Measurement of photon and photon+jet production cross sections at $\sqrt{s} = 7$ TeV and constraints to PDFs

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On behalf of the ATLAS collaboration

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Isolated prompt photon production

- In proton-proton collisions, high-\(p_T\) prompt photons can be produced via two mechanisms:
  - fragmentation (F) process
  - direct photon (DP) process

\[
\sigma_{pp \to \gamma + X} \sim \int_0^1 \int_0^1 dx_1 dx_2 f_i/p(x_1, \mu_F) f_j/p(x_2, \mu_F) \sigma^{ij \to \gamma(l)k} \{ D_l(z, \mu_f) \}
\]

- "sanity checks" of perturbative QCD (pQCD);
- constraint on the gluon PDF in the proton;
- constraint on the contribution of photon fragmentation processes;
- background to Higgs studies and beyond standard model searches;
Inclusive isolated prompt photon production at $\sqrt{s} = 7$ TeV with $\mathcal{L} = 4.7 \text{ fb}^{-1}$

Photon selection

- Photon candidates required to have passed an 80 GeV trigger.
- $E_T^\gamma > 100$ GeV and $0.0 < |\eta^\gamma| < 2.37$ (excluding crack region $1.37 < |\eta^\gamma| < 1.52$)
- **Tight ID** criteria based on the electromagnetic shower profiles.
- Photon isolation selection $E_T^{iso} < 7$ GeV
  - computed using calorimeter cells in a cone of radius $\Delta R = 0.4$.
  - the contribution from photon cells excluded in the calculations.
  - $(\eta \times \phi = 5 \times 7$ second layer ECAL cells)
  - small signal leakage from the photon shower outside the $5 \times 7$ region estimated from MC and subtracted.
The background ($\pi^0, \eta^0 \rightarrow \gamma\gamma$) is strongly reduced after ID and isolation cuts. Residual background is estimated using the “two-dimensional side bands” data driven method.

Based on the definition of a “tight-isolated” signal region A and three background control regions B, C, D: “tight-nonisolated”, “nontight-isolated”, and “nontight-nonisolated”.

\[
\begin{array}{c|c|c}
\text{Region} & \text{E}_{T}^{\text{iso}} [\text{GeV}] & \gamma_{ID} \\
\hline
A & -5 & 0 \ 
B & 5 & 10 \ 
C & 15 & 20 \ 
D & 25 & 30 \ 
\end{array}
\]
Systematic uncertainties

The largest uncertainties are:

- Uncertainty on the photon identification efficiency → \( \lesssim 2\% \)
- Uncertainty on the photon energy scale → \( \sim 2\% \) at low \( E_T^\gamma \) and 6% at large \( E_T^\gamma \)
- Uncertainty on the photon energy resolution → \( \sim 2\% \)
- Uncertainty on the model dependence → \( \sim 2\% \) at low \( E_T^\gamma \) to 4% at \( E_T^\gamma > 800 \text{ GeV} \)
- Uncertainty on the background subtraction → varies between 2% and 3%
- Uncertainty on the luminosity value → 1.8%. Fully correlated among all \( E_T \) and \( \eta \) bins

→ Total systematic uncertainty is estimated by summing in quadrature all the contributions

→ Final systematic uncertainty on the differential and total cross section in the \( 0.0 < |\eta^\gamma| < 1.37 \) (\( 1.52 < |\eta^\gamma| < 2.37 \)) region is below 6% (7%)
Theoretical predictions

- The NLO QCD \(O(\alpha\alpha_s^2)\) calculations were computed using the program JETPHOX.
  - **parton-level isolation**: total \(E_T\) from partons inside a cone \(\Delta R = 0.4\)
  - calculation uses BFG set II photon fragmentation function
  - calculation done using CT10 and MSTW2008NLO proton PDFs
  - \(\mu_R = \mu_F = \mu_f = E_T^\gamma\)
  - hadronization + UE correction estimated using PYTHIA and HERWIG with different UE tunes \(\rightarrow\) effect of \(\pm 1\%\)

- **Theoretical uncertainties**:
  - **scale uncertainty** evaluated by varying the three scales \([E_T^\gamma/2, 2E_T^\gamma]\) \(\rightarrow\) between 12\% and 20\%
  - **PDFs uncertainty** evaluated by repeating the JETPHOX calculation for 52 eigenvector sets of the CT10 PDF \(\rightarrow\) 5\% at \(E_T^\gamma = 100\) GeV and 15\% at \(E_T^\gamma \approx 900\) GeV
  - uncertainty on the value of the \(\alpha_s\) evaluated using different CT10 PDF sets with \(\alpha_s\) value varied by \(\pm 0.002\) around \(\alpha_s = 0.118\) \(\rightarrow\) 4.5\% with small dependence on \(E_T^\gamma\)
Cross sections corrected for detector effects using the bin-by-bin method:

\[
\left(\frac{d\sigma}{dA}\right)_i = \frac{N_{\text{dat}, \text{bgs}}^i}{C_i^{\text{MC}} \Delta A_i \mathcal{L}}, \quad \text{with} \quad C_i^{\text{MC}} = \frac{N_{i, \text{det}}^{\text{MC}}}{N_{i, \text{truth}}^{\text{MC}}},
\]

→ NLO lower than data for low \(E_\gamma^T\) but in agreement within theoretical uncertainties

→ PYTHIA model describes fairly well the data.

→ HERWIG falls below the data by 10%-20%
Sensitivity to the proton parton distributions

- Inclusive prompt photon production dominated by $u$-$g$ process.
  - larger charge of $u$-type quark and their prevalence in the proton.
  - sensitive to the gluon pdf.
Sensitivity to the proton parton distributions

- ABM11_5N PDF has a softer gluon distribution at high-$x$
  → contribution from processes with gluons in the initial state is smaller at high $E_T^\gamma$ than that obtained using CT10.
Sensitivity to the proton parton distributions

- Comparison between JETPHOX prediction with different PDF sets and data.

- Tension between data and the predictions of the current PDF sets

- At intermediate $E_T^\gamma$ where data are most precise → scale uncertainty is dominant
  → NNLO calculations (currently unavailable) may be necessary to fully exploit the measurement.

Josu Cantero (On behalf of the ATLAS collaboration)
Dynamics of isolated-photon and jet production at $\sqrt{s} = 7$ TeV with $L = 37 \, pb^{-1}$

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Dynamics of isolated-photon and jet production: measurements

- The kinematics and dynamics of isolated photon plus jet production was studied by measuring the following cross sections:
  - photon and jet properties: \( d\sigma/dE_T^\gamma, d\sigma/dP_T^{\text{jet}}, d\sigma/d|y^{\text{jet}}| \)
  - photon plus jet properties: \( d\sigma/d\Delta\phi^{\gamma j}, d\sigma/dM^{\gamma j}, d\sigma/d|\cos \theta^{\gamma j}| \)

- Cuts \(|\eta^{\gamma} + y^{\text{jet}}| < 2.37, |\cos \theta^{\gamma j}| < 0.83\) and \(M^{\gamma j} > 161\) GeV were applied for unbiased measurements of \(d\sigma/dM^{\gamma j}\) and \(d\sigma/d|\cos \theta^{\gamma j}|\)

  \[ \rightarrow \]  angular distribution \(d\sigma/d|\cos \theta^{\gamma j}|\) sensitive to the spin of the exchange (virtual) particle: quark \((1/2)\) vs gluon \((1)\).
Photon/jet selection and background subtraction

- **Photon:**
  - Photon candidates required to have passed an 40 GeV trigger.
  - $E_T^\gamma > 45$ GeV and $0.0 < |\eta^\gamma| < 2.37$ (excluding crack region $1.37 < |\eta^\gamma| < 1.52$)
  - **Tight ID** criteria based on the electromagnetic shower profiles.
  - Photon isolation selection $E_{T}^{\text{iso}(\text{reco})} < 3$ GeV

- **Jet:**
  - jets reconstructed with Anti-kt algorithm with $R = 0.6$
  - $p_T^{\text{jet}} > 40$ GeV and $0.0 < |y^{\text{jet}}| < 2.37$
  - $\Delta R^{\gamma-jet} > 1.0$

- Background subtracted using 2D side-band method ($\sim 10\%$)
**Systematic uncertainties**

- **Main sources of systematic uncertainty (uncertainty quoted for $|\cos \theta^{\gamma-jet}|$ cross section):**
  - jet energy scale: $\approx 5.0\%$
  - jet energy resolution: $\approx 1.0\%$
  - photon energy scale: $\approx 1.0\%$
  - photon energy resolution: $\approx 0.2\%$
  - background subtraction: $\approx 3.6\%$
  - detector material uncertainty: $\approx 5.0\%$
  - jet efficiency uncertainty: $\approx 2.0\%$
  - fudge factor uncertainty: $\approx 2.0\%$
  - model dependence (HERWIG vs PYTHIA): $\approx 1.0\%$
  - Brem/Hard admixture dependence: $\approx 2.0\%$
  - luminosity uncertainty ($37.1 \pm 1.3 \text{ pb}^{-1}$): $3.4\%$

- **Total systematic uncertainty** is estimated by summing in quadrature all the contributions.

- **Final systematic uncertainty** on the differential cross sections varies between $8\%$ and $15\%$ depending on the phase space region of the measurements.
Dynamics of isolated-photon and jet production

→ “sanity checks” of perturbative QCD (pQCD)
→ theoretical calculation estimated with JETPHOX (corrected by the effect of hadronization and UE)

→ Good description of data by NLO pQCD for $d\sigma/dE_T^\gamma$, $d\sigma/dp_T^{\text{jet}}$
→ Similar prediction for CTEQ6.6 and CT10 proton PDFs; MSTW2008nlo 5% higher
Good description of data by NLO pQCD for $d\sigma/d|y^{\text{jet}}|$.

→ Bad description for $d\sigma/d\Delta\phi^{\gamma^{-}\text{jet}}$ (expected, in NLO pQCD calculation $\Delta\phi^{\gamma^{-}\text{jet}} > \pi/2$ due to transverse momentum conservation).

→ Good description of $d\sigma/d\Delta\phi^{\gamma^{-}\text{jet}}$ by PYTHIA.
Dynamics of isolated-photon and jet production

- Good description of data by NLO pQCD for $d\sigma/dM_{\gamma j}$, $d\sigma/d|\cos \theta_{\gamma j}|$
- The shape of the measured $d\sigma/d|\cos \theta_{\gamma^-\text{jet}}|$ is much closer to that of DP than that of F processes which is consistent with dominance of processes in which the exchanged particle is a quark.
- Useful for tuning the relative contributions of the DP and F components.
Conclusions

- Measurements of inclusive isolated prompt-photon production have the potential to constrain the gluon density in the proton.
  → NNLO calculations may be necessary to fully exploit the measurements.

- NLO pQCD calculations give an adequate description of data in a wide range of the phase-space.
  → regions of the phase space have been identified which are particularly sensitive to the contributions from fragmentation
  → the measured dependence with $|\cos \theta_{\gamma-jet}|$ is consistent with the dominance of processes in which a quark is being exchanged.

- An understanding of isolated photon production at LHC in terms of the SM has been achieved
  → Useful for Higgs studies ($H \rightarrow \gamma\gamma$) and BSM searches.
Dynamics of isolated-photon and jet production

\[ \frac{d\sigma}{dE_T^\gamma} \sim 10^{-1} \text{pb/GeV} \]

\( \gamma_T \)

\[ \sigma d \sim 10^{-2} \text{pb/GeV} \]

\( \gamma_T \)

\( \text{ATLAS ( } \sqrt{s} = 7 \text{ TeV, 37 pb}^{-1} ) \)

\( p_T^{\text{jet}} > 40 \text{ GeV} \)

\( \gamma_T \)

\( \text{ATLAS ( } \sqrt{s} = 7 \text{ TeV, 37 pb}^{-1} ) \)

\( E_T^\gamma > 45 \text{ GeV} \)

\[ d\sigma/dp_T^{\gamma} \sim 10^{-1} \text{pb/GeV} \]

\( \gamma_T \)

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