Recent results on soft QCD topics, and jet and photon production from ATLAS

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on behalf of the ATLAS Collaboration

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ATLAS has performed several measurements of phenomena connected to QCD at soft scales or at the
transition to the hard regime

● Sensitive to non-perturbative models of soft QCD
  ■ inelastic cross section in pp collisions (ATLAS-CONF-2015-038) 13 TeV
  ○ properties of the underlying event interactions (ATL-PHYS-PUB-2015-019) 13 TeV
  ○ properties of minimum bias (ATLAS-CONF-2015-028) 13 TeV
  ○ particle production and their correlations, as well as diffractive and exclusive events

● Sensitive to hard QCD, parton densities of the proton, as well as fragmentation models
  ○ inclusive jet production differential cross section (ATLAS-CONF-2015-034) 13 TeV
  ○ jet production properties and determination of the strong coupling constant $\alpha_s$

Due to time constraints, this presentation will focus on most recent results!

A complete list of ATLAS Standard Model results can be found here: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/StandardModelPublicResults
pp inelastic cross section at 13 TeV

ATLAS-CONF-2015-038

● June 2015: 13 TeV but mean number of pp interactions per bunch crossing was $\mu = 2.3 \times 10^{-3}$ (integrated luminosity $63 \pm 6 \mu b^{-1}$)

● Using Minimum Bias Trigger Scintillators (MBTS) mounted in front of the forward calorimeters:
  ○ at $\pm 3.6$ m from IP, covering $2.07 < |\eta| < 3.86$

● Inelastic interaction: at least one of the two protons dissociates

● Fiducial measurement limited by the phase space where the larger of the invariant masses $M_x$ is within the detector acceptance: $\xi = M_x^2 / s > 10^{-6}$
pp inelastic cross section at 13 TeV
ATLAS-CONF-2015-038

- Fiducial measurement limited by the phase space where the larger of the invariant masses $M_x$ is within the detector acceptance

$$\sigma_{\text{inel}}(\tilde{x} > 10^{-6}) = \frac{N - N_{\text{BG}}}{\epsilon_{\text{trig}} \times L} \times \frac{1 - f_{\tilde{x}<10^{-6}}}{\epsilon_{\text{sel}}}$$

- Measurement compared to MC predictions

<table>
<thead>
<tr>
<th>Source</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>This measurement</td>
<td>$65.2 \pm 0.8$ (exp.) $\pm 5.9$ (lum.) mb</td>
</tr>
<tr>
<td>Pythia8 DL, $\epsilon = 0.06$</td>
<td>71.0 mb</td>
</tr>
<tr>
<td>Pythia8 DL, $\epsilon = 0.085$</td>
<td>69.1 mb</td>
</tr>
<tr>
<td>Pythia8 DL, $\epsilon = 0.1$</td>
<td>68.1 mb</td>
</tr>
<tr>
<td>Pythia8 A2</td>
<td>74.4 mb</td>
</tr>
<tr>
<td>EPOS LHC</td>
<td>71.2 mb</td>
</tr>
<tr>
<td>QGSJET-II</td>
<td>72.7 mb</td>
</tr>
</tbody>
</table>

- Values used in the calculation:

<table>
<thead>
<tr>
<th>Factor</th>
<th>Value</th>
<th>Rel. unc.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of selected events ($N$)</td>
<td>4159074</td>
<td>$-$</td>
</tr>
<tr>
<td>Number of background events ($N_{\text{BG}}$)</td>
<td>43512</td>
<td>$\pm 100%$</td>
</tr>
<tr>
<td>Luminosity [$\mu$b$^{-1}$] ($L$)</td>
<td>62.9</td>
<td>$\pm 9%$</td>
</tr>
<tr>
<td>Trigger efficiency ($\epsilon_{\text{trig}}$)</td>
<td>99.7%</td>
<td>$\pm 0.1%$</td>
</tr>
<tr>
<td>MC Correction factor $((1 - f_{\tilde{x}&lt;10^{-6}})/\epsilon_{\text{sel}})$</td>
<td>0.993</td>
<td>$\pm 0.5%$</td>
</tr>
</tbody>
</table>
Extrapolation to full inelastic cross section using models of inelastic interactions

Depending on models, acceptance ranges from 87.6% to 93.7%

Final value is

$$73.1 \pm 0.9 \text{ (exp.)} \pm 6.6 \text{ (lum.)} \pm 3.8 \text{ (extr.) mb.}$$

About 1-1.5 standard deviations below theoretical predictions currently available
Detector-level underlying event distributions at 13 TeV

ATLAS-PHYS-PUB-2015-019

- **UE:** any hadronic activity not associated with hard scattering process

- Typically modelled with
  - multiple parton interactions
  - initial/final-state radiation
  - colour reconnection with beam remnants

- **Strategy:**
  - Identify a “hard scatter” using a reference object (eg. jet/Z/track)
  - Define azimuthal regions with respect to this leading object
    - Toward and transverse regions most sensitive to the underlying event
    - High $p_T$ recoil important in away region $\rightarrow$ perturbative QCD
  - Reconstruct kinematics from charged tracks

![Diagram showing azimuthal regions](image-url)
Detector-level underlying event distributions at 13 TeV
ATLAS-PHYS-PUB-2015-019

- Preliminary result: detector-level distributions
- Predictions show good agreement with data in toward region
- Greater discriminating power in transverse region
  - Still only minor discrepancies from the data
  - MPI energy extrapolation working well
Inclusive charged-particle measurements in pp collisions provide insight into the strong interaction in the low energy, non-perturbative QCD region.
Track-based minimum bias at 13 TeV

- Inclusive charged-particle measurements in pp collisions provide insight into the strong interaction in the low energy, non-perturbative QCD region

- MC tunes describe the data reasonably well at this new centre-of-mass energy
Inclusive jet cross section at 13 TeV

ATLAS-CONF-2015-034

● Preliminary results on the inclusive-jet cross section using 78 pb$^{-1}$ of data at 13 TeV

● Differential measurement as a function of
  ○ jet transverse momentum: $346 < p_T^{\text{jet}} < 838$ GeV, in the jet rapidity range of $|y^{\text{jet}}| < 0.5$

● Data unfolded to particle-level using modified Bayesian technique

• NLO pQCD predictions, corrected for non-perturbative effects, are consistent with the data
Four-jet cross section at 8 TeV

- Measurement of differential cross sections for events with at least four jets

- Test of prediction at
  - LO: PYTHIA, HERWIG and MADGRAPH+PYTHIA
  - NLO pQCD: Blackhat/Sherpa and Njet/Sherpa
  - HEJ: exclusive MC generator

  - based on approximate all-orders calculations (for $n_{\text{jet}} \geq 2$)

- $H_T$ (scalar sum of jet $p_T$) is well described by both NLO and HEJ

- $m_{4j}$ is well described by both NLO up to 3 TeV and HEJ at high masses

- NLO uncertainties are relatively large O(30%) at low momenta
Diffractive di-jet production at 7 TeV

- A 6.8 nb\(^{-1}\) low pile-up sample of pp collision data (peak \(\langle \mu \rangle \sim 0.04\text{–}0.14\))
- Events with at least two jets with \(p_T > 20\text{ GeV}\) and \(|\eta^{\text{jet}}| < 4.4\)
- Quantum numbers of respective initial and final states are the same in diffractive interaction
- Diffractive processes can be identified by
  - the presence of a space devoid of particles, rapidity gap
  - detecting intact forward protons

\[
M_X^2 = \sqrt{s} \sum p_T e^{-|\eta|}
\]
\[
\xi \simeq \frac{M_X^2}{s} = \sum p_T e^{-|\eta|} / \sqrt{s}
\]

- Diffractive process with hard scale for pQCD calculations
- Sensitivity to underlying parton dynamics and colour singlet exchange
- Sensitivity to soft survival probability, \(S^2\)
Diffractive di-jet production at 7 TeV

- Non-diffractive MC describe the data over a wide kinematic range
- Diffractive component required for a more complete description
  - particularly when both large $\Delta \eta^F$ and small $\zeta$ are required
- PYTHIA8 gives the best description of the shape and normalisation
- Application of a cut $\Delta \eta^F > 2$ significantly reduces non-diffractive background
- The lowest log $\zeta$ bin gives model-dependent estimate of the rapidity-gap survival probability

$S^2 = 0.16 \pm 0.04$ (stat.) $\pm 0.08$ (exp. syst.)
Jet charge in di-jet events at 8 TeV

Jet charge: momentum-weighted sum of the charges of tracks associated to a jet: 
\[ Q_J = \frac{1}{(p_{T,J})^k} \sum_{i \in \text{Tracks}} q_i \times (p_{T,i})^k \]
- sensitive to charge of initiating quark or gluon
- depends on jet flavor, driven by $x$-dependence of PDFs, and energy-dependence of fragmentation functions
- can provide constraint on models of jet formation

Average charge expected to increase with jet $p_T$ due to increased contribution from up-quark initiated jets

Dijet events:
- $p_T > 50 \text{ GeV}$
- $p_{T1}/p_{T2} < 1.5$
- $|\eta_{\text{jet}}| < 2.1$
- Tracks for reco-jet + charged particles for particle-jets
- Track multiplicity and JES are the major systematics

Comparison with NLO/LO MCs for more central (left) and forward (right) jets.
- Data consistently above predictions, possibly due to fragmentation modelling (not PDFs alone).
Jet charge in di-jet events at 8 TeV


- The charge of up/down quark-initiated jets can be extracted from data using the fraction of such quarks computed in the MC (Pythia with CT10 PDF and AU2 tune)

- Scale violation parameter can be defined as a function of \( k \) and then extracted from data using

\[
\langle Q_i \rangle \approx \sum_f \alpha_{f,i} \bar{Q}_f (1 + c_k \log(p_{T,i}/\bar{p}_T))
\]

\( \alpha_{f,i} \): flavour fraction in the i-th \( p_T \) bin
\( \bar{Q}_f \): mean charge at fixed \( p_T = 700 \text{ GeV} \)

- Data supports prediction: \( c_k < 0 \) and \( \partial c_k / \partial k < 0 \)
Transverse energy-energy correlation (TEEC):
- Event shape used in $e^+e^-$, adapted to pp
- 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:
- 158 pb$^{-1}$ of data at 7 TeV
- at least two jets with $p_T > 50$ GeV
- $p_{T1} + p_{T2} > 500$ GeV
- $|y_{jet}| < 2.5$
- Total uncertainty is about 5%
  - dominated by the JES
  - pileup
  - MC parton-shower modeling

Pythia/Alpgen predictions agree reasonably well with data, Herwig++ deviates from data by up to 20%
TEEC in multi-jet events at 7 TeV: $\alpha_s(m_Z)$ measurement


TEEC measurement:
- good agreement with NLO pQCD calculations
- small sensitivity to non-perturbative effects
- theoretical scale unc. dominate over experimental uncertainties

- $\alpha_s(m_Z)$ extraction from $\chi^2$ fit of NLO predictions to data

$\alpha_s(m_Z) = 0.1173 \pm 0.0010$ (exp.) $+0.0063$ (scale) $\pm 0.0017$ (PDF) $+0.0002$ (NPC)

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

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

- 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
Inclusive isolated photon distributions at 13 TeV

ATLAS-PHYS-PUB-2015-016

- Inclusive isolated-photon distributions using 6.4 pb$^{-1}$ (pp $\rightarrow$ $\gamma + X$)
- Photon selection:
  - $E_T^{\gamma} > 125$ GeV and $|\eta^{\gamma}| < 2.37$, excluding the region $1.37 < |\eta^{\gamma}| < 1.56$
  - Photon isolation: $E_T^{\text{iso}} (R = 0.4) < 4.8$ GeV $+ 4.2 \cdot 10^{-3} \times E_T^{\gamma}$
- Clear observation of isolated photon signal at 13 TeV
- Comparison to normalised LO MC predictions. Good description of data by SHERPA 2.1
Diphoton distributions at 13 TeV

ATLAS-PHYS-PUB-2015-020

- Isolated photon-pair distributions using 6.4 pb$^{-1}$ ($pp \rightarrow \gamma\gamma + X$)
- Photon pair selection:
  - $E_T^{\gamma} > 15$ GeV and $|\eta^{\gamma}| < 2.37$, excluding the region $1.37 < |\eta^{\gamma}| < 1.52$
  - photon isolation: $E_T^{\gamma,iso} (R = 0.4) < 4$ GeV
  - $\Delta R^{\gamma\gamma} > 0.4$

- Clear observation of isolated photon-pair signal at 13 TeV
Summary

- ATLAS performed a wide range of measurements covering a variety of SM physics aspects

- Soft QCD
  - Inelastic proton-proton cross section at 13 TeV
  - Underlying event at 13 TeV
  - Charged particle multiplicities at 13 TeV

- Jet production and properties
  - Inclusive jet cross section at 13 TeV
  - Four-jet cross section at 8 TeV
  - Diffractive di-jet production at 7 TeV
  - Jet charge in di-jet events at 8 TeV
  - Extraction of QCD coupling constant from TEEC in multi-jet events at 7 TeV

- Photon production
  - First measurements of isolated photon and di-photon distributions at 13 TeV

- ... and much more

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/StandardModelPublicResults
Thanks