FORWARD PROTON MEASUREMENTS WITH ATLAS[*] [**]

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In special runs of the LHC, elastic-scattering events were recorded using both ATLAS and the forward subdetector ALFA, thanks to which two new measurements are presented here. The first is exclusive pion-pair production, measured at $\sqrt{s} = 7$ TeV, using 80 μb^{-1} of low-luminosity data. A cross-section measurement is performed in two fiducial regions. The results of $4.8 \pm 1.0(\text{stat.})^{+0.3}_{-0.2}(\text{syst.})$ μb and $9 \pm 6(\text{stat.})^{+1}_{-1}(\text{syst.})$ μb are compared with theoretical models to provide a demonstration of the feasibility of this kind of measurement. The second is an elastic cross section, measured differentially in the Mandelstam t variable at $\sqrt{s} = 13$ TeV using 340 μb^{-1} of low-luminosity data. From a fit to $\mathrm{d}\sigma/\mathrm{d}t$, the total cross section, the ρ-parameter, and parameters of the nuclear slope are also determined. The results are $\sigma_{\text{tot}}(pp \to X) = 104.7 \pm 1.1$ mb, $\rho = 0.098 \pm 0.011$. The energy evolution of σ_{tot} and ρ, connected through dispersion relations, is compared to several models. Furthermore, the total inelastic cross section is determined from the difference of the total and elastic cross section, and the ratio of the elastic to the total cross section is calculated.

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1. Exclusive pion-pair production in pp collisions at $\sqrt{s} = 7$ TeV

The data were recorded in October 2011 during a special run with high β^* (90 m) and very low pile-up ($\mu = 0.035$). The integrated luminosity and uncertainty were $L_{\text{int}} = 78.7 \pm 0.1(\text{stat.}) \pm 1.9(\text{syst.})$ μb^{-1}. Two topological configurations are used in this analysis, referred to as elastic and anti-elastic, according to the sign of the product of the y-axis projection of

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proton momenta (elastic has a negative sign, while anti-elastic a positive one) [1].

The event consists of two oppositely-charged pions detected by the ATLAS Inner Detector (ID) [2], accompanied by a leading outgoing proton entering each of the ATLAS forward regions and detected by ALFA. There should be no other activity in the ATLAS ID and in the inner cells of the Minimum Bias Trigger Scintillators (MBTS) [2]. One source of background consists of centrally-produced pion pairs that are accidentally accompanied by one or more beam-halo protons which are detected in ALFA. Such background is suppressed by the event selections to a low level, as visible in figure 1 [3], which shows (left panel) the total multiplicity distribution of the MBTS inner rings for events that satisfy the selection criteria, except for requirements on the MBTS selection criteria and momentum balance, and after all the selections are applied (right panel).

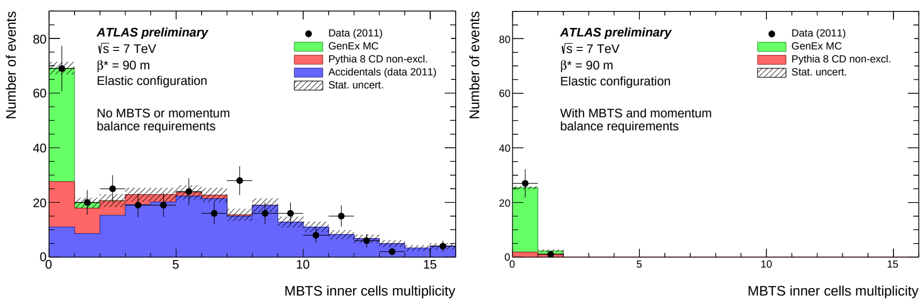

Fig. 1. Total multiplicity of the MBTS inner cells, comparing data with MC signal simulation (GenEx), MC background simulation (Pythia 8 central diffraction (CD)), and accidental coincidences. Left: the MBTS selection criteria and selections for momentum balance in the x and y projections are not applied; Right: all the selection criteria are applied. The MC and accidental coincidences histograms are stacked. Statistical uncertainties of MC events and accidentals are combined.

The cross section for exclusive pion-pair production is measured separately for the two non-overlapping configurations and the results are: $4.8 \pm 1.0(\mathrm{stat.})^{+0.3}_{-0.2}(\mathrm{syst.}) \pm 0.1(\mathrm{lumi.}) \pm 0.1(\mathrm{model})$ μb for the elastic configuration and $9 \pm 6(\mathrm{stat.})^{+1}_{-1}(\mathrm{syst.}) \pm 0.2(\mathrm{lumi.}) \pm 1.0(\mathrm{model})$ μb for the anti-elastic configuration. The overall systematic uncertainty on the cross section is estimated as $^{+6.4}_{-4.2}\%$ for the elastic configuration and $^{+6.0}_{-4.4}\%$ for the anti-elastic configuration. Table 1 [3] summarizes the main sources of systematic uncertainty.

Table 1. Summary of the exclusive pion-pair cross section systematic uncertainties.

Source of uncertainty	Uncertainty [%]	
	elastic	anti-elastic
Trigger efficiency	± 0.1	± 0.3
Signal and background corrections:		
Beam energy	± 0.1	± 0.1
ID material	$+4.8$	$+4.1$
Veto on MBTS signal	± 0.9	± 0.9
ALFA single-track selection	± 0.9	± 0.9
ALFA reconstruction efficiency	± 0.9	± 0.8
ALFA geometry selection	± 0.5	± 0.5
Optics	± 1.1	± 1.0
Overall systematic uncertainty	$^{+6.4}_{-4.2}$	$^{+6.0}_{-4.4}$
Statistical uncertainty	± 21.1	± 61.6
Theoretical modelling	± 2.8	± 8.0
Luminosity	± 2.3	± 2.3

2. Measurements of the total cross section and ρ-parameter from elastic scattering in pp collisions at $\sqrt{s} = 13$ TeV

The data for these measurements were recorded in 2016 during special runs with high β^* (2.5 km) and very low pile-up ($\mu = 0.02\%$). The integrated luminosity and uncertainty were $L_{\text{int}} = 339.9 \pm 0.1(\text{stat.}) \pm 7.3(\text{syst.})\ \mu\text{b}^{-1}$.

The data were selected following stringent data quality requirements for events triggered by a left–right coincidence in the elastic back-to-back configuration with tracks reconstructed in the ALFA subdetector. Further geometrical requirements were applied to the left–right acollinearity. The irreducible background is composed of events from central diffraction, estimated from simulations, and of accidental halo coincidences, determined in a data-driven method. The total background level is below 0.1%.

From a fit to the differential elastic cross section in the range from $-t = 4.5 \times 10^{-4}$ GeV^2 to $-t = 0.2$ GeV^2, the total cross section and ρ-parameter are determined to be: $\sigma_{\text{tot}}(pp \to X) = 104.68 \pm 1.08(\text{exp.}) \pm 0.12(\text{th.})$ mb, $\rho = 0.0978 \pm 0.0085(\text{exp.}) \pm 0.0064(\text{th.})$, where the first error accounts for all experimental systematic uncertainties and includes the statistical component, and the second is related to the model uncertainties. The experimental systematic uncertainty is dominated by the uncertainty in the luminosity and the alignment of the ALFA detector. The differential elastic cross section and fit to theoretical prediction are shown in figure 2 (a).

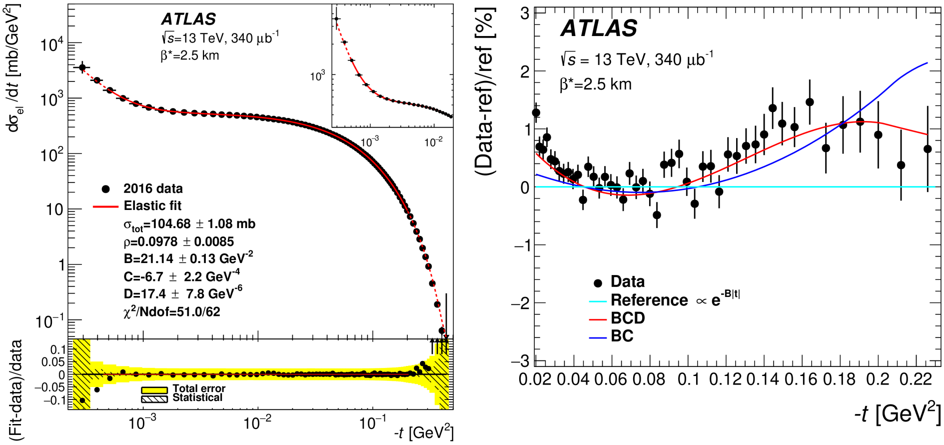

Fig. 2. Left: A fit of the theoretical prediction with σ_{tot}, ρ, B, C, and D as free parameters to the differential elastic cross section. Right: The data normalized to a reference exponential function compared to models of the nuclear amplitude with a t-dependent exponential slope [4].

Evidence for the t-dependent slope of $\mathrm{d}\sigma/\mathrm{d}t$ motivating the introduction of the terms B, C, and D in the nuclear amplitude parametrization is shown in figure 2 (b). The data and models are normalized to a reference exponential function fitted in a restricted range at small $|t|$, where the slope is approximately constant. The precision of the present data requires two additional parameters C and D to fit the observed curvature [4]. The theoretical form of the t-dependence of the cross section is obtained by the following equation:

$$\begin{aligned}\frac{\mathrm{d}\sigma}{\mathrm{d}t} &= \frac{4\pi\alpha^2(\hbar c)^2}{|t|^2} \times G^4(t) - \sigma_{\text{tot}} \times \frac{\alpha G^2(t)}{|t|}[\sin(\alpha\phi(t)) + \rho\cos(\alpha\phi(t))] \\ &\quad \times \mathrm{e}^{-\frac{-B|t|-Ct^2-D|t|^3}{2}} + \sigma_{\text{tot}}^2 \frac{1+\rho^2}{16\pi(\hbar c)^2} \times \mathrm{e}^{-B|t|-Ct^2-D|t|^3}\,,\end{aligned}$$

where G is the proton form factor and ϕ the Coulomb phase. The first term in the equation corresponds to the Coulomb interaction, the second to the Coulomb–nuclear interference, and the last to the hadronic interaction. This parameterization is used to fit the differential elastic cross section to extract the physics parameters σ_{tot} and ρ, and the terms B, C, and D relevant to the nuclear slope. The results are summarized in Table 2 [4].

Table 2. Results of the profile fit to the differential elastic cross section.

	σ_{tot} [mb]	ρ	B [GeV^{-2}]	C [GeV^{-4}]	D [GeV^{-6}]
Central value	104.68	0.0978	21.14	−6.7	17.4
Statistical error	0.22	0.0043	0.07	1.1	3.8
Experimental error	1.06	0.0073	0.11	1.9	6.8
Theoretical error	0.12	0.0064	0.01	0.04	0.15
Total error	1.09	0.0106	0.13	2.3	7.8

The hadronic part of the total elastic cross section is extrapolated to the full phase space by integrating the nuclear part of the fitted prediction. The value of $\sigma_{\text{el}} = 27.27 \pm 1.14$ mb can be subtracted from the value of σ_{tot} to obtain the total inelastic cross section, which is found to be $\sigma_{\text{inel}} = 77.41 \pm 1.09$ mb. From these measurements, the ratio of the elastic-to-total cross section is calculated: $\frac{\sigma_{\text{el}}}{\sigma_{\text{tot}}} = 0.257 \pm 0.012$.

Theoretical uncertainties are evaluated by changing the assumptions on the form of the nuclear amplitude and by taking into account the uncertainties of the proton form factor and Coulomb phase parameterization. Different models of the nuclear phase were also considered.

The energy evolution of σ_{tot} and ρ are studied simultaneously because they are connected through dispersion relations. Several models were developed to describe the energy evolution. The predictions of some widely used models are shown in figure 3. The COMPETE Collaboration performed global fits to elastic-scattering data based on the Regge theory using a crossing-even amplitude, leading to an energy evolution of σ_{tot} described at high energy by a combination of terms in $\ln(s)$ and $\ln^2(s)$. The ALFA measurements of σ_{tot} are in good agreement with the COMPETE prediction, but it exceeds the ρ value at 13 TeV by about 3σ [4]. The new value of the total cross section is about 5.8 mb lower than the measurement from the TOTEM Collaboration [5], corresponding approximately to a tension of 2.2σ. The low value of ρ can possibly be explained by a contribution from a crossing-odd amplitude in the scattering process, corresponding to the exchange of the Odderon. The FMO model features a maximal Odderon exchange and was tuned to the TOTEM data up to 13 TeV, but it exceeds the ALFA σ_{tot} data.

A global fit to the data was performed using a damped $\ln^2(s)$ amplitude with a slower energy dependence of σ_{tot} and without an assumption of an Odderon, and obtained a good description of both σ_{tot} and ρ (curve labeled BCBM in figure 3). A good description of both σ_{tot} and ρ without an assumption of an Odderon is also obtained for the KMR model [4].

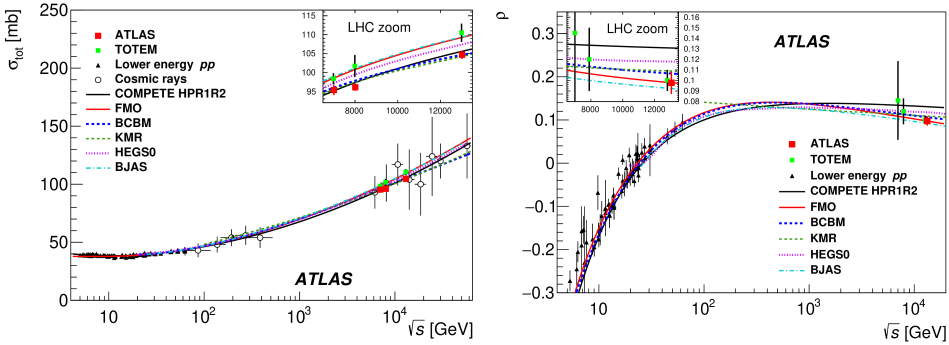

Fig. 3. Energy evolution of the total cross section (left) and the ρ-parameter (right) compared to different model predictions [4].

3. Conclusions

A first measurement of the purely exclusive pion-pair cross section at the LHC is presented, using 80 μb^{-1} of $\sqrt{s} = 7$ TeV low-luminosity pp collision data. The limited statistical precision obtained precludes the possibility of tuning or excluding any of the existing physical models for the process, but the two models, GenEx and Dime, provide preliminary theoretical estimates. The use of the forward ALFA detectors distinguishes the present measurement from others performed at comparable energies, since the outgoing protons were detected directly and possible contamination of the measurement by proton remnants was minimized. This measurement demonstrates the potential to measure exclusive diffractive hadronic processes using forward sub-detectors in combination with the ATLAS central detector.

The same subdetector has been used to measure the total cross section, ρ-parameter, and nuclear slope parameters using elastic pp scattering data at $\sqrt{s} = 13$ TeV in 2016 in a special LHC run with $\beta^* = 2.5$ km optics, corresponding to an integrated luminosity of 340 μb^{-1}. From a fit to the differential elastic cross section in the range from $-t = 4.5 \times 10^{-4}$ GeV^2 to $-t = 0.2$ GeV^2, the total cross section and ρ-parameter are determined to be: $\sigma_{\mathrm{tot}}(pp \to X) = 104.68 \pm 1.08(\mathrm{exp.}) \pm 0.12(\mathrm{th.})$ mb, $\rho = 0.0978 \pm 0.0085(\mathrm{exp.}) \pm 0.0064(\mathrm{th.})$, where the first error accounts for all experimental systematic uncertainties (mainly luminosity and alignment) and includes the statistical component, and the second is related to the model uncertainties. This new value of the total cross section is about 5.8 mb lower than the measurement from the TOTEM Collaboration, corresponding approximately to a 2.2σ tension. A similar difference was already observed at 7 and 8 TeV. The main difference is traced back to the normalization of the differential elastic cross section measured by ATLAS and TOTEM.

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