Measurements of single diffraction using forward proton tagging at ATLAS

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On behalf of the ATLAS collaboration

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Diffractive pp interactions

Schematic illustrations of single-diffractive dissociation (SD), double-diffractive dissociation (DD) and central diffraction (CD)

- Is it always possible to disentangle diffractive and non-diffractive processes?
- Interactions mediated by Pomerons
  - t-channel exchange of vacuum quantum numbers
- Phenomenological approach (QCD + models)
- Previous studies based on rapidity gap.

<table>
<thead>
<tr>
<th></th>
<th>Forward intact protons</th>
<th>Central detector visible mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>SD</td>
<td>1</td>
<td>$M_X$</td>
</tr>
<tr>
<td>DD</td>
<td>0</td>
<td>$M_X, M_Y$</td>
</tr>
<tr>
<td>CD</td>
<td>2</td>
<td>$M_X$</td>
</tr>
</tbody>
</table>

Exploit the potential of forward proton tag with the ATLAS detector for diffractive physics
ATLAS central detector
The ALFA detector

• The Roman Pots:
  – Made of stainless steel
  – Bellows allowing the movement of the pots
  – Secondary vacuum with respect to LHC UHV
  – Thickness of the wall in front: 500µm
  – Thin window thickness: 200µm

• Detectors:
  – Main Detector (MD): 20 staggered layers of 0.5 mm thick scintillating fibers (64 fibres/layer) inclined with respect to vertical direction (±45°) to provide a spatial resolution of about 30µm
  – Overlap Detector (OD): fibers placed horizontally are used to measure the vertical coordinate for the alignment of the upper and lower detectors
  – The trigger is provided by 3 mm thick plastic scintillators covering the area of the detectors

• Readout with MAPMT
Rapidity gap ($\Delta \eta$), Fractional proton energy loss ($\xi$), Four-momentum transfer squared ($t$)

- $\sqrt{s} = 2E_p = 8$ TeV
- $|t| < 1$ GeV$^2$
- $\theta_{p'} = 10 - 100$ mrad
- $M_X$ up to hundreds GeV
- ATLAS forward detector measurements: $p_T$ and $E_{p'}$
- ATLAS central detector measurements: $M_X$ and $\Delta \eta$
- $\eta_{edge}$: pseudo-rapidity of the ID edge on the side of the scattered proton ($\pm 2.5$)
- $\eta_{track}$: pseudo-rapidity of the 1st ID reconstructed track
Diffraction model

- SD cross section is factorized into a Pomeron (IP) flux and a $p$+IP cross section
  - Triple Pomeron amplitudes as implemented in the Monte Carlo simulations

\[
\Delta \eta \propto \log \left( \frac{1}{\xi} \right) \rightarrow \frac{d\sigma}{d\Delta \eta} = \text{const.}
\]

\[
\alpha(0) \sim 1 \text{ (Pomeron intercept)}
\]

\[
\alpha' \sim 0.25 \text{ GeV}^{-2}
\]
• Rapidity gap spectrum indicates large diffractive contribution.
  — Diffractive plateau is visible
• However:
  — Significant ND contributions due to random fluctuations in the hadronisation process.
  — No direct access to $\xi$ and $t$ dynamics
• The proton tag in the forward detector helps to improve SD event selection
  — ND and DD contributions are suppressed

• Motivations for better SD constraints
  — Improve the precision in direct measurements of the total inelastic $pp$ cross section
  — Understanding the low Bjorken-$x$ region of proton structure
  — Better understanding of cosmic ray air showers
  — Possible relations to the string theory of gravity
Data sample used for this analysis

- Dedicated data-taking period in July 2012, which has also been used to measure the elastic and total cross sections [Phys. Lett. B 761 (2016) 15].
- The mean number of inelastic interactions per bunch crossing ($\mu$) is low to suppress random coincidences between protons in ALFA and unrelated activity in the central detector.
- Special high $\beta^*$ optics to produce almost collinear protons at zero crossing angle.
  - The ALFA detector can approach the beam to detect protons at very small deflection angles.

$\sqrt{s} = 8$ TeV
$\beta^* = 90$ m
$L = 1.67$/nb
$\mu < 0.08$
Single Diffractive events in ALFA

- Tracks reconstruction with a local precision of 30 μm in each coordinate
- Proton kinematics (ξ, t) relies on the alignment via elastic scattering and beam halo

**Trigger:**
- Minimal activity in MBTS and opposite ALFA arms

**Event Selection:**
- A reconstructed vertex
- At least 1 ID track with \( p_T > 200 \text{ MeV} \) and \( \eta < 2.5 \)
- Exactly one reconstructed track in ALFA
- Mean position and angle between stations within 3σ ellipse
Monte Carlo simulation

Background modeling (ND, DD, CD), unfolding detector effects (SD) and ALFA efficiency (EL)

- **PYTHIA8** implements the “triple Regge” formalism
  - Proton PDF: NNPDF23 LO
  - Pomeron PDF: H1 2006 Fit B

- **Two PYTHIA8 tunes with different Pomeron flux factor**
  - A2: Donnachie-Landshoff (base model)
  - A3: Schuler-Sjöstrand

- **HERWIG7** implements a different hadronisation model
  - Proton PDF: MMHT2014lo68cl
  - Pomeron PDF: H1 2006 Fit A

- Diffractive protons are transported to the ALFA location through the LHC matrix elements (thin lens approximation)

PYTHIA8 is tuned to the previous ATLAS data without proton tag ($\Delta \eta$ and $\sigma_{tot}$).

Fiducial cuts

\[ 0.016 < |t| \leq 0.43 \text{ GeV}^2 \]
\[ -4.0 < \log_{10}(\xi) \leq -1.6 \]
\[ \rightarrow 80 < M_X < 1270 \text{ GeV} \]
Overlay Background

- Pile-up between a proton in ALFA and an uncorrelated activity in ID/MBTS
  - Dominant effect: elastic protons in ALFA overlapping to beam induced background (beam halo)
  - Estimated with data-driven technique using strongly enriched ND sample

Overlay background control region

- Largest background (about 25 %)
- ND enrichment
  - All 32 MBTS segments fired
  - At least 1 track with $p_T > 200$ MeV
  - $|\Delta \eta| < 0.5$
- Overlay background normalization: 0.8 %
  - Fraction of the ND enriched events sample with a proton in ALFA
- Overlay background control region
  - In addition to the main event selection, a 2$^\text{nd}$ ALFA armlets with a reconstructed proton is required

Good description of shape and normalization
Physics Background

- Physics processes which "look" like SD
  - Forward protons in ALFA with correlated activity in ID/MBTS
- Dominant physics background (CD) is estimated from simulations
  - ND and DD neglected

CD background control region

- Second largest background (about 10 %)
- CD enrichment in the control region
  - 2-10 MBTS segments fired
  - Two ALFA armlets with a reconstructed proton
- $\xi$ distributions reweighted to match data

Good description of shape and normalization
Comparison data/simulations

**ATLAS Preliminary**

σ[mb] @ 8 TeV

- **ND**: 51
- **SD**: 12.5
- **DD**: 8.3

Good description of shape and normalization after SD rescaling by 0.64

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Systematic uncertainties

- The largest systematic uncertainty mostly arises from overlay background subtraction

- Further relevant systematics
  - SD, DD and CD normalization to CDF data
  - Hadronisation model (PYTHIA vs HERWIG)
  - Unfolding of instrumental effects (closure test)
  - Luminosity precision from vdM scan
**SD differential cross section ($\Delta\eta$)**

- Diffractive plateau is visible
- Cross section increase @ small rapidity gaps
  - Pile-up of all events with gap ending before the inner tracker acceptance
- Cross section decrease @ large rapidity gaps
  - Loss of small-$\xi$ events close to the $\xi$-edge ($10^{-4}$).

\[ \sigma_{SD} \] excess in PYTHIA8 is compatible with previous ATLAS data

**MC model** | $\sigma_{MC} / \sigma_{Data}$
--- | ---
PYTHIA 8 A2 | 2.3
PYTHIA 8 A3 | 1.5
HERWIG 7.1 | 3.0

- Unfolded hadron level cross sections after background subtraction
- Error bars display statistical and systematic error added in quadrature
Main systematic uncertainty comes from overlay background subtraction
The measured values lies between PYTHIA8 tune predictions A2 and A3.

First value published by an LHC experiment.
**SD differential cross section ($\xi$)**

\[
\frac{d\sigma}{d \log_{10}(\xi)} \propto \left(\frac{1}{\xi}\right)^{\alpha(0)-1} e^{B_{\text{high}} - e^{B_{\text{low}}}} \frac{B}{B}
\]

\[
B = B_0 - 2\alpha' \ln(\xi)
\]

Measured Pomeron intercept

\[
\alpha(0) = 1.07 \pm 0.02_{\text{stat}} \pm 0.06_{\text{syst}} \pm 0.06_\alpha'
\]

- Main systematic uncertainty comes from $\alpha' = 0.25 \pm 0.25$ GeV$^{-2}$
- Measured $\alpha(0)$ value lies between PYTHIA8 tune predictions A2 and A3.
### Cross section extrapolation

<table>
<thead>
<tr>
<th>Distribution</th>
<th>$\sigma_{SD}^{\text{fiducial}}(\xi,t)$ [mb]</th>
<th>$\sigma_{SD}^{t-\text{extrap}}$ [mb]</th>
<th>$\sigma_{SD}^{\xi,t-\text{extrap}}$ [mb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data</td>
<td>1.59 ± 0.13</td>
<td>1.88 ± 0.15</td>
<td>6.6</td>
</tr>
<tr>
<td>PYTHIA8 A2 (Schüler-Sjostrand)</td>
<td>3.69</td>
<td>4.35</td>
<td>12.48</td>
</tr>
<tr>
<td>PYTHIA8 A3 (Donnachie-Landshoff)</td>
<td>2.52</td>
<td>2.98</td>
<td>12.48</td>
</tr>
<tr>
<td>HERWIG7</td>
<td>4.96</td>
<td>6.11</td>
<td>24.0</td>
</tr>
</tbody>
</table>


- Extrapolation to $0 < |t| < \infty$ is done using the $t$-slope extracted from data.
- Extrapolation to the full $\xi$ range not yet well constrained by LHC data
  - Since the measured $\alpha(0)$ lies between A2 and A3 predictions, total $\sigma_{SD}$ in PYTHIA8 is scaled by the average ratio between A2 and A3 predictions.

- ATLAS and CMS data are in agreement
  - Small overlapping $\xi$ range
  - CMS measurement is based on rapidity gap-based, therefore it contains a small DD admixture
Conclusions

- ATLAS provided the first measurement of single diffractive proton-proton cross section @ $\sqrt{s} = 8\,\text{TeV}$ with tagged protons
  - Reduced background from non-diffractive and central-diffractive events
  - Access to kinematics of diffracted protons ($\xi, t$)

<table>
<thead>
<tr>
<th>t-slope</th>
<th>$B = 7.60 \pm 0.23_{\text{stat}} \pm 0.22_{\text{syst}} ,\text{GeV}^{-2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pomeron intercept</td>
<td>$\alpha(0) = 1.07 \pm 0.02_{\text{stat}} \pm 0.06_{\text{syst}} \pm 0.06\alpha'$</td>
</tr>
</tbody>
</table>

- The measured shape of $\xi$ and $t$ differential single diffractive cross sections is in agreement with Monte Carlo prediction
  - Integrated single diffractive cross section is significantly smaller than the predictions