The New Role of Transverse Diffusion in LArTPC Energy Scale Calibration

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Introduction

- Diffusion in the direction transverse to the drift field elongates the thickness of charged particles that a wire (or pixel) in a LArTPC is sensitive to
  - This changes the distribution of energy loss seen by each channel
- I will introduce this effect and its impact on LArTPC calibration
  - This is written up in arxiv:2205.06745
- I am also applying these results in my work calibrating the energy scale in the ICARUS detector
- I will show the (very) initial results from this work and discuss whether we can use this effect to measure transverse diffusion in LAr

Outline

1. Description of the effect
2. Impact on LArTPC detectors
3. Application at ICARUS / SBN

1. Description of the Effect

Energy Loss by Elastic Scattering

- Charged particles (such as muons) lose energy in elastic collisions with atomic electrons
- Above the mean excitation energy, this is described by the Rutherford formula:

$$\rho_e \frac{d\sigma}{dT} = \zeta T_{max} \frac{1 - \beta^2 T/T_{max}}{T^2}$$

- T: energy transfer to the electron
- T_{max}: maximum energy transfer in a single collision
- $1/\zeta$: electron scattering length
- β: charged particle velocity
- ρ_e: electron number density

Energy Loss by Elastic Scattering

- Rutherford Formula:

$$\rho_e \frac{d\sigma}{dT} = \zeta T_{max} \frac{1 - \beta^2 T/T_{max}}{T^2}$$

Important Parameters

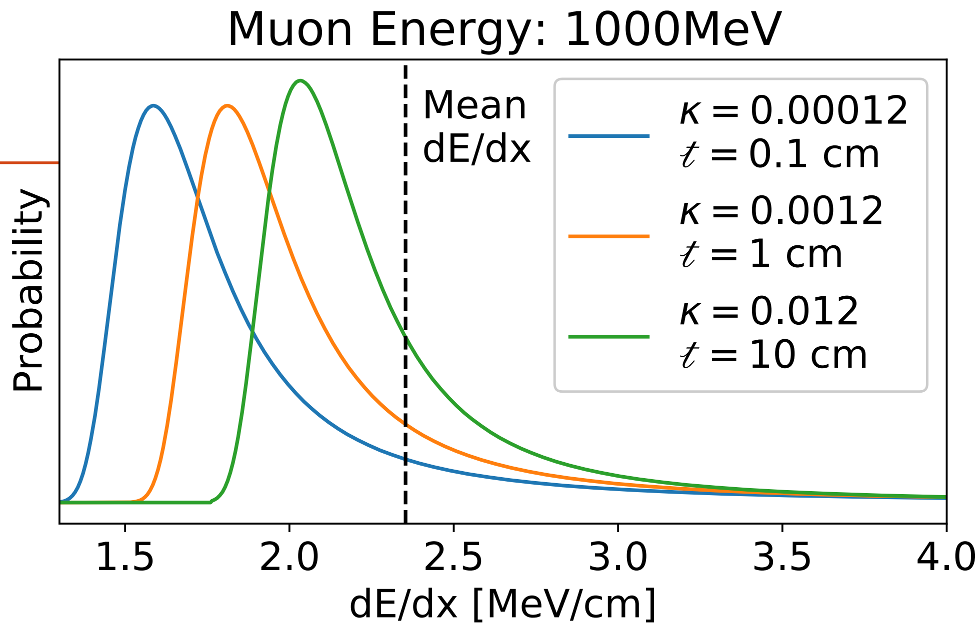
- T_{max}: decreases with decreasing particle energy
- ζ: increases with decreasing particle energy

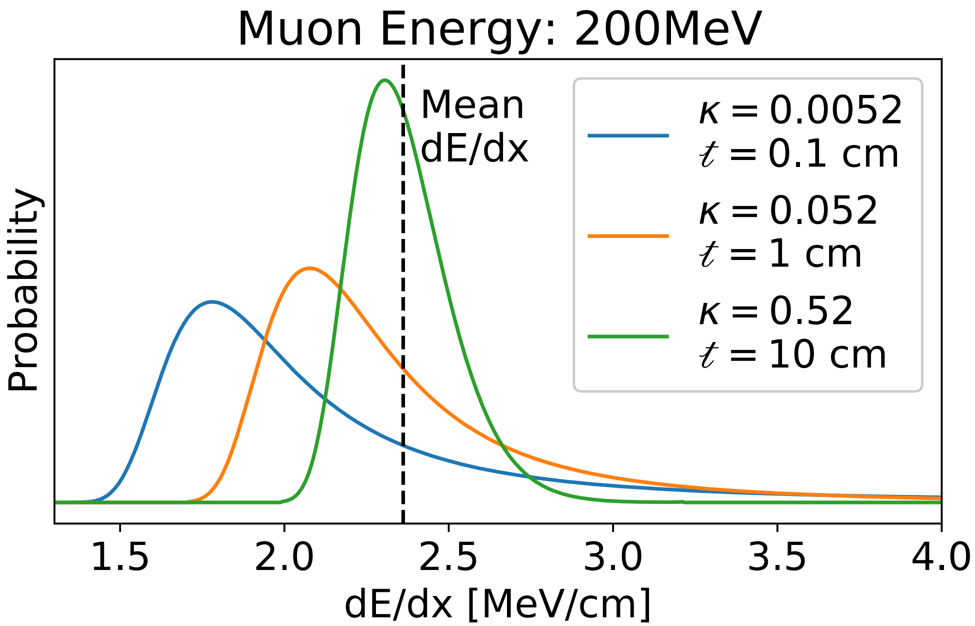
Due to the power-law behavior of Rutherford scattering, muons lose much of their energy in a small number of large energy-transfer collisions (delta rays)

Energy Loss: Landau-Vavilov

- The distribution of energy loss observed by a channel is strongly affected by the chance it will include a delta ray
- This depends on the film-thickness κ:
  - $\kappa = \zeta \times (\text{Channel Thickness}, t)$

$\kappa < 0.01$	$\kappa > 0.01$
Landau Distribution	Landau-Vavilov Distribution

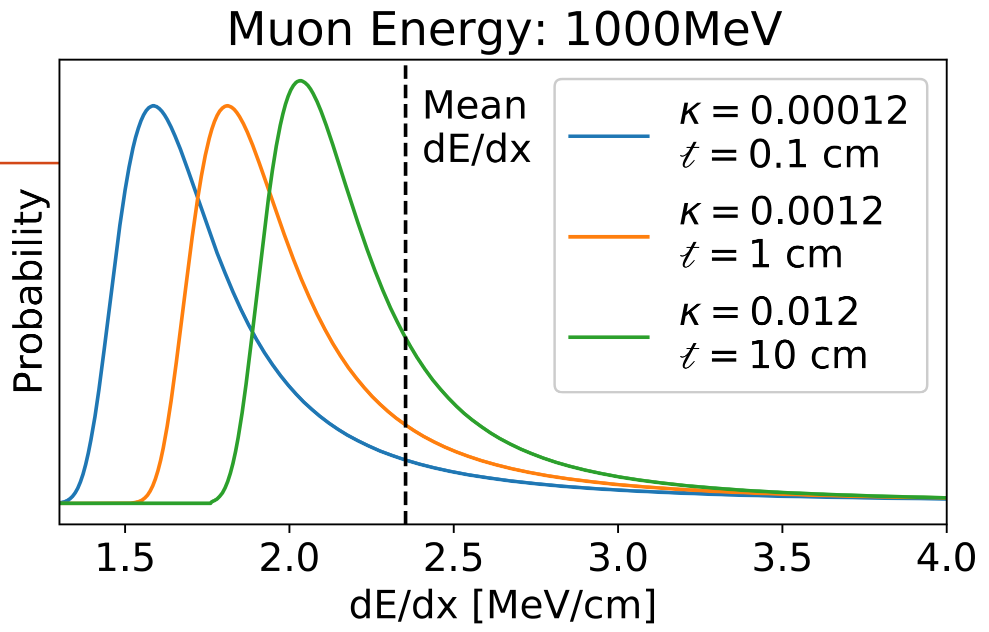


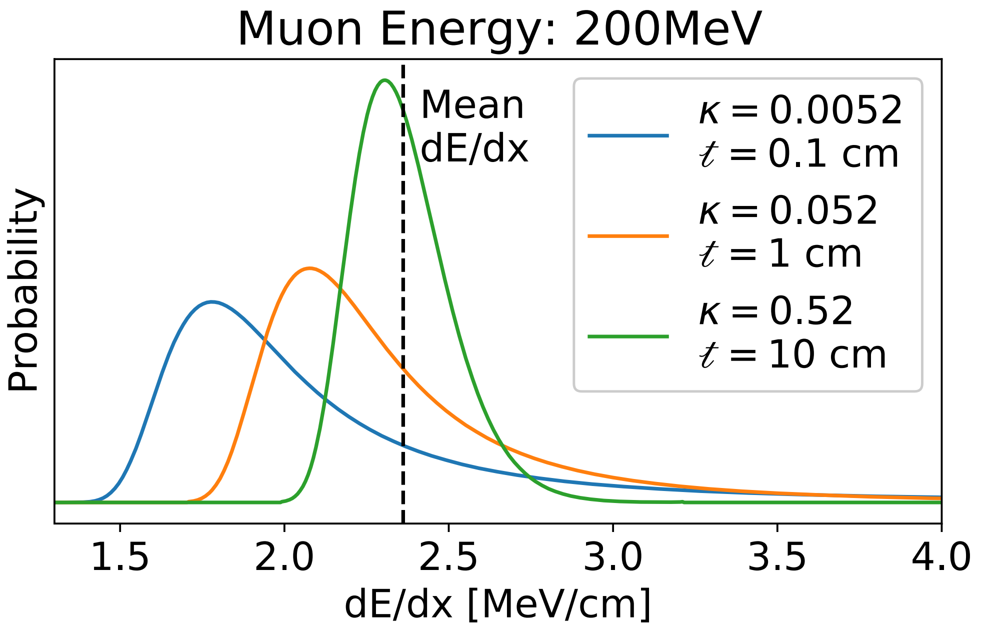


Energy Loss: Landau-Vavilov

- $\kappa = \zeta \times (\text{Channel Thickness}, t)$

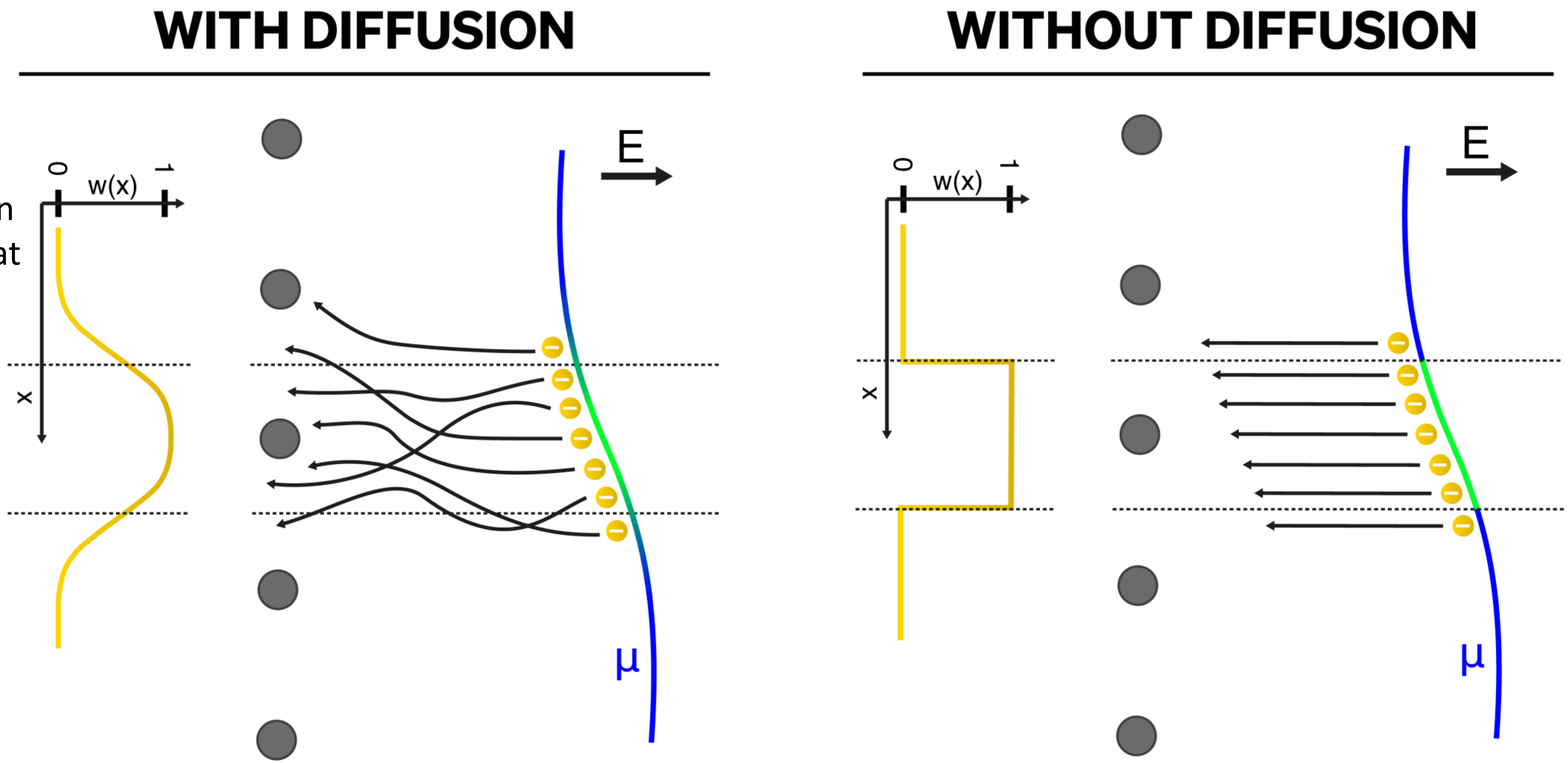
$\kappa < 0.01$	$\kappa > 0.01$
Landau Distribution	Landau-Vavilov Distribution
$\frac{dE}{dx}_{MPV} = \overline{\frac{dE}{dx}} + \zeta T_{max}(\log\kappa + 0.2 + \beta^2)$	No analytic formula for the MPV dE/dx
Mean dE/dx depends on atomic effects not modelled by the Rutherford cross section	
Logarithmic dependence of MPV on thickness	Sub-logarithmic dependance of MPV on thickness





Diffusion Changes the Thickness!

w(x): **weight function** which gives a weight to how much ionization charge a wire will see at each point along the muon trajectory.



- Diffusion transverse to the drift direction (and the wire direction) thickens the length of the muon that each wire is sensitive to

Energy Loss in the Presence of Diffusion

	$\kappa < 0.01$	$\kappa > 0.01$
No Diffusion	Landau Distribution Thickness determined by wire pitch: $\wp = \int w(x)\, dx$ w(x): step function.	Landau-Vavilov Distribution
With Diffusion	Landau Distribution Thickness: $t = \wp\, e^{-\int w(x) \log w(x) dx\, /\wp}$ w(x): convolution of the step-function wire and Gaussian diffusion	Diffuse-Landau-Vavilov Distribution

Details of derivation in arxiv:2205.06745

Energy Loss in the Presence of Diffusion

	$\kappa < 0.01$	$\kappa > 0.01$
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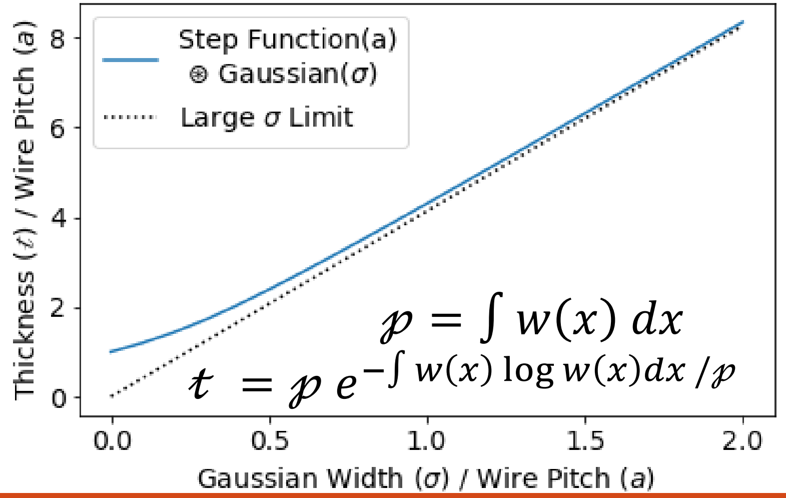
With Diffusion	Landau Distribution Thickness:	Diffuse-Landau-Vavilov Distribution

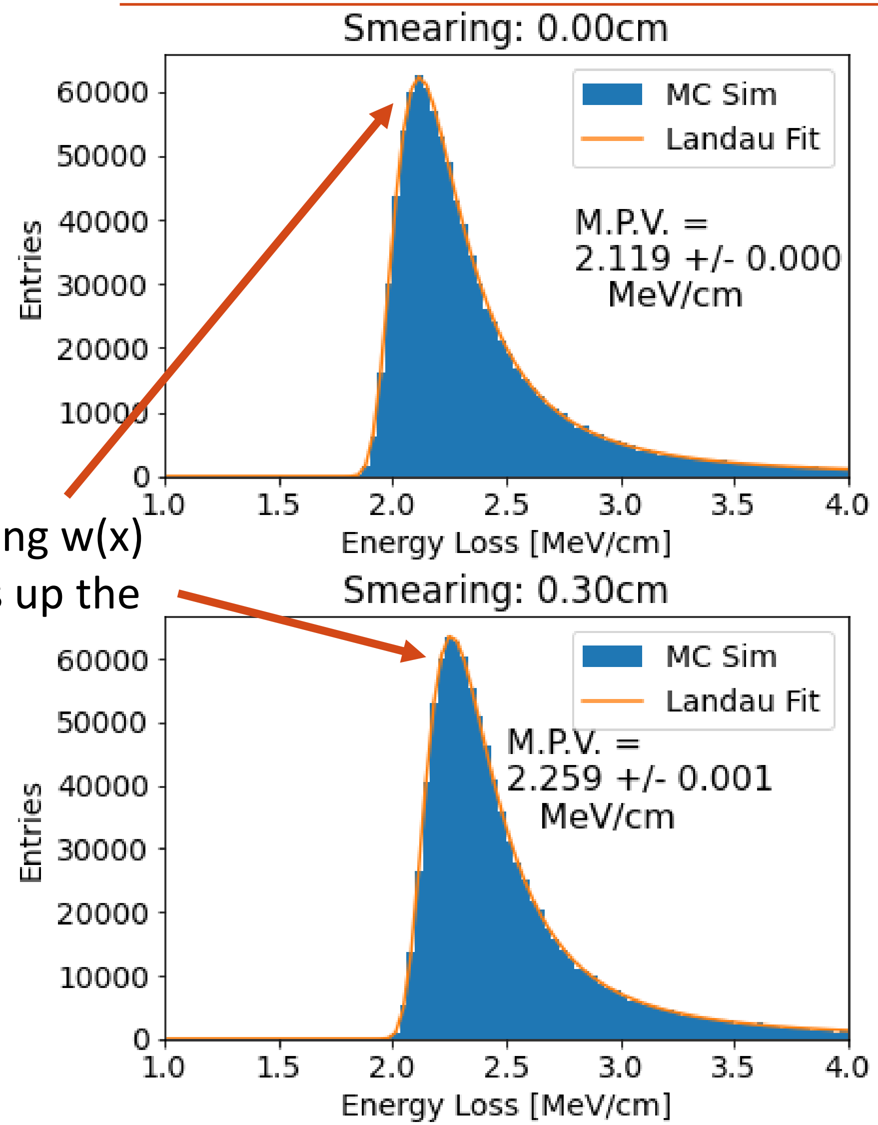


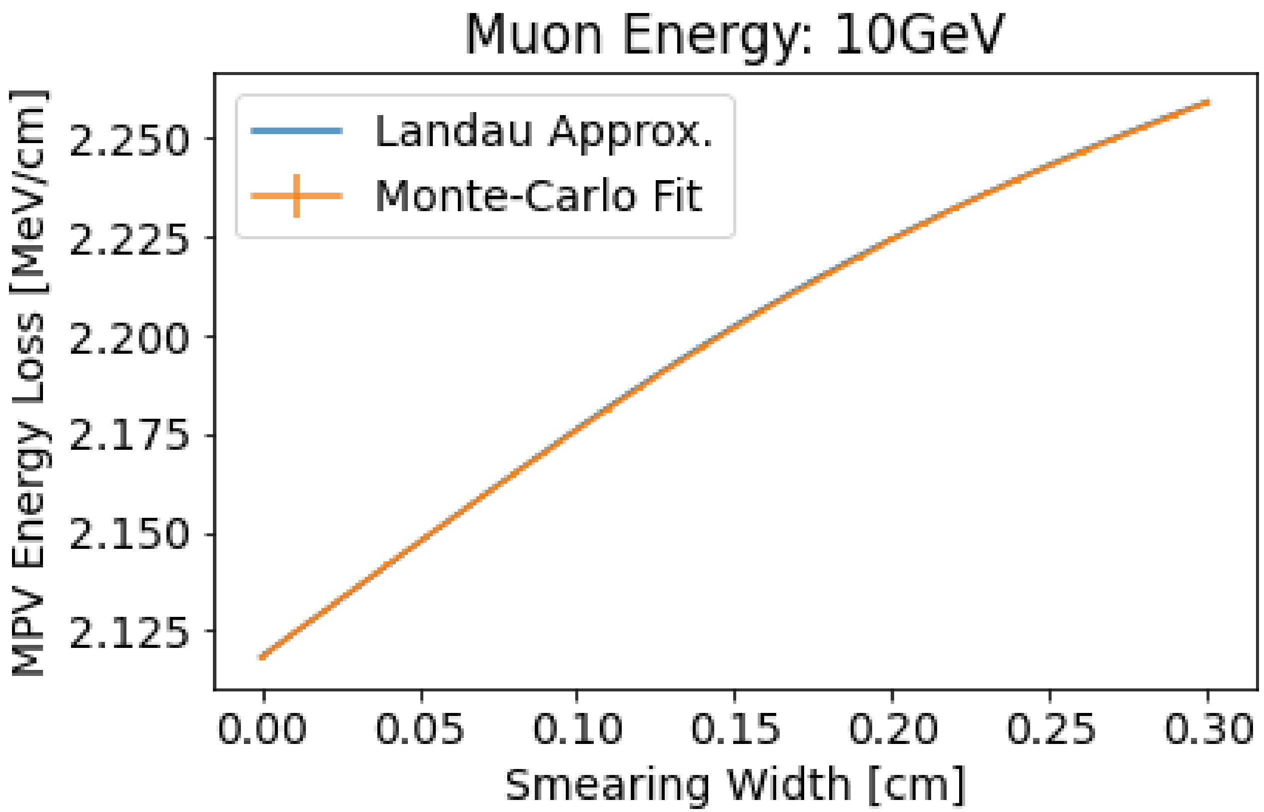
Details of derivation in arxiv:2205.06745

Effect on the MPV: Toy MC

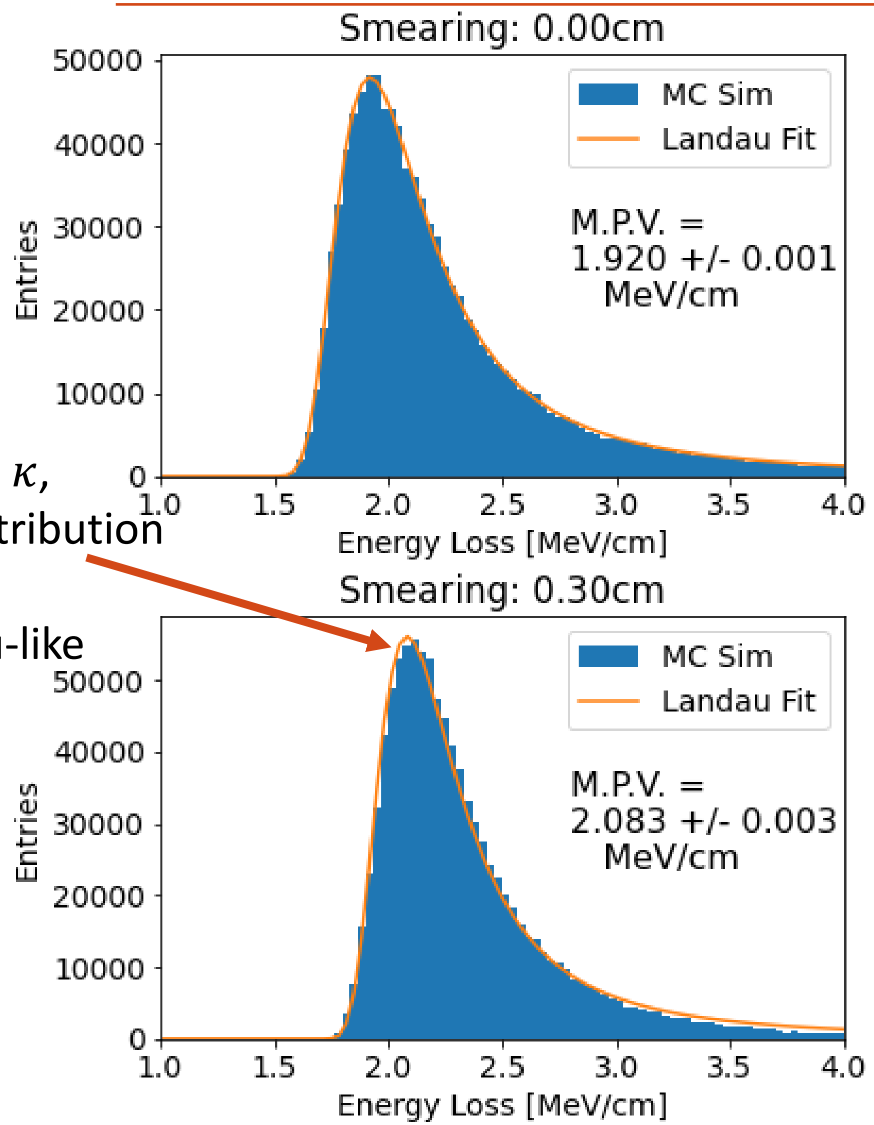
- Results from a toy MC of muon energy loss in LAr, for a wire spacing of 3mm

Smearing w(x) Pushes up the MPV!



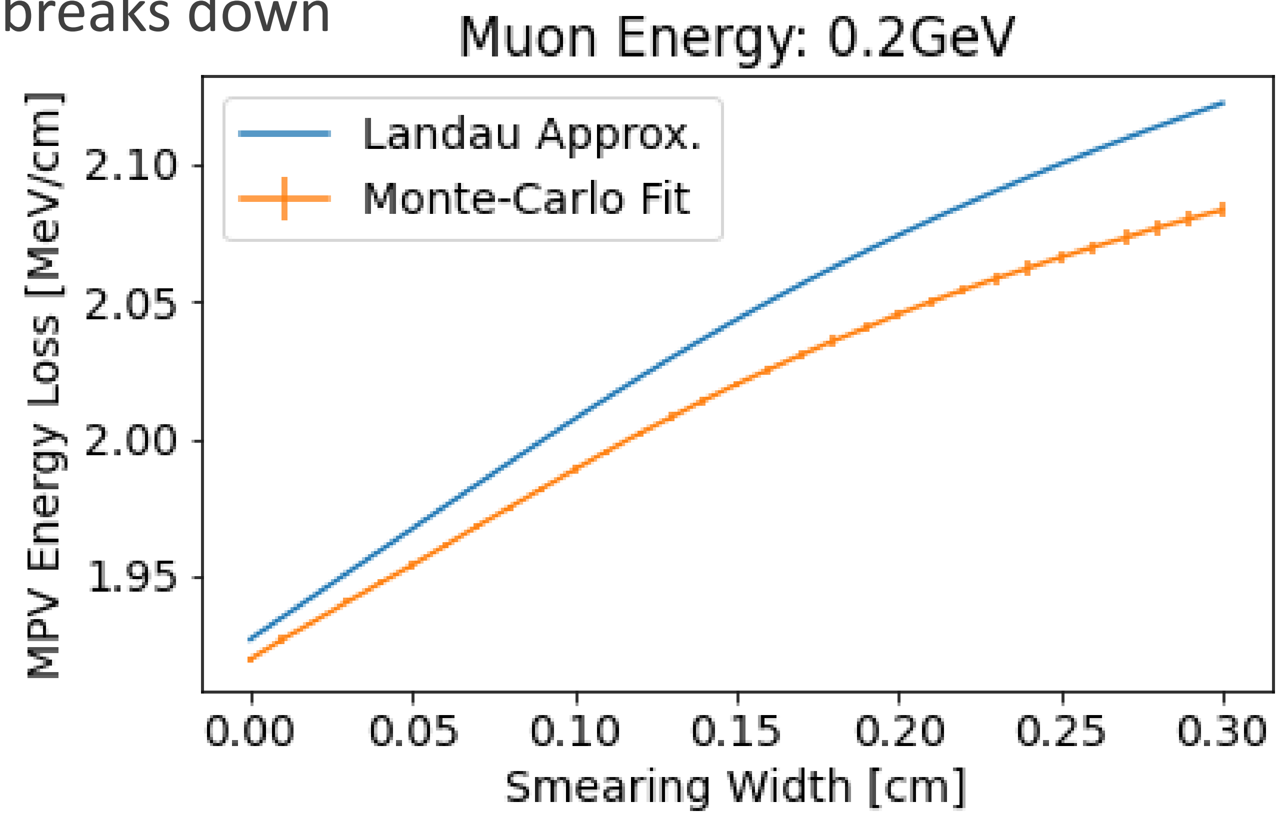


Effect on the MPV at Large Thickness



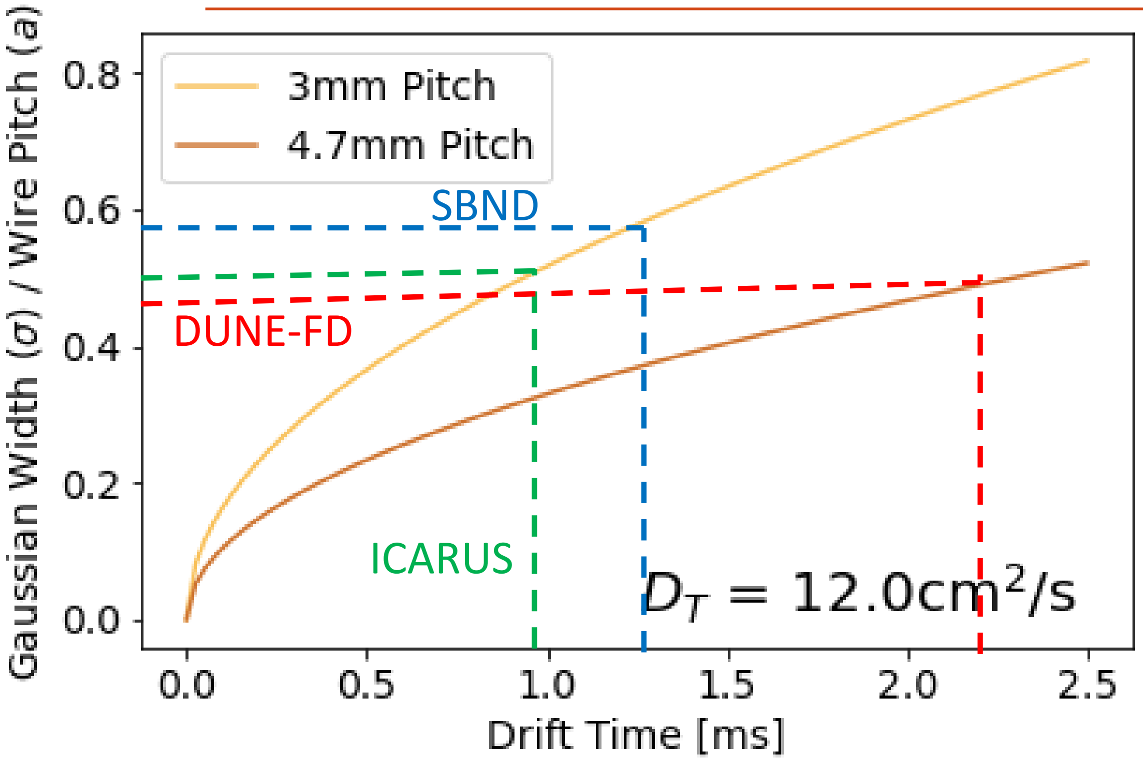
At high κ, the distribution is less Landau-like

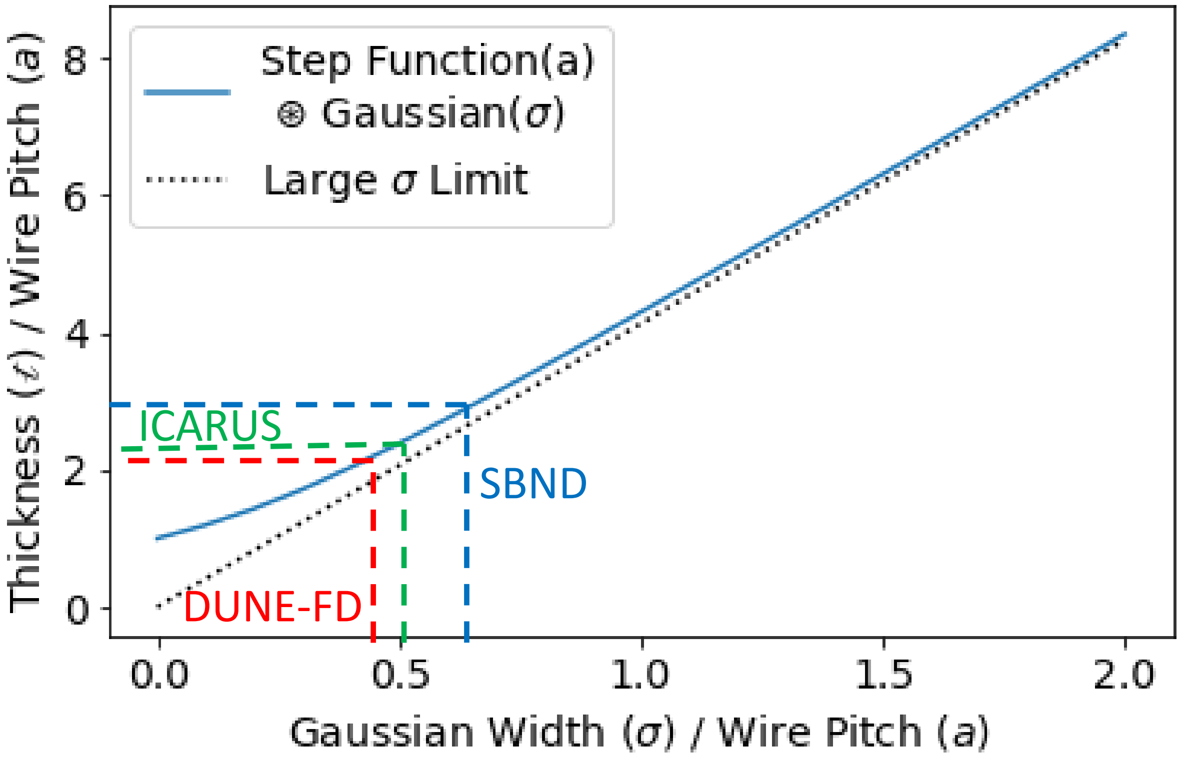
- Results from a toy MC of muon energy loss in LAr, for a wire spacing of 3mm
- At large thickness (κ), the Landau approximation breaks down



2. Impact on Detectors

Impact of Diffusion on Thickness at Detectors





$$\sigma_T = \sqrt{2 D_T t_{drift}}$$

$$p = \int w(x)\, dx$$

$$t = p\, e^{-\int w(x) \log w(x) dx \,/ p}$$

w(x): convolution of the step-function wire and Gaussian diffusion

- At the cathode, the effect of diffusion about doubles the channel thickness relative to the wire pitch

Impact on MPV in Relevant Detectors

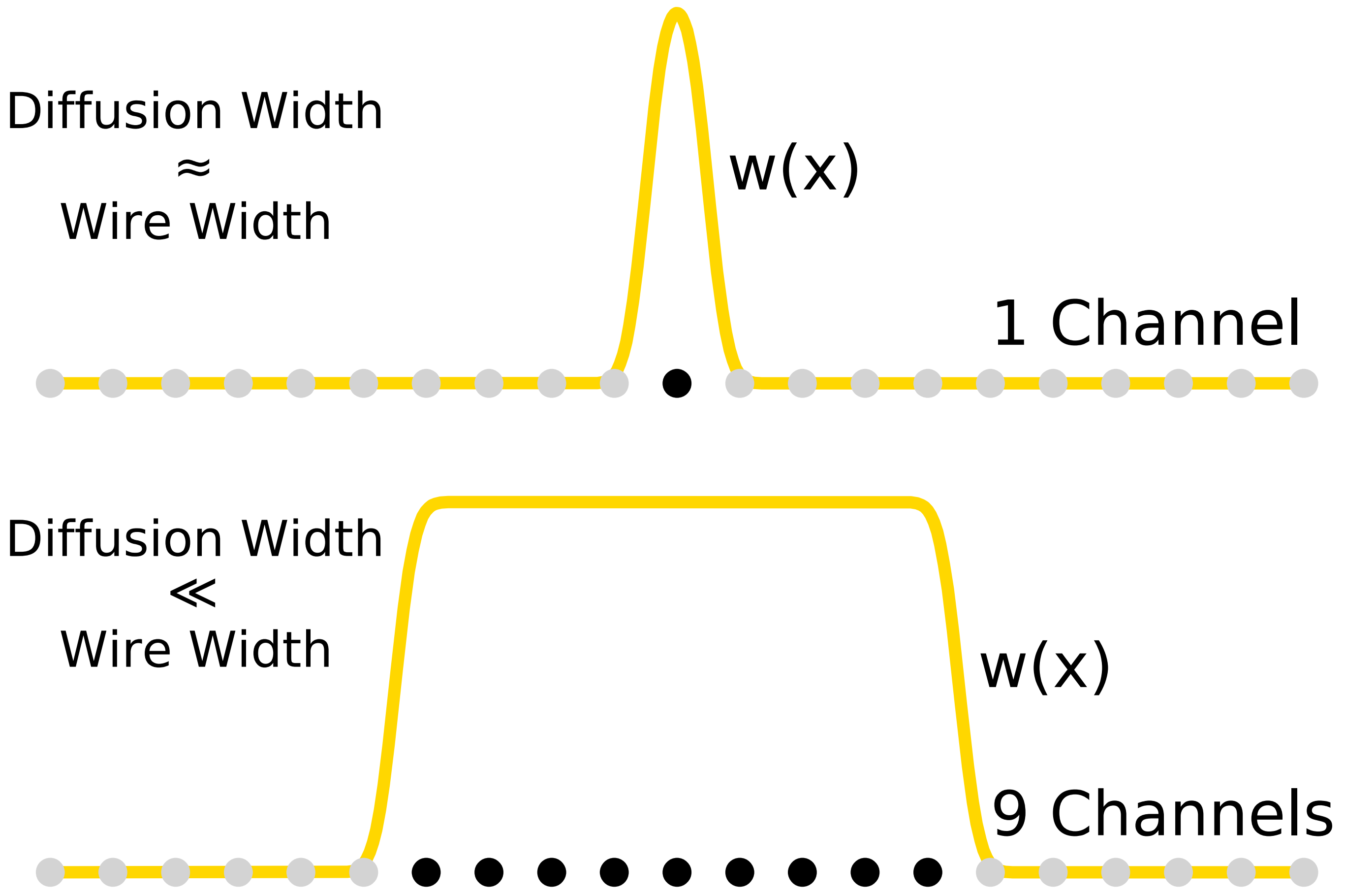
MPV Energy Loss for a 1 GeV Muon

Detector	Wire Pitch [mm]	Drift Time [ms]	Diff. Const. D_T [cm^2/s]	MPV dE/dx, No Diffusion [MeV/cm]	MPV dE/dx at Cathode (Full Diff.) [MeV/cm]
MicroBooNE [4]	3.00	2.33	5.85	1.69	1.79
ArgoNeuT [3]	4.00	0.295	12.0 (9.30)	1.72 (1.72)	1.76 (1.75)
ICARUS [5]	3.00	0.960	12.0 (9.30)	1.69 (1.69)	1.78 (1.77)
SBND [5]	3.00	1.28	12.0 (9.30)	1.69 (1.69)	1.79 (1.78)
DUNE-FD (SP) [7]	4.71	2.2	12.0 (9.30)	1.74 (1.74)	1.82 (1.81)

- This translates into a few percent change to the MPV dE/dx at the cathode

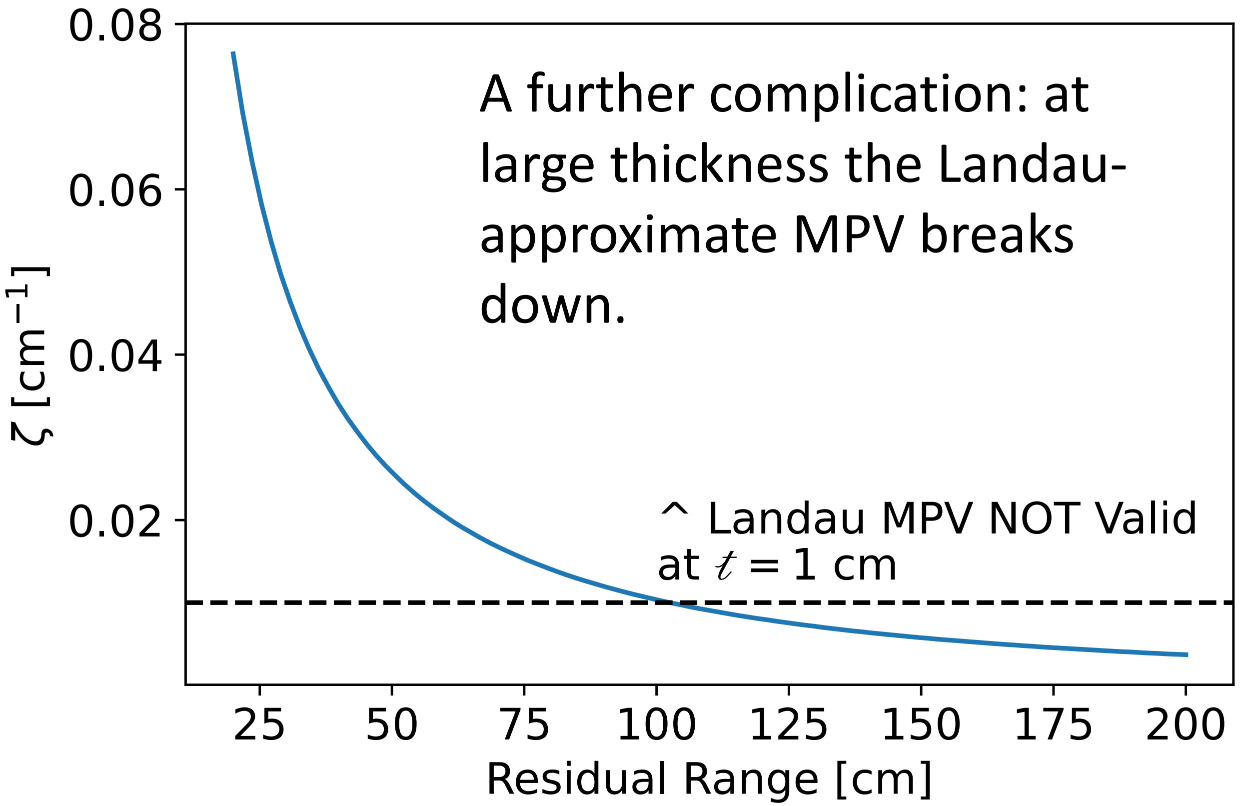
Effect on Calibration: Detector Normalization

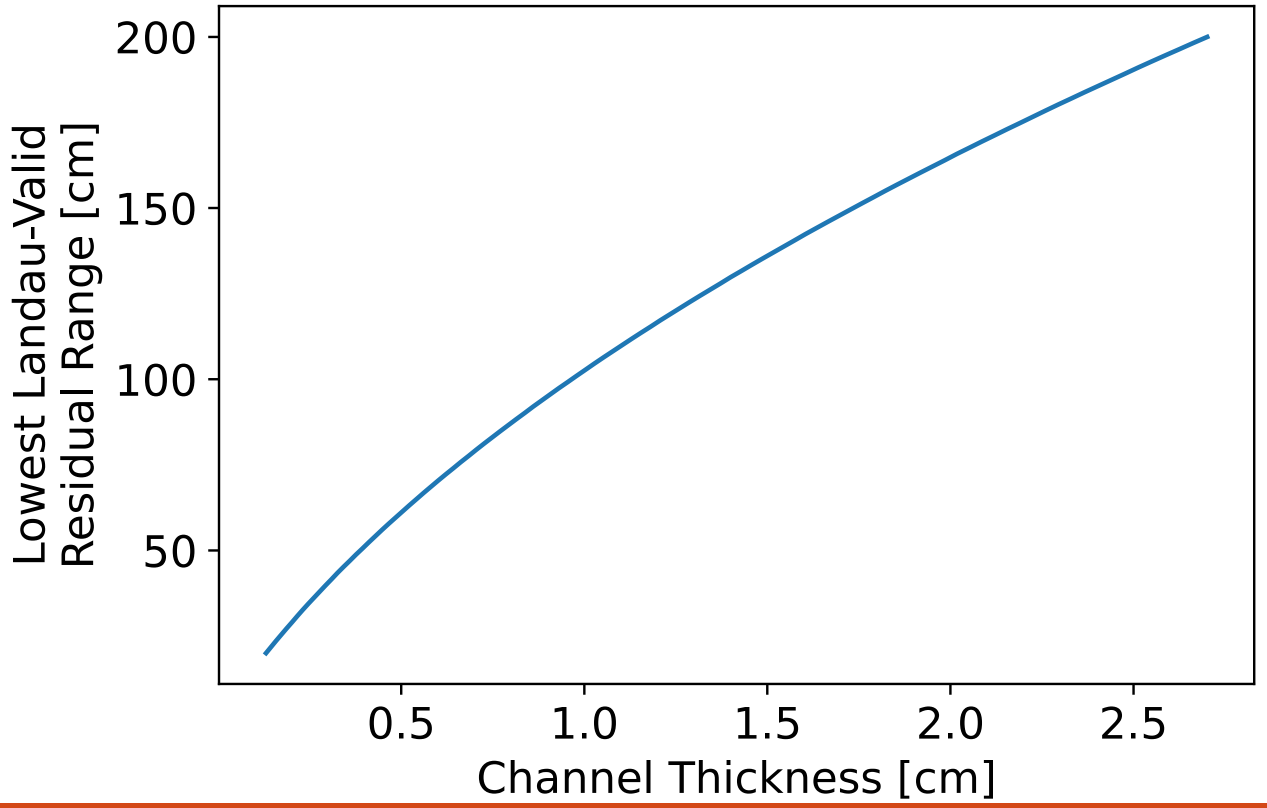
- A usual step in the calibration: look at dQ/dx from cosmic muons, make it flat across the detector
- In the presence of diffusion: we cannot assume the dQ/dx should be flat across the drift time
  - Since the **underlying dE/dx distribution is changing**
- A remedy for this: coarse-grain the detector



Effect on Calibration: Energy Scale Calibration

- In order to calibrate to the correct energy scale, one needs to include the effect of diffusion
- Bin hits in terms of the (diffusion influenced) thickness!





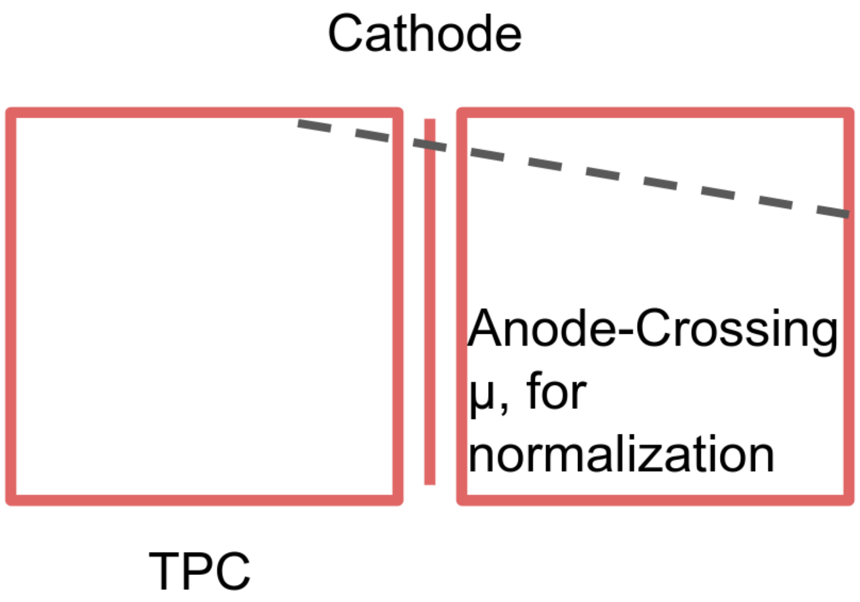
ICARUS Calibration So Far

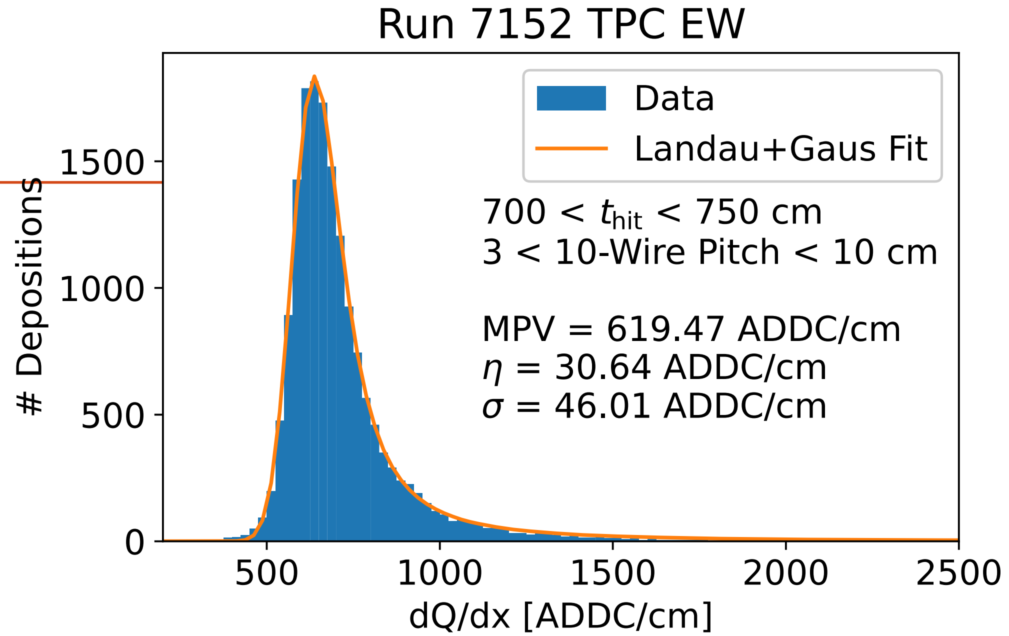
Preliminary ICARUS Calibration Procedure

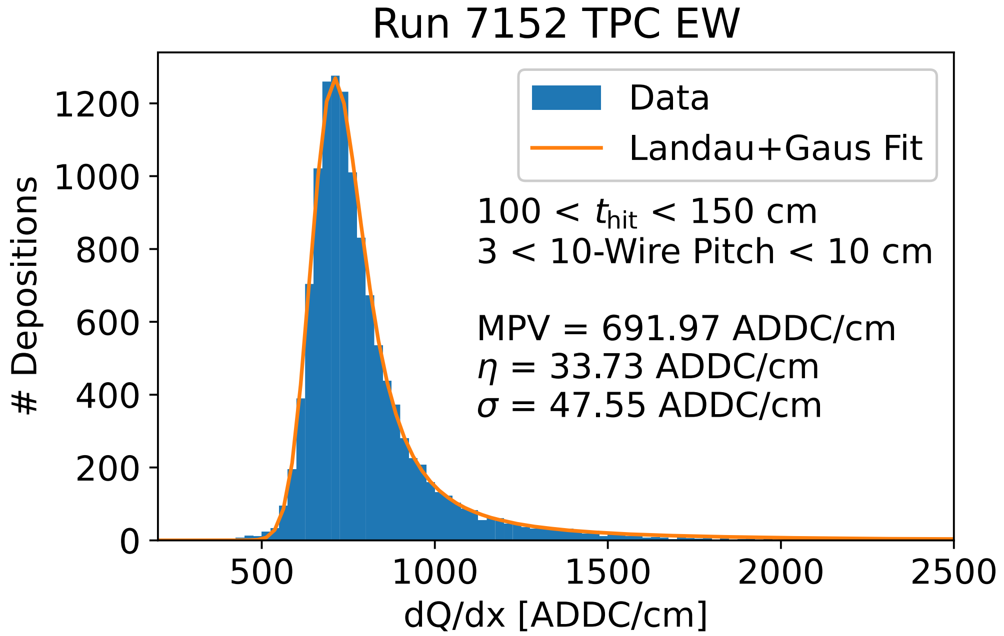
- Two steps:
  - Normalize the detector response in the drift direction
  - Calibrate the energy scale
- We have not yet included corrections for field distortions
- Normalizing the detector response across other axes (such as the wire number) is being worked on

Drift Normalization

- Use depositions from cathode+anode crossing tracks to normalize the detector response in the drift direction
- Compute per-TPC per-run
- Reconstruct dQ/dx in groups of 10 wires







ADDC: Analog to Digital Deconvolved Count

Drift Normalization

- Use depositions from cathode+anode crossing tracks to normalize the detector response in the drift direction
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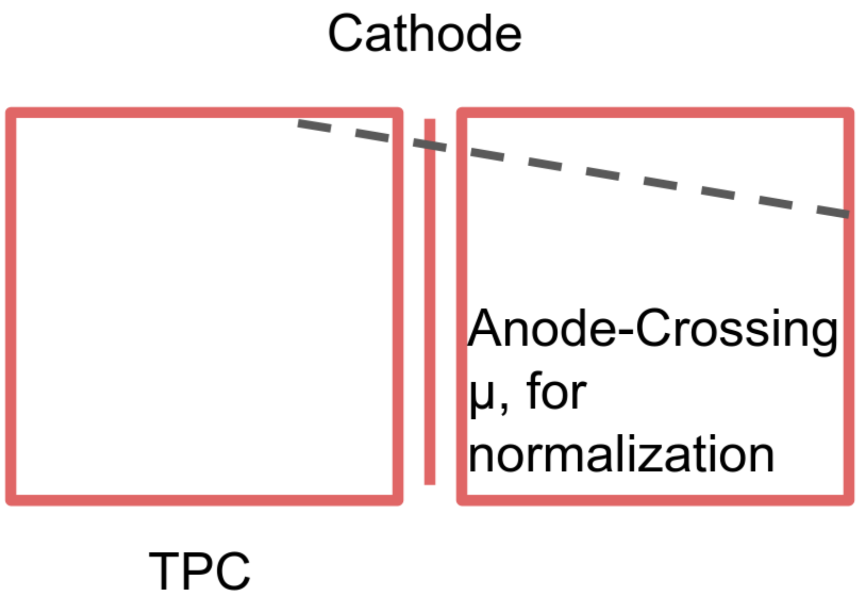
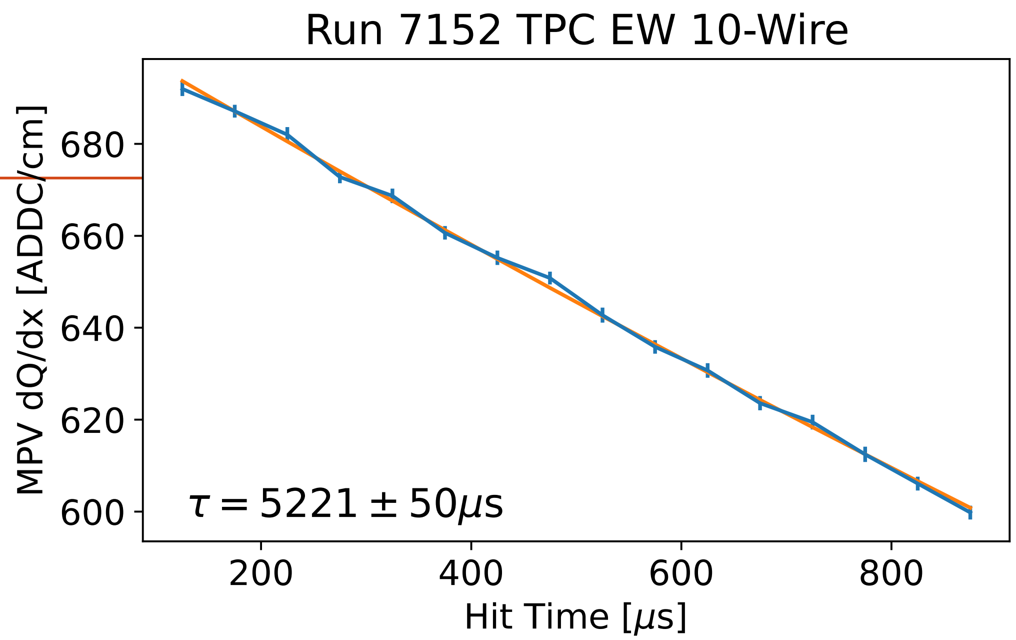
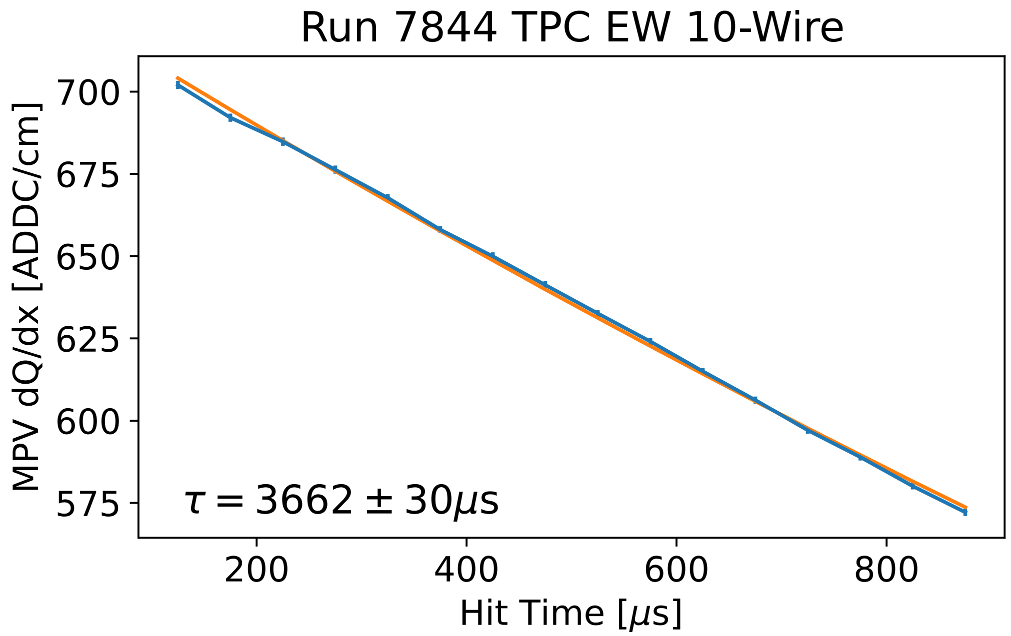
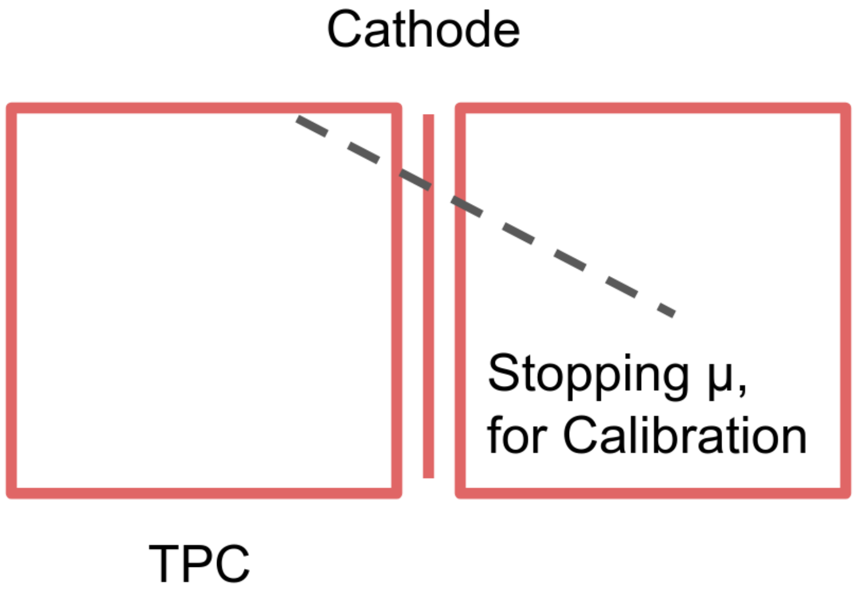


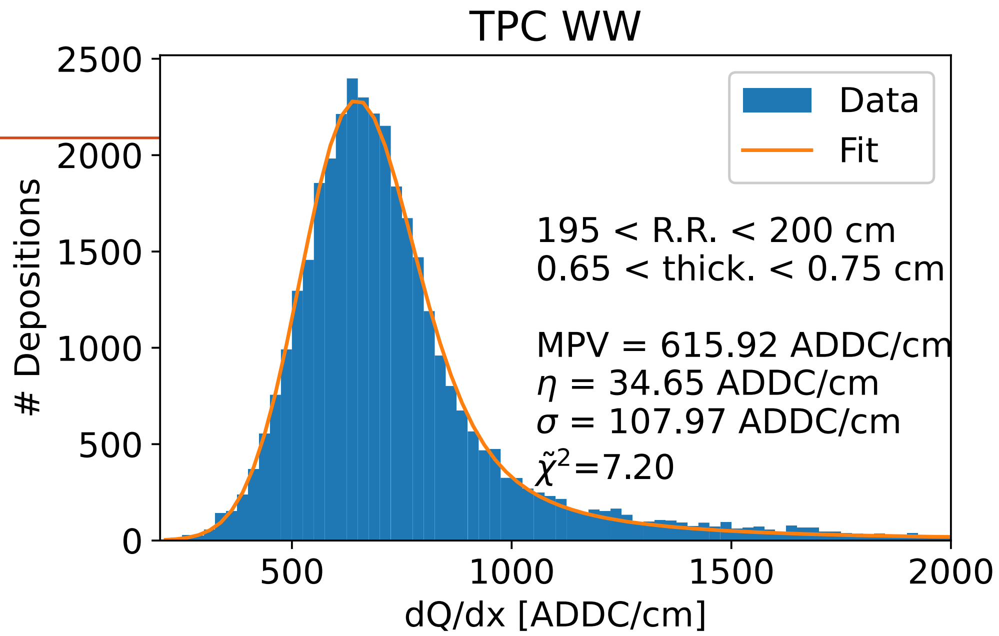


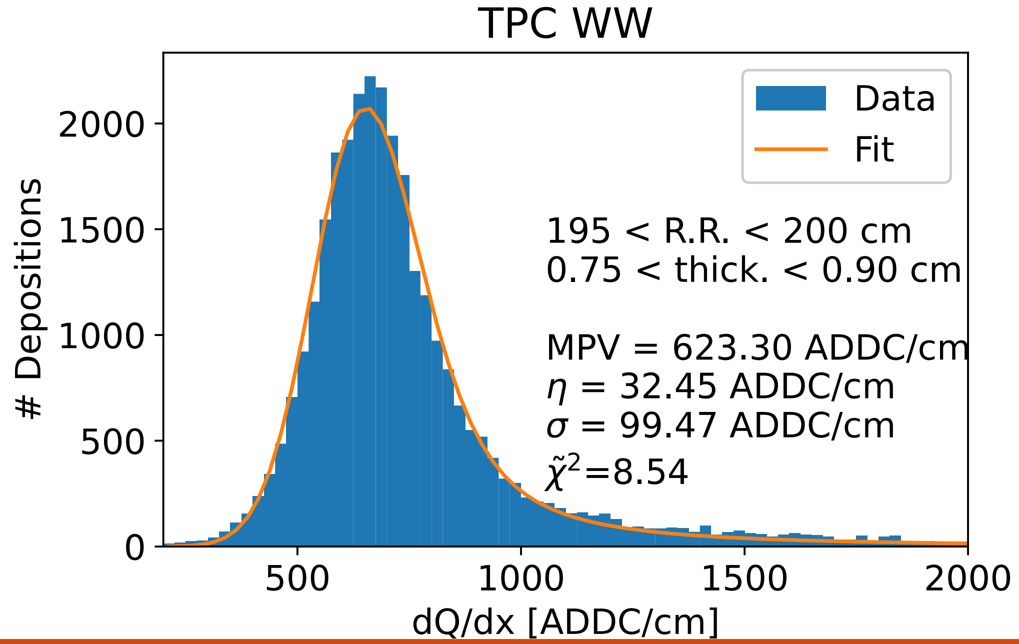


Energy Scale Calibration

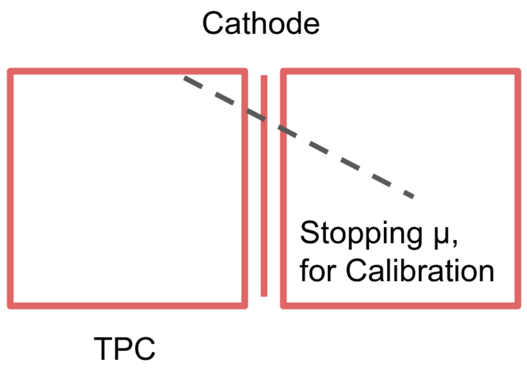
- Use depositions from stopping tracks to calibrate the energy scale
- Bin hits in TPC, thickness, and Residual Range



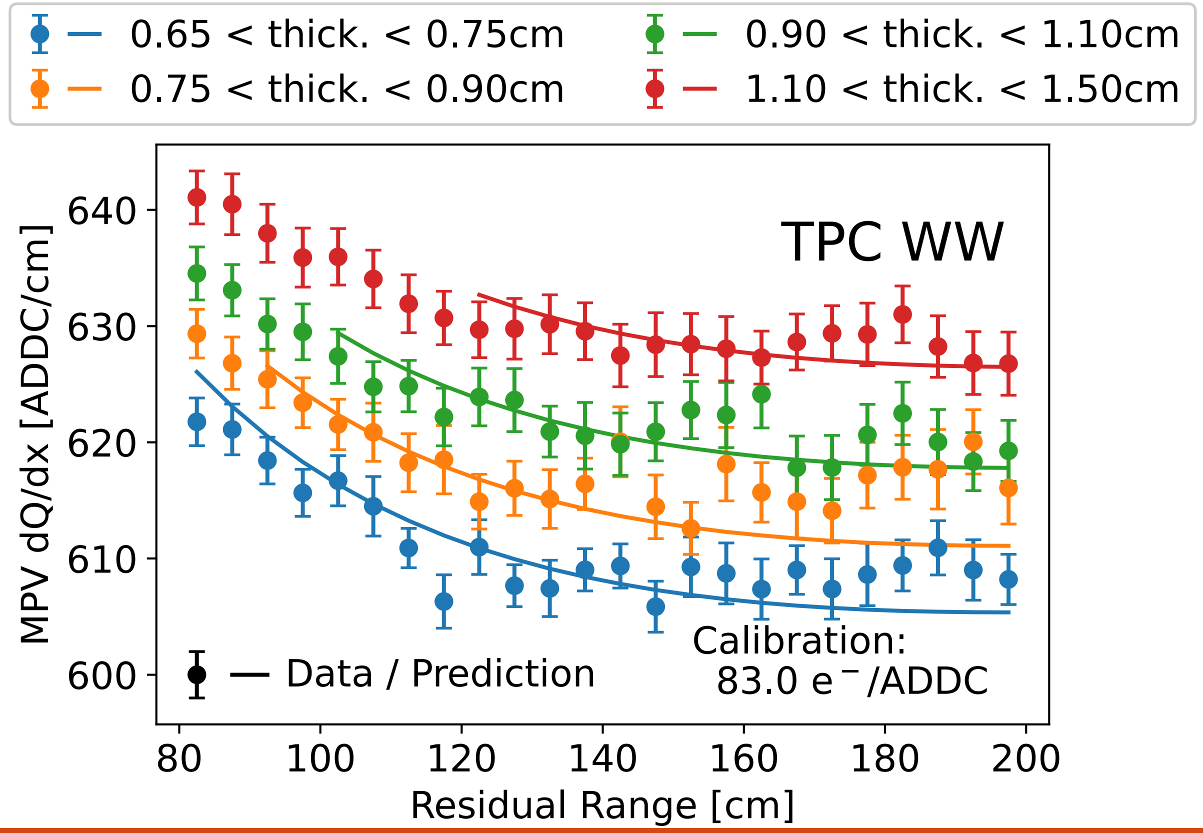


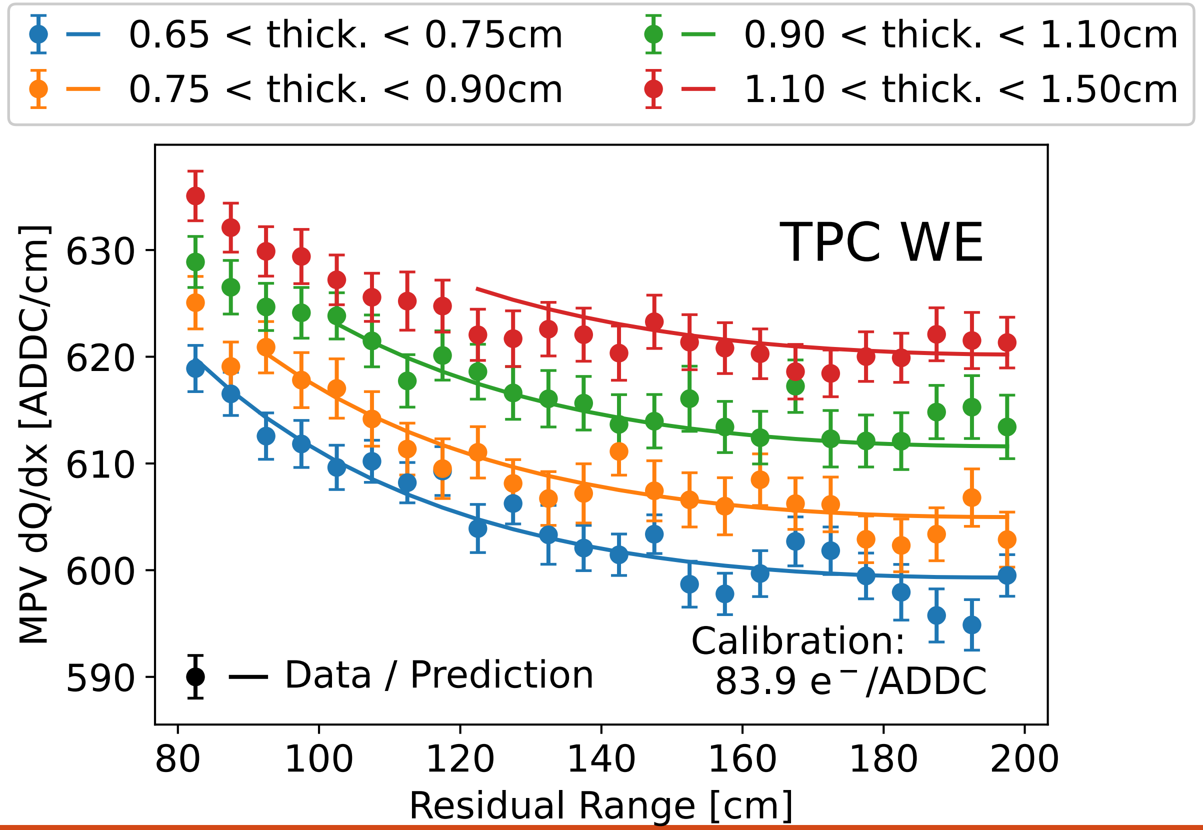


Energy Scale Calibration: Fit



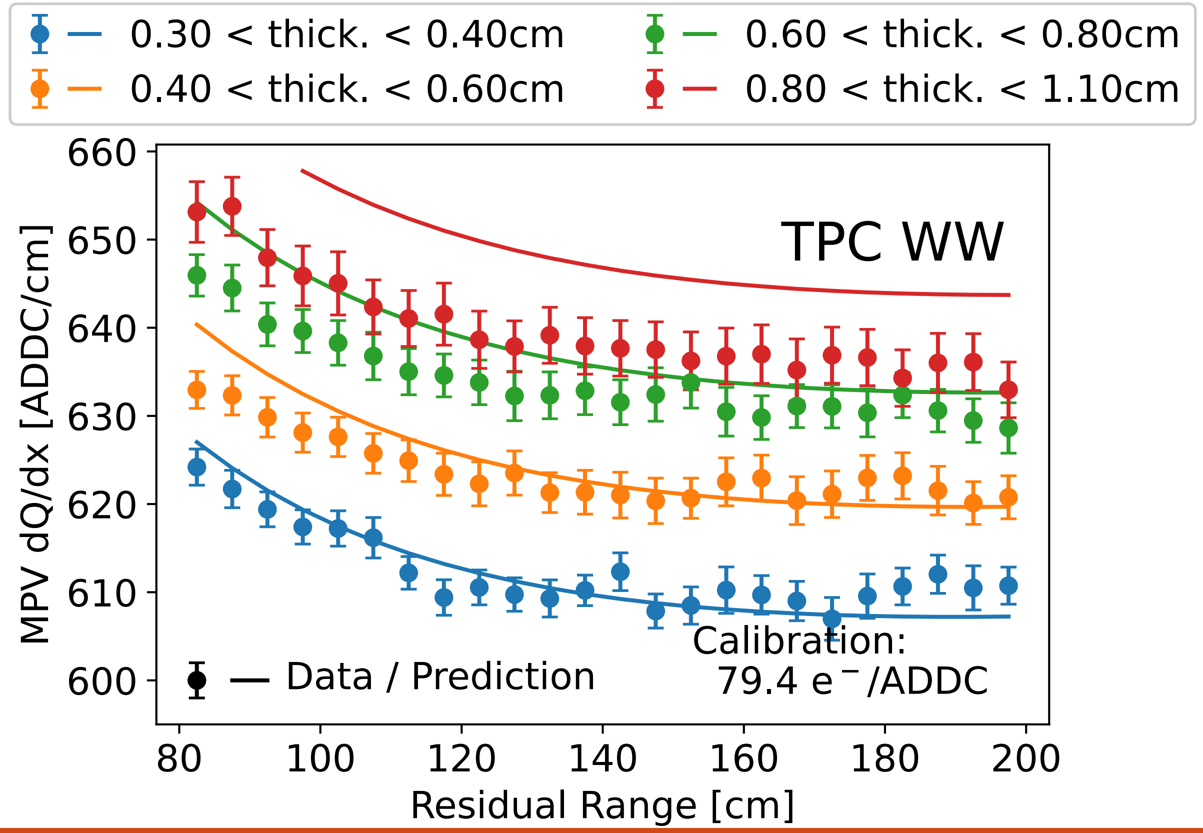
- Fit calibration constant using Landau MPV dE/dx with ArgoNeuT Recombination model
- Fit done on lowest thickness; higher bins show extrapolation (where $\kappa < 0.01$)

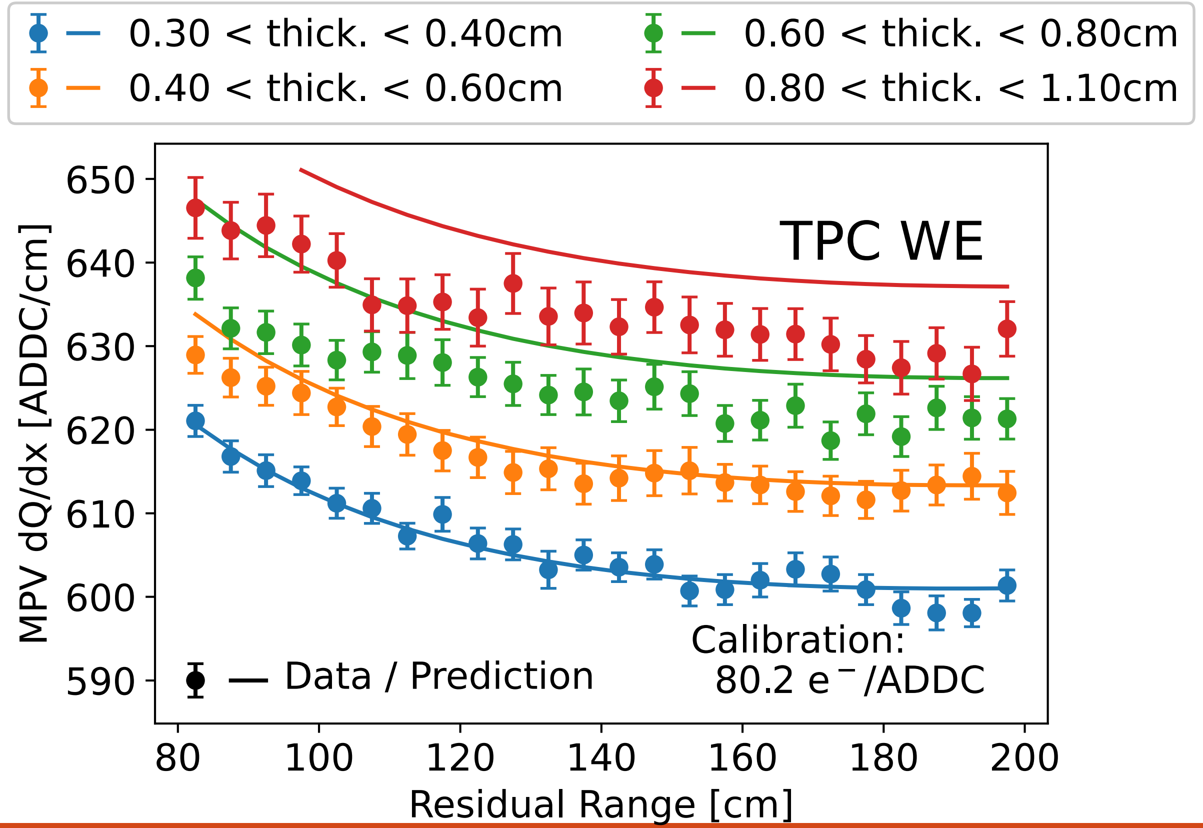




No Diffusion Energy Scale Calibration

- If you neglect diffusion in the thickness, the extrapolation doesn't work!
- Diffusion increases the thickness and smears it between bins – the change in the MPV is over-estimated if you neglect it





Can We Measure Transverse Diffusion?

- The energy scale we calibrate to depends on transverse diffusion, and right now represents a large systematic uncertainty
- ….so why don't we use the dataset to measure transverse diffusion using a "calorimetric" method?
- The early indication is that we can use different angle and drift time bins to fit for the diffusion constant
- In addition to producing a new measurement, it would also provide a more precise calibration

How do Systematics Compare to Width Measurements?

- We can use the MicroBooNE result to look at the relevant systematics in large-scale detectors
- Of the relevant uncertainties, only the Response Function applies to the "calorimetric" measurement
  - Contamination from longitudinal diffusion also does not apply here
- One downside: the "calorimetric" measurement likely has less statistical power

Systematic	**Value**
Response Function	6.5%
Drift Velocity	+3.9%, -4.1%
D_T	$< 1\%$
Waveform Summation	$< 1\%$
Noise and microphysics	$< 1\%$
Total	+7.6%, -7.7%

Systematics in the MicroBooNE width-based measurement of longitudinal diffusion

Conclusion

- Transverse diffusion changes the wire thickness in a LArTPC, and therefore the Most-Probable-Value of energy loss
- At ICARUS we have designed an energy scale calibration that is resilient to these effects
- As part of the calibration, we may be able to measure the transverse diffusion constant