Photon and photon+jet production measurements with the ATLAS detector

Martin Bessner
On behalf of the ATLAS collaboration
Why look for photons?

- Experimentally clean signature
- Allows to probe perturbative QCD and PDFs
- Study inclusive photon, diphoton, and photon+jet production

Diphoton production is background to $H\rightarrow\gamma\gamma$, $G\rightarrow\gamma\gamma$, ...

Compton (dominant)

Annihilation (problematic to describe)
Photons in the ATLAS detector

- Energy deposit in electromagnetic calorimeter, not in HCAL
- No track (unconverted) or 1-2 tracks (converted)
- Require photon isolation: $\Sigma E_T < 7$ (or 4) GeV in $\Delta R=0.4$ cone
  - Reduces fragmentation component

http://arxiv.org/abs/1202.1762
Photon identification and background

- Background from high-energetic $\pi^0$ in jets ($\sim 10^5$ jets/photon)
- Use 9 variables to describe shape of shower
  - distinguish between signal and background

Also background from electrons – subtraction based on $Z \rightarrow ee$
reconstructed as ee or eγ
Analyses and results

  Nucl. Phys. B 875 (2013) 483: 37 pb\(^{-1}\) @ 7 TeV: \(E_T^\gamma\) up to 400 GeV

  PRD 89, 052004 (2014): 4.6 fb\(^{-1}\) @ 7 TeV: \(E_T^\gamma\) up to 1000 GeV

  JHEP 1301 (2013) 086: 4.9 fb\(^{-1}\) @ 7 TeV: \(m_{\gamma\gamma}\) up to 800 GeV

- Photon production in 13 TeV collisions – new!
  Isolated diphoton candidates with 6.4 pb\(^{-1}\)
  Isolated inclusive photons with 6.4 pb\(^{-1}\)
Photon + jet dynamics

- Study of pp → photon + jet + X
- Photon from hard interaction
- Angular distributions depend on exchange particle:
  - $\sigma \sim (1 - |\cos \theta^*|)^{-1}$ for spin 1/2 (Compton+annihilation, “direct production” (DP))
  - $\sigma \sim (1 - |\cos \theta^*|)^{-2}$ for spin 1 (fragmentation (F))
- Jets: anti-$k_t$, $R=0.6$
- Motivation:
  - Test the fraction of quark-exchange processes
  - Constrain gluon density in proton
  - Tune MC generators
  - Reducible background to $H \rightarrow \gamma\gamma$

$\cos \theta^* = \tanh(\Delta y/2)$
$\Delta y$ is difference between photon and leading jet rapidities

http://arxiv.org/abs/1307.6795
Photon + jet dynamics

> Fragmentation (F) and Compton/direct production (DP)
> Different distributions. Weighted sum in MC describes data well
> Weighted MC used for unfolding

\[ \alpha \text{ is relative weight of DP/F} \]

http://arxiv.org/abs/1307.6795
Photon + jet dynamics

- Cos θ distribution distorted by η/y and p_T acceptance
- Cuts on photon+jet system to avoid biased phase space
- Good description by NLO QCD
- Data closer to quark exchange (direct photon) spectrum

\[ p_T^{\text{jet}} > 40 \text{ GeV}, \quad E_T^{\gamma} > 45 \text{ GeV} \]
\[ m^{\gamma j} > 161 \text{ GeV}, \quad |\eta^{\gamma} + \eta^{\text{jet}}| < 2.37 \]

http://arxiv.org/abs/1307.6795
Photon + jet dynamics

- Full (biased) spectrum without additional cuts
- Relevant as background in $H \rightarrow \gamma\gamma$
- Also good description by NLO QCD

Experimental uncertainty only.
Gluon pdf from $x = 0.01$ to $x \approx 1$

http://arxiv.org/abs/1307.6795
Inclusive photons

> 4.6 fb⁻¹, extend range up to $E_T^\gamma = 1000$ GeV

> Large theoretical uncertainties → improve theory predictions and PDFs

See also ATL-PHYS-PUB-2013-018
http://arxiv.org/abs/1311.1440

http://arxiv.org/abs/1202.1762

Gluon PDF uncertainty went down by 20%. Need NNLO for further improvement.
> 4.9 fb\(^{-1}\), \(p_T^{\gamma_1} > 25\) GeV, \(p_T^{\gamma_2} > 22\) GeV, \(\Delta R > 0.4\)

> Measure di-photon mass, \(p_T\), azimuthal separation, \(\cos \theta^*\)

> Missing \((N)NLO\) effects in Pythia notable

> NNLO predictions agree with data

\[http://arxiv.org/abs/1211.1913\]
13 TeV cross-section expectations

> Completely new energy range

> Large increase in cross-sections: factor $\sim 30$ at high $p_T$

Calculations by Sergei Chekanov, plots by Claudia Glasman Kuguel
13 TeV collisions: diphotons

- Diphoton candidate spectra in early 13 TeV data, $p_T^\gamma > 10$ GeV
- No background subtraction!
- Isolation spectrum gives purity estimate: 50 to 60%

**ATLAS Preliminary**

Data 2015 ($\sqrt{s} = 13$ TeV, $\int L dt = 6.4\,pb^{-1}$)

$|\eta| < 2.37$ (1.37 < $|\eta|$ ≤ 1.52 excluded)

$E_T^\gamma > 15$ GeV, $E_T^{iso}(R = 0.4) < 4$ GeV, $\Delta R_{\gamma\gamma} > 0.4$

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$E_T^\gamma > 15$ GeV, $\Delta R_{\gamma\gamma} > 0.4$

Tight leading $\gamma$, $E_T^{iso}(R = 0.4) < 4$ GeV

- Tight subleading $\gamma$ candidate
- Non-tight subleading $\gamma$ candidate (normalized at $E_T^{iso} > 10$ GeV)
13 TeV collisions: diphotons

> Diphoto mass and diphoton $p_T$ spectra
> Up to $m_{\gamma\gamma} = 200$ GeV
13 TeV collisions: inclusive photons

- Background subtracted, up to $E_T^γ = 350$ GeV
- Shape agrees with Sherpa
Summary

- Photons allow to test QCD and improve PDFs
- Multiple measurements up to 1 TeV complement each other
- Overall good agreement with pQCD
- NNLO calculations important
- Measure gluon PDFs for $0.005 < x < 1$
- Began to analyze 13 TeV data
- Run 2 just started
Backup
2D sideband method: data-driven background estimate

- Split photon candidates by tight ↔ non tight and isolated ↔ not isolated
- 4 (16) categories for 1 (2) photons
- Estimate small effects with MC
- Data allows to find signal+BG contributions
Shower shapes

Variables and Position

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<th>2nd</th>
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<td>Ratios</td>
<td>$f_1$, $f_{side}$</td>
<td>$R_\eta^*$, $R_\phi$</td>
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<td>Widths</td>
<td>$w_{3,3}$, $w_{5,\text{tot}}$</td>
<td>$w_{\eta,2}^*$</td>
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<td>Shapes</td>
<td>$\Delta E$, $E_{\text{ratio}}$</td>
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Energy Ratios

$$R_\eta = \frac{E_{S2}^{3\times7}}{E_{T}^{7\times7}}$$

$$R_\phi = \frac{E_{S2}^{3\times3}}{E_{T}^{3\times7}}$$

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

Shower Shapes

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

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

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 $3\times5$ ($\Delta\eta \times \Delta\phi$) region of cells in the second layer.

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

$w_{3} = w_{s}$; uses 3 strips in $\eta$; $w_{\text{stot}}$ is defined similarly, but uses 20 strips.
> $p_T$ and eta acceptance can lead to bias in distribution

http://arxiv.org/abs/1307.6795
Photon efficiency with 13 TeV collisions

**ATLAS Preliminary Simulation**

Pythia prompt photon MC
\( \sqrt{s} = 13 \text{ TeV} \)

- \( |\eta| < 0.60 \)
- \( E_T^{iso} < 4 \text{ GeV} \)

- Converted
- Unconverted

![Graph 1](image1)

![Graph 2](image2)

Pythia prompt photon MC
\( \sqrt{s} = 13 \text{ TeV} \)

- \( 0.60 < |\eta| < 1.37 \)
- \( E_T^{iso} < 4 \text{ GeV} \)

- Converted
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![Graph 3](image3)

![Graph 4](image4)
Barrel

$$\text{JetPHOX } \sqrt{s} = 8 \text{ TeV}$$

$$\text{JetPHOX } \sqrt{s} = 13 \text{ TeV}$$

PDF: CT10

$$|\eta'| < 1.37$$

Endcap

$$\text{JetPHOX } \sqrt{s} = 8 \text{ TeV}$$

$$\text{JetPHOX } \sqrt{s} = 13 \text{ TeV}$$

PDF: CT10

$$1.56 < |\eta'| < 2.37$$

Calculations by Sergei Chekanov,
plots by Claudia Glasman Kuguel