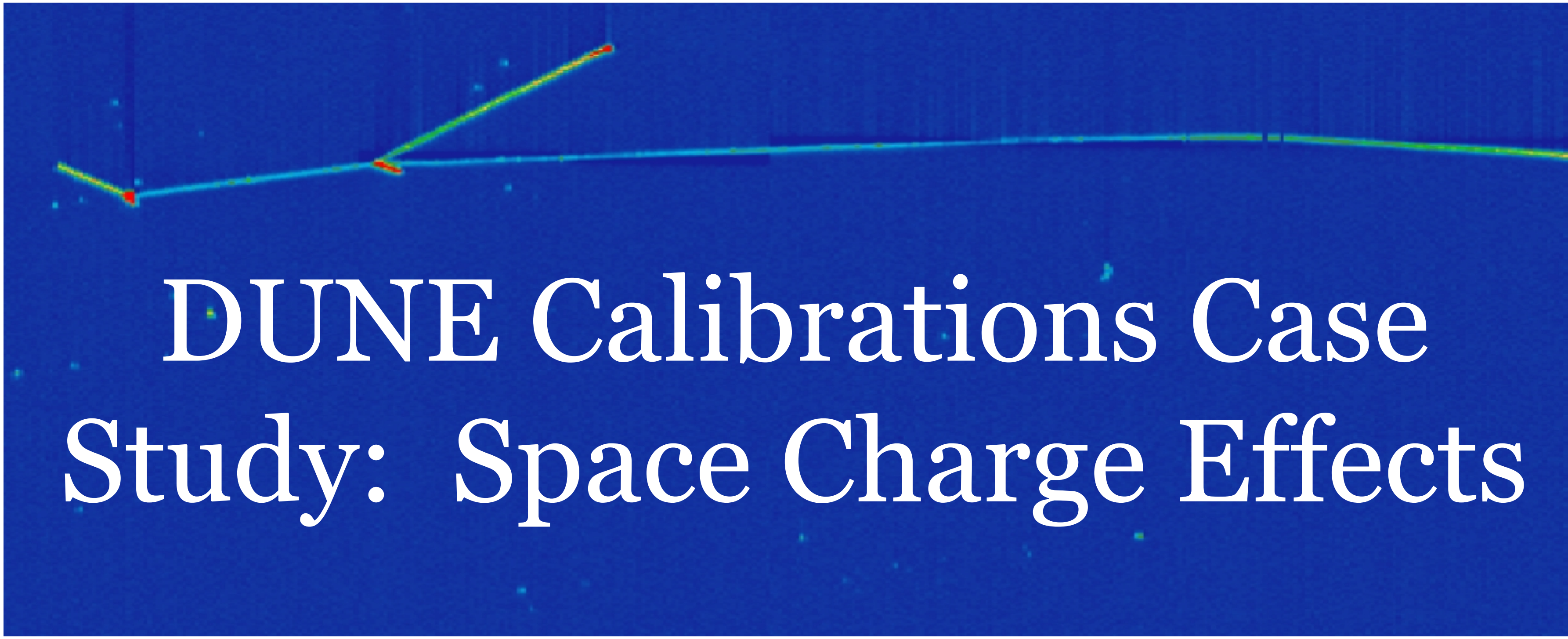

DUNE Calibrations Case Study: Space Charge Effects

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DUNE Physics Week

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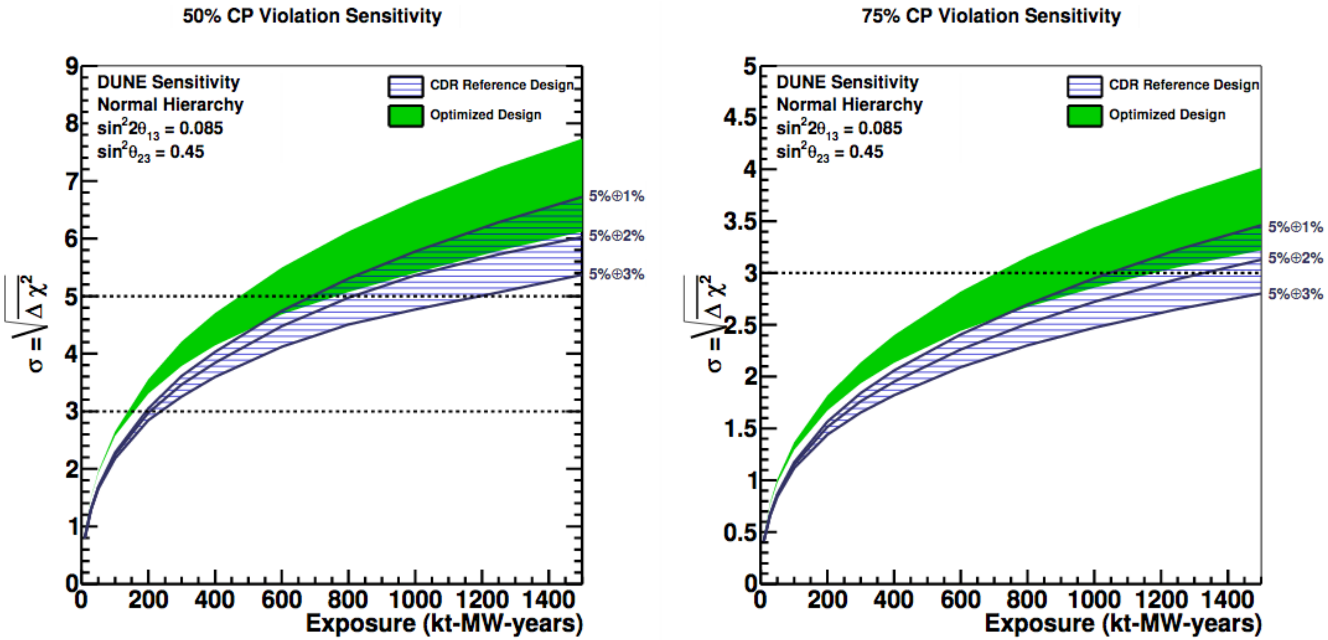
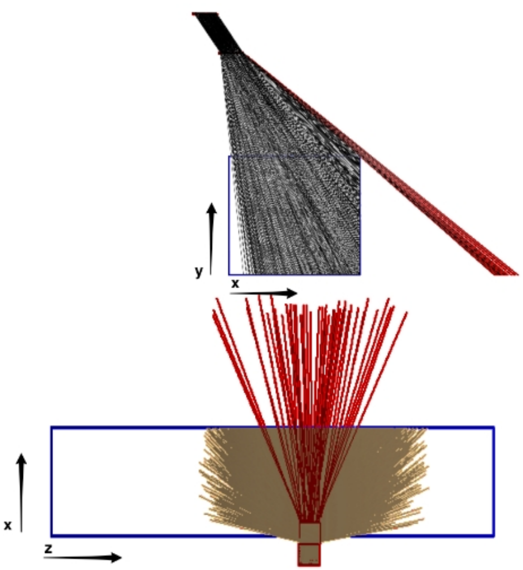
Introduction

- Yesterday I described a variety of different (TPC) calibrations that are relevant for DUNE, and some handles for them
  - Careful percent-level calibration of DUNE FD will be **critical** to achieving CP violation result within lifetime of experiment
- Focus today on one as a case study: **space charge effects**



Space Charge Effect

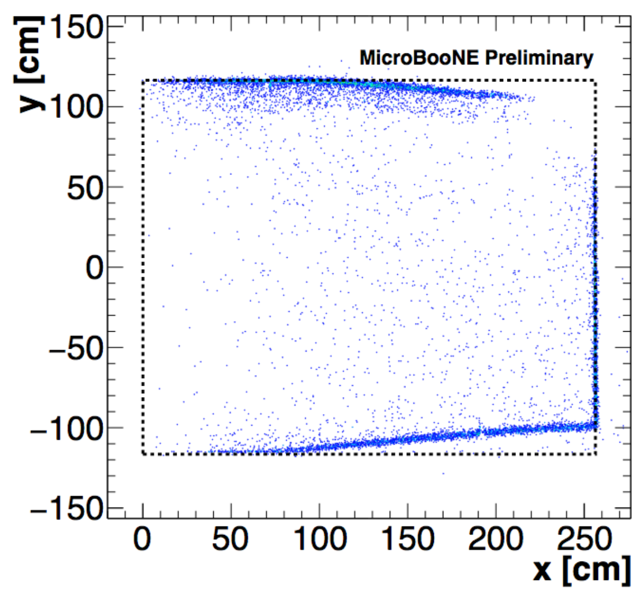
- Space Charge Effect (SCE): distortion of E field and ionization drift trajectories due to build-up of slow-moving argon ions produced from cosmic muons impinging TPC
  - E field distortions impact recombination (**dQ** bias)
  - Spatial distortions lead to squeezing of charge (**dx** bias)
- See **MicroBooNE public note on SCE** for more details



t_0 tags from MuCS

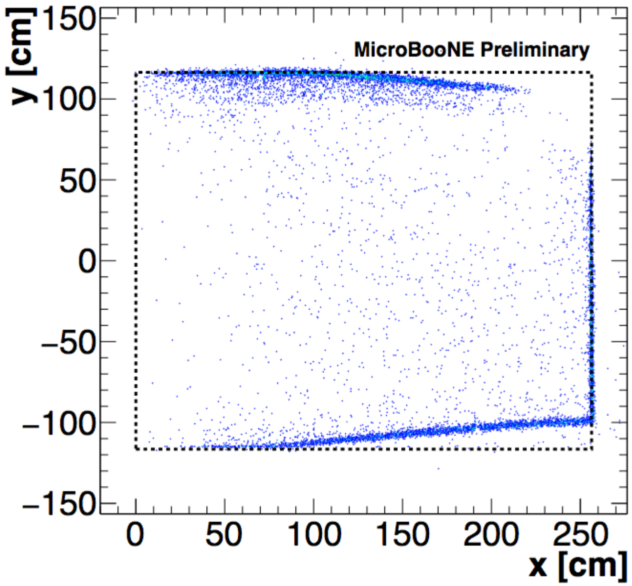
→

plot TPC track start/end points



Motivation to Study SCE

- Why study space charge effects at DUNE?
  - Impacts neutrino reconstruction at ProtoDUNE (on surface)
    - Cosmic removal
    - Reconstruction efficiencies
    - dQ/dx (PID, calorimetry)
  - Necessary to understand to extrapolate study of standard candles at ProtoDUNE to DUNE FD
  - Should be tiny at DUNE FD (deep underground), but must demonstrate this



- <u>This talk</u>: describe space charge effect simulation, present validation of SCE simulation with MicroBooNE data, and show predictions of SCE at ProtoDUNE and DUNE FD

SCE Simulation

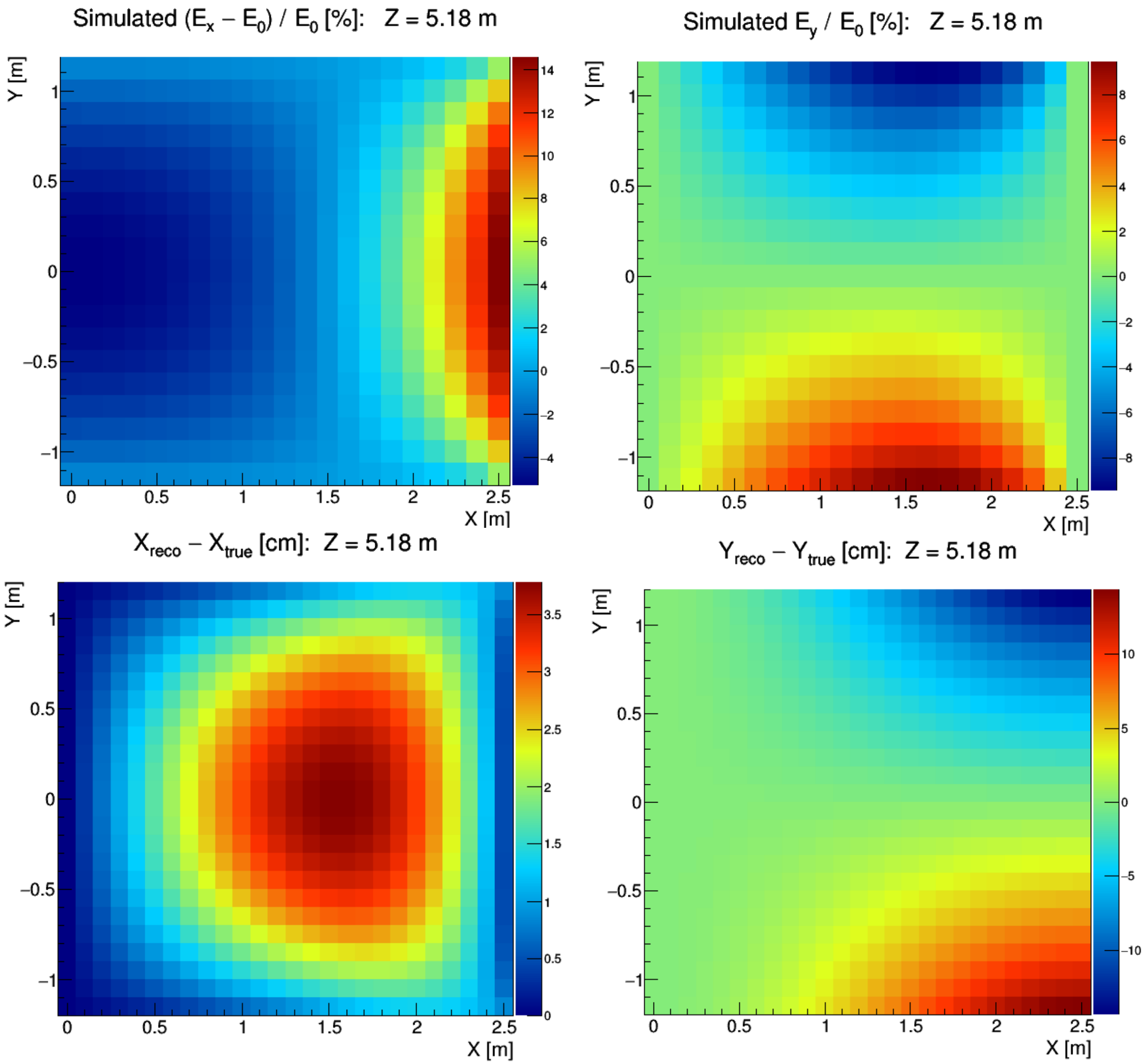
- Code written (by Mike M.) in C++ with ROOT libraries
- Also makes use of external libraries (ALGLIB)
- Primary features:
  - Obtain E fields analytically (on 3D grid) via **Fourier series**
  - Use **interpolation** scheme (RBF – radial basis functions) to obtain E fields in between solution points 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
- Can simulate arbitrary ion charge density profile if desired
  - Linear space charge density approximation for present studies
- Output: E field and spatial distortion maps (vs. {x,y,z})

SCE Sim. Results for μBooNE

Central Z Slice

$\Delta E_x/E_{drift}$ →

$\Delta E_y/E_{drift}$ ←



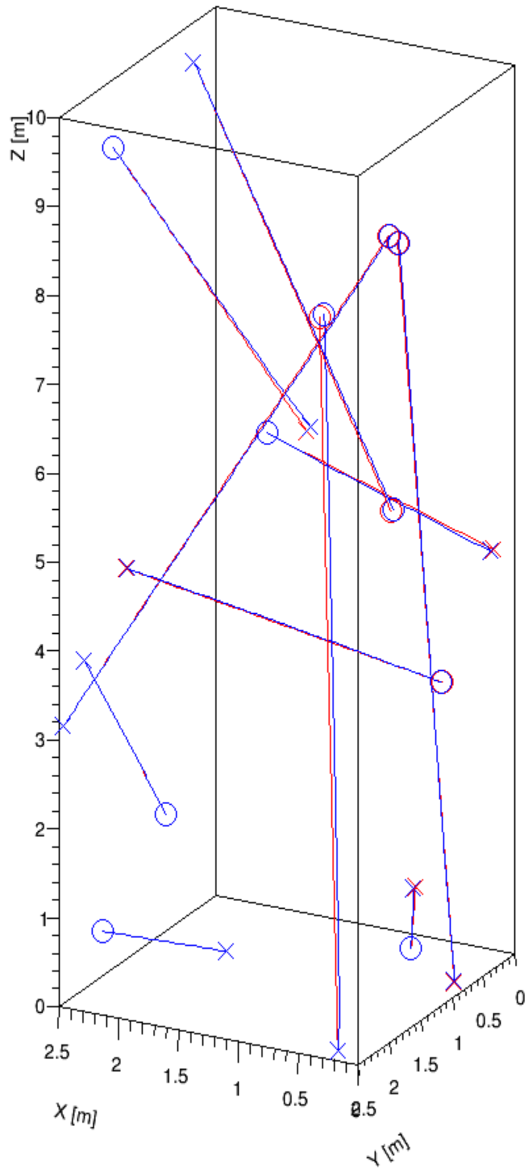
Δx →

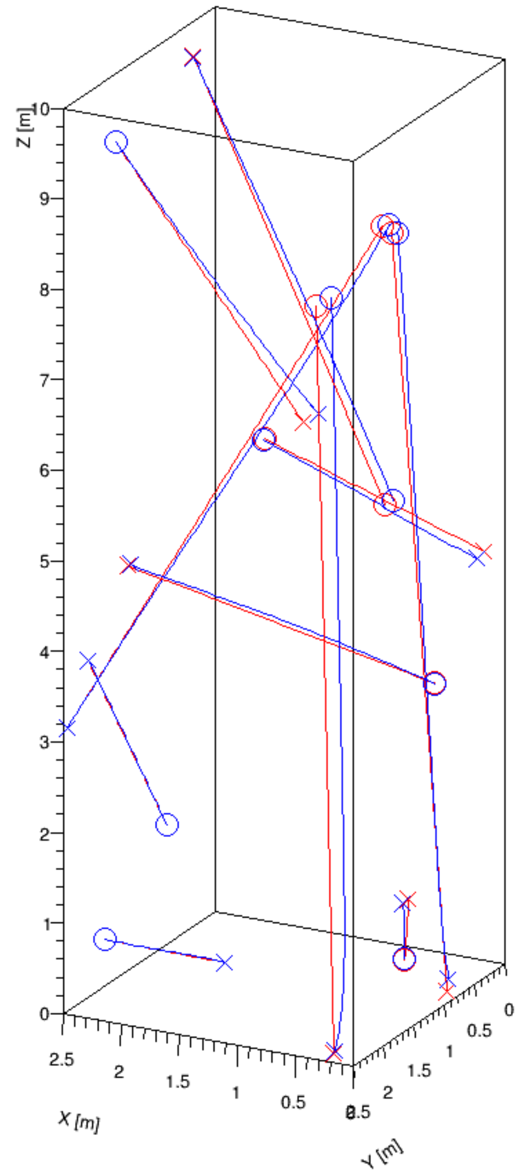
Δy ←

Example Event w/ SCE

Nominal Drift Field

500 V/cm

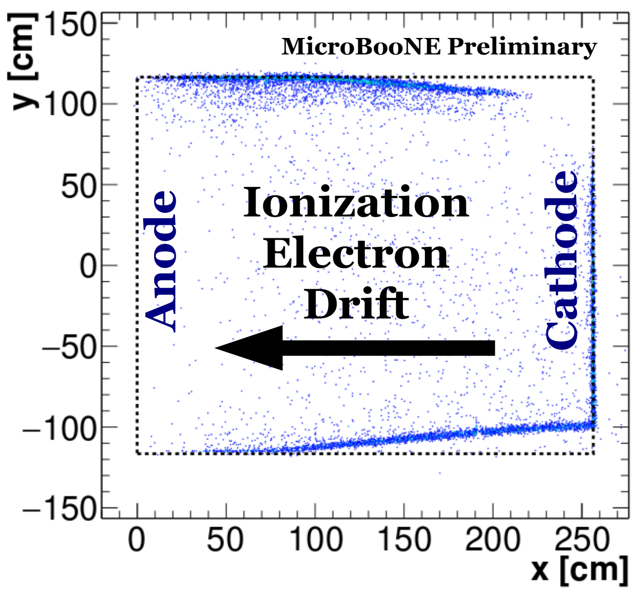


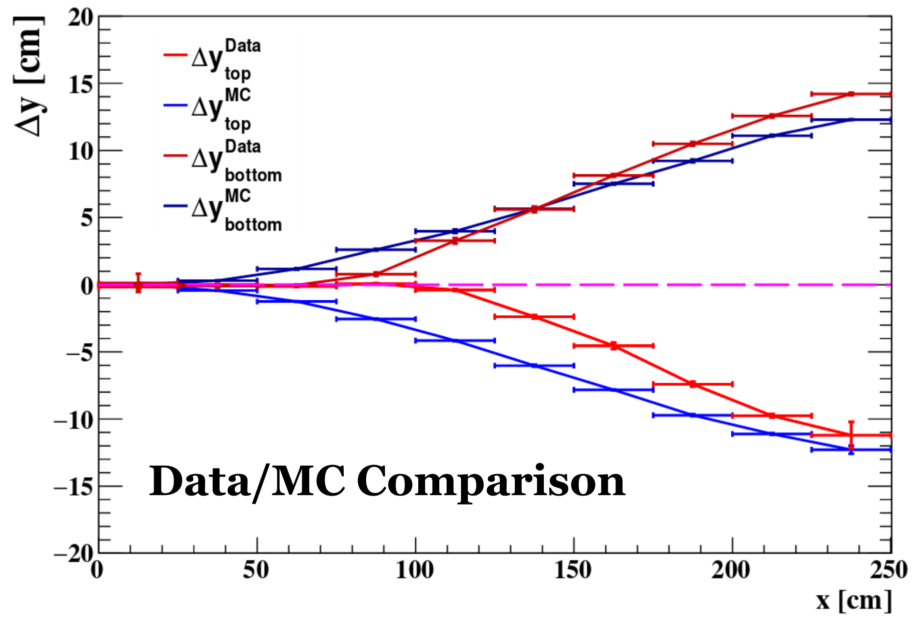


Half Drift Field

250 V/cm

SCE Sim. Validation at μBooNE





- Studied SCE spatial distortions w/ muon counter system at μBooNE
- SCE simulation qualitatively reproduces effect
  - Agreement in normalization, basic shape features, but offset near anode in data… impact from **liquid argon flow?**
  - Calibration in progress using UV laser system, cosmic muons
- See **MicroBooNE public note on SCE studies**

Storing SCE Offsets in LArSoft

- Can use simulation tool to produce displacement maps
  - **Forward transportation**: $\{x, y, z\}_{\mathbf{true}} \rightarrow \{x, y, z\}_{\mathbf{reco}}$
    - 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:
  - **Parametric** representation (for now, $5^{th}/7^{th}$ order polynomials) – fewer parameters (thanks to Xin Qian for parametrization)
  - **Matrix** representation – more generic/flexible
- LArSoft module exists to utilize maps (parametric only for now)

Accessing SCE Offsets in LArSoft

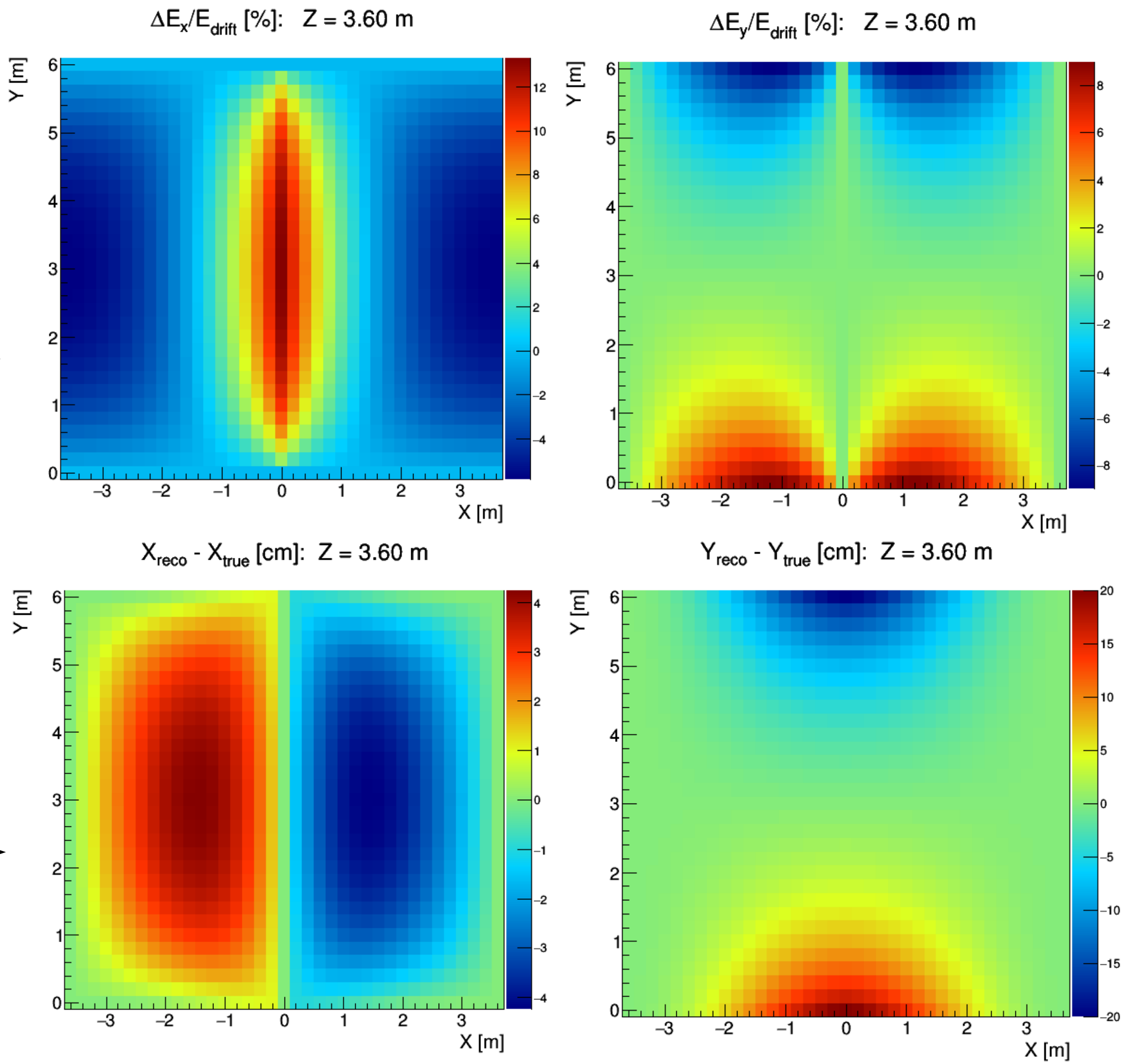
- Can easily access offsets using "SpaceCharge" service
  - Implementation of spatial and E field distortions in **larsim** (LArVoxelReadout and ISCalculationSeparate, respectively)
  - Detector-specific implementations for accessing E field and spatial distortion maps in each experiment's repository (e.g. **dunetpc**)
- To enable SCE, add these lines to your g4 stage .fcl file:
  - **services.SpaceCharge.EnableSimEfieldSCE: true**
  - **services.SpaceCharge.EnableSimSpatialSCE: true**
- Currently implemented for MicroBooNE, 35-ton, and ProtoDUNE-SP
  - Not yet implemented for DUNE FD, but a relatively simple addition
  - SBND, ICARUS maps exist as well, will be ported into LArSoft soon
  - Will also add for case of ProtoDUNE-DP

SCE at ProtoDUNE-SP

Central Z Slice

$\Delta E_x/E_{drift}$ →

← $\Delta E_y/E_{drift}$



Δx →

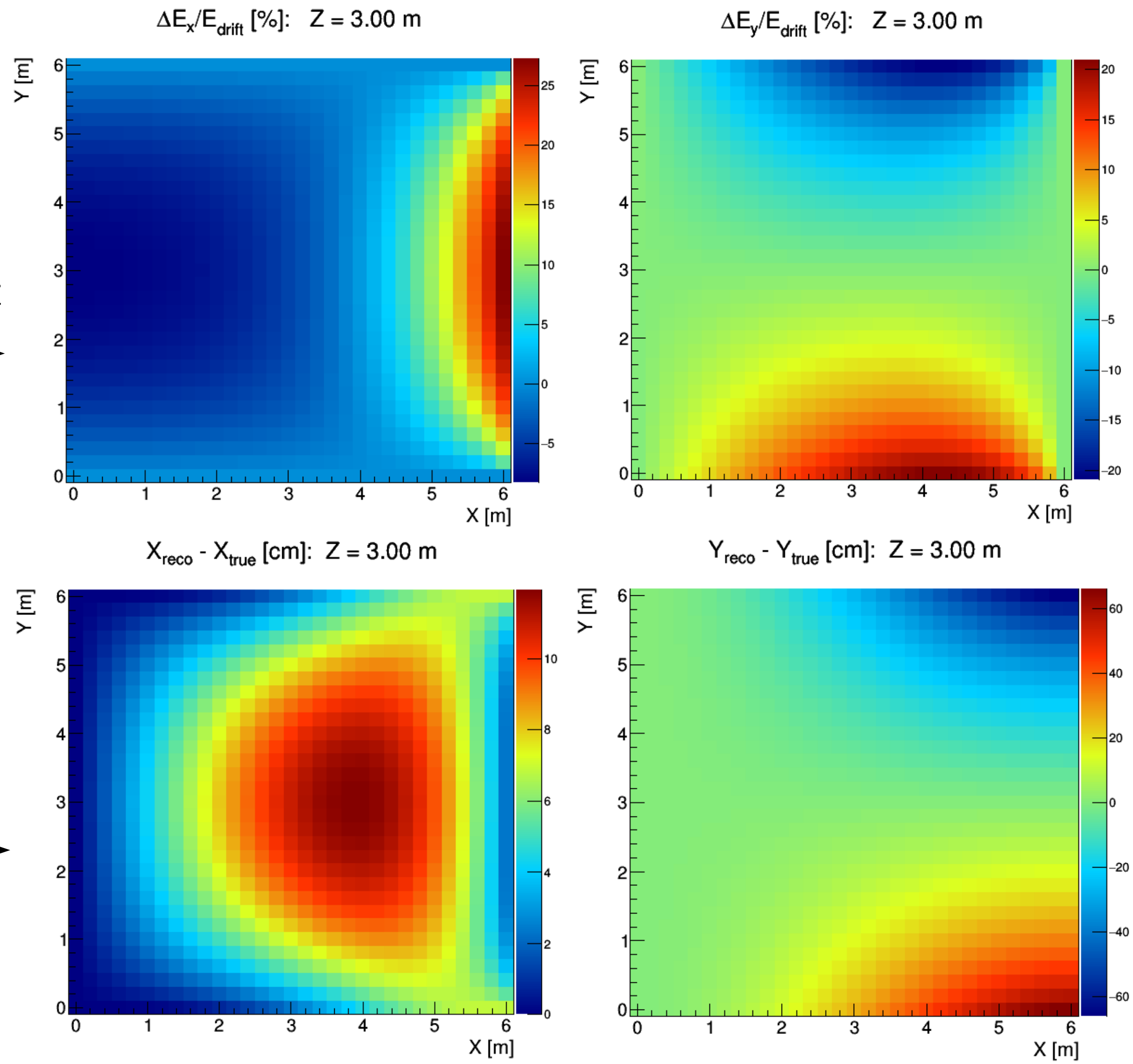
← Δy

SCE at ProtoDUNE-DP

Central Z Slice

$\Delta E_x/E_{drift}$ →

$\Delta E_y/E_{drift}$ ←



Δx →

Δy ←

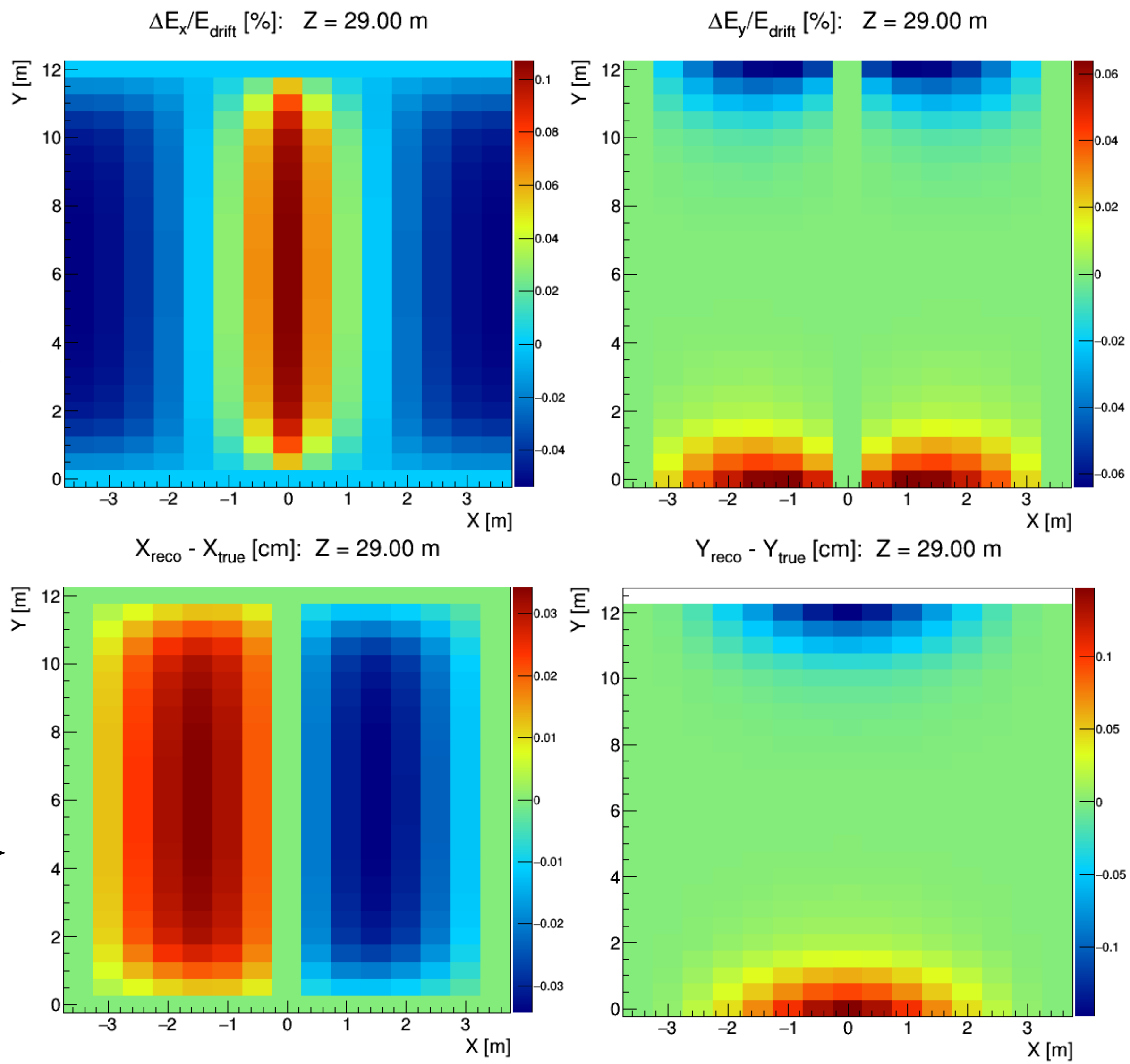
What about DUNE FD?

- Start with some simple calculations
- Expected cosmic rate at DUNE FD (one 10 kt module):
  - If on surface: **O(30000)/second** (projection from μBooNE)
  - On 4850L: **O(4000)/day → O(0.01)/second**
- Space charge scales with cosmic rate, and is **roughly three million times less bad** than if on surface. Negligible!
  - Effect highly stochastic/local (unlikely to impact ν events)
- What about contribution from Ar-39?
  - Assume 1 Bq/kg → **ten million decays/second** in DUNE FD
  - Roughly 1.0×10^{-12} C/m^3/s vs. 2.0×10^{-10} C/m^3/s from cosmics on surface → small, but might not be negligible
- Study SCE sim. using prediction of space charge from **Ar-39**

SCE at DUNE SP FD

Central Z Slice

$\Delta E_x/E_{drift}$ →



← **$\Delta E_y/E_{drift}$**

Δx →

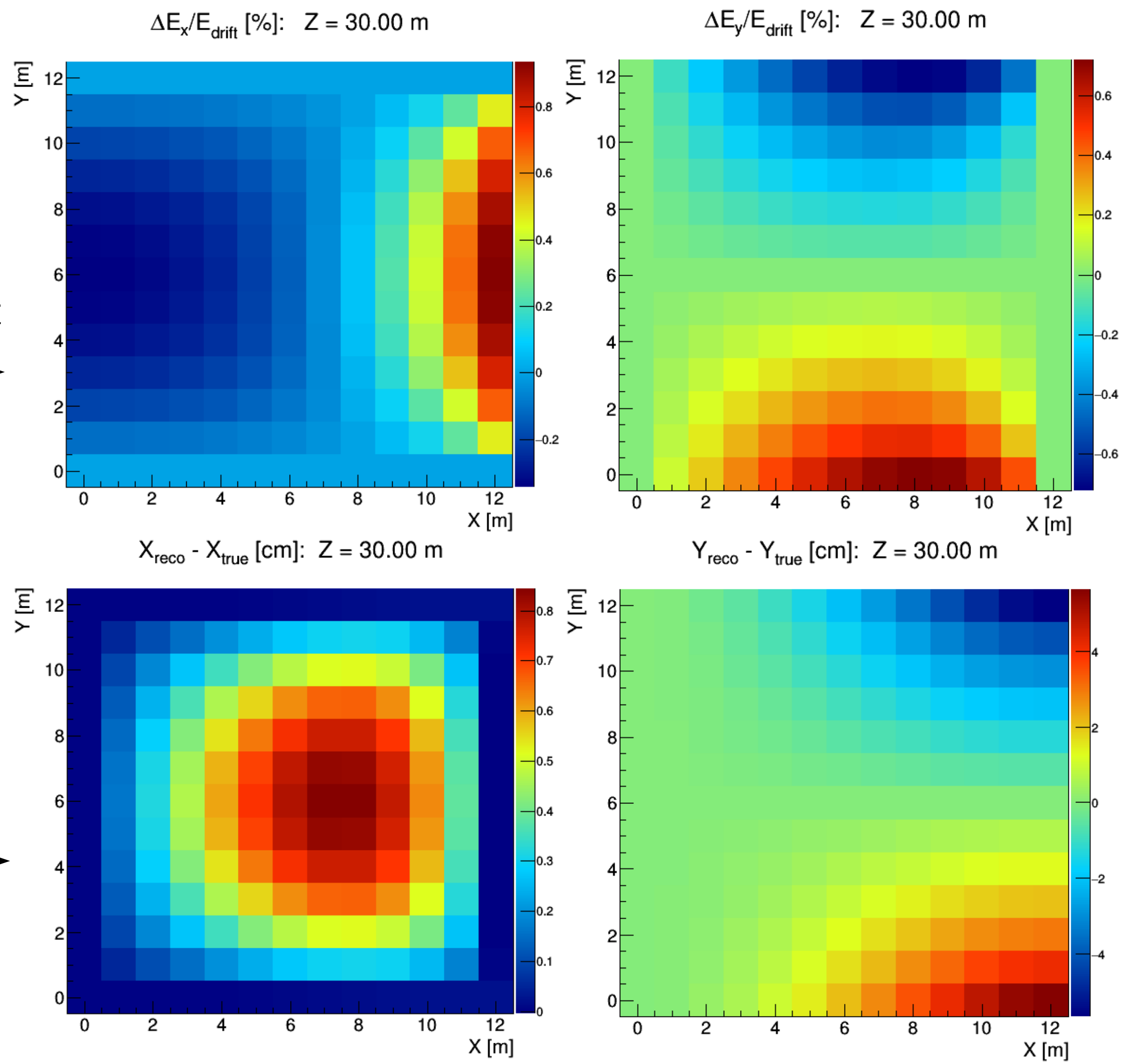
← **Δy**

SCE at DUNE DP FD

Central Z Slice

$\Delta E_x/E_{drift}$ →

$\Delta E_y/E_{drift}$ ←

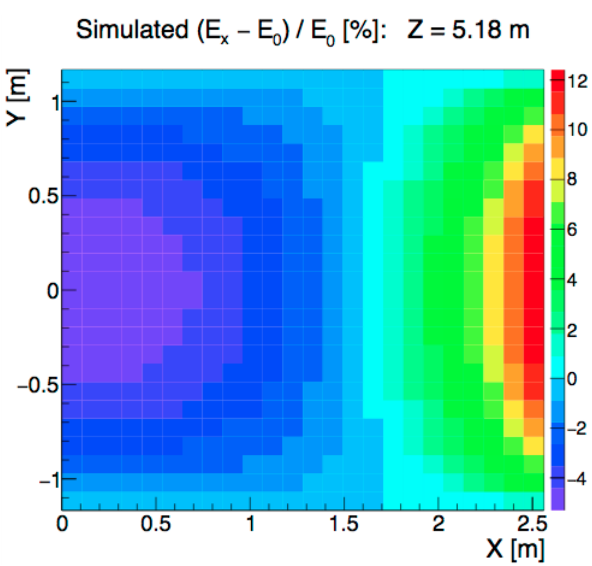


Δx →

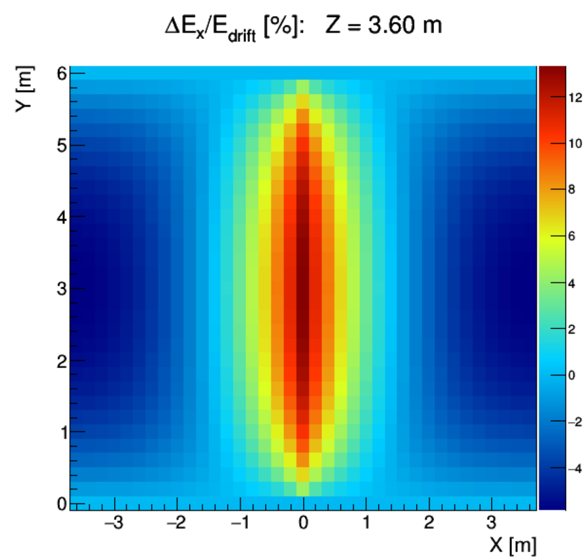
Δy ←

Comparing Across Detectors

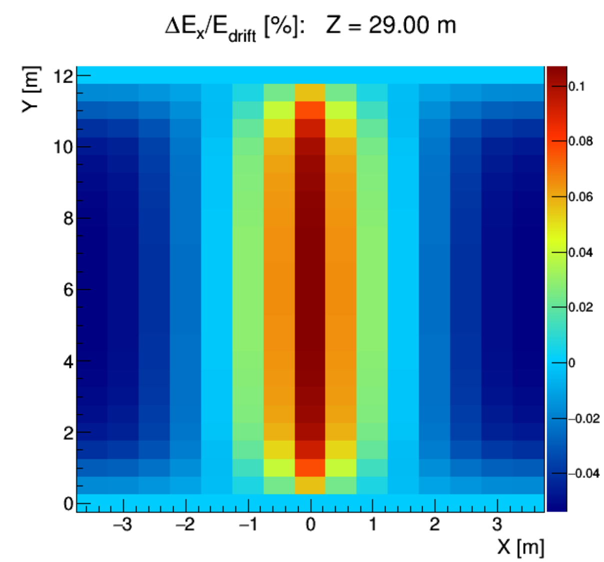
- Space charge effects worse for detectors on surface
  - MicroBooNE and ProtoDUNE-SP see significant distortions
  - DUNE SP FD sees negligible impact (unless space charge piles up due to liquid argon flow pattern – not observed at MicroBooNE)



MicroBooNE:
O(15%) E Field Distortions
5-7% dQ/dx Bias



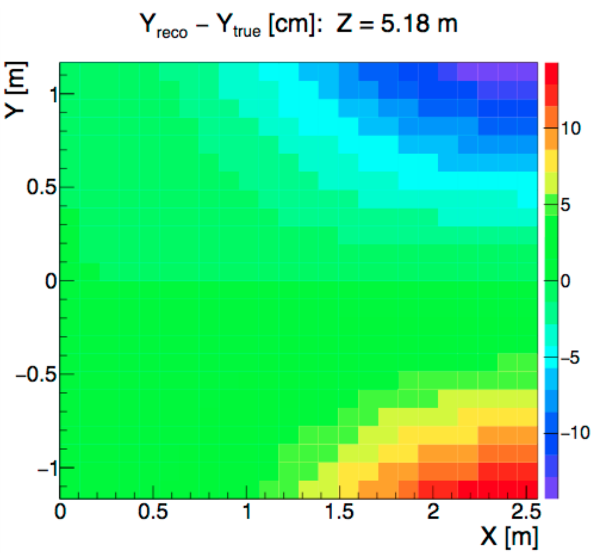
ProtoDUNE-SP:
O(15%) E Field Distortions
6-8% dQ/dx Bias



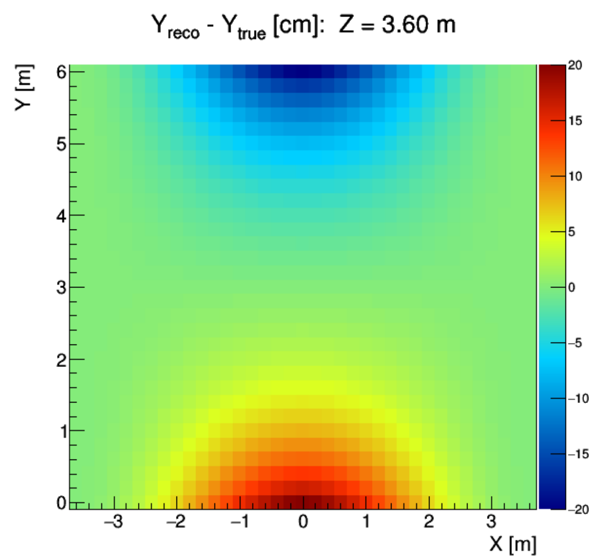
DUNE SP FD:
O(0.1%) E Field Distortions
< 0.1% dQ/dx Bias

Comparing Across Detectors

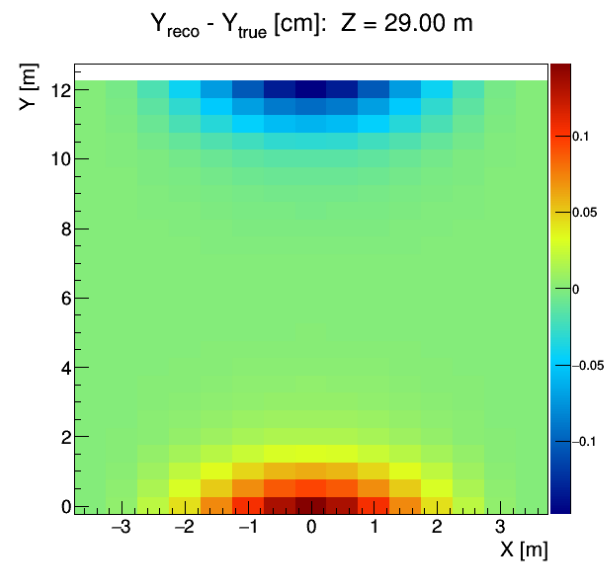
- Space charge effects worse for detectors on surface
  - MicroBooNE and ProtoDUNE-SP see significant distortions
  - DUNE SP FD sees negligible impact (unless space charge piles up due to liquid argon flow pattern – not observed at MicroBooNE)



<u>MicroBooNE</u>:
O(15 cm) Spatial Distortions
5-7% dQ/dx Bias

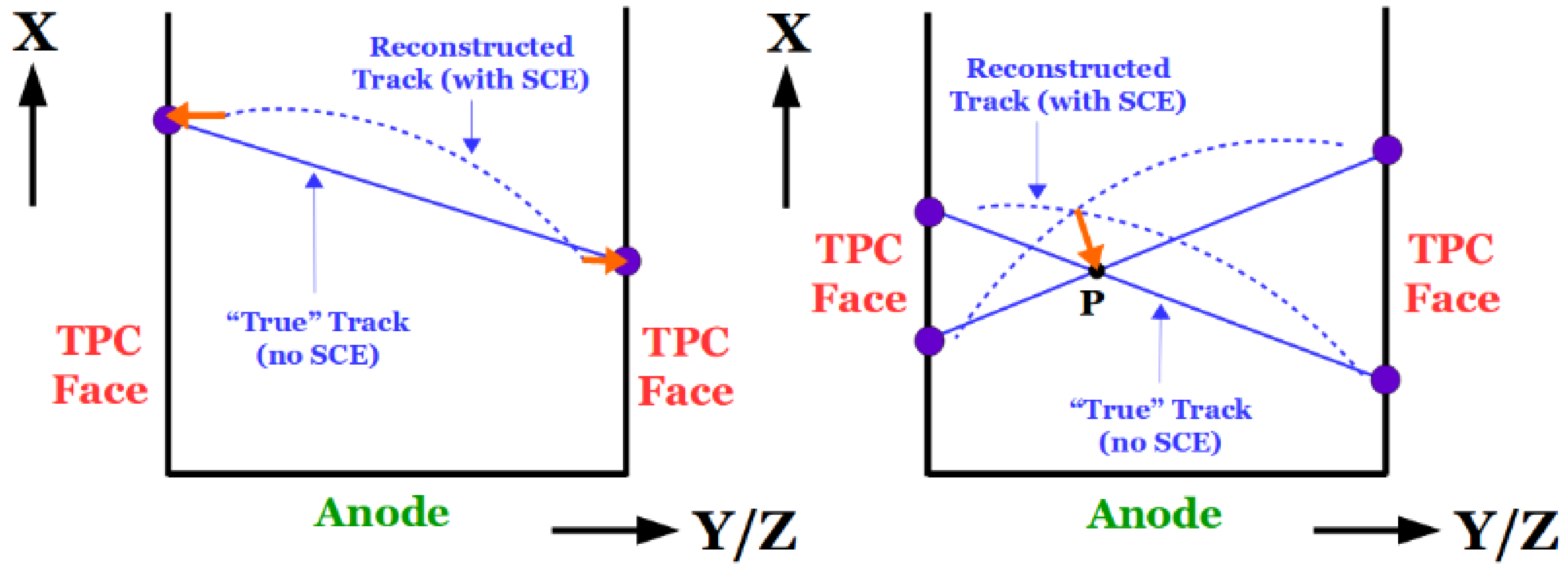


<u>ProtoDUNE-SP</u>:
O(20 cm) Spatial Distortions
6-8% dQ/dx Bias



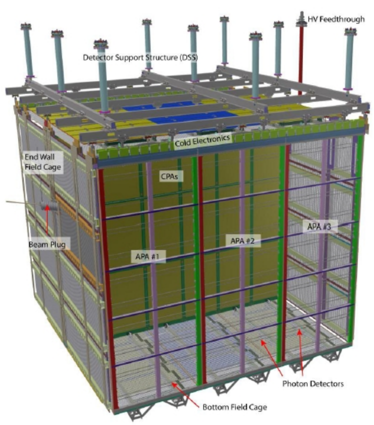
<u>DUNE SP FD</u>:
O(0.1 cm) Spatial Distortions
< 0.1% dQ/dx Bias

SCE Calibration Scheme



- Two samples of t_0-tagged tracks can provide SCE corrections:
  - Single tracks – enable corrections at TPC faces by utilizing endpoints of tracks (correction vector approximately orthonormal to TPC face)
  - Pairs of tracks – 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)

- Space charge effects not large at DUNE SP FD, but are significant at ProtoDUNEs
  - **Necessary to understand at ProtoDUNE** so we can extrapolate studies of standard candles in data from ProtoDUNE to DUNE FD
  - Also, SCE not negligible at DUNE DP FD (may be even worse than predictions due to contributions from gas phase)
  - A lot of discussion about ProtoDUNE (and DUNE FD) calibrations in ProtoDUNE “DRA” meetings (Thursdays, 8 am CT)
    - ProtoDUNE-SP calibrations convener: Mike M.



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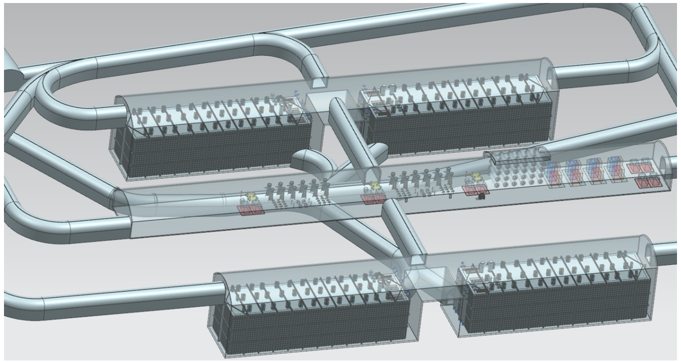


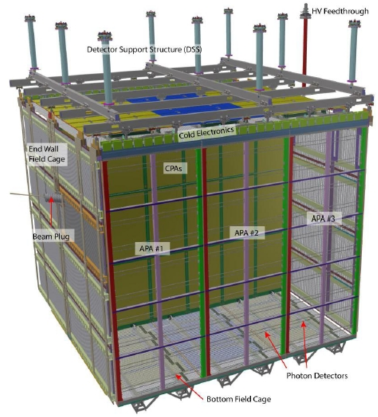
BACKUP SLIDES

TPC Calibration Items

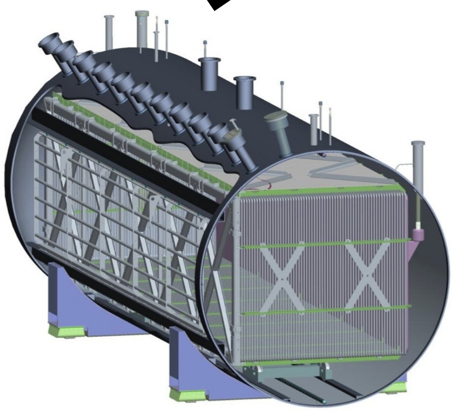
- Break calibrations items into three categories: ex-situ, in-situ w/ pulser, in-situ w/ ionization signals
- Ex-situ (can also be performed in-situ, at least in principle):
  - Diffusion (longitudinal and transverse)
  - Recombination (angular/energy dependence, fluctuations)
  - Wire field response (modulo potential wire-to-wire variations)
- In-situ w/ pulser:
  - Electronics response (gain, shaping time, pole-zero effects, etc.)
  - ADC ASIC calibrations (linearity, other "features" like stuck codes)
- In-situ w/ ionization signals:
  - Electron lifetime (including spatial/temporal variations)
  - Space charge effects and other field effects (e.g. field cage resistor failure)
  - Wire field response wire-to-wire variations (negligible? should check)
- Nail these, then study "standard candles" in data (e.g. Michels)

Differing Concerns

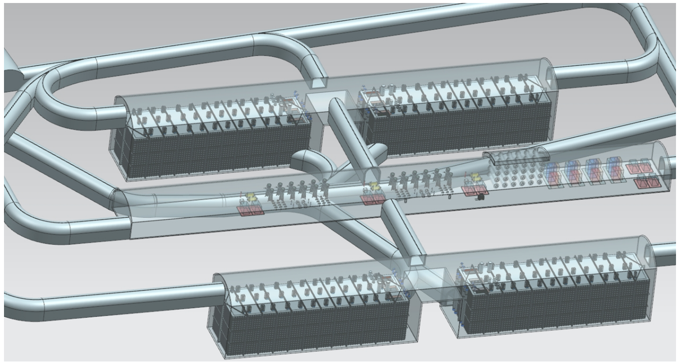
- Different experiments face somewhat different issues



All Items:
SCE Worse,
ADC Issues



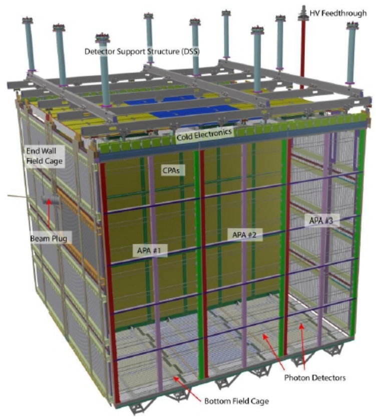
All Items Except ADC Issues
(And Less Requirements)



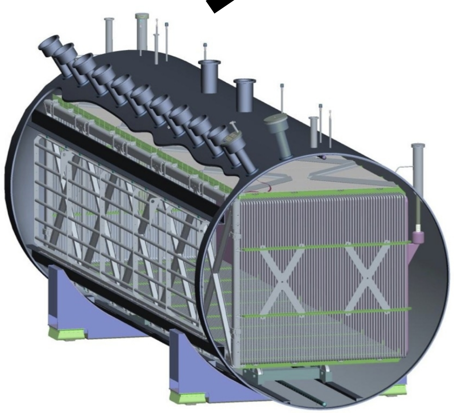
All Items Except
SCE, ADC Issues

Differing Tools

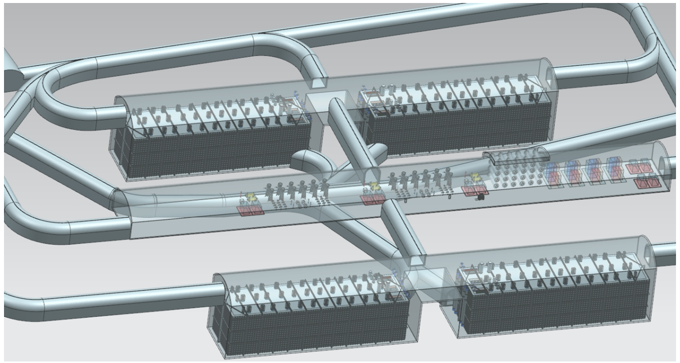
- Each experiment has different calibration tools to utilize



Partial CRT, Plenty of Cosmics/Michels, Ar-39



UV Laser System, Full CRT, Plenty of Cosmics/Michels, Ar-39



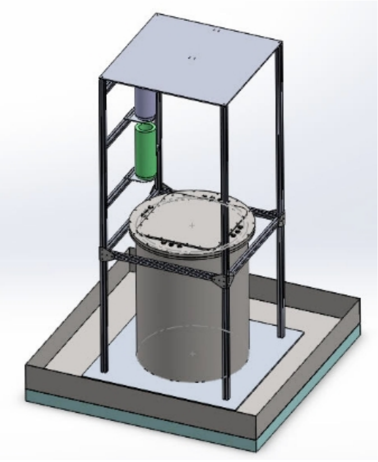
UV Laser System (?), Radioactive Sources (?), Few Cosmics/Michels, Ar-39

Calibrations with Ar-39

- Can use Ar-39 beta decays for two types of calibrations: **normalization** and **shape**
- Normalization (reconstructed energy):
  - Electron lifetime (spatial/temporal variations)
  - Recombination (at low energies)
- Shape (shape of signal on wires):
  - Field response (variations across wires)
  - Diffusion (longitudinal and transverse)
- Also measure Ar-39 rate, study low-energy charge detection/reconstruction (e.g. for SN neutrino studies), use methods to study other radiological sources in TPC, etc.
- Can't t_0 tag, but **uniform in x**, enabling calibrations use

Recombination and Ar-39

- Lack of knowledge of recombination will complicate use of spectrum for nailing down electron lifetime
  - Need to know both mean recombination and fluctuations in recombination at this energy scale
  - Chatting with experts, conclusion is that we don't know this very well for argon, needs study for precision calibration
- Ahead of DUNE, **measure Ar-39 charge spectrum**
  - Being studied by CSU group at MicroBooNE (ongoing)
  - In separate TPC setup for precision measurement
    - Underground
    - Short drift
    - t_0 tag from light



M. Mooney, D. Warner

Conceptual design for portable cryostat