Space Charge Effect at protoDUNE: Simulation/Calibration

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BNL

protoDUNE Science Workshop

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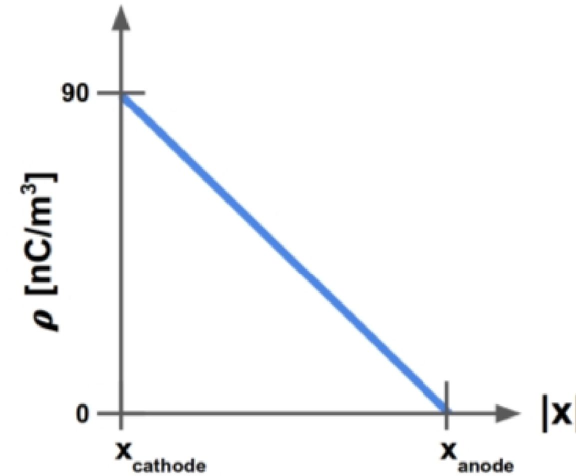
Introduction

- Reality: protoDUNE is a LArTPC prototype on the **surface**
  - Large cosmic flux means build-up of space charge from slow-moving (~8 mm/s) argon ions created from cosmic muons
- Need to prepare for running conditions that include sizable space charge effects (SCE)
  - **Simulation** with stand-alone code suite (SpaCE) to learn magnitude of problem and features to expect in reconstruction
  - Organize **calibration** strategy that utilizes cosmic muons and possibly a UV laser system
  - Learn from experiences at **MicroBooNE** – essential!
- Scope of this talk is to touch on the above three items
  - Launching point for more work to be done at this workshop
  - Focus is on single-phase (SP) protoDUNE but comparison made to dual-phase (DP) protoDUNE

protoDUNE TDR

- Thorough (6-7 pages) discussion of space charge effect, including simulation and calibration strategy, going into protoDUNE TDR

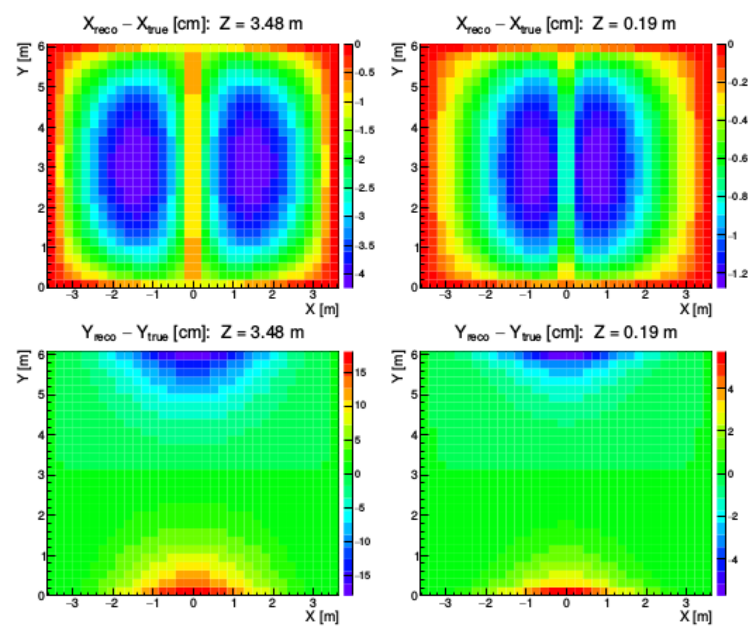


1 Space Charge Effect

1.1 Introduction

In order to correctly reconstruct the trajectories of particles that travel through the active volume of the TPC as well as precisely determine calorimetric information for these particles, it is essential to know very well the magnitude and direction of the drift electric field throughout the TPC bulk. Nominally the electric field should be uniform throughout the TPC volume. However, field effects such as the space charge effect (SCE) may cause distortions in the electric field that result in distortions in the reconstructed position of ionization electron clusters detected by the TPC wire planes as well as variation in the relative level of electron-ion recombination in different parts of the TPC [1]. The space charge effect is the build-up of slow-moving positive ions in a detector due to, for instance, ionization from cosmic muons. As protoDUNE is a detector on the surface with little overburden, the cosmic muon flux is expected to create a significant amount of space charge (positive argon ions) that could modestly impact the drift electric field within the TPC active volume.

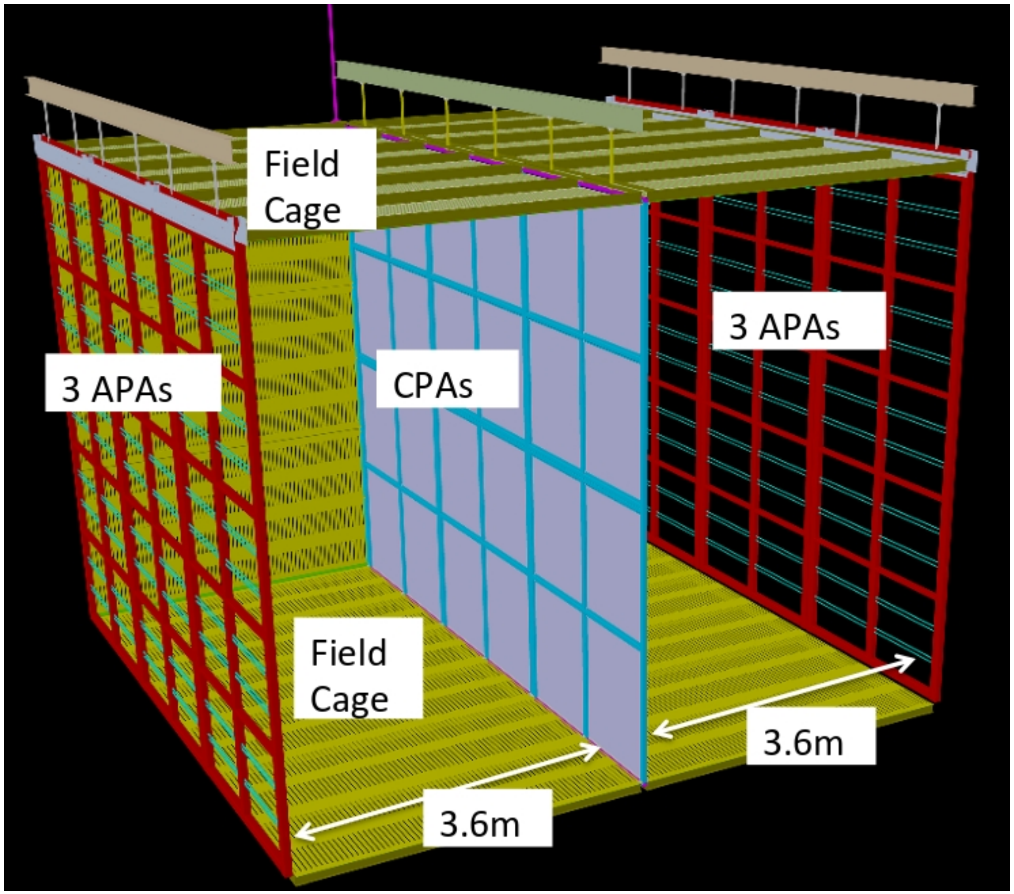
In principle this effect could have modest impact in any TPC (liquid or gaseous) if the dimensions of the detector are large enough (in particular the maximal drift distance) to accumulate a high ion density. In these cases, having a robust calibration method is necessary in order to account for the effect in particle trajectory reconstruction and calorimetry. An example of



SpaCE: Brief Overview

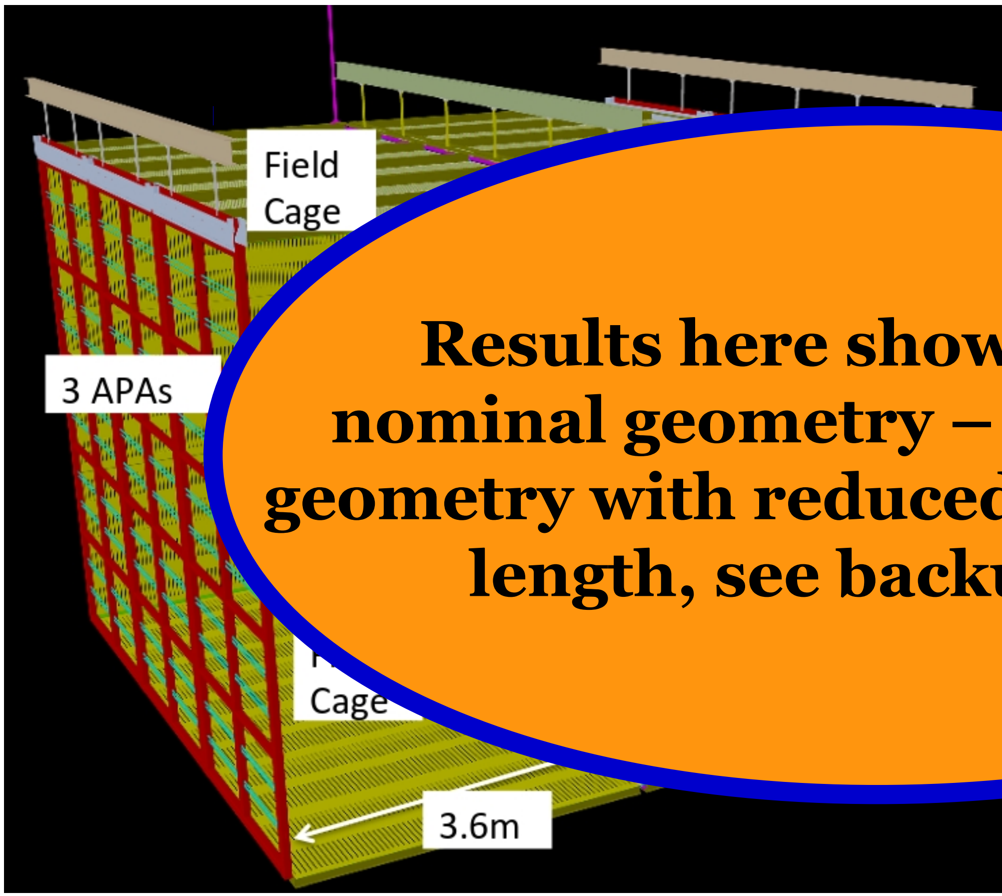
- Code written in C++ with ROOT libraries
- Also makes use of external libraries (ALGLIB)
- Primary features:
  - Obtain E fields analytically (on 3D grid) via **Fourier series**
  - Use **interpolation** scheme (RBF – radial basis functions) to obtain E fields in between solution points on grid
  - 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 (linear space charge density)
  - Also can use **arbitrary space charge configuration**
    - Can model liquid argon flow effects or beam-induced space charge

Nominal SP Geometry



- Nominal SP 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 SP Geometry



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

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  - t (Y): 5.9 m
  -): 7.0 m
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Modified E Field (Central Z)

BROOKHAVEN NATIONAL LABORATORY

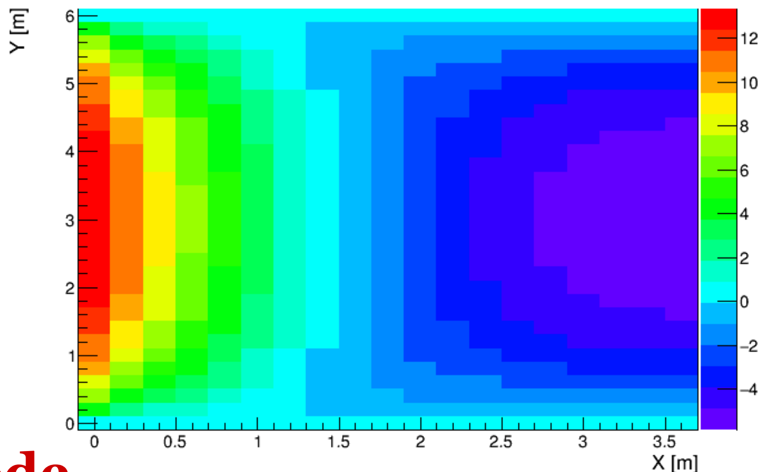
Nominal Geometry

$E_{nominal}$ = 500 V/cm

$E_{nominal}$ = 250 V/cm

E_X

Actual $\Delta E_x/E_{nominal}$ [%]: Z = 3.60 m



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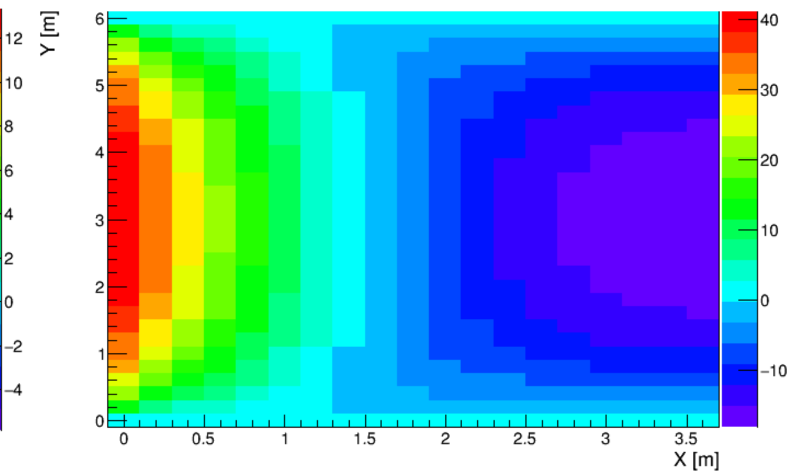
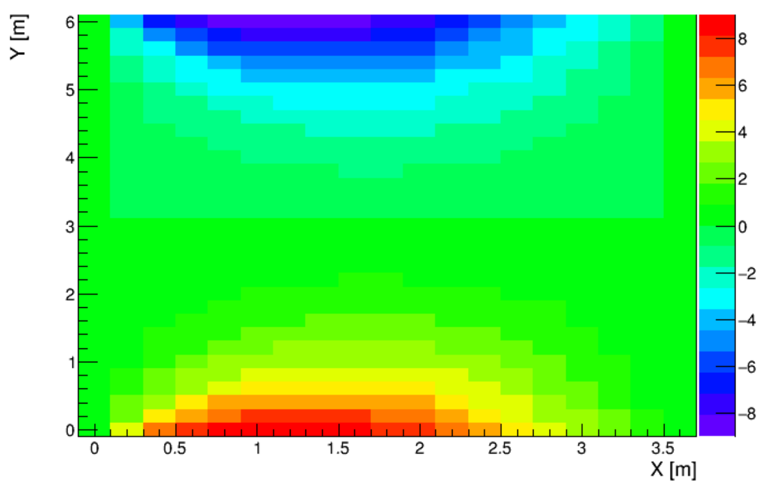


cathode

anode

E_Y

Actual $\Delta E_y/E_{nominal}$ [%]: Z = 3.60 m



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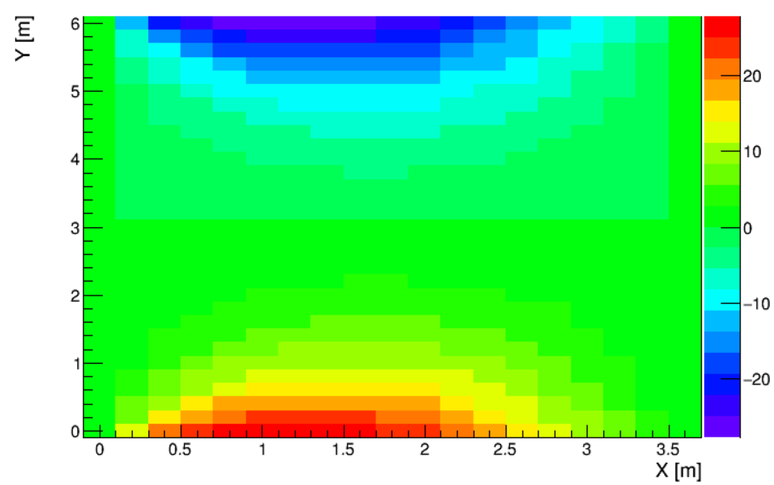


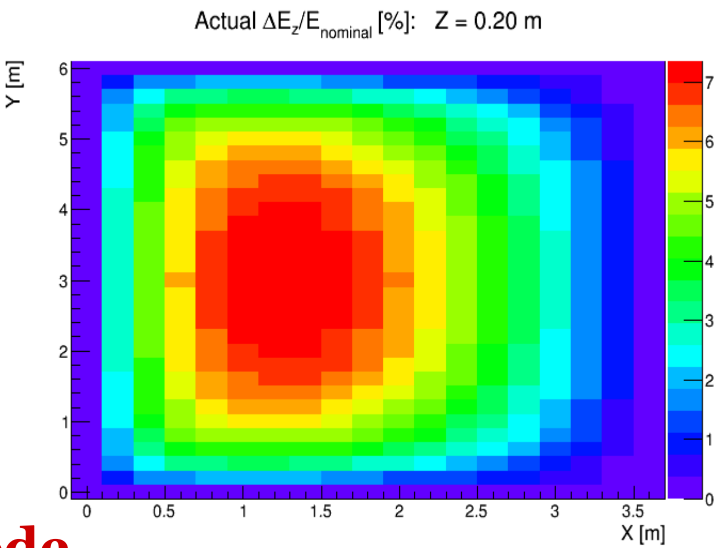
Modified E Field (TPC End)

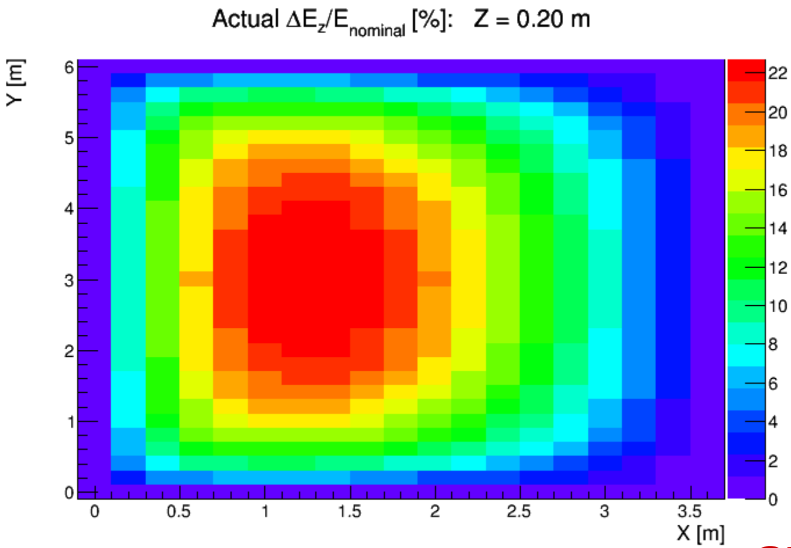
Nominal Geometry

$E_{nominal}$ = 500 V/cm

$E_{nominal}$ = 250 V/cm

E_Z





cathode

anode

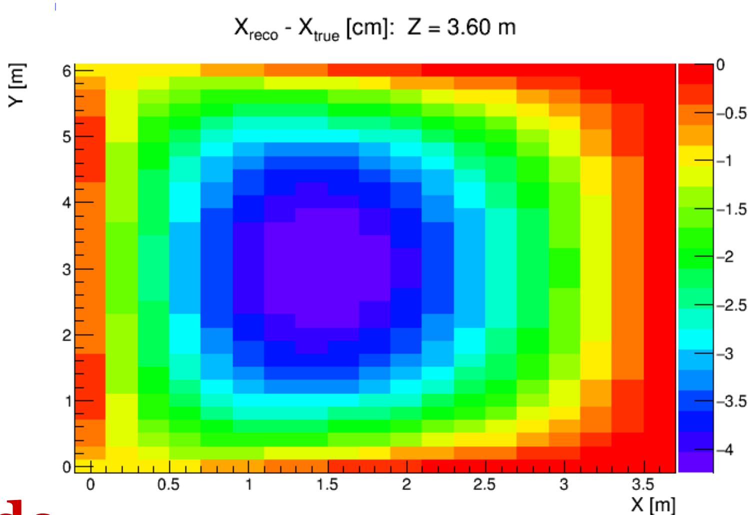
Spatial Distortions (Central Z)

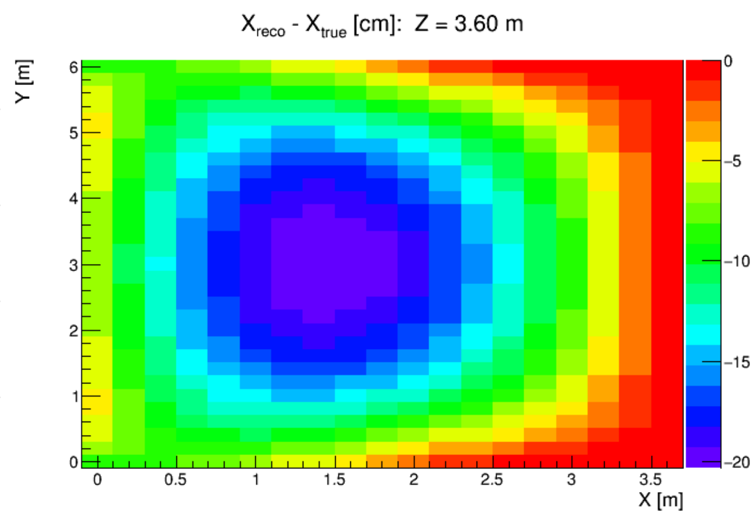
BROOKHAVEN NATIONAL LABORATORY

Nominal Geometry

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

ΔX





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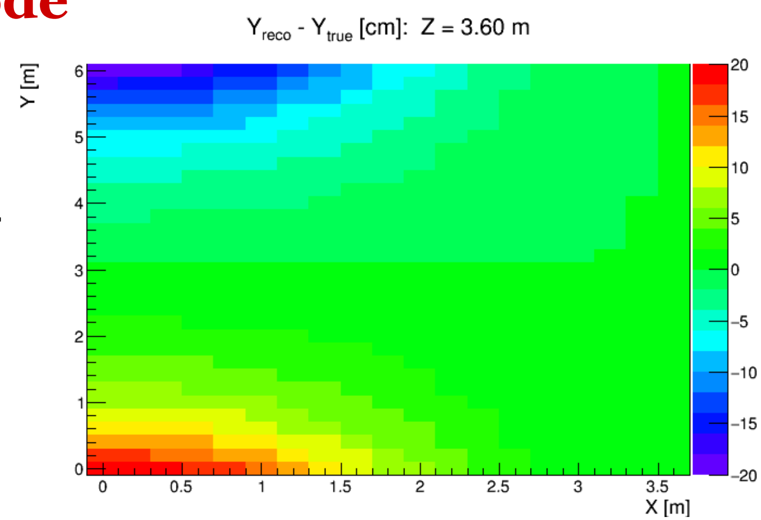
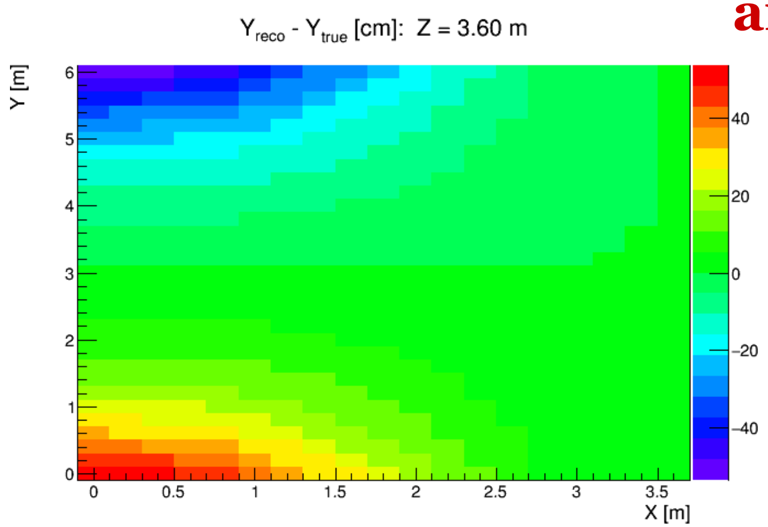
ΔY





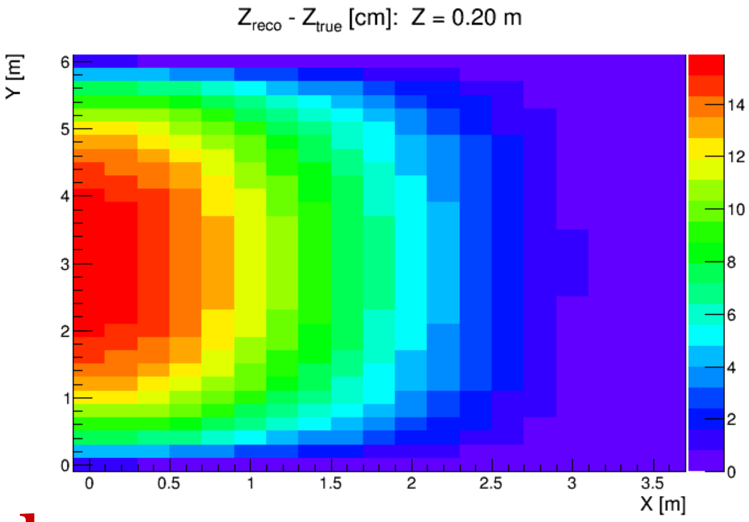
Spatial Distortions (TPC End)

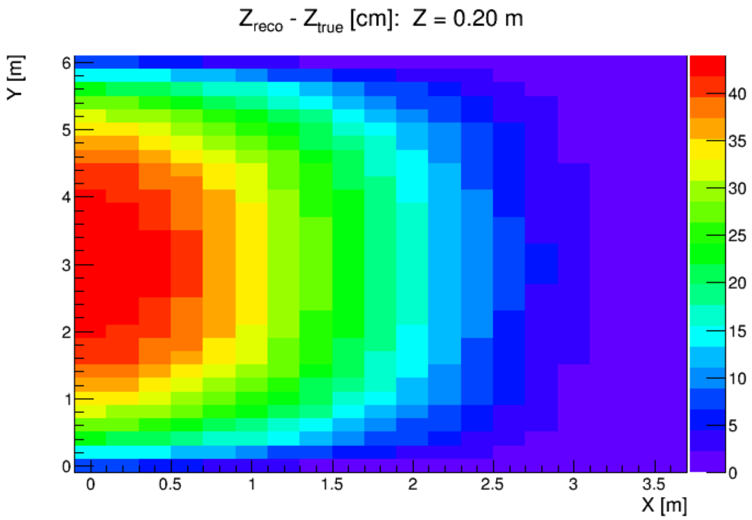
Nominal Geometry

$E_{nominal}$ = 500 V/cm

$E_{nominal}$ = 250 V/cm

ΔZ





cathode

anode

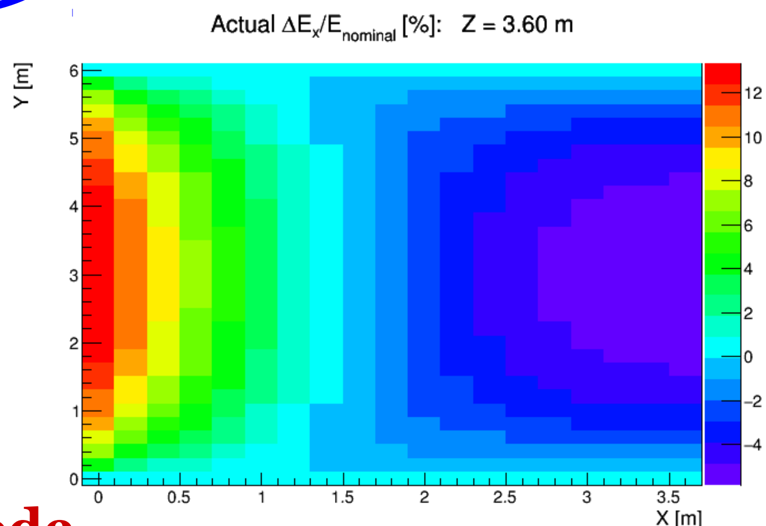
SP/DP Comp. – E Field Dist.

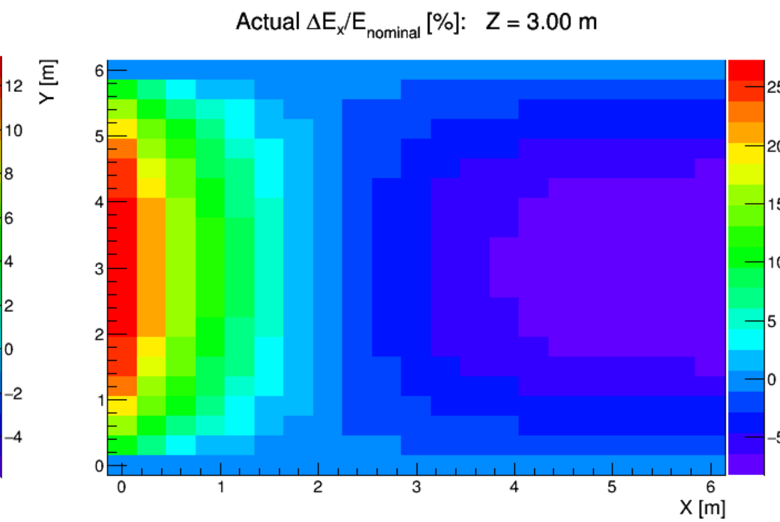
Nominal Geometry

SP (500 V/cm) DP

6 m × 6 m × 6 m

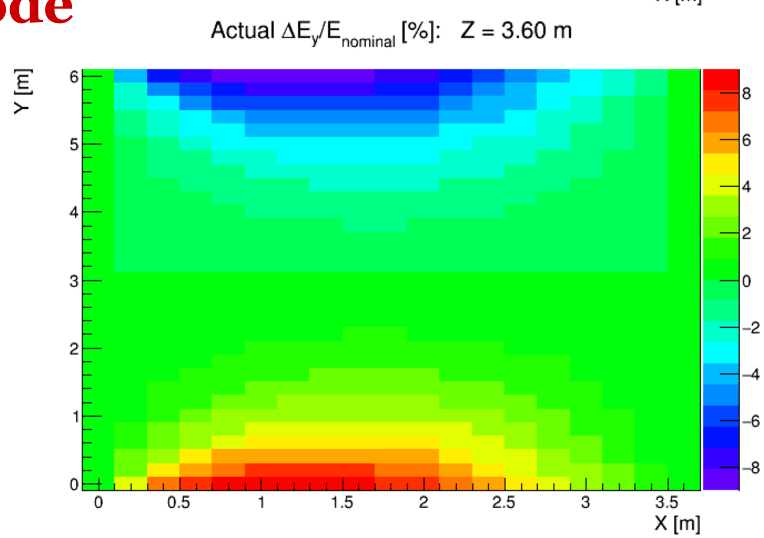
E_X

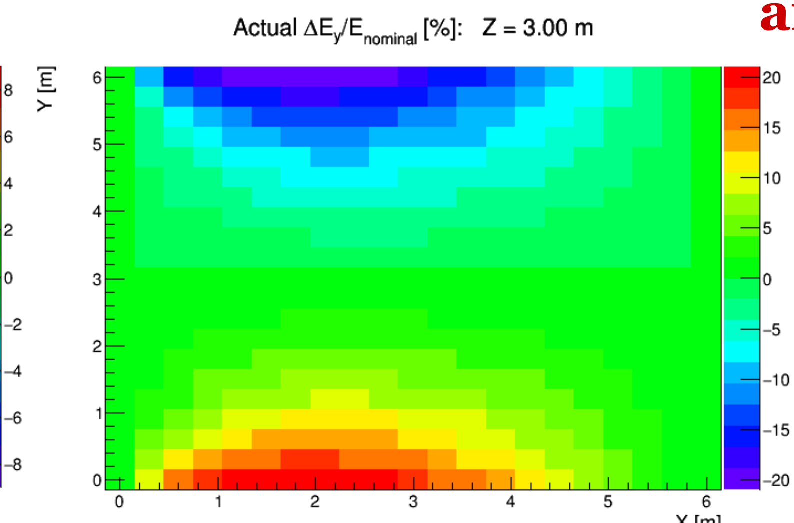




cathode **anode**

E_Y





SP/DP Comp. – E Field Dist.

Nominal Geometry

SP (500 V/cm) **DP**

6 m × 6 m × 6 m

Actual $\Delta E_x/E_{nominal}$ [%]: Z = 3.60 m

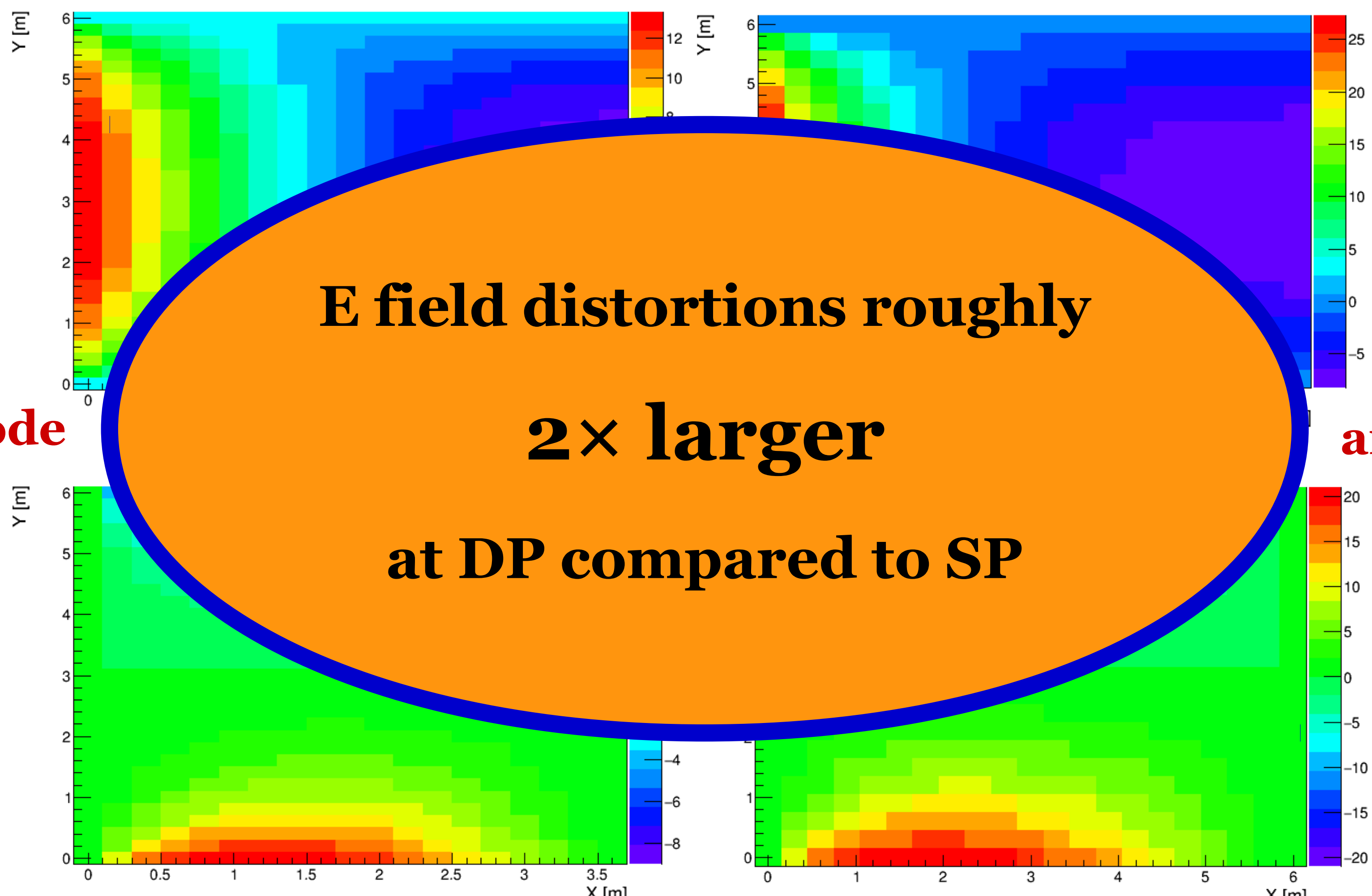
Actual $\Delta E_x/E_{nominal}$ [%]: Z = 3.00 m

E_X

cathode

anode

E_Y



E field distortions roughly

2× larger

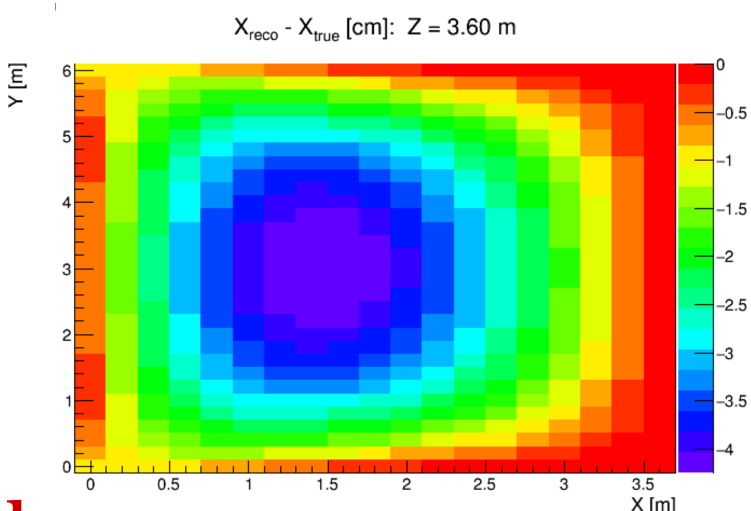
at DP compared to SP

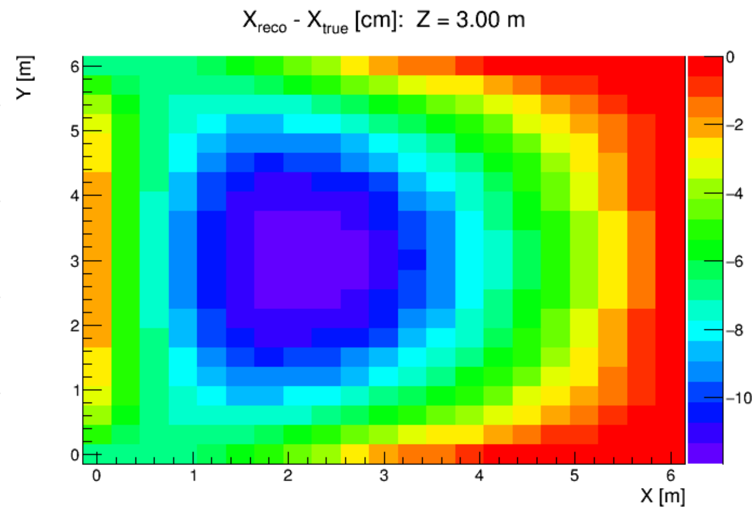
Nominal Geometry

SP (500 V/cm) DP

6 m × 6 m × 6 m

ΔX

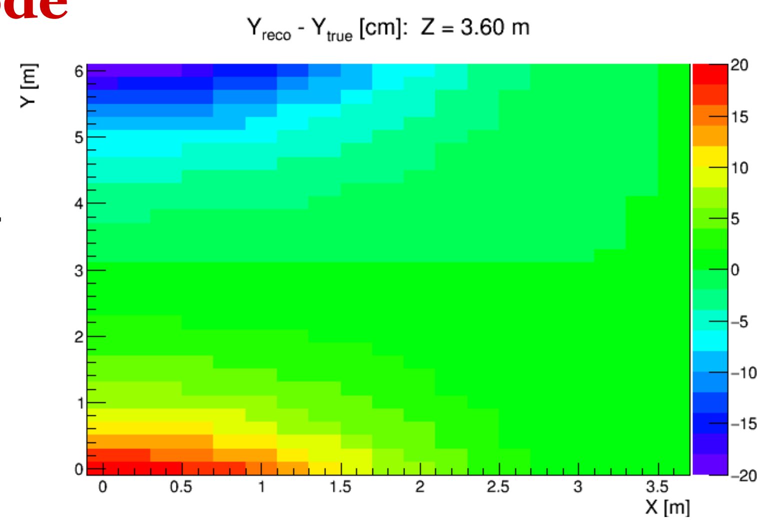


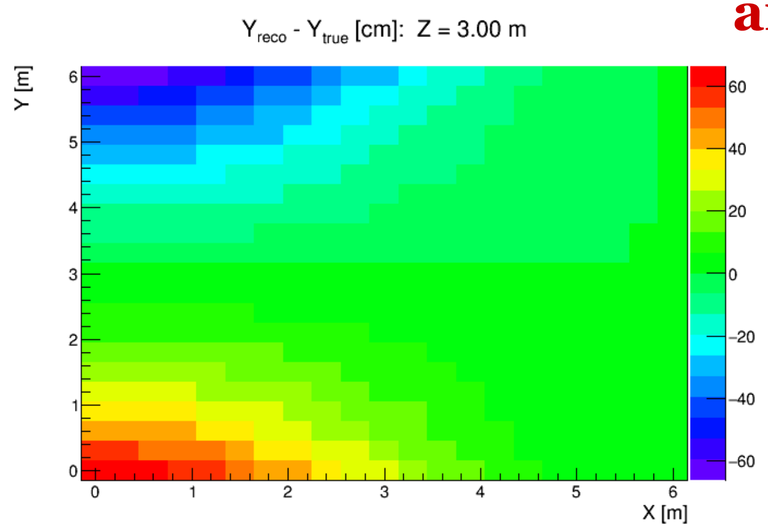


cathode

anode

ΔY





SP/DP Comp. – Spatial Dist.

Nominal Geometry

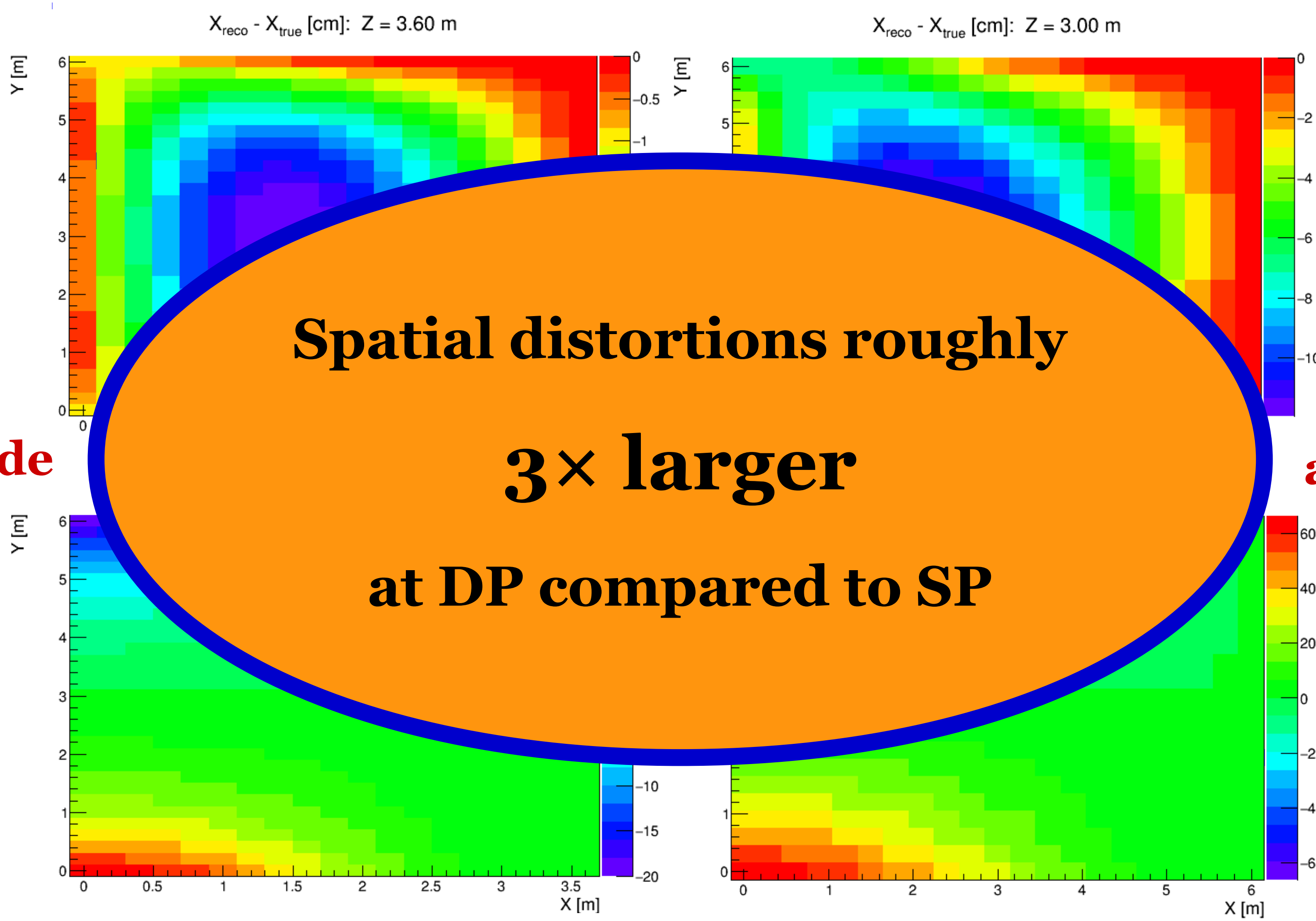
SP (500 V/cm) **DP**

6 m × 6 m × 6 m

ΔX

ΔY

cathode



anode

Spatial distortions roughly

3× larger

at DP compared to SP

How SCE Impacts Physics

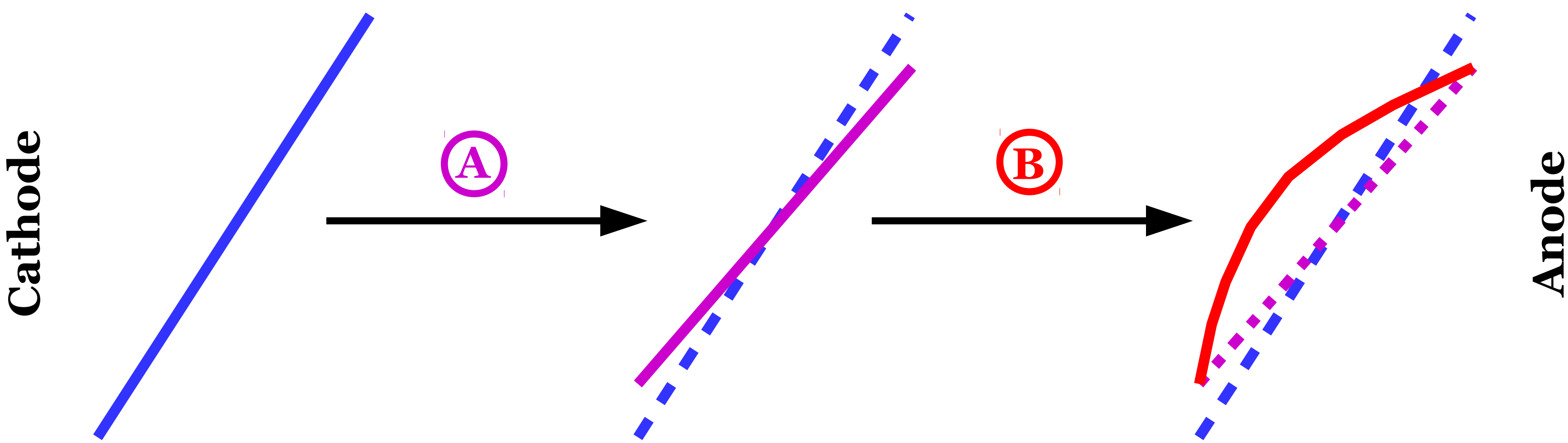
- Two major impacts of SCE on physics:

  - **Track reconstruction** (tracks bend from spatial distortions)

  - **Calorimetry** (E field distortions lead to variation in level of recombination)

Impact on Track Reco.

- Two separate effects on reconstructed **tracks**:
  - (A) Reconstructed track shortens laterally (looks rotated): **~15 cm**
  - (B) Reconstructed track bows toward cathode (greater effect near center of detector): **~4 cm**
- Can obtain straight track (or multiple-scattering track) by applying corrections derived from data-driven calibration

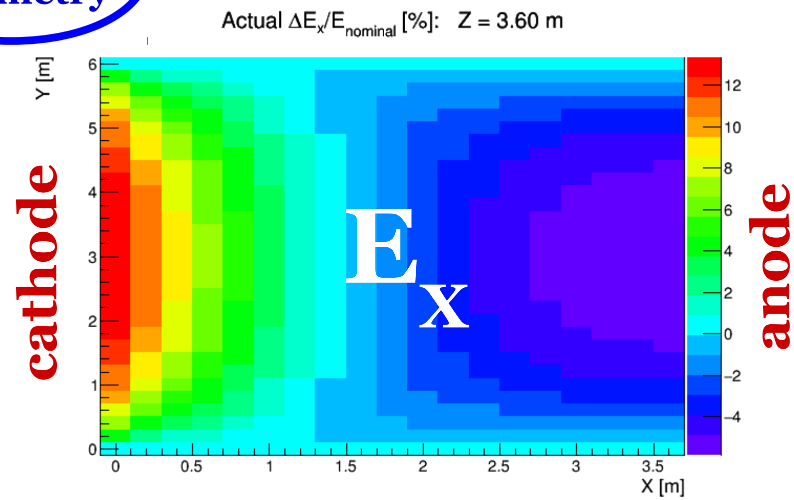


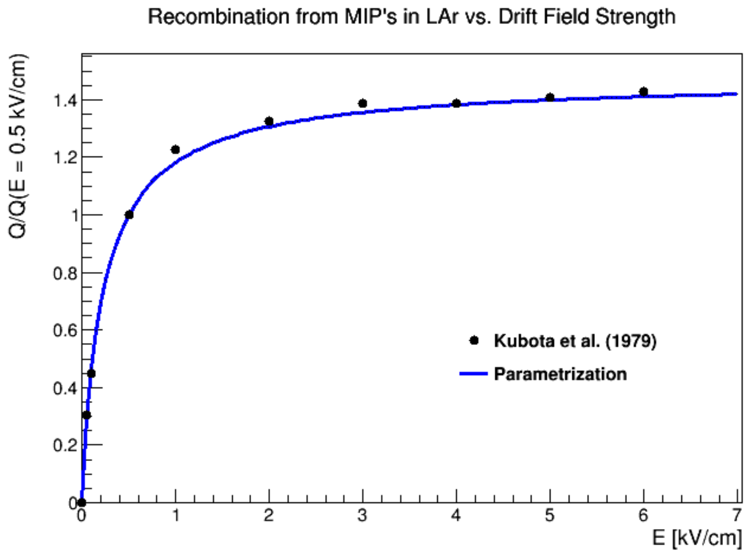
Impact on Calorimetry

- E field distortions from SCE leads to varying E field magnitude throughout TPC → recombination level varies
  - Shape closely follows that of E_x distortions
  - Nominal protoDUNE geometry/field: **~10%** variation in recombination throughout TPC!
  - MicroBooNE has seen "negative electron lifetimes" with TPC tracks which is very likely this effect (can correct with calibration)

Nominal Geometry

$E_{nominal}$ = 500 V/cm





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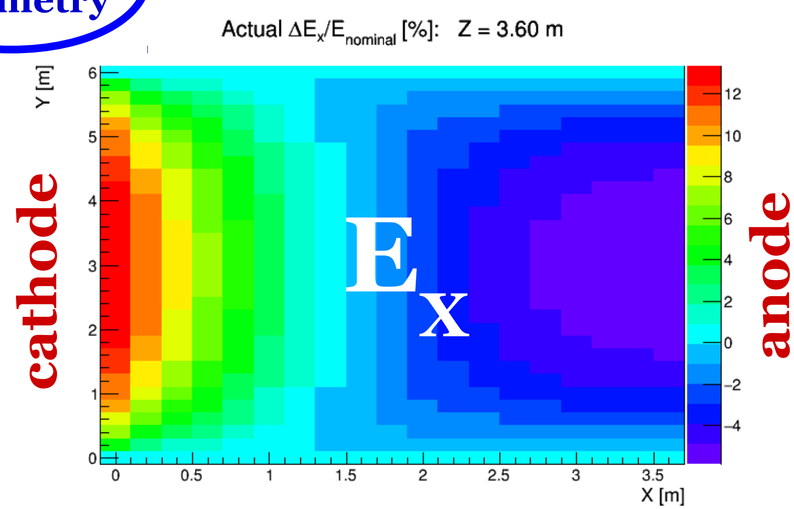
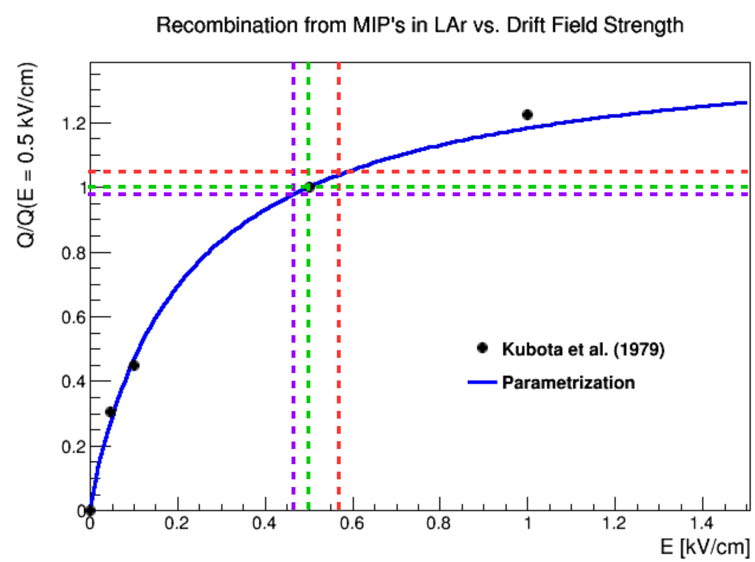
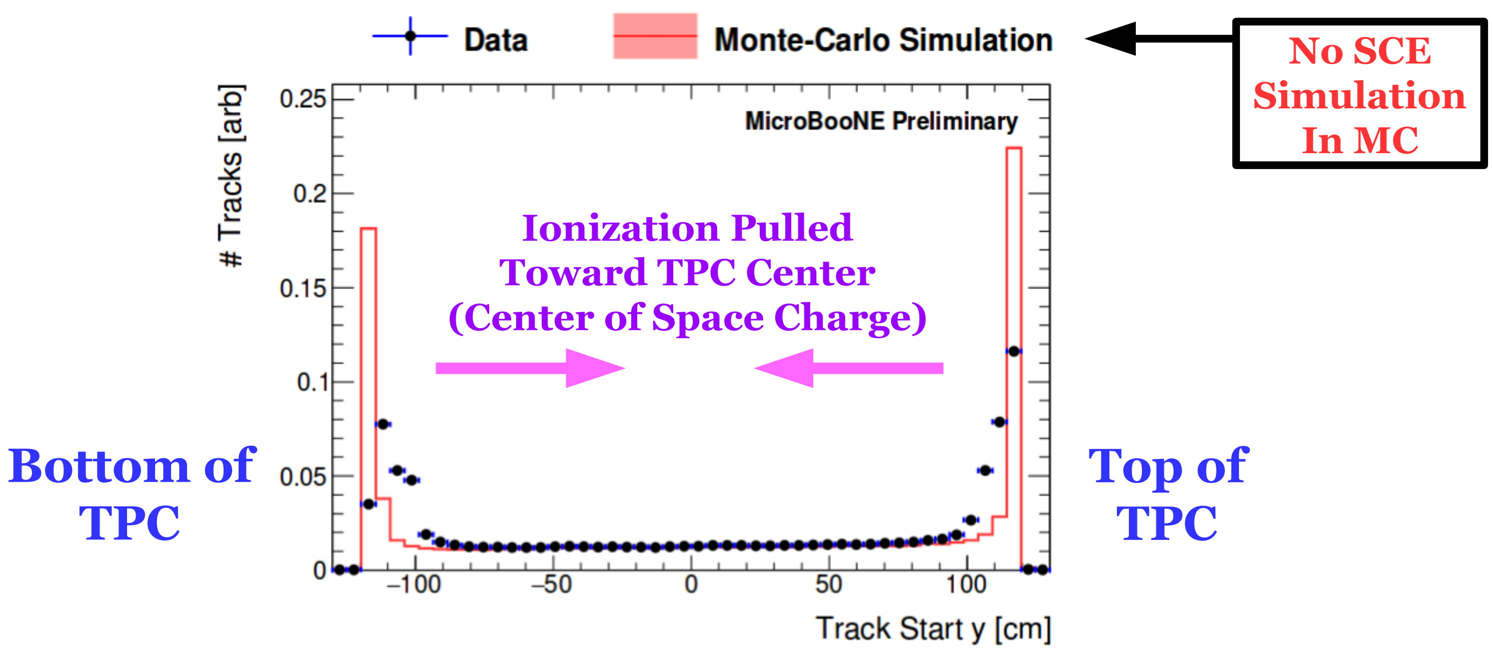




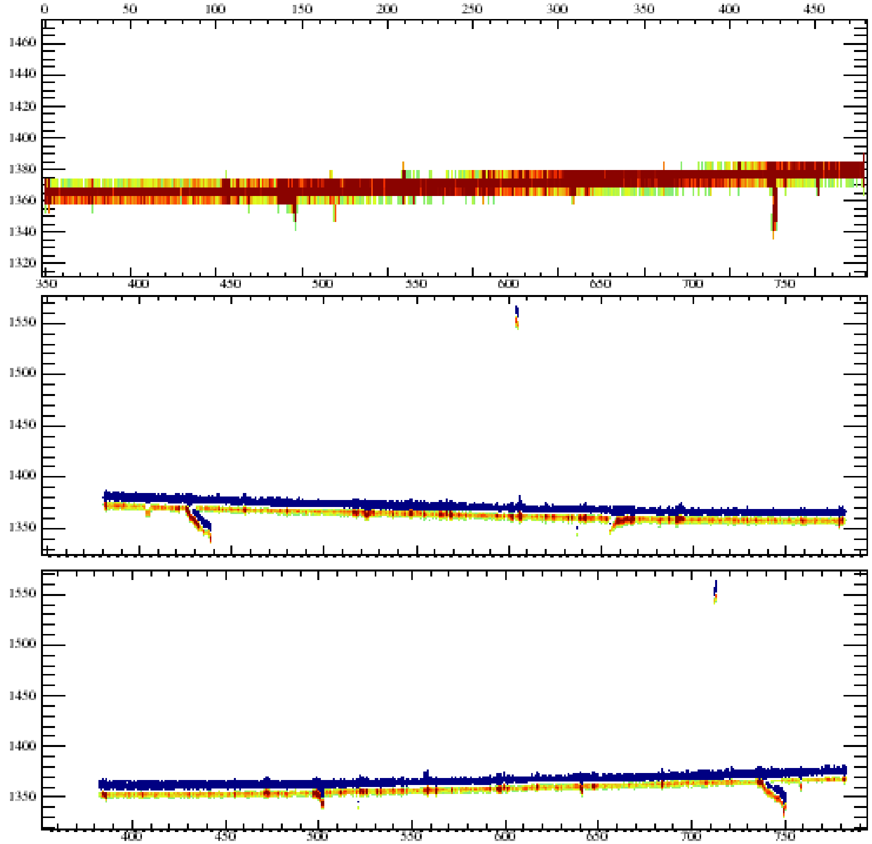
SCE at MicroBooNE?

- Upcoming SCE note from MicroBooNE undergoing approval process
  - Things look on-target for ICHEP… but **not ready yet**
- However, data/MC comparisons public note has been approved already – offsets of track start/end points from sides of TPC very suggestive…

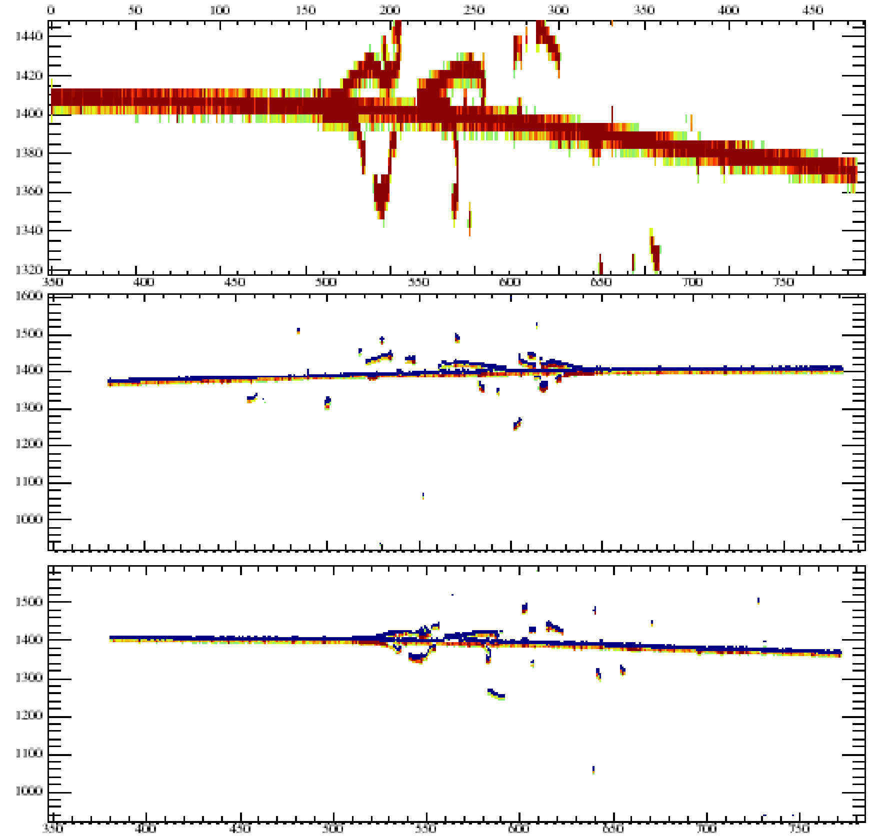


Simulation in LArSoft

Without SCE

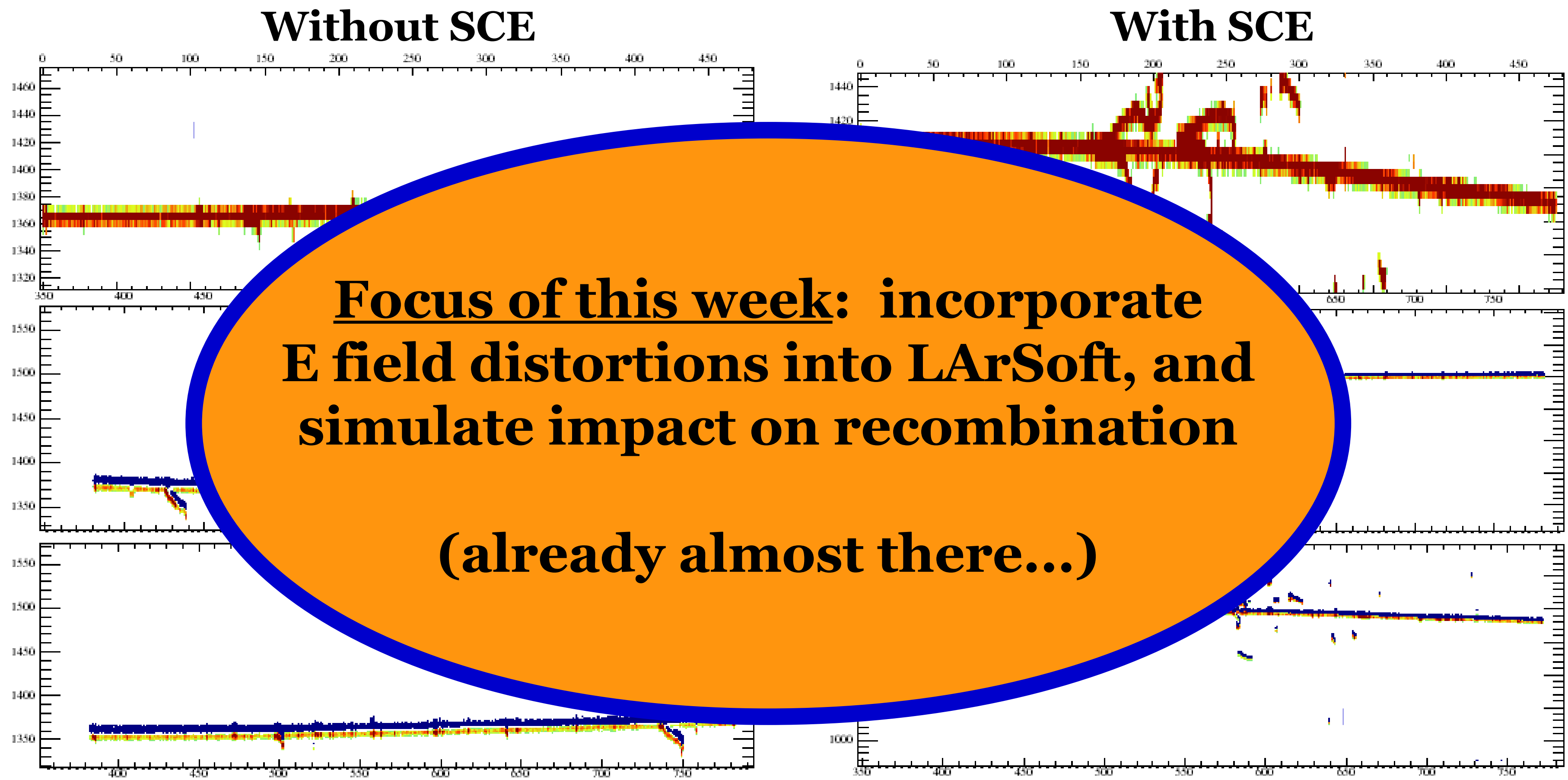


With SCE



- ♦ LArSoft implementation of spatial distortions exists
  - Compare without SCE (left) to with SCE (right)
  - Different events but same track angle

Simulation in LArSoft



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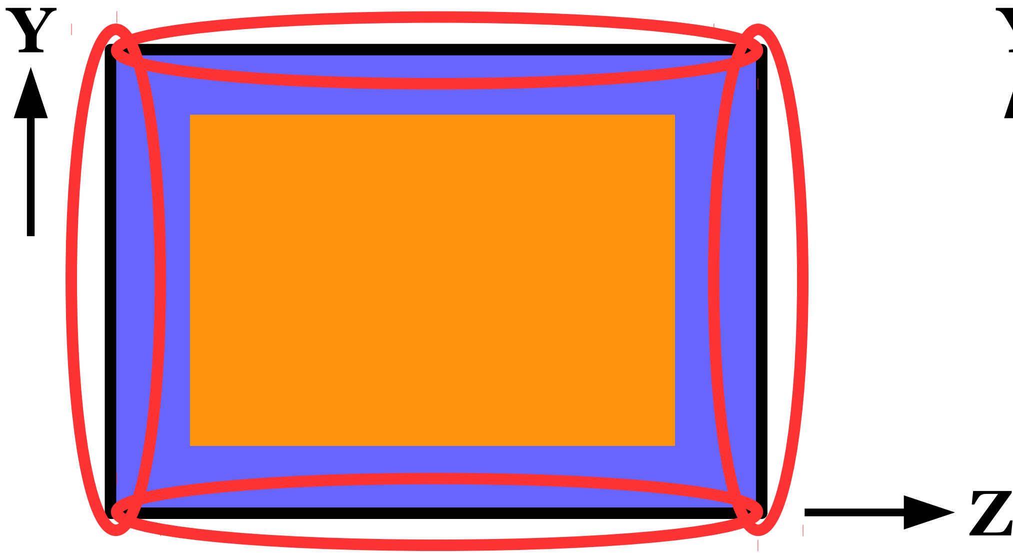
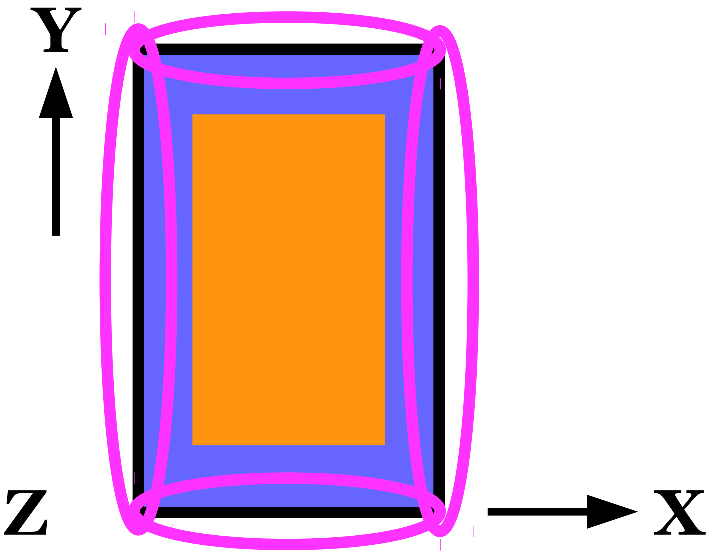
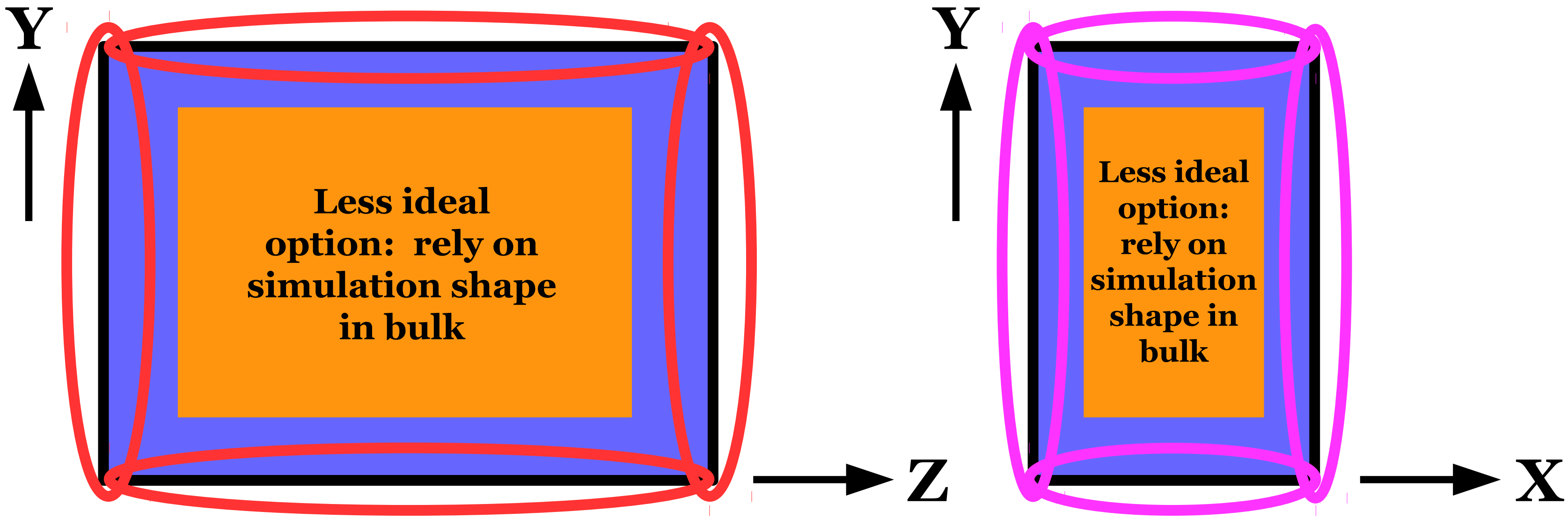
SCE Calibration Scheme





- 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 must combine all of the above to obtain full correction map
- Light-collection system can help pin down track t_o, aiding calibration in bulk of TPC

SCE Calibration Scheme



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What If We Don't Have a Laser?

- If this unfortunate circumstance arises, then we have, as far as I see, two options:

    - Use **cosmic muons** to calibrate SCE in TPC bulk

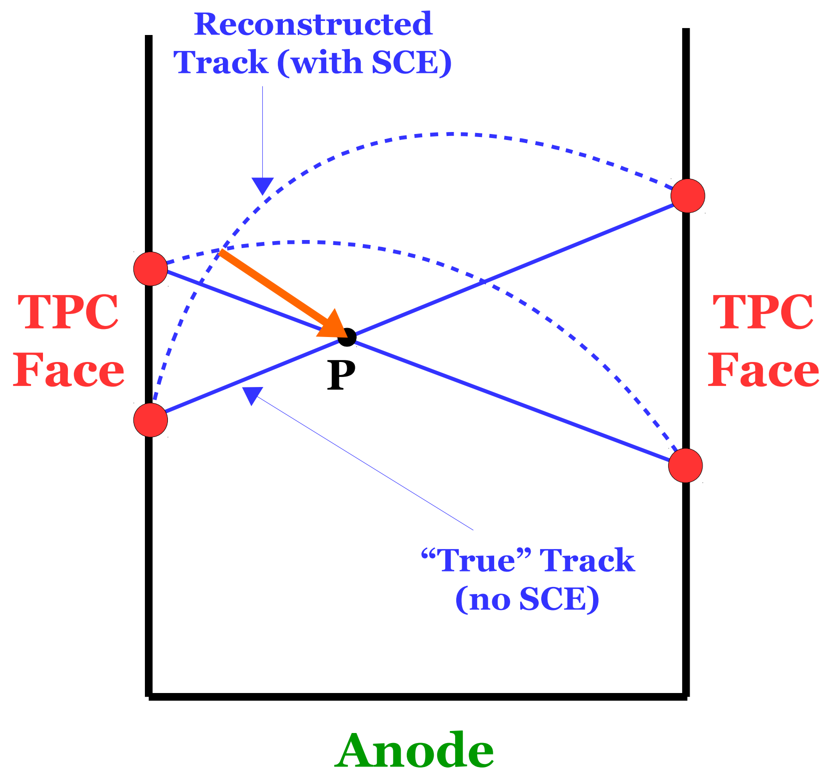
    - Depend on **simulation** in TPC bulk

- Realistically would want to do the former as much as possible, and the latter to "fill in the gaps"

Bulk Calibration w/ Cosmics

- Fill in displacement correction map gaps using **cosmic muons**
- One idea: correction from center of line connecting points of closest approach (separation **d**) between two tracks (before and after SCE)
  - Get "true" muon track from PCA fit to already-calibrated points
  - Weight each contribution by $\mathbf{e}^{-\mathbf{d}/\mathbf{D}}$ (where **D** is tunable parameter)
  - Use only **high-momentum cosmics** to minimize MCS effects
- Relies on first correcting points at boundaries, high stats to average out MCS, and knowing track t_o

M. Mooney
arxiv:1511.01563



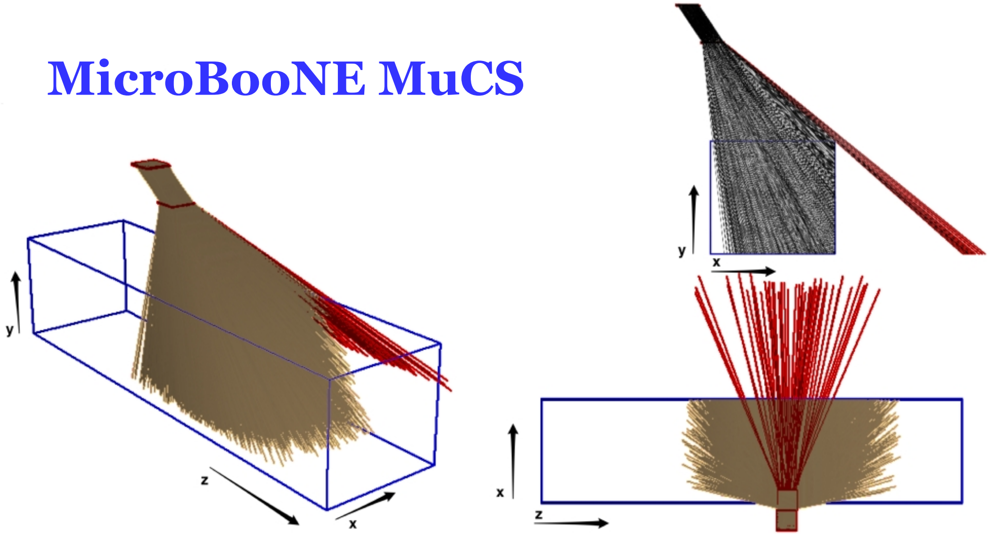
Update Correction to Point P

Cognitive Dissonance

- We are considering several restrictions now for protoDUNE:
  - (1) No laser system
  - (2) Significant reduction in CRT coverage
  - (3) Tight constraints on data volume
- Without a laser system, you need a **large** sample of cosmics (especially if there are time-dependent effects):
  - High enough statistics to average out MCS in each voxel
  - Compensate for filtering out events to keep those with low track density, so track-flash matching with light-collection system reliably (> 98% of time) yields correct t_0 (MicroBooNE: **ε < 5%**)
- Part of the problem, extremely reliable t_0 determination, would be ameliorated with substantial CRT coverage
- <u>Bottom line</u>: if (1), doing (2) and (3) not a good idea…

Calibrations at MicroBooNE

MicroBooNE MuCS



- Plan is to utilize calibration strategy from previous slide at MicroBooNE
- SCE public note not ready as mentioned before, but preliminary correction utilizing the MuCS (muon counter system) serves as a calibration microcosm – stay tuned!
- Looking at top/bottom of TPC: space charge configuration stable over long timescales **(November → March)**

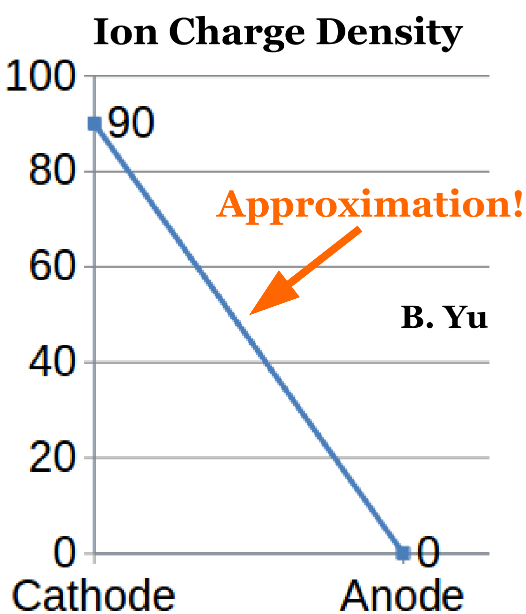
Summary

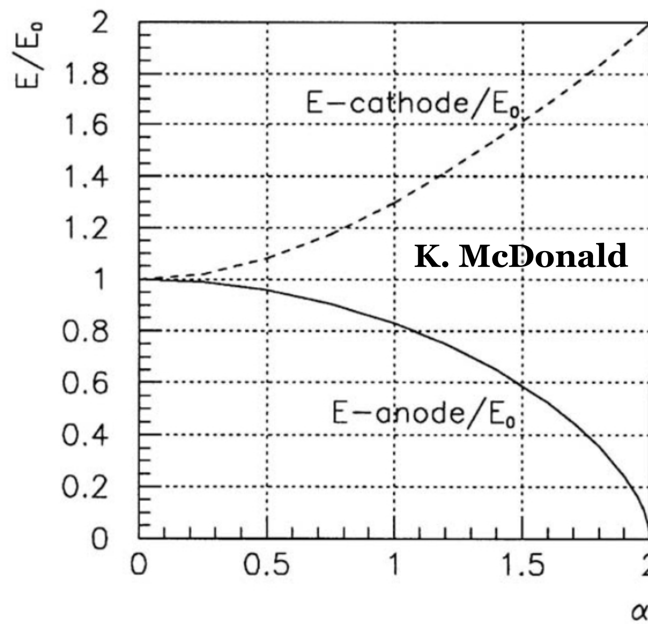
- SCE will impact tracking and calorimetry at protoDUNE
- Spatial distortions at SP protoDUNE for **nominal geometry** are quite severe (and 3× worse for DP)!
  - **500 V/cm** drift field: **~5 cm** longitudinal, **~20 cm** transverse
  - **250 V/cm** drift field: **~20 cm** longitudinal, **~60 cm** transverse
- E field distortions will lead to **~10%** variation in **recombination** throughout TPC (for 500 V/cm drift field)
  - Roughly 2× worse for DP
- Can calibrate out space charge effects throughout TPC by combining multiple subsystem information: TPC, light-collection system, muon counters, and laser system
- Upcoming public note on SCE from MicroBooNE – should be an interesting read!

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, $E^{-1.7}$



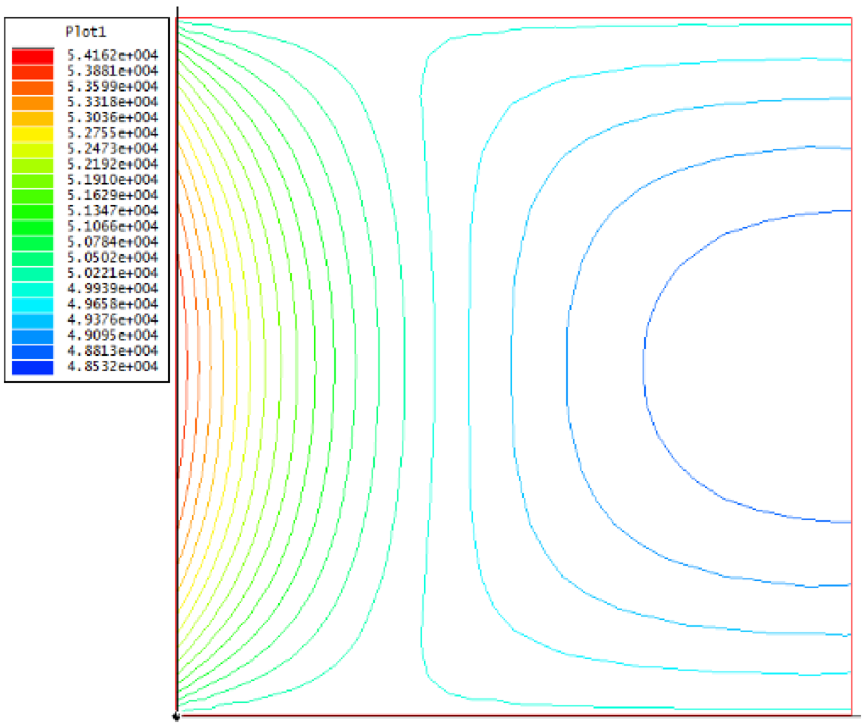


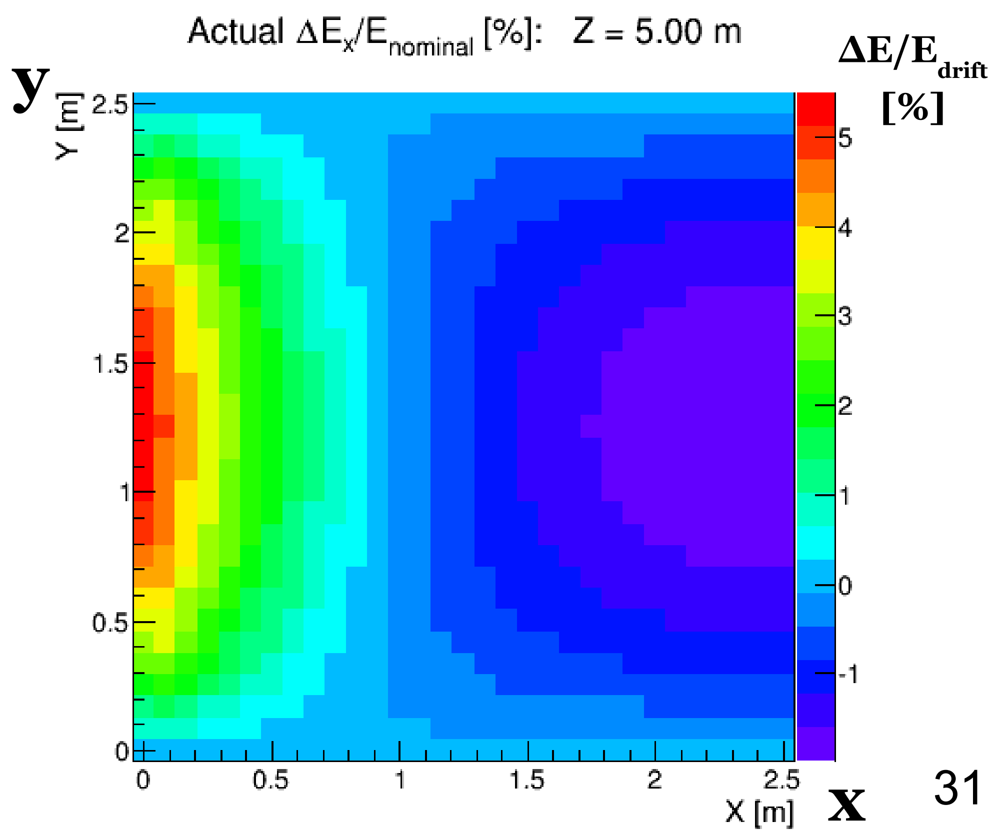
$$\alpha = \frac{D}{E_0}\sqrt{\frac{K}{\epsilon\mu}}$$

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

Compare to FE Results: E_x

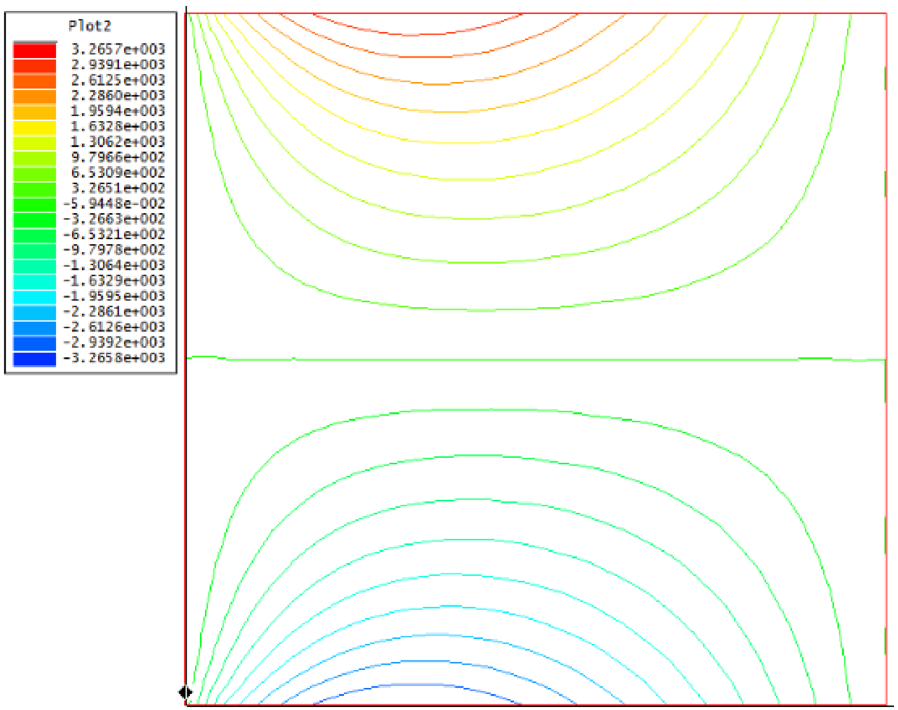
- Looking at central z slice (z = 5 m) in x-y plane (**MicroBooNE**)
- Very good shape agreement compared to Bo Yu's 2D FE (Finite Element) studies
- Normalization differences understood (using different rate)

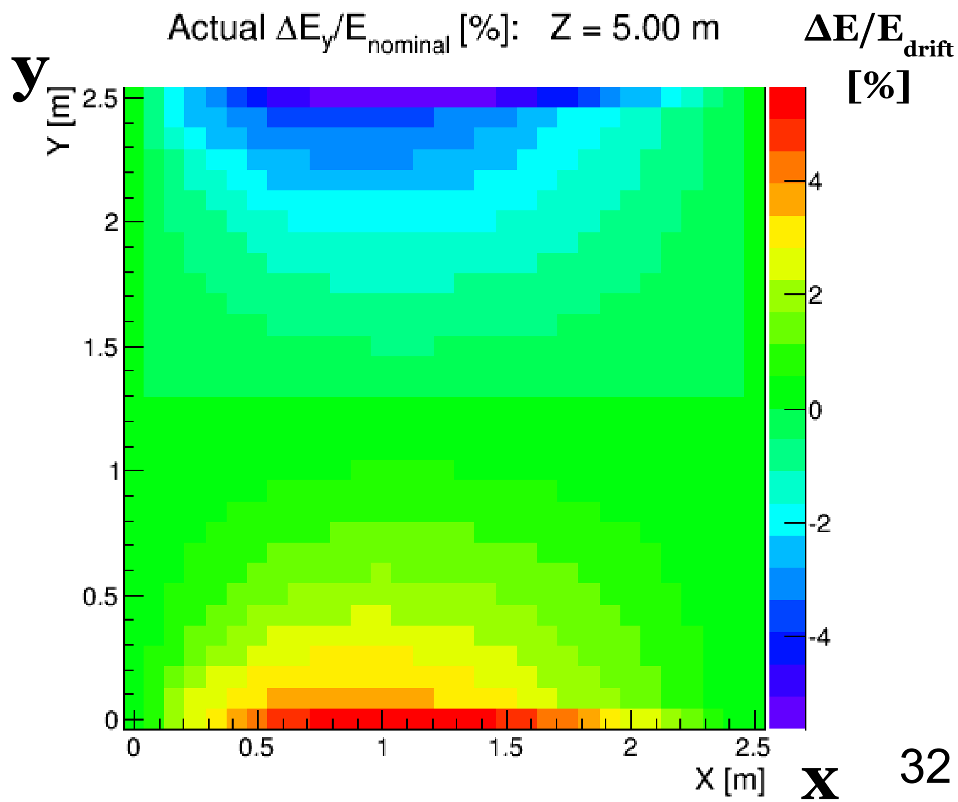




Compare to FE Results: E_y

- 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

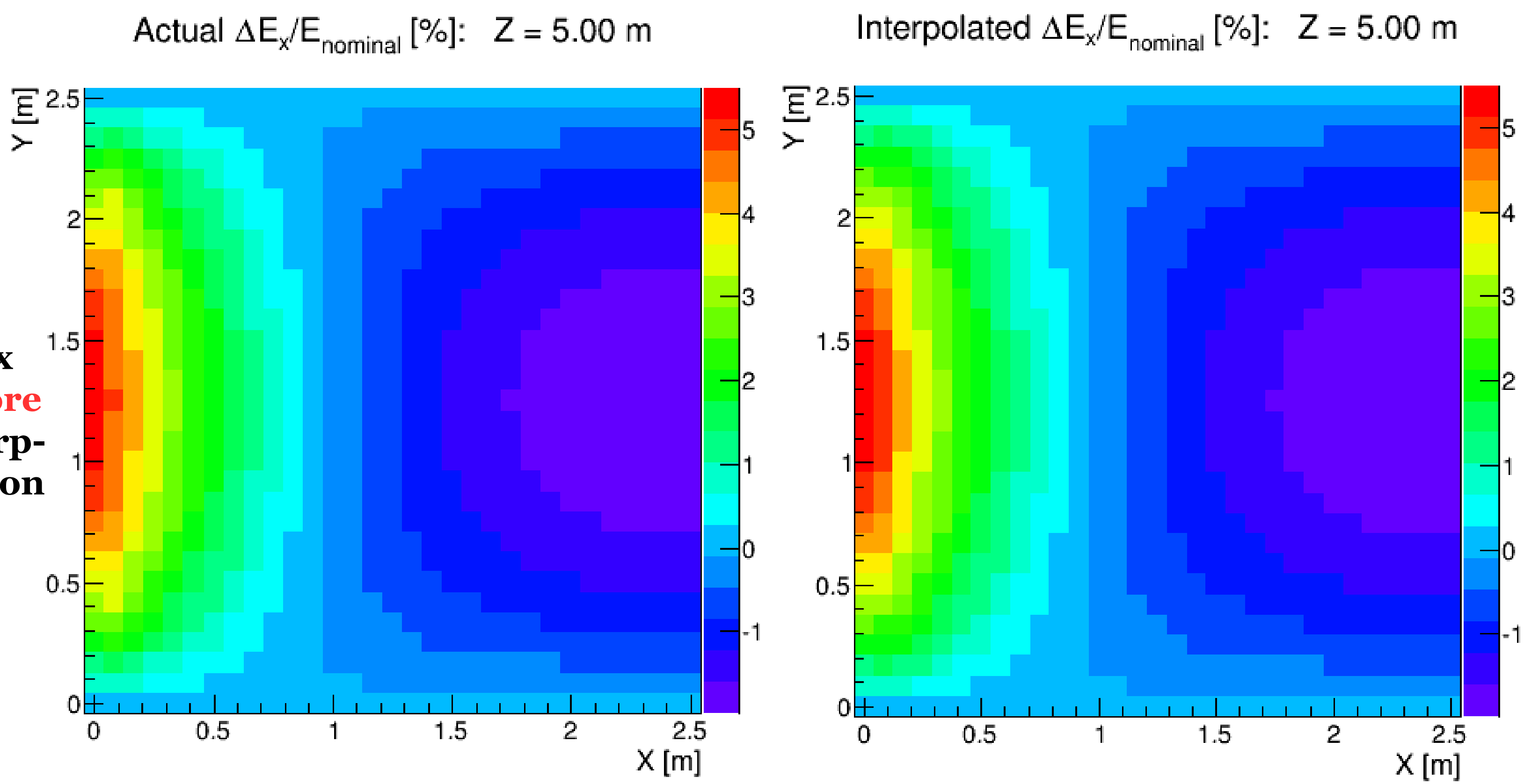




E Field Interpolation

- 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

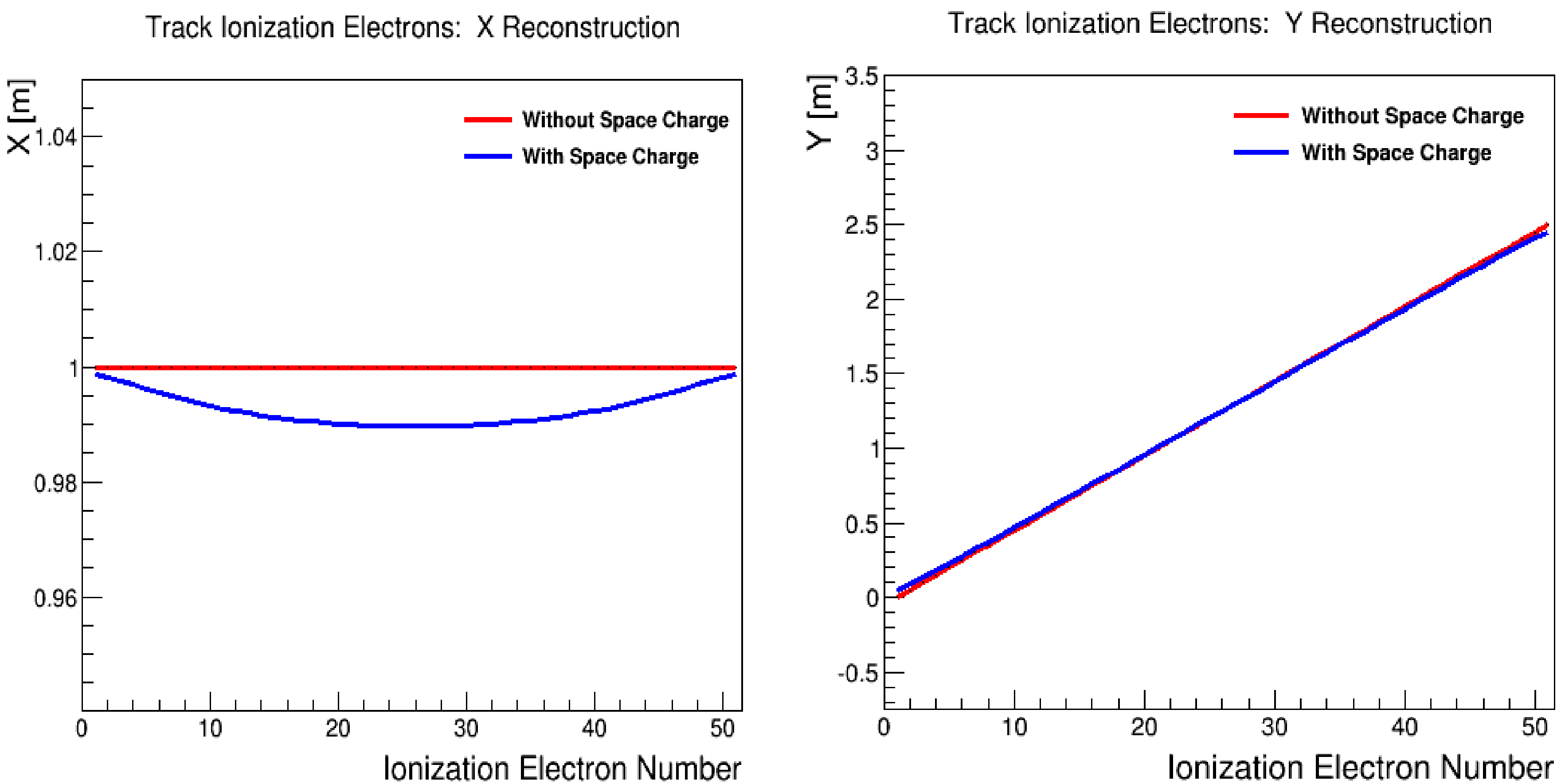


E_x
After
Interp-olation

Ray-Tracing

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

MicroBooNE

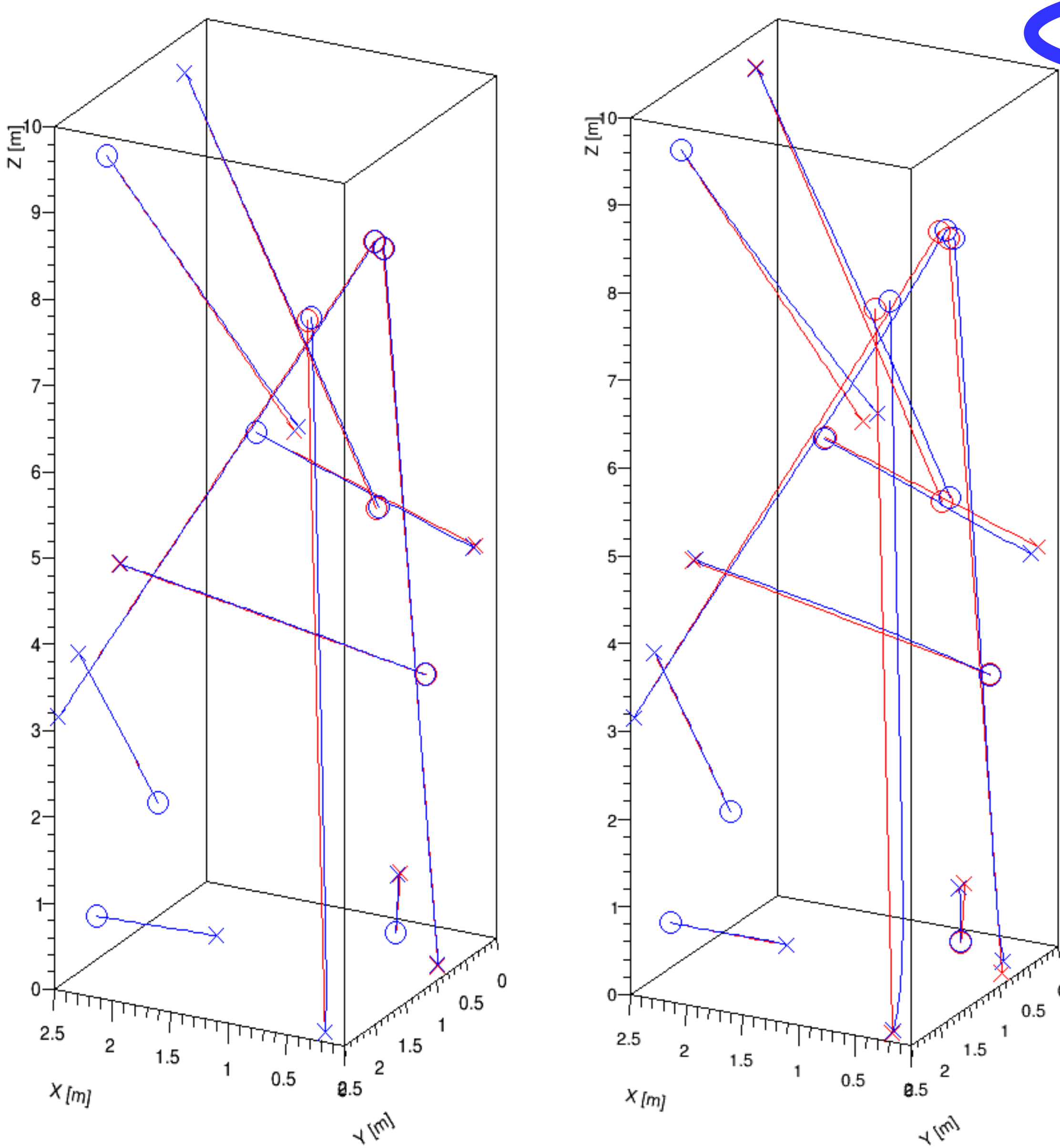


Sample "Cosmic Event"

MicroBooNE

Nominal Drift Field

500 V/cm



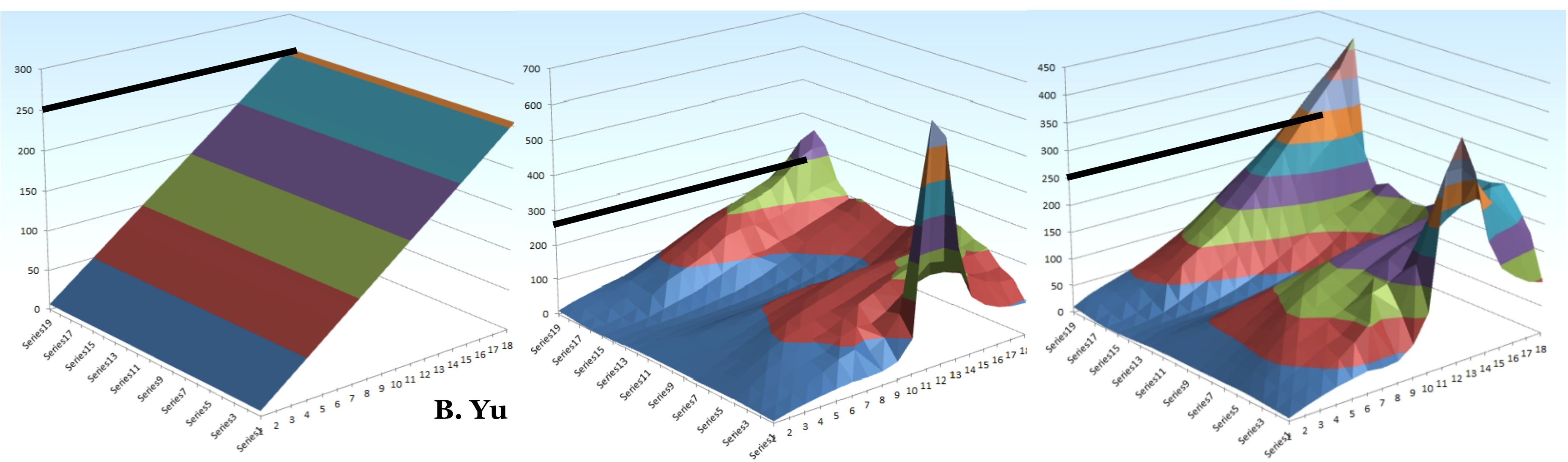
Half Drift Field

250 V/cm

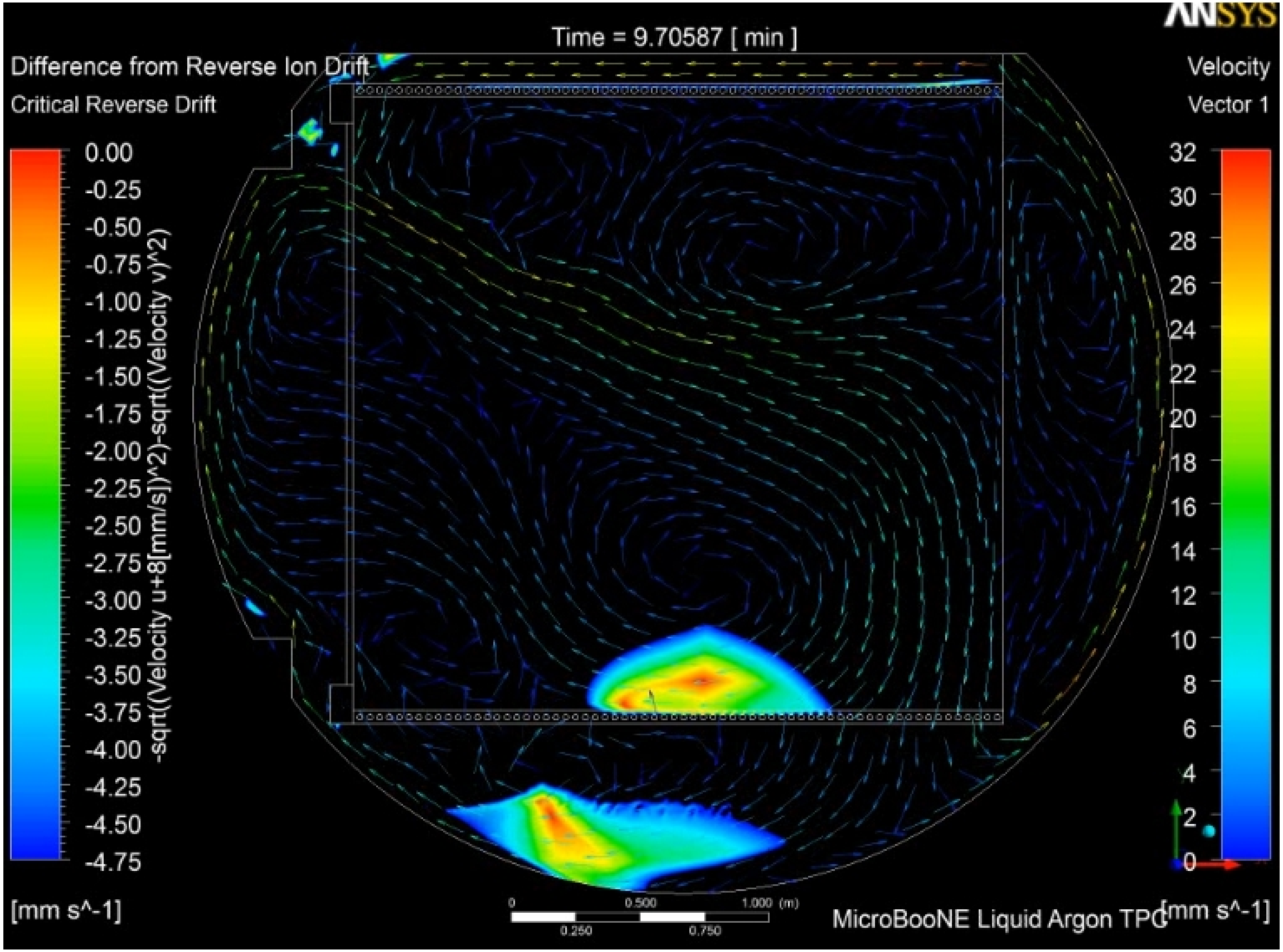
Complications

- 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**



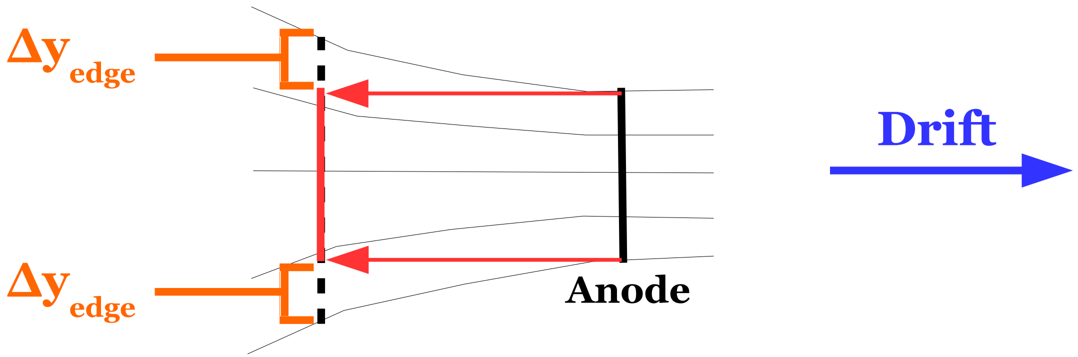
Liquid Argon Flow



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

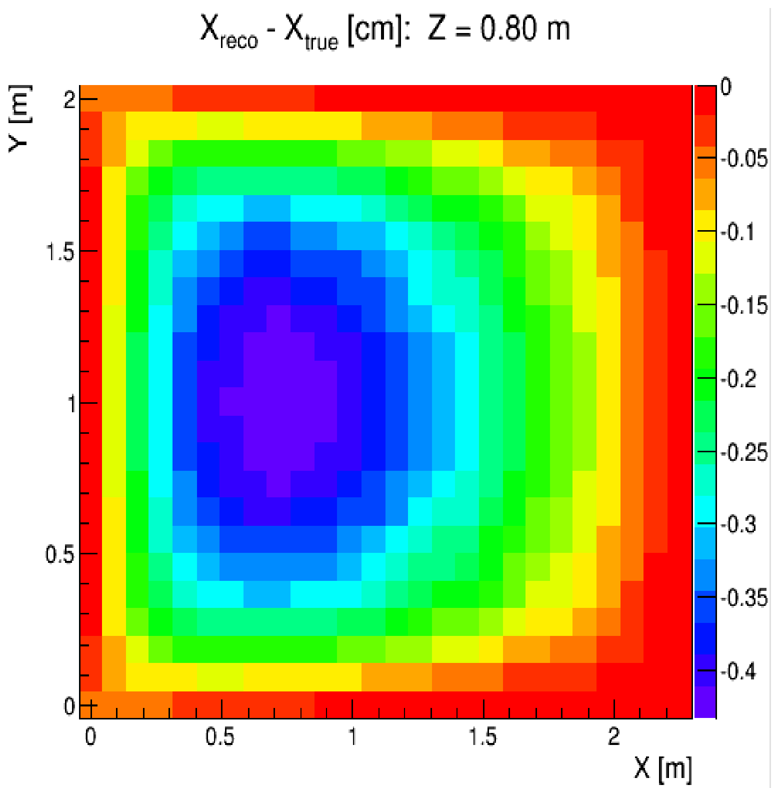


35-ton with LAr Flow

central z slice

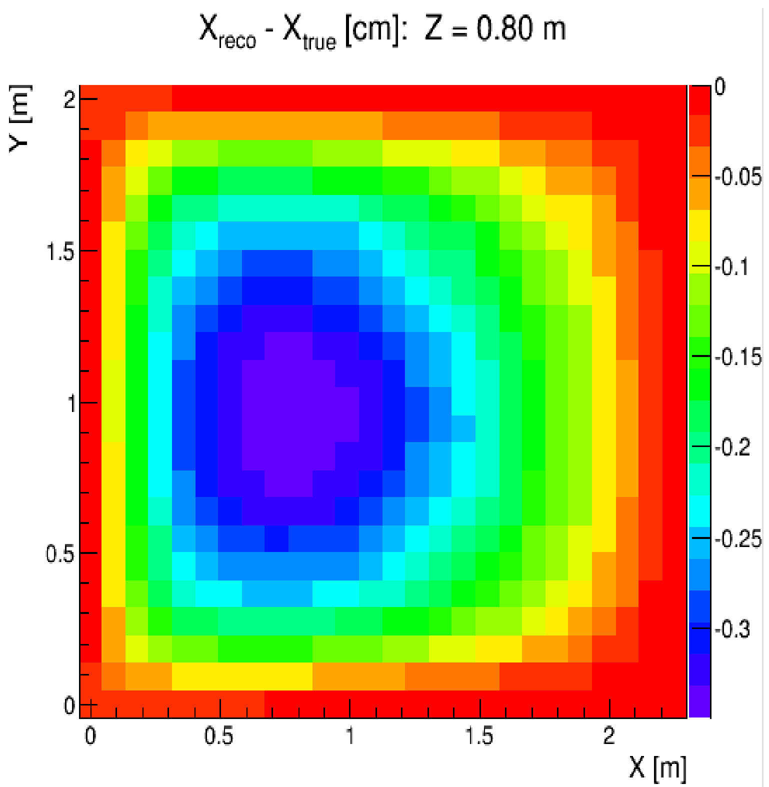
Δx

Without
LAr Flow



Δx

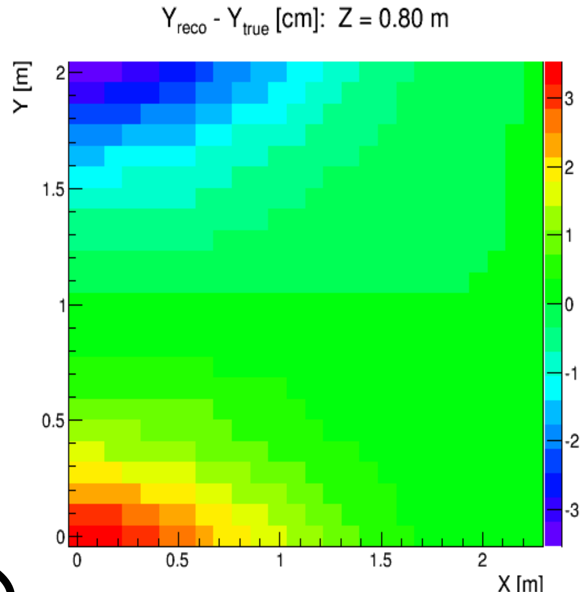
With
LAr Flow

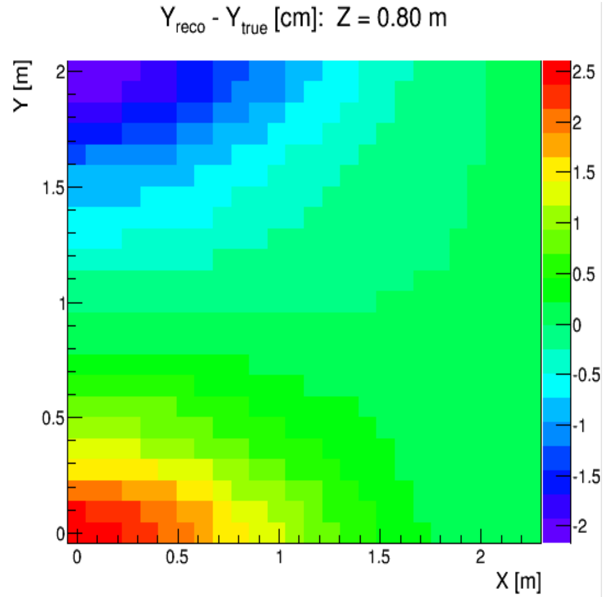


Q map from E. Voirin

35-ton with LAr Flow (cont.)

Δy
Without
LAr Flow



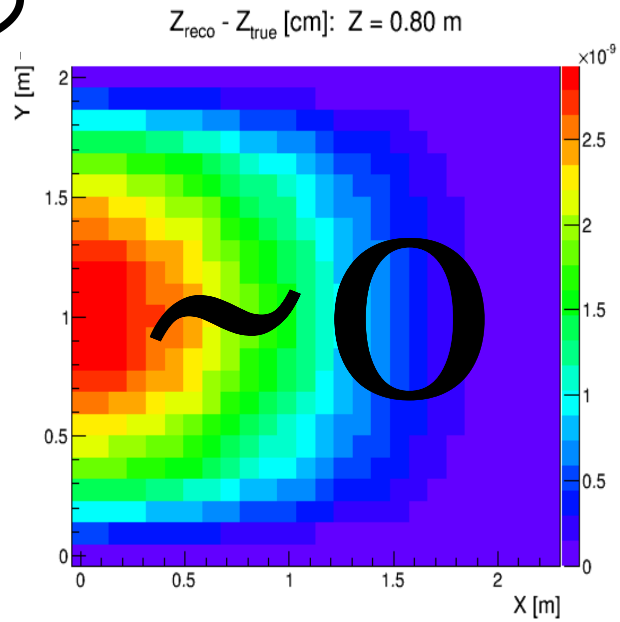


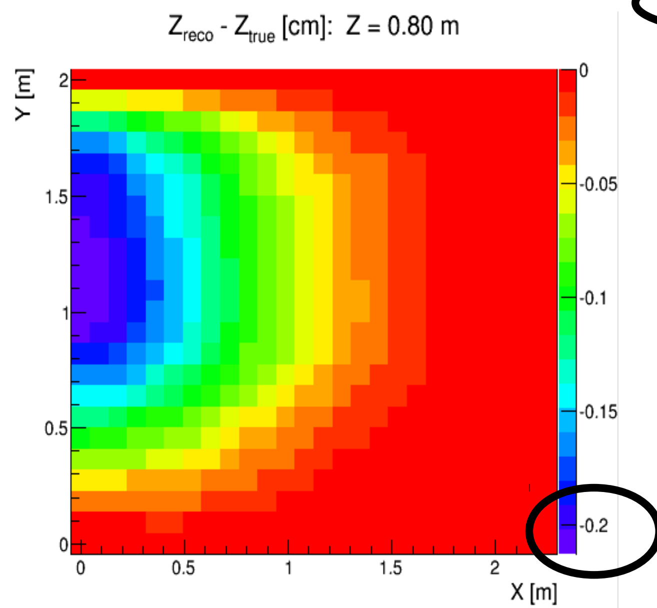
Δy
With
LAr Flow

Q map from E. Voirin

central z slice

Δz
Without
LAr Flow



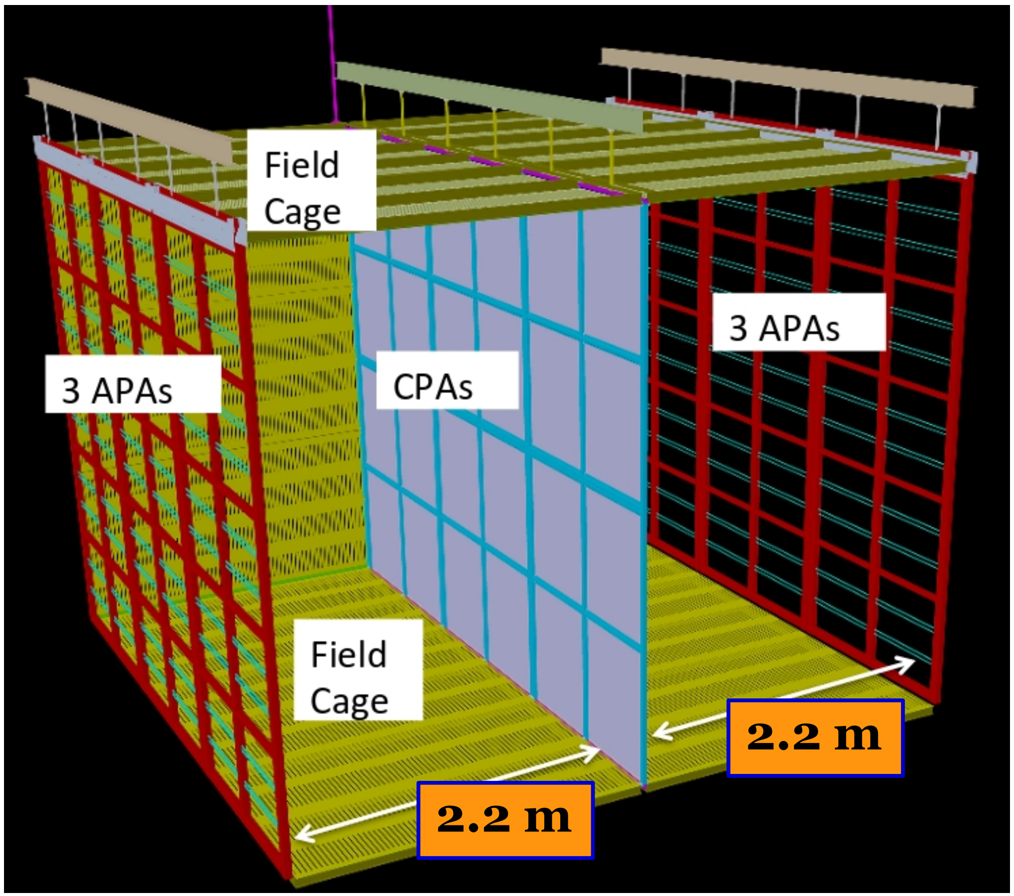


Δz
With
LAr Flow

Simulation of SC Effect

- Can use SpaCE to produce displacement maps
  - **Forward transportation**: $\{x, y, z\}_{\textbf{true}} \rightarrow \{x, y, z\}_{\textbf{sim}}$
    - Use to **simulate** effect in MC
    - Uncertainties describe accuracy of simulation
  - **Backward transportation**: $\{x, y, z\}_{\textbf{reco}} \rightarrow \{x, y, z\}_{\textbf{true}}$
    - 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 SP Geometry



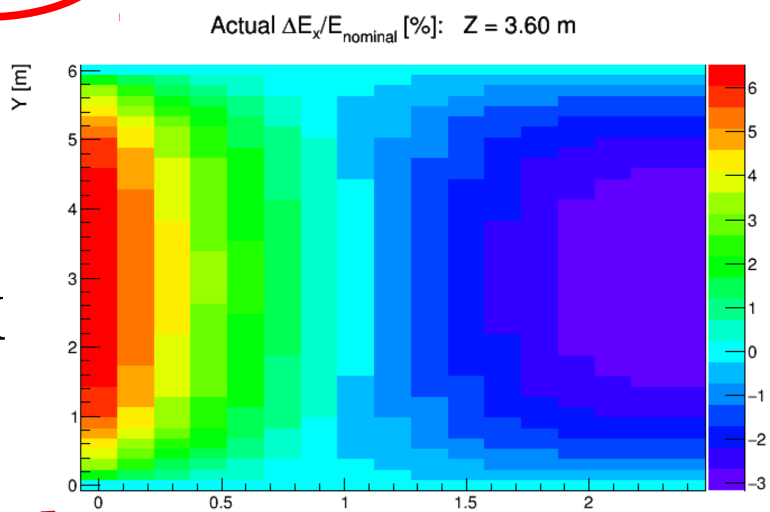
- Modified SP protoDUNE geometry:
  - **Drift (X): 2.2 m**
  - Height (Y): 5.9 m
  - Length (Z): 7.0 m
- Dimensions used for simulations slightly different (to simplify calculations):
  - **Drift (X): 2.4 m**
  - Height (Y): 6.0 m
  - Length (Z): 7.2 m

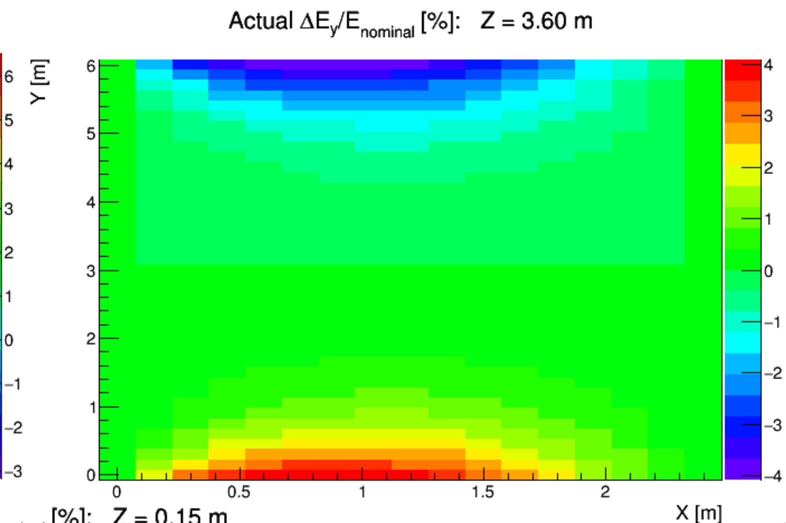
Modified E Field (Mod. Geo.)

Modified Geometry

$E_{nominal}$ = 500 V/cm

E_X

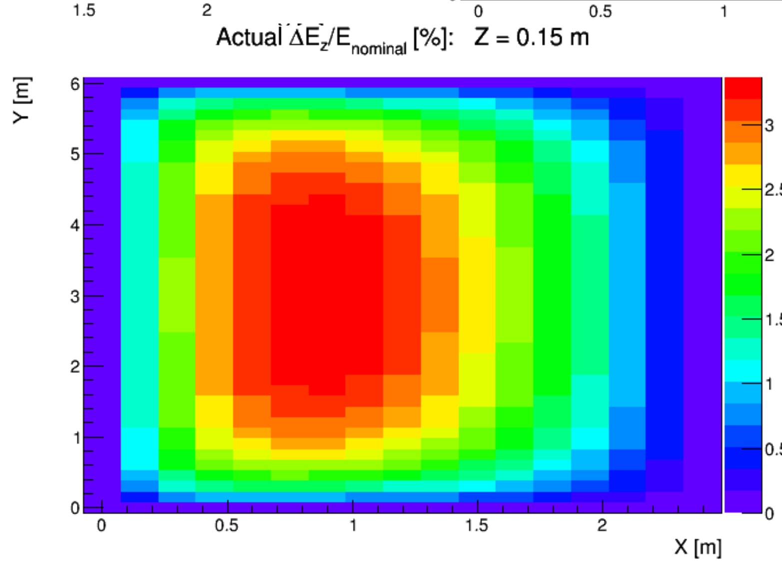




E_Y

cathode

anode

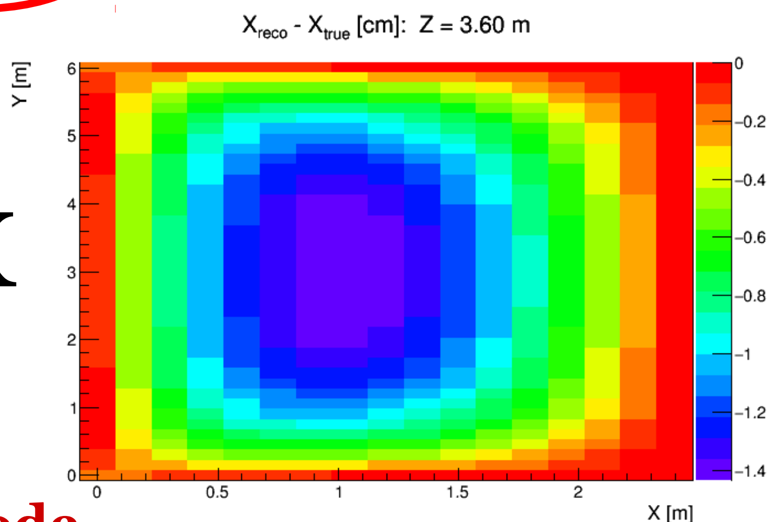


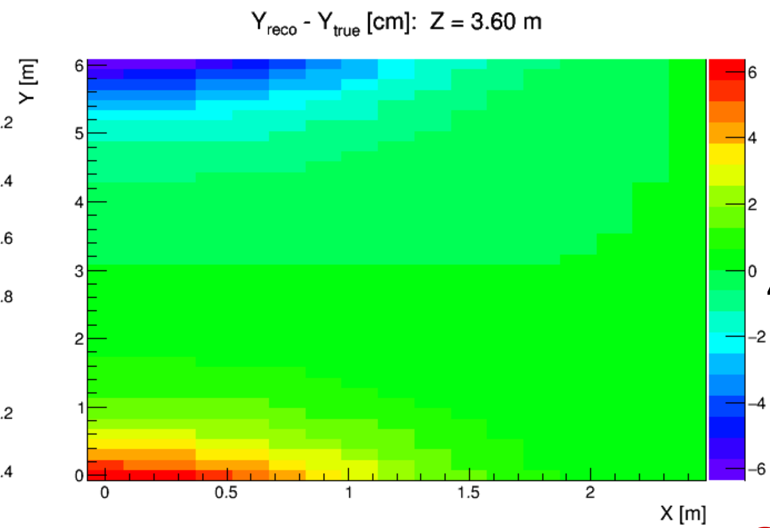
E_Z

Modified Geometry

$E_{nominal} = 500$ V/cm

ΔX

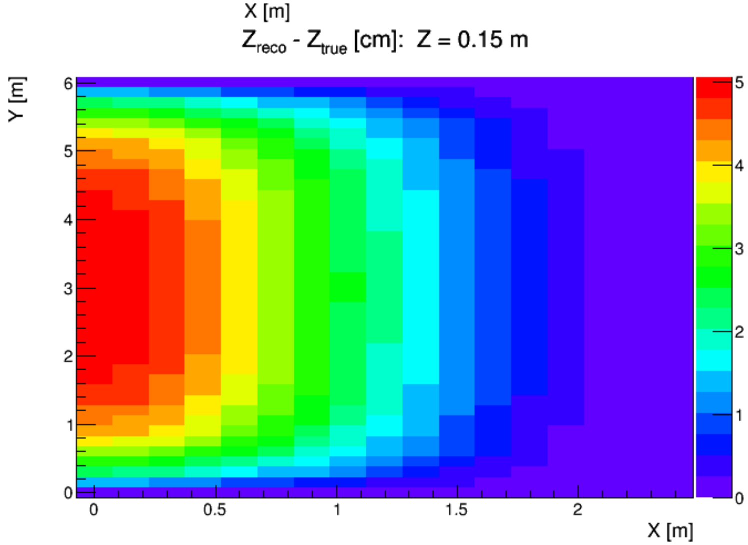




ΔY

cathode

anode



ΔZ

LArSoft Implementation

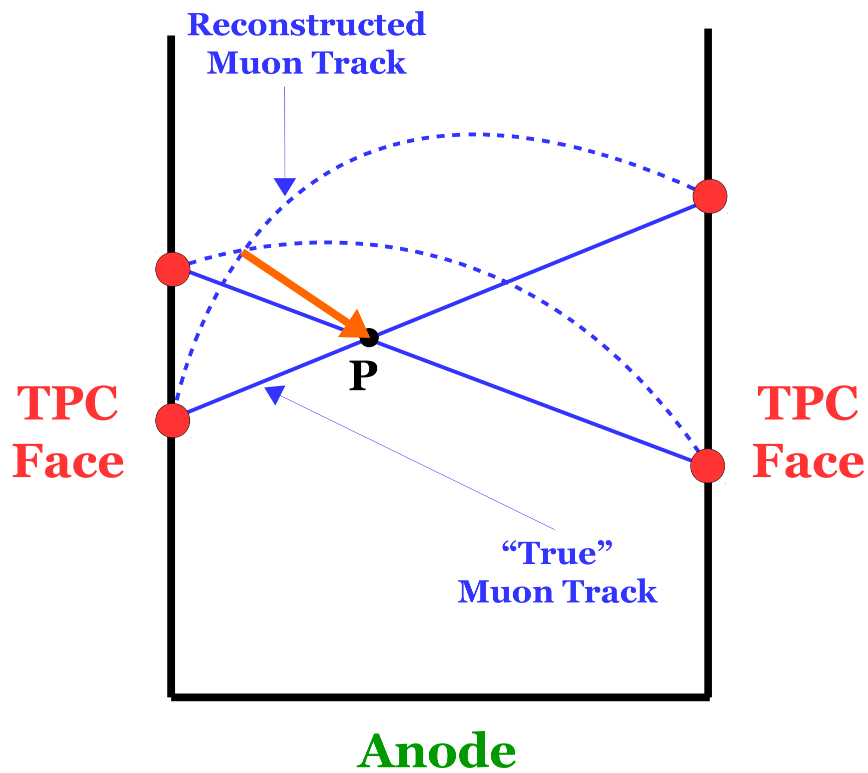
- LArSoft implementation of SCE simulation still waiting to be blessed by LArSoft Coordination Team (next week?)
  - Currently resides on feature/mrmooney_SpaceChargeMay6th2016
  - Works with **larsoft v5_11_00**
  - Check out this branch for the following packages:
    - **larsim** (carries out simulation 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**

Calibration Scheme: SCT

- Fill in displacement correction maps (in between where laser system can reach) using **cosmic muons**
  - Approximately **10 cosmics** per event time window (4.8 ms)
- Algorithm: **Space Charge Tomography (SCT)**
- Step definitions:
  - Use (near) laser crossings – **"X"**
  - Update cosmic muon "truth track" using fit (PCA) to corrected track points that pass through previously-calibrated regions – **"T"**
  - Use (near) crossings of single laser track and single cosmic track – **"L"**
  - Use (near) crossings of two cosmic muons – **"μ"**
- **Progression of SCT steps**: **X → T → L → T → μ → T → L → ...**
  - Obtain cosmic muon t_o from PMT system
  - With high enough statistics, **multiple-scattering averaged out** (also use high-momentum tracks to minimize effect)

SCT "μ" Step

- Calibration scheme details (using **"μ"** step as example):
  - Correction from center of line connecting points of closest approach (separation **d**) between two tracks (before and after SCE)
  - Get "true" muon track from **"T"** step (see previous slide)
  - Weight each contribution by factor $\mathbf{e^{-d/D}}$ (D is tunable parameter)
  - Use only **high-momentum cosmics** to minimize MCS effects



Update Correction to Point P