PROCEEDINGS OF SCIENCE

Overview of ATLAS forward proton detectors: status, performance and new physics results

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A key focus of the physics program at the LHC is the study of head-on proton-proton collisions. However, an important class of physics can be studied for cases where the protons narrowly miss one another and remain intact. In such cases, the electromagnetic fields surrounding the protons can interact producing high-energy photon-photon collisions. Alternatively, interactions mediated by the strong force can also result in intact forward scattered protons, providing probes of quantum chromodynamics (QCD). In order to aid identification and provide unique information about these rare interactions, instrumentation to detect and measure protons scattered through very small angles is installed in the beam pipe far downstream of the interaction point. We describe the ATLAS Forward Proton 'Roman Pot' Detectors (AFP and ALFA), including their performance and status. The physics interest, as well as the newest results on diffractive interactions, are also discussed.

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1. Introduction

There are two detector systems designed to detect forward protons from proton-proton collisions recorded by the ATLAS detector [1] at the Large Hadron Collider (LHC) [2]: the ATLAS Forward Proton (AFP) detector [3] and the Absolute Luminosity For ATLAS (ALFA) detector [4]. These forward protons originate from scatterings involving the exchange of colourless objects (either photons or Pomerons), in which the protons remain intact.

The protons are scattered at very small angles of only a few microradians and remain within the LHC beam pipe. They are then deflected outside the beam envelope by the LHC magnets [5]. For this reason, the detectors are placed far away from the interaction point, at distances of ~210 m and ~240 m for AFP and ALFA, respectively, as illustrated in Figure 1. The detectors are installed in Roman pots, which are used to move them very close (within a few millimetres from the beam centre) to the LHC beam when it is stable.

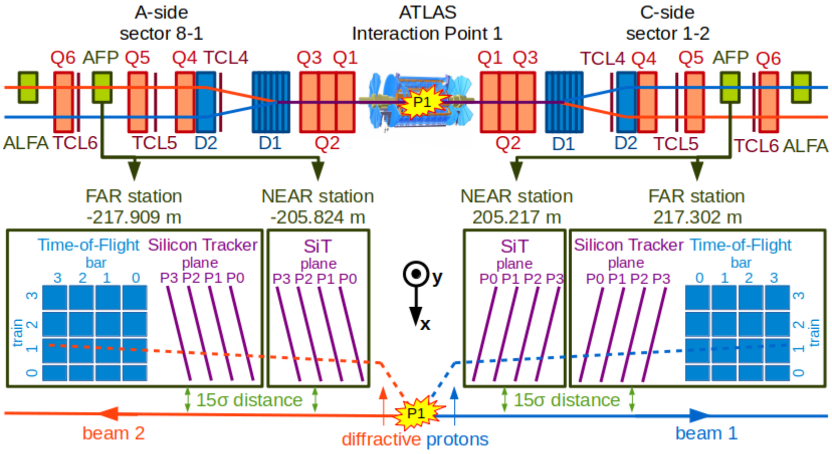


Figure 1: A schematic diagram showing the location of the AFP and ALFA detectors relative to the ATLAS interaction point, and the structure of the AFP detector stations. The dashed lines illustrate the paths of scattered protons through the AFP detectors.

There are four AFP stations in total: a Near and a Far station on each side of the interaction point. Each station contains a silicon tracker [6], consisting of four planes, each of which has 336 × 80 pixels, with pixel size 50×250 μm^2. The planes are tilted at 14° with respect to the x-axis to increase resolution in the x-direction and staggered to increase resolution in the y-direction, resulting in a resolution of about 6 μm in the x-direction and 30 μm in the y-direction [7].

In addition, the far stations also contain Time-of-Flight (ToF) detectors, designed to measure the z-position of the primary vertex to reduce backgrounds. They are positioned behind the silicon tracker with respect to the interaction point, and consist of 4 × 4 quartz bars which are read out by microchannel plate photomultiplier tubes (MCP-PMTs).

ALFA also consists of four stations, each hosting two Roman pots approaching the beam from above and below. Each pot is equipped with 10 plates containing two layers of 64 scintillating fibres oriented at 90° to each other, which are read out by multi-anode photomultiplier tubes (MAPMTs). Its resolution is 30 μm in the x and y directions.

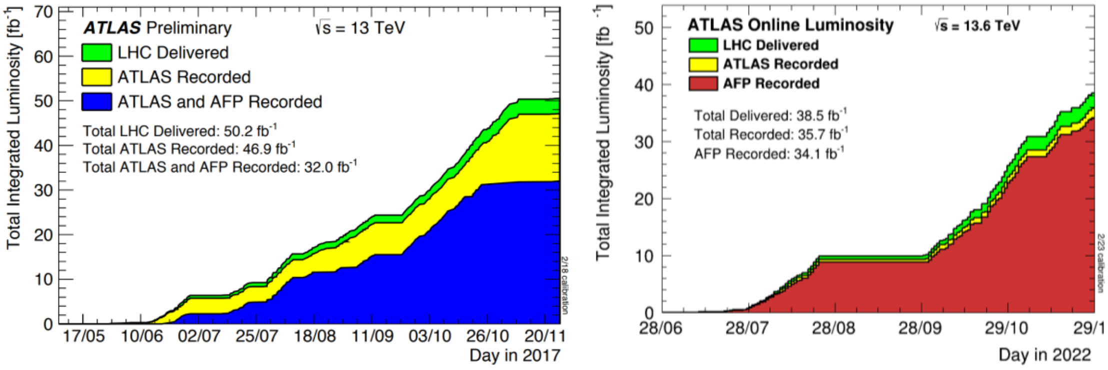
ALFA was designed to measure elastic processes, and AFP is more optimised for diffractive ones. Diffractive processes can be identified by rapidity gaps, defined as areas without any particles above a particular transverse momentum threshold and caused by absence of colour exchange. Analyses using such an approach may suffer from backgrounds due to low-multiplicity non-diffractive events. AFP and ALFA enable reconstruction of kinematics of the incoming particle (either photon or Pomeron) and suppression of these backgrounds. In addition, the measurement of the arrival time of protons helps to further supress the background.

This makes it possible to extract (semi)exclusive processes and has the potential to expand the ATLAS physics program, which is largely based on inclusive processes. Measurements already done include Standard Model processes (see Ref. [8] about exclusive dileptons) and beyond SM processes (see Ref. [9] about the axion-like particle searches in exclusive diphoton measurement). There is a large potential for other measurement, see e.g. SM exclusive dijets [10], SM exclusive $t\bar{t}$ [11, 12], the gluon Wigner function [13], exclusive Higgs boson [14], ALP searches [15] or dark matter searches [16, 17].

2. Performance

AFP participates in both standard, high pile-up LHC data-taking runs, used to study rare processes, and special, low pile-up runs used to study processes with relatively large cross sections for which clean environments are required.

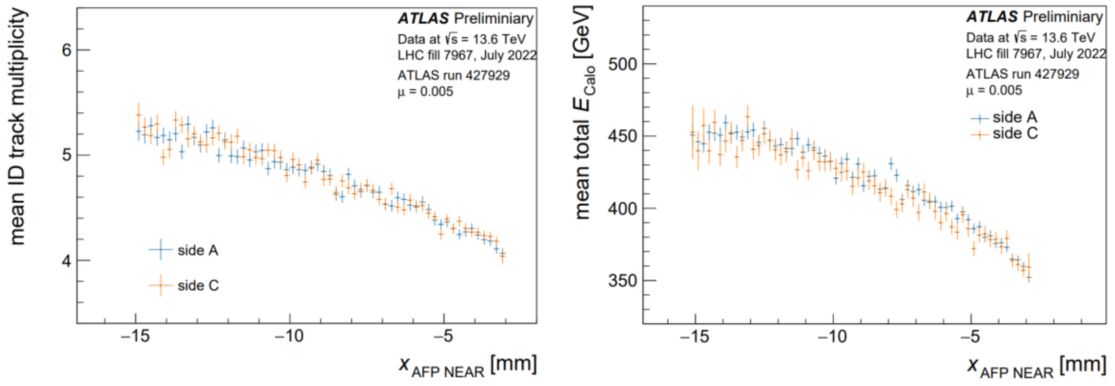
Figure 2 shows the cumulative luminosity recorded by AFP in 2017, its first year of data-taking, and in 2022, the first year of LHC Run 3, compared to the luminosity delivered by the LHC and recorded by ATLAS. It clearly shows an increase in the luminosity recorded by AFP relative to that recorded by ATLAS, demonstrating improved AFP operation.



(a) (b)

Figure 2: Cumulative luminosity versus time delivered to (green) and recorded by ATLAS (yellow) during stable beams for proton-proton collisions at (a) 13 TeV centre-of-mass energy in 2017 [18] and (b) at 13.6 TeV centre-of-mass energy in 2022 [19]. Also shown (blue in 2017 and red in 2022) is the luminosity recorded while all AFP detector stations were in physics position and AFP was being read out by the ATLAS data acquisition system.

Figure 3 shows the correlations of the x-position of reconstructed proton tracks with the charged track multiplicity in the ATLAS Inner Detector (ID) and with the total energy measured by the ATLAS calorimeters, with $x = 0$ at the centre of the beam. The absolute value of x is thus the distance from the beam centre and proportional to the energy lost by the proton in the proton-proton scattering. Hence the bigger this distance, the bigger the energy loss and thus the larger the track multiplicity and the energy measured in calorimeters that are expected. As Figure 3 shows, this is indeed observed.



(a) (b)

Figure 3: Correlation between the x-position of reconstructed tracks in Near stations and (a) the charged track multiplicity in the ATLAS Inner Detector (ID), (b) the total energy measured by the ATLAS calorimeters, shown separately for events with a proton on side A and C. Only events with a reconstructed primary vertex and exactly one reconstructed AFP track in each station on one side were considered. The ID track selection included requirements of $p_T > 500$ MeV and $|\eta| < 2.5$. The error bars show the statistical uncertainty of the mean value. Figures taken from Reference [18].

ALFA has been taking data since 2011 in dedicated low pile-up runs, with special LHC beam optics with high values of β^* at the interaction point. This is required for ALFA to be able to measure protons scattered through very small angles. It is scheduled to take data for elastic scattering measurements at 13.6 TeV in 2023, which is its last year of data taking.

3. New Physics Results

The latest AFP physics result is a search for an axion-like particle with forward proton scattering in association with photon pairs [9]. The analysis used the 2017 proton-proton collision data at a centre-of-mass energy $\sqrt{s} = 13$ TeV, corresponding to an integrated luminosity of 14.6 fb^{-1} (after applying data quality requirements). A search was performed for a narrow resonance in the diphoton mass distribution, corresponding to an axion-like particle with mass in the range 150-1600 GeV. No excess was observed, and the inferred upper limit on the coupling constant is in the range 0.04-0.09 TeV^{-1} at 95% confidence level. These results are comparable to those of the CMS-TOTEM collaboration [20], obtained using a similar approach, and extend their measured mass range to lower values.

For ALFA, there are two recent results. The first is the measurement of the total cross section and ρ-parameter from elastic scattering in proton-proton collisions at $\sqrt{s} = 13$ TeV using 340 $\mu\mathrm{b}^{-1}$ of data from a special 2016 LHC run with $\beta^* = 2.5$ km [21]. The measured value of ρ was 0.098 ± 0.011, in good agreement with the TOTEM result [22] and lower than would be expected assuming a $\ln^2 s$ rise of the total cross section, where s is the centre-of-mass energy squared.

The second is the measurement of exclusive pion pair production in proton-proton collisions at $\sqrt{s} = 7$ TeV in the process $pp \to pp\pi^+\pi^-$, which is the first use of proton tagging to measure an exclusive hadronic final state at the LHC [23].

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