Space Charge Effect at DUNE 35-ton

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BNL

DUNE 35-ton Sim/Reco/Analysis Meeting

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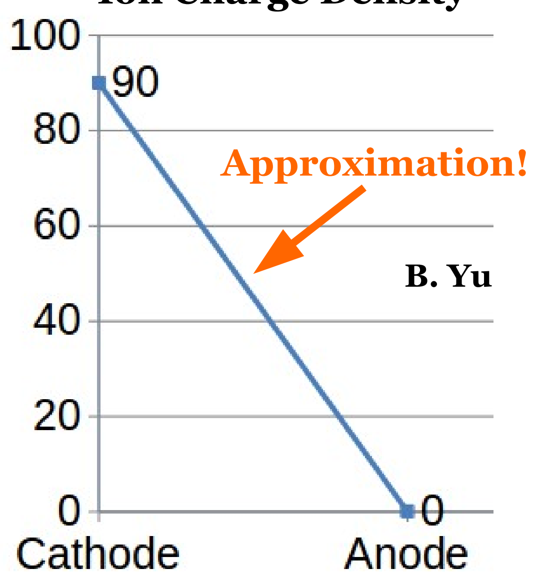
Introduction

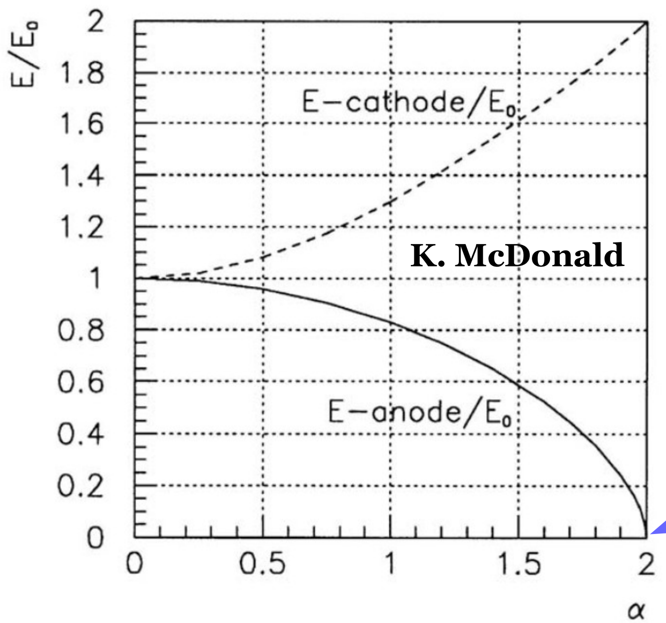
- Tool exists to study space charge effect at the **MicroBooNE detector**
  - **SpaCE** – Space Charge Estimator
  - Study **simple problems** first in detail with dedicated simulations
  - Also performs calibration using MicroBooNE's UV laser system and cosmic muons (in progress)
  - LArSoft module exists to hold/access SCE offsets
  - Now: extend SCE simulation to **DUNE 35-ton detector**
- Outline:
  - Brief review of Space Charge Effect (SCE) and SpaCE
  - SCE at DUNE 35-ton detector
  - Updated LArSoft implementation

Space Charge Effect

- **Space charge**: excess electric **charge** (slow-moving ions) distributed over region of **space** due to cosmic muons passing through the liquid argon
  - Modifies E field in TPC, thus track/shower reconstruction
  - Effect scales with L^3, $E^{-1.7}$

Ion Charge Density





$$\alpha = \frac{D}{E_0}\sqrt{\frac{K}{\epsilon\mu}}$$

$$\mathbf{v} = \mu\mathbf{E}$$

No Drift!

SpaCE: Overview

- Code written in C++ with ROOT libraries
- Also makes use of external libraries (ALGLIB)
- Primary features:
  - Obtain E fields analytically (on 3D grid) via **Fourier series**
  - Use **interpolation** scheme (RBF – radial basis functions) to obtain E fields in between solution points on grid
  - Generate tracks in volume – line of uniformly-spaced points
  - Employ **ray-tracing** to "read out" reconstructed {x,y,z} point for each track point – RKF45 method
- First implemented effects of uniform space charge deposition without liquid argon flow (only linear space charge density)
  - Also can use **arbitrary space charge configuration**
    - Can model effects of liquid argon flow (but can we trust CFD simulations?)

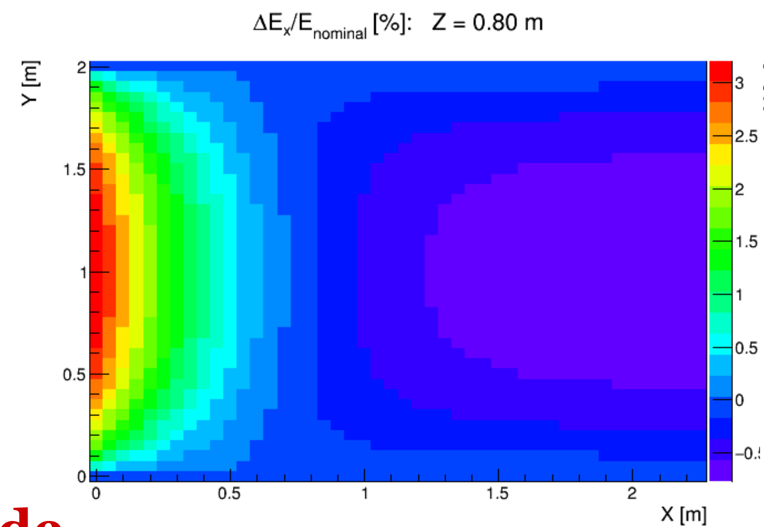
Simulation of SC Effect

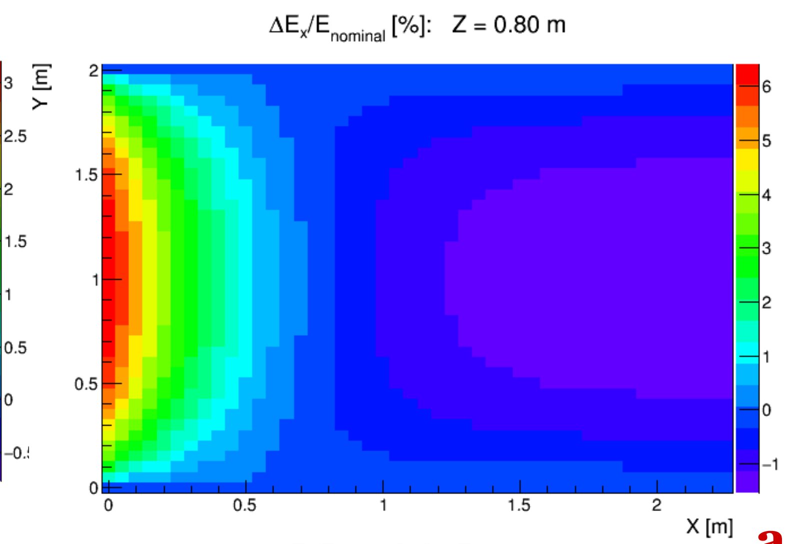
- Can use SpaCE to produce displacement maps
  - **Forward transportation**: $\{x, y, z\}_{\mathbf{true}} \rightarrow \{x, y, z\}_{\mathbf{sim}}$
    - Use to **simulate** effect in MC
    - Uncertainties describe accuracy of simulation
  - **Backward transportation**: $\{x, y, z\}_{\mathbf{reco}} \rightarrow \{x, y, z\}_{\mathbf{true}}$
    - Derive from **calibration** and use in data or MC to correct reconstruction bias
    - Uncertainties describe remainder systematic after bias-correction
- Two principal methods to encode displacement maps:
  - **Matrix representation** – more generic/flexible
  - **Parametric** representation (for now, $5^{th}/7^{th}$ order polynomials) – fewer parameters
    - Uses matrix representation as input → **use for LArSoft implementation**

Modified E field in 35-ton

$E_{nominal}$ = 500 V/cm | $E_{nominal}$ = 250 V/cm

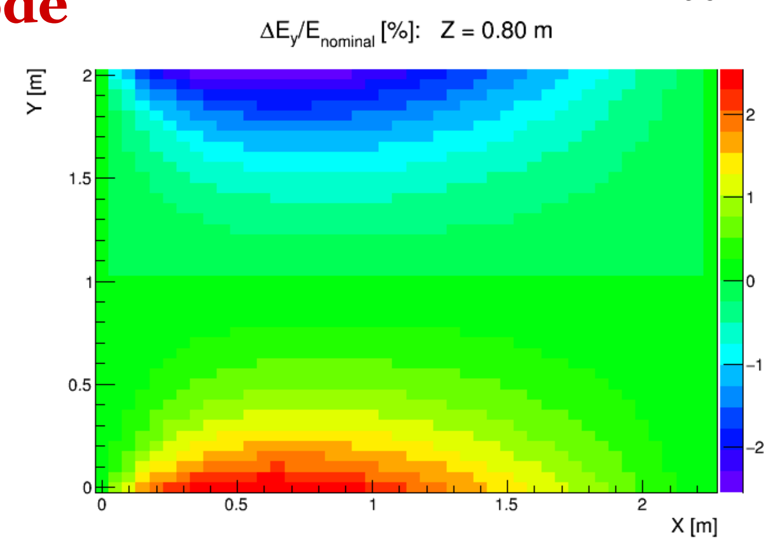
E_X

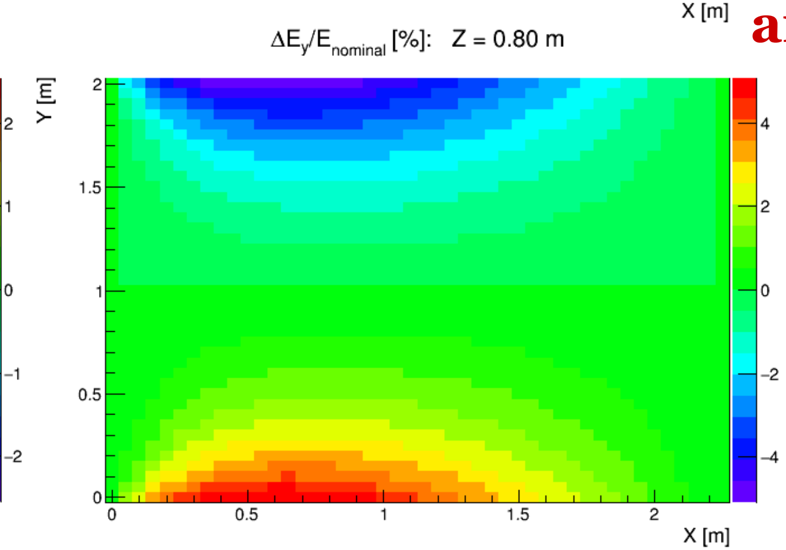




cathode **anode**

E_Y

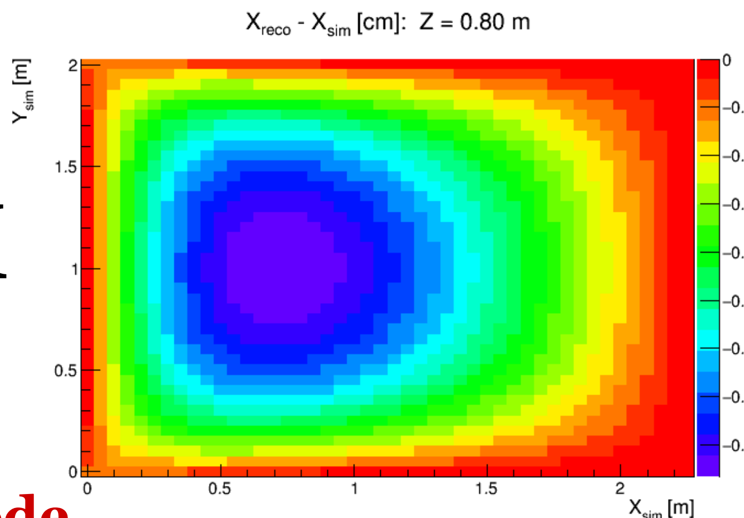


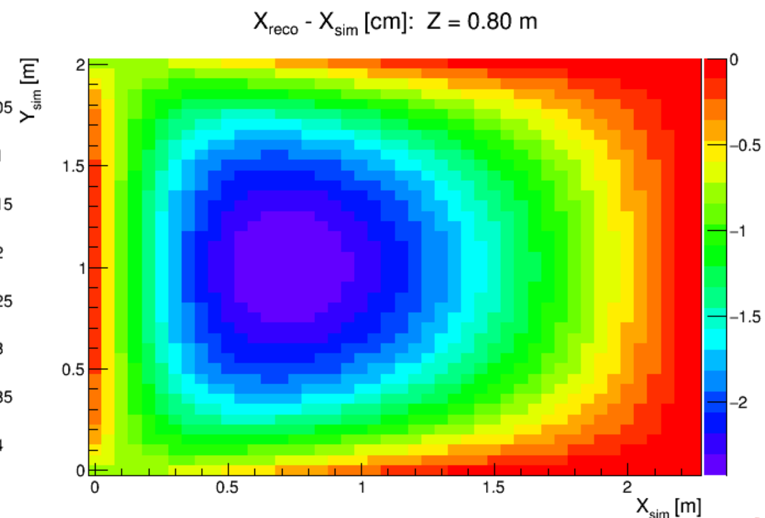


Distortions in 35-ton

	$E_{nominal}$ = 500 V/cm	$E_{nominal}$ = 250 V/cm

ΔX

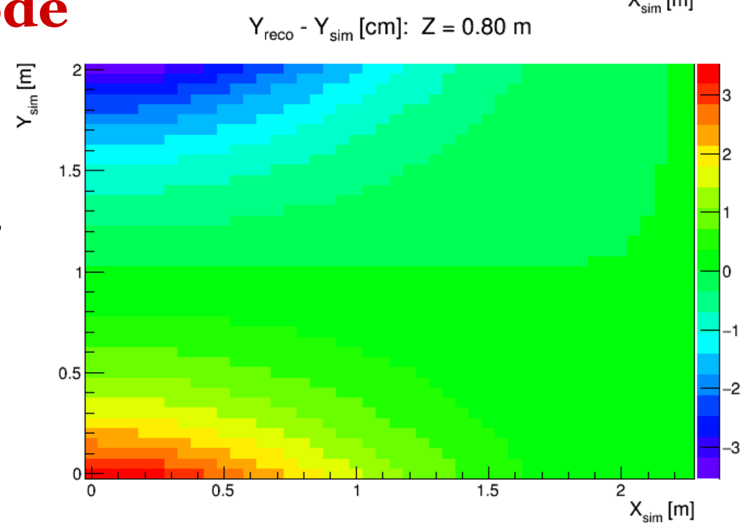


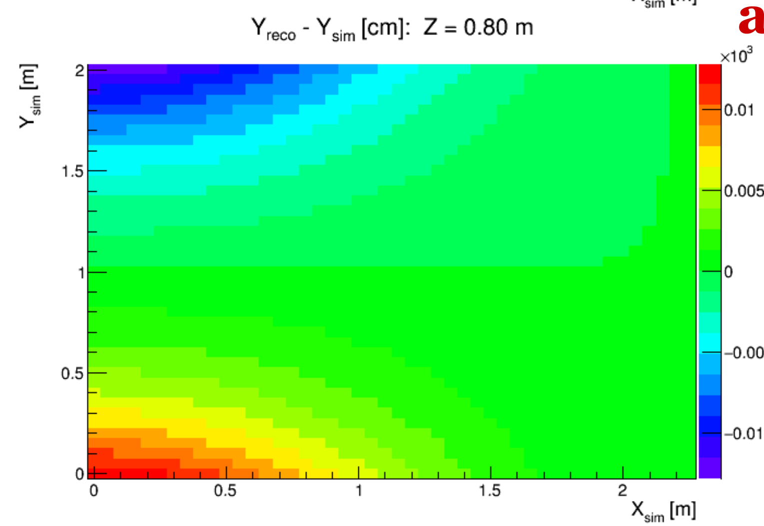


cathode

anode

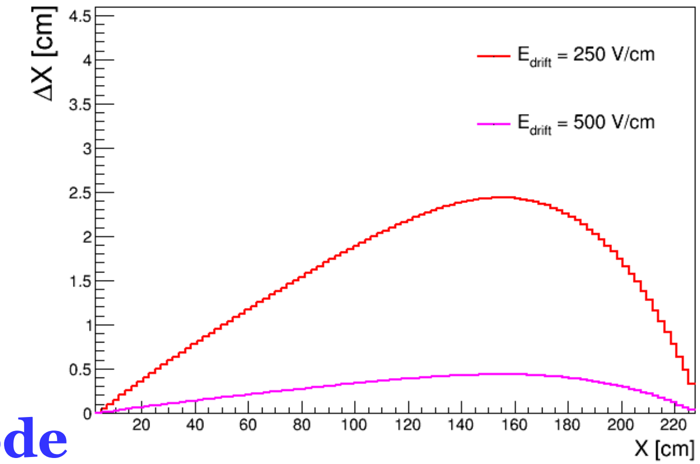
ΔY





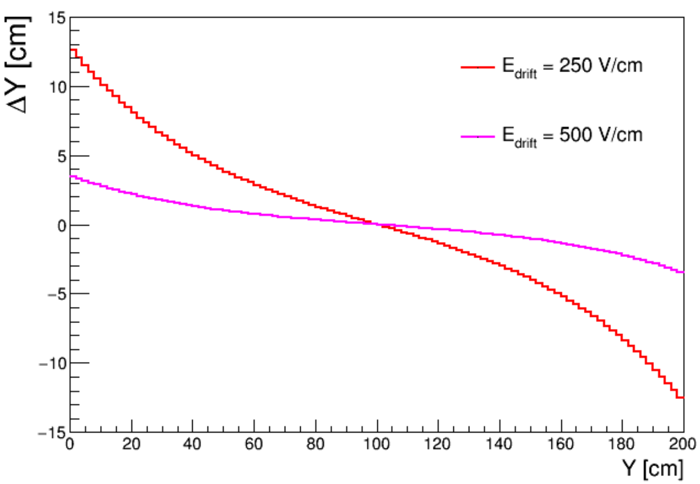
Distortions in 35-ton (cont.)

ΔX (center in Y/Z)

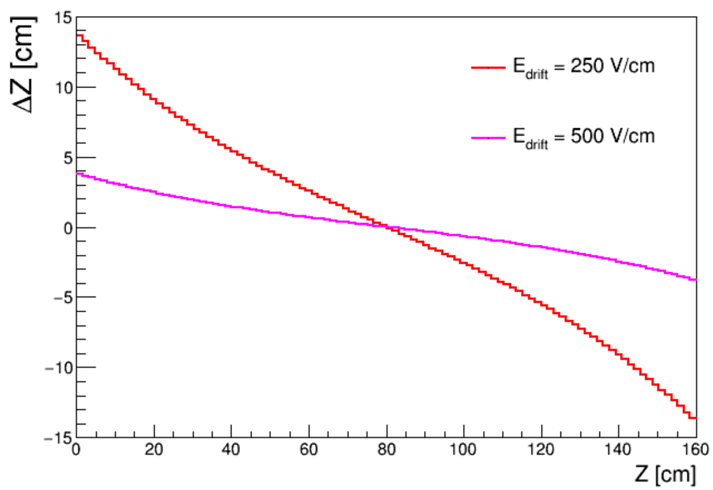


anode **cathode**

ΔY (center in Z, X at cathode)



ΔZ (center in Y, X at cathode)

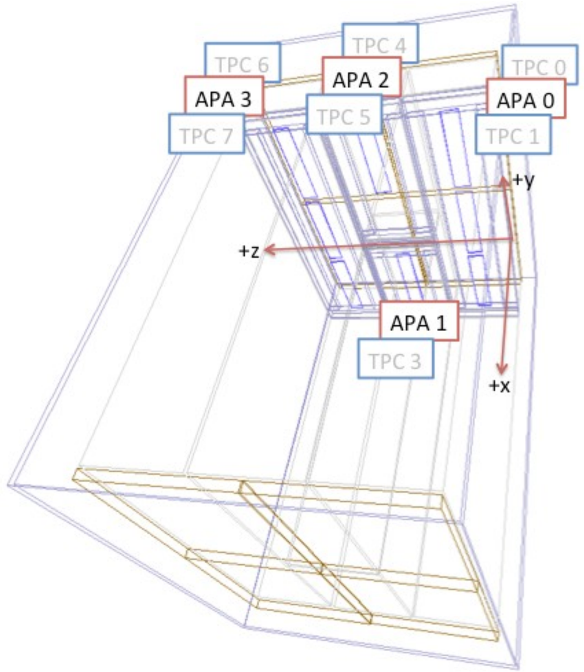


35-ton LArSoft Implementation

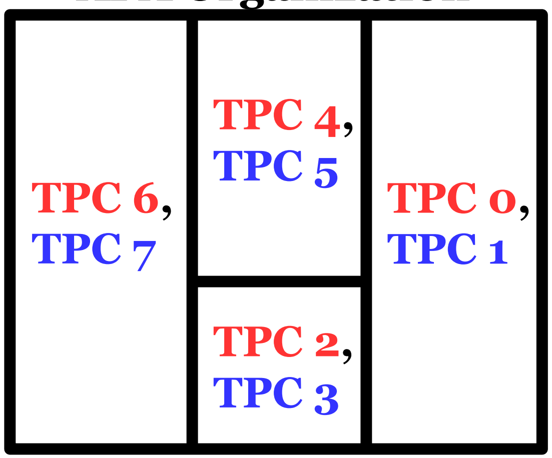
- Some things changed in LArSoft code to make work for DUNE 35-ton:
  - New parameters related to specific geometry of detector
    - Different coordinate transforms in larevt's **SpaceCharge** service for different detector geometries – modified "CoordinateType" in dunetpc/lbne/SpaceCharge/spacecharge_lbne35t.fcl
  - New ionization electron displacement (distortion) maps
    - Generated by **SpaCE code suite**
    - Using parametrization with polynomials for distortions
- DUNE 35-ton setup also requires additional features:
  - Storage of several maps to allow for scan over different HV values
    - Use different input files (250-500 V/cm), store in dedicated area
  - Ability to account for multiple TPC's
    - 35-ton has **eight** – see next slide

35-ton Geometry and SCE

- 35-ton has four APA's, each of which are split into two TPC's corresponding to the two sides of the APA's (see top)
  - APA's are of different sizes (see bottom)
  - Two drift lengths (different sides) per APA: **225 cm** and **27.5 cm**
- Current implementation:
  - Only simulate space charge effect for TPC's with **longer drift length**
    - L^3 dependence of offsets means difference of **~500** in magnitude
    - For now use hard cut on TPCGeo DriftDistance of **50 cm** to exclude short TPC's (LArVoxelReadout.cxx)
  - Use **one** map for other four TPC's
    - APA gaps affect results minimally

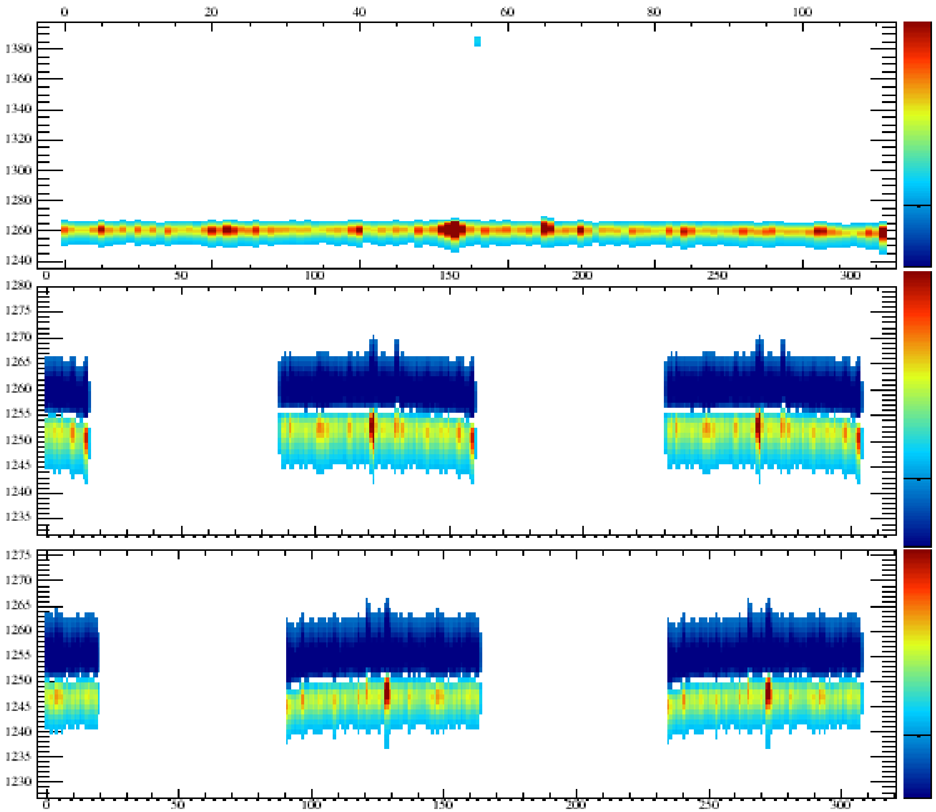


APA Organization

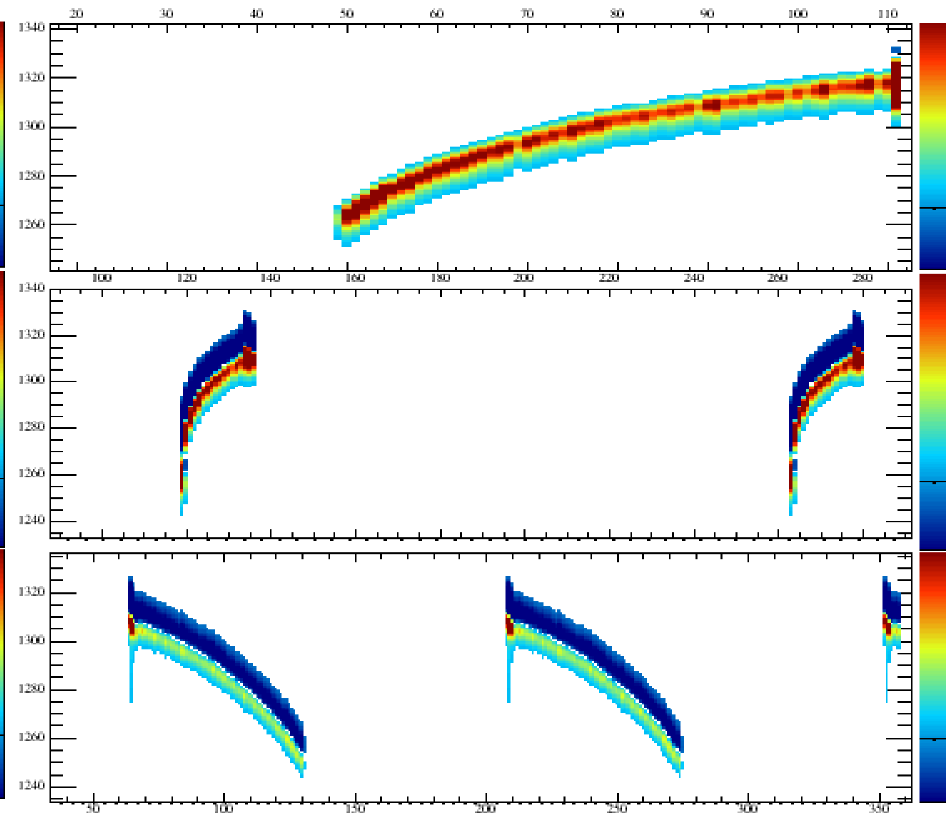


LArSoft Validation

No SCE



30X SCE
(500 V/cm)

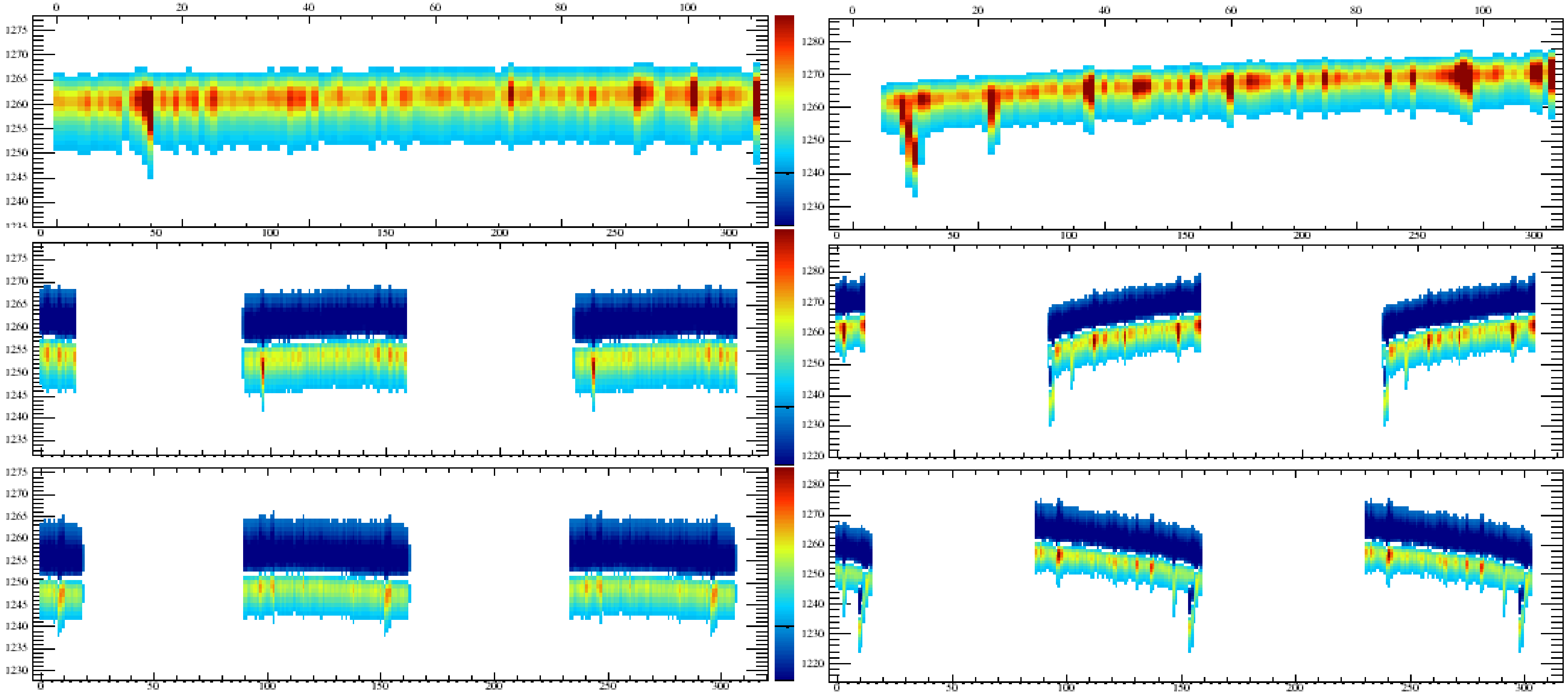


APA 0

LArSoft Validation (cont.)

1X SCE (500 V/cm)

1X SCE (250 V/cm)



APA 0

Summary

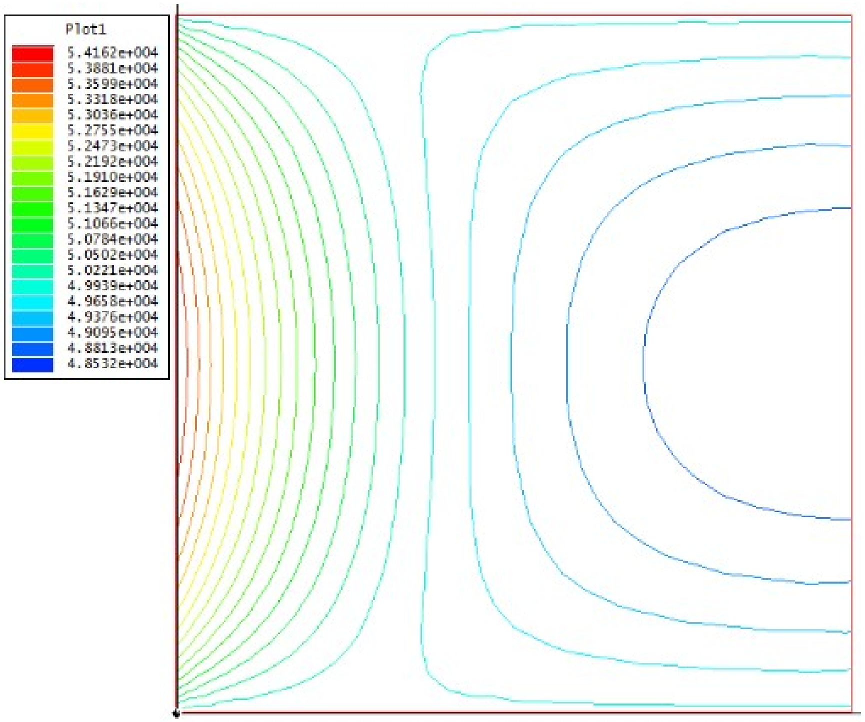
- **SpaCE** – use to study space charge effect and produce SCE distortions throughout a TPC
  - Stand-alone C++ code with ROOT/ALGLIB libraries
- Incorporated simulations into **LArSoft**, which have now been extended to 35-ton
  - Multiple drift E fields supported (250, 300, 350, 400, 450, 500 V/cm)
  - Excludes drift volumes with especially short maximal drift length (hard cut at **50 cm**) – for DUNE 35-ton, this means four out of eight TPC's are excluded
  - See **feature/mrmooney_spacechargeupdate**
    - Packages: larsim, larevt, dunetpc
- Very simple to turn on SCE in your FHICL file:
  - **services.user.LArG4Parameters.EnableSCE = true**

BACKUP SLIDES

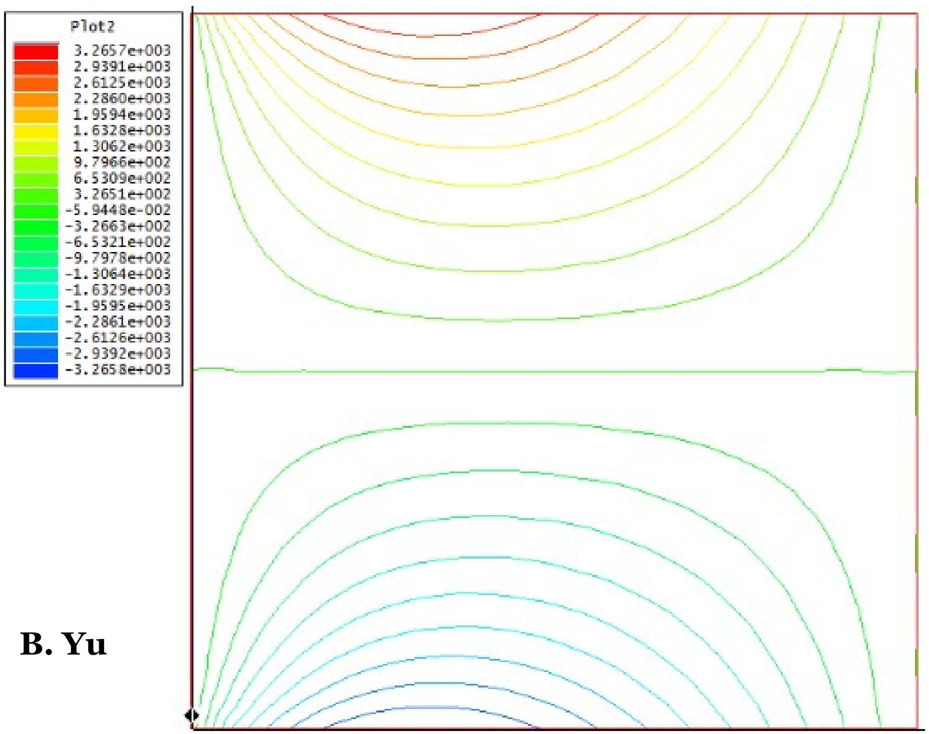
Impact on E Field

- Visualization of impact on E field (Bo Yu's Maxwell-2D studies)
- Assumptions:
  - Constant charge deposition rate throughout detector
  - No liquid argon flow – **serious complication**

Drift Direction



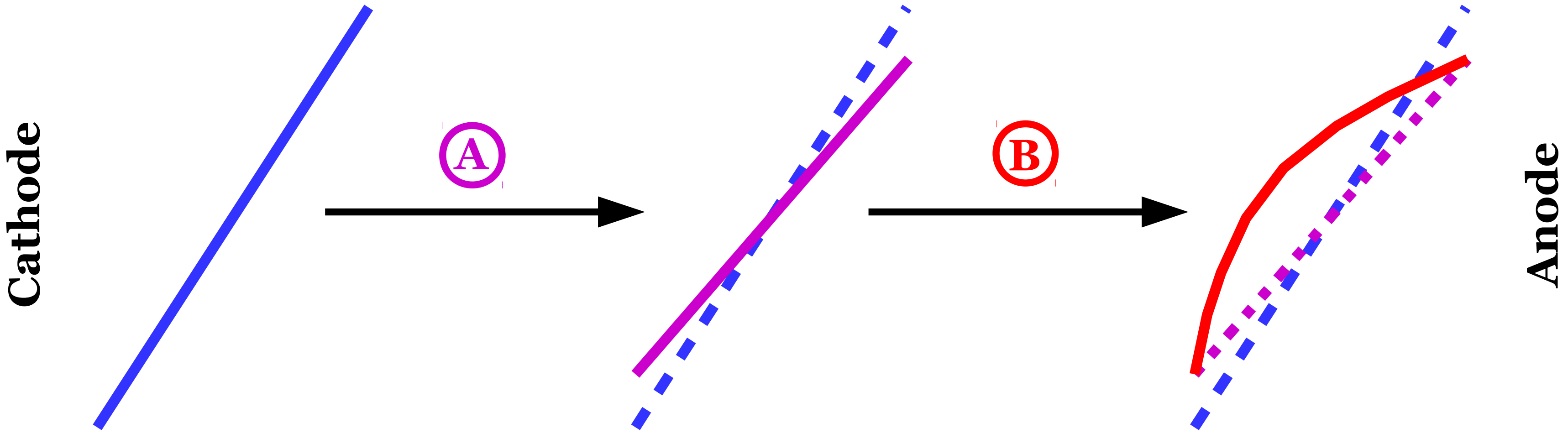
Lateral Directions



B. Yu

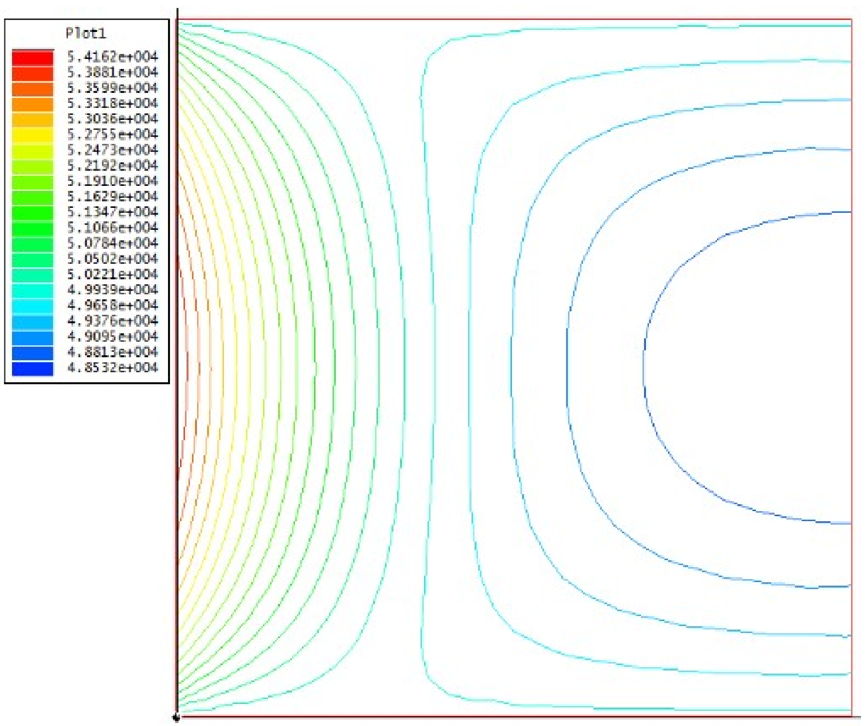
Impact on Track Reco.

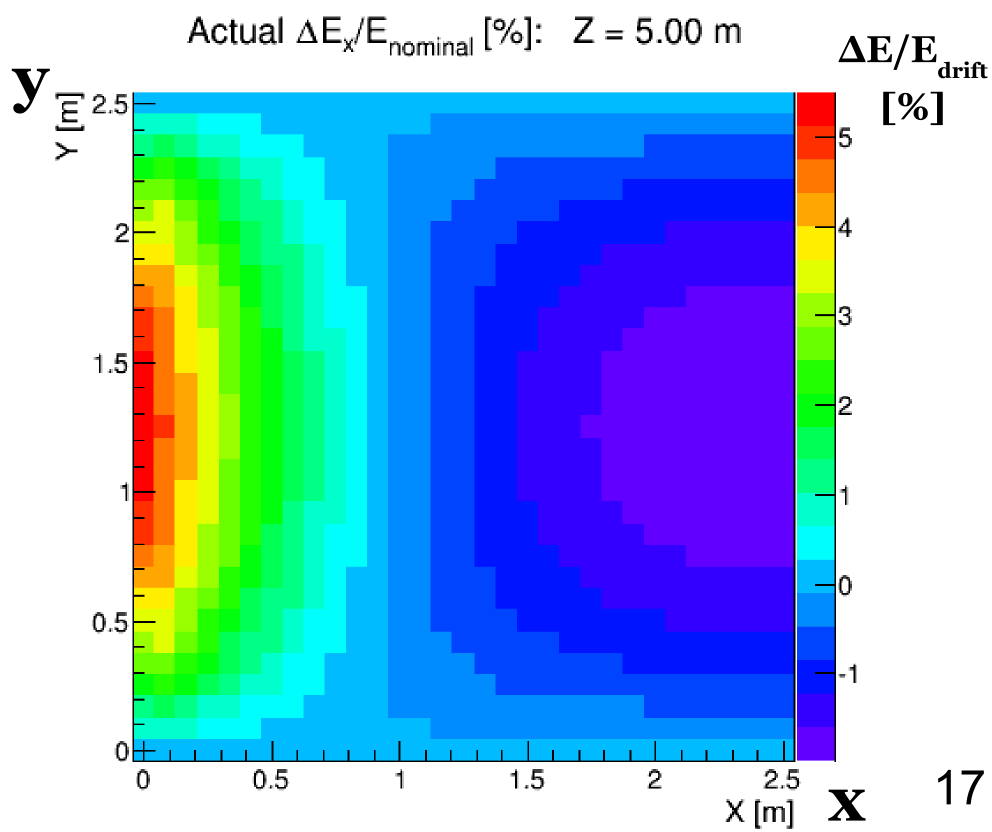
- Two separate effects on reconstructed **tracks**:
  - (A) • Reconstructed track shortens laterally (looks rotated)
  - (B) • Reconstructed track bows toward cathode (greater effect near center of detector)
- Can obtain straight track (or multiple-scattering track) by applying corrections derived from data-driven calibration



Compare to FE Results: E_x

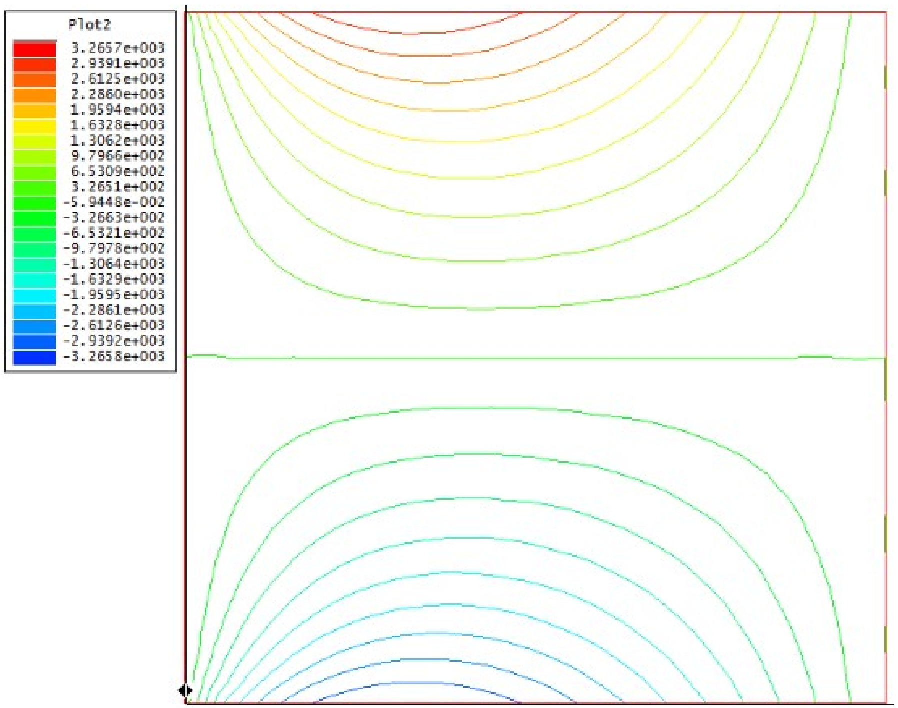
- Looking at central z slice (z = 5 m) in x-y plane
- Very good shape agreement compared toBo's 2D FE (Finite Element) studies
- Normalization differences understood (using different rate)

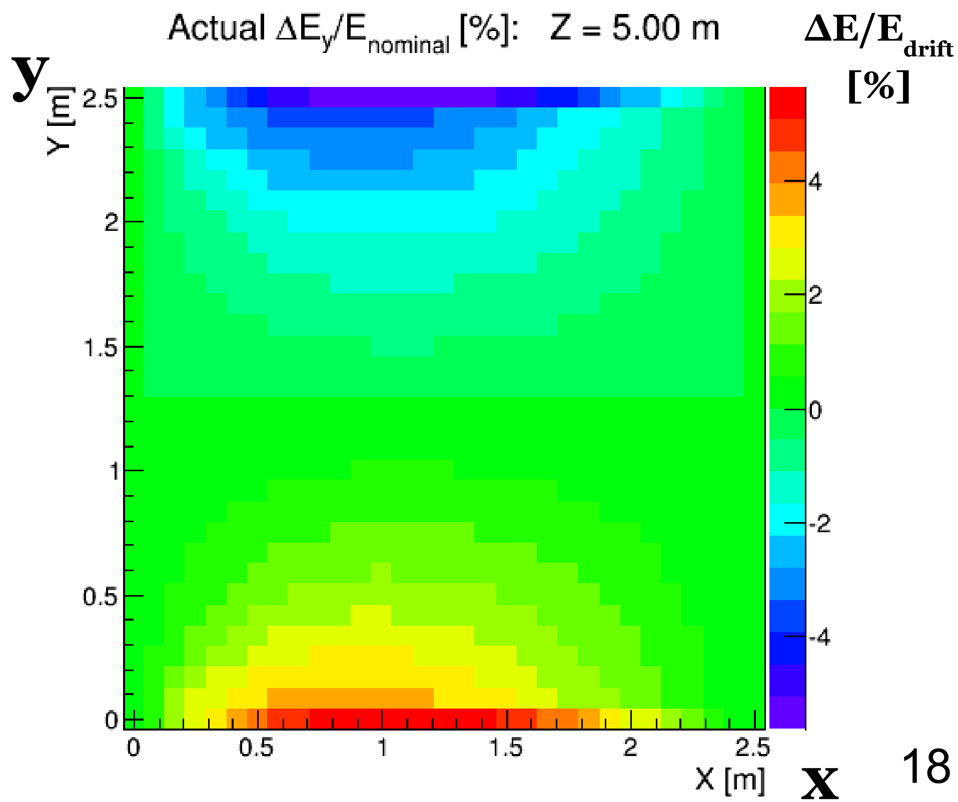




Compare to FE Results: E_y

- Looking at central z slice (z = 5 m) in x-y plane
- Very good shape agreement here as well
  - Parity flip due to difference in definition of coordinate system

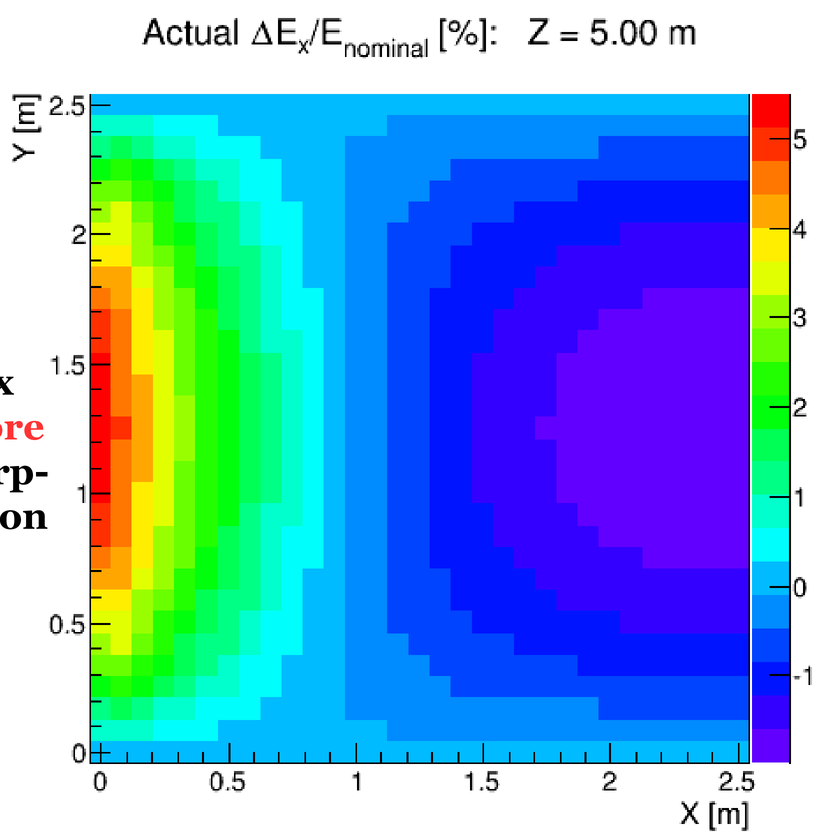


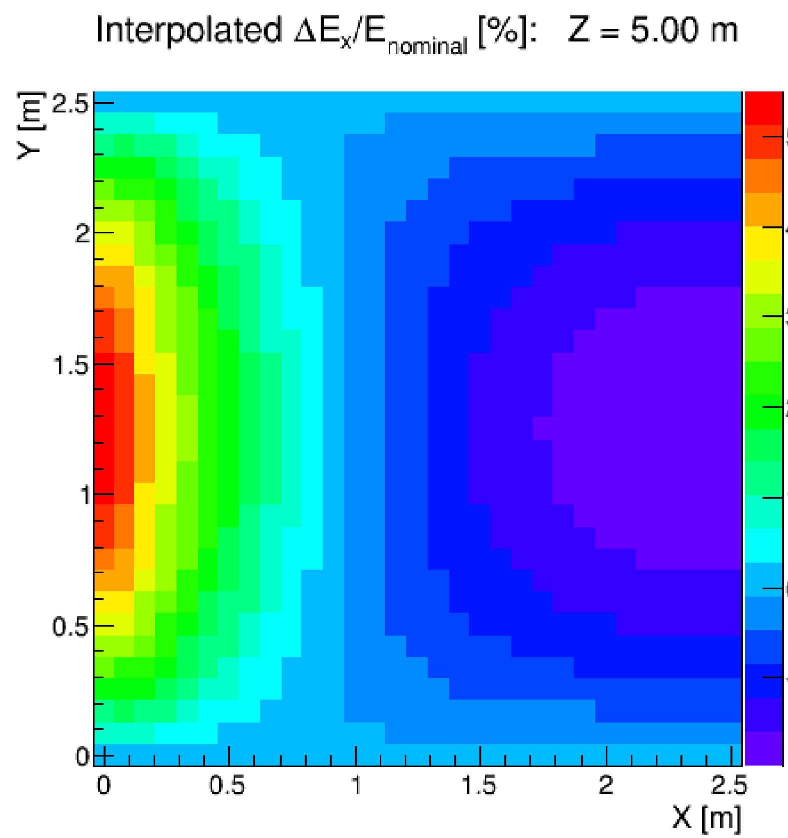


E Field Interpolation

- Compare 30 x 30 x 120 field calculation (left) to 15 x 15 x 60 field calculation with interpolation (right)
- Include analytical continuation of solution points **beyond** boundaries in model – improves performance near edges

E_x
Before
Interp-olation

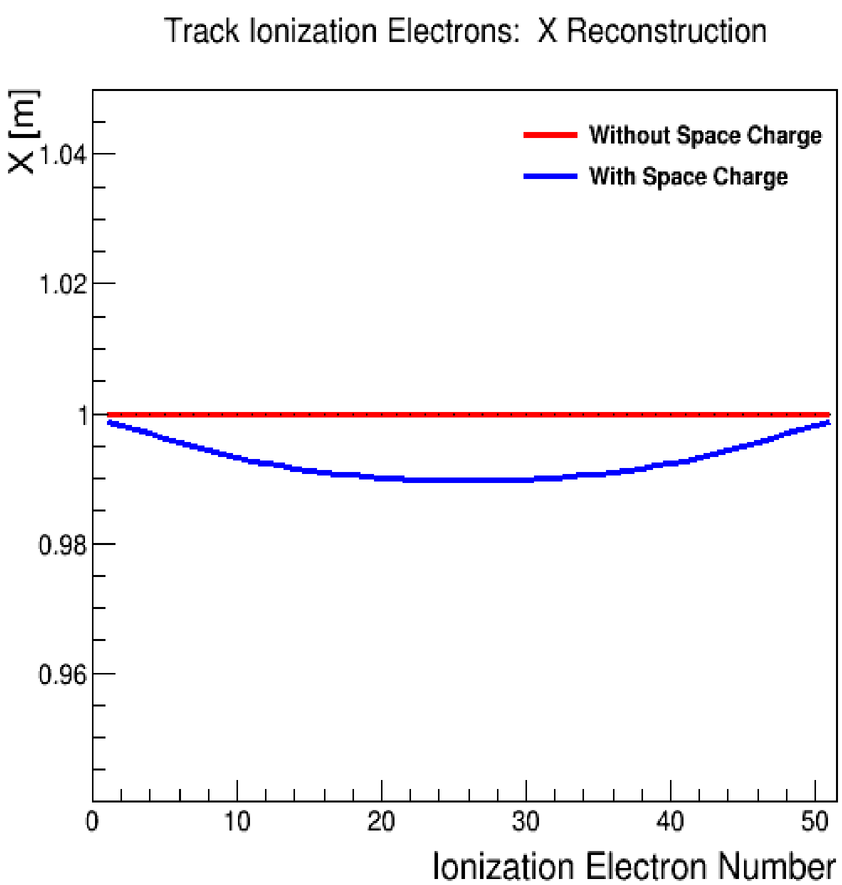


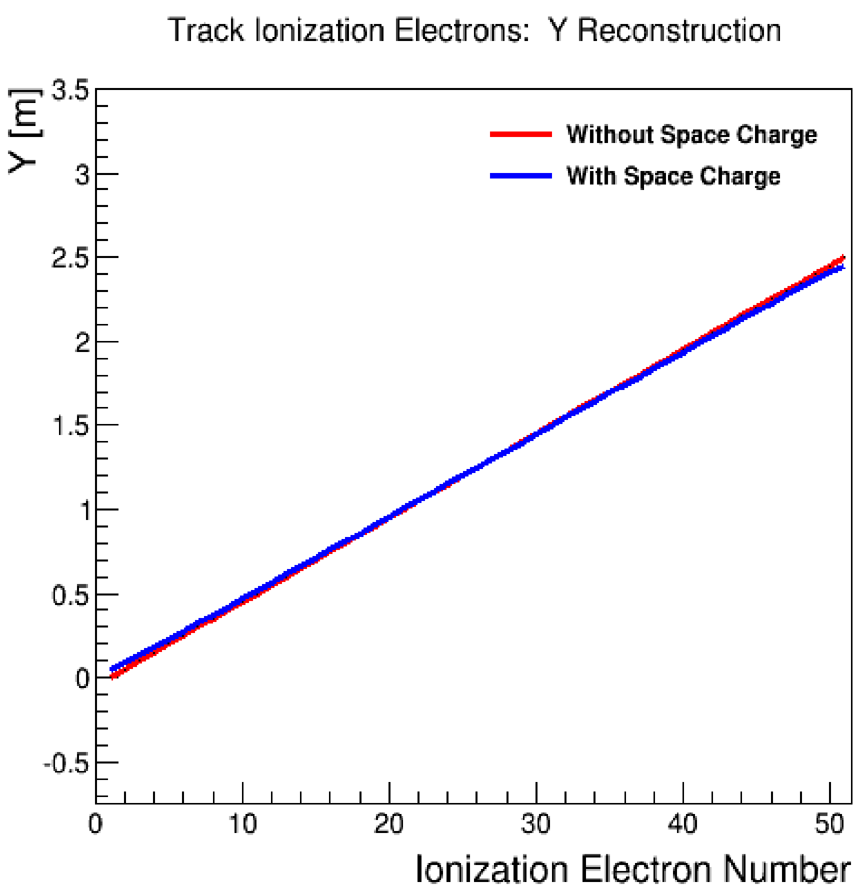


E_x
After
Interp-olation

Ray-Tracing

- Example: track placed at **x = 1 m** (anode at x = 2.5 m)
  - z = 5 m, y = [0,2.5] m

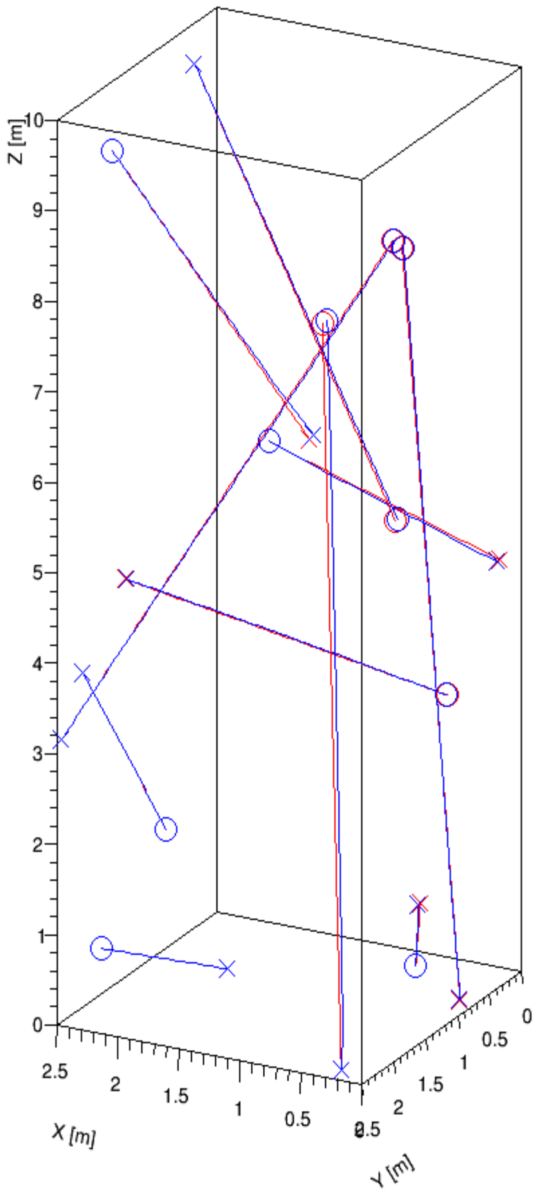


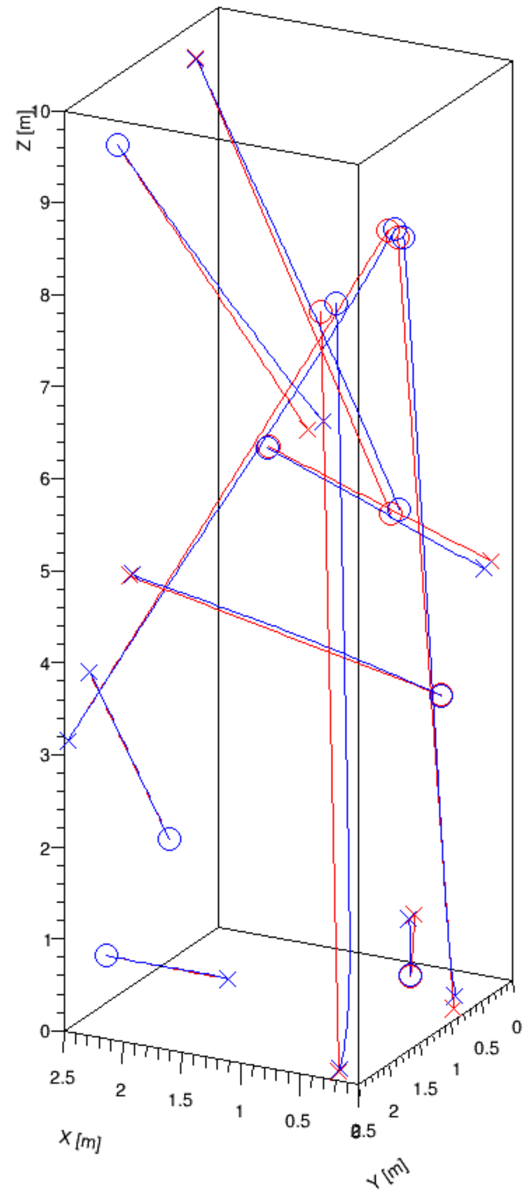


Sample “Cosmic Event”

Nominal Drift Field

500 V/cm





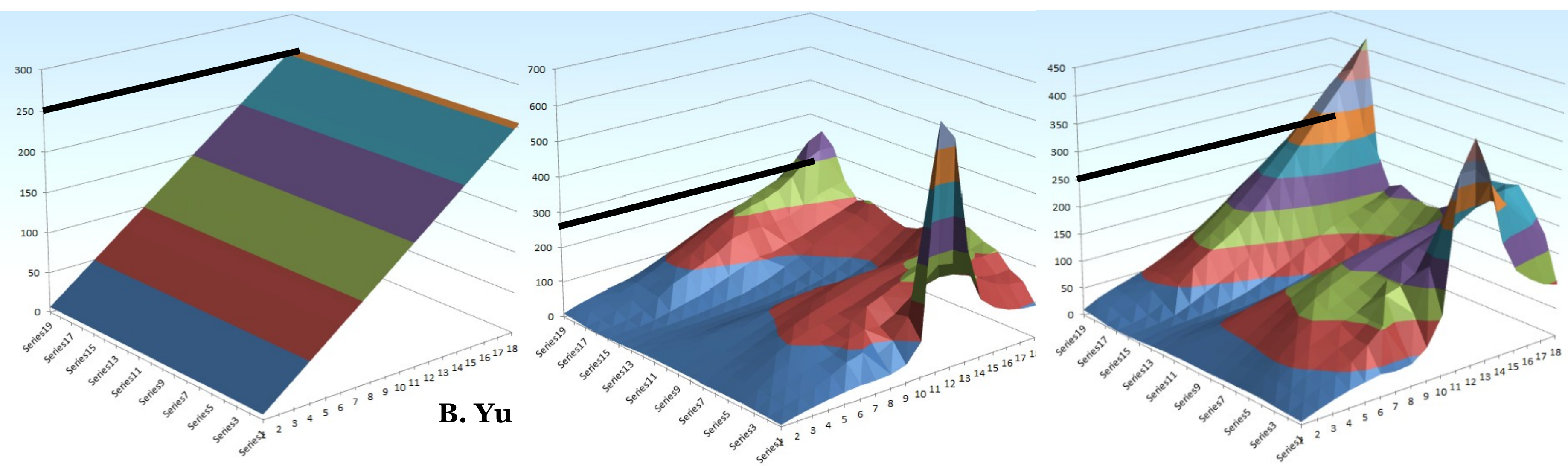
Half Drift Field

250 V/cm

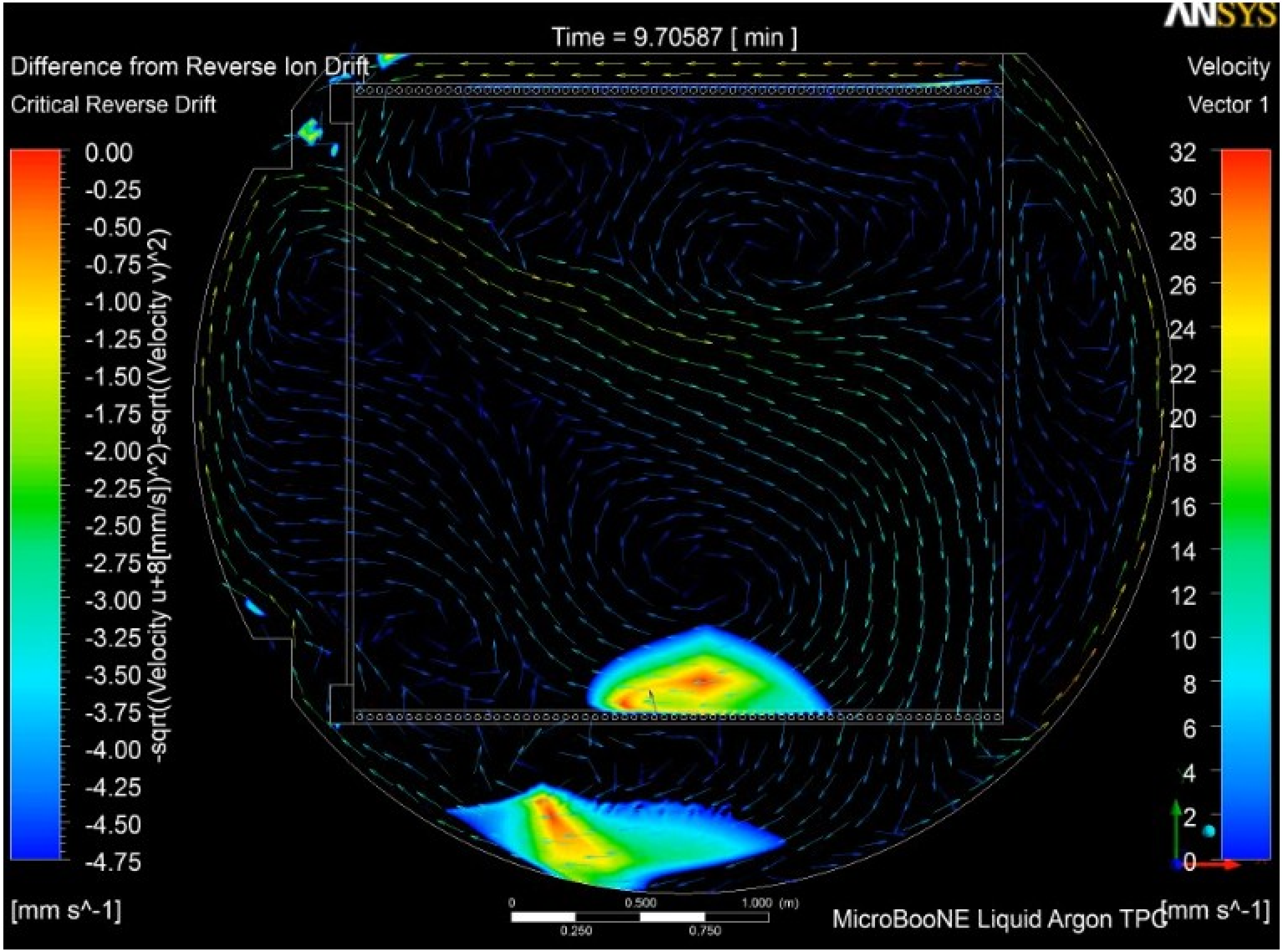
Complications

- Not accounting for non-uniform charge deposition rate in detector → significant modification?
- Flow of liquid argon → likely significant effect!
  - Previous flow studies in 2D… differences in 3D?
  - Time dependencies?

No Flow | **Flow w/o Turbulence** | **Flow w/ Turbulence**



Liquid Argon Flow



B. Yu

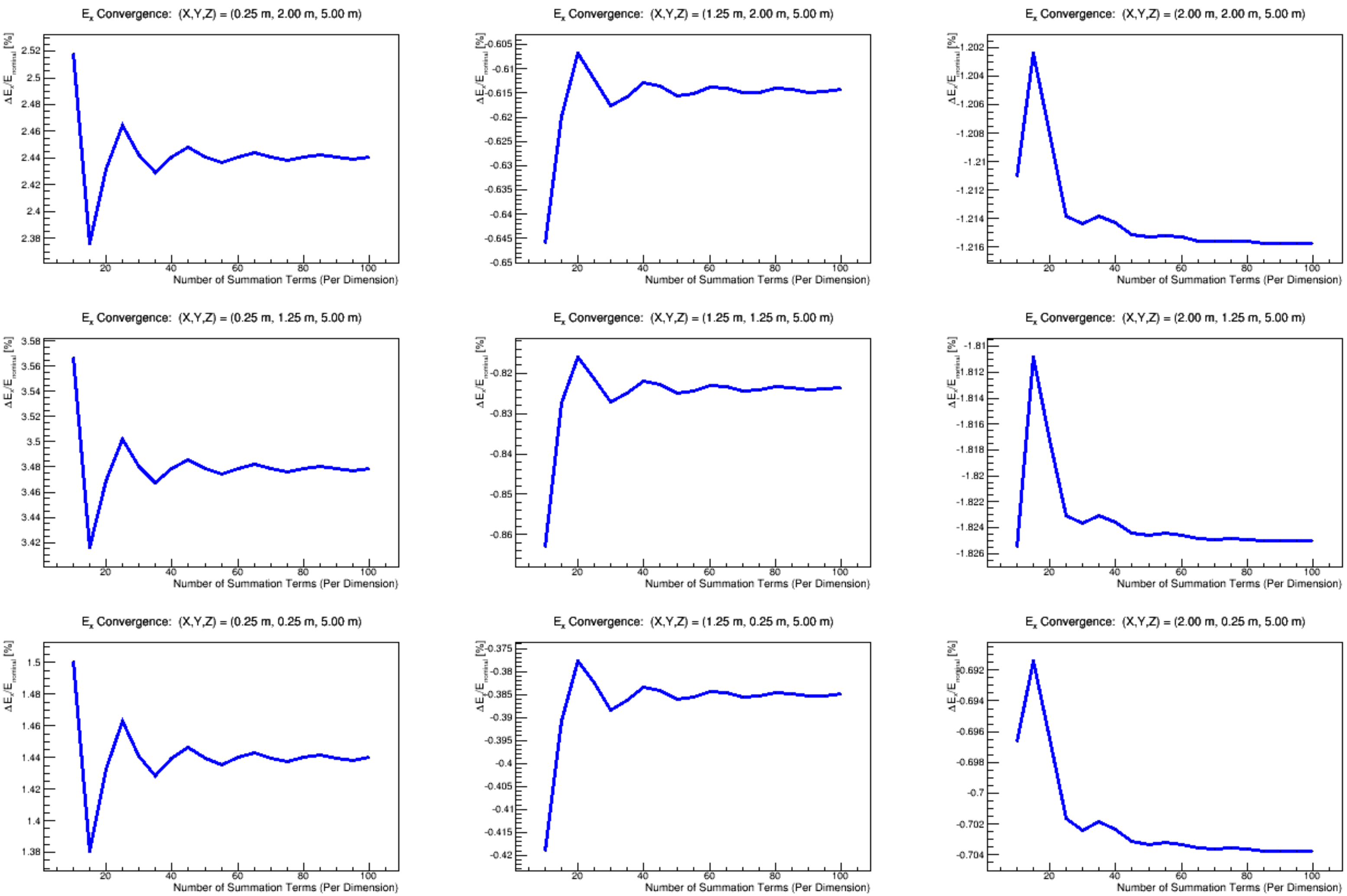
E Field Calc. Convergence

<u>Example</u>: E_x Convergence in x-y Plane (z = 5 m)

y = 2 m

y = 1.25 m

y = 0.25 m

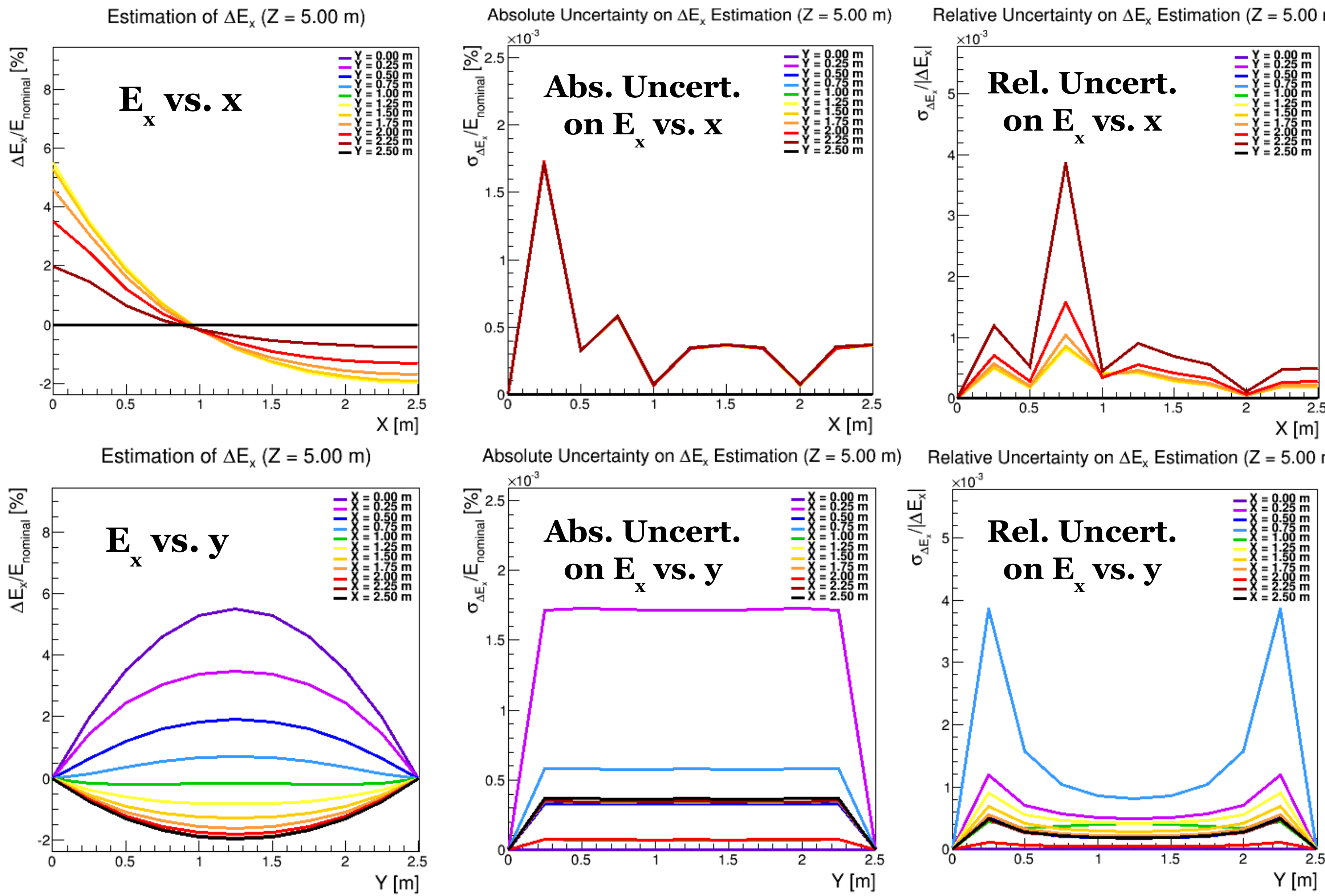


x = 0.25 m

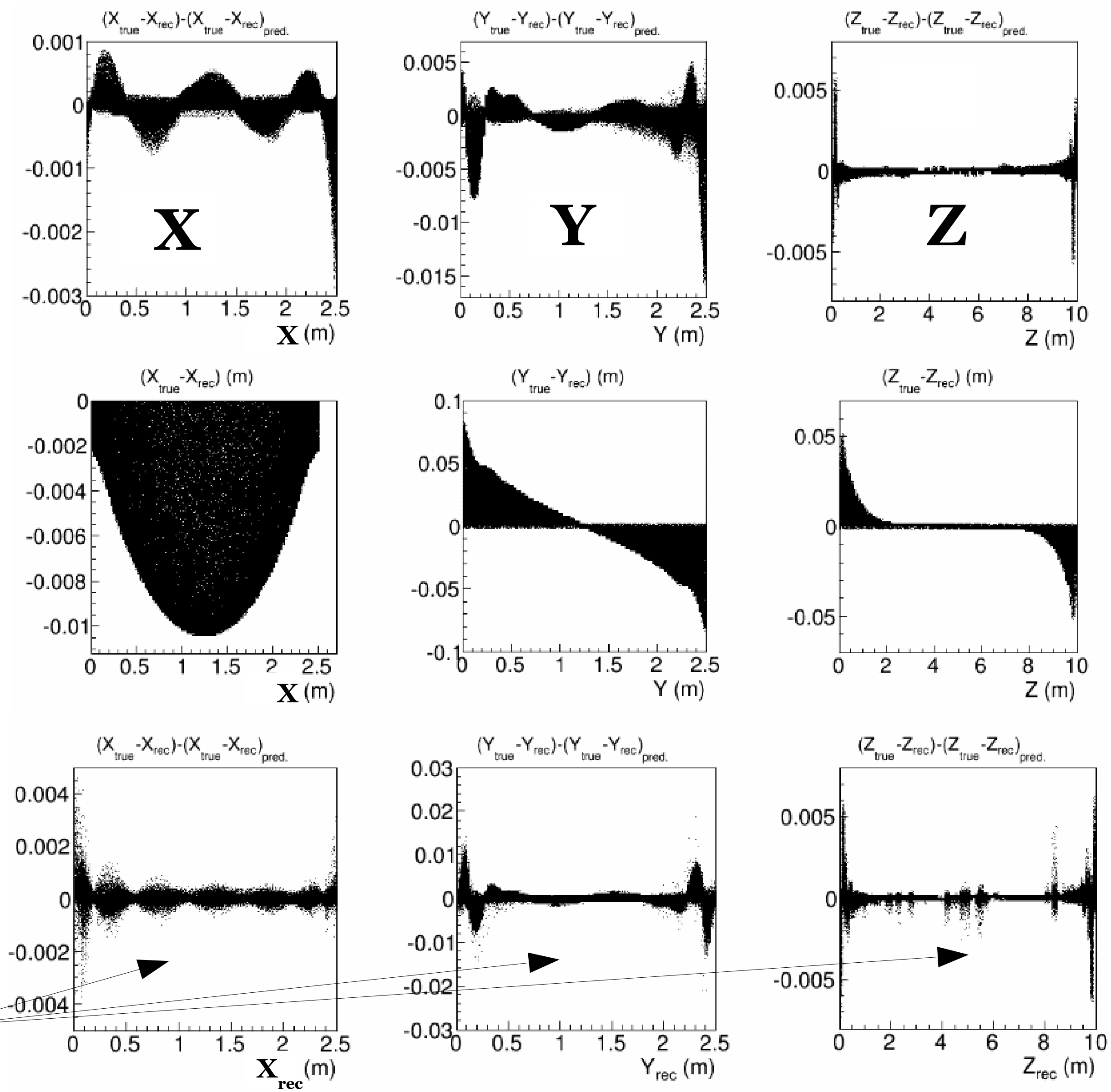
x = 1.25 m

x = 2 m

E Field Calc. Uncertainty



Simulation: Parametric Rep.



Residuals of Forward Transportation (Uncert. in Simulation of Effect)

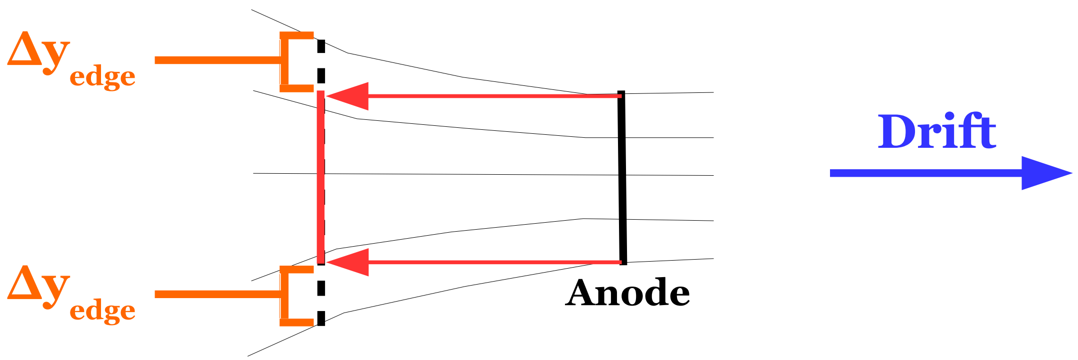
Impact of Space Charge Effect (Reconstruction Bias)

Residuals of Backward Transportation (Post-bias-correction Uncert. for <u>Perfect</u> Calibration)

Reality: these will be larger!

Smoking-gun Test for SCE

- Can use cosmic muon tracks for calibration
  - Possibly sample smaller time scales more relevant for a particular neutrino-crossing time slice
  - Minimally: data-driven cross-check against laser system calibration
- **Smoking-gun test**: see lateral charge displacement at track ends of non-contained cosmic muons → space charge effect!
  - No timing offset at transverse detector faces (no E_x distortions)
  - Most obvious feature of space charge effect

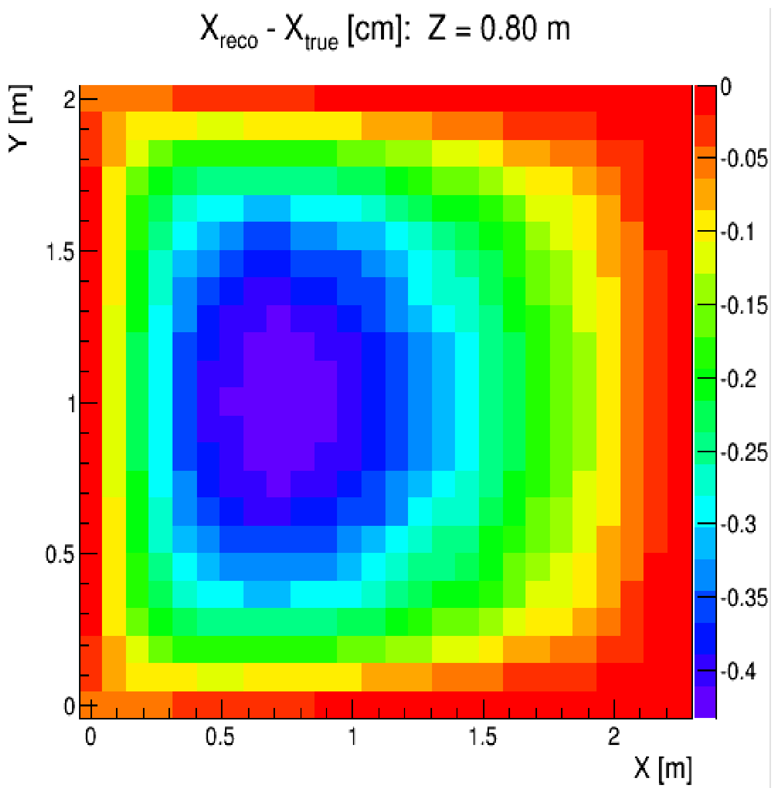


35-ton with LAr Flow

central z slice

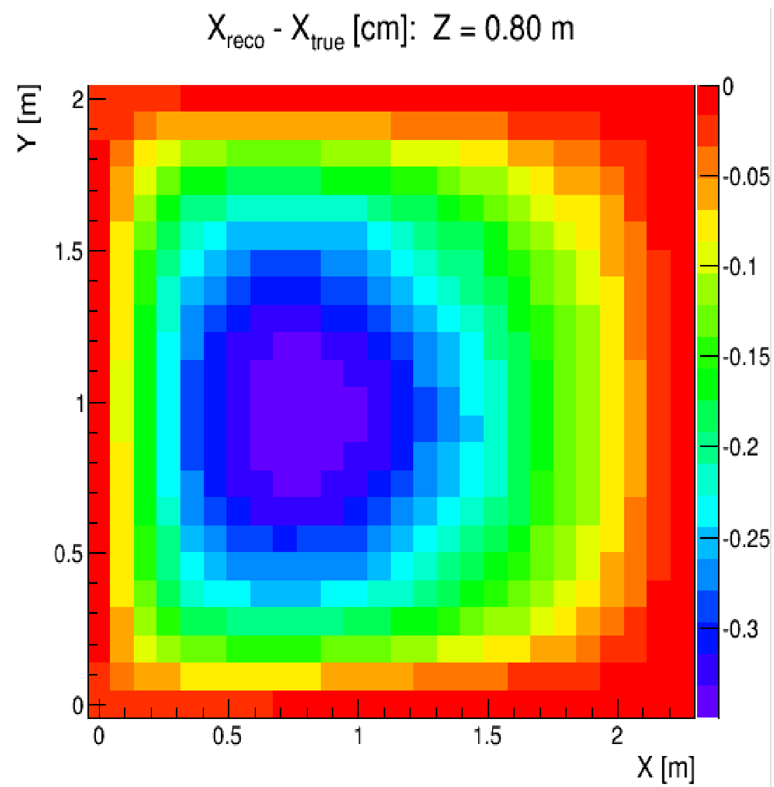
Δx

Without LAr Flow



Δx

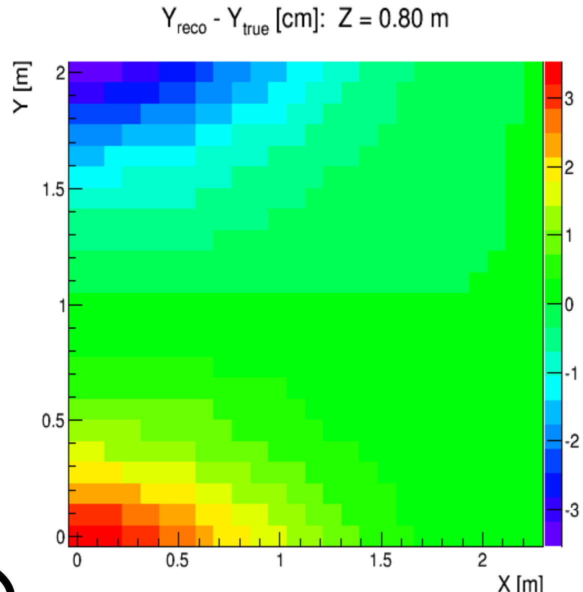
With LAr Flow

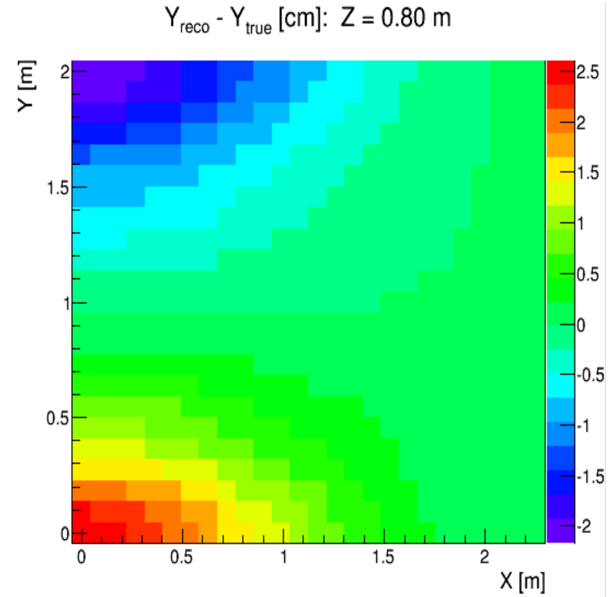


Q map from E. Voirin

35-ton with LAr Flow (cont.)

Δy
Without
LAr Flow



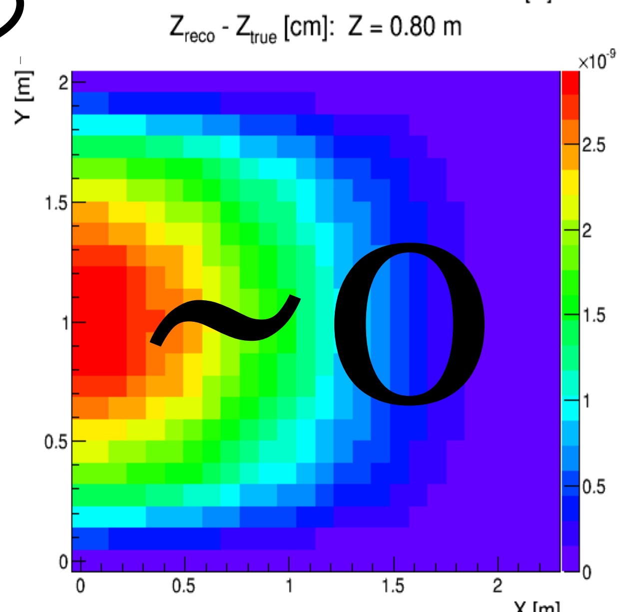


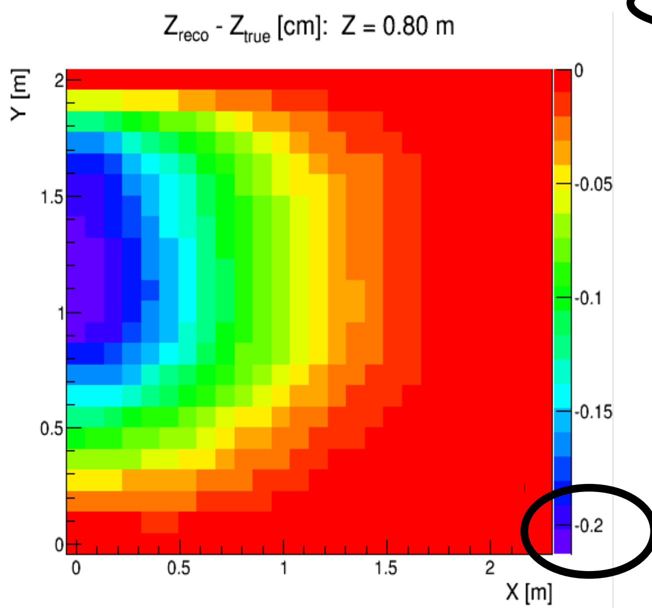
Δy
With
LAr Flow

Q map from E. Voirin

central z slice

Δz
Without
LAr Flow





Δz
With
LAr Flow