The ATLAS Electron and Photon Trigger

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Outline

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

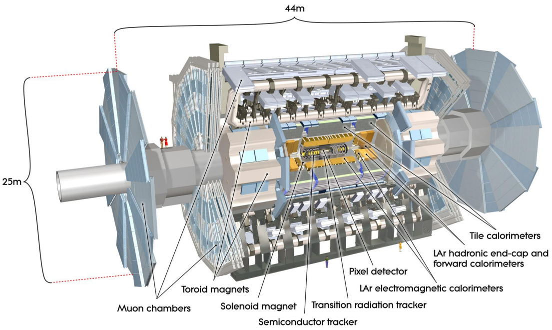
- Energy calibration and identification methods

e/γ **Trigger Performance in Run 2**

- e/γ trigger performance in 2016 + 2017 data

Introduction to the ATLAS Electron and Photon Trigger

The ATLAS detector



https://cds.cern.ch/images/CERN-GE-0803012-01

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/γ) 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, $W \to e\nu$, $Z \to ee$, ...

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

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

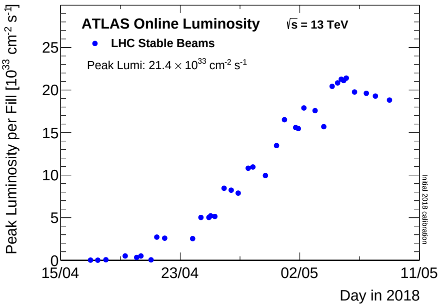
Year	$\sqrt{s}$ [TeV]	Peak inst. lumi [10^{33} cm^{-2}s^{-1}]	Pileup $<\mu>$	$\int L$ fb^{-1}
2011	7	3.65	9.1	5.08
2012	8	7.73	20.7	21.3
2015	13	5.0	13.4	3.9
2016	13	13.8	25.1	35.6
2017	13	20.9	37.8	46.9
2018	13	6.9	21.4	$\sim$ 60

2018 values correct at time of writing

Higher than ever instantaneous luminosity

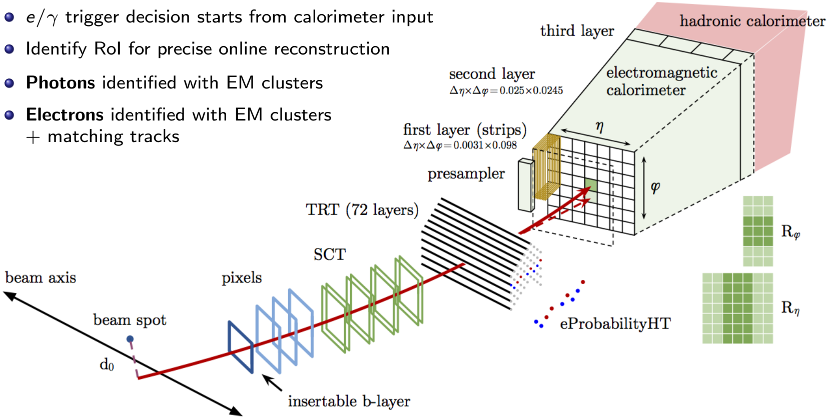
- Run 1 peak lumi: 7.73×10^{33}cm^{2}s^{-1}
- Run 2 peak lumi: 21.4×10^{33}cm^{2}s^{-1} $> 2\times$ larger!
- Want to keep as much physics as possible
- Online e/γ selection should be as close as possible to offline to keep efficiency high
- 25 ns bunch spacing $\to$ 40 MHz bunch crossing rate
- Only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

https://atlas.web.cern.ch/Atlas/GROUPS/DATAPREPARATION/PublicPlots/2018/DataSummary/figs/peakLumiByFill.pdf



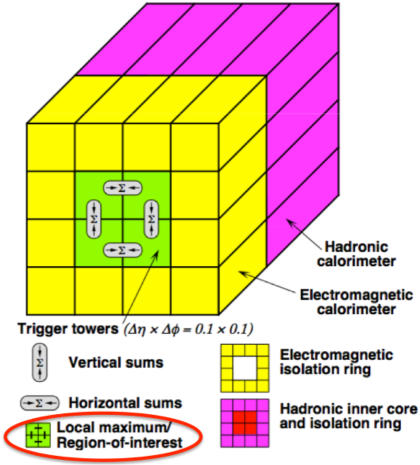
The ATLAS e/γ triggers

- e/γ 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 0.1×0.1
- η-dependent E_{T} thesholds take into account energy loss in detector material
- Sliding-window algorithm (2×2 trigger towers) identifies local energy maxima (RoI)
- Jet rejection using energy sum in hadronic isolation ring and core



L1 Naming conventions: **V** indicates η dependent E_{T} threshold, **H** indicates hadronic core isolation, **I** indicates electromagnetic isolation

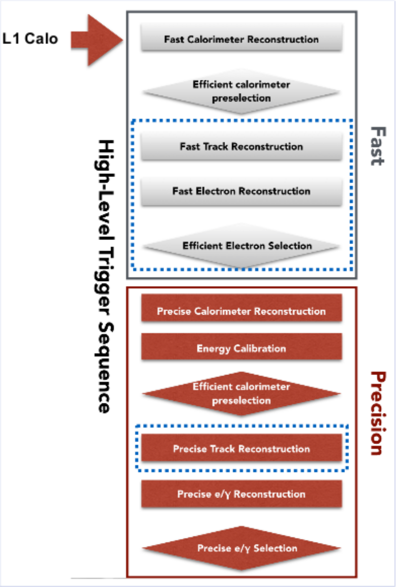
The Electron and Photon Trigger (HLT)

High Level Trigger (HLT)

- e/γ 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:
  - $p_T^{track} > 1$ GeV, $\Delta\eta < 0.3$ for $E_T < 20$ GeV
  - $p_T^{track} > 2$ GeV, $\Delta\eta > 0.2$ for $E_T > 20$ GeV



High Level Trigger (HLT)

- e/γ HLT algorithm flow consists of two main steps
  - Fast algorithms to reject events early
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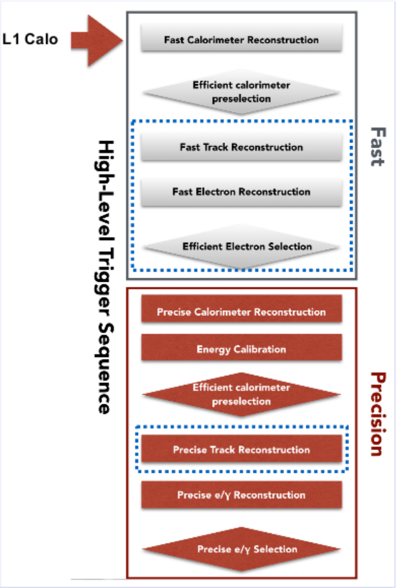
Precision algorithm step:

- 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)

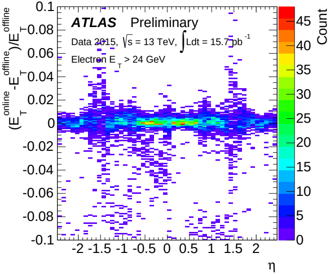


Calibration and Identification

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

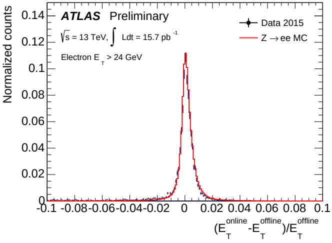
https://twiki.cern.ch/twiki/pub/AtlasPublic/EgammaTriggerPublicResults/EleETResVsEta.pdf



Energy resolution

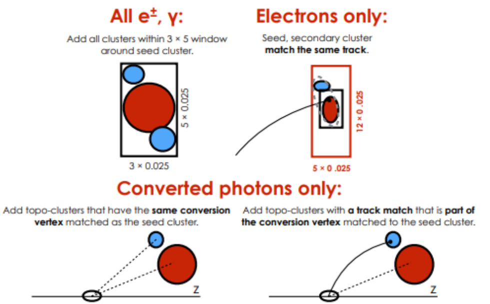
- Excellent resolution in most regions
- Larger deviations in the crack region ($1.37 < |\eta| < 1.52$) where significant quantity of material servicing the detector causes energy loss and reduction in performance

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



An alternative algorithm: Topological Superclusters

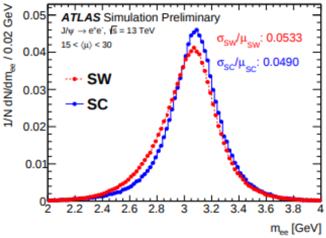
https://cds.cern.ch/record/2298955/files/ATL-PHYS-PUB-2017-022.pdf?version=1



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, $\mathcal{O}(100\ \text{MeV})$

https://cds.cern.ch/record/2298955/files/ATL-PHYS-PUB-2017-022.pdf?version=1



SC = supercluster **SW** = sliding window

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

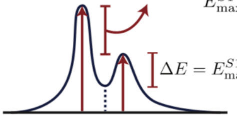
Variables and Position

	Strips	2nd	Had.
Ratios	f_1, f_{side}	R_η*, R_ϕ	$R_{\text{Had.}}$*
Widths	$w_{s,3}$, $w_{s,tot}$	$w_{\eta,2}$*	-
Shapes	ΔE, E_{ratio}		

* Used in PhotonLoose.

Shower Shapes

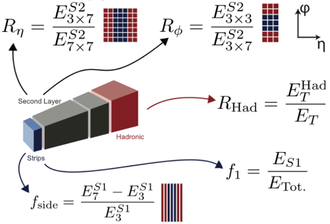
$$E_{\text{ratio}} = \frac{E^{S1}_{\text{max},1} - E^{S1}_{\text{max},2}}{E^{S1}_{\text{max},1} + E^{S1}_{\text{max},2}}$$



$$\Delta E = E^{S1}_{\text{max},2} - E^{S1}_{\text{min}}$$

Energy Ratios

$$R_\eta = \frac{E^{S2}_{3\times7}}{E^{S2}_{7\times7}} \qquad R_\phi = \frac{E^{S2}_{3\times3}}{E^{S2}_{3\times7}}$$



$$R_{\text{Had}} = \frac{E_T^{\text{Had}}}{E_T}$$

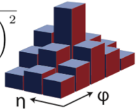
$$f_1 = \frac{E_{S1}}{E_{\text{Tot.}}}$$

$$f_{\text{side}} = \frac{E_7^{S1} - E_3^{S1}}{E_3^{S1}}$$

Widths

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

Width in a 3x5 (Δη×Δφ) 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 $d_{\mathcal{L}}$

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

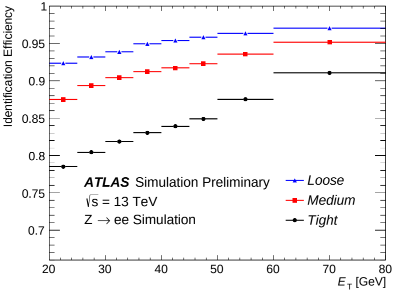
- 20% lower rate for same efficiency as cut-based selection used in Run 1

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

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2016-024/fig_01a.png



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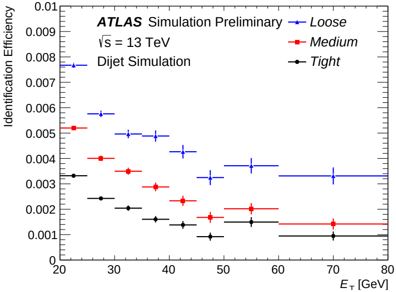


Online Electron Identification

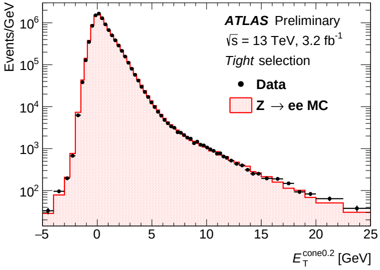
Keep as close as possible to offline selection

- 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)
- μ instead of N_{vtx} for the pileup correction

Isolation

- Isolation requirement provides further discrimination against eg. electrons originating from converted photons and hadronic activity
- Variable track isolation applied for electrons at HLT
  - ivarloose: ptvarcone20/$p_T < 0.1$
  - p_T sum of non-electron associated tracks in cone of size 10 GeV / p_T surrounding electron candidate (maximum cone size 0.2)
- Calometric isolation now applied for photons at HLT
  - Using the E_T sum of topo-clusters in a cone surrounding the photon candidate
- Note: no background subtraction applied in figures

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2016-024/fig_02a.pdf



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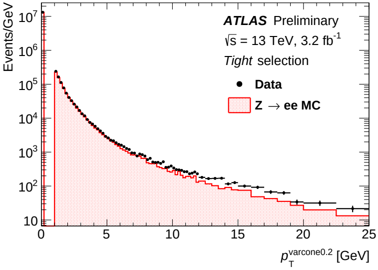
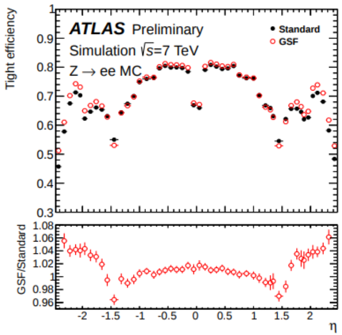


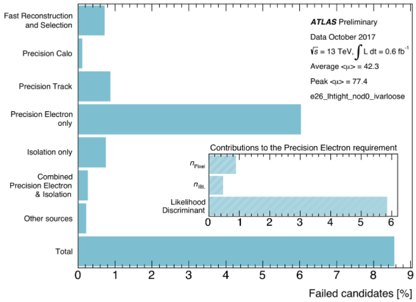
Online Tracking

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

https://cds.cern.ch/record/1449796/files/ATLAS-CONF-2012-047.pdf?version=1





Gaussian Sum Filter (GSF)

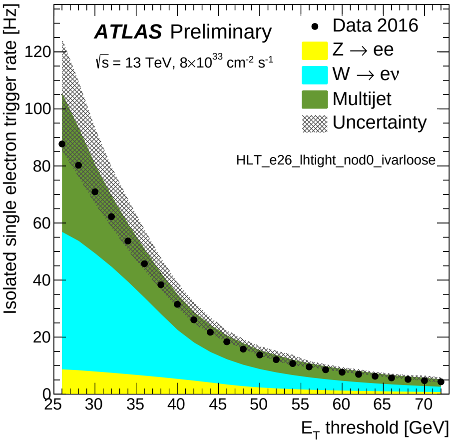
- Generalisation of the Kalman fitter, splitting experimental noise into Gaussian components, using Kalman filter to process each one
- Improved reconstruction efficiency (up to 6%) for most η
- Introduced offline in 2012, soon to be implemented at HLT
- Expect similar improvements due to improved resolution in tracking variables

Electron Trigger Rates

https://twiki.cern.ch/twiki/pub/AtlasPublic/EgammaTriggerPublicResults/el_trigger_composition_8e33.pdf

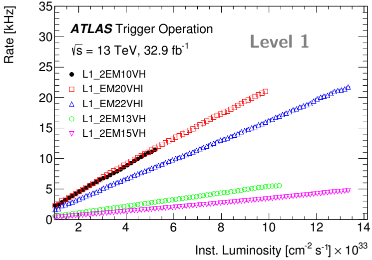
Trigger rates depend heavily on E_T threshold

- Single electron dominated by $W \to e\nu$
- 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. *lhmedium* $\to$ *lhtight* gives $\sim$ 20% rate reduction

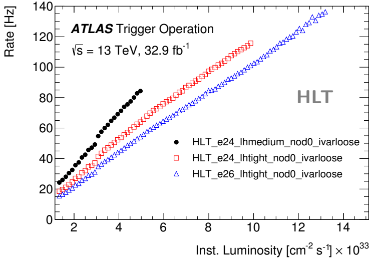


Run 2 Trigger Progression

https://twiki.cern.ch/twiki/pub/AtlasPublic/EgammaTriggerPublicResults/L1_EM_Full2016.pdf



https://twiki.cern.ch/twiki/pub/AtlasPublic/EgammaTriggerPublicResults/Rate_single_electron_full2016.pdf



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

Year		HLT E_T	HLT	HLT track		L1 E_T	L1
2015	e	24	lhmedium	no isolation	L1EM	20V	H
2016	e	26	lhtight	ivarloose	L1EM	22V	HI
2017	e	26	lhtight	ivarloose	L1EM	22V	HI
2018	e	26	lhtight	ivarloose	L1EM	22V	HI

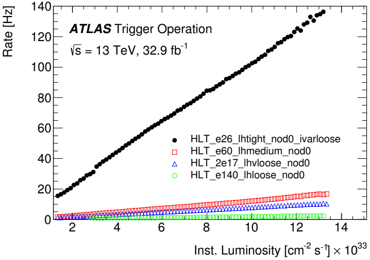
e/γ Trigger Performance in Run 2

Electron Trigger Performance

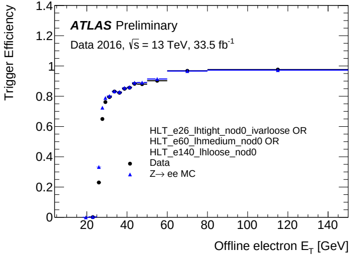
Electron trigger performance for full 2016 dataset

- Efficiency measured using *Tag and Probe* method with $Z \to ee$
- 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

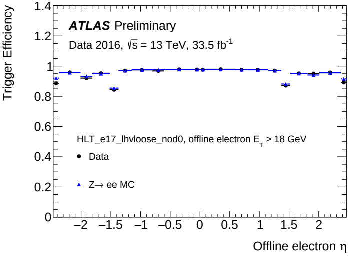
https://twiki.cern.ch/twiki/pub/AtlasPublic/EgammaTriggerPublicResults/Rate_electron_full2016.pdf



https://twiki.cern.ch/twiki/pub/AtlasPublic/EgammaTriggerPublicResults/Eff_eta_singleOR_full2016.pdf



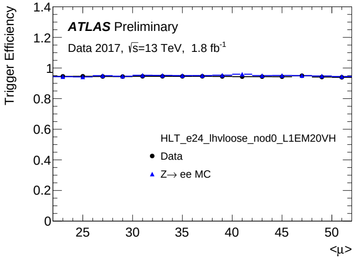
https://twiki.cern.ch/twiki/pub/AtlasPublic/EgammaTriggerPublicResults/Eff_eta_e17_lhvloose_nod0_full2016.pdf



Electron trigger performance in 2017

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

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/EgammaTriggerPublicResults#Electron_and_photon_trigger_AN1



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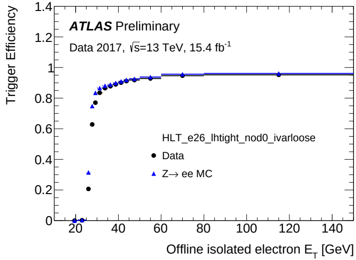

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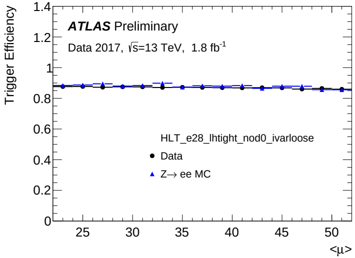
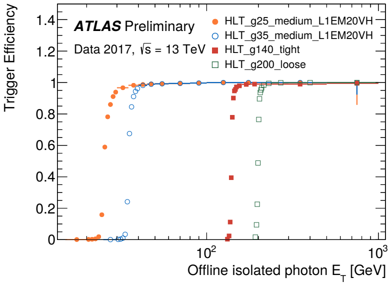


Photon Trigger Performance

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



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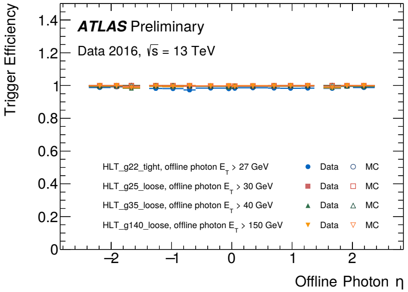


Conclusions

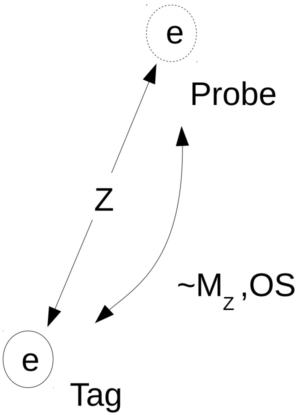
Performance in Run 2

- 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

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

Type	Description	Name
Hadronic leakage	Ratio of E_T in the first layer of the hadronic calorimeter to E_T of the EM cluster (used over the range $\|\eta\| < 0.8$ or $\|\eta\| > 1.37$)	R_{had1}
	Ratio of E_T in the hadronic calorimeter to E_T of the EM cluster (used over the range $0.8 < \|\eta\| < 1.37$)	R_{had}
Back layer of EM calorimeter	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.	f_3
Middle layer of EM calorimeter	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 η_i is the pseudorapidity of cell i and the sum is calculated within a window of 3×5 cells	$w_{\eta 2}$
	Ratio of the energy in 3×3 cells over the energy in 3×7 cells centered at the electron cluster position	R_ϕ
	Ratio of the energy in 3×7 cells over the energy in 7×7 cells centered at the electron cluster position	R_η
Strip layer of EM calorimeter	Shower width, $\sqrt{(\Sigma E_i (i - i_{max})^2)/(\Sigma E_i)}$, 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 η, and i_{max} is the index of the highest-energy strip	w_{stot}
	Ratio of the energy difference between the largest and second largest energy deposits in the cluster over the sum of these energies	E_{ratio}
	Ratio of the energy in the strip layer to the total energy in the EM accordion calorimeter	f_1
Track conditions	Number of hits in the innermost pixel layer; discriminates against photon conversions	n_{Blayer}
	Number of hits in the pixel detector	n_{Pixel}
	Number of total hits in the pixel and SCT detectors	n_{Si}
	Transverse impact parameter with respect to the beam-line	d_0
	Significance of transverse impact parameter defined as the ratio of d_0 and its uncertainty	d_0/σ_{d_0}
	Momentum lost by the track between the perigee and the last measurement point divided by the original momentum	$\Delta p/p$
TRT	Likelihood probability based on transition radiation in the TRT	eProbabilityHT
Track-cluster matching	$\Delta\eta$ between the cluster position in the strip layer and the extrapolated track	$\Delta\eta_1$
	$\Delta\phi$ between the cluster position in the middle layer and the track extrapolated from the perigee	$\Delta\phi_2$
	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	$\Delta\phi_{res}$
	Ratio of the cluster energy to the track momentum	E/p

Photon Discriminating Variables

Category	Description	Name	Loose	Tight
Acceptance	$\|\eta\| < 2.37$, $1.37 < \|\eta\| < 1.52$ excluded	–		✓
Hadronic leakage	Ratio of E_T in the first sampling of the hadronic calorimeter to E_T of the EM cluster (used over the range $\|\eta\| < 0.8$ and $\|\eta\| > 1.37$)	R_{had_1}	✓	✓
	Ratio of E_T in all the hadronic calorimeter to E_T of the EM cluster (used over the range $0.8 < \|\eta\| < 1.37$)	R_{had}	✓	✓
EM Middle layer	Ratio in η of cell energies in 3×7 versus 7×7 cells	R_η	✓	✓
	Lateral width of the shower	w_2	✓	✓
	Ratio in ϕ of cell energies in 3×3 and 3×7 cells	R_ϕ		✓
EM Strip layer	Shower width for three strips around maximum strip	$w_{s\,3}$		✓
	Total lateral shower width	$w_{s\,\text{tot}}$		✓
	Fraction of energy outside core of three central strips but within seven strips	F_{side}		✓
	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	ΔE		✓
	Ratio of the energy difference associated with the largest and second largest energy deposits over the sum of these energies	E_{ratio}		✓

Run 2 Trigger Progression

Primary electron trigger progression with inst. luminosity

Peak instantaneous luminosity [10^{34} cm^{-2}s^{-1}]		HLT E_T threshold [GeV]	HLT ID	HLT track isolation		L1 E_T threshold [GeV]	L1 isolation
$<$ 0.8 (Run 1)	e	24	medium	-	L1EM	18V	H
$<$ 0.5 (Run 2)	e	24	lhmedium	-	L1EM	18V	H
$<$ 1.0 (Run 2)	e	24	lhtight	ivarloose	L1EM	18V	HI
$>$ 1.0 (Run 2)	e	26	lhtight	ivarloose	L1EM	22V	HI
backup (Run 2)	e	28	lhtight	ivarloose	L1EM	24V	HI