The upgrade of the LHCb trigger system

Conor Fitzpatrick
On behalf of the LHCb Collaboration

WIT 2014
Philadelphia
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: $\sim 40$ 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)
A typical event

The LHCb Event Display

9.10. 2011 14:07:51
Run 103180 Event 1878017019 bId 2718
Typical Signatures

- Beauty and charm hadron typical decay topologies:

  **Beauty Hadrons**

  ![Beauty Hadron Diagram]

  ![Beauty Hadron Diagram]

  **Charm Hadrons**

  ![Charm Hadron Diagram]

  ![Charm Hadron Diagram]

- $B^\pm$ mass $\sim 5.28$ GeV, daughter $p_T \mathcal{O}(1$ GeV)

- $\tau \sim 1.6$ ps, Flight distance $\sim 1$ cm

- Important signature: Detached muons from $B \to J/\psi X$, $J/\psi \to \mu\mu$

- $D^0$ mass $\sim 1.86$ GeV, appreciable daughter $p_T$

- $\tau \sim 0.4$ ps, Flight distance $\sim 4$ 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
2011-2012 trigger architecture

- The present 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
L0 trigger

- L0 hardware trigger in Run I: high $p_T$ and $E_T$ signatures:
  - L0 muon:
    - $\Delta p/p \sim 20\%$
    - Single- and Di-muon $p_T$ thresholds
    - 90% efficient for most dimuon channels
  - L0 calo: High $E_T$ hadrons, $e^\pm$, $\gamma$
    - 50% efficient on hadronic B decays
    - 80% efficient for radiative $B \rightarrow X\gamma$ decays
Deferred trigger

- L0-accepted events 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 25% Extra CPU allowed us to lower tracking thresholds from $p_T = 500 \rightarrow 300$ MeV
- Increased efficiency for charm signatures
- Peak disk usage, 88% after $>16$h fill

Disk usage as a function of time

- Possible thanks to the ingenuity of the LHCb online team!
HLT1

- 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)
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]

  **Inclusive \( \phi \)**

  ![Inclusive \( \phi \) diagram]

  **Topo N-body**

  ![Topo N-body diagram]

- Extremely flexible, powerful software environment: Supports MVA-based selections
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 $m_{corr}$, corrected mass:

\[
m_{corr} = \sqrt{m^2 + |p_{T\text{miss}}|^2 + |p_{T\text{miss}}|}
\]

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

- Very efficient on fully hadronic B decays
Inclusive Charm

\( D^*+ \rightarrow D^0 \pi^+ \)

- Charm is an important part of the LHCb physics programme:
  - Observation of \( D^0-\overline{D}^0 \) oscillations: [PRL 110 (2013) 101802]
  - Measurement of \( D^0-\overline{D}^0 \) mixing parameters: [PRL 111 (2013) 251801]
  - 600 kHz of c\( \bar{c} \) in 2012: Easy to swamp the output bandwidth unless exclusive selections are used
  - Exception: \( D^* \rightarrow D^0 \pi \) inclusive trigger uses \( M(D^*) - M(D^0) \) to reduce the rate
  - \( D^0 \) inclusively reconstructed in K K, \( \pi \pi \), K \( \pi \), \( \pi K \) final states, any in mass window are kept
  - Cabbibo favored \( D^0 \rightarrow K^- \pi^+ \) is \( \sim 300 \) times more abundant than Doubly cabbibo suppressed \( D^0 \rightarrow K^+ \pi^- \)
Run I 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>$\epsilon(L0)$ [%]</td>
<td>$D \rightarrow hh  h$</td>
<td>$B \rightarrow hh$</td>
<td>$B^+ \rightarrow J/\psi K^+$</td>
</tr>
<tr>
<td>$\epsilon$(HLT</td>
<td>L0) [%]</td>
<td>93</td>
<td>85</td>
</tr>
<tr>
<td>$\epsilon$(HLT $\times$ L0) [%]</td>
<td>84</td>
<td>57</td>
<td></td>
</tr>
</tbody>
</table>

- Extremely pure samples after offline selection:

$D^* \rightarrow D^0\pi$ [1211.1230]

$B^0_s \rightarrow J/\psi \phi$ [1304.2600v3]

$B^0 \rightarrow K^*\gamma$, $B^0_s \rightarrow \phi\gamma$ [1202.6267]

$B^0 \rightarrow \mu\mu$ [1211.2674]
Post-LS1 trigger

- Run II: No significant changes to detector, but the trigger architecture changes:

  - Goal: make trigger more compatible with offline analysis environment
  - Requires HLT to perform detector alignment and calibration
    - Move buffering to after HLT1: Buffer at kHz instead of MHz
    - Buffer to disk while alignment is performed
    - Run HLT2 after alignment
  - Allows us to use selections similar to offline:
    - 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.
The Upgrade

- From 2018, LHCb will run at $\mathcal{L} = 2 \times 10^{33}$ cm$^{-2}$ s$^{-1}$

- VELO moves from $r, \phi$ strips to pixels: LHCb-TDR-013
- RICH replaces photon detectors, SPD, PRS, M1 removed: LHCb-TDR-014
- Trackers replaced: scintillating fibers + silicon microstrips: LHCb-TDR-015
The Upgrade Trigger

TDR in preparation

- At $\mathcal{L} = 2 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$, 1 MHz readout becomes a bottleneck:
  - Saturation problem: at increased lumi signal less well separated in L0.

- Readout upgraded to 40 MHz: Full readout of 30 MHz Visible pp interactions
  - L0-hardware trigger removed, software Low-Level Trigger (LLT) as replacement
  - Acts as 'handbrake' during commissioning, 1 – 40 MHz scaleable output rate
### Upgrade conditions

**LHCb-PUB-2014-027** in preparation

- Average inelastic + elastic pp collisions per visible bunch crossing: \( \nu = 2.0 \rightarrow 7.6 \)

<table>
<thead>
<tr>
<th></th>
<th>Run I</th>
<th>Upgrade</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Per event</td>
<td>with vertex in VELO</td>
</tr>
<tr>
<td>b-hadrons</td>
<td>0.0258 ± 0.0004</td>
<td>0.0029 ± 0.0001</td>
</tr>
<tr>
<td>c-hadrons</td>
<td>0.297 ± 0.001</td>
<td>0.0422 ± 0.0005</td>
</tr>
<tr>
<td>light, long-lived hadrons</td>
<td>8.04 ± 0.01</td>
<td>0.511 ± 0.002</td>
</tr>
</tbody>
</table>

### Upgrade trigger challenge

- Upgrade trigger challenge is one of categorisation, not event rejection
- Use the maximum available information to distinguish between signals
Upgrade tracking strategy

LHCb-PUB-2014-028 in preparation

- Offline-quality tracking at 30 MHz is possible in software!

- Tracking sequence uses 5.4 ms/event
- LHCb trigger and farm budget: 2.8 MCHf, $\mathcal{O}(1000)$ nodes
- Trigger timing budget: 13 ms/event
- Robustness and flexibility are a major advantage
- See Umberto’s talk next for more details

- LHCb will be the first collider experiment to operate an all-software trigger at full event rate
Robustness

- Timing of the tracking sequence has been studied at three working points:
  - $\mathcal{L} = 1 \times 10^{33} \text{cm}^{-2} \text{s}^{-1} [\nu = 3.8]
  - $\mathcal{L} = 2 \times 10^{33} \text{cm}^{-2} \text{s}^{-1} [\nu = 7.6]$ (Nominal running)
  - $\mathcal{L} = 3 \times 10^{33} \text{cm}^{-2} \text{s}^{-1} [\nu = 11.4]$

- Global Event Cut (GEC): Event multiplicity cut also used in Run 1
- Several optimisations can be made to enhance timing and efficiency for different working points
Upgrade channels

Implications of LHCb measurements & future prospects: [EPJC 73 (2013) 2373]

- LHCb will need to trigger on a very broad range of physics processes:

<table>
<thead>
<tr>
<th>Type</th>
<th>Observable</th>
<th>Current precision</th>
<th>LHCb 2018</th>
<th>Upgrade (50 fb⁻¹)</th>
<th>Theory uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_s^0$ mixing</td>
<td>$2\beta_s (B_s^0 \to J/\psi \phi)$</td>
<td>0.10 138</td>
<td>0.025</td>
<td>0.008</td>
<td>~ 0.003</td>
</tr>
<tr>
<td></td>
<td>$2\beta_s (B_s^0 \to J/\psi f_0(980))$</td>
<td>0.17 214</td>
<td>0.045</td>
<td>0.014</td>
<td>~ 0.01</td>
</tr>
<tr>
<td></td>
<td>$a_s^s$</td>
<td>$6.4 \times 10^{-3}$ 43</td>
<td>0.6 $\times 10^{-3}$</td>
<td>0.2 $\times 10^{-3}$</td>
<td>0.03 $\times 10^{-3}$</td>
</tr>
<tr>
<td>Gluonic penguins</td>
<td>$2\beta_s^{off} (B_s^0 \to \phi \phi)$</td>
<td>–</td>
<td>0.17</td>
<td>0.03</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>$2\beta_s^{eff} (B_s^0 \to K^{*0} K^{*0})$</td>
<td>–</td>
<td>0.13</td>
<td>0.02</td>
<td>&lt; 0.02</td>
</tr>
<tr>
<td></td>
<td>$2\beta_s^{eff} (B_s^0 \to \phi K^0_S)$</td>
<td>0.17 43</td>
<td>0.30</td>
<td>0.05</td>
<td>0.02</td>
</tr>
<tr>
<td>Right-handed currents</td>
<td>$2\beta_s^{eff} (B_s^0 \to \phi \gamma)$</td>
<td>–</td>
<td>0.09</td>
<td>0.02</td>
<td>&lt; 0.01</td>
</tr>
<tr>
<td></td>
<td>$\tau^{eff} (B_s^0 \to \phi \gamma/\gamma)$</td>
<td>–</td>
<td>5%</td>
<td>1%</td>
<td>0.2%</td>
</tr>
<tr>
<td>Electroweak penguins</td>
<td>$S_3 (B^0 \to K^{*0} \mu^+ \mu^-; 1 &lt; q^2 &lt; 6$ GeV²/c⁴)</td>
<td>0.08 67</td>
<td>0.025</td>
<td>0.008</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>$s_0 A_{FB} (B^0 \to K^{*0} \mu^+ \mu^-)$</td>
<td>25% 67</td>
<td>6%</td>
<td>2%</td>
<td>7%</td>
</tr>
<tr>
<td></td>
<td>$A_1 (K^{*0} \mu^+ \mu^-; 1 &lt; q^2 &lt; 6$ GeV²/c⁴)</td>
<td>0.25 76</td>
<td>0.08</td>
<td>0.025</td>
<td>~ 0.02</td>
</tr>
<tr>
<td></td>
<td>$B(B^+ \to \pi^+ \mu^+ \mu^-)/B(B_s^0 \to K^{+} \mu^+ \mu^-)$</td>
<td>25% 85</td>
<td>8%</td>
<td>2.5%</td>
<td>~ 10%</td>
</tr>
<tr>
<td>Higgs penguins</td>
<td>$B(B_s^0 \to \mu^+ \mu^-)$</td>
<td>$1.5 \times 10^{-9}$ 13</td>
<td>$0.5 \times 10^{-9}$</td>
<td>$0.15 \times 10^{-9}$</td>
<td>$0.3 \times 10^{-9}$</td>
</tr>
<tr>
<td></td>
<td>$B(B_s^0 \to \mu^+ \mu^-)/B(B^0 \to \mu^+ \mu^-)$</td>
<td>–</td>
<td>~ 100%</td>
<td>~ 35%</td>
<td>~ 5%</td>
</tr>
<tr>
<td>Unitarity</td>
<td>$\gamma (B \to D^{(<em>)} K^{(</em>)})$</td>
<td>$\sim 10–12^\circ$ 244 258</td>
<td>$4^\circ$</td>
<td>$0.9^\circ$</td>
<td>negligible</td>
</tr>
<tr>
<td>triangle angles</td>
<td>$\gamma (B_s^0 \to D_s K)$</td>
<td>–</td>
<td>11°</td>
<td>2°</td>
<td>negligible</td>
</tr>
<tr>
<td></td>
<td>$\beta (B^0 \to J/\psi K^0_S)$</td>
<td>$0.8^\circ$ 43</td>
<td>$0.6^\circ$</td>
<td>$0.2^\circ$</td>
<td>negligible</td>
</tr>
<tr>
<td>Charm</td>
<td>$A_\Gamma$</td>
<td>$2.3 \times 10^{-3}$ 43</td>
<td>$0.40 \times 10^{-3}$</td>
<td>$0.07 \times 10^{-3}$</td>
<td>–</td>
</tr>
<tr>
<td>CP violation</td>
<td>$\Delta A_{CP}$</td>
<td>$2.1 \times 10^{-3}$ 18</td>
<td>$0.65 \times 10^{-3}$</td>
<td>$0.12 \times 10^{-3}$</td>
<td>–</td>
</tr>
</tbody>
</table>

- Several studies of the upgrade trigger on these channels underway. Not all shown here
Upgrade Topo

LHCb-PUB-2014-031 in preparation

- Same principle as Run I topo, preselects displaced tracks with sum-$p_T$ requirements
- Timing: 0.1 ms per event. At 25-50kHz, large efficiency gains over Run I:

- $B^0 \rightarrow K^+[K^+\pi]\mu^+\mu^-$
- $B^0 \rightarrow \phi[K^+K]\phi[K^+K^-]
- $B^+ \rightarrow D^0[K^+\pi]\mu^+\nu_\mu$
- $B^0_s \rightarrow \psi(1S)[\mu^+\mu^-]\phi[K^+K^-\pi^-]
- $B^+ \rightarrow \pi^+KK^+$
- $B^+ \rightarrow D^+_s[\pi^+\pi^-]\pi^+\pi^+[K^+]$

- red (green): Run I efficiency (x2)
How pure is the Topo?

- Rates of $\mathcal{O}(10 \text{ kHz})$ sound trifling
- But these are pure $b\bar{b}$ signal:

- Above even loose BBDT values data is consistent with inclusive $b\bar{b}$ MC
Lifetime unbiased
LHCb-PUB-2014-031 in preparation

- First fully lifetime unbiased selections on a hadron collider

<table>
<thead>
<tr>
<th>Mode</th>
<th>B → hh</th>
<th>D → hh</th>
<th>B_S → ϕϕ</th>
</tr>
</thead>
<tbody>
<tr>
<td>track p_T</td>
<td>&gt; 1.0 GeV/c</td>
<td>&gt; 0.5 GeV/c</td>
<td>&gt; 0.5 GeV/c</td>
</tr>
<tr>
<td>M − M(TRUE)</td>
<td>± 250 MeV/c^2</td>
<td>± 75 MeV/c^2</td>
<td>± 250 MeV/c^2</td>
</tr>
<tr>
<td>τ</td>
<td>&gt; 0.3 ps</td>
<td>&gt; 0.2 ps</td>
<td>&gt; 0.3 ps</td>
</tr>
<tr>
<td>∑</td>
<td>p_T</td>
<td></td>
<td>&gt; 4.5 GeV/c</td>
</tr>
<tr>
<td>DIRA</td>
<td>&lt; 3.6°</td>
<td>&lt; 3.6°</td>
<td>&lt; 3.6°</td>
</tr>
<tr>
<td>parent IP</td>
<td>&lt; 0.1 mm</td>
<td>&lt; 0.1 mm</td>
<td>&lt; 0.1 mm</td>
</tr>
<tr>
<td>Max DOCA</td>
<td>&lt; 0.1 mm</td>
<td>&lt; 0.1 mm</td>
<td>&lt; 0.1 mm</td>
</tr>
<tr>
<td>Timing</td>
<td>0.13 ms</td>
<td>0.13 ms</td>
<td>0.10 ms</td>
</tr>
<tr>
<td>Efficiency</td>
<td>60%</td>
<td>10%</td>
<td>89%</td>
</tr>
</tbody>
</table>

- Charm modes also require slow pion from D^* → Dπ, p_T > 200 MeV, M(D^*) − M(D^0) < 160 MeV/c^2
- RICH particle ID separates final states: CF charm can be prescaled

Mode Rate
B → π^+π^- 1 kHz
B → K^+K^- 0.1 kHz
D^0 → K^+K^- 2 kHz
CF D^0 → K^-π^+ 20 kHz
D^0 → π^+π^-, K^+π^- 40 kHz
B_S^0 → ϕϕ 12 Hz
Conclusions

- The LHCb Run I trigger covered an extremely wide range in a challenging environment:
  - From the rarest B decay at high efficiency:
    - $\mu^+\mu^-$ candidates / (44 MeV/$c^2$)
  - to the largest charm samples at high purity:

- The Upgrade trigger builds on the successes of Run I, introducing several firsts:
  - Full software triggering at 30 MHz, doubling of many signal efficiencies
  - Disk buffering for calibration and alignment
  - Lifetime unbiased beauty and charm selections in a hadronic environment

- Thank you for listening
The Run I LHC environment

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

  - 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
    
    \[
    \begin{array}{c|cccc}
    N_{PV} & 1 & 2 & 3 & > 4 \\
    P(\%) & 55 & 30 & 11 & 4 \\
    \end{array}
    \]

  - $\mu \sim 1.6$ interactions per bunch crossing

- $\sigma_{b\bar{b}} = 75.3 \pm 14.1 \mu\text{b}$ [Phys. Lett. B694 (2010)]

- $\sigma_{c\bar{c}} = 1419 \pm 134 \mu\text{b}$ [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:

\[
\text{Nsig/Nbkg}
\]

B$^+\rightarrow J/\psi K$, Real Data

\[
\begin{array}{c}
N_{PV} \\
2 & 4 & 6 \\
5 & 10
\end{array}
\]
The LHCb Run I dataset

![Graph showing data points with labels:]

- 2.21 fb
- 2.08 + 1.11 fb
- pp 18 x10^{13}
- \(\overline{c}\overline{c}\) 59 x10^{11}
- bb 26 x10^{10}

Dates along the x-axis:
- Apr 12
- Jun 12
- Aug 12
- Oct 12
- Dec 12
Run I Online Monitoring

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

Online monitoring plots as seen in the control room, straight from HLT2.
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 $E_T > 2.5 - 3.5$ 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: $\sim 150$ kHz
- L0 hadron rate: $\sim 450$ kHz
Run I L0 efficiencies

Figure 3. Efficiency $\varepsilon_{\text{TOS}}$ 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 $\varepsilon_{\text{TOS}}$ 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 $\varepsilon_{\text{TOS}}$ of L0Electron is shown for $B^0 \rightarrow J/\psi (e^+ e^-)K^*$ as a function of $p_T$ ($J/\psi$).
Run I HLT1 efficiencies

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

Figure 7. Efficiency $\varepsilon^{\text{TOS}}$ of Hlt1TrackAllL0 is shown for $B^- \to D^0\pi^-$, $B^0 \to D^-\pi^+$, $D^0 \to K^-\pi^+$ and $D^+ \to K^-\pi^+\pi^+$ as a function of $p_T$ and $\tau$ of the $B$-meson and prompt $D$-meson respectively.
Run I 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>$\mu$</th>
<th>$\mu$</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>
<td></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
Run I HLT2 inclusive dimuon

- Makes use of 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 \( \sim 51 \text{pb}^{-1} \)
- Offline \( \sigma(\Upsilon(1S)) \sim 43 \text{ MeV} \) [JHEP 06 (2013) 064]
Run I HLT2 $\mu$, charm efficiencies

Figure 8. Efficiencies $\varepsilon^{\text{TOS}}$ of $\text{Hlt2DiMuonJPsiHighPT}$ and $\text{Hlt2DiMuonDetachedJPsi}$ 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 $\text{Hlt2CharmHadD2HHH}$ and $\text{Hlt2CharmHadD02HH_D02KPi}$ 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 $\text{Hlt1TrackAllL0}$. 
Run 1 HLT2 Topo efficiencies

Figure 9. Efficiency $\epsilon^{\text{TOS}}$ if at least one of the lines $\text{Hlt2TopoBody}$, with $n = 2\cdot3$, selected the event for $B^{-} \rightarrow D^{0}\pi^{-}$ and one of the lines with $n = 2\cdot3\cdot4$ 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 $\text{Hlt1TrackAllL0}$.

Figure 10. Efficiency $\epsilon^{\text{TOS}}$ if at least one of the lines $\text{Hlt2TopoBody}$ or $\text{Hlt2TopoMuBody}$, with $n = 2\cdot3$, 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 $n = 2\cdot3$, 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 $\text{Hlt1TrackMuon}$. 
Upgrade selections

- Lifetime unbiased selections on a pp collider:
  - No vertex displacement requirements
  - Unbiased above minimum decay time cut
  - 60% efficient on \( B \rightarrow hh \), \( \sim 1 \text{kHz} \) rate
  - 0.1 – 0.15 ms typical
  - \( D^* \pm \rightarrow \{D \rightarrow hh\} \pi^\pm \) tagged with VELO-UT pion
  - \( D \rightarrow hh \) uses PID to separate final states
- Exclusives:
  - IP cuts reduce rate: 10 Hz and negligible timing
  - 95% efficient on \( B^0_s \rightarrow \phi\phi \)

- Inclusive dimuon:
  - 75-80% efficient for \( B^0 \rightarrow K^* \mu\mu \)
  - 50-70% efficient for \( \tau \rightarrow 3\mu \)
  - Low and High mass lines for EW + exotic decays
  - Negligible timing, 1 – 3 kHz rate
Exclusive Triggers

- Offline selections in Run I become trigger selections in the upgrade.
- Displaced track requirements mean timing is negligible
- Hadronic beauty and charm strategy:
  - track $p_T > 500\text{MeV}/c$ except for slow pions from $D^*$ decays
  - loose RICH PID applied where necessary
  - $D^0$ modes use $M(D^*) - M(D^0)$ to further reduce rate

<table>
<thead>
<tr>
<th>mode</th>
<th>$B_s^0 \rightarrow \phi \phi$</th>
<th>$D^0 \rightarrow K_s^0 \pi \pi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>track $p_T$</td>
<td>$&gt; 500\ \text{MeV}/c$</td>
<td>$&gt; 500\ \text{MeV}/c$</td>
</tr>
<tr>
<td>$\sum</td>
<td>p_T</td>
<td>$</td>
</tr>
<tr>
<td>track $\chi^2_IP$</td>
<td>$&gt; 4$</td>
<td>$&gt; 4$</td>
</tr>
<tr>
<td>$M - M(\text{PDG})$</td>
<td>$\pm 250 \ \text{MeV}/c^2$</td>
<td>$\pm 60 \ \text{MeV}/c^2$</td>
</tr>
<tr>
<td>$\tau$</td>
<td>$&gt; 0.3 \ \text{ps}$</td>
<td>$0.2 \ \text{ps}$</td>
</tr>
<tr>
<td>candidate $p_T$</td>
<td>$p_T(\phi_1) \times p_T(\phi_2) &gt; 2\ (\text{GeV}/c)^2$</td>
<td>$&gt; 2\ \text{GeV}/c$</td>
</tr>
<tr>
<td>$\chi^2_{\text{vertex}}/n_{\text{dof}}$</td>
<td>$&lt; 15$</td>
<td>$&lt; 15$</td>
</tr>
<tr>
<td>Output rate</td>
<td>$&lt; 10\text{Hz}$</td>
<td>$1.3\text{kHz}$</td>
</tr>
<tr>
<td>Efficiency</td>
<td>95%</td>
<td>40%</td>
</tr>
</tbody>
</table>

- Negligible timing requirements mean many exclusive selections are possible
Inclusive di-muon

- Several important analyses at LHCb have two muons in the final state:
  - Rarest B decay $B_s^0 \rightarrow \mu\mu$: [PRL 111, 101805 (2013)]
  - CP "golden mode" $B^0_s \rightarrow J/\psi\phi$: [PRD87 112010 (2013)]
  - $B^0 \rightarrow K^*\mu\mu$: [arXiv:1403.8044]

- Inclusive dimuon trigger for modes containing displaced dimuons:
  - Uses the same muon ID strategy as offline: [LHCb–DP–2013–001]
  - Tracks identified as muons combined with vertex quality and flight distance requirements. Output rate 1-3kHz,
  - 75-80% efficient for $B^0 \rightarrow K^*\mu\mu$
  - 50-70% efficient for $\tau \rightarrow 3\mu$

- Several 'similar-but-different' dimuon lines for high + low mass regimes, prescaled prompt di-$\mu$
### Performance & Cost effectiveness

- The upgrade EFF will make **13ms** available per event (See talk by U. Marconi)

- Tracking + PV finding timing in software (using 2014 farm nodes):

<table>
<thead>
<tr>
<th>Timing ms</th>
</tr>
</thead>
<tbody>
<tr>
<td>VELO tracking</td>
</tr>
<tr>
<td>VELO-UT tracking</td>
</tr>
<tr>
<td>Forward tracking</td>
</tr>
<tr>
<td>PV finding</td>
</tr>
<tr>
<td><strong>Total</strong></td>
</tr>
</tbody>
</table>

- TPU provides tracks using last 16 of 26 VELO + 2 UT stations.

- Additional work is needed to incorporate TPU tracks into the HLT tracking sequence:

<table>
<thead>
<tr>
<th>Timing ms</th>
</tr>
</thead>
<tbody>
<tr>
<td>TPU track preparation</td>
</tr>
<tr>
<td>VELO (10)</td>
</tr>
<tr>
<td>Forward tracking</td>
</tr>
<tr>
<td>PV</td>
</tr>
<tr>
<td><strong>Total</strong></td>
</tr>
<tr>
<td><strong>Timing reduction</strong></td>
</tr>
</tbody>
</table>

- 1.5 ms saving per event using the hardware assisted option, at a cost of 940kCHF

- '[For LHCb, The TPU] ...does not provide a significant cost benefit with respect to an all software based trigger'
# Upgrade TOPO performance

<table>
<thead>
<tr>
<th>Decay</th>
<th>Run I</th>
<th>Upgrade TOPO Output Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>10 kHz</td>
</tr>
<tr>
<td>$b \rightarrow s$ penguins</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$B^0 \rightarrow K^+ K^- \pi^+ \pi^- \mu^+ \mu^-$</td>
<td>89%</td>
<td>85%</td>
</tr>
<tr>
<td>$B^0 \rightarrow K^+ K^- \pi^+ \pi^- e^+ e^-$</td>
<td>43%</td>
<td>38%</td>
</tr>
<tr>
<td>$B^0_s \rightarrow \phi[K^+ K^-] \phi[K^+ K^-]$</td>
<td>20%</td>
<td>49%</td>
</tr>
<tr>
<td>semi-leptonic decays</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$B^0 \rightarrow D^{*+} \pi^- D^0[K^+ K^-] \mu^+ \nu_\mu$</td>
<td>63%</td>
<td>58%</td>
</tr>
<tr>
<td>$B^0 \rightarrow D^- [K^+ K^- \pi^-] \pi^0 \mu^+ \nu_\mu$</td>
<td>40%</td>
<td>27%</td>
</tr>
<tr>
<td>$B^+ \rightarrow \bar{D}^0[K^+ K^-] \mu^+ \nu_\mu$</td>
<td>58%</td>
<td>48%</td>
</tr>
<tr>
<td>$B^+ \rightarrow \bar{D}^* D^0[K^+ K^- \pi^-] \mu^+ \nu_\mu$</td>
<td>39%</td>
<td>25%</td>
</tr>
<tr>
<td>$B^+ \rightarrow \bar{D}^0[K^0_s \pi^+ \pi^- \pi^0 \pi^-] \mu^+ \nu_\mu$</td>
<td>32%</td>
<td>17%</td>
</tr>
<tr>
<td>$B^0_s \rightarrow K^- \mu^+ \nu_\mu$</td>
<td>59%</td>
<td>52%</td>
</tr>
<tr>
<td>$B^0_s \rightarrow D^- [K^+ K^- \pi^- \pi^0] \mu^+ \nu_\mu$</td>
<td>47%</td>
<td>29%</td>
</tr>
<tr>
<td>$\Lambda^0 \rightarrow p^+ \mu^- \bar{\nu}_\mu$</td>
<td>54%</td>
<td>44%</td>
</tr>
<tr>
<td>charmless decays</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$B^+ \rightarrow \pi^+ K^- K^+$</td>
<td>36%</td>
<td>77%</td>
</tr>
<tr>
<td>$B^0_s \rightarrow K^- K^+ \pi^0$</td>
<td>21%</td>
<td>32%</td>
</tr>
<tr>
<td>decays with charmonium</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$B^0_s \rightarrow \psi(1S)[\mu^+ \mu^-] \phi[K^+ K^-]$</td>
<td>91%</td>
<td>85%</td>
</tr>
<tr>
<td>$B^0_s \rightarrow \psi(2S)[\mu^+ \mu^-] \phi[K^+ K^-]$</td>
<td>93%</td>
<td>86%</td>
</tr>
<tr>
<td>$B^0_s \rightarrow \psi(1S)[\mu^+ \mu^-] K^+ K^- \pi^+ \pi^-$</td>
<td>91%</td>
<td>79%</td>
</tr>
<tr>
<td>hadronic open charm decays</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Lambda^0 \rightarrow \Lambda^+_c [p^+ K^+ \pi^-] \pi^-$</td>
<td>33%</td>
<td>67%</td>
</tr>
<tr>
<td>$B^+ \rightarrow \bar{D}^0[K^0_s \pi^+ \pi^- \pi^+ \pi^-] K^+$</td>
<td>25%</td>
<td>43%</td>
</tr>
<tr>
<td>$B^+ \rightarrow D^0[K^+ K^- \pi^-] K^+ \pi^-$</td>
<td>26%</td>
<td>30%</td>
</tr>
<tr>
<td>$B^0 \rightarrow D^+[K^- \pi^+ \pi^-] D^- [K^+ \pi^-]$</td>
<td>18%</td>
<td>7%</td>
</tr>
<tr>
<td>hadronic $\tau$ lepton mode</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$B^0 \rightarrow D^{*-} [\pi^- \bar{D}^0[K^+ K^-] \tau^+] \pi^+ \pi^- \pi^- \bar{\nu}<em>\tau \nu</em>\tau$</td>
<td>17%</td>
<td>1%</td>
</tr>
</tbody>
</table>
Global Event Cuts

- Very high multiplicity events take disproportionate time to reconstruct
- Global Event Cuts (GECs) are used to remove these events, freeing processing power for low. mult. events
- GEC requires Sum of HCAL + ECAL multiplicities < 1200:

- 10% inefficiency on $B_s^0 \to \phi\phi$ but
- Reduces track reconstruction time by 20% and more than halves the timing of multibody selections
- Reduced timing means looser selection requirements: Higher overall efficiency