Alignment of CSC chambers using beam-halo muons

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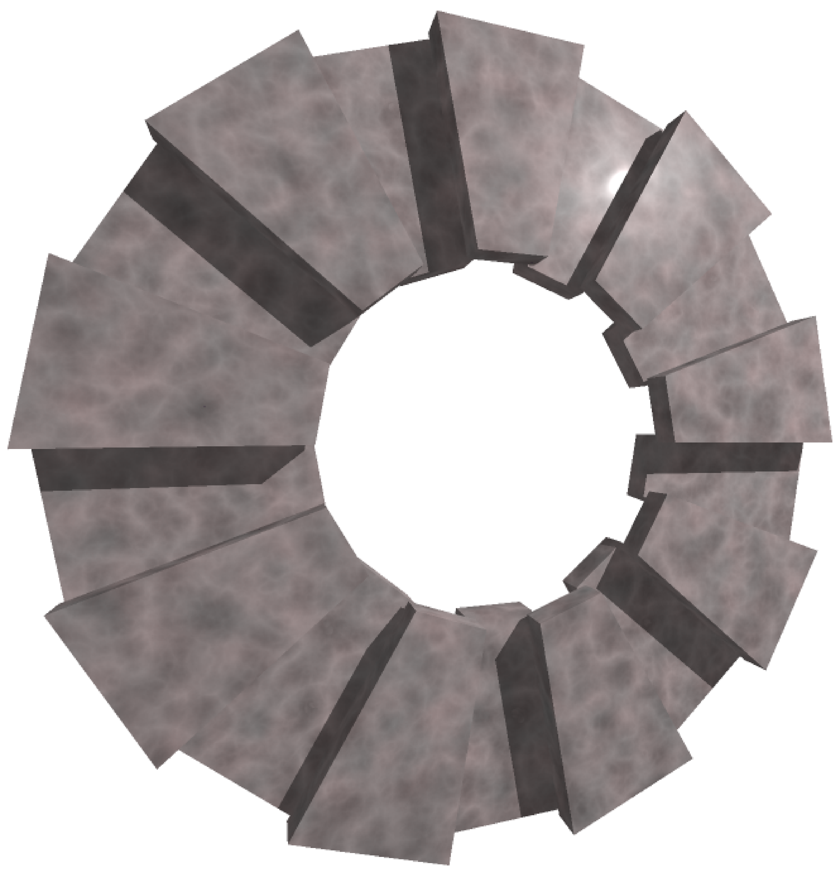
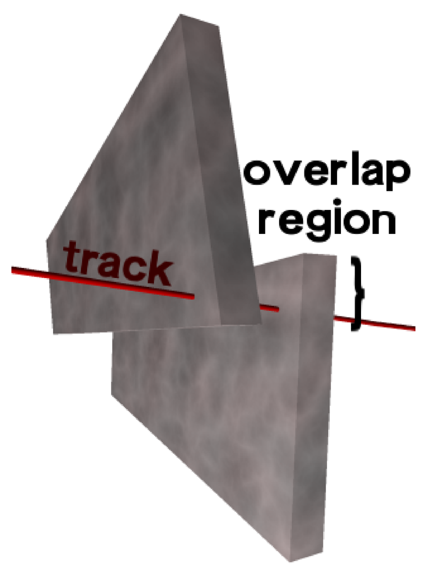
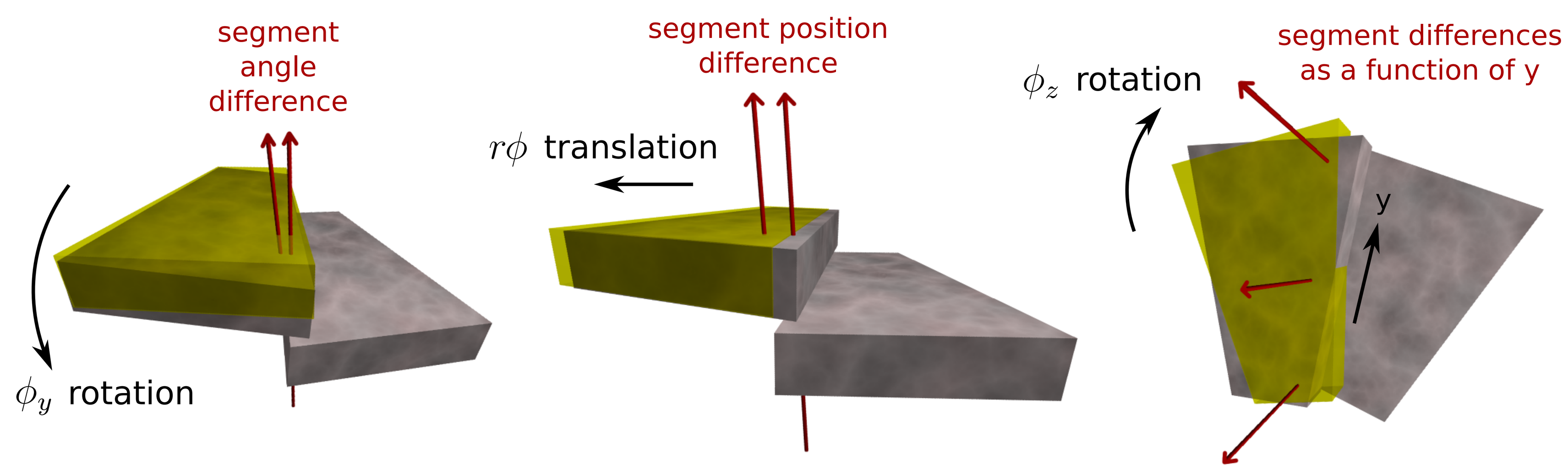
Cathode strip chambers (CSC) in the muon endcap overlap slightly along their edges





Tracks which pass through these overlap regions encounter minimal material between measurements, so track segments in each chamber pair should be collinear with high precision

Differences in segment slopes and positions can be used to determine relative positions in three degrees of freedom:



To propagate relative alignment measurements around the ring, we solve a system of equations.

The general alignment minimization problem

$$\chi^2 = \sum_i^{\text{chambers}} \sum_j^{\text{tracks}} \left(\Delta\vec{x}_{ij} - A_j \cdot \vec{\delta}_i - B_i \cdot \delta\vec{p}_j\right)^T \left({\sigma_{ij}}^2\right)^{-1} \left(\Delta\vec{x}_{ij} - A_j \cdot \vec{\delta}_i - B_i \cdot \delta\vec{p}_j\right)$$

where $\Delta\vec{x}_{ij}$ are residuals, $\vec{\delta}_i$ alignment corrections, $\delta\vec{p}_j$ track corrections, and A_j, B_i are matrices relating alignment and track corrections to residuals

simplifies in this case to

$$\chi'^2 = \sum_i^{\text{chambers}} \left[\Delta\xi_{i,i+1} - (\delta_i - \delta_{i+1})\right]^2 + \left(\frac{1}{N} \sum_i^{\text{chambers}} \delta_i\right)^2$$

$$\text{where } \Delta\xi_{i,i+1} = \sum_j^{\text{tracks}} \left(\text{segment}_{ij} - \text{segment}_{i+1,j}\right) \text{ and } \delta_i = \begin{cases} \phi_y \text{ correction, from segment angles} \\ r\phi \text{ correction, from segment positions} \\ \phi_z \text{ correction, from } \frac{\partial}{\partial y} \text{ positions} \end{cases}$$

χ'^2 can be minimized analytically by setting its derivative to zero

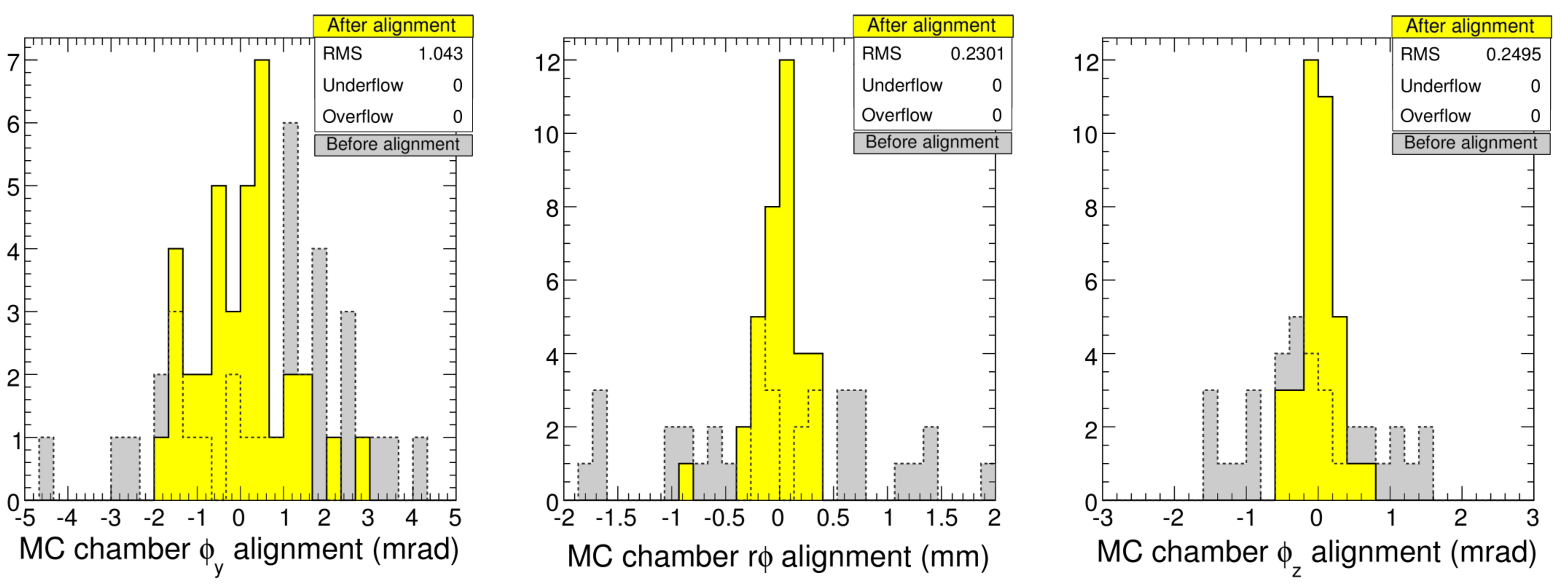
$$\frac{1}{2}\frac{\partial \chi'^2}{\partial \delta_i} = \left[\Delta\xi_{i-1,i} - (\delta_{i-1} - \delta_i)\right] - \left[\Delta\xi_{i,i+1} - (\delta_i - \delta_{i+1})\right] + \frac{1}{N^2} \sum_i^{\text{chambers}} \delta_i = 0$$

In matrix form, the equation above becomes

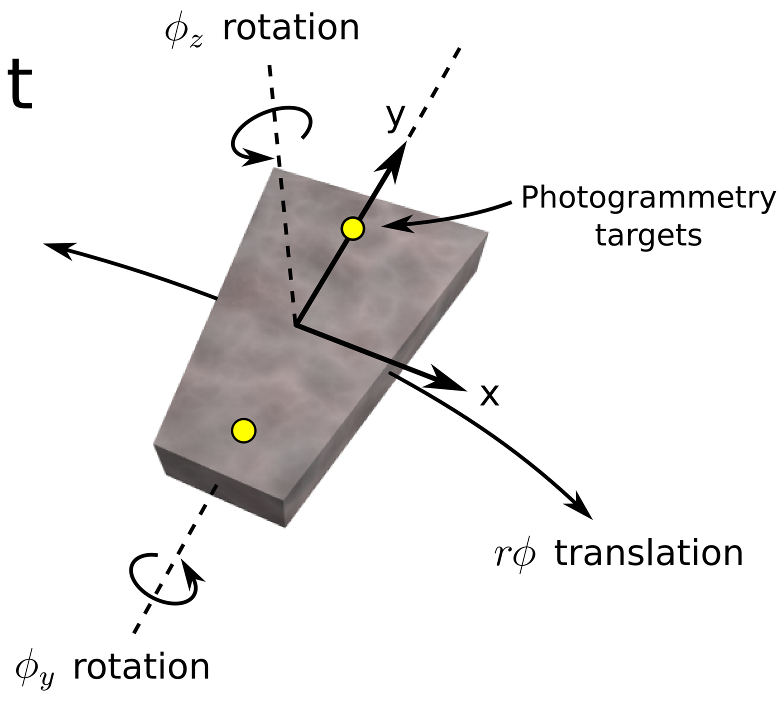
$$\begin{pmatrix} \Delta\xi_{1,2} - \Delta\xi_{N,1} \\ \Delta\xi_{2,3} - \Delta\xi_{1,2} \\ \vdots \\ \Delta\xi_{N-1,N} - \Delta\xi_{N-2,N-1} \\ \Delta\xi_{N,1} - \Delta\xi_{N-1,N} \end{pmatrix} = \left[\begin{pmatrix} 2 & -1 & & & -1 \\ -1 & 2 & -1 & & \\ & & \ddots & & \\ & & -1 & 2 & -1 \\ -1 & & & -1 & 2 \end{pmatrix} + \frac{1}{N^2} \begin{pmatrix} 1 & 1 & \cdots & 1 \\ 1 & 1 & & \\ \vdots & & \ddots & \\ 1 & & & 1 \end{pmatrix} \right] = \begin{pmatrix} \delta_1 \\ \delta_2 \\ \vdots \\ \delta_{N-1} \\ \delta_N \end{pmatrix}$$

The alignment corrections δ_i are determined from the residuals $\Delta\xi_{i,i+1}$ by inverting a small matrix of constants (N = 18 or 36).

Monte Carlo results: differences between aligned and true parameter values



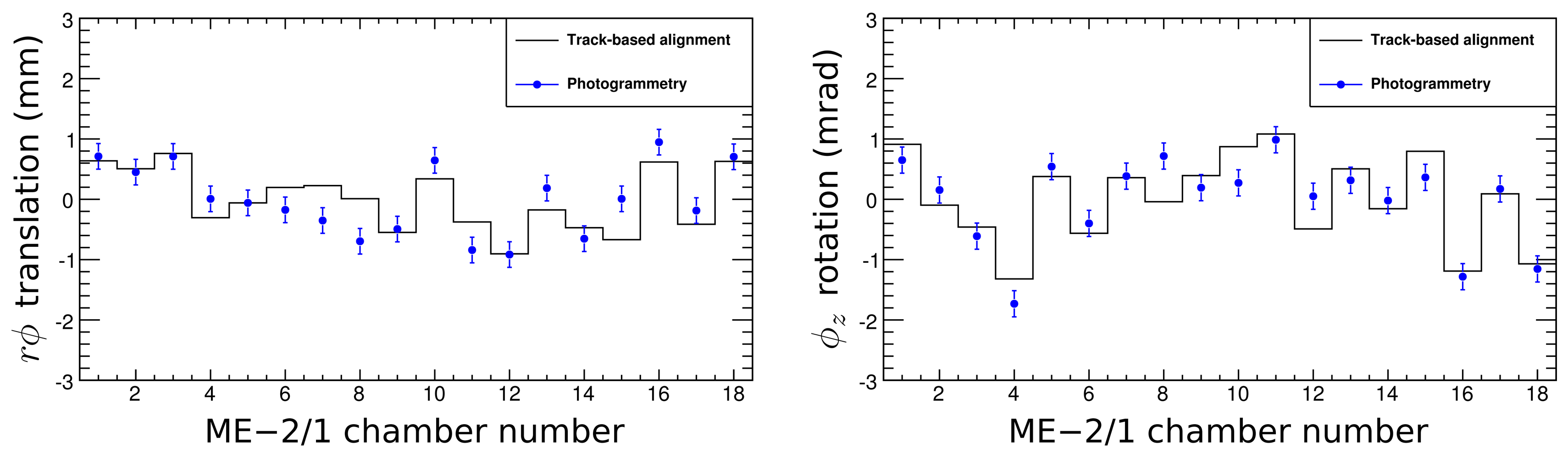
2008 beam-halo alignment



9 minutes of data: 33k overlaps
(primarily ME−2/1 and ME−3/1)

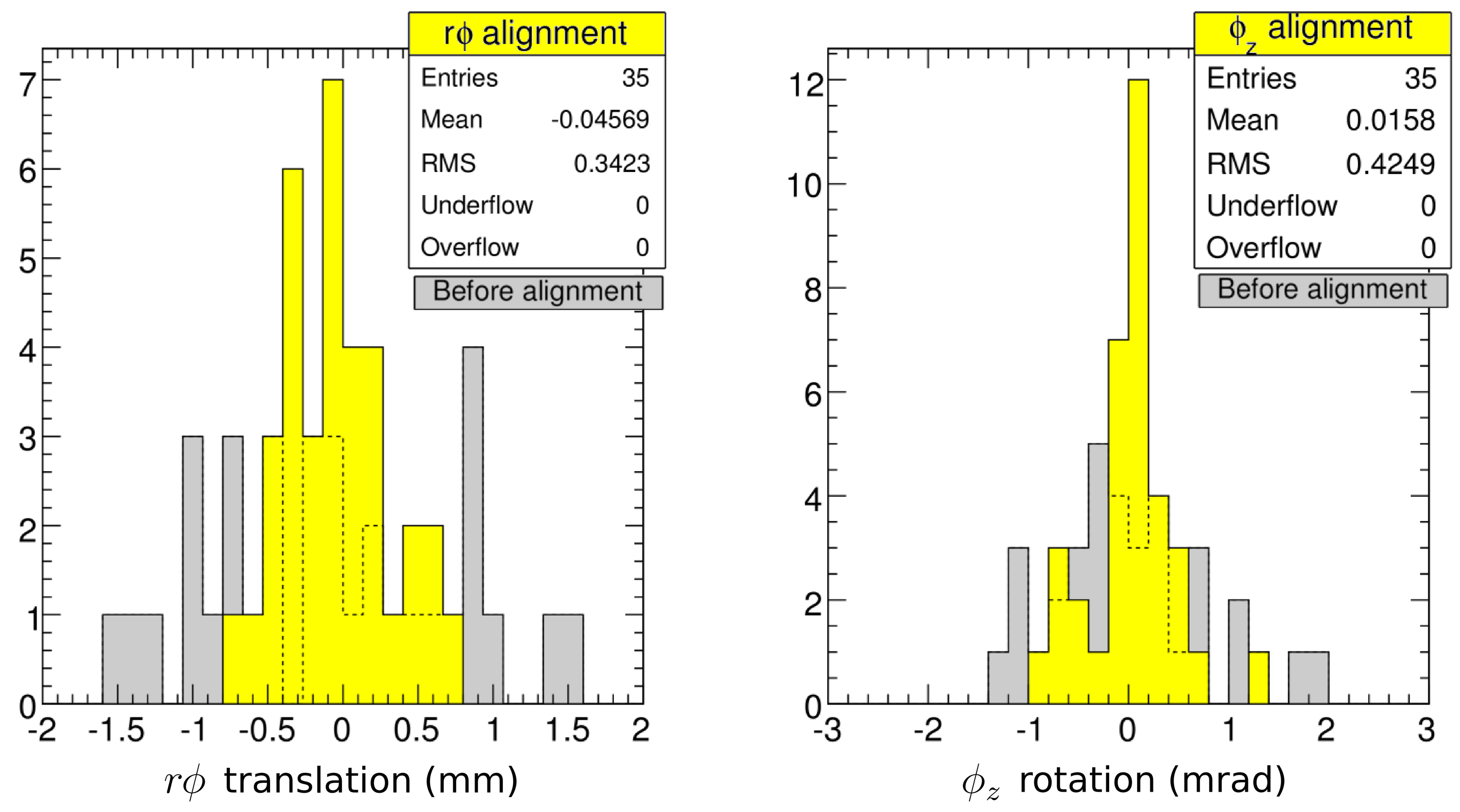
Comparison of results with photogrammetry, completely independent of beam-halo data

Alignment corrections from beam-halo and photogrammetry, relative to design, overlaid for each chamber in ME−2/1:



Alignment accuracy: differences between the two methods

Accounting for the 300 μm uncertainty in the photogrammetry,
beam-halo alignment accuracy in rϕ is 270 μm
in ϕ_z is 0.35 mrad



2009 beam-halo data

229 overlaps in runs 121964 and 122294

Inner ring off for safety
(primarily ME+1/2, +2/2, +3/2)

Very clean beams, confirmed by Beam Scintillation Counter

First look at outer ring:
residuals consistent with ~1 mm misalignments in design geometry