LHCb Run 2 trigger performance

Barbara Sciascia (INFN) on behalf of LHCb Collaboration
Recent past (Run 1, 2010 - 2012)
Very successful running and triggering
312 publications so far [22 April 2016]
21 conference-report and 14 detectors papers
Still a lot to do with Run 1 data

Present (Run 2, 2015 - 2018)
- Increased beam energy 7/8TeV→13TeV
- Similar luminosity as in Run 1
- Identical LHCb detector
- Completely revised trigger

Future, called upgrade (Run 3, 2020++)
- see G. Simi [Thu] and F. Teubert [Fri] talks
More and more (and better) data!

For LHCb, more data is more important than higher energy:

- Direct searches: at new energy, new particles could appear above threshold

- Precision measurements: gain in increased production rates
Data taking

Luminosity leveling:
stable running and trigger conditions for LHCb even with LHC running at high luminosity

Extremely large $\sigma(bb)$ and $\sigma(cc)$ in LHC hadron collisions.

- Barbara Sciascia (INFN/LNF) - LHCb Trigger in Run 2 - Beauty 2016, 4 May -
Conditions for Run 2:
- $\sigma_{bb} \sim 45$ kHz and $\sigma_{cc} \sim 1$ MHz cc
  [at 13 TeV, in acceptance]
  [HF cross section $\sim 2 \times$ with respect to Run 1]
- Bunch spacing 25 ns (smaller pileup)
- LHCb: $\sim$ same luminosity

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LHCb detector

Vertex and track finding
VELO, TT, T1-3

Particle Identification

First level trigger
CALO and MUON

[LHCb, A. Alves et al., The LHCb Detector at the LHC, JINST 3 (2008) S08005]
### Trigger system in Run 1

**Hardware trigger (L0)**

Reduce bunch crossing-rate to ~1 MHz
[fixed latency of 4 μs]
[LHCb detector read out at 1 MHz]

**Muon trigger** [2012 thresholds]:
- Single Muon: $p_T > 1.76$ GeV
- Di Muon: $(p_{T1} \times p_{T2}) > 1.6$ GeV$^2$

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**Trigger system in Run 1**

**Hardware trigger (L0)**

Reduce bunch crossing-rate to ~1 MHz
[fixed latency of 4 µs]
[LHCb detector read out at 1 MHz]

**Calorimeter trigger** [2012 thresholds]:
- Hadrons: $E_T > 3.7$ GeV
- Photons and electrons: $E_T > 3$ GeV

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**Trigger system in Run1**

**Hardware trigger (L0)**

Reduce bunch crossing-rate to ~1 MHz
[fixed latency of 4 µs]
[LHCb detector read out at 1 MHz]

Also:
- Low multiplicity triggers
- Filters out very complex events

**Run 1, Run 2, and beyond:**
- **same in Run 2 as in Run 1**
- removal planned for Run 3
  - [LHCb detector readout at 40 MHz]
  - requires redesigned DAQ and trigger
  - **recovers L0 hadron efficiency at low \( p_T \)**

[LHCb Trigger and Online Upgrade Technical Design Report, LHCb-TDR-016]
**Trigger system in Run1**

**Software trigger (HLT)**
- Runs on HLT farm
- Split in two stages: HLT1 and HLT2

**HLT1** performs a partial event reconstruction and an inclusive selection of signal candidates

**HLT2** [~40 kHz rate]
- full simplified event reconstruction, with preliminary alignment and calibration of the detector and only marginal use of RICH PID information
- a set of inclusive and exclusive selections

**Output rate 3.5 kHz (2011)**
[saved for later offline analysis]

Total time budget: O(35 ms)/event
LHCb 2012 Trigger Diagram

40 MHz bunch crossing rate

L0 Hardware Trigger: 1 MHz readout, high $E_T/P_T$ signatures

- 450 kHz $h^\pm$
- 400 kHz $\mu/\mu\mu$
- 150 kHz $e/\gamma$

Defer 20% to disk

Software High Level Trigger

- 29000 Logical CPU cores
- Offline reconstruction tuned to trigger time constraints
- Mixture of exclusive and inclusive selection algorithms

5 kHz (0.3 GB/s) to storage

Same hardware trigger (L0)
- 20% of L0 events buffered to allow processing out of fill

Software trigger (HLT)
- HLT2 [~80 kHz rate]
- Output rate 5 kHz (2012)
**Trigger system in Run1**

**Online**: compromise between performance and stringent timing requirements

**Differences**: pattern recognition, detector alignment and calibration, candidate selection

**Offline**: best available performance without stringent timing requirements
Trigger system in Run 1

Differences:
pattern recognition, detector alignment and calibration, candidate selection.

Online: compromise between performance and stringent timing requirements.

Offline: best available performance without stringent timing requirements.
Trigger system in Run2

Disadvantages of Run 1 model:
- Takes time: alignment and calibration applied after data taking, reconstruction run twice
- Costs money: uses a lot of computing resources
- Costs physics: loss of imperfectly reconstructed data in trigger

For Run 2:
- Aim at online same reconstruction as offline
- Need “online” calibrations and alignments

Same hardware trigger (L0)
[optimized (typically higher) thresholds]

Software trigger (HLT):
- HLT splits in two applications: HLT1 and HLT2
- Events buffered after HLT1
- Alignment and calibration run on dedicated HLT1 samples
LHC stable beams 30% of the time. Buffer events for out of fill processing
Run 1: Defer 20% of L0 accepted evts.
[25% more effective CPU power]
Run 2: Defer all HLT1 accepted evts.

5 PiB [Run 2, 2015]: space for 160 hours of data with 150 kHz of 60 kiB events out of HLT1

From 2012 experience: ~1 disk per day is replaced due to unrecoverable errors.
- un-mirroring the disks doubles our buffer with the risk of per mil loss of data
- keeping them mirrored means, e.g.
  reduction in charm of ~15% OR reduced online-offline compatibility

Total farm disk space is 10PiB [Run 2, 2016; in 2015 mirrored to 5PiB for redundancy]

Event Filter Farm doubled in Run 2 (now~50k logical cores)
Larger real-time (HLT1) reduction allows more efficient use of buffers
More resources, improved code: tracking down to \( p_T = 500 \) MeV

**Inclusive charm and beauty trigger:**
- Single and two tracks MVA selections (~100 kHz) [e.g. efficient 2-body charm triggers, \( 2 \times \) wrt Run 1]

**Inclusive muon trigger:**
- Single and dimuon selections
- Additional low \( p_T \) track reconstruction (~40 kHz)

**Exclusive trigger, e.g.:**
- Lifetime unbiased beauty and charm selections [no selection criteria on quantities correlated with the signal particle’s decay-time]
- Selections for alignment

Low multiplicity trigger for central exclusive production [CEP] analyses

Alignment and calibration

• **Alignments:** VELO, Trackers, RICH mirrors, Muon

• **Calibrations:** RICH refractive index and HPDs, OT time, Calorimeters
Alignments Run on the HLT-farm at the beginning of every fill

[Automatic update of constants]

- **VELO alignment:** Alignment of both halves for translations and rotations in x, y and z
- **Tracker alignment:** Alignment of TT, IT and OT for translations in x, rotations and translations in z.

[Monitor only]

- **RICH mirror alignment:** Alignment of all individual mirrors for rotations around x and y
- **Muon alignment:** Alignment of both halves of each station for translations in x and y

[Stable L0 conditions]
Calibrations run on the monitoring histograms for ~every run;

- **OT calibration**: global time alignment of the OT wrt LHC clock

- **RICH**: refractive index calibration and HPD image calibration

- **Calorimeter** calibrations run on monitoring histograms for ~every fill

[stable L0 conditions]

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**Full event reconstruction:**
- Start from HLT1 vertices and tracks
- Reconstruct all tracks
  [In Run 1 $p_T>300$ MeV, no redundancy]
- Neutral particles, RICH, Muon and Calo PID
- Full particle identification for long tracks
  [new in Run 2]
Same strategy as offline
30% speedup achieved

<table>
<thead>
<tr>
<th>Reconstruction</th>
<th>Run II</th>
<th>Run I</th>
</tr>
</thead>
<tbody>
<tr>
<td>HLT1 rate</td>
<td>$\sim 150$ kHz</td>
<td>$\sim 80$ kHz</td>
</tr>
<tr>
<td>HLT1 time</td>
<td>$\sim 35$ ms</td>
<td>$\sim 20$ ms</td>
</tr>
<tr>
<td>Track finding</td>
<td>$\sim 200$ ms</td>
<td></td>
</tr>
<tr>
<td>Track fit</td>
<td>$\sim 100$ ms</td>
<td></td>
</tr>
<tr>
<td>Calorimeter reco</td>
<td>$\sim 50$ ms</td>
<td></td>
</tr>
<tr>
<td>RICH PID</td>
<td>$\sim 180$ ms</td>
<td></td>
</tr>
<tr>
<td>Muon ID</td>
<td>$\sim 200$ ms</td>
<td></td>
</tr>
<tr>
<td>Total HLT2</td>
<td>$\sim 650$ ms</td>
<td>$\sim 150$ ms</td>
</tr>
<tr>
<td>HLT2 rate</td>
<td>$\sim 12.5$ kHz</td>
<td>$\sim 5$ kHz</td>
</tr>
</tbody>
</table>
Inclusive beauty selections:
- MVA based 2, 3, and 4 body detached vertices
- Dimuon selections

Exclusive beauty selections:
E.g. $B \rightarrow \phi \phi$, $B \rightarrow \gamma \gamma$

Charm selections:
- Inclusive selection of $D^{*} \rightarrow (D^{0} \rightarrow X)\pi^{+}$
- Charmed baryons
- Final states with $K_{S}$
- 2,3,4,5-body final states

Electroweak bosons

Nearly 400 selections in total

[e.g. HLT2 efficiency for inclusive b trigger: $B^{+} \rightarrow D^{0} \pi^{+}$ increased from ~75% to >90%]
Online has offline quality: use it for physics!

**Turbo Stream + Tesla Application:**
- store full information of trigger candidates
- remove most of detector raw data
- save more than 90% space
- ideal for very high signal yield [millions]
- very quick turn around [24 h]

- [2016] Persistency of the reconstruction information for the full event, higher level variables available for a few selections

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Summary

- LHCb is the first HEP experiment implementing a fully automatic tracking system alignment, PID calibration and track reconstruction in the online system

- Full offline-quality reconstruction available online

- Achieved thanks to the huge effort in tracking improvements and development of the new automatic procedure during LS1 [HLT reorganized to allow buffering after HLT1; additional HLT farm purchased: effectively 2 times larger, 1800 servers, 27000 physical cores, 10 PiB disk space; software optimized to fit reconstruction in time budget]

- New tool (Turbo + Tesla) for direct analysis: saves space and allow to achieve physics results few days after data taking

A working model for future experiments

 Much better trigger in Run 2 than in Run 1

"All I'm saying is now is the time to develop the technology to deflect an asteroid."
Back on track!

Event 24238378
Run 172949
Sat, 23 Apr 2016 10:34:49

[Run 2 year 2 physics commissioning with stables beams]
(Nearly…) Back on track!

http://kdungs.github.io/WeaselDefense/

Open Controls

IN A PERFECT WORLD
THE PROJECT WOULD
TAKE EIGHT MONTHS.

BUT BASED ON PAST
PROJECTS IN THIS
COMPANY, I APPLIED
A 1.5 INCOMPETENCE
MULTIPLIER.

AND THEN I APPLIED
A D.W.F. OF 6.3.

D.W.F?
DEAD
WEASEL
FACTOR.

1.5 x 8
= 12
MONTHS

- Barbara Sciascia (INFN/LNF) - LHCb Trigger in Run 2 - Beauty 2016, 4 May -
**HLT1 event reconstruction**

- **Inclusive selections:**
  - Single and two track MVA selections
  - $\sim 100$ kHz
- **Inclusive muon selections**
  - Single and dimuon selections
  - Additional low $p_T$ track reconstruction
  - $\sim 40$ kHz
- **Exclusive selections**
  - Lifetime unbiased beauty and charm selections
  - Selections for alignment
- **Low multiplicity trigger for central exclusive production analyses**

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**HLT1 event reconstruction**

- **Offline Velo tracking**
- **Kalman filter**
- **Offline PV**

**Velo → TT:**
- Initial momentum estimate

**TT → T-stations:**
- Full track

**Offline Kalman filter:**
- Optimal track parameters

- **Muon identification**

- **Improved sequence (Velo → TT)**
- Code optimization
- **New offline:**
  - PV fit only with Velo tracks
  - Kalman filter with fast geometry description
  - No performance degradation

→ Consistent PV and track parameters
Track reconstruction

Dipole magnet implies an intrinsic charge asymmetry (left-right differences in the detector).

Direction of magnetic field changed regularly and data sets combined.
Heavy flavour signatures

B hadrons

- mass \( m(B^+) = 5.28 \text{ GeV} \)
- lifetime \( \tau(B^+) \sim 1.6 \text{ ps} \)
- flight distance \( \sim 1 \text{ cm} \)
- common signature: detached \( \mu\mu \)
  \( B \rightarrow J/\psi X \) with \( J/\psi \rightarrow \mu\mu \)

At 13TeV \( \sigma(bb) \sim 45 \text{ kHz} \) and \( \sigma(cc) \sim 1 \text{ MHz} \) cc in LHCb acceptance

charmed hadrons

- mass \( m(D^0) = 1.86 \text{ GeV} \)
- lifetime \( \tau(D^0) \sim 0.4 \text{ ps} \)
- flight distance \( \sim 4 \text{ mm} \)
- can be produced in \( B \) decays
Data driven performance

**PID samples [Run 1 and Run 2]:**
- low-multiplicity modes with large BRs
- without using PID variables (e.g. $D^0 \rightarrow K\pi$)
- tag-and-probe method (e.g. $J/\psi \rightarrow \mu\mu$)

<table>
<thead>
<tr>
<th>Species</th>
<th>Soft</th>
<th>Hard</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e^\pm$</td>
<td>—</td>
<td>$J/\psi \rightarrow e^+e^-$</td>
</tr>
<tr>
<td>$\mu^\pm$</td>
<td>$D_s^+ \rightarrow \mu^+\mu^-$</td>
<td>$J/\psi \rightarrow \mu^+\mu^-$</td>
</tr>
<tr>
<td>$\pi^\pm$</td>
<td>$K_s^0 \rightarrow \pi^+\pi^-$</td>
<td>$D^* \rightarrow D^0\pi^+$, $D^0 \rightarrow K^-\pi^+$</td>
</tr>
<tr>
<td>$K^\pm$</td>
<td>$D_s^+ \rightarrow K^+K^-\pi^+$</td>
<td>$D^* \rightarrow D^0\pi^+$, $D^0 \rightarrow K^-\pi^+$</td>
</tr>
<tr>
<td>$p^\pm$</td>
<td>$\Lambda^0 \rightarrow p\pi^-$</td>
<td>$\Lambda^0 \rightarrow p\pi^-$, $\Lambda_c^+ \rightarrow pK^-\pi^+$</td>
</tr>
</tbody>
</table>

Selected directly in the trigger [Run 2]:
- larger statistics
- easier trigger-decorrelation
  [Muon and CALO are used in L0 and HLT1]
PID samples are used in data-driven techniques to measure the PID performance.

PID information built in the trigger with offline-quality; keep the chance of further improvements (e.g. high-CPU-load)

**Dedicated Stream:**
- online/trigger information plus full raw event (can be reconstructed).
- key tool for the quality validation of “online data analyses” (TURBO stream / Tesla)
Interplay between LHC schedule and farm behaviour is hard to predict: study it with toys.
- 2012 running period machine availability used as input. Technical stops follow 2016 calendar
- assuming HLT2 throughput of 60 kHz
- percent level probability of reaching 10 PiB
Toys will be regularly re-run through the year as LHC schedule and farm performance is better understood.
[Tesla: an application for real-time data analysis in High Energy Physics, 1604.05596v1]
LHC bunch crossing (30MHz) → L0 hardware trigger (1MHz) → HLT1 software trigger (150kHz) → Buffer → Real-time alignment and calibrations → HLT2 software trigger (12.5kHz) → Offline reconstruction and associated processing → User analysis → 

Offline reconstruction and associated processing → 

Full → 

Turbo → 

Calibration → 

Maximum achievable rates shown in parentheses.
Physics out of the trigger with Turbo Stream:

- Raw info discarded, candidates directly available few hours after being recorded

- More decays can be collected and therefore more precise measurements performed than would have been possible under the Run-I computing model.

- [2016] Persistency of the reconstruction information for the full event, higher level variables available for a few lines.
Alignment and calibration

The idea: do physics directly on HLT output

Challenges:
- do the full reconstruction in few ms achieving offline performance quality;
- alignment and calibration of the detector “on real time”;
- efficient trigger selection of signal candidates.

Strategy:
- speed-up/improve reconstruction;
- HLT split: HLT1 output stored on disk;
- Enough time to perform alignment and calibration tasks between HLT1 and HLT2.

- Automatic evaluation at regular intervals (beginning of the run or fill depending on the task)
- Dedicated data sample collected with a specific trigger selection line for each task
- Compute the new alignment or calibration constants in a few minutes
- Update the constants only if needed

The same new constants will be used both by the trigger and the offline reconstruction