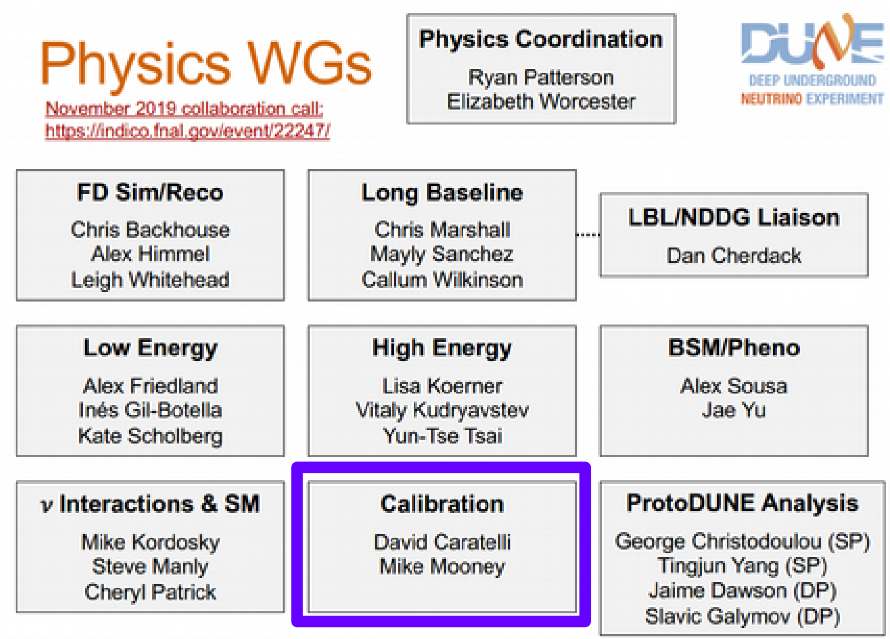
Calibrations at DUNE FD Using Natural Sources

Michael Mooney
Colorado State University

DUNE Calibration/Cryogenic Instrumentation Workshop

May 26th, 2020

DUNE Calibration WG



R. Patterson
E. Worcester

- Calibration WG is relatively new (Nov. 2019) working group in DUNE physics structure – replaced Calibration Task Force
  - Calibration Task Force: first calibration studies for **DUNE TDR**
  - Calibration WG: develop full DUNE calibration chain and study impact on physics measurements; focus on **natural sources**
- Work closely w/ Calibration Consortium on calibration items

Goals of Calibration WG

- Principal goals of Calibration WG:
  - (1) Develop strategy for low-level calibrations at DUNE
    - Electron lifetime measurement, electric field distortions, etc.
  - (2) Develop strategy for high-level calibrations, making use of "standard candles" to probe particle-level detector systematics
    - Use of Michel electrons, $\pi^0 \rightarrow \gamma\gamma$ decays, ^{39}Ar beta decays, etc.
  - (3) Evaluate impact on DUNE physics measurements/sensitivities
    - Includes LBL, SNB, BNV physics; in principle all DUNE physics
- Requires coordination with Calibration Consortium
  - What is the complementarity of dedicated calibration hardware and using natural sources in accomplishing (1) and (2)?
- Also important to incorporate lessons learned from ProtoDUNEs where applicable

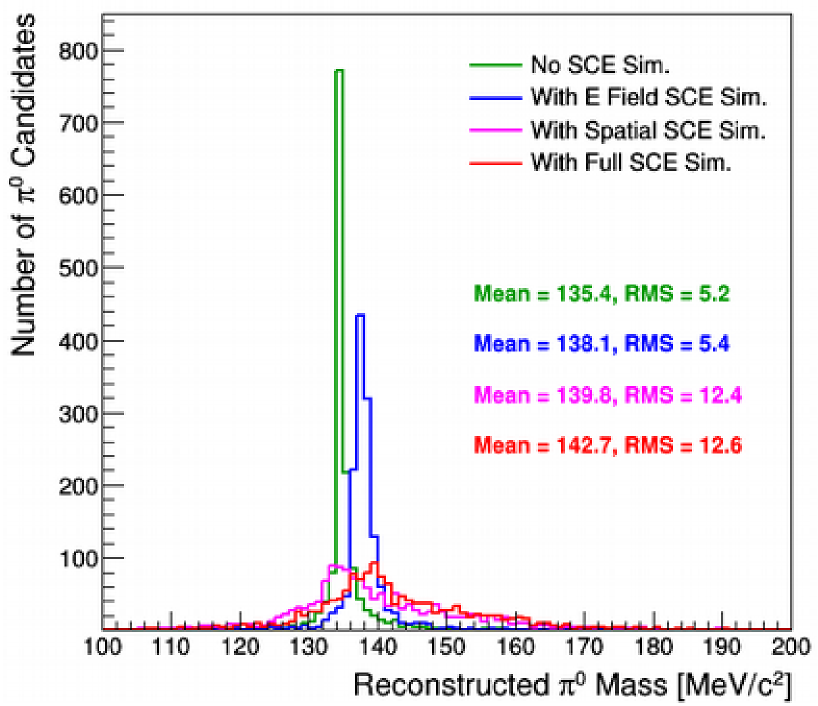
Low-level Calibrations

- Want to calibrate several low-level detector effects that impact particle reconstruction and particle energy scale
  - Electron lifetime
  - Electric field distortions, including space charge effects (SCE) and detector misalignment
  - Electron-ion recombination
  - TPC noise levels
  - Electronics gain
  - Signal shape (field/electronics response)
- Goal is **1-2%** for total energy scale bias allowance (to our knowledge, current LBL physics requirement)
  - Is it possible? Is it necessary? **Our task to investigate**

High-level Calibrations

- Also want to procure samples of "standard candles" to study particle-level quantities such as energy scale – examples:
  - Cosmic muons
  - Michel electrons
  - $\pi^o \rightarrow \gamma\gamma$ decays
  - Delta rays
  - ^{39}Ar beta decays
- As opposed of using for calibration, could instead use samples as high-level "test" of low-level calibrations
  - Proof that we understand energy scale after calibration

Low-level + High-level



ProtoDUNE-SP study of SCE impact on π^o mass by M. Mooney

- Low-level calibrations and high-level calibrations may have interplay – e.g. reconstructed π^o mass being impacted by electric field distortions (such as SCE) if not corrected!
  - Above: "perfect" reconstruction with/without SCE simulated at ProtoDUNE-SP

Natural Source Event Rates

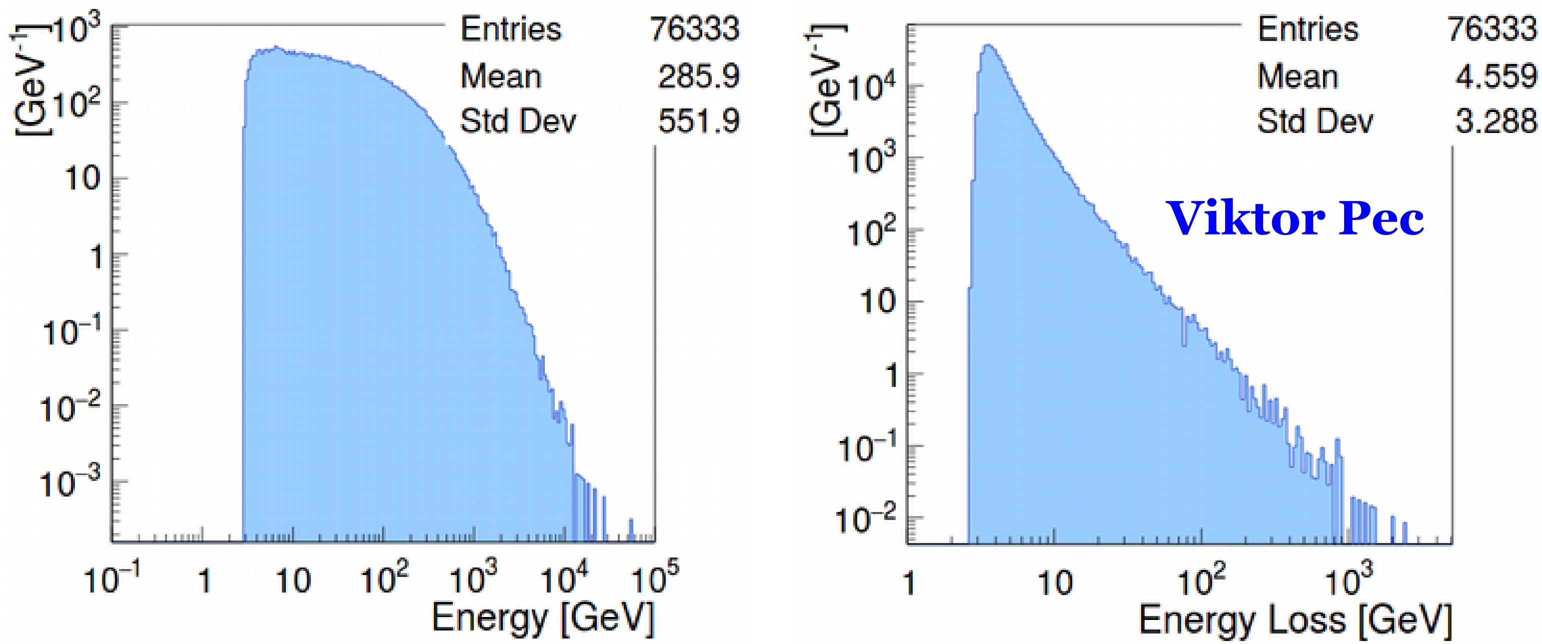
Viktor Pec

	N	Per Day	[%]	
Generated	431500	14101		
Primary μ in TPC	143461	4688	33	fraction of generated →
Any stopping μ	5421	177	3.8	fraction of TPC muons
Primary stopping μ	2631	86	1.8	
All Michel	4466	146	3.1	
Michel from primary	1871	61	1.3	
π^0	7142	233	5.0	Produced in 1133 events
Kaons	621	20		Produced in 160 events

	Counts	[%]	Per Day
Total	143461		4688
1 APA	79083	55.1	2584
2 APA	4388	3.1	143
3 APA	125	0.09	4
1 CPA	53214	37.1	1739
2 CPA	2301	1.6	75
APA+CPA	28466	19.8	930

- Updated studies have been carried out in the Calibration WG on natural source event rates at the DUNE FD (10 kt)
  - Rates determined using MUSUN generator (Sheffield)
  - Includes different categories of cosmic muons – certain measurements may need special track orientations, e.g. **anode-cathode-crossing muons** or "APA+CPA" for electron lifetime measurement (see right table)

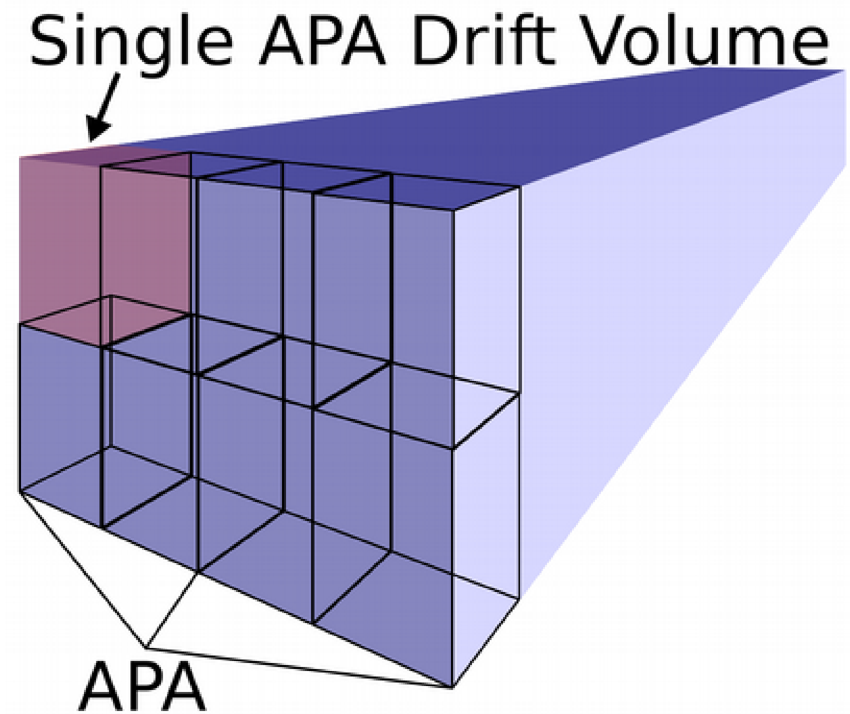
Cosmic Muons



- Cosmics muons: ~4700/day/10-kt
  - Above: energy and energy loss for top-bottom-crossing muons
- Key question: how well can we calibrate **electron lifetime** using cosmic muons given low rate underground?
  - Cosmics can be used for other measurements, but electron lifetime measurement is resource driver

Single-APA Drift Volume

Viktor Pec



- For discussion in the next slides, define the "single-APA drift volume": drift volume seen by <u>one side</u> of a single APA
  - Distinct collection plane wires for each side of APA
  - **200** single-APA drift volumes in one 10-kt module (as opposed to 150 APAs in one 10-kt module)

Previous Studies w/ Cosmics

Josh Klein

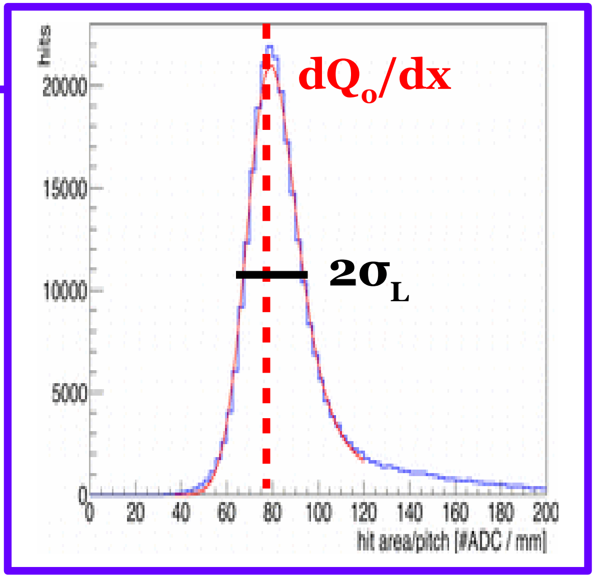
$$\frac{\delta(\frac{dE}{dx})}{\frac{dE}{dx}} = \boxed{\frac{\sigma_L}{dQ_0/dx}}\sqrt{\frac{3}{N_\mu}}$$

ICARUS fits Gaussian to truncated distribution, says fractional σ_L is about 14%
They require at least 100 collection wires hit for each cosmic, no showers→20% of μs
Truncation removes 30% of hits

So for DUNE FD-SP:

$$\frac{\delta(\frac{dE}{dx})}{\frac{dE}{dx}} = 0.14\sqrt{\frac{3}{4500/\mathrm{day} \times 0.14}} = 0.0097/\mathrm{day}$$

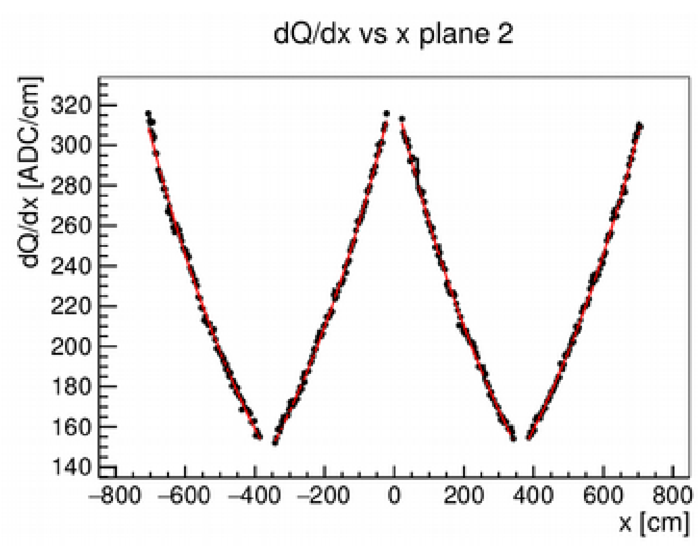
If we average over entire volume



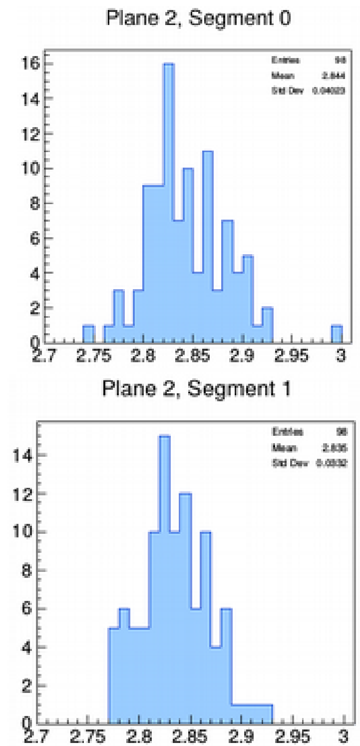
- Previous study of electron lifetime calibration using cosmic muons predicted 1% dE/dx resolution per day <u>integrating across entire 10-kt module</u> – more info **here**
  - Per single-APA drift volume: **14%/day** **(1% in 200 days)**
- However, this uses Landau+Gaussian width as measurement uncertainty → **conservative estimate!**

New Studies w/ Cosmics

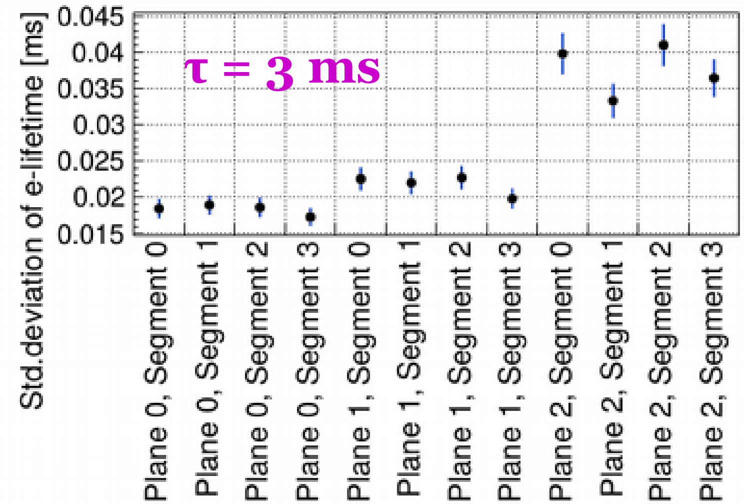
Viktor Pec



$$\frac{\delta\left(\frac{dE}{dx}\right)}{\frac{dE}{dx}} = \frac{t_{\max}}{2\tau}\frac{\delta\tau}{\tau}$$

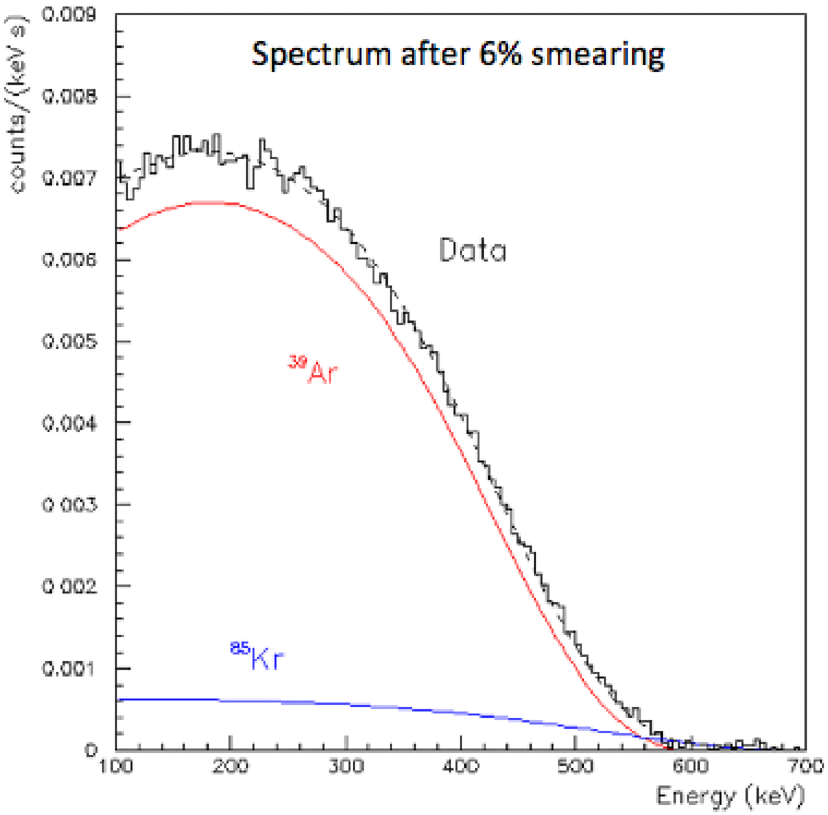


7.5-hour exposure, 50 APAs
All muons used



- New study uses full MC simulation, fit to dQ/dx MPV vs. x distribution → **better performance** than naive calculation
  - Per single-APA drift volume: **4-10%/day** **(1% in 16-100 days)**
  - Range due to different N_μ used: 4% for all anode-cathode-crossing muons, 10% for non-showering ones w/ 100+ collection-plane hits

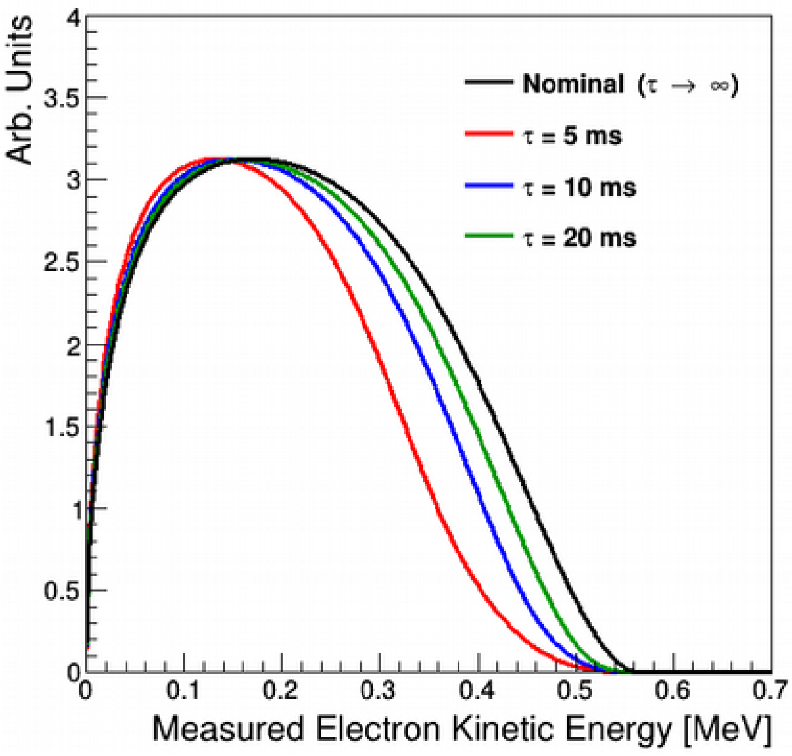
^{39}Ar Beta Decays



Benetti et al., "Measurement of the specific activity of Ar-39 in natural argon" (2006).

- ^{39}Ar beta decays: 1 Bq/kg with decay cut-off energy of 565 keV
  - Roughly **half** of the energy deposited on a single wire by a MIP at DUNE
- Several things smear observed **charge spectrum**, e.g.:
  - Electronics noise
  - Recombination fluctuations
  - Unknown location of ^{39}Ar decay in drift direction
- For last point: we know decays are **uniform in x**

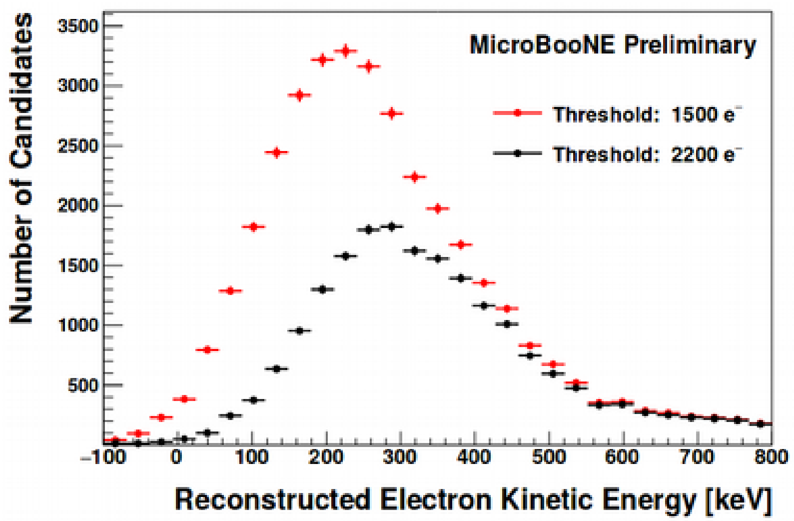
^{39}Ar Beta Decays

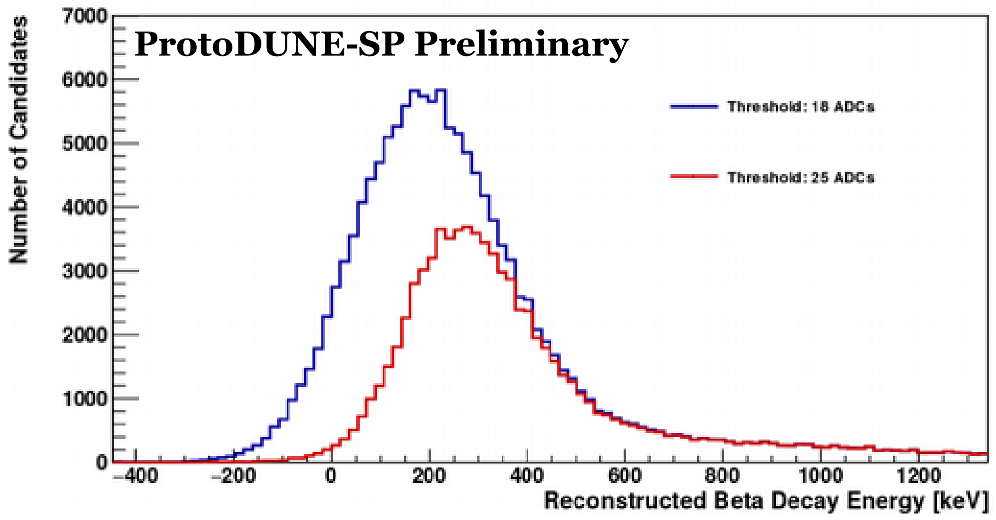


Example Use Case:
Fine-Grained Electron Lifetime Measurement

- ^{39}Ar beta decays: 1 Bq/kg with decay cut-off energy of 565 keV
  - Roughly **half** of the energy deposited on a single wire by a MIP at DUNE
- Several things smear observed **charge spectrum**, e.g.:
  - Electronics noise
  - Recombination fluctuations
  - Unknown location of ^{39}Ar decay in drift direction
- For last point: we know decays are **uniform in x**

Preliminary ^{39}Ar Results





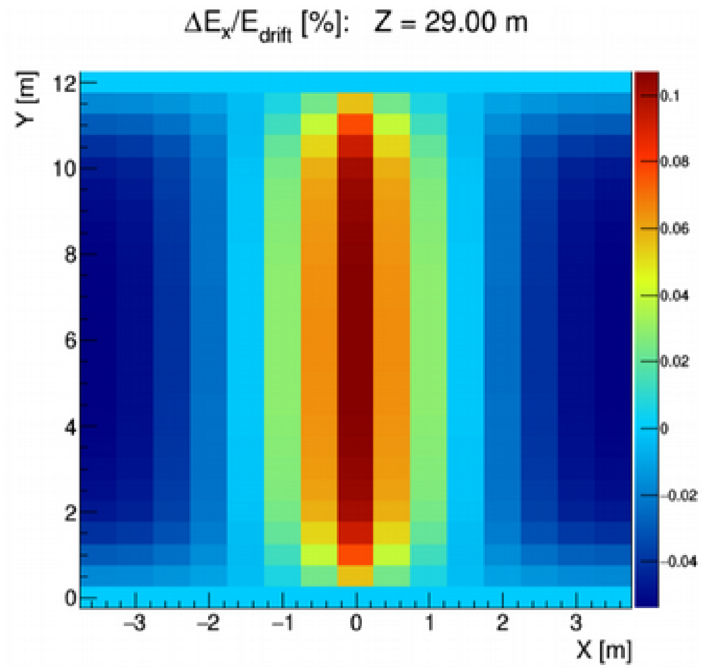
- ^{39}Ar beta decay reconstruction first studied at MicroBooNE
  - See MicroBooNE **public note** for more information
- First studies completed at ProtoDUNE-SP using identical technique as at MicroBooNE – similar results!
  - Still broader due to longer wires, thus higher noise
  - Lower energy reach due to less recombination at ProtoDUNE-SP
- Next: study elec. lifetime measurement sensitivity vs. N_{events}

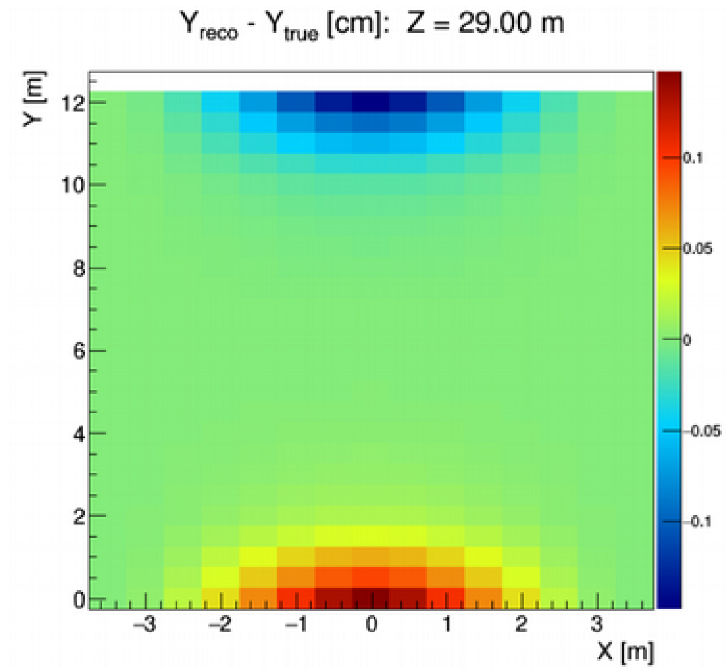
Measurement Rate Needs

- How often should we be making electron lifetime measurement with ^{39}Ar beta decays?
  - Guess: once a day (currently being done at roughly this rate at MicroBooNE with cosmics) – maybe more/less often, but may not know ahead of DUNE FD operations what necessary rate is
- Need O(200k) readouts in one day to calibrate every m^2 independently to **~1%** (preliminary): **~2 Hz** trigger rate
- This is a lot of data, but:
  - Can reduce requirement of spatial precision (greatly, if necessary)
  - Can reduce rate of measurement (e.g. every few days)
  - Zero-suppression would help a lot – just need to keep ±1 wire, ±20 time ticks within signal above threshold
  - Can promptly do measurement offline and then throw away data (best bet?) – **analysis is simple, O(10) sec./APA/event**

Space Charge Effects

Mike Mooney

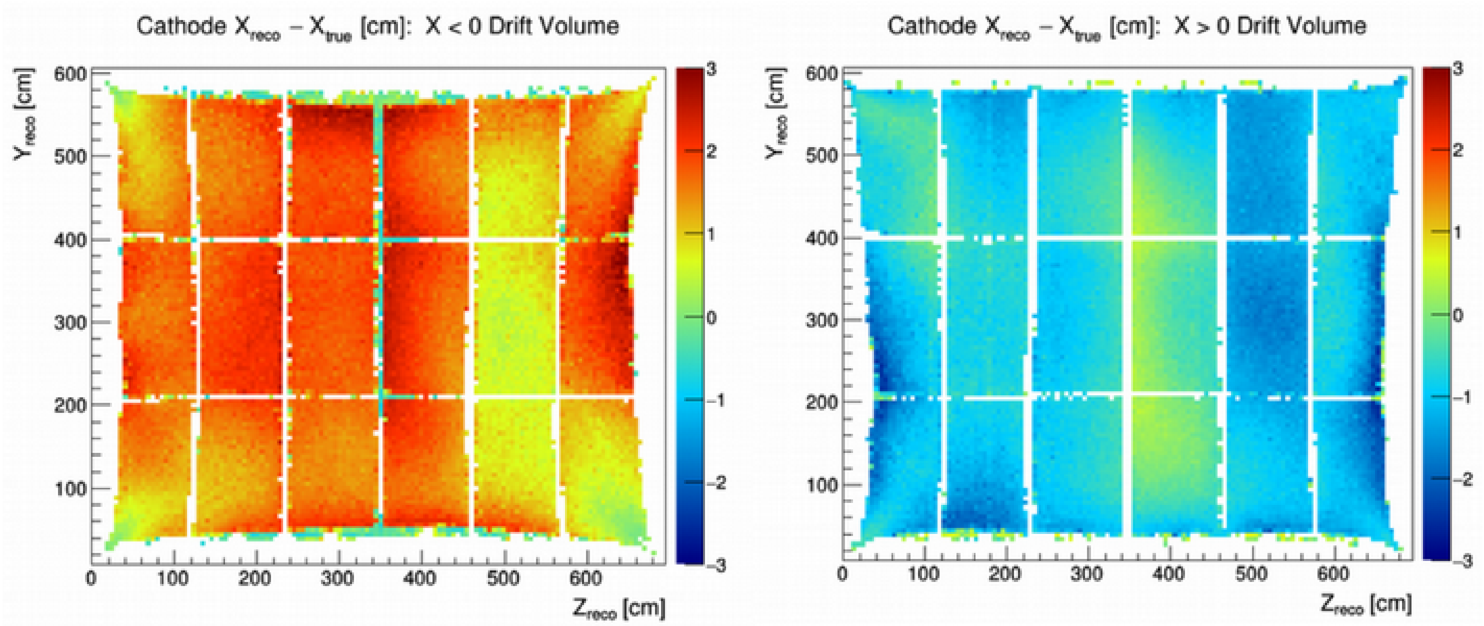




- Space charge effects are very large at ProtoDUNE-SP! However, expected to be **very small at DUNE SP FD**
  - Driven by ^{39}Ar decays; expected to contribute **< 0.1%** dE/dx bias
  - But non-negligible at DUNE DP FD (2-3% dE/dx bias, and even more if ion feedback in gas phase significant)

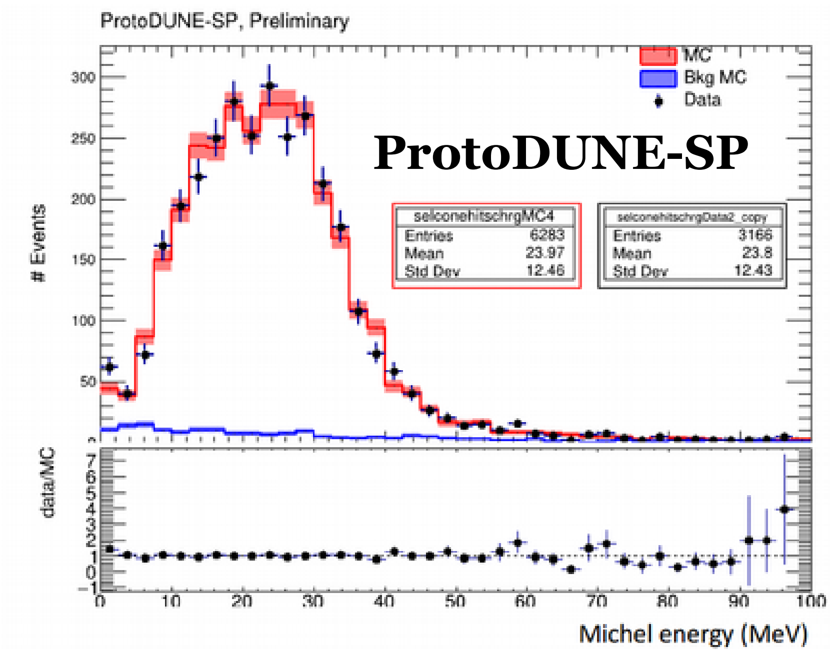
Detector Misalignment

Ajib Paudel, Mike Mooney



- Space charge effects small at DUNE SP FD, but detector misalignment may cause electric field distortions
  - CPA displacement/rotations observed at ProtoDUNE-SP using cosmic muons (above) – found to be static over time
  - If need O(1k) cosmic muons per CPA panel, would take **roughly one year** to calibrate – UV laser system can help here

Michel Electrons



Aleena Rafique

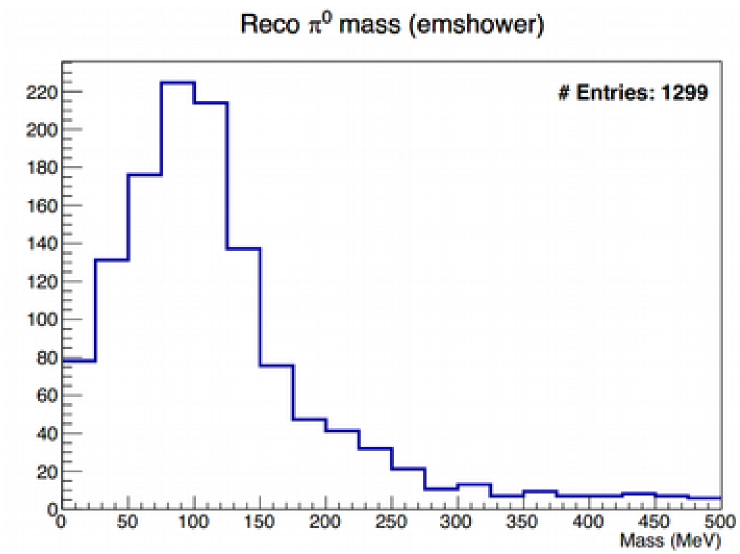
DUNE FD Performance:

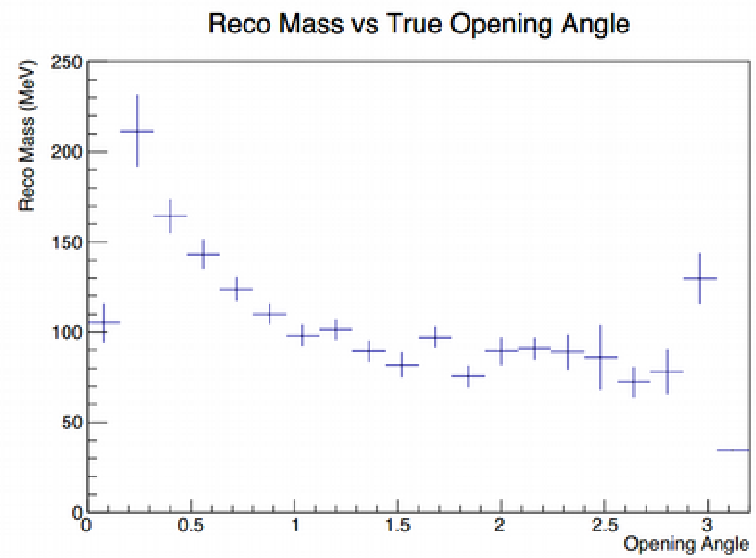
Efficiency: ~30%
Purity: ~80%

- Also working on Michel electron reconstruction in DUNE FD
  - Utilize ProtoDUNE-SP algorithm, but can loosen up background rejection cuts in underground charge environment
  - Current limitation is comic muon track reco. – **being studied**
- Helpful standard candle for constraining energy scale of low-energy electrons/photons using data

Neutral Pions

Jacob Larkin





- Neutral pions being studied for higher-energy electron/photon energy scale constraint at DUNE FD
  - Beam-induced $\pi^o \to \gamma\gamma$: 35/day/10-kt (single π^o: 10/day/10-kt)
  - Cosmogenic $\pi^o \to \gamma\gamma$: 230/day/10-kt
- Currently studying beam-induced π^o: need reconstruction improvements to eliminate measurement biases

BACKUP SLIDES

Low-level Calibrations

- Want to calibrate several low-level detector effects that impact particle reconstruction and particle energy scale
  - Electron lifetime – can we calibrate w/ cosmics to sufficient temporal/spatial precision? Can ^{39}Ar beta decays help here?
  - Electron-ion recombination – do we need to measure in-situ? Use measurements at ProtoDUNE? Other measurements (NEST)?
  - Space charge effects (SCE) – bigger deal at ProtoDUNEs, less so for ND/FD LArTPCs… but other electric field distortions may arise from e.g. partial HV failure? Also, SCE large in dual phase!
  - TPC noise, electronics gain, signal shape (field/electronics) – study with cosmic muons and/or ^{39}Ar? External measurements?
- Goal is **1-2%** for total energy scale bias allowance (to our knowledge, current LBL physics requirement)
  - Is it possible? Is it necessary? **Our task to investigate**

High-level Calibrations

- Also want to procure samples of "standard candles" to study particle-level quantities such as energy scale – examples:
  - Cosmic muons – many uses such as field distortions, signal shape, electron lifetime... but not many (~4700/day/10-kt); even fewer stopping muons for abs. energy scale studies (~90/day/10-kt)
  - Michel electrons – for low-energy electrons, but ~60/day/10-kt
  - $\pi^0 \rightarrow \gamma\gamma$ decays – handle on higher-energy electrons, but will we have enough in the FD? Can/should we use sample at ProtoDUNEs?
  - Delta rays – correlation between opening angle and energy for data-driven energy calibration handle?
  - ^{39}Ar beta decays – tons available for gain/lifetime/recombination studies, but can DAQ provide necessary triggering and event rate?
- Again... goal is **1-2%** for total energy scale bias allowance (to our knowledge, current LBL physics requirement)
  - Is it possible? Is it necessary? **Our task to investigate**

DUNE TDR as Benchmark

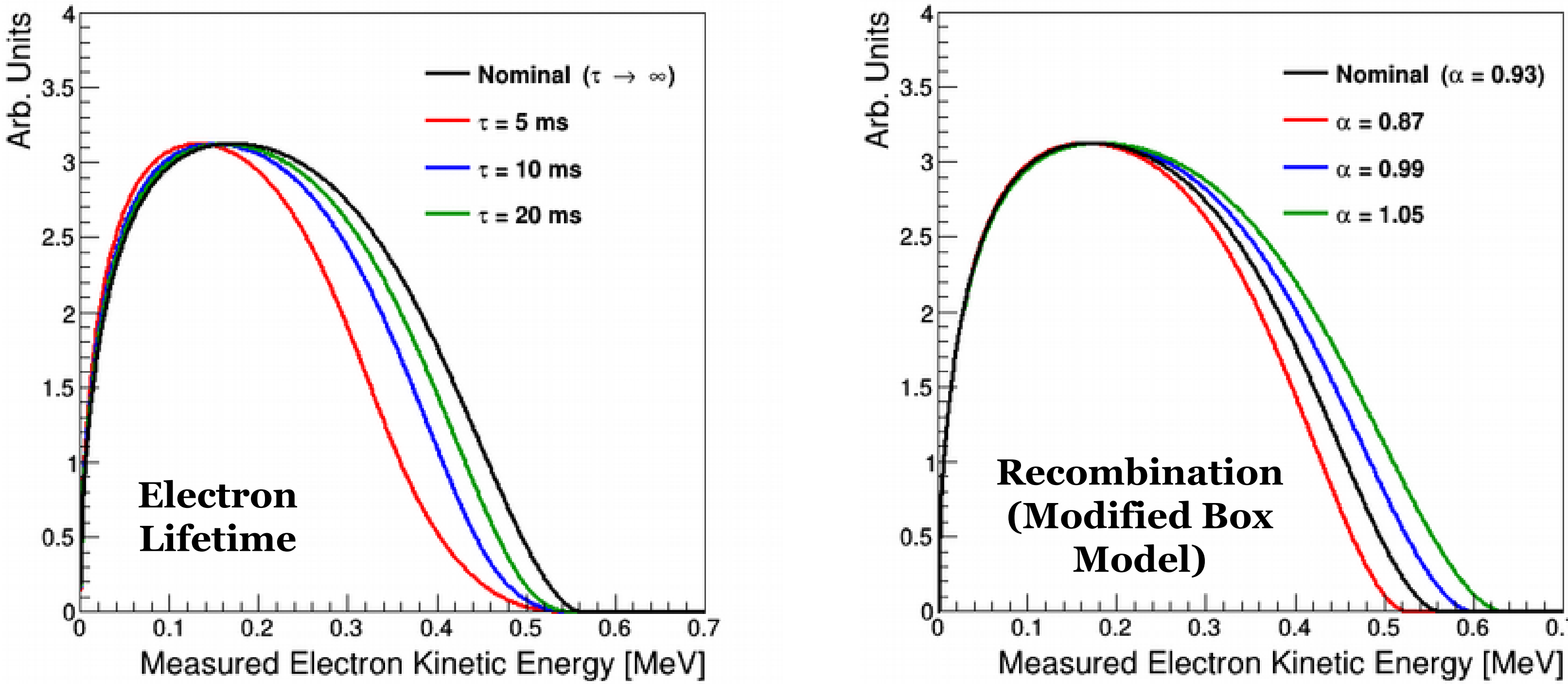
Table 5.9: Uncertainties applied to the energy response of various particles. p_0, p_1, and p_2 correspond to the constant, square root, and inverse square root terms in the energy response parameterization given in Equation 5.12. All are treated as uncorrelated between the ND and FD.

Particle	p_0	p_1	p_2
all (except muons)	2%	1%	2%
μ (range)	2%	2%	2%
μ (curvature)	1%	1%	1%
p, $\pi^{\pm}$	5%	5%	5%
e, γ, π^0	2.5%	2.5%	2.5%
n	20%	30%	30%

$$E'_{rec} = E_{rec} \times (p_0 + p_1\sqrt{E_{rec}} + \frac{p_2}{\sqrt{E_{rec}}})$$

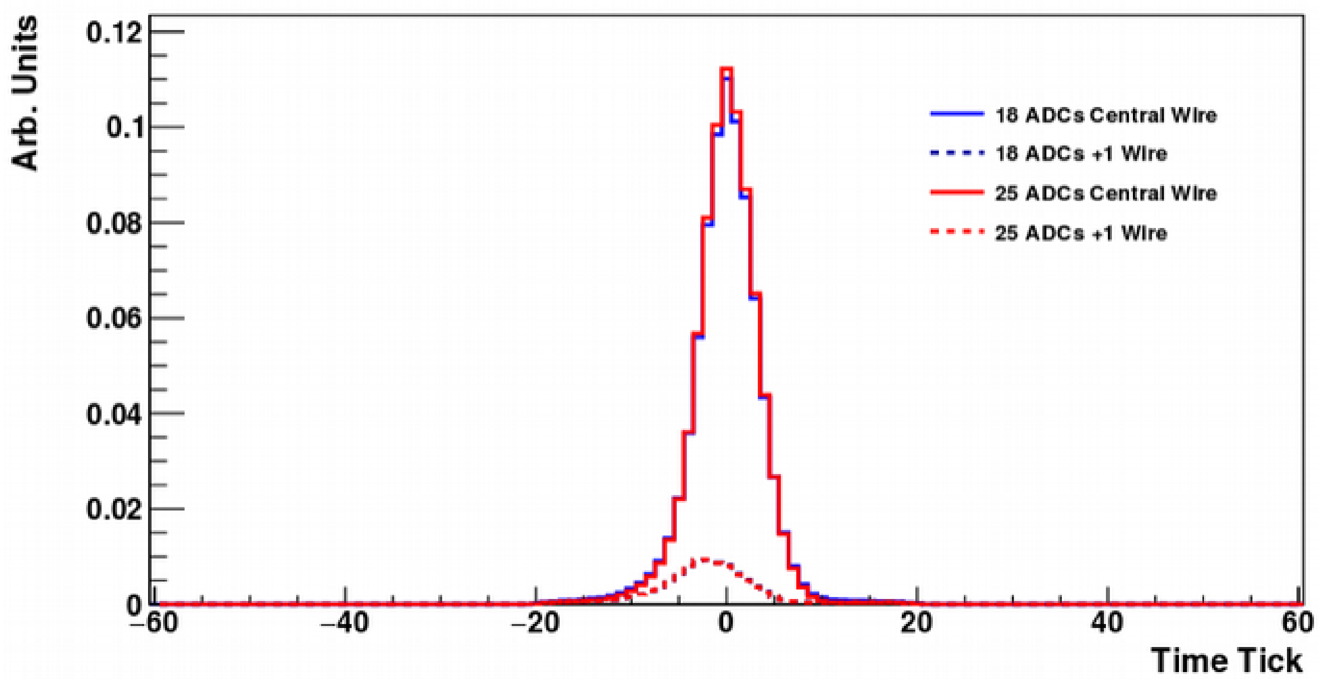
- We currently have estimates for particle-level energy response uncertainties (see Physics Volume of DUNE TDR), but need to better pin these down in the context of how (and how well) we perform calibrations – ProtoDUNEs will help!

e⁻ Lifetime vs. Recomb.



- Electron lifetime and recombination both impact spectrum, but in different ways → largely separable
- Noise also leads to smearing, but this can be measured very precisely with noise data

^{39}Ar Beta Decay Signal Shape



- Also looked at average ^{39}Ar signal shape at ProtoDUNE-SP
- Side wires see very little relative signal – diffusion is not too significant of an effect, on average
  - Helps that wire spacing is 5 mm (3 mm at MicroBooNE)
- Can see hints of induced charge here as well