Novel Real-time Alignment and Calibration of the LHCb detector in Run2

Maurizio Martinelli on behalf the LHCb collaboration
École Polytechnique Fédérale de Lausanne, 1015 Lausanne, Switzerland
E-mail: maurizio.martinelli@epfl.ch

Abstract. LHCb has introduced a novel real-time detector alignment and calibration strategy for LHC Run2. Data collected at the start of the fill are processed in a few minutes and used to update the alignment parameters, while the calibration constants are evaluated for each run. This procedure improves the quality of the online reconstruction. For example, the vertex locator is retracted and reinserted for stable beam conditions in each fill to be centred on the primary vertex position in the transverse plane. Consequently its position changes on a fill-by-fill basis. Critically, this new real-time alignment and calibration procedure allows identical constants to be used in the online and offline reconstruction, thus improving the correlation between triggered and offline-selected events. This offers the opportunity to optimise the event selection in the trigger by applying stronger constraints. The required computing time constraints are met thanks to a new dedicated framework using the multi-core farm infrastructure for the trigger. The motivation for a real-time alignment and calibration of the LHCb detector is discussed from both the operational and physics performance points of view. Specific challenges of this novel configuration are discussed, as well as the working procedures of the framework and its performance.

1. Introduction
The LHCb Experiment is a spectrometer with acceptance in the forward region designed to measure with high efficiency and resolution the decays of $B$ mesons [1]. Its design is optimised to contain most of the $b$ hadrons produced by collisions at the LHC. A schematic view of the experiment is given in Fig. 1. The detector includes a high-precision tracking system consisting of a silicon-strip vertex detector (Velo) surrounding the $pp$ interaction region, a large-area silicon-strip detector (TT) located upstream of a dipole magnet with a bending power of about 4 Tm, and three stations of silicon-strip detectors (IT) and straw drift tubes (OT) placed downstream of the magnet. The tracking system provides a measurement of momentum, $p$, of charged particles with a relative uncertainty that varies from 0.5% at low momentum to 1.0% at 200 GeV/c. Two ring-imaging Cherenkov (RICH) detectors are able to discriminate between different species of charged hadrons. The rate of recorded events is regulated by an extremely flexible hardware and software trigger, which consists of a hardware stage, based on information from the calorimeter and muon systems, followed by a software stage, which applies a full event reconstruction. The detectors allow a broad range of high-precision physics measurement to be made, ranging from flavor physics, to electroweak interaction properties and exotic particles searches.

The LHC produces proton-proton collisions with a rate of 40 MHz. Of these, very few are relevant for physics analysis. The LHCb trigger system is designed to record interesting events
among the multitude of those produced at the LHC and reduce the data rate to disk to an acceptable level. This is made possible by a hardware trigger (L0) followed by a software high level trigger divided in two levels (HLT1 and HLT2). The L0 has a 1 MHz readout, and selects interesting events by means of high transverse energy and momentum signatures. The HLT performs a reconstruction of the particles in the event tuned to its time constraints and runs a mixture of exclusive and inclusive selection algorithms. In 2011, approximately 26000 logical CPU cores were employed in the HLT farm to achieve an output rate of 3.5 kHz, corresponding to 0.2 GB/s [2]. This rate improved to 5 kHz (0.3 GB/s) in 2012 by introducing the deferred triggering scheme [3], which exploits the dead time between LHC machine fill preparations to process data that was buffered during the previous fill. To achieve the aforementioned rate, 20% of the L0 output was deferred to disk and the farm was enlarged to 29000 cores.

The success of the deferral trigger scheme inspired further improvements for Run2 (2015–2018). Instead of buffering L0, a looser HLT1 is run and buffered. The HLT1 event (partial) reconstruction, where displaced tracks and vertices are selected, allows to run an online detector calibration, after which a full offline-like particle reconstruction is used to perform the exclusive and inclusive trigger selections [4]. The main advantage of this new framework is the perfect consistency between online and offline reconstruction, which makes the latter redundant. Approximately 12.5 kHz (0.6 GB/s) of data are now stored.

2. Impact of Alignment on Physical Observables
The online calibration is crucial in the Run2 triggering scheme. A detector properly aligned in the online trigger enables the selection of particles by their invariant mass with the best possible resolution. A fully calibrated detector also allows to employ particle identification criteria to separate reflections from misidentified particles in the signal sample. Typical effects of alignment and particle identification are shown in Fig. 2 and Fig. 3, respectively. The obvious benefit of
Figure 2. The dimuon invariant mass in the range [8500, 10900] MeV/c² is shown for data taken with preliminary alignment (left) and the same data after applying the final alignment (right). With proper alignment the resolution is reduced almost by a factor 2 and the three mass peaks corresponding to the Υ resonances are better separated.

Figure 3. The dipion invariant mass in the range [5, 5.8] GeV/c² is shown for data selected with no particle identification requirement (left) and for the same data after particle identification requirements are made (right). The signal $B^0 \rightarrow \pi^+ \pi^-$ candidates are overwhelmed by background from other decays in the first case, while they are the main component of the signal region when particle identification is applied [5].

Having this information already at the trigger level is getting best quality data out of the trigger farm, without any need of offline reconstruction. Consequent optimised selections imply a more effective use of the disk buffer.

3. Real-time Alignment and Calibration Procedure

The alignment of the LHCb detector can be separated in four tasks, corresponding to the alignment of the Velo, Tracker, Muon and RICH mirrors subdetectors. The framework is designed to provide new alignment constants as quickly as possible. The following requirements have to be fulfilled: fast since it should not unnecessarily delay the processing of data in the disk buffer; iterative to find convergence; automatic because it cannot rely on the operators input.

As soon as enough data to perform the alignment job are collected, the event reconstruction is run in parallel on about 1700 nodes of the LHCb online farm, as shown in Fig. 4. Once all the events have been reconstructed and $\chi^2$ contributions from each node are calculated following the approach described in [6], a global $\chi^2$ is minimised on a single node to compute
the updated alignment constants. If needed, a new iteration is requested, otherwise the constants are propagated to the Online and to the Offline databases. The former keeps track of Online conditions and the latter is available for future updates of alignment and calibration conditions.

The propagation of constants happens in three stages. At first the database is transferred by copying the alignment job output (in the form of xml files) to the Trigger and Online databases. Then a consistency check is run between the Online files. A dedicated job reads the xml files to compare the alignment output and the Online database entry. Finally, a comparison between online- and offline-configured jobs is run to verify the consistency of the Online and Offline databases. After this check, the run is flagged as OK for offline processing.

It should be noted that the constants have a per-run granularity and are common between HLT1, HLT2 and Offline. To guarantee the same constants between HLT1 and HLT2, the constants are used starting from the next run. Each run in LHCb lasts for about 1 hour and the alignment constants are produced in about 10 minutes. In case the alignment constants are not yet ready at the start of the new run, previous conditions are used.

4. Alignment of the Tracking System

The alignment of the tracking system is made by three independent tasks responsible for the Velo, Tracker and Muon stations alignments. Each of them requires a dedicated data sample that comprises minimum bias events for the Velo, $D^0 \rightarrow K\pi$ decays for the Tracker and $J/\psi \rightarrow \mu\mu$ decays for the Muon stations. The alignment technique is based on the Kalman filter track fit used for the default track reconstruction at LHCb, which has the advantage of accounting for multiple scattering and energy loss corrections but depends on the magnetic field map. All the detector elements can be aligned and constraints on the detector position can be fixed as well as mass and vertex constraints on the fitted particle candidates.

About 700 elements are automatically aligned for every LHC fill. A control system based on the variation of the alignment global $\chi^2$ and the element’s position is used to determine whether an update of the constants is needed. Each of the three tasks is quite fast, requiring about 7 minutes. The constants are updated with a frequency that depends on the alignment task. Since the Velo is built as two halves which are retracted during beams injection and close around the beams when they are stable, the mechanical stress could introduce an internal misalignment.

**Figure 4.** Alignment procedure.
The automatic alignment procedure showed that significant changes (larger than 1 μm) of Velo alignment constants happen every few fills (≈ 5). The Tracker system is more stable, requiring an update about every 10 fills, unless a magnet polarity switch or a detector intervention has happened, after which the conditions are more likely updated. Muon stations are extremely stable; no update has been required until now as expected, and the jobs are run as monitoring to ensure optimal hardware trigger performance. The variation of the constants in 2016 are shown in Fig. 5 and Fig. 6 for a few selected elements of Velo and Tracker, respectively.

**Figure 5.** The plot shows the stability of the alignment of the VELO halves during all Run2 fills. Filled dots represent variation of alignment constants which triggered an update and empty dots correspond to variation considered consistent with statistical fluctuation. The two horizontal broken lines at ±2 μm indicate the level at which an update is considered significant.

**Figure 6.** The plot shows the stability of the Tracker alignment during all Run2 fills. In particular, translations in z of the Inner Tracker boxes are shown. Filled dots represent variation of alignment constants which triggered an update and empty dots correspond to variation considered consistent with statistical fluctuation. The two horizontal broken lines at ±200 μm indicate the level at which an update is considered significant.

5. Alignment of the RICH Mirrors

LHCb uses two Ring Imaging Cherenkov (RICH) detectors to separate particles of different mass by means of the Cherenkov light rings they produce while traveling in air. This light is focused by spherical and flat mirrors on planes of Hybrid Photo Detectors outside the LHCb acceptance. Mirror misalignment will bias the Cherenkov ring reconstruction and therefore reduce the discrimination power of the system. This misalignment is corrected with a procedure described elsewhere [5]. The system is composed of 110 mirror planes that are all aligned corresponding to 1090 constants. The alignment job is run every fill, although the observed variations are small enough that the alignment constants are very rarely updated.

6. Calibration

The RICH detector also requires an online calibration of the refractive index of the gas mixture (2 parameters) and of its photodetectors (1940 parameters). This job is performed automatically for every run and an update of the conditions is always prompted. Since particle identification is not used in HLT1, the calibration is directly used in HLT2 when ready. Its performance has been stable during data collection and is monitored by the stability of the Cherenkov angle resolution. The online calibration of the gas mixture and the photodetectors reduced the ratio of misidentified pion per correctly identified kaons in Run2 with respect to Run1 by 1% to 5% depending on kaon identification efficiency.
The other calibration run online regards the Outer Tracker drift time. The Outer Tracker is a straw tube gas detector and the drift time in its tubes may be biased by incorrect timing in the readout electronics. The effect has been found in Run1 and related to a global offset between the collision time and the LHCb clock. This mismatch introduced a timing resolution of about 0.5 ns that translated into a tracking inefficiency of approximately $2.5 \times 10^{-3}$. To solve this issue, the drift time is calibrated automatically in each run by measuring the drift time residuals in the Outer Tracker channels and by correcting for the found offset. As shown in Fig. 7, a correction of the global offset is applied whenever the measured mean of the residuals is outside the ±0.1 ns range. It is interesting to notice that this calibration allows to spot very quickly issues with the LHCb clock, as for example with the large $-0.9$ ns variation corresponding to run number 650 in the plot.

![Figure 7. The results of the Outer Tracker drift time calibration. The blue empty dots show the results of a typical calibration job, while the red filled dots indicate a change requiring the update of the calibration parameter.](image)

7. Conclusions
The LHCb collaboration is working hard to exploit the best from the detector. Within a constant budget, it still manages to expand the physics program of the experiment thanks to innovation. Looking forward, in a high-luminosity scenario offline computing resources may not be able to cope with the enormous output rates from online. Allowing to perform physics analysis (Turbo) [4] on the trigger output with identical quality to the offline processed data, real-time alignment and calibration play a fundamental role in the preparation for the upcoming challenges. Run2 is now giving the opportunity to put many new approaches under full test, with potential expansion in the upgraded LHCb experiment (Run3). Its success will set the LHCb framework as a working model for future experiments.

References
[1] Alves Jr A A et al. (LHCb collaboration) 2008 JINST 3 S08005
[2] Aaij R et al. 2013 JINST 8 P04022 (Preprint 1211.3055)
[3] Albrecht J 2015 Journal of Physics: Conference Series 623 012003 URL http://stacks.iop.org/1742-6596/623/i=1/a=012003
[4] Raven G 2016 22nd Internation Conference on Computing in High Energy and Nuclear Physics CHEP 2016 (CHEP 2016) San Francisco, CA, October 14-16, 2016
[5] Adinolfi M et al. 2013 The European Physical Journal C 73 2431 ISSN 1434-6052 URL http://dx.doi.org/10.1140/epjc/s10052-013-2431-9
[6] Amoraal J et al. 2013 Nucl. Instrum. Meth. A712 48-55 (Preprint 1207.4756)