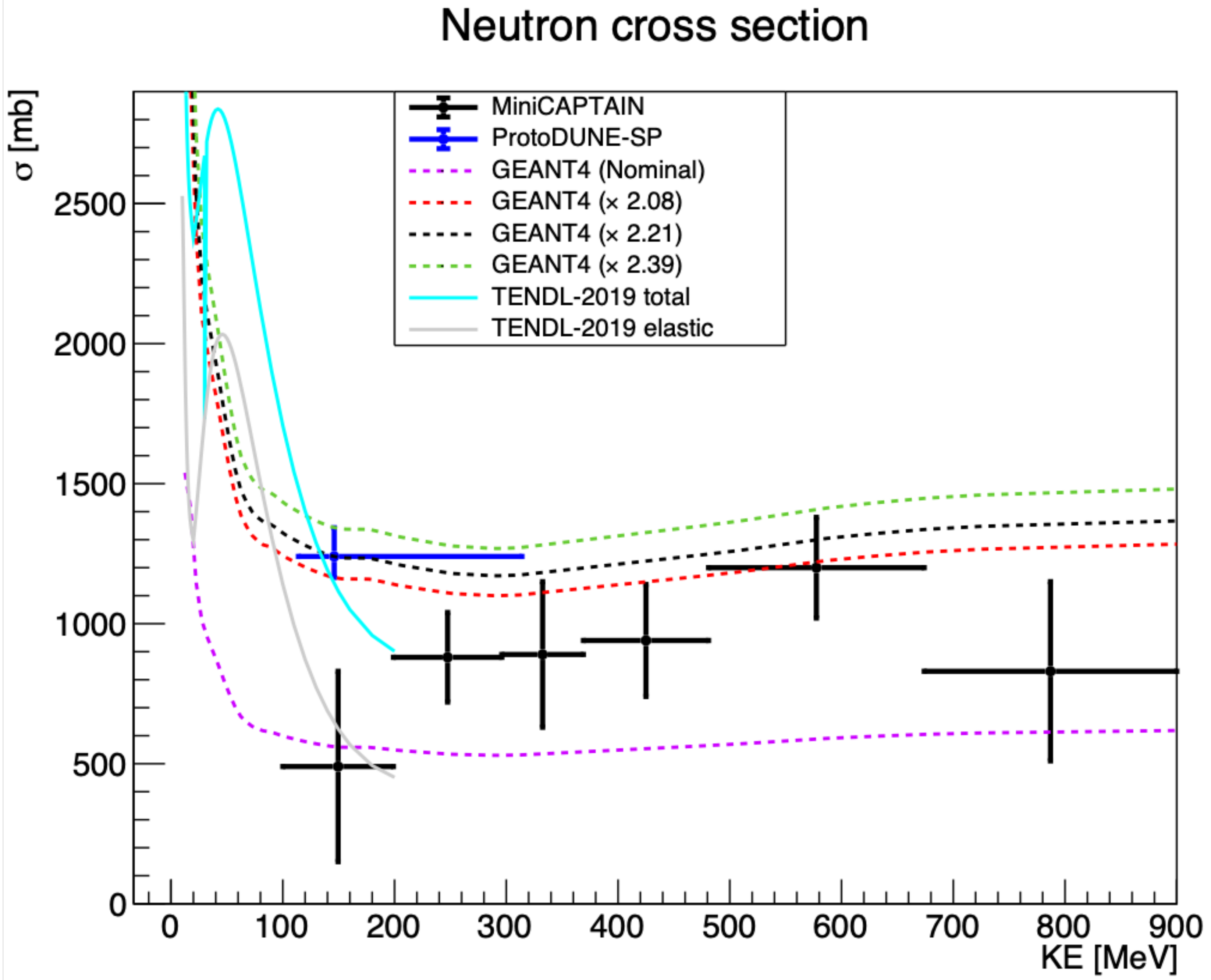




Neutron Inelastic Cross Section

- Charged particle beam has no primary neutrons
  - Look for neutrons produced in pion interactions
  - Tag them based on scattered protons
  - Distance from pion interaction to proton is the observable - the neutron scattering length
- Neutrons are a source of missing energy in the DUNE-FD
  - Needs to be well modelled for energy measurements
- Preliminary result shows G4 significantly underestimates the cross section
  - Agreement with TENDL is better
- Aim for publication later this year





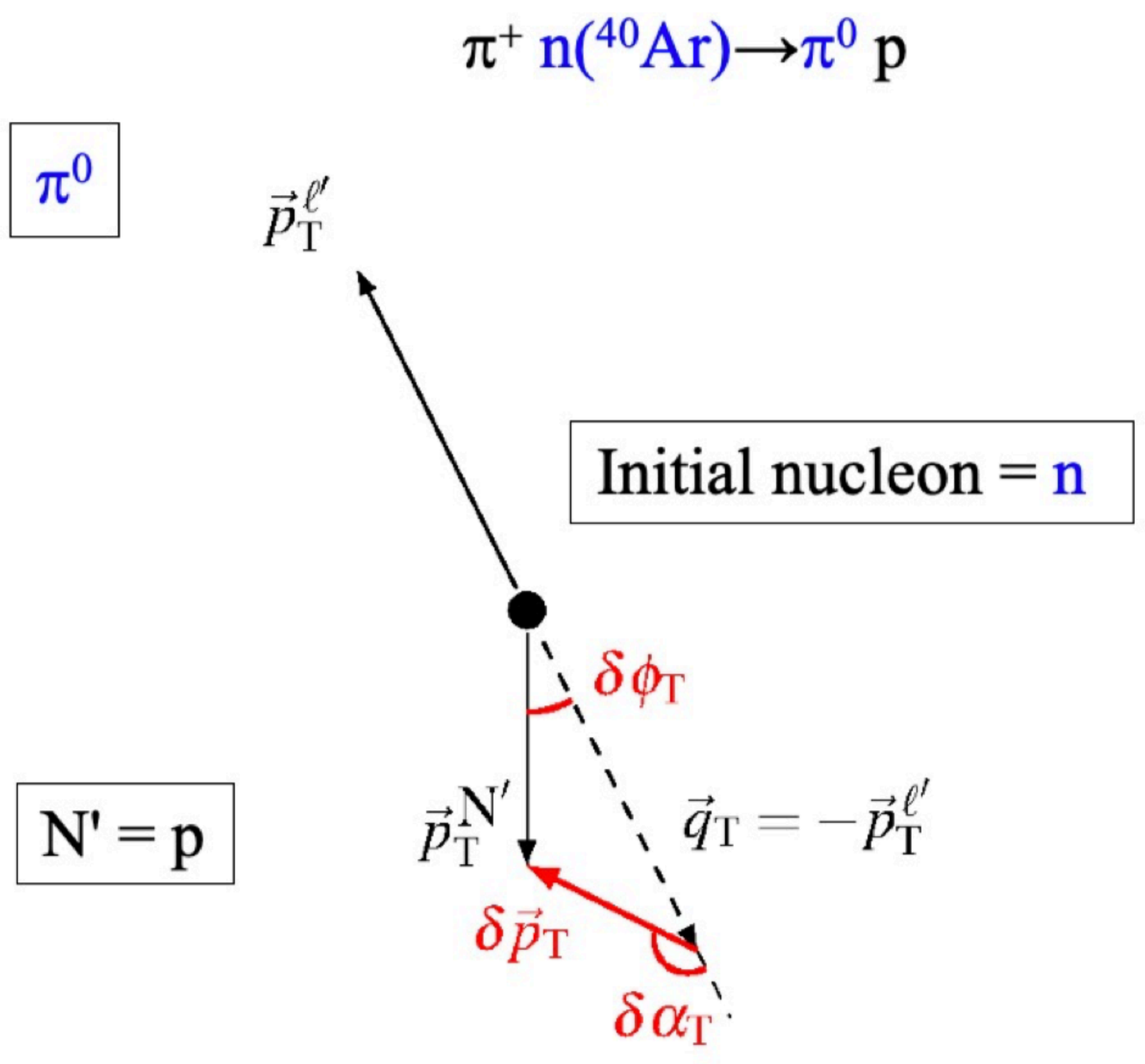
Summary

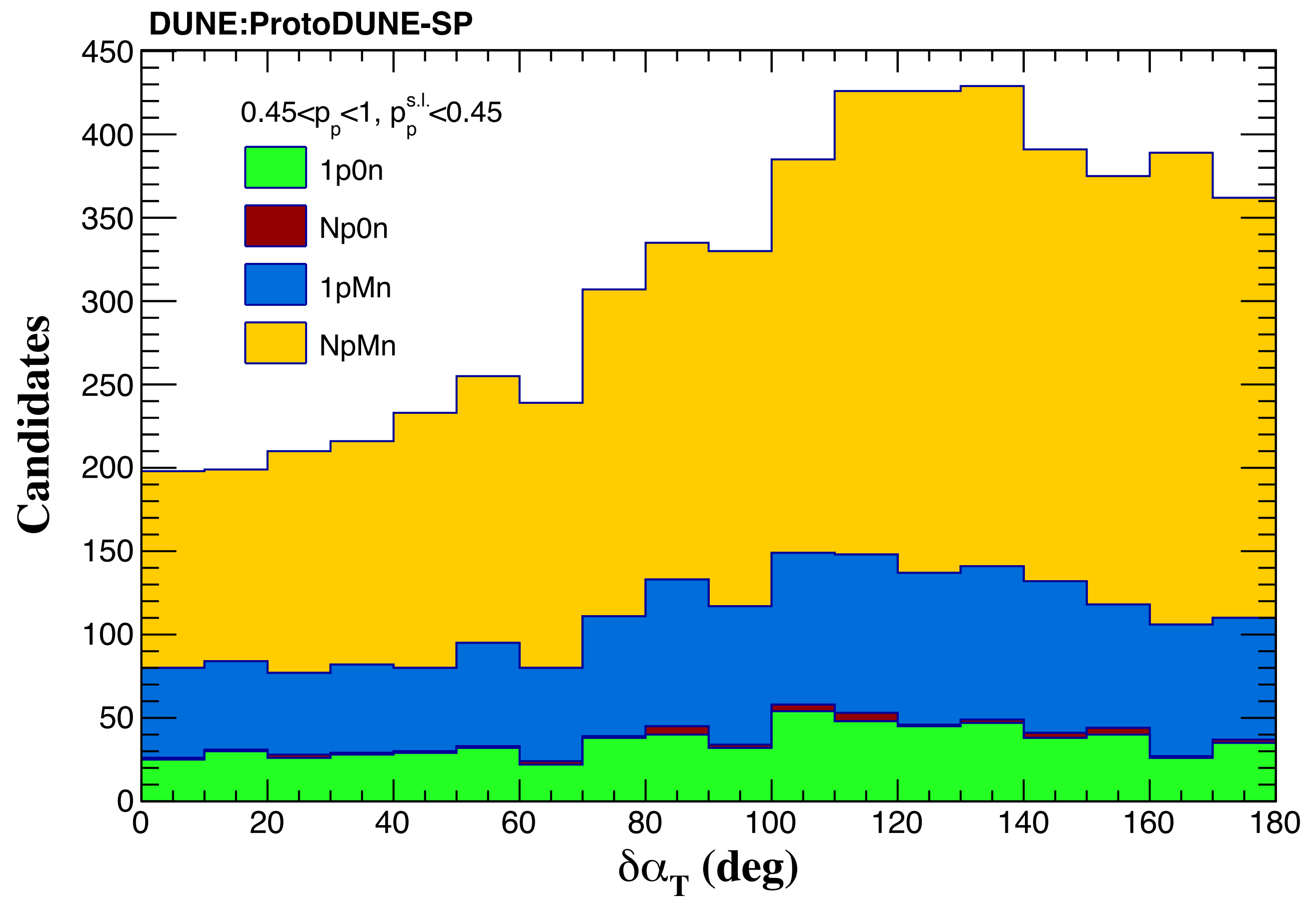
- Lots of progress on ProtoDUNE-SP analyses
  - Two papers now on the arXiv, and two more in the DUNE review process
  - Many hadron cross section analyses to unblind in the coming months
    - Expect a number of analysis papers submitted by the end of the year

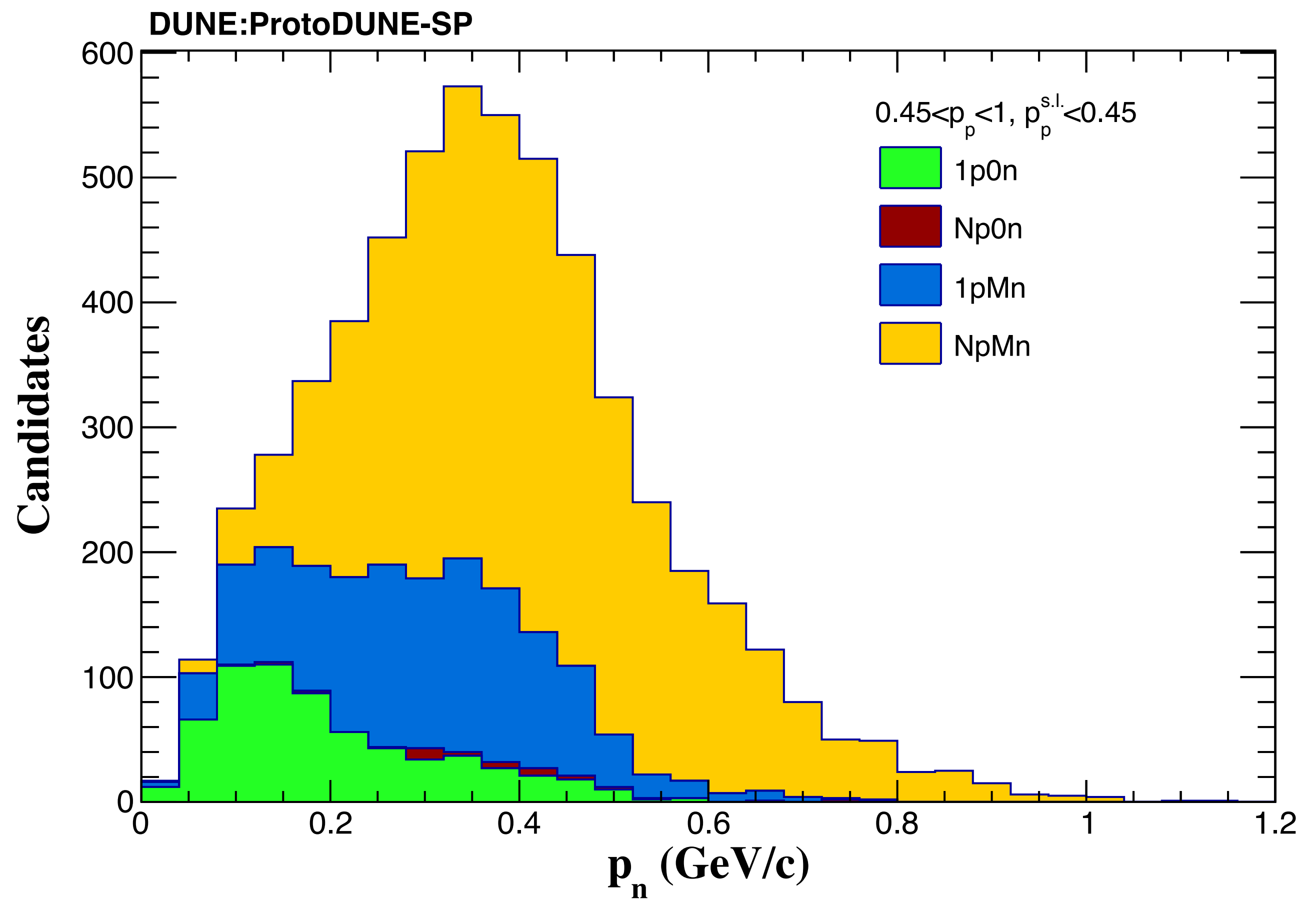
- Thank you for listening
  - Feel free to ask questions now or later in the week

Transverse Kinematic Inbalance

- TKI probes nuclear effects and final state interactions of hadrons in neutrino events
  - The same method can be applied to the ProtoDUNE beam events
- Pion charge exchange channel: $\pi^+ + n(^{40}Ar) \longrightarrow \pi^0 + p$
- Probe the initial state neutron momentum
- Boosting angle $\delta\alpha_T$ is uniform without FSI
- Analysis is advanced
- Analysis of proton TKI also underway: $p + p(^{40}Ar) \longrightarrow p + p$

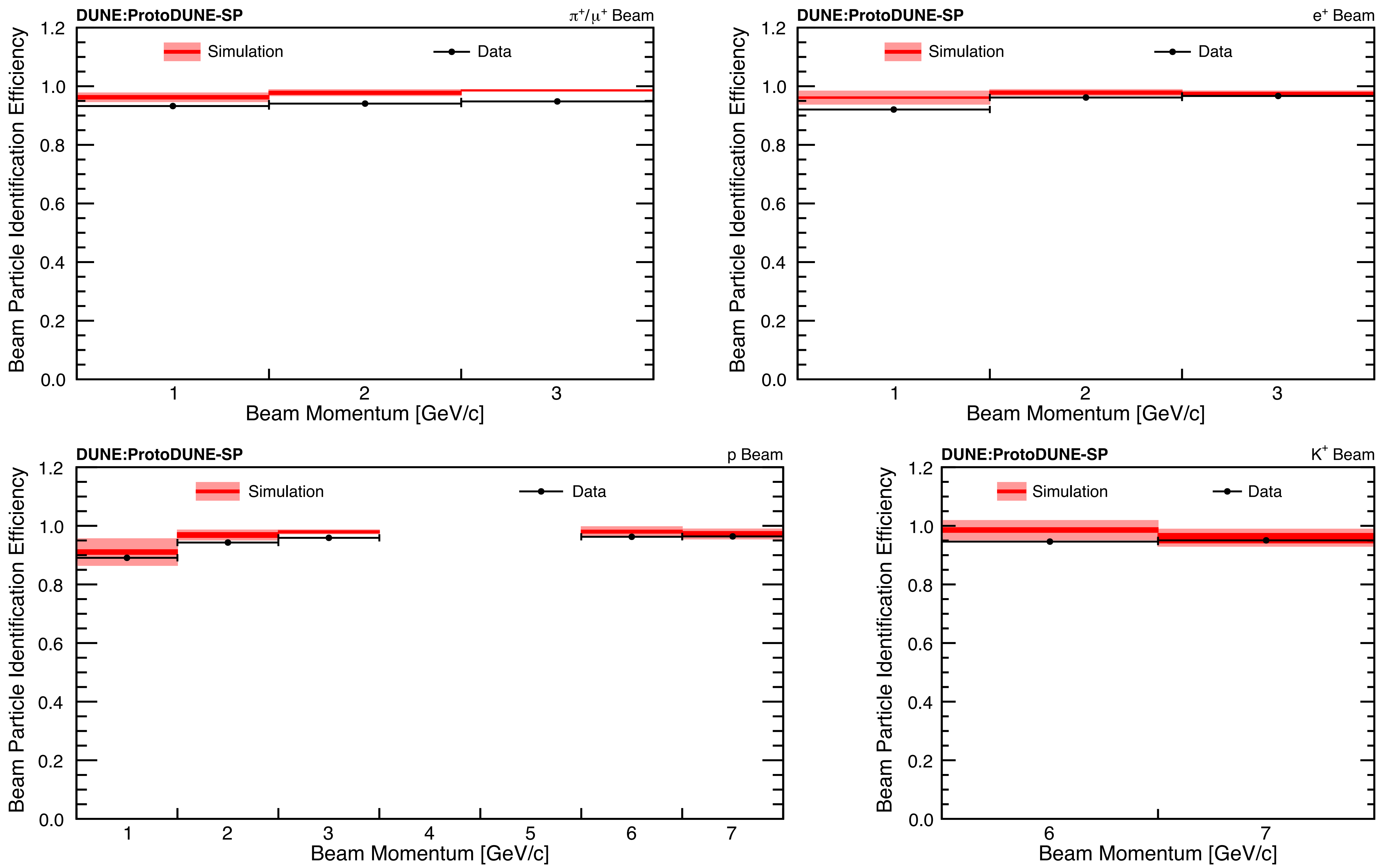






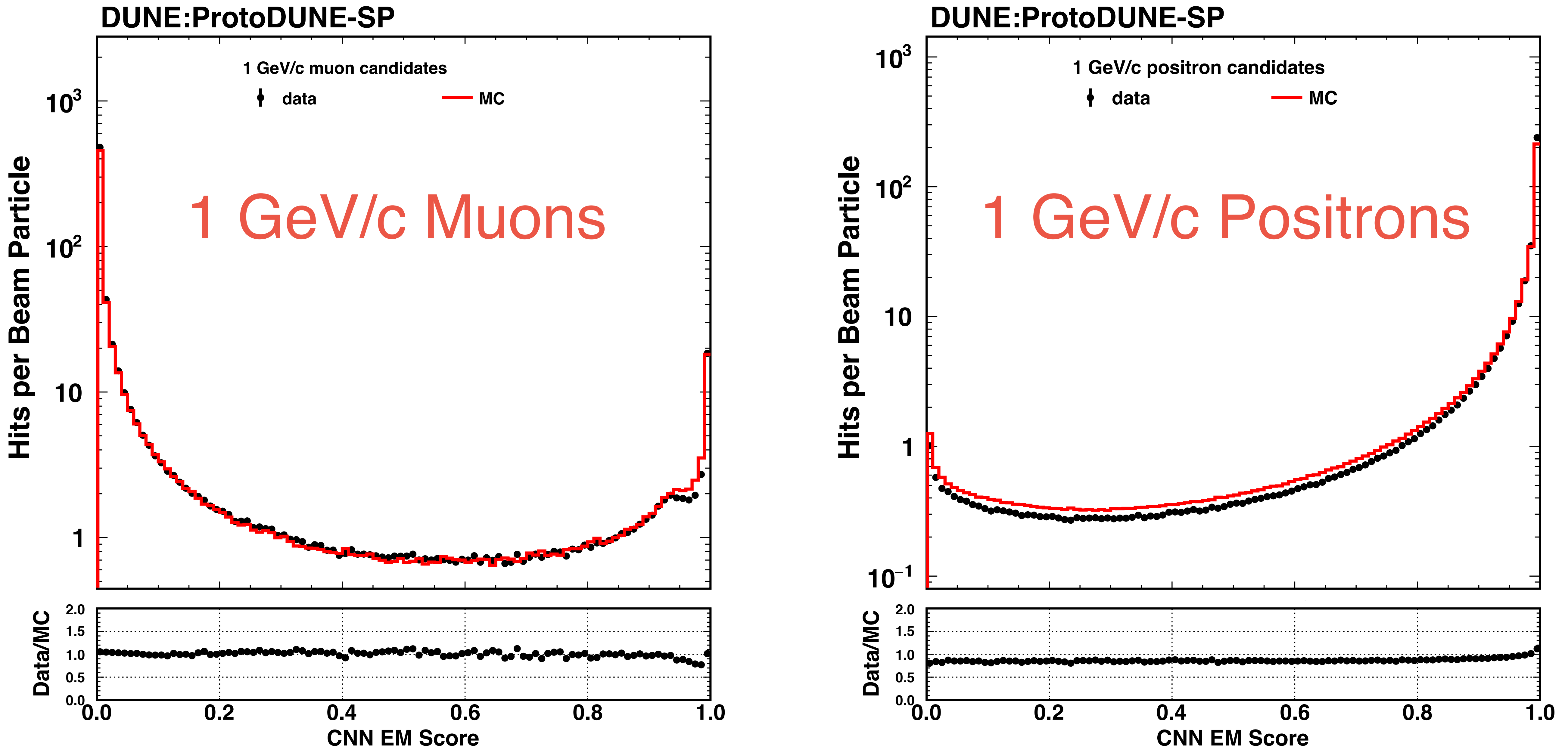
Pandora Event Reconstruction

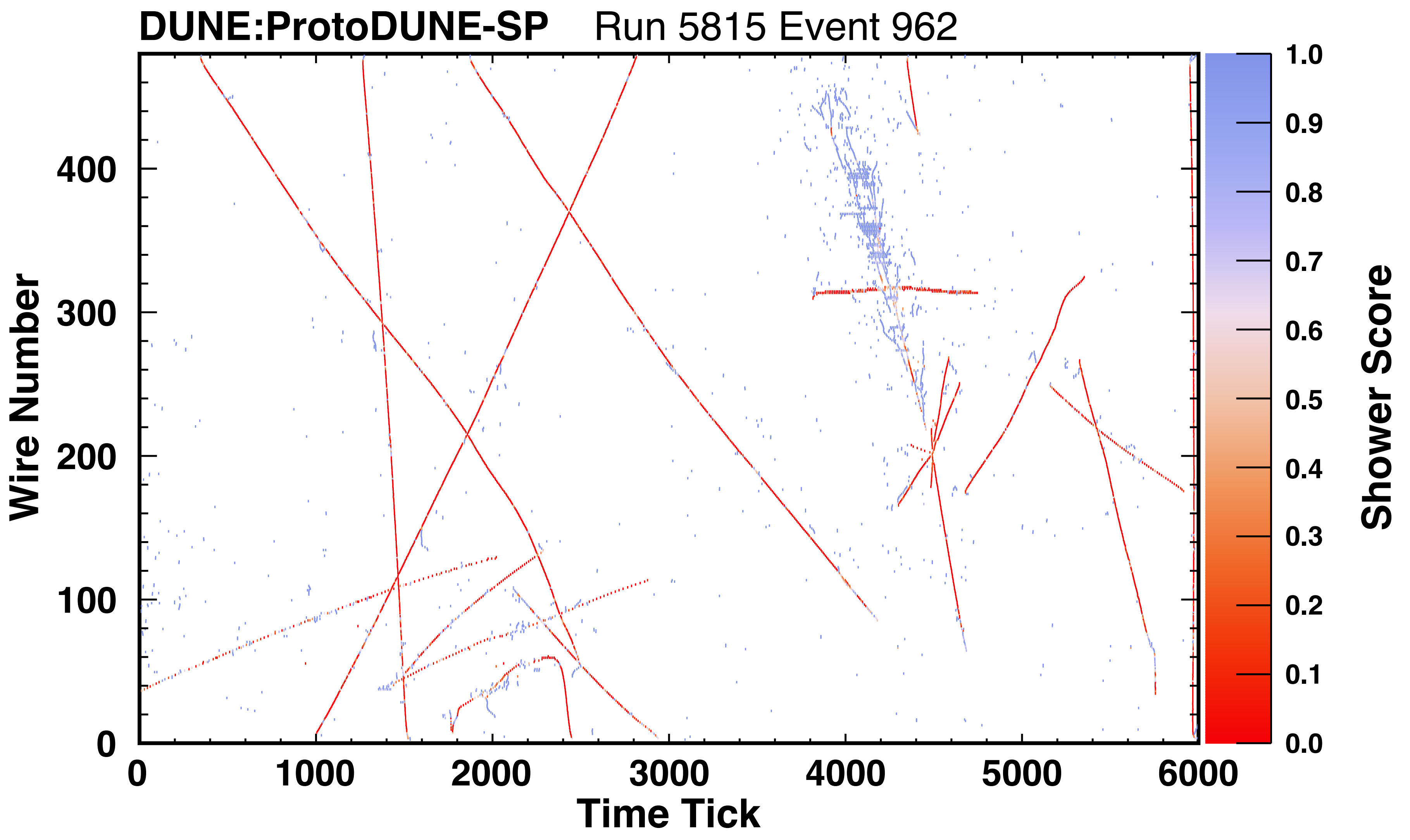
- Pandora is the primary event reconstruction software used in all of the TPC analyses
- Cosmic-ray reconstruction efficiency and quality
- Beam reconstruction efficiency and quality
- Comparison of efficiency to reconstruct and identify beam particles
- Paper written and in collaboration review



Hit-tagging CNN

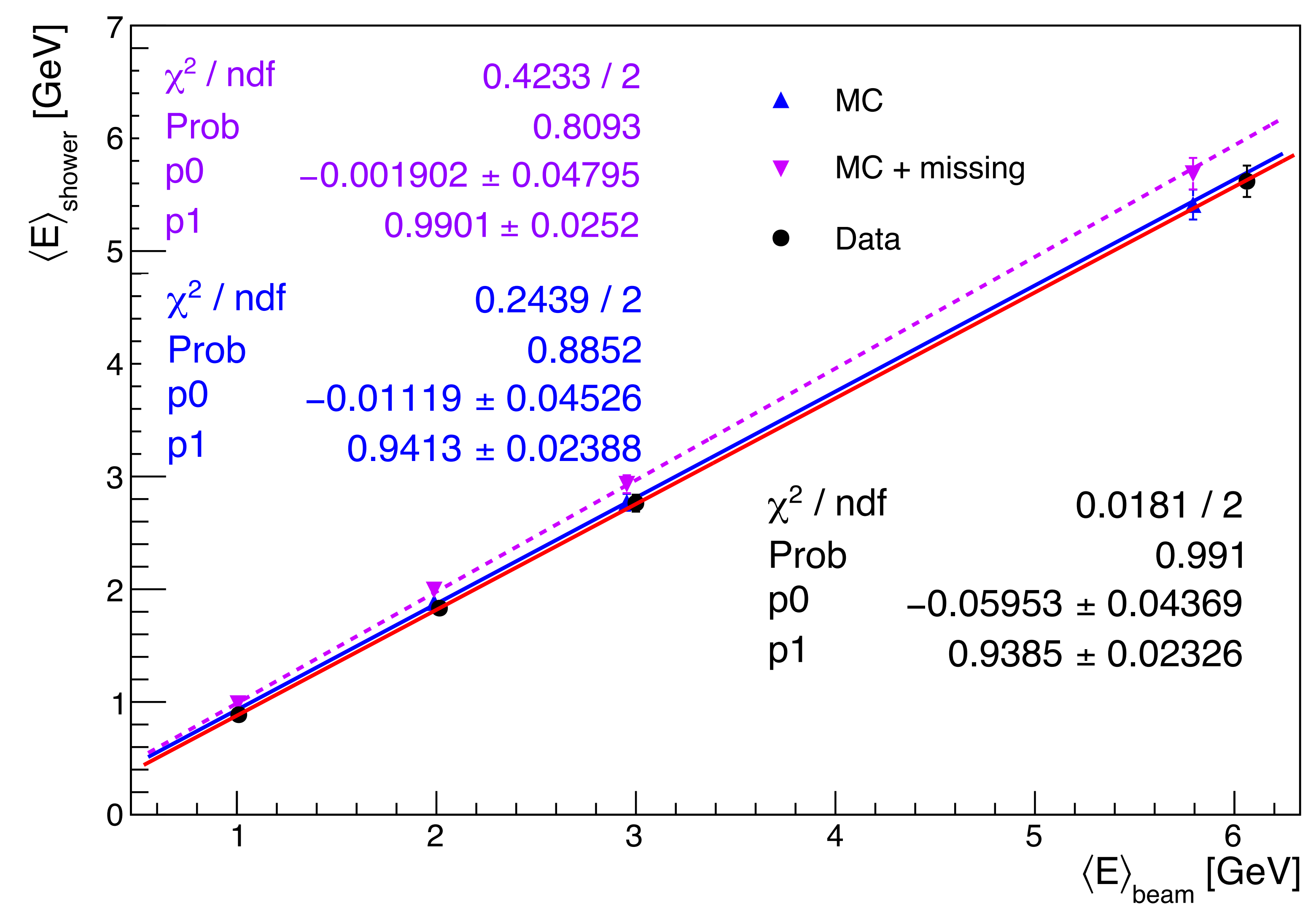
- CNN designed to tag hits as either track- or shower-like
  - Uses a novel “small patch” approach
- Used in the majority of analyses
- Excellent performance seen for beam and cosmic
  - Minimal difference in performance between data and MC
- Paper posted to the arXiv and submitted to EPJC
  https://arxiv.org/abs/2203.17053

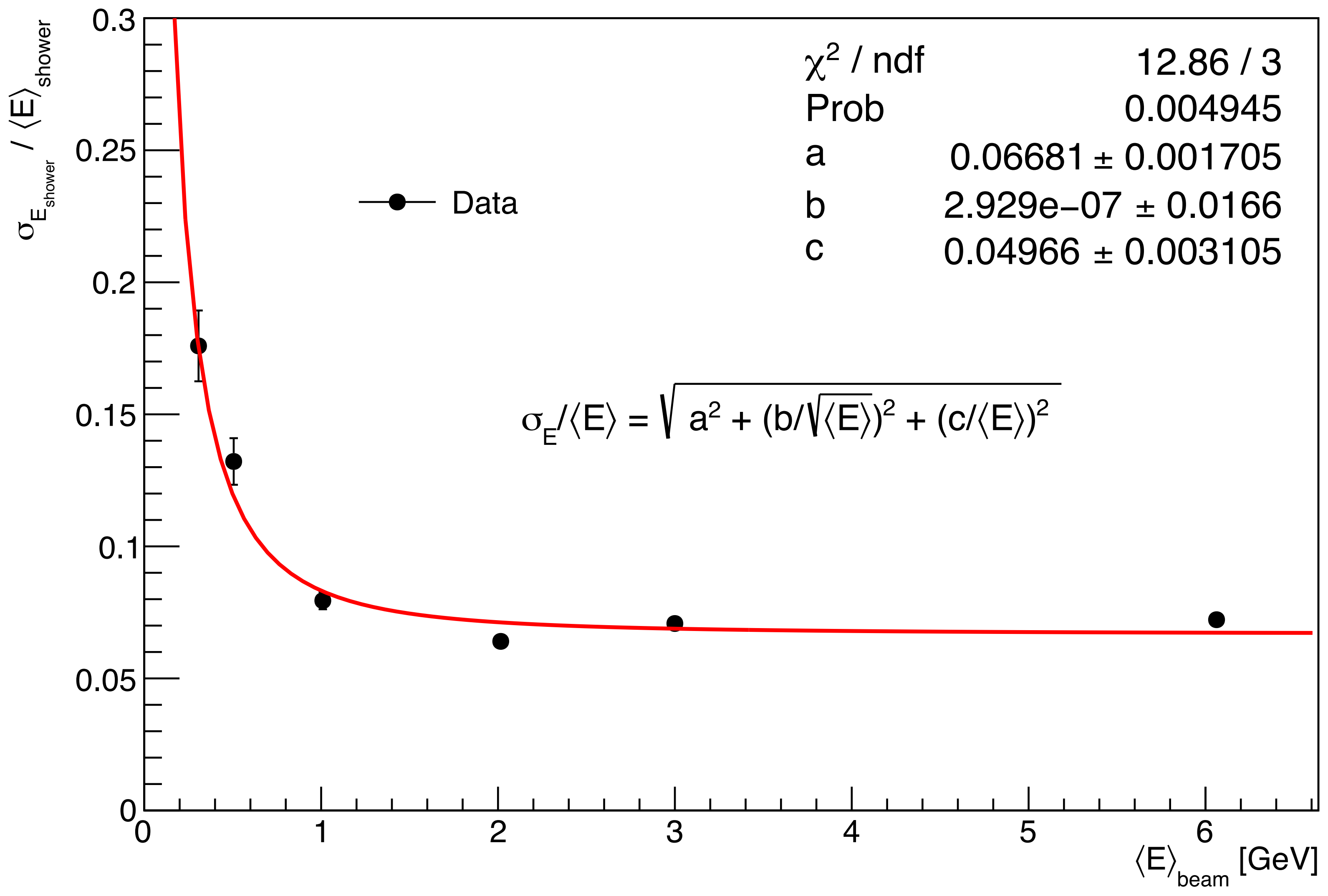




Reconstruction of beam electron energy

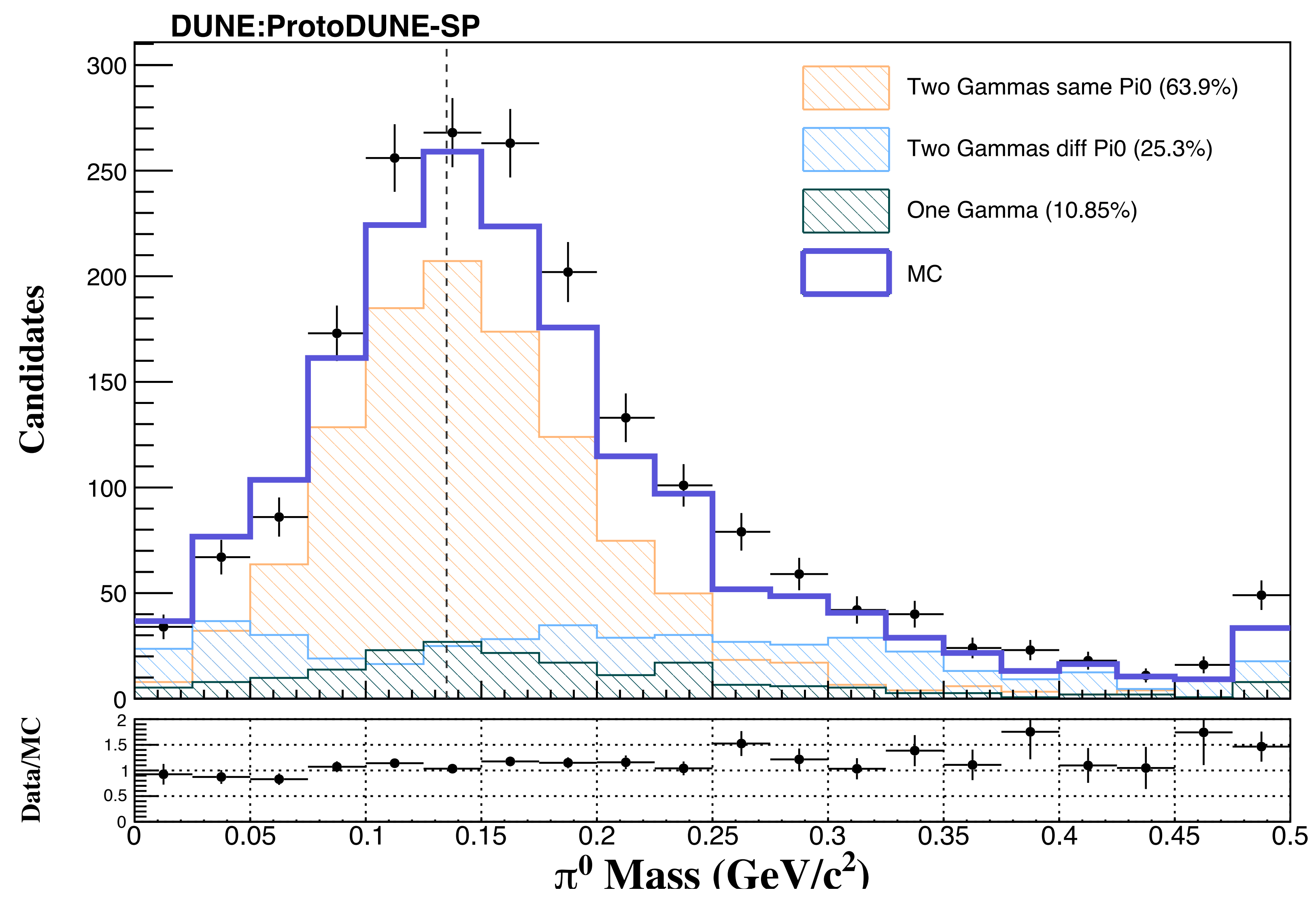
- Electron energy reconstruction and resolution is critical for the ν_e analyses in DUNE
- Use ProtoDUNE-SP beam positrons from 0.3 to 6 GeV/c
- Measured energy is corrected for hits below the energy threshold
  - Clear linear relationship between reconstructed and beam energy
- Resolution limited by the spread of positron energies in the beam line (5-6%)
- Particle gun MC approach yields 2.9% for 0.3 GeV/c and 0.7% for 7 GeV/c

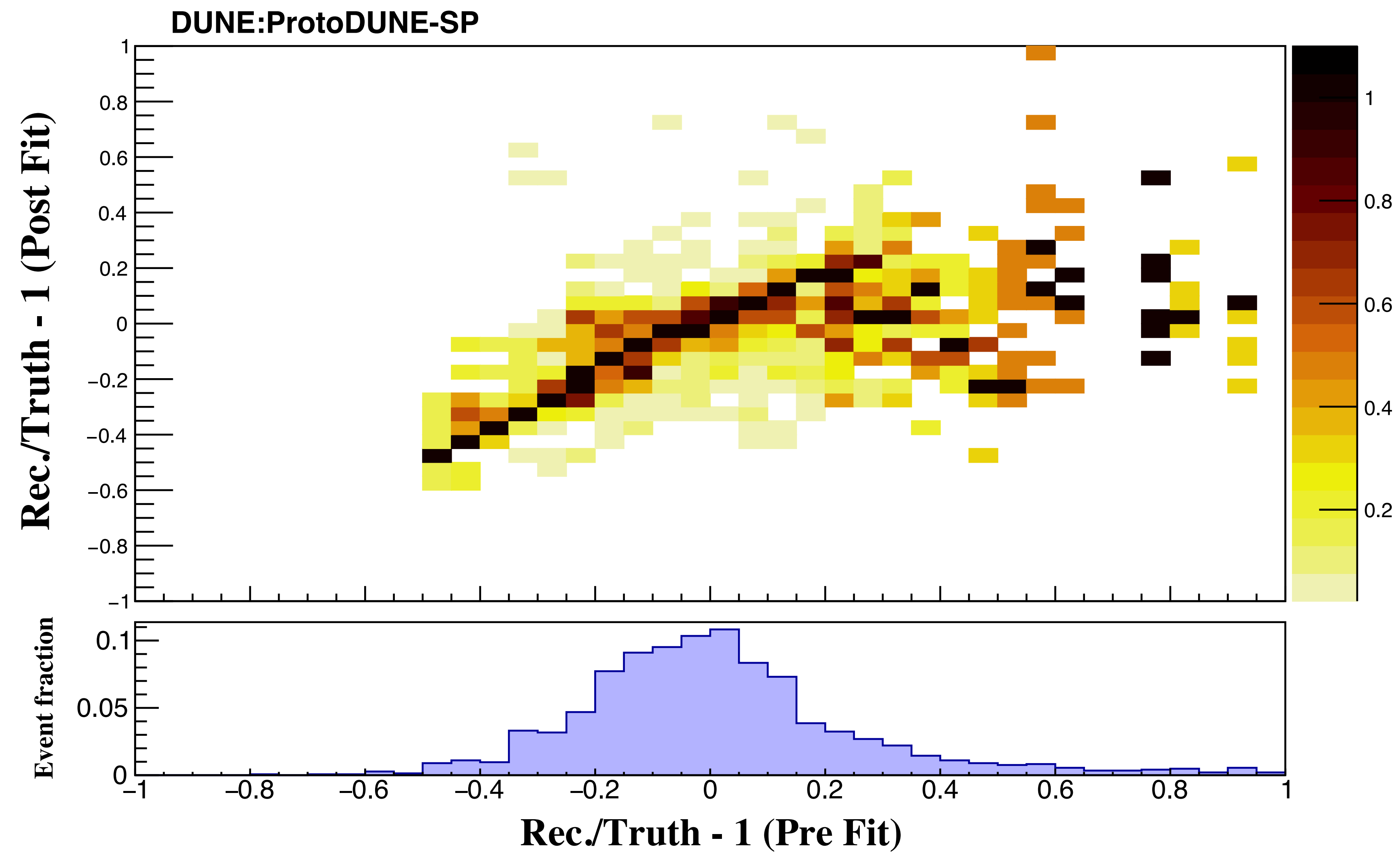




Reconstruction of pi-zero energy

- Look at π^0s produced in pion charge exchange events
  - Search for two reconstructed decay photons
  - Used for the energy reconstruction in the TKI analysis
- Uses a kinematic fitting technique to improve the π^0 energy resolution
  - Uses covariance matrix between three measured values: the photon energies E_1 and E_2, and the angle between them
- Good resolution obtained with good agreement between data and MC

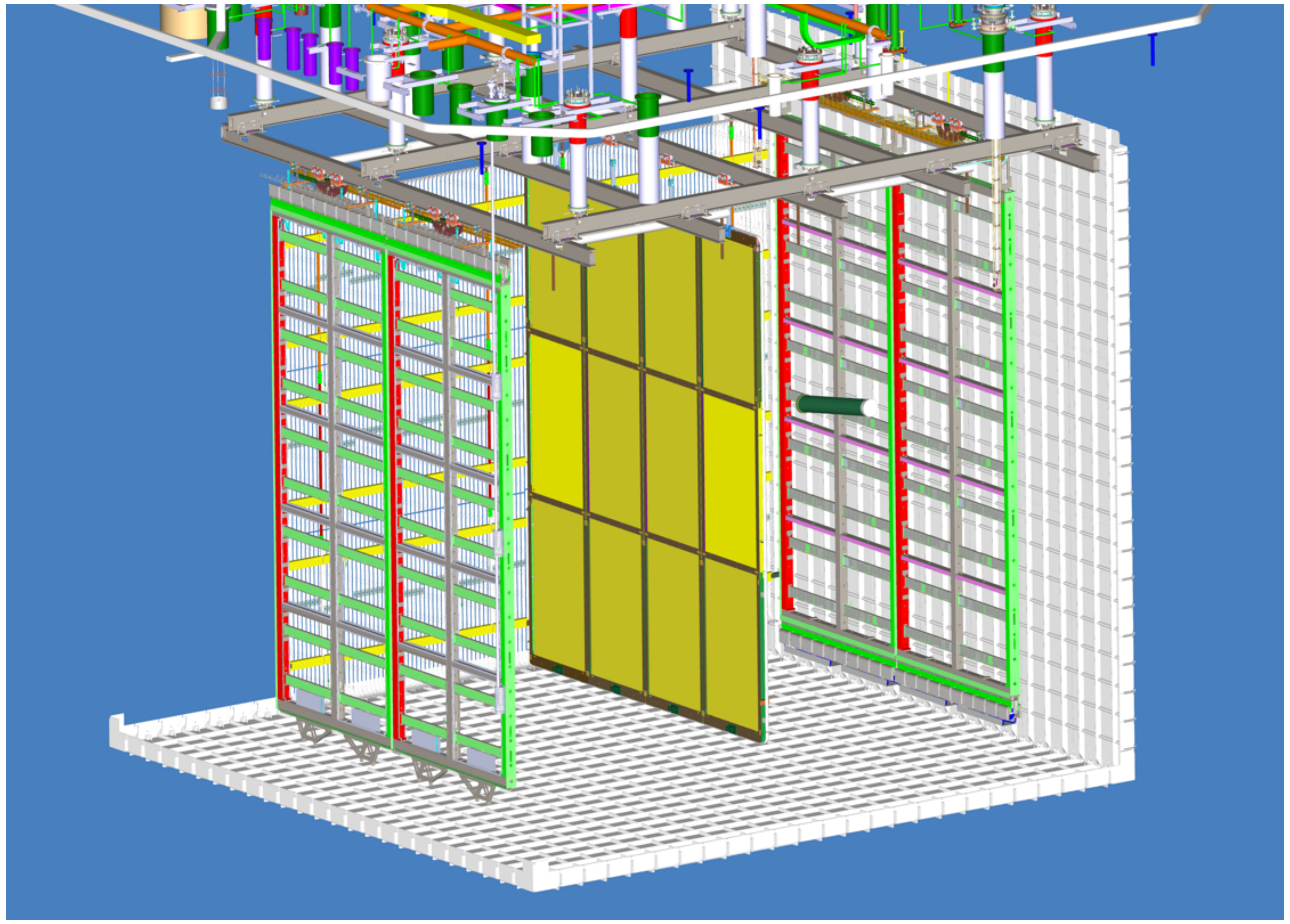




ProtoDUNE-HD

ProtoDUNE-HD: Introduction

- ProtoDUNE-HD will be the *module 0* for the DUNE FD Horizontal Drift detector
  - The APAs will actually be part of the FD
  - It reuse the ProtoDUNE-SP cryostat and infrastructure
- Differences from ProtoDUNE-SP:
  - There will be four APAs instead of six
    - Allows the distance between the cryostat walls and the TPC to match the FD
    - Two will be upside-down to mimic the bottom APAs in the FD
  - New cold electronics
  - Modified cathode for better planarity

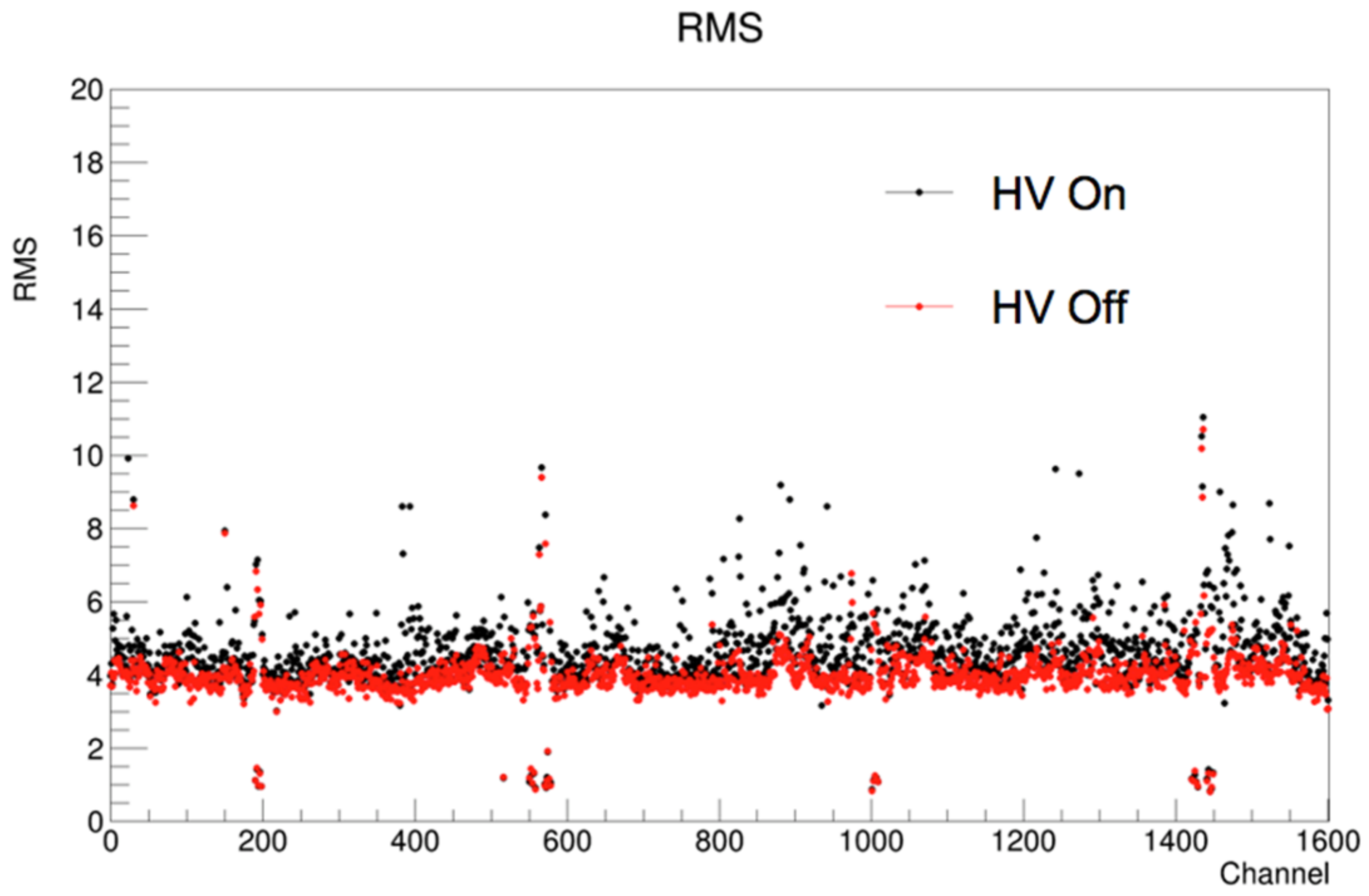


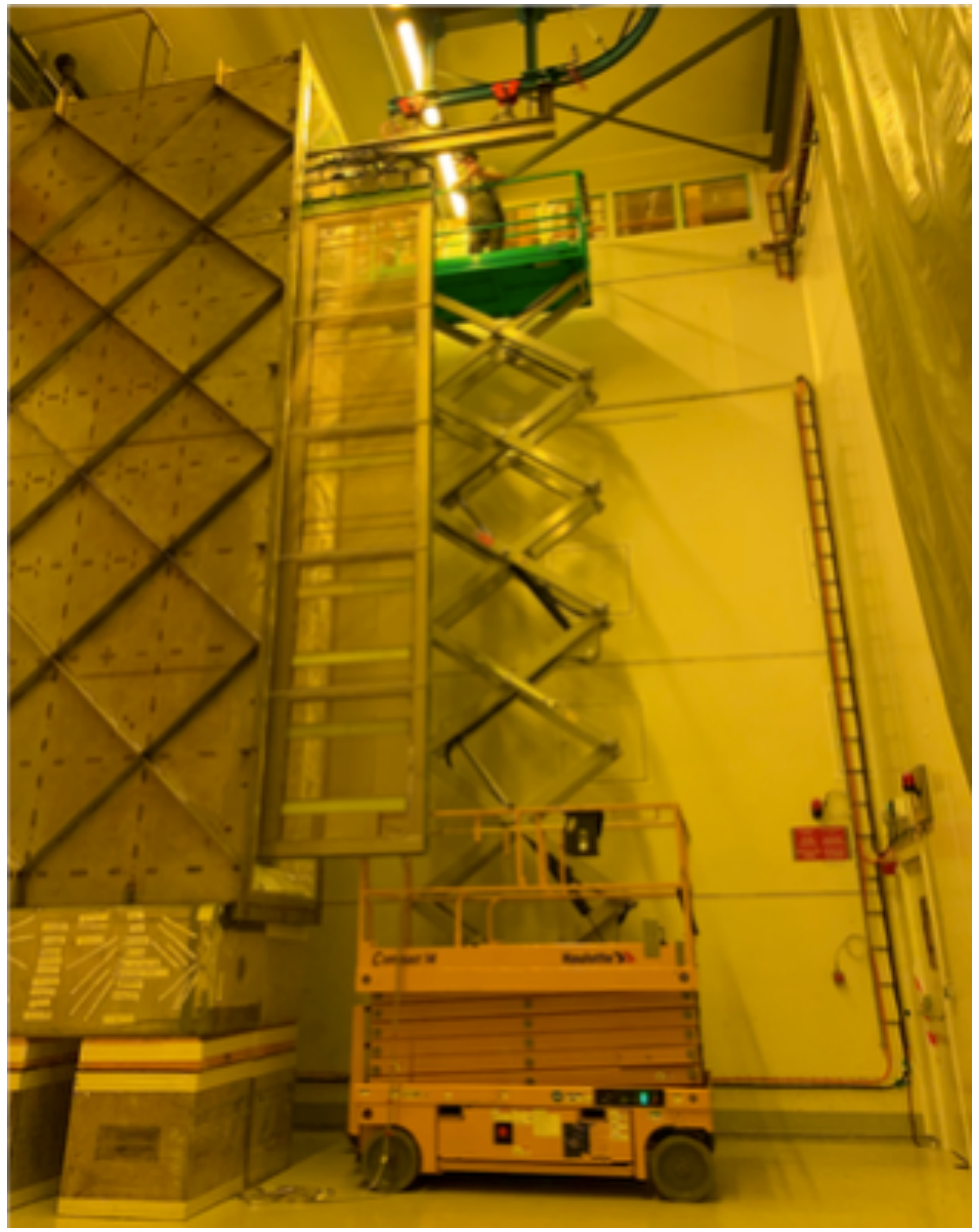
Modification of existing infrastructure

- ProtoDUNE-II will test final component designs
  - Reduced to 4 APAs to match FD distances between the field cage and the cryostat
  - Two APAs “upside-down” to mimic the bottom APAs in the FD, which will hang down with the electronics at the bottom
  - Updated cold electronics
    - Including full length cables for the FD
  - Neutron calibration source, lasers (next slide)
  - Temperature sensors on APAs
  - Improved cryogenics
- Required cryostat modifications finished

Cold box test of first APA

- The first of the DUNE-FD APAs arrived in October from Daresbury
  - Tested in the cold box with the ProtoDUNE-SP era cold electronics
  - Performance consistant with what was seen in ProtoDUNE-SP
    - Small noise increase with wire bias voltages on
    - No effects seen when switching on the photon detectors or temperature sensors

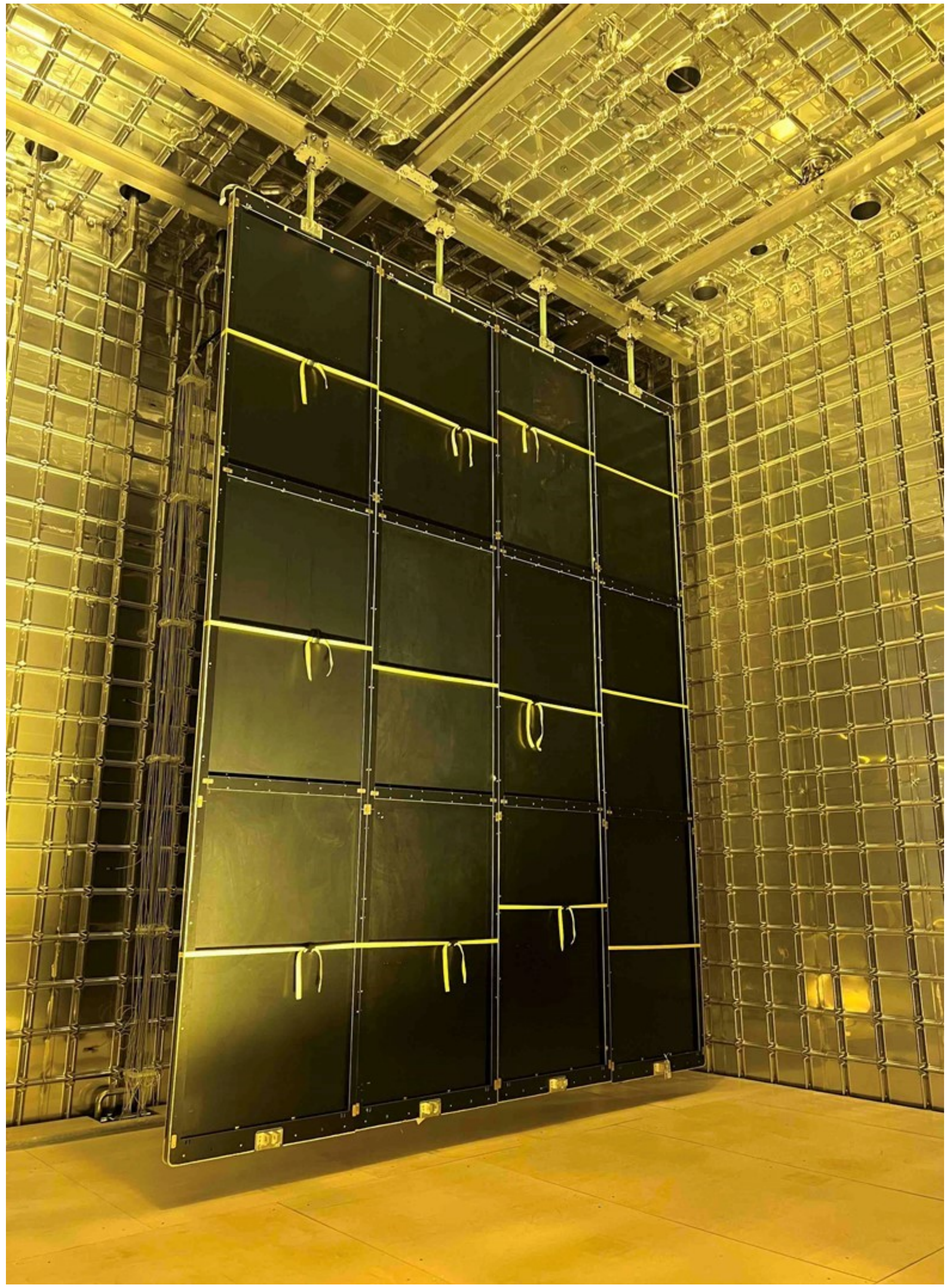




CPA and field-cage end-wall assembly

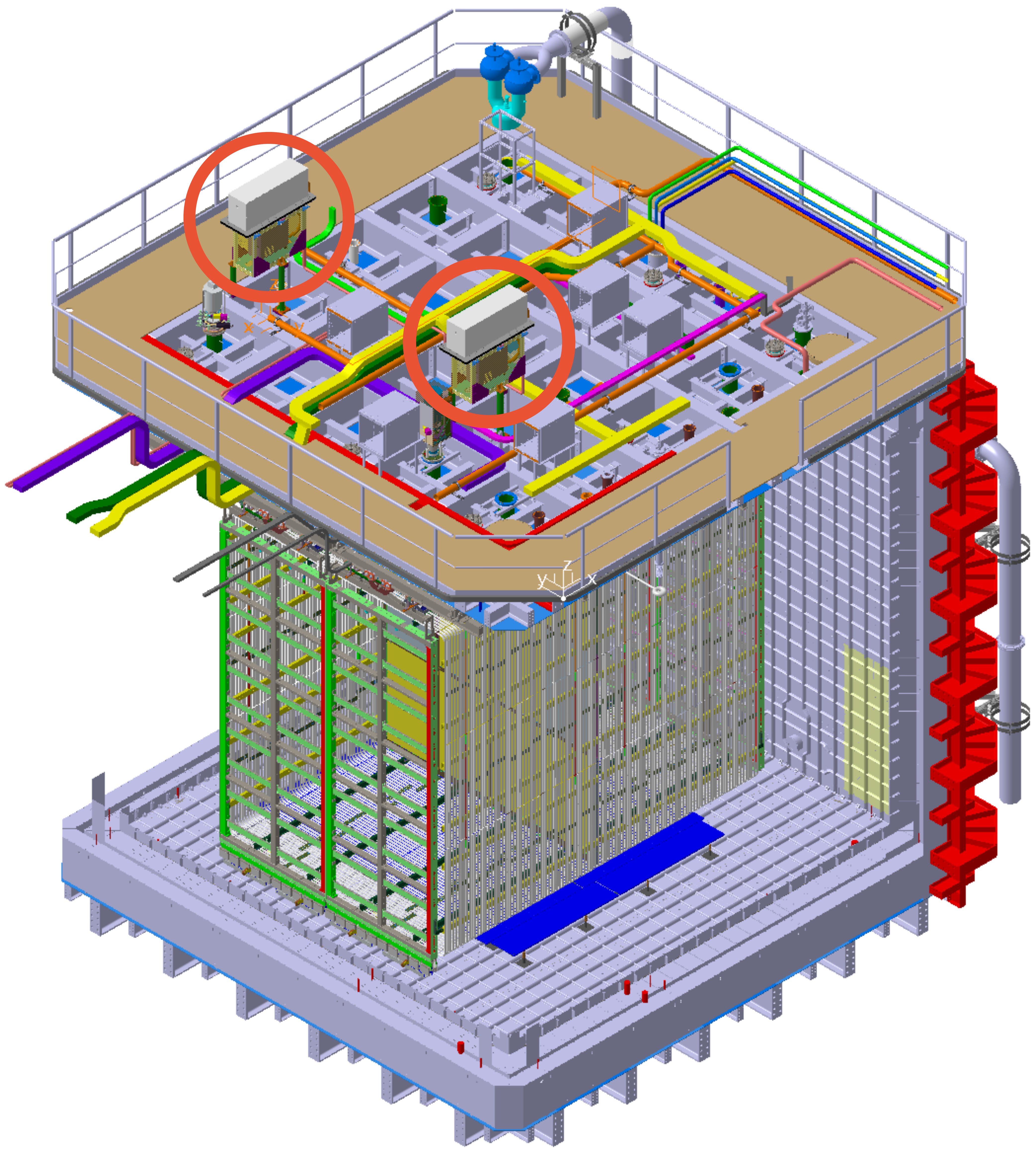
- CPA design remains similar to in ProtoDUNE-SP
  - Frame was rebuilt but panels remain the same
  - Anti-rotation system added to improve planarity
  - Modified hanging system
  - Now has 4 columns instead of six to match the 4 APAs

- All 12 field cage end-wall panels assembled



Calibration systems

- Install and test a new laser calibration system
  - Lasers mounted on top of the cryostat
  - Periscope and feedthrough system direct and rotate the beam into the TPC
  - Installation planned for July 2022
- Produces ionisation tracks in the LArTPC
  - Should be perfectly straight in absence of electric field distortions
  - Measure the drift velocity
  - Probe space charge and other E-field distortions



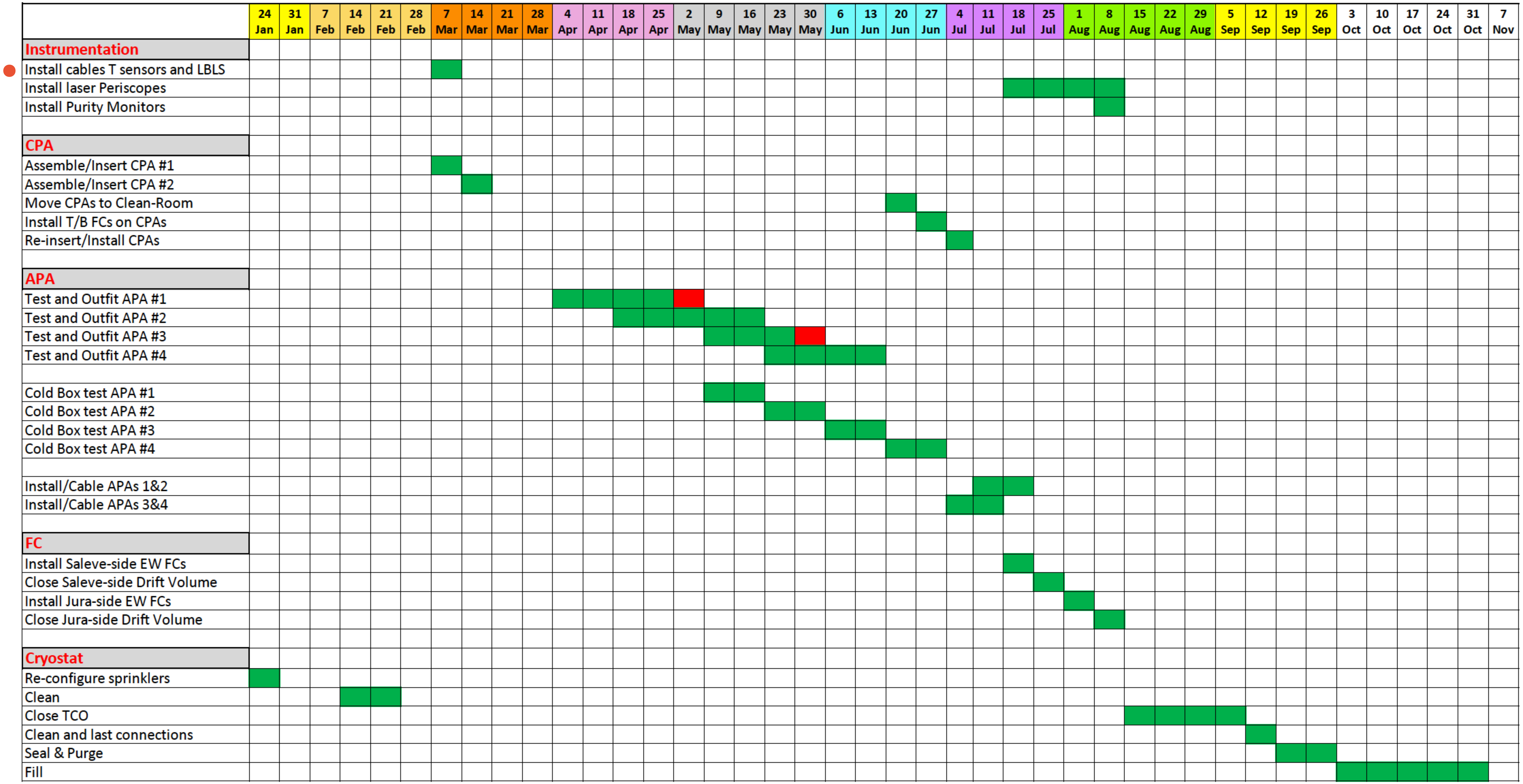
Plans and schedule

- Schedule driven by arrival of new cold electronics and related cold cables
  - Preparations underway to test APA1 in the cold box with new CE
  - All four APAs should be cold-box tested and in the cryostat by the end of June 2022

- To mitigate this, will now handle 3 APAs simultaneously in the clean room
  - More logistically complicated, but feasible

- Two weeks of beam requested for the end of this year
  - Longer period of beam time to be requested for spring 2023

Full schedule



PhD theses

- 2020
  - Aidan Reynolds, Evaluating the low-energy response of the ProtoDUNE-SP detector using Michel electrons, University of Oxford
- 2021
  - Ajib Paudel, A pion-argon cross section measurement in the ProtoDUNE-SP experiment with cosmogenic muon calibrations, Kansas State University
  - Milo Vermeulen, A blessing in disguise: characterisations of ProtoDUNE photon shower for neutrino measurements in DUNE, University of Amsterdam & Nikhef
  - Richard Diurba, Evaluating the ProtoDUNE-SP detector performance to measure a 6 GeV/c positive kaon inelastic cross section on argon, University of Minnesota
  - Jake Calcutt, Measurement of the π^+ - argon absorption and charge exchange interactions using ProtoDUNE-SP, Michigan State University
  - Francesca Stocker, Measurement of the pion absorption cross section with the ProtoDUNE experiment, University of Bern
  - David Rivera, Neutron cross section measurement in the ProtoDUNE-SP experiment, Pennsylvania University