Performance of the photon reconstruction and identification in ATLAS

Phillip Hamnett
on behalf of the ATLAS collaboration

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Motivation

The ATLAS detector

Reconstruction of photons in ATLAS

Identification of photons in ATLAS

Strategy for Run 2

Conclusion

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Performance of the photon reconstruction and identification in ATLAS
Photons in ATLAS

Demanding requirements placed on γ reconstruction and identification in ATLAS

- Higgs studies (e.g. \( H \rightarrow \gamma\gamma \)).
  - High efficiency.
  - Superb background rejection.
- Standard model measurements.
- High \( E_T \) signatures for new exotic physics.

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The ATLAS detector

A general purpose detector

- Designed to make a broad range of measurements.
- To search for beyond the Standard Model physics.

- Detector consists of:
  - An inner tracker system.
  - A electromagnetic and hadronic calorimeter.
  - A muon system.
  - Magnets, for bending charged particles.

Electromagnetic calorimeter

- Sampling calorimeter (lead and liquid argon).
- Barrel and two end caps provide coverage $|\eta| < 2.47$.
- Additional ‘pre-sampler’ in region $|\eta| < 1.8$.
- Accordion geometry to ensure full $\phi$ coverage.
- $165 \times 10^3$ readout channels.

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Performance of the photon reconstruction and identification in ATLAS
Reconstruction Strategy

Cluster size in $\eta$ and $\phi$ for different particle in Run 1.

<table>
<thead>
<tr>
<th>Particle type</th>
<th>Barrel</th>
<th>Endcap</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron</td>
<td>$0.075 \times 0.175$</td>
<td>$0.125 \times 0.125$</td>
</tr>
<tr>
<td>Converted photon</td>
<td>$0.075 \times 0.175$</td>
<td>$0.125 \times 0.125$</td>
</tr>
<tr>
<td>Unconverted photon</td>
<td>$0.075 \times 0.125$</td>
<td>$0.125 \times 0.125$</td>
</tr>
</tbody>
</table>

Involves several steps

1. Search for energy clusters within the second layer of the EM calorimeter.
2. Create ‘preclusters’ with $p_T > 2.5$ GeV.
3. Clusters matched to tracks.
   - Matched based on position.
   - Use track information to classify particles: electron, converted photon, or unconverted photon.
4. Rebuild clusters, where the cluster size depends on the particle type and location in the calorimeter.
Photon Conversions

Conversions and pileup

- Photons often interact with material before the calorimeter, and convert into an electron/positron pair.
- These are ‘converted’ photons. If this doesn’t happen, then they are ‘unconverted’ photons.
- Converted photons can be categorised as having one or two tracks.
- Pileup can lead to misreconstructing unconverted photons as converted photons.

This is under control:

- 3% migration of 2-track conversions to 1-track conversions.
  → 1-track conversion is when either the two tracks are highly collimated or one track is too soft to be reconstructed.
- Fraction of converted vs unconverted photon candidates is stable to 1% between extreme pileup values.

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Performance of the photon reconstruction and identification in ATLAS.
Identifying photons with ATLAS

Definitions

- Identification performed by applying cuts over discriminating variables (shower shapes) from the calorimeter layers.
- There is a ‘loose’ and ‘tight’ selection of cuts.
- Cuts are binned in $\eta$, and by converted/unconverted photons.

Measuring ID efficiency

- There are three data driven methods for measuring ID efficiency:
  1. Radiative Z decays.
  2. Electron extrapolation ($Z \to ee$).
  3. The matrix method.
- Results are for 7 TeV, but the same methods are used in 8 TeV data, which provides a larger $E_T$ range.
- See ATLAS-CONF-2012-123 for more details.

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Isolated photons

- Computed from topological clusters with $\Delta R < 0.4$.
- Pileup and underlying event contributions are suppressed using event-by-event ambient energy density correction.
- Isolation is applied independently of the identification.
- But is used by all analyses, and the data driven identification methods.
- Varying isolation has little impact on ID efficiency.

ID efficiency as a function of transverse energy for different isolation cuts. This plot is for 7 TeV and uses all cells in the isolation cone. The more recent data driven methods use topological clusters.

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Data driven methods

Radiative Z decays - $15 < E_T < 50$ GeV

ATLAS Preliminary

- Look at $Z \rightarrow ee$ and $Z \rightarrow \mu\mu$ events with a radiated photon.
- Discriminating variables are unbiased because cuts are only kinematic.
- Method gives results in region $15 < E_T < 50$ GeV.
- Can combine the $ee$ and $\mu\mu$ channels, as they are independent.
- Only look at events where $80 < M_{ll\gamma} < 96$ GeV to reduce $Z+\text{jet}$ backgrounds.

Uncertainties

- Very pure sample $\approx 98\%$ at high $E_T$!
- Suffers from low statistics (due to low cross-section) $\rightarrow$ dominant uncertainty at $\approx 5\%$.

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Data driven methods

Electron extrapolation - $20 < E_T < 80$ GeV

Method

1. Look at discriminating variables for pure electron samples ($Z \rightarrow ee$).
2. Map them to photon discriminating variables using Smirnov transforms.

Advantages and disadvantages

- Very high statistics.
- Converted photons are very similar to electrons $\rightarrow$ easy to transform (5% uncertainty for Smirnov transform).
- Unconverted photons are less similar and have larger uncertainties (15% uncertainty for Smirnov transform).
Data driven methods

Matrix method - $20 < E_T < 500$ GeV

Using track isolation

- An inclusive sample of photons is selected using single photon triggers with energy greater than 20 GeV.
- This method relies on knowing the track isolation efficiency, so that we can separate signal from background events.

\[ \epsilon_{ID} = \frac{N_{Signal}^{\text{pass}}}{N_{\text{pass}}^{\text{Signal}}} + N_{\text{fail}}^{\text{Signal}} \]

- Where $N_{\text{Signal}}^{\text{pass}}$ is extracted by looking at track isolation.
- And efficiency of $N_{\text{Background}}^{\text{pass}}$ passing track isolation is derived in dedicated control regions.

Track isolation efficiency with 7 TeV data

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Data driven methods

Results

Methods at 7 TeV overlayed.

Independent methods

- Because the three methods are independent and the results overlap, they can be combined.
- Gives errors ranging from 1% to 10%.

7 and 8 TeV

- Methods are same between 7 and 8 TeV.
- However, 8 TeV gives wider range for $E_T$ distribution.

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Strategy for Run 2

Pileup dependence

- Identification efficiency depends on the amount of pileup.
- Attempted to mitigate this effect by reoptimising the rectangular cuts using most recent Monte Carlo samples, which cover a wider range of pileup.
- Average pileup:
  - 7 TeV: $<\mu> = 9.1$
  - 8 TeV: $<\mu> = 20.7$
  - 13 TeV: $<\mu>$ up to 40?

Improved ID efficiency dependence on high $E_T$

- ID efficiency ranges from 70% to 95%.
- Especially optimised for very high $E_T$, improving the signal yield for exotic searches.

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Summary and outlook

Reconstruction
- Fake conversions are under control.
- Robust reconstruction with respect to higher pileup conditions.

Identification
- Data driven methods from Run 1 give concurring results, which have been combined.
- New optimisation has been performed.
- Pileup dependence still exists, but at an acceptable level.
- Efficiency at high $E_T$ has been improved.
- We are ready for Run 2!
References

Links to external papers and images

- Complete list on eGamma public results
- Calorimeter Clustering Algorithms: Description and Performance
- Expected photon performance in the ATLAS experiment
- Efficiency of the photon identification for 2015
- Photon Shower Shapes Data/MC Comparisons from Z+\gamma events
- Event display \(\gamma / \pi^0\)
- The ATLAS Experiment at the CERN Large Hadron Collider
- ATLAS Photos
- Stability of photon conversion reconstruction with pile-up
- Photon conversion plots for Summer conferences 2011
- Photon reconstruction and performance in ATLAS and CMS
Inner detector

ATLAS inner detector

- Pixel detector has 3 silicon layers and the IBL.
- Semiconductor tracker: 4 silicon strip layers.
- Transition radiation tracker: Straw tube system.
- Altogether, provides fantastic tracking up to $|\eta| < 2.5$, as well as excellent vertex reconstruction, b-tagging, etc.

<table>
<thead>
<tr>
<th>Position</th>
<th>Resolution (µm)</th>
<th>Channels $(10 \times 10^6)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 removable barrel layer</td>
<td>$R_\phi = 12, z = 66$</td>
<td>16</td>
</tr>
<tr>
<td>2 barrel layers</td>
<td>$R_\phi = 12, z = 66$</td>
<td>81</td>
</tr>
<tr>
<td>4 end-cap disks</td>
<td>$R_\phi = 12, z = 77$</td>
<td>43</td>
</tr>
<tr>
<td>4 barrel layers</td>
<td>$R_\phi = 16, z = 580$</td>
<td>3.2</td>
</tr>
<tr>
<td>9 end-cap wheels</td>
<td>$R_\phi = 16, z = 580$</td>
<td>3.0</td>
</tr>
<tr>
<td>Axial barrel straws</td>
<td>170 (per straw)</td>
<td>0.1</td>
</tr>
<tr>
<td>Radial end-cap straws</td>
<td>170 (per straw)</td>
<td>0.32</td>
</tr>
</tbody>
</table>

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Performance of the photon reconstruction and identification in ATLAS
Calorimeter

ATLAS electromagnetic calorimeter

Details

- Energy resolution: \( \frac{\sigma(E)}{E} = \frac{10\%}{\sqrt{E}} \oplus 0.7\% \).
- Angular resolution: \( \frac{50\text{mrad}}{\sqrt{E}} \).
- Hermetic in \( \phi \).

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Performance of the photon reconstruction and identification in ATLAS
Photon conversions

Distributions of conversion positions

Photons more likely to convert in areas with high material

- Plots show the positions of the photon conversions taken from 7 TeV data.
- Can clearly see the 3 pixel layers and first 2 strip layers of the inner tracker.
- Photons which convert after $R = 0.8$ m are not defined as converted.

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Performance of the photon reconstruction and identification in ATLAS
Photon conversions

Fractions of converted and unconverted photons with 2015 data

Relative fractions of photon conversions

- Distributions are relatively flat with respect to transverse energy.
- But vary with $\eta$, due to different amounts of material in different $\eta$ regions.

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Performance of the photon reconstruction and identification in ATLAS
Pileup

Mean Number of Interactions per Crossing

Delivered Luminosity [pb⁻¹/0.5]

How pileup could contribute to fake conversion rates

- Very large difference in number of tracks when going from \( \mu = 2 \) to \( \mu = 20 \).
- Currently already averaging \( \mu = 20 \) for Run 2.
- Could increase to as much as an average of \( \mu = 40 \).
- More tracks increases the likelihood of any one track matching an unconverted or single-track converted photon.

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Performance of the photon reconstruction and identification in ATLAS
Variation in efficiency due to isolation

- Variations in isolation cause change in photon ID efficiency of up to $\approx 1\%$.
- Effect is the same on Monte Carlo and Data, so effectively cancels out.

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Discriminating variables for photon identification

**Variables and Position**

<table>
<thead>
<tr>
<th>Strips</th>
<th>2nd</th>
<th>Had.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ratios</td>
<td>$f_1$, $f_{side}$</td>
<td>$R_{\eta}^*$, $R_{\phi}$</td>
</tr>
<tr>
<td>Widths</td>
<td>$w_{5,3}$, $w_{5,\text{tot}}$</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**

$$R_{\eta} = \frac{E_{S1}^{3\times7}}{E_{T}^{7\times7}} \quad R_{\phi} = \frac{E_{S2}^{3\times3}}{E_{T}^{3\times3}}$$

$$R_{\text{Had.}} = \frac{E_{T}^{\text{Had.}}}{E_{T}}$$

$$f_{\text{side}} = \frac{E_{S1}^{7\times3} - E_{S1}^{3\times3}}{E_{T}^{3\times3}}$$

**Shower Shapes**

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

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

**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 ($\Delta\eta \times \Delta\phi$) region of cells in the second layer.

$$w_s = \sqrt{\frac{\sum E_i (i - i_{\text{max}})^2}{\sum E_i}}$$

$w_{s3} = w_s$ uses 3 strips in $\eta$; $w_{s\text{tot}}$ is defined similarly, but uses 20 strips.

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Distributions

Data-MC comparison for identification discriminating variables

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Efficiency vs pileup

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Efficiency for Run 2

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Performance of the photon reconstruction and identification in ATLAS
Radiative Z decays

Event selection

1. Two opposite charged leptons, $p_T > 15$ GeV, $|\eta| < 2.47$.

2. For muon channel:
   - Require one hit for each muon in pixel tracker, and 6 hits in SCT.
   - Isolation: ratio of tracks with $p_T > 500$ MeV in a cone $\Delta R = 0.2$ and the muon $p_T$ is less than 0.1.
   - $\Delta R > 0.2$ between the photon and the muons.

3. For electron channel:
   - Passes tight identification.
   - $E_T$ based calorimeter isolation cut of 5 GeV.
   - $\Delta R > 0.4$ between the photon and the muons.

4. Three body invariant mass $80 < M_{ll\gamma} < 96$ GeV.

5. Dilepton invariant mass $40 < M_{ll} < 83$ GeV.
Electron extrapolation

Event selection

1. Two opposite charged electrons, $80 < M_{ee} < 100$ GeV.
2. Both electrons $E_T > 25$ GeV.
3. Both electrons $|\eta| < 1.37$ or $1.52 < |\eta| < 2.37$.
4. Tag electron has to pass tight identification. Probe electron has to pass the tracker part of tight identification.
5. Both electrons $E_T^{\text{iso}}(R = 0.4) < 5$ GeV.
6. No jet with $E_T > 20$ GeV must be within $\Delta R = 0.4$ of tag electron.

Uncertainties

- Main uncertainties come from:
  - Material in front of calorimeter $\rightarrow 5\%$ for converted, 15\% for unconverted.
  - Differences in $\eta$ and $E_T$ distributions (within a bin) between electrons and photons $\rightarrow < 1\%$.

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Matrix Method

Equations

\[ N_{P}^{\text{Total}} = N_{P}^{S} + N_{P}^{B} \]
\[ N_{F}^{\text{Total}} = N_{F}^{S} + N_{F}^{B} \]
\[ N_{P}^{\text{Total, Iso}} = \epsilon_{P} N_{P}^{S} + \epsilon_{P} N_{P}^{B} \]
\[ N_{F}^{\text{Total, Iso}} = \epsilon_{F} N_{F}^{S} + \epsilon_{F} N_{F}^{B} \]

Signal Purity (before) Tight Cuts = \( \frac{\epsilon_{F} - \epsilon_{F}^{B}}{\epsilon_{F} - \epsilon_{F}^{S}} \)

Signal Purity (after) Tight Cuts = \( \frac{\epsilon_{P} - \epsilon_{P}^{B}}{\epsilon_{P} - \epsilon_{P}^{S}} \)
Finding the track isolation efficiency

- A track isolated photon must have no track with more than 500 GeV within a cone of size $0.001 < \Delta R < 0.3$.
- The four efficiencies for the track isolation are made by splitting the tight requirements into four sections.

Uncertainties

- Signal leakage in background enriched samples. Conservatively estimated looking at difference between data and Monte Carlo.
  $\rightarrow$ 20% for efficiency of background passing tight photon selections.
- Signal track isolation uncertainty, conservatively estimated by comparing data and Monte Carlo. Additional uncertainty here for differences between 1 and 2 track converted photons.
  $\rightarrow$ 5% for converted photons failing tight, and 1% or less for other cases.
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**Results**

**Data driven results at 7 TeV**

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Performance of the photon reconstruction and identification in ATLAS
Data driven results at 8 TeV

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Results

Data driven results at 8 TeV combined

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Performance of the photon reconstruction and identification in ATLAS
Impact on measurements

Case study: $H \rightarrow \gamma\gamma$

<table>
<thead>
<tr>
<th>Date</th>
<th>Uncertainty on signal yield resulting from photon ID</th>
</tr>
</thead>
<tbody>
<tr>
<td>July 2012</td>
<td>10.8 %</td>
</tr>
<tr>
<td>December 2012</td>
<td>5.3 %</td>
</tr>
<tr>
<td>March 2013</td>
<td>2.4 %</td>
</tr>
<tr>
<td>June 2014</td>
<td>1 %</td>
</tr>
</tbody>
</table>

Systematic uncertainties from photon ID efficiency

- Photon ID systematic has significant impact on coupling strength and fiducial cross-section measurements.
- Uncertainty has been significantly reduced!

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