Overall Calibration Plans

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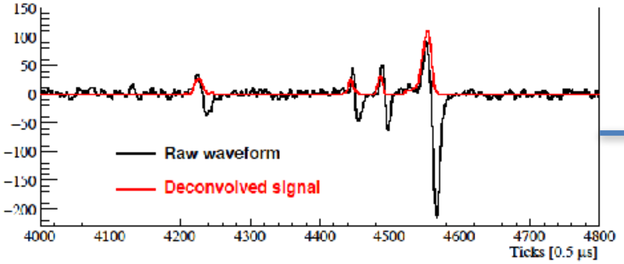
Calibration and Cryogenic Instrumentation Scope Review
May 26, 2020

LABORATÓRIO DE INSTRUMENTAÇÃO
E FÍSICA EXPERIMENTAL DE PARTÍCULAS

From data to physics

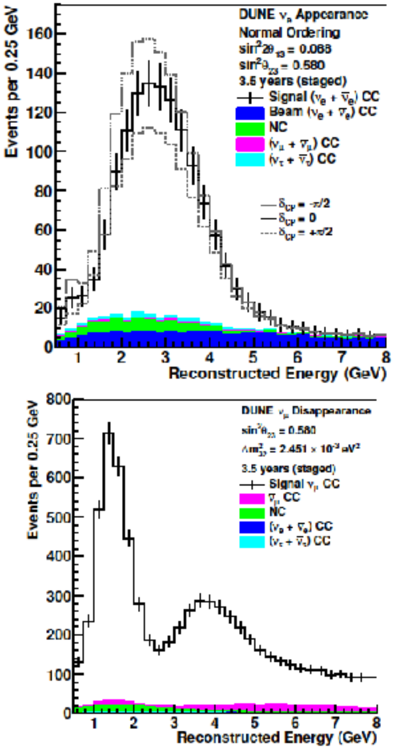
- Why we need calibrations and how to get them

FD raw data

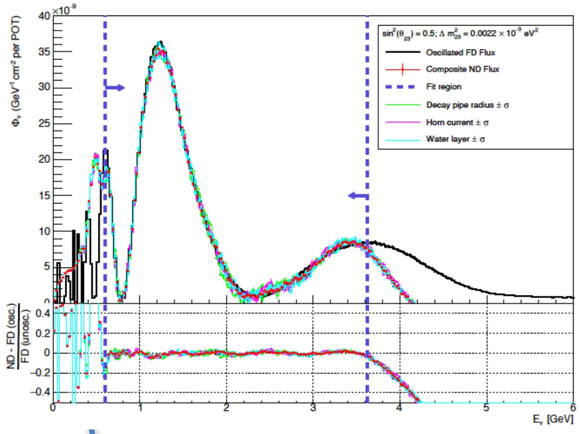


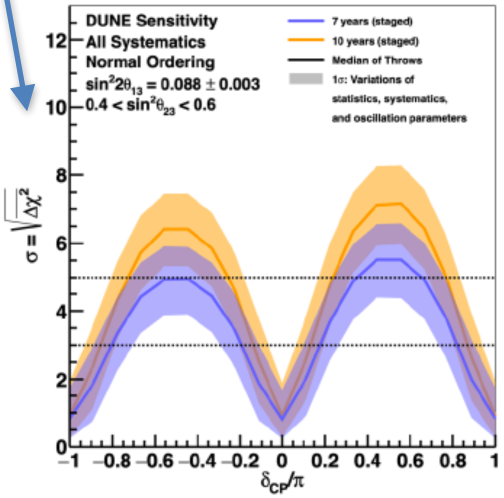
FD Calibrations

FD energy spectra



ND predicted flux, xs





[Physics TDR]

Outline

- **LBL Physics Requirements: Position**
  - Drift velocity, E-field and alignment
- **LBL Physics Requirements: Energy**
  - Oscillation fit systematics
  - Calibration in MicroBooNE and ProtoDUNE
  - Overview of energy signal path and breakdown of model parameters
    - Charge readout and collection
    - Charge transport (lifetime) and recombination
- **Performance Validation: High Energy**
- **Calibration Strategy**
  - Calibration Sequence Plan
  - Dealing with Time Variations
- Conclusions

[Caveat: Not the whole story here. For the full picture, see also talks by Mike Mooney (natural sources) and Bob Svoboda (low energy)]

LBL Physics Requirements Position

Position precision requirement

- What does the Fiducial Volume uncertainty requirement (1%) imply on the knowledge of the drift velocity?

> ***"The SP requirement that it be possible to determine the fiducial volume to 1% implies a vertex resolution of 1.5 cm along each coordinate direction. The 4.7mm wire pitch achieves this for the y and z coordinates."***

[TDR v.4, APA chapter]

- Individual **coordinate precision requirement: 1.5 cm**
  - 1.5 cm is 0.43% of the full 3.5 m drift
- **Drift velocity magnitude should be known to about 0.5%**
  - At least close to the CPA. Can be less stringent close to APA
  - (position uncertainty also impacts uncertainty on dQ/dx)

Drift Velocity

$$\vec{v_d} = -\mu\vec{E}$$

$$\mu = f(E,T)$$

$$\frac{\Delta v_d}{v_d}[\%] = (-1.97)\% \cdot \Delta T[K]$$

$$\frac{\Delta v_d}{v_d}[\%] = 0.37 \cdot \frac{\Delta E}{E}[\%]$$

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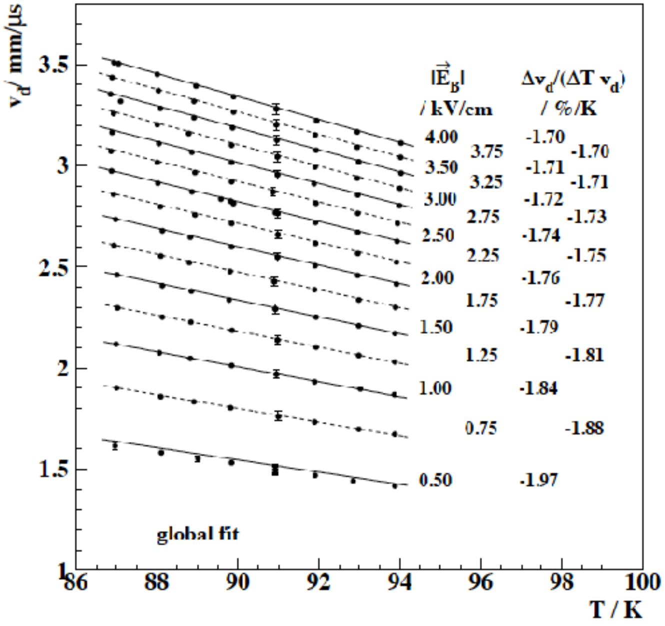
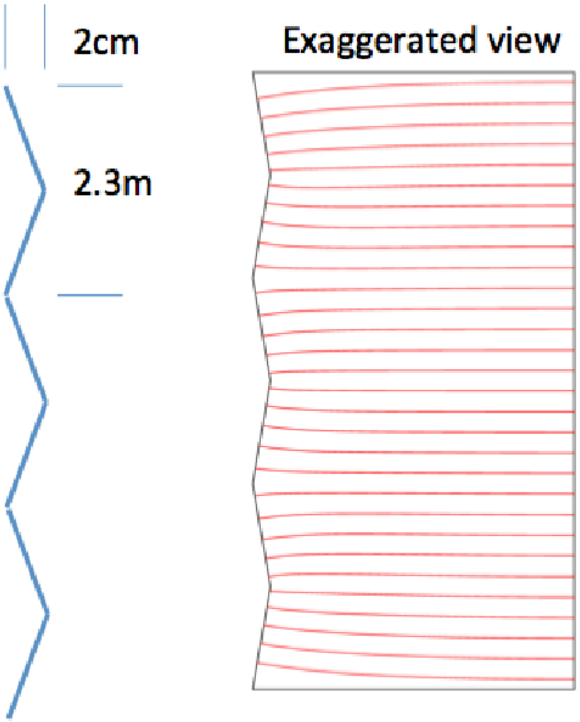


- Changes of **ΔE/E ~1.4% or ΔT~250 mk lead to Δ v_d ~0.5%**
  - E field uncertainty can't take "full budget" of v_d uncertainty
- Therefore, **1% req on FV leads to ~1% req. on electric field**
  - (as we'll see ahead, energy requirement leads to same E-field precision requirement of 1%)

E-field distortions



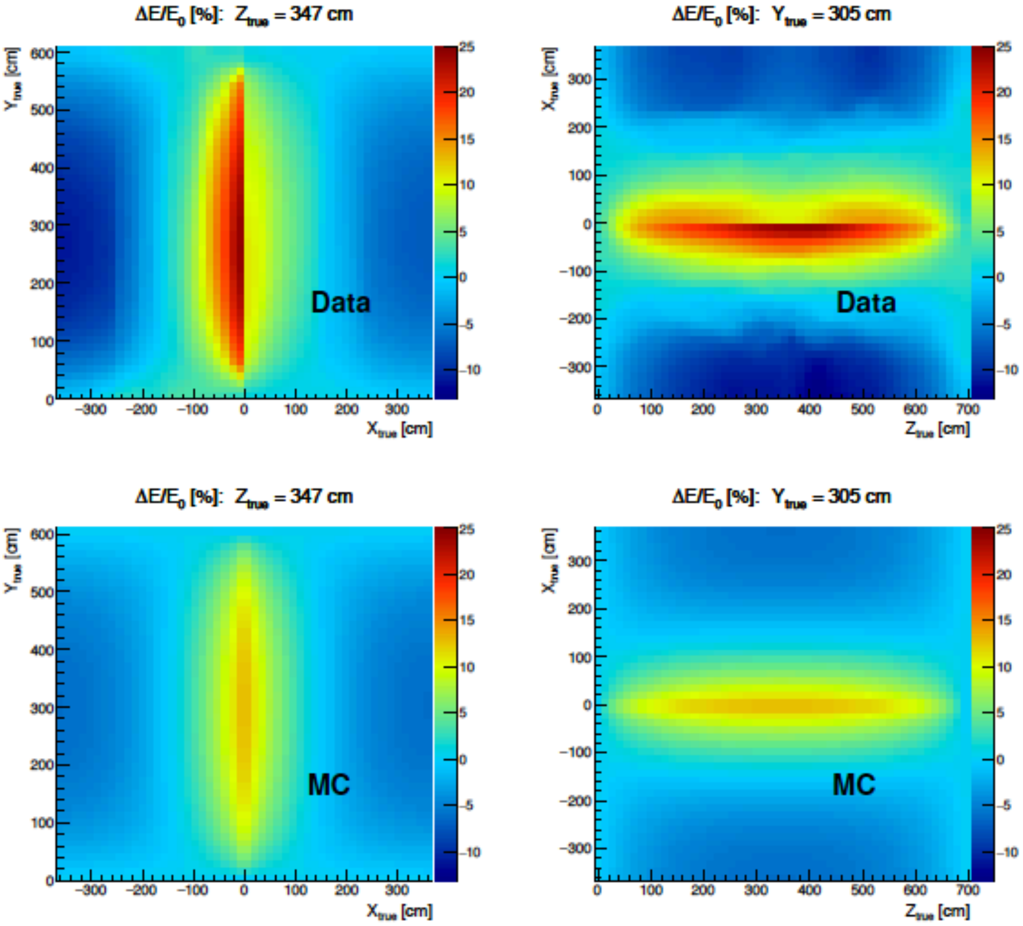
- **Space charge**, from ^{39}Ar
  - Static model in SP: **ΔE/E ~0.1%** (15% for DP)
  - Unknowns: effect of fluid flow? eddies?
- HV system problems
  - e.g. **CPA tilts**. Actually seen in PD-SP-I (~ 1.5 cm). Leads to variations of **>1%** close to CPA
  - **FC resistor failures**. Not seen, but can lead to variations of **1-4% in 1 m^3** close to FC profile
- APA distortion modes

  - Bent APA: harder to see than steps at gaps. Can't rely on single muons due to multiple scattering.
  - Crumpling of array: also hard since gaps are similar to nominal

ProtoDUNE measurements, cosmics

- Distortions in ProtoDUNE up to 25%, with 5% systematic estimated
- MicroBooNE had up to 15% maximum (see extra)
- CFD simulation: up to ~12%

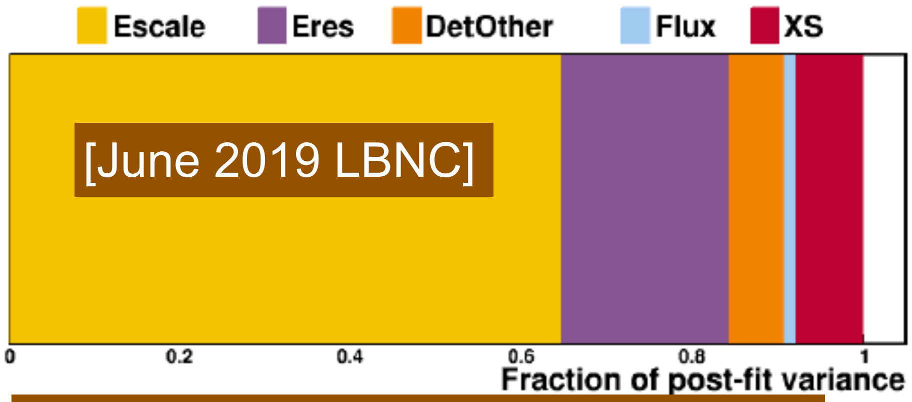
- A factor of 2x discrepancy!
  - Large fluid flow uncertainty.



LBL Physics Requirements
Energy

Energy Systematics

Contributions to δ_{CP} systematic:



earlier iteration of oscillation analysis

Detector effects impact the event selection efficiency as well as the reconstruction of quantities used in the oscillation fit, such as neutrino energy. The main sources of detector systematic uncertainties are limitations of the expected calibration and modeling of particles in the detector.

[LBL paper]

Energy scale

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%

- When ND data and constraints are used, energy response are, **by far**, the largest systematics.
  - Overall energy scale: **2%** (same for resolution)
  - Plus particle dependent uncertainties

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

Breakdown of Detector and LAr Model Requirements for Energy

TPC signal path only, PDS in extra slides

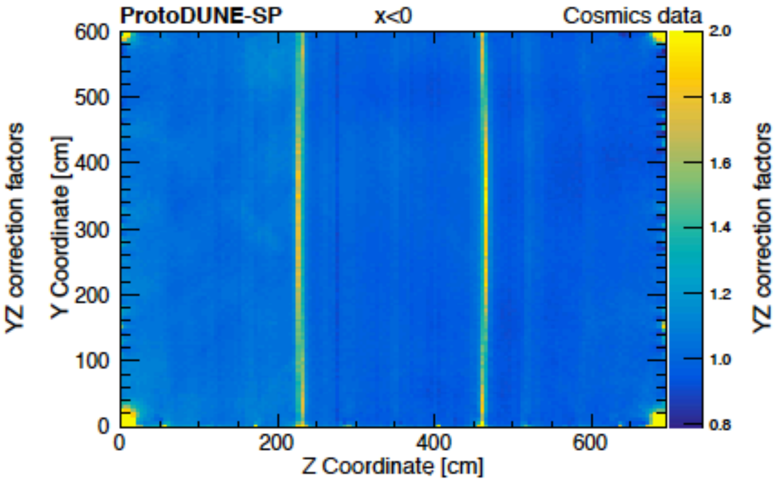
Reconstruction

Simulation

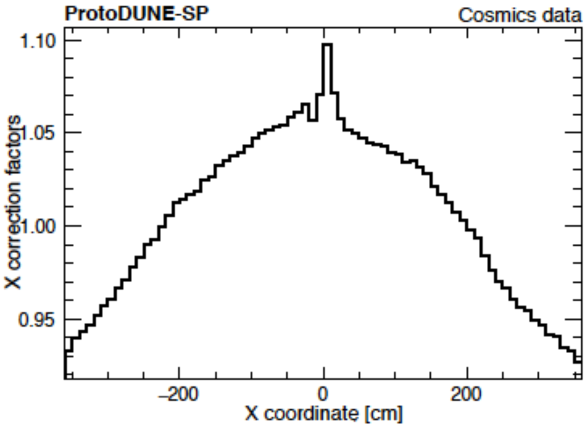
Object	Process	Parameters	Where we get them?
e, mu, hadrons			
	Interaction of particles in LAr	Cross-sections dE/dX	Other expts. ProtoDUNE
tracks hit clusters			
	Recombination	Work function Birks, Box model	Other expts. ProtoDUNE in-situ
Electron clouds at x, y, z			
	Electron transport	drift velocity lifetime diffusion coeff.	in-situ
Electron clouds at x’=0, y’, z’			
	Detection in APA	transparency	in-situ
Charge in wires			
	Digitization	FE gain	internal calibration pulser
ADC cts/TDC ticks			

Overall calibration (ProtoDUNE)

- Response look-up table maps
  - Technique similar to MicroBooNE, 2% precision, [10x5x5 cm (X, Y, Z)] map
  - Using cathode crossing cosmic ray tracks for space charge and lifetime
  - ~100 k cathode-crossing tracks
  - How long to do the same in FD?
    - W/ APA crossing-tracks? ~ 15 years
    - All tracks? Need 1M in DUNE: at least **14 months** considering 50% track selection efficiency (20% in ICARUS)



(b) YZ correction factors, $x < 0$



(b) X correction factors vs drift dimension x

Energy calibration requirements

$$\begin{aligned} dE_{hit}(x,y,z)[MeV] = & C_{recombination}(x,y,z)[MeV/e]\times \\ & C_{transport}(x,y,z)\times \\ & C_{collection}(wire)\times \\ & C_{electronics}(channel)[e/ADC]\times \quad dQ(channel)[ADC] \end{aligned}$$

- The goal of calibration is to determine these correction factors/ functions/maps
- The product of recombination, transport, collection and electronics corrections $C_r \times C_t \times C_c \times C_e$ must be known to **2% or better**

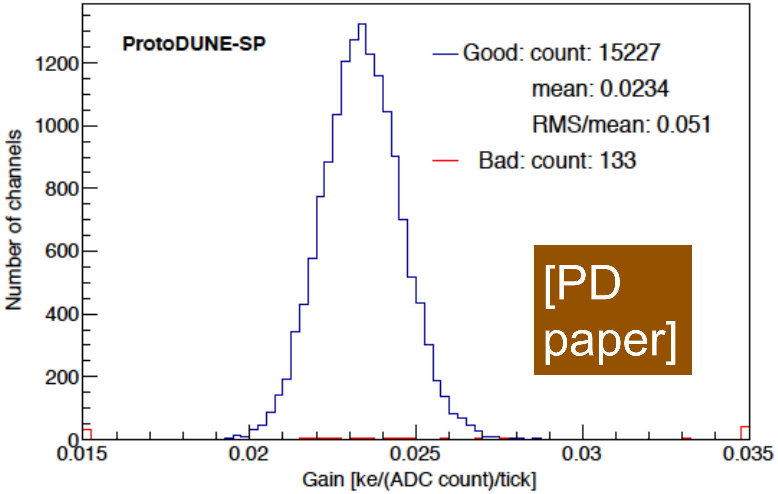
- Aim for 0.5% - 1% for each correction factor

Charge readout / Electronics

[see dedicated talk by Marco Verzocchi]

- Electronics gain
  - Good linearity observed in PD-SP-I
  - Channel-to-channel variations gain variations measured in PD-SP-I and have an RMS of 5.1%
  - These are measured by the dedicated internal calibration pulser
  - "Channel-to-channel and chip-to-chip variation in the calibration capacitor are typically **less than 1%**"

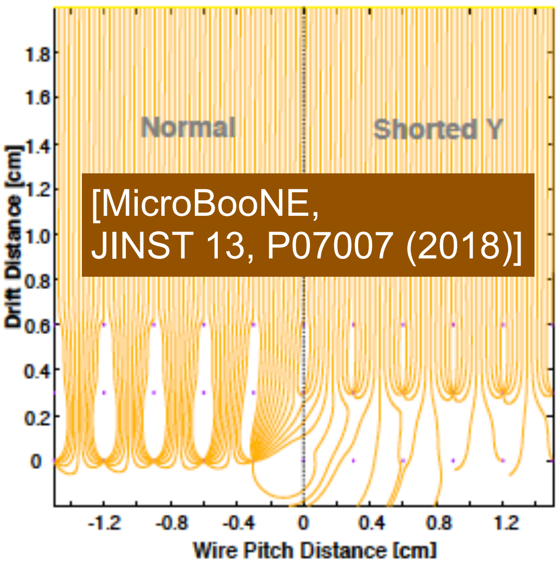
[TDR]



[PD paper]

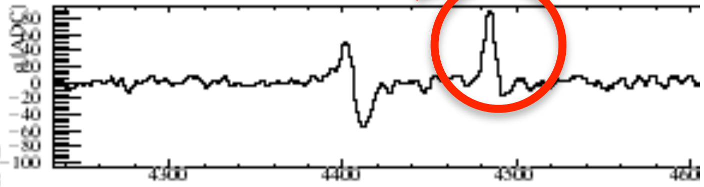
Charge collection 1/2

- “The operating voltages of the APA layers [..] were calculated to maintain a **100% ionization electron transparency** as they travel through the grid and induction wire planes.” [TDR]
- Previous experiments had problems
  - ICARUS transparency correction with 5% uncertainty [ICARUS Coll. NIMA 523, 275-286 (2004)]
  - Wire plane shorts seen in MicroBooNE. (Maybe 4% uncertainty for corrections?)
  - Even ProtoDUNE has seen some cases of collection on induction wires (unipolar pulse)



[MicroBooNE, JINST 13, P07007 (2018)]

(b) Shorted-Y region.



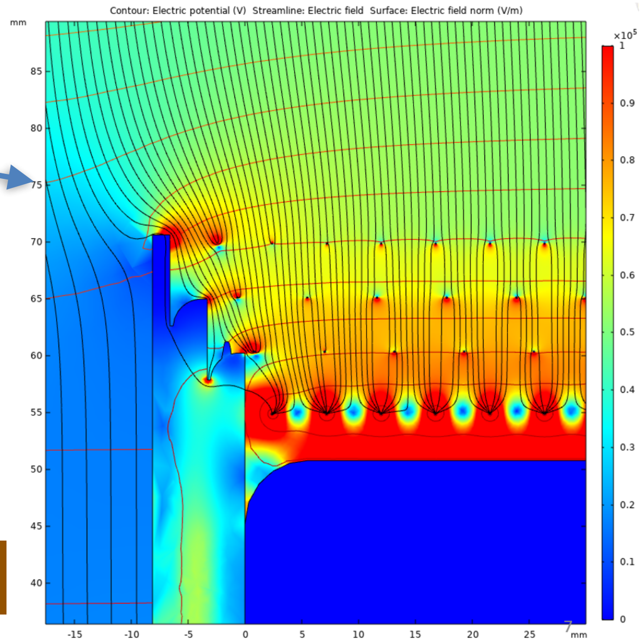
[Tom Junk, Tech. Board, Nov. 15, 2019]

Charge collection 2/2

- And for DUNE FD?

[Electron diverters TF, DocDB 14950]

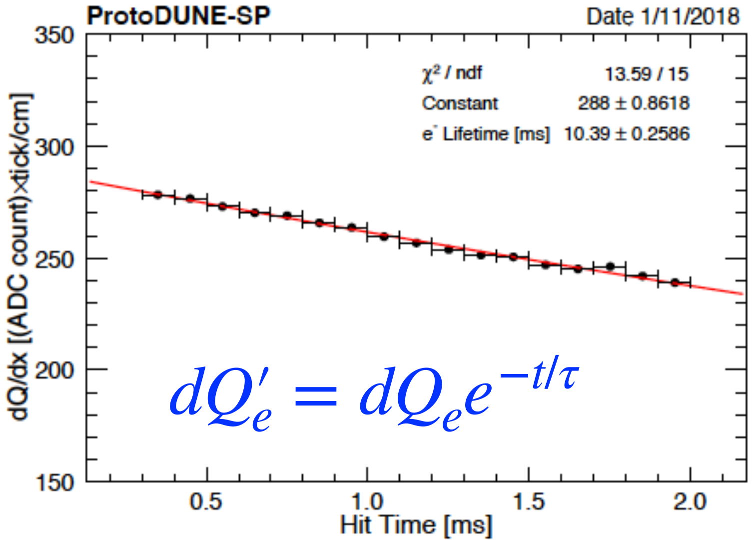
  - Simulations say charge collection on induction wires is expected on APA edges due to lack of electron diverters
    - wires affected: only a few C; all U, V
  - We need to either remove that region from analysis or have a calibration plan for it
    - Cosmics: 4 useful muons per APA vertical gap/day [Tom Junk, DocDB 5585]
    - Is this enough for 1% precision?
  - IoLaser tracks: plentiful and can be parallel to APA (independent of lifetime correction)



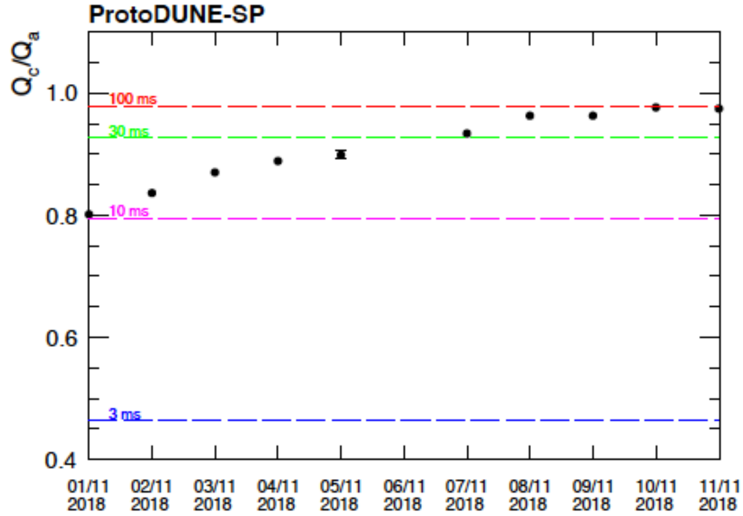
Wire capacitance?

- Recent ProtoDUNE analysis shows a 4% energy scale discrepancy between MC and data [W. Gu, PD sim/reco, May 20, 2020]
- It was suggested that culprit is the wire capacitance
  - COMSOL estimates 150 pF (including 30 pF parasitic), so that non-transferred charge is estimated at 4.3%
- Concerns for DUNE FD
  - This can't be measured by the calibration pulser
  - How uncertain is it, especially the parasitic component?
  - Does is change wire-to-wire? With time?
- A single overall calibration factor could conceivably come from stopping muons. But if we need wire-level, time-varying measurements, need dedicated sources.

Charge Transport: Lifetime, ProtoDUNE



$$dQ'_e = dQ_e e^{-t/\tau}$$



$$\frac{\delta\left(\frac{dE}{dx}\right)}{\frac{dE}{dx}} = \frac{t}{\tau}\frac{\delta\tau}{\tau}$$

- ProtoDUNE performance
  - Extremely high purities reached
  - Q ratio (C_t) at CPA: **precision of 0.5%** (stat) achieved
    - not clear the stats used, probably ~100k
  - Large day-to-day variations observed
  - Reasonable agreement with purity some of the purity monitors
    - which also indicated stratification

Charge Transport: Lifetime, DUNE FD

- Estimations of statistics needed
  - Scaling considerations using ICARUS efficiencies, uncertainties
    - 1% /day on whole volume
    - 17% /day for half an APA (3.5x3x2.3)m
  - Further studies with simulation ongoing by Viktor Pec in Calibration Physics WG
- Cosmics will likely only be able to track lifetime to needed precision for full detector, not space/time variations
  - Other methods: ^{39}Ar and pulsed neutron source. Laser too, will test in PD

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

[Josh Klein, docDB 14926]

[see talks by Mike Mooney, Sowjanya Gollapinni, Jingbo Wang]

Charge Recombination 1/2

Experiment	Mass	Particle	Precision on		Ref.	Formula used
			A	k		
ArgoNeut all angles	0.76 ton	p	1.2%	2%	arXiv: 1306.1712v1	$dE/dx = \frac{dQ/dx}{A_B/W_{ion} - k_B \cdot (dQ/dx)/\mathscr{E}}$.
ArgoNeut angle bin			2.2%	5%		
ICARUS	3 ton	μ, p	0.4%	1.2%	ICARUS Coll. NIMA 523, 275-286 (2004)	$Q = A\frac{Q_0}{1 + k/\mathcal{E}\frac{dE}{dx}}$
ICARUS	600 ton	μ	6.2%	10%		

- ProtoDUNE analysis using ArgoNeut values (but for Box model)

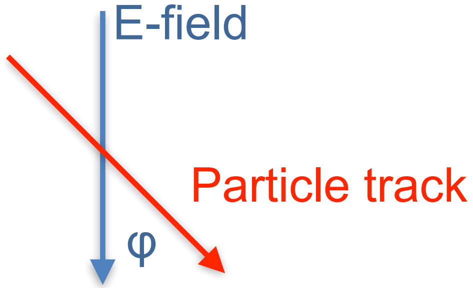
- We need:
  - uncertainty on A to improve substantially, to < 1%
  - Impact of E-field to be ~0.5 %
  - **E-field precision requirement of 1%**, similar to position

precision needed for 0.5% on C_r

dE/dx [MeV/cm]	ΔA/A [%]	Δk/k [%] or ΔE/E [%]
2.1 (mip)	0.5%	3.6%
5		1.8%
10 (electrons)		1.2%
20		0.8%

Charge Recombination: angle

$$dE/dx = \frac{dQ'_e/dx}{A_B/W_{ion} - k_B \frac{dQ'_e/dx}{\epsilon \times \boxed{sin\phi}}}$$



- ArgoNeut measures angular dependence, smaller than model
- The effect is large. Response decrease between 90 deg and 45 deg:
  - 5%, 10%, 15% for a dE/dx of, respectively, 2.1, 5, 10 MeV/cm
- Need to clarify this for DUNE analysis
  - very hard at FD to get cosmics at low angles, better at ProtoDUNE
- Maybe possible to use laser system to measure this underground
  - Higher laser intensity to increase dE/dx
  - Laser tracks at low angles w.r.t. E-field to enhance the 1/sinφ term

Correction parameters overview 1/2

- **Charge readout:** 1% should be feasible with internal pulser
- **Charge collection:**
  - Collection on induction wires will happen close to APA gap. Grounded, shorted wires, bad voltages, may affect larger regions
    - Either live with larger FV gaps or calibrate. Slow with cosmics
  - And wire transparency? Do we need/want the capability of individual wire calibration?
- **Charge transport/ lifetime:**
  - ProtoDUNE achieved Qratio 0.5%, but saw large time and space variations
  - Fluid flow impurity variations of 2% predicted with CFD. If they reach 5%, that’s 1% on charge. Will be hard with cosmics.

Correction parameters overview 2/2

- **Drift velocity -> E-field and alignment**
  - detector effects on E-field stronger near walls, also where they affect fiducial volume more. I.e. 1% effects near CPA are important.
  - Granularity to measure CPA tilts: 1/4 of CPA resistive panel (unit):
    - Statistics in DUNE FD: 90 crossing tracks/year (180)
- **Charge recombination -> E-field and parameters**
  - Need to push in many fronts:
    - bring parameter uncertainty to below 1%
    - clarify angular dependence.
    - Really know the field to 1% (even with laser it will not be easy)

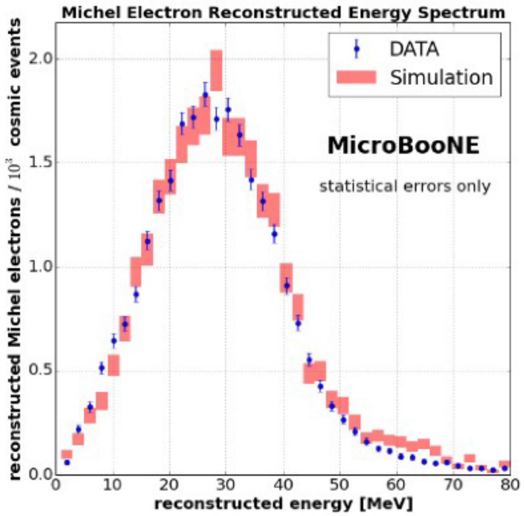
Performance Validation: High Energy

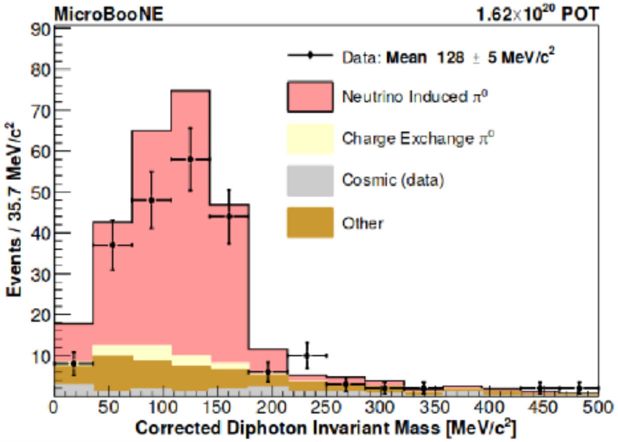
[Much more on this in talks by
Mike Mooney (natural sources)
and Bob Svoboda (low energy)]

Performance assessment

- Once the model parameters/maps are measured, need to validate their final effect on particle energy response
- We do not have the luxury of
  - plentiful Z^0 bosons as in LHC…
  - LINAC as in SK
- What we can do
  - beam neutrino and rock muon events
  - stopping muons, Michels, π^0 decays
  - ^{39}Ar decays
  - low energy dedicated sources (neutron gamma) [see talk by Bob Svoboda]

[see talk by Mike Mooney]





Calibration Strategy

Strategy considerations

- **Statistics**
  - Use higher stat sources (dedicated) for fine mappings, then sources with lower stat (cosmics) or no-X position (^{39}Ar) to cross -check
- **Correlations: many different effects piling up on energy response**
  - Use different data samples/sources to break correlations
  - Proceed in steps:
    - Position-based measurements (alignment, drift velocity, E-field) first
    - Then, charge-based ones (wire response, lifetime, recombination)
    - Full response validation at the end
- **Time-variations**
  - Extensive and frequent calibrations with dedicated sources during commissioning and before beam.
  - Use them to tune CFD (E-field and purity) maps and see how much they vary
  - During normal data-taking, validate CFD maps with regular calibrations

Calibration Sequence

1. **Drift velocity/E-field/alignment (position-based)**
    1. Dedicated fine-grained (10 cm) IoLaser, as frequently as possible in each phase. PE laser scans in between.
    2. Cross-check with cosmics and CFD maps
2. **Wire response/lifetime/diffusion (charge-based)**
    1. The same data, but with drift/E-field corrections
    2. Cross-check with cosmics, ^{39}Ar, PNS
3. **Recombination**
    1. Apply all charge transport and collection corrections to all relevant sources: stopping muons (+ protons, etc)
    2. Use laser data at low angle (w/r to field) for angular dependence cross-checks
4. **Energy scale and resolution**
    1. Apply all the above corrections to data and MC of stopping muons, Michels, $\pi 0$ and dedicated low energy sources (PNS, RSDS)
    2. Obtain final scalings if needed, estimate systematics by data/MC comparison

Deal with time variations

1. Before beam
    1. Dedicated fine-grained laser scans +PNS/RSDS as frequently as possible, taking care to avoid being SNB-blind
    2. These samples, compared to CI-tuned CFD simulations, will tell us how much we can expect detector to change with time
    3. This period is crucial for us to hit the ground running. **Dedicated sources are the only way to get enough statistics in this phase**
2. After beam
    1. Take full IoLaser and PNS scans every 6 months, with PE laser (shorter) scans in between
    2. “Calibrations-of-opportunity”. Beam-on data taking will take priority but use beam-off periods for additional calibrations if possible.
    3. Continuously use Cryogenic Instrumentation (mostly PrM and T sensors) and natural sources (and PE laser) to look for problems and variations
    4. “Calibrations-of-need”. If variatios are noted, do a fine scan in affected regions

Best source for this
Some limitations

Goal	Measurement	Natural sources	Laser system	Gamma sources
Determine parameters	Detector defects, alignment	Cosmics (low or 0 stats)	IoLaser, PE laser (CPA)	X
	Drift velocity/ E-field	Cosmics (low stat)	IoLaser, PE laser (int. only)	PNS, RSDS (?)
	Electron lifetime, diffusion	Cosmics (low stat), Ar39 (not in x)	IoLaser (not proven yet)	PNS, RSDS (lim. cov.)
	Recombination	Cosmics, beam	IoLaser (angular dependence ?)	PNS, RSDS ?
Measure Physics response	High energy: μ track dE/dx	Cosmics, beam: muon tracks	X	X
	High/Mid energy e/γ	Cosmics, beam: π^0 decays, Michels	X	X
	Well-defined e/γ scale/resolution	X	X	PNS, RSDS
	Neutrons	X	X	PNS
	Low E singles trigger efficiency	X	X	RSDS

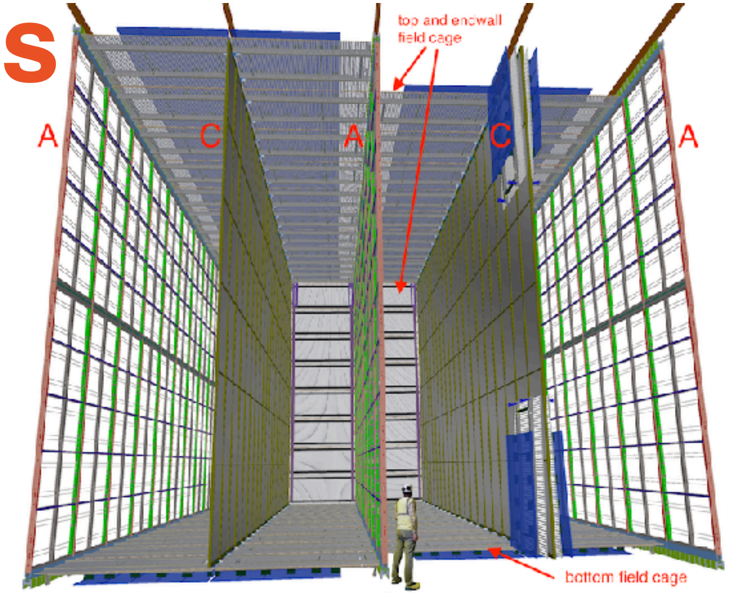
Conclusions

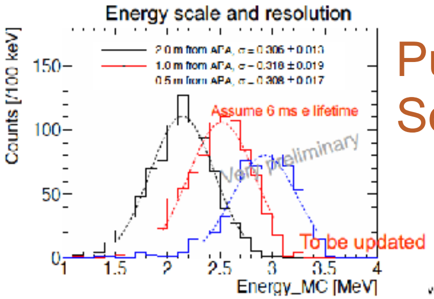
- Unprecedentedly tight physics requirements for DUNE
    - It does not seem easy to achieve all at the same time, for the whole detector, and stably for many years.
- **At least for the first FD, it is critical to learn as much as possible and optimize for the second and subsequent detectors**
- **“Space charge will be small" is not the whole story**
    - for a believable physics results, we need to demonstrate it's small
    - several other effects within plausible reach of affecting physics
    - energy response is our main systematic, it is essential to have more than one way to show we reached the needed precision
- Integrated calibration sequence plan
    - **No one single source to do it all**

Extra

What CALCI measures

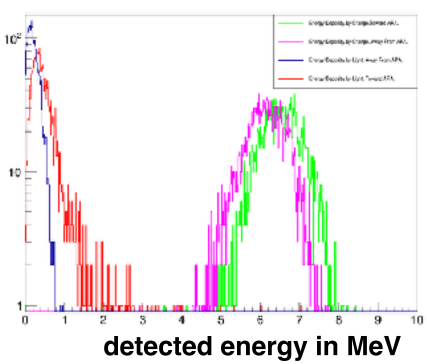
- **Monitor** crucial detector **operations**
    - Cool-down, fill, re-circulation
- Argon properties, computational fluid dynamics (CFD), detector **model parameters**
    - temperature, purity, levels, electron lifetime and diffusion
    - detector alignment, APA wire checks, HV resistor failures
    - drift velocity/E-field mapping
    - possibly PDS timing, efficiency
- Detector/trigger **response to physics** events
    - neutron propagation
    - well-know energy deposits from gammas





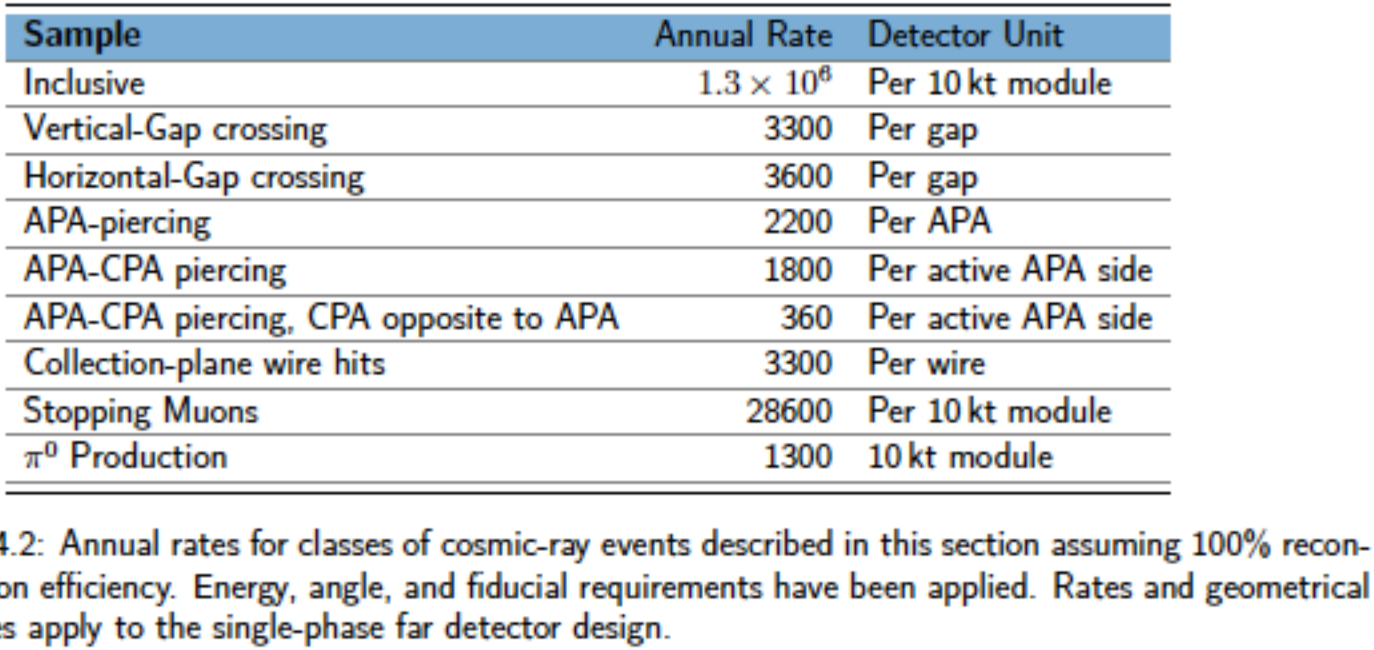
Pulsed Neutron Source

ve energy collected by TPC and Type



9 MeV gamma source

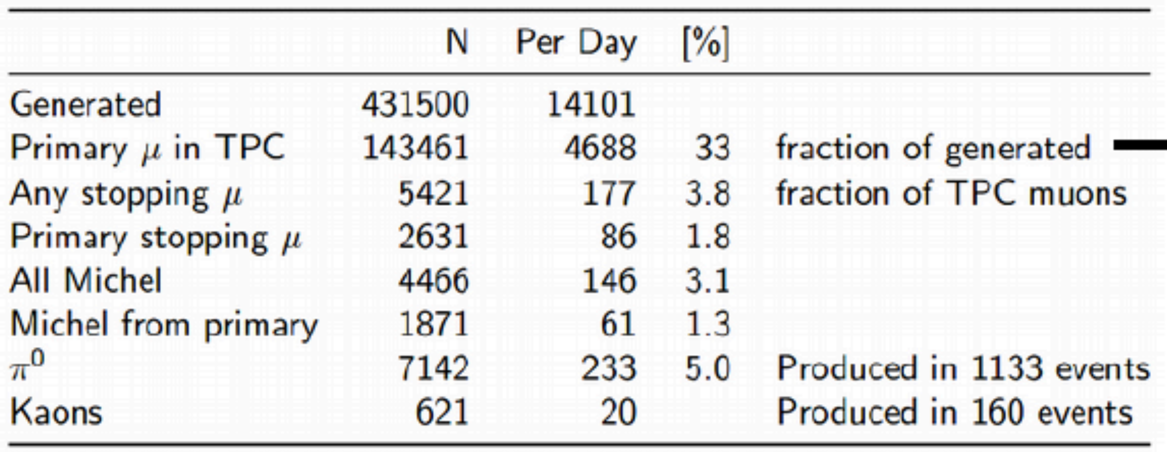
Cosmics rates



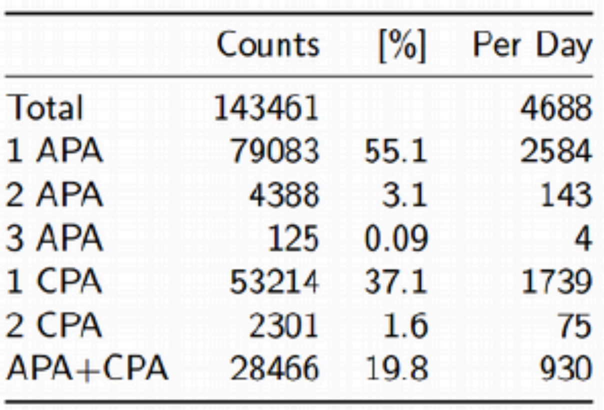
Sample	Annual Rate	Detector Unit
Inclusive	1.3×10^6	Per 10 kt module
Vertical-Gap crossing	3300	Per gap
Horizontal-Gap crossing	3600	Per gap
APA-piercing	2200	Per APA
APA-CPA piercing	1800	Per active APA side
APA-CPA piercing, CPA opposite to APA	360	Per active APA side
Collection-plane wire hits	3300	Per wire
Stopping Muons	28600	Per 10 kt module
π^0 Production	1300	10 kt module

Table 4.2: Annual rates for classes of cosmic-ray events described in this section assuming 100% reconstruction efficiency. Energy, angle, and fiducial requirements have been applied. Rates and geometrical features apply to the single-phase far detector design.

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

Size of detector elements

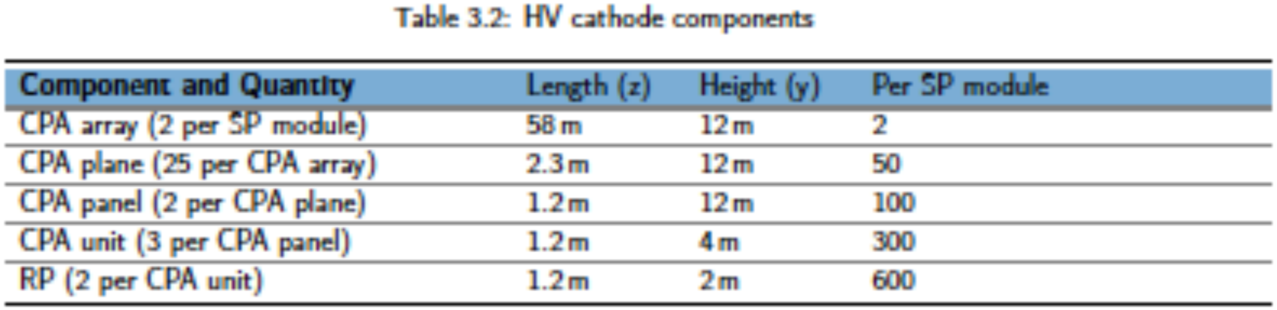
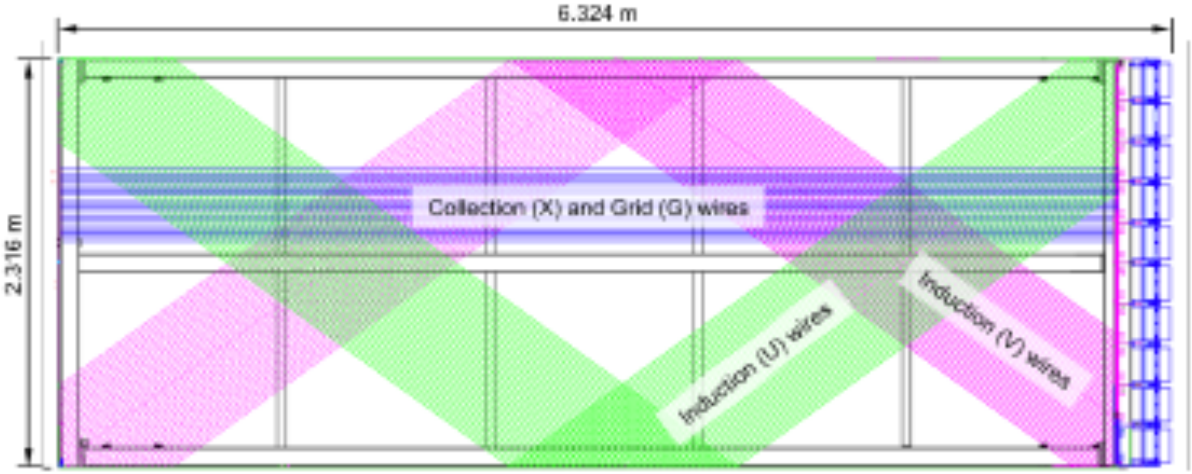


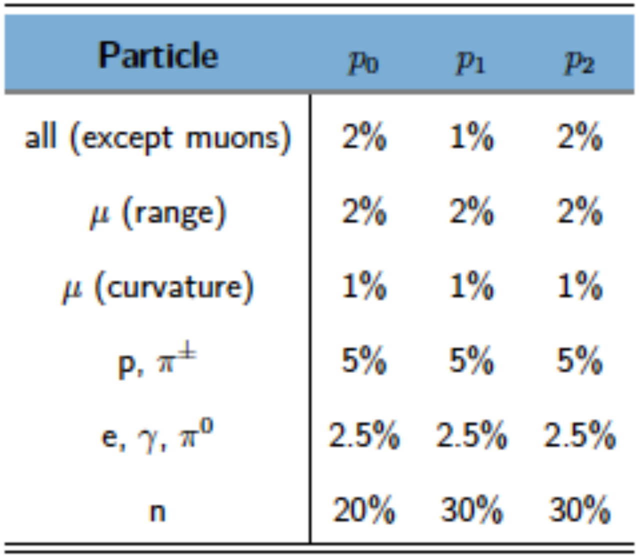
Table 3.2: HV cathode components

Component and Quantity	Length (z)	Height (y)	Per SP module
CPA array (2 per SP module)	58 m	12 m	2
CPA plane (25 per CPA array)	2.3 m	12 m	50
CPA panel (2 per CPA plane)	1.2 m	12 m	100
CPA unit (3 per CPA panel)	1.2 m	4 m	300
RP (2 per CPA unit)	1.2 m	2 m	600



Systematics

some portion of the energy response. The full list of assumed energy scale uncertainties is given as Table 9. In addition to the uncertainties on the energy scale, uncertainties on energy resolutions are also included. These are treated as fully uncorrelated between the near and far detectors and are taken to be 2% for muons, charged hadrons, and EM showers and 40% for neutrons.



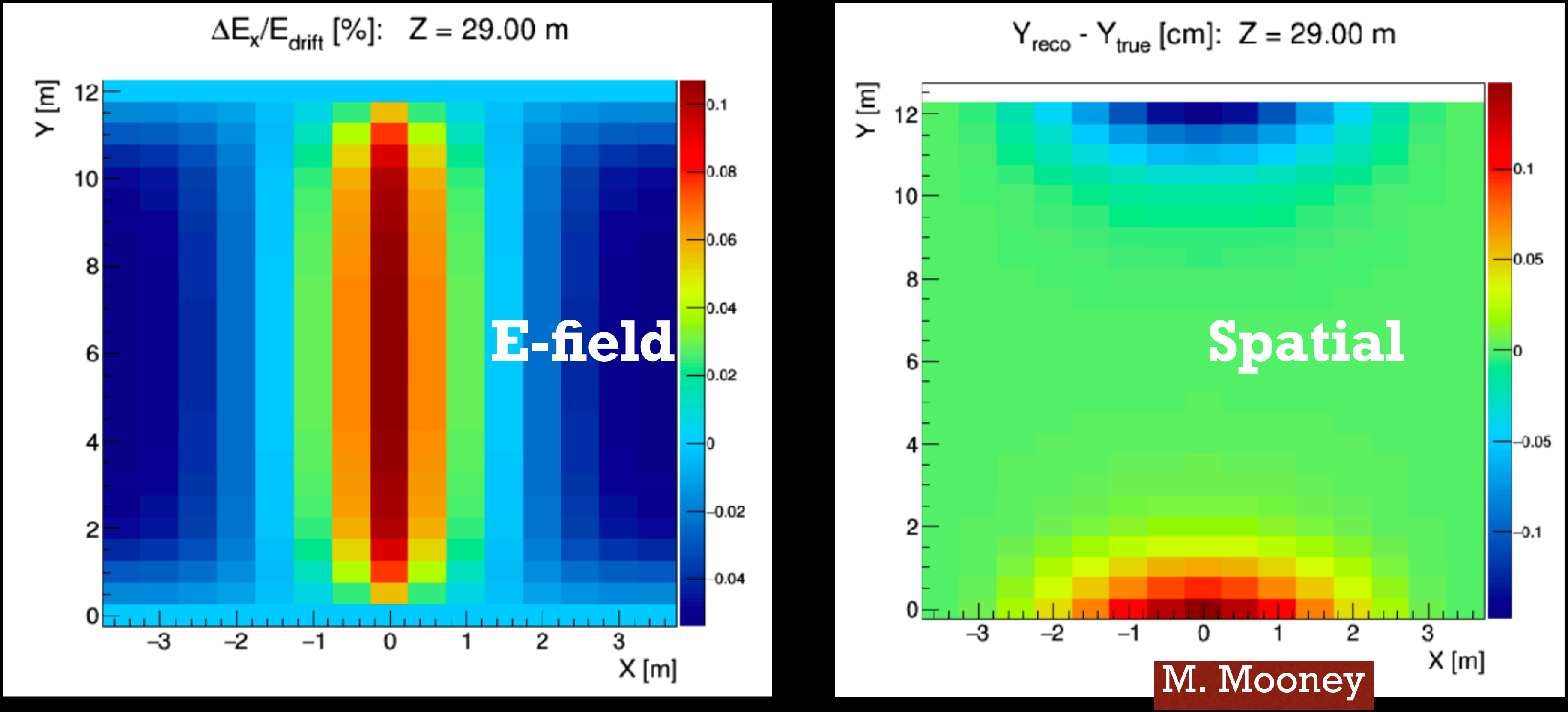
Particle	p_0	p_1	p_2
all (except muons)	2%	1%	2%
μ (range)	2%	2%	2%
μ (curvature)	1%	1%	1%
p, $\pi^{\pm}$	5%	5%	5%
e, γ, π^0	2.5%	2.5%	2.5%
n	20%	30%	30%

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.

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

Object	Process	Parameters	Where we get them?
e, mu, hadrons			
	Interaction of particles in LAr	Cross-sections dE/dX	Other expts. ProtoDUNE
tracks hit clusters			
	Recombination Scintillation	Work function Birks, Box model	Other expts. ProtoDUNE ?
Photons at x, y, z			
	Light propagation	Absorption and scatt. lengths Reflectivities	?
Photons at x’=0, y’, z’			
	Detection in ARAPUCA	Absorption lengths, re-emission yields	?
Photons at SiPM			
	Digitization	SiPM and PDS FE gain	?
ADC cts			

E-field distortions: Ionization Sources (SP)



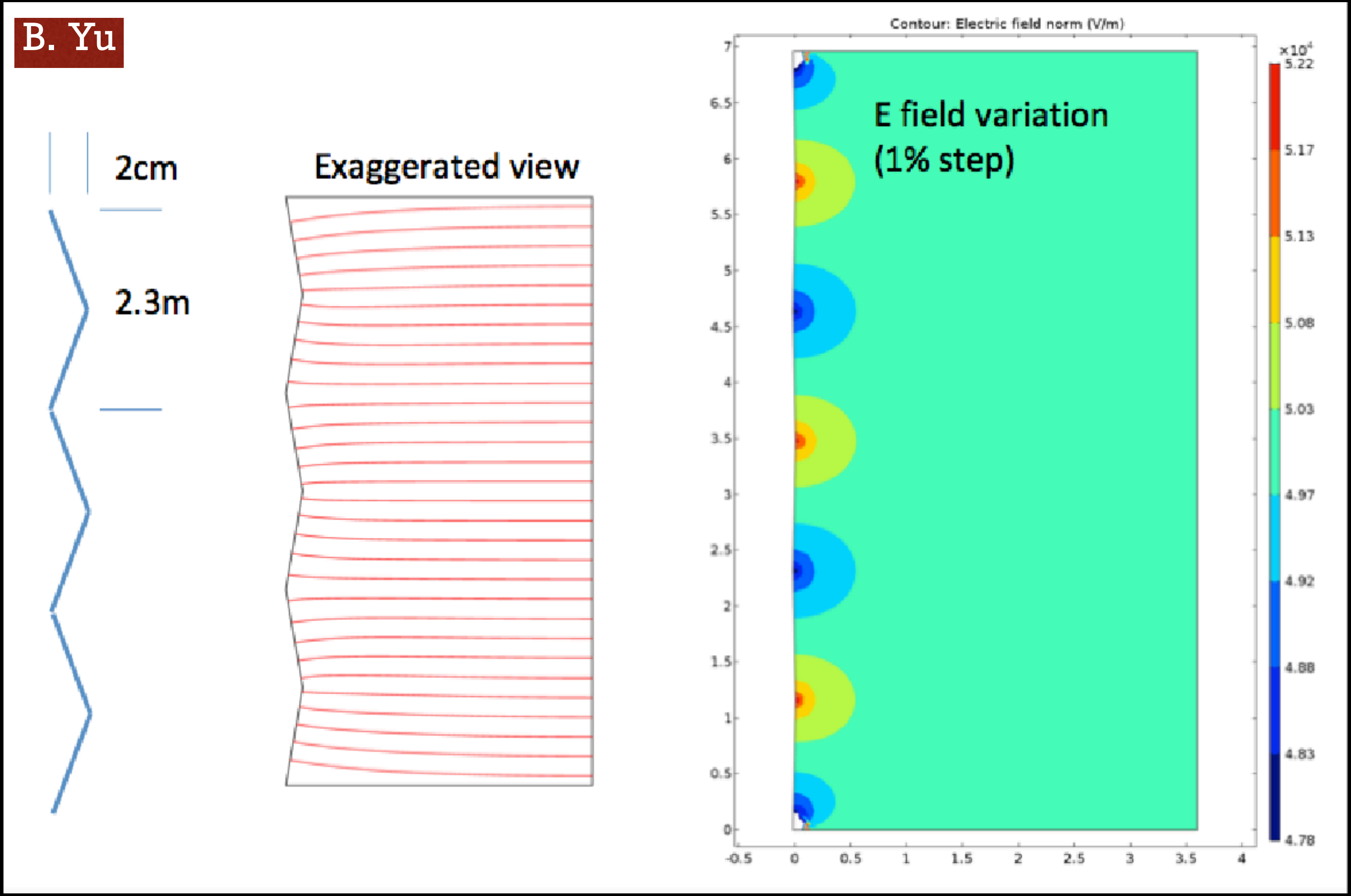
$\Delta E_x/E_{drift}$ [%]: Z = 29.00 m

$Y_{reco} - Y_{true}$ [cm]: Z = 29.00 m

M. Mooney

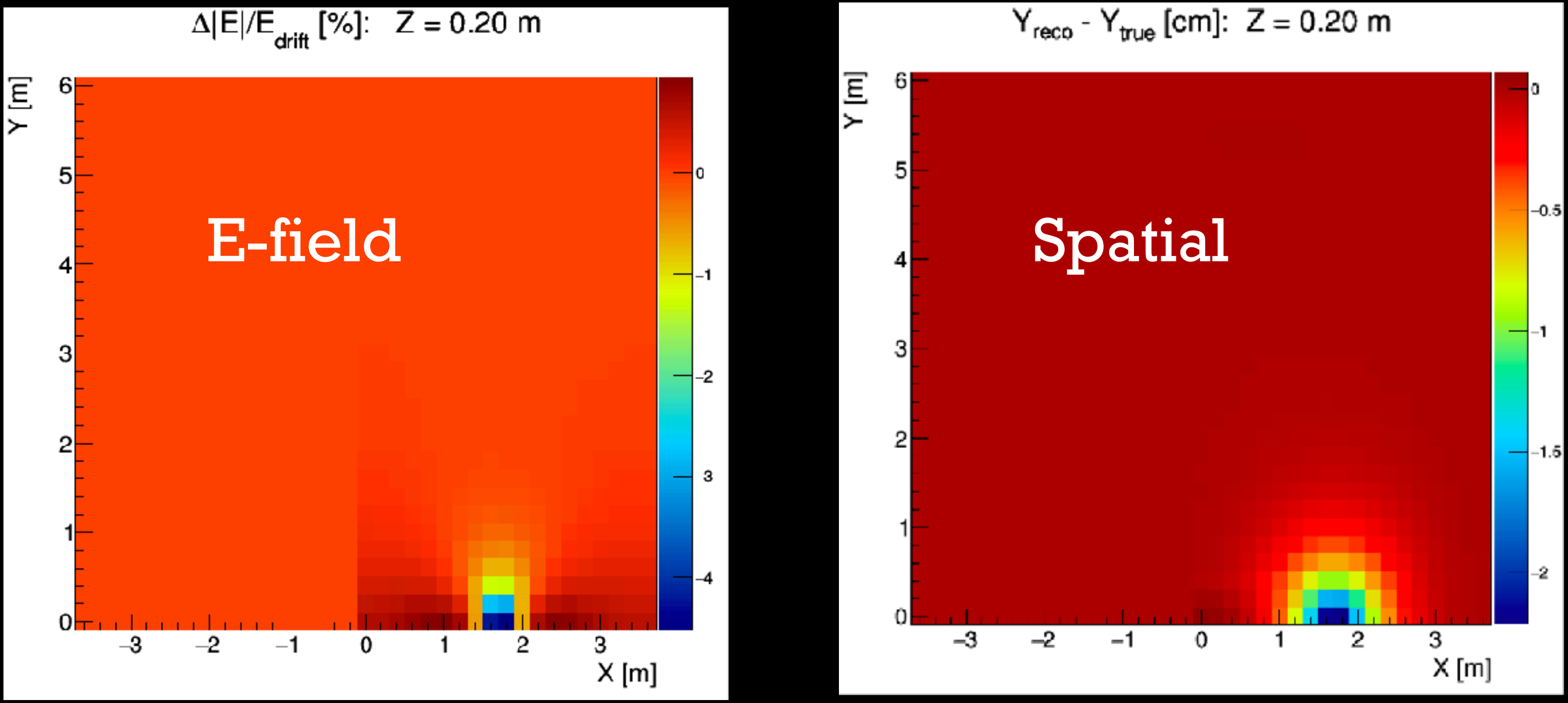
- Very small
- E-field distortions: 0.1%; Impact on dQ/dx: 0.03%
- Spatial distortions: 1-1.5 mm; Impact on dQ/dx (including Recombination): <0.1%

E-field distortions: CPA position tilts (SP)



- Assuming 2 cm CPA position tilts results in few % effect on E-field

E-field distortions: Field Cage Resistor Failure (SP)

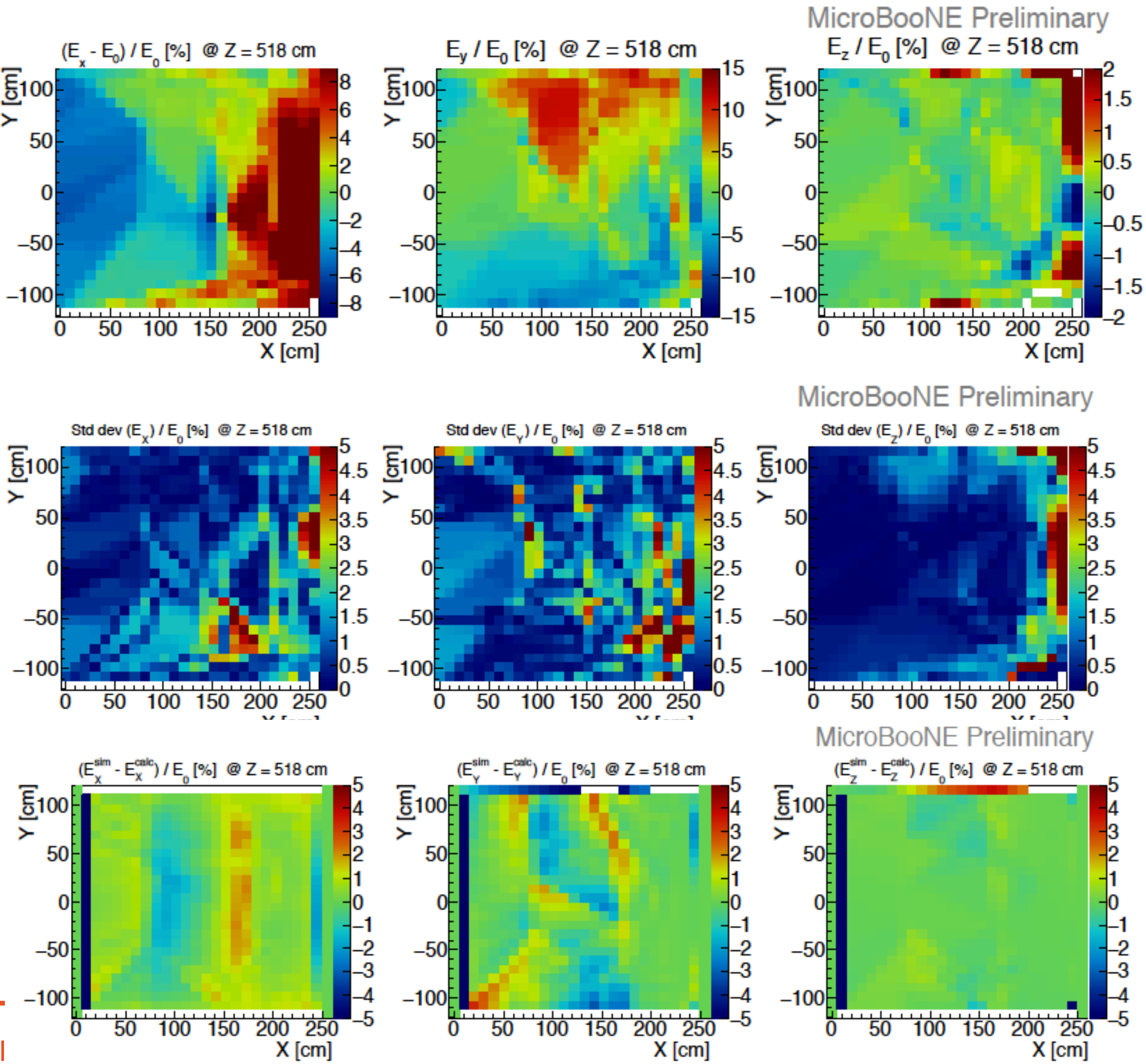


- Single FC resistor failure in ProtoDUNE-SP geometry
- Up to 4% effect on total E-field and up to 2 cm offset in the Y-direction
- Effect is not completely local, but strongest in the ~1 m^3 volume around the defect
- Impact on dQ/dx = 1-2%

B. Yu, M. Mooney

MicroBooNE measurements, laser

- Up to 15% distortions
- Stat. uncertainty mostly within 2%
- Syst. uncertainty mostly within 2% as well
- 1% precision is hard even with laser! Need good coverage

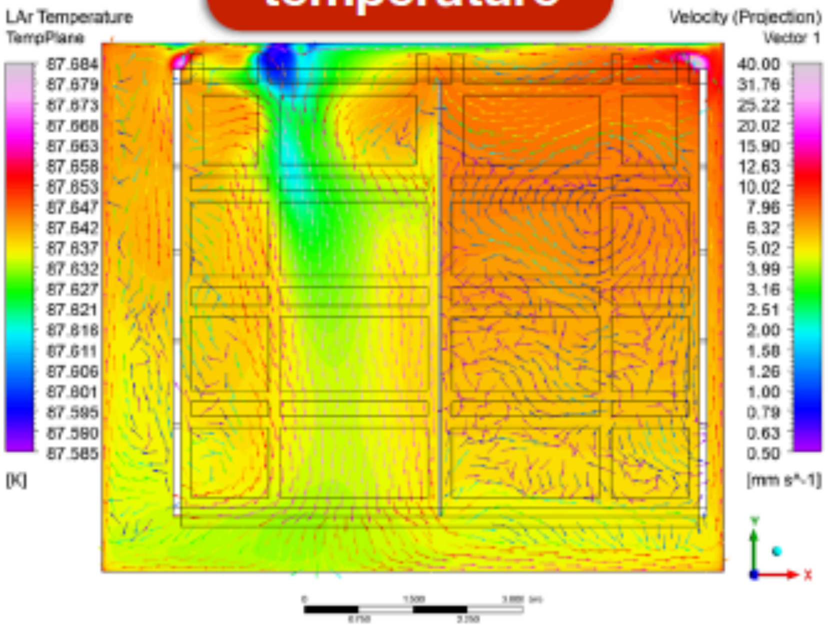


In ProtoDUNE-SP

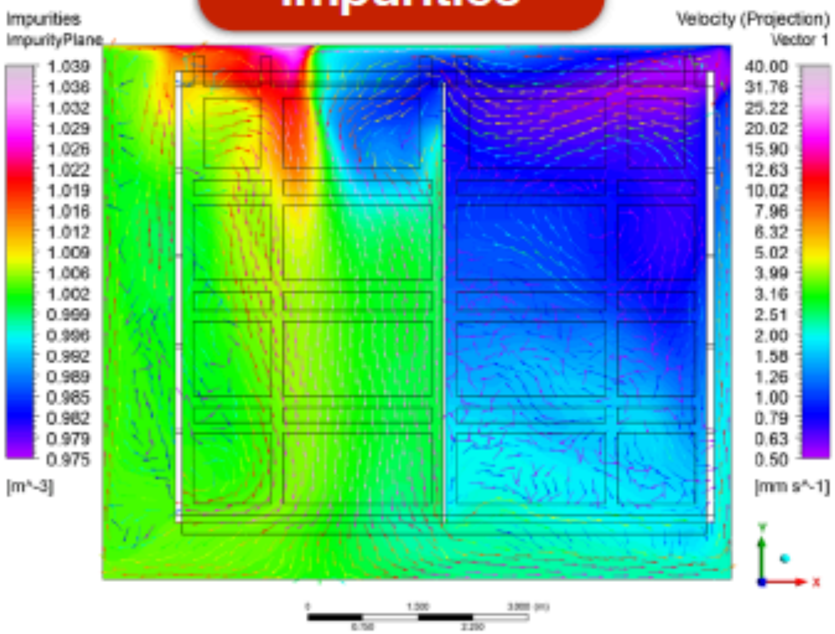
E. Voirin DUNE-doc-928-v5

- 15 mK gradient observed
- CFD predicts 5% impurity variation, which for 15 ms lifetime translates into 5% charge attenuation
- Assuming a direct relation between temperature and purity we need 1.5 mK precision for 0.5% abs. error on charge attenuation correction

temperature



impurities

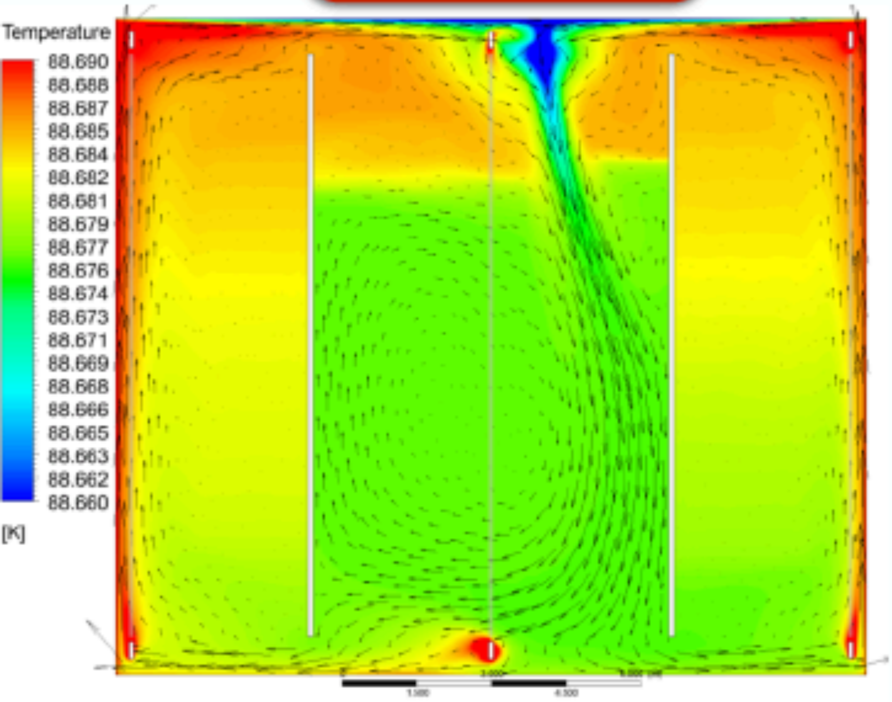


CFD simulations in DUNE

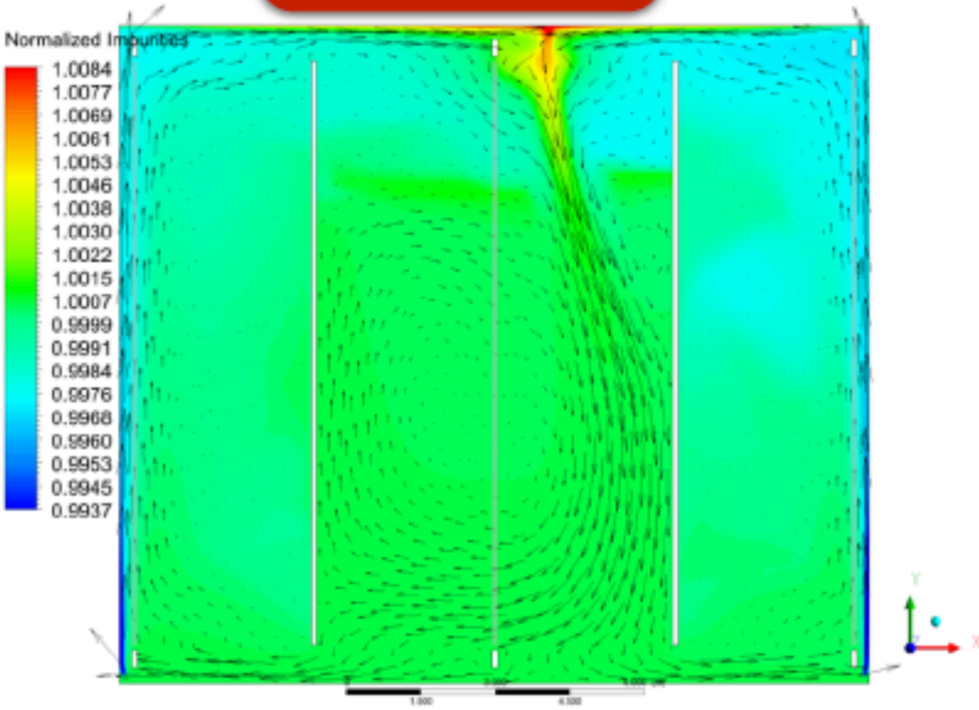
E. Voirin DUNE-doc-1046-v2

- There is a clear correlation between temperature and purity
- Predicted vertical temperature gradient is ~15 mK

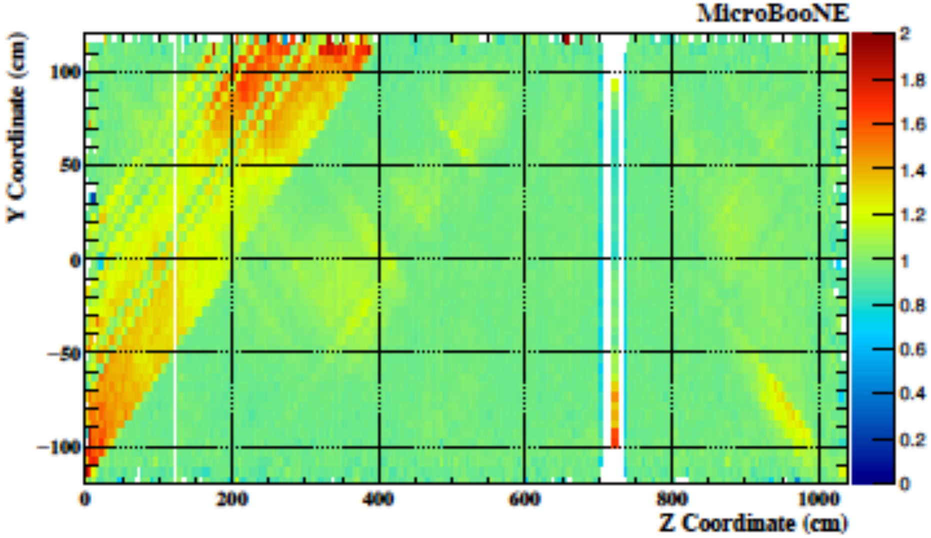
temperature

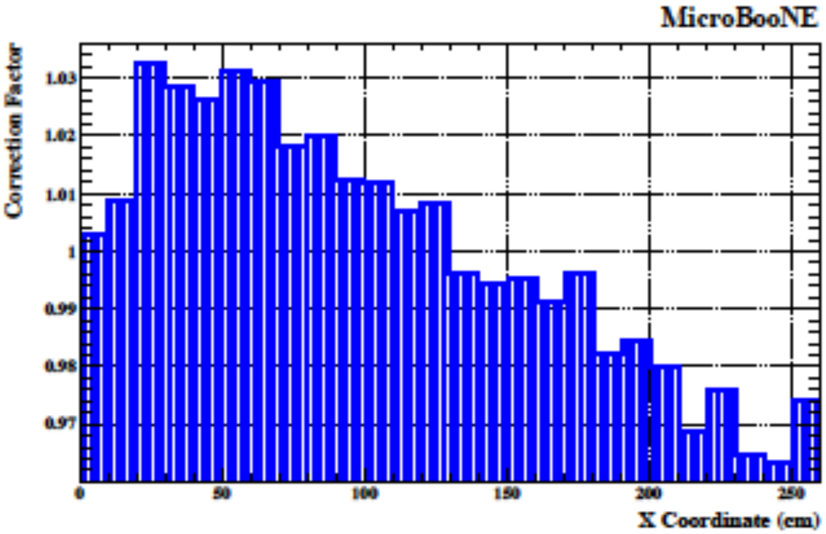


impurities



Overall calibration (MicroBooNE)





[arxiv: 1907.11736]

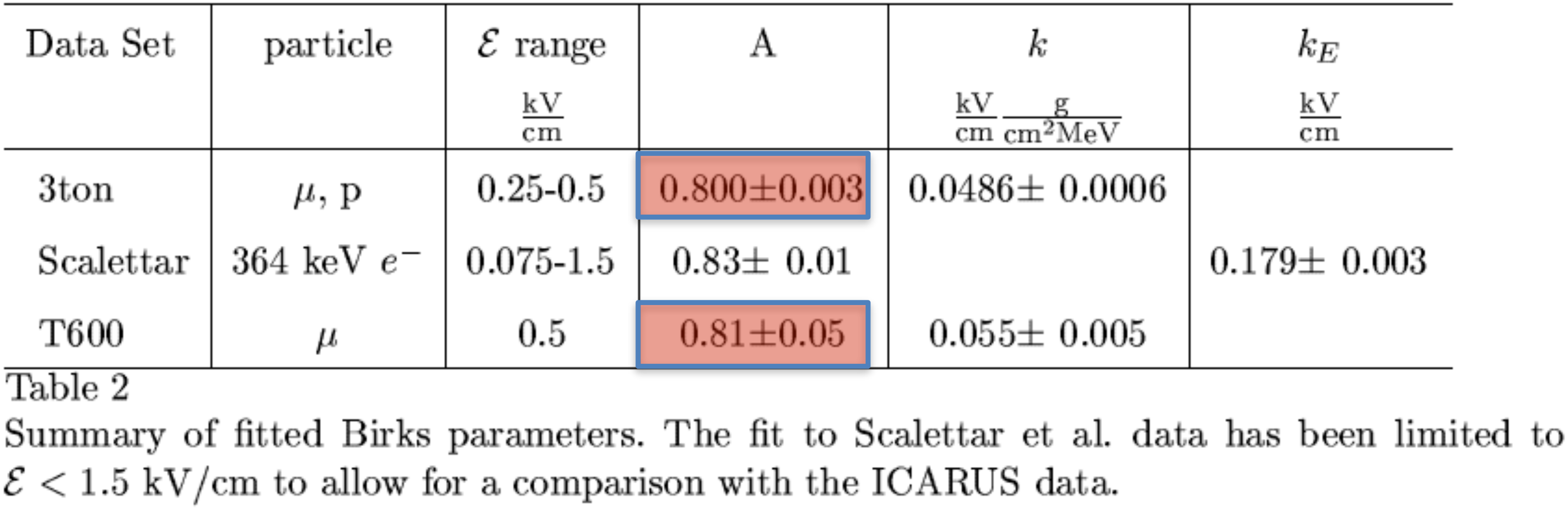
- Overall response maps with 2% precision
  - using anode-cathode crossing cosmic ray tracks for space charge and lifetime
  - protons for recombination and energy response
- Very fine granularity in time [daily] and space variations [10x5x5 cm (X, Y, Z)]
  - Should take much, much longer to do with underground muons

Recombination measurements (cosmics)

S. Amoruso et al. (ICARUS Collaboration), Study of electron recombination in liquid argon with the ICARUS TPC, NIMA 523, 275-286 (2004), https://doi.org/10.1016/j.nima.2003.11.423

ICARUS

$$Q = A\frac{Q_0}{1 + k/\mathcal{E}\frac{dE}{dx}}$$



Data Set	particle	$\mathcal{E}$ range $\frac{\text{kV}}{\text{cm}}$	A	k $\frac{\text{kV}}{\text{cm}}\frac{\text{g}}{\text{cm}^2\text{MeV}}$	k_E $\frac{\text{kV}}{\text{cm}}$
3ton	μ, p	0.25-0.5	0.800±0.003	0.0486± 0.0006	
Scalettar	364 keV e^-	0.075-1.5	0.83± 0.01		0.179± 0.003
T600	μ	0.5	0.81±0.05	0.055± 0.005	

Table 2

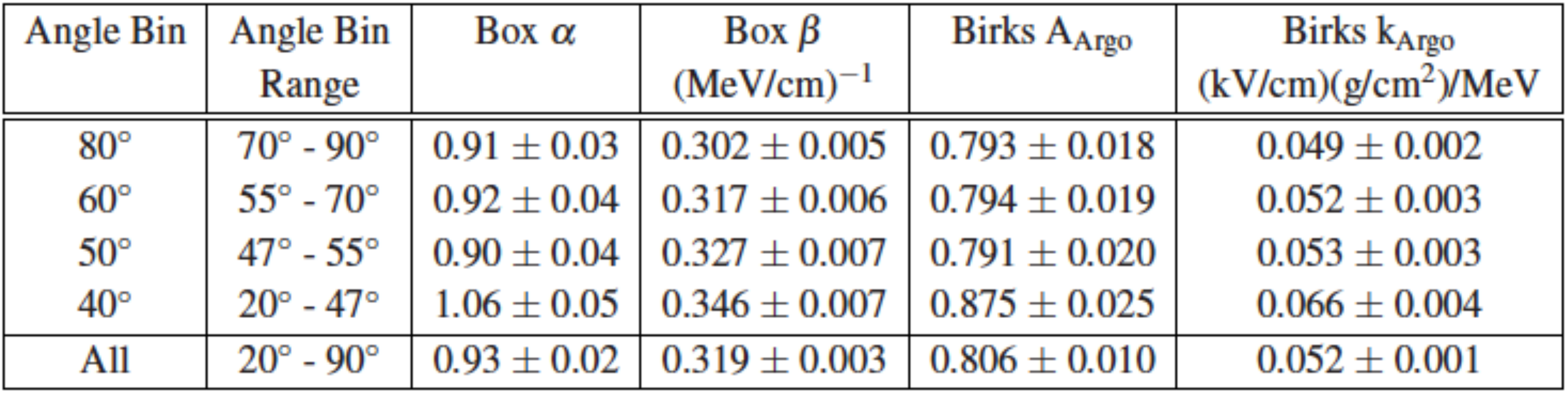
Summary of fitted Birks parameters. The fit to Scalettar et al. data has been limited to $\mathcal{E} < 1.5$ kV/cm to allow for a comparison with the ICARUS data.

- 3 ton prototype: 0.4% precision on A, 1.2% on k
- 600 ton: 6.2% precision on A, 10% on k

Recombination measurements (cosmics)

ArgoNeuT arXiv:1306.1712v1

$$dE/dx = \frac{dQ/dx}{A_B/W_{ion} - k_B \cdot (dQ/dx)/\mathscr{E}}.$$



Angle Bin	Angle Bin Range	Box α	Box β $(\mathrm{MeV/cm})^{-1}$	Birks A_{Argo}	Birks k_{Argo} $(\mathrm{kV/cm})(\mathrm{g/cm^2})/\mathrm{MeV}$
80°	70° - 90°	0.91 ± 0.03	0.302 ± 0.005	0.793 ± 0.018	0.049 ± 0.002
60°	55° - 70°	0.92 ± 0.04	0.317 ± 0.006	0.794 ± 0.019	0.052 ± 0.003
50°	47° - 55°	0.90 ± 0.04	0.327 ± 0.007	0.791 ± 0.020	0.053 ± 0.003
40°	20° - 47°	1.06 ± 0.05	0.346 ± 0.007	0.875 ± 0.025	0.066 ± 0.004
All	20° - 90°	0.93 ± 0.02	0.319 ± 0.003	0.806 ± 0.010	0.052 ± 0.001

Table 2. Summary of Birks and modified Box model fits for the proton sample.

Caveat: ArgoNeuT is small: 0.76 t

- Birks A: 1.2% precision overall, 2.2% individual measurements
- Birks k: 2% precision overall, 5% individual measurements
- Striking result: the dependence with angle is smaller than predicted (could be due to low purity)

Calibration Sequence 1/2

1. **Drift velocity/E-field/alignment**
    1. Dedicated fine-grained (10 cm) IoLaser scan dedicated to CPA/APA alignment, drift velocity and E-field mapping, as frequently as possible in each phase. PE laser scans in between.
    2. Use available cosmics to cross-check
    3. Use T sensors data and inspection camera (tilts?) to tune CFD and compare to measured maps
2. **Wire response and lifetime**
    1. The same data should be enough for wire response, lifetime (and diffusion) analysis, but should use drift/E-field corrections
    2. Again, cross-check with cosmics and ^{39}Ar.
    3. Take Pulsed Neutron Source data to cross-check lifetime

Calibration Sequence 2/2

3. Recombination

1. Use previous calibrations to calculate charge transport and collection corrections
2. Apply them to stopping muon (+ electrons, pions, protons) data sample MC and reconstruction
3. Use transport- and collection- corrected data and MC to determine recombination parameter uncertainties
4. Use laser data at low angle (w/r to field) for angular dependence cross-checks

4. Energy scale and resolution

1. Take dedicated PNS and RSDS scans for energy response
2. Apply all the above corrections to simulation and reconstruction of relevant data samples (stopping muons, Michels, π^0, PNS, RSDS)
3. Estimate scale and resolution systematics by data/MC comparison