The ATLAS Trigger in Run-2
Design, Menu and Performance

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Outline

- Introduction
- ATLAS Trigger and DAQ System Overview
- ATLAS Trigger Menu & Online Performance
- ATLAS Trigger Rates, CPU Usage & Software Validation
- Highlights ATLAS Trigger Signature Performance
- Conclusions
Introduction

* Trigger system decides online whether or not to keep an event
  - Crucial **impact on quality** of data used in physics analysis!

* Successful operation of ATLAS Trigger System during first part of Run-2 at the LHC
  - Thanks to **several upgrades and improvements since Run-1** to cope with:
    - **Increase of rate**
    - **Increase of number of interactions per bunch crossing / pileup**
      due to:
      - higher centre-of-mass energy collisions
      - higher instantaneous luminosity

ATLAS Trigger: **Level 1 Trigger (L1)**

- **Upgraded L1 Calo, L1 Muon and CTP (Central Trigger Processor)**
  - **L1 Calo**: new Multi-Chip Module (nMCM) allows more flexible signal processing, more thresholds
  - **L1 Muon**: coincidences with inner detector, additional chambers in the feet of the barrel region and from Tile extended barrel region
  - **CTP**: more resources, support multi-partition running

- **L1Topo**
  - Allows for topological selections between L1 trigger objects (e.g. ΔR) to keep L1 thresholds low

- **40 MHz → 100 kHz rate reduction with a fixed latency of 2.5 μs**
- **Fast custom-made electronics find regions of interest (RoIs) using calorimeter and muon data with coarse information**
ATLAS Trigger: **High Level Trigger (HLT)**

- Single farm (merged L2-EF) for better resource sharing and overall simplification
- Fast offline-like algorithms running mostly in L1 RoIs
- Average 350 ms latency
- Full upgrade of readout and data storage systems
- ~1 kHz of physics (full event building) output rate achieved
- Partial event building used for Trigger Level Analysis, detector monitoring and calibrations
- Once HLT is passed, the event is accepted and written into data streams
- Then offline software is run at Tier-0 to reconstruct the objects

**FTK under commissioning**

*Hardware accelerated tracking:* reconstructs all tracks for all L1 accepted events and provides track information to HLT
The trigger menu comprises the list of L1→HLT trigger chains with prescale factors

- reflects the physics goals of the collaboration
  - high acceptance for BSM searches & Higgs/SM precision measurements
- takes into account available data taking resources (L1, HLT and Tier-0)

Trigger menu strategy based on:

- **primary triggers**: for physics measurements, typically un-prescaled
- **support triggers**: for efficiency and performance measurements, monitoring
- **alternative triggers**: running alternative online reconstruction algorithms
- **backup triggers**: tighter selections in case rate of primary trigger too high
- **calibration triggers**: run at high rate but store only part of the event
**ATLAS Trigger Menu: content**

For illustration:

<table>
<thead>
<tr>
<th>Trigger</th>
<th>Typical offline selection</th>
<th>Trigger Selection</th>
<th>Level-1 Peak Rate (kHz)</th>
<th>HLT Peak Rate (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single leptons</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Single isolated $\mu$, $p_T &gt; 27 \text{ GeV}$</td>
<td>20</td>
<td>26 (i)</td>
<td>13</td>
<td>133</td>
</tr>
<tr>
<td>Single isolated tight $e$, $p_T &gt; 27 \text{ GeV}$</td>
<td>22 (i)</td>
<td>26 (i)</td>
<td>20</td>
<td>133</td>
</tr>
<tr>
<td>Single $\mu$, $p_T &gt; 52 \text{ GeV}$</td>
<td>20</td>
<td>80</td>
<td>15</td>
<td>48</td>
</tr>
<tr>
<td>Single $e$, $p_T &gt; 61 \text{ GeV}$</td>
<td>22 (i)</td>
<td>60</td>
<td>20</td>
<td>13</td>
</tr>
<tr>
<td>Single $\tau$, $p_T &gt; 170 \text{ GeV}$</td>
<td>60</td>
<td>160</td>
<td>15</td>
<td></td>
</tr>
<tr>
<td>Two leptons</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Two $\mu$'s, each $p_T &gt; 15 \text{ GeV}$</td>
<td>2 $\times$ 10</td>
<td>2 $\times$ 14</td>
<td>1.5</td>
<td>21</td>
</tr>
<tr>
<td>Two $\mu$'s, $p_T &gt; 23.9 \text{ GeV}$</td>
<td>20</td>
<td>22.8</td>
<td>13</td>
<td>30</td>
</tr>
<tr>
<td>Two loose $e$'s, each $p_T &gt; 18 \text{ GeV}$</td>
<td>2 $\times$ 15</td>
<td>2 $\times$ 17</td>
<td>8</td>
<td>7</td>
</tr>
<tr>
<td>One $e$ &amp; one $\mu$, $p_T &gt; 8.25 \text{ GeV}$</td>
<td>20 ($\mu$)</td>
<td>7.24</td>
<td>13</td>
<td>2</td>
</tr>
<tr>
<td>One loose $e$ &amp; one $\mu$, $p_T &gt; 18, 15 \text{ GeV}$</td>
<td>15, 10</td>
<td>17, 14</td>
<td>1.5</td>
<td>2.6</td>
</tr>
<tr>
<td>Two $\tau$'s, $p_T &gt; 40, 30 \text{ GeV}$</td>
<td>20 (i), 12 (i) ($+$jets)</td>
<td>35, 25</td>
<td>6</td>
<td>35</td>
</tr>
<tr>
<td>One $\tau$ &amp; one isolated $\mu$, $p_T &gt; 30, 15 \text{ GeV}$</td>
<td>12 (i), 10 ($+$jets)</td>
<td>25, 14 (i)</td>
<td>1.5</td>
<td>7</td>
</tr>
<tr>
<td>One $\tau$ &amp; one isolated $e$, $p_T &gt; 30, 18 \text{ GeV}$</td>
<td>12 (i), 15 (i) ($+$jets)</td>
<td>25, 17 (i)</td>
<td>3</td>
<td>9</td>
</tr>
<tr>
<td>Three leptons</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Three loose $e$'s, $p_T &gt; 18, 11, 11 \text{ GeV}$</td>
<td>15, 2 $\times$ 8</td>
<td>17, 2 $\times$ 10</td>
<td>15</td>
<td>$&lt; 0.1$</td>
</tr>
<tr>
<td>Three $\mu$'s, each $p_T &gt; 7 \text{ GeV}$</td>
<td>3 $\times$ 6</td>
<td>3 $\times$ 6</td>
<td>0.1</td>
<td>3</td>
</tr>
<tr>
<td>Three $\mu$'s, $p_T &gt; 21, 2 \times 5 \text{ GeV}$</td>
<td>20</td>
<td>20, 2 $\times$ 4</td>
<td>13</td>
<td>4</td>
</tr>
<tr>
<td>Two $\mu$'s &amp; one loose $e$, $p_T &gt; 2 \times 11, 13 \text{ GeV}$</td>
<td>2 $\times$ 10 ($\mu$'s)</td>
<td>2 $\times$ 10, 12</td>
<td>1.5</td>
<td>0.2</td>
</tr>
<tr>
<td>Two loose $e$'s &amp; one $\mu$, $p_T &gt; 2 \times 13, 11 \text{ GeV}$</td>
<td>2 $\times$ 8, 10</td>
<td>2 $\times$ 12, 10</td>
<td>1.1</td>
<td>0.1</td>
</tr>
<tr>
<td>One photon</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>One loose $\gamma$, $p_T &gt; 145 \text{ GeV}$</td>
<td>22 (i)</td>
<td>140</td>
<td>20</td>
<td>30</td>
</tr>
<tr>
<td>Two photons</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Two loose $\gamma$'s, $p_T &gt; 40, 30 \text{ GeV}$</td>
<td>2 $\times$ 15</td>
<td>35, 25</td>
<td>8</td>
<td>40</td>
</tr>
<tr>
<td>Two tight $\gamma$'s, $p_T &gt; 27, 27 \text{ GeV}$</td>
<td>2 $\times$ 15</td>
<td>2 $\times$ 22</td>
<td>8</td>
<td>16</td>
</tr>
<tr>
<td>Single jet</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jet ($R = 0.4$), $p_T &gt; 420 \text{ GeV}$</td>
<td>100</td>
<td>380</td>
<td>3</td>
<td>38</td>
</tr>
<tr>
<td>Jet ($R = 1.0$), $p_T &gt; 460 \text{ GeV}$</td>
<td>100</td>
<td>420</td>
<td>3</td>
<td>35</td>
</tr>
<tr>
<td>$E_{\text{T}}^{miss}$</td>
<td>$E_{\text{T}}^{miss} &gt; 200 \text{ GeV}$</td>
<td>50</td>
<td>110</td>
<td>6</td>
</tr>
<tr>
<td>Multi-jets</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Four jets, each $p_T &gt; 110 \text{ GeV}$</td>
<td>3 $\times$ 50</td>
<td>4 $\times$ 100</td>
<td>0.4</td>
<td>18</td>
</tr>
<tr>
<td>Five jets, each $p_T &gt; 80 \text{ GeV}$</td>
<td>4 $\times$ 15</td>
<td>5 $\times$ 70</td>
<td>3.5</td>
<td>14</td>
</tr>
<tr>
<td>Six jets, each $p_T &gt; 70 \text{ GeV}$</td>
<td>4 $\times$ 15</td>
<td>6 $\times$ 60</td>
<td>3.5</td>
<td>5</td>
</tr>
<tr>
<td>Six jets, each $p_T &gt; 55 \text{ GeV},</td>
<td>4 $\times$ 15</td>
<td>6 $\times$ 45</td>
<td>3.5</td>
<td>18</td>
</tr>
<tr>
<td>$b$–jets</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>One $b$ ($e = 60%$), $p_T &gt; 235 \text{ GeV}$</td>
<td>100</td>
<td>225</td>
<td>3</td>
<td>24</td>
</tr>
<tr>
<td>Two $b$'s ($e = 60%$), $p_T &gt; 160, 60 \text{ GeV}$</td>
<td>100</td>
<td>150, 50</td>
<td>3</td>
<td>20</td>
</tr>
<tr>
<td>One $b$ ($e = 70%$) &amp; three jets, each $p_T &gt; 85 \text{ GeV}$</td>
<td>4 $\times$ 15</td>
<td>4 $\times$ 75</td>
<td>3.5</td>
<td>19</td>
</tr>
<tr>
<td>Two $b$'s ($e = 60%$) &amp; one jet, $p_T &gt; 65, 65, 110 \text{ GeV}$</td>
<td>2 $\times$ 20, 75</td>
<td>2 $\times$ 55, 100</td>
<td>2.7</td>
<td>25</td>
</tr>
<tr>
<td>Two $b$'s ($e = 60%$) &amp; two jets, each $p_T &gt; 45 \text{ GeV}$</td>
<td>4 $\times$ 15</td>
<td>4 $\times$ 35</td>
<td>3.5</td>
<td>56</td>
</tr>
<tr>
<td>$b$–physics</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Two $\mu$'s, $p_T &gt; 6, 6 \text{ GeV}$</td>
<td>6.6</td>
<td>6.6</td>
<td>4.7</td>
<td>20</td>
</tr>
<tr>
<td>Plus dedicated $b$–physics selections</td>
<td>6.6</td>
<td>6.6</td>
<td>4.7</td>
<td>20</td>
</tr>
<tr>
<td>Total</td>
<td>(including more triggers than listed here)</td>
<td>85</td>
<td>1500</td>
<td></td>
</tr>
</tbody>
</table>

* HLT rate expensive trigger

Over 3000 trigger chains running online and covering a large spectra of physics objects and processes!

- Menu designed for different peak luminosities
- In 2016 reached $1.4 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ luminosity
  - above LHC design luminosity!
- In 2017, baseline menu designed for $2 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ luminosity
- Primary triggers kept stable within a menu
- Flexibility to adjust to changing conditions during LHC ramp-up

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Menu deployed with different prescale sets depending on luminosity
- as luminosity decreases throughout the fill, the bandwidth usage is optimised by increasing the rate of supporting triggers
Event size ~ 1.6 MB (uncompressed) for $\langle \mu \rangle = 24.9$ in 2016

**Physics trigger group rates in a fill taken in July 2016 with a peak luminosity of $L = 1.02 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$ and $<\mu>= 24.2.$**
Distributions of HLT-level quantities monitored online

Automatic data quality (DQ) checks applied based on standardised histogram analyses and comparisons to reference histograms

Track performance of the HLT via red (alarm), yellow (warning) and green (OK) DQ

Similar procedure followed offline to declare data good for physics

Menu-aware monitoring scheme allows to update monitoring configuration out-of-sync with software releases with very small latency (~hr)
ATLAS Trigger Rates & CPU usage

- Trigger rate predictions and HLT farm performance studies essential for all menu developments and validation of HLT algorithms
  - Special dataset (EnhancedBias) collected every time data-taking condition changes to provide rate predictions
    - For the EB dataset, events are selected by the L1 trigger system that emphasises **higher energies and object multiplicities**, and the selection bias is corrected for with event weights
- Significant improvement in timing for tracking ID trigger

### Online rate monitoring:
Level-1 trigger rates online (red) compared with predictions based on luminosity-scaling (green)

- **Group CPU monitoring**
  - **ATLAS** Preliminary
  - **CPU Usage Per Group**
    - B Jet
    - Electron Photon
    - B Physics
    - Muon
    - Tau
    - Jet
    - Missing Energy
    - Beam Spot
    - Detector
    - Other
    - Inner Detector
    - Zero Bias
    - Tau Overlay
    - Minimum Bias

- **Trigger rates (kHz)**
  - L1_EM22VHI
  - L1_TAU60
  - L1_MU20
  - L1_XE50
  - L1_4J15

- **ATLAS Trigger Operations**
  - (July 22, 2016)

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[ATL-DQA-PUB-2016-002]

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**ATLAS Trigger software validation**

- Full trigger menu and HLT software run **offline** over the EnhancedBias dataset for algorithm validation

- **Weekly** HLT release validation involving experts in trigger menu, HLT release, software validation, and trigger signature experts

- **High memory** consumption jobs run in the Grid

- **New in 2017:**
  - Improved CPU usage of trigger chains
  - Automation of release build and distributed every night w/o expert action

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[Image of flowchart and text diagram related to ATLAS Trigger software validation]
ATLAS Trigger signature performance (I)

Several improvements in L1 and HLT Trigger Systems reflected in the performance of the trigger objects, some examples new in 2017:

Trimming and mass-cut for large-R jet trigger
- Trimming: procedure to remove soft contamination (from pileup) in large-radius jets

Pile-up mitigation is main challenge for $E_T^{miss}$ triggers
- MHT algorithm based on $p_T$ sum of HLT jets default in 2016
- pufit: new baseline in 2017 (pileup estimated event-by-event and subtracted)
Electron, photon, and muon triggers performing well in 2017!

L1Topo is default in 2017 trigger.

Likelihood-based identification for electrons

Photon triggers
Conclusions

- Hardware and software modified and improved during the shutdown to cope with challenges during LHC Run 2
- Trigger successfully commissioned in 2015
- Smooth trigger operation in 2016 despite the very challenging LHC conditions
- Impressive improvements were made in preparation for the expected highest ever luminosities and pileup in the 2017/18 LHC run
- Further improvements ahead:
  - Integration of FTK
The Run 2 HLT Inner Detector tracking trigger processing time for the Fast Track Finder stage for the tau signature. Shown are the times for the single-stage, and the two-stage tracking. In the single-stage tracking, the tracking is performed in a single, large Region of Interest (RoI) with $\Delta \eta = 0.4$, $\Delta \varphi = 0.4$ and $\Delta z = 225$ mm with respect to the RoI direction and position $z=0$ along the beamline. In the two-stage tracking, the tracking is first performed in an RoI with $\Delta \eta = 0.1$, $\Delta \varphi = 0.1$ and $\Delta z = 225$ mm with respect to the RoI direction, to identify the core tracks, and then a second tracking stage is performed in an updated RoI centred on the highest $p_T$ track with $\Delta \eta = 0.4$, $\Delta \varphi = 0.4$ and $\Delta z = 10$ mm with respect to that track. The total mean time for the two-stage tracking is 44.5 ms corresponding to a fractional saving in processing time for the fast tracking with respect to the single-stage tracking of greater than 30%. The data were taken during collisions in August 2015 with the LHC colliding with a 25 ns bunch spacing. The mean number of interactions per bunch crossing was $\langle \mu \rangle \sim 14.$