Calibration: Overview & Current Status

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DUNE FD Calibration Workshop
Fermilab

Calibration Needs

- Calibration quantities/needs span broadly across commissioning, operations, reconstruction, physics, and monitoring

Calibration parameters → High-level quantities

Calibration parameters

TPC response model
- t0 offset
- Recombination
- Drift velocity
- Electron diffusion
- Electron lifetime
- Electronics gain
- Ionization energy
- Electric field
- Electronics noise
- space charge
- …

Photon detector response
- t0 offset
- light yield
- gain
- noise
- timing
- …

High-level quantities

Systematics
- Energy bias
- Position bias
- Energy resolution
- Position resolution
- …

Efficiencies
- particle ID
- noise removal
- reconstruction
- …

Particle responses
- Charged hadrons
- neutrons
- low-energy muons
- …

Standard Candles
- Michel electrons
- Pi0 mass peak
- …

- Spatial/temporal variation?
- *Non-trivial correlations*
- precision needs

- How to constrain? (*in-situ, ex-situ, ad situm*)
- Extrapolations from ex-situ?
- Past measurements
- Universal constants, calculable parameter,…

Calibration Sources

Beam induced & Atmospheric

- ν_μ *CC* events
- Stopped muons
- Stopped protons
- Michel electrons
- beam induced rock muons
- Muons from atmospheric neutrinos
- Muons from atmospheric neutrino-rock interactions
- Other decays (e.g. Kaons)
- Neutral pions
- …

Cosmic rays

- muons
- stopped muons
- APA-CPA crossers
- APA/CPA piercers
- Michel electrons
- Other decays
- …

Other

- Ar-39
- Ar-42
- Purity Monitors
- Temperature Monitors
- Current Monitors
- Past Experiments
- …

External Calibration systems one can consider

- Laser System
- Radioactive sources
- Photon Detector Calibration system
- Cosmic Ray Tagger (CRT)
- Field response calibration device

Note:
- Each calibration source comes with its own challenges
- Option of multiple ways to calibrate helps
- Past experiments: ***ICARUS, MicroBooNE, 35-ton, LArIAT, ProtoDUNEs etc.*** To what extent do can we rely on ProtoDUNE?

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T. Junk (today) *Cosmic rays*

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Proposed Calibration Systems

talk may focus more on SP

External Calibration Systems (currently considered)

- Laser (e.g. MicroBooNE, SBND)
- Photo-electron (Laser) Calibration System (e.g. T2K)
- Radioactive source Calibration
- Portable (external) Neutron source
- Photon Detector Calibration system
- Cosmic Ray Tagger (CRT)
- Field response calibration devices

- None of these systems currently exist as projects
- However, Feedthrough (FT) accommodations have been made for SP by the Task Force
- The potential calibrations systems should mitigate these risks and ensure the physics performance DUNE requires
- No luxury of cosmics at DUNE

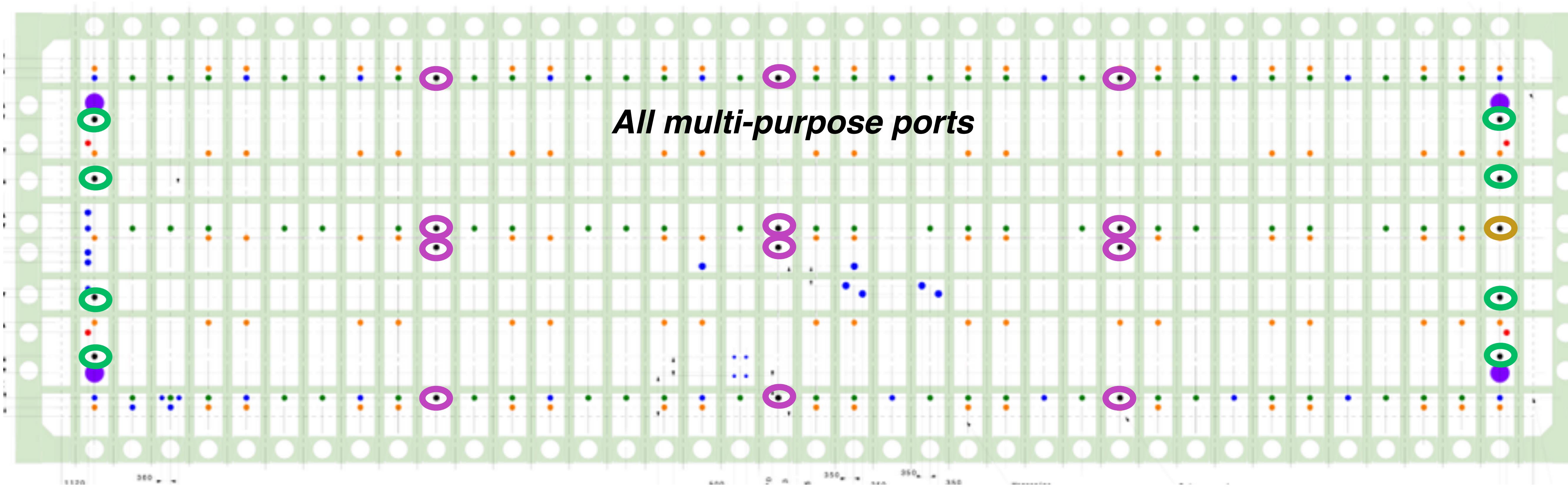
Calibration Feedthroughs (Single Phase)

= Calibration FTs

= Calibration FT (outside the FC)

= Cryogenic Instrumentation FT

Full volume calibration of E-field map and associated diagnostics (e.g. HV) requires crossing tracks



Pos.	Diameter [mm]	Quantity	Description
1	Ø250	100	Support
2	Ø250	75	Cable
3	Ø250	4	High voltage
4	Ø250	21	Instrumentation
5	Ø800	4	Manholes

Laser FTs (Magenta & Green) every 14 m or so. 10 m laser range demonstrated in MicroBooNE.

Proposed Calibration Systems

All talks on Thursday

External Calibration Systems (currently considered)

- Laser (e.g. MicroBooNE, SBND) **K. Mahn**
- Photo-electron (Laser) Calibration System (e.g. T2K) **K. Mahn**
- Radioactive source Calibration **J. Reichenbacher**
- Portable (external) Neutron source **R. Svoboda**
- Photon Detector Calibration system **Z. Djuricic (SP); C. Cuesta (DP)**
- Cosmic Ray Tagger (CRT) **J. Klein**
- Field response calibration devices **Not discussed**

The next slides will give a *brief* overview of where things stand w.r.t. these systems and existing sources

Proposed Calibration Systems: Key questions/concerns

All talks on Thursday

External Calibration Systems (currently considered)

- Laser (e.g. MicroBooNE, SBND) **K. Mahn**
- Photo-electron (Laser) Calibration System (e.g. T2K) **K. Mahn**
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- Field response calibration devices **Not discussed**

We have collected key questions/concerns from the collaboration over February and will discuss those in the allotted talks: https://docs.dunescience.org/cgi-bin/private/RetrieveFile?docid=7449&filename=Calib_KeyQuestionsConcerns.pdf&version=1

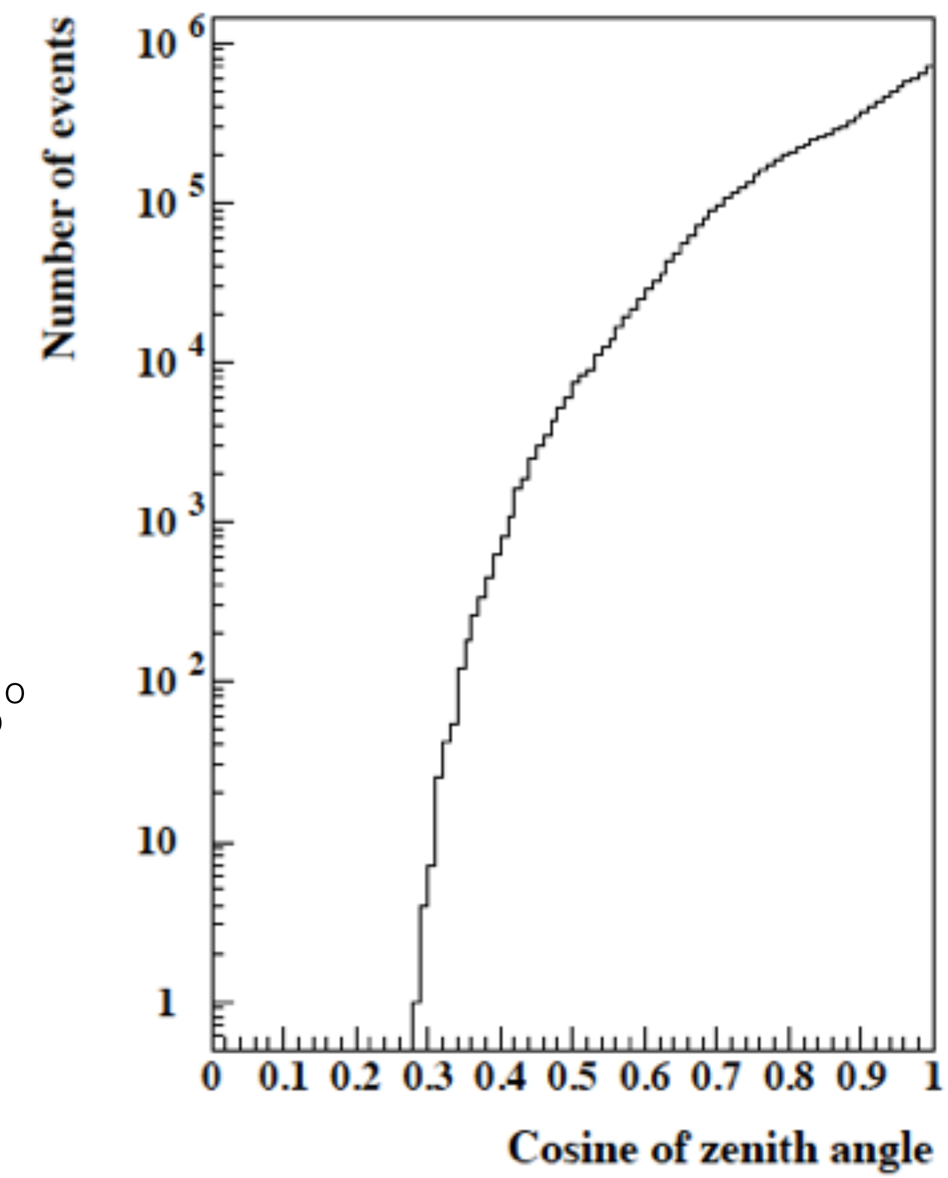
(Next talk, Kendall)

Muon Sources (see also backup)

- *Overall cosmic rate:* 4000 per day per 10 kt module
  - Vitaly*:* https://indico.fnal.gov/getFile.py/access?contribId=3&resId=0&materialId=slides&confId=14909
  - *Stopping muons:* 30/d/10kt
  - *APA-CPA crossers:* 200-500/d/10kt
  - Limited angular coverage: No muons at zenith angles >75^{o}

Tom will talk more this afternoon

Roughly, each collection plane wire is hit only every 2-3 days at best (assuming 100% efficiency and no geometry considerations)



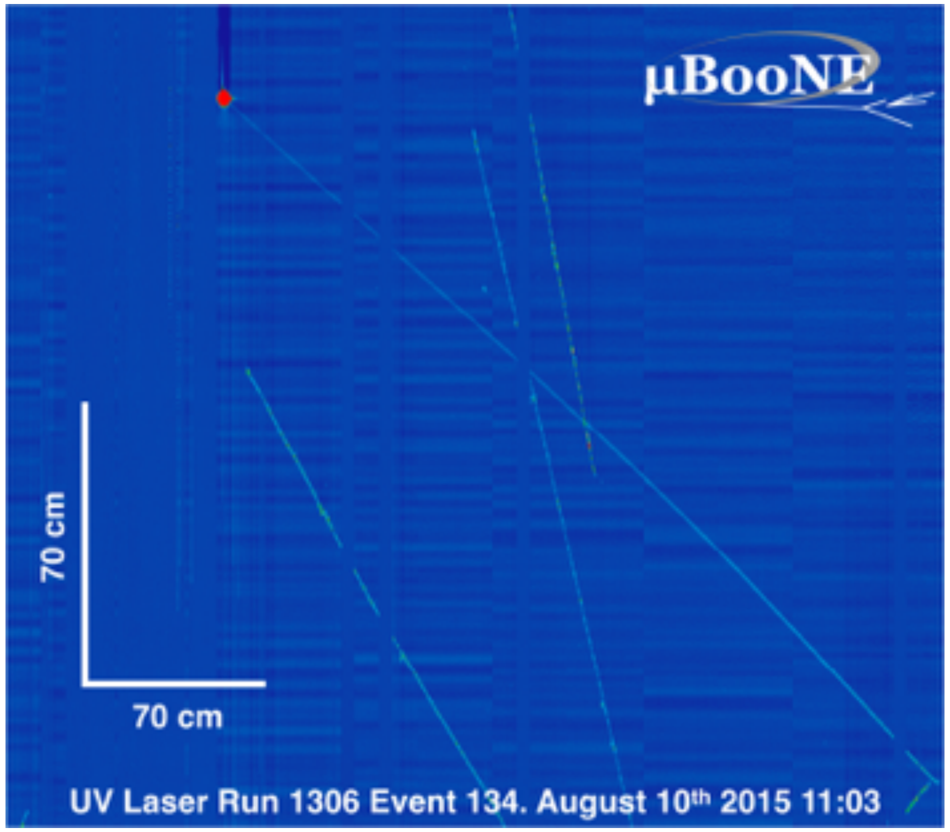
- *Beam induced rock muons:* 1 - 3/d/10kt
- *Atmospheric neutrinos:* Typically lower energy, MCS effects dominate
  - ICARUS saw 0.3 neutrinos/day (476 ton AV), implies 7/d/10kt for DUNE. Also muons from atmospheric ν - rock interactions.

Laser System

Kendall's talk tomorrow

- ***Two types of Laser:*** Ionization track (e.g. ***uB/SBND***) Vs. Photo-calibration (e.g. *T2K*)
- For the purposes of arguments here, the uB/SBND style Laser (see backup) is considered as the default design choice.
- Laser is useful in many ways:
  - Alignment, Stability Monitoring
  - Diagnosing failures *(need crossing tracks)*
  - E-field map *(need crossing tracks)*
  - ….

I. Kreslo
M. Weber



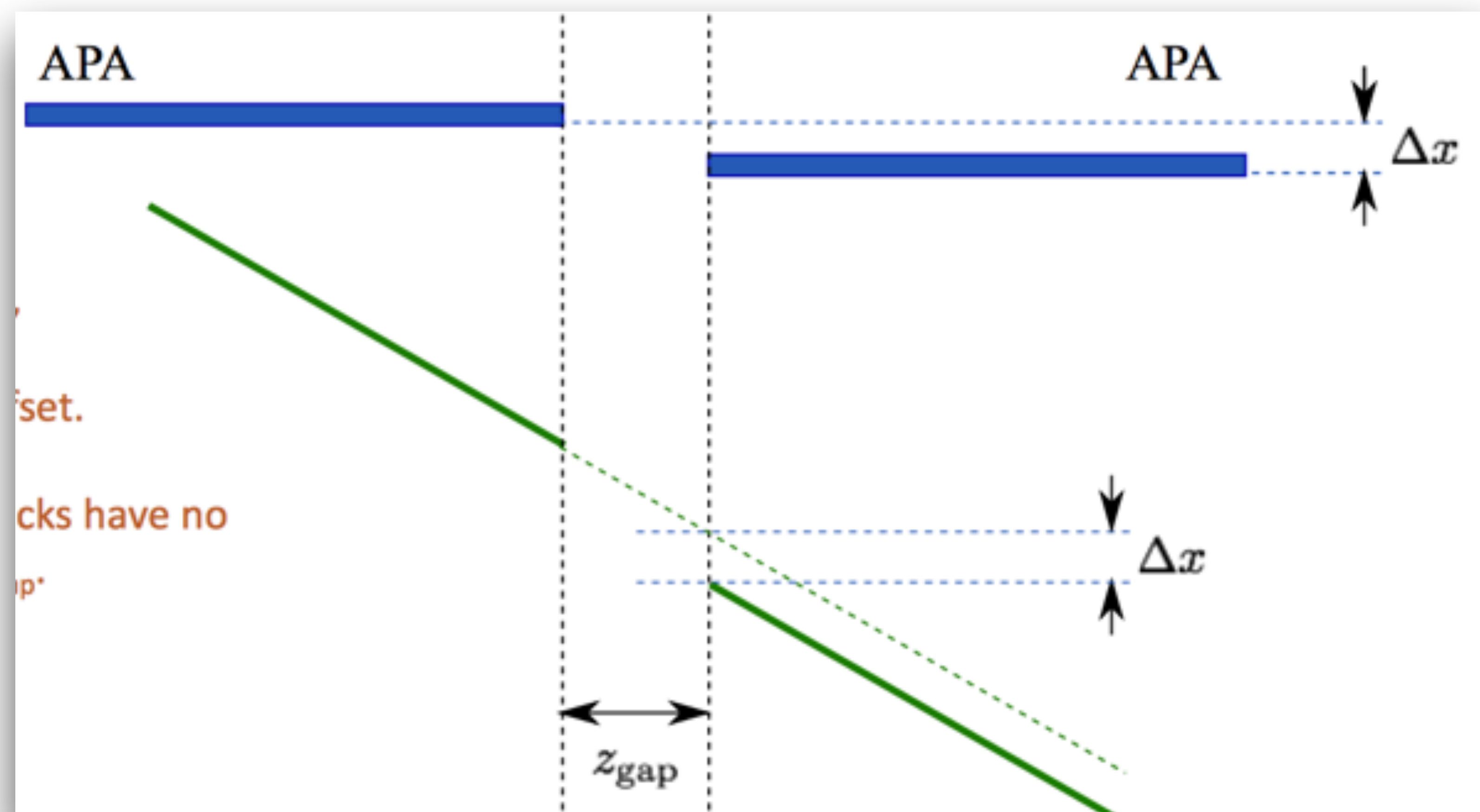
- ***Big picture of Cosmics vs Laser - specific cases in following slides***
  - Generally, while cosmics can be used to map the entire TPC volume, it will take few months to a year ***vs*** Laser on the scale of days. Some measurements are not possible with cosmics, especially related to mapping spatial effects.

Tom will talk more this afternoon

Alignment scale, issues

- *Alignment affects* drift distance, measurement of muon momentum from Multiple Coulomb Scattering etc.

- Mechanical changes during cool down can also affect *APA-CPA alignment; non-uniform gaps across APAs in the Z direction; motion of support structure*



APA-APA "local" alignment

- https://indico.fnal.gov/getFile.py/access?contribId=15&resId=0&materialId=slides&confId=14909 (35-ton)

- 35-ton saw Δx, Δz ~3mm at precision of 0.05mm -

- Laser has comparable precision (sub-mm) and can provide range of angles

Diagnosing failures & stability monitoring

- *Cathode flatness*

- *APA flatness:* APA frames can twist, modifying plane spacing which impacts transparency conditions between wire planes. Induction plane signals may only get partially to the collection planes. +/- 0.5 mm shift is correctable, but beyond that it is risky.

- *Failure of electronics to readout:* wait for cosmics to hit wire/region. *Other (preferred):* external charge injection, pulsing cathode etc.

- *Voltage variations across cathode:* unlikely event, but impossible with cosmics?

- You can use cosmics for most of this, but, questions to ask:

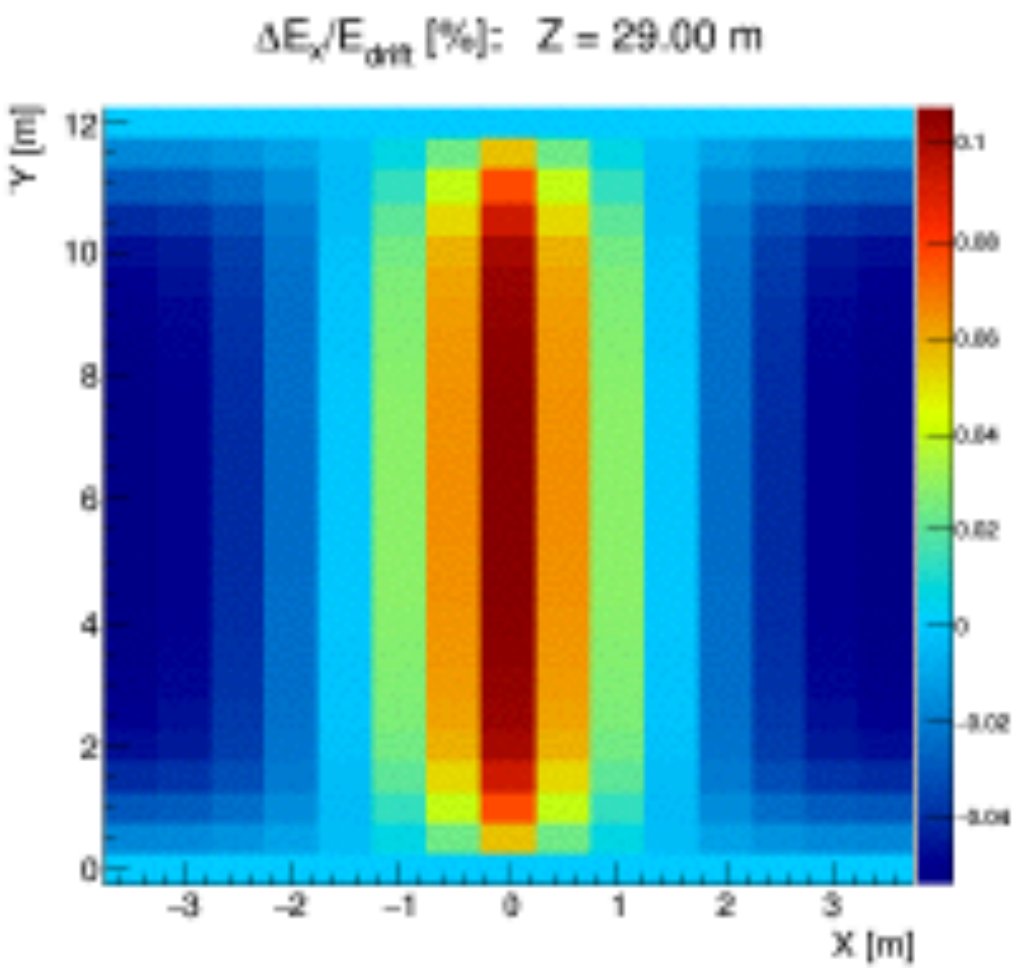
    - Are stability measurements from cosmics possible on a short timescale? (current estimation is No); Tests of spatial effects across whole detector are also (too) coarse

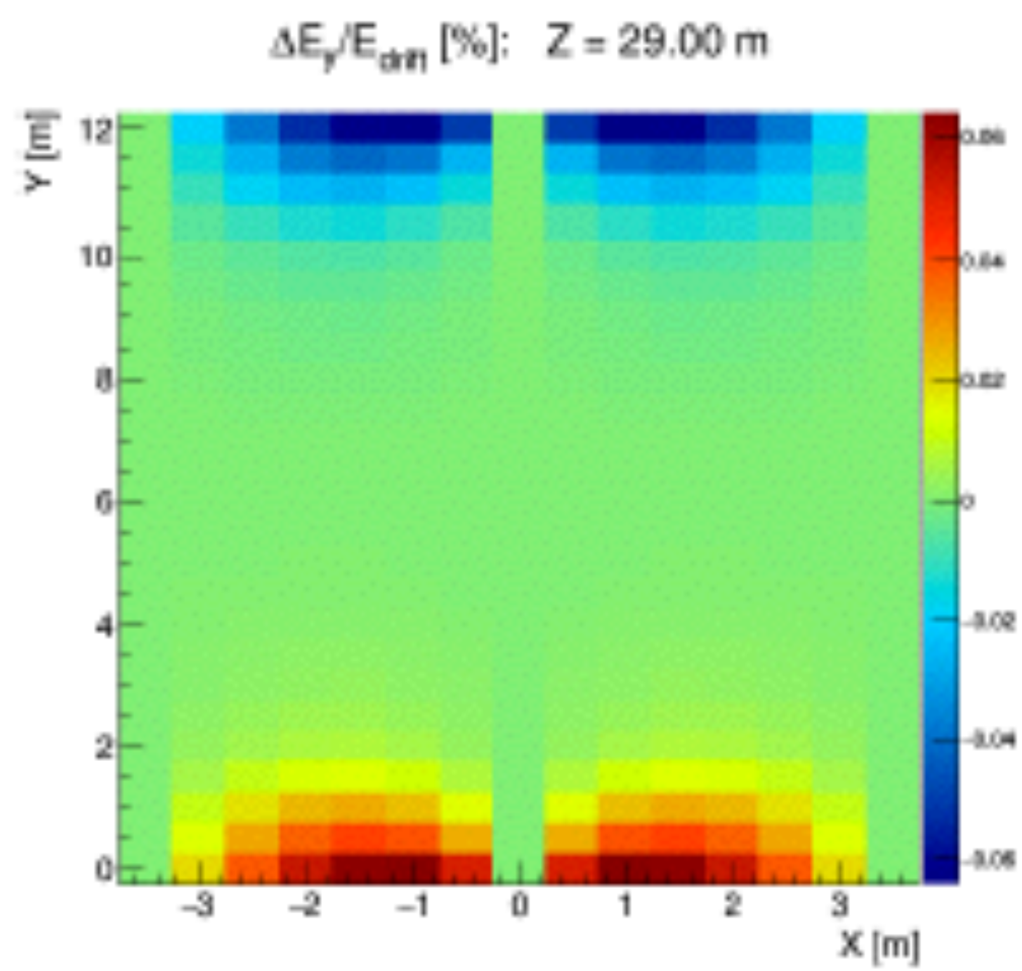
E-field distortions: Ionization sources

- Strong dependence of various calibration parameters on E-field (e.g. Recombination, drift velocity, track distortions,…)
- ***E-field distortions from Ionization sources (Cosmics, Ar-39, Ar-42,..)***
  - https://indico.fnal.gov/event/15245/contribution/0/material/slides/0.pdf
  - *Space charge from Cosmics for SP/DP:* negligible!
  - *Space charge from Ar-39 for SP:* small, but not negligible
    - E-field distortions: 0.1%; dQ/dx ~0.03%
    - Spatial distortions: 1.0 to 1.5 mm; dQ/dx <0.1%
  - *Space charge from Ar-39 for DP:* not small, will need calibration
    - E-field distortions: 1.0%; impact on dQ/dx < 0.3%
    - Spatial distortions: 5 cm; impact on dQ/dx 2 – 3%

- *Fluid flow can complicate all this: turbulent (uB) or static (35-ton)*
- *Effect even more complicated for DP due to liquid-gas interface*

SCE for DUNE SP FD





- DUNE SP FD – looking at one half of central Z slice
  - APA+CPA+APA
- E field distortions on order of **0.1%** – very small!
  - Impact on dQ/dx from recombination ~ **0.03%**

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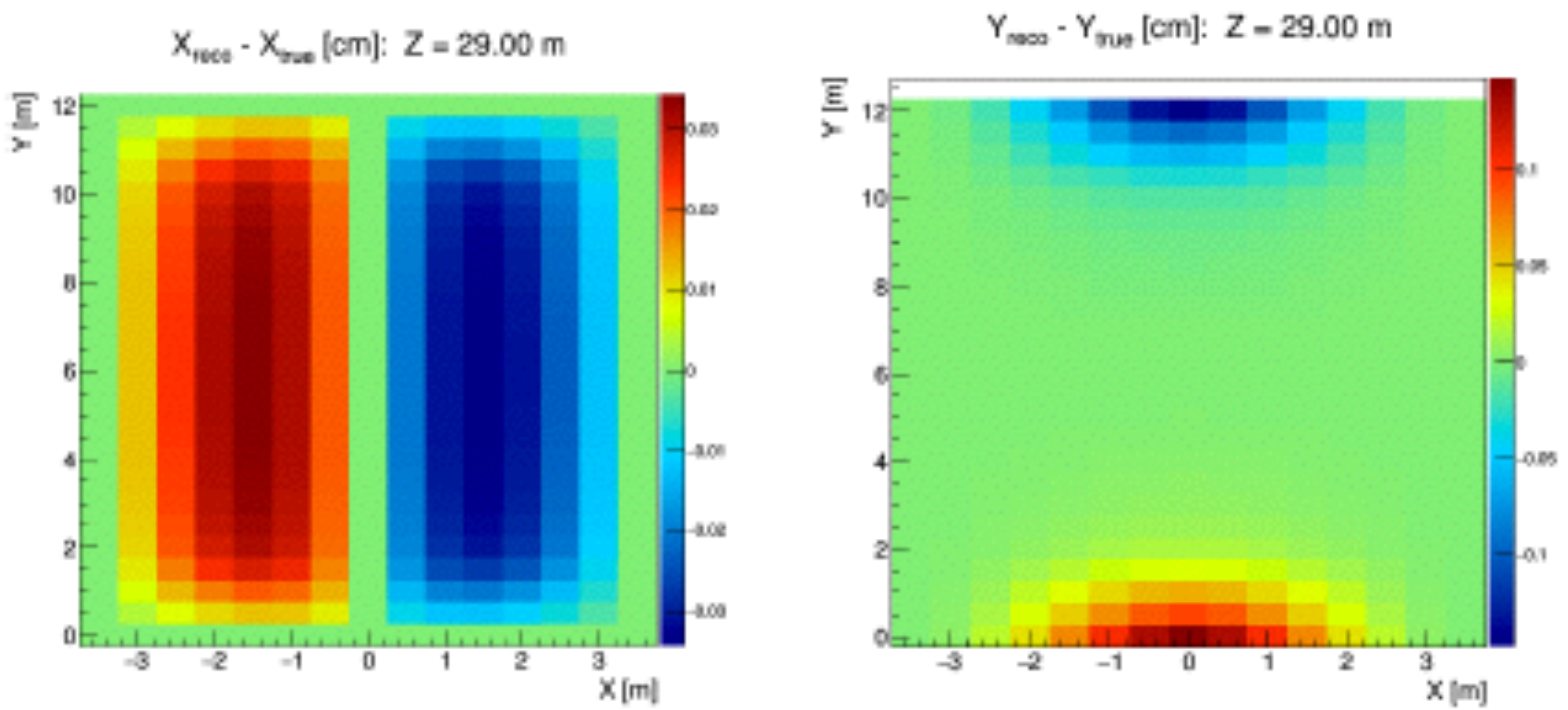
M. Mooney

SCE for DUNE SP FD (cont.)



- DUNE SP FD – looking at one half of central Z slice
  - APA+CPA+APA
- Spatial distortions on order of **1.0-1.5 mm** – very small!
  - Total impact on dQ/dx (including recomb.) **< 0.1%**

M. Mooney

E-field distortions

B. Yu

https://indico.fnal.gov/event/15245/

Drift field deformations that can impact E-field

- Resistor failure across the FC (E-field distorts 3 to 5 kV)
- CPA misalignment
- CPA structural deformations (e.g. CPA plane bows)
- Resistivity on dividers not uniform, sorting order:
- Penetrating FC for Laser (SBND example)
- APA/CPA offsets, voltage variations in cathode,…

- Many individual deformations lead to small variations within 1% E field distortions. But these effects can add in quadrature and get significant
- *Valuable to have an independent measure of the E field (e.g. Laser) to diagnose location and confirm size of correction.*

TPC Calibration

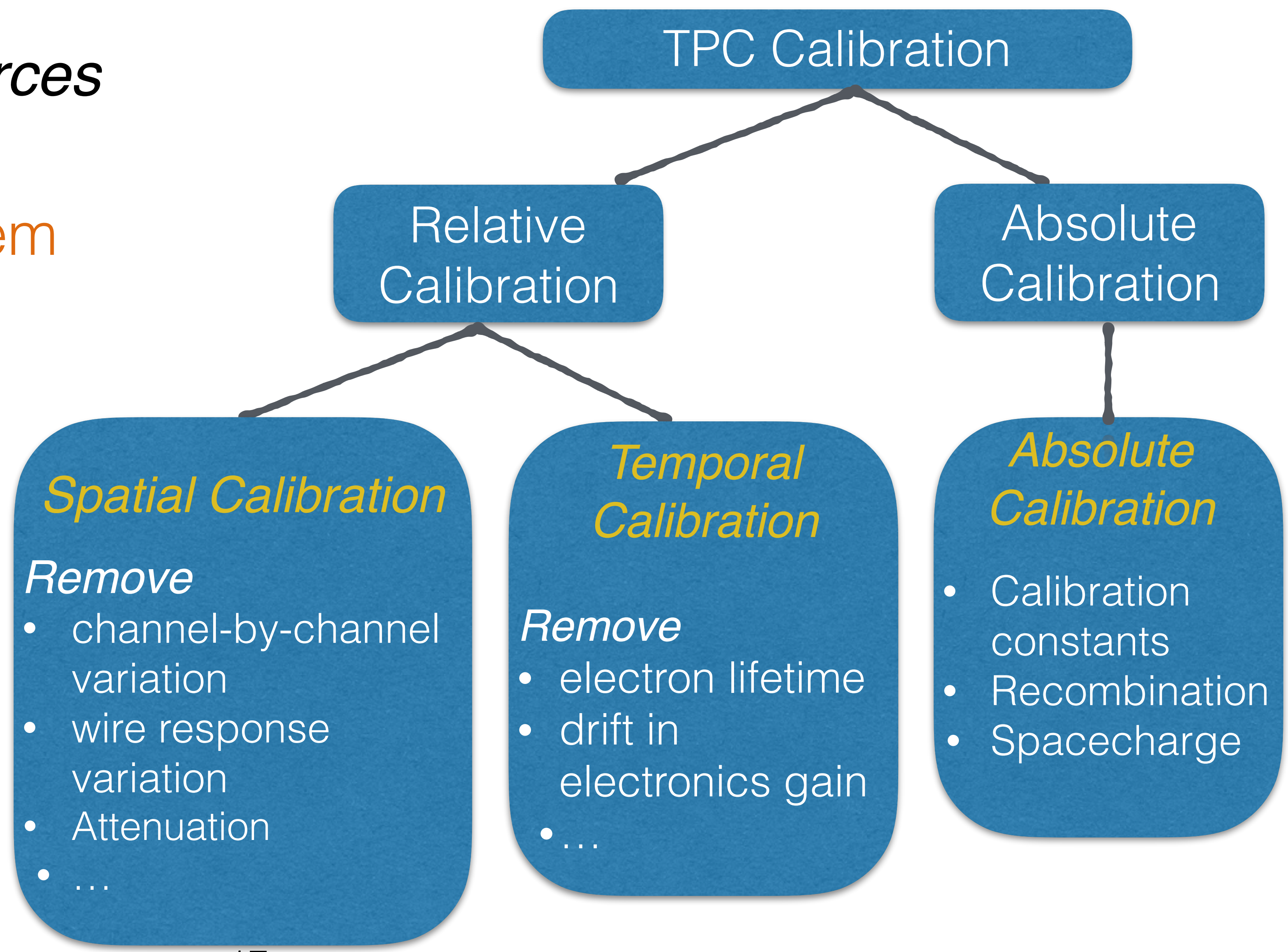
Goal: Achieve uniform detector response in space and over time and provide reliable energy information for physics analyses

Possible Calibration sources

- Charge Injection System
- Cosmic muons
- Laser system

https://indico.fnal.gov/event/15240/contribution/1/material/slides/0.pdf

T. J. Yang

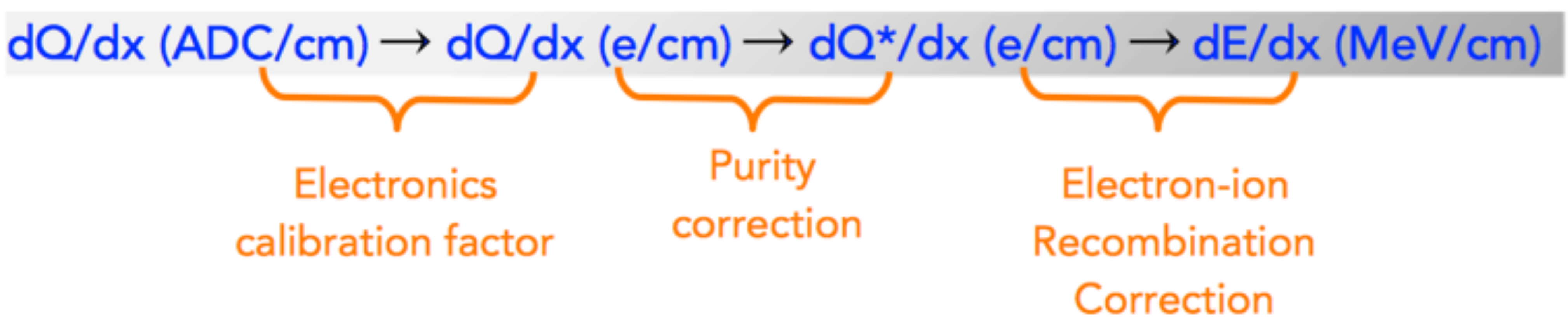


TPC Spatial calibration

- *Channel-by-Channel Calibration:* remove gain variations
  - Can use charge injection system to remove gain and linearity of each channel; uB: 1-2% variation. Laser useful here
- *Wire response Calibration:* non-uniformity in response due to shorted/touching wires
  - Cosmics — statistically challenging for DUNE to do this; Laser can be very helpful here
- *Attenuation Calibration:* Attenuation along drift due to impurities
  - uB saw excellent purity, measurement using cosmic ray Anode-Cathode crossers
  - One can combine all cosmic rays for this calibration
  - Laser system is potentially good for this calibration (arXiv:1304.6961)
  - Another potential source: Ar-39

Absolute Energy Calibration

- Once spatial effects are removed, use cosmic rays or laser (if response well understood) to remove temporal variations
- Absolute energy calibration (convert dQ/dx to dE/dx)



- Standard handle: Stopping muons
- Can combine stopping muons over several months or a year to get needed statistics. Laser partially helpful
- Many other issues: angular dependence of dQ/dx; dE/dx separation b/n tracks and showers at the start; reconstruction vs detector/physics effects,…

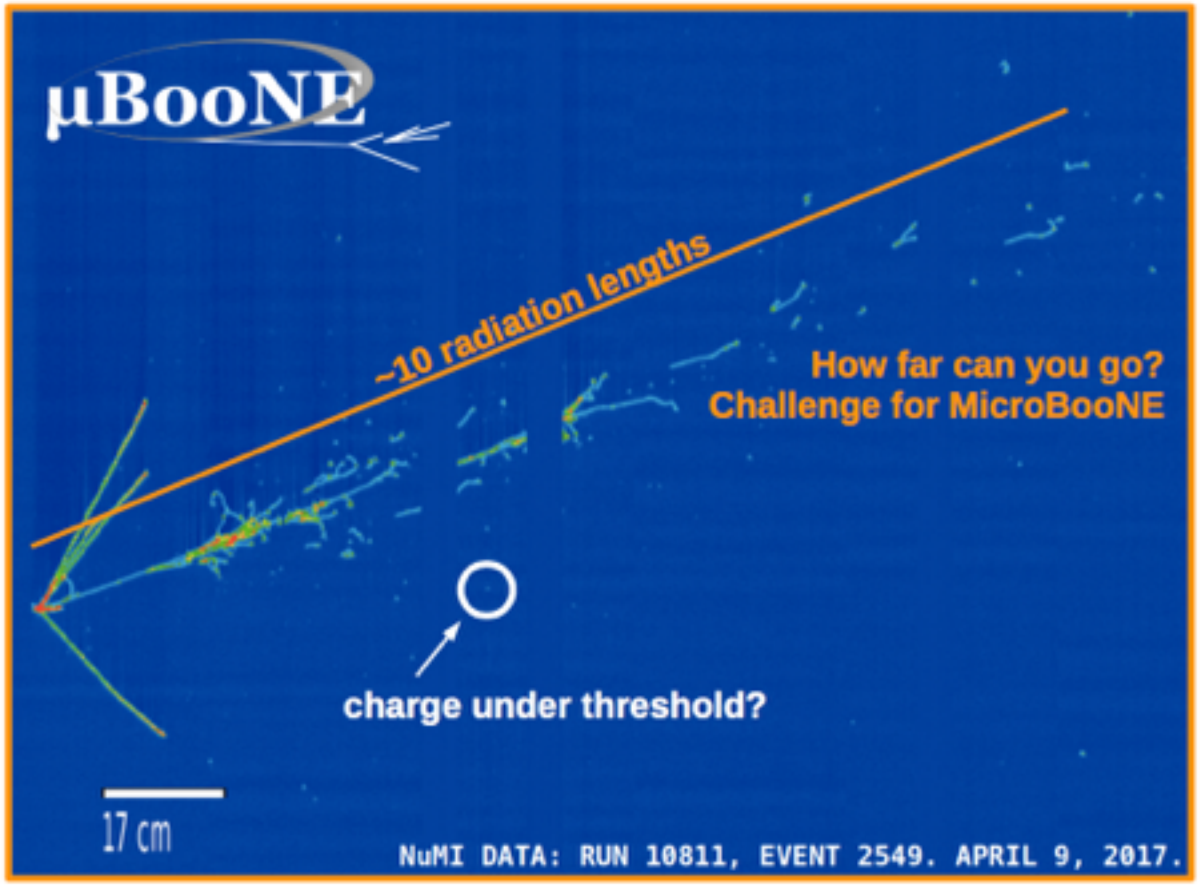
Calibrating EM Response

Measuring e^- from ν_e activity with good energy resolution a necessity for both MicroBooNE and DUNE.

Absolute calibration of EM activity more complex then for tracks.

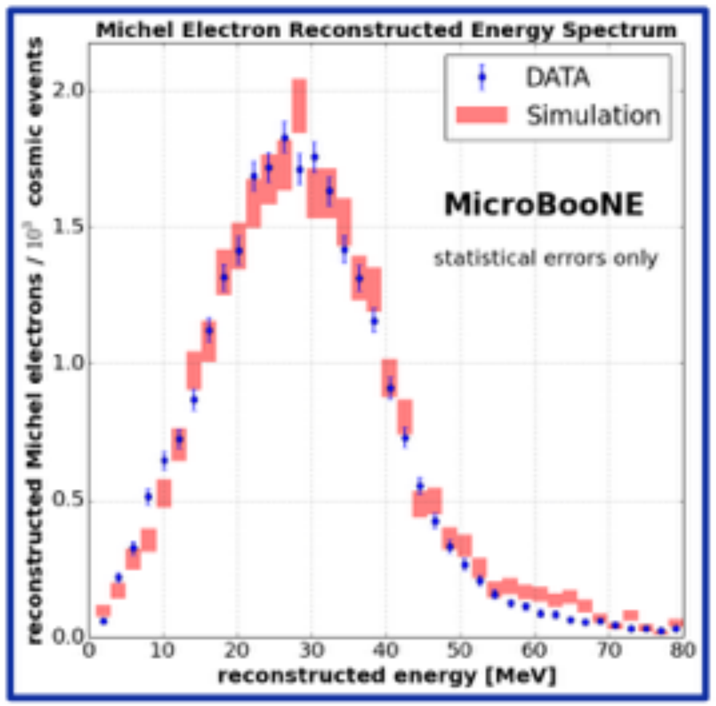
- cannot rely on accurate range measurement.
- Deficient energy measurement which must be corrected.
- Shower topology makes calibration harder.

More heavily rely on simulation → need to test simulation.



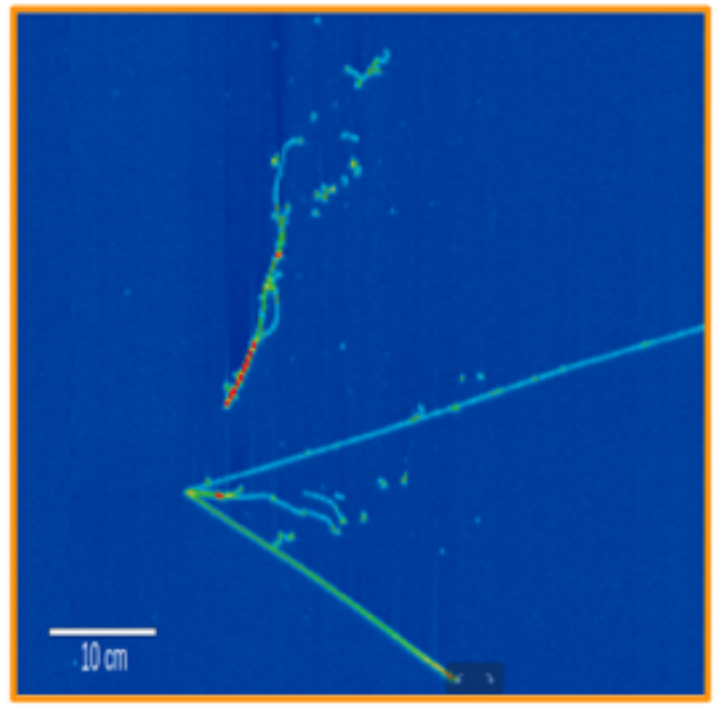
Calibrating EM Response : Sources

JINST 12 P09014 (2017)



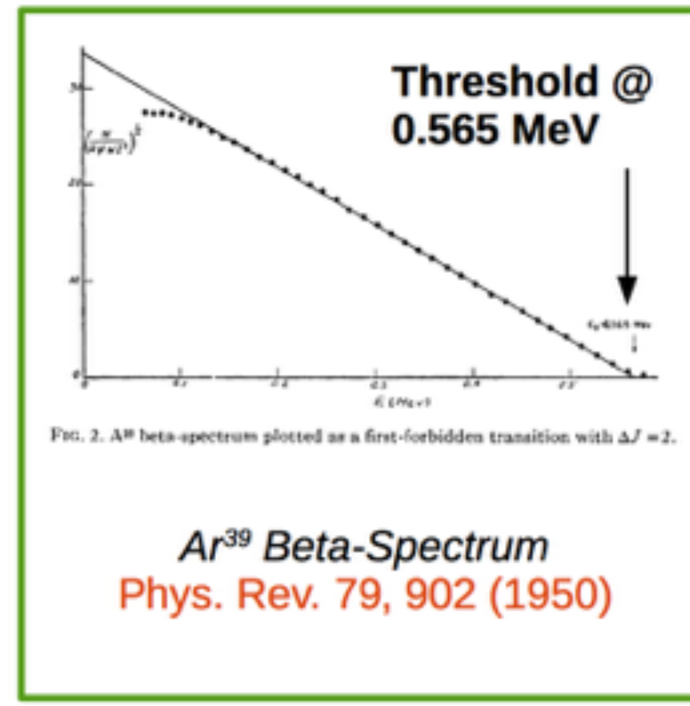
Michel electrons [0-50 MeV]

- SNB/LE physics.
- study radiative losses.
- broad spectrum → not a calibration.



$\pi^0 \rightarrow \gamma\gamma$

- Invariant mass peak.
- broad & interesting energy range.



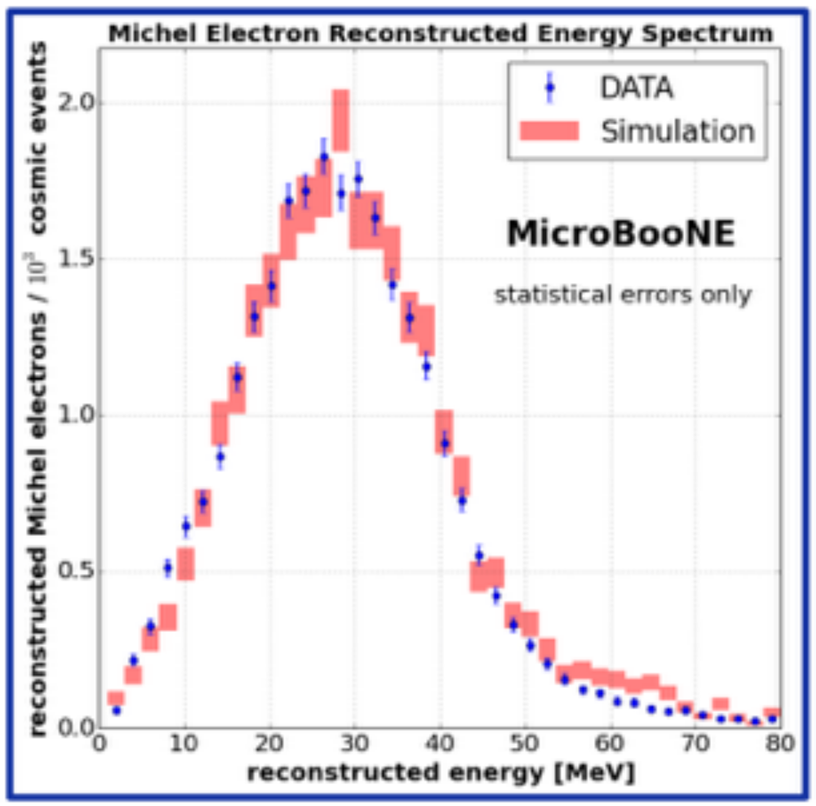
Ar^{39}

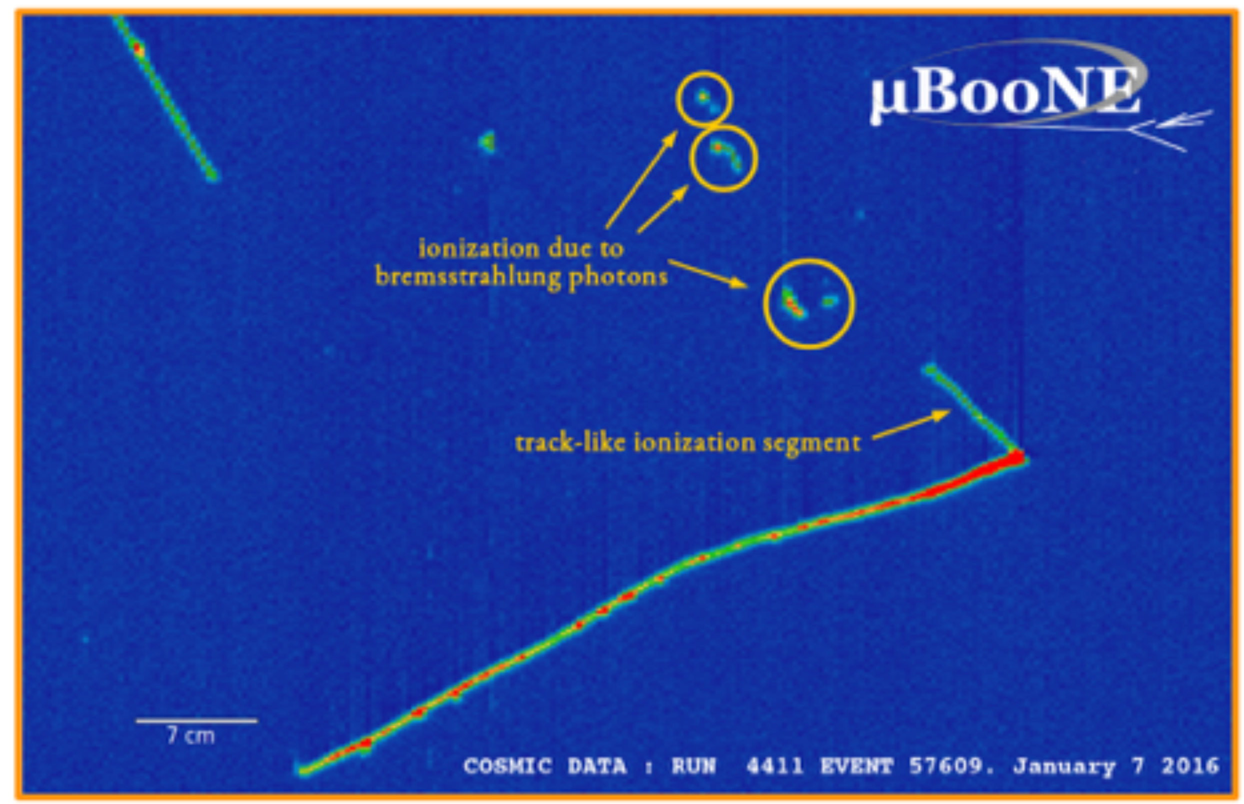
- Threshold studies.

What sources are lacking: 1) fixed-energy (radioactive) sources. 2) sample of 100 MeV – 1 GeV electrons.

Experience with Michel Electrons

Michel Electron Reconstruction Using Cosmic-Ray Data from the MicroBooNE LArTPC
[JINST 12 P09014 (2017)]





Reconstructed spectrum deficient due to escaping charge:

1) thresholding 2) clustering.

~20% energy resolution.

Spectrum encompasses e- critical energy.
→ interesting EM topology, complex reconstruction.

First study of radiative photons from tens-MeV e- in LArTPC.

More useful to study EM activity then to calibrate energy-scale.

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- Past experiments: ICARUS, MicroBooNE, 35-ton, LArIAT, ProtoDUNEs etc. To what extent do can we rely on ProtoDUNE?

Low-energy calibration

J. Reichenbacher, R. Svoboda

- *Motivation:*
  - Calibrate the energy response in the SNB region (e.g. validate light yield response/model (light yield, timing response, measured charge etc.) and electron lifetime,…)
- *Multiple ways to approach*
  1. Direct activation of Argon (e.g. D+T→n+4He ; E_n =14.1 MeV; inside Super-K; outside SNO and SNO+)
  2. External Radioactive Source Deployment (e.g. 58Ni-252Cf source emits E_γ=8-9 MeV — right range)
  3. Portable Neutron source generator (DD generator) Supernovae energy reconstruction requiring detection of neutron capture by measuring gamma cascades
  4. Can also use Michel electrons (~50 MeV range) but not as useful for calibrating responses ~10 MeV and below. A ***well-defined*** Radioactive source system will do well here
- Risks involved in both 1 (e.g. unintended products) and 2 (e.g. source getting stuck); careful assessment needed

 lot of active discussions/work recently

Photon Detector Calibration (SP)

- *Motivation*

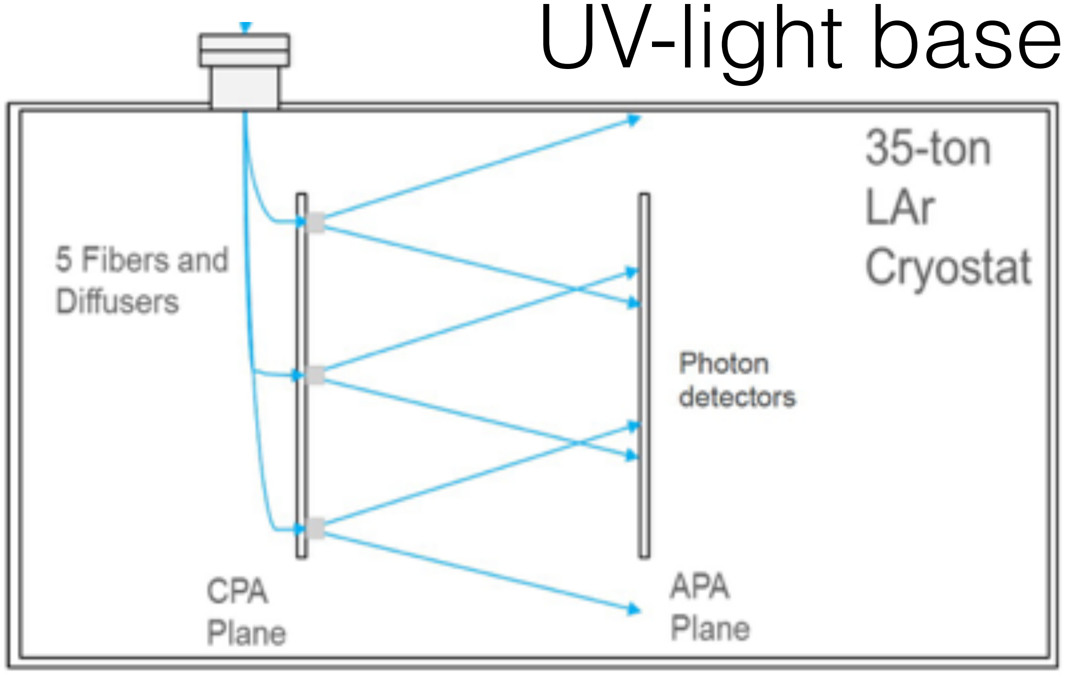
R. Dharmapalan, Z. Djurcic

  - https://indico.fnal.gov/getFile.py/access?contribId=3&resId=0&materialId=slides&confId=15243
  - Verify photon gain monitoring and timing resolution;
  - Monitor stability and response over time
  - Useful during commissioning (before detector is filled with LAr) to test photon detectors
  - Provides a quick reliable test of Photon system when a change is made. Don't have to wait for cosmic muon coverage over the entire detector.

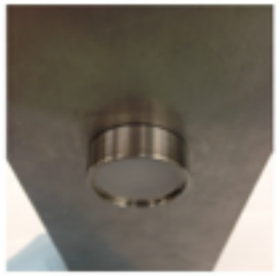
work being carried out within the SP-PDS consortium

- In DUNE 35t performance of various photon detectors was tested
- Plan to use ProtoDUNE to optimize the requirement for DUNE PDS calibration system

UV-light based



Diffusers



Cosmic Ray Tagger System (CRT)

(Josh Klein, Richard Diurba)

- *What would a CRT buy us?*
    - Independent (from TPC) beam-like tests of reconstruction and PID
    - Independent definition of *t0*
    - Test field map from laser in regions not illuminated well
    - Cosmics are sparse, overall less ambiguity (compared to a surface detector) on *t0.* But, PDS to TPC calibration on a short time scale might have issues given the low cosmic ray rate.
    - Light from Ar-39 *might* impact *t0* tagging; Highly unlikely, but need to prove
- *Diagnosing failures*
    - Drift field distortions (space charge, detector deformations etc.) might add up and displace cosmics. CRT can give additional handle
    - In the case of a FC resistor failure, CRT can be handy as one knows where exactly the comics went resulting in location tagging for where the failure happened

Cosmic Ray Tagger System (CRT)

(Josh Klein, Richard Diurba)

- *Where to put the CRT? Need to get biggest bang for the buck*
  - Probably little value on sides (cosmics angular coverage bottleneck)
  - Most useful in the front for both cosmics & dirt muons and/or put in regions where laser has limited coverage
  - How useful are dirt muons and how far can they travel?
  - Reuse old counters (e.g. MINOS)?
  - Pixel size? Understand space around the cryostat? Ongoing
- *January Collaboration meeting input*
  - Folks still skeptical of motivations for the CRT
  - General feedback: something more small scale and portable will be more beneficial

Closing Thoughts

- More details/discussions on each topic in dedicated talks
- We will discuss key questions & concerns as we go through the talks
- Keep in mind *SP vs DP differences* and think special considerations DP would require

Something to keep in mind

- The option of multiple ways to calibrate will be valuable especially given the low cosmic rates and non-trivial correlations b/n detector parameters
- Currently we have no independent probe for calibration and this can put our physics & operations at risk

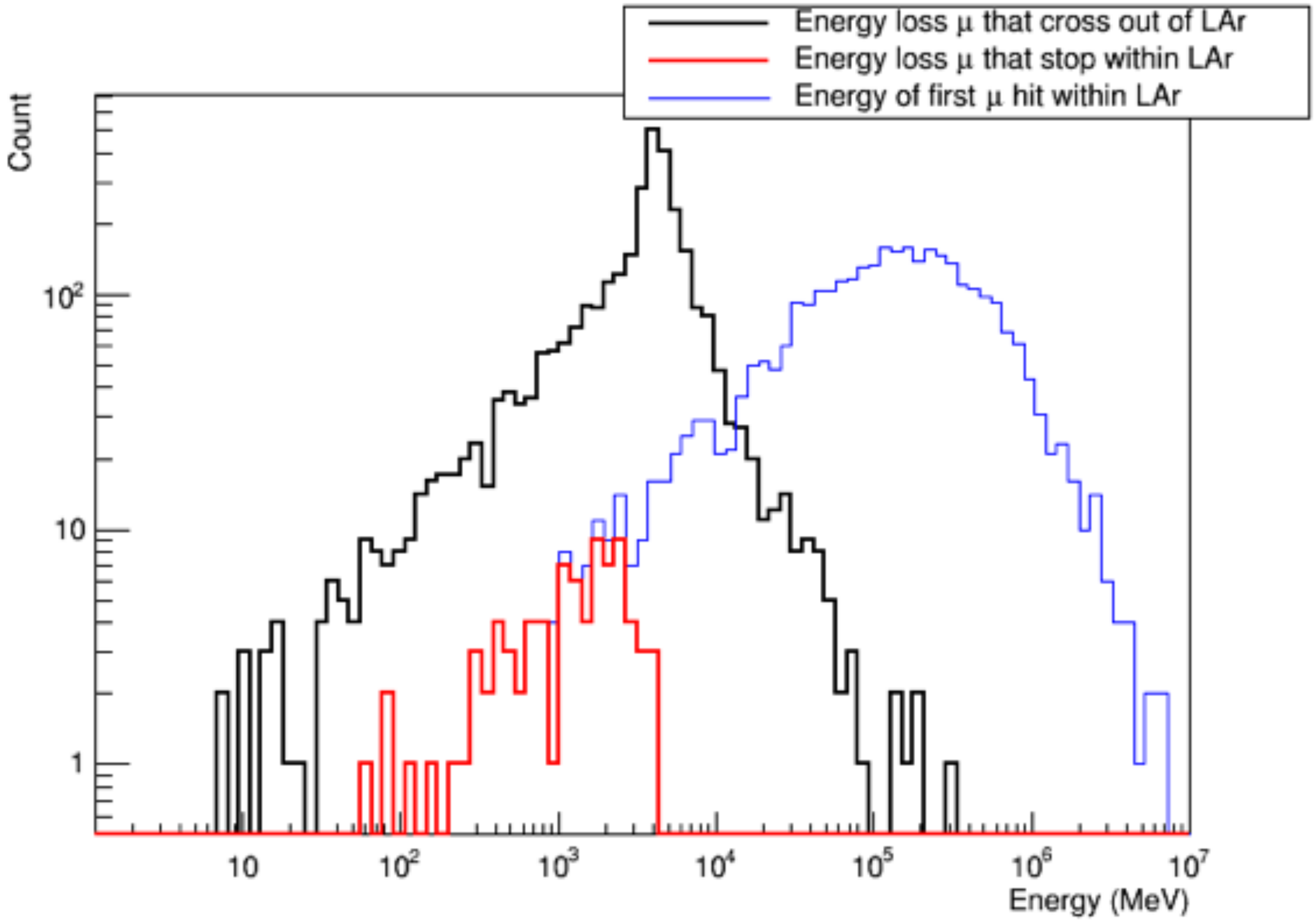
BACKUP

Cosmics Backup

Cosmics

V. Kudryavtsev

https://indico.fnal.gov/conferenceDisplay.py?confId=14909



Back of the envelope calculations

(showing collection wires are hit only 2-3/day)

- Assume 200 crossing tracks/day/10kt,
- Assume 1000 wires hit per cosmic.
- From CDR:
  - 384,000 wires/10kt cryostat => 380k/1000/200=2
- Roughly implies 2 days to hit all wires.

Back of the envelope calculations
(of extrapolation of atmospheric neutrino rate from ICARUS to DUNE)

Atmospheric neutrino rate, scale up from ICARUS:

- ICARUS saw 1 neutrino per 3 days => 0.33333 nu per day
- ICARUS has 476 tons of active volume
- DUNE active volume for a 10kt detector is 10 kt which results in about 7 muons per day per 10 kt volume

Alignment Backup

T. Junk

Back of the envelope calculations

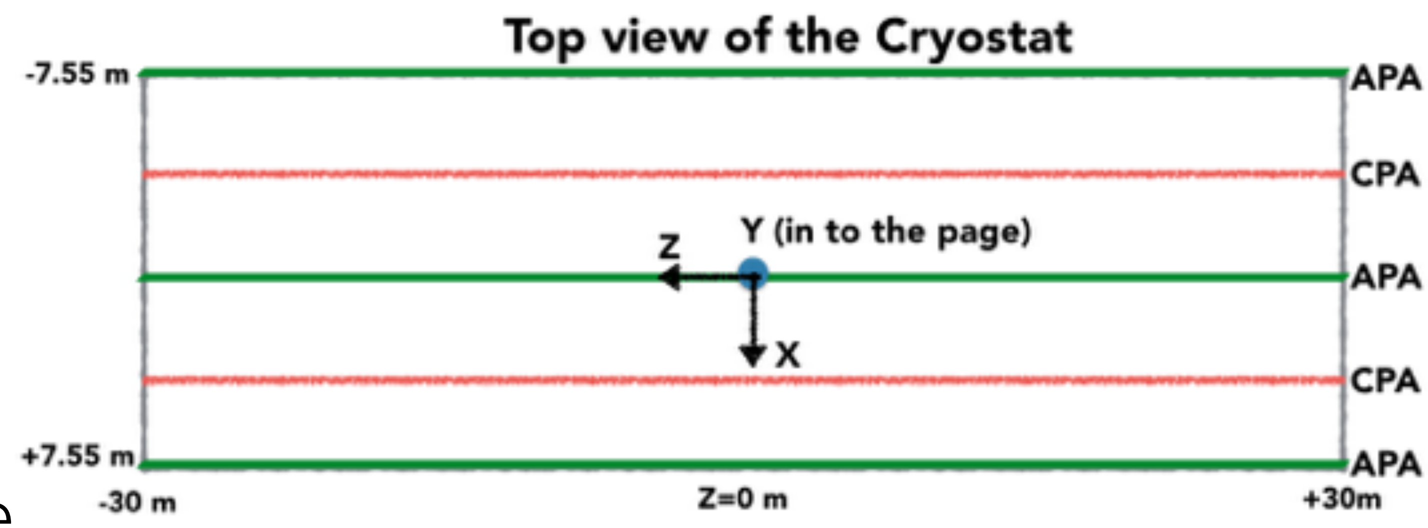
(of how many muons will pass through a vertical gap between two APA's)

"As a very crude estimate of how many muons will pass through the plane parallel to the (x, y) plane going through a vertical gap between two APA's is obtained by multiplying its area, 6 m × 3.6 m by the tangent of the average incident angle (divided by Sqrt(2) to get its projection in the (x, z) plane for a typical muon, and multiplying this by the number of muons per unit area per day. An additional factor of 0.5 is assessed on the area as parts of the plane close to the edges will in general leave too-short track segments on one side if the muon passes through them. With four muons per m2 per day, this results in 15 muons crossing each vertical gap per day. Folding in the no-shower and angle requirements, this gives approximately four useful muons per vertical gap per day."

Dune doc-db 5585, p. 5

Alignment during cool down

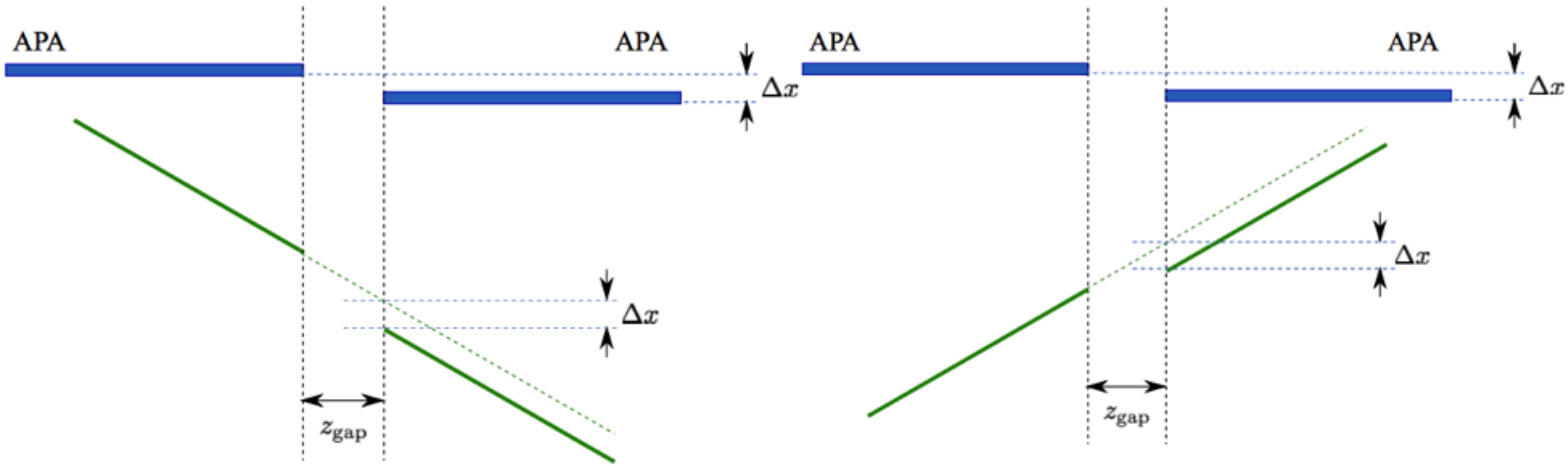
- *Mechanical changes during cool down:* (V. Guarino, J. Fowler)
  - *Δx (drift):* +/- 3mm before and after cool down; 7 mm due to bowing during cool down at half height of the CPA
  - *Δy (vertical):* 36 mm shrinkage



  - *Δz (beam direction):* about 180 mm shrinkage over the entire length (25 APAs results in 24 gaps with each gap around 2.32 m. Expect about 6.5 mm shrinkage in each gap. For 58 m length, results in about 180 mm)

(Tom Junk)

Need Tracks With + and - Angles



Need positive Δx or positive Δz to fix this track (really a combination)

Need positive Δx or negative Δz to fix this track (really a combination)

Alignment: Motion of Support Structure

- APAs hang from a support structure and frictions are involved; currently unpredictable as to how it impacts APA/CPA offsets
- Mechanical support of APA/CPA not on the same pitch, can also result in unpredictable gaps.
- Cool down shifts the support structure and may not agree with models/expectation

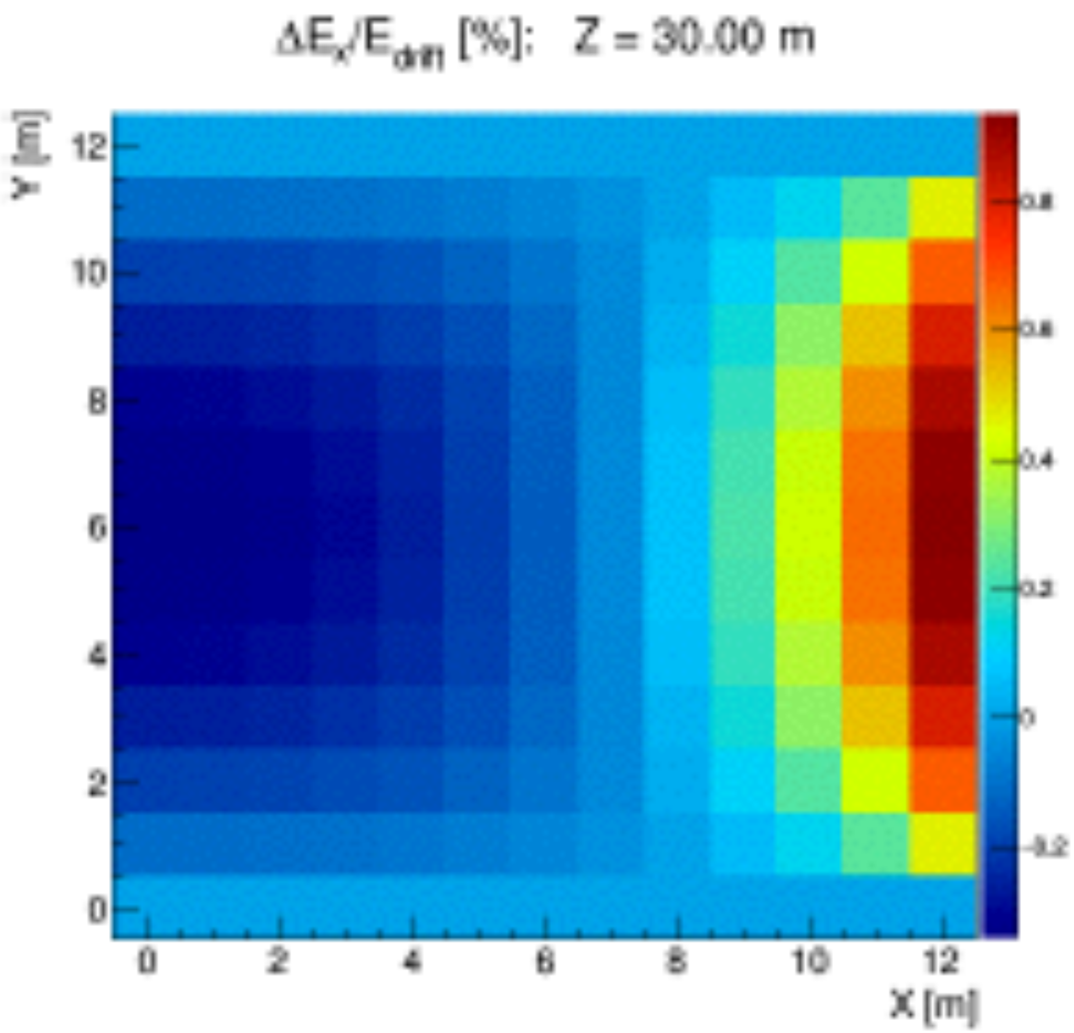
Stability & Failure diagnosis
Backup

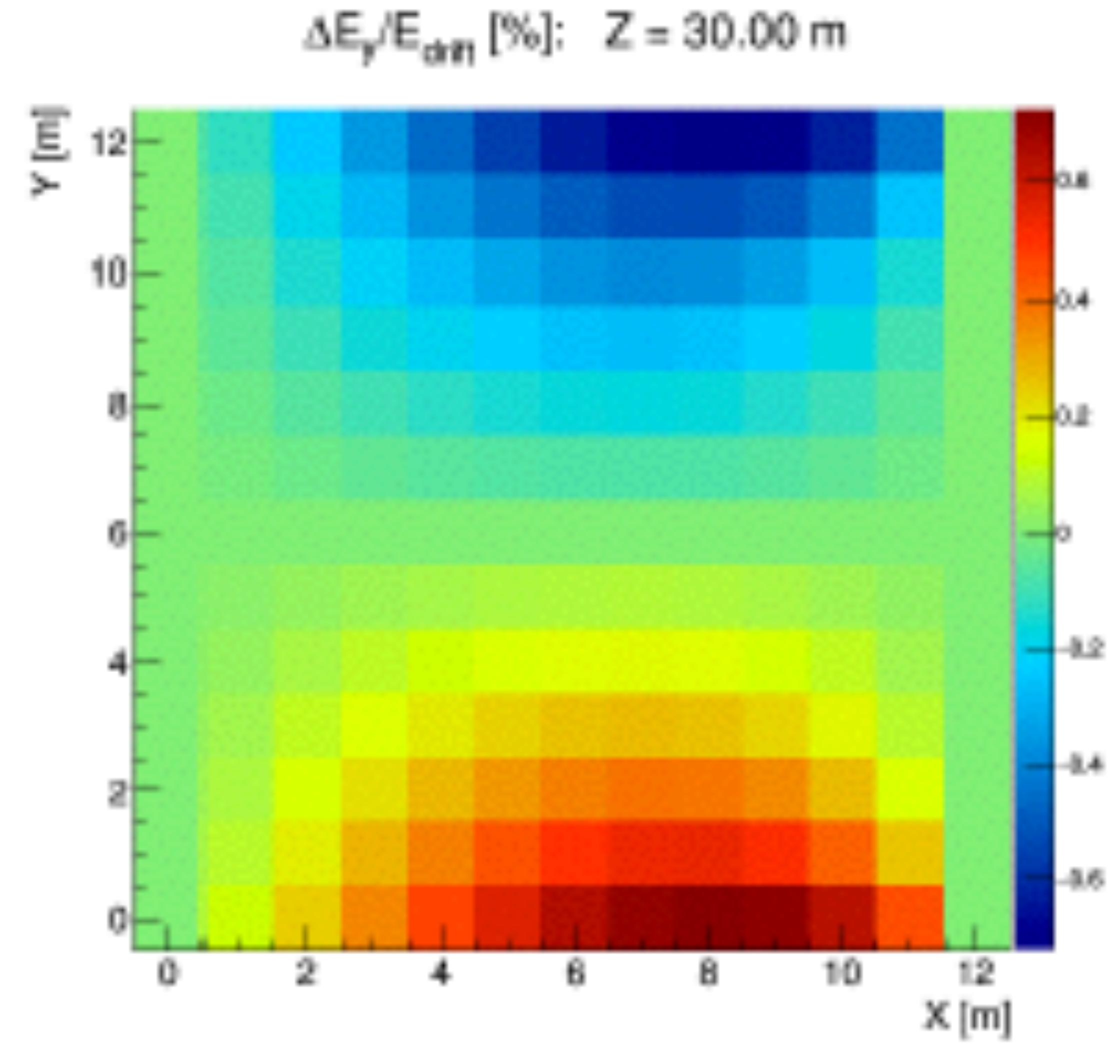
Diagnosing failures and stability monitoring

- *Cathode flatness*
    - ICARUS measured (empty, warm) cathode flatness, consistent with cosmics (~6 months). After refurbishment, residual distortions from simulation at ~2mm level.

E-field Backup

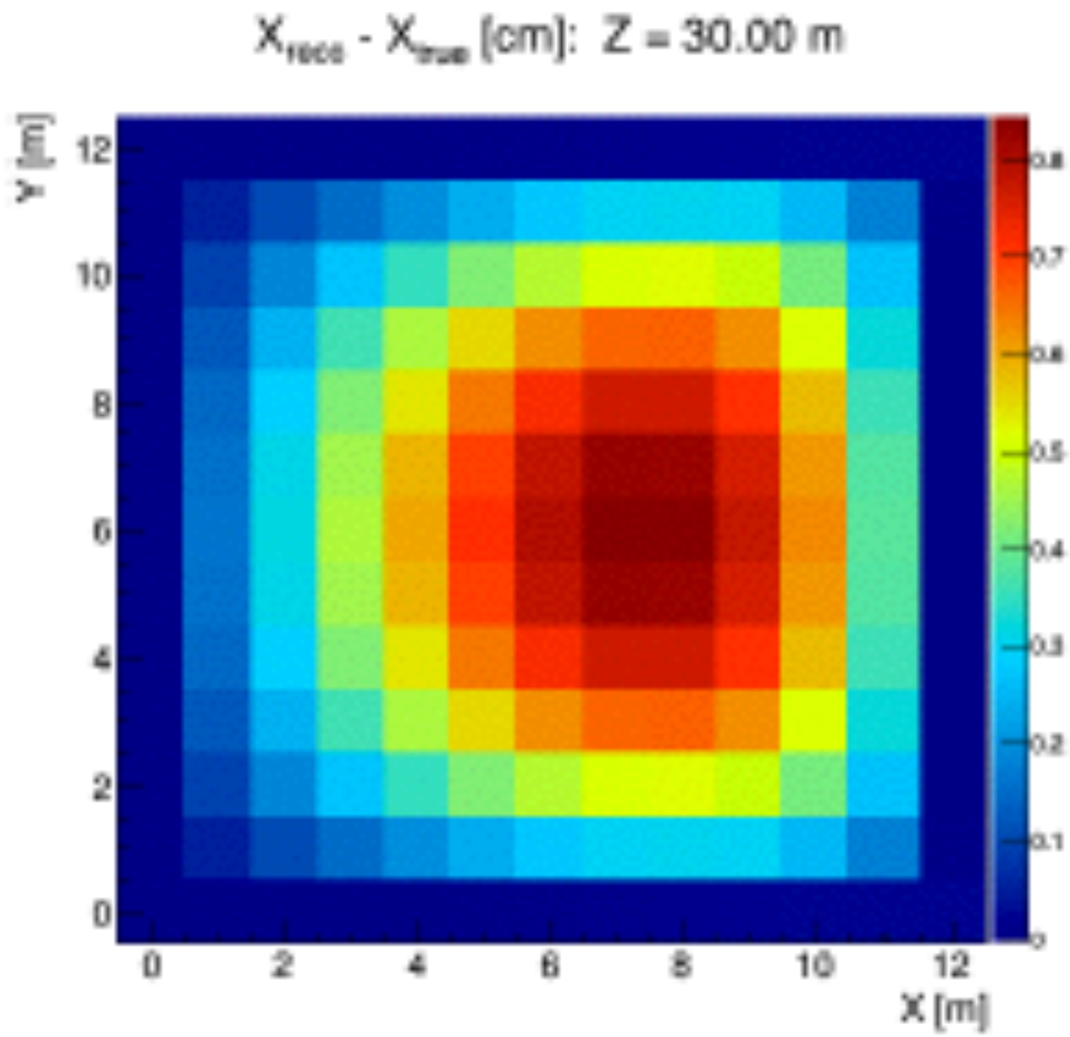
SCE for DUNE DP FD

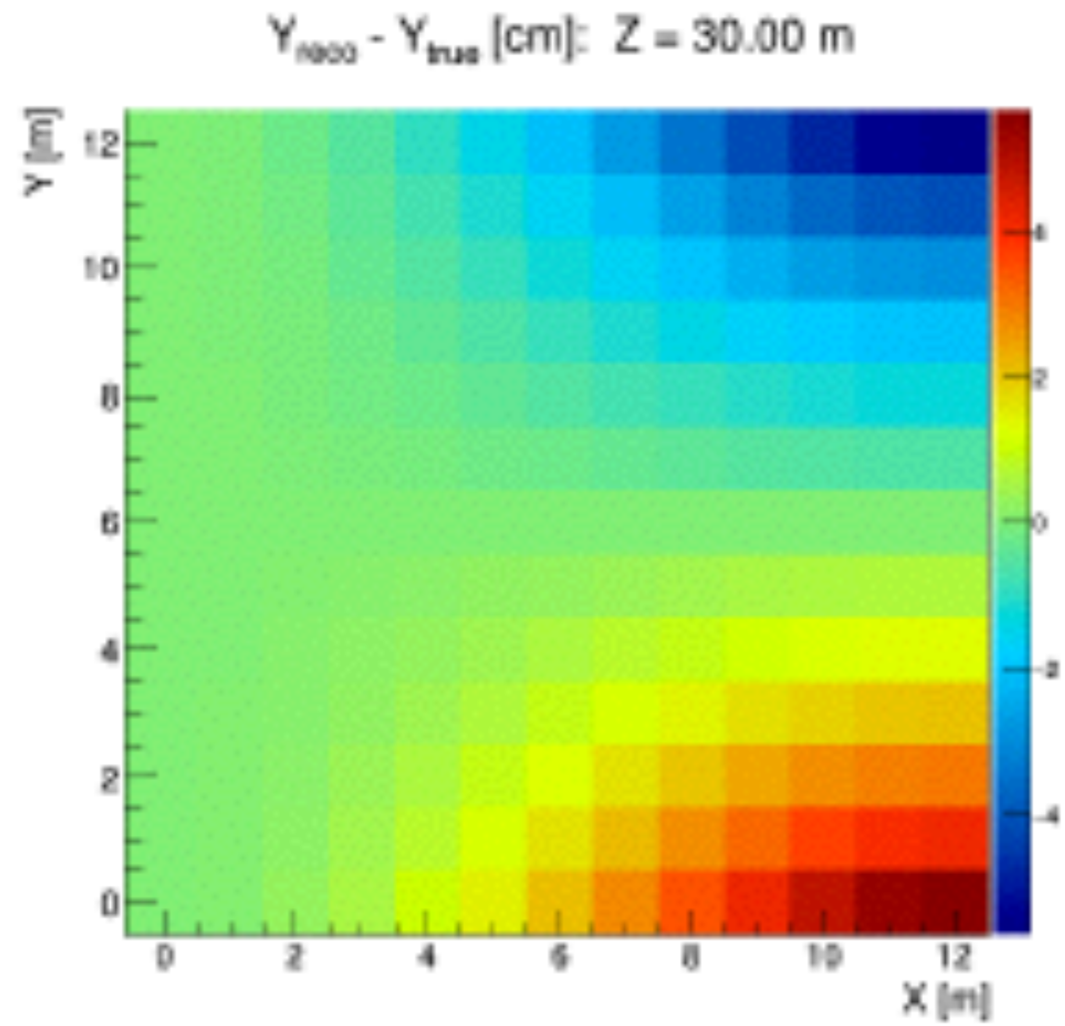




- DUNE DP FD – looking at full detector, central Z slice
  - Ionization **drift is to the left** (anode on left, cathode on right)
- E field distortions on order of **1%** – larger than for SP case
  - Impact on dQ/dx from recombination **~ 0.3%**

SCE for DUNE DP FD





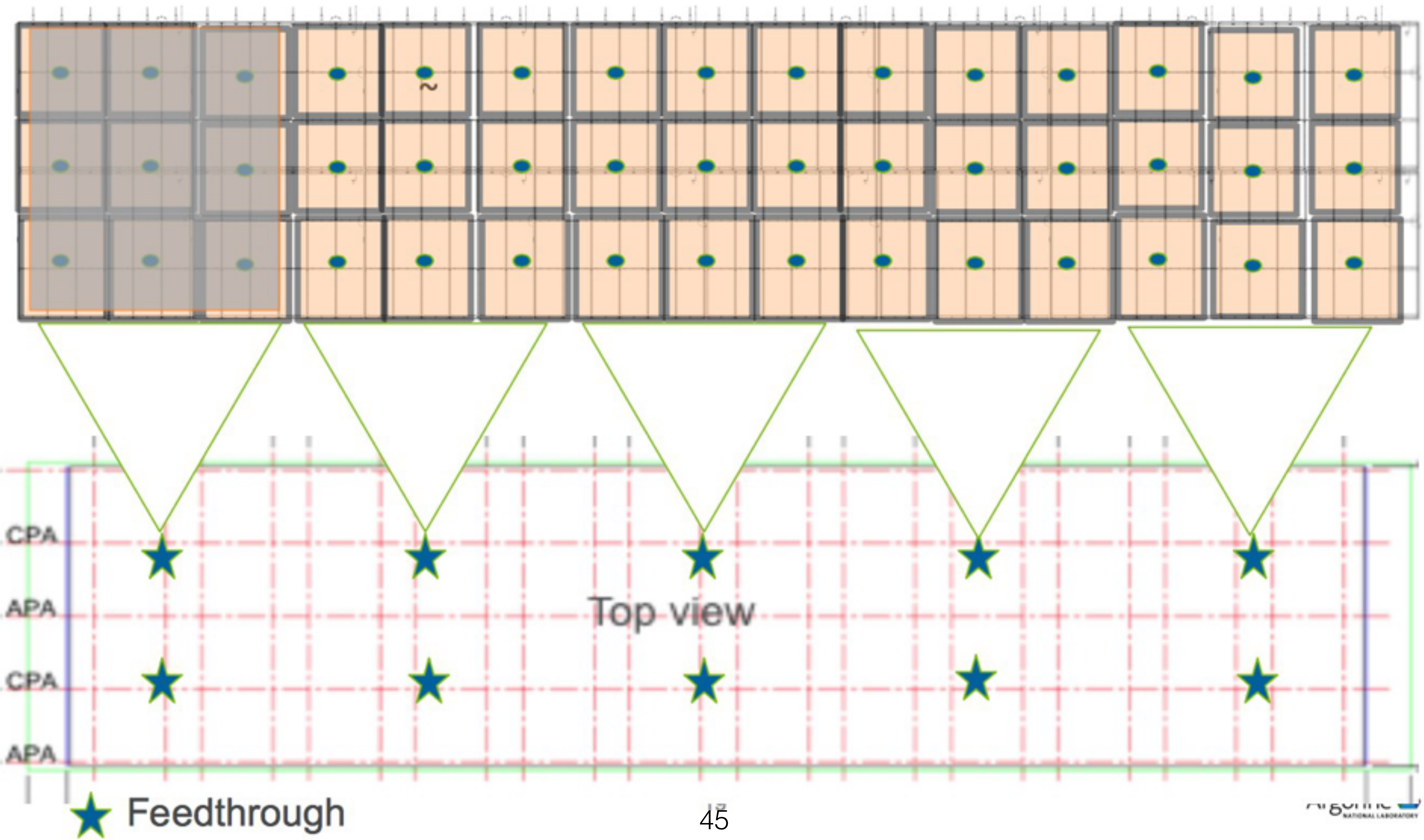
- DUNE DP FD – looking at full detector, central Z slice
  - Ionization **drift is to the left** (anode on left, cathode on right)
- Spatial distortions on order of **5 cm** – not negligible!
  - Total impact on dQ/dx (including recomb.) ~ **2-3%**

PDS Calibration Backup

DUNE photon calibration system

R. Dharmapalan, Z. Djurcic

- 18 penetrations on each of 5 feedthrough on one CPA
- 9 penetrations each on 5 of second CPA.



R. Dharmapalan, Z. Djurcic

PDS calibration

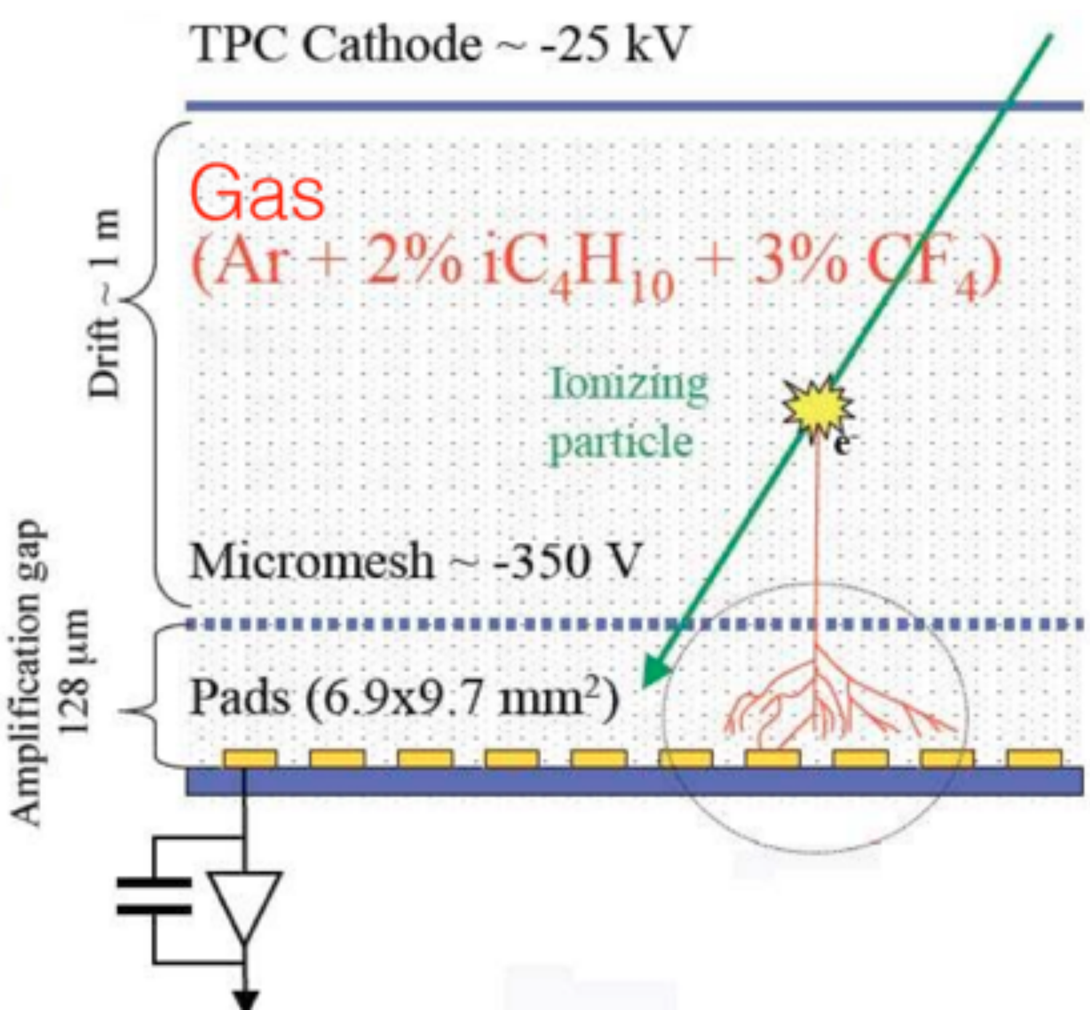
- *Design*
  - Light Diffusers on one side of CPA1 and on two sides of CPA2
  - Optic fibers for HV signal; highly insulating
  - Each CPA side is split into 45 cells with optical fiber feeding into each cell.
  - For 3 sides of CPAs this results in 135 (45*3) individual penetrations. But, the fiber can be grouped together to reduce the number of overall FTs required
- *Fiber optic safety*
  - The fibers are highly resistive. The spec sheets quotes the quartz/silica resistance to be 10^18 ohm-cm and the coating to have 10^16 ohm-cm.
  - We carried an independent test of fiber resisitivity by DUNE CPA group
    - Glenn Horton-Smith from KSU did a test by applying 36 kV over a 4.0 cm length of fiber with a setup sensitive down to 0.1 nA, and observed no current.
    - His conclusion was that it is basically an excellent insulator. In addition, as mentioned above the same fiber has been used with 35t with filed at about 55 KV in the TPC.

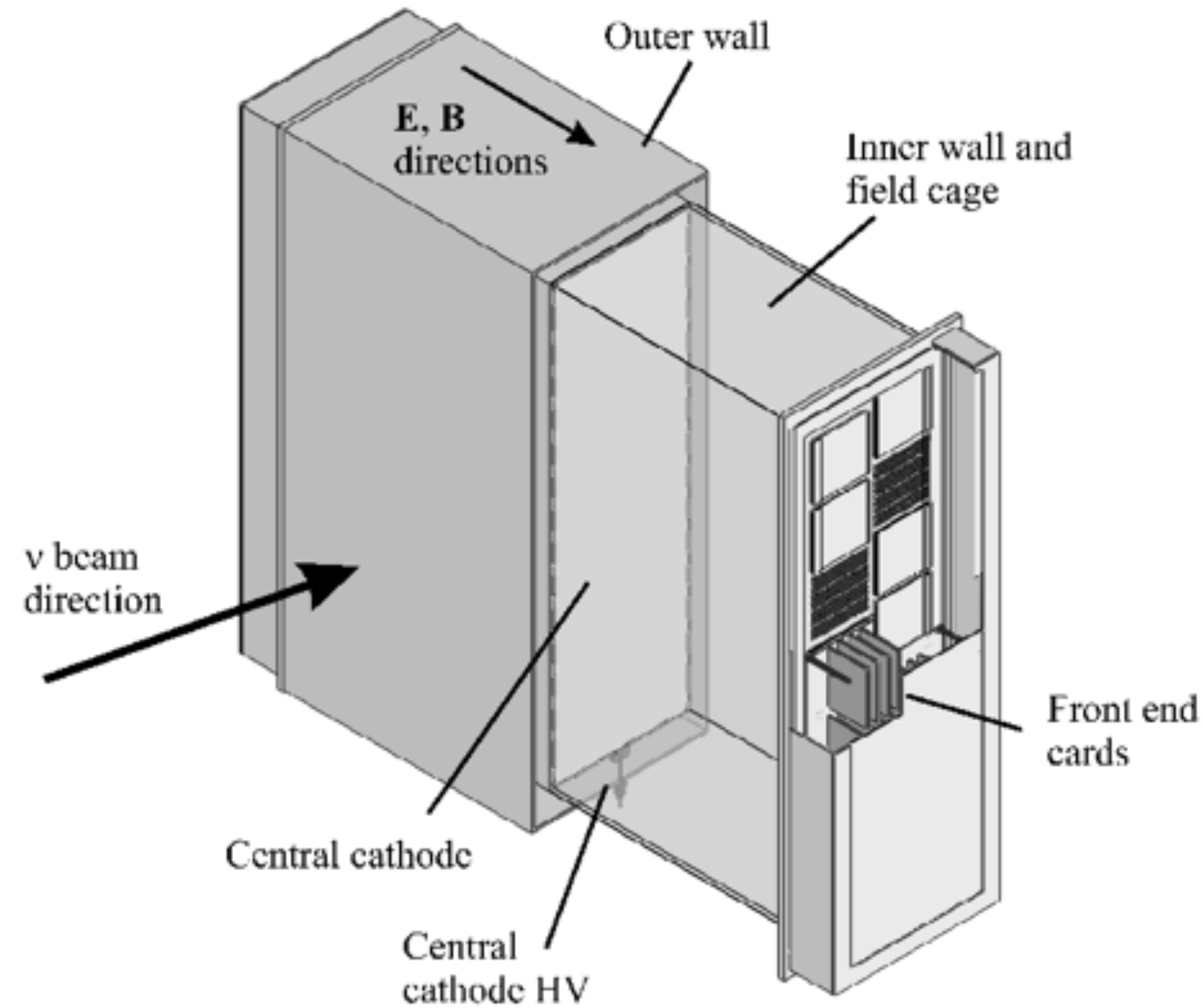
Laser Backup

T2K TPC system

3 Gas TPCs operated in a 0.2T field measure particles from neutrino interactions

- MicroMegas micro pattern gas detectors

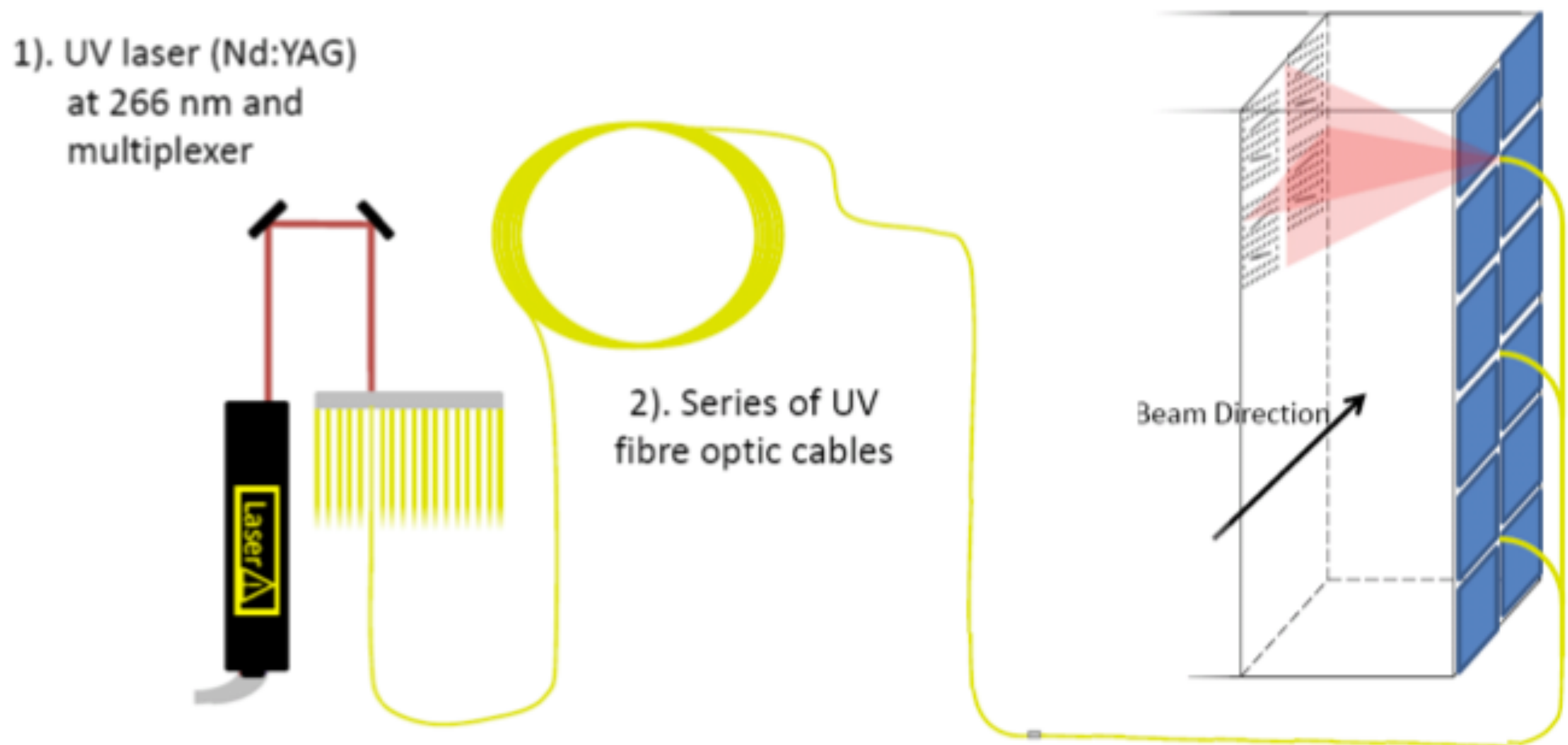




2% momentum scale goal with mom. resolution goal of:

$$\delta p_\perp / p_\perp = 0.1 p_\perp [GeV/c]$$

Photo-calibration (laser) system

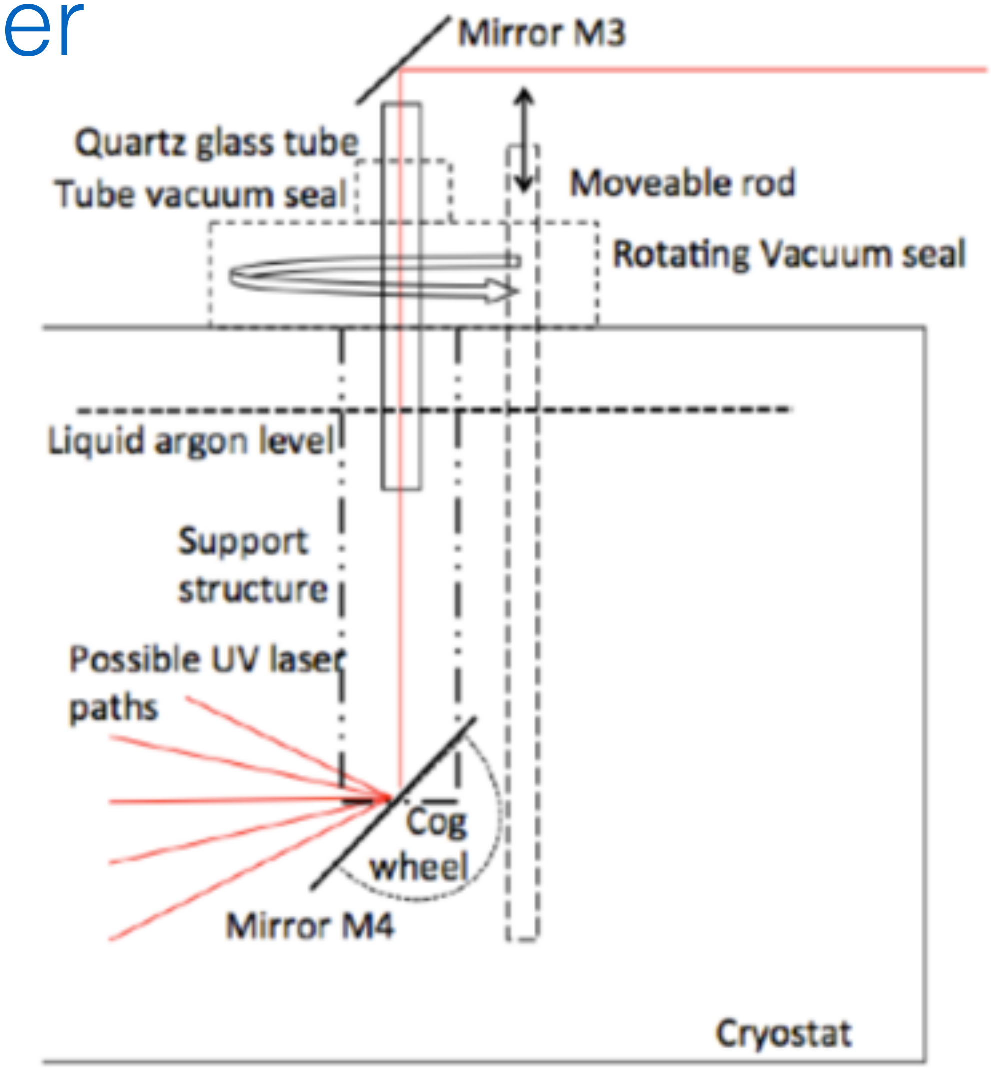


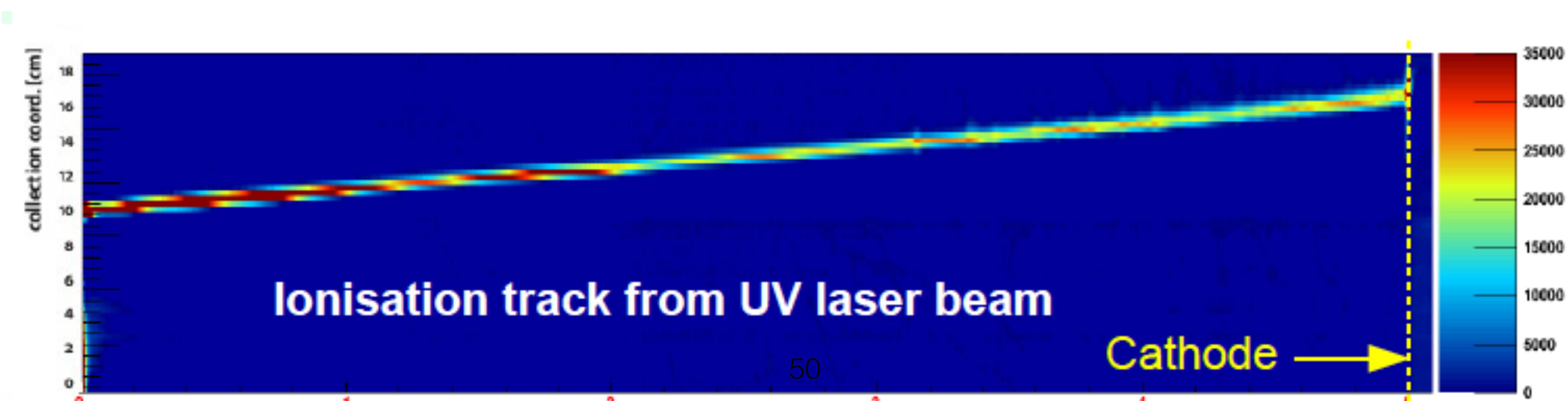
- UV laser light illuminates Al targets on TPC cathode. Motorized multiplexer couples light to 1 of 3 fibre optic cables.
- Ejected photo-electrons drift full length and are read out
- Integrated along drift information about E field (unlike SBND style laser system). *Is integrated information valuable?*

MicroBooNE, SBND laser system

I. Kreslo, M. Weber

- Ionize the liquid Ar using 266nm laser
- Steerable mirror to alter path, crossing tracks for field map:
- Straight tracks (no MCS, no delta rays), *no recombination*



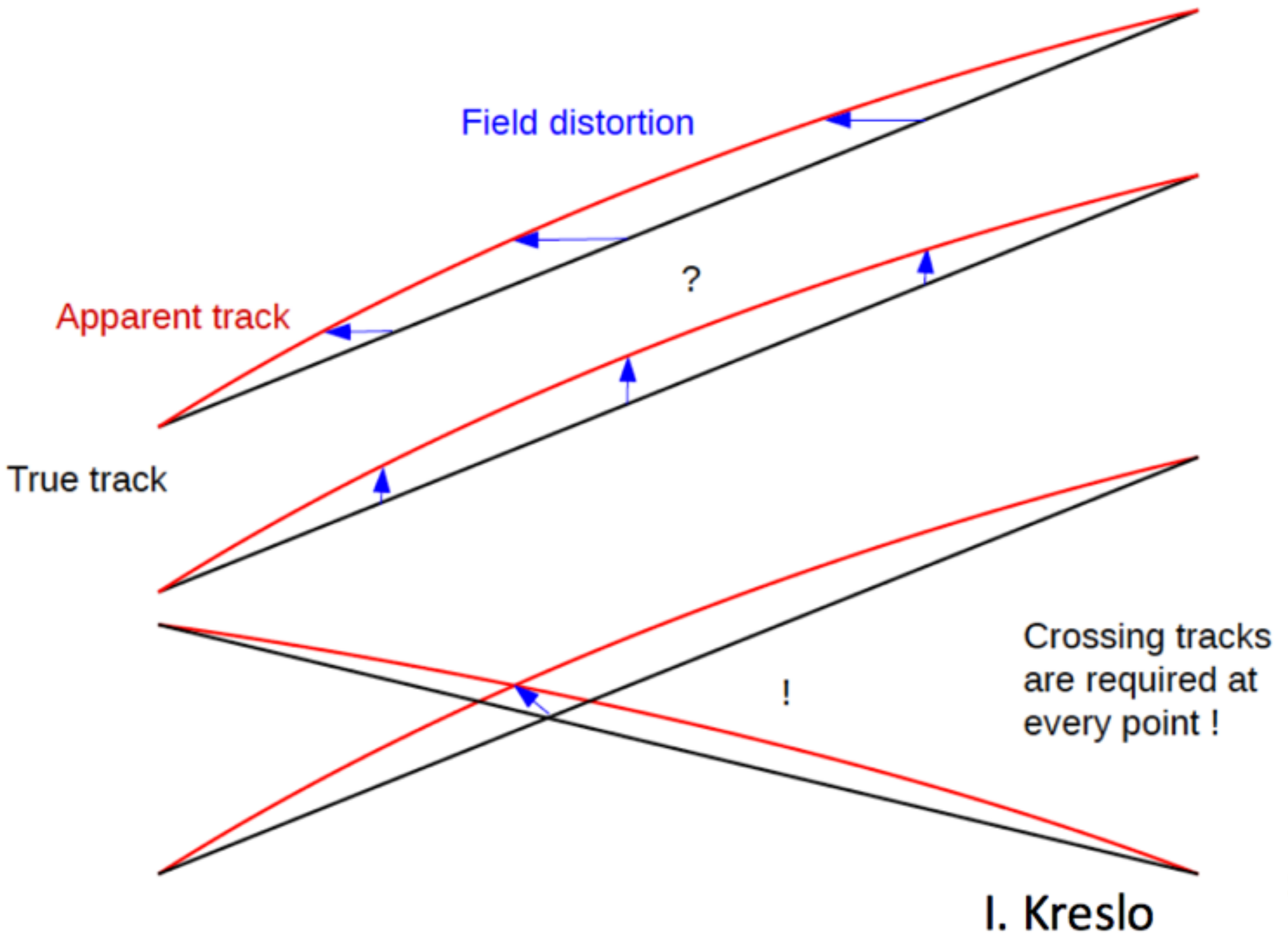


Observable ionization depends on:

M. Weber, ***mini-workshop:*** *https://indico.fnal.gov/getFile.py/access?contribId=9&resId=0&materialId=slides&confId=14909*

- Beam divergence: nominal 0.5 mrad (can change at the mirrors!)
- Beam absorption: does not seem to be an issue…
  λ_{att}> 100 m at 266 nm
  "Attenuation of vacuum ultraviolet light in liquid argon" , Eur. Phys. J. C (2012)
- Rayleigh scattering (40m at 266 nm)
- Refraction on density gradients
- Non-linear effects (Kerr-induced self-focusing)
- *MIP-like charge?* Laser tracks are wider (5mm vs. 50nm) than cosmics. But, charge on a wire is comparable to a MIP (integrated over 3 mm)

How crossing tracks determines E field?

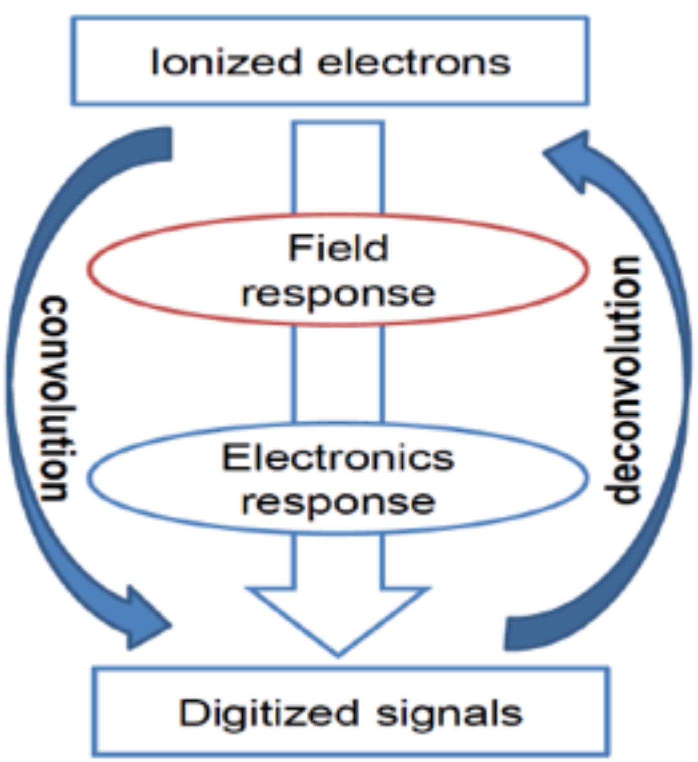


Field Response Calibration Backup

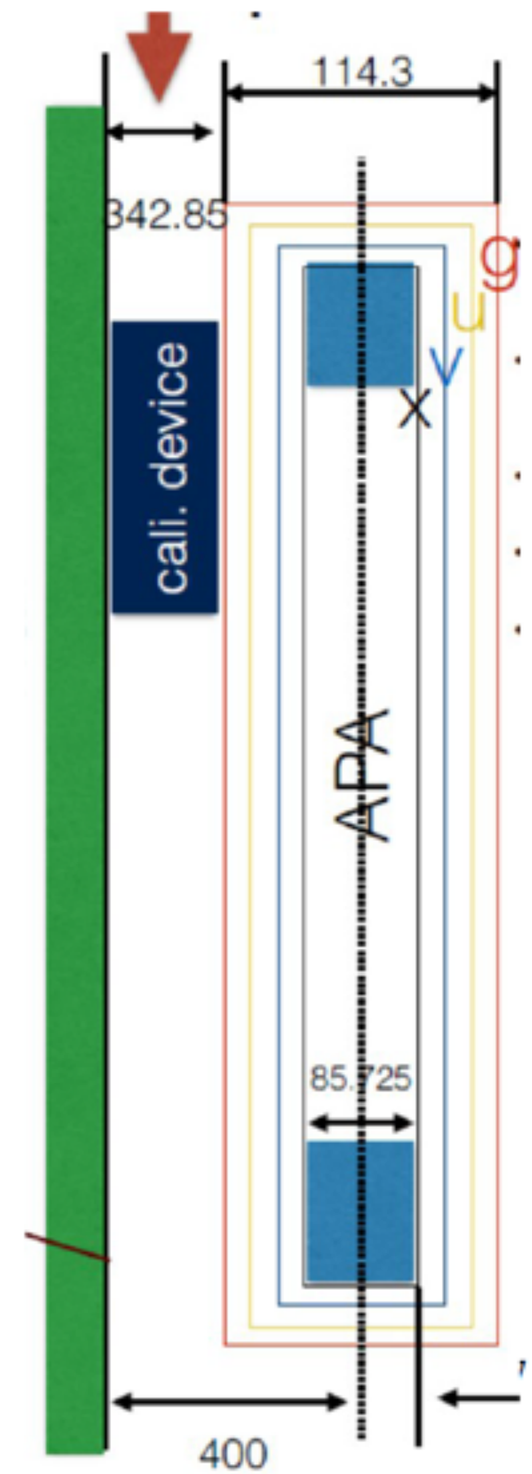
Field Response Calibration

C. Zhang, Y. Li

- https://indico.fnal.gov/getFile.py/access?contribId=4&resId=0&materialId=slides&confId=15234
- Motivation
  - Induction plane signals significantly depend on field response due to their bipolar nature of the signal
  - Current field response based on simulation; proposal to directly measure field response at BNL test stand
  - With DUNE, want to preserve the option to do in-situ field response calibration



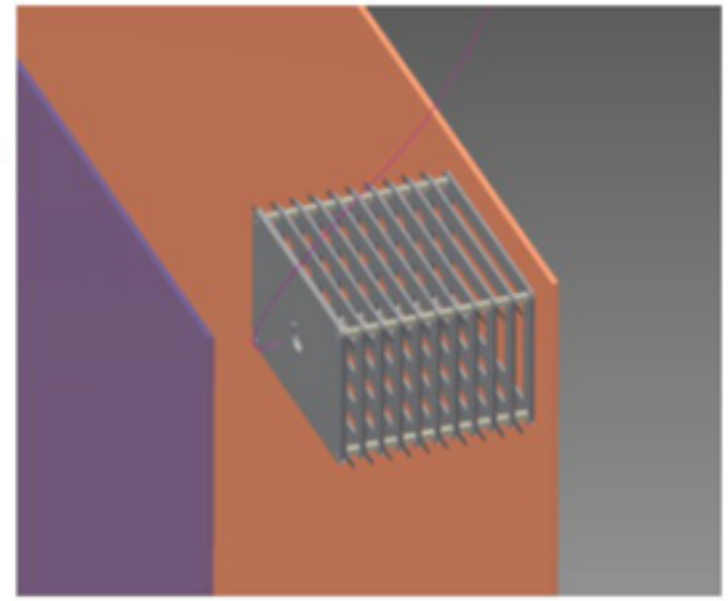
- The device will sit in the space b/n outer APA and the cryostat side wall
- Would like FT as close as possible but limited by the GTT membrane feature of the cryostat
- Also limited by the clearance on top of the proposed location of the device

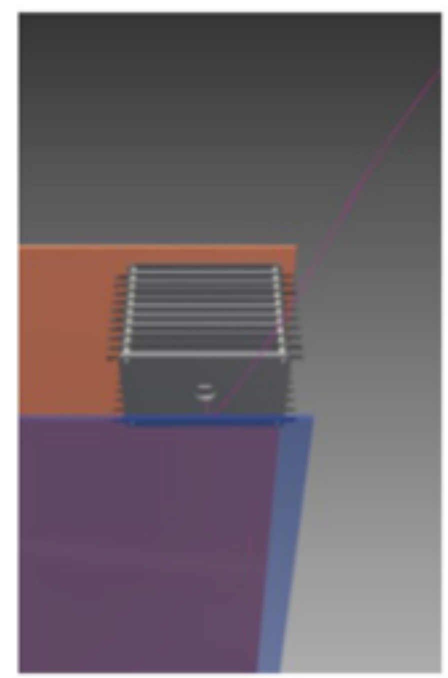


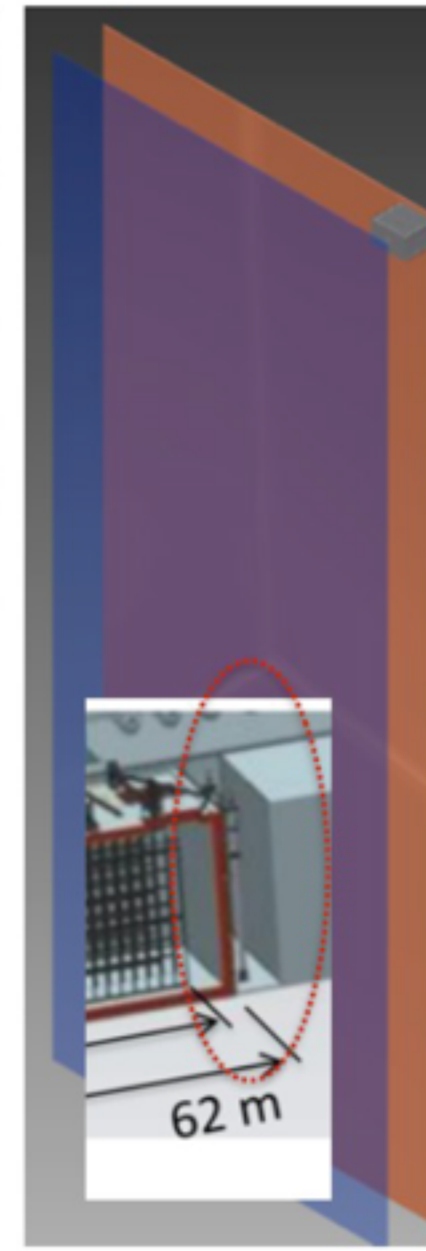
Field Response Calibration

C. Zhang, Y. Li

- *Possible In-situ proposal*
  - Proposal for 2 devices for DUNE, placed at two different vertical locations behind two different APAs. Reduces the risk that one APA doesn't work or had bad performance
  - Supporting structure for the device need to be installed as well at both locations
  - Challenging given the space and risks exist
- *Will an In-situ measurement make sense?*
  - Unclear how 1 or even a set of devices can conclude about the behavior of all TPCs in DUNE? (one can expect huge variations point to point across the planes)
  - Probably best done with a test stand and ProtoDUNE and then extrapolate to DUNE to map it out (although extrapolation comes with its own challenges)







Local Setup @BNL

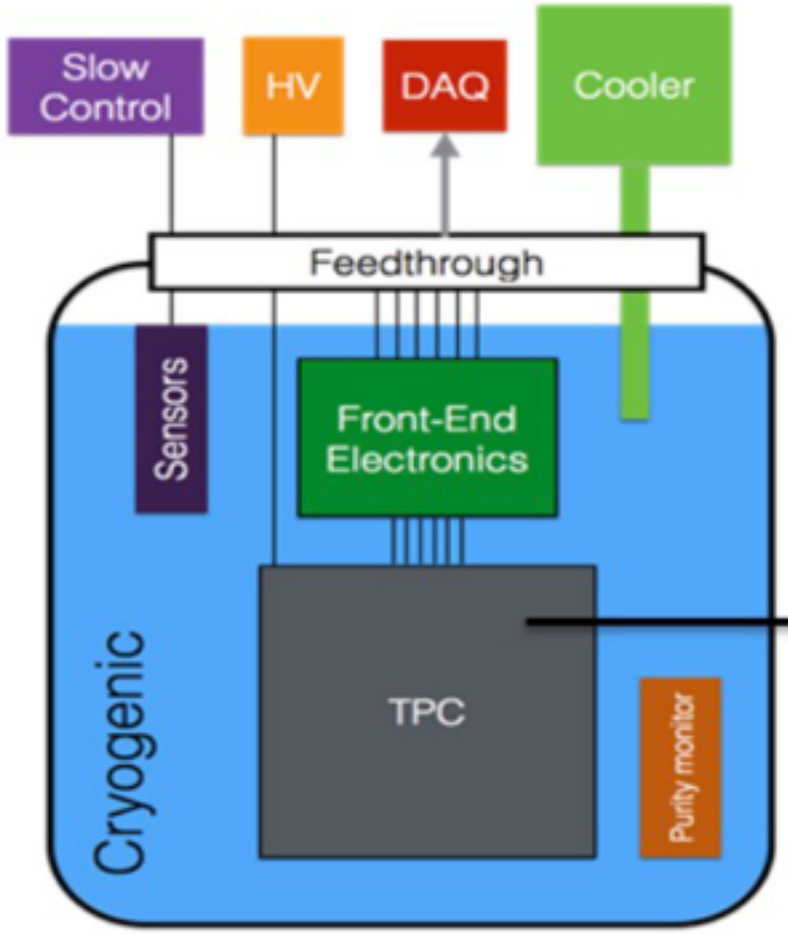
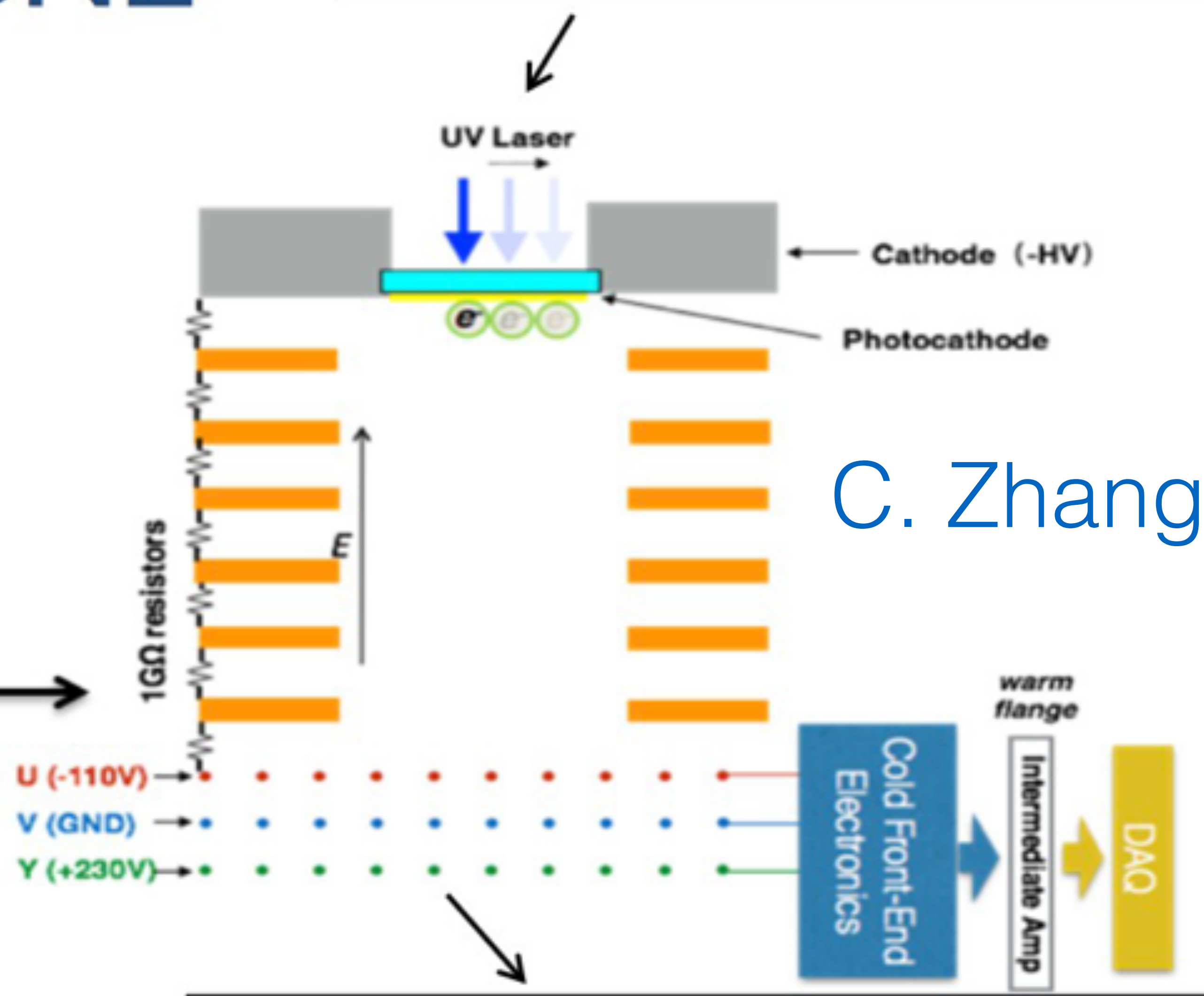


Figure 6. Schematic of the liquid argon field calibration system (LArFCS).

Illuminate Au-photocathode with precise scan of electron locations



C. Zhang, Y. Li

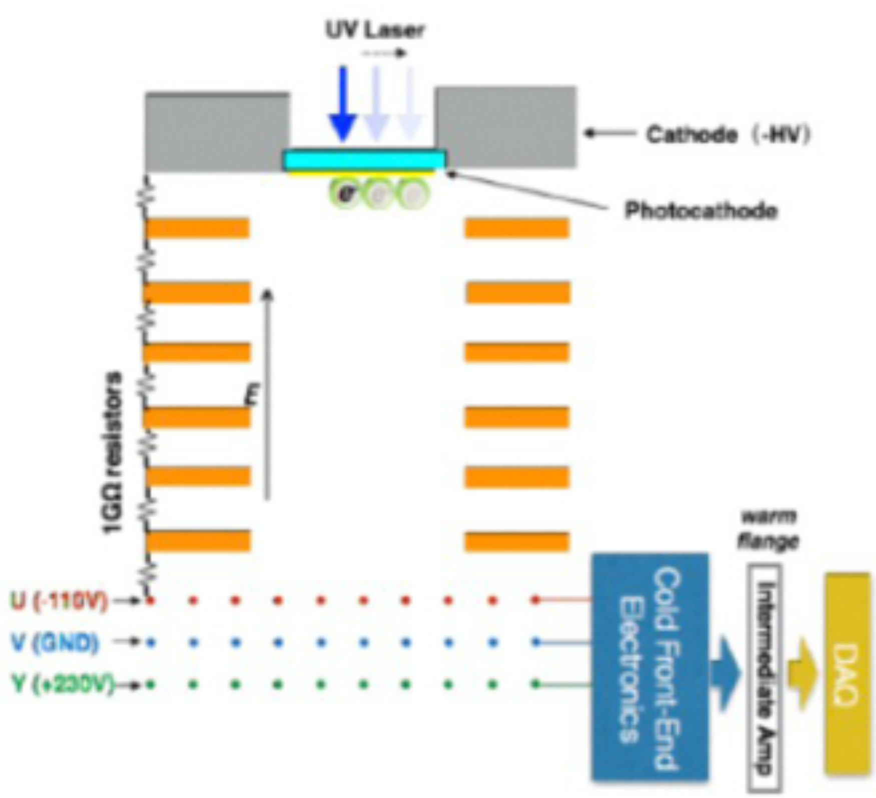
Reproduce MicroBooNE and DUNE wire patterns and configurations

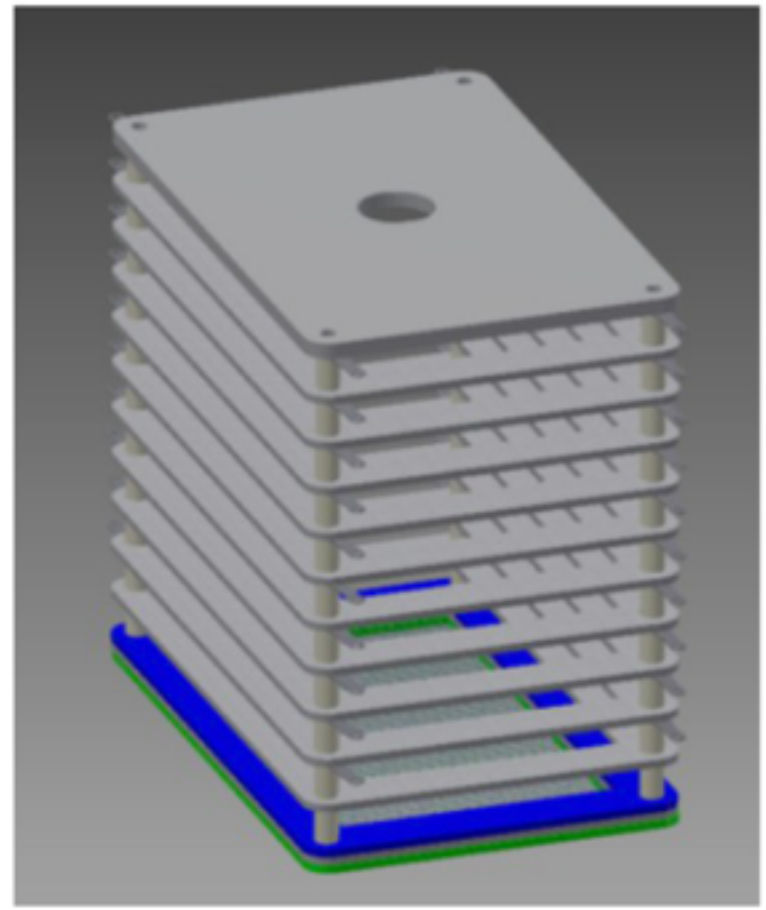
- Sub systems: Cryogenic, TPC, Laser, Front-end electronics, DAQ, etc.
- Goal: precisely measure field response function versus position, compare with 2D and 3D simulations such as Garfield and BEM

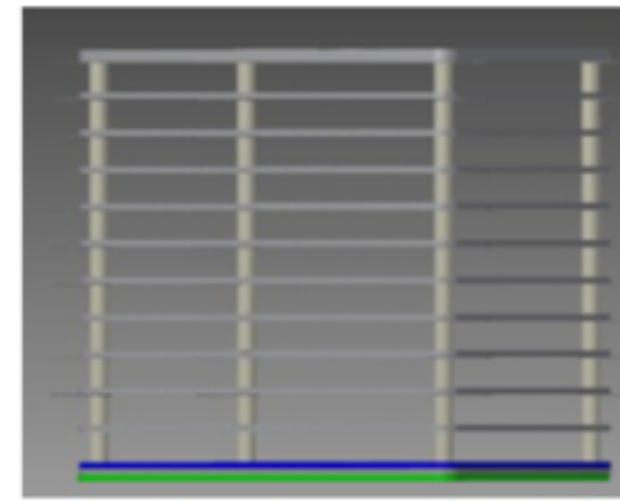
LArFCS TPC Design

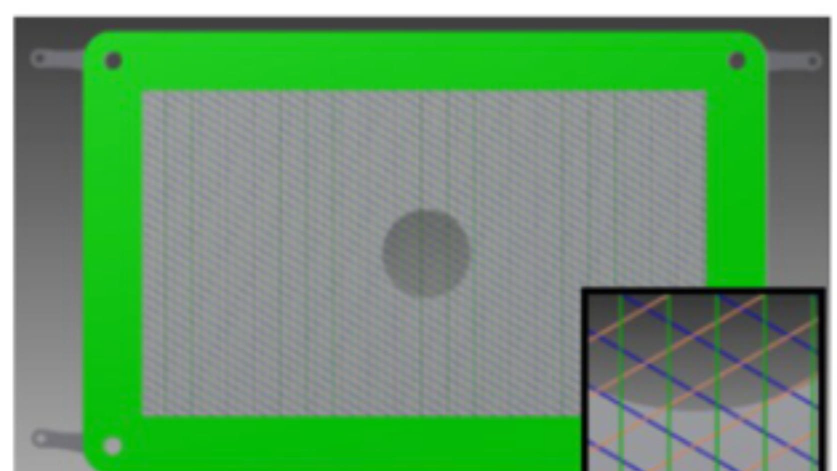
C. Zhang, Y. Li

- TPC fiducial volume
  192 mm(L) x 111mm(W) x 200 mm(H)
  Nominal volume:
  232 mm (L) x 151 mm(W) x 220 mm(H)
  (The drawing is in the actual dimensions)
- The field cage contains 11 stages
- The photocathode diameter is 30 mm
- Anode wire pattern is the same as MicroBooNE, 3 mm pitch, 60 degrees, 192 wires in total, 64 wires each plance
- Front end motherboard is not included









LArFCS

C. Zhang, Y. Li

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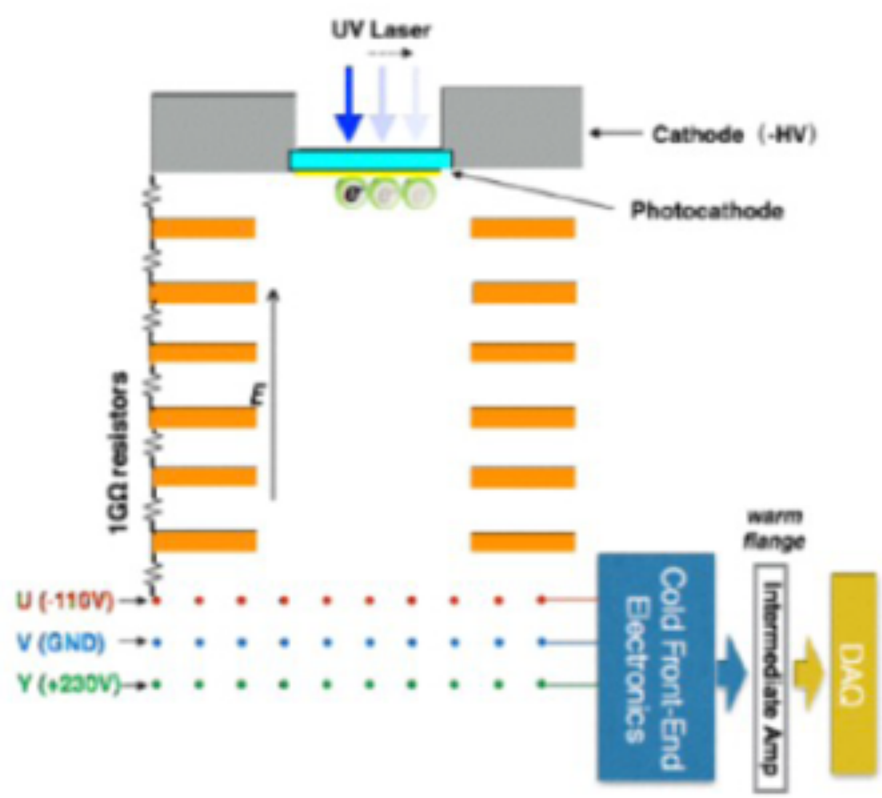
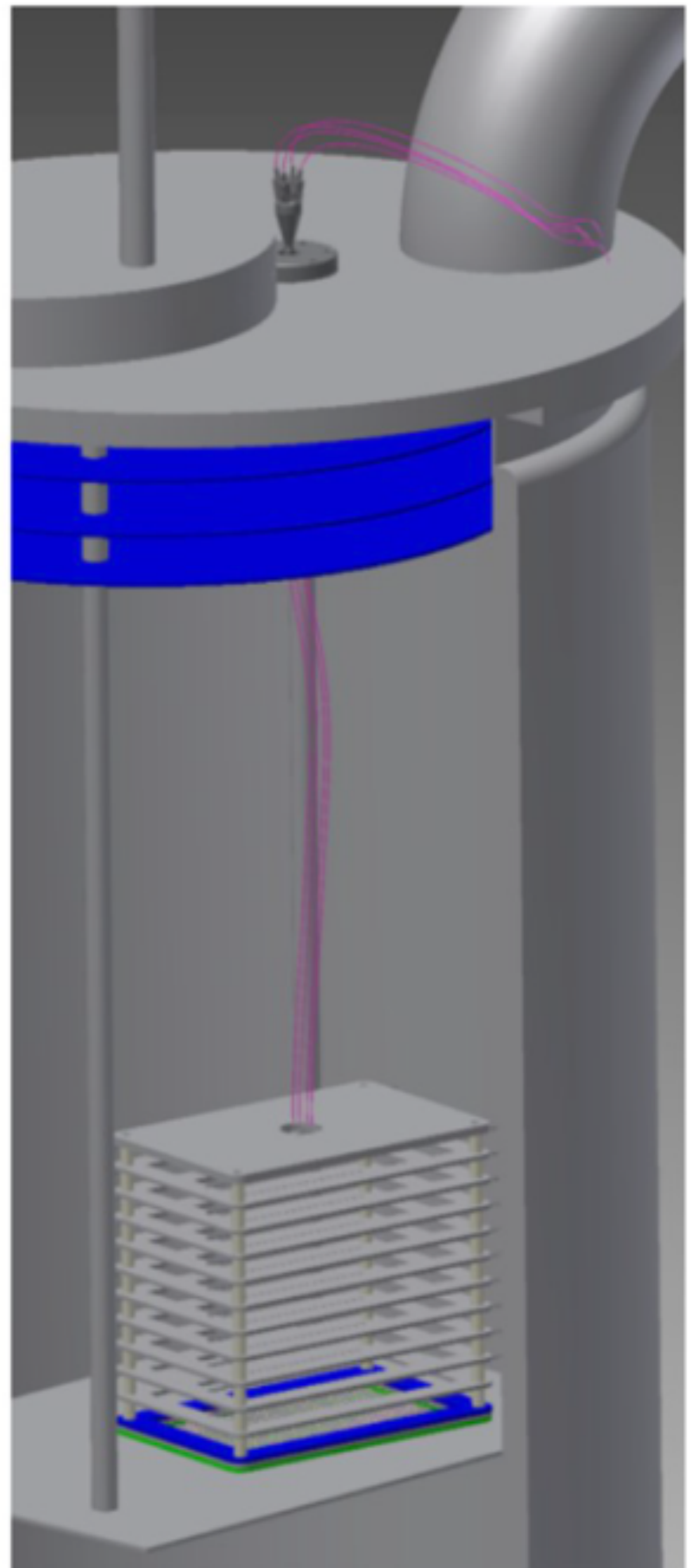


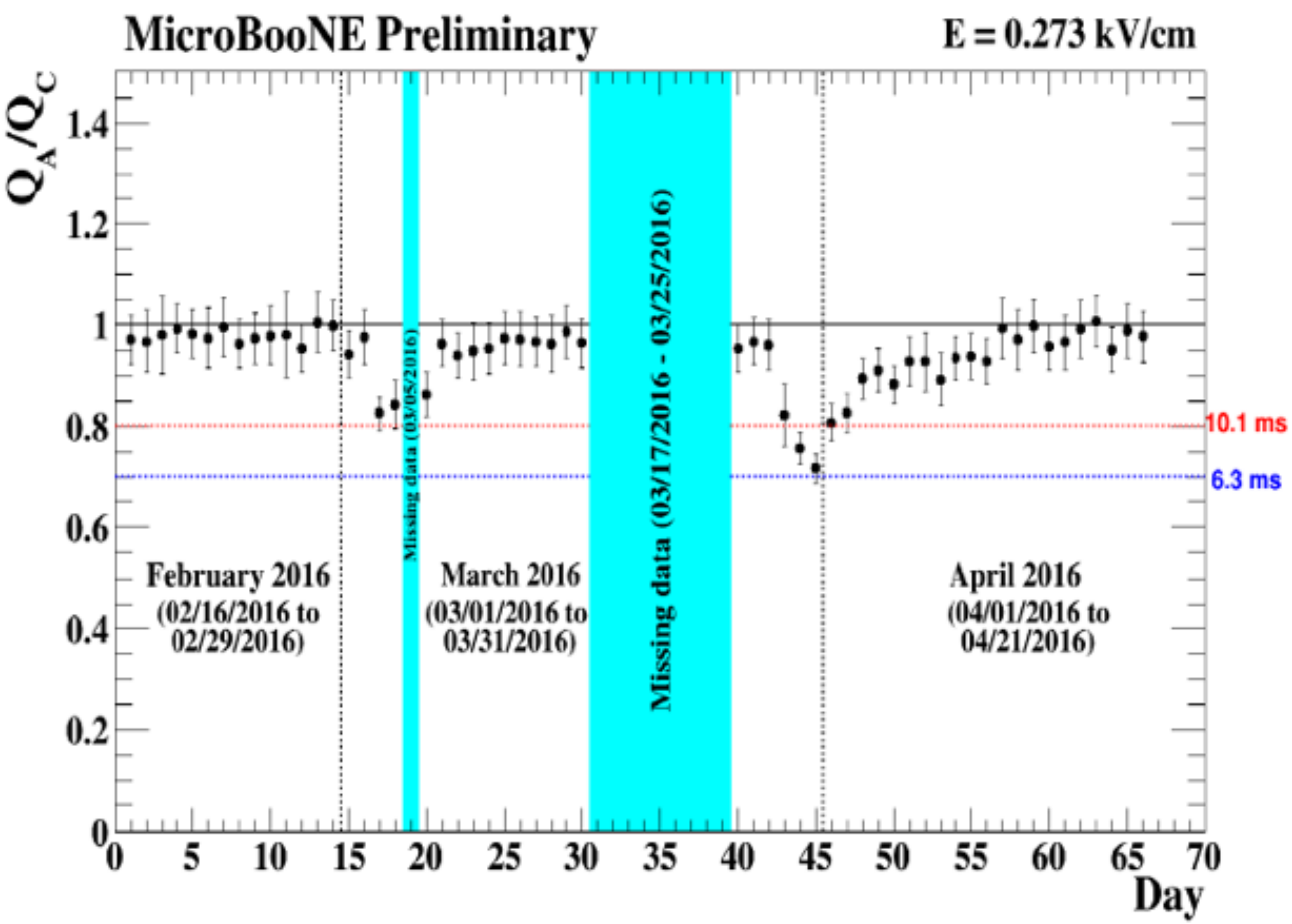


Other Results (uB, 35-ton etc.)

Need to add more stuff here

S. Gollapinni

Electron Attenuation after systematics



Systematic name	Uncertainty (%)
Space charge correction	5.0
Recombination model	1.0
Diffusion	2.0
Total	5.5

(% of final space-charge correction Q_A/Q_C value)

Overall Period:

- $Q_A/Q_C > 0.72 +/- 0.04$
- Lower bound
  - 6.8 ms electron lifetime
  - O_2 contamination < 44 ppt
  - Maximum charge loss 28%

Normal Operation:

- $Q_A/Q_C > 0.88 +/- 0.04$
- Lower bound
  - 18.0 ms electron lifetime
  - O_2 contamination < 16 ppt
  - Maximum charge loss 12%

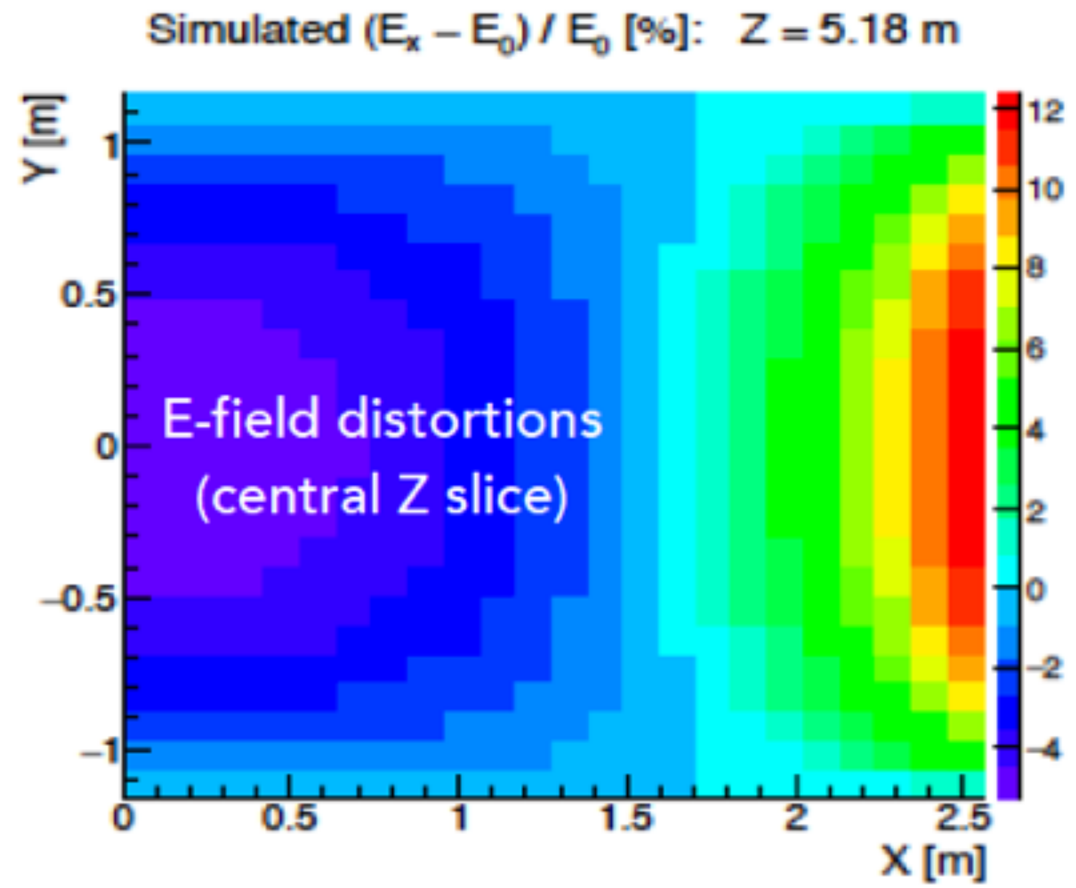
S. Gollapinni

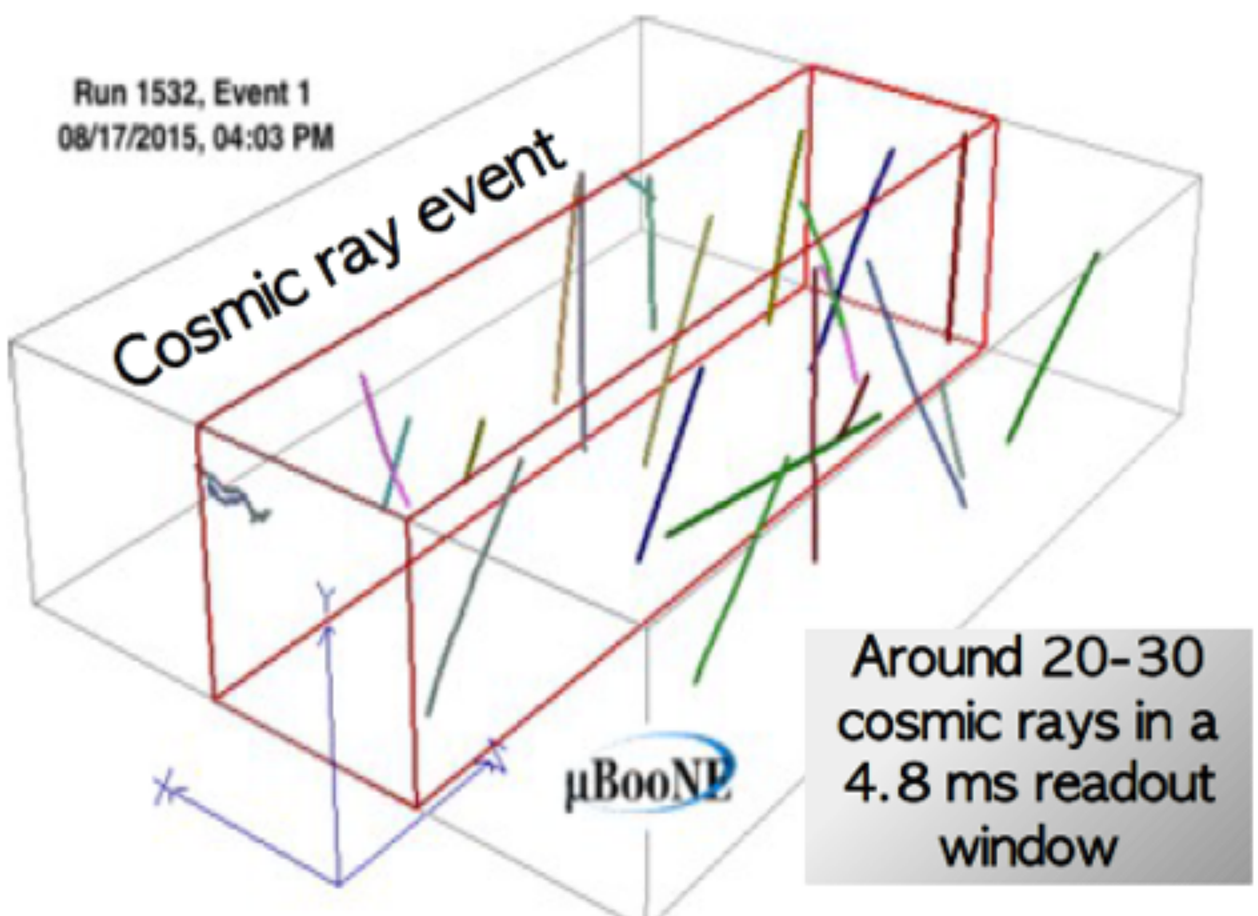
Space charge effects in MicroBooNE

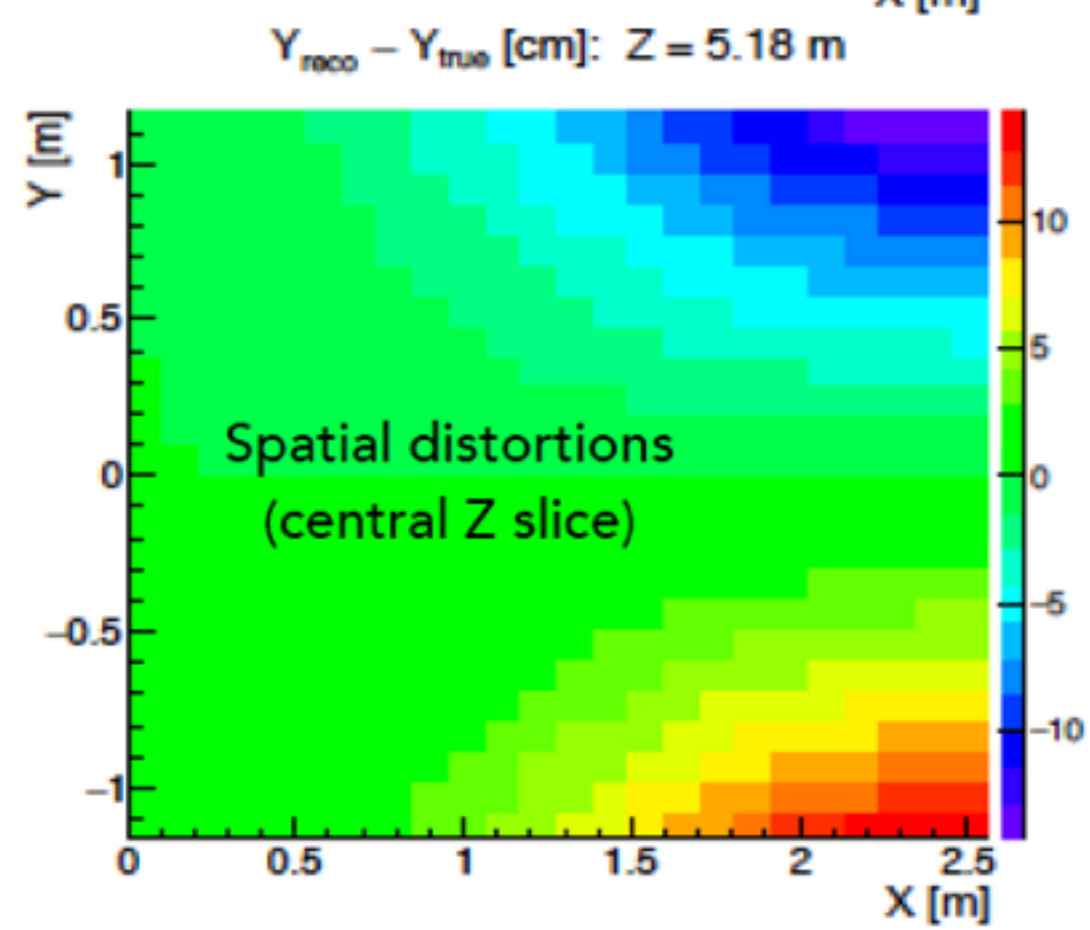
- MicroBooNE is surface detector → abundant cosmic rays
- Build up of slow moving Ar^+ ions in the detector due to, for example, cosmic rays, which results in:

  Local variations of E-field: 12% increase at Cathode; 5% decrease at Anode

  Spatial variations in ionization position: Around 5cm distortion along drift; Around 12 to 15 cm along non-drift directions







S. Gollapinni

Space charge effects in MicroBooNE

Measurement using MuCS tracks

- Data and MC reasonably agree in terms of basic shape and normalization
- Offset near anode in data:
  - Is liquid argon flow pushing the ions near the anode?
  - Interesting ideas on testing this theory: e.g. vary pump flow and see how it effects ion SCE