Measurement of photon production cross sections with the ATLAS detector

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July 6th, 2017

EPS Conference
- Increase in instantaneous luminosity
- Increase $\sqrt{s} = 7, 8, 13$ TeV
- Increase in pileup: $\langle \mu \rangle = 9.1, 20.7, 23.7$
- New collisions in 2017 at 13 TeV: already 6 fb$^{-1}$

- Photon clusters reconstructed in the EM calorimeter with a sliding window
- Search for matching to tracks (electrons) and conversion vertices
- Identification based on shower shapes and hadronic leakage
Inclusive photon fiducial cross sections

<table>
<thead>
<tr>
<th>γγ, p_T &gt; 125 GeV</th>
<th>σ = 399 ± 0.4 ± 16 pb (data) JETPHOX+MMHT2014 (NLO) (theory)</th>
</tr>
</thead>
<tbody>
<tr>
<td>γγ, p_T &gt; 25 GeV</td>
<td>σ = 359 ± 3 ± 16 pb (data) JETPHOX (NLO) (theory)</td>
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<tr>
<td>−</td>
<td>σ = 236 ± 2 ± 13 pb (data) JETPHOX (NLO) (theory)</td>
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<tr>
<td>−</td>
<td>σ = 123 ± 1 ± 9 pb (data) JETPHOX (NLO) (theory)</td>
</tr>
<tr>
<td>γγ, ∆Rγγ &gt; 0.4</td>
<td>σ = 16.82 ± 0.07 ± 0.75 − 0.78 pb (data) 2γNNLO + CT10 (ref. theory), Sherpa 2.2.1 (MEPS@NLO) + NNPDF 3.0 (NNLO) (theory)</td>
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<tr>
<td></td>
<td>σ = 44 ± 3.2 − 4.2 pb (data) 2γNNLO (ref. theory), DIPHOX+GAMMA2MC (NLO) (theory)</td>
</tr>
</tbody>
</table>

ATLAS Preliminary
Run 1,2 √s = 7, 8, 13 TeV

Inclusive Photon Fiducial Cross Section Measurements

Status: July 2017

ATLAS Preliminary
Run 1,2 √s = 7, 8, 13 TeV

Data

LHC pp √s = 7 TeV

LHC pp √s = 8 TeV

LHC pp √s = 13 TeV

NNLO QCD
NLO QCD

ratio to best theory
Testing pQCD with a hard colourless probe, sensitive at LO to the gluon PDF.

Cross sections as functions of $E_T$ in four different $\eta$ regions.

- Selection: $E_T > 125$ GeV, $|\eta| < 2.37$ except $1.37 < |\eta| < 1.56$, photon-ID, calo-isolation $E_{\text{iso}}^T < 4.8$ GeV + $4.2 \times 10^{-3} E_T$.

- Fiducial region: mirror of the selection.

- Background subtracted with data-driven technique.

- Compared with SHERPA and PYTHIA: good agreement.

- Compared with JETPHOX (NLO, direct + fragmentation) with different PDFs.
Inclusive photon at 13 TeV

\[ \sigma = 399 \pm 13(\text{exp.}) \pm 8(\text{lumi}) \text{ pb} \quad \sigma_{\text{JETPHOX}} = 352^{+36}_{-29}(\text{scale}) \pm 3(\text{pdf}) \pm 6(\alpha_s) \pm 4(\text{non-pert}) \text{ pb} \]

- NLO predictions provide an adequate description.
- Theoretical uncertainties > experimental: NNLO pQCD corrections are needed
Angular correlations between the photon and the jets
- Probe the dynamics of the hard-scattering process
- Useful in constraining the gluon density in the proton
- **New results**: up to $E_T^\gamma \simeq 1.5$ TeV

- Same selection as for inclusive photon analysis ($E_T^\gamma > 125$ GeV)
- Jet anti-$k_T$ ($R = 0.4$), $p_T^{\text{jet}} > 100$ GeV, $|y^{\text{jet}}| < 2.37$, $\Delta R_{\gamma,\text{jet}} > 0.8$
- Purity data-driven: $> 90\%$ everywhere

Compared to:
- LO MC: PYTHIA and SHERPA
- NLO: JETPHOX (parton level + PYTHIA corrections), SHERPA ME+PS@NLO (particle level)
- PYTHIA cannot describe $p_{Tj}$: large contribution from photon bremsstrahlung predicted by the tune of PYTHIA
- Both JETPHOX and SHERPA ME+PS@NLO gives good predictions.
- JETPHOX cannot describe $\Delta \phi_{\gamma j}$ due to the limitation in the number of final-state partons
  - SHERPA NLO ME 2 $\rightarrow n$ processes with $n = 4, 5$
- high-$p_T^{\text{jet}}$: better Sherpa LO
- Theoretical uncertainties are larger than experimental, main contribution: terms beyond NLO.
\( \gamma + 1, 2, 3 \) jets studied in 6 phase space regions. Observables:

- \( E_T^\gamma, p_T^{j1/2/3}, m_{\gamma,j1}, |\cos \theta^*|, \Delta \phi_{\gamma,j2/3}, \Delta \phi_{j1/1/2,j2/3/3}, \)
- Radiation pattern around \( \gamma \) or \( j1: \beta^\gamma, \beta^j1 \)

- Photon selection: \( E_T^\gamma > 130 \text{ GeV, } |\eta| < 2.37 \) except \( 1.37 < |\eta| < 1.56 \), photon-ID, calo-isolation \( E_{\text{iso}}^j < 4.8 \text{ GeV} + 4.2 \times 10^{-3} E_T \)
- Jet selection (anti-\( k_t \) R=0.6): \( E_T^j > 50 \text{ GeV, } |y^j| < 4.4 \)

- Monte Carlo: SHERPA (LO ME \( \leq 4j + \) PS), PYTHIA
- Blackhat + SHERPA (\( \gamma + 3j \) NLO ME direct production only)
- JETPHOX (\( \gamma + 1j \) NLO ME direct and fragmentation)
Photon+jet(s) at 8 TeV

- SHERPA better than Pythia in multijet region
- Visible deviation for $E_T > 750$ GeV wrt NLO prediction in $\gamma + 2j$
**Photon+jet(s) at 8 TeV**

- First observation of different **QCD radiation pattern** around the photon and 1st jet require $1 < \Delta R_{\gamma j_1} < 1.5$ for $\beta^\gamma$, require $1 < \Delta R_{j_1 j_2} < 1.5$ for $\beta^{j_1}$.

- Enhancements in the directions towards the beams, $\beta = 0$ and $\pi$.
- Agreement with SHERPA.

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**ATLAS**

$\sqrt{s} = 8$ TeV, 20.2 fb$^{-1}$

$pp \rightarrow \gamma + 2$ jets + X

(\frac{d\sigma}{d\beta^\gamma})/(\frac{d\sigma}{d\beta})
- Sensitive to $\alpha_s$ corrections
- Sensitive to QCD infrared emission
- Main background for $H \rightarrow \gamma\gamma$

Fiducial cross section and differential. Variables
- Sensitive to New Physics: $m_{\gamma\gamma}$, $|\cos(\theta^*_\eta)|$
- Sensitive to higher order and QCD IR: $p_{T,\gamma\gamma}$, $\Delta\phi_{\gamma\gamma}$
- New variables sensitive to QCD IR emissions: $a_T$, $\phi^*_\eta$
Diphoton selection

- Well separated photon $\Delta R_{\gamma\gamma} > 0.4$
- $E_T^{(1)} > 40 \text{ GeV}, \ E_T^{(2)} > 30 \text{ GeV}$
- $|\eta| < 2.37$ except $1.37 < |\eta| < 1.56$
- Photon identification based on shower shapes and hadronic leakage
  - Track-isolation $p_{T}^{\text{iso}}(\Delta R = 0.2) < 2.6 \text{ GeV}$
  - Calo-isolation $E_{T}^{\text{iso}}(\Delta R = 0.4) < 6 \text{ GeV}$
- Fiducial region defined using the same values at particle level
  - $E_{T}^{\text{iso,particle}}(\Delta R = 0.4) < 11 \text{ GeV}$
- Background subtraction evaluated with two methods
- Purity around 75%
Diphoton fiducial cross section at 8 TeV

\[ \sigma^{\text{fid}} = 16.8 \pm 0.8 \text{ pb} = 16.8 \pm 0.1(\text{stat}) \pm 0.7(\text{exp}) \pm 0.3(\text{lumi}) \text{ pb} \]

Main experimental systematic: photon identification and isolation. Less than factor 2 wrt 7 TeV.

Cross section from fixed order calculation lower than data. Improvement NLO \(\to\) NNLO.
Improvement NLO $\rightarrow$ NNLO. In most parts of the phase space, the fixed order predictions are unable to reproduce the data.
Fixed-order calculations are not expected to give reliable predictions in regions sensitive to infrared emissions (low values of $p_T, \gamma\gamma, a_T$ and $\phi^*_\eta$ or $\Delta \phi_{\gamma\gamma} \sim \pi$)

The effects of infrared emissions are well reproduced by the inclusion of soft-gluon resummation at NNLL (low $a_T$, low $\phi^*_\eta$)
Conclusions

Direct photons at 13 TeV

- NLO predictions provide an adequate description.
- Theoretical uncertainties > experimental: NNLO pQCD corrections are needed

Photon+jet at 13 TeV: new results. Comparison with SHERPA ME+PS@NLO.

Photon+jet(s) at 8 TeV

- Very detailed analysis: 6 regions, 35 cross sections
- First observation of different QCD radiation pattern around the photon and 1st jet
- Stringent tests of pQCD up to $O(\alpha_{EM}\alpha_s^4)$

Diphoton at 8 TeV:

- Systematic uncertainty decreased by a factor 2 wrt 7 TeV on the cross section
- Precise probe of QCD infrared emissions ($a_T$, $\phi_\eta^*$) complementary to Drell-Yan
- Improvement with NNLO but still more than 2$\sigma$ away
- Soft gluon resummation at NNLL (RESBOS) provides a good description of infrared emissions.
- SHERPA 2.2.1 (ME+PS at NLO) provides good predictions at particle level: $H \rightarrow \gamma\gamma$ background
Section 1

Backup
Photon+jet 13 TeV tree level

ATLAS Preliminary
\[ \sigma \frac{d}{dE_T} \]

MC/Data

0.5
1
1.5

Jet lead \( p_T \) > 100 GeV

Jet lead \( p_T \) > 125 GeV

\[ \Delta \phi_{\gamma-jet} \]

MC/Data

0.5
1
1.5

Jet lead \( m_{\gamma-jet} \) > 450 GeV

Jet lead \( |\cos \theta'| \) < 0.83

Jet lead \( |\eta_{\gamma-jet}| \) < 2.37

MC/Data

0.5
1
1.5

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Photon cross sections at ATLAS
Jul 6th 2017