# TPC Distortion Software

Ross Corliss *for the task force*

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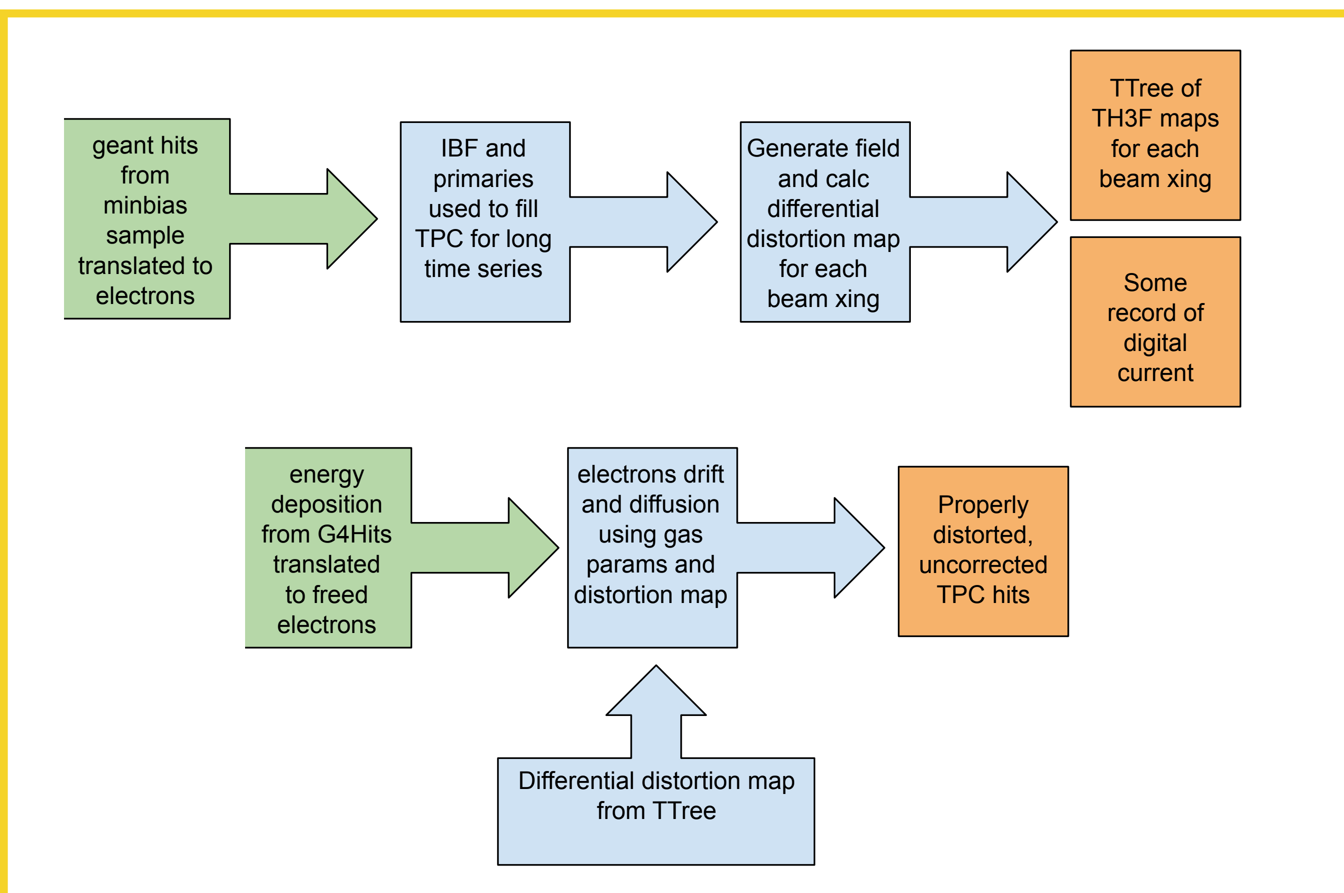
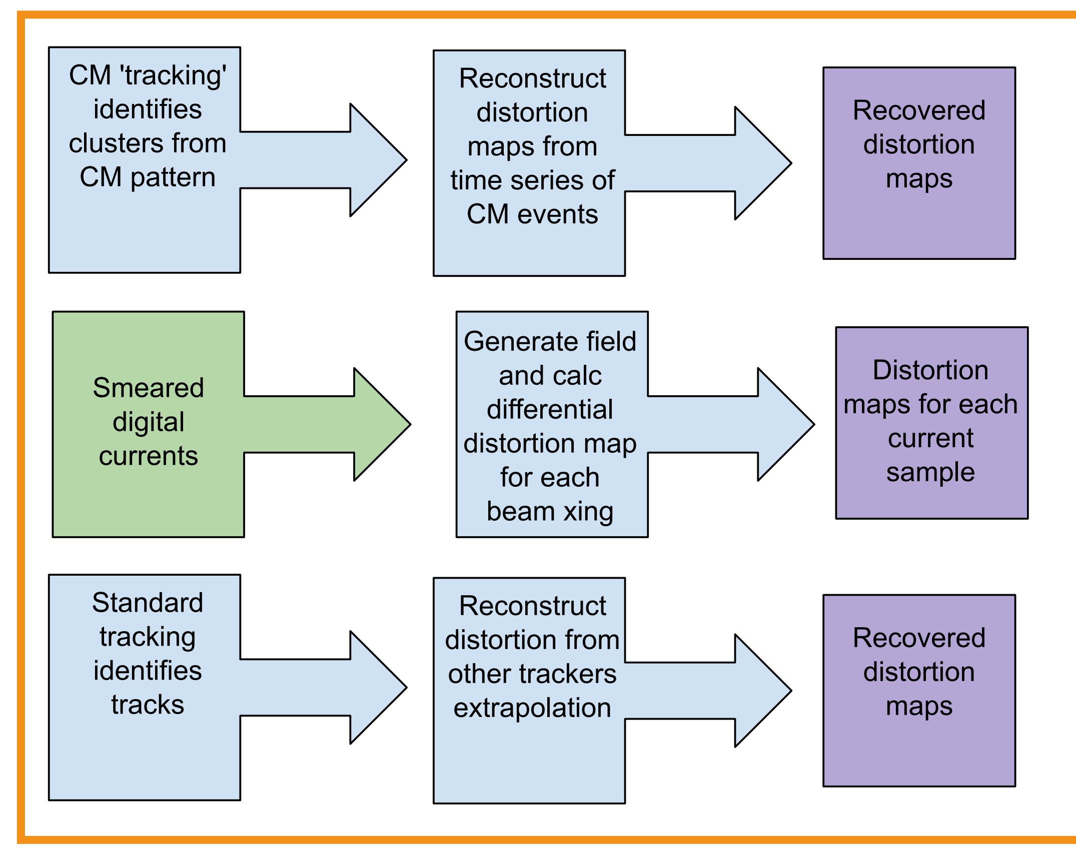
# Overview

- Integrate and expand spacecharge modeling in Fun4All
- Implement and study calibration of spacecharge distortions through tracking, lasers, and digital current measurements.

**Model and Generation**




**Reco and Calibration**



# Projects and Milestones

| Brainpower | Task | *Early July* | *Mid July* | *Late July* | *Early August* | *Mid August* | *Late August* |
|---|---|---|---|---|---|---|---|
| Chris P | generate HIJING events | ***improved HIJING with proper vertex distribution and Calorimeter backsplash*** | | | | | |
| Ananya P, Evgeny S | current / SC maps from HIJING | ***low-res SC maps for early distortion studies*** | | ***tool to gen. SC time series for desired luminosity and IBF factors*** | | | |
| Jordan S, Ross | generate distortions from SC maps | ***compare and select tiling scheme for field*** | | *study and select MC truth resolution* | | ***validate against analytic models*** | |
| Henry K | implement MC truth distortions | ***static dist. map in sim.*** | ***time series distortion maps in simulation.*** | | | | |
| Evgeny S | distortions from currents | | | | *Reconstruct SC from dig.current* | *Reconstruct distortion map from digital current, study* | |
| Sara K | Simulate laser events | ***generate CM stripe G4Hits in event*** | | | | | |
| Sara K | Reconstruct laser events | | | ***reconstruct CM hits*** | | | |
| Sara K, Ross | distortions from laser events | | | | *implement CM calibration loop; extract distortion maps* | | |
| in collab. with other Subcom | Distortions from tracks | ***repeat Hugo's analysis with static distortion map*** | | *study with time-varying map, look at correlations* | | | |
| TBD | Cross-validate methods | | | | | *study fast distortion maps with slow already subtracted* | |
| Ross, Chris P, Others | Define MC-truth and correction formats | ***revise format for slow+fluctuations*** | | | | | |
| Joe | Corrections in reco | *implement movable hits in ACTS...* | | | *distortion maps in reco.* | | |
| Tony, Hugo, Others | Tracking w/wo correction | *prepare diagnostic tools.* | | | *check tracking eff. w/ and wo/ distortions and corrections.* | | |
| TBD | Studies of Physics Impact | | ***develop analysis modules to track physics observables w/wo corrections*** | | | | |

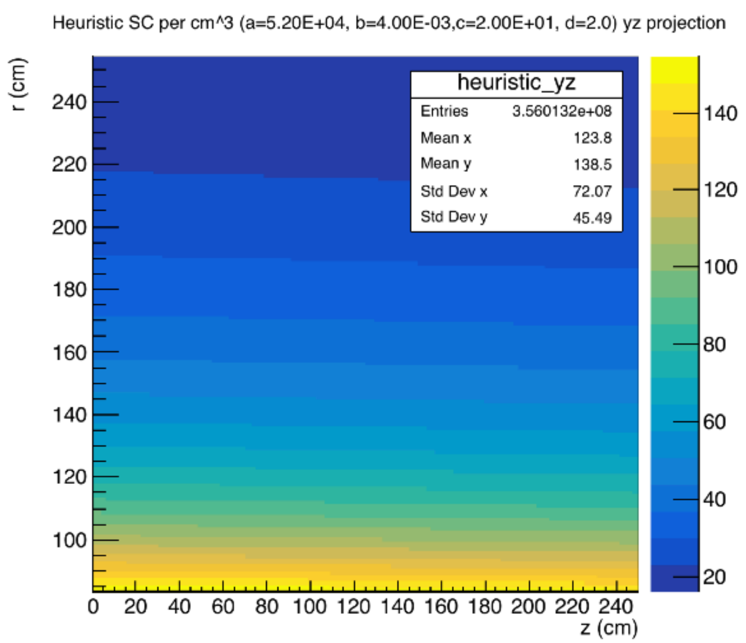
Key:

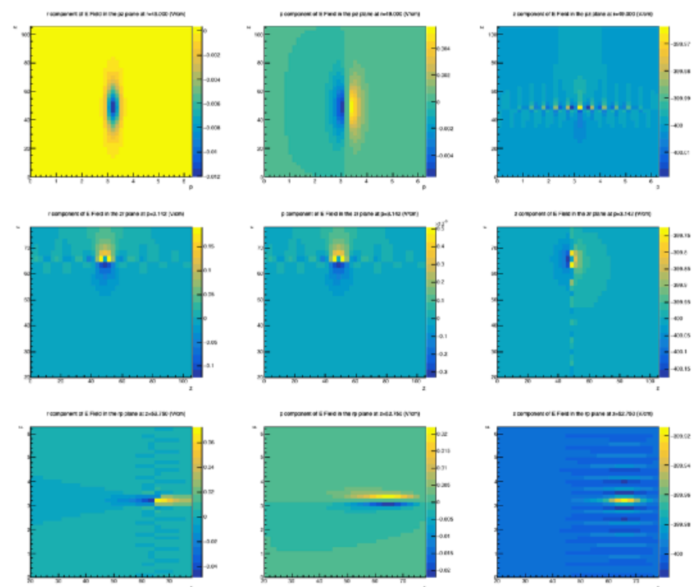
| | | |
|---|---|---|
| ***DONE*** | ***Nearly done*** | *In Progress* |

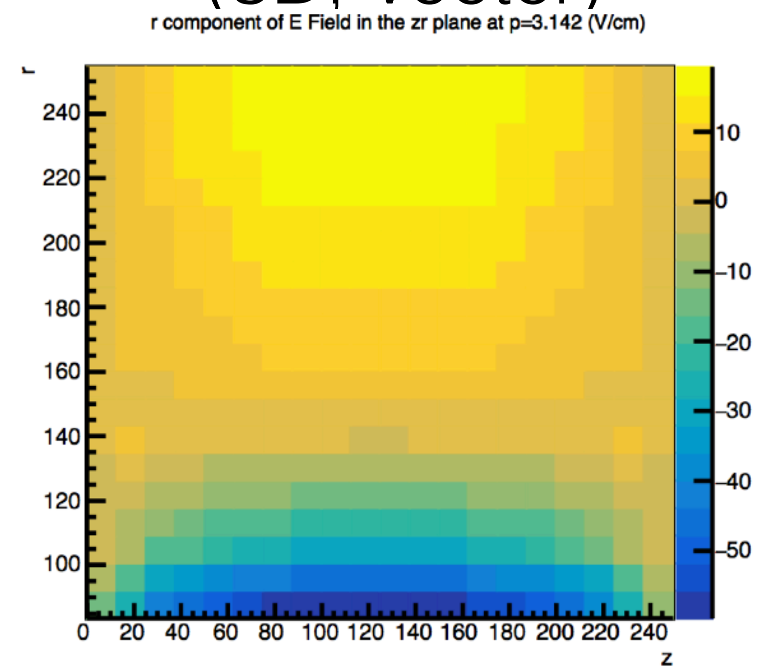
# Model and Generation

- Generate Field Map from MC Spacecharge:

Charge Distribution (3D, Scalar) x Greens functions (6D, Vector) = 3D Electric Field Map (3D, Vector)





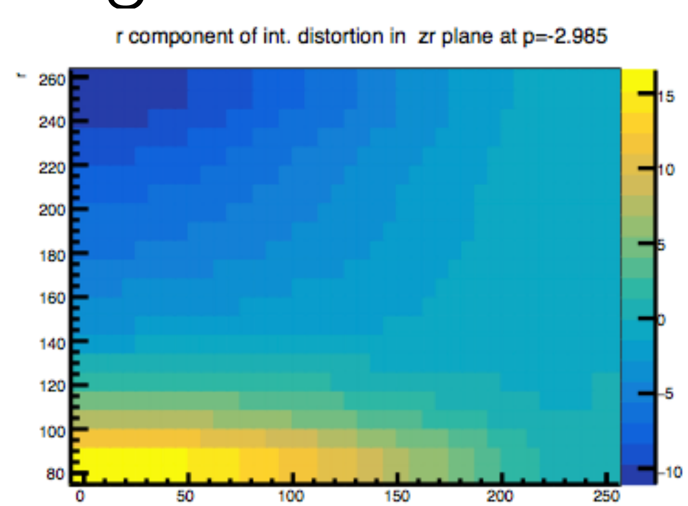

- Swim test particles through binned fields using Langevin Eqn:

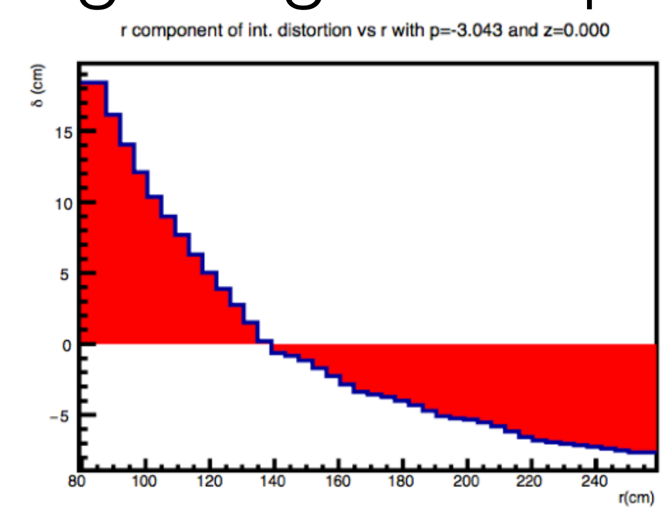
<u>Cylindrical Coordinates:</u>

$$\begin{pmatrix} \delta_{rE} \\ r\delta_{\phi E} \end{pmatrix} = \begin{pmatrix} c_0 & c_1 \\ -c_1 & c_0 \end{pmatrix} \begin{pmatrix} \int \frac{E_r}{E_z}\, dz \\ \int \frac{E_\phi}{E_z}\, dz \end{pmatrix}$$

$$\begin{pmatrix} \delta_{rB} \\ r\delta_{\phi B} \end{pmatrix} = \begin{pmatrix} c_2 & -c_1 \\ c_1 & c_2 \end{pmatrix} \begin{pmatrix} \int \frac{B_r}{B_z}\, dz \\ \int \frac{B_\phi}{B_z}\, dz \end{pmatrix}$$

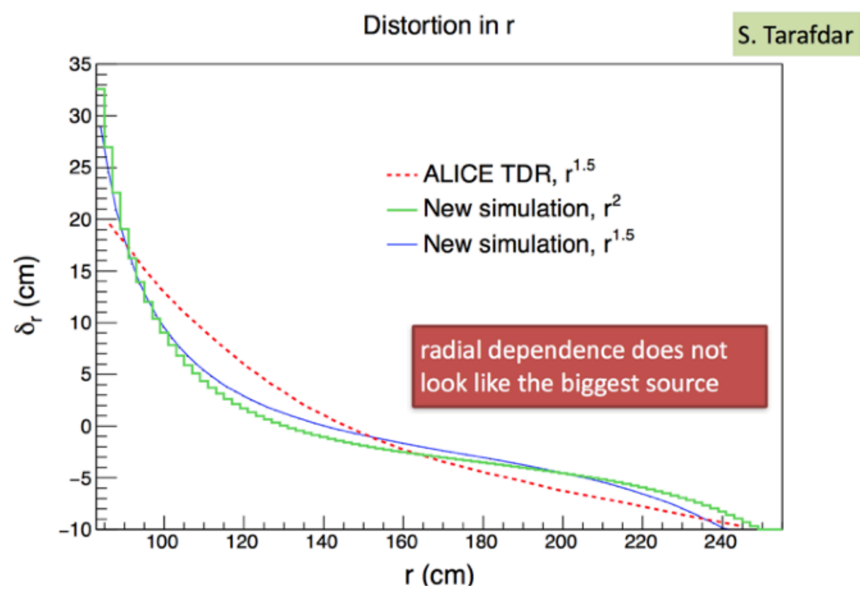
==>

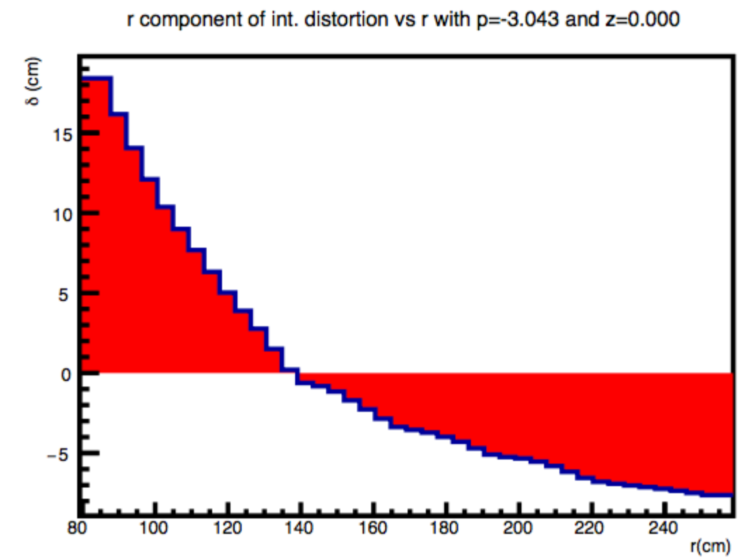


# Validating Against Analytic Models

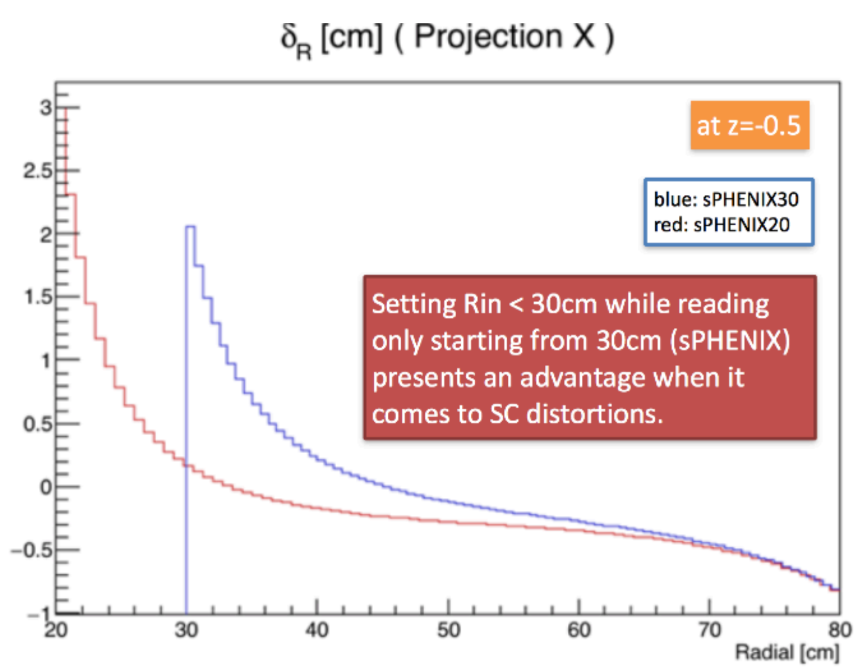
- Heuristic charge with ALICE params produces good match to ALICE distortion:

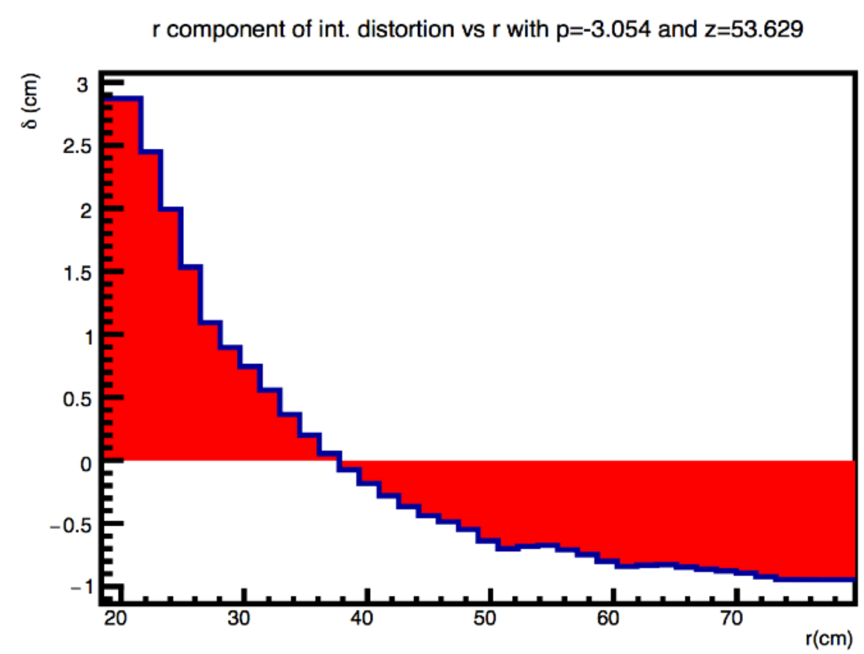



ca. 2016

- Heuristic charge with old sPHENIX params (rebuilt charge model from Carlos's 2016 presentation: total Q=135nC) matches to those predictions:




ca. 2016

# ALICE projected performance

## Space-charge fluctuations

ALICE

**Contributions**

- Relative fluctuation of the number of pileup events: $\frac{1}{\sqrt{N^{ion}_{pileup}}} \approx 1.1\,\%$
- Multiplicity fluctuations: $\frac{\sigma_{N_{mult}}}{\mu_{N_{mult}}} \approx 1.4\,\%$
- Variations of the ionization of a single track: $\frac{\sigma_{Q_{track}}}{\mu_{Q_{track}}} \approx 1.7\,\%$
- Spatial range over which space-charge fluctuations are relevant for the distortions

our mult. fluctuations are probably larger?

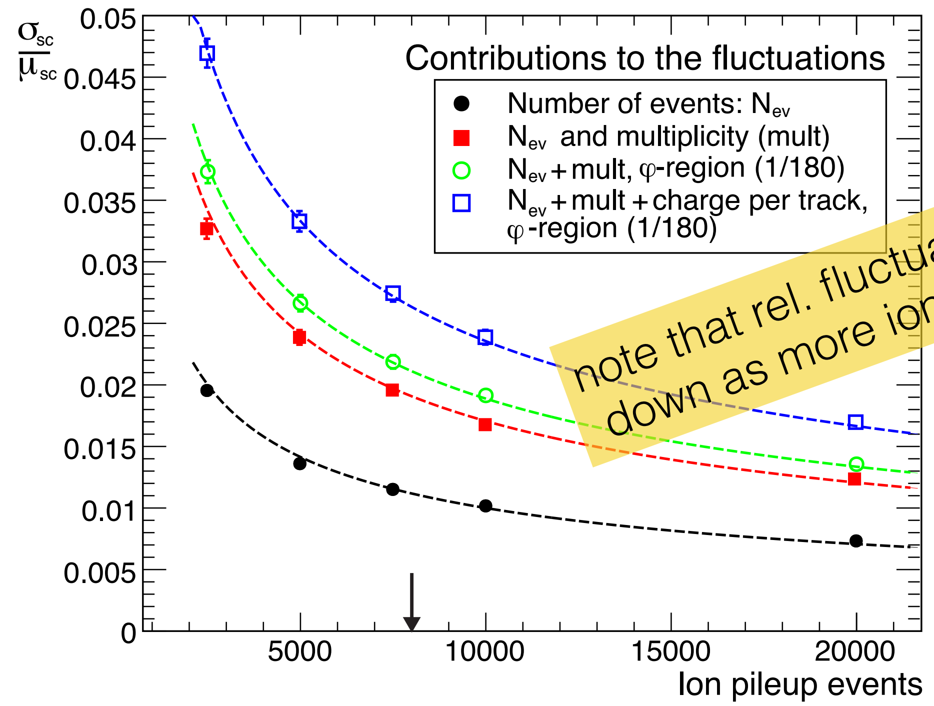
90:10 has 2x more ionization; our fluctuations are probably smaller.

$$\frac{\sigma_{SC}}{\mu_{SC}} = \frac{1}{\sqrt{N^{ion}_{pileup}}}\sqrt{1 + \left(\frac{\sigma_{N_{mult}}}{\mu_{N_{mult}}}\right)^2 + \frac{1}{F\mu_{N_{mult}}}\left(1 + \left(\frac{\sigma_{Q_{track}}}{\mu_{Q_{track}}}\right)^2\right)}$$

**Fast MC agrees well with analytical formula**

**Fluctuations of 2.5 - 3.5 %**

- 5 - 7 mm in r, 2 - 3 mm in r$\varphi$
  - Required precision: 200 µm

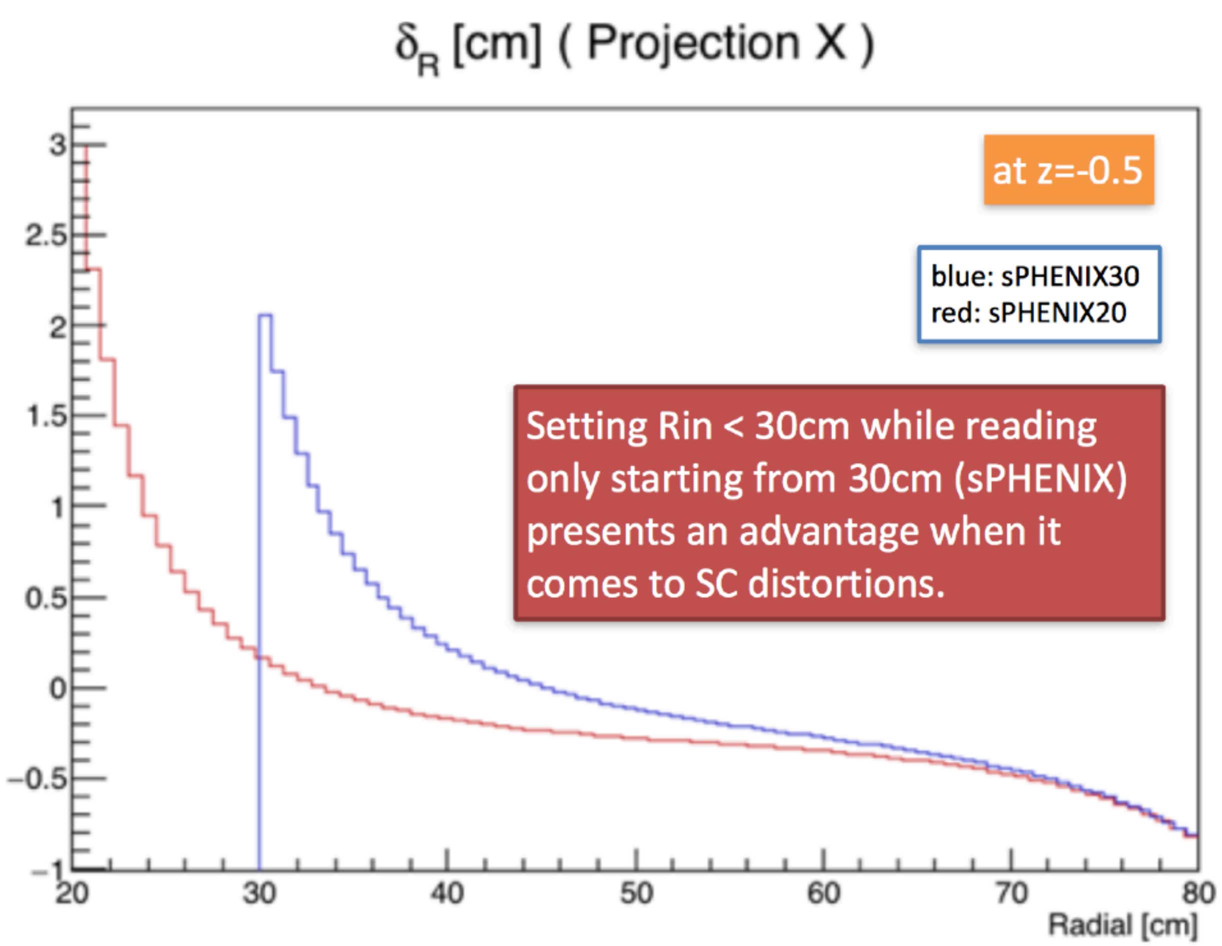



note that rel. fluctuations go down as more ions pile up

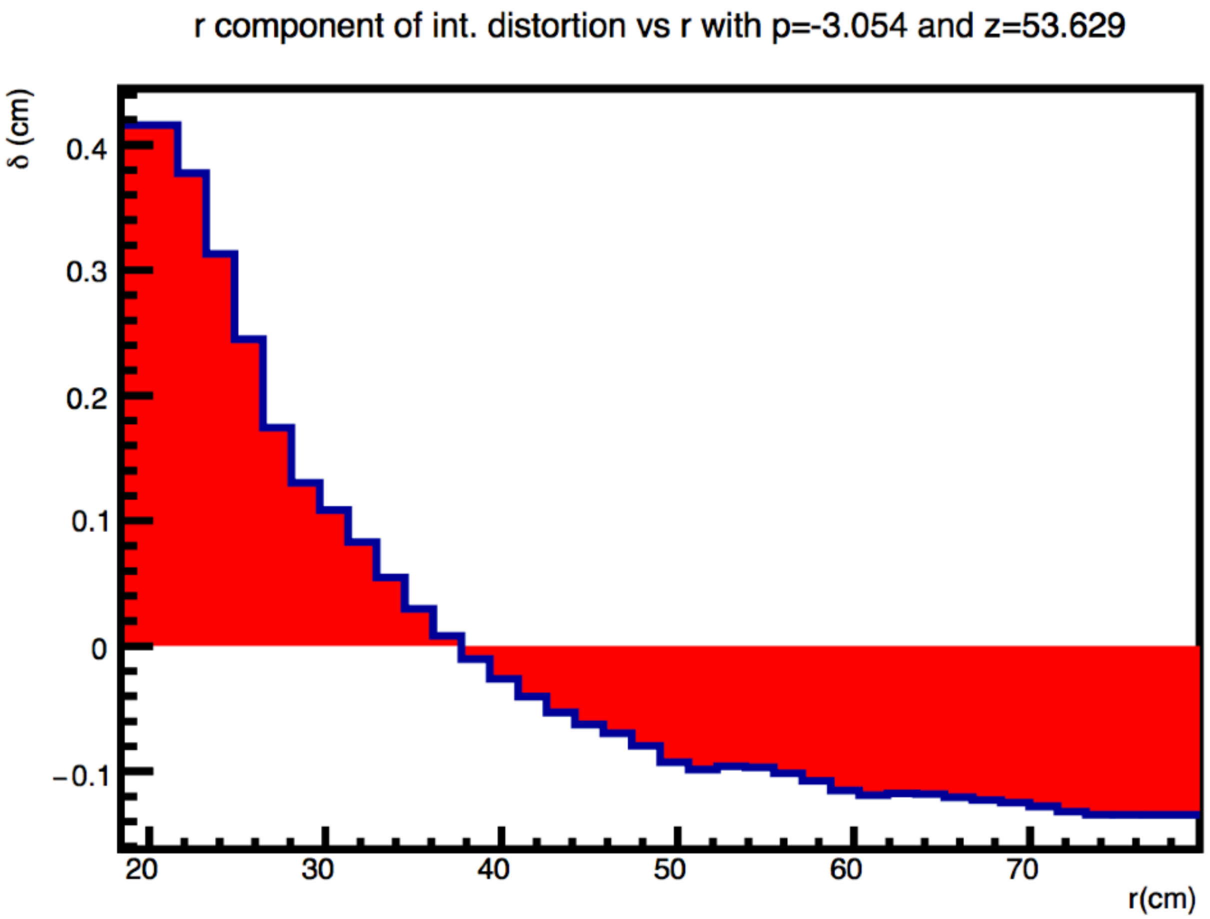
11-Jul-2019 ALICE: Space-charge calibration overview Ernst Hellbär - Goehte-Universität Frankfurt 6

# Updating Expectations for sPHENIX

- 2016 sPHENIX simulations:
  90:10 Ar:CF4 gas, drift velocity =4cm/us, B=0.5T ==> **ωτ=0.5**
- New assumptions:
  50:50 Ar:CF4 gas, velocity = 8cm/us, B=1.4T ==> **ωτ=2.8**
- Ion pileup will also change, but if we use the same heuristic charge density:

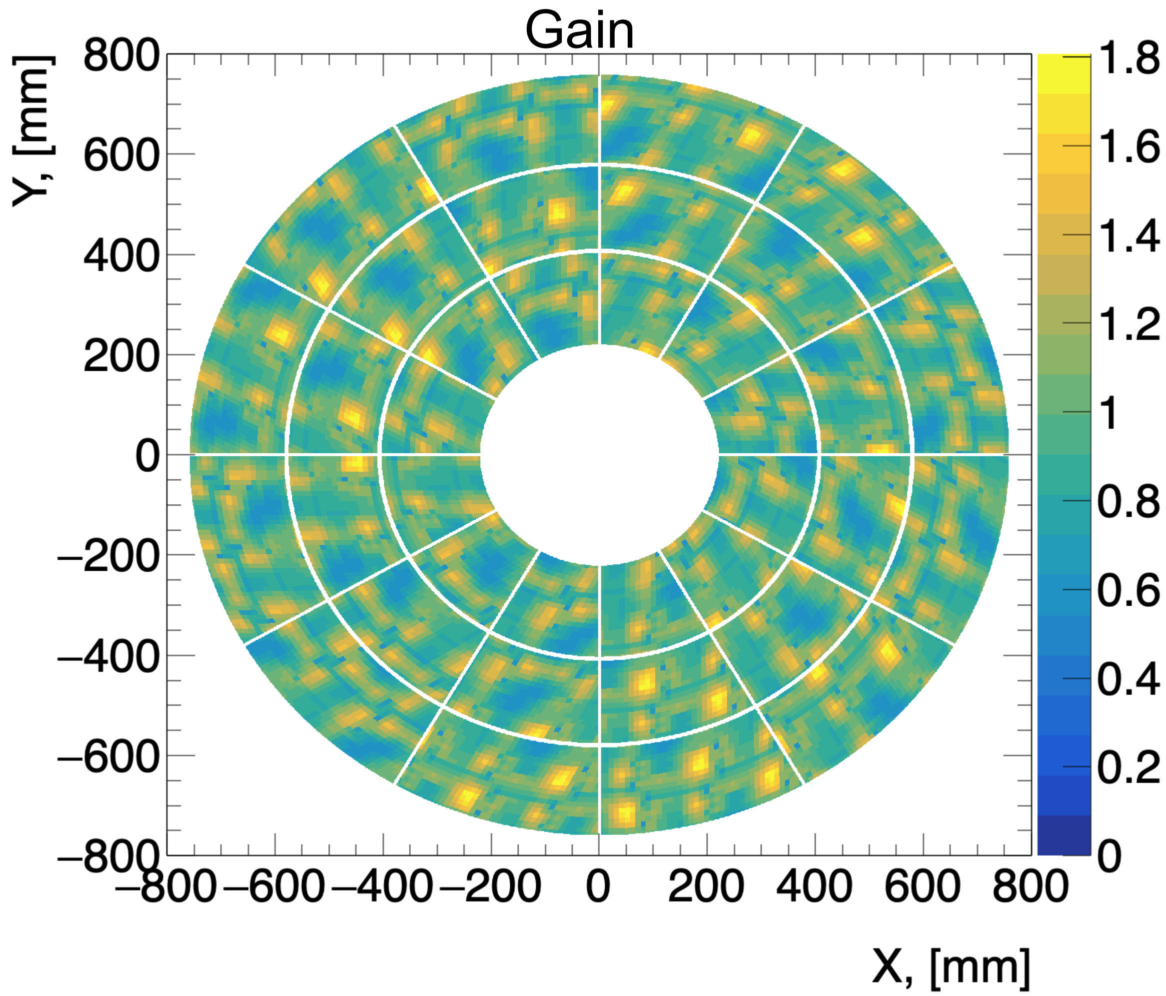


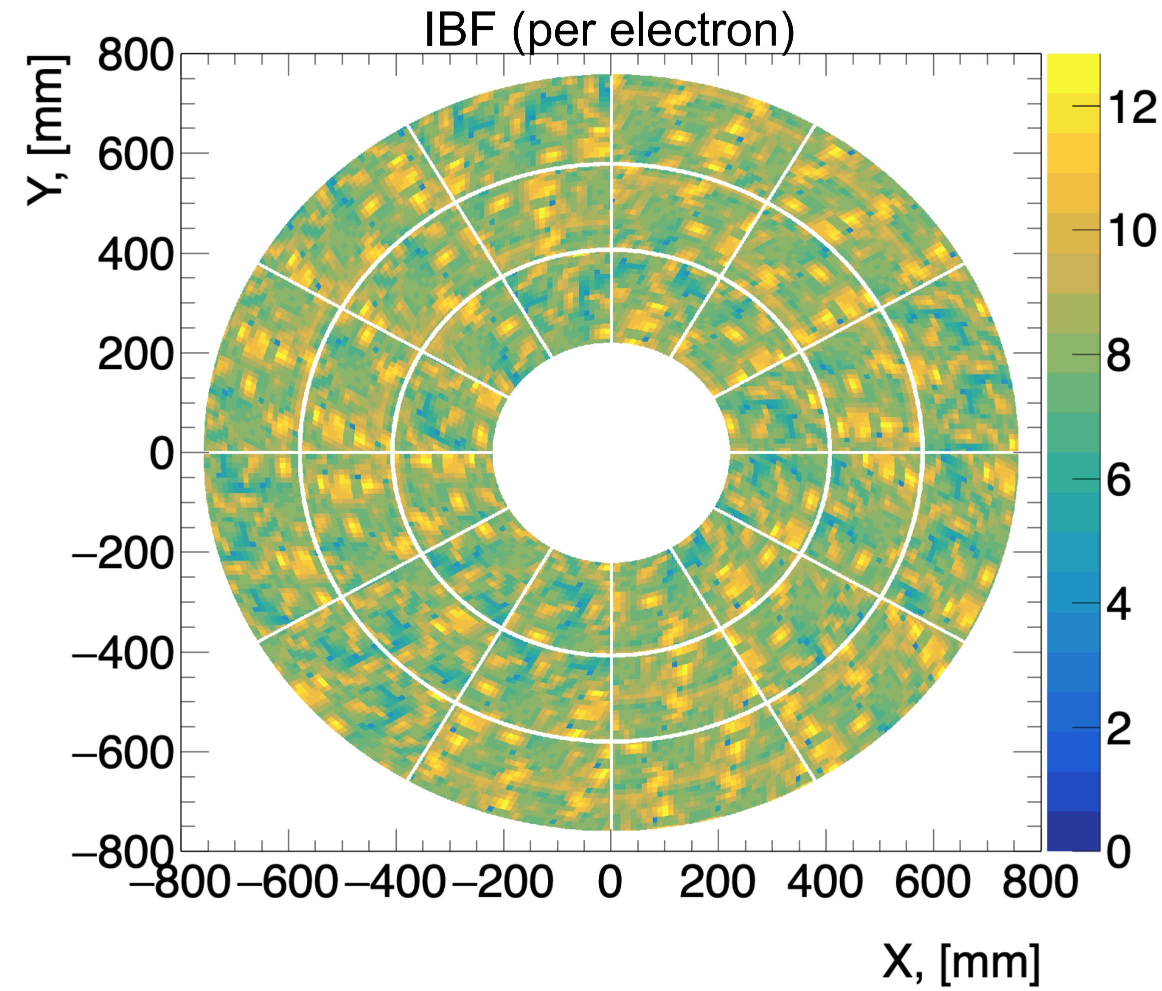

ca. 2016



# MC Spacecharge Maps

- Evgeny Shulga (WIS): realistic gain/IBF maps for the GEMs by sampling ALICE IROC measurements:

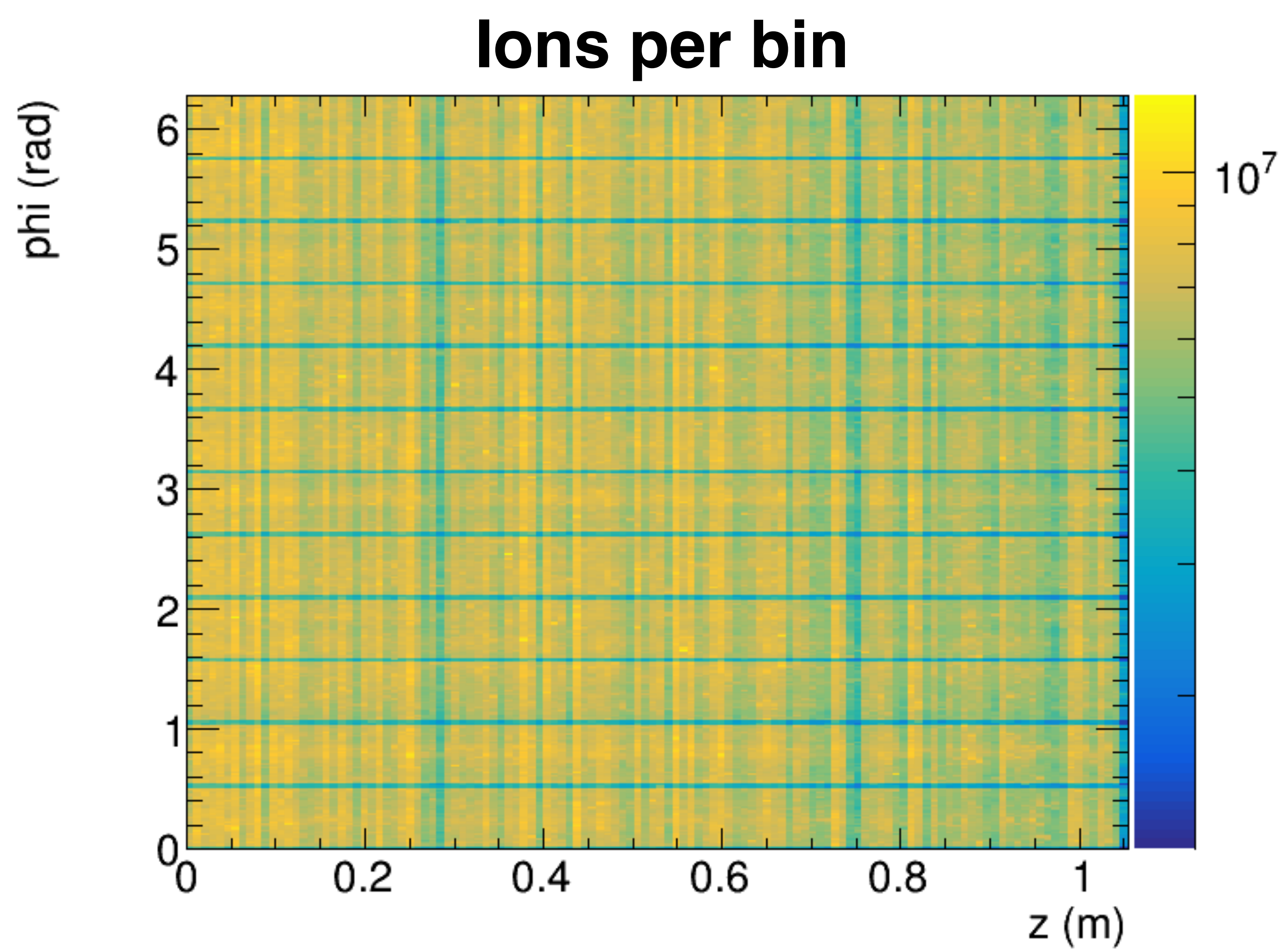



**IBF (per electron)=Gain*IBF*2000*0.44%**

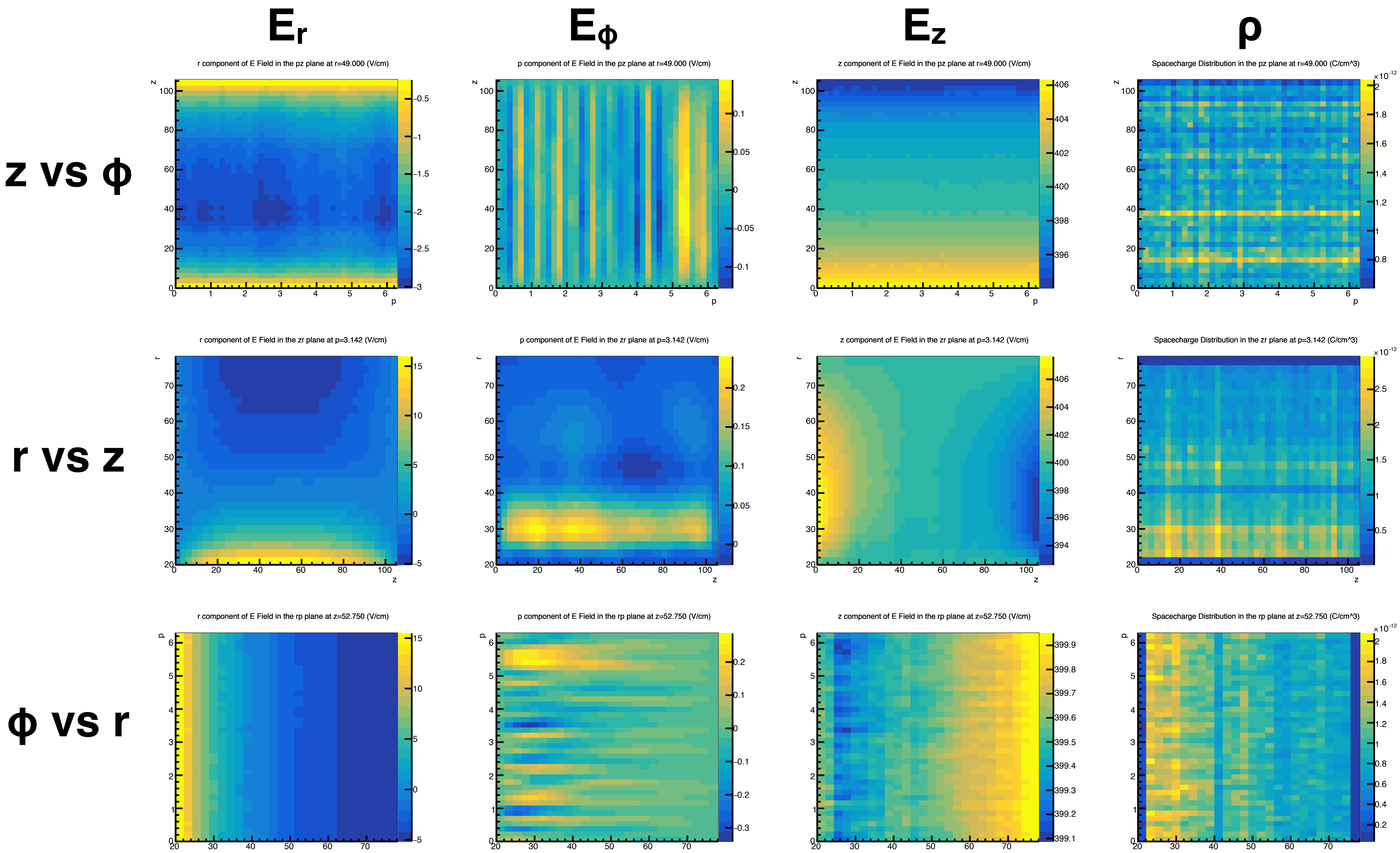
# MC Spacecharge Maps

- Poisson distribution of events with mean of 50kHz with realistic vertex
- Spacecharge = primary + z-projection × IBF × Gain
- Shifted in z by drift speed × time
- 50:50 Ar:$CF_4$ has 0.5× drift speed, slightly higher primary ionization, GEM gain lowered to keep overall pad signal constant
- Total charge ==> ~40nC (compared to 2016 model's 135nC)



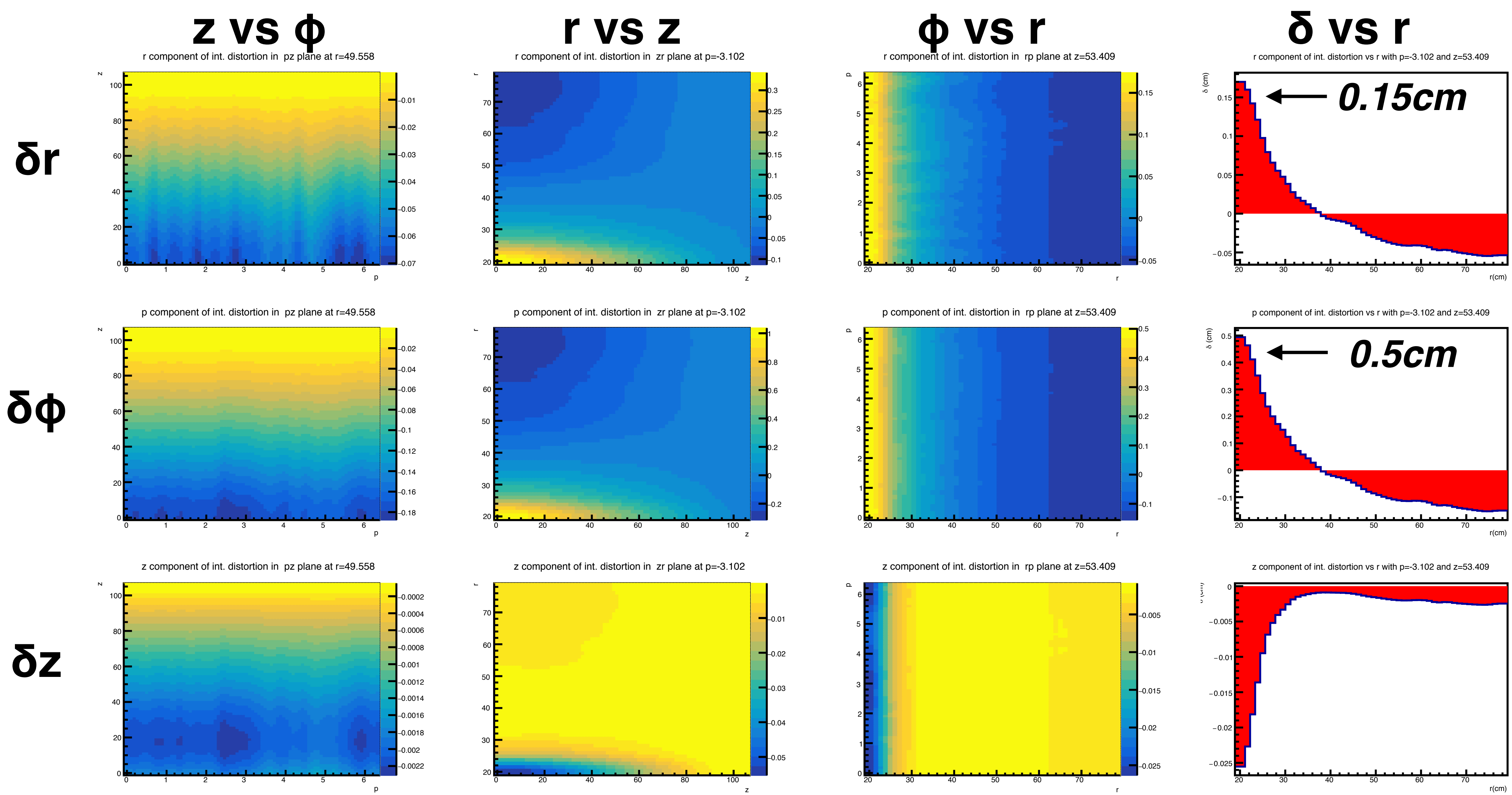
# Fields from MC Spacecharge

- Gain map creates noticeable φ structure
- event-to-event fluctuations produce additional φ and z structure



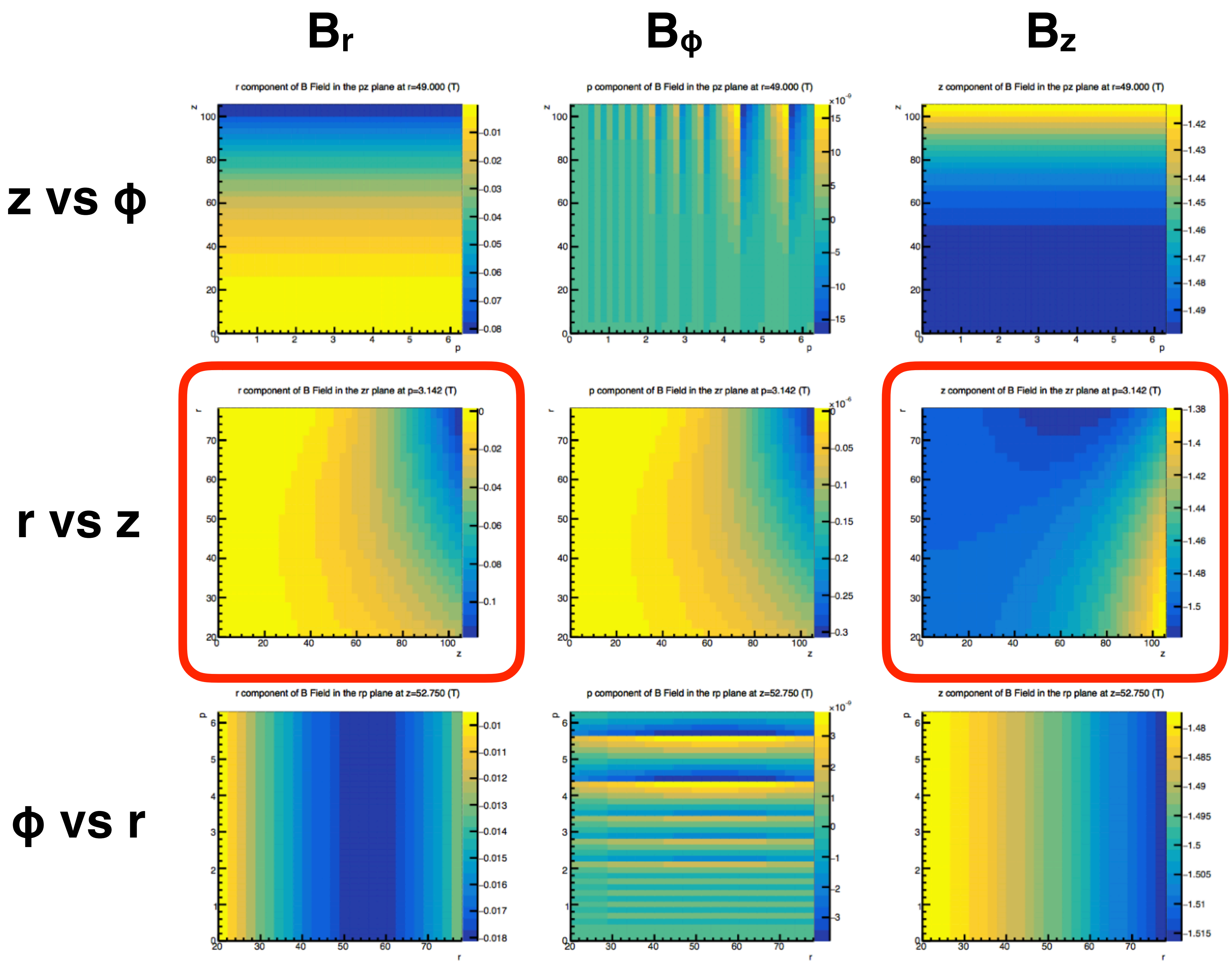
# Distortions from MC Spacecharge

- Using ideal z-only B and E fields, distortions << 2016 estimate. 3x less charge, 3x higher B field, doubled drift velocity.



# Real Fieldmaps

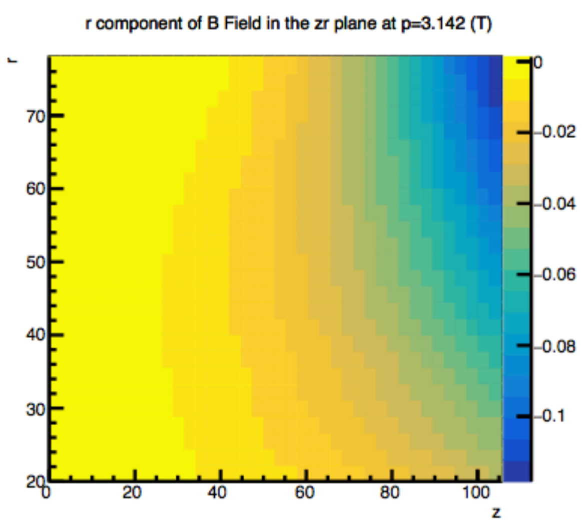
- Phi-Symmetric (1.5 Tesla) B field from non-chimney half of magnet:

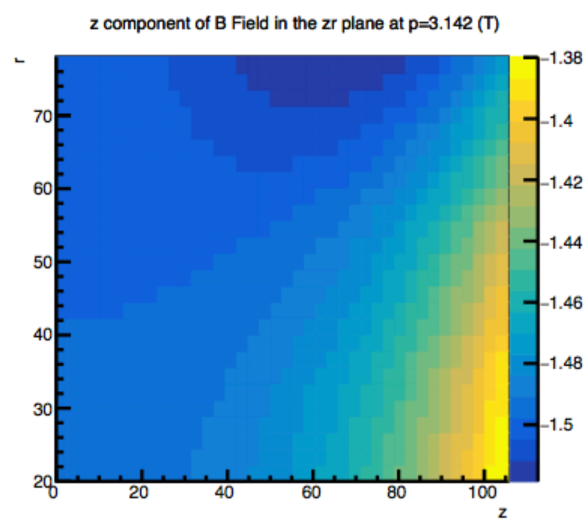


# Distortions in Real Fieldmaps

- Expect contributions from magnetic field map to dominate
- at E=400V/cm, B=1.4T, **$\omega\tau$~3**, $T_1=T_2=1$ (but we need to measure these)

$$c_0 = \frac{1}{(1+T_2^2\omega^2\tau^2)}, \qquad c_1 = \frac{T_1\omega\tau}{(1+T_1^2\omega^2\tau^2)}, \quad \text{and} \quad c_2 = \frac{T_2^2\omega^2\tau^2}{(1+T_2^2\omega^2\tau^2)}$$



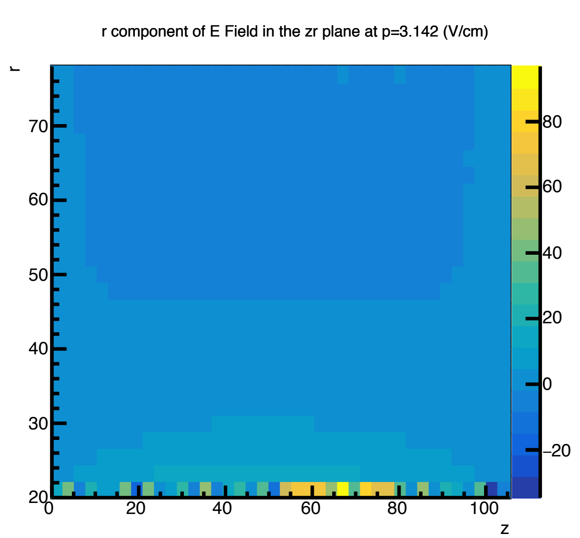



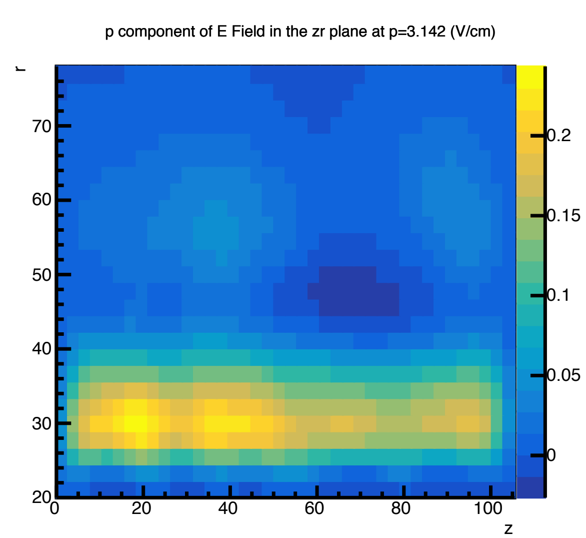

Cylindrical Coordinates:

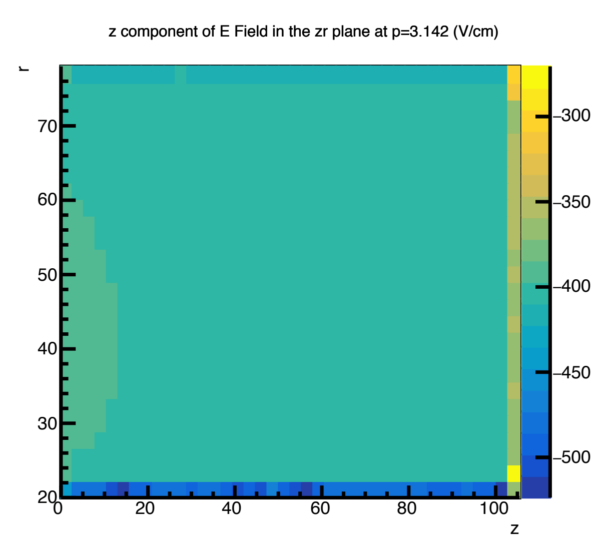
$$\begin{pmatrix} \delta_{rE} \\ r\delta_{\phi E} \end{pmatrix} = \begin{pmatrix} c_0 & c_1 \\ -c_1 & c_0 \end{pmatrix} \begin{pmatrix} \int \frac{E_r}{E_z}\, dz \\ \int \frac{E_\phi}{E_z}\, dz \end{pmatrix}$$

$$\begin{pmatrix} \delta_{rB} \\ r\delta_{\phi B} \end{pmatrix} = \begin{pmatrix} c_2 & -c_1 \\ c_1 & c_2 \end{pmatrix} \begin{pmatrix} \int \frac{B_r}{B_z}\, dz \\ \int \frac{B_\phi}{B_z}\, dz \end{pmatrix}$$

**c2~3×c1**

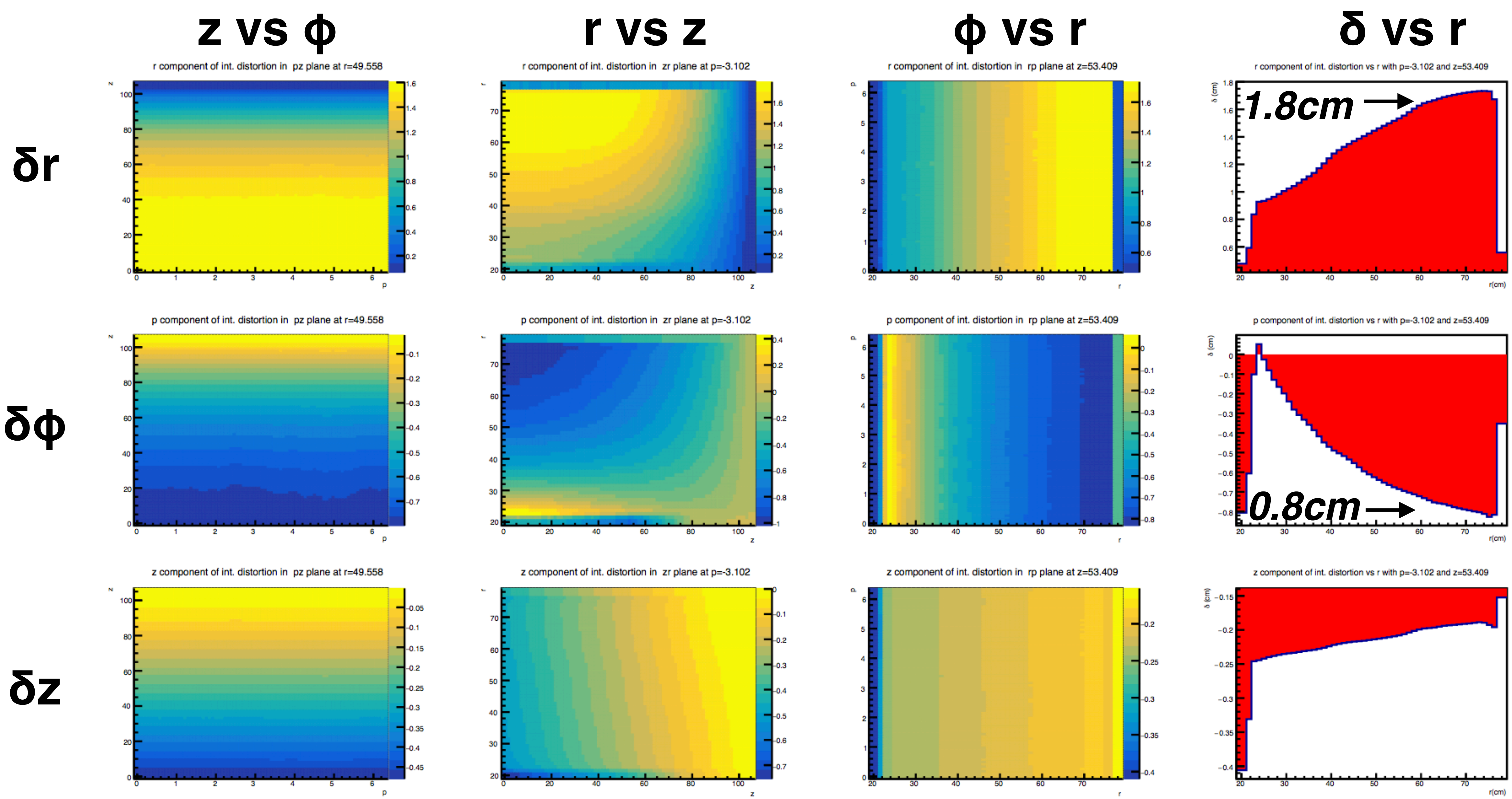


# Distortions in Real Fieldmaps

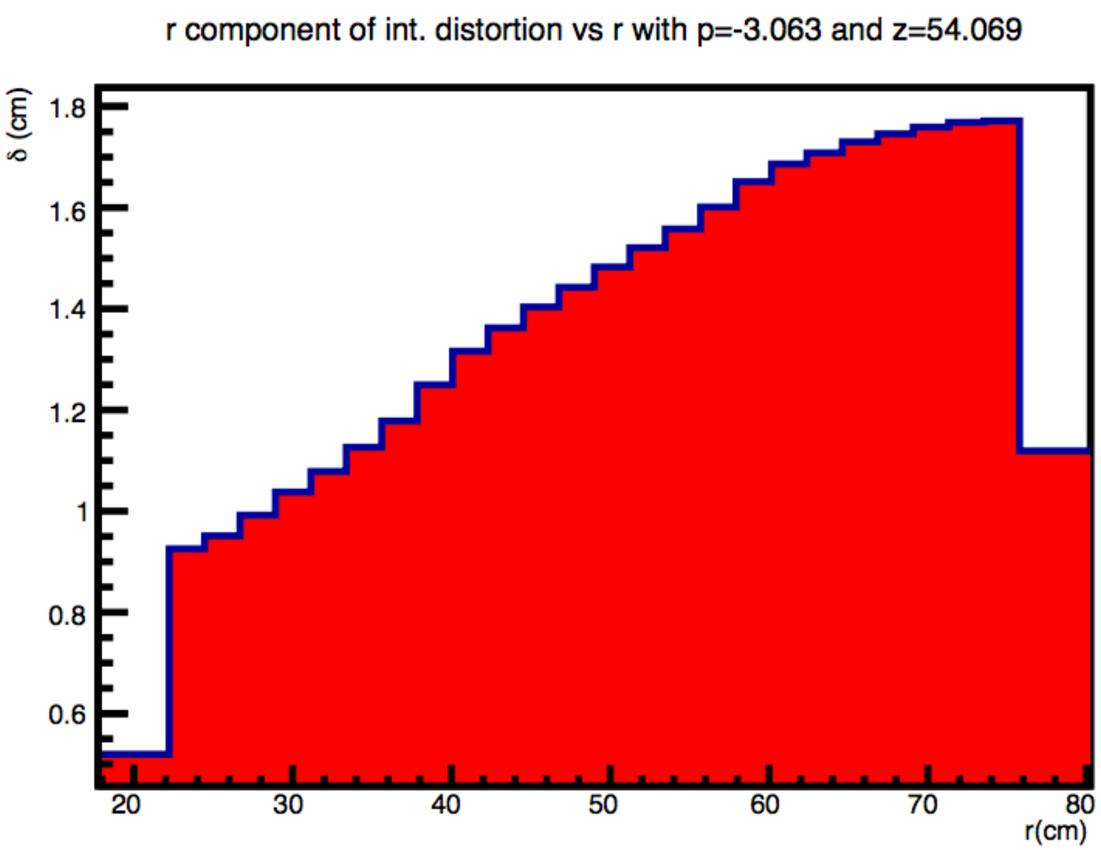
- Transverse components of B field dominate distortion

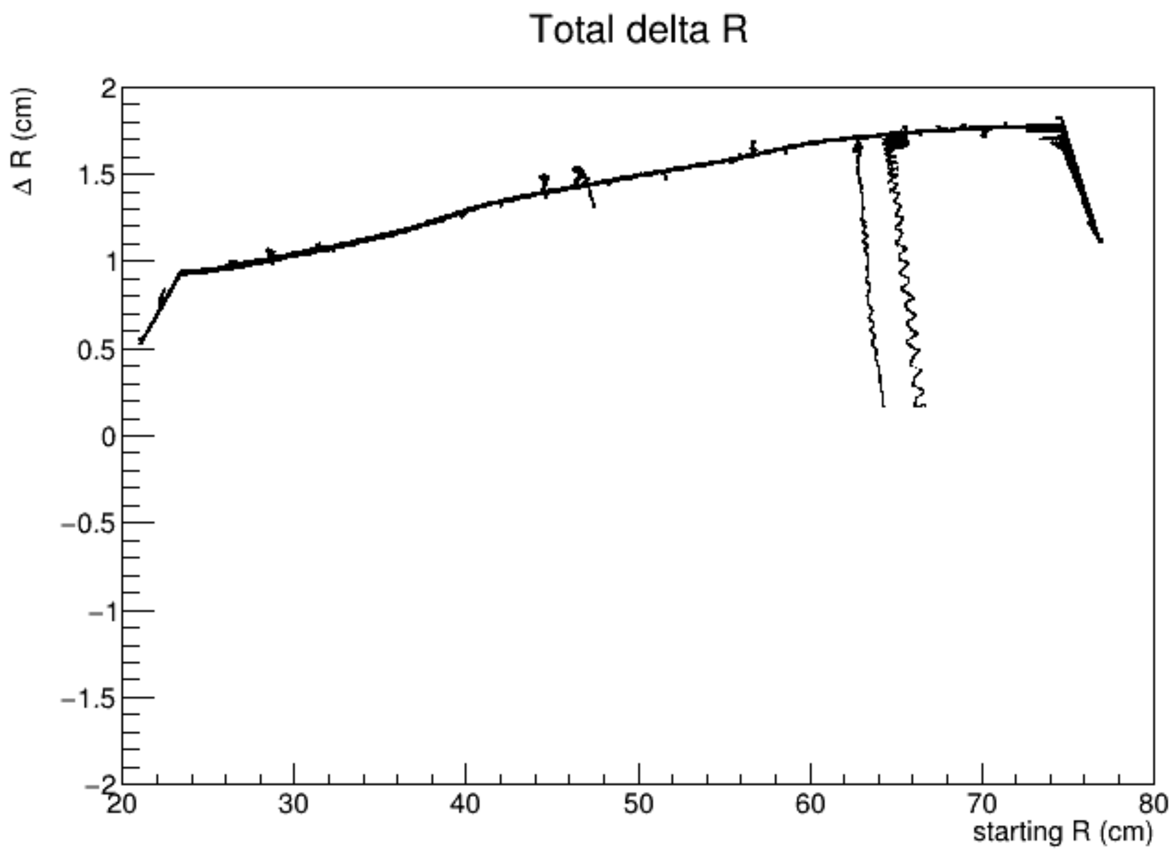



**E:externalEfield.ttree.root:fTree, B:sPHENIX.2d.root:fieldmap**
**SC from file: evgeny_sept/Summary_bX1508071_10_20_events.root:h_Charge_evt_12. Qtot=4.700808E-08 Coulombs. native dims: (159,360,124)(20.0cm,0.0,0.0cm)-(78.0cm**
**Drifting grid of (rp)=(54 x 82) electrons with 500 steps**
**PhiSlice (26 x 40 x 40) with (26 x 1 x 40) roi**
**vdrift=8.00cm/us, Enom=400.00V/cm, Bnom=1.40T, omtau=-2.8000E+00**

# Distortions in Fun4All

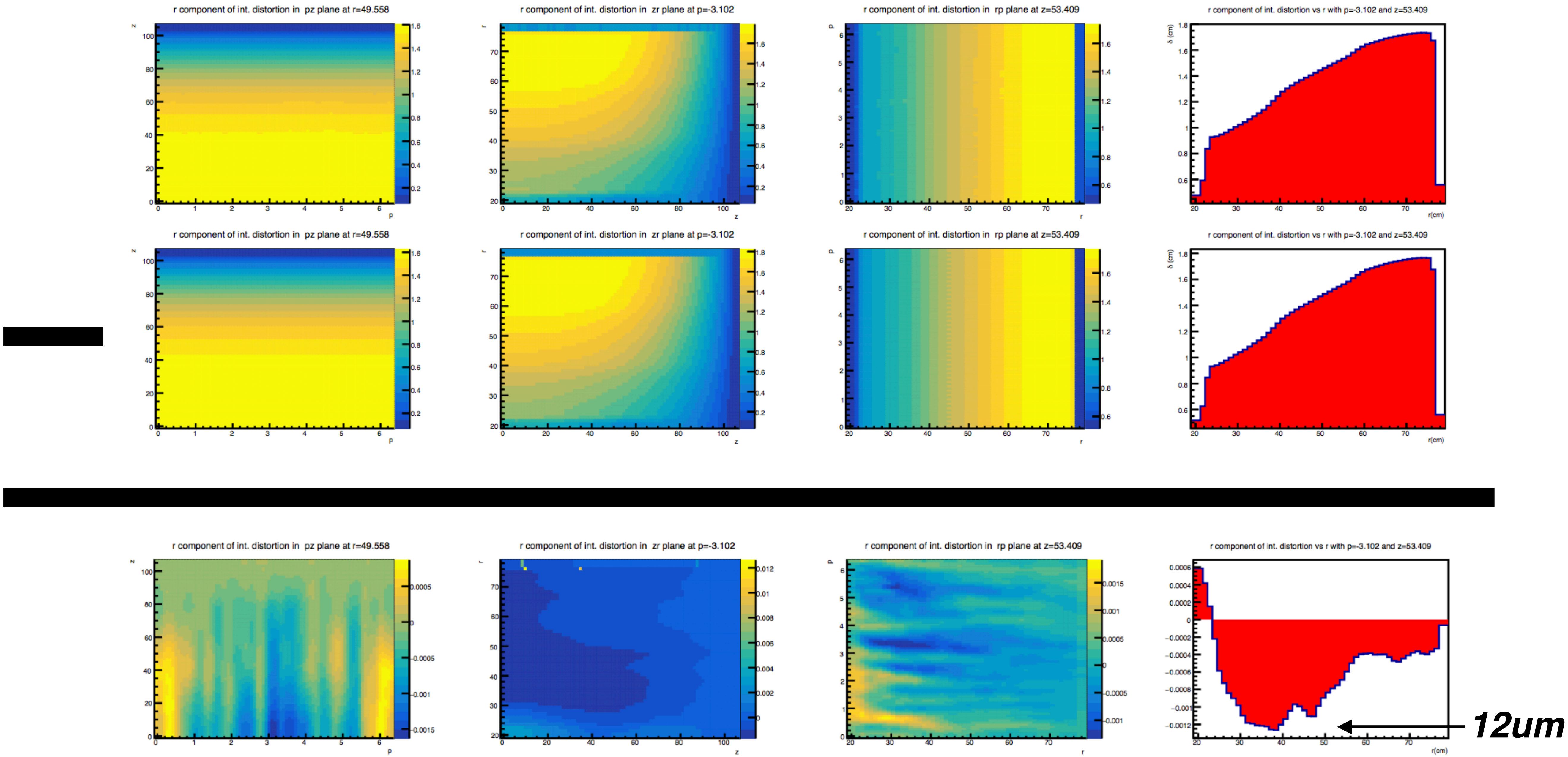
- Henry Klest (SBU) has implemented reading these distortion maps in Fun4All
- Distortion of TPC hits from MC events (z vertex=54, eta=0) matches input map



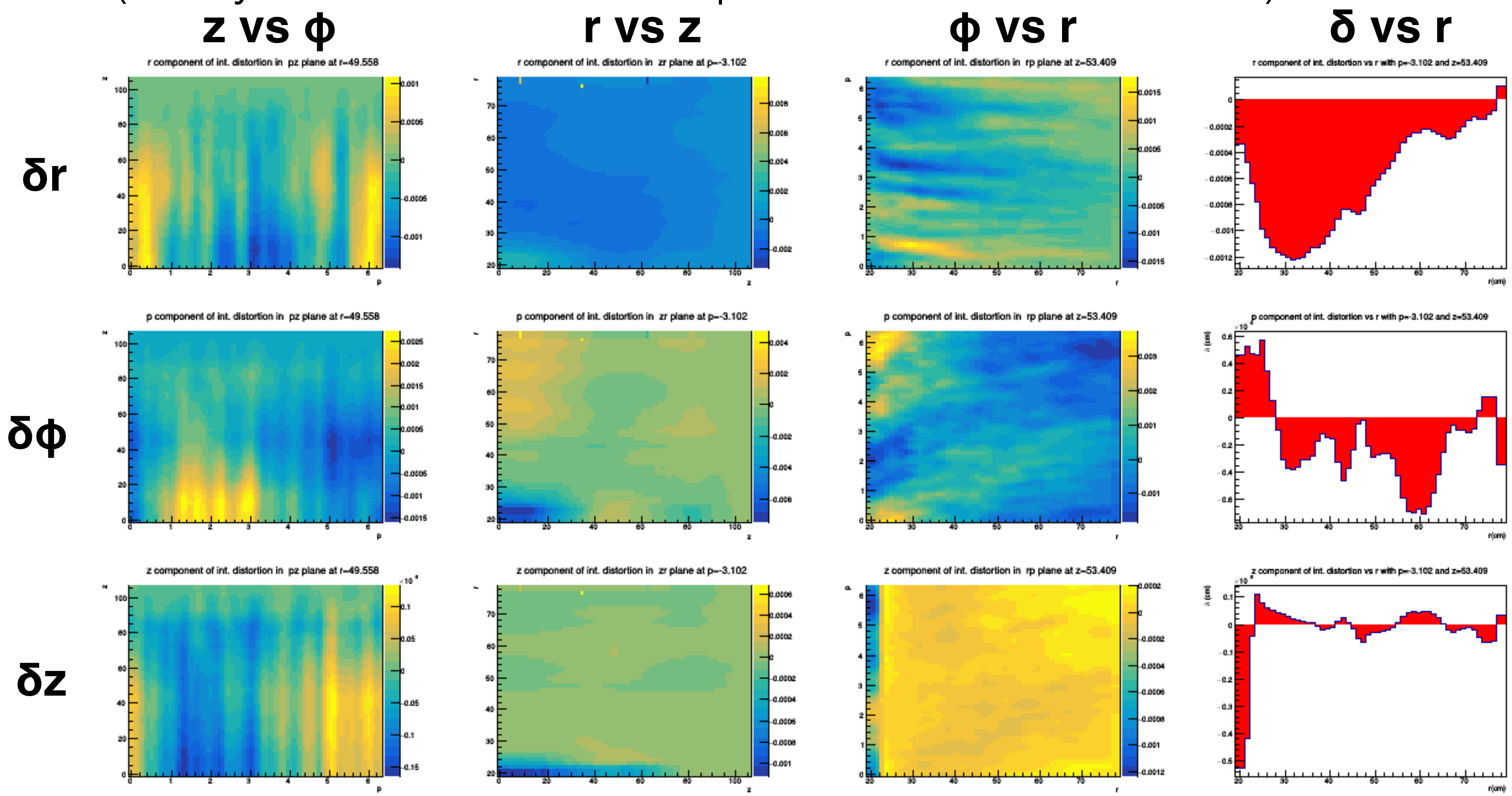
# Extract Fluctuations

- Subtract off average spacecharge distortion to see distortions due to event-by-event fluctuations:



# Surveying Fluctuations

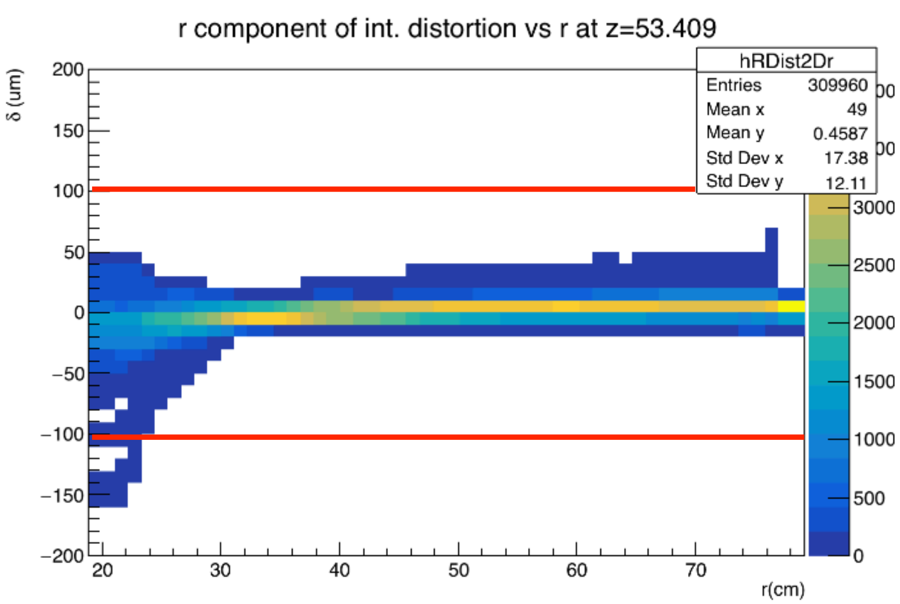
- Fluctuations are correlated across z (particles share partial path)
- (every 20 frames is a complete refresh of the TPC):

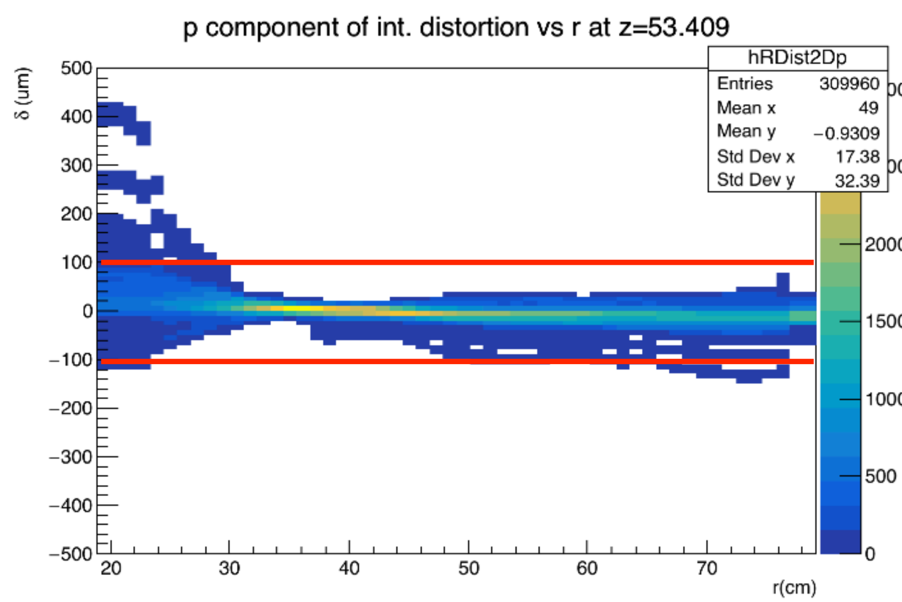


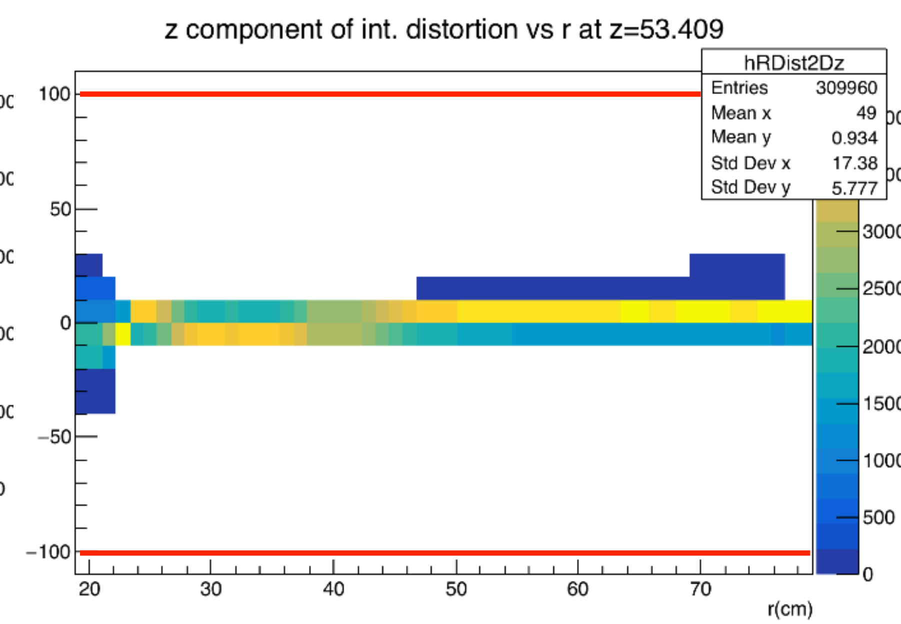

Post-hoc slices of integral distortion
Drifting grid of (rp)=(54 x 82) electrons with steps per file
Lookup per file: 15khz_output_B1.5/fluct_rev2/fluct_output.file0.h_Charge_0.real_B-1.5_E-400.0.ross_phi1_sphenix_phislice_lookup_r26xp40xz40.distortion_map.hist.root
Gas per file: 15khz_output_B1.5/fluct_rev2/fluct_output.file0.h_Charge_0.real_B-1.5_E-400.0.ross_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

# Surveying Fluctuations

- Average distortion subtracted from each element of time series. Residuals plotted below
- MC fluctuations at z~50cm (full 2π) are generally within 100 um over instrumented range
- *if average distortion is precisely known.*



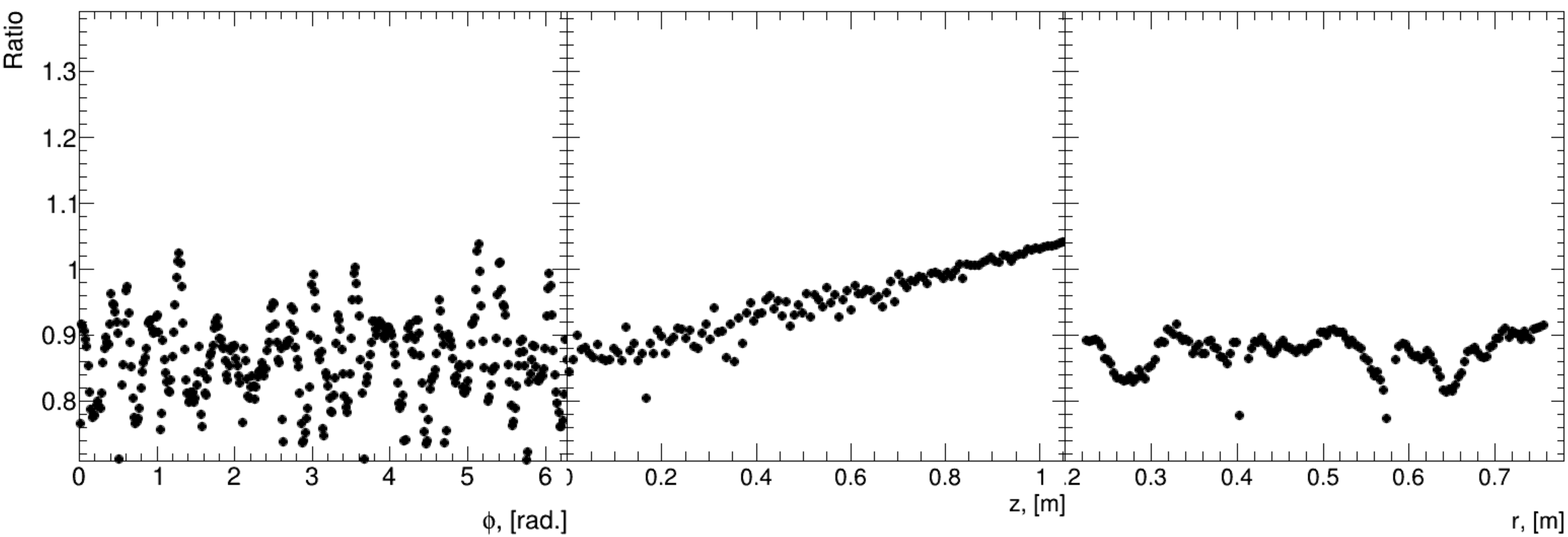



# Simulation Status

- Generated spacecharge models fairly realistic
  - real t and z-vertex distributions
  - spatially-varying gain and IBF
  - still limited by geant thresholds
- Generated distortions are reasonably matched to earlier models, some improvements still desired:
  - Update field maps to full-3D (chimney)
  - Simulate both TPC halves simultaneously (phi distortion from E field will change sign)
  - Study stability vs resolution with realistic inputs
- Observed fluctuations < 100 um on ~1 cm average distortions

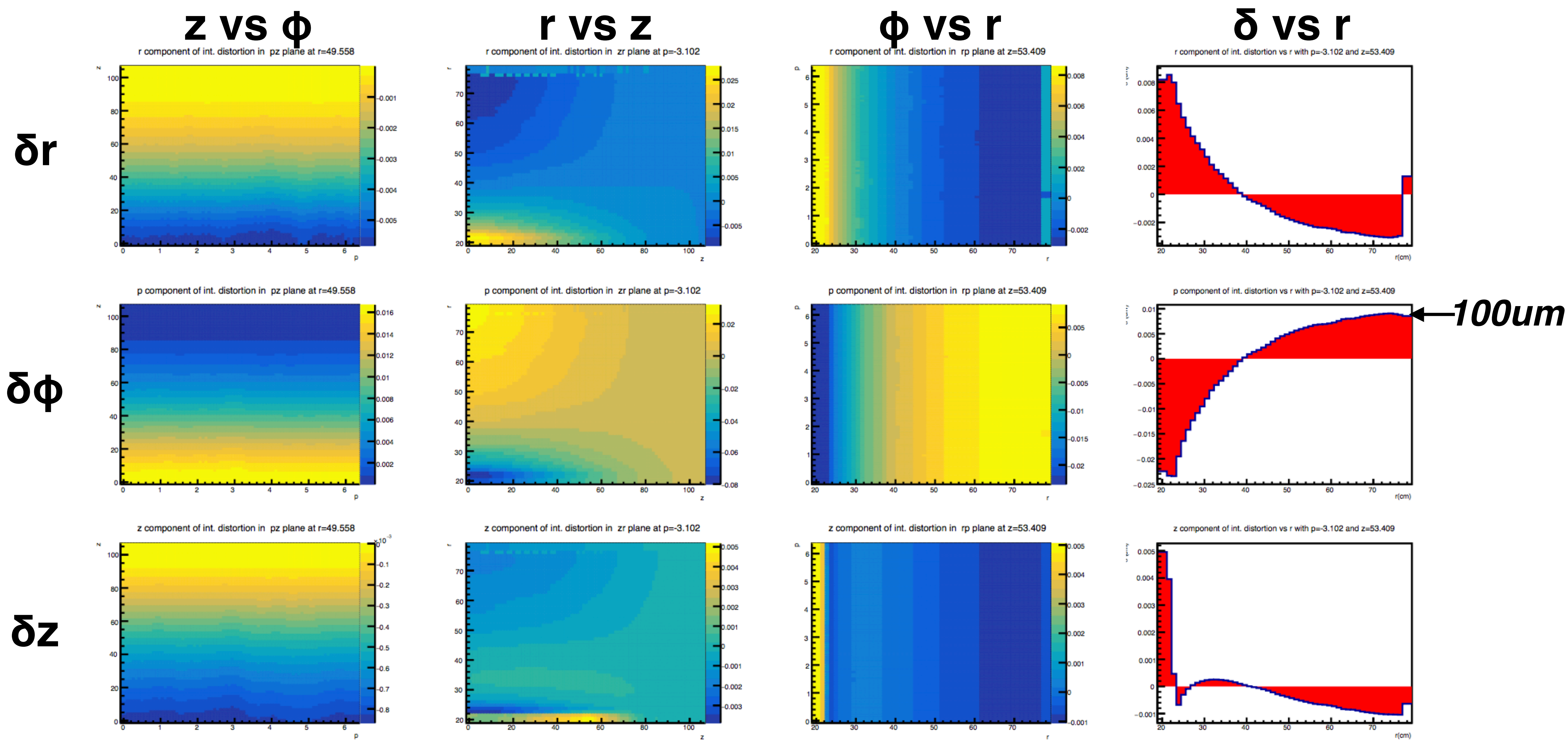
# Digital Current

- reco IBF model: fixed IBF fraction, charge reco is exact
- Still need to implement smearing and random processes
- reco/true shows ~10% difference due to primaries



# Residuals with perfect Dig. Current

- Distortion from IBF model without primaries does not get right average shape. (MC Truth)-IBF:




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

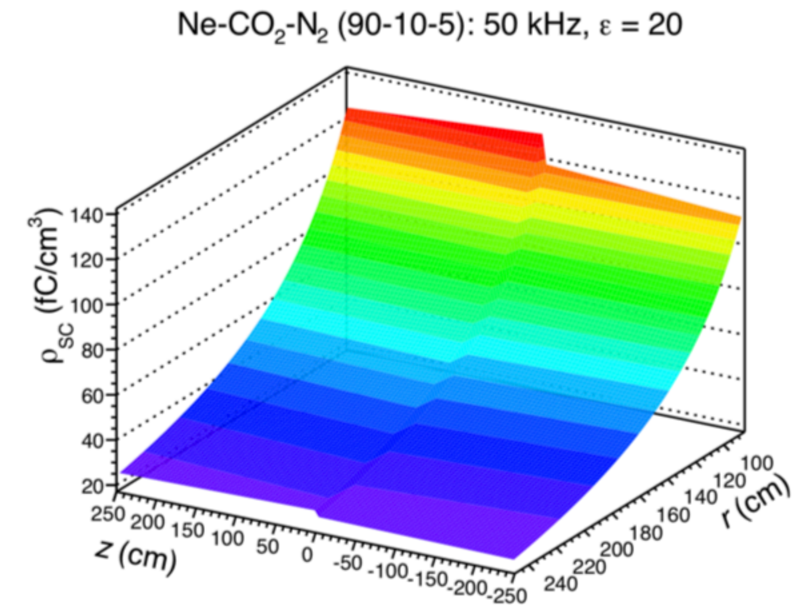
# Status and Outlook

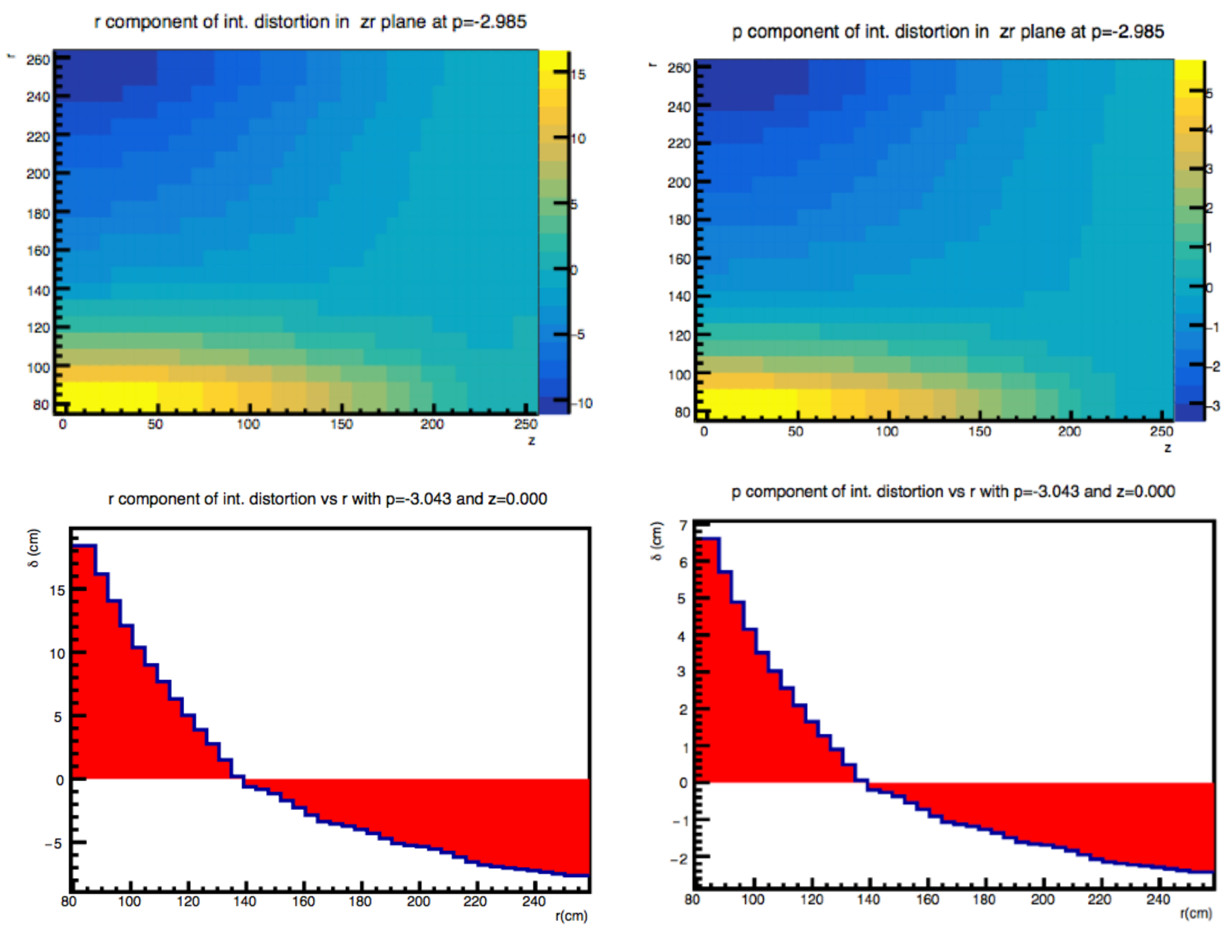
- Distortion generator and Fun4All integration mature enough to proceed with reconstruction studies.
  - r, phi, and z distortions calculated
  - full distortion and fluctuations from average generated,
  - small O(100) time series sets available
  - continuing to improve and optimize
- Fluctuations about the average distortion seem to be ~<100um
- Developing CM and Digital current reconstruction
- Exploring how well we can reconstruct average distortion
  - Tracks (and line lasers) can directly measure average distortion
  - CM pattern cannot measure static z-dependent structure
  - Digital current without primary model has no z structure, depends on Green's functions.

# Further Matching to ALICE

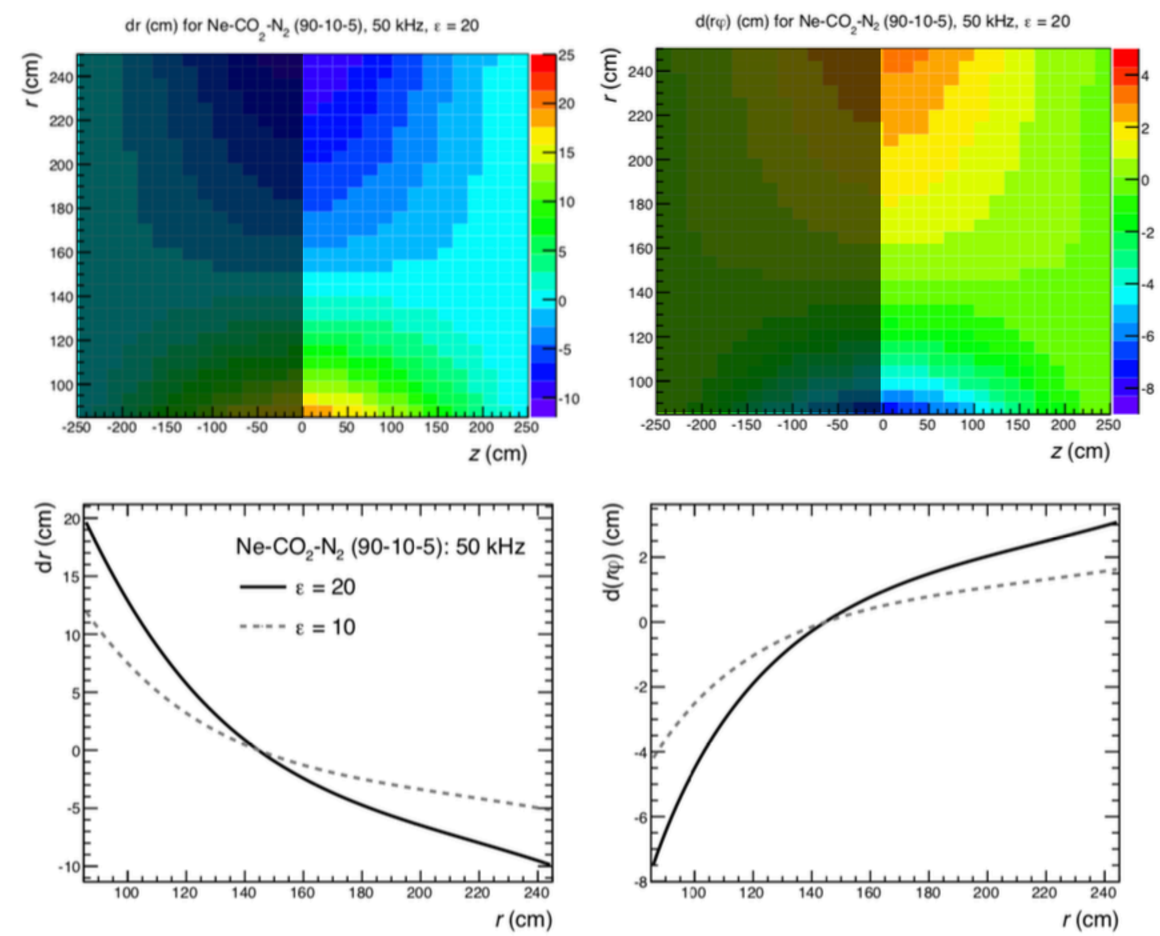
- Flipped field sign swaps phi sign, but magnitudes match to ~10%.
- These models don't have extra curvature at large R

$$\rho_{SC}(r,z) = \frac{a - bz + c\varepsilon}{r^d}$$



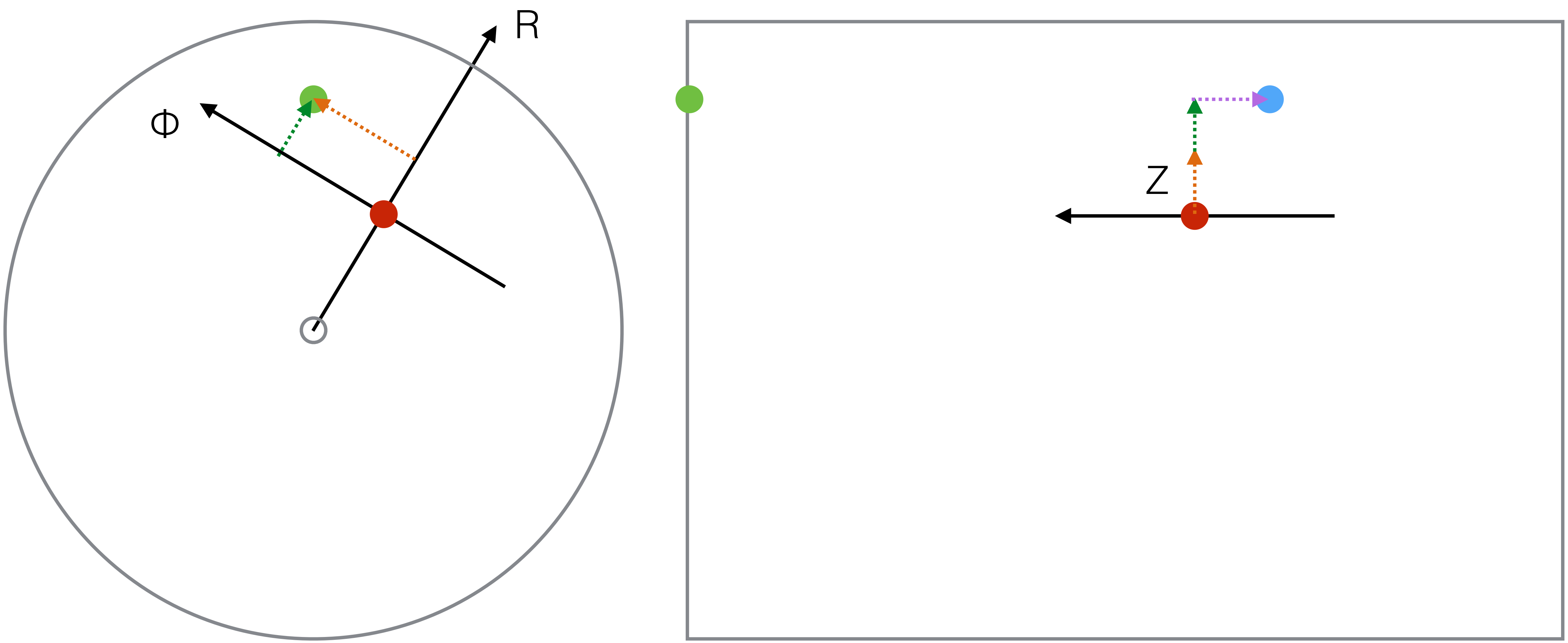

sPHENIX reconstruction of ALICE geometry and conditions, 2020




11-Jul-2019 ALICE: Space-charge calibration overview Ernst Hellbär - Goehte-Universität Frankfurt

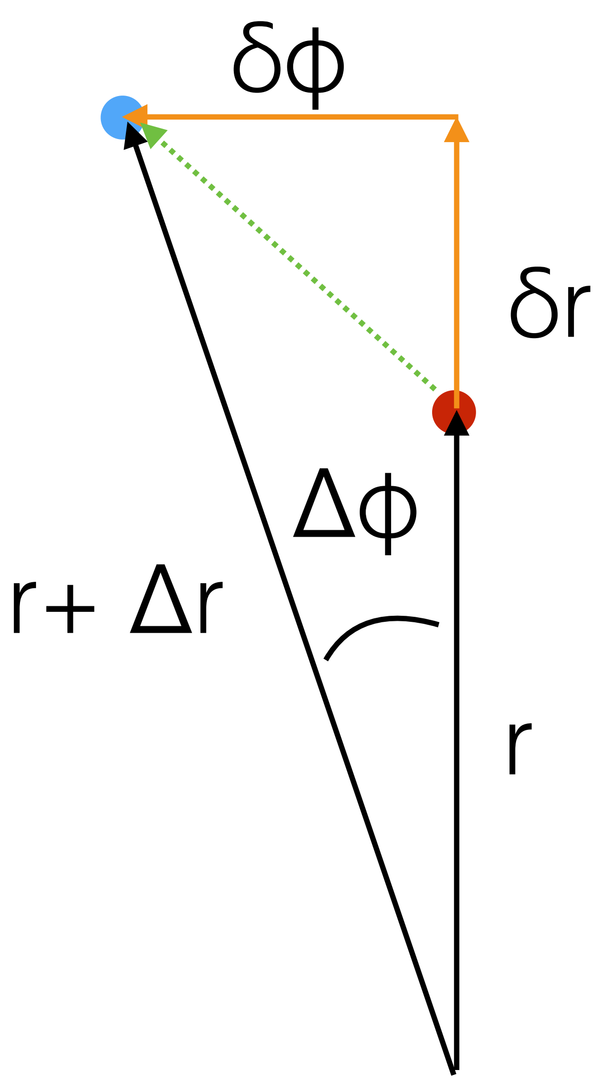
# Nomenclature

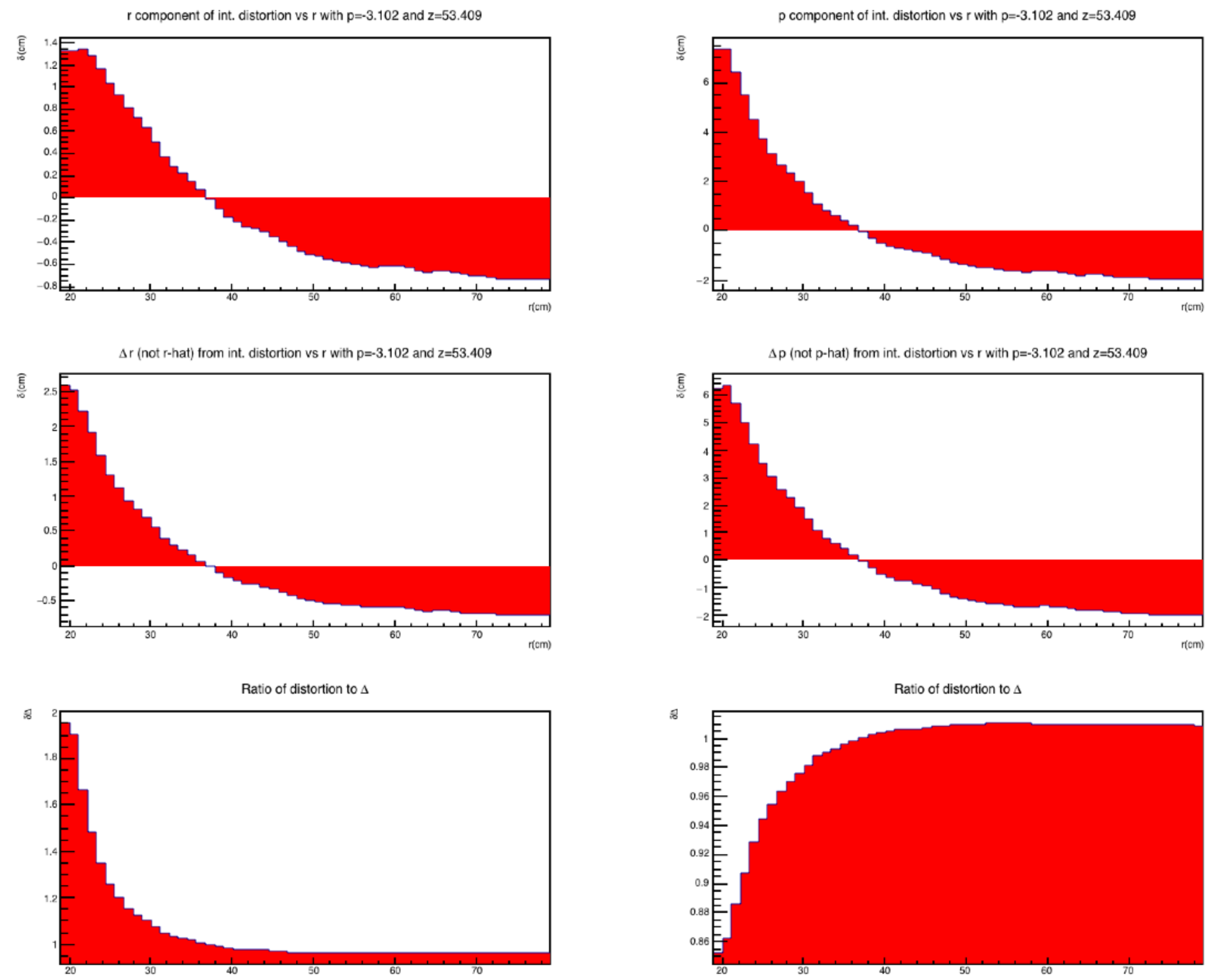
- Electron from ● arrives at ● and is naively assumed to have come (assuming straight-line drift) from ●
- Distortions are δϕ(cm) in the Φ-hat direction. δr in the r-hat, δz in the z-hat
- If small, rδϕ~Δϕ, δr~Δr.



# Comparison of Δ vs δ for sPHENIX

- Definitions of ϕ and R are signficiantly different at small R (large ωτ and hence ϕ distortions):

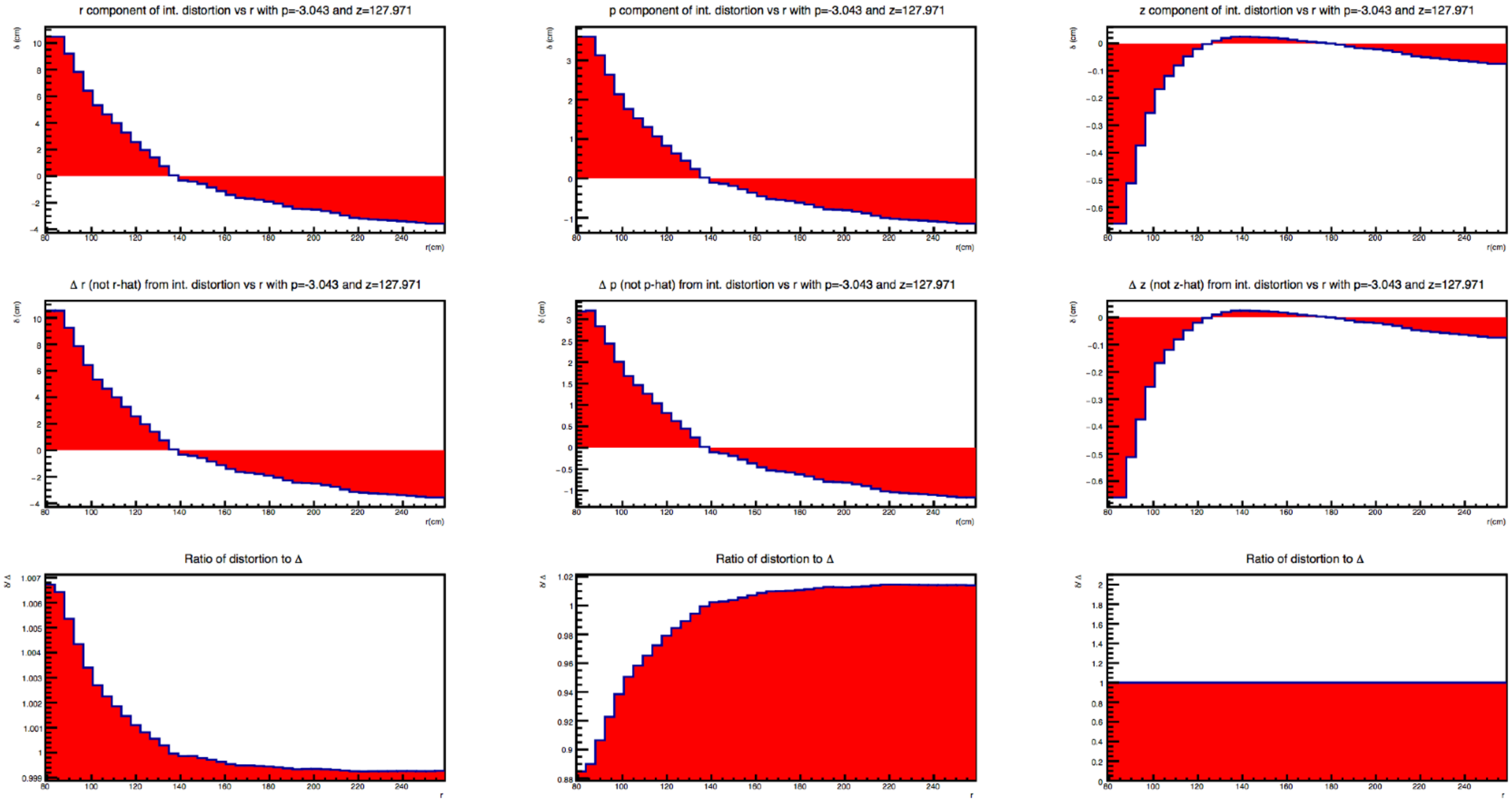



**Post-hoc slices of distortion. Top row: r-hat, ϕ-hat, z-hat. Bottom row Δ r, Δ ϕ, Δ z**
**Drifting grid of (rp)=(54 x 82) electrons with steps per file**
**Settings per file: HeuristicSc_sPHENIX2020.hist0.flat_B1.4_E-400.0.ross_phi1_sphenix_phislice_lookup_r26xp40xz40.di**
**Δ R=sqrt((r+δ r)^2+δ ϕ^2)**
**Δ ϕ=r * atan2(δ ϕ,r+δ r)**

# Comparison of Δ vs δ for ALICE

- Definition of R distortions not very sensitive. Definition of ϕ is, at small R:

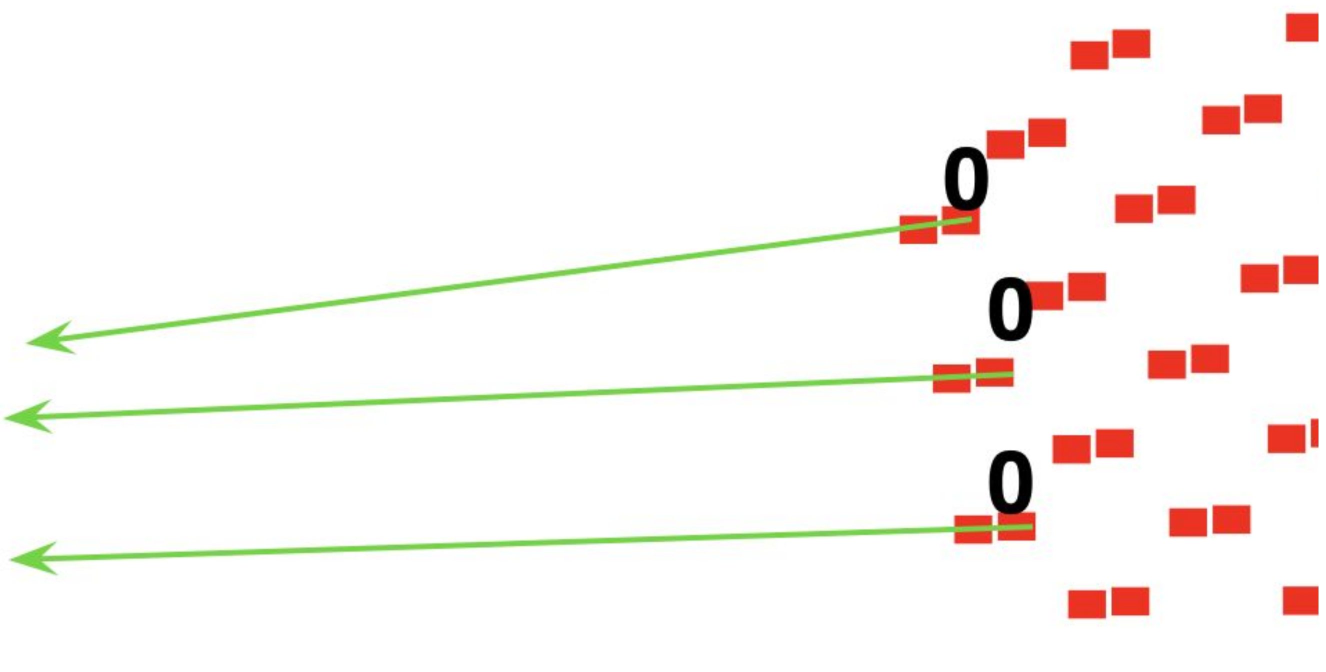



**Post-hoc slices of distortion. Top row: r-hat, ϕ-hat, z-hat. Bottom row Δ r, Δ ϕ, Δ z**
**Drifting grid of (rp)=(42 x 34) electrons with steps per file**
**Settings per file: HeuristicSc_ALICE.hist0.flat_B0.5_E-400.2.ross_phi1_alice_phislice_lookup_r20xp16xz20.distortion_map.hist.root**
**Δ R=sqrt((r+δ r)^2+δ ϕ^2)**
**Δ ϕ=r * atan2(δ ϕ,r+δ r)**

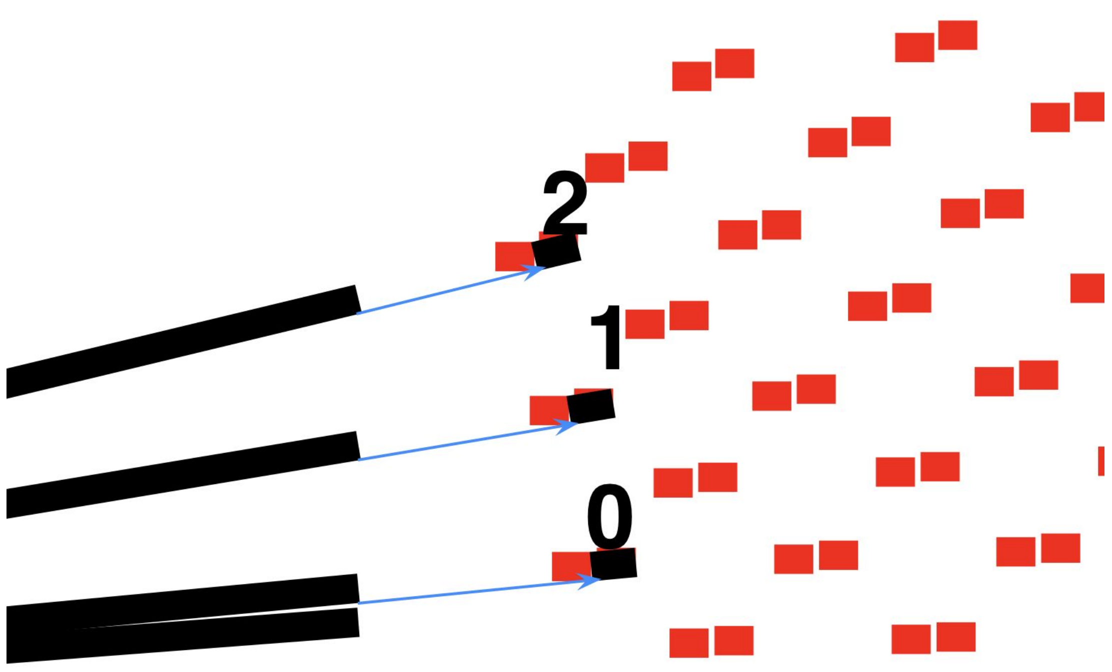
# Stripe Reconstruction

## Oth Pass Reconstruction

- Code to check if a point is on a stripe and if so, which stripe
- Encountered problem while testing: stripes weren't angled to go through the origin
- Corrected the angle, can now continue with stripe identification
- Next to work on: where is the nearest stripe to the point



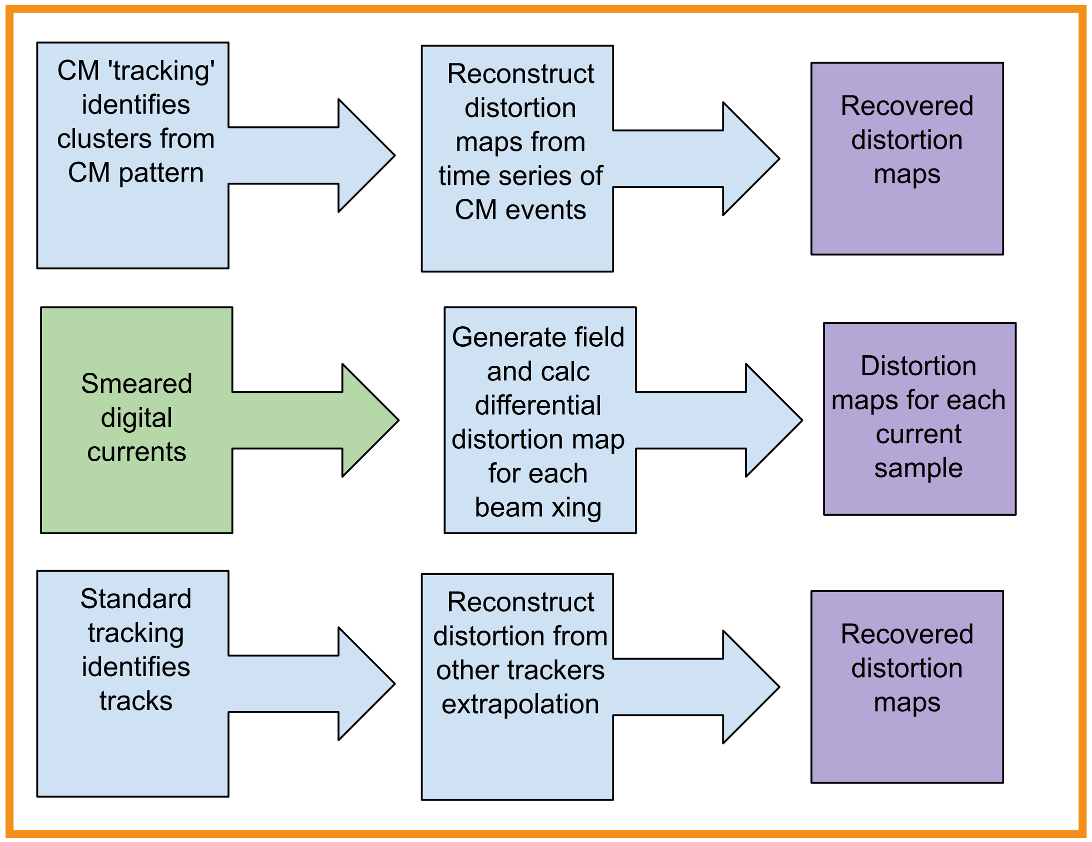

Hand-drawn arrows to approximately show that the angle of the stripes wouldn't go through the origin.

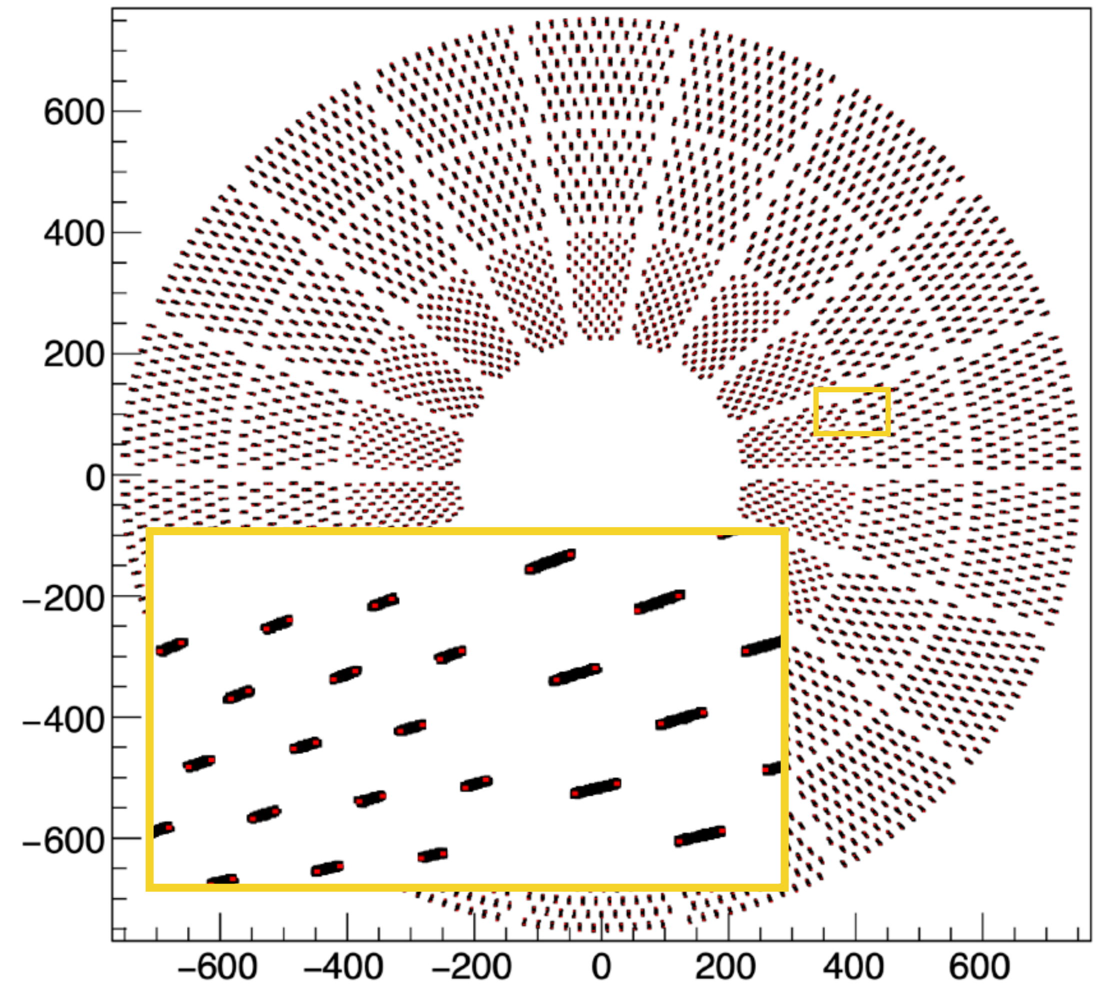



Blue hand-drawn arrows connecting to programmed lines to show that angle has been corrected.

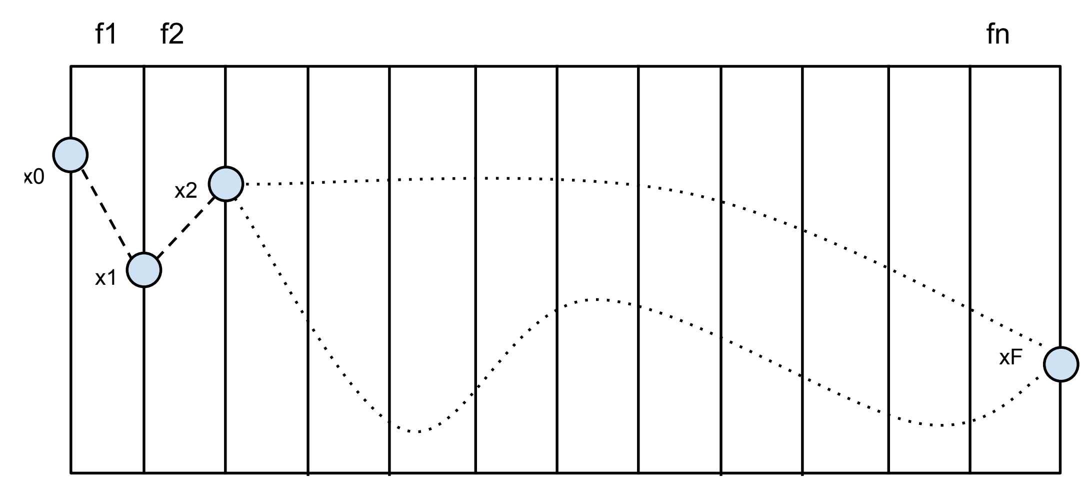
# Reconstructing Using Central Membrane

**Reco and Calibration**



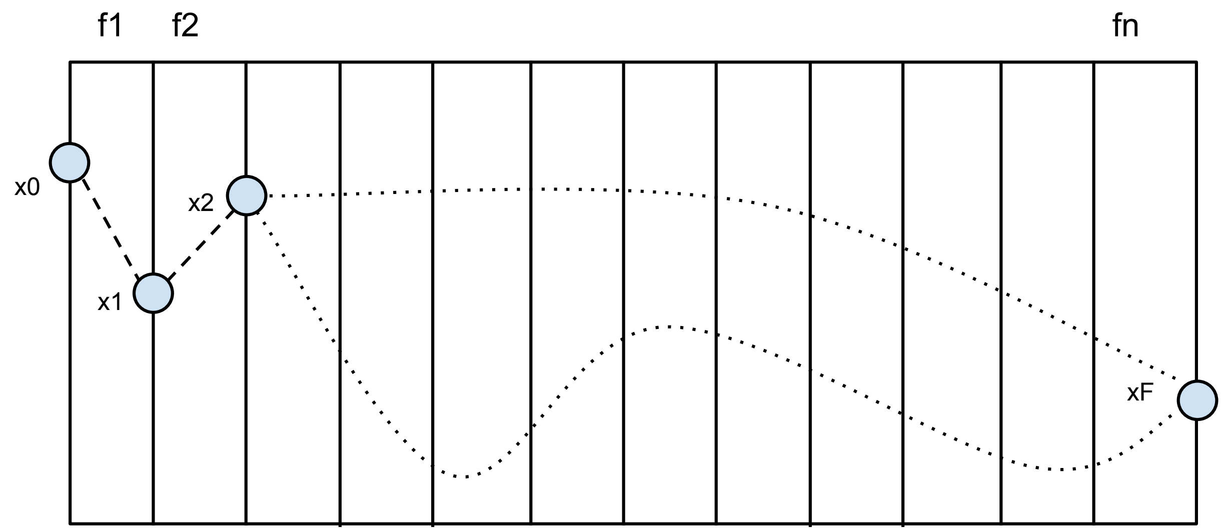




- Henry Klest distorting the CM hits in Fun4All
- Sara Kurdi matching them back to particular stripes
- Revising toy code for realistic case

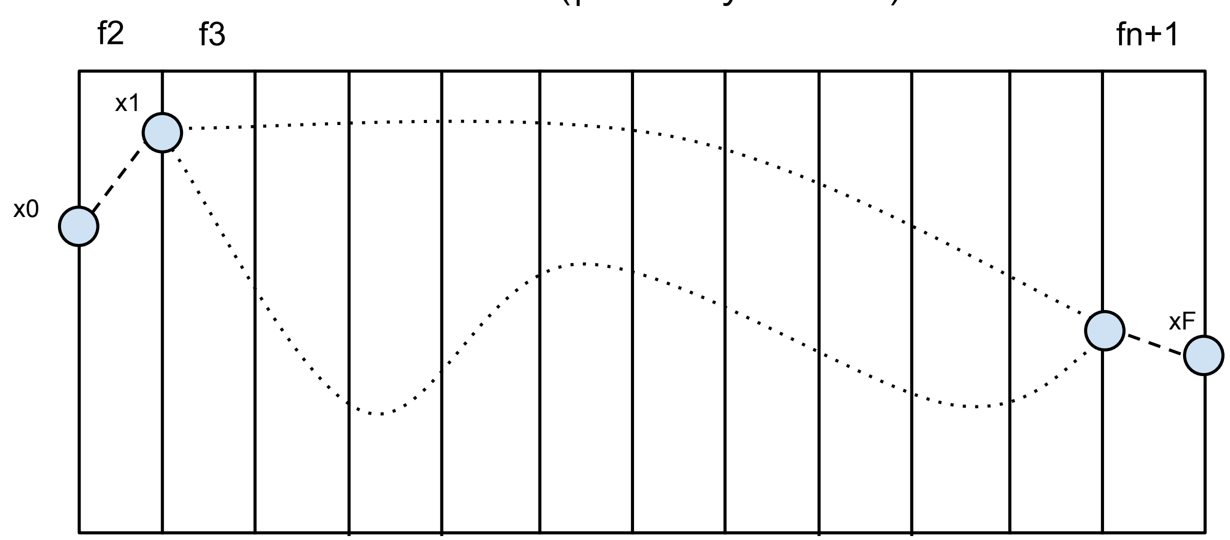


# Toy Model of CM Differential Reco

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):




(improved drawing courtesy Sara Kurdi)

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.

# Assumptions

- Distortions all move linearly with time (static distortions are okay, but everything in motion has the same velocity)
  - Static B and E distortions can't be measured with this method
- Distortion magnitudes are independent of z-position (distortions do not evolve due to z-position in the tpc, only position relative to spacecharge)
  - Not strictly true.  Boundary conditions present
- Perfect Reconstruction -- all electrons are magically associated with their true origin pad...

# Real Fieldmaps

- Phi-symmetric simulated E-Field + MC charge map
- Edges come from slightly different dimensions in field and distortion TPC

**$E_r$** **$E_\phi$** **$E_z$** **$\rho$**

**z vs ϕ**

**r vs z**

**ϕ vs r**