Measurement of differential cross sections for Single Diffractive Dissociation in $\sqrt{s} = 8$ TeV pp collisions using the ATLAS detector

James Kendrick, on behalf of the ATLAS collaboration*

School of Physics and Astronomy, University of Birmingham, UK

Abstract

Preliminary LHC results on proton-tagged measurements of Single Diffractive Dissociation ($pp \rightarrow pX$) are presented from ATLAS using $\sqrt{s} = 8$ TeV data. The central ATLAS detector is used to reconstruct the dissociative X system, and the forward spectrometer ALFA is used to tag the intact proton. Differential cross sections are measured as a function of ξ , the fractional energy loss of the intact proton; $|t|$, the squared four-momentum exchanged and $\Delta\eta$, the observable rapidity gap. The unfolded t differential cross section is consistent with an exponential dependence $d\sigma/dt \propto e^{Bt}$ with a slope parameter $B = 7.60 \pm 0.32 \text{ GeV}^{-2}$. The unfolded ξ differential cross section is interpreted in the framework of Regge phenomenology to extract a Pomeron intercept of $\alpha(0) = 1.07 \pm 0.09$.

Keywords: ATLAS, QCD, Single diffraction, ALFA, Forward

1. Introduction

Single diffractive dissociation (SD) in proton proton collisions ($pp \rightarrow pX$) results in one proton remaining intact and the other dissociating into the diffractive system X . The process is understood as the exchange of a Pomeron - a strongly interacting, net colour singlet composite object. SD is depicted in Figure 1, with the Pomeron denoted with $\mathbb{P}$.

In the measurement presented here, the cross section of SD is measured differentially in three variables:

- The squared four-momentum transfer, t , reconstructed from the transverse momentum of the intact proton measured by ALFA.
- The fractional energy loss of the intact proton, $\xi = 1 - E'_p/E_p$, reconstructed from the dissociated X system using the approximation $\xi \approx \sum_i (E^i \pm p_z^i) / \sqrt{s}$. Inner detector (ID) tracks are used to reconstruct the dissociated system.

Figure 1: A diagram of Single Diffractive Dissociation (SD). One proton remains intact and the other dissociates to form the X system. The process is understood as the strong interaction exchange of a net colour singlet, the Pomeron, marked as $\mathbb{P}$.

- The observable rapidity gap, $\Delta\eta$, measured from the edge of the ID on the side of the proton tag to the nearest track with $p_T > 200$ MeV. The colour singlet nature of the Pomeron results in large gaps in rapidity space devoid of final state particles. In comparison, the size of rapidity gaps in Non-Diffractive (ND) collisions are typically small and exponentially suppressed.

Prior to this measurement, the cross section of SD

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at LHC energies was not well constrained despite making a large ($\sim 10\text{--}20\%$) contribution to the total proton-proton cross section. Both ATLAS and CMS have previously published measurements on diffractive cross sections by exploiting the characteristic large rapidity gap seen in such events [1, 2]. This method has two major drawbacks. It does not clearly discriminate between processes. Neither does it allow measurement of the dynamics within an SD event such as $|t|$ or ξ .

2. ATLAS Detector

The components of the ATLAS detector relevant to this measurement are the inner tracking detector (ID), the minimum bias trigger scintillators (MBTS) and ALFA [3].

2.1. Central detector

The ID provides coverage for charged particles in the range $|\eta| < 2.5$. It consists of a silicon pixel detector, silicon micro-strip tracker and a transition radiation tracker. A 2 T magnetic field, provided by a solenoid magnet, enabling momentum reconstruction of ID tracks.

The MBTS provides coverage in the range $2.1 < |\eta| < 3.8$. A total of 32 tiles are arranged in 2 concentric circles of 8 on either side of the detector. As the name implies, it is designed to provide a trigger for minimum bias events.

2.2. ALFA

ALFA is a forward proton spectrometer consisting of 4 ‘Roman Pots’ (RPs) on each side of ATLAS, above and below the outgoing beam-lines, 237 and 241 m away from the interaction point [4]. The detector components within two RPs are depicted in Figure 2. ALFA allows the tagging and reconstruction of outgoing intact protons and has been used to measure the pp elastic cross section at $\sqrt{s} = 7$ and 8 TeV [5, 6].

ALFA is very sensitive to radiation damage, so it is only used during special low pile-up runs of the LHC. The reconstruction tools exploit the special LHC magnet configurations in these runs, known as ‘parallel-to-point’ optics.

3. Data samples and event selection

3.1. MC samples

The A3 tune of PYTHIA8 was used to generate Monte Carlo samples of SD, ND, double diffraction (DD $pp \rightarrow XY$) and Central Diffraction (CD $pp \rightarrow$

Figure 2: An ALFA station with two Roman Pots (RPs), one above and one below the beam-line. Perpendicular planes of scintillating fibres are visible in each of the main detectors (indicated as MD). The overlay detectors (OD) are mechanically fixed to the main detector and allow the calculation of the position of the upper and lower RPs relative to each other. Trigger tiles are also contained within each RP but not shown here [6].

pXp , shown in figure 3) [7, 8]. PYTHIA8 models diffractive processes using the ‘triple Regge’ formalism; the A3 tune models the ξ and t dependence of the Pomeron flux factor using the ‘Donnachie-Landshoff’ model [9, 10].

Figure 3: A diagram of Central Diffraction (CD). Both protons remain intact and two Pomerons form the central dissociative system.

Additional SD MC samples were generated using the A2 tune of the PYTHIA8 generator, which uses the Schuler and Sjöstrand Pomeron flux factor, and HERWIG7 which uses a more complex diffractive model and a cluster-based approach to hadronization [11, 12, 13].

3.2. Data conditions

The data analysed in this measurement were recorded in July 2012, part of a special high $\beta^* = 90$ m $\sqrt{s} = 8$ TeV run of the LHC. The average number of collisions

per bunch crossing was relatively low (< 0.08) throughout the entire run.

3.3. Event selection

Data events were selected online using a trigger requiring signals in ALFA and the MBTS on opposing sides of ATLAS. The offline event selection required the following:

- A primary vertex, reconstructed using a special low- p_T algorithm, was required to enable kinematic reconstruction of the intact proton.
- Proton tracks reconstructed in both the near ($|z| = 237$ m) and far ($|z| = 241$ m) RPs of a single arm of ALFA. Each RP was required to contain a track reconstructed from at least twelve overlapping fibres. The average x coordinate of the tracks and the angle relative to the z -axis were also used to reduce contamination from background sources.
- At least 5 MBTS tiles above an offline threshold on the side opposing the ALFA proton, to ensure reasonable trigger efficiency.
- A single ID track with $p_T > 200$ MeV was required to measure, and correct for, the trigger efficiency.

3.4. Fiducial range and acceptance

The acceptance of the measurement was assessed using the A3 MC sample of SD and this is shown in Figure 4. The fiducial range in ξ was chosen to cover a region of approximately constant acceptance of $\sim 30\%$ giving the range $-4.0 < \log_{10} \xi < -1.6$. The range in $|t|$ was chosen to ensure at least 10% acceptance within the ξ range. Therefore the fiducial range was $0.016 \text{ GeV}^2 < |t| < 0.43 \text{ GeV}^2$. The bin widths were decided using the experimental resolution predicted by MC.

4. Backgrounds

Single source backgrounds were assessed through the MC samples, of which CD was the largest contributor due to the intact outgoing protons as shown in Figure 3.

An additional background, the ‘overlay’ background, occurred due to the coincidence of separate background activity in both the ATLAS central detector and ALFA. This includes contributions from pile-up collisions as well as beam-based backgrounds. It was assessed by applying a ND selection to data requiring activity in all MBTS tiles, a reconstructed primary vertex and small rapidity gaps on both sides of the detector. Following this selection, the majority of ALFA activity was

Figure 4: The predicted acceptance of the measurement assessed using the A3 tune of PYTHIA8 [14].

expected to be from the overlay background which allowed its contribution to be estimated.

Figure 5: Reconstructed distribution of $\log_{10} \xi$ in the two-proton control sample [14].

The modelling of the overlay background is assessed using a two-proton control region. The event selection for this control region is identical to that in the nominal analysis except for the requirement of an additional proton. Figure 5 shows an example of a reconstructed distribution in this region, $\log_{10} \xi$, which demonstrates reasonable agreement between data and MC where the overlay background is dominant. An additional control region was used to assess the CD uncertainty. This was the same as the two-proton control region with the requirement that ≤ 10 MBTS tiles were above threshold.

The reconstructed distributions of $\Delta\eta$, $|t|$ and $\log_{10} \xi$ for the main analysis sample are shown in Figure 6. In each distribution the SD cross section has been renormalized to the result found in the measurement, to demonstrate that the shape agreement is good but there

is normalization disagreement. The other MC samples used the default PYTHIA8 cross sections.

5. Unfolding and systematic uncertainties

5.1. Unfolding

Iterative Bayesian unfolding was used to unfold the data distributions using the A3 tune of SD as a prior [15]. MC indicated that the response matrices were approximately diagonal with reasonable purity across all of the bins. The number of iterations used were chosen to minimise the systematic uncertainty arising from the unfolding procedure.

5.2. Systematic uncertainties

The major sources of systematic uncertainty were:

- The overlay background. The uncertainty was assessed using the bin-by-bin fractional difference between the data and MC samples in the two-proton control region.
- The CD shape and cross section. The CD cross section was varied between 1.12 mb and 1.66. A ξ re-weighting was also applied to the CD distributions to provide a better description of data in the CD control region.
- Unfolding. The ability of the procedure to accurately unfold a data-like distribution was assessed.
- Hadronization. The uncertainty was assessed by comparing the response predicted with the PYTHIA8 A3 sample to the HERWIG7 SD MC sample.

Other, more minor sources of systematic uncertainty investigated include the ALFA track reconstruction efficiency; the calculated alignment of the ALFA RPs; the ID track reconstruction efficiency; the trigger efficiency and the MBTS thresholds.

The total systematic uncertainty in each bin is calculated by adding all of the upward and downward shifts in quadrature and selecting the largest of the two values. The total systematic uncertainty was less than 10% throughout the ξ range and, with the exception of one bin, throughout the $\Delta\eta$ range. The first and last bin in the $|t|$ distribution had larger uncertainties of $\sim 15\%$ and $\sim 20\%$, respectively, both due to the overlay background. The statistical uncertainties are mostly negligible.

(a)

(b)

(c)

Figure 6: Reconstructed distributions using the nominal selection [14]. (a) shows the rapidity gap distribution, (b) shows the Mandelstam $|t|$ distribution and (c) shows the $\log_{10} \xi$ distribution.

6. Results

6.1. Rapidity gap

The event variable $\Delta\eta$ is defined as the rapidity gap between the edge of the ID tracker ($|\eta| = 2.5$) on the side of the proton tag and the nearest ID track with $p_T > 200$ MeV. The truth-level variable is defined with respect to charged particles with $p_T > 200$ MeV.

The unfolded distribution of $\Delta\eta$ is shown in Figure 7. The large number of events in the first few bins is understood to be due to the limited η coverage of the ID. The flat plateau, characteristic of diffractive processes, is then visible between 1.5 and 3.5. Above this point, the cross section falls due to the fiducial selection in ξ and is not shown further than $\Delta\eta = 4$. The plot shown in Figure 7 also compares the unfolded data distribution to predictions from MC event generators. All three of the samples compared show reasonable shape agreement. The normalisation disagreement is obvious, however. The A3 tune of PYTHIA8 provided the best normalisation, disagreeing by a factor of 1.5. The observed distribution is compatible with previous results, if the default PYTHIA8 DD contribution is correct [1].

Figure 7: Hadron-level differential cross section as a function of $\Delta\eta$. Statistical and systematic uncertainties are added in quadrature and shown on the error bars. Hadron-level predictions from PYTHIA8 A2, PYTHIA8 A3 and HERWIG7 are also shown [14].

6.2. Mandelstam $|t|$

The differential cross section in $|t|$ is shown in Figure 8. Data points are plotted at the average $|t|$ value in each bin, as is appropriate for the fast-falling distribution, instead of the bin centres. The average $|t|$ value per bin is predicted by the PYTHIA8 A3 MC sample.

The fit, of the form $d\sigma/dt \propto e^{Bt}$, is overlaid on the figure in red. The result is $B = 7.65 \pm 0.26$ (stat.)

± 0.22 (syst.) GeV^{-2} . The systematic error on the fit is obtained by re-fitting to each upwards or downwards shift and adding the differences in quadrature. The result corresponds to an average over ξ , which is predicted to be $\langle \log_{10} \xi \rangle = -2.88 \pm 0.14$, obtained from the PYTHIA8 MC samples. PYTHIA8 A3, using the Donnachie-Landshoff Pomeron flux factor, predicts $B = 7.10 \text{ GeV}^{-2}$, and A2 using the Schuler-Sjöstrand Pomeron flux factor predicts $B = 7.82 \text{ GeV}^{-2}$. The result is compatible with both predictions within 2σ .

Figure 8: Hadron-level differential cross section as a function of $|t|$. Statistical errors are shown as inner error bars, statistical and systematic errors are added in quadrature and shown as outer error bars. An exponential fit, explained in the text, is shown in red [14].

6.3. Fractional energy loss ξ

The differential cross section in $\log_{10} \xi$ is shown in Figure 9. The distribution is compatible with a flat distribution, as is expected from $d\sigma/d\xi \sim 1/\xi$. A fit is also applied using the expected ξ dependence from Regge phenomenology [9]. When integrated over the fiducial range in $|t|$, the cross section is expected to follow

$$\frac{d\sigma}{d\xi} \propto \left(\frac{1}{\xi}\right)^{\alpha(0)} \frac{e^{Bt_{\text{high}}} - e^{Bt_{\text{low}}}}{B}, \quad (1)$$

where $B = B_0 + 2\alpha' \ln \xi$. This fit is applied to the data, as shown in Figure 9, leaving the normalisation and $\alpha(0)$ as the free parameters. The Donnachie-Landshoff value is used for $\alpha' = 0.25 \text{ GeV}^2$ with a systematic error of 100% [16]. The fit results in a value of $\alpha(0) = 1.07 \pm 0.02$ (stat.) ± 0.06 (syst.) ± 0.06 (α'). The same approach applied to the PYTHIA8 samples gives predictions of 1.14 and 1.00 for the A3 and A2 tunes, respectively.

6.4. Extrapolated cross section

The total cross section within the fiducial range of the analysis is 1.59 ± 0.03 (stat.) ± 0.13 (syst.) mb. The

Figure 9: Hadron-level differential cross section of $\log_{10} \xi$. Errors are displayed as in figure 8. The triple Regge fit, shown in red, is explained in the text [14].

measured slope parameter B can be used to extrapolate over the full t range to measure the cross section as 1.88 ± 0.15 (stat. + syst.) mb. The measured cross section is substantially lower than that predicted by MC as can be seen in Table 1.

Table 1: The measured cross section of SD compared with that predicted by MC. Systematic and statistical uncertainties are combined for data [14].

Distribution	$\sigma_{SD}^{\text{fiducial}(\xi, t)}$ [mb]	$\sigma_{SD}^{\text{all } t, \text{fiducial}(\xi)}$ [mb]
Data	1.59 ± 0.13	1.88 ± 0.15
PYTHIA8 A2	3.69	4.35
PYTHIA8 A3	2.52	2.98
HERWIG7	4.96	6.11

7. Summary

The dynamics of SD have been measured directly in the fiducial range $-4.0 < \log_{10} \xi < -1.6$ and $0.016 \text{ GeV}^2 < |t| < 0.43 \text{ GeV}^2$ using ATLAS data from LHC $\sqrt{s} = 8 \text{ TeV}$ collisions. The rapidity gap sizes have also been measured, and the shape with a flat plateau between 1.5 and 3.5, is well predicted by PYTHIA8. All three MC samples used over-predict the cross section. The $\Delta\eta$ distribution is compatible with the previous rapidity gap based ATLAS measurement.

The differential cross section in $|t|$ is well described by $d\sigma/dt \propto e^{Bt}$ with $B = 7.60 \pm 0.32 \text{ GeV}^2$. The differential cross section in ξ is described by a Pomeron intercept of $\alpha(0) = 1.07 \pm 0.09$. Both values are compatible with the predictions of the A2 and A3 tunes of PYTHIA8.

The inclusive SD cross section is over-predicted by both the A2 and A3 tunes of PYTHIA8 and HERWIG7.

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