The Trigger System of LHCb

Eduardo Rodrigues, CERN

I. “Facts” of Physics and trigger strategy
II. Trigger overview

III. Level-0
- components
- decision unit
- status and performance

IV. Level-1
- basic principles
- decision
- status and performance

V. HLT - High Level Trigger
- basic principles
- exclusive and inclusive strategies

VI. Summary
VII. Open questions and ongoing studies
I. “Facts” of Physics ...

LHC environment

- pp collisions at $E_{CM} = 14$ TeV
- $\langle L \rangle = 2 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1} = 2 \times 10^5 \text{ mb}^{-1} \text{ s}^{-1}$
- $\Delta t_{\text{bunch}} = 25 \text{ ns} \leftrightarrow \text{bunch crossing rate} = 40 \text{ MHz}$

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>$\sigma_{\text{total}}$</td>
<td>$\sim 100 \text{ mb}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\sigma_{\text{visible}}$</td>
<td>$\sim 60 \text{ mb}$</td>
<td>$\sim 12 \text{ MHz}$</td>
<td></td>
</tr>
<tr>
<td>$\sigma_{(c\text{-cbar})}$</td>
<td>$\sim 3.5 \text{ mb}$</td>
<td>$\sim 700 \text{ kHz}$</td>
<td>$\sim 7 \times 10^{12} \text{ pairs}$</td>
</tr>
<tr>
<td>$\sigma_{(b\text{-bbar})}$</td>
<td>$\sim 0.5 \text{ mb}$</td>
<td>$\sim 100 \text{ kHz}$</td>
<td>$\sim 10^{12} \text{ pairs}$</td>
</tr>
</tbody>
</table>

Expected B-signal rates

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

B-hadrons are heavy and long-lived!
... and trigger strategy

3-level trigger system

<table>
<thead>
<tr>
<th>Level</th>
<th>description</th>
<th>trigger rate [Hz]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level-0</td>
<td>high $E_T$ particles, output 1 MHz, custom hardware</td>
<td>$10^8$</td>
</tr>
<tr>
<td>Level-1</td>
<td>high $E_T$ /IP particles, output 40 kHz, software</td>
<td>$10^7$</td>
</tr>
<tr>
<td>HLT</td>
<td>full reconstruction, output ~200 Hz, software</td>
<td>$10^6$</td>
</tr>
</tbody>
</table>
II. Trigger overview

**L0:** high $E_T / P_T$ particles
- hardware trigger with fixed latency
- pipelined operation, fixed latency of 4 $\mu$s
- rate reduction $40 \, MHz \rightarrow 1 \, MHz$

**L1:** high $E_T / P_T$ & high impact parameter particles
- software reconstruction on part of the data (from a few sub-detectors)
- algorithm runs on large PC farm, average latency of 1 ms
- rate reduction $1 \, MHz \rightarrow 40 \, kHz$

**HLT:** high $E_T / P_T$ & high IP particles & displaced vertices & B-mass & …
- software - full event reconstruction
  - tracking / vertexing with accuracy close to offline
- selection and classification of interesting physics events
- inclusive / exclusive selections run
- algorithm runs on large PC farm (shared with L1)
- rate reduction $40 \, kHz \rightarrow \sim 200 \, Hz$
**Goal**

- select high $E_T / P_T$ particles
  - hadrons / electrons / photons / $\pi^0$'s / muons
- reject complex / busy / empty events
  - more difficult to reconstruct in L1 & HLT
  - take longer to reconstruct in L1 & HLT
  - uninteresting for future analysis

---

**III. Level-0**

L0 thresholds on $E_T / P_T$ of candidates

- hadrons / electrons / photons / $\pi^0$'s / muons

- more difficult to reconstruct in L1 & HLT
- take longer to reconstruct in L1 & HLT
- uninteresting for future analysis
L0 calorimeter trigger

Detector components
- 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)

Strategy
- identify hadrons / e / $\gamma$ / $\pi^0$'s using all 4 sub-detectors

Output for L0DU
- highest-$E_T$ candidate of each type
  - hadron / e / $\gamma$ / $\pi^0$ local & global
- global event variables
  - total $E_T$ in HCAL $\leftrightarrow$ rejection of empty events
  - SPD hit multiplicity $\leftrightarrow$ rejection of busy events
**L0 muon trigger**

**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)

**Output for L0DU**
- 2 muon candidates per each of the 4 quadrants
**L0 pile-up system**

**Detector components**
- 2 silicon planes upstream of nominal IP

**Strategy**
- calculate $z_{vtx}$ of vertices for all combinations of $A$ and $B$
- find highest peak in histogram of $z_{vtx}$
- remove hits contribution to that peak
- find the second highest peak

**Output for L0DU**
- pile-up system multiplicity
- height of second peak (with sum of directly adjacent bins)
  - also the $z$-position is transferred, together with same info for 1st peak
**L0 decision unit**

- **Calorimeter**
  - SPD multiplicity
  - total $E_T$ in HCAL
  - highest- $E_T$ candidates: $h, e, \gamma, \pi^0$ local, $\pi^0$ global

- **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

- **L0DU report**
**L0 decision unit**

**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></td>
</tr>
</tbody>
</table>

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

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

<table>
<thead>
<tr>
<th>Trigger</th>
<th>Threshold (GeV)</th>
<th>Rate (kHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hadron</td>
<td>3.6</td>
<td>705</td>
</tr>
<tr>
<td>Electron</td>
<td>2.8</td>
<td>103</td>
</tr>
<tr>
<td>Photon</td>
<td>2.6</td>
<td>126</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>145</td>
</tr>
<tr>
<td>Muon</td>
<td>1.1</td>
<td>110</td>
</tr>
<tr>
<td>Di-muon</td>
<td>1.3</td>
<td>145</td>
</tr>
</tbody>
</table>
**L0 status**

**Software**
- packages up-to-date (honest simulation) and ready for DC'04
  - L0 Muon package re-written recently
  - new L0Checker package for performance checks
    and providing information for subsequent studies of L0

**Optimization**
- L0 bandwidth division performed for the Trigger TDR
- DC'04 data will provide means for performance cross-checks
  and further studies

**Performance**
- hadronic channels: $\varepsilon \sim 50\%$
- electromagnetic channels: $\varepsilon \sim 50-70\%$
- muon channels: $\varepsilon \sim 90\%$
L0 performance

Each curve corresponds to considering separately the combination L0 trigger = sub-trigger + global event cuts

(di-electron trigger “à la di-muon trigger”)
**L0 performance**

**Single-channel inclusive curves**

![Graph showing M.B. retention (MHz) vs. L0 efficiency (%)](image)

- Hadron
- Muon
- Electron
- Photon
- Di-muon
- Pi0 local
- Pi0 global

\[ B_s \rightarrow D_s K \]

**L0 bandwidth division optimization**

![Graph showing L0 efficiency (%) vs. L0 output rate (MHz)](image)

- \( B_d \rightarrow \pi \pi \)
- \( B_s \rightarrow K^0 \gamma \)
- \( B_s \rightarrow J/\psi(\mu\mu)\varphi(KK) \)
- \( B_d \rightarrow J/\psi(\text{ee}) K_s(\pi\pi) \)
**IV. Level-1**

**Goal**
- select events with long-lived particles and high $P_T$
  - multiple scattering can fake high impact parameters → need $P_T$ measurement as well

**Detector components**
- VELO and TT stations (+ L0 information)

**Strategy**
- fast 2D tracking in VELO (forward and backward tracks)
  - R-Z straight-line tracking (VELO R-sensors only)
- primary vertex reconstruction (VELO sector number is used as $\phi$ measurement)
- selection of tracks with large IP ($IP \in [0.15, 3.0]$ mm)
- matching to L0 calorimeter and muon “objects”
- 3D tracking for those selected tracks
  - because $P_T$ measurement from extrapolation to TT necessitates 3D tracks
- $P_T$ measurement on selected tracks
- issue a L1 decision based on the $\log(P_{T1}) + \log(P_{T2})$ of these 2 tracks and on the “bonus” from the L0 matching
**L1 reconstruction**

Impact parameter measurement
- use VELO stations
  - R-Z projection contains most of the IP information

**P_T measurement**
- use TT for extrapolation of tracks
  - and momentum determination
- $\sigma(\mathrm{P_T}) / \mathrm{P_T} \sim 30\%$

Clean B-signatures
- $\mathrm{P_T}$ can also be determined from a matching to L0 candidates!
  - VELO tracks are matched to L0 muons / calorimeter clusters
  - high $E_T e / \gamma$, high mass $\mu\mu$
- extra information used in the making of the L1 decision ...
**L1 decision**

**Input from L1 reconstruction**
- $P_T$ of 2 highest-$P_T$ tracks among those with signed IP $\in [0.15, 3.0]$ mm
- "bonus" L0-matched objects

$L1$ Decision unit

$L1$ score

• L1 decision based on a 1-dim. cut on $\log(P_{T1})+\log(P_{T2})$ (+ bonus)

4% M. B. retention
Example of “bonus” …

**Di-muon invariant mass @ L1**

- $J/\Psi$ peak visible
- $B_s$ peak visible

**Graphs:**

- $B_d \rightarrow J/\psi(\mu^+\mu^-) \phi / K_S$
- $B_s \rightarrow \mu^+\mu^-$
- $B_d \rightarrow \mu^+\mu^- K^*$
- Minimum Bias

Eduardo Rodrigues

NIKHEF B Physics Seminar, 18th June 2004
**L1 status**

**Software**
- new version of whole L1 packages ready for DC'04
  - tracks reconstruction
  - primary vertex finder (also treatment of multiple PV)
  - decision package re-written (very modular <-> flexibility)

**Optimization**
- whole reconstruction has been optimized/tuned on pre-production data
  - tracks reconstruction (track quality cuts, clone killing)
  - VELO-TT track matching (quality cuts)
  - vertex finder (cuts on min. # tracks, min. distance between vertices)

**Performance**
- efficiencies expected to be ~10% better compared to TDR!
  - improvements mainly due to faster and better reconstruction
    (improved tracking, bug fixed in handling of vertices)
- fast algorithm within the design time budget: ~ 4.7 ms (compared to ~ 8 ms @ TDR time)
**L1 performance**

**Primary vertex resolution** (of only the 1st PV)

<table>
<thead>
<tr>
<th>Distribution</th>
<th>χ²/ndf</th>
<th>1st PV resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>122.3</td>
<td>52</td>
</tr>
<tr>
<td>Mean</td>
<td>-0.7131E-03</td>
<td>-0.3741E-04</td>
</tr>
<tr>
<td>Sigma</td>
<td>0.2122E-01</td>
<td>0.2260E-01</td>
</tr>
</tbody>
</table>

- **σₓ** = 21 µm
- **σᵧ** = 23 µm
- **σᶻ** = 86 µm

(Slightly worse than for TDR)
V. HLT - High Level Trigger

Re-reconstruct L1 from RawBuffers

Classify

Lepton-like

Rest

Find/clean μ/e “Lepton column”

Inclusive selection, generic
Reject uds, ε > 90%

Reconstruct all long tracks
Particle pre-selection

Specific algorithms
In/exclusive selections

Generic algorithm

Full reconstruction / Storage
**HLT – exclusive selections**

**Case of \( B^0 \rightarrow h \ h \)**

Efficiency: offline selected

- offline selections were used as baseline, applied after L0xL1
- offline tracks and vertices used
- unique set of HLT (loose) cuts for the 4 “hh” channels
**HLT – L1 confirmation**

**Idea**
- re-do the L1 algorithm @ HLT
  - with improved tracking ($\sigma(p)/p \sim 0.6\%$)

**Performance**
- ~ 5% efficiency loss for 1/4 minimum bias retention
  (i.e. @ 20kHz)
**HLT – generic algorithms**

- The discriminating variables:
  - **Kinematics:**
    - \( L_{1\text{con}} = \log(pt_0) + \log(pt_1) + \text{bonus} \)
    - \( pt_0, pt_1 \) from T1-T3 measurements
    - Bonus = function from L0 objects
      - \( E_T \) from cal (gamma,e)
  - **Geometry**
    - Z- Flight distance:
      - Between primary and secondary vertex

![Graph showing z distance primary-signal (mm)](image)

\[ L_{1\text{con}} = \log(pt_0) + \log(pt_1) + \text{bonus} \]
Results:

- Relax scenario: cuts\{ip\'=1.5mm,'chi2\'=2.5\}
- Output rate 10kHz = 8 (generic) +2 (dimuon) at >90% efficiency
- Point of view: Inclusive: from right, Generic: from Left
**HLT status**

**Software**
- new version of whole Trg packages has just been released for DC’04
  - tracking
  - primary vertex finder

**Optimization**
- to be done with DC’04 data
  - tracking optimization done to some extent on “old” data

**Performance**
- the best possible ...
- fast algorithms within the design time budget
- exclusive selections show that individual signal channels give
  HLT rates ~ 10 Hz for \( \varepsilon > 95\% \)
VI. Summary

TDR performances

Event composition

<table>
<thead>
<tr>
<th>Event composition</th>
<th>b-bbar (%)</th>
<th>c-cbar (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>generated</td>
<td>1.1</td>
<td>5.6</td>
</tr>
<tr>
<td>after L0</td>
<td>3.0</td>
<td>10.6</td>
</tr>
<tr>
<td>after L1</td>
<td>9.7</td>
<td>14.2</td>
</tr>
</tbody>
</table>
VII. Open questions

ongoing studies

Level-0

- implementation of di-electrons
- monitoring / performance from real data

Level-1

- L1 decision strategy
- improved usage of L0 muon and calorimeter information
- treatment of events with multiple primary vertices
- nature of minimum-bias / signal events passing L1

HLT

- development of reconstruction
- development of generic / exclusive selections
- RICH information @ HLT -> improvement in physics reach from PID?
  - main use: K/π separation for similar final states (e.g. B0 -> ππ, Kπ)
  - lower rates of channels with high rates without K/π separation
  - efficient reconstruction of inclusive decays (e.g. B -> K+ X)