Space Charge Effect at ProtoDUNE: LArSoft Implementation

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BNL

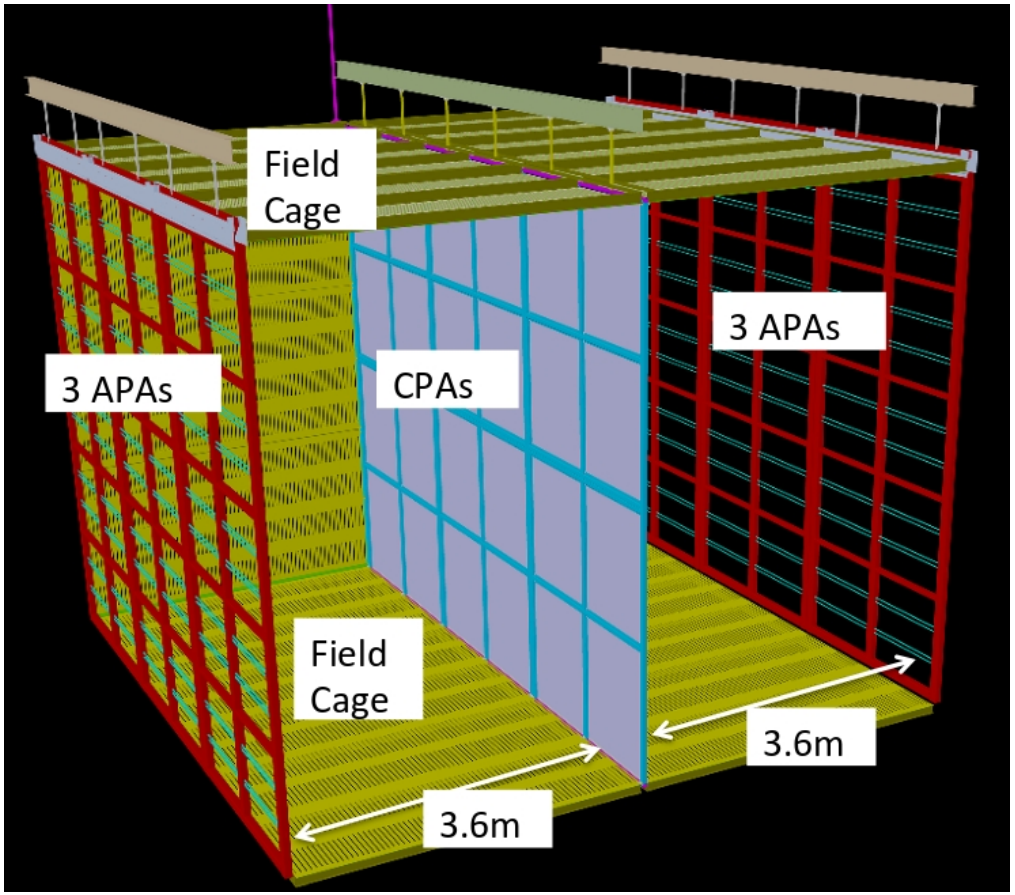
ProtoDUNE Measurements Meeting

May 10th, 2016

Introduction

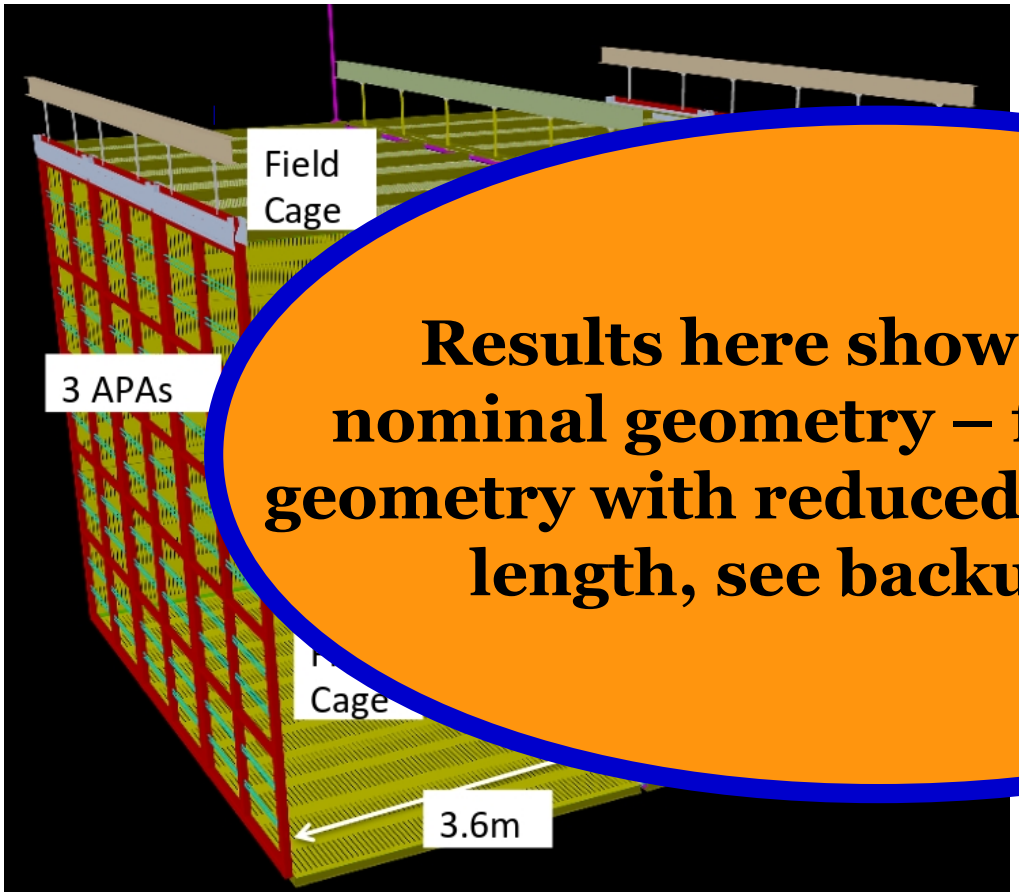
- Tool exists to study space charge effect at the **MicroBooNE detector**
  - Home-brewed software suite: **SpaCE** – Space Charge Estimator
  - Previously showed relative magnitude of space charge effect in ProtoDUNE using SpaCE simulations
  - LArSoft module exists to hold/access SCE offsets for MicroBooNE
  - Now: include generic LArTPC implementation of space charge effect simulation in LArSoft
- Outline:
  - Brief review of expected SCE characteristics at ProtoDUNE
  - Discussion of new LArSoft module (and how to use)
  - SCE calibration scheme discussion

Nominal Geometry



- Nominal ProtoDUNE geometry:
  - Drift (X): 3.6 m
  - Height (Y): 5.9 m
  - Length (Z): 7.0 m
- Dimensions used for simulations slightly different (to simplify calculations):
  - Drift (X): 3.6 m
  - Height (Y): 6.0 m
  - Length (Z): 7.2 m

Nominal Geometry



Results here shown only for nominal geometry – for modified geometry with reduced maximal drift length, see backup slides.

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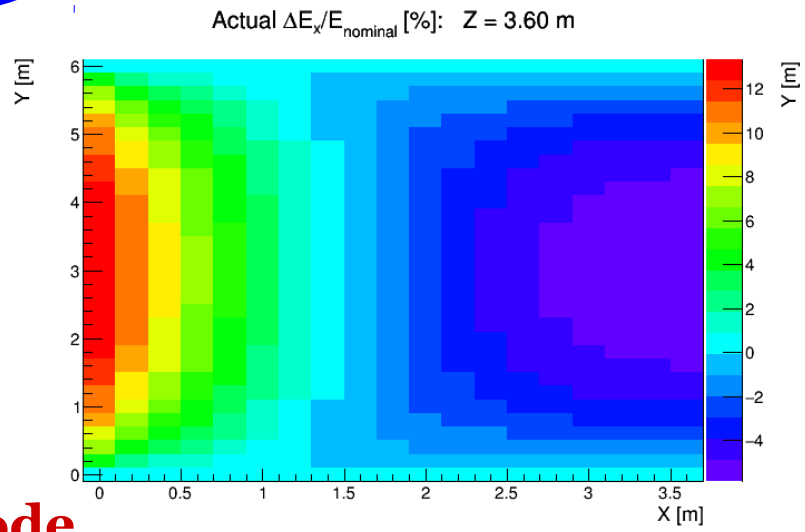
Modified E Field (Central Z)

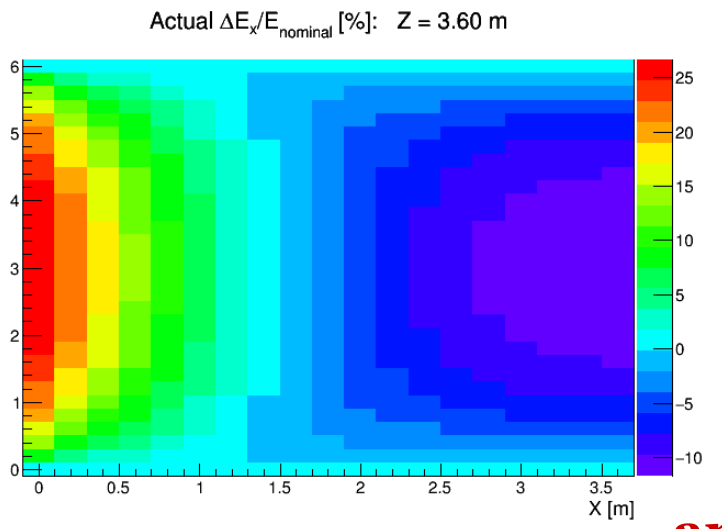
Nominal Geometry

$E_{nominal}$ = 500 V/cm

$E_{nominal}$ = 250 V/cm

E_X

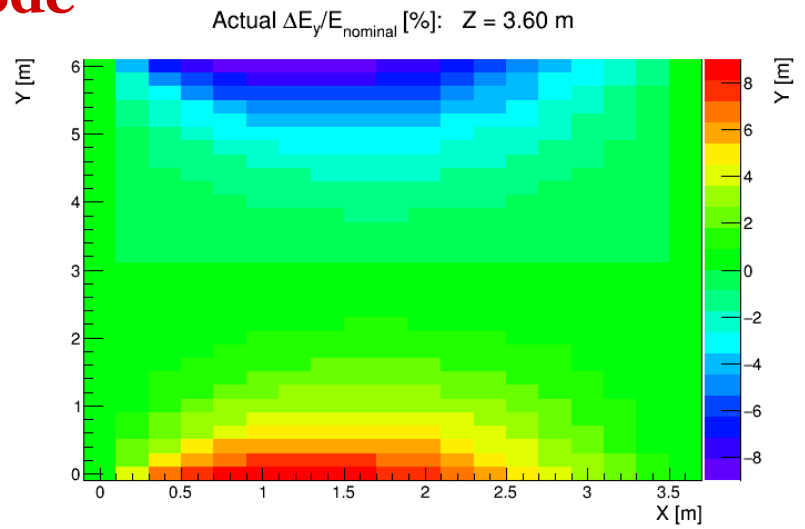


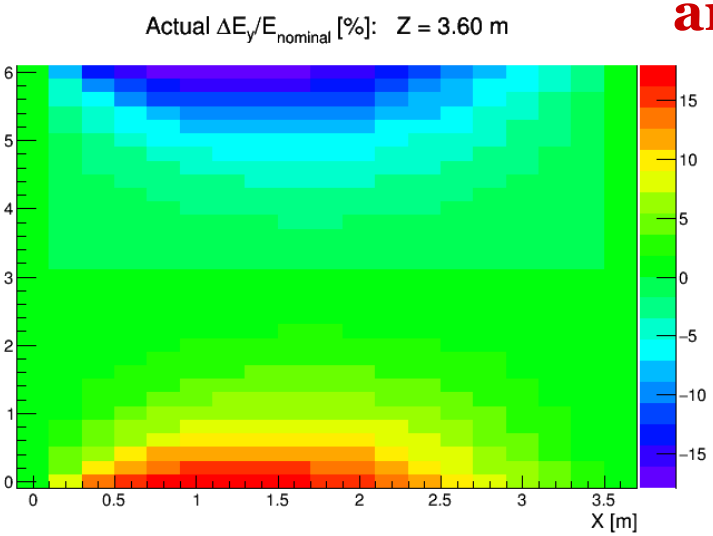


cathode

anode

E_Y





Modified E Field (TPC End)

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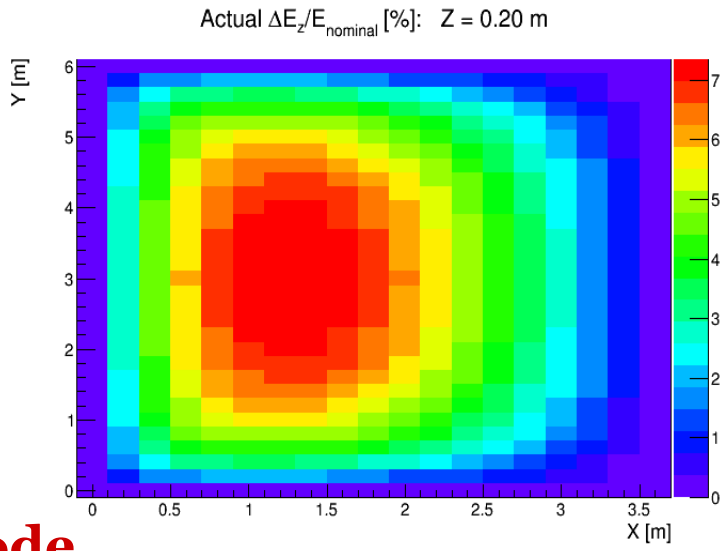
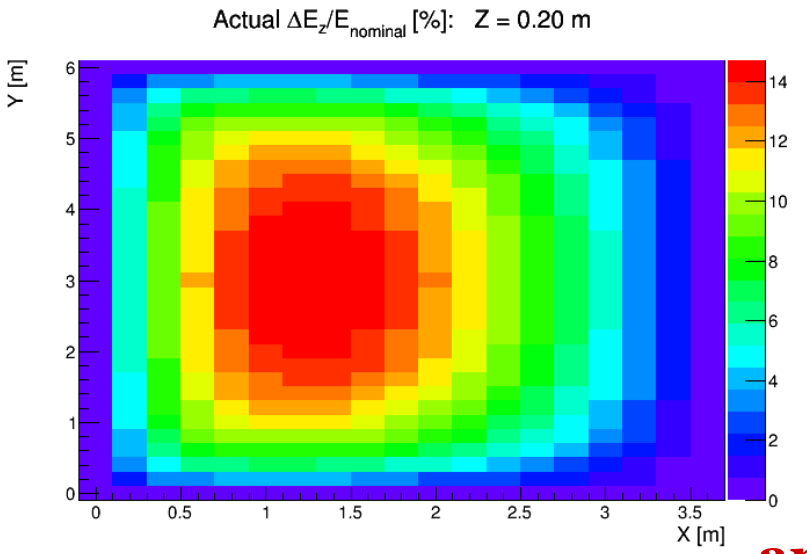
E_Z





cathode

anode

Distortions (Central Z)

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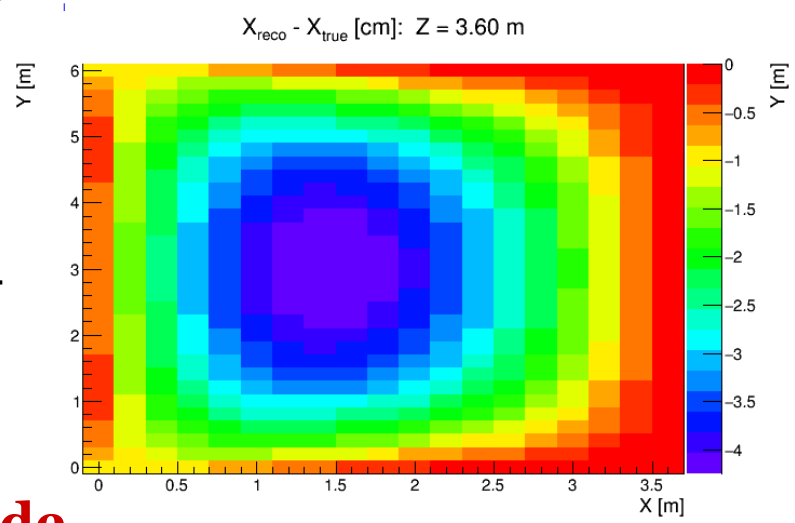
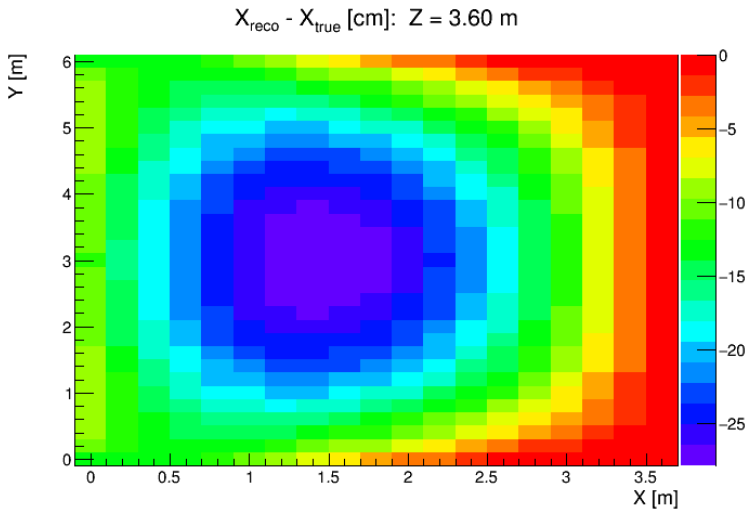
ΔX

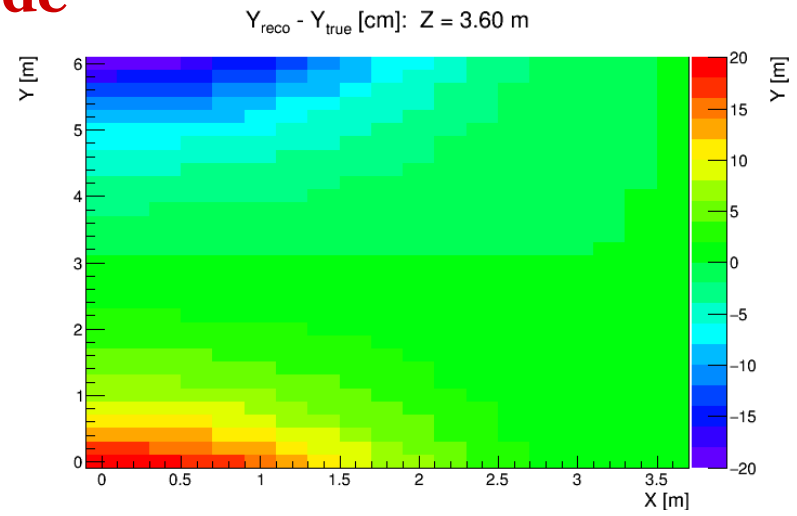


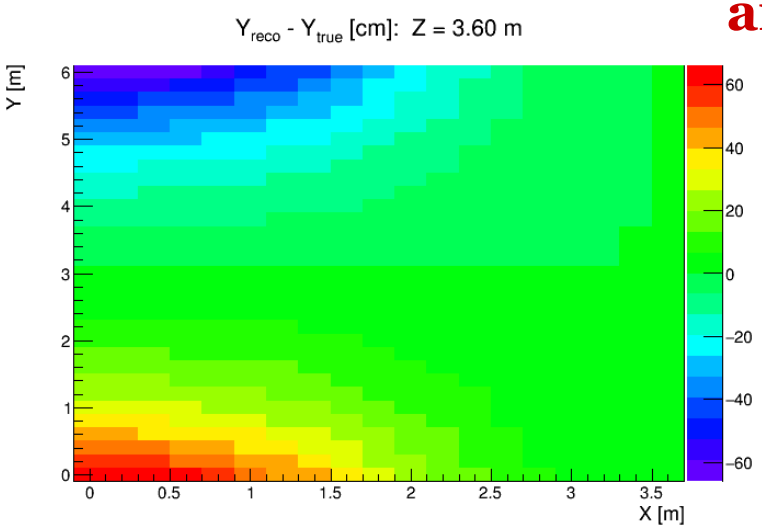


cathode

anode

ΔY





Distortions (TPC End)

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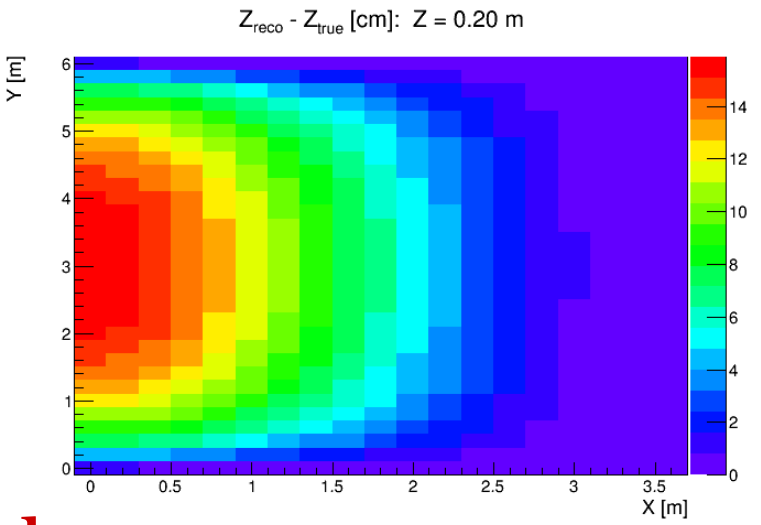
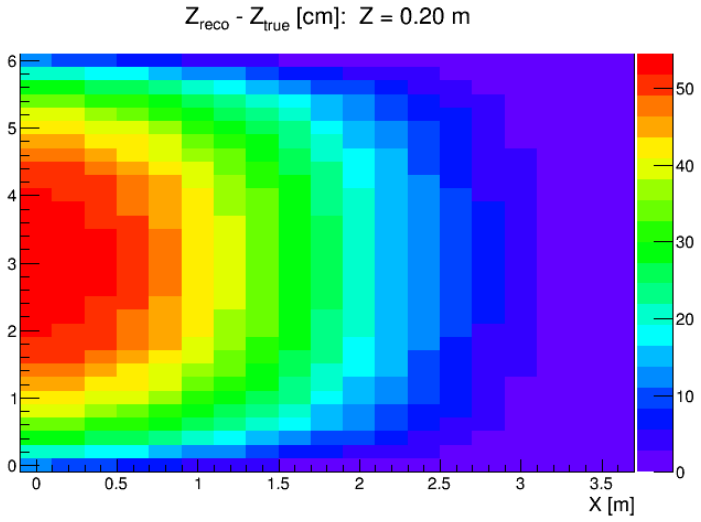




cathode

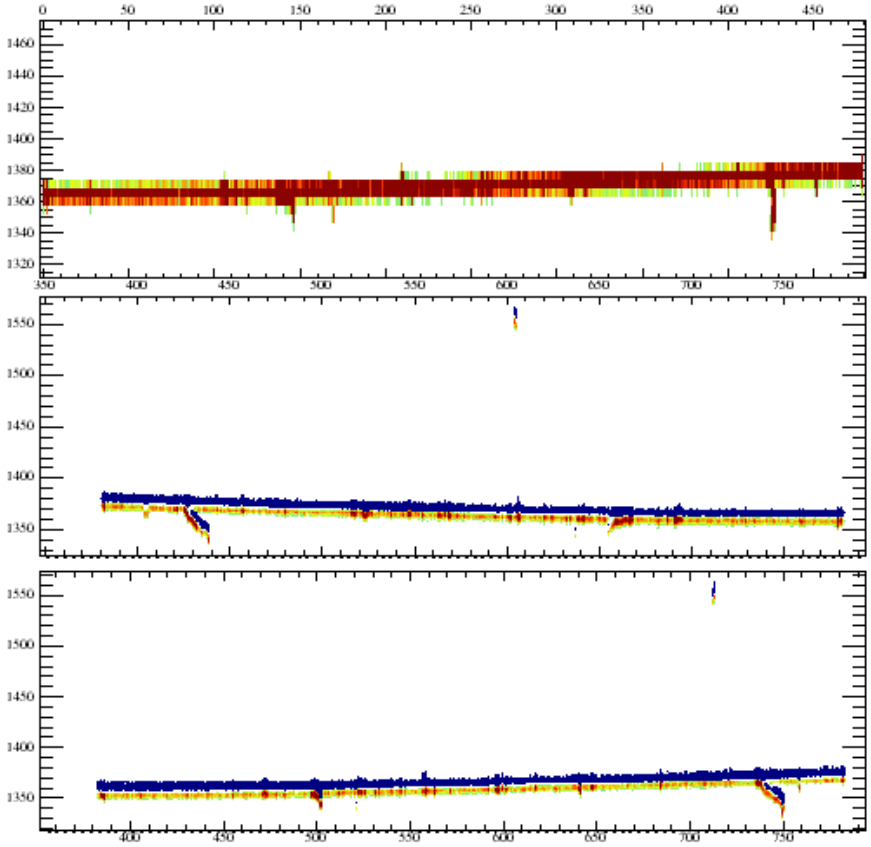
anode

LArSoft Implementation

- LArSoft implementation of SCE simulation still waiting to be blessed by LArSoft Coordination Team (next week?)
  - Currently resides on feature/mrmooney_SpaceChargeMay6th2016
  - Works with **larsoft v5_11_00**
  - Check out this branch for the following packages:
    - **larsim** (carries out simulation of effect in LArVoxelReadout.cxx)
    - **larevt** (holds SpaceCharge base class/service)
    - **dunetpc** (provides access to ProtoDUNE-specific distortions)
  - Also require file containing SCE offsets for ProtoDUNE
    - Will eventually be located in ${LARSOFT_DATA_DIR}
    - For now, email me and ask for the (small) file
- To turn on SCE simulation (**spatial distortions only** – will include E field magnitude distortions in later release):
  - **services.user.SpaceCharge.EnableSimulationSCE: true**

LArSoft Validation

Without SCE



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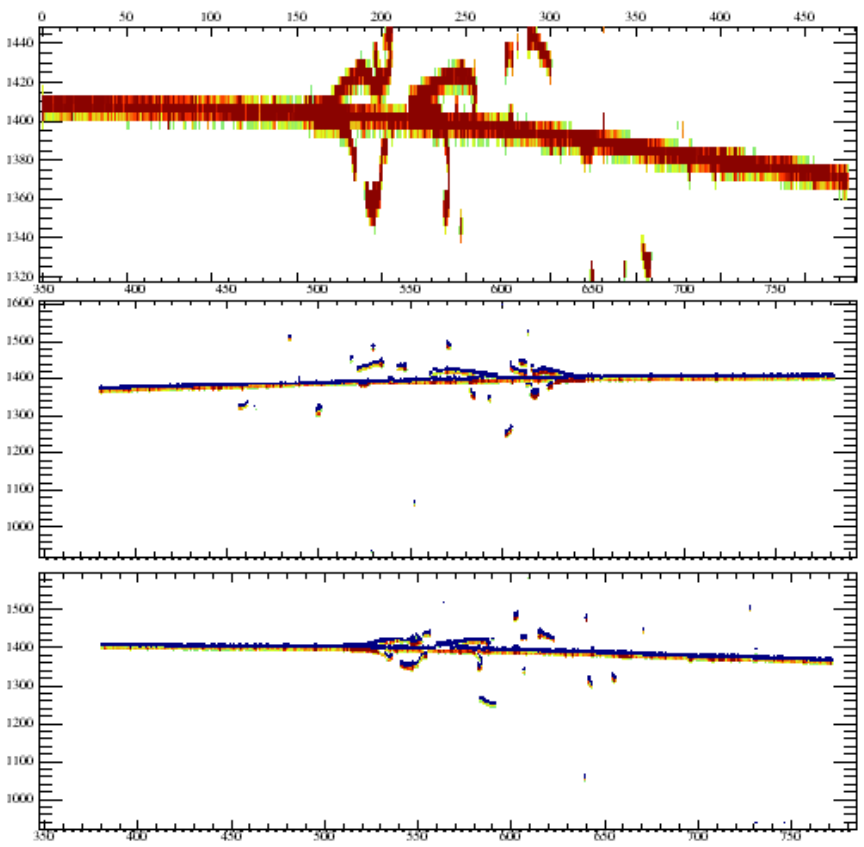
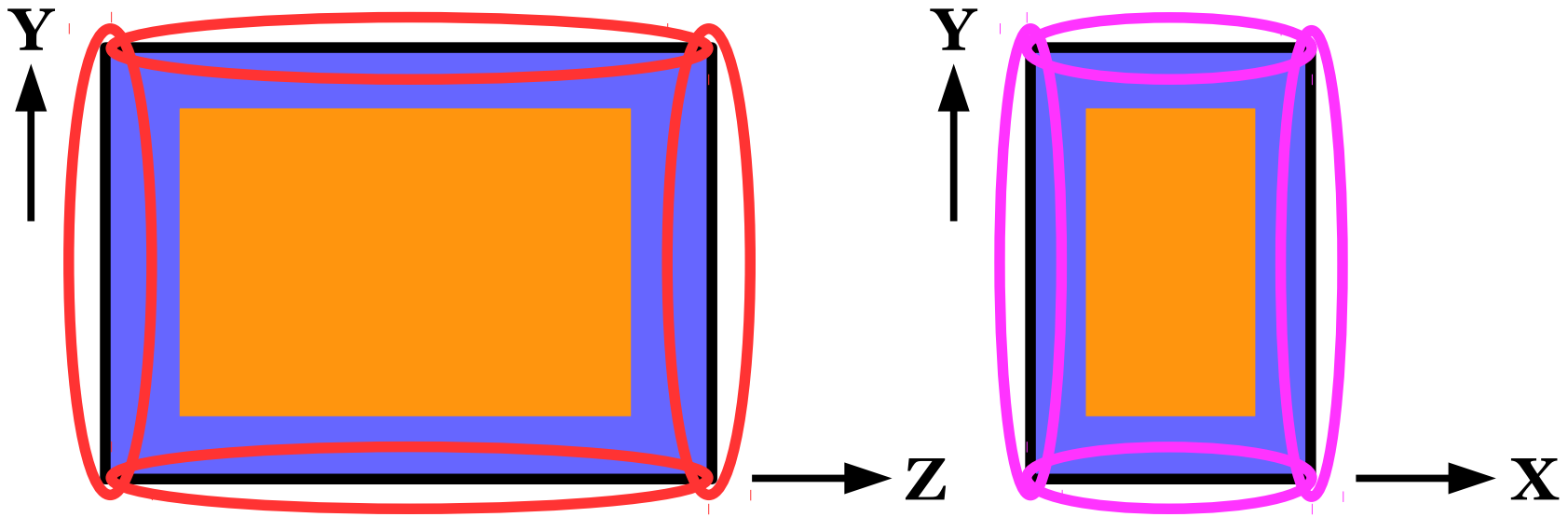


- LArSoft implementation seems to be working
  - Compare without SCE (left) to with SCE (right)
  - Different events but same track angle

SCE Calibration Scheme



- Multiple handles on space charge effect offsets within **TPC**:
  - Muon counter system: use to find **ΔY(x)**, **ΔZ(x)** at TPC boundaries
  - Tracks in TPC: use to find **ΔY(z)** and **ΔZ(y)** at TPC boundaries
  - Laser system: can calibrate out SCE in **TPC bulk**
- Likely need to combine all of the above to obtain full calibration map
- Light-collection system can help pin down track t_o, aiding calibration in bulk of TPC

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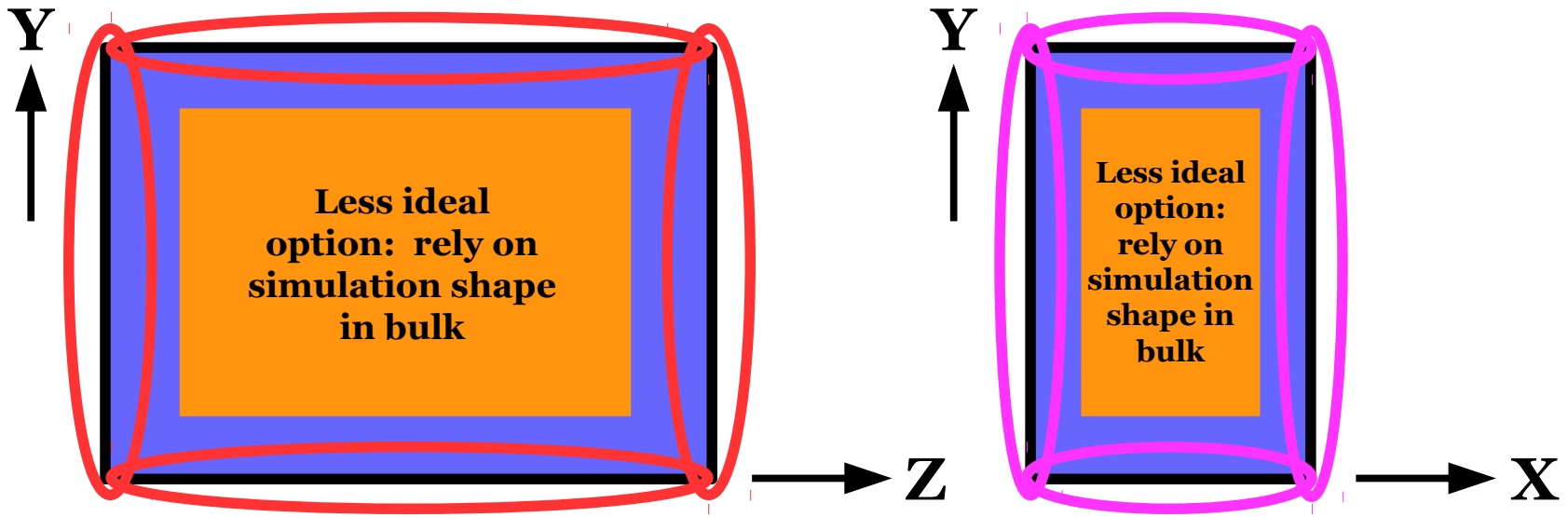

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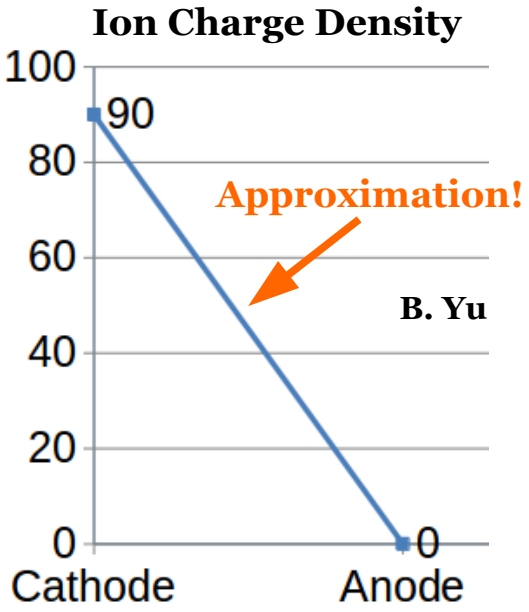
Summary

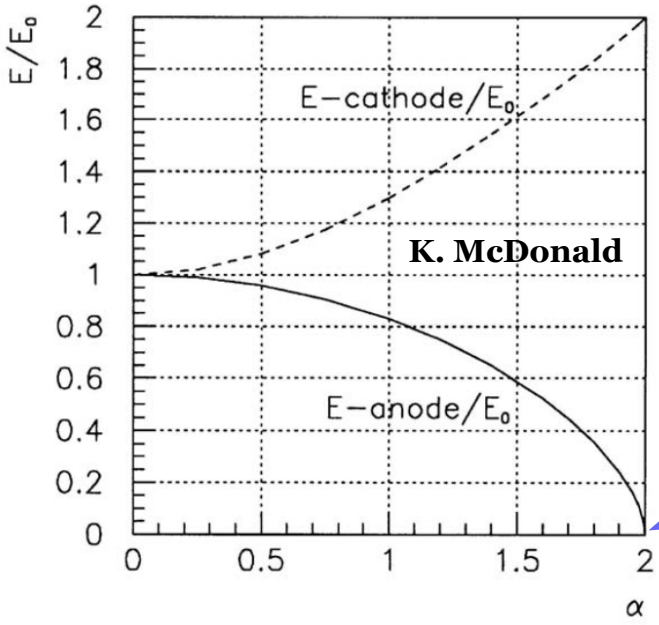
- Distortions at ProtoDUNE for **nominal geometry** are quite severe! Much larger than those at MicroBooNE (~5 x)
  - **500 V/cm** drift field: **~5 cm** longitudinal, **~25 cm** transverse
  - **250 V/cm** drift field: **~20 cm** longitudinal, **~60 cm** transverse
- Need to take a look at simulation of space charge effect to understand impact of effect on physics measurements
  - SpaCE: C++/ROOT simulation of SCE
  - LArSoft implementation now exists for ProtoDUNE
  - **services.user.SpaceCharge.EnableSimulationSCE: true**
- Can calibrate out space charge effects throughout TPC by combining multiple subsystem information: TPC, light-collection system, muon counters, and laser system

BACKUP SLIDES

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, $E^{-1.7}$





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

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

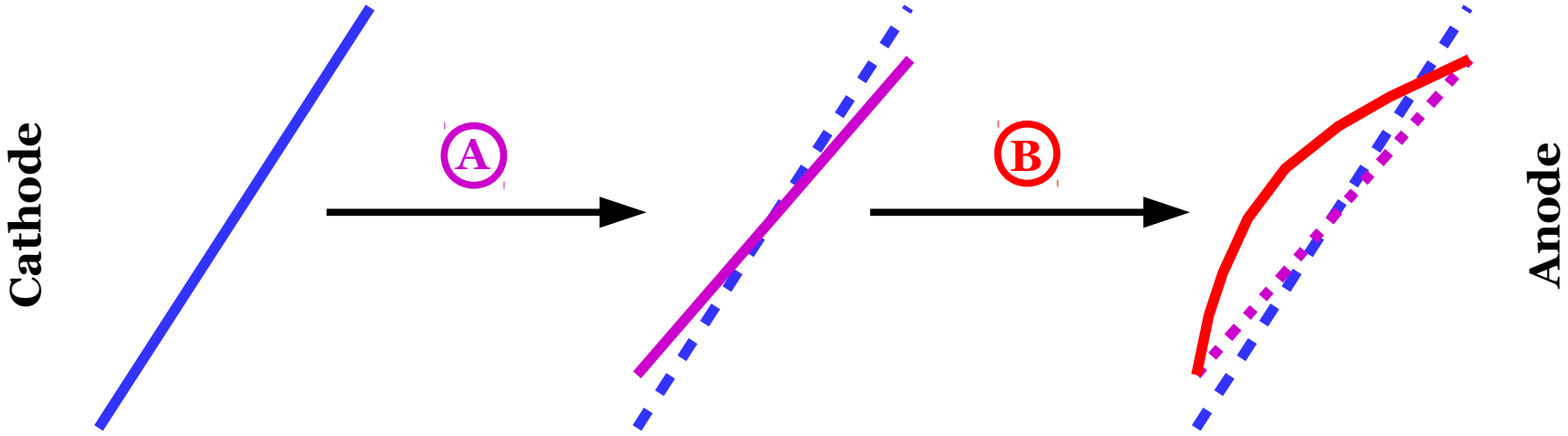
No Drift!

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 (however, interpretation is difficult)

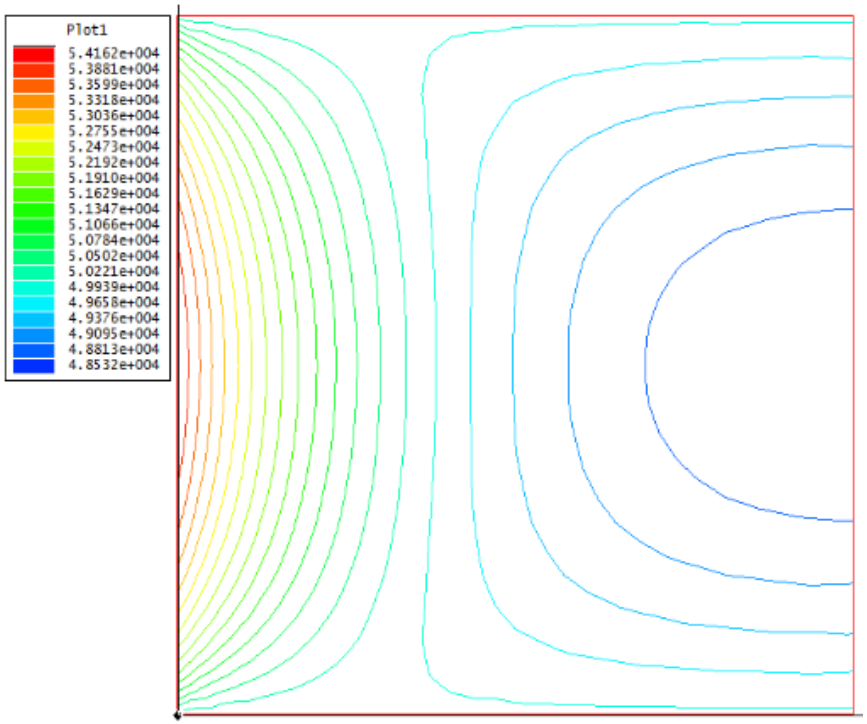
Impact on Track Reco.

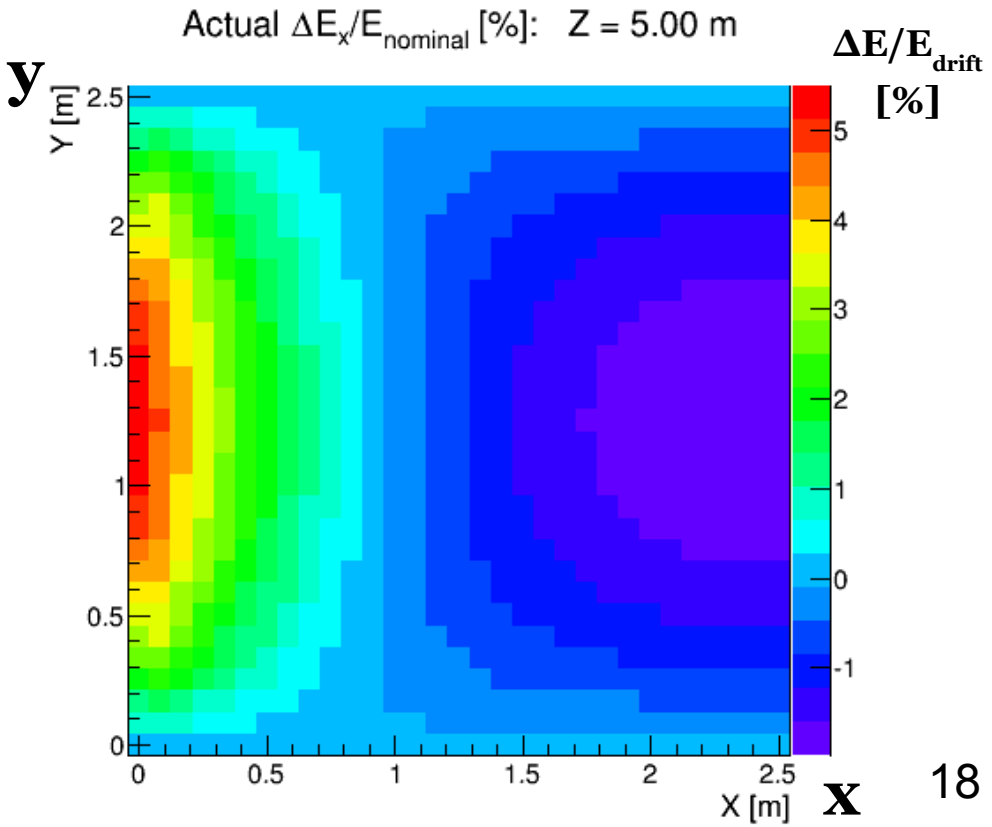
- Two separate effects on reconstructed **tracks**:
  - (A) Reconstructed track shortens laterally (looks rotated)
  - (B) Reconstructed track bows toward cathode (greater effect near center of detector)
- Can obtain straight track (or multiple-scattering track) by applying corrections derived from data-driven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



Compare to FE Results: E_x

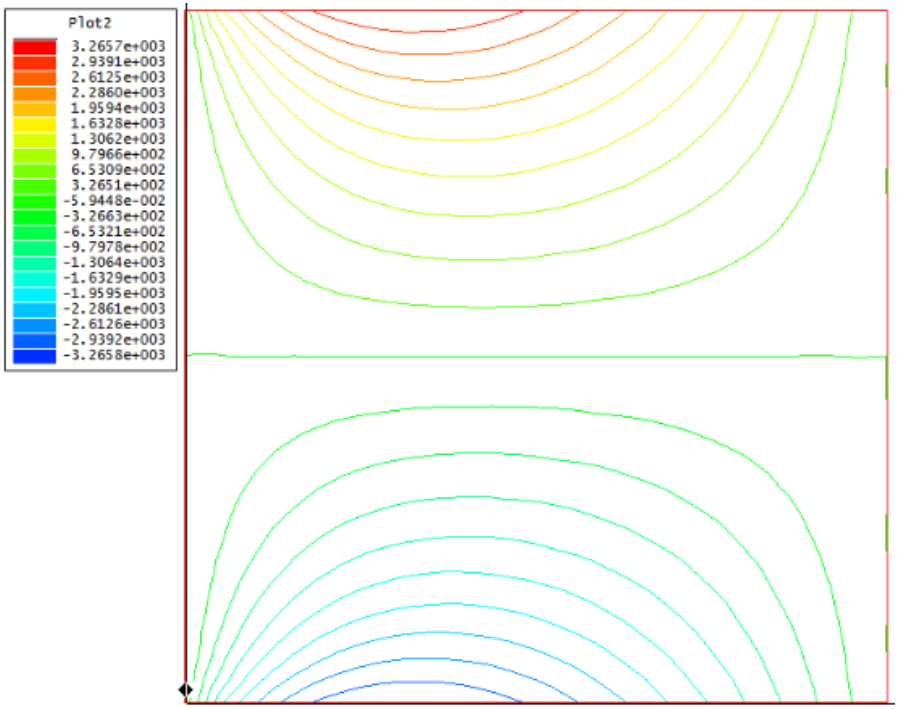
- Looking at central z slice (z = 5 m) in x-y plane (**MicroBooNE**)
- Very good shape agreement compared to Bo Yu's 2D FE (Finite Element) studies
- Normalization differences understood (using different rate)

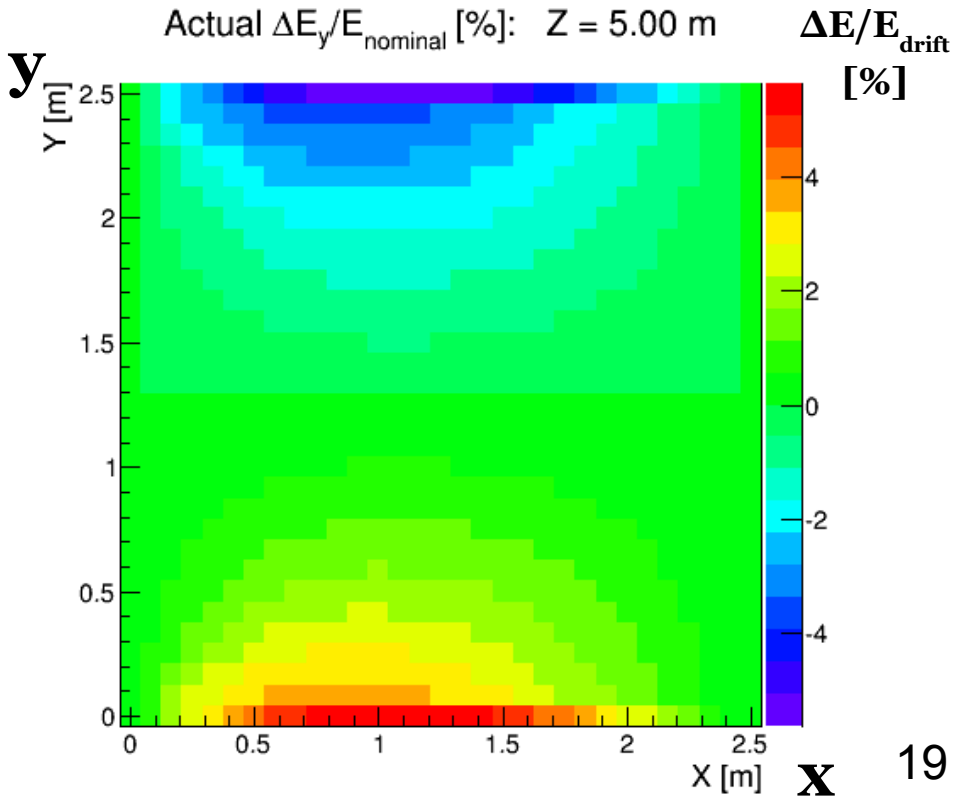




Compare to FE Results: E_y

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

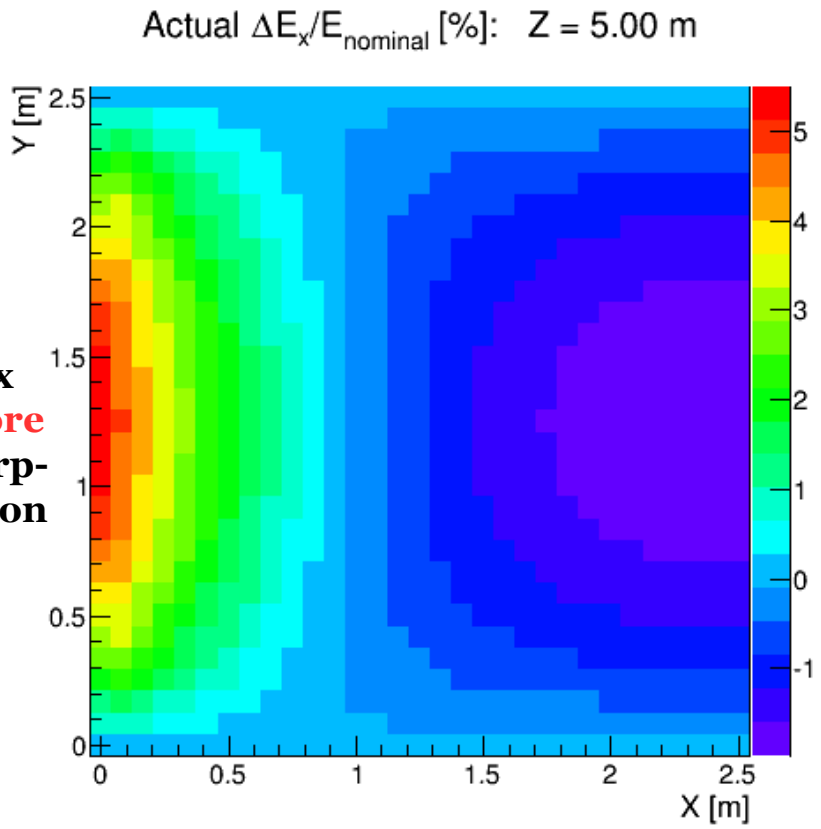


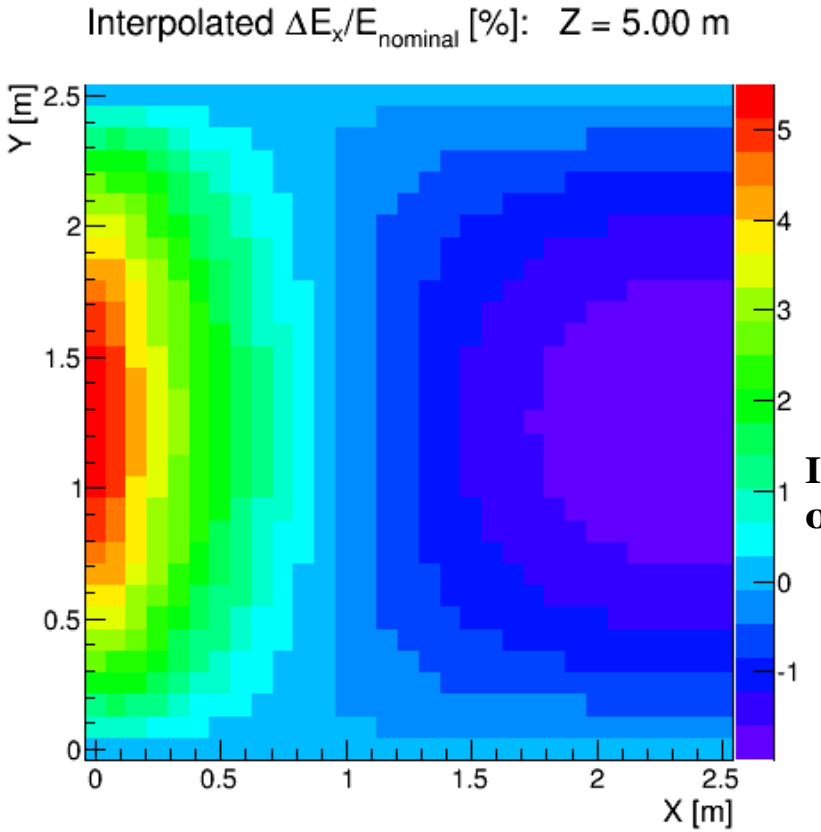


E Field Interpolation

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

E_x Before Interp-olation



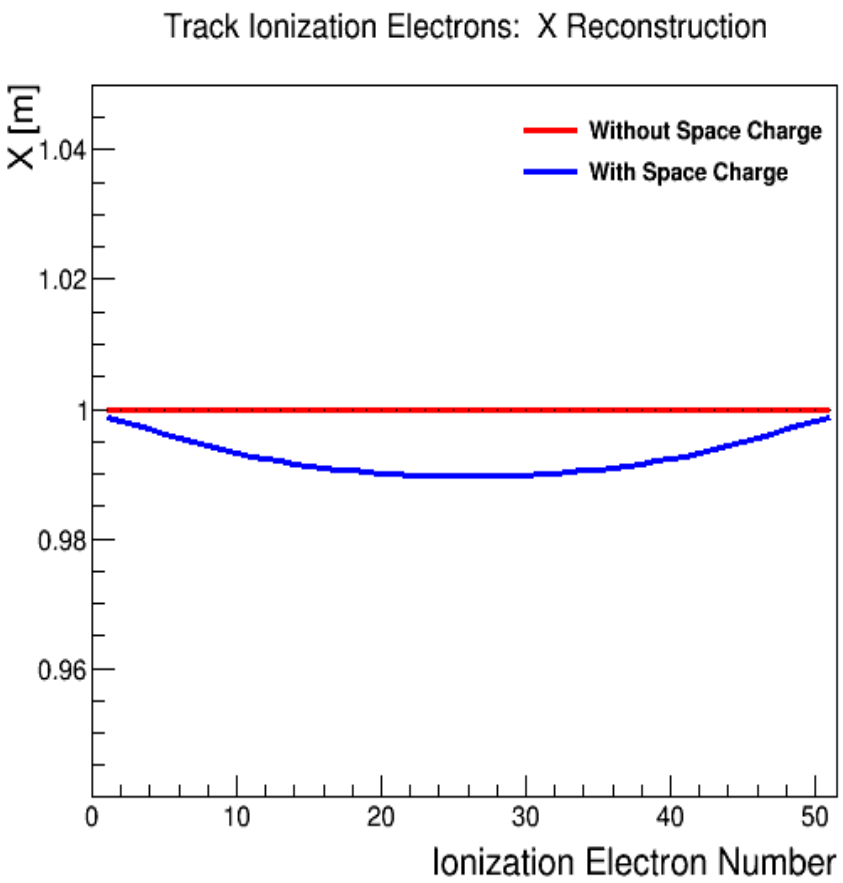


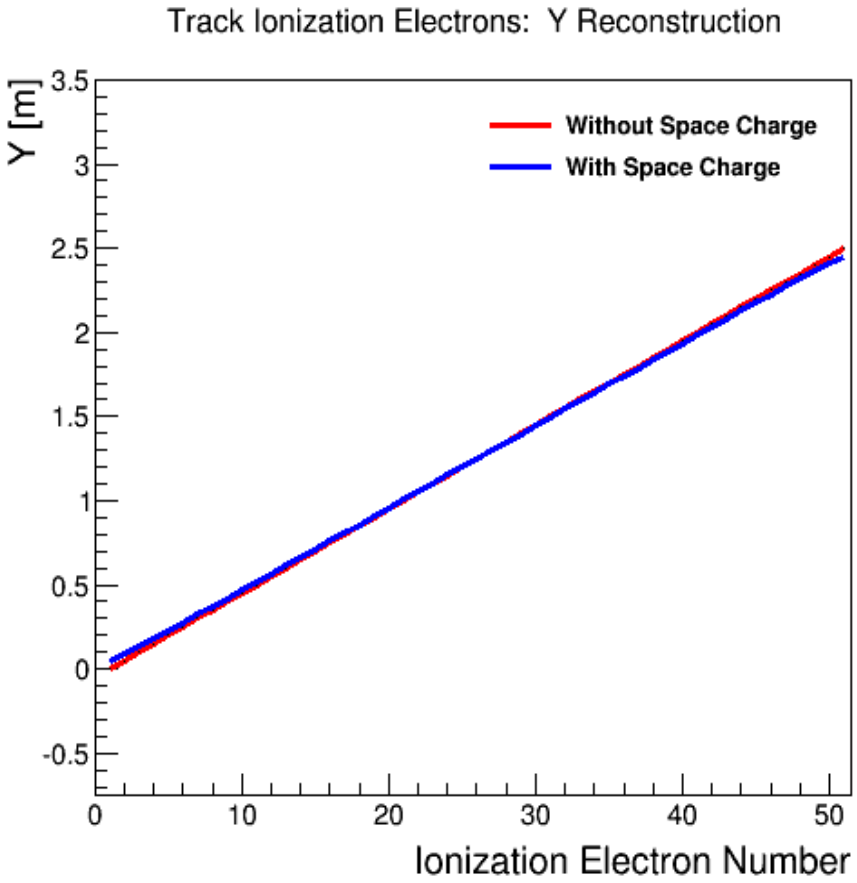
E_x After Interp-olation

Ray-Tracing

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

MicroBooNE



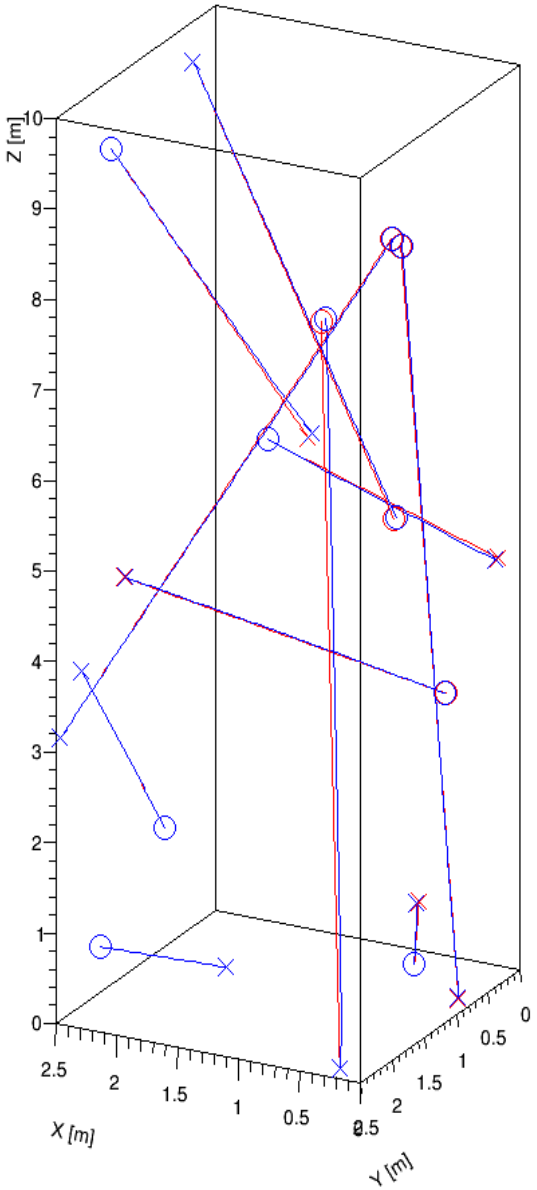


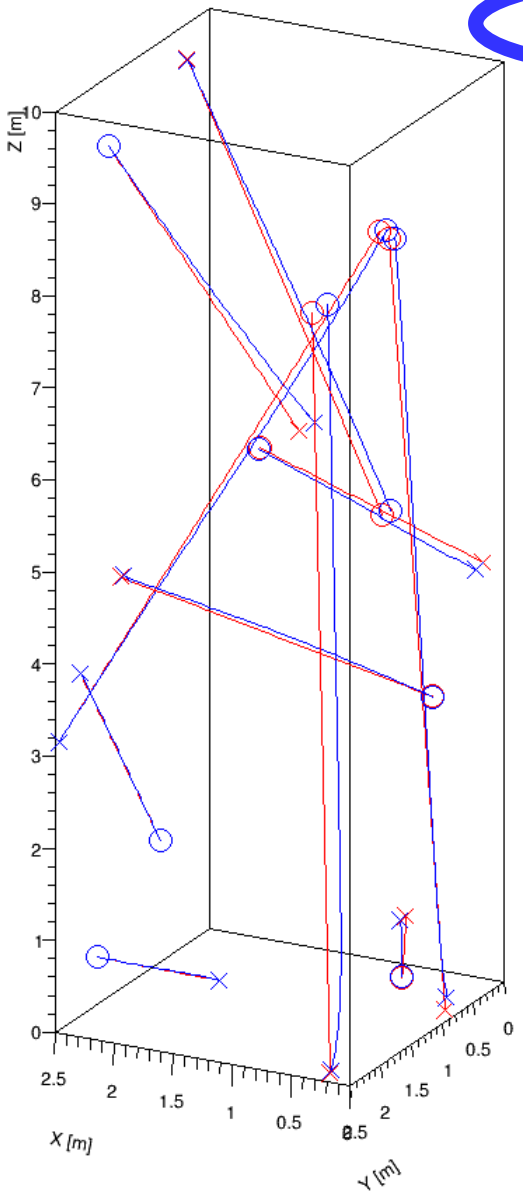
Sample “Cosmic Event”

MicroBooNE

Nominal Drift Field

500 V/cm





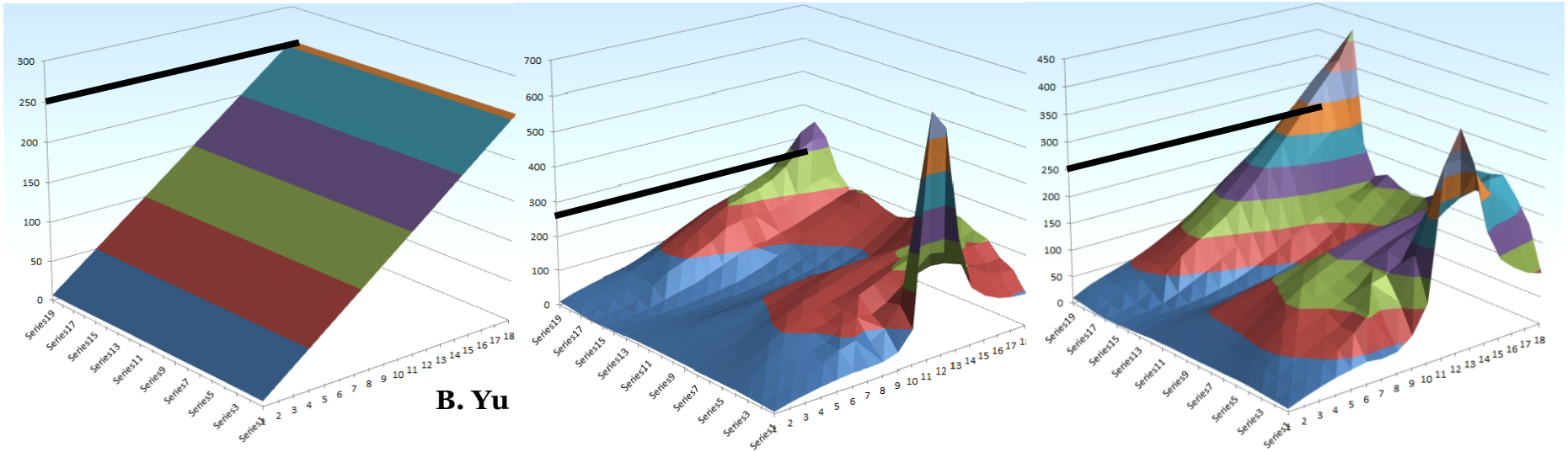
Half Drift Field

250 V/cm

Complications

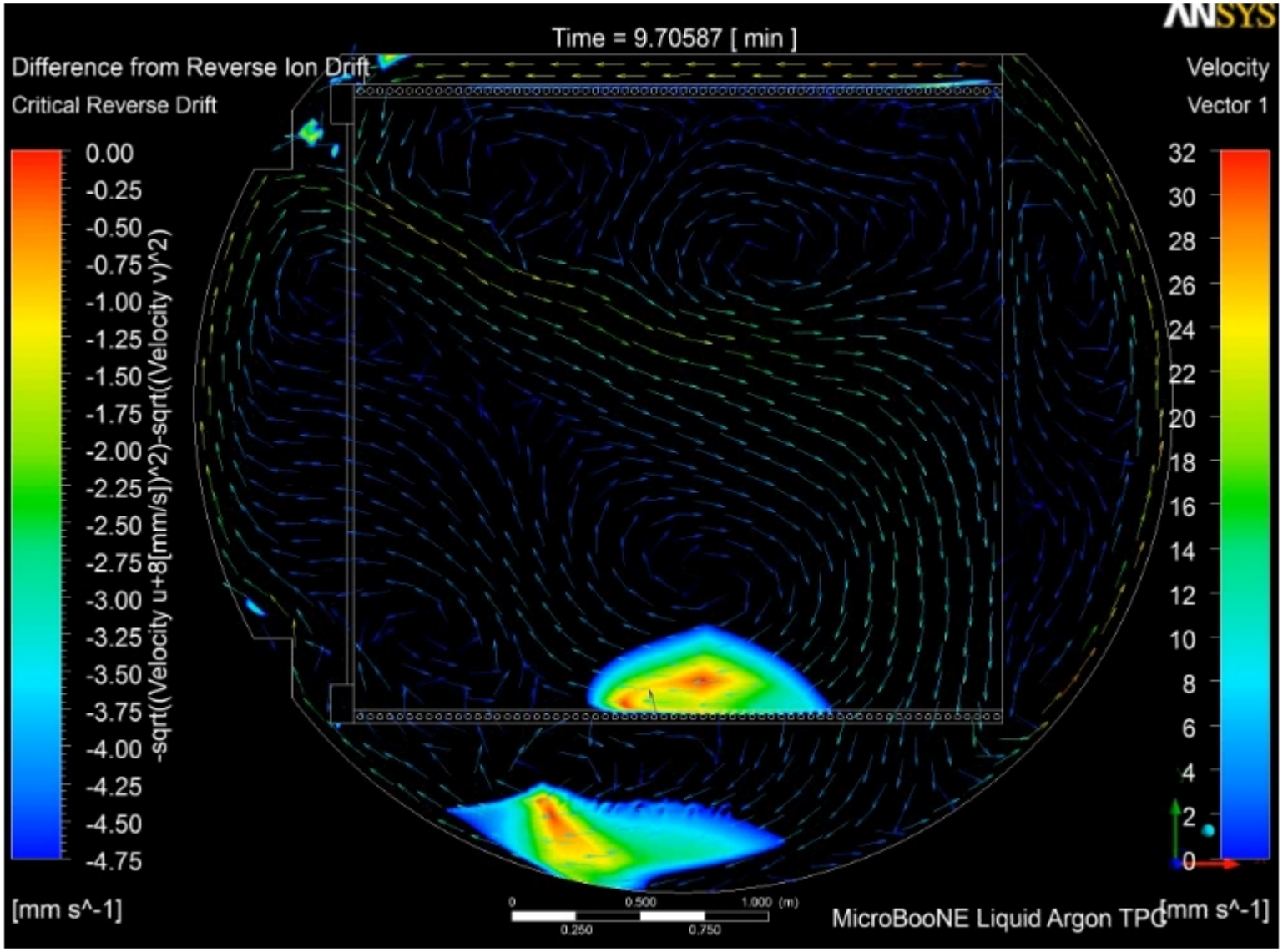
- Not accounting for non-uniform charge deposition rate in detector → significant modification?
- Flow of liquid argon → likely significant effect!
  - Previous flow studies in 2D… differences in 3D?
  - Time dependencies?

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



B. Yu

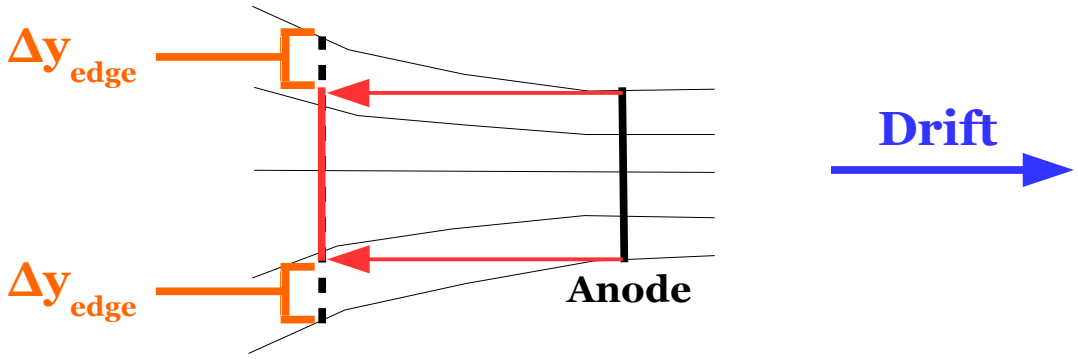
Liquid Argon Flow



B. Yu

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

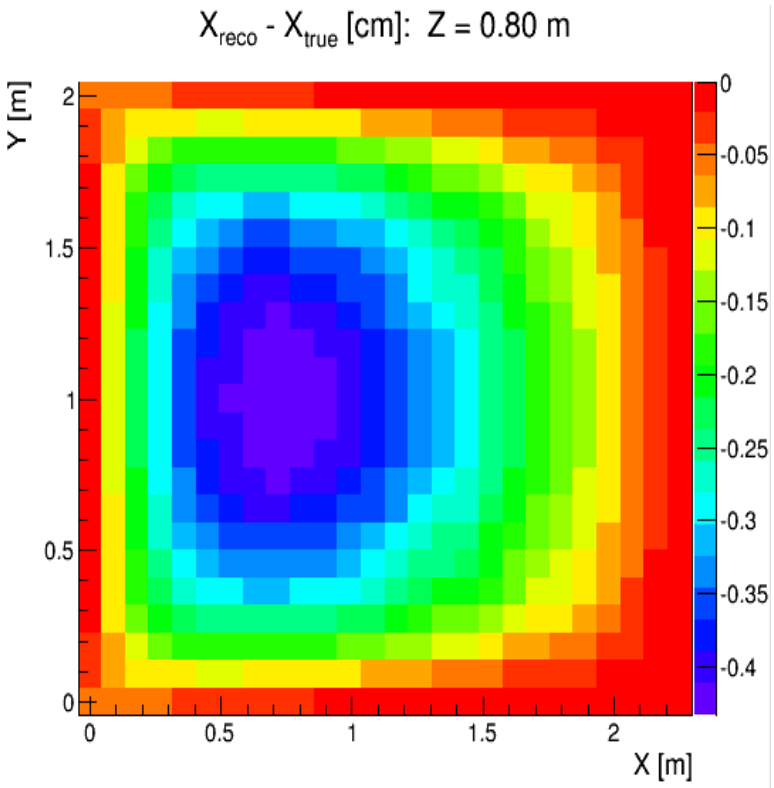
Δx

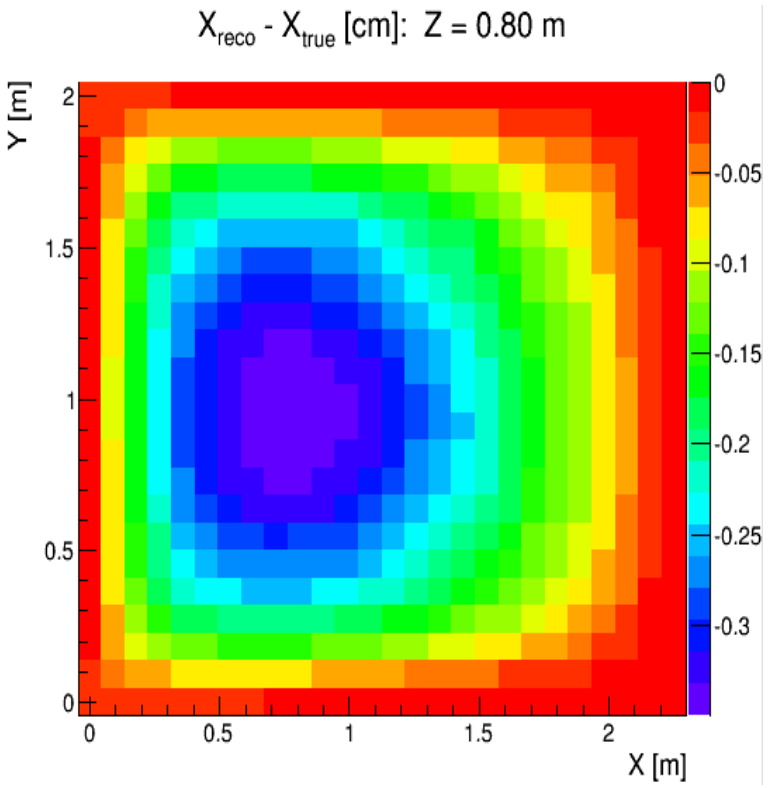
Without
LAr Flow

central z slice

Δx

With
LAr Flow

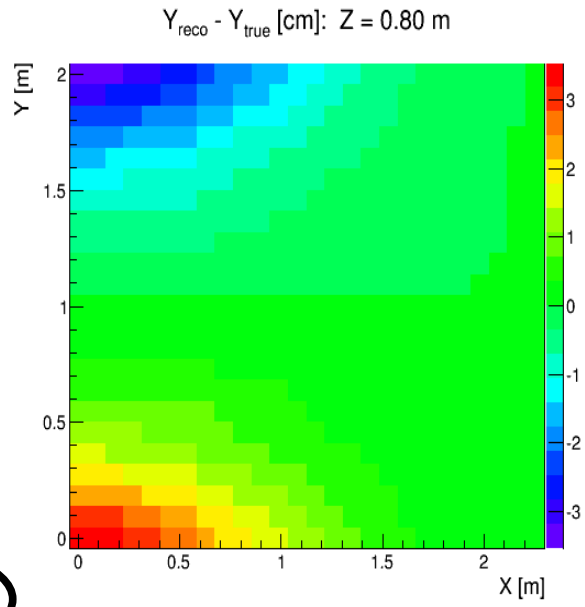




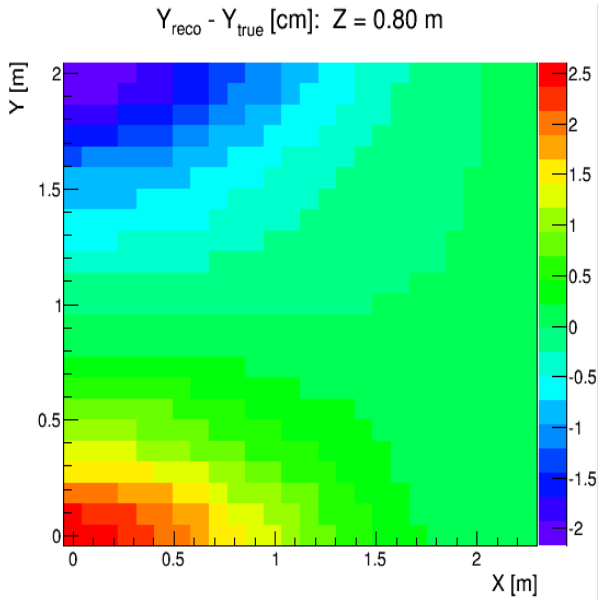
Q map from
E. Voirin

35-ton with LAr Flow (cont.)

Δy
Without
LAr Flow



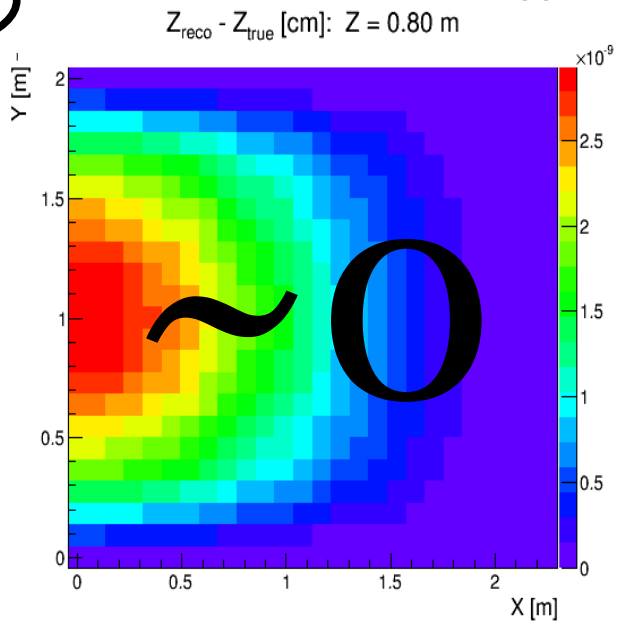
Δy
With
LAr Flow



Q map from E. Voirin

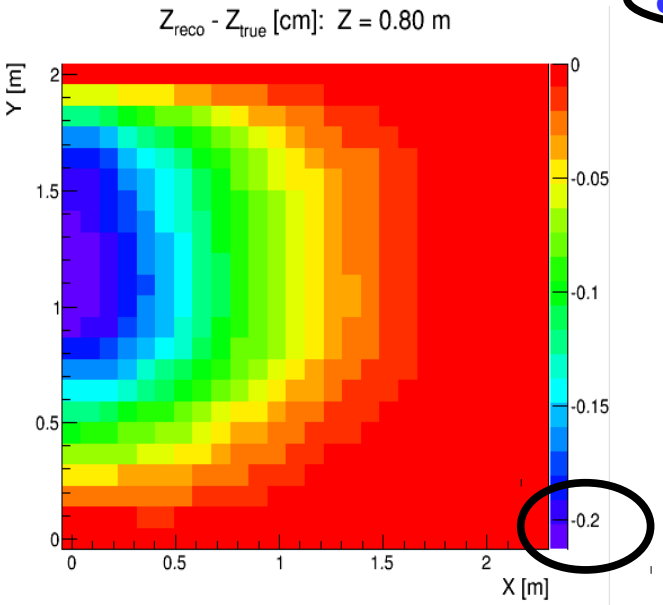
central z slice

Δz
Without
LAr Flow



~0

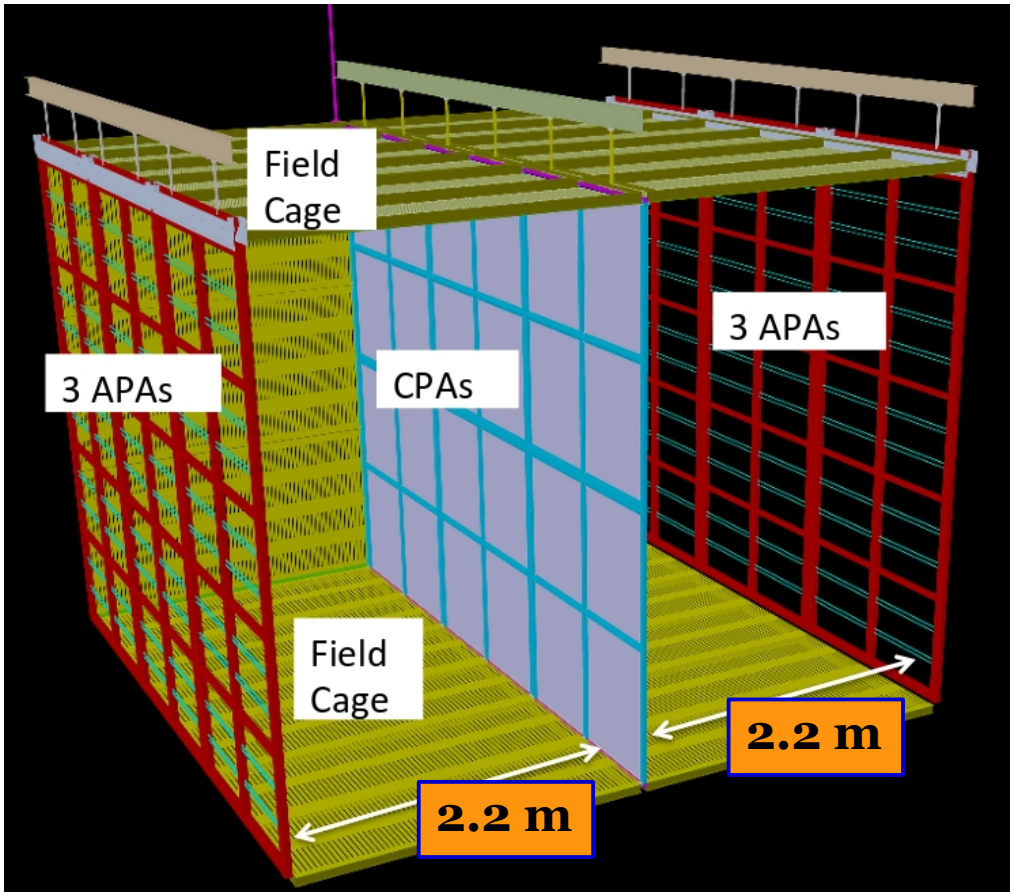
Δz
With
LAr Flow



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 Geometry



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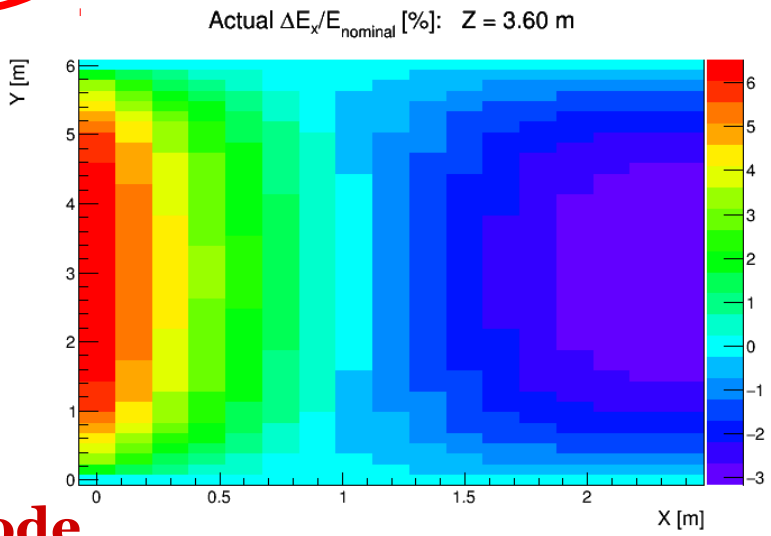
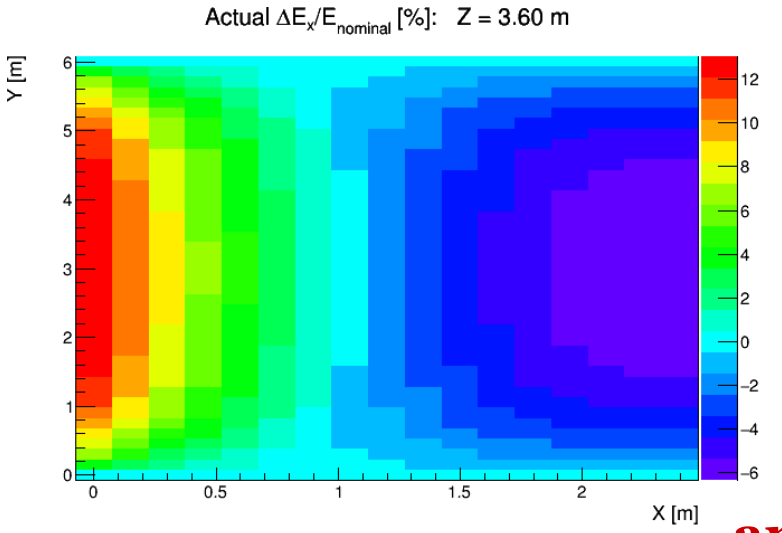
$E_{nominal}$ = 250 V/cm

E_X

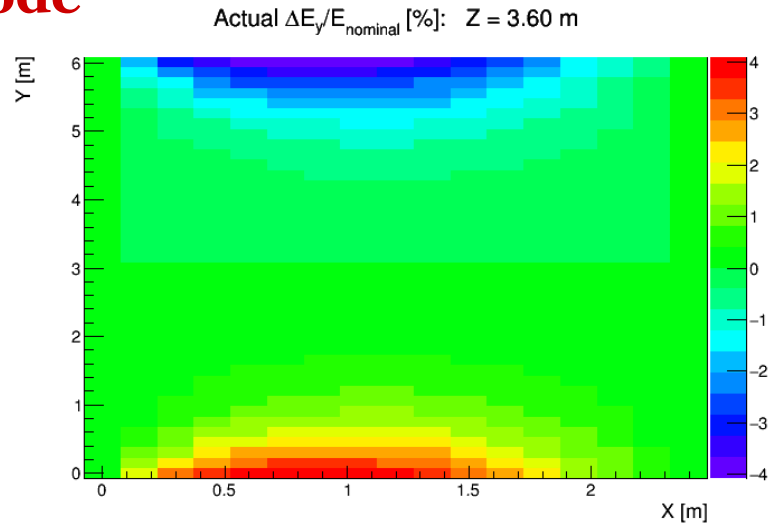


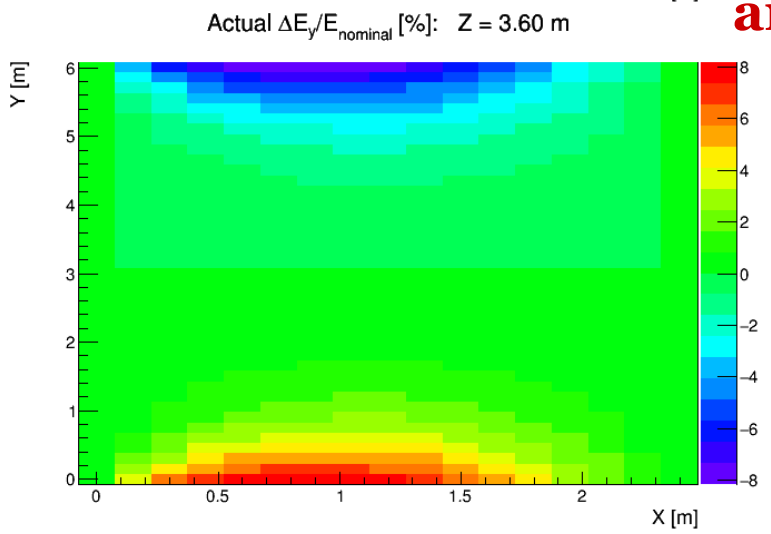


cathode

anode

E_Y





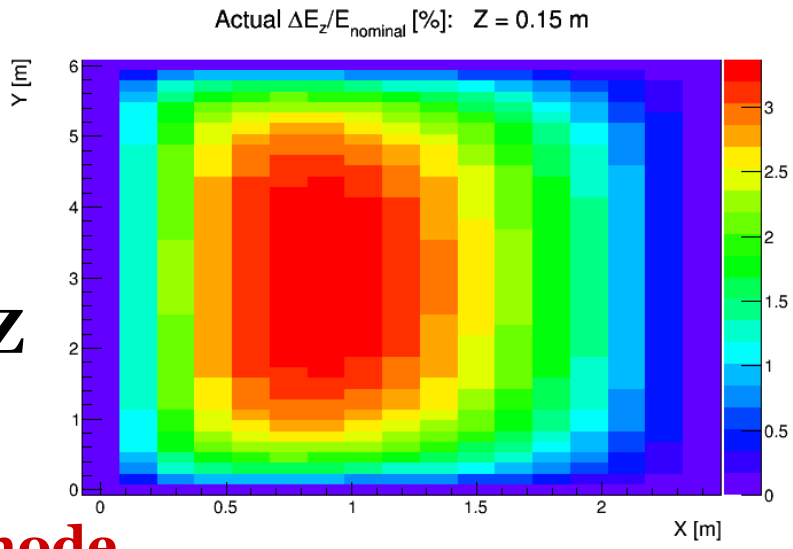
Modified E Field (TPC End)

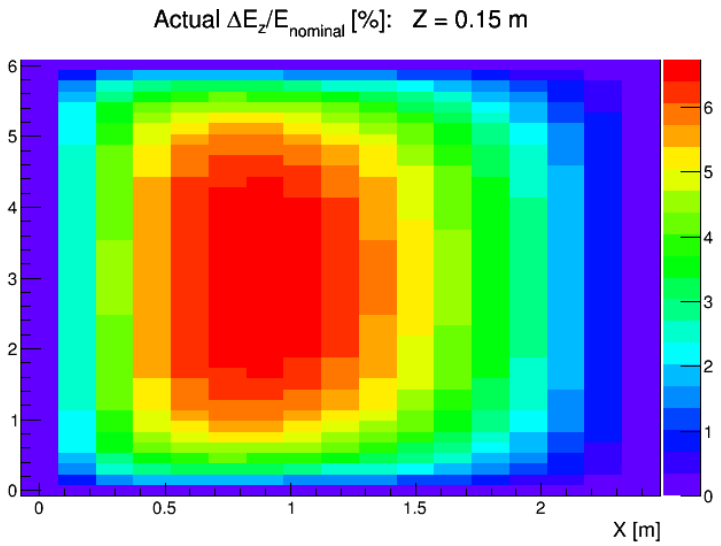
Modified Geometry

$E_{nominal}$ = 500 V/cm

$E_{nominal}$ = 250 V/cm

E_Z





cathode

anode

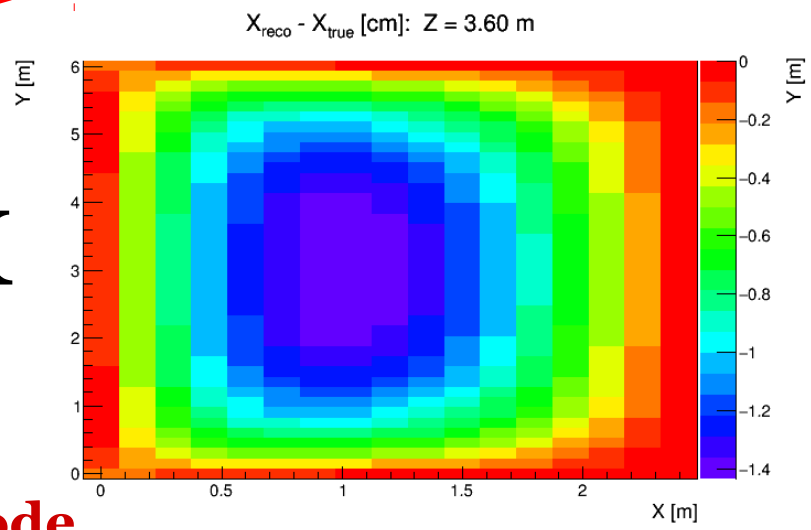
Distortions (Central Z)

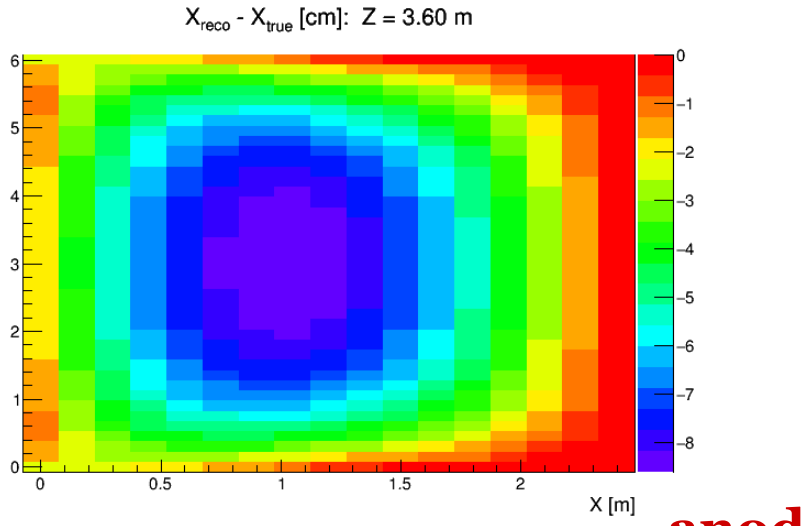
Modified Geometry

$E_{nominal}$ = 500 V/cm

$E_{nominal}$ = 250 V/cm

ΔX

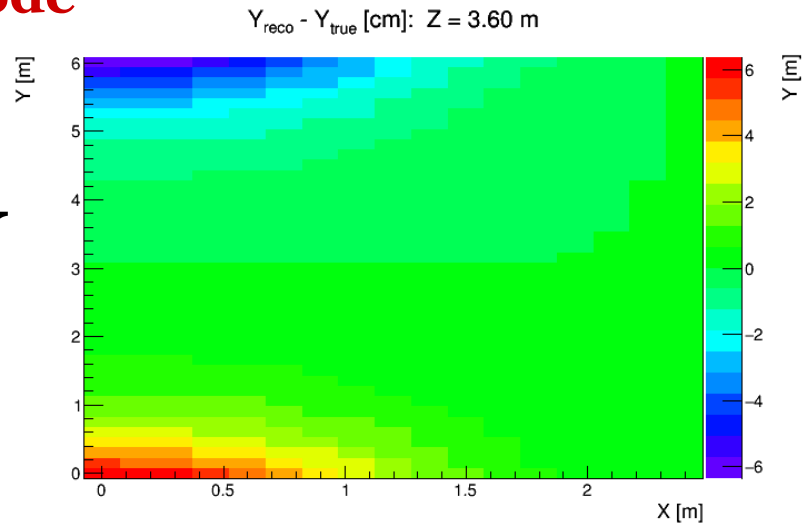


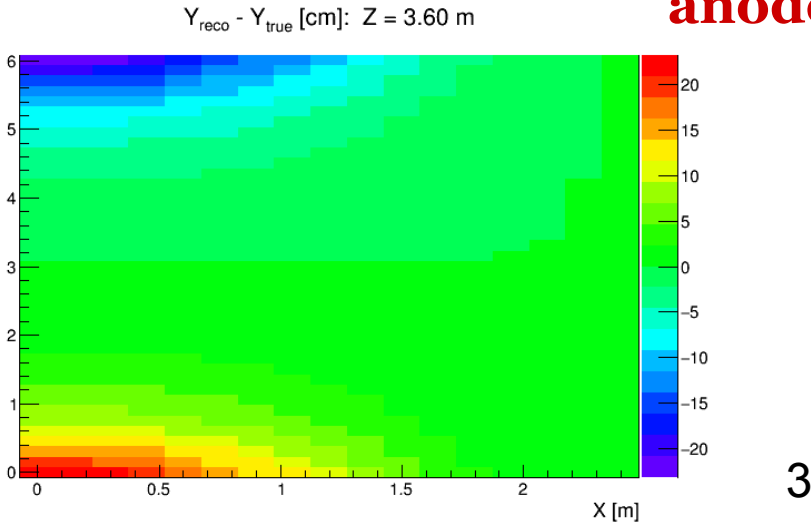


cathode

anode

ΔY





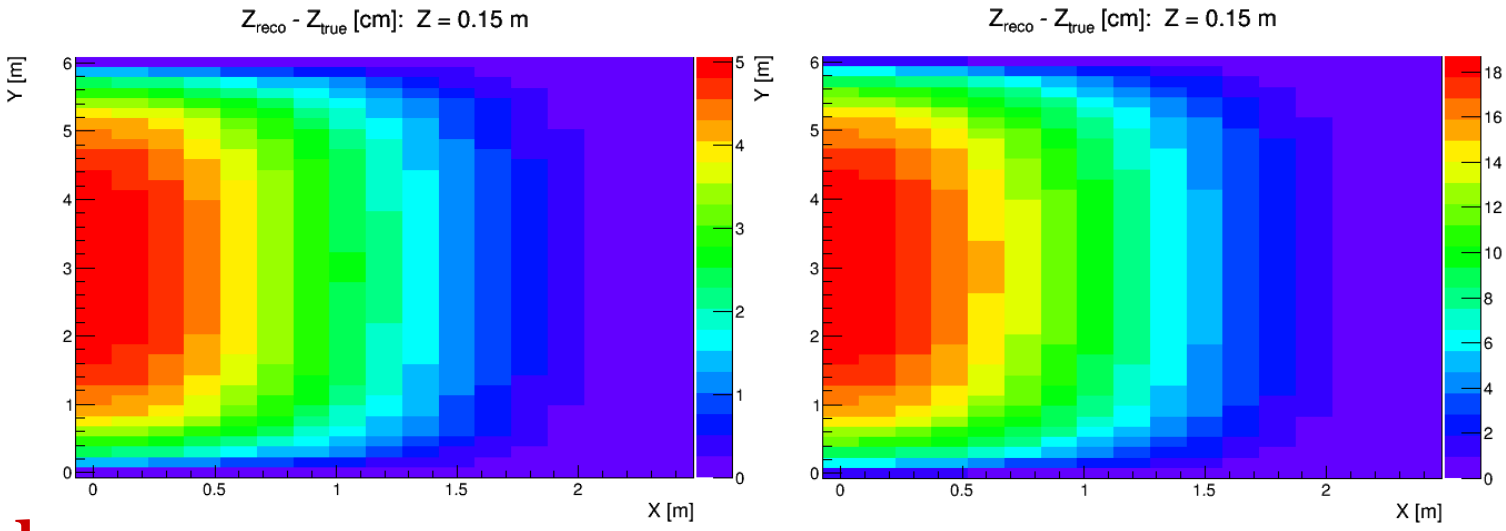
Distortions (TPC End)

Modified Geometry

$E_{nominal}$ = 500 V/cm

$E_{nominal}$ = 250 V/cm

ΔZ



cathode

anode