TPC Distortion Calibration Software

Ross Corliss
(on behalf of the entire subcommittee*)

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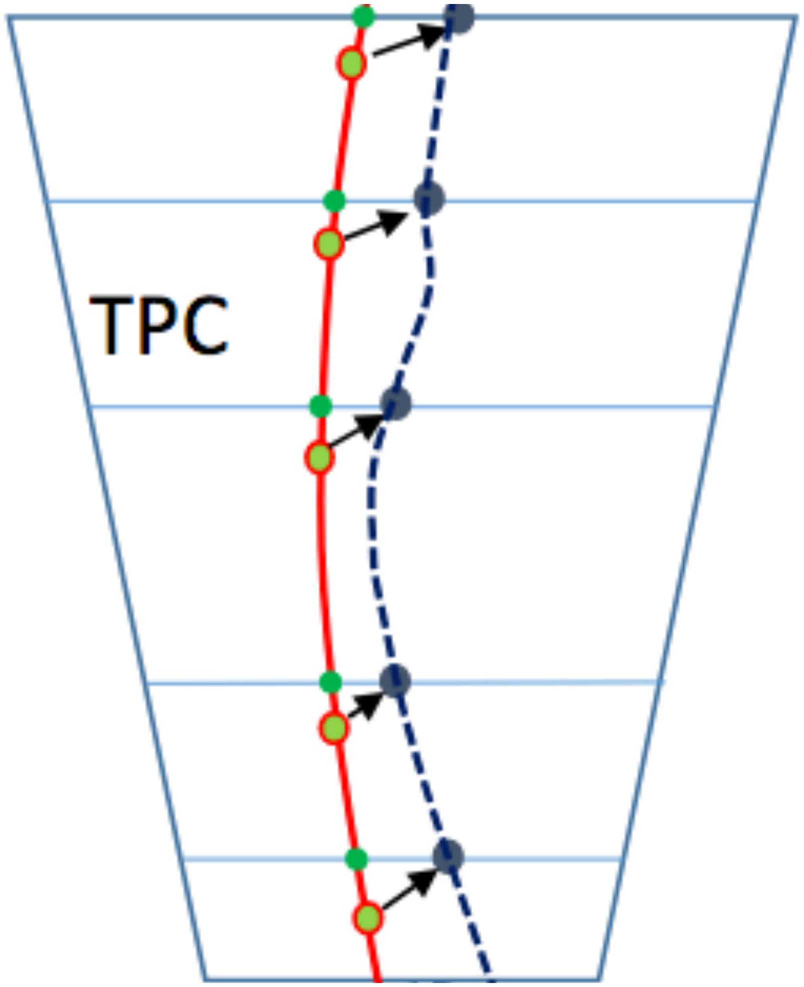
Joe Osborn, Chris Pinkenburg, Christof Roland, Takao Sakaguchi

TPC Distortions

- Due to electric and magnetic fields, electrons do not drift purely in z*
- Deviations from uniform drift must be corrected in order to correctly reconstruct tracks



courtesy ALICE

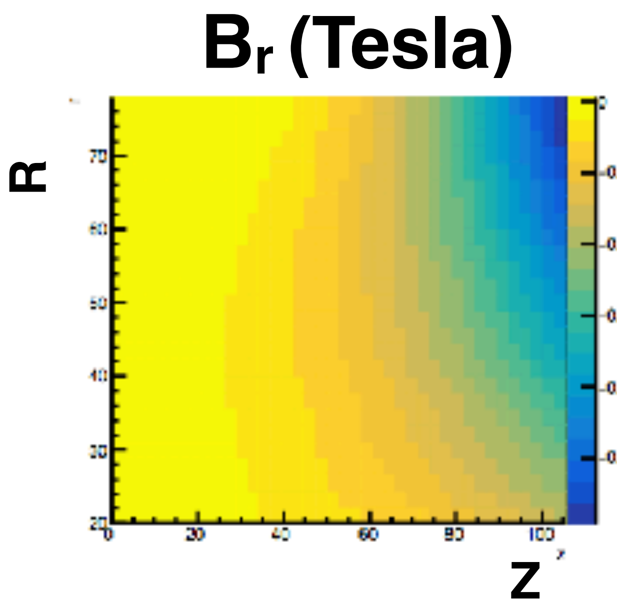
*and their drift speed in z can vary, too

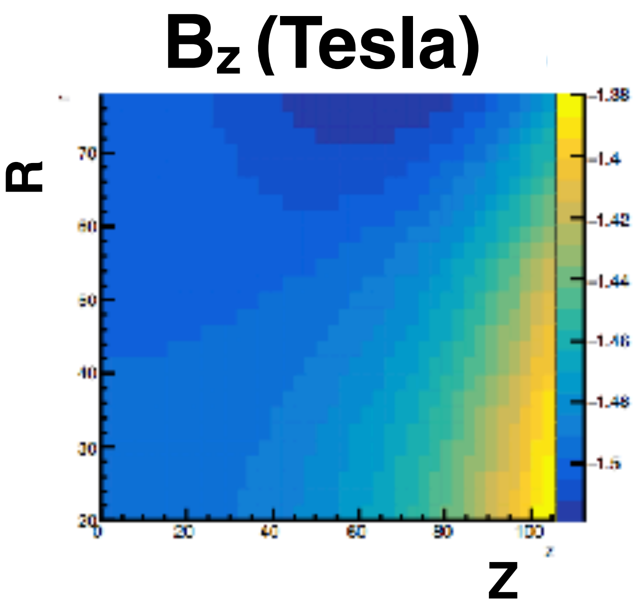
Structure of TPC Distortions

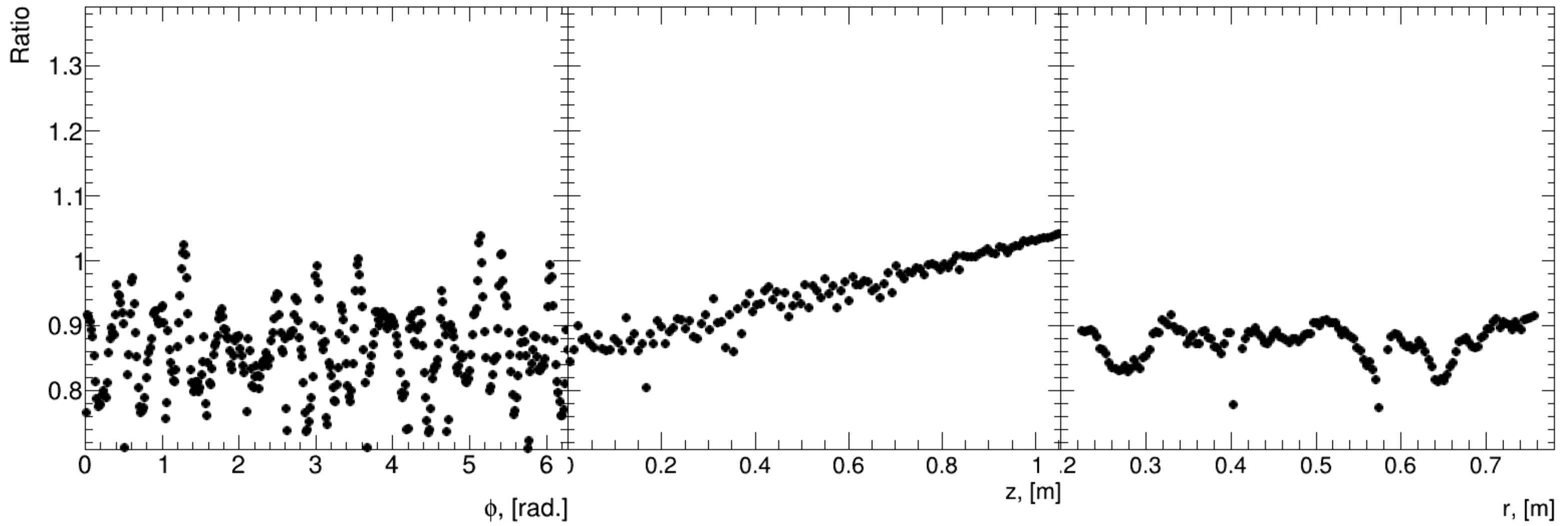
- Static: fieldmap and alignment, especially field at large z

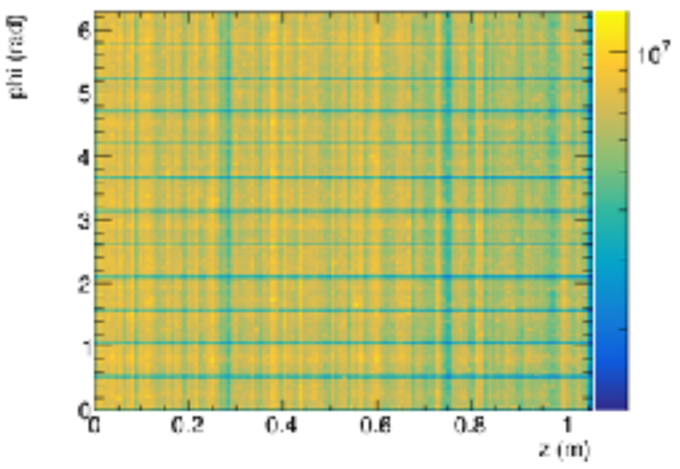
- Quasistatic: gas and variation of average spacecharge

- Fluctuations: IBF pancakes differ event-to-event, drift for ~78ms


B_r (Tesla)


B_z (Tesla)





Generating Distortions

geant hits from minbias sample translated to electrons

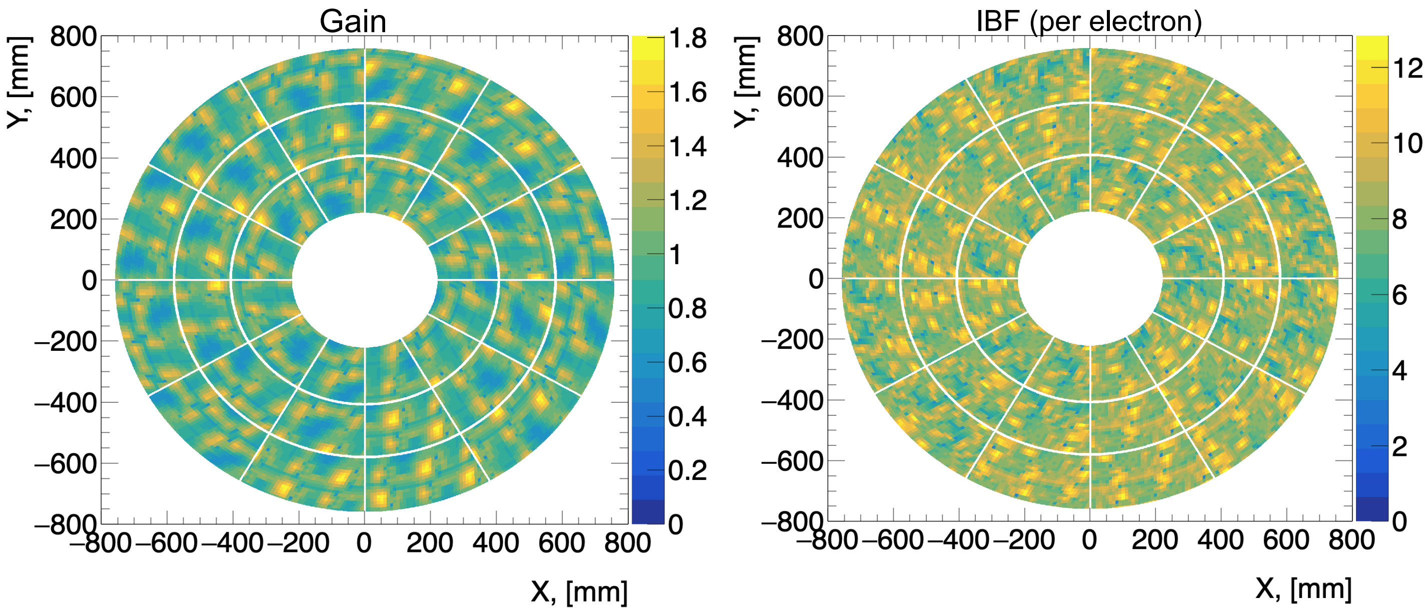
IBF and primaries used to fill TPC for long time series

Calculate field due to SC using Rossegger

Fill distortion map by drifting test electrons through net E and B field

Real or sim maps of E and B fields in TPC

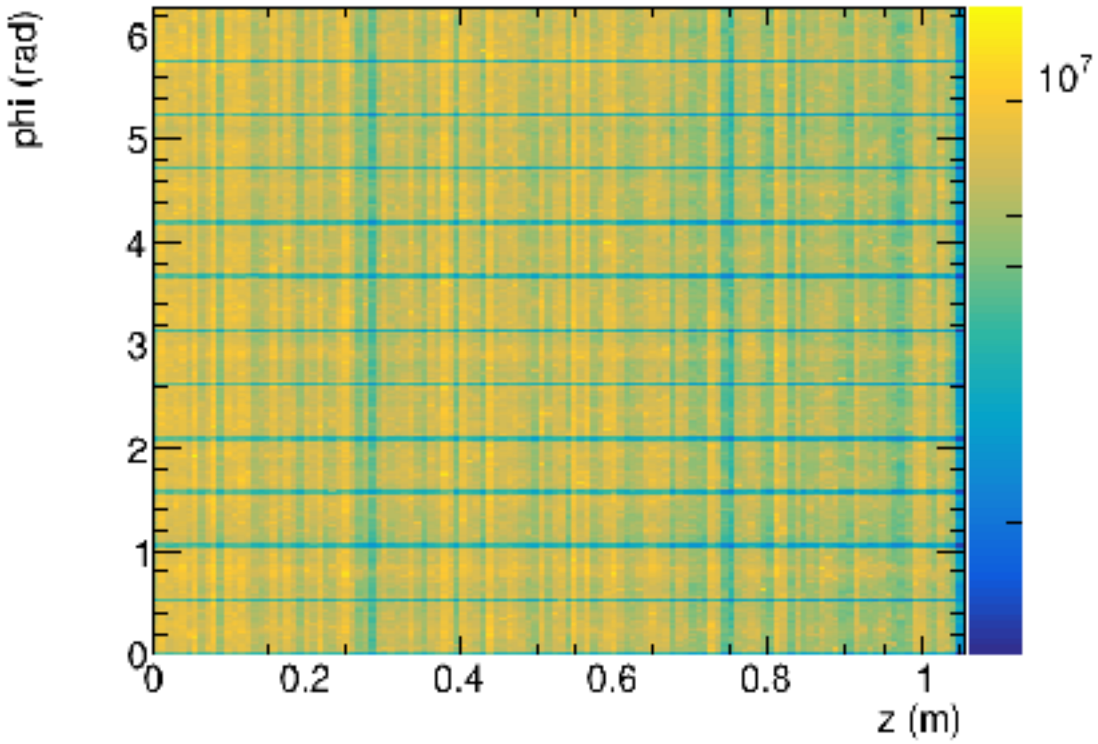
TTree of TH3F maps for each beam xing



IBF (per electron)=Gain*IBF*2000*0.44%

- MC gain/IBF maps sampled from ALICE
- Time-ordered HIJING events sync'd to reconstruction
- average and per-event TPC snapshots with IBF + primaries

(Evgeny Shulga (WIS))



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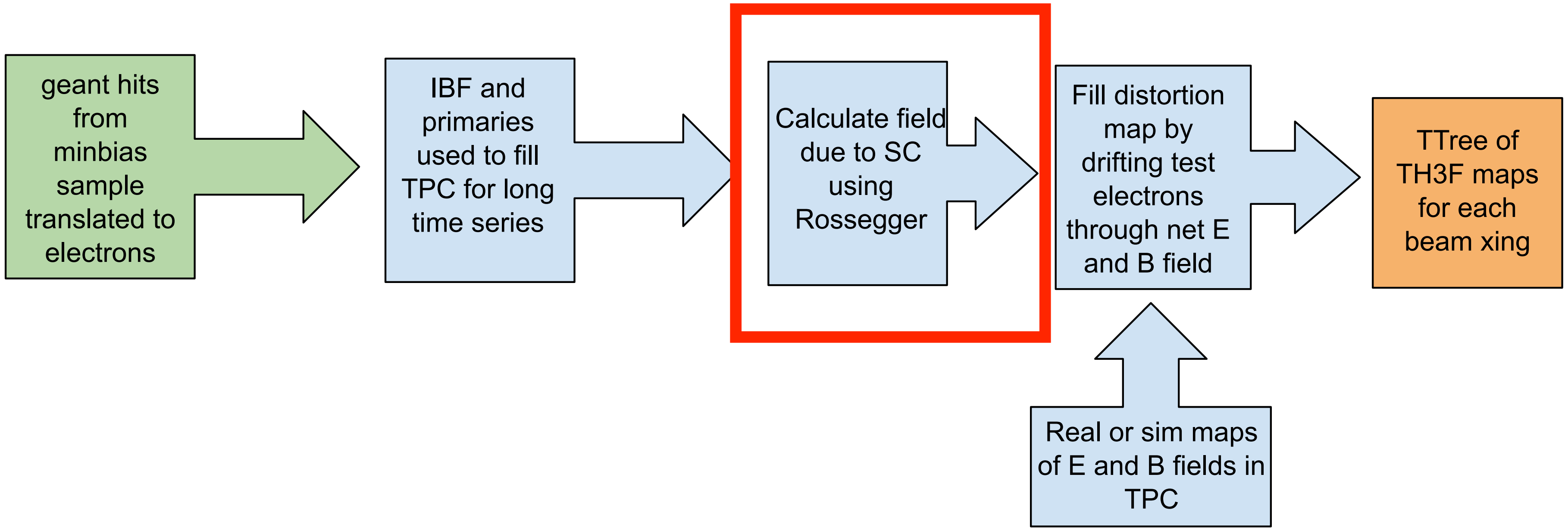

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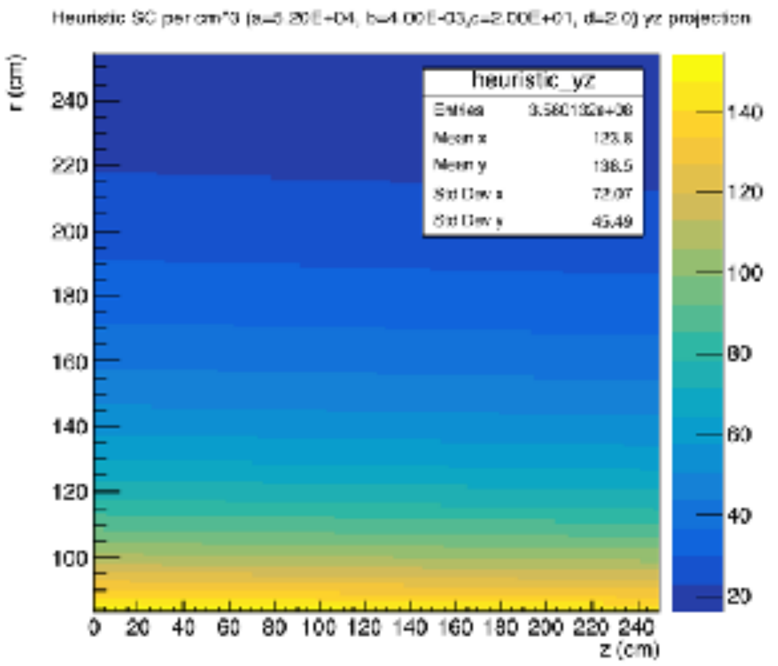
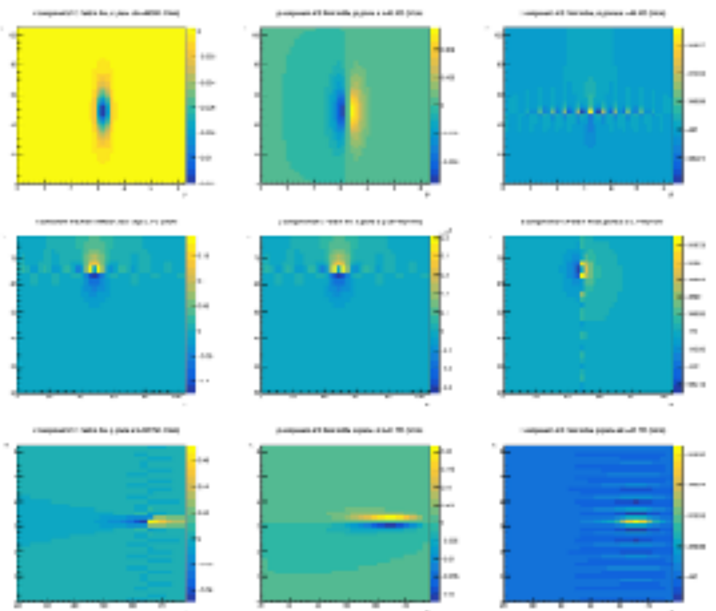
Charge Density
(3D, Scalar)



x

Greens functions
(6D, Vector)



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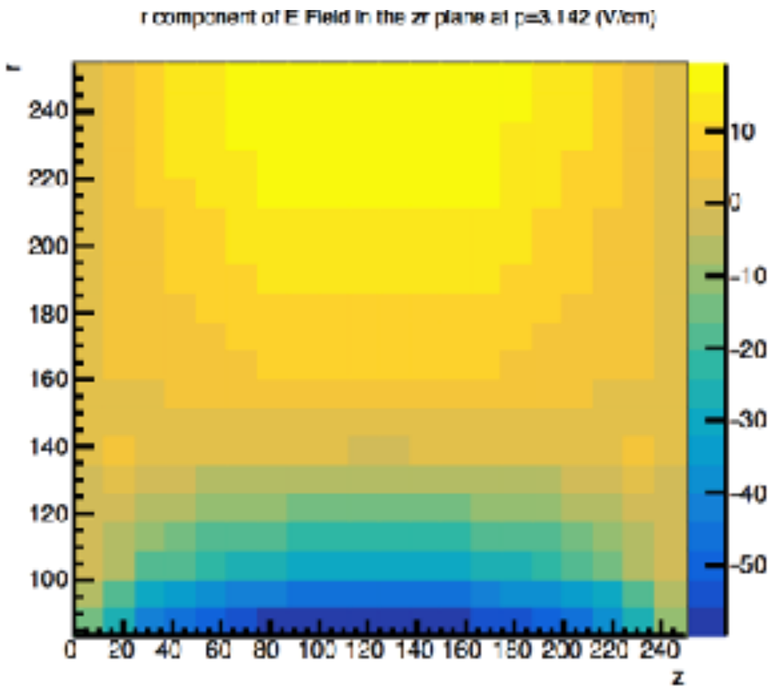
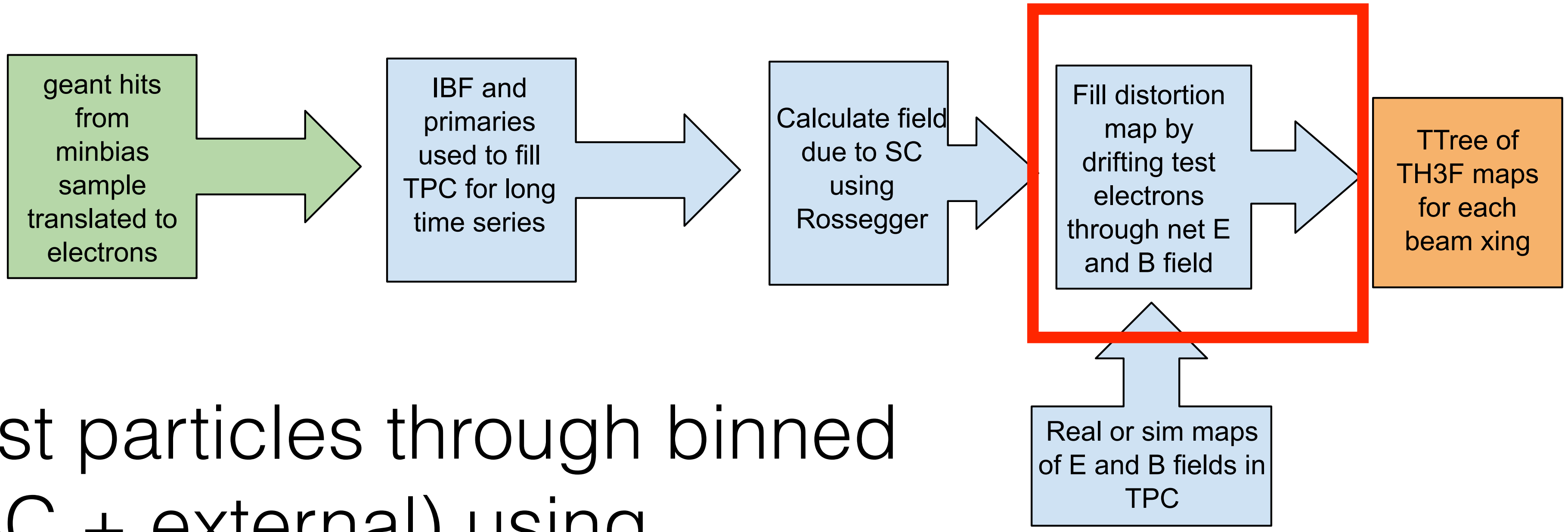
3D Electric Field Map
(3D, Vector)



Generating Distortions



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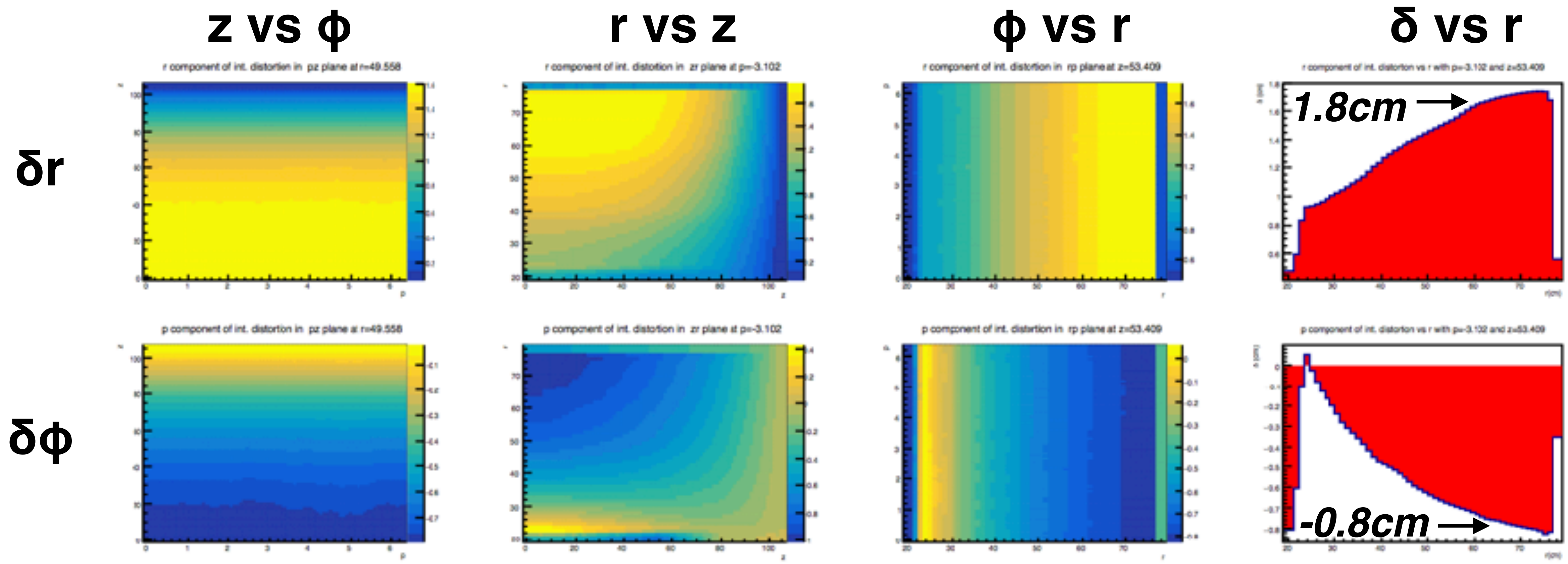
Real or sim maps of E and B fields in TPC

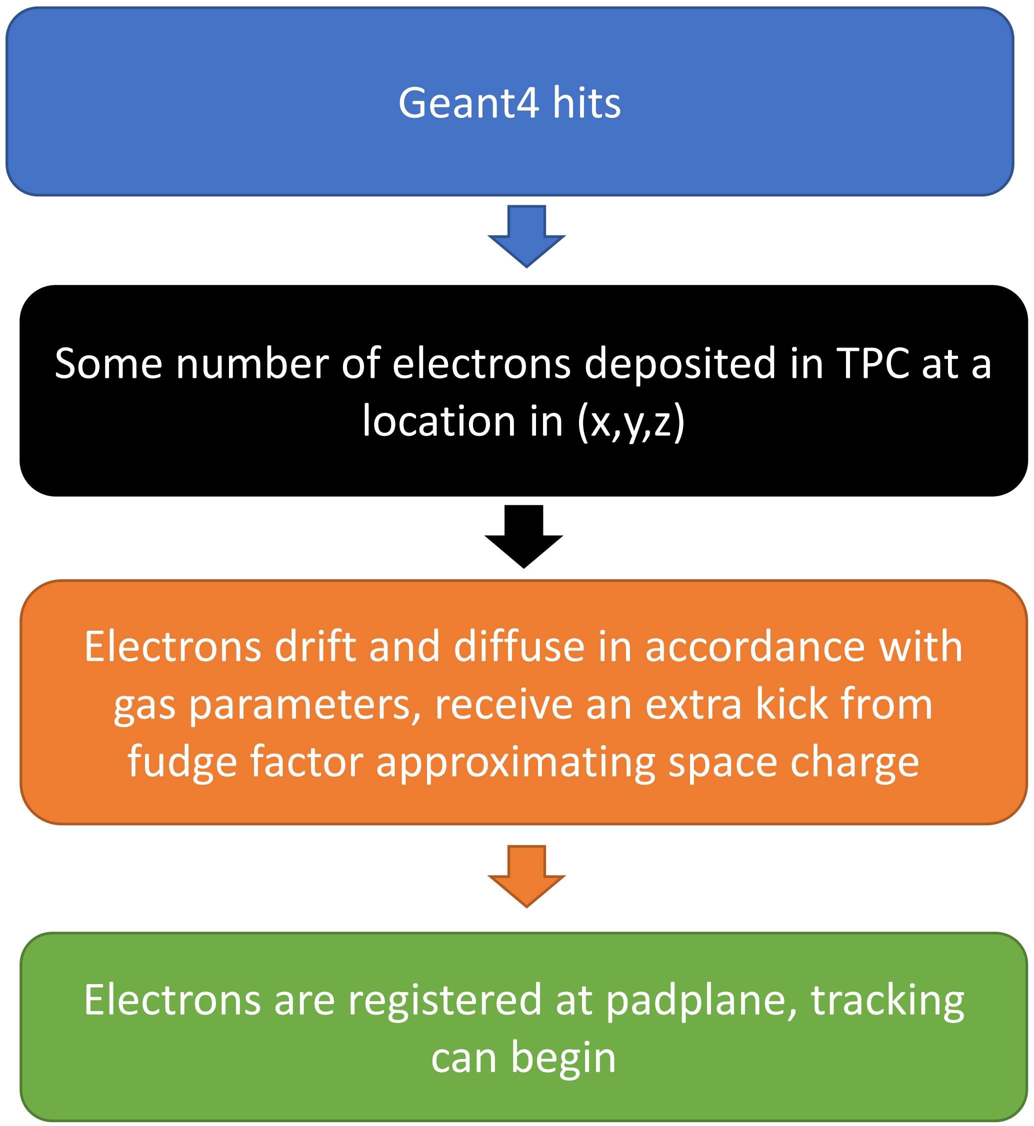
- Swim test particles through binned fields (SC + external) using Langevin Eqn, store results in TH3F:



Applying Distortions in Fun4All

- PHG4TpcElectronDrift reads external maps, applies shifts to each deposited electron (Henry Klest (SBU))

Previously in Simulation



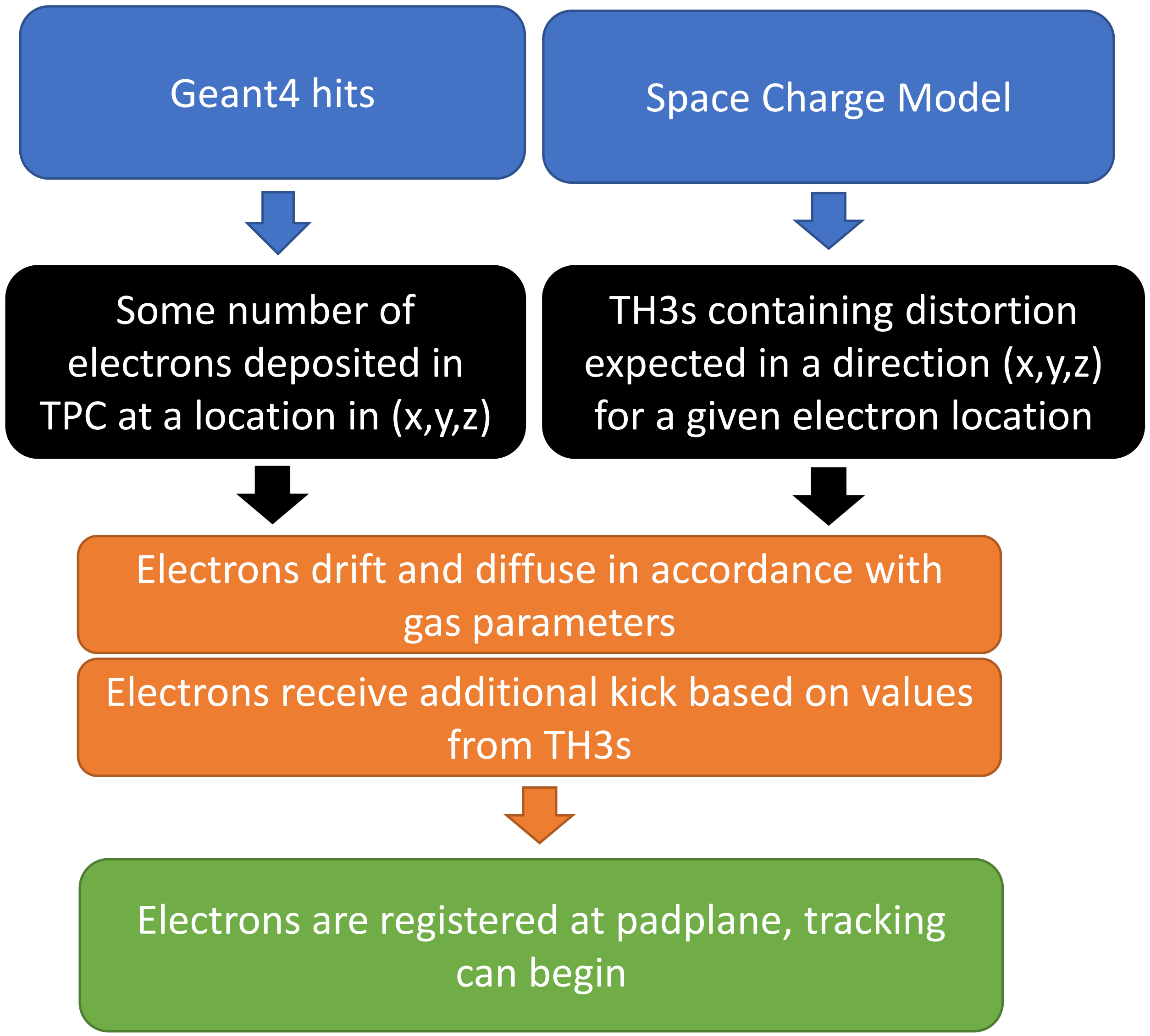
Geant4 hits

Some number of electrons deposited in TPC at a location in (x,y,z)

Electrons drift and diffuse in accordance with gas parameters, receive an extra kick from fudge factor approximating space charge

Electrons are registered at padplane, tracking can begin

Currently in Simulation



Geant4 hits

Space Charge Model

Some number of electrons deposited in TPC at a location in (x,y,z)

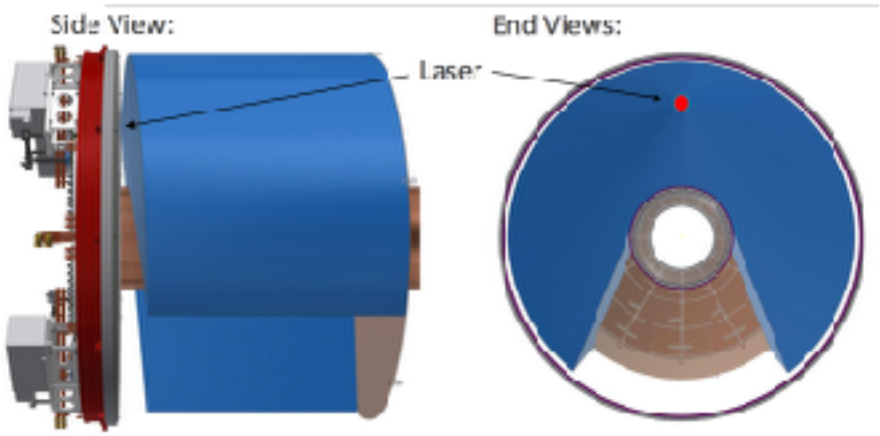
TH3s containing distortion expected in a direction (x,y,z) for a given electron location

Electrons drift and diffuse in accordance with gas parameters

Electrons receive additional kick based on values from TH3s

Electrons are registered at padplane, tracking can begin

Monitoring Distortions Directly



The phi coverage of one laser for theta in [0°,85°]

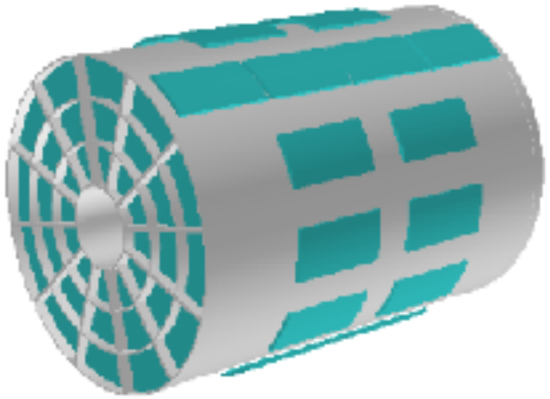
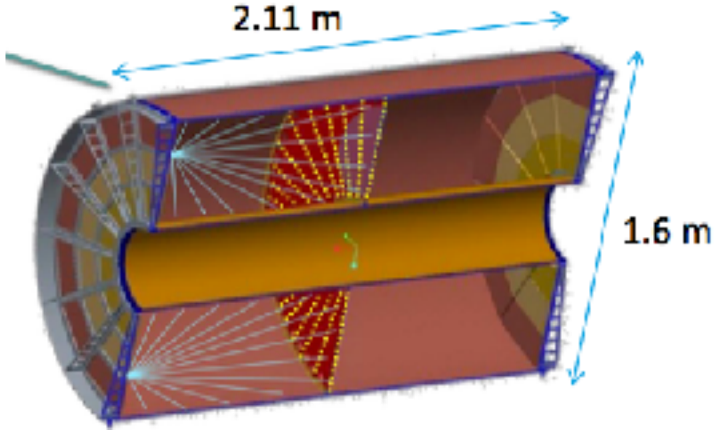
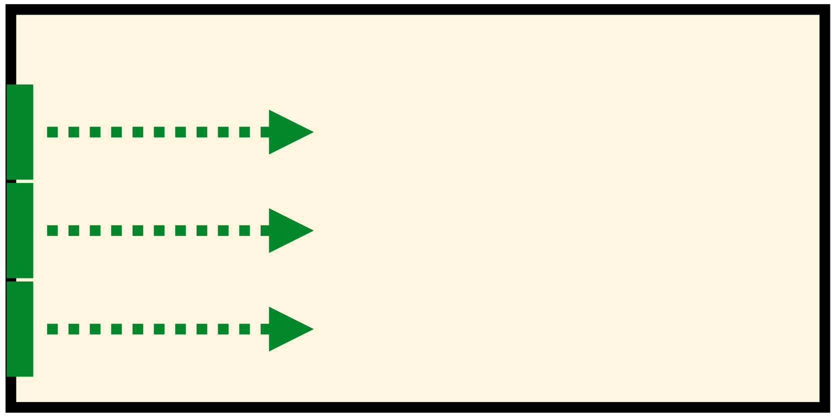


Fig. 2: Baseline configuration for 26 Outer Tracker modules located outside of the TPC



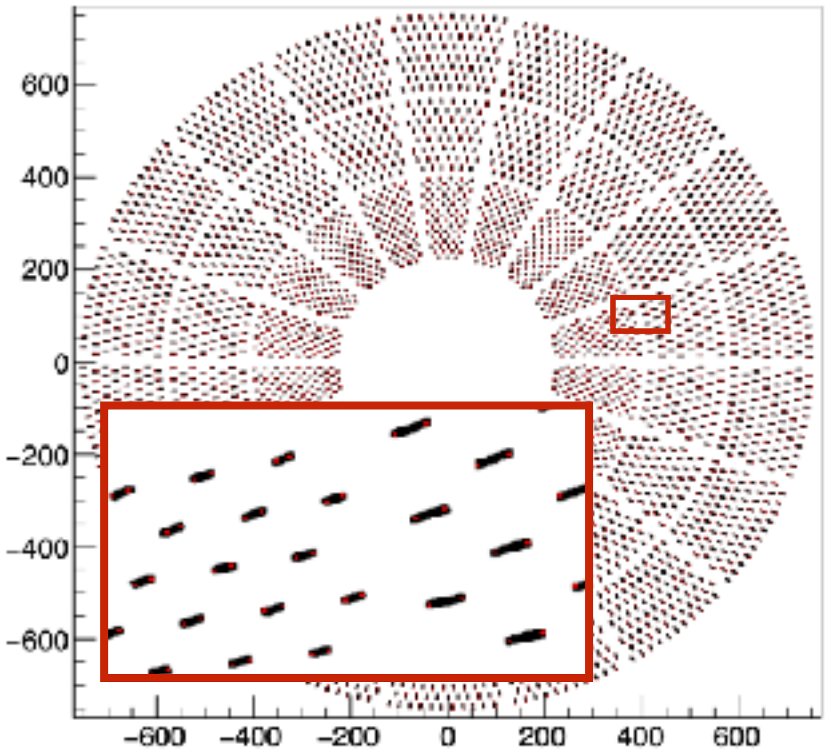
- Static Distortions mapped (full 3D) by **line laser**. B field also mapped directly.
- Average distortions monitored (full 3D) by **tracking with TPOT** after statics removed.
- Distortion fluctuations monitored (2D) by **CM pattern/diffuse laser** after averages removed.

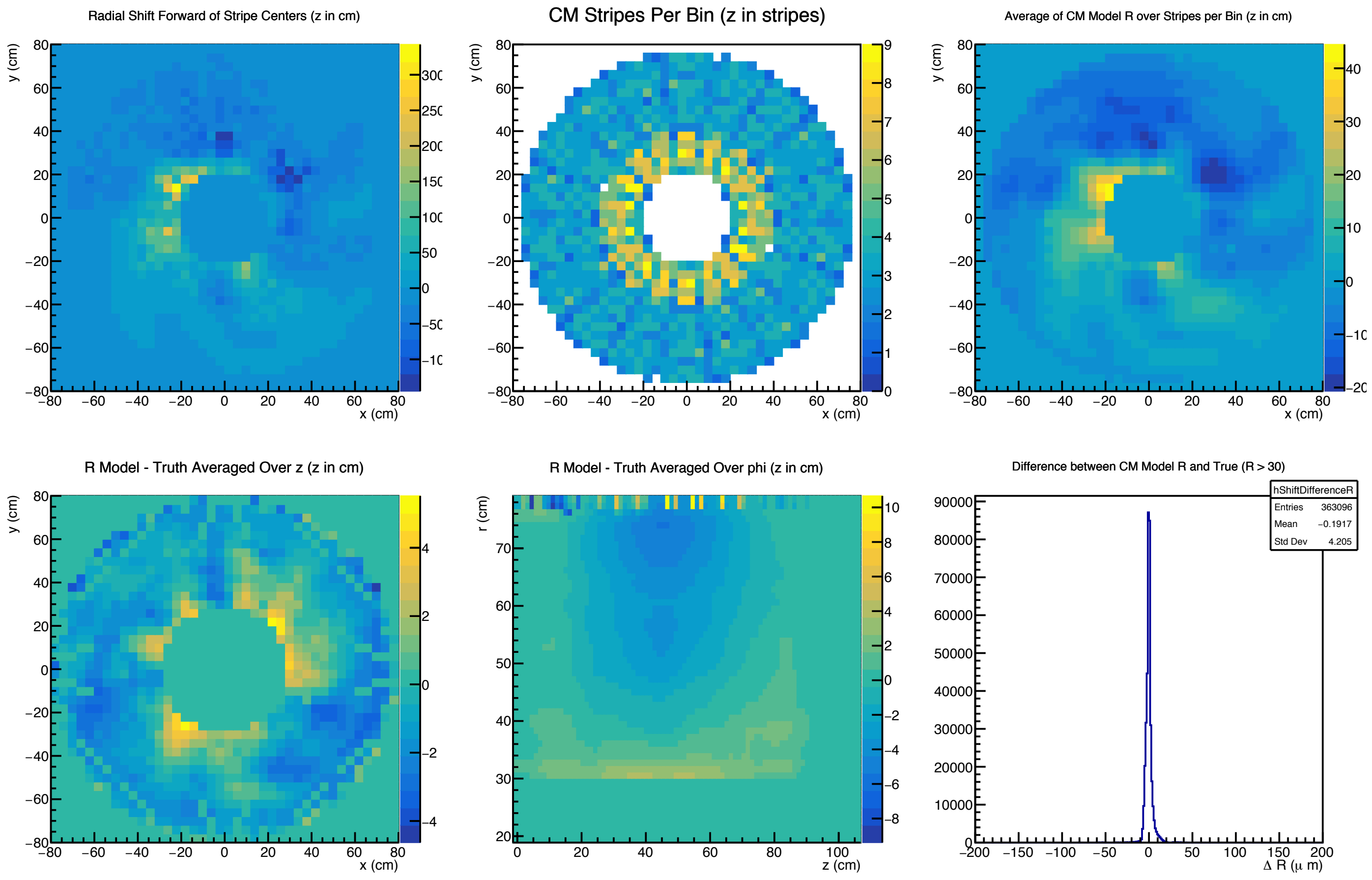


- ***Digital current*** *provides orthogonal, but indirect, measure of SC distortion*

Monitoring with CM

- Al pads on CM release charge when strobed with diffuse laser (15kHz)
- Sampling distortion map at each pad location as proxy for pad reco
- With average distortion removed, z-linear model has residual width of ~few um for fluctuations (Sara Kurdi (SBU))

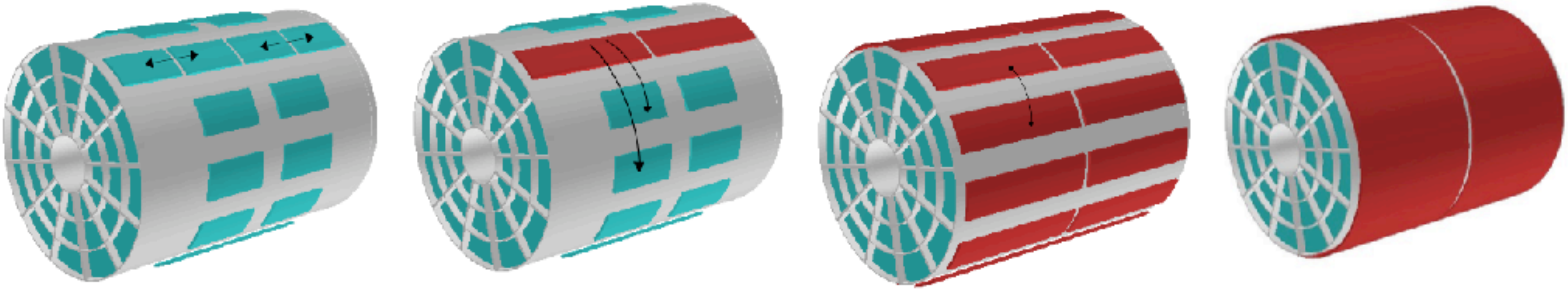




(will update with slide/plot from Sara)

Monitoring with Tracks

- TPOT allows measuring track residuals precisely
- Matrix inversion procedure extracts (Hugo Pereira Da Costa (LANL))
- Procedure demonstrated in stand-alone code and in Fun4All:



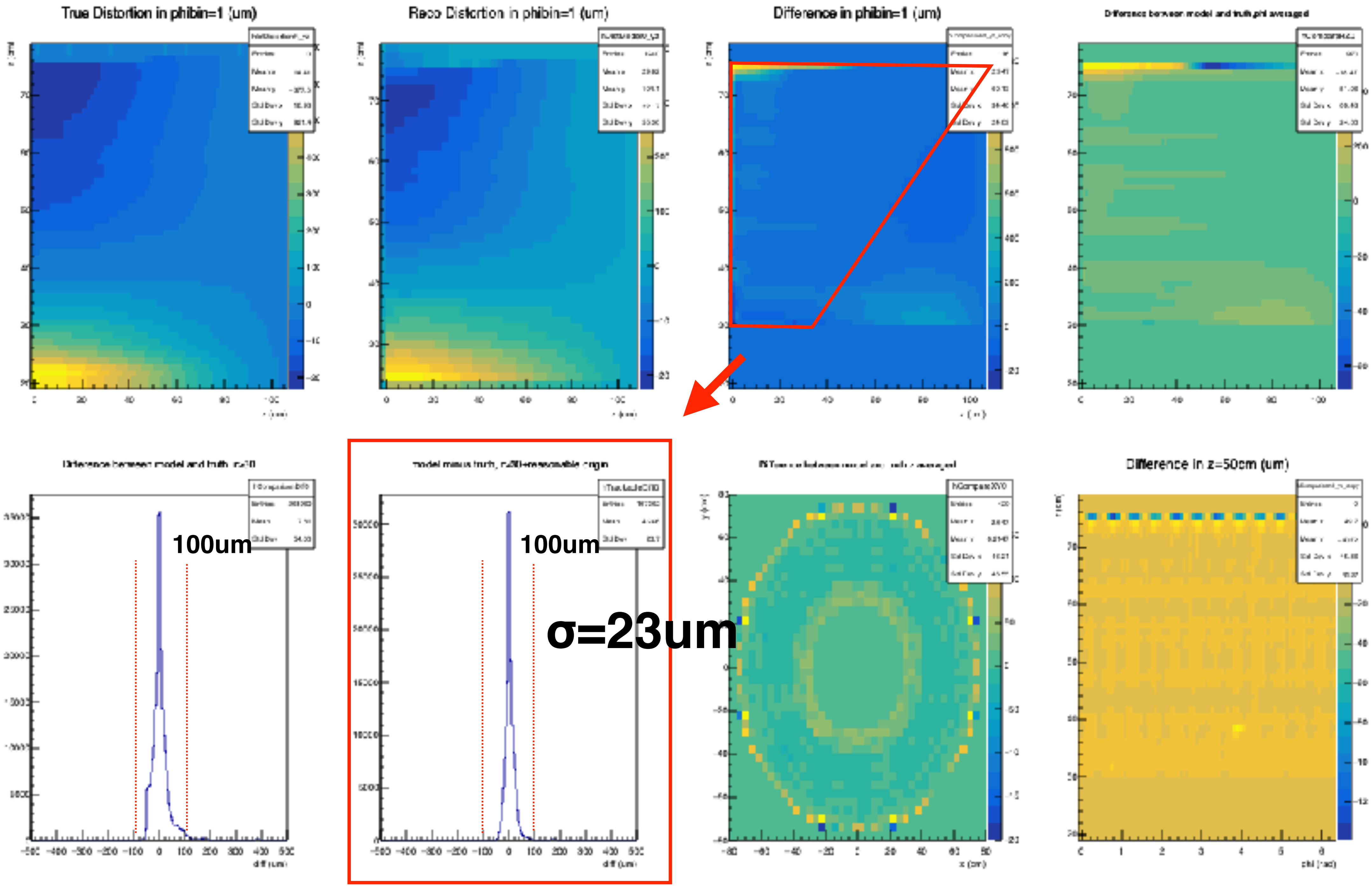
1. small z interpolation between MM modules

2. copy z dependence in fully equipped sector to other sectors, normalized by local measurement

3. interpolate between sectors to cover full acceptance, **normalized by time-averaged CM measurement**

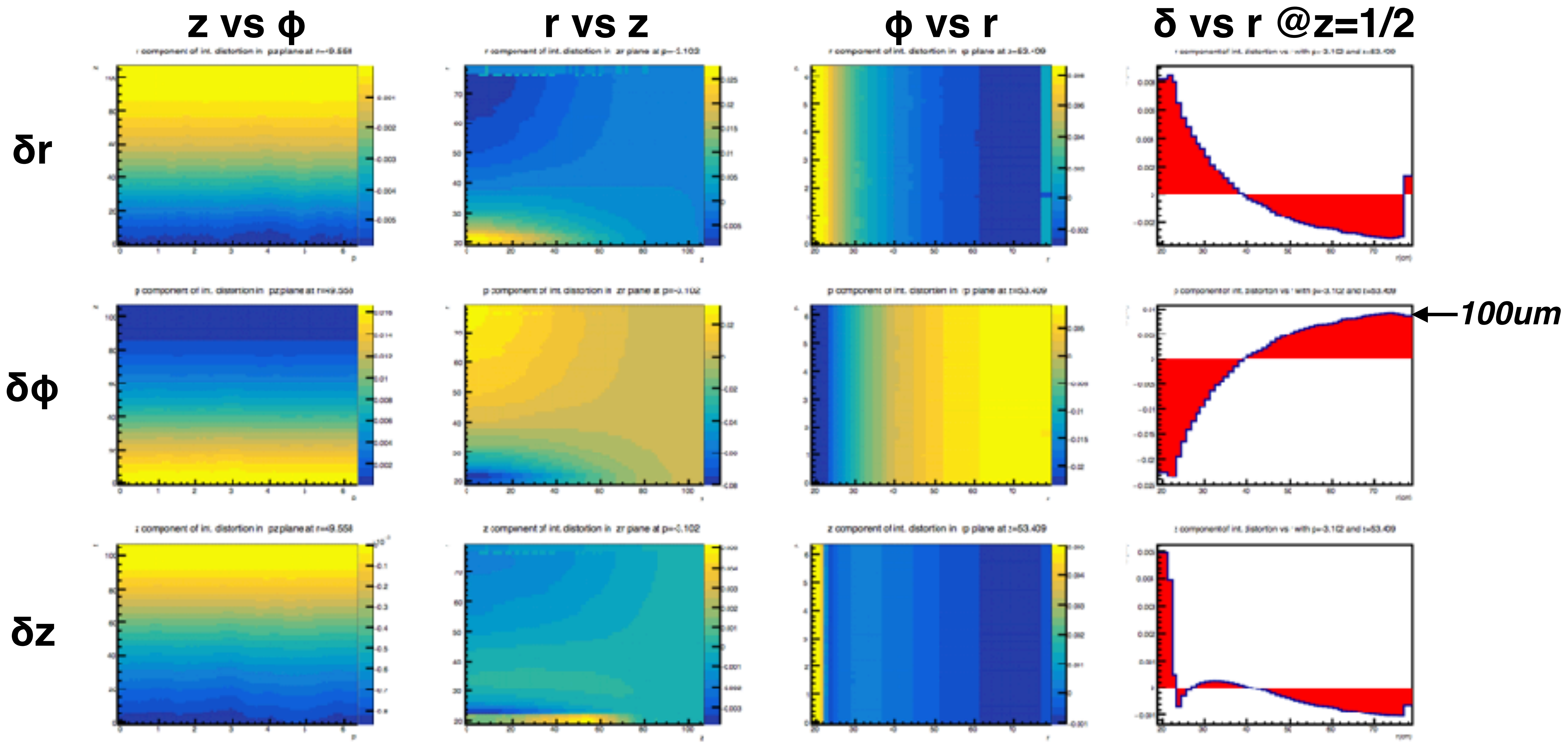
Monitoring with Tracks

- Sampling distortion map as proxy for track residual procedure, using realistic low-res binning for reco:



Monitoring with Digital Current

- Independent measure of distortions via Rossegger model of TPC
- Studying how to properly mock-up current measurement limitations/ model discrepancies (Evgeny Shulga (WIS))
- Without primaries, discrepancies are large, but better assumptions can be made:



Status and Outlook

- Distortion code has been validated against earlier ALICE and sPHENIX models
- Realistic distortions integrated into Fun4All simulation (still improving)
- Distortion map reconstruction demonstrated for diffuse/CM and TPOT tracking

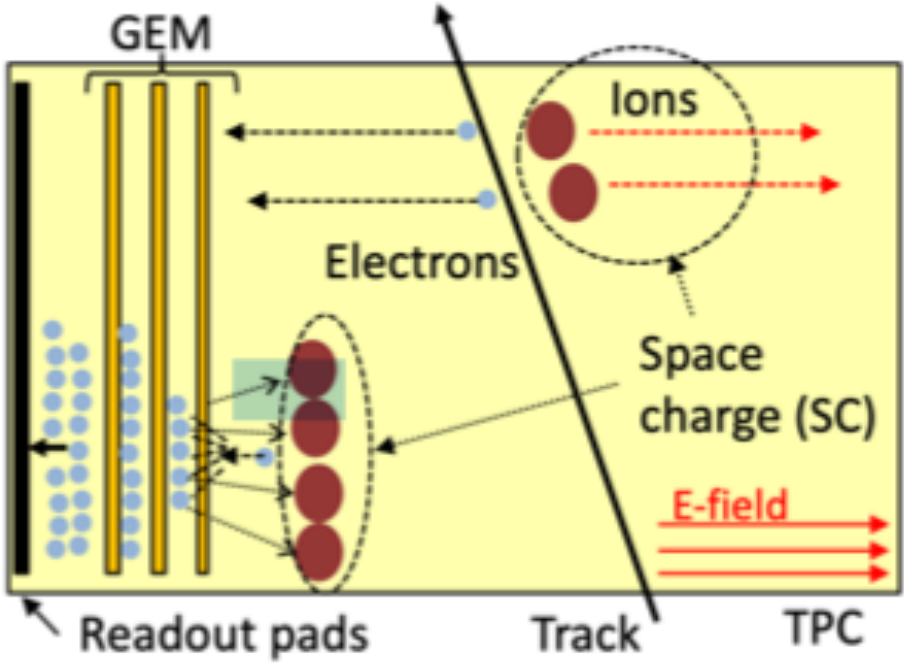
- Working on:
  - Integration of CM into Fun4All
  - Refining+combining CM+tracking maps
  - Digital current reconstruction
- Upcoming tasks:
  - Line laser map reconstruction
  - Reco map integration into Fun4All

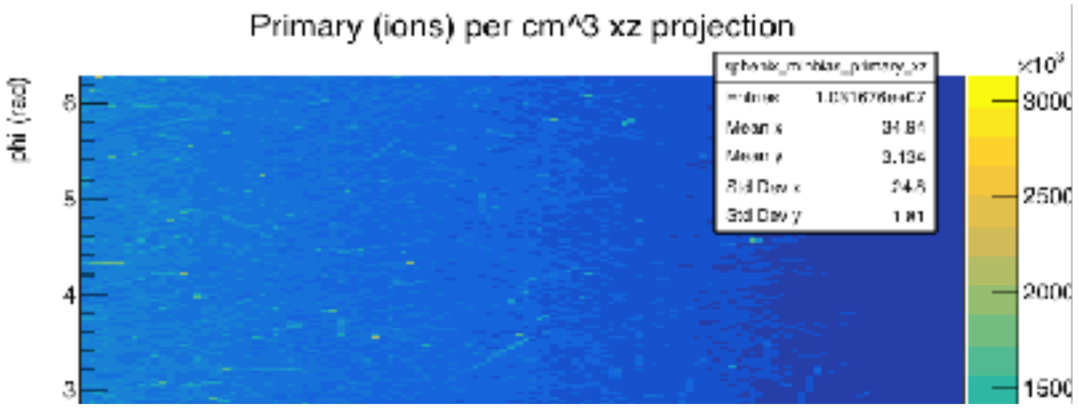
- Results so far very promising for <100um track residuals

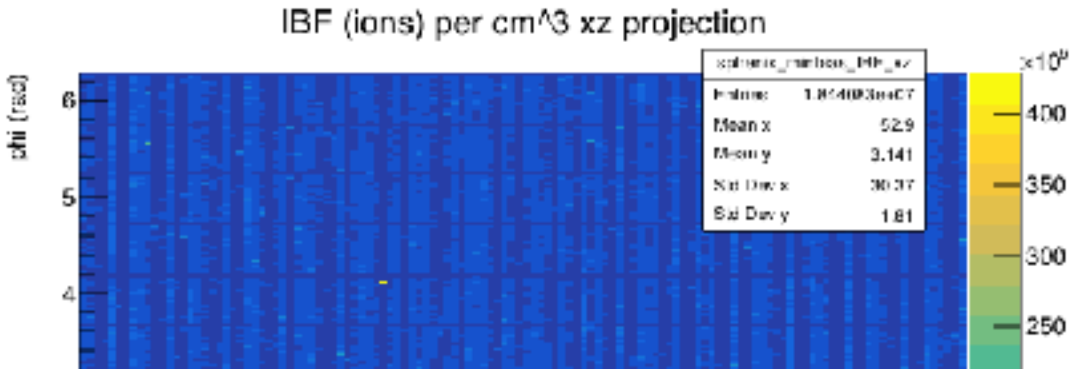
Structure of Spacecharge

$$\rho(r,z) = A\frac{1}{r^d}\left(1-\frac{z}{z_0}+c\right)$$

- Heuristic:
  A=Luminosity, multiplicity, TPC parameters
  z_0=drift length
  c=IBF ions per primary
  d=radial dependence of track density
- Ions drift ~1.3cm/ms (78ms to cross TPC), 5000x slower than electrons
- Pancakes and volume:
  Primary ions are created from charged particles traversing TPC.
  Ion Backflow (IBF) pancakes are created from electrons avalanching at readout.
- Average and fluctuations:
  Average SC governed by luminosity and fixed TPC parameters. Expect few-mm R distortions on average
  Local fluctuations from event-by-event statistics.

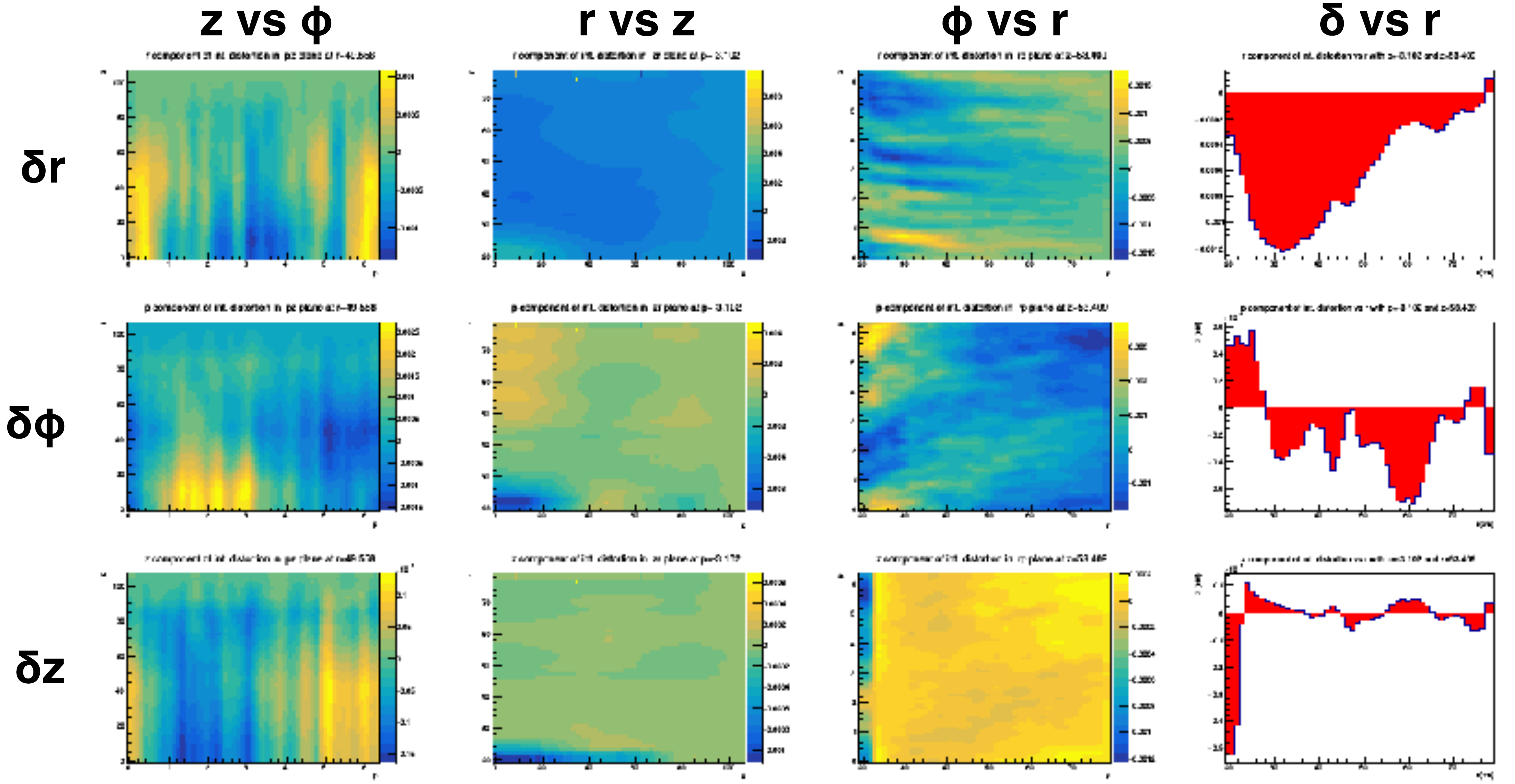






Surveying Fluctuations

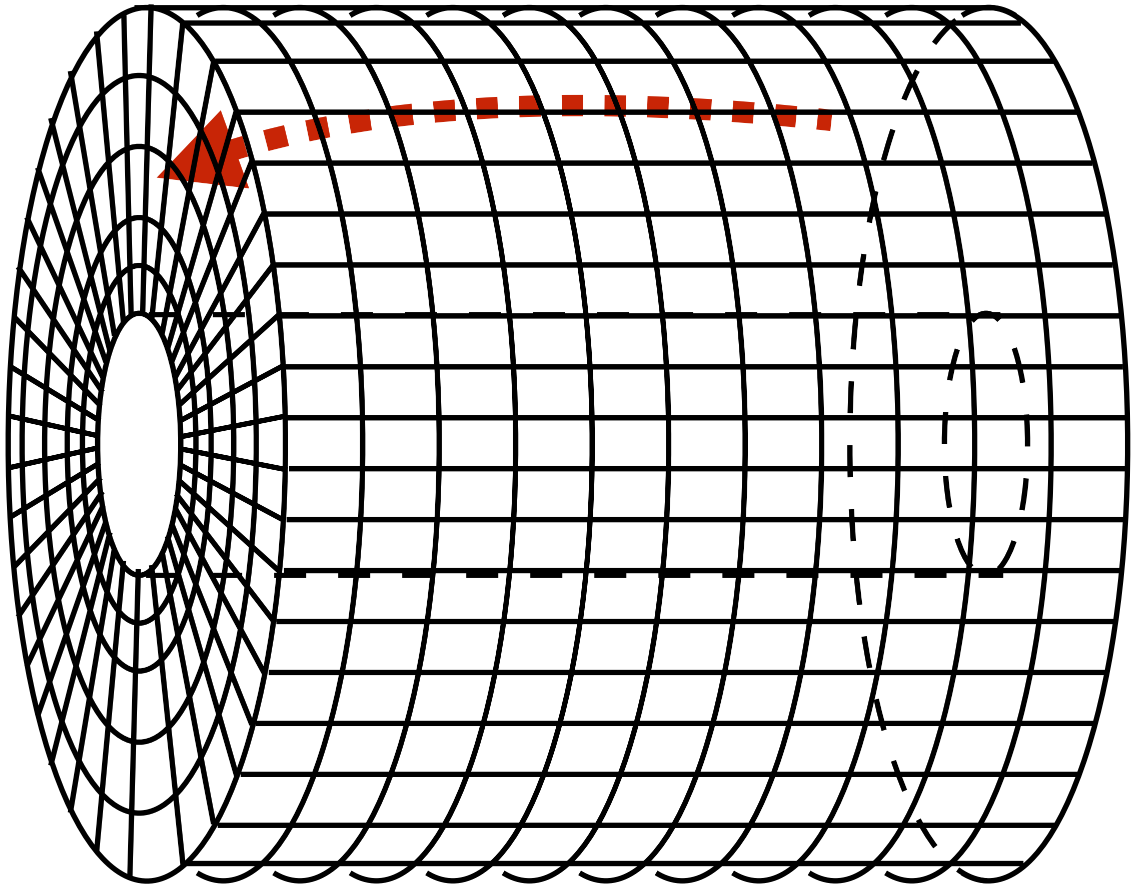
- Fluctuations are correlated across z (particles share partial path)
- (every 20 frames is a complete refresh of the TPC):

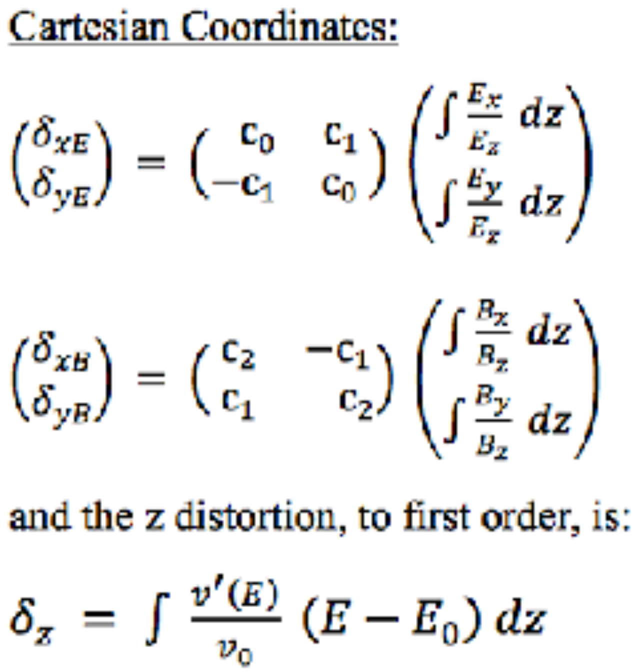


Post-hoc slices of integral distortion
Drifting grid of (rp)=(54 x 82) electrons with steps per file
Lookup per file: 15khz_output_B1.5/fluct_rev2/fluct_output.file0.h_Charge_0.real_B-1.5_E-400.0.ross_phi1_sphenix_phislice_lookup_r26xp40xz40.distortion_map.hist.root
Gas per file: 15khz_output_B1.5/fluct_rev2/fluct_output.file0.h_Charge_0.real_B-1.5_E-400.0.ross_phi1_sphenix_phislice_lookup_r26xp40xz40.distortion_map.hist.root

From Spacecharge to Distortions

- Divide TPC into Pieces of Cake (POC) grid
- Compute cell-to-cell Green's functions
- Use SC distribution to sum field vector per cell*
- Propagate each electron using 2nd order Langevin eqn.
  - pre-compute integrals
  - interpolate between r,phi adjacent cells





Cartesian Coordinates:

$$\begin{pmatrix} \delta_{xE} \\ \delta_{yE} \end{pmatrix} = \begin{pmatrix} c_0 & c_1 \\ -c_1 & c_0 \end{pmatrix} \begin{pmatrix} \int \frac{E_x}{E_z}\, dz \\ \int \frac{E_y}{E_z}\, dz \end{pmatrix}$$

$$\begin{pmatrix} \delta_{xB} \\ \delta_{yB} \end{pmatrix} = \begin{pmatrix} c_2 & -c_1 \\ c_1 & c_2 \end{pmatrix} \begin{pmatrix} \int \frac{B_x}{B_z}\, dz \\ \int \frac{B_y}{B_z}\, dz \end{pmatrix}$$

and the z distortion, to first order, is:

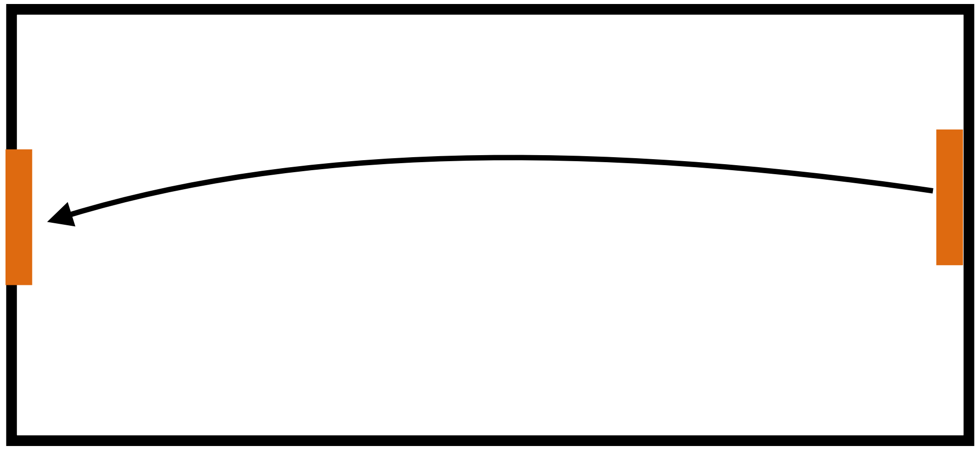
$$\delta_z = \int \frac{v'(E)}{v_0} (E - E_0)\, dz$$

Creating Distorted Events

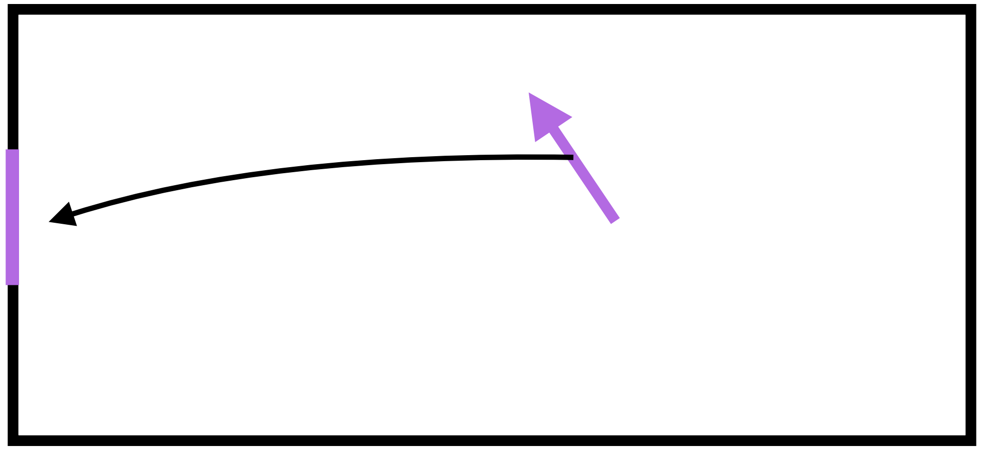
- Henry Klest (SBU) implemented proper 3D distortions from computed maps
- Two routes for how to associate these maps:
  1. Simulated events do not affect distortions:
     Distortions can be treated like embedding.
     Generate distortions independently from minbias MC sample, drift events and TPC pile-up tracks through distortion map selected from pre-computed time series.
  2. Simulated events impact distortions:
     MC sample generated with time stamps. Pile-up is reflected in SC and hence distortion map.
     Simulated events appear downstream in time series.

Distortion Handles

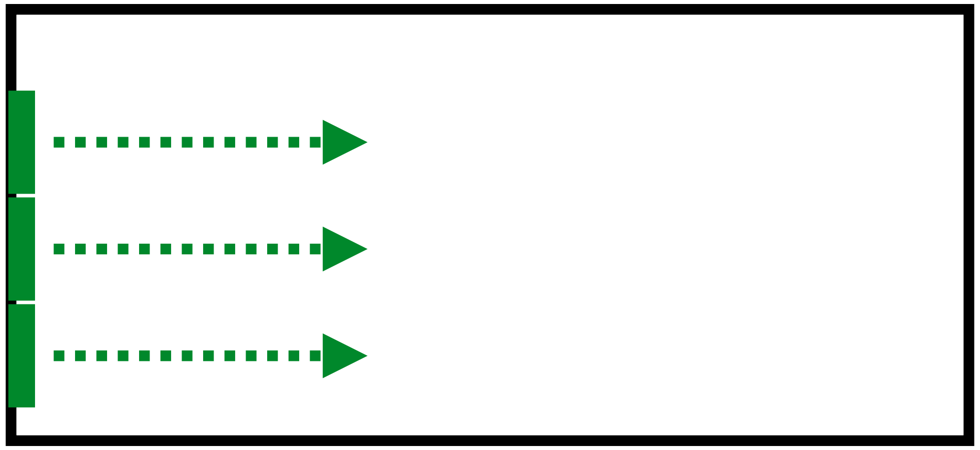
- Central Membrane Stripes: illuminated with diffuse laser (kHz), produces clusters at known position, integrates over entire distortion column



- Tracks: (*eff. ~Hz) produces clusters at uncertain position extrapolated from inner tracking, integrates over partial distortion column. Direct laser does this too, but not available during data-taking



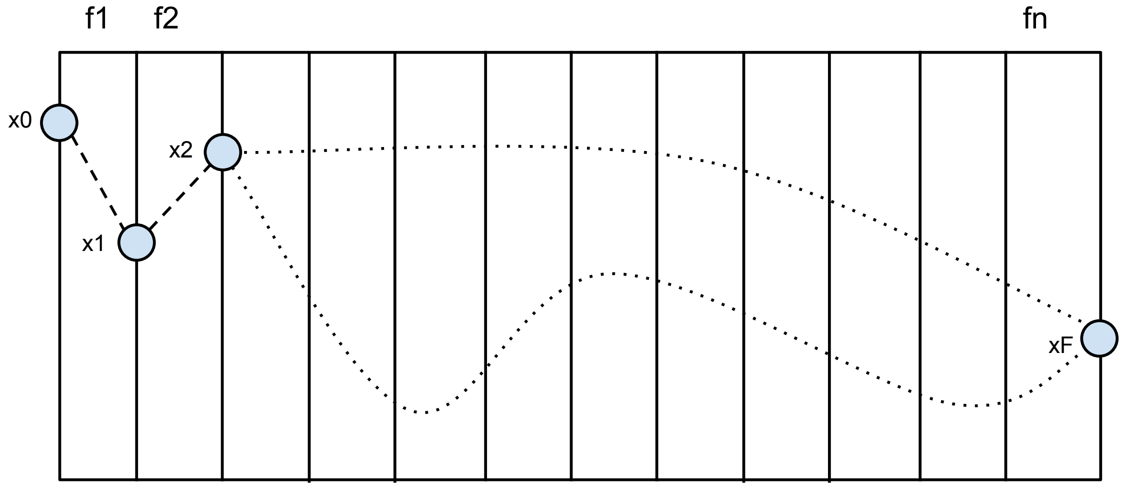
- Digital current: infers spacecharge current from electrons at readout (kHz), model computes distortions from charge



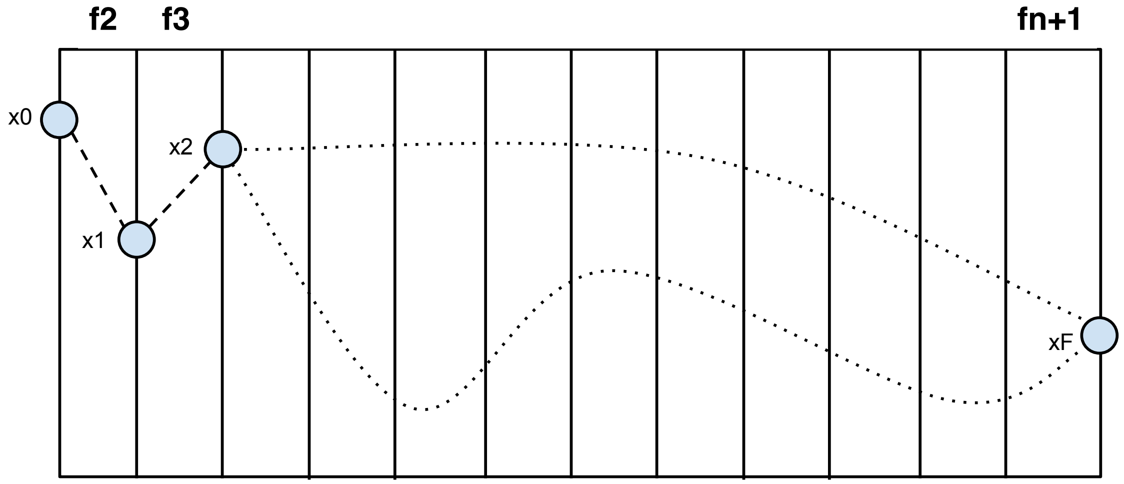
- *Simulation: model expected average spacecharge shape, compute distortions for a given luminosity*

Extracting differentials?

The position of an electron at readout is the sum of the distortion in each z-step along the way. Electrons from the CM stripe pattern integrate over the entire z-column (and tracks over a partial column):



The distortions evolve with the motion of the ions (primary<<IBF):



By comparing the reconstructed CM stripe position at two consecutive times, we learn about the portions of the z-column they do not have in common, and can use this to extract differential information about the distortions. The number of iterations where you can link differential information is limited by intrinsic detector resolutions.

Greens functions

- Free Space: $\vec{E}(\vec{x}_{at}, \vec{x}_{from}) = \frac{\vec{x}_{at} - \vec{x}_{from}}{|\vec{x}_{at} - \vec{x}_{from}|^3}$
- Analytic: $\vec{E}(\vec{x}_{at}) = \mathrm{ChargeModel} \rightarrow \mathrm{GetE}(\vec{x})$
- TPC Boundary Solutions (Rossegger thesis):

$$\frac{\partial}{\partial\phi}G(r,\phi,z,r',\phi',z') =$$

$$\frac{1}{L}\sum_{k=1}^{\infty}\sum_{n=1}^{\infty}\sin(\beta_n z)\sin(\beta_n z')\frac{R_{nk}(r)R_{nk}(r')}{N_{nk}^2}\frac{\partial}{\partial\phi}\left(\frac{\cosh[\mu_{nk}(\pi-|\phi-\phi'|)]}{\mu_{nk}\sinh(\pi\mu_{nk})}\right) \quad (5.66)$$

$$\text{with} \quad \frac{\partial}{\partial\phi}\left(\cosh[\mu_{nk}(\pi-|\phi-\phi'|)]\right) =$$

$$= \begin{cases} -\mu_{nk}\sinh[\mu_{nk}(\pi-(\phi-\phi')), & \text{for } 0 \le \phi' < \phi \le 2\pi \\ \mu_{nk}\sinh[\mu_{nk}(\pi-(\phi'-\phi)), & \text{for } 0 \le \phi < \phi' \le 2\pi \end{cases}$$

+ R,Z terms through clever choice of basis.