Tests of Perturbative QCD with Photon Final States using the ATLAS Experiment

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Motivation

Studies of the production of photons in proton-proton collisions at the LHC provide…

• testing ground for wide range of Standard Model predictions in new kinematic regimes.
  - Unique colourless probe to test pQCD predictions.

• constraints on the content of the proton.

• description of background event kinematics for different searches for new physics.
  - Identify regions of phase space that require improved MC modelling.
  - Study impact of treatment of heavy quarks in ME and PS computations.
What we measure?

Cross-sections in fiducial volume

\[
\frac{d\sigma}{dX}(i) = \frac{N^{(i)}_{\text{sig}} \Delta X^{(i)} \mathcal{L} \epsilon_{\text{trigger}} C^{(i)}_{\text{unfolding}}}{dX}
\]

- Number of background-subtracted data events
- Width of bin \(i\)
- Corrections for detector resolution, reconstruction and selection efficiencies
ATLAS data samples

Run 1

2010, 0.0489 fb$^{-1}$ (7 TeV)

2011, 5.6 fb$^{-1}$ (7 TeV)

2012, 23.3 fb$^{-1}$ (8 TeV)

13 TeV

Run 2

2015, 4.2 fb$^{-1}$

2016, 38.5 fb$^{-1}$

2017, 50.6 fb$^{-1}$

Total Integrated Luminosity Delivered (fb$^{-1}$)

Date (CET)
Outline

- **Inclusive prompt photon (13 TeV)**
  

- **Di-photon (8 TeV)**
  

- **Tri-photon (13 TeV)**
  

- **Photon+jets (13 TeV)**
  

- **Photon+b/c (8 TeV)**
  
Photon reconstruction

• "Prompt" photons: Photons that are not secondaries from hadron decays.

• Photon reconstruction:
  - EM calorimeter cell cluster.
  - Consider both unconverted and converted candidates.

• Photon identification:
  - Nine variables quantifying the shower shape.
  - Fine granularity of first calorimeter layer suppresses $\pi^0$ background.
  - "Tight" identification efficiency > 90% for $E_T > 40$ GeV.

• Photon isolation:
  - Require low amount of energy around photon.
  - Suppresses jets mis-identified as photons.

See talks:
- N. Proklova, “Electron and photon identification with the ATLAS detector”.
- S. Morgenstern, “Electron and photon energy measurement calibration with the ATLAS detector”
- P. Podberezko, “The ATLAS Electron and Photon Trigger”.
Inclusive photon

\[ pp \to \gamma + X \]

- Sensitivity at LO to gluon density in proton.
- NLO pQCD calculations provide adequate description of measurements; however, test sensitivity limited by theoretical uncertainties associated with missing higher-order terms in pQCD.
Inclusive photon

- NNLO pQCD calculations now available.

- Theoretical uncertainties reduced by a factor of \(~ 2\), and now of the same order as experimental uncertainties.

- This opens up a new opportunity for precision QCD at LHC and inclusion of prompt photon data into PDF fits.


Di-photon

\[ pp \rightarrow \gamma\gamma + X \]

• Cross-section at 8 TeV measured differentially as function of 6 kinematic observables: \( m_{\gamma\gamma}, |\cos \theta^{*}_\eta|, \Delta\phi_{\gamma\gamma}, p_{T,\gamma\gamma}, a_T, \phi^{*}_\eta. \)

• Systematic uncertainties reduced by up to x2 compared to measurements at 7 TeV, due to improvements in background estimation.
  - Despite higher pile-up conditions

Prediction from ME+PS at NLO (Sherpa) is in agreement with measurement.
Di-photon

- Measurements are well-described by SHERPA (ME+PS at NLO).
- Specific regions of phase space particularly sensitive to soft gluons emissions.
  - Low $a_T$ region well described by parton shower (SHERPA) or inclusion of soft-gluon resummation (RESBOS)
- In some regions, disagreements of up to $x2$ between NLO and data.
  - Inclusion of NNLO corrections not sufficient to reproduce the measurements.
Tri-photon

$pp \rightarrow \gamma\gamma\gamma + X$

• Rare process: At LO contribution is order $\alpha_{EM}^3$.

• Complementary phase space to inclusive photon and di-photon production.

• Study topology and kinematics of individual photons, pairs of photons and three-photon system (13 kinematic variables).

• Main background: electron and jet mis-identification.
  - Electron mis-identified as a photon
    ‣ Estimated from $ee\gamma$, $ee\gamma\gamma$, $e\nu\gamma\gamma$ MC events (LO Sherpa).
    ‣ Mis-ID rate corrected to match measurement in $Z \rightarrow ee$ data.
  - Jet mis-identified as a photon
    ‣ 2D sideband applied to account for all combinations of photons meeting or failing to meet the tight identification or isolation criteria.
Tri-photon

- NLO predictions underestimate measured cross-section by \( \sim x1.5-2 \).
- NLO fails to describe regions of low \( E_T \).
- Addition of PS to NLO improves agreement.
- Need improved MC modelling of this process.

\[
\sigma_{\text{meas}} = 72.6 \pm 6.5 \text{ (stat.)} \pm 9.2 \text{ (syst.) fb}
\]

\[
\sigma_{\text{NLO}} = 31.5^{+3.2}_{-2.5} \text{ fb (MCFM)}
\]

\[
\sigma_{\text{NLO+PS}} = 46.6^{+5.7}_{-3.6} \text{ fb (MadGraph5\text{\_aMC\@NLO})}
\]
Photon + jets

\[ pp \rightarrow \gamma + \text{jets} \]

- Study dynamics of \( \gamma + \text{jets} \) production.
- Differential cross-sections measured as function of \( E_T^\gamma, p_T^{\text{lead}}, \Delta \phi^{\gamma-\text{jet}}, m^{\gamma-\text{jet}}, |\cos \theta^*| \).
- NLO calculations provide good description of measurements.
- For most of the phase space studied, theoretical uncertainties are larger than experimental uncertainties.
Photon + jets

Cross-section as function of $\theta^*$ provides insight into relative contributions of direct vs fragmentation components, as well as possibility of testing dominance of t-channel quark exchange.

Quark exchange diagrams observed to dominate.
Photon + b/c

- \( pp \rightarrow \gamma + b/c \)

- Sensitive to b/c-quark content of proton.
  - Sensitive to intrinsic charm hypothesis.
- Test modelling of b-quark in MC generators
  - Test flavour number scheme: 4F vs 5F.
- Analysis overview:
  - Select photon + jets events.
  - Photon purity estimated using data-driven 2D sideband method.
  - Use template fit method to extract b and c fractions.

**New**

**Compton**

**Gluon splitting**

**ATLAS**
- \( \sqrt{s} = 8 \) TeV, 20.2 fb\(^{-1}\)
- \( 1.56 < |\eta| < 2.37 \)
- \( 300 < E_T^\gamma < 350 \) GeV

**MV1c b-jet efficiency**

**ATLAS**
- \( \sqrt{s} = 8 \) TeV, 4.58 pb\(^{-1}\) - 20.2 fb\(^{-1}\)

**HF jet fraction**

Photon + b/c

\[ pp \rightarrow \gamma + b \]

- LO: Sherpa provides good description of data.
- NLO: 5F scheme provides better description of data up to 200 GeV.
  - Higher-order calculations expected to improve modelling at higher \( E_T \).

\[ pp \rightarrow \gamma + c \]

- Within uncertainties, LO and NLO provide good description of data.
- Predictions with IC predict higher cross-section at high \( x \).
Summary

• Large data samples, well-understood detector performance and effective pile-up mitigation techniques make it possible to perform precision measurements of known Standard Model processes.

• Study of photon production in $pp$ collisions provides stringent tests of QCD.
  - Calculations beyond NLO needed to reduce theoretical uncertainties and improve modelling.

• Measurements can be used to set constraints on proton PDFs.
Backup
b/c-jet identification

- MV1c neural network trained to differentiate b-jets from c-jet and light jets
  - Takes as input three types of parameters
    - **Impact parameter** information
    - **Secondary vertex** information
    - **Decay chain path** information, up to tertiary vertex

- Efficiency calibrated in independent analyses for the three flavours of jets
Electron/photon energy calibration

Schematic overview of the procedure used to calibrate the energy response of electrons and photons in ATLAS.

- S. Morgenstern, “Electron and photon energy measurement calibration with the ATLAS detector”