The ATLAS Level-1 Topological Processor: experience and upgrade plans

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ATLAS Trigger System in Run-2

EVENT FLOW

LHC $pp$ collisions at a rate of 40 MHz

Rate reduction to ~100 kHz

Average final rate ~1 kHz

- The trigger system efficiently reduces the event rate by recording the *interesting* ones
- This selection is done in two levels:
  - **Level-1 Trigger (L1):** hardware-based system using only the calorimeter and muon information
  - **High Level Trigger (HLT):** software-based system applying offline-based reconstruction criteria
- Efficient ways of reducing background:
  - Minimum energy and multiplicity objects
  - Kinematic and angular cuts: *Topological trigger*

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TriggerOperationPublicResults
ATLAS Level-1 Trigger in Run-2

• Three independent hardware systems were used in Run-2:
  - **L1Calo** → multiplicities/thresholds from calorimeter readout
  - **L1Muon** → multiplicities/thresholds from muon chambers
  - **L1Topo** → angular/kinematic cuts

• All the Level-1 information is collected in the **Central Trigger Processor (CTP)** and a final L1accept issued
Level-1 Topological (L1Topo) Trigger in Run-2

- L1Topo was installed and commissioned in Run-2

- **IN:** Receives information from L1Calo and L1Muon

- **OUT:** Provides trigger decisions based on topological variables
  - Up to 128 decisions available
  - Sent directly to CTP

- Consists of two boards, each with:
  - 2 Virtex 7 FPGAs to compute algorithms
  - 1 Kintex 7 FPGA for communication and readout

- High input bandwidth (~1Tb/s)

- High speed inter-FPGA communication (238Gb/s)
L1Topo functionality and implementation

- Combination of calorimeter and muon detectors information
- Angular selections:
  - $\Delta \phi$, $\Delta R$, $\Delta \eta$, angular window, objects disambiguation
- Mass selections:
  - Invariant and transverse mass
- Access to trigger objects from different bunch crossings

Implementation

- ~75 ns used for algorithms
- L1Topo receives energy and position of all trigger objects (TOBs) → reduced into lists
- TOBs are processed by algorithms producing up to 128 trigger decisions
- Final decisions are sent to the CTP
Validation Process

- Different ways to validate L1Topo performance:
  - Standalone VHDL simulation
  - Using well defined data and studying the algorithm outputs
- One of the most powerful methods: integrated simulation in HLT
  - Runs online for almost every accepted event
  - Reproduces bitwise all the L1Topo decisions
  - Both hardware and simulation decisions are stored
- The rates of simulation false positives/negatives are computed for each L1Topo trigger
  - Events showing hardware-simulation discrepancies are studied in detail offline
  - Can be used to understand unexpected behaviour of different triggers

Hardware-simulation discrepancy rates lower than 10^{-3}
Physics Motivation

- Used in a variety of physics searches
  - Helps to keep trigger rates low by rejecting background events
  - Very useful to target challenging signatures
  - Equivalent to cut-based analysis results at L1!
- Helpful in the commissioning of new systems
  - FastTracker system

ATLAS Simulation
\[ \sqrt{s} = 14 \text{ TeV} \]
- VBF $H \rightarrow \tau_1 \tau_h$
- $Z \rightarrow \tau_h \tau_h$
- Minimum Bias

Angular separation between taus

- L1Topo efficiently identifies jet sub-structure
- Comparison of two algorithms
  - Energy inside a cone higher than 111 GeV (L1Topo)
  - Energy inside a square window higher than 100 GeV (non-topo)
- High number of subjets $\rightarrow$ energy is more spread
  - L1Topo shows higher efficiency

ATLAS Preliminary
Data 2017, $\sqrt{s} = 13$ TeV, 0.28 fb$^{-1}$

Level-1 trigger:
- $\sum_{R=1/\text{cone}} E_T > 111$ GeV
- $E_T > 100$ GeV

Offline subjets: $k_t$ $R = 0.2$, $p_T > 20$ GeV
- 1 subjet
- 2 subjets
- $\geq 3$ subjets

Offline jet: trimmed anti-$k_t$ $R = 1.0$, $|\eta| < 2.0$
trimming: $f_{cut} = 0.05$, $R_{sub} = 0.2$

Leading offline jet $p_T$ [GeV]

Per-event trigger efficiency

ATLAS-TDR-023
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/JetTriggerPublicResults
Physics Performance: di-jet triggers

- Di-jet triggers have high rates at low jet momentum
  - Cut on invariant mass helps to keep low thresholds
- High trigger efficiency for $M_{jj} > 1.3$ TeV
  - Designed to reduce trigger rate while enhancing signal over background
- Combined with lepton triggers in different physics analysis
  - Higgs to di-$\tau$
  - VBF Higgsino production

**HLT di-jet trigger efficiency**

**L1 di-jet trigger rate**

[Graph showing L1 di-jet trigger rate vs. inst. luminosity]

[Graph showing HLT di-jet trigger efficiency vs. offline $M_{jj}^{\text{max}}$]

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TriggerOperationPublicResults

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Physics Performance: di-muon triggers

- Very useful for final states with low momentum leptons
  - Di-muon triggers used in B-physics analyses
- Topological cuts result in rate reduction of ~4x
  - Region optimized for high signal acceptance
  - Large background rejection already at L1!
- Comparison of invariant mass distribution for topo and non-topo triggers
  - No bias introduced by L1Topo trigger
  - No significant loss in efficiency

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**ATLAS** Preliminary
Simulation
\( \sqrt{s} = 7 \text{ TeV} \)
signal channel: \( B^0 \rightarrow \mu \mu \) events passing 2MU4
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/BPhysicsTriggerPublicResults

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

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**ATLAS** Preliminary
Data 2016, \( \sqrt{s} = 13 \text{ TeV} \)
L1Topo Commissioning
Run taken on Aug 25, 2016
Physics Performance: di-tau triggers

- Critical use in analyses targeting di-τ final states: $H \rightarrow \tau \tau, Z \rightarrow \tau \tau$
  - High rate signature, L1Calo triggers need higher energy thresholds
- Including topological cuts reduces trigger rate while rejecting background
- For $H \rightarrow \tau \tau$ analysis: ΔR selection and extra jet requirement
  - Extra jet not overlapping with $\tau \rightarrow$ possible only in L1Topo!
  - Large rate reduction
  - No efficiency loss
Moving towards LHC Run-3

- **Successful data taking during Run-2**
- **Next milestone: get ready for Run-3 during Long-Shutdown-2 (LS2)**
- **LHC will be upgraded: different conditions during Run-3**
  - Higher pileup → lower calorimeter resolution and harder particle isolation
  - Higher trigger rates
- **ATLAS calorimeters, muon spectrometer and trigger systems will be upgraded**
  - Try to keep trigger thresholds as low as possible
Level-1 Trigger in Run-3

- **Changes in L1Muon:**
  - End-cap Sector Logic enhanced
  - New MuCTPi with extra bandwidth
    ‣ Sends more information to L1Topo and CTP

- **L1Calo** → Feature Extractor boards (FEX):
  - Electron Feature Extractor (eFEX)
  - Jet Feature Extractor (jFEX)
  - Global Feature Extractor (gFEX)

- **L1Topo** → new hardware

- Run-2 hardware will be kept during the commissioning phase → **Legacy**
L1Topo in Run-3

- Consists of **three new hardware boards** with
  - 2 Xilinx UltraScale+ FPGAs for algorithm computation
  - 118 input fibers per FPGA
  - 24 output fibers per FPGA
- L1Calo threshold/multiplicity triggers will be formed in L1Topo
- Higher granularity from L1Calo and L1Muon
- Enhanced processing power for higher algorithm complexity, e.g.
  - Invariant mass of three objects
  - Simultaneous cuts in invariant mass and angular variables
  - Use of muon charge in computations
- Prototypes delivered and tested with good results
- Production of final boards starting soon!
L1Topo Commissioning Plan

0 Pre-commissioning
- First tests with prototype

1 Commissioning of integrated system
- System-level tests and communication with neighbouring systems

2 Pre-beam commissioning
- Use calorimeter tower patterns and cosmic rays and compare with simulation

3 Commissioning with LHC beam
- First year of data taking
- Legacy system and new hardware will run in parallel
- Trigger menu adaptation is needed

Data taking with new L1Topo
- Legacy system will be removed once commissioning is done
- Online simulation will run at the HLT

Start of Run-3
Conclusions

• Successful commissioning and routine operation of Level-1 Topological Trigger during Run-2

• Increased signal acceptance in analysis targeting challenging signatures with high trigger rates
  - Useful to discriminate between signal and background already at the trigger level!

• Performance continuously validated with online simulation
  - Achieved an agreement level between simulation and hardware of better than 99%!

• Upgraded L1Topo system in Run-3 will allow higher complexity in topological algorithms
  - Parallel commissioning with the new upgraded L1Calo and L1Muon systems