BESIII MDC Tracking Calibration and CGEM Alignment

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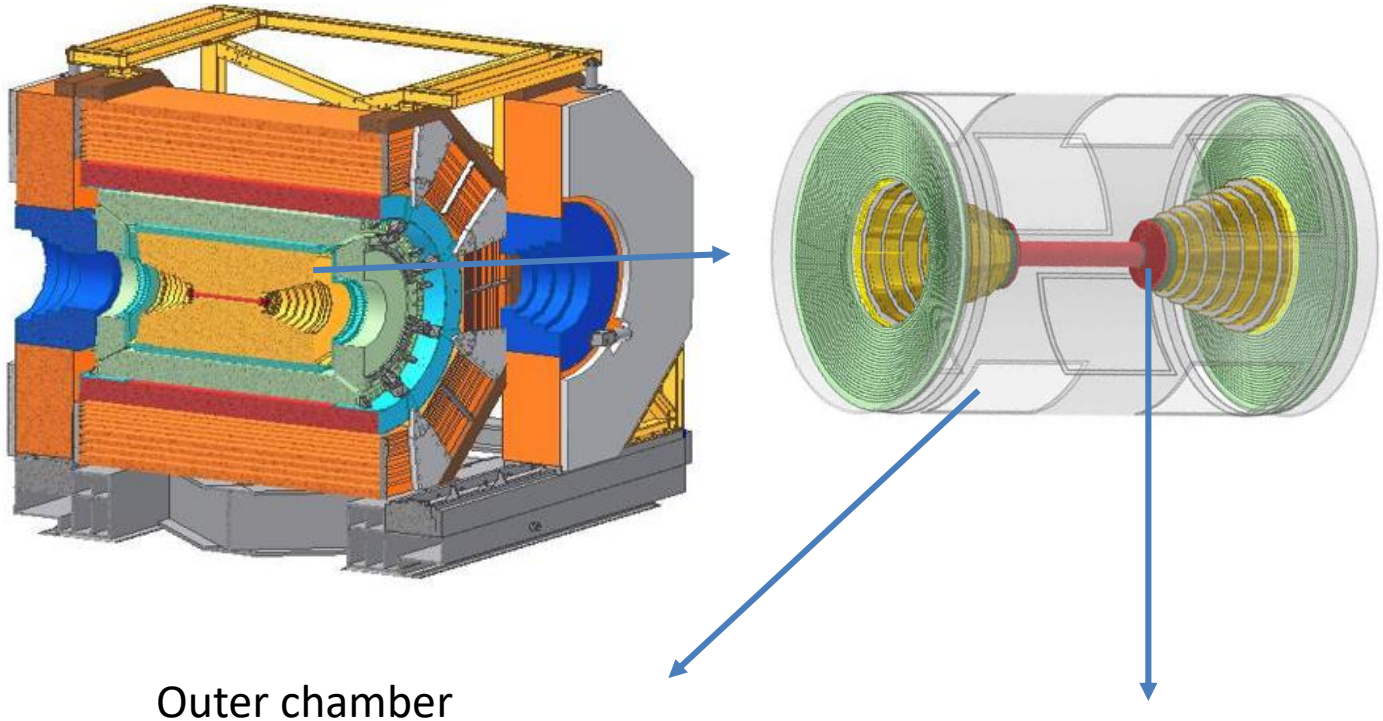
For the BESIII Tracking software group

Outline

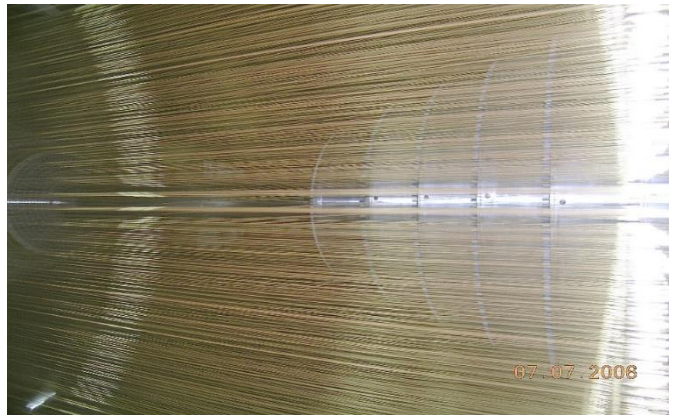
- MDC tracking calibration and alignment
- Alignment of CGEM Inner Tracker (CGEM-IT)

BESIII drift chamber

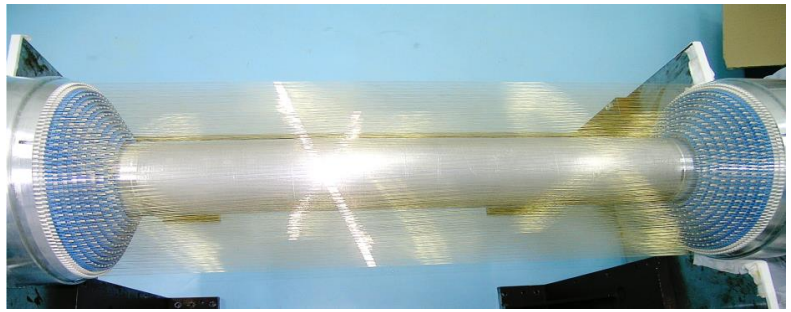
- Purpose:
  - Tracking for momentum measurement, vertex reconstruction and track extrapolation
  - PID for charged hadrons
- 6792 cells in 43 cylindrical layers
  - Inner chamber: Layer 1 ~ 8
  - Outer chamber:
    - Layer 9 ~ 20 in six steps
    - Layer 21 ~ 43 fixed at big out endplates



Outer chamber



Inner chamber



Motivation of MDC calibration

- Calibrate time-to-distance relation (X-T relation)
- Determine Time shift (T0) for each channel
- Extract Time-walk function
- Correct the displacement of each component

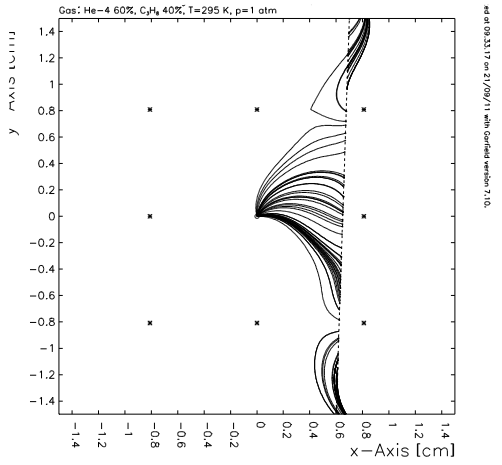
$$\chi^2 = \sum_{i=1}^{N_{hit}} \frac{(d_{meas}^{(i)} - d_{track}^{(i)})^2}{\sigma_i^2}$$

- For d_{meas}: X-T relation, T0, Time-walk function
- For d_{track}: correction of sense wire position

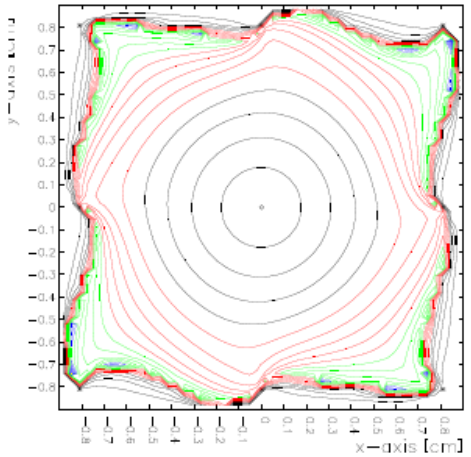
X-T relation calibration

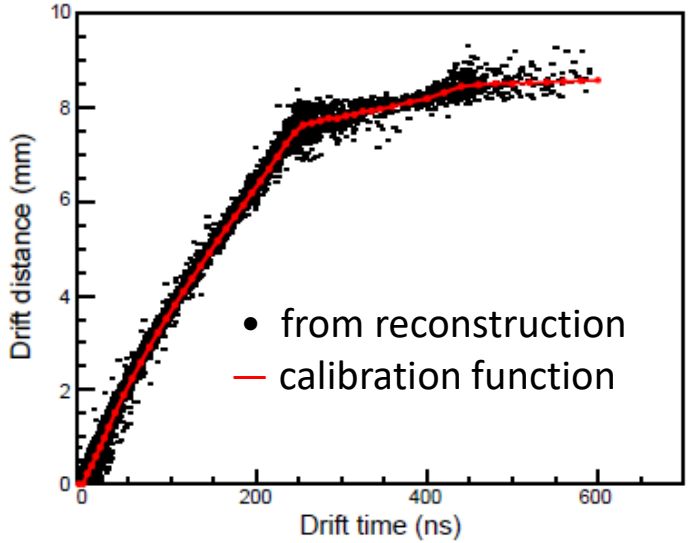
- Preliminary result estimated from the drift time distribution
- Layer by layer calibration due to difference of cell size and HV in different layer
- Considering the dependence on both left-right and incident angle
- It is an iterative process

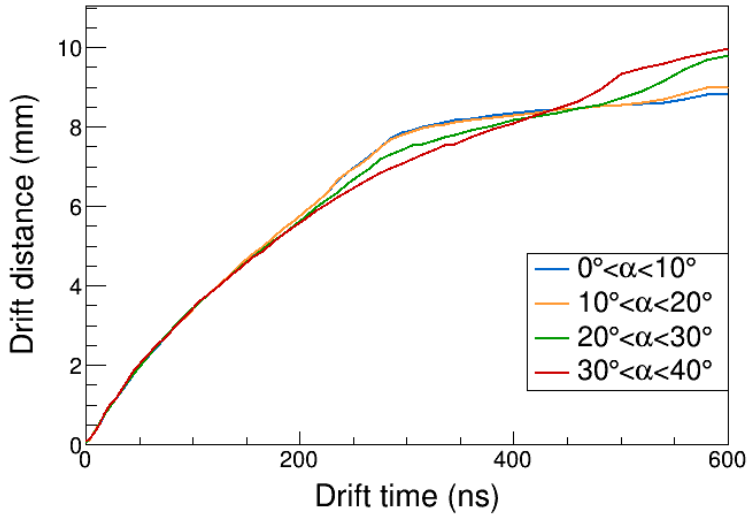
Drift lines



Contour of drift time



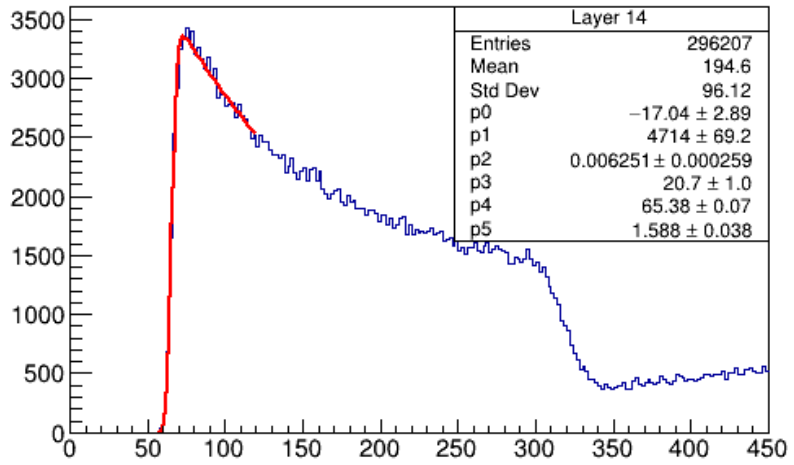




T0 calibration

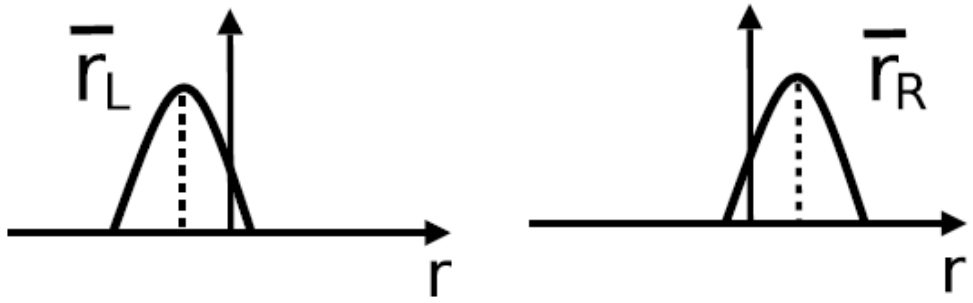
- Fit the leading edge to determine the preliminary T0 for each layer
- Cell-by-cell precise calibration using residual distribution

T0 fit



$$f(t) = p_0 + p_1 \frac{e^{-p_2(t-p_3)}}{1 + e^{\frac{-(t-p_4)}{p_5}}}$$

Track-based cell-by-cell calibration

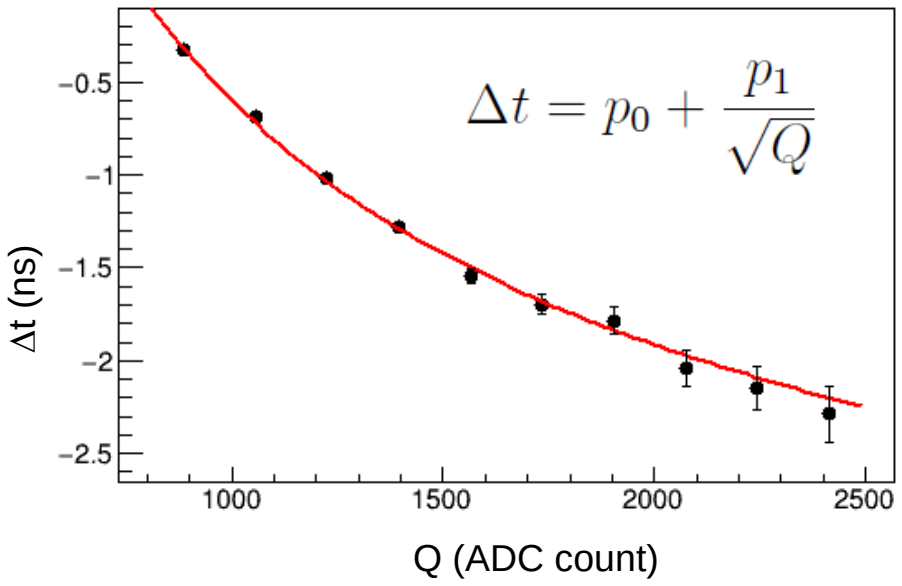


$$\Delta T_0 = \frac{\overline{r_R} - \overline{r_L}}{2v}$$

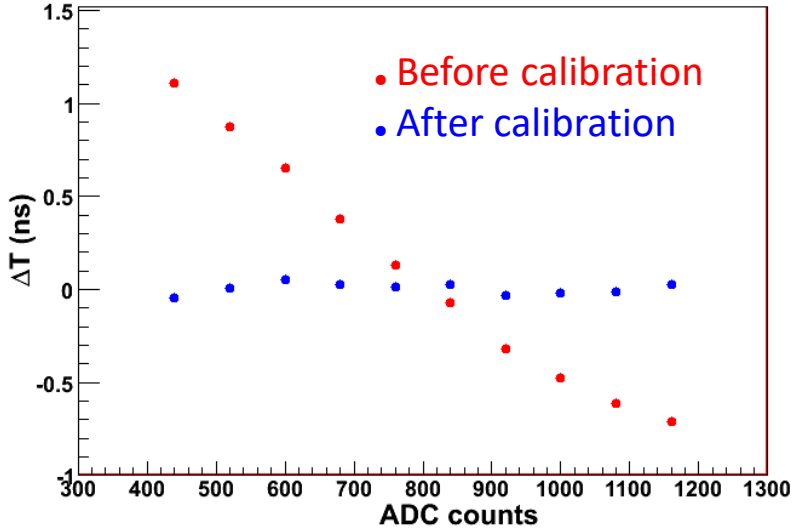
Time-walk calibration

- Correction of the correlation between timing difference and pulse height of the signal
- Layer by layer calibration

Time-walk function

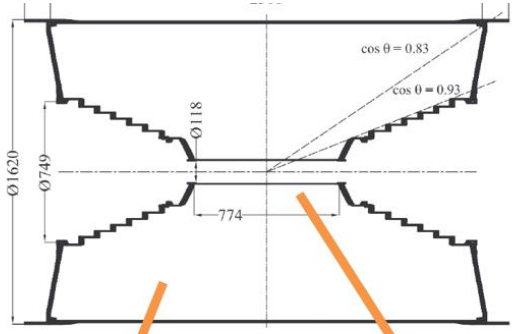


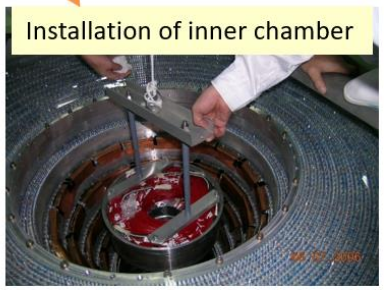
ΔT vs Q (layer 29)

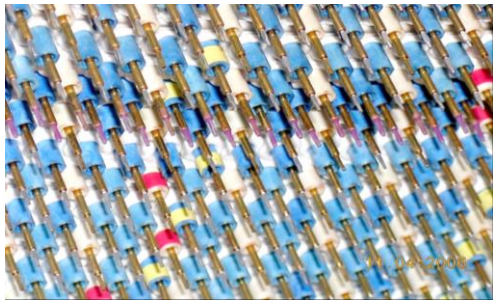


MDC alignment

- Mechanical imperfection in the construction and assembly of the detector (a few hundred microns) may has significant impact on momentum measurement
- Track-based alignment is essential for track reconstruction
- Sources of displacements
  - Mechanical imperfection in assembly of endplates (more than 200μm)
    - 16 components: Inner DC, 6 steps and outer section of both ends
  - Single wire displacement (~ 40μm)







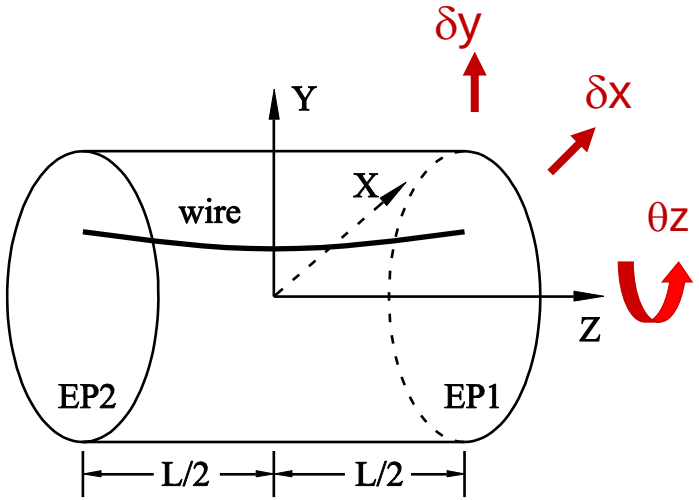
Errors of single wire position

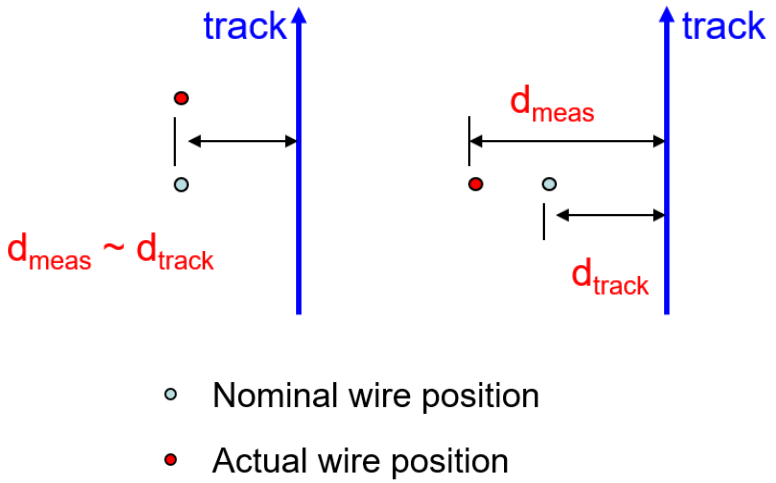
item	rms/μm	
	sense wire	field wire
hole location	25.0	25.0
feedthrough in hole	6.3	6.3
crimp pin hole	12.5	12.5
wire in pin hole	31.3	10.0
total rms	42.4	30.3

Much less than the position error of endplates

Alignment parameters

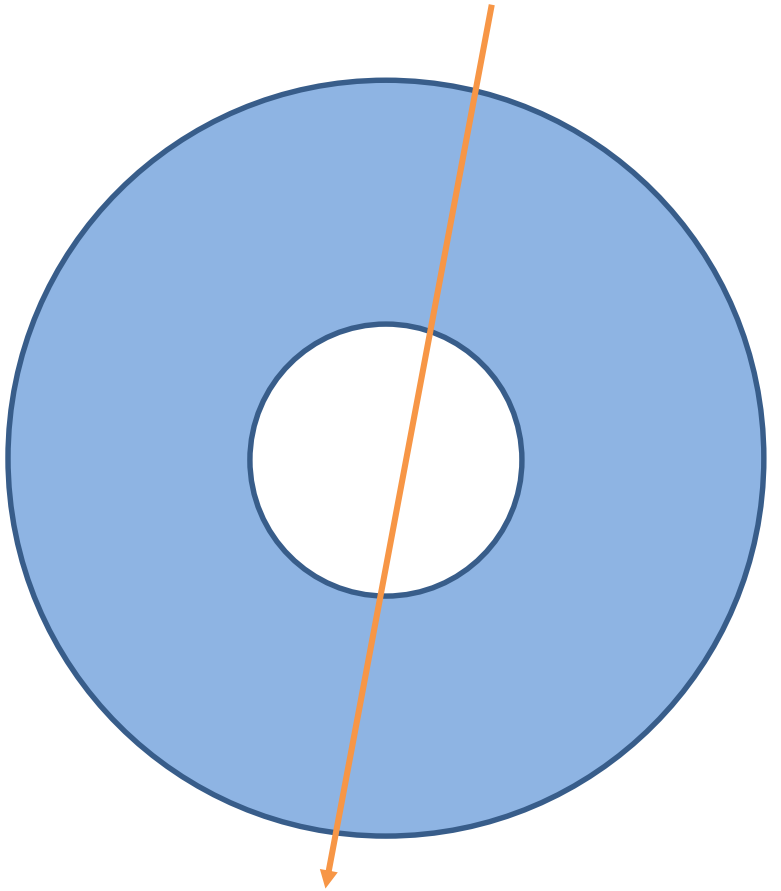
- 6 degree of freedoms for each component
  - Translation in x, y and z
  - Rotation in x, y and z
- Some degree of freedoms constrained to guarantee the stability and avoid weak modes
  - θx, θy, δz
- 48 alignment parameters in total and the average displacement of both big endplates fixed



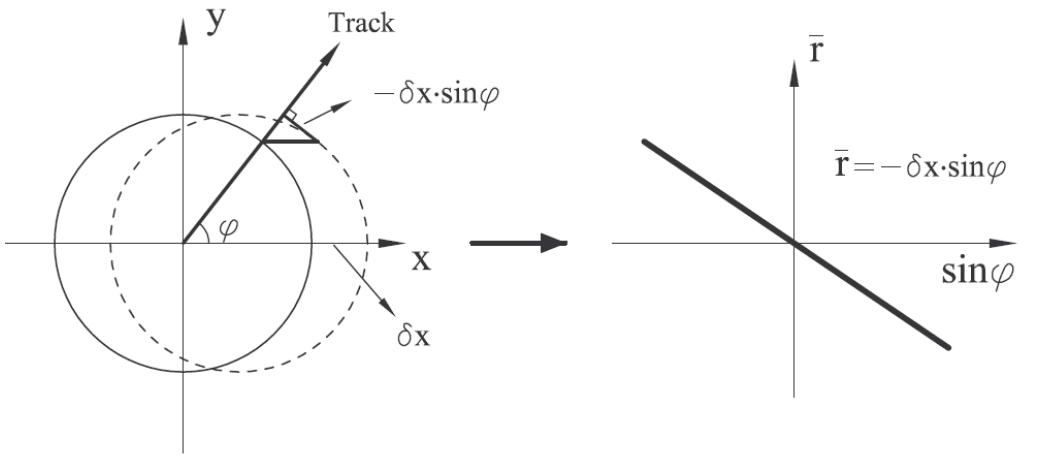


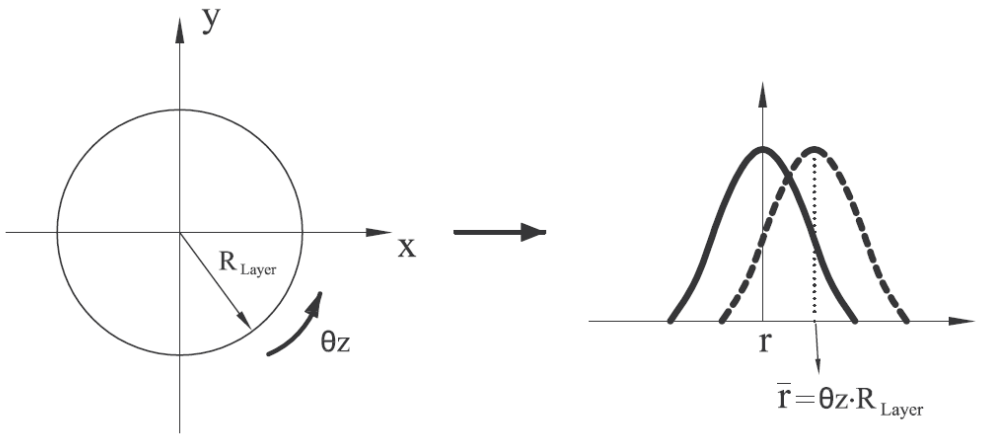
Alignment procedure

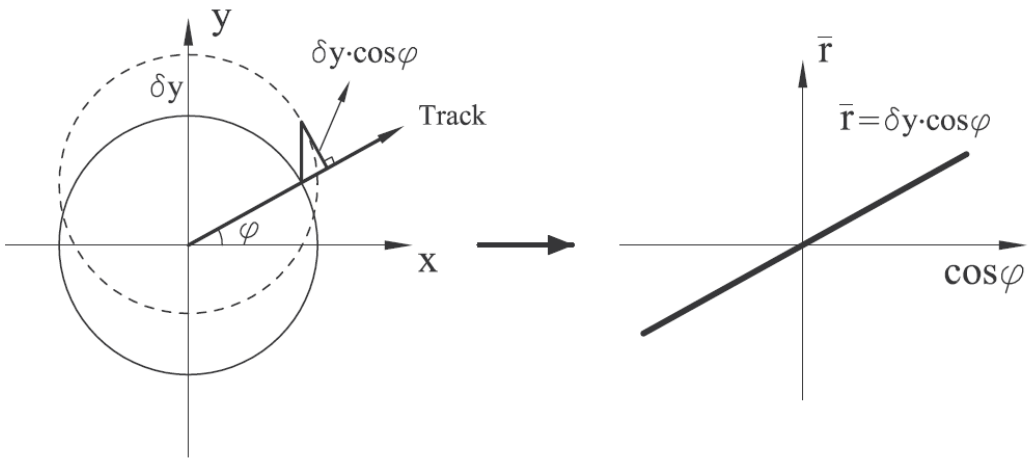
- Preliminary result using parameterization of residual dependence to correct big displacements
  - Track fit using hits of the big outer endplate to align the inner components
- Precise alignment with Millepede matrix method
  - MillepedeII implemented to combine cosmic and dimuon data samples

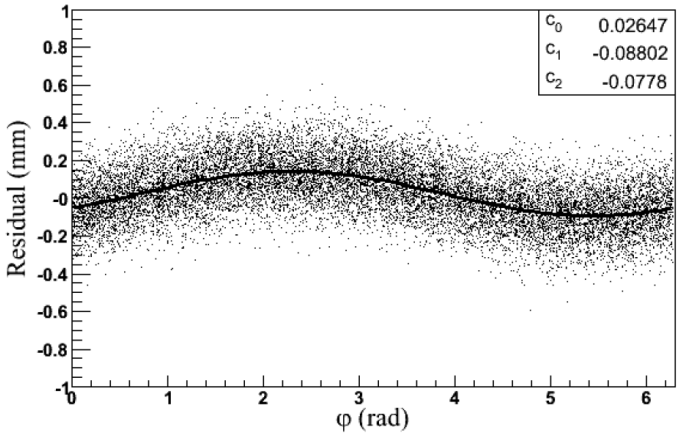


Parameterization of residual









- Estimate alignment parameters from fitting residual distribution
- Used for pre-alignment

Millepede method

- Residual definition (measured value - fitted value)
- Constructing the Chi-Square of least square method
- Minimize Chi-Square and construct parameter equations
- Solve the equation to get the estimation of alignment parameters

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

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

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

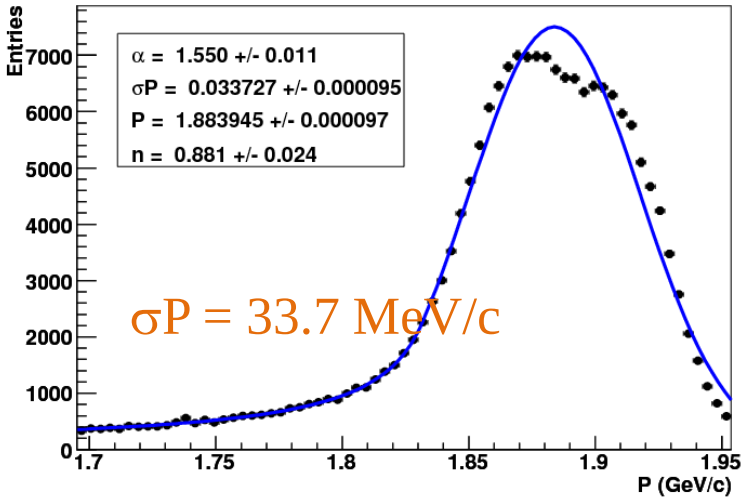
$$\left(\begin{array}{c|cc} C & \cdots\ H_k\ \cdots & \\ \hline \vdots & \ddots\ 0\ 0 & \\ H_k^T & 0\ \Gamma_k\ 0 & \\ \vdots & 0\ 0\ \ddots & \end{array}\right) \times \left(\begin{array}{c} \boldsymbol{a} \\ \hline \vdots \\ \boldsymbol{p}_k \\ \vdots \end{array}\right) = \left(\begin{array}{c} \boldsymbol{b}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

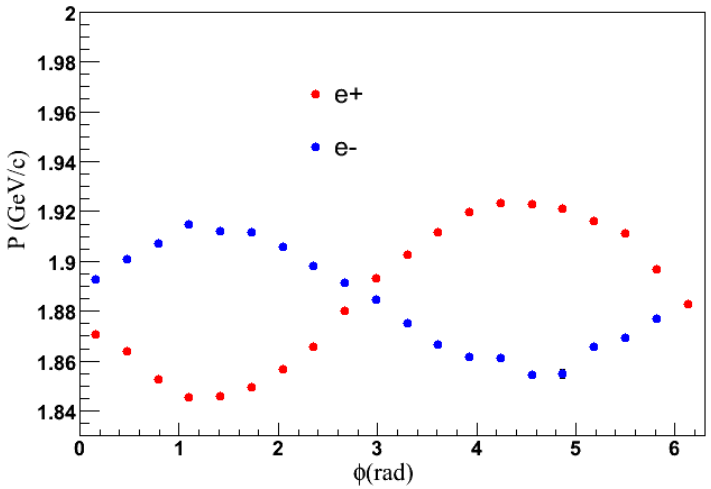
Alignment results

Momentum distribution

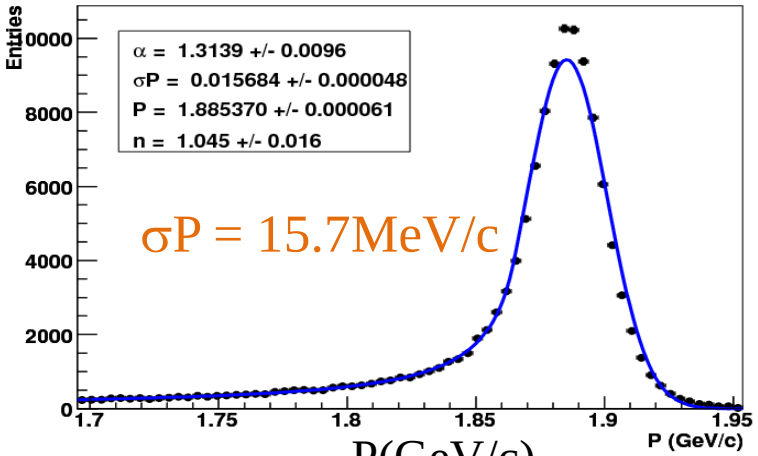
P vs ϕ

Before alignment

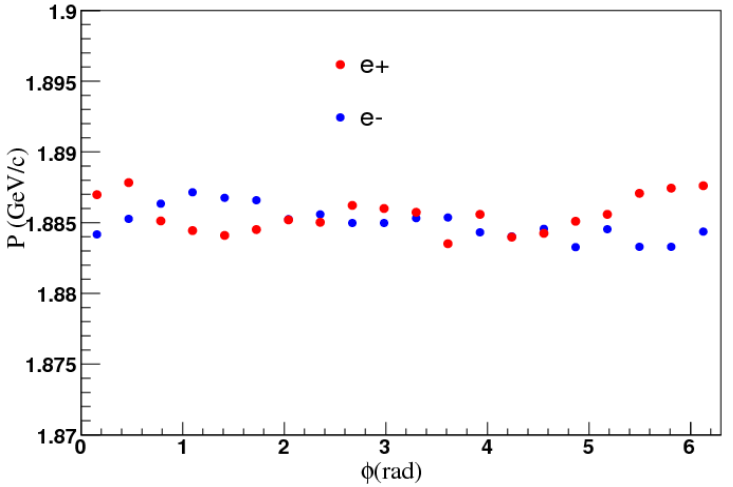




After alignment

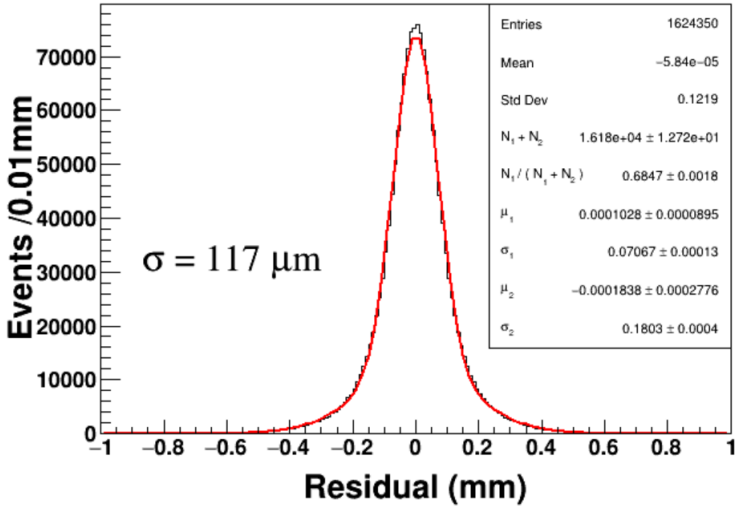


P(GeV/c)

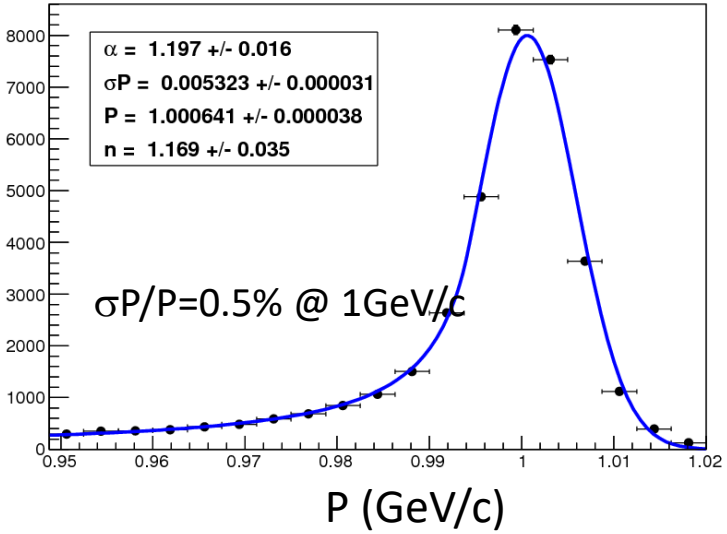


MDC performance

Residual distribution



Momentum distribution

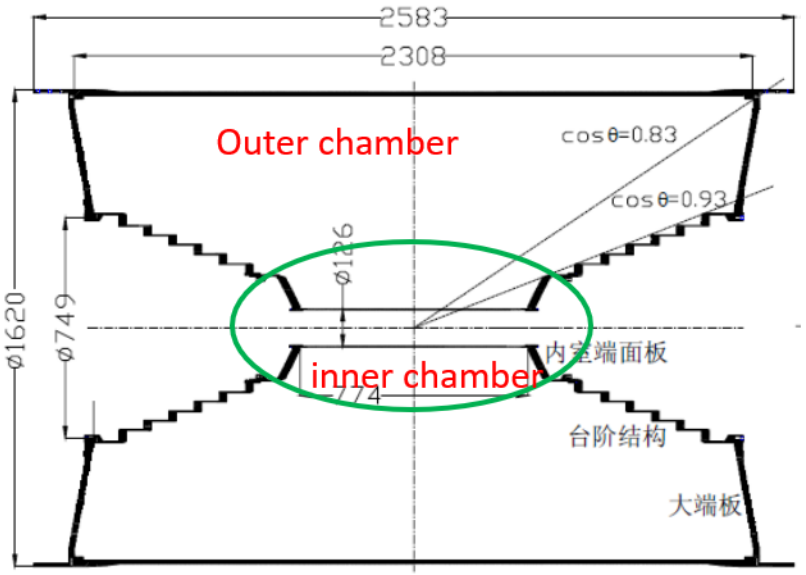


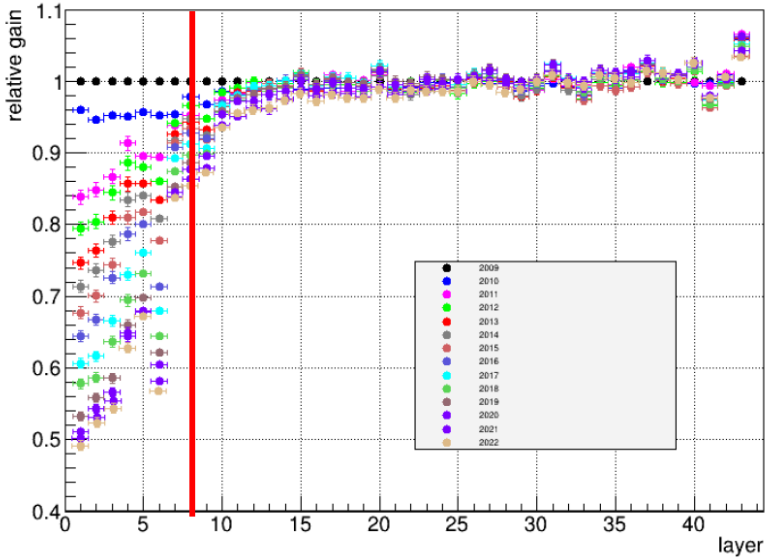
Outline

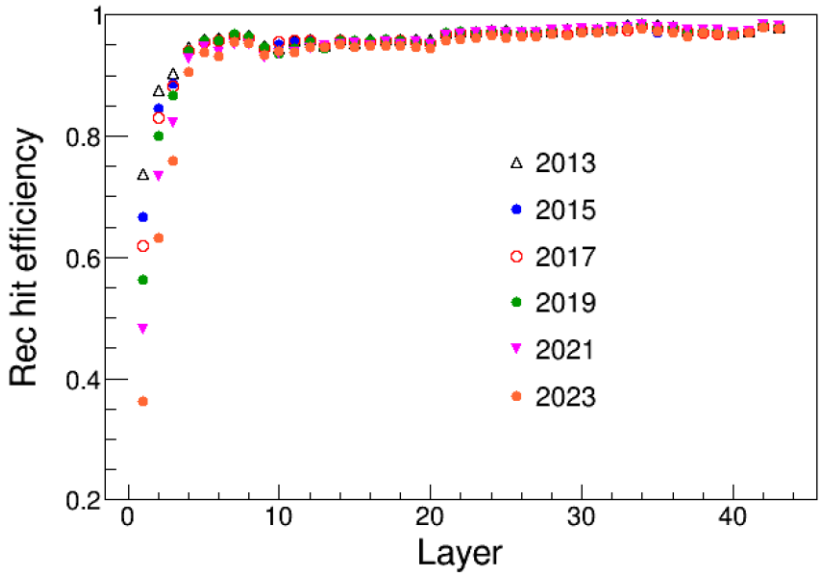
- MDC tracking calibration and alignment
- Alignment of CGEM Inner Tracker (CGEM-IT)

Aging of BESIII inner drift chamber

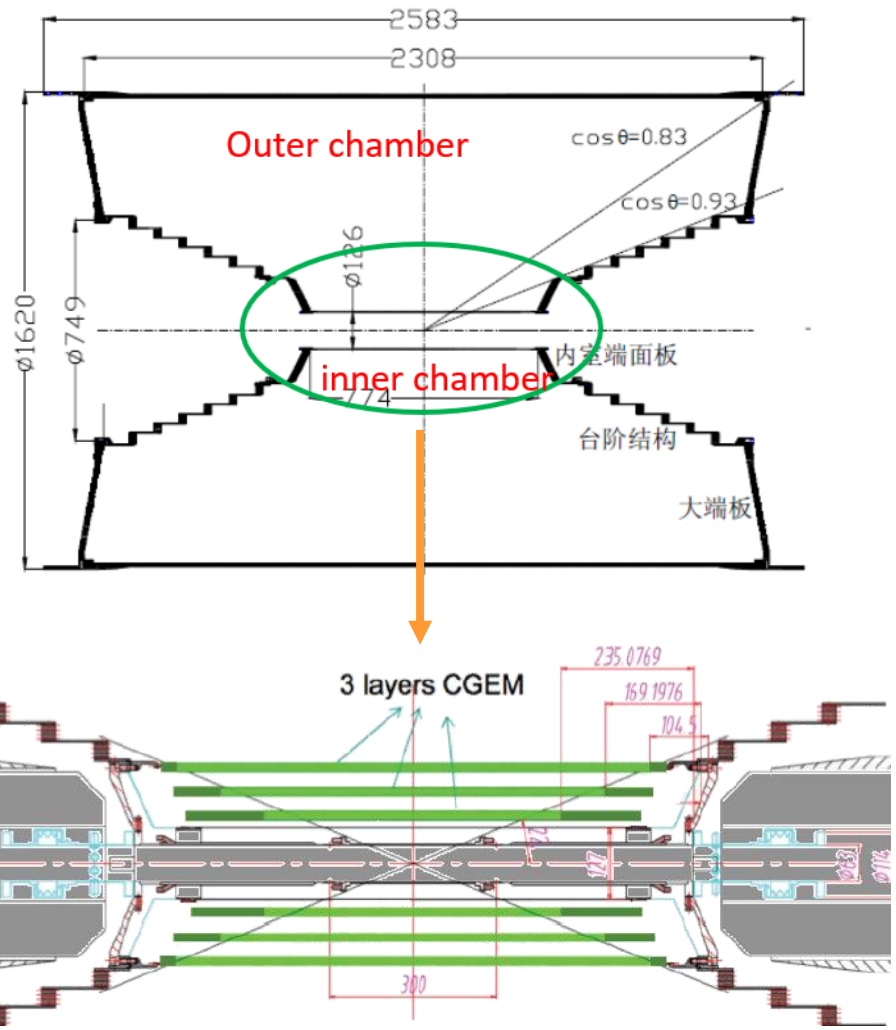
- Operating since 2008
- Close to beam pipe → aging due to high beam induced background
  - Gain deceases with time
  - Degradation of hit efficiency and spatial resolution year by year



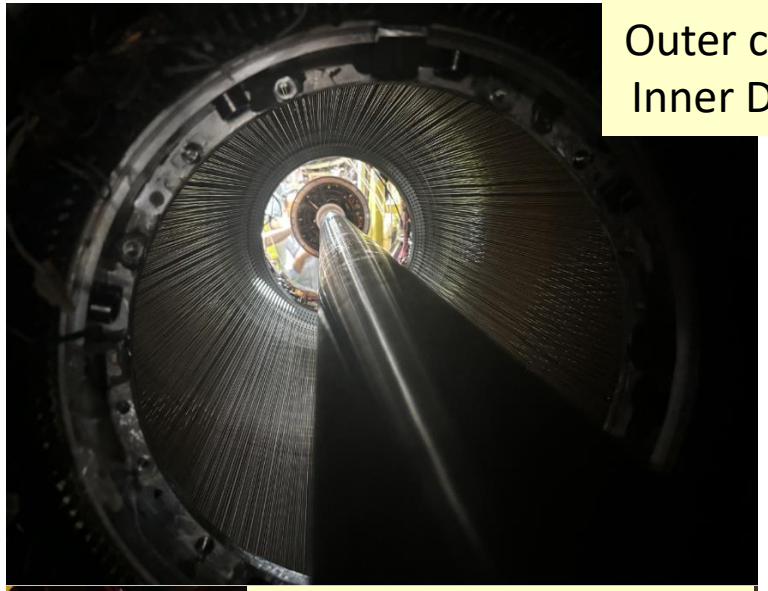




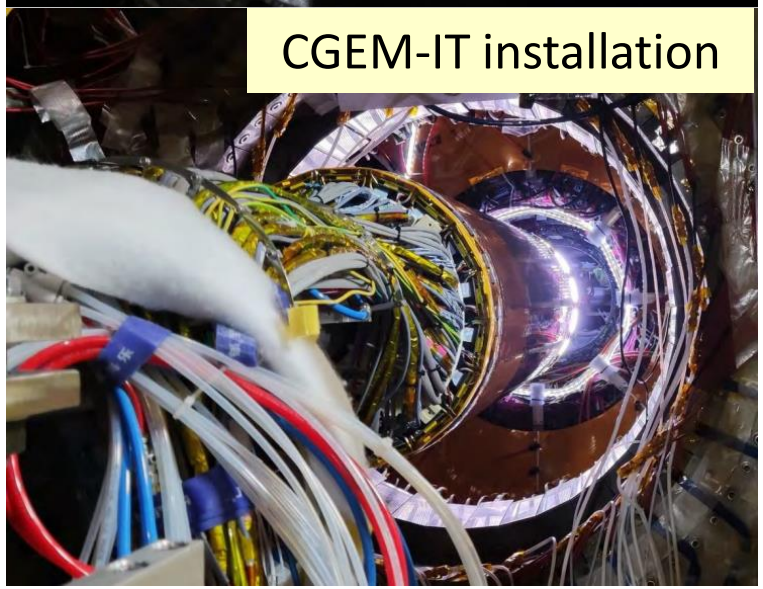
Upgrade of Inner Tracker: CGEM-IT



Data taking started in 2025

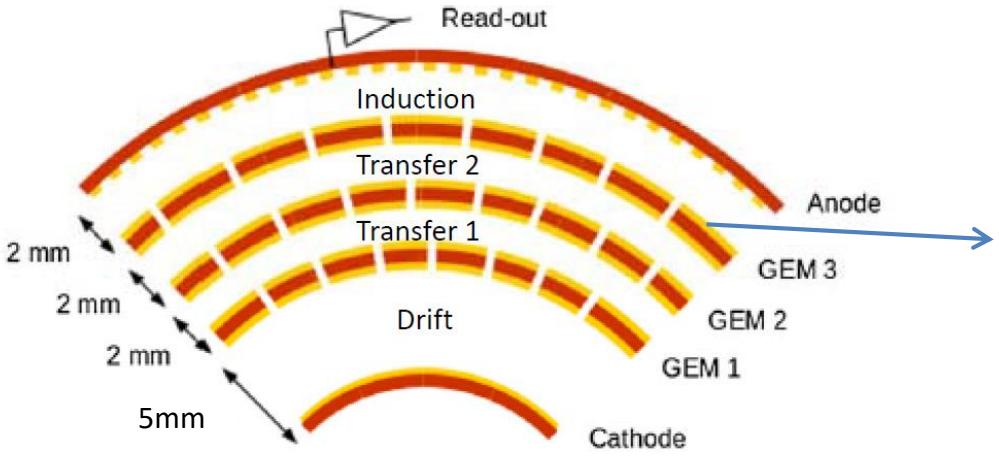


Outer chamber with Inner DC pulled out

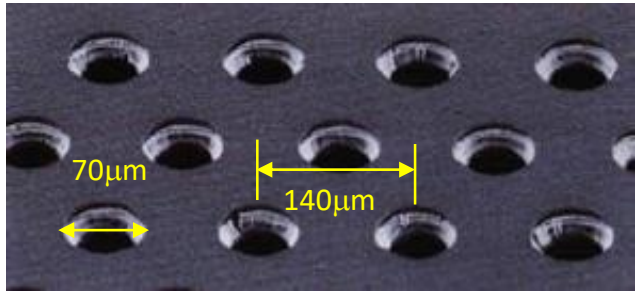


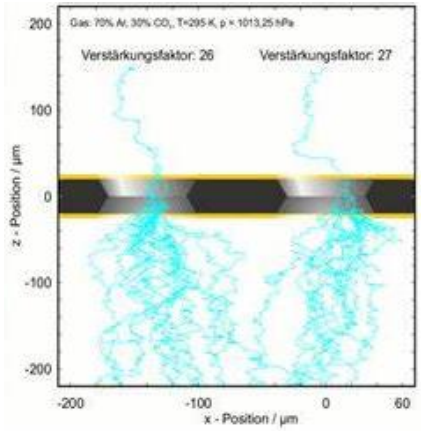
CGEM-IT installation

Structure

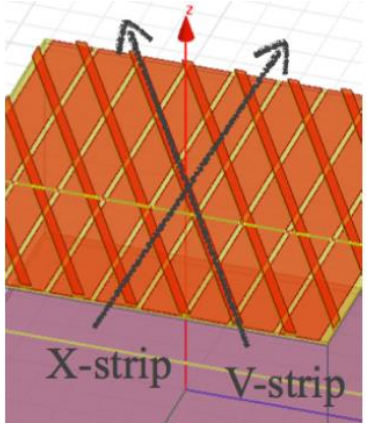


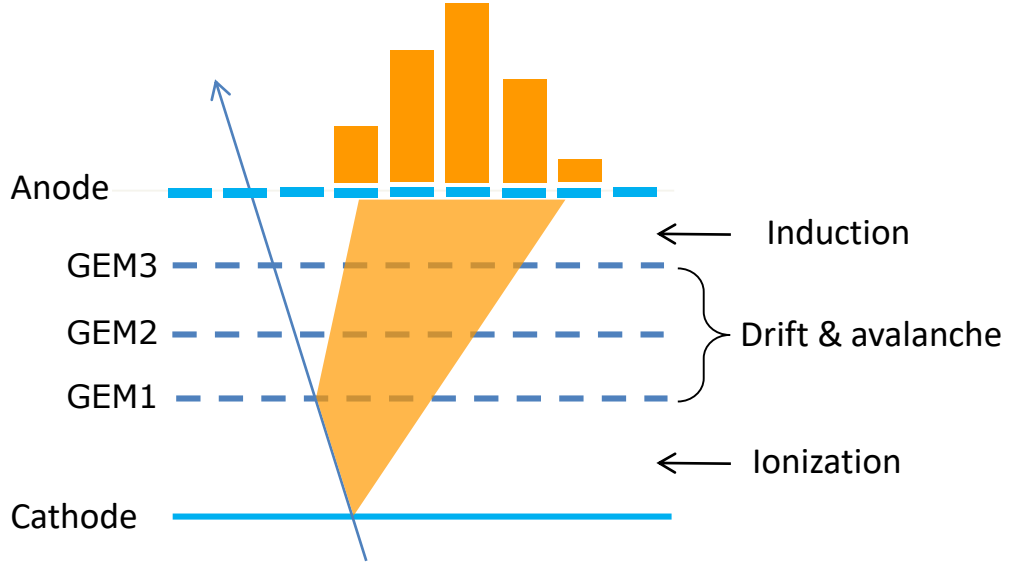
GEM foil





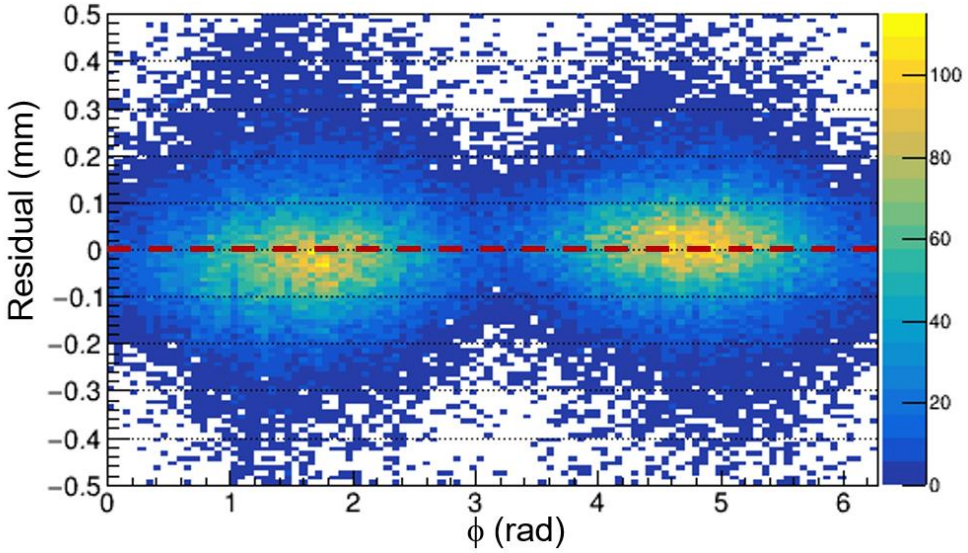
Anode readout



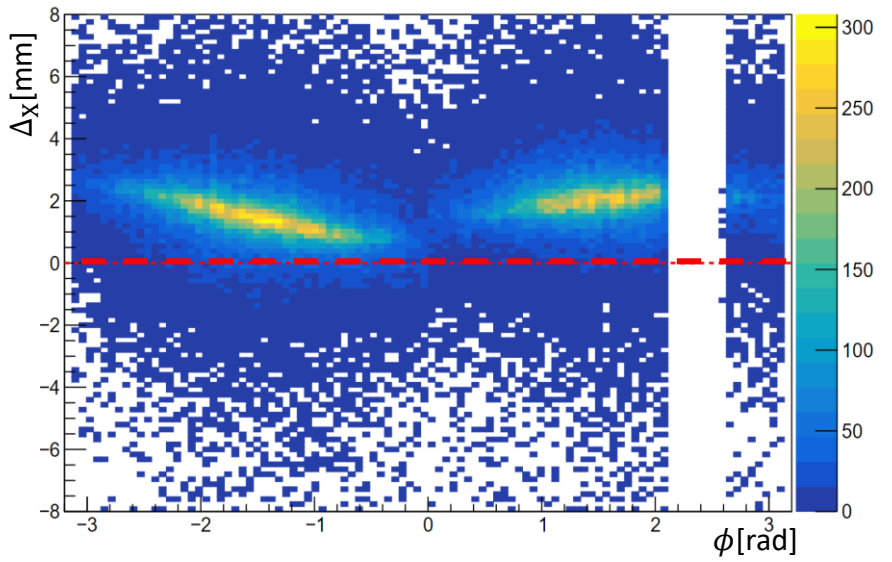


Misalignment effect from cosmic-ray data

- Significant misalignment effects were observed in CGEM during the cosmic-ray data analysis
  - the shift of residual distributions is up to 3 mm
  - which could lead to a degradation of momentum resolution.
- This work focused on the CGEM alignment using tracks reconstructed by outer MDC



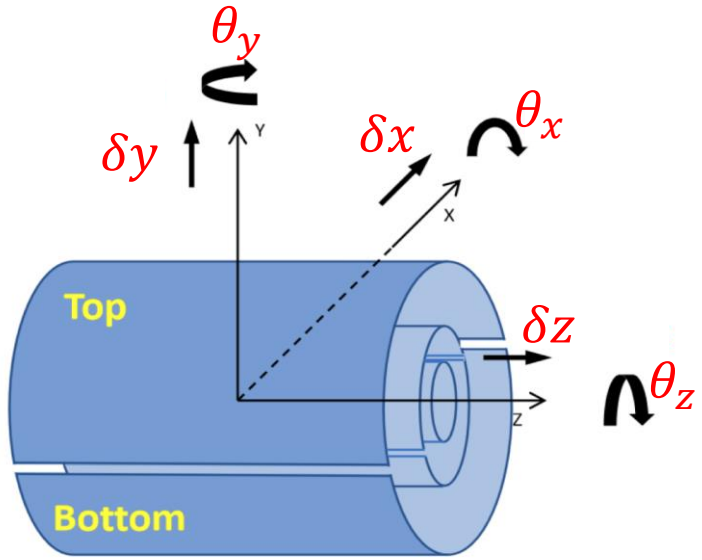
Misalignment of MDC (layer 11)

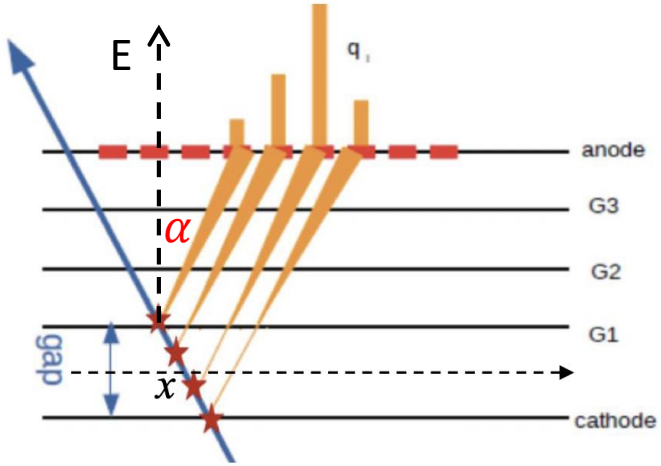


Misalignment of CGEM (layer 3)

CGEM Alignment Parameters

- 5 parts : layer 1, top/bottom sheet in layer 2/layer 3
- 6 degrees of freedom for each part:
  - Translation: $\delta x, \delta y, \delta z$
  - Rotation: $\theta_x, \theta_y, \theta_z$
- Lorentz angle in magnetic field has a similar effect to θ_z
  - combining track samples with / without magnetic field to decouple the correlation
- Deformation of the cylinders not considered currently





Alignment Strategy

Step	Data sample	Track reconstruction	Alignment method	Target parameters	Status
1	cosmic-ray without magnetic field	Only ODC	Residual parameterization	$\delta x, \delta y, \delta z, \theta_z$ (two sheets in the same layer as one part)	√
2	cosmic-ray with magnetic field	Only ODC or ODC + CGEM	Residual parameterization or Millepede	Lorentz angle	Ongoing
3	cosmic-ray + dimu	ODC + CGEM	Millepede	All parameters	

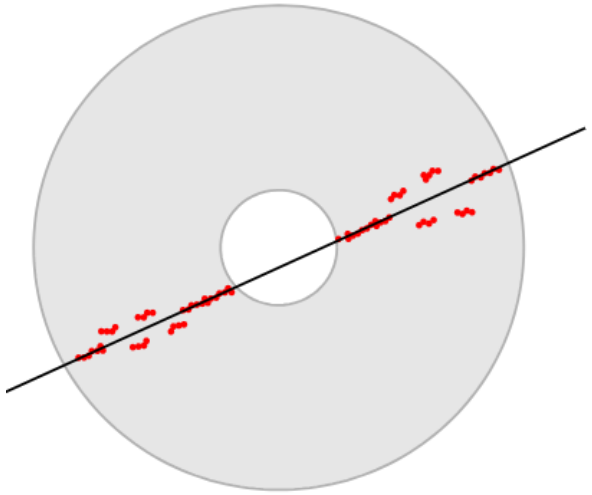
Definition of residuals:

- Residual in X: $\Delta_X = X_{measurement} - X_{fitted\ track}$
- Residual in V: $\Delta_V = X_{measurement} - X_{fitted\ track}$

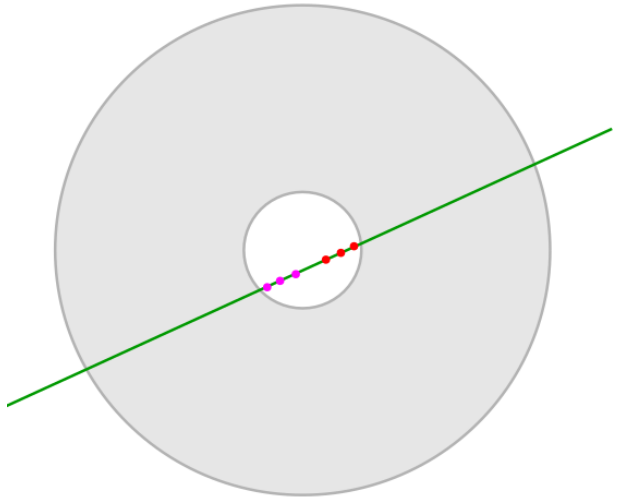
Residual parameterization-based Alignment

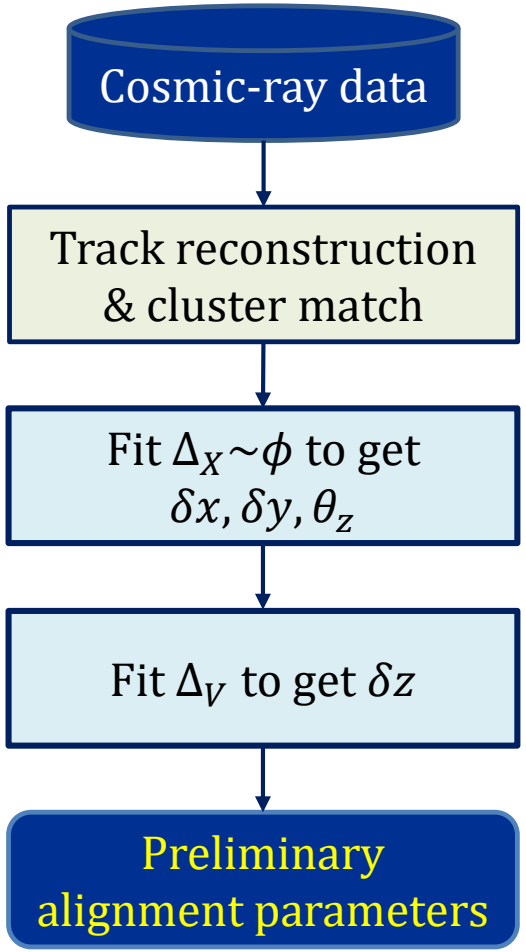
- Data samples: Cosmic ray test without magnetic field
- Tracking Reconstruction Algorithm:
  Hough Transform Method + Least Square Fit

track reconstruction with ODC hits

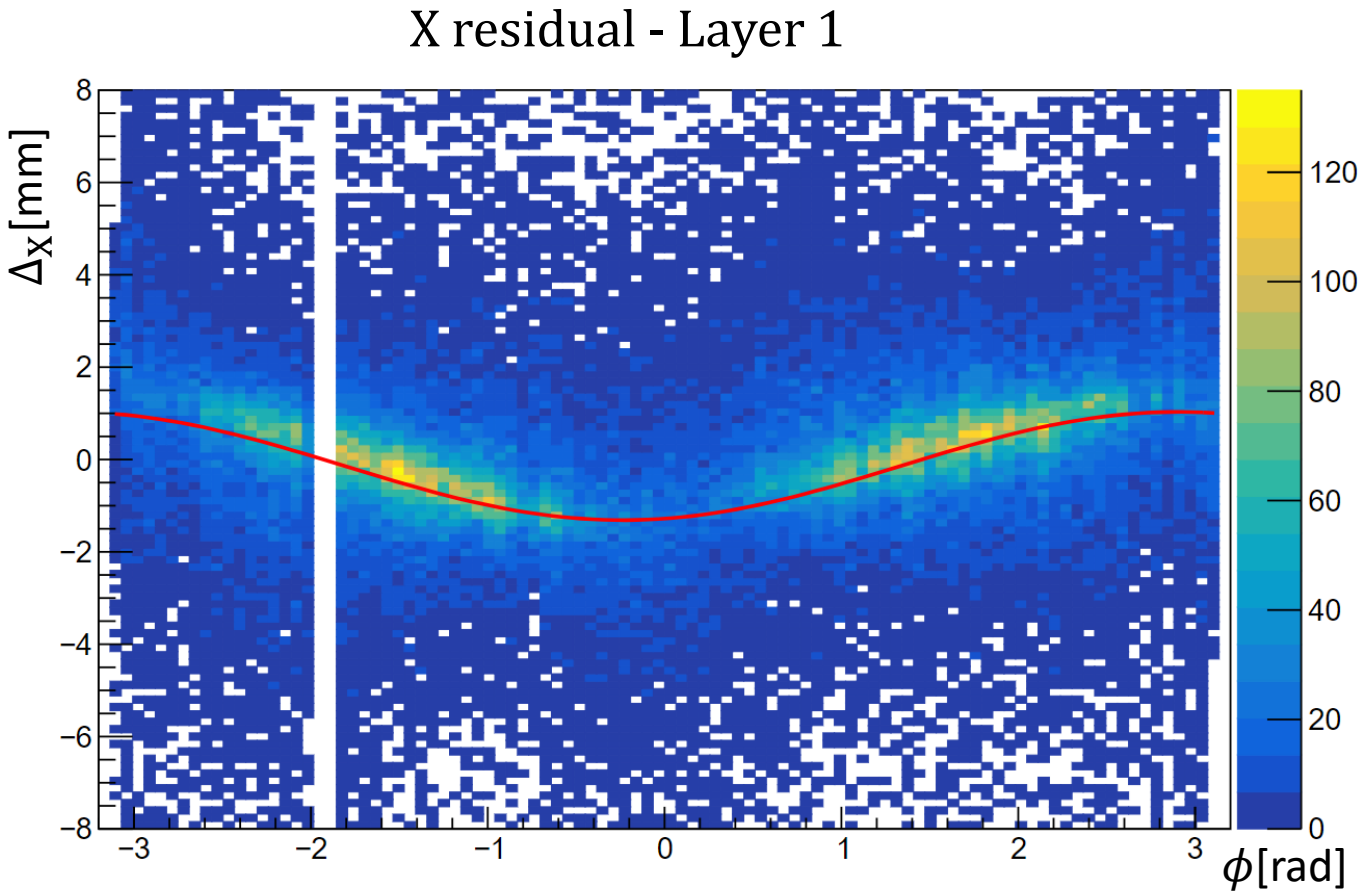


CGEM cluster match





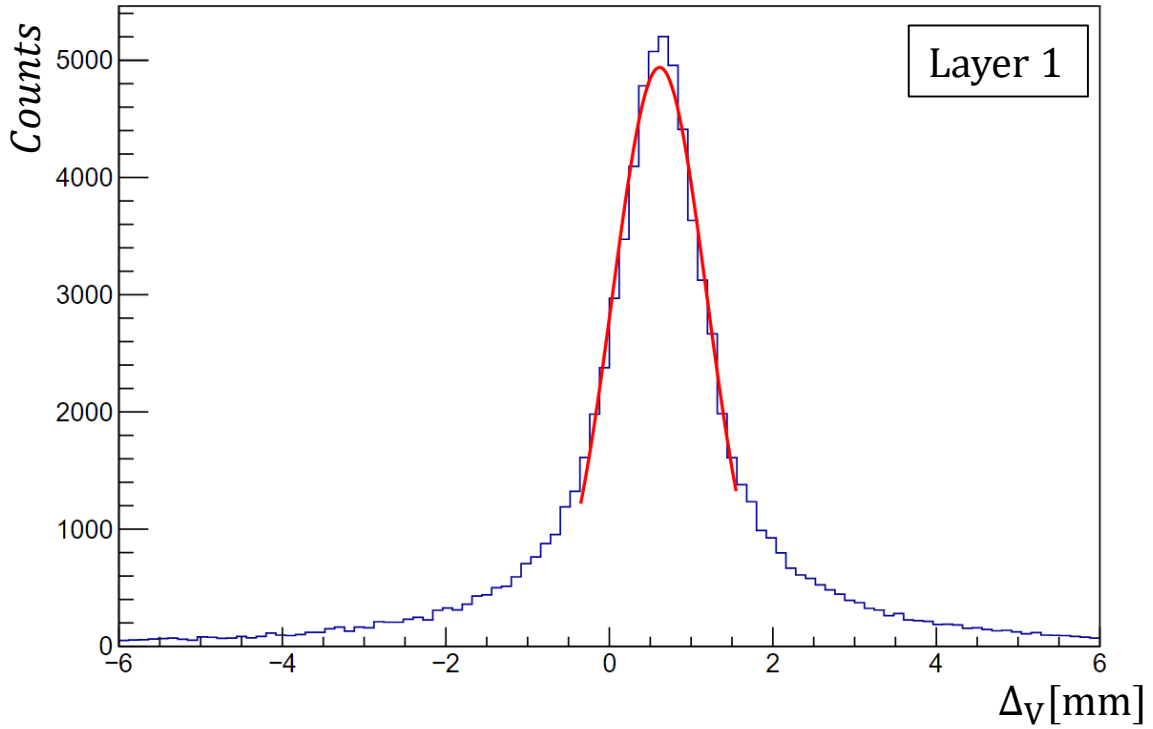
the Alignment of Parameter $\delta x, \delta y, \theta_z$



$$\Delta_X = \delta x * \sin\phi - \delta y * \cos\phi - \theta_z * \mathrm{R}_{\mathrm{layer}}$$

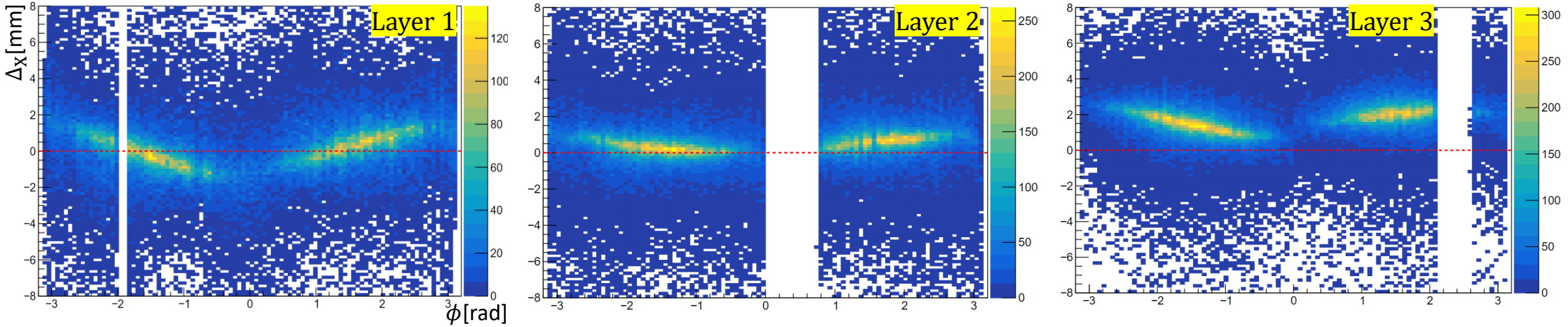
the Alignment of Parameter δz

$$\delta z = \frac{\Delta_V}{\sin\alpha}$$ (α: the stereo angle of V strips)

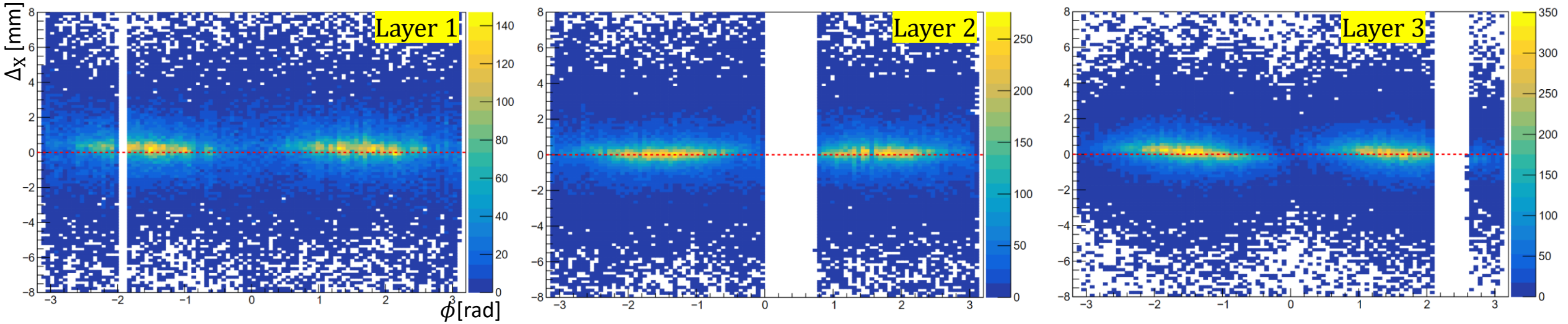


X Residuals vs. ϕ

Before the alignment

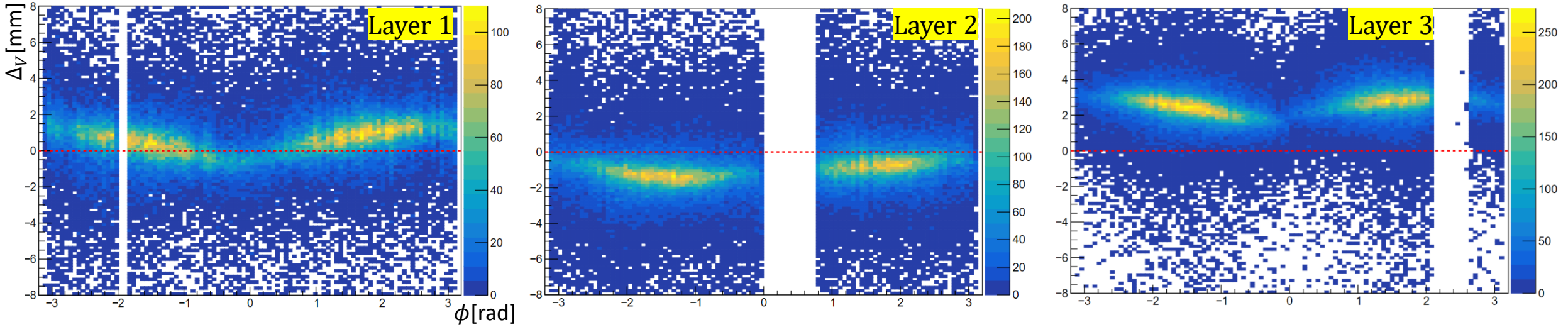


After the alignment

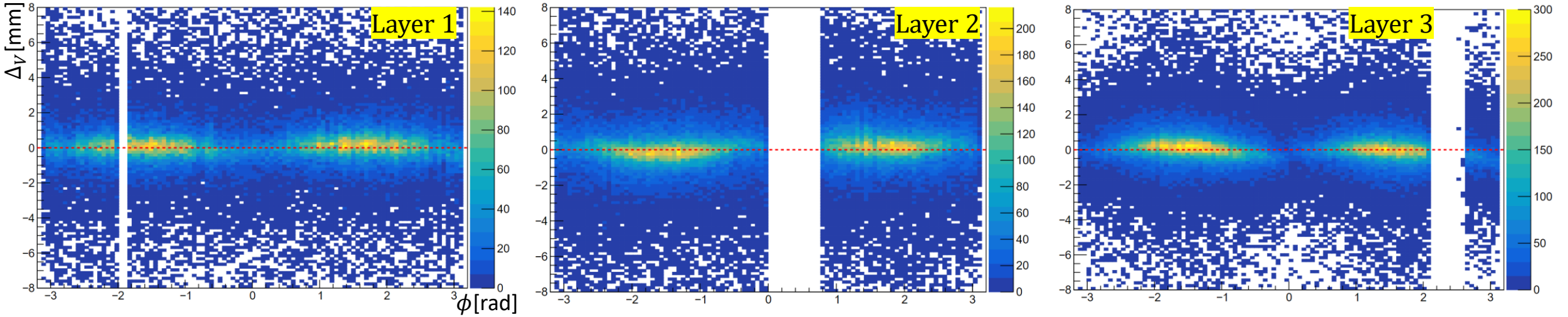


V Residuals vs. ϕ

Before the alignment

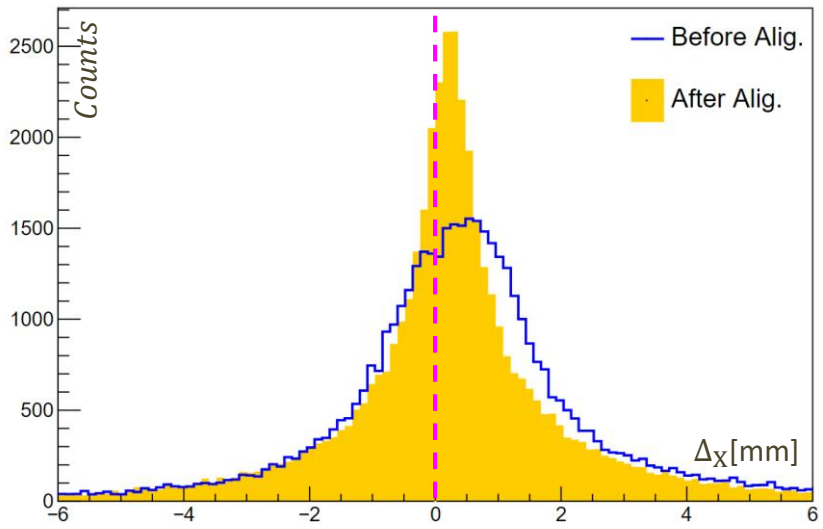


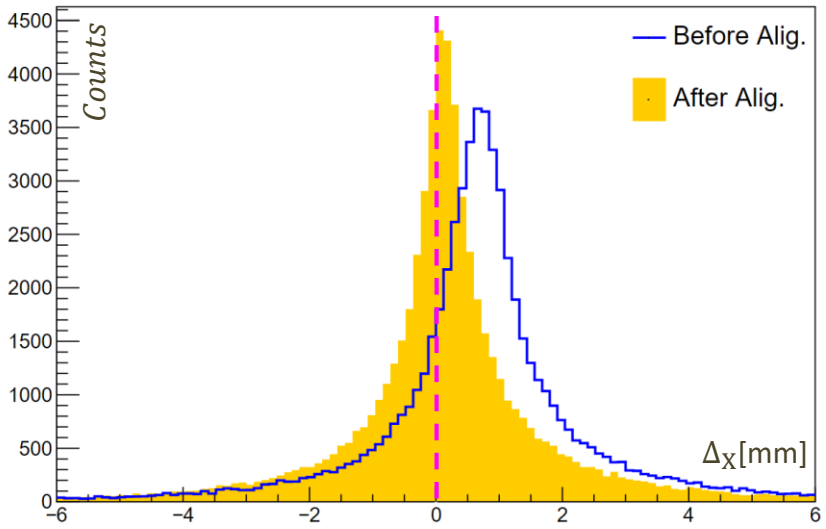
After the alignment

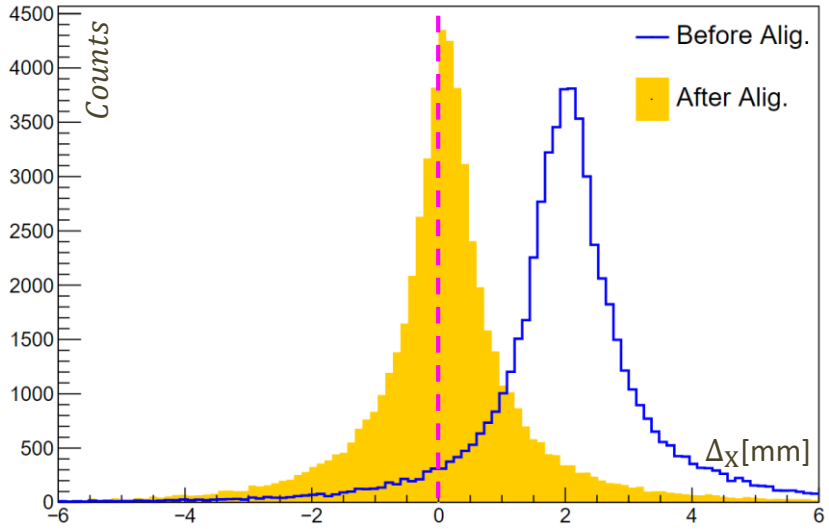


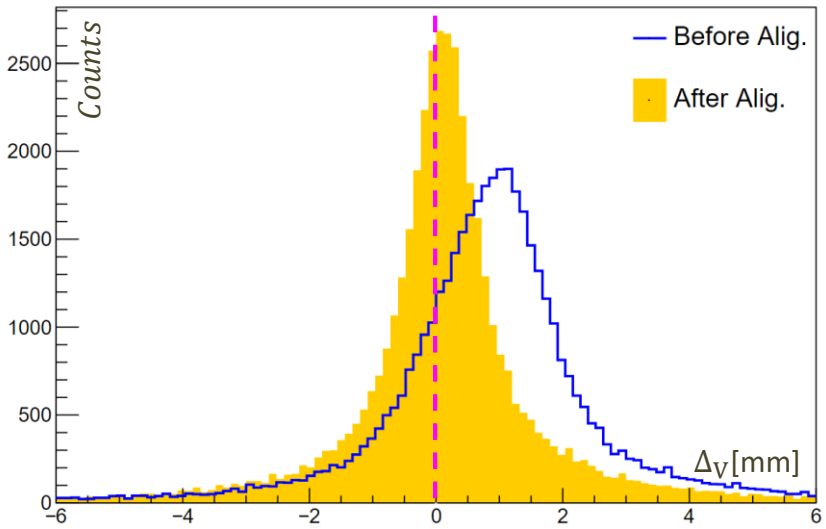
Improvement of Residual Distributions

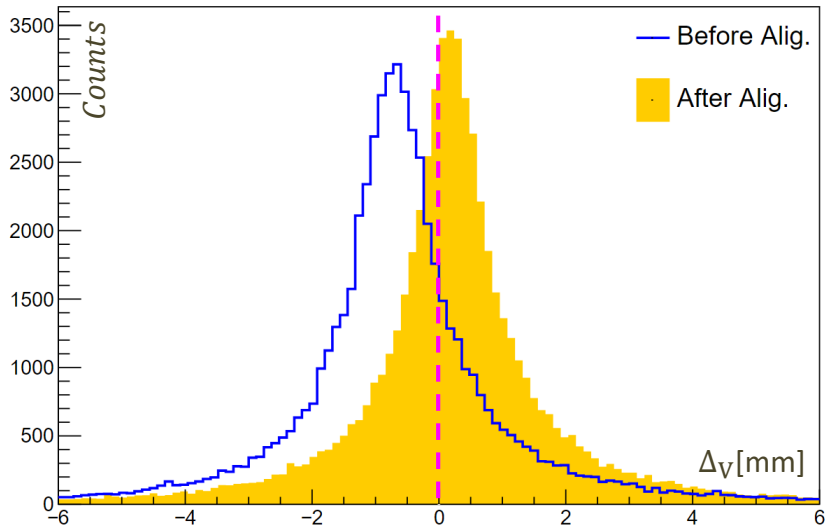
Layer 1 | Layer 2 | Layer 3

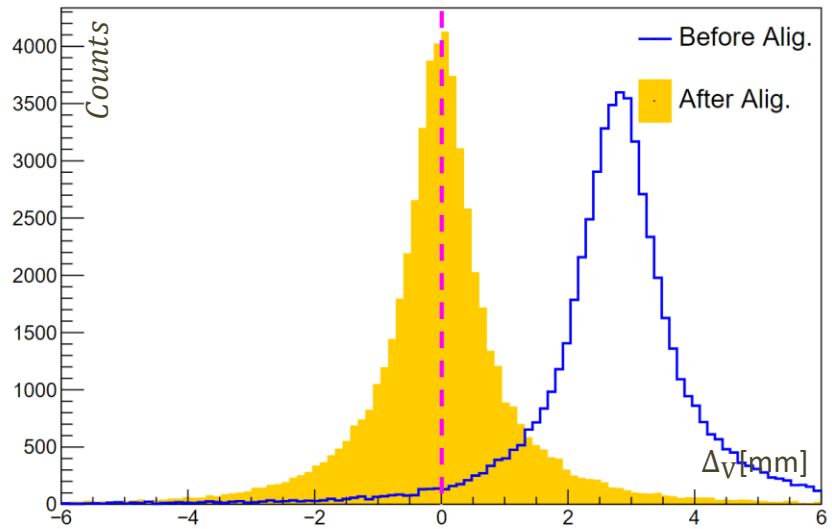












Summary

- Good spatial resolution and momentum resolution achieved with MDC after calibration and alignment
- A preliminary alignment of CGEM, based on residual parametrization, was performed. Further study and precise alignment ongoing

Thanks!