Track-based alignment of the BESIII tracker with cosmic-ray data

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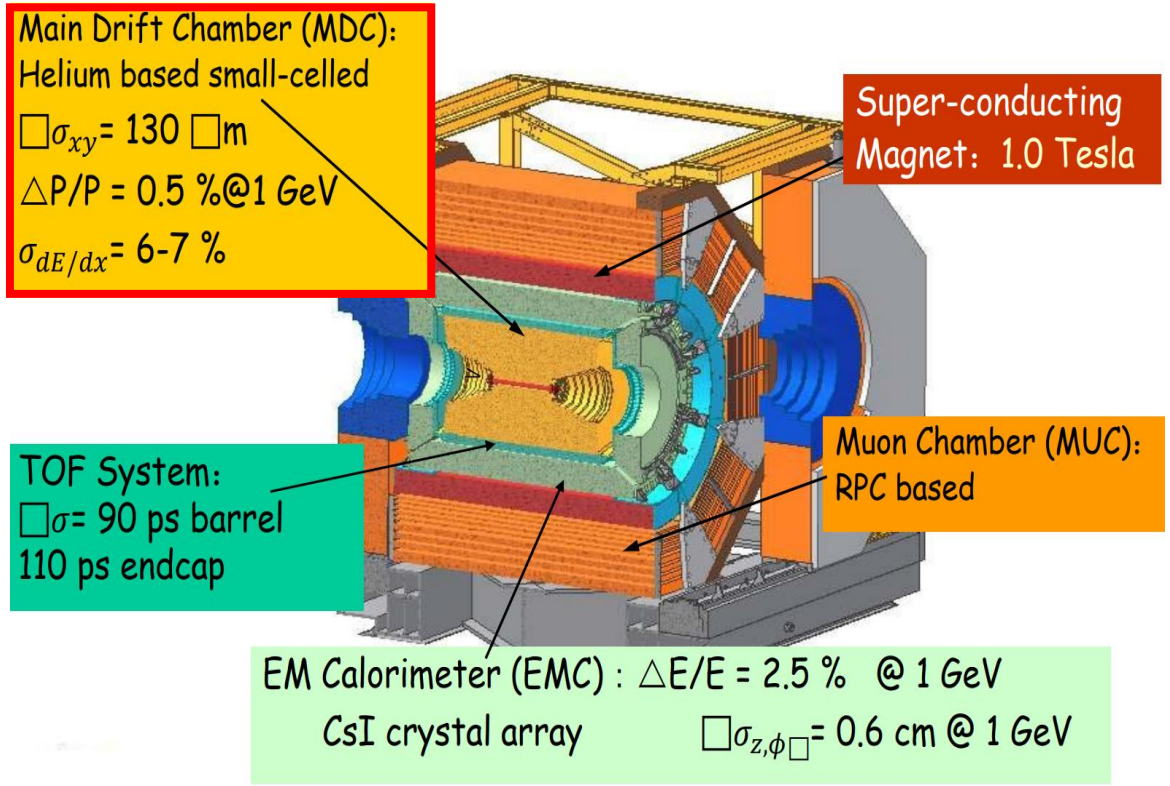
July 23, 2025

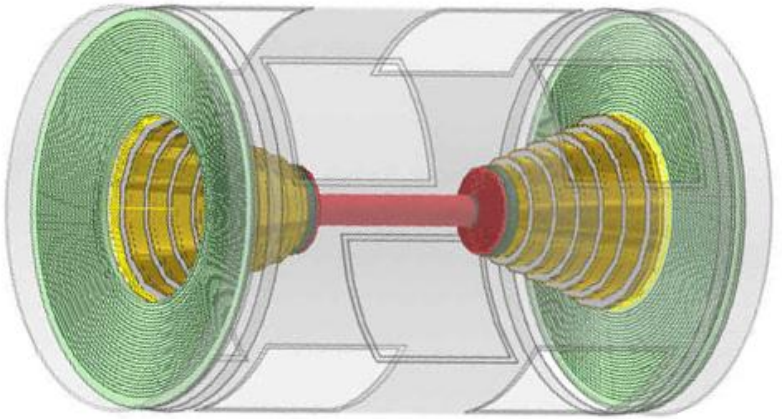
Beijing Spectrometer (BESIII) Experiment

- BESIII at the BEPCII accelerator is for the studies of hadron physics and τ-charm physics with the highest accuracy achieved until now
- The Multilayer Drift Chamber (MDC) used to measure the trajectory, momentum, and dE/dx of charged particles for particle identification (PID)

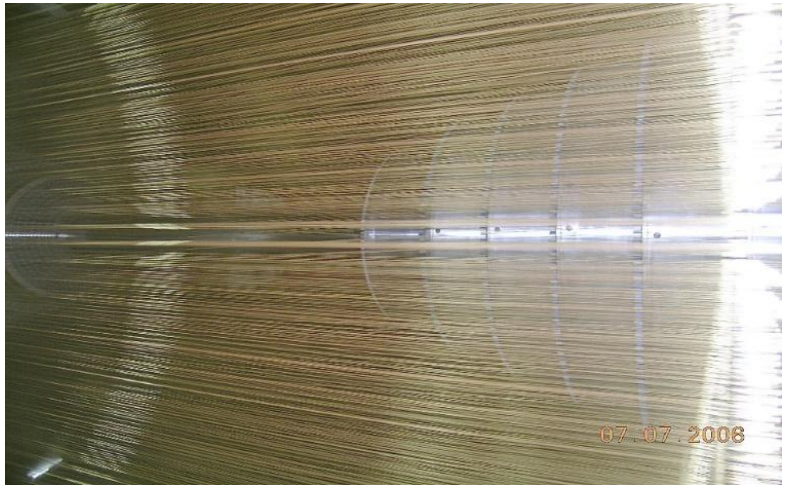


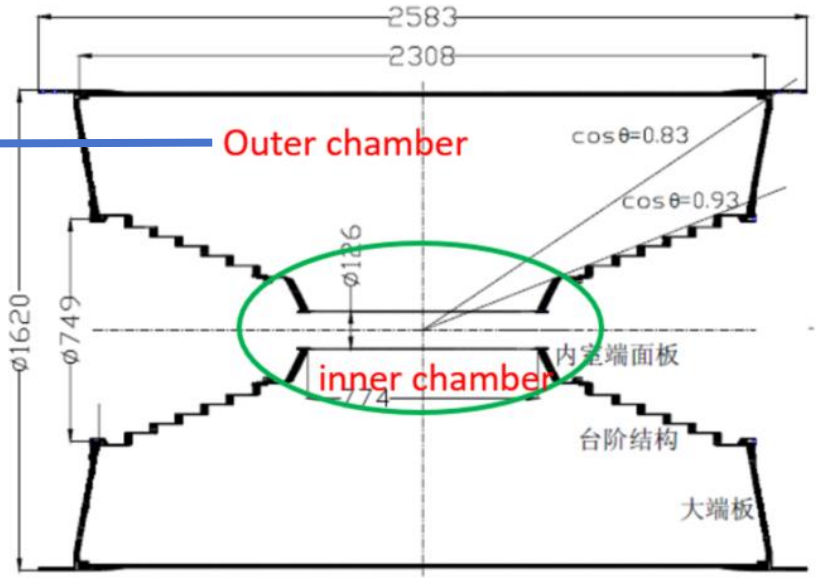
BESIII MDC

- 6792 cells in 43 cylindrical layers
  - ➢ Inner chamber: Layer 1~8
  - ➢ Outer chamber:
    - ✓ Layer 9~20 in six steps
    - ✓ Layer 21~43 fixed at big out endplates



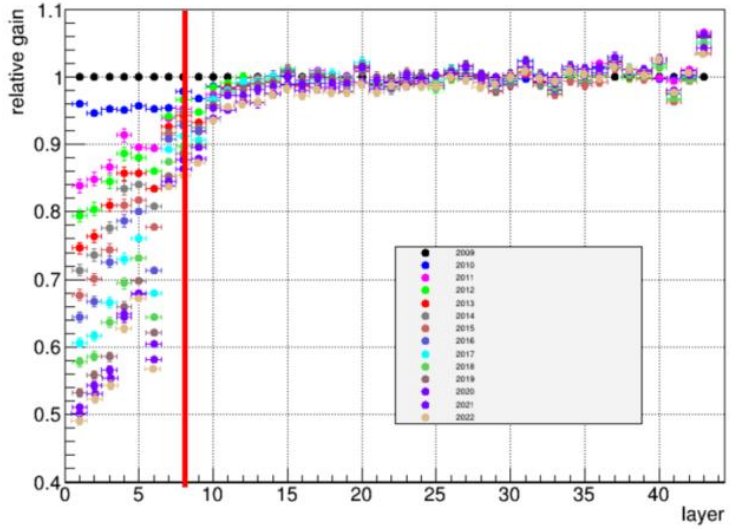
Outer chamber

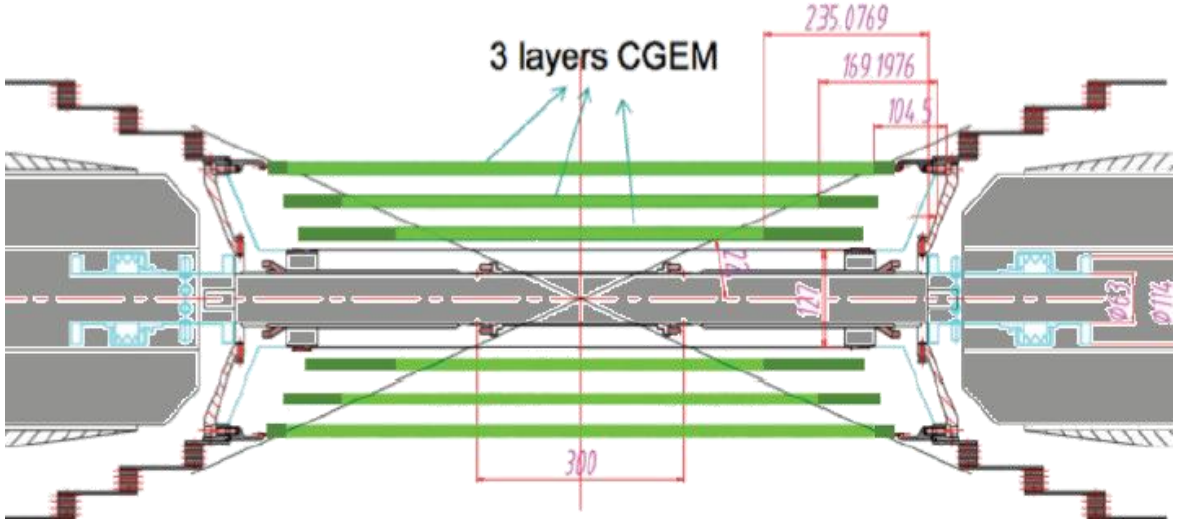


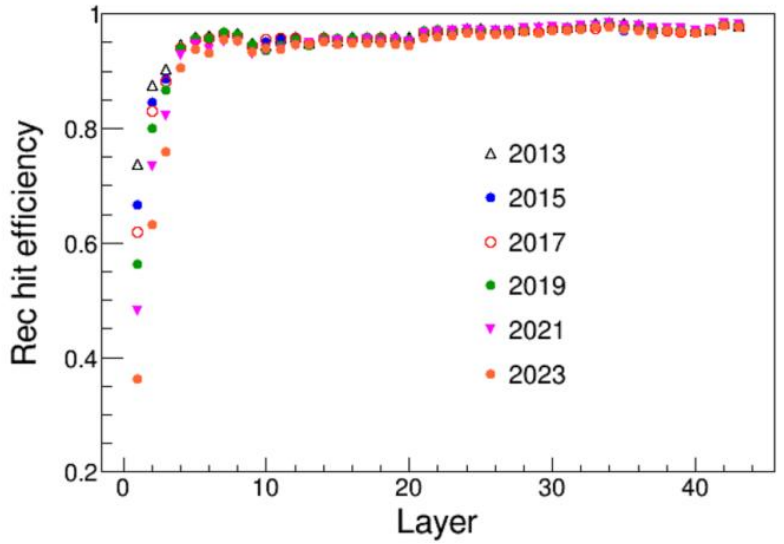


Upgrade of inner tracker

- Significant aging effect observed in the inner chamber
  - ➢ Gain decreases with time
  - ➢ Degradation of hit efficiency and spatial resolution year by year
- Inner chamber upgraded to **CGEM** (Cylindrical Gas Electron Multiplier) in 2024

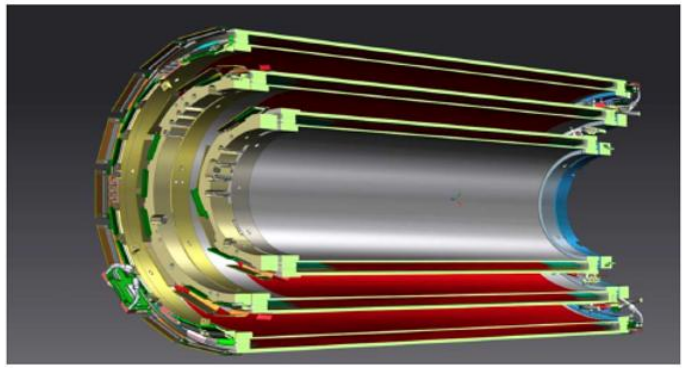




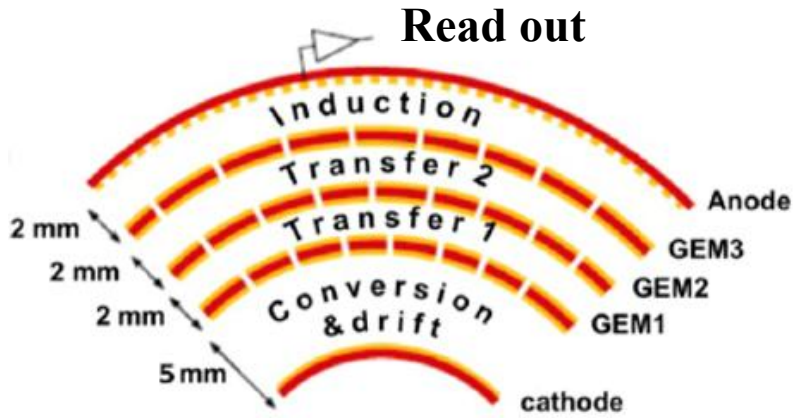


CGEM Inner Tracker

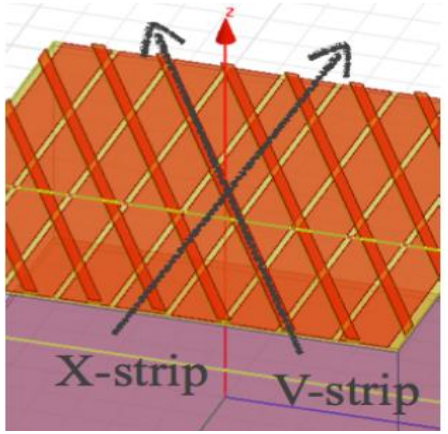
- CGEM structure (5 sheets of 3 layers)
  - Layer1 (1 sheet); Layer2 (2 sheets); Layer3 (2 sheets)
- Each layer consists of
  - Cathode
  - GEM1, GEM2, GEM3
  - Anode
  - Readout
- Readout: X strips and V strips



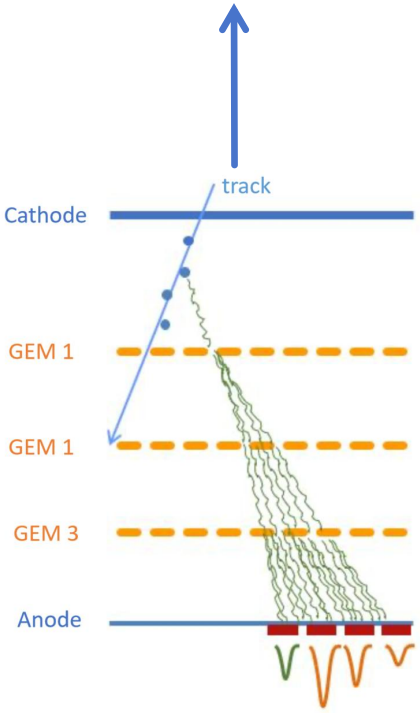
Structure of CGEM



Structure of each layer



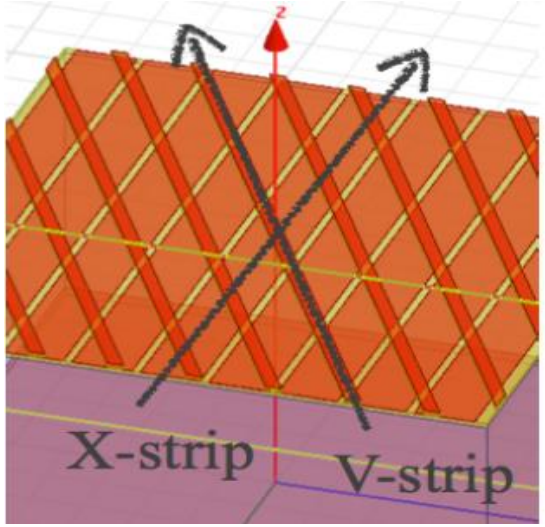
Anode readout strips



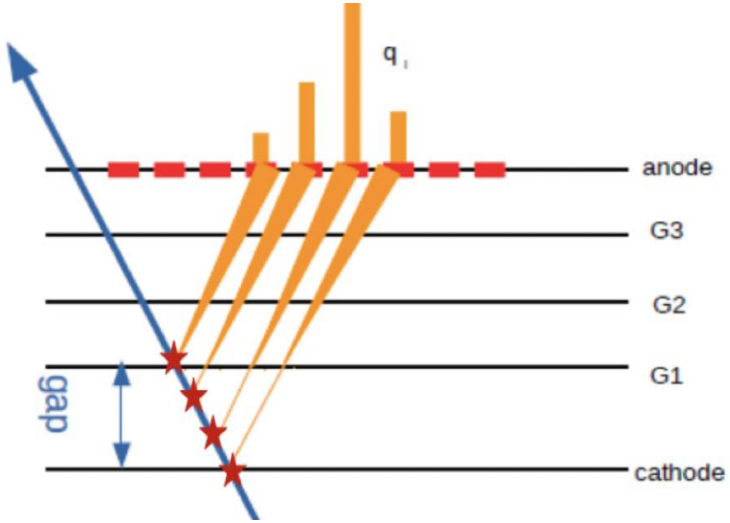
Avalanche drift diffusion

Readout strip and cluster reconstruction

- Readout structure
  - ➢ X strips parallel to the Z-axis
  - ➢ V strips have an angle with Z-axis around 30 - 40 degrees
  - ➢ Combine signals on both X and V strips to reconstruct the 2D cluster
- Cluster reconstruction method
  - ➢ Charge Centroid (CC): applied to the current alignment
    - ✓ For track direction close to the ionization electrons drifting
  - ➢ Micro-TPC method
    - ✓ For track direction very different from the ionization electrons drifting

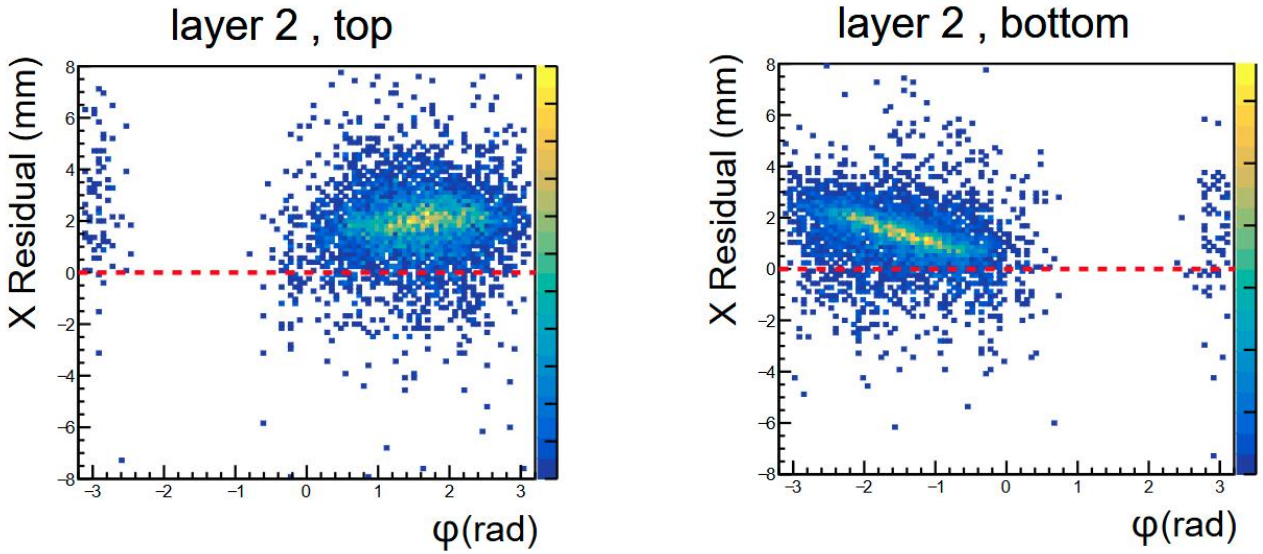


Anode readout strips



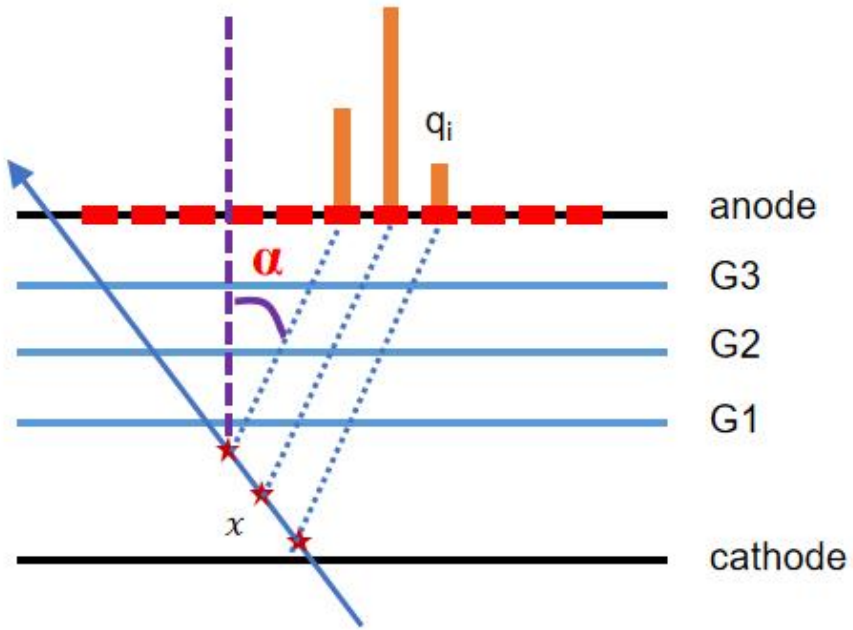
Mechanical imperfection during upgrade

- During the upgrade, the displacement between the CGEM and MDC could exceed 1 mm
- Relative displacement between different CGEM layers, especially in z could be more than 1mm
  - ➢ Refer to A.Q. Guo, L.H. Wu et al., NIM A 1050 (2023)
- Significant misalignment effect observed in the cosmic-ray data analysis
- Track-based alignment is essential for track reconstruction



Strategy of Alignment

- **Step I**: Preliminary alignment, especially for estimating the rotation around z of CGEM, with cosmic-ray data without magnetic field
  - Strong correlation between Lorentz angle and rotation of the cylinder around z (both cause a shift of clusters in φ)
- **Step II**: Preliminary calibration of the Lorentz angle combining the cosmic-ray data with magnetic field
- **Step III**: Precise alignment combining cosmic-ray and collision data, based on preliminary results from cosmic-ray data

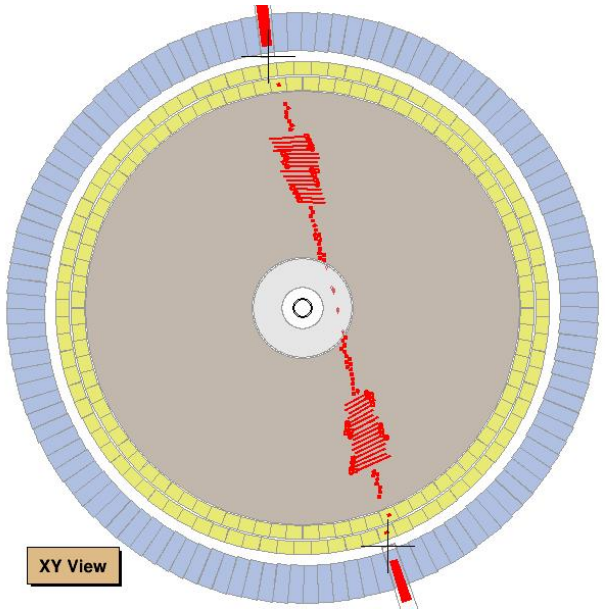


$B = 0, \alpha = 0$

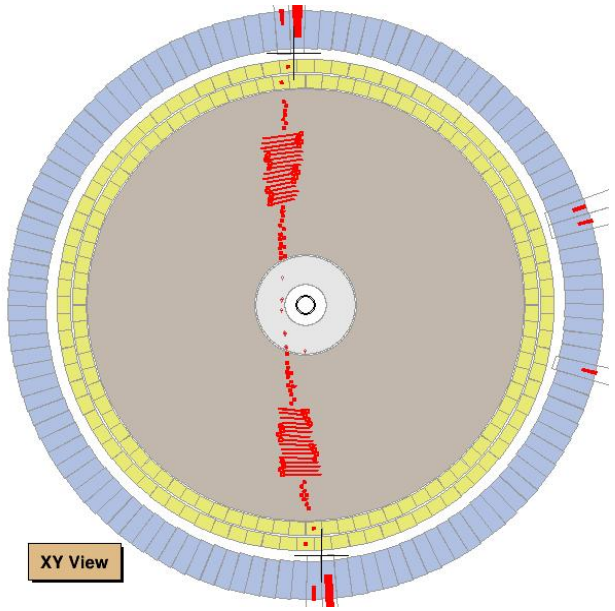
$B \neq 0, \alpha \neq 0$

Cosmic-ray data sample

- Cosmic-ray data with and without magnetic field (taken in March and April, 2025)



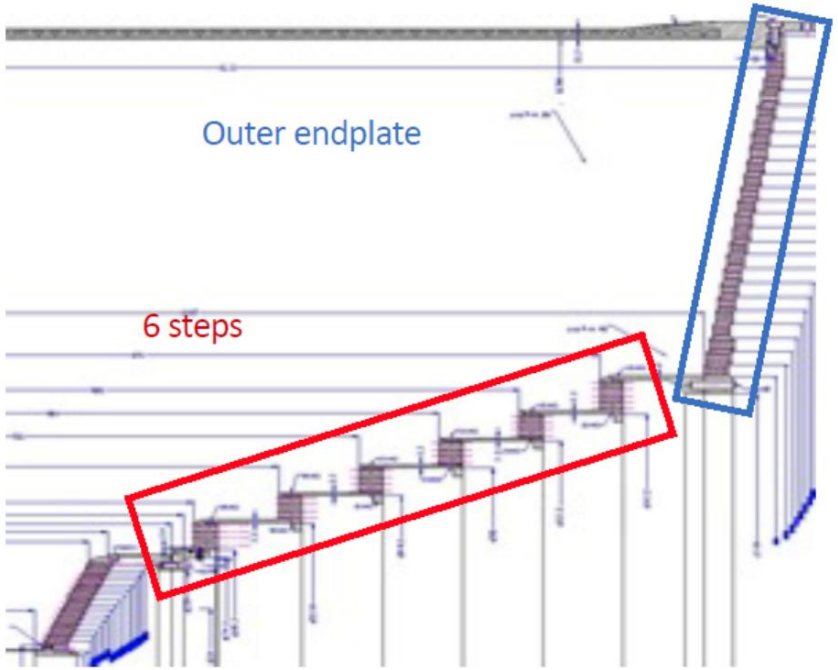
Without Magnetic field

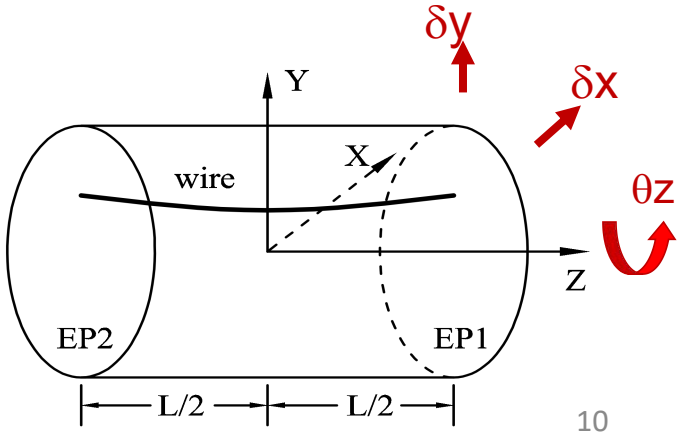


With Magnetic field

Alignment parameters of MDC

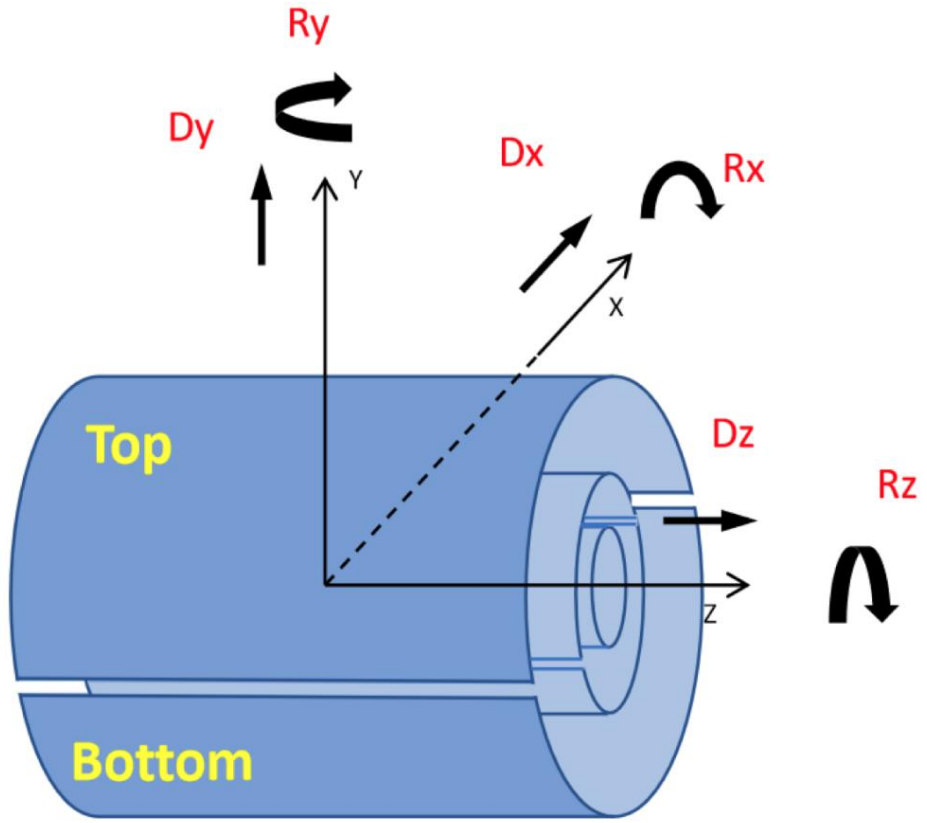
- 6 steps + 1 outer endplate for each side
- 6 degrees of freedom for each component
  - ➢Translation in x, y and z (Dx, Dy, Dz)
  - ➢Rotation in x, y and z (Rx, Ry, Rz)
- Some degrees of freedom constrained to guarantee the stability and avoid weak modes
  - ➢Rx, Ry, Dz
- 42 alignment parameters in total





Alignment parameters of CGEM

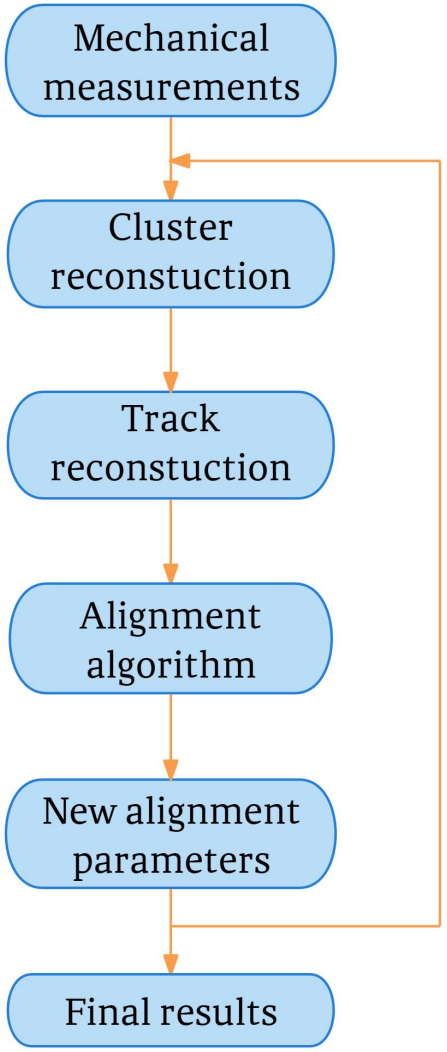
- 3 layers (5 sheets)
  - ➢2 sheets in layer 2 and 3
- 6 degrees of freedom for each component
  - ➢Translation in x, y and z (Dx, Dy, Dz)
  - ➢Rotation in x, y and z (Rx, Ry, Rz)
- 30 alignment parameters in total



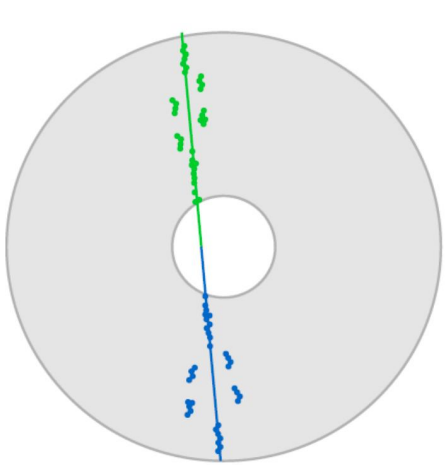
Constraints of alignment parameters

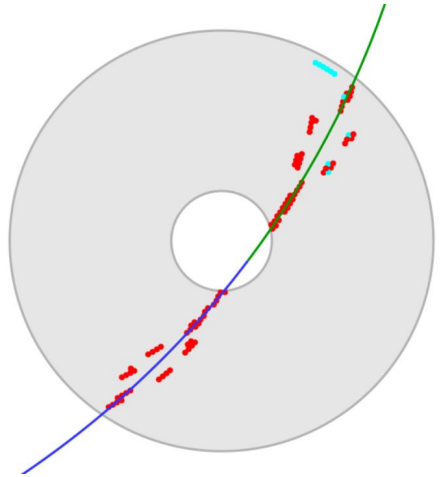
- Choose the outer endplates of MDC as reference
  - ➢The average displacement of both outer endplates fixed
- For cosmic-ray data, Dy of each component fixed due to lack of horizontal tracks
- Each cylinder of CGEM assumed as rigid body, deformation not considered at the first stage

Workflow



- CGEM cluster reconstruction
- Track reconstruction: Refer to Yaxuan's talk in the morning session
  - Hough Transform method for track reconstruction without magnetic field
  - Legendre Transform method for track reconstruction with magnetic field





Alignment method

- Millepede method:

① Residual (measured value - fitted value)

② Constructing the Chi-Square of least square method

③ Minimize Chi-Square and construct parameter equations.

④ Solve the equation to get the estimation of alignment parameters

$$d_{track} = f(\boldsymbol{p}^{local}; \boldsymbol{a}^{global})$$

$$r_{ki} = d_{meas}^{(k,i)} - d_{track}^{(k,i)}$$

$$\chi^2 = \sum_{data\ sets} \left(\sum_{events} \left(\sum_{tracks} \left(\sum_{hits} w_{ki} r_{ki}^2 \right) \right) \right)$$

$$\left(\begin{array}{c|cc} C & \cdots\ H_k & \cdots \\ \hline \vdots & \ddots\ 0 & 0 \\ H_k^T & 0\ \Gamma_k & 0 \\ \vdots & 0\ 0 & \ddots \end{array}\right) \times \left(\begin{array}{c} \boldsymbol{a} \\ \hline \vdots \\ \boldsymbol{p}_k \\ \vdots \end{array}\right) = \left(\begin{array}{c} \boldsymbol{b} \\ \hline \vdots \\ \boldsymbol{\beta}_k \\ \vdots \end{array}\right)$$

Alignment results

- First attempts to align CGEM+ODC using cosmic-ray
  - Preliminary results of cosmic-ray data without magnetic field
  - Alignment of cosmic-ray data with magnetic field ongoing

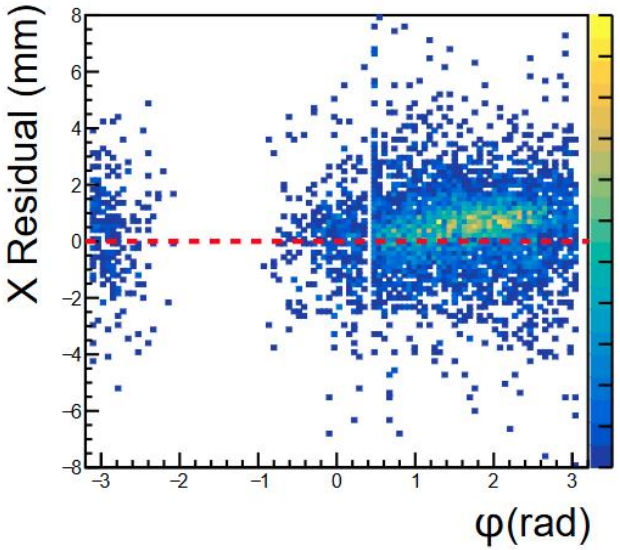
X residual vs φ

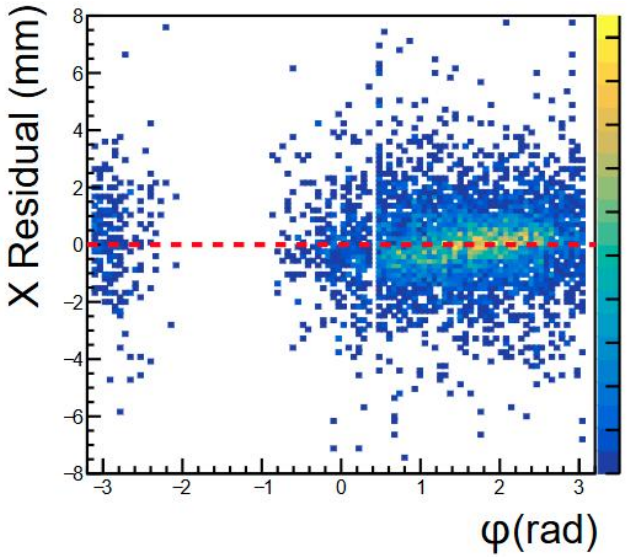
Preliminary Result

Before Alignment

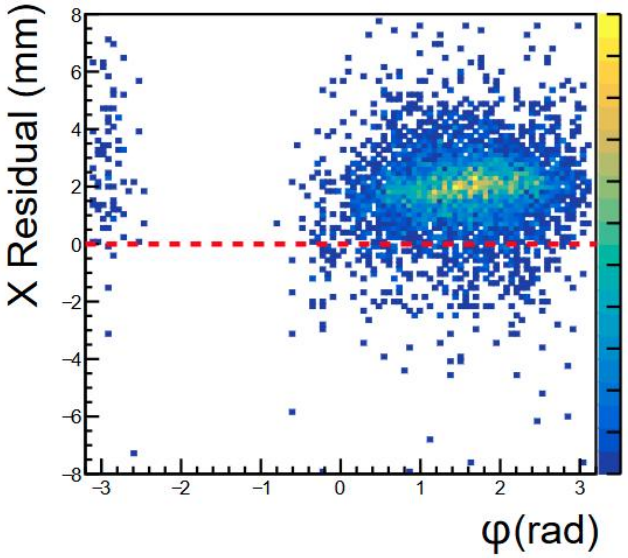
After Alignment

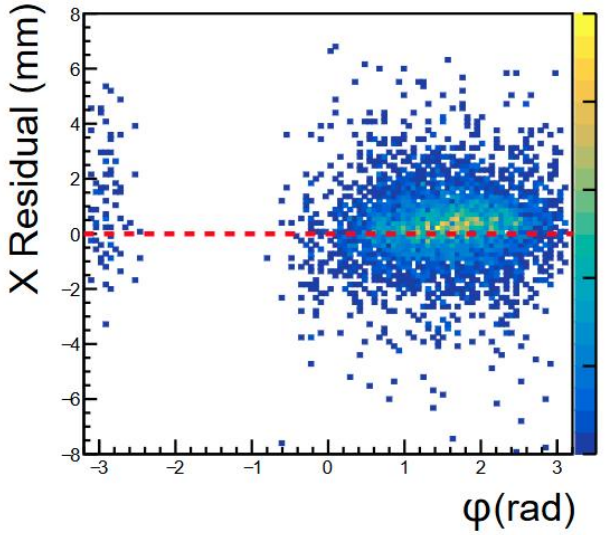
Layer 2, Top





Layer 3, Top





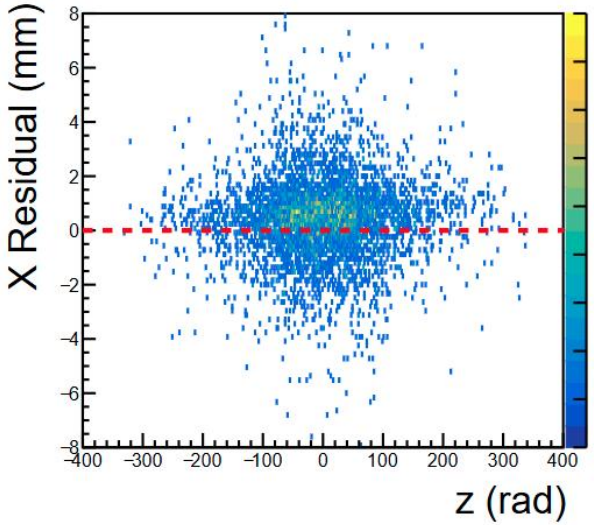
X residual vs z

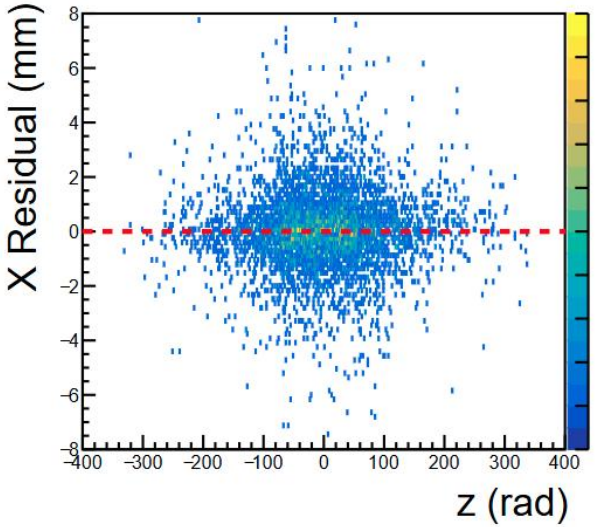
Preliminary Result

Before Alignment

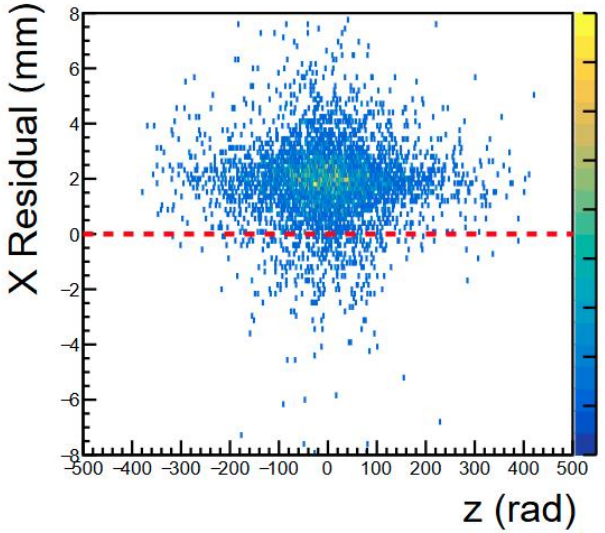
After Alignment

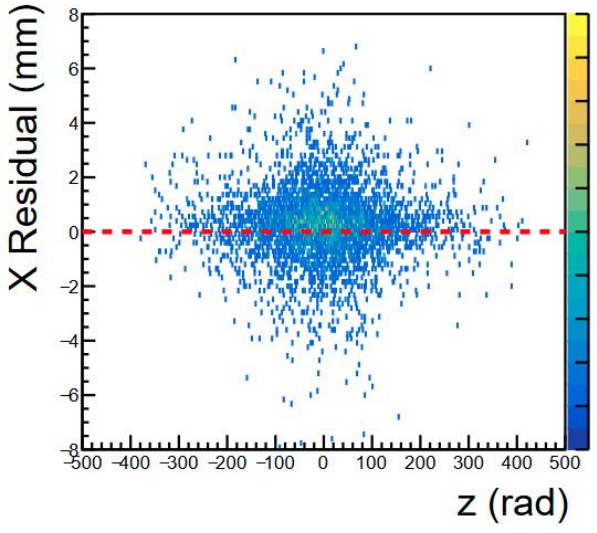
Layer 2, Top





Layer 3, Top





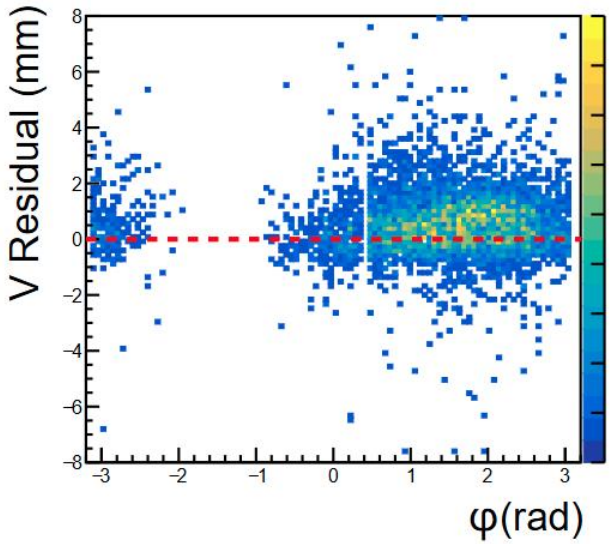
V residual vs φ

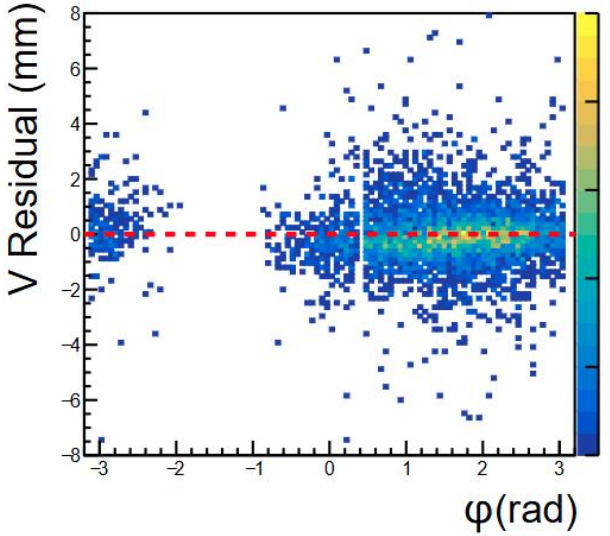
Preliminary Result

Before Alignment

After Alignment

Layer 2, Top





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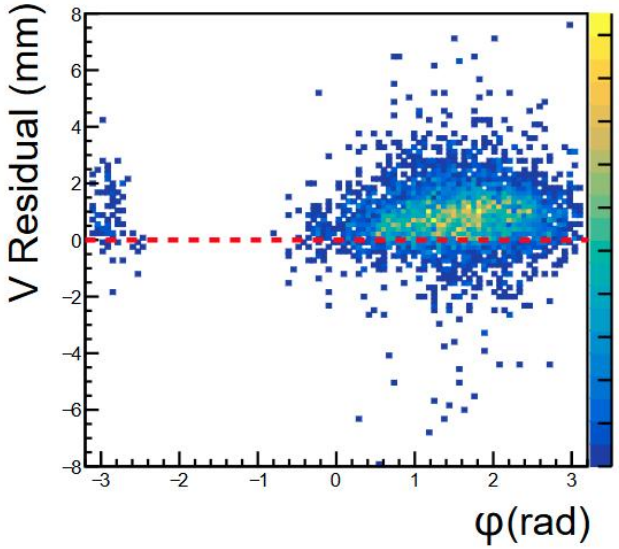
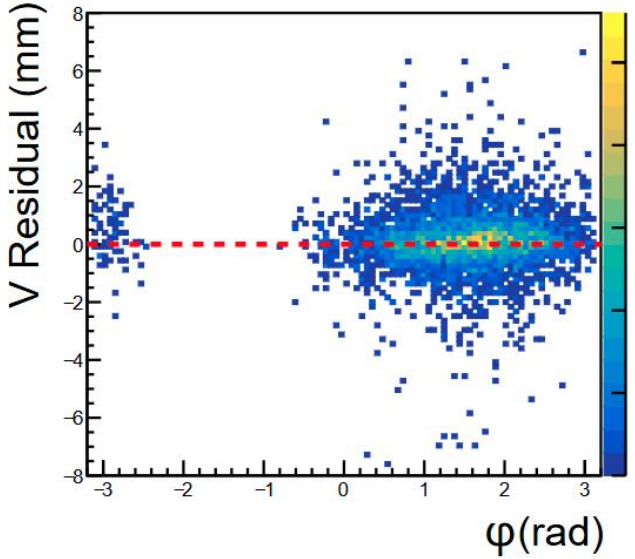




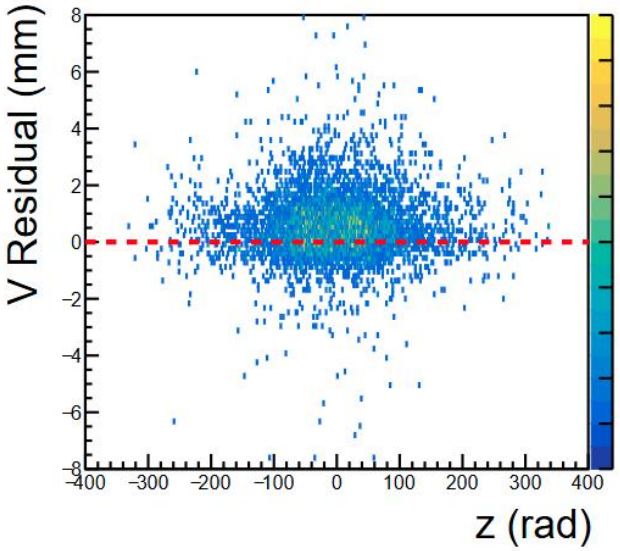
V residual vs z

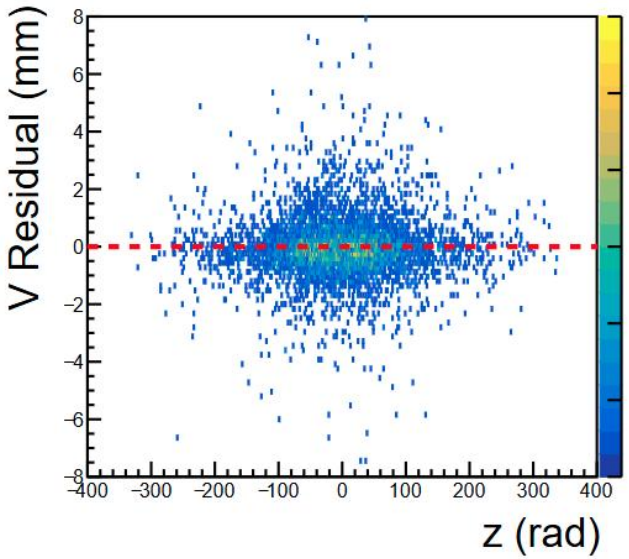
Preliminary Result

Before Alignment

After Alignment

Layer 2, Top





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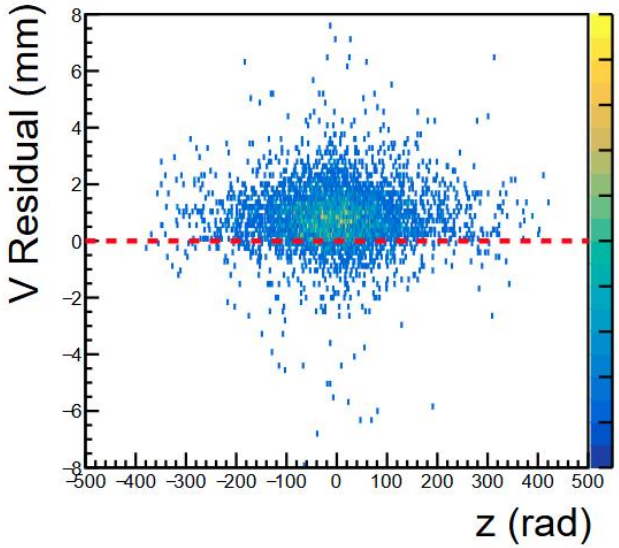

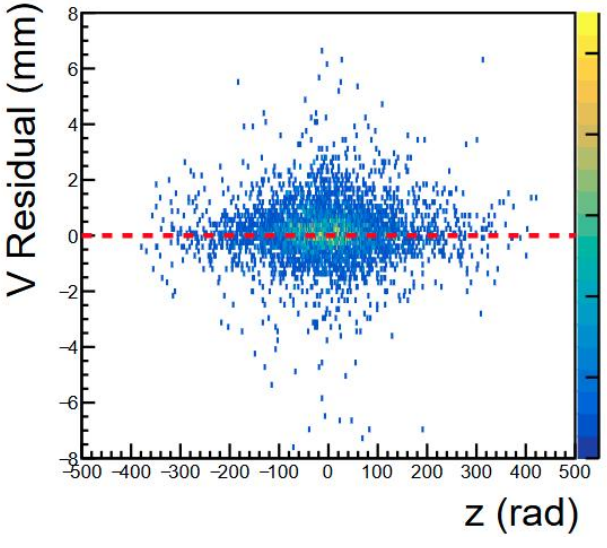

Summary

- Significant misalignment effect in tracking observed after inner tracker upgrade
- First attempts to align CGEM+ODC using cosmic-ray (with/without magnetic field) are underway

Thanks!

Back up

Misalignment effect

- Mechanical imperfection during the detector construction and assembly can cause the bias of track reconstruction and degradation of momentum resolution