Probing QCD with Photons and Jets produced in proton-proton collisions with the ATLAS Detector

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On behalf of the ATLAS collaboration

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Pheno 2018
Physics with Jets
- Inclusive jet and dijet at 13 TeV ($p_T^{\text{jet}}, m_{jj}$)
  Submitted to JHEP
- Jet soft drop mass at 13 TeV
  Submitted to PRL

Physics with Photons
- $\gamma +$ jet at 13 TeV
- $\gamma +$ HF jet at 8 TeV
- $\gamma\gamma$ at 8 TeV
  Phys. Rev. D 95 (2017) 112005
- $\gamma\gamma\gamma$ at 8 TeV

$\gamma +$ jet: $E_T^\gamma$, $p_T^{\text{jet}}$, $|\cos\theta^*|$, $m_{\gamma j}$ and $\Delta\phi_{\gamma j}$

$\gamma +$ HF jet: $E_T^\gamma$ for b and c-jets

$\gamma\gamma$: $m_{\gamma\gamma}$, $p_T, \gamma\gamma$, $\Delta\phi_{\eta}$, $a_T$, $|\cos\theta^*|$, and $\Delta\phi_{\gamma\gamma}$

$\gamma\gamma\gamma$: $m_{\gamma\gamma\gamma}$, $m_{\gamma\gamma}$, $\Delta\phi_{\gamma\gamma}$, $\Delta\eta_{\gamma\gamma}$ and $E_T^\gamma$
Jets
Jet production is the dominant high-$p_T$ process at the LHC.

Jet observables play an important role in the study of:

→ The structure of the proton
→ The color interaction and its coupling strength $\alpha_s$
→ Physics beyond the Standard Model.

\[
\sigma_{pp\rightarrow\text{jets}} = \sum_{i,j} \int dx_1 \, f_{i/1}(x_1, Q) \int dx_2 \, f_{j/2}(x_2, Q) \, \hat{\sigma}_{ij\rightarrow\text{jets}}(x_1, x_2) \quad (1)
\]

Experimental reconstruction:

→ 3D topological clusters of calorimeter cells as inputs of jet algorithms
→ Anti-$k_T$ with $R = 0.4, 0.6$
→ Multi-step process to calibrate the energy of the jet
Inclusive jet and dijet production at $\sqrt{s} = 13$ TeV

**Inclusive jets**
- $L = 3.2$ fb$^{-1}$
- $100 \, \text{GeV} \leq p_T \leq 4.0 \, \text{TeV}$
- $|y| < 3$, in equal steps of 0.5

![Graph showing $d^2\sigma/dp_T\,dy$ for inclusive jets with ATLAS data and NLOJET++ predictions.]

- 9 (8) orders of magnitude in central (most forward) rapidity region
- Adequate description (in log scale) of data by NLO QCD calculations

**Dijet**
- $L = 3.2$ fb$^{-1}$
- $300 \, \text{GeV} \leq m_{jj} \leq 9 \, \text{TeV}$
- $|y^*| = \left| \frac{y_{j1} - y_{j2}}{2} \right| < 3$, in equal steps of 0.5

![Graph showing $d^2\sigma/dm_{jj}\,dy^*$ for dijets with ATLAS data and NLOJET++ predictions.]

- Adequate description (in log scale) of data by NLO QCD calculations
Inclusive jet and dijet production at $\sqrt{s} = 13$ TeV

- JES uncertainties $\sim 5\%$ for $p_T < 1$ TeV ($15\text{-}30\%$ at $p_T > 2$ TeV)
- Small effect due to JER uncertainty
- Single-hadron energy response main uncertainty at high-$p_T$
Inclusive jet and dijet production at $\sqrt{s} = 13$ TeV

→ NLO (NNLO) pQCD with NLOJet++ (NNLOJet)
- $\mu_R = \mu_F = p_T^{\text{jet}} (p_T^{\text{jet,max}})$
- PDFs: CT14, MMHT2014, NNPDF3.0, HERAPDF2.0 and ABMP16
- PDFs, scale choice and $\alpha_s$ as theoretical uncertainties.

- $\sigma_{\text{theory}} = \sigma_{\text{NLO}} \times k_{\text{NP}} \times k_{\text{EW}}$
- $k_{\text{NP}} = \frac{\sigma(\text{hadrons})}{\sigma(\text{partons})}$
- $\Delta_{\text{NP}}$ envelope of several LO MC predictions.
- $K_{\text{EW}}$ electroweak correction factor
Inclusive jet and dijet production at $\sqrt{s} = 13$ TeV

- NLO (NNLO) pQCD with NLOJet++ (NNLOJet)
  - $\mu_R = \mu_F = p_T^{jet} \left( p_T^{jet,max} \right)$
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Inclusive jet and dijet production at $\sqrt{s} = 13$ TeV

**Inclusive jets** ($\mu_R = \mu_F = p_T^{\text{jet}}$)

- NLO pQCD above the measurements for $p_T \lesssim 200$-500 GeV
- Toward higher $p_T$ NLO pQCD closer to data
- $p_T > 300$ GeV and high $y$ rise of NLO pQCD with respect to data ($>20\%$)
- Similar behaviour for different PDF sets
- Good description by NNLO
Inclusive jet and dijet production at $\sqrt{s} = 13$ TeV

**Inclusive jets** ($\mu_R = \mu_F = p_T^{\text{jet,max}}$)

- NLO pQCD describes the measurements within uncertainties.
- Toward higher $p_T$ NLO pQCD closer to data
- $p_T > 300$ GeV and high $y$ rise of NLO pQCD with respect to data (>20%)
- NNLO above measurements for $p_T < 500$ GeV

ATLAS

$L = 81 \text{ nb}^{-1} - 3.2 \text{ fb}^{-1}$

$\sqrt{s} = 13$ TeV

anti-$k_t$ $R=0.4$

- Data
- NLO QCD
- $k_{\text{EW}} \otimes k_{\text{NP}}$
- NNLO QCD
- $k_{\text{EW}} \otimes k_{\text{NP}}$
- $\mu_R = \mu_F = p_T^{\text{max}}$

**NLO**
- MMHT 2014 NLO

**NNLO**
- MMHT 2014 NNLO
Inclusive jet and dijet production at $\sqrt{s} = 13$ TeV

Dijet ($\mu_R = \mu_F = p_T \cdot e^{0.3y^*}$)

- Good description of data by NLO pQCD within the uncertainties.
- Similar shape predicted by the studied PDF sets.
- For $|y^*| > 2$, tendency for the NLO pQCD prediction to overestimate the measured cross-section in the high $p_T$ range.

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Soft-drop jet mass at $\sqrt{s} = 13$ TeV

- Normalized differential cross section as a function of $\log_{10}(\rho^2)$ ($\rho = m_{\text{soft drop}}/p_T$);
- Soft drop condition:
  $$\min \left( \frac{p_{T1}^2}{(p_{T1} + p_{T2})^2} \right) > z_{\text{cut}} \left( \frac{\Delta R_{12}}{R} \right)^\beta;$$
  $z_{\text{cut}} = 0.1$ and $\beta = 0, 1, 2$
- $\Delta_{\text{sys}} \sim 5-20\%$ ($5\%$) for $\log_{10}(\rho^2) < (> ) -3.5$

$\rightarrow$ More dependence on soft radiation at higher $\beta$.
$\rightarrow$ Resummation region $-3.7 < \log_{10}(\rho^2) < -1.7$. 
Photons
Physics with Photons

- Photon production allows to test pQCD and PDFs information.
- Prompt photons represent a cleaner probe of a hard interaction than jet production.
- Inclusive photons can be produced by two main mechanism:
  - Direct-photon: $\gamma$ produced in the hard interaction
  - Fragmentation: $\gamma$ coming from the fragmentation of a high-$p_T$ parton

\[
\sigma_{pp\rightarrow\gamma+X} = \sum_{i,j,b} \int dx_1 \ f_{i/1}(x_1, Q) \int dx_2 \ f_{i/2}(x_2, Q) \ \hat{\sigma}_{ij\rightarrow\gamma b} + \sum_{i,j,a,b} \int_{z_{min}}^{1} dz \ D_{a}^{\gamma}(z, \mu_f) \int dx_1 \ f_{i/1}(x_1, Q) \int dx_2 \ f_{i/2}(x_2, Q) \ \hat{\sigma}_{ij\rightarrow ab}
\]

- Essential to require the photon to be isolated; $E_T^{iso} < E_T^{max}$ in a cone of radius $R=0.4$ (suppress $\pi^0(\eta^0...) \rightarrow \gamma\gamma$ and fragmentation contribution)
\( \gamma + \text{jet}, \sqrt{s} = 13 \text{ TeV} \)

- \( E_T^\gamma \geq 125 \text{ GeV}, p_T^{\text{jet}} > 100 \text{ GeV} \)
- \( E_T^{\text{iso}} < 4.2 \cdot 10^{-3} \cdot E_T^\gamma + 10 \text{ GeV} \)

\( \gamma + \text{HF jet}, \sqrt{s} = 8 \text{ TeV} \)

- \( E_T^\gamma \geq 25 \text{ GeV}, p_T^{\text{jet}} > 20 \text{ GeV} \)
- \( E_T^{\text{iso}} < 4.2 \cdot 10^{-3} \cdot E_T^\gamma + 4.8 \text{ GeV} \)

\( \gamma + \text{HF jet}: \Delta_{\text{sys}} \sim 15\% \rightarrow \text{main contribution due to jet flavour determination (stat. dominated in the } E_T^\gamma \text{ tails 13-37\%).} \)

- Good description within the uncertainties.
**$\gamma + \text{jets production}$**

### $\gamma + \text{jet, } \sqrt{s} = 13 \text{ TeV}$

- **Jetphox (NLO) and Sherpa (NLO @0j and @1j) used for QCD calculations.** ($\Delta_{\text{th}} \sim 10\%-30\%$, dominated by $\mu_R$ and $\mu_F$ choice.)
  - Tend to be above the measurements at high $p_T^{\text{jet}}$

- **$\gamma + \text{HF jet: }$** MG5\_aMC@NLO (NLO) with several PDF sets $\rightarrow$ different IC content/model and 5F/4F flavor-schemes comparison.
  - 4F worse description at high $E_T^{\gamma}$ (large $\log(m_b/E_T^{\gamma})$ terms).
\( \gamma\gamma + X, \sqrt{s} = 8 \text{ TeV} \)

- \( E_T^{\gamma} \geq 40 \text{ GeV} \) and \( 30 \text{ GeV} \)
- \( E_T^{\text{iso}} < 11 \text{ GeV}, \Delta R_{\gamma\gamma} > 0.4 \)

\( \gamma\gamma\gamma + X, \sqrt{s} = 8 \text{ TeV} \)

- \( E_T^{\gamma} \geq 27 \text{ GeV}, 22 \text{ GeV} \) and \( 15 \text{ GeV} \)
- \( E_T^{\text{iso}} < 10 \text{ GeV}, \Delta R_{\gamma\gamma} > 0.45 \)

- \( \gamma\gamma\gamma \): \( \Delta_{\text{sys}} \sim 13\% (P_{\gamma\gamma\gamma} \approx 55\%) \to \) dominated by uncertainties on \( \gamma\gamma\gamma \) yield estimation.

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\( \gamma\gamma + X, \sqrt{s} = 8 \text{ TeV} \)

**\( \gamma\gamma \) production**

\( \gamma\gamma + X, \sqrt{s} = 8 \text{ TeV} \)

- **\( \gamma\gamma \):** NLO (DIPHOX and RESBOS), 2\( \gamma \)-NNLO and SHERPA (NLO @0j and @1j).
  - NLO underestimate the measurements by 40-50%.
  - Adequate description by beyond NLO calculations.

- **\( \gamma\gamma\gamma \):** NLO MCFM and NLO+PS (MG5_AMC@NLO).
  - NLO underestimate the measurements by 36-55%.
  - Beyond NLO calculations not available.
Conclusions

- Measurements with jets or photons produced in the final state in \( pp \) collisions at \( \sqrt{s} = 8 \) and 13 TeV have been presented.
- NLO QCD calculations overestimate jet measurements at low \( p_T \) \((\mu_F = \mu_R = p_T^{jet})\):
  - good description by NNLO calculations
  - Using \( \mu_F = \mu_R = p_T^{jet,max} \) data/NNLO agreement gets worse.
- Adequate description by NLO within uncertainties of \( d\sigma/dm_{jj} \) and jet soft-drop mass.
- Adequate description by the NLO of \( d\sigma/dE_T^\gamma \) for \( \gamma + \text{jet} \) and \( \gamma + \text{HF jet} \) processes.
  - NLO tends to overestimate the measurements at high \( p_T^{jet} \).
- NLO predictions underestimate \( \sigma_{\gamma\gamma} \) and \( \sigma_{\gamma\gamma\gamma} \):
  - Addition of PS effects improve the description of \( \Delta\phi_{\gamma\gamma} \) in \( \gamma\gamma\gamma \) production.
  - Beyond NLO calculations improve the description of \( \sigma_{\gamma\gamma} \).
Backup
Photon + jets production

ATLAS
\( \sqrt{s} = 13 \text{ TeV}, 3.2 \text{ fb}^{-1} \)

Data statistics
- total systematic
- jet energy scale
- photon energy scale
- photon identification

ATLAS
\( \sqrt{s} = 13 \text{ TeV}, 3.2 \text{ fb}^{-1} \)

NLO/Data

SHERPA
(ME+PS@NLO QCD)
JETPHOX
(NLO QCD)

ATLAS
\( \sqrt{s} = 13 \text{ TeV}, 3.2 \text{ fb}^{-1} \)

Data

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Photon + jets production

ATLAS
\(\sqrt{s} = 13 \text{ TeV}, 3.2 \text{ fb}^{-1}\)

Relative uncertainty

\[
\begin{align*}
\Delta \phi^{\gamma\text{-jet}} [\text{rad}] \\
\text{Data statistics} & \quad \text{total systematic} \\
\cdots & \quad \text{jet energy scale} \\
\cdots & \quad \text{photon energy scale} \\
\cdots & \quad \text{photon identification}
\end{align*}
\]

\[
\begin{align*}
\Delta \phi^{\gamma\text{-jet}} [\text{rad}] \\
\text{Data statistics} & \quad \text{total systematic} \\
\cdots & \quad \text{jet energy scale} \\
\cdots & \quad \text{photon energy scale} \\
\cdots & \quad \text{photon identification}
\end{align*}
\]

Data statistics

- total systematic
- jet energy scale
- photon energy scale
- photon identification

ATLAS
\(\sqrt{s} = 13 \text{ TeV}, 3.2 \text{ fb}^{-1}\)

\[
\begin{align*}
\text{NLO/Data} & = 0.5 \quad 1 \quad 1.5 \\
\text{NLO/Data} & = 0.5 \quad 1 \quad 1.5
\end{align*}
\]

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ATLAS
\(\sqrt{s} = 8\) TeV, 4.58 pb\(^{-1}\) - 20.2 fb\(^{-1}\)
1.56 < |\(\eta^\prime\)| < 2.37

\(\gamma + b\)

\(\gamma + C\)

\(E_T^\gamma\) [GeV]

Data 2012
SHERPA
PYTHIA
MG5\_aMC+PY8 \(\otimes\) NNPDF3.1nlo 5F
MG5\_aMC+PY8 \(\otimes\) NNPDF3.0nlo 4F

NLO/Data

\(\frac{d\sigma}{dE_T^\gamma}\) [pb/GeV]
**γ + jets production**

**γ + jet, √s = 13 TeV**

- γ + jet: good description → spin of exchanged particle compatible with fermions.
- γ + HF jet: cancellation of syst. uncert. on the ratio (higher stat. uncertainty)
  → Sensitive to IC content of the proton (higher contribution at high ηγ)

![Graph showing ATLAS, SHERPA, and JETPHOX comparisons for γ + jet production at √s = 13 TeV.](image)

**γ + HF jet, √s = 8 TeV**

![Graph comparing ATLAS, SHERPA, and JETPHOX predictions for γ + HF jet production at √s = 8 TeV.](image)
$\gamma\gamma$ and $\gamma\gamma\gamma$ production

$\gamma\gamma + X, \sqrt{s} = 8$ TeV

$\gamma\gamma\gamma + X, \sqrt{s} = 8$ TeV

- $\gamma\gamma$: NLO (DIPHOX and RESBOS), 2$\gamma$-NNLO and SHERPA (NLO @0j and @1j).
  - Description highly improved by including beyond NLO terms.

- $\gamma\gamma\gamma$: NLO MCFM and NLO+PS (MG5_aMC@NLO).
  - PS allows to improve the description as function of $\Delta\phi_{\gamma_1\gamma_2}$, $\Delta\phi_{\gamma_1\gamma_3}$ and $\Delta\phi_{\gamma_2\gamma_3}$. 
Inclusive jet and dijet production at $\sqrt{s} = 13$ TeV

<table>
<thead>
<tr>
<th>Rapidity ranges</th>
<th>$P_{\text{obs}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CT14</td>
</tr>
<tr>
<td>$p_T^{\text{max}}$</td>
<td></td>
</tr>
<tr>
<td>$</td>
<td>y</td>
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<tr>
<td>$0.5 \leq</td>
<td>y</td>
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<tr>
<td>$1.0 \leq</td>
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<td>$1.5 \leq</td>
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<tr>
<td>$2.0 \leq</td>
<td>y</td>
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<tr>
<td>$2.5 \leq</td>
<td>y</td>
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</tbody>
</table>

$|y| < 0.5$  67%  65%  62%  31%  50%
$0.5 \leq |y| < 1.0$ 7.4%  8.9%  8.6%  3.4%  2.0%
$1.0 \leq |y| < 1.5$ 69%  62%  68%  45%  54%
$1.5 \leq |y| < 2.0$ 1.3%  1.6%  1.4%  0.1%  0.5%
$2.0 \leq |y| < 2.5$ 8.7%  6.6%  7.4%  1.0%  3.6%
$2.5 \leq |y| < 3.0$ 65%  72%  72%  28%  59%

$P_T^{\text{jet}}$

| $\chi^2$/dof all $|y|$ bins | CT14 | MMHT 2014 | NNNPDF 3.0 | HERAPDF 2.0 | ABMP16 |
|-----------------------------|------|-----------|-------------|-------------|--------|
| $p_T^{\text{max}}$         | 419/177 | 431/177  | 404/177    | 432/177    | 475/177 |
| $p_T^{\text{jet}}$         | 399/177 | 405/177  | 384/177    | 428/177    | 455/177 |

$y^*$ ranges

<table>
<thead>
<tr>
<th></th>
<th>CT14</th>
<th>MMHT 2014</th>
<th>NNNPDF 3.0</th>
<th>HERAPDF 2.0</th>
<th>ABMP16</th>
</tr>
</thead>
<tbody>
<tr>
<td>$y^* &lt; 0.5$</td>
<td>79%</td>
<td>59%</td>
<td>50%</td>
<td>71%</td>
<td>71%</td>
</tr>
<tr>
<td>$0.5 \leq y^* &lt; 1.0$</td>
<td>27%</td>
<td>23%</td>
<td>19%</td>
<td>32%</td>
<td>31%</td>
</tr>
<tr>
<td>$1.0 \leq y^* &lt; 1.5$</td>
<td>66%</td>
<td>55%</td>
<td>48%</td>
<td>66%</td>
<td>69%</td>
</tr>
<tr>
<td>$1.5 \leq y^* &lt; 2.0$</td>
<td>26%</td>
<td>26%</td>
<td>28%</td>
<td>9.9%</td>
<td>25%</td>
</tr>
<tr>
<td>$2.0 \leq y^* &lt; 2.5$</td>
<td>43%</td>
<td>35%</td>
<td>31%</td>
<td>4.2%</td>
<td>21%</td>
</tr>
<tr>
<td>$2.5 \leq y^* &lt; 3.0$</td>
<td>45%</td>
<td>46%</td>
<td>40%</td>
<td>25%</td>
<td>38%</td>
</tr>
<tr>
<td>all $y^*$ bins</td>
<td>8.1%</td>
<td>5.5%</td>
<td>9.8%</td>
<td>0.1%</td>
<td>4.4%</td>
</tr>
</tbody>
</table>

- Quantitative comparison between the measurements and the NLO pQCD for different PDF sets.
- Syst. and theor. uncertainties inclcused in the $\chi^2$. Asymm. and correlations also considered.
- Each syst. and theor. uncert. uncorr. among each other and fully correlated across $p_T$, $|y|$.
- Correlations of stat. uncer. considered using covariance matrices.