Drift-field distortions in the ALICE TPC in LHC Run 3

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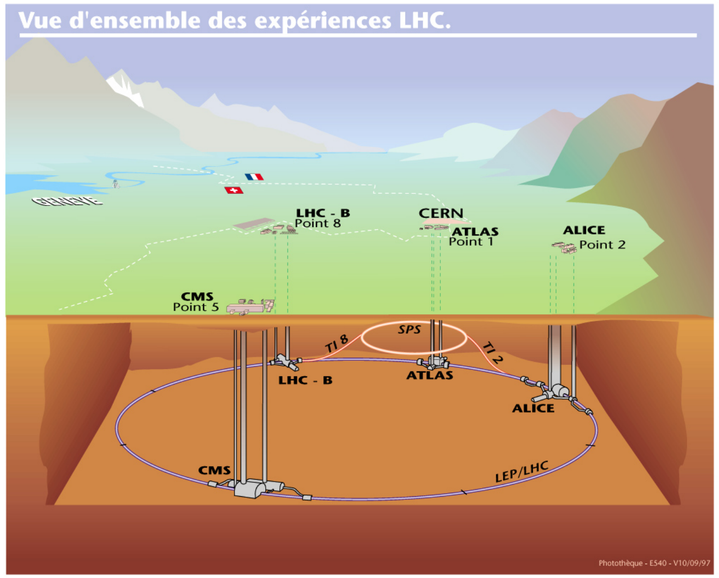
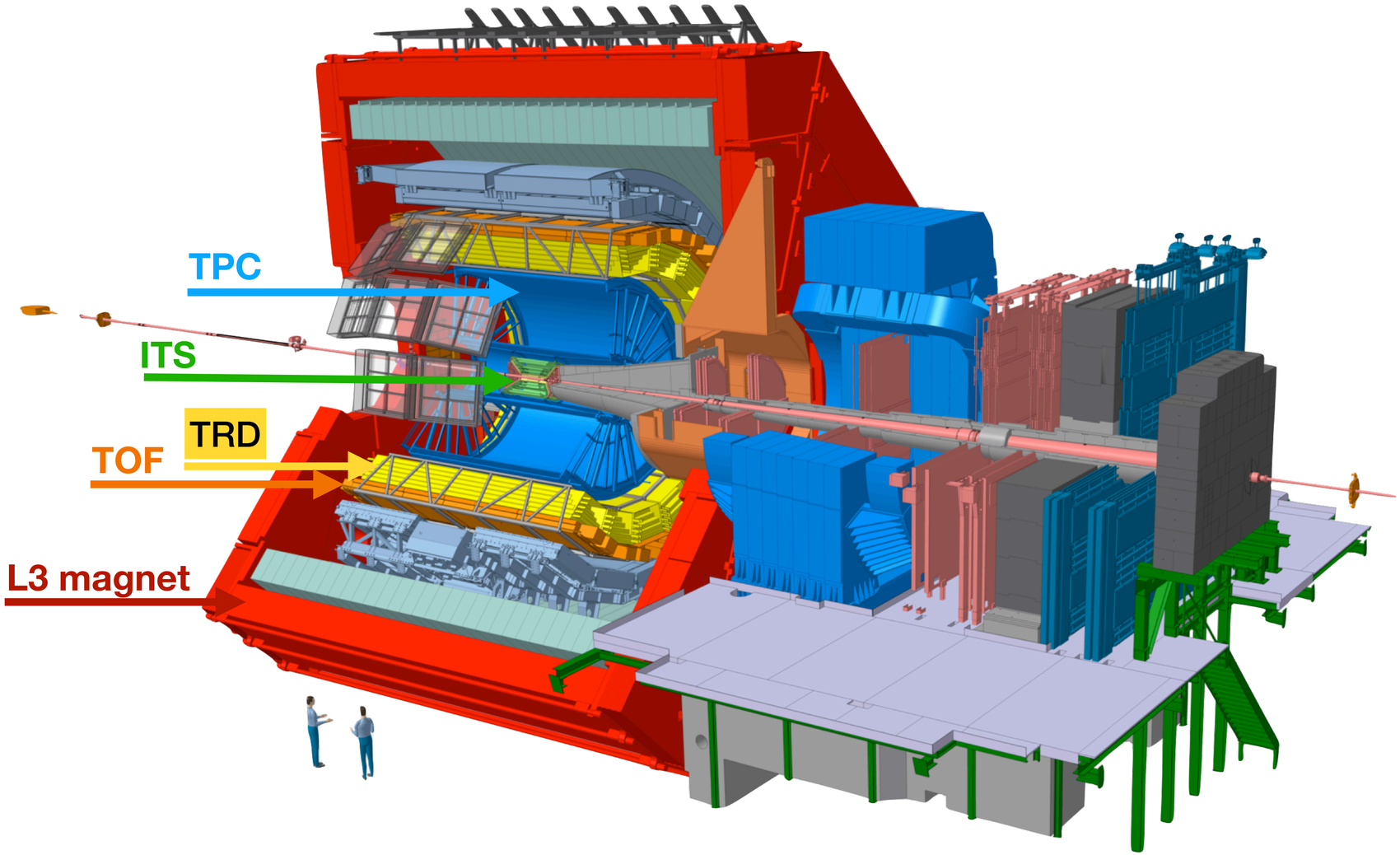
A Large Ion Collider Experiment

CERN LHC

One of the four large experiments at the CERN LHC





ALICE Time Projection Chamber

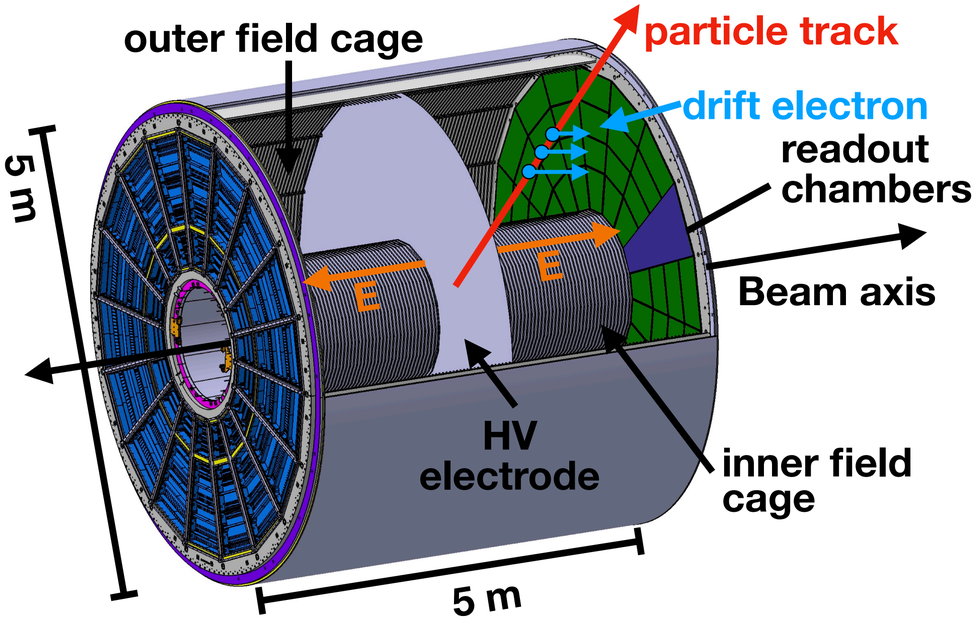
Main tracking and charged-particle identification (PID) detector

Properties

- Total length: 5m
- Radial dimension: $83\,\text{cm} < r < 250\,\text{cm}$
- Gas mixture: Ne-CO_2-N_2 (90-10-5)
- Central electrode and field cage
  - Uniform electric field 400 V/cm along beam (z) axis
- Electrons from ionization drift towards readout chambers

Run 3 upgrade

- Run 1 and Run 2: Multi-Wire Proportional Chambers
  ➡ ~1 kHz Pb—Pb: triggered readout
- Run 3 (2022): Gas Electron Multipliers (GEM)
  ➡ 50 kHz Pb—Pb: continuous readout



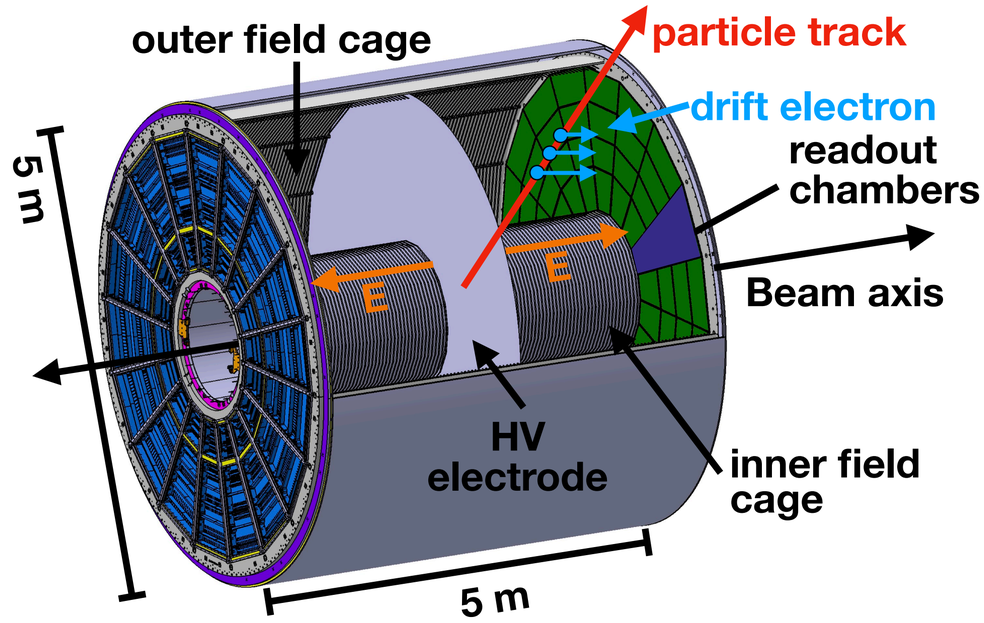
Overview of drift-field distortions

Sources of distortions

- IR dependent
  - Space-charge from ion back flow and primary ionization $\mathcal{O}$(10ms)
  - Time-dependent distortions at the sector edges at $\mathrm{rates} > 25\mathrm{kHz}$ $\mathcal{O}$(s to min)
  - Inner field cage charging up on C-side
    - Charging up: $\mathcal{O}$(min)
    - Discharge: $\mathcal{O}$(10min), $\mathcal{O}$(s)
- Semi static
  - Charging of GEM frames
- Static
  - Misalignment of electric and magnetic field
- Time dependent
  - “M-shape” distortions

➡ 50 kHz Pb—Pb: ~10 cm distortions

➡ 500 kHz pp: ~3 cm distortions



Space-Charge Distortions

Readout system

Multiplication of primary electrons

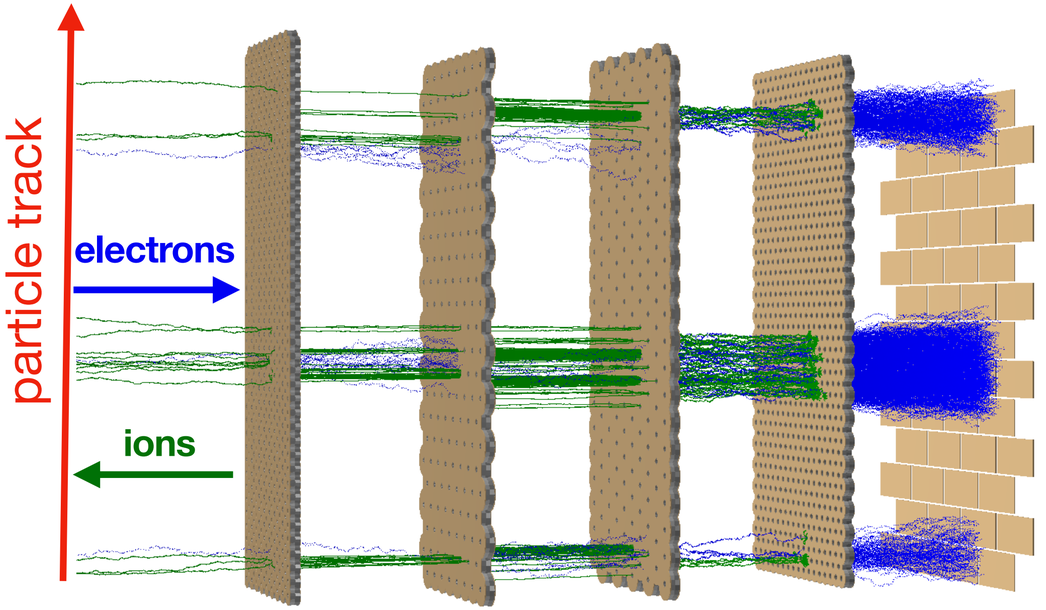
- Stacks of four Gas Electron Multipliers (GEM)

Ions from amplification enter drift volume

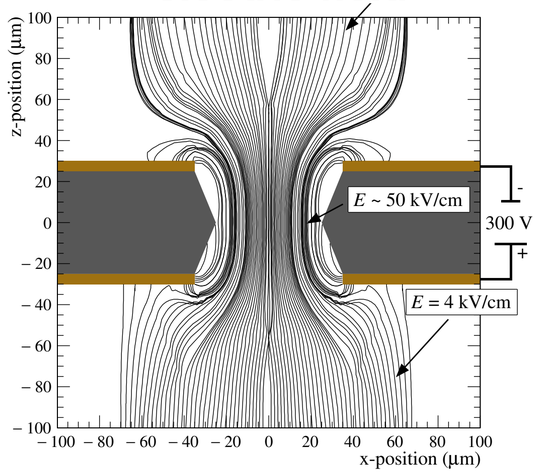
- Optimisation of $\langle IBF \rangle$ to ~1% (gain ~ 2000)
- Slow drift velocity compared to electrons
  - $T_{\mathrm{Electron}} \approx 100\,\mu\mathrm{s}$ vs $T_{\mathrm{Ion}} \approx 200\,\mathrm{ms}$
- Ions from *n* events piling up in the drift volume
  - e.g. 10.000 events for 50 kHz Pb—Pb

Space-charge density

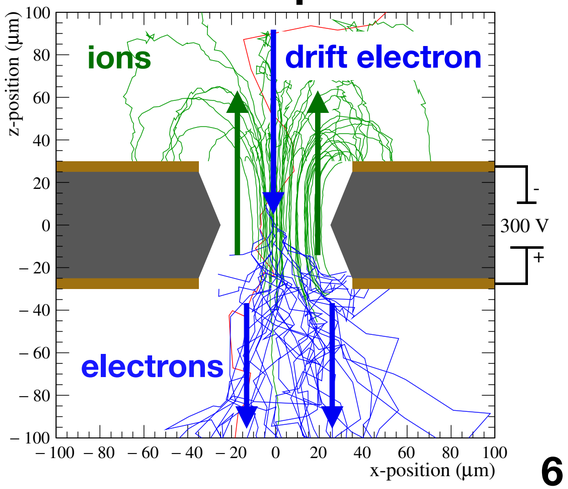
- **Back drifting ions cause space-charge accumulation in the drift volume of the TPC!**



electric field



electron amplification



Space-charge density simulations

Space-charge density

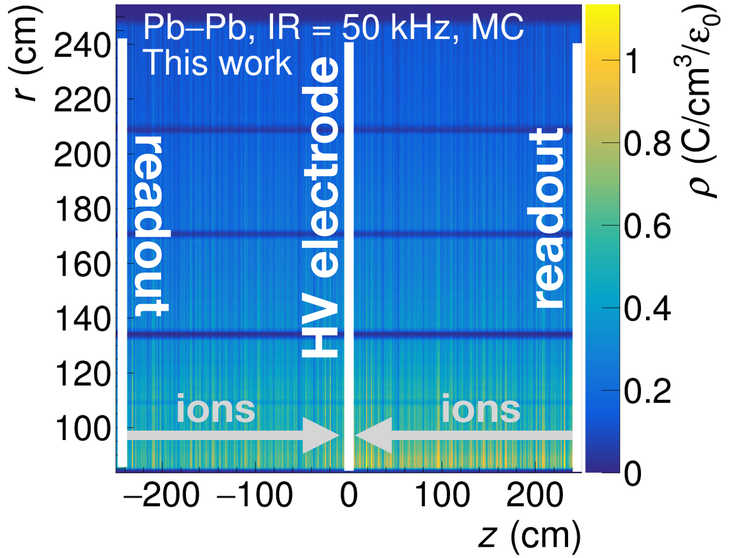
- 50 kHz Pb—Pb collisions
  - Nominal Pb—Pb rate in Run 3
- Ion drift time: 200 ms
- Variations in the number of produced particles in the collisions
  - Compressed time-dependent space-charge discs

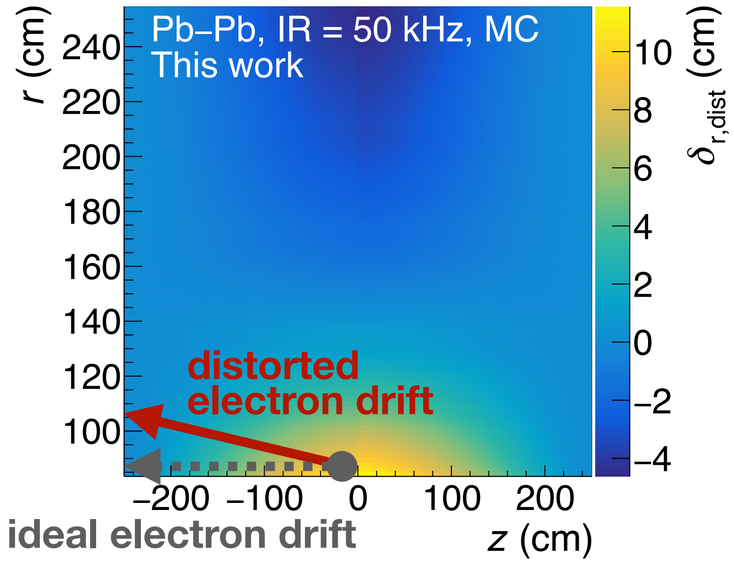
Space-charge distortions

- $\rho \rightarrow \Phi \rightarrow E_{(r,\phi,z)} \rightarrow \text{Langevin} : \delta_{(r,\phi,z)}$
- Position dependent
- Radial distortions up to 10 cm
  - Fluctuations $\mathcal{O}(\text{mm})$
  - Relevant on short time scales $\mathcal{O}(\text{ms})$

Space-charge correction

1. 3D-correction maps needed
2. Precise estimate for space-charge density needed





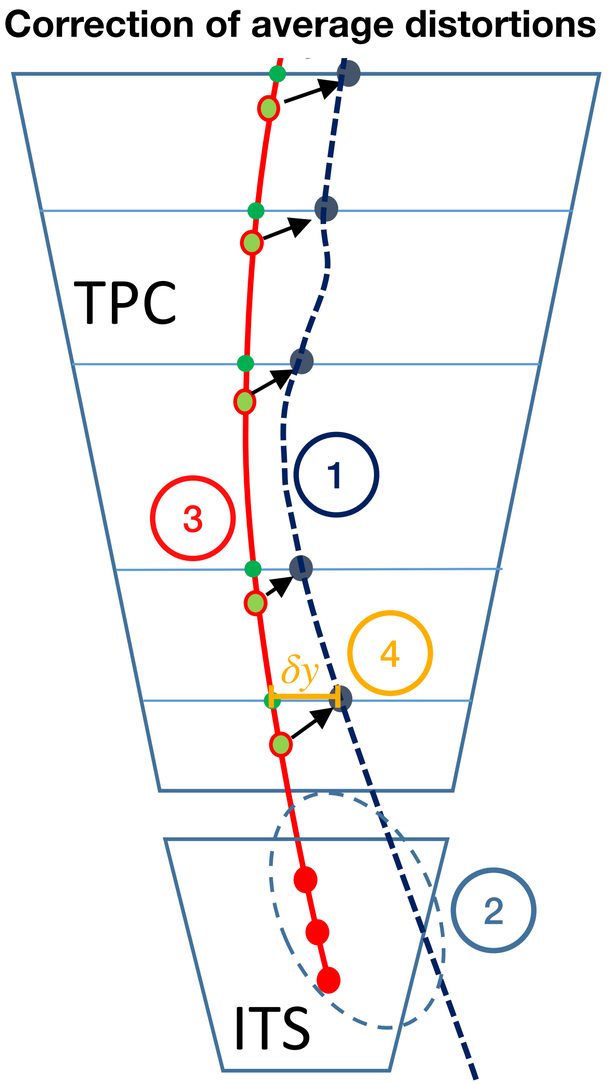
Data driven approach to extract corrections

Correction of average distortions

- Already performed during LHC Run 2

Procedure

1. Reconstruction of distorted TPC track
   - Tracking with relaxed tolerances
2. Track matching with ITS (and TRD-TOF) track segments
3. Residuals between TPC clusters and reference ITS track
   - Measurement of $\delta y, \delta z$
   - Storage in 3D map



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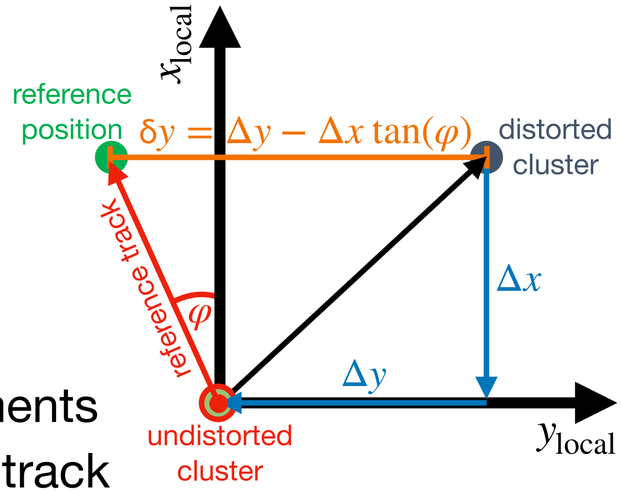
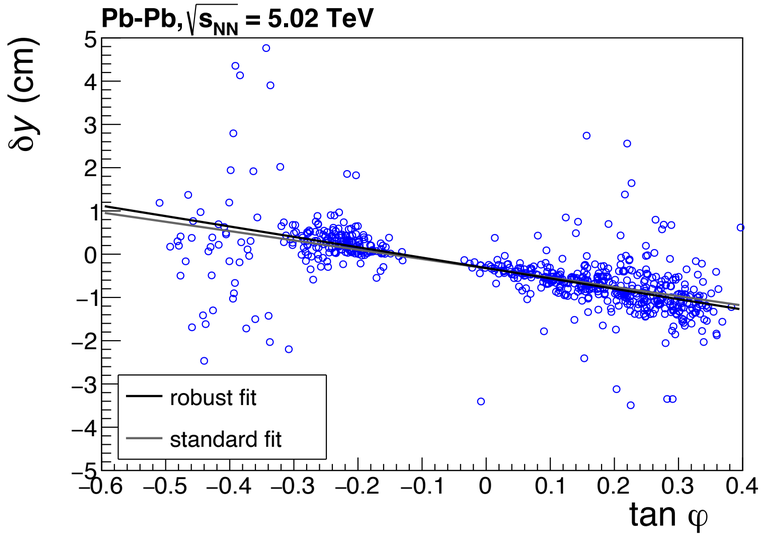
4. Collect data for full TPC volume $\left(\mathcal{O}(\mathrm{s})\right)$
   - $\delta y, \delta z \rightarrow \Delta x, \Delta y, \Delta z$





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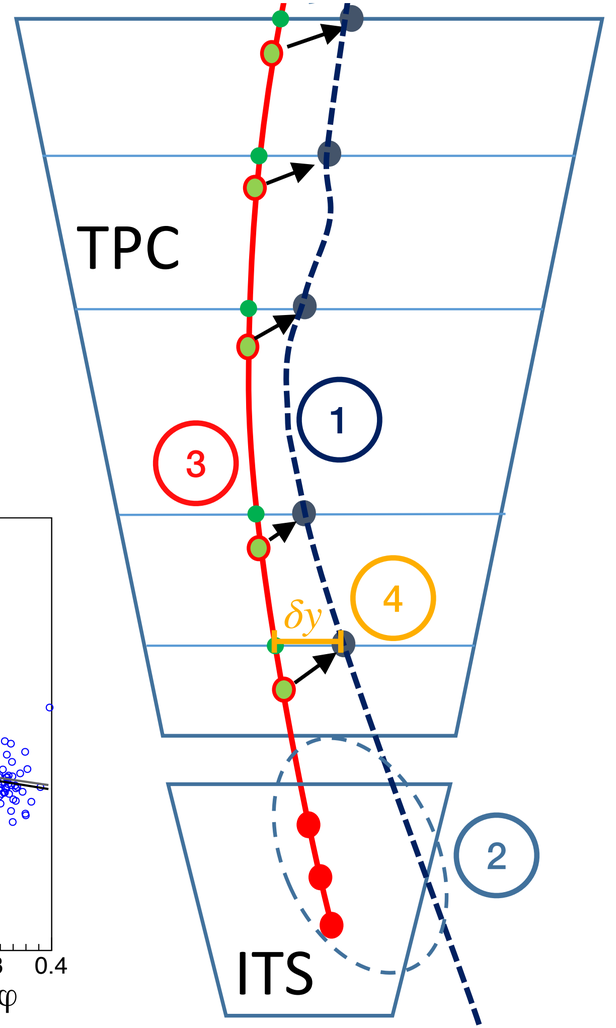

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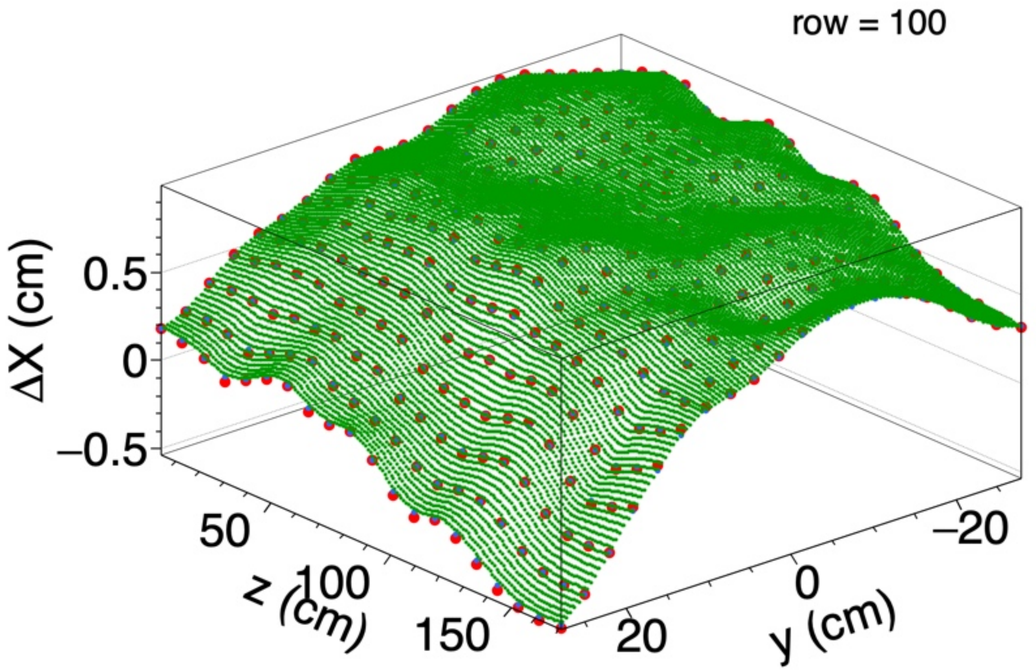
4. Collect data for full TPC volume $\left(\mathcal{O}(\mathrm{s})\right)$
   - $\delta y, \delta z \rightarrow \Delta x, \Delta y, \Delta z$
5. Smooth parametrisation of extracted corrections with 2D splines

- 2D spline in y-z-plane for each pad row

Example of 2D spline for one pad row



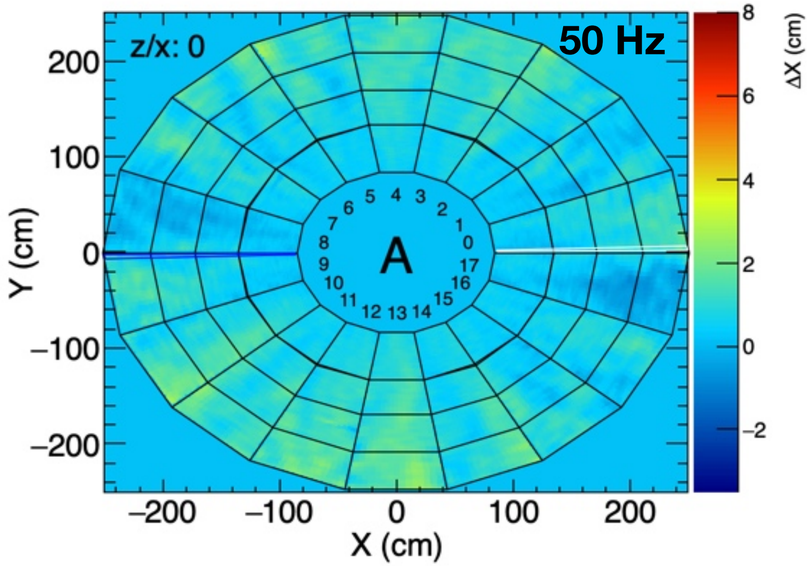
Extracted correction maps for Pb—Pb

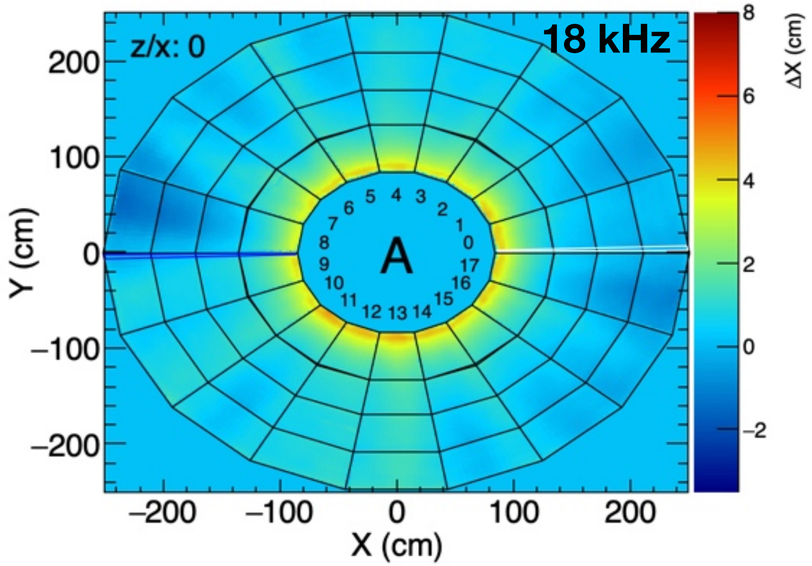
Low IR (50 Hz)

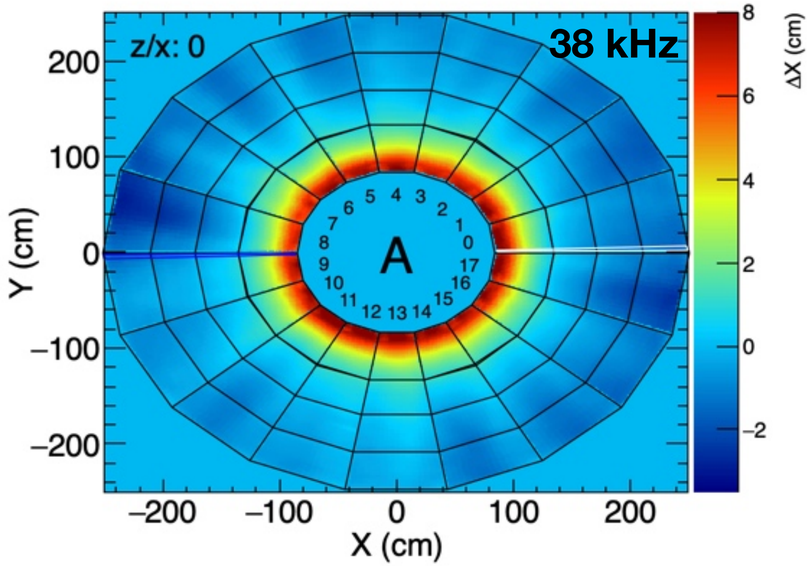
- IR independent distortions
- Static distortions
  - ExB misalignment etc.

High IR

- IR dependent distortions
  - Space-charge
  - Large distortions at inner radii



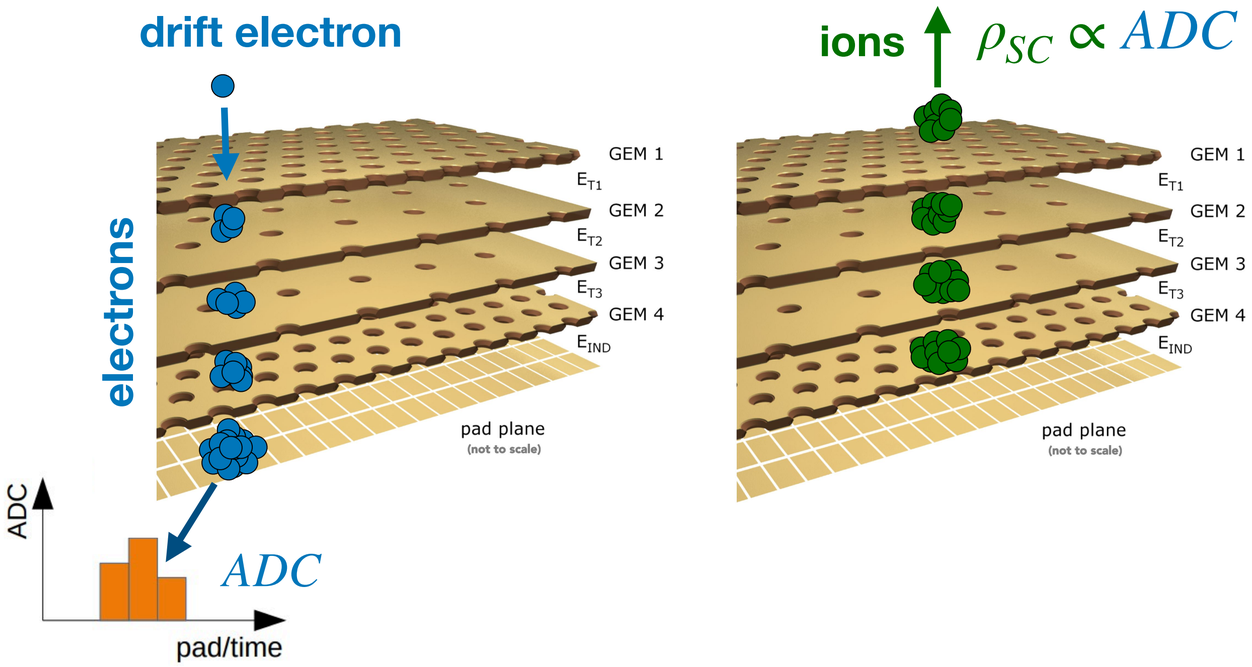


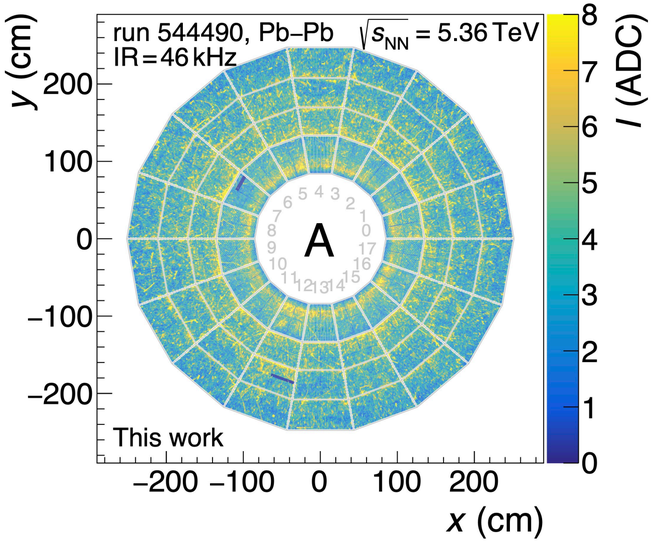


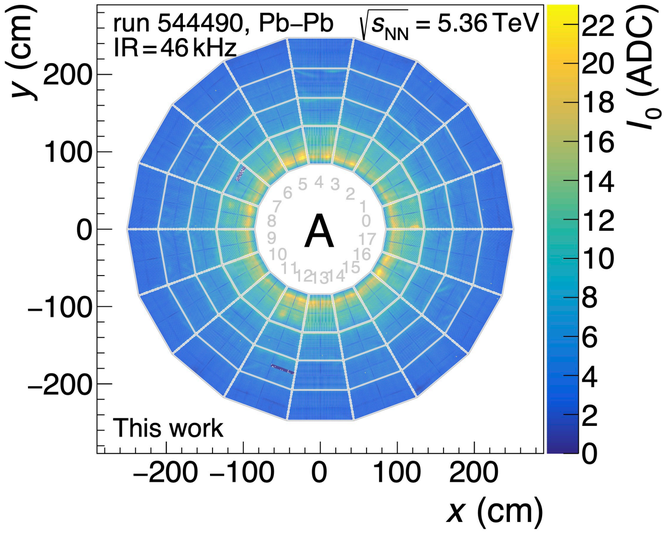
Estimating space-charge density

Integrated digital currents (IDCs)

- Integration of *ADC* values over ~1ms
- Proportional to space-charge density
- Online processed
  - Storage in the CCDB (calibration database)







Estimating space-charge density

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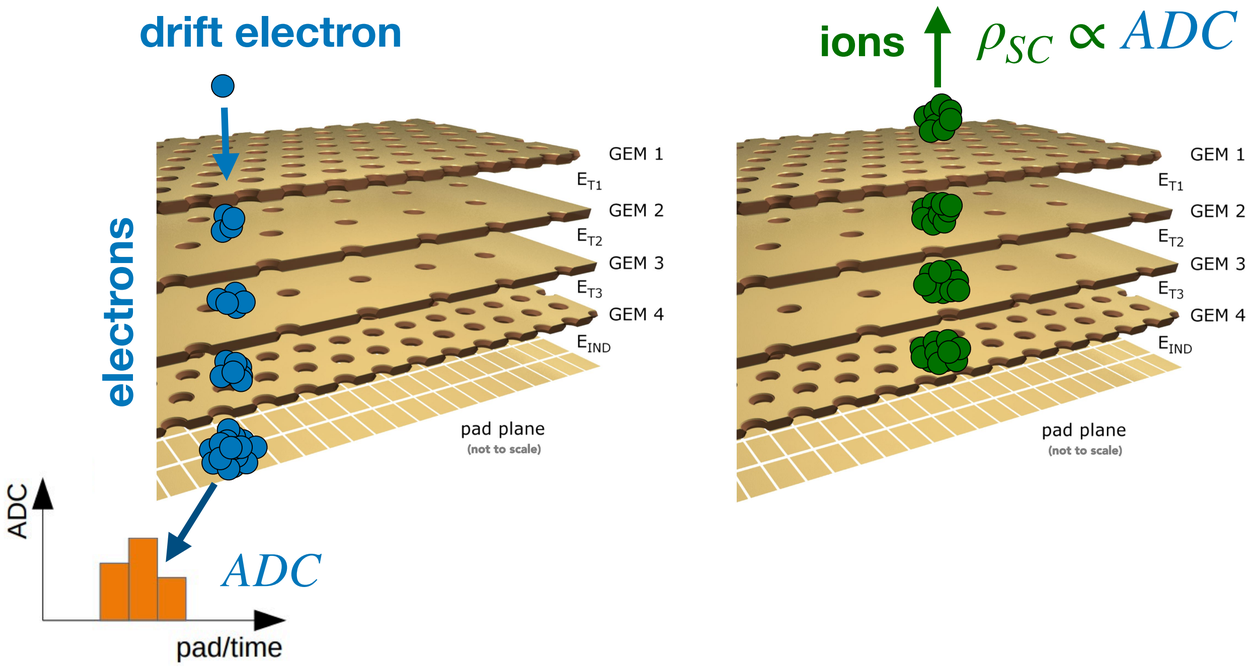
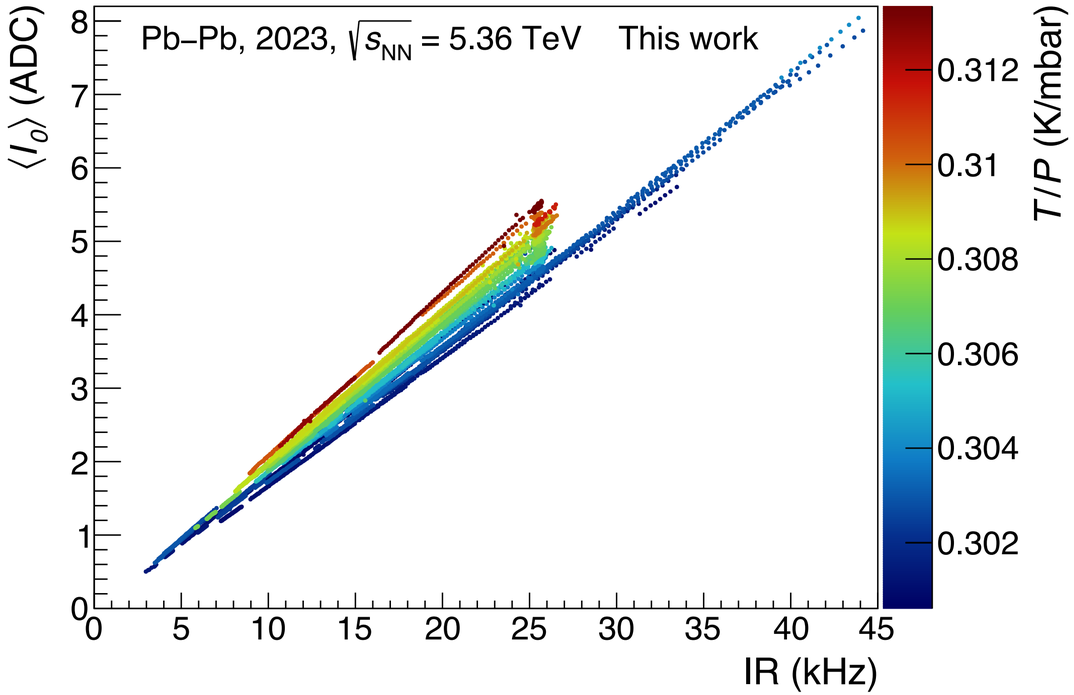
- Temperature and pressure dependence followed

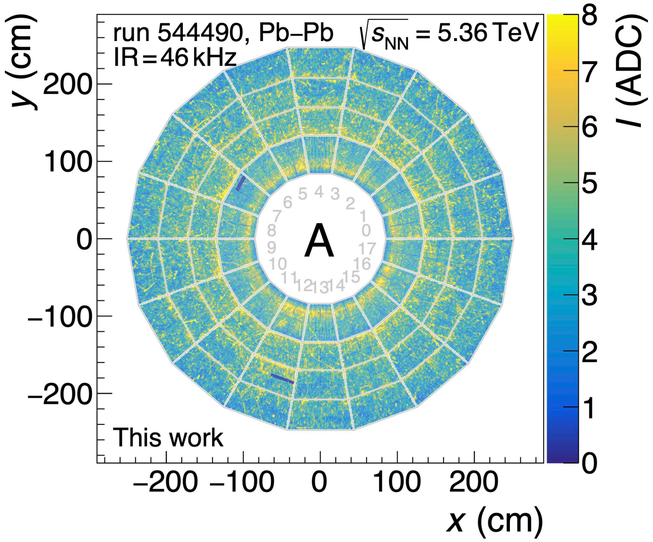




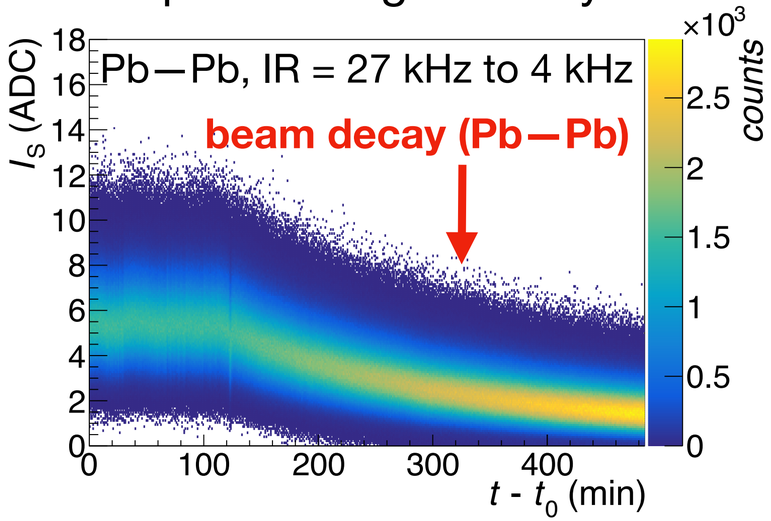
Estimating space-charge density

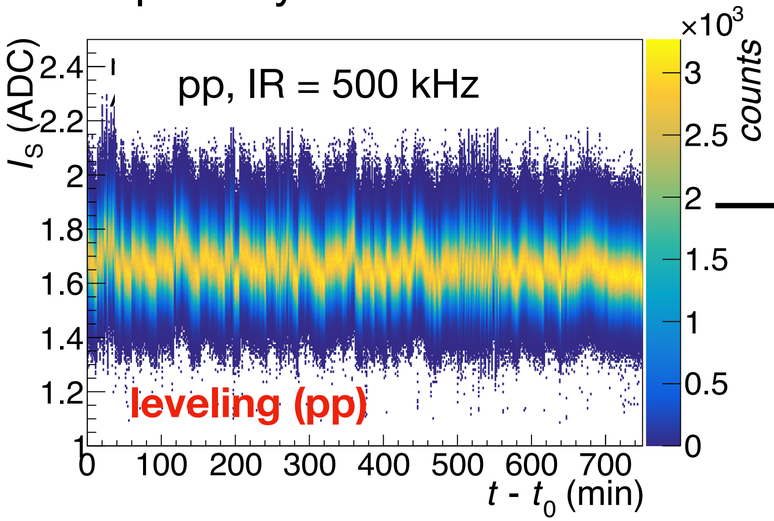
Integrated digital currents (IDCs)

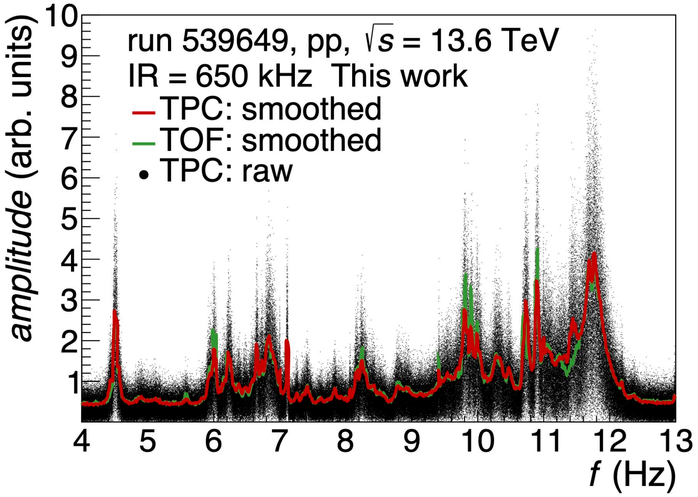
- Integration of *ADC* values over ~1ms
- Proportional to space-charge density
- Online processed
  - Storage in the CCDB (calibration database)
- Temperature and pressure dependence followed
- $I_S(t)$: Mean IDC for each ms → Input for space-charge corrections
  - Beam decay, levelling, beam oscillations in pp
  - Space-charge density fluctuations especially in Pb—Pb



beam oscillation (pp)



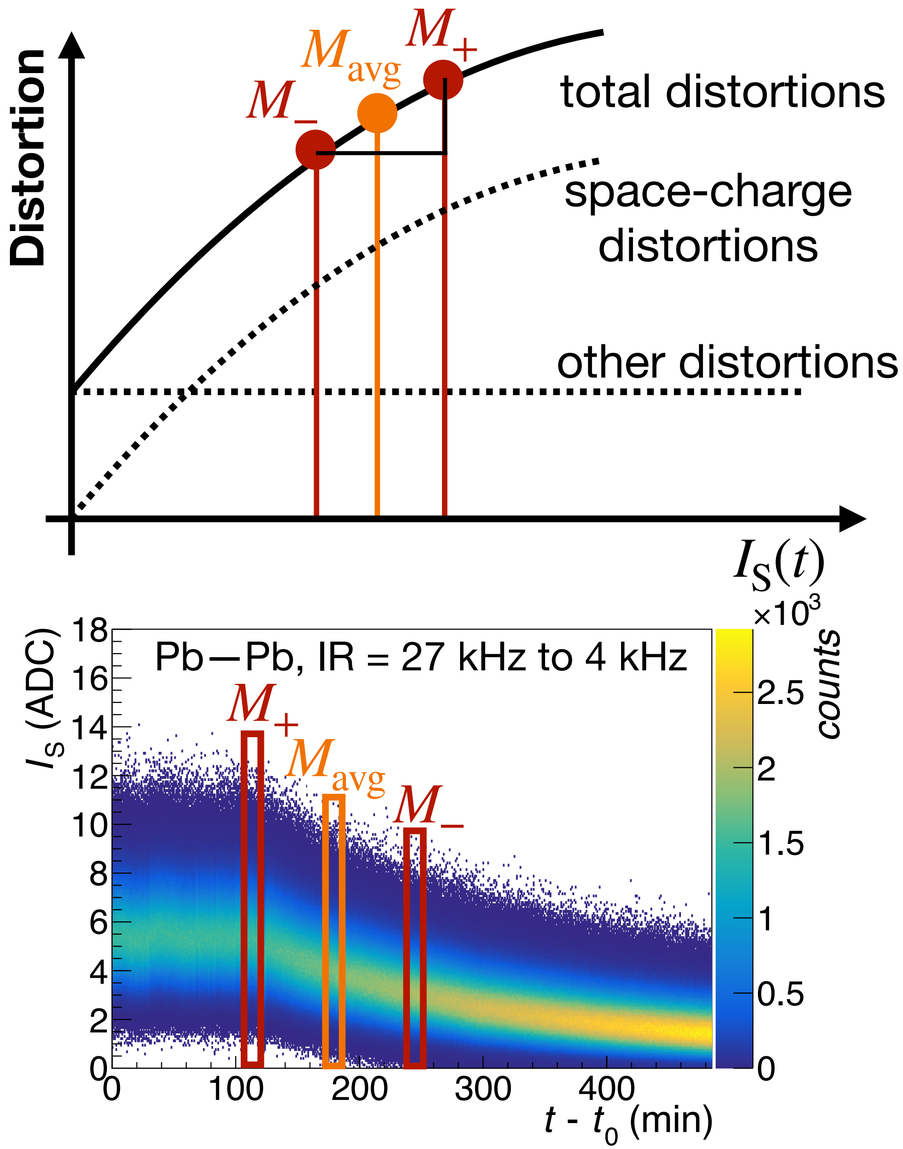




Space-charge correction procedure

Space-charge correction

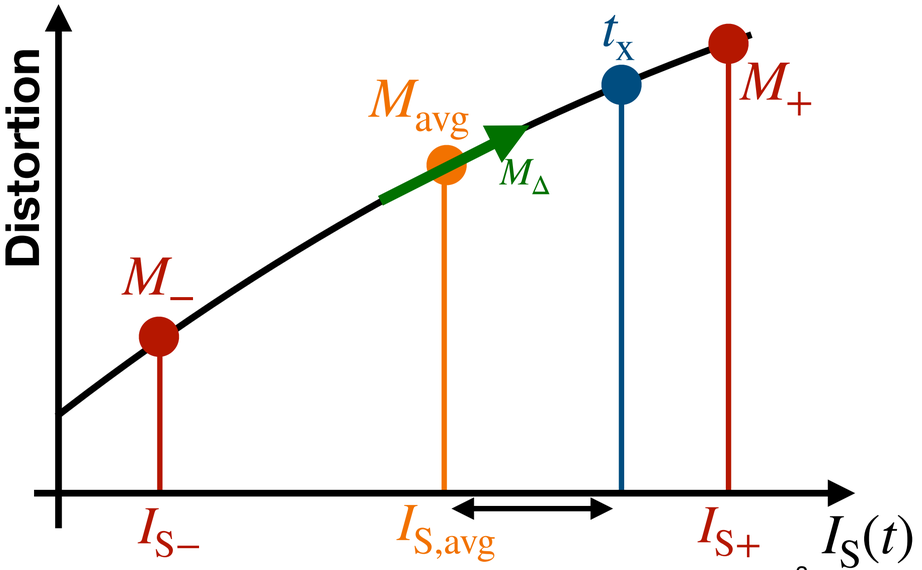
- Input: 3 (or 2) correction maps
- M_{avg}: Average space-charge correction
- M_{+} und M_{-}
  - Correction maps for slightly higher/lower space-charge density



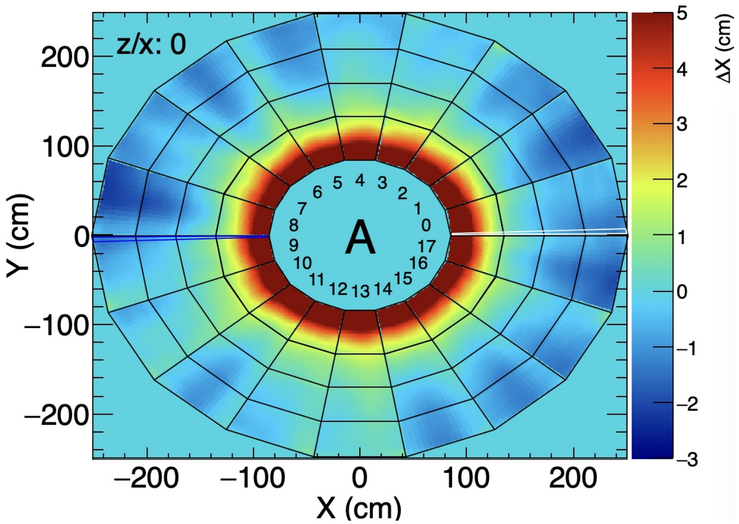
Time-dependent space-charge correction

Creation of time-dependent corrections

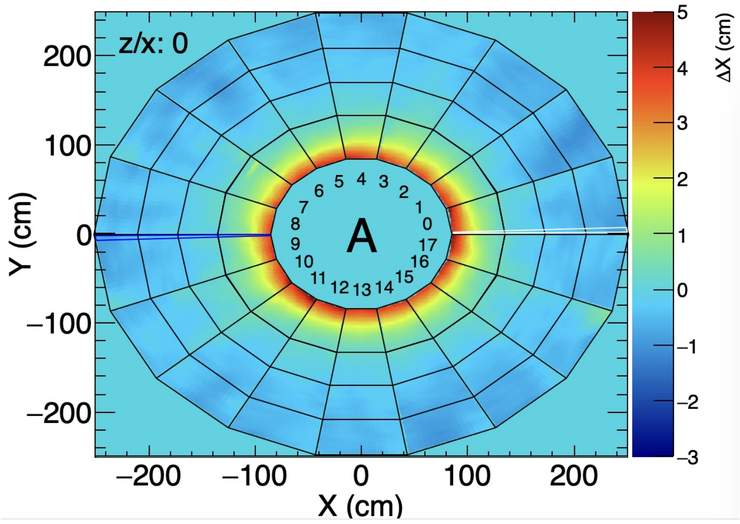
- Derivative correction map: $M_\Delta = \dfrac{M_+ - M_-}{I_{S+} - I_{S-}}$
- Linear combination with time-dependent scaling parameter $S(t)$
  - $M(t) = M_{\text{avg}} + M_\Delta \cdot S(t)$

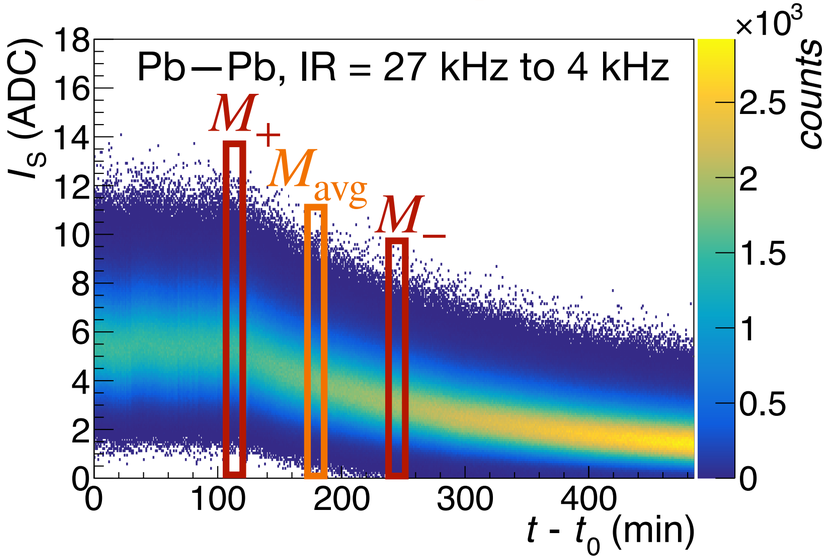


M_{avg}



$M_+ - M_-$



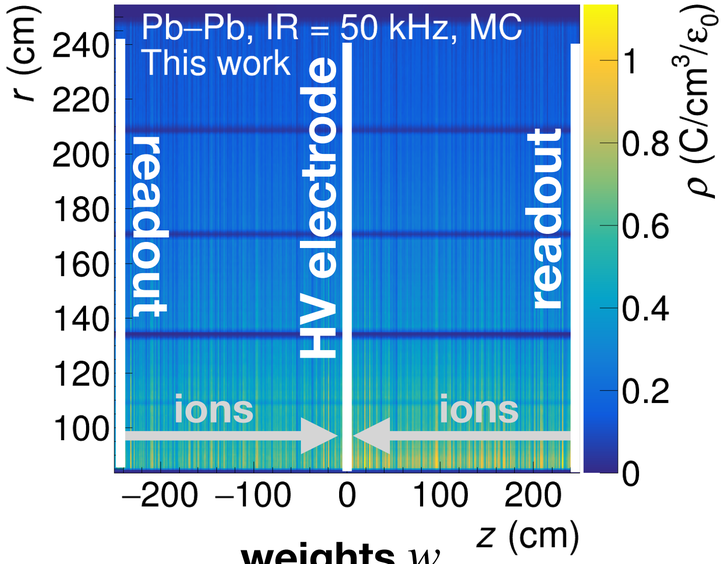


Time-dependent space-charge correction

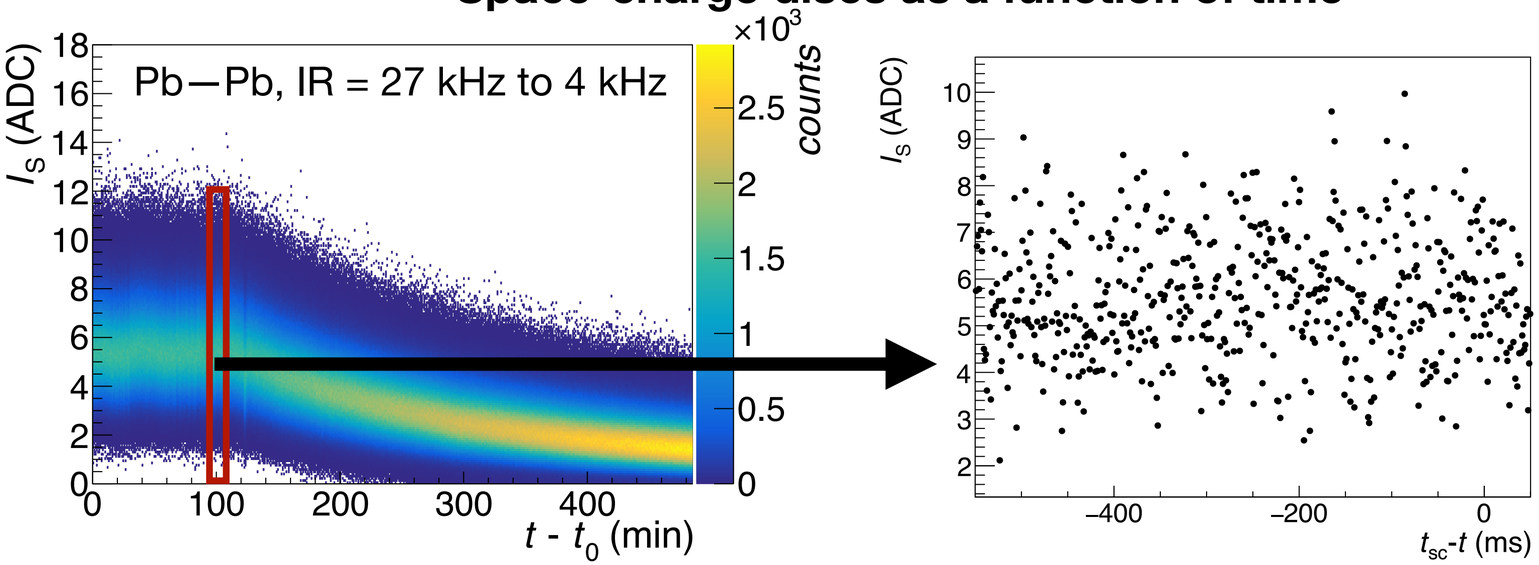
Time-dependent scaling factor $S(t)$

- Weighted mean space-charge density for time t
  - $S(t) = \dfrac{\sum_{t_{sc}=t_c}^{t} w(t_{sc}-t)\cdot I_S(t_{sc})}{\sum_{t_{sc}=t_c}^{t} w(t_{sc}-t)} - \langle I_{S,avg}\rangle$

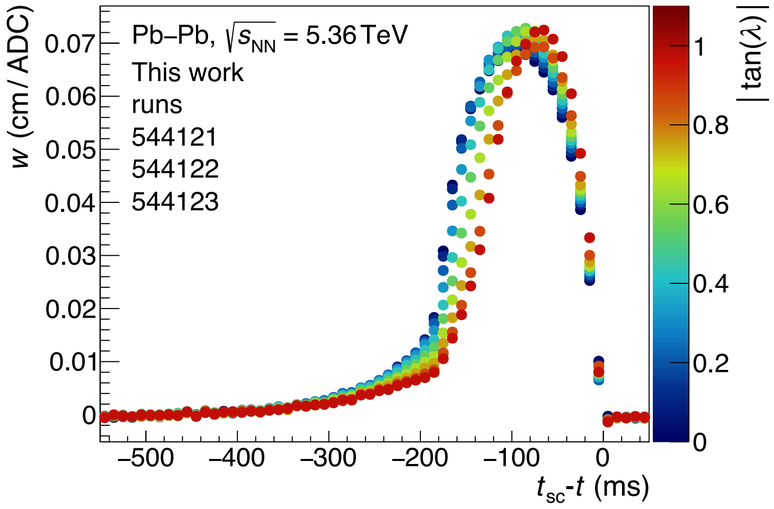
Simulation: space-charge discs



Space-charge discs as a function of time



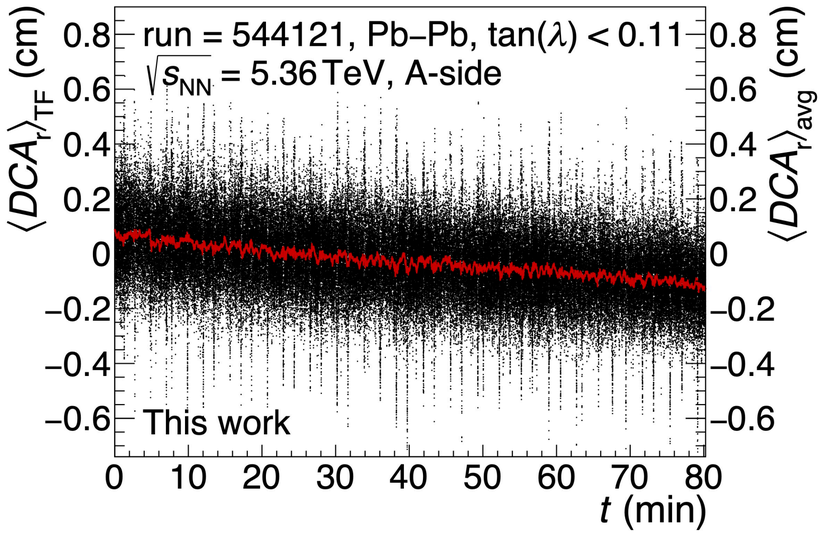
weights w

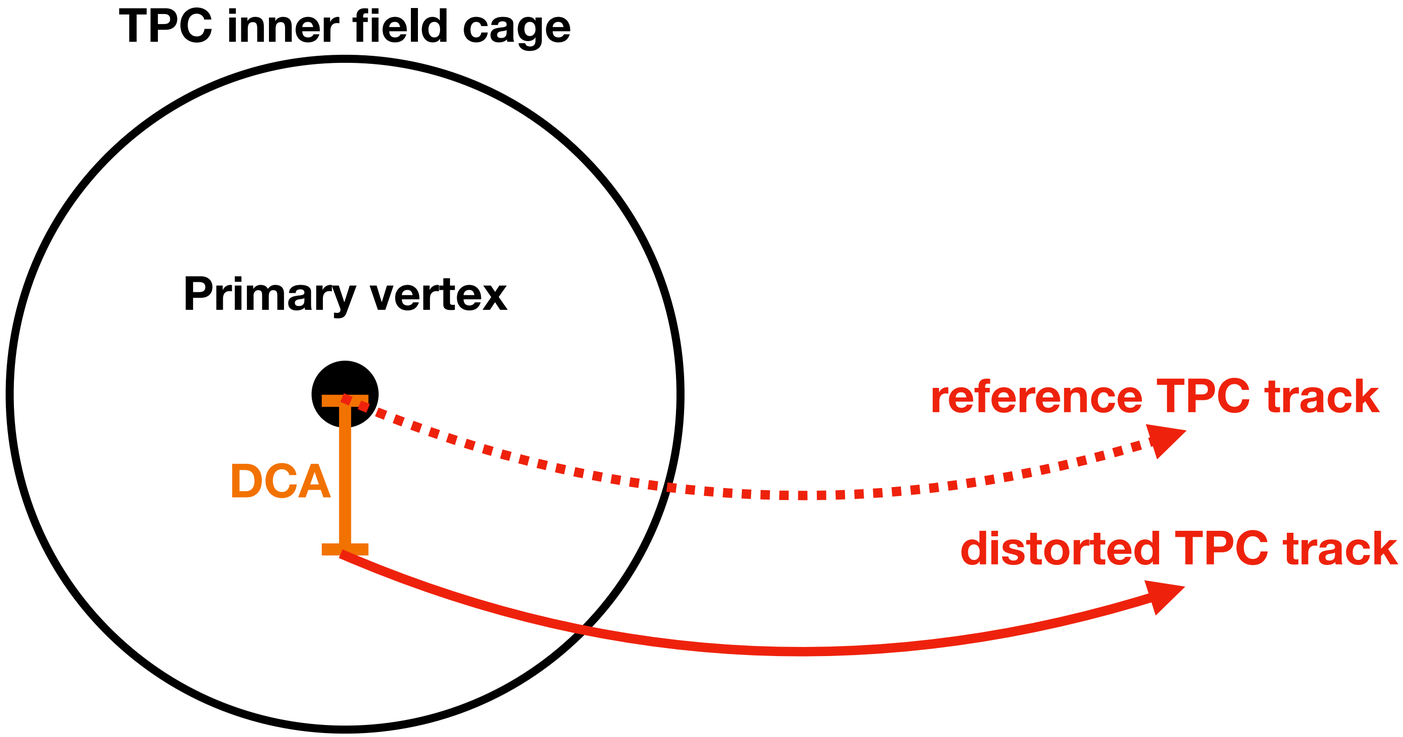


Extraction of the weights

DCA as a proxy of distortions and corrections

- Extrapolation of (distorted) TPC tracks to primary vertex
  - Average DCA as a function of time (~3ms) and $\tan(\lambda)$

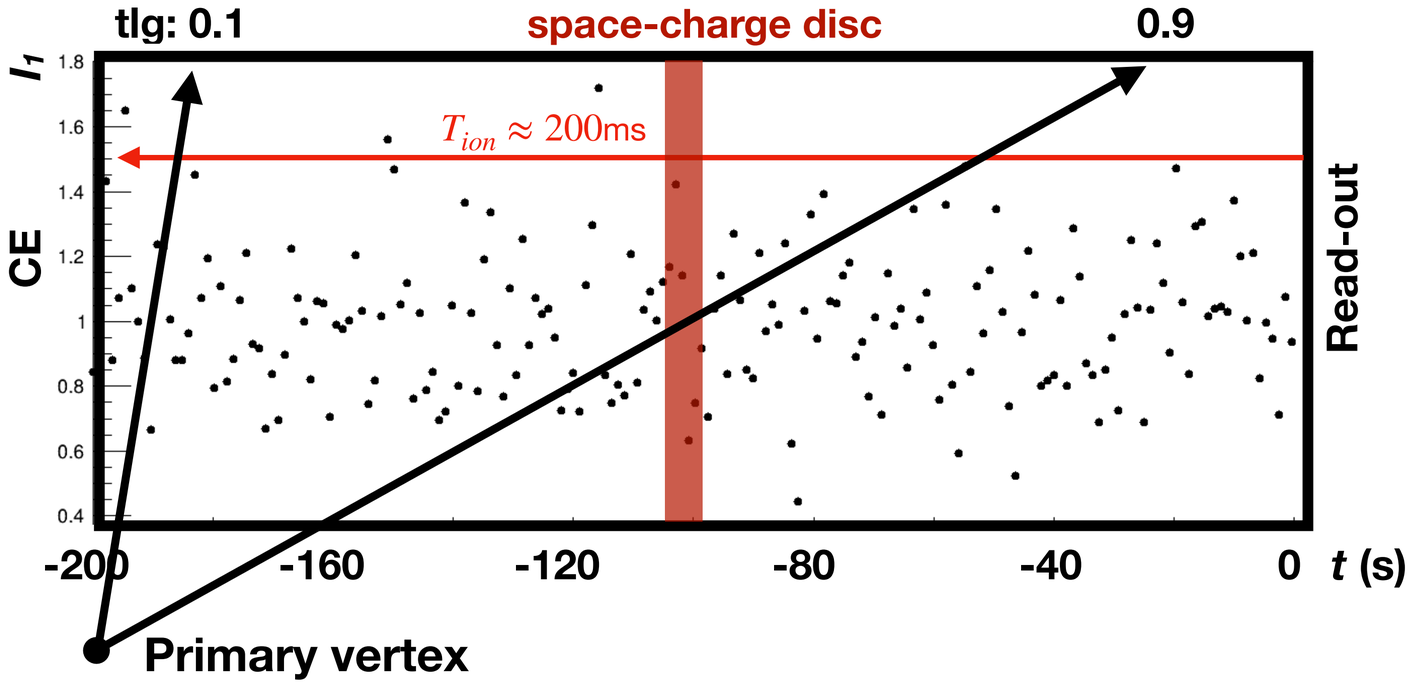


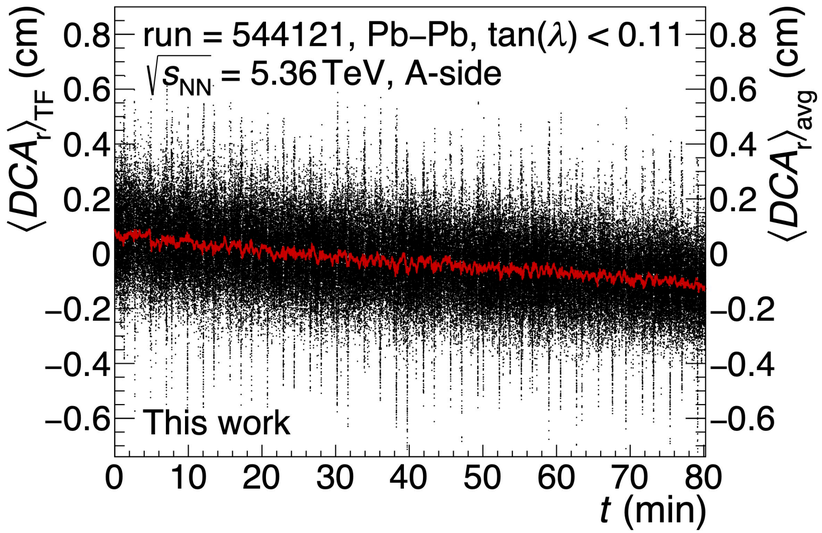


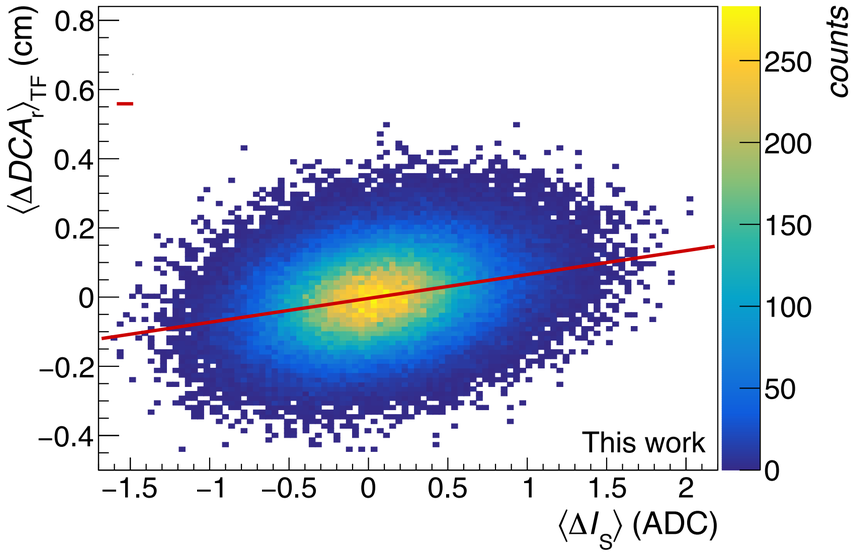
Space-charge distortion fluctuations correction

DCA as a proxy of distortions and corrections

- Extrapolation of (distorted) TPC tracks to primary vertex
  - Average DCA as a function of time (~3ms) and $\tan(\lambda)$
- Monitoring of distortions as a function of time and $\tan(\lambda)$
- Correlation of $\langle DCA \rangle$ with IDCs from past
  - Weight (w) how much each IDC contributes to distortion







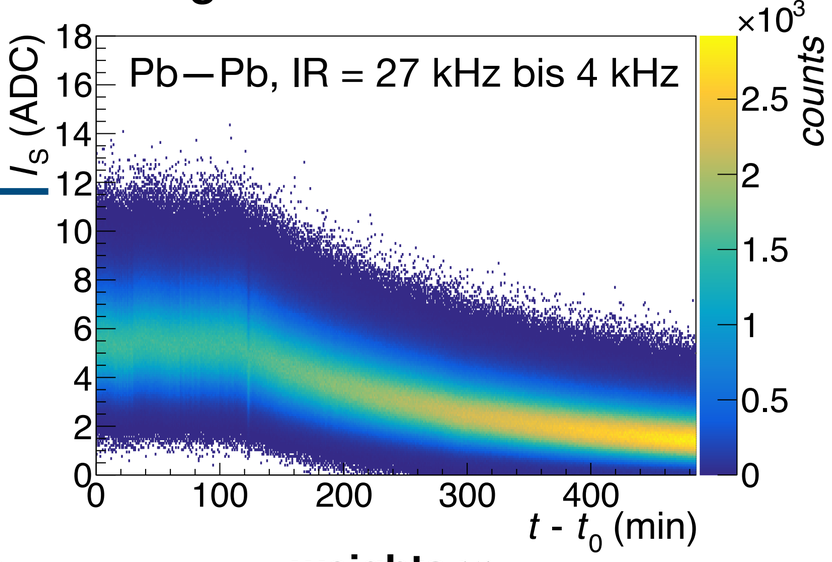
Composition of the correction map

Fast approach to create a correction map for each time stamp

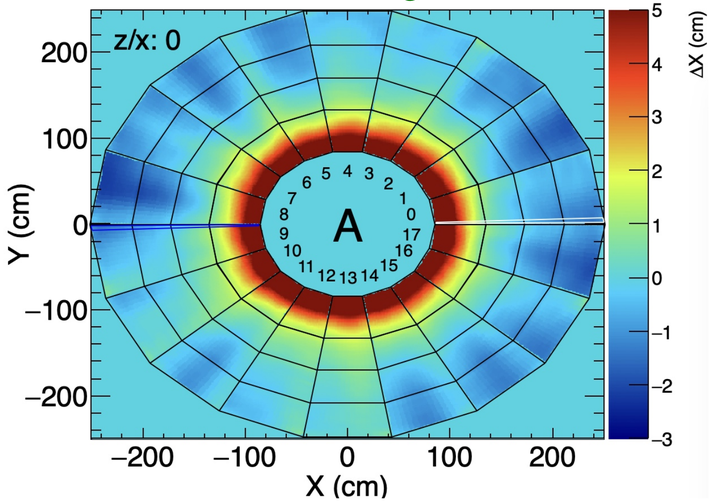
- Weights are currently averaged over $\tan(\lambda)$

$$M(t) = M_{\text{avg}} + M_{\Delta} \cdot \left(\frac{\sum_{t_{\text{sc}}=t_{\text{c}}}^{t} w(t_{\text{sc}} - t) \cdot I_{\text{S}}(t_{\text{sc}})}{\sum_{t_{\text{sc}}=t_{\text{c}}}^{t} w(t_{\text{sc}} - t)} - \langle I_{\text{S,avg}} \rangle \right)$$

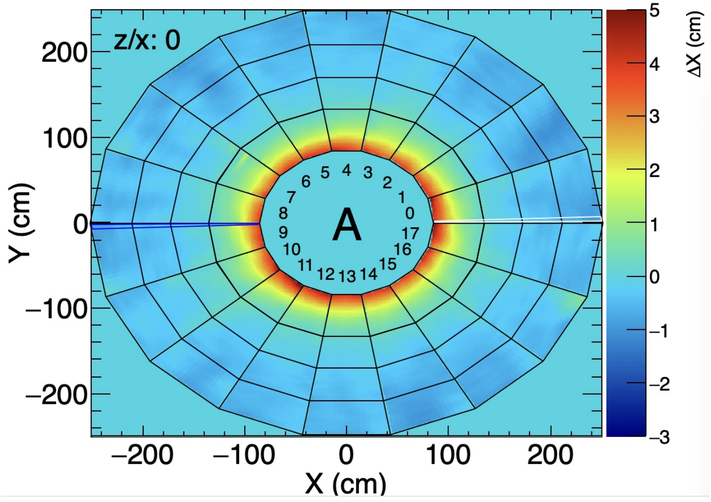
Space-charge discs as a function of time



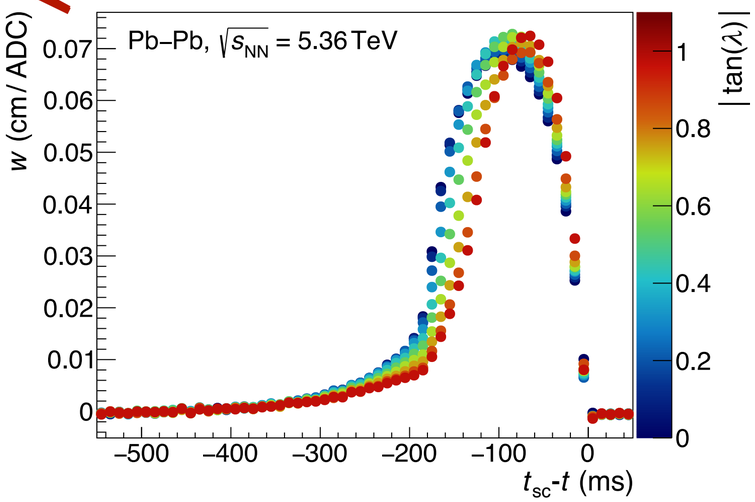
M_{avg}



M_{Δ}



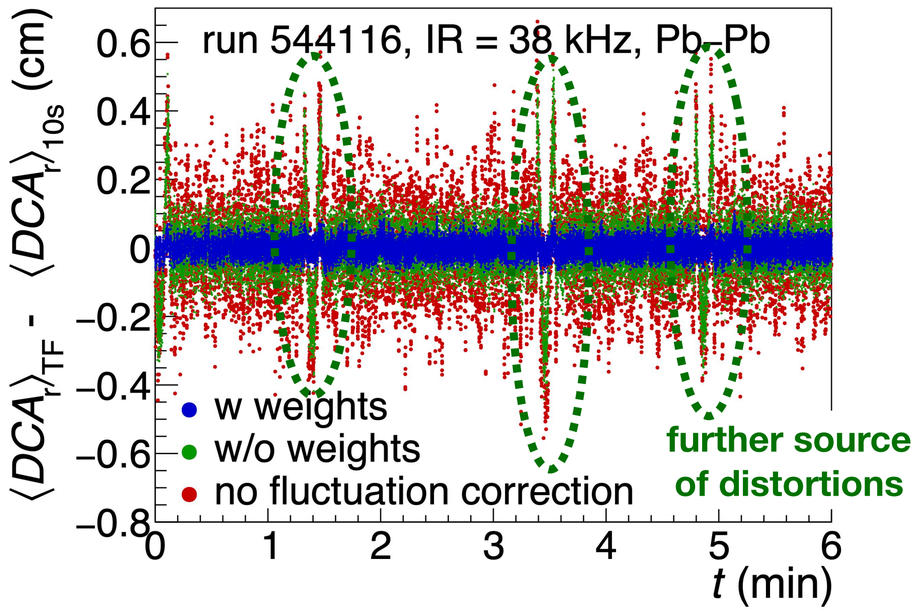
weights w

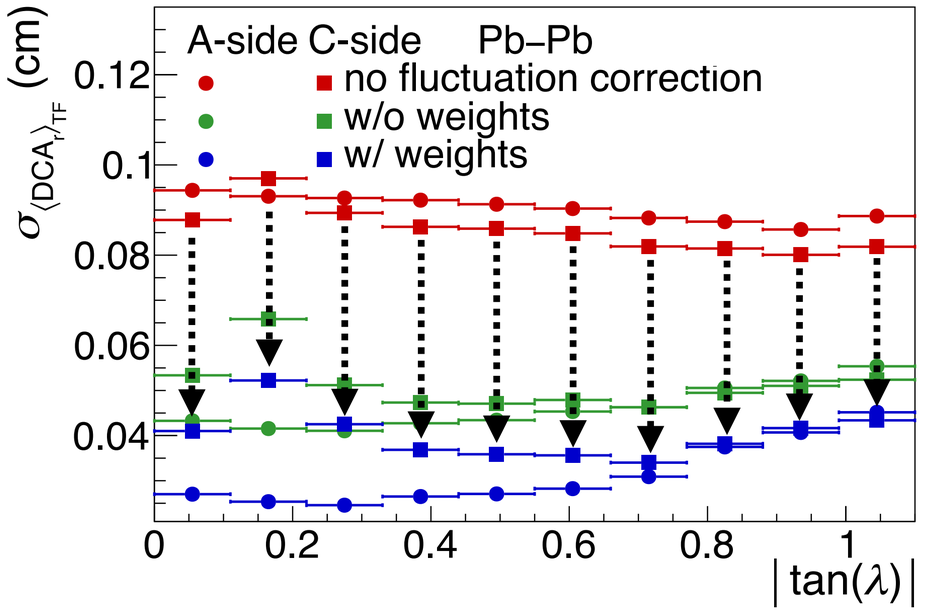


Space-charge correction precision

Schätzung für die Verzerrungskorrektur

- $\sigma_{\langle \mathrm{DCA_r} \rangle_{\mathrm{TF}}}$: Width of the DCAs a measure for the precision of the correction procedure
- Up to 3x smaller fluctuations of the DCAs



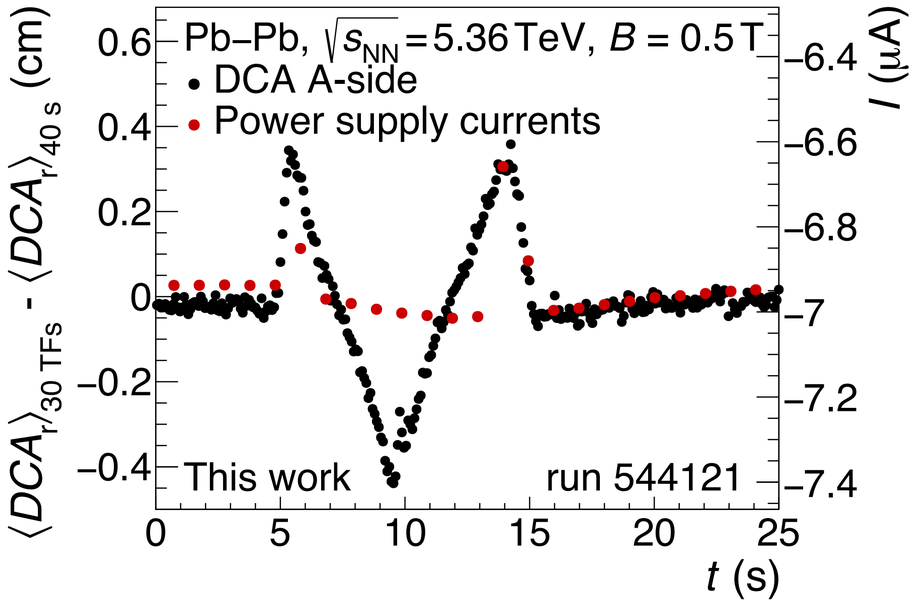


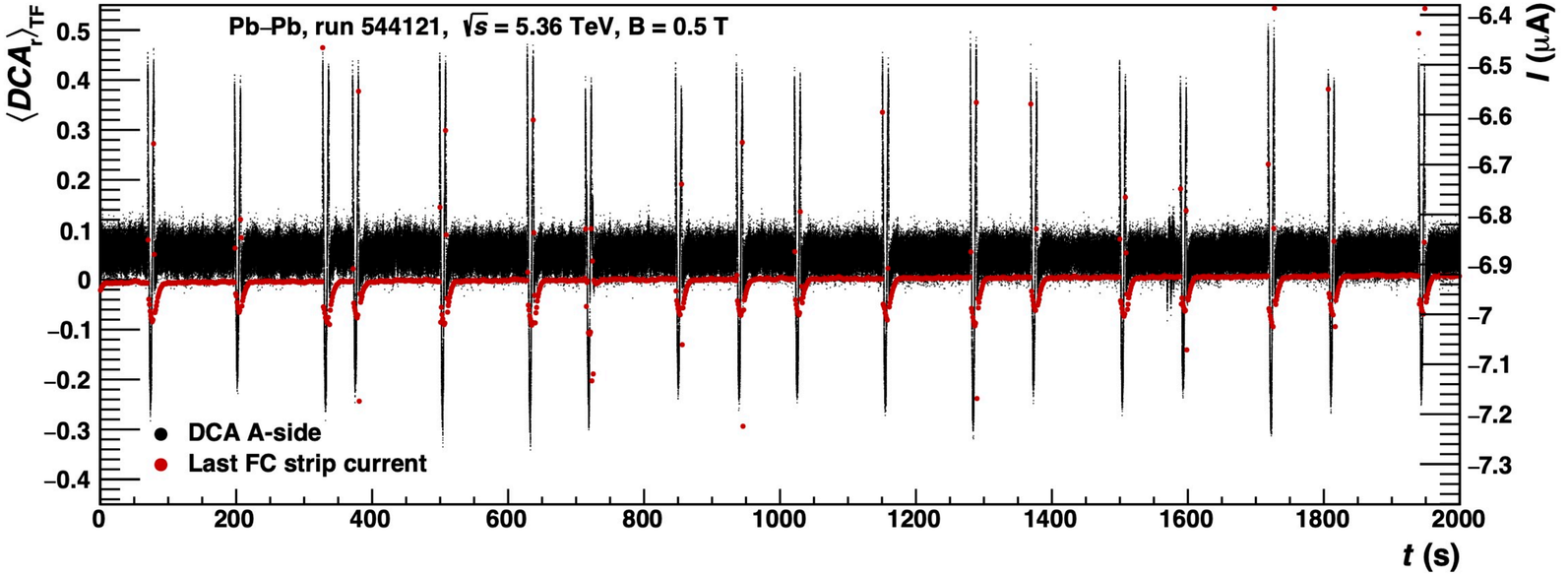
M-Shape distortions

M-shape distortion observation

Observation

- Distinct M-shaped pattern in DCAs on A-side only
- Coincides with spikes in power supply currents





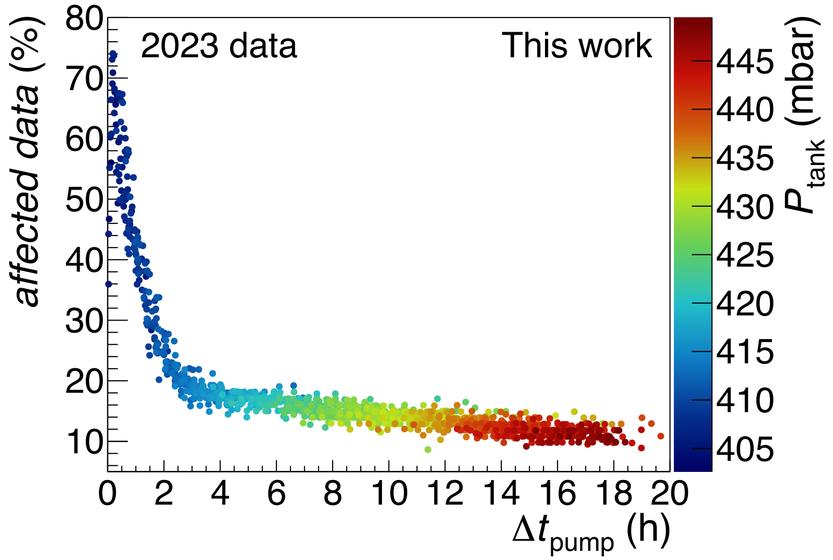
M-shape distortions origin

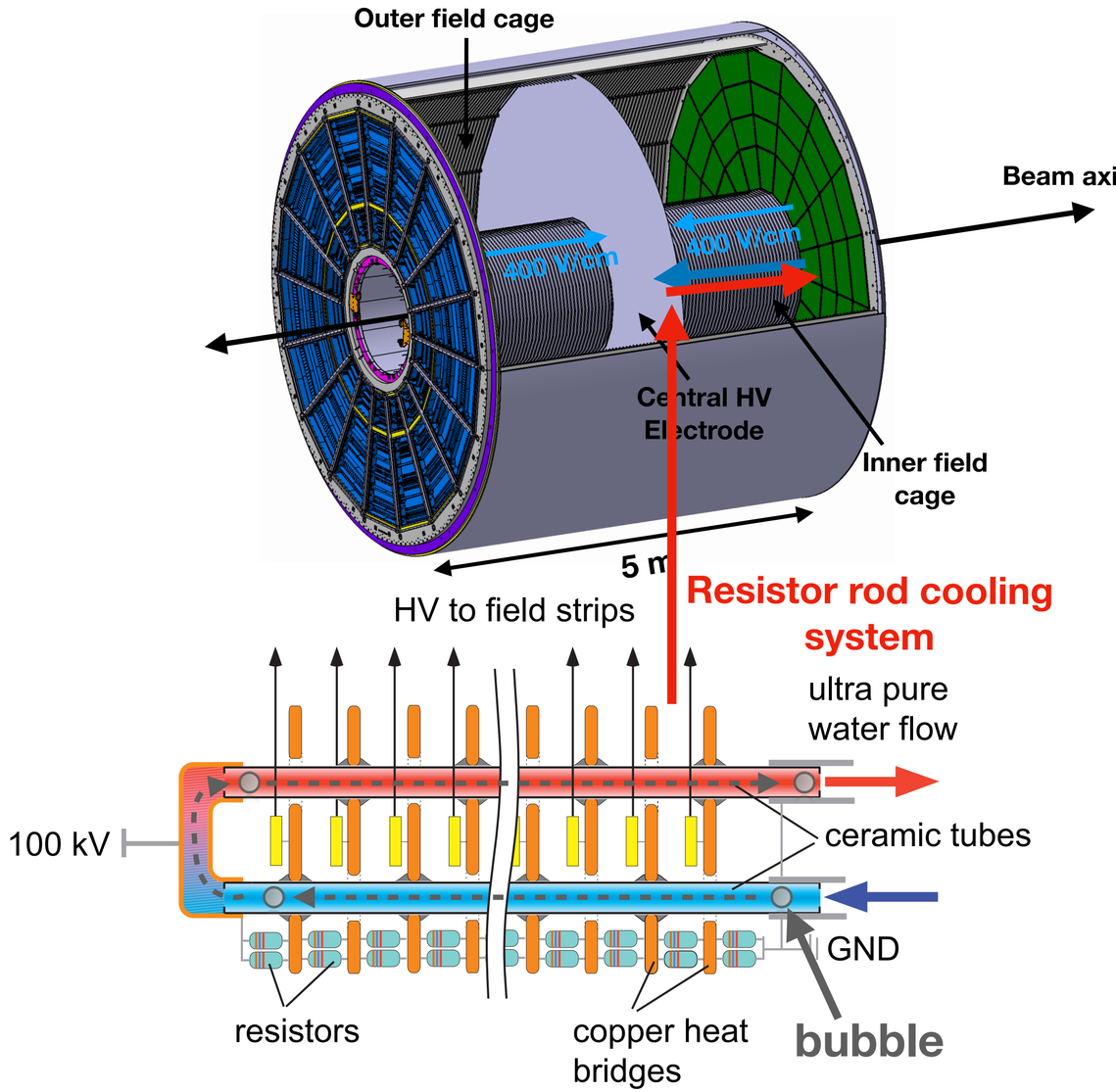
Observation

- Distinct M-shaped pattern in DCAs
- Coincides with spikes in power supply currents
- Correlation with vacuum pump of cooling system

Origin

- Leakage in the under pressure cooling system
- Bubble drawn into the cooling system
- Change in the inner field cage boundary potential





M-shape distortions simulation

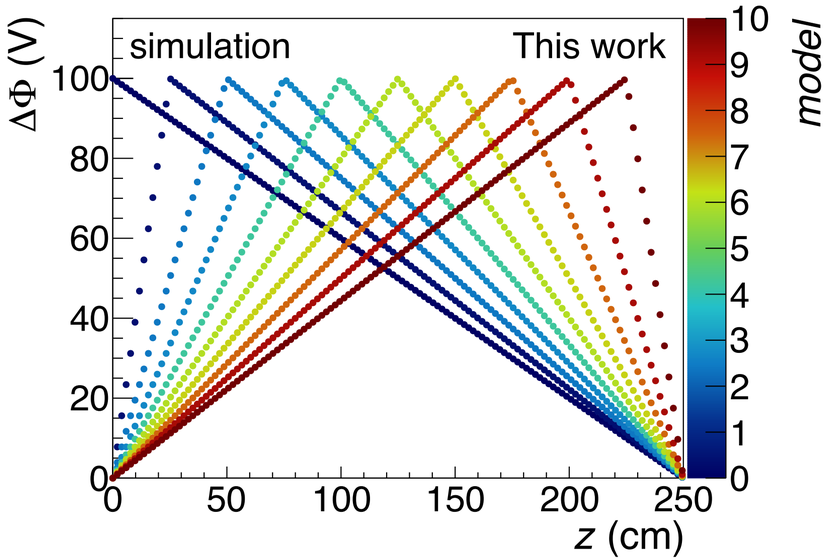
Calibration

- Change in currents of power supply + bubble drifting through cooling system → non trivial distortions
  ➡ ITS-TPC correction procedure not feasible for frequent time dependent distortions!

➡ Solution: Fitting analytical models to observed DCAs as a function of time

Analytical models

1. Simulation of 10 inner field cage boundary potentials and resulting distortions



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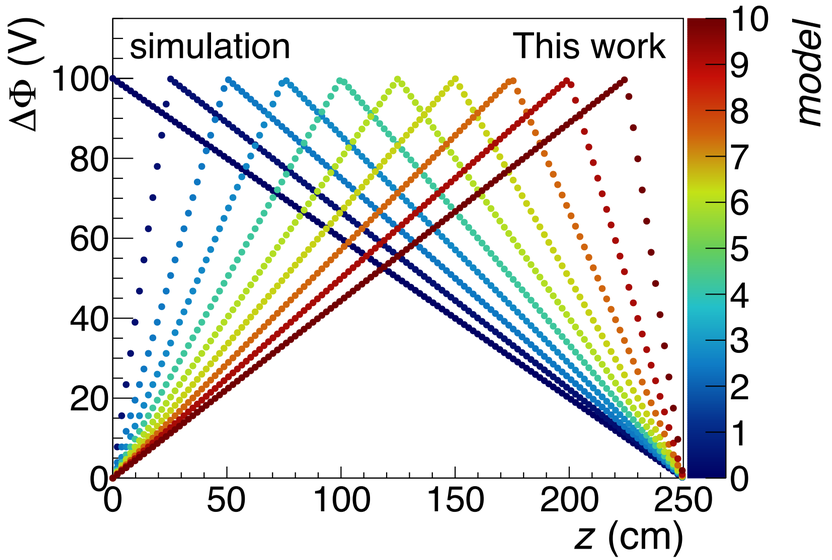
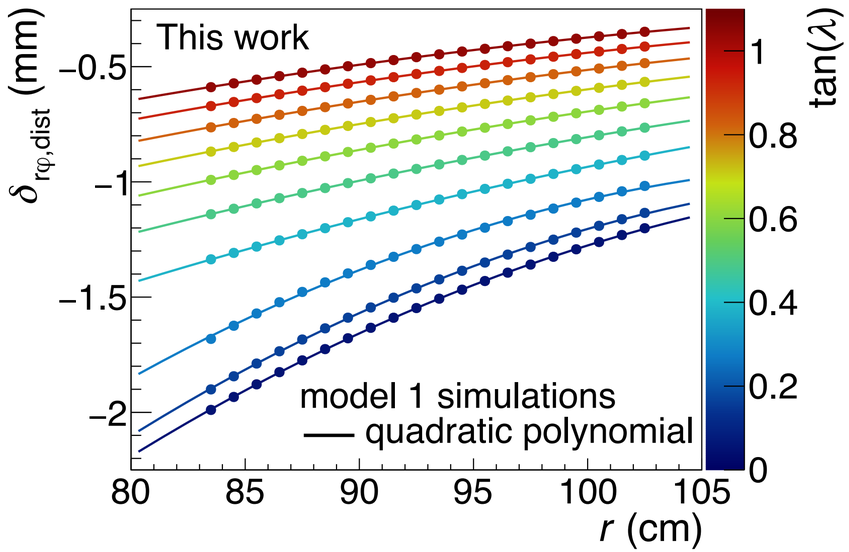
2. Calculation of DCAs for each model as a function of $\tan(\lambda)$ → fitting $r\varphi$ distortions





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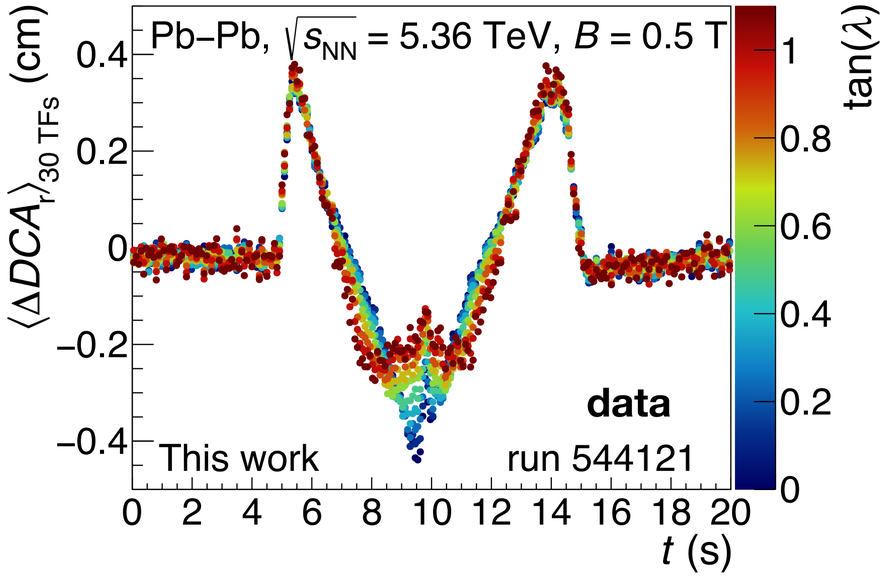

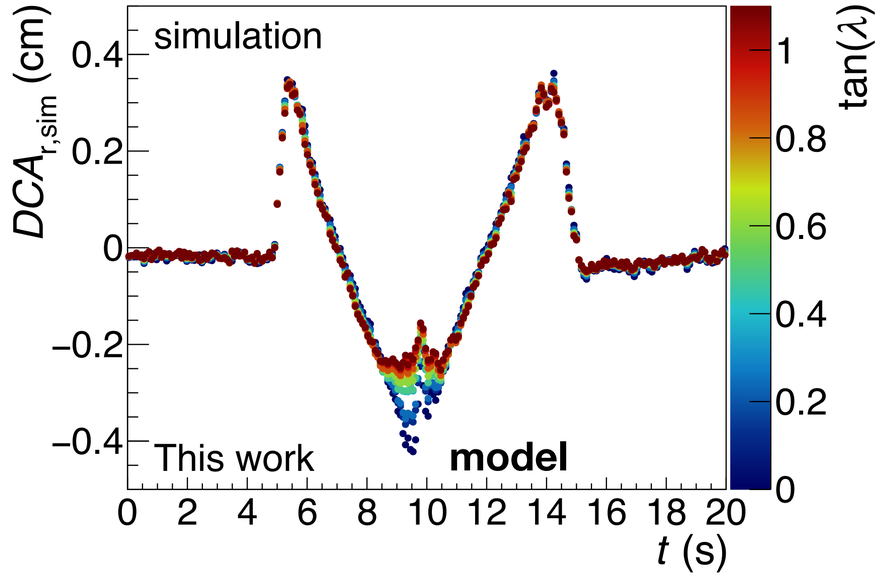

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Composition of correction map

- Linear combination of different correction maps

$$M(t) = M_{\text{avg}} + M_{\Delta} \cdot \left(\frac{\sum_{t_{\text{sc}}=t_{\text{c}}}^{t} w(t_{\text{sc}} - t) \cdot I_{\text{S}}(t_{\text{sc}})}{\sum_{t_{\text{sc}}=t_{\text{c}}}^{t} w(t_{\text{sc}} - t)} - \langle I_{\text{S,avg}} \rangle \right) + M_{\text{MShape}}(t)$$

M-shape distortions correction

Calibration

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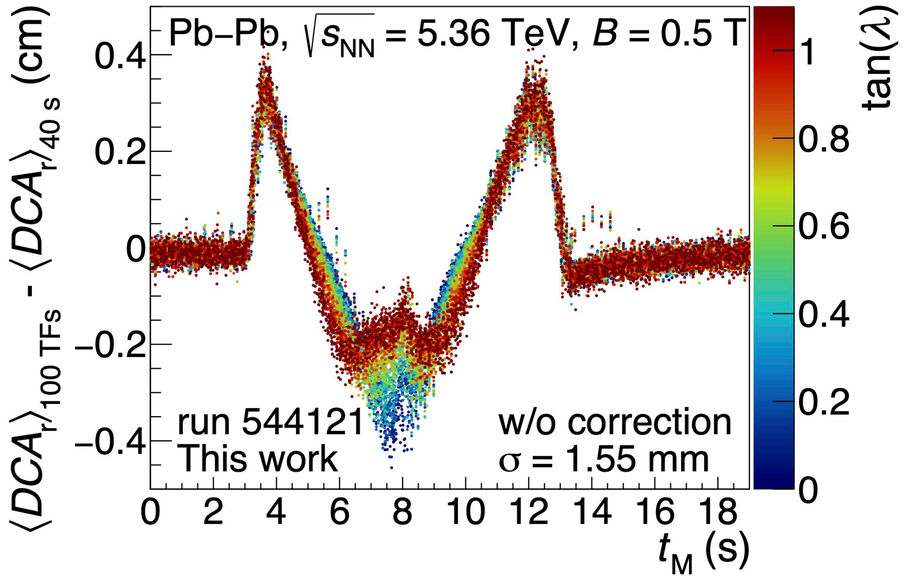
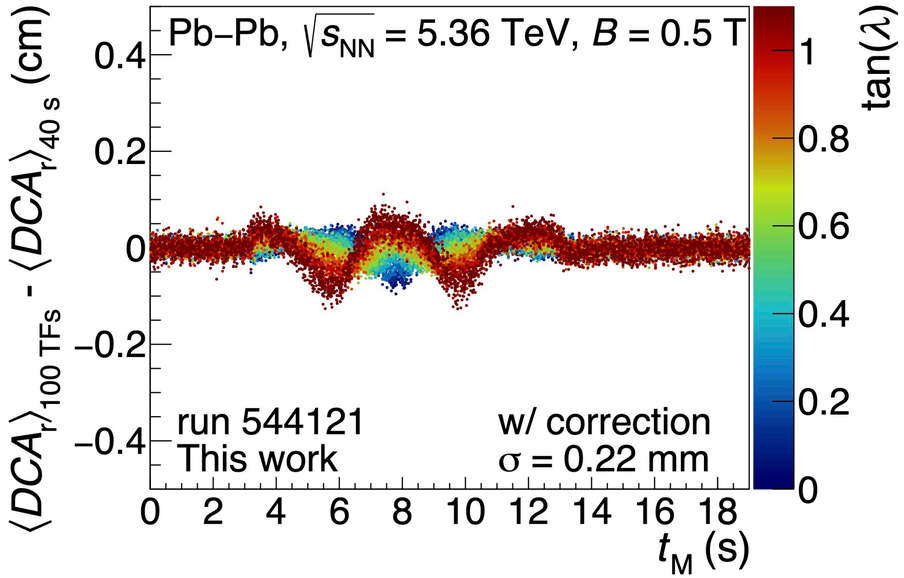


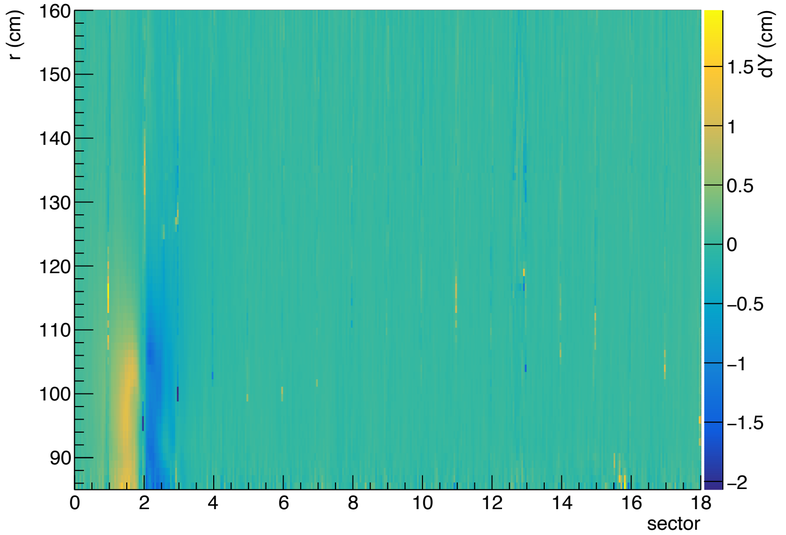


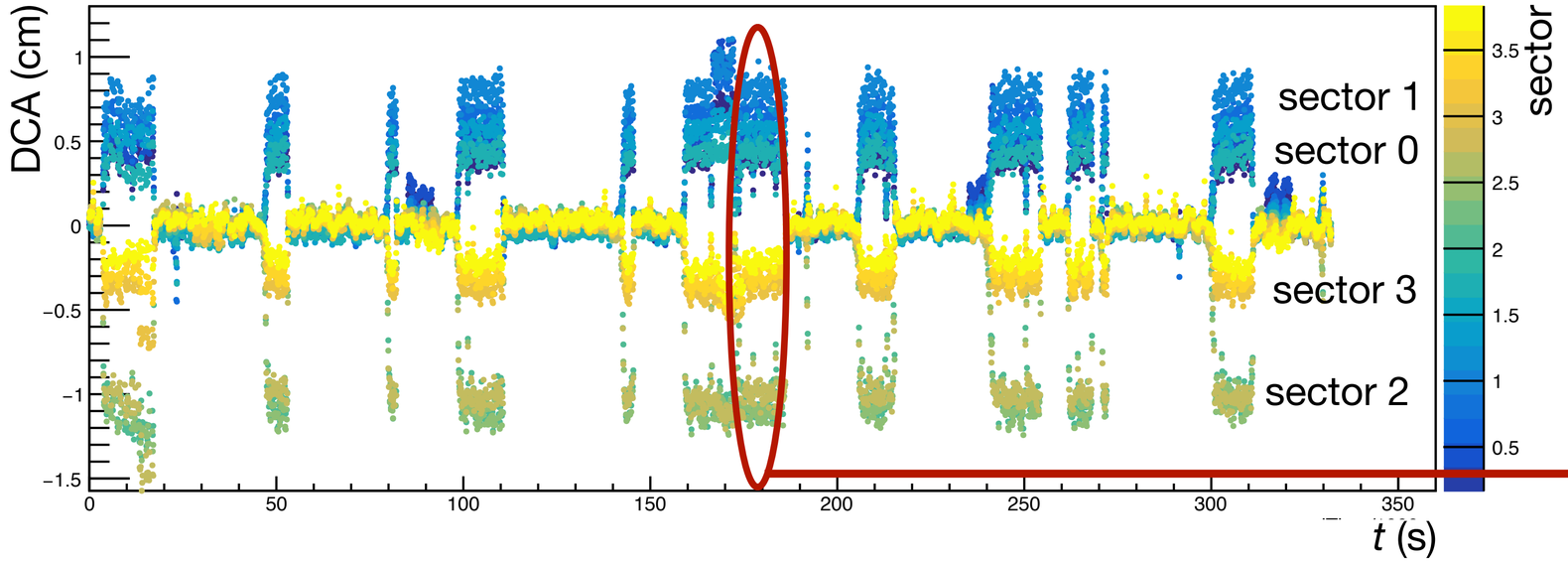
Sector edge distortions

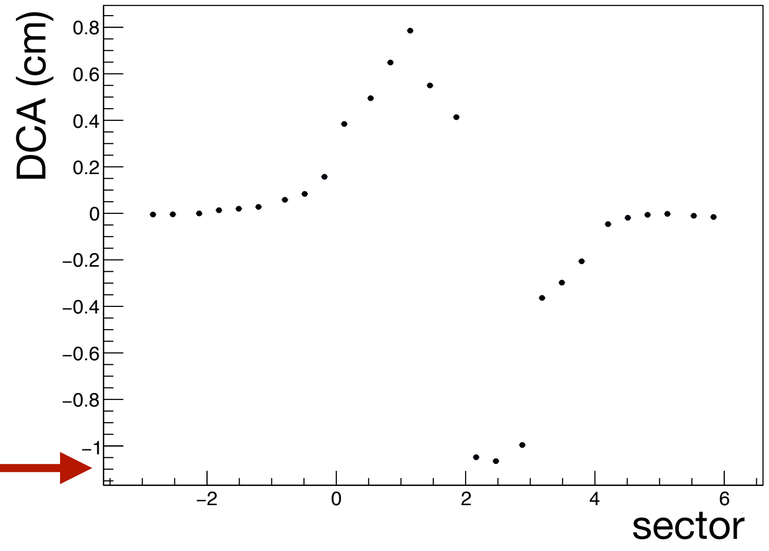
Sector edge distortions

Distortions observed mainly between two sectors

- Mainly on the C-side (sectors C1 and C2)
- Also appearing for other sectors at high rates > 25 kHz
- Visible in IDCs and DCAs
- Spreading to C0 and C3 with alternating DCA sign
- Origin unclear
- Time intervals rejected for physics analysis







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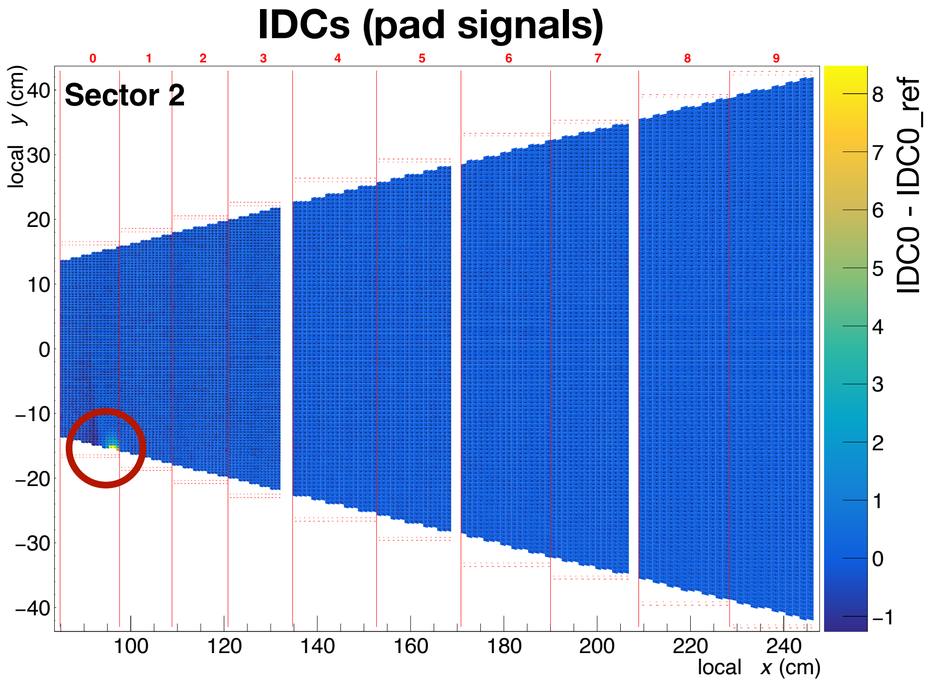

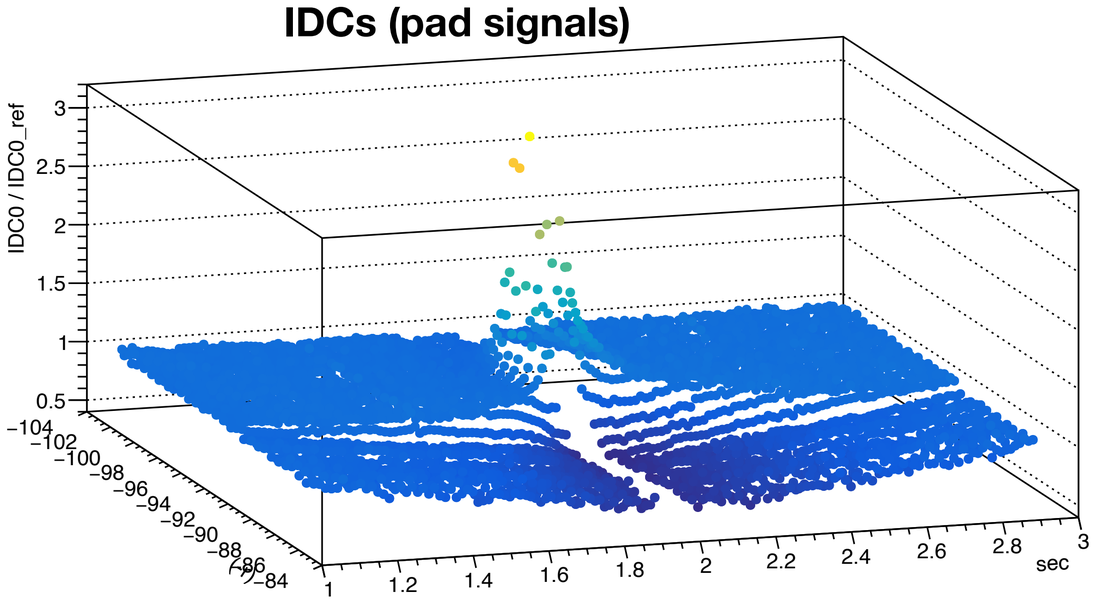

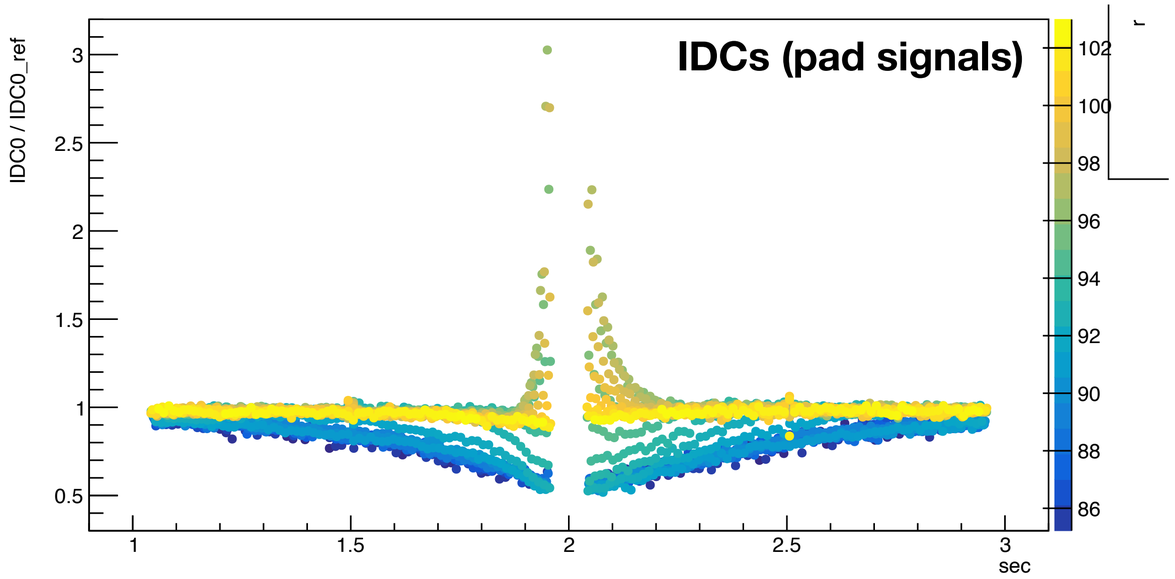

Summary

Space-charge distortions

- 50 kHz Pb-Pb: ~15 cm distortions
- 500 kHz pp: ~3 cm distortions
- Correction with data driven ITS-TPC map
- Space-charge density fluctuations and LHC beam variations
  - Scaling of space-charge correction map with weighted IDCs

- Others sources of distortions are also very important and non trivially to correct for!