The Evolution and Performance of the ATLAS Calorimeter-Based Triggers in 2011 and 2012

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Introduction

- CERN Large Hadron Collider

- Trigger Signatures

- Electron and photon: EM
- Tau (τ -leptons): TAU
- Jet: J
- Total ($\sum E_T$) and Missing (E_T^{miss}) Transverse Energy (E_T): TE and XE
- XE-Significance: $XS \sim \frac{XE}{\sqrt{TE}}$

- ATLAS calorimeter

- ATLAS Trigger input rate $\leq 40 \text{ MHz}$

event selection	time	out. rate
Level-1 (L1)	$< 2.5 \mu\text{s}$	$< 75 \text{ kHz}$
Level-2 (L2)	$\sim 60 \text{ ms}$	$\sim 5 \text{ kHz}$
Event Filter (EF)	$\sim 1 \text{ s}$	$\sim 0.4 \text{ kHz}$

L1 (hardware) and HLT (software)

High Level Trigger (HLT): L2 and EF

LHC Luminosity Evolution in 2011-2012

- Change of beam parameters → steady increase of instantaneous luminosity and average number of interactions per bunch crossing (pile-up) → higher event rates → higher load on all trigger levels, $\text{rate} = \text{luminosity} \times \text{cross section}$

	2011	2012	nominal
energy per beam [TeV]	3.5	4.0	7.0
bunch crossing (BC) frequency [MHz]	20	20	40
bunch spacing [ns]	50	50	25
number of filled bunches	1380	1380	2808
β^* amplitude function [m]	1.0	0.6	0.55
L_{peak} peak luminosity [$10^{33} \text{ cm}^{-2} \text{ s}^{-1}$]	3.65	6.0(6.8)	10
$\langle \mu \rangle$ average number of interactions per BC	17	28(35)	19

Level-1 Calorimeter Trigger (L1Calo)

- Receives ~ 7200 analog signals (trigger tows) from the ATLAS calorimeter
- Digitisation, E_T calibration (ADC $\rightarrow$ GeV, suppress signal if $E_T < E_{T, \text{thresh.}}$)

Trigger signature identification

- trigger towers E_T , $\Delta\eta \times \Delta\phi$ sliding window algorithm
- identify regions of interest (Rols) with largest local E_T
- count number of Rols above given E_T threshold, ie $E_T > 3 \text{ GeV (EM3)}$
- compute global quantities $\sum E_T$, E_T^{miss} , $E_T^{\text{miss-sig.}}$
- Rols locations in (η, ϕ) sent to L2

Jet algorithm:

EM cluster algorithm:

L1Calo Forward Region Noise Suppression

- Clear pile-up dependence in width, σ , of the ADC count (noise) distribution in the forward calorimeter region (FCAL)

— Pile-up noise width varies as a function η , e.g., FCAL regions in η :

bin 1 $3.1 < |\eta| < 3.2$

bin 2 $3.2 < |\eta| < 3.5$

bin 3 $3.5 < |\eta| < 4.2$

bin 4 $4.2 < |\eta| < 4.9$

L1Calo Forward Region Noise Suppression

- Pile-up noise from FCAL dominated E_T^{miss} trigger rate in 2011
 - E_T^{miss} trigger thresholds increased several times in 2011
 - Raised noise cuts in FCAL region to strongly suppress rate
 - Have checked this has minimal impact on trigger efficiency
 - This allowed thresholds to be lowered at L1 → great benefit for physics analysis

L1Calo-Based Trigger Signatures

- Need to provide robust selection and keep rates under control as the average number of interactions per bunch crossing (pile-up) increases
- Understanding how current rates behave allows us to predict them at different LHC conditions
- Single-object rates: **TAU15**, **J75**, **EM30**
 - Almost pile-up independent
- Multi-object rates: **4J10**
 - Non-linear dependence expected and can be explained on statistical basis
- FJ75**, **L1_XE50**
 - Exponential rise caused by higher occupancy in the forward calorimeter region supported by the larger trigger tower sizes
 - Non-linear rates controlled by increase of pile-up noise cuts in the forward calorimeter region (previous page)
 - XE50_BGRP7**: removed triggering on the first few bunches per train where calorimeter response is elevated (out-of-time pile-up)

Electron Trigger Signature: Evolution and Performance

- Adjust thresholds to fit within rate budget
- Tightened (T) L1 selection
 - EM16 → EM16VH → EM18VH
 - 2EM7 → 2EM10 → 2EM10VH
 - E_T threshold varied (V) vs η and $E_T < 1 \text{ GeV}$ in hadron (H) isolation ring, achieved 50% rate reduction compared to EM16
- Raised HLT threshold 20 → 22 → 24 GeV
- Tighter shower shape ID, *medium* → *medium1*
- Electron efficiencies remain high ($Z \rightarrow ee$ tag-and-probe method used)

Photon Trigger Signature: Rates and Performance

- Photon triggers serve a broad physics programme

- Standard Model γ -production cross section, the Higgs search channel $H \rightarrow \gamma\gamma$, searches of physics beyond the SM

- Stable rates and high efficiencies throughout 2011 and 2012

- Rapid turn on curves, no significant dependence on η

- No strong dependence on pile-up (number of reconstructed primary vertices)

Tau Trigger Signature: Rates

L1 rates

- L1 rates well behaved

- L1 trigger rates scale linearly with luminosity
- 2012: moderate increase of E_T thresholds, EM isolation (I) < 5 GeV

EF rates

- E_T in EM-cone of size 0.4, cone size very sensitive to pile-up

- EF single and di-tau triggers saturate at high luminosity
- Combined triggers rise non-linearly with luminosity
- Non-linear rates may lead to loss of efficiencies

Tau Trigger Signature: Various Improvements

- Move to pile-up robust variables
 - Smaller cone sizes: from 0.4 to 0.2
 - ΔZ cut in track-based parameters
- More offline-like variables used
- EF now uses multivariate selection
 - Boosted decision tree (BDT)
 - Log-likelihood (LLH)

Good example of moving offline selection into the trigger to maintain high efficiency at low rate

- Loss of efficiency recovered and improved pile-up dependence, 2011 data reprocessed with 2012 algorithms:

Jet Trigger Signature: 2011

unseeded jet finding
with sliding windows
using L1Calo towers

Level 1

Calorimeter
Readout
System

L1 jets

cells

cone jets
from calorimeter cells
seeded by L1 jets

L2 jets

clusters
formed from
all calorimeter cells

clusters

unseeded anti- k_T jets
using clusters

EF jets

Level 2

Event
Filter

Regions of Interest (RoI)

• Rol approach, limited performance as pile-up increased

- Poor resolution, efficiency loss for close-by jets in multi-jet events
- L1: (0.2×0.2) jet elements and 4×4 JE sliding window
- L2: Jet finding using calorimeter cells in L1 RoI cone
- EF: Full calorimeter
- Clusters from all calorimeter cell, anti- k_T algorithm using clusters
- Improved position resolution
- Increased acceptance for wide jets

Jet Trigger Signature: 2012

- **New: L1.5 trigger**

- Allows to run anti- k_T , etc. algorithms at L2 using all 1Calo trigger towers
- Better resolution, improved L1 efficiency for multi-jet events

- **New at L2: anti- k_T jets from cells seeded by L1.5 jets**

- **New at EF: towers using all calorimeter cells**

Jet Trigger Signature: Performance

- L1.5 jet finding within the L2 timing requirements

- Readout full L1Calo trigger-tower information
- Run offline-like algorithms using trigger towers
- Tested in *Pb-Pb* collisions in 2011
- Optimised in 2012 for increased pile-up conditions

- Improved resolution and efficiency (due to anti- k_T)

- anti- k_T (L1.5) more precise than sliding window (L1) clusters
- Resolution improved for jets at low E_T
- Efficiency recovered for events with ≥ 6 jets

E_T^{miss} Trigger Signature: Evolution

- Trigger on global quantities: $\sum E_T$, E_T^{miss} , $\frac{E_T^{\text{miss}}}{\sqrt{\sum E_T}}$
 - Sensitivity to detector resolution (noise, pile-up) at low E_T^{miss} $\rightarrow$ rates to depend non-linearly on instantaneous luminosity and $\mu \rightarrow$ model needed to predict rates at various LHC conditions
- Evolution in 2011 and 2012
 - 2011: L1 output = EF input rate as only Rols available at L2, thresholds raised
 - 2012: At L2, access to digitised signals from all calorimeter cells using calorimeter readout
 - Resolution improves by about 50%, rejection rate improved by a factor of 5-6, trigger thresholds lowered
 - 2012: At EF, topological cluster algorithms use local weight calibration
 - No BCID dependent cell energy corrections yet, significant gain in resolution, processing time (computing cost) pile-up dependent

Summary

- In 2011 and 2012: The LHC parameters steadily increased, the luminosity from 0.1 to $\sim 6.7 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ and the pile-up from 1 to ~ 30
- The ATLAS calorimeter-based trigger signatures represented about 2/3 of the Level-1 trigger bandwidth of $\lesssim 60 \text{ kHz}$
- The flexibility of the Level-1 Calorimeter Trigger allowed various improvements to be implemented to cope with the evolving LHC conditions
 - η -dependent noise-cut optimisation in the forward calorimeter region for high pile-up
- The software-based High Level Trigger continuously evolved
 - Faster and advanced algorithms implemented at trigger level to perform more offline-like selection, i.e., using larger amounts, finer-granularity and more precise readout information
- The performance of the trigger signatures was studied in detail to ensure rapid feedback and unbiased selection for physics analyses
 - Electron and photon: increased thresholds to reduce rate, isolation/veto and tighter selection criteria used at negligible loss of efficiency
 - Tau: various improvements based on the use of additional variables and improved selection techniques, loss of efficiencies recovered
 - Jet: improved rates, efficiency and position resolution for multi-jet events and low E_T jets
 - E_T^{miss} : Understanding how rates depend on pile-up allows for more reliable rate predictions and the development of pile-up robust triggers

BACKUP E_T^{miss} Trigger Signature: Significance

- E_T^{miss} -significance trigger motivation and performance

– LHC pile-up spans a wide range, up to $\mu \approx 30$ in 2012

- Both $\sum E_T$ and E_T^{miss} increase with pile-up due to detector effects

- Use pile-up independent quantity: $\frac{E_T^{\text{miss}}}{a(\sqrt{\sum E_T} - b)}$

- Trigger active at L1 since 2011

- L1Calo firmware updated during 2010-2011
- Benefit from L1Calo pile-up noise cuts in 2012 → allows to keep $\sum E_T$ low