ALICE: Space-charge calibration overview

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Overview

Expectations and requirements

Calibration approach

Calculation of distortions and current activities

Space charge in the ALICE TPC

Sources of space charge

- Primary ionization
- Ion backflow (IBF)

Dependencies

- Interaction rate (IR)
  - Up to **50 kHz in Pb-Pb collisions**
- Ion drift time
  - **160 ms - 200 ms** in Ne-CO_2-N_2 (90-10-5)
    - ➡ **Ions from 8000 to 10000 events** contributing to space-charge density at IR of 50 kHz
- Number of back-drifting per primary electron: ε = IBF × gain
  - IBF ~1 % with 4-GEM stack and optimized voltage settings
  - Gain = 2000

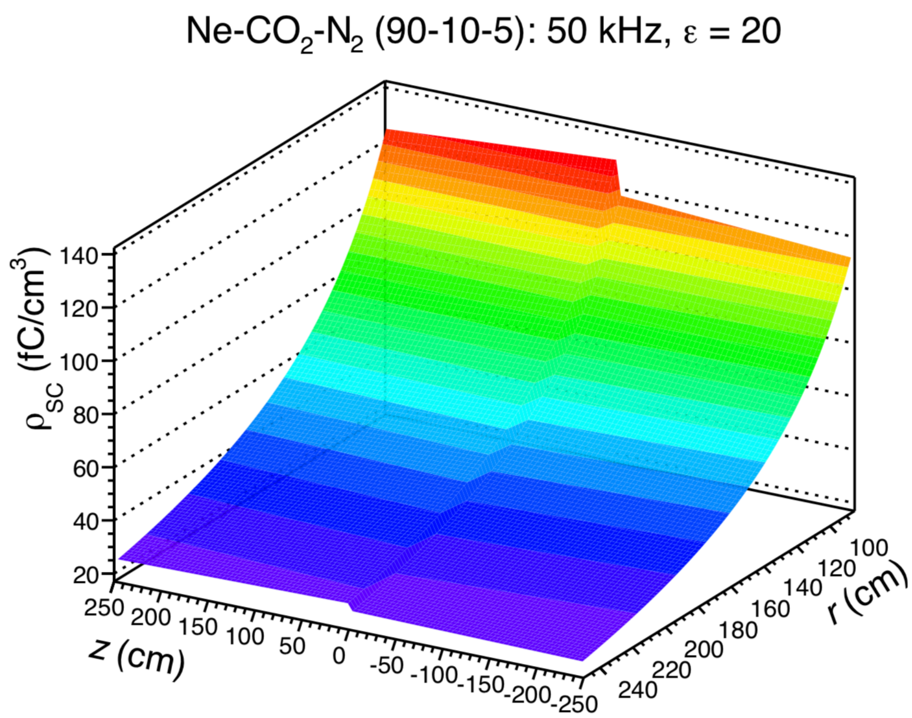
  ➡ **ε = 20**

Parameterization of space-charge density

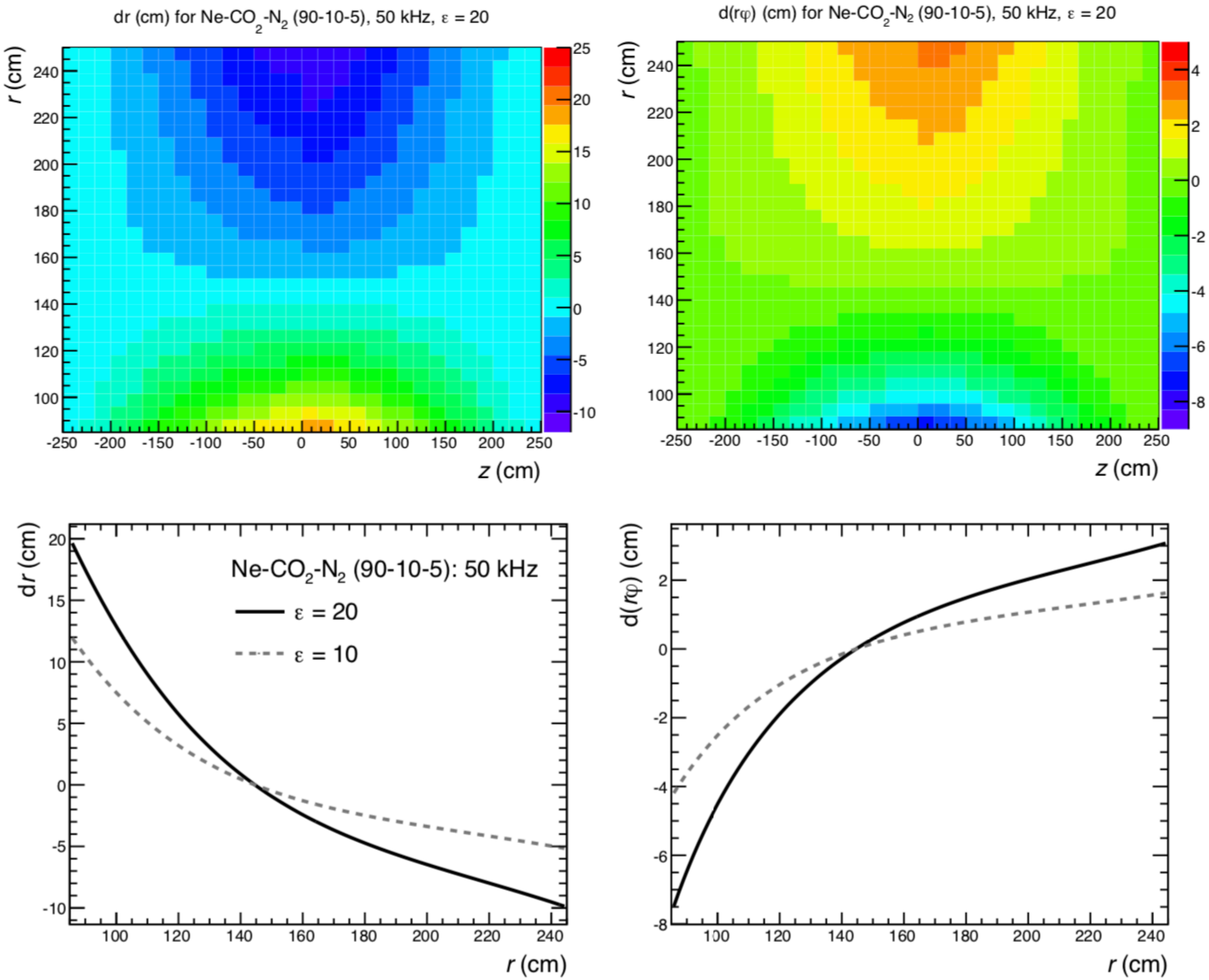
Assuming φ symmetry

- Gain variations across the GEM and dead zones between (parts of) chambers will introduce a φ modulation

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



Expected space-charge distortions

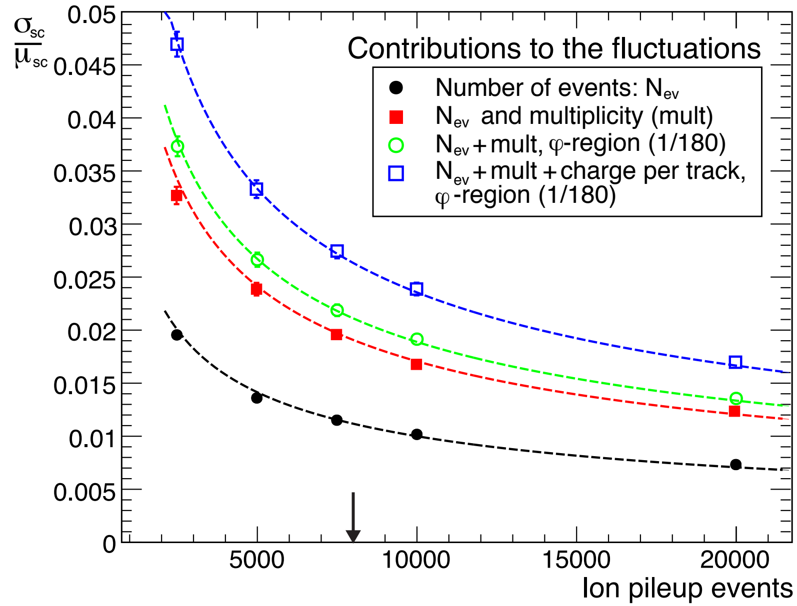


Space-charge fluctuations

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

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



Fast MC agrees well with analytical formula

Fluctuations of 2.5 - 3.5 %

- 5 - 7 mm in r, 2 - 3 mm in rφ
  - Required precision: 200 µm

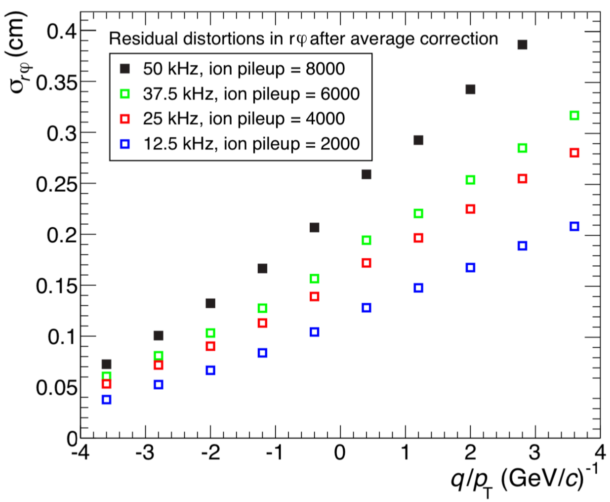
Fluctuation studies

Fluctuation scenarios

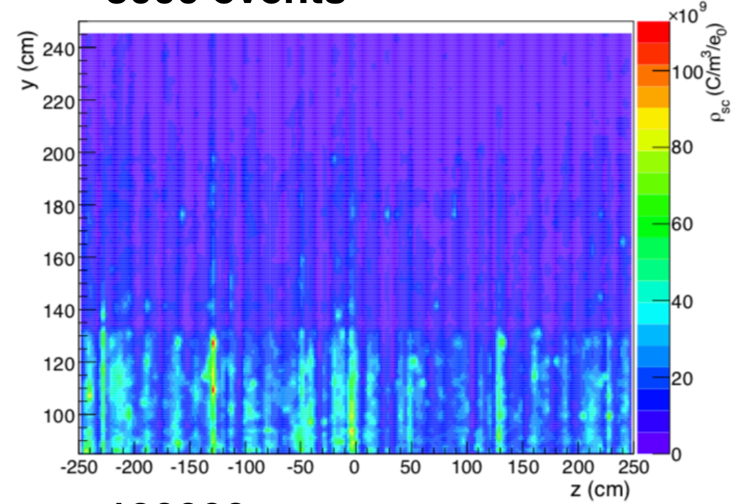
- Randomly distributing discs of ions in z
  - Different number of pileup events
- Average scenario with ion discs from 130k events
- Scaled to corresponding number of pileup events

Residual distortions

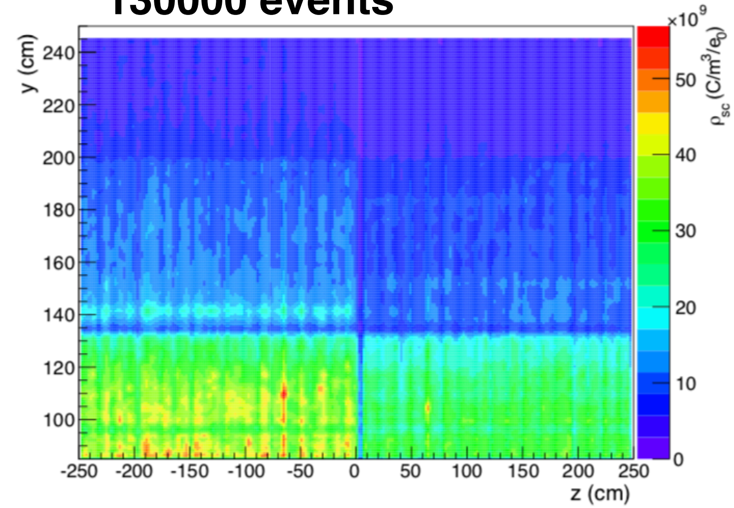
- Fluctuation map used for distortion
- Average map used for correction



8000 events



130000 events



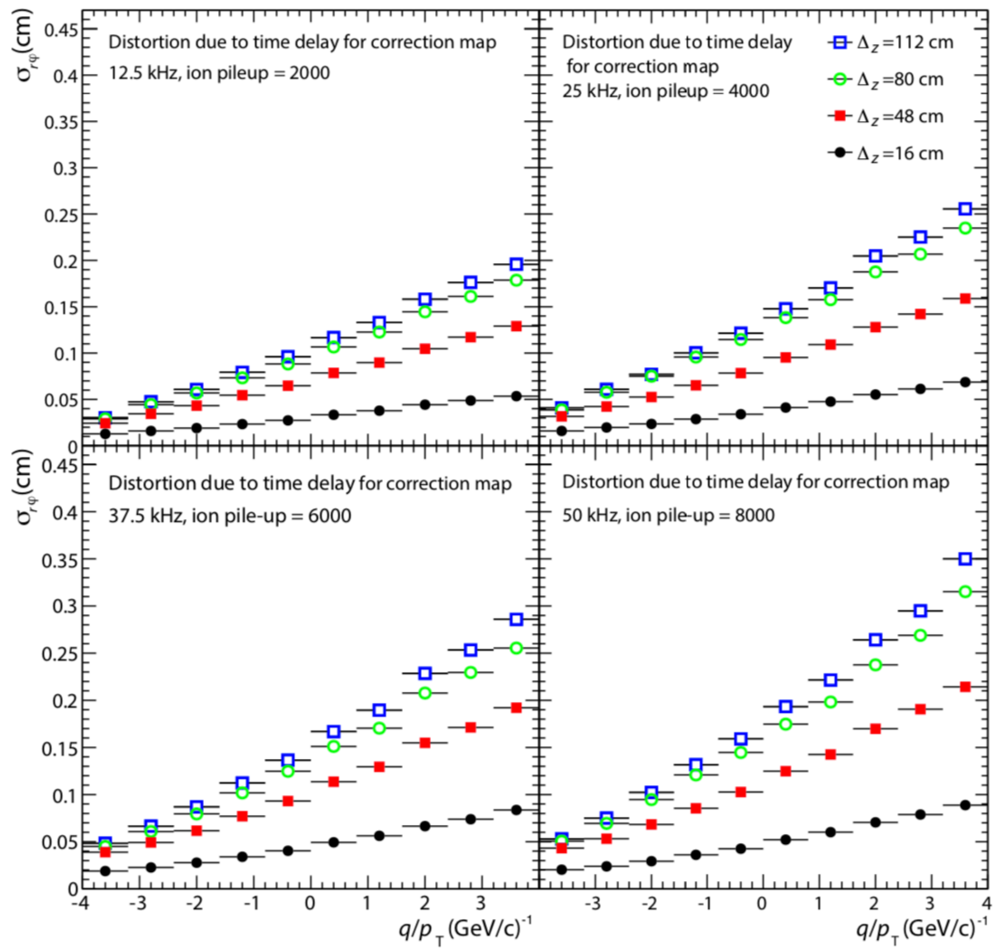
Update frequency of correction map

Corrections performed with the same space-charge density map as the distortions but shifted by Δz in z

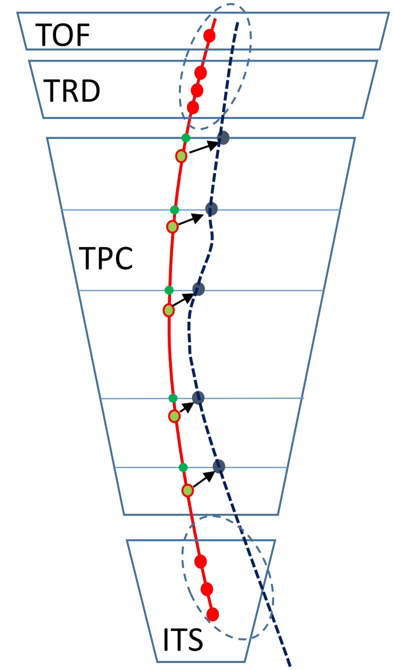
Shift by Δz = 16 cm already results in residual distortions of a few 100 μm

- Corresponds to 10 ms for an ion drift time of 160 ms

➡ **Update interval of $\mathcal{O}$(5 ms) required**



Calibration procedure in 2015 - 2018



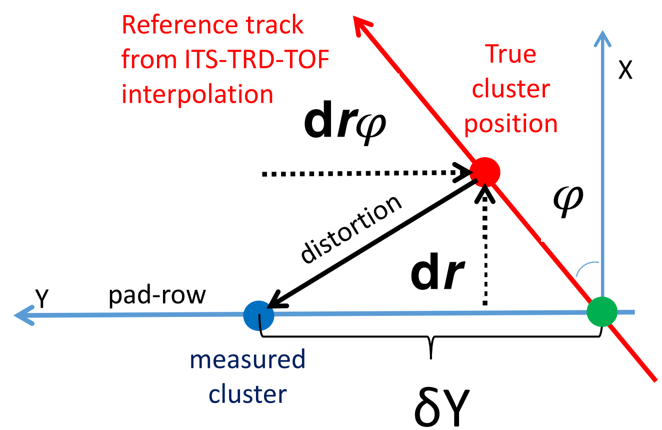
TPC track finding and matching to external detectors ITS, TRD and TOF

Refitted ITS, TRD and TOF **track segments** are interpolated to the TPC as **reference points** for the **true track position** at every padrow

Measurement of δY, δZ residuals between distorted TPC clusters and reference points

Relation between 2D residuals and real 3D distortion vector {dr, d$r\varphi$, dz}

- $\delta Y = \mathrm{d}r\varphi - \mathrm{d}r \times \tan(\varphi)$ φ: local inclination angle
- $\delta Z = \mathrm{d}z - \mathrm{d}r \times \tan(\lambda)$ λ: dip angle



Correction of each TPC cluster by smooth Chebyshev parameterization of extracted distortion vectors

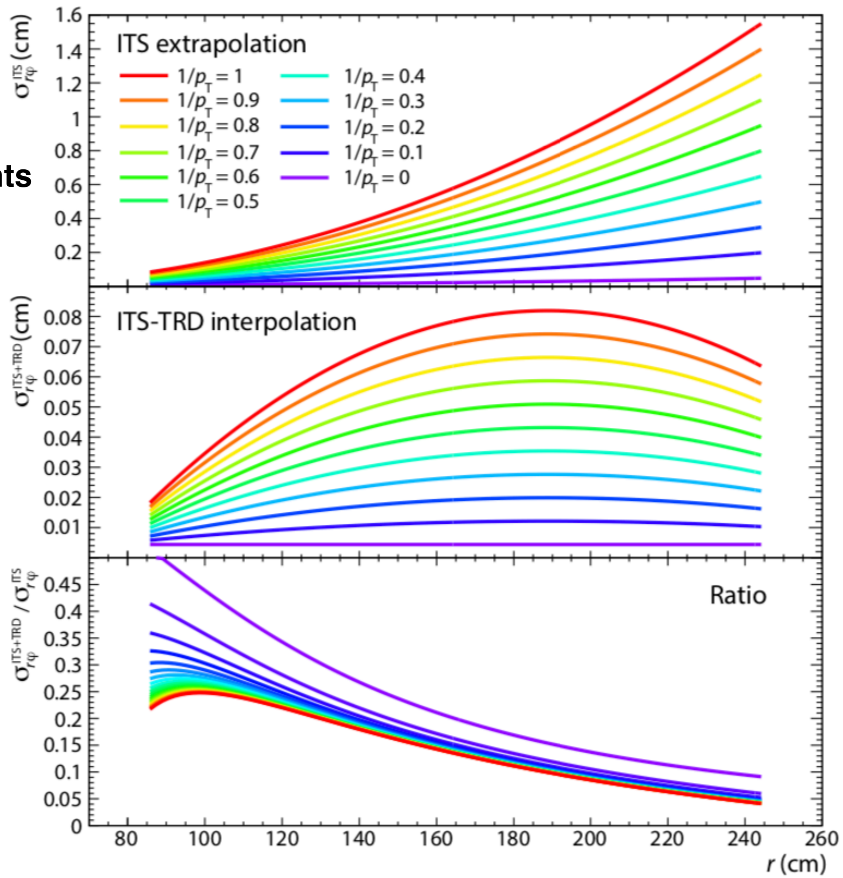
Performance of ITS-TRD interpolation

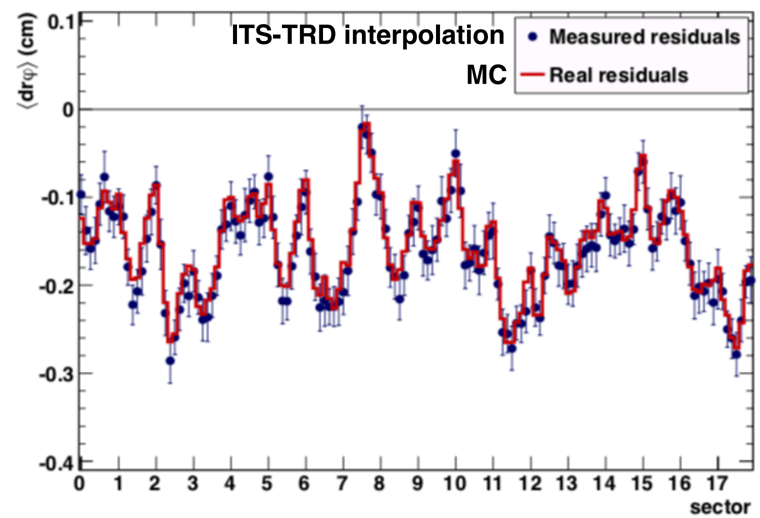
Critical parameters

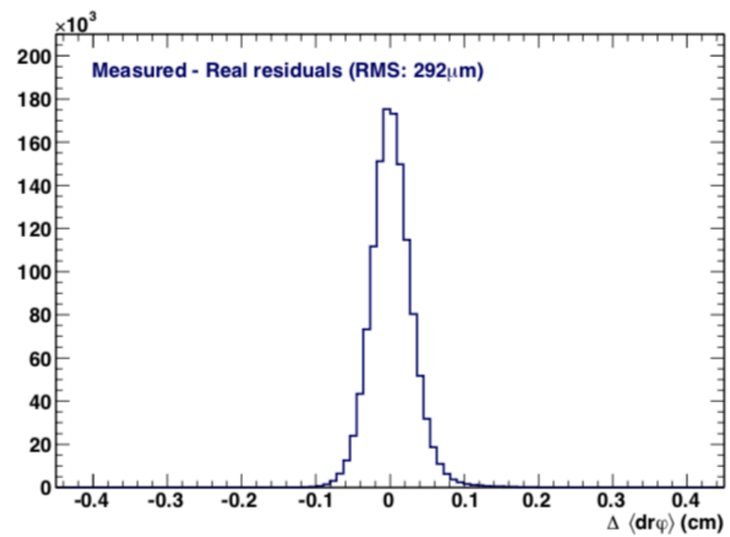
- Size of the volume elements (voxels)
- Track statistics in calibration interval

10 cm (z),
16 cm (r),
1/72 π in rφ

250 MB events







Integrated digital currents

Signals at ROCs integrated over 160 ms are proportional to the current space-charge density in the TPC drift volume

- $\rho_{SC} \sim I_{ROC} \times \varepsilon$

Precise measurement of the space-charge density in space and time

Calculation of distortions from measured space-charge density challenging in required time intervals

➡ Approach of storing the derivative of the space-charge density

- Different luminosity intervals as the space-charge density does not scale with the interaction rate

$$\vec{\Delta} = \vec{\Delta}_{\mathrm{ref}} + \sum_i \frac{\partial \vec{\Delta}_{\mathrm{ref}}}{\partial \rho_{\mathrm{sc}}^i} \delta \rho_{\mathrm{sc}}^i$$

Space-charge calibration

Calibration in two steps:

1) Synchronous stage
   - Corrections to $\mathcal{O}$(mm) required for cluster-to-track association and tracking

2) Asynchronous stage
   - Corrections to restore the intrinsic track resolution of $\mathcal{O}$(100 µm)

Space-charge calibration

1) **Synchronous stage**

- Pre-calculated correction map obtained by averaging over time intervals of $\mathcal{O}$(min)
  - Simulation or ITS-TRD interpolation of previous data
  - Regularly **updated and scaled to the average particle density** to account for fluctuations in time
    - Integrated digital currents
    - Mean interaction rate

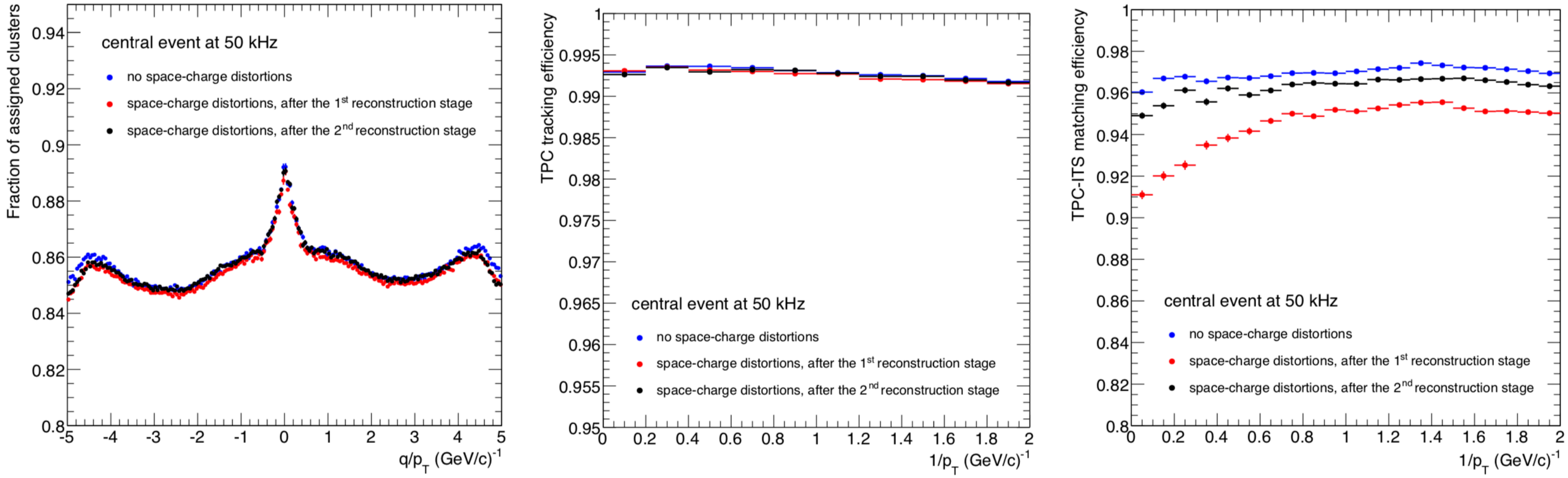
➡ **Correction of average distortions and part of the fluctuations**

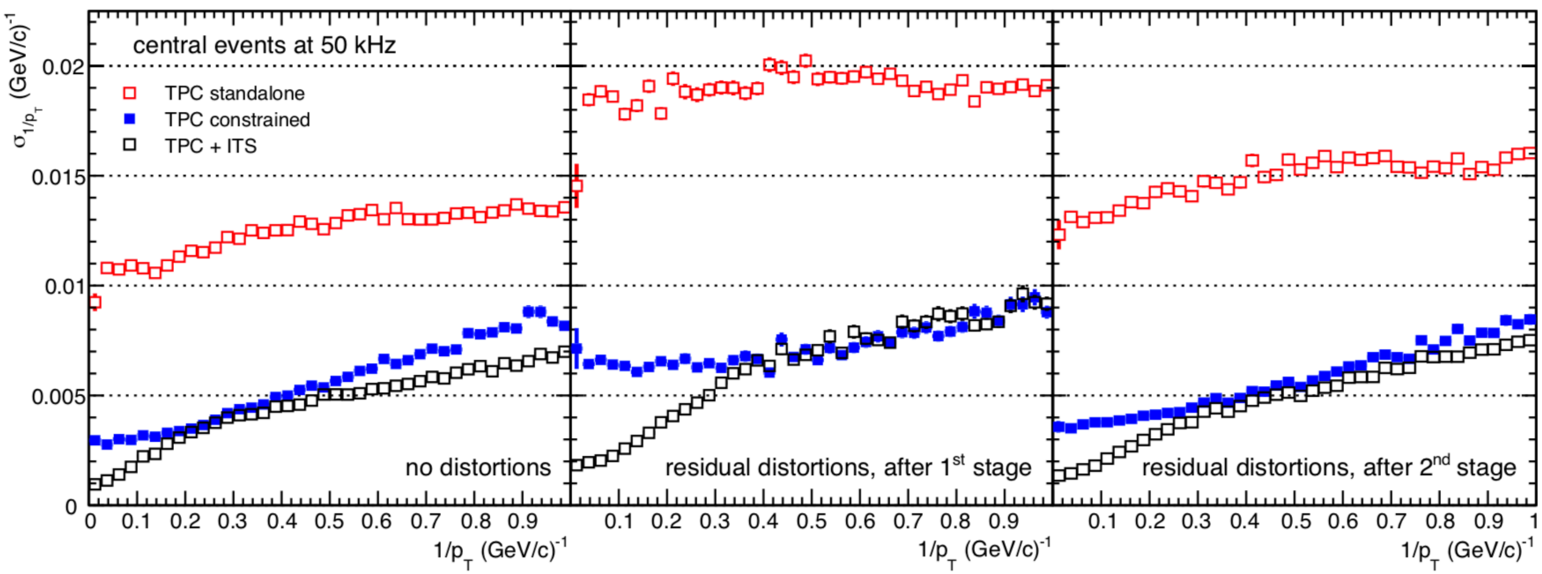
2) **Asynchronous stage**

- High resolution correction map obtained by ITS-TRD interpolation of the same data over a time interval $\mathcal{O}$(min)
  - Scaling by **3D digital current measurement in time intervals $\mathcal{O}$(ms) $\ll t_{ion}$** to account for fluctuations in space and time

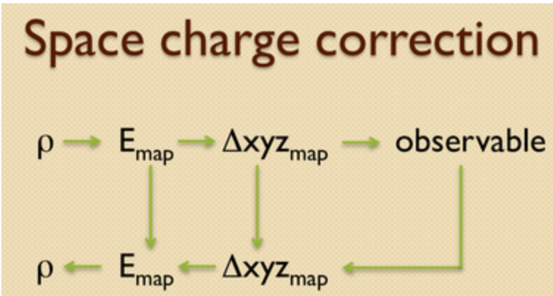
➡ **Correction of fluctuations remaining after first stage**

Expected TPC performance





Calculation of space-charge distortions



1. $\nabla^2 V(r,\rho,z) = -\frac{1}{\epsilon_0}\rho(r,\phi,z)$

2. $\vec{E}(r,\rho,z) = -\nabla V(r,\rho,z)$

3. $$\hat{\delta}_{rE}(r_i,\phi_j,z_k) = c_1 \int_{z_k}^{z_{k+1}} \frac{E_r}{E_z} dz + c_2 \int_{z_k}^{z_{k+1}} \frac{E_\phi}{E_z} dz$$
$$r\hat{\delta}_{\phi rE}(r_i,\phi_j,z_k) = c_2 \int_{z_k}^{z_{k+1}} \frac{E_r}{E_z} dz - c_1 \int_{z_k}^{z_{k+1}} \frac{E_\phi}{E_z} dz$$
$$\hat{\delta}_z(r_i,\phi_j,z_k) = \int_{z_k}^{z_{k+1}} \frac{v'(E)}{v_0}(E - E_0) dz$$

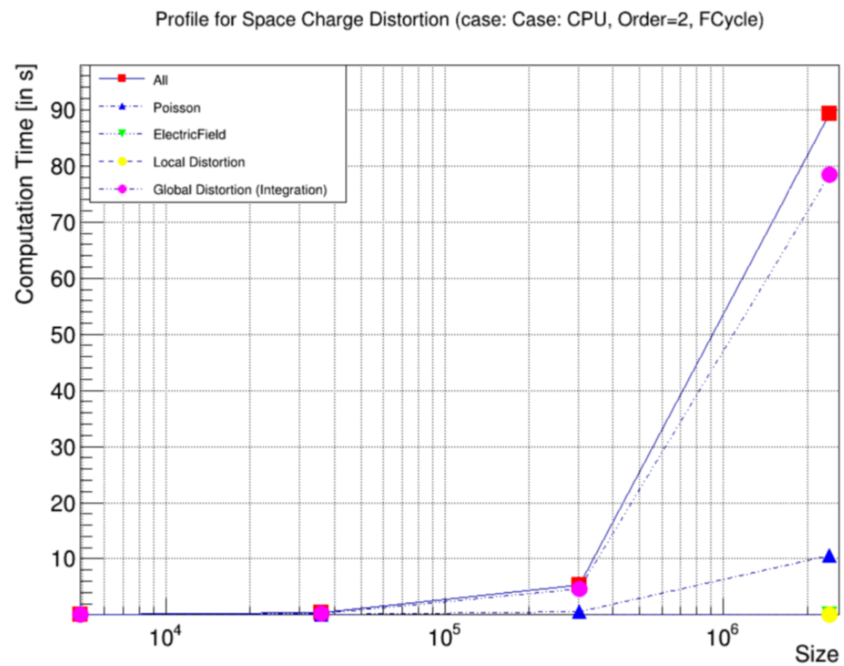
4. Follow the driftline from $(r_i,\phi_j,z_k) \rightarrow (r_i+\delta r_i, \phi_j+\delta\phi_j, z_0+\delta z_k)$

5. Assign distortion $\mathrm{Dist}(r_i,\phi_j,z_k) = (\delta_r, r\delta_\phi, \delta z)$

Solution of Poisson equation by 2D (3D) multi-grid method

Most time spent in integration of distortions along electron drift lines

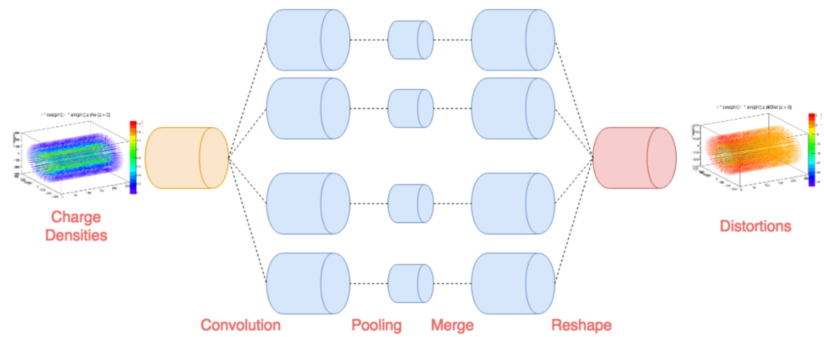
- Significant speed-up by integrating one full z slice after the other



Convolutional neural network studies

Work in progress

TMVA, Keras and ROOT6

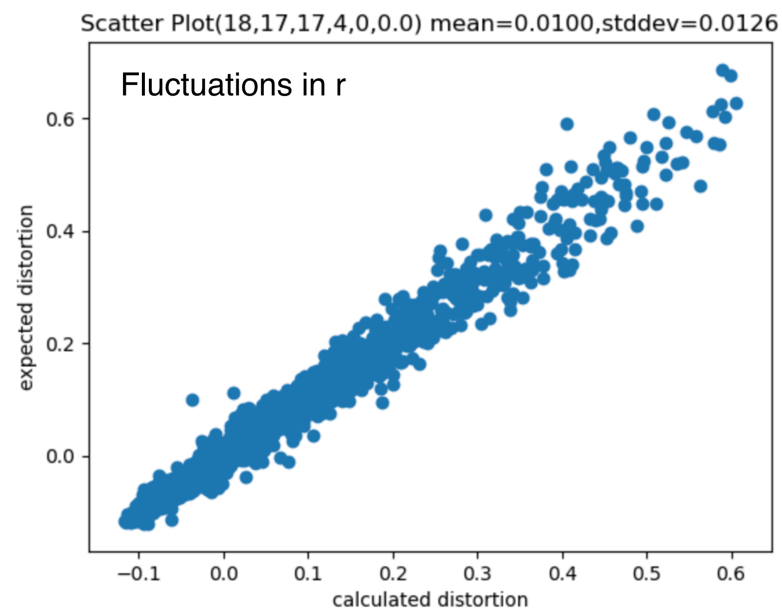


Supervised learning using iterative simulations as input

Significant speed-up of distortion calculation from space-charge density or digital currents

Current activities

- Required granularity for precise modelling of flutuations
- Organizing GPU resources for large scale studies

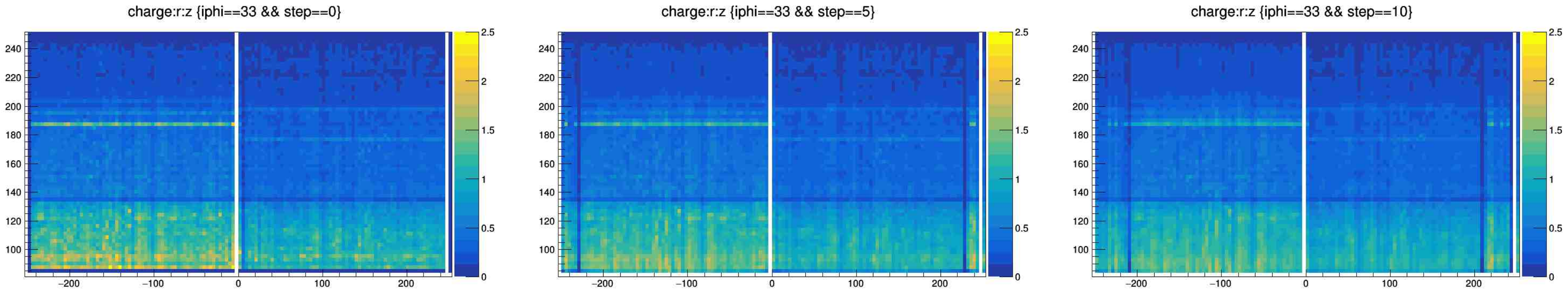


Simulation of space-charge movement

Work in progress

Realistic simulation of ion movement through the TPC drift volume

- **Propagate space-charge density** on a regular grid over time
  - Continuity equation: $\frac{\partial \rho}{\partial t} = -\nabla(\rho \mathbf{u})$
- Slow iterative procedure
  - Digital currents + Density → E field → Ion drift + distortions
- Prerequisite for precision studies of distortion correction
  - **Time intervals** for average and residual correction maps
  - Scaling of correction maps by **integrated digital currents**
  - Input for CNN



Summary

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Requirements for space-charge distortion calibration

- Correct space-charge distortions down to the intrinsic performance of the TPC
    - **Tracklet resolution of $\mathcal{O}$(100 µm)**
- **Update interval of $\mathcal{O}$(5 ms)** to account for fluctuations
    - Fast distortion / correction calculation

Calibration approach

- First correction by **scaled average map**
    - Precision $\mathcal{O}$(1 mm) **sufficient for tracking**
    - Stored average maps $\mathcal{O}$(min) from simulation or ITS-TRD interpolation
    - Scaling by integrated digital currents to current particle density
- Second correction to account for **fluctuations in space and time**
    - **ITS-TRD interpolation** for time intervals $\mathcal{O}$(min) on the actual data
    - **High precision scaling by 3D digital currents** for time intervals $\mathcal{O}$(5 ms)