Real-time alignment procedure at the LHCb experiment for Run 3

Connecting The Dots 31 May - 2 June 2022

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on behalf of the LHCb collaboration

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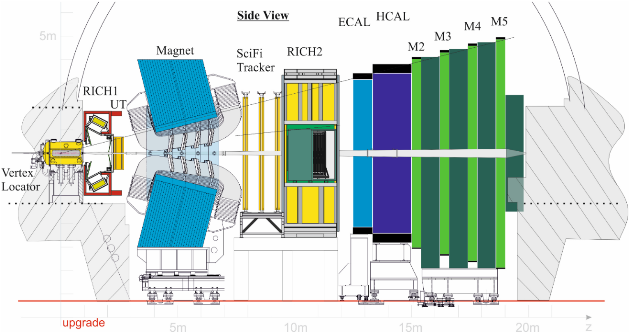
The University of Manchester

Introduction



[LHCb-TDR-12]

LHCb Upgrade detector

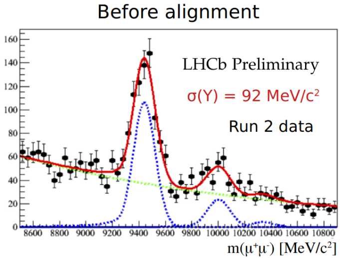
- many hardware changes
- fully software-based trigger at 30 MHz

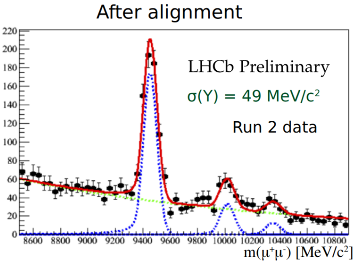
Introduction

To achieve ultimate LHCb physics potential

- best possible momentum resolution
- best possible particle-identification performance
- best possible distinction of primary and secondary vertices

→ precise alignment & calibration is needed



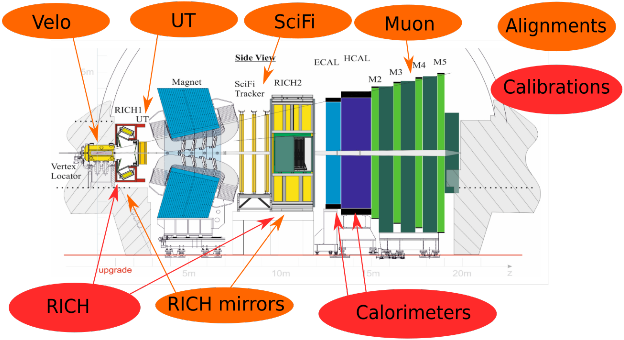


[2015 J. Phys.: Conf. Ser. 664 082010]

- automatic real-time alignment pioneered for Run 2
  [JINST 14 (2019) P04013]

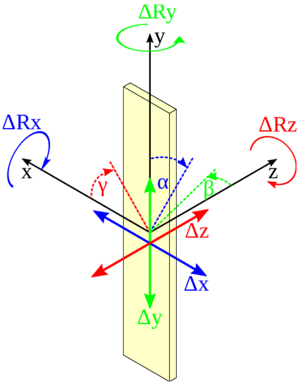
→ essential for Run 3

What we need to align and calibrate?



Tracker alignment

Align VELO, UT, SciFi, Muon system



Degrees of freedom α for tracker alignment (alignment constants)

- 3 translations T_x, T_y, T_z
- 3 rotations R_x, R_y, R_z

for each 'alignable' element

Tracker alignment

To align the tracking detectors

- reconstruct tracks with initial alignment parameters α_i
- tracks fitted using Kalman filter [Nucl.Instrum.Meth.A 600 (2009) 471-477]
- new alignment parameters α_{i+1} obtained by χ^2 minimisation
- can include vertex and mass constraints [Nucl.Instrum.Meth.A 712 (2013) 48-55]

Tracker alignment

Use states and covariance matrices from Kalman filter for alignment [Nucl.Instrum.Meth.A 600 (2009) 471-477]

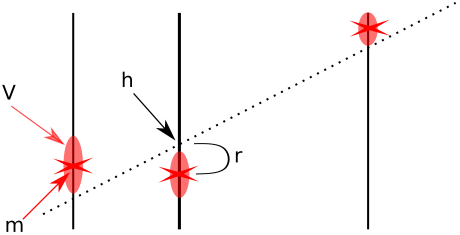
$$\chi^2 = r^T V^{-1} r$$

$$r = m - h(x, \alpha)$$

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

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

$$\alpha_1 = \alpha_0 - \left(\frac{d^2\chi^2}{d\alpha^2}\right)^{-1}\Bigg|_{\alpha_0} \frac{d\chi^2}{d\alpha}\Bigg|_{\alpha_0}$$



- r: track residuals
- m: measurement
- h: track model
- R: covariance matrix of residuals
- V: measurement covariance matrix

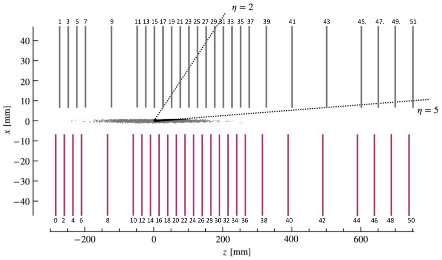
Tracker alignment

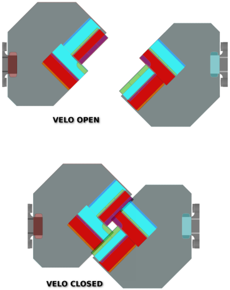
Iterative procedure until convergence
$\frac{\Delta\chi^2}{ndof} < 4$ and $\Delta\chi^2 < 25$ for each alignment degree of freedom

$$\Delta\chi^2 = -\Delta\alpha^T Cov(\alpha)^{-1}\Delta\alpha$$

If not converged, start next iteration from reconstruction with updated set of alignment constants

VELO alignment

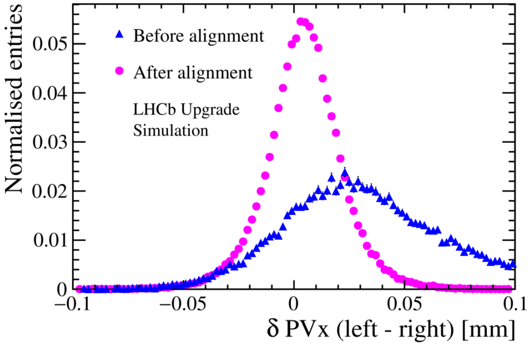


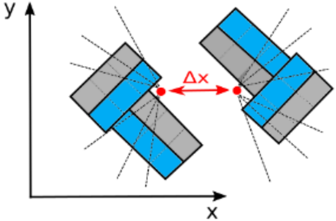


- silicon pixel detector
- two halves with 26 modules consisting of 4 sensors
- open when beam is injected ($\approx 29\,\mathrm{mm}$)
- closed when beams are stable ($\approx 5.1\,\mathrm{mm}$)
- need to compensate for displacement from closing for each LHC fill
- precise alignment needed to identify primary and secondary vertices
- make use of primary vertex constraints

VELO alignment

VELO alignment quality from measurement of the distance of the PV position reconstructed using only tracks in the right or left half





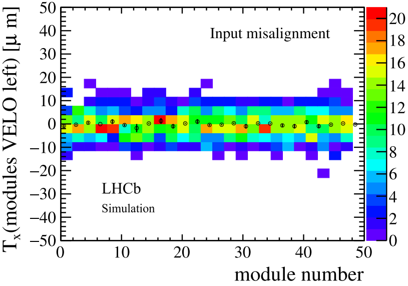
[LHCB-FIGURE-2019-003]

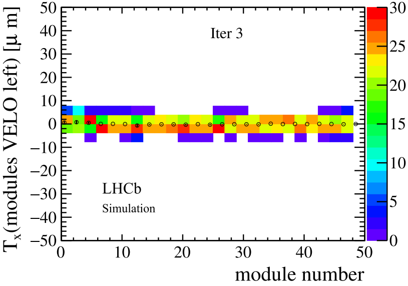
- bias would indicate misalignment

VELO alignment

to evaluate expected alignment precision

- start with random non-zero alignment constants (input misalignment)
- run alignment until convergence
- repeat and study distribution of residual misalignment
  - mean: bias in alignment
  - width: expected precision



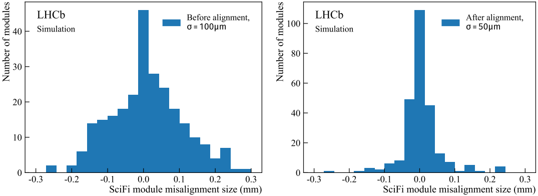


[LHCB-FIGURE-2022-006]

- similar procedure for other trackers

SciFi alignment

- scintillating fibers
- alignment important for momentum resolution

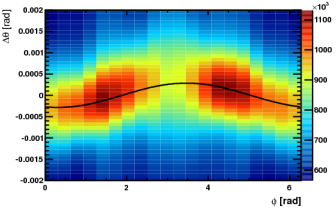


[LHCB-FIGURE-2022-006]

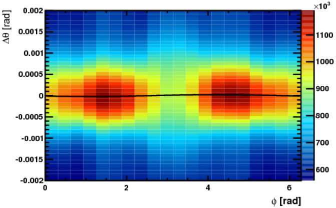
- use mass constraints ($D^0 \to K\pi$, $J/\psi \to \mu^+\mu^-$) to improve alignment quality

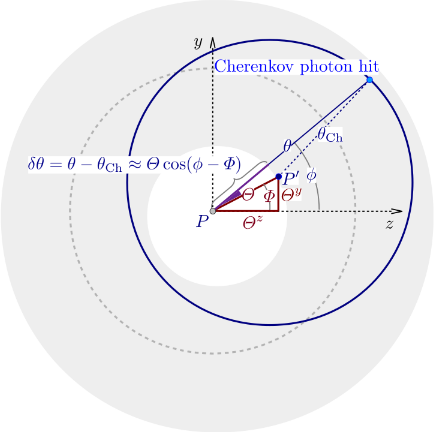
RICH mirror alignment

before mirror alignment



after mirror alignment





[Eur. Phys. J. C 73 (2013) 2431]

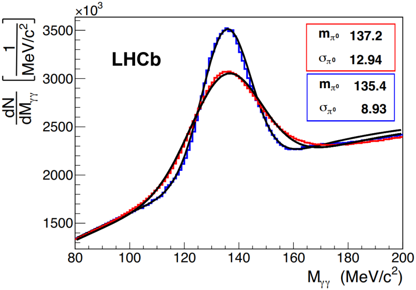
- align RICH mirrors to improve particle-identification performance

Calorimeter calibration

Calibrate calorimeter to account for ageing effects

- relative calibration
- absolute calibration

$\rightarrow$ adjust high voltage



[arXiv:2008.11556]

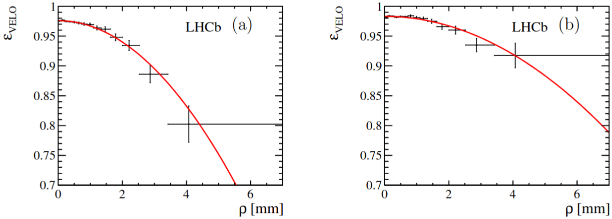
e.g. fit $\pi^0 \rightarrow \gamma\gamma$ mass peak for absolute ECAL calibration

Real-time alignment

For Run 2 pioneered offline-like quality in online reconstruction

- avoid re-running offline
- reduce differences between offline and online

As illustrative example Run 1 VELO tracking efficiency:
(not a problem for Run 3 VELO)



[JHEP04(2014)114]

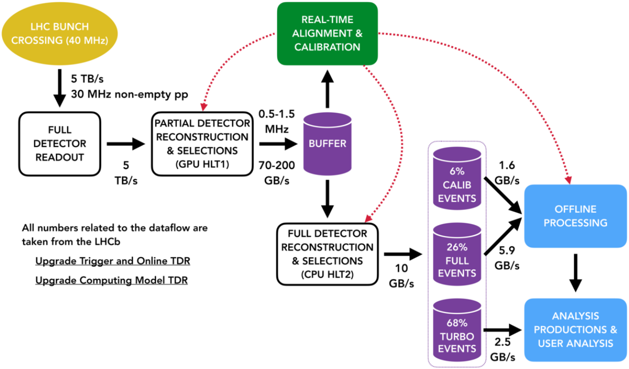
left: online, right: offline

ρ: distance of closest approach of track to z-axis

Real-time alignment

For Run 3 real-time alignment is even more important

- purer selections with less backgrounds to reduce bandwidth
- majority of events will be only partially recorded (Turbo)



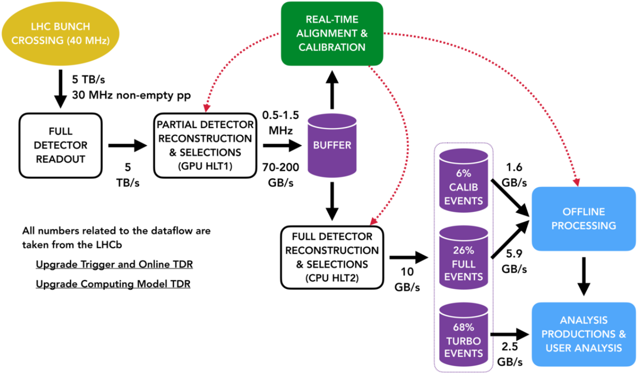
[LHCB-FIGURE-2020-016]

- HLT1
  - ▶ Tom
  - ▶ Alessandro
  - ▶ Brij
- HLT2
  - ▶ André
  - ▶ Izaac
  - ▶ Sevda

→ not possible to reconstruct full event offline

→ need best alignment&calibration online for trigger selection

Real-time alignment

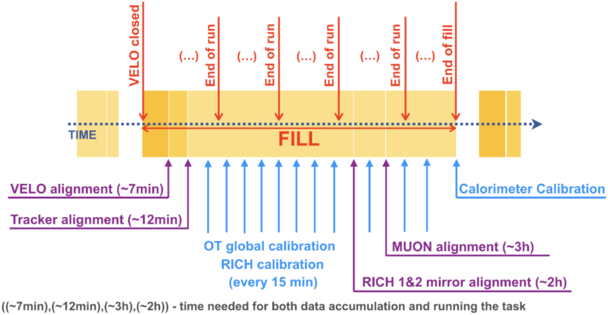


[LHCB-FIGURE-2020-016]

- alignment uses samples selected by HLT1 saved in the buffer
- alignment is executed at the start of each fill
- alignment&calibration used in the trigger → "real-time"

Real-time alignment

Run 2:

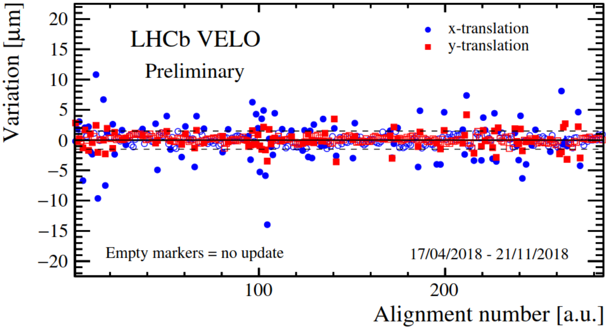


[JINST 14 (2019) P04013]

- tracker alignment finished in few minutes
  - can be used in HLT1
- RICH alignment has larger time window
  - only used in HLT2
- in case of significant variation, update database for HLT1 and HLT2

Real-time alignment

Run 2:

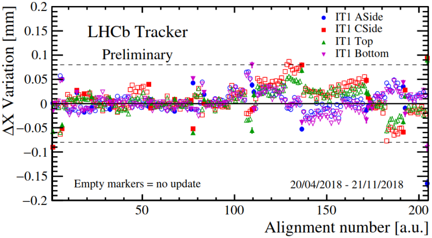


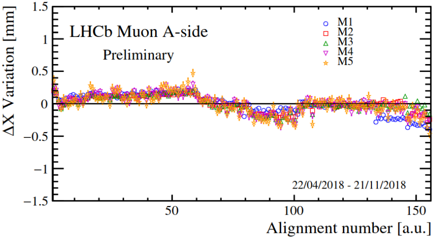
[LHCB-FIGURE-2019-015]

- frequent updates due to closing procedure
- typical sample of ≈ 40000 minimum bias events (proton-proton and proton-gas)

Real-time alignment

Run 2:





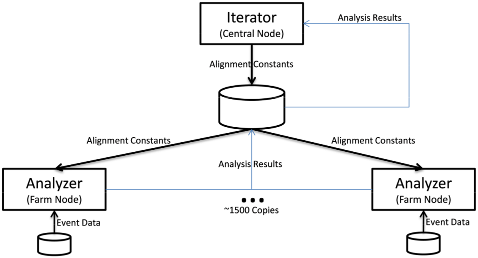
[LHCB-FIGURE-2019-015]

- tracker
  - typical sample of ≈ 70000 $D^0 \to K\pi$ decays
  - update every few weeks
- muon system
  - typical sample of ≈ 200000 $J/\psi \to \mu^+\mu^-$ decays
  - update only expected after technical intervention

Real-time alignment

Tracker alignment can be split in two parts:

- Analyzer
  - read current constants α_i
  - reconstruct tracks
  - calculate derivatives
  - write derivatives to file
- Iterator
  - read derivatives files
  - perform minimization
  - write out new constants α_{i+1}
  - trigger update if necessary



$\rightarrow$ analyzer can be easily split over multiple processes/threads

- RICH mirror alignment also can be split up in similar manner

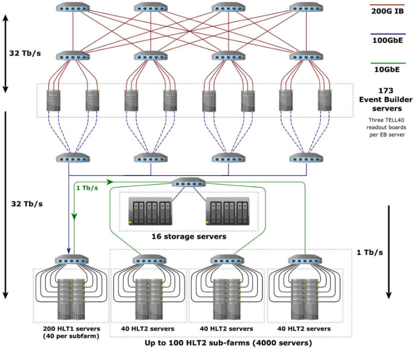
Real-time alignment

Run 2:

- single-threaded reconstruction
- alignment processes distributed over event-filter farm ($\approx$ 1600 nodes)

Run 3:

- multi-threaded reconstruction
- fewer nodes prioritizing alignment jobs (163 nodes)

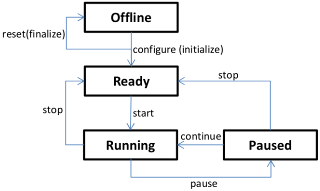


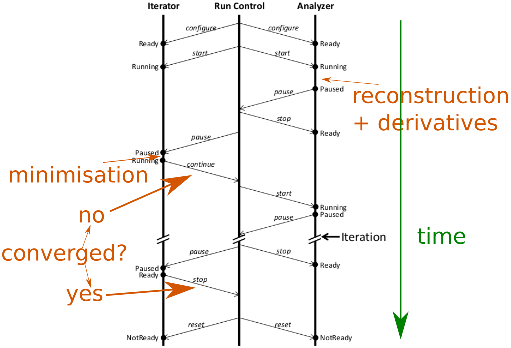
[Comput.Softw.Big Sci. 6 (2022) 1, 1]

- alignment jobs expected to take similar or less time w.r.t to Run 2

Real-time alignment

Implemented as finite-state machine steered by Run Control





Summary

- fully automated real-time alignment pioneered for Run 2
- for Run 3 new detector and fully software-based trigger
  - real-time alignment essential for best performance
  - exploits multi-threaded execution
  - currently building up system

Tune system over time with the feedback from taking real data