Real-time alignment at the LHCb experiment

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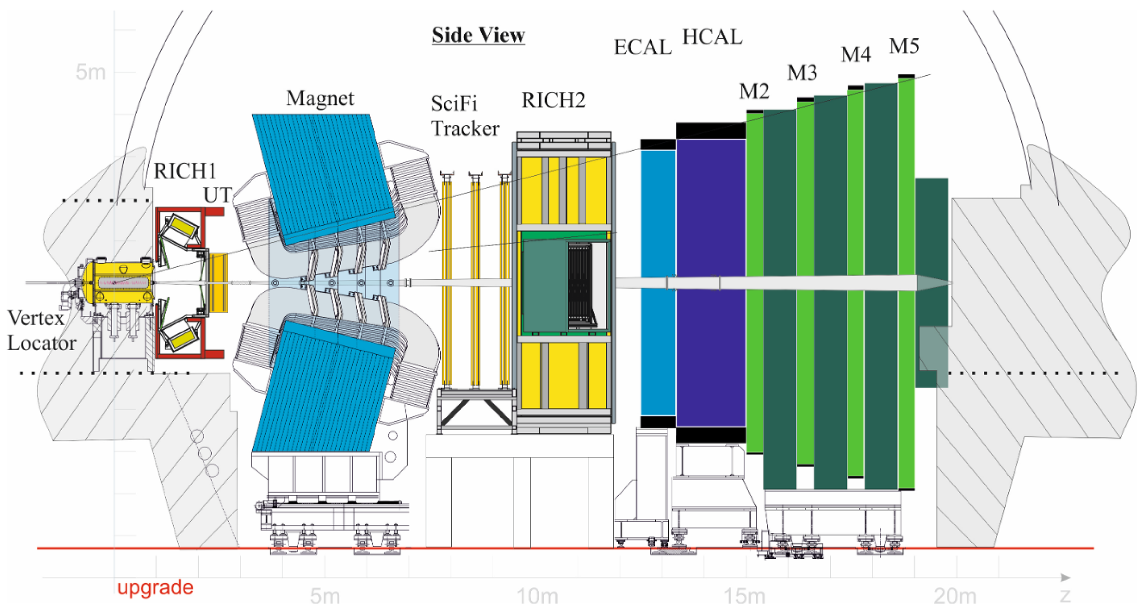
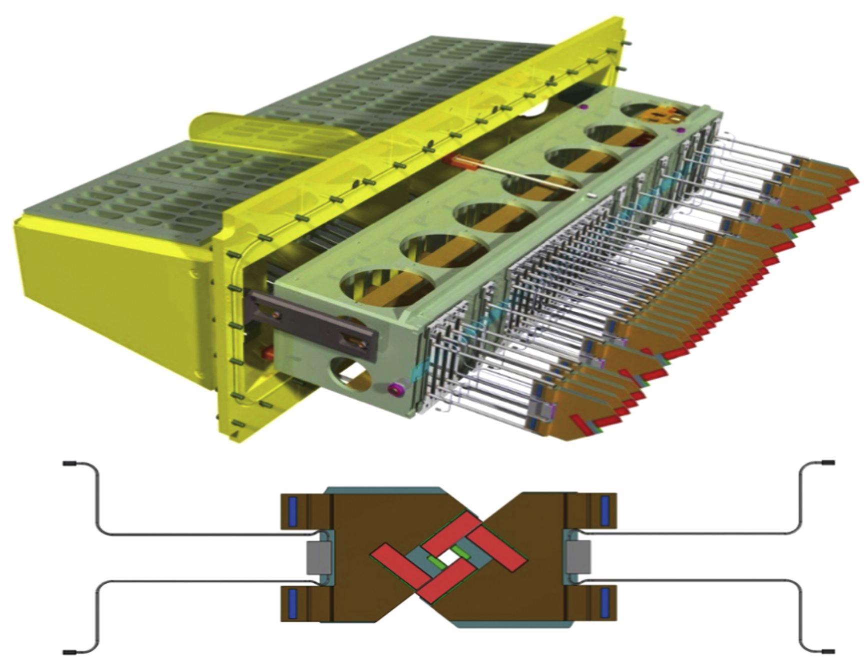
LHCb Upgrade Detector

- The LHCb upgrade I detector is designed for approximately five times the instantaneous luminosity compared with Run I and Run II of LHCb [LHCB-TDR-012]
- The **Vertex Locator**(VELO) is placed around the interaction region to reconstruct primary vertices (PVs).
- The particle trajectory and momentum measurement is determined by the tracking system with subdetectors upstream and downstream the magnet. It is composed of the VELO, **Upstream Tracker** (UT) and the **scintillating fiber tracker** (SciFi)
- Particle identification information is provided by the **Ring Imaging Cherenkov** detectors RICH1 and RICH2
- Calorimetry and neutral particle identification is performed by the electromagnetic (**ECAL**) and and hadronic (**HCAL**) calorimeters,
- Additional muon information is provided by muon stations **M2-M5**



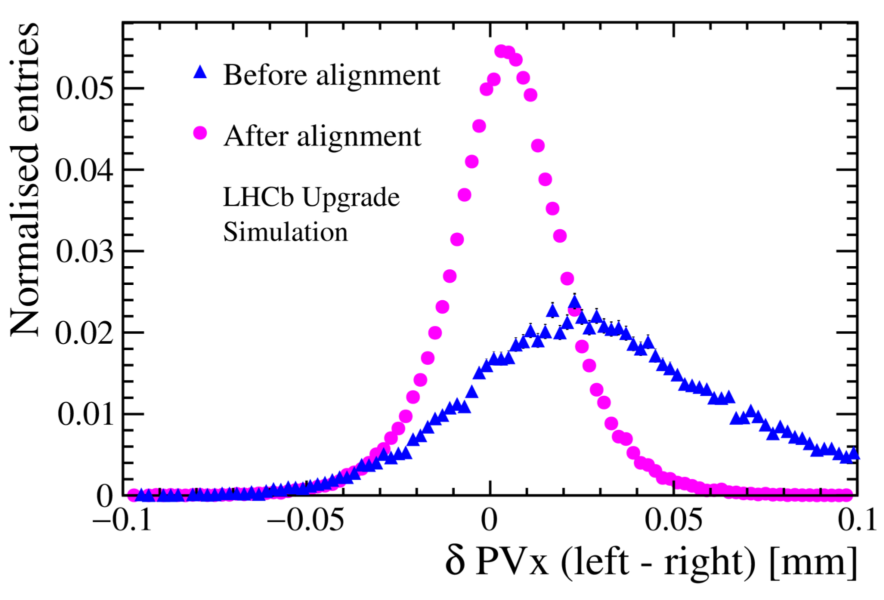
VELO Alignment



[2019 IEEE NSS/MIC, 2019, pp. 1-5]

Minimal distance to beam $\sim$ 5mm

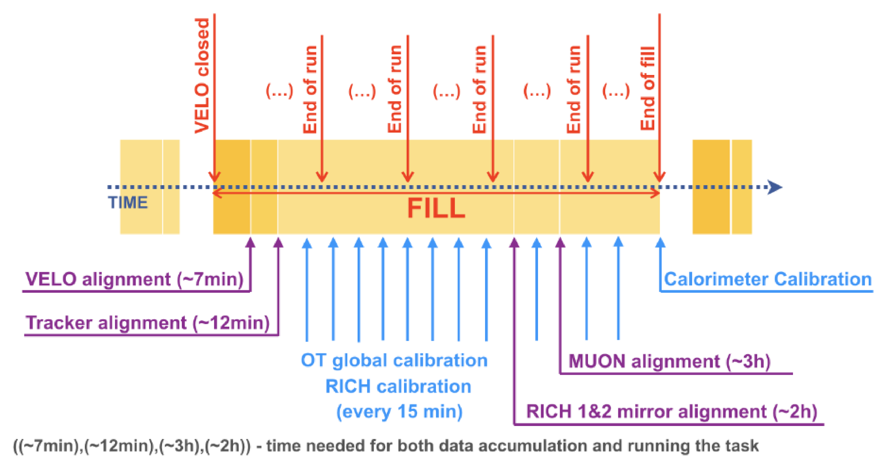
- The VELO closely surrounds the interaction point to provide precise PV measurements. Such precise measurements are essential for analyses of b and c hadron decays which have displaced vertex signatures [LHCB-TDR-013]
- TThe VELO consists of two halves each consisting of 26 pixel silicon modules. A retractable system enables the VELO halves to be opened and closed around the beam with an accuracy of $\sim$ 10μm when a stable beam is declared at the beginning of each fill
- Due to this closing procedure, **translational and rotational misalignment** in modules and halves is introduced which must be corrected for.
- Below is a distribution of the difference between the x-position of PVs reconstructed with tracks in only one VELO half before and after alignment of the VELO halves



[LHCB-FIGURE-2019-003]

Alignment Procedure

- The alignment uses buffered samples from HLT1. These samples are then processed in $O(\sim$**minutes**) at the start of each fill for the VELO and the tracking stations alignment, to be used directly in HLT1. The other alignment tasks for the RICH and MUON, used only in the HLT2 or for monitoring, are processed in $O(\sim$**hours**). This process with approximate timings by sub-detector is illustrated below [JINST 14 (2019) P0401319]



- Tracking sub-detectors (VELO, T1-3, muon stations) utilise reconstructed tracks obtained using a Kalman filter with initial alignment parameters, α_0 [Nucl.Instrument.Meth.A 600 (2009) 471-477]. This reconstruction process is performed in parallel on thousands of computing nodes
- The χ^2 is minimised ieratively and the alignment parameters, α, are updated only if there is significant variation. This minimisation is done by inverting the measurement covariance matrix V

$$\frac{d\chi^2}{d\alpha} = 2\sum_{tracks} \frac{dr}{d\alpha}^T V^{-1} r$$

$$\frac{d^2\chi^2}{d\alpha^2} = 2\sum_{tracks} \frac{dr}{d\alpha}^T V^{-1} R V^{-1} \frac{dr}{d\alpha}$$

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

where r is the track residual and R is the covariance matrix of residuals

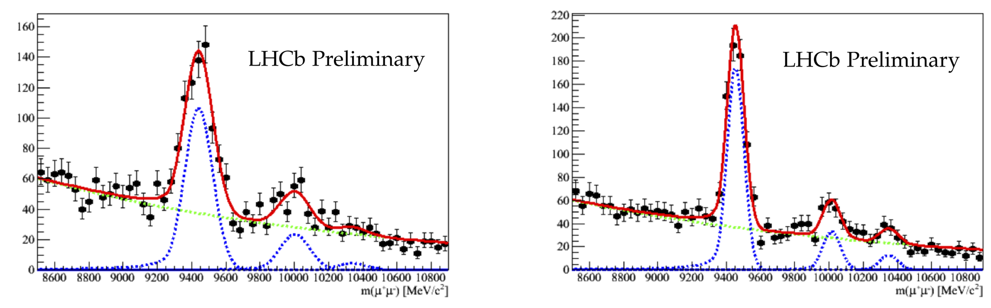
- For Run 2 the above procedure can include **mass and vertex constraints** to **reduce** the impact of global distortions [Nucl.Instrument.Meth.A 712 (2013) 48-55]

Motivation

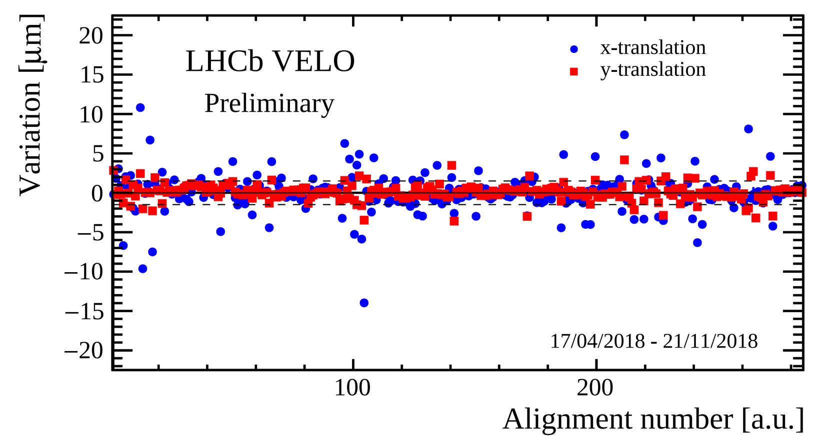
- During Run 2, LHCb was able to achieve **offline-quality performance** with **automatic online alignment and calibration** for the full detector
- In Run 3, the LHCb upgrade detector will use an entirely **software based trigger**
- Analysis will be performed directly on reconstructed candidates in the trigger and only candidate related information will be stored, making offline reconstruction impossible [LHCB-TDR-016]
- **Real-time** alignment and calibration will be vital to produce clean datasets with the best reconstruction performance possible

Alignment Performance in Run 2

- Alignment of the tracking system is essential in obtaining the best resolution (of mass and momentum). Shown below is the improvement in resolution of $m(\mu^+\mu^-)$ before (92 MeV$/c^2$) and after alignment (49 MeV$/c^2$) in Run 1. [J. Phys.: Conf. Ser.664 082010]

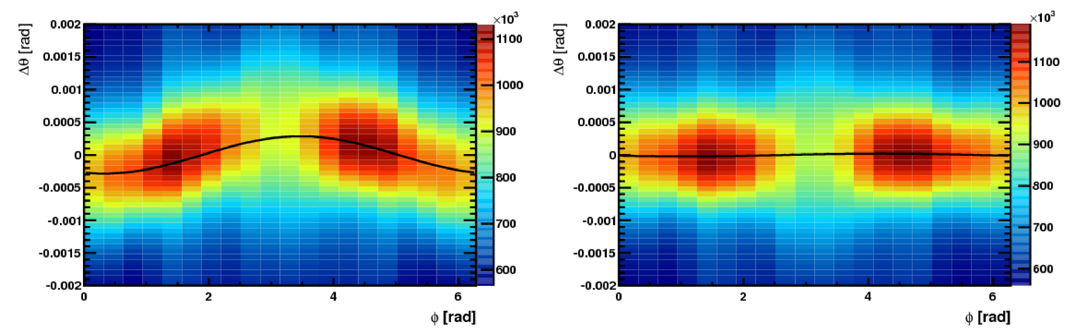


- In order to ensure the quality of physics reconstruction, the alignment procedure must be stable. Shown below is the stability of the VELO alignment for the VELO halves. The alignment parameters are only updated if there is a variation above a selected threshold ($\pm 2\mu$m in Tx, Ty for the VELO)

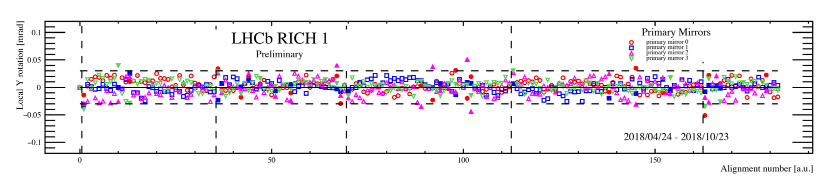


LHCb-FIGURE-2019-015

- Alignment is also crucial for reliable particle identification. The Cherenkov ring centers will not be reconstructed at the intersection of the particle track and RICH material if misaligned.
  - Corrected by fitting the angle between the reconstructed and measured ring centers ($\Delta\theta_c$) as a function the azimuthal angle ϕ iteratively.
  - Shown below are misaligned (left) and aligned (right) mirrors [Eur. Phys. J. C 73 (2013) 2431]



- The RICH alignment stability is shown below. The parameters are updated every magnet polarity change as well as for large variance.



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