The ATLAS Trigger System: Past, Present and Future

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Valencia, July 3rd 2014
Prelude: LHC growing performance

LHC upgrades to: extend physics potential and respond to radiation damage
LHC design parameters will be reached after long shutdown one (LS1). The upgrades for Run2 present an important stepping stone
LHC experiments must enhance their physics performance as well
Expected (dirty) environment for Run2…

Z→μμ event from 2012 data with 25 reconstructed vertices

- LHC energy increase from 7/8 to 13 TeV: x2-4 production cross-sections for EW processes (W, Z, H)
- Higher peak luminosity by increasing the number of interactions per p-p bunch collision
  - higher density of interactions in space and time, and detectors occupancy
- Smaller bunch spacing (25 ns): smaller in-time pile-up (same bunch), increased out-of-time pile-up (close bunches)

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<tr>
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<th>Energy</th>
<th>Luminosity [cm⁻²s⁻¹]</th>
<th>peak pile-up</th>
<th>bunch spacing</th>
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<tr>
<td>Run1</td>
<td>7 TeV</td>
<td>7x10³³</td>
<td>40</td>
<td>50 ns</td>
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<td>Run2</td>
<td>13 TeV</td>
<td>2x10³⁴</td>
<td>~55</td>
<td>25 ns</td>
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ATLAS: past, present & future

1964

Peter Higgs 1964

2013

~2030
ATLAS physics interest

- ATLAS priorities are the precision measurements of the Higgs boson parameters and the extended search of New Physics (NP)

- Higgs mass at 125 GeV opens access to many Higgs decay channels, and then to the measurements of its coupling constants

- Investigate EW energy scale, open towards NP
  - Higgs studies: with leptons at relatively low momentum and increased importance of final states with forward jets and taus
  - Extend SUSY parameter space: with soft leptons, missing $E_T$ or $b$-quarks
  - Other exotic scenarios: with either very energetic signatures or multi-body decays

Main Higgs decay channels

Extension of SUSY parameter space
ATLAS physics interest

- ATLAS priorities are the precision measurement of the Higgs boson parameters and the extended search for New Physics (NP).

- Higgs mass at 125 GeV opens access to many decay channels, and then to the measurement of coupling constants.

- ATLAS Run1 to Run2 Trigger Inc.
  
  Updated Trigger hardware and software

- Main Higgs decay channels

- Other exotic scenarios: with either very energetic signatures or multi-body decays

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The ATLAS trigger system

- Selects a few hundred events/s for permanent storage, discarding online low-momentum-transfer interactions

**ATLAS Run1:**
20 MHz -> 700 Hz: rejection factor 30,000

**First-level trigger (L1)**
- Synchronous at 40MHz, with fixed latency: **2.5 μs**
- Identifies Region-of-Interest (RoI) in the muon spectrometer and/or in the calorimeter, with coarse resolution
- No tracking information can be used due to limited latency

**High-level trigger (HLT)**
- Handles complexity with custom fast software on commercial CPUs
- Accessing the full resolution of all the detectors
- Accessing both partial event (Level-2 RoIs) and full event (Event Filter)

Event display of a 2-tau event in the ATLAS detector. Run number: 204153, Event number: 35369265. The taus decay into an electron (blue line) and a muon (red line).
Run1 trigger performance

Great success of the ATLAS trigger system

**ATLAS Trigger Operation 2012**

- Jets/missing $E_T$ (delayed)
- B-physics (delayed)
- Minimum Bias
- Electrons/photons
- Jets/taus/missing $E_T$
- Muons/B-physics

**Efficiency wrt offline** ~86 (70)% in endcap (barrel); robust against pileup

**Electrons**

- Efficiency wrt offline ~95 % at plateau, with track isolation

**Muons**

- Efficiency wrt offline ~86 (70)% in endcap (barrel); robust against pileup

**Jets**

- Large variety of triggers e.g. for various sizes of jets down to ~15 GeV

**Missing Energy**

- Optimized algorithms against in-time and out-of-time pileup
**ATLAS trigger/DAQ architecture in Run1**

- **Event rates design (2012 peak)**
  - 40 MHz (20 MHz)
  - <2.5 μs
  - 75 kHz (~65 kHz)
  - ~40 ms (~100 ms)
  - 3 kHz (~6.5 kHz)
  - ~4 s (~1 s)
  - ~200 Hz (~1000 Hz)

- **Trigger**
  - Level 1
    - Custom Hardware
    - Level 1 Accept
  - Level 2
    - Processing Unit
    - Roi fragments
    - L2 Accept

- **ROC data access**
- **Network speed**
- **Storage budget**

- **ATLAS Event**
  - 1.5 MB/25 ns (1.6 MB/50ns)
  - ~110 GB/s (~105 GB/s)
  - ~4.5 GB/s (~10.5 GB/s)
  - ~300 MB/s (~1600 MB/s)

- **Data Collection Network**
- **Event Builder**
- **Data Logger**

- **Successful at and beyond design values during Run1**
- **Bottlenecks** do not scale well with Run2 specifications and need to be overcome
A new architecture is needed for Run2

- Limited evolution of the TDAQ since its conception (late 90s): only rolling replacements of commodity hardware and no changes to L1 custom electronics
- **Run2**: move to a system more scalable/resilient/maintainable exploiting new technologies

- **New DAQ architecture**: better traffic sharing and more scalable design
  - Upgrade Readout System (ROS)
  - New network architecture
  - *see W. Panduro Vazquez’s talk at this Conference*

- **New HLT architecture**: merged L2 and EF levels into one processing unit (matching the network evolution)
  - Unlimited memory transfer allows tighter coupling and reduces CPU/network use
  - Flexible event building depending on trigger request
  - Opportunity for re-optimization of algorithms

- **Storage resources**: further rationalisation of computing resources to allow running with 1 kHz HLT output rate
Run2 TDAQ architecture

- Increased rates
- Merged HLT
- Increase Readout bandwidth
- Increase HLT rate (1 kHz)
- Unified network

L1 output limit will be decided by detector occupancy
New architecture tested successfully
The trigger challenge towards Run2

- Reduce trigger inefficiency at high pile-up
- Add safety margins on top of predictions


2012 triggering already improved to mitigate against pile-up

- Increased fake rate
  - High radiation in the forward regions
  - Jets mimicking electrons (helped by isolation)
- Reduced rejection power of the algorithms
  - Worse resolution in calorimeters
  - Less effective isolation and pattern recognition

L1 single electron with and without isolation

Tighter MET L1 noise thresholds

L2 and EF tracking efficiencies (for electron $E_T > 15$ GeV)

三文魚 - IHEP 2014, Valencia (Spain)
The trigger strategy for Run2

- Ensure that trigger works efficiently and with full physics coverage
  - Strategy still under development

- Maintain sensitivity to Electroweak scale with
  - Inclusive single leptons (electrons, muons)
    - Similar electrons and muons share (L1 < 25 kHz each) with moderate energy thresholds
  - Exclusive / multi-object triggers
  - Increased importance of tau and hadronic (MET) triggers

- While rates increase x2 (Energy) x2-3 (Luminosity): at least x5 increase of first-level trigger rates
  - larger increase for jets (due to higher $p_T$)
  - lower for muons (dominated by fakes)

- Run1 trigger strategy does not scale to new conditions
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Improve the trigger performance!

not all the predictions of the various upgrades are included in the table

$H$=Hadronic isolation
$l$= EM isolation
$V$=eta dependent thresholds

Simply scaling Run1 L1 menu to the new conditions, L1 rate would be over limit ($E_{cm}$=14TeV, L=3x10^{34}cm^{-2}s^{-1})
L1 Muon trigger

- Rate of L1 single-muon triggers ($p_T > 20$ GeV/c) ~30 kHz
- Background mainly from:
  - slow turn-on curve $\geq 20$ GeV
  - late triggers from low energy protons in the forward regions (out-of-time pileup)

For Run2

- Increase ~3% trigger coverage in the barrel (70%) completing installation in the holes of the toroid structure
- Reduce the dominant rates in the forward regions with:
  - additional coincidence chambers upstream of the toroids
  - and/or additional coincidence with the outer-most layer of the Tile Calorimeter
  - and/or excluding the low field regions (< 5% acceptance loss)

Run3 plans:
add new (trigger) detectors in the inner forward region (NSW project)
L1 Calorimeter trigger

**Plans for Run2:** EM L1 rate (30 GeV, 38 GeV offline) ~14 kHz, increase efficiency for Missing Energy and multi-jet, reducing rates by more x5

- Improving energy scale and resolution with first-order pedestal shifts based on global cell occupancy and in-bunch-train position
  - crucial for Missing Energy thresholds distorted by the out-of-time pile-up
- See poster on electron/photon trigger by Alexey Ezhilov

**With limited upgrades of the electronics**

- new FADCs to provide faster digitisation with low noise
- change from ASIC to FPGA technology to increase flexibility and implement digital filters and BCID algorithms
- exploit full bandwidth to increase output details (fast optical links and x4 in crates)

**Run3 plans:**
full replacement of the L1 electronics with Front-End digitisation and increased cell resolution
Combining signatures at L1 in Run2

L1-Topological processor (ATL-DAQ-PROC-2012-041)

- Combine electron/photon, muon, tau, jets and Emiss
- Calculate angles, invariant masses, … with algorithms implemented in FPGA, 100 kHz output results (no objects)

Physics cases:
- Dominant backgrounds from di-jet reduced with angular cuts
- Muon+jet: pass-through jets or improved b-tagging with soft muons
  - $b(b)H/A \rightarrow b(b)bb$ rate reduced x5 (33% efficiency loss), x2 significance
- Exclusive requirements made anyway in the physics analyses

Latency = 100 ns
Bandwidth = 1 Tbps

ATCA technology

ZH → νν bb: Δφ between L1 MET and central jets

H → tau tau in VBF process, Δη

ATLAS Simulation

| $\mathbf{s} = 14 \text{ TeV}$ |

- VBF $H \rightarrow \tau_1 \tau_2$
- $Z \rightarrow \tau_1 \tau_2$
- Minimum Bias

Events with at least two L1 central jets

Events per 0.07°
Higher performance of clustering and tracking algorithms with offline(-like) algorithms

- better resolution, to raise the thresholds
- use more event-level quantities, for pile-up suppression
- avoid unnecessary inefficiency introduced by different online-offline criteria (and apply closer thresholds)

Challenge: improve **timing performance**, while the number of combinations increase

Calorimeter clustering algorithms: improve resolution and restore the calorimeter response

- Calculate median $p_T$ density (removing the hard physics) to **measure pile-up activity event-by-event and jet-by-jet**
- Maximal efficiency if made for each hadronically-triggered event: requires full calorimeter read-out $>20$ kHz (ROS upgrade)
- Request of CPU resources for the **topological clustering** (iterative event-level jet-finding algorithms) and calibration close to offline

**See talk on jet trigger by Susan Cheatham**

- Increased MET resolution using topological cluster algorithm *(already in Run1)*

\[
\int L dt \approx 275 \text{ pb}^{-1} \quad \sqrt{s} = 8 \text{ TeV}
\]
Tracking trigger as early as possible

**HLT software tracking**: speed-up the algorithms
- merged L2+EF system allows reuse of tracklet results
- next: use GPUs

**Fast TracKer (FTK)**: Level-1.5 hardware processor for full silicon tracking at L1 output rate (100 kHz)
- reduce timing required for software tracking
- selection more closely matched to offline
- provides primary vertex position and multiplicity

**FTK resolution**
- very close to offline
- See poster by Daniele Madaffari at this conference

**FTK: steeper turn-on for tau selection**
- See poster by Takashi Mitani at this conference

**Run4 plans:**
- use of tracking trigger at limited latency Level-1 trigger (see talk by A. De Santo at this conference)
Conclusions

- ATLAS trigger system is **being prepared** to improve successful performance of Run1 and meet the challenges of Run2, starting by the end of this year.
- The main skeleton will be **enriched** with more sophisticated/flexible algorithms, in hardware and software:
  - L1 topology, pile-up corrections/robustness, fast tracking
  - Complex trigger menu and optimized algorithms
  - Homogeneous architecture (one HLT farm)
  - Redesign trigger tools to support physics analyses
- For **example**, expected during Run2:
  - $H \rightarrow \tau\tau$ increase 22–28% event yield
  - $ZH \rightarrow \nu\nu bb$ improved 30–40% rejection of di-jets
- **Thanks to the great effort of hundreds people involved during LS1**
  - Prototyping and development on-going
  - Leave time for careful validation before restart
- **...following the road-map for future LHC expansions**
  - Preparation to Run3 upgrade has already started, mainly for L1 systems (New Small Wheel detectors for muons and brand new electronics for almost all the calorimeter).
References

- ATLAS TDAQ Phase-1 Technical Design Report
- ATLAS TDAQ Phase-2 Letter of Intent
- ATLAS FTK Technical Designing Report
- ATLAS Public Result twiki
Backup slides
LHC schedule beyond LS1

LS2: starting in 2018 (July) => 18 months + 3 months BC
LS3: LHC: starting in 2023 => 30 months + 3 months BC
Injectors: in 2024 => 13 months + 3 months BC

30 fb⁻¹

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300 fb⁻¹

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(Extended) Year End Technical Stop: (E)YETS

3'000 fb⁻¹

LHC schedule approved by CERN management and LHC experiments spokespersons and technical coordinators (December 2013)
Phases of the trigger evolution

- **Phase-0 (Run2):** be prepared for $L = 10^{34}/\text{cm}^2/\text{s}$ (PU~25)
  - Complete detector & consolidate operations
  - Allow L1 topological criteria / more exclusive selections

- **Phase-1 (Run3):** be prepared for $L = 3\times10^{34}/\text{cm}^2/\text{s}$ (PU~40)
  - Add more flexibility, without major architectural changes:
    - Additional coincidence layers in the forward muon spectrometer
    - Increased granularity in the calorimeter

- **Phase-2 (Run4):** be prepared for $L = 5\times10^{34}/\text{cm}^2/\text{s}$ (PU~140)
  - Major upgrade for HL-LHC era: ensure appropriate rejection
  - Expected L1 rates over the limit allowed by detector FE
  - A new tracker will be available…

Any component installed in Phase-I must be fully operational also through Phase-II

2013

2018

2022