

Overview of ATLAS Forward Proton (AFP) detectors in Run-2 and outlook for Run-3 analyses

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We describe the status of the ATLAS Forward Proton (AFP) detectors in Run-2 and the outlook for Run-3 analyses. The performance is discussed. This includes the Tracking and Time-of-Flight detectors, the luminosity, the alignment, the trigger, and data quality monitoring. Additionally, key physics results from the first AFP analyses are showcased.

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1 Status of ATLAS Forward Proton (AFP) detectors

The AFP detectors are located at about -200 m and $+200\text{ m}$ from the Interaction Point (IP) in the central ATLAS detector [1]. For example in $\gamma\gamma \rightarrow \ell\ell$ or $\gamma\gamma \rightarrow \gamma\gamma$ events, the final state proton can be intact and be record in the AFP detectors. The AFP detectors took data during LHC Run-2 operation and they are taking data in Run-3.

The Silicon Tracker (SiT) consists of four layers of silicon pixel detectors, two NEAR and two FAR stations. Only FAR stations are equipped with Time-of-Flight (ToF) detectors [1].

2 Luminosity

In 2017, 32.0 fb^{-1} data at 13 TeV , and in 2022, 36.1 fb^{-1} data at 13.6 TeV were taken in co-incidence with the ATLAS central detector (Fig. 1 [1, 2]).

In 2018 AFP data, the average number of interactions per bunch crossing, μ , for each luminosity block (60 s) was determined from the average number of AFP tracks. From 31 runs of data-taking (12-24 hours), μ values were measured and compared to measurements by the ATLAS luminometer LUCID. The agreement is within 1% between July and October 2018 (Fig. 1 [1, 2]).

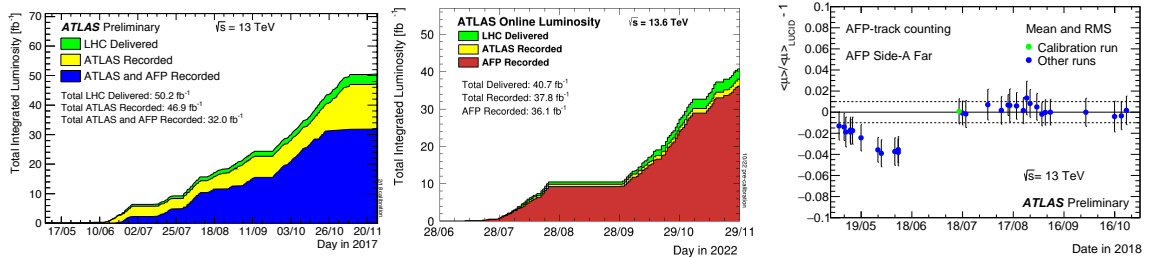


Figure 1: Luminosity 2017 (left), 2022 (center) and long-term AFP luminosity versus ATLAS reference luminosity, determined by the LUCID luminometer (right) [1, 2].

3 SiT data-taking, hit map July 2022 LHC Run-3

The SiT planes of the AFP detector are 336×80 (row \times column) pixels with dimensions of $50\ \mu\text{m} \times 250\ \mu\text{m}$. The hit map shows a clear correlation between SiT Raw ID and SiT Column ID, indicating the beam position (Fig. 2 [1]).

4 Alignment

The alignment of the SiT was performed with respect to the actual beam (later, it is planned with respect to the beam-pipe). The $300\ \mu\text{m}$ mean of alignment over stations and data-taking is taken as systematic uncertainty (Fig. 2 [1]).

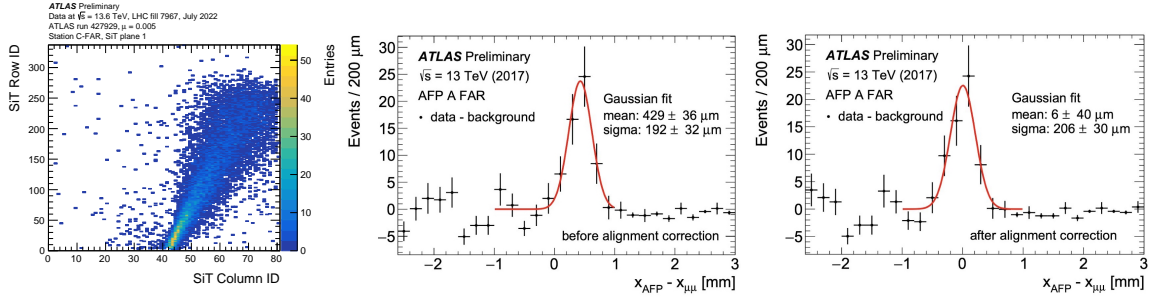


Figure 2: Hit map recorded by the SiT detector (left), detector position before (center) and after global AFP alignment (right) [1].

5 Trigger

The AFP is part of the ATLAS data acquisition system. The trigger rates are sent from the AFP detector at a nominal 20 sigma position from the beam. Figure 3 [1] shows the trigger rate as a function of the number of colliding bunches during LHC luminosity ramp-up for 2015-2016 data-taking.

6 ToF vertex reconstruction

In the 2017 data, the expected and measured vertex resolution is about 5 mm (Fig. 3 [1]). First results with the 2022 data have been obtained operating in Run-3 data taking.

7 SiT track with ToF single train signal

The SiT-ToF correlation was determined by studying the x position of tracks reconstructed in the SiT detector (FAR station) in events with a single-train signal in the ToF detector. Different colors are used to visualize the SiT regions corresponding to individual trains (Fig. 3 [1]). The machined x widths of the ToF bars are 3/3/5/5.5 mm for train 0/1/2/3.

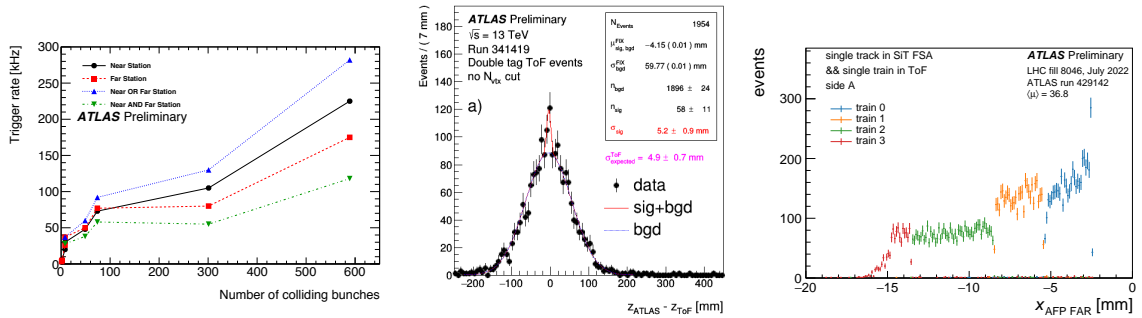


Figure 3: Trigger (left), ToF resolution (center) and SiT-ToF correlation (right) [1].

8 SiT correlation with central ATLAS inner detector tracker/calorimeters

The correlations are shown between the x position of reconstructed tracks in the AFP NEAR stations with a proton on side A or C and the charged track multiplicity in the ATLAS Inner Detector (ID), as well as the correlations with the total energy measured by the ATLAS calorimeters (Fig. 4 [1]). Exactly one reconstructed AFP track is required in each station and side, and a reconstructed primary vertex is required. The ID track selection requires $pT > 500$ MeV and $|\eta| < 2.5$. Events with smaller x AFP values are further away from the beam and are thus expected to originate from protons with higher energy loss.

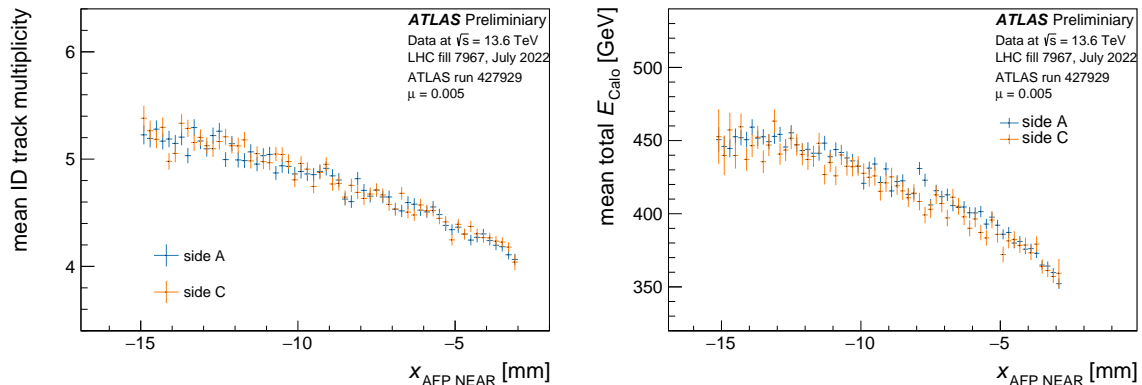


Figure 4: SiT correlation with ID tracker (left), SiT correlation with calorimeters (right). The statistical uncertainty of the mean values for each bin are shown [1].

9 Matching of proton energy loss with ATLAS central di-leptons/di-photons

The photon-induced di-lepton production with forward proton tag at 13 TeV was studied in the AFP acceptance range $0.02 < \xi < 0.12$, where ξ is the relative proton energy loss [3]. The signal and combinatorial background processes are shown in Fig. 5 [3]. Di-lepton events are studied in the rapidity $y_{\ell\ell}$ versus $m_{\ell\ell}$ plane using 14.6 fb^{-1} [3]. Event are selected with the kinematic matching $|\xi_{\text{AFP}} - \xi_{\ell\ell}| < 0.005$ on at least one side (Fig. 5 [3]). Shaded (hatched) areas denote the acceptance (no acceptance) for the AFP stations. Areas neither shaded nor hatched correspond to ξ outside $[0,1]$.

For the light-by-light scattering mediated Axion-Like-Particle (ALP) production, the matching of a photon pair and the proton kinematics is required. Figure 6 [4] shows 441 single matching events in 2017 data. There are no double matching events. The matching requirement is $|\xi_{\text{AFP}} - \xi_{\gamma\gamma}| < 0.004 + 0.1\xi_{\gamma\gamma}$.

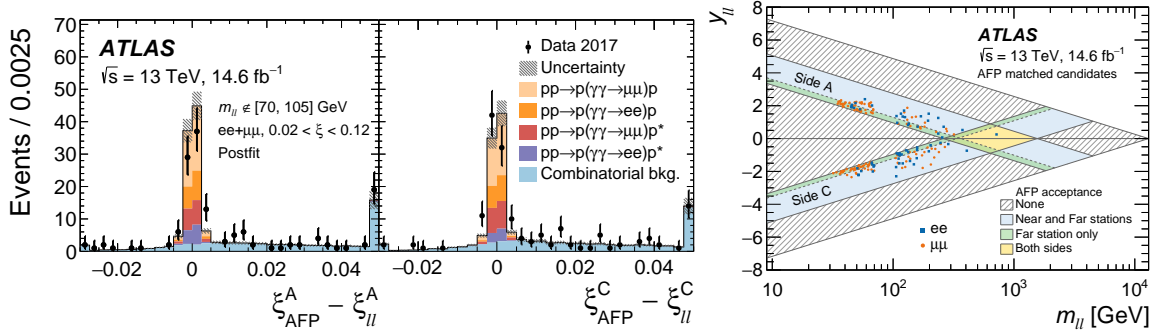


Figure 5: Di-lepton matching with AFP proton kinematics (left and center), di-lepton selected events (right) [3].

10 Key physics results

For the $\gamma\gamma \rightarrow \ell\ell$ analysis, 57 (123) candidates $e^+e^- + p(\mu\mu + p)$ events are selected [3]. The background-only hypothesis is rejected with a significance $> 5\sigma$ in each channel. Cross-section measurements in the fiducial detector acceptance $\xi \in [0.035, 0.08]$ yield: $\sigma(ee + p) = 11.0 \pm 2.6(\text{stat}) \pm 1.2(\text{syst}) \pm 0.3(\text{lumi})$ fb, and $\sigma(\mu\mu + p) = 7.2 \pm 1.6(\text{stat}) \pm 0.9(\text{syst}) \pm 0.2(\text{lumi})$ fb.

A comparison with proton soft survival (no additional soft re-scattering) models gives: 10.0 ± 0.8 fb ($ee+p$) and 9.4 ± 0.7 fb ($\mu\mu+p$) [3].

The Axion-Like-Particle (ALP) search in the reaction $\gamma\gamma \rightarrow \gamma\gamma$ uses an AFP proton tag to reduce the background, and it leads to limits on the ALP production cross-section and ALP coupling (Fig. 6 [4]). There is a further rich analysis programme using the AFP detector [1].

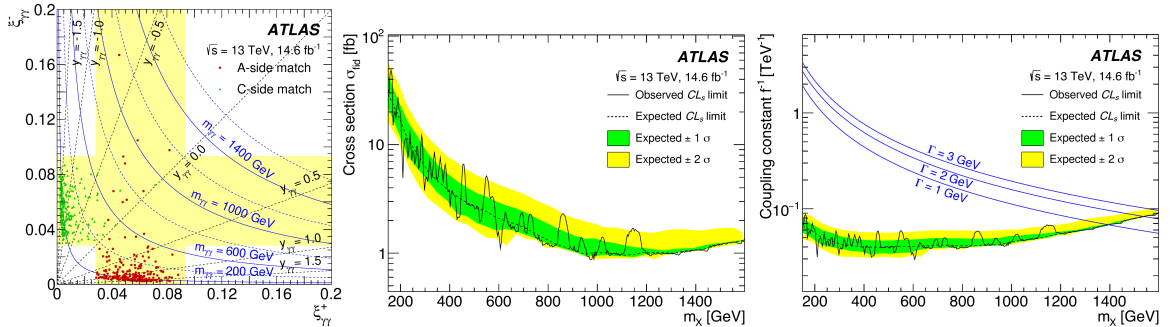


Figure 6: 441 di-photon events with AFP tag (left), limit on ALP production cross-section (center) and ALP coupling (right) [4].

11 Outlook for Run-3

The LHC Run-3 proton-proton interactions have a large potential for the AFP detector operation. There are several LHC operation modes:

- High- μ runs for regular data taking (AFP integrated luminosity expected to match ATLAS reference), purpose: high pT exclusive processes and Beyond the Standard Model searches.
- Low- μ runs (various pile-up conditions, $0.005 < \mu < 1$) during LHC ramp-ups, purpose: soft diffraction, low pT hard diffraction.
- “LHCf run $\beta = 19$ m”, purpose: diffractive studies, connection to cosmic ray physics.
- Medium- μ runs ($\mu \approx 2$) with 1 fb^{-1} of data planned to be collected, purpose: excellent sample to study medium/high pT hard diffractive processes. The process $pp \rightarrow \text{PbPb}$ will be used as reference run for diffractive studies at lower energy.

12 Conclusions

The ATLAS Forward Proton (AFP) detector has operated successfully at LHC Run-2 and Run-3 for both silicon Tracker (SiT) and Time-of-Flight (ToF). Single dissociative (soft QCD) and re-scattering were probed in photon-induced di-lepton production with a forward proton tag. Light-by-light scattering were used in Beyond the Standard Model searches using a forward proton tag.

Future precision increases with the analysis of Run-3 data is anticipated using larger data sets (2022-2025) and using the ToF data for improved vertex reconstruction and further background rejection.

Acknowledgments

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