QCD with jets and photons at ATLAS and CMS

Jonathan Bossio - McGill University
on behalf of the ATLAS and CMS collaborations

MoriondQCD2019
La Thuile - 23–30 March 2019
The measurements presented here collectively probe:

- Precision QCD predictions (inclusive cross sections that probe PDFs and NLO QCD)
- Event topologies in interesting phase space regions (i.e. multijet production, dijet decorrelations, very forward region)
- Jet substructure (substructure observables, trimming and soft-drop, $g \rightarrow b\bar{b}$).
**Measurement performed in inclusive 2- and 3-jet events**

- LO MCs: Pythia, Herwig++ and MadGraph+Pythia8
- NLO MCs: Powheg(2→2)+HERWIG++, Powheg(2→2)+Pythia8 and Powheg(2→3)+Pythia8
- Discrepancies with the unfolded data are as large as 15%, mainly in $177^\circ < \Delta\phi_{12} < 180^\circ$
- The 2- and 3-jet measurements are not simultaneously described by any of models

---

**Inclusive 2-jet events**

- CMS
  - Total exp. unc.
  - PH-2J + PYTHIA8
  - PH-3J + PYTHIA8
  - PH-2J + Herwig++

<table>
<thead>
<tr>
<th>$200 &lt; p_T^{max} &lt; 300$ GeV</th>
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<td>1.15</td>
<td>1.10</td>
<td>1.05</td>
</tr>
</tbody>
</table>

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**Inclusive 3-jet events**

- CMS
  - Total exp. unc.
  - PH-2J + PYTHIA8
  - PH-3J + PYTHIA8
  - PH-2J + Herwig++

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</tr>
</tbody>
</table>

The two highest $p_T$ jets must satisfy $|y| < 2.5$ and $p_T > 100$ GeV. For inclusive 3-jet events a third jet with $p_T > 30$ GeV and $|y| < 2.5$ is required.
Azimuthal correlations in 2-, 3-, and 4-jet events at $\sqrt{s} = 13$ TeV

- $\Delta\phi_{2j}^{\text{min}}$: minimum azimuthal angles between any two of the three or four leading $p_T$ jets
- NLO Herwig7 gives a better overall description than Powheg
Measurement of the rapidity and $p_T$ dependence of dijet azimuthal decorrelations

- $R_{\Delta \phi}$: fraction of dijet events w/ $\Delta \phi < \Delta \phi_{\text{max}}$
- $R_{\Delta \phi}$ is measured as a function of the dijet rapidity interval $y^*$, the event total scalar transverse momentum $H_T$, and $\Delta \phi_{\text{max}}$
- NLO pQCD predictions from NLOJET++, corrected for non-perturbative effects
- The theoretical predictions describe the unfolded data in the whole kinematic region

- Determination of $\alpha_S$ and its running
- Combination of the data at all momentum transfers results in $\alpha_S = 0.1127^{+0.0063}_{-0.0027}$
Cross sections are measured in proton-lead collisions as a function of jet energy

- Phase-space sensitive to the parton densities and their evolution at low fractional momenta
- Models incorporating various implementations of gluon saturation have been used
- Discrepancies btw. unfolded data and predictions of more than two orders of magnitude
- No model is currently able to describe all aspects of the data

Inclusive very forward jet cross sections at $\sqrt{s_{NN}} = 5.02$ TeV

<table>
<thead>
<tr>
<th>E [GeV]</th>
<th>Data</th>
<th>Sys. uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1500</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2500</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>p+Pb/Pb+p ratio</th>
<th>Data</th>
<th>Sys. uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td></td>
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<tr>
<td>0.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

CMS, $\sqrt{s_{NN}} = 5.02$ TeV
Event shape variables (ESVs) are sensitive to the flow of energy in hadronic final states

- ESVs are measured in different $H_{T,2} = (p_{T\text{jet}1} + p_{T\text{jet}2})/2$ bins

The *complement of transverse thrust* is defined as $\tau_\perp \equiv 1 - T_\perp$ where $T_\perp \equiv \max \frac{\sum_i |\vec{p}_{T,i} \cdot \hat{n}_T|}{\sum_i p_{T,i}}$

$\tau_\perp$ is zero for a perfectly balanced two-jet event and is $1 - 2/\pi$ for an isotropic multijet event

The agreement generally improves as $H_{T,2}$ increases
Measurement of the soft-drop jet mass at $\sqrt{s} = 13$ TeV


Measurement of the cross section as a function of $\log_{10} \rho^2$ in dijet events

Jet reclustering: $\frac{\min(p_{Tj_1}, p_{Tj_2})}{p_{Tj_1} + p_{Tj_2}} > \zeta_{\text{cut}} \left( \frac{\Delta R_{12}}{R} \right)^{\beta}$

Smaller $\beta \rightarrow$ remove more soft particles

$\rho \equiv m^{\text{soft drop}} / p_T^{\text{ungroomed}}$

LO+NNLL perform well for $\beta = 0$

MC event generators better for higher $\beta$

Unfolded data is compared to MC simulation samples and pQCD calculations

Bottom-up method to estimate (cluster-level) systematic uncertainties
Jet substructure observables in $t\bar{t}$ and inclusive jet events

- anti-$k_t$ $R = 1.0$ jets groomed using two different techniques: trimming ($R_{\text{sub}} = 0.2$, $f_{\text{cut}} = 5\%$) and soft-drop ($\beta = 0, \zeta_{\text{cut}} = 0.1$)

- Unfolded data distributions are compared to various MC event generators

- Cluster-level uncertainties on the overall shape and scale of the observables

Observable: $D_{\beta} = \frac{e_3(\beta)}{(e_2(\beta))^3}$

In general, reasonable agreement within uncertainties, with some discrepancies
Main background source in analyses involving boosted Higgs decaying into $b$-quarks

- $R = 0.2$ anti-$k_T$ jets from tracks are ghost-matched to $R = 1.0$ anti-$k_T$ trimmed jets
- The contribution from $R = 1.0$ jets that don’t have 2 track-jets containing B-hadrons is subtracted from data using template fits
- Unfolding to the particle level
- Significant differences observed b/w data and MC predictions
Inclusive isolated-photon and $\gamma+\text{jet}$ cross sections measured as a function of $E_T^{\gamma}$ in different $|y^\gamma|$ bins

- Allows to test gluon PDF in different $x$ and $Q^2$ values
- Prompt photons are identified with a boosted decision tree algorithm
- All measurements are in agreement with the NLO pQCD predictions

Inclusive isolated-photon cross section

| $|y^\gamma| < 0.8$ | Data stat. uncertainty | Data total unc. | NLO JETPHOX scale unc. | NLO JETPHOX total unc. |
|---|---|---|---|---|
| $2.26 \text{ fb}^{-1} (13\text{ TeV})$ |

Photon+jet cross section

| $|y^\gamma| < 1.44, |y^\text{jet}| < 1.5, p_T^{\text{jet}} > 30\text{ GeV}$ | Data stat. uncertainty | Data total unc. | NLO JETPHOX scale unc. | NLO JETPHOX total unc. |
|---|---|---|---|---|
| $2.26 \text{ fb}^{-1} (13\text{ TeV})$ |
The ratio \(R_{13/8}\) is measured as a function of the \(E_T^\gamma\) in different \(|\eta^\gamma|\) ranges

- Reduced systematic and theoretical uncertainties by taking into account the correlations between the CMEs
- Photon energy scale is no longer the dominant uncertainty (with some exceptions at high \(E_T^\gamma\))
- A small background contribution still remains after imposing the photon identification and isolation requirements and is subtracted using a data-driven method
- NLO pQCD predictions calculated with JETPHOX are corrected for non-perturbative effects
- Predictions using several PDFs agree with the unfolded data within uncertainties
Isolated-photon plus jet production cross section at $\sqrt{s} = 13$ TeV

- Photons with $E_T^\gamma > 125$ GeV
- Anti-$k_t$ $R = 0.4$ jets with $p_T > 100$ GeV
- ME+PS@LO predictions from Sherpa and Pythia8 as well as NLO pQCD predictions from JETPHOX and Sherpa describe the data

$\cos \theta^* \equiv \tanh (\Delta y/2)$ is sensitive to spin of exchange parton for $|\cos \theta^*| \to 1$
Many great results from ATLAS and CMS experiments

New interesting results for different phase spaces, jet substructure, and ratio of cross sections at different centre-of-mass energies

Most of the results are well modelled by predictions

Discrepancies are observed in some results

Gives room to improve MC event simulations and pQCD predictions

Huge effort made by performance groups to reduce experimental systematic uncertainties
Back-up slides
Monte Carlo event generators, parton densities, and underlying event tunes used for comparison with measurements

<table>
<thead>
<tr>
<th>Matrix element generator</th>
<th>Simulated diagrams</th>
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<th>Tune</th>
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<tr>
<td>Pythia 8.219</td>
<td>$2 	o 2$ (LO)</td>
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Δφ_{12} in nearly back-to-back jet topologies at \( \sqrt{s} = 13 \) TeV

Azimuthal correlations in 2-, 3-, and 3-jet events at $\sqrt{s} = 13$ TeV

$\Delta \phi_{2j}^{\text{min}}$: minimum azimuthal angles between any two of the three or four leading $p_T$ jets

### CMS

**Number of Jets $\geq 3$**

- Anti-$k_T$, $R = 0.4$
- Experimental uncertainty

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<td></td>
<td>$p_T^{\text{max}}$ &gt; 1000 GeV</td>
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</tr>
<tr>
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<td></td>
</tr>
<tr>
<td></td>
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<td></td>
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<td></td>
</tr>
<tr>
<td></td>
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### CMS

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- Anti-$k_T$, $R = 0.4$
- Experimental uncertainty

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<td></td>
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<tr>
<td></td>
<td>$p_T^{\text{max}}$ &gt; 1000 GeV</td>
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Monte Carlo event generators used for comparison in this analysis

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<td>2→2 (LO)</td>
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<td>CUETHppS1 [13]</td>
</tr>
<tr>
<td><strong>GRAPH5_aMC@NLO 2.3.3 [17, 18]</strong> + <strong>PYTHIA 8.219 [9]</strong></td>
<td>2→2, 2→3, 2→4 (LO)</td>
<td>NNPDF2.3LO [14, 15]</td>
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<tr>
<td><strong>HERWIG 7.0.4 [23]</strong></td>
<td>2→2 (NLO), 2→3 (LO)</td>
<td>MMHT2014 [29]</td>
<td>H7-UE-MMHT [23]</td>
</tr>
</tbody>
</table>
The values of the parameters and the requirements that define the analysis phase space

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_{T\text{min}}$</td>
<td>100 GeV</td>
</tr>
<tr>
<td>$y_{\text{max}}$</td>
<td>0.5</td>
</tr>
<tr>
<td>$y^*$</td>
<td>2.0</td>
</tr>
<tr>
<td>$p_{T1}/H_T &gt; 1/3$</td>
<td></td>
</tr>
</tbody>
</table>

Fit result for $\alpha_s (m_Z)$, determined from the $R_{\Delta \phi}$ data for $\Delta \phi_{\text{max}} = 7\pi/8$ with $0.0 < y^* < 0.5$ and $0.5 < y^* < 1.0$

<table>
<thead>
<tr>
<th>$\alpha_s (m_Z)$</th>
<th>Total Statistical</th>
<th>Experimental</th>
<th>Non-perturb. correlated</th>
<th>Non-perturb. corrections</th>
<th>MMHT2014 uncertainty</th>
<th>PDF set</th>
<th>$\mu_{R,F}$ variation</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1127</td>
<td>$^{+6.3}_{-2.7}$</td>
<td>$^{+0.5}_{-1.7}$</td>
<td>$^{+1.8}_{-1.7}$</td>
<td>$^{+0.3}_{-0.1}$</td>
<td>$^{+0.6}_{-0.6}$</td>
<td>$^{+2.9}_{-0.0}$</td>
<td>$^{+5.2}_{-1.9}$</td>
</tr>
</tbody>
</table>

All uncertainties have been multiplied by a factor of $10^3$
Inclusive very forward jet cross sections at $\sqrt{s_{NN}} = 5.02$ TeV

The contribution in percentage of various sources of systematic uncertainty in the highest and lowest common energy bins

<table>
<thead>
<tr>
<th>Energy bin [TeV]</th>
<th>p+Pb</th>
<th>Pb+p</th>
<th>p+Pb/Pb+p</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.6</td>
<td>+2</td>
<td>+18</td>
<td>+19</td>
</tr>
<tr>
<td>2.5</td>
<td>+150</td>
<td>+41</td>
<td>+160</td>
</tr>
<tr>
<td>0.6</td>
<td>-2</td>
<td>-18</td>
<td>-19</td>
</tr>
<tr>
<td>2.5</td>
<td>-71</td>
<td>-41</td>
<td>-72</td>
</tr>
<tr>
<td>0.6</td>
<td>+120</td>
<td>+4</td>
<td>+140</td>
</tr>
<tr>
<td>2.5</td>
<td>+78</td>
<td>+1</td>
<td>+100</td>
</tr>
<tr>
<td>0.6</td>
<td>-2</td>
<td>+2</td>
<td>-11</td>
</tr>
<tr>
<td>2.5</td>
<td>+77</td>
<td>+2</td>
<td>+27</td>
</tr>
</tbody>
</table>

Model dependence

- Energy scale
  - +2
  - +18
  - -2
  - -18

- Model dependence
  - +1
  - +4
  - +41

- Alignment
  - +4
  - -4

- Jet identification
  - +2
  - +24

- Total
  - +19
  - -19

Model dependence

- Energy scale
  - +2
  - +18
  - -2
  - -18

- Model dependence
  - +1
  - +4
  - +41

- Alignment
  - +4
  - -4

- Jet identification
  - +2
  - +24

- Total
  - +19
  - -19

The CMS Collaboration

Jonathan Bossio — McGill University
Event divided into upper (U) and lower (L) regions. Jets in U (L) satisfy $\vec{p}_{T,i}.\hat{n}_T > 0$ ($< 0$)

The total jet broadening is defined as $B_{\text{Tot}} \equiv B_U + B_L$, $B_X \equiv \frac{1}{2P_T} \sum_{i \in X} p_{T,i} \sqrt{(\eta_i - \eta_X)^2 + (\phi_i - \phi_X)^2}$

$$\eta_X \equiv \frac{\sum_{i \in X} p_{T,i} \eta_i}{\sum_{i \in X} p_{T,i}}, \quad \phi_X \equiv \frac{\sum_{i \in X} p_{T,i} \phi_i}{\sum_{i \in X} p_{T,i}},$$

and $P_T$ is the scalar $p_T$ sum of all jets in the event.

The agreement generally improves as $H_{T,2}$ increases.
The normalized squared invariant mass of the jets in the U and L regions of the events is defined by:

\[ \rho_X \equiv \frac{M_X^2}{P^2} \]

where \( M_X \) is the invariant mass jets in the region \( X \), and \( P \) is the scalar sum of the momenta of all central jets.

The total jet mass is defined as follows:

\[ \rho_{\text{Tot}} \equiv \rho_U + \rho_L \]

The total transverse jet mass \((\rho_{\text{Tot}}^T)\) is similarly calculated using \( \vec{p}_{T,i} \) of jets.
Evolution of the mean of $\tau_\perp$, $B_{\text{Tot}}$, $\rho_{\text{Tot}}$, and $\rho^T_{\text{Tot}}$ with increasing $H_{T,2}$
Measurement of the soft-drop jet mass at $\sqrt{s} = 13$ TeV


ATLAS

$\sqrt{s} = 13$ TeV, 32.9 fb$^{-1}$

Soft drop, $\beta = 0$, $z_{\text{cut}} = 0.1$

anti-$k_t$, $R=0.8$, $p_T^{\text{lead}} > 600$ GeV

Relative Uncertainty

Total uncertainty
MC statistical error
Data statistical error
QCD Modeling
Nonclosure
Cluster angular resolution
Cluster energy scale shift
Cluster energy scale smearing
Pileup modeling

$\log_{10}(m_{\text{soft drop}} / p_{T,\text{ungroomed}}^2)$

ATLAS

$\sqrt{s} = 13$ TeV, 32.9 fb$^{-1}$

Soft drop, $\beta = 2$, $z_{\text{cut}} = 0.1$

anti-$k_t$, $R=0.8$, $p_T^{\text{lead}} > 600$ GeV

Relative Uncertainty

Total uncertainty
MC statistical error
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Nonclosure
Cluster angular resolution
Cluster energy scale shift
Cluster energy scale smearing
Pileup modeling

$\log_{10}(m_{\text{soft drop}} / p_{T,\text{ungroomed}}^2)$
Measurement of the soft-drop jet mass at $\sqrt{s} = 13$ TeV

Jet reclustering: $\frac{\min(p_{Tj_1}, p_{Tj_2})}{p_{Tj_1} + p_{Tj_2}} > \zeta_{\text{cut}} \left( \frac{\Delta R_{12}}{R} \right)^{\beta}$

Smaller $\beta \rightarrow$ remove more soft particles

- $\rho \equiv \frac{m_{\text{soft drop}}}{p_{T}^{\text{ungroomed}}}$
- Unfolded data is compared to MC simulation samples and pQCD calculations
- Bottom-up method to estimate (cluster-level) systematic uncertainties
- LO+NNLL perform well for $\beta = 0 \implies$
- MC event generators better for higher $\beta \downarrow$

Data

Pythia 8.1
Sherpa 2.1
Herwig++ 2.7
LO+NNLL, large NP effects
LO+NNLL
NLO+NLL
NLO+NLL+NP

Ratio to Data

Jonathan Bossio — McGill University
Jet substructure observables in $t\bar{t}$ and inclusive jet events

- anti-$k_t$ $R = 1.0$ jets groomed using two different techniques: trimming ($R_{\text{sub}} = 0.2$, $f_{\text{cut}} = 5\%$) and soft-drop ($\beta = 0$, $\zeta_{\text{cut}} = 0.1$)

- Unfolded data distributions are compared to various MC event generators

- Cluster-level uncertainties on the overall shape and scale of the observables

\[
e^{(\beta)}_n = \frac{E_{\text{CF}n}(\beta)}{E_{\text{CF}1}(\beta)^n} \quad ; \quad E_{\text{CF}1}(\beta) = \sum_{i \in J} p_{Ti}
\]
\[
E_{\text{CF}2}(\beta) = \sum_{i < j \in J} p_{Ti}p_{Tj}(\Delta R_{ij})^\beta
\]
\[
E_{\text{CF}3}(\beta) = \sum_{i < j < k \in J} p_{Ti}p_{Tj}p_{Tk}(\Delta R_{ij}\Delta R_{ik}\Delta R_{jk})^\beta
\]

In general, reasonable agreement within uncertainties, with some discrepancies

Dijet selection

\[
D_2^{(\beta)} \equiv \frac{e_3^{(\beta)}}{(e_2^{(\beta)})^3}
\]

W selection
Summary of systematic uncertainty sizes for each observable for the normalized differential cross sections

<table>
<thead>
<tr>
<th>Uncertainty Source</th>
<th>( \Delta R(b, b) )</th>
<th>( \Delta \theta_{ppg,gbb} )</th>
<th>( z(p_T) )</th>
<th>( \log(m_{bb}/p_T) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calorimeter jet energy</td>
<td>2–3%</td>
<td>2–3%</td>
<td>2–6%</td>
<td>2–4%</td>
</tr>
<tr>
<td>Flavor tagging</td>
<td>&lt;1%</td>
<td>&lt;1%</td>
<td>&lt;1%</td>
<td>&lt;1%</td>
</tr>
<tr>
<td>Tracking</td>
<td>1–2%</td>
<td>1–2%</td>
<td>2–4%</td>
<td>1–2%</td>
</tr>
<tr>
<td>Background fit</td>
<td>1%</td>
<td>1%</td>
<td>1–2%</td>
<td>2%</td>
</tr>
<tr>
<td>Unfolding method</td>
<td>2–3%</td>
<td>2%</td>
<td>2–4%</td>
<td>2–5%</td>
</tr>
<tr>
<td>Theoretical modeling</td>
<td>3–10%</td>
<td>2–13%</td>
<td>3–10%</td>
<td>4–11%</td>
</tr>
<tr>
<td>Statistical</td>
<td>1%</td>
<td>1%</td>
<td>2%</td>
<td>1%</td>
</tr>
<tr>
<td>Total</td>
<td>3–10%</td>
<td>3–10%</td>
<td>3–14%</td>
<td>4–12%</td>
</tr>
</tbody>
</table>
The contribution from large-\(R\) jets that do not have two associated track-jets containing B-hadrons is subtracted from data, before correcting for detector effects.

Correction factors are determined from data template fits to the signed impact parameter distribution (\(s_{d_0}\)) and applied for each bin of the four observables.

In each bin, the distribution of \(s_{d_0}\) is fitted to data using templates from simulation while letting the fraction of each flavor component float in the fit.

For a given track, \(s_{d_0} = s_j |d_0|/\sigma(d_0)\), where \(d_0\) is the transverse impact parameter relative to the beam-line, \(\sigma(d_0)\) is the uncertainty in \(d_0\) from the track fit, and the variable \(s_j\) is the sign of \(d_0\) with respect to the jet axis: \(s_j = +1\) if \(\sin(\phi_{\text{jet}} - \phi_{\text{track}}) \cdot d_0 > 0\) and \(s_j = -1\) otherwise.

\[ s_{d_0} \text{ versus } s_{d_0} \text{ for } L+C, B, \text{ and } BB. \]
Properties of $g \rightarrow b\bar{b}$ at small opening angles at $\sqrt{s} = 13$ TeV


Main background source in analyses involving boosted Higgs decaying into $b$-quarks

- $R = 0.2$ anti-$k_t$ jets from tracks are ghost-matched to $R = 1.0$ anti-$k_t$ trimmed jets
- The contribution from $R = 1.0$ jets that don’t have 2 track-jets containing B-hadrons is subtracted from data using template fits
- Unfolding to the particle level
- Significant differences observed b/w data and MC predictions
Impact on cross sections, in percent, for each systematic uncertainty source  
(The ranges, when quoted, indicate the variation over photon ET between 190-1000 GeV)

| Source                  | $|y^\gamma| < 0.8$ | $0.8 < |y^\gamma| < 1.44$ | $1.57 < |y^\gamma| < 2.1$ | $2.1 < |y^\gamma| < 2.5$ |
|-------------------------|------------------|-------------------|-------------------|-------------------|
| Trigger efficiency      | 0.7–8.5          | 0.2–13.4          | 0.6–20.5          | 0.3–7.8           |
| Selection efficiency    | 0.1–1.3          | 0.1–1.3           | 0.1–5.3           | 0.1–1.1           |
| Data-to-MC scale factor | 3.7              | 3.7               | 7.1               | 7.1               |
| Template shape          | 0.6–5.0          | 0.1–10.2          | 0.5–4.9           | 0.6–16.2          |
| Unfolding               | 3.8–5.5          | 1.2–4.1           | 2.0–8.5           | 2.3–10.3          |
| Total w/o luminosity    | 5.4–12.0         | 5.9–18.2          | 8.2–26.9          | 8.6–21.7          |
| Integrated luminosity   |                  |                   |                   | 2.3               |
Relative theoretical uncertainty in $R_{13/8}^\gamma$ as a function of $E_T^\gamma$ for different $|\eta^\gamma|$ regions.
Relative systematic uncertainty in $R^{\gamma}_{13/8}$ as a function of $E_{T}^{\gamma}$ for different $|\eta^{\gamma}|$ regions.
Total relative systematic uncertainty in $R_{13/8}$ as a function of $E_T^\gamma$ for different $|\eta^\gamma|$ regions.
Theoretical uncertainties in $R_{13/8}^\gamma$:

- The uncertainties due to the PDFs, $\alpha_s$, beam energy and non-perturbative effects are fully correlated between the two centre-of-mass energies.
- The relative uncertainty in $R_{13/8}^\gamma$ due to the uncertainties in $\alpha_s$, the PDFs and the beam energy are significantly smaller with respect to the individual predictions.
- However, for the scale uncertainties, the correlation is a priori unknown.
- Varying the scales coherently or incoherently at both centre-of-mass energies leads to very different uncertainties.
- A second approach is also investigated, which is free from ambiguity in the correlation. It consists of considering the difference between the LO and NLO predictions for $R_{13/8}^\gamma$.
- The results of this second approach support the use of coherent variations of the scales; an incoherent variation of the scales leads to an overestimation of the theoretical uncertainty.
Experimental uncertainties in $R_{13/8}^\gamma$:

- A proper estimation of the systematic uncertainties requires taking into account inter-$\sqrt{s}$ correlations for each source of systematic uncertainty.
- Assuming no correlation provides a conservative estimate and full correlation is used only when justified.
- The uncertainty arising from the $\gamma$ energy scale is estimated by decomposing it into uncorrelated sources for both the 8 and 13 TeV measurements
- A total of 22 individual components are considered
- Twenty of these components are common to both centre-of-mass energies
- The remaining two components are specific to the 13 TeV measurement
- All the components are taken as fully correlated except for the uncertainty in the overall energy scale adjustment using $Z \rightarrow e^+ e^-$ events, which for 2015 includes the effects of the changes in the configuration of the ATLAS detector, and the uncertainties specific to the 13 TeV measurement
- The uncertainties due the $\gamma$ energy resolution are treated as uncorrelated between $\sqrt{s} = 13$ TeV and 8 TeV since they include the effects of pile-up, which was different in the 2012 and 2015 data-taking periods
- Other sources of uncertainty are treated as uncorrelated
In addition, the $R_{13/8}^\gamma$ ratio to that of the fiducial cross sections for $Z$ boson production at 13 and 8 TeV using the decay channels $Z \rightarrow e^+ e^-$ and $Z \rightarrow \mu^+ \mu^-$ is made and compared with the theoretical predictions.

In this double ratio, a further reduction of the experimental uncertainty is obtained because the uncertainties arising from the luminosity measurement cancel out.

The predictions describe the measurements of the double ratio within the theoretical and experimental uncertainties.
Isolated-photon plus jet production cross section at $\sqrt{s} = 13$ TeV

Isolated-photon plus jet cross-sections as a function of several observables

- Photons with $E_T^\gamma > 125$ GeV
- anti-$k_t$ $R = 0.4$ jets with $p_T > 100$ GeV
- ME+PS@LO predictions from Sherpa and Pythia8 as well as NLO pQCD predictions from JETPHOX and Sherpa describe the data

$\cos \theta^* \equiv \tanh (\Delta y/2)$ is sensitive to spin of exchange parton for $|\cos \theta^*| \to 1$
Requirements on photons

\( E_T^\gamma > 125 \text{ GeV}, \ |\eta^\gamma| < 2.37 \) (excluding \( 1.37 < |\eta^\gamma| < 1.56 \))

\( E_{iso}^T < 4.2 \cdot 10^{-3} \cdot E_T^\gamma + 10 \text{ GeV} \)

Requirements on jets

\( k_t \) algorithm with \( R = 0.4 \)

the leading jet within \( |y^{\text{jet}}| < 2.37 \) and \( \Delta R^{\gamma-\text{jet}} > 0.8 \) is selected

\( p_T^{\text{jet-lead}} > 100 \text{ GeV} \)

UE subtraction using \( k_\perp \) algorithm with \( R = 0.5 \) (cf. Section ??)

Additional requirements for \( d\sigma/dm^{\gamma-\text{jet}} \) and \( d\sigma/d|\cos \theta^\ast| \)

\( |\eta^\gamma + y^{\text{jet-lead}}| < 2.37, \ |\cos \theta^\ast| < 0.83 \) and \( m^{\gamma-\text{jet}} > 450 \text{ GeV} \)