Energy reconstruction and calibration techniques of the DUNE LArTPC

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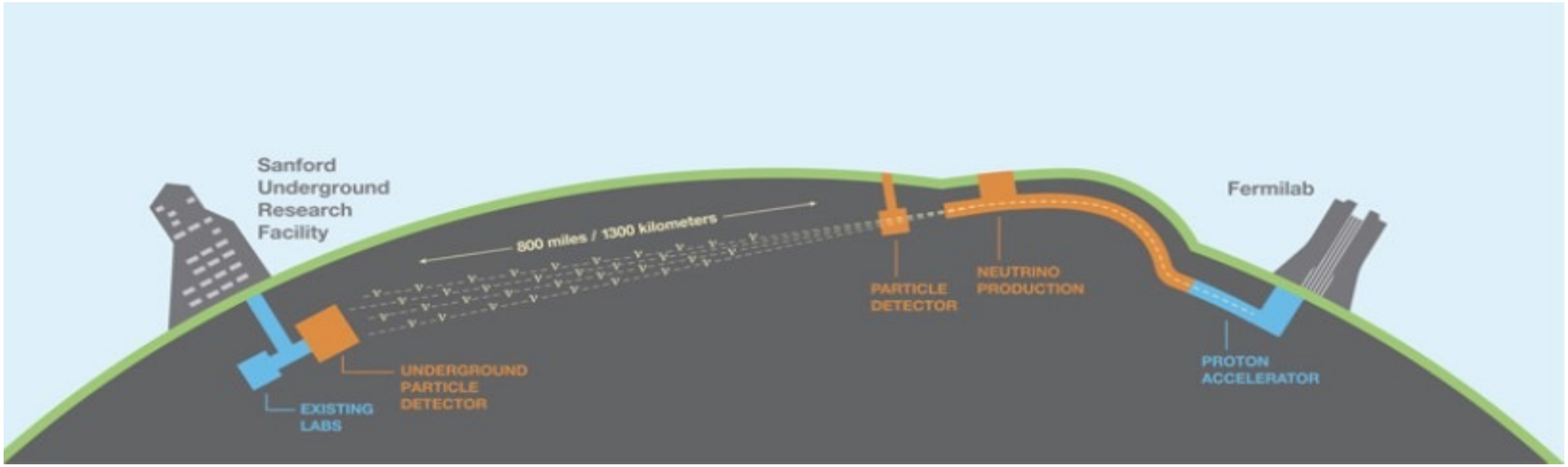
Deep Underground Neutrino Experiment (DUNE)



- The DUNE science program includes:
  - Neutrino oscillations
  - Detection of astrophysical neutrinos
  - Beyond Standard Model searches

Far Detector (FD)
- At SURF, SD, USA
- LArTPC
- 1.5 km underground
- 4 × 17 kt modules

Near Detector (ND)
- At Fermilab
- 3 components
- LArTPC, GArTPC, non-TPC
- Neutrino beam source

LArTPC Calibration

- Motivation
  - Calibrate energy scale
  - Energy resolution
  - Low energy reconstruction
- Calibration approach
  - Develop the procedures to determine the detector response which the measurements depend on such as:
    - Electron lifetime, recombination, electron diffusion, electronics/gain
  - Measure detector response to “standard candles”
    - Stopping muons, charged pions, protons
    - Through-going muons
    - π^0 decay

Calibration Sources

- Existing sources
  - Cosmogenic activities
  - Beam neutrino events
  - Intrinsic radioactive isotopes

- Dedicated calibration systems
  - Ionisation laser system
  - Pulsed neutron source
  - Fixed/injected radioactive sources

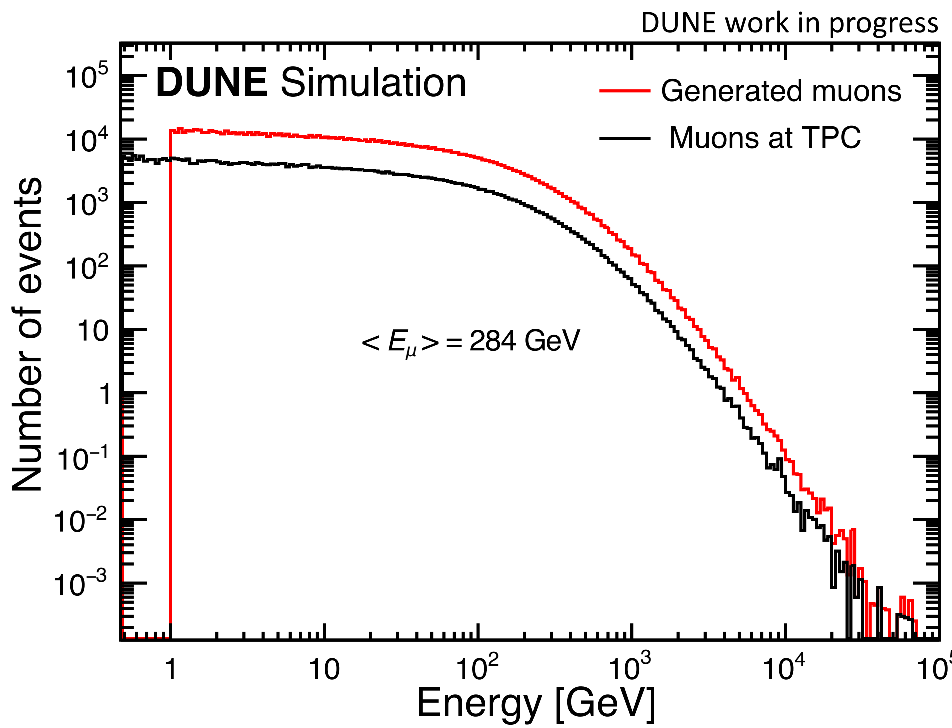
Calibration with Cosmic Muons

- It is free and useful
- ~ 90 cosmic muons stopping per-day/module

Cosmic muon events are generated using Muon Simulation Underground (MUSUN) generator

- A total of 1.85×10^6 simulated events corresponding to 131 days of DUNE FD data
- ~ 4,800 muons per-day/module
- ~ 33% of generated muons in DUNE FD

Muon Energy Distribution



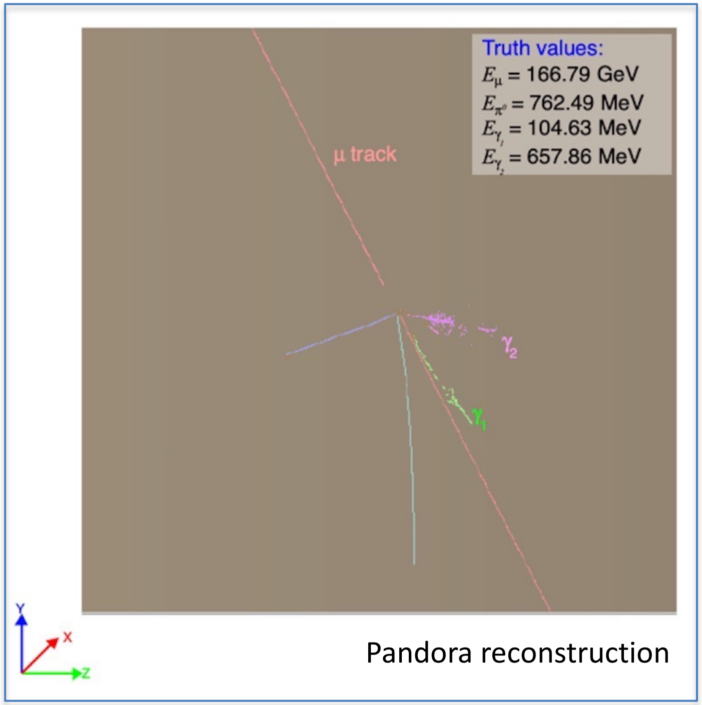
- $< E_{\mu} >$ = 284 GeV; busy event activities in DUNE FD
  - Different from ProtoDUNE ($< E_\mu >$ = 4 GeV)

Reconstruction and identification of π^0

- π^0 invariant mass is a standard candle
- Useful for calibrating the detector to electromagnetic activity response
- Also, a background to the ν_e appearance signal
  - A thorough analysis is required for the identification of such events

DUNE Simulation

DUNE work in progress



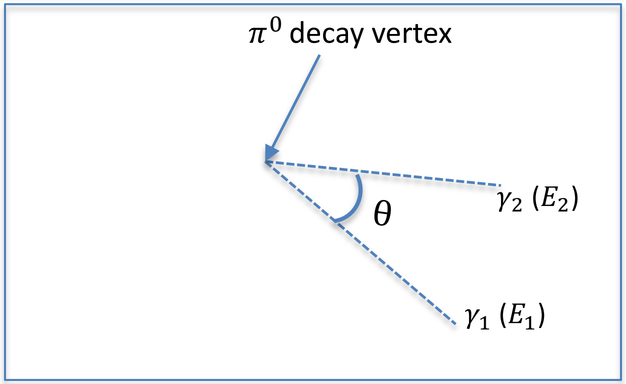
Pandora reconstruction

- $\pi^0 \rightarrow 2\gamma$
- The (γ, γ) invariant mass is given by:

$$m_{\pi^0} = \sqrt{2E_1E_2(1-\cos\theta)}$$

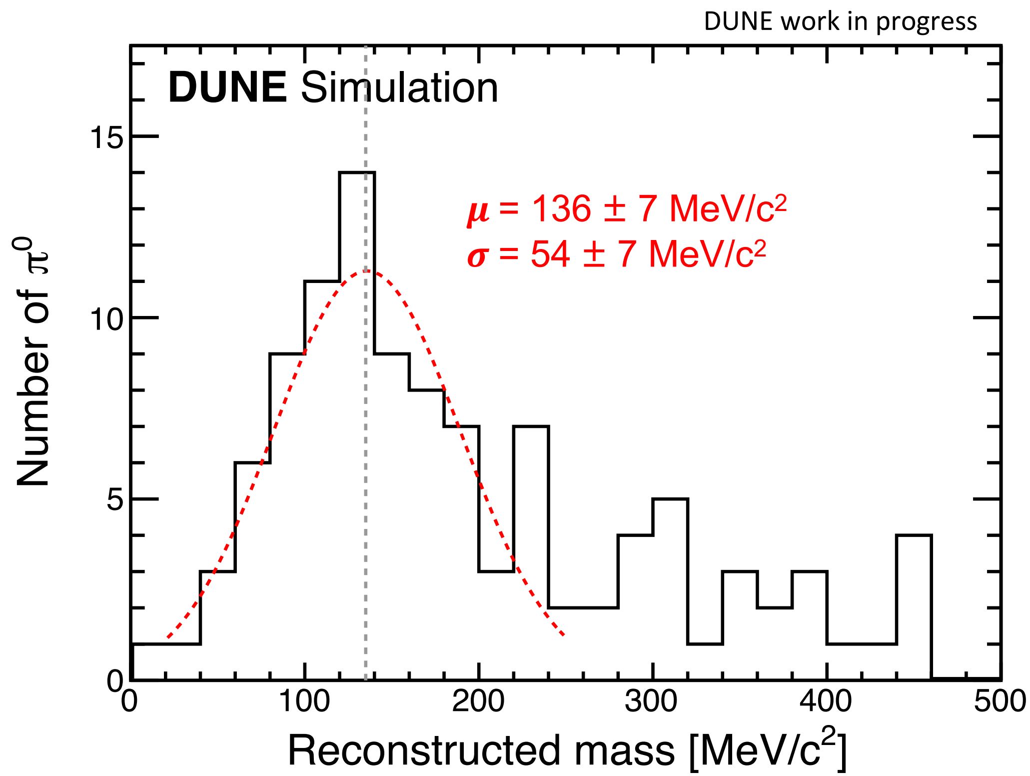
(where E_1 and E_2 are the photon energies and

θ is the angle between the two photons)



Reconstructed π^0 Mass

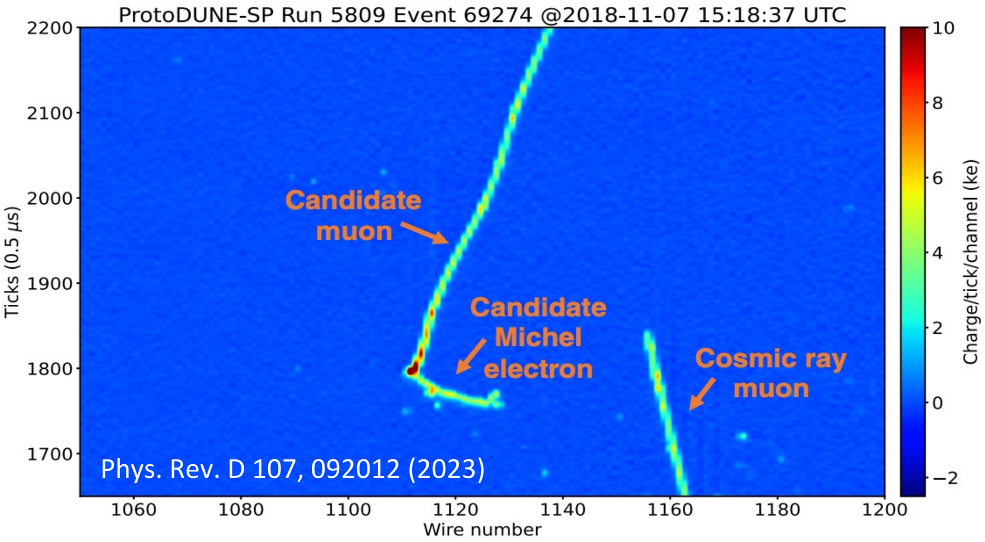
- Based on simulation, performance cuts are applied as follows:
  - The number of reconstructed showers hits >100
  - Reconstructed opening angle > 20 degrees
- 156 π^0 events
- 104 days of data taking in single module



- ➢ Gaussian fit applied within a range [20, 250] MeV/c^2
- ➢ Extracted gaussian mean consistent within the statistical uncertainty of 5% of true π^0 mass

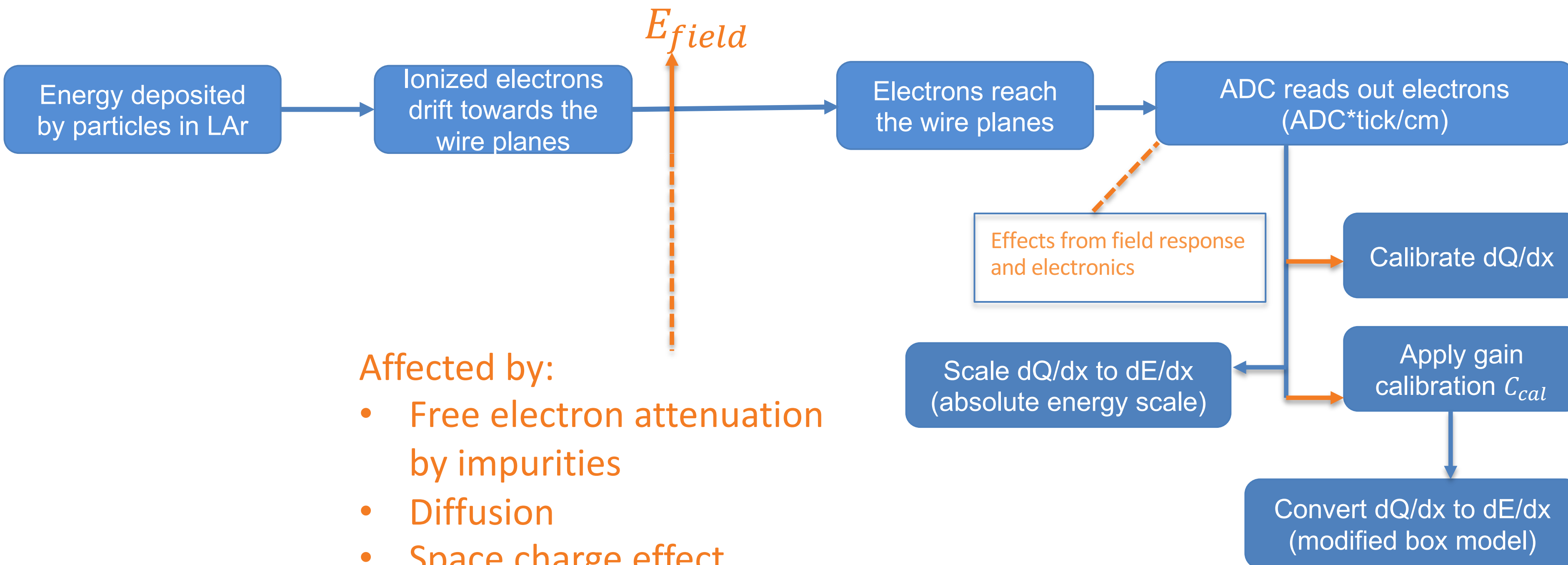
Energy Calibration of DUNE FD

- Using stopping muons
  - Well-understood energy loss profile
  - Can be used as an absolute energy scale
  - Can be used for electron-ion recombination measurements
- 371,000 simulated cosmic muon events
- 26 days of data at DUNE
- 2,169 stopping muons in DUNE
- Energy calibration methods:
  - Model dependent: modified box model
  - Model-independent: absolute energy scale



dE/dx Calibration

- Calibration is performed to convert ionisation electrons into measurable dE/dx



Affected by:

- Free electron attenuation by impurities
- Diffusion
- Space charge effect
- Recombination

Modified Box Model

- Precise dE/dx measurement is required for the cross-section and Bragg peak measurement for muons, pions, and protons
- Formula developed by ArgoNeut which is a modification of Birks' law

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

$\left(\frac{dQ}{dx}\right)_{calibrated}$: Charge per step as reconstructed on the wire, calibrated for the effects such as e^{-} lifetime correction

C_{cal}: Calibration constant used to convert from wire response (ADC*tick) to electrons

ξ: Local electric field

$W_{ion}, \rho, \alpha, \beta'$ are constants measured previously [1]

Measurements are needed for C_{cal}, ξ to convert $\frac{dQ}{dx}$ to $\frac{dE}{dx}$

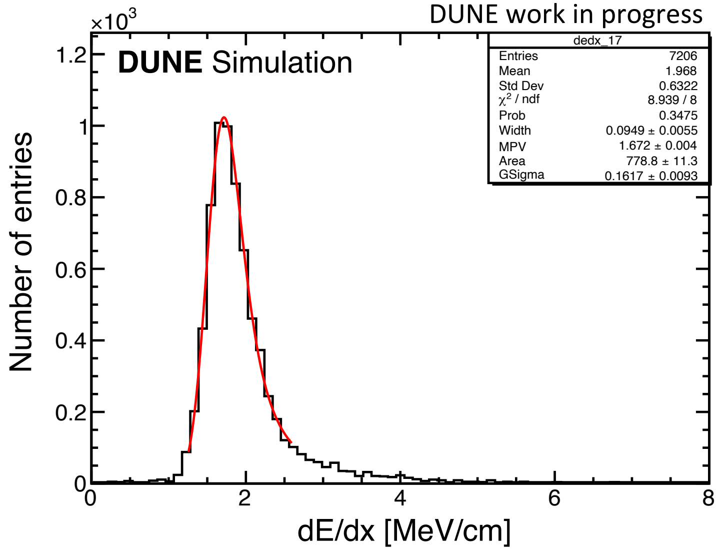
[1] JINST 8(2013) P08005

dE/dx Calibration Method

Utilise cosmic stopping muons at high residual ranges, as their dE/dx is well-defined with less than 1% theoretical uncertainty based on the Landau-Vavilov theory [2]

- For each track, residual range (distance from the end of the track) of 200 cm is considered
- Selected tracks are divided into small residual range bins and the most probable value (MPV) of each dE/dx distribution is determined
- Use residual range (120 - 200 cm) which correspond to the minimum ionising region
- Use a χ^2 optimisation to measure C_{cal}
- $C_{cal} = 5 \times 10^{-3}$ ADC $\times$ tick/e, if the detector is perfectly modelled
- Minimum χ^2 corresponds to final C_{cal}

$$\chi^2 = \sum \left(\frac{(\mathrm{MPV}(dE/dx)_{\mathrm{prediction}} - \mathrm{MPV}(dE/dx)_{\mathrm{measured}})^2}{\sigma^2} \right)$$

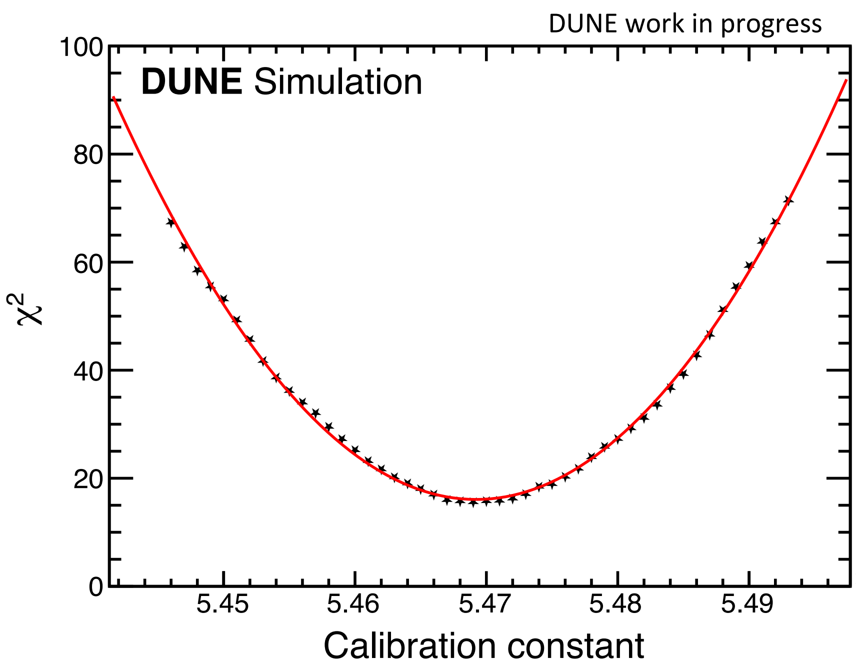


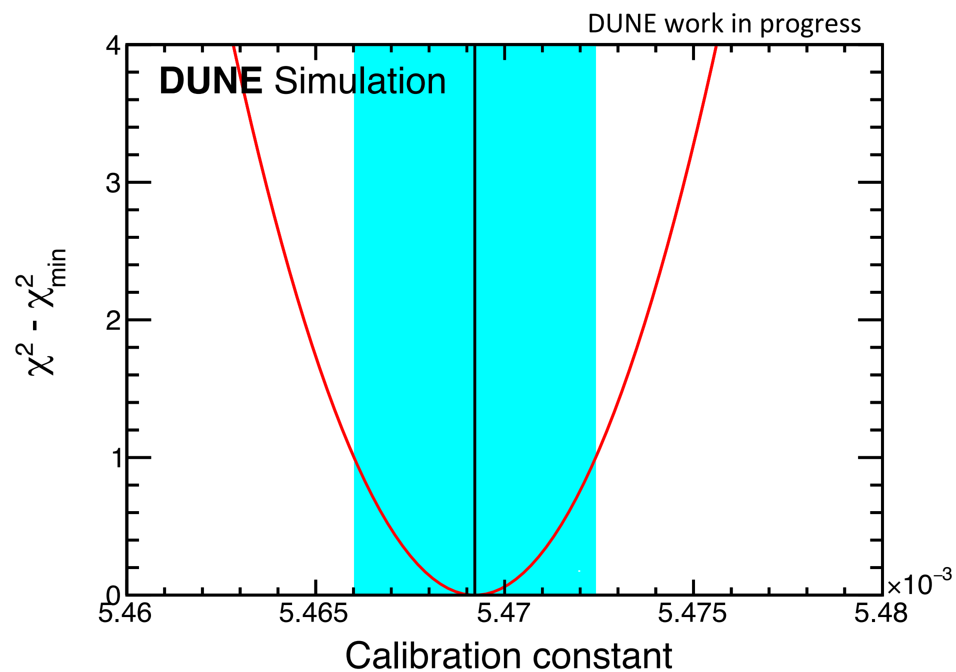
Example of dE/dx distribution fitted with Landau convoluted Gaussian function

- 5 cm residual range bin

[2] Phys. Rev. D **98**, 030001

χ^2 vs. Calibration Constant

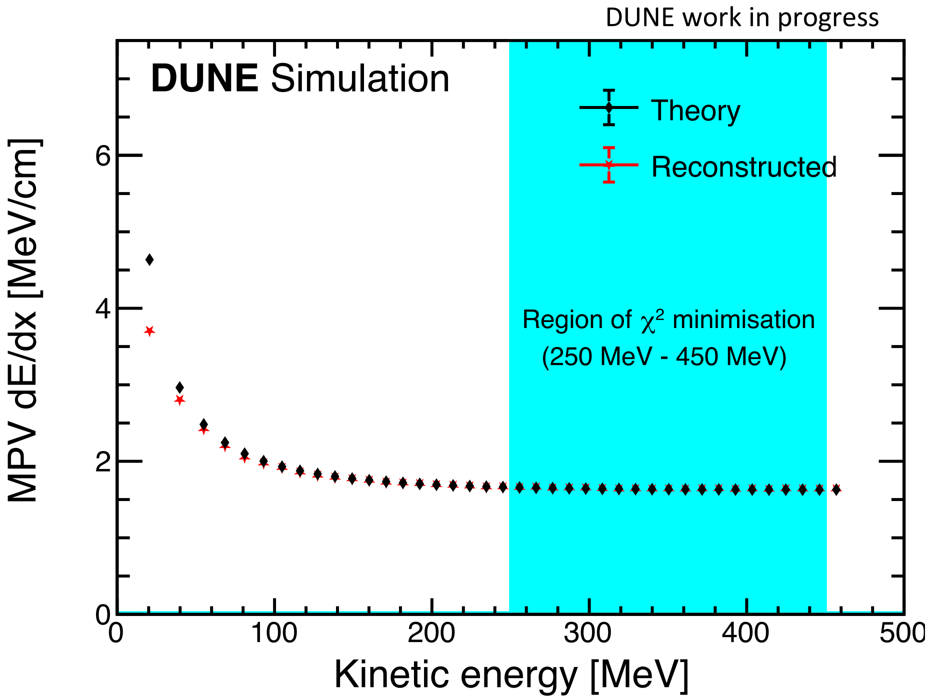


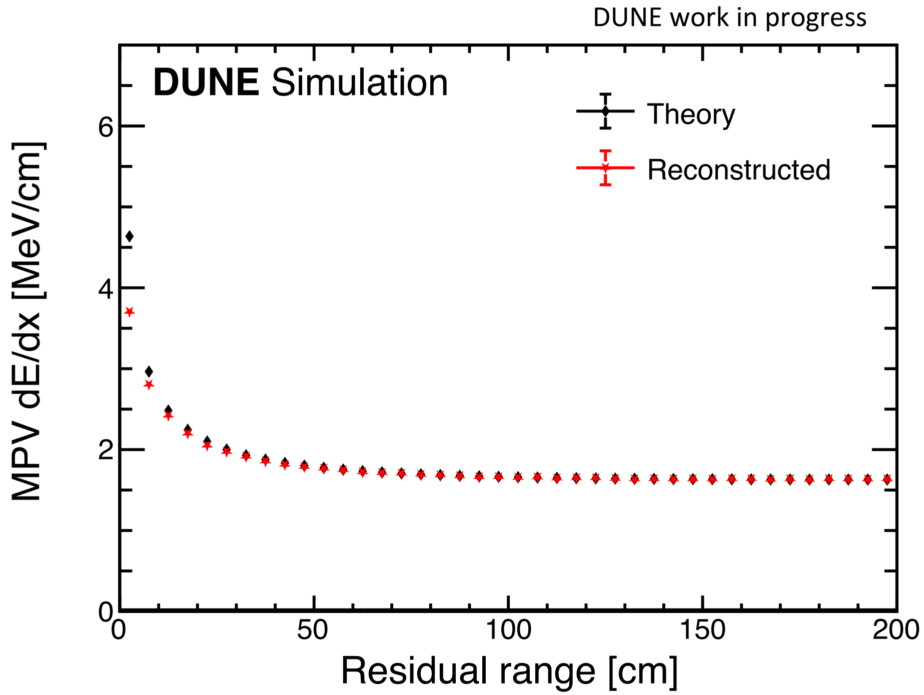


For statistical uncertainty:
$\chi^2 - \chi^2_{\text{min}} = 1$

C_{cal} **= (5.469 ± 0.003) × 10^{-3} ADC × tick/e**

Measured and Theoretical dE/dx





C_{cal} = (5.469 ± 0.003) × 10^{-3} ADC × tick/e

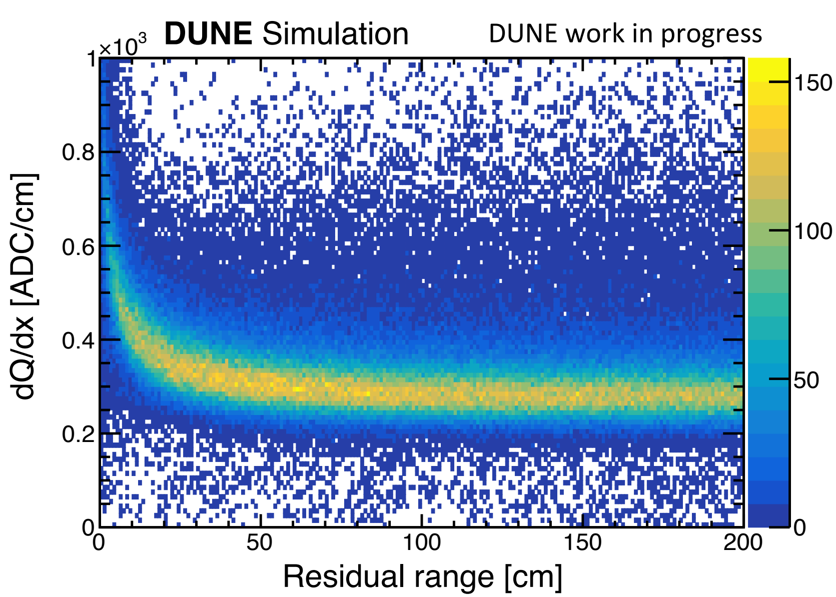
- Good agreement with the theoretical prediction at higher residual range and kinetic energy
- Reconstruction bias at the end of the track

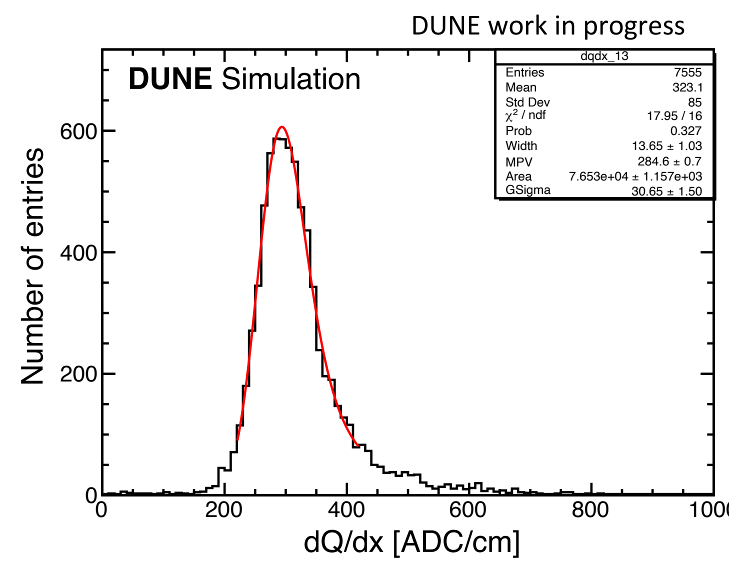
Absolute energy scale

Convert dQ/dx to dE/dx without biasing the empirical model

- Independent of any modelling
- Independent of any parameters from other experiments

- 5 cm residual range bin
- For each residual range bin, the dQ/dx distribution is fitted to a Landau-Gaussian distribution
- Determine the MPV of dQ/dx for each residual range bin

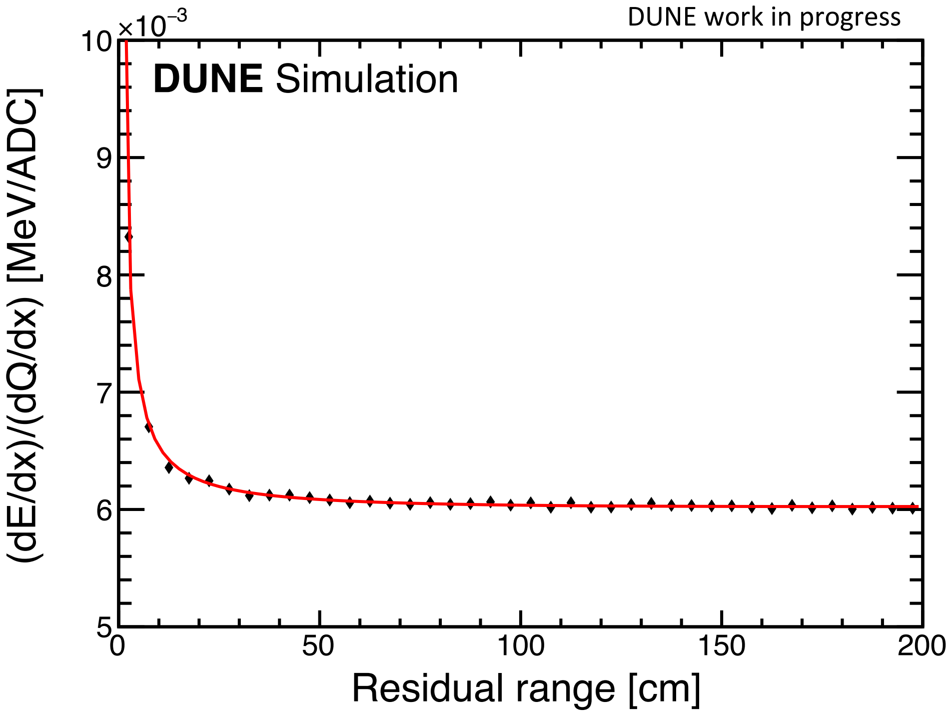




Reconstructed dQ/dx distribution fitted to a Landau function convolved with a Gaussian

Scaling dQ/dx to dE/dx

- Ratio $(dE/dx)_{theoretical}$ / $(dQ/dx)_{reconstructed}$ for each 5 cm bin of residual range is calculated
- The ratio vs. residual range is fitted with an empirical function.



Fit function:

$$f(r) = p_0 + p_1 \times 1/r + p_2 \times r$$

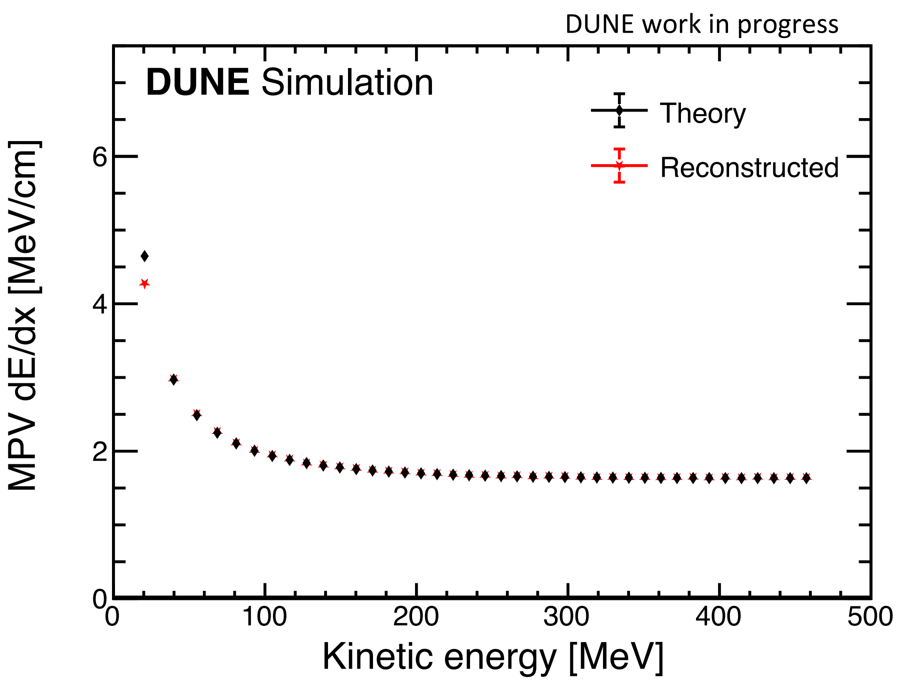
$$\frac{MPV(dE/dx)_{reconstructed}}{MPV(dQ/dx)_{reconstructed}} = p_0 + p_1 \times 1/r + p_2 \times r$$

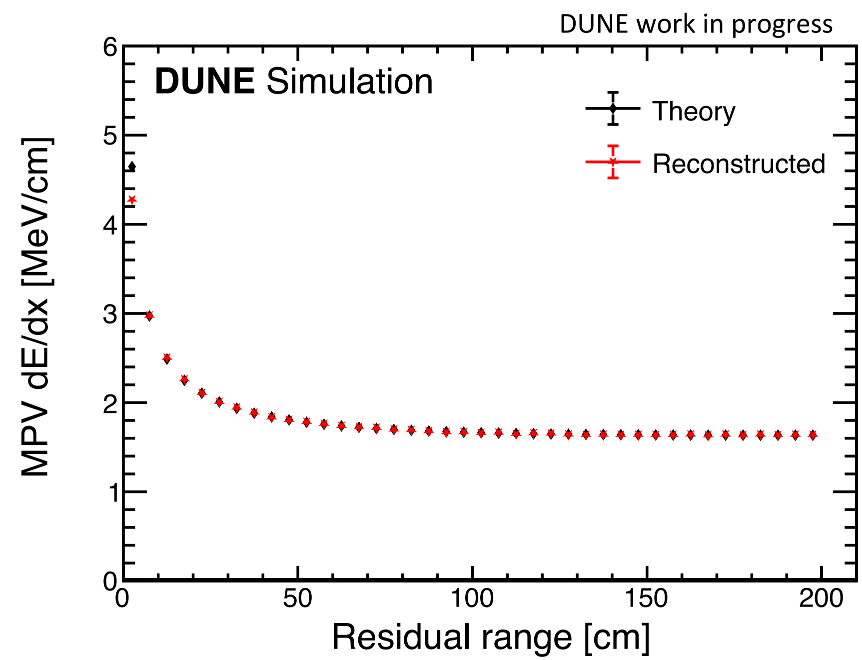
r: residual range

p_0	p_1	p_2
$(5.962 \pm 0.007) \times 10^{-3}$	$(5.731 \pm 0.087) \times 10^{-3}$	$(1.613 \pm 0.499) \times 10^{-7}$

Measured and theoretical dE/dx

- 5 cm bin for residual range 0 to 200 cm.
- Using the equation obtained from the fit, reconstructed dE/dx is obtained from reconstructed dQ/dx values

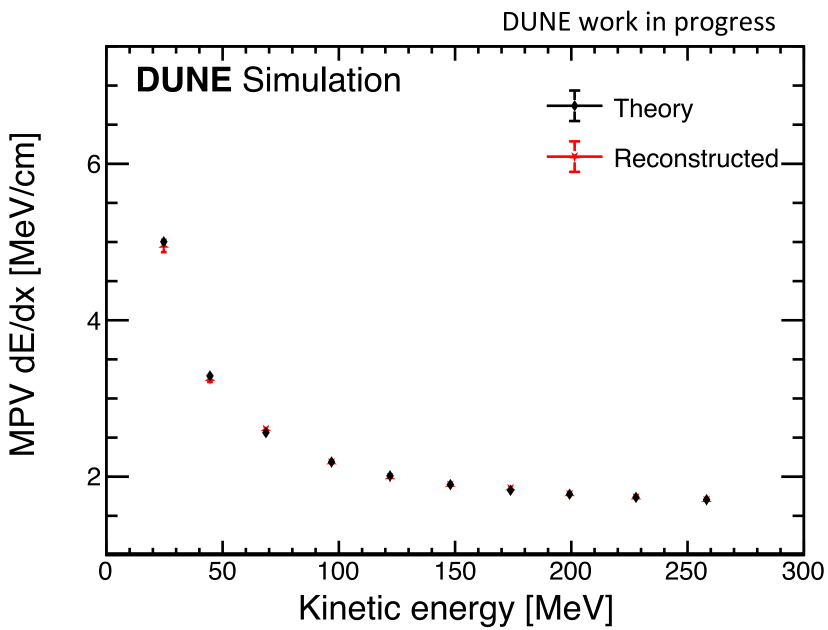


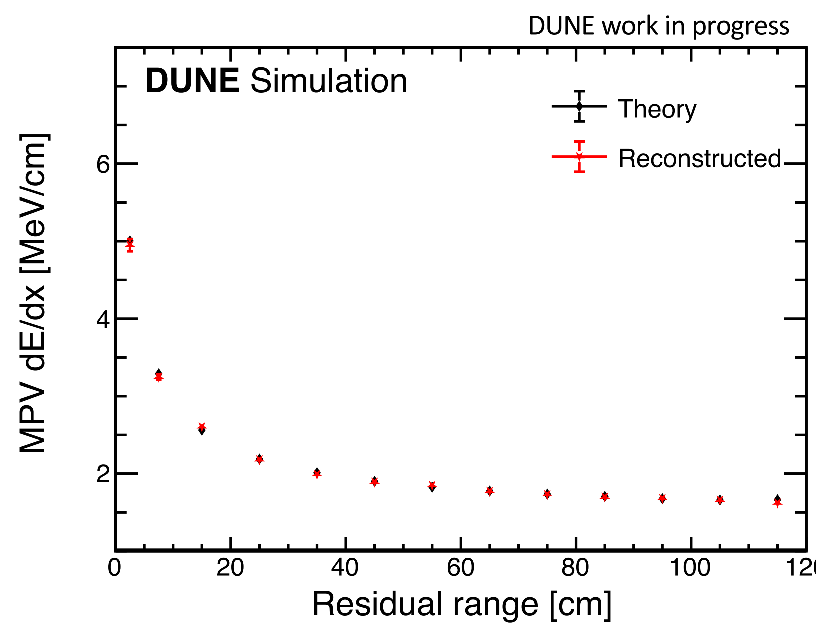


➢ Reconstructed dE/dx show good agreement with theoretical prediction even in the low kinetic energy and residual range

dE/dx reconstruction of stopping charged pions

- 9298 stopping charged pions
- Using the same absolute energy scale method used for stopping muons
  - 5 cm bin size for residual range 0 to 10 cm
  - 10 cm bin size taken for the residual range 10 to 150 cm

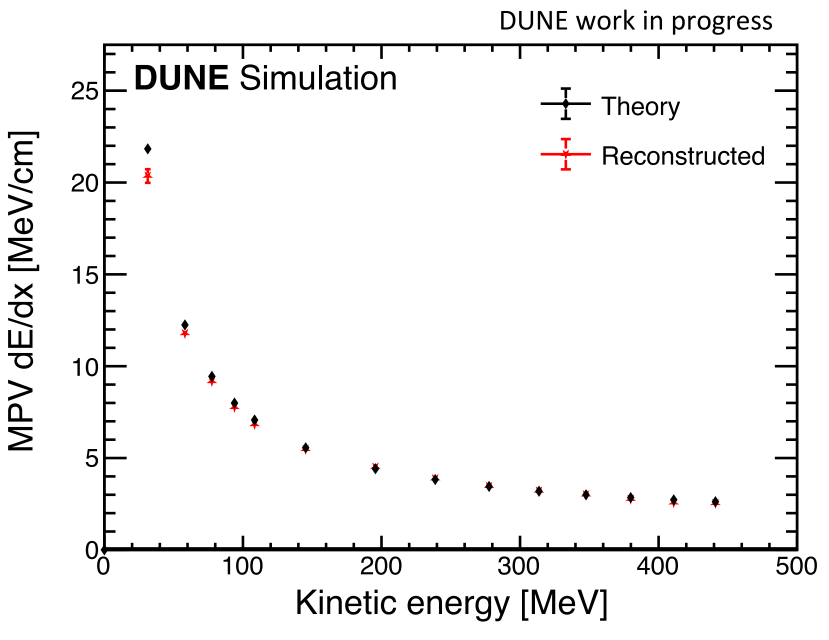


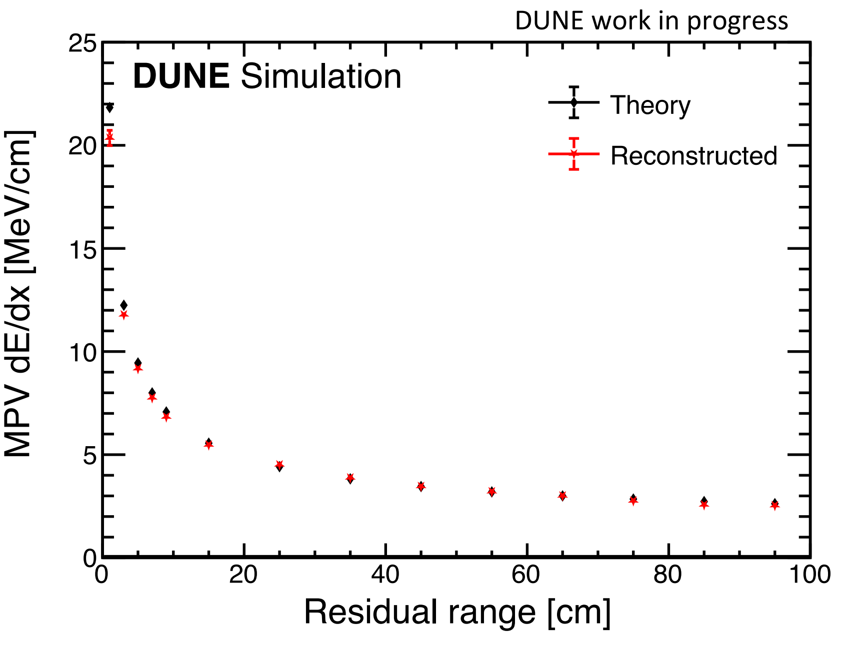


➢ Reconstructed dE/dx show good agreement with theoretical prediction, even in the low kinetic energy and residual range

dE/dx reconstruction of stopping protons

- 5.43×10^4 stopping protons
- Using the same absolute energy scale method used for stopping muons
  - 2 cm bin size for residual range 0 to 10 cm
  - 10 cm bin size taken for the residual range 10 to 100 cm

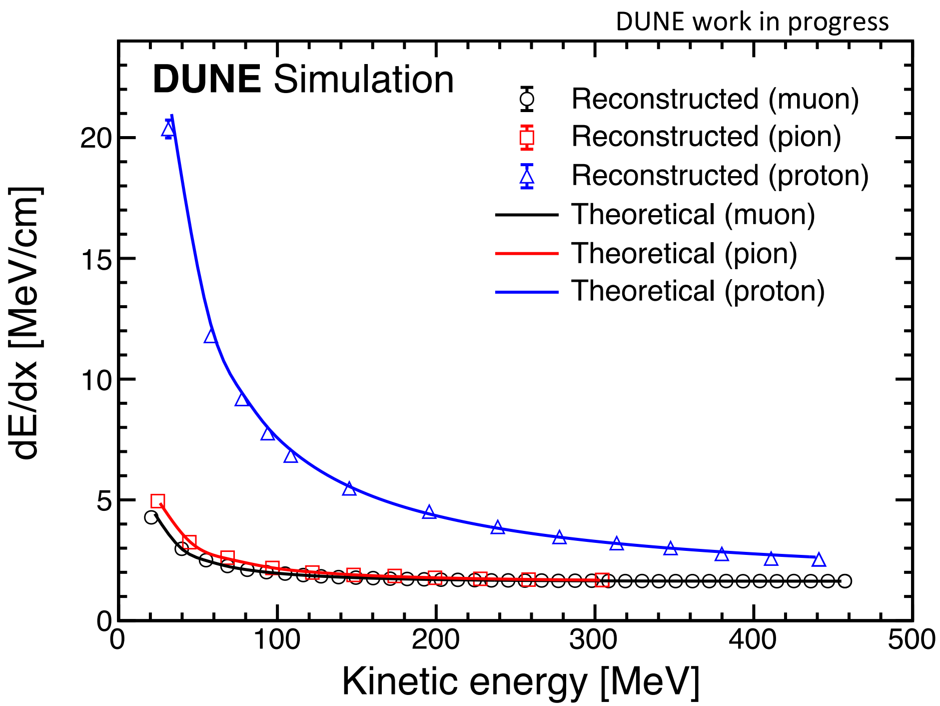


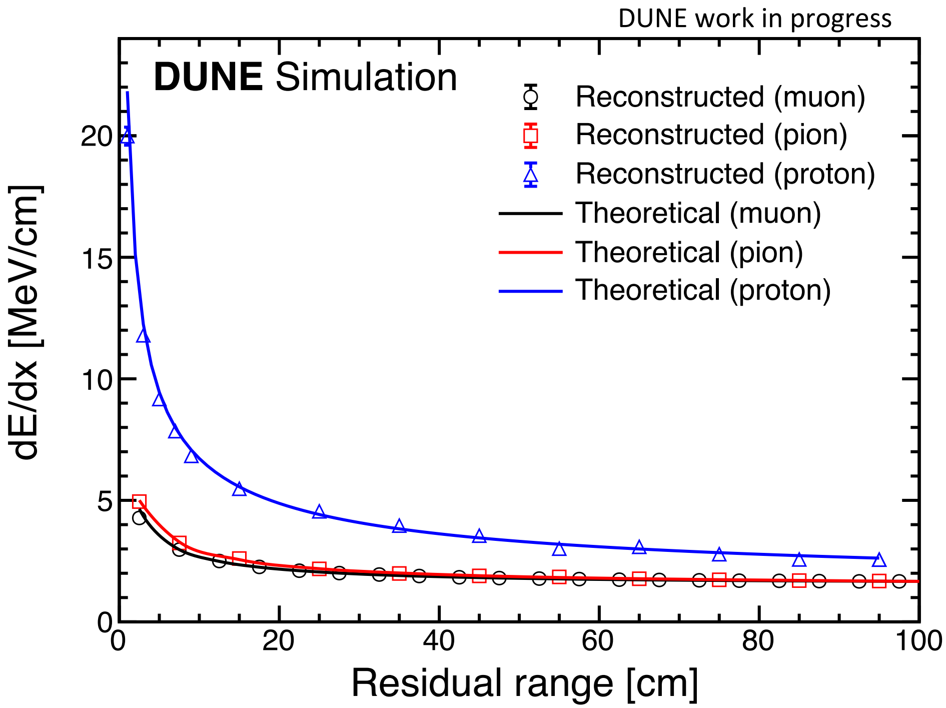


➢ Reconstructed dE/dx show good agreement with theoretical prediction

Comparison of dE/dx reconstruction

- Stopping muons, charged pions, and protons

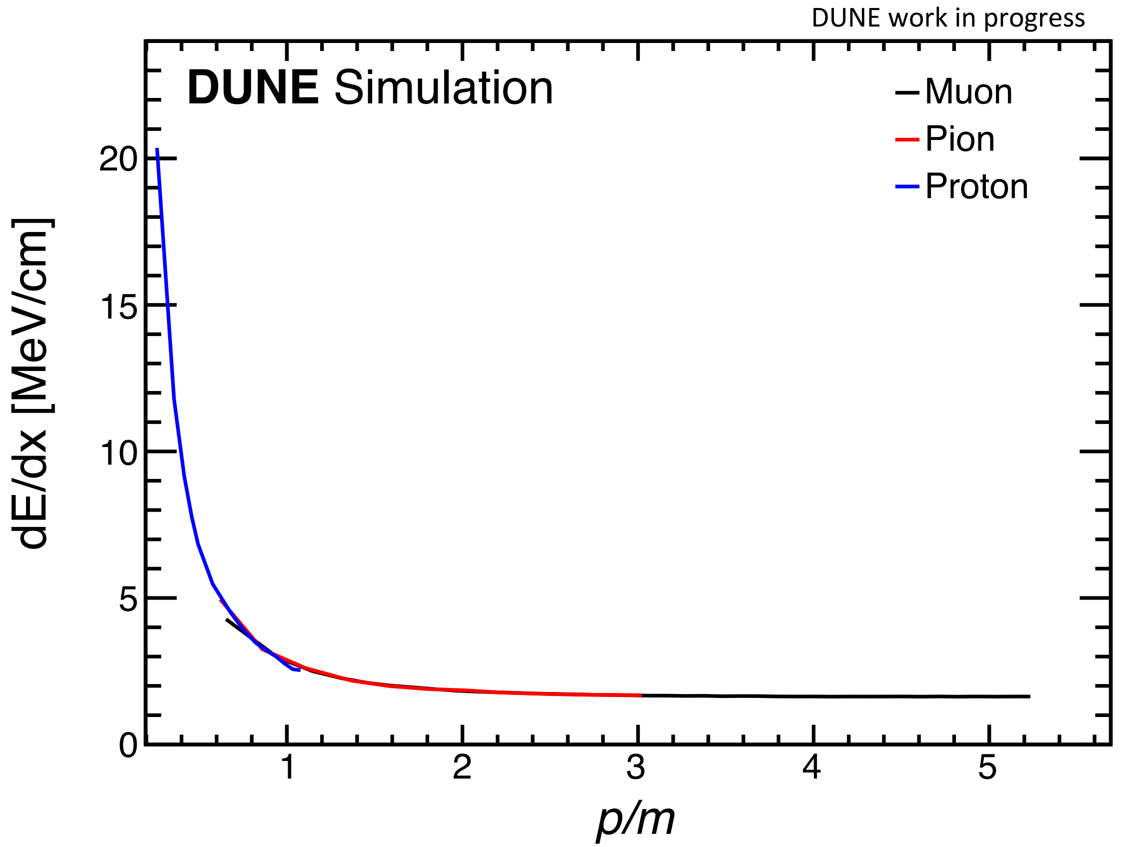




- ➢ Good agreement between reconstructed and theoretical prediction based on the Landau-Vavilov theory
- ➢ At low value bins, difference in theoretical and reconstructed value may be due to inefficient reconstruction at the end of the tracks

p/m vs. reconstructed dE/dx

- dE/dx as a function of momentum-to-mass ratio (p/m) is independent of particle type



➢ Validate the absolute energy calibration method in DUNE FD

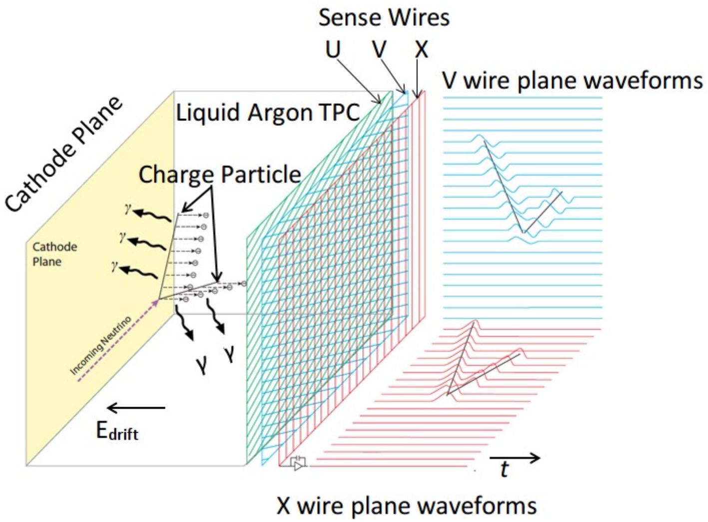
Summary

- Cosmic muon events are produced using the cosmic muon generator MUSUN for the DUNE FD
- Cosmic-ray muons are a valuable source for detector calibration
- π^0 is useful in calibrating the electromagnetic energy reconstruction
- Two calibration methods using stopping muons are presented which are useful for calibrating DUNE LArTPC
- The energy calibration techniques are validated using stopping charged pions and protons

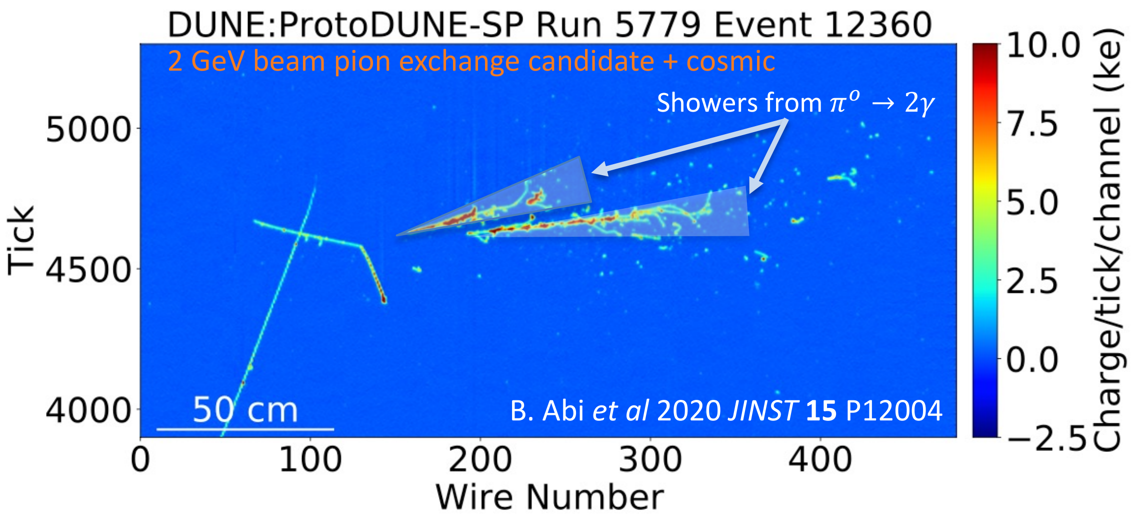
Thanks !

Backup Slides

Liquid Argon Time Projection Chamber (LArTPC)



B. Abi *et al* 2020 *JINST* 15 T08009



- Charge and light production
- LArTPC has excellent imaging, tracking and particle identification capabilities

Reconstructed tracks and showers in LArTPC. Photons produce electromagnetic showers and muons produce long straight tracks

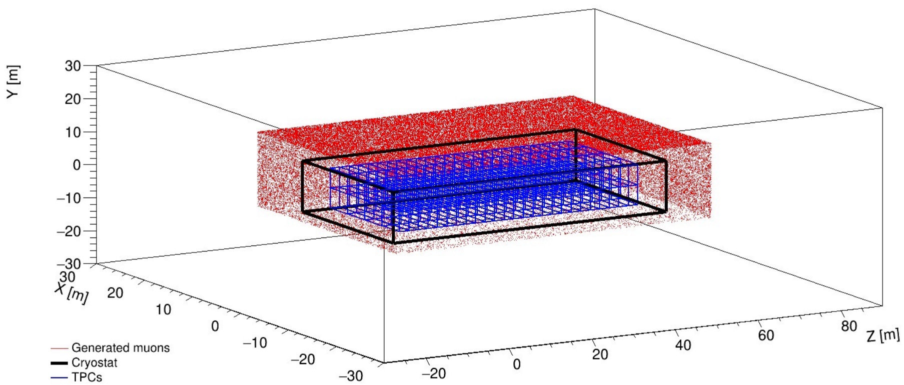
Calibration with Cosmic Muons

- Cosmic muon events are generated using Muon Simulation Underground (MUSUN) generator
- A total of 1.85×10^6 simulated events corresponding to 131 days of DUNE FD data
- ~ 4800 cosmic muons per-day in DUNE FD
- ~ 90 cosmic muons stopping per day in DUNE FD

Statistics

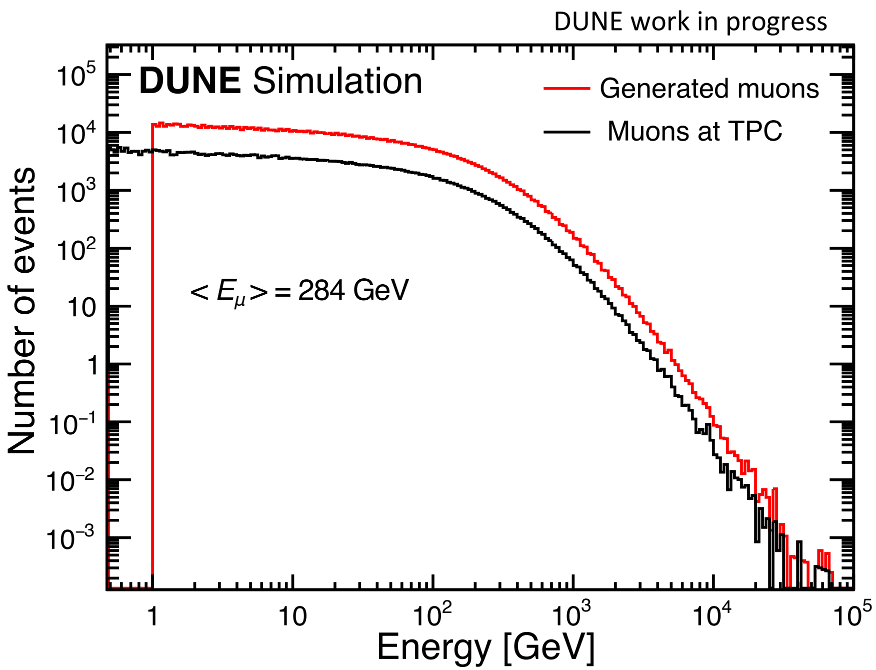
Characterisation	Total number	Per day	Fraction [%]
Total generated events	1.85×10^6	1.41×10^4	
Primary μ in TPC	6.24×10^5	4.76×10^3	33.72 ± 0.04
Any stopping μ in TPC	2.28×10^4	174	3.65 ± 0.02
Primary stopping μ in TPC	1.13×10^4	86	1.81 ± 0.02
All Michel electrons in TPC	2.01×10^4	153	3.21 ± 0.02
Michel from primary μ in TPC	6.84×10^3	52	1.10 ± 0.01
π^0 in TPC	2.76×10^4	210	4.42 ± 0.03
Events in which π^0 are produced	4.89×10^3	37	0.78 ± 0.01
Stopping π^+ in TPC	2.72×10^4	207	4.35 ± 0.03
Events in which π^+ are produced	4.71×10^3	36	0.75 ± 0.01
Stopping π^- in TPC	3.15×10^4	240	5.04 ± 0.03
Events in which π^- are produced	4.90×10^3	37	0.78 ± 0.01
Stopping protons in TPC	3.32×10^5	2.53×10^3	53.20 ± 0.09
Events in which protons are produced	2.05×10^4	156	3.28 ± 0.02
Stopping K^+ in TPC	1.50×10^3	11	0.24 ± 0.01
Events in which K^+ are produced	5.66×10^2	4	0.09 ± 0.00
Stopping K^- in TPC	6.68×10^2	5	0.11 ± 0.00
Events in which K^- are produced	3.38×10^2	3	0.05 ± 0.00

DUNE work in progress

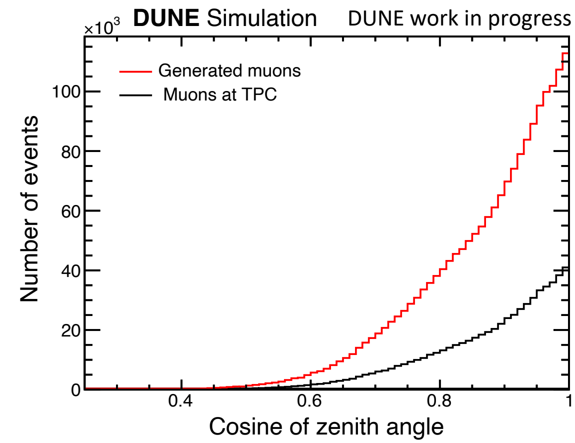


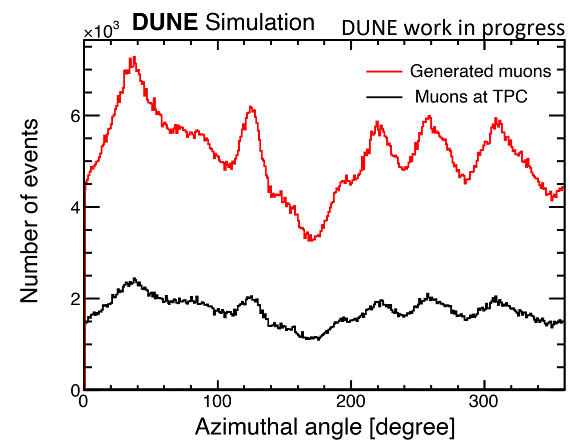
Muon Distributions

Energy of generated and entering μ in TPC



Zenith and Azimuthal angle





- 1.85×10^6 generated events
- 6.24×10^5 primary μ in active volume
- 131 days of data at DUNE FD
- Zenith distribution tells us the muons are mostly going downwards
- Azimuthal distribution depicts the surface profile above the DUNE FD

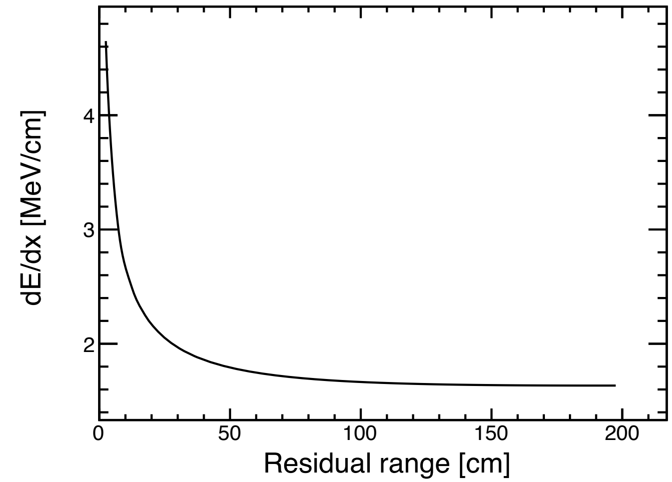
Theoretical MPV dE/dx

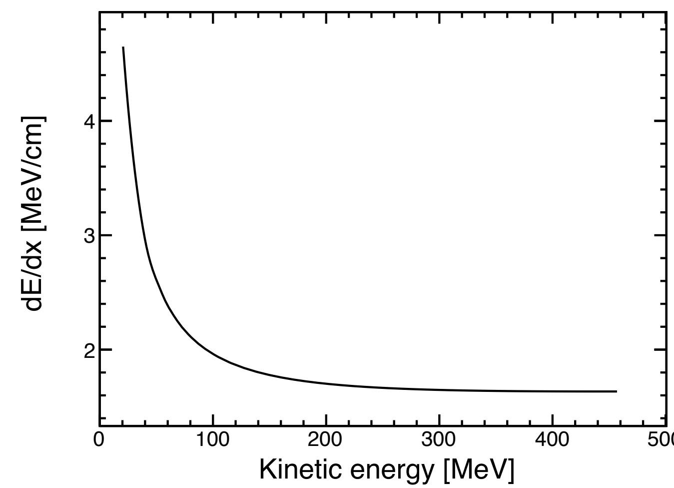
- The kinetic energy and residual range data is obtained from [3].
- For each residual range bin, considering the mid value of the bin, the corresponding theoretical most probable value of dE/dx is calculated
- Based on the Landau-Vavilov theory [4], MPV is calculated

$$\Delta_p = \xi \left[\ln \frac{2mc^2\beta^2\gamma^2}{I} + \ln \frac{\xi}{I} + j - \beta^2 - \delta(\beta\gamma) \right]$$

All symbols and their value from [4]

- The density of argon is calculated at 87 K

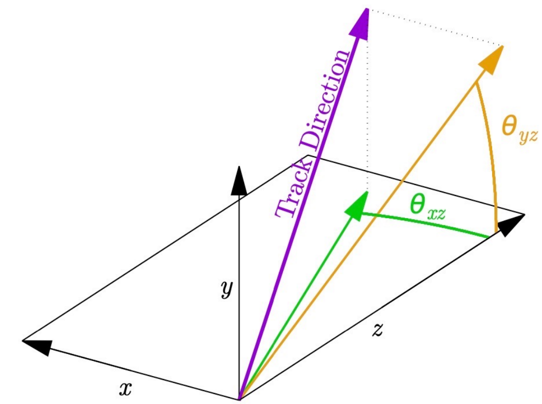




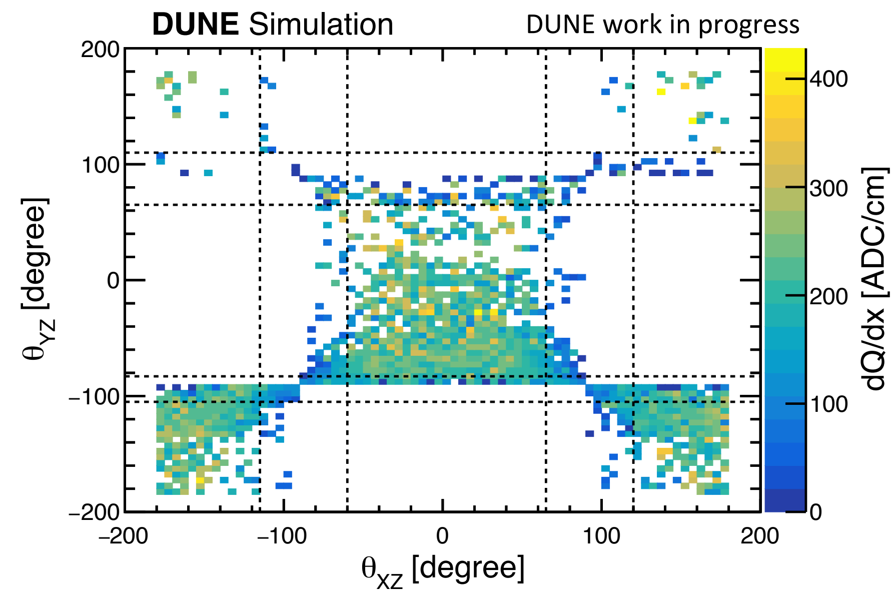
[3] https://pdg.lbl.gov/2020/AtomicNuclearProperties/HTML/liquid_argon.html
[4] Prog. Theor. Exp. Phys. 2020, 083C01 (2020)

Reconstructed track angle vs. dQ/dx of stopping muons

- The reconstruction capability of a LArTPC is limited for tracks passing parallel to a wire or in the plane containing drift direction and a wire.
- For such tracks, all the charge from the incident particle gets deposited in a single wire thus leading to the poor reconstruction of the deposited charge.
- To avoid geometrical effects, removed tracks with certain track angles:
  - $-115° < \theta_{xz} < -60°$ or $65° < \theta_{xz} < 120°$
  - $-105° < \theta_{yz} < -83°$ or $65° < \theta_{yz} < 110°$
- Removed broken tracks



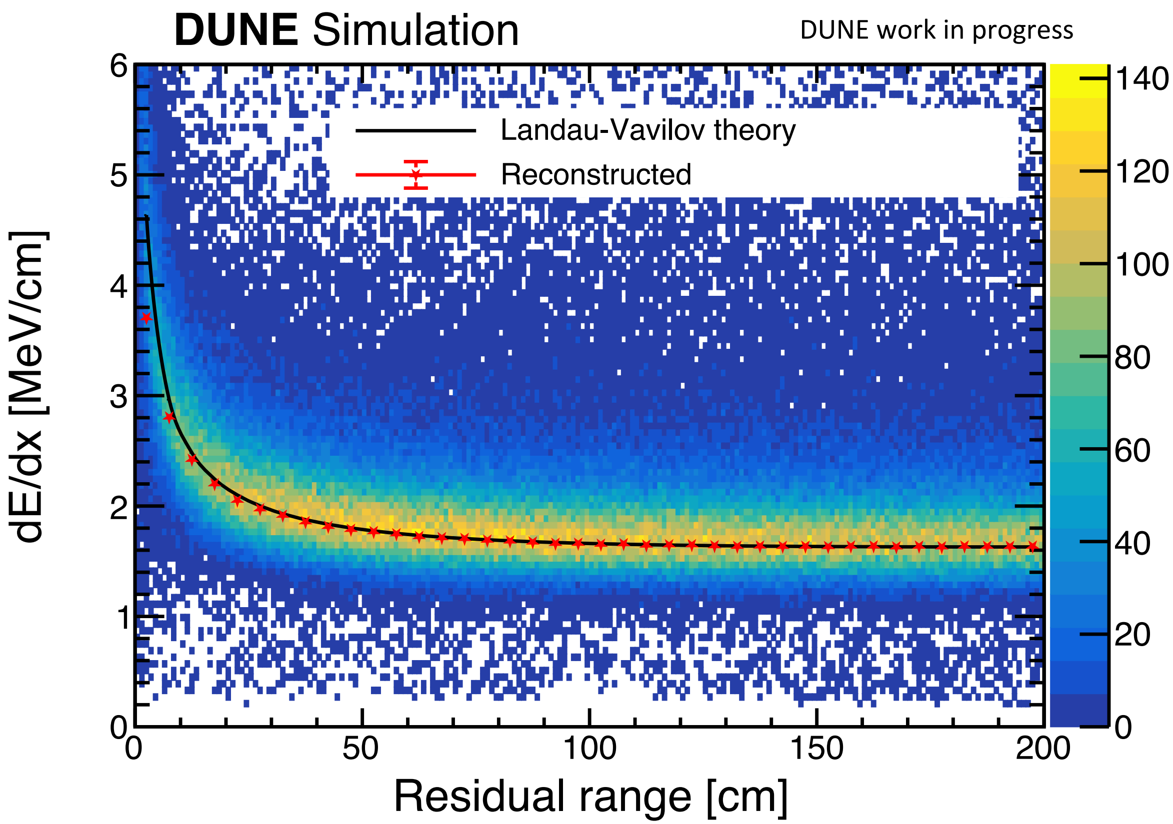
The track direction angles θ_{xz} and θ_{yz} defined in DUNE FD



Average dQ/dx distribution as a function of θ_{xz} and θ_{yz} in the collection plane. The colour scale represents the average dQ/dx for a track in each bin

Modified box model

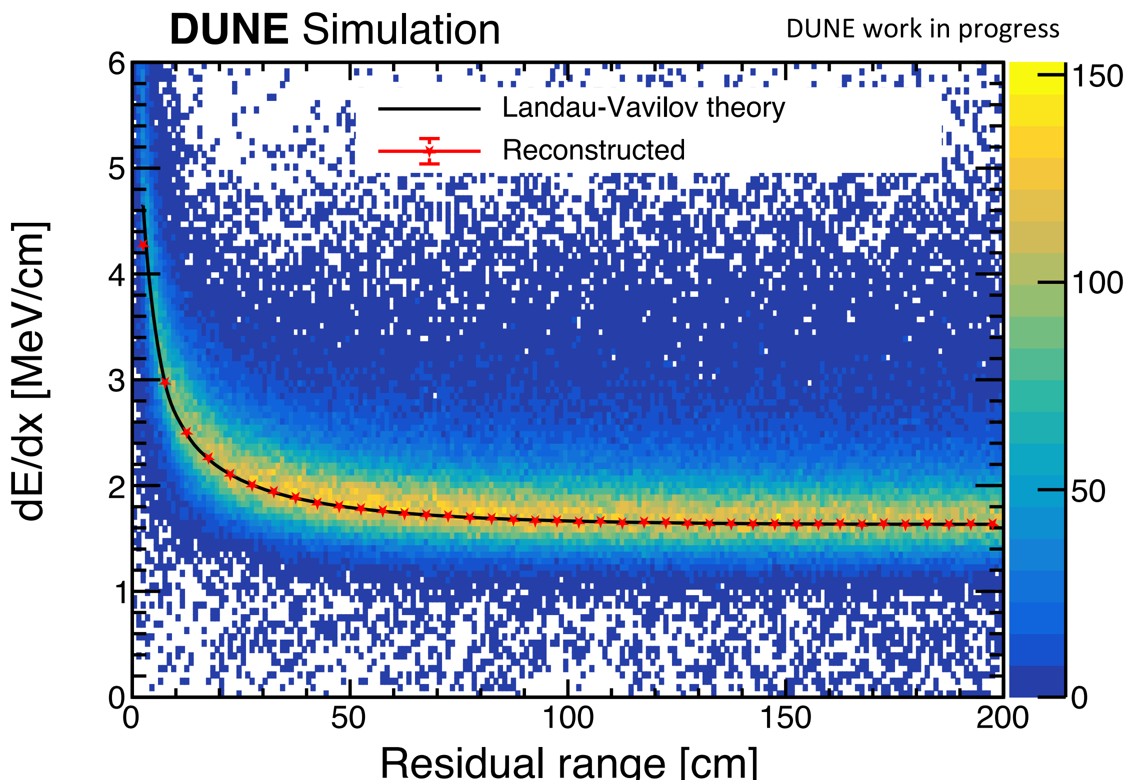
- dE/dx vs. residual range
- Stopping muons



C_{cal} = (5.469 ± 0.003) × 10^{-3} ADC × tick/e

Absolute energy scale

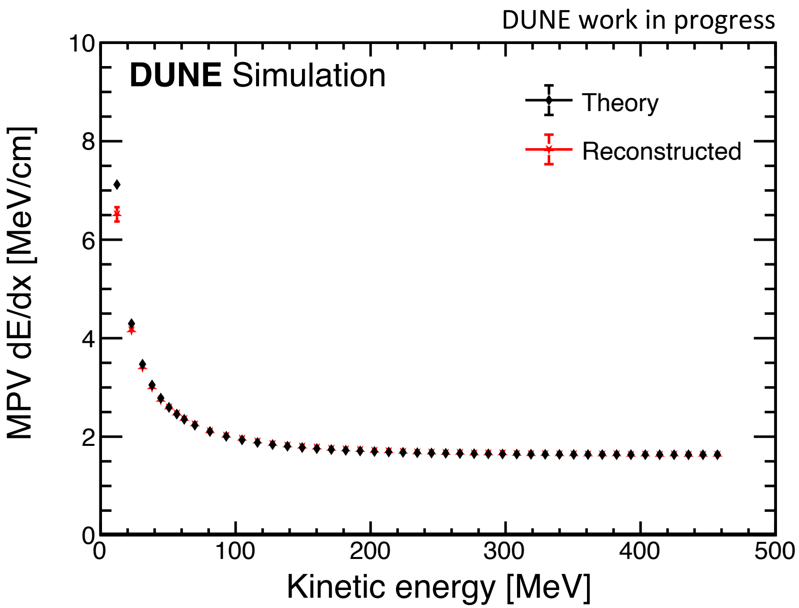
- dE/dx vs. residual range
- Stopping muons

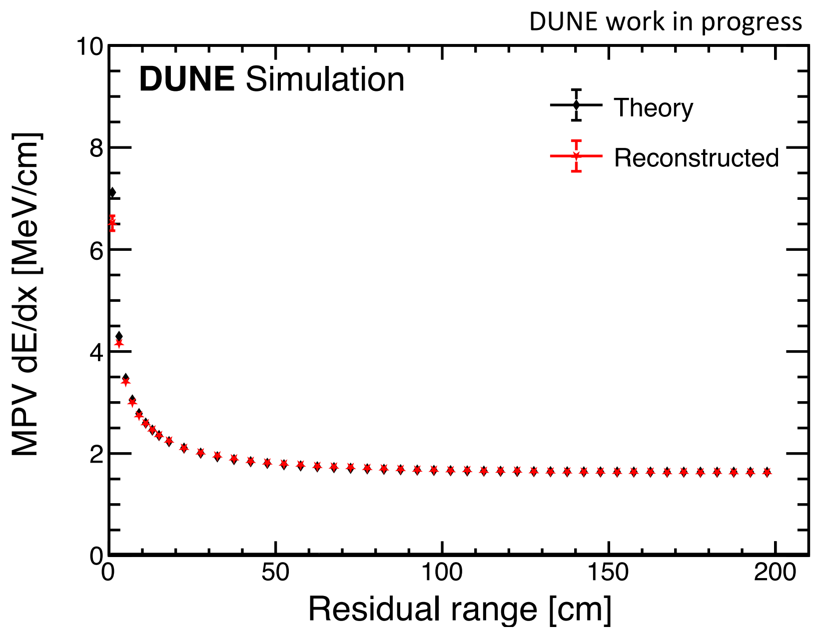


5 cm residual range bin

Absolute Energy Scale

- To improve the agreement between theory and reconstruction at low residual range, the variable bin size is considered for stopping muons
  - 2 cm bin for residual range 0 to 16 cm
  - 5 cm bin from residual range 20 to 200 cm
- Help to distinguish muon and pions

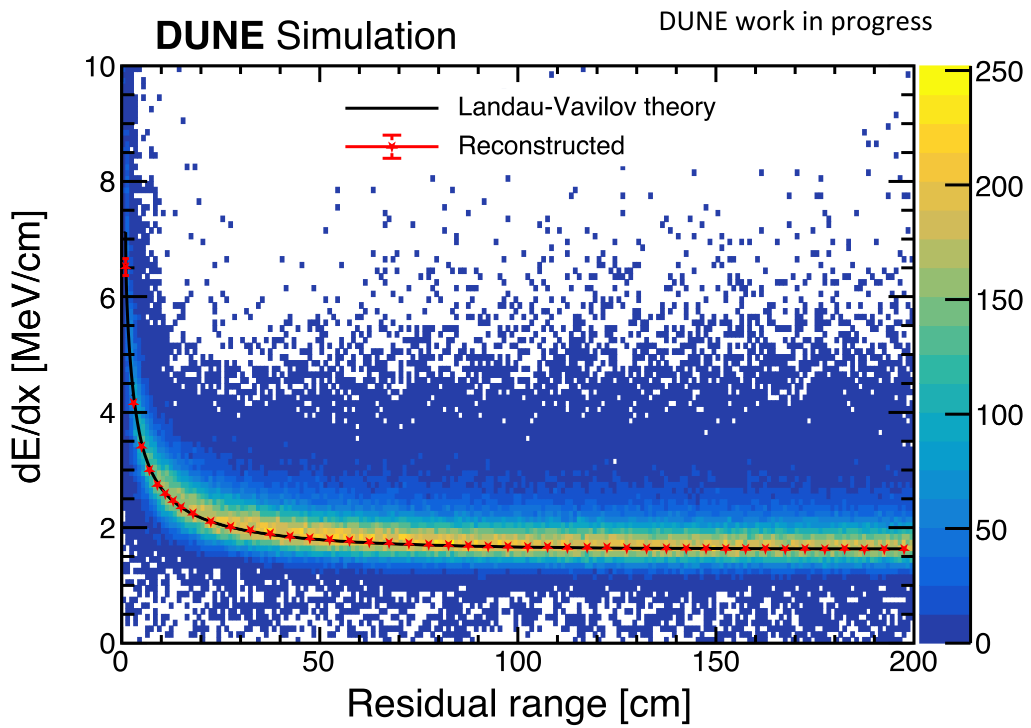




- ➢ Reconstructed dE/dx show good agreement with theoretical prediction even in the low kinetic energy and residual range
- ➢ Smaller range bin have low statistics and higher statistical uncertainty than bigger range bins

Absolute energy scale

- dE/dx vs. residual range
- Stopping muons



2 cm residual range bin from 0 to 16 cm
5 cm residual range bin from 20 to 200 cm

Reconstructed track angle vs. dQ/dx of stopping charged pions

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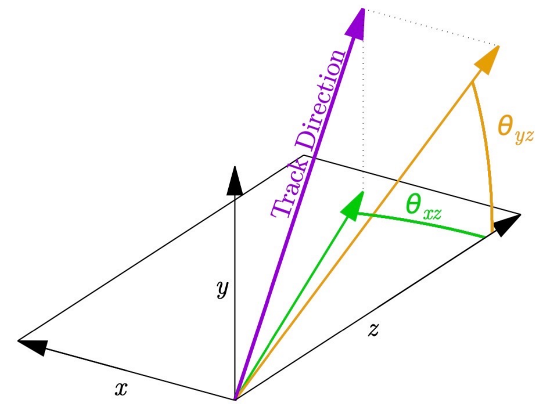
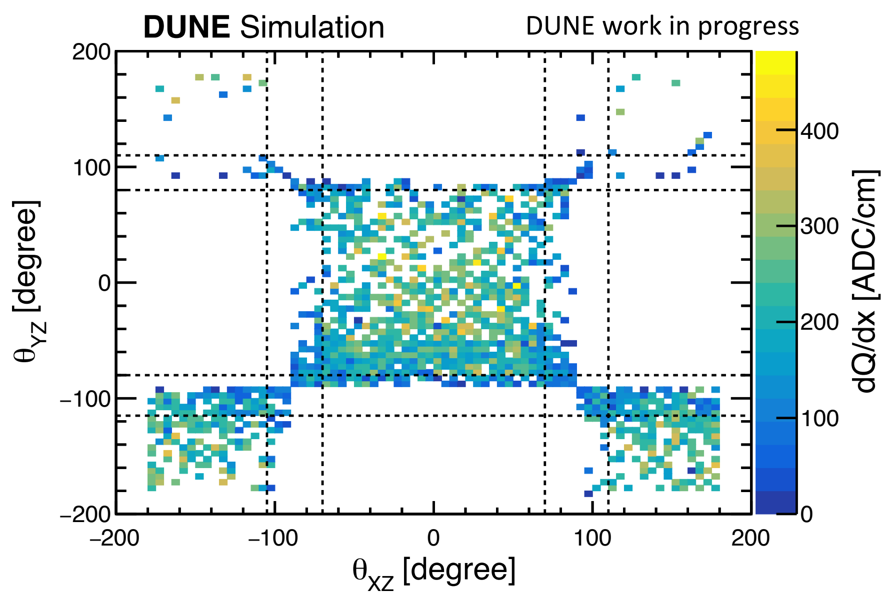
- To avoid geometrical effects, removed tracks with certain track angles:
  - $-105° < \theta_{xz} < -70°$ or $70° < \theta_{xz} < 110°$
  - $-115° < \theta_{yz} < -80°$ or $80° < \theta_{yz} < 110°$
- Removed broken tracks

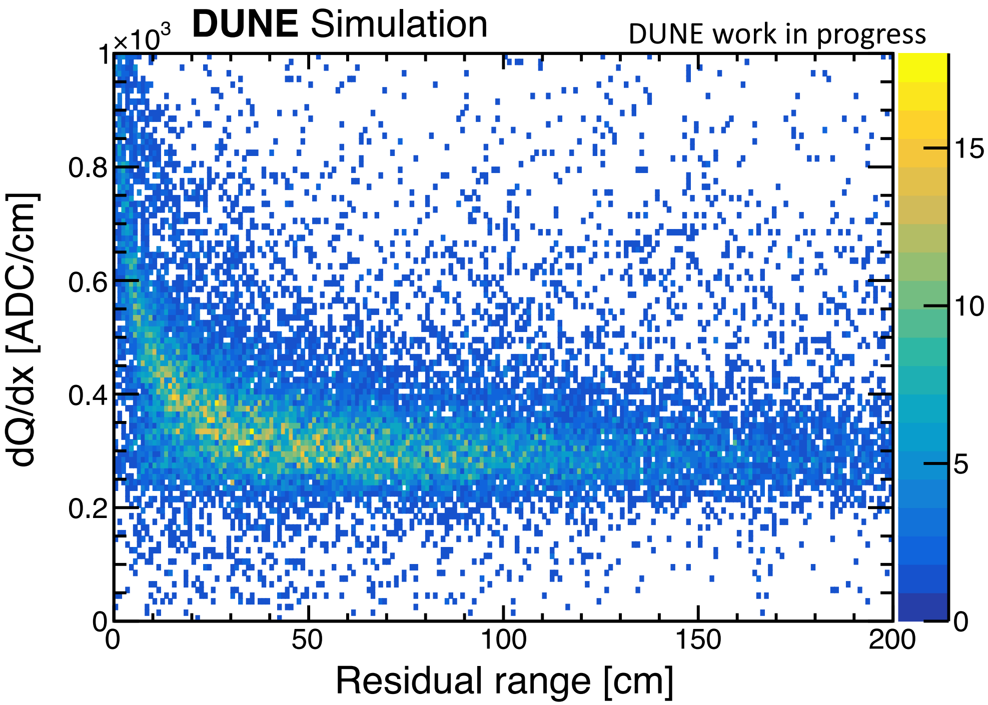


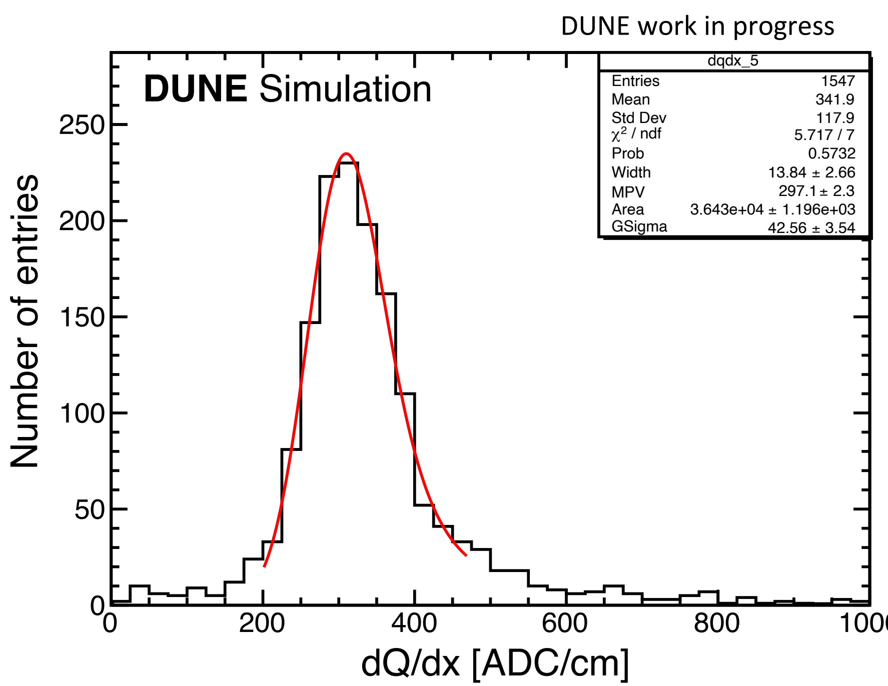
The track direction angles θ_{xz} and θ_{yz} defined in DUNE FD



Average dQ/dx distribution as a function of θ_{xz} and θ_{yz} in the collection plane. The colour scale represents the average dQ/dx for a track in each bin

Absolute energy scale (stopping charged pions)

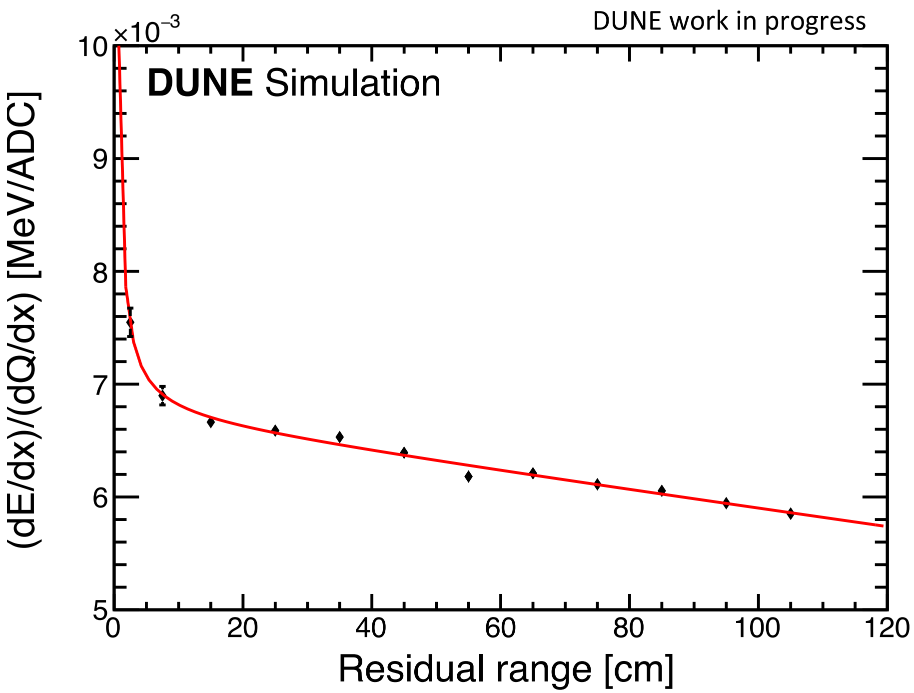




Reconstructed dQ/dx distribution fitted to a Landau function convolved with a Gaussian

Scaling dQ/dx to dE/dx

- Ratio $(dE/dx)_{theoretical}$ / $(dQ/dx)_{reconstructed}$ for each 5 cm bin of residual range is calculated
- The ratio vs. residual range is plotted and fitted with a function.



Fit function:

$$f(r) = p_0 + p_1 \times 1/r + p_2 \times r$$

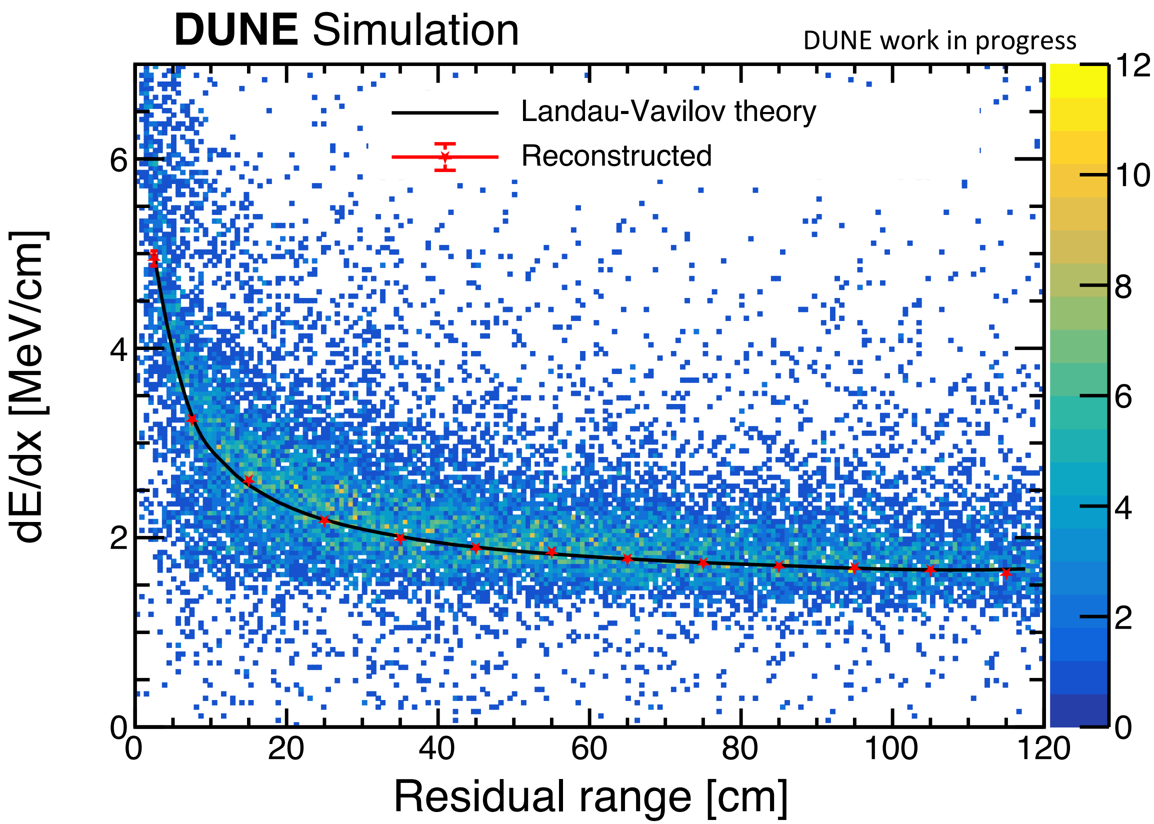
$$\frac{MPV(dE/dx)_{reconstructed}}{MPV(dQ/dx)_{reconstructed}} = p_0 + p_1 \times 1/r + p_2 \times r$$

r: residual range

p_0	p_1	p_2
$(6.683 \pm 0.042) \times 10^{-3}$	$(2.149 \pm 0.350) \times 10^{-3}$	$(-8.031 \pm 0.532) \times 10^{-6}$

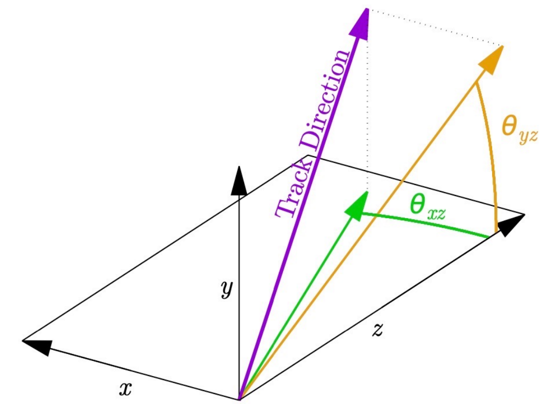
Absolute Energy Scale

- dE/dx vs. residual range
- Stopping charged pions

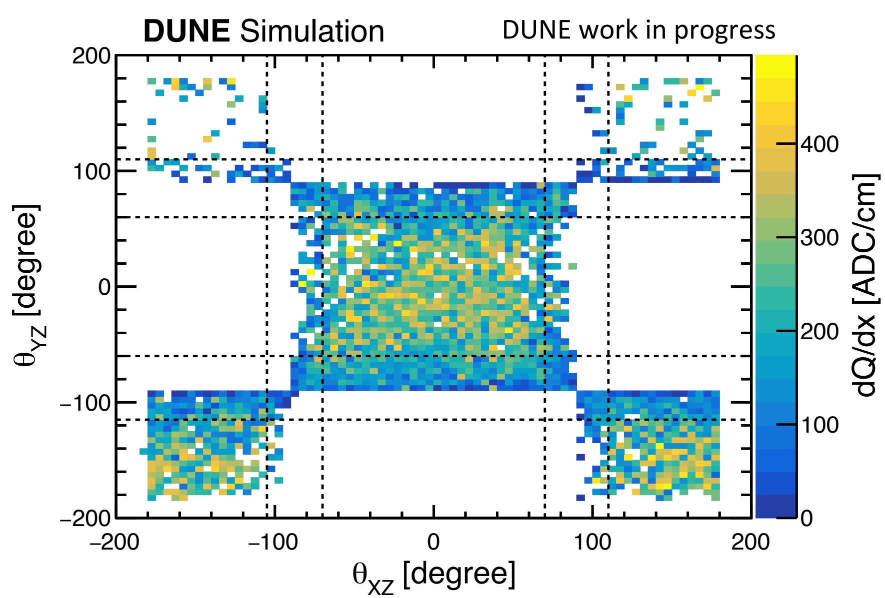


Reconstructed track angle vs. dQ/dx of stopping protons

- The reconstruction capability of a LArTPC is limited for tracks passing parallel to a wire or in the plane containing drift direction and a wire.
- For such tracks, all the charge from the incident particle gets deposited in a single wire thus leading to the poor reconstruction of the deposited charge.
- To avoid geometrical effects, removed tracks with certain track angles:
  - $-105° < \theta_{xz} < -70°$ or $70° < \theta_{xz} < 110°$
  - $-115° < \theta_{yz} < -60°$ or $60° < \theta_{yz} < 110°$
- Removed broken tracks

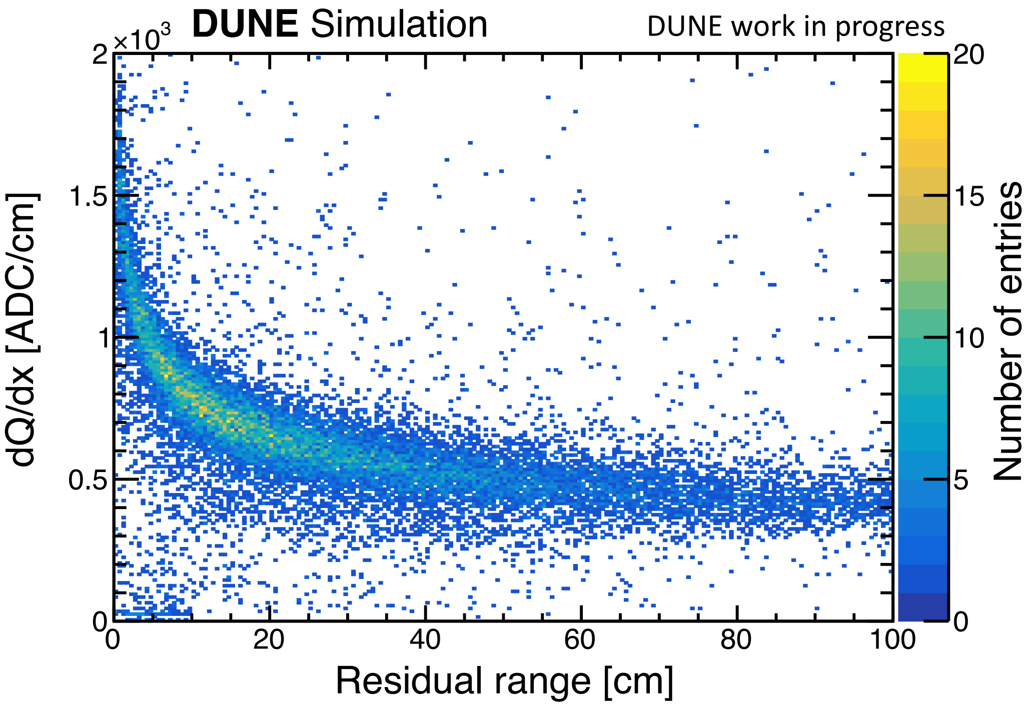


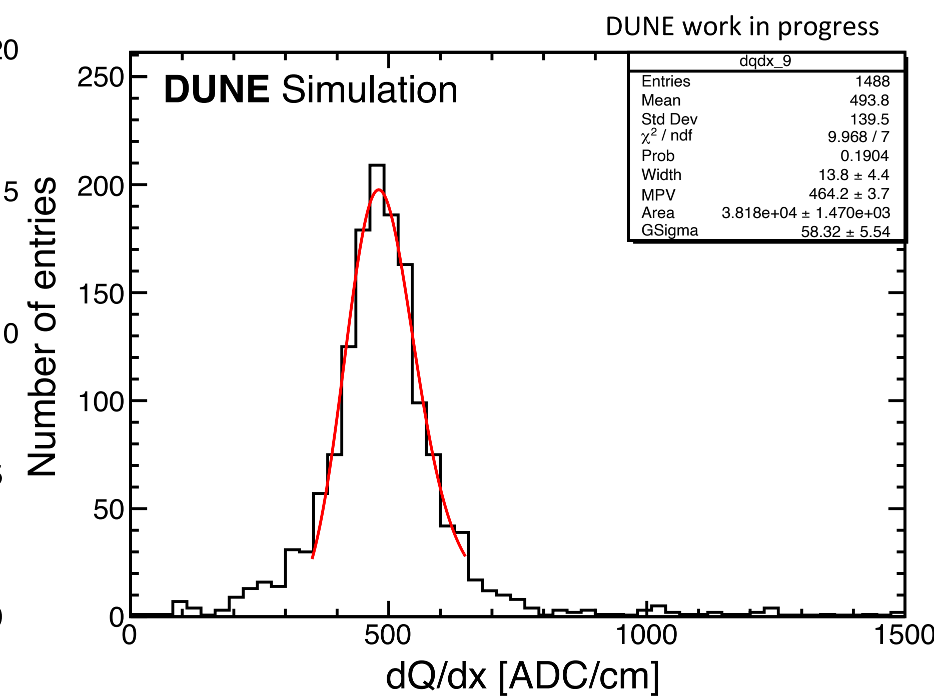
The track direction angles θ_{xz} and θ_{yz} defined in DUNE FD



Average dQ/dx distribution as a function of θ_{xz} and θ_{yz} in the collection plane. The colour scale represents the average dQ/dx for a track in each bin

Absolute energy scale (stopping protons)

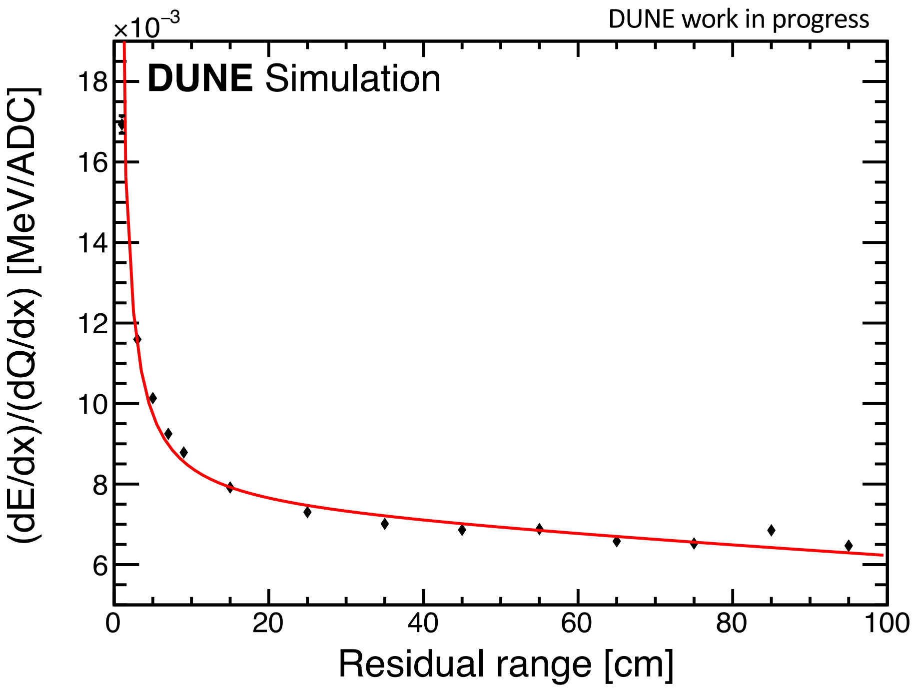




Reconstructed dQ/dx distribution fitted to a Landau function convolved with a Gaussian

Scaling dQ/dx to dE/dx

- Ratio $(dE/dx)_{theoretical}$ / $(dQ/dx)_{reconstructed}$ for each 5 cm bin of residual range is calculated
- The ratio vs. residual range is plotted and fitted with a function.



Fit function:

$$f(r) = p_0 + p_1 \times 1/r + p_2 \times r$$

$$\frac{MPV(dE/dx)_{reconstructed}}{MPV(dQ/dx)_{reconstructed}} = p_0 + p_1 \times 1/r + p_2 \times r$$

r: residual range

p_0	p_1	p_2
$(7.253 \pm 0.023) \times 10^{-3}$	$(1.262 \pm 0.018) \times 10^{-2}$	$(-1.152 \pm 0.041) \times 10^{-5}$

Absolute Energy Scale

- dE/dx vs. residual range
- Stopping protons