Recent ATLAS Results on Diffraction and QCD

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on behalf of
the ATLAS Collaboration

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Workshop on QCD and Diffraction
Saturation 1000+
5th December 2016
**Diffractive signature:** large rapidity gap due to colourless exchange
**Exchange type:** electromagnetic (photon) or strong (Pomeron)

- elastic scattering
- single diffraction (SD)
- central diff. (CD)
- double diff. (DD)
- non-diff. scatt. (ND)

**Elastic cross-section:** elastic scattering measurement
**Inelastic cross-section:** single + double + central diff. + non-diff. scattering
**Total cross-section:** inferred from the elastic measurement via the optical theorem

**Measurements of:**
- single diffractive jet production
- exclusive di-lepton production
• General purpose experiment equipped with detectors for forward physics: MBTS, ZDC, ALFA, AFP.
• Excellent data taking performance.
• Recorded data:
  • 45 pb\(^{-1}\) in 2010 and 5.08 fb\(^{-1}\) in 2011 at \(\sqrt{s} = 7\) TeV,
  • 21.3 fb\(^{-1}\) in 2012 at \(\sqrt{s} = 8\) TeV,
  • 3.9 fb\(^{-1}\) in 2015 and 36 fb\(^{-1}\) in 2016 at \(\sqrt{s} = 13\) TeV.
• Most of data were taken in high pile-up conditions, but we had several runs at low-\(\mu\) dedicated for diffractive studies.
Total and Elastic Cross-Section: Measurement Idea

- elastic signature: two protons (scattered at small angle)
- dedicated detectors needed: **Absolute Luminosity For ATLAS**
- several LHC magnets (Dipoles and Quadrupoles) coll. point and ALFA
- LHC run conditions: special magnet settings (so-called $\beta^* = 90$ m optics) needed to enhance detector acceptance
- data sample:
  - $80 \mu b^{-1}$ of integrated luminosity at $\sqrt{s} = 7$ TeV,
  - $500 \mu b^{-1}$ of integrated luminosity at $\sqrt{s} = 8$ TeV.
From Elastic Scattering to Total Cross Section

**Optical theorem**

*Total cross section is directly proportional to the imaginary part of the forward elastic scattering amplitude extrapolated to zero momentum transfer:*

\[ \sigma_{\text{tot}} = 4\pi \cdot \text{Im}[f_{\text{el}}(t = 0)] \]

\[ \sigma_{AB}^{\text{tot}} = \sum_{n} \left| \begin{array}{c} 2 \\ \sigma_{AB} \end{array} \right| = \sum_{n} \left| \sigma_{AB} \right| = \text{Im} \]

**Elastic scattering:**
- both protons stay intact,
- described by the four momentum transfer, \( t \),
- protons are scattered at very small angles.

\[ \frac{dN}{dt} \bigg|_{t=0} = L\pi \left| f_C + f_N \right|^2 \approx L\pi \left| -\frac{2\alpha_{EM}}{|t|} + \frac{\sigma_{\text{tot}}}{4\pi} (i + \rho) \exp \left( \frac{-b|t|}{2} \right) \right|^2 \]

red – Coulomb part, blue – nuclear part

\[ \rho = \frac{\text{Re} \ f_{\text{el}}}{\text{Im} \ f_{\text{el}}} \bigg|_{t \to 0} \]
Total and Elastic Cross-Section: 7 and 8 TeV Results

**Total cross-section:**

\[
\sigma_{\text{ALFA}}^{\text{tot}}(7\,\text{TeV}) = 95.35 \pm 0.38 \text{ (stat.)} \pm 1.25 \text{ (exp.)} \pm 0.37 \text{ (extr.)} \text{ mb}
\]

\[
\sigma_{\text{ALFA}}^{\text{tot}}(8\,\text{TeV}) = 96.07 \pm 0.18 \text{ (stat.)} \pm 0.85 \text{ (exp.)} \pm 0.31 \text{ (extr.)} \text{ mb}
\]

**Nuclear slope:**

\[
B_{\text{ALFA}}(7\,\text{TeV}) = 19.73 \pm 0.14 \text{ (stat.)} \pm 0.26 \text{ (syst.)} \text{ GeV}^{-2}
\]

\[
B_{\text{ALFA}}(8\,\text{TeV}) = 19.74 \pm 0.05 \text{ (stat.)} \pm 0.23 \text{ (syst.)} \text{ GeV}^{-2}
\]

**Elastic cross-section:**

\[
\sigma_{\text{ALFA}}^{\text{el}}(7\,\text{TeV}) = 24.00 \pm 0.19 \text{ (stat.)} \pm 0.57 \text{ (syst.)} \text{ mb}
\]

\[
\sigma_{\text{ALFA}}^{\text{el}}(8\,\text{TeV}) = 24.33 \pm 0.04 \text{ (stat.)} \pm 0.39 \text{ (syst.)} \text{ mb}
\]

**Inelastic cross-section:**

\[
\sigma_{\text{ALFA}}^{\text{inel}}(7\,\text{TeV}) = 71.34 \pm 0.36 \text{ (stat.)} \pm 0.83 \text{ (syst.)} \text{ mb}
\]

\[
\sigma_{\text{ALFA}}^{\text{inel}}(8\,\text{TeV}) = 71.73 \pm 0.15 \text{ (stat.)} \pm 0.69 \text{ (syst.)} \text{ mb}
\]
Inelastic Cross-Section: Measurement Idea

Use events (single + double + central diffraction + non-diffractive scattering) triggered by ATLAS Minimum Bias Trigger Scintillators

\[ M_X - \text{larger of invariant masses of the two proton dissociated systems, } M_X^2 = \sqrt{s} \sum p_T e^{\pm \eta} \]
\[ \xi = \frac{M_X^2}{s} - \text{energy lost by proton} \]

<table>
<thead>
<tr>
<th>c.m. energy</th>
<th>7 TeV</th>
<th>13 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>integrated luminosity</td>
<td>20.3 ± 0.7 (\mu b^{-1})</td>
<td>63 ± 6 (\mu b^{-1})</td>
</tr>
<tr>
<td>mean number of int. per bunch crossing</td>
<td>0.01</td>
<td>0.0023</td>
</tr>
<tr>
<td>MBTS coverage</td>
<td>2.09 &lt; (</td>
<td>\eta</td>
</tr>
<tr>
<td>relative energy loss range</td>
<td>(\xi &gt; 5 \cdot 10^{-6})</td>
<td>(\xi &gt; 10^{-6})</td>
</tr>
<tr>
<td>minimal invariant mass</td>
<td>(M_X &gt; 15.7 \text{ GeV})</td>
<td>(M_X &gt; 13 \text{ GeV})</td>
</tr>
</tbody>
</table>

MC generators

- **Pythia 6**, 
- **Pythia 8**, **Phojet**

**Pythia 8** (various tunes), **EPOS**, **QGSJET-II**

Backgrounds: collisions of the beam with gas particles in the beam-pipe or with material upstream from the detector, and slowly-decaying, collision-induced radiation (**afterglow**).
Inelastic Cross-Section: Results

Results for 7 TeV:

<table>
<thead>
<tr>
<th>Source</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLAS Data 2010</td>
<td>$60.33 \pm 2.10\text{(exp.)}$</td>
</tr>
<tr>
<td>Schuler and Sjöstrand</td>
<td>66.4</td>
</tr>
<tr>
<td>PHOJET</td>
<td>74.2</td>
</tr>
<tr>
<td>Ryskin et al.</td>
<td>$51.8 - 56.2$</td>
</tr>
</tbody>
</table>

Extrapolated cross-section:

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

Results agree within the error with MC and general predicted trend.

More details in:
- 7 TeV analysis: Nature Commun. 2 (2011) 463
Single Diffractive Jets: Measurement Idea

Signature: at least two jets with $p_T > 20$ GeV + presence of gap in rapidity.

Data sample:
- c.m. energy: 7 TeV
- total integrated luminosity: 6.8 nb$^{-1}$
- average number of collisions per bunch crossing: 0.12

Jets:
- $p_T > 20$ GeV, $|\eta| < 4.4$
- anti-$k_T$ algorithms (R=0.4 and R=0.6)

Rapidity gap $\Delta \eta^F$ – larger of the two empty pseudorapidity regions between detector edge and first reconstructed object:
- $|\eta| < 2.5$: track with $p_T > 200$ MeV or
- $|\eta| < 4.8$: calorimeter cell with signal greater than $5\sigma$ above noise
Single Diffractive Jets: Results

- diffractive component is required for more complete description of data
- Pythia8 (DL model) gives a good description of shape and normalisation
- rapidity gap survival factor – probability of non-emission by other soft processes (e.g. underlying event) into the gap: $S^2 = 0.16 \pm 0.04$ (stat.) $\pm 0.08$ (exp. syst.)
**Signal signature:** two scattered protons (not measured) + two leptons + nothing else!

**Data sample:**
- c.m. energy: 7 TeV
- total integrated luminosity: 4.6 fb$^{-1}$

**Electron channel:**
- electron and positron originating from the same vertex,
- each with $p_T^e > 12$ GeV and $|\eta^e| < 2.4$
- invariant mass: $m_{e^+e^-} > 24$ GeV

**Muon channel:**
- $\mu^+$ and $\mu^-$ originating from the same vertex,
- each with $p_T^{\mu} > 10$ GeV and $|\eta^{\mu}| < 2.4$
- invariant mass: $m_{\mu^+\mu^-} > 20$ GeV

**Exclusivity criteria:**
- no additional charged particle with $p_T > 400$ MeV from di-lepton vertex
- no additional track or vertex within 3 mm from di-lepton one
- remove Z-peak mass region: $70 < m_{l^+l^-} < 105$ GeV
- transverse momentum of lepton pair: $p_T^{l^+l^-} < 1.5$ GeV
Exclusive Lepton Pair Production: Results

- Result consistent with the recent CMS measurement
- Suppression (20%) with respect to the Equivalent Photon Approximation prediction
- Suppression expected due to the contribution of re-scattering effects
AFP TDR: CERN-LHCC-2015-009, ATLAS-TDR-024

Phase-1: AFP0+2 (2016)
- 2 horizontal Roman Pot stations at 205 (NEAR) and 217 m (FAR) in ATLAS C side – installed!
- study beam background in low and high intensity runs
- measure diffractive and exclusive events with one tag in a special low-$\mu$ runs (AFP trigger ATLAS)

Phase-2: AFP2+2 (2017+)
- add 2 horizontal RPs at 205 and 217 m on A side
- install time-of-flight detectors in far stations on both sides – new AFP trigger
- measure double tagged diffractive and exclusive events
- deliver diffractive triggers to ATLAS during standard runs
**Physics of Interest**

**Special, low-$$\mu$$ runs**
- diffractive physics:
  - soft diffraction (particle, gap, $$\xi$$ spectra)
  - diffractive jets, jet-gap-jet, $$\gamma$$+jet, W, etc.
  - exclusive jets (low-$$p_T$$, single tagged)
- AFP can trigger ATLAS for presence of proton in:
  - one side (single difraction)
  - both sides (double Pomeron exchange)
- special trigger menu based on AFP
- expect to collect 1 – 10 pb$$^{-1}$$ of data in special low-$$\mu$$ runs in 2017 and 2018

**Standard, high-$$\mu$$ runs**
- exclusive events (gluon/Pomeron and photon induced), e.g. exclusive di-jets
- trigger based on coincidence (double tag) in AFP
- search for new, heavy resonances or anomalous couplings

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Recent ATLAS Results on Diffraction and QCD

14/15
• ATLAS precisely measured elastic, inelastic and total cross sections as well as the nuclear slope.
• Obtained values are in agreement with each other, MC predictions and expected global trend.
• Measurement of jets with a gap indicates that diffractive component is needed to describe data.
• Rapidity gap survival was measured.
• Exclusive di-leptons were measured in electron and muon channels with a good precision.
• Results in agreement with theoretical predictions and the ones obtained by the CMS experiment.

• Many new diffractive results based on AFP data are expected in the near future.

The work of M.T. is supported by Polish Ministry of Science and Higher Education under the Mobility Plus programme (1285/MOB/IV/2015/0).