The ATLAS Level-1 Topological Trigger Design and Operation in Run 2

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on behalf of ATLAS collaboration
Use elaborate trigger system and adjust continuously with increasingly harsher LHC conditions.
LHC luminosity

Already operating at Luminosity higher than nominal $1 \times 10^{34}/\text{cm}^2\text{s}$

Run 1
2011-2012

Run 2
2015-2018

Run 3
2020-2023

HL LHC
2026-

Phase-0

Phase-1

Phase-2

14 TeV

$7.5 \times 10^{34}/\text{cm}^2\text{s}$

$\sim 3000 \text{ fb}^{-1}$

Detector is optimized for $1 \times 10^{34}/\text{cm}^2\text{s}$

13 TeV

$3 \times 10^{34}/\text{cm}^2\text{s}$

$\sim 300 \text{ fb}^{-1}$

7.8 TeV

$0.5-2 \times 10^{34}/\text{cm}^2\text{s}$

$\sim 150 \text{ fb}^{-1}$

Run 1
2011-2012

Run 2
2015-2018

Run 3
2020-2023

HL LHC
2026-
ATLAS Upgrades

**Phase-0:**
- New inner pixel layer
- New L1 topological trigger

**Phase-1:**
- New forward muon detectors
- Increase L1 calorimeter granularity

**Phase-2:**
- Most electronics replaced
- New Inner Tracker
- New L1Track trigger

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**Run 1**
2011-2012

**Run 2**
2015-2018

**Run 3**
2020-2023

**HL LHC**
2026-

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- **13 TeV**
  - 0.5-2x10^{34}/cm^2s,
  - ~150 fb^{-1}

- **14 TeV**
  - 3x10^{34}/cm^2s
  - ~300 fb^{-1}

- **14 TeV**
  - 7.5x10^{34}/cm^2s
  - ~3000 fb^{-1}

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Today
Detector is optimized for 1x10^{34}/cm^2s
ATLAS Trigger Model

**L1**: hardware
find energetic clusters and muon segments

**HLT**: fast software
find energetic e, µ, τ etc in Region of Interest, full detector for some events

**Offline**: precise software
complete event reconstruction

Decision within 2.5 µs
100 kHz output (hard limit)

Decision within 1s
1 kHz output (limited by storage/Tier0)

**L1 in Run 1**: cut on multiplicity of clusters/muons above given thresholds
Operating at highest acceptable thresholds already
Why not raise thresholds?

Need solution for $H \rightarrow \tau \tau$ for $L > 10^{34} \text{ cm}^{-2}\text{s}^{-1}$

Current di-tau trigger is already at maximum allowed rate

Not possible to keep B-physics program with conventional single or di-muon triggers

Need topological selection at L1

Olya Igonkina

TWEPP 2016
Topological Algorithms for L1

Latest FPGAs technology allows to analyse geometrical information at L1 applied to different type of input objects (muons, jets, etc)

<table>
<thead>
<tr>
<th>Purpose</th>
<th>Input objects</th>
<th>Algorithm</th>
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</thead>
<tbody>
<tr>
<td>B-physics</td>
<td>muons</td>
<td>ΔR, Mass</td>
</tr>
<tr>
<td>H→ττ</td>
<td>tau_had, muons, electrons</td>
<td>Δη, Δφ, Mass</td>
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<tr>
<td>SUSY</td>
<td>Miss E_T, jets</td>
<td>minΔφ, H_T</td>
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<tr>
<td>W→ev</td>
<td>electrons, jets, Miss E_T</td>
<td>Isolation, m_T</td>
</tr>
<tr>
<td>Long lived Particles</td>
<td>late muons, Miss E_T, jets</td>
<td>Muon in next bunch</td>
</tr>
<tr>
<td>etc</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Example: trigger for $H \rightarrow \tau \tau$

Allow trigger of very challenging and rare channels like $H \rightarrow \tau \tau$

maintain the same acceptance efficiency at half the L1 rate
Example: trigger for B-physics

**B_s → μμ Signal**

*ATLAS Preliminary*

Simulation

$s = 7$ TeV

signal channel: $B_s^0 \rightarrow \mu \mu$ events passing 2MU4

**Background**

*ATLAS Preliminary*

$\int L dt = 100 \, pb^{-1}$ $s = 8$ TeV

Run 212967 events passing 2MU4

**ATLAS Preliminary**

$L_0 = 5 \times 10^{33} \, cm^{-2} \, s^{-1}$

8 TeV Level-1 rate

**L1 di-muon thresholds**

- $B_s^0 \rightarrow \mu \mu \, (x \, 10^3)$ at 7 TeV
- $B_s \rightarrow J/\psi \phi, J/\psi \rightarrow \mu \mu$ at 8 TeV
- $Y(1S) \rightarrow \mu \mu$ at 8 TeV

**Level-1 rate [Hz]**

- $10^{-2}$
- $10^{-1}$
- $1$
- $10$

**L1 Mass(μμ)**

L1 $\Delta R(\mu\mu)$

Preserve B physics program:

- Reduce $p_T$ while maintaining the same rate
- Higher efficiency for rare B meson decays
Olya Igonkina  TWEPP 2016

Not reviewed, for internal circulation only

ATLAS is one of the multi-purpose experiments at the Large Hadron Collider (LHC) at the European Centre of Nuclear Research (CERN) in Switzerland. The LHC collides bunches of opposing protons at a frequency of 40 MHz. The ATLAS Trigger system filters out collision events of little physics interest, lowering the average output rate to a level of about 1 kHz. This is achieved using a multi level trigger system. The fully hardware based Level-1 trigger uses muon and calorimeter signals to determine “Regions of Interest” (RoI) and, based on counting clusters of jets, tau, electron/\( g \) and missing \( E_T \) at various energy thresholds, reduces the event rate to about 100 kHz. The next stage High Level Trigger (HLT) is implemented in software. The HLT uses Level-1 RoIs to reconstruct detailed physics properties for a further rate reduction to approximately 1 kHz.

The ATLAS Level-1 Trigger is a fixed latency, 40 MHz, pipelined, synchronous system, built to operate at the LHC design instantaneous luminosity of \( 10^{34} \text{cm}^{-2}\text{s}^{-1} \). The Level-1 trigger system consists of three sub-systems: The Level-1 Calorimeter Trigger (L1Calo), the Level-1 Muon Trigger (L1Muon), and the Central Trigger Processor (CTP). The hardware of the Level-1 Trigger is primarily based on field-programmable gate arrays (FPGAs). Including cabling, the maximum latency budget of the Level-1 electronics chain is 2.5 \( \mu \text{s} \).

L1Topo - processing 1 Tb/s / module with latency budget of 150 ns
2 modules with 3 FPGAs each
(2 Xilinx Virtex7 XC7V690T for event processing and Kintex 7 for control and readout)
80 multi-gigabit receivers per FPGA (up to 13 Gbit/s)
dedicated boards converting input data into required format are also installed
Physics performances with the new ATLAS Level-1 Topological trigger in Run 2

Sebastian Artz

The 128 bit words can contain differing amounts of Trigger OBjects (TOBs). On each fiber 4 jet TOBs, 5 cluster (Em/ \( E_T \)/Tau) TOBs, 16 muon TOBs or energy sum information can be received resulting in a total of 64 Jet TOBs, 120 Em/ \( E_T \) TOBs, 120 Tau TOBs, 32 muon TOBs and one missing energy TOB. These TOB words are then decoded to obtain the angular values (\( h \), \( F \)) and the transverse energy \( E_T \). These lists of TOBs are then fed into the topological algorithms.

3.2 Algorithm Structure

The topological algorithms often combine all the elements of one TOB type with another. Due to the large amount of input data and combinatorics inside the algorithms, the amount of resources required would allow only a very low number of algorithms. To mitigate this the TOB lists of the different types are shortened in a first stage and then fed into the actual topological decision algorithms (see Fig. 2).

Figure 2: General algorithm structure

The timing constraint for the algorithms is currently given as three LHC bunch ticks (3 \( \times \) 25ns). The first two of them are used for the mentioned data reduction. This can be done in two different ways. In a sort algorithm the TOBs are sorted by their \( E_T \) value resulting in a sorted list of 6 TOBs. If there are more TOBs, an overflow bit is set. The alternative is a selection algorithm that applies an \( E_T \) cut and provides an output list of 10 TOBs. The length of these output lists is mainly limited by the logic delay of these algorithms.

During the third bunch tick the topological decision algorithms are applied on the shortened TOB lists. Their output consists of a decision and an overflow bit. In the realtime data path the overflow sets the decision to true so the high level trigger will rerun the algorithm. The decision bits are then sent directly to the CTP.

4. Physics Triggers with L1Topo

L1Topo triggers have various use cases in the fields of Standard Model, Higgs and B-Physics measurements, searches of Supersymmetry and Exotic particles, as well as for detector calibration (e.g. with J/\( \Psi \), W Tag-and-Probe or for Liquid Argon Calorimeter tests).

Physics triggers (see Fig. 3), including cuts on the invariant mass between jets (vector boson fusion), scalar sum of jet \( E_T \) (Susy, Exotics), \( D_R = \sqrt{D_{hh}^2 + D_{hf}^2} \) between muons (B-Physics),...
All algorithms are validated using

- VHDL simulation
- Processing selected events through the hardware via playback mechanism
- Hot tower setup for algorithm checks
- Data Quality infrastructure (Online Monitoring)
- Comparison to L1Topo Simulation for each L1 accepted event
Rate and efficiencies

**ATLAS** Trigger Operations
Data 2016, $\sqrt{s} = 13$ TeV
L1Topo Commissioning
Run taken on Aug 25, 2016

- L1: $2 \times p_T > 6$ GeV
- L1Topo: $2 \times p_T > 6$ GeV, $m_{\mu\mu} \in [2,9]$ GeV, $\Delta R_{\mu\mu} \in [0.2,1.5]$

**ATLAS** Preliminary
Data 2016, $\sqrt{s} = 13$ TeV
L1Topo Commissioning
Run taken on Aug 25, 2016

- L1: $2 \times p_T > 6$ GeV
- HLT: $2 \times p_T > 6$ GeV, $m_{\mu\mu} \in [4.0,8.5]$ GeV
- L1Topo: $2 \times p_T > 6$ GeV, $m_{\mu\mu} \in [2,9]$ GeV, $\Delta R_{\mu\mu} \in [0.2,1.5]$
- HLT: $2 \times p_T > 6$ GeV, $m_{\mu\mu} \in [4.0,8.5]$ GeV

L1Topo improves purity of L1 selection, while maintaining high efficiency at HLT
Rate and Efficiencies

SUSY trigger to select events with high hadronic activity (energetic jets)
Maintaining high efficiency while reducing L1 rate significantly
Excellent agreement of actual L1Topo performance w.r.t. expectations

\[ H_T = \sum p_{T^\text{jet}} \]

ATLAS Operation
Data 2016, \( \sqrt{s} = 13 \text{ TeV} \)
L1Topo Commissioning

ATLAS Operation
Data 2016, \( \sqrt{s} = 13 \text{ TeV} \)
L1Topo Commissioning

Prediction obtained by running trigger simulation on data

Luminosity \([10^{30} \text{ cm}^{-2}\text{s}^{-1}]\)
Summary

- LHC excellent performance beyond the designed values requires advanced modifications to ATLAS trigger system

- L1 topological processor triggers on geometrical coincidence of objects of interest and therefore maintains low $p_T$ thresholds at higher luminosities

- L1Topo system is put in place in 2016, and is being commissioned
  - The validation is done both using hardware tools, monitoring at HLT as well as in physics analysis
  - Stable performance of commissioned algorithms

- L1Topo boards are being used for physics data taking since this summer
  - Will become a crucial ingredient in 2017 data taking