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

Sara Alderweireldt (CERN) on behalf of the ATLAS Collaboration

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The ATLAS Trigger System

The LHC delivers proton–proton collisions at a rate of 40 Mhz. The Level-1 hardware trigger (L1), using calorimeter and muon inputs, makes decisions within 2.5 µs after events occur, and reduces the rate to 100 kHz for input to the High-Level trigger (HLT). Further processing in this second, software-based layer results in a final event recording rate of 1 kHz on average.

In Run-2, the Level-1 Topological processor (L1Topo) was added to the L1 system, providing algorithms using kinematic and angular restrictions, and significantly improving the background event rejection rate and acceptance for physics signals.

Run-2 Hardware

The L1 Topological Processor trigger system combines inputs from the L1Calo and L1Muon systems. Decisions are based on topological algorithms, applying kinematic and angular requirements on electromagnetic clusters, hadronic jets, muons or total reconstructed energy. The system combines high input bandwidth, and low latency.

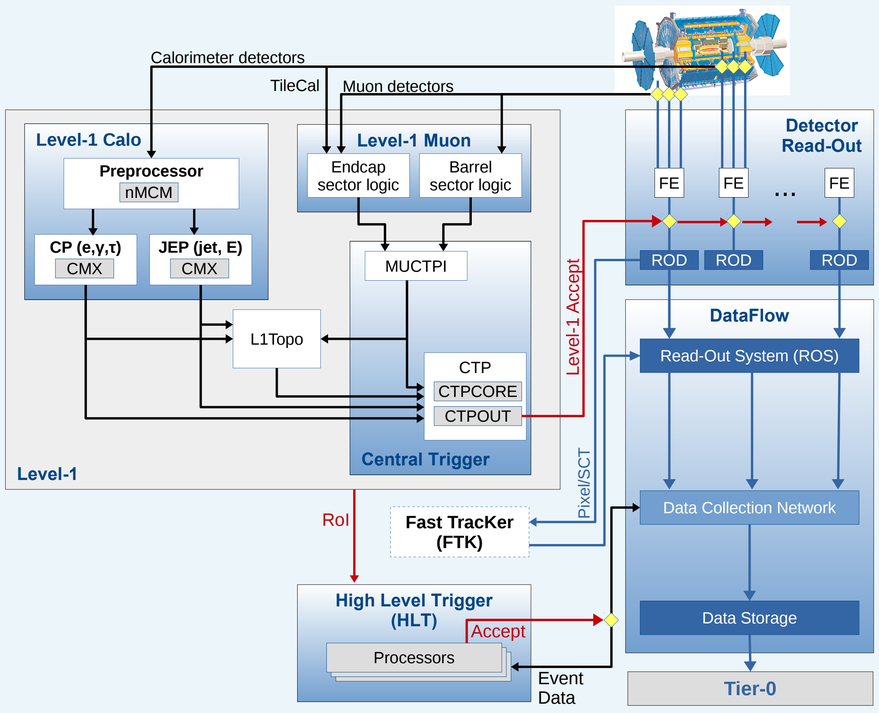

Figure 1: Schematic of the ATLAS Trigger and Data Acquisition system in Run-2 [1].

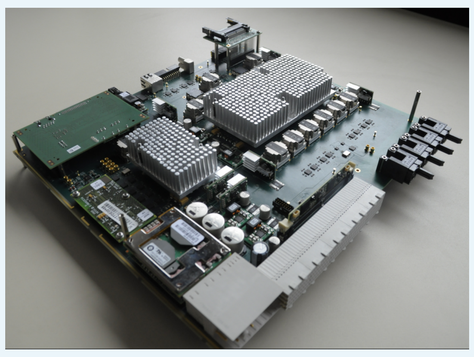

Figure 2: Level-1 Topological Processor board for Run-2 [2].

During Run-2 two identical boards were commissioned, each including:

- 2 Virtex 7 FPGAs for algorithm processing
- 1 Kintex 7 FPGA for module control & readout

A total of 128 decision bits are available, of which 113 were used in 2018.

A bitwise simulation of the algorithms is set up within the HLT system, running for each L1 accepted event.

Toplogical algorithms include:

- angular algorithms: $\Delta\phi$, $\Delta\eta$, ΔR, disambiguation, …
- mass selections: invariant, transverse
- event selection: event hardness, missing transverse energy corrections
- combined L1Calo + L1Muon information
- information from objects from different bunch crossings

Perspectives for Run-3 Hardware

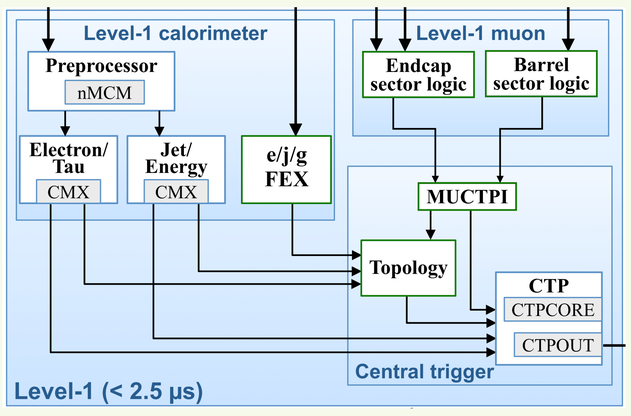

Figure 3: Evolution of the ATLAS Trigger and Data Acquisition system towards Run-3 [3].

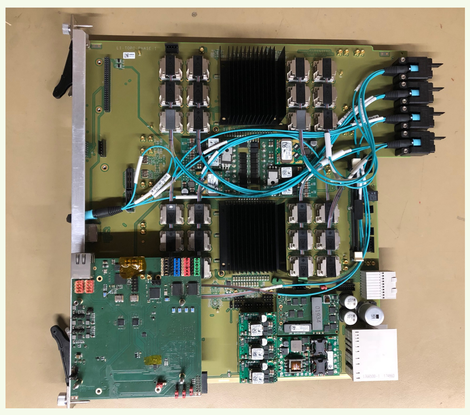

Figure 4: Run-3 Level-1 Topological Processor board prototype [3].

Updates for both the L1Calo and L1Muon systems are foreseen for Run-3:

- the old L1Calo system will be replaced by three Feature Extraction (FEX) systems (electron/jet/global), providing higher granularity calorimeter towers
- in the L1Muon system the endcap & barrel sector logic will be enhanced and a new MuCTPi will provide increased bandwidth towards L1Topo and CTP

The new L1Topo system will consist of three boards, each including:

- 2 Xilinx UltraScale+ FPGAs for algorithm computation & processing
- 118 input / 24 output fibres per FPGA

To assure stable physics data taking at the start of Run-3 (2021), the new system will run in parallel with the legacy Run-2 system during the commissioning phase. The new L1Topo system will also run multiplicity triggers in addition to topological ones.

Validation

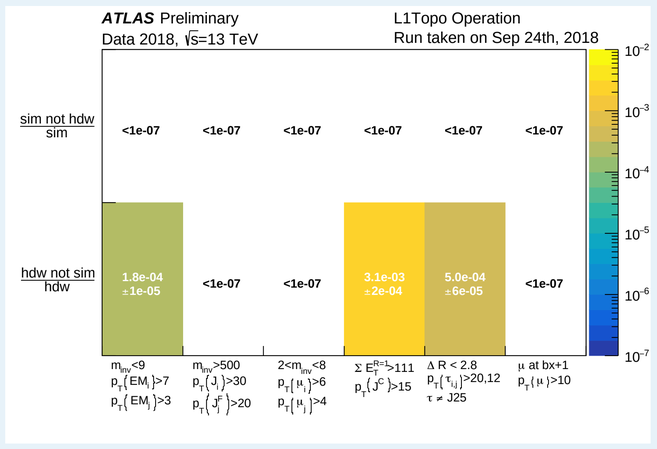

Figure 5: Mismatch rates between L1Topo hardware and simulation [1].

Multiple levels of validation are in place:

- Standalone VHDL simulation of the algorithms
- Full bitwise simulation of each algorithm, running standalone and at HLT level
- Hardware vs. simulation comparisons online and for recorded events

Figure 5 shows the mismatch rates between L1Topo hardware and simulation for a subset of algorithms. The first row indicates the false negatives, while the second row indicates the false positives. *All algorithms used for physics show agreement better than 99%.*

Performance

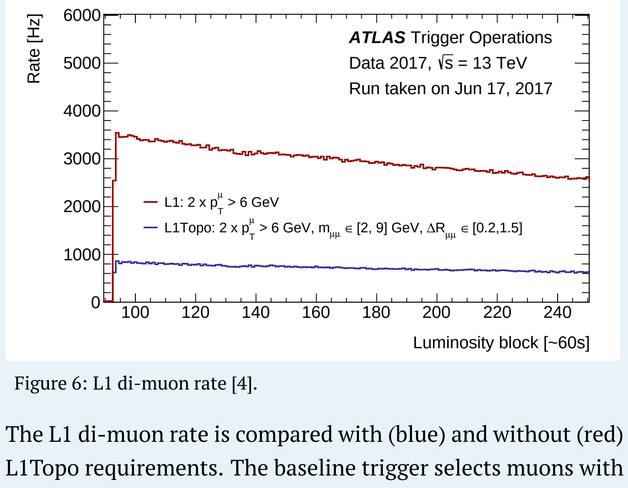

Figure 6: L1 di-muon rate [4].

The L1 di-muon rate is compared with (blue) and without (red) L1Topo requirements. The baseline trigger selects muons with transverse momenta larger than 6 GeV, while the topological trigger selects invariant masses of the di-muon pair between 2 and 9 GeV, combined with an angular separation $\Delta R \in [0.2, 1.5]$.

A large rate reduction without any significant loss in efficiency opens up a lot of possibilities in the area of B-physics

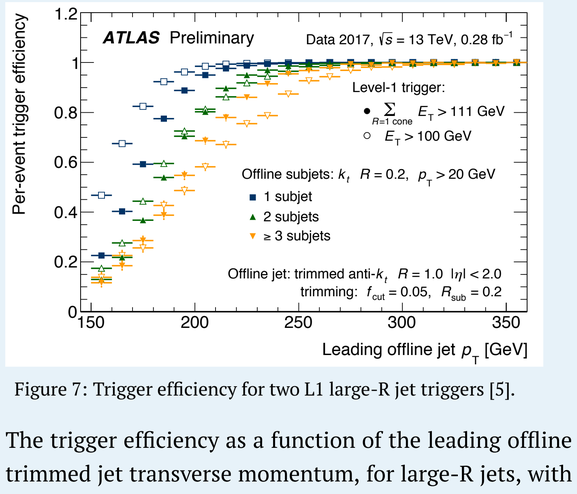

Figure 7: Trigger efficiency for two L1 large-R jet triggers [5].

The trigger efficiency as a function of the leading offline trimmed jet transverse momentum, for large-R jets, with different numbers of subjets, is compared for regular and L1Topo algorithms. The baseline L1 trigger requires $E_T > 100$ GeV in a $\Delta\eta \times \Delta\phi$ window of 0.8×0.8, while the topological algorithm requires $\sum E_T > 111$ GeV within a cone of radius 1.0. The 111 GeV threshold is chosen to give equal rate performance.

For jets with large numbers of subjets, the topological Level-1 trigger recovers efficiency with respect to the sliding-window algorithm.

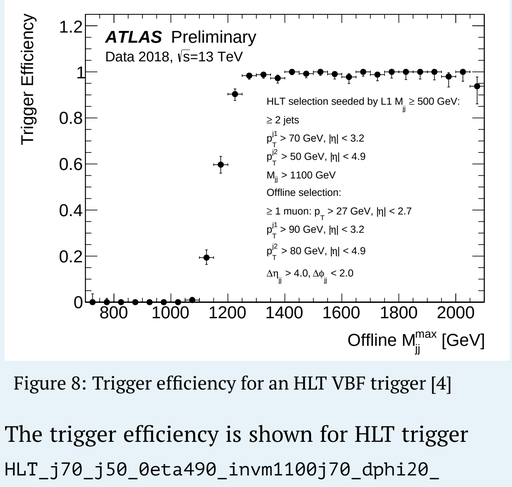

Figure 8: Trigger efficiency for an HLT VBF trigger [4]

The trigger efficiency is shown for HLT trigger `HLT_j70_j50_0eta490_invm1100j70_dphi20_deta40_L1MJJ-500-NFF` as a function of offline maximum dijet mass.

Dedicated triggers such as this, combining signature specific selections on for example invariant mass and angles, are increasingly important for the study of difficult signatures such as VBF Higgs.

Highlights

- The **ATLAS Level-1 Topological Processor** system was successfully commissioned and operated during Run-2
  - combining L1Calo & L1Muon inputs
  - allowing kinematic and angular selections
- Hardware performance is well-understood following thorough **validation**, with hardware vs. simulation agreement better than 99% for triggers used for physics
- L1Topo has an important impact on **performance** by lowering rate as well as increasing acceptance for various physics channels
  - especially at low transverse momentum or small invariant mass
  - even more important for Run-3
- **Phase-I upgrades**, including a new L1Topo system, are moving from design to production and commissioning in time for Run-3

[1] DAQ Public Results – https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ApprovedPlotsDAQ
[2] The ATLAS Level-1 Topological Processor: from design to routine usage in Run-2 – https://cds.cern.ch/record/2649959
[3] Technical Design Report for the Phase-I Upgrade of the ATLAS TDAQ System, CERN-LHCC-2013-018 – http://cds.cern.ch/record/1602235
[4] Trigger Operation Public Results – https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TriggerOperationPublicResults
[5] Jet Trigger Public Results – https://twiki.cern.ch/twiki/bin/view/AtlasPublic/JetTriggerPublicResults