Towards a cosmic ray dE/dx calibration procedure at the DUNE FD

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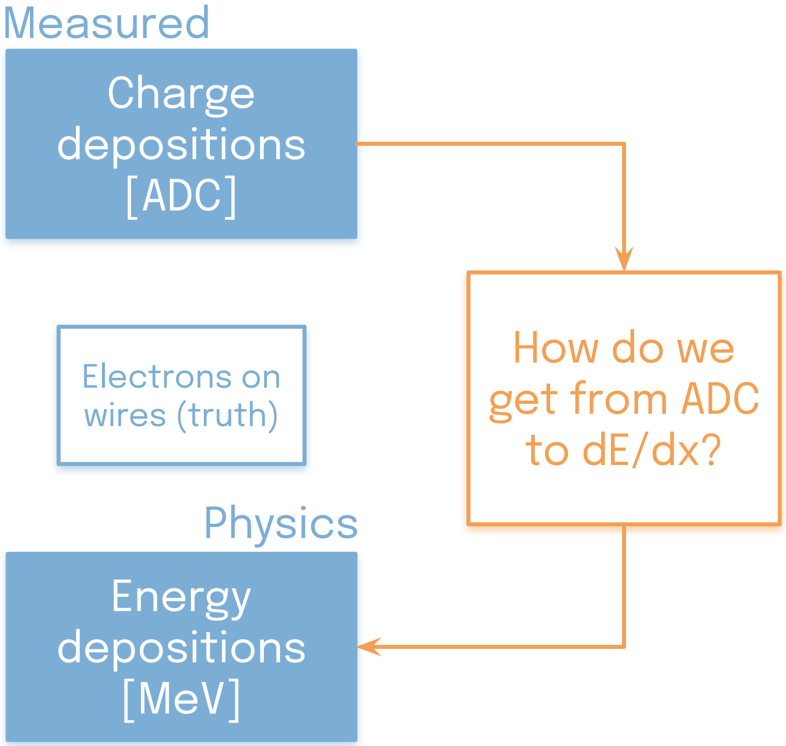
Introduction

- I started at the University of Sheffield in the middle of July
  - I was previously working on SBN(D) at Liverpool
- My goal is to develop a cosmic ray (CR)-based energy calibration procedure at the DUNE far detector
  - Working in parallel with Viktor's e^- lifetime measurement studies
- As you may have guessed from the timeline, this work is in the very early stages of development
- We thought it would be good to introduce myself, the topic and a few studies I have performed along with future plans towards this goal

dE/dx calibration introduction

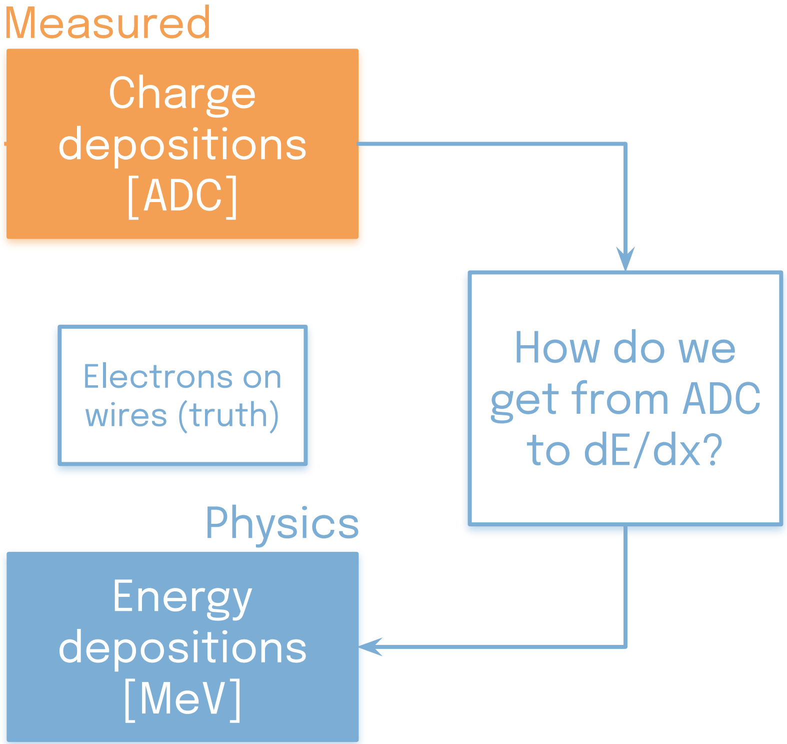
- We need to understand how to convert from the measured charge [ADC] at the wire planes to the energy deposited [MeV] as particles traversed the detector
- It is useful to use CR muons for this, since
  - They are capable of providing reasonably consistent dE/dx behaviour
  - Available before beam is switched on
  - They are a natural (free) source of calorimetry data
- Major consideration in the DUNE FD: Very low rate of CR muons so deep underground
  - Methods used previously by surface detectors may not be feasible



Electron lifetime studies

Viktor has done a lot of work towards accounting for the electron lifetime and diffusion in measurements of the dQ/dx of a CR muon

Viktor's most-recent update, from the May 2021 CM, is here.



Looking into the true and reconstructed contents of the sample

Inputs to the truth and reco-level studies

For testing I look at around 450,000 total events which corresponds to around 1 month of data (at 14118/day total from Viktor's studies) in one 17 kt FD module.

CR events were simulated using the Sheffield muon generator, MUSUN, and propagated through GEANT4, Detsim and Reconstruction.

Truth-level selection requirements

I then look at GEANT4 tracks to select:

- Those which enter the TPC geometry
- Primary muons
- Longer than 2m (arbitrary length, aiming for some consistency in the dE/dx shape)

I then study truth-level calorimetric quantities from Hits associated with them.

Reconstructed selection requirements

From the reconstructed tracks, I select:

- Those with a truth-level muon pdg code
  - Can't check whether it is primary yet
- Longer than 2m (arbitrary length, aiming for some consistency in the dE/dx shape)

I then study reconstructed calorimetric quantities associated with the tracks.

True and reconstructed sample breakdown

Truth-level sample contents

Statistic	Rate / 31.87 Days	% All Events
Events	450,000	-
TPC μ	154,646	34.366 %
Primary TPC μ	152,080	33.796 %
Long, primary TPC μ	140,992	31.332 %
Crosses top or bottom	137,804	30.623 %
Crosses top and bottom	78,716	17.492 %
Crosses $\geq$ 1 APA/CPA	70,977	15.773 %
Crosses $\geq$ 2 APA/CPA	17,080	3.7956 %
Stopping	2280	0.50667 %

I first break down the sample into the various muon contributions.

I then check which planes the muons have crossed,

- 51.8% of all primary muons cross both the top and the bottom planes of the detector
- Only 11.2% cross both an APA and a CPA

Reconstructed sample contents

Statistic	Rate / 31.87 Days	% All Events
Events	450,000	-
Tracks	280,898	62.422 %
Muons	274,619	61.026 %
μ > 2m	155,854	34.634 %
Crosses top or bottom	133,792	29.732 %
Crosses top and bottom	67,589	15.02 %
Crosses $\geq$ 1 APA/CPA	73,095	16.243 %
Crosses $\geq$ 2 APA/CPA	11,269	2.5042 %
Stopping	37,586	8.3524 %

The track reconstruction is not working perfectly, resulting in the following selection features,

- There are many more reconstructed muons than in truth
- The muon rate improves drastically w.r.t truth when adding the >2m track length requirement
- The stopping muon rate varies the most from truth when considering the planes crossed

Lifetime corrections

Some of the following slides will have a lifetime correction applied to the number of electrons reaching the readout (truth) and the charge depositions (reco)

- τ_{Sim} = 3 ms (default in simulation)
- τ_{Calc} = 2.88 ms (from Viktor's work)
  - Bias introduced with diffusion

Using the assumption that charge and N_e are linearly correlated quantities for the correction.

The true and reco energy depositions are corrected for in the simulation using τ_{Sim}.

- Charge is always reconstructed
- Number of electrons is always true
- Energy can be reconstructed or true

Relationship between discussed quantities

$$\text{ADC} = 200e^-$$

$$dQ = \int A_{\text{Hit}} \left[\text{ADC/ticktime}\right]$$
$$\rightarrow dQ \propto N_{e^-}$$

$$dQ \propto N_{e^-} \rightarrow dQ_{Corr} \propto N_{e^-,Corr}$$
$$dQ_{Corr} = dQ \cdot \exp(-t_{Drift}/\tau)$$
$$N_{e^-,Corr} = N_{e^-} \cdot \exp(-t_{Drift}/\tau)$$

$$dQ/dx \rightarrow dE/dx$$

Modified Box Model

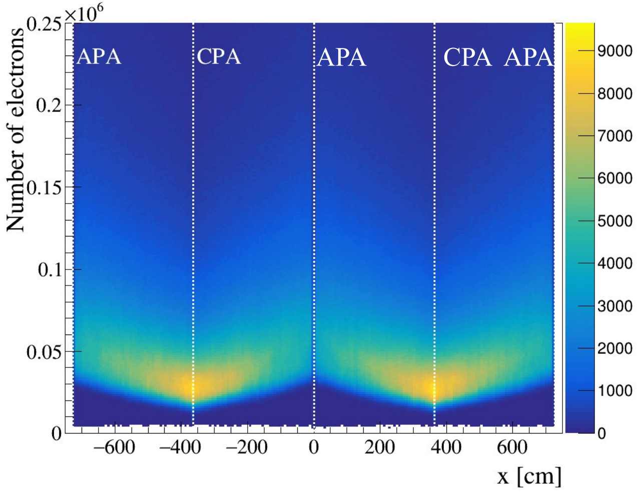
Calorimetry study overview

- Ultimately, want to determine a factor by which we can convert from measured values (charge) to physics quantities (energy)
  - To begin with, I am focussing on the x (drift)-dependence of the conversion
- Before it is possible to determine the conversion factor, detector (specifically drift)-dependent effects must be considered and accounted for
  - Including electron lifetime & diffusion
- The electron lifetime correction discussed on the previous slide is applied to true and reconstructed quantities as follows,
  - The number of electrons (truth) is corrected by the simulated lifetime, τ_{Sim} = 3 ms
  - The charge (reco) is corrected by the measured electron lifetime, τ_{Calc} = 2.88 ms
  - The energy has already had the simulated electron lifetime correction applied. In reconstruction, a corrected-correction factor, C_{New}, is applied to account for the bias in the measured lifetime

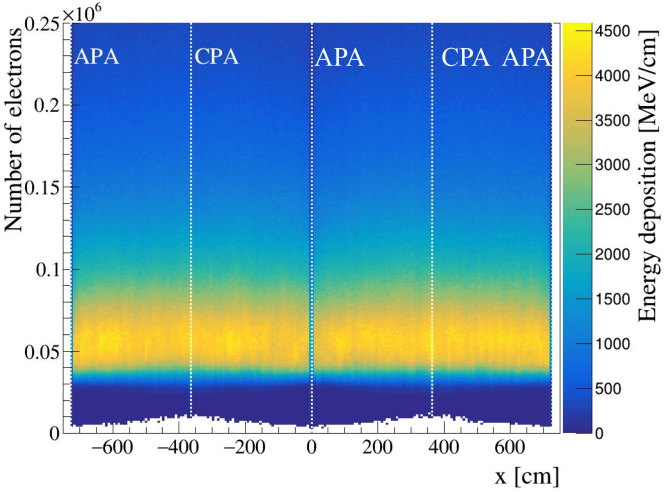
$$\boxed{C_{New} = \exp(-t_{Drift}/\tau_{Calc})/\exp(t_{Drift}/\tau_{Sim})}$$

Truth | Plane 2 (collection)

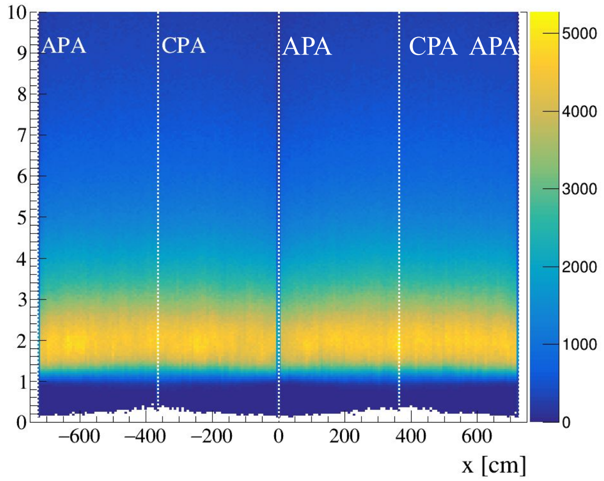
Number of electrons



Lifetime-corrected number of electrons



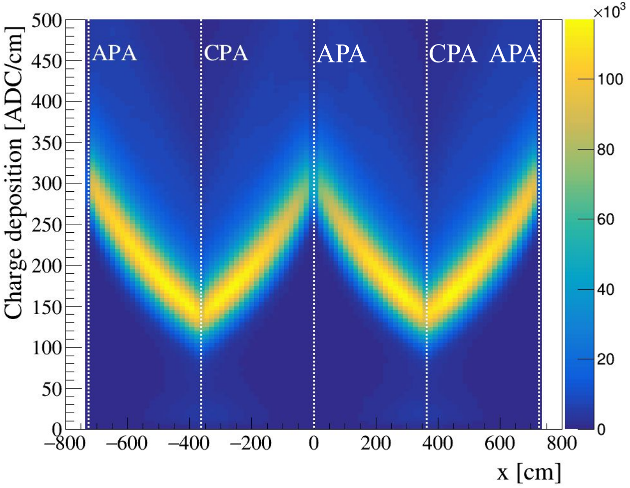
True energy depositions



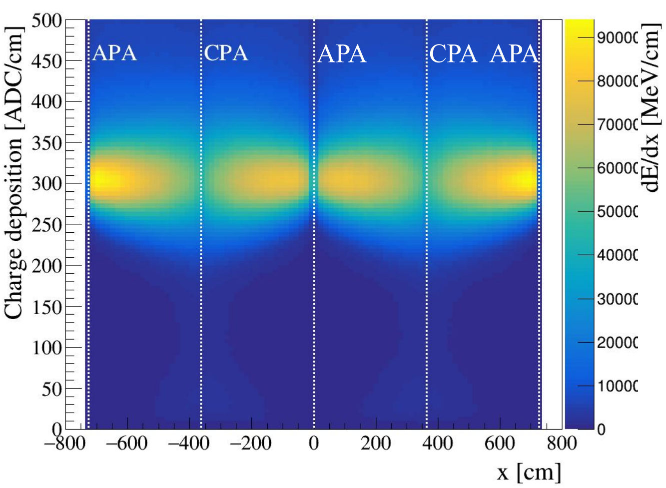
The lifetime correction appears to be doing something sensible to the number of electrons: A substantial amount of the x-dependence has been removed

Reco | Best plane (most hits)

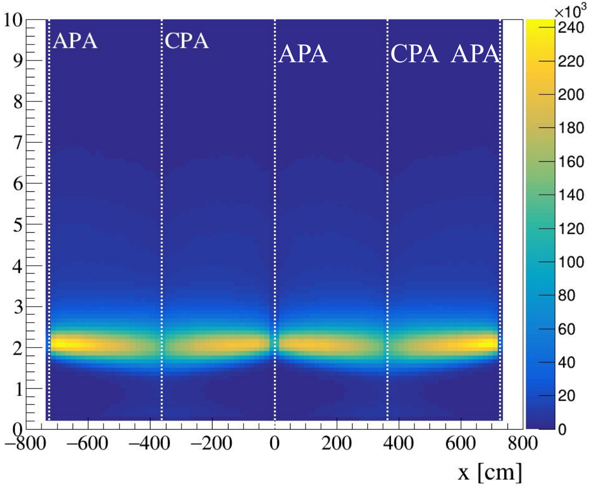
Charge depositions



Lifetime-corrected charge depositions



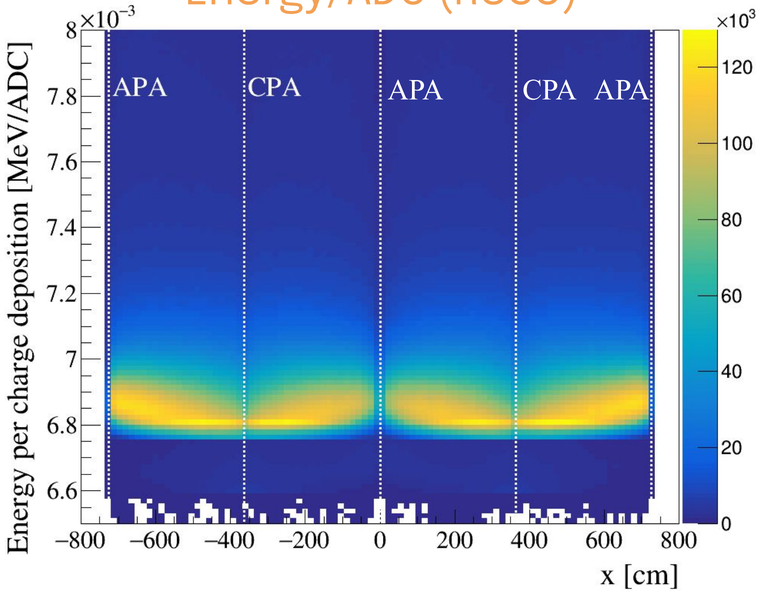
Reco energy depositions



This time, the lifetime correction has smeared-out the charge distribution, resulting in what appears to be slight build-ups at the APAs. Similar for reconstructed energy.

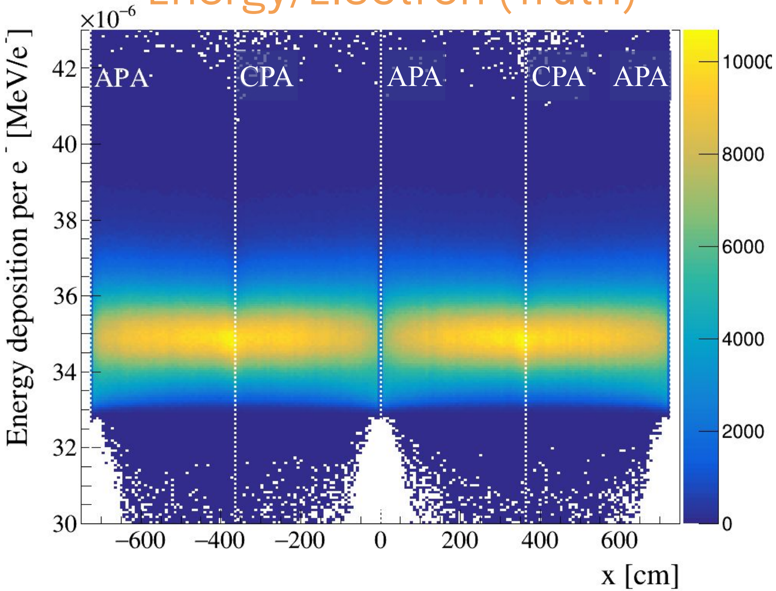
Converting to energy depositions

Energy/ADC (Reco)



The ratio remains quite flat across the CPAs, however there is a definite increase towards the APAs

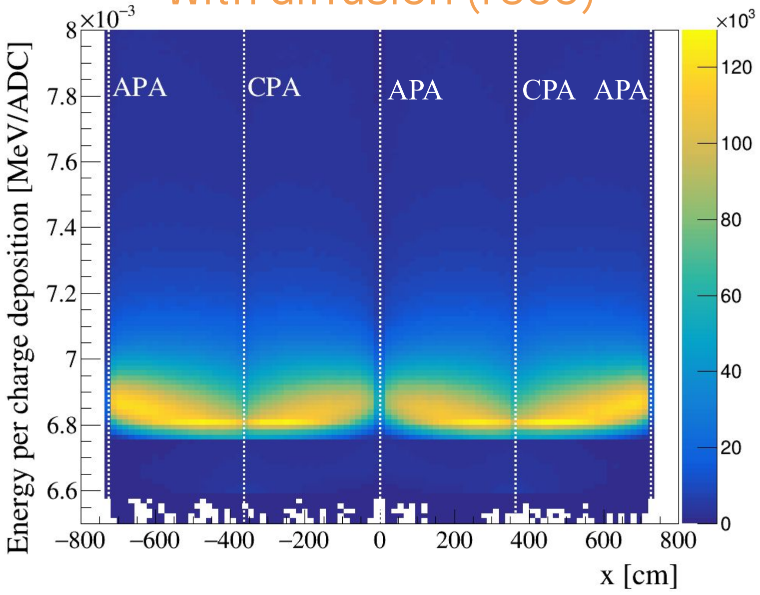
Energy/Electron (Truth)



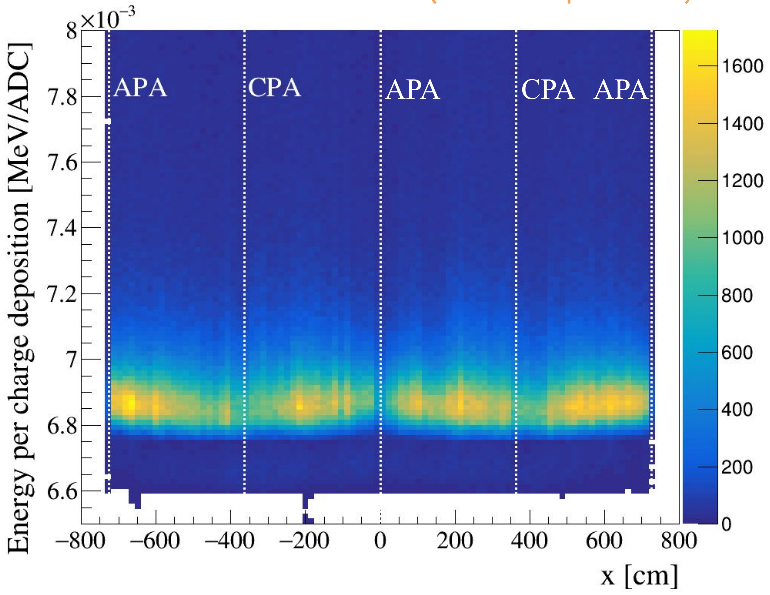
In truth, this ratio remains perfectly flat (by eye). The build-ups in this case surround the CPA planes

Converting to energy depositions, removing diffusion

With diffusion (reco)



Without diffusion (1.1% sample size)



Removing diffusion definitely does not solve the x-dependence problem, however the sample size is too small to know if it is helping at all

Discussion so far

- In reconstruction, there appears to be some residual x-dependence when finding the energy deposited per lifetime-corrected charge, which needs to be investigated
  - Stats aren't sufficient to tell by eye whether removing diffusion does anything to help that
- Next steps could include determining the MPV's with respect to x of the ratios, (in a similar way to Viktor's lifetime method) in order to calculate the absolute factor which will translate from measured ADC/charge to the energy deposited by the track
- One important consideration is the energy dependence of the muon track's dE/dx
  - Higher energy tracks are likely to produce many δ-rays, resulting in a larger muon energy loss
  - Will study this and determine if an energy threshold makes sense for the calibration
- I will now briefly discuss the MicroBooNE/ProtoDUNE approach to energy calibration and the issues with using this approach at the DUNE far detector

MicroBooNE & ProtoDUNE calibration procedure

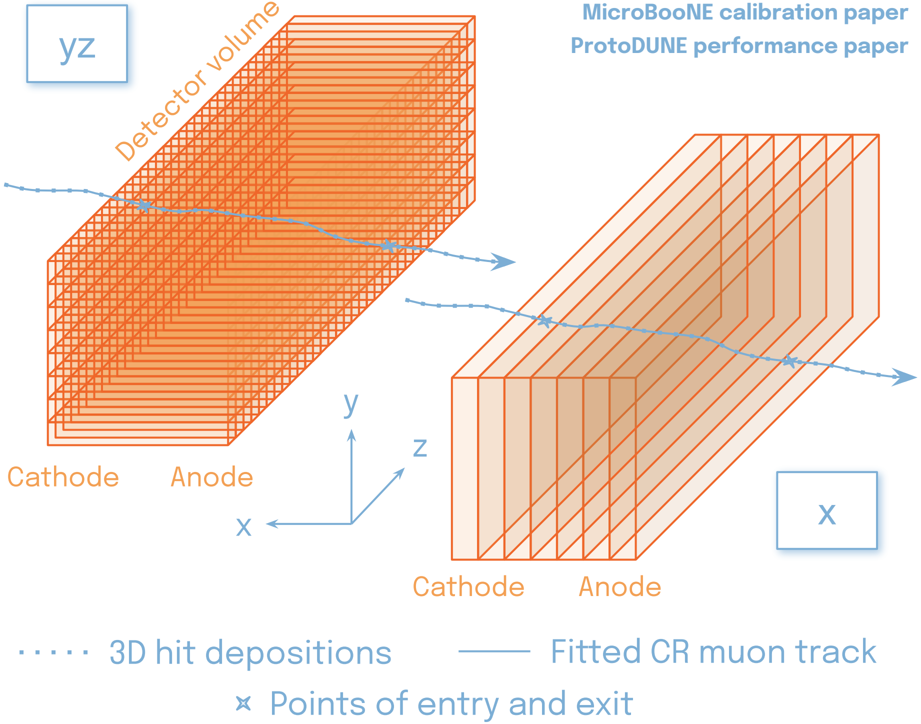
Introduction to existing approaches

- MicroBooNE and ProtoDUNE each use the same general approach
  - Different analysis techniques are used for MC and data samples, will only summarise MC
- Use Anode-Cathode (AC)-crossing muons to calibrate dQ/dx through normalisations across the entire detector and stopping muons to determine the absolute energy scale
  - AC-crossing muons can aid in the mitigation of drift-dependent effects
- Substantial differences between the cosmic ray muon characteristics in DUNE compared with MicroBooNE means this method may not be directly applicable
  - MicroBooNE is on the surface, where a huge flux (5 kHz) of cosmic rays have a peak energy of around 7 GeV and enter the TPC from a range of angles
  - DUNE is deep underground, with a much lower CR flux (0.05 Hz / module) where the muon energy profile has changed after travelling so far, and the peak is much higher, ≈280 GeV
    - Very few AC-crossing and ‘stopping’ muons in the TPC volume, muons predominantly enter from the top and leave towards the bottom
    - Muon energy spectrum results in higher muon ‘activity’. Many more secondary particles are produced, such as δ-rays, making it harder to reconstruct only the muon hits and calculate the dE/dx

Using AC-crossing and stopping muons for calorimetry calibration

- The detector is first split into 5x5 cm cells in order to calibrate dQ/dx in the yz plane and is then split into 5 cm bins to calibrate dQ/dx in the x dimension
- In these cells & bins, charge depositions are equalised using the ratio of median depositions in the entire plane/dimension (global) to the median in the cell (local)
- Following the calibration of dQ/dx, the absolute energy scale is determined using stopping CR muons
    - ‘Modified box model’ used
    - Cathode-crossing muons are also required here in order to reconstruct t_0
    - See slides **22-26** for much more detail on these methods in MicroBooNE & ProtoDUNE

MicroBooNE calibration paper
ProtoDUNE performance paper



$$\left(\frac{dE}{dx}\right)_{\text{Calibrated}} = \frac{\exp\left(\frac{\left(\frac{dQ}{dx}\right)''}{C_{\text{Cal}}} \cdot \frac{\beta' W_{\text{ion}}}{\rho\epsilon}\right) - \alpha}{\frac{\beta'}{\rho\epsilon}}$$

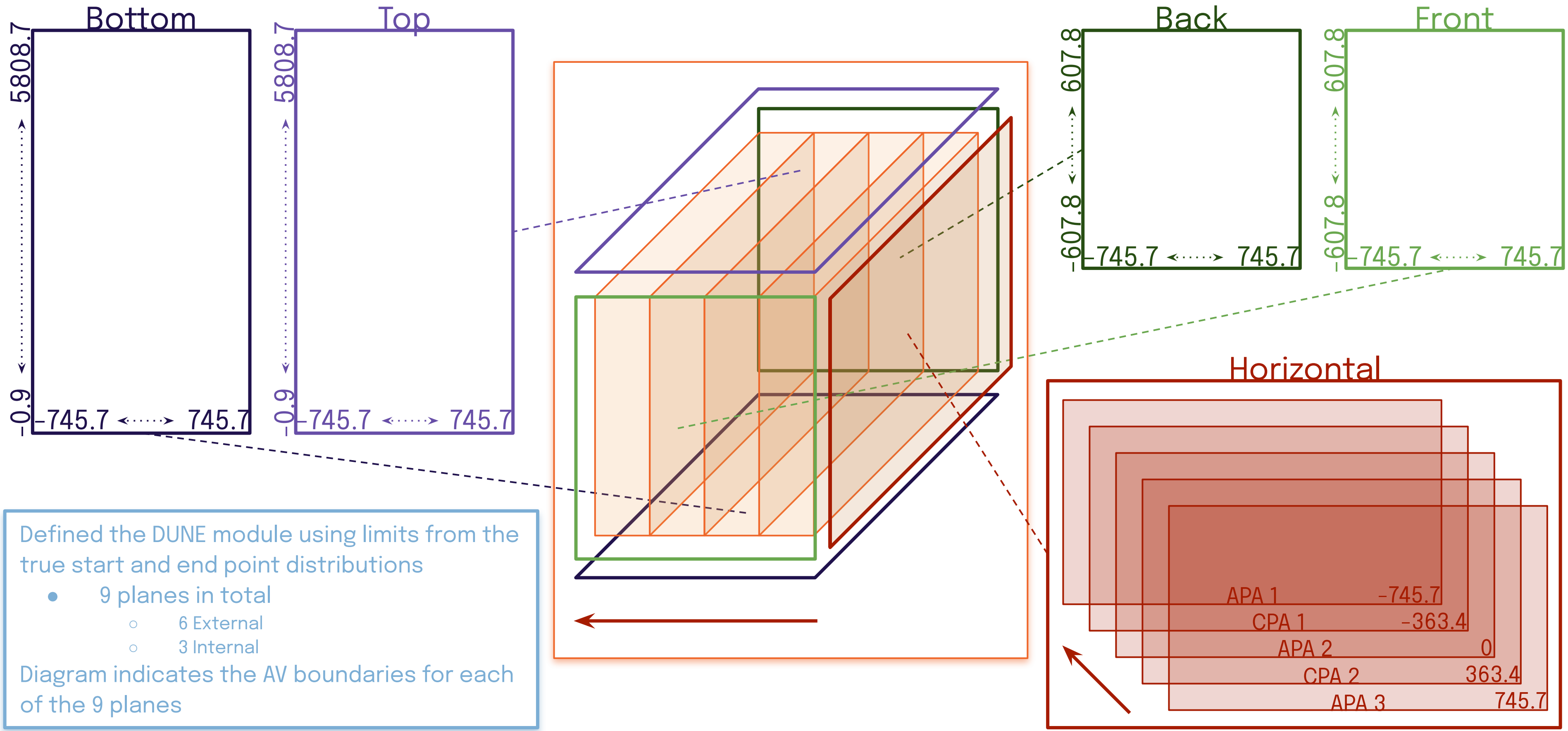
Modified Box Model

Discussion in the context of DUNE

- In an ideal world, we could use the CR calibration techniques developed by MicroBooNE and ProtoDUNE to perform the calorimetry calibration in DUNE
- Unfortunately, this may not be possible, since splitting the detector into yz & x cells will not provide enough hits-per-cell
    - Only around 4000 total events per day in DUNE across the entire module, 200 TPCs
    - The MicroBooNE/ProtoDUNE studies use AC-crossing and stopping muons, which make up 12% and <2% of our primary, long muons respectively
    - Ideally want to be able to calibrate the detector in around 1 day, not 1 month...
- It might instead be possible to use similar techniques across an entire DUNE module (200 TPCs), rather than splitting the detector up into cells
- For now, I'll continue along the initial path, where I flatten everything into x-dependent quantities and work towards mitigating drift-dependent effects

Thank you

Detector geometry: DUNE SP 17 kt Module



Defined the DUNE module using limits from the true start and end point distributions

- 9 planes in total
  - 6 External
  - 3 Internal

Diagram indicates the AV boundaries for each of the 9 planes

Planes crossed

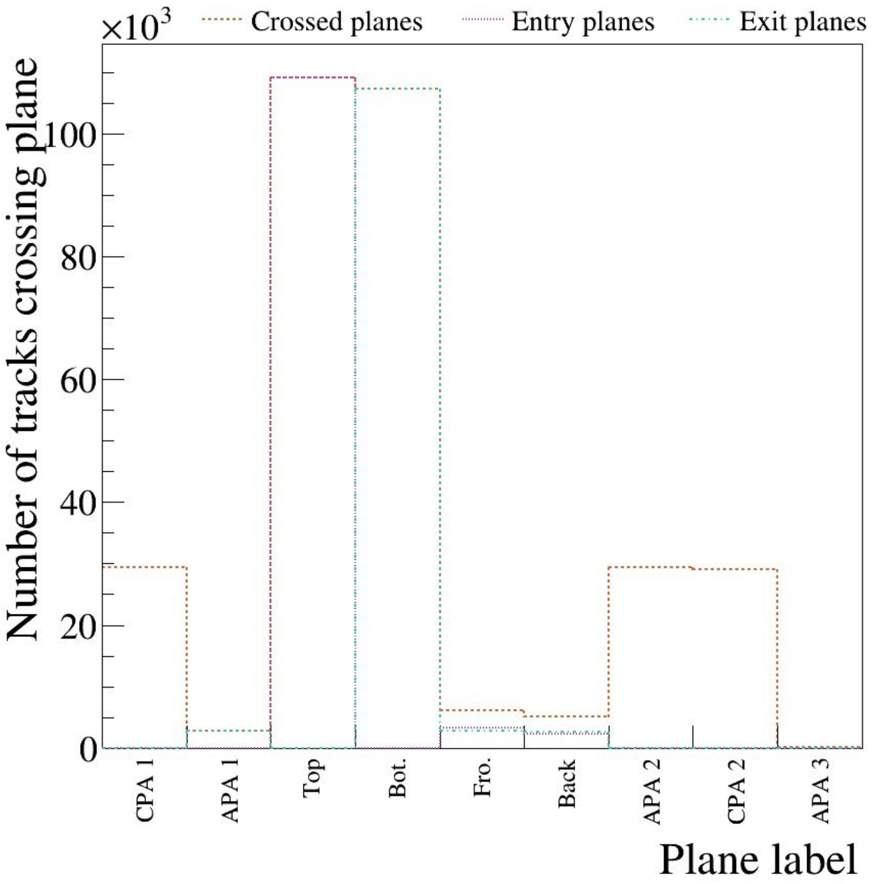
Looking entirely in truth for these studies

Determined **which** plane the track entered (exited) through by finding the distance to each from the TPC start (end) point and taking the smallest

Determined if a track crossed a plane in general by looking at the distance from the start of the track to the plane, with respect to its length and direction

As expected, most enter (leave) through the top (bottom) with a very low fraction entering (leaving) through the front, back and sides (APA 1,3)

This method depends strongly on my definition of the TPC AV: Imperfect



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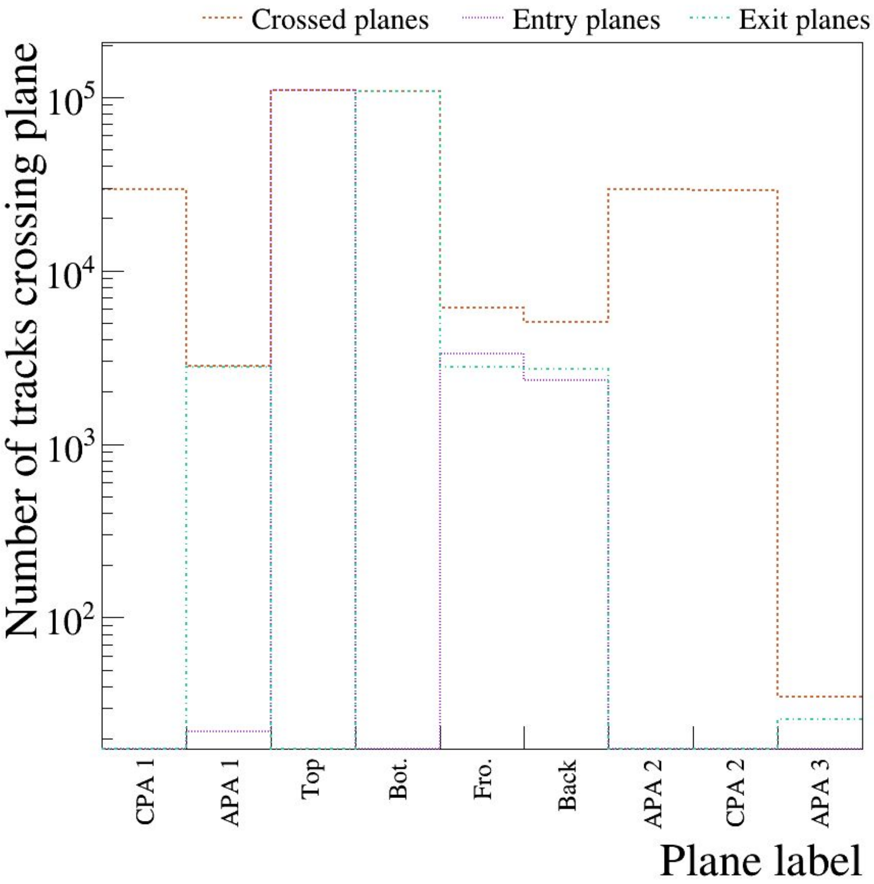
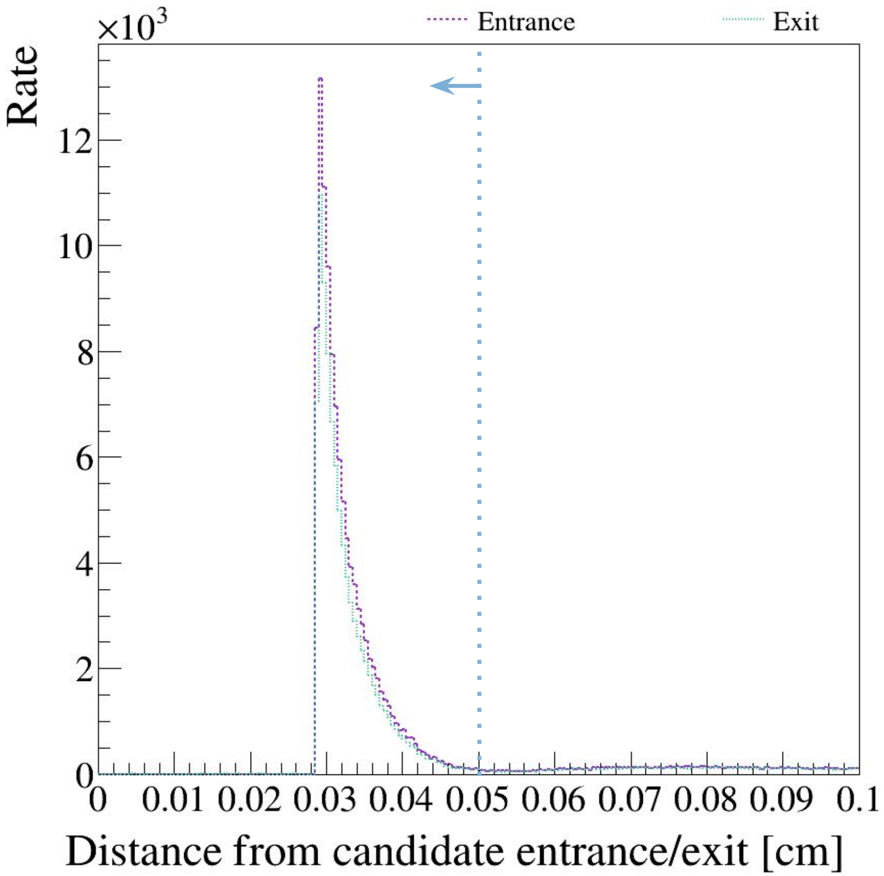


Distances to candidate entry and exit planes

Cutoff below 0.028 cm is likely due to my TPC AV definitions being slightly offset with respect to the true top and bottom locations in the production

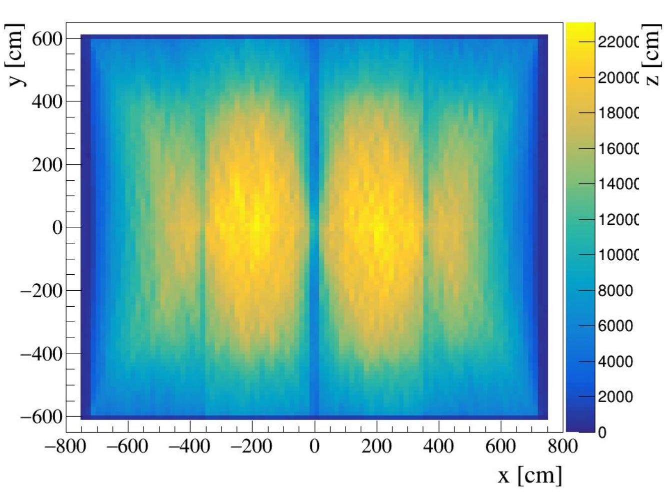
Following this distribution, I require that the candidate entrance or exit is defined only if this distance is **below 0.05 cm**

This is only for interest, the 'entrance' and 'exit' labels do not impact the remainder of the studies

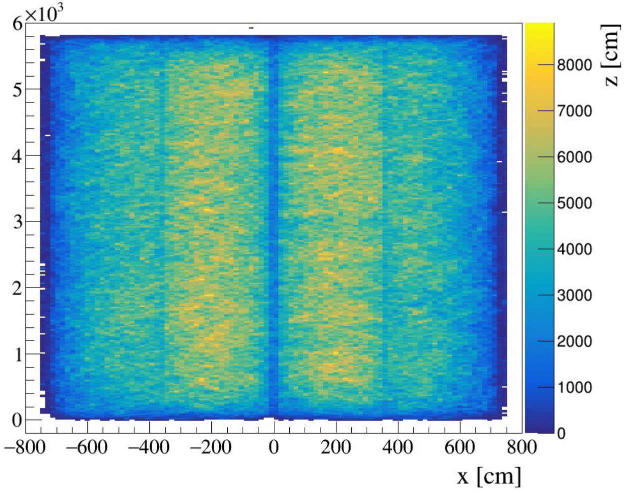


Primary, long muon hit distributions: 32 days

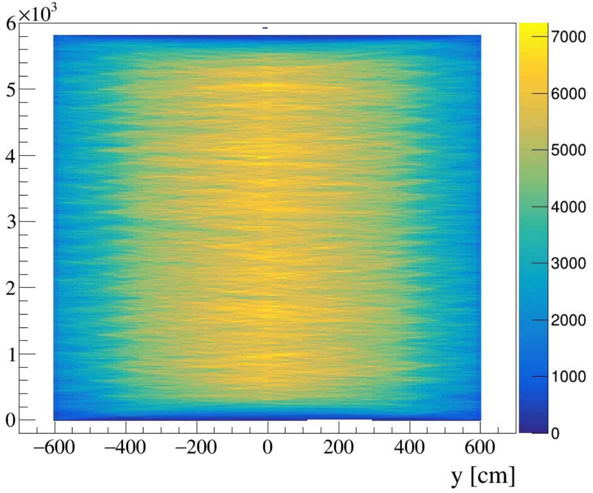
X–Y



X–Z



Y–Z



Anode-Cathode (AC)-crossing CR muons

A through-going muon is characterised as a MIP with no Bragg peak.

Such muons should therefore deposit a constant amount of charge/hit along the entire reconstructable track.

AC-crossing muons span the entire drift distance and can aid in the mitigation of drift-dependent effects.

One possible calibration technique:

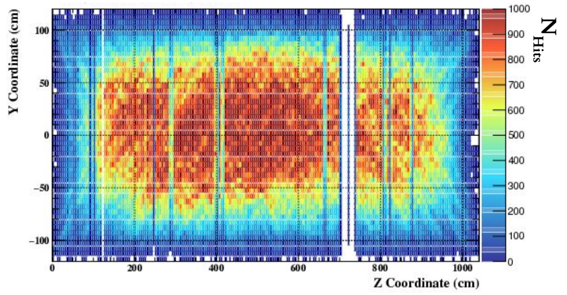
Normalise the charge depositions in the yz plane and drift direction according to the global median charge depositions in the entire plane/direction.

Track selection requirements

- Projected x-length between 2.5 & 2.7m to ensure AC crossing occurs
- Not orthogonal to the wire planes (not in $75 < |\theta_{xz}| < 105°$)
- Not parallel to any wires (not in $80 < |\theta_{yz}| < 100°$)

MicroBooNE calibration paper

This method is applied assuming electron lifetime corrections have already been made.



Distributions of number of hits in 5cm by 5cm yz plane cells in the collection plane.

Anode-Cathode (AC)-crossing CR muons

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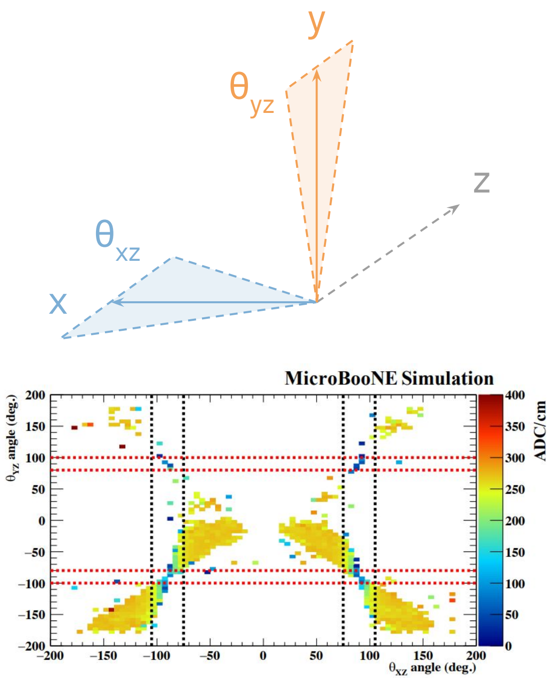
MicroBooNE calibration paper



Angular requirements on tracks to mitigate reconstruction issues.

AC-crossing CR muons (yz & x)

yz & x planes of the detector are each segmented into 5x5cm cells & 5cm bins respectively.

Each 3D hit is assigned a cell/bin based on its reconstructed yz/x coordinate.

Median charge deposition per unit length is calculated in each cell/bin (Local) and across the entire phase space (Global).

- Provided at least 5 hits in cell
- Use of *median* mitigates delta contamination, mis-reconstructed calorimetry and long dQ/dx tails
- First defined for each yz cell, followed by the correction factor definition
- Then repeated for the already-corrected x bins

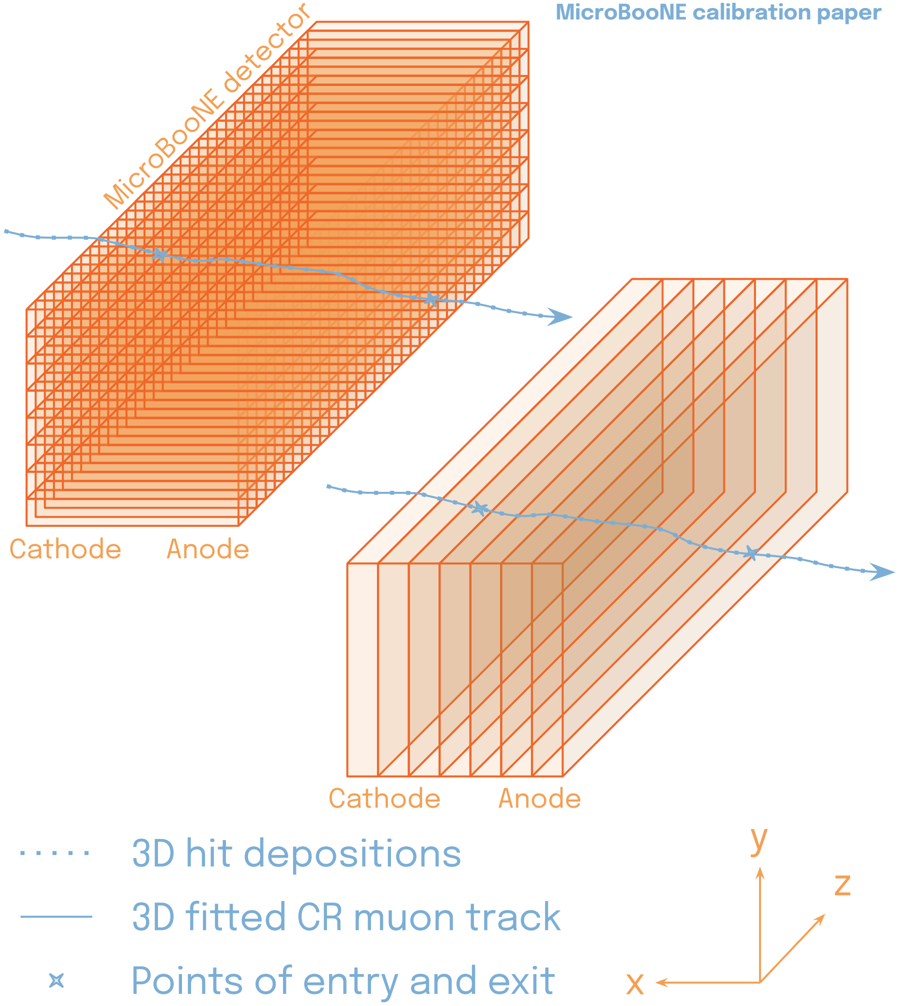
Correction factors:

$$C(y_i, z_i) = \frac{[dQ/dx]_{\text{Global}}}{[(dQ/dx)(y_i,z_i)]_{\text{Local}}}$$

$$C(x_i) = \frac{[(dQ/dx)']_{\text{Global}}}{[(dQ/dx)'(x_i)]_{\text{Local}}}$$

$\left(\frac{dQ}{dx}\right)'$ yz correction factor applied

MicroBooNE calibration paper



Stopping ν-induced muons for dE/dx calibration

Track selection requirements (MC)

- Minimum track length requirement of 1.5m
- Not orthogonal to the wire planes (**not** in 75 < $|\theta_{xz}|$ < 105°)
- Not parallel to any wires (**not** in 80 < $|\theta_{yz}|$ < 100°)
- Truth-match muons
- <5cm between reconstructed and true vertex

Nominal value of C_{Cal}

= 1/200 ADC/electron

= 5x10^{-3} ADC/electron

Analysis method (MC)

1. Begin at the end position of the stopping track and work backwards by 2m (or the track length if <2m)
   a. Ensures the Bragg Peak is considered regardless of track length
2. Segment the <2m length of track into 5cm residual range bins & fill with the Modified Box Model dE/dx, setting C_{Cal} to an arbitrary value
3. Fit Landau-Gaussian to dE/dx distribution in each bin and extract the MPV (much like Viktor's lifetime method)
4. Plot MPV's against the kinetic energy (KE) of the particle, by converting the residual range bin central value into KE using CDSA tables
5. Compare MPV vs KE with expectation from the Landau-Vavilov function using:

$$\chi^2 = \sum \left(\frac{(MPV(dE/dx)_{\text{Predicted}} - MPV(dE/dx)_{\text{Measured}})^2}{\sigma^2} \right), 250 < \text{KE} < 450\text{MeV}$$

where σ is the uncertainty associated with the MPV from the fit

Modified Box Model

$$\left(\frac{dE}{dx}\right)_{\text{Calibrated}} = \frac{\exp\left(\frac{\left(\frac{dQ}{dx}\right)''}{C_{\text{Cal}}} \cdot \frac{\beta' W_{\text{ion}}}{\rho\epsilon}\right) - \alpha}{\frac{\beta'}{\rho\epsilon}}$$

$\left(\frac{dQ}{dx}\right)''$ = Calibrated charge depositions

C_{Cal} = Calibration constant to convert ADC values to number of electrons

W_{ion} = 23.6 x10^{-6} MeV/electron

ε = 0.273 kV/cm (electric field strength)

ρ = 1.38 g/cm^3

β = 0.212 (kV/cm)(g/cm^3)/MeV

α = 0.93

Measured by ArgoNeuT

Stopping ν-induced muons for dE/dx calibration

- Repeat steps 2-through-5 from the previous slide a few times (~10), varying C_{Cal} with every iteration
- Plot χ^2 vs C_{Cal} and fit with a second-order polynomial to determine the value of C_{Cal} which corresponds to the lowest χ^2
- Re-calculate dE/dx using this value of the constant
  RHS: ($5.077 \pm 0.001 \times 10^{-3}$) ADC/e
- Compare with the un-corrected dE/dx distribution