Measurement of photon (also +jets) production cross sections, jets production cross sections and extraction of the strong coupling constant

ISMD2017
Tlaxcala City, Mexico

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on behalf of the ATLAS Collaboration

September 11, 2017
Outlook

- **Photon physics**
  - Diphoton at 8 TeV. (Phys. Rev. D 95 (2017) 112005)
  - Inclusive $\gamma + \text{jet}$ at 8 TeV. (Nucl.Phys. B918 (2017) 257-316)
  - Inclusive $\gamma + \text{jet}$ at 13 TeV. (ATLAS-CONF-2017-059)

- **Jet physics**
  - Inclusive-jet cross-section at 8 TeV (20.2 fb$^{-1}$) (arXiv:1706.03192)
  - Inclusive-jet and dijet cross-sections at 13 TeV (3.2 fb$^{-1}$) (ATLAS-CONF-2017-048)
  - TEEC measurements and extraction of $\alpha_s$ (arXiv:1707.02562)

A complete list of ATLAS Standard Model results can be found here: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/StandardModelPublicResults
Prompt photons in pp collisions

- Measurements of the production of high $p_T$ prompt photons (in association with jets) and pairs of photons in hadron colliders provide
  - tests of pQCD predictions
  - constraints on the proton PDFs
  - input to understand QCD background to Higgs production and BSM searches

- Prompt photons in pp collisions are produced via two mechanisms: direct-photon and fragmentation processes

![Diagram showing prompt photon (plus jet) production and diphoton production](image-url)
Inclusive isolated photons at 13 TeV

- Testing pQCD with a hard colourless probe
- Sensitive at LO to the gluon PDF
- Photon selection:
  - $E_T^\gamma > 125$ GeV and $|\eta^\gamma| < 2.37$, excluding the region $1.37 < |\eta^\gamma| < 1.56$
  - photon ID
  - photon isolation: $E_T^{iso} (R = 0.4) < 4.8$ GeV + $4.2 \cdot 10^{-3} \times E_T^\gamma$
- Background subtracted with data-driven technique
Photon energy scale is the dominant uncertainty at high $E_T$

Background subtraction largest at low $E_T$

Identification uncertainty $\sim 5\%$ at high $E_T$

Uncertainties are larger in the forward regions
Inclusive isolated photons at 13 TeV

- NLO pQCD predictions (JetPhox)
  - underestimate the measurements
  - Theoretical uncertainties > experimental in most regions
  - Statistical uncertainty takes over beyond 1 TeV
  - Different PDFs show up to 15% difference
  - Demonstrates sensitivity to help constrain PDFs. Especially for large $E_T$

- Comparisons would benefit from reduced scale uncertainties
Inclusive isolated photons at NNLO (8 TeV)

- New prediction for inclusive photon production at NNLO available! (ArXiv:1612.04333)
- QCD NNLO predictions have been compared to ATLAS inclusive photon measurements at 8 TeV
  - Theoretical uncertainty reduced by a factor ~3 with respect to PeTeR
  - Trend of the calculations to be above the data at high $E_T$
**Diphoton at 8 TeV**

*Phys. Rev. D 95 (2017) 112005*

- Sensitive to $\alpha_s$ corrections
- Sensitive to QCD infrared emission
- Main background for $H \rightarrow \gamma\gamma$

<table>
<thead>
<tr>
<th>Selection</th>
<th>Leading $\gamma$</th>
<th>Subleading $\gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min. transverse energy</td>
<td>$E_{T,1}^\gamma &gt; 40$ GeV</td>
<td>$E_{T,2}^\gamma &gt; 30$ GeV</td>
</tr>
<tr>
<td>Pseudorapidity</td>
<td>$</td>
<td>\eta\gamma</td>
</tr>
<tr>
<td>Min. angular separation</td>
<td>$\Delta R_{\gamma\gamma} &gt; 0.4$</td>
<td></td>
</tr>
<tr>
<td>Max. transverse isolation energy</td>
<td>$E_{T}^{\text{iso,part}}(\Delta R = 0.4) &lt; 11$ GeV</td>
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- Variables sensitive to new physics: $m_{\gamma\gamma}$, $|\cos(\theta_\eta^\ast)|$
- Variables sensitive to higher order and QCD ISR: $p_{T,\gamma\gamma}$, $\Delta \Phi_{\gamma\gamma}$
- New variables sensitive to QCD ISR emissions: $a_T$, $\Phi_{\eta}^\ast$
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→NNLO

$$\sigma_{\text{fid}} = 16.8 \pm 0.8 \text{ pb} = 16.8 \pm 0.1(\text{stat}) \pm 0.7(\text{exp}) \pm 0.3(\text{lumi}) \text{ pb}$$
• Fixed-order calculations are not expected to give reliable predictions in regions sensitive to infrared emissions

• The effects of infrared emissions are well reproduced by the inclusion of soft-gluon resummation at NNLL

• Sherpa and RESBOS do a good job at low $a_T$ or $\phi_\eta^*$
  ○ PS and resummation

• DIPHOX and 2γNNLO do not
Jet production is the dominant high-$p_T$ process in the LHC.

Jet observables play an important role in the study of:
- The structure of the proton
- The color interaction and its coupling strength $\alpha_s$

- Anti-$k_T$ jets

- Built considering topological clusters of calorimeter cells

- Clusters corrected for pileup prior to jet building

- Multi-stage calibration scheme

- Larger energy scale uncertainty than photons
Photon + jets at 8 TeV


- Constrain gluon PDF
- Tests kinematics of photon+multijet production
- Provides input for PDFs
- Testing ground for BSM physics

- Photon selection:
  - $E_T^\gamma > 130$ GeV and $|\eta^\gamma| < 2.37$, excluding the region $1.37 < |\eta^\gamma| < 1.56$
  - Photon ID
  - Photon isolation:
    - $E_T^{iso} (R = 0.4) < 4.8$ GeV + $4.2 \times 10^{-3} \times E_T^\gamma$

- Jet selection:
  - $P_T > 50$ GeV, $|y_j| < 4.4$

- 15 observables of the following types:
  - Kinematic: $E_{T,\gamma}$, $P_{T,jet}$
  - Dynamic: $m_{\gamma,jet}$, $\Delta \phi_{\gamma,jet}$, $\Delta \phi_{jet,jet}$
  - Virtual particle spin: $|\cos \theta^*|$
  - New: parton radiation around $\gamma$ or jet1: $\beta_\gamma$, $\beta_{jet1}$
NLO predictions with JetPhox + CT10 PDF
  ○ Give a good agreement in both normalization and shape
Photon + 2 jets at 8 TeV

- SHERPA better than Pythia in multijet region
- Data are well described by BlackHat
  - Visible deviation for $E_T > 750$ GeV wrt NLO prediction
Photon + 2 jets at 8 TeV

- First observation of different QCD radiation pattern around the photon and 1st jet
- Enhancements in the directions towards the beams
- Better agreement with SHERPA
Photon + 3 jets at 8 TeV

- First measurement at ATLAS
- BlackHat calculation slightly overestimates the data
Photon + 1 jet at 13 TeV
ATLAS-CONF-2017-059

- Extended reach to $E_T = 1.5$ TeV
- Sherpa describes well the data
- Pythia overestimates jet $P_T$
  - large contribution from photon bremsstrahlung
- Both simulations describe angular distributions
Photon + 1 jet at 13 TeV
ATLAS-CONF-2017-059

- NLO predictions

JetPhox does the best job
- Sherpa (ME+PS@NLO QCD) fails to describe high jet $P_T$
- Theoretical uncertainties > experimental. Main contribution: terms beyond NLO
Inclusive jet production at 13 TeV


- Measurement based on 3.2 fb⁻¹ of data taken in 2015
  - R=0.4 anti-\(k_T\) jets
  - jet \(p_T > 100\) GeV, jet rapidity \(|y| < 3\)

- Double differential measurement in jet \(p_T\) and \(y\)
  - jet energy scale and resolution uncertainties generally below 5% central, 10% forward
Increased $p_T$ reach wrt Run1 measurement (up to 3 TeV!)
Good agreement with NLO predictions at log scale
Generally good agreement with NLO pQCD within uncertainties
- Shape consistent between various PDF sets
  - Exceptions are HERAPDF 2.0 and ABMP16 in the central region
- LO tends to overshoot data for |y| > 2.0 with CT14, MMHT 2014 & NNPDF 3.0
Inclusive jet production at 13 TeV

ATLAS-CONF-2017-048

- Generated using the NNLOJET program & MMHT 2014 NNLO PDF
- Ratio of NLO and NNLO theory predictions to data

\[ p_T^{\text{jet}} \] better than \[ p_T^{\text{max}} \] for the QCD scale
Dijet production at 13 TeV
ATLAS-CONF-2017-048

- Measurement based on 3.2 fb$^{-1}$ of data taken in 2015
  - $R=0.4$ anti-$k_T$ jets
  - jets with $p_T > 75$ GeV, jet rapidity $|y| < 3$
  - $H_{T2} = p_{T1} + p_{T2} > 200$ GeV
    - Reduces instabilities in the NLO cross-section calculation

- Double differential measurement in $M_{jj}$ and $y^* = |y_1 - y_2| / 2$

- Experimental systematic uncertainties near 5% for medium $M_{jj}$, rising to 30% at highest $M_{jj}$
Dijet production at 13 TeV

ATLAS-CONF-2017-048

- First measurement of dijet cross-section at 13 TeV
- Good agreement between NLO pQCD and data within uncertainties
- Detailed $\chi^2$ tests made for each PDF set
  - fair agreement in individual $M_{jj}$ and $y^*$ bins
  - fair agreement as well when fitting to all $y^*$ regions
Transverse energy-energy correlation (TEEC):

\[
\frac{1}{\sigma} \frac{d\Sigma}{d(\cos \phi)} = \frac{1}{\sigma} \sum_{ij} \int \frac{d\sigma}{dx_{T_i} dx_{T_j} d(\cos \phi)} x_{T_i} x_{T_j} d(\cos \phi)
\]

where \( x_{T_i} = E_{T_i}/E_T \) and \( E_T = \sum_i E_{T_i} \)

Event shape used in \( e^+e^- \), adapted to pp
Essentially an energy-weighted ratio of three-jet to two-jet cross-sections
Exhibits quadratic dependence on \( \alpha_s \)
Measures angular distributions of jet pairs weighted by

\[
w_{ij} = x_{T_i} x_{T_j} = \frac{E_{T_i} E_{T_j}}{(\sum_k E_{T_k})^2}
\]

Analysis strategy:
- at least 2 jets with \( p_T > 100 \text{ GeV}, |y^{\text{jet}}| < 2.5 \)
- \( p_{T1} + p_{T2} > 800 \text{ GeV} \)
- Total uncertainty is about 5%
TEEC in multi-jet events at 8 TeV

arXiv:1707.02562

- Resulting detector-level distributions are normalized to the total number of events
- Data distributions are unfolded back to the particle level
  - Iterative Bayesian method. Pythia used to build transfer matrix
- Compared with Pythia8, Sherpa, and Herwig++


**TEECE in multi-jet events at 8 TeV: $\alpha_s(m_Z)$ measurement**

- $\alpha_s(m_Z)$ extraction from $\chi^2$ fit of TEECC and ATEEC NLO predictions to data varying the value of $\alpha_s$ in NLOJet++

![Diagram](image)

- Excellent compatibility between World Average and ATLAS jet-based measurements
- Very good experimental precision. Uncertainty dominated by the unc. in theory predictions

\[ \alpha_s(m_Z) = 0.1162 \pm 0.0011 \text{ (exp.)} \pm 0.0076 \text{ (scale)} \pm 0.0018 \text{ (PDF)} \pm 0.0003 \text{ (NP)}. \]

\[ \alpha_s(m_Z) = 0.1196 \pm 0.0013 \text{ (exp.)} \pm 0.0061 \text{ (scale)} \pm 0.0017 \text{ (PDF)} \pm 0.0004 \text{ (NP)}. \]
 Photon physics

- Direct photons at 13 TeV
  - NLO predictions provide an adequate description.
  - Theoretical uncertainties > experimental: NNLO pQCD corrections are needed

- 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

- 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 $O(\alpha_{EM} \alpha_s^4)$

- Photon+jet at 13 TeV
  - Comparison with SHERPA ME+PS@NLO
Summary

- **Jet pythics**
  - Inclusive jet cross section at 7, 8 and 13 TeV
    - Good agreement of pQCD at NLO
    - NNLO comparisons
    - Test of PDFs particularly in the forward rapidities
  - First measurement of dijet cross-sections at 13 TeV
  - Transverse energy-energy correlations in dijet events
    - Used to extract the strong coupling constant
    - TEEC/ATEEC:
      \[
      \alpha_s(m_Z) = 0.1162 \pm 0.0011 \text{ (exp.)}^{+0.0076}_{-0.0061} \text{ (scale)} \pm 0.0018 \text{ (PDF)} \pm 0.0003 \text{ (NP)},
      \]
      \[
      \alpha_s(m_Z) = 0.1196 \pm 0.0013 \text{ (exp.)}^{+0.0061}_{-0.0013} \text{ (scale)} \pm 0.0017 \text{ (PDF)} \pm 0.0004 \text{ (NP)}.
      \]
    - Comparable to 7 TeV result:
      \[
      \alpha_s(m_Z) = 0.1173 \pm 0.0010 \text{ (exp.)}^{+0.0065}_{-0.0026} \text{ (theo.)}
      \]
Thanks
The ATLAS detector
Prompt photon in pp collisions

- In addition to prompt photons, photons are produced copiously inside jets (e.g., $\pi^0$ decays)
  - It is essential to require isolation to study prompt photons in hadron colliders

- The isolation requirement is based on the energy deposited inside a circle of radius $R$ centered on the photon in the $\eta$–$\phi$ plane (not counting energy depositions coming from the photon itself)

  $$E_T^{\text{iso}} \equiv \sum_i E_T^i < E_T^{\text{max}}$$

- It is able to suppress most of the contribution of photons inside jets (from $\pi^0$’s and other neutral mesons decays) and the fragmentation contribution
In most parts of the phase space, the fixed order predictions are unable to reproduce the data.

- Improvement NLO -> NNLO
- SHERPA provides the best description
- $2\gamma$NNLO performs well at high mass and $P_T$
Inclusive jet production at 8 TeV

arXiv:1706.03192

- Selection
  - jet $p_T > 70$ GeV
  - jet rapidity $|y| < 3$

- Measurement made with both R=0.4 and 0.6 jets

- Double differential measurement in jet $p_T$ and $y$

- 11 orders of magnitude for central rapidity!
- Good agreement with NLO theory on log scale
Inclusive jet production at 8 TeV
arXiv:1706.03192

- Dominant experimental uncertainties are jet energy scale and resolution
  - both well below 10% except at highest jet $p_T$

- PDFs, renormalization and factorization scales, $\alpha_s$ variations in theory systematic uncertainty
Inclusive jet production at 8 TeV

arXiv:1706.03192

- Theory predictions corrected for non-perturbative and electroweak effects
- Use a variety of PDFs

- Good agreement with NLO pQCD prediction (NLOJet++) at higher jet $p_T$
- NLO overestimates data for jet $p_T$ below 100 GeV and above 1 TeV
- HERAPDF2.0 is significantly lower than data in $300 < p_T < 1000$ GeV
Inclusive jet production at 8 TeV
arXiv:1706.03192

- Powheg (NLO+PS) below NLOJet++ at low $p_T$
  - tendency to be below the data toward higher $p_T$
  - for $p_T > 1$ TeV different behaviour than NLO QCD
- Powheg prediction less dependent on the jet radius
TEEC in multi-jet events at 8 TeV
arXiv:1707.02562

- Compared to NLO pQCD predictions using NLOJET++
  - corrected for non-perturbative effects
  - renormalization scale set to $H_{T^2}$
  - factorization scale set to $H_{T^2} / 2$

\[ \sqrt{s} = 8 \text{ TeV}; \ 20.2 \ \text{fb}^{-1} \]

\[ \text{NNPDF 3.0 (NNLO)} \]

\[ \text{ATLAS} \]

- pQCD correctly describes the data within uncertainties