Cosmic Ray Muon Calibration

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DUNE UK Project Meeting
January 12th 2023

Overview

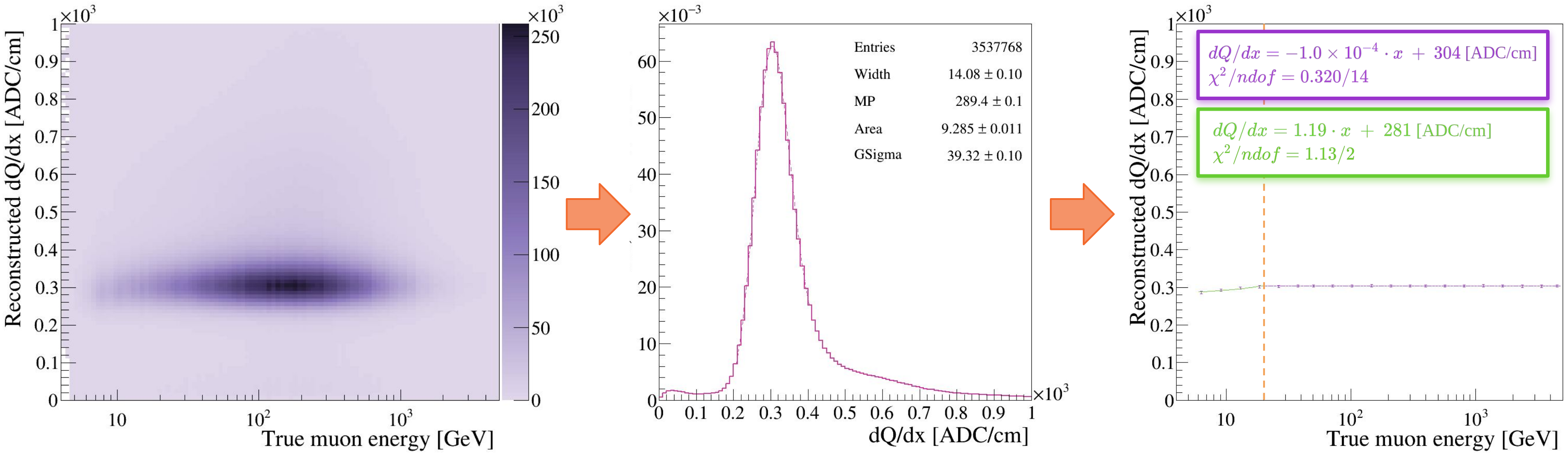
- Summary of progress since my last DUNE-UK update (January 2022)
- DUNE Far Detector calibration status, progress in the last 12 months
- Plans for the future of this work
- Calibration working group summary

Introduction

- We need to know the absolute energy scale of the DUNE FD precisely in order to achieve the required precision of all the DUNE physics goals
- I have been working on a simple method of extracting the absolute energy scale and addressing possible contributions to a reduction in the precision of this calculation with a 3 month sample of DUNE FD CR muons (~ 2M events)
- I have only implemented two systematic parameters into the calculation so far, but this contributes < 2% uncertainty when assessing a systematically-limited sample
- I am going to apply the procedure to ProtoDUNE simulations/data in order to fully understand any contributions to a reduction in this precision

Status as of January 2022

- The energy scale calibration method was largely in place
  - With a few now-fixed definitions like the slice errors & the method of fitting to dQ/dx vs E_μ
- Some sample tuning was tested but most of the work has now been superseded



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Highlights from the last 12 months

Since then,

- I have finalised the method of calculating the absolute energy scale at the DUNE FD
- Utilise the abundance of delta rays along the muon tracks to tune the sample and reduce the energy dependence observed below ~50 GeV
- Defined and calculated two systematic uncertainties to apply to the energy scale
  - The first accounts for a miscalculation of the electron lifetime
  - The second accounts for the remaining energy dependence of the measurement
- I am now testing this work on ProtoDUNE-SP simulations to validate the method and will eventually measure the energy scale using ProtoDUNE-SP (and hopefully HD) data

I will run through each of these briefly now

DUNE FD CR muon calibration

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DEEP UNDERGROUND NEUTRINO EXPERIMENT

Energy scale calibration in the wild

Energy reconstruction problem

- In the energy range spanned by the FD CR muons, the dQ/dx varies across the true energy space
- There will be little-to-no muon energy reconstruction in data
- I therefore have to use alternative reconstructable quantities to reduce the effect

Alternative methods of calculating the absolute energy scale

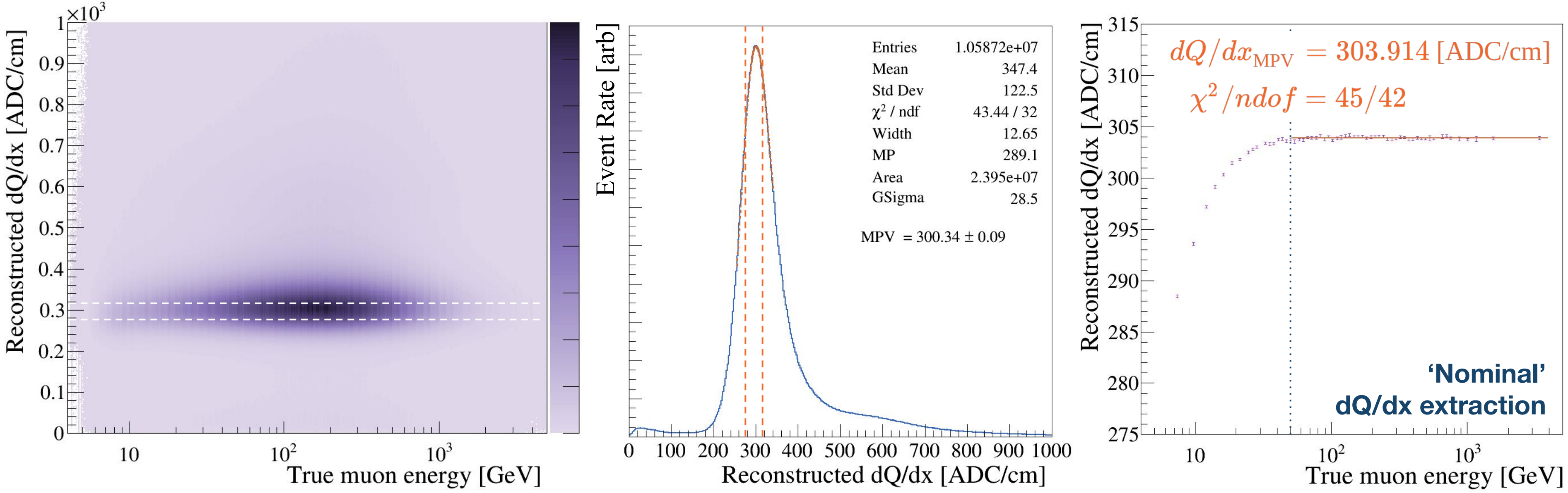
- Of course, there is an existing method of calculating this scale which is implemented in a similar way by ProtoDUNE & MicroBooNE

DUNE FD CR muons

- The rate of CR muons at the far detector will be **much** lower (~4000 through-going/day) than that of the surface detectors
- The muons will also be at much higher energies (~300 GeV)
- These features facilitate ROI studies and reduced energy-dependence at such high energies
- Can also define a more-simple approach to the energy scale calculation

DUNE FD absolute energy scale calibration

- Looking at through-going CR muons (selected using truth information)
- Correct the charge depositions according to the electron lifetime as calculated by Viktor (2.88 ms)



Dashed regions indicate zoom in RH plot

DUNE FD absolute energy scale calibration

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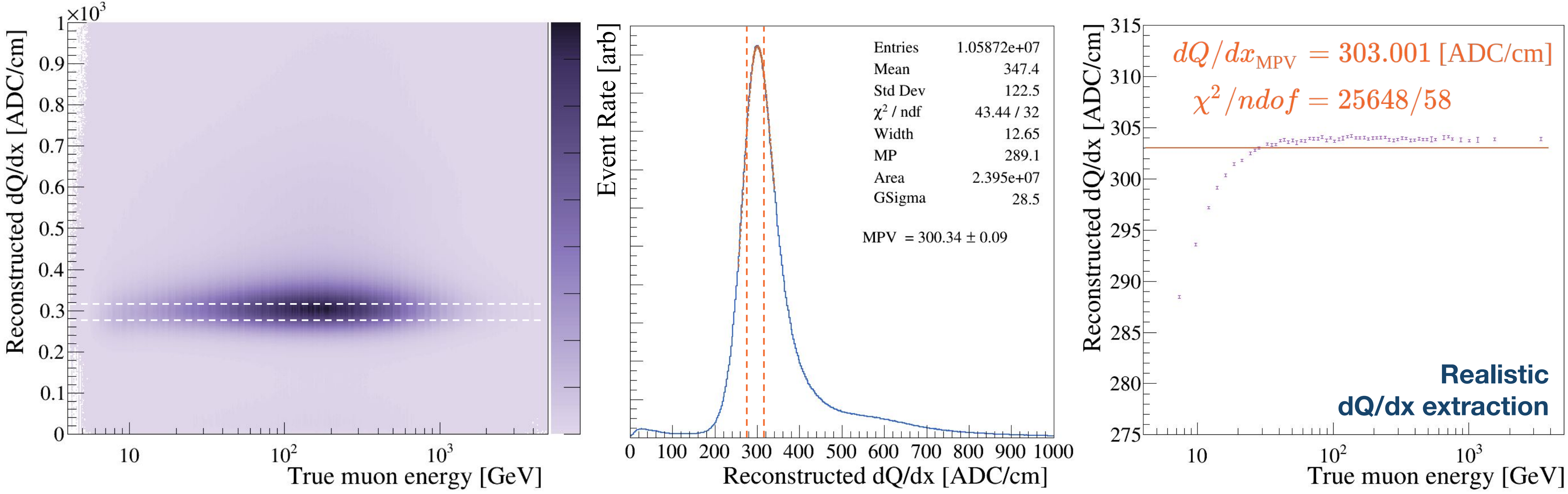
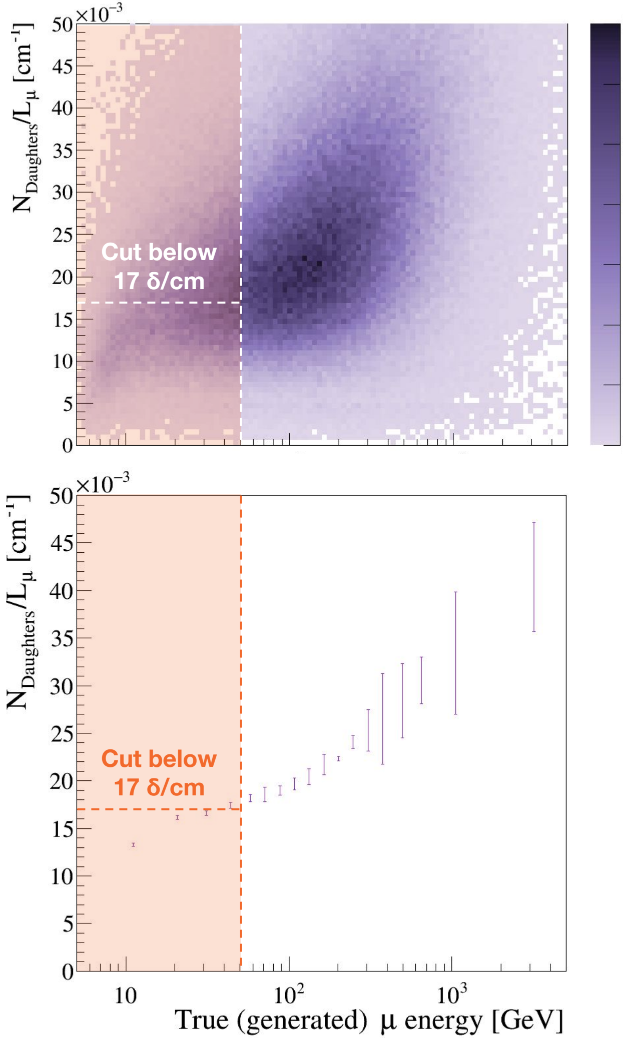


Dashed regions indicate zoom in RH plot

Sample tuning

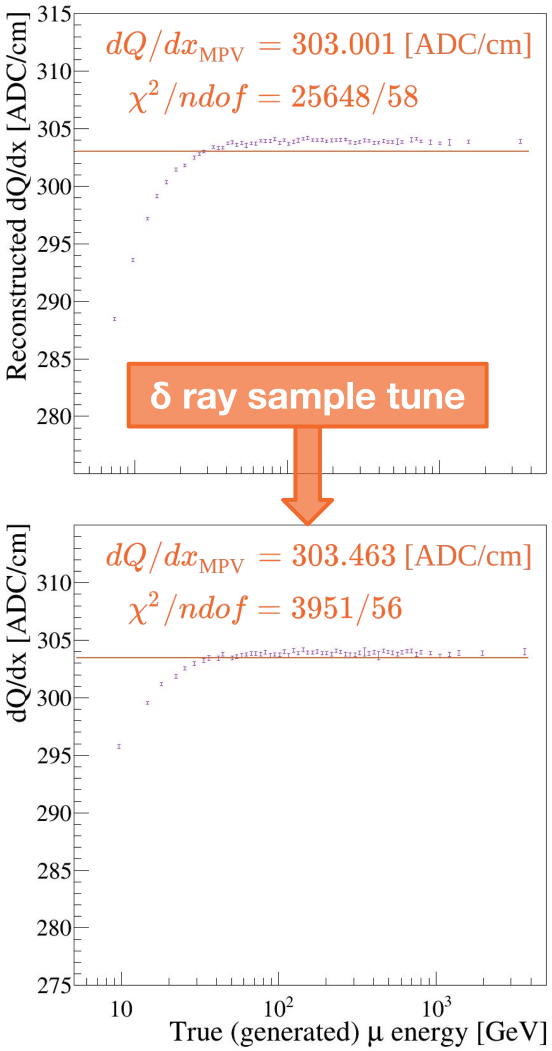
- Use the rate of δ-ray activity surrounding the CR muons to characterise the energy dependence of the charge depositions
- Cut muons with fewer than 17 δ/cm from the sample to mitigate some of the energy dependence below 50 GeV
  - This corresponds to a ~9% reduction in the sample statistics



Sample tuning

Nominal:
$dQ/dx_{\mathrm{MPV}} = 303.914$ [ADC/cm]

- Use the rate of δ-ray activity surrounding the CR muons to characterise the energy dependence of the charge depositions
- Cut muons with fewer than 17 δ/cm from the sample to mitigate some of the energy dependence below 50 GeV
  - This corresponds to a ~9% reduction in the sample statistics
- Recalculate the best-fit value of dQ/dx after cutting the sample to quantify the reduced energy dependence
- Define a systematic parameter which quantifies the effect and apply the residual variation as an uncertainty on the energy scale measurement



Systematic parameters

Focussing on two systematic parameters at the moment:

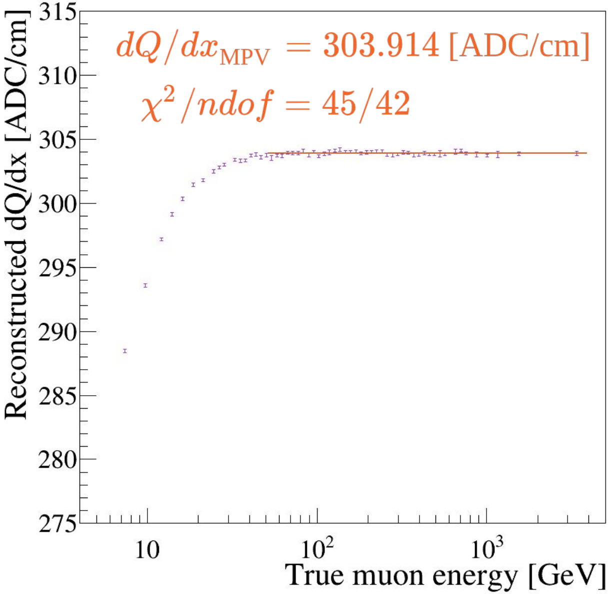
1. Systematic uncertainty due to the energy-dependence of the charge depositions (dQ/dx)
   Since we can't establish the true dependence in data, define a systematic and attempt to reduce it with selection cuts

2. Systematic uncertainty due to incorrect calculation of the electron lifetime
   We will of course measure the electron lifetime in data, but currently the input lifetime (3 ms) does not match what is calculated (2.88 ms) due to things like diffusion effects
   This systematic compares the dQ/dx correction with the simulated and calculated τ_e

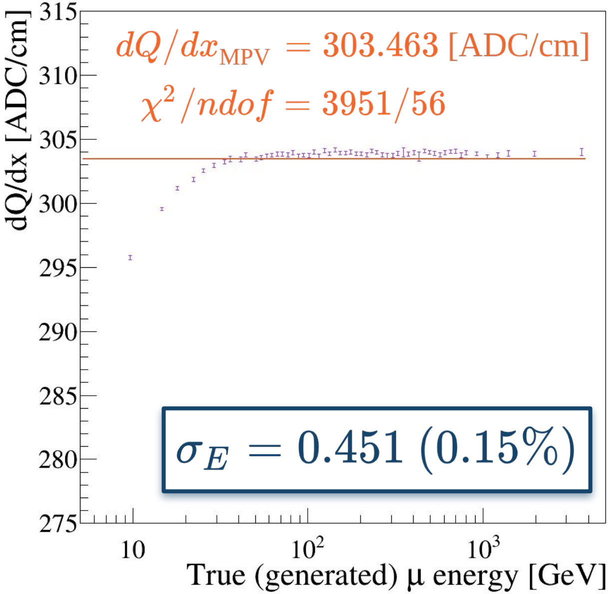
Systematics

$$\sigma_{E,\tau} = dQ/dx_{\text{Nominal}} - dQ/dx_{E,\tau}$$

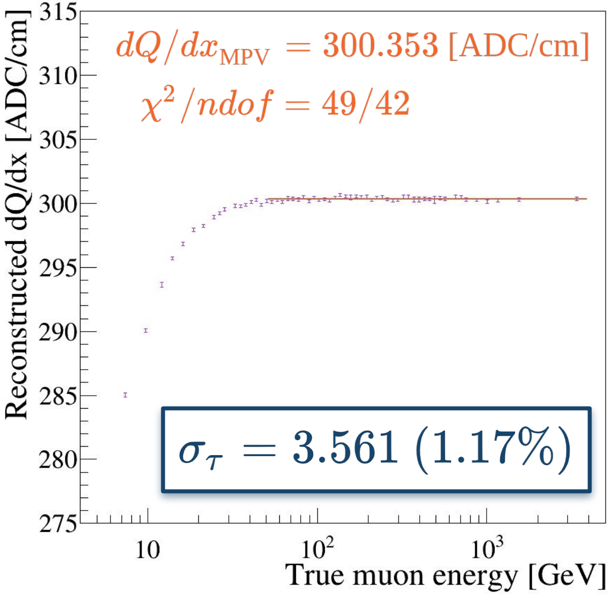
Nominal MPV



Tuned energy-dependence



Simulated lifetime correction



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Applying the method

The absolute energy-scale calculation on 'data' can be extremely simple owing to the lack of energy reconstruction

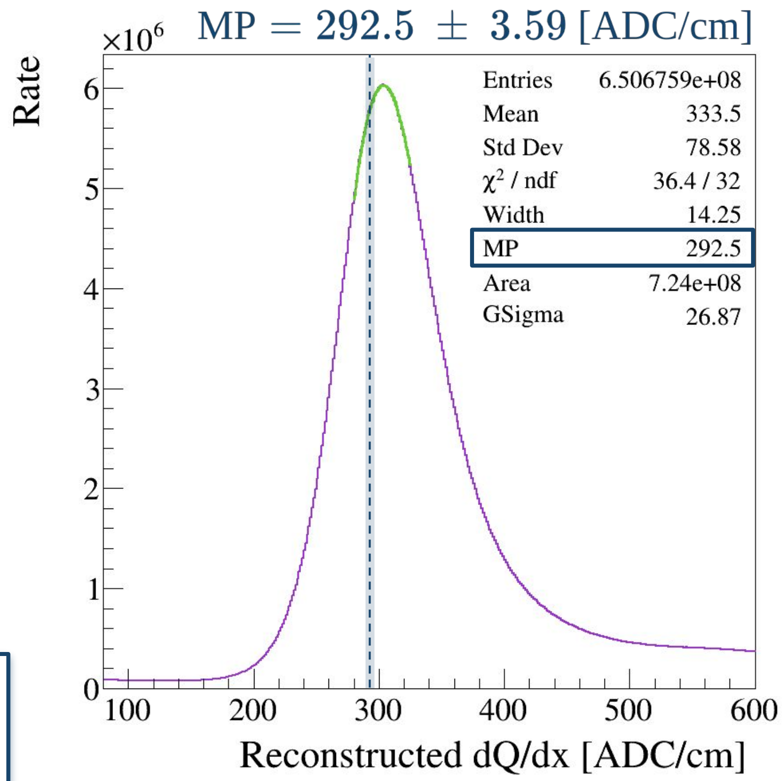
1. Plot the charge depositions for reconstructed CR muons
2. Extract the Landau MP value from a Landau x Gaussian fit to the 1D distribution
3. Calculate a scaling factor from the theoretical Landau-Vavilov MP for the expected energies in the distribution (determined using simulation at the truth level)

$$S = dE/dx_{MP} \, / \, dQ/dx_{MP}$$

4. Apply any uncertainties to the scale-factor
5. Scale the entire dQ/dx distribution to dE/dx

S = (6.16 ± 0.08) x10-3 [MeV/ADC] (stat+syst, 1.23%)

$dE/dx_{L\text{-}V}$ = 1.804 MeV/cm (μ: 292 GeV @ 5.3 mm thickness)

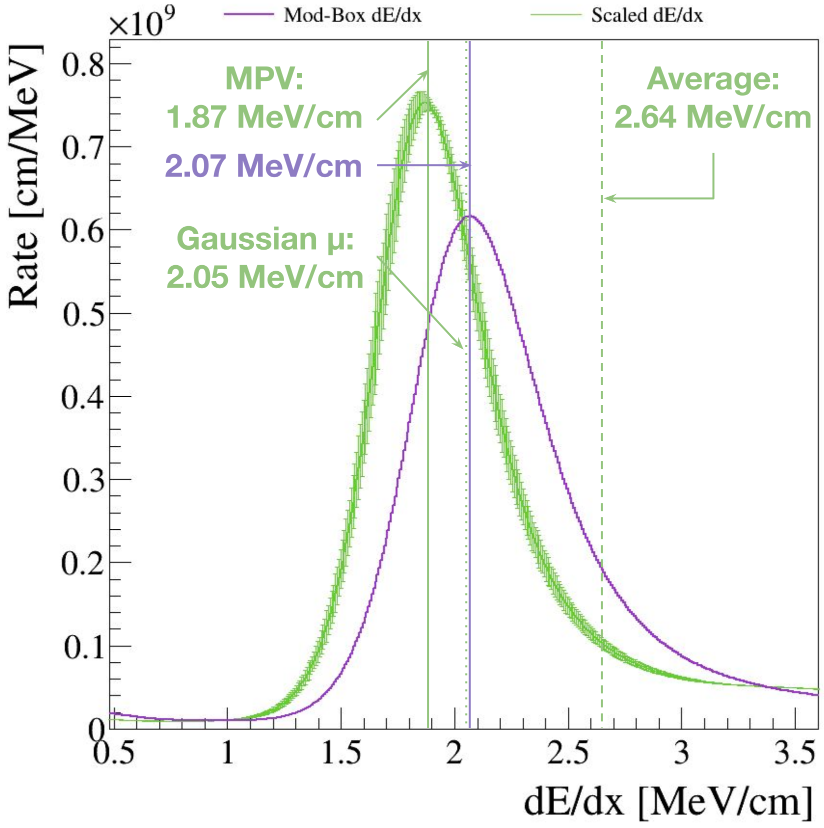


Reconstructed dE/dx

For comparison:

This is how the dE/dx calculated using the un-tuned Modified-Box model applied to the through-going muon charge depositions, with input parameters from ArgoNeuT, compares with dE/dx calculated from the absolute energy scale.

The uncertainties were applied by throwing 2000 toys within the 1σ scale-factor uncertainty and extracting the 1σ dE/dx uncertainty from that.



Current work and future plans

- Successfully completed all the calibration milestones to date!
- The next step is to utilise ProtoDUNE data to test the energy scale procedure
- This is in progress at the moment, starting with simulation-based testing
    - It's still all very preliminary so I haven't included it this time, see the backup

M/D	Milestone or deliverable	Date	Status
M1.4-1	dQ/dx calibration (electron lifetime)	10/20	Done
M1.4-2	dQ/dx calibration (absolute energy scale)	12/21	Done
M1.4-3	Demonstrations with simulated cosmics in DUNE FD	04/22	Done
D1.4-1	Demonstrations with ProtoDUNE data	10/22	In progress

Calibration WG update

I have been co-convener with Mike Mooney since June 2022

- We are starting to liaise between various working groups and consortia to understand the scope and status of the calibration task across the experiment
  - Update the set of requirements for detector uncertainties in each specific analysis
  - What can we use and/or learn from ProtoDUNE?
  - What intersections are there between software and hardware calibration techniques?
  - What are the required timescales and frequencies of each calibration measurement?
- So far we have had joint sessions at recent collaboration meetings with
  - ProtoDUNE DRA & Computing - September 2022
  - CALCI - January 2023
- Will extend this communication to specific analysis groups & other consortia

Calibration WG update

*Part of the UK effort

- There are many areas already being actively contributed to
  - Absolute energy scale*
  - Electron lifetime*
  - Diffusion
  - Recombination
  - Vertical drift
  - π^0 energy calibration*
  - Calibrations with δ-rays & Michel electrons
  - …

Summary

- It's an exciting time to be working on calibration
- We have lots going on, but there is still more work to do
- If you or your students are interested, this is a group with a great amount of opportunities to take a visible role in the collaboration while learning about practical detector operations, this is a great opportunity
  - Contact me, or whoever you like in the collaboration group
- Thanks for listening to how we're helping maximise DUNE physics potential!

Backup

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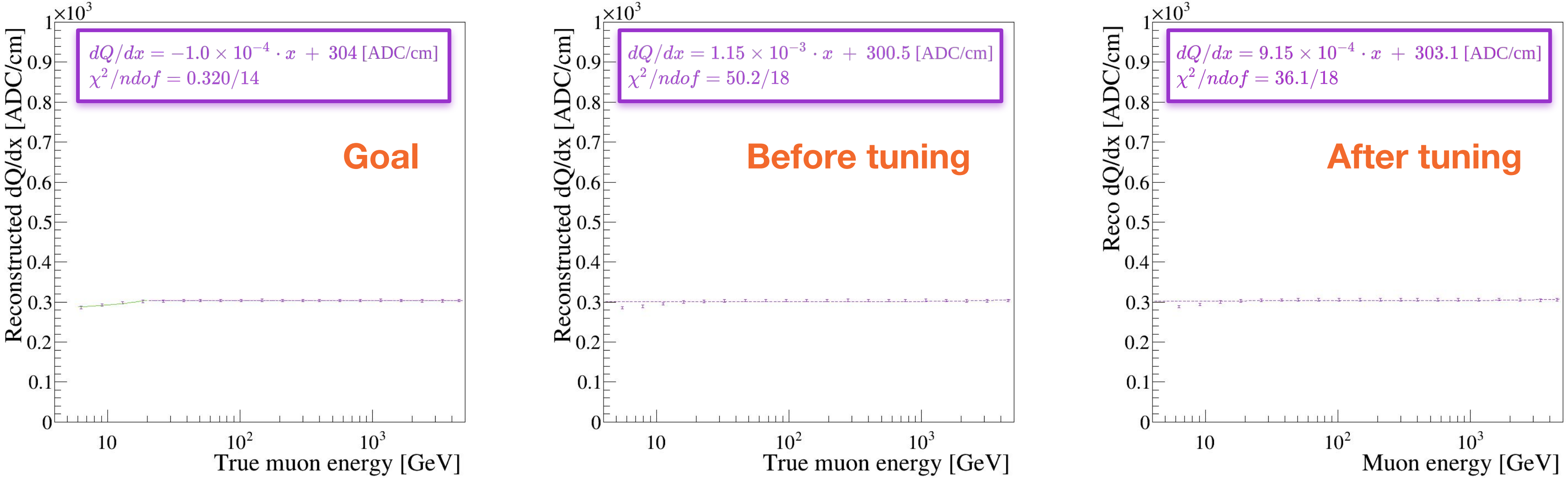
DEEP UNDERGROUND NEUTRINO EXPERIMENT

Status as of January 2022

- The energy scale calibration method was largely in place
  - With a few now-fixed definitions like the slice errors & the method of fitting to dQ/dx vs E_{μ}
- I was tuning the sample with $\cos\theta_{Drift}$ to mitigate the energy dependence of the energy scale
  - The $\cos\theta_{Drift}$ cut resulted in an 8% statistical reduction



Calibration procedure for systematics

Use truth information to determining the expected size of energy-dependent systematic uncertainties on the energy-scale calculation

1. Look at the reconstructed dQ/dx vs true energy distributions of through-going muons
2. Slice the 2D parameter space in energy and fit a Landau$\times$Gaussian function to each slice
3. Extract the MPV from each slice & calculate the corresponding uncertainty
4. Look at the reconstructed dQ/dx MPV’s vs true energy distributions
5. Extract the MP dQ/dx according to the energy dependence
6. Perform systematic study to quantify the uncertainty on the absolute energy scale
7. Repeat with sample tuning to try and mitigate true energy-dependence
8. Convert to dE/dx according to the expectation of through-going muon track behaviour

Reconstructed statistics

Statistic	Rate / 140.5 Days	% $\mu > 2$ m
Events	1,967,224	-
Tracks	10,248,425	1605.7 %
Muons	9,684,297	1517.3 %
$\mu > 2$ m	638,270	100 %
Crosses top or bottom	614,439	96.266 %
Crosses top and bottom	348,552	54.609 %
Crosses ≥ 1 APA/CPA	428,462	67.129 %
Crosses ≥ 2 APA/CPA	115,498	18.095 %
Stopping	23,139	3.6253 %
Exiting	600,698	94.113 %

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'Long' muons, along with checking if Pandora defines the track as primary, will be used to select muons without using truth information (association to the true primary muon).

Removes reconstructed δ-rays.

Higher rate of reconstructed than true stopping muons (1.8%) indicative of some remaining tracks being split, substantially better than **11%** in the **ν chain**.

The rate of AC-crossing muons might be sufficient for use in similar calibration procedures to surface LAr experiments.

Exiting tracks are our most-abundant source for CR muon calibrations.

(Small) sample comparisons

I have generated the same table using a small (1 day) subset of each sample

Statistic	Rate / 1.063 Days		
	ν chain v08_50	CR chain v09_10	CR chain v09_41
Events	5000	5000	5000
Tracks	3189	23,942	27,606
Muons	3118	23,524	25,638
$\mu > 3$ m	1755	1574	1628
Crosses top or bottom	2048	8747	9526
Crosses top and bottom	790	904	937
Crosses ≥ 1 APA/CPA	1306	3568	4001
Crosses ≥ 2 APA/CPA	159	277	320
Stopping	101	30	28
Exiting	582	944	938

(Small) sample comparisons

This highlights why we are exclusively using CR-reconstruction in the muon calibration work.

same table using a

As expected, there is not a substantial change between CR-reconstruction versions but some of the neutrino vs CR reconstruction variations (and similarities) are made apparent.

	ν chain v08_50	CR chain v09_10	CR chain v09_41
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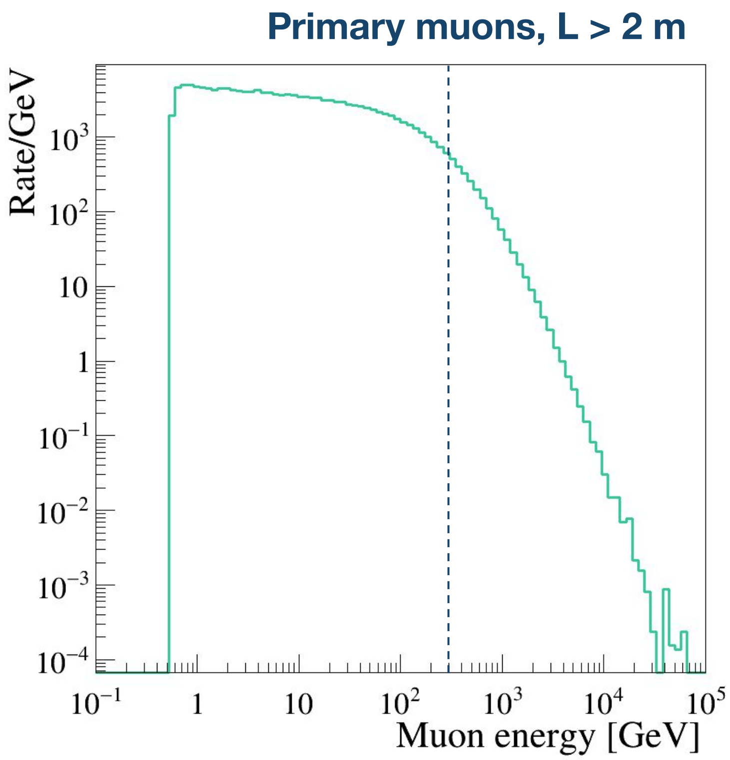
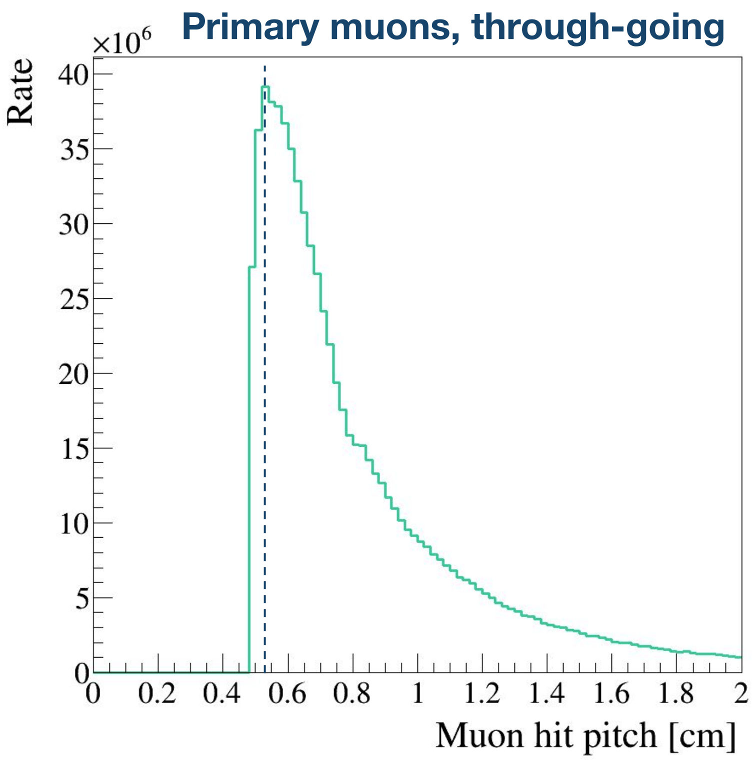
Average energy, peak pitch





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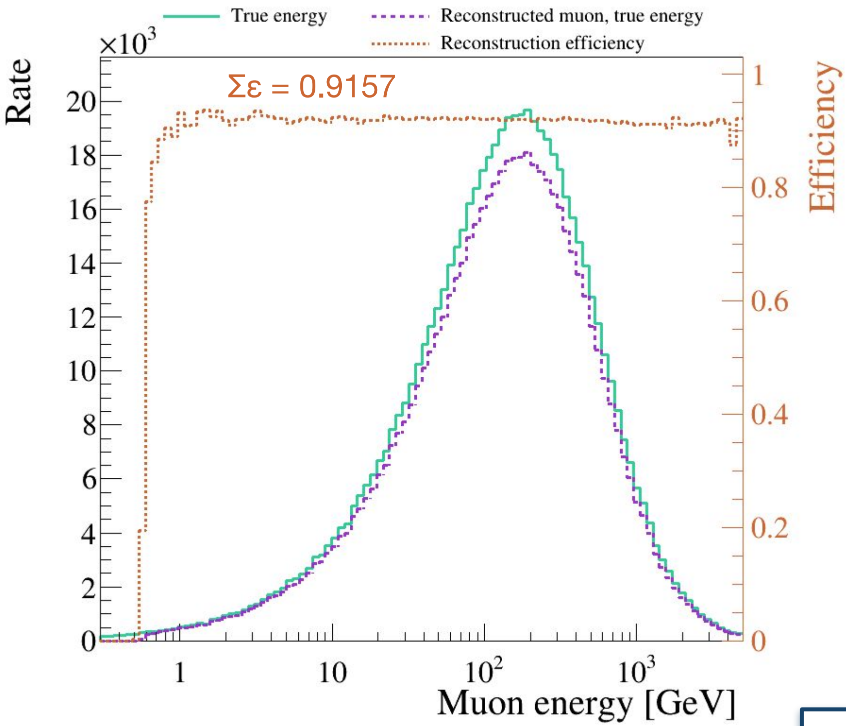
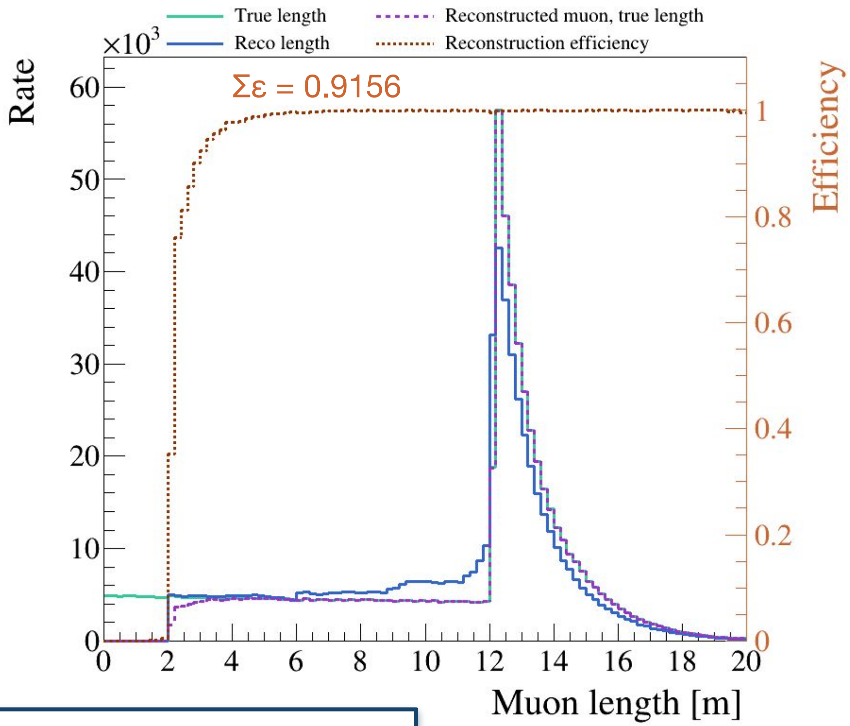
Reconstruction efficiencies

Integrated efficiency: 91.6%

$$\varepsilon = \frac{N_{True,\,Reconstructed}}{N_{True}}$$





NO δ-cut applied in the assessment of the track reconstruction

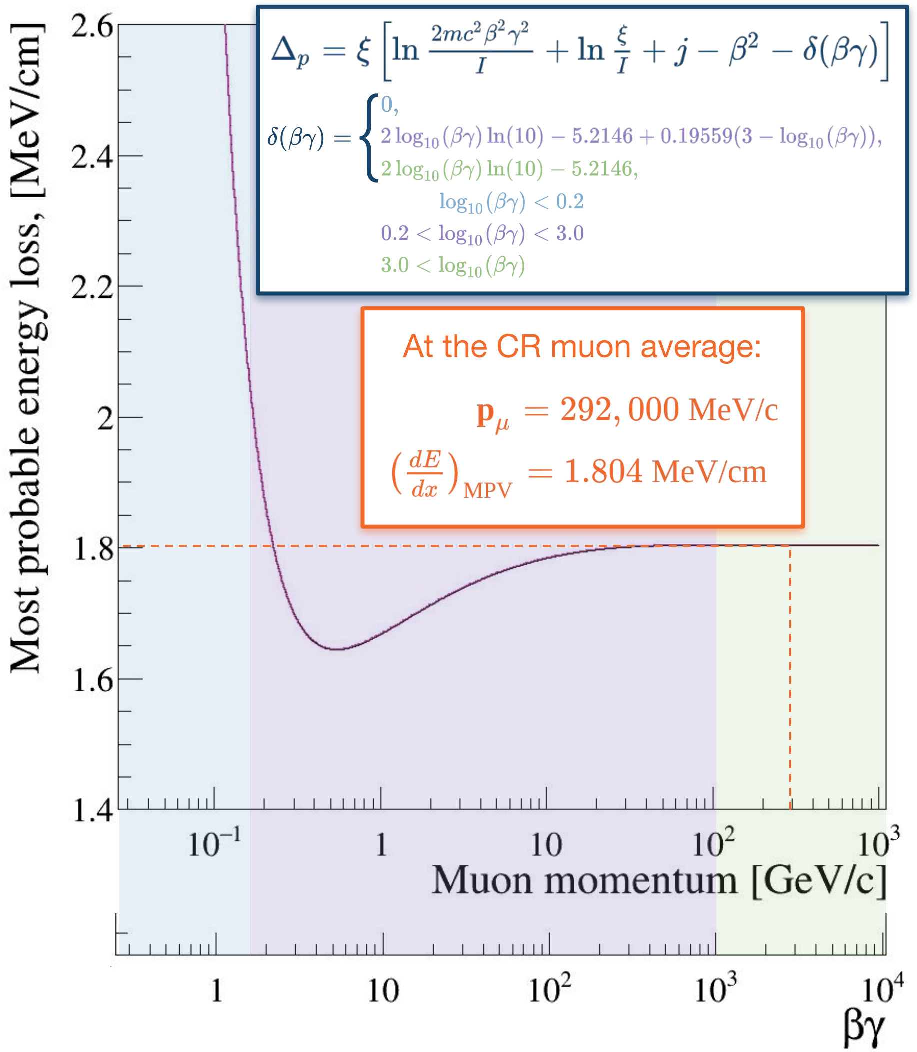
Landau-Vavilov

The Landau-Vavilov formula dictates the expected behaviour of **muon energy depositions per unit length** with respect to its **energy** and **'thickness'** (density*pitch).

It should be possible to use this formula in the calibration of the energy scale of our detector.

This could either be defined in an energy-dependent or independent way.

Though energy-dependent is very difficult due to the previously-discussed reconstruction complications with through-going muons.

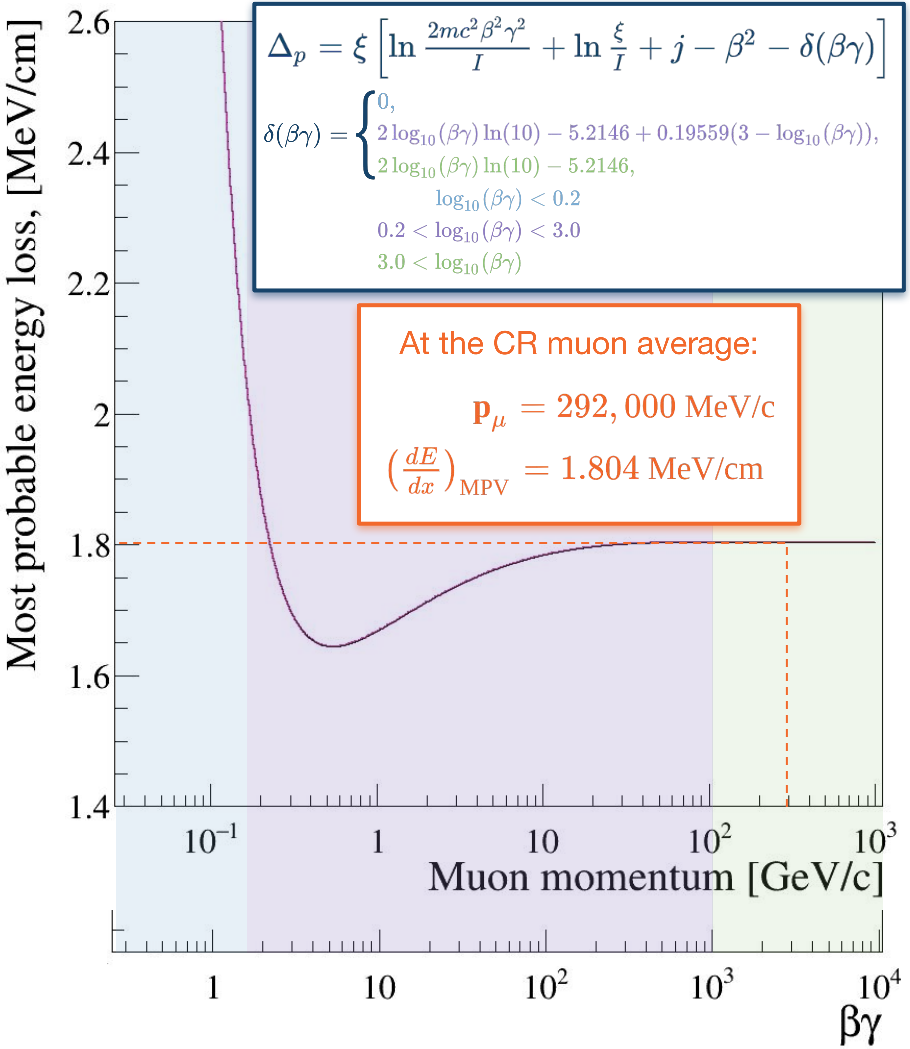


Landau-Vavilov

Param.	Value	Comment
m	0.511 MeV/c^2	Electron mass
I	188x10^{-6} MeV	Mean excitation energy
j	0.2	Value from here
δ(βγ)	See RHS of slide, based on Sternheimer	Density effect coefficient
β	v/c	Relativistic beta
γ	p/m$_\mu$	Relativistic gamma
ξ	(k/2)*(Z/A)*(x/β^2) MeV	-
k	0.307075	4π N_A r_e m MeV cm / mol
x	(ρ*dp) kg/cm^2	Thickness (density * pitch)
Peak values used to construct plot on RHS		
dp	0.53 cm	**Peak** pitch in CR muon sample

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

$$\delta(\beta\gamma) = \begin{cases} 0, & \log_{10}(\beta\gamma) < 0.2 \\ 2\log_{10}(\beta\gamma)\ln(10) - 5.2146 + 0.19559(3-\log_{10}(\beta\gamma)), & 0.2 < \log_{10}(\beta\gamma) < 3.0 \\ 2\log_{10}(\beta\gamma)\ln(10) - 5.2146, & 3.0 < \log_{10}(\beta\gamma) \end{cases}$$



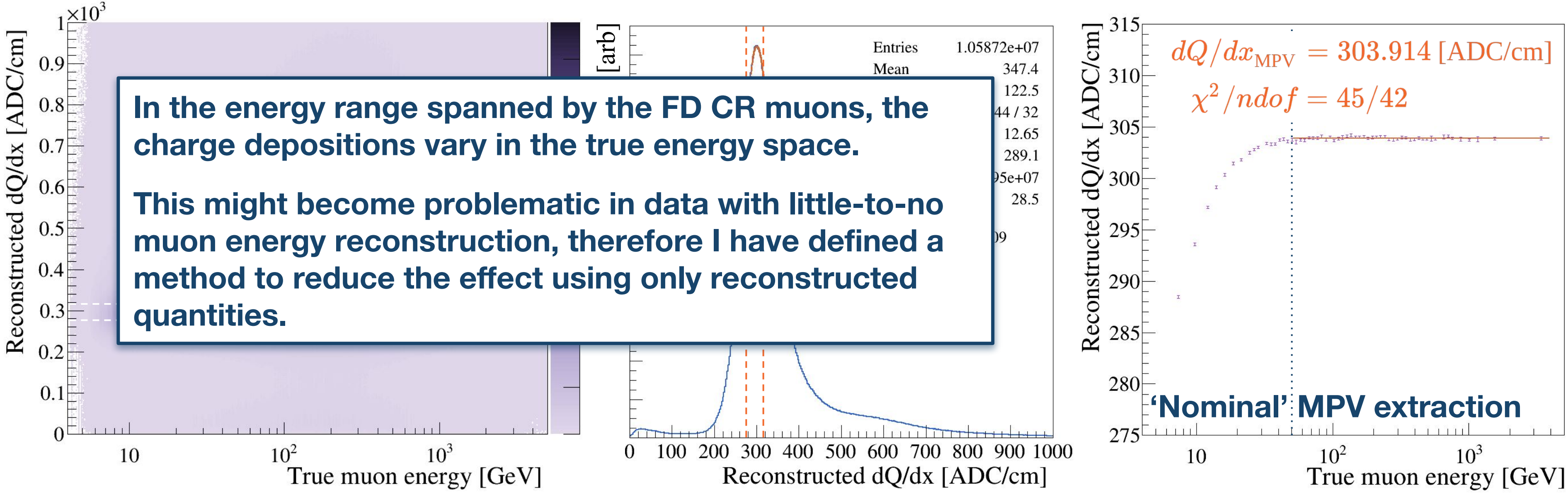
At the CR muon average:

$$\mathbf{p}_\mu = 292,000 \text{ MeV/c}$$

$$\left(\frac{dE}{dx}\right)_{\text{MPV}} = 1.804 \text{ MeV/cm}$$

DUNE FD absolute energy scale calibration

- Looking at through-going CR muons (selected using truth information)
- Correct the charge depositions according to the electron lifetime as calculated by Viktor (2.88 ms)



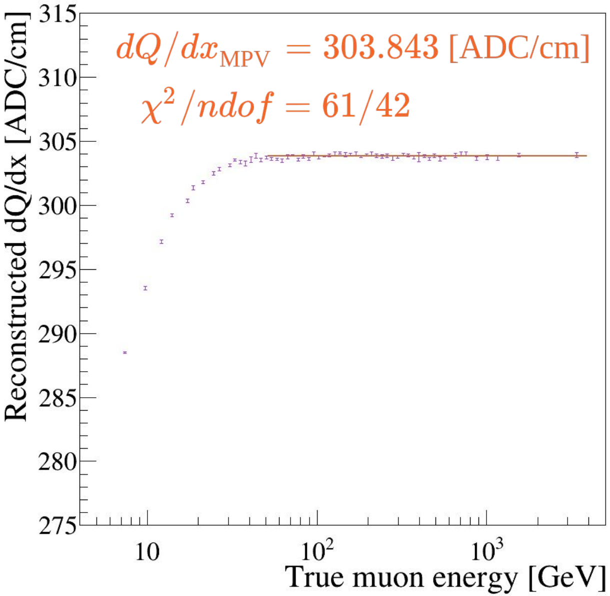
In the energy range spanned by the FD CR muons, the charge depositions vary in the true energy space.

This might become problematic in data with little-to-no muon energy reconstruction, therefore I have defined a method to reduce the effect using only reconstructed quantities.

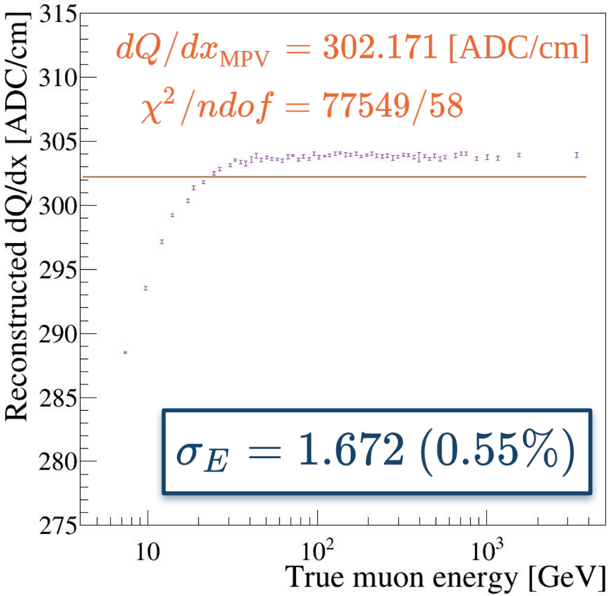
Dashed regions indicate zoom in RH plot

Systematics ~1M events

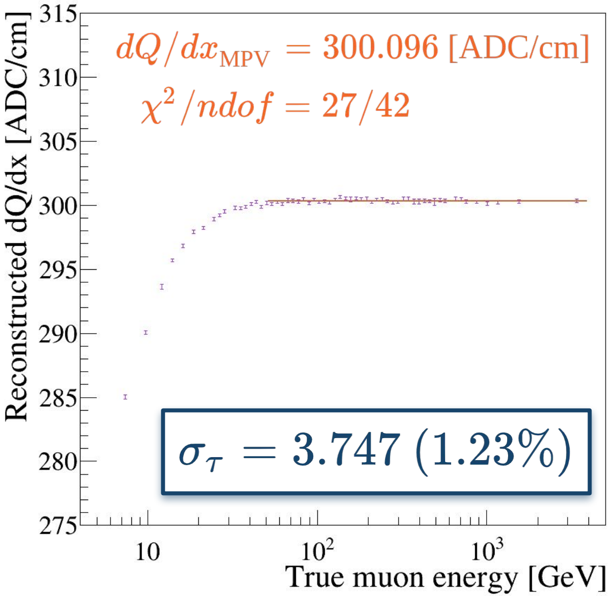
Nominal MPV



Energy-dependent MPV

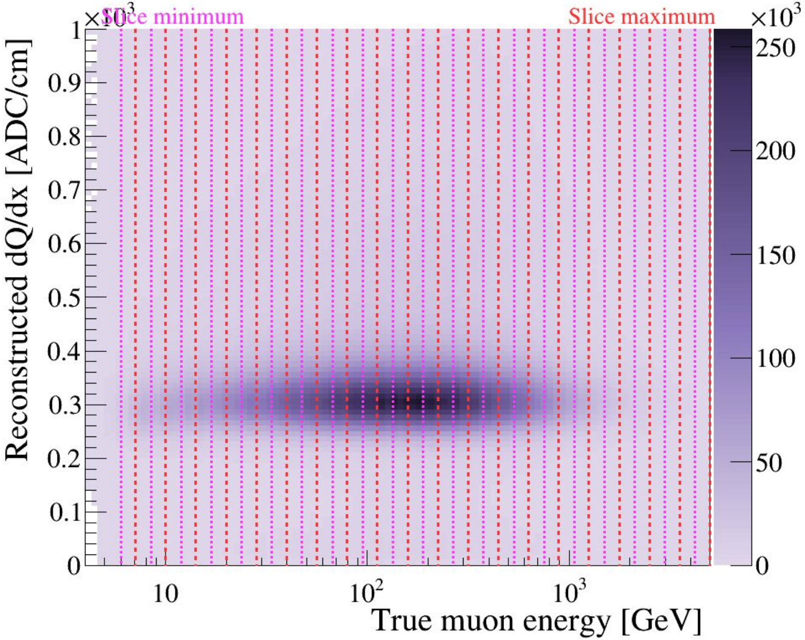


No lifetime correction MPV

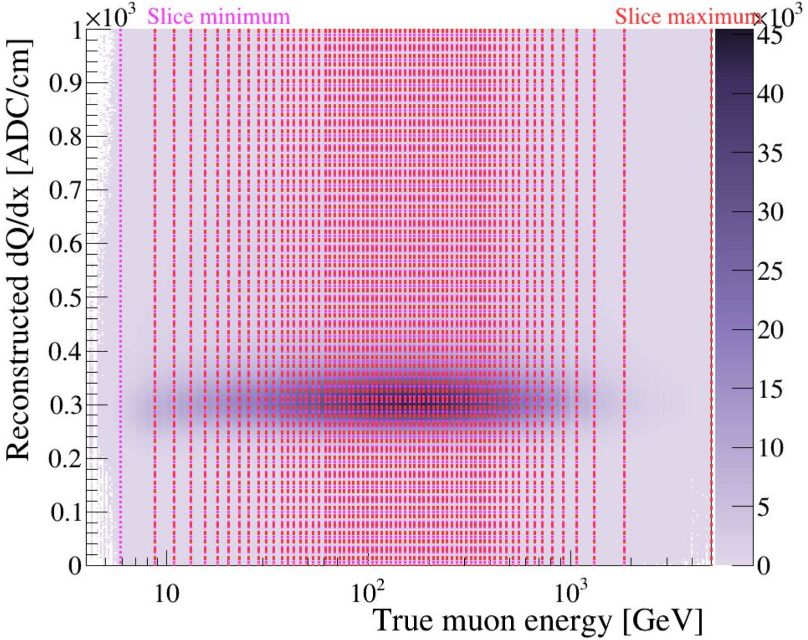


Updated slicing definition

Previously: 100 bins, 20 slices 2.5% wide evenly spaced



Now: 400 bins, 100 slices distributed approximately by rate



MPV slice uncertainty definition

- I define the MPV as a function using Landau MP and Gσ from the fit:

$$MPV = MP + \lambda \cdot G\sigma$$

- MPV is given by simply finding the maximum of the fit in each slice, and is located between MP < MPV < MP+Gσ
- It is therefore possible to calculate λ from the known MPV, MP and Gσ values
- MPV uncertainty can then be extracted using a standard differential analysis:

f = MPV
a = MP
b = Gσ

$$\sigma_f^2 = \left|\frac{\delta f}{\delta a}\right|^2 \sigma_a^2 + \left|\frac{\delta f}{\delta b}\right|^2 \sigma_b^2$$

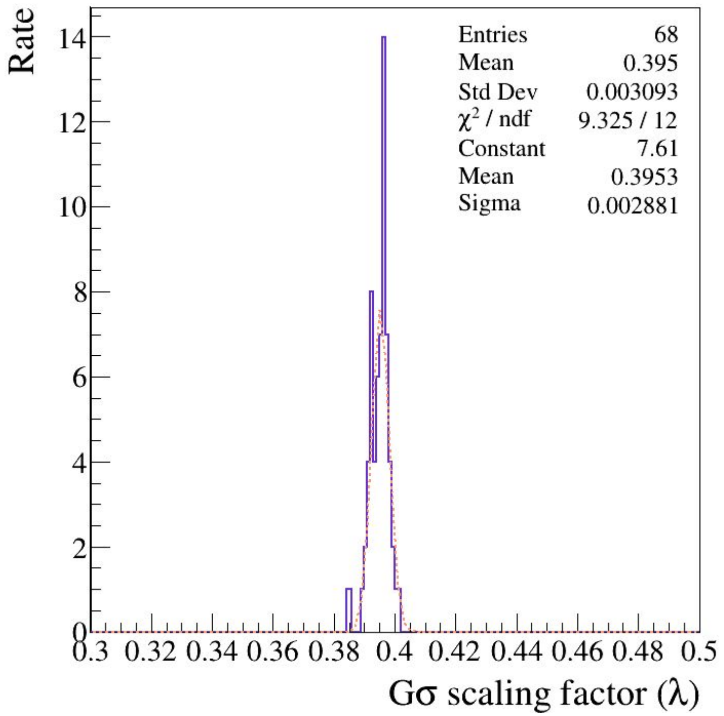
$$\sigma_{MPV}^2 = \sigma_{MP}^2 + \lambda^2 \sigma_{G\sigma}^2$$

λ distribution to sanity check MPV calculation

- Sanity-checking the MPV calculation method
- Checked the spread of λ values across the slices to ensure they are consistent (very poor stats)
- As you can see, they are very close to a delta peak
- The approximate variation in MPV due to the width of this distribution (0.8%) is **0.03%**

Given that ~40% of Gσ (which is usually ~30) is added to the MP (which is usually ~280):

((0.4*30)/280)*0.8 = 0.03%



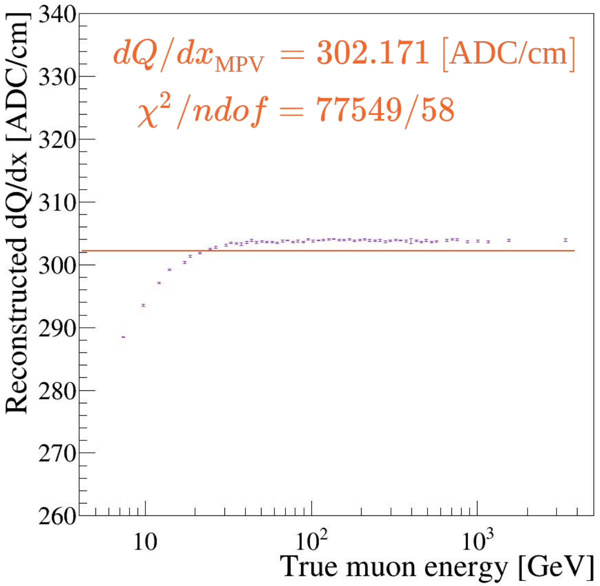
Uncertainty from the slicing procedure

Calculating the average uncertainty from the calculation of dQ/dx_{MPV} using the uncertainties on the fit to each slice gives:

dQ/dx_{MPV} = 302.171 + 0.017 (0.006%) [Negligible]

Where the uncertainty is calculated according to:

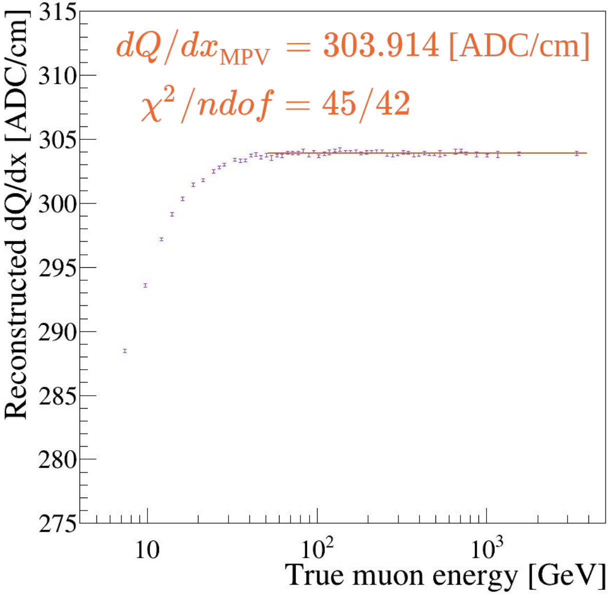
$$\sigma_{\mathrm{MPV}_N} = \frac{1}{N}\sqrt{\sum_i^N \sigma^2_{MPV_i}}$$



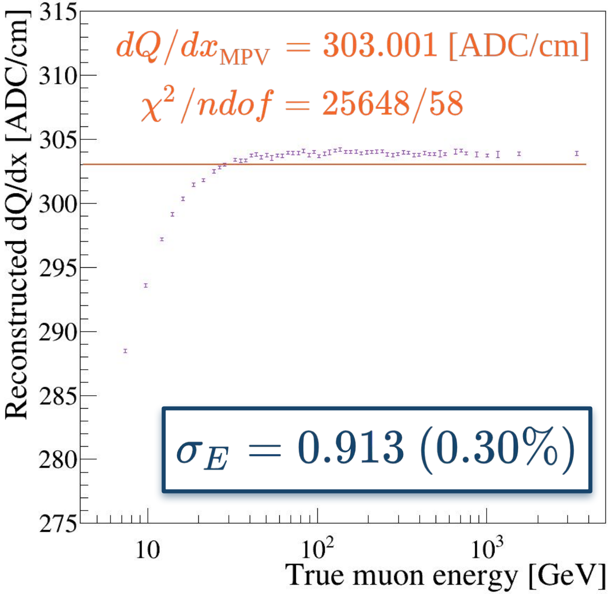
Systematics

$$\sigma_{E,\tau} = dQ/dx_{\mathrm{Nominal}} - dQ/dx_{E,\tau}$$

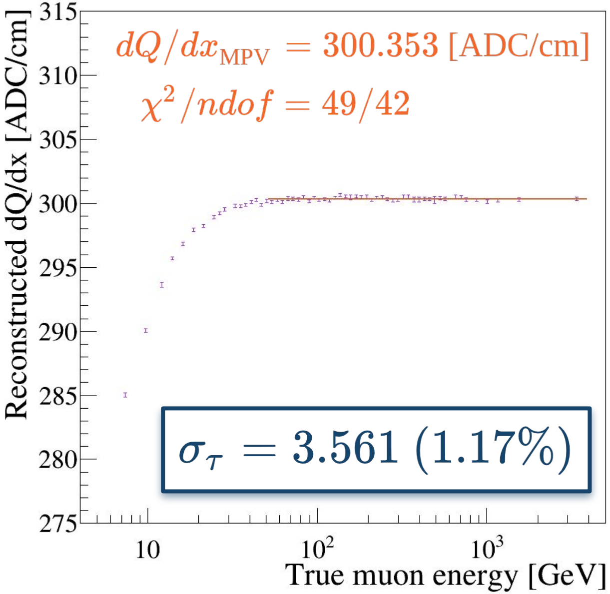
Nominal MPV



Energy-dependence



Simulated lifetime correction



Muon selection

Select **reconstructed** muons with the following criteria:

- **PFPrimary** - to maximise primary purity
- **L > 2 m** - to maximise muon purity*
- **$N_{\delta}/L > 17 \times 10^{-3}$ cm^{-1}** - to minimise energy-dependence

**I'm not explicitly selecting reconstructed through-going tracks as I was initially interested in maximising the efficiency of the selection, I will check how much the efficiency is reduced with the addition of a reconstructed through-going requirement down-the-line*

Muon selection

$$\varepsilon = \frac{N_{True,\,Selected}}{N_{True}} \quad \rho = \frac{N_{True,\,Selected}}{N_{Reconstructed}}$$

Assessed the efficiency of selecting **true through-going** muons

Purity: The percentage of selected, reconstructed primary particles which are associated to a true, primary, through-going muon is **99.96%** with the delta-ray cut

Efficiency: The percentage of true, primary, through-going muons which are reconstructed under the selection criteria is: **92.52%**

Absolute energy scale

MP error is:

$$\sigma_{\text{MP}} = \sqrt{\sigma^2_{\text{MP,fit}} + \sigma^2_{E_{dep}} + \sigma^2_{\tau} + \sigma^2_{N}}$$

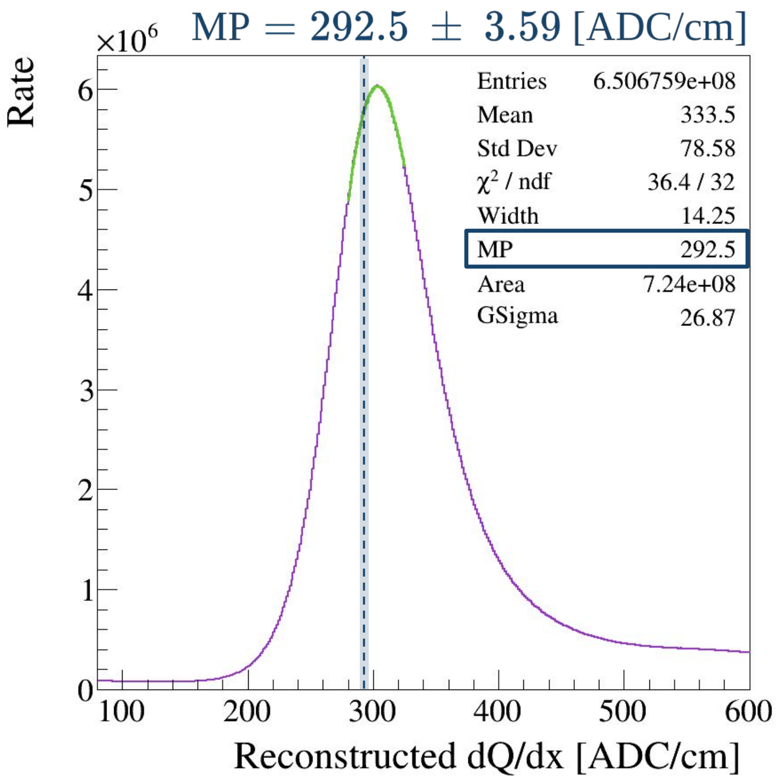
- $\sigma^2_{\text{MP,fit}}$: From the fit
- $\sigma^2_{E_{dep}}$: Energy-dependence
- σ^2_{τ}: Lifetime
- σ^2_{N}: Statistics

Scale factor: **$dE/dx_{L\text{-}V}$ / dQ/dx_{MP}**

S = (6.16 ± 0.08) x10^{-3} [MeV/ADC] (stat+syst, 1.23%)

$dE/dx_{L\text{-}V}$ = 1.804 MeV/cm (μ: 292 GeV @ 5.3 mm thickness)

https://lar.bnl.gov/properties/



Migration to ProtoDUNE-SP beam muons

Key differences between the DUNE FD & ProtoDUNE-SP beam muon simulations and samples relevant to this analysis*

Quantity	DUNE FD CR	ProtoDUNE beam
Number of events	~2,000,000	~10,000
Muon primary direction	$-\hat{y}$	$+\hat{z}$
Simulated lifetime	3 ms	35 ms
ADC	200 e^-	1,000 e^-

*Non-exhaustive, e.g. geometries not evaluated here

*Work in progress

ProtoDUNE-SP beam muons*

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DEEP UNDERGROUND NEUTRINO EXPERIMENT

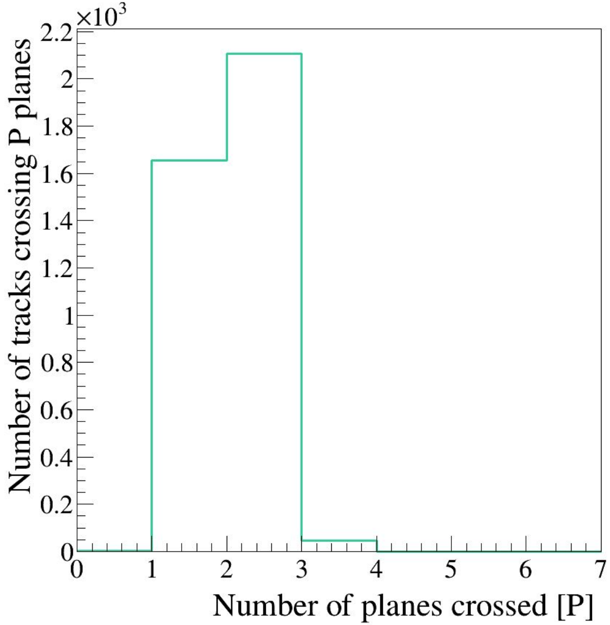
ProtoDUNE simulation plans

In progress
Not yet started

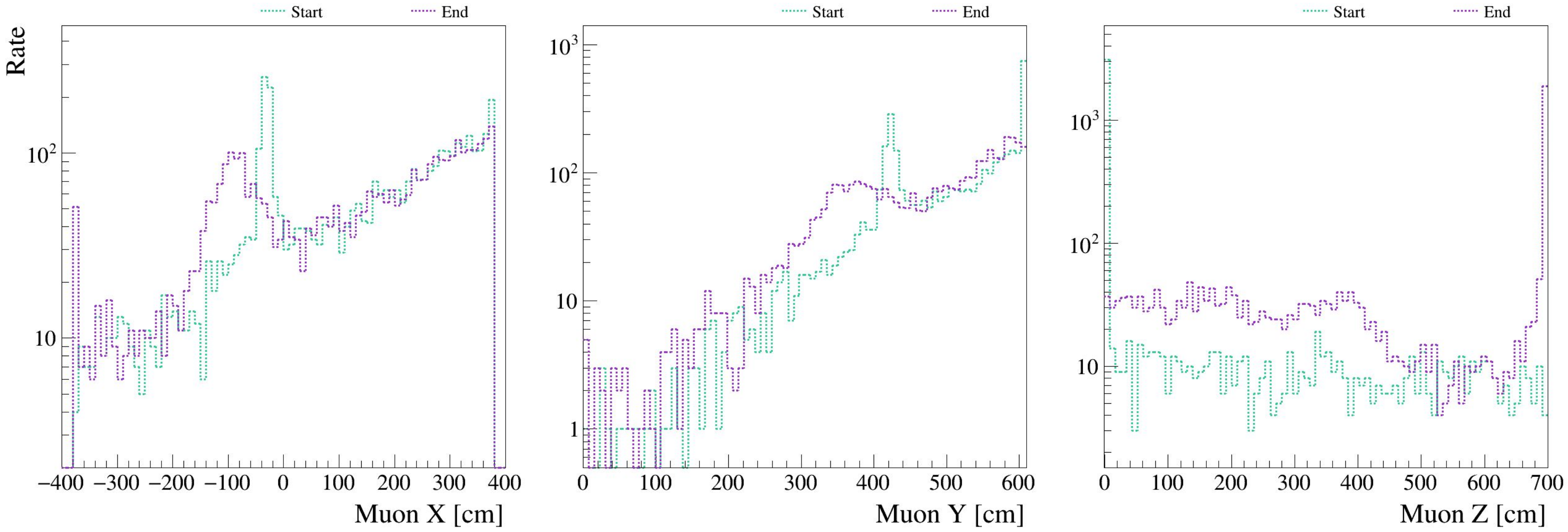
1. Characterise the beam and CR muon profiles in simulation
2. Understand key differences between muons from each detector/source
3. Calculate the electron lifetime applying all known corrections to the charge depositions
    a. SCE & Diffusion effects
4. Correct the charge depositions according to the calculated electron lifetime
5. Define muon selection criteria
6. Run the FD absolute energy scale calibration procedure
7. Evaluate energy-dependence of charge depositions & apply systematic
8. Evaluate lifetime-dependence of charge depositions & apply systematic
9. Analyse the result & prepare to run on data

Statistical breakdown (with front & back)

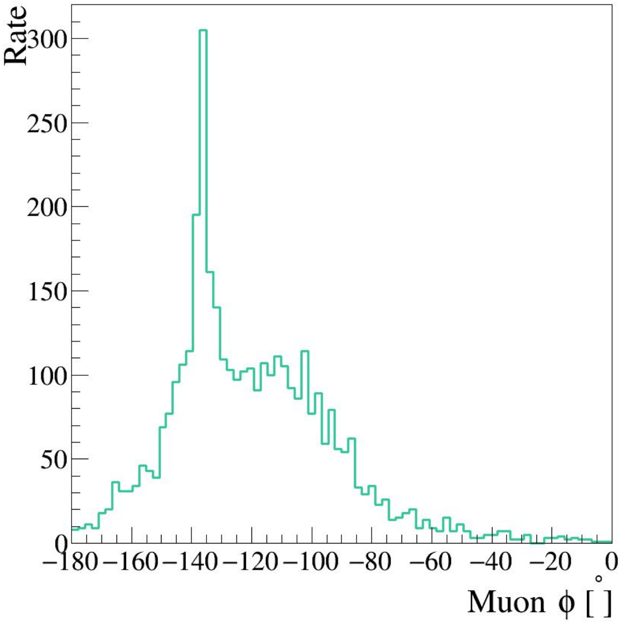
Statistic	Rate / 33.9 Days	% Long TPC μ
Events	9548	-
TPC μ	3753	134.37 %
Long TPC μ	2793	100 %
Crosses top or bottom	408	14.608 %
Crosses top and bottom	0	0 %
Crosses front or back	2734	97.888 %
Crosses front and back	1375	49.23 %
Crosses 1 APA or CPA	189	6.7669 %
Crosses $\geq$ 2 APA or CPA	0	0 %
Stopping	952	34.085 %
Exiting	1841	65.915 %

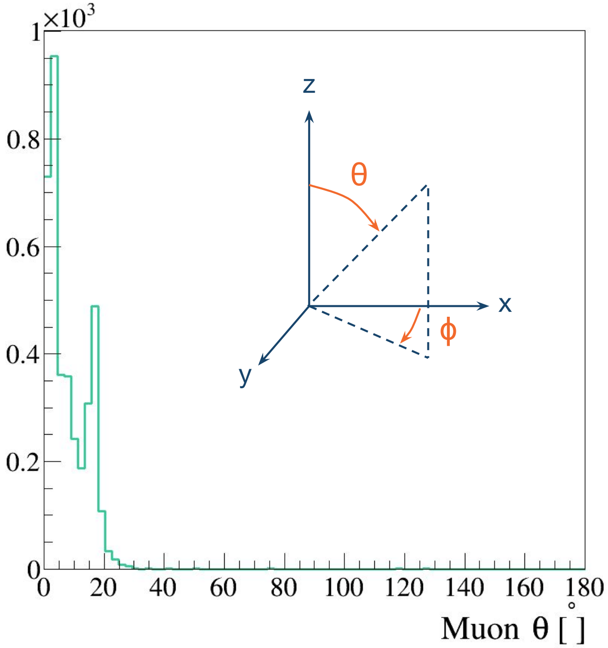


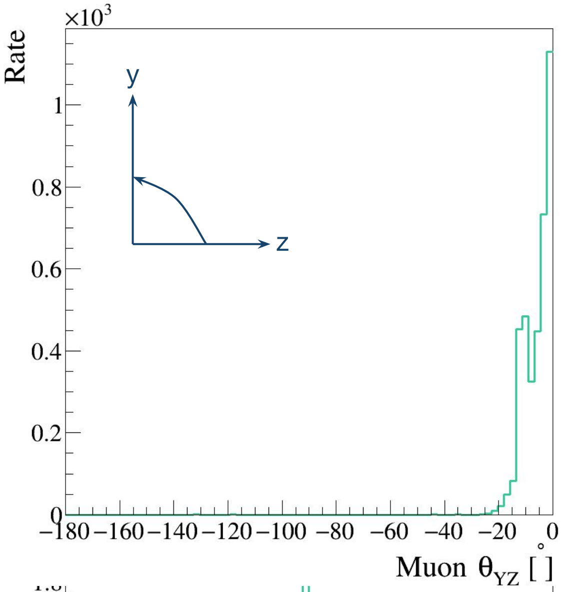
Start and end positions

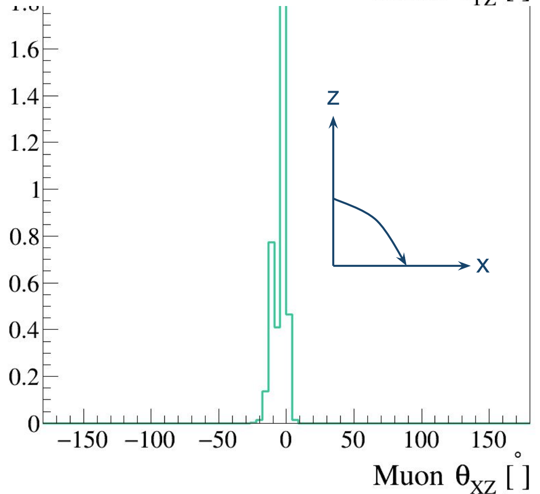


Angular distributions

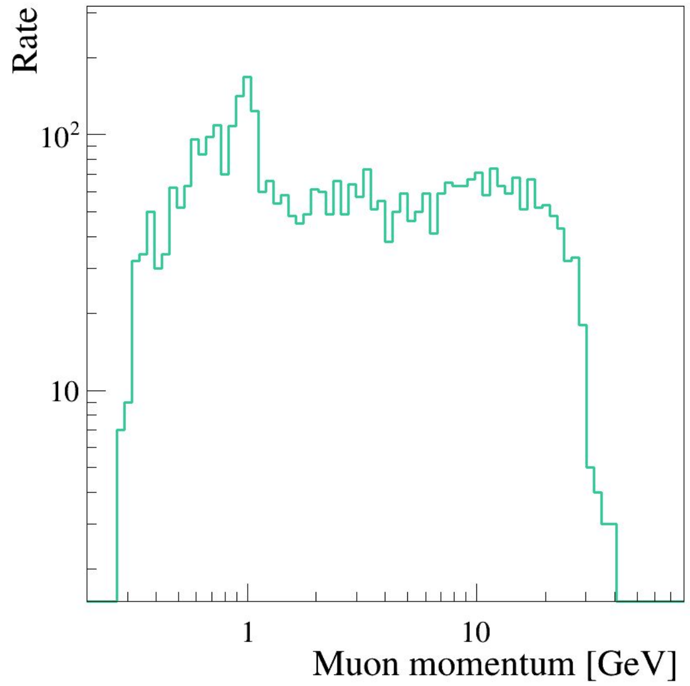


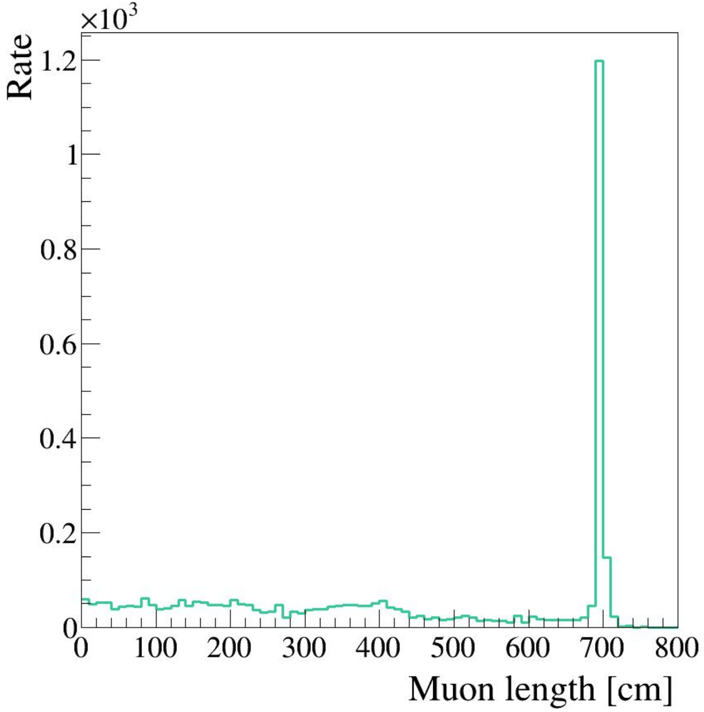




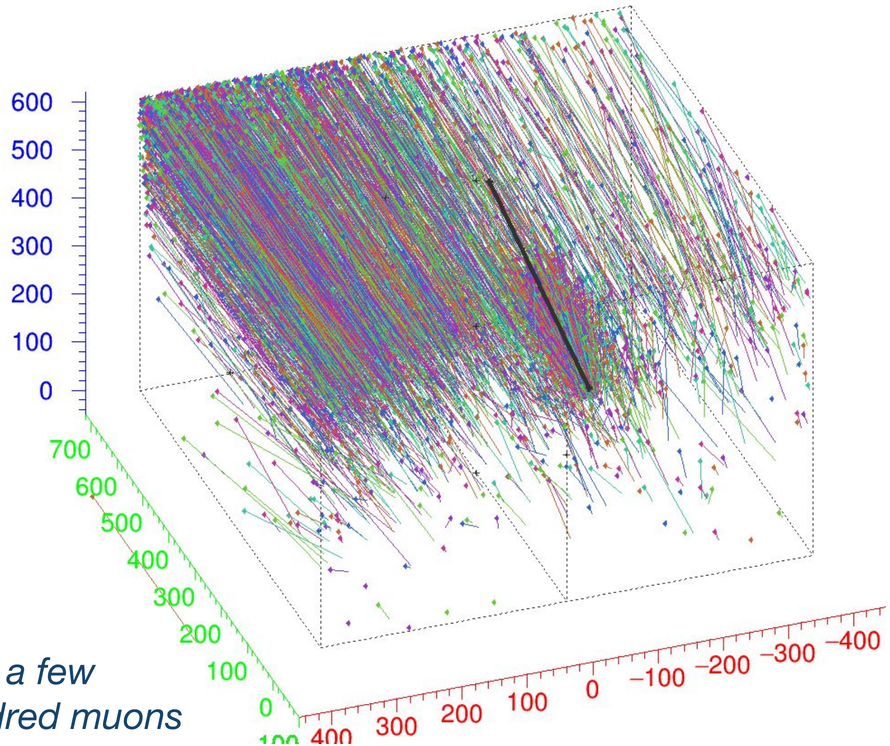


Momenta and length

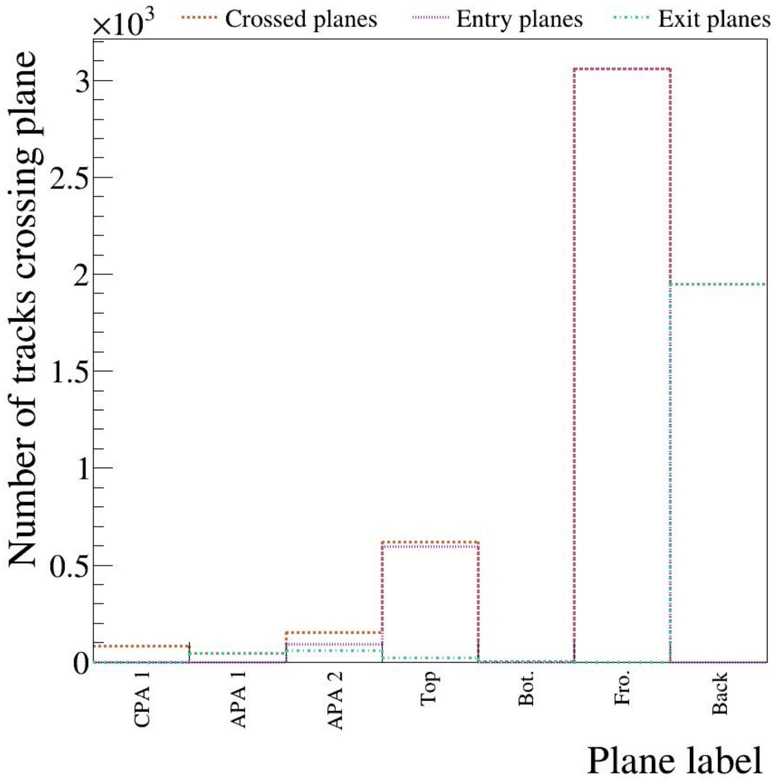




Looking at the muons



Only a few hundred muons



Location of the beam plug

Beam plug start position:
(-34.52, 431.90, 0.00) cm
Taken from the ProtoDUNE gdml files

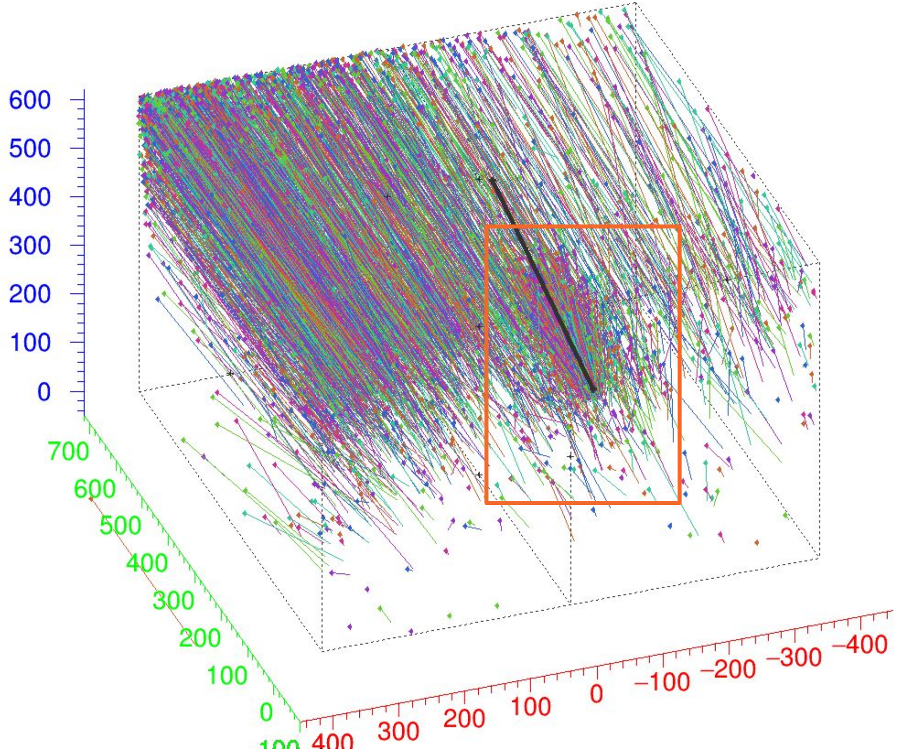
The black line shows the location of the beam plug on the front face of the detector, and is projected along its direction onto the back face of the detector.

The activity surrounding this path is clear in the high-intensity plot on the RHS.

The angle of the beam is:

“It points down 11° from the horizontal, and towards the APA on the negative x side, 10° to the right of the z direction.”

From the First Results paper.



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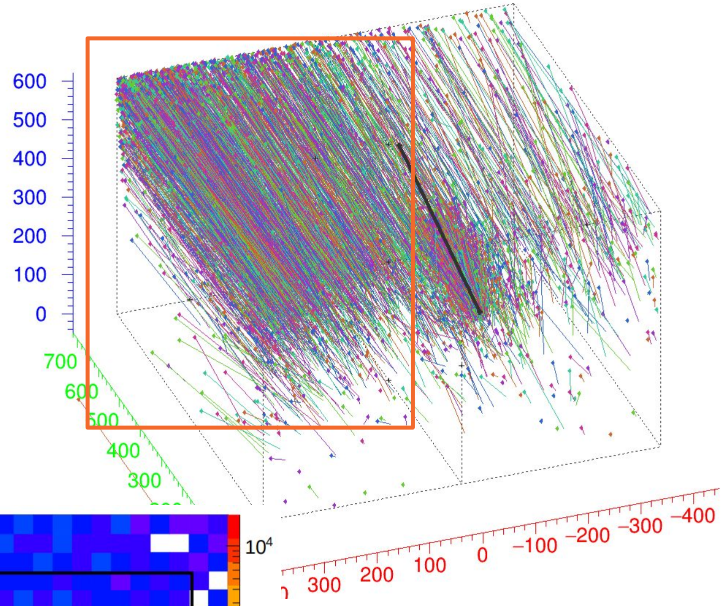
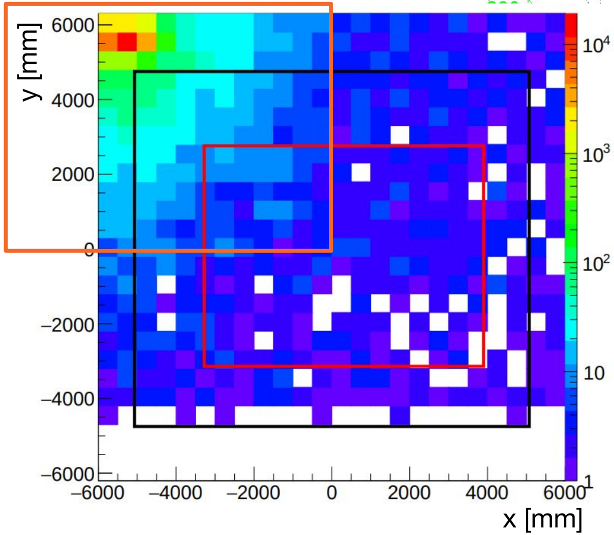
DUNE

Location of the beam plug

There is also a known 'muon halo' which originates from the decay of charged pions as they travel along the beamline, resulting in muons entering the TPC *"slightly upward and sidewards of the H4 beamline".* ProtoDUNE TDR.

According to the TDR this should be in the negative x-direction, however I'm not **yet** confident in the consistency of the direction definitions and looking at the TDR's expected behaviour of this halo I'm reasonably convinced that this is what we're seeing.





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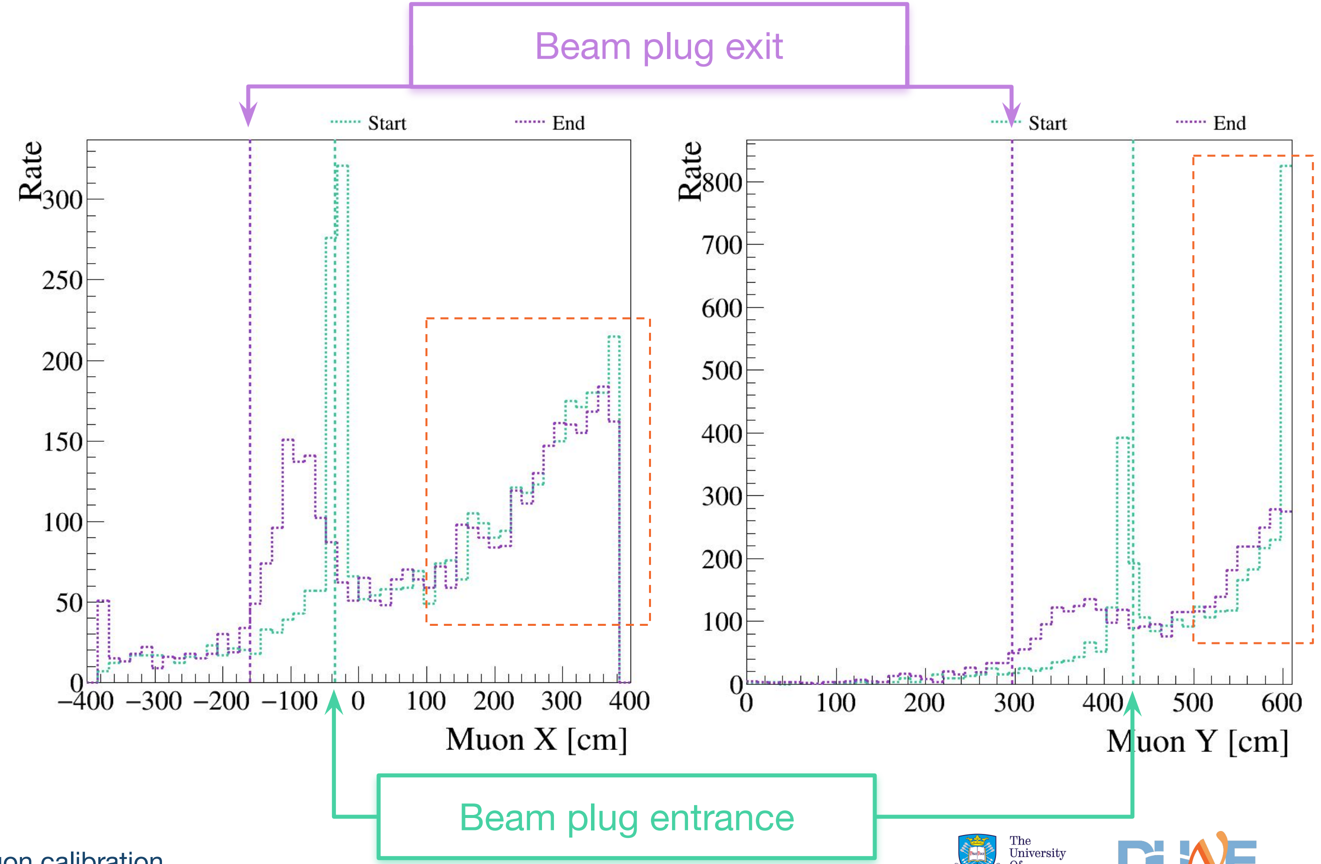
Start and end positions, w.r.t beam plug

I think now that I have found the location of the beam plug and projected it onto the back face, the start and end X & Y position distributions make some sense.

I'm guessing that the end-point peak slightly before the beam end-point on the back face is due to non-exiting tracks.

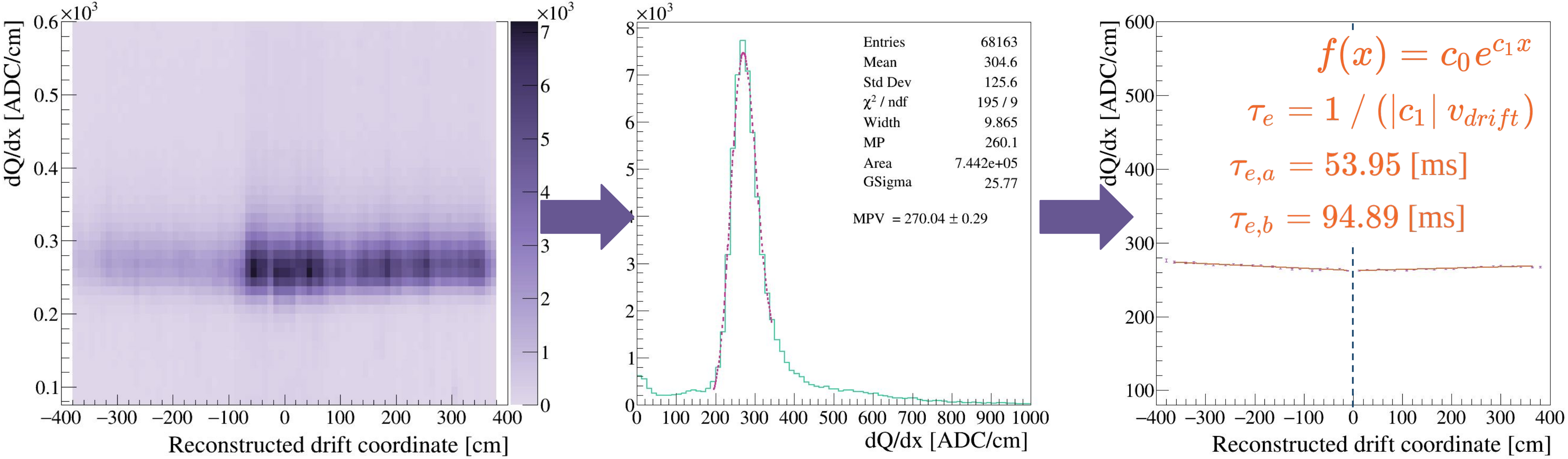
Adding in the muon halo 'slightly upwards and slightly sidewards' would also explain the increase in particles entering and leaving the detector towards the top-right.



ProtoDUNE lifetime calculation*

Using Viktor’s method, I calculate the electron lifetime in each TPC of ProtoDUNE-SP

1. Slice the 2D dQ/dx vs x histogram, calculate MPVs in each slice and fit exponentials to the MPVs in each TPC in dQ/dx vs x space (best plane only here)



ProtoDUNE lifetime calculation

$$\frac{Q_c}{Q_a} = \exp\left(\frac{-t_{fulldrift}}{\tau}\right)$$

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- The values of τ_e presented on the previous slide vary substantially from the simulated value for many reasons & I don't want to reinvent the wheel
  - I will look into doing this properly before looking at data
- Whilst setting up the energy scale calibration tools to work at ProtoDUNE I will likely correct for the simulated lifetime to begin with
- I have instead evaluated the likely impact of a variation in the lifetime on the charge depositions at ProtoDUNE compared with the Far Detector (RHS)

A 10% variation in τ_e corresponds to a variation in Q_a/Q_c of:
15.4% at the FD 1.3% at ProtoDUNE