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

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The LHCb detector has undergone a major upgrade for Run 3 of the Large Hadron Collider (LHC) to take data at a baseline instantaneous luminosity increased to $\mathcal{L} = 2 \times 10^{33}$ cm^{-2}s^{-1}, a factor of five times larger than in Run 2. A central feature of this upgrade concerns the realization of a completely software-based trigger system that performs a full reconstruction of tracks and particle candidates in real time. The new trigger system allows for a more refined and efficient event selection, made possible by a real-time alignment and calibration of the detector. These proceedings present the status and performance of the real-time alignment and calibration of the LHCb experiment during Run 3 of the LHC.

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1. Introduction

Following a successful operation during Runs 1 and 2 of the Large Hadron Collider (LHC), the LHCb experiment underwent a major upgrade during the long shutdown period before the start of Run 3 in 2022. To improve the statistical precision of key flavor physics observables, the detector was completely redesigned to enable increasing the instantaneous luminosity by a factor of 5 with respect to Run 2, corresponding to a target of $\mathcal{L} = 2 \times 10^{33}$ cm^{-2}s^{-1} [1].

Operating the detector at a higher instantaneous luminosity presents a major challenge: data must also be processed at a higher rate. During Run 1 and Run 2, a first reduction of the input rate was realized by a hardware-level trigger (L0), which discriminated between events containing heavy-flavor decays and soft QCD backgrounds based on information from the calorimeter and muon systems. While it provided an efficient background rejection, the limited maximum output rate of the L0 trigger would have prevented a full exploitation of the increased instantaneous luminosity. The trigger yield — the number of selected signal candidates per unit time— for decays containing hadrons or electrons in the final state would quickly saturate at higher luminosities, resulting in an efficiency loss. To overcome these limitations, the trigger system was completely redesigned: the L0 trigger was removed, and data are now processed by a fully software-based trigger system that performs a real-time event reconstruction and filters events applying more refined selections on specific heavy-flavor decays. A precise alignment and calibration of the detector with corrections computed in real time is necessary to ensure a high trigger efficiency and purity of the selected samples. The following sections present a summary of the various alignment and calibration activities integrated into the dataflow, and the impact they have on data quality.

2. The LHCb trigger system and dataflow

The complete trigger and real-time alignment structure is fully discussed in [2, 3]. A diagram of the Upgrade I LHCb dataflow is shown in Figure 1.

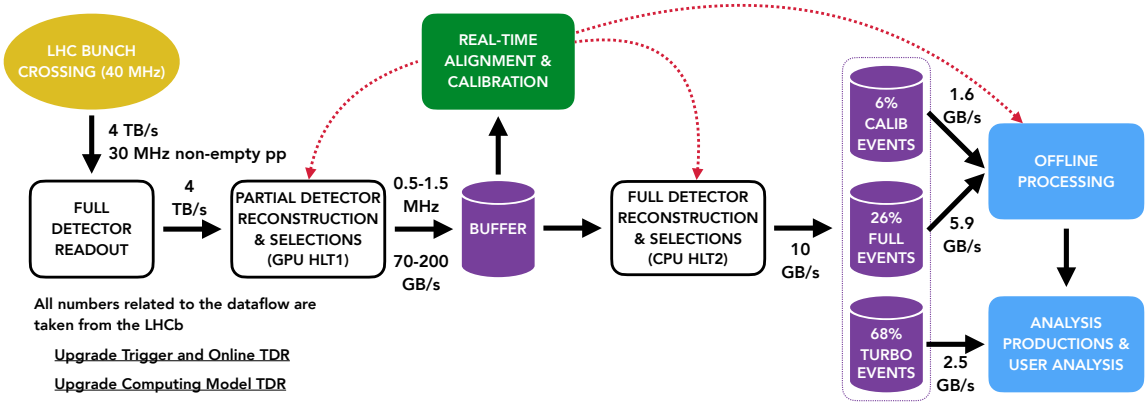

Figure 1: Dataflow of the LHCb upgrade [4].

Data are processed through a two-stage trigger system designed to reduce the input rate and select signal candidates. After the detector readout, a partial event reconstruction and a set of coarse selections are applied at the HLT1 level, which runs on GPUs [5]. Data selected by HLT1 are stored

in a buffer for further processing by HLT2, running on CPUs. HLT2 performs a full, analysis-level event reconstruction and applies a set of higher-level selections targeting specific physics channels. Events passing HLT2 are written to storage for offline processing through different streams, to be used for physics analyses.

Part of the data stored in the buffer, selected by dedicated HLT1 lines, is used for alignment and calibration. These alignment and calibration tasks are executed in real time, and the resulting corrections are propagated to both HLT1 and HLT2.

The new trigger system improves the efficiency to select heavy-flavor candidates containing electrons and hadrons in the final state, particularly at low transverse momentum (p_T). A comparison of Run 2 and Run 3 trigger efficiencies is shown in Figure 2.

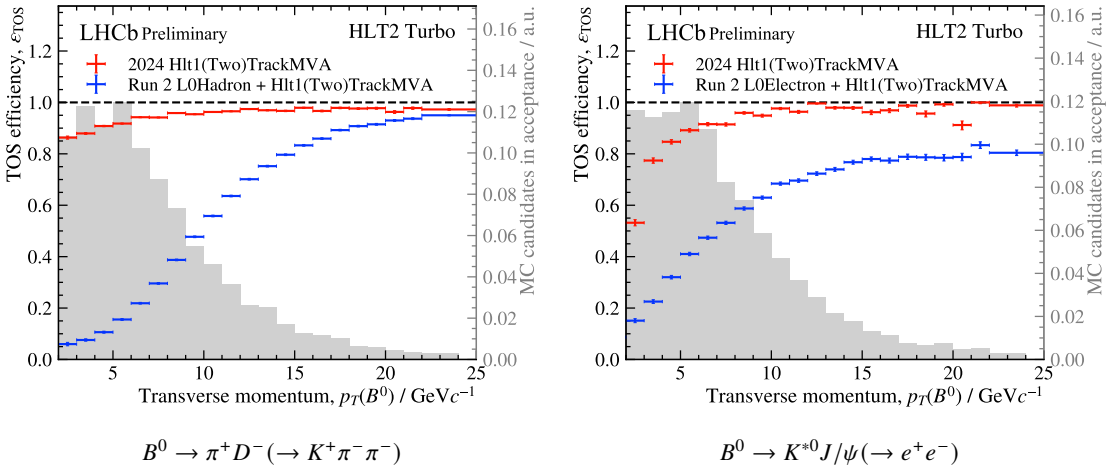

Figure 2: Comparison of the trigger efficiency as a function of p_T for two decay channels involving hadrons and electrons in the final state in Run 2 and Run3 conditions [6].

3. Real-time alignment and calibration

The real-time alignment and calibration procedure builds upon the success of the strategy developed and applied during Run 2 [7]. Alignment corrections are obtained using a common algorithm that minimizes the residuals of reconstructed charged particle tracks. A track residual is the distance vector from the extrapolated hit position of a reconstructed track on the sensor plane to the measured position of the hit. Therefore, minimizing track residuals improves the quality of the reconstructed tracks and decay vertices.

The alignment algorithm determines corrections to the geometry of the detector elements to account for shifts and rotations. The parameters adjusted by this process, known as *alignment constants*, represent rotations and translations applied to the detector components. Corrections are obtained iteratively employing the Newton-Raphson method, minimizing the track residuals as a function of these constants [8].

Alignment constants are updated whenever the newly computed values differ significantly from the starting ones, given the expected alignment precision. In general, real-time alignment and calibration corrections are required for most components of the detector. A schematic overview of the LHCb detector is shown in Figure 3.

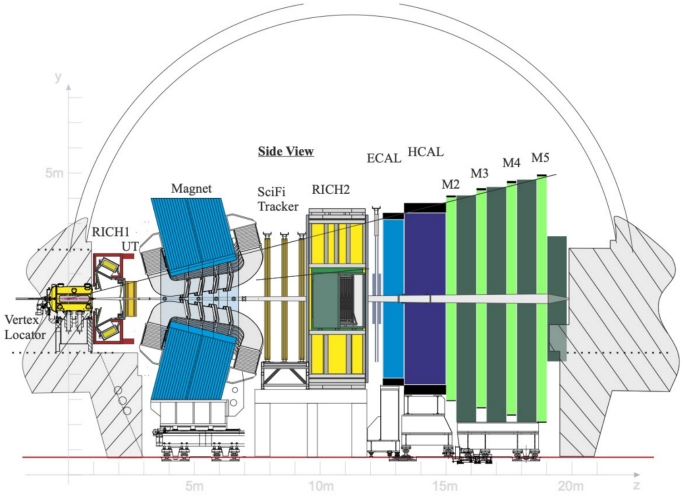

Figure 3: Side view of the LHCb detector after the upgrade [1].

3.1 VELO alignment

The VELO detector is built in two retractable halves that close around the interaction region when stable beams are declared [9]. This closing procedure can potentially introduce misalignments between the two sides, which are corrected in real time at the beginning of each LHC fill. The relative alignment between VELO halves is continuously monitored by comparing the position of primary vertices (PVs) independently reconstructed using tracks that cross each half. This is illustrated in Figure 4.

The alignment of the VELO modules and sensors is not updated in real time, as these are not expected to move, but it is continuously monitored. The improvement on reconstructed track residuals after the latest update in 2024 is shown in Figure 5.

3.2 Tracker alignment

The global alignment of the LHCb tracking system —comprising VELO, UT, and SciFi— [11] is regularly updated to account for changes in data-taking conditions that can affect the relative

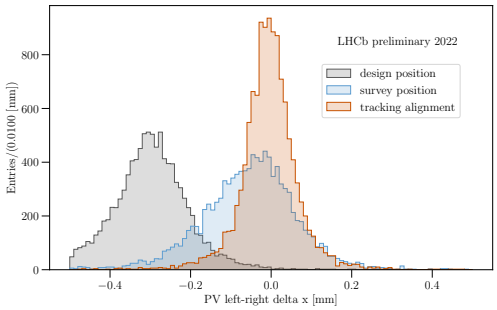

Figure 4: Difference between the x components of reconstructed PVs using tracks only crossing the right or the left side of the VELO, assuming the design geometry (grey), the surveyed geometry (blue), and after alignment corrections (orange) [10].

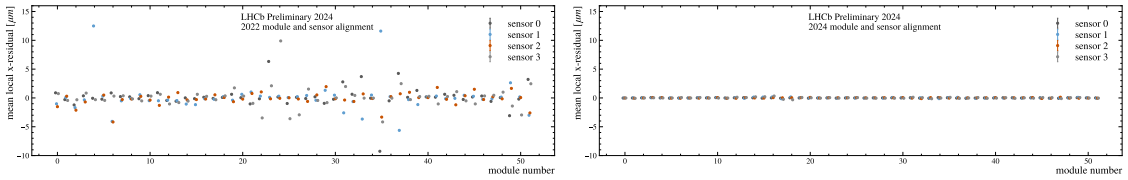

Figure 5: Mean values of the x component of track residuals per VELO module employing the module and sensor alignment obtained in 2022 (left) and after the new alignment from 2024 (right). Residuals are evaluated on data taken in 2024 [12].

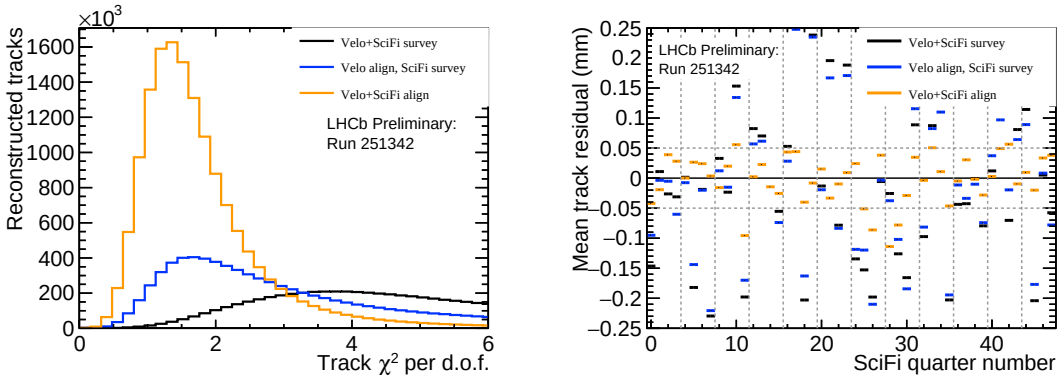

Figure 6: (Left) Reconstructed track χ^2 distribution. (Right) Mean values of the x component of track residuals per SciFi quarter. Tracks are reconstructed employing the surveyed geometry for VELO and SciFi (black), after VELO alignment (blue), and after both VELO and SciFi alignment (yellow). Data from 2022 [14].

alignment between the sub-detectors. These include mechanical interventions, changes in the magnet polarity, or global VELO misalignments introduced by the VELO motion system. The first global tracker alignment was obtained offline through a multi-stage procedure designed to sequentially account for various effects and known biases. This included the use of data collected with the magnetic field switched off, allowing for decoupling effects from misalignments and inaccuracies in the magnetic field description. Figure 6 shows the impact of the global tracker alignment on track residuals and track χ^2 distributions. A smaller track χ^2 indicates a better fit quality of the reconstructed track.

3.3 RICH alignment and calibration

RICH detectors provide particle identification, which is essential to the LHCb physics program [13]. They operate by reconstructing the rings of Cherenkov radiation emitted by charged particles traversing gaseous radiators. The emitted light is reflected by spherical mirrors onto photomultipliers, where it is converted into an electronic signal. The refractive index of the radiator gas is sensitive to variations in temperature and pressure, which can modify the angle at which the Cherenkov light is emitted. Likewise, misalignments of the spherical mirrors can introduce spherical aberrations that distort the shape of the Cherenkov rings. The value of the refractive index is calibrated in real time applying correction factors obtained by comparing the expected and reconstructed Cherenkov angles, as shown in Figure 7. The alignment of the RICH mirrors is also performed in real time.

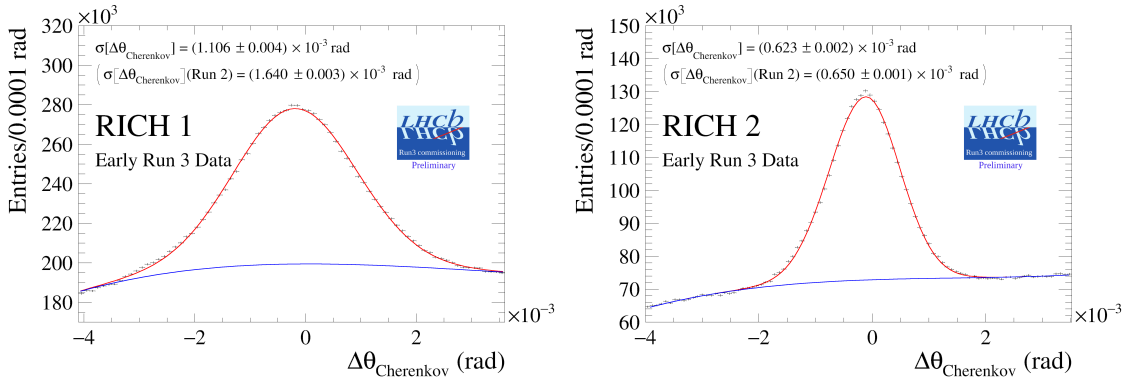

Figure 7: Distribution of the difference between the expected and reconstructed Cherenkov angle of charged particles in RICH 1 (left) and RICH2 (right) on data from 2022. The width of the distributions provides a measure of the Cherenkov angle resolution [15].

3.4 SciFi mat-end contraction calibration

The SciFi tracker is built of scintillating fibers arranged into mats [11]. Light generated by the fibers is collected by Silicon Photomultipliers (SiPMs) attached to the outer ends of the mats. To reduce thermal noise, the detector is operated with the SiPMs cooled to a nominal temperature of -50 °C. The different thermal expansion coefficients of the SiPMs and the mats generate a relative contraction that modifies the mapping of fibers to SiPM channels.

The *mat-end contraction calibration* algorithm corrects the channel-to-hit mapping by fitting a linear model to the mean of the track residuals per SiPM channel for each SiPM. From the fitted model, calibration parameters are extracted and applied to the detector geometry to account for the temperature-induced contraction. This calibration method was specifically developed for the upgraded LHCb SciFi tracker and has been validated using data collected with the SciFi cooled to different temperatures. The resulting improvement in SciFi track residuals is shown in Figure 8. This calibration is executed on demand when significant temperature changes are observed.

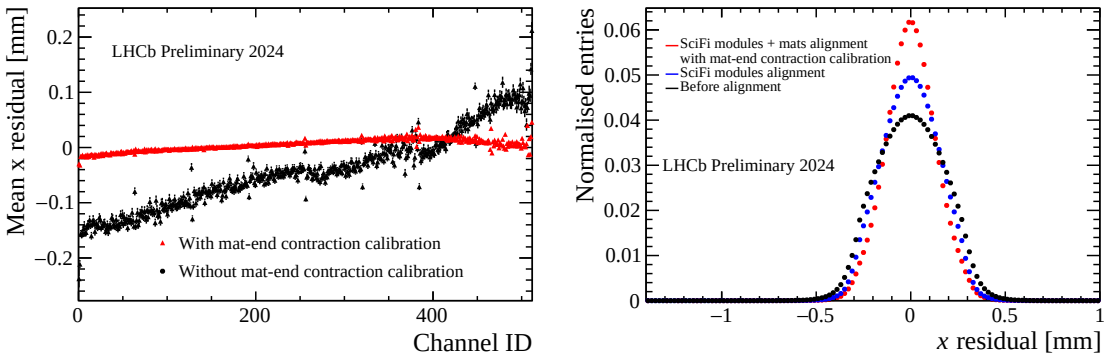

Figure 8: (Left) Mean values of the x component of track residuals per SiPM channel before (black) and after (red) mat-end contraction calibration. (Right) Mean x component of track residuals across the entire SciFi before alignment (black), after alignment (blue), and after mat-end contraction calibration (red) [12].

3.5 ECAL π^0 calibration

The ECAL is a shashlik-type calorimeter composed of 6016 scintillating cells that serve as the active material to absorb and measure the energy from electromagnetic showers [16]. To compensate for the ageing of the scintillating material and the photomultipliers used to collect the signal, the energy scale of each calorimeter cell must be calibrated in real time using $\pi^0 \to \gamma\gamma$ candidates. The resulting calibration constants are derived to correct the reconstructed π^0 mass and improve both the absolute energy scale and the energy resolution. The impact of one of the calibrations performed in 2024 is illustrated in Figure 9.

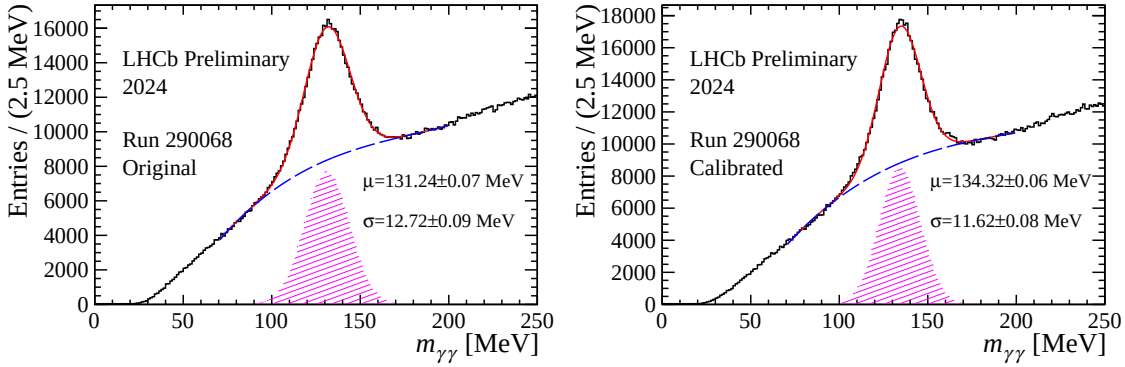

Figure 9: Reconstructed invariant mass of $\gamma\gamma$ pairs from π^0 decays before (left) and after calibration (right). Calibration constants are obtained from a Gaussian fit to the signal peak [12].

4. Conclusions

The ability to compute alignment and calibration corrections in real time is crucial for the successful operation of the LHCb detector. These have a large impact on trigger performance and data quality. As an example, the improvement on the reconstruction efficiency and mass resolution of $\Upsilon \to \mu^+\mu^-$ candidates after alignment is illustrated in Figure 10.

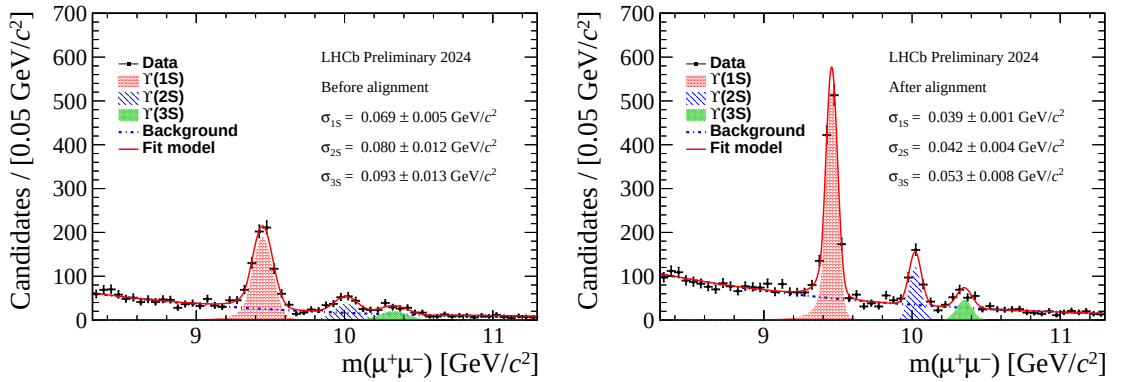

Figure 10: Reconstructed invariant mass of $\mu^+\mu^-$ pairs in the $\Upsilon(nS)$ mass range before (left) and after (right) tracker alignment. Data collected in 2024 [17].

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