ATLAS Trigger: design and commissioning

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ICCMSE Symposium: Computing in Experimental High Energy Physics
September 29th - October 4th 2009  Rhodes, Greece
Outline of the talk

- Motivations
- Trigger architecture
- Trigger performance
- Commissioning with cosmic rays and first beams
- Trigger strategies and preparation for first collisions
The ATLAS detector @ LHC

- LHC design parameters: $\sqrt{s} = \SI{14}{TeV}$ and $L = \SI{10^{34}}{cm^{-2} s^{-1}}$
- Providing $100 \text{ fb}^{-1}$/year
- Initially running at $7 \text{ TeV}$, rising towards $10 \text{ TeV}$, and much lower luminosity
- Bunch-crossing rate $40 \text{ MHz}$ ($25 \text{ ns}$ bunch spacing)
- Only $80\%$ of bunched will be filled, effective bunch-crossing rate $32 \text{ MHz}$

ATLAS is a general-purpose detector to explore SM physics and beyond
**Trigger motivations**

- Total non-diffractive pp cross section at $\sqrt{s}=14$ TeV is $\sim 70$ mb
  - Collision rate: $L \times \sigma = O(10^9)$ Hz

- Huge range of cross-sections and production rates (example with design L)
  - Beauty (0.7 mb) $\sim 10^3$ Hz
  - W/Z (200/60 nb) $\sim 100$ Hz
  - Top (0.8 nb) $\sim 10$ Hz
  - Higgs - 150 GeV (30 pb) $\sim 0.1$ Hz

- The output rate is limited by the offline computing budget and storage capacity
  - Only a small fraction of production rate can be used in the analysis

*Trigger must reduce event rates from GHz to $\sim 200$ Hz*
Average 23 interaction per Bunch Crossing at L=$10^{34}$ cm$^{-2}$ s$^{-1}$

- Pile-up of interactions in the event
- Simulated H $\rightarrow$ 4$\mu$ event + 17 minimum-bias events
### Trigger signatures

<table>
<thead>
<tr>
<th>Object</th>
<th>Physics Measurements Examples</th>
<th>Trigger Chains</th>
</tr>
</thead>
<tbody>
<tr>
<td>electrons</td>
<td>Higgs, new gauge bosons, extra dim, SUSY, W, top</td>
<td>e25i, 2e15i</td>
</tr>
<tr>
<td>photons</td>
<td>Higgs, extra dim, SUSY</td>
<td>γ60i, 2γ20i</td>
</tr>
<tr>
<td>muons</td>
<td>Higgs, new gauge bosons, extra dim, SUSY, W, top</td>
<td>μ20i, 2μ10</td>
</tr>
<tr>
<td>jets</td>
<td>SUSY, compositeness, resonances</td>
<td>j400, 3j165, 4j110</td>
</tr>
<tr>
<td>jet+missing $E_T$</td>
<td>SUSY, leptoquarks</td>
<td>j70 + xE70</td>
</tr>
<tr>
<td>tau+missing $E_T$</td>
<td>Extended Higgs models, SUSY</td>
<td>τ35 + xE45</td>
</tr>
</tbody>
</table>

- Selection is based on **inclusive high-$p_T$** signatures, with low multiplicity (single/di-objects)
- SM physics overlap with Tevatron and sensitive to un/predicted New Physics
- Allow reasonable safety factors to account for physics (cross-sections, cavern background....) and detector-performance uncertainties
- Must include triggers for **monitoring and calibration/energy scale determination**
  - Instrumental and physics backgrounds not completely known
  - Detector and trigger efficiency from data

**Table Examples**

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To reduce the dataflow requirements, ATLAS chose a three-level trigger architecture, exploiting the “region-of-interest” (RoI) approach.

- Complex dataflow architecture based on local readout buffers.

- Redundancy of selection criteria leads to high trigger efficiency and the possibility to measure it from the data.

- Use of “Trigger Menus”.

- Must be sufficiently flexible to face possible variations of LHC luminosity.

- Pile-up: event characteristics vary with luminosity and bunch structure, since the number of pp interactions per bunch-crossing varies.
Level-1 system

Requirements

- Rate reduction of $10^4$ (100 kHz output)
- Trigger decision identifies uniquely the Bunch Crossing (25 ns)
  - Logic decisions by custom hardware
  - Data held in pipelines, with a fixed latency (max 2.5 µs)
  - Fast detector response and data movement

- Identifies physics objects from Calorimeters and Muon detectors with coarse granularity
  - EM, τ, jet, μ, $\Sigma E_T$, $E_T^{miss}$
  - Based on $E_T$, $p_T$ (thresholds) and isolation criteria

Central Trigger Processor

- Maximum 256 trigger items, combinations of one or more trigger inputs, can be deployed at any time
- Different pre-scale factors can be applied on each item to tune rates as luminosity varies during a fill
  - Most important items are never pre-scaled
High Level Trigger selection

Inclusive trigger
- Confirm L1, inclusive and semi-incl., simple topology, vertex rec.

Confirm L2, more refined topology selection, near offline

Goal: Reduce decision latency and network traffic
- Seeded reconstruction and early rejection
- Alternate steps of feature extraction with hypothesis testing: events can be rejected at any step with a complex algorithm scheduling

 Regions of Interest at Level-2
- Custom algorithms (optimized for timing performance) selectively access and analyze data from the regions selected by L1 (2% of the event size)
- The average number of RoIs per event is ~1.6

- Level-2 and Event Filter (HLT) software trigger
- Same selection infrastructure, implemented on Linux PC farms
- Full granularity detector data, including tracking systems
Muon trigger design

- Dedicate trigger detectors (TGC and RPC) with optimal timing resolution
- Strong rejection of fake muons (induced by noise and physics background) using algorithms on 2 views (air-toroid structure)
- Requirement for cosmic-ray and beam-halo triggers included in the design
- Wide $p_T$-threshold range to allow B-physics studies
- Most significant contribution to L1 rate is given by low-$p_T$ muons ($<3.5\,\text{GeV}$)
- HLT uses combined tracks in the Muon Spectrometer and the Inner detectors and isolation criteria based on energy deposit in the calorimeters

RPC time resolution $\sigma=1.9\,\text{ns}$

Inclusive $\mu$ cross-section @ LHC (prompt $\mu$ and $\pi/K$ decay)
Calorimeter trigger design

- e, γ, τ, jets, $E_T\text{miss}/\Sigma E_T$
- Various combinations of cluster sums and isolation criteria
- Level-1
  - Peak finder for BC identification
  - $E_T$ conversion using LUT: 8-bit $E_T$, linear up to 255 GeV
  - Sliding-window technique to find clusters
  - Dedicated processors apply the algorithms, using programmable $E_T$ thresholds
- High-Level trigger
  - More topological variables and tracking information for electrons from Inner Detectors
  - Isolation criteria can be imposed to control the rate (reducing jet background at low energies thresholds)

Level-1 clustering algorithm

- ~7200 projective trigger towers: $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$
- Acceptance coverage: $|\eta|=4.9$ (FCAL)
Trigger efficiency is calculated on samples of simulated signal events, with respect to the offline reconstruction. Described by turn-on curves whose sharpness is related to the finite $p_T/E_T$ resolution. Efficiency dependency on $p_T/E_T$ and pseudo-rapidity ($\eta$) must be minimized.

**Expected trigger performance**

- **e10 trigger efficiency as a function of $E_T$ and $\eta$**

L1 effective threshold (95% efficient by design)
Trigger efficiency measurement from data

- “Tag and Probe” method used where possible
- Clean signal sample (Z, J/ψ to leptons)
- Select track that triggered the event (Tag)
- Find the other offline track (Probe)
- Apply trigger selection on Probe

The systematic uncertainties of the method are compared with Montecarlo

Needs deep studies on background contamination to double-lepton sources

Muon trigger efficiency (with 1 fb⁻¹)

Fractional efficiency difference w.r.t. MC truth
Commissioning of the trigger

Many competing demands on trigger for early running
- Commissioning of Level-1 trigger and HLT
- Detector commissioning
- Timing-in of the detectors (readout and trigger)
- Commissioning of Tier-0 (reconstruction)
- Provide calibration and alignment samples
- Provide samples for initial physics studies

Cosmic-rays runs and first experience with beams in September 2008
- Timing-in and energy calibration of the L1 trigger
- Test of HLT algorithms and architecture

LHC start-up luminosity (up to to $10^{31} \text{ cm}^2 \text{ s}^{-1}$)
- Trigger and detector commissioning
- Standard Model processes
- Selection strategy focused on
  - Low thresholds and loose selection criteria
  - HLT algorithms in pass-through mode (only at the very beginning)
Status of the trigger architecture

- **Level-1 trigger**
  - Tested in readout up to 80 kHz
  - Timing-in in progress

- **High-Level triggers**
  - 850 HLT nodes (35% final system) tested at 60 kHz
  - Finalization of the system will be luminosity driven
    - Expected: 500 Level-2 nodes + 1800 Event-Filter nodes
      (8 cores @ 2.5 GHz, 2 GB Memory/node)
  - Stress-test system with $10^{31} \text{ cm}^{-2} \text{s}^{-1}$ trigger menu during Technical Runs
    - Simulated raw data preloaded into the readout systems and played back through the HLT/DAQ system

- **DAQ routinely running since 2008**
  - All ROS PCs installed and working
  - Dataflow networking infrastructure fully in place
  - Local storage farm (SFO) of 5 nodes with a total storage area of 50 TB
On September 10th 2008 first LHC beams reached ATLAS detector
- Single beams initially with no RF
- Series of splash events generated by dumping beams on closed collimators 140m from ATLAS
- Then circulating beams

ATLAS was ready
- All the trigger infrastructure was running (HLT available)
- Crucial test for the L1 trigger
  - Test of triggers dedicated to detect the beams
  - Time alignment
Detecting beams

- Provides a filled-bunch trigger
- Monitor the beam activity
  - Identifies the bunches in the beams
  - Measures their individual intensity and phase relative to the LHC clock, assigning the Bunch crossing
- Monitor of timing signals

**Beam Pick-up Timing Experiment (BPTX)**

**Tertiary Collimators**

175 m

140 m

**LUCID, a Cherenkov Luminosity monitoring**

**Minimum Bias Trigger Scintillators**
Oscilloscope traces of discriminated signals during an injection of 1 bunch without RF capture

- The bunch circulated a few times
  - After 7 turns its intensity falls below the threshold of the BPTX discriminator.
  - The first few turns give only small activity in the MBTS, while after 3 or 4 turns they show saturated signals
The first event – triggered with cosmic settings
Some LHC events

Beam-halo events are important for End-cap calibrations
Exploiting the excellent timing of BPTX and MBTS, much progress on timing set-up over two days

- With circulating beams BPTX was pre-scaled and trigger relied on combinations with MBTS and calorimeter
- Detectors worked on adjusting readout timing in parallel

With single beam, downstream timing similar to that for collisions
L1 timing-in is going on with cosmic events,
Precise timing adjustment will need collision data

**Timing distribution of L1 triggers from the first and third days of single-beam data.**
Reference triggers have BC=0 (note change of scale and log vertical scale)
L1 trigger commissioning

**Splash event:** the colors are proportional to the transverse energy deposited in each trigger tower.

- Cosmic rays used to check timing and calibrate $E_T$ and $p_T$ thresholds (or validate procedure done with pulses and sources).

**Energy map**

**RPC timing alignment:**

- RMS = 5.5 ns

**TGC:** more than 99% of the triggers within the correct BC

- 0.70%
- 99.14%
- 0.16%

**Cosmic $E_T$ spectrum:** large tail of higher energies mainly due to large showers
HLT performance with cosmic rays

- More than 200 trigger items tested online
- Level-2 processing time is compatible with the design (40 ms)
- The HLT acceptance/rejection is consistent with offline running

- Shower shape used for electron and photon selections
- Muon isolation variable based on the Inner Detector (ID)

L2 tracking efficiency

ATLAS preliminary

Event Filter
Level-2
Cosmic ray run 2008

ATLAS preliminary

ATLAS Preliminary
2008 Cosmic-Ray data

Level 2 Trigger
Inner Detector Based Muon Isolation

ISO = p_T^/p_T^{R=0.2}
Trigger rates allocation

- Target is Event Filter output rate = 200 Hz
- Trigger rate allocation on each trigger item based on
  - Physics goals (plus calibration, monitoring samples)
  - Required efficiency and background rejection
  - Bandwidth consumed

- Trigger rates are calculated from large samples of simulated data, including large cross-section backgrounds (minimum-bias and QCD)
  - Large samples of background events are required (7 million non-diffractive events @ 70mb used as minimum-bias sample for $10^{31}$ cm$^{-2}$ s$^{-1}$ menu)

\[
R_i = \mathbb{L} \int_{p_T - \text{inf}}^{p_T - \text{cutoff}} \frac{d\sigma_i}{dp_T} \epsilon(p_T) d\epsilon
\]

- Given by convolution, over a given $E_T/p_T$ range, of the estimated efficiency with the cross sections representing the main trigger source

- Large uncertainties due to detector response and jet cross-sections
  - To be tuned with early data
Expected trigger rates @ start-up $L=10^{31} \text{ cm}^{-2} \text{ s}^{-1}$

Muon trigger
- Selection based on muon spectrometer only
- Largest source of muons are from b/c quarks and $\pi/K$ in-flight decay

**EF single muon trigger rate at start-up**

Calorimeter trigger

**Single e/$\gamma$ L1 rates at start-up**

Open = non-isolated
Closed = isolated

For E/p and jet calibration, the trigger has to guarantee SM channels as $W$, $J/\psi$, Drell-Yan, direct-$\gamma$ production.
Running strategy

- At start-up $L=10^{31} \text{ cm}^{-2} \text{ s}^{-1}$
  - L1: low $p_T$ thresholds and loose selection criteria (adding pre-scales to control rates)
  - L1: deploy high thresholds and multi-objects triggers for validation (to be used as back-up triggers)
  - HLT: running in pass-through mode for offline validation or with low thresholds
- As LHC luminosity reaches the design, complex signatures and higher $p_T$ thresholds will be necessary to reach the physics goals

Start-up trigger Menu contains ~130 Level-1 items and ~180 HLT selection chains
- $e/\gamma$ and muon triggers are unprescaled, except EM3

<table>
<thead>
<tr>
<th>Object</th>
<th>L1 (Hz)</th>
<th>L2 (Hz)</th>
<th>EF (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single-electrons</td>
<td>5580</td>
<td>176</td>
<td>27.3</td>
</tr>
<tr>
<td>Multi-electrons</td>
<td>6490</td>
<td>41.1</td>
<td>6.9</td>
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<tr>
<td>Multi-photons</td>
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<td>2.9</td>
<td>&lt; 0.1</td>
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<tr>
<td>Single-photons</td>
<td>common</td>
<td>33.4</td>
<td>9.1</td>
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<tr>
<td>Multi-Jets</td>
<td>221</td>
<td>7.9</td>
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<tr>
<td>Single-Jets</td>
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<tr>
<td>Multi-Fjets</td>
<td>2.7</td>
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<td>Single-Fjets</td>
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<td>12.9</td>
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<tr>
<td>Single-bjets</td>
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<td>11.6</td>
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<tr>
<td>Multi-taus</td>
<td>465</td>
<td>14.5</td>
<td>12.4</td>
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<tr>
<td>Single-taus</td>
<td>148</td>
<td>32.9</td>
<td>22.3</td>
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<tr>
<td>Multi-muons</td>
<td>68.6</td>
<td>5.8</td>
<td>2.3</td>
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<tr>
<td>Single-muons</td>
<td>1730</td>
<td>204</td>
<td>21.8</td>
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<tr>
<td>Missing $E_T$</td>
<td>37.9</td>
<td>31.</td>
<td>3.8</td>
</tr>
<tr>
<td>Total $E_T$</td>
<td>6.3</td>
<td>6.3</td>
<td>1</td>
</tr>
<tr>
<td>Total Jet $E_T$</td>
<td>1.6</td>
<td>1.6</td>
<td>1.6</td>
</tr>
<tr>
<td>BPhysics</td>
<td>common</td>
<td>25</td>
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<tr>
<td>Multi-Object</td>
<td>5890</td>
<td>134</td>
<td>48</td>
</tr>
<tr>
<td>Minimum Bias</td>
<td>1000</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>12000</strong></td>
<td><strong>620</strong></td>
<td><strong>197</strong></td>
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</table>

Example of possible sharing of bandwidth
The preparations for commissioning with beam are well advanced
Considerable progress made in short period with single beams last year
First steps made in timing set-up
Much useful experience gained – improved tools, procedures, etc
Partitioning of the trigger architecture allows commissioning in parallel
Detectors can work in parallel on different partitions
Events that are selected are sent, inclusively, to one or several “streams”, providing samples enriched in events relevant for commissioning.

Trigger menus take into account the needs of the detectors
Calibration, alignment, commissioning

Much effort to ensure flexibility and ability to react quickly
E.g. triggers to address ad hoc needs for detector commissioning
Back-up slides
Data acquisition performance tests

- Dedicated Technical Runs to establish performance and scalability during system deployment
  - Simulated data as input (background + signal)
  - Test with \( L = 10^{31} \) trigger menu
  - 70% of L2, 20% of EF
  - Small event size: 800 kB, expected is 1.6 MB

- Stress test for the Data Acquisition system

- Readout system (ROS) request rate up to 30 kHz
  - Maximum expected is 20 kHz (20% of L1)
- Event Building rate (L2-driven): 4.2 kHz (3.5 kHz by design)
- Data storage (SFO) I/O rate: 550 MB/s, with peak > 700 MB/s

ICCSME 2009 - ATLAS trigger
Muon trigger performance

- Use of Inner Detector for muon $p_T<50$ GeV tracks helps:
  - L2 low rejection at low-$p_T$ due to large scattering angles in the Muon Spectrometer
  - $p_T$ resolution in regions of inhomogeneous magnetic field
  - Rejection of muons from K/$\pi$ decays (small kink)
- Efficiency determination validated on Z and J/$\psi$ decays
e/γ trigger performance

- e/γ $E_T$ spectrum covers few GeV to several TeV ($Z$, $J/\psi$, $Y$ to $ee$, $\gamma$-jets)
- Huge challenge to L1 calorimeter trigger due to low $E_T$ thresholds required (5 GeV) for $J/\psi$ and $Y$ decay into electrons (more than 6 kHz rate)
- Pile-up affects reconstruction efficiency and isolation performance (3% at design Luminosity)

**e20 trigger efficiency from “Tag and Probe”**

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ATLAS Combined performance

Differences in track parameters in the muon spectrometer and the ID (preliminary alignment).

3 GeV/c energy loss in the calorimeter.
  – Multi-thread per HLT e legge di moore
  – Da studiare…. Rule of thumb
  – Trigger menu, efficienza
  – HLt performance, trigger strategy
  – Trigger strategy for early running
  – Overall description
• http://agenda.infn.it/getFile.py/access?contribId=114&amp;sessionId=5&amp;resId=0&amp;materialId=slides&amp;confId=759
  – Trigger strategy and menu, rates L1
  – Timing L1