The LHCb trigger system
Performance and outlook

Cristina Lazzeroni
University of Birmingham
On behalf of the LHCb Collaboration

Triggering Discoveries in High Energy Physics Conference
University of Jammu, India
The LHCb Trigger

Introduction

The current trigger
Level 0
Event buffering
HLT1
HLT2
Performance
Post-LS1 and Upgrade
LHC run 2
Upgrade
Conclusions

C. Lazzeroni
09-14/09/2013

The LHCb Experiment

- LHCb is a single-arm \((2 < \eta < 5)\) spectrometer at the LHC
  - Precision beauty and charm physics: \(CP\) violation measurements, rare decays, heavy flavor production
  - Exploits the correlated production of \(b\bar{b}\) pairs in the LHC environment

- Time-dependent analyses require good time resolution: \(\sim 45\) fs (VELO)
- Flavor tagging, final state discrimination needs excellent particle ID: (RICH)
- Rare decays and extremely small asymmetries require pure data samples with high signal efficiency: (Trigger)
The LHC environment

- The LHC is a great place to study precision beauty and charm physics, but it isn’t easy:

  - 40 MHz bunch crossing frequency
  - Luminosity
    \[ \mathcal{L} = 4 \times 10^{32} \text{cm}^{-2} \text{s}^{-1} \]
    (2 \times \text{design})
  - 15 MHz visible pp interaction rate
    \[
    \begin{array}{cccc}
    N_{PV} & 1 & 2 & 3 & >4 \\
    P(\%) & 55 & 30 & 11 & 4 \\
    \end{array}
    \]
  - \( \mu \sim 1.6 \) interactions per bunch crossing

- \( \sigma_{b\bar{b}} = 75.3 \pm 14.1 \ \mu b \) [Phys. Lett.B694(2010)]
- \( \sigma_{c\bar{c}} = 1419 \pm 134 \ \mu b \) [Nucl. Phys. B871 (2013)]
- Corresponds to 30 kHz \( b\bar{b} \) pairs, 600 kHz \( c\bar{c} \) pairs in acceptance.
- Signal purity is independent of pileup:
Typical Signatures

- Beauty and charm hadron typical decay topologies:

  ![Diagram](image)

  - **B ±** mass \( \sim 5.28 \text{ GeV} \), daughter \( p_T \sim O(1 \text{ GeV}) \)
  - \( \tau \sim 1.6 \text{ ps} \), Flight distance \( \sim 1 \text{ cm} \)
  - Important signature: Detached muons from \( B \rightarrow J/\psi X \), \( J/\psi \rightarrow \mu \mu \)
  - **D^0** mass \( \sim 1.86 \text{ GeV} \), appreciable daughter \( p_T \)
  - \( \tau \sim 0.4 \text{ ps} \), Flight distance \( \sim 4 \text{ mm} \)
  - Also produced as ‘secondary’ charm from B decays.

Underlying trigger strategy:

- **Inclusive triggering** on displaced vertices with high-\( p_T \) tracks
- **Exclusive triggering** for anything else
Trigger consists of three stages:
- Level 0 (L0) near-detector hardware, readout decision in 4 µs
- Higher Level Trigger (HLT) 1&2: flexible software triggers running on dedicated Event Filter Farm (EFF), 29,000 cores
- Documented in [JINST 8 (2013) P04022]
L0 muon trigger

- Momentum resolution $\Delta p/p \sim 20\%$
- Single- and Di-muon triggers: $p_T > 1.5$ GeV, $p_{T1} \times p_{T2} > 1.3$ GeV^2
- 90% efficient for most dimuon channels
- L0 muon rate: 400 kHz
L0 calo trigger

- Selects High $E_T$ hadrons, $e^\pm$, $\gamma$
- Threshold $E_T > 2.5 - 3.5\text{GeV}$
- Preshower and SPD discriminate between $e^\pm$, $\gamma$

- Hadronic B-decay efficiency 50%
- 80% efficient for radiative $B \rightarrow X\gamma$ decays
- L0 $e^\pm/\gamma$ rate: $\sim 150 \text{kHz}$
- L0 hadron rate: $\sim 450 \text{kHz}$
Deferred trigger

- L0-accepted events are sent to the Event Filter Farm to be processed by the HLT
- Farm nodes idle between fills, large disks (1PB total) not used by HLT software
- Instead: Buffer 20% of L0 events on EFF disks, process in inter-fill time
- Effective 20% Extra CPU allows us to lower tracking thresholds from $p_T = 500 \rightarrow 300\text{MeV}$
- Increases efficiency for charm signatures
- Peak disk usage, 88% after > 16h fill

Possible thanks to the ingenuity of the LHCb online team!
- HLT1 Adds tracking and PV information:
- VErtex LOcator (VELO) tracking + PV reconstruction
- Tracks matched to L0muon hits or with large IP are selected for forward tracking into the Inner & Outer trackers (IT&OT)
**HLT1 forward tracking**

- Forward tracking looks for corresponding hits in IT & OT
- $p_T$ dependent search windows for single muon, dimuon and high-$p_T$ track categories:

<table>
<thead>
<tr>
<th>track</th>
<th>$\mu$</th>
<th>$\mu\mu$</th>
<th>other</th>
</tr>
</thead>
<tbody>
<tr>
<td>min. $p_T$ [GeV]</td>
<td>1.0</td>
<td>0.5</td>
<td>1.6</td>
</tr>
</tbody>
</table>

- HLT1 efficiencies vs. $p_T$ [JINST 8 (2013) P04022]
  - left: $B^+ \rightarrow J/\psi K^+$ candidates with HLT1 muon triggers
  - right: Hadronic modes
### HLT2 Full reconstruction

- HLT2 fully reconstructs the event
- Allows for a range of selection criteria of varying complexity
- Close to offline reconstruction performance
- Combination of Inclusive and Exclusive lines, eg:

#### Inclusive dimuon

![Inclusive dimuon diagram](image)

- **μ⁻**
- **μ⁺**

#### Inclusive φ

![Inclusive φ diagram](image)

- **K⁻**
- **K⁺**

#### B → hh

![B → hh diagram](image)

- **h**

#### Topo N-body

![Topo N-body diagram](image)

- **h**
- **PV**

- Extremely flexible, powerful software environment: Supports MVA-based selections

- Composition of trigger lines and individual prescales can be adjusted to suit running conditions
HLT2 inclusive dimuon

- Many important analyses at LHCb have two muons in the final state:
  - Rarest B decay $B^0_s \rightarrow \mu\mu$: [LHCb-PAPER-2013-046]
  - $CP$ "golden mode" $B^0_s \rightarrow J/\psi\phi$: [PRD87 112010 (2013)]
  - $B^0 \rightarrow K^*\mu\mu$: [LHCb-PAPER-2013-037]

- Make use of the same muon ID strategy as offline: [LHCb-DP-2013-001]
  - "Prompt and Detached" strategy:
    - Prompt lines avoid lifetime-biasing cuts but are prescaled (unless high $p_T$)
    - Detached lines use IP cuts to increase purity
  - 92% efficient on $B^+ \rightarrow J/\psi K^+$ [LHCb-PUB-2011-017]

- $\Upsilon$ spectrum with
  - $\sim 51\text{pb}^{-1}$
  - $\sigma(\Upsilon(1S)) \sim 43$ MeV [JHEP 06 (2013) 064]
Topological $N$–body lines

- Inclusive trigger on 2,3,4-body detached vertices [LHCb-PUB-2011-016]
- Primary trigger for $B$ decays to charged tracks
- Uses modified BDT algorithm [JINST 8 (2013) P02013]
- BDT inputs: $p_T$, $IP\chi^2$, Flight distance $\chi^2$, mass and $m_{\text{corr}}$, corrected mass:

$$m_{\text{corr}} = \sqrt{m^2 + |p_{\text{Tmiss}}|^2} + |p_{\text{Tmiss}}|$$

- $p_{\text{Tmiss}}$: missing momentum transverse to flight direction

- Very efficient on fully hadronic $B$ decays
The LHCb Trigger

Introduction

The current trigger
Level 0
Event buffering
HLT1
HLT2

Performance

Post-LS1 and Upgrade
LHC run 2
Upgrade

Conclusions

C. Lazzeroni

09-14/09/2013

Trigger performance

- Trigger efficiencies for selected channels:

<table>
<thead>
<tr>
<th>Mode</th>
<th>Hadronic</th>
<th>Dimuon</th>
<th>Radiative</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D \rightarrow hh$</td>
<td>27</td>
<td>62</td>
<td>93</td>
</tr>
<tr>
<td>$B \rightarrow hh$</td>
<td></td>
<td></td>
<td>85</td>
</tr>
<tr>
<td>$B^+ \rightarrow J/\psi K^+$</td>
<td>93</td>
<td>92</td>
<td>67</td>
</tr>
<tr>
<td>$B^0 \rightarrow K^*\gamma$</td>
<td>85</td>
<td></td>
<td>57</td>
</tr>
</tbody>
</table>

- Extremely pure samples after offline selection:

$D^* \rightarrow D^0 \pi$ [Phys Rev Lett 110 (2013)]

$B^0_s \rightarrow J/\psi \phi$ [PRD87 112010 (2013)]

$B^0_d \rightarrow K^*\gamma$, $B^0_s \rightarrow \phi \gamma$ [PRD85 (2012)]

$B^0_s \rightarrow D_s \pi$ [New J Phys 15 (2013)]
Online Monitoring

- It isn't just offline selected data that is clean:

- Online monitoring plots as seen in the control room, straight from HLT2
Post-LS1 trigger

- Work is ongoing to improve trigger performance for LHC run 2:
  - **Goal**: make trigger more compatible with offline analysis environment
  - **Requires** HLT to perform detector alignment and calibration
    - Move buffering to after HLT1
    - Buffer to disk while alignment is performed
    - Run HLT2 after alignment
  - Allows us to use selection-level cuts in the trigger
    - eg: full RICH PID [EPJC 73 2431], currently used in a limited capacity
  - Major advantage: Allows prescaling of Cabbibo-favored charm decays while keeping 100% of DCS.
Upgrade trigger

- Post LHC-upgrade: \( \mathcal{L} = 2 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1} \)
- 1 MHz detector readout becomes a bottleneck, particularly for fully hadronic modes
- Upgrade LHCb will be able to read out full detector at 40 MHz
- L0 trigger becomes the Low-Level Trigger (LLT); increasing the LLT accept rate greatly improves efficiency

Initially use LLT to reduce input rate to HLT

HLT will consist of exclusive/inclusive line strategy similar to present design

As farm size increases, LLT progressively loosened
Conclusions

- The LHCb trigger is a powerful and flexible design that covers an extremely wide range
- From the rarest $B$ decay at high efficiency:
- to the largest charm samples at high purity:
- Combination of exclusive and inclusive lines for maximum coverage
- Deferral of trigger makes optimal use of resources
- Exciting prospects for the post-upgrade trigger
L0 efficiencies

Figure 3. Efficiency $\varepsilon^{TOS}$ of $B^+ \rightarrow J/\psi (\mu^+ \mu^-)K^+$ as a function of $p_T (J/\psi)$ for L0Muon and L0DiMuon lines.

Figure 4. The efficiency $\varepsilon^{TOS}$ of L0Hadron is shown for $B^0 \rightarrow D^- \pi^+$, $B^- \rightarrow D^0 \pi^-$, $D^0 \rightarrow K^- \pi^+$ and $D^+ \rightarrow K^- \pi^+ \pi^+$ as a function of $p_T$ of the signal $B$ and $D$ mesons.

Figure 5. The efficiency $\varepsilon^{TOS}$ of L0Electron is shown for $B^0 \rightarrow J/\psi (e^+ e^-)K^*0$ as a function of $p_T (J/\psi)$. 
**HLT1 efficiencies**

**Figure 6.** Efficiency $\varepsilon^{TOS}$ of Hlt1TrackMuon, Hlt1DiMuonHighMass and Hlt1DiMuonLowMass for $B^+ \rightarrow J/\psi (\mu^+\mu^-)K^+$ as a function of the $p_T$ and lifetime of the $B^+$.

**Figure 7.** Efficiency $\varepsilon^{TOS}$ of Hlt1TrackAllL0 is shown for $B^- \rightarrow D^0\pi^-$, $B^0 \rightarrow D^-\pi^+$, $D^0 \rightarrow K^-\pi^+$ and $D^+ \rightarrow K^-\pi^+\pi^+$ as a function of $p_T$ and $\tau$ of the $B$-meson and prompt $D$-meson respectively.
**Figure 8.** Efficiencies $\varepsilon_{\text{TOS}}$ of Hlt2DiMuonJPsiHighPT and Hlt2DiMuonDetachedJPsi for $B^+ \rightarrow J/\psi K^+$ as a function of $p_T$ and $\tau$ of the $B^+$.  

**Figure 11.** Efficiency $\varepsilon_{\text{TOS}}$ of the lines Hlt2CharmHadD2HHH and Hlt2CharmHadD02HH_D02KPi for $D^+ \rightarrow K^- \pi^+ \pi^+$ and $D^0 \rightarrow K^- \pi^+$ respectively as a function of $p_T$ and $\tau$ of the $D$-meson. The efficiency is measured relative to events that are TOS in Hlt1TrackAllL0.
**HLT2 Topo efficiencies**

![Graph 1](image1.png)

**Figure 9.** Efficiency $\epsilon_{\text{TOS}}$ if at least one of the lines $\text{Hlt2TopoBody}$, with $n = 2, 3$, selected the event for $B^- \rightarrow D^0 \pi^-$ and one of the lines with $n = 2, 3, 4$ for $B^0 \rightarrow D^- \pi^+$ as a function of $p_T$ and $\tau$ of the $B$-meson. The efficiency is measured relative to events that are TOS in $\text{Hlt1TrackAllL0}$.

![Graph 2](image2.png)

**Figure 10.** Efficiency $\epsilon_{\text{TOS}}$ if at least one of the lines $\text{Hlt2TopoBody}$ or $\text{Hlt2TopoMuBody}$, with $n = 2, 3$, selected events for $B^+ \rightarrow J/\psi K^+$, as a function of $p_T$ and $\tau$ of the $B$-meson. Also shown is $\epsilon_{\text{TOS}}$ if the line $\text{Hlt2TopoBody}$, with $n = 2, 3$, selected the events. $\text{Hlt2Topo2Body}$ shows the inclusive performance of the topological lines. The efficiency is measured relative to events that are TOS in either $\text{Hlt1TrackAllL0}$ or $\text{Hlt1TrackMuon}$. 

---

LHCb
The LHCb dataset

![Graph showing data points with labels: pp 18 x10^{13}, c\bar{c} 59 x10^{11}, b\bar{b} 26 x10^{10} and additional text information.](image)