Novel real-time alignment and calibration, and tracking performance for LHCb Run II

Espen Eie Bowen

on behalf of the LHCb collaboration

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Overview

Introduction

The LHCb Trigger

Real-time alignment and calibration

Track reconstruction

Validation

Conclusion
The LHCb experiment

- LHCb is the dedicated heavy flavour physics experiment at the LHC
- Its primary goal is to look for indirect evidence of new physics in CP violation and rare decays of beauty and charm hadrons
- This requires:
  1. Excellent tracking (momentum, impact parameter and primary vertex resolution)
  2. Excellent decay time resolution
  3. Excellent particle identification

![Graphs and plots](Image)
Vertex Locator (VELO)

- Surrounds interaction point
- 42 silicon micro-strip stations with $r$-$\phi$ geometry
- Two retractable halves, 8 mm from beam when closed
- Closed for each fill
- PV resolution of 13 $\mu$m in $x$/$y$ and 71 $\mu$m in $z$
- Decay time resolution of 45 fs for a 4 track vertex
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Tracking system (TT, IT, OT)

Tracker Turicensis (TT)

- Upstream of magnet
- Four planes of silicon micro-strip sensors

Magnet

T stations

- Downstream of magnet
- Consists of inner and outer detector regions (Inner Tracker (IT) and Outer Tracker (OT))
- IT: Three stations each with four planes of silicon micro-strip sensors
- OT: Three stations each with four planes of straw tubes
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RICH detectors

**RICH1**
- Upstream of magnet
- $C_4F_{10}$ radiator
- $2 < p < 40$ GeV/c
- 25 - 300 mrad

**RICH2**
- Downstream of magnet
- $CF_4$ radiator
- $15 < p < 100$ GeV/c
- 15 - 120 mrad
Why is alignment important?

- Spatial alignment of the detector is vital to achieve the best possible physics performance
- Correct alignment of the VELO is crucial to be able to distinguish the secondary vertices of the decays of $b$- and $c$-hadrons
- Misalignment of the tracking system would cause deterioration of the mass resolution
Why is calibration important?

- An exclusive selection making use of hadron identification criteria requires the complete calibration of the RICH detectors.
The LHCb Trigger
Trigger for Run I

Level 0 (L0)
- Implemented in hardware
- High $p_T$ and $E_T$ signatures in muon and calorimeter systems
- 1 MHz detector readout

Higher Level Trigger (HLT)
- Flexible software triggers
- Two stages (HLT1 and HLT2)
- Track reconstruction and PV finding performed
  - Simplified reconstruction w.r.t offline
  - Preliminary alignment and calibration
  - No RICH PID used
- Combination of inclusive and exclusive selections
Novel idea for Run II

- We would like to be able to perform physics analysis directly on the output of the HLT
  - Especially interesting for charm physics measurements

- Need to achieve offline-quality event reconstruction online
- Extremely challenging to keep full tracking efficiency whilst staying within the stringent timing budget
- Want to have best possible physics performance including use of RICH PID online
- Real-time alignment and calibration!
Trigger for Run II

- After hardware stage (L0) and partial event reconstruction (HLT1), selected events are buffered to disk
- Automatic alignment and calibration is performed
- Larger farm \(\rightarrow\) larger timing budget
- Full offline reconstruction with same alignment and calibration
- RICH PID now available

Improvements

- Increased selection efficiencies and purity
- Can perform physics analysis directly on trigger output
Real-time alignment and calibration
VELO, Tracker and Muon alignment

- Uses an iterative procedure to minimise the residuals of a Kalman fit to a sample of reconstructed tracks
- Multiple scattering and the magnetic field are taken into account and both particle masses and information from vertices are used as global constraints

Iterate until $\chi^2$ difference is below threshold
RICH mirror alignment

- Misalignment of RICH w.r.t tracking system is observed as a shift of the track projection point on the photodetector plane from the centre of the corresponding Cherenkov ring
- Distribution of $\Delta \Theta$ as a function of $\phi$ shows sinusoidal shape
- Histogram fitted to determine alignment constants
  - Iterative procedure, separate for RICH1 and RICH2
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Online alignment framework

- Real-time alignment and calibration uses dedicated data samples selected by HLT1 at the start of a fill
- Computation of alignment parameters are highly parallelised using \(~1700\) nodes of the HLT farm
- Details for ① Tracker alignment and ② RICH mirror alignment

<table>
<thead>
<tr>
<th>Analyser (multiple nodes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>① Performs track reconstruction</td>
</tr>
<tr>
<td>② Performs photon reconstruction and fills histograms</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Iterator (single node)</th>
</tr>
</thead>
<tbody>
<tr>
<td>① Combines output of analysers and minimises (\chi^2) to extract alignments constants</td>
</tr>
<tr>
<td>② Fits combined histograms and extracts alignments constants</td>
</tr>
</tbody>
</table>

★ Complete real-time alignment possible within only a few minutes of data taking!
Online alignment framework

- Automatic alignment procedure runs at the start of each fill
- Only update alignment constants when necessary
- VELO is opened and closed with each fill
  - Expect to update constants every few fills
- Tracking system (TT, IT, OT)
  - Expect to update constants every few weeks
- Alignment procedure of the muon stations only used for monitoring
- RICH mirror alignment also only used for monitoring
RICH Calibration

- RICH automatic calibration consists of calibrating:
  - RICH refractive index
  - Hybrid photon detector (HPD) images

Refractive index

- Refractive index of gas radiators depends on the temperature, pressure, and composition so can change with time
- The difference between the reconstructed and expected Cherenkov angle is fitted to extract a scale factor

HPD images

- Correction applied to account for magnetic and electric field effects
- Calibrate anode image
- Evaluated and updated every run!
OT drift time calibration

- Measured drift time may be different from that estimated due to distance of track from wire
- Due to differences between collision time and LHCb clock
- Automatic procedure computes calibration using drift time residual

- Evaluated each run and updated for the next run (if difference is above threshold)
Track reconstruction
Track reconstruction

- In Run II, the full offline reconstruction will run within the trigger
- In order to maintain full reconstruction efficiency, while keeping within a strict timing budget many improvements were needed
  - Changes to the reconstruction chain and optimisation of pattern recognition algorithms
  - Optimisation of code (e.g. vectorisation)
Tracking in HLT1 for Run II

- Improved sequence forming Velo-TT tracks as an intermediate stage
- Momentum estimate allows a preselection on the $p_T$ of tracks
- Charge estimate allows greatly reduced search windows downstream of the magnet
  - Vast reduction in both ghost rate (factor 4) and execution time (factor 3)
Speed up through vectorisation

- Many areas of code are heavy on vector algebra
- Can utilise faster implementations exploiting vector instructions
- Large gains in speed (~30%) from vectorising areas of the code e.g. Kalman filter (takes large fraction of total HLT time)
Validation
Validation with early measurements

- Offline reconstruction now available online
- Use it for physics analysis!
- Turbo stream
- Only write out information of signal candidates
- Large saving in space
- Ideal for channels with high signal yield ($\mathcal{O}(10^6)$)
- Very quick turn around!

Measurement of differential $J/\psi$ cross-section [LHCb-PAPER-2015-037]

Measurement of differential charm cross-section [LHCb-PAPER-2015-041]
Conclusion

- First experiment of this scale to be able perform a complete real-time alignment and calibration within only a few minutes of data taking!
- Vast improvements made to the track reconstruction sequence to allow the same reconstruction online and offline
- Full offline track reconstruction, PV reconstruction and PID at software trigger level
- Can perform physics analysis directly on trigger output!
Tracking alignment procedure

Reconstruct the tracks using the current alignment constants

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

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

Compute a new set of alignment constants (\(\alpha\)) minimizing a global \(\chi^2\):

\[
\alpha = \alpha_0 - \left( \frac{d^2\chi^2}{d\alpha^2} \right)^{-1} \left| \frac{d\chi^2}{d\alpha} \right|_{\alpha_0}
\]

Iterate until the \(\chi^2\)-difference is below a threshold

\(r\): tracks residuals, \(V\): covariance matrix, \(R\): residuals’ covariance matrix
Finite state machine

- Offline
  - configure (initialise) ~2min
  - new constants

- Ready
  - start
  - stop
  - reset (finalize)

- Running
  - continue
  - pause

- Paused
  - stop

- Alignment