ATLAS RESULTS ON DIFFRACTION*

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Over many years of operation, the ATLAS detector at the LHC has proved its capabilities in studies of diffractive processes. The paper presents an overview of the measurements performed.

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1. Introduction

Diffraction in hadron physics is a class of strong interactions, where a colour-singlet object, the Pomeron, is exchanged. Contrary to the non-diffractive processes, they are characterised by the presence in the final state of an intact proton or a large rapidity gap. Diffractive processes constitute a significant fraction of the proton–proton total cross section. However, their inherently non-perturbative nature makes them difficult to understand. Performing additional measurements is necessary to improve this understanding. This paper provides a short overview of the measurements of diffractive processes performed at the LHC using the ATLAS detector [1].

2. Elastic scattering

The elastic proton–proton scattering, $pp \to pp$, is the most fundamental diffractive process. Its scattering-angle distribution exhibits a dip-and-bump structure resembling the optical diffractive pattern. In both cases, it is an effect of a part of the incoming wave being absorbed. In the pp scattering, absorption is caused by inelastic interactions.

At the LHC, the scattering angles in elastic processes are very small. Trajectories of the scattered protons are very close to the trajectories of non-interacting protons of the beam. In fact, the scattering angles can be smaller

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than the typical angular divergence of the colliding beams. Measurements of such small angles are possible with special settings of the LHC quadrupole magnets, the so-called machine optics, that lead to much weaker focusing of the beams before the interaction region, reducing the angular divergence.

Registering the scattered protons requires dedicated detectors. In ATLAS, this is done with its ALFA component [2]. The detectors are placed about 240 m away from the interaction region, on both sides. In addition, they have to be positioned very close to the LHC beams. This is achieved with the Roman Pot mechanism, which allows one to insert the detectors inside the LHC beam pipe and register protons separated by even one millimetre from the proton beam. When the detectors are not taking data, they are retracted to a safe home position.

The ALFA detectors measure the position of the passing protons. Selection of the elastic event candidates exploits the energy and momentum conservation in the event, which leads to strong correlations between the measured positions. For example, the vertical coordinate of the proton registered on one side of the interaction point is anti-correlated with the same component measured on the other side. Knowing the magnetic fields between the interaction point and the detectors, it is possible to reconstruct the scattering angle from the measured positions.

The central result of the measurement is the differential elastic cross section. The ATLAS Collaboration performed measurements at the centre-of-mass energy of 7 TeV [3], 8 TeV [4], and 13 TeV [5]. The most recent result is presented in figure 1.

Fitting theoretical formulae allows for extraction of the physics parameters of interest: the total proton–proton cross section, the elastic slope, and the complex phase of the scattering amplitude. The results are presented in

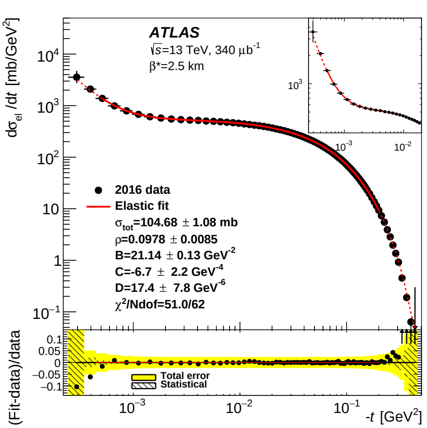

Fig. 1. Differential elastic pp scattering cross section as a function of the four-momentum transfer, t. From [5].

Table 1. They have interesting consequences. It is not possible to simultaneously describe the measurement of σ_{tot} and ρ with a model assuming: (a) the present rate of growth of the total cross section with energy continuing above the LHC energies, and (b) lack of colour-singlet C-odd (odderon) exchange. Thus, the results suggest that either the growth of σ_{tot} slows down or the effects of the odderon contribution are seen.

Table 1. Results of the measurements of physics parameters based on the fits to the elastic differential cross section at 13 TeV: σ_{tot} — total cross section, B — elastic slope, ρ — ratio of the real-to-imaginary parts of the elastic scattering amplitude at $t = 0$.

Parameter	Value
σ_{tot}	104.7 ± 1.1 mb
B	21.14 ± 0.13 GeV^{-2}
ρ	0.0978 ± 0.0085

3. Diffractive dissociation

Diffractive dissociation is a process similar to elastic scattering — a colour-singlet exchange is also present, but with one or both protons dissociating into a multi-particle state. If one proton dissociates, the process is called single diffractive dissociation or single diffraction (SD). If both protons dissociate, the name double diffractive dissociation, or double diffraction (DD), is used.

One of the ways of identifying diffractive-dissociation events is based on the identification of regions of the detector where no particles are produced — the rapidity gap method. It is illustrated in figure 2 (left), where the distribution of the rapidity gap size measured using ATLAS calorimeters in minimum bias events [6] is presented.

Comparison of the observed distribution with the predictions of the PYTHIA MC generator provides insight into the origin of the observed shape. Non-diffractive events dominate the region of small gaps and exhibit a very steeply falling distribution. When the gap is larger than 5 units, they are suppressed, and the sample becomes composed predominantly of diffractive processes.

It is important to note that the method does not distinguish between single and double diffraction, since their gap-size distributions are nearly identical. One can also see that the data are not well described by the MC, which shows the need for additional tuning. However, despite the fact that the measurement has been published already more than a decade ago, this situation has not significantly improved.

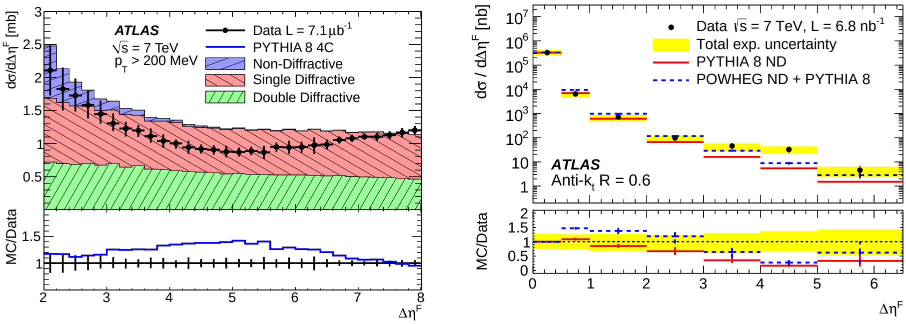

Fig. 2. Distribution of the rapidity gap size in minimum-bias event [6] (left) and events with reconstructed jets [7] (right).

The rapidity-gap method can also be measured in other classes of events. Figure 2 (right) presents the measurements of the gap-size distribution for events containing high-p_{T} jets [7]. For these hard events, the fraction of diffractive events is not as high as for the minimum-bias sample. The non-diffractive processes have a steeply falling gap-size distribution, but they do not become negligible at higher-gap sizes. However, they alone are not sufficient to describe the observed yields, which is a sign of diffractive jet production. This observation allowed for extracting physics parameters relevant to the description of the diffractive production, namely the rapidity gap survival probability

$$S^2 = 0.16 \pm 0.04(\mathrm{stat.}) \pm 0.08(\mathrm{syst.})\,.$$

When only one proton dissociates, it is possible to identify the event as diffractive with an alternative method — by detecting the intact proton. This is possible using the ALFA detectors. Contrary to the rapidity-gap method, this one distinguishes between single and double dissociation. The results of such a measurement [8] are presented in figure 3. Reconstructing the scattering angle of the proton allows for measuring the four-momentum transfer distribution. Detection of the dissociated state provides sensitivity to the mass of the dissociated system and allows for measuring the ξ distribution (ξ is the relative energy loss of the proton in the interaction). Fits to both those distributions deliver physics parameters: the Pomeron intercept, $\alpha(0)$, and the slope parameter B

$$\begin{aligned} \alpha(0) &= 1.07 \pm 0.02\ (\mathrm{stat.}) \pm 0.06\ (\mathrm{syst.}) \pm 0.06\ (\mathrm{theor.})\,, \\ B &= 7.60 \pm 0.23\ (\mathrm{stat.}) \pm 0.22\ (\mathrm{syst.})\ \mathrm{GeV}^{-2}\,. \end{aligned}$$

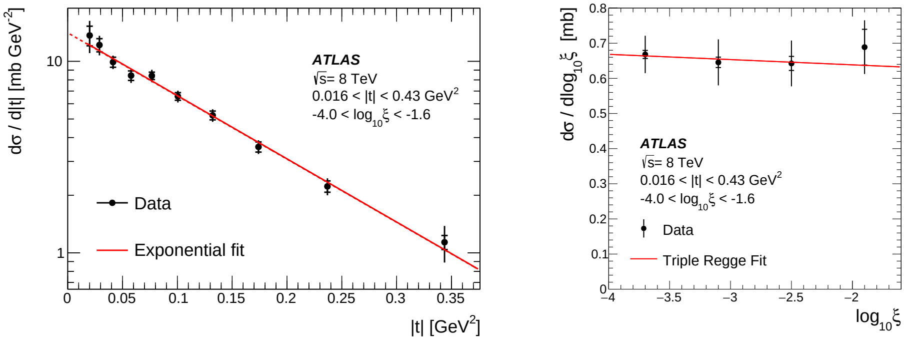

Fig. 3. Distributions describing the scattered-proton kinematics in SD events: four-momentum transfer, t (left) and relative energy loss, ξ (right). From [8].

4. Exclusive diffraction

Another interesting class of diffractive processes is exclusive diffraction, where both protons are scattered intact, but additional particles are also produced. Such a final state allows for registration of all produced particles, *i.e.* an exclusive measurement. The protons are measured in the ALFA detectors, while the other particles in the central detector (usually the central trackers). One process of this type is the exclusive pion-pair production $pp \to p\pi^+\pi^-p$.

In order to ensure the exclusivity of the process, *i.e.* that no other particles were produced, two strategies are employed. First, it is checked if no signal is observed in the ATLAS Minimum Bias Trigger Scintillators (MBTS) [9]. Second, only events where the total transverse momentum of the four measured final-state particles is close to zero are accepted. The distributions of the number of fired MBTS segments and of the total p_y of the system are presented in figure 4. The result of the measurement [10] is

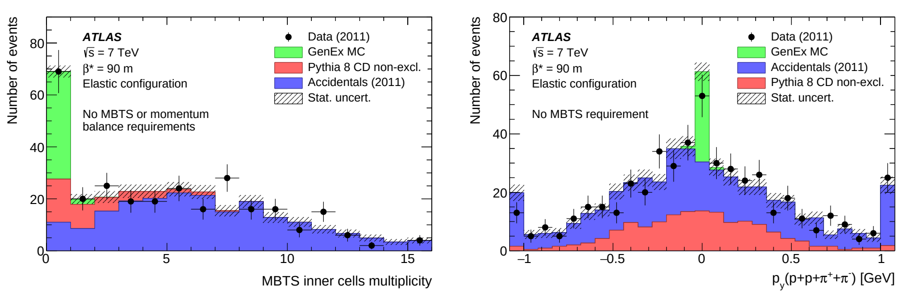

Fig. 4. Distributions of variables used to ensure exclusivity of the $\pi^+\pi^-$ event: MBTS multiplicity (left) and p_y imbalance (right). From [10].

the fiducial cross section in two categories: elastic-like (where the vertical components of momenta of both protons have the opposite signs) and anti-elastic (when the signs are the same)

$$\begin{aligned}\sigma_{\text{elastic-like}} &= 4.8 \pm 1.0(\text{stat.})^{+0.3}_{-0.2}(\text{syst.}) \pm 0.1(\text{lumi.}) \pm 0.1(\text{model})\ \mu\text{b}\,,\\ \sigma_{\text{anti-elastic}} &= 9 \pm 6(\text{stat.}) \pm 1(\text{syst.}) \pm 1(\text{lumi.}) \pm 1(\text{model})\ \mu\text{b}\,.\end{aligned}$$

5. Summary

ATLAS uses two methods for the identification of diffractive processes in pp collisions at the LHC. One method uses the calorimeter to select events with large rapidity gaps. Applied to minimum-bias events, it allows for obtaining a clean sample of diffractive events. Applied to events containing high-p_{T} jets, it provides sensitivity to hard diffraction, allowing for extraction of the gap survival probability.

Using the ATLAS-ALFA detectors, it becomes possible to directly register intact protons scattered in diffractive interactions. This allowed for measurement of elastic scattering, single diffraction and exclusive production of charged-pion pairs, and extracting cross sections and various properties of those processes.

The results of the measurements provide important input to improve our understanding of the phenomenon of diffraction in hadron physics.

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