PROCEEDINGS OF SCIENCE

PoS(ICHEP2024)900

Real-time alignment and calibration performance of LHCb with Run 3 data

---

Zehua Xu[a,*]

On behalf of LHCb Collaboration
[a] *European Organization for Nuclear Research (CERN),*
1211, Geneva, Switzerland

E-mail: `zehua.xu@cern.ch`

The upgraded LHCb detector is taking data at a five times higher instantaneous luminosity than in Run 2. To cope with the harsher data taking conditions, LHCb deployed a purely software based trigger composed of two stages: in the first stage the selection is based on a fast and simplified event reconstruction, while in the second stage a full event reconstruction is used. This gives room to perform a real-time alignment and calibration after the first trigger stage, allowing to have an offline-quality detector performance in the second stage of the trigger. In this talk we will present the framework and the procedure for a real-time alignment of the LHCb detector and show key figures such as tracking and PID performance on Run 3 data.

42nd International Conference on High Energy Physics (ICHEP2024)
18-24 July 2024
Prague, Czech Republic

---

[*] Speaker

1. Introduction

The LHCb experiment underwent a major upgrade between 2019 and 2024, increasing its capabilities to handle an average of 5 visible proton-proton collisions per bunch crossing. This upgrade significantly enhances the experiment's sensitivity in the flavor physics sector, while expanding the overall scope of the LHCb physics program [1, 2].

To manage the higher instantaneous luminosity, the trigger system must be both fast and flexible to accommodate the wide range of physics studies conducted at LHCb. These include heavy flavor studies, electroweak physics, forward physics, and heavy-ion collisions. This challenge is met by a software-only trigger system, which is divided into two stages: High Level Trigger 1 (HLT1) and High Level Trigger 2 (HLT2). Both stages rely on real-time data analysis, incorporating a full online event reconstruction and selection process. Achieving the detector's design performance requires precise real-time alignment and calibration of its subsystems. This includes aligning the tracking detectors and calibrating the particle identification systems. Since the trigger operates in real time, these alignment and calibration procedures must be carried out online. The overall trigger structure and the real-time alignment and calibration processes are fully discussed in [3, 4] and are illustrated in Figure 1.

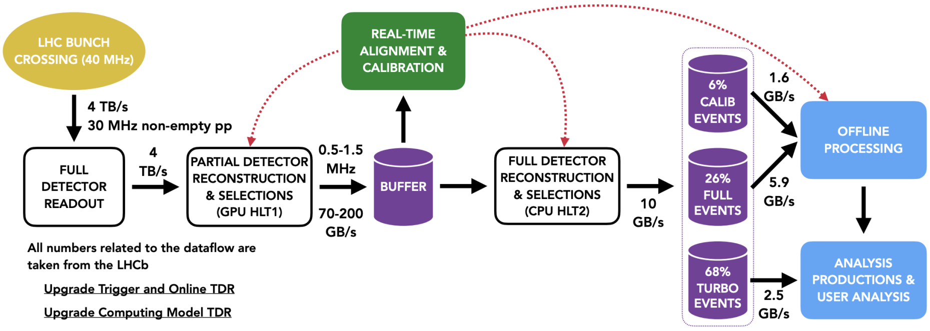

Figure 1: LHCb upgrade dataflow.

In the following sections, we describe the real-time alignment and calibration process and present the corresponding performance results for each sub-detector.

2. Process of real-time alignment and calibration

Two key procedures are employed at LHCb: alignment (applied to VELO, RICH mirrors, UT, SciFi, and Muon systems) and calibration (for RICH and ECAL), as illustrated in Fig. 2. Both processes are initiated at the start of each LHC fill and are fully integrated into the LHCb control system. Dedicated HLT1 trigger lines select events relevant for alignment and calibration. These selected events are temporarily stored in a buffer until sufficient statistics are accumulated, allowing the alignment and calibration procedures to be executed before HLT2. This approach ensures that HLT2 uses the most up-to-date and precise alignment and calibration constants.

The alignment of the tracking detectors (VELO, UT, SciFi, and Muon) is achieved by minimizing the residuals with respect to the selected alignment parameters, which account for translations

PoS(ICHEP2024)900

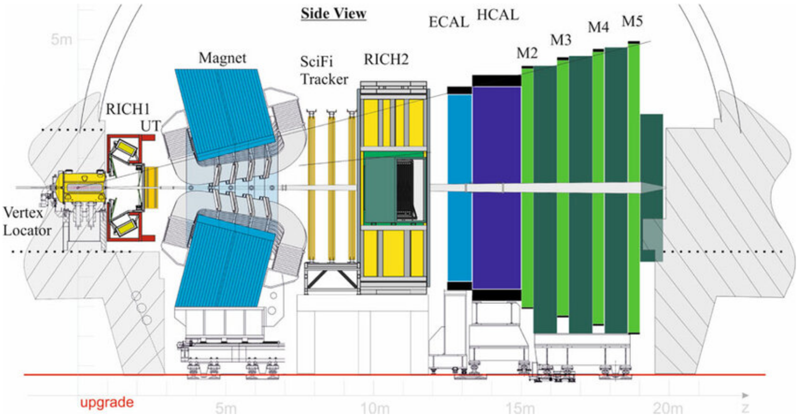

Figure 2: Side view of the LHCb upgrade detector.

and rotations of the detector elements. This minimization process employs the iterative Newton-Raphson method, with the first and second derivatives calculated using a Kalman filter, as used in track reconstruction. Additional constraints, such as vertex and mass constraints, can be incorporated to further increase precision [5]. Technically, the alignment procedure is divided into two components: the Analyzer and the Iterator. The Analyzer performs track reconstruction, computes the necessary derivatives, and stores them in binary files. The Iterator then gathers the derivatives, executes the minimization step, and performs a convergence check. If a significant change is detected between the previous and newly computed alignment constants, the updated constants are applied in HLT2. As the Analyzer utilizes multi-threaded reconstruction across 163 nodes, the time required for alignment is expected to be comparable to that in Run 2 [6]. The overall real-time alignment and calibration process for Run 3 is illustrated in Fig. 3. The sub-detectors are aligned and calibrated using the initial runs within each fill, and the corresponding performance will be discussed in the following section.

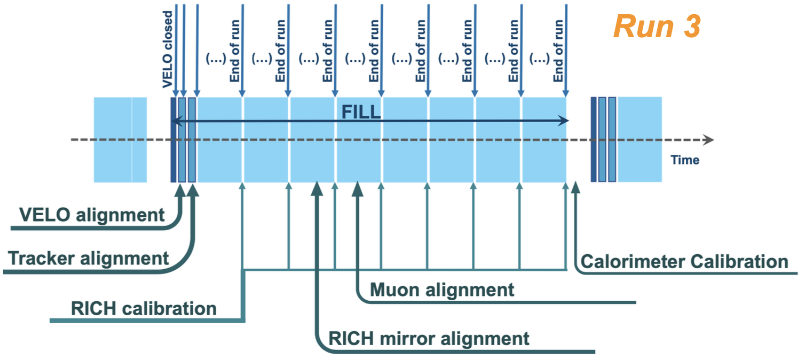

Figure 3: Process of real-time alignment and calibration at Run 3.

3. Alignment and calibration of sub-detectors

The alignment of the VELO detector is monitored by tracking the primary vertex (PV) position [7]. Any misalignment is detected through biases in the PV, and the residuals are minimized during the alignment process. After alignment, the mean of residuals are smaller than 0.4 μm in absolute term, demonstrating a good quality of the alignment, as shown in Fig. 4.

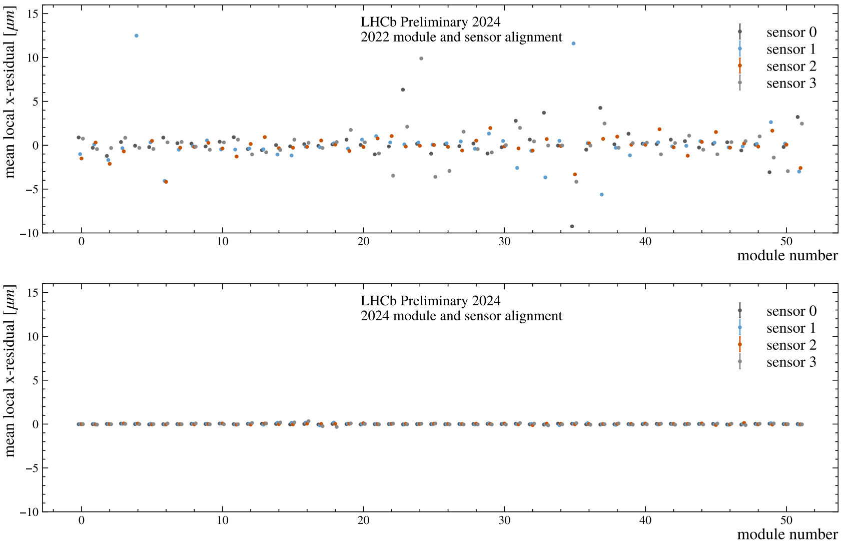

Figure 4: Mean values of residuals in local x-direction of VELO tracks using the module and sensor alignment obtained with 2022 data (Top), shown for each sensor of each module. The residuals are evaluated using data taken in April 2024 (Top). Mean values of residuals in local x-direction of VELO tracks using the module and sensor alignment obtained with 2024 data (Bottom).

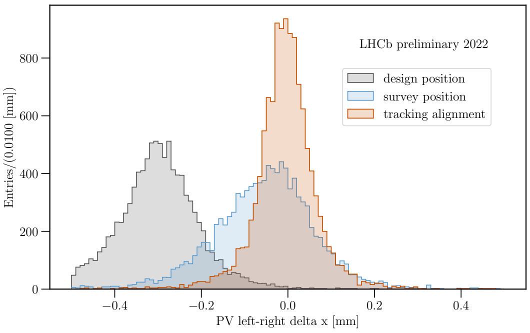

Figure 5: Distance of the x position of PVs reconstructed using tracks crossing only the left or right VELO half using the design position (grey), survey measurement corrections (blue) and tracking alignment corrections (orange).

Additionally, the VELO closes at the beginning of stable beam collisions. The quality of VELO alignment can be inferred by measuring the distance between the reconstructed PV positions using tracks from only the right or left half of the detector. Any discrepancy between the two sides may indicate misalignment, as shown in Fig. 5.

The SciFi tracker [8], composed of fiber modules, shows significant improvements after alignment, particularly in terms of hit resolution and track fitting quality. The active part of the modules are composed of 8 sub-modules, named mats. The alignment compensates for mat contraction effects caused by SiPM cooling, greatly enhancing the momentum resolution of the tracks. Track quality and hit residuals are displayed in Fig. 6 and Fig. 7, with residuals reaching approximately 100 μm.

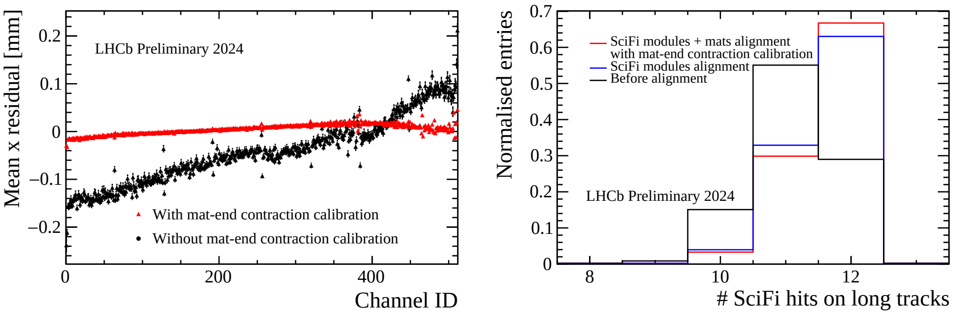

Figure 6: (Left) Mean of the track residual in x as a function of the channel ID in one of the mats of the SciFi (mat number 10). Evaluated for two different configurations of the SciFi with (red) and without (black) mat-end contraction calibration. Applying the mat contraction calibration yields in residuals centred around zero. (Right) Number of ScFi hits on long tracks evaluated for three different configurations of the SciFi.

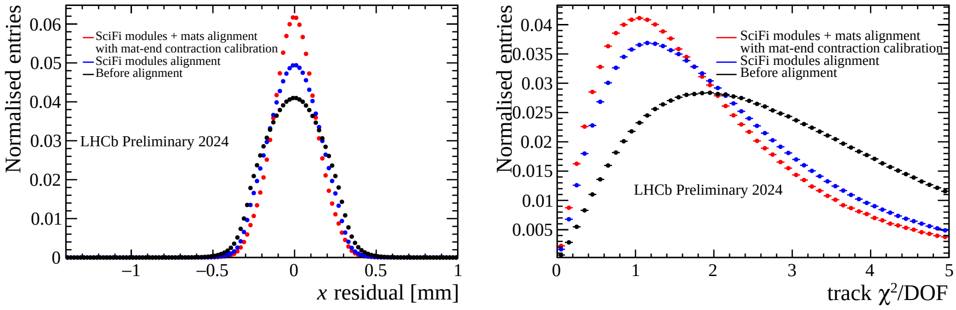

Figure 7: (Left) Track residual in the x direction for long tracks evaluated for three different configurations of the SciFi alignment. (Right) Track χ^2 per degrees of freedom for the SciFi segment of long tracks evaluated for three different configurations of the SciFi alignment.

The electromagnetic calorimeter (ECAL) calibration corrects the energy measurements for each of its 6016 cells [9]. The calibration is based on the reconstructed π^0 mass, and after applying the calibration constants, the mass resolution improves significantly. These corrections are crucial for obtaining accurate energy measurements, especially in events involving photons and electrons. The results from calibration, using 2024 data with and without the calibration constants, are shown in Fig. 8.

4. Conclusions and prospects

The real-time alignment and calibration framework has substantially improved tracking precision and particle identification during Run 3, delivering offline-quality reconstruction in real time.

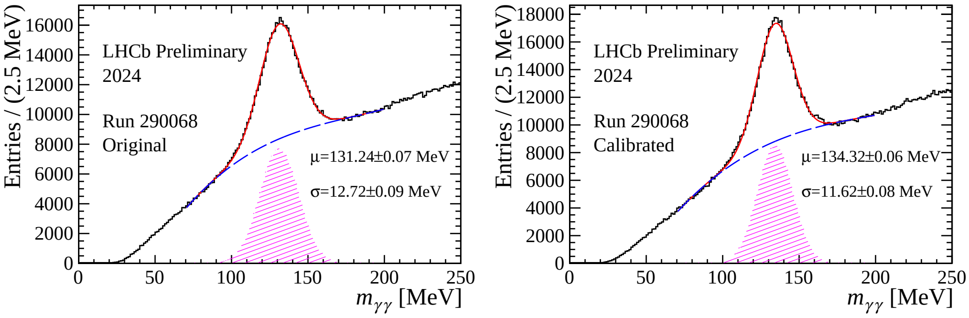

Figure 8: Photon-photon invariant mass before (left) and after (right) applying the calibration constants. The shown fit uses a Gaussian for the π^0 signal and a second-order polynomial for the background.

As more data is collected, the system will continue to be refined, further optimizing performance and allowing LHCb to explore new frontiers in flavor physics and other areas of particle physics.

References

[1] LHCb collaboration, "Letter of Intent for the LHCb Upgrade", CERN-LHCC-2011-001, 03/2011

[2] LHCb collaboration, "Framework TDR for the LHCb Upgrade", CERN-LHCC-2012-007, 05/2012

[3] LHCb collaboration, "LHCb Trigger and Online Upgrade Technical Design Report", CERN-LHCC-2014-016, 05/2014

[4] LHCb collaboration, "Computing Model of the Upgrade LHCb experiment", CERN-LHCC-2018-014, 05/2018

[5] J. Amoraal et.al., "Application of vertex and mass constraints in track-based alignment", Nucl. Instrum. Meth. A 712 (2013)

[6] S. Borghi, "Novel real-time alignment and calibration of the LHCb detector and its performance", Nucl. Instrum. Meth. A 845 (2017)

[7] LHCb collaboration, "LHCb VELO Upgrade Technical Design Report", CERN-LHCC-2013-021, 11/2013

[8] LHCb collaboration, "LHCb Tracker Upgrade Technical Design Report", CERN-LHCC-2014-001

[9] LHCb collaboration, "LHCb calorimeters : Technical Design Report", CERN-LHCC-2000-036 ; LHCb-TDR-2