Performance of the real-time alignment and calibration of the LHCb detector in Run 3 of the Large Hadron Collider

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

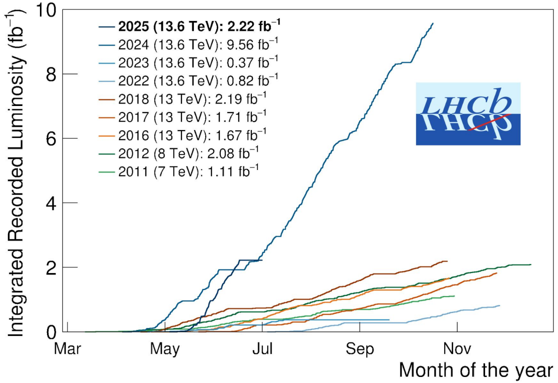
The LHCb detector

The LHCb detector underwent a **major upgrade for Run3**

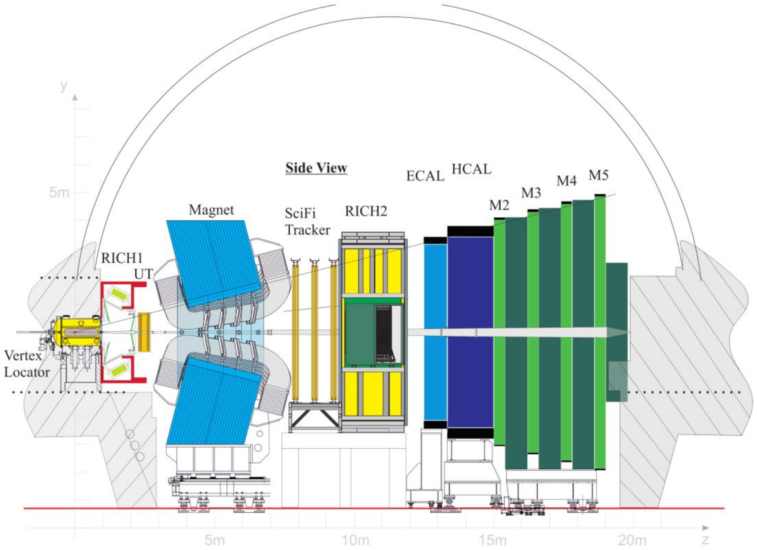
- Many key flavor **physics observables remain statistically limited**
- Now we take data at a **x5 larger instantaneous luminosity** compared to Run 2

Key points of the upgrade:

- Renovated **tracking system** with increased granularity and faster response
- Faster **RICH photodetectors** and improved **optics**
- Upgraded read-out **electronics and Data Acquisition (DAQ)** system
- New full **software-based trigger** system



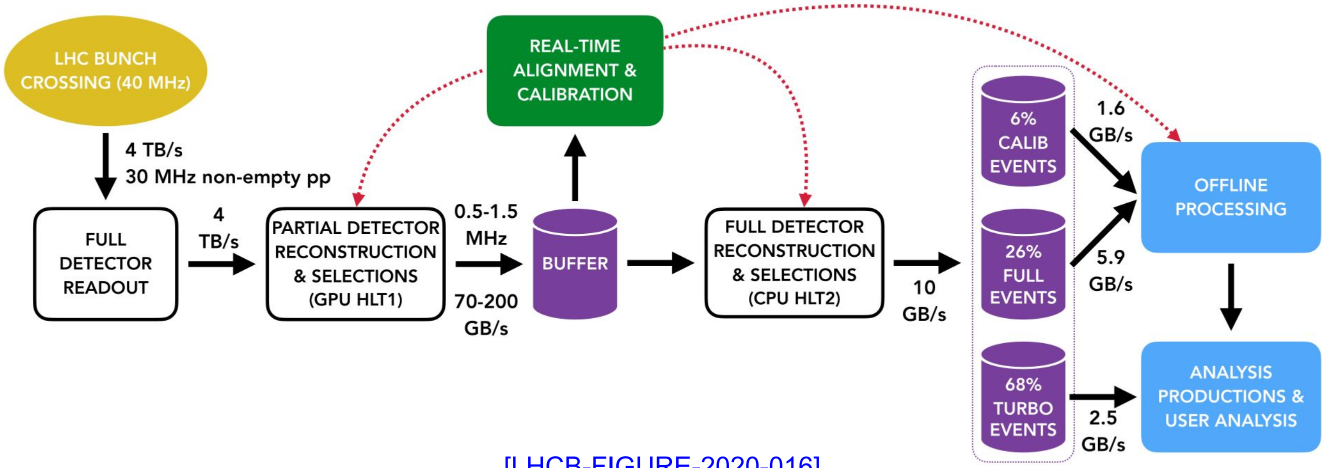
LHCb detector In Run 3



[JINST 19 (2024) P05065]

Only in 2024 we collected more pp data than in Run 1 and Run 2 combined!

The LHCb dataflow



[LHCB-FIGURE-2020-016]

- Data processed through a two-stage **full software-based trigger system** ➝ Novel approach implemented for Run 3!
- **HLT1** applies a **partial event reconstruction** and a set of more inclusive selections: 30 MHz input rate ➝ ~ 1 MHz output rate
  - Running on GPUs
- **HLT2** runs an **offline-level reconstruction** and more refined selections targeted to specific analyses
  - Running on CPUs
- Dedicated HLT1 algorithms collect **data for alignment and calibration** purposes ➝ Corrections computed and propagated in real time to both HLT1 and HLT2

More details in: “The upgraded LHCb trigger system”, Dorothea von Bruch

Performance of the trigger system

Hardware level **L0 trigger operating in Run 1 and Run 2** employed calorimeter and muon system information to reduce the HLT1 input rate to 1 MHz

- Inefficient for low momentum heavy-flavor hadron decays
- Main bottleneck to operate the detector at larger luminosity and pile-up

New trigger selects **heavy-flavor decays at low p_T** more efficiently

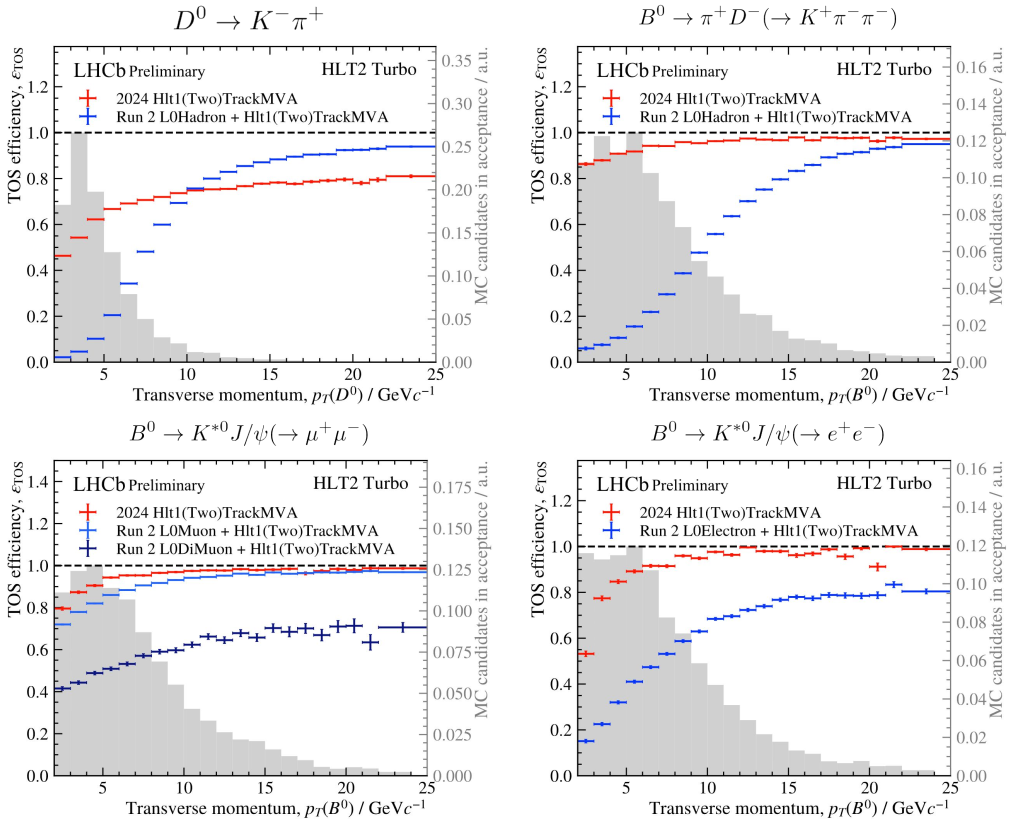
- Overall performance substantially better than in Run 2
- Largest improvements for channels involving hadrons and electrons in the final state

HLT performance relies on precise alignment and calibration of the detector

Real-time alignment and calibration now more important than ever!

See also: "BuSca: New Strategies for LLP Searches at 30 MHz at LHCb", Jiahui Zhuo

Trigger efficiencies compared to Run 2

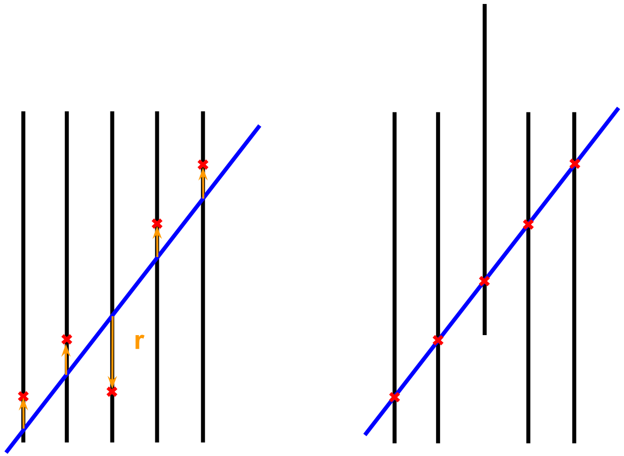


[LHCB-FIGURE-2024-030]

The alignment algorithm

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
α: set of alignment constants
r: vector of track residuals
V: covariance matrix of track residuals

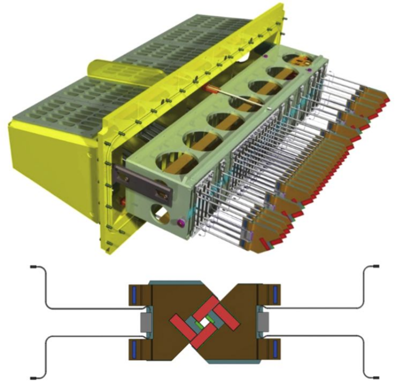
- Minimization is **performed iteratively** starting from input geometry with constants α_0

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

Newton-Raphson's equation for $\mathrm{d}\chi^2/\mathrm{d}\alpha$

- **Survey measurements** taken during construction and survey campaigns and **mass and vertex constraints** from reconstructed particle candidates are employed to support the minimization [Nucl.Instrum.Meth.A 712 (2013) 48-55]

Alignment of the VELO



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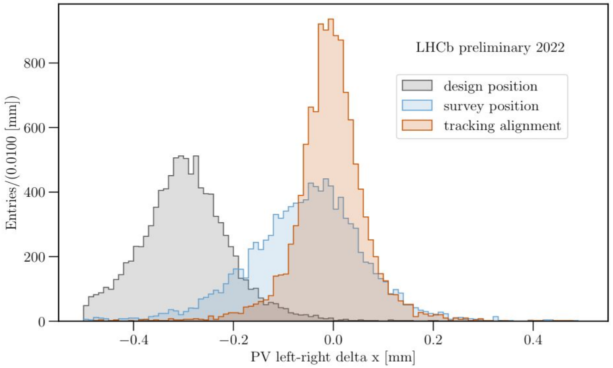
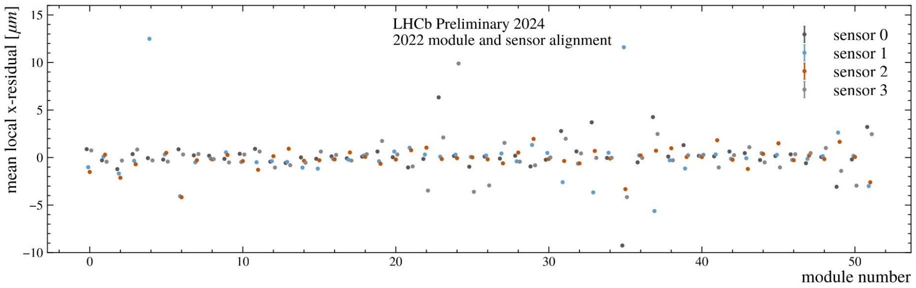


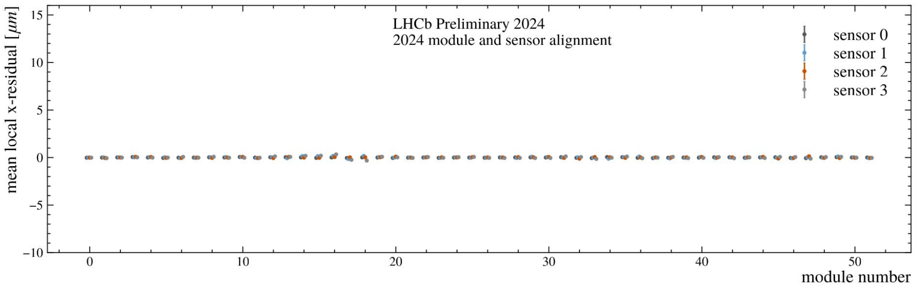
[LHCB-FIGURE-2022-016]

- The VELO is in an open position when beams are injected and **closes around the interaction region when stable beams** are declared ➝ Need to **correct for misalignments in real-time**
  - ~2.5 µm precision in the x-y plane and ~15 µm along the beam axis
- Alignment quality **monitored in real-time** employing reconstructed primary vertices
- **Alignment of VELO modules and sensors** also performed regularly

Before alignment



After alignment



[LHCB-FIGURE-2024-009]

Alignment of the tracker

First global tracker alignment (VELO, UT, and SciFi) **performed in 2024 in several stages**

Coarse alignment between detectors obtained employing data taken with the **LHCb magnet turned off**

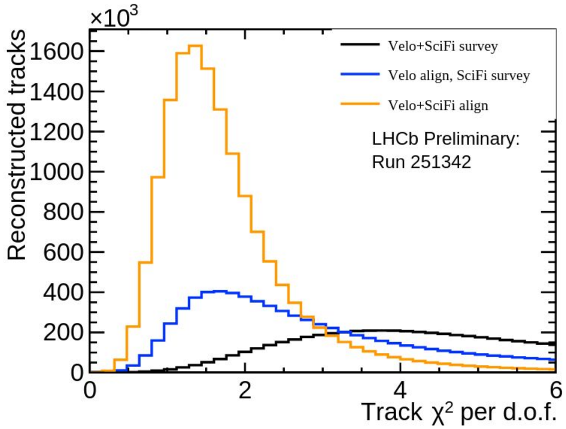
→

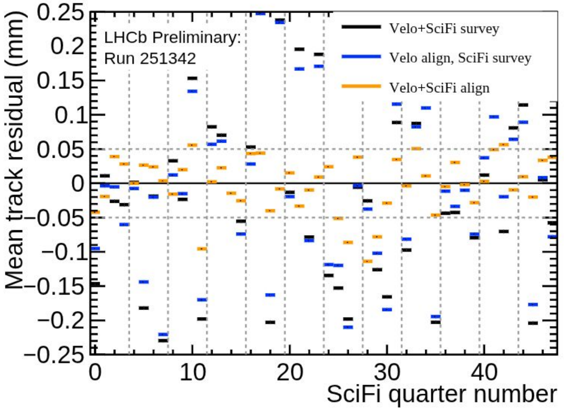
Alignment of the **relative z scale** employing mass constraints from $\mathbf{D^0 \rightarrow K^-\pi^+}$ and $\mathbf{J/\psi \rightarrow \mu^-\mu^+}$ candidates

→

Inclusion of **internal dof** from all the sub-detectors

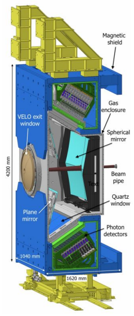
- Full tracker **realigned in 2025** to account for changes on the conditions caused by interventions at the beginning of the year
- Tracker alignment **running in real time** and automatic update of constants active since this year

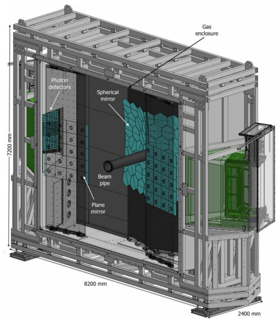




[LHCB-FIGURE-2022-018]

RICH alignment and calibration



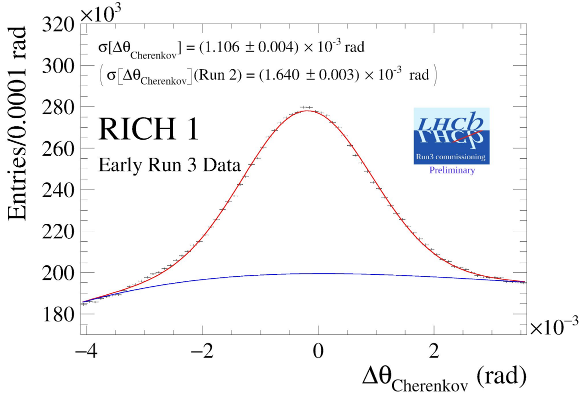


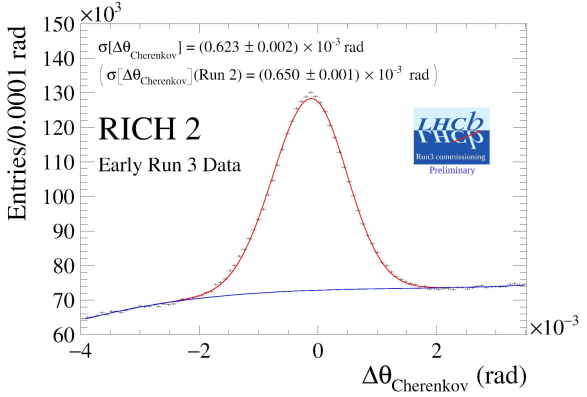
[JINST 19 (2024) P05065]

- **Refractive index calibration** ➞ Compute calibration factors comparing the expected and reconstructed Cherenkov angle of charged particles

$$\cos\theta_c = \frac{1}{n\beta}$$

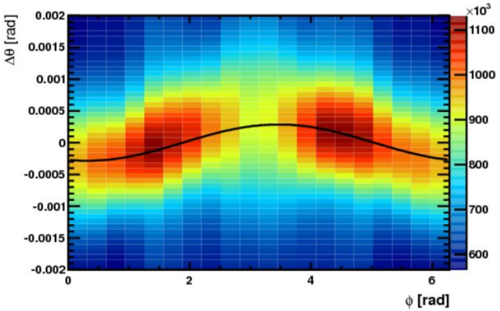
- Refractive index affected by **changes in pressure and temperature** ➞ Continuously monitored and calibrated
- **Misalignment of RICH mirrors** ➞ Biases on the reconstructed angle across the RICH
- Mirror **alignment corrected in real time**



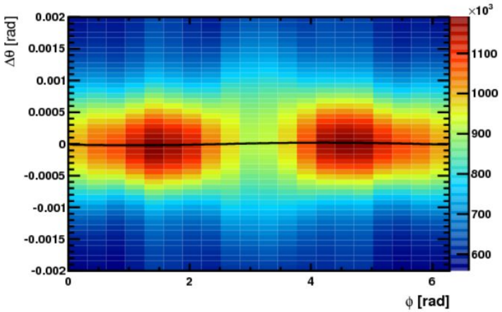


[LHCB-FIGURE-2023-007]

Before alignment

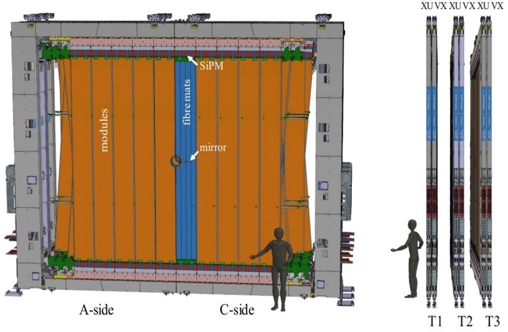


After alignment



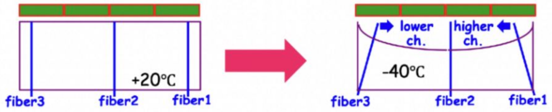
[Eur. Phys. J. C 73 (2013) 2431]

Calibration of the SciFi mat-end contraction



[JINST 19 (2024) P05065]

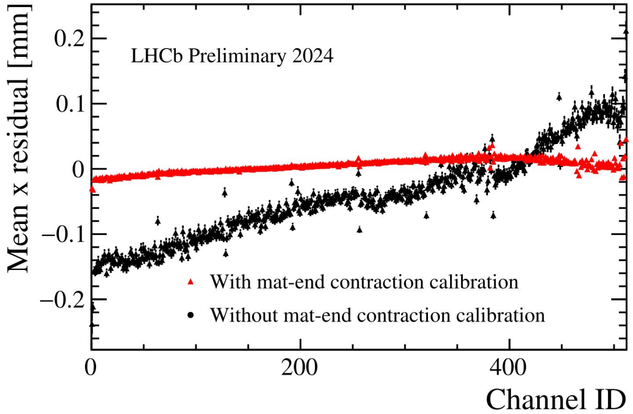
- **Scintillating fibers** are assembled into mats and **read out by Silicon Photomultipliers (SiPMs) cooled to -50 °C** in nominal conditions
- Fiber mats and SiPMs have **different thermal expansion** coefficients ➙ Relative contraction of mats-ends with respect to the SiPMs ➙ **Wrong SiPM channel to hit mapping**

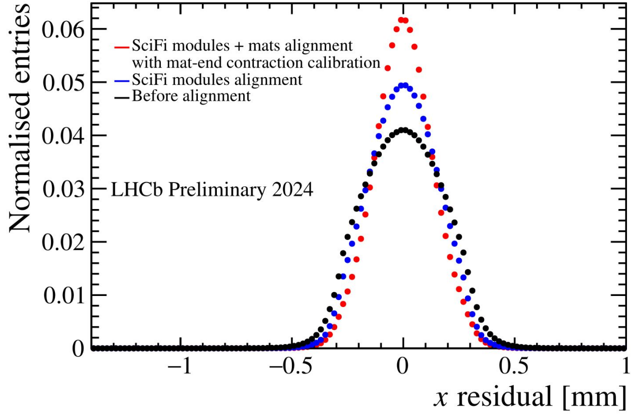


Contraction can reach ~250 μm

- **Calibration corrects the channel to hit mapping** fitting a linear model to the track residuals in each SiPM

Effect currently being studied employing data collected with SciFi cooled to different temperatures

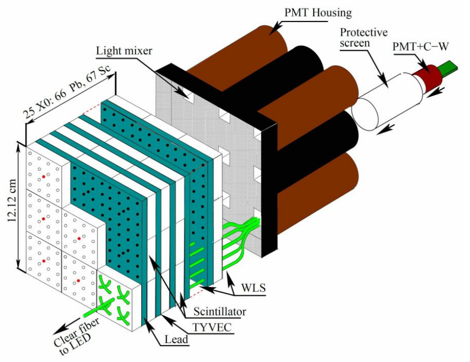




[LHCB-FIGURE-2024-009]

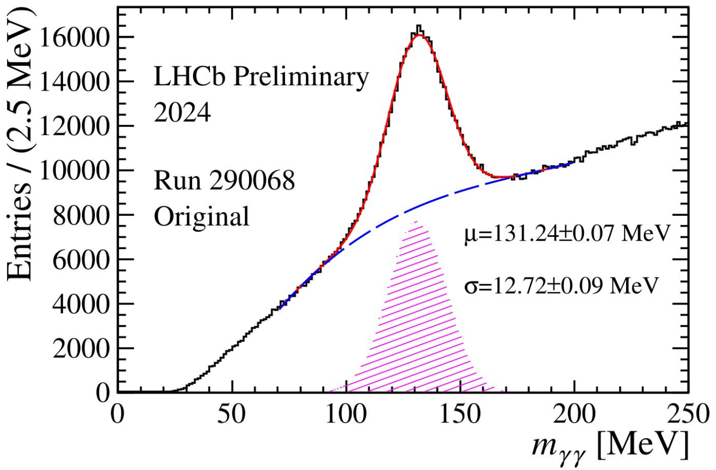
ECAL π^0 calibration

- Calibration of the **ECAL energy scale** applied cell-by-cell using $\pi^0 \rightarrow \gamma\gamma$ decays
- **Running in real time** and new corrections applied if changes on the reconstructed π^0 mass are significant
  - ~6000 cells are continuously monitored and calibrated!
- Necessary to **compensate aging of scintillators and photomultipliers** due to large radiation doses

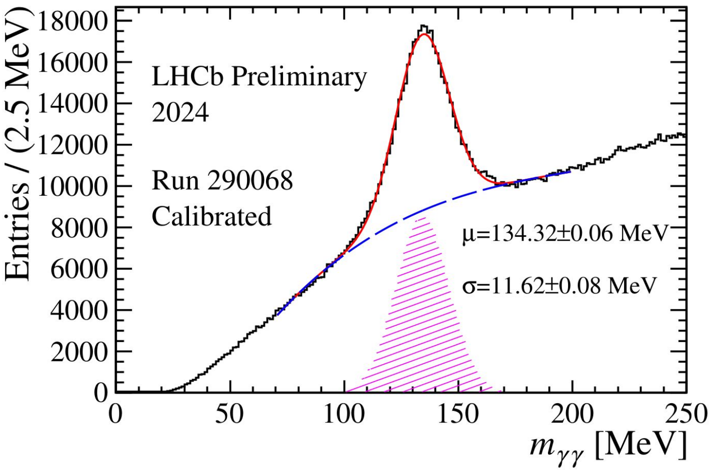


[JINST 19 (2024) P05065]

Before calibration



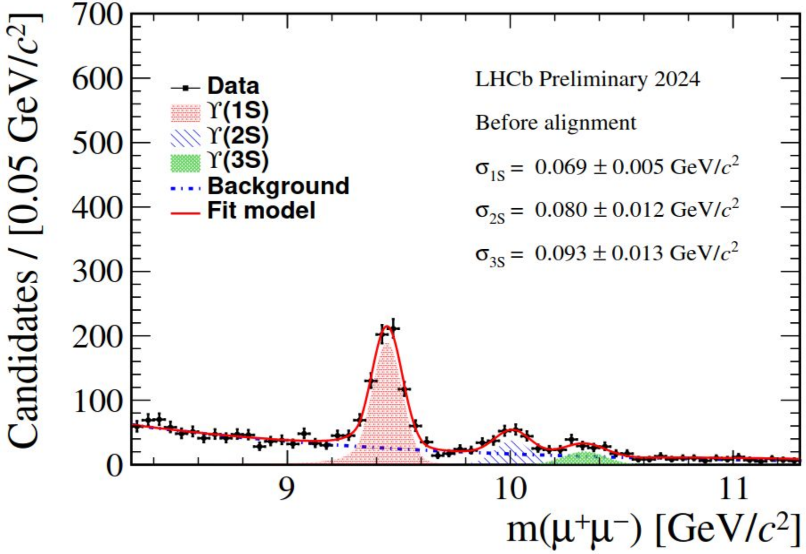
After calibration



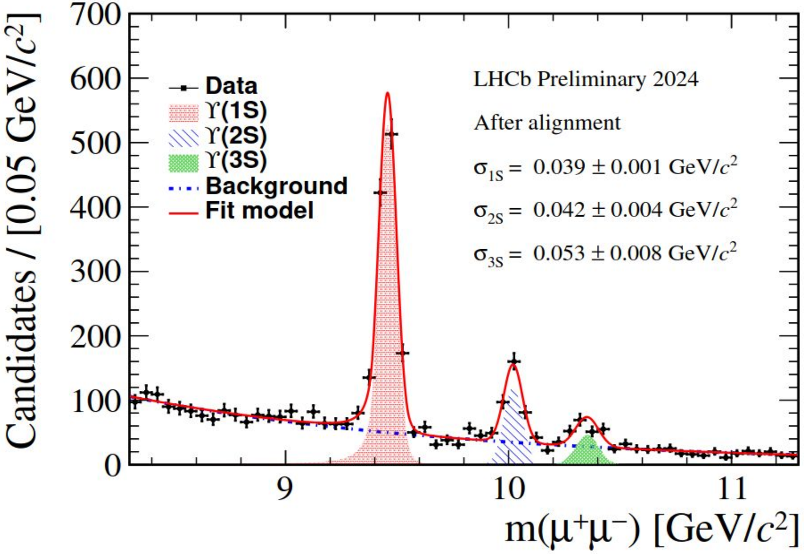
[LHCB-FIGURE-2024-009]

Mass resolution

Before alignment



After alignment

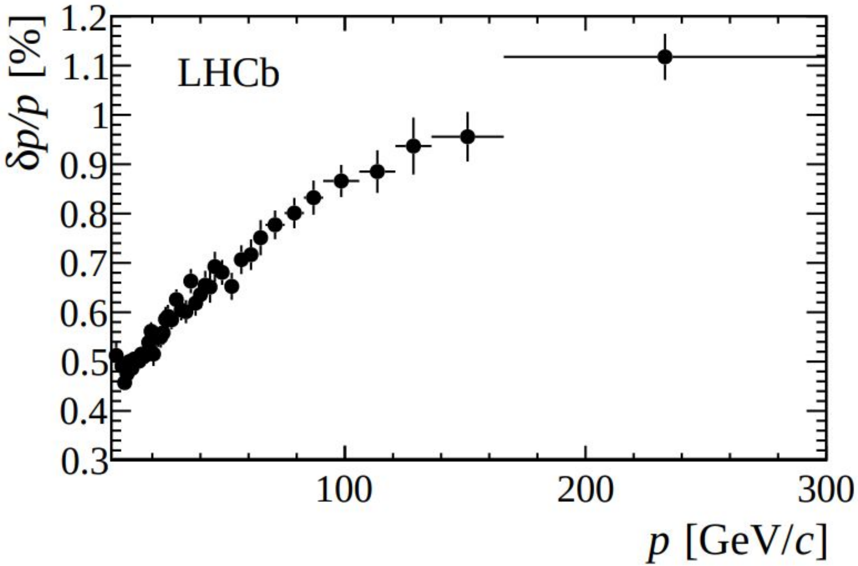


[LHCb-FIGURE-2024-037]

Large impact on mass resolution and signal efficiency!

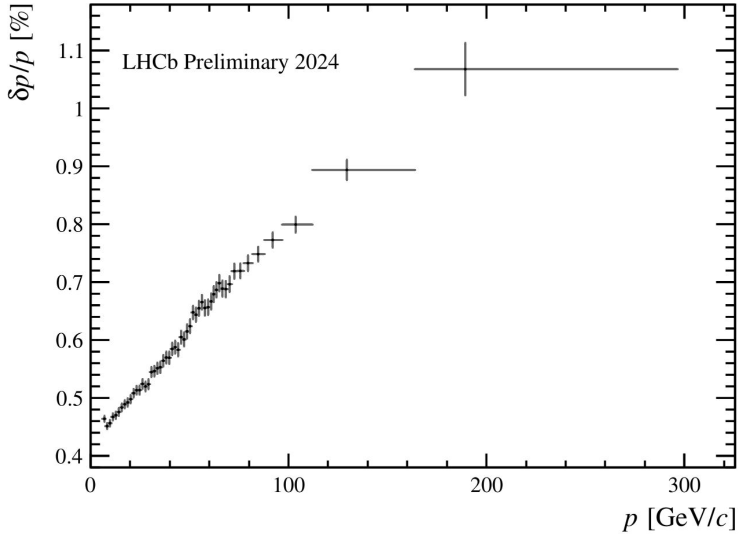
Momentum resolution

Run 2



[Int. J. Mod. Phys. A 30 1530022 (2015)]

Run 3



[LHCb-FIGURE-2024-040]

Compatible with Run 2 performance in a much harsher environment

For more performance highlights see: “Tracking and PID performance with the upgraded LHCb detector”, Giovanni Cavallero

Summary

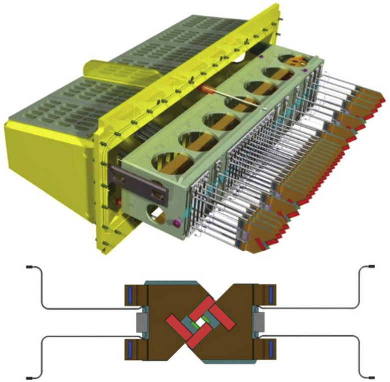
- The **LHCb detector underwent a large upgrade** for Run 3 allowing us to take data at **x5 more luminosity**
- Designed a **full software-based trigger system** to cope with the larger data rates
- **Real-time alignment and calibration** corrections are crucial to operate the new trigger

Thank you!

Backup

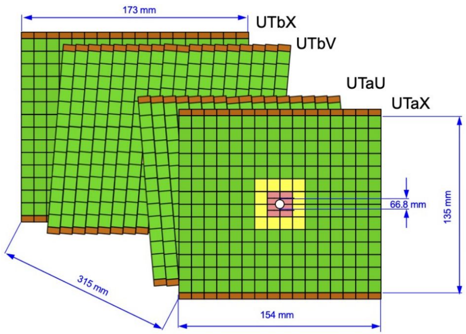
The new tracking system

Vertex Locator (VELO)

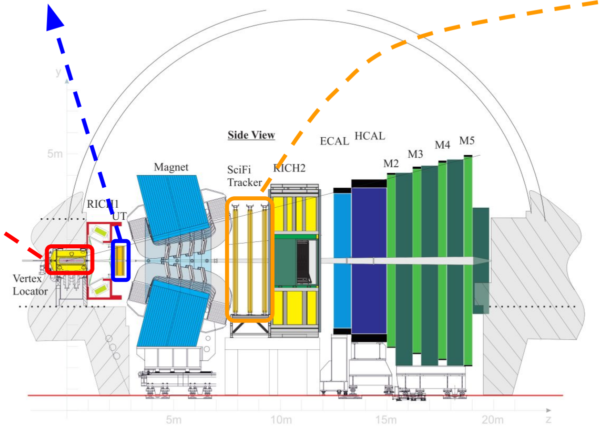


- L-shaped **silicon pixel modules** arranged along **two retractable halves**
- **≤15 μm hit resolution** in the x-y plane

Upstream Tracker (UT)

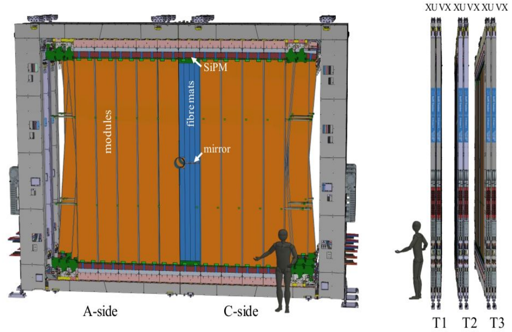


- **Silicon strip detector** with **sensors assembled in modules**
- **≤50 μm hit resolution** in the x axis



[JINST 19 (2024) P05065]

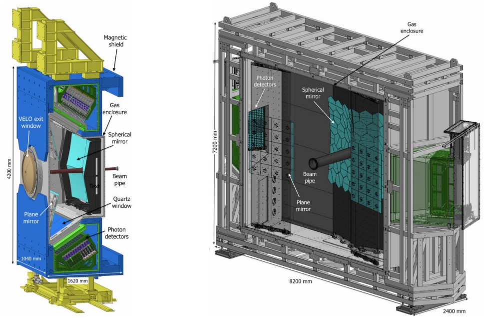
Scintillating Fiber Tracker (SciFi)



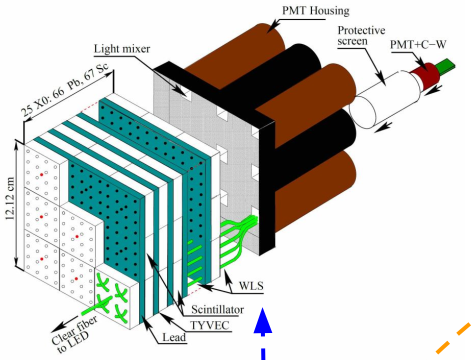
- 5 m long **scintillating fibers arranged into modules** in the vertical direction
- **Modules split into halves** by a mirror to increase light yield collected by Silicon Photomultipliers
- **≤100 μm hit resolution** in the x axis

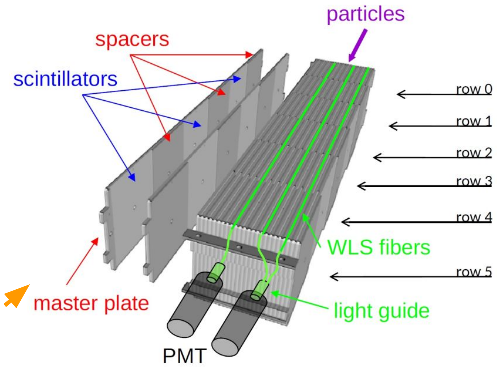
Further upgrades

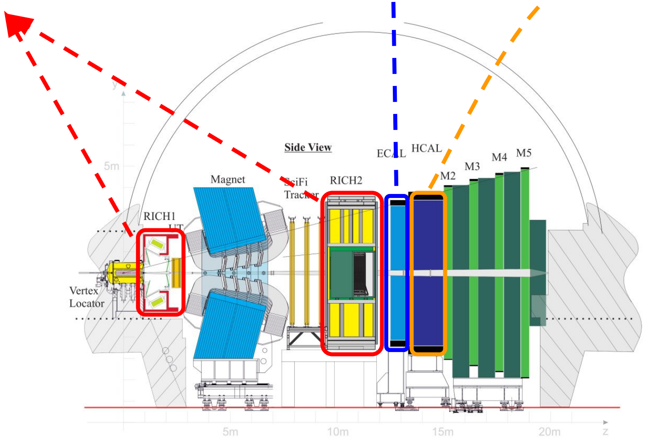
Ring Imaging Cherenkov Detectors (RICH1 and RICH2)



Electromagnetic and Hadronic Calorimeters







- New Multi-anode Photomultiplier tubes for with **x40 faster read-out electronics**
- **Improved RICH1 optical mirrors** to reduce occupancy
- Provide **PID information** for charged hadrons in the **2.6-100 GeV/c range**

[JINST 19 (2024) P05065]

- Shashlik-type sampling calorimeters from Run 2 with **faster read-out electronics**
- **Energy measurements** and complementary **PID information** including leptons and photons