A track-based alignment for the LHCb tracker at the LHC

Miguel Ruiz Díaz

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UNIVERSITÄT HEIDELBERG ZUKUNFT SEIT 1386

IMPRS for Precision Tests of Fundamental Symmetries
INTERNATIONAL MAX PLANCK RESEARCH SCHOOL

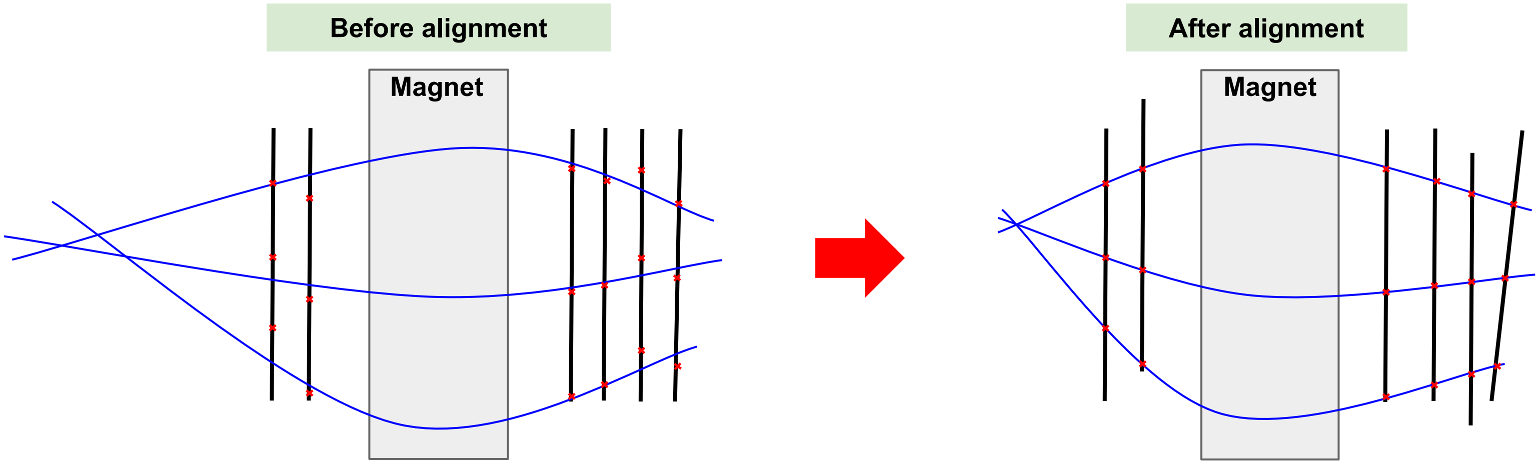
Outline

- **Introduction to track-based alignment**
- The LHCb detector and its tracker
- Impact of track-based alignment
- Determination of the alignment precision
- Alignment in 2025
- Summary

What do we need alignment for?

- Ultimate goal of alignment is to **find the relative position and orientation** of the different detector components
  - Actual detector geometry will always differ from design geometry
  - Essential and often overlooked ingredient to calibrate any particle detector and maximize its performance

- Typical **corrections in high energy physics experiments are of O(10-100 µm)** ➝ Significant impact on physics precision measurements

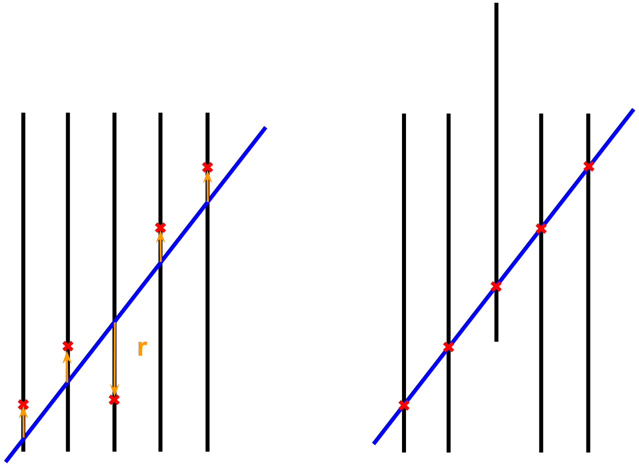


Alignment **improves track quality and tracking efficiency** and has a large impact on **mass and momentum resolution**

The alignment algorithm (1)

Idea: employ information from reconstructed charged particle tracks to determine the position and orientation of the detector elements

[Nucl.Instrum.Meth.A 600 (2009) 471-477]



Adapted from: [CERN-THESIS-2022-105]

The rotations and translations applied to the detector elements are known as **alignment constants**

- **Track residual:** distance vector from the extrapolated hit position of a fitted track on the sensor plane to the measured position of the hit associated to the track [CERN-THESIS-2017-076]
- Corrections to the geometry obtained by **minimizing the track residuals** as a function of the **alignment constants**
- The algorithm minimizes the **global track χ^2:**

$$\chi^2 = \sum_i^{n_{\text{tracks}}} \chi_i^2(\mathbf{x}_i, \alpha)$$

$$\chi_i^2(\mathbf{x}_i, \alpha) = \mathbf{r}(\mathbf{x}_i, \alpha)^{\mathrm{T}} V^{-1} \mathbf{r}(\mathbf{x}_i, \alpha)$$

$\mathbf{x}_i$: vector of track parameters for track i
$\boldsymbol{\alpha}$: set of alignment constants
r: vector of track residuals
***V*:** covariance matrix of track residuals

The alignment algorithm (2)

Minimization is done **iteratively:**

1. Perform the **track fit** assuming an initial detector geometry with set of **alignment constants α_0**
2. Compute **derivatives of the track residuals** with respect to the alignment constants
3. **Update alignment constants** minimizing the global track χ^2

$$\alpha = \alpha_0 - \left(\frac{\mathrm{d}^2\chi^2}{\mathrm{d}\alpha^2}\right)^{-1}\Bigg|_{\alpha_0} \frac{\mathrm{d}\chi^2}{\mathrm{d}\alpha}\Bigg|_{\alpha_0}$$

Newton-Raphson's equation for dχ^2/dα

4. Calculate the **change in the global track χ^2** to evaluate the convergence

$$\Delta\chi^2 = -(\alpha - \alpha_0)^{\mathrm{T}}\ \mathrm{Cov}(\alpha)^{-1}\big|_{\alpha_0} (\alpha - \alpha_0)$$

Condition for convergence → **$\Delta\chi^2$/ndof < 4**

5. After convergence **update detector geometry** if the **changes on the alignment constants are significant**
   - Decision to update the alignment based on expected alignment precision → Varies for each detector element and dof

Weak modes and constraints

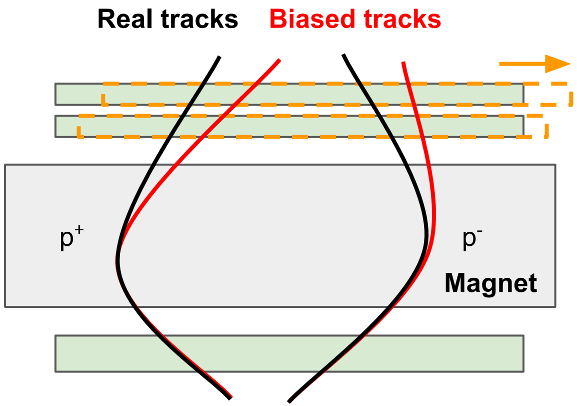
- In real-life scenarios we need to deal with complex **high-dimensional χ^2 functions**
  - Latest alignment of the LHCb tracker in 2024 involved 6686 degrees-of-freedom (dof) correlated with each other!
- **Weak modes:** unconstrained alignment modes with (almost) no impact on track residuals
  - Lead to misaligned configurations with potentially large biases on track properties
- Add **constraints to the global track χ^2** to improve the convergence:
  - **Lagrange constraints:** remove known weak modes by fixing the change on certain combinations of dof

$$\chi^2_{\text{lagrange}} = \lambda f(\alpha_{\text{weak}})$$

  - **Survey constraints:** employ information from detector survey measurements

$$\chi^2_{\text{survey}} = \left(\frac{\alpha - \alpha_{\text{survey}}}{\sigma(\alpha_{\text{survey}})}\right)^2$$

  - **Mass and vertex constraints:** χ^2 contributions from fits to primary and secondary vertices and gaussian constraints to the known masses of particle candidates [Nucl.Instrum.Meth.A 712 (2013) 48-55]



Typical weak mode for the LHCb tracking system known as “curvature bias”

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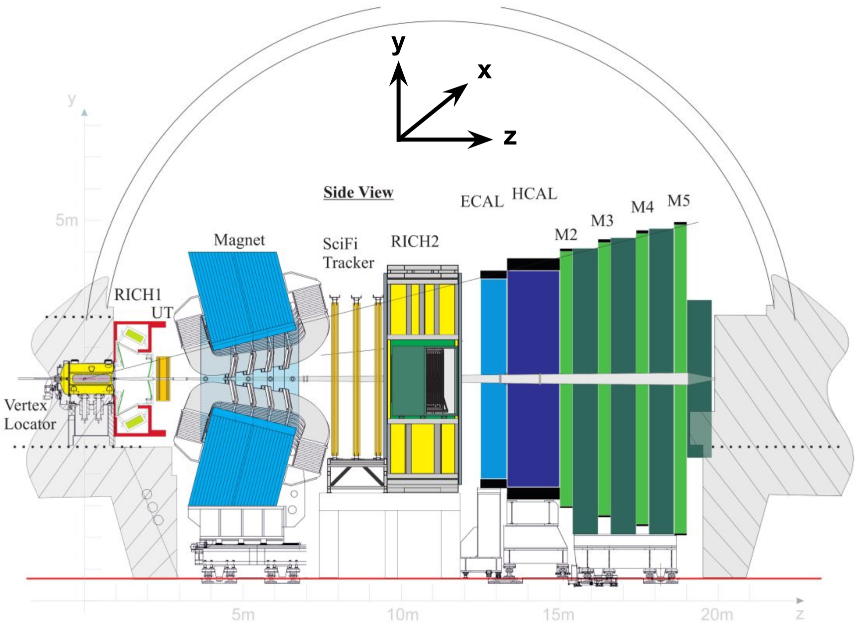
The Upgrade I LHCb detector

The **LHCb experiment** is a dedicated flavor physics experiment operating at the Large Hadron Collider (LHC) at CERN:

- **Asymmetric forward spectrometer**
- Tracks are fitted from hits recorded on the various tracking detectors employing a **Kalman filter** [Journal of Basic Engineering 82 (1960) 35]
- Charged particle trajectories are bent by a **dipole magnet** ➞ Curvature provides a **measurement of the momentum**
- **Ring Imaging Cherenkov (RICH) detectors** provide Particle IDentification (PID) information for charged particles
- Energy measurements are provided by the **calorimeter system**
- Low interacting muons are detected and identified at the **muon stations**

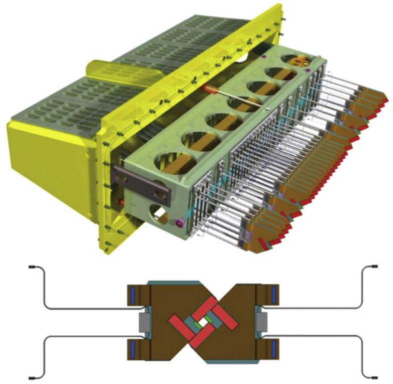
LHCb detector after Upgrade I



[arXiv:2305.10515]

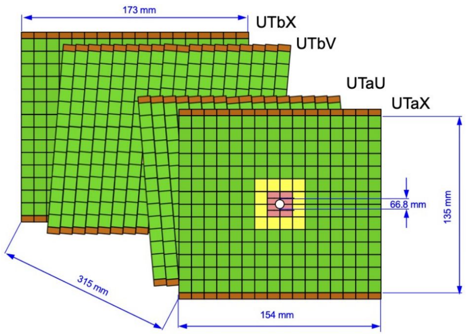
The tracking system

Vertex Locator (VELO)

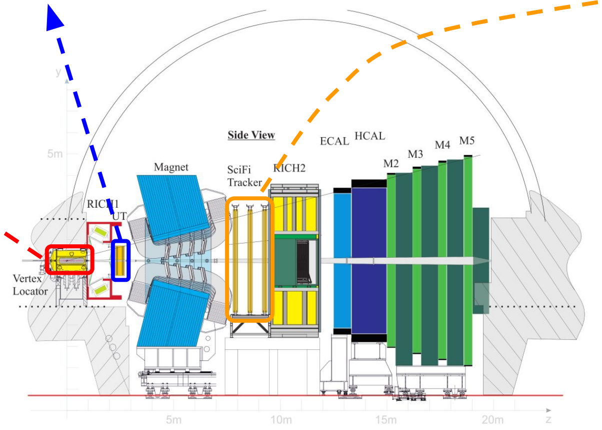


- **Hybrid pixel detector** consisting on L-shaped **silicon pixel modules** arranged along **two retractable halves**
- **≤15 μm hit resolution** in the x-y plane

Upstream Tracker (UT)

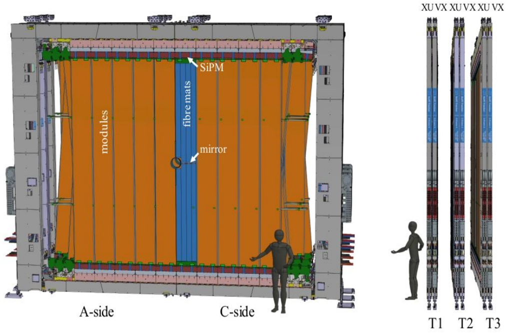


- **Silicon strip detector** with **sensors assembled in modules** on both faces of **vertical staves**
- **≤50 μm hit resolution** in the x axis



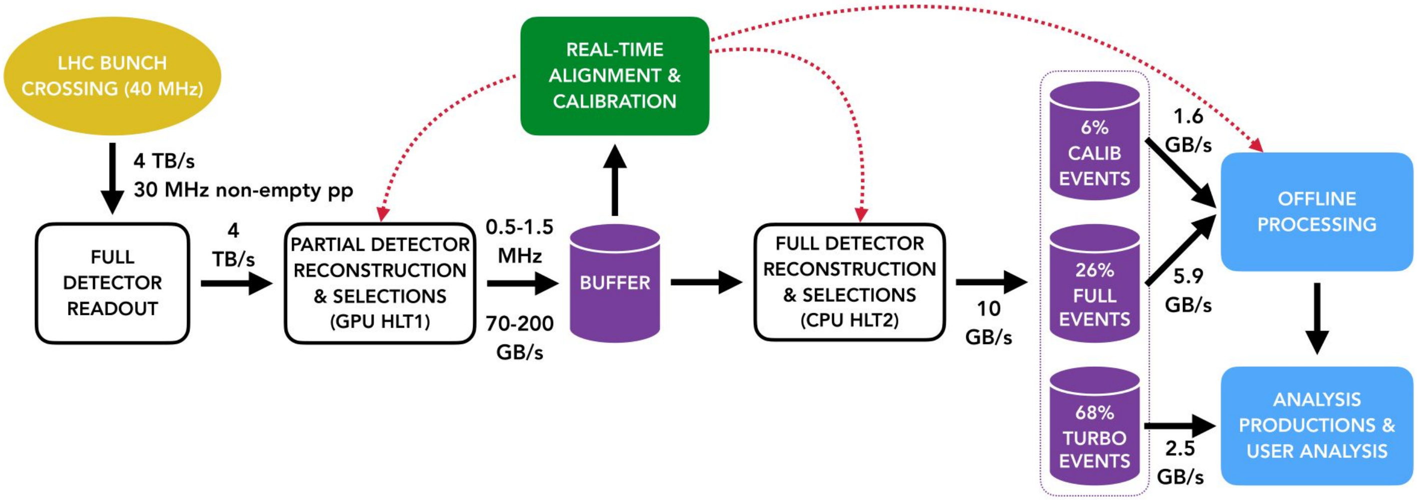
[arXiv:2305.10515]

Scintillating Fiber Tracker (SciFi)



- 5 m long **scintillating fibers arranged into modules** in the vertical direction
- **Modules split into halves** by a mirror to increase light yield collected by Silicon Photomultipliers
- **≤100 μm hit resolution** in the x axis

Real-time alignment and calibration



[LHCB-FIGURE-2020-016]

- Full software-based trigger system ➝ **Offline-level event reconstruction** performed in real time ➝ **Alignment and calibration corrections** computed **in real time** by automatized jobs

- **Alignment automatically updated** if the variation of alignment constants exceed certain thresholds ➝ See later!

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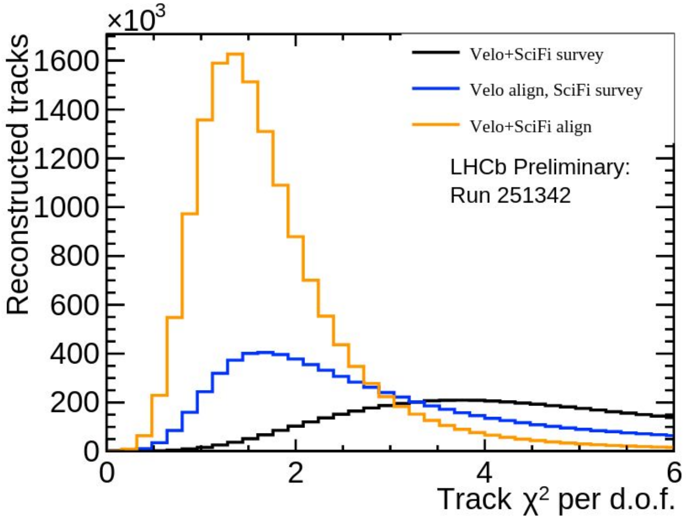
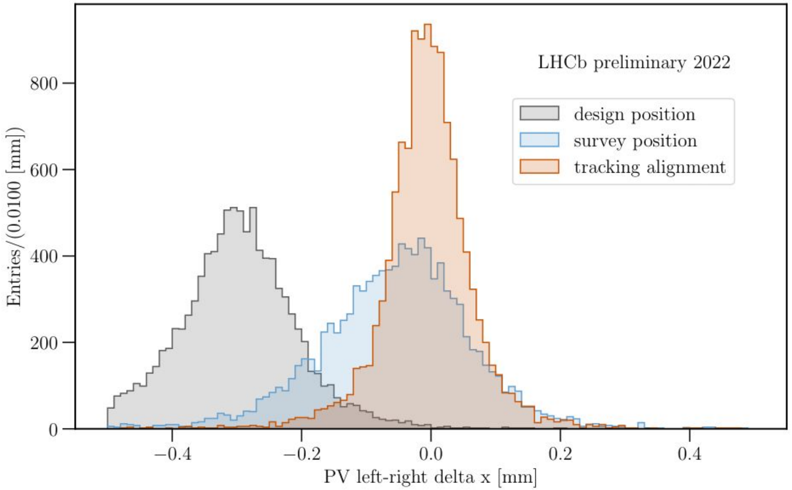
Impact on track and vertex quality



[LHCB-FIGURE-2022-018]

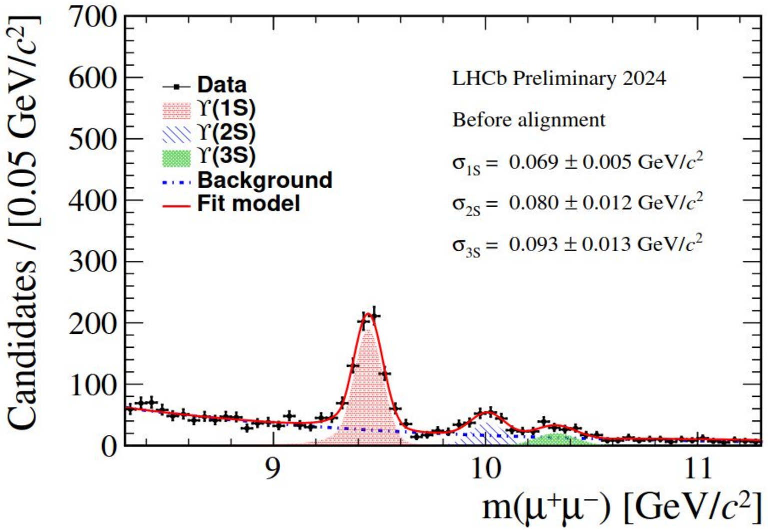


[LHCB-FIGURE-2022-016]

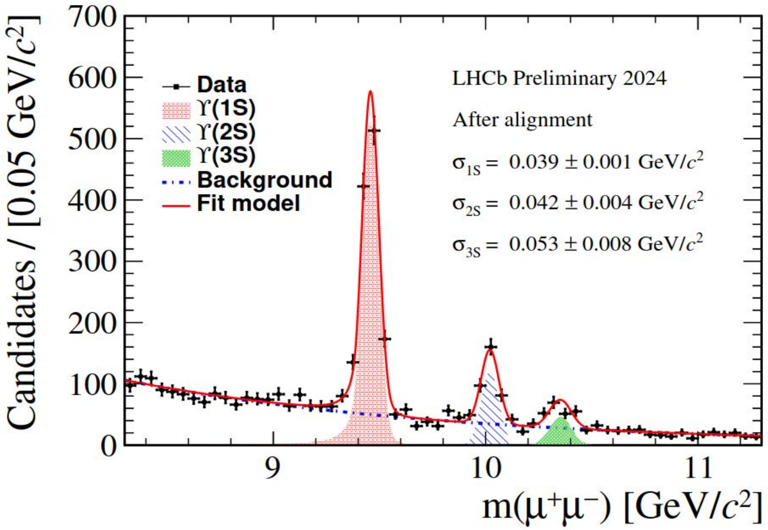
Plots from the **2022 commissioning** period after the **first alignment with data from Run 3**

Impact on mass distributions

Before track-based alignment



After 2024 tracker alignment



[LHCb-FIGURE-2024-037]

Impact of alignment on **mass resolution and signal purity of reconstructed Υ(nS) candidates** employing data collected in 2024

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Determining the alignment precision

Knowing the expected alignment precision is **crucial to assess if changes on the conditions are significant**. We have **two sources of information:**

Data driven approach

Run alignment jobs on data samples taken with the same detector conditions and extract alignment precision from the spread of the constants

Simulation based approach

Employ simulated data injecting random misalignments on the geometry to evaluate the ability of the alignment to correct for them. Distribution of the constants after alignment provides a measurement of the precision

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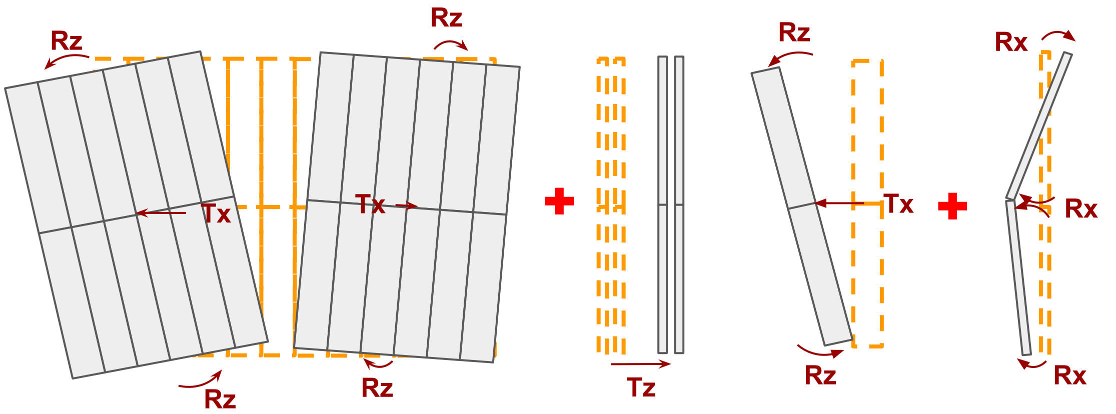
Employ simulated data injecting random misalignments on the geometry to evaluate the ability of the alignment to correct for them. Distribution of the constants after alignment provides a measurement of the precision

I will present the results of the simulation based method to estimate the expected alignment precision for the SciFi tracker

Input random misalignments



Most important dof

- **Layer halves:** shifts along the x and the z axes (Tx and Tz)
- **Modules:** shifts along the x axis and rotations around z (Tx and Rz)
- **Module halves:** symmetric rotations around x (Rx) ➝ Bending of modules about the center

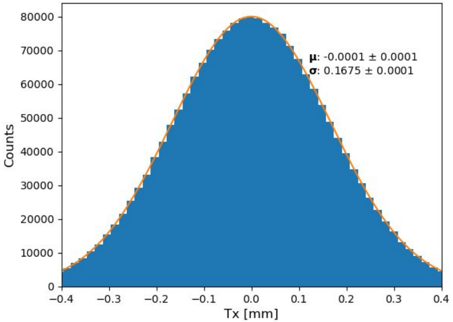
Half-layers and modules Tx

External modules excluded

Input misalignments

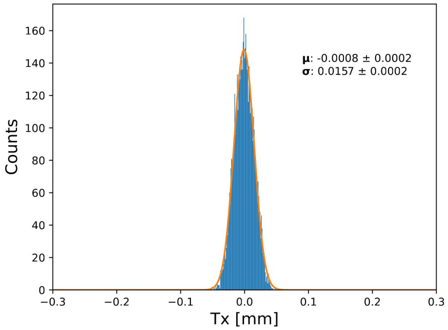
After alignment

All modules



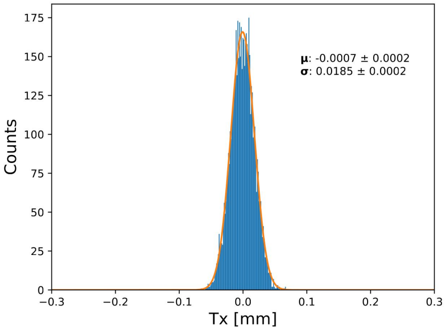
σ [μm] = 167.5 ± 0.1

Modules in station 1



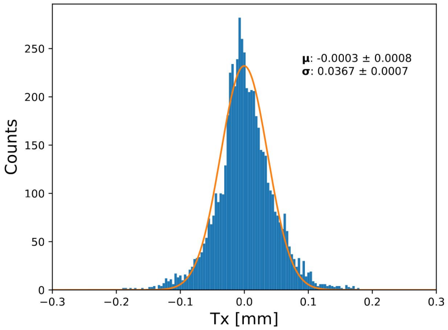
σ [μm] = 15.7 ± 0.2

Modules in station 2



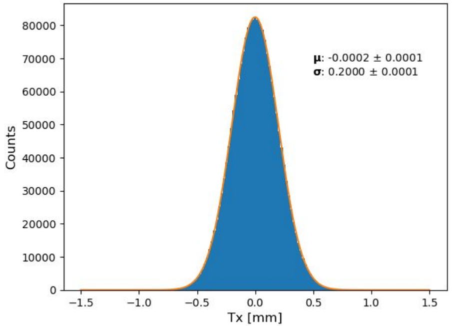
σ [μm] = 18.5 ± 0.2

Modules in station 3



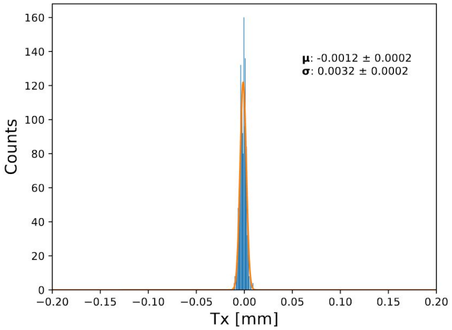
σ [μm] = 36.7 ± 0.7

All Layers



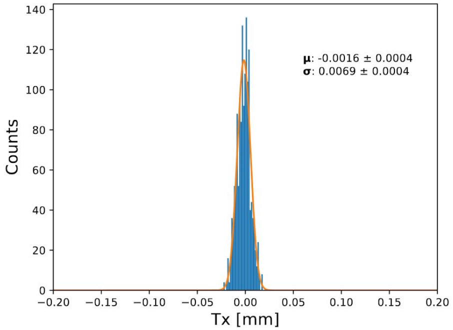
σ [μm] = 200.0 ± 0.1

Layers in station 1



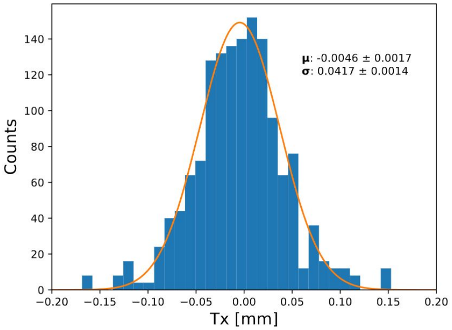
σ [μm] = 3.2 ± 0.2

Layers in station 2



σ [μm] = 6.9 ± 0.4

Layers in station 3

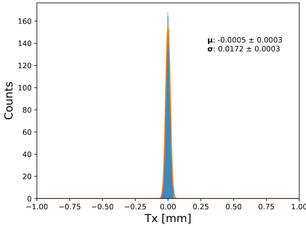


σ [μm] = 42 ± 1

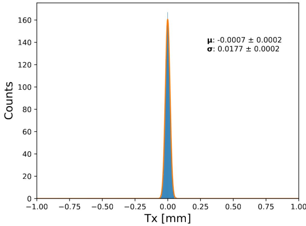
Correlation with module position

Last station excluded

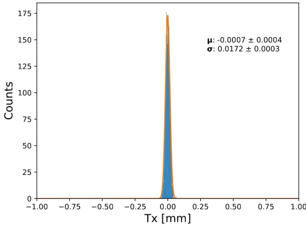
Precision on Tx alignment for modules in different positions



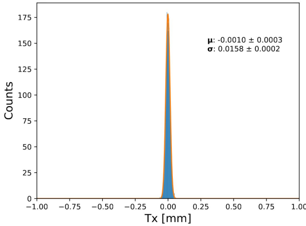
σ [μm] = 17.2 ± 0.3



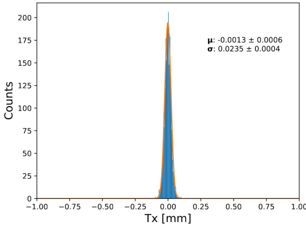
σ [μm] = 17.7 ± 0.2



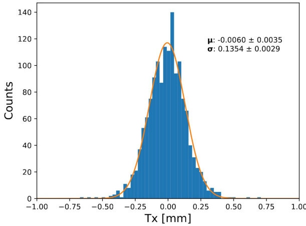
σ [μm] = 17.2 ± 0.3



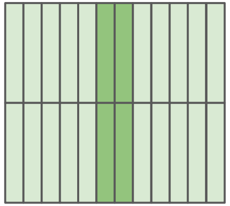
σ [μm] = 15.8 ± 0.3

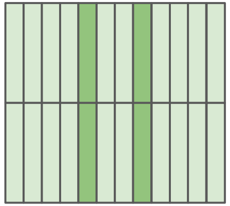


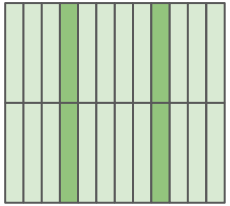
σ [μm] = 23.5 ± 0.4

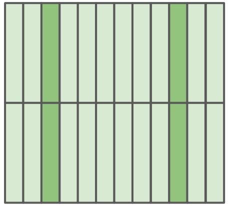


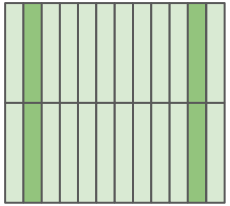
σ [μm] = 135 ± 3

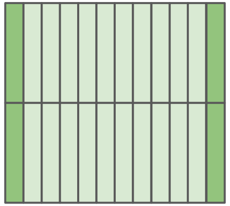












- Alignment precision much **lower for the outermost modules**
  - Limited amount of statistics in MC simulated samples
  - Modules populated by low momentum tracks with a larger bending angles ➝ Less sensitive to misalignments
- **Same** trend **for all dof**

Summary of the results

Tx [µm]

	Half-layers			Modules		
Configurations	T1	T2	T3	T1	T2	T3
Half-layers TxTz Modules TxRz	3.2 ± 0.2	6.9 ± 0.4	42 ± 1	15.7 ± 0.2	18.5 ± 0.2	36.7 ± 0.7
Half-layers Tx Modules TxRz Half-modules Rx	1.1 ± 0.1	7.2 ± 0.3	35 ± 2	15.2 ± 0.3	17.9 ± 0.3	33.5 ± 0.6
Half-layers TxTz Modules TxRz Half-modules Rx	2.2 ± 0.1	6.5 ± 0.3	37 ± 1	15.7 ± 0.2	18.2 ± 0.1	32.0 ± 0.6

All numbers for modules computed excluding the outermost modules

- Overall **good sensitivity to align modules and layer halves**
  - 2-40 µm for layers and 15-35 µm for modules in the x direction
  - Well below the SciFi hit resolution → ~100 µm
- Decided to employ a **threshold of 40 µm** to automatically **update the alignment of layer halves in real time**
  - Ongoing studies to establish a strategy for the real-time alignment of modules

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Re-alignment of the tracking system in 2025

- Beam **collisions resumed** at the LHC at the **beginning of May** after the end of the 2024 data-taking period in December
- Experts carried out various **interventions on the tracking system** ➝ Need **new alignment** to account for changes in the detector

Alignment corrections evaluated in two steps

First alignment

- Correct for misalignments in the x-y plane expected from hardware interventions
- Employed a sample from J/ψ ➝ $\mu\mu$ candidates collected within the first days of data-taking
- Preferable to use J/ψ ➝ $\mu\mu$ data with mass and vertex constraints for the first alignment instead of D^0 ➝ Kπ because its sensitivity to misalignments is enhanced due to the larger momentum of the daughter tracks

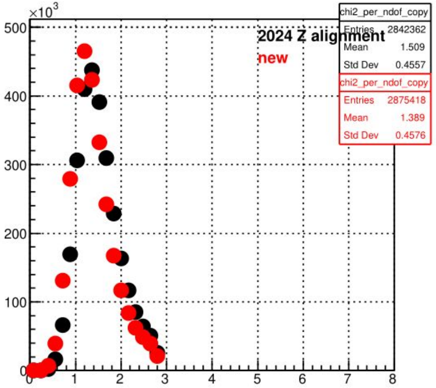
Second alignment

- Include remaining dof and detector components to obtain finer corrections and account for misalignments in z
- Employ a mixture of J/ψ ➝ $\mu\mu$ and D^0 ➝ Kπ candidates with mass and vertex constraints
- Data for the second alignment collected within ~1 week after the first alignment update
- Applied on top of the first alignment

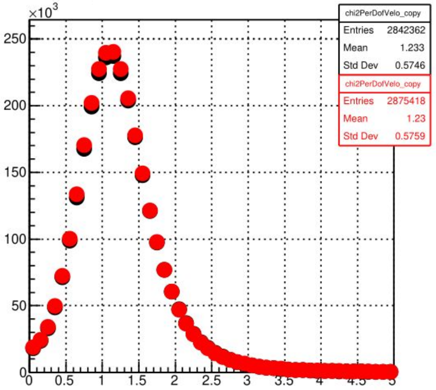
Improvement on track quality

Distribution of χ^2/ndof from track fit

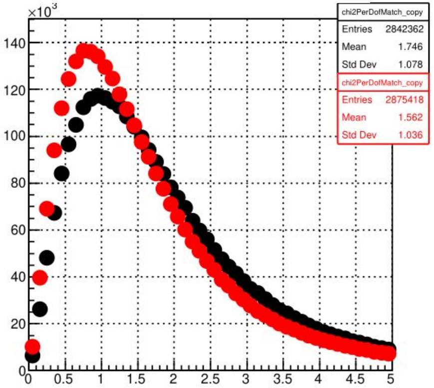
Full tracks



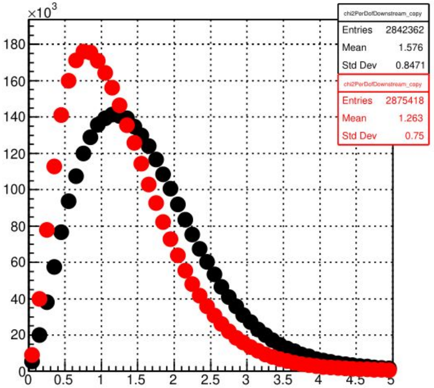
VELO - UT segments



UT - SciFi segments



SciFi - Muon segments

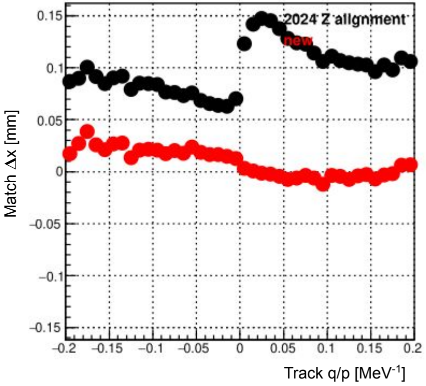


● **Alignment from 2024** ● **New alignment**

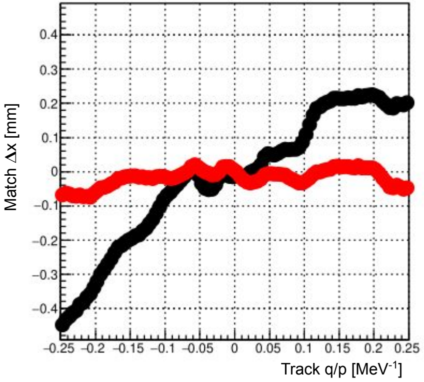
Largest impact from UT and SciFi ➝ Expected from hardware intervention and confirmed after alignment

Monitoring global alignment between sub-detectors

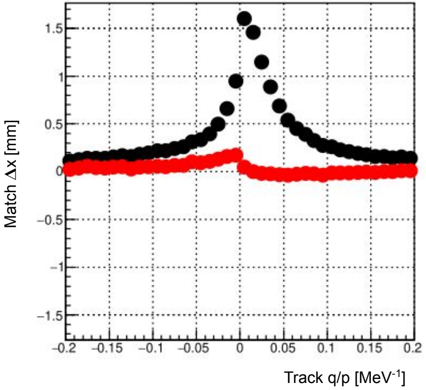
VELO - UT segments



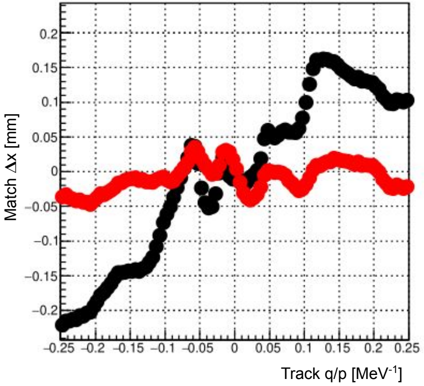
UT - SciFi segments



Pulls



Pulls



- **Alignment from 2024**
- **New alignment**

- The y axes show **average shifts in x** between **segments of full tracks** and **tracks fitted from hits on each pair of sub-detectors** and matched to the full tracks
- Shifts shown as a function of the **track q/p** ➝ Proportional to the track curvature
- **Main effects:**
  - Global shift in x between VELO and UT corrected after alignment
  - Relative rotation between UT and SciFi also corrected after alignment

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Summary

- **Track-based alignment** is a crucial ingredient to operate any particle physics detector
  - Apply corrections to account for mismatches between the design and the actual detector geometry
- We compute corrections by **minimizing the track residuals** as a function of parameters related to the detector geometry
- The algorithm is applied to the **LHCb tracking system** ➞ Alignment needs to be precise down to the level of ~10 μm
- Studied the **precision of the SciFi alignment** on MC-simulated data
  - Precision of 2-40 μm for layers and 15-35 μm for modules in the x direction
  - Some loss in performance for the outermost modules
  - Values employed to determine thresholds for automatic alignment updates
- Alignment **algorithm applied** to correct for movements on the detector **after the technical stop in 2025**

Thank you!

Backup

First alignment with 2025 data

- Some changes are expected with respect to 2024 alignment due to **operations carried out during YETS**

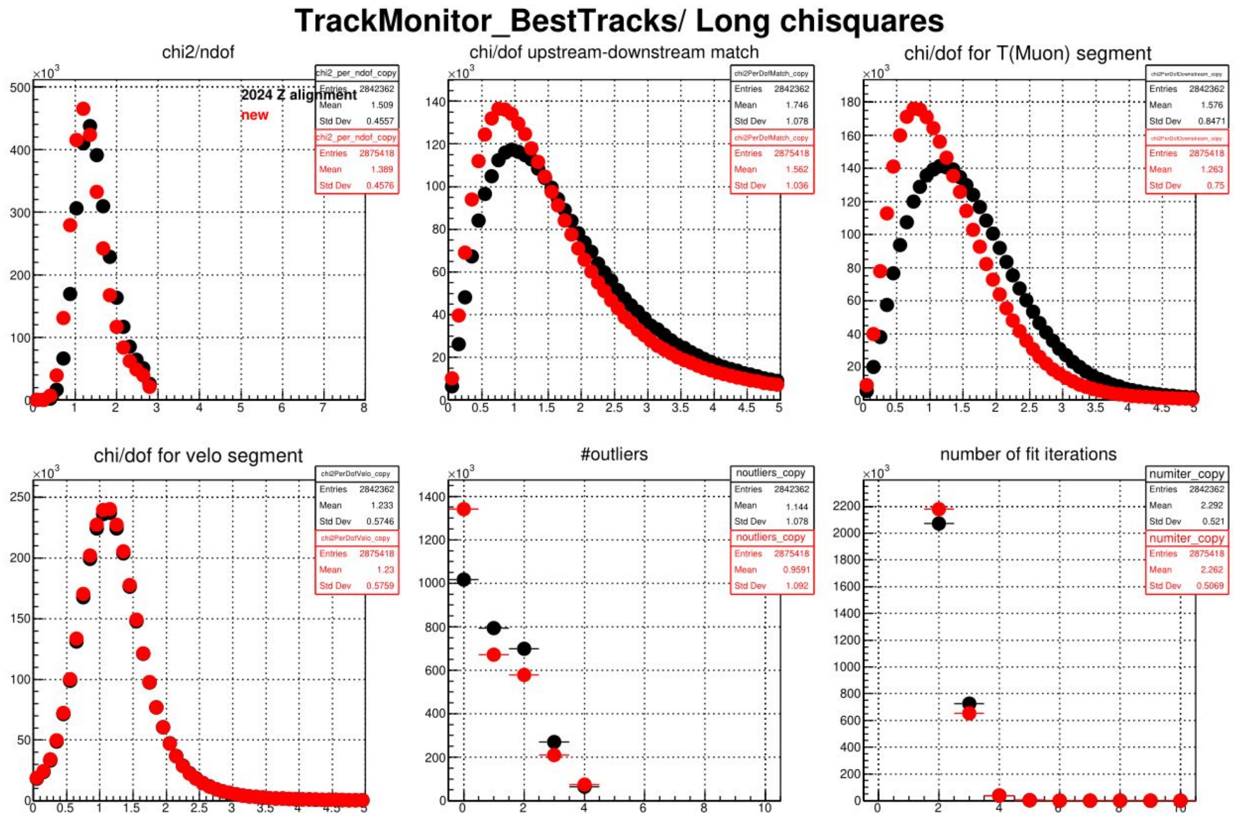
- **First version of the tracker alignment in 2025** computed from **7k events from $J/\psi \rightarrow \mu\mu$ data** collected during the first fill with stable beams
  - Preferred to use $J/\psi \rightarrow \mu\mu$ rather than the usual $D^0 \rightarrow K\pi$ as they are better to constrain weak modes due to the larger track momentum

- Some considerations:
  - The **starting position** were the alignment constants obtained last year with $Z^0 \rightarrow \mu\mu$ data → Best alignment we had in 2024
  - Main **expected differences with respect to 2024:**
    - VELO: global orientation and internal alignment will be different because of operations during YETS and removal of shims
    - UT: possible movements in x and rotations around z of layer halves due to opening and closing
    - SciFi: shifts in x at the level of layer halves for the same reason
  - We do **not expect changes on the internal dof of UT and SciFi** but it is **better to re-align them** together with half-layers due to correlations
  - We need **high momentum tracks to align detectors in z**

- **Alignment configuration** employed to compute first constants:
  - **VELO:**
    - Global: RxRyRz
    - Right half: TxTyTzRxRyRz → Velo drift mostly on the right half → Align only the right half wrt the left half to mitigate it
  - **UT:**
    - Half-layers: TxRz
    - Staves: TxRz
  - **SciFi:**
    - Half-layers: Tx
    - Modules: TxRz

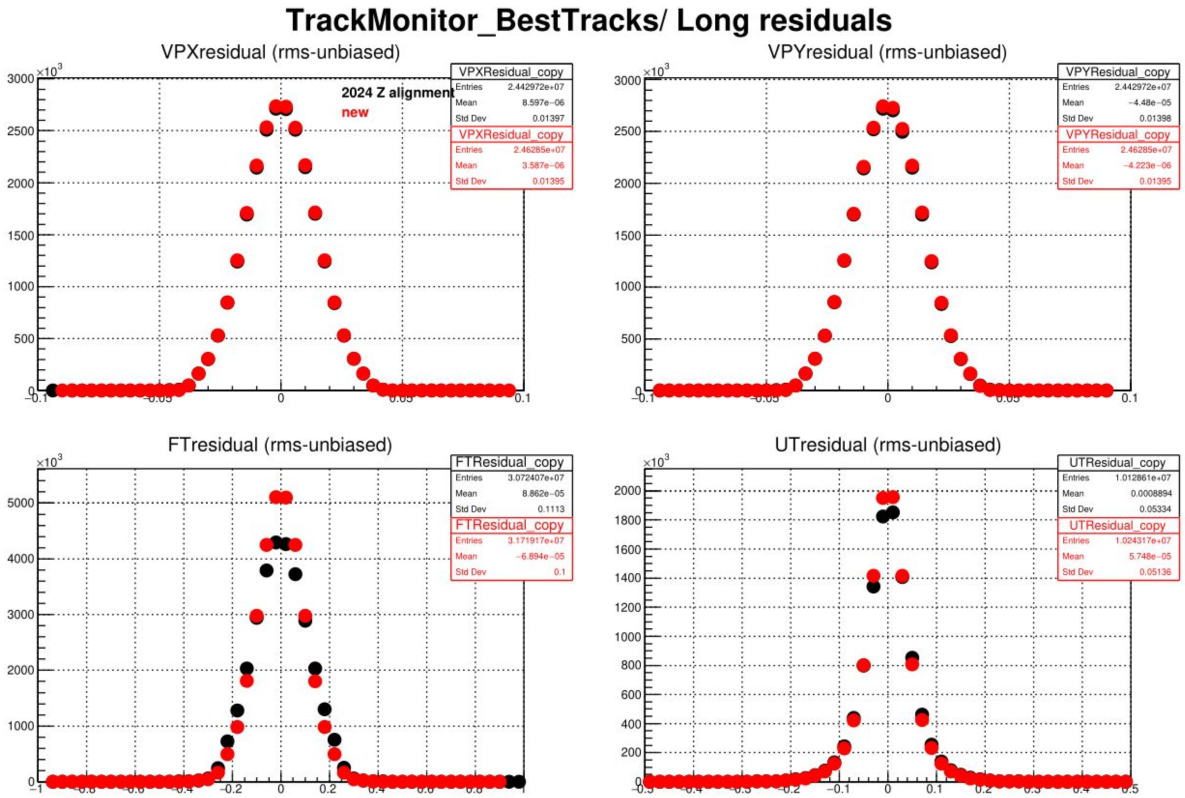
- Plan to **re-align detectors in z** as well as VELO modules and sensors when we have enough statistics with high momentum tracks

Improvements with the new tracker alignment



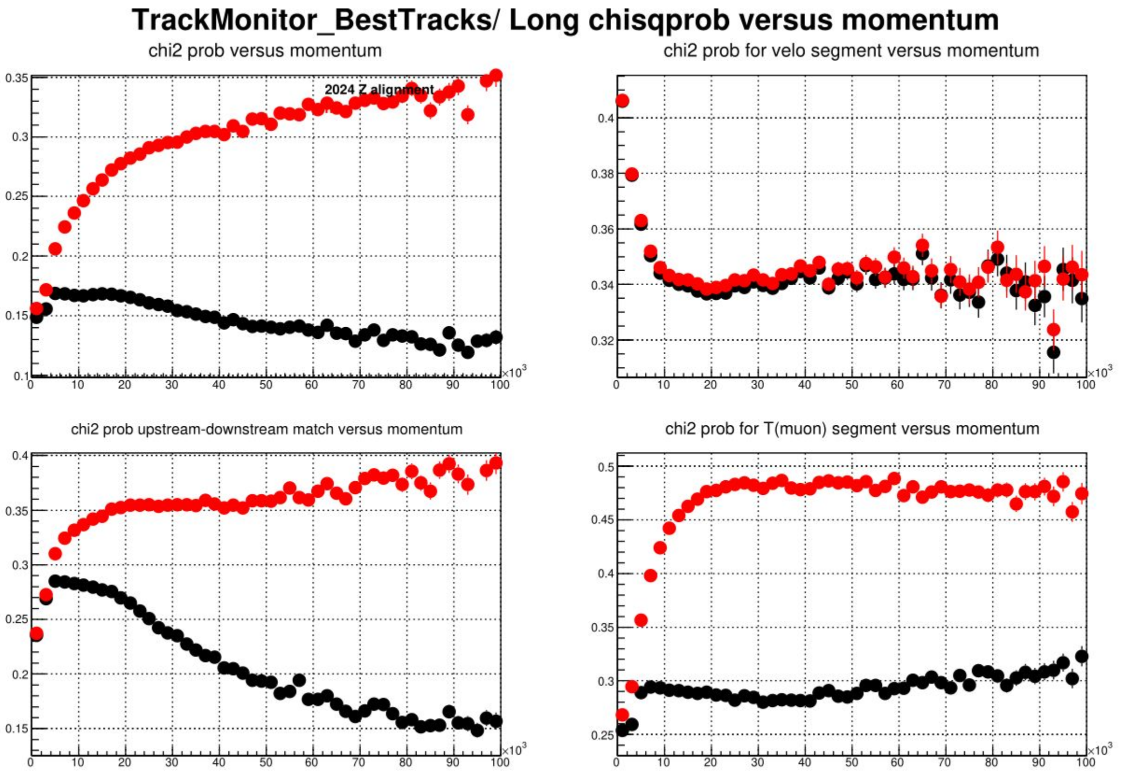
- **Overall improvement on track quality** compared to the starting conditions
- This reflects **movements of the detectors during YETS** that had to be corrected by alignment

Improvements with the new tracker alignment



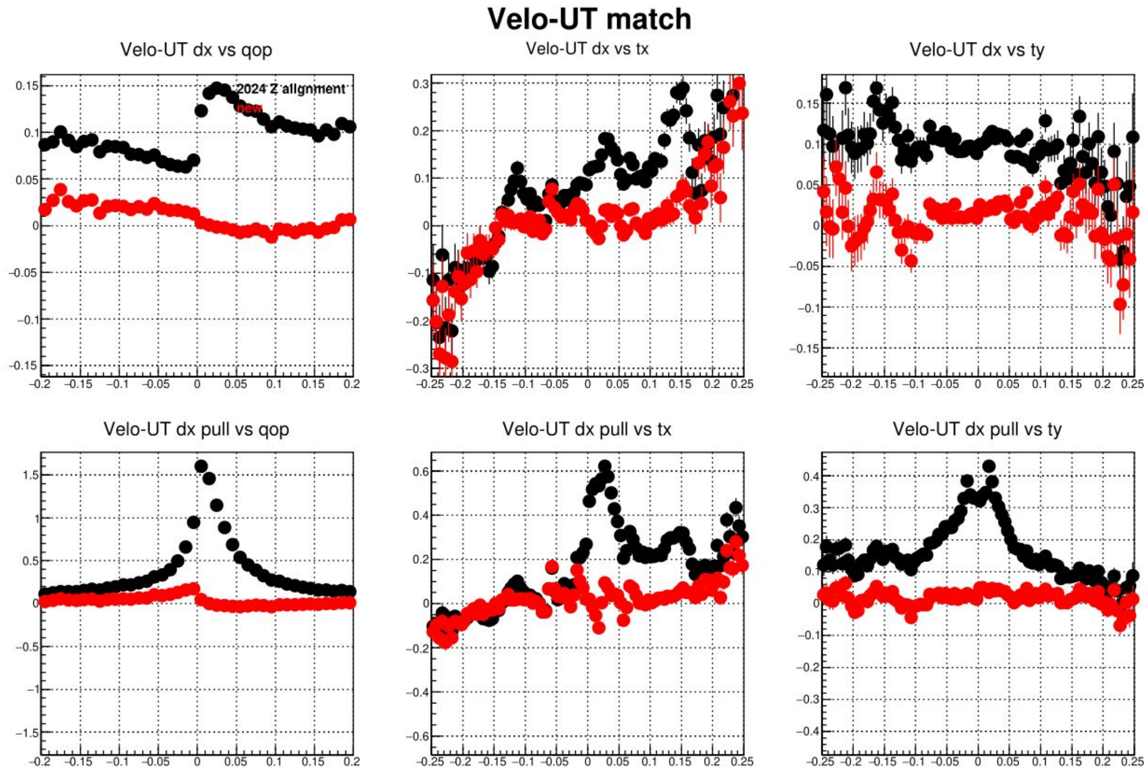
- Visible improvements on **UT and SciFi residuals**
- **VELO residuals** are also expected to improve once we re-align VELO modules

Improvements with the new tracker alignment



- **Better track χ^2 across the whole momentum range** for UT-SciFi and SciFi-Muon track segments

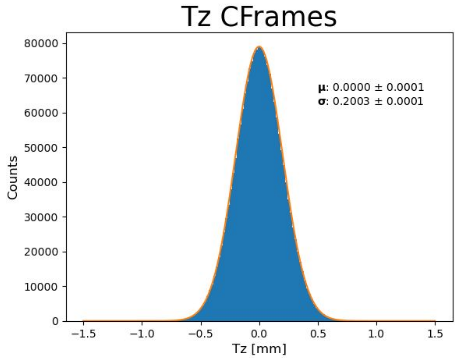
Improvements with the new tracker alignment

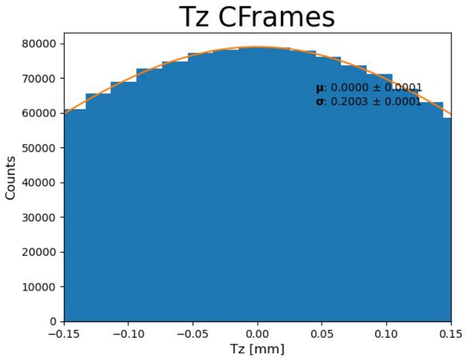


- **Matching plots for VELO-UT** segments become much flatter and centered around 0 ➝ much better VELO-UT relative global alignment

Configuration 1: CFrames Tz

Input misalignments

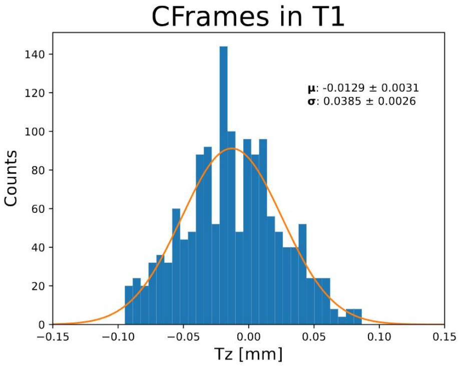


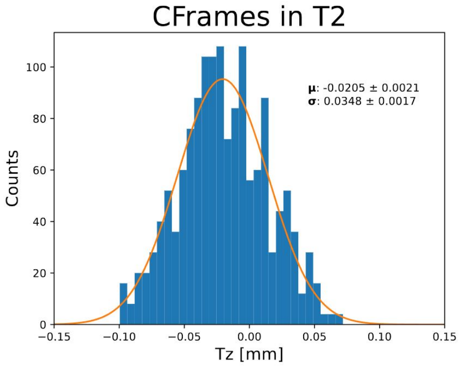


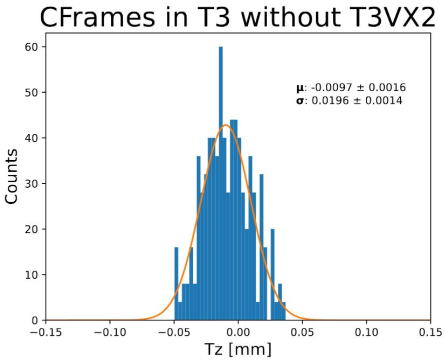
Same x-scale as below

σ [μm] = 200.3 ± 0.1

After alignment







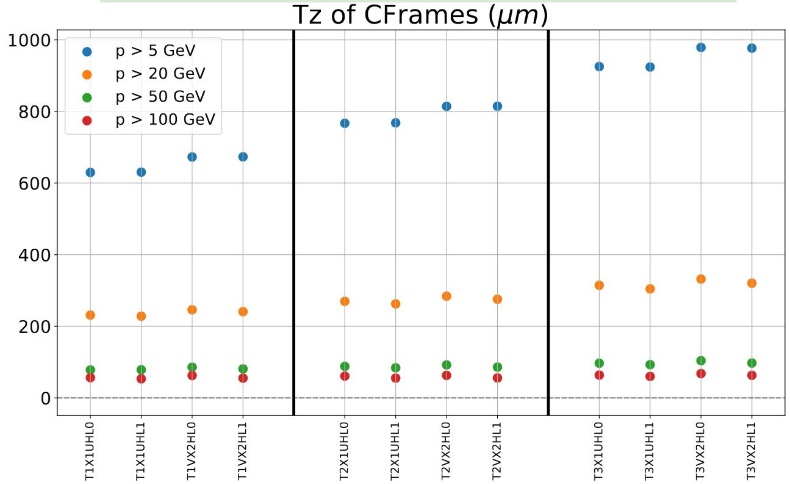
σ [μm] = 38 ± 3

σ [μm] = 35 ± 2

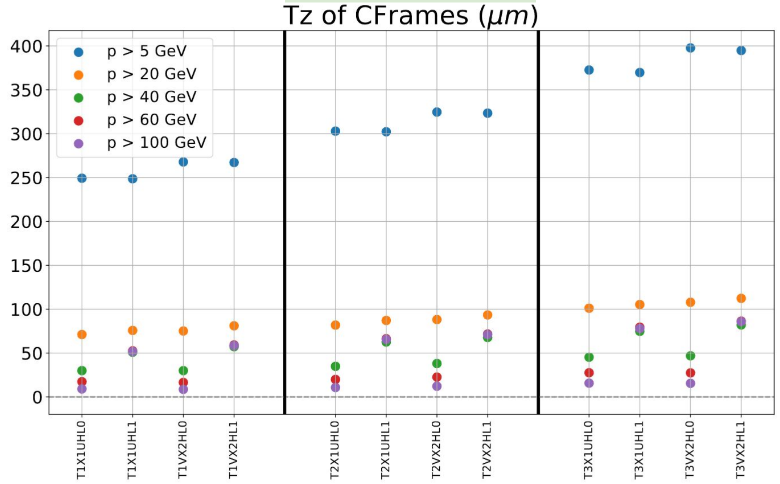
σ [μm] = 20 ± 1

Bias on the z scale: CFrames Tz

With D^0 + J/ψ + $\Upsilon(1S)$ mixture

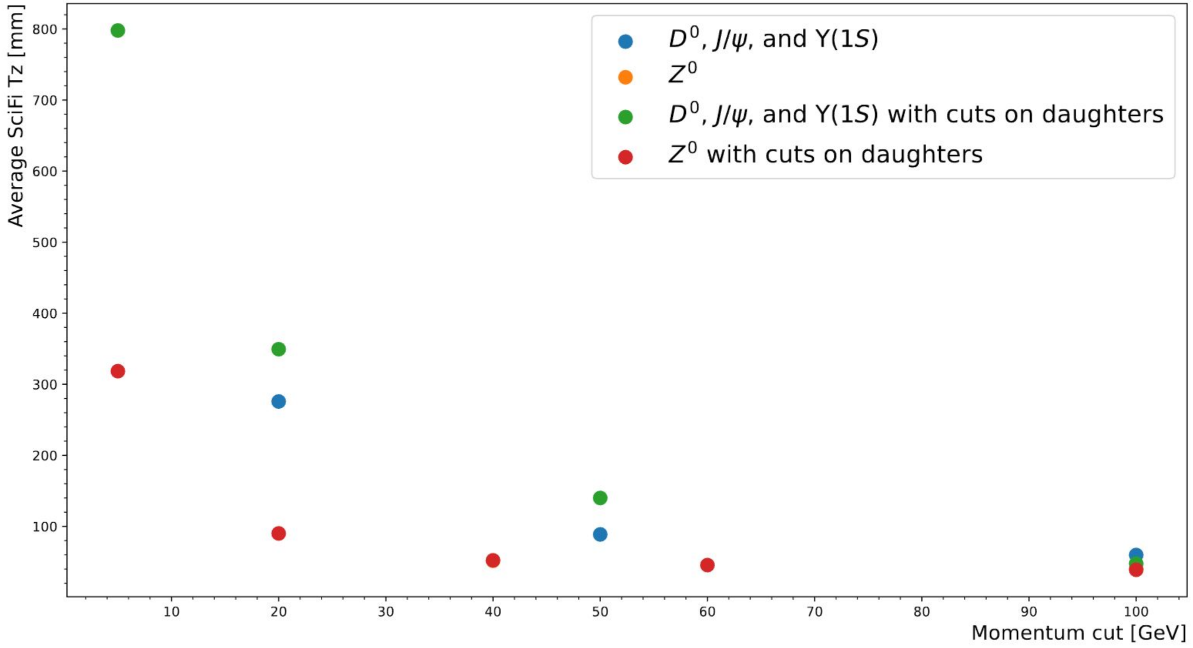


With Z^0



- **Alignment dof:** Tz for CFrames
- Quite **strong momentum dependence** → Large z bias of ~ 800 μm almost completely gone when using tracks with p > 50 GeV
- Clear indication that **something is biasing the reconstruction of low momentum tracks**
  - Wrong estimation of scattering corrections
  - Inaccuracies in the magnetic field integration during tracking
  - …
- Bias present in both samples but **smaller when employing Z^0** → Larger amount of high momentum tracks

Overall size of the bias



- Plot **average z movement of SciFi as a function of the momentum cut**
- Results from **configuration with only CFrames Tz** as dof
  - Similar results with the configuration including modules and half-modules
- **Better results if momentum selections are only applied to tracks selected for alignment** and not to particle daughters for the mixed sample
  - Mass constraints beneficial to fix the z scale even if lower momentum tracks are biased

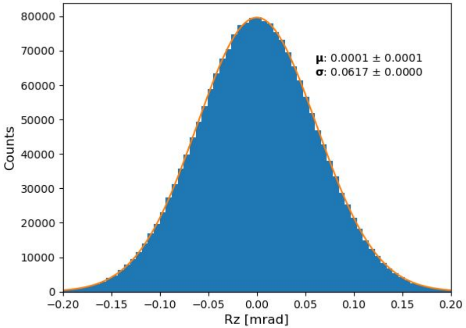
We can achieve a similar performance as with Z^0 employing **D^0 + J/ψ with a tight momentum cut of ~50 GeV**

Modules Rz

External modules excluded

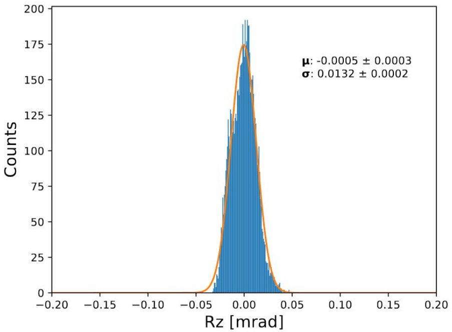
Input misalignments | **After alignment**

All modules



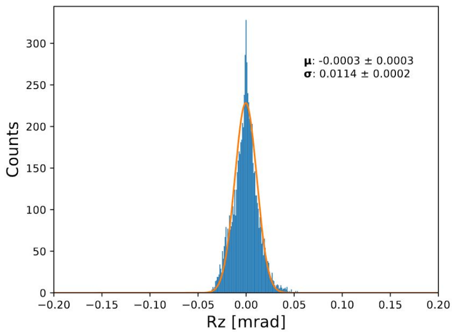
σ [μrad] = 61.7 ± 0.1

Modules in station 1



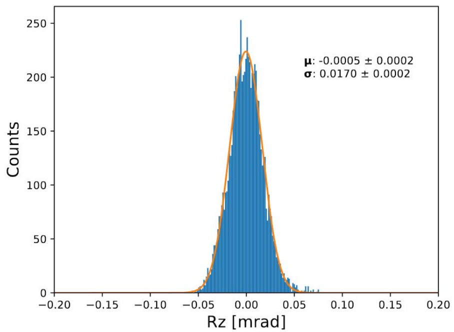
σ [μrad] = 13.2 ± 0.2

Modules in station 2



σ [μrad] = 11.4 ± 0.2

Modules in station 3



σ [μrad] = 17.0 ± 0.2