Photon Reconstruction and Identification with the ATLAS detector

Mauro Donegà
on behalf of the ATLAS Collaboration

Department of Physics and Astronomy
University of Pennsylvania
Main sources of high $p_T$ isolated $\gamma$ at the LHC: QCD processes. Main background: jets

The search for new phenomena with photons requires:
- efficient photon reconstruction
- accurate photon energy and direction measurement
- particle identification: jets rejection
LHC design luminosity: $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ (~20 proton-proton interactions per bunch crossing):

- **Pile up in space:** high granularity of all sub-detectors (in particular the tracker)
- **Pile up in time:** (25 nsec BC) fast read out
- **High radiation environment** over 10 years of data taking
  - $10^{15}$ neutrons/cm$^2$
  - 200 kGy

**Photon driven detector design goals:**

- mass resolution of 1% on $H \rightarrow \gamma\gamma$ :
  - $\sigma/E \sim 10%/\sqrt{E}$ with a constant term < 1 %
  - linearity: $(E_{\text{mean}}-E_{\text{true}})/E_{\text{true}}$ better than 0.5 %
  - absolute precision of the e.m. scale 0.1 %
  - angular resolution 50 mrad/$\sqrt{E}$

- jets rejection:
  - ~5 orders of magnitude
ATLAS sub-detectors used in photon reconstruction

2T Solenoid

LAr hadronic end-cap (HEC)
LAr electromagnetic end-cap (EMEC)
LAr electromagnetic barrel
LAr forward (FCal)

Tile barrel
Tile extended barrel

ATLAS Tracker

Coverage |η| < 2.0
3 pixel layers
8 strip layers (4 space points)
~36 measurements on track straw detector
electron PID capability

Liquid Argon e.m. calorimeter
Coverage |η| < 3.2 (precision < 2.5)
Total thickness: >24X₀
170k channels

Δϕ = 0.0245
Δη = 0.025

Δϕ = 0.0982
Δη = 0.1

Coverage |η| < 2.0
3 pixel layers
8 strip layers (4 space points)
~36 measurements on track straw detector
electron PID capability
LAr calorimeter upstream material

LHC trackers: heavier than any previous one (LEP, TeVatron):

**ATLAS Inner Detector ~ 4.5 ton**

Large amount of material in front of the EM calorimeter means:
- large energy losses of electrons through bremsstrahlung
- high photon conversion probability
- a complex calibration procedure for the EM calorimeter

The conversion probability ranges from 40% ($\eta = 0$) up to 80% ($\eta = 1.8$)

Knowing the exact amount and position of the upstream material is of paramount importance!

**physics**: in reconstruction and identification need a dedicated treatment

**conversions** as a tool to reconstruct the 3D material map of the detector
Precise 3D mapping of the material with low-energy conversions from minimum bias data
Enough statistics for a 1% material map in a few months of data taking

Conversion ingredients: Tracking + Vertexing

Tracking efficiency

Silicon Tracks:
- inside-out: it seeds in the silicon detector and extends outward
- outside-in: it use as a seed a TRT segment and extends inward

TRT Tracks: TRT segments without silicon hits extensions
Conversion reconstruction efficiency

- **Radial resolution**: $\sim 3$ mm for low $p_T$ photons

- **Other tools** are available to understand the material distribution in the detector:
  - tail of the $E/p$ distributions
  - dedicated brem-fitting tools
  - resonances ($J/\psi, K^0_s$ ...) **mass stability** as a function of the tracks $p_T$

Material in ID has been checked to a **few %** by weight and component lists.
Clustering algorithm for photons:
- slide a window $\Delta \eta \Delta \varphi = 5 \times 5$ in the middle layer (Molière radius $\sim 2$ cm); find local maximum
- track/vertex matching to disentangle electrons from unconverted and converted photons
- re-build the cluster: $\Delta \eta \Delta \varphi = 3 \times 5$ cells for unconverted photons
  $\Delta \eta \Delta \varphi = 3 \times 7$ cells for converted photons (wider phi to account for B-field opening; like electrons)

Energy and position reconstruction:
- See Olivier Arnaez “Electron Reconstruction and Identification with the ATLAS Detector” this conference

- cells in the clusters are summed
- position dependent energy corrections are applied.

Photon energy resolution

\[ E = 100 \text{ GeV single photons MC} \]

\[
\begin{align*}
|\eta| &= 1.075 \\
\sigma &= (1.37 \pm 0.05)\% \\
\sigma &= (1.26 \pm 0.05)\% \\
\end{align*}
\]

- All photons
- Unconverted photons
- Conversions
Relative resolution

Unconverted photons
(45 ÷ 75) mrad/\sqrt{E}

Converted photons
width 0.42 mrad
Photon/Jets discrimination based on their characteristics features:

- **Photons** narrow objects, contained in the e.m. calorimeter.
- **Jets** broader profile and have significant energy deposition in the hadronic calorimeter

### Hadronic leakage

Plots shown for: 
| | <0.7 20<E_{T}<30GeV

### Shower shapes in the middle layer of the electromagnetic calorimeter:

- $R_\eta = 3\times7 \div 7\times7$
- $R_\phi = 3\times3 \div 3\times7$

Mauro Donegà - Penn
Example of a variable built with the strips (first layer) of the electromagnetic calorimeter:

\[ \Delta E_s = E_{\text{max}2} - E_{\text{min}} \]
After shower shape cuts the remaining background is dominated by low track multiplicity jets containing a high pT $\pi^0$

**Track Isolation** = sum of the pT of all tracks with pT>1 GeV within $\Delta R<0.3$

(tracks from conversions are excluded)
Cut based Photon Identification performance

Example: photons $E_T > 25$ GeV from $H \rightarrow \gamma\gamma$

After all cuts 70% of the remaining fake photons are high momentum $\pi^0$
Example: $\gamma E_T > 100 \text{ GeV}$ from Randall Sundrum $G \rightarrow \gamma\gamma$ ($m_G = 500 \text{ GeV}$)

High $p_T \gamma$ shower shape distributions similar to the ones of $H \rightarrow \gamma\gamma$

Calorimeter isolation $\Delta R = 0.45$ around the cluster
More ambitious photon identification methods

Log-Likelihood-Ratio: combines the same variables used with the cut based method.

\[ LLR = \sum_{i=1}^{n} \ln \left( \frac{L_{si}}{L_{bi}} \right) \]

Index \( i \) runs over the variables

For equal efficiencies the LLR and the cut-based method perform comparably
Summary

• The performance of the ATLAS electromagnetic liquid Argon calorimeter and tracker have been extensively studied with beam tests, with simulations and with cosmics data.

• The large amount of upstream material affects the photon reconstruction and identification. Different approaches are being developed to measure its distribution with collision data.

• Different methods are available to identify photons. Detailed MC studies show that the efficiency and rejection levels are adequate for physics analysis.
Backup
Liquid Argon e.m. calorimeter

Design goals:
- Energy resolution: $\frac{\sigma}{E} \sim \frac{10\%}{\sqrt{E}}$ + constant term
- Energy resolution: < 1% to have 1% mass resolution in $\text{H} \rightarrow \gamma \gamma$
- Signal linearity: 0.5%
- Absolute e.m. energy scale: 0.1%
- Angular resolution: $\frac{50\text{mrad}}{\sqrt{E}}$
- Electron reconstruction: [1 GeV, 5 TeV]
- Photon/jet, electron rejection: $10^6$
- Noise: 1 GeV to have $\sim$1% on $\text{H} \rightarrow \gamma \gamma$ mass:
  this drive the max granularity
  $\Delta\eta \times \Delta\phi = 0.3 \times 0.3$ for the precision region

Fast electronics: for noise reduction and for trigger
Radiation hardness in 10 years: $10^{15}$ 1 MeV qeq/cm$^2$
200 kGy

From accordion to cells: cells are created ganging signals from the appropriate electrodes together:
- Strips: 16 electrodes in $\phi$; L2 4 electrodes in $\phi$

HV = 2 kV/gap = 10 kV/cm
450 nsec drift time
# Liquid Argon e.m. calorimeter

<table>
<thead>
<tr>
<th></th>
<th>Barrel</th>
<th>End-cap</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>EM calorimeter</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of layers and $</td>
<td>\eta</td>
<td>&lt; 1.52$ coverage</td>
</tr>
<tr>
<td>Presampler</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Calorimeter</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>3</td>
</tr>
<tr>
<td>1.35 &lt; $</td>
<td>\eta</td>
<td>&lt; 1.475$</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>2.5 &lt; $</td>
<td>\eta</td>
<td>&lt; 3.2$</td>
</tr>
<tr>
<td>**Granularity $\Delta \eta \times \Delta \phi$ versus $</td>
<td>\eta</td>
<td>$**</td>
</tr>
<tr>
<td>Presampler</td>
<td>0.025 × 0.1</td>
<td>0.025 × 0.1</td>
</tr>
<tr>
<td>Calorimeter 1st layer</td>
<td>0.025/8 × 0.1</td>
<td>0.050 × 0.1</td>
</tr>
<tr>
<td></td>
<td>0.025 × 0.025</td>
<td>0.025 × 0.1</td>
</tr>
<tr>
<td></td>
<td>1.40 &lt; $</td>
<td>\eta</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.025/6 × 0.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.025/4 × 0.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.025 × 0.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.1 × 0.1</td>
</tr>
<tr>
<td>Calorimeter 2nd layer</td>
<td>0.025 × 0.025</td>
<td>0.050 × 0.025</td>
</tr>
<tr>
<td></td>
<td>0.075 × 0.025</td>
<td>0.025 × 0.025</td>
</tr>
<tr>
<td></td>
<td>1.40 &lt; $</td>
<td>\eta</td>
</tr>
<tr>
<td>Calorimeter 3rd layer</td>
<td>0.050 × 0.025</td>
<td>0.050 × 0.025</td>
</tr>
<tr>
<td><strong>Number of readout channels</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Presampler</td>
<td>7808</td>
<td>1536 (both sides)</td>
</tr>
<tr>
<td>Calorimeter</td>
<td>101760</td>
<td>62208 (both sides)</td>
</tr>
</tbody>
</table>
• Hadronic leakage
• Variables in the **middle layer** of the electromagnetic calorimeter:

\[ R_\eta = \frac{3 \times 7}{7 \times 7} \quad R_\varphi = \frac{3 \times 3}{3 \times 7} \]

\[ w_2 = \text{lateral width in } \eta \]

• Variables using the **strips** (first layer) of the electromagnetic calorimeter:

\[ \Delta E_s = E_{\text{max}2} - E_{\text{min}} \]

\[ R_{\text{max}2} = \frac{E_{\text{max}2}}{1 + 0.009 \ ET/\text{GeV}} \]

\[ F_{\text{side}} = \frac{[E(\pm 3) - E(\pm 1)]}{E(\pm 1)} \]

\[ w_{s3} = \text{shower width around the strip with the maximal energy deposit} \]

\[ w_{\text{stot}} = \text{shower width over 20 strips} \]
H-matrix

Covariance-based (H-matrix): combines different shower shape variables

\[ M_{ij} = \frac{1}{N} \sum_{n=1}^{N} (y_{i}^{(n)} - \bar{y}_i)(y_{j}^{(n)} - \bar{y}_j) \]

Indices i, j runs over the variables
N = number of photons used for training
\( \bar{y}_j \) = mean value for the variable y

The photon likeness then is defined as

\[ \chi^2 = \sum_{i,j=1}^{\text{dim}} (y_{i}^{(m)} - \bar{y}_i) H_{ij} (y_{j}^{(m)} - \bar{y}_j) \]

\( H = M^{-1} \)
\( y_{j}^{(m)} \) = measured value of the variable