

Alignment of the ATLAS Muon Spectrometer with Tracks

Oliver Kortner

Max-Planck-Institut für Physik

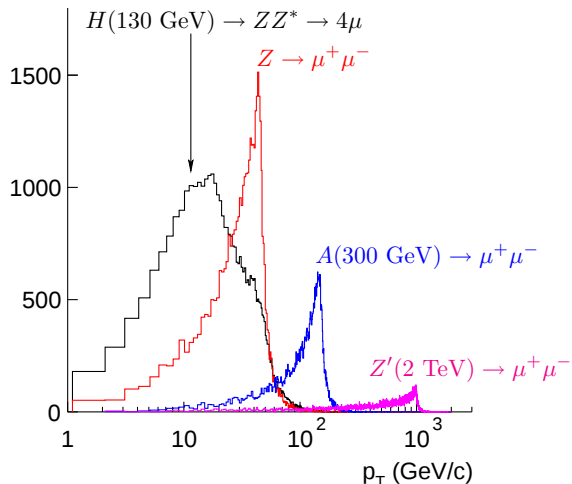
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- 1 Role of muons at the LHC
- 2 Muon identification with the ATLAS muon spectrometer
- 3 Alignment of the ATLAS muon spectrometer with optical sensors
- 4 Alignment of the ATLAS muon spectrometer with tracks

Muons at the LHC

- Muons are the only charged primary collision products traversing the calorimeters.
- Clean signature of muonic final states.
- Example physics processes with muonic final states:
 - $H \rightarrow ZZ^* \rightarrow \mu\mu\ell\ell$,
 - $A \rightarrow \mu\mu$,
 - $Z' \rightarrow \mu\mu$.
- Good muon identification and reconstruction is crucial for physics at the LHC.

Characteristic muon momentum spectra



Need for efficient muon detection and identification over a wide momentum range!

Muon identification with the ATLAS muon spectrometer

Basics of the muon momentum measurement

- As for other charged particles, muon momenta are determined from their deflection in a magnetic field.
- Contrary to electrons muons do not significantly lose energy by emission of synchrotron radiation.

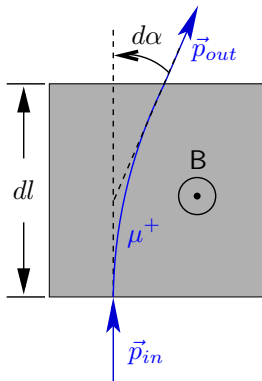
Explanation:

Power P of emitted synchrotron radiation $\propto (\text{acceleration of the charged particle})^2 \propto \frac{1}{m^2}$.

$$\Rightarrow \left(\frac{P_\mu}{P_e} \right)^2 = \left(\frac{m_e}{m_\mu} \right)^2 = \left(\frac{0.5 \text{ MeV}}{100 \text{ MeV}} \right)^2 \sim 10^{-5}.$$

Deflection of a muon in a magnetic field

Infinitesimal path dl , $B = \text{const}$ along dl , $\vec{B} \perp \mu\text{on path}$.



$$|\vec{p}_{in}| = |\vec{p}_{out}| =: p$$

$$d\alpha = \frac{|\vec{p}_{out} - \vec{p}_{in}|}{p} = \frac{F \cdot dt}{p} = \frac{qvBdt}{p} = \frac{q}{p} B dl.$$

Macroscopic path, B non-uniform, $\vec{B} \perp \mu\text{on path}$.

$$\text{Deflection angle } \alpha = \int_{\mu \text{ path } \mathcal{P}} B dl = \frac{q}{p} \int_{\mathcal{P}} B dl.$$

$$\Rightarrow p = \frac{q}{\alpha} \int_{\mathcal{P}} B dl \Rightarrow \frac{\delta p}{p} = \frac{\delta \alpha}{\alpha} = \frac{p}{q \int_{\mathcal{P}} B dl} \delta \alpha.$$

1. Spatial resolution of the muon detectors

The spatial resolution of the muon detectors determines the angular resolution σ_α , hence the contribution of the spatial resolution of the detector to the muon momentum resolution.

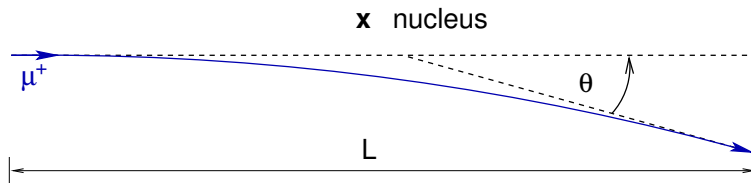
ATLAS muon spectrometer:

$$\left. \begin{array}{l} \int_{\mathcal{P}} B \, dl \approx 3 \, \text{Tm} \\ \sigma_\alpha \sim 10^{-4} \end{array} \right\} \quad \frac{\delta p}{p} \sim \frac{10^{-4}}{3 \, \text{Tm}} \cdot \frac{p}{q} \approx \frac{0.1\%}{\text{GeV}/c} \cdot p.$$

2. Multiple scattering

Multiple scattering of the muons on the nuclei of the detector material leads to an additional smearing of the measured deflection angle.

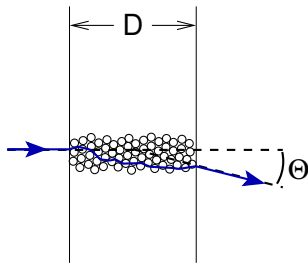
Scattering on a single nucleus



$$p = |\vec{p}_{in}| = |\vec{p}_{out}|,$$
$$\theta = \frac{\Delta p_T}{p} = \frac{\bar{F} \Delta t}{p} \approx \frac{\bar{F} \cdot \frac{\Delta L}{c}}{p} \propto \frac{1}{p}.$$

Momentum resolution and its limitations

Scattering on a many nuclei in a thin layer of a certain material



$$\Theta = \sum_k \theta_k; \quad \theta_k : \text{single scattering angle.}$$

$$\text{Var } \Theta = \sum_k \text{Var } \theta_k = N \cdot \text{Var } \theta \propto \frac{D}{p^2};$$

N : number of nuclei along the muon path $\propto D$.

$$\Rightarrow \sigma_\Theta = \sqrt{\text{Var } \Theta} \propto \frac{\sqrt{D}}{p}.$$

A more detailed calculation leads to

$$\sigma_\Theta = \frac{13.6 \text{ MeV}}{\beta c p} \sqrt{\frac{D}{X_0}};$$

X_0 : radiation length of the material. $\beta c \approx 1$.

Impact of multiple scattering on the momentum resolution

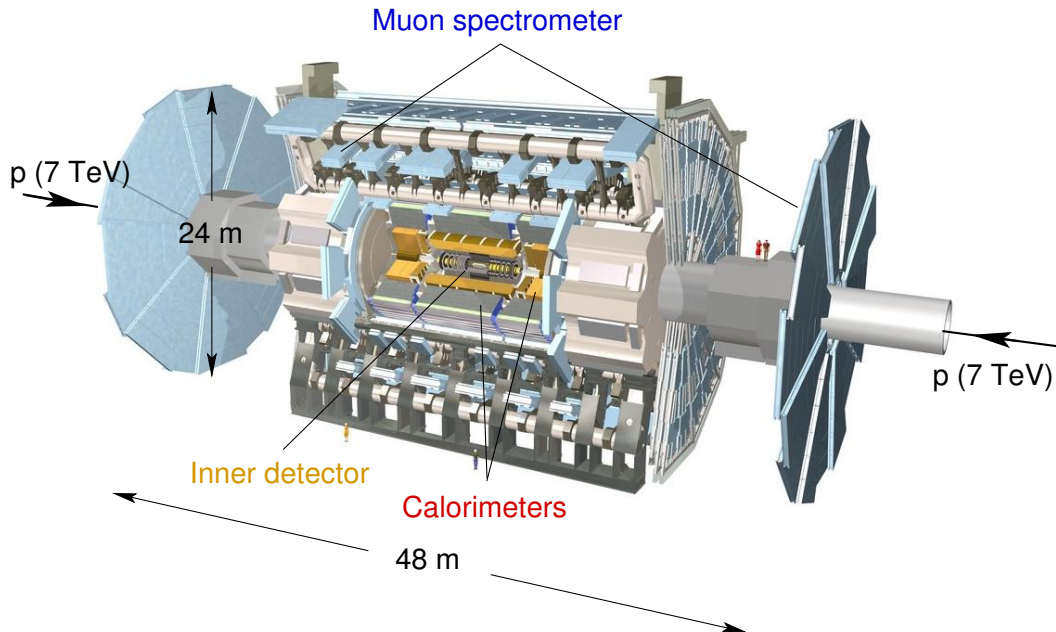
$$\left. \frac{\delta p}{p} \right|_{mult.scatt.} = \frac{\sigma_{\Theta}}{\int_{\mathcal{P}} B, dl} \cdot \frac{p}{q} = \frac{13.6 \text{ MeV}/c}{\int_{\mathcal{P}} B dl} \sqrt{\frac{D}{X_0}} q, \text{ independent of } p!$$

→ The achievable maximum momentum resolution is given by $\frac{\sqrt{D/X_0}}{\int_{\mathcal{P}} B dl}$, i.e. the ratio of the material along the muon trajectory and the field integral.

ATLAS muon spectrometer

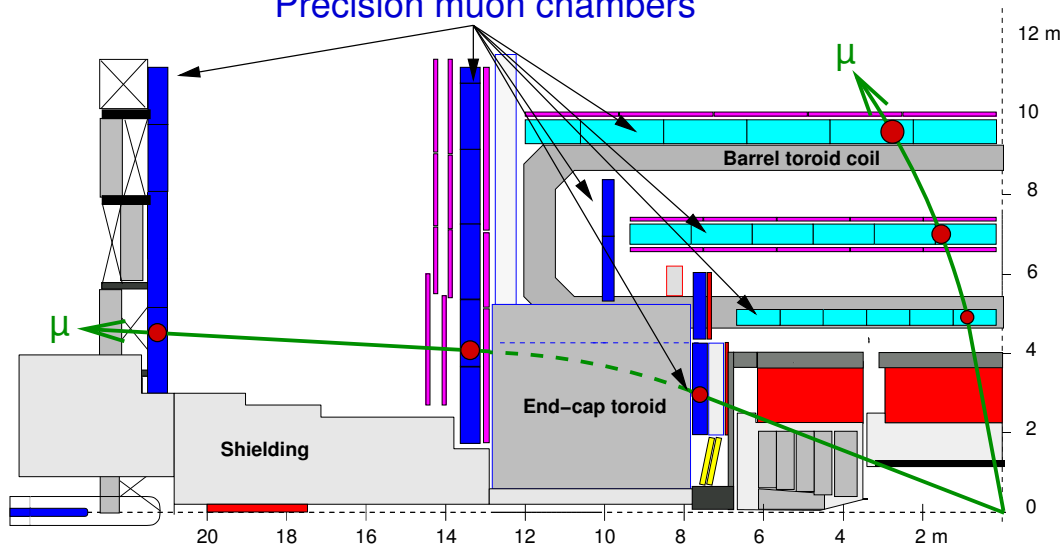
$$\frac{D}{X_0} \approx 1 \Rightarrow \left. \frac{\delta p}{p} \right|_{mult.scatt.} \approx 2\%$$

The ATLAS detector



The ATLAS muon spectrometer

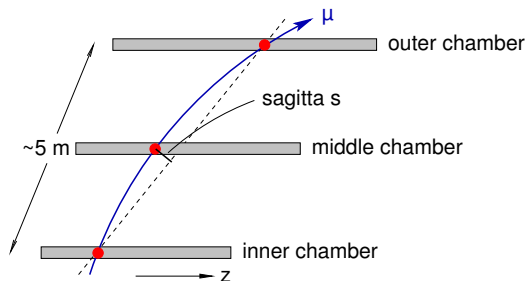
Precision muon chambers



★ Goal: Accurate momentum reconstruction up to $p_T=1$ TeV/c.

- Air core toroid magnet to minimize multiple scattering: 2.5-7 Tm.
- 3 layers of drift-tube chambers for accurate position measurement.

Chamber alignment requirements



$$s \approx 500 \mu\text{m} \frac{\text{TeV}}{p_T}.$$

$$\left. \frac{\delta p_T}{p_T} \right|_{p=1 \text{ TeV}} = \frac{\delta s}{s} = 10\% \leftrightarrow \delta s = 50 \mu\text{m}.$$

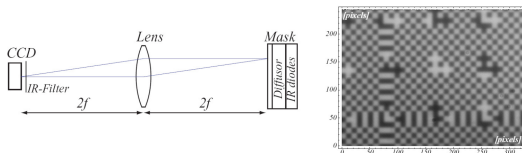
• Spatial resolution of the muon chambers: $35 \mu\text{m}$. $\Rightarrow \delta s = 40 \mu\text{m}$.

$\Rightarrow \delta s = 50 \mu\text{m}$ requires **$30 \mu\text{m}$ chamber alignment accuracy** in sagitta direction.

Optical alignment system for the muon spectrometer

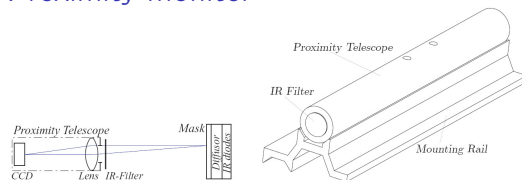
Optical alignment sensors

RASNIK straightness monitor



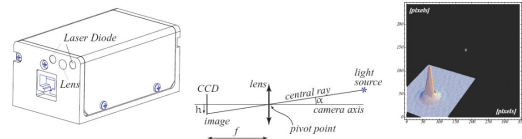
- 3-point imaging system.
- Accuracy of $1 \mu\text{m}$ in transverse plane.
- Operational distance is limited by air turbulence along the optical path ($\sim\text{m}$).

Proximity monitor



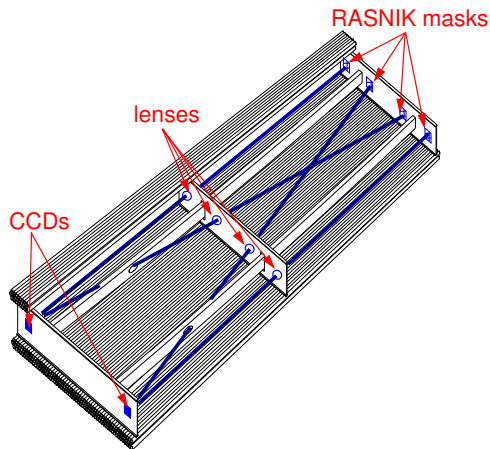
- RASNIK based with CCD and lens combined in one unit.
- Accuracy of $1 \mu\text{m}$ in transverse plane.

BCAM angle monitor



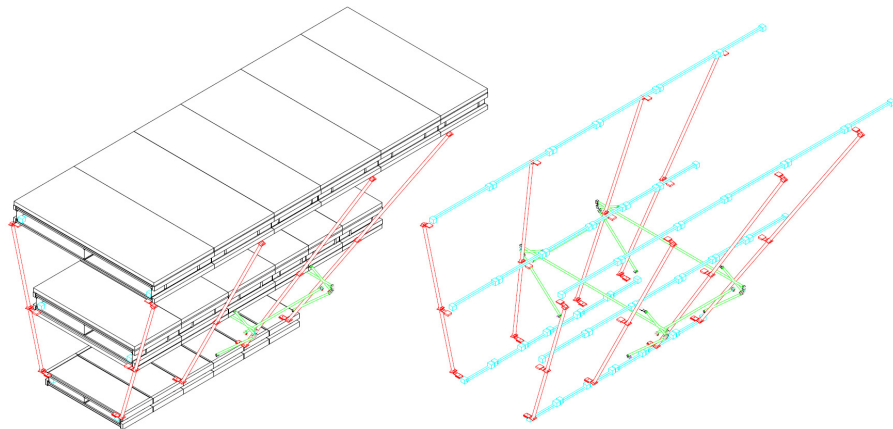
- Angular resolution $5 \mu\text{m}$ over a dynamic range of 40 mrad .
- Needs two light sources to measure axial displacements.
- Works over any distance.

Chamber internal alignment system



- Inplane system monitors deformations of the muon chambers.
- Based on 4 RASNIK sensors.
- Calibrated during chamber assembly.
- Precision: $\sim 10 \mu\text{m}$.

The barrel optical alignment monitoring system

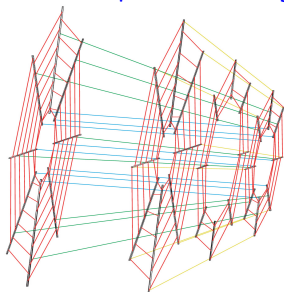


4 systems

- **Projective:** Measurement of chamber movements in sagitta direction.
- **Axial/praxial:** Measurement of the aplanarity of layers of muon chambers.
- **Reference:** Measurement of coil movements and chamber positions with respect to the coils.
- **Chamber-to-chamber:** Measurement of movements of chambers without projective alignment.

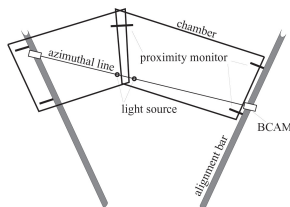
The end-cap alignment monitoring system

End-cap reference grid



- Alignment bars (black) are instrumented with internal RASNIKS and temperature sensors for the determination of their shape.
- Polar bar-to-bar BCAM lines (green, blue and yellow) form a quasi-projective layout of light rays.
- Azimuthal bar-to-bar BCAM lines (red) control relative positions of bars within one layer of endcap muon stations.

End-cap chamber-to-bar alignment



- Pairs of adjacent small and large chambers form a logical unit.
- Two proximity sensors on ?bar-sides? of each chamber measure displacements with respect to alignment bars.
- Connection between a small and a large chamber maintained by one proximity sensor and one azimuthal BCAM pair (monitor of out-of-plane movements in the overlap region).

Alignment of the ATLAS muon spectrometer with tracks

Calibration of the optical alignment monitoring system

- Barrel

- Calibrated optical system.

→ Absolute alignment accuracy $\lesssim 100 \mu\text{m}$.

- $30 \mu\text{m}$ absolute alignment accuracy requires calibration with tracks.

- Barrel

- Absolute optical alignment $\sim 100 \mu\text{m}$ in most of the parts.

- Absolute optical alignment $> 500 \mu\text{m}$ in some areas where sensor mounting platform positions are not known with sufficient accuracy.

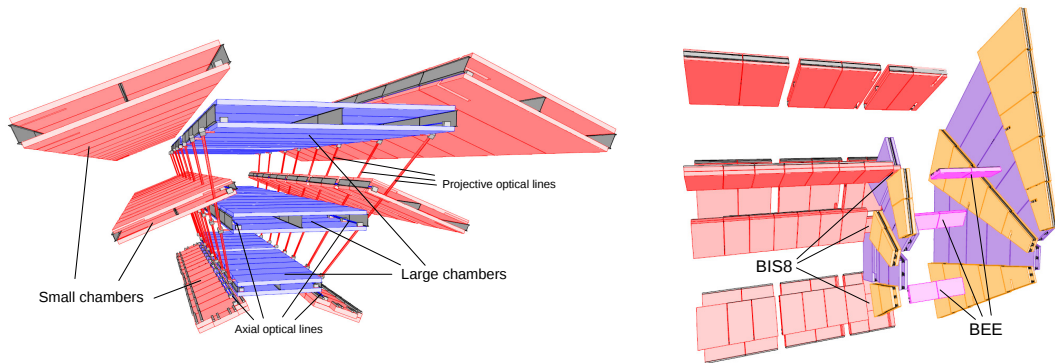
→ Alignment with straight tracks needed for $100 \mu\text{m}$ and $30 \mu\text{m}$ absolute alignment accuracy to be provided in a special run with no toroidal field.

Recurring track alignment tasks

- **Overlap alignment**

Alignment of barrel muon chambers with partial sets of optical sensors (small barrel, BEE, and BIS8 chambers).

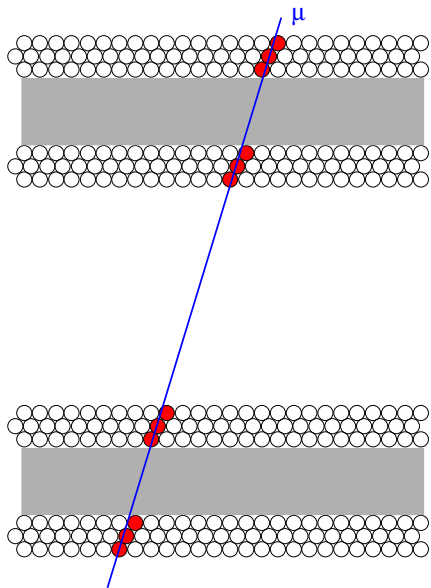
→ These chambers must be aligned with respect to optically aligned chambers using muon tracks in the overlap regions.



- **Barrel end-cap alignment**

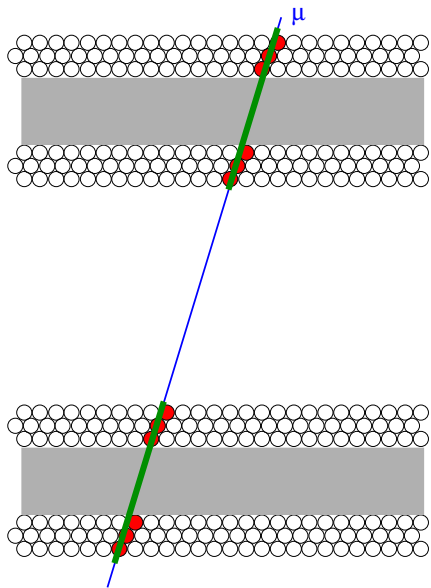
Alignment of the endcaps with respect to the barrel for the muon spectrometer.

Alignment of two chambers with straight tracks



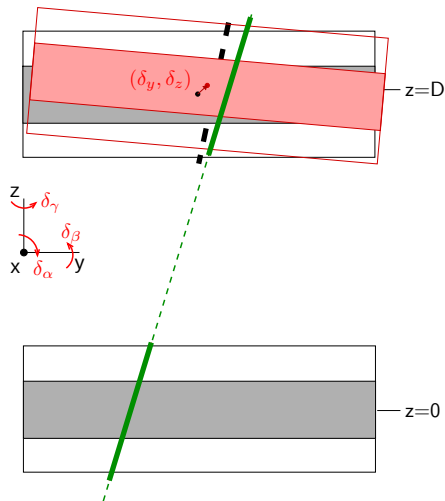
- Straight muon track through two chambers.

Alignment of two chambers with straight tracks



- Straight muon track through two chambers.
- Reconstruct track segments in both chambers.
- Use the track segments to determine the position and orientation of the upper chamber with respect to the lower chamber.

Alignment of two chambers with straight tracks



Reconstructed segments

- Upper chamber: $y = m_{up}z + b_{up}$.
- Lower chamber: $y = m_{down}z + b_{down}$.

Extrapolation of the lower segment upwards

$$\begin{aligned}
 y_{down}(D) - y_{up}(D) &= (m_{down} - m_{up}) \cdot D \\
 &\quad + b_{down} - b_{up} \\
 &\quad + m_{up}\delta_z + m_{up}x\delta_\beta.
 \end{aligned}$$

$$m_{down} - m_{up} = \delta_\alpha,$$

$$b_{down} - b_{up} = \delta_y + x\delta_\gamma.$$

- δ_α from difference of reconstructed slopes.
- δ_y, δ_γ : Plot $\Delta y(D)$ versus x . $\rightarrow$ Straight line with intercept δ_y and slope δ_γ .
- δ_z, δ_β : Measurement required angular spread of the tracks ($\text{Var}(m_{up}) > 0$).

Required statistics for the alignment of two chambers

- $m_{down} - m_{up} = \delta_\alpha$ for perfect angular resolution.
- $\langle m_{down} - m_{up} \rangle = \delta_\alpha$ for limited angular resolution $\sigma(m) \approx 4 \cdot 10^{-4}$.
- Required accuracy $\sigma(\delta_\alpha)$: $D\sigma(\delta_\alpha) \lesssim 30 \text{ } \mu\text{m} \Rightarrow \sigma(\delta_\alpha) < \frac{30 \text{ } \mu\text{m}}{D(\approx 5 \text{ m})} = 0.6 \cdot 10^{-5}$.
- Required number of tracks N : $\frac{\sigma(m)}{\sqrt{N}} \leq 0.6 \cdot 10^{-5} \Rightarrow N \geq 10^4$.

$\Rightarrow 12 \cdot 10^4 \sim 10^5$ straight muon tracks needed for the alignment of a sector.

Alignment of an entire sector

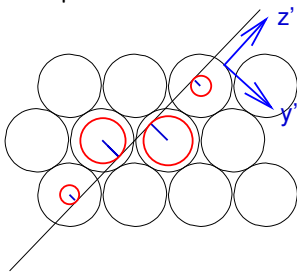
- The chamber positions and orientations are determined by minimizing the sum of the track χ^2 s in the chamber positions and orientations.
- Track χ^2 :

$$\sum_{hits\ h} \frac{[r(t_h) - d_h]^2}{\sigma_h^2};$$

$r(t_h)$: drift radius of the h th hit;

d_h : distance of the track from the wire of the h th hit tube.

- The Euclidian distance d_h is non-linear in the track and alignment parameters.



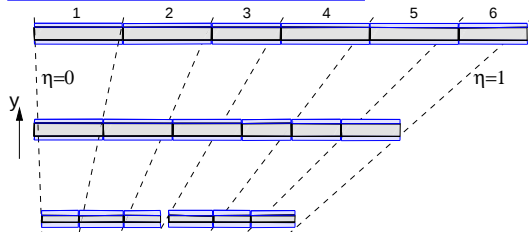
Linearization by change to track reference frame:

- $r(t_h) \rightarrow y'_h = \pm r(t_h)$.
- $d_h \rightarrow y'_h = \pm d_h$.

→ Analytic solution of the χ^2 minimization.

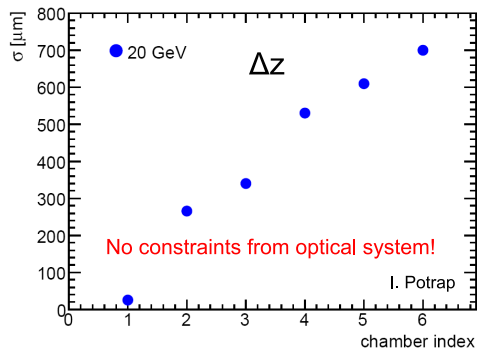
Monte-Carlo test of the straight-track alignment

Tower structure of a sector



- 100,000 straight muon tracks per barrel sector.
- $p_T = 20 \text{ GeV}/c$.

Measurement of horizontal chamber displacements

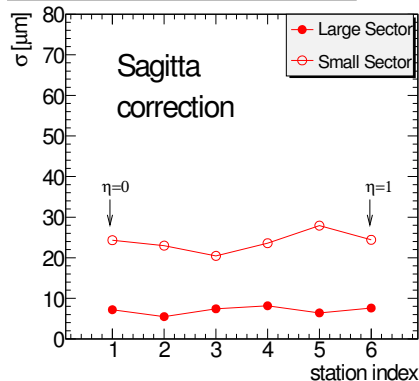


- Angular spread of projective tracks in tower overlaps too small $\Rightarrow$ system underconstrained.
- Constraints from optical axial system on the difference in height between two adjacent chambers solve the problem.

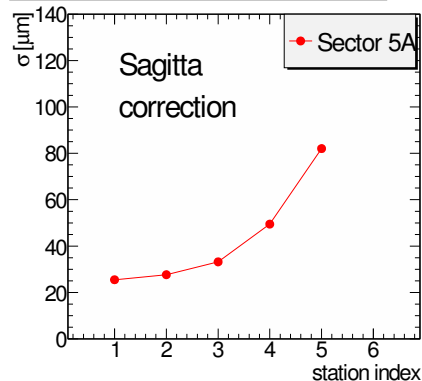
Performance of the straight-track alignment method

- Successful on MC data samples of 20 GeV projective straight muon tracks and on cosmics commissioning data.
- Accuracy of the alignment correction on the sagitta.

Monte-Carlo, pp collisions



Cosmic commissioning data



MC sample of $\sim 100,000$ projective tracks

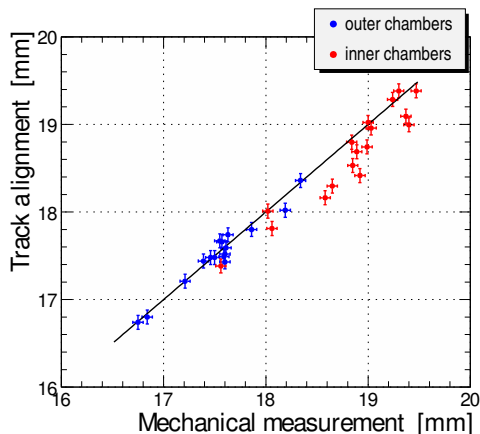
$\sim 400,000$ cosmic muon tracks

- Require statistics for 30 μm alignment accuracy:
 - 100,000 20 GeV projective tracks per barrel sector.
 - ~ 1 million cosmic tracks for top and bottom barrel sectors.

Comparison with mechanical measurements

Interchamber distances were measured for the inner and outer chambers of the top barrel sector.

Measured distances



Outer chambers

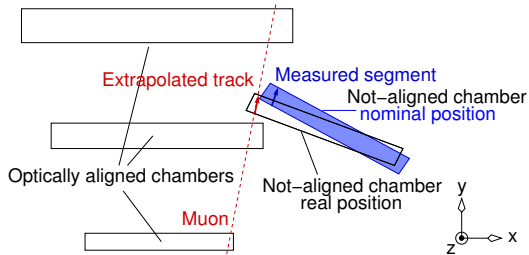
- Excellent agreement of track alignment and mechanical measurements.
- $\sigma(d_{tracks} - d_{mech.}) = 85 \mu\text{m}$.

Inner chambers

- Track alignment and mechanical measurements are correlated.
- $\langle d_{tracks} - d_{mech.} \rangle = -190 \mu\text{m}$ caused, most likely, by solid spacer between inner chambers deforming tubes (remeasurement planned).

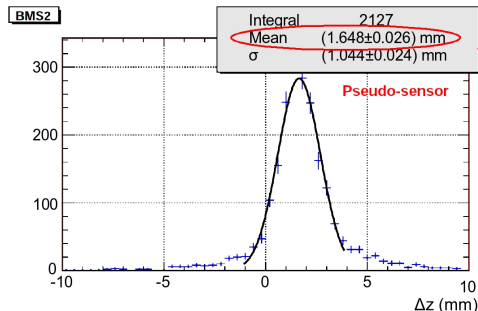


Alignment with overlap tracks



- Measurement of the muon momentum with the optically aligned part of the spectrometer.
- Extrapolation of the muon trajectory to the unaligned chambers in the overlap region.
- The results of the track alignment is provided to the optical alignment system as pseudo-sensor data.

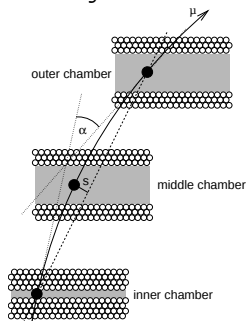
Results of a Monte-Carlo study



- Shifts of small chambers well monitored.
 - 10,000 20 GeV overlap tracks needed for 10 μm accuracy.
- A dedicate overlap muon stream at 200 Hz will be provided at the end of the muon trigger.

Sector alignment with curved tracks

- Alignment with curved tracks difficult due to limited redundancy in the muon momentum measurement.
- Redundancy in the momentum measurement



Barrel and end caps:

- Sagitta.
- Deflection angle.

Barrel

- Curvature of muon trajectory in the middle chambers for $p_T \lesssim 6$ GeV.

- Preliminary result of Monte-Carlo studies:
 - Momentum measurement in the middle chamber of limited use due to high sensitivity to distortions of the chamber geometry and the space drift-time relationship.
 - Alignment accuracy of $30 \mu\text{m}$ hard to achieve with curved tracks.
 - $100 \mu\text{m}$ alignment accuracy seems feasible, sufficient for monitoring the geometry.
- Studies ongoing.

- The chambers of the ATLAS muon spectrometer need to be aligned with $30\text{ }\mu\text{m}$ accuracy to provide 10% momentum resolution at 1 TeV.
- Relative movements of the muon chambers are monitored by optical alignment sensors with the required accuracy for most of the spectrometer.
- Gaps in the acceptance of the optical system have to be aligned with curved muon tracks with respect to optically aligned parts of the spectrometer.
- The absolute alignment of the chambers will be determined in a special run with no magnetic field at the start of ATLAS.
- The top and bottom of the barrel muon spectrometer are well illuminated with cosmic muons which are used to align these regions with the required accuracy.
- Curved alignment procedures to monitor the geometry during LHC operation are under development.