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

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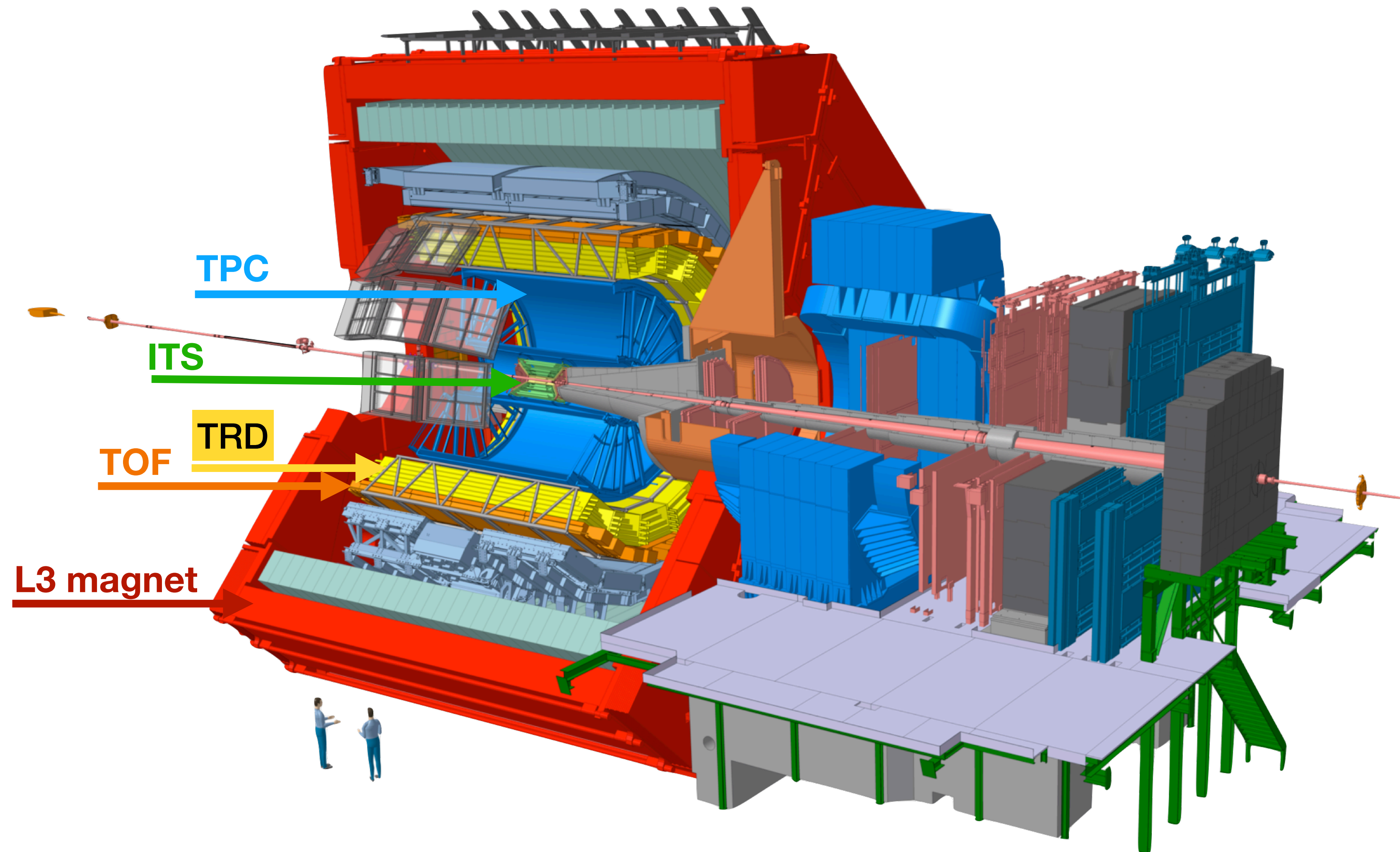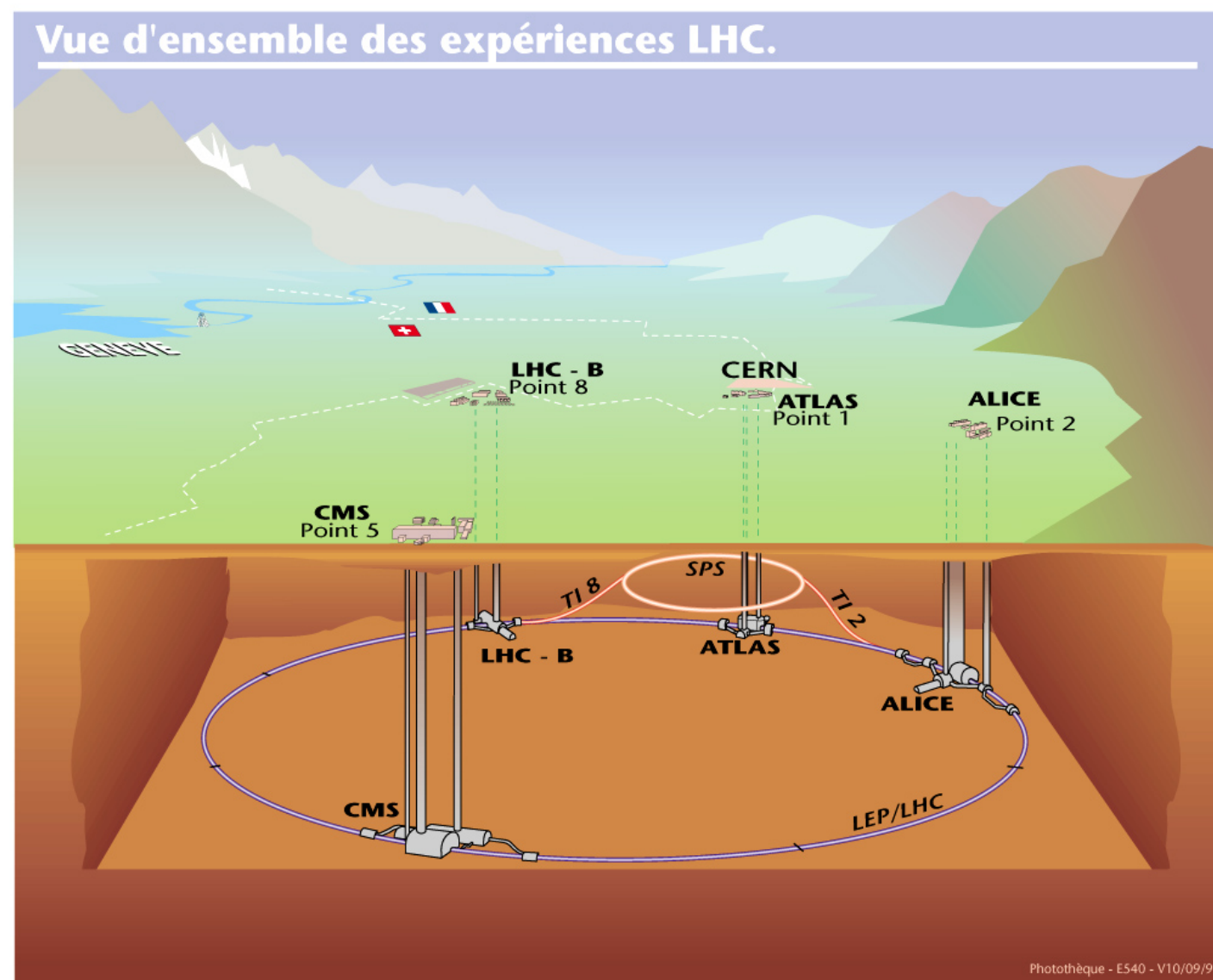**The 2025 International Workshop on**
the High Energy Circular Electron Positron Collider
Nov 8, 2025

A Large Ion Collider Experiment

CERN LHC

One of the four large experiments at the CERN LHC

ALICE

TPC

ITS

TRD

TOF

L3 magnet

Vue d'ensemble des expériences LHC.

LHC - B
Point 8

CERN

ATLAS
Point 1

ALICE
Point 2

CMS
Point 5

SPS

TI 8

TI 2

LHC - B

ATLAS

ALICE

CMS

LEP/LHC

Photothèque - E540 - V10/09/97

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
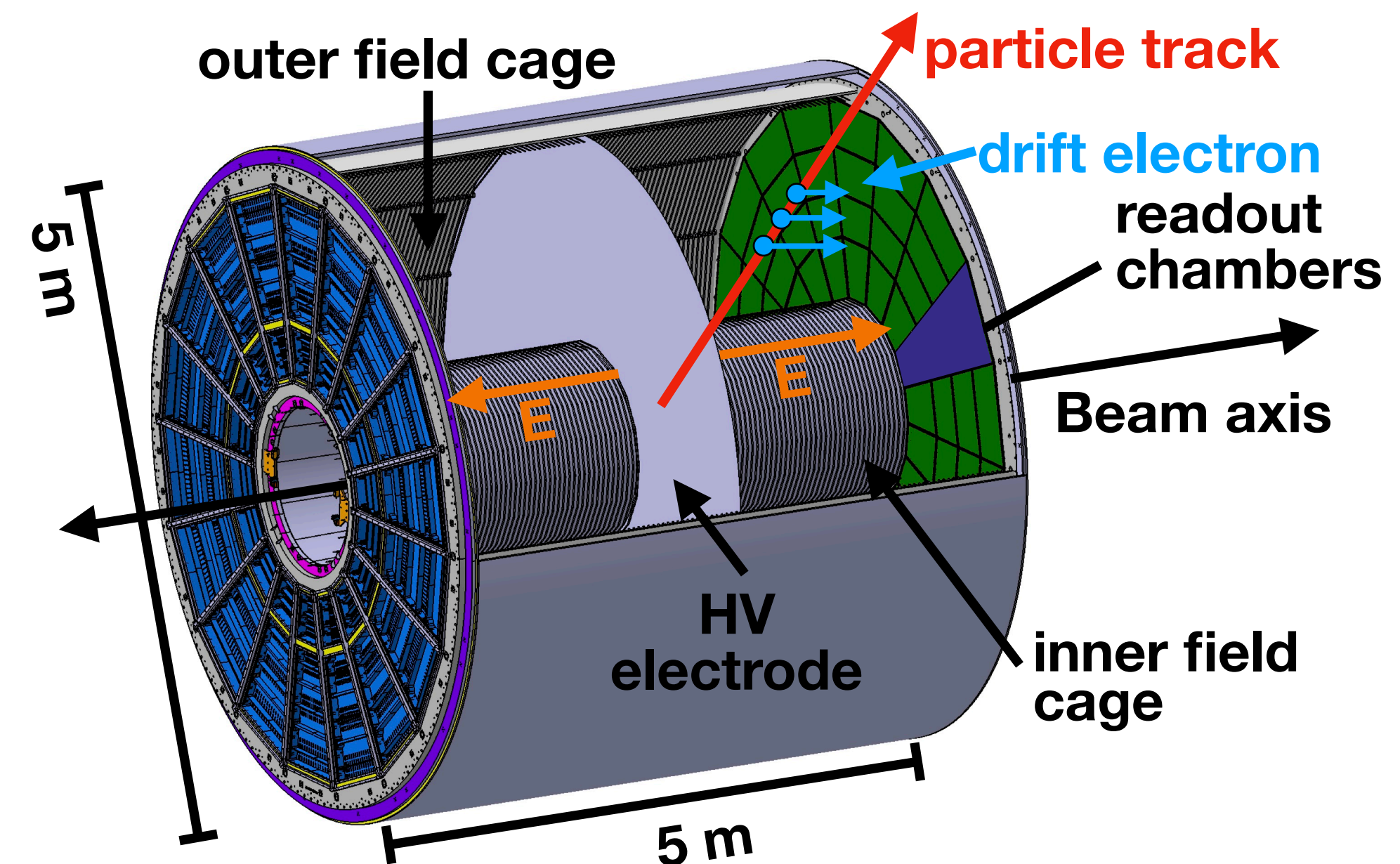
Overview of drift-field distortions

IR dependent

1. Space-charge from ion back flow and primary ionization + fluctuations $\mathcal{O}$(10ms)

2. Time-dependent distortions at the sector edges at rates $> 25\text{kHz}$ $\mathcal{O}$(s to min)

3. Time- and rate-dependent inner field cage charging up

Semi static

4. Charging of GEM frames (most relevant for cosmics)

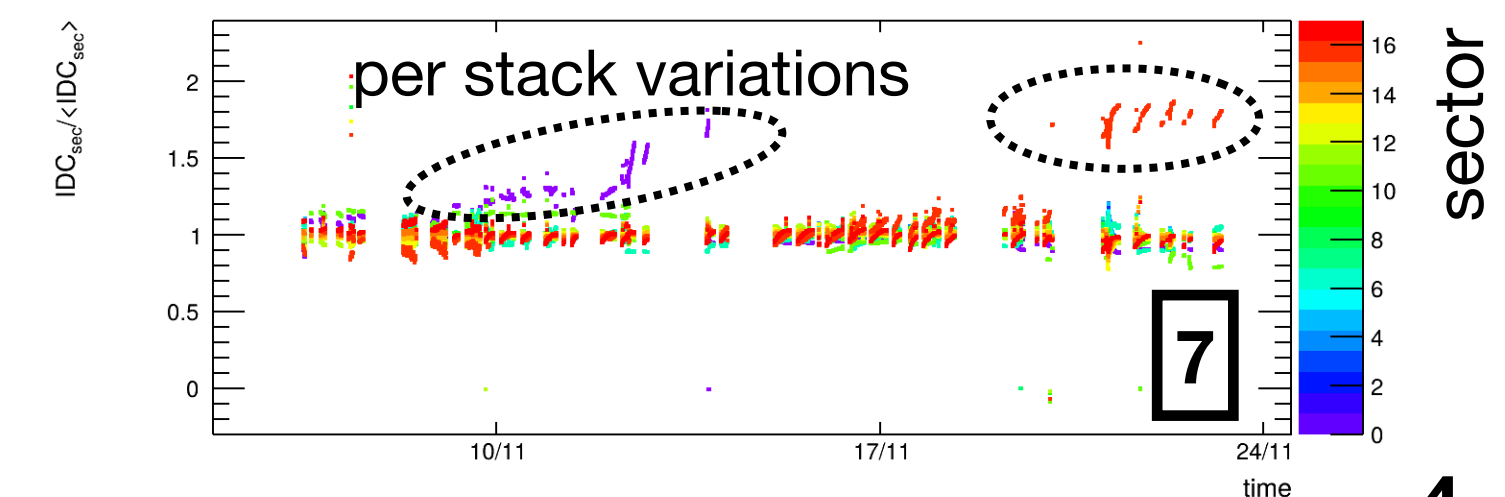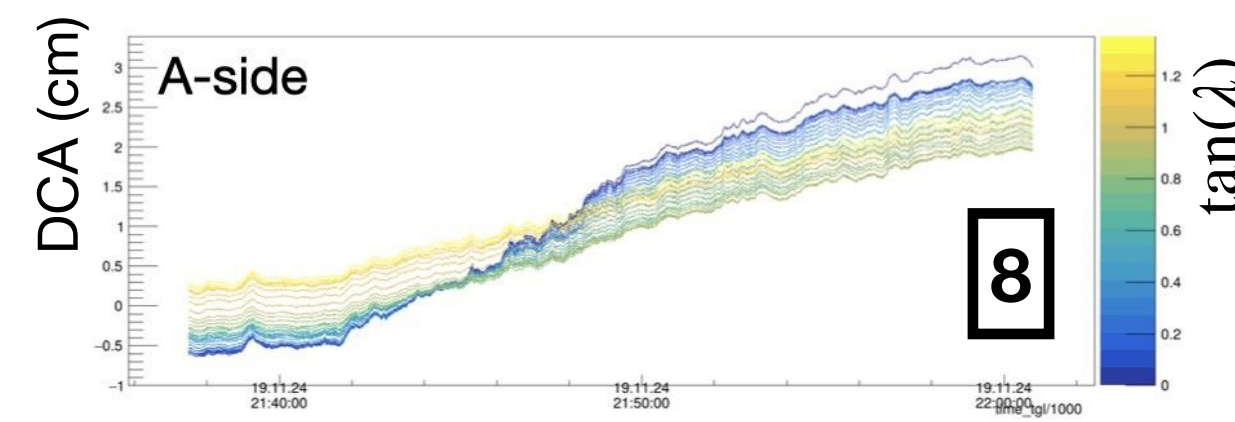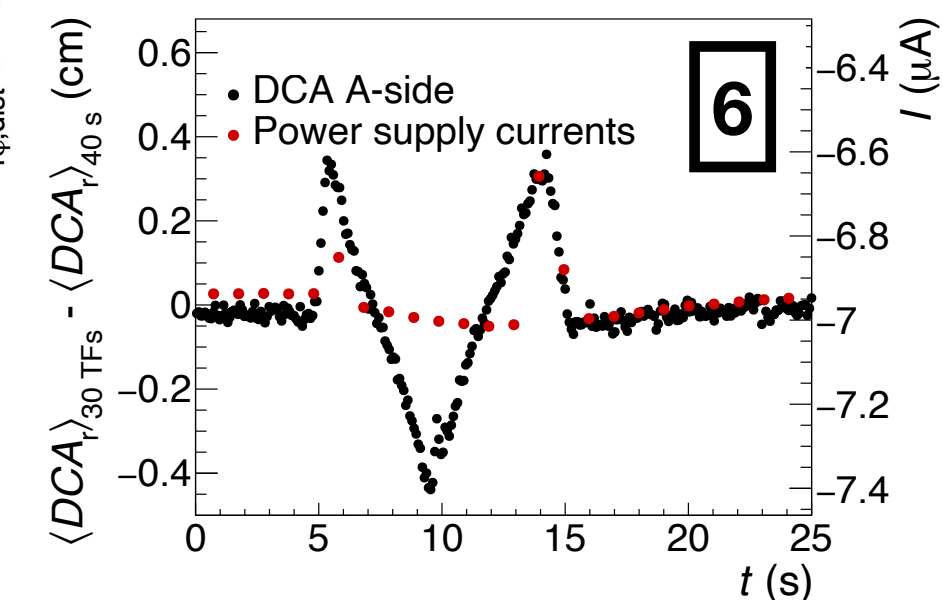**Static**
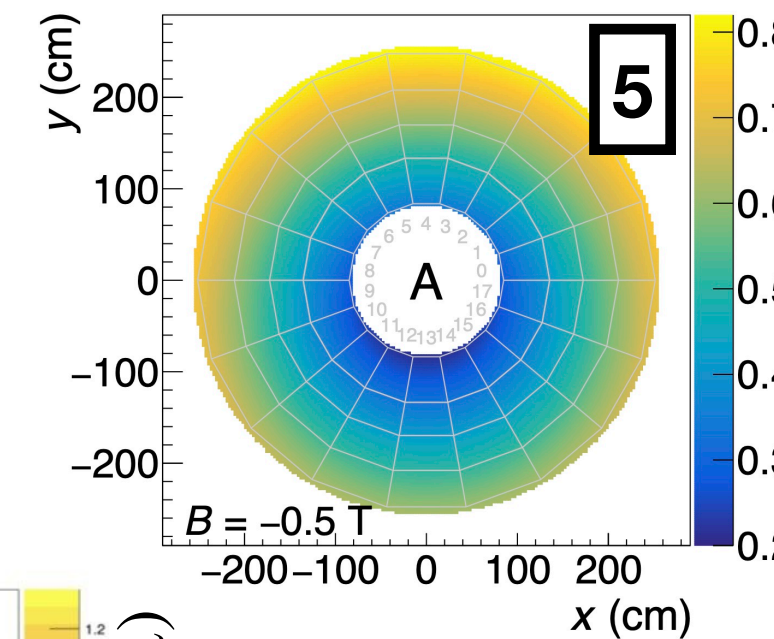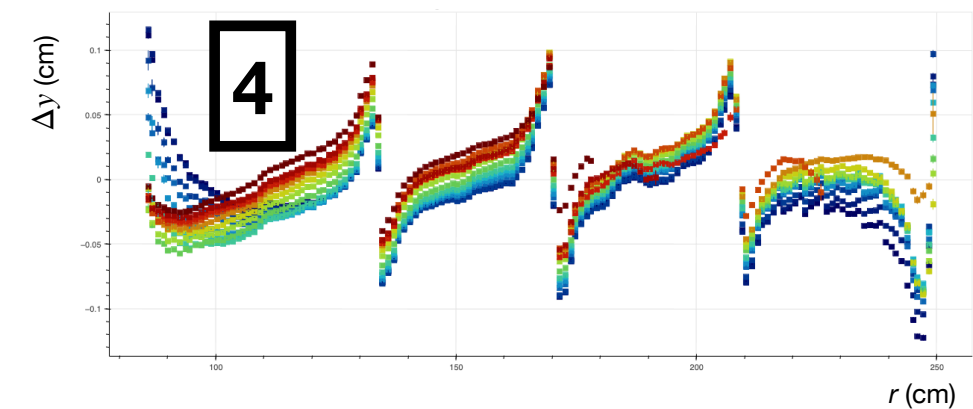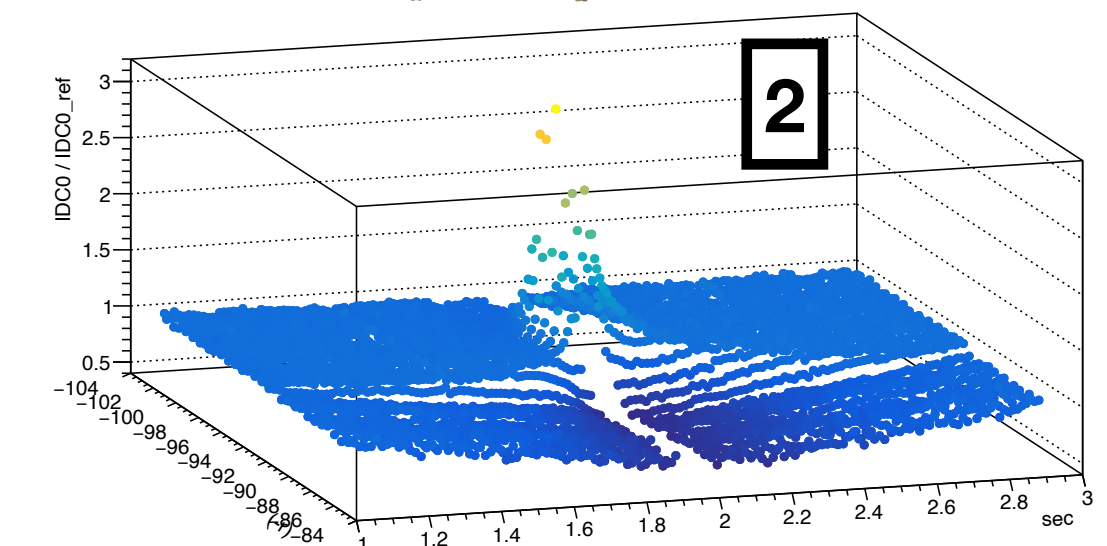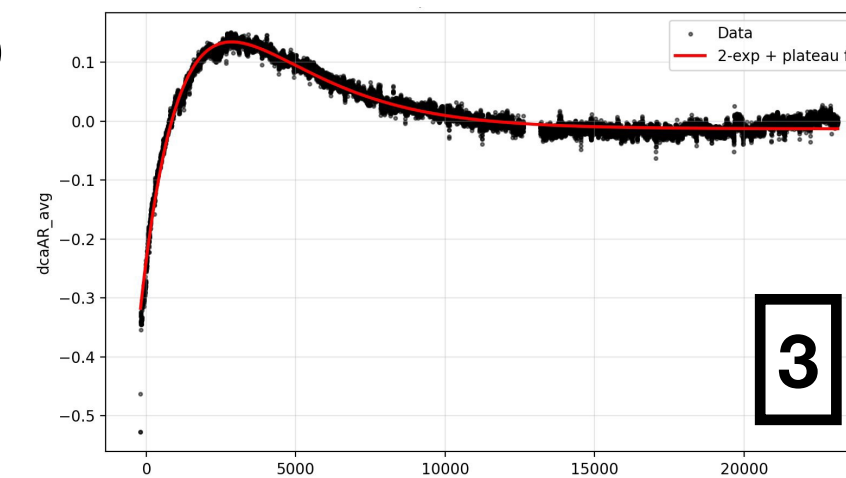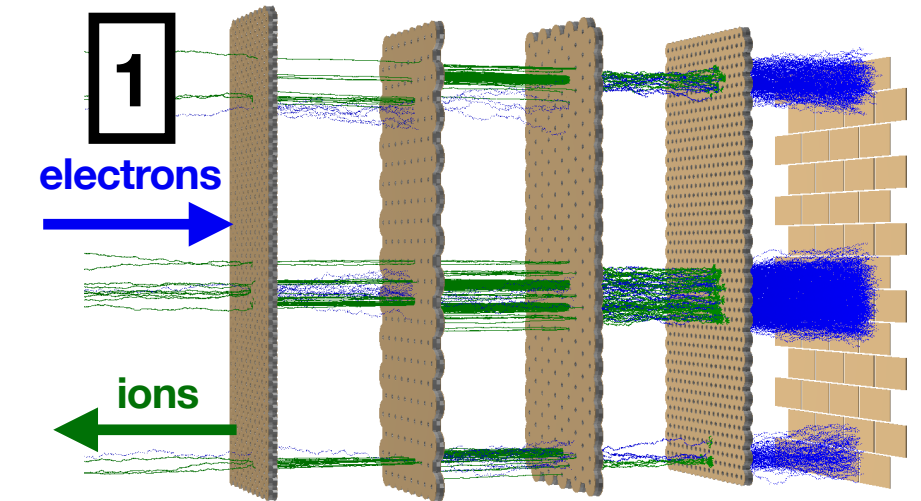
5. Misalignment of electric and magnetic field

Time dependent

6. "M-shape" distortions

7. GEM stack variations of the gain

8. End of 2024 FC instabilities at high rates

➡ 50 kHz Pb−Pb: ~10 cm distortions

➡ 500 kHz pp: ~3 cm distortions

➡ **A lot of people are involved in calibration the TPC**

Space-Charge Distortions

Readout system

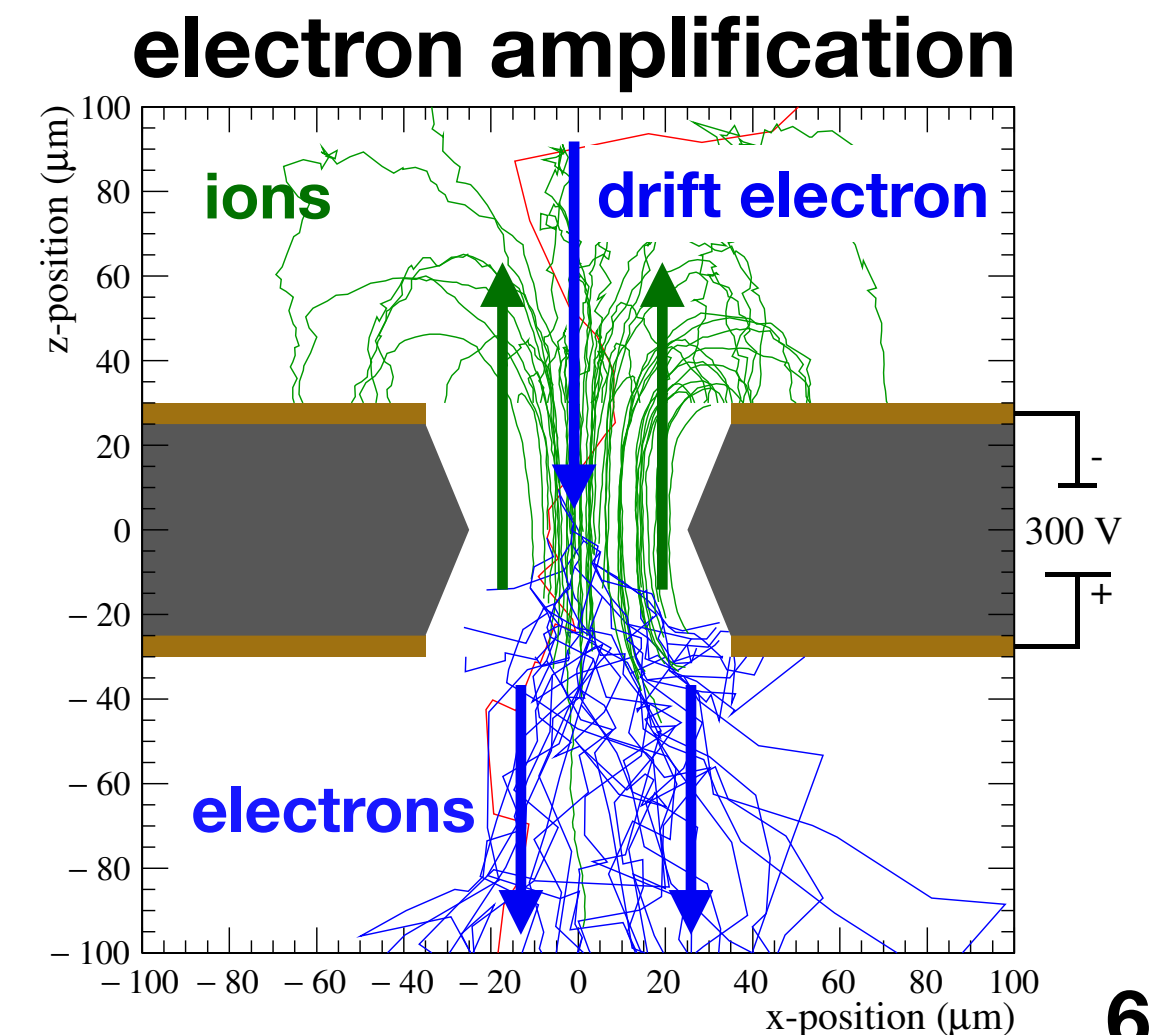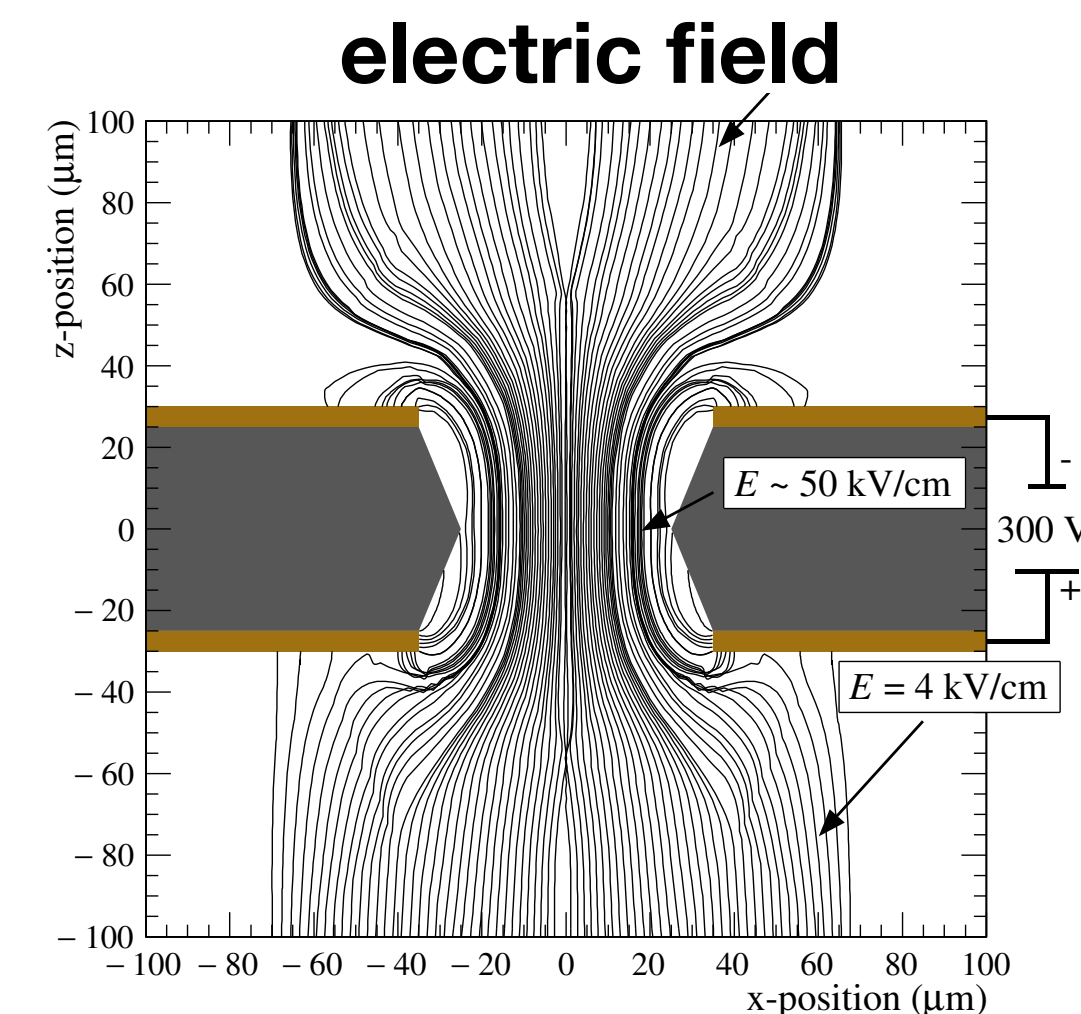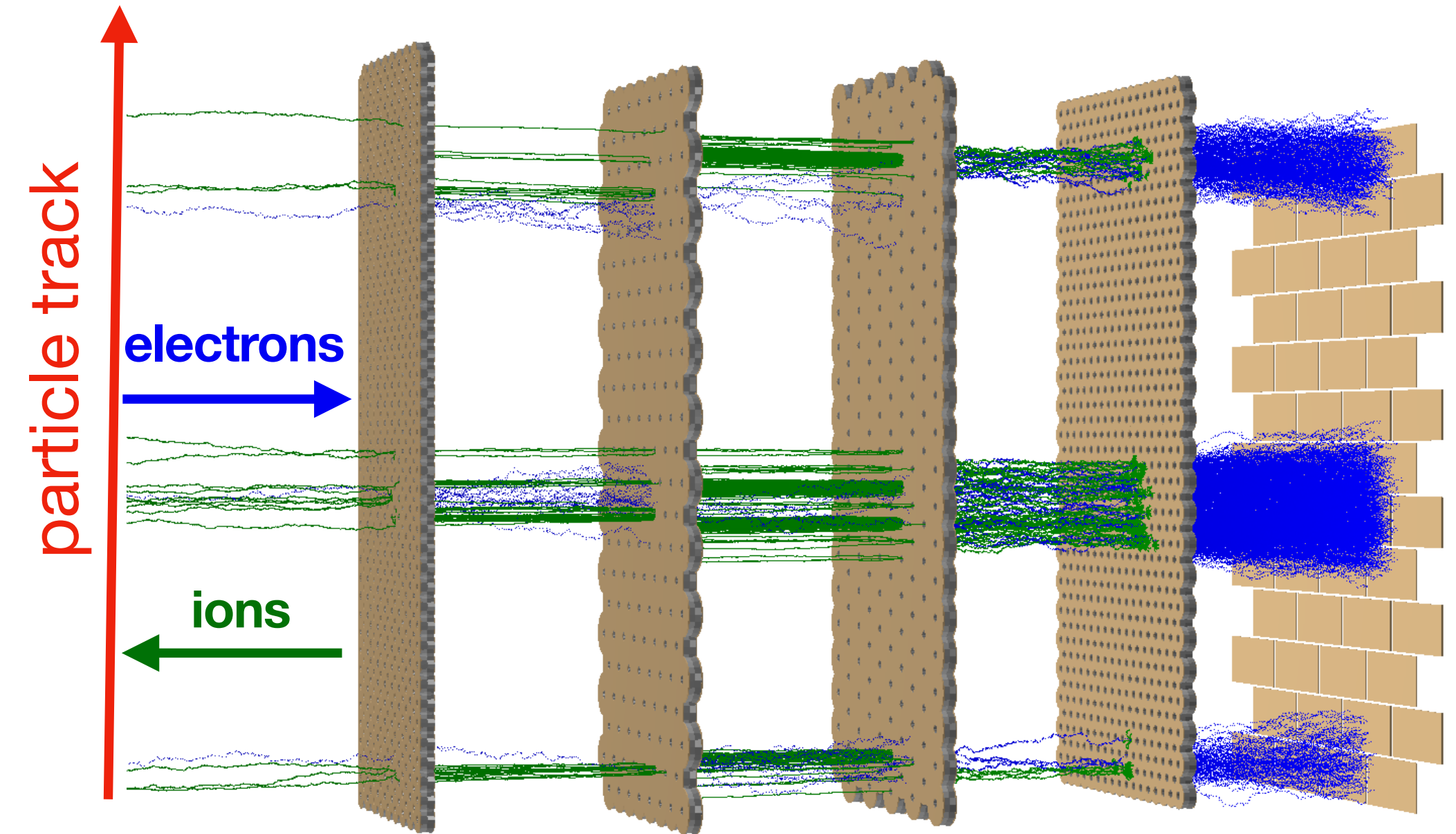**Multiplication of primary electrons**

- 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
  - ‣ $T_{\text{Electron}} \approx 100 \, \mu\text{s}$ vs $T_{\text{Ion}} \approx 200 \, \text{ms}$
- 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!**

particle track

electrons

ions

electric field

$E \sim 50 \, \text{kV/cm}$

300 V

$E = 4 \, \text{kV/cm}$

electron amplification

ions   **drift electron**

300 V

electrons

Space-charge density simulations

Space-charge density

- 50 kHz Pb—Pb collisions
  - ‣ Maximum 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

- $\rho \to \Phi \to E_{(r,\phi,z)} \to \text{Langevin} : \delta_{(r,\phi,z)}$
- Position dependent distortions
- 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
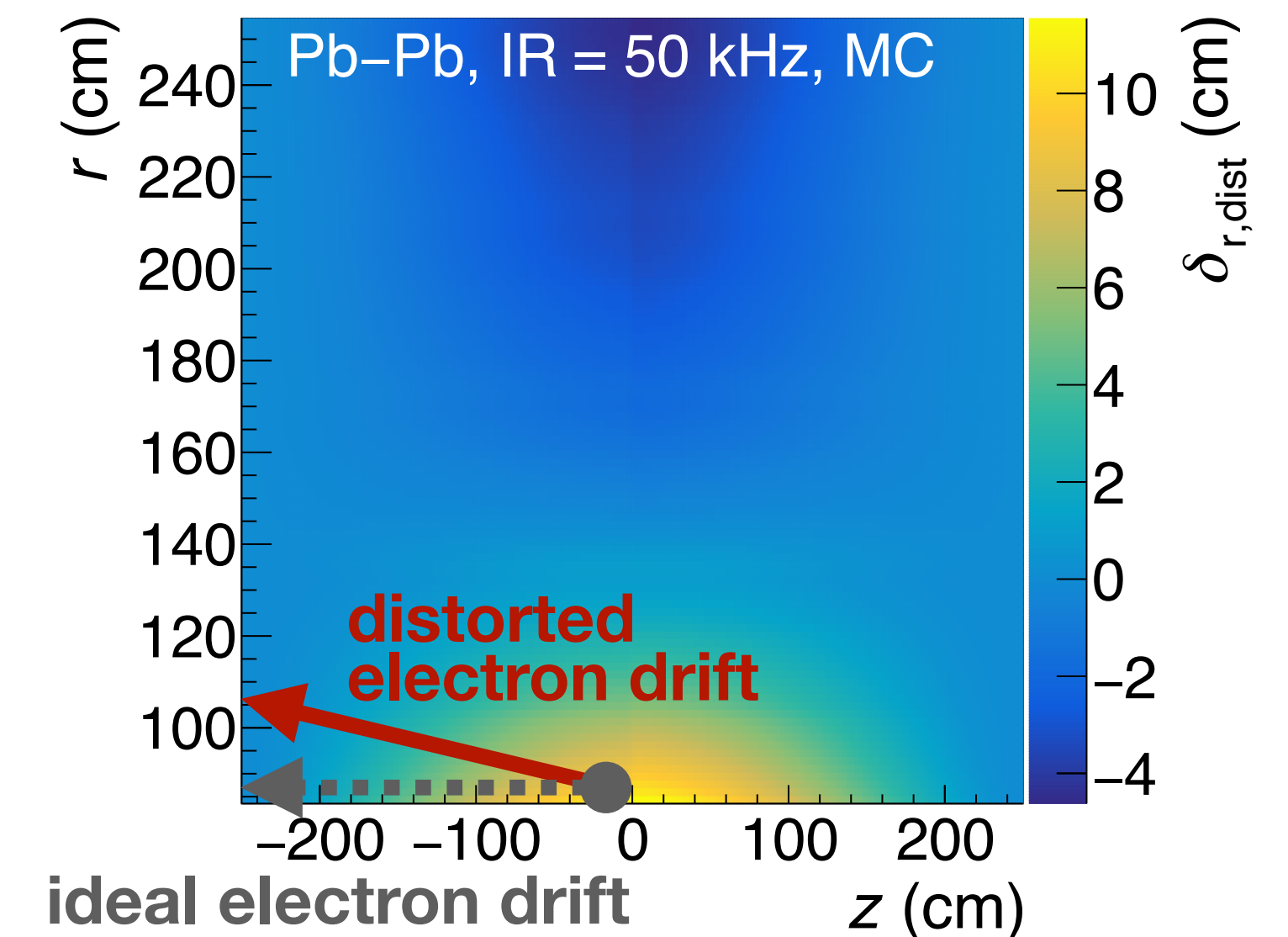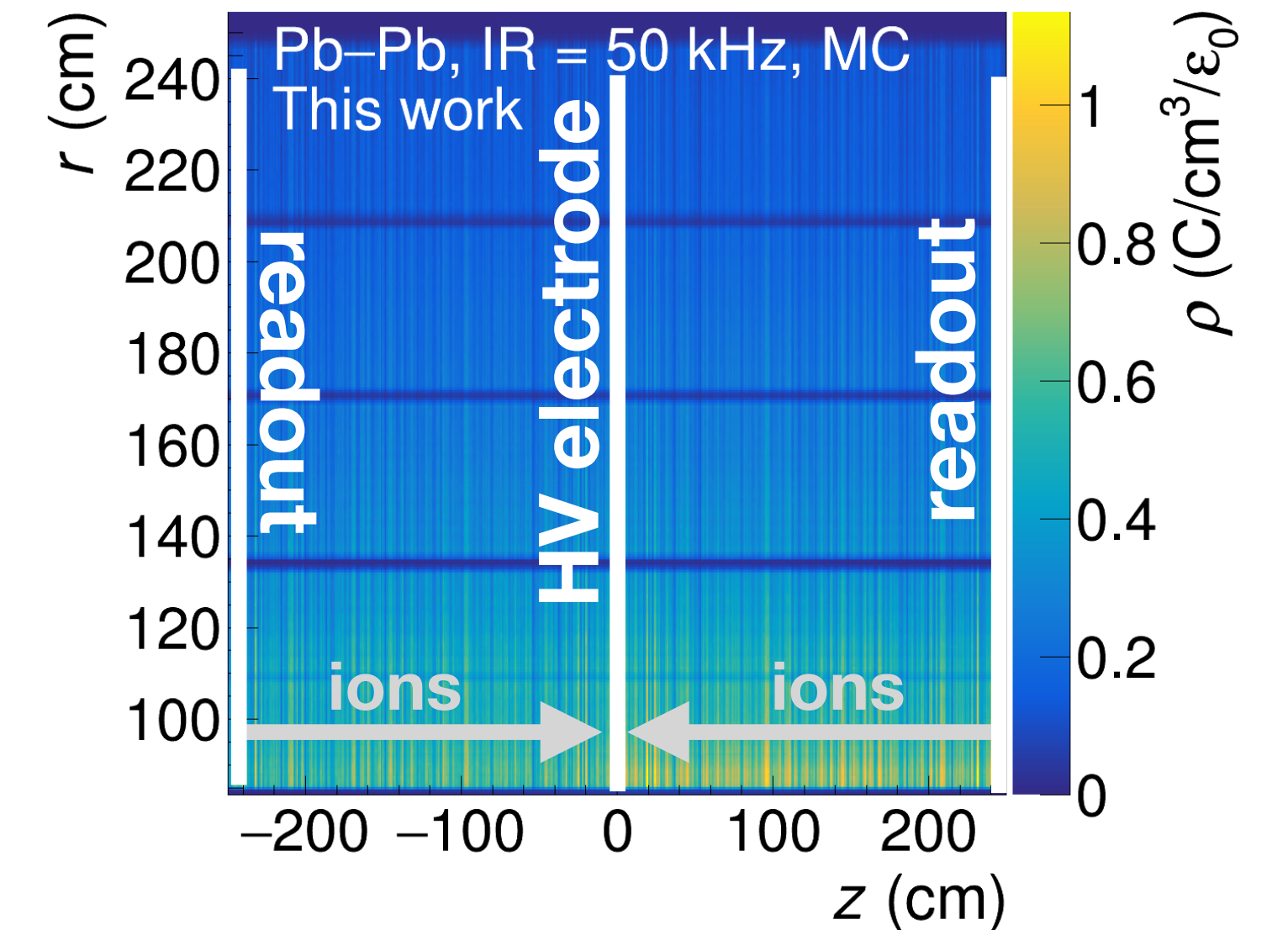
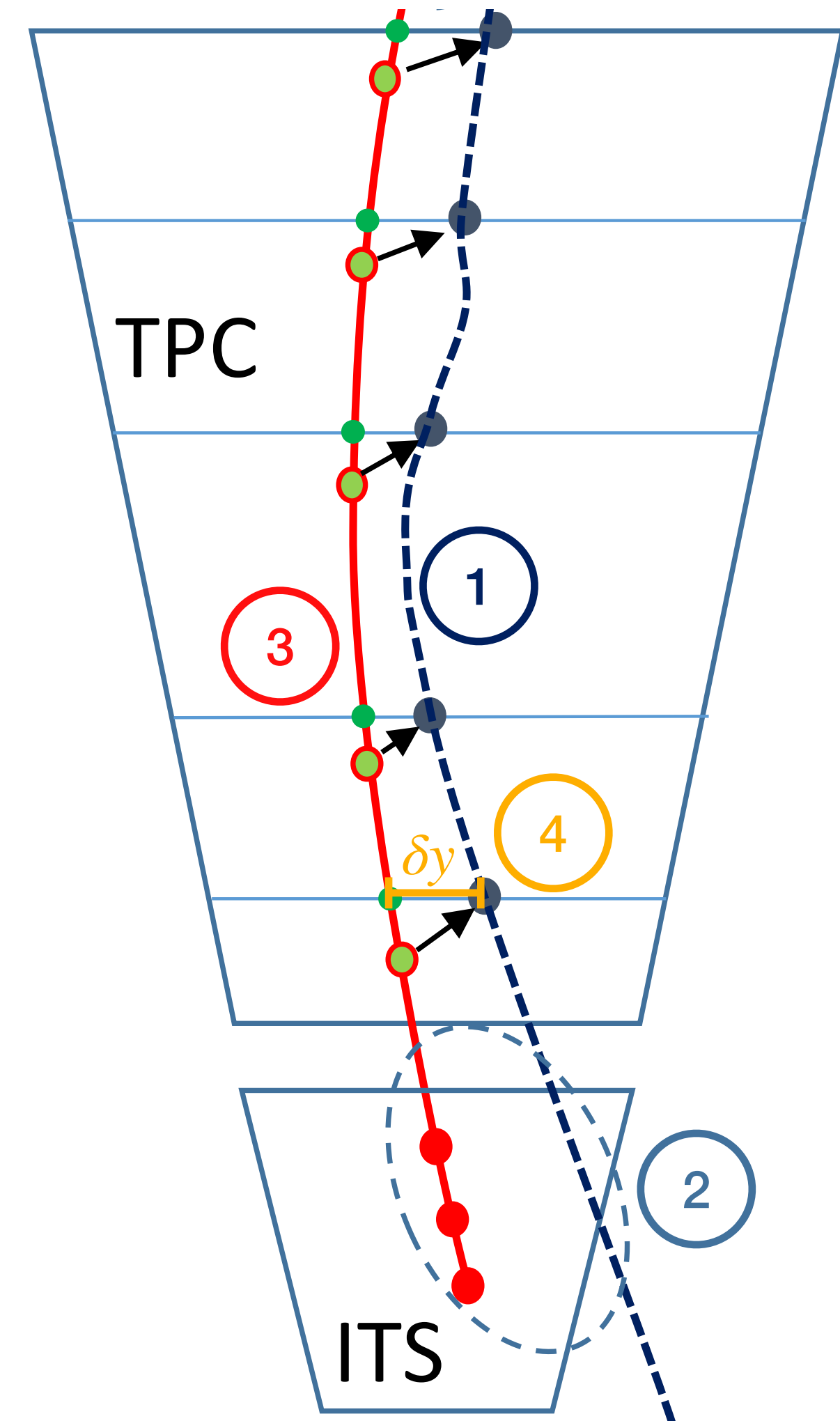# Data driven approach to extract corrections

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 $\delta y, \delta z$
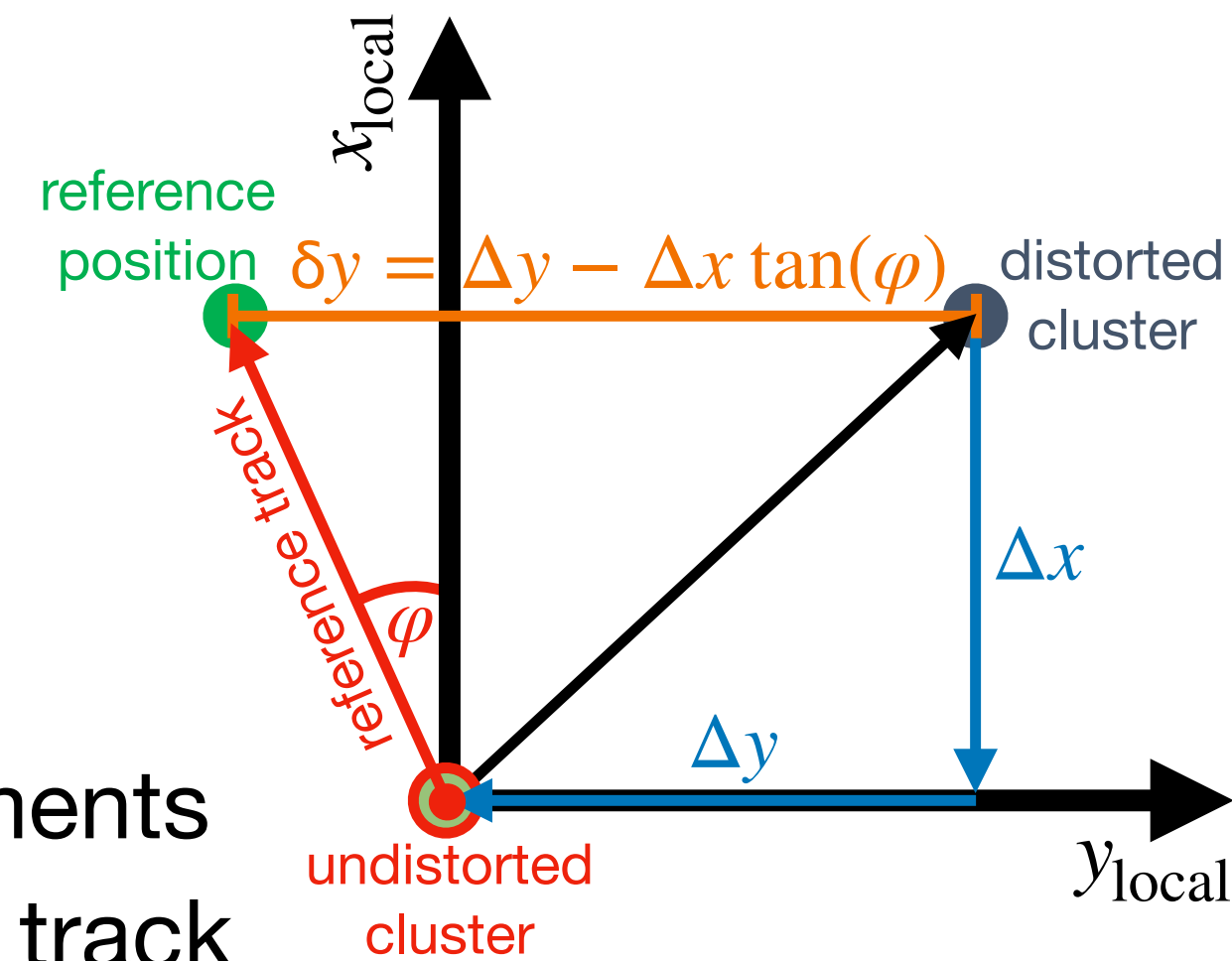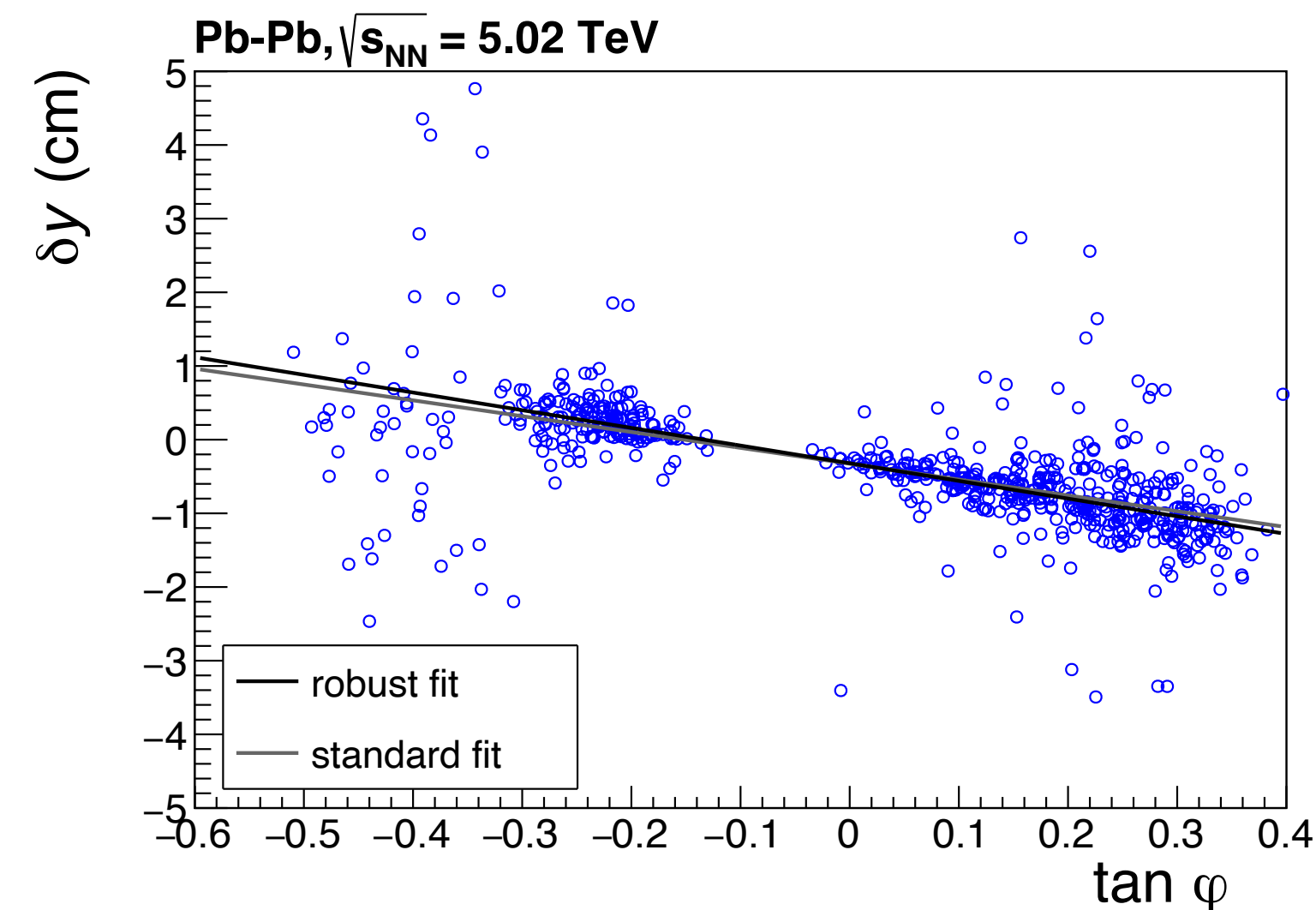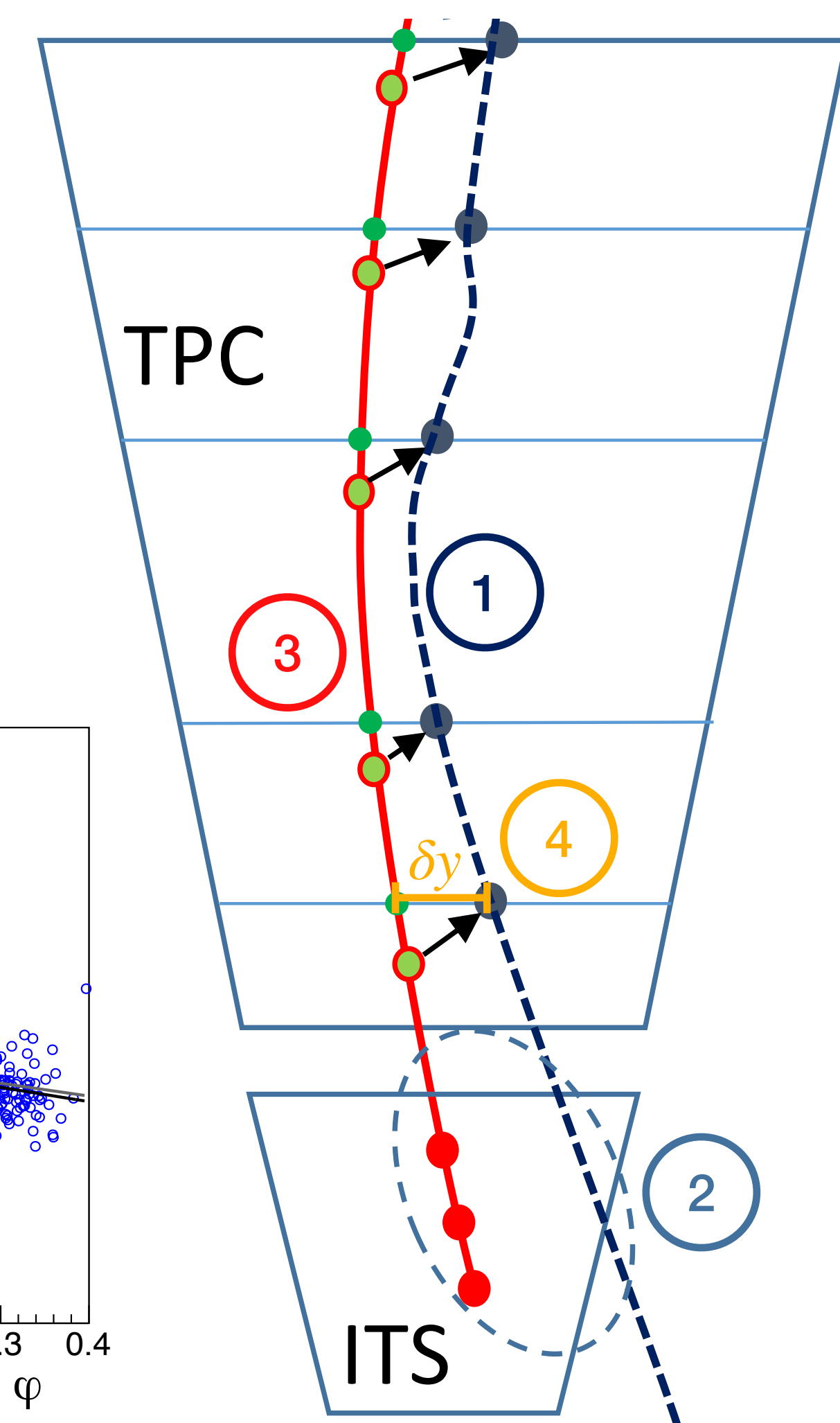   - Storage in 3D map

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   ‣ Storage in 3D map
4. Collect data for full TPC volume $\left(\mathcal{O}(\text{s}) \right)$
   ‣ $\delta y, \delta z \rightarrow \Delta x, \Delta y, \Delta z$
5. Smooth parametrisation with 2D splines
- 2D spline in y-z-plane for each pad row

$$x_{\text{local}}$$

reference position

$$\delta y = \Delta y - \Delta x \tan(\varphi)$$

distorted cluster

reference track

φ

Δx

Δy

y_{local}

undistorted cluster

Correction of average distortions

TPC

3

1

4

δy

2

ITS

Pb-Pb, $\sqrt{s_{NN}}$ = 5.02 TeV

δy (cm)

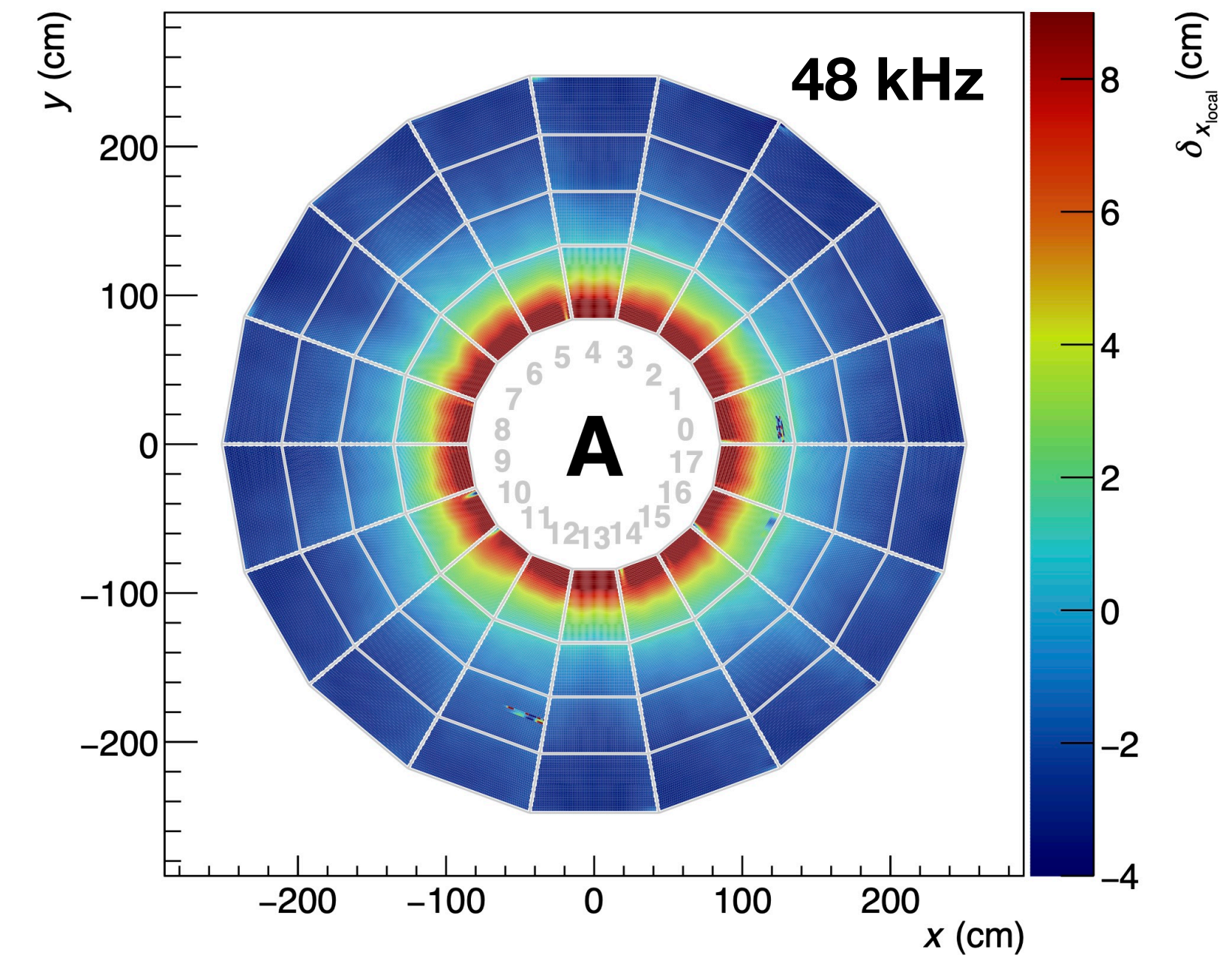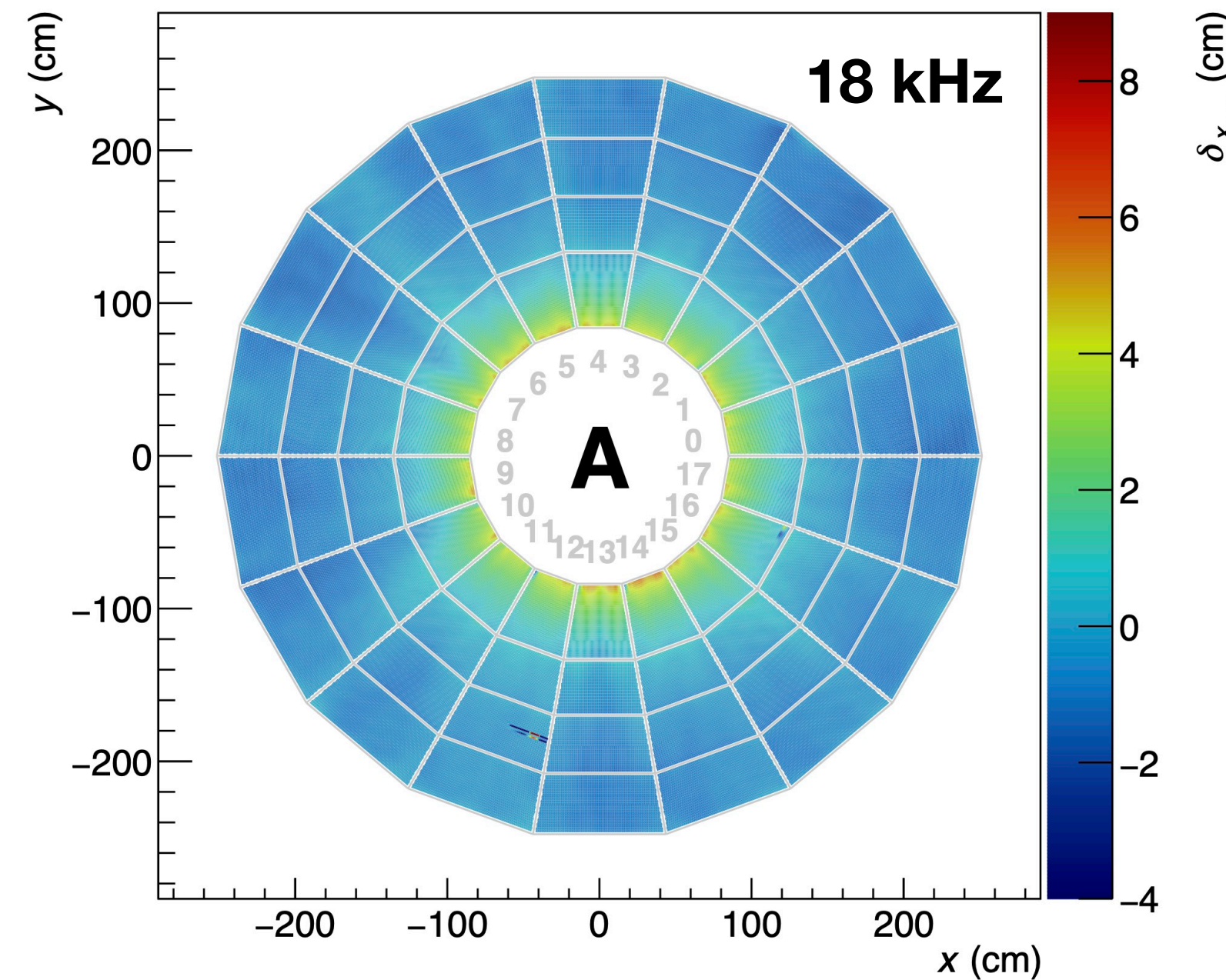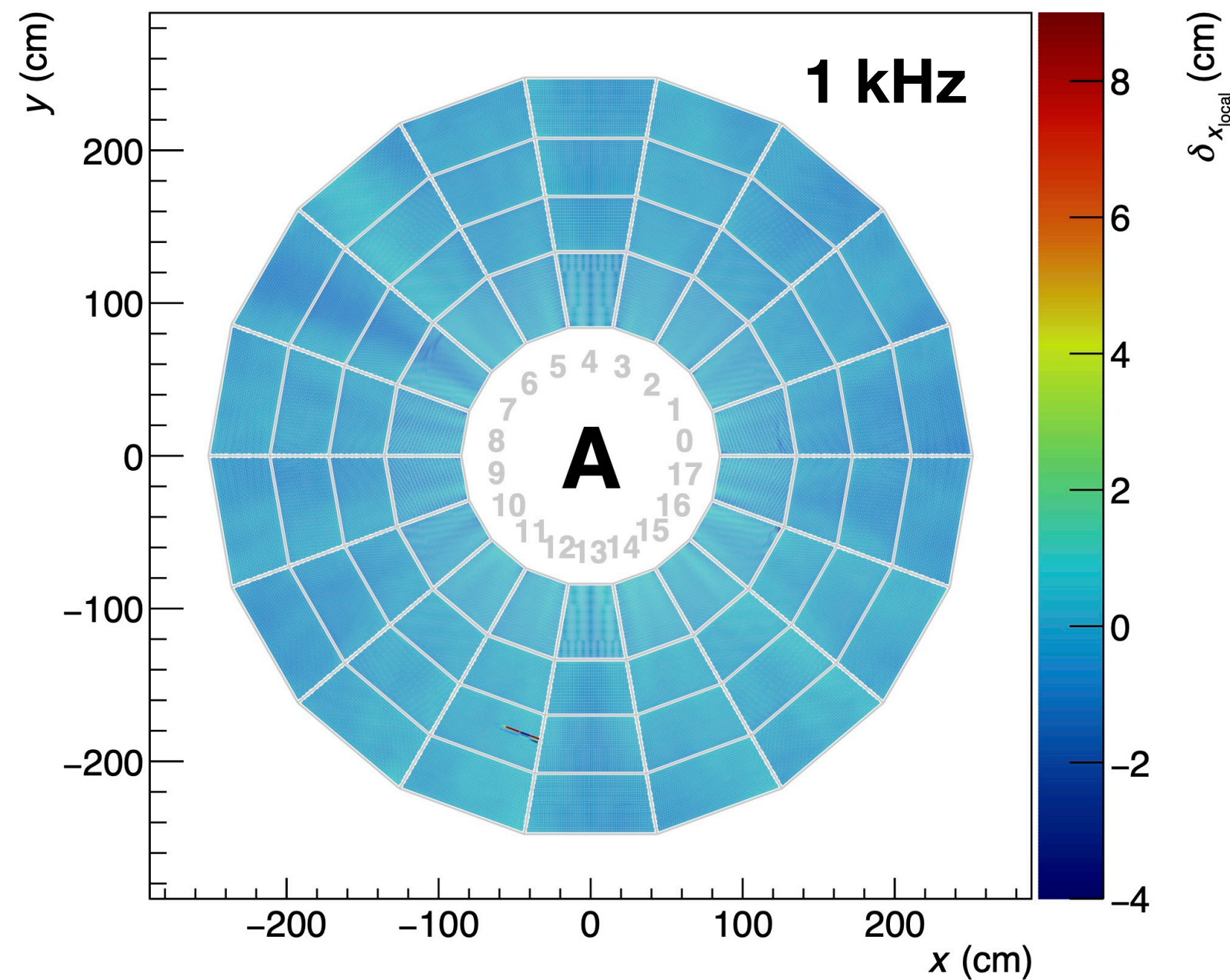— robust fit

— standard fit

$\tan \varphi$

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
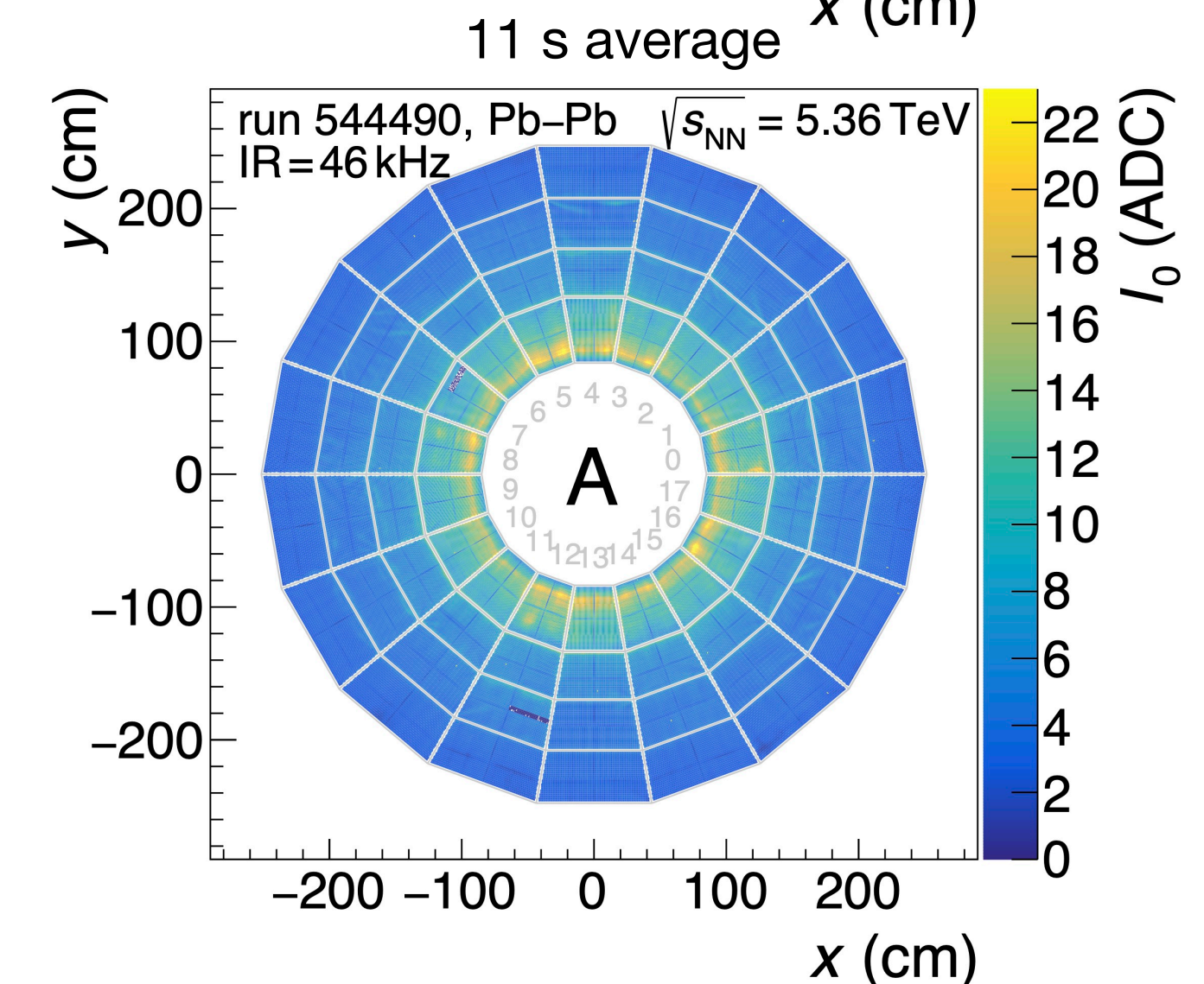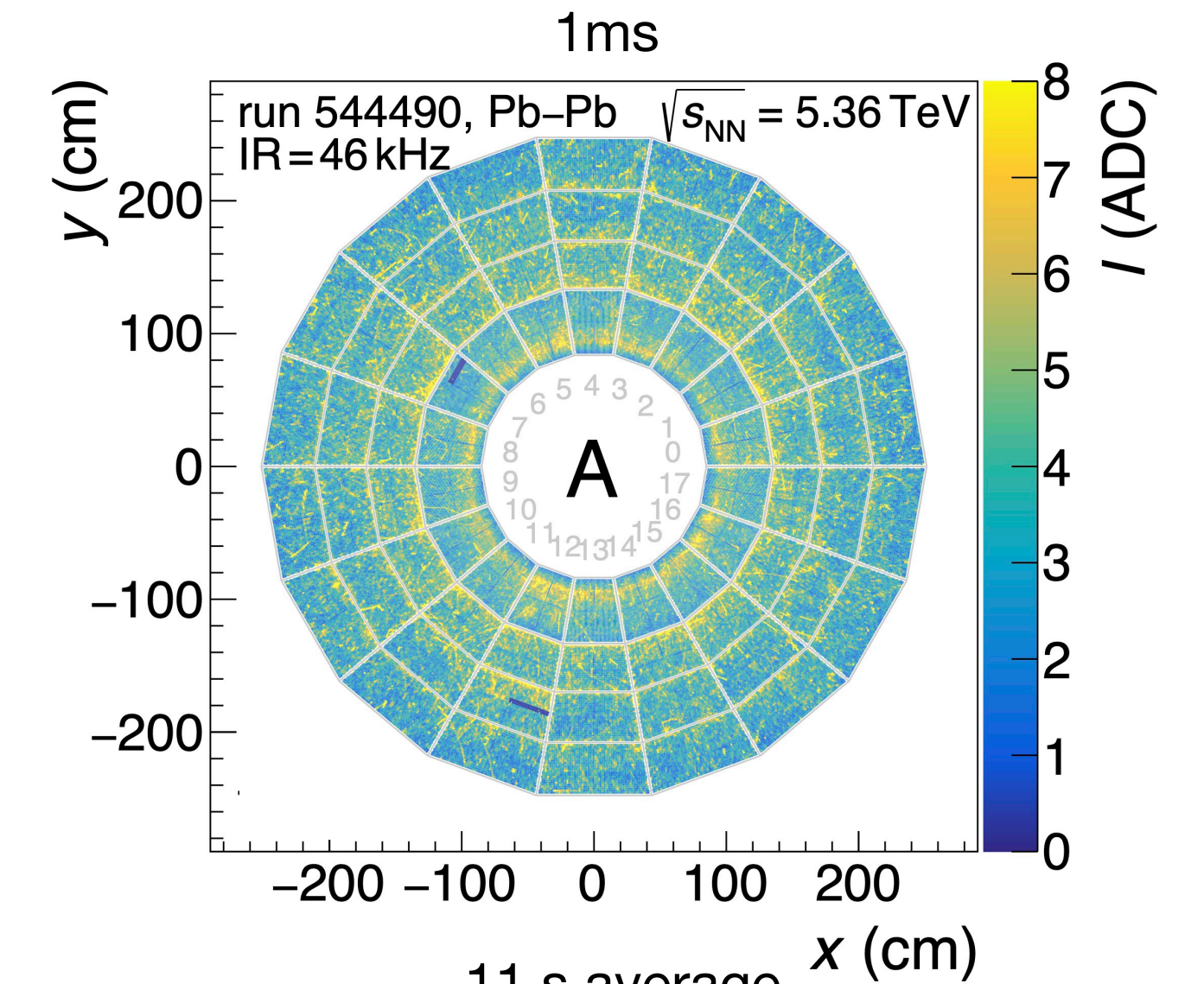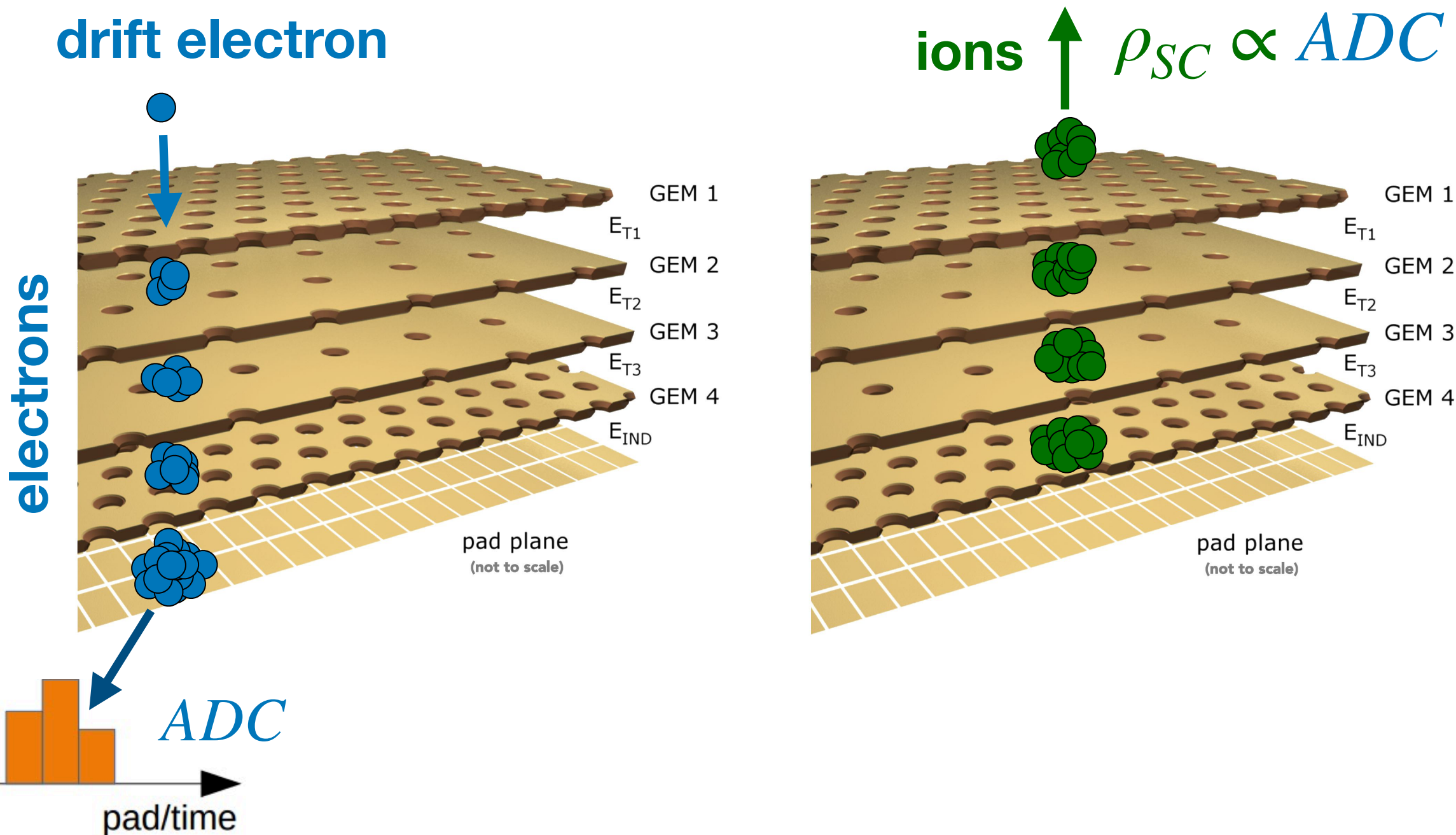 - ‣ Large distortions at inner radii

Estimating space-charge density

Integrated digital currents (IDCs)

- Integration of *ADC* values over ~1ms

- Proportional to space-charge density

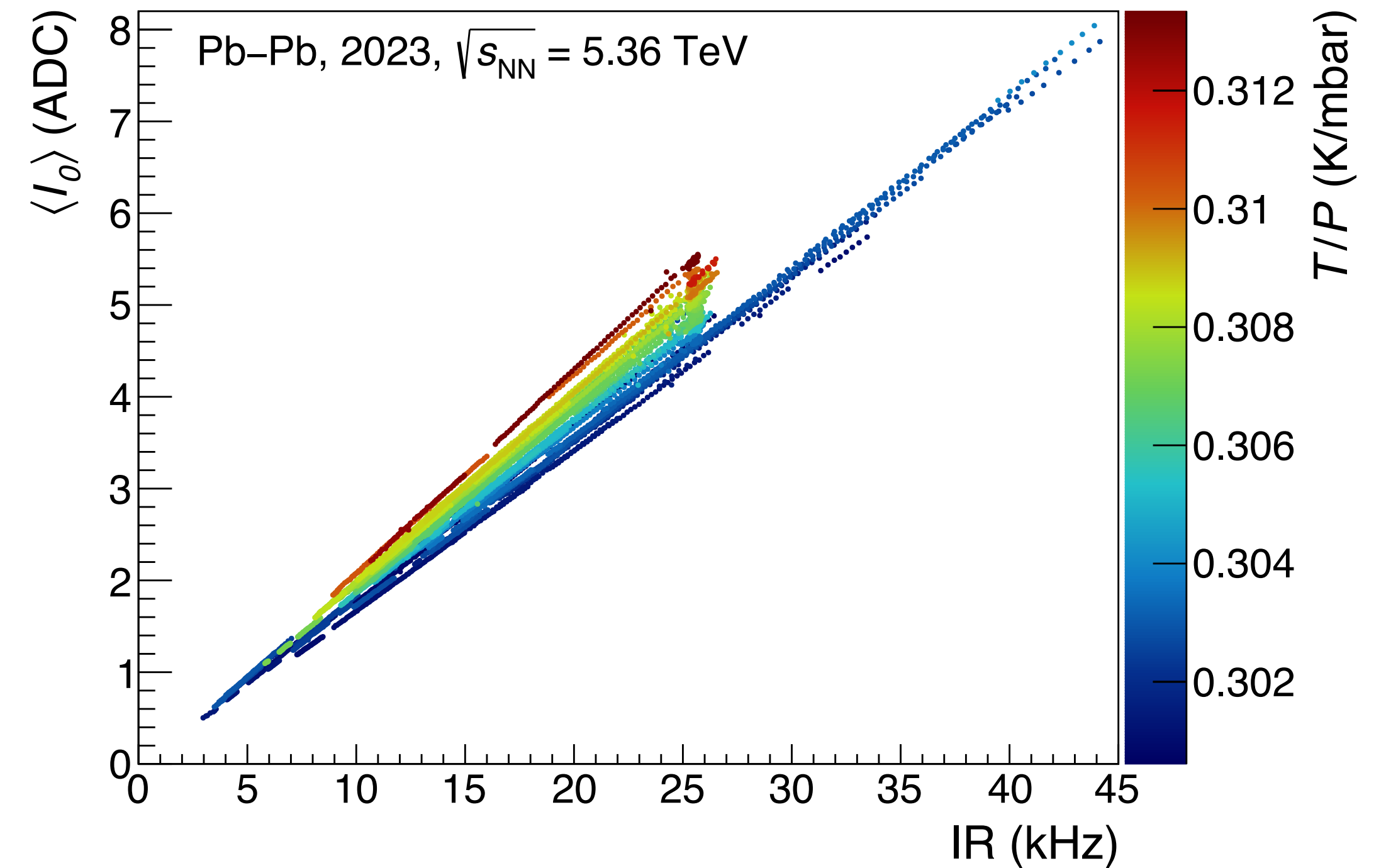- Online processed

  ‣ Storage in the CCDB (calibration database)

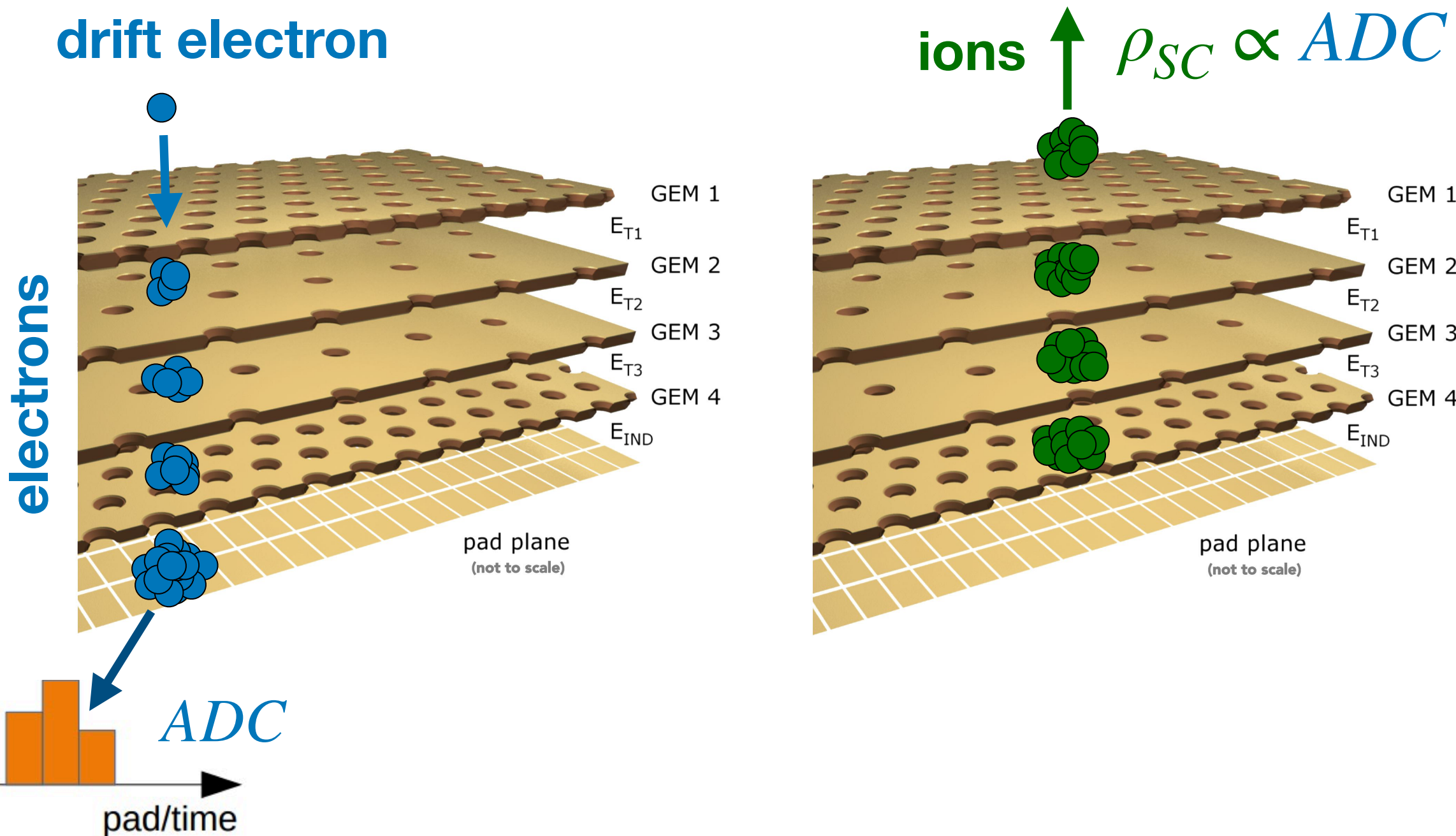# Estimating space-charge density

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

drift electron

ions $\rho_{SC} \propto ADC$

GEM 1
E_{T1}
GEM 2
E_{T2}
GEM 3
E_{T3}
GEM 4
E_{IND}

pad plane
(not to scale)

electrons

ADC

ADC

pad/time

Pb–Pb, 2023, $\sqrt{s_{NN}}$ = 5.36 TeV

$\langle I_0 \rangle$ (ADC)

IR (kHz)

T/P (K/mbar)

12

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
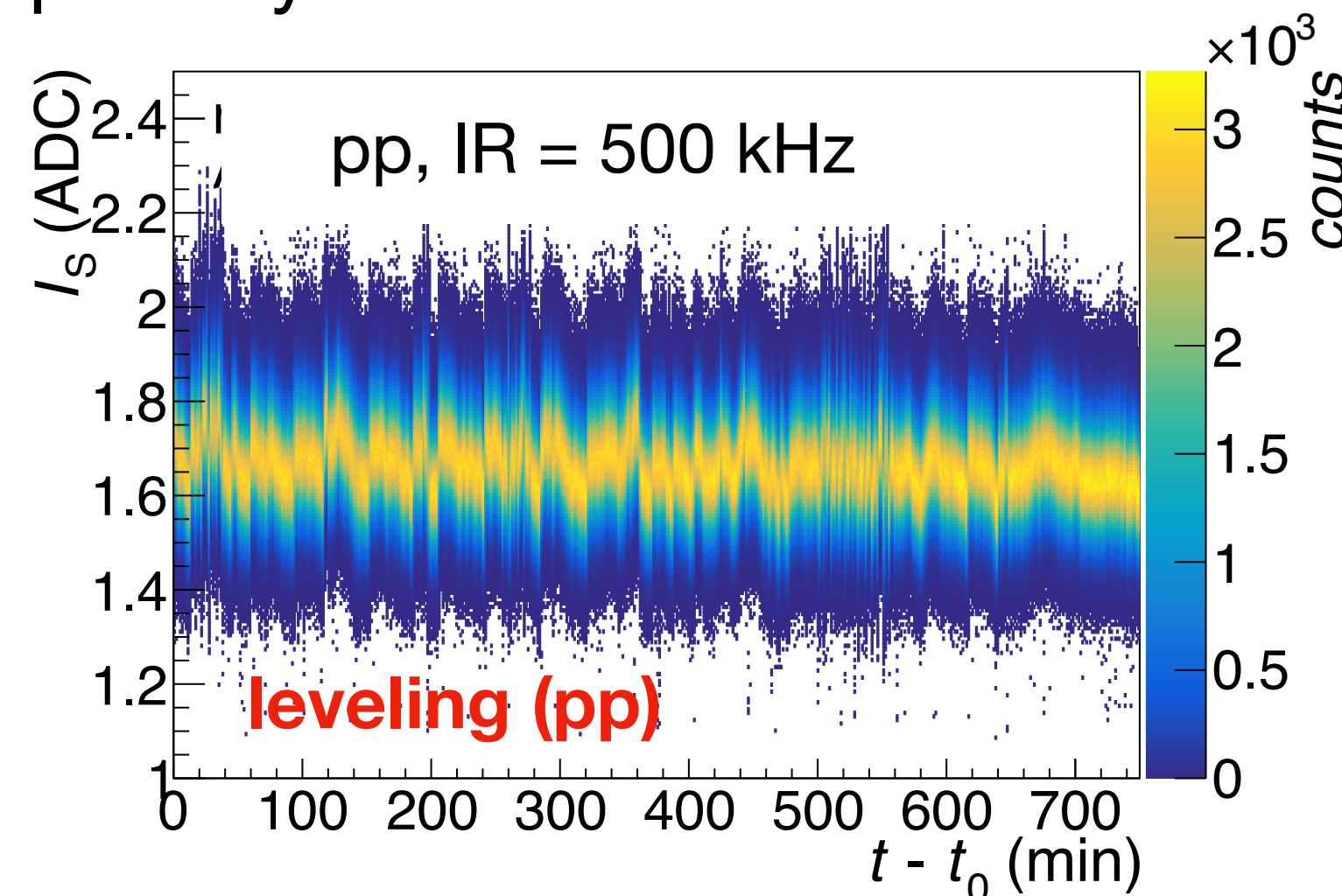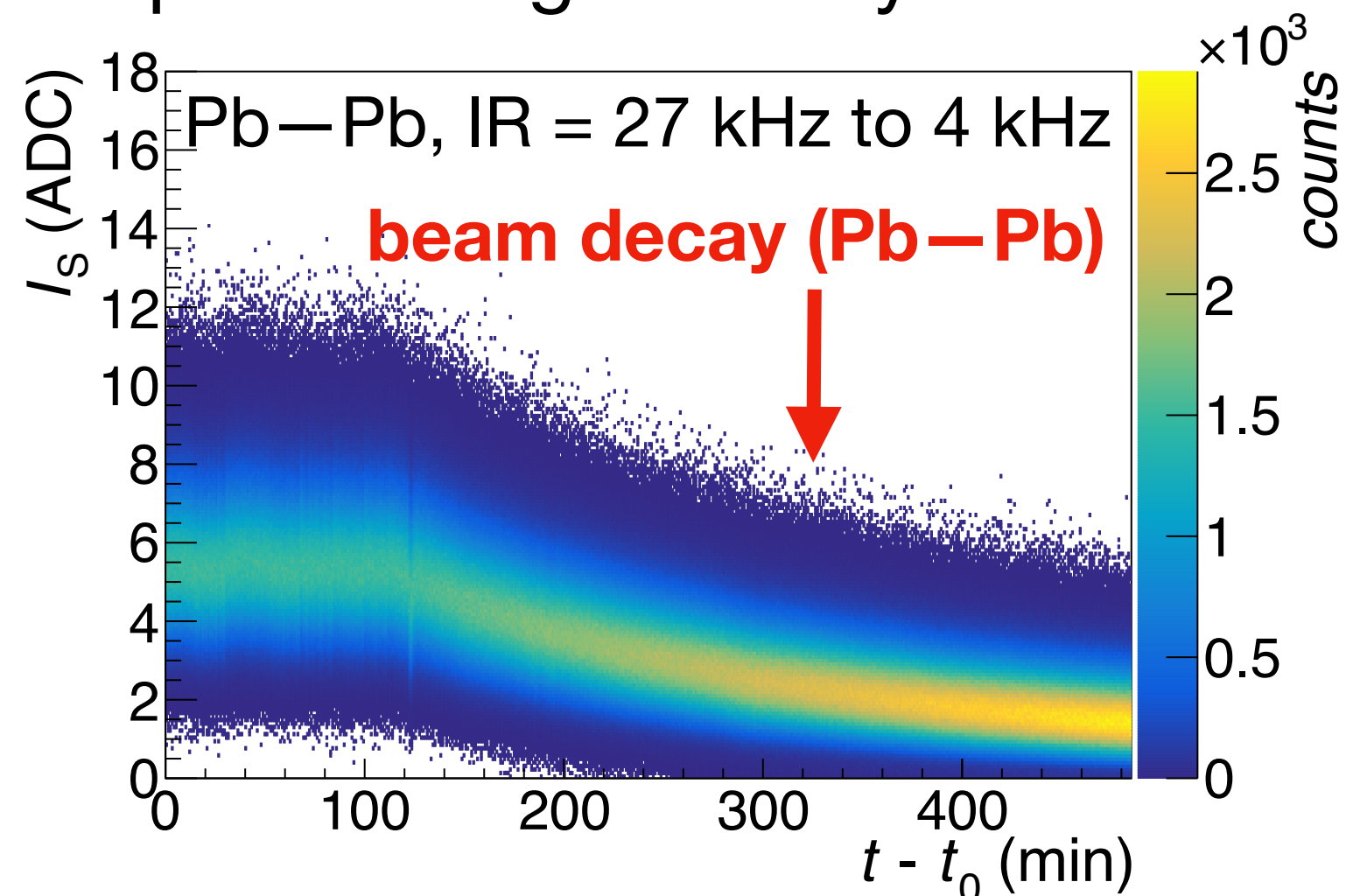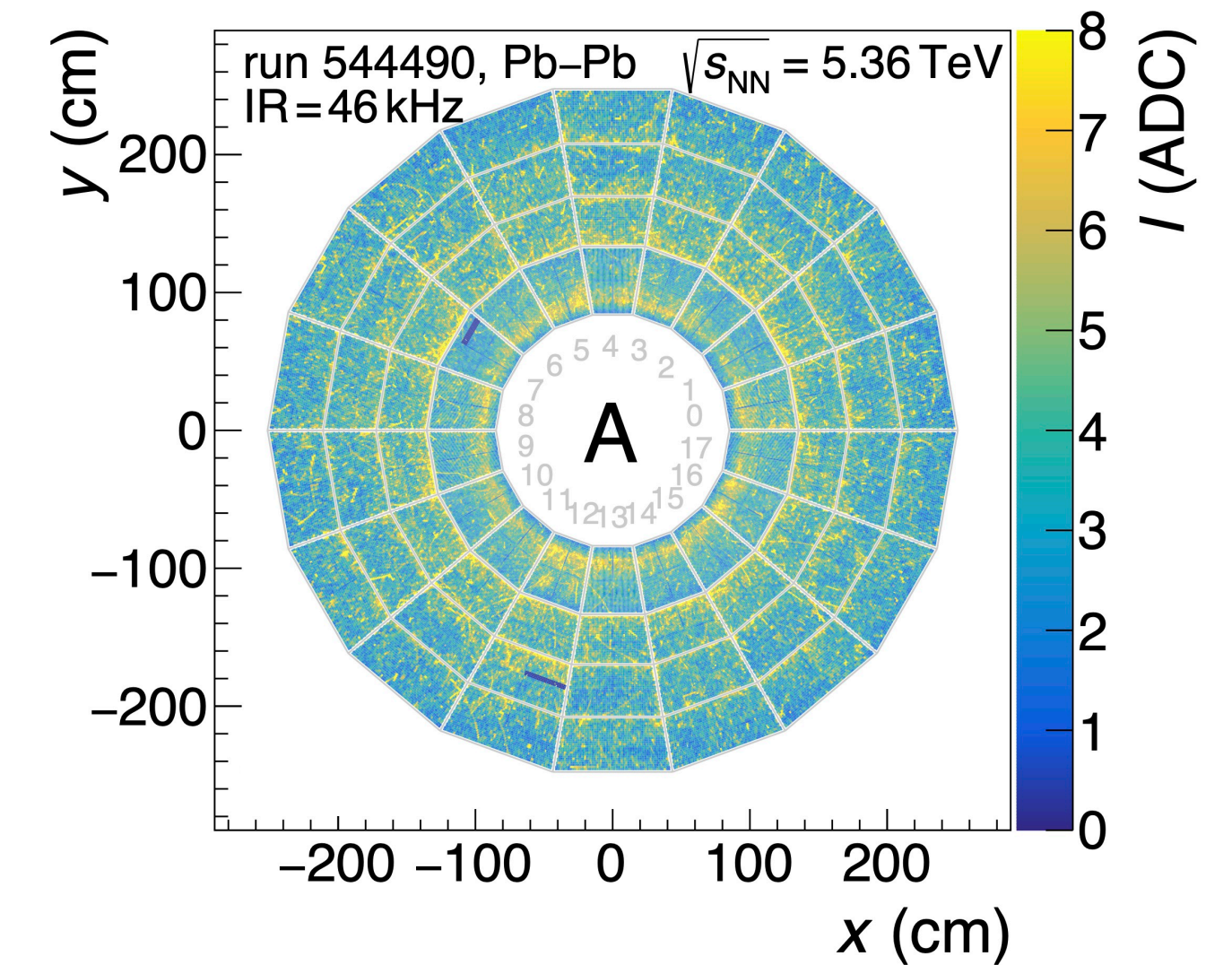
Space-charge correction procedure

Space-charge correction

- Input: 3 (or 2) correction maps

- M_{avg}: Average space-charge correction

- M_+ und M_-

  ‣ Correction maps for slightly higher/lower
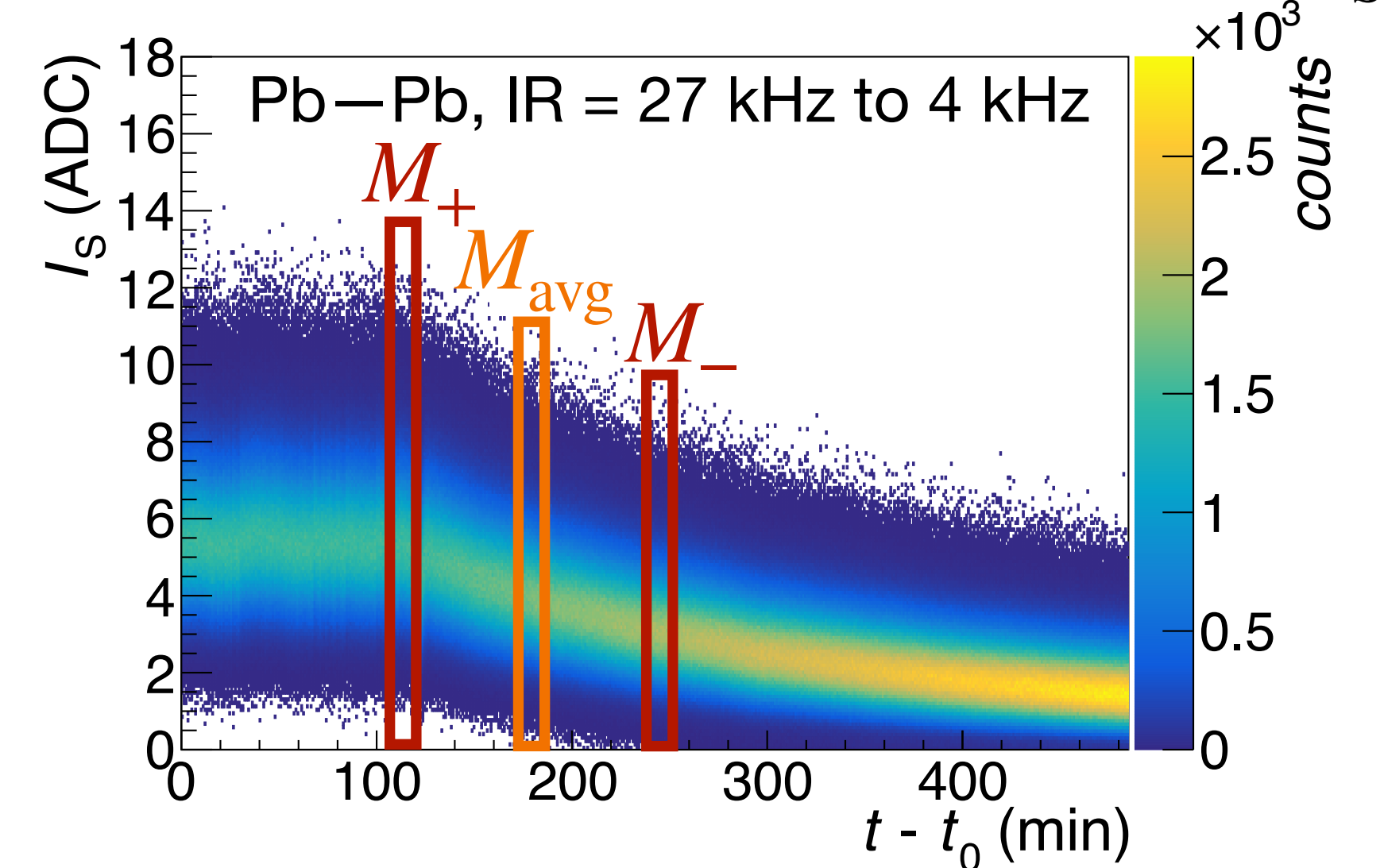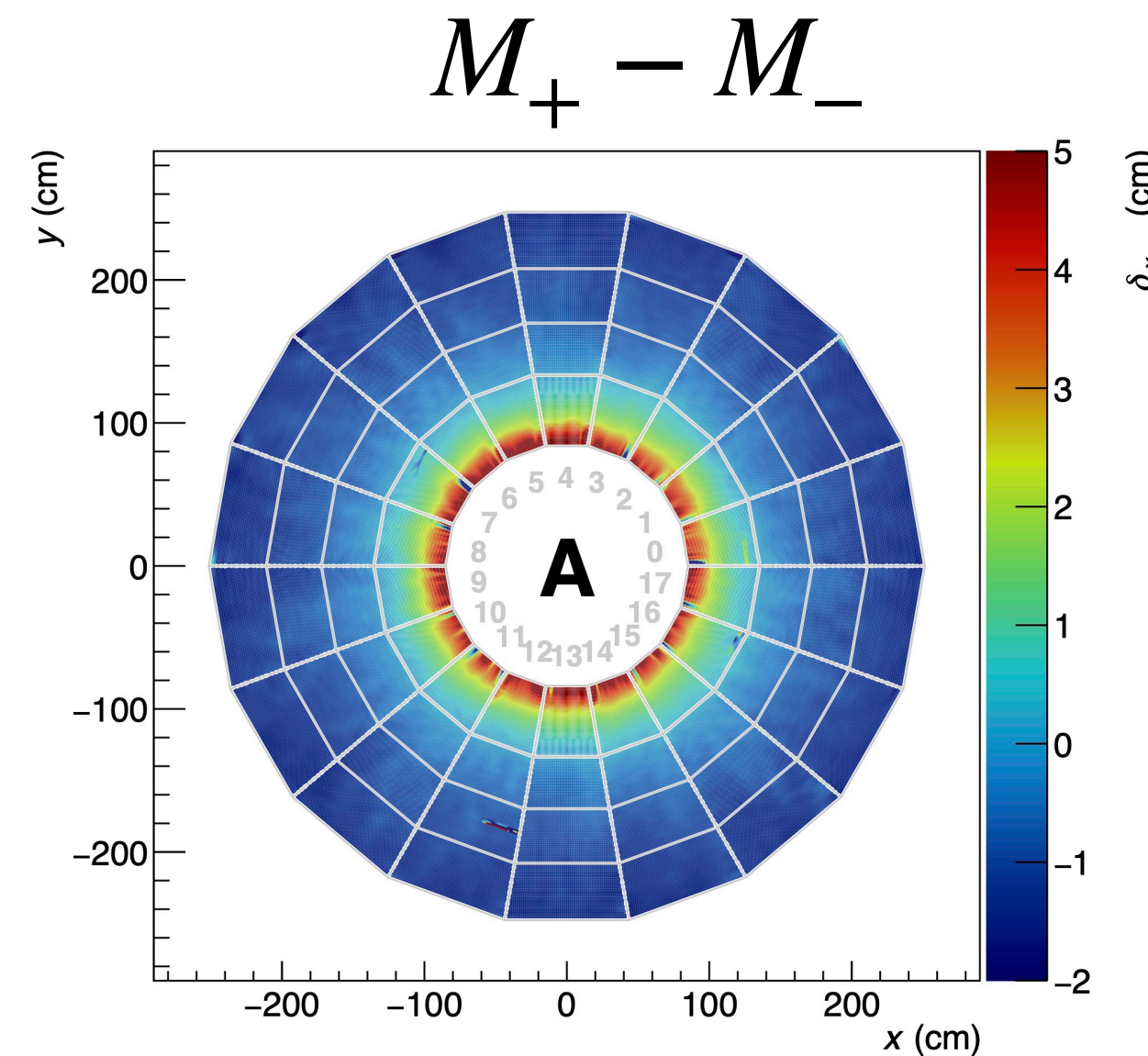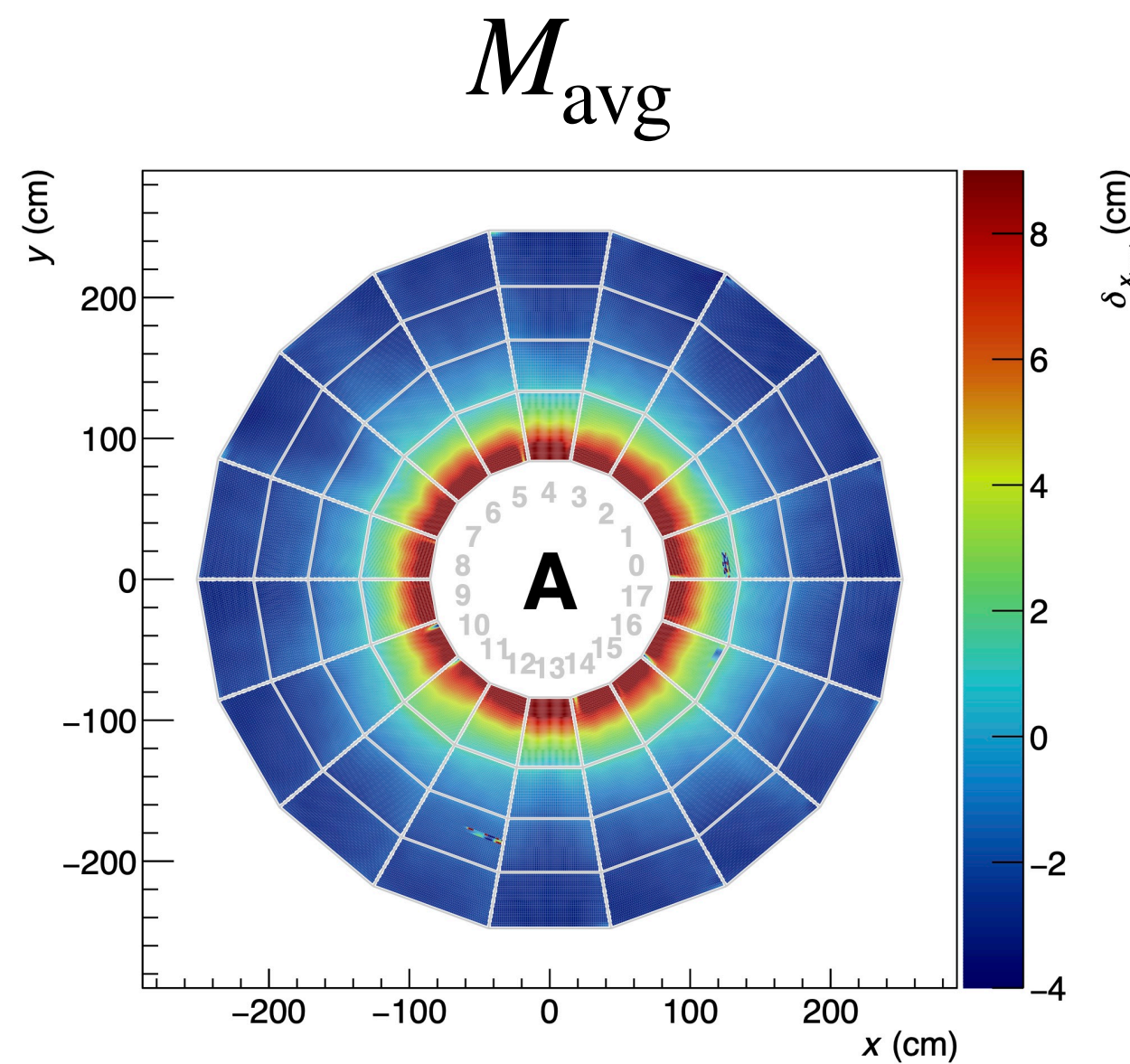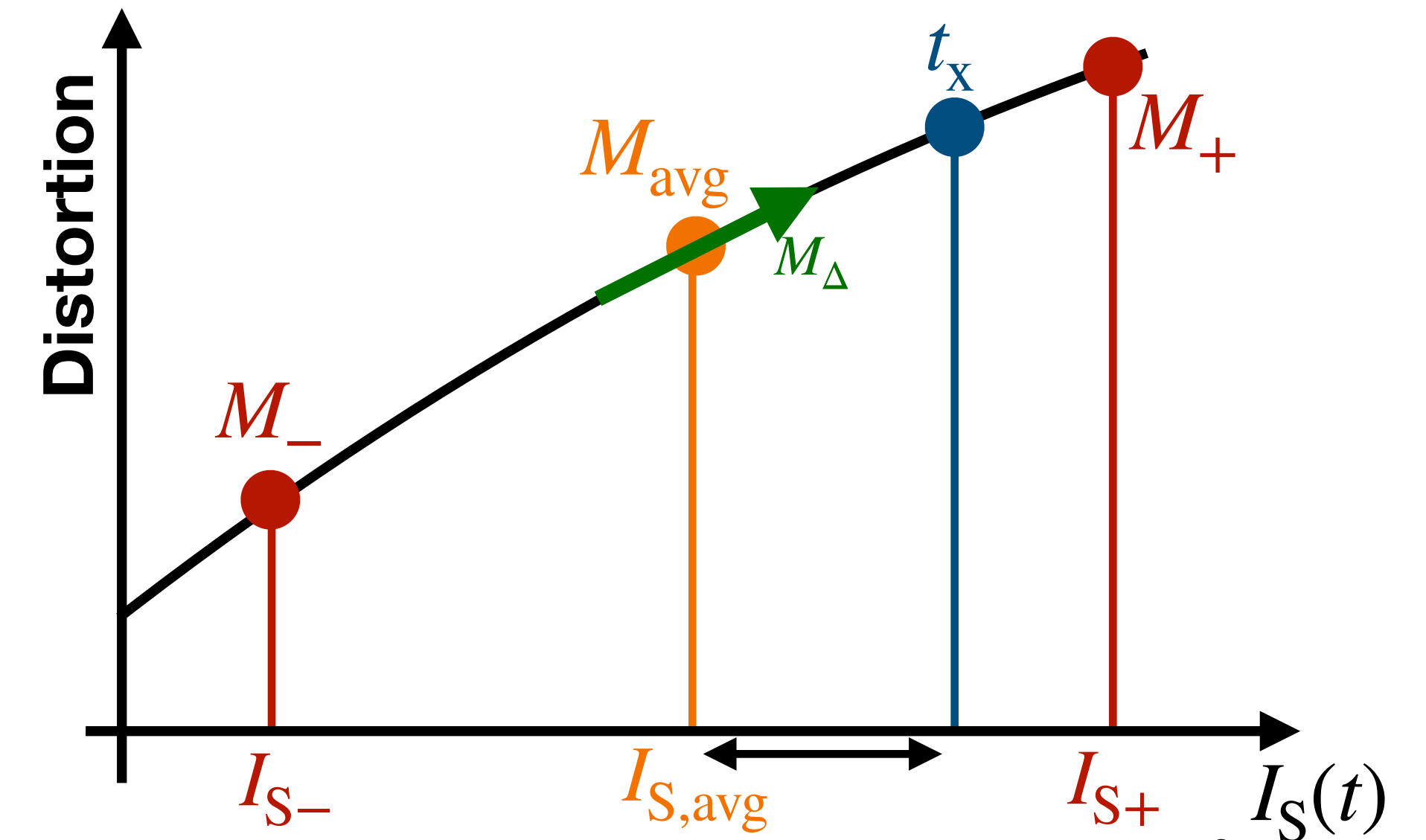   space-charge density ($\pm 20\,\%$)
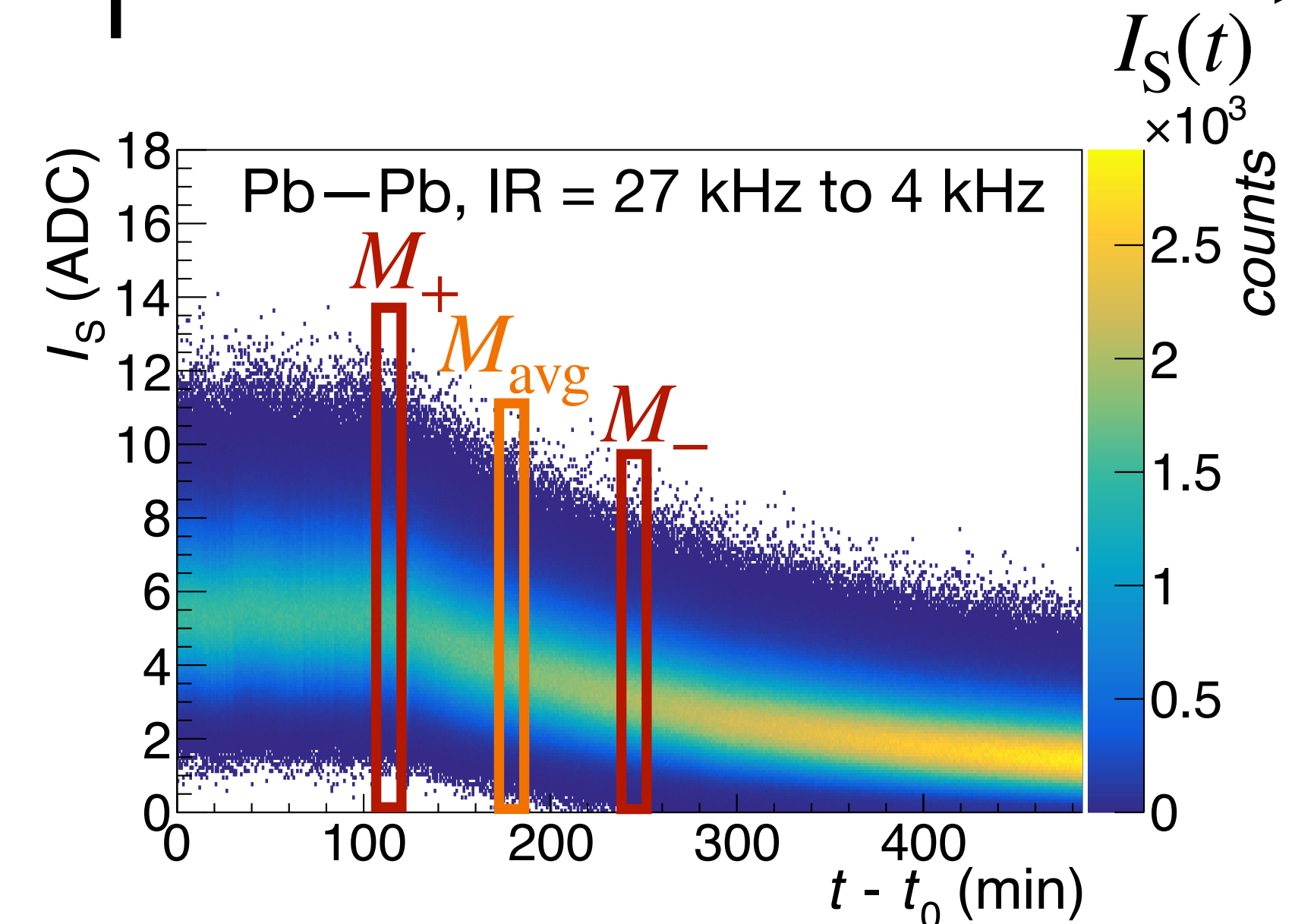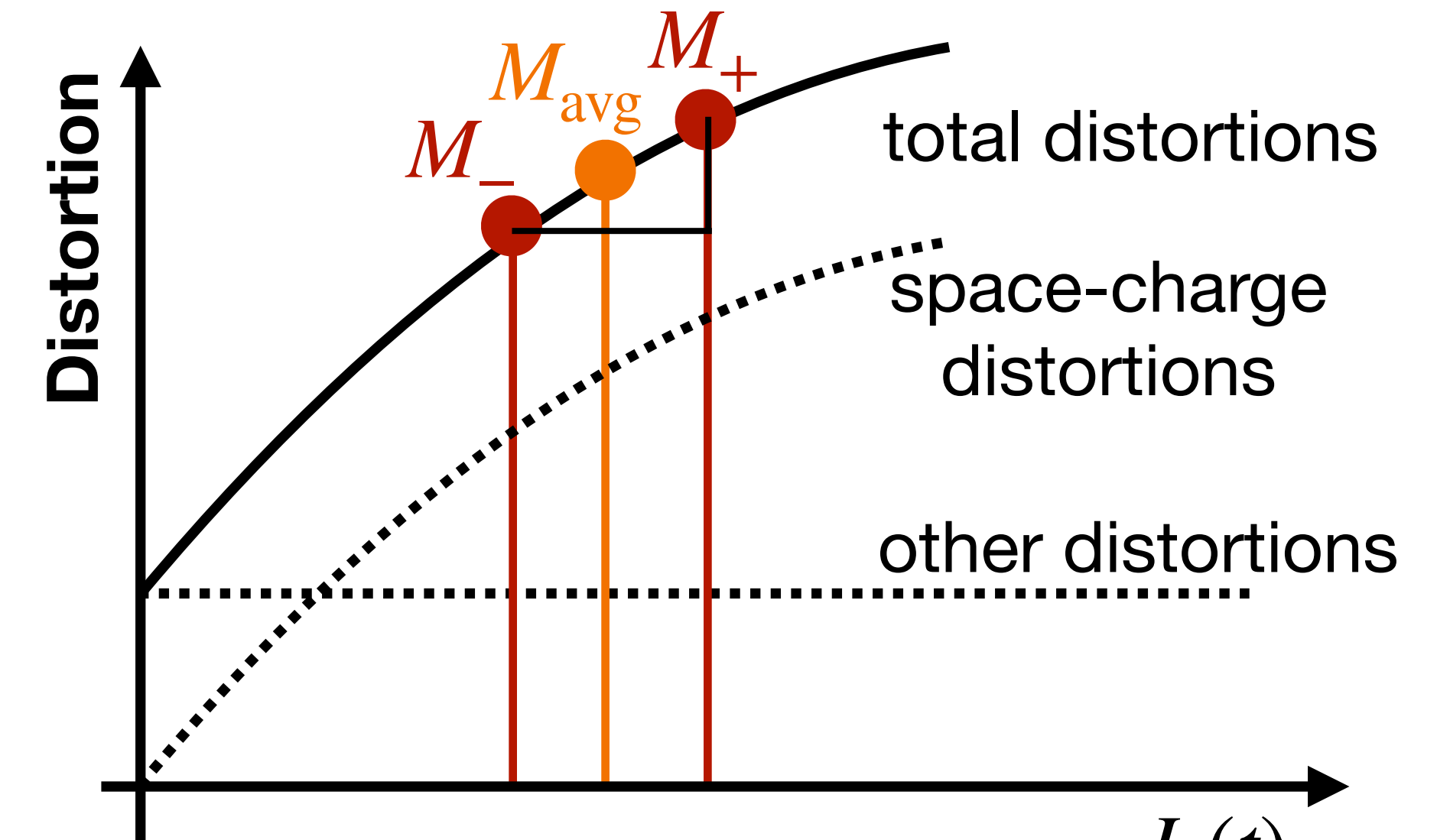
Time-dependent space-charge correction

Creation of time-dependent corrections

- Derivative correction map: $M_\Delta = \dfrac{M_+ - M_-}{I_{S+} - I_{S-}}$

- Linear combination with time-dependent scaling parameter $S(t)$
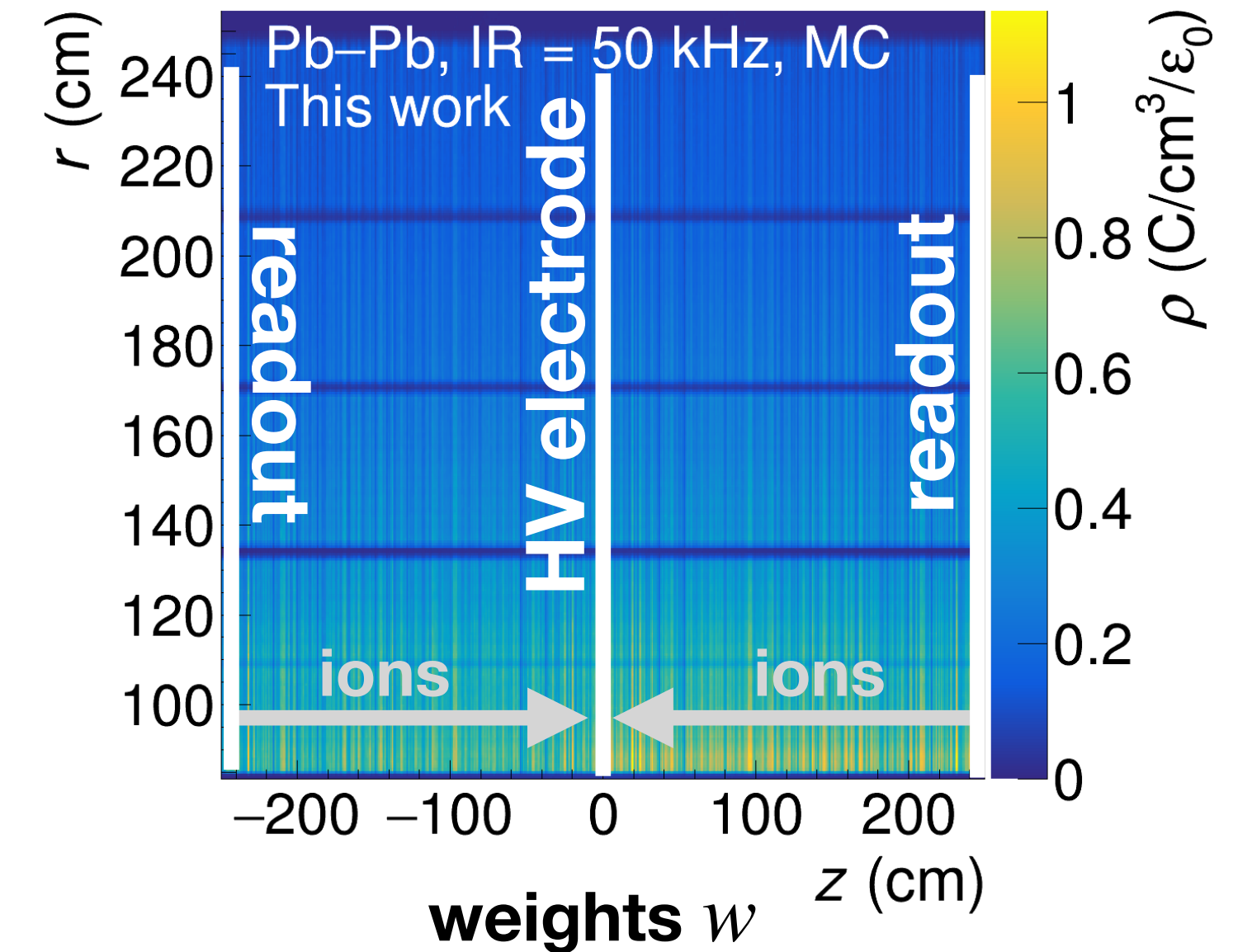
  ‣ $M(t) = M_{\text{avg}} + M_\Delta \cdot S(t)$

M_{avg}

$M_+ - M_-$

Time-dependent space-charge correction

Time-dependent scaling factor $S(t)$

- Weighted mean space-charge density for time t

$$\blacktriangleright \quad S(t) = \frac{\sum_{t_{sc}=t_c}^{t} w(t_{sc} - t) \cdot I_S(t_{sc})}{\sum_{t_{sc}=t_c}^{t} w(t_{sc} - t)} - \langle I_{S,avg} \rangle$$

Simulation: space-charge discs

Space-charge discs as a function of time
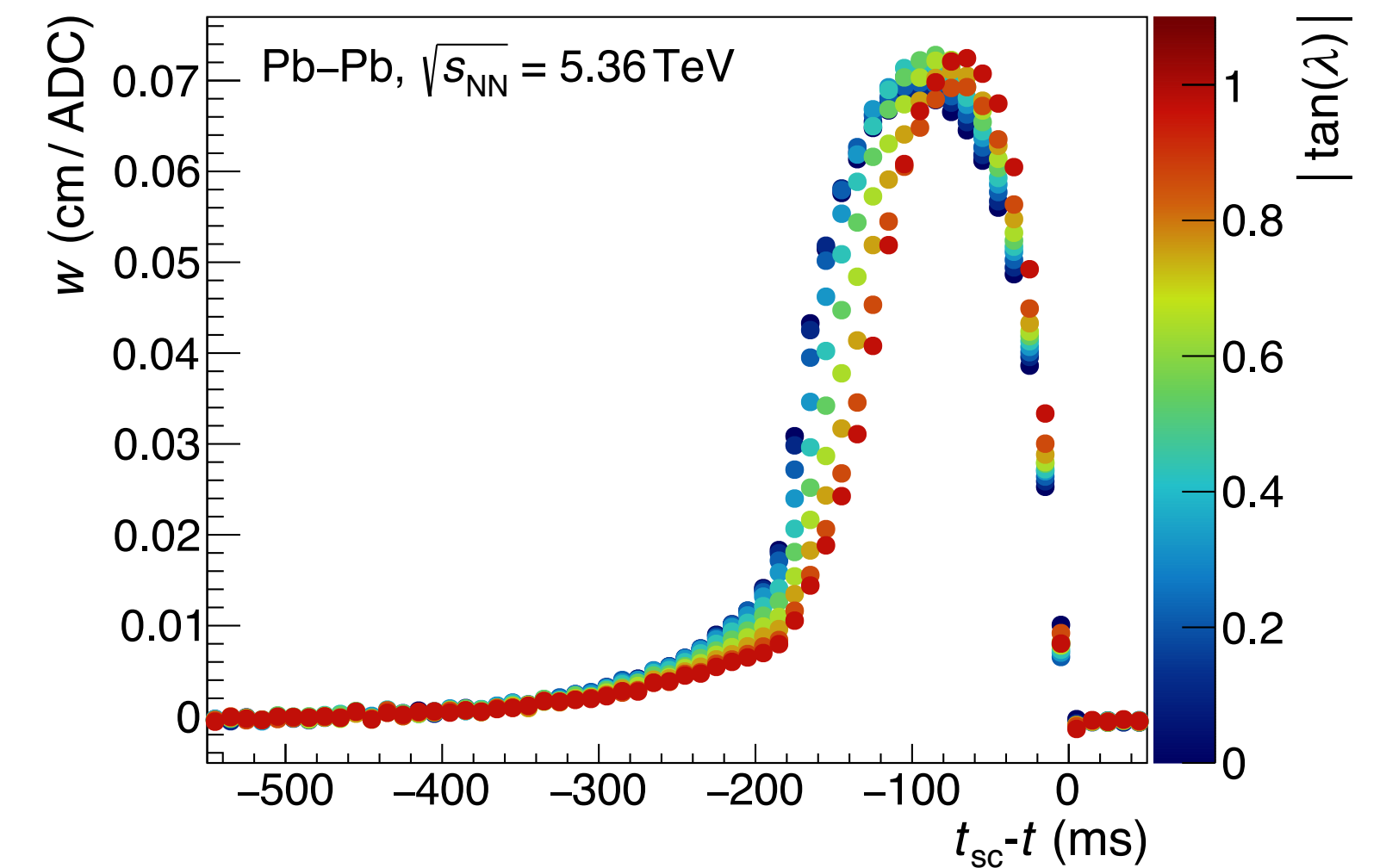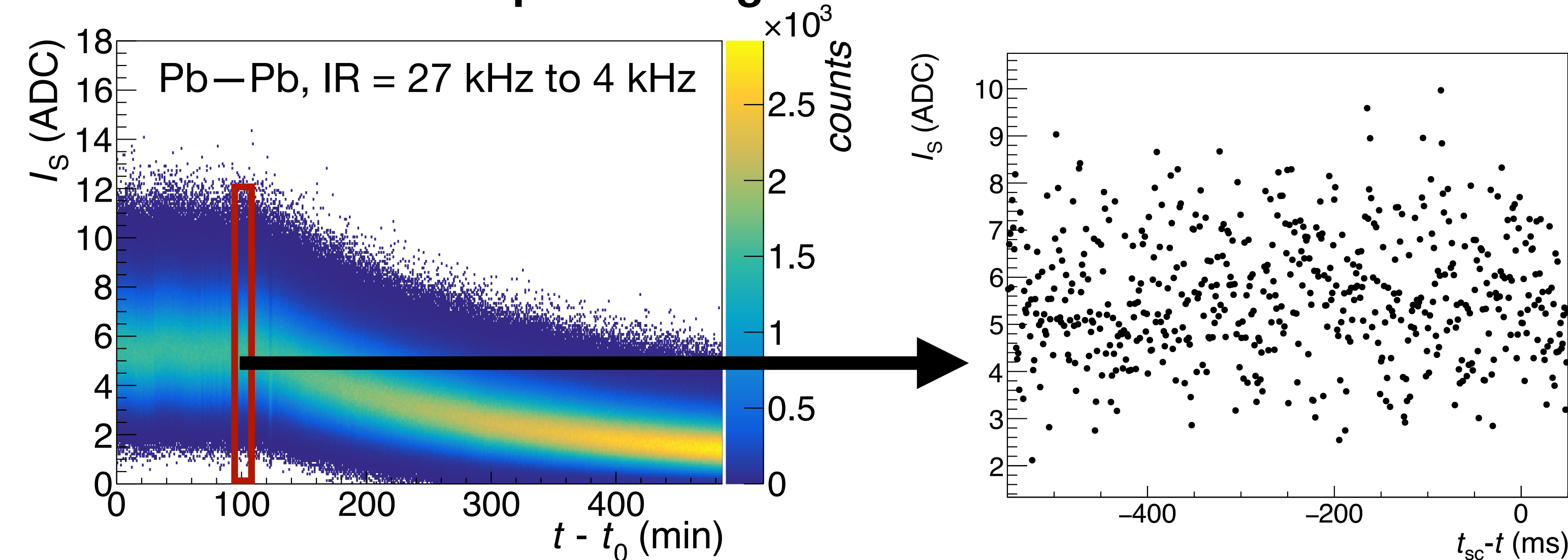
weights w

Composition of the correction map

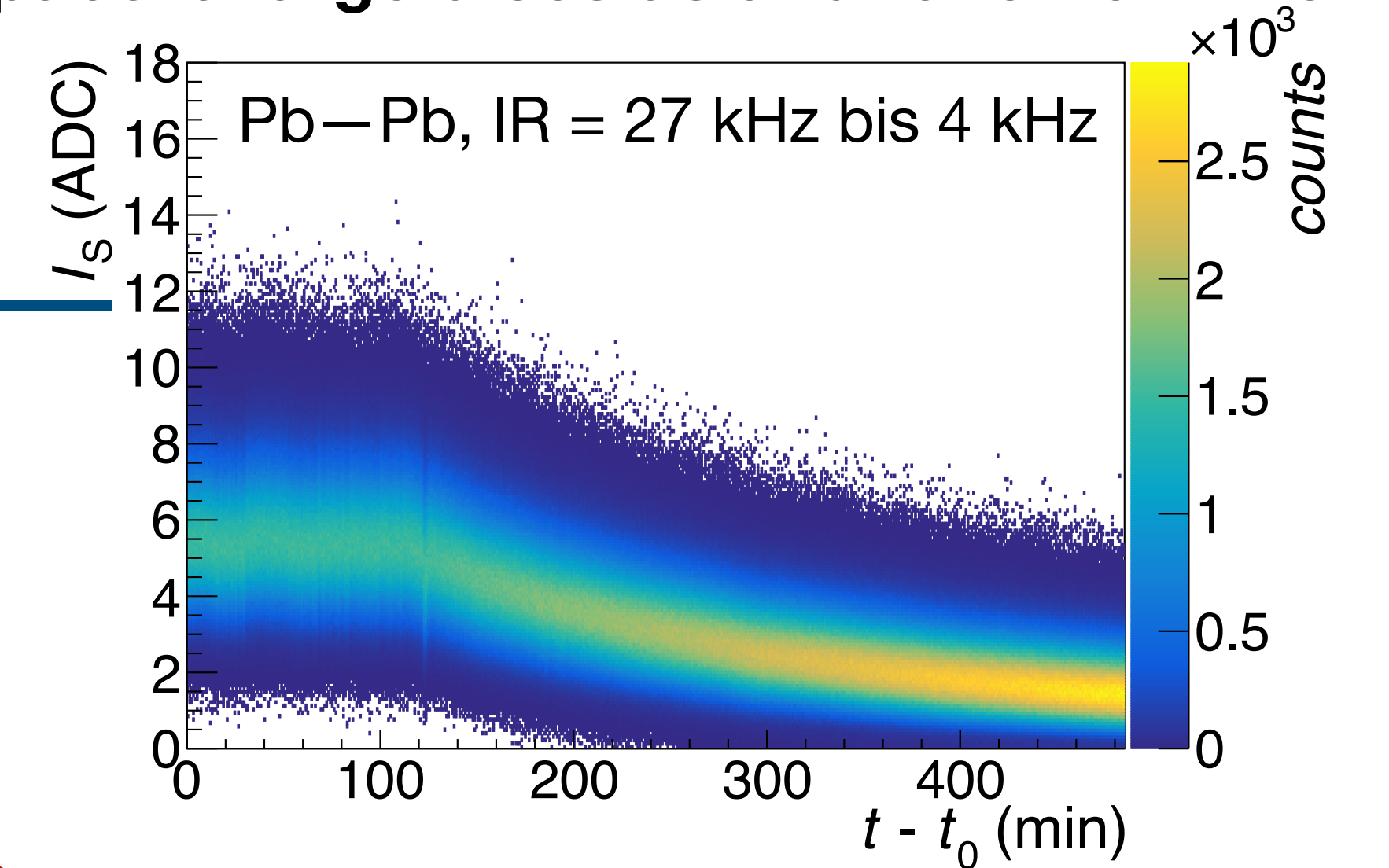**Space-charge discs as a function of time**

Fast approach to create a correction map for each time stamp

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

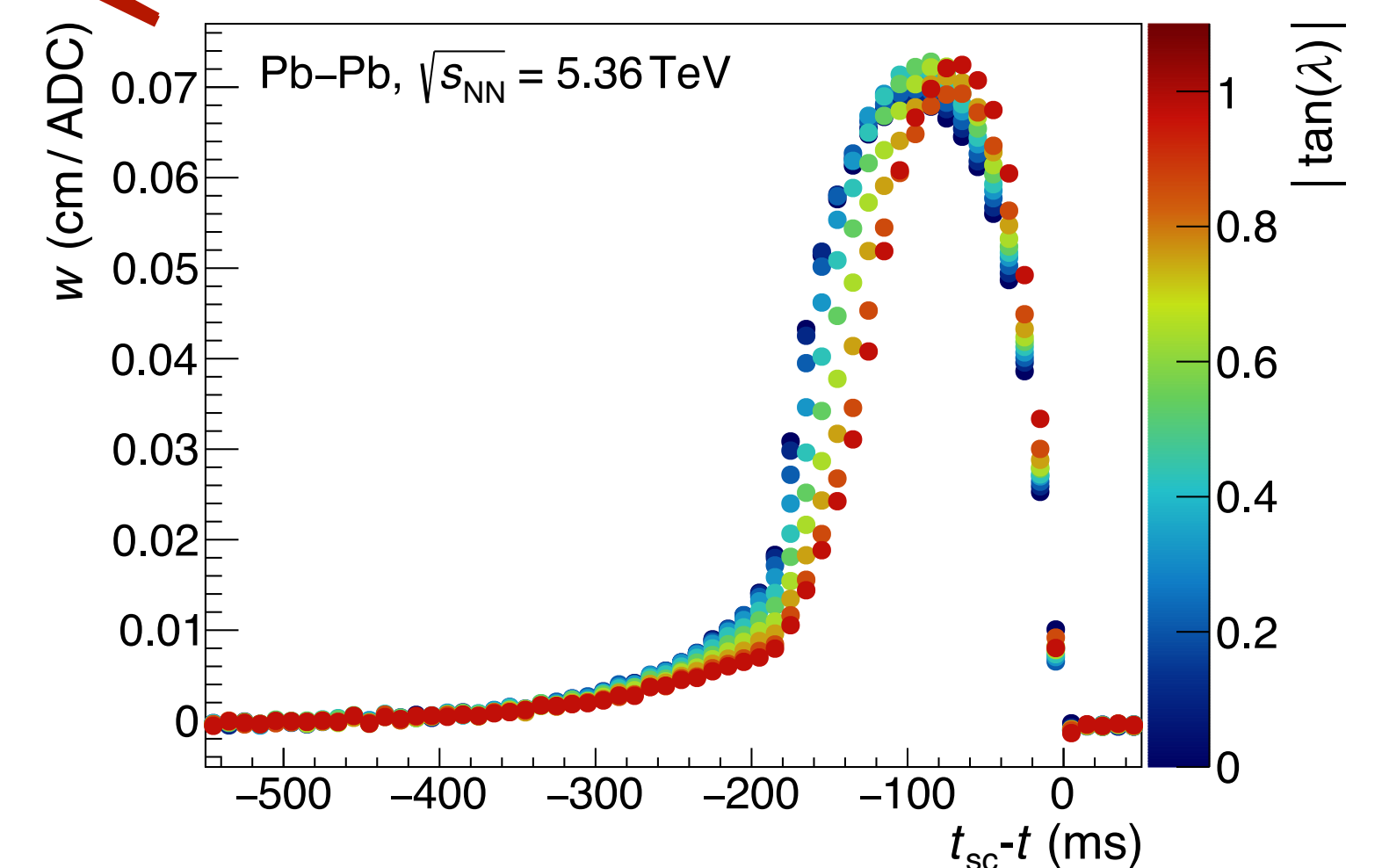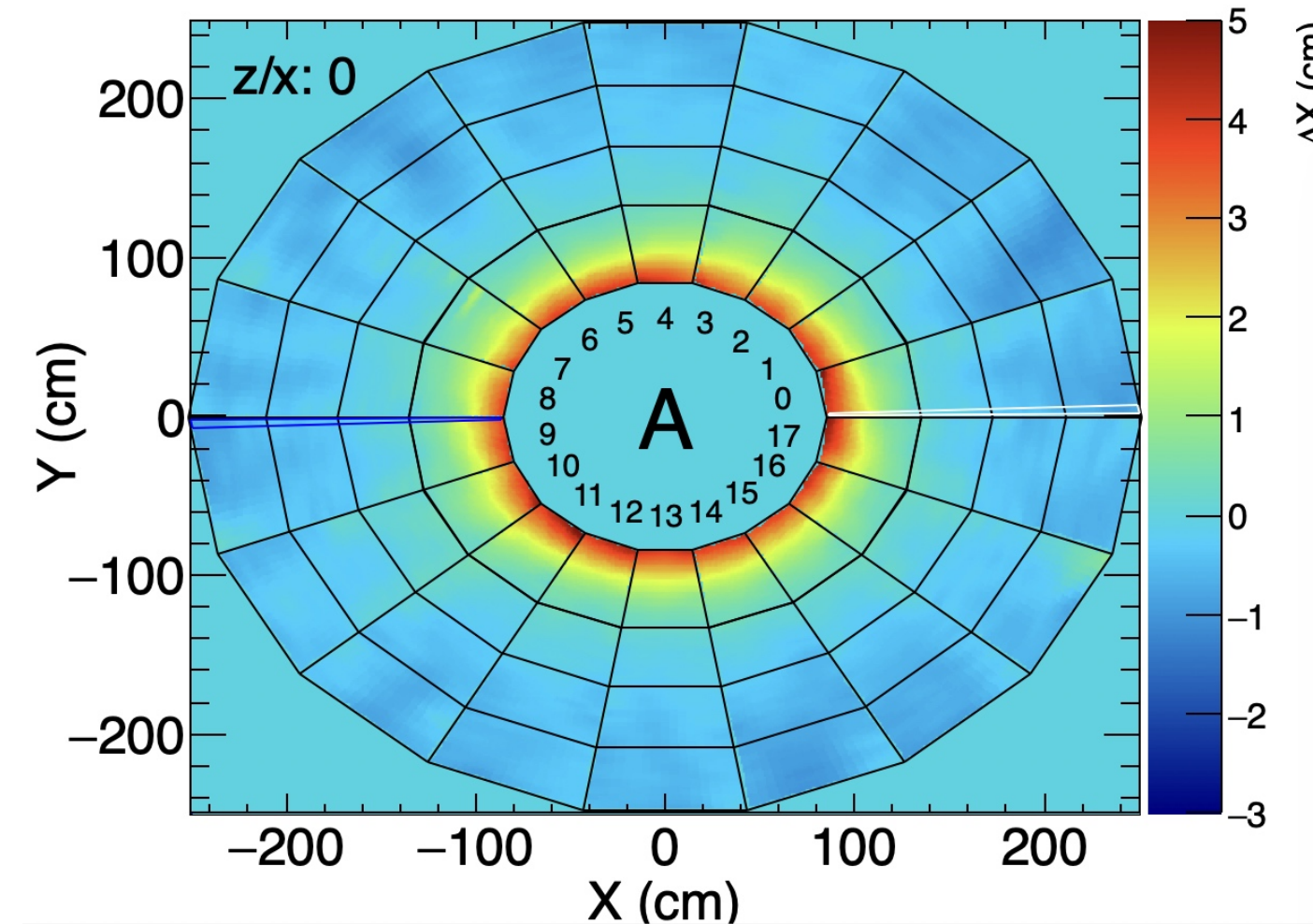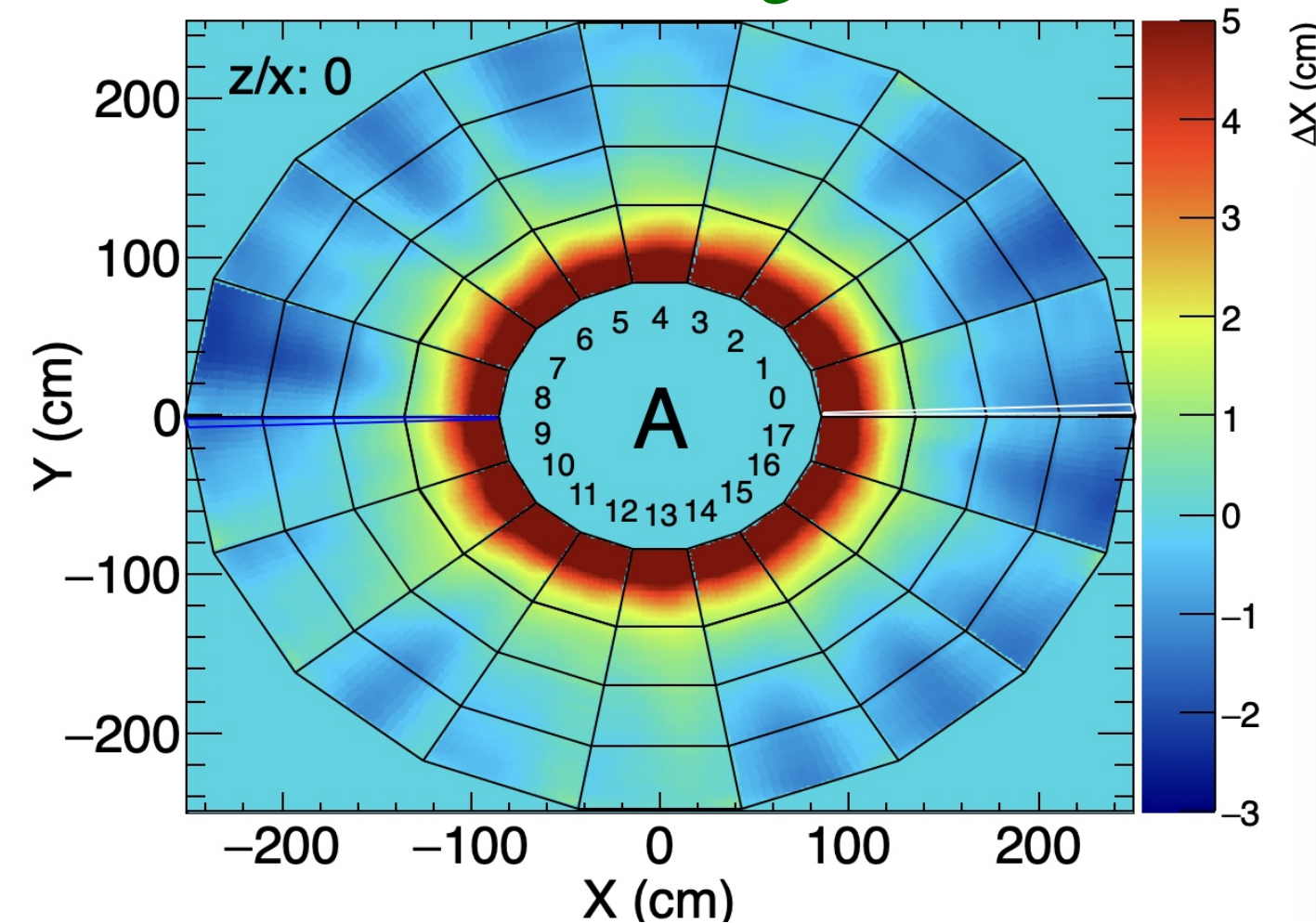$$M(t) = M_{\mathrm{avg}} + M_{\Delta} \cdot \left(\frac{\sum_{t_{sc}=t_c}^{t} w(t_{sc} - t) \cdot I_S(t_{sc})}{\sum_{t_{sc}=t_c}^{t} w(t_{sc} - t)} - \langle I_{S,\mathrm{avg}} \rangle \right)$$

M_{avg}

M_{Δ}

weights w

Estimator for precision of corrections

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 $\tan(\lambda)$

TPC inner field cage