The LHCb detector

- Located at point 8 of the LHC
- General-purpose detector in the forward region
- Specialised in studying $b$- and $c$-decays

- Instrumented in the forward region to exploit forward-production of $c$- and $b$-hadrons

LHCb MC $\sqrt{s} = 14$ TeV
The LHCb detector

- Instrumentation in the forward region (2 < \( \eta \) < 5)
- Excellent secondary vertex reconstruction
- Precise tracking before and after magnet
- Good PID separation up to \( \sim 100 \text{ GeV}/c \)
LHCb timeline

Run I  LS 1  Run II  LS 2  Run III  LS 3  Run IV  LS 4  Runs V+

LHC  HL-LHC

2010  2012  2014  2016  2018  now  2022  2024  2026  2028  2030  2032

Phase I Upgrade
Triggerless readout at 40 MHz

Phase Ia Upgrade
Possible stepping stone

Phase II Upgrade
Upgrade for HL

9 fb\(^{-1}\)

50 fb\(^{-1}\)

300 fb\(^{-1}\)

Belle 2
50 ab\(^{-1}\)

LHCb may be only dedicated B-physics experiment

timetable may shift
Calibration and alignment of Run I data performed “offline” weeks after data taking
- Trigger reconstruction different from offline

In Run II, data buffered before final trigger stage
- Allows for real-time alignment and calibration
- Offline-like reconstruction within the trigger
- Many analyses use “Turbo-stream” data – online reconstruction, full raw event not saved
Real-time reconstruction in Run II

- Real-time alignment and calibration performed for vertex locator, RICH detectors, tracking stations, calorimeter and muon stations
- Will focus on velo and RICH
- Alignment particularly important for velo, which opens and closes between fills
- Gas-filled RICH detectors also require frequent calibration
Each alignment task performed once per fill

Alignment begins once a large enough dataset has been collected

Calibration of RICH gas refractive index performed regularly to account for temperature/pressure changes within the radiator gas

((~7min), (~12min), (~3h), (~2h)) - time needed for both data accumulation and running the task
Real-time alignment of the Velo

- Vertex locator modules sit 5 mm from the LHC beam
- Consists of two retractable halves (one shown)
- Modules formed of two sections – one on each velo half
- During beam injection, velo retracted to 35 mm for safety
- Closed once LHC beams are stable
- Moves every fill → align every fill
Real-time alignment of the Velo

- Alignment of velo based on minimising residuals between hits and reconstructed tracks
- Plot shows $x$ and $y$ translation between the two velo halves
- Tolerance of $\pm 2 \, \mu \text{m}$ allowed without alignment update (empty markers)
- Updates may also be caused by other degrees of freedom
  - e.g. offsets or rotations within a velo half

```
<table>
<thead>
<tr>
<th>Variation [µm]</th>
</tr>
</thead>
<tbody>
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<td></td>
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</tr>
</tbody>
</table>
```

```
LHCb VELO
Preliminary
Empty markers = no update
17/04/2018 - 21/11/2018
```

Dan Craik (MIT)  Trigger & Real-time Reconstruction @ LHCb  2019-12-09  8 / 23
Real-time calibration of the RICH

- RICH detectors provide particle ID information based on angle of Cherenkov radiation
- Index of refraction of the gas radiators sensitive to changes in temperature, pressure and composition
- These features are monitored but data-driven calibration also required
- Compare recorded and expected Cherenkov angles (bottom left)
- Alignment of mirrors also calibrated (bottom right)
The turbo stream

- Save only parts of the event needed for offline analysis
- Multiple persistence levels
  - Only candidate ($\sim 7$ kB)
  - Part of event ($\sim 16$ kB)
  - Full event ($\sim 48$ kB)
  - cf. Non-turbo ($\sim 69$ kB)

Used by many analyses, e.g.

- CP violation in charm decays
  - PRL 122 (2019) 211803
- Search for dark photons decaying to dimuons
  - PRL 120 (2018) 061801
- Observation of $\Xi^{++}$
  - PRL 119 (2017) 112001
The LHCb detector: Run III upgrade

Why do we want to upgrade for Run III?
• We currently level our luminosity at
• Huge gains available if we can run at higher luminosities

Why do we run at lower luminosity?
• Design choices for our physics programme
• Detector and trigger limitations

Note that upgrading for Run 3 is before the HL-LHC era in Run 4 onwards

Run I + II target: 8 fb⁻¹
Run III + IV target: 50 fb⁻¹

A real fill with the upgrade overlaid

- Run at 5× higher luminosity
- Triggerless readout at 40 MHz
- New vertex locator
- New tracking (UT, SciFi)
Challenges in Run III

- At increased luminosity, charm (beauty) in 24% (2%) of bunch crossings
  - Cannot write out charm at 7 MHz
- Trigger must distinguish signal from less-interesting signal as well as from background
- No longer feasible to have first trigger based on calorimeters and muon detectors alone
- Need as much information about an event as soon as possible
LHCb trigger in Run III

<table>
<thead>
<tr>
<th>Run 1</th>
<th>Run 2</th>
<th>Run 3: Baseline</th>
</tr>
</thead>
<tbody>
<tr>
<td>pp Collisions</td>
<td>1 TB/s</td>
<td>5 TB/s</td>
</tr>
<tr>
<td>Hardware L0</td>
<td>50 GB/s</td>
<td>50 GB/s</td>
</tr>
<tr>
<td>EB</td>
<td>50 GB/s</td>
<td>50 GB/s</td>
</tr>
<tr>
<td>x86 CPU farm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>HLT1</td>
<td>6 GB/s</td>
<td>buffer on disk</td>
</tr>
<tr>
<td>4 GB/s</td>
<td>calibration and alignment</td>
<td>calibration and alignment</td>
</tr>
<tr>
<td>HLT2</td>
<td>6 GB/s</td>
<td>10 GB/s</td>
</tr>
<tr>
<td>Storage</td>
<td>0.3 GB/s</td>
<td>10 GB/s</td>
</tr>
<tr>
<td>Buffer will reduce from $\mathcal{O}(\text{weeks}) \rightarrow \mathcal{O}(\text{days})$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Significant increase in data transfer rates</td>
<td></td>
<td></td>
</tr>
<tr>
<td>New trigger setup offers up to $\sim 10 \times$ efficiency improvement for some physics channels</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- Hardware trigger to be removed from Run III
- HLT1 software trigger must perform at $30 \times$ higher rate with $5 \times$ the pileup
- Buffer will reduce from $\mathcal{O}(\text{weeks}) \rightarrow \mathcal{O}(\text{days})$
- Significant increase in data transfer rates
- New trigger setup offers up to $\sim 10 \times$ efficiency improvement for some physics channels
Run III baseline HLT1 performance

- Significant progress made to optimise tracking algorithms
- $\sim 4 \times$ improvement in throughput from vectorising, improvements to event model and optimisation

**Figure 4.2:** Throughput of the displaced-track reconstruction sequence, as a function of the product of the number of processes and number of threads, for different number of threads per process, as indicated in the legend. The throughput peak performance is 12400 evt/s/node for 2 processes and 20 threads per process. The “non-Hive” line indicates the performance that is achieved without multithreading.

**Figure 4.3:** Maximum throughput of the displaced-track reconstruction sequence, as a function of the cut on the impact parameter (in $\mu m$), for different transverse momentum thresholds in the pattern recognition algorithms, as indicated in the legend.

- Multi-threaded processes offer gains over running more processes in parallel
- Optimal CPU architecture under investigation – new AMD architecture offers significant cost/benefit improvements
Run III baseline HLT1 performance

- Allows for a flexible and configurable sequence
- Physics performance of single-track and two-track selections studied
- Loose (L) and tight (T) versions of algorithms simulated with different $p_T$ thresholds ($500 - 1000 \text{ MeV/c}$)
- (Top) $\sim 1 \text{ MHz}$ output rate achievable based on “minimum bias” simulation
- Two-track selection remains efficient
- Single-track selection still requires work
LHCb trigger in Run III

Run 1 Run 2 Run 3: Baseline Run 3: GPU-enhanced

<table>
<thead>
<tr>
<th></th>
<th>pp Collisions</th>
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<th>pp Collisions</th>
</tr>
</thead>
<tbody>
<tr>
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<td>50 GB/s</td>
</tr>
<tr>
<td>x86 CPU farm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HLT1</td>
<td>6 GB/s</td>
<td>6 GB/s</td>
<td>6 GB/s</td>
</tr>
<tr>
<td>buffer on disk calibration</td>
<td></td>
<td>buffer on disk calibration</td>
<td>buffer on disk calibration</td>
</tr>
<tr>
<td>HLT2</td>
<td>0.3 GB/s</td>
<td>10 GB/s</td>
<td>10 GB/s</td>
</tr>
<tr>
<td>Storage</td>
<td>0.7 GB/s</td>
<td>Storage</td>
<td>Storage</td>
</tr>
</tbody>
</table>

- **Option to move to a GPU-based HLT1 with GPUs installed on the Event Builder servers**
- **Free up full CPU farm for HLT2 and save on networking between event builders and CPU farm**
- **Demonstrated technical feasibility**
- **Decision due in early 2020**
Why GPUs?

- Moore’s law still holds but single-thread performance has levelled off
- Gains now to be made through parallelisation
- GPUs specialised for massively parallel operations (100s–1000s of cores)
**HLT1**

- HLT1 involves decoding, clustering and track reconstruction for all tracking subdetectors.
- Algorithms also perform Kalman filter and trigger selection.
- All stages of the process may be parallelised.

```
Raw data

Global Event Cut

Velo decoding and clustering

Velo tracking

Simple Kalman filter

Find primary vertices

UT decoding

UT tracking

SciFi decoding

SciFi tracking

Parameterized Kalman filter

Find secondary vertices

Muon decoding

Muon ID

Select events

Selected events
```

Dan Craik (MIT)
Trigger & Real-time Reconstruction @ LHCb
2019-12-09 18 / 23
The Allen project

- Generic configurable framework for GPU-based execution of an algorithm sequence
  - Data passed to GPU device
  - All algorithms executed in order
  - Results passed back to the host
- Process thousands of events in a single sequence
  - Opportunity for massive parallelisation
- Configurable sequences at compile time
- Configurable algorithms at run time
- Custom GPU memory management – no dynamic allocation
- Built in validation and monitoring
- Cross-platform compatibility with CPU architectures
- Named for Frances E. Allen
- Implement HLT1 on GPUs

Photo: User:Rama / Wikimedia Commons / CC-BY-SA-2.0
Selections

- One track
- Two tracks
- Single muon
- Two muons (displaced)
- Two muons (high-mass)
## Allen performance

<table>
<thead>
<tr>
<th>Trigger</th>
<th>Rate [kHz]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-Track</td>
<td>249 ± 18</td>
</tr>
<tr>
<td>2-Track</td>
<td>663 ± 30</td>
</tr>
<tr>
<td>High-$p_T$ muon</td>
<td>1 ± 1</td>
</tr>
<tr>
<td>Displaced dimuon</td>
<td>50 ± 8</td>
</tr>
<tr>
<td>High-mass dimuon</td>
<td>101 ± 12</td>
</tr>
<tr>
<td>Total</td>
<td>971 ± 36</td>
</tr>
</tbody>
</table>

- **Total rate reduced** $30 \rightarrow 1 \text{ MHz}$
- **Physics performance consistent with x86 baseline**

<table>
<thead>
<tr>
<th>Signal</th>
<th>GEC</th>
<th>TIS-OR- TOS</th>
<th>TOS</th>
<th>GEC × TOS</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^0 \rightarrow K^{*0} \mu^+ \mu^-$</td>
<td>89 ± 2</td>
<td>85 ± 2</td>
<td>78 ± 3</td>
<td>69 ± 3</td>
</tr>
<tr>
<td>$B^0 \rightarrow K^{*0} e^+ e^-$</td>
<td>84 ± 3</td>
<td>69 ± 4</td>
<td>62 ± 4</td>
<td>53 ± 3</td>
</tr>
<tr>
<td>$B_s^0 \rightarrow \phi \phi$</td>
<td>83 ± 3</td>
<td>70 ± 3</td>
<td>65 ± 4</td>
<td>54 ± 3</td>
</tr>
<tr>
<td>$D_s^+ \rightarrow K^+ K^- \pi^+$</td>
<td>82 ± 4</td>
<td>62 ± 5</td>
<td>38 ± 5</td>
<td>32 ± 4</td>
</tr>
<tr>
<td>$Z \rightarrow \mu^+ \mu^-$</td>
<td>78 ± 1</td>
<td>97 ± 1</td>
<td>97 ± 1</td>
<td>75 ± 1</td>
</tr>
</tbody>
</table>

GEC = global event cut, TIS = trigger independent of signal, TOS = trigger on signal
Full HLT1 algorithm can be run on $\sim 500$ current GPUs

Buy GPUs instead of networking

Performance scales with GPU so can expect more from 2021 GPUs

- Not yet limited by Amdahl’s law
- Potential to perform more tasks within HLT1
Real-time reconstruction and calibration a success story for LHCb in Run II
Offline-quality reconstruction allowed for many trigger selections to be moved to the turbo stream
- Selections can be based on offline-quality features
- Smaller event size $\rightarrow$ higher event rate for same disk rate
- Tradeoff – full raw event not saved $\rightarrow$ cannot rerun reconstruction offline
- Already crucial for charm decays in Run II

LHCb detector and DAQ upgrades for Run III
- No hardware trigger
- First-stage software trigger must perform track reconstruction at bunch-crossing rate

Baseline x86 implementation of first-stage trigger significantly optimised to deal with higher throughput

Allen project offers a GPU-implementation
- Generic framework allows for configurable algorithm sequence
- Feasibility for possible use in LHCb Run III already demonstrated