DUNE LArTPC Calibration w/ Low-Energy Radioactive Decays

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On behalf of the DUNE Collaboration

Conference on Science at the Sanford Underground Research Facility (CoSSURF 2024)

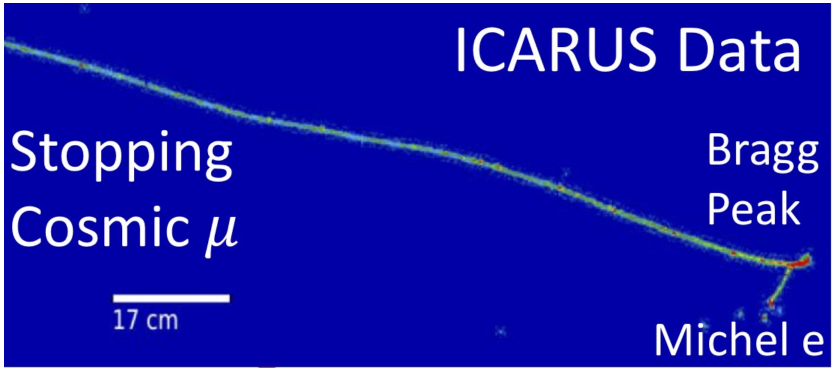
May 16th, 2024

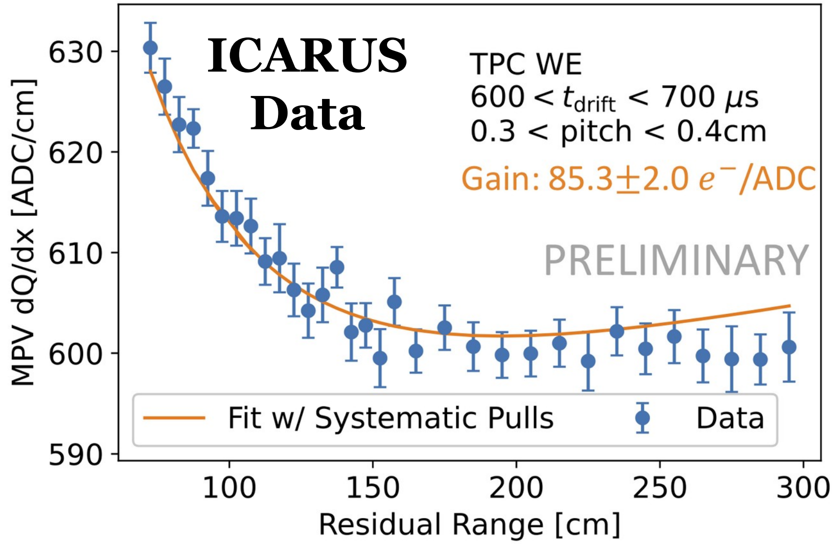
Introduction

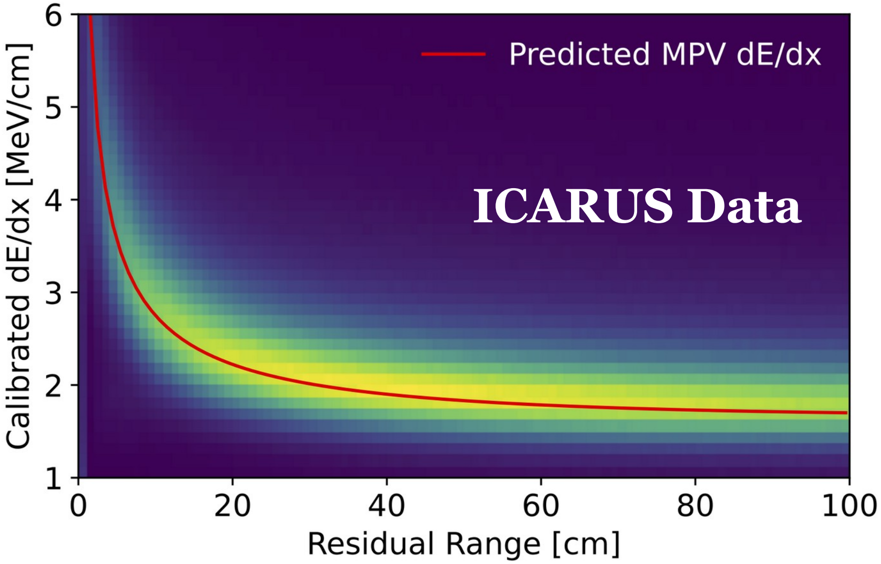
- Most calibrations done at near-surface LArTPC detectors utilize cosmic rays
  - Example: MicroBooNE on surface → **~4000 cosmics/second**
- Not a reliable option at DUNE FD due to being **almost a mile underground**
  - DUNE FD: **~4000 cosmics/day** (per 17 kt module)
  - Corresponds to ~5 cosmics/day/m^3
  - DUNE **ND-LAr ~60 m underground**, with similar concern
- Cosmics can still help (also rock muons for ND-LAr), but need alternative charge/light sources for calibrations
- Plenty of ^{39}**Ar beta decays** at DUNE FD/ND-LAr
  - Due to use of atmospheric argon (AAr) at DUNE: ~1 Bq/kg
  - Other low-energy radioactive decays very useful as well

Cosmic Ray Calibrations @ ICARUS

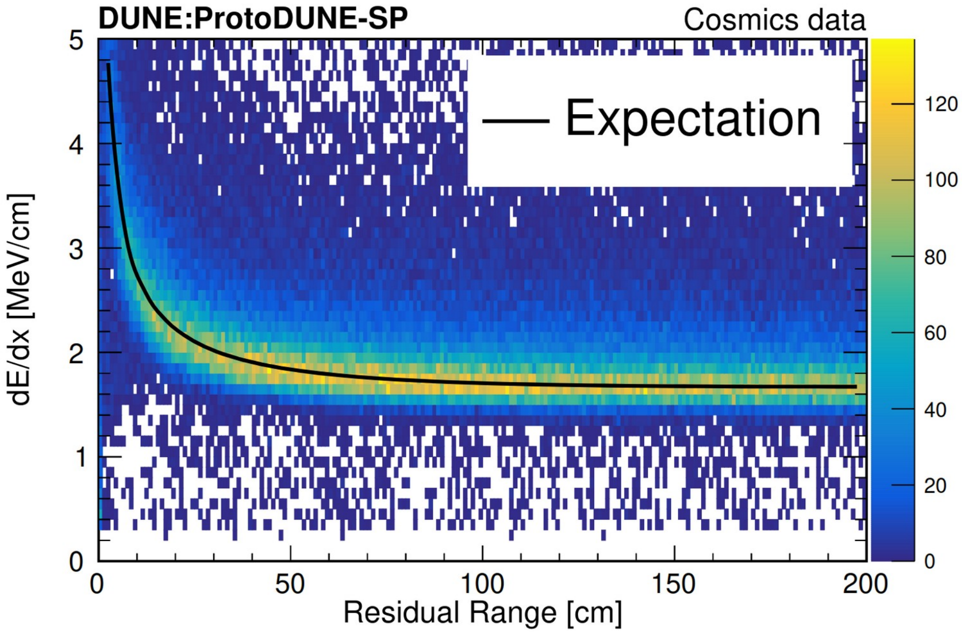
- Case study: ICARUS (SBN Program far detector, on surface) relies on cosmic muons for most calibrations
  - Stopping muon: use known dE/dx vs. "residual range" (distance from stopping point)
- Example: use for TPC gain, recombination corrections

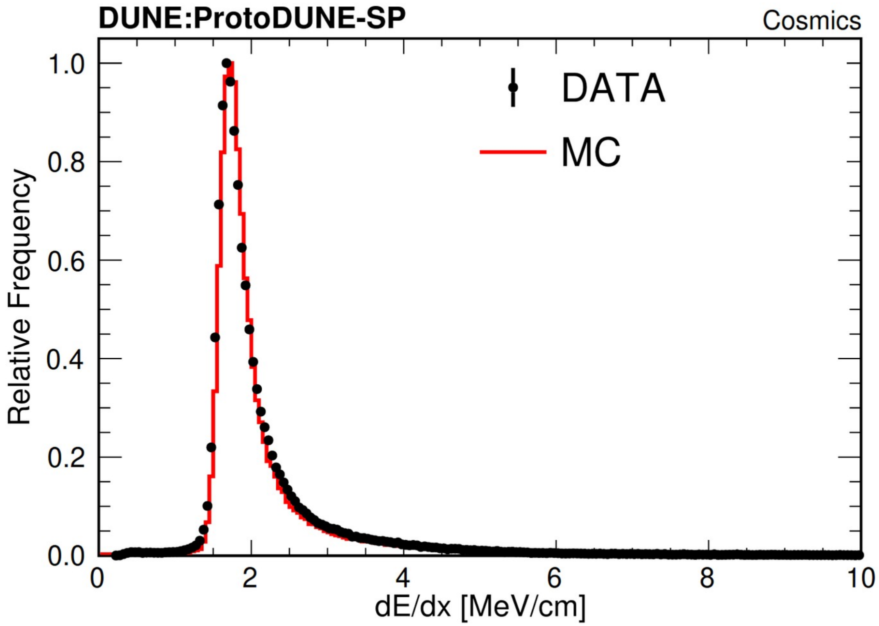






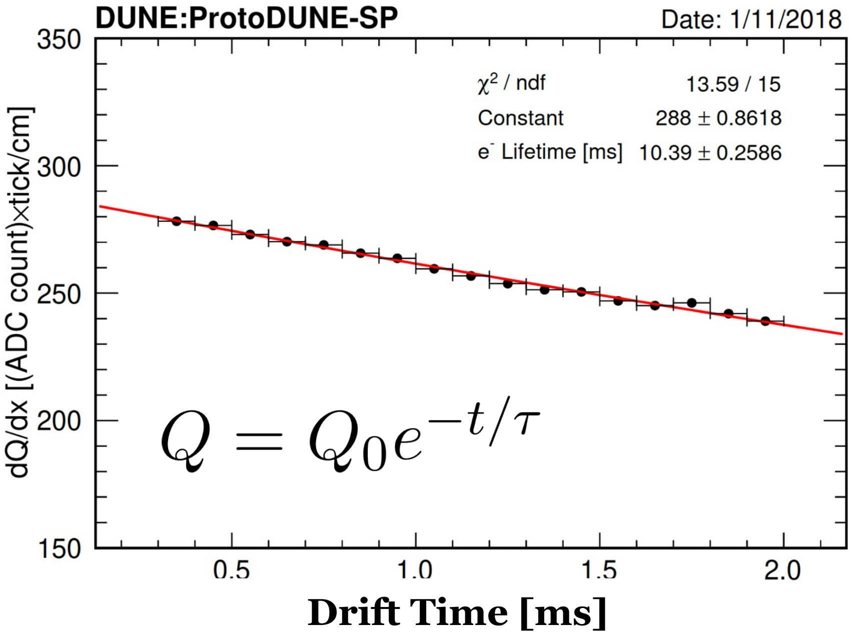
Cosmic Ray Calibrations @ ProtoDUNE-SP

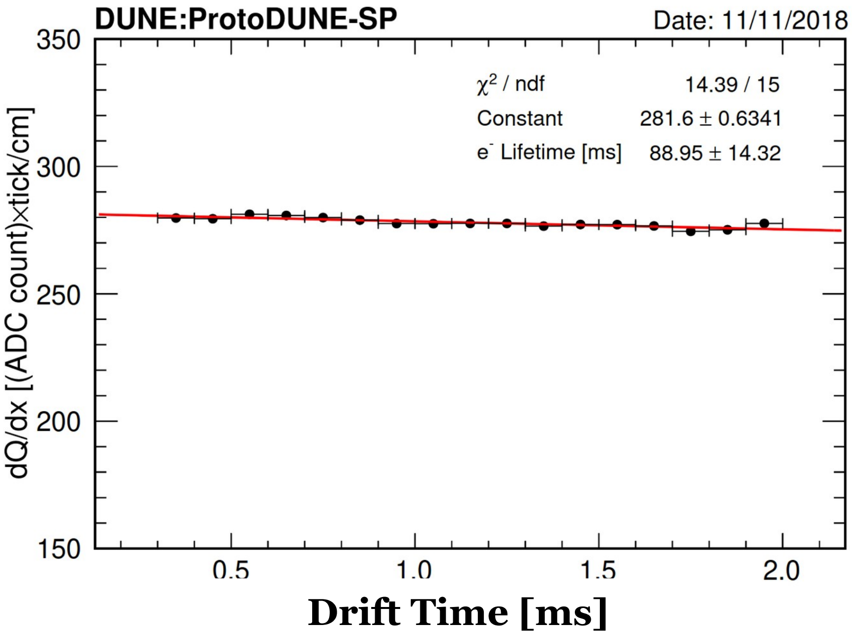




- First results from ProtoDUNE-SP (first DUNE FD prototype, data-taking in 2018) relied on calibrations w/ cosmic muons
  - Above left: dE/dx vs. residual range for stopping cosmic muons (data)
  - Above right: dE/dx distribution of stopping cosmic muons (data vs. MC)
  - See **JINST 15 P12004** for full set of results: “First results on ProtoDUNE-SP liquid argon time projection chamber performance from a beam test at the CERN Neutrino Platform”

Cosmic Ray Calibrations @ ProtoDUNE-SP





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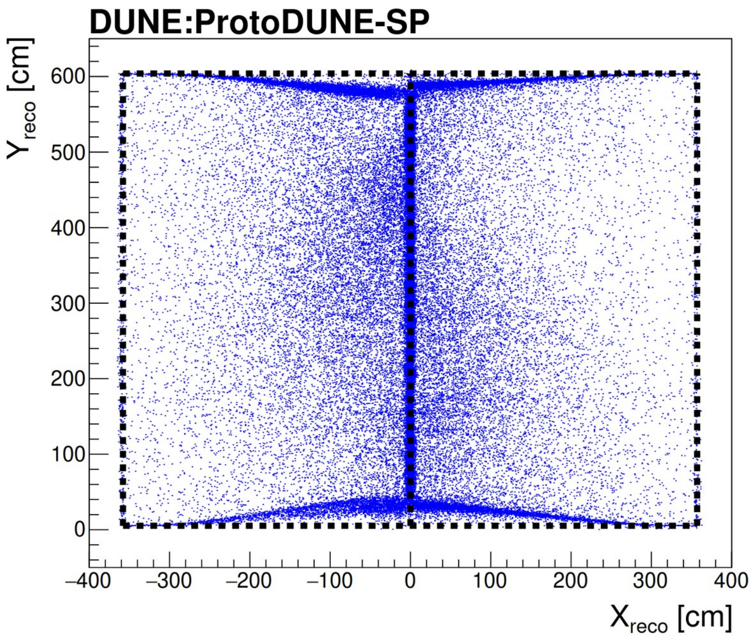
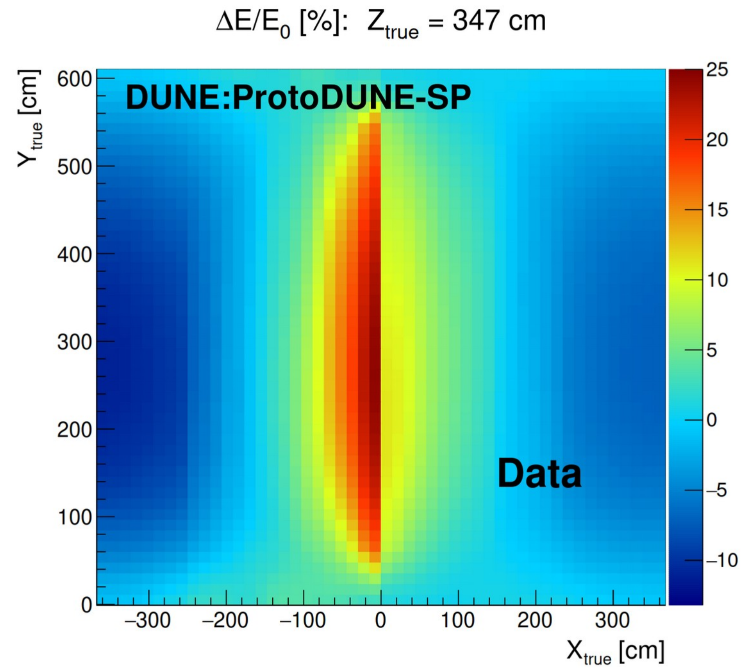
  - Above left: through-going muon dQ/dx vs. drift time (electron lifetime measurement) at **lower purity** (data)
  - Above right: through-going muon dQ/dx vs. drift time (electron lifetime measurement) at **higher purity** (data)
  - See **JINST 15 P12004** for full set of results

Cosmic Ray Calibrations @ ProtoDUNE-SP

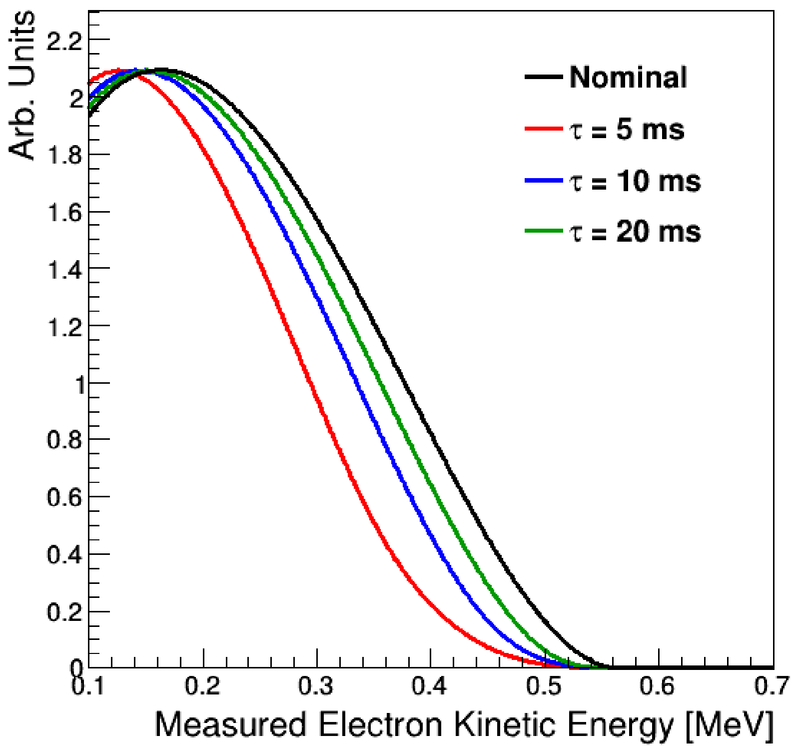




- First results from ProtoDUNE-SP (first DUNE FD prototype, data-taking in 2018) relied on calibrations w/ cosmic muons
  - Above left: reconstructed end points of through-going cosmic muons, pushed inward due to **space charge effects** (data)
  - Above right: result of space charge effect E field calibration, carried out using cosmic muons (data)
  - See **JINST 15 P12004** for full set of results

^{39}Ar Beta Decays

Measured ^{39}Ar Spectrum w/ Electron Lifetime Impact

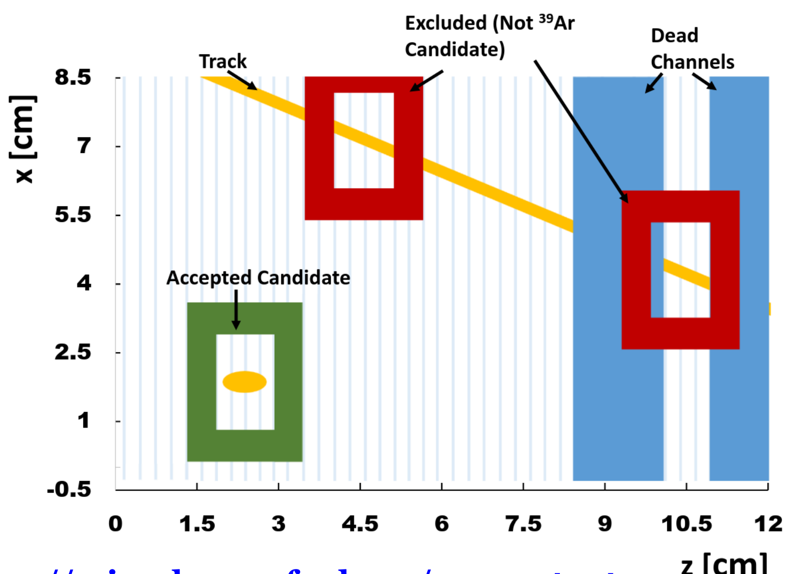


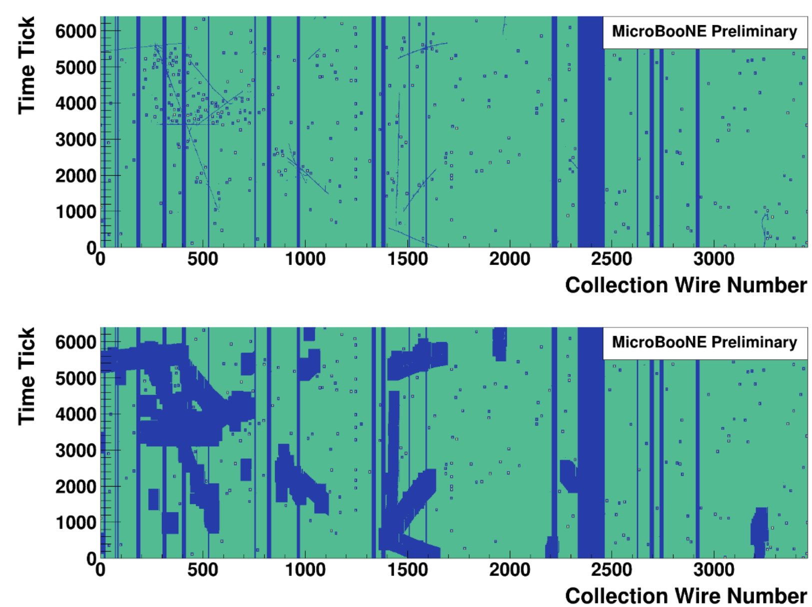
$$Q = Q_0 e^{-t/\tau}$$

- ^{39}Ar beta decay end point energy is 565 keV
  - Roughly ½ of energy deposited on a single wire by a MIP at DUNE FD
  - Should see > 100 keV at DUNE
- Must associate ionization charge ("S2") to scintillation light ("S1") to find drift coordinate
  - Tough at large DUNE detectors for sub-MeV activity
  - But decays are **uniform in drift direction** → fold into *statistical measurements* (e.g. spectral shift due to electron lifetime effects)

^{39}Ar Beta Decays at MicroBooNE

- Initial studies of ^{39}Ar decays done at MicroBooNE in 2017
  - Released in **public note** in 2018 (study led by CSU undergrad)
  - Reconstruction of "blips" in 2D (collection plane only)
- Showed great promise for use in calibrations of interest
  - Significant complications from cosmogenic activity necessitated **track proximity veto** – not an issue at DUNE FD/ND-LAr





https://microboone.fnal.gov/wp-content uploads/MICROBOONE-NOTE-1050-PUB.pdf

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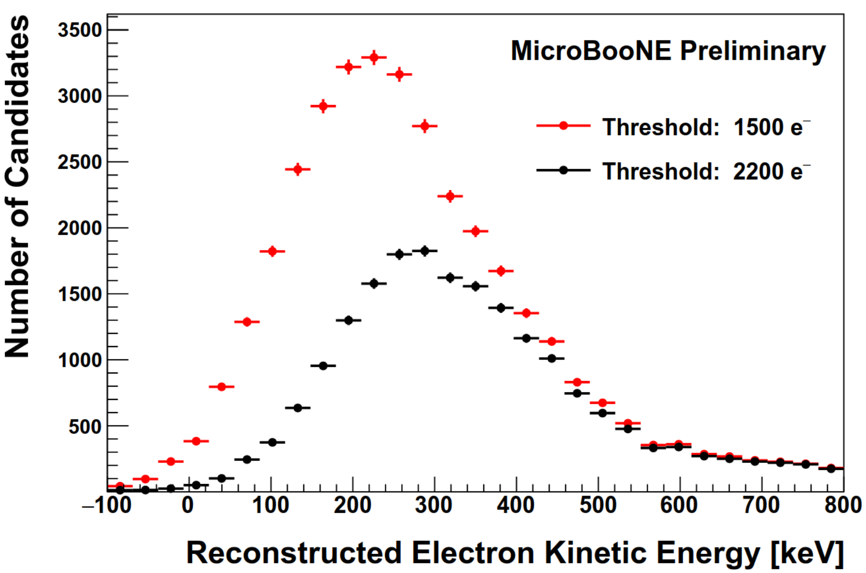
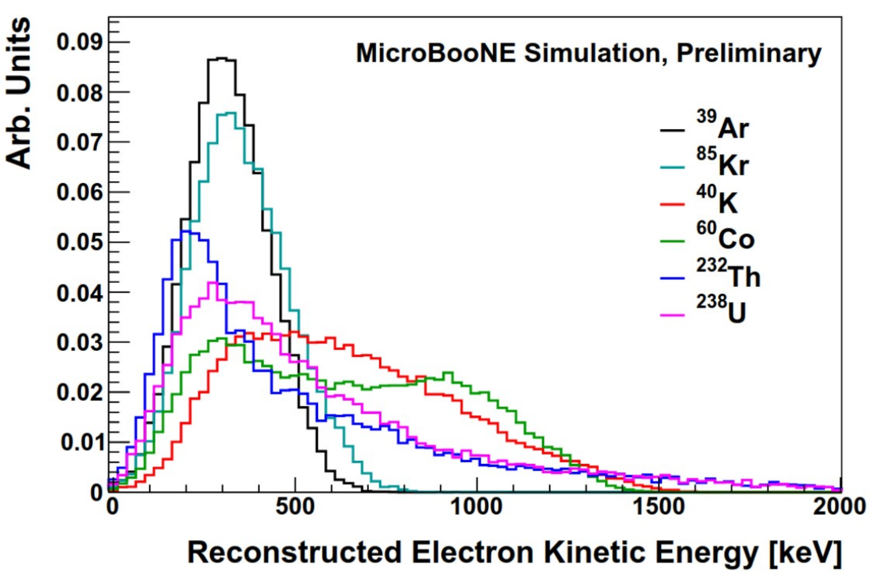
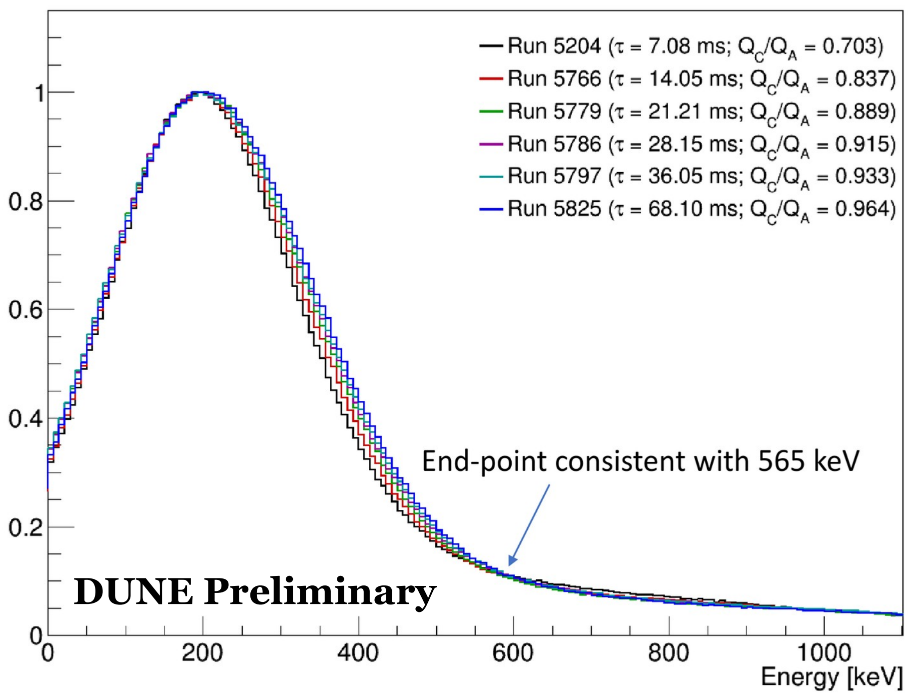
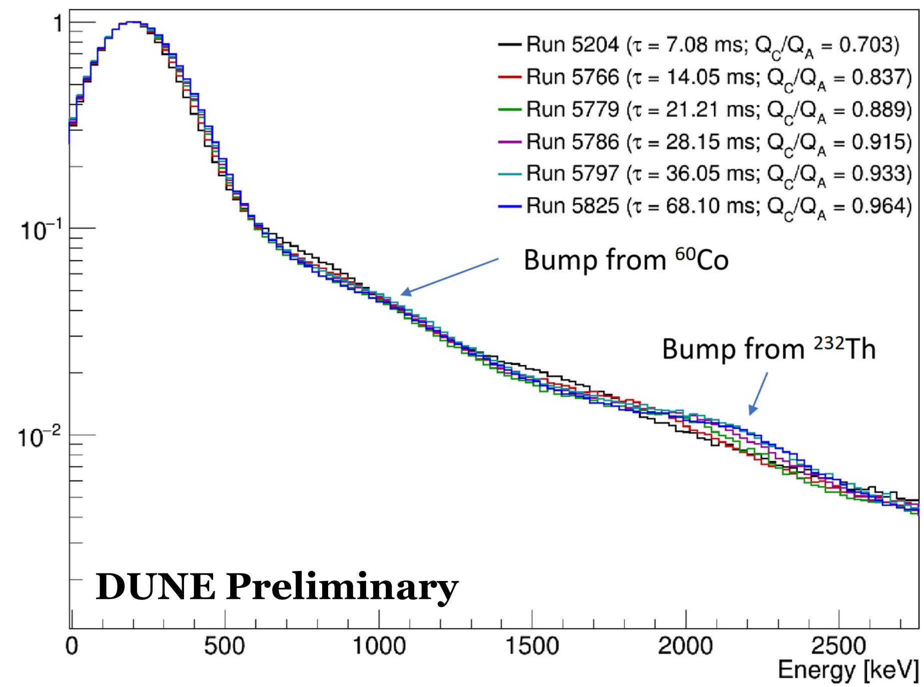




^{39}Ar Beta Decays at ProtoDUNE-SP

- ^{39}Ar also studied at ProtoDUNE-SP in 2020 by same CSU undergraduate student
- Uses for DUNE FD calibrations shown here: **electron lifetime measurement**, wire signal response shape estimation





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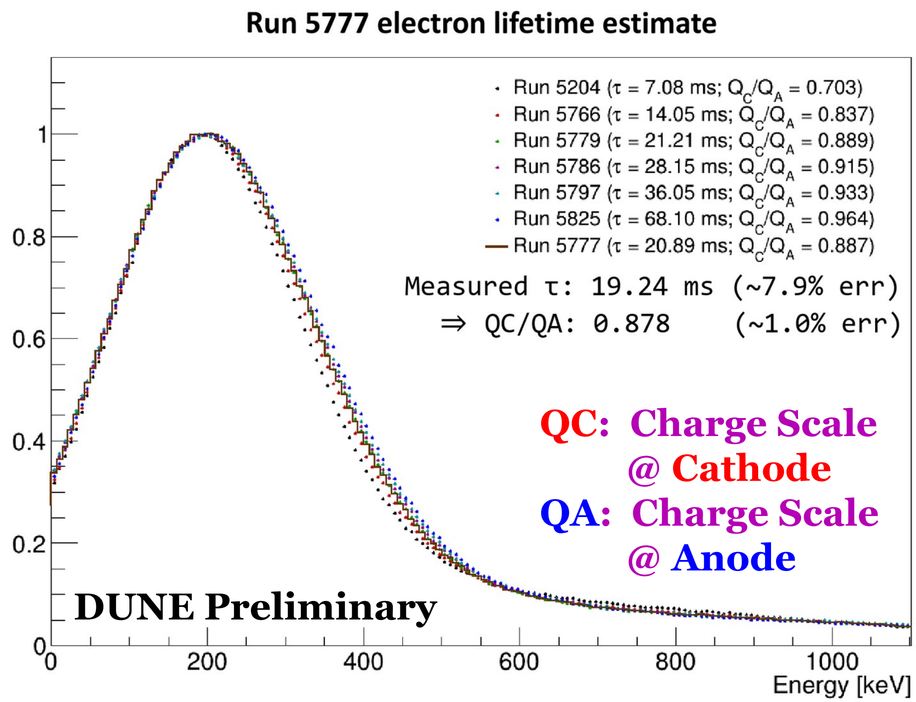

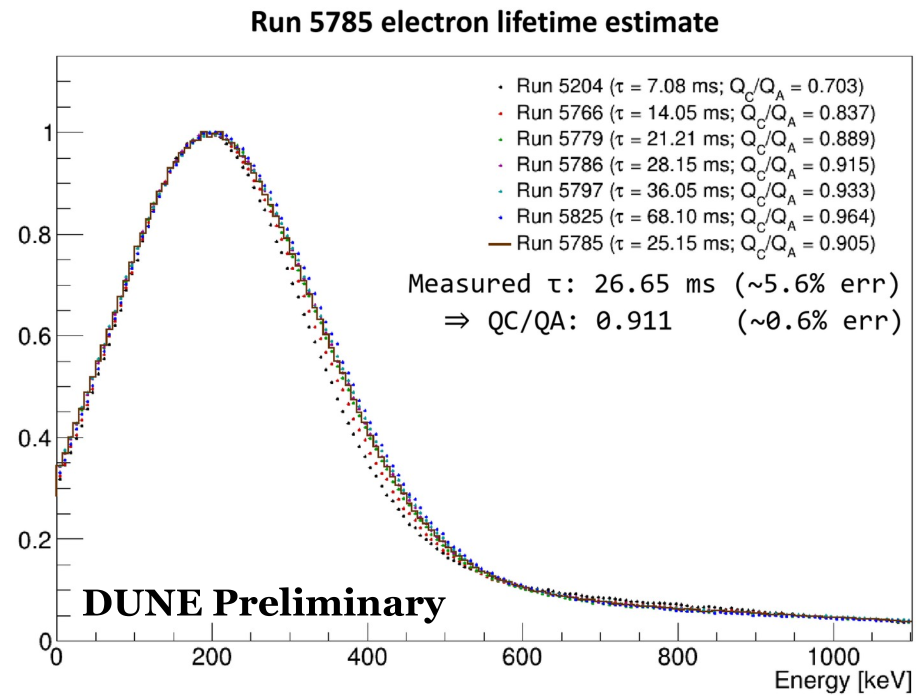

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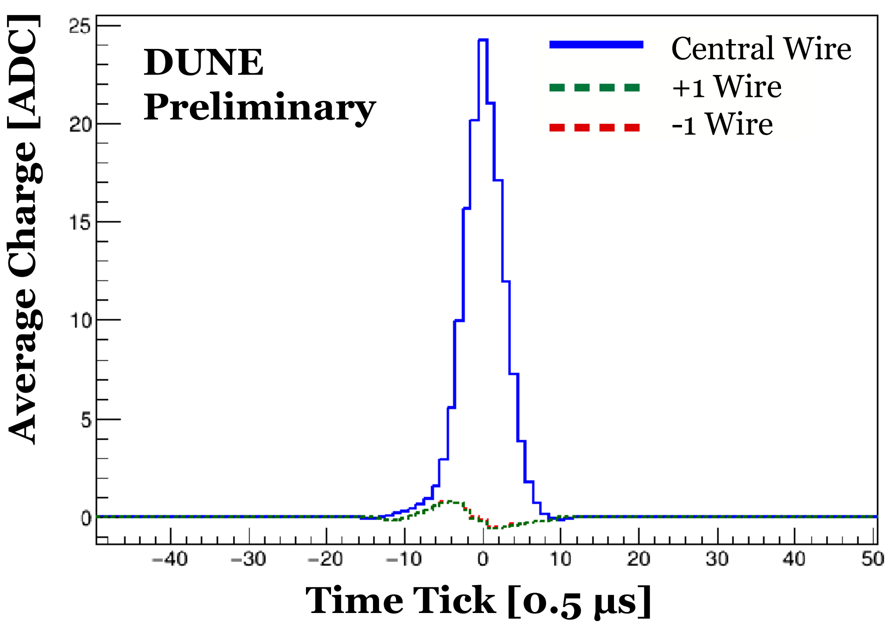
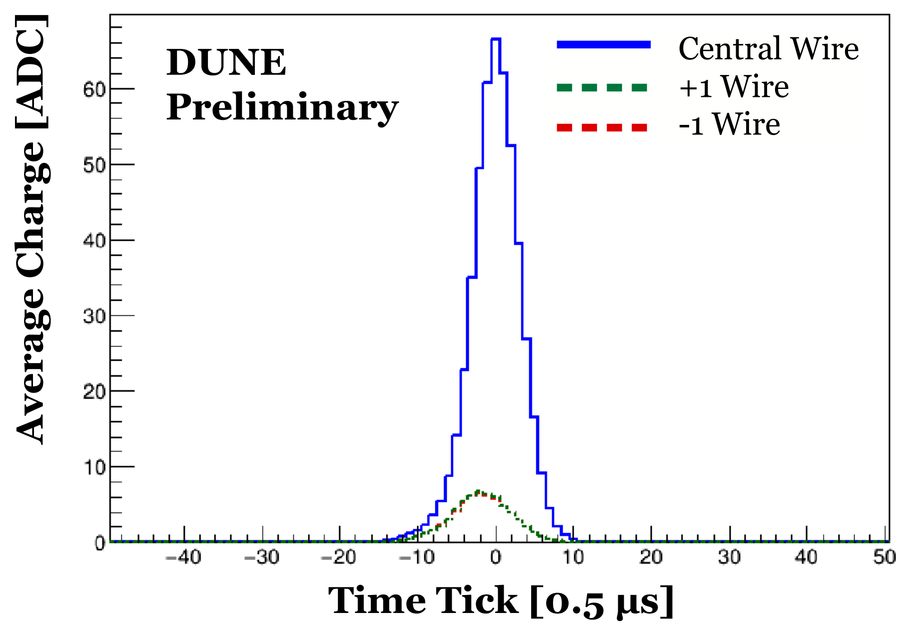
Measured Energy: [100, 150] keV

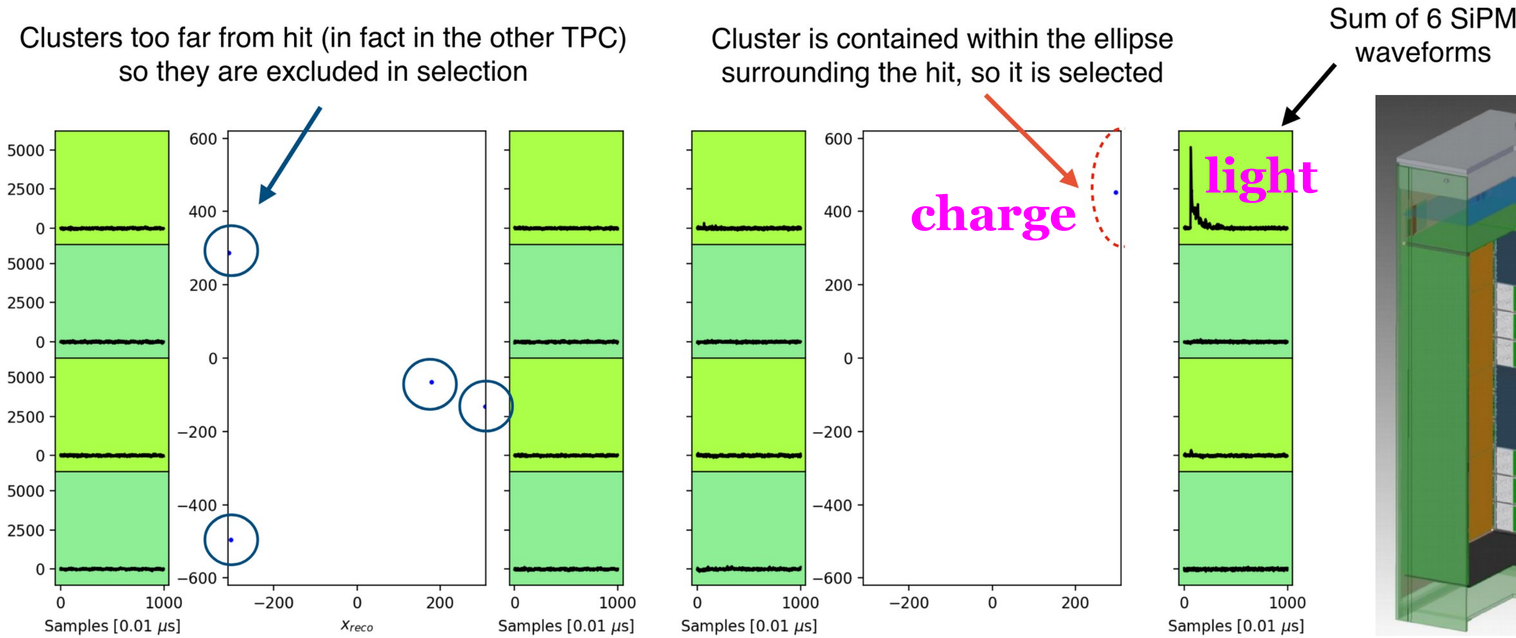


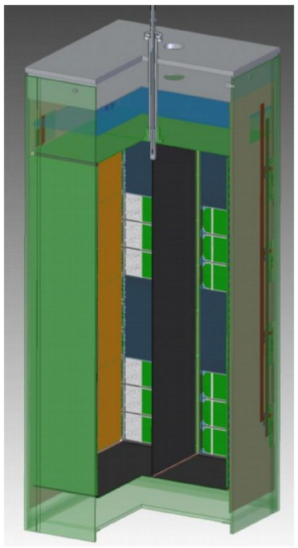
Measured Energy: [550, 600] keV



ND-LAr 2x2 Prototype Studies

- More recent work by Sam Fogarty (CSU graduate student) at the 2x2 prototype for DUNE ND-LAr, starting with data from single-module runs carried out at University of Bern
- Includes **charge+light matching** of low-energy activity
  - Yields known drift coordinate → enhances calibration power
  - Plan on exploring this at ProtoDUNE II as well





DUNE ND-LAr 2x2 Module

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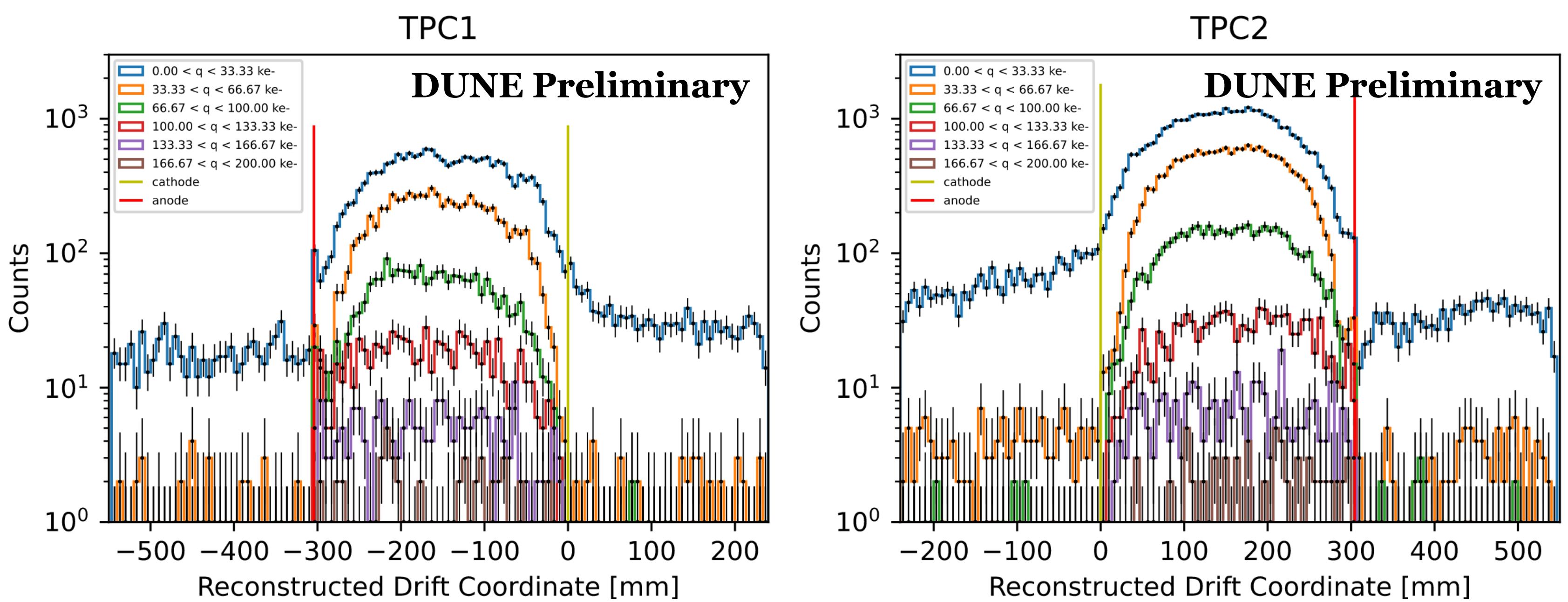

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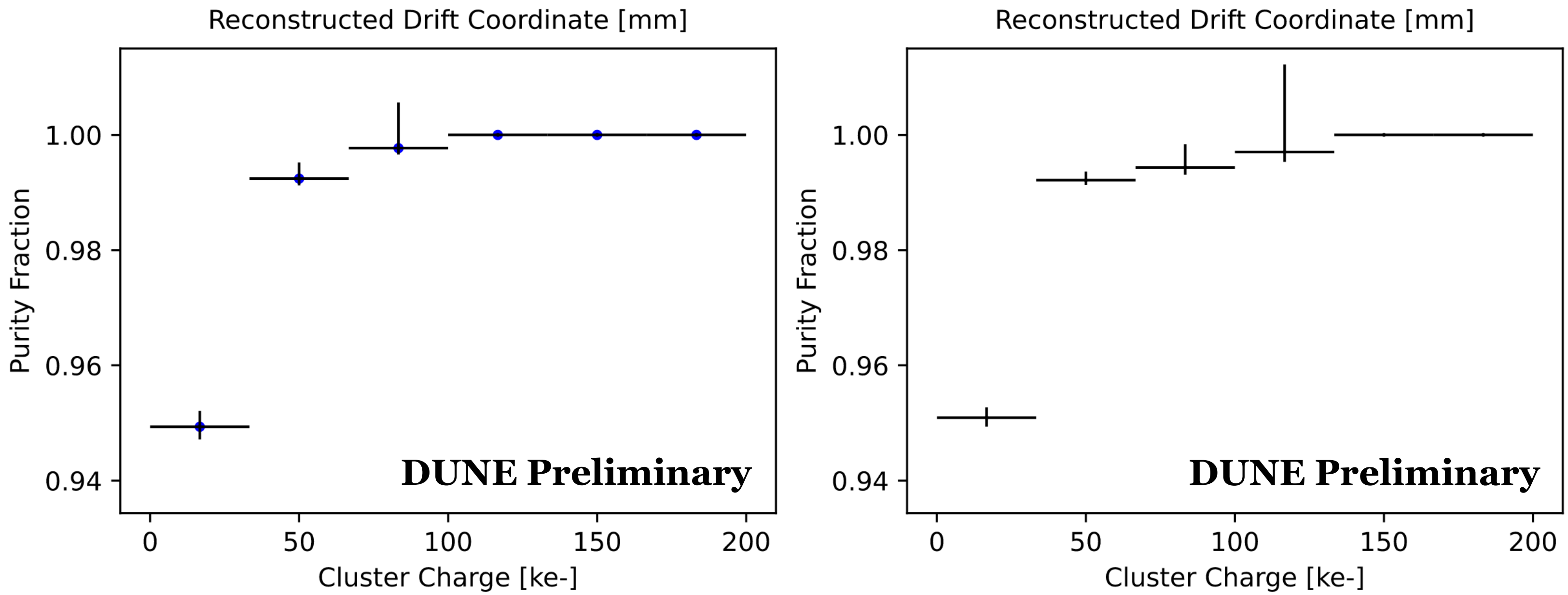

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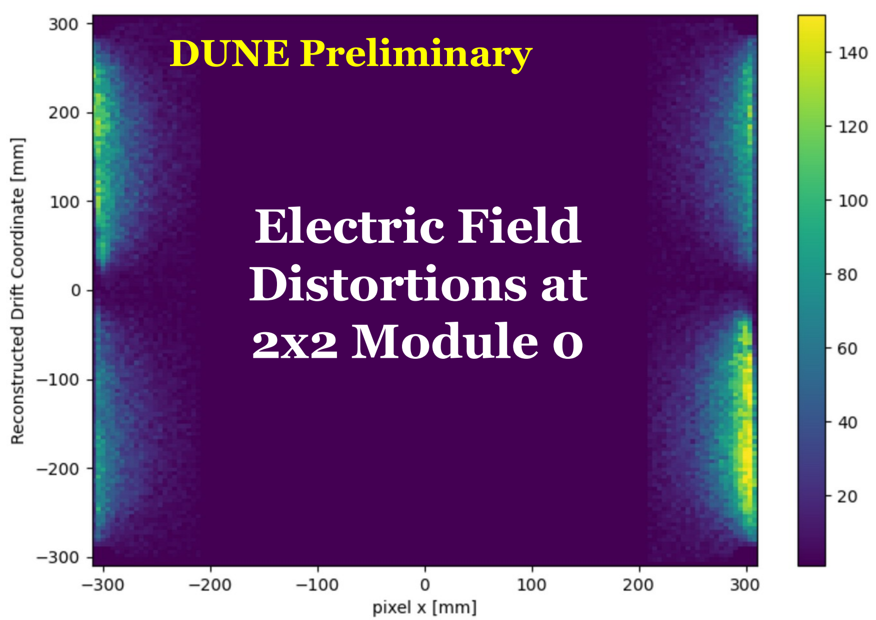
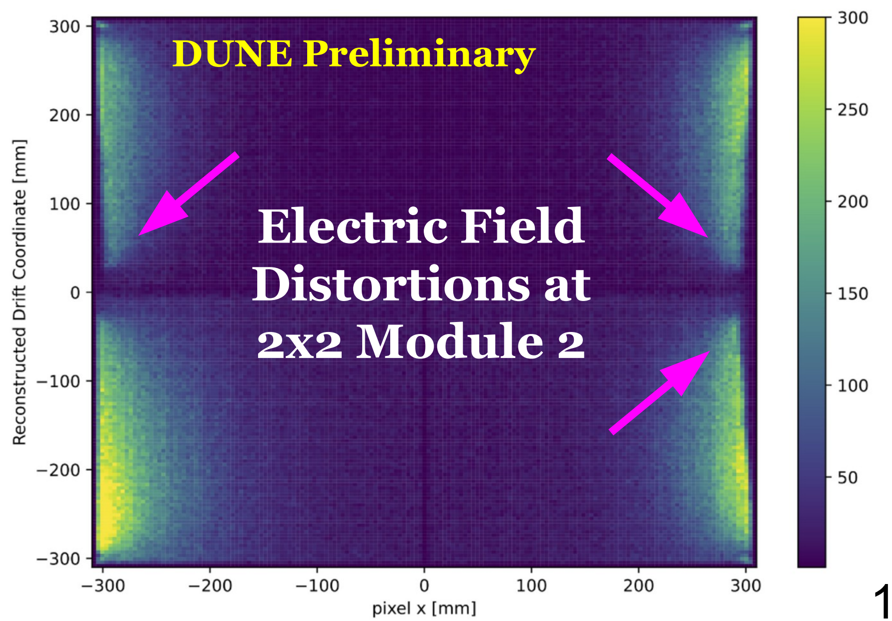




^{220}Rn Source Injection in LAr

- ^{39}Ar beta decays very useful for calibrations, but so are higher-energy radioactive decays – more charge, light produced
  - Natural rate may be high enough for some calibrations of interest
- Another idea: injection of radioactive sources directly into the LAr – specifically, radon:
  - **^{222}Rn** explored at MicroBooNE (**JINST 17 P11022**); useful if avoid LAr filter (copper getter removes ^{222}Rn) but long-lived decay product ^{210}Pb plates out on light detectors (long-term background source)
  - **^{220}Rn** used in LXe dark matter detectors (**Phys Rev. D 95, 072008**) but not previously explored in LAr for use at DUNE
- Currently investigating ^{220}Rn injection for DUNE FD and ND-LAr calibrations, with proposed tests at both the 2x2 ND-LAr prototype and ProtoDUNE II

^{220}Rn Calibrations @ DUNE

^{220}RnPo α-decays: measure LAr flow… *maybe*

^{212}Pb β^{-}-decay: low-energy calibration

^{212}BiPo decay: a ton of applications!

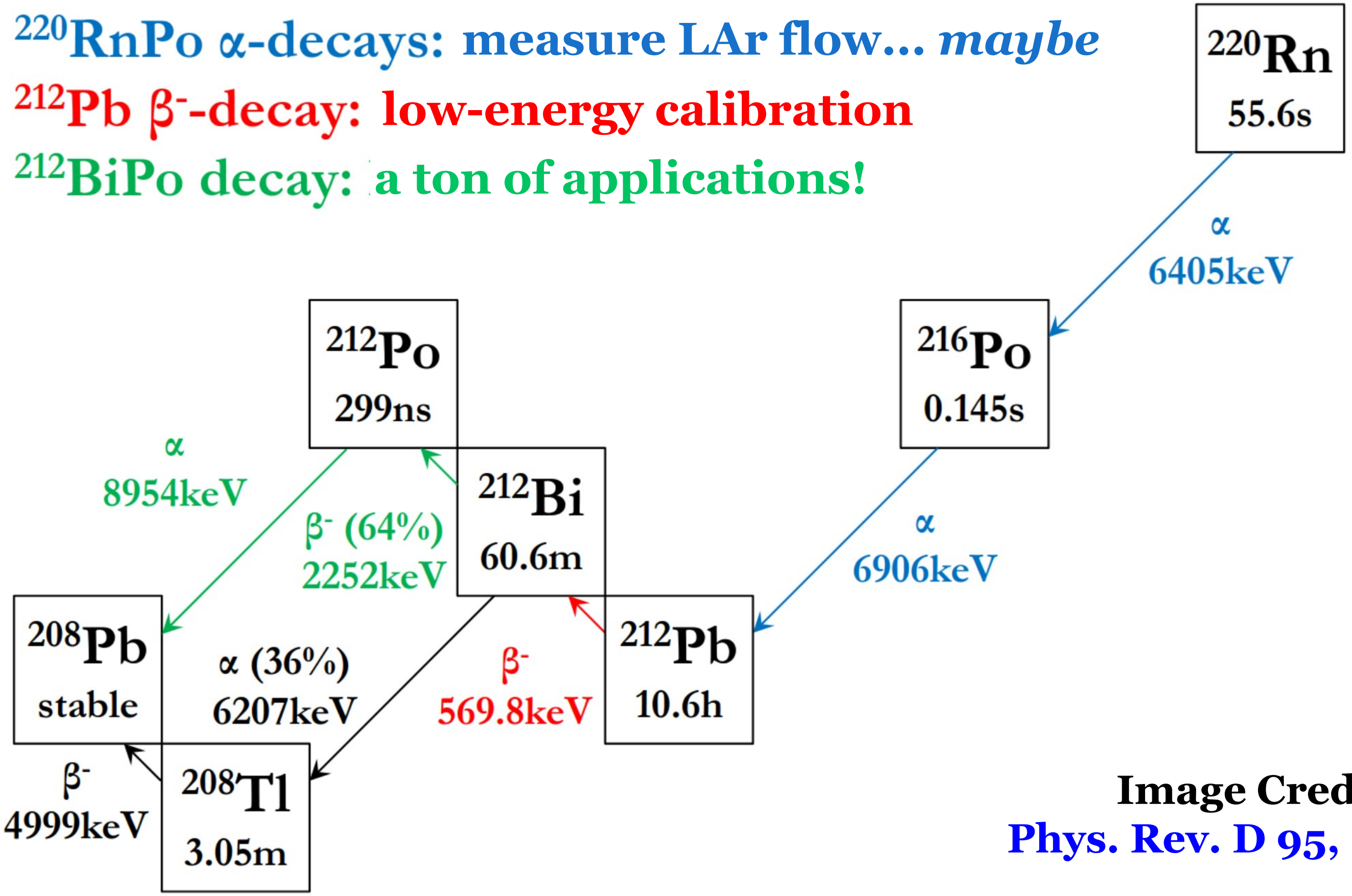
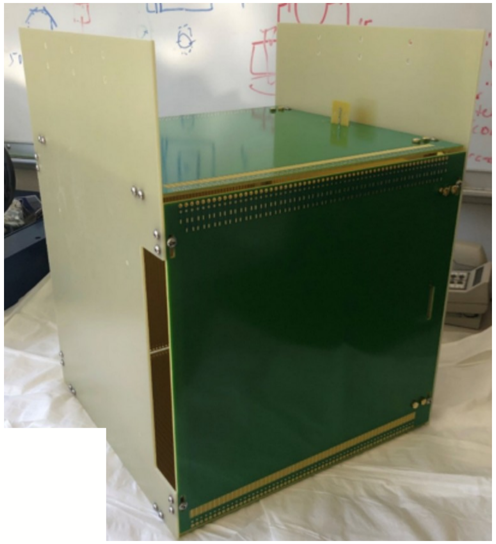


Image Credit:
Phys. Rev. D 95, 072008

^{220}Rn Injection Test @ CSU

- Considering test of ^{220}Rn injection at ProtoDUNE II and/or 2x2 ahead of operations of DUNE FD/ND-LAr
  - Proposal still under discussion
- First test w/ ^{220}Rn at CSU R&D LArTPC
  - Cubic-foot LArTPC w/ pixel readout (using “LArPix” ND-LAr technology)
  - Setup recently achieved **~0.5 ms** electron lifetime w/o recirculation; testing requires > 0.3 ms
  - Installing custom light detector, light trap w/ SiPMs similar to DUNE FD design – ready this summer
  - **Collaborating w/ SDSMT** on tests of fixed radioactive sources for DUNE using same setup



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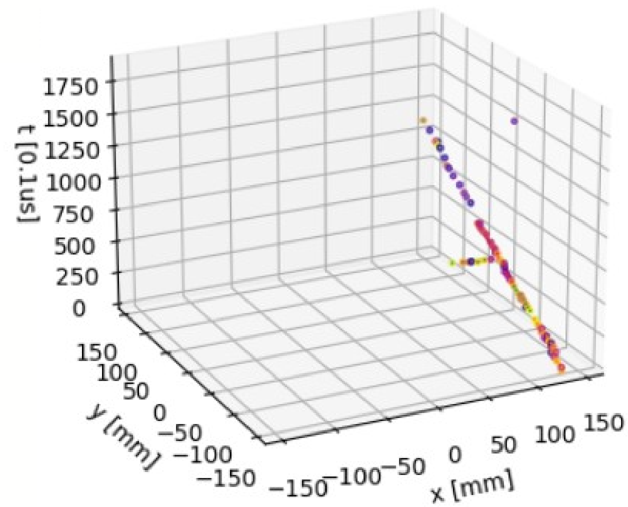

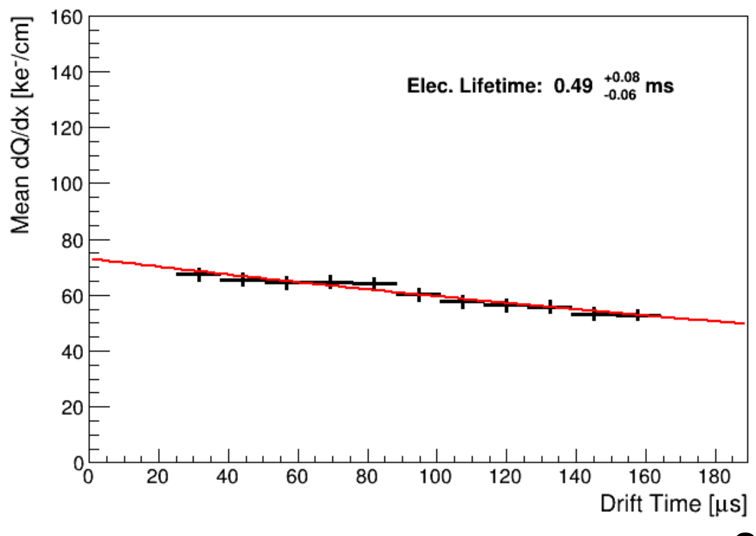

Summary

- Low cosmic flux at DUNE's large underground LArTPC detectors complicates detector calibration program

- Natural low-energy radioactive activity in LAr (e.g. ^{39}Ar beta decays) provides much help in fleshing out DUNE calibration program

- Currently exploring ^{220}Rn injection at DUNE FD/ND-LAr for enhanced calibrations using low-energy activity

BACKUP SLIDES

^{39}Ar Beta Decays at MicroBooNE

- Initial studies of ^{39}Ar decays done at MicroBooNE in 2017
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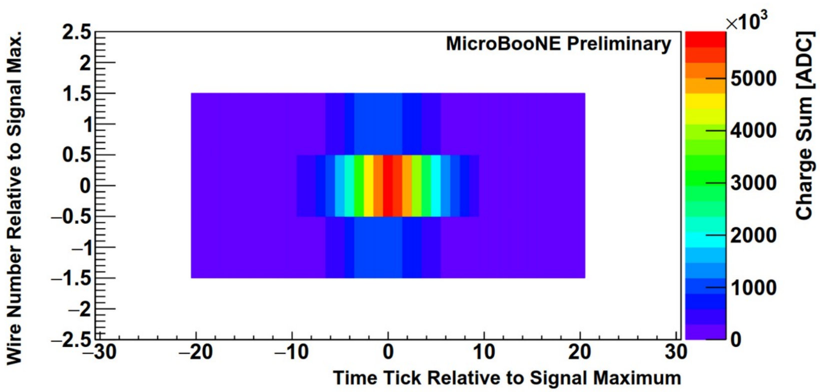
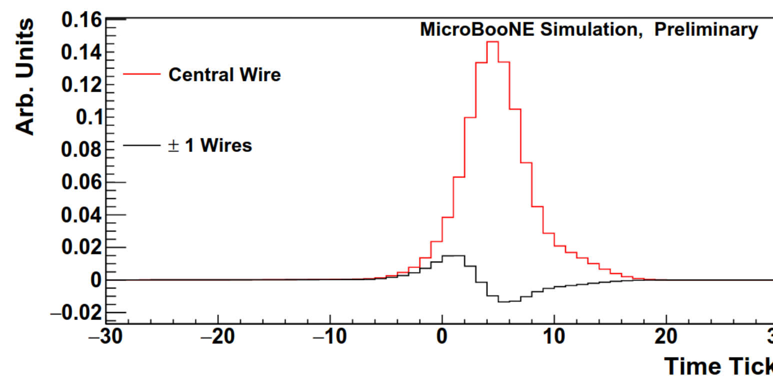
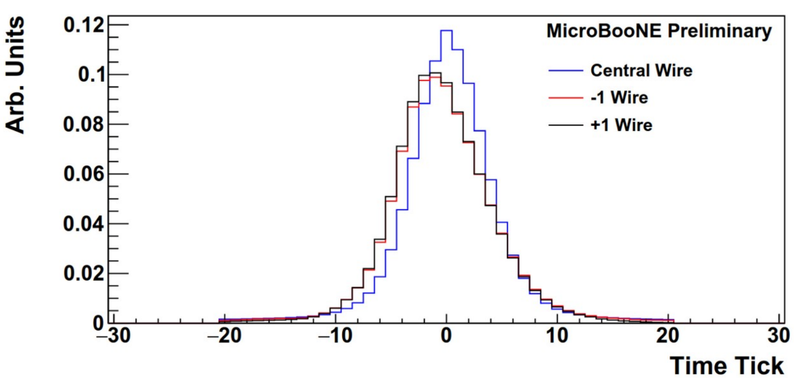
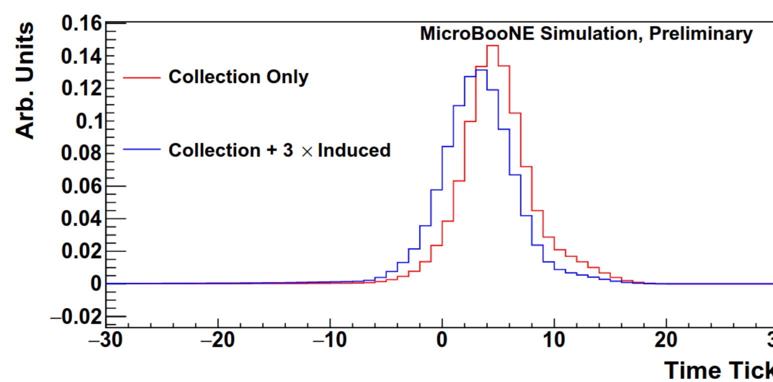
  - Reconstruction of “blips” in 2D (collection plane only)



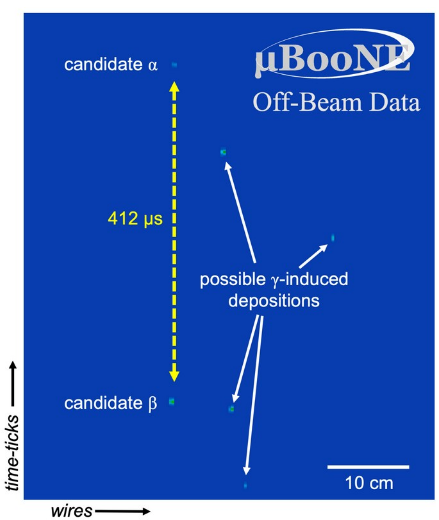


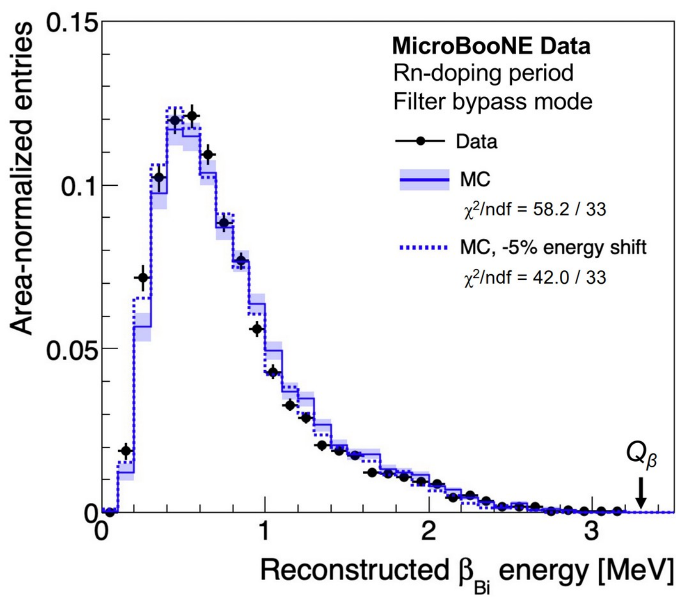


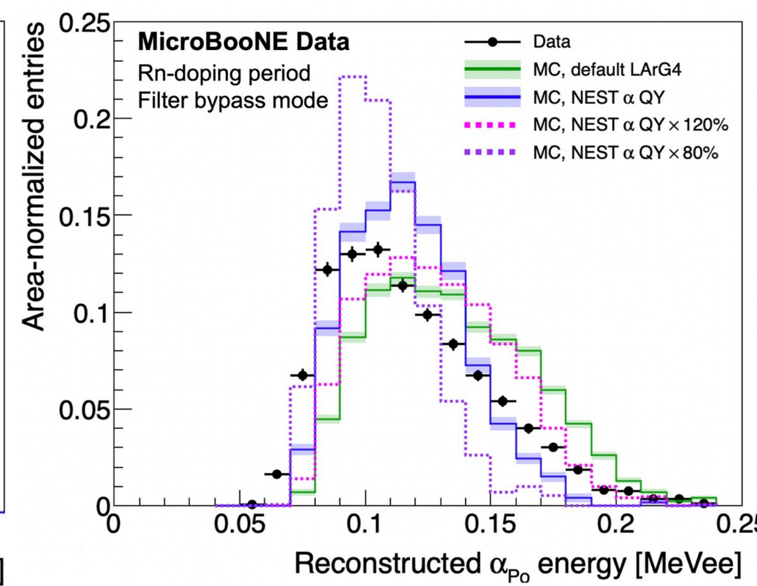


^{222}Rn Bi-Po Decays at MicroBooNE

- New MicroBooNE studies of ^{214}Bi → ^{214}Po decays from ^{222}Rn decay chain published in 2024 (Phys. Rev. D 109, 052007)
  - Reasonable data/MC agreement for betas; less good agreement for alphas (even when using LArNEST)
  - Can be useful for studying electron-ion recombination at DUNE: larger physical separation allows ionization charge to be separable



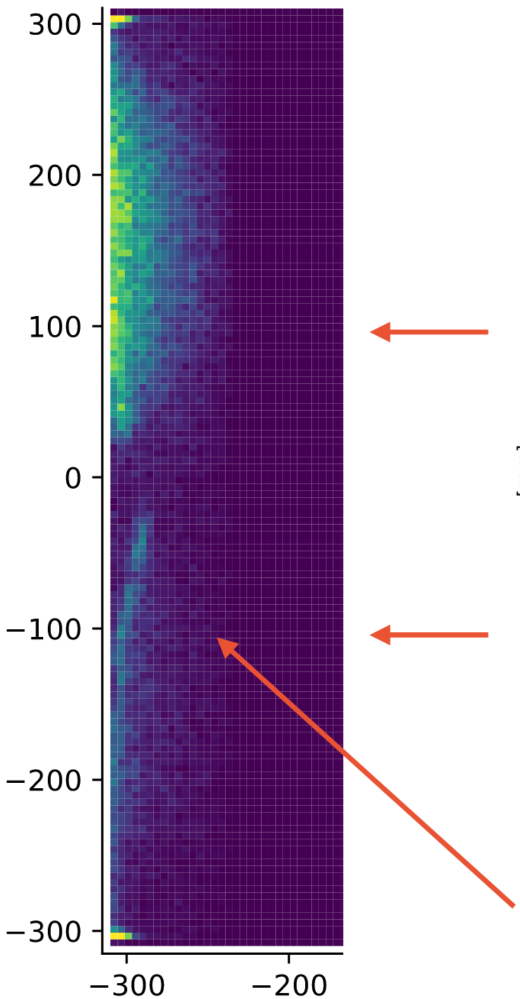


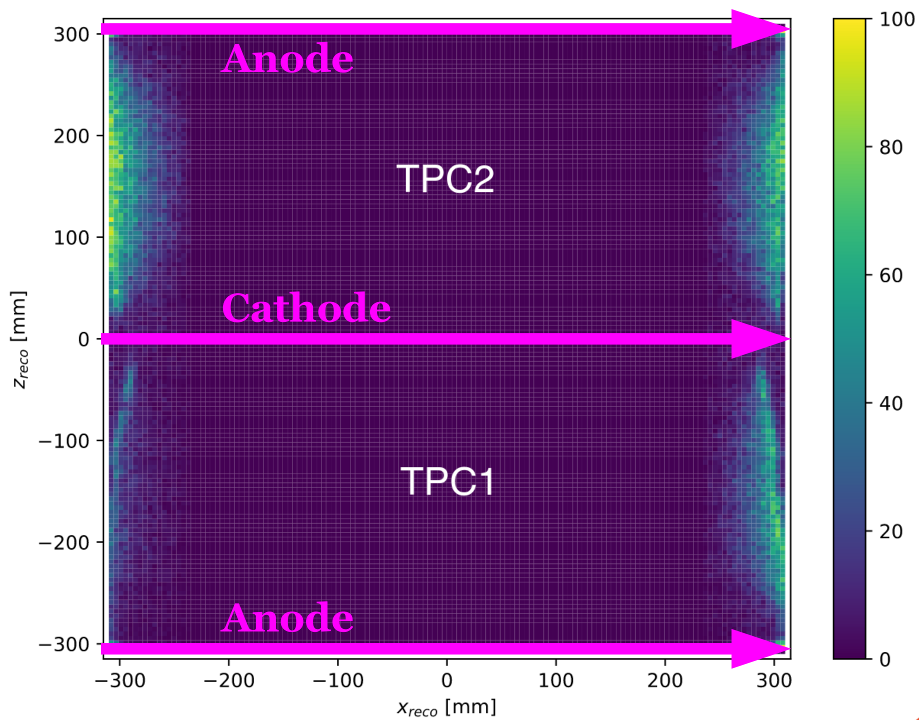


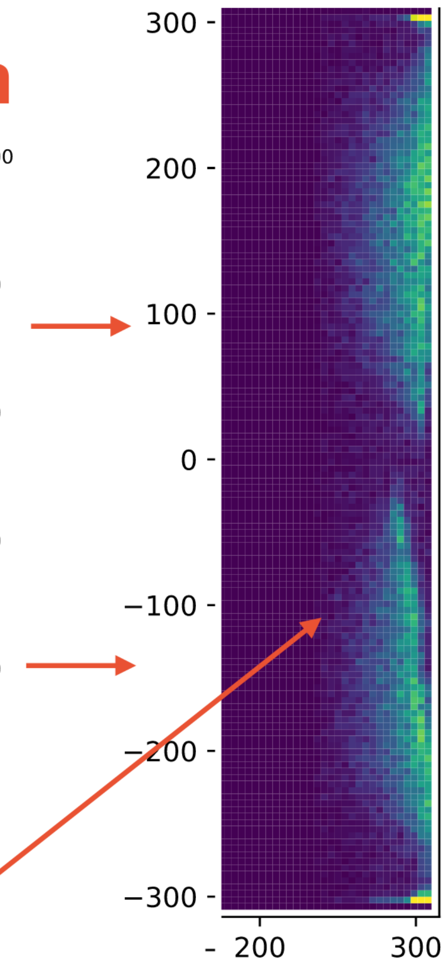
E Field Distortions in 2x2 TPC Module

5 hours of data
(on surface @ Bern)

x_{reco} vs z_{reco} - distribution







Indication of E-field distortions in TPC1,
caused by non-zero transverse E-field component
(~2.2cm offset at y ~ -35 mm)

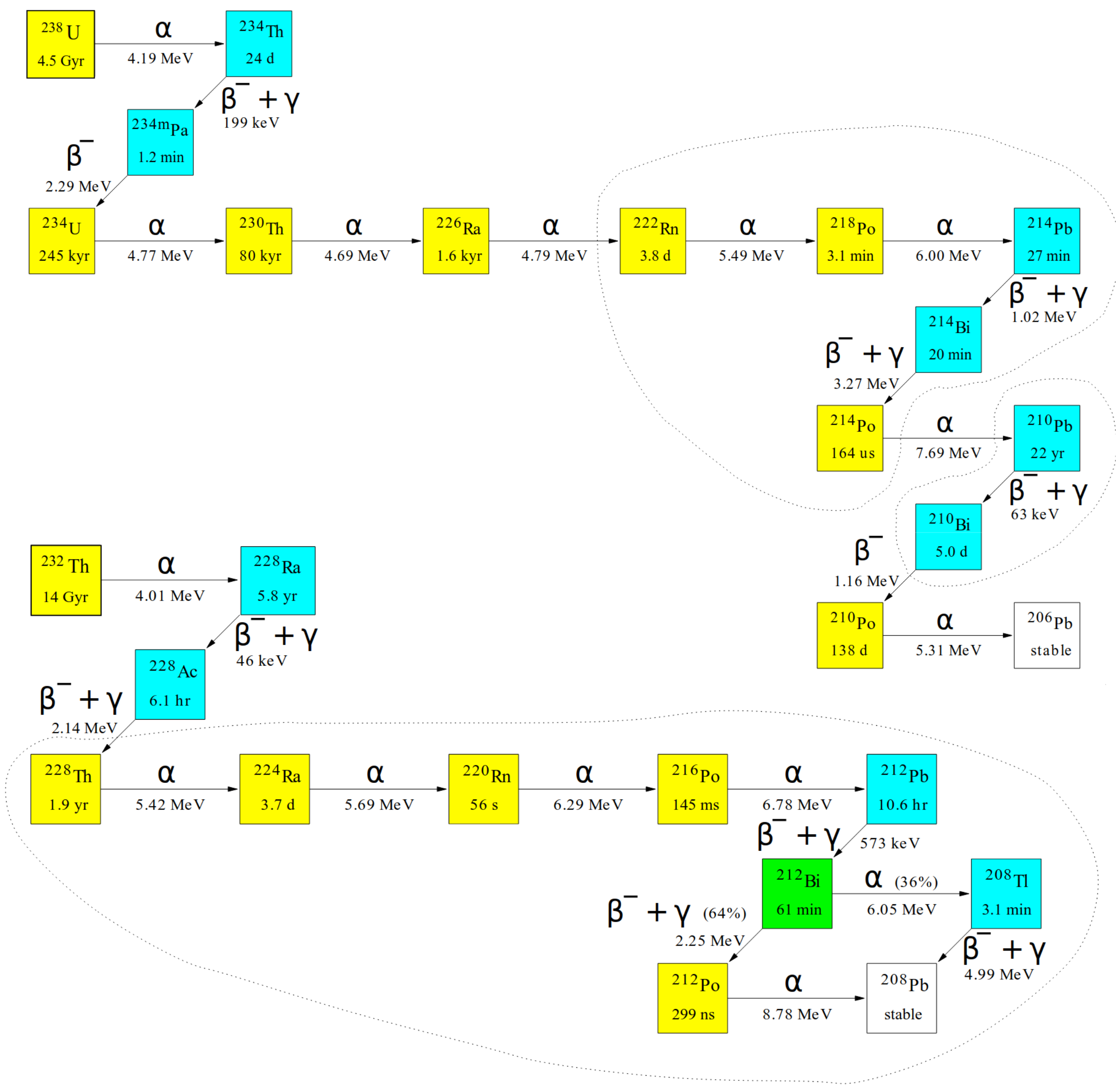
Calibrations w/ ^{212}Bi → ^{212}Po → ^{208}Pb

- ^{212}Pb (parent isotope of ^{212}Bi) half-life of 10.6 hours long enough to enable spreading throughout even large LArTPC detectors
  - Convective currents will mix isotope into and throughout active volume
- ^{212}Bi → ^{212}Po **beta electron end point of 2.3 MeV** produces charge yield well above charge readout threshold (100-300 keV)
- ^{212}Po → ^{208}Pb **alpha energy of 9 MeV** ~300 ns later yields "huge" amount of light for t_0 tag (reconstruct point-like activity **in 3D**)
  - Roughly 350,000 photons produced at single point in detector
- Calibration applications (a sampling, potentially more):
  - **Extract spatial variations in light yield (use to tune simulation)**
  - Light detector timing resolution studies (~300 ns between decays)
  - Electron lifetime measurement
  - **Measure electric field** (spatial offsets, recomb. E-field dependence)
  - Mapping LAr flow via migration of decays through detector over time

Triggers, Event Rates

- Plenty of ^{39}Ar beta decays in detector, so just need to take minimum-bias readouts (continuously)
  - External trigger (e.g. pulser) will suffice
- ^{39}Ar beta decay rate is about 1 Bq/kg
  - 10 kt fiducial → O(50k) decays per 5 ms readout (entire module)
- From studies at MicroBooNE (CSU undergraduate Alex Flesher), O(100k) decays can provide high-precision electron lifetime measurement
  - Integrated over entire FD module: O(2) events
  - Every square meter: O(40k) events
  - Every wire pitch: O(1M) events
- Ideally, measure electron lifetime every m^2
  - Wire-to-wire response variations: every wire pitch

$^{238}U/^{232}Th$ Decay Chains



Modeling Decay Rate

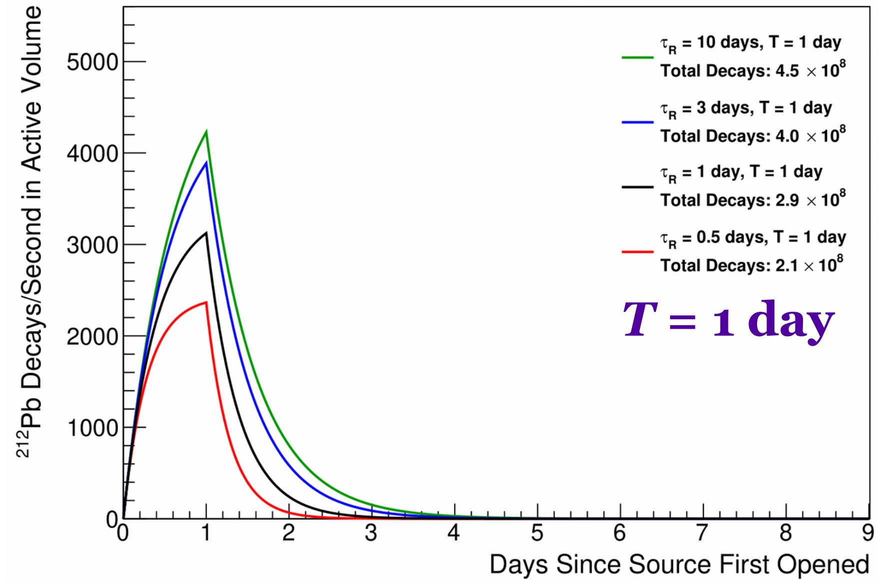
- Assume secular equilibrium for upstream decays in decay chain (^{228}Th → ^{224}Ra → ^{220}Rn) and ^{220}Rn → ^{216}Po → ^{212}Pb instantaneous
- Model amount of ^{212}Pb in total volume, *N(t)*, assuming constant source activity *S*, ^{212}Pb lifetime τ, LAr recirculation timescale τ_R (included as a "decay" term), and time source "open" *T*
- Finally, compute ^{212}Pb decay rate in <u>active</u> volume, *D(t)*, assuming uniform distribution of decays throughout detector and active-volume-to-total-volume ratio *f*

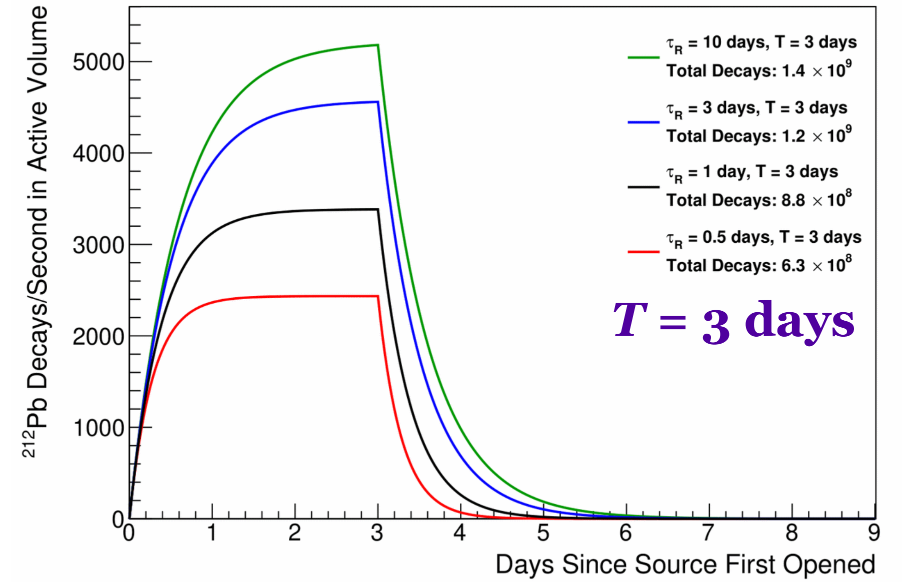
$$\frac{d}{dt}N(t) = S\left(\theta(t) - \theta(t-T)\right) - \lambda N(t) - \lambda_R N(t)$$

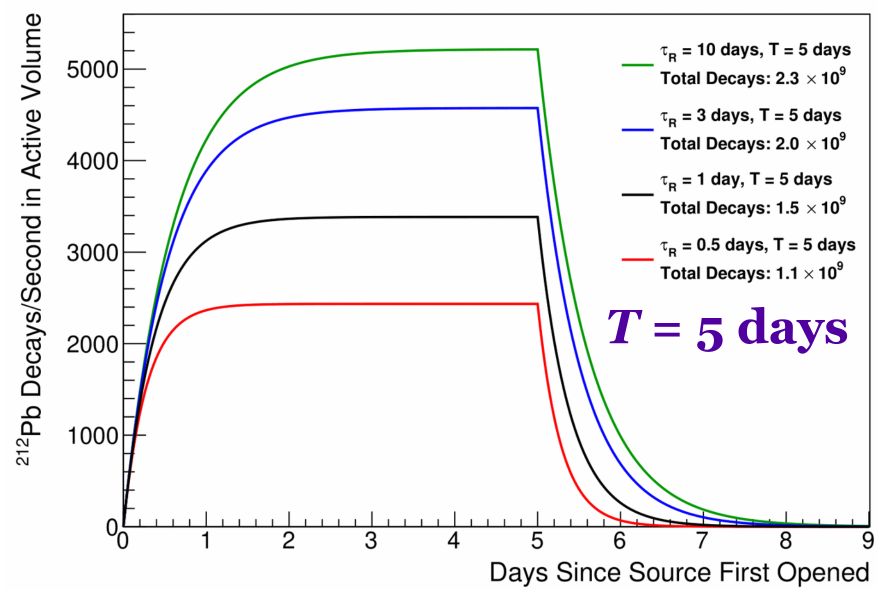
$$N(0) = 0 \qquad \lambda \equiv \frac{1}{\tau} \qquad \lambda_R \equiv \frac{1}{\tau_R}$$

$$D(t) \equiv f\lambda N(t) = fS\frac{\lambda}{\lambda+\lambda_R}\left[\left(1-e^{-(\lambda+\lambda_R)t}\right)\left(\theta(t)-\theta(t-T)\right) + \left(1-e^{-(\lambda+\lambda_R)T}\right)e^{-(\lambda+\lambda_R)(t-T)}\theta(t-T)\right]$$

Results: Decay Rate vs. Time



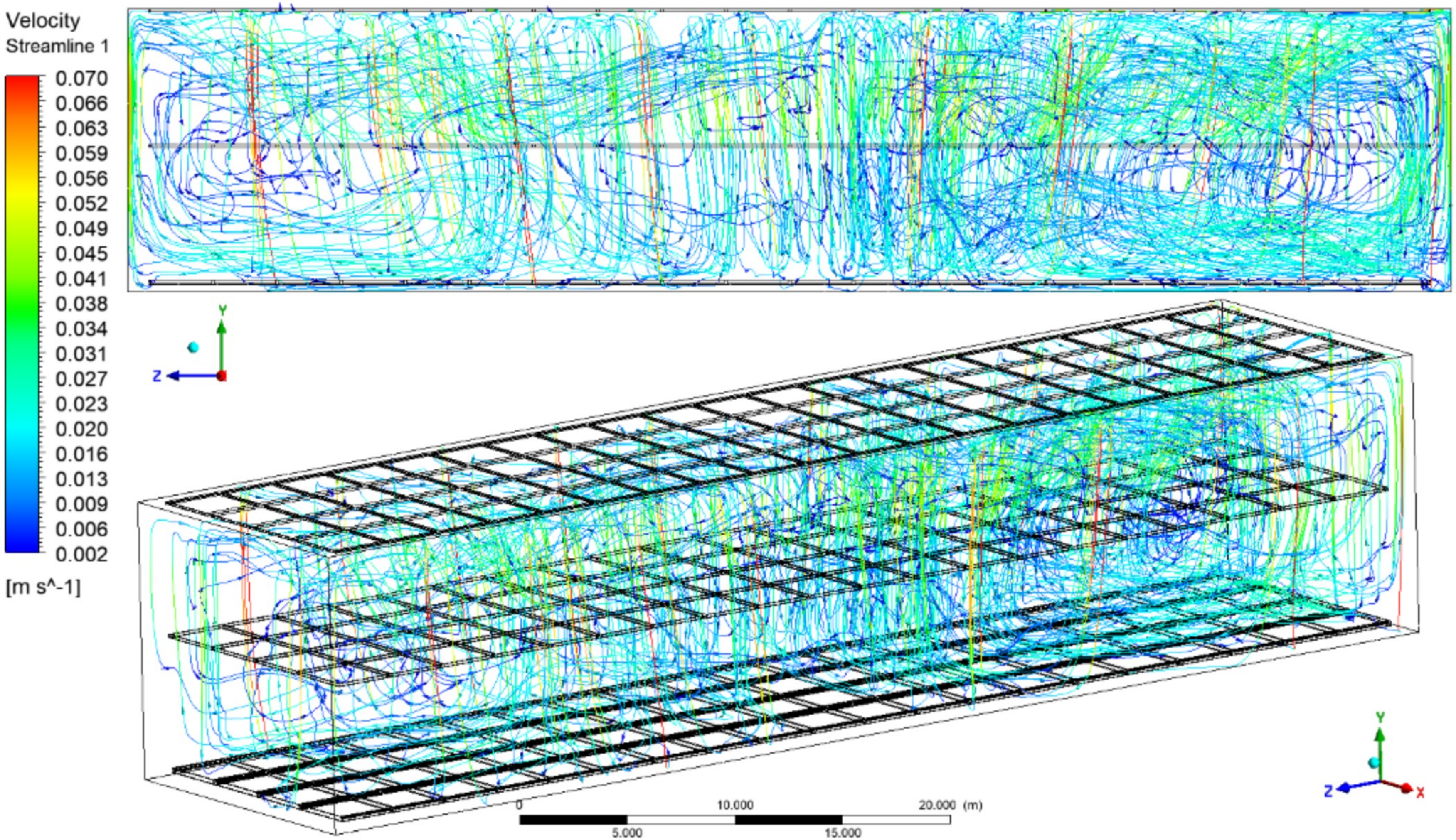




Assumptions:

S = 18.5 kBq
f = 0.3
τ = 0.64 days
τ_R: varies (see plots)
T: varies (see plots)

DUNE VD FD CFD Model



DUNE VD FD CFD Model