Beam-based detector alignment in the MICE Muon Beam

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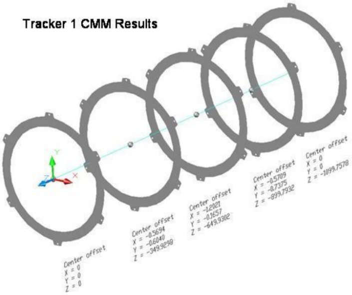
July 28, 2016

Surveys as the baseline for the alignment

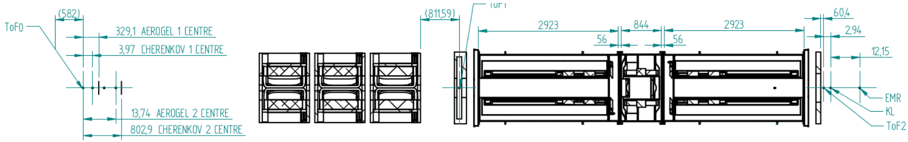
Known to great accuracy from the surveys:

- → Position of each detector module along the beam line, z_M
- → Misalignment and Tait-Bryan angles of the PID detectors $x_M, y_M, \alpha, \beta, \gamma$
- → Misalignment of the tracker stations wrt each other (CMM)



Analysis measurements:

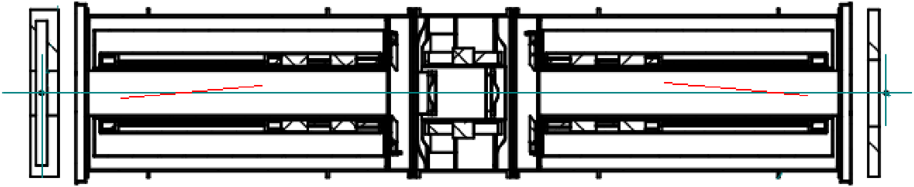
- → **Misalignment and Tait-Bryan angles of the two trackers**



Analysis method

As the parameters of the TOF detectors are well understood:

- $\rightarrow$ the axis that joins the centres of TOF1/2 is used the reference axis
- $\rightarrow$ the axes of the two trackers are aligned with respect to it



For each straight track, 4 parameters from the pattern recognition code:

- $\rightarrow$ The position of the track at the centre x, y ($+z$ from survey)
- $\rightarrow$ The gradients of the track x', y' (fits of 5 stations)
- $\rightarrow$ Local coordinates only (no assumption on the geometry)

Analysis method (2)

The position of the space point in global coordinate translates to

$$\begin{pmatrix} \xi \\ \upsilon \\ \zeta \end{pmatrix} = \begin{pmatrix} x - \gamma y + \beta z + x_{\mathrm{M}} \\ y + \gamma x - \alpha z + y_{\mathrm{M}} \\ z - \beta x + \alpha y + z_{\mathrm{M}} \end{pmatrix} = \begin{pmatrix} x - \gamma y + x_{\mathrm{M}} \\ y + \gamma x + y_{\mathrm{M}} \\ \beta x + \alpha y + z_{\mathrm{M}} \end{pmatrix} \tag{1}$$

With x_{12} the coordinate predicted by the TOF12 axis, we have, on average

$$\begin{gathered} \langle \xi_{12} - \xi \rangle = 0 \\ \boxed{\langle \xi_{12} - x \rangle = -\gamma \langle y \rangle + x_M} \end{gathered} \tag{2}$$

and $\langle \xi_{12} - x \rangle$ can easily be measured as a function of a binned out $\langle y \rangle$ to find x_M and a first estimate of the roll γ. Similarly:

$$\begin{gathered} \langle \upsilon_{12} - y \rangle = \gamma \langle x \rangle + y_M, \\ \langle \xi'^{12} - x' \rangle = -\gamma \langle y' \rangle + \beta, \\ \langle \upsilon'^{12} - y' \rangle = \gamma \langle x' \rangle - \alpha \end{gathered} \tag{3}$$

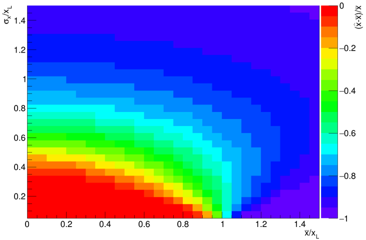
Sampling bias

Formulas only true for an unbiased sample of particles. In a perfect world, the sample mean and the true mean are the same and we have:

$$x_{12} - x \sim N\left(x_M, \theta_E^2 \Delta z^2\right) \rightarrow \langle x_{12} - x \rangle = x_M \tag{4}$$

But in fact, if the true mean $\overline{x}$ is non-zero, the true spread is σ_x and the half width of the sampling is x_L, the sample mean reads

$$\begin{aligned}
\hat{x} &= \int_{-x_L}^{x_L} x \times N(\overline{x}, \sigma_x^2) dx \\
&= \frac{\overline{x}}{2}\left(\text{erf}\left[\frac{x_L - \overline{x}}{\sqrt{2}\sigma_x}\right] - \text{erf}\left[\frac{-x_L - \overline{x}}{\sqrt{2}\sigma_x}\right]\right) \\
&- \sqrt{\frac{2}{\pi}}\sigma_x \exp\left[\frac{-x_L^2 - \overline{x}^2}{2\sigma_x^2}\right] \sinh\left[\frac{x_L \overline{x}}{\sigma_x^2}\right]
\end{aligned}$$



Sampling bias (2)

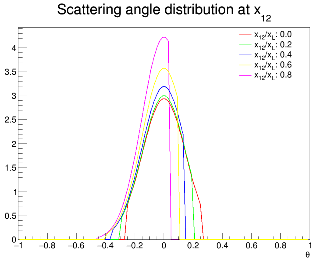
For a given predicted x_{12}, the distribution of scattering angle reads

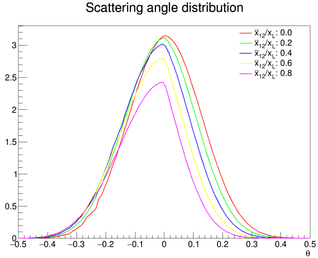
$$f_{x_{12}}(\theta) = \frac{C_{12}}{\sqrt{2\pi}\theta_E} \exp\left[-\frac{1}{2}\frac{\theta^2}{\theta_E^2}\right] \times D_\theta\left(\frac{-x_L - x_{12}}{\Delta z}, \frac{x_L - x_{12}}{\Delta z}\right)$$

For a given distribution of x_{12}, $g(x_{12})$, this globally translates to

$$f(\theta) = \int_{-x_L}^{x_L} g(x_{12}) f_{x_{12}}(\theta) dx_{12}$$

$$= C\mathcal{N}(0, \theta_0^2) \int_{-x_L - \theta\Delta z H(-\theta)}^{x_L - \theta\Delta z H(\theta)} \frac{C_{12}}{\sqrt{2\pi}\sigma_{x_{12}}} \exp\left[-\frac{1}{2}\frac{(x_{12} - \overline{x_{12}})^2}{\sigma_{x_{12}}^2}\right] \mathrm{d}x_{12}$$





Sample selection

No control on the natural mean $\overline{x}$ of the beam but can select an unbiased sample of events that we expect to be contained.

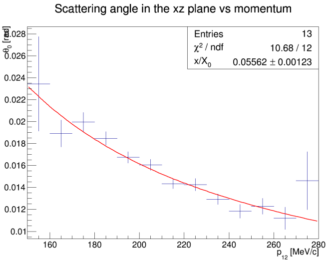
→ The sample has to be composed of particles with a zero mean scattering angle, i.e. $\langle\theta\rangle = 0$ so that $\langle x_{12} - x\rangle = x_M$

→ On a particle by particle basis, reject the ones likely to scatter out

The boundaries of the tracker are so that $x_L^2 + y_L^2 = R_L^2$, with R_L the radius of the fiducial circle of the tracker stations. If the track is predicted to hit (x, y) and the effective mean scattering angle is θ_E, reject the track if the condition

$$(|x| + 2\theta_E\Delta_z)^2 + (|y| + 2\theta_E\Delta_z)^2 < R_L^2$$

is not satisfied.



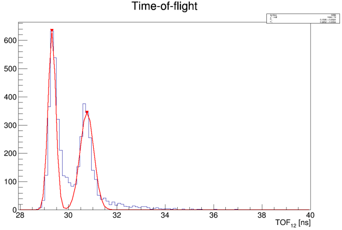
Tracker alignment fitting algorithm

Fit TOF12 distribution for PID:

→ Accumulate 5000 tracks

→ Identify peaks with TSpectrum, fit with 2-peaks Gaussian, reject $e^{\pm}$ tag muons and pions

→ Tag muons and pions



Reconstruct a gross momentum from TOF12 under PID assumption

→ $p_{12} = m_i / \sqrt{(ct/D_{12})^2 - 1}$

Infer the effective mean scattering angle θ_E from PID and p_{12}

→ $\theta_E = \frac{13.6\,\mathrm{MeV}/c}{\beta_{12} p_{12} c} \sqrt{x/X_0}\,[1 + 0.038 \ln(x/X_0)]$

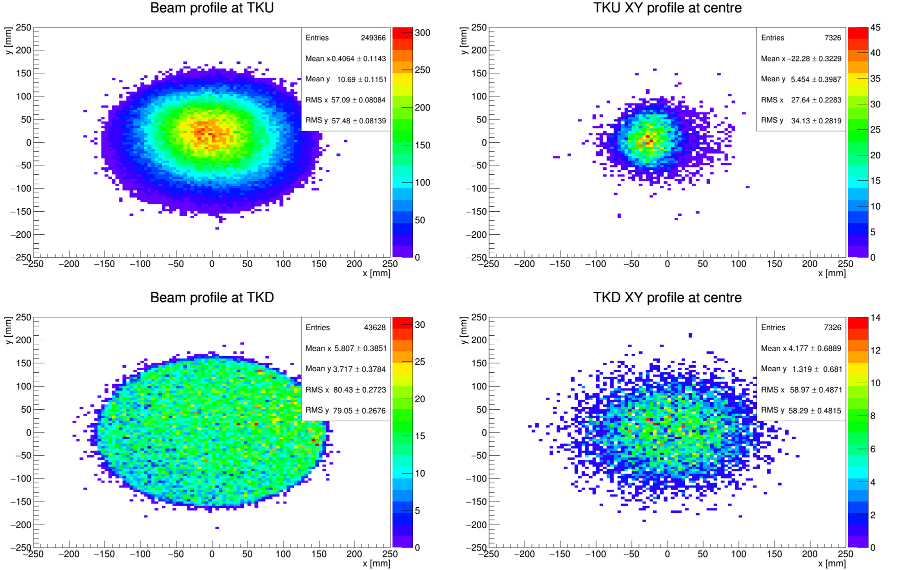
Plot $\langle x_{12} - x \rangle$ as a function of y, fit with a line so that

→ The gradient of the line fit is $-\gamma$

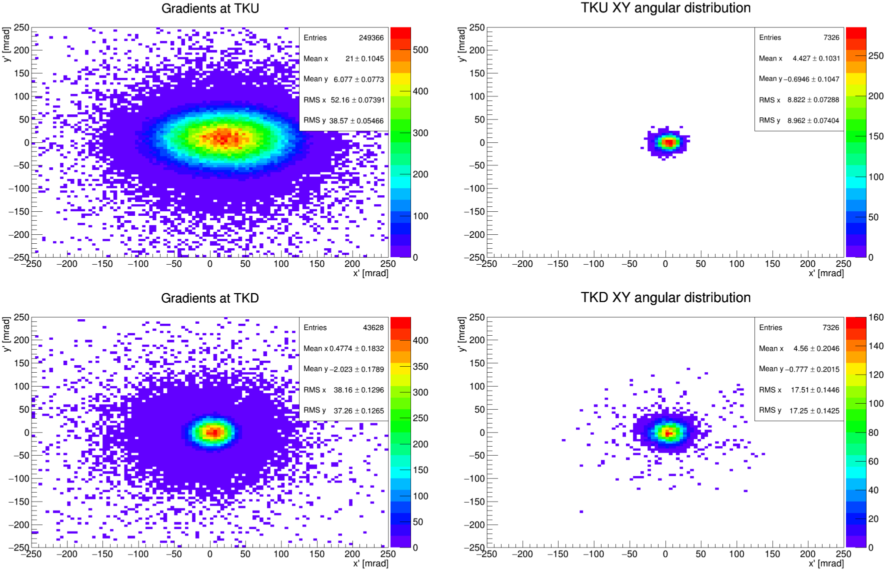
→ The y-interceptof the line fit is x_M

→ Take the first fit as an input, repeat 4 times

Effects of the cut on the particle sample (x, y)



Effects of the cut on the particle sample (x', y')



Results for a single run (07418, 280 MeV/c pion beam)

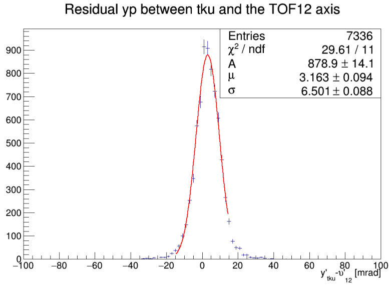
Example of results 7418

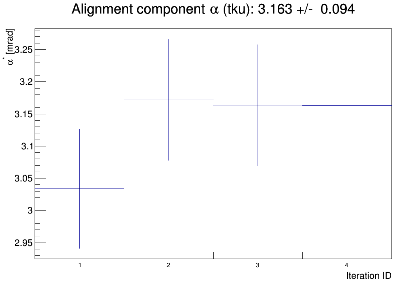
→ 8 pairs of plots produced per data set

→ These show the best fit for the tracker upstream pitch α

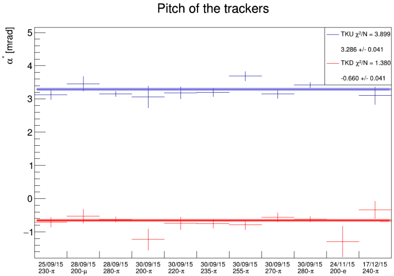
→ The fit converges at the second iteration

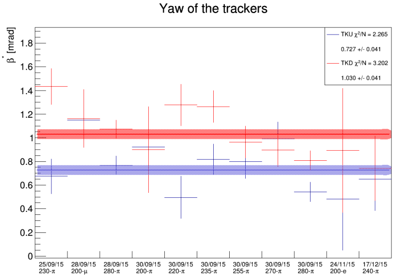
→ In this plot and the subsequent ones, the roll is ignored due to a resolution being poorer the expected order of it (10 mrad vs 1 mrad)

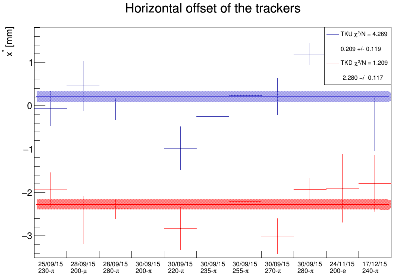


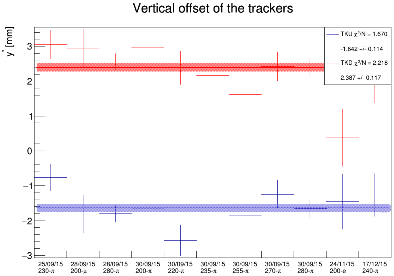


Stability of the fits across 2015 (2015/09-2015/12)

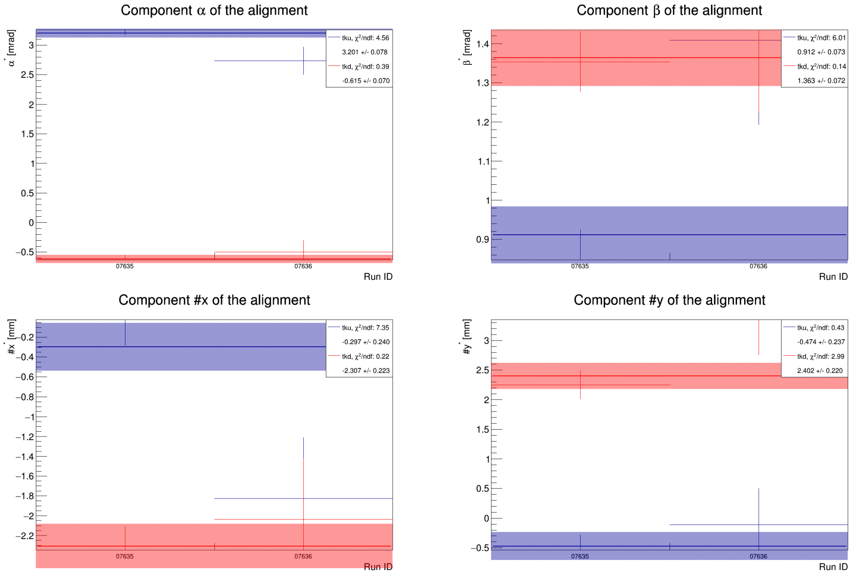




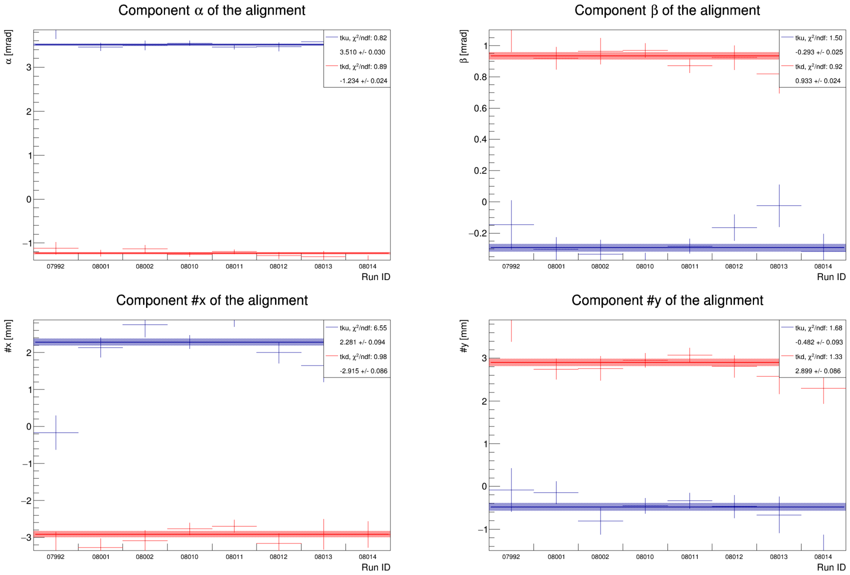




Alignement in February-March 2016



Alignement in July 2016



Best global fits

	x_T [mm]	y_T [mm]	α_T [mrad]	β_T [mrad]
TKU	0.209±0.119	-1.670±0.114	3.286±0.041	0.727±0.041
TKD	-2.280±0.117	2.387±0.117	-0.660±0.041	1.030±0.041

Table: September-December 2015

	x_T [mm]	y_T [mm]	α_T [mrad]	β_T [mrad]
TKU	-0.297±0.240	-0.474±0.237	3.201±0.078	0.912±0.073
TKD	-2.307±0.223	2.402±0.220	-0.615±0.070	1.363±0.072

Table: February-March 2016

	x_T [mm]	y_T [mm]	α_T [mrad]	β_T [mrad]
TKU	2.281±0.094	-0.482±0.093	3.510±0.030	-0.293±0.025
TKD	-2.915±0.086	2.899±0.086	-1.234±0.024	0.933±0.024

Table: July 2016

Cross check global alignment

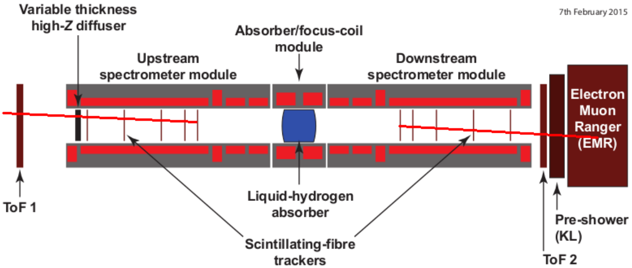
Make the pattern recognition variables global using the optimal parameters

$$\begin{pmatrix}\xi\\ \upsilon\\ \zeta\end{pmatrix} = \begin{pmatrix}x-\gamma^* y + x^*\\ y+\gamma^* x + y^*\\ \beta^* x + \alpha^* y + z^*\end{pmatrix},\ \begin{pmatrix}\xi'\\ \upsilon'\end{pmatrix} = \begin{pmatrix}x'-\gamma^* y' + \beta^*\\ y'+\gamma^* x' - \alpha^*\end{pmatrix} \qquad (5)$$

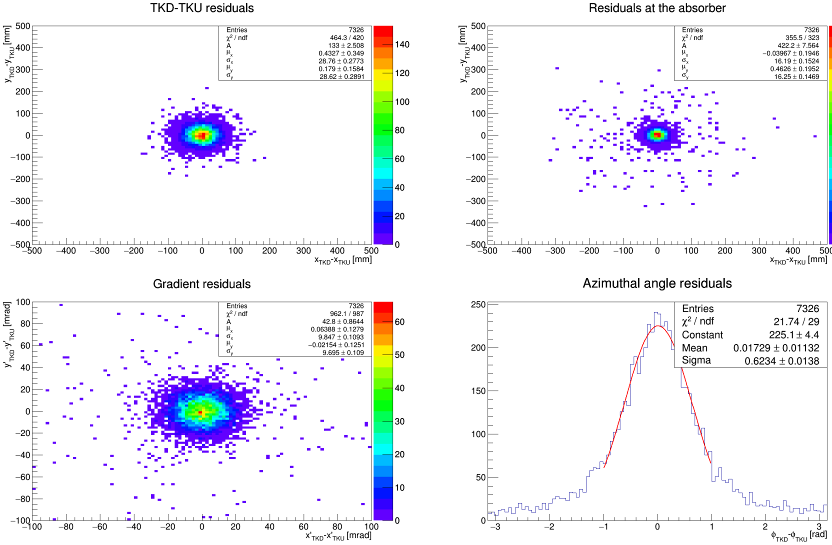
→ Propagate TKU tracks in TOF1 $\psi_{U,i} = \psi + \psi'(\zeta_i - \zeta_U)$, $\psi = \xi, \upsilon$

→ Propagate TKD tracks in TOF2, KL, EMR $\psi_{D,i} = \psi + \psi'(\zeta_i - \zeta_D)$

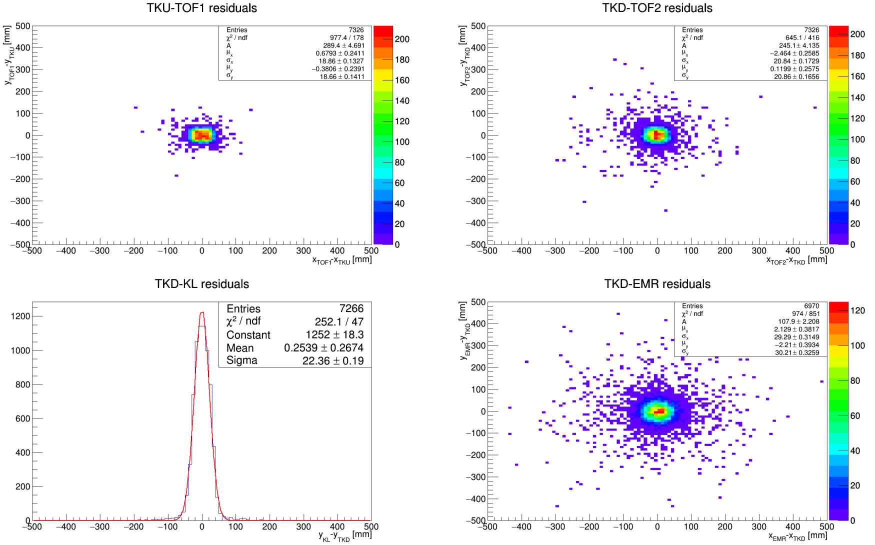
→ Check that $\langle \psi_{U,i} - \psi_i \rangle \sim 0$ and $\langle \psi_{D,i} - \psi_i \rangle \sim 0$ for each detector



Tracker to tracker alignment (aligned trackers)



PID detector alignment (aligned trackers)



Conclusions

Highlights of the analysis:

→ Great alignment from TOF1 all the way to the EMR

→ Robust sample selection and fitting, consistency through step IV

→ Analysis performed on all the alignment data currently held

→ Alignment code streamlined and easy to run, uploaded to:
https://code.launchpad.net/ francois-drielsma/maus/detector_alignment

→ Alignment requires 1M triggers at TOF1 with the 300 or 400 MeV/c pion beam, matter of 5 hours with DS

→ Showed movement between March and July but none after powering the SS or FC in July

→ Alignment note fully written, under review with CR