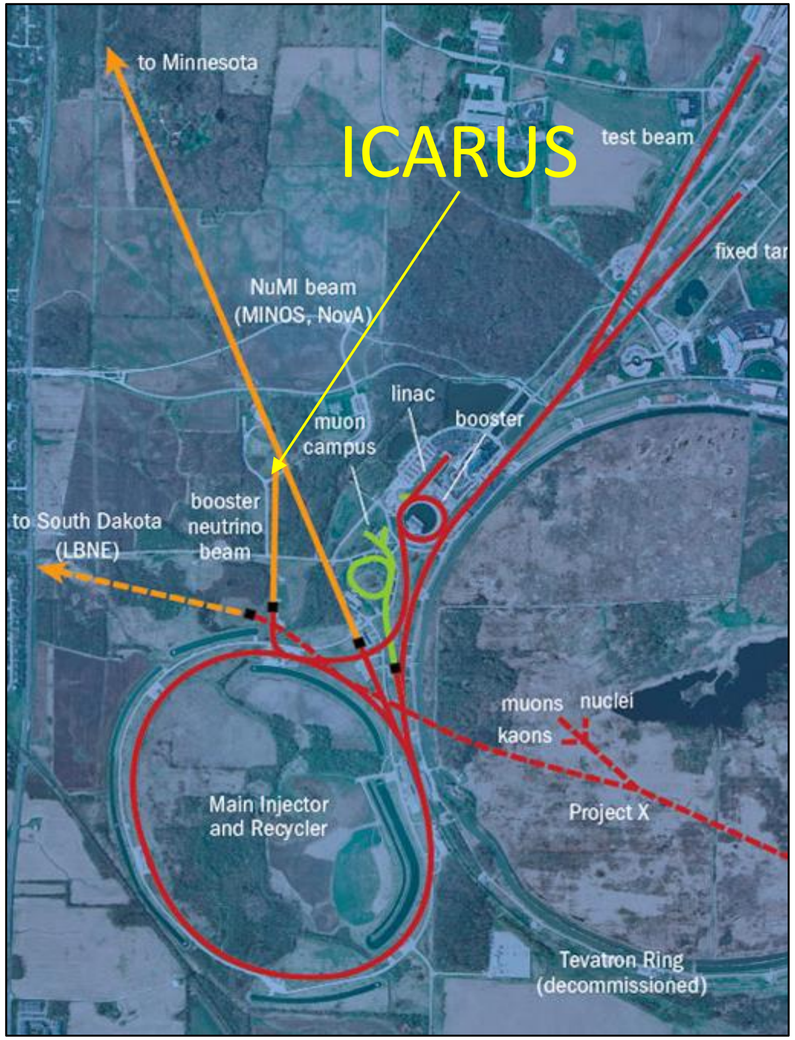
Calibrating for Precision Calorimetry in LArTPCs at ICARUS and SBN

GRAY PUTNAM

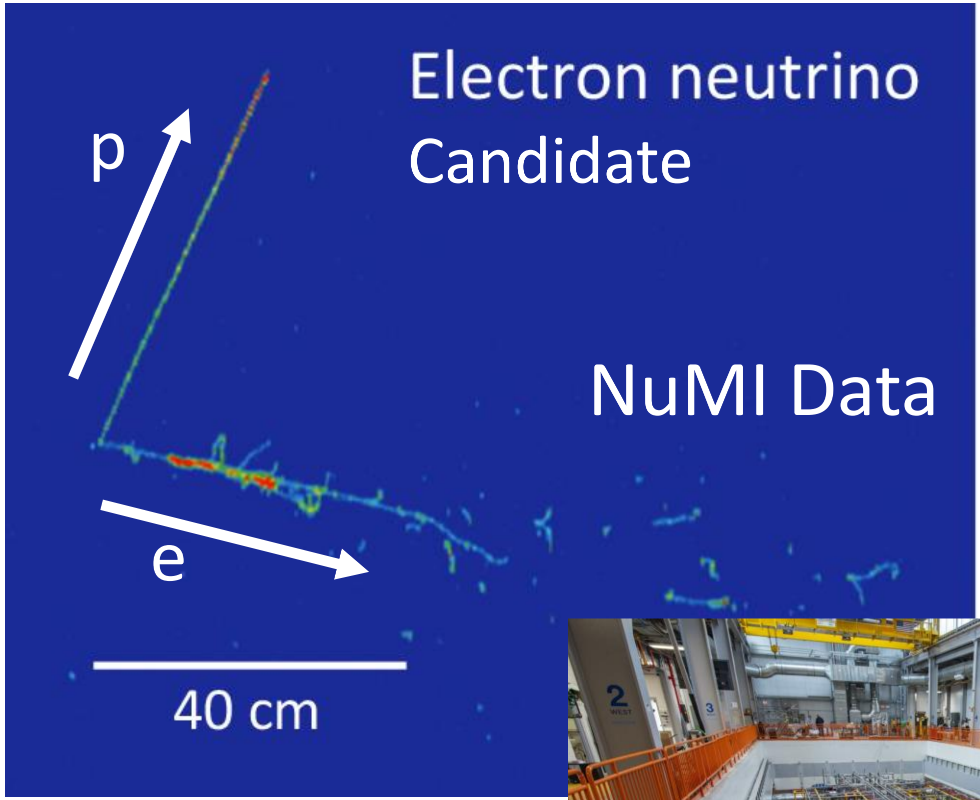
UNIVERSITY OF CHICAGO

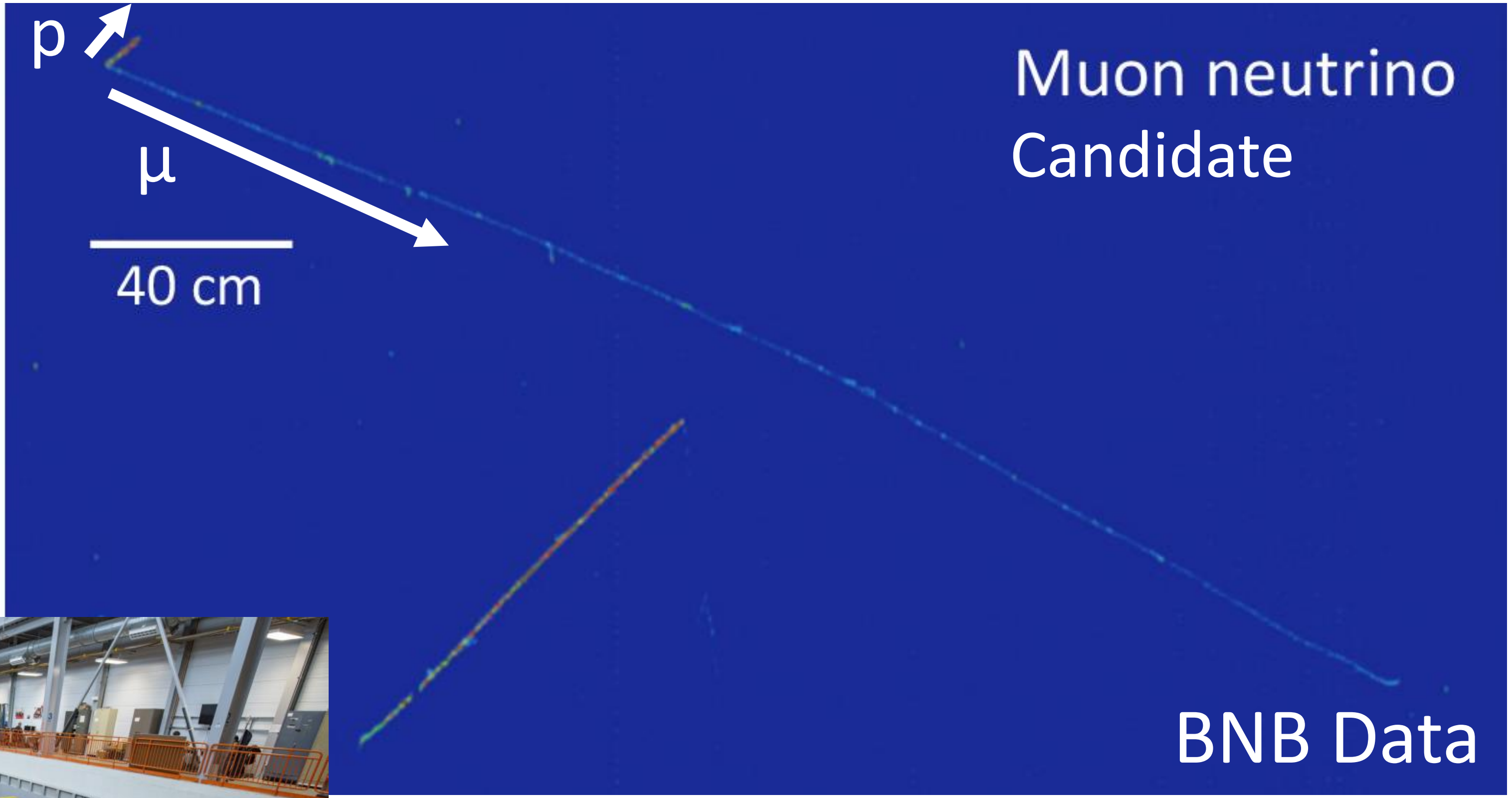
ICARUS and SBN at Fermilab

- ICARUS is the Far Detector in the Short Baseline Neutrino (SBN) Program
- SBN program physics:
  - eV-scale sterile neutrino search
  - GeV-scale neutrino cross section measurements
  - Single Detector BSM physics searches



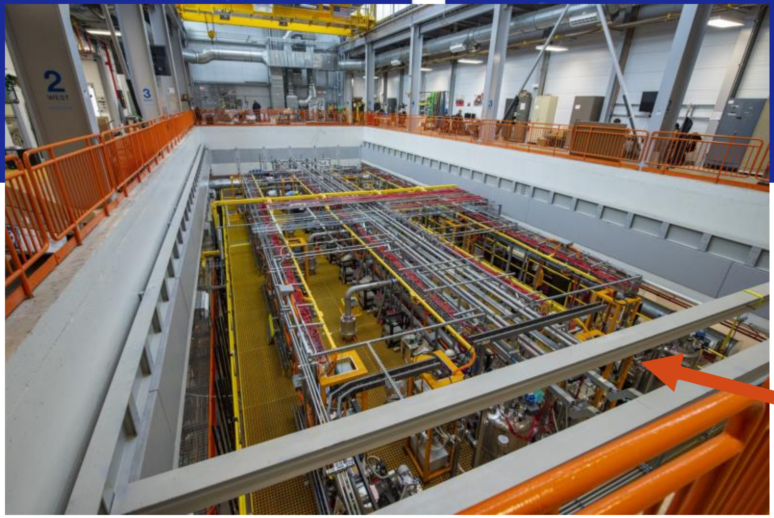
Neutrino Images from the ICARUS LArTPC





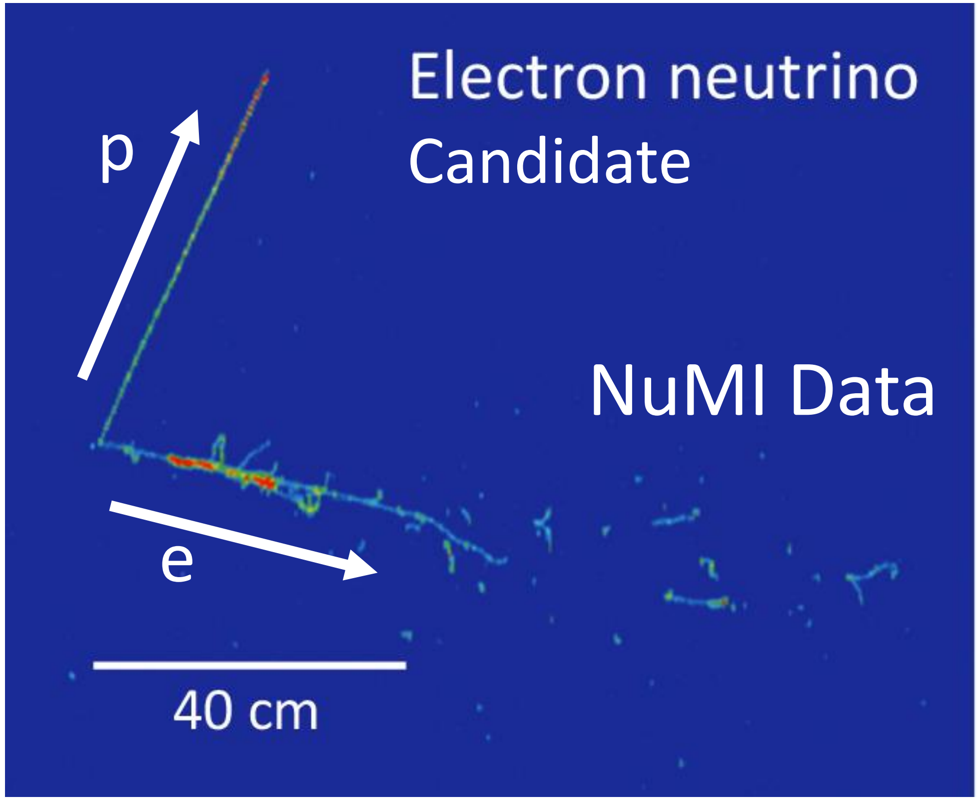
https://news.fnal.gov/2021/05/icarus-gets-ready-to-fly

ICARUS Detector at FNAL:



Each image is from one TPC inside each cryostat

ICARUS: A Liquid Argon Time Projection Chamber (LArTPC)



A LArTPC is a calorimeter for measuring charged particles produced in ν interactions

What measurements can you do with charge calorimetry in a LArTPC?

Easy

- μ/p, e/γ Separation
- Electron showers
- Low-energy particles from νs
- Low-energy electron tracks
- Very low energy electron blips

Hard

Using Charge at DUNE: Low Energy Electrons

Supernova neutrino burst detection with the deep underground neutrino experiment

DUNE Collaboration

DUNE as the Next-Generation Solar Neutrino Experiment

Francesco Capozzi,[1,2,3,*] Shirley Weishi Li,[1,2,4,†] Guanying Zhu,[1,2,‡] and John F. Beacom[1,2,5,§]
[1] *Center for Cosmology and AstroParticle Physics (CCAPP), Ohio State University, Columbus, Ohio 43210, USA*
[2] *Department of Physics, Ohio State University, Columbus, Ohio 43210, USA*
[3] *Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), 80805 München, Germany*
[4] *SLAC National Accelerator Laboratory, Menlo Park, California 94025, USA*
[5] *Department of Astronomy, Ohio State University, Columbus, Ohio 43210, USA*

(Received 4 September 2018; published 27 September 2019)

Xenon-Doped Liquid Argon TPCs as a Neutrinoless Double Beta Decay Platform

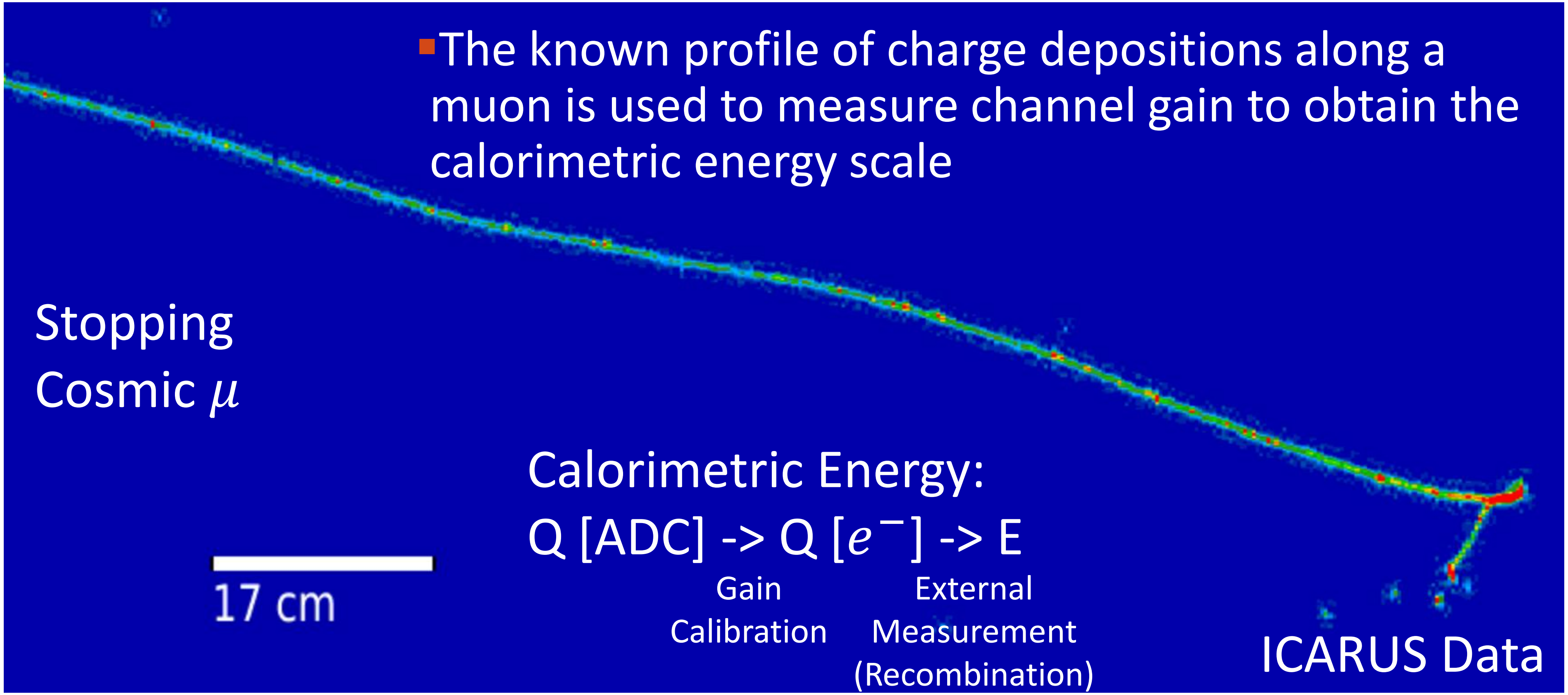
A. Mastbaum,[1] F. Psihas,[2] and J. Zennamo[2]
[1] *Rutgers University, Piscataway, NJ, 08854, USA*
[2] *Fermi National Accelerator Laboratory (FNAL), Batavia, IL 60510, USA*
(Dated: March 29, 2022)

Physics goals for DUNE include a variety of signatures from low energy electrons, which would apply calorimetric energy measurements.

How Well Can We Calibrate LArTPCs?

Cosmic Muons as a Standard Candle

- In LArTPC experiments, depositions from cosmic muons are used as a "standard candle" to calibrate the energy scale



Accuracy of Energy Measurements

- In LArTPC experiments, depositions from cosmic muons are used as a "standard candle" to calibrate the energy scale
- The predicted ionization per length of a cosmic muon combines the Bethe-Bloch energy loss with a recombination model to map energy to charge

How well do we know the most-probable $\frac{dQ}{dx}$ from a 1GeV muon deposition with 1ms of drift time?

Source	CV with Uncertainty	Percent Impact on dQ/dx	
Recombination Modeling	$\alpha = 0.93 \pm 0.02$, $\beta = 0.212 \pm 0.001$	3.8	ArgoNeuT Collab, JINST (2013) Recombination model: $\frac{dQ}{dx} = \frac{\ln\left(\alpha + \frac{dE}{dx}\beta\right)}{W_{ion}\beta}$
Mean Excitation Energy (I_0)	188 ± 17 eV	1.0	ICRU 37, plus uncertainty from GAr v. LAr
Transverse Diffusion (D_T)	8.8 ± 4.4 cm^2/s	1.0	Extrapolation from longitudinal diffusion through Wannier relation

Accuracy of Energy Measurements

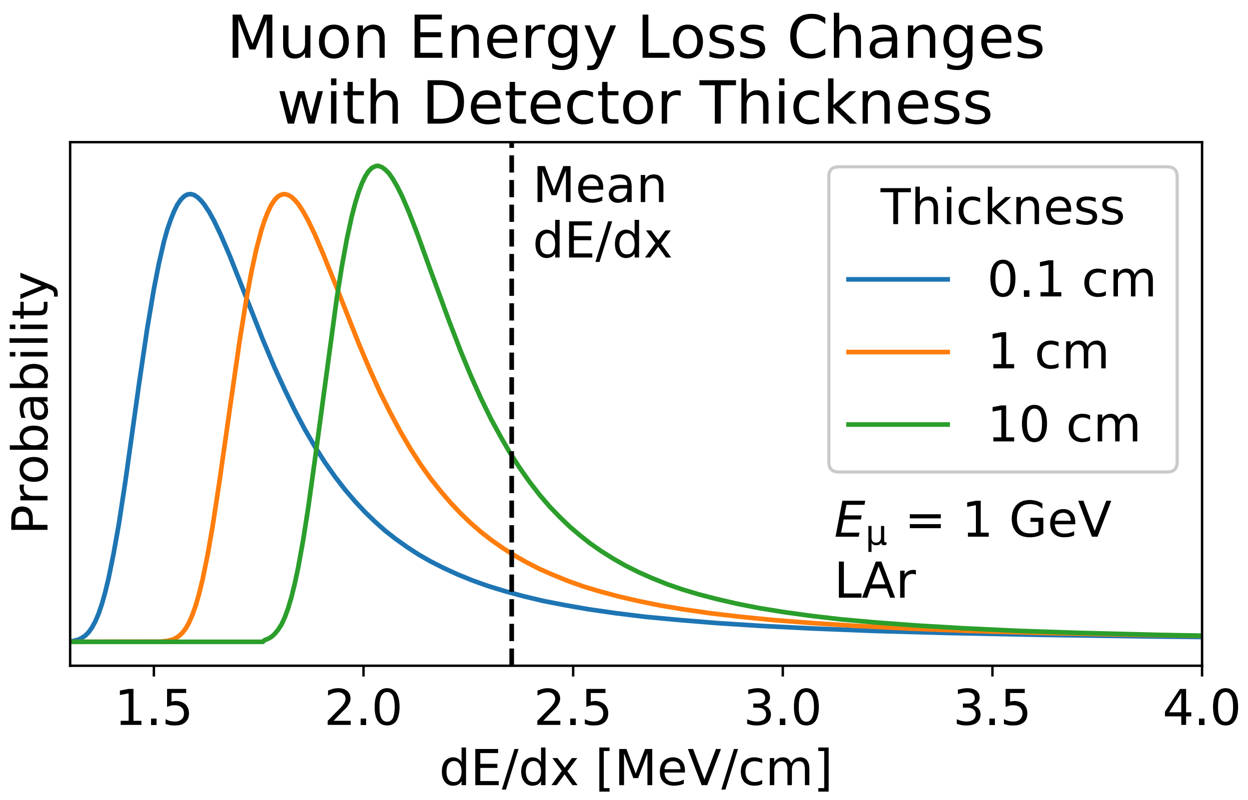
- In LArTPC experiments, depositions from cosmic muons are used as a "standard candle" to calibrate the energy scale
- The predicted ionization per length of a cosmic muon combines the Bethe-Bloch energy loss with a recombination model to map energy to charge

How well do we know the most-probable $\frac{dQ}{dx}$ from a 1GeV muon deposition with 1ms of drift time?

Source	CV with Uncertainty	Percent Impact on dQ/dx	
Recombination Modeling	$\alpha = 0.93 \pm 0.02$, $\beta = 0.212 \pm 0.001$	3.8	ArgoNeuT Collab, JINST (2013) Recombination model: $\frac{dQ}{dx} = \frac{\ln\left(\alpha + \frac{dE}{dx}\beta\right)}{W_{ion}\beta}$
Mean Excitation Energy (I_0)	188 ± 17 eV	1.0	ICRU 37, plus uncertainty from GAr v. LAr
Transverse Diffusion (D_T)	8.8 ± 4.4 cm^2/s	1.0	Extrapolation from longitudinal diffusion through Wannier relation

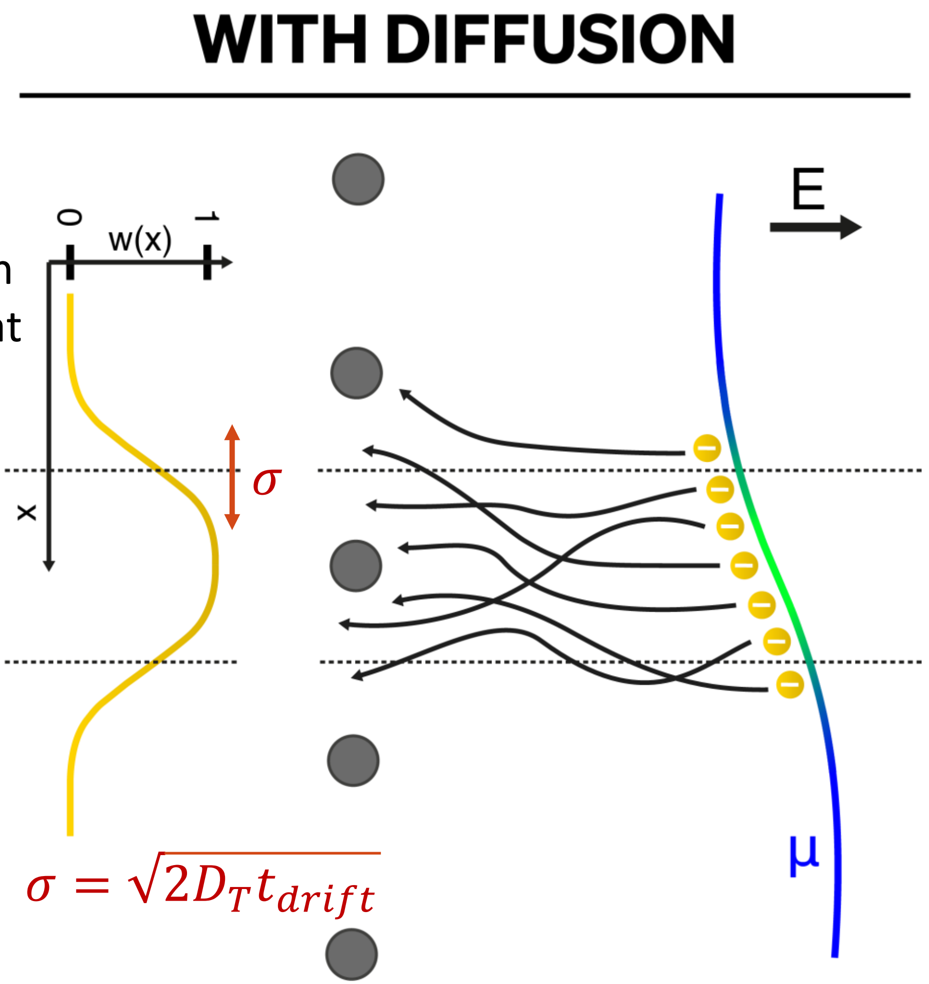
The Landau Energy Loss Distribution Depends on Wire Thickness

- The distribution of energy loss is a Landau distribution
- The peak of a Landau distribution has a dependence on the length of the particle observed by the wire
- As the thickness goes up, the most-probable-value (MPV) of energy loss goes up

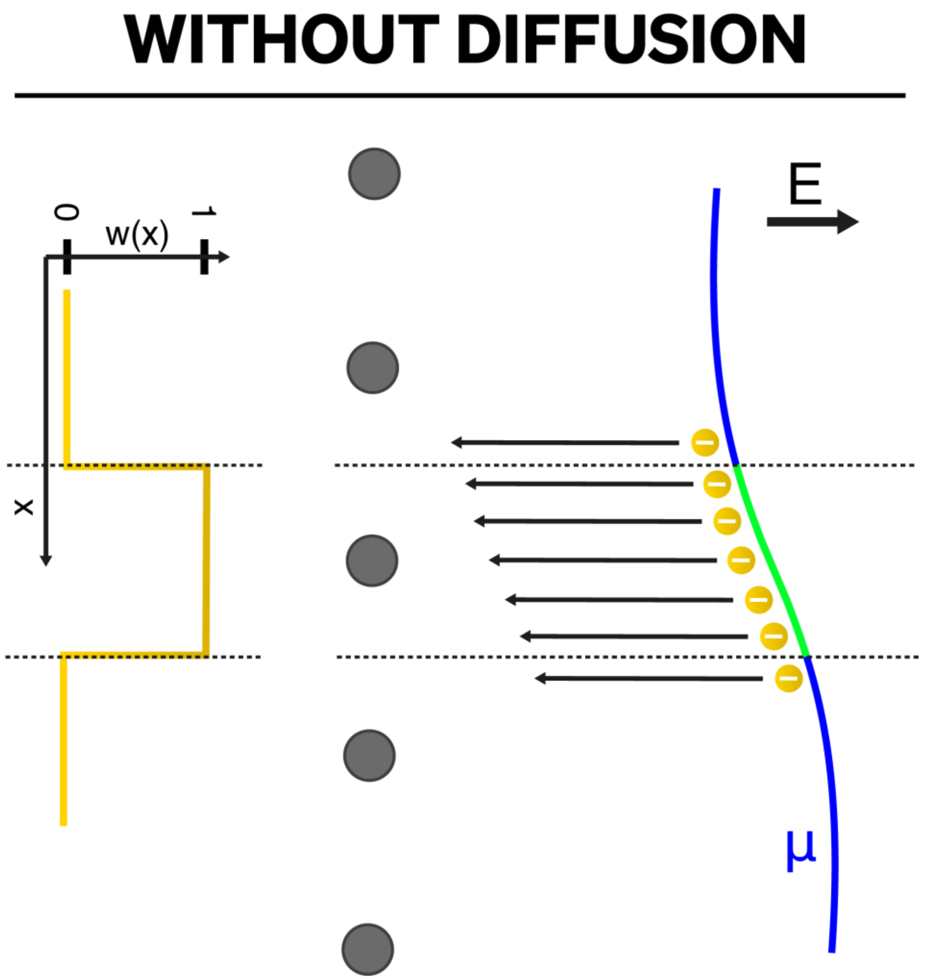


Diffusion Changes the Thickness!

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



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



From: G Putnam and D Schmitz (arxiv: 2205.06745)

- Diffusion transverse to the drift direction (and the wire direction) thickens the length of the muon that each wire is sensitive to – **this changes the MPV energy loss**

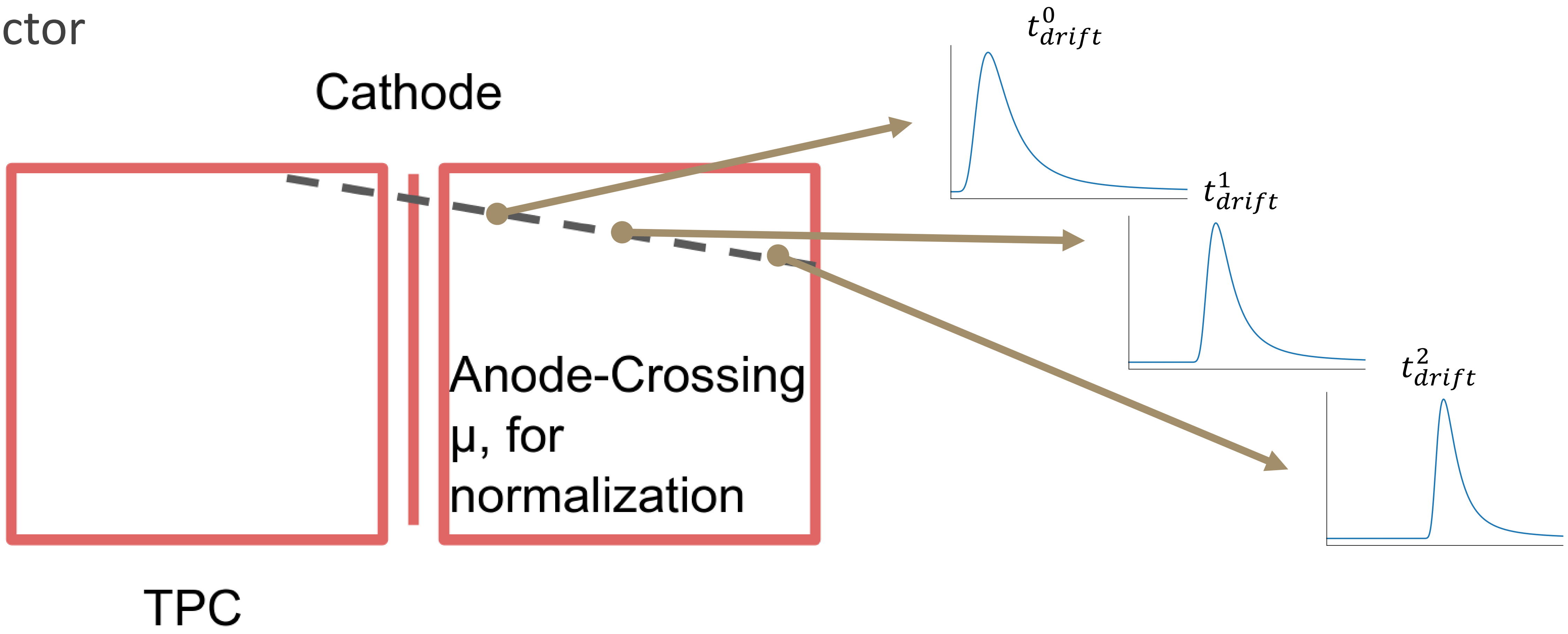
Energy Scale Calibration at ICARUS

Energy Scale Calibration Procedure

- Step 1: **normalize** the detector response in the drift direction
  - This removes detector effects such as argon impurities which attenuate the signal
- Step 2: **calibrate** the energy scale
  - Examination of the systematic uncertainties and results at ICARUS
- For both steps, we have devised a procedure which addresses possible biases from diffusion

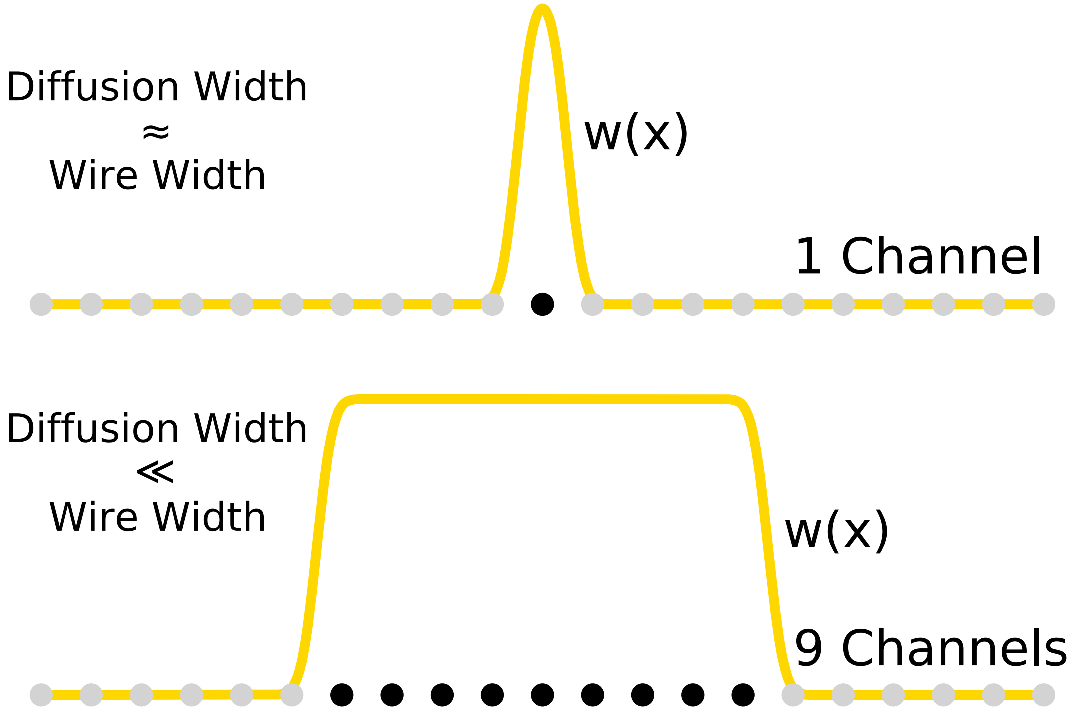
Normalizing the Drift Direction Detector Response

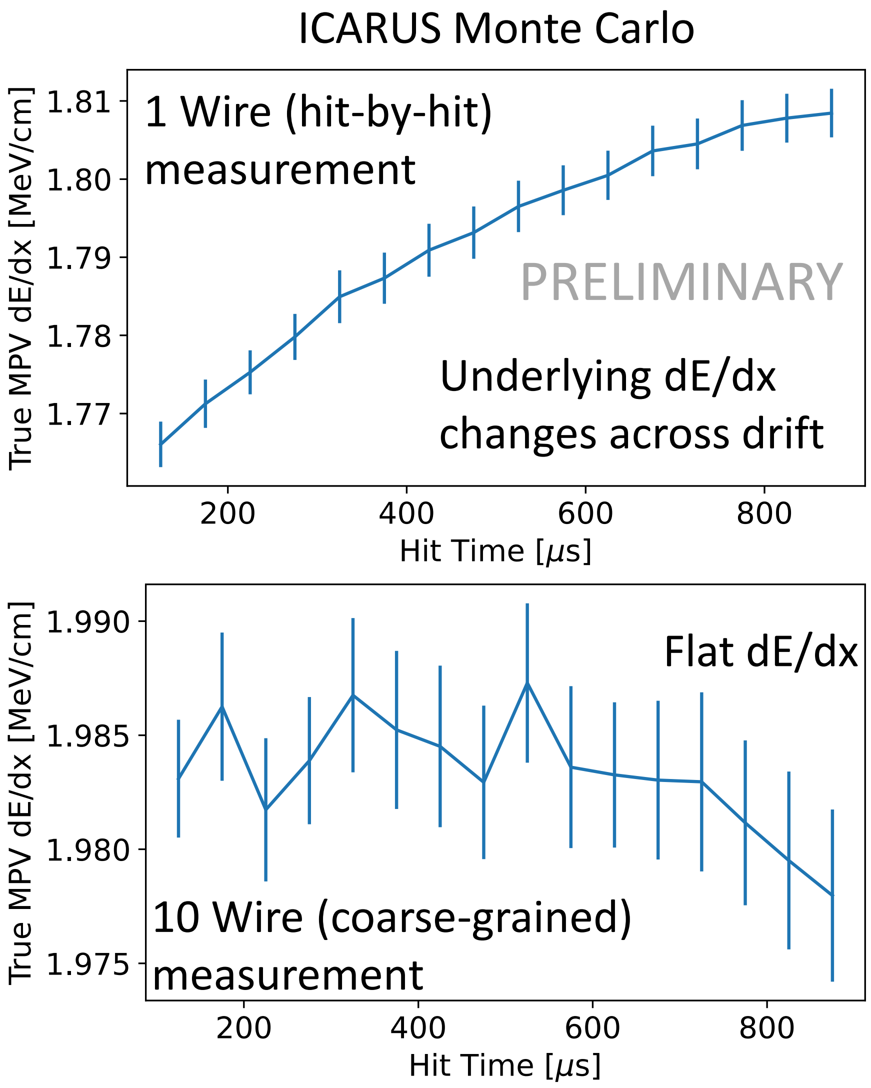
- Impurities in the argon attenuate ionization electrons as a function of drift time
- To remove this effect: look at dQ/dx from cosmic muons, make it flat across the detector



Drift Direction Response Normalization with Diffusion

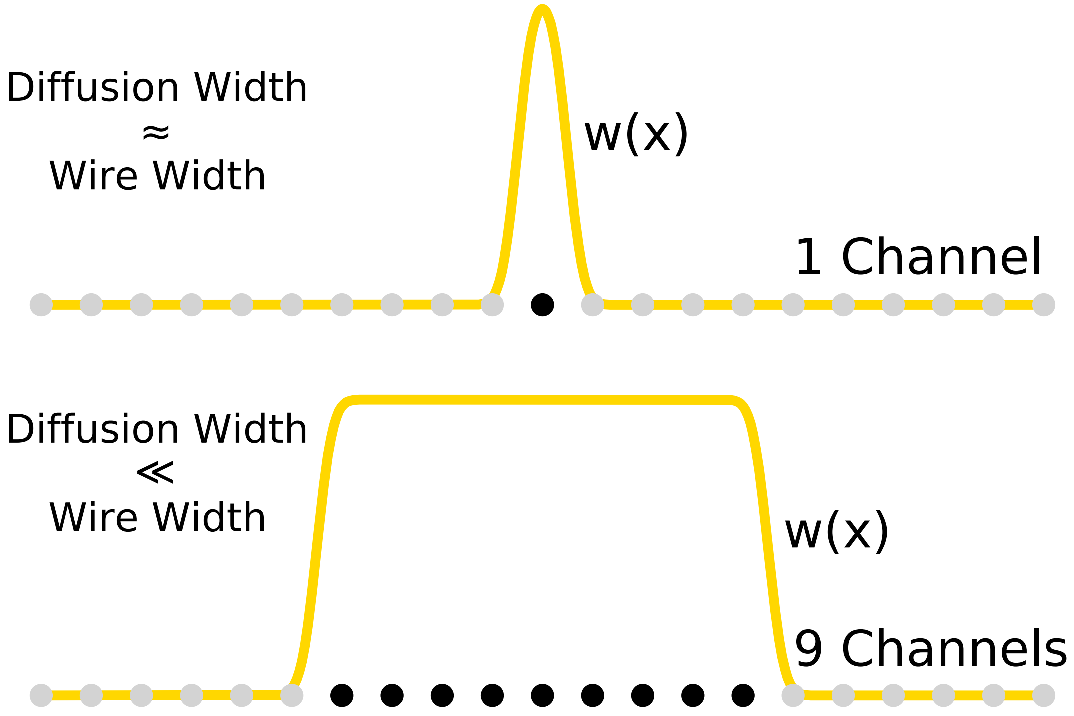
- Diffusion changes the underlying dE/dx of muon depositions across the drift direction
- We can remove this effect by coarse-graining the detector



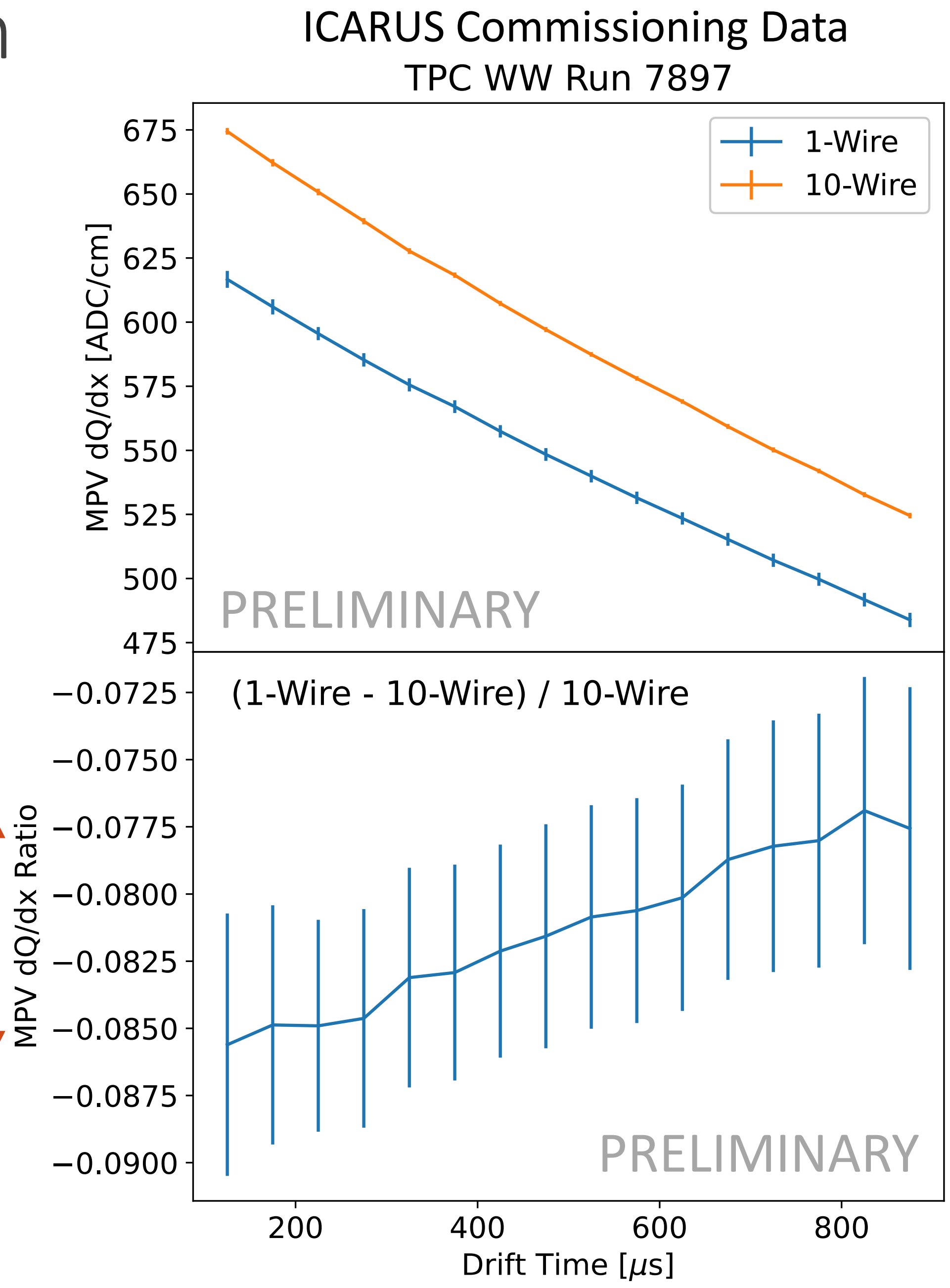


Drift Direction Response Normalization with Diffusion

- Diffusion changes the underlying dE/dx of muon depositions across the drift direction
- We can remove this effect by coarse-graining the detector

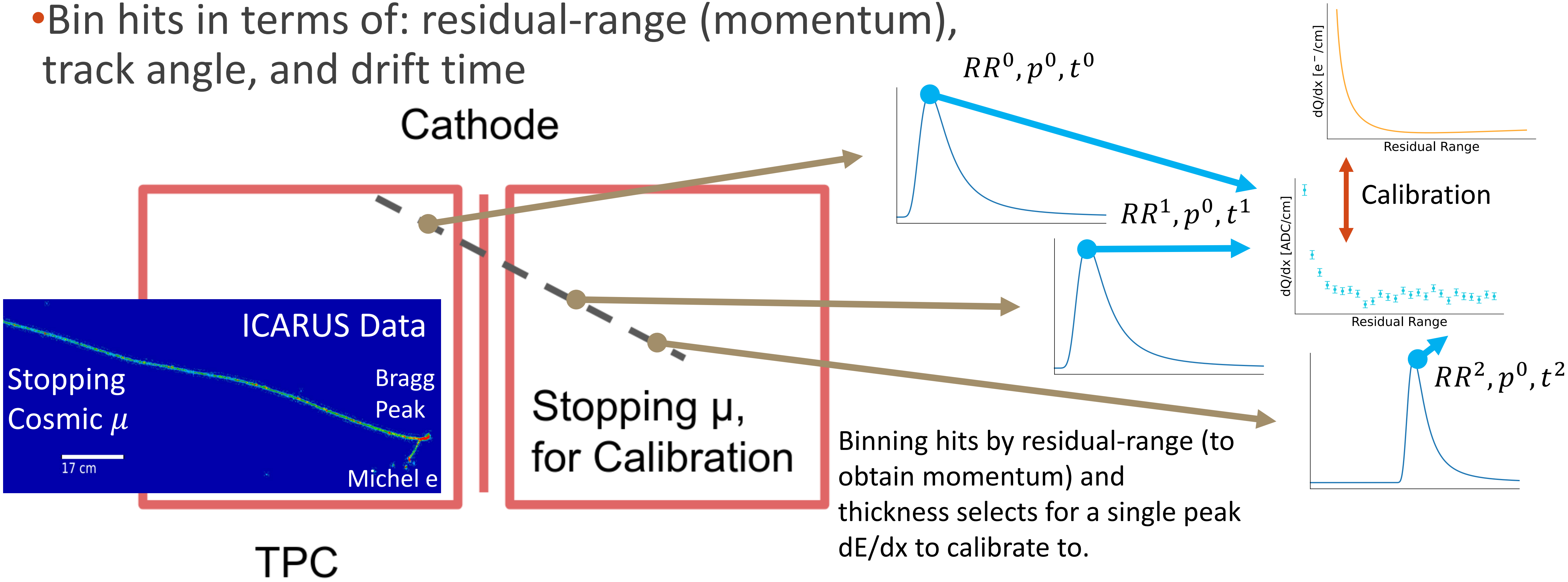


The difference in thickness (and thus dE/dx) narrows across the drift.



Energy Scale Calibration Procedure

- After normalizing detector response, we calibrate the energy scale by fitting to the dQ/dx profile of stopping cosmic muons
- Bin hits in terms of: residual-range (momentum), track angle, and drift time

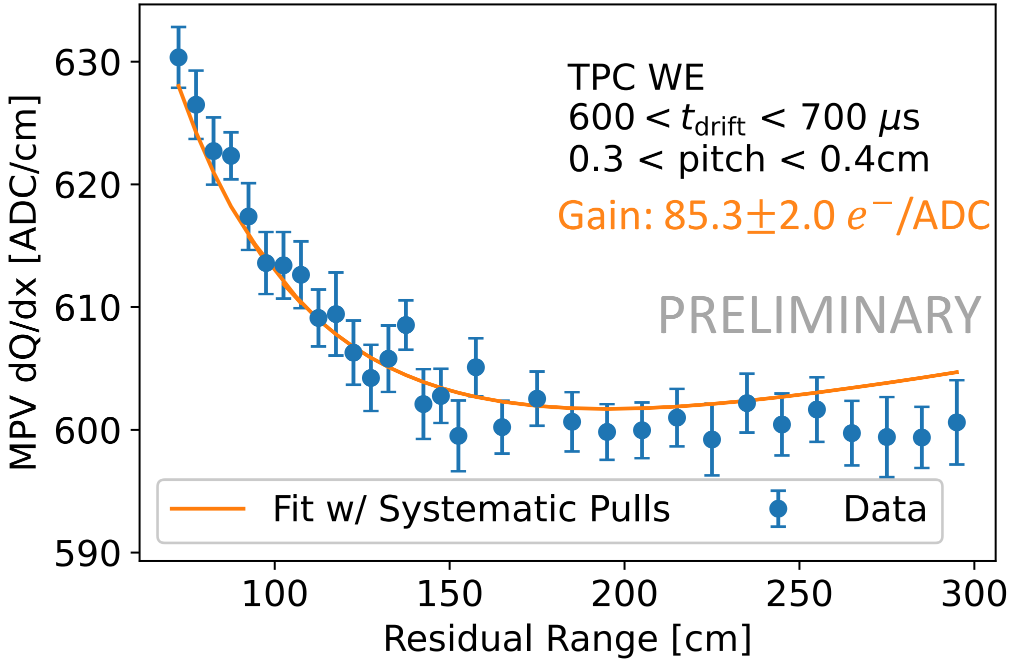


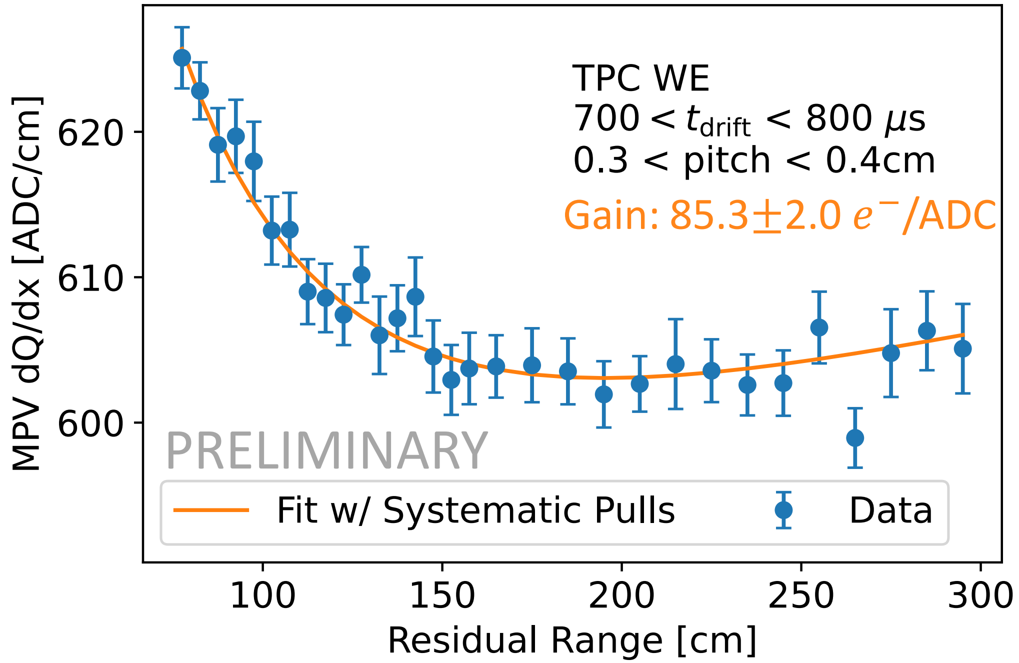
Binning hits by residual-range (to obtain momentum) and thickness selects for a single peak dE/dx to calibrate to.

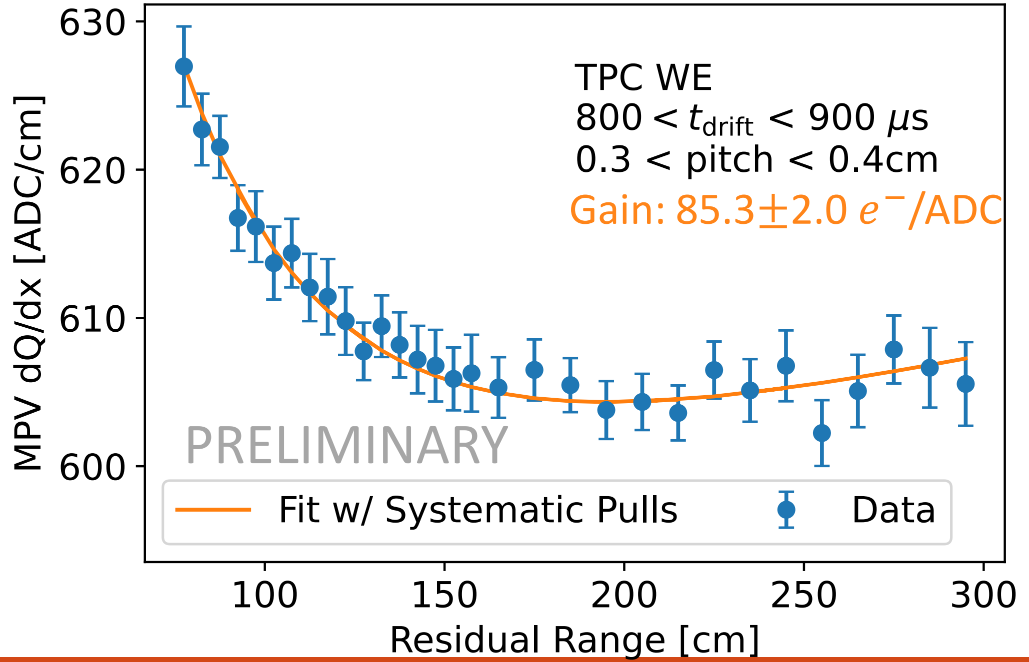
Example dQ/dx Profile Data

ICARUS Commissioning Data

TPC WE

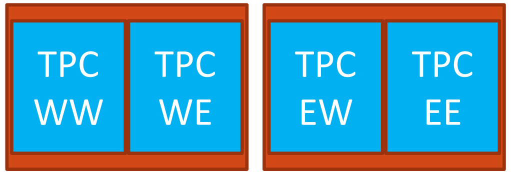






- Fit across all drift bins, with a separate gain in each TPC and "pulls" for systematics

TPC Enumeration:

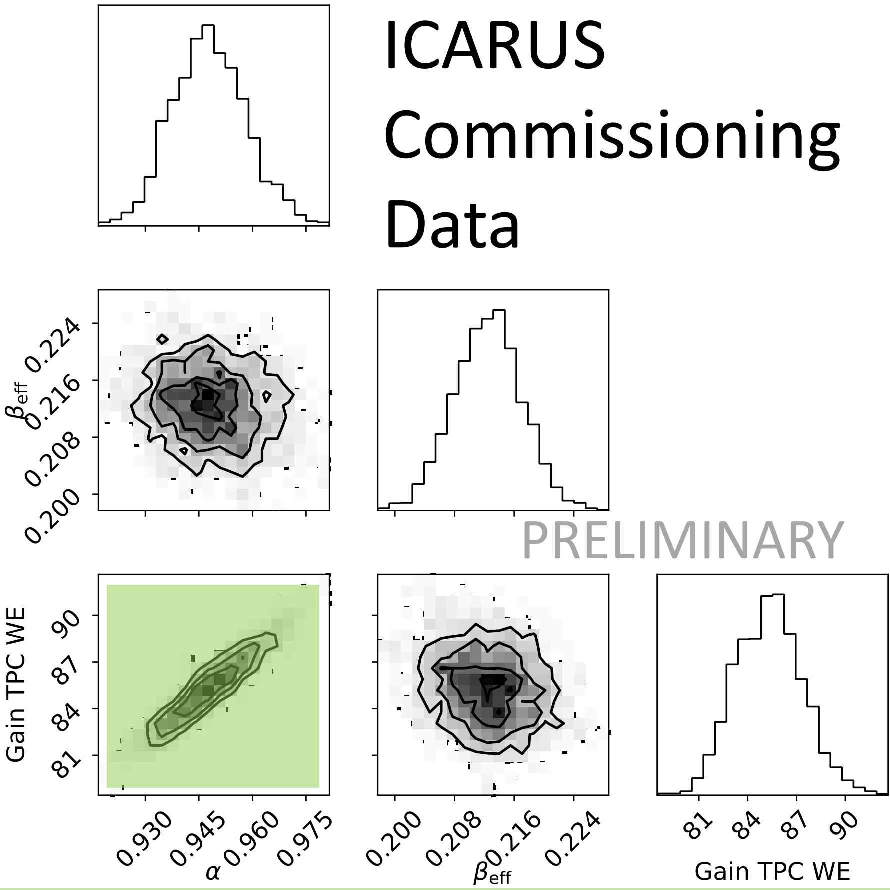


Cryo. West Cryo. East

Calibration Fit Results

	Parameter	Prior CV	Prior Unc.	Posterior CV	Posterior Unc.
Systematic Parameters	Recombination α	0.93	0.02	0.948	0.010
	Recombination β_{eff} [cm^3/g][cm/kV]	0.212	0.005	0.212	0.005
	Transverse Diffusion D_T [cm^2/s]	8.8	4.4	9.1	2.2
	Mean Excitation Energy I_0 [eV]	188	17	194	15
Gain Measurement	Gain TPC EE [e$^-$/ADC]			83.4	2.0
	Gain TPC EW [e$^-$/ADC]			81.8	2.0
	Gain TPC WE [e$^-$/ADC]			85.3	2.0
	Gain TPC WW [e$^-$/ADC]			84.3	2.0

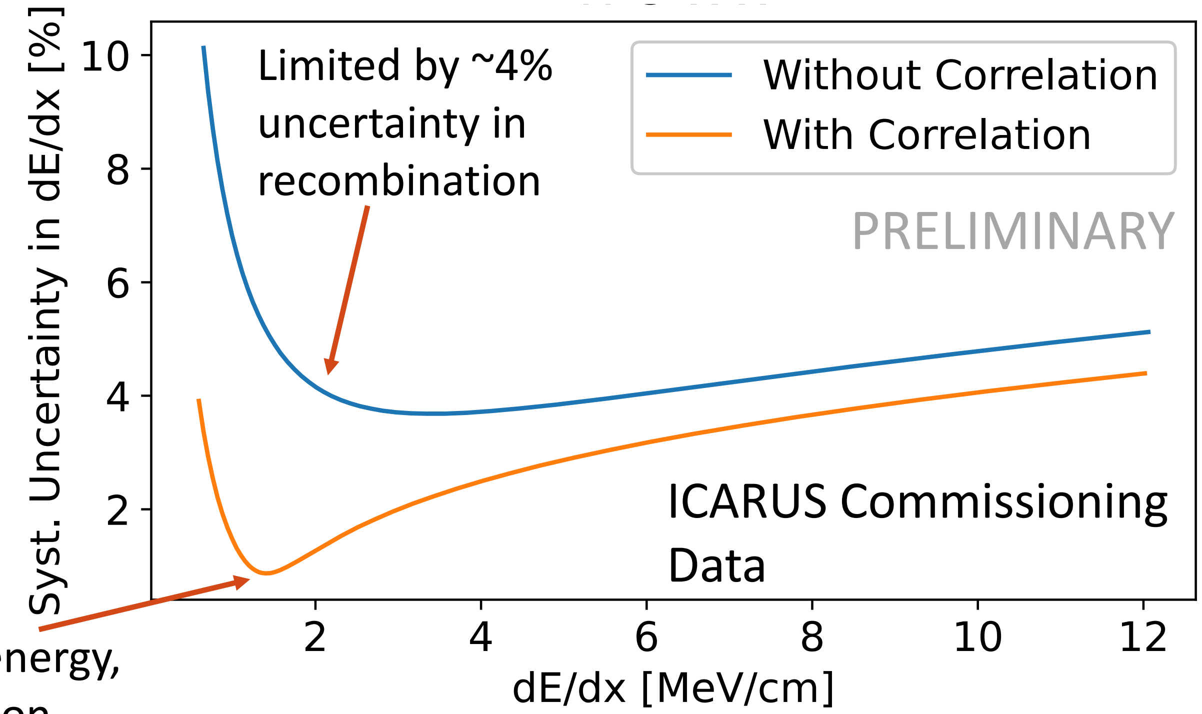
ICARUS Commissioning Data



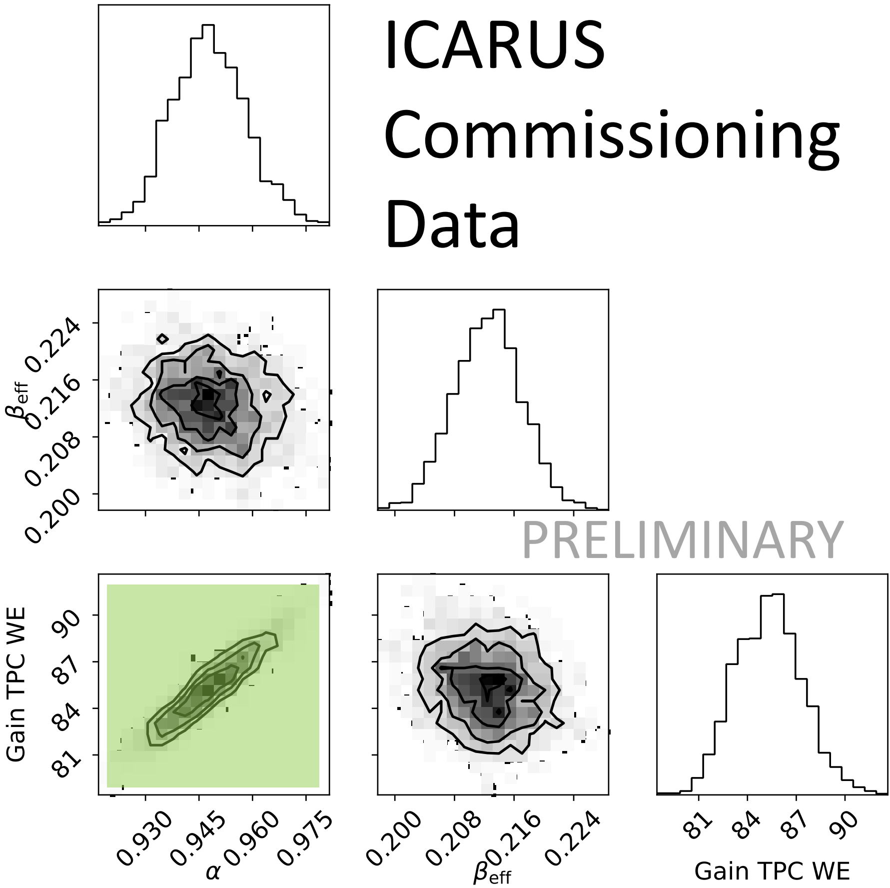
Strong correlation between gain and recombination α (α determines behavior near the MIP dE/dx).

Marginalize Over Recombination

- By leveraging the correlation between gain and recombination in our dataset, we can lower the systematic uncertainty in dE/dx
  - i.e.: marginalize over gain and recombination together



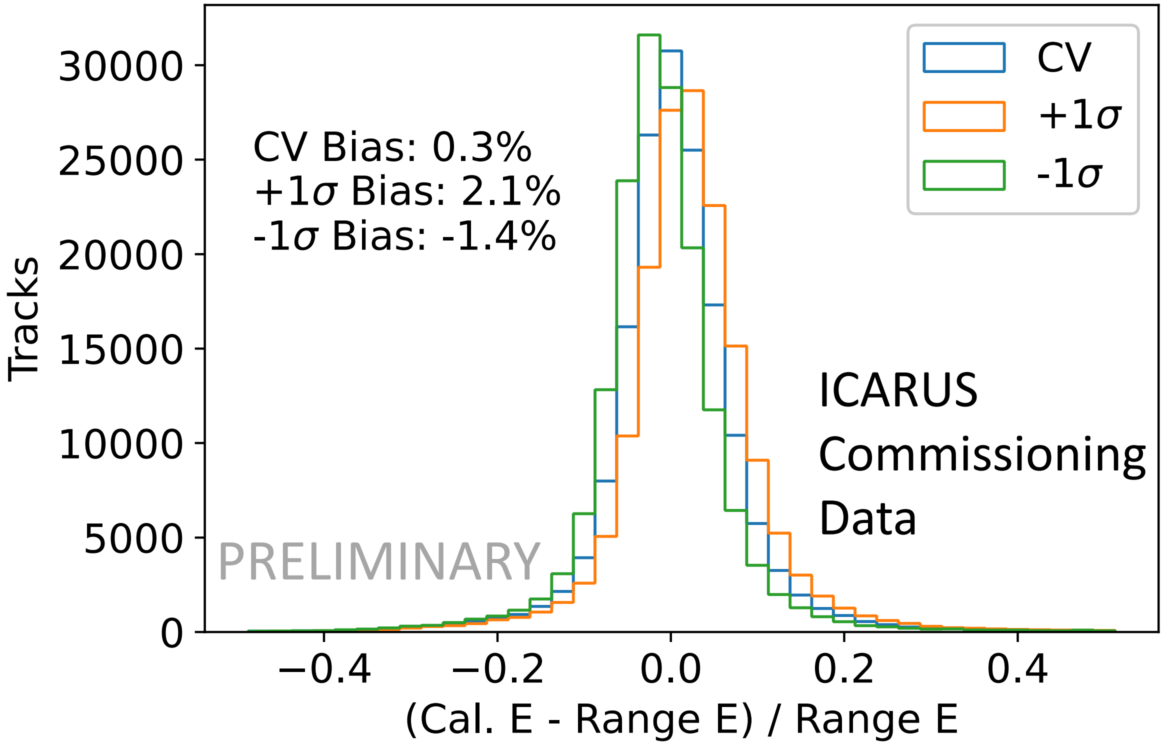
Limited by ~1% uncertainty from mean excitation energy, transverse diffusion

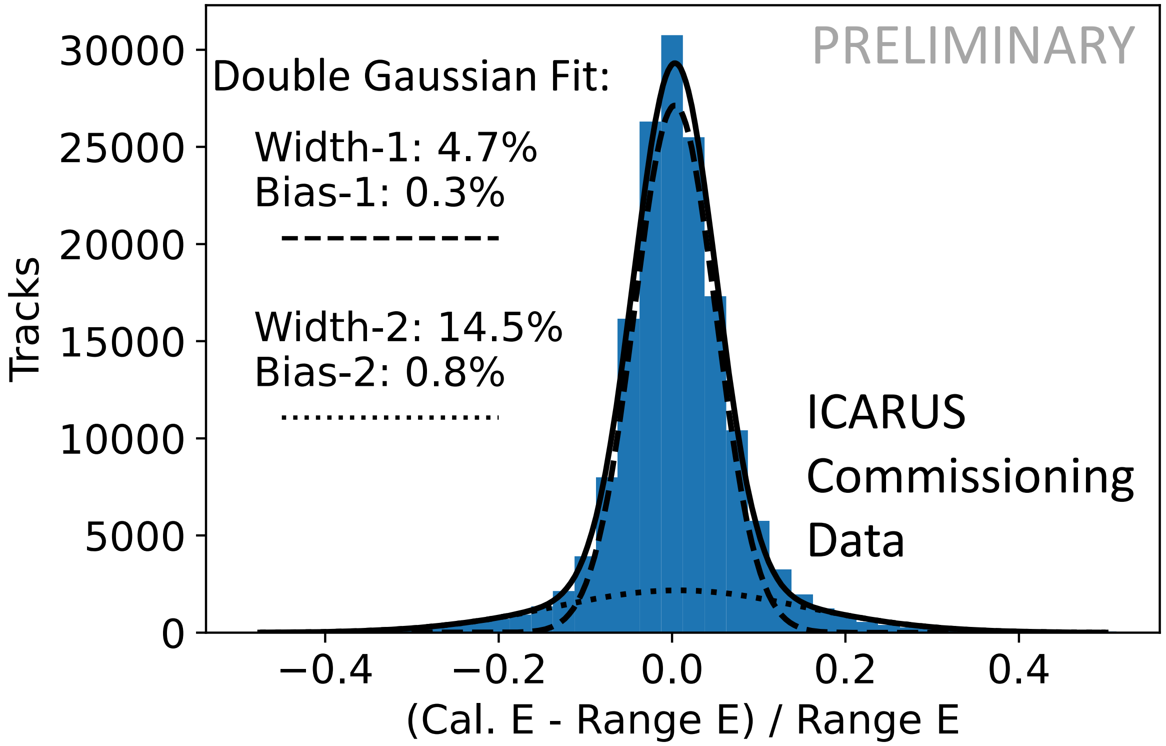


Strong correlation between gain and recombination α (α determines behavior near the MIP dE/dx).

Closure Test with Energy Reconstruction

- Compare calorimetric to range kinetic energy reconstruction for the stopping muon dataset

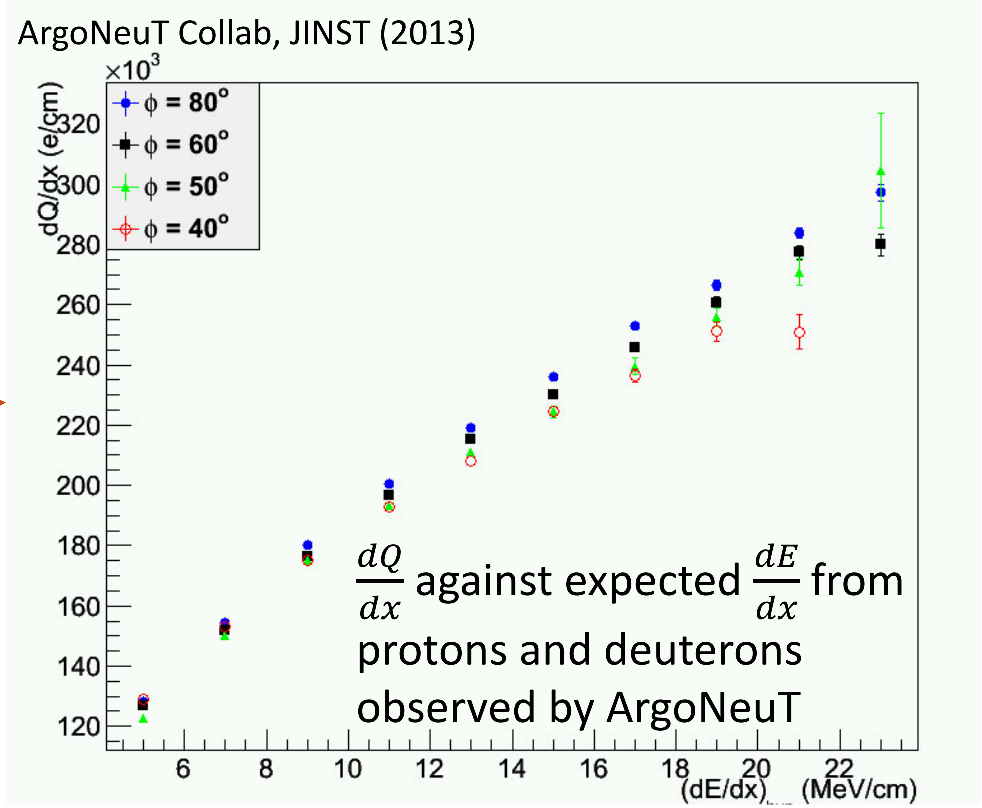




- 4.7% resolution in bulk of distribution (2% intrinsic resolution from range)
- Bias within 1σ range expected from systematic uncertainties

Looking Forward: We Need More Measurements

- This procedure works well inside the (cosmic μ) dataset we have, but will it generalize to others?
  - ArgoNeuT recombination found evidence for angular variations in recombination
  - Could there be particle-type dependence in recombination (at the percent level)?



- To obtain the best possible energy measurements, we need to better understand the argon
  - At ICARUS we can measure recombination and diffusion

Conclusion

- Accurate and precise energy measurements are needed to unlock the physics potential of SBN and DUNE
- Systematic uncertainties in liquid argon properties limit the accuracy of calibrating the energy scale
  - One of these, transverse diffusion, plays a role not appreciated in LArTPC experiments that we are now accounting for in ICARUS
- In ICARUS, we’ve implemented a calibration procedure that limits the effects of these systematic uncertainties
- Looking forward, more measurements of LAr properties are needed to get the best possible energy measurements

Backup Slides

Energy Loss by Elastic Scattering

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

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

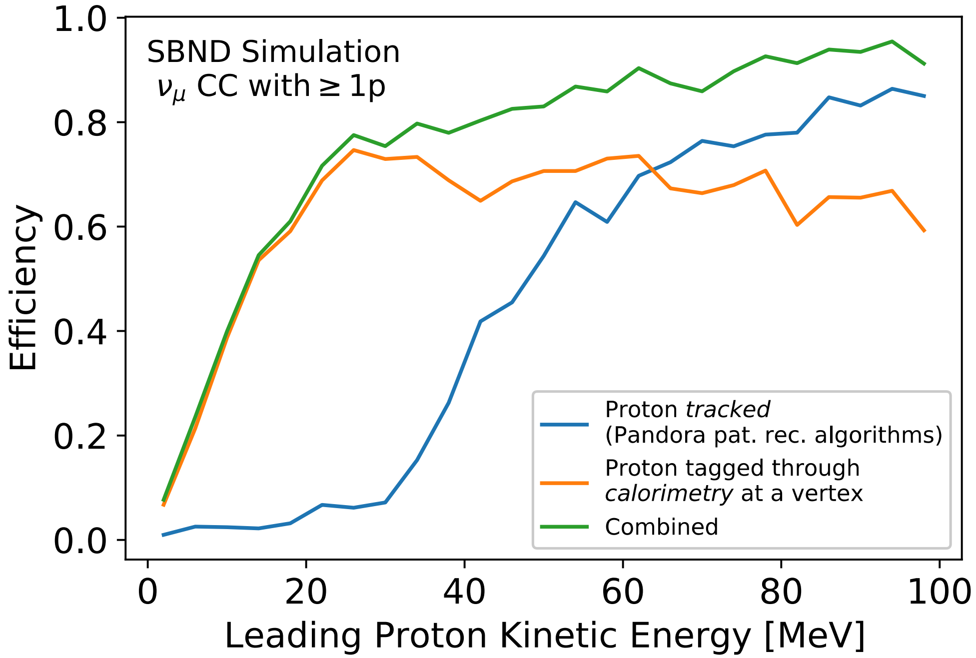
Due to the power-law behavior of Rutherford scattering, muons lose much of their energy in a small number of large energy-transfer collisions (delta rays)

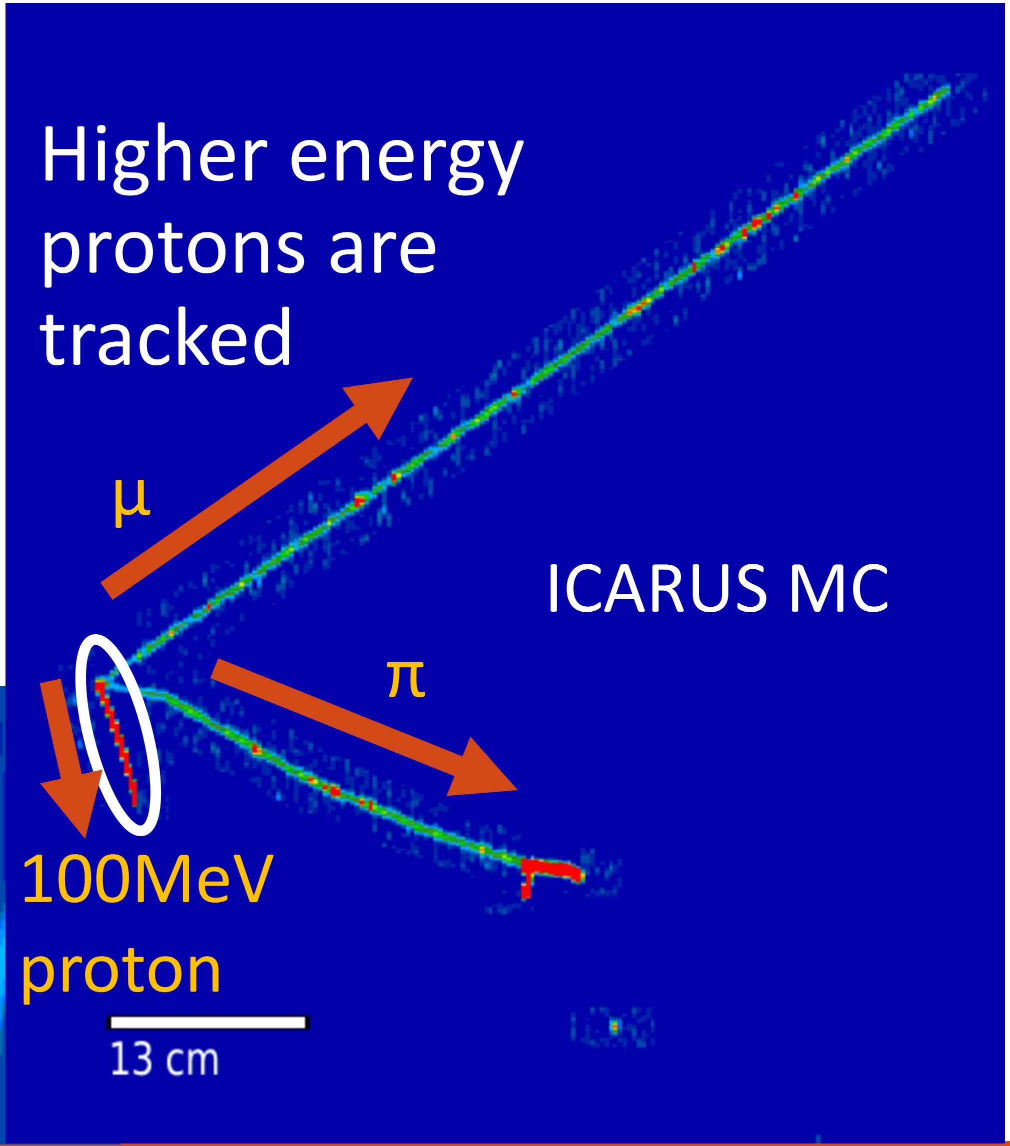
Mean: $\sim\int dT\, T \frac{d\sigma}{dT} \rho_e$ -- diverges at low T -> atomic effects important

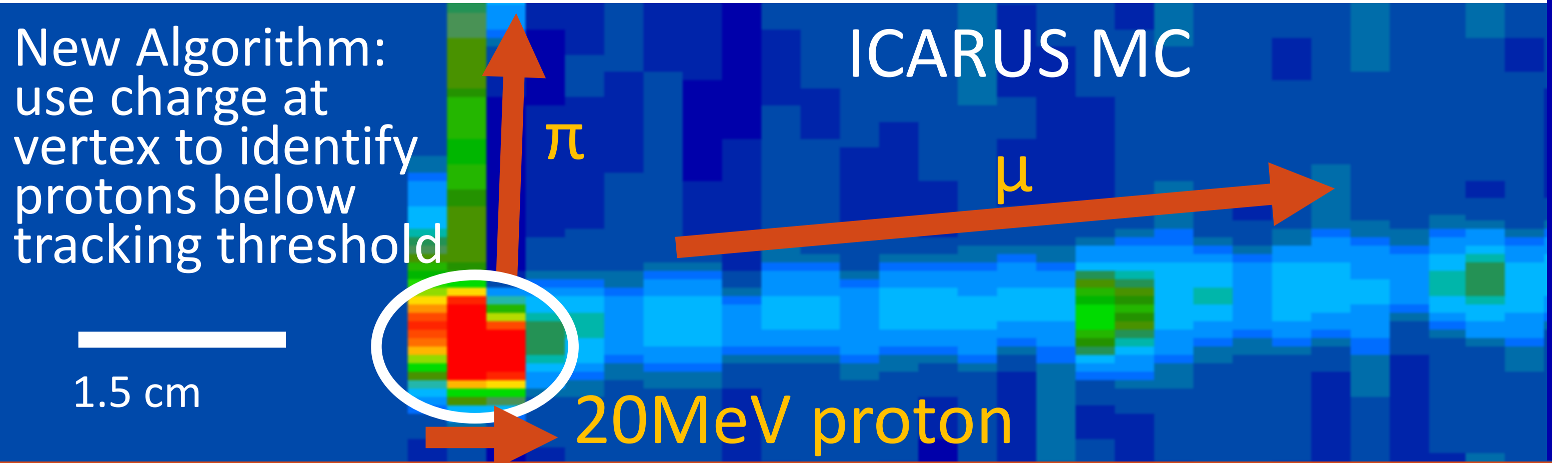
Variance: $\sim\int dT\, T^2 \frac{d\sigma}{dT} \rho_e$ -- converges at low T -> *delta rays determine variance*

Using Charge at SBN: Low Energy Protons

Charge-based reconstruction lowers the proton identification threshold, which can improve neutrino energy and topology reconstruction

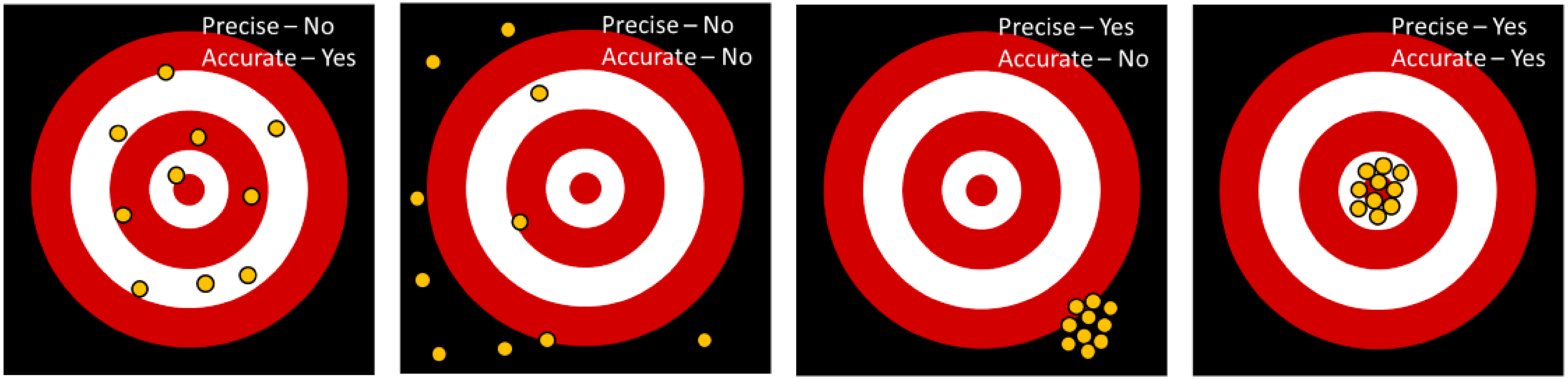






How Well Can We Measure E using Q in LAr?

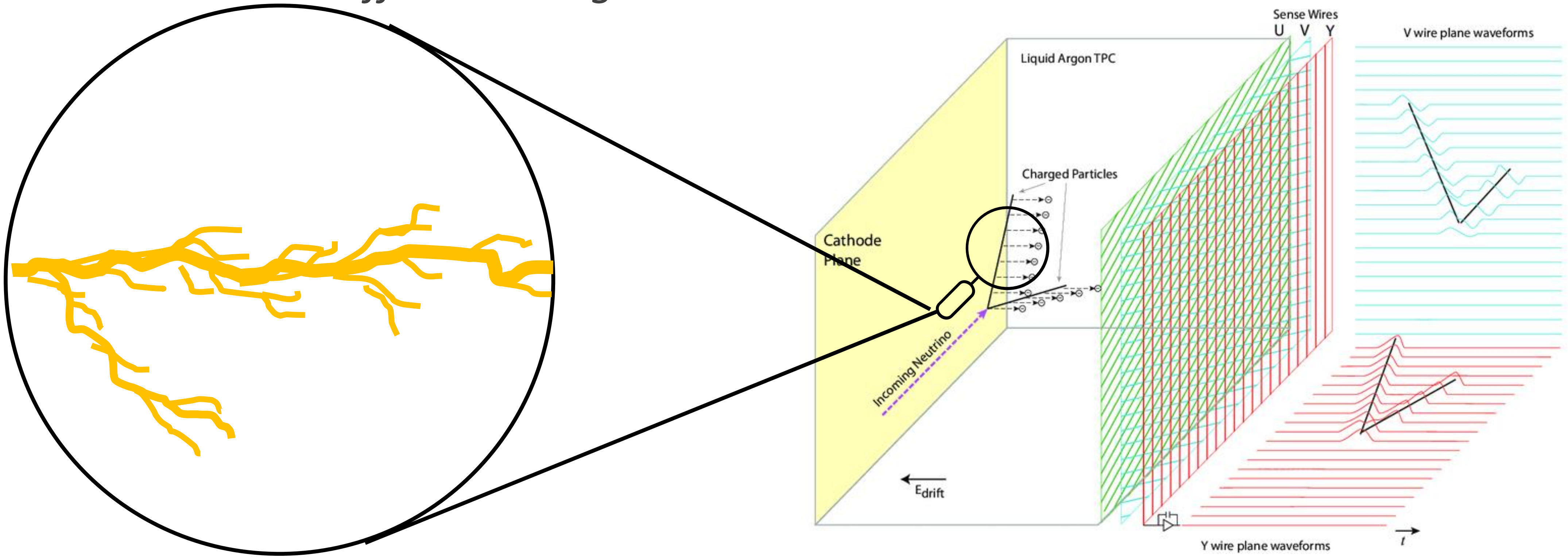
- Developments in LArTPC technology (cold electronics, high argon purity) increasingly provide excellent charge measurements
- How well can we turn those measurements of charge into energy?



How *accurately* and *precisely* does charge measure energy in liquid argon?

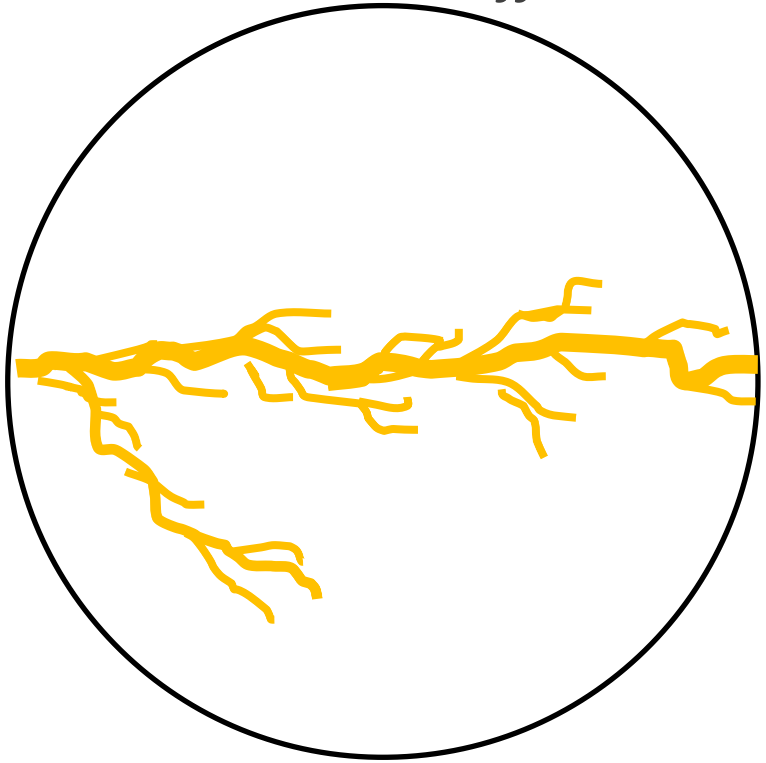
Energy Resolution with Charge in LAr

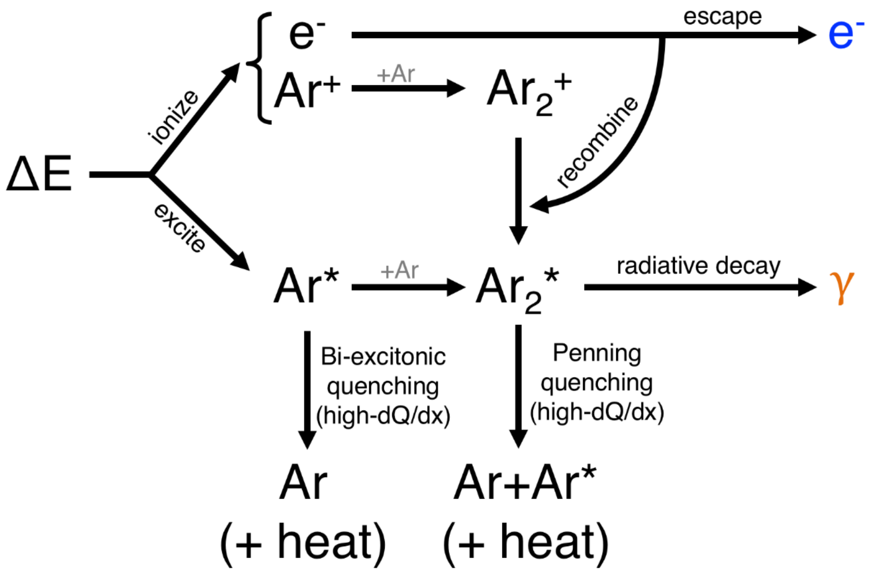
- Charged particles traversing argon create a cascade of delta rays
- The same energy loss across a wire can be produced by different spectra of delta rays, which recombine differently
  - *This produces a resolution effect in charge measurements!!*



Energy Resolution with Charge in LAr

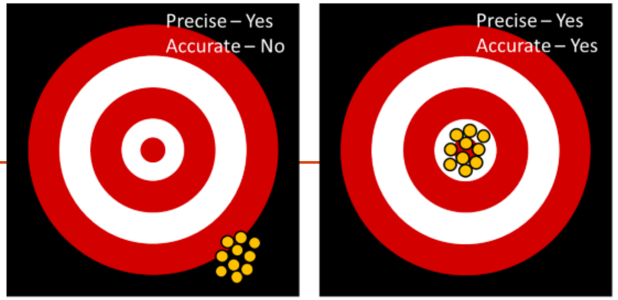
- Charged particles traversing argon create a cascade of delta rays
- The same energy loss across a wire can be produced by different spectra of delta rays, which recombine differently
  - *This produces a resolution effect in charge measurements!!*



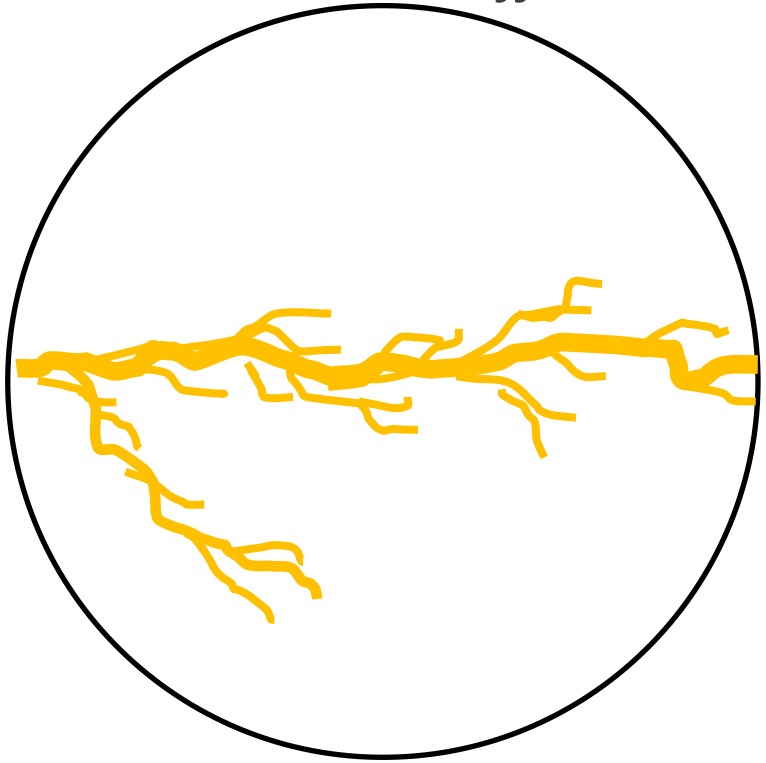


Ionization electrons *recombine* into exited Ar states along each ionization column.

Energy Resolution with Charge in LAr



- Charged particles traversing argon create a cascade of delta rays
- The same energy loss across a wire can be produced by different spectra of delta rays, which recombine differently
  - *This produces a resolution effect in charge measurements!!*



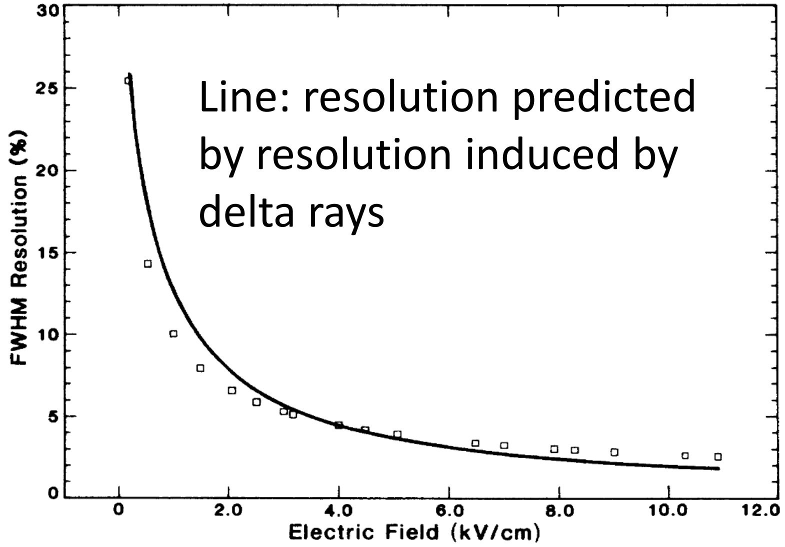
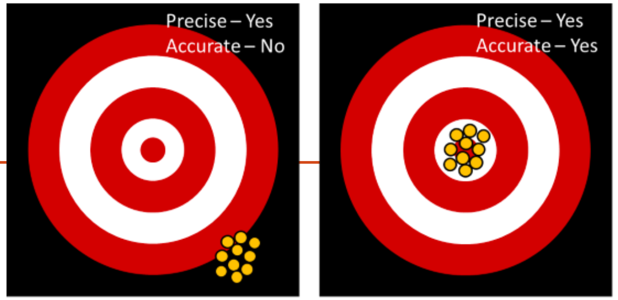


FIG. 3. A fit of Eq. (3) to the measured resolution of a 976-keV electron in liquid argon (Ref 12).

Thomas, Imel, and Biller PR A (1988)

Can Resolution be Improved for DUNE?

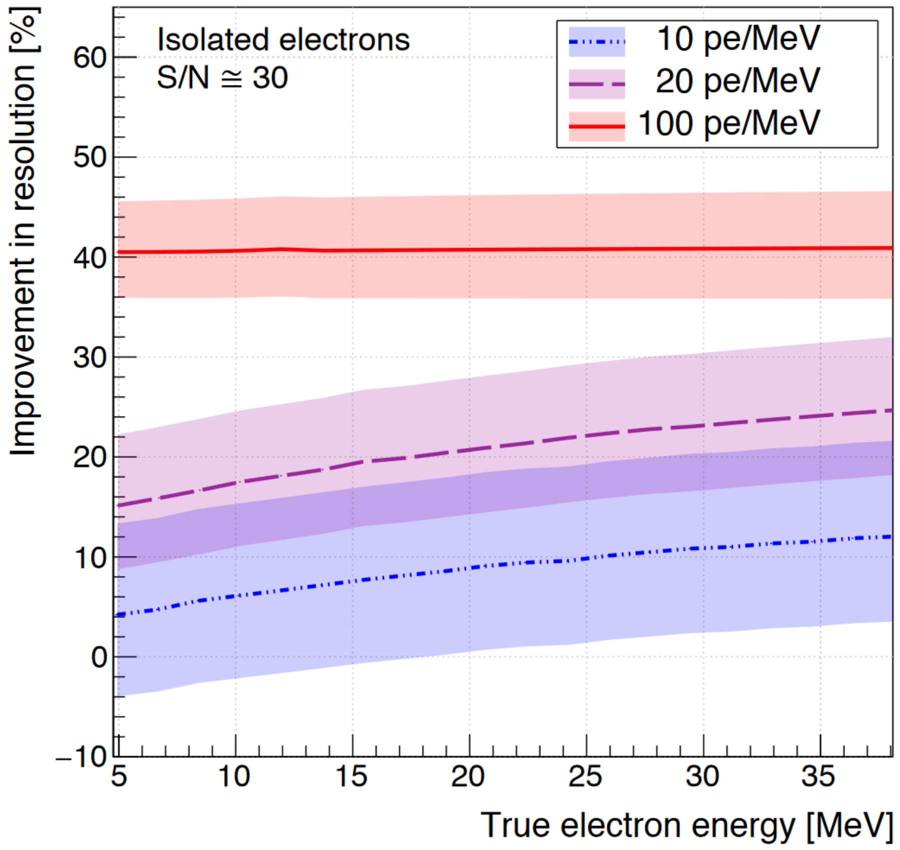


- Collecting both the charge and light from energy depositions could remove the resolution from recombination

Projected improvement in energy resolution using Q+L from LArIAT

There is not a significant improvement at the projected DUNE light yield (5 pe / MEV)

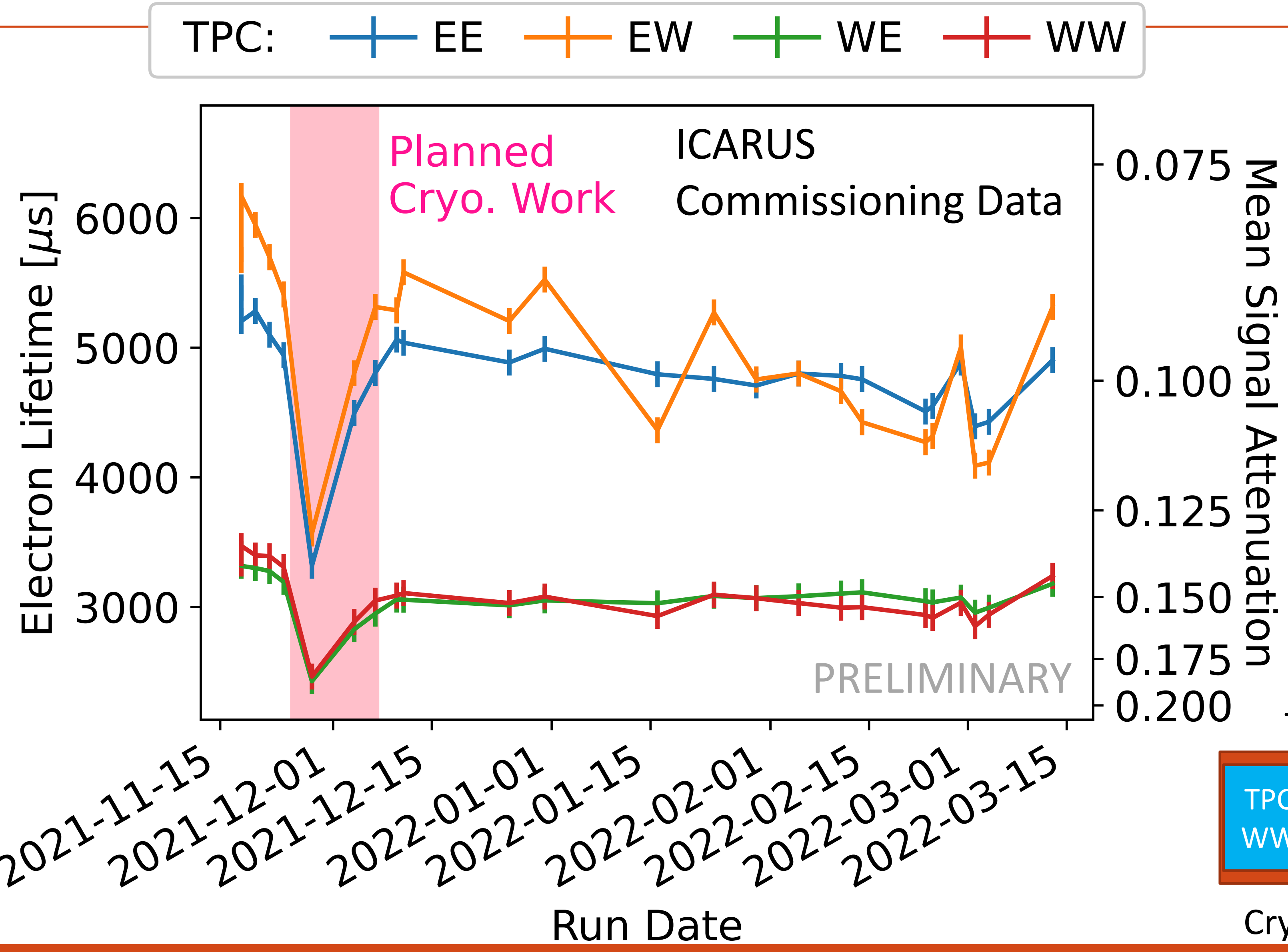
W Foreman et al., PR D (2020)



… however, adding a photosensitive dopant to the argon in DUNE would increase light-yield by turning it into charge collection.

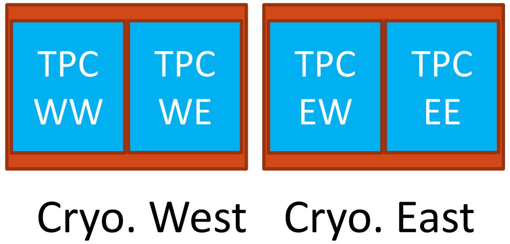
Suggested by A Mastbaum, F Psihas, and J Zennamo (arxiv:2203.14700)

Electron Lifetime Result on Calibration Dataset



Error on lifetime is systematic effect from (uncorrected) field distortions.

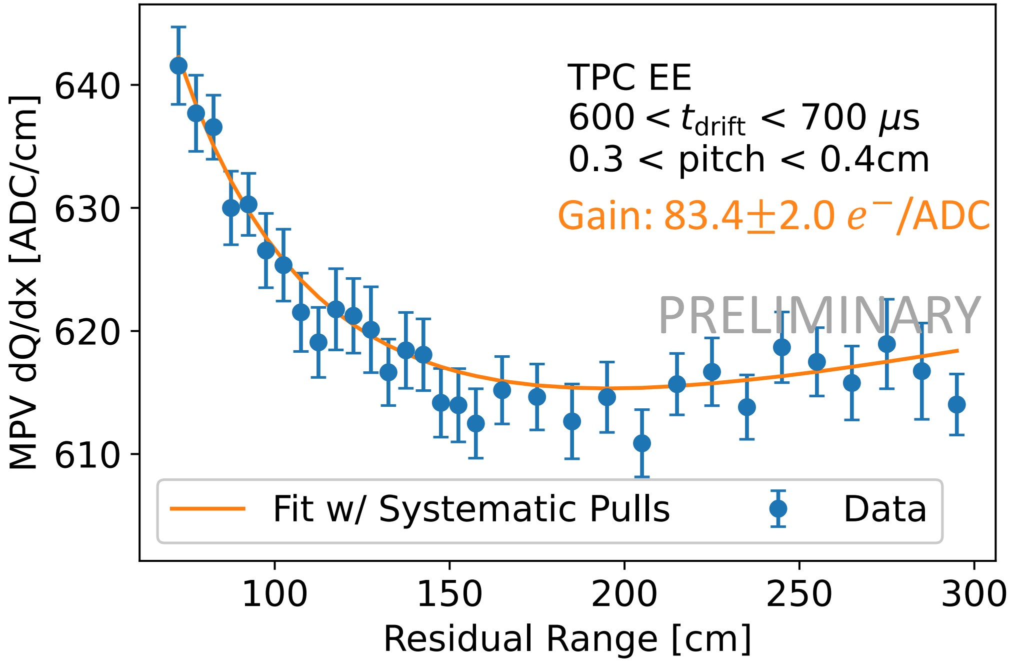
TPC Enumeration:

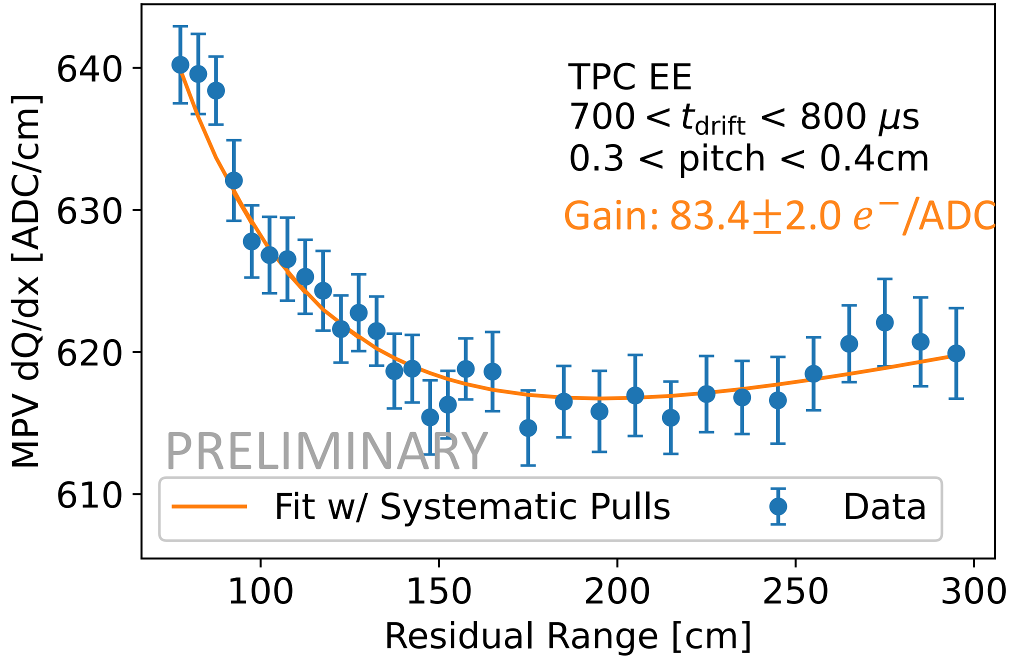


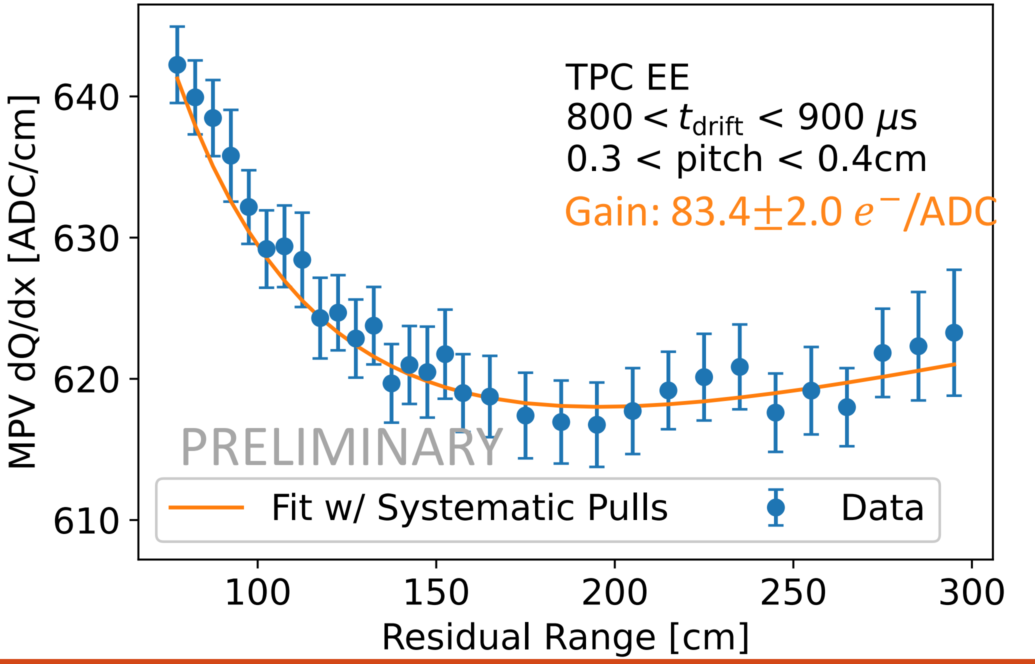
Example dQ/dx Profile Data

ICARUS
Commissioning
Data

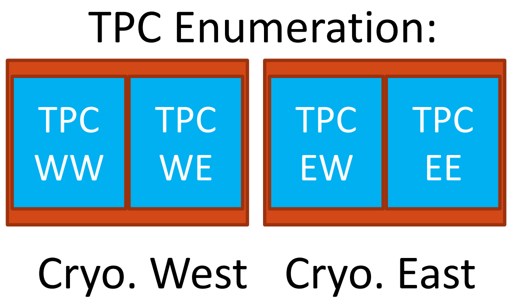
TPC WE







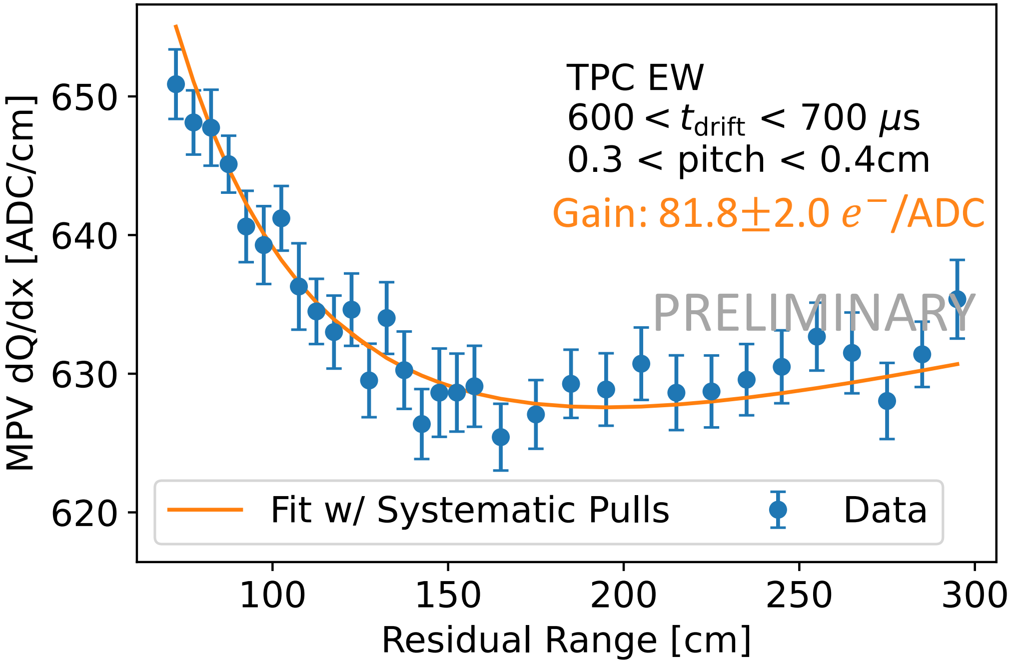
- Fit across all drift bins, with a separate gain in each TPC and "pulls" for systematics

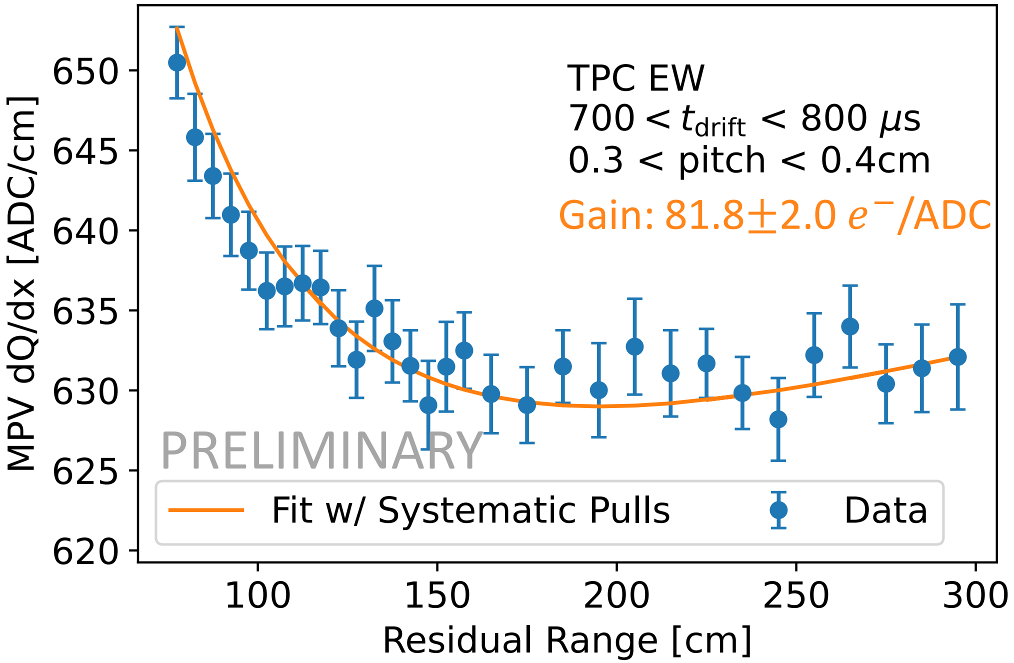


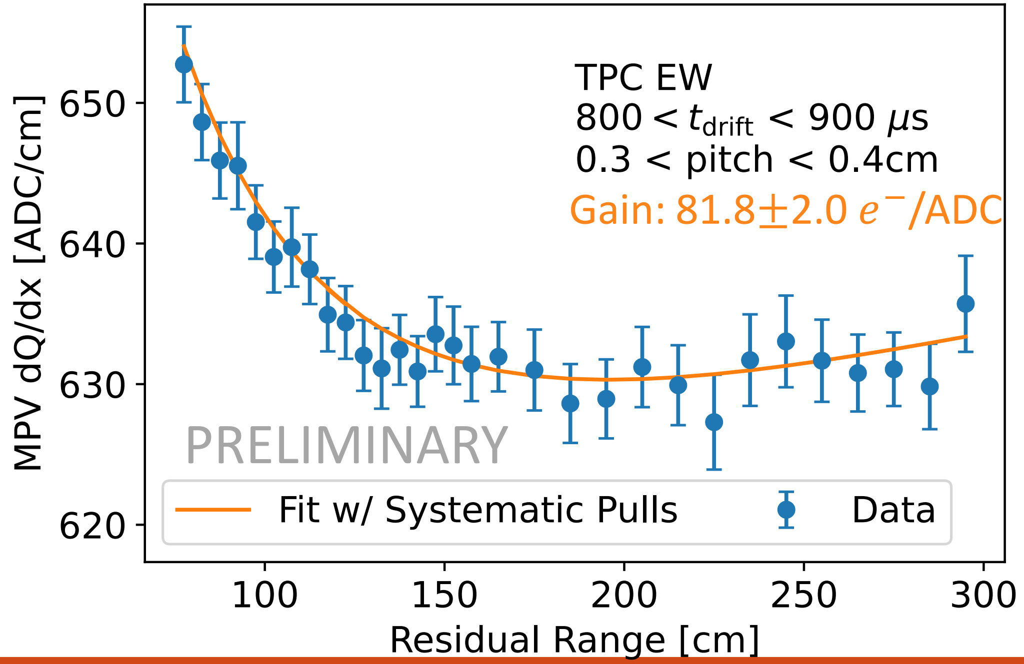
Example dQ/dx Profile Data

ICARUS Commissioning Data

TPC WE

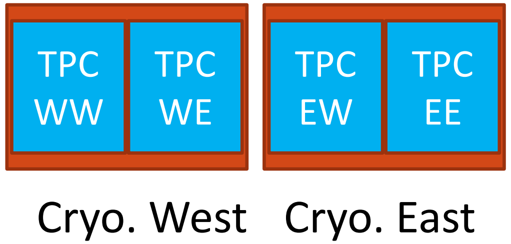






- Fit across all drift bins, with a separate gain in each TPC and “pulls” for systematics

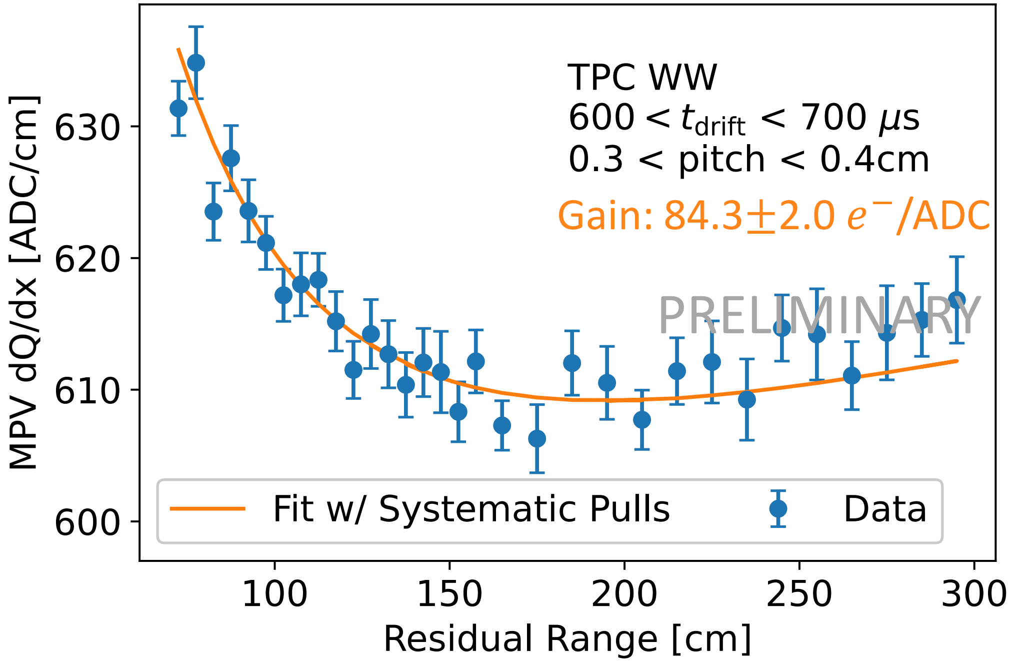
TPC Enumeration:

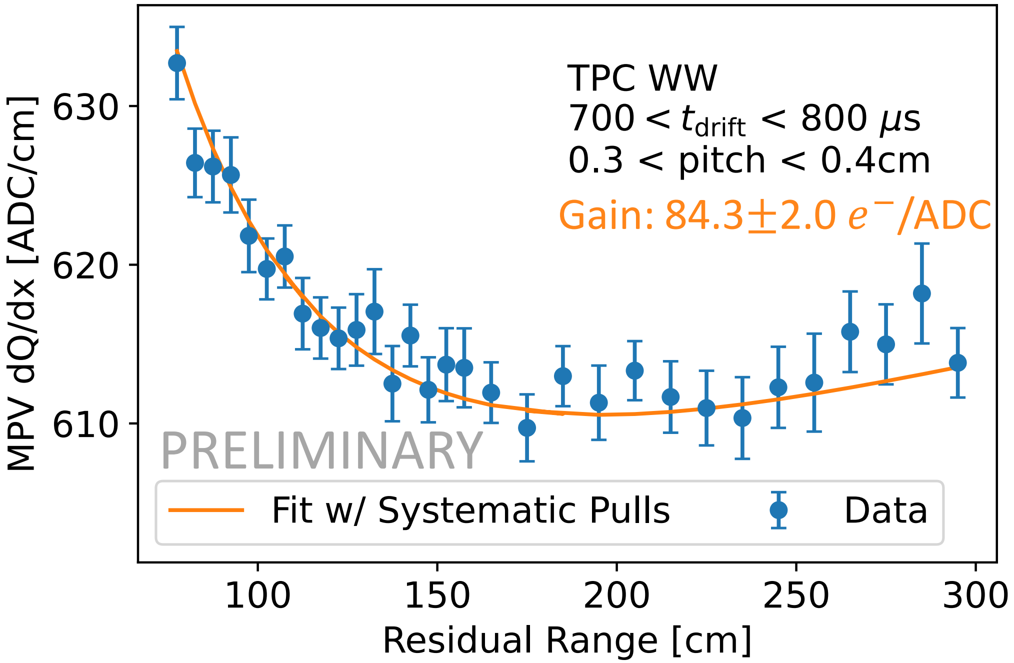


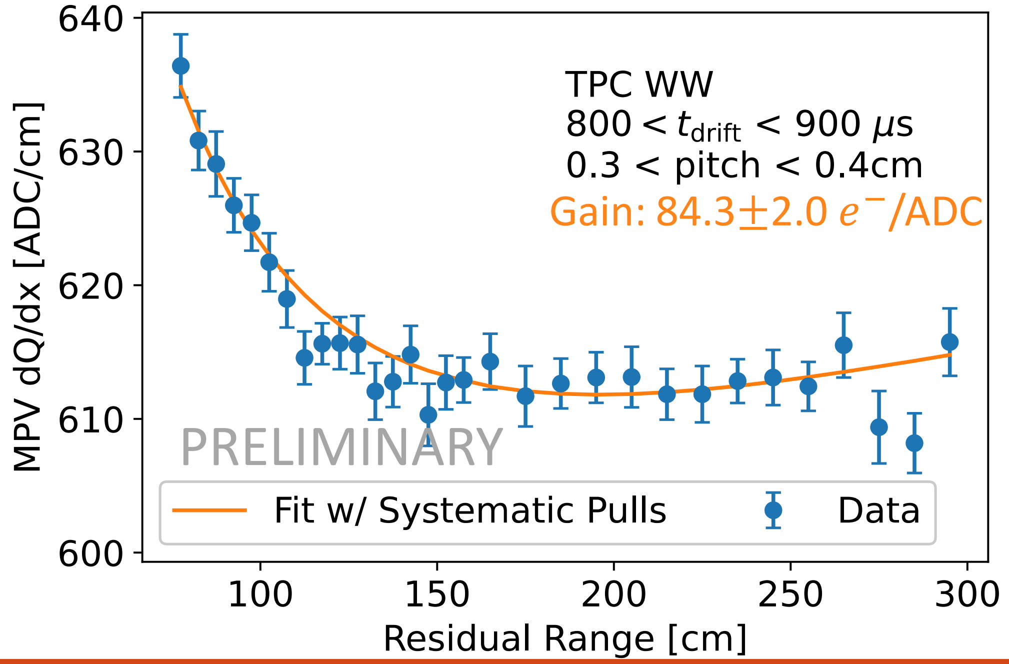
Example dQ/dx Profile Data

ICARUS Commissioning Data

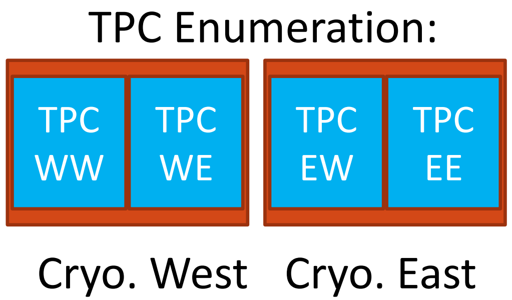
TPC WE



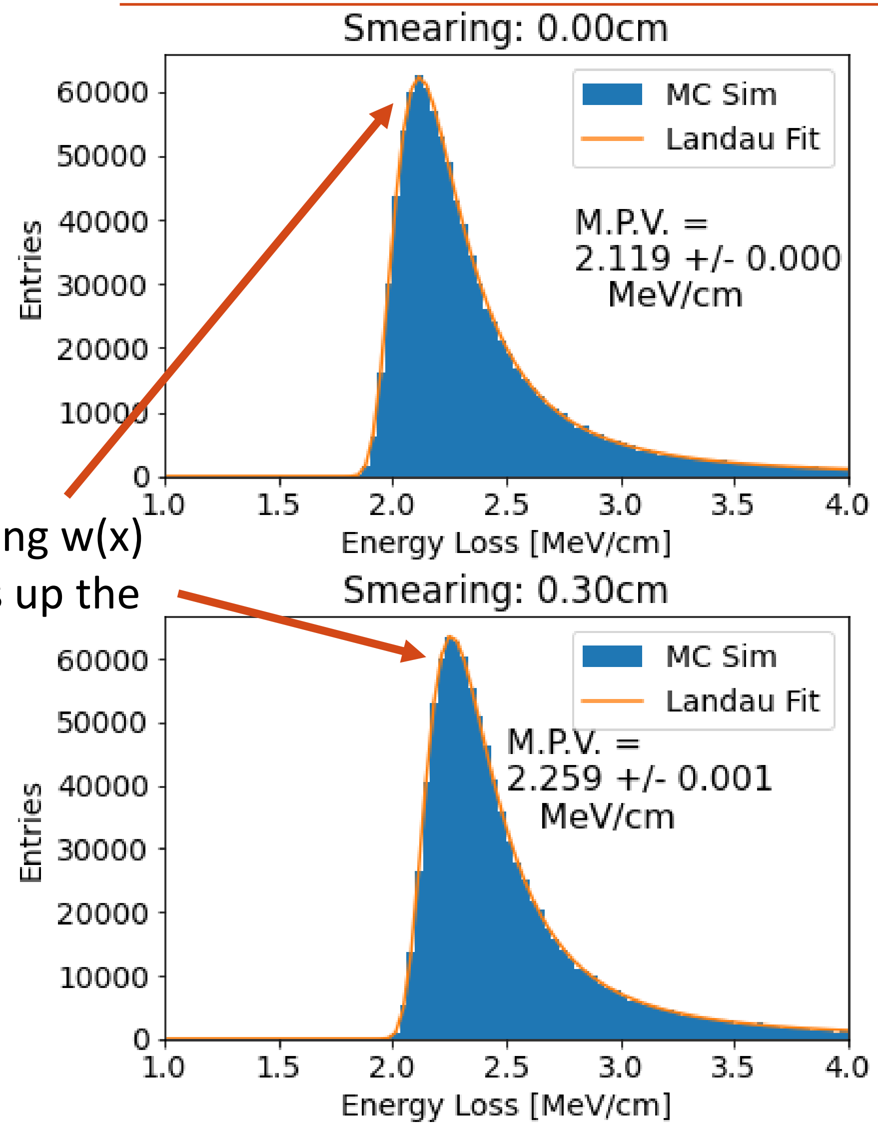




- Fit across all drift bins, with a separate gain in each TPC and "pulls" for systematics

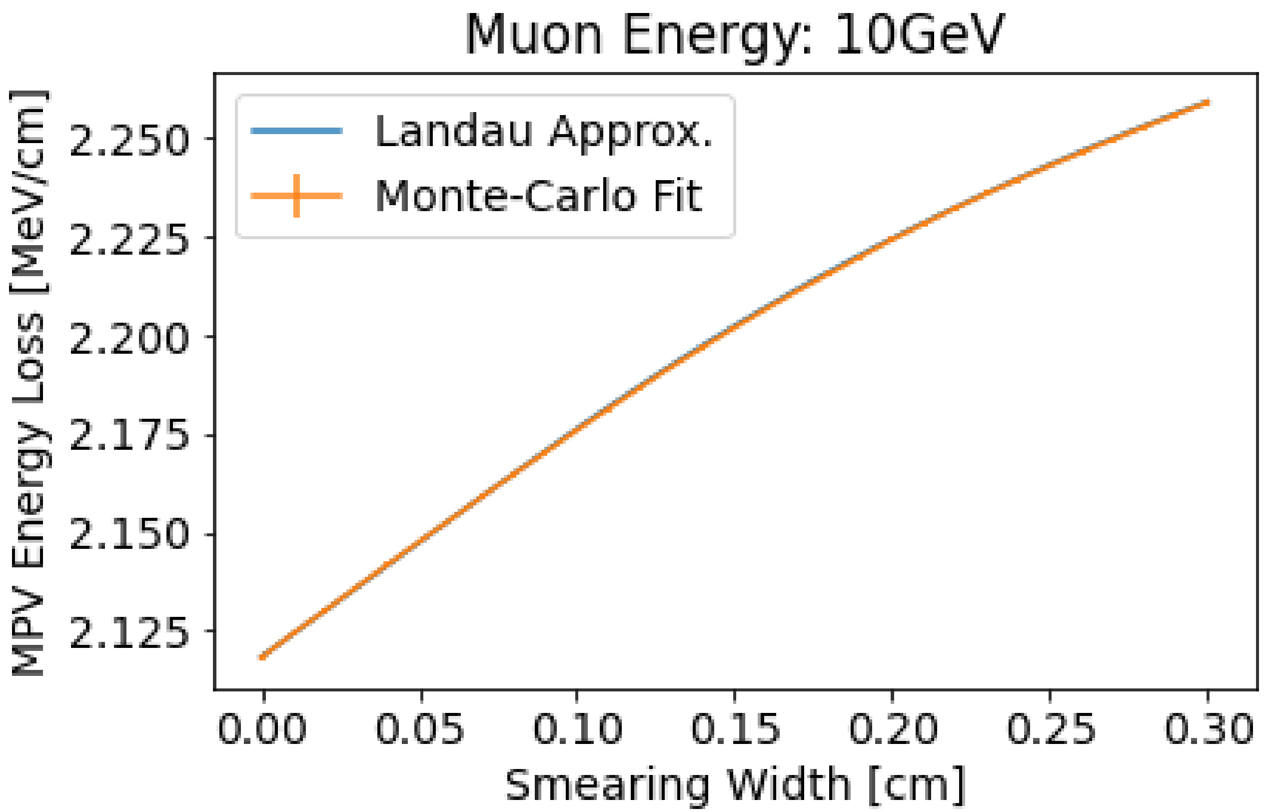


Effect on the MPV: Toy MC



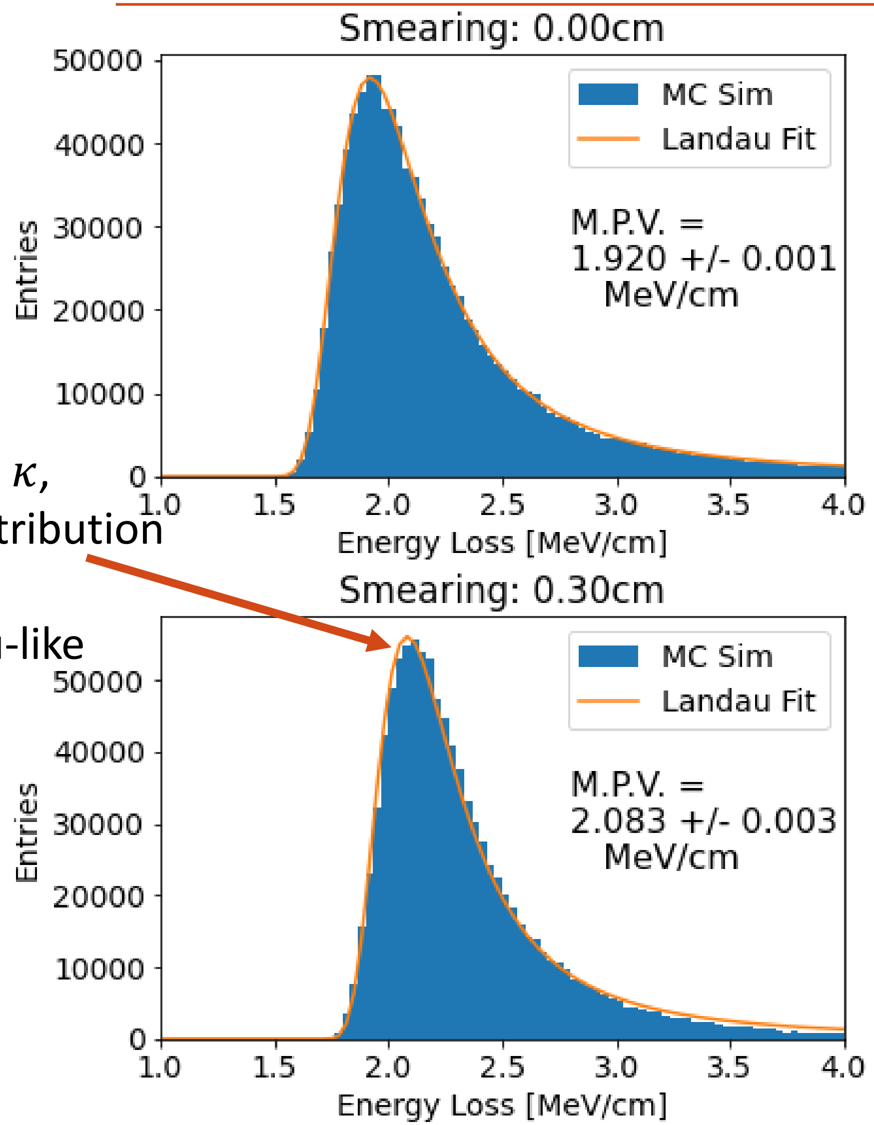
Smearing w(x)
Pushes up the
MPV!

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

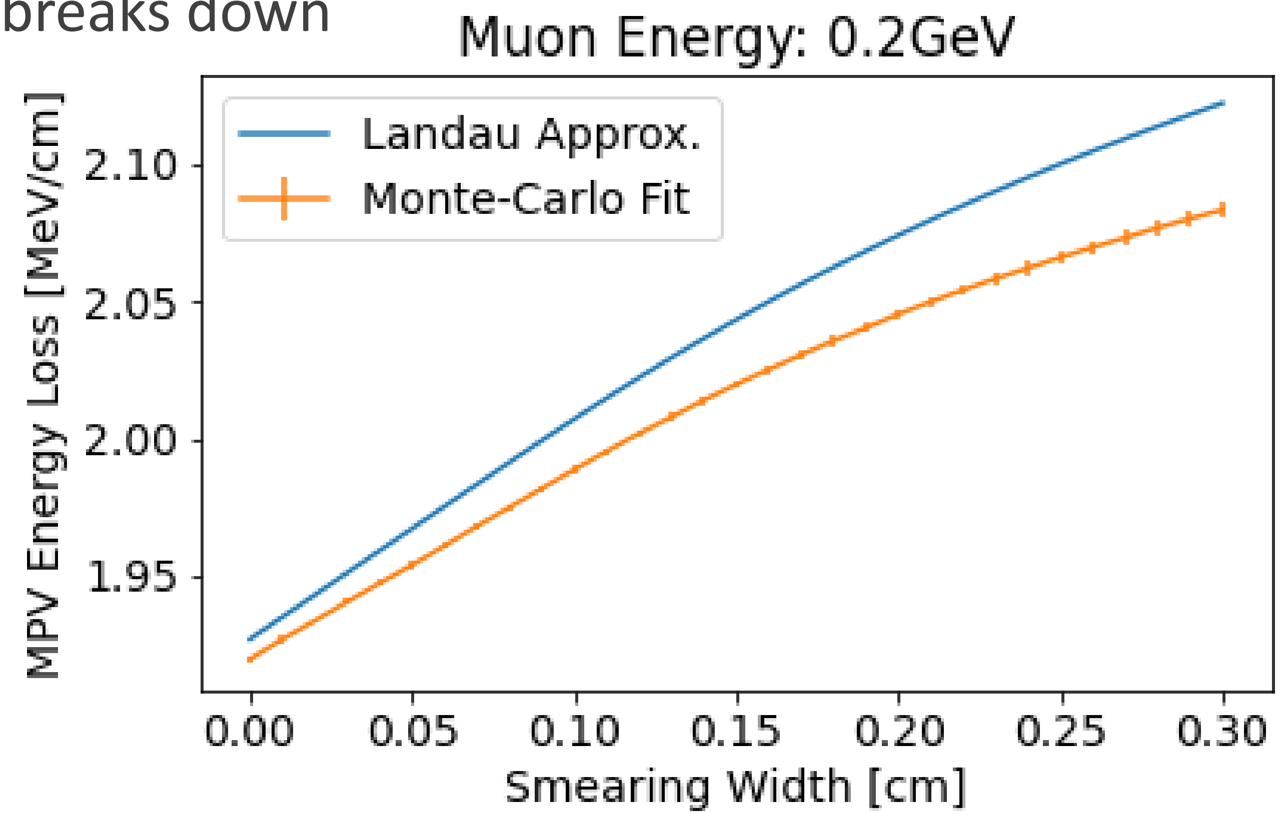


Effect on the MPV at Large Thickness

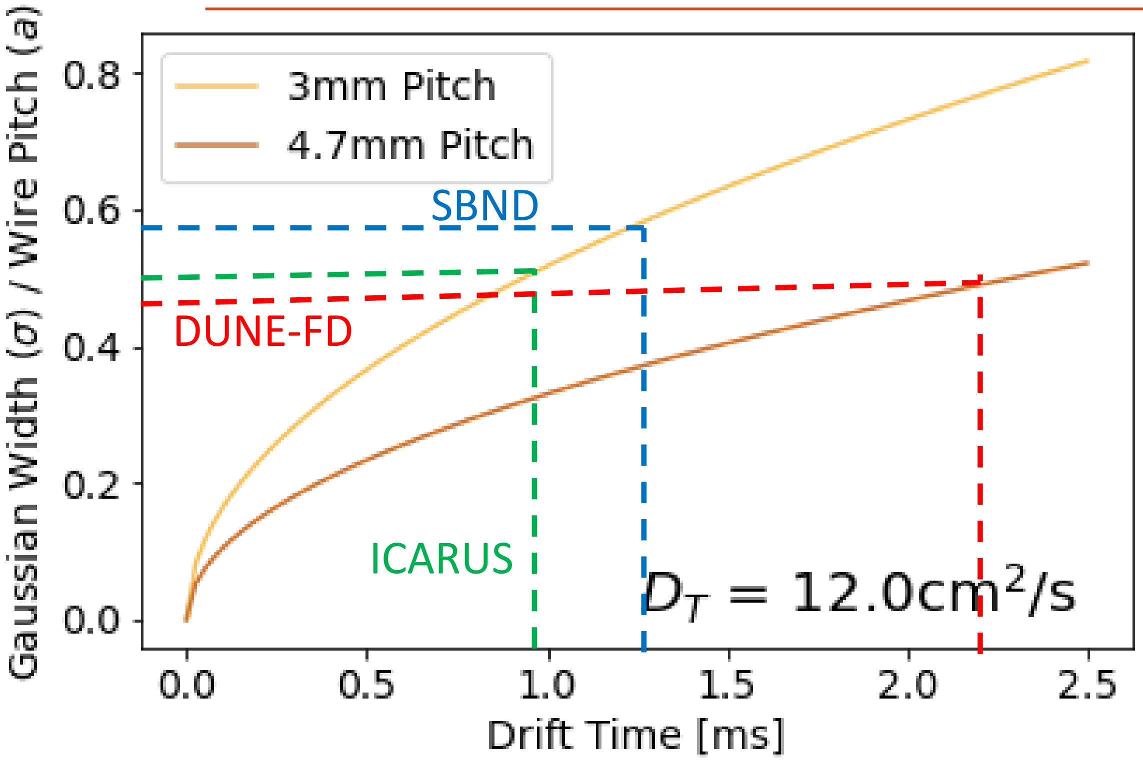
At high κ, the distribution is less Landau-like

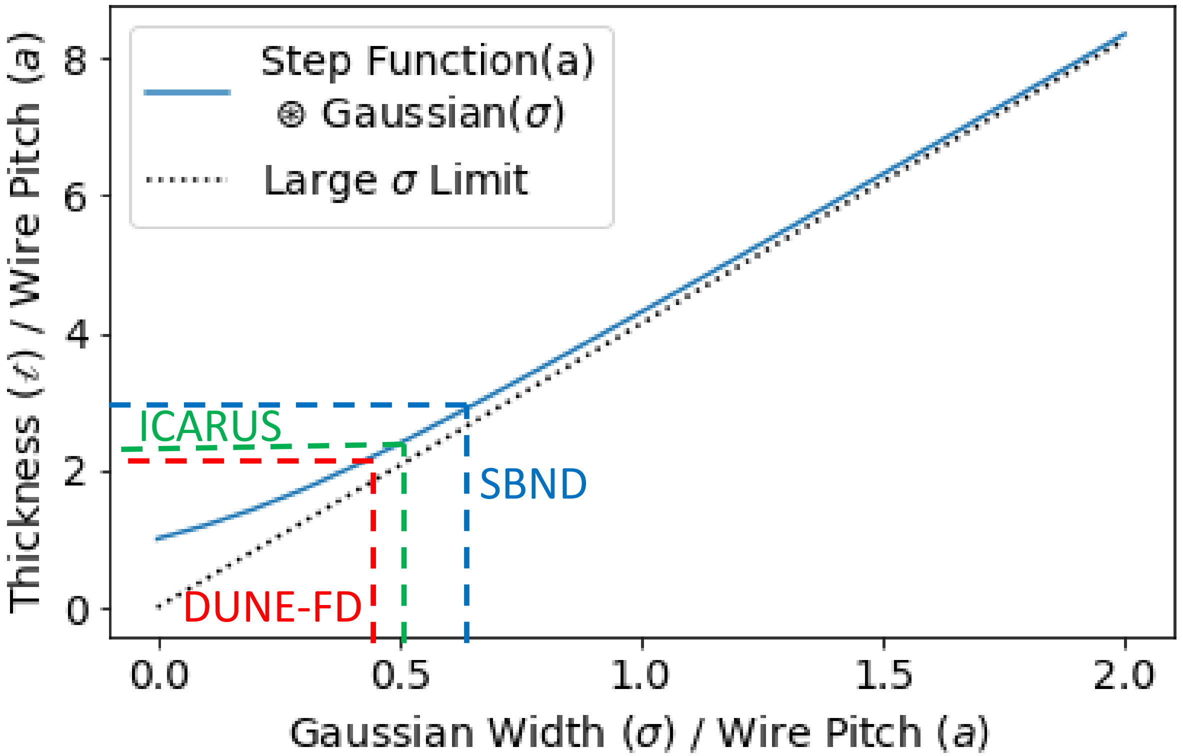


- Results from a toy MC of muon energy loss in LAr, for a wire spacing of 3mm
- At large thickness (κ), the Landau approximation breaks down



Impact of Diffusion on Thickness at Detectors





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

$$\mathscr{p} = \int w(x)\, dx$$

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

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]	Diffusion Const. D_T [cm^2/s]	MPV dE/dx, No Diffusion [MeV/cm]	MPV dE/dx at Cathode (Full Diff.) [MeV/cm]	Difference [%]
MicroBooNE [4]	3.00	2.33	5.85	1.69	1.79	5.9
ArgoNeuT [3]	4.00	0.295	12.0 (9.30)	1.72 (1.72)	1.76 (1.75)	2.3 (1.7)
ICARUS [5]	3.00	0.960	12.0 (9.30)	1.69 (1.69)	1.78 (1.77)	5.3 (4.7)
SBND [5]	3.00	1.28	12.0 (9.30)	1.69 (1.69)	1.79 (1.78)	5.9 (5.3)
DUNE-FD (SP) [7]	4.71	2.2	12.0 (9.30)	1.74 (1.74)	1.82 (1.81)	4.6 (4.0)

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