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Prospects for Photon-Photon and Photon-Proton Measurements with Forward Proton Taggers in ATLAS

M. Trzebiński, on behalf of the ATLAS Collaboration
Institute of Nuclear Physics Polish Academy of Sciences, Cracow, Poland

Abstract
ATLAS forward detectors, ALFA and AFP, are described with a focus on their geometric acceptance. The main results of the total, elastic and inelastic cross sections measurements performed with the ATLAS/ALFA detectors are presented. Possibility of diffractive bremsstrahlung and exclusive pion-pair photoproduction studies with the data from ATLAS/ALFA are discussed. Finally, the advantage of using a proton tagging technique for a high-statistics data recorded by the AFP detectors in the precision measurements of anomalous gauge couplings and invisible objects is discussed.

Keywords
ATLAS, ALFA, AFP, proton tagging, elastic scattering, diffractive bremsstrahlung, exclusive processes, anomalous gauge couplings

1 Introduction

In the majority of events of photon-photon and photon-proton scatterings at the LHC one or both outgoing protons stay intact. Since photon is a colourless object, such an exchange results in a presence of the rapidity gap between the centrally produced system and scattered protons. Thus, such events are of diffractive nature.

Diffractive studies are one of the important parts of the physics programme for the LHC experiments. This is also true for ATLAS, where a large community works on both phenomenological and experimental aspects of diffraction. In this report, the results of the total and elastic cross-sections measurements from the ATLAS experiment are presented. Moreover, predictions for new diffractive measurements, such as exclusive di-pion production, bremsstrahlung and anomalous gauge couplings, are summarized.

2 Forward Detectors

Diffractive production could be recognised by a search for a rapidity gap in the forward direction or by measuring forward protons. In this report, the proton tagging technique will be discussed.

Diffractive protons are usually scattered at very small angles (hundreds of microradians). In order to measure them, special devices that allow for the detector movement (so-called Roman pots, RP) are commonly used. In ATLAS [1] two systems of such detectors were installed: ALFA [2, 3] and AFP [4].

The ALFA (Absolute Luminosity For ATLAS) set-up consists of four detector stations placed symmetrically with respect to the ATLAS Interaction Point (IP) at 237 m and 245 m. Each ALFA station contains two Roman pot devices allowing vertical movement of the detectors. The spatial resolution of the ALFA detectors is of about 30 μm in the horizontal (x) and vertical (y) direction.

Since 2016 a new set of forward detectors is also installed far away form the ATLAS Interaction Point – the ATLAS Forward Proton (AFP). These detectors are placed symmetrically with respect to the ATLAS IP at 204 m and 217 m. Stations located closer to the IP contain the tracking detectors, whereas the further ones are equipped with tracking and timing devices. The reconstruction resolution of tracking detectors is estimated to be of 10 and 30 μm in x and y, respectively. The precision of Time-of-Flight measurement is expected to be of about 20 ps.

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3 Geometric Acceptance

There are several LHC machine running configurations at which the ALFA and AFP detectors could take data. In the simplest possible way they could be characterized by the value of the betatron function at the Interaction Point, β^*. For simplicity, one can put them into two categories: a standard ($\beta^* < 1$ m) and a special high-β^* ($\beta^* \gg 1$ m) optics. The details of these optics are described in Ref. [5], while here only the key features are presented.

The standard optics is a typical setting for all LHC high-luminosity runs – the beam is strongly focused at the IP and the non-zero value of the crossing angle is introduced in order to avoid proton collisions outside the IP region. The high-β^* (90, 1000 and 2500 m) optics was developed in order to measure the properties of the elastic scattering. Due to the high value of the betatron function, the beam angular divergence is very small and the beam is not as strongly focused as in the case of the standard optics. In these settings the value of the crossing angle could be either zero or non-zero.

Not all scattered protons can be measured in the forward detectors. A proton can be too close to the beam to be detected or it can hit the LHC accelerator components (collimator, beam pipe, magnet) upstream the AFP or ALFA station. The geometric acceptance is defined as the ratio of the number of protons of a given relative energy loss ($\xi = 1 - E_{proton}/E_{beam}$) and transverse momentum (p_{T}) that reached the detector station to the total number of scattered protons with the same ξ and p_{T}. Since AFP (ALFA) is intended to operate mostly during standard (special) optics settings, only these cases are shown in Fig. 1. In the calculations, the beam properties at the IP, the beam pipe geometry, the LHC lattice magnetic properties and the distance between the beam centre and the detector edge were taken into account. The distance from the beam centre was set to 15 σ for the standard optics, and to 10 σ for the high-β^* ones, where σ is the beam size at the location of the detector station.

In order to account for the dead material of the Roman pot window, a 0.3 mm distance was added in all cases. The acceptance of ALFA and AFP detectors at various optics are complementary. For the AFP run with the standard optics the region of high acceptance (black area, >80%) is limited to $p_{\mathrm{T}} < 3$ GeV and $0.02 < \xi < 0.12$). For the ALFA detectors and high-β^* optics the acceptance starts from $\xi = 0$ as these settings are optimised for the elastic scattering measurement.

4 Elastic Scattering and Total Cross Section Measurement

The elastic scattering process has the simplest signature that can be imagined: two protons exchange their momentum and are scattered at small angles.

The measurements described in this section were done using the following data samples collected by ATLAS: 80 $\mu\mathrm{b}^{-1}$ at $\sqrt{s} = 7$ TeV and 500 $\mu\mathrm{b}^{-1}$ at $\sqrt{s} = 8$ TeV, both taken with $\beta^* = 90$ m. The detailed description of these analyses can be found in [6] (7 TeV) and [7] (8 TeV) and here only the main results are presented.

The measured elastic cross-sections and the nuclear slope parameters, B, are:

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

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

$$B_{\mathrm{nucl}}^{\mathrm{ALFA}}(7\ \mathrm{TeV}) = 19.73 \pm 0.14\ (\mathrm{stat.}) \pm 0.26\ (\mathrm{syst.})\ \mathrm{GeV}^{-2},$$

$$B_{\mathrm{nucl}}^{\mathrm{ALFA}}(8\ \mathrm{TeV}) = 19.74 \pm 0.05\ (\mathrm{stat.}) \pm 0.23\ (\mathrm{syst.})\ \mathrm{GeV}^{-2},$$

where the first error is statistical and the second accounts for all experimental systematic uncertainties, from which the largest one is due to the luminosity uncertainty.

By using the optical theorem [8], the total cross section was determined:

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

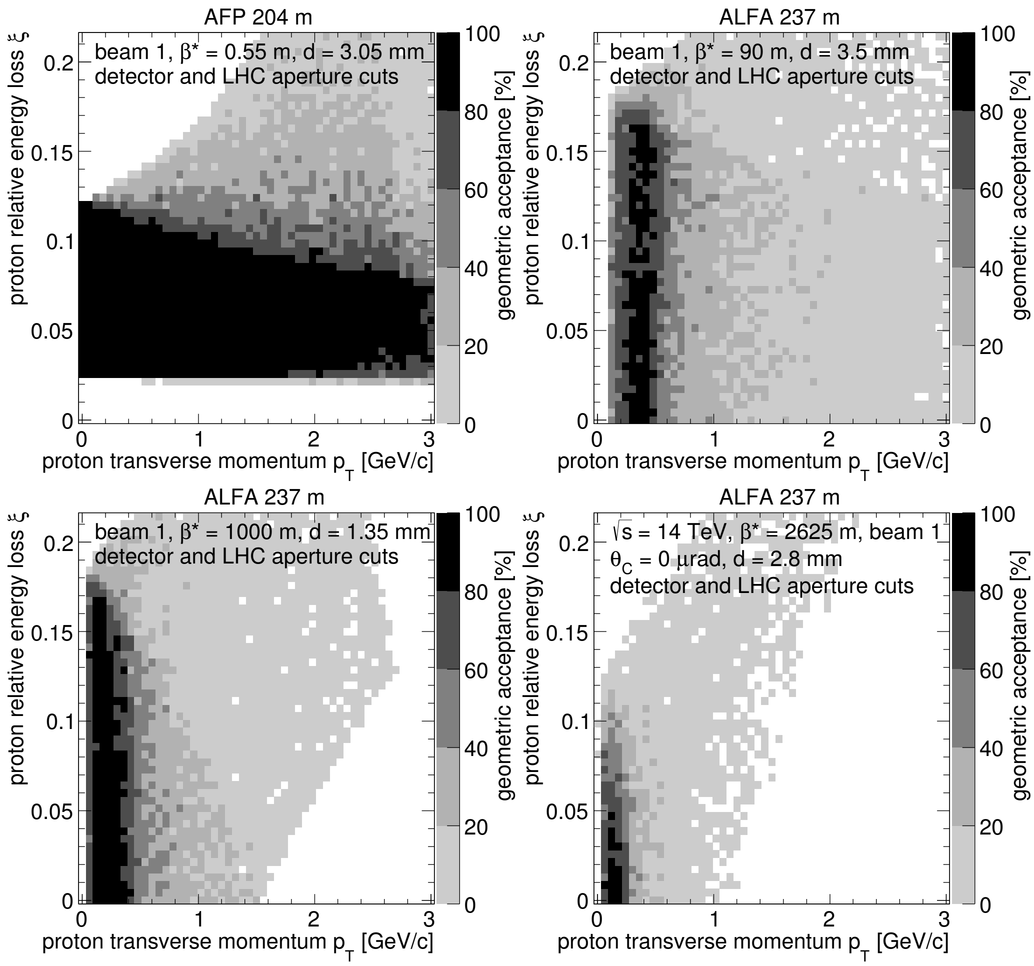

Fig. 1: Geometric acceptance for: AFP with $\beta^* = 0.55$ m and ALFA with $\beta^* = 90,\ 1000$ and 2625 m.

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

where the last error is related to uncertainties on the extrapolation to the zero four-momentum transfer ($|\text{t}| \to 0$).

Finally, by subtracting the elastic cross section from the total cross section, the inelastic cross section was calculated:

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

$$\sigma_{\text{inel}}^{\text{ALFA}}(8\text{ TeV}) = 71.73 \pm 0.15\,(\text{stat.}) \pm 0.69\,(\text{syst.})\text{ mb}.$$

All these results are in agreement with Monte Carlo predictions and the expected global trend [6, 7]. It is also worth noting that the results from data taken at 8 TeV with $\beta^* = 1000$ m and at 13 TeV with $\beta^* = 2500$ m are on the way. One could expect that with these new data taken with a higher value of betatron function, Coulomb-nuclei interference and even Coulomb regions will be accessible [8].

5 Diffractive Bremsstrahlung

Diffractive bremsstrahlung is typically an electromagnetic process (see Fig. 2 (left)). However, as postulated in [9], high energy photons can be radiated in the elastic proton-proton scattering – see Fig. 2 (right). This idea was extended in [10] by introducing the proton form-factor into the calculations and by considering also other mechanisms leading to the $pp\gamma$ final state, such as a virtual photon re-scattering.

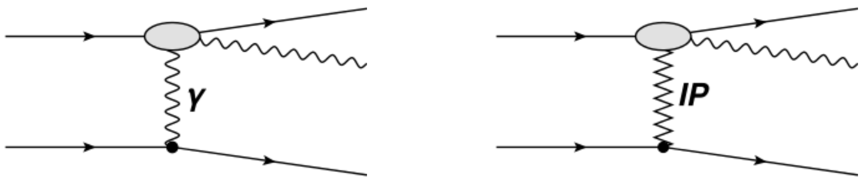

Fig. 2: Diagrams of electromagnetic (left) and diffractive (right) bremsstrahlung. The blobs represent various mechanisms of photon emission.

Recently, diffractive bremsstrahlung was implemented into the GenEx Monte Carlo generator [11, 12], and feasibility studies were preformed assuming $\sqrt{s} = 13$ TeV, $\beta^* = 90$ m and ALFA (ATLAS Zero Degree Calorimeter, ZDC) detectors as proton (photon) taggers [13]. It was shown that a measurement should be possible in ATLAS assuming about 10 h of data taking.

6 Exclusive Pion Pair Production

Exclusive pion pair production is a $2 \to 4$ process. The dominant diagram is a Pomeron-induced continuum, see Fig. 3 (left). Possibility of measurement of such process with ATLAS/ALFA detectors and high-β^* optics was discussed in [14]. Recently, the production of a photon-induced continuum (middle) and a resonant ρ^0 photoproduction (right) was calculated [15]. These processes are being currently implemented to the GenEx MC generator. It is worth mentioning that exclusive pion measurements at 7 and 8 TeV with ATLAS/ALFA are under way.

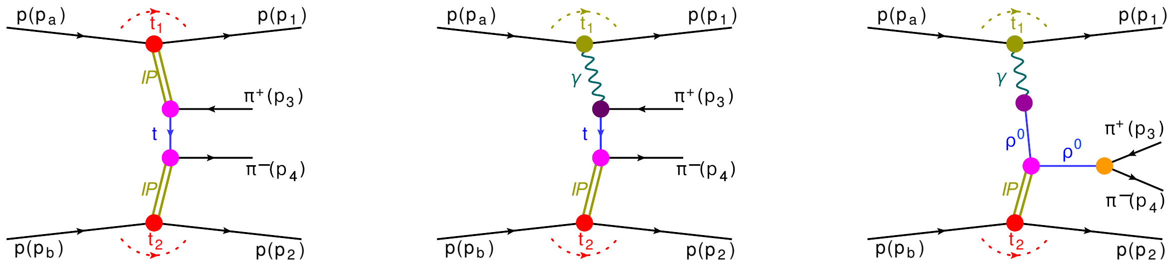

Fig. 3: Diagrams of exclusive non-resonant Pomeron-induced (left), non-resonant photon-induced (middle) and resonant ρ^0 (right) production.

7 Anomalous Gauge Couplings and New Physics Searches

Measurement of W and Z boson pair production via the exchange of two photons (see Fig. 4 (left)) allows to perform a stringent test of the electroweak symmetry breaking [16]. Standard Model predicts the existence of $\gamma\gamma WW$ quartic couplings while there is no $\gamma\gamma ZZ$ coupling. As was shown in [17, 18], collecting 30 – 300 fb^{-1} of data with the ATLAS detector and using protons tagged in AFP should result in a gain in the sensitivity of about two orders of magnitude over a standard ATLAS analysis.

Proton tagging may also serve as a powerful technique for new physics searches as the backgrounds can be significantly reduced by the kinematic constraints coming from the AFP proton measurements. The general idea of background reduction was presented in [19–21] on a basis of the exclusive jet measurement.

Proton tagging technique might be also used for the invisible object searches. As an example, the case of magnetic monopoles produced by the photon exchange can be considered. From a diagram (*cf.* Fig. 4 (right)) one can conclude that, even if the centrally produced system escapes detection (or is not

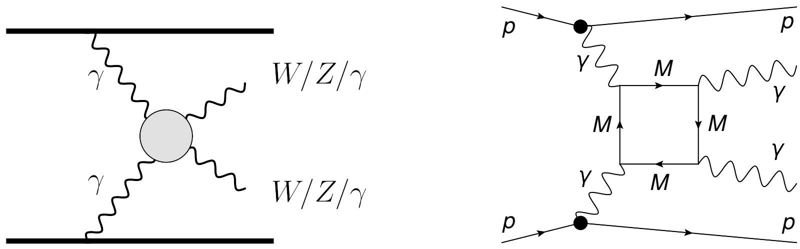

Fig. 4: Diagrams of anomalous gauge coupling (left) and magnetic monopole (right) production.

measurable) in ATLAS, one can measure scattered protons in AFP. In general, any production of new objects (with mass up to 2 TeV) via photon or gluon exchanges should be possible to be observed.

8 Summary

Two forward detectors systems are currently installed in ATLAS: ALFA (vertical RPs located $\sim$240 m from IP) and AFP (horizontal RPs located around 210 m from IP). ALFA successfully took data at: 7 TeV with $\beta^* = 90$ m, 8 TeV with $\beta^* = 90$ m, 8 TeV with $\beta^* = 1000$ m and 13 TeV with $\beta^* = 2500$ m. AFP so far collected data at $\sqrt{s} = 13$ TeV in few special, low-luminosity runs with $\beta^* = 0.4$ m and plans to join ATLAS data-taking on a regular basis.

Properties of the elastic scattering were measured by ALFA for both runs with $\beta^* = 90$ m. Results from data taken at 8 TeV with $\beta^* = 1000$ m and 13 TeV with $\beta^* = 2500$ m (Coulomb-Nuclear Interference and potentially Coulomb regions) are on the way. When ALFA is used together with ZDC it would be possible to measure diffractive bremsstrahlung. It should be also possible to measure a photon-induced exclusive pion-pair production continuum with a resonant ρ^0 photoproduction on top of it.

AFP took data in two special low luminosity runs in 2016 (with detectors on one side). In 2017 a fully equipped AFP detector will take data with a proton tag on both sides during special and standard LHC runs. It is planned to measure anomalous gauge couplings (W , Z and photon pairs) with the AFP data. A gain in sensitivity of about two orders of magnitude over a standard analysis, which uses the data from the central detector, is expected. In principle one can try to search for any production of a new object produced via photon or gluon exchanges (magnetic monopoles, invisible particles, ...). Forward proton measurements can be used for a significant background reduction.

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