Cosmic Ray Calibrations at DUNE

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DUNE Calibration Mini-Workshop – July 27th, 2017

Introduction

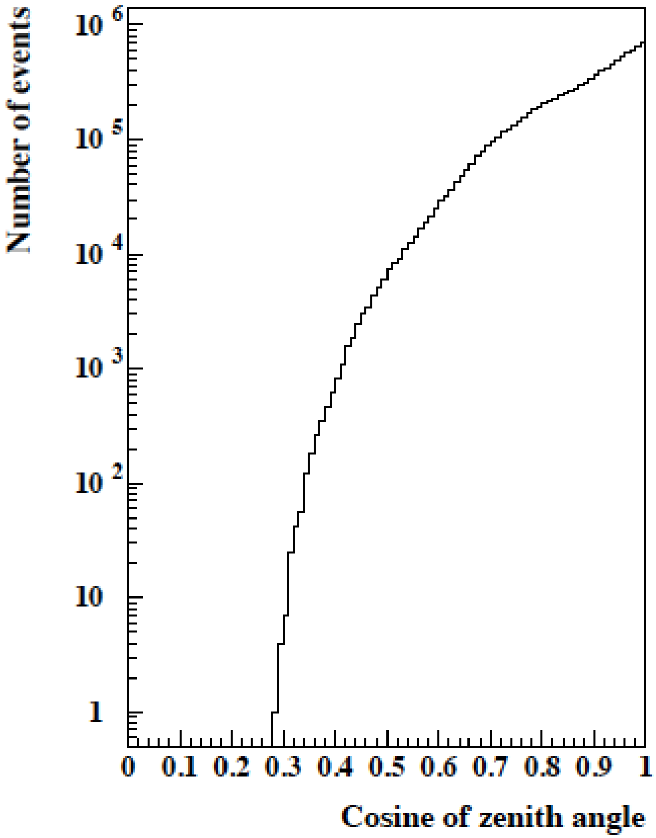
- Discussion topic: TPC calibrations with cosmic muons
  - Will add thoughts about other methods where applicable
- Discussed primary focus of MicroBooNE calibration program yesterday – now focus on DUNE FD
  - Single phase is the primary focus for today
  - Will touch on ProtoDUNE-SP as well
- Was tasked with discussing three items:
  - E-field distortion
  - Purity measurements
  - Absolute energy scale
- Note: regarding E field, Tom will cover alignment, while I will only discuss space charge effects and cathode flatness

Measurement Ordering

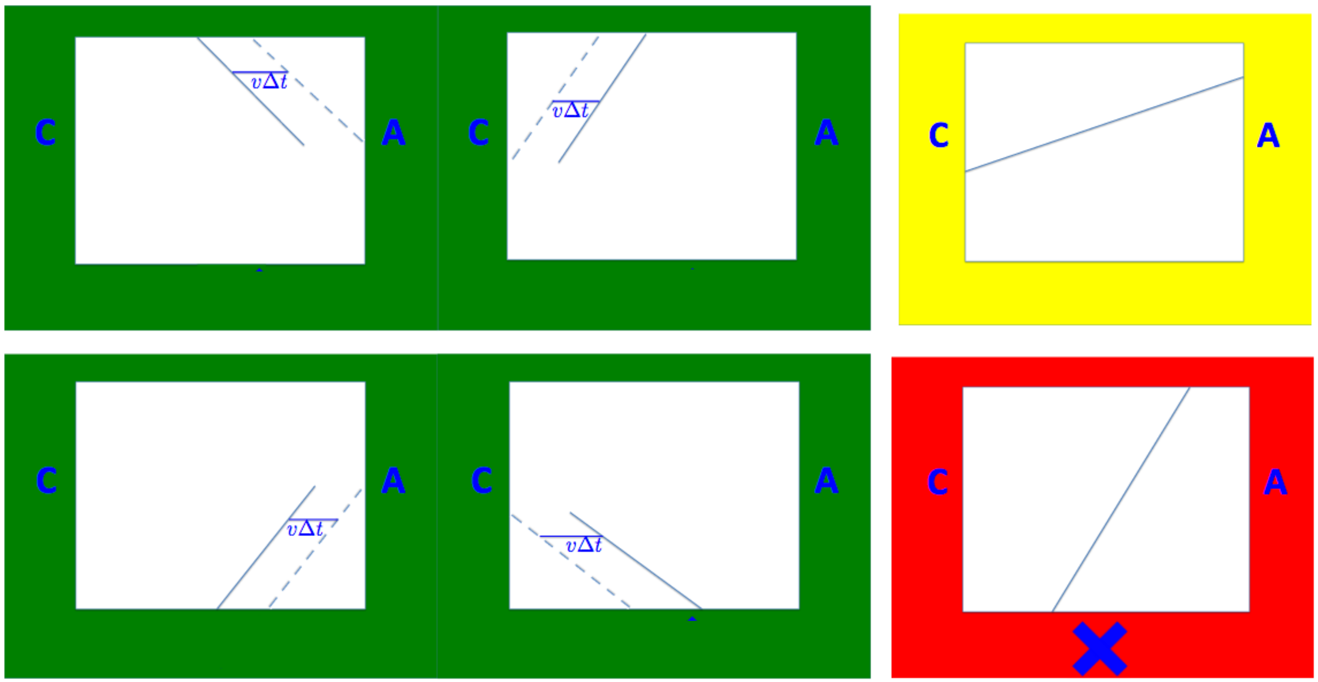
- Natural ordering: E field → purity → abs. energy scale
- This is because we should target E field distortions with spatial information only (position/time of reconstructed "hits"), while this effect will impact calorimetry
- Then, with calorimetry calibrated, can target purity (electron lifetime)
- Calibrate electron lifetime next in "drift columns" which allows us to obtain correct deposited dQ/dx (assuming recombination is well understood)
- Then can go to absolute energy scale using MIPs with known range (e.g. stopping muons or Michels)
- So, for absolute energy scale, <u>must know E field and purity</u>

Statistics

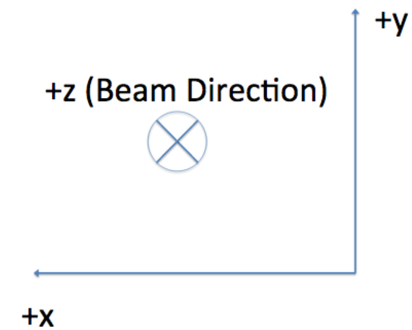
- We don't have many events to work with, unfortunately
  - Through-going muons: 4000/day
  - Stopping muons: 30/day
  - Michels: 20/day
- Numbers above for 10 kt module
- Need to fully use each one!
- Must tag t_0 of each cosmic to use
  - To correct elec. lifetime
- Angular coverage is limited
  - Less stats for collection plane
  - Must extrapolate to beam events
- **CRT triggering** would increase stats



t_o-tagged Tracks



C. Barnes,
D. Caratelli,
M. Mooney



- Can tag cosmic muon t_o with TPC/LCS info (purify with LCS)
  - Side-piercing tracks: assume through-going, use geometry
  - Cathode-anode crossers: projected *x* distance is full drift length
  - ProtoDUNEs and DUNE FD also get cathode-crossers
  - Also: at DUNE FD, can tag top-down cosmics w/ LCS (to ~10 cm?)

t_0-tagged Tracks

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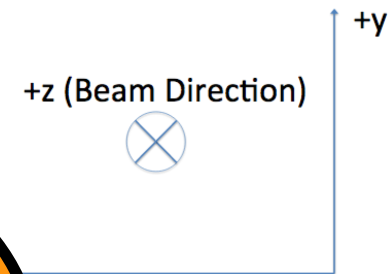


Should be able to tag t_0 of most cosmics using light collection system, at least (though less spatial precision in drift direction, O(10 cm))

Can we improve that at DUNE?

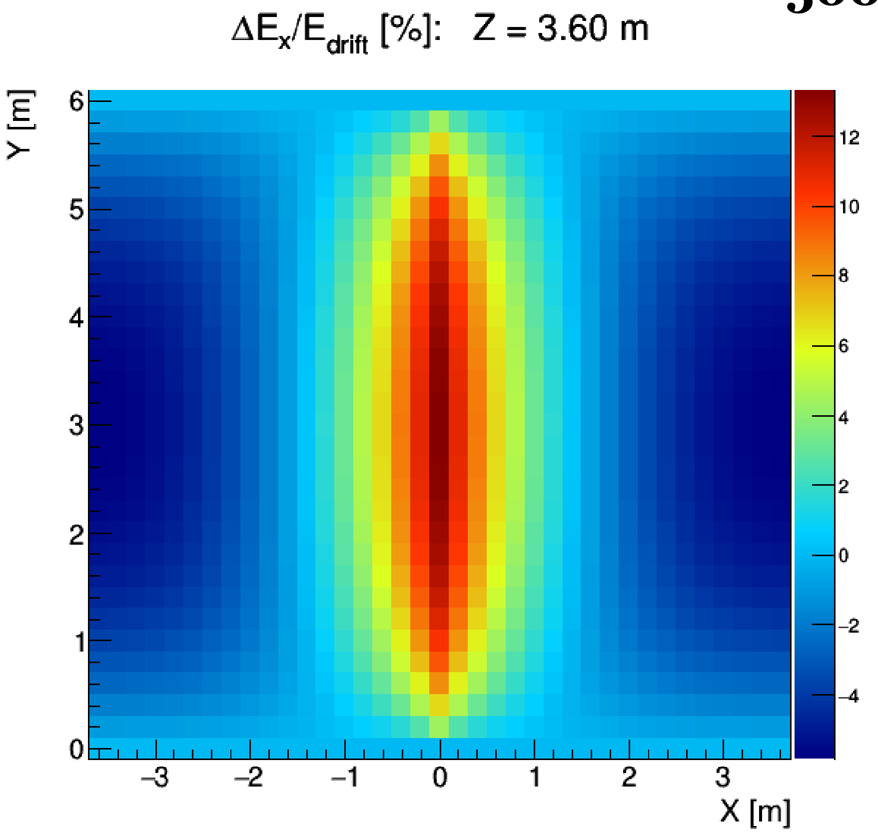
- ♦ Can tag cos ... urify with LCS)
  - Side-piercing tracks ... going, use geometry
  - Cathode-anode crossers: projected *x* distance is full drift length
  - ProtoDUNEs and DUNE FD also get cathode-crossers
  - Also: at DUNE FD, can tag top-down cosmics w/ LCS (to ~10 cm?)

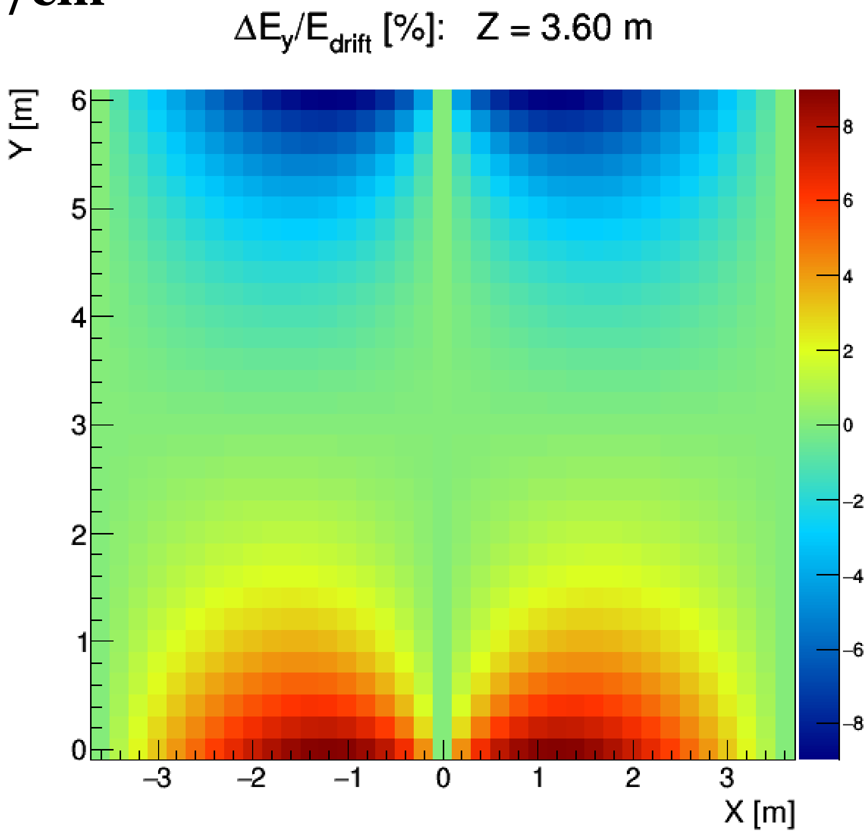
Space Charge Effect

- Again, two topics I focus on:
  - Space charge effect
  - Cathode flatness
- Basically space charge effect is a non-issue for SP DUNE FD
  - Will be bad for ProtoDUNE-SP though (see following slides)
  - However, dual phase FD may see some (small) effect due to much longer drift (12 m)
- However, we will want to make some measurements at ProtoDUNE-SP that will inform the calibration program at DUNE FD
  - e.g. data-driven checks of wire field response, recombination, diffusion, energy scale, measuring electron lifetime precisely, etc.
  - Space charge effects will complicate this – must calibrate out

ProtoDUNE-SP E Field SCE Dist.

500 V/cm

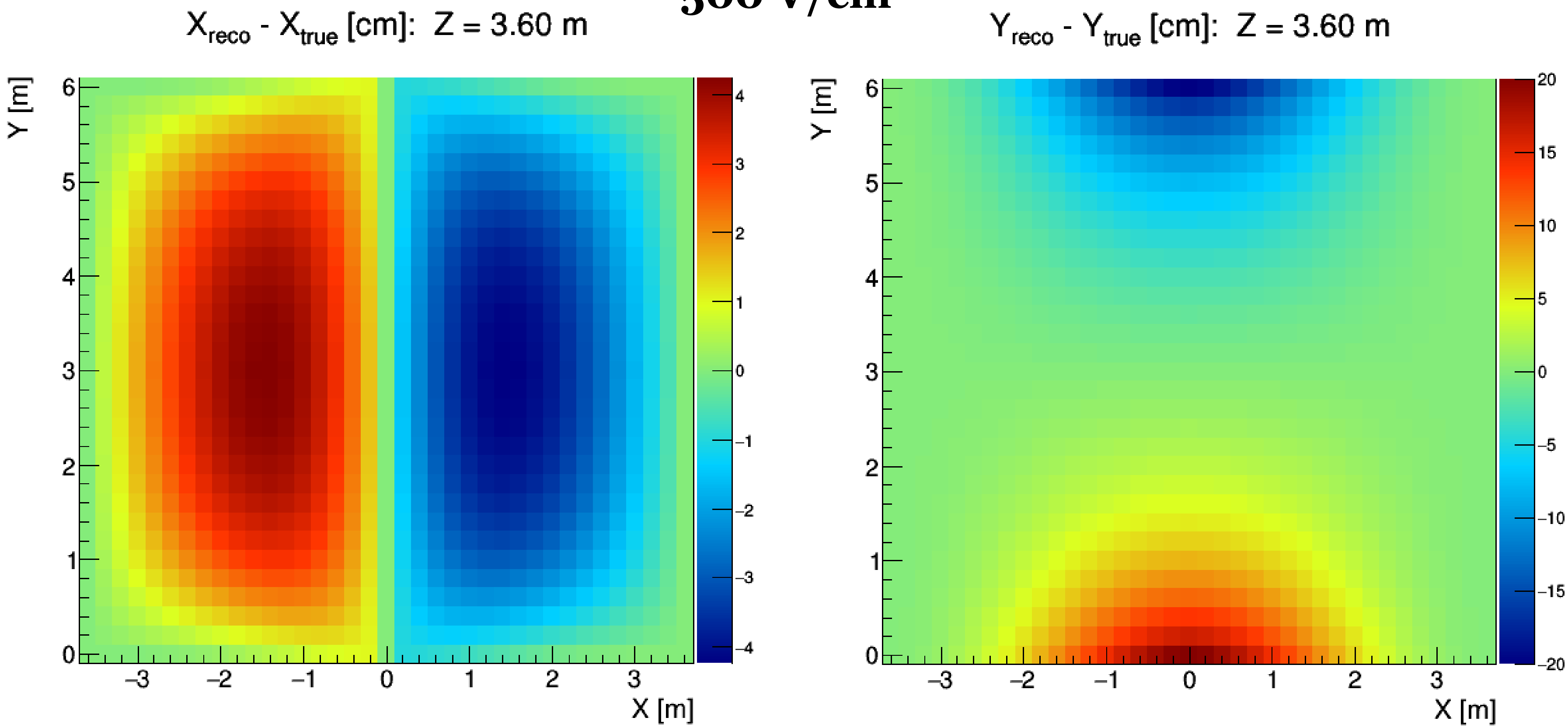




Central Z Slice (Max Effect)
Cathode In Middle (Two Drift Volumes)
Drift Coordinate: X
Beam Direction: +Z (Into Page)

ProtoDUNE-SP Spatial SCE Dist.

500 V/cm



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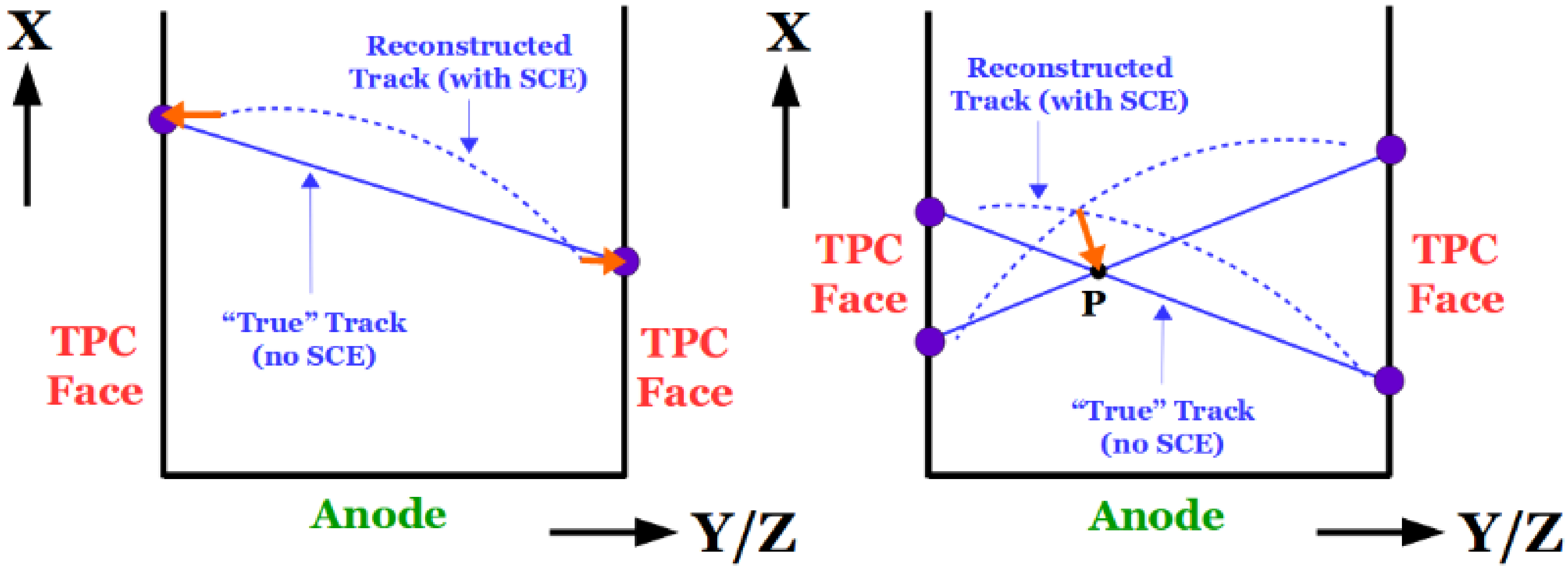
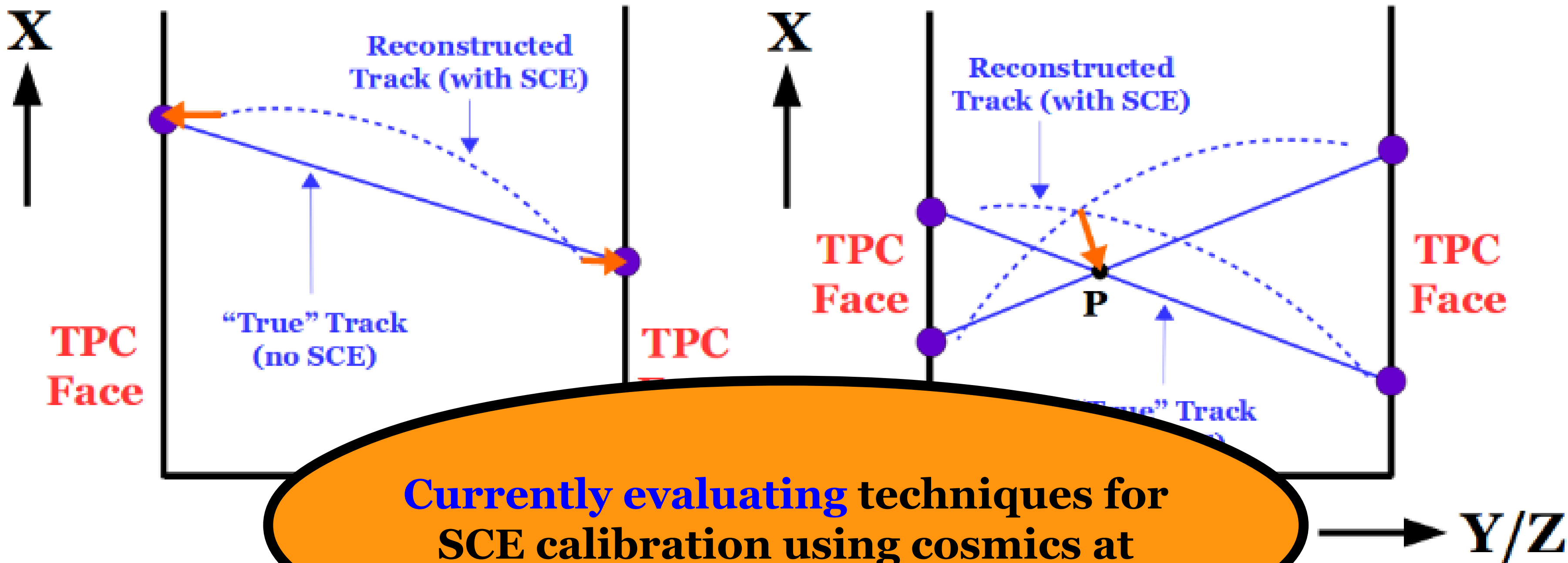
SCE Calibration w/ Tracks



- 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)

SCE Calibration w/ Tracks



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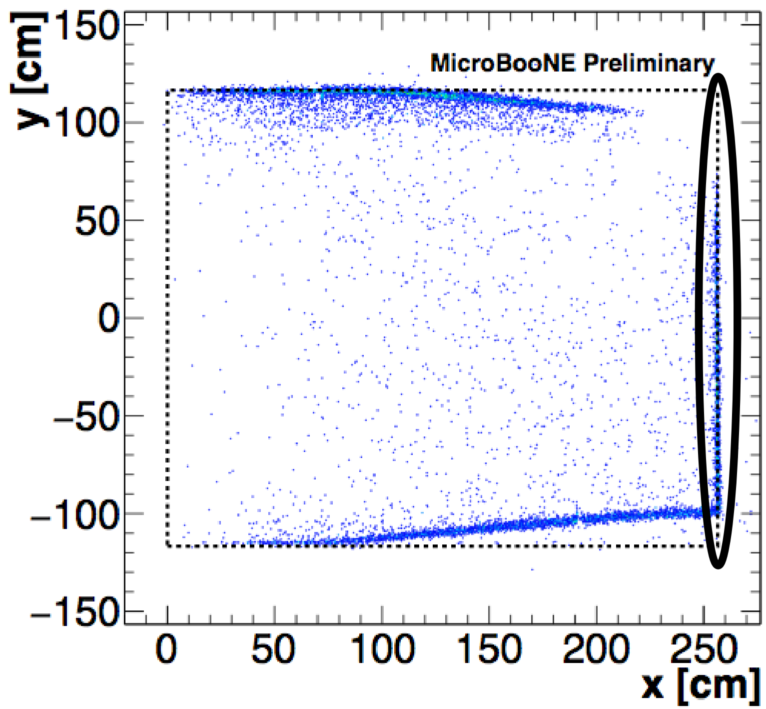
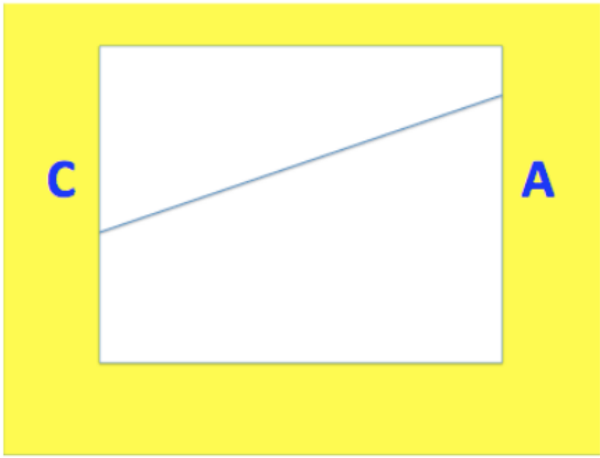
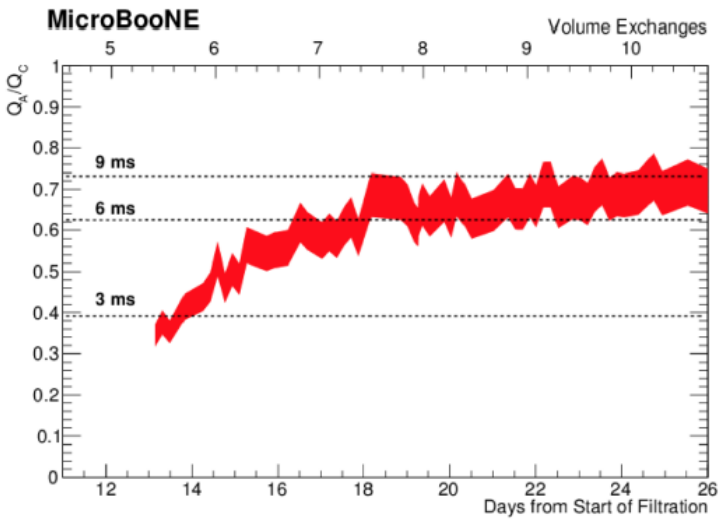
Cathode Flatness

- Can use cosmics that cross cathode to study flatness of cathode as well
- 3D track reconstruction gives position in directions transverse to drift – create flatness map of cathode
- Right: use of t_0-tagged cosmics (using MuCS) to look at SCE distortions, showing points at cathode
- Requiring cathode crossing brings rate down, but cathode flatness static
- Requiers knowledge of other E field distortions



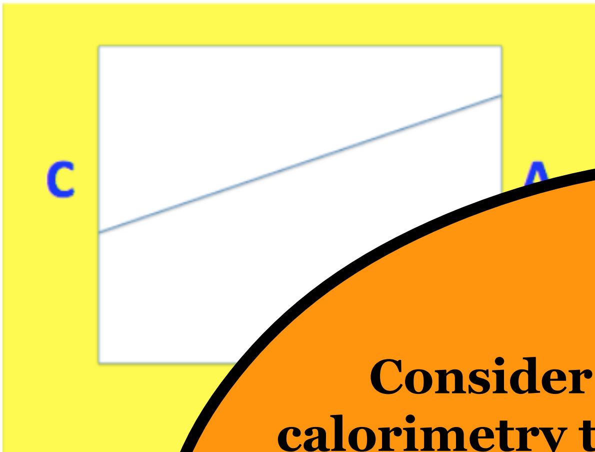
Electron Lifetime

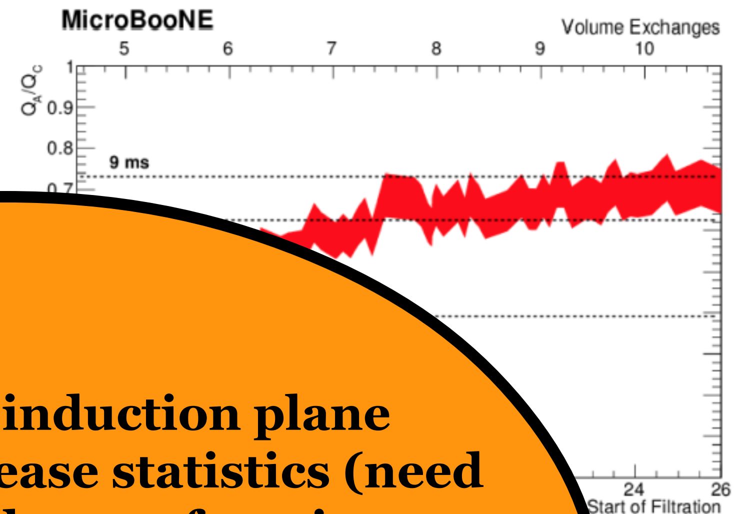




- At MicroBooNE, use cathode-anode crossers (left) to calibrate out electron lifetime (which is quite high at MicroBooNE, see right)
  - Can't rely on light in PMTs due to busy track environment
  - Also O(mm) precision instead of O(10 cm) from PMTs
- Different story at DUNE FD – unambiguous t0 from light
- Can we get away with poor spatial resolution?
  - Maybe if we know the level of smearing?

Electron Lifetime





Consider using induction plane calorimetry to increase statistics (need to test methodology as function of noise levels)

Do we need points in bulk, or will measurements at cathode and anode suffice? Much higher rate…

- At Micro … librate out electron … ee right)
  - Can … ironment
  - Also O(… m PMTs
- Different story a… us to from light
- Can we get away with poor spatial resolution?
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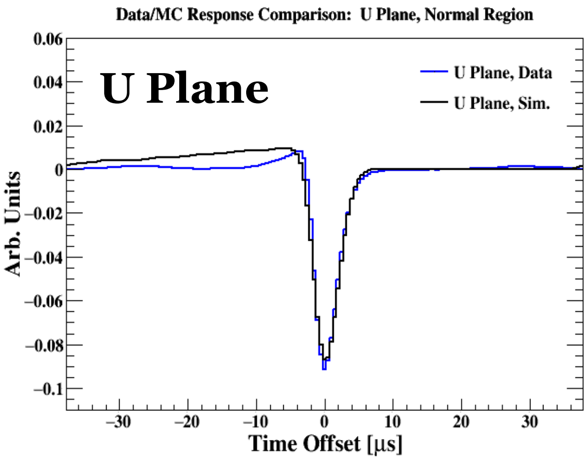
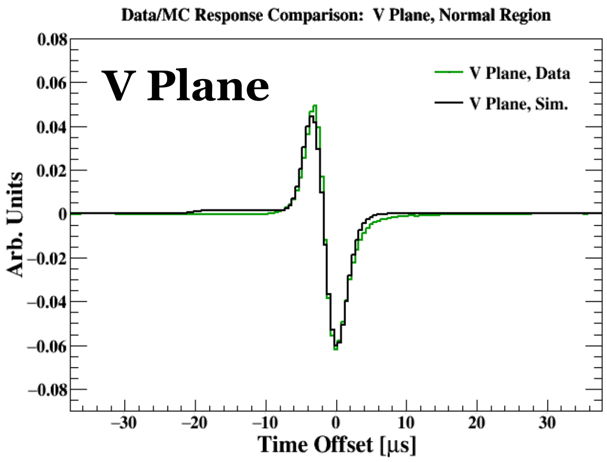
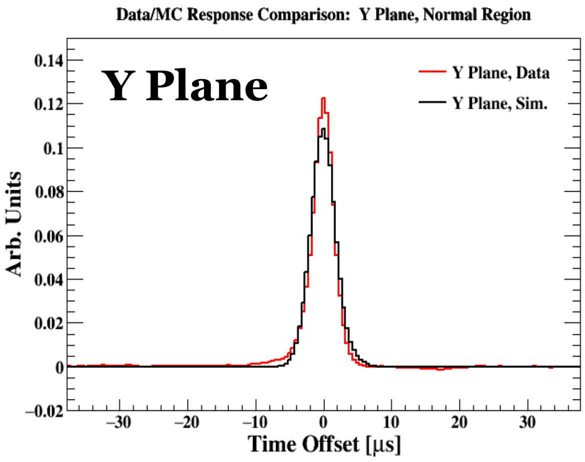
Elec./Wire Response Uniformity

- Measure electronics response using pulser signals
- Calculate wire field resp. w/ Garfield-2D, use in simulation
  - Use comparison to data-driven response (obtained by utilizing t_o-tagged cosmic tracks) to **tune simulated responses**
  - Can do at ProtoDUNE-SP, but wire-to-wire variations must be done in situ – can do this at DUNE FD with t_o-tagged cosmics
- A single cosmic passes many wires – helps with statistics





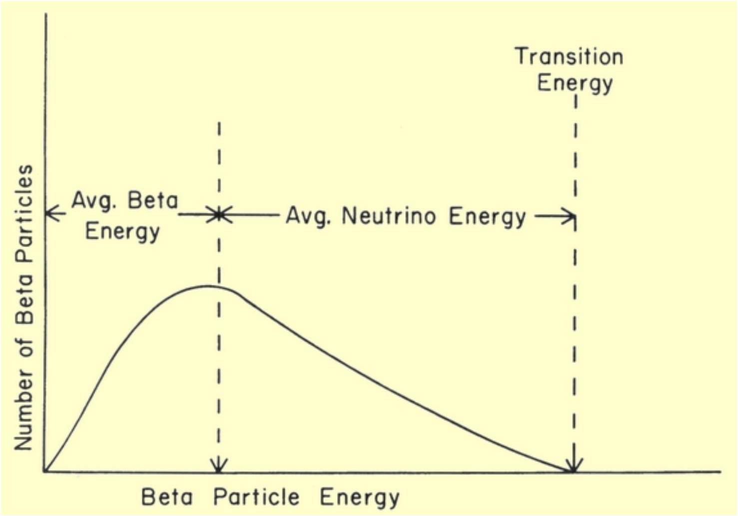


Absolute Energy Scale

- With E field distortions calibrated out and electron lifetime known, can address absolute energy scale
  - In principle, should know this from calibrated gain of electronics, known wire field response, and understanding of recombination
  - Good to test to use MIP-based method
- Utilize stopping muons and Michels for this, but only O(30) and O(20) per day, respectively, in entire 10 kt module
- If we calibrate out effects of non-uniformity (e.g. electronics/field response), use events across entire detector
  - Would take a long time for this, still… triggering with CRT would help a lot, if that were feasible…
- MIP $\longrightarrow$ showers? G4 very good at QED, should be okay
  - But need to be careful about recombination in shower bulk

Using Ar-39 for Calibration?

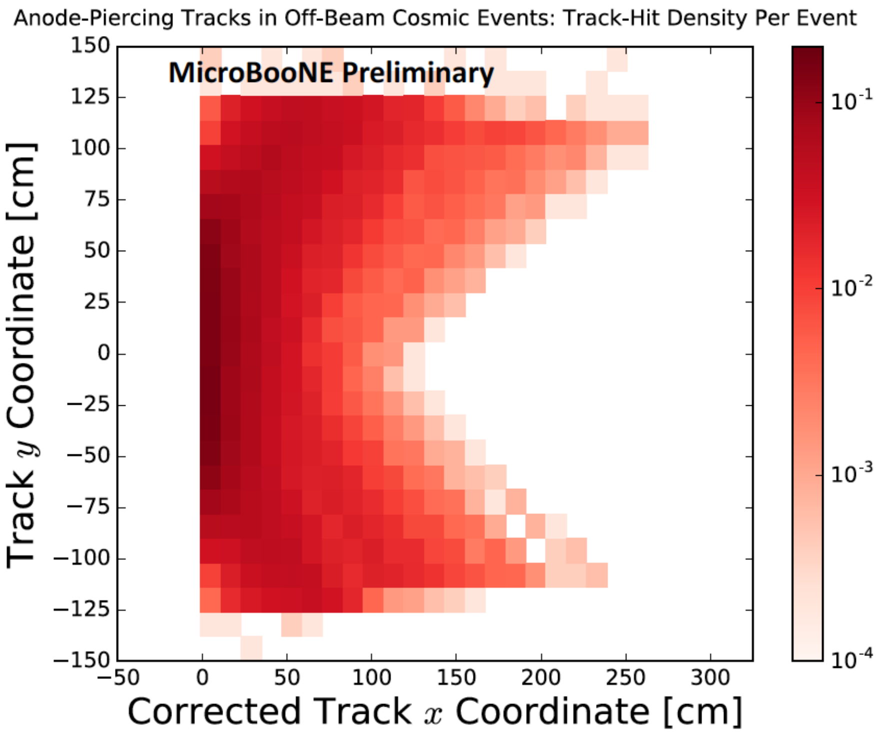
- Warning: off-topic
- Haven't thoroughly investigated, but can we use Ar-39 for calibration?
  - No t_o tag, but know it is uniformly distributed in drift direction
  - Known energy spectrum
  - Plenty to go around, covers entire detector
- Can construct different spectral hypotheses depending on electron lifetime → best fit spectrum gives you electron lifetime
- Just thinking out loud...

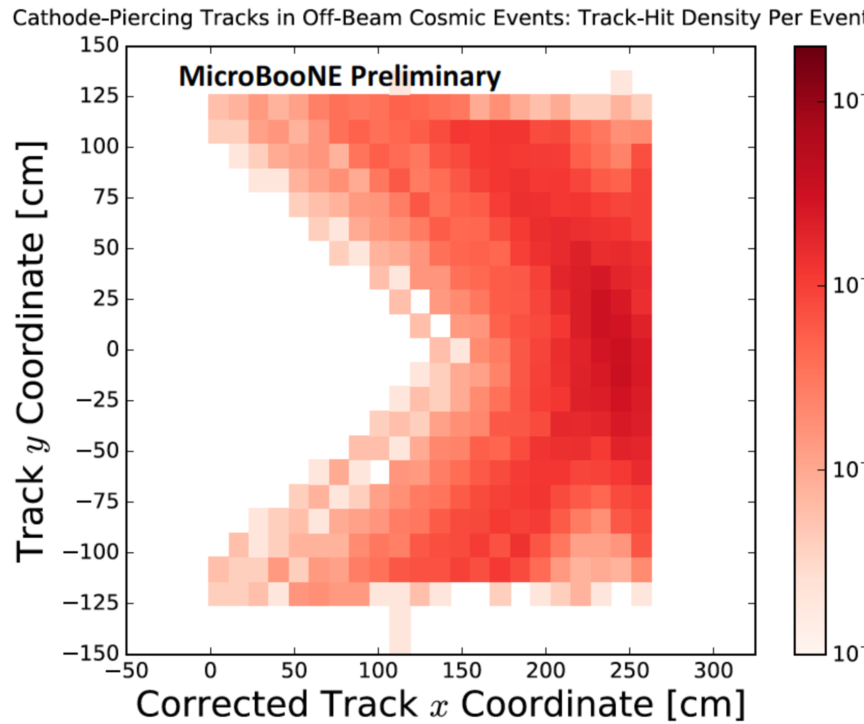


BACKUP SLIDES

t_o-tagged Track Coverage

Anode-Piercing Tracks / **Cathode-Piercing Tracks**

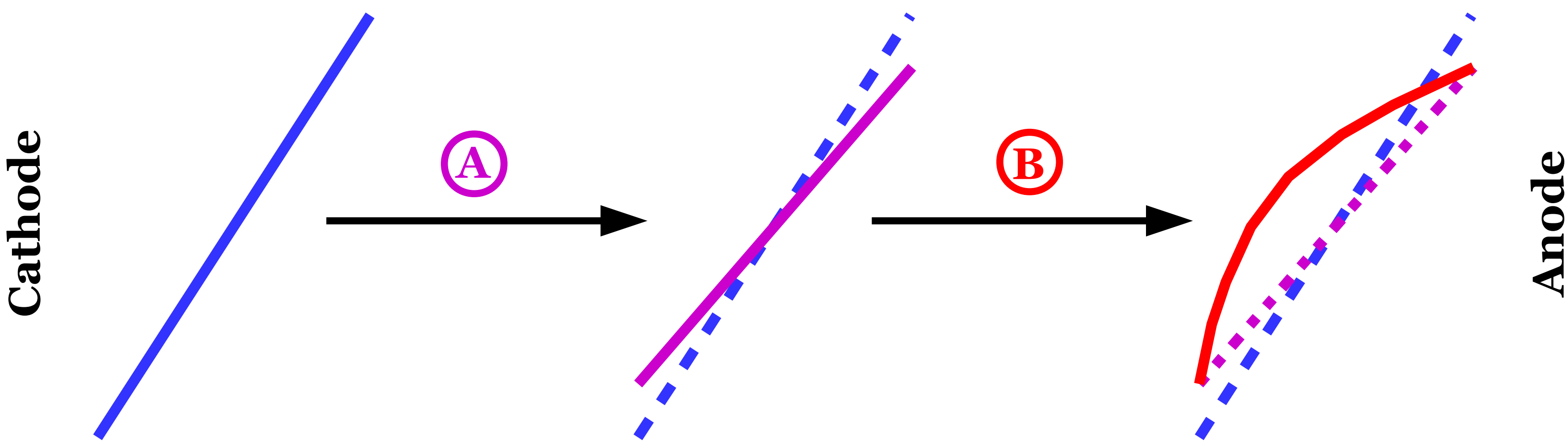




- Obtain O(1) t_o-tagged track per event, ~98% purity
  - Tracks crossing Y faces shown (sample also exists for Z faces)
- Gap in center of TPC – CRT will significantly add coverage

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



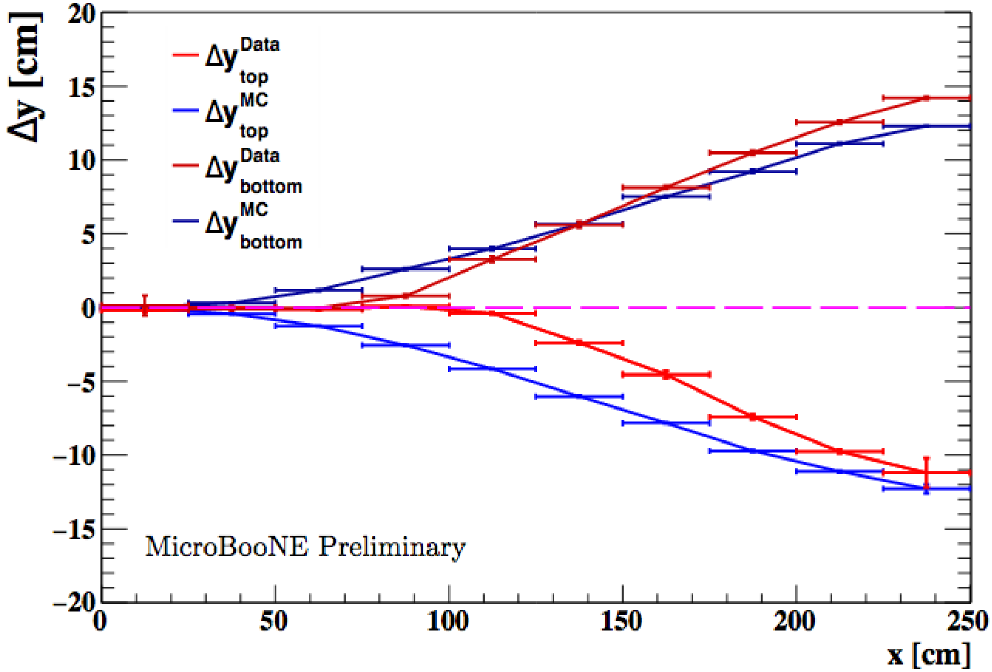
SpaCE: Space Charge Estimator

- 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
- Can simulate arbitrary ion charge density profile if desired
  - Linear space charge density approximation for now
- Output: E field and spatial distortion maps (vs. {x,y,z})

SCE Simulation

- Can use SpaCE to produce displacement maps
  - **Forward transportation**: e.g. $\{x, y, z\}_{\mathbf{true}} \rightarrow \{x, y, z\}_{\mathbf{reco}}$
    - Use to simulate effect in MC
    - Uncertainties describe accuracy of simulation
  - **Backward transportation**: e.g. $\{x, y, z\}_{\mathbf{reco}} \rightarrow \{x, y, z\}_{\mathbf{true}}$
    - 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
- Module in LArSoft ready to utilize maps (E field, spatial)

µBooNE SCE Data/MC Comp.



- Compare data to SCE simulation at top/bottom of TPC
  - See **MicroBooNE space charge effect public note**
  - Good agreement, small shape deviations (liquid argon flow?)
- Calibrate out of data with laser/cosmic tracks, vary residual differences as systematic in physics analyses