The ATLAS Electron and Photon Trigger

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ACAT, Seattle, August 21, 2017
Introduction the Photon and Electron ($e/\gamma$) Trigger at ATLAS

- Brief tour of the most important aspects of the ATLAS detector for $e/\gamma$ triggers
- Motivation and design
- Run 2 upgrades to the $e/\gamma$ trigger system

Calibration and Identification

- Energy calibration and identification methods
- Recent improvements

$e/\gamma$ Trigger Performance in 2016 and early 2017

- Performance with full 2016 dataset
- Early look at performance in 2017 data
Introduction to the ATLAS Electron and Photon Trigger
The ATLAS detector

**Calorimeter**
- Finely segmented calorimeter system
- Liquid Argon 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
e/γ triggers are essential at ATLAS

- SM measurements / backgrounds, diphoton, $W \rightarrow e\nu$, $Z \rightarrow ee$, ...

$$\sigma = \frac{N_{\text{obs}} - N_{\text{background}}}{L \cdot \epsilon \cdot \text{BR}}$$

- New physics, SUSY, $Z' \rightarrow ee$, $G_{KK} \rightarrow \gamma\gamma$, ...

Higher than ever instantaneous luminosity

- Run 1 peak lumi: $7.73 \times 10^{33}\text{cm}^2\text{s}^{-1}$
- Run 2 peak lumi: $16.8 \times 10^{33}\text{cm}^2\text{s}^{-1} > 2\times$ larger!
- Want to keep as much physics as possible
- 25 ns bunch spacing $\rightarrow$ 40 MHz bunch crossing rate
- Only $\sim 1$ kHz can be recorded
- Need to keep the rates under control
The Electron and Photon Trigger (L1)

Level 1 (L1) Trigger

- $e/\gamma$ L1 trigger decisions start from calorimeter input (L1Calo)
- 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 (2×2 trigger towers) identifies local energy maxima for reconstruction of EM clusters
- Jet rejection using energy sum in hadronic isolation ring and core

Run 2 Upgrades

- New Multi Chip Module (nMCM) in Pre-Processor $\rightarrow$ improved energy resolution
- Firmware upgrade of Cluster Processor Module (CPM): $E_T$-dependent EM / hadronic core isolation cuts with a precision of $\Delta E_T \sim 0.5$ GeV.
- New Extended Common Merger Module (CMX) $\rightarrow$ doubles number of $E_T$ thresholds
High Level Trigger (HLT)
- Full detector granularity used at HLT in ROIs
- Photons identified with EM cluster with no matching track requirement
- Electrons identified with EM clusters with matching charged track and minimum number of hits in inner Silicon tracking devices

Run 2 Upgrades
- Two-level HLT in Run 1 composed of Level 2 (L2) and Event Filter (EF)
- Now merged to run on a single computer farm
- Common data preparation for fast and precision online reconstruction
- Final online precision improved
  - New electron and photon energy calibrations
  - New electron identification based on Likelihood of relevant variables

Based on MVA techniques
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
- Suffers in the crack region ($1.37 < |\eta| < 1.52$) between the barrel and endcap EM calorimeter (as expected)
Common set of discriminating variables used for photon and electron ID

- **Likelihood-based** MVA method for electron ID
- **Cut-based** selection for photon ID

### Variables and Position

<table>
<thead>
<tr>
<th>Strips</th>
<th>2nd</th>
<th>Had.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ratios</td>
<td>$f_1$, $f_{\text{side}}$</td>
<td>$R_\eta^*$, $R_\phi$</td>
</tr>
<tr>
<td>Widths</td>
<td>$w_{s,3}$, $w_{s,\text{tot}}$</td>
<td>$w_{\eta,2}^*$</td>
</tr>
<tr>
<td>Shapes</td>
<td>$\Delta E$, $E_{\text{ratio}}$</td>
<td><em>Used in PhotonLoose.</em></td>
</tr>
</tbody>
</table>

### Energy Ratios

- $R_\eta = \frac{E_{3\times7}^{S_2}}{E_{7\times7}^{S_1}}$
- $R_\phi = \frac{E_{3\times3}^{S_2}}{E_{3\times7}^{S_1}}$
- $R_{\text{Had}} = \frac{E_{T}^{\text{Had}}}{E_T}$
- $f_1 = \frac{E_{S_1}^{S_1}}{E_{T}^{\text{Tot.}}}$

### Shower Shapes

- $E_{\text{ratio}} = \frac{E_{\text{max,1}}^{S_1} - E_{\text{max,2}}^{S_1}}{E_{\text{max,1}}^{S_1} + E_{\text{max,2}}^{S_1}}$
- $\Delta E = E_{\text{max,2}}^{S_1} - E_{\text{min}}^{S_1}$

### Widths

- $w_{\eta,2} = \sqrt{\sum E_i \eta_i^2 - \left(\sum E_i \eta_i \right)^2}$

Width in a 3x5 ($\Delta \eta \times \Delta \phi$) region of cells in the second layer.
Electron ID

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

$$d_L = \frac{\mathcal{L}_S}{\mathcal{L}_S - \mathcal{L}_B}, \quad \mathcal{L}_{S(B)}(\vec{x}) = \prod_{i=1}^{n} P_{S(B),i}(x_i)$$

- 20% lower rate for same efficiency as cut-based selection used in Run 1
- LH default for electrons at HLT in Run 2

- Three ID operating points (OPs) defined for electron ID
  - Referred to as *loose*, *medium*, *tight*
  - Each uses the same variables to define the LH discriminant
  - Different selection on the LH discriminant for each OP
  - Sample selected by each OP are subsets of one another

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**ATLAS Simulation Preliminary**

- $\sqrt{s} = 13$ TeV
- $Z \rightarrow ee$ Simulation

<table>
<thead>
<tr>
<th>$E_T$ [GeV]</th>
<th>Identification Efficiency</th>
<th>Loose</th>
<th>Medium</th>
<th>Tight</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>0.7</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>0.75</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>40</td>
<td>0.8</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>0.85</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>60</td>
<td>0.9</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>70</td>
<td>0.95</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>80</td>
<td>1</td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

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- $\sqrt{s} = 13$ TeV
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<th>Medium</th>
<th>Tight</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>0.001</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>40</td>
<td>0.002</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>0.003</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>60</td>
<td>0.004</td>
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<td></td>
<td></td>
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<tr>
<td>70</td>
<td>0.005</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>80</td>
<td>0.006</td>
<td></td>
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</tbody>
</table>
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 (24 GeV for single electron trigger) for as long as possible
- Tightening the ID level at HLT can significantly reduce the rate e.g. $lh_{medium} \rightarrow lh_{tight}$ gives around 45% rate reduction
Run 2 Trigger Progression

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
- L1 progression:
  - Non-isolated $\rightarrow$ isolated
  - $E_T$ threshold 18 $\rightarrow$ 22 $\rightarrow$ 24 GeV
- HLT progression:
  - Isolated, likelihood (LH) based electrons default in Run 2
  - $E_T$ threshold 24 $\rightarrow$ 26 $\rightarrow$ 28
  - medium $\rightarrow$ tight
- Without improvement, tighter selections can harm the physics goals of the experiment
**New Medium L1 working point**

- New in 2017
- \( V \) indicates pseudorapidity dependent \( E_T \) threshold
- \( H \) indicates upper cut on hadronic energy behind em cluster
- \( I(M) \) indicates isolation requirement
- Significant rate reduction for small efficiency reduction

<table>
<thead>
<tr>
<th>Level-1 ( E_T )</th>
<th>Efficiency loss</th>
<th>Rate reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>22 GeV</td>
<td>1.3%</td>
<td>14.6%</td>
</tr>
<tr>
<td>24 GeV</td>
<td>1.0%</td>
<td>10.8%</td>
</tr>
</tbody>
</table>

![Efficiency graph](image1)

**Table 1**: Level-1 trigger efficiency loss and rate reduction applying the new medium isolation on the electromagnetic (EM) clusters with \( E_T > 22 \text{ GeV} \) and \( E_T > 24 \text{ GeV} \) with respect to the default isolation used in 2016 data taking.

Medium (default) isolation is applied for EM clusters with \( E_T < 50 \text{ GeV} \), where the transverse energy in an annulus of calorimeter towers around the EM candidate relative to the EM cluster \( E_T \) is required to be less than \( \max\{2 \text{ GeV}, \frac{E_T}{8}\} \) or \( \max\{1 \text{ GeV}, \frac{E_T}{2}, 2 \text{ GeV}\} \). The efficiency is measured with respect to the offline reconstructed electron candidates satisfying a likelihood-based tight identification and with \( E_T \) at least 5 GeV above the Level-1 trigger threshold. The efficiencies are measured with a tag-and-probe method using \( Z \rightarrow \text{ee} \) decays in data using trigger reprocessings. The rate predictions are obtained with a trigger reprocessing of enhanced bias data extrapolated to a luminosity of \( 2 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1} \).

New Level-1 EM medium isolation cuts have been implemented to reduce the rate of the lowest unprescaled Level-1 triggers while keeping the efficiency loss as low as possible, to cope with the increasing luminosity in 2017, and are compared with the default isolation cuts used for 2016 data taking.
Upgrade to fast calorimeter preselection step

- Alternative approach to cut-based methods
- Neural network classifier performs particle ID targeting high efficiency of the complete trigger chain with significant reduction on the number of calls to tracking (usually much heavier in terms of computing)
- Explores conic geometry, building rings in layers of the calorimeter
- Sum of energy in a ring over sum of energy in all rings provides a vector of discriminating variables (generalise shower shapes)

Total number of Rings per layer (covering 0.4 x 0.4 region in \( \eta \times \varphi \))

<table>
<thead>
<tr>
<th></th>
<th>PS</th>
<th>EM1</th>
<th>EM2</th>
<th>EM3</th>
<th>HAD1</th>
<th>HAD2</th>
<th>HAD3</th>
</tr>
</thead>
<tbody>
<tr>
<td>PS</td>
<td>8</td>
<td>64</td>
<td>8</td>
<td>8</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
</tbody>
</table>
Upgrade to fast calorimeter preselection step

- Achieves $\times 2$ better background rejection with efficiency almost unchanged
- Plots refer to 2016 tunes, smoother efficiency in 2017
- Ringer algorithm now the default in electron triggers
\textbf{e/\gamma Trigger Performance in 2016 and 2017}
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
- Excellent data / MC agreement

![Graph showing electron trigger performance](image_url)
Electron trigger performance for full 2016 dataset

- *lhvloose* trigger used for di-electron triggers
- Efficiency measured for single leg *e17_lhvloose_nod0*
- Excellent data / MC agreement
A first look at 2017 data

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

Photon trigger efficiency for full 2016 dataset

- Measured using Bootstrap method using L1 trigger
- Fully efficient at 5 GeV above threshold
- Lowest threshold triggers:
  - Single photon - g140_loose
  - Multi photon - g35_loose_g25_loose

![Graph showing data for HLT_g35_loose_g25_loose, HLT_g140_loose, HLT_2g22_tight, HLT_g140_loose]

![Graph showing trigger efficiency for offline photon E_T > 27 GeV, E_T > 30 GeV, E_T > 40 GeV, and E_T > 150 GeV]

![Graph showing trigger efficiency for offline photon E_T > 27 GeV, E_T > 30 GeV, E_T > 40 GeV, and E_T > 150 GeV]

![Graph showing trigger efficiency for offline photon E_T > 27 GeV, E_T > 30 GeV, E_T > 40 GeV, and E_T > 150 GeV]
A first look at 2017 data

- Good trigger performance, excellent data / MC agreement
- Robust against pileup
Conclusions

**Improved L1**
- Run 2 upgrades improve resolution and granularity
- New working point gives significant rate reduction

**Improved HLT**
- Run 2 likelihood IDs improve cut-based ID used in Run 1
- Further improvements from ringer algorithm at L2 (fast calorimeter step)

**Electron and photon triggers performing well in Run 2**
- Consistent performance for 2015-2017 data taking
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 $E_T^{miss}$
- 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, $\sqrt{(\sum E_i \eta_i^2)/(\sum E_i) - ((\sum E_i \eta_i)/(\sum E_i))^2}$, 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 x 5 cells</td>
<td>$w_{\eta2}$</td>
</tr>
<tr>
<td></td>
<td>Ratio of the energy in 3x3 cells over the energy in 3x7 cells centered at the electron cluster position</td>
<td>$R_{\phi}$</td>
</tr>
<tr>
<td></td>
<td>Ratio of the energy in 3x3 cells over the energy in 7x7 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, $\sqrt{(\sum E_i (i - i_{\text{max}})^2)/(\sum E_i)}$, 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>$w_{\text{stot}}$</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>$e_{\text{ProbabilityHT}}$</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


<table>
<thead>
<tr>
<th>Category</th>
<th>Description</th>
<th>Name</th>
<th>Loose</th>
<th>Tight</th>
</tr>
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<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>
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<td>✓</td>
</tr>
<tr>
<td></td>
<td>Ratio in $\phi$ of cell energies in $3\times3$ and $3\times7$ 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>
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<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>
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<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>
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<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>
Electron Identification

Pileup Dependence

- Shower shape variables are dependent on level of pileup in the event
- Increased instantaneous luminosity + higher $\sqrt{s}$ → greatest pileup for 2017 data taking
- Cut on discriminant is loosened as a function of the number of primary vertices to maintain efficiency at high pileup

Isolation

- Isolation requirement provides further discrimination against electrons originating from converted photons and hadronic activity
- Track isolation used at HLT
- Defined as $p_T$ sum of non electron associated tracks in a cone surrounding the electron candidate