The ATLAS Electron and Photon Trigger

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The e/gamma Trigger at ATLAS

- Brief tour of the most important aspects of the ATLAS detector for e/gamma triggers
- Motivation and design

Calibration and Identification

- Energy calibration and identification methods

$e/\gamma$ Trigger Performance in Run 2

- $e/\gamma$ trigger performance in 2016 + 2017 data
Introduction to the ATLAS Electron and Photon Trigger
The ATLAS detector

Calorimeter
- Finely segmented calorimeter system
- Liquid Argon Electromagnetic (EM) Calorimeter
- Liquid Argon Hadronic Calorimeter
- Tile Hadronic Calorimeter

Inner detector
- Pixel detector
- SemiConductor tracker
- Transition Radiation Tracker (TRT) provides electron / hadron separation by detection of transition radiation photons

Trigger system
- Reduces event rate to 1 kHz (around 20% allocated to $e/\gamma$) from beam crossing rate of 40 MHz
- Based on Region-of-Interest (RoI) concept
- Software based High-Level-Trigger is seeded by hardware based Level 1 (L1) trigger
**Introduction**

**e/γ triggers are essential at ATLAS**

- SM measurements / backgrounds, diphoton, \( W \rightarrow e\nu, Z \rightarrow ee, \ldots \)
  
  \[
  \sigma = \frac{N_{\text{obs}} - N_{\text{background}}}{\mathcal{L} \cdot \epsilon \cdot \text{BR}}
  \]

- New physics, SUSY, \( Z' \rightarrow ee, G_{KK} \rightarrow \gamma\gamma, \ldots \)

**Higher than ever instantaneous luminosity**

- Run 1 peak lumi: \(7.73 \times 10^{33} \text{ cm}^2 \text{s}^{-1}\)
- Run 2 peak lumi: \(21.4 \times 10^{33} \text{ cm}^2 \text{s}^{-1}\) > 2× larger!
- Want to keep as much physics as possible
- Online e/γ selection should be as close as possible to offline to keep efficiency high
- 25 ns bunch spacing → 40 MHz bunch crossing rate
- Only \(\sim 1 \text{ kHz}\) can be recorded
- Need to keep the rates under control

**2018 values correct at time of writing**
The ATLAS $e/\gamma$ triggers

- $e/\gamma$ trigger decision starts from calorimeter input
- Identify RoI for precise online reconstruction
- **Photons** identified with EM clusters
- **Electrons** identified with EM clusters + matching tracks
Level 1 (L1) hardware-based trigger

- L1Calo trigger seeds RoI for EM cluster reconstruction
- Based on trigger towers in $\eta - \phi$ plane with granularity $0.1 \times 0.1$
- $\eta$-dependent $E_T$ thresholds take into account energy loss in detector material
- Sliding-window algorithm ($2 \times 2$ trigger towers) identifies local energy maxima (RoI)
- Jet rejection using energy sum in hadronic isolation ring and core

L1 Naming conventions: $V$ indicates $\eta$ dependent $E_T$ threshold, $H$ indicates hadronic core isolation, $I$ indicates electromagnetic isolation
High Level Trigger (HLT)

- $e/\gamma$ HLT algorithm flow consists of two main steps
  - Fast algorithms to reject events early
  - Precise algorithms for efficient identification of electrons and photons

**Fast** algorithm step:

- Cut-based selection for photons with requirements on calorimeter variables
- Calorimeter selection for electron clusters is based on an ensemble of Neural Networks (ringer algorithm)
- See today’s dedicated talks:
  - “The ATLAS High-Level Calorimeter Trigger in Run-2”
  - “An Ensemble of Neural Networks for Online Electron Filtering at the ATLAS Experiment.”
- Tracks associated to clusters:
  - $p_T^{\text{track}} > 1 \text{ GeV}$, $\Delta\eta < 0.3$ for $E_T < 20 \text{ GeV}$
  - $p_T^{\text{track}} > 2 \text{ GeV}$, $\Delta\eta > 0.2$ for $E_T > 20 \text{ GeV}$

......................... electrons only
High Level Trigger (HLT)
- $e/\gamma$ HLT algorithm flow consists of two main steps
  - Fast algorithms to reject events early
  - Precise algorithms for efficient identification of electrons and photons

**Precision** algorithm step:
- Cut-based identification of photons
- Likelihood identification of electrons
- As close as possible to offline selection
  - Super-clustering is not currently used (coming soon!)
  - Gaussian Sum Filter is not currently used (coming soon!)
  - No difference between converted and unconverted photons (no tracking)
Calibration and Identification
Energy Resolution

Cluster energy calibration
- Corrects for energy loss / leakage upstream and outside of calorimeter
- Simplified version of offline reconstruction
- BDT used to determine correction factors
- Separate calibrations for electrons and photons
- No separation between unconverted / converted photons → major source of difference wrt. offline reconstruction

Energy resolution
- Excellent resolution in most regions
- Larger deviations in the crack region (1.37 < |\eta| < 1.52) where significant quantity of material servicing the detector causes energy loss and reduction in performance


https://twiki.cern.ch/twiki/pub/AtlasPublic/EgammaTriggerPublicResults/EleRes_includeCrack.png
Topological Superclusters

- Introduced for offline identification in 2017
- Soon to implemented online
- Alternative to sliding-window algorithm
- Dynamic superclusters built from topo-clusters
- Allow reconstruction of low energy showers, $\mathcal{O}(100 \text{ MeV})$

Selecting topo-clusters to build superclusters

- can be associated to electron or converted photon to form a supercluster
- Allow recovery of energy lost to bremsstrahlung
- 30 – 40% improvement in energy resolution (largest improvements at low $E_T$)
- These translate into 5-10% improvement in mass resolution (tested in $J/\psi \to ee$, $Z \to ee$, $H \to \gamma\gamma$, $H \to 4l$ simulations)
- Similar improvement expected at HLT
Common set of calorimeter discriminating variables used for photon and electron ID

- **Cut-based** selection for photon ID
- **Likelihood-based** MVA method for electron ID + additional tracking and cluster-track matching variables

### Variables and Position

<table>
<thead>
<tr>
<th>Ratios</th>
<th>f₁, f_side</th>
<th>Rₜ, Rₚ</th>
<th>R_Had.*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Widths</td>
<td>wₛ.₃, wₛ.tot</td>
<td>wₜ,₂*</td>
<td></td>
</tr>
<tr>
<td>Shapes</td>
<td>ΔE, E_{ratio}</td>
<td>* Used in PhotonLoose.</td>
<td></td>
</tr>
</tbody>
</table>

**Energy Ratios**

- \( R_\eta = \frac{E_{Σ²x7}^{S₂}}{E_{Σ²x7}^{S₁}} \)
- \( R_φ = \frac{E_{Σ³x3}^{S₂}}{E_{Σ³x7}^{S₁}} \)
- \( R_{Had.} = \frac{E_{T,Had.}}{E_T} \)
- \( f₁ = \frac{E_{S₁}}{E_{Tot.}} \)
- \( f_{side} = \frac{E_{Σ²x7}^{S₁} - E_{Σ³x1}^{S₁}}{E_{Σ³x1}^{S₁}} \)

**Shower Shapes**

\[
E_{\text{ratio}} = \frac{E_{Σ₁,max,1}^{S₁} - E_{Σ₁,max,2}^{S₁}}{E_{Σ₁,max,1}^{S₁} + E_{Σ₁,max,2}^{S₁}}
\]

\[
ΔE = E_{Σ₁,max,2}^{S₁} - E_{Σ₁,min}^{S₁}
\]

**Widths**

\[
w_{η,2} = \sqrt{\frac{\sum E_i η_i^2}{\sum E_i} - \left(\frac{\sum E_i η_i}{\sum E_i}\right)^2}
\]

Width in a 3x5 (ΔηxΔφ) region of cells in the second layer.
Electron ID

- Likelihood (LH) based MVA technique: construct signal / background PDFs from electron discriminating variables
- Combine into discriminant $d_L$

$$d_L = \frac{L_S}{L_S + L_B}, \quad L_{S(B)}(\vec{x}) = \prod_{i=1}^{n} P_{S(B),i}(x_i)$$

- 20% lower rate for same efficiency as cut-based selection used in Run 1
Electron Identification

LH used to define four ID operating points (OPs)

- Referred to as \(lhvloose, lhloose, lhmedium, lhtight\)
- Each uses the same variables to define the LH discriminant
- Sample selected by each OP are subsets of one another
- OPs differ by efficiency versus purity
- Plot show offline efficiencies

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![Identification Efficiency vs. \(E_T\) for Z → ee Simulation](https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2016-024/fig_01a.png)

![Identification Efficiency vs. \(E_T\) for Dijet Simulation](https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2016-024/fig_01b.png)
Keep as close as possible to offline selection

- Some important differences between online and offline LH
- No transverse impact parameter cut applied
- $\Delta p/p$ not used since the GSF algorithm is not implemented yet (time consuming)
- Ratio $E/p$ not used at high $E_T$ (loose ID electron trigger used)
- $\mu$ instead of $N_{vtx}$ for the pileup correction
Online Electron Identification

Isolation

- Isolation requirement provides further discrimination against eg. electrons originating from converted photons and hadronic activity
- Variable track isolation applied for electrons at HLT
  - \texttt{ivarloose}: $p_{\text{T}}\text{varcone20}/p_{\text{T}} < 0.1$
  - $p_{\text{T}}$ sum of non-electron associated tracks in cone of size 10 GeV / $p_{\text{T}}$ surrounding electron candidate (maximum cone size 0.2)
- Calometric isolation now applied for photons at HLT
  - Using the $E_{\text{T}}$ sum of topo-clusters in a cone surrounding the photon candidate
  - Note: no background subtraction applied in figures

\[ \begin{array}{c}
\text{ATLAS Preliminary} \\
\bar{s} = 13 \text{ TeV}, 3.2 \text{ fb}^{-1} \\
\text{Tight selection}
\end{array} \]

- Data
- \(Z \rightarrow \text{ee MC}\)

\[ \end{array} \]
Online Tracking

Sources of inefficiency at HLT

- Precision tracking is a major source of inefficiency at HLT, measured wrt. offline + L1 reconstruction
- Kalman filter is currently used for electron tracking at HLT
- For electrons, radiative losses can be substantial, altering the track
- Non-linear fitter more suitable for estimating track parameters under such conditions


Gaussian Sum Filter (GSF)

- Generalisation of the Kalman fitter, splitting experimental noise into Gaussian components, using Kalman filter to process each one
- Improved reconstruction efficiency (up to 6%) for most $\eta$
- Introduced offline in 2012, soon to be implemented at HLT
- Expect similar improvements due to improved resolution in tracking variables
Trigger rates depend heavily on $E_T$ threshold:

- Single electron dominated by $W \rightarrow e\nu$
- Sample purity is affected by trigger threshold
- In Run 2 HLT threshold kept at Run 1 level for as long as possible
- As instantaneous luminosity increases, trigger selection tightened to keep rates under control
- Tightening the ID level at HLT can significantly reduce the rate eg. $l_hmediu m \rightarrow l_htight$ gives $\sim 20\%$ rate reduction.

*ATLAS* Preliminary

$\sqrt{s} = 13$ TeV, $8 \times 10^{33}$ cm$^{-2}$ s$^{-1}$

- Data 2016
- $Z \rightarrow ee$
- $W \rightarrow e\nu$
- Multijet
- Uncertainty

Isolated single electron trigger rate [Hz]

$E_T$ threshold [GeV]

ATLAS Electron Trigger Rates
Run 2 Trigger Progression

**ATLAS** Trigger Operation
\( \sqrt{s} = 13 \text{ TeV}, 32.9 \text{ fb}^{-1} \)

- **Level 1**
  - L1_2EM10VH
  - L1_EM20VHI
  - L1_EM22VHI
  - L1_2EM13VH
  - L1_2EM15VH

**ATLAS** Trigger Operation
\( \sqrt{s} = 13 \text{ TeV}, 32.9 \text{ fb}^{-1} \)

- **HLT**
  - HLT_e24_lhmedium_nod0_ivarloose
  - HLT_e24_lhtight_nod0_ivarloose
  - HLT_e26_lhtight_nod0_ivarloose

Rates are dependent on instantaneous luminosity / pileup conditions

- Linear correlation (as expected)
- As these increase, it becomes necessary to tighten trigger selections to manage rates
- Try to maintain stability in trigger selection for physics analyses

<table>
<thead>
<tr>
<th>Year</th>
<th>HLT ( E_T )</th>
<th>HLT</th>
<th>HLT track</th>
<th>L1 ( E_T )</th>
<th>L1</th>
</tr>
</thead>
<tbody>
<tr>
<td>2015</td>
<td>e 24</td>
<td>lhmedium</td>
<td>no isolation</td>
<td>L1EM 20V</td>
<td>H</td>
</tr>
<tr>
<td>2016</td>
<td>e 26</td>
<td>lhtight</td>
<td>ivarloose</td>
<td>L1EM 22V</td>
<td>HI</td>
</tr>
<tr>
<td>2017</td>
<td>e 26</td>
<td>lhtight</td>
<td>ivarloose</td>
<td>L1EM 22V</td>
<td>HI</td>
</tr>
<tr>
<td>2018</td>
<td>e 26</td>
<td>lhtight</td>
<td>ivarloose</td>
<td>L1EM 22V</td>
<td>HI</td>
</tr>
</tbody>
</table>
$e/\gamma$ Trigger Performance in Run 2
Electron Trigger Performance

Electron trigger performance for full 2016 dataset

- Efficiency measured using Tag and Probe method with $Z \rightarrow ee$
- At high $E_T$ track isolation losses become important
- Lowest unprescaled electron trigger ORed with non-isolated high-threshold triggers
- $lhvloose$ triggers used as single leg for di-electron triggers
- Excellent data / MC agreement


Electron trigger performance in 2017

- Good trigger performance, excellent data / MC agreement
- Robust against pileup
- Tighter identification more pileup dependent (as expected)
Photon Trigger Performance

Photon trigger performance for 2016 / 2017

- Measured using Bootstrap method using L1 trigger
- Fully efficient at 5 GeV above threshold
- Lowest threshold triggers in 2017:
  - Single photon - g140_tight
  - Multi photon - g35_medium_g25_medium
- Good trigger performance, excellent data / MC agreement

https://twiki.cern.ch/twiki/pub/AtlasPublic/EgammaTriggerPublicResults/Eff_Et.photon.25m_35m_140t_200l.LHCC_Sep2017.pdf

Performance in Run 2

- Physics signatures with electrons and photons form an essential part of the ATLAS physics program.
- Increased instantaneous luminosity and pileup present significant challenges for data collection.
  - Improvements to background rejection (LH, isolation) allow low thresholds to be maintained.
- The ATLAS electron and photon triggers have operated at high efficiency throughout Run 2.
- Keep offline and online selections as close as possible.
  - Further improvements (GSF, superclusters) will bring these closer.
Backup
The Tag and Probe Method

Need a clean, unbiased sample of electrons for efficiency measurement

- Use $Z \rightarrow ee$ / $J/\psi \rightarrow ee$ / $W \rightarrow e\nu$ characteristic decays
- Apply strict selection criteria to one of the decay electrons, the tag
- For $W$ T&P, trigger in $E_T^{\text{miss}}$
- The second decay electron, the probe is identified with the tag by $m_{ee}$ within the mass window
- Probe electrons are used for the efficiency measurement
**Electron Discriminating Variables**

<table>
<thead>
<tr>
<th>Type</th>
<th>Description</th>
<th>Name</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Hadronic leakage</strong></td>
<td>Ratio of $E_T$ in the first layer of the hadronic calorimeter to $E_T$ of the EM cluster (used over the range $</td>
<td>\eta</td>
</tr>
<tr>
<td></td>
<td>Ratio of $E_T$ in the hadronic calorimeter to $E_T$ of the EM cluster (used over the range $0.8 &lt;</td>
<td>\eta</td>
</tr>
<tr>
<td><strong>Back layer of EM calorimeter</strong></td>
<td>Ratio of the energy in the back layer to the total energy in the EM accordion calorimeter. This variable is only used below 100 GeV because it is known to be inefficient at high energies.</td>
<td>$f_3$</td>
</tr>
<tr>
<td><strong>Middle layer of EM calorimeter</strong></td>
<td>Lateral shower width, $\sqrt{(\Sigma E_i \eta_i^2) / (\Sigma E_i)} - ((\Sigma E_i \eta_i) / (\Sigma E_i))^2$, where $E_i$ is the energy and $\eta_i$ is the pseudorapidity of cell $i$ and the sum is calculated within a window of $3 \times 5$ cells</td>
<td>$w_{\eta2}$</td>
</tr>
<tr>
<td></td>
<td>Ratio of the energy in $3 \times 3$ cells over the energy in $3 \times 7$ cells centered at the electron cluster position</td>
<td>$R_{\phi}$</td>
</tr>
<tr>
<td></td>
<td>Ratio of the energy in $3 \times 3$ cells over the energy in $7 \times 7$ cells centered at the electron cluster position</td>
<td>$R_{\eta}$</td>
</tr>
<tr>
<td><strong>Strip layer of EM calorimeter</strong></td>
<td>Shower width, $\sqrt{(\Sigma E_i (i - i_{\text{max}})^2) / (\Sigma E_i)}$, where $i$ runs over all strips in a window of $\Delta \eta \times \Delta \phi \approx 0.0625 \times 0.2$, corresponding typically to 20 strips in $\eta$, and $i_{\text{max}}$ is the index of the highest-energy strip</td>
<td>$w_{\text{atot}}$</td>
</tr>
<tr>
<td></td>
<td>Ratio of the energy difference between the largest and second largest energy deposits in the cluster over the sum of these energies</td>
<td>$E_{\text{ratio}}$</td>
</tr>
<tr>
<td></td>
<td>Ratio of the energy in the strip layer to the total energy in the EM accordion calorimeter</td>
<td>$f_1$</td>
</tr>
<tr>
<td><strong>Track conditions</strong></td>
<td>Number of hits in the innermost pixel layer; discriminates against photon conversions</td>
<td>$n_{\text{Blayer}}$</td>
</tr>
<tr>
<td></td>
<td>Number of hits in the pixel detector</td>
<td>$n_{\text{Pixel}}$</td>
</tr>
<tr>
<td></td>
<td>Number of total hits in the pixel and SCT detectors</td>
<td>$n_{\text{Si}}$</td>
</tr>
<tr>
<td></td>
<td>Transverse impact parameter with respect to the beam-line</td>
<td>$d_0$</td>
</tr>
<tr>
<td></td>
<td>Significance of transverse impact parameter defined as the ratio of $d_0$ and its uncertainty</td>
<td>$d_0/\sigma_{d_0}$</td>
</tr>
<tr>
<td></td>
<td>Momentum lost by the track between the perigee and the last measurement point divided by the original momentum</td>
<td>$\Delta p/p$</td>
</tr>
<tr>
<td><strong>TRT</strong></td>
<td>Likelihood probability based on transition radiation in the TRT</td>
<td>eProbabilityHT</td>
</tr>
<tr>
<td><strong>Track-cluster matching</strong></td>
<td>$\Delta \eta$ between the cluster position in the strip layer and the extrapolated track</td>
<td>$\Delta \eta_1$</td>
</tr>
<tr>
<td></td>
<td>$\Delta \phi$ between the cluster position in the middle layer and the track extrapolated from the perigee</td>
<td>$\Delta \phi_2$</td>
</tr>
<tr>
<td></td>
<td>Defined as $\Delta \phi_2$, but the track momentum is rescaled to the cluster energy before extrapolating the track from the perigee to the middle layer of the calorimeter</td>
<td>$\Delta \phi_{\text{res}}$</td>
</tr>
<tr>
<td></td>
<td>Ratio of the cluster energy to the track momentum</td>
<td>$E/p$</td>
</tr>
</tbody>
</table>
## Definitions of the shower shape variables


### Category Description Name

<table>
<thead>
<tr>
<th>Category</th>
<th>Description</th>
<th>Name</th>
<th>Loose</th>
<th>Tight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acceptance</td>
<td>$</td>
<td>\eta</td>
<td>&lt; 2.37, 1.37 &lt;</td>
<td>\eta</td>
</tr>
<tr>
<td>Hadronic leakage</td>
<td>Ratio of $E_T$ in the first sampling of the hadronic calorimeter to $E_T$ of the EM cluster (used over the range $</td>
<td>\eta</td>
<td>&lt; 0.8$ and $</td>
<td>\eta</td>
</tr>
<tr>
<td></td>
<td>Ratio of $E_T$ in all the hadronic calorimeter to $E_T$ of the EM cluster (used over the range $0.8 &lt;</td>
<td>\eta</td>
<td>&lt; 1.37$)</td>
<td>$R_{\text{had}}$</td>
</tr>
<tr>
<td>EM Middle layer</td>
<td>Ratio in $\eta$ of cell energies in $3 \times 7$ versus $7 \times 7$ cells</td>
<td>$R_{\eta}$</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td>Lateral width of the shower</td>
<td>$w_2$</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td>Ratio in $\phi$ of cell energies in $3 \times 3$ and $3 \times 7$ cells</td>
<td>$R_{\phi}$</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>EM Strip layer</td>
<td>Shower width for three strips around maximum strip</td>
<td>$w_{s,3}$</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Total lateral shower width</td>
<td>$w_{s,\text{tot}}$</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fraction of energy outside core of three central strips but within seven strips</td>
<td>$F_{\text{side}}$</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Difference between the energy associated with the second maximum in the strip layer, and the energy reconstructed in the strip with the minimal value found between the first and second maxima</td>
<td>$\Delta E$</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ratio of the energy difference associated with the largest and second largest energy deposits over the sum of these energies</td>
<td>$E_{\text{ratio}}$</td>
<td>✓</td>
<td></td>
</tr>
</tbody>
</table>

Table 5: Variables used for loose and tight photon identification cuts.
## Primary electron trigger progression with inst. luminosity

<table>
<thead>
<tr>
<th>Peak instantaneous luminosity $[10^{34} \text{ cm}^{-2} \text{s}^{-1}]$</th>
<th>HLT $E_T$ threshold [GeV]</th>
<th>HLT ID</th>
<th>HLT track isolation</th>
<th>L1 $E_T$ threshold [GeV]</th>
<th>L1 isolation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$&lt; 0.8$ (Run 1)</td>
<td>e</td>
<td>24</td>
<td>medium</td>
<td>-</td>
<td>L1EM</td>
</tr>
<tr>
<td>$&lt; 0.5$ (Run 2)</td>
<td>e</td>
<td>24</td>
<td>lmedium</td>
<td>-</td>
<td>L1EM</td>
</tr>
<tr>
<td>$&lt; 1.0$ (Run 2)</td>
<td>e</td>
<td>24</td>
<td>lhtight</td>
<td>ivarloose</td>
<td>L1EM</td>
</tr>
<tr>
<td>$&gt; 1.0$ (Run 2)</td>
<td>e</td>
<td>26</td>
<td>lhtight</td>
<td>ivarloose</td>
<td>L1EM</td>
</tr>
<tr>
<td>backup (Run 2)</td>
<td>e</td>
<td>28</td>
<td>lhtight</td>
<td>ivarloose</td>
<td>L1EM</td>
</tr>
</tbody>
</table>