PROCEEDINGS OF SCIENCE

Tracking and vertexing in LHCb

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The LHCb detector is a multipurpose single-arm forward spectrometer. The main goal of its design is heavy flavor physics, covering broad range of topics such as rare beauty and charm decays, CP violation and dark matter searches.
The LHCb tracking system consists of the VErtex LOcator (VELO), the Trigger Tracker (TT), three Tracking Stations (T - Stations) and in the most upstream region, five rectangular muon stations (MUON). This design is very heterogeneous and requires a complex system of charged particle reconstruction algorithms. LHCb has developed a real-time fully automated alignment and calibration system to ensure offline reconstruction quality already at the online level.
LHCb's unique trigger setup allows prompt access to calibration and data samples. Such robust techniques with fast accessibility to data do not only directly impact the quality of the LHCb results, but also serve as a basis for the upcoming upgrade.

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1. Introduction

The LHCb detector [1] is a single-arm forward spectrometer designed for the study of particles containing b or c quarks. The detector includes a high-precision tracking system consisting of a silicon-strip vertex detector (VELO) [2] surrounding the pp interaction region and covering the pseudorapidity range $2 < \eta < 5$, a large-area silicon-strip detector, TT [3], located upstream of a dipole magnet with a bending power of about 4 Tm; and three stations of silicon-strip detectors (Inner Tracker) [4] and straw drift tubes (Outer Tracker) [5] placed downstream of the magnet, called T stations. The tracking system provides a measurement of momentum, p, with a relative uncertainty that varies from 0.5% at 5 GeV/c to 1% at 200 GeV/c. The minimum distance of a track to a primary vertex, the impact parameter, is measured with a resolution of $(15 + 29/p_T)$ μm, where p_T is the momentum component transverse to the beam, in GeV/c. Different types of charged hadrons are distinguished using information from two ring-imaging Cherenkov detectors [6]. Photon, electron and hadron candidates are identified by a calorimeter system consisting of scintillating-pad and preshower detectors, an electromagnetic calorimeter, and a hadronic calorimeter. Muons are identified by a system composed of alternating layers of iron and multiwire proportional chambers [7]. The trigger [8] 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 [9].

2. Track reconstruction

In order to describe the track reconstruction algorithms used by LHCb, it is necessary to first define the different track types. The track types are described in Sec. 2.1. The track reconstruction algorithms themselves are then described in Sec 2.2.

2.1 Track types

The LHCb design allows for defining several track types depending on the subdetectors where the traversing particle was registered. A diagram of these track types is shown in Fig. 1. The track types and their properties are as follows:

- **Long Tracks**
  These tracks traverse the full tracking system. They are the most commonly used tracks due to the fact they give the best momentum and position estimate.

- **VELO tracks**
  These are tracks only having hits in the VELO. They are not matched to hits in any other subdetector. These tracks are crucial mainly for the LHCb trigger since they are used for primary vertex reconstruction.

- **Upstream tracks**
  These tracks have only hits in the VELO and the TT-stations. Upstream tracks are typically created by low-momentum particles, that are bent by the magnet out of the detector acceptance. These tracks can serve as an input for reconstructing long tracks.

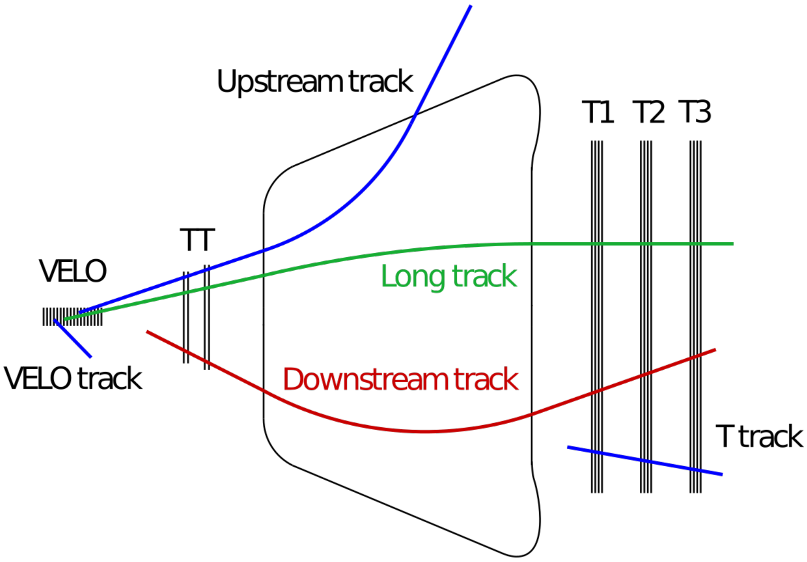

Figure 1: LHCb track types. Most commonly used track types are Long tracks (green) that traverse the whole LHCb tracking system, and Downstream tracks (red) that originate from neutral particles, hence there are no hits in the VELO.

- **T tracks**
  Tracks having only hits in the T-stations, typically originating from decays of long-lived particles or from interactions with the material. These tracks have no momentum information.

- **Downstream tracks**
  Tracks that have hits in TT-stations and T-stations are called downstream tracks. They are often decay products of long-living particles. These tracks are commonly used in analyses exploiting K_s^0 or Λ particle decays.

2.2 Track reconstruction algorithms

Reconstructing a track at LHCb consists of two phases: finding a track and fitting a track. A track is found using pattern-recognition algorithms. There are several ways to use the pattern-recognition algorithms, depending on the type of the track. There are two stand-alone algorithms, VELO tracking and T-seeding. The other algorithms use input from these two algorithms in order to perform further track reconstruction

Starting from the VELO tracking, either VELO-TT tracking or Forward matching is done. In the first case, momentum estimation of the track is done. This reduces the search window in the T-stations and results in an upstream track candidate. In the second case, seeds from VELO and T-stations are matched, resulting in a long track candidate. On the other hand, starting from the T-seeding algorithm, the T-track is extended into TT, resulting in a downstream candidate.

The last option is to combine the VELO tracking and T-seeding. VELO tracks are matched with the seeds from the T-stations. This also returns long track candidates. This algorithm is referred to as Track matching.

Forward tracking and Track matching both reconstruct a long track, being complementary to each other. This means any efficiency losses in one algorithm can be compensated by the other, guaranteeing the best final efficiency.

3. Alignment and calibration

Alignment and calibration of the LHCb detector are crucial for any measurements. The detector conditions change constantly: most significant is the actual physical movement of the VELO, which is moved close to the beams at the beginning of every fill only after the beams are stable and the background conditions well controlled. Moreover, the magnet polarity flips in regular intervals. The conditions in the cavern, such as humidity or pressure, affect the detector properties. All these have an impact on the resolution of primary vertices, impact parameter, particle identification, or track reconstruction efficiency.

Therefore, a timely, iterative and automatic alignment and calibration is performed at LHCb for every fill. A real time alignment of VELO, TT, T-stations, MUON stations and both RICH detectors is performed in regular intervals, as described in Fig 2. Moreover, automatic calibrations of OT and calorimeters are performed, ensuring the conditions to be the same online and offline.

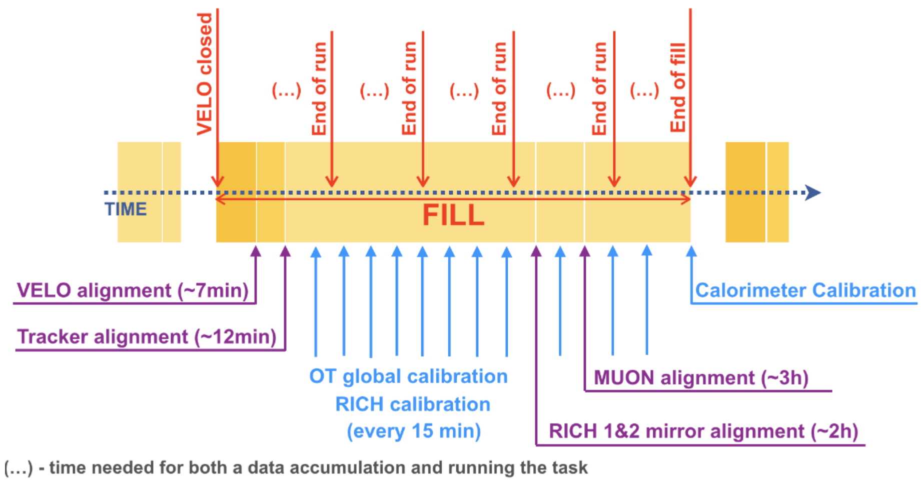

Figure 2: LHCb alignment and calibration timeline.

4. Trigger selection

The LHCb trigger consists of two levels: first is the hardware Level 0 trigger (L0), second is the software high level trigger (HLT). The detailed design of the trigger is described in Fig. 3.

Since the LHCb alignment and calibration constants are the same offline and online, the signal candidate selection is enabled directly at the trigger level. This is done using so called *Turbo stream*, making a real-time analysis possible. Real-time here is defined as "...the interval between the collision in the detector and the moment the data are sent to permanent storage." [10]. The turbo stream format allows to store data at higher interaction rates, it is less CPU-demanding and uses less disk-space compared to the full stream. This is achieved by not saving the detector raw banks, gaining up to 90% of space. and by performing the offline-like selection already at the trigger level.

There are three types of Turbo events, categorized by objects to be saved: Turbo, Turbo++ and TurboSP. In a Turbo event, only the objects involved in the trigger decision and all primary vertices are saved. Turbo++ saves the entire HLT reconstruction. Even this stream saves resources, as raw banks are not saved anymore. A bridge between Turbo and Turbo++ is TurboSP, where SP stands for Selective Persistence. TurboSP allows for a completely flexible specification of additional objects to be saved.

This is a novel approach of saving events. The turbo stream makes possible analyses requiring very large statistics or a lot of computation power. Moreover, this significantly speeds up the process of releasing the recorded data to the analysts, and so the analysis process itself.

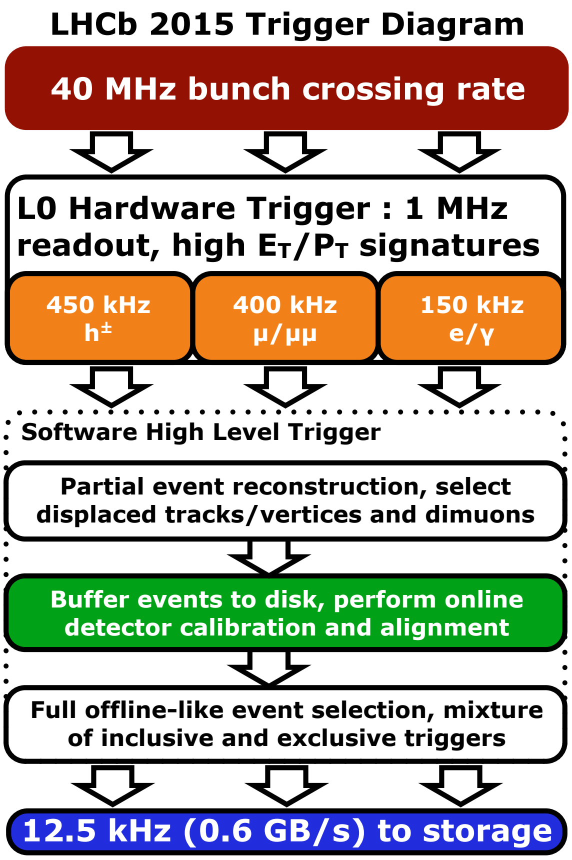

Figure 3: LHCb trigger scheme. The bunch crossing rate is 40 MHz. This is then filtered by L0 hardware trigger, based on high E_T or p_T signatures, being passed to software HLT1, where a partial event reconstruction is performed. The output of HLT1 is buffered to a disk, where a full offline-like event selection is performed, resulting in 12.5 kHz of data being written out.

5. Track reconstruction efficiency

Estimating track reconstruction efficiency is an important part of any analysis. Therefore, a careful calculation of the track reconstruction efficiency is crucial. This task is especially intricate since LHCb is designed to have minimal number of layers of subdetectors in order to minimize multiple scattering.

To estimate the track reconstruction efficiency, a tag-and-probe approach is applied, using the decay $J/\psi \to \mu^+\mu^-$. This decay is an ideal candidate since muons transverse the whole LHCb tracking system and the J/ψ resonance gives a clean signal in the detector. Moreover, J/ψ candidates detached from the primary vertex of the collision are used, making the signal even clearer and allowing for a dedicated trigger selection in order to minimize biases.

Three different tag-and-probe methods are used to probe the whole LHCb track reconstruction efficiency. These methods are described in detail in Figs. 4, 5 and 6.

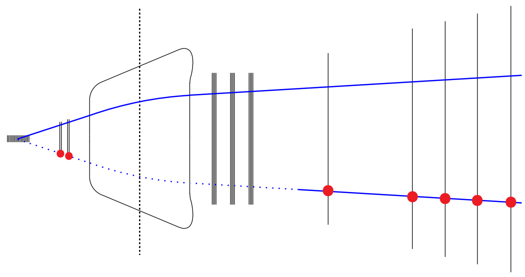

Figure 4: Long method estimation of track reconstruction efficiency scheme. This method probes VELO and T-stations reconstruction efficiency. Tracks reconstructed from hits in the TT and MUON (red circles) are used as a probe.

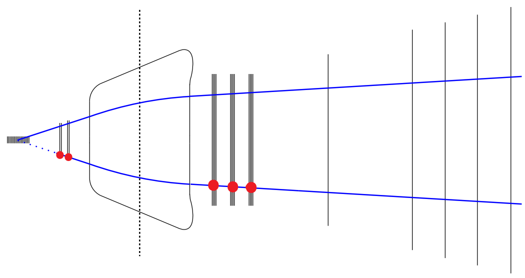

Figure 5: Velo method estimation of track reconstruction efficiency scheme. This method probes VELO reconstruction efficiency. Tracks reconstructed from hits in the TT and T-stations (red circles) are used as a probe.

To estimate the track reconstruction efficiency of the whole LHCb detector, Long method (Fig. 4) can be used standalone. On the other hand, using the product of Velo (Fig. 5) and T-station (Fig. 6) is another independent way of estimating the efficiencies, called Combined method. Having two independent methods allows for improving the uncertainty on the efficiency by using weighted average of the Long and Combined methods as the final overall LHCb track reconstruction efficiency.

To account for the discrepancies between the MC and the data, 2-dimensional maps of the ratio of $\varepsilon^{\text{data}}/\varepsilon^{\text{MC}}$ are produced. This results in first order systematic uncertainties being canceled. Most analyses rely rather on MC than on data-driven efficiencies, meaning most LHCb

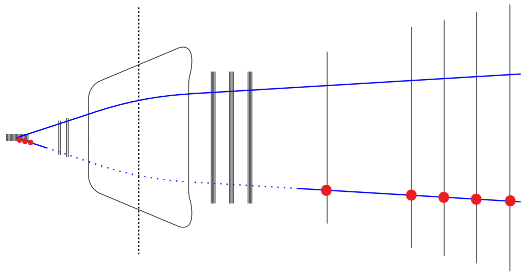

Figure 6: T-station method estimation of track reconstruction efficiency scheme. This method probes T-stations reconstruction efficiency. Tracks reconstructed from hits in the VELO and MUON (red circles) are used as a probe.

analyses can profit from these ratios and use them independently. These maps are typically created in dependence of p and η and used by the analysts as correction tables.

The LHCb track reconstruction efficiency is well above 95%, as can be seen in Fig. 7.

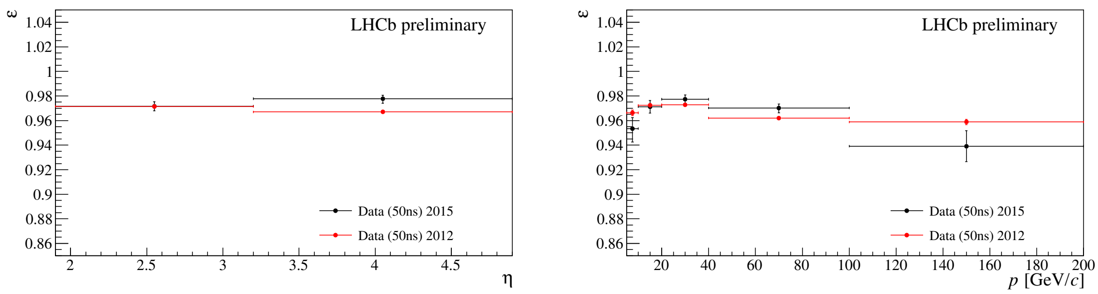

Figure 7: Track reconstruction efficiency for 2012 and 2015, early measurements period (50 ns collision frequency). Only statistical errors are shown. Systematics errors are of less importance due to their cancellation in the tracking efficiency ratios. On the left, η dependence is investigated, p dependence is on the right.

6. Electron track reconstruction efficiency

Electron track reconstruction efficiency measurement will allow to improve control over absolute electron efficiencies. This is most notable in tests of lepton universality, where until now the measurements relied on relative efficiencies between rare and resonant electron modes, opening the path to perform measurements where no suitable control mode exists.

Recently, a significant effort was made to estimate also the electron track reconstruction efficiency. This is a very complex task due to the fact that electrons loose momenta when traversing LHCb by bremsstrahlung in the material. This then has an impact on the reconstruction after the electrons pass the magnet.

In this case, the tag-and-probe approach is applied as well. The decays of $B^+ \to J/\psi(e^+e^-)K^+$ are used, where one electron is the probe and the second electron paired with the kaon are used as a tag. The probe is consisting only of a VELO track, where the track reconstruction efficiency is ∼98%, and the momentum of the probe is inferred from the constraint on the J/ψ mass.

7. Conclusion

LHCb is the first experiment with an automatic, real-time full calibration, alignment and reconstruction. The smart choice of the trigger scheme allows LHCb to achieve offline data quality already at the online level, and the Turbo stream approach increases even further our physics program, using the same resources without any performance loss.

The LHCb tracking reconstruction is constantly improving. The overall performance of the detector is exceptional since ten years, exceeding the design expectations greatly.

8. Acknowledgement

I would like to thank the whole LHCb collaboration for their hard work allowing me to report on its outstanding performance. My gratitude goes to the LHCb Tracking and Alignment group for stimulating discussions and encouragement. I express my gratitude to our colleagues in the CERN accelerator departments for the excellent performance of the LHC. I thank the technical and administrative staff at the LHCb institutes. Last but not least, I wish to thank the Heidelberg Graduate School of Fundamental Physics (HGSFP) as well as the research training group Particle Physics Beyond the Standard Model (GRK 1940) for financial support.

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