Trigger and reconstruction for the LHCb upgrade

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LHC, opportunity for flavour physics

- LHC provides 30 MHz of proton bunch crossings

- LHCb, per crossing 1.1 collisions, times 5 for the Upgrade, …
LHC, opportunity for flavour physics

- LHC provides **30 MHz** of proton bunch crossing

- Large beauty and charm production:
  
  ~45 kHz $\bar{b}b$ pairs and ~1 MHz $\bar{c}c$ pairs now, times 5 for the Upgrade, ...

  Most events are interesting.
LHC, challenge for flavour physics

- Detection of collisions and the originating particles (I rely on Chris here)
- Huge data rate, O(TB/s), limited storage capacity
  → Reject “non-interesting” events, keep the interesting
- Limited computing power
  → Need to be fast in event analysis
LHCb physics goals

LHCb – General purpose detector in forward direction

- Focus here on Heavy Flavour physics
- But LHCb trigger enables and has to enable a wide range of physics
- Unique rapidity coverage at hadron collider
- Rich program of:
  - Electroweak physics
  - Production and spectroscopy
  - Heavy Ion and fixed target physics
  - Strange physics
The LHCb experiment

Vertex and track finding

Particle identification

$B \rightarrow K^+ \pi^- \mu^- e$

~1cm
Event selection and analysis (now)

Heavy flavour decays:
- High transverse energy or momentum
- Particles with high impact parameter
- Identify particle species to reconstruct decay

(Will explain individual boxes)
L0 Hardware trigger (now)

Heavy flavour decays:
• High transverse energy or momentum
• Particles with high impact parameter
• Identify particle species to reconstruct decay
• “Easier” when muon in decay

- Only calorimetry and muons
- ~1 MHz read-out limit

Efficiency of B decays

Limits efficiency at higher luminosities
L0 Hardware trigger (Upgrade)

Heavy flavour decays:

- High transverse energy or momentum
- Particles with high impact parameter
- Identify particle species to reconstruct decay

$B \sim 1\text{cm}$

$K^+$

$\pi^-$

$\mu^-$

$e^-$
Trigger-less readout

Opportunity:
• Removes efficiency bottleneck of hardware trigger
• Flexible and adaptable software trigger running on non-custom hardware
  – New physics ideas can easily be added
  – LHCb trigger continuously expanded and improved during Run 1 and Run 2 (examples later, some Upgrade concepts already deployed)
  – People without much previous knowledge can quickly contribute

Challenge:
• Software trigger has to process 30*5 more collisions in real-time
Event selection and analysis (Upgrade)

Requirements:

- **First trigger stage (Hlt1):**
  - Process events at 30 MHz
  - Select interesting decays with high efficiency
  - Discard as much background as possible

- **Second trigger stage (Hlt2):**
  - Process Hlt1 output
  - Time per event orders of magnitude larger than in Hlt1 (Run 2 factor 20)
  - Do not fill buffer
First trigger stage

Heavy flavour decays:
- High transverse (energy or) momentum
- Particles with high impact parameter
- Identify particle species to reconstruct decay
- “Easier” when muon in decay

Essential event reconstruction to be fast
- Primary vertices
- High pt tracks
- Muon ID

Combine information to 1- and 2-track signatures

~1cm
Hlt1 inclusive trigger lines

- Inclusive charm and beauty triggers:
  - Developed for Run 2
  - Based on 1- and 2-track signatures
  - Track quality and displacement cuts
    (2-track lower pt per track)
  - Multivariate selections using
    momentum, impact parameter and
    corrected mass (2-body)
- Tuned for Upgrade conditions (next slide)

<table>
<thead>
<tr>
<th></th>
<th>Run 2 rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-Track</td>
<td>76 kHz</td>
</tr>
<tr>
<td>2-Track</td>
<td>30 kHz</td>
</tr>
<tr>
<td>1- or 2- Track</td>
<td>89 kHz</td>
</tr>
<tr>
<td>Hlt1</td>
<td>120 kHz</td>
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</tbody>
</table>
Hlt1 trigger selection (Upgrade)

• Studied for different track pt thresholds
  – L(oose) = 0.5 MHz,
    T(ight) = 1 kHz
  per line
• Result:
  – 1-Track line, high rate,
    low purity and efficiency
    (needed for some topologies)
  – 2-Track line, much better
    efficiency and purity
→ Need secondary vertexing
capabilities in Hlt1
Event selection and analysis (Upgrade)

Buffer:
- Store events for immediate alignment and calibration
- Allows to use computing farm in and out fill
Real-time alignment and calibration

- Need optimal tracking system alignment for Hlt1 selections
  - E.g. the Velo is moved in and out for every fill
- Optimal particle identification in Hlt2
  - E.g. calibration of RICH depends on pressure
- Align and calibrate all subdetectors while taking data
- Process second trigger stage only after full alignment and calibration
Real-time alignment and calibration

• System very successfully implemented in Run 2
• Tracking system aligned and calibrated within minutes after start of fill
  – Update of alignment parameters automatically triggered if necessary
• Particle identification systems calibrated and aligned within hours
  – HLT2 waits before analysing HLT1 output
Disk Buffer (Now)

- Asynchronous processing of Hlt2 allows to optimally use farm resources

![Graph showing disk occupancy and event processing rate over time]
Disk Buffer (Now)

- Asynchronous processing of Hlt2 allows to optimally use farm resources to maximise physics output.
Disk Buffer in Upgrade?

- Asynchronous processing of Hlt2 allows to optimally use farm resources to maximise physics output.

Now 10 PB
Filled in 1 day at 1 MHz Hlt1 output.
Increase by orders of magnitude???

Now takes weeks to empty if full.
Months to process?

Week in 2016
Disk Buffer in Upgrade?

- Asynchronous processing of Hlt2 allows to optimally use farm resources to maximise physics output.

Filled in 1 day at 1 MHz Hlt1 output.

Increase by orders of magnitude???

Now 10 PB

Now takes weeks to empty if full.

How does the model scale in the upgrade?

Different model: e.g. fill faster and empty faster?
Event selection and analysis (Upgrade)

Hlt2:
- Reconstruct full event including particle identification
- Reduce bandwidth written to storage
  - Pure and efficient event selection
  - Reduce event information

LHCb Upgrade Diagram
- 30 MHz inelastic event rate (full rate event building)
- Full event reconstruction, inclusive and exclusive kinematic/geometric selections
- Buffer events to disk, perform online detector calibration and alignment
- Add offline precision particle identification and track quality information to selections
- Output full event information for inclusive triggers, trigger candidates and related primary vertices for exclusive triggers
- 2-5 GB/s to storage
Output bandwidth

- Limit to tape storage 2 – 5 GB/s
- Upgrade events size 100 kB
- Assume 10 (5) % efficiency of full selection chain
  
  \[ \text{Beauty bandwidth} = 100 \text{ kB} \times 200 \text{ kHz} \times 0.1 = 2 \text{ GB/s}, \]
  \[ \text{Charm bandwidth} = 100 \text{ kB} \times 5 \text{ MHz} \times 0.05 = 25 \text{ GB/s} \]

→ No way to write out full information of all signal events, beauty and charm
Turbo stream

- Save objects reconstructed in trigger, discard raw detector information
  - Order of magnitude reduction in event size
- Analyses done on trigger output
  - Requires best detector calibration, and precise and efficient reconstruction in trigger
- Most published LHCb Run 2 analyses done with Turbo stream
  - Run 2 online reconstruction equals Run 2 offline reconstruction
  - Charm yields factors higher in Run 2 compared to Run 1
Turbo stream options

- Turbo concept evolved over last years to give flexibility to analysts
  - Choose what you want to persist with a given bandwidth
  - Trade off between number of events and information per event
- Turbo: E.g. ideal for high rate charm (25 GB/s → 2.5 GB/s), beauty
- Turbo SP: E.g. save B-hadron candidate and opposite B for flavour tagging, spectroscopy, jets, dark photons, ...
- Turbo++: E.g. rare decays with small trigger rate, to later optimize selection and event classification
Online = Offline (Best quality)

- High precision measurements require understanding of efficiencies
  - Efficiencies determined via combination of simulation and data-driven methods
- Any big inefficiency leads to systematic uncertainties in analysis
  - Best to have fewer inefficiencies
    → Online = Offline
  - And high efficiency reconstruction from the start
- Also: Better use of resources
  - No offline processing needed
  - More resources for analysis and simulation

Example: Lifetime measurement

$B^0 \rightarrow J/\psi \phi$

\begin{align*}
J & = 1 \\
H & = 1 \\
E & = 1 \\
P & = 4 (2014)
\end{align*}

\begin{align*}
J & = 1 \\
H & = 1 \\
E & = 1 \\
P & = 4 (2014)
\end{align*}

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Conclusion

- Everything is awesome...

- ... wait
Coming back to challenges

30 MHz

- Farm budget for 1000 computing nodes
- Benchmark on today’s CPUs and extrapolate to 2021

\[ T = N \times t \times g^{\Delta y} \]

- Farm throughput $T$, Number of nodes $N$, node throughput $t$, growth factor per year $g$, years until data taking $\Delta y$
- Goal:

\[ T > 30 \text{ MHz} \]
Farm throughput estimates

$g \approx 1.365$ (TDR)  \quad g \approx 1.1$

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<table>
<thead>
<tr>
<th>Reconstruction</th>
<th>T in 2012</th>
<th>T in 2017</th>
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<tbody>
<tr>
<td>PVs + high pt tracks</td>
<td>33 MHz</td>
<td>5 MHz</td>
</tr>
<tr>
<td>+ Kalman filter</td>
<td>14 MHz</td>
<td>2.4 MHz</td>
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Changing CPUs

- Clock frequency increase slowed down since a decade
- Made up by more cores per processor (multi-threading) and more instructions per cycle (vectorisation)
  → Both need optimised software
Multi-threaded framework

- Currently, run many independent instances of same application.
- **First prototype** with new software framework running one instance with multiple threads
  - Significant work was needed
  - Tested on special hardware with many more cores than usual CPUs
  - Small increase in memory per thread
  - Nearly optimal scaling with number of cores
- How much does it gain us compared to old framework?
Being smarter and avoiding work

(one of many examples)

• One step further “Parameterized Kalman”
  – Parameterize material look-up and B-field propagation with analytic functions
  – Very fast and already good performance

• Track fit (Kalman filter) time consuming
  – Material lookup
  – B-Field propagation

• From Run 1 to Run 2 replaced detailed material map with a simplified map
Conclusion

- Full software trigger is a unique opportunity to fully exploit increased luminosity
- Several concepts for Upgrade already up and running
  - Real-time alignment and calibration
  - Real-time event analysis (Turbo stream)
- Challenging and exciting to
  - Solve a big computing problem in the next years
  - Provide high quality for precision measurements
• Backup
Efficiency comparison (backup)

Run 1 L0 efficiency

Hlt1 efficiency estimates for Upgrade
Run 2 summary

- Run2 **software** trigger really nice
  - Coherent reconstruction from Hlt1 to offline (alignments, calibrations, algorithms)
  - Hlt1 very efficient, learned how to adjust purity in times of high LHC efficiency
  - Hlt2 runs previous offline reconstruction upfront
  - Turbo provides great flexibility to trade event size vs. event rate