The ATLAS Run-2 Trigger Menu for higher luminosities: Design, Performance and Operational Aspects

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Introduction

◦ LHC proton-proton collisions at $\sqrt{s} = 13$ TeV in Run-2 (2015-2018)

◦ Record peak luminosity: $1.74 \times 10^{34}$ cm$^{-2}$s$^{-1}$
  ⇒ Design LHC luminosity: $10^{34}$ cm$^{-2}$s$^{-1}$
  ⇒ Peak lumi reached in 2016: $1.38 \times 10^{34}$ cm$^{-2}$s$^{-1}$
  ⇒ Trigger menu designed in 2017 for $2 \times 10^{34}$ cm$^{-2}$s$^{-1}$

◦ A total of 17.9 fb$^{-1}$ delivered so far (LHC goal for 2017 is 45 fb$^{-1}$)

◦ Increased number of interactions per bunch crossing (pileup): $\langle \mu \rangle = 32.2$ in 2017

◦ Extremely challenging environment!

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ATLAS Online Luminosity

**LHC Stable Beams**

Peak Lumi: $17.4 \times 10^{33}$ cm$^{-2}$s$^{-1}$

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Delivered Luminosity [fb$^{-1}$]

**ATLAS Online Luminosity**

- 2011 pp $\sqrt{s} = 7$ TeV
- 2012 pp $\sqrt{s} = 8$ TeV
- 2015 pp $\sqrt{s} = 13$ TeV
- 2016 pp $\sqrt{s} = 13$ TeV
- 2017 pp $\sqrt{s} = 13$ TeV

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Mean Number of Interactions per Crossing

\[
\begin{align*}
2015: & \langle \mu \rangle = 13.5 \\
2016: & \langle \mu \rangle = 24.9 \\
2017: & \langle \mu \rangle = 32.2 \\
\text{Total:} & \langle \mu \rangle = 26.4
\end{align*}
\]
In Run-2, ATLAS uses a two level trigger system to efficiently select interesting events and reduce the interaction rate of 40 MHz to 1 kHz:

- **Hardware-based Level-1 (L1) trigger:**
  - **Level-1 Calo:** new Multi-Chip Module (nMCM) allows more flexible signal processing, more thresholds
  - **Level-1 Muon:** coincidences with inner detector, additional chambers in the feet of the barrel region and from Tile extended barrel region
  - **Central Trigger:** support multi-partition running

- **Software-based High Level Trigger (HLT):**
  - Single farm (merged Level-2 and Event Filter farms used in Run-1) for better resource sharing
  - Fast offline-like sophisticated algorithms running mostly in L1 Regions-of-Interest
  - Full upgrade of readout and data storage systems
  - Events accepted at HLT are stored for offline event reconstruction at Tier-0 to be used in physics analyses

**New systems installed in Run-2:**

- **Level-1 Topological Trigger (L1Topo):** topological cuts to reduce the rate and keep the thresholds low
- **Fast TracKer (FTK):** hardware-based tracking which provides full track information to HLT after every Level-1 accept, currently under commissioning
Level-1 Topological Trigger

- Level-1 Topological Trigger module combines calorimeter and muon information at Level-1 and applies topological selections to reduce the rate (e.g., angular distances, di-object invariant mass, transverse mass)
- FPGA-based algorithms used to analyse geometrical information on trigger objects
- L1Topo activated and commissioned in 2016 and used in several primary triggers in 2017

\[ \Delta \Phi, \Delta \eta \]
Isolation, overlap removal, b-tagging...

\[ H_T, M_{\text{eff}}, E_T \]
Transverse Mass, \( \Delta \Phi(\text{jet}, E_T) \)

B-physics topological trigger

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**ATLAS** Trigger Operations
Data 2017, \( \sqrt{s} = 13 \text{ TeV} \)
Run taken on Jun 17, 2017

- L1: \( 2 \times p_T^\mu > 6 \text{ GeV} \)
- L1Topo: \( 2 \times p_T^\mu > 6 \text{ GeV}, m_{\mu\mu} \in [2,9] \text{ GeV}, \Delta R_{\mu\mu} \in [0.2,1.5] \)
ATLAS Trigger Menu strategy

- **Trigger menu:**
  - **L1 menu** consists of 512 single items and combinations
  - **HLT menu** consists of $O(1000)$ chains
  - Rates are adjusted via prescale sets, where each prescale set corresponds to a fixed value of instantaneous luminosity

- **Chains are grouped into signatures:** electrons, photons, muons, taus, jets, etc.
- **Chains require either full event building (EB) or partial EB with only subdetector information for recording into data streams**
- **Different streams defined such as:**
  - **Main Physics:** including majority of the events
  - **Express:** stream for fast offline monitoring and detector calibration
  - **Trigger Level Analysis:** using partial EB for di-jet resonance searches

- **Trigger menu strategy based on:**
  - **Primary triggers:** used for physics analyses, typically running unprescaled
  - **Support triggers:** used for efficiency and performance measurements or monitoring
  - **Alternative triggers:** running alternative online reconstruction algorithms
  - **Backup triggers:** tighter selections and lower expected rate
  - **Calibration triggers:** used for detector calibrations
ATLAS Trigger rates and bandwidth

ATLAS Trigger Operation
HLT Stream Rates (with overlaps)
pp Data June 2017, $\sqrt{s} = 13$ TeV

ATLAS Trigger Operation
HLT Stream Rates (incl. overlap)
pp Data June 2017, $\sqrt{s} = 13$ TeV

ATLAS Trigger Operation
HLT Output Bandwidth
pp Data June 2017, $\sqrt{s} = 13$ TeV
Trigger Level Analysis (TLA)

- Novel idea to circumvent the bandwidth limitation using partial event building (< 5% standard event size recorded)
- Prescale factors normally applied to the HLT jet triggers in the standard stream
- Large gain in statistics for the data scouting stream for $p_T < 400$ GeV
- Important for low mass dijet searches → Increase sensitivity

**ATLAS-CONF-2016-030**
ATLAS Level-1 Trigger rates

○ Representative Level-1 triggers running unprescaled in a fill taken in June 2017:
  ○ **EM**: electromagnetic clusters
  ○ **MU**: muon candidates
  ○ **J**: jet candidates
  ○ **XE**: missing energy
  ○ **TAU**: tau candidates

○ Exponential decay with decreasing luminosity during an LHC fill

○ The rates periodically increase due to LHC luminosity re-optimisations, dips are due to deadtime and spikes are caused by detector noise

**Single Level-1 trigger items**

**Multi Level-1 trigger items**
ATLAS HLT Trigger rates

- Physics trigger group rates at the HLT as a function of time in a fill taken in June 2017
- Overlaps are only accounted for in the total Main Physics Stream rate
- Exponential decay with decreasing luminosity during an LHC fill
- The rates periodically increase due to LHC luminosity re-optimisations, dips are due to deadtime and spikes are caused by detector noise

![ATLAS Trigger Operation](image_url)

- HLT Physics Group Rates (with overlaps)
- pp Data June 2017, $\sqrt{s} = 13$ TeV
- Time [h:m] from 08:25 to 13:25
ATLAS Trigger CPU usage

- HLT is computer farm of up to approximately 40,000 CPU cores
- Higher CPU-usage **partially scaling exponentially with pileup**
- Improved CPU usage of the trigger chains in 2017
- Summary of the CPU consumption for all chains as assigned to physics groups

**ATL-Daq-Pub-2016-002**

**Physics use cases:**

- **B Jet**: \( H \rightarrow b \bar{b}, t \bar{t}, \) etc.
- **Electron**: Generic analyses \((W, Z, \) dibosons, \( t \bar{t}, \) etc.\)
- **Photon**: \( H \rightarrow \gamma \gamma, \gamma \) production, etc.
- **B Physics**: \( J/\psi, \Upsilon, \) etc.
- **Muon**: Generic analyses \((W, Z, \) dibosons, \( t \bar{t}, \) etc.\)
- **Tau**: \( H \rightarrow \tau \tau, \) searches, etc.
- **Jet**: jet production, dijet resonances searches, etc.
- **Missing Energy**: SUSY searches, etc.
launch the reprocessing of EB data to test the HLT software. This processing consists of three steps, first the processing of raw EB data emulating the HLT, followed by the reconstruction of the accepted data (mimicking the reconstruction chain during online data-taking), followed by production of output metrics for validation. Once the data has been processed, the software validation expert then makes available the output metrics to the signature experts and solicits their feedback. If sign-off is given by every signature group then the software release can be deployed for running in ATLAS, if not then new bug tickets are created and the process begins anew. Overall this cycle typically takes between three and seven days.

Figure 3. The HLT software validation cycle and participants.

6. Tools and Strategies

The trigger software validation is an ongoing effort that requires coordination with the online trigger operation and the various experts involved at different stages of the validation process, and a seamless transition from week to week between experts. This section highlights the main tools and strategies that are used to ensure the ongoing integrity of the validation process.

6.1. Daily Coordination Meetings

Every day there is a general trigger operations coordination meeting that ties together all ongoing trigger-related tasks (online and offline). In this meeting an update of the software validation status is given, providing a forum for the coordinator to highlight important revelations, to...
Level-1 EM isolation optimization for 2017

- The unprescaled single Level-1 EM trigger is the item with the highest rate in the Level-1 menu
- Level-1 EM isolation tightened to reduce the trigger rate and keep the single-electron trigger threshold low
- Default Level-1 EM isolation used in 2016:
  \[
  \max\{2 \text{ GeV}, \frac{E_{\text{T, cluster}}}{8} - 1.8 \text{ GeV}\} \quad \text{for } E_{\text{T, cluster}} < 50 \text{ GeV}
  \]
- New Level-1 EM medium isolation implemented in 2017:
  \[
  \max\{1 \text{ GeV}, \frac{E_{\text{T, cluster}}}{8} - 2.0 \text{ GeV}\} \quad \text{for } E_{\text{T, cluster}} < 50 \text{ GeV}
  \]

Medium isolation (IM) with respect to the default isolation (I)

<table>
<thead>
<tr>
<th>Level-1 $E_T$</th>
<th>Efficiency loss</th>
<th>Rate reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>22 GeV</td>
<td>1.3%</td>
<td>14.6%</td>
</tr>
<tr>
<td>24 GeV</td>
<td>1.0%</td>
<td>10.8%</td>
</tr>
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Table 1: Level-1 trigger efficiency loss and rate reduction applying the new medium isolation on the electromagnetic (EM) clusters with $E_T > 22$ GeV and $E_T > 24$ GeV with respect to the default isolation used in 2016 data taking.
First 2017 performance

Electron trigger efficiencies

- Likelihood-based electron identification applied at HLT, different working points defined: tight, medium, loose, very loose
- Lowest unprescaled single-electron trigger HLT_e28_lhtight_nod0_ivarloose (trigger seeded by L1_EM24VHI)
- HLT track-based isolation applied (ivarloose: $\sum p_{T}^{\text{trk}} / p_{T} < 0.1$ in $\Delta R < 0.2$)
- Efficiency with respect to offline isolated tight electrons using $Z \rightarrow ee$ Tag & Probe
- No background subtraction applied

![Graphs showing trigger efficiency vs. offline isolated electron variables](image-url)
First 2017 performance

Electron trigger efficiencies

- Likelihood-based electron identification applied at HLT, different working points defined: tight, medium, loose, very loose
- Leg of the unprescaled di-electron trigger HLT\_2e24\_lhvloose\_nod0 (trigger seeded by L1\_2EM20VH)
- Efficiency with respect to offline loose electrons using $Z \to ee$ Tag & Probe
- No background subtraction applied

![Graph showing trigger efficiency vs. offline electron $E_T$ and $\eta$](image-url)

$E_T > 25 \text{ GeV}$

ATLAS Preliminary

Data 2017, $\sqrt{s}=13$ TeV, 1.8 fb$^{-1}$

HLT\_e24\_lhvloose\_nod0\_L1EM20VH

- Data
- $Z \to ee$ MC
First 2017 performance

Photon trigger efficiencies

- Cut-based photon identification applied at HLT, different working points defined: tight, medium, loose
- Leg of the unprescaled di-photon trigger HLT\_g35\_medium\_g25\_medium\_L12EM20VH (trigger seeded by L1\_2EM20VH) → Main trigger used for $H \to \gamma\gamma$
- Efficiency with respect to offline isolated tight photons using the bootstrap method
- No background subtraction applied
First 2017 performance

Barrel muon trigger efficiencies

- Muons reconstructed combining Inner Detector + Muon Spectrometer information (reduced barrel geometrical acceptance)
- Lowest unprescaled single-muon triggers `HLT_mu26_ivarmedium || HLT_mu60` (triggers seeded by `L1_MU20`)
- HLT track-based isolation applied (ivarmedium: $\sum p_T^{\text{trk}}/p_T < 0.07$ in $\Delta R < 0.3$)
- Efficiency with respect to offline isolated medium muons using $Z \rightarrow \mu\mu$ Tag & Probe
- No background subtraction applied
**First 2017 performance**

**Endcap muon trigger efficiencies**

- Muons reconstructed combining Inner Detector + Muon Spectrometer information
- Lowest unprescaled single-muon triggers HLT\_mu26\_ivarmedium || HLT\_mu60 (triggers seeded by L1\_MU20)
- HLT track-based isolation applied (ivarmedium: $\sum p_{T}^{\text{trk}}/p_{T} < 0.07$ in $\Delta R < 0.3$)
- Efficiency with respect to offline isolated medium muons using $Z \rightarrow \mu\mu$ Tag & Probe
- No background subtraction applied

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**ATLAS Preliminary**

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<th>$\sqrt{s}$=13 TeV, Data 2017, 1.2 fb$^{-1}$</th>
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**Efficiency**

- $Z \rightarrow \mu\mu$
- $p_{T}^{\mu} > 27$ GeV, $1.05 < |\eta^{\mu}| < 2.4$

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**Efficiency**

- $Z \rightarrow \mu\mu$
- $p_{T}^{\mu} > 27$ GeV, $1.05 < |\eta^{\mu}| < 2.4$
First 2017 performance
Jet trigger efficiencies

- Jets reconstructed using the **anti-\( k_t \) \( R = 0.4 \)** algorithm and calibrated at HLT
- Comparison of **different calibrations**:  
  - Updated calibration using only calorimeter information  
  - Updated calibration including additional track information  
  - The Global Sequential Calibration (GSC) corrects jets according to their longitudinal shower shape and associated track characteristics without changing the overall energy scale  
- Efficiencies computed using the **bootstrap method**

Unprescaled single-jet trigger

Unprescaled multi-jet trigger

ATLAS Preliminary

Data 2017, \( \sqrt{s} = 13 \text{ TeV} \)

Offline selection:
- \( \geq 1 \) jet with \( |\eta| < 2.8 \)
- HLT, \( p_T > 450 \text{ GeV} \)
- 2016 calibration steps
- 2017 calib., calorimeter-only
- 2017 calib., with tracks

Offline selection:
- \( \geq 6 \) jets with \( |\eta| < 2.8 \)
- HLT, 6 jets \( p_T > 60 \text{ GeV} \)
- 2017 calib., calorimeter-only
- 2017 calib., with tracks
First 2017 performance

Large-$R$ jet trigger efficiencies

- **Trimming** ([JHEP 02 (2010) 084](https://jhepjournal.org)) applied to mitigate contamination from soft radiation (initial state radiation, multiple parton interactions, pileup)
- Jet trimming procedure:
  - **anti-$k_t$ $R = 1.0$ algorithm** used for large-$R$ jets
  - Within a jet, recluster the constituents into subjets with radius $R_{\text{sub}} = 0.2$
  - Discard subjets if $p_{T,i} < f_{\text{cut}} \cdot \Lambda_{\text{hard}}$ ($f_{\text{cut}} = 0.05$ used)
  - Remaining subjets assembled into the trimmed jet
- Mass cut also applied

![Graphs showing per-event trigger efficiency](image-url)

- Leading large-$R$ trimmed offline jet $p_T$ [GeV]
- Second leading large-$R$ trimmed offline jet $p_T$ [GeV]

Offline selection:
- ≥2 jets with $p_T > 400$ GeV, $|\eta| < 2$
- anti-$k_t$, $R = 1.0$
- trimming: $f_{\text{cut}} = 0.05$, $R_{\text{sub}} = 0.2$
- HLT: 2 jets $p_T > 330$ GeV, mass > 30 GeV

A. Ruiz (Carleton)
First 2017 performance

*b*-jet trigger efficiencies

- The *b*-jet trigger uses a Boosted Decision Tree (BDT) algorithm to separate *b*-jets from light and *c*-jet backgrounds
- BDT re-optimized to improve the *b*-tagging performance
- The performance of the *b*-tagging algorithms measured using *t\bar{t}* Monte Carlo
- *b*-tagging algorithms used for *b*-jet triggers:
  - 2017 data: MV2c10 (multivariate algorithm with a 10% *c*-jet fraction in the training)
  - 2016 data: MV2c20 (multivariate algorithm with a 20% *c*-jet fraction in the training)
  - 2015 data: IP3D+SV1 (impact parameter tagger, secondary vertex finding algorithm)
First 2017 performance

Missing $E_T$ trigger efficiencies

- **Pileup mitigation is the main challenge** → significant effort to mitigate the impact on the trigger rates and deliver more efficient pileup suppression algorithms
- Efficiency of the lowest unprescaled $E_T^{\text{miss}}$ triggers using events with reconstructed $E_T^{\text{miss}} > 150$ GeV and a $W \rightarrow \mu \nu$ selection
- **pufit**: baseline algorithm in 2017, $E_T^{\text{miss}}$ calculated as the negative of the $p_T$ sum of all calorimeter topological clusters corrected for pileup
- **mht**: default algorithm in 2016, $E_T^{\text{miss}}$ calculated as the negative of the $p_T$ sum of all jets reconstructed by the anti-$k_t$ jet algorithm
Prospects

- The upgrades of the detectors and trigger system will be essential in the coming years to take full advantage of the physics potential of the LHC.
- LHC Run-3 (2021-2023) begins after the Phase-1 detector upgrades.
- HL-LHC (High Luminosity LHC) starting in 2024 with the Phase-2 detector upgrades followed by Run-4.
- The goal of the Phase-2 upgrades in ATLAS is to cope with an instantaneous luminosity of up to $7.5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ and a pileup of 200 collisions per crossing.
Conclusions

- **Significant improvements in many areas**, several hardware and software improvements during the LHC shutdown (2013-2014) to cope with the challenges to face in the LHC Run-2 (2015-2018)
- **Surpassed the initial design**, trigger menu prepared for twice the design luminosity \( (2 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}) \) and high pileup conditions \( (\mu \sim 60) \) expected in 2017 data taking
- **Rock-solid well-established validation procedures** to ensure a smooth trigger operation
- **First performance studies using 2017 data** of different trigger signatures (electrons, photons, muons, jets and \( E_{T}^{\text{miss}} \)) have been presented
- More results in: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TriggerPublicResults