Triggers at ATLAS and CMS

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Why having a trigger?

- Cross sections for many processes of interest are up to 13 orders of magnitude smaller than the total $pp$ cross section.
- LHC bunch spacing 25 ns, peak $\langle \mu \rangle$ about 60 $pp$ interactions per bunch crossing.
  - Beyond capabilities of data readout & storage infrastructure (~1 MB/event).

Trigger is the mechanism to promptly select the events to be recorded for offline analyses.
ATLAS and CMS triggers

- ATLAS and CMS are both general-purpose detectors with similar physics programs.

- Similar two-level trigger designs in Run-2:
  - Hardware Level-1 (L1) trigger gives a fast first guess if the event is interesting, using muon detectors and calorimeters.
  - High Level Trigger (HLT): software-based (computer farm), with a much better energy and position resolution than at L1.

- Differences between ATLAS & CMS triggers:
  - At L1 calorimeter trigger ATLAS uses sliding window (e/gamma, taus, jets) and simple cone (jets); CMS uses sliding window (jets) and dynamic clustering (e/γ, taus).
  - Muon trigger: ATLAS uses a subset of the Muon spectrometer for L1 trigger; whole muon system used for L1 in CMS.
  - At L1 accept, ATLAS reads out Regions of Interest (RoI), while CMS reads out full detector.

What about the physics content?

<table>
<thead>
<tr>
<th></th>
<th>ATLAS, CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1 input rate</td>
<td>40 MHz</td>
</tr>
<tr>
<td>L1 output rate</td>
<td>100 kHz</td>
</tr>
<tr>
<td>L1 latency</td>
<td>2.5 μs, 3.8 μs</td>
</tr>
<tr>
<td>HLT output rate</td>
<td>O(1) kHz</td>
</tr>
<tr>
<td>HLT average processing time</td>
<td>About 200 ms*</td>
</tr>
</tbody>
</table>

*at $1.4 \times 10^{34}$ cm$^{-2}$s$^{-1}$, $\langle \mu \rangle \sim 40$, highly sensitive to pileup, take with caution.
• Bandwidth allocated for various trigger objects follows the experiment priorities
• Combined triggers (based on multiple signatures) allow maintaining low energy thresholds
• Similar $p_T$ thresholds for lowest unprescaled triggers for ATLAS and CMS
• Rich trigger menu provided by both experiments

ATLAS trigger menu table

<table>
<thead>
<tr>
<th>Trigger Type</th>
<th>ATLAS HLT (GeV)</th>
<th>CMS HLT (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single electron</td>
<td>26 (i)</td>
<td>32</td>
</tr>
<tr>
<td>Single muon</td>
<td>26 (i)</td>
<td>24 (i)</td>
</tr>
<tr>
<td>Dimuon</td>
<td>22, 8</td>
<td>17, 8</td>
</tr>
<tr>
<td>$e + \mu$</td>
<td>26, 8 (7, 24)</td>
<td>23, 8</td>
</tr>
<tr>
<td>Single gamma</td>
<td>140</td>
<td>110 (i)</td>
</tr>
<tr>
<td>Two photons</td>
<td>2x20</td>
<td>30, 18</td>
</tr>
<tr>
<td>Two taus</td>
<td>35, 25</td>
<td>35, 35</td>
</tr>
<tr>
<td>Single jet</td>
<td>460</td>
<td>500</td>
</tr>
<tr>
<td>Two b-jets (e=60%)</td>
<td>175, 60</td>
<td>-</td>
</tr>
<tr>
<td>Missing $E_T$</td>
<td>110</td>
<td>120</td>
</tr>
<tr>
<td>Total $H_T$</td>
<td>-</td>
<td>1050</td>
</tr>
<tr>
<td>Number of HLT items</td>
<td>~1500</td>
<td>~650</td>
</tr>
</tbody>
</table>
LHC luminosity evolution

- In 2016 LHC went above the design luminosity. Experiments triggers needed to accommodate:
  - Raise energy thresholds (loosing data)
  - Prescale triggers (loosing data)
  - Use more robust methods (topological L1 trigger, combined triggers, optimize HLT software)
- 2017: “Gruffalo” problem: beam dumps due to fast beam losses in sector 16L2 (gas leakage)
  - As a remedy, LHC changed the injection pattern: 8 filled bunches followed by 4 empty bunches
  - 8b4e has 20% less bunches than nominal scheme -> lower instantaneous luminosity
  - To keep the same luminosity, LHC increased number of protons/bunch and squeezed the beams
  - Number of pileup interactions $<\mu>$ increased to ~80; ATLAS & CMS requested luminosity leveling
Luminosity leveling

• For both experiments, in September 2017 the limit of trigger systems was reached at average $<\mu> = 60$
  ➢ CMS: L1 rate limit (L1 output rate too high)
  ➢ ATLAS: HLT farm limit (limited by number of CPU cores)
• Solution: ATLAS and CMS requested to level the instantaneous luminosity at $1.5 \times 10^{34}$ cm$^{-2}$s$^{-1}$ and $<\mu> = 55...59$
  ➢ Number of options to level: not head-on beam collisions, change beams crossing angle, change $\beta^*$

Leveling proved to be a successful approach to preserve physics reach of the experiments!
ATLAS: topological L1 trigger

- New component in Run-2
- Better selection at L1 by using geometrical and kinematic information (e.g. invariant masses) in addition to energy thresholds to reduce the rate and remain efficient for physics signals
  - Input: L1Calo and L1Muon Trigger Objects (TOBs)
  - Outputs up to 128 result bits to the central trigger (equivalent to having 128 cut-based analyses running online at L1)
- Example impact: significant reduction of rate by applying DeltaR requirements

**Di-tau trigger, used by H → ττ**

**Di-muon trigger**
CMS: upgraded L1 trigger

- Since 2016: increased trigger tower granularity at L1 (4x finer granularity in both eta and phi than in Run-1); dynamic clustering at L1
- L1 global trigger: allows triggering on complex object correlations (e.g. invariant masses) for muons, electrons, taus, jets and $E_{T,\text{miss}}$ (2017: 486 algorithms implemented)
  - Example L1 algorithm: VBF trigger
    - At least one L1 jet with $E_T > X_1$ GeV
    - At least one L1 other jet with $E_T > X_2$ GeV ($X_1 > X_2$)
    - Among L1 jets with $E_T > X_2$ GeV, at least one pair with $m_{jj} > X_3$ GeV

- L1 VBF trigger efficiency vs offline is measured in data and MC. L1 selection:
  - $X_1 = 115$ GeV
  - $X_2 = 40$ GeV
  - $X_3 = 620$ GeV
ATLAS: L1Calo bunch-by-bunch pedestal correction

- LAr calorimeter pulses are longer than time between bunch crossings → increase of the L1Calo rate at the beginning of the bunch train due to interplay of in-time and out-of-time pileup
- Apply the dynamic correction by subtracting the average input (averaging over $O(1000)$ orbits, for each bunch position individually): significantly reduced the rates of jet and missing $E_T$ triggers
  - Helped to adapt fast to the 8b4e filling scheme, for which the LAr calorimeter pileup correction was not optimized initially

- CMS applies “donut” pile-up correction: subtract average activity in calorimeter trigger towers around jet
  - Activity around jet scales linearly with the pileup

Trigger at ATLAS and CMS
Performance: jet triggers

**CMS public jet trigger**
- Efficiency vs offline jet $p_T$ for jets matched to HLT, $|\eta| < 3.0$
- HLT (and offline) jets reconstructed with particle flow algorithm, clustering with anti-$k_T$ algorithm $R=0.4$

**ATLAS public jet trigger**
- Efficiency vs leading offline jet $p_T$
- Jet clustering algorithm over calorimeter cells
- Updated calibration in 2017:
  - Global sequential calibration (GSC): improves jet energy resolution by taking into account shower shape
  - In situ corrections using tracking information (eta-intercalibration)
Performance: tau triggers

- HLT efficiency vs offline $p_T(\tau)$ for $Z \rightarrow \tau^+ \tau^- \rightarrow \mu \tau_h$ events with the tag ($\mu$) and probe ($\tau$) method

- ATLAS: seeded by L1 tau RoI
  - Two-stage fast tracking at HLT
  - Particle identification provided by a boosted decision tree

- CMS: seeded by $\mu + \tau$ at L1
  - Efficiency in data affected by changing conditions of the pixel detector
  - Higher performance of the updated CMS L1 trigger brings additional improvement

Both experiments were able to observe $H \rightarrow \tau \tau$ signal with optimized $\tau$ triggers

ATLAS-CNF-2017-061

CMS public tau

- p$_T$(\tau) > 27 GeV
- p$_T$(\tau) > 25 GeV

Efficiency vs offline $p_T(\tau)$ for $Z \rightarrow \tau^+ \tau^- \rightarrow \mu \tau_h$ events with the tag ($\mu$) and probe ($\tau$) method
Performance: missing $E_T$ trigger

- **ATLAS:** HLT efficiency for $E_T^{\text{miss}} > 110$ GeV as calculated for $Z \rightarrow \mu \mu$ data selected events
- Dependence on $p_T(Z)$ is given
  - Muons are treated as invisible objects by the trigger concerned
- “Pufit” algorithm calculates the negative of the transverse momentum vector sum of calorimeter topological clusters corrected for pileup

- **CMS:** HLT efficiency for $H_T^{\text{miss}} > 120$ GeV for a single muon dataset
- $H_T^{\text{miss}}$ obtained from the vector sum of transverse momenta of jets reconstructed with the particle flow algorithm, after removing muons (i.e. hadronic contribution only)
Performance: dependence on pileup (ATLAS)

- Good stability of the efficiency vs pileup

ATLAS public HLT tracking

- Offline medium Muons $p_T > 4$ GeV
- 10 GeV Muon trigger: Fast Track Finder
- 10 GeV Muon trigger: Precision Tracking
- 24 GeV Muon trigger: Fast Track Finder
- 24 GeV Muon trigger: Precision Tracking

ATLAS Preliminary
Data 2017 $\sqrt{s} = 13$ TeV

Electron

ATLAS e/gamma public

- Tight, isolated electron trigger, $E_T > 28$ GeV

- ATLAS MET public

- Missing $E_T$

- ATLAS MET public

- $Z \rightarrow \mu\mu$
- $p_T (Z) > 150$ GeV
- $L_1 \_XE50$
- $\text{HLT} \_xe110\_purif\_xe65 \_L1XE50$
- $\text{HLT} \_xe110\_purif\_xe70 \_L1XE50$

ATL-COM-DAQ-2017-182

Trigger at ATLAS and CMS

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LHCP2018
ATLAS & CMS Trigger Upgrades

• 2018 is the final year of LHC Run-2, followed by two years Long Shutdown 2 (LS2):
  ➢ ATLAS working on redesigning HLT software to use multithreading and on L1 hardware improvements (e.g. superclusters for L1Calo)
  ➢ CMS L1 trigger is Phase-I upgraded since 2016

• Upgrades for LS3 (2023-2025):
  ➢ Major improvement is the inclusion of silicon trackers at L1
    ▪ L1 latency will increase (2.5 ⟜ 40 µs ATLAS, 4 ⟜ 12.5 µs CMS)
  ➢ Use full calorimeter granularity
  ➢ ATLAS: include MDT into trigger
  ➢ L1 output rates: ATLAS 400 kHz, CMS 750 kHz
Summary

• ATLAS and CMS triggers demonstrate excellent performance and flexibility
  ➢ Continuously developed following the evolution of the LHC instantaneous luminosity above the design value
  ➢ Very good coordination between LHC and experiments
• High pileup environment in 2017 posed a difficulty for triggers of both experiments; helps for better understanding of bottlenecks towards Run-3 (even higher pileup)
• Work on upgrades towards Run-3 and HL-LHC ongoing in both experiments
Backup
References

- CMS trigger public results, https://twiki.cern.ch/twiki/bin/view/CMSPublic/HighLevelTriggerRunIIResults, https://twiki.cern.ch/twiki/bin/view/CMSPublic/L1TriggerDPGResults
- CMS trigger performance, 6th international Conference on New Frontiers in Physics – Kolymbary – August 2017
- The Phase-2 Upgrade of the CMS DAQ Interim TDR, CMS-TDR-018
- ATLAS TDR for the Phase-II upgrade of the TDAQ system, ATLAS-TDR-029
ATLAS: Multi-jet trigger

- Efficiency of the unprescaled 6-jet trigger
- Using data driven eta-intercalibration correction improves the efficiency in the turn-on region
ATLAS: L1Topo trigger for large-R jets

- L1J100 trigger requires $E_T > 100$ GeV in a $\Delta \eta \times \Delta \phi$ window of 0.8 x 0.8 (RoI) within a sliding-window algorithm
  - Misses large-R jets with substructure

- SimpleCone L1Topo item L1_SC111 avoids this problem by summing $E_T$ RoIs with $E_T > 15$ GeV within a cone of radius 1.0
- The threshold of 111 GeV gives equal rate to L1J100 trigger
  - Trigger efficiency is improved for jets with $\geq 3$ subjets
Performance: ATLAS e/gamma triggers

- HLT electron trigger efficiency vs offline electron $E_T$
- New in 2017: HLT uses Ringer algorithm, based on ensemble of neural networks fed by ring-shaped energy description

- HLT photon trigger efficiency vs offline photon $E_T$
- Selection of triggers with loose, medium and tight identification requirements