Alignment of the ZEUS Micro-Vertex Detector Using Cosmic Tracks

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X International Workshop on Advanced Computing and Analysis Techniques in Physics Research (ACAT05)
DESY, Zeuthen, May 22-27, 2005

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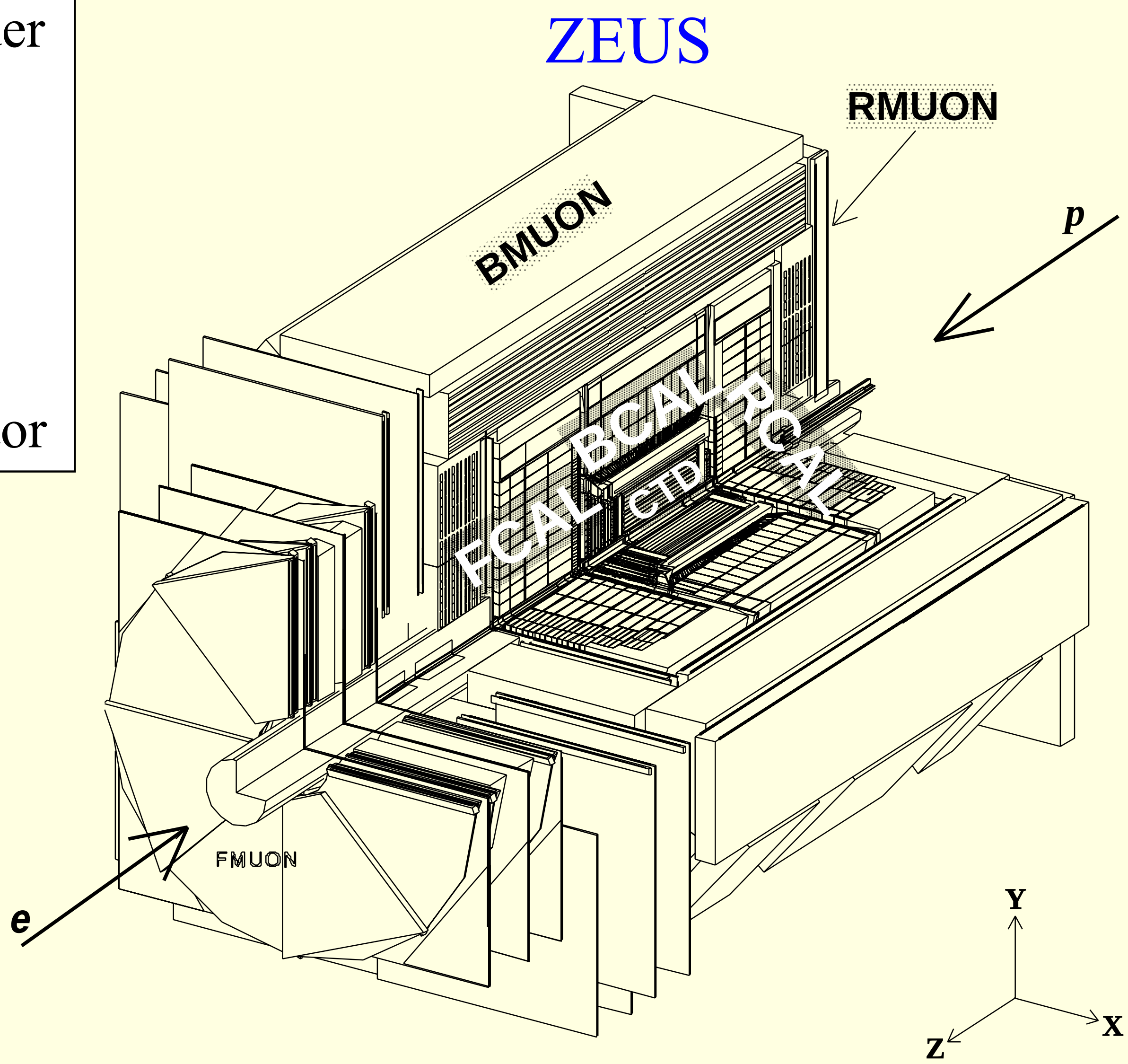
ZEUS experiment

HERA: Electron-proton collider at DESY, Hamburg.
E_p=920 GeV
E_e=27.5 GeV

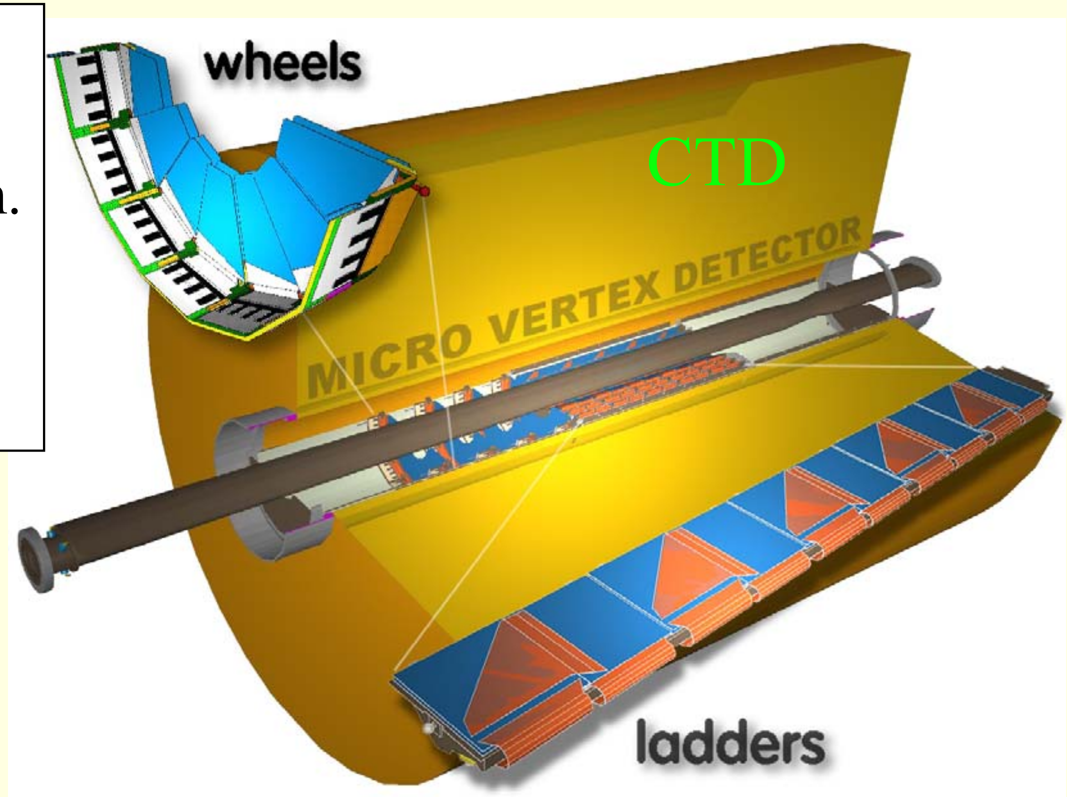
ZEUS detector:
Multi-purpose particle detector



HERA-II and ZEUS Upgrade

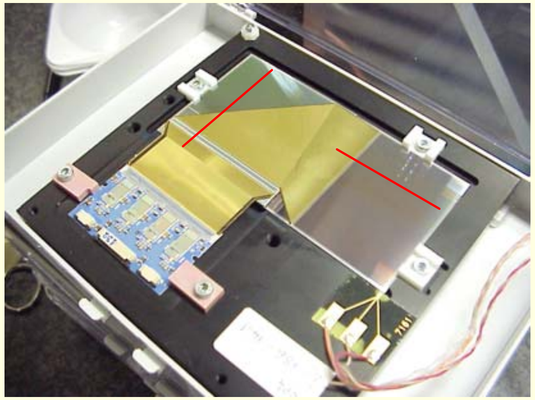
HERA upgrade
- Luminosity increase (× 5)
- Electron longitudinal polarization.

ZEUS detector upgrade
- Micro-Vertex Detector (MVD)



- Polarization depended charged current interaction.
- Improve the efficiency of tagging charm and beauty particles using their lifetime information.

ZEUS Micro-Vertex Detector (MVD)

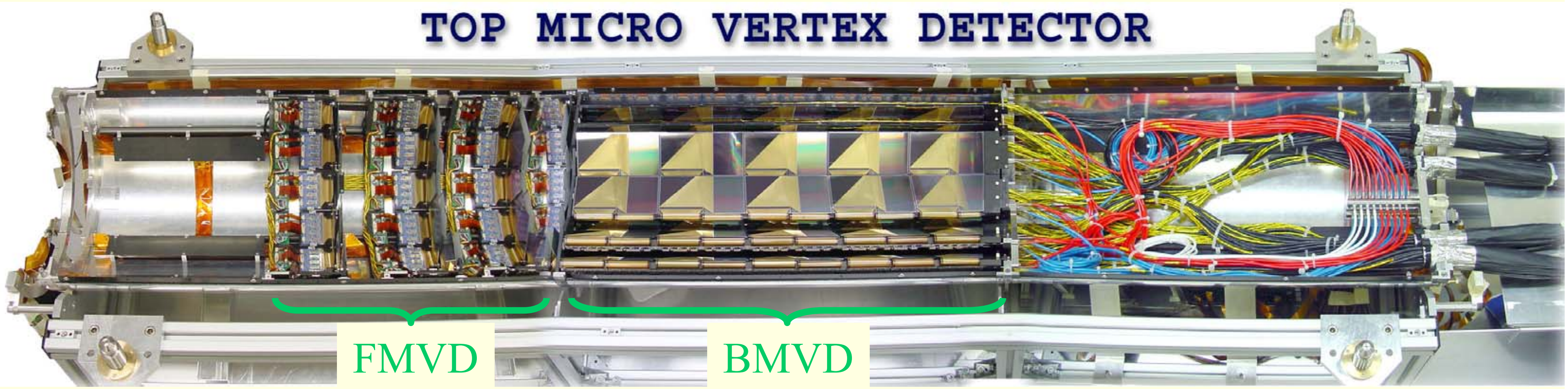


Single-sided Si strip sensor with
120 μm readout pitch
(intermediate strips : 20 μm)

<u>Motivation of installing the MVD</u>

- Precise tracking of charged particle near the interaction point.
- Reconstruction of secondary vertex from long-lived particles, like c- or b-hadrons.

Precise position measurement required!



Alignment of the MVD

Position measurement of the hit on a sensor ~ 20 μm.
Track reconstruction : fitting hits on various sensors with a helix.

Necessary to know real positions of sensors at high precision.

From the 3D survey during construction, we know
- positions of sensors on each ladder were measured to 5 μm during construction.

Most unknown factors
- relative positions of ladders
- position of the entire MVD wrt. ZEUS.

Knowledge of real positions of ladders.
→ Alignment

Goal : Alignment precision < 10 μm.

Alignment method

Basic strategy
Use particle tracks and
minimize the residuals between the hit and the track.

$$\chi^2 = \sum_{\text{all hits in all tracks}} \frac{\left|\vec{Q}' - \vec{P}'\right|^2}{\sigma_D^2} = \sum \frac{\left|\vec{D}'\right|^2}{\sigma_D^2} = \sum \frac{\left|(\vec{D}' - \vec{D}) + \vec{D}\right|^2}{\sigma_D^2}$$

$\vec{Q}'$: hit position

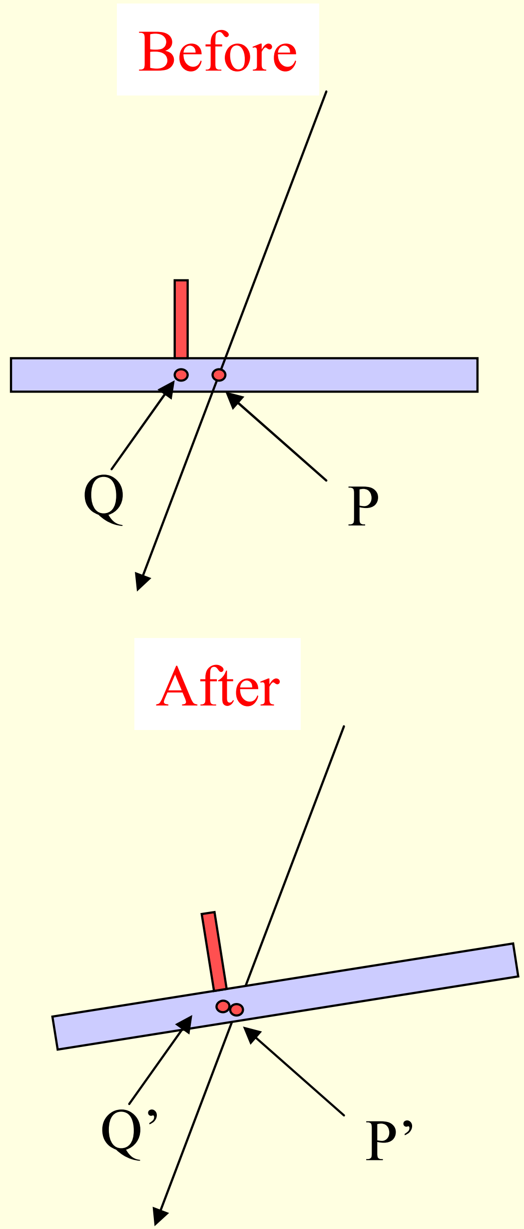
$\vec{P}'$: track intersection

' : for after movement

Measurable

Small → linearize wrt. alignment parameters : $\vec{X}$

$$\vec{D}' - \vec{D} = \vec{a}_x{}^T \vec{X}$$



χ^2 minization

$$\chi^2 = \sum \frac{\left|(D' - D) + D\right|^2}{\sigma^2}$$

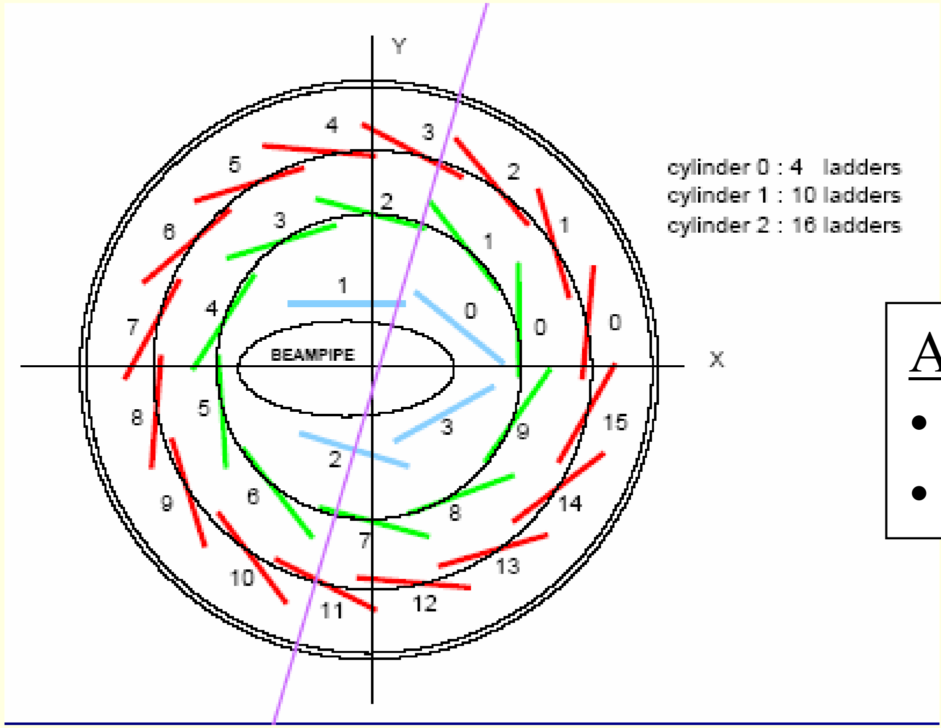
$$= \sum \frac{\left|\vec{a}^T \vec{X} + D\right|^2}{\sigma^2}$$

$$= \sum \frac{1}{\sigma^2}\left\{\vec{X}^T\left(\vec{a}\vec{a}^T\right)\vec{X} + 2\left(\vec{a}^T\vec{X}\right)D + D^2\right\}$$

$$\frac{\partial \chi^2}{\partial X^a} = 0 \quad \Rightarrow \quad \vec{X} = M^{-1}\vec{v}, \quad M = \sum \frac{\vec{a}\vec{a}^T}{\sigma^2}, \quad \vec{v} = \sum\left(-\frac{D\vec{a}}{\sigma^2}\right)$$

Alignment parameters : calculated by one 6 × 6 matrix inversion + matrix-vector product

Alignment using cosmic tracks



- 30 ladders in 3 layers
- 3 translation + 3 rotation degrees of freedom → 180 parameters

<u>Advantage</u>

- Tracks with many MVD hits.
- Less ambiguities in pattern recognition.

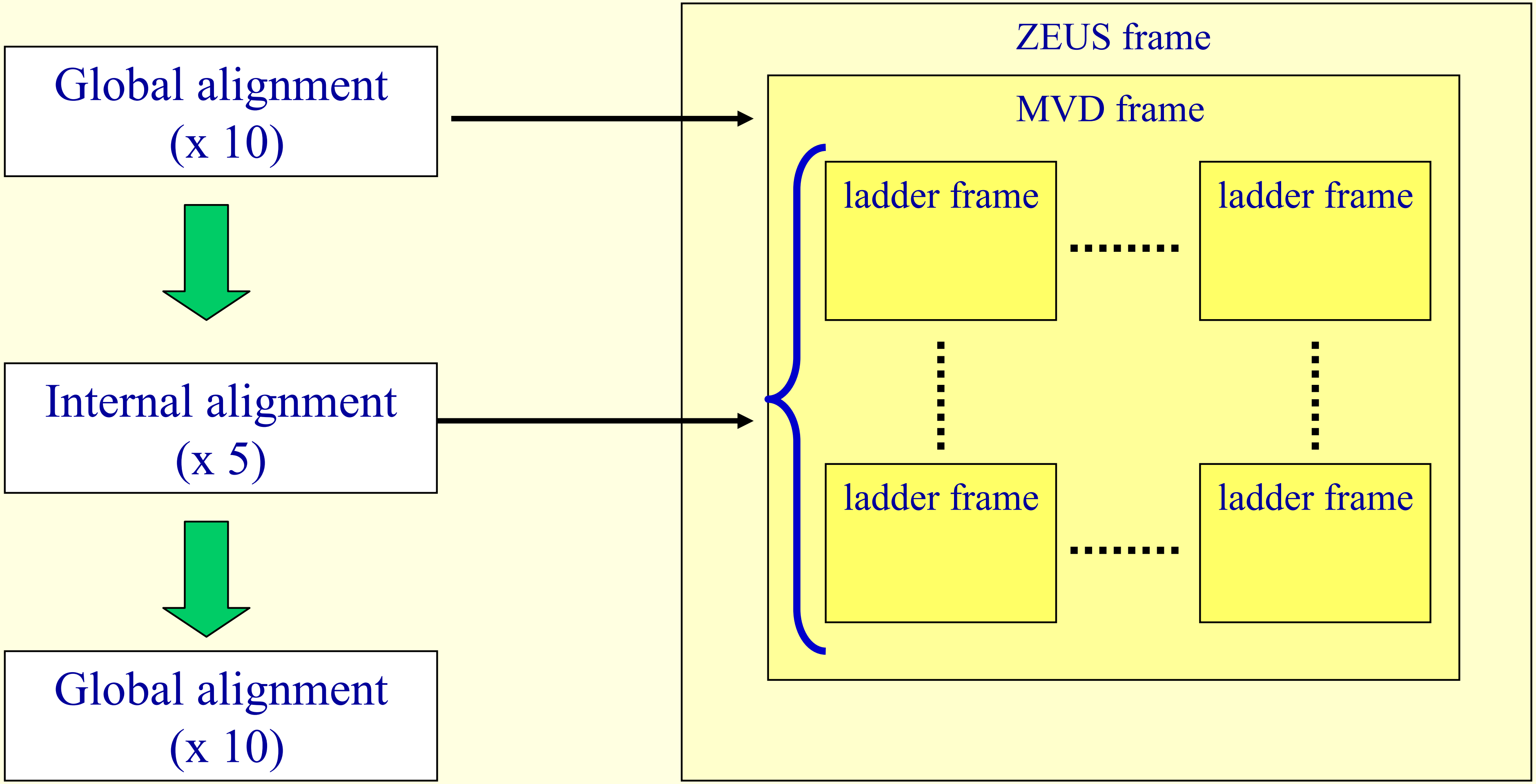
<u>Disadvantage</u>

- Non-uniform angular coverage.
- Only possible for the barrel MVD.
- Needs a special cosmic run.

Track sample (cosmic muons) :

- Rate ~ few Hz
- 1 week of dedicated cosmic runs → 60k cosmic tracks for the alignment.

Alignment procedure



Iteration is needed in each step due to,

1. the linear approximation used in the formula and
2. for the internal alignment, alignment of one ladder depends on the geometry of other ladders.

Global alignment

Extrapolate the CTD track into the MVD.
- residual information
- 3D position of the hit.

r-ϕ hit

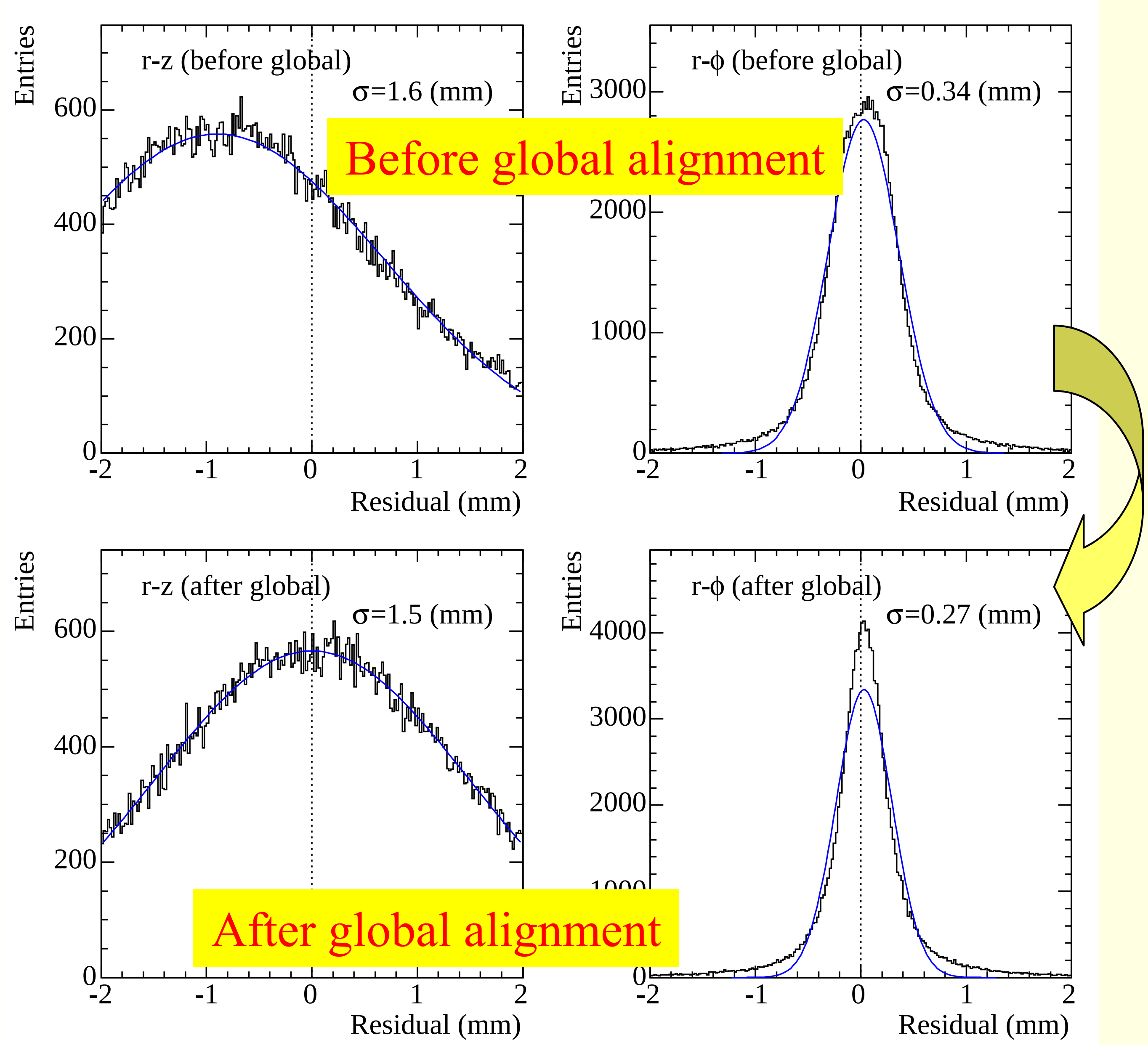
$$(D' - D)_i \approx \underbrace{\begin{pmatrix} 1 & 0 & 0 & 0 & Z & -Y \\ 0 & 1 & 0 & -Z & 0 & X \\ 0 & 0 & 1 & Y & -X & 0 \end{pmatrix}}_{\vec{a}_i^T} \underbrace{\begin{pmatrix} T_X \\ T_Y \\ T_Z \\ R_X \\ R_Y \\ R_Z \end{pmatrix}}_{\vec{X}}$$

r-z hit

$$\vec{X} = M^{-1}\vec{v},$$

$$M = \sum \frac{\vec{a}\vec{a}^T}{\sigma^2}, \quad \vec{v} = \sum \left(-\frac{D\vec{a}}{\sigma^2} \right)$$

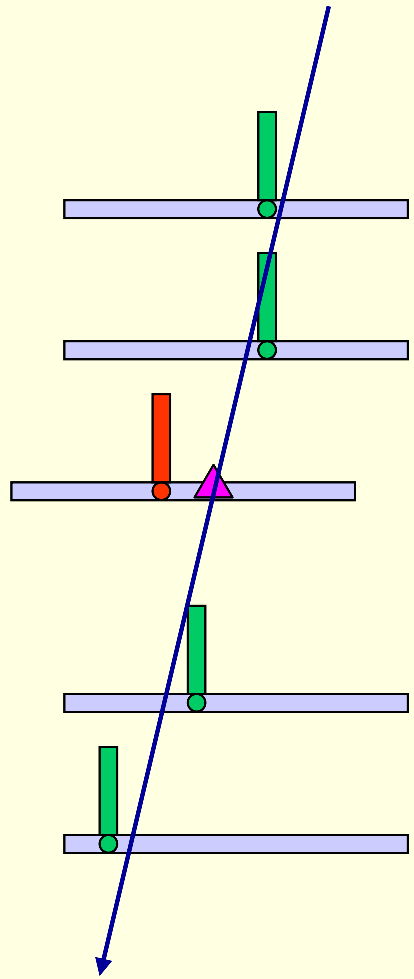
Effect on residual distributions.



- Residual centered
- Resolution by CTD

Internal alignment (among MVD ladders)

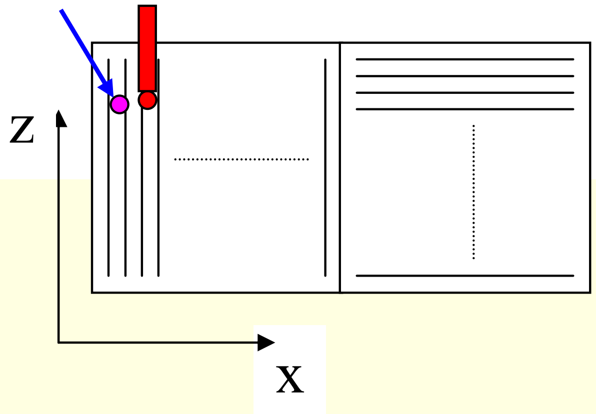
1. Define χ^2 for each ladder. (30 χ^2 with 6 DOF each)
2. Loop over all events
    1. Loop over all tracks in the event
        1. Loop over all hits in the track
            1. Find the ladder where the hit resides
            2. Exclude all hits in the ladder.
            3. Refit the track with all other hits.
            4. Calculate the intersection of the refitted track and the ladder.
            5. Calculate the residual between the hit and the intersection.
            6. Update the matrix (M) and the vector (V) using the track direction, intersection and the residual.
3. Once M and V are calculated using all hits/tracks, calculate the alignment parameters.



refitted track (no geometry of the ladder to be aligned)

Expression for internal alignment (X-measurement)

$$D'_x - D_x = \underbrace{\begin{pmatrix} 1 & -p_x/p_y & 0 & p_x/p_y \cdot z & z & -p_x/p_y \cdot z \end{pmatrix}}_{\vec{a}^T} \underbrace{\begin{pmatrix} T_X \\ T_Y \\ T_Z \\ R_X \\ R_Y \\ R_Z \end{pmatrix}}_{\vec{X}}$$



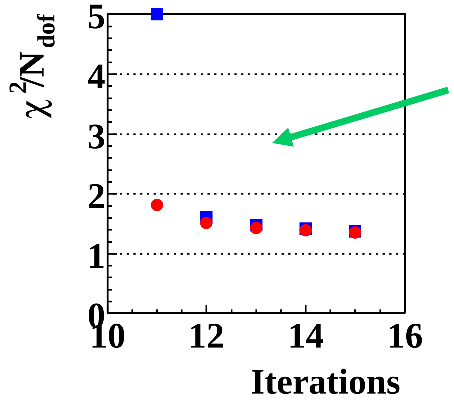
$$\vec{X} = M^{-1}\vec{v},$$

$$M = \sum \frac{\vec{a}\vec{a}^T}{\sigma^2}, \quad \vec{v} = \sum \left(-\frac{D\vec{a}}{\sigma^2} \right)$$

Ingredients for the χ^2 minimization

- the residual of the hit to the track with the starting geometry. → D
- the hit position on the sensor and
- the direction of the track at the intersection. } → $\vec{a}$

Convergence after iterations

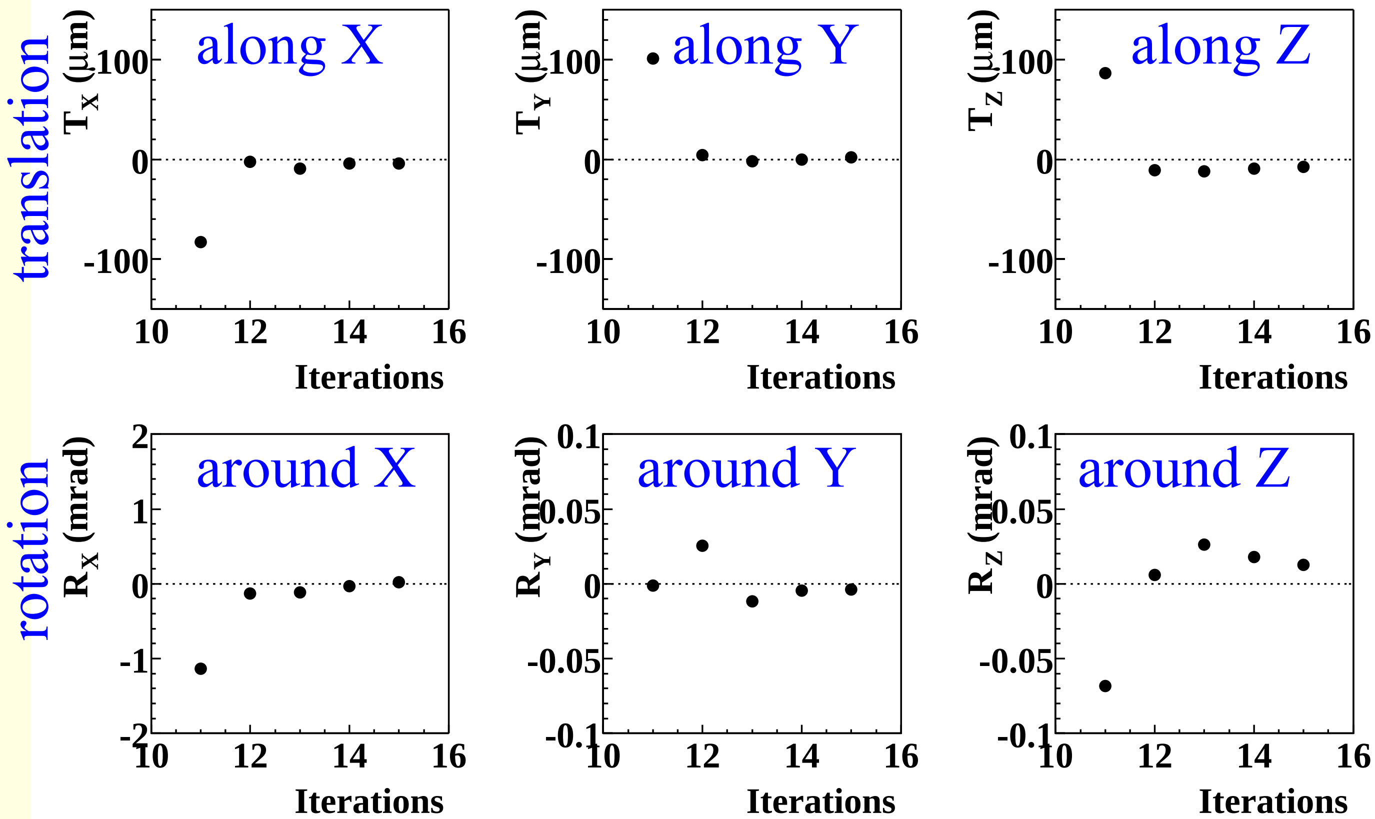


Improvement of χ^2 after each iteration (single ladder).

- ■ before
- ● after

(Similar convergences seen for all ladders)

Computation time : ~10 hours on a single CPU (Intel XEON 2.4 GHz)



Good convergence after a few iterations.

< 5 μm

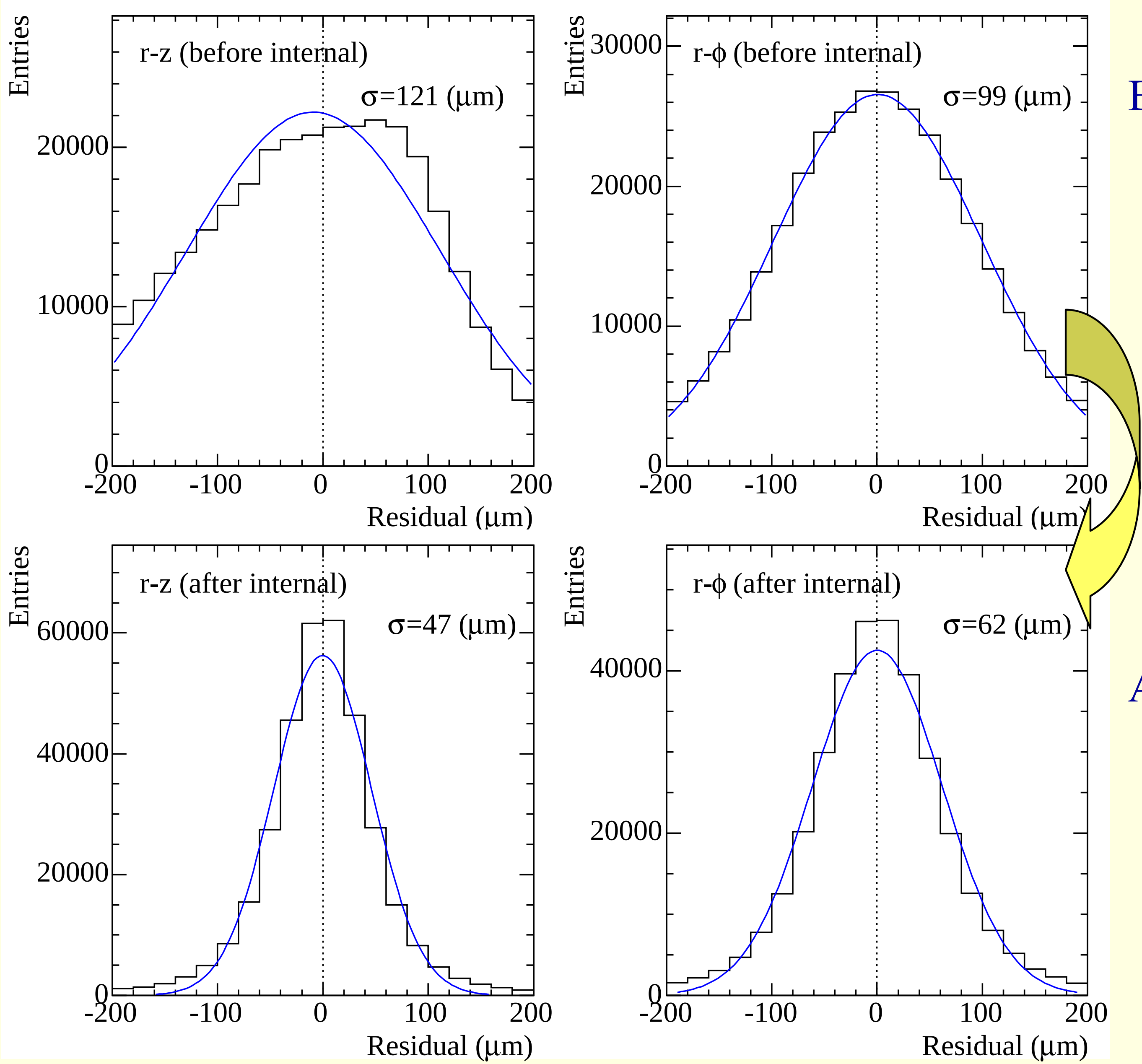
< 0.1 mrad

Size of the alignment

~< 100 μm

~< 1 mrad

Effect on residual distributions



Before internal alignment

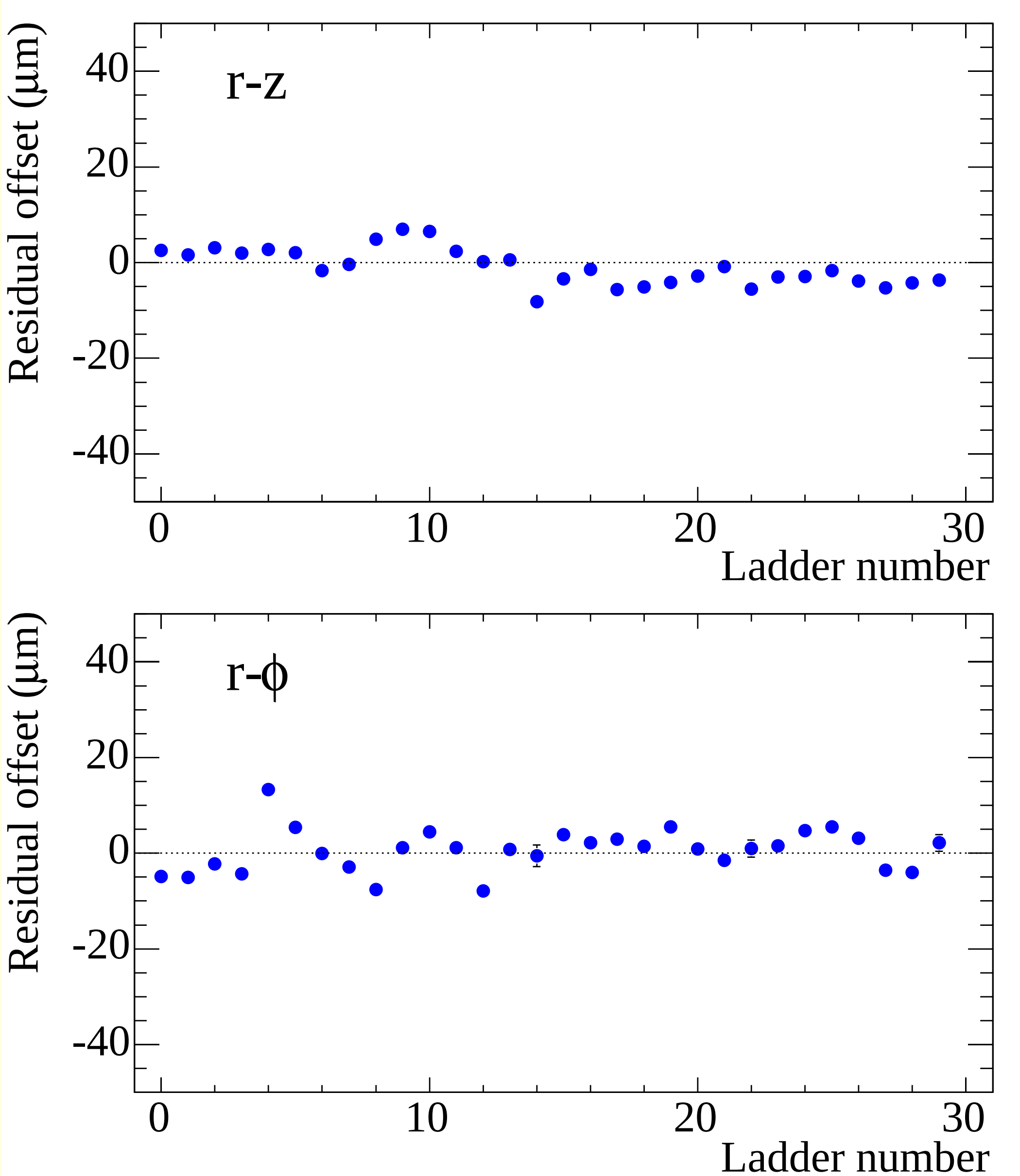
- Residual centered
- Width became narrow

After internal alignment

$$\sigma_{rz} = 47\ \mu\text{m}$$

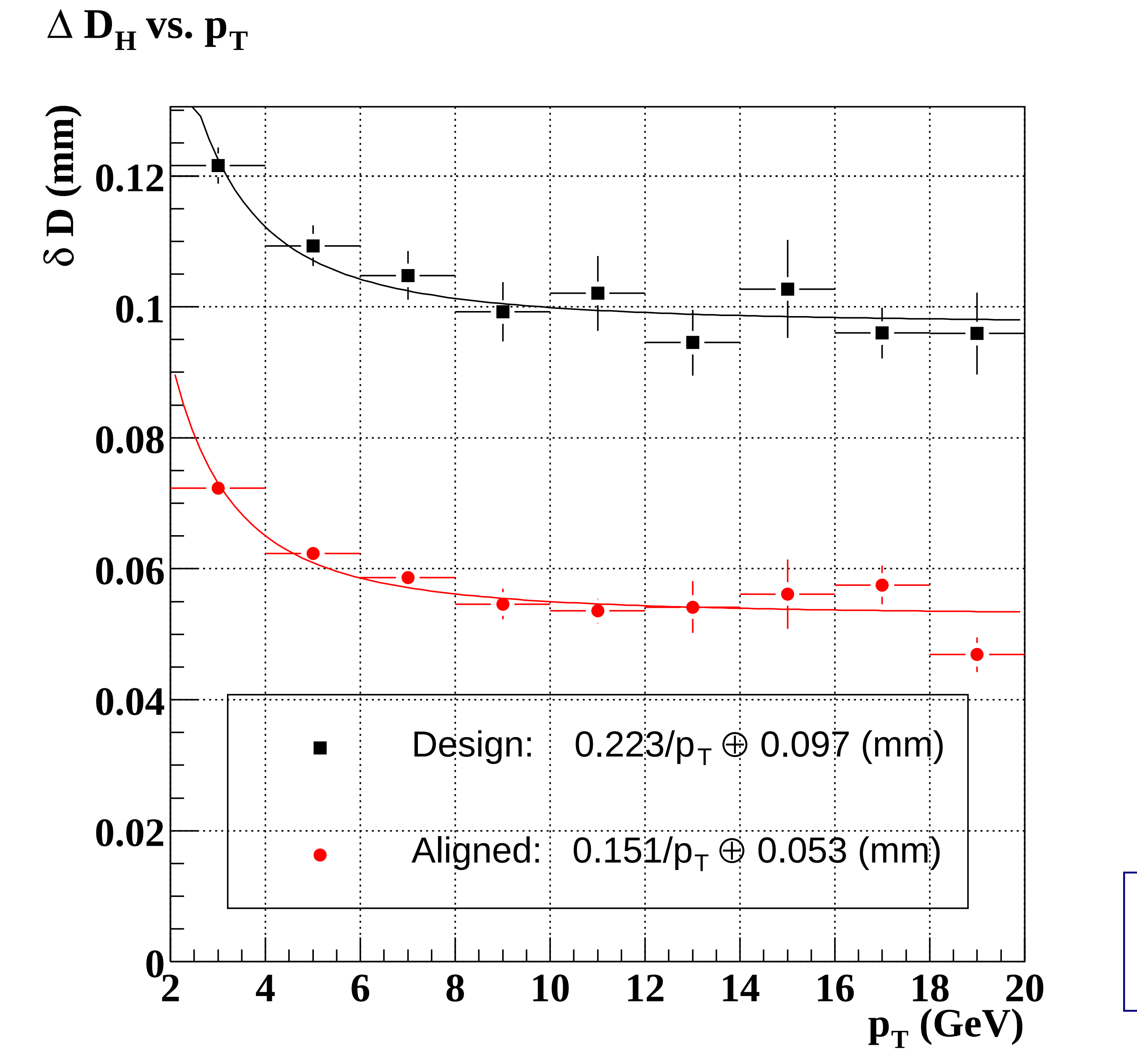
$$\sigma_{r\phi} = 62\ \mu\text{m}$$

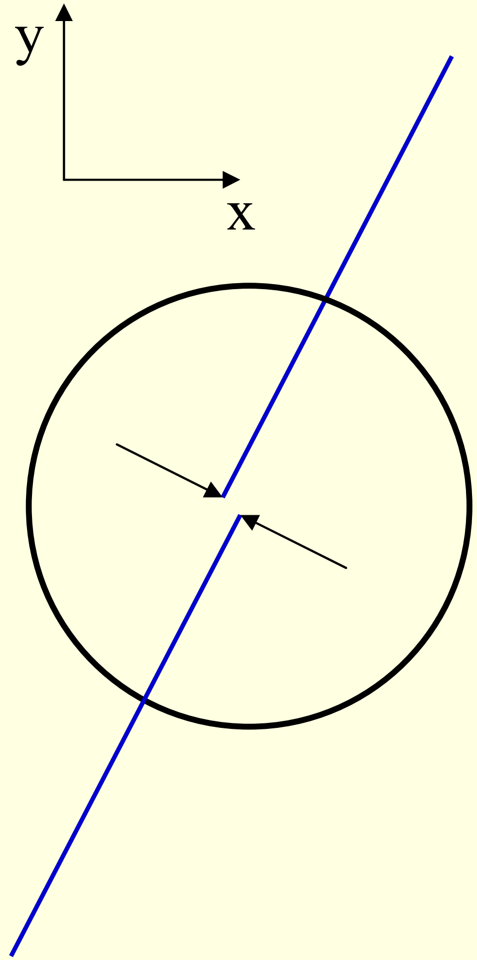
Residual offsets after alignemnt



- Residual offsets of centered around zero, within 10 μm.
- Both r-z and r-ϕ directions.

Effect on impact parameter resolution





Improvement

σ (D_H): 97 → 53 μm

Summary & Conclusion

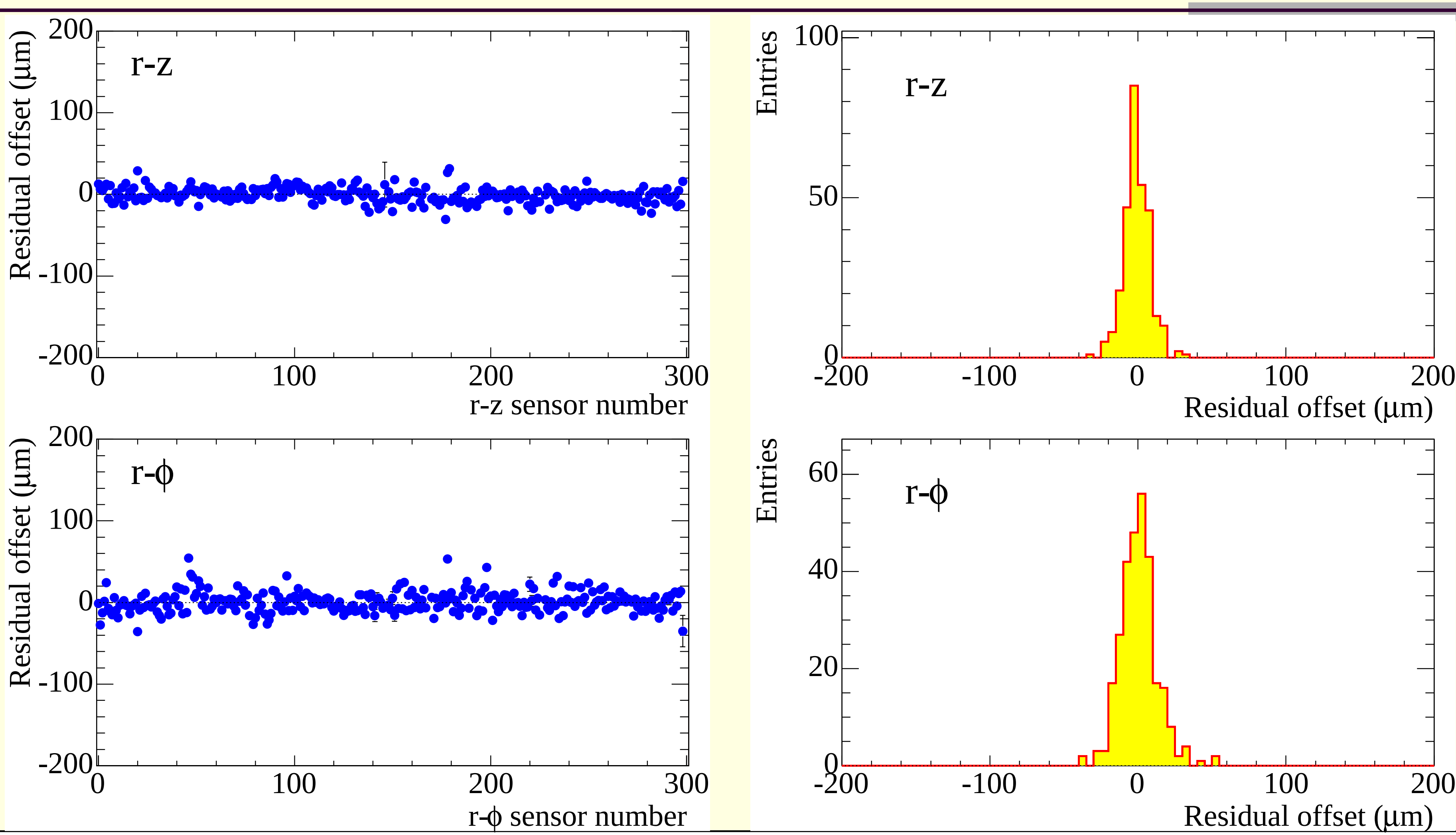
- Alignment of the ZEUS barrel MVD using cosmic tracks.
- Local χ^2 minimization with linear approximation.

- Good convergence observed after a few iterations to < 5 µm.
- Alignment precision estimated from the residual offset → <10 µm.

- Impact parameter resolution : 100 µm → 50 µm.

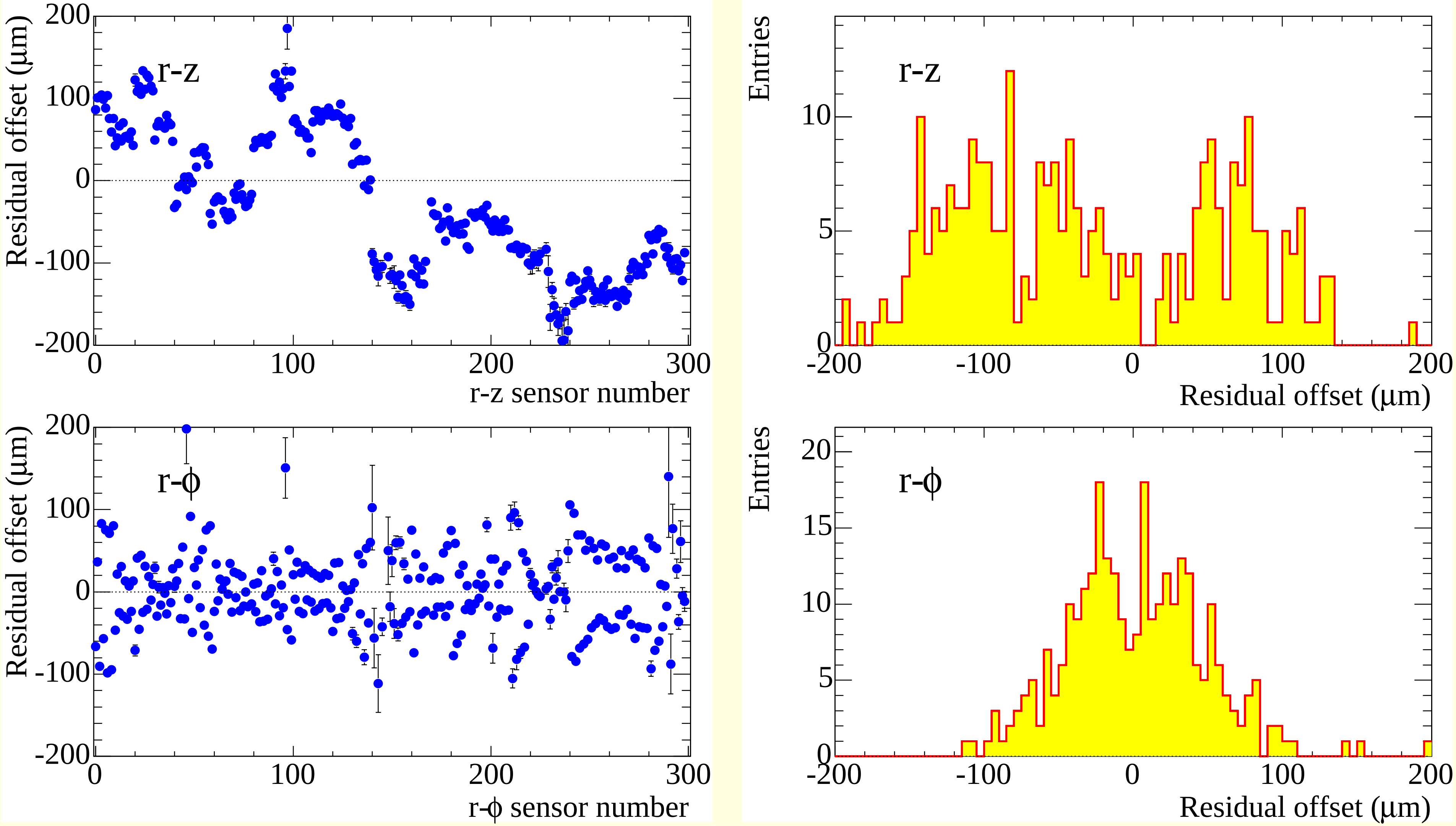
Backup slides

Residual offsets on individual sensors (after alignemnt)



- Residual offsets of centered around zero. (sensors with more than 50 hits)
- Offsets more spread around zero than in the whole ladder .(σ~10 μm)
    - Non-uniform distribution of hits in sensors. Some sensors not well constrained.
    - Residual mis-alignment of sensors in ladders.

Residual offsets on individual sensors (no alignemnt)



Before the internal alignment, residuals not centered at zero.
Sensors scattered around within ±100 μm especially for r-z sensors.