Space Charge Effect Calibration: Planning

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BNL

ProtoDUNE Measurements Meeting

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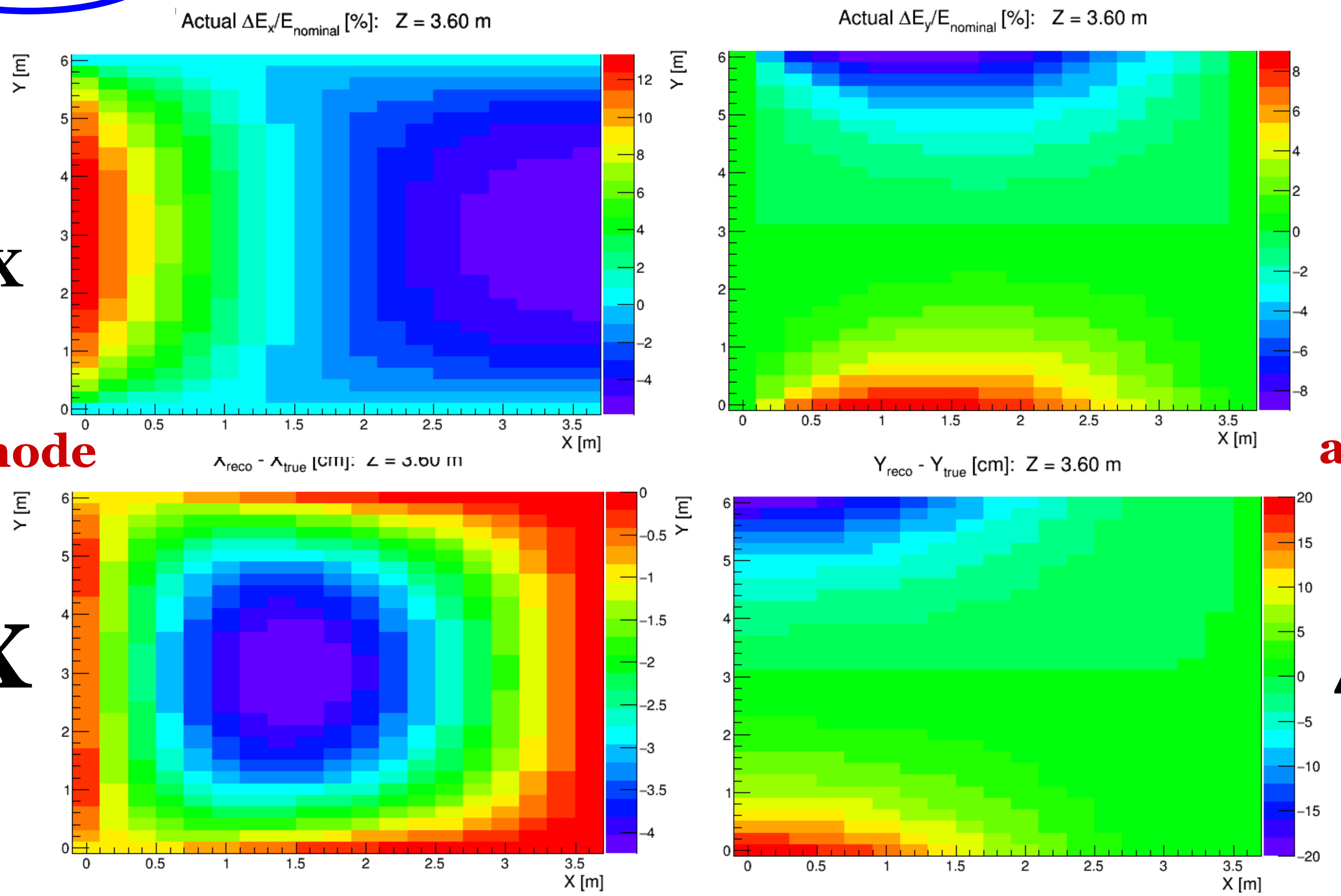
Introduction

- We have heard recently that it is very likely that there will be no UV laser system at protoDUNE with which to calibrate out space charge effects (SCE), among other things
  - This will impact our calibration strategy significantly!
- Placement of CRT panels important consideration for properly calibrating out SCE
  - It has not been shown yet at e.g. MicroBooNE that we can obtain a clean sample of t_0-tagged tracks with the light-collection system
- Highlight considerations for cosmic ray tagger (CRT) in this talk, including placement and how to do calibration
  - Jacob's talk: preliminary answers to partial set of relevant questions
  - This talk: more questions to be answered; also calibration strategy, impact on CRT needs, and required inputs

Quick Look at SCE Impact

Nominal SP Geometry

$E_{nominal} = 500\ \mathrm{V/cm}$



E_X

E_Y

cathode

anode

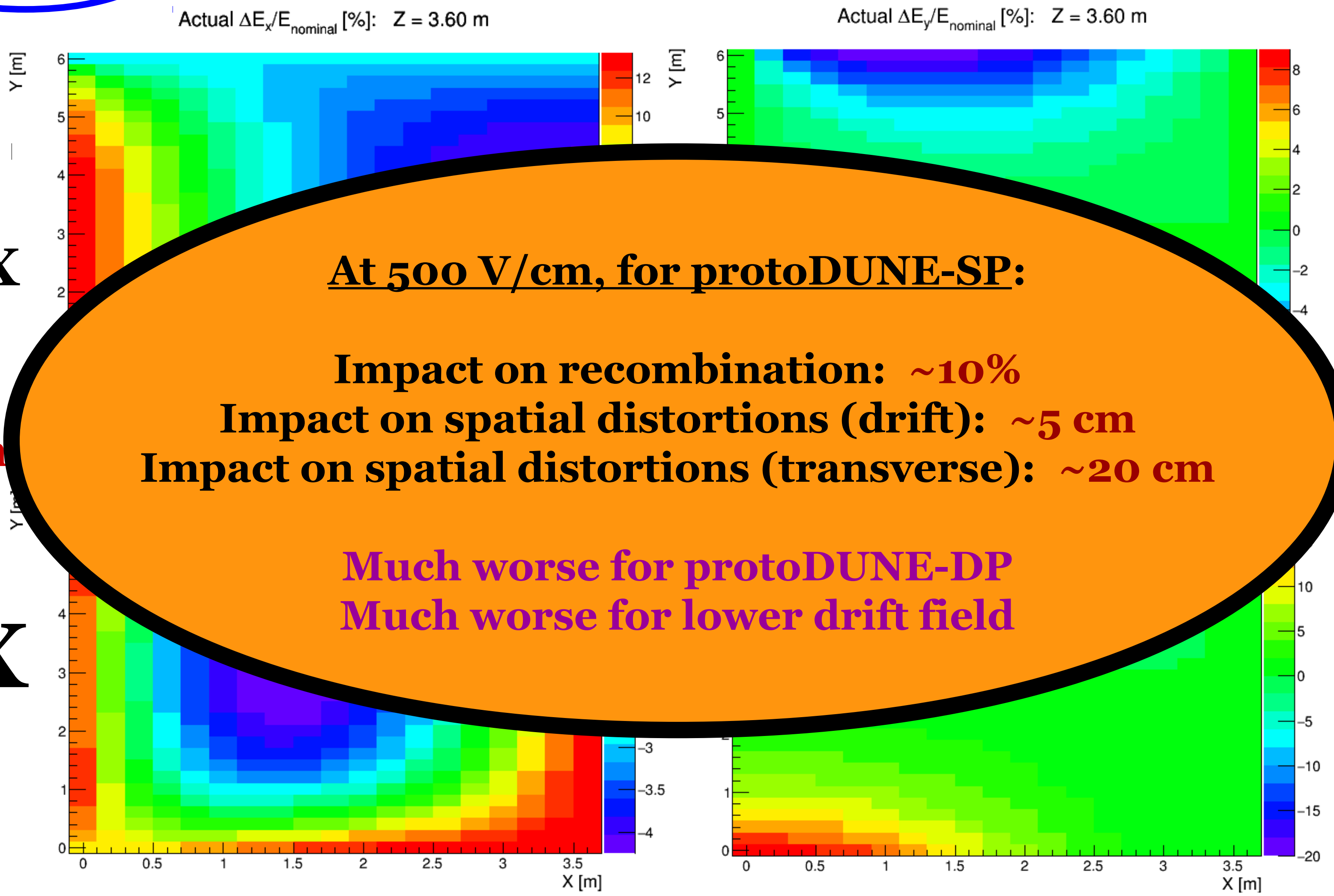
ΔX

ΔY

Quick Look at SCE Impact

Nominal SP Geometry

$E_{\text{nominal}} = 500$ V/cm



E_X

E_Y

cath

node

ΔX

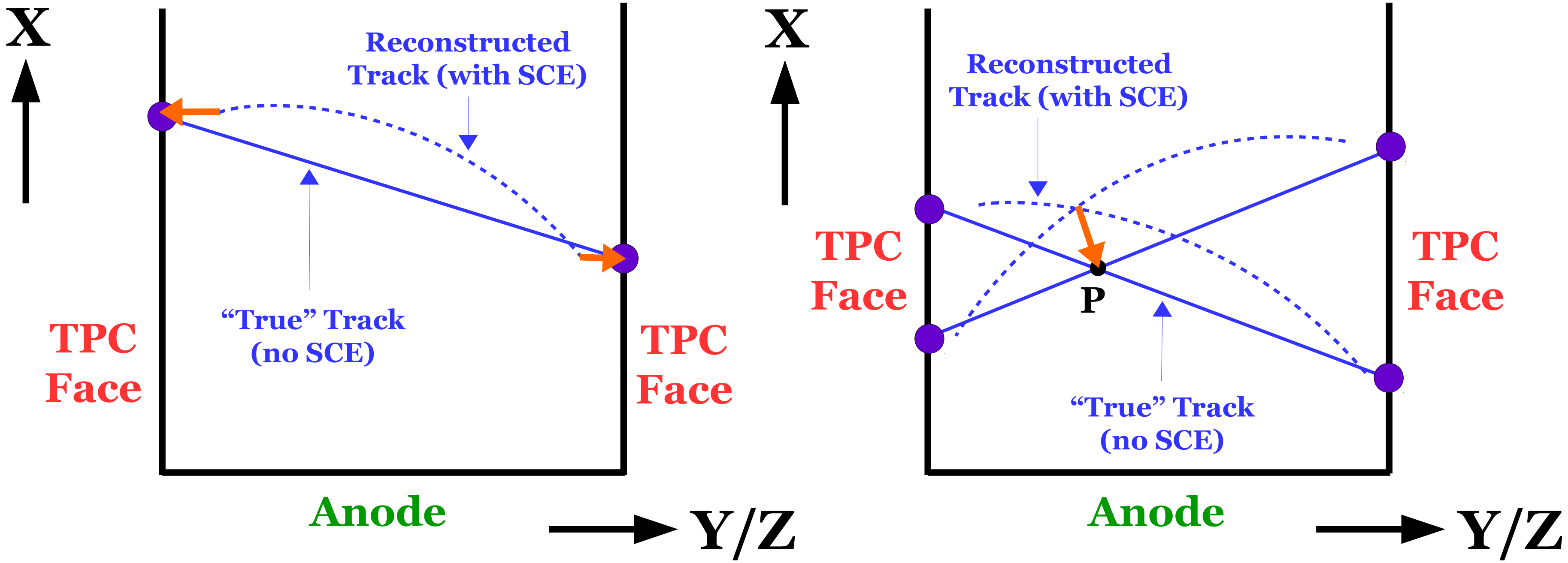
ΔY

<u>At 500 V/cm, for protoDUNE-SP</u>:

Impact on recombination: ~10%
Impact on spatial distortions (drift): ~5 cm
Impact on spatial distortions (transverse): ~20 cm

Much worse for protoDUNE-DP
Much worse for lower drift field

Calibrating w/ Muon Tracks



- Two samples of t_o-tagged tracks can provide SCE corrections:
  - <u>Single tracks</u> – enable corrections at TPC faces by utilizing endpoints of tracks (correction vector approximately orthonormal to TPC face)
  - <u>Pairs of tracks</u> – enables corrections in TPC bulk by utilizing unambiguous point-to-point correction looking at track crossing points
- Require high-momentum tracks (plenty from cosmics, beam halo)

Corrections at TPC Faces

cathode

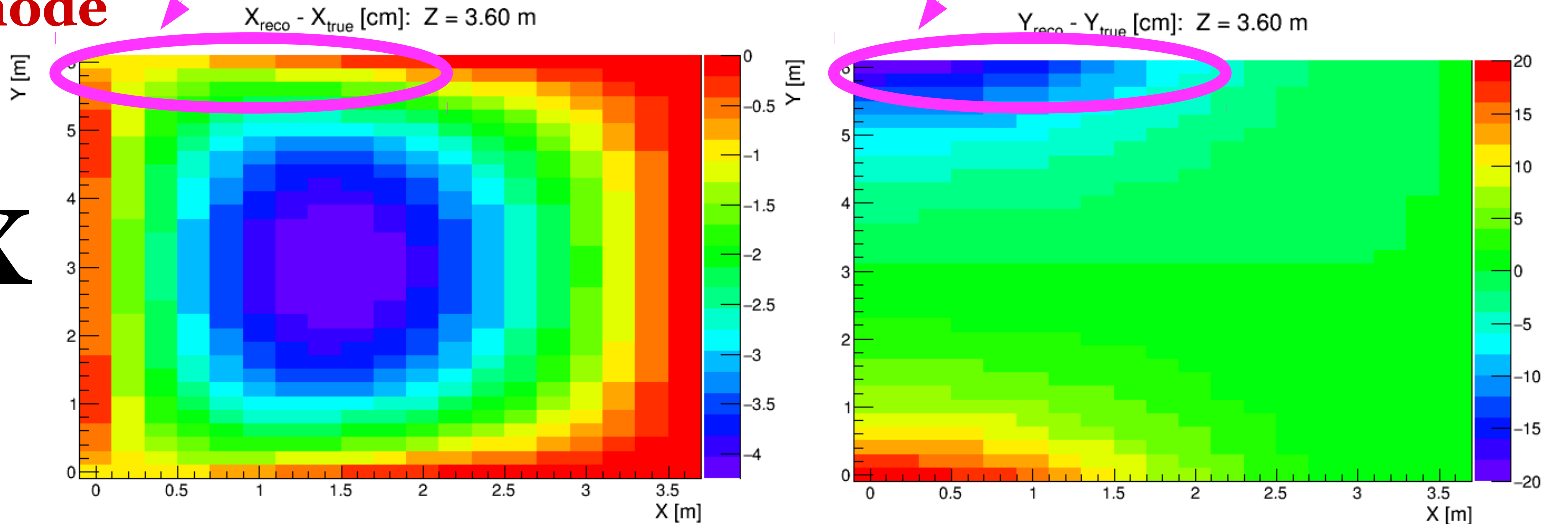
SMALL

LARGE

anode

ΔX

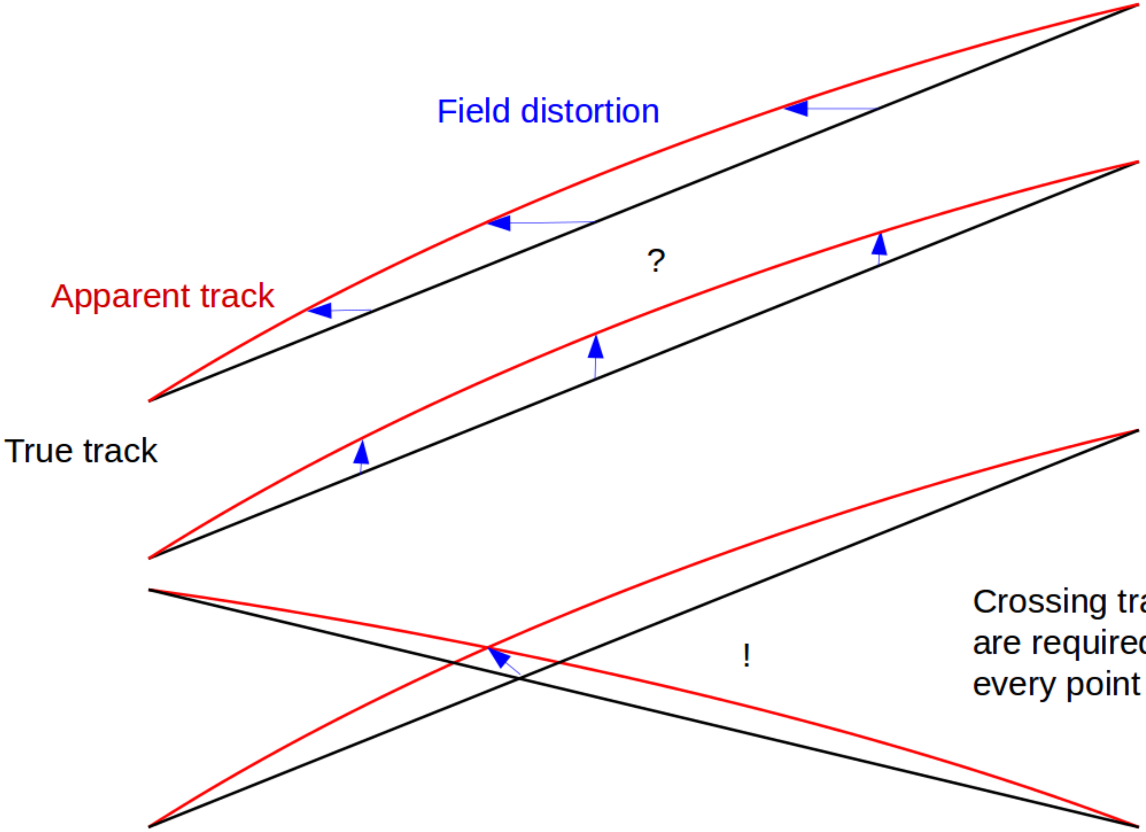
ΔY



- Claim on previous slide is that the correction at TPC faces using single tracks is the correction vector obtained by projecting the track end point onto the closest TPC face
- True at most boundaries as only one SCE component is large
- TPC edges (boundaries in Y and Z) will still need pairs of tracks

Why Crossing Points?

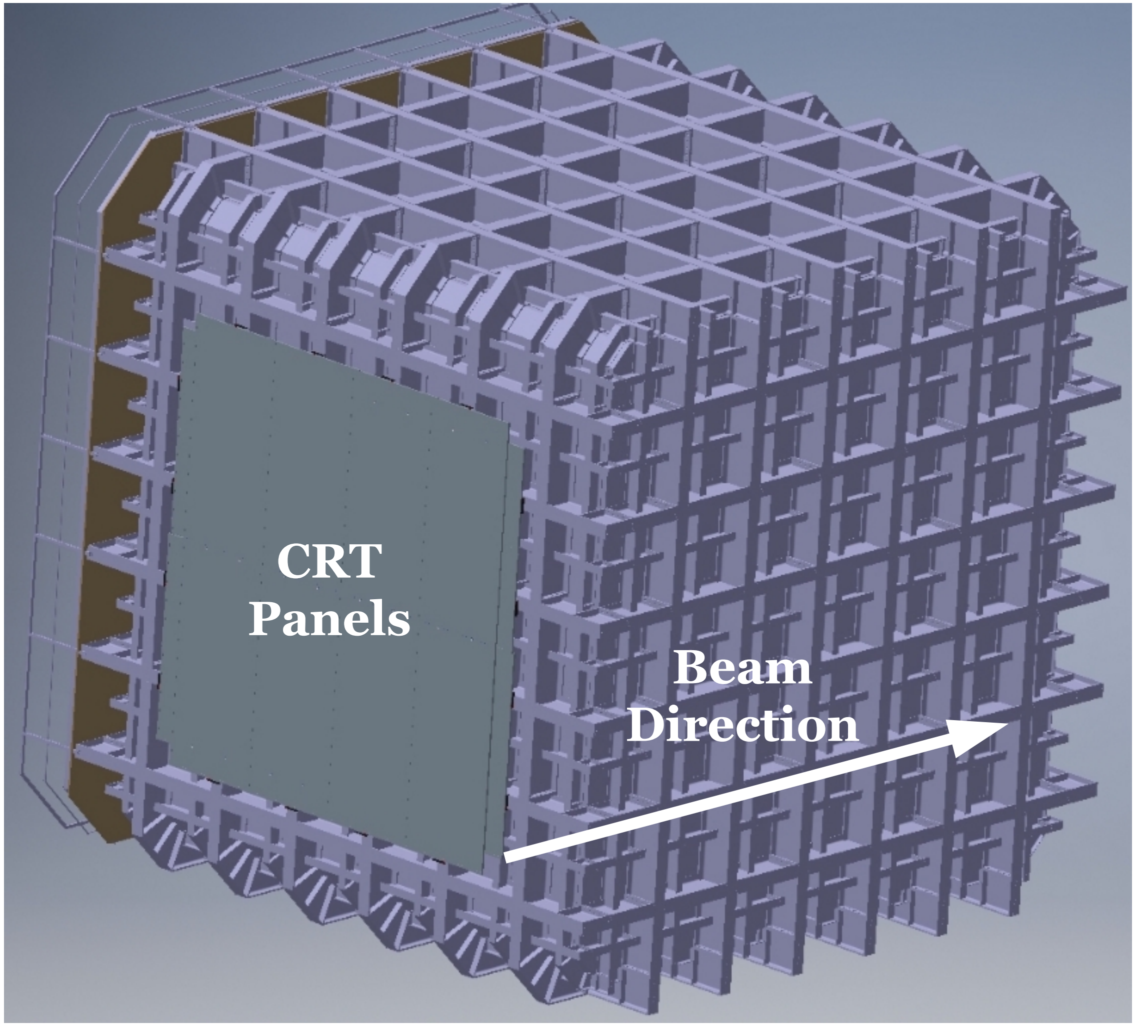
I. Kreslo



Crossing tracks
are required at
every point !

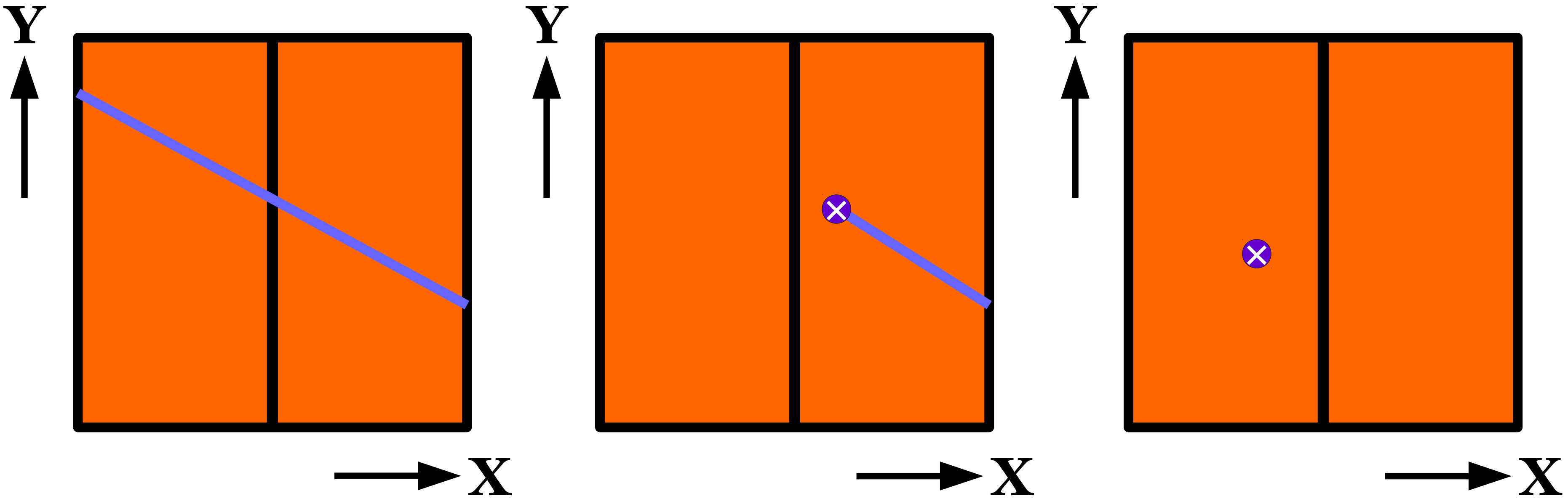
- As Igor pointed out at protoDUNE Science Workshop, a single laser track is not enough to obtain the SCE correction vector
- Principle applies to calibration with muon tracks as well!

Front/Back CRT Panels



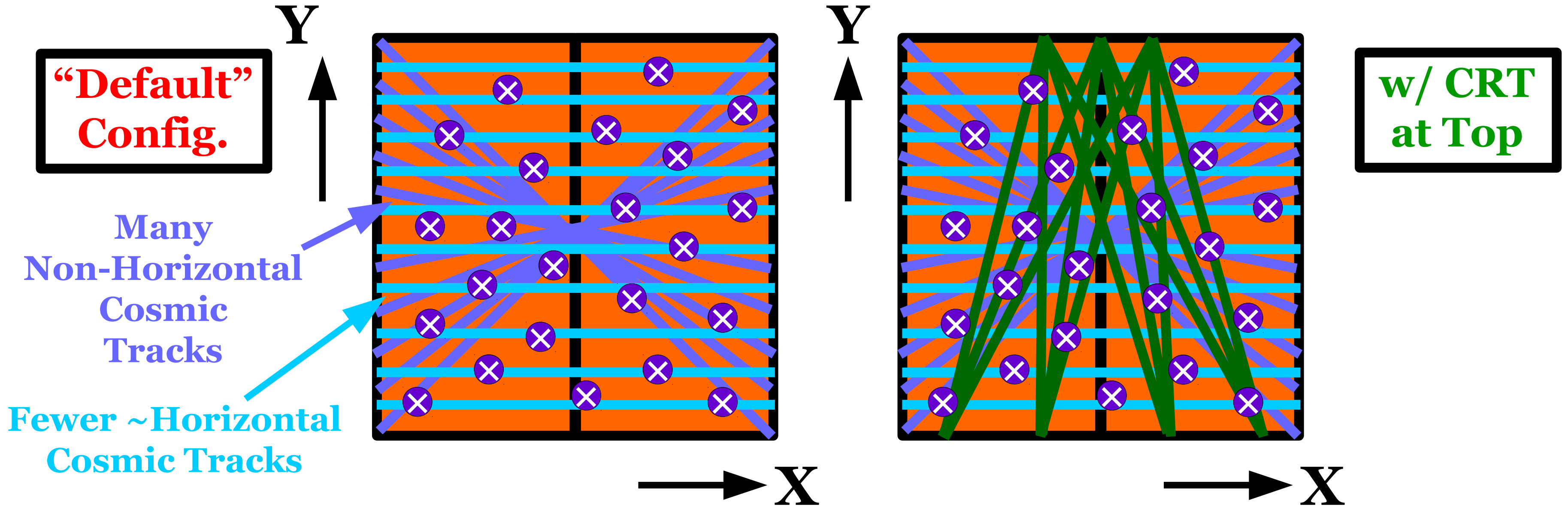
- Discussed with Flavio possible arrangement of CRT panels on front and back of detector
- 8+8 panels on front, 8+8 panels on back
- Would be useful to tag t_0 for both muon halo tracks and cosmic muon tracks
- 32 panels in total, but possibly more to use elsewhere?

Track Samples



- With anode planes and front/back CRT panels, you get three samples of t_o-tagged tracks:
  - Cosmics crossing both anode planes (left)
  - Cosmics crossing a CRT panel (middle)
  - Muon halo tracks crossing a CRT panel (right)

Total Track Coverage



"Default" Config.

Many Non-Horizontal Cosmic Tracks

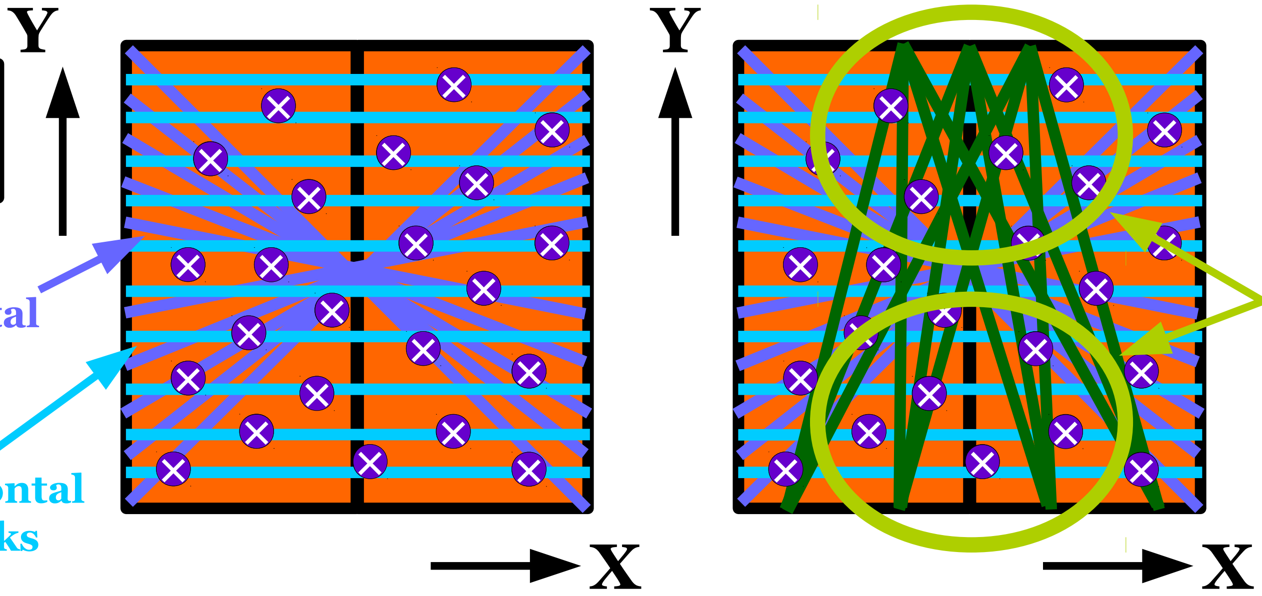
Fewer ~Horizontal Cosmic Tracks

w/ CRT at Top

- Combining these t_o-tagged track samples, we get complete coverage for single tracks!
- However, if you want to calibrate in the bulk, you need track pairs, and they should be at relatively large angle w.r.t. each other
- Near top of TPCs would have much lower statistics – CRT coverage on top helps (muon halo, tag from top CRT)
    - Front/back CRT cosmics will help fill in these areas as well (not shown)

Total Track Coverage

"Default" Config.



Many Non-Horizontal Cosmic Tracks

Fewer ~Horizontal Cosmic Tracks

w/ CRT at Top

Additional Coverage in Important Regions!

- Combining these t_0-tagged track samples, we get complete coverage for single tracks!
- However, if you want to calibrate in the bulk, you need track pairs, and they should be at relatively large angle w.r.t. each other
- Near top of TPCs would have much lower statistics – CRT coverage on top helps (muon halo, tag from top CRT)
  - Front/back CRT cosmics will help fill in these areas as well (not shown)

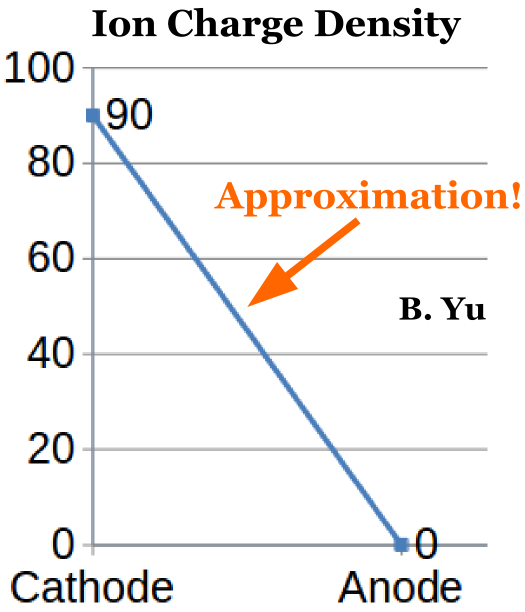
Summary

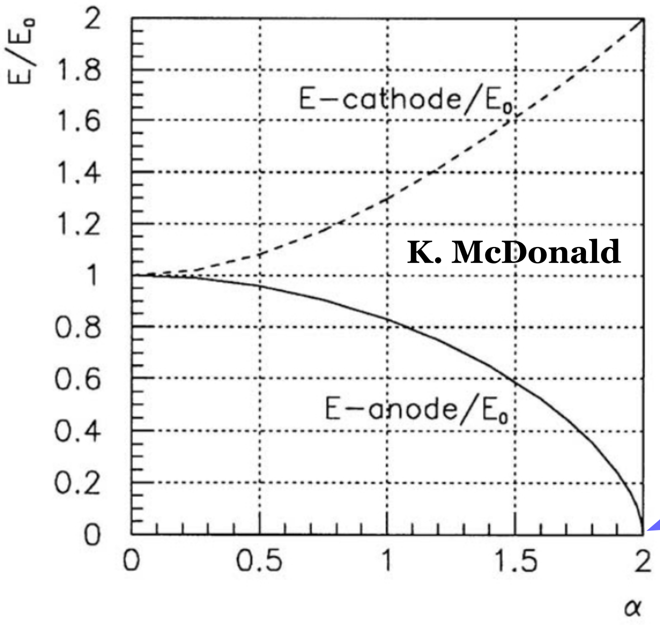
- We can perform a calibration of SCE w/o a laser system using cosmic tracks,muon halo tracks **IF** we can tag t_o with high reliability
  - Use both single tracks and track pairs for calibration of TPC faces and TPC bulk, respectively
- Best way to do this is extensive CRT system
  - Light-collection system likely not able to reliably (high degree of certainty as required in calibration) tag t_o
- Installing CRT panels on front/back of detector in discussion
  - Need to know number of tracks we can utilize for the measurement per unit time – including all possible calibration samples
  - Jacob has looked at **cosmic tracks** passing through front/back CRT
  - Need to combine this with look at e.g. anode-anode crossing tracks, but preliminary conclusion is that **top CRT panels probably not necessary, but helpful** (more statistics in crucial regions)
  - Also need input about **beam halo** rate and spatial distribution!

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, $E^{-1.7}$





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

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

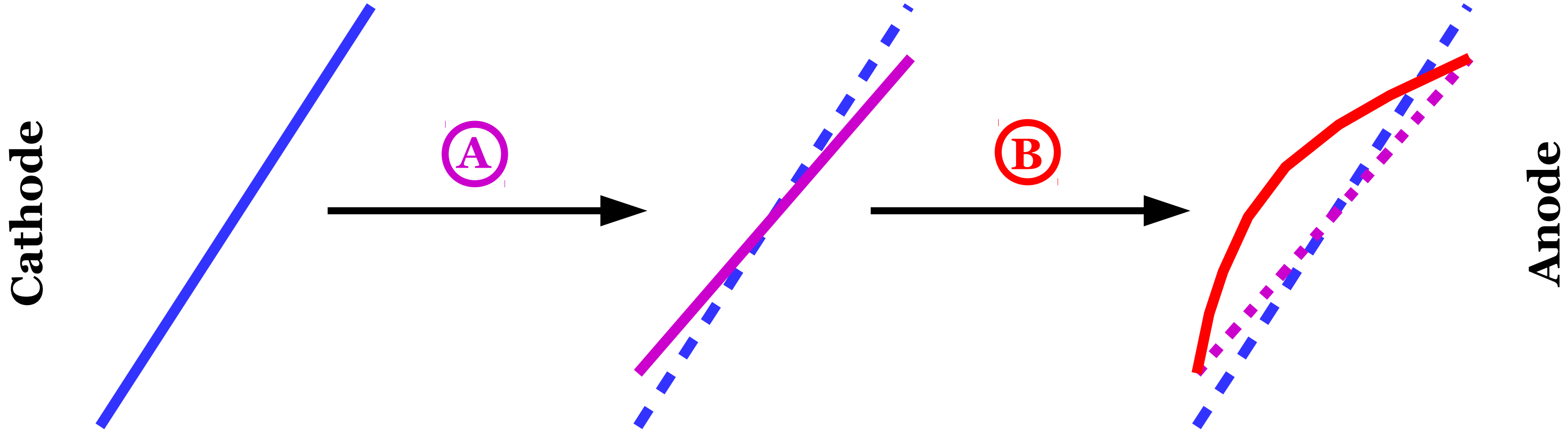
No Drift!

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)

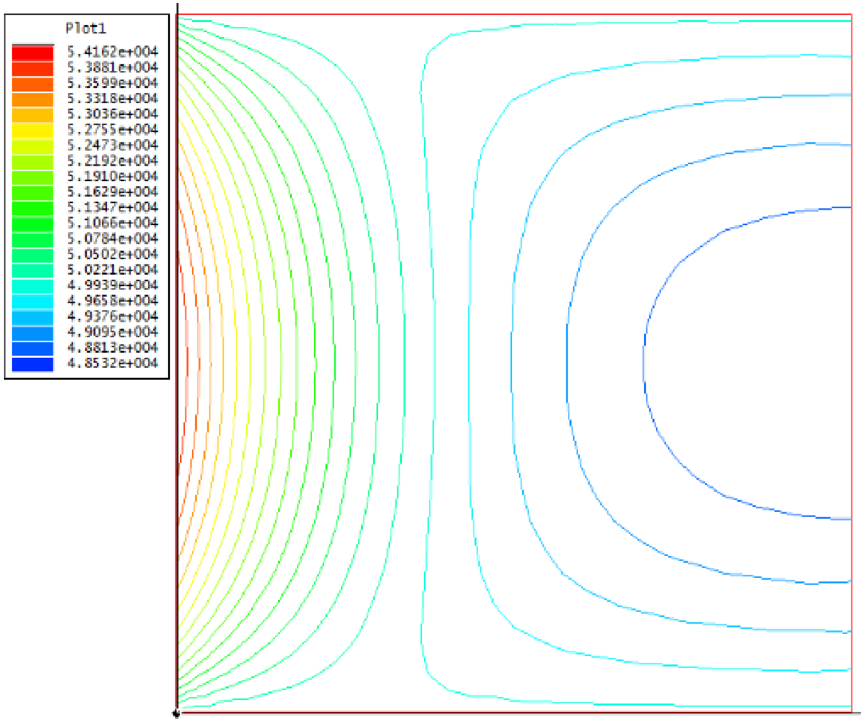
Impact on Track Reco.

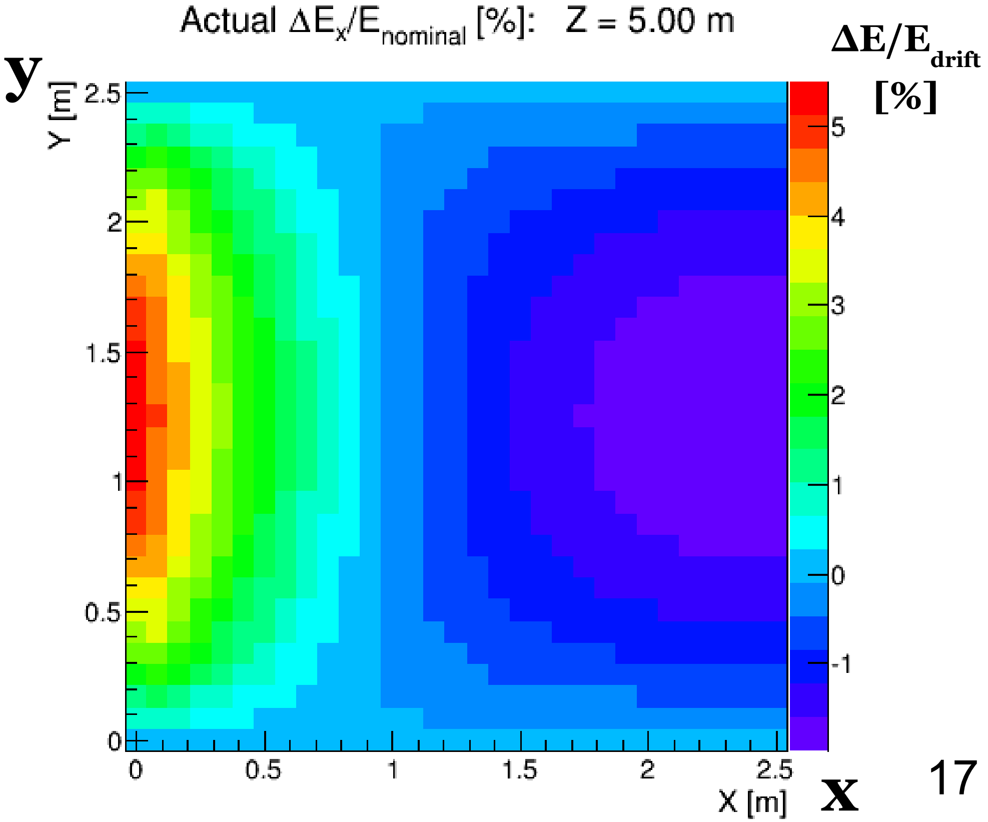
- Two separate effects on reconstructed **tracks**:
  - Ⓐ Reconstructed track shortens laterally (looks rotated)
  - Ⓑ Reconstructed track bows toward cathode (greater effect near center of detector)
- Can obtain straight track (or multiple-scattering track) by applying corrections derived from data-driven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



Compare to FE Results: E_x

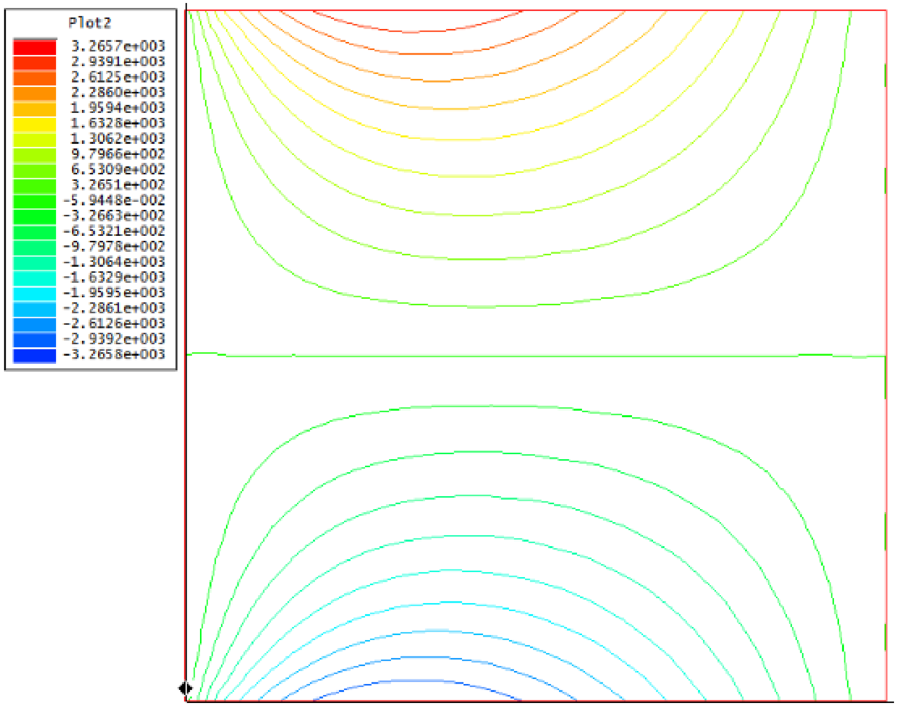
- Looking at central z slice (z = 5 m) in x-y plane (**MicroBooNE**)
- Very good shape agreement compared to Bo Yu's 2D FE (Finite Element) studies
- Normalization differences understood (using different rate)

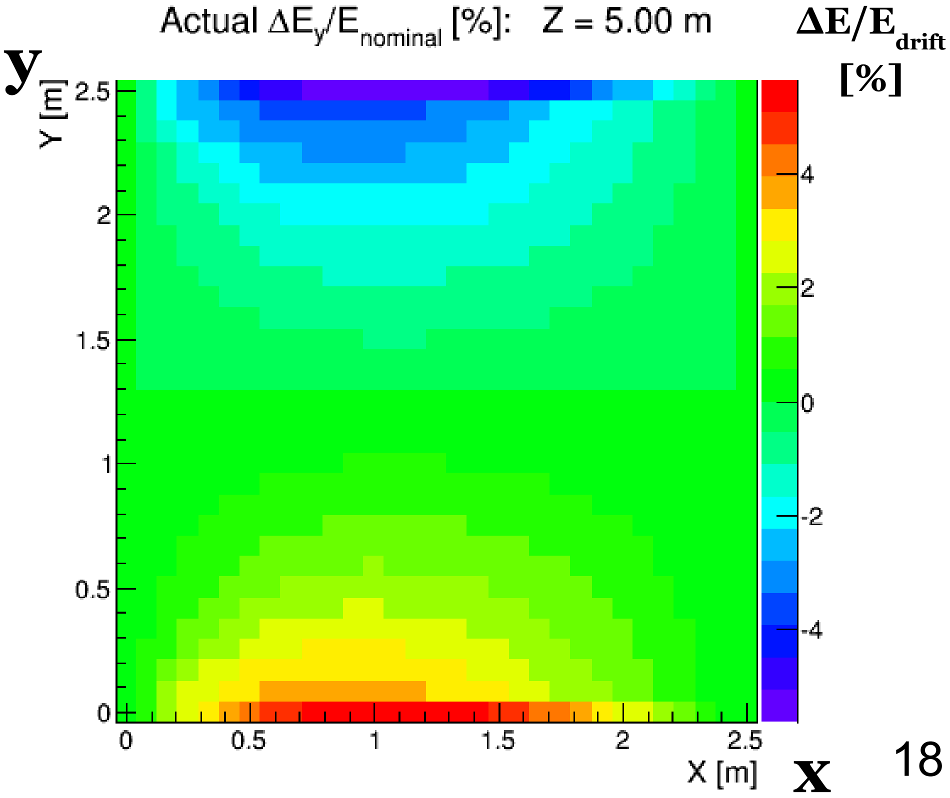




Compare to FE Results: E_y

- 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

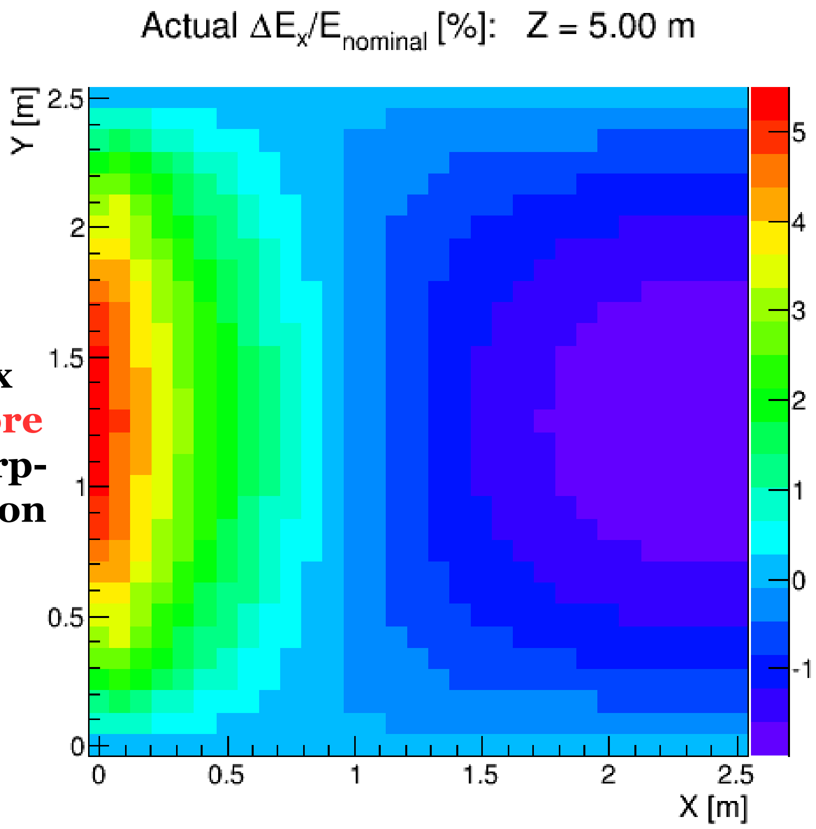


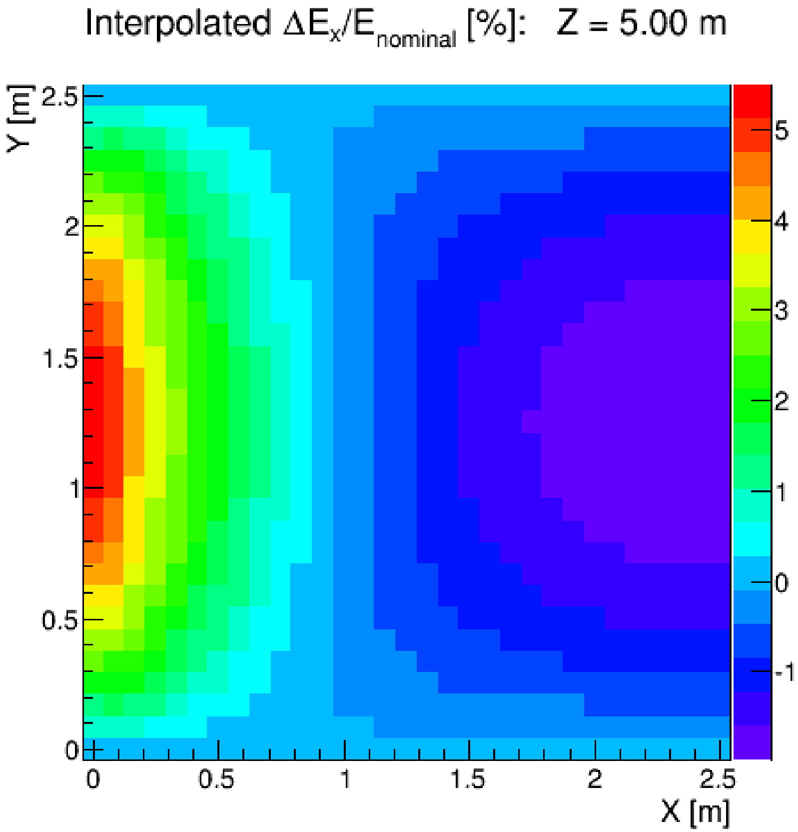


E Field Interpolation

- 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
Interpolation


Actual $\Delta E_x/E_{nominal}$ [%]: Z = 5.00 m

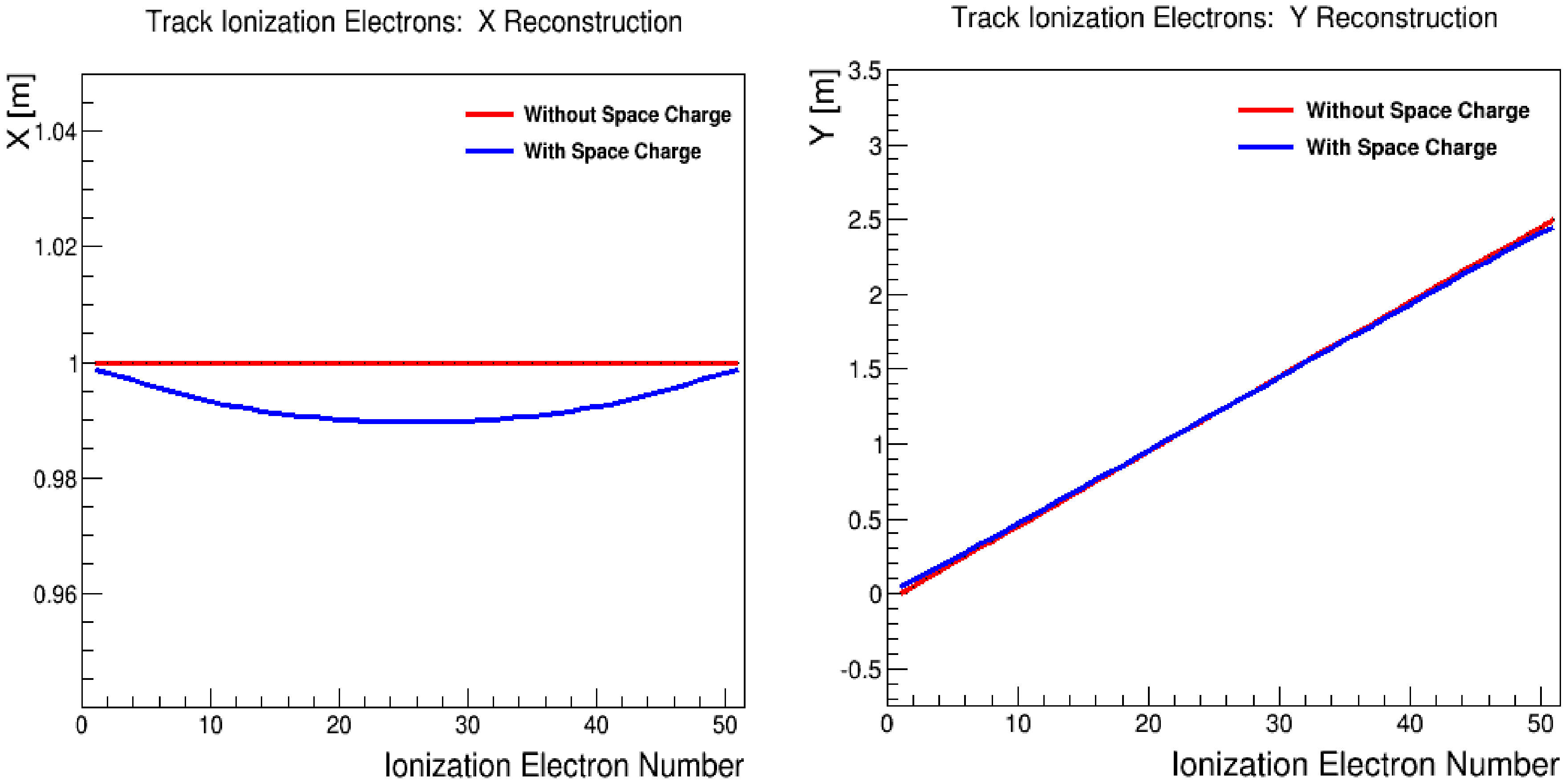

Interpolated $\Delta E_x/E_{nominal}$ [%]: Z = 5.00 m

E_x
After
Interpolation

Ray-Tracing

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

MicroBooNE

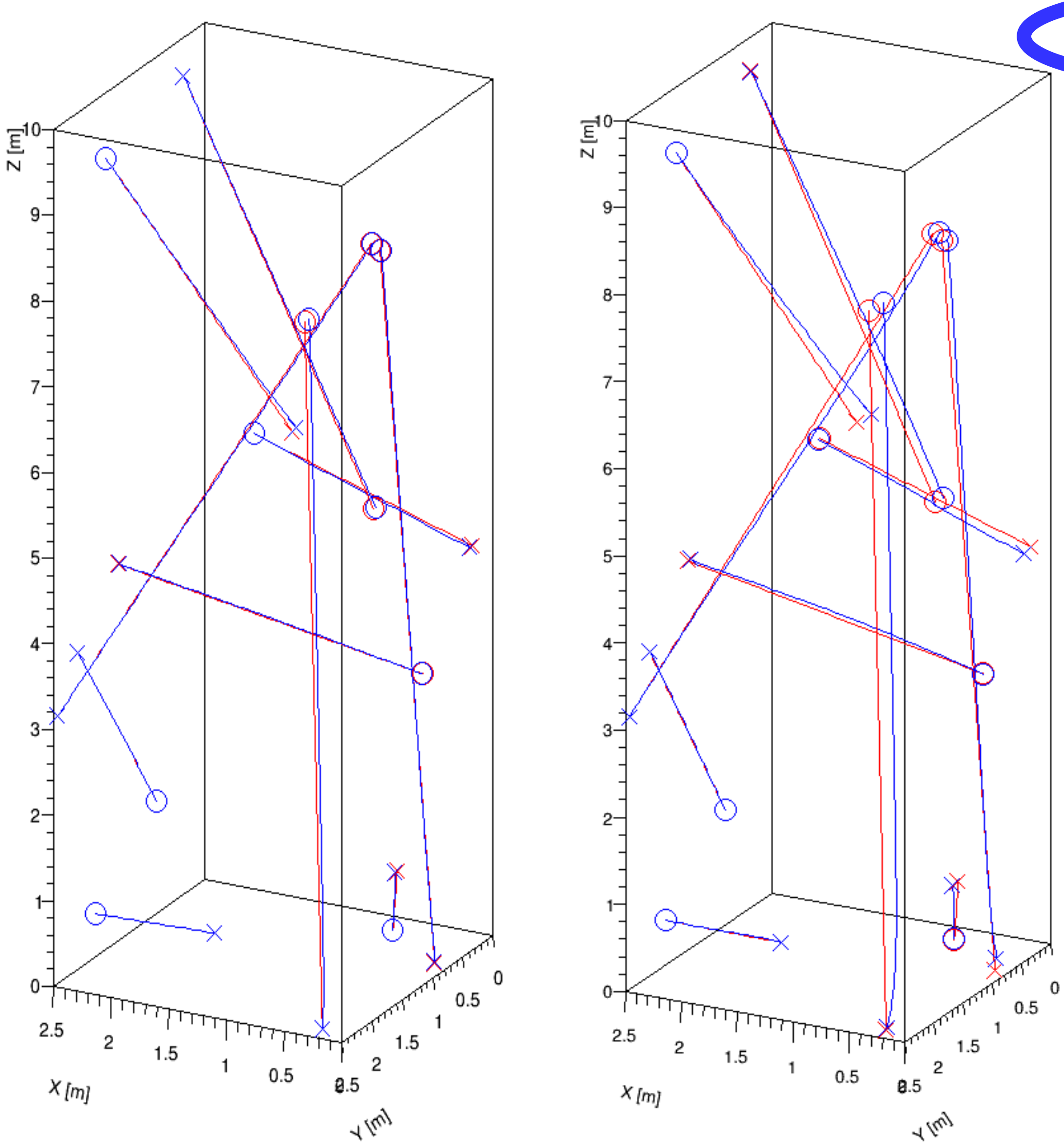


Sample “Cosmic Event”

MicroBooNE

Nominal Drift Field

500 V/cm



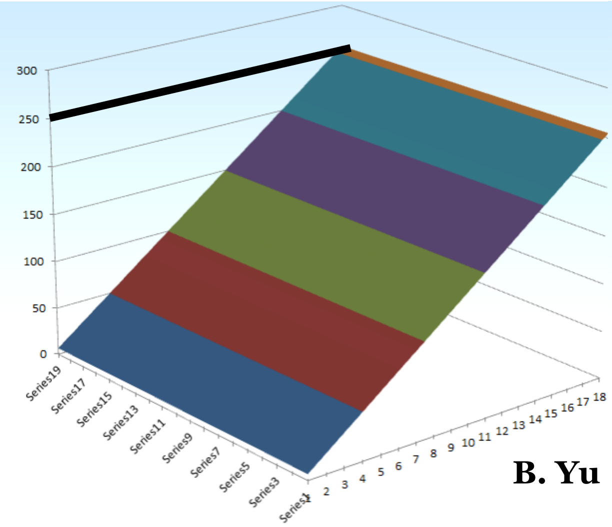
Half Drift Field

250 V/cm

Complications

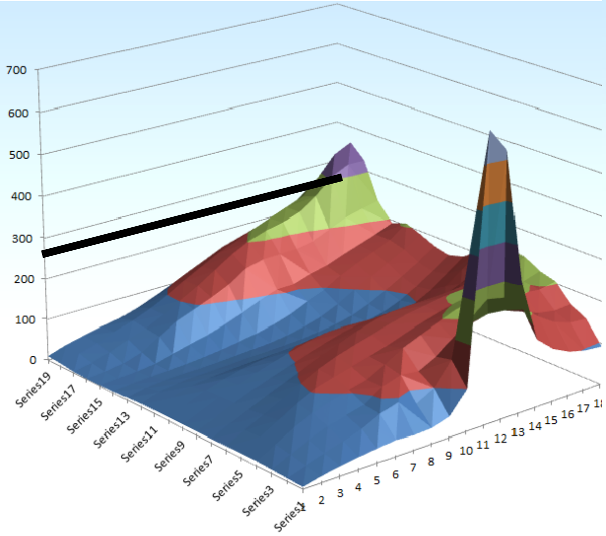
- Not accounting for non-uniform charge deposition rate in detector → significant modification?
- Flow of liquid argon → likely significant effect!
  - Previous flow studies in 2D… differences in 3D?
  - Time dependencies?

No Flow

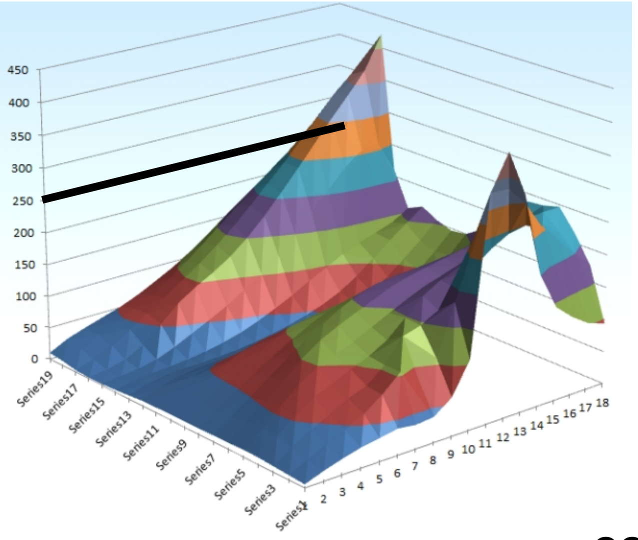


B. Yu

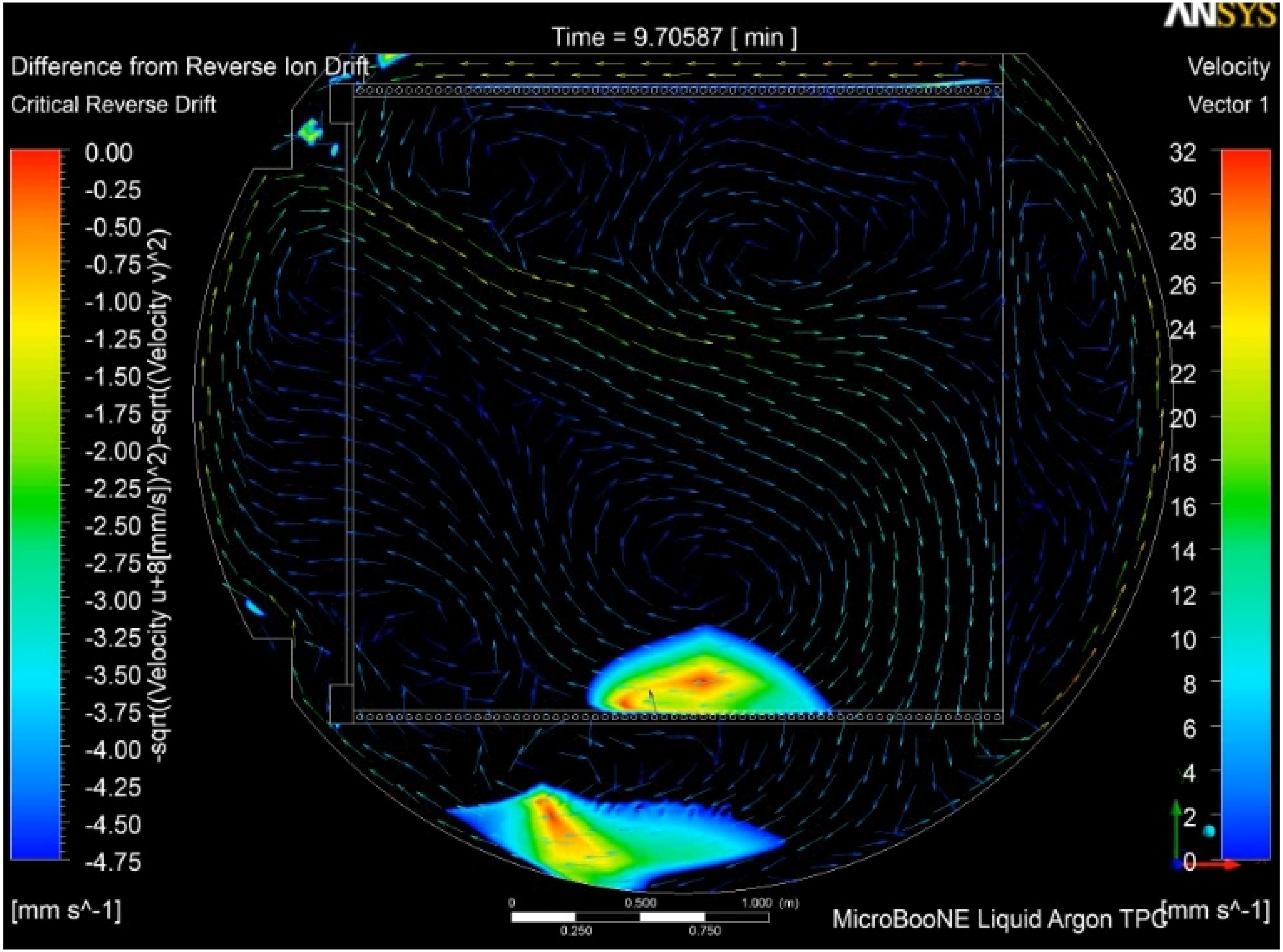
Flow w/o Turbulence



Flow w/ Turbulence



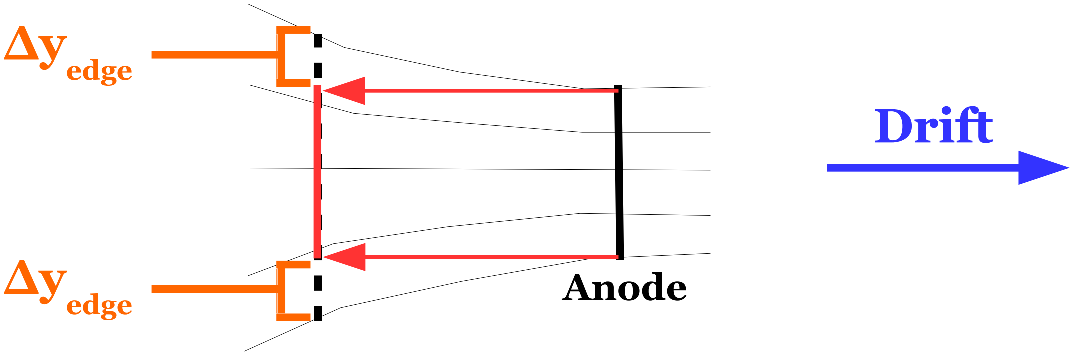
Liquid Argon Flow



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

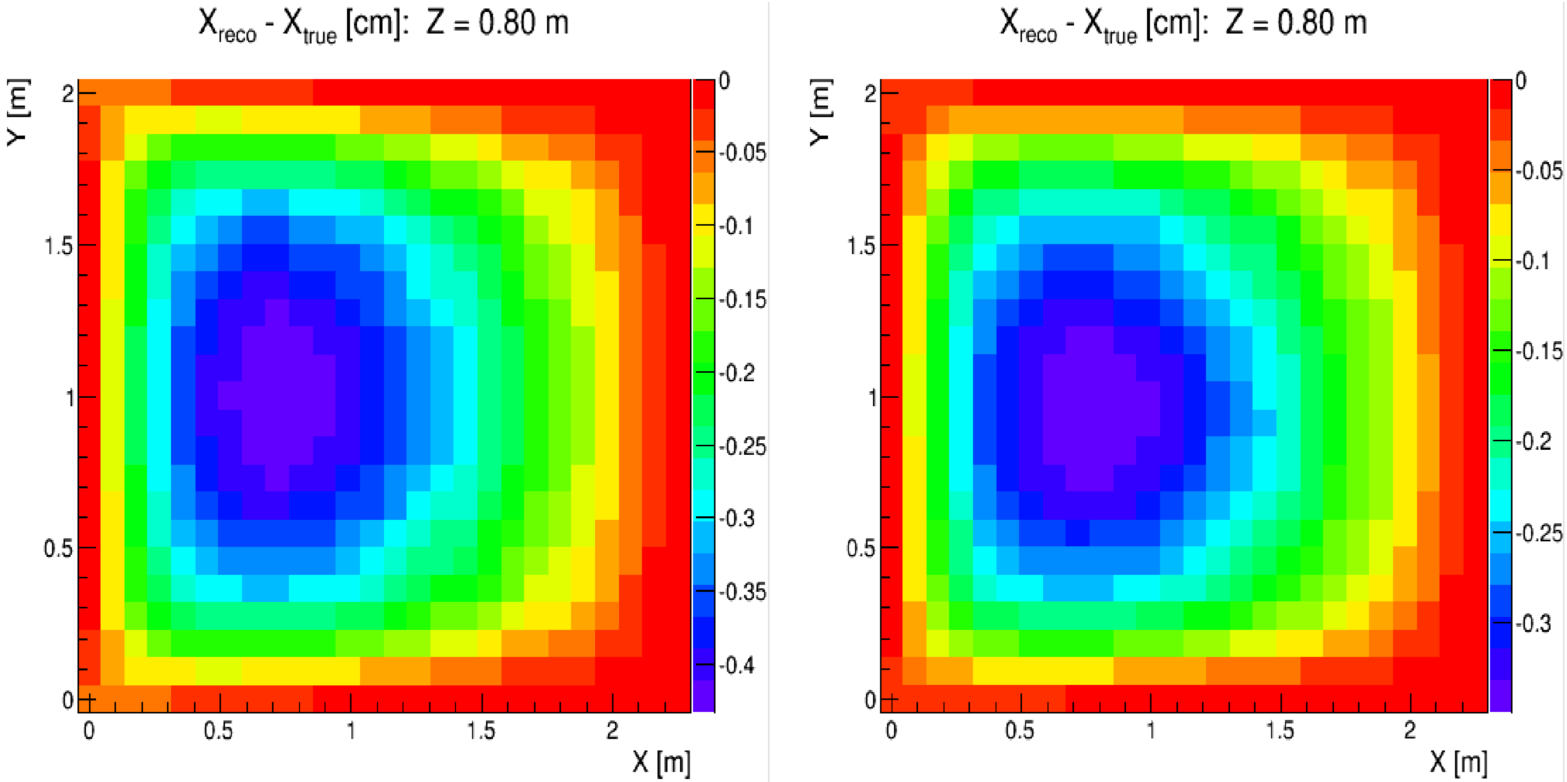
Δx

Without
LAr Flow

central z slice

Δx

With
LAr Flow

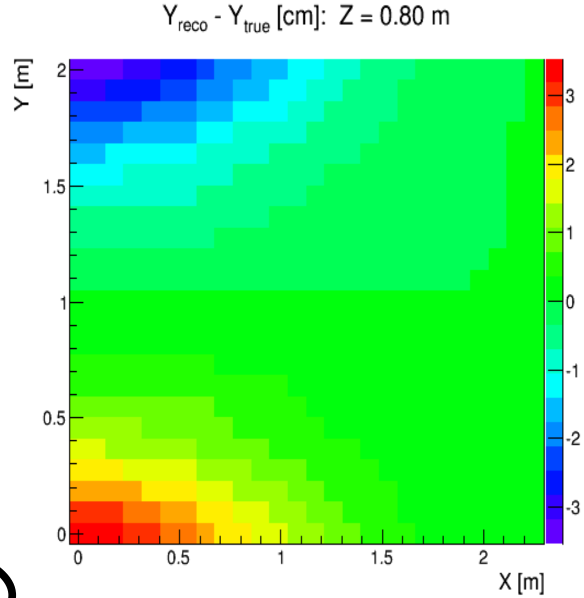


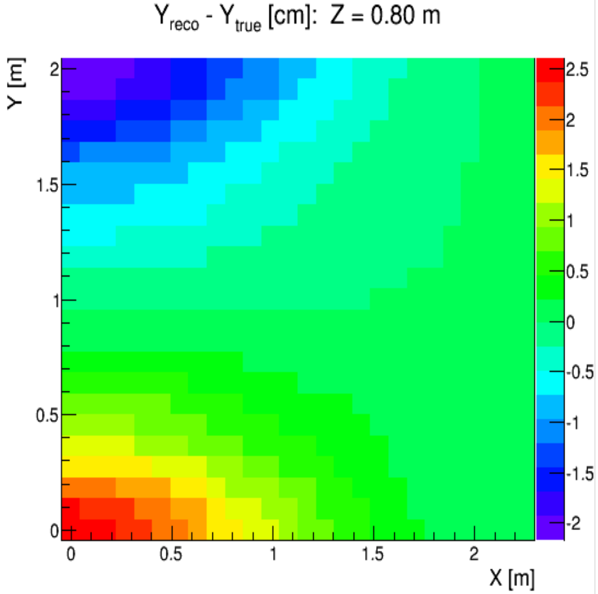
Q map from
E. Voirin

35-ton with LAr Flow (cont.)

Δy

Without
LAr Flow





Δy

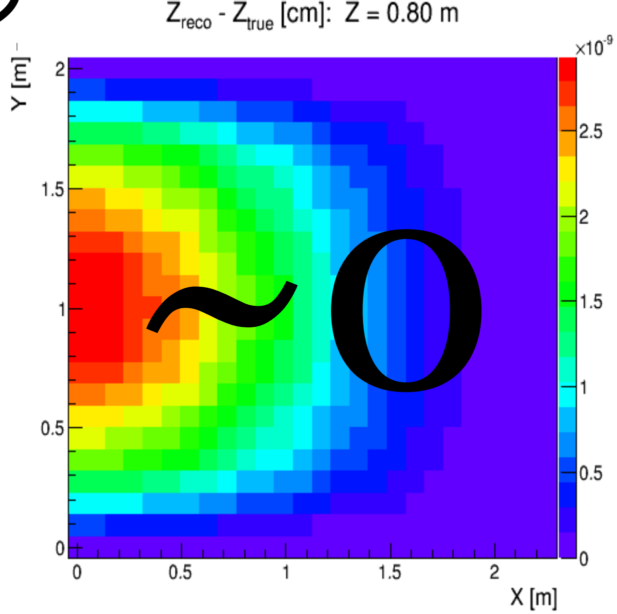
With
LAr Flow

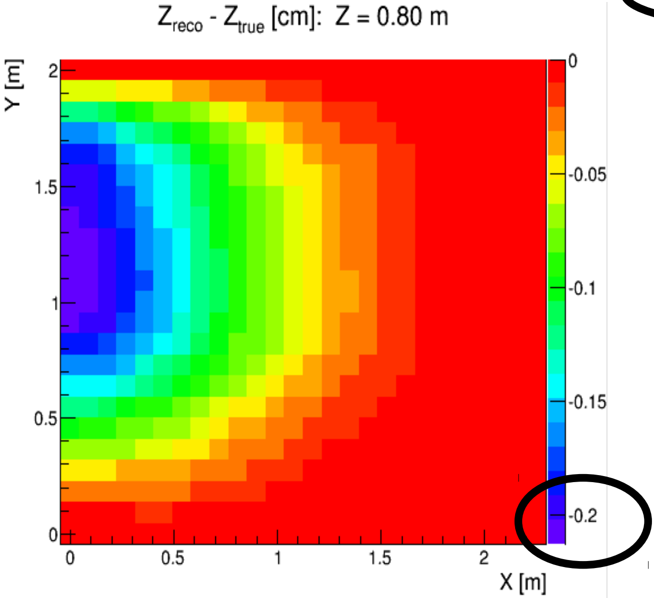
Q map from
E. Voirin

central z slice

Δz

Without
LAr Flow





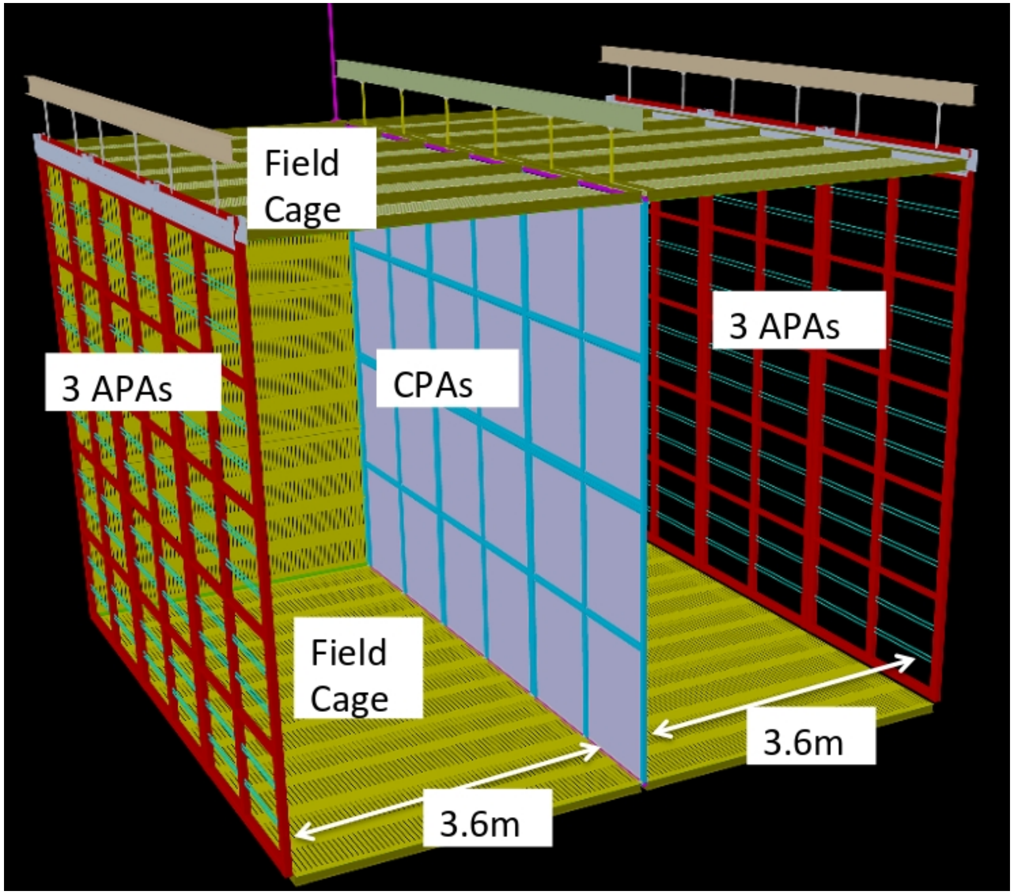
Δz

With
LAr Flow

Simulation of SC Effect

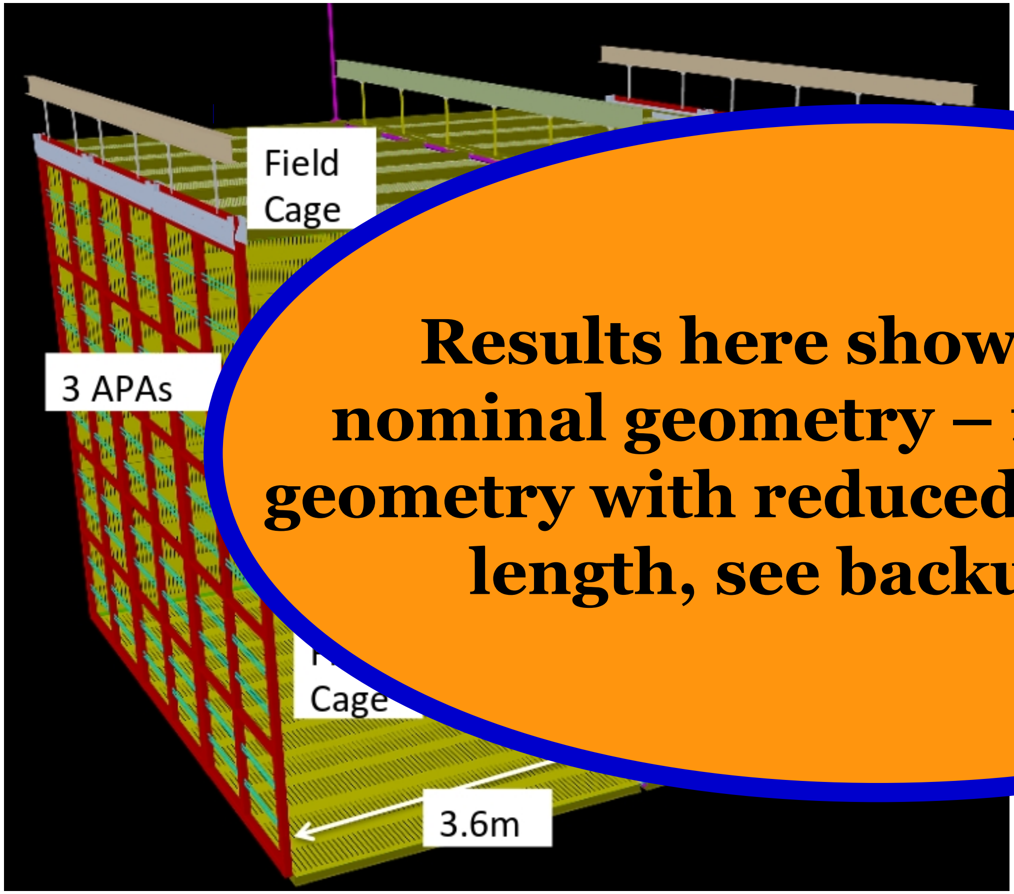
- Can use SpaCE to produce displacement maps
  - **Forward transportation**: $\{x, y, z\}_{\textbf{true}} \rightarrow \{x, y, z\}_{\textbf{sim}}$
    - Use to **simulate** effect in MC
    - Uncertainties describe accuracy of simulation
  - **Backward transportation**: $\{x, y, z\}_{\textbf{reco}} \rightarrow \{x, y, z\}_{\textbf{true}}$
    - 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, 5th/7th order polynomials) – fewer parameters
    - Uses matrix representation as input → **use for LArSoft implementation**

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



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  -): 7.0 m
- ed for
ghtly
mplify
s):
  - Drift (X): 3.6 m
  - Height (Y): 6.0 m
  - Length (Z): 7.2 m

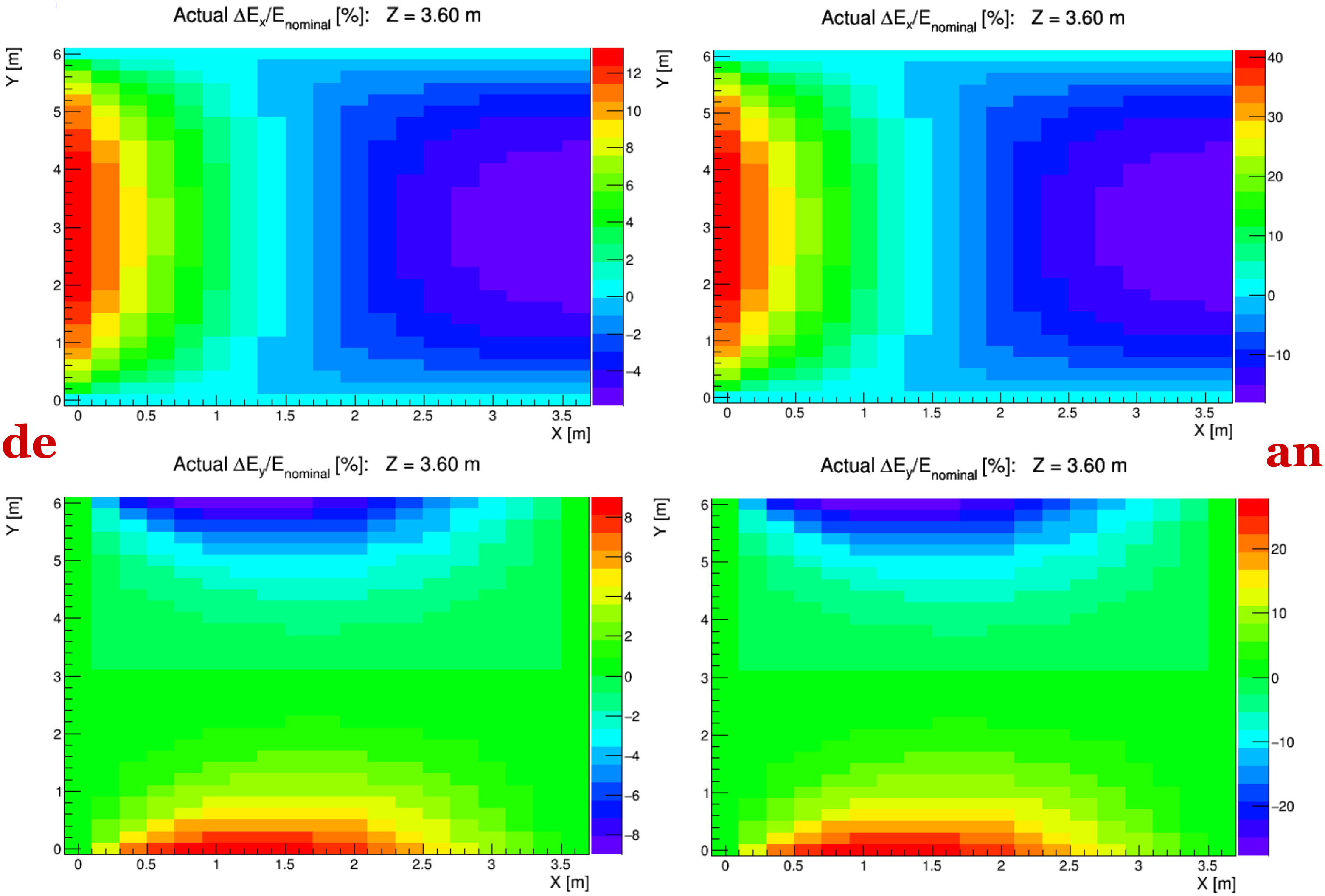
Results here shown only for nominal geometry – for modified geometry with reduced maximal drift length, see backup slides.

Modified E Field (Central Z)

Nominal Geometry

$E_{\text{nominal}} = 500$ V/cm

$E_{\text{nominal}} = 250$ V/cm



E_X

E_Y

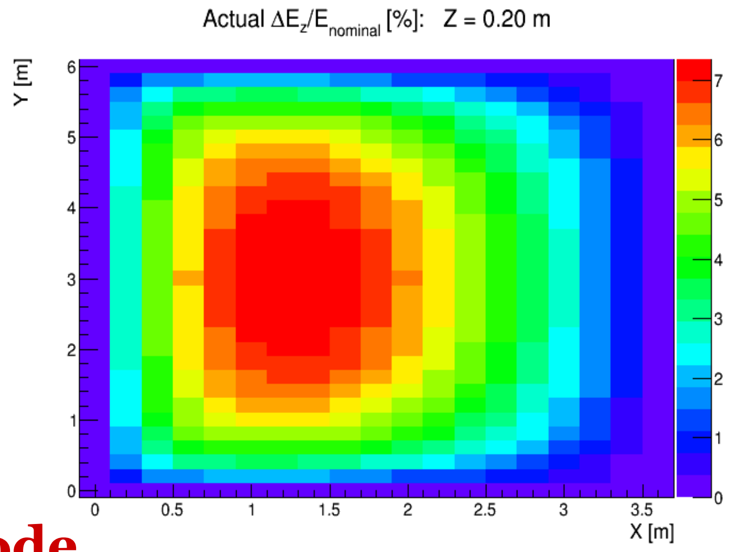
cathode

anode

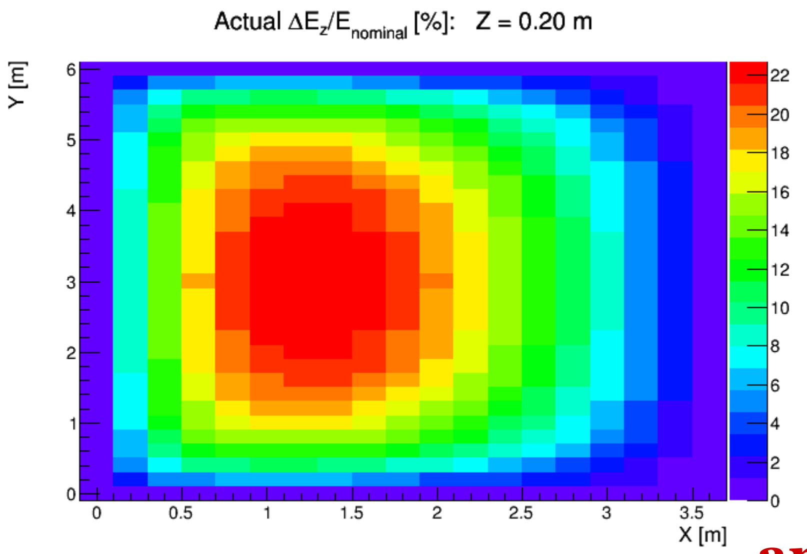
Modified E Field (TPC End)

Nominal Geometry

$E_{nominal}$ = 500 V/cm



$E_{nominal}$ = 250 V/cm



E_Z

cathode

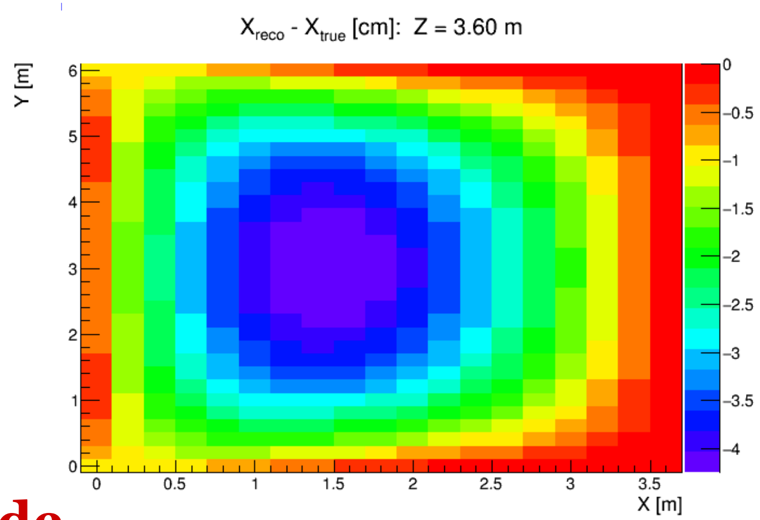
anode

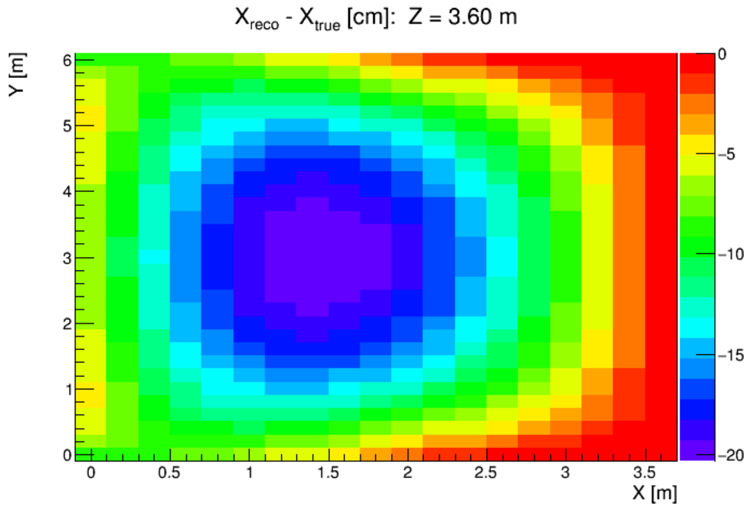
Spatial Distortions (Central Z)

Nominal Geometry

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

ΔX

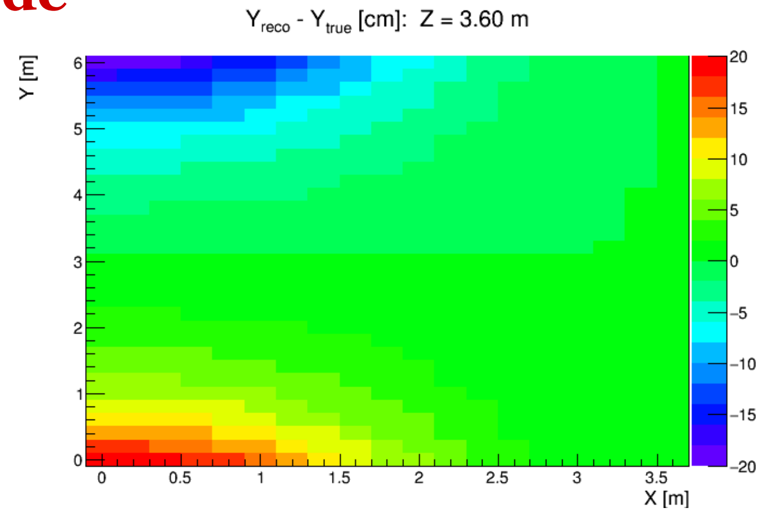


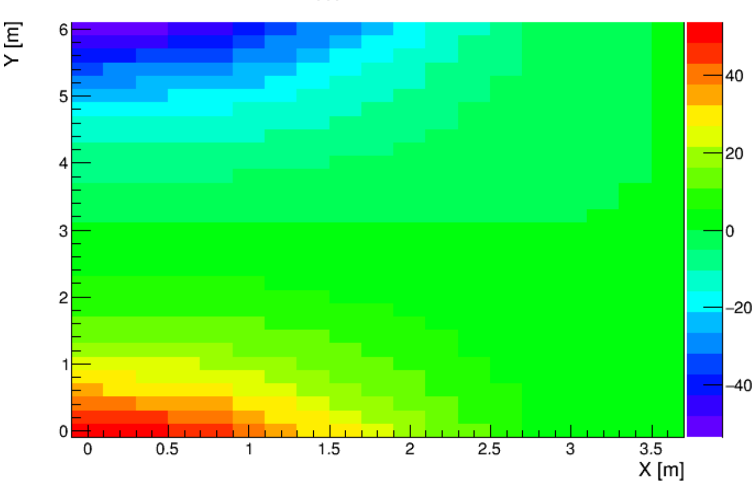


cathode

anode

ΔY





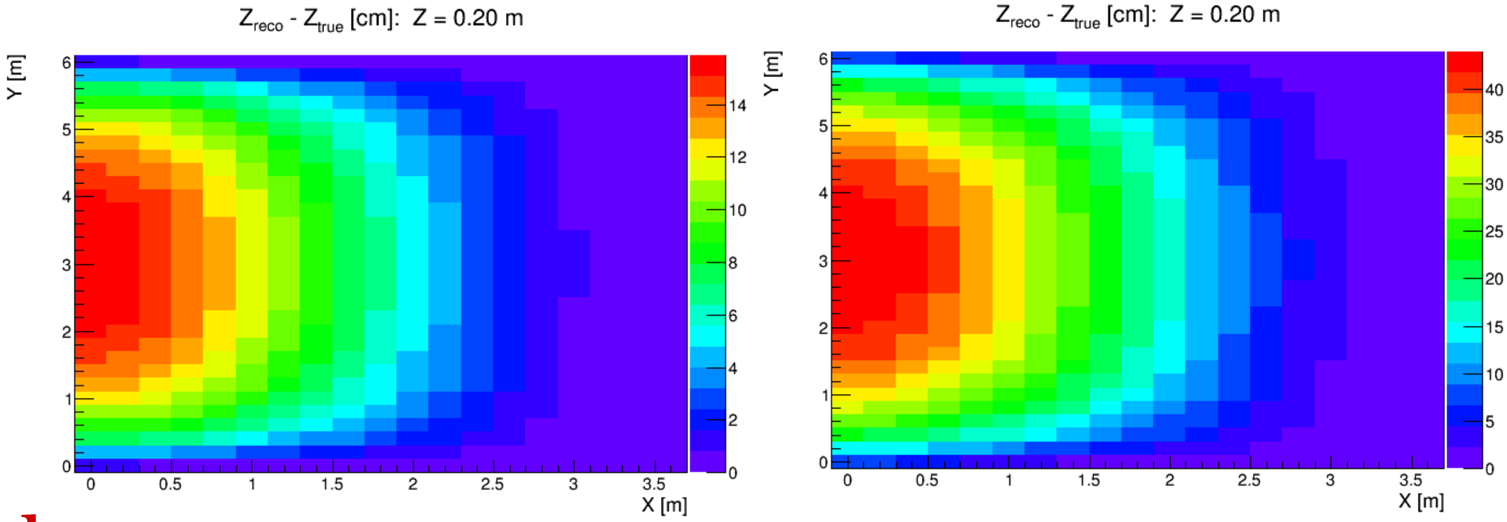
Spatial Distortions (TPC End)

Nominal Geometry

$E_{nominal}$ = 500 V/cm

$E_{nominal}$ = 250 V/cm

ΔZ



cathode

anode

SP/DP Comp. – E Field Dist.

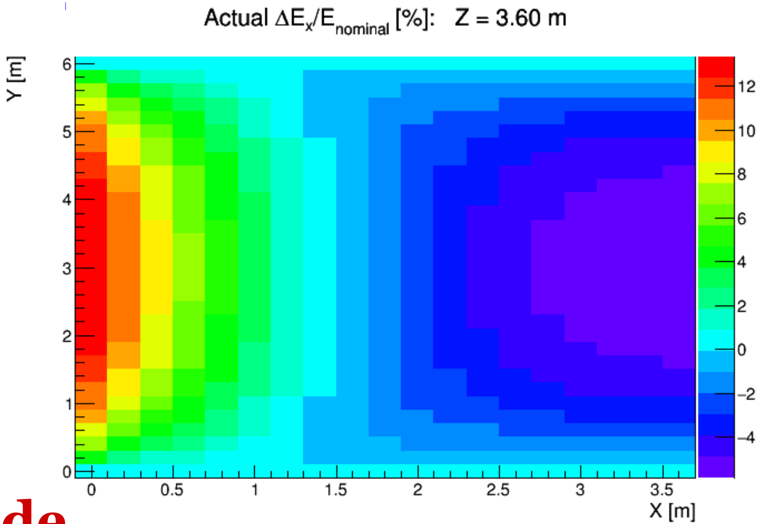
Nominal Geometry

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

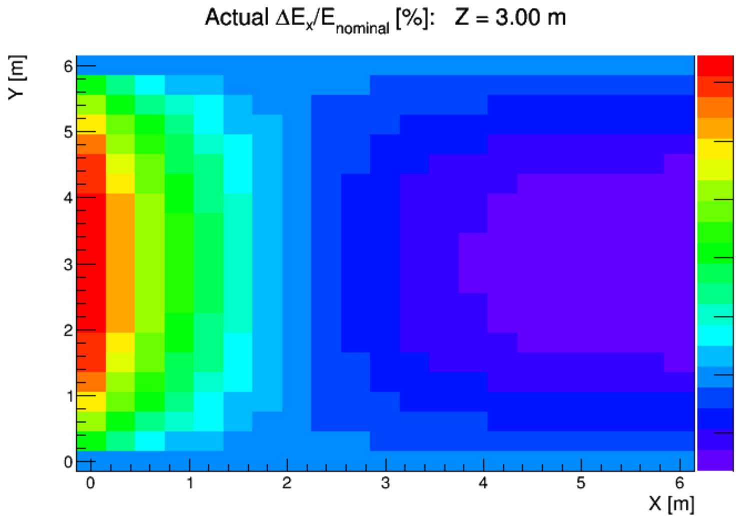
6 m × 6 m × 6 m

E_X

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



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

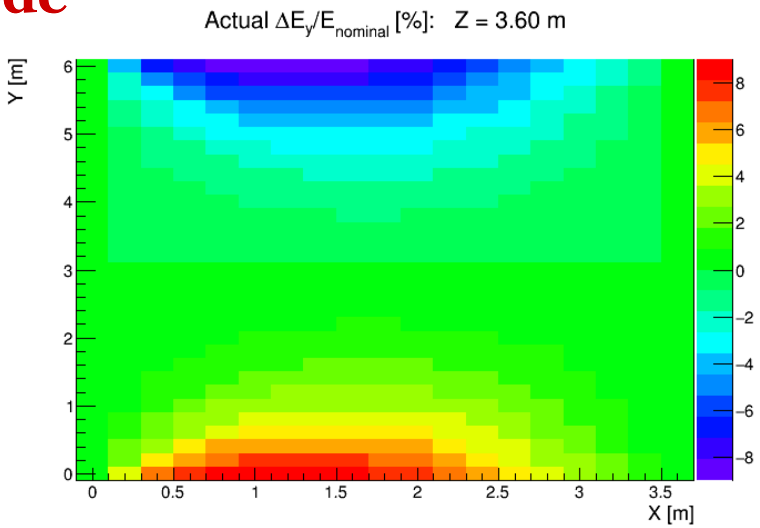


cathode

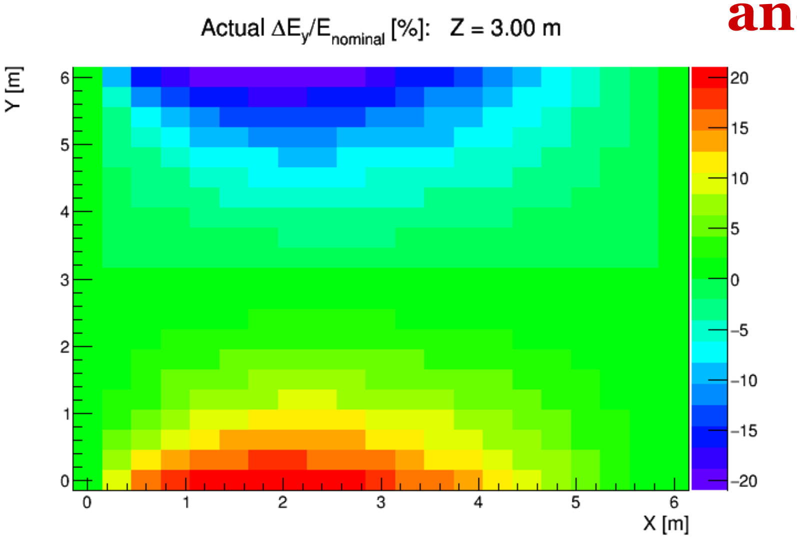
anode

E_Y

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



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



SP/DP Comp. – E Field Dist.

Nominal Geometry

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

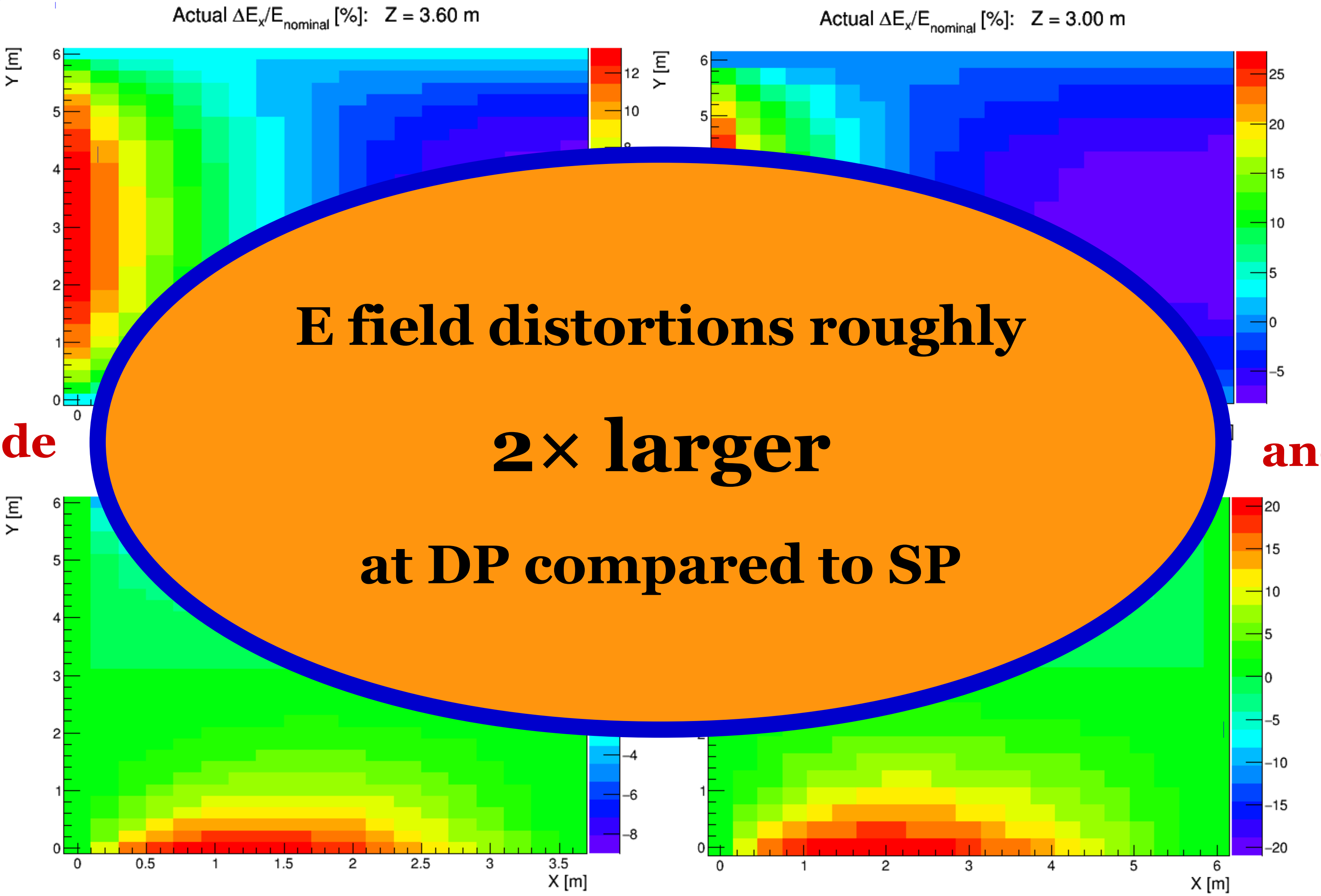
6 m × 6 m × 6 m

E$_X$

E$_Y$

cathode

anode



E field distortions roughly

2× larger

at DP compared to SP

SP/DP Comp. – Spatial Dist.

Nominal Geometry

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

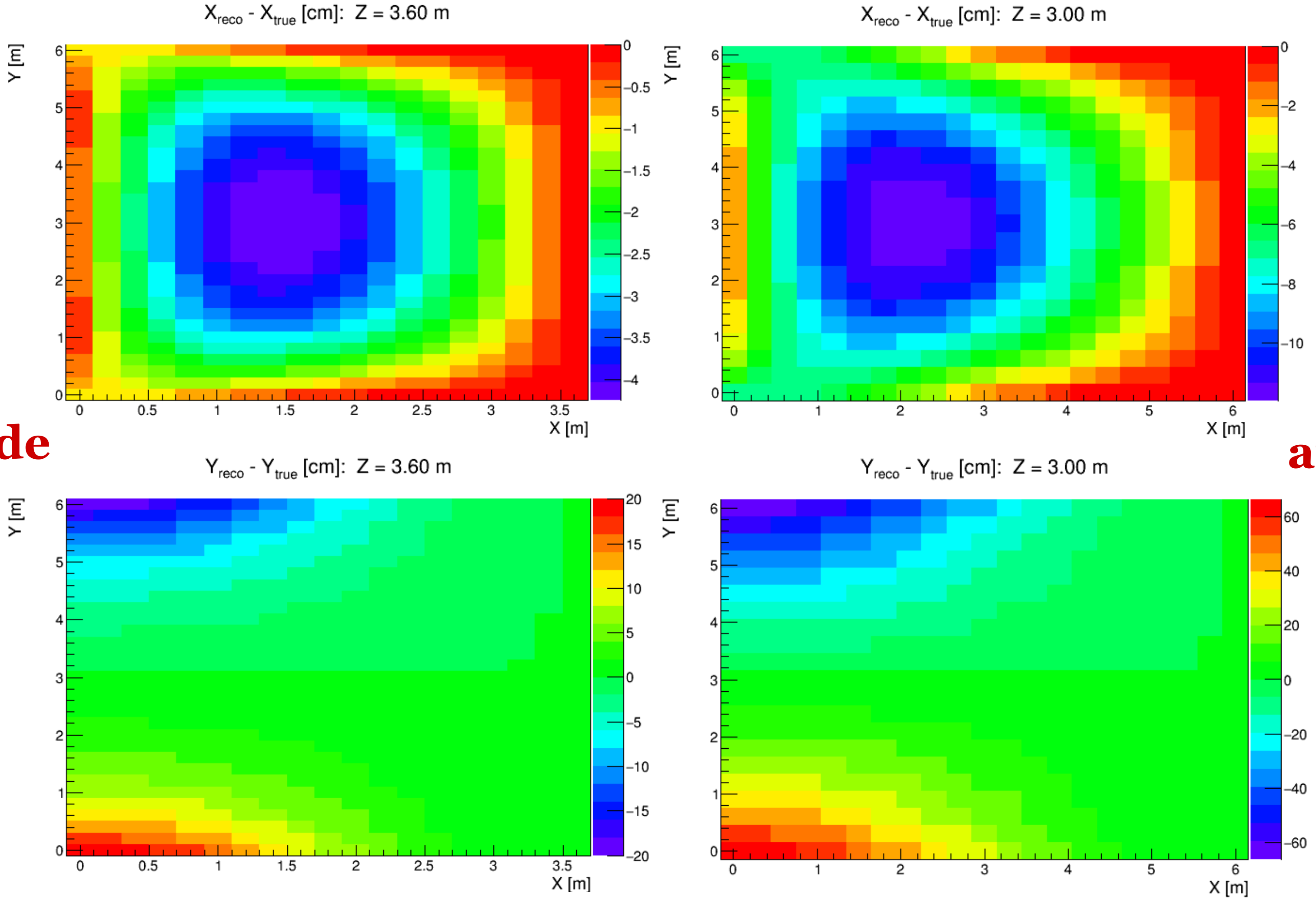
6 m × 6 m × 6 m

ΔX

cathode

anode

ΔY



SP/DP Comp. – Spatial Dist.

Nominal Geometry

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

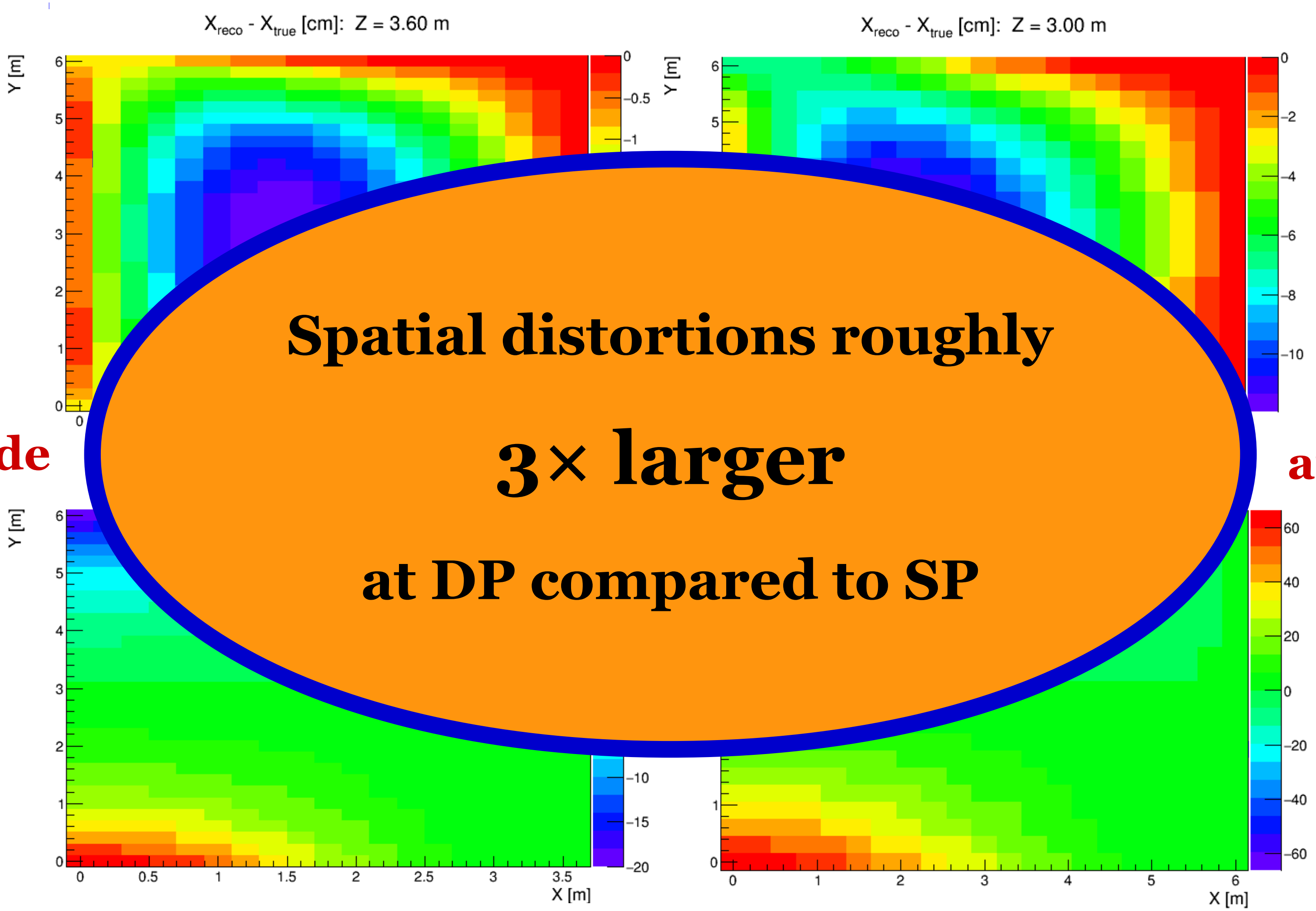
6 m × 6 m × 6 m

ΔX

cathode

anode

ΔY

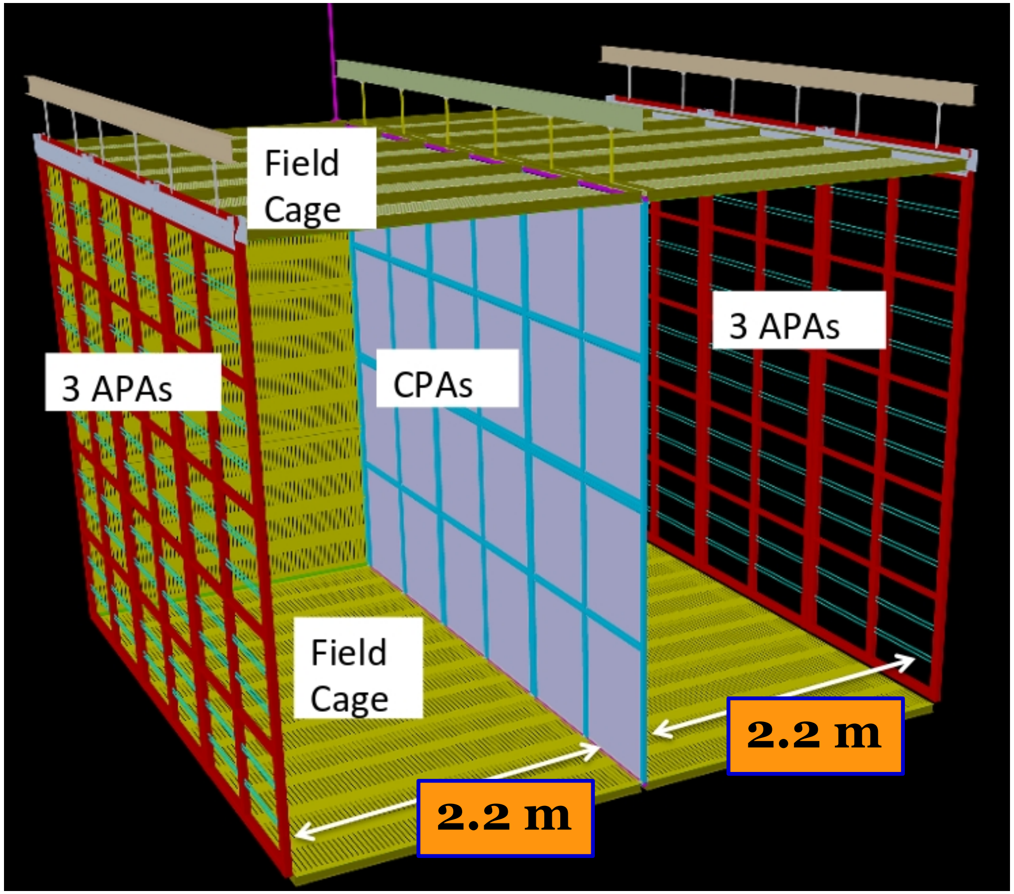


Spatial distortions roughly

3× larger

at DP compared to SP

Modified Geometry



- Modified 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 (Central Z)

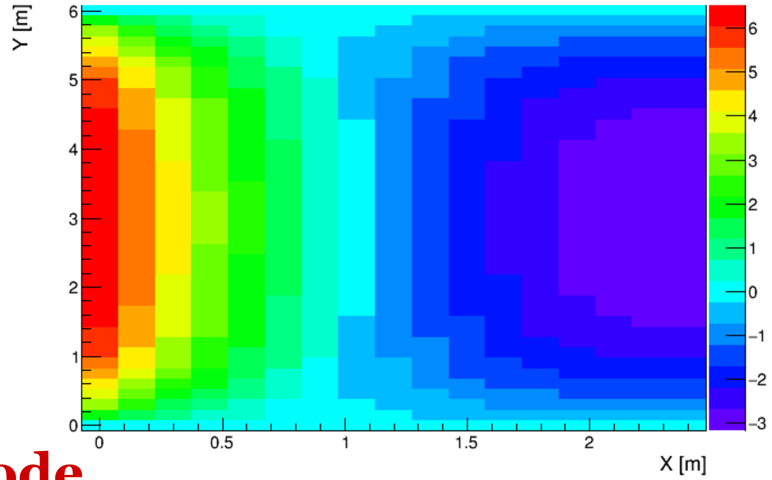
Modified Geometry

$E_{nominal}$ = 500 V/cm

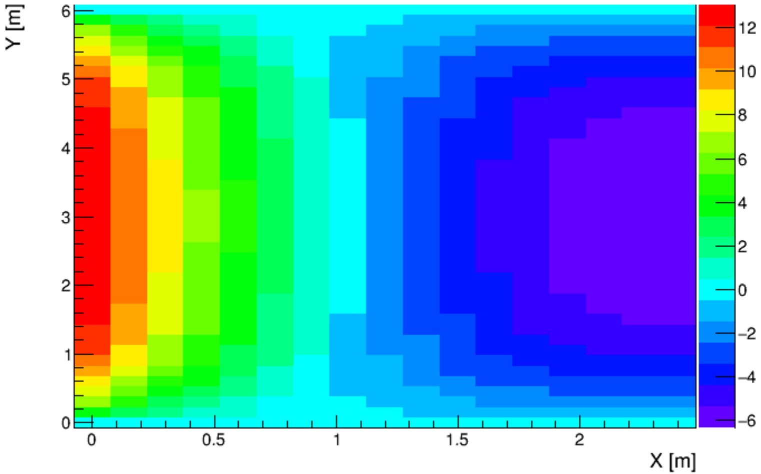
$E_{nominal}$ = 250 V/cm

E_X

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



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

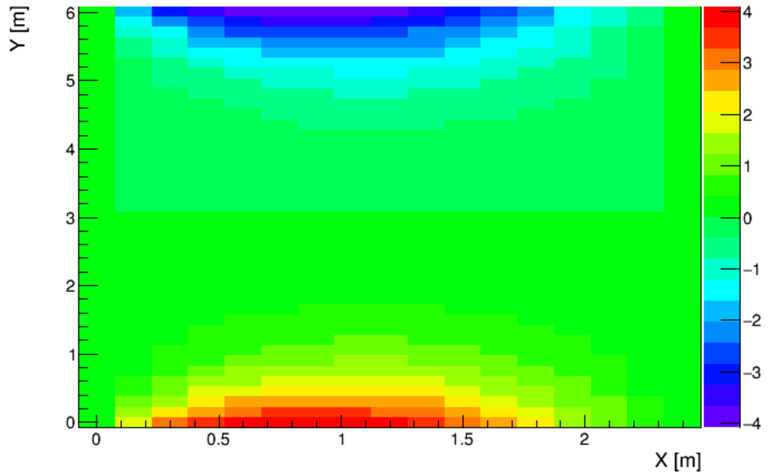


cathode

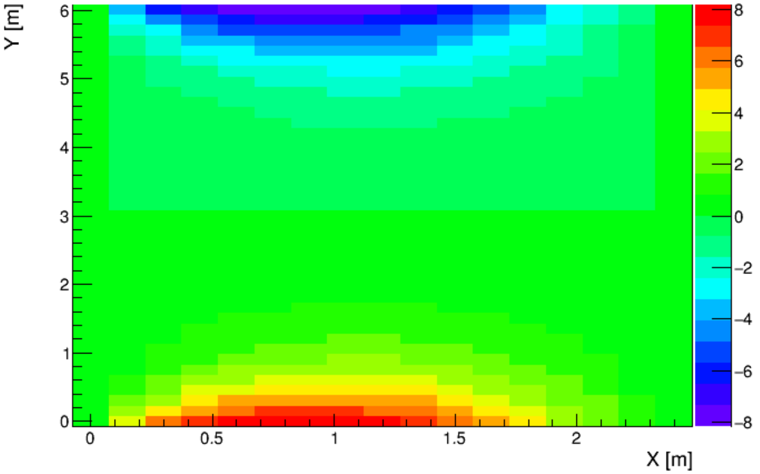
anode

E_Y

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



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



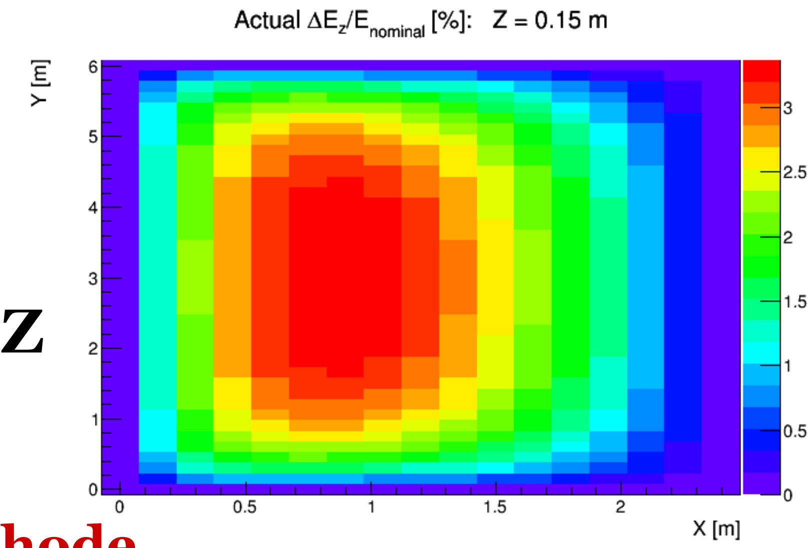
Modified E Field (TPC End)

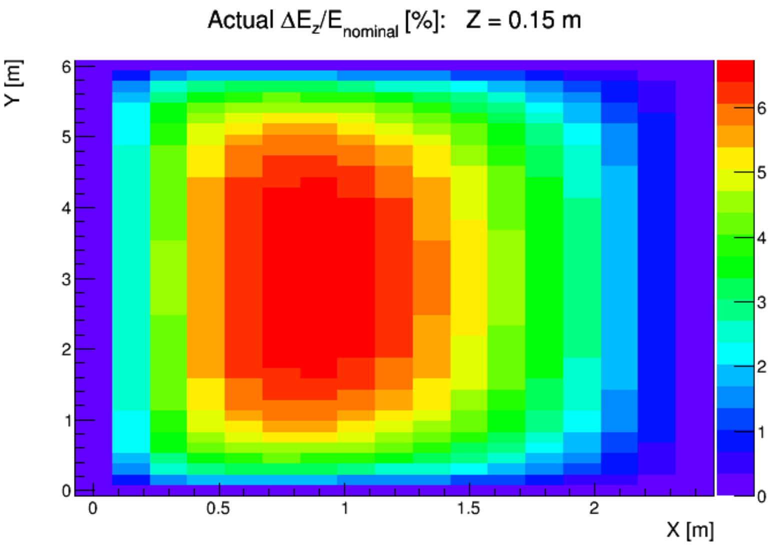
Modified Geometry

$E_{nominal}$ = 500 V/cm

$E_{nominal}$ = 250 V/cm

E_Z





cathode

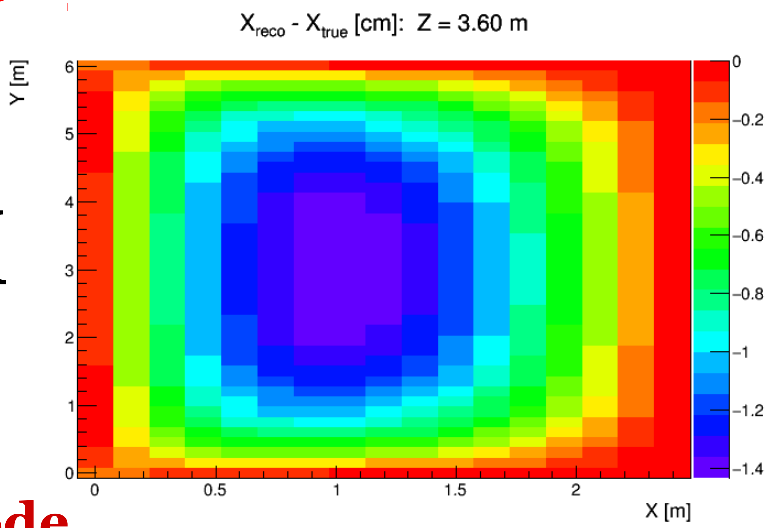
anode

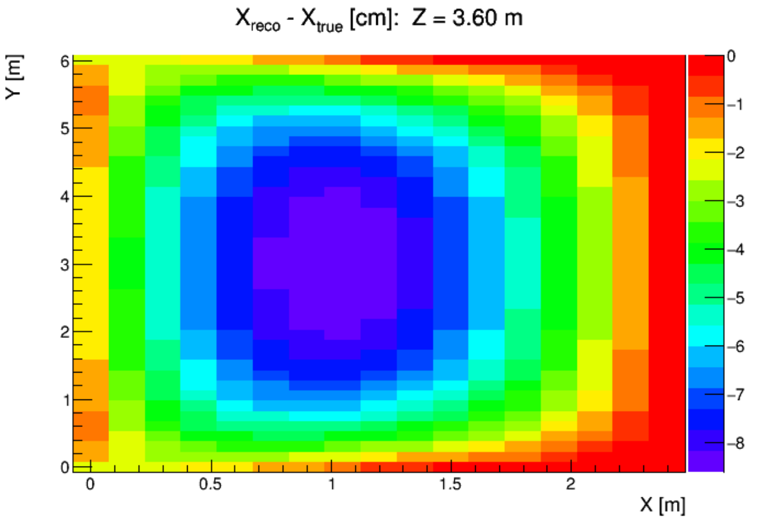
Distortions (Central Z)

Modified Geometry

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

ΔX

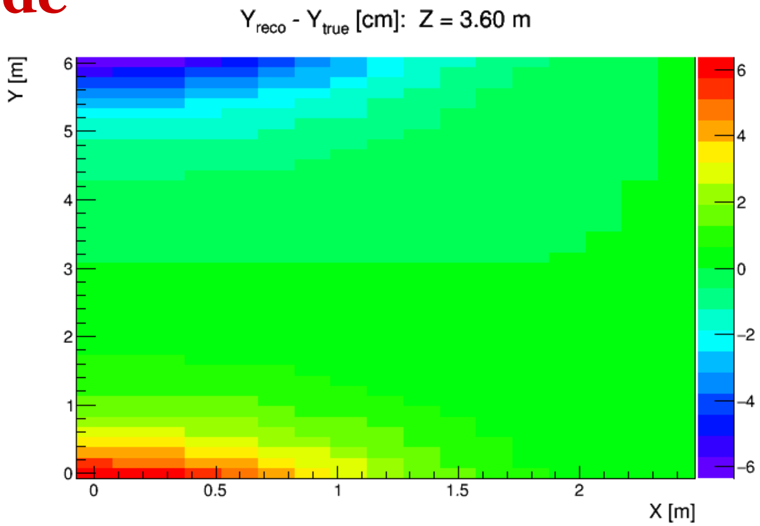

$X_{reco} - X_{true}$ [cm]: Z = 3.60 m

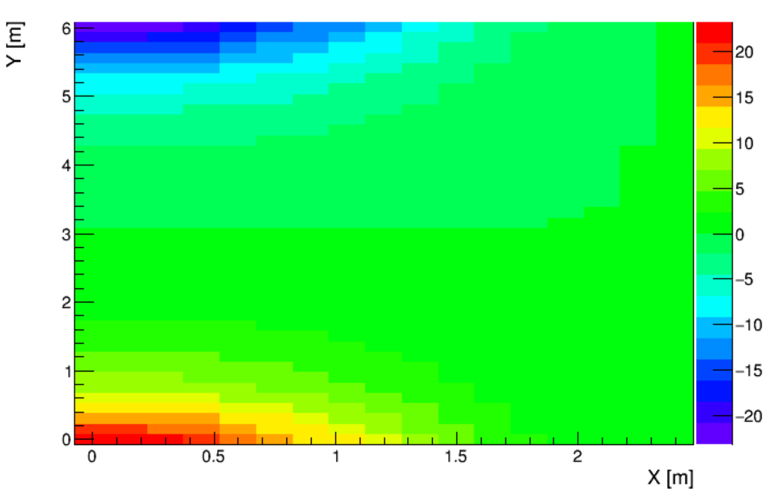

$X_{reco} - X_{true}$ [cm]: Z = 3.60 m

cathode

anode

ΔY


$Y_{reco} - Y_{true}$ [cm]: Z = 3.60 m


$Y_{reco} - Y_{true}$ [cm]: Z = 3.60 m

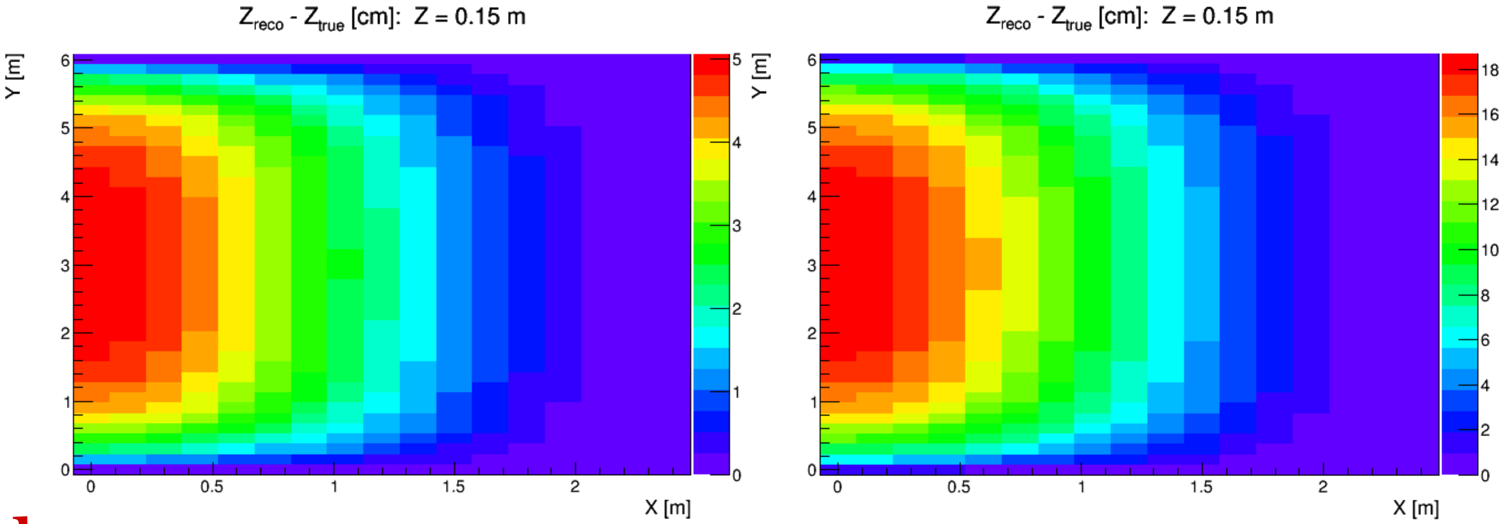
Distortions (TPC End)

Modified Geometry

$E_{nominal} = 500$ V/cm

$E_{nominal} = 250$ V/cm

ΔZ



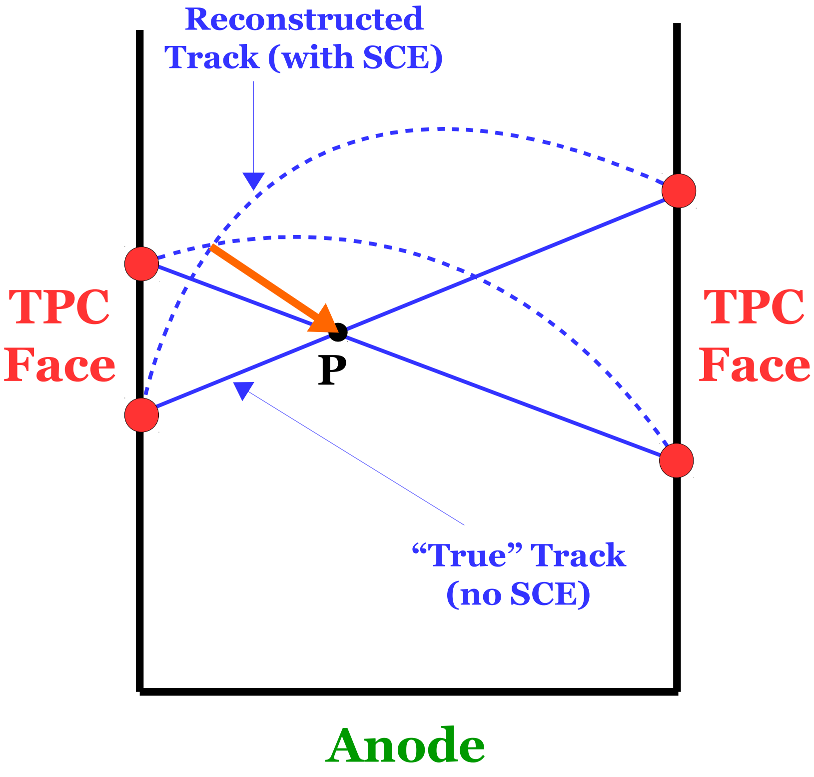
cathode

anode

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 $\mathbf{e^{-d/D}}$ (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