The LHCb Trigger System

Eduardo Rodrigues
NIKHEF

On behalf of the LHCb Collaboration


- LHCb Experiment and Detector
- Trigger strategy and overview
- Hardware trigger: Level-0 components, decision unit, performance
- Software trigger: High Level Trigger farm, alleys, exclusive and inclusive strategies, decision, performance
- Outlook
The LHCb Trigger System

9 km diameter

Geneva

Jura

LHC

CERN
LHCb Detector

Ring Imaging Cherenkov
Calorimeters

Acceptance
250/300 mrad
10 mrad

Muon System

« Tracking » detectors

pp collision

LHCb Detector (side view)
Trigger Strategy & Overview

- LHC(b) Environment
- Trigger Overview & Strategy
LHC(b) Environment

LHC environment

- pp collisions at $E_{CM} = 14$ TeV
- $t_{bunch} = 25$ ns $\leftrightarrow$ bunch crossing rate = 40 MHz
- $<L> = 2 \times 10^{32}$ cm$^{-2}$ s$^{-1}$ @ LHCb interaction region
  - $\approx$ 10-50 times lower than for ATLAS/CMS

Cross sections

<table>
<thead>
<tr>
<th>Physical quantity</th>
<th>Value</th>
<th>Event rate</th>
<th>Yield / year</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma$ total</td>
<td>$\sim 100$ mb</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\sigma$ visible</td>
<td>$\sim 60$ mb</td>
<td>$\sim 12$ MHz</td>
<td></td>
</tr>
<tr>
<td>$\sigma$ (c-cbar)</td>
<td>$\sim 3.5$ mb</td>
<td>$\sim 700$ kHz</td>
<td>$\sim 7 \times 10^{12}$ pairs</td>
</tr>
<tr>
<td>$\sigma$ (b-bbar)</td>
<td>$\sim 0.5$ mb</td>
<td>$\sim 100$ kHz</td>
<td>$\sim 10^{12}$ pairs</td>
</tr>
</tbody>
</table>

Expected B-signal rates

- branching ratios $\sim 10^{-9} - 10^{-4}$
- $10 - 10^6$ events / year?

B-hadrons are heavy and long-lived!
The LHCb Trigger System

**Trigger Overview**

- **Level-0**
  - 12 MHz
  - pp collisions
  - Custom hardware
  - High $E_T$ particles
  - Partial detector information

- **HLT**
  - 1 MHz
  - CPU farm -> software trigger
  - High $E_T$ / IP particles
  - Full detector information

- **Storage**
  - ~2 kHz
  - Event size ~35 kb

---

*Eduardo Rodrigues*

*Beauty 2006, Oxford, 28th Sept 2006*
Trigger Strategy

Two-level Trigger

**L0**: high $E_T / P_T$ particles
- hardware trigger, sub-detector specific implementation
- pipelined operation, fixed latency of 4 $\mu$s
- (minimum bias) rate reduction $\sim 12$ MHz $\rightarrow 1$ MHz

**HLT**: high $E_T/P_T$ & high Impact Param. particles & displaced vertices & B-mass & …
- algorithms run on large PC farm with $\sim 1800$ nodes
- several trigger streams to exploit and refine L0 triggering information
- software reconstruction on part/all of the data
  - tracking / vertexing with accuracy close to offline
- selection and classification of interesting physics events
  - inclusive / exclusive streams
- rate reduction 1 MHz $\rightarrow 2$ kHz
- estimated event size $\sim 30$ kb

---

Eduardo Rodrigues  

Be alert!
**Level-0 Trigger**

- Pile-up system
- Calorimeter
- Muon system

- **L0 Decision unit**
- **L0DU report**
- **1 MHz**
L0 Strategy

- **select high** $E_T / P_T$ **particles**
  - hadrons / electrons / photons / $\pi^0$s / muons

- **reject complex / busy events**
  - more difficult to reconstruct in HLT
  - take longer to reconstruct in HLT

- **reject empty events**
  - uninteresting for future analysis

L0 thresholds on $E_T / P_T$ of candidates

Public event variables
LO Pile-up System

Detector components
- 2 silicon planes upstream of nominal IP, part of the Vertex Locator (VELO)

Strategy: identify multi-PV events
- calculate z of vertices for all combinations of A & B
- find highest peak in histogram of z
- remove hits contribution to that peak
- find the second highest peak
  - 2-interactions crossings identified with efficiency ~60% and purity ~95%

Output for L0DU
- pile-up system (hit) multiplicity
- number of tracks on second peak/vertex
LO Calorimeter Trigger (1/2)

- ECAL and HCAL
  - ECAL: ~6000 cells, 4x4 to 12x12 cm²
  - HCAL: ~1500 cells, 13x13 to 26x26 cm²
- Scintillator Pad Detector (SPD)
- Preshower (Prs)
Strategy

- identify high-$E_T$ hadrons / e’s / $\gamma$’s / $\pi^0$’s using all 4 sub-detectors:
  - ECAL and HCAL
    - large energy deposits $\leftrightarrow$ $E_T$ in 2x2 cells
  - Scintillator Pad Detector (SPD) & Preshower (Prs)
    - used for charged/electromagnetic nature of clusters, respectively (PID)

Output for LO Decision Unit (LODU)

- highest-$E_T$ candidate of each type
  - hadron / e / $\gamma$ / 2 $\pi^0$’s (“local” and “global”)

- global event variables
  - total $E_T$ in HCAL $\leftrightarrow$ rejection of empty events
  - SPD hit multiplicity $\leftrightarrow$ rejection of busy events
**Detector components**

- M1 – M5 muon stations (4 quadrants each)

**Strategy**

- straight-line search in M2–M5 and extrapolation to M1 for momentum determination
- momentum determination from M1-M2 assuming muons from primary vertex
  (using a look-up table):
  \[ \sigma_p/p \sim 20\% \text{ for b-decays} \]

**Output for LODU**

- 2 muon candidates per each of the 4 quadrants
LO Trigger Hardware Status

- for general status / commissioning of LHCb:
  - see Lluís Garrido’s / Gloria Corti’s talks

**LO Trigger**

- commissioning due to start early 2007
  - ready for end of Summer 2007
- L0 candidates selection/validation cards ready for production

**Muon System for LO**

- chambers production and tests progressing well (tests with cosmics also performed)
- chambers installation to start now in October …
- full L0-muon trigger electronics chain being tested

**Calorimeter for LO**

- all CAL parts installed; ECAL & HCAL being commissioned, SPD, Prs will follow …
- L0-CAL trigger tests with realistic configuration in Autumn ‘06
L0 Decision Unit (1/2)

Calorimeter
- total $E_T$ in HCAL
- SPD multiplicity
- highest- $E_T$ candidates: h, e, $\gamma$, 2 $\pi^0$'s

Muon system
- 2 $\mu$ candidates per each of 4 quadrants

Pile-up system
- total multiplicity
- # tracks in second peak

L0 Decision unit
- cuts on global event variables
- thresholds on the $E_T$ candidates

1 MHz

L0DU report
LO Decision Unit (2/2)

**Global Event Variables** applied first …

<table>
<thead>
<tr>
<th>Global event cuts</th>
<th>Cut</th>
<th>Rate (MHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Sigma E_T )</td>
<td>5.0 GeV</td>
<td>( \sim 8.3 )</td>
</tr>
<tr>
<td>SPD multiplicity</td>
<td>280 hits</td>
<td>( \sim 7 )</td>
</tr>
<tr>
<td>Tracks in 2(^{nd} ) vertex</td>
<td>3</td>
<td>( \sim 13 )</td>
</tr>
<tr>
<td>Pile-up multiplicity</td>
<td>112 hits</td>
<td>( \sim 7 )</td>
</tr>
</tbody>
</table>

... and then cuts on the \( E_T / P_T \) candidates

**Di-muon trigger is special**
- not subject to the global event selection
- \( P_T^{\mu_1} = P_T^{\mu_1} + P_T^{\mu_2} \) with \( P_T^{\mu_2} = 0 \) possible
- “tags” clean B-signatures

<table>
<thead>
<tr>
<th>Trigger</th>
<th>Threshold (GeV)</th>
<th>Approx. rate (kHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hadron</td>
<td>3.6</td>
<td>700</td>
</tr>
<tr>
<td>Electron</td>
<td>2.8</td>
<td>100</td>
</tr>
<tr>
<td>Photon</td>
<td>2.6</td>
<td>130</td>
</tr>
<tr>
<td>( \pi^0 ) local</td>
<td>4.5</td>
<td>110</td>
</tr>
<tr>
<td>( \pi^0 ) global</td>
<td>4.0</td>
<td>150</td>
</tr>
<tr>
<td>Muon</td>
<td>1.1</td>
<td>110</td>
</tr>
<tr>
<td>Di-muon</td>
<td>1.3</td>
<td>160</td>
</tr>
</tbody>
</table>
LO Performance

Dedicated sub-triggers most relevant for each « channel type »

<table>
<thead>
<tr>
<th>Event composition</th>
<th>b-bbar (%)</th>
<th>c-cbar (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Generated, visible</td>
<td>1.1</td>
<td>5.6</td>
</tr>
<tr>
<td>after L0</td>
<td>3.0</td>
<td>10.6</td>
</tr>
</tbody>
</table>
**Strategy**

**Independent Alleys:**

Follow the L0 triggered candidate

→ Muon, Muon + Hadron,

Hadron, ECAL streams

**Partial Reconstruction:**

- A few tracks selected per alley (cuts e.g. on $P_T$, Impact Parameter, mass)
- Full reconstruction done at the end of the alleys

**Summary Information:**

decision, type of trigger fired, info on what triggered
Trigger Farm

- Event Filter Farm with ~1800 nodes (estimated from 2005 Real-Time Trigger Challenge)
- Sub-divided in 50 sub-farms
- Readout from Level-0 at 1 MHz ➔ 50 Gb/s throughput
- Scalable design ↔ possible upgrade

HLT algos CPU time tested on a real farm ➔ will fit in the size of the farm foreseen
The LHCb Trigger System

**HLT Tracking / Reconstruction**

- **Trigger Tracker (TT):**
  - $\sigma_{p/p} \sim 20-40\%$
  - (using B-field before magnet)

- **Tracker stations (T):**
  - $\sigma_{p/p} \sim 1\%$

- **Muon stations:**
  - $\sigma_{p/p} \sim 20\%$ standalone
  - $\sigma_{p/p} \sim 5\%$ matched
  - with VELO tracks

- **VErtex LOcator (VELO):**
  - $R\Phi$ geometry
  - ~ 70 tracks/event after L0

**Reconstruction strategy**

- Do reconstruction with VELO and select tracks with Impact Parameter
- Fast measurement of $P_T$ (use TT or match VELO tracks with the muon stations)
- Refine $P_T$ measurement (use T stations)
**Hadron Alley - Strategy**

**L0-Hadron Entry**
- 700 kHz

**Hadron PreTrigger**
- Reconstruct VELO Tracks and Primary Vertices
  - $\sigma_Z \sim 60 \, \mu m$, $\sigma_{X,Y} \sim 20 \, \mu m$
- Select tracks with $|IP|>150 \, \mu m$
- Measure $P_T$ adding hits in Trigger Tracker:
  - $\sigma_p/p \sim 20-40\%$

**Hadron Trigger**
- Select tracks with $|IP|>100 \, \mu m$
- Measure $P_T$ using Tracking Stations: $\sigma_p/p \sim 1\%$
- Make secondary vertices
**Hadron Alley - Performance**

**Hadron PreTrigger**
- Single hadron: IP > 150 μm, $P_T > 2.5$ GeV
- Double hadron: IP > 150 μm, $P_{T1} > 1.1$ GeV, $P_{T2} > 0.9$ GeV
- 14% b content
- Signal efficiency:
  - ~80% for e.g. $B \rightarrow \pi \pi$, $B_s \rightarrow D_s K$

**Hadron Trigger**
- $|IP| > 100$ μm, $P_T > 1$ GeV
- Make 2 track vertices:
  - Dist. Of Closest Approach < 200 μm
- Vertex “pointing” to PV
- 48% b content, 17% c content
- Signal efficiency: ~90% $B_s \rightarrow D_s K$, $B \rightarrow \pi \pi$

Rate (kHz)

Preliminary

Efficiency

- $B_s \rightarrow DsK$
- $B_s \rightarrow \Phi \Phi$
- $Bd \rightarrow \pi \pi$
- $Bd \rightarrow D^* \pi$
- $Bd \rightarrow D_o K^*$

~4 kHz
Muon Alley - Strategy

**L0-μ Entry**
- ~200 kHz

**Muon Pre-trigger**
- ~20 kHz

**Muon Trigger**
- ~1.8 kHz

**Muon PreTrigger**
- Standalone μ reconstruction: $\sigma_{p/p} \sim 20\%$
- VELO tracks reconstruction
- Primary vertex reconstruction
- Match VELO tracks and muons: $\sigma_{p/p} \sim 5\%$

**Muon Trigger**
- Tracking of VELO track candidates in the downstream T stations: $\sigma_{p/p} \sim 1\%$
- Refine μ identification:
  - match long (VELO-T) tracks and muons
Muon Alley - Performance

**Muon PreTrigger**
- $b \rightarrow \mu \sim 11\%$
- Signal efficiency: $\sim 88\%$

**Muon Trigger**
- Single muon
  - $p_T > 3\text{GeV}$ and IPS $> 3$
  - $B \rightarrow \mu$ content $60\%$
- Dimuon
  - mass $> 0.5\text{GeV}$ and IPS $> 100\mu m$
  - $J/\psi$: mass $> 2.5\text{GeV}$ (no IP cut!)
- Signal efficiency: $\sim 87\%$

- $\sim 20$ kHz
- $\sim 1.8$ kHz

Dimuon mass (MeV): $< 1s$ of LHCb
Inclusive Streams

**Strategy**
- Full tracking reconstruction at a few kHz
- Select Inclusive streams (e.g. D*, D_s, Φ, ...)

**D* Inclusive Stream**
- Clear signal of \( D^* \rightarrow D^0(K^-\pi^+)\pi^+ \)
- With very high statistics
- Useful to calibrate Particle Identification

**Muon Inclusive Streams**
- **Single Muon**: enhanced b-sample: \( B \rightarrow \mu X \)
  - 70% B-purity, enables trigger-check on unbiased other B-meson
  - Could be used for studying the tagging performance
- **Dimuon**:
  - \( J/\psi, \Psi(2S) \), etc.
  - Propertime resolution studies from prompt \( J/\psi \) events
  - Use narrow mass to study alignment, momentum calibration due to B-field
  - Select a di-muon with no lifetime bias!

\( J/\psi \) from \( B \rightarrow J/\psi K_s \): 17 MeV width
**Exclusive Selections**

**Exclusive selections**
- Use common available reconstructed and selected particles ($D_s, D^0, K^*, \Phi, \ldots$)
- Wide B-mass windows (typically ~ 500 MeV)
- Efficiency: e.g. ~90\% for $B \rightarrow \pi\pi$

$B_s \rightarrow D_s K$

$B_s \rightarrow D_s \pi$

$\phi \rightarrow K K$

$B_s \rightarrow \phi \gamma$

$B_s \rightarrow \phi \phi$

$B_s \rightarrow D_s \pi$

$D_s \rightarrow K K \pi$

$\pi, K$

**Off-line $B \rightarrow \pi\pi$**

$\sigma = (15.29\pm 0.46) \text{MeV/cm}^2$

$\mu = (5278.72\pm 0.56) \text{MeV/cm}^2$

$\chi^2/\text{ndf} = 12.24/14$

**On-line $B \rightarrow \pi\pi$**

$\sigma = (31.85\pm 1.10) \text{MeV/cm}^2$

$\mu = (5284.81\pm 1.30) \text{MeV/cm}^2$

$\chi^2/\text{ndf} = 46.43/36$

~200 Hz
Outlook

- **LHCb Triggers in good shape**

- **Level-0**
  - strategy well defined
  - good performance for B-decays
  - rather flexible, robust, with built-in redundancy
  - production of hardware components well under way
  - commissioning early 2007

- **HLT**
  - strategy details being finalized
  - exploitation of Level-0 triggering information
  - high efficiency for B-decays
  - flexible and robust