Charge and energy calibration of the ProtoDUNE-SP detector using cosmic ray muons

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DEEP UNDERGROUND NEUTRINO EXPERIMENT

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INTRODUCTION

biggest LArTPC to date

ProtoDUNE-SP

- Liquid Argon Time Projection Chamber (LArTPC) built at CERN neutrino platform.
- The active volume is 6 m high, 7 m wide and 7.2 m along the drift direction.
- Consists of 2 drift volumes of 3.6m drift length each.
- Exposed to H4 beamline at CERN with known particle species of kaons(K^+), positrons(e^+), pions(π^+) and protons(p).

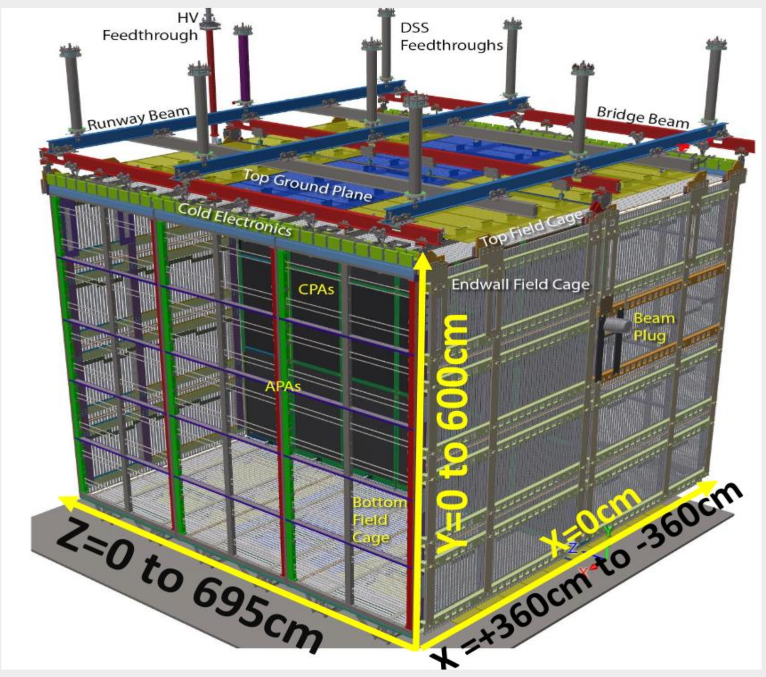

Fig 1: Major components of ProtoDUNE-SP

LArTPC Calibration

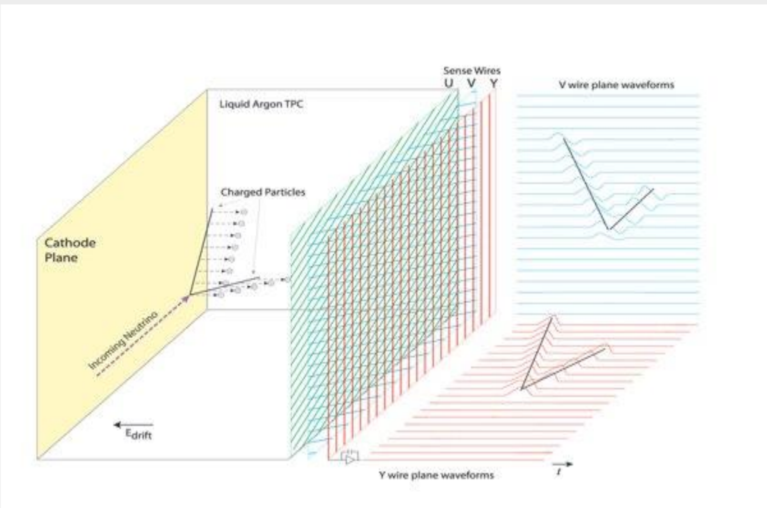

Fig 2: LArTPC and time vs wire readout

Motivation for calibration:
- Hadronic cross-section on argon
- Detector response

Why Cosmics?
- ~10,000 muons/(minute.m^2) reaches earth's surface.
- Cosmic ray muons cover the entire TPC in a short time (a few hours).
- dE/dx vs Kinetic energy well known

dQ/dx non-uniformity

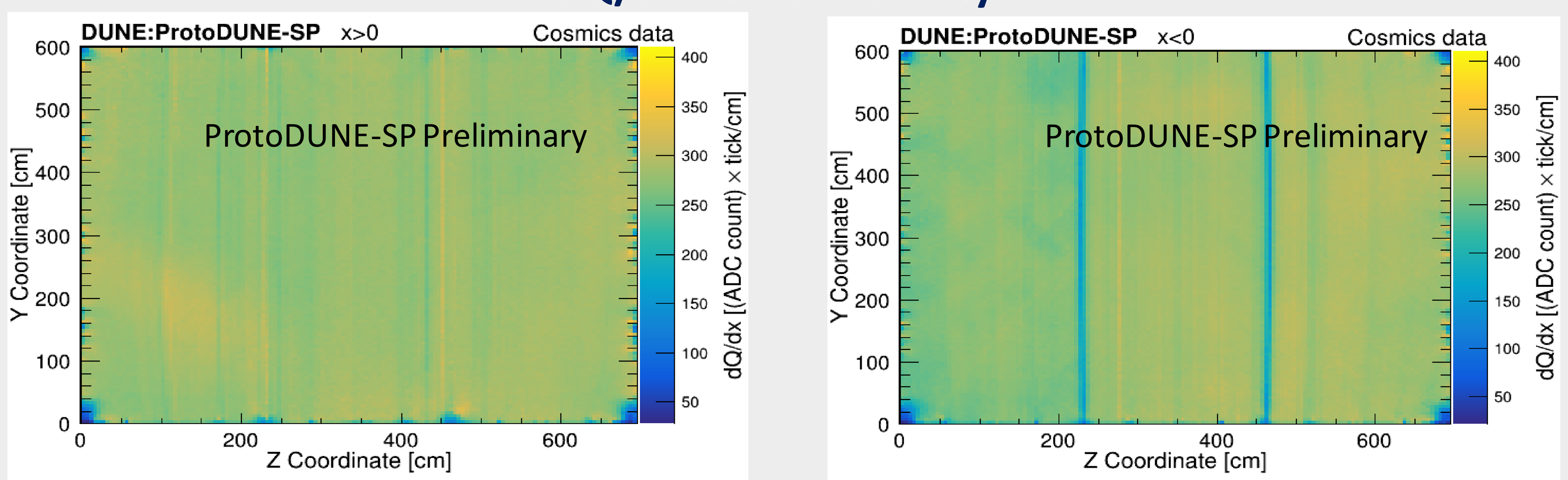

Fig 3: dQ/dx distribution for YZ plane for x>0 drift volume, left plot and x<0 drift volume, right plot

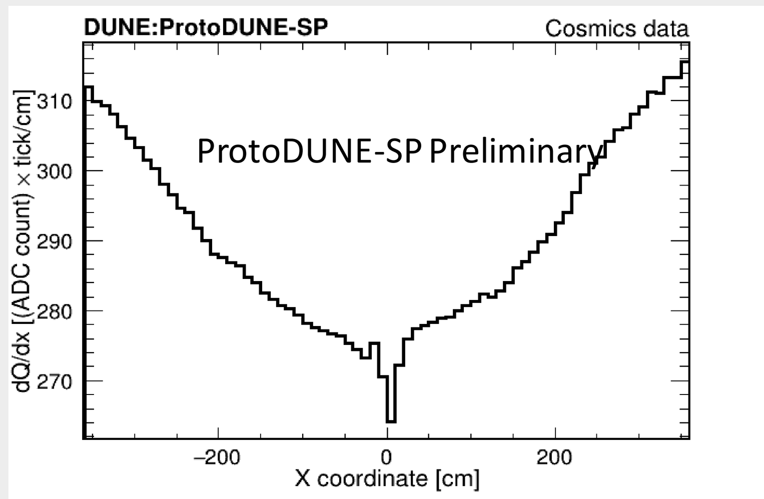

Fig 4: dQ/dx distribution vs drift coordinate

The charge deposition per unit length (dQ/dx) is affected by several factors including:

- Space-Charge Effect (SCE)
- Recombination Effect
- Electron attenuation
- Diffusion
- Electronics gain variation

The low dQ/dx stripes in YZ distribution for x<0 region is due to the presence of electron diverters at APA boundaries for x<0 (which moves charge away from the boundaries) , while electron diverters are not present in x>0 region.

SCE and electronics gain variation are calibrated out using dedicated calibrations.

Detector response for *the energetic through-going cosmic muons* used as a data-driven correction, to remove remaining non-uniformities.

We are using a method like the MicroBooNE detector [1], which is discussed in next steps.

METHODOLOGY

Charge calibration(dQ/dx calibration)

Using energetic through-going cosmic ray muons, charge calibration is carried out in two steps:

Step 1: YZ calibration
Divide YZ plane into 5 × 5 cm^2 bins
The YZ correction factor is:

$$C(y,z) = \frac{median\ dQ/dx\ for\ each\ bin}{median\ dQ/dx\ for\ the\ entire\ TPC}$$

Step 2: X calibration
Divide X coordinate into 5cm bins, apply YZ correction to each hit

The X correction factor is:

$$C(x) = \frac{median\ dQ/dx\ for\ each\ bin}{median\ dQ/dx\ for\ the\ entire\ TPC}$$

Charge normalization constant,

$$N(Q) = \frac{median\ dQ/dx\ at\ the\ anode}{median\ dQ/dx\ for\ the\ entire\ TPC}$$

Final calibrated dQ/dx is:
(dQ/dx)_calibrated=N(Q).C(x).C(y,z).(dQ/dx)_reconstructed

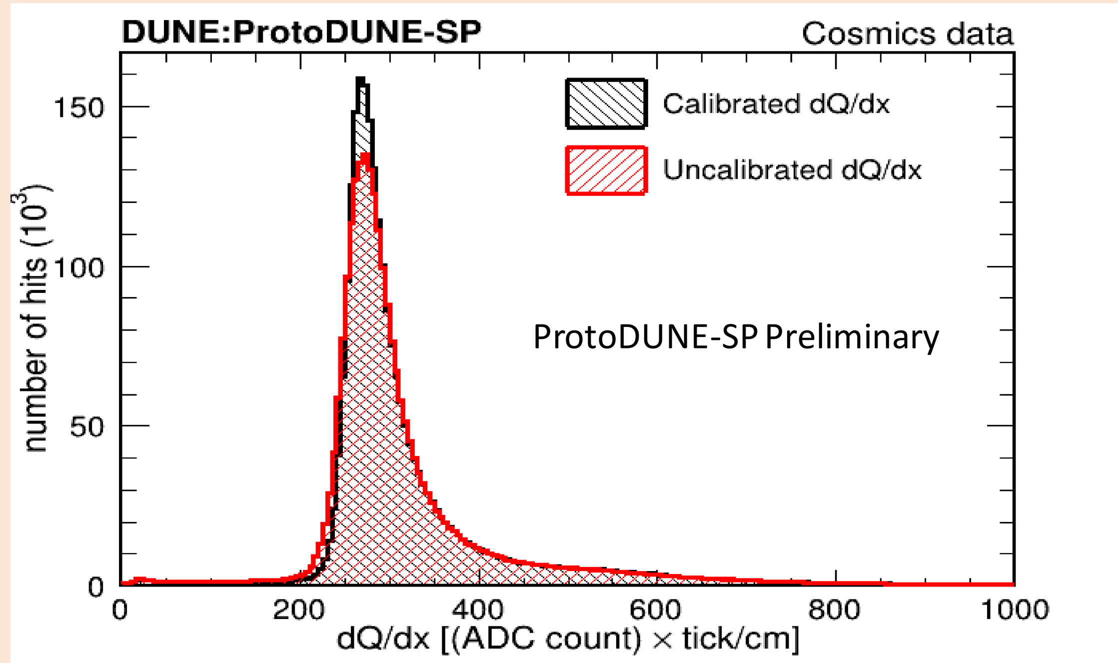

Fig5: dQ/dx distribution before and after charge calibration

Energy Scale Calibration (dE/dx calibration)

Stopping cosmic ray muons are used for energy scale calibration.

Landau-Vavilov [2] theory predicts stopping muon dE/dx vs kinetic energy(or residual range).

Calibrated dQ/dx $\xrightarrow[C_{cal}]{\text{Modified Box Model}}$ dE/dx, C_{cal} is a free parameter in the χ2 minimization.

Modified Box Model [3]

$$\left(\frac{dE}{dx}\right)_{calibrated} = \left(\exp\left(\frac{\left(\frac{dQ}{dx}\right)_{calibrated}\beta' W_{ion}}{C_{cal}\,\rho\mathscr{E}}\right) - \alpha\right)\left(\frac{\rho\mathscr{E}}{\beta'}\right),$$

where

C_{cal} = Calibration constant used to convert ADC values to number of electrons,
W_{ion} = 23.6×10^{-6} MeV/electron (the work function of argon),
$\mathscr{E}$ = E field based on the measured space charge map,
ρ = 1.38 g/cm^3 (liquid argon density at a pressure of 124.106 kPa),
α = 0.93, and
β' = 0.212 (kV/cm)(g/cm^2)/MeV.

The last two parameters were measured by the ArgoNeuT experiment at an operational electric field strength of 0.481 kV/cm.

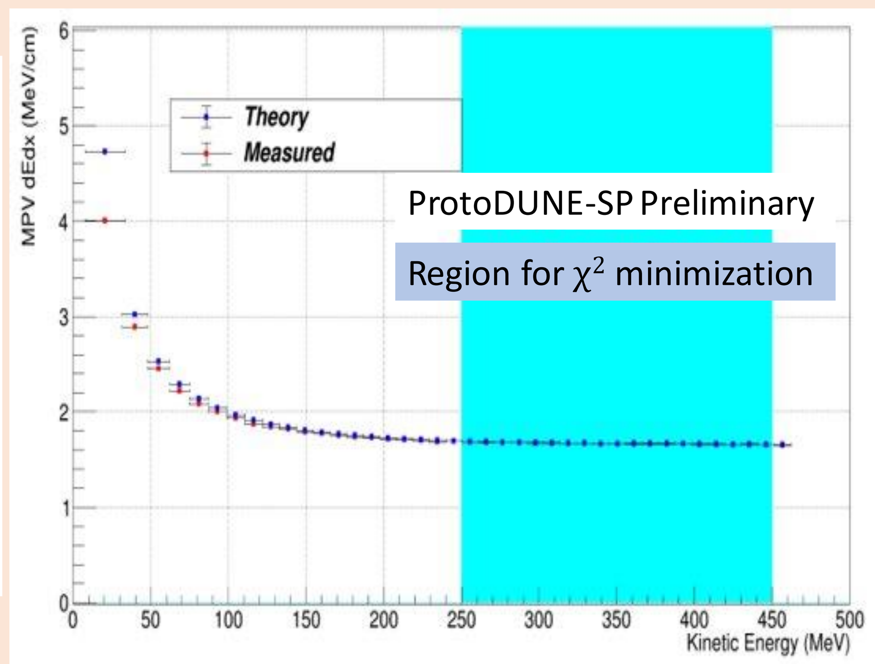

Fig 6: dE/dx vs KE

Calibration factor for ProtoDUNE-SP is measured to be Ccal=(5.3955±0.0035)e-3 ADC/electrons.

References:

[1] https://arxiv.org/abs/1907.11736

[2] Particle Data Group

[3] ArgoNeuT collaboration, R. Acciarri et al., A Study of Electron Recombination Using Highly Ionizing Particles in the ArgoNeuT Liquid Argon TPC, JINST 8 (2013) P08005, [1306.1712].

RESULTS

dE/dx vs residual range for Stopping cosmic muons

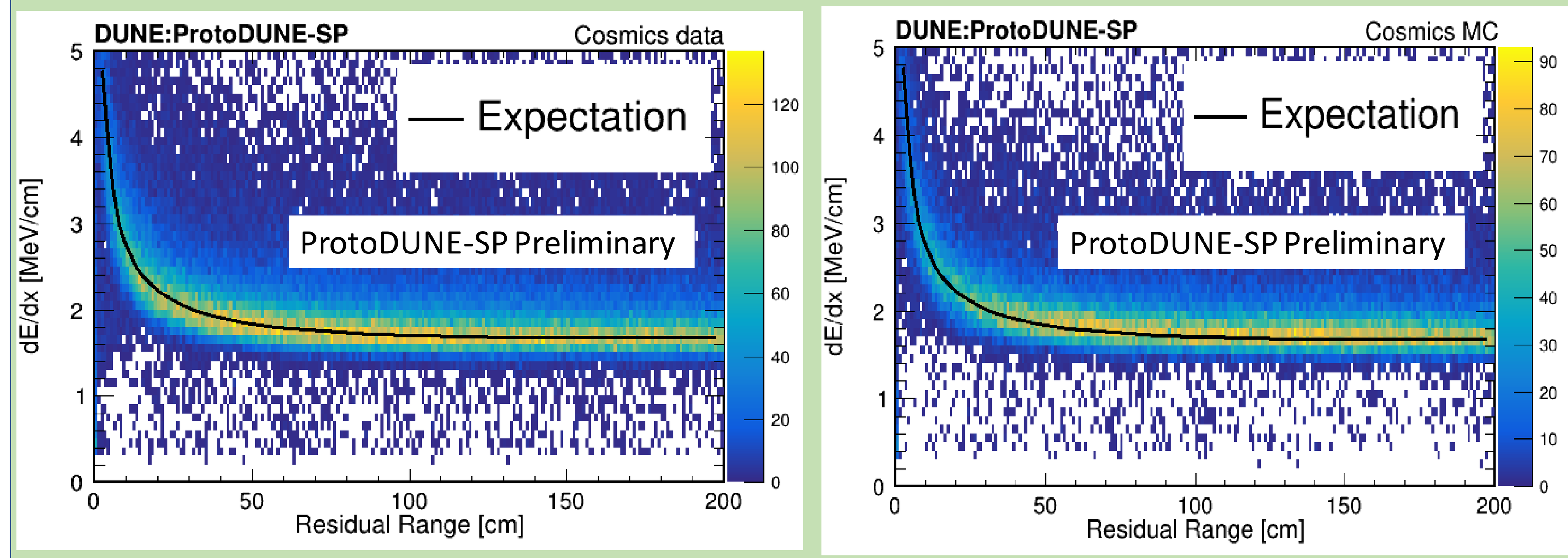

Fig 7: dE/dx vs residual range, ProtoDUNE-SP data, left and ProtoDUNE-SP simulation, right (Expectation is the Modified Box Model)

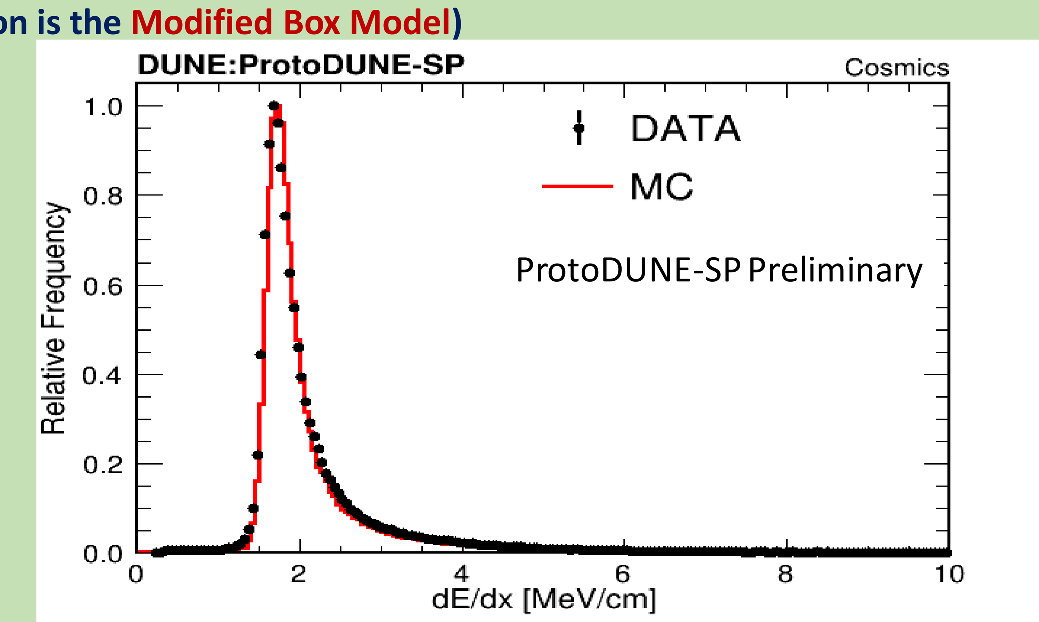

Fig 8: calibrated dE/dx for stopping muons

Cosmic Muon Based calibration constants applied to beam protons and muons:

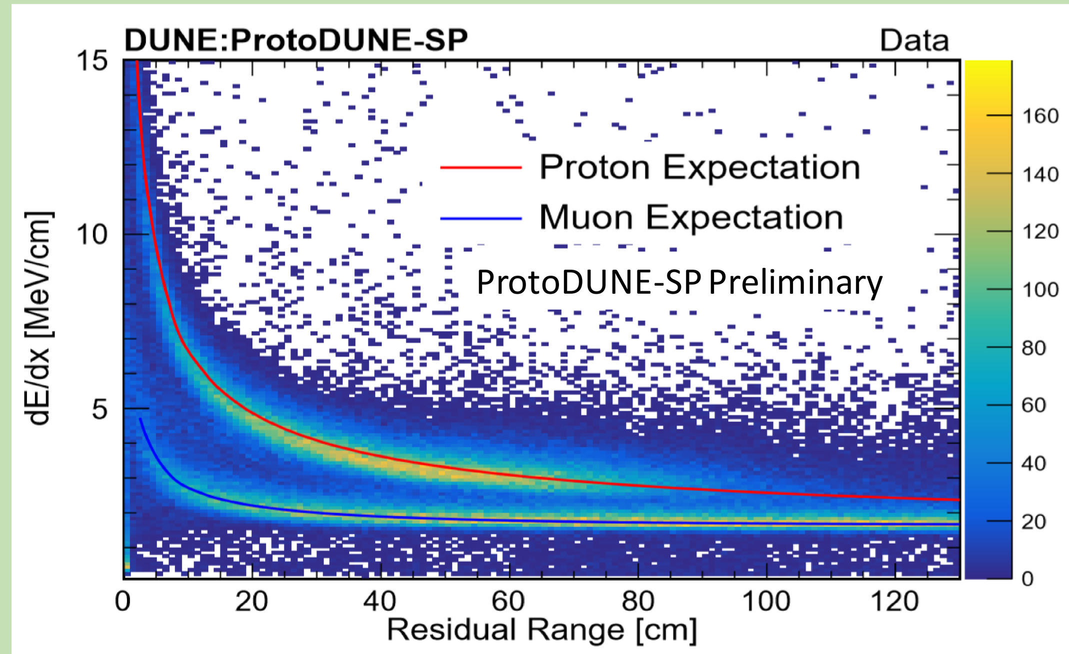

Fig 9: Proton-muon separation

Cosmic muon-based calibration factors has been used for test beam particles including pions, protons, muons, kaons and positrons. The agreement with theoretical prediction looked good.

Fig 8 shows good agreement between Monte-Carlo simulation dE/dx and data dE/dx for stopping muons.

Fig 9 shows, how well we can separate 1GeV/c beam protons and muons in ProtoDUNE-SP.

SUMMARY:

- **Cosmic muon calibration shows good results for test-beam particles as well.**
- **Shows excellent proton-muon separation.**
- **The result demonstrates high quality of the ProtoDUNE-SP detector.**