THE UPGRADE OF THE ATLAS FIRST LEVEL CALORIMETER TRIGGER

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on behalf of the ATLAS Collaboration
Outline

Introduction

- ATLAS Liquid Argon calorimeter and level-1 trigger
- Challenges toward high luminosity runs

Upgrading ATLAS level-1 calorimeter trigger

- New Liquid Argon calorimeter trigger readout
- New system architecture for trigger processing
- Expected performances

Summary
**ATLAS Calorimetry**

- **Liquid Argon (LAr) electromagnetic calorimeter**
  - Lead absorber, LAr as active material and copper/kapton electrode
  - Has fine segmentation: 4 layers, ~200k readout channels in total

- **Hadronic calorimeters**: Tile (steel&scintillator), LAr endcap/forward

- Plays a major role in identifying/measuring \( e, \gamma, \tau, \) jet and missing \( E_T \) (offline) and provides inputs for their triggers at the hardware level (**L1Calo** triggers)
  - Higgs discovery! Lots of searches in variety of channels, precise measurements, ..
LHC and ATLAS trigger upgrade timelines

Staged upgrade plan:

- **Run 1 (2010-2012)**
  7-8TeV, L~0.8×10^{34} cm^{-2}s^{-1}, <μ>~20
  \[\Leftarrow \text{LS1/Phase-0 upgrade (2013-2014)}\]

  13-14TeV, L~1.6×10^{34} cm^{-2}s^{-1}, <μ>~40
  \[\Leftarrow \text{LS2/Phase-1 upgrade (2018-2019)}\]

- **Run 3 (2020-2022)**
  14TeV, L~3.0×10^{34} cm^{-2}s^{-1}, <μ>~80
  \[\Leftarrow \text{LS3/Phase-2 upgrade (2018-2019)}\]

- **Run 4 (2025-2027)**
  14TeV, L~7.0×10^{34} cm^{-2}s^{-1}, <μ>~200

**Pile-up effects** significantly degrade the trigger performance:

- **Instantaneous luminosity getting increased!!**
  - Number of interactions per bunch crossing (μ) doubled, tripled and much more..

- **Degraded LAr signal due to its long drift time**: ~450ns drift time (with 2mm gap at 2 kV) vs. 25ns LHC bunch spacing (40MHz)

- **Triggering electromagnetic objects suffers from huge multi-jets background**
Utilize more calorimeter shower shape information & event topology as in software algorithms — high-level triggers use this information as well.

\[ R_\eta = \frac{E_{T, \Delta \eta \times \Delta \phi = 0.075 \times 0.2}}{E_{T, \Delta \eta \times \Delta \phi = 0.175 \times 0.2}} \]

\[ f_3 = \frac{E_{T, \Delta \eta \times \Delta \phi = 0.2 \times 0.2}}{E_{T, \Delta \eta \times \Delta \phi = 0.075 \times 0.2} + E_{T, \Delta \eta \times \Delta \phi = 0.2 \times 0.2} + E_{T, \Delta \eta \times \Delta \phi = 0.175 \times 0.2} \]

Already partially implemented in Run-2: L1Calo provides trigger capabilities based on event topologies.

- New module “L1Topo” installed. Can apply selection with topological variables as \( \Delta \phi, \Delta \eta, \Delta R, H_T, \) …

(More details in the backup.)
To achieve these trigger features, develop new hardware for trigger readout and processing.

- **LAr trigger readout**
  - Fully digitized readout with finer granularity & digital filtering for out-of-time pile-up correction and bunch-crossing identification

- **L1Calo trigger processing**
  - Pile-up subtraction, employ selection fully based on object features and event topology information

**Challenges:**
- Highly dense electrical & optical circuit boards & high-speed optical links (up to ~10 Gb/s)
- Signal mapping and data duplication among readout modules
Trigger tower
Analog sum in $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$ (60 cells)

Run-2 readout geometry

Super Cells

(box: minimal readout element)

- Finer granularity: trigger tower $\Rightarrow$ **10 Super Cells (SCs)**
  - 60 cells $\Rightarrow$ 4-8 cells in each layer
- Analog readout $\Rightarrow$ **40MHz digital readout**
Upgrading LAr trigger readout: Scheme

```
Existing cell-readout
Sampled at 40MHz, stored in analog pipelines.
Digitized and transmitted when Level-1 accept received.
```

```
"Layer-sum board" renewed to produce SCs
```

New LAr Trigger Digitizer front-end Board (LTDB)

New LAr Digital processing back-end Board (LDPB)
**LTDB & LDPB**

**LTDB**
- 12-bit ADC (custom ASIC) @40MHz
  - Multiplexing 8 channels to 5.12Gb/s optical link, 200Gb/s for each board
- Handle up to 320 SC signals
- 124 boards in total (~25Tb/s)

**LDPB**
- ATCA standard, 4 Advanced Mezzanine Cards (AMCs) for each
- AMC:
  - high-speed optical transceivers to process 320 SCs with a short latency
  - Energy&timing measurements by FPGA digital filtering

Both LTDB and LDPS prototypes integrated in the detector system and being demonstrated during Run-2 running.
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LDPB can enhance performance on the SC energy reconstruction by processing 40MHz ADC samplings with dedicated digital filtering.

Filtering algorithms under study.

e.g. Wiener filter:

- Nice "energy reconstruction" and "bunch-crossing identification"
- Expected to be pile-up robust by adopting an active forward pile-up correction

Filter output

ATLAS Simulation

SC signal (40MHz ADC sampling)
Upgraded L1Calo: System architecture

Feature extractor modules integrated for Run-3.

**eFEX:**
Identify e/γ/τ using isolation & cluster shape variables. Flexible rejection algorithms.

**jFEX:**
Identify jet/τ and calculate H\text{\textscript{T}}, missing E\text{\textscript{T}}.
Enables pile-up suppression using event energy density

**gFEX:**
For global event processing, e.g. large-area jets for dedicated physics cases (boosted bosons, …)
Expected performance: single-object triggers

- **EM trigger rate:**
  - Adopting jet rejection using shape variables, the threshold can be lowered by 7 GeV
    - Compared at reference points of 20kHz (Run-2 rate budget) and 95% efficiency
    - Can maintain high photon efficiency (>96%)

- **Better trigger turn-on for jet and missing \( E_T \) triggers**
  - Thanks to pileup suppression and dedicated jet reconstruction algorithm

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**Figure 15.**

- multijet triggers. Such an algorithm can only be applied to a Level-1 jet trigger based on Super Cells.
- The trigger efficiency as a function of the fourth-highest \( E_T \) is compared to that of the sliding window algorithm based on Super Cells (red points) for jets within simulated QCD dijet events. The performance of the default sliding window algorithm (black points) is shown.

- The trigger efficiency in Minimum Bias (electrons) with one or more hadrons. The challenge at the trigger level, especially at the low-\( p_T \) region, is to efficiently reconstruct high-\( p_T \) jets. This is achieved by applying an algorithm that has been used to reconstruct heavy ion collision events in the PHENIX experiment at RHIC.

- The trigger thresholds require four jets with \( p_T > 20 \) GeV,
  - for the front and middle EM layer trigger readouts are lowered to \( 10 \) GeV.
  - The Level-1 jet thresholds require four jets with \( p_T > 20 \) GeV.

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Summary

- Upgrade activities ongoing in order to explore full physics of the high-luminosity LHC runs.

- ATLAS is developing new hardware and system for calorimeter trigger readout and processing.
  
  - Expect improved trigger performances with the upgraded system even in severe pile-up conditions.
  
  - R&D, design and production in progress toward installation in 2018-2019 (Phase-1 upgrade)

- Some of them are already integrated for ATLAS Run-2 running:
  
  ▶ LTDB & LDPS prototypes for demonstration
  
  ▶ Topological trigger with new L1Calo architectures
Backup
Super Cells

Trigger towers ⇒ 10 Super Cells (SCs)

### Elementary Cell

<table>
<thead>
<tr>
<th>Layer (barrel)</th>
<th>$[\Delta \eta \times \Delta \phi]$</th>
<th>$[n_\eta \times n_\phi]$</th>
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</tr>
</thead>
<tbody>
<tr>
<td>Presampler (layer 0)</td>
<td>0.025 × 0.1</td>
<td>4 × 1</td>
<td></td>
<td></td>
<td>4 × 1</td>
</tr>
<tr>
<td>Front (layer 1)</td>
<td>0.003125 × 0.1</td>
<td>32 × 1</td>
<td></td>
<td></td>
<td>8 × 1</td>
</tr>
<tr>
<td>Middle (layer 2)</td>
<td>0.025 × 0.025</td>
<td>4 × 4</td>
<td></td>
<td></td>
<td>1 × 4</td>
</tr>
<tr>
<td>Back (layer 3)</td>
<td>0.05 × 0.025</td>
<td>2 × 4</td>
<td></td>
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### Trigger Tower

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### Super Cell

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### Notes

- **Super Cells** are formed by combining 10 Trigger Towers, each with a specific $[\Delta \eta \times \Delta \phi]$ and $[n_\eta \times n_\phi]$.
- **Trigger Tower** dimensions for each layer are shown, along with the corresponding Super Cell dimensions.
- **Electromagnetic calorimeter** and **Hadronic inner core** are highlighted in the diagram.
- **Isolation ring** and **Electromagnetic isolation ring** are also indicated for isolation and energy sum calculations.
LTDB & LDPB specifications

**LTDB**
- Handle up to 320 SC signals
- 12-bit ADC @40MHz with low power consumption (custom ASIC)
  - <145 mW/channel
- Multiplexing 8 channels to 5.12Gb/s optical link, 200Gb/s for each board
- 124 boards in total (25Tb/s)

**LDPS**
- ATCA standard, 4 Advanced Mezzanine Cards (AMCs) for each
- AMC designed with FPGA and high-speed optical transceivers to process 320 SCs with a required latency (17 bunch crossings)
- Energy measurement & bunch-crossing identification by FPGA digital filtering
- Receive 25Tb/s (from LTDB) and transmit 41Tb/s (to L1Calo)
**Upgraded L1Calo: Run-2 system architecture**

**Phase-0 upgrade (for Run 2)**

**New Multi Chip module (nMCM):**
- ASIC→FPGA replacement for digital signal processing
- Better treatment of pile-up (autocorrelation FIR filter & dynamic pedestal subtraction)
- Dedicated calibration for EM and hadron energy scale using dual-channel ADCs

**New(extended) Common Merger Module (CMX):**
- 160Mb/s backplane (data from processor modules), multiplicities→trigger objects.
- Link to L1Topo (24 opt. fibers at 6.4Gb/s)

**Topological trigger module (L1Topo):**
- Enables composite triggers using trigger objects. Topological algorithms.

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**ATLAS Simulation**

\[ \bar{s} = 14 \, \text{TeV}, \langle \mu \rangle = 54, \, 25 \text{ns} \]

- **FCal1**
  - Matched (start)
  - Matched (bulk)
  - Auto-correlation (start)
  - Auto-correlation (bulk)

**Figure 22: Performance of digital filters**

- **Auto-correlation (bulk)**
- **Auto-correlation (start)**
- **Matched (start)**
- **Matched (bulk)**
- **Signal Truth \( E_T \)**

**Figure 21: The new Pre-Processor Multi-Chip Module**

- **MUX**
- **nMCM**
- **2x ADCs**
- **Signal Generator**
- **2x Diff. OpAmps**
- **CALIPPR FPGA**
- **4x analogue trigger signals**
- **real-time LVDS data to CP & JEP**
- **configuration, monitoring (VME) event data readout (DAQ)**
- **To RODs**

**Figure 18: System Architecture during Run 2. New components are shown in green.**

- **L1Calo**
- **Jet Energy Processor**
- **Cluster Processor**
- **CMX**
- **TOBs**
- **Hit Counts**
- **To RODs**
- **L1Topo**
- **L1CTP**
- **Jets, \( \Sigma E_T E_n^{mix} \)**
- **0.2 \times 0.2 (n, b)**
- **0.1 \times 0.1 (n, b)**

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**System architecture during Run 3**

**L1Calo**
- The electromagnetic and jet feature extractors, see Figure 18.

**L1Topo**
- Provides ROI and read-out data to the HLT and DAQ systems. These data are transmitted via ONWARD transmission to eFEXs and jFEXs. These data will be further summed to provide the output of the L1Topo module.

**L1CTP**
- The CMMs are each replaced by an enhanced version of that module, the CMX, capable of providing ROI and read-out data to the HLT and DAQ systems. These data are transmitted via ONWARD transmission to eFEXs and jFEXs. These data will be further summed to provide the output of the L1CTP module.

**System architecture during Run 2**

**Upgraded L1Calo: Run-2 system architecture**
- The nMCM includes a programmable analogue signal generator which may be used for standalone tests. The amplitude, width and pedestal level of the generated analogue signals are controlled from the CALIPPR FPGA.

**Figure 12: System Architecture during Run 2. New components are shown in green.**

- **ECAL** (analogue)
- **HCAL** (analogue)
- **Pre-processor**
- **Jet Energy Processor**
- **Cluster Processor**
- **CMX**
- **TOBs**
- **Hit Counts**
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**Technical Design Report**

**3.3 System Evolution**

- During LS1, a number of upgrades will be made to the existing RODs with updated firmware.
- During LS2 there will be further upgrades, both to the existing RODs with updated firmware.
- The CALIPPR FPGA reads out event data to DAQ on receipt of a L1A signal. It can also provide ROI and read-out data to the HLT and DAQ systems. These data are transmitted via ONWARD transmission to eFEXs and jFEXs. These data will be further summed to provide the output of the L1CTP module.

**5.2 L1 Calorimeter Trigger**

**L1Calo**
- The electromagnetic and jet feature extractors, see Figure 18.

**L1Topo**
- The new Pre-Processor Multi-Chip Module
- **CMX**
- **nMCM**
- **MUX**
- **2x ADCs**
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**Topological trigger module (L1Topo):**
- Enables composite triggers using trigger objects. Topological algorithms.
Expected performance: L1Topo, FEX

L1Topo (already installed for Run-2)
- Can apply selection with topological variables: $\Delta \varphi$, $\Delta \eta$, $\Delta R$, $H_T$, ...
- Challenging analyses will benefit from that.
  ▶ ZH$\rightarrow$vvbb, di-tau etc.

jFEX (Run-3)
- Gaussian filter: jet energy reconstruction using Gaussian weights
  ▶ Less sensitive to pile-up, significant rate reduction thanks to improved trigger turn-on.
  ▶ Expect much better performance by adopting calibrations and optimizing in terms of pile-up.