Track based alignment of the ATLAS Muon Spectrometer

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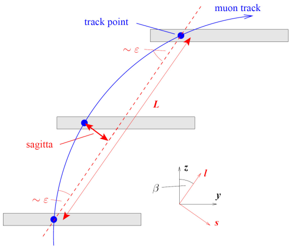
1. Overview of the ATLAS Muon Spectrometer alignment
2. Track based alignment of the muon chambers without projective optical sensors
3. Track based alignment of muon chambers within one sector using MILLEPEDE approach
4. Segment based alignment of muon chamber triplets with curved tracks
5. Conclusions and plans

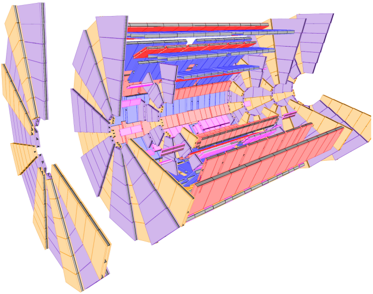
Overview of the ATLAS Muon Spectrometer alignment

- Design goal for muon reconstruction: $\delta p_t/p_t = 10\%$ for 1 TeV muons $\Rightarrow$ sagitta of 500 μm measured with 50 μm accuracy
- Muon chambers ($\sim$ 1200 in total) are high-precision objects by construction: sense wires are placed with 20 μm precision during chamber assembly
- Single muon chamber spatial resolution is $\sim$ 40μm $\Rightarrow$ muon chambers must be aligned to 30 μm accuracy in order to provide the required momentum resolution

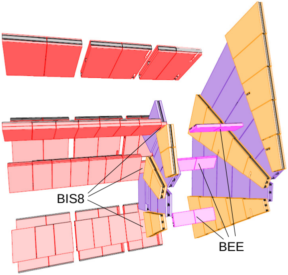


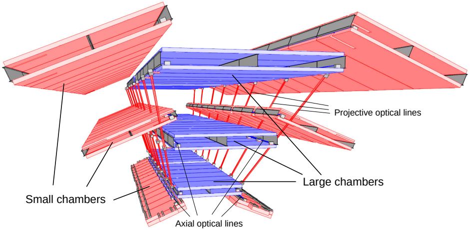
- In the first order, only the relative alignment of triplets of chambers (towers) traversed by the same muon track is important for momentum measurement
- This tower alignment is provided by the optical alignment system:
  - in the barrel region 3-point straightness monitors (RASNIKs) installed on the inner/middle/outer chambers form projective lines
  - in the endcap regions high precision reference rulers – alignment bars form alignment grid together with angular and proximity monitors installed on the chambers and bars (BCAMs and Proximity Telescopes)
- In addition to optical alignment, track based alignment is needed for the muon spectrometer in several alignment tasks. Some of these activities are being pursued by MPI MDT group
  - alignment of the muon chambers without projective optical sensors (overlap alignment)
  - MILLEPEDE approach to alignment of muon chambers within one sector
  - segment based stepwise alignment of muon chambers

Alignment of the muon chambers without projective optical sensors



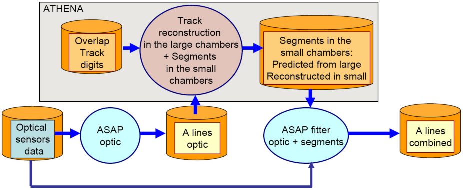
- Many muon chambers don't have all necessary optical sensors for their alignment
  - small barrel chambers
  - BEE chambers
  - BIS8 chambers
- Muon tracks in overlap regions must be used to align them
- Additional tasks for track based alignment
  - MS barrel to endcap alignment
  - Muon Spectrometer to Inner Tracker alignment

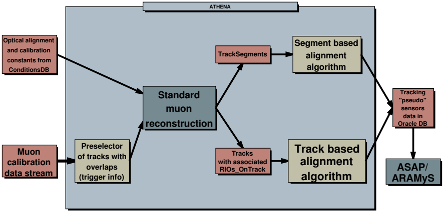




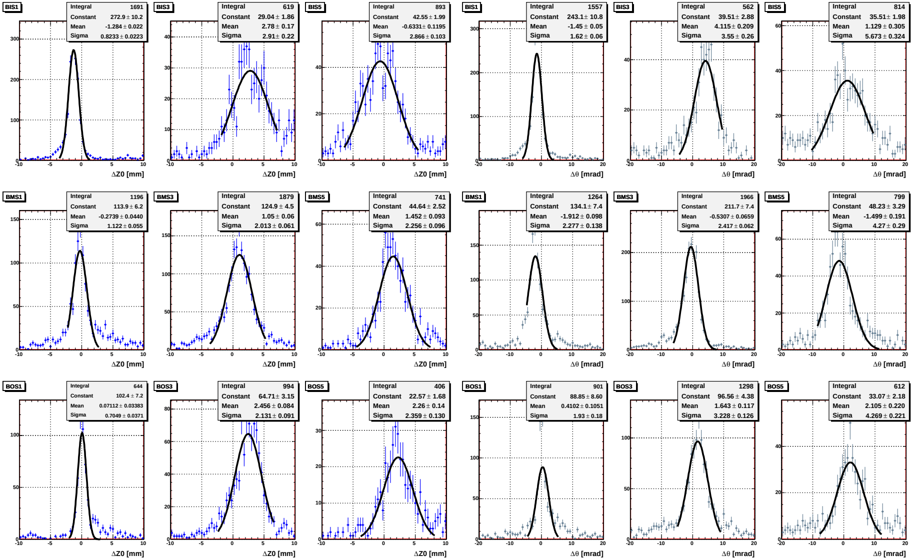
Combining optical and track based alignment

- In the first run of optical reconstruction (done in ATLAS pit) a partial set of alignment constants is calculated
- Standard muon reconstruction is run on a special data stream from muon LVL2 trigger at Munich Tier-2 center and pseudo-sensor data from reconstructed tracks is stored in the Conditions database
- Track pseudo-sensor data is the difference between the extrapolated “base” track parameters in a particular “not-aligned” chamber (BIS/BMS/BOS, BIS8, BEE) and the measured muon segment parameters in this chamber
- Full set of alignment constants is calculated in the second run of optical reconstruction software (ASAP/ARAMyS) combining optical sensors data and tracks pseudo-sensor data
- An algorithm for calculating track pseudo-sensor data is being developed by MPI MDT group
  - fully integrated within ATHENA framework
  - based on the common tracking EDM (uses its data objects and tools)
  - runs on the standard muon reconstruction track output (Mounboy or MOORe)
  - suitable for all track based alignment tasks

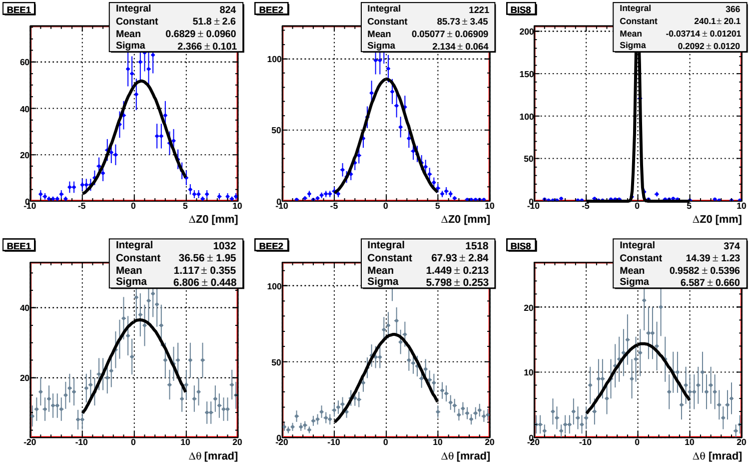




Track pseudo sensors: Small-to-Large in Sector2, precision coordinate Δz, $\Delta\theta$



Track pseudo sensors: BEE, BIS8 in Sector4, precision coordinate Δz, $\Delta\theta$



Performance of the algorithm for overlap alignment

- The algorithm for overlap alignment is working for all use cases of track pseudo-sensors
- It sees the misalignments but:

Accuracy of a single track pseudo sensor

- for the z-coordinate in the precision plane: 0.8-3 mm depending upon chamber position in η
- for the θ-angle: 1-5 mrad depending upon chamber position in η
- for the x- and y-coordinates: 2-7 mm depending upon chamber position in ϕ and η
- for the ϕ-angle: 3-30 mrad

- The main reasons for low accuracy of track pseudo-sensors are the imprecise measurements of muon track second coordinate (ϕ angle) and material effects (multiple scattering)
- To achieve the required 30 μm accuracy in the precision plane about 3000-10000 tracks per overlap region is needed $\Rightarrow$ with the expected rate of overlap tracks (0.2 Hz for the design luminosity) this amounts to 4-15 hours of data taking
- Integration of optical and track based alignment is still to be done

Description of MILLEPEDE approach (linear least squares fit model)

- Measurements (hits) in a linear model:

$$y_k = a_1 \cdot d_{k1} + a_2 \cdot d_{k2} + ... + a_n \cdot d_{kn} \; + \; \alpha_1 \cdot \delta_{k1} + \alpha_2 \cdot \delta_{k2} + ... + \alpha_\nu \cdot \delta_{k\nu} = \mathbf{a} \cdot \mathbf{d}_k + \boldsymbol{\alpha} \cdot \boldsymbol{\delta}_k$$

where:

$\mathbf{a}$, $\boldsymbol{\alpha}$ - *vectors of alignment and track parameters*

$\mathbf{d}_k$, $\boldsymbol{\delta}_k$ - *vectors of alignment and track parameter derivatives for k-th measurement*

$$\chi^2 = \sum_k \frac{(y_k^{meas} - y_k)^2}{\sigma_k^2}$$

- Minimization of χ^2 leads to a system of linear equations:

$$\left(\begin{array}{c|ccc} \sum \mathbf{C}_i & \dots & \mathbf{G}_i & \dots \\ \hline \vdots & \ddots & 0 & 0 \\ \mathbf{G}_i^T & 0 & \boldsymbol{\Gamma}_i & 0 \\ \vdots & 0 & 0 & \ddots \end{array}\right) \cdot \left(\begin{array}{c} \mathbf{a} \\ \hline \vdots \\ \boldsymbol{\alpha}_i \\ \vdots \end{array}\right) = \left(\begin{array}{c} \sum \mathbf{b}_i \\ \hline \vdots \\ \boldsymbol{\beta}_i \\ \vdots \end{array}\right)$$

Index i corresponds to different tracks;

Size of Matrix =

NumOfAlignmentParameters +

NumOfTracks $\cdot$ NumOfTrackParameters

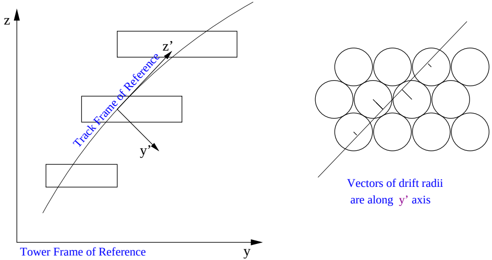
- Vector of alignment parameters can be determined as follows:

$$\boxed{\mathbf{a} = \mathbf{C}'^{-1} \cdot \mathbf{b}'^{-1}} \qquad \textit{where} \quad \mathbf{C}' = \sum_i \mathbf{C}_i - \sum_i \mathbf{G}_i \boldsymbol{\Gamma}_i^{-1} \mathbf{G}_i^T, \quad \mathbf{b}' = \sum_i \mathbf{b}_i - \sum_i \mathbf{G}_i \left(\boldsymbol{\Gamma}_i^{-1} \boldsymbol{\beta}_i \right)$$

- Direct solution without iterations!
- Can be used in cases with a large number of strongly correlated alignment parameters

MILLEPEDE-like algorithm for alignment using straight muon tracks

- Measurements in the muon spectrometer (hit coordinates) are not linear in track parameters
- Linearization is possible by transformation to 'Track Frame of Reference'



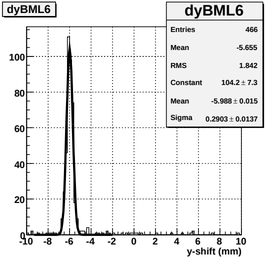
A MILLEPEDE-like algorithm was written for alignment of a sector of the ATLAS Muon Detector using straight muon tracks

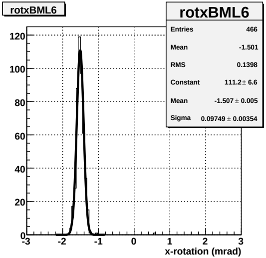
- Alignment procedure is performed within Muon Calibration Framework
- Reconstructed muon segments from the special muon data stream from LVL2 trigger are used
- Alignment parameters of only one chamber from an entire sector need to be fixed (some equivalent constraint can be used)

Optimization of the algorithm

- Muon Scattering poses a serious problem for MILLEPEDE-like alignment algorithms $\Rightarrow$ one bad track is enough to spoil the whole matrix
- Effects of multiple scattering in the muon spectrometer are much higher in comparison with the inner tracker $\Rightarrow$ standard MILLEPEDE outlier suppression needs modification
- Optimization of outlier suppression (iterative procedure):
  - CUT ON RESIDUALS
    measurement pulls: $\Delta_{pull} = \Delta_{res}/\sigma_{res}$; $\quad \sigma^2_{res} = \sigma^2_{tr} + \sigma^2_{sr}$;
    $\Delta_{pull} < \Delta_{cut}$ $\quad$ ($\Delta_{cut} = 20(2.5)$ - *first (last) iteration*);
    a track is rejected if any of its hits fails the cut
  - TRACK χ^2 CUT
    χ^2_{norm} - value of χ^2/ndf corresponding to 3 standard deviations
    $\chi^2/ndf < 10 * \chi^2_{norm}$ (*last iteration, no cut for the first iteration*)
  - OUTLIER DOWNWEIGTING (Millepede II)
    additional hit weight multiplier defined as:
    $$w = \left[\begin{array}{cc} 1 & \text{if } |\Delta| < c \\ c/|\Delta| & \text{if } |\Delta| > c \end{array} \right.$$
    $\Delta = \Delta_{res}/\sigma_{sr}\,, \quad c = 1.345$
- Outlier suppression procedure needs several iterations (5 iterations are used)

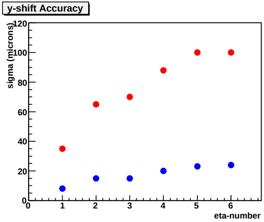
Algorithm performance with two alignment paremeters per chamber (I)

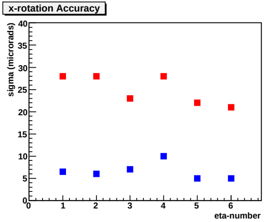




- Determination of shift and rotation of a BML chamber (each entry corresponds to a matrix solution for 100 tracks)
- y-shift uncertainty - $15\mu m$, x-rotation uncertainty - $5\mu rad$

- Uncertainties on the alignment parameters of BOL chambers for 20GeV and 3GeV muons (multiple scattering effects)





Algorithm performance with two alignment paremeters per chamber (II)

- Results of alignment procedure for 20 GeV muons in the case of two alignment parameters per chamber – *shift along Y-axis* and *rotation around X-axis* – with just one chamber parameters fixed from a whole Sector

par Num	Input Value	Output Value	Error
111	−3	−3.012	12
112	−1.5	−1.511	11
131	**fixed**	–	–
132	**fixed**	–	–
151	2	2.008	8
152	−0.5	−0.507	7
211	1	1.000	0
212	1	0.999	1
231	3	3.005	5
232	−1	−0.993	7
251	−3	−2.985	15
252	1	0.991	9

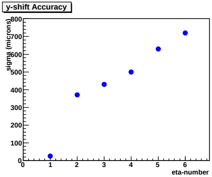
par Num	Input Value	Output Value	Error
311	−6	−5.995	5
312	−0.5	−0.506	6
331	−2	−2.014	14
332	2	1.979	21
351	−7	−6.992	8
352	−1.5	−1.520	20
411	4	3.976	24
412	−2	−2.011	11
431	−5	−4.985	15
432	1	1.001	1
451	5	4.984	16
452	1	1.004	4

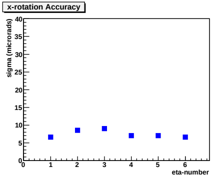
par Num	Input Value	Output Value	Error
511	−6	−6.009	9
512	1	0.994	6
531	4	4.013	13
532	1.5	1.501	1
551	−3	−3.022	22
552	2	2.007	7
611	5	4.984	16
612	2	2.000	0
631	−6	−6.000	0
632	−1.5	−1.512	12
651	−8	−7.980	20
652	−1.5	−1.491	9

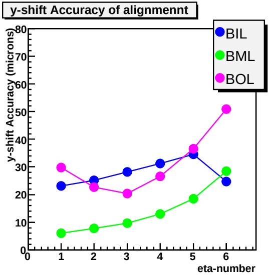
- Shifts are given in *mm*, rotations - in *mrad* Errors are given in μm and μrad
- ParameterNumber (NNN):
  - first digit - etaNumber of Tower (1,...,6)
  - second digit - stationName (1 - BIL; 3 - BML; 5 - BOL)
  - third digit - type of parameter (1 - Y-shift; 2 - X-rotation)

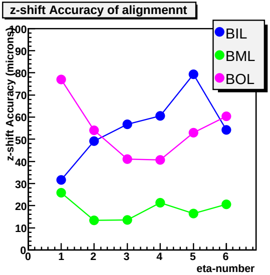
Problems of alignment with more than two alignment parameters per chamber

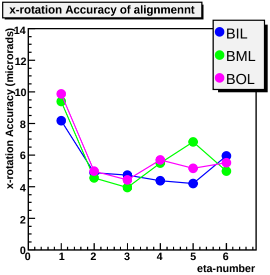
- In the case of more than two alignment parameters per chamber uncertainties in the parameter determination get much worse
- Some cross links between the towers are needed for the Millepede algorithm to work:
  - muon tracks in the gaps between the chambers of the same layer
  - measurements from axial optical sensors
- Integration of track data and optical data is required again









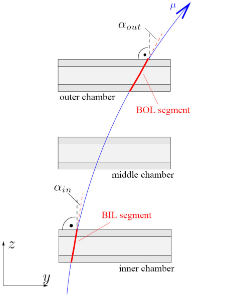


Segment based alignment of large chamber triplets with curved tracks

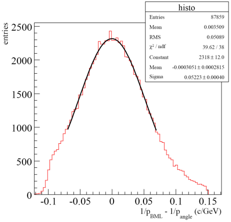
- A complementary tool for cross-checking of the optical projective alignment

Method outline

- use track segments associated with the same muon track to calculate the track momentum: $\Delta\alpha = \alpha_{out} - \alpha_{in} = \frac{q}{p} \int Bdl$
- the middle chamber segment is extrapolated into the inner and outer chambers using the calculated momentum from $\Delta\alpha$ (a custom Runge-Kutta extrapolator is used)
- relative translations and rotations of the inner and outer chambers with respect to the middle chamber are calculated from the discrepancies between the extrapolated and measured segments



- Relative rotation between the inner and outer chambers has to be determined beforehand ⇒ can be obtained from independent measurement of muon momentum in the single middle chamber by using the track deflection angle between the middle chamber multilayers, but
  - to achieve the final 30 μm alignment precision about 10^6 of 6 GeV muon tracks per tower is needed which corresponds to 50 hours of data taking
  - realistically, the precision of 100 μm can be achieved with 5 hours of data taking



Conclusions and plans

- The algorithm for overlap alignment is in a good shape
  - track pseudo sensors data is extracted for all use cases of the “track based muon alignment” (Small-to-Large, BEE, BIS8, Barrel-to-Endcaps)
  - the algorithm is running in release 13.0.x
  - some code development on the interface to an Oracle database and estimates on pseudo-sensor “measurement uncertainty” is ongoing
- A MILLEPEDE-like algorithm for aligning a sector of muon chambers has been developed
  - good results are obtained for 20 GeV muons in the case of two alignment parameres per chamber
  - axial optical measurement are needed for the algorithm to be applicable for the full parameter alignment of a sector of the muon spectrometer
- Studies of segment based alignment of muon chambers with curved tracks have been performed and a proof of principle has been shown

Plans:

- The algorithm for overlap alignment
  - integration with the optical alignment reconstruction software (end of October)
- The Millepede algorithm
  - adding optical measurements for the full parameter alignment
  - optimization of outlier suppression for low p_t muons
  - adopting described method for curved muon tracks in the ATLAS magnetic field
- Application of the two methods to cosmics commissioning data

Backup slides

Determination of vectors of derivatives in MILLEPEDE approach

- Derivatives for alignment parameters:

Rotation Matrix of Tower to Track transformation	*Misalignment Rotation Matrix*	*Displacement Shift*
$\begin{bmatrix} 1 & 0 & 0 \\ 0 & R_{22} & R_{23} \\ 0 & R_{32} & R_{33} \end{bmatrix}$	$\begin{bmatrix} 1 & -\phi_z & \phi_y \\ \phi_z & 1 & -\phi_x \\ -\phi_y & \phi_x & 1 \end{bmatrix}$	$\begin{bmatrix} \Delta_x \\ \Delta_y \\ \Delta_z \end{bmatrix}$

- Coordinates of a hit in the "Track Frame of Reference" (including misalignment):

$$\begin{bmatrix} x' \\ y' \\ z' \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & R_{22} & R_{23} \\ 0 & R_{32} & R_{33} \end{bmatrix} \cdot \left\{ \begin{bmatrix} 1 & -\phi_z & \phi_y \\ \phi_z & 1 & -\phi_x \\ -\phi_y & \phi_x & 1 \end{bmatrix} \cdot \begin{bmatrix} x \\ y \\ z \end{bmatrix} + \begin{bmatrix} \Delta_x \\ \Delta_y \\ \Delta_z \end{bmatrix} \right\}$$

- Measurement is performed along y' axis, so only this component shoud be calculated:

$$y' = \mathbf{a} \cdot \mathbf{d}_k$$

Vector of alignment parameters $\mathbf{a} = \begin{bmatrix} \Delta_y \\ \Delta_z \\ \phi_x \\ \phi_y \\ \phi_z \end{bmatrix}$

Vector of derivatives $\mathbf{d}_k = \begin{bmatrix} R_{22} \\ R_{23} \\ R_{23} \cdot y_k - R_{22} \cdot z_k \\ -R_{23} \cdot x_k \\ R_{22} \cdot x_k \end{bmatrix}$

- Derivatives for track parameters:

$$y' = \boldsymbol{\alpha} \cdot \boldsymbol{\delta}_k = \alpha_1 + \alpha_2 \cdot z'_k + \alpha_3 \cdot I_k$$

where $I_k = \iint B_\perp d^2 l$ *double integral over B-field along the track of muon*

$$\boldsymbol{\delta}_k = \begin{bmatrix} 1 \\ z' \\ I_k \end{bmatrix}$$