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ATLAS Forward Proton Detectors – Special 2017 Low Pile-up Runs

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The performance of the ATLAS Forward Proton (AFP) Silicon Tracker detector is studied using the dedicated low-luminosity ATLAS LHC data collected in the 2017 running period of LHC Run 2. A brief description of the AFP spectrometer is given, followed by the discussion of unique opportunities of diffractive physics studies in low pile-up conditions. Additionally, some features of 2017 data are explored, including trigger efficiency and creation of particle showers within the detectors.

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1. Studies of diffractive physics with AFP

The predictions of forward proton scattering arise in a diverse range of physics, including the hard [1, 2] and nonperturbative QCD [3], interactions at electroweak scale [4–7], and searches for physics beyond Standard Model [8–13]. Such events, usually called diffractive, involve an exchange of a colourless object between interacting protons, one or both of which may remain intact. Moreover, a *rapidity gap* will be present – an absence of particles produced into kinematic vicinity of the intact proton. Historically, rapidity gap is a standard experimental signature of a diffractive event, however, it is frequently outside the acceptance of detector, or is destroyed due to background, i. e. particles coming from *pile-up* – independent collisions happening in the same bunch crossing. An alternative method of identifying diffractive events is a direct measurement (*tagging*) of the scattered proton. This solves the problems of identifying the gap in the very forward region, as well as the presence of pile-up. However, since protons are deflected at very small angles (few hundreds micro-radians), additional devices called *forward detectors* are needed far downstream from the interaction point.

2. The AFP spectrometer

The ATLAS [14] Forward Proton (AFP) spectrometer is a set of instruments housed in Roman Pot devices registering the protons scattered at very small angles. A proton scattered at the interaction point (IP) is deflected outside the beam envelope by dipole and quadrupole magnets of the LHC [15]. Then its momentum can be determined by measuring points on its trajectory [16, 17]. Figure 1 shows a schematic diagram of the AFP system. Two Roman Pot units are located on both

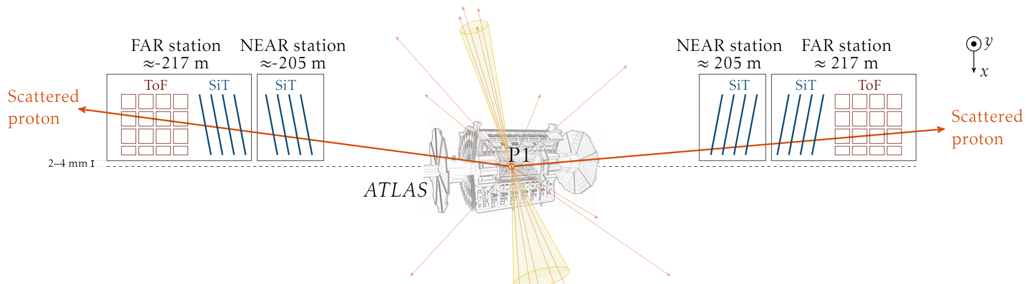

Figure 1: A schematic diagram of the ATLAS Forward Proton detectors.

sides of the ATLAS IP (*side A* – towards LHCb, *side C* – towards ALICE) at longitudinal distances of approximately 205 m (*Near* stations) and 217 m (*Far* stations). Each station houses four planes of 3D silicon pixel sensors [18–21] forming the silicon tracker (SiT), which measures the trajectories of the scattered protons. The sensors have 336×80 pixels with 50×250 μm^2 area each. The combined spatial resolution of reconstructed proton tracks is 6 μm and 30 μm in x and y directions, respectively [22]. Optimal resolution in x coordinate is achieved with the sensors tilted by 14 degrees about the x-axis. The reconstruction of position of protons traversing the AFP detectors (see Figure 2), in a known magnetic field, allows the estimation of proton energy and transverse momentum [23]. The main observable measured by the AFP is the proton fractional energy loss, defined as: $\xi = 1 - \frac{E_{\text{proton}}}{E_{\text{beam}}}$. The typical acceptance in ξ and p_T is illustrated in Figure 2.

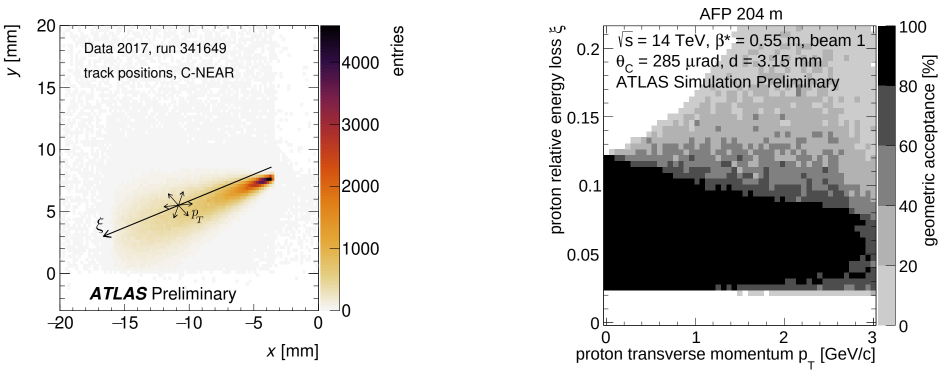

Figure 2: Left: example distribution of reconstructed track positions (x and y, transverse to the beam); the beam spot is approximately at (0,10) mm and deviations from this position are related to proton energy loss, as well as its transverse momentum. Right: Simulated geometric acceptance of the AFP detector as a function of the proton relative energy loss (ξ) and its transverse momentum (p_T) for the LHC collision optics (plot taken from [16]).

The Far stations are additionally equipped with the Time-Of-Flight (ToF) detectors. For processes in which protons are reconstructed on both sides of the IP, this allows rejection of background from pile-up by using the difference between the A and C-side ToF measurements to reconstruct the primary vertex position. The ToF detectors are based on Cherenkov radiation in quartz crystals, which leads to a timing resolution of around 25 ps, or equivalently a longitudinal vertex position resolution of about 5 mm [24, 25].

3. Low pile-up conditions

The AFP stations were inserted for the majority of the 2017 LHC operation, collecting 46 fb^{-1} of data. This includes the integrated luminosity of ≈204 pb^{-1} delivered to ATLAS in special, low pile-up conditions between June and November 2017. With the mean pile-up ranging from $\mu\approx0.05$ up to $\mu\approx2$, the low number of vertices reconstructed in the ATLAS central detector allows a great reduction of the physics background in the studies of events of two main categories:

1. Soft single and central diffraction – the high cross section for soft processes leads to an overwhelming background from pile-up events. Thus, the conditions of $\mu \approx 0$ are particularly relevant for studies of non-perturbative region of QCD.

2. Single, or double diffractive production of jets – rare events involving high-p_T momentum transfer through an exchange of a Pomeron may frequently be indistinguishable from non-diffractive production of jets, combined with a forward proton originating from soft interactions in pile-up events.

3.1 AFP SiT Trigger Efficiency

The AFP Silicon Tracker has a capability of producing trigger signals for the ATLAS Central Trigger Processor, selecting data dedicated for diffractive physics analysis. It was found that the dead time of the SiT detectors might influence the trigger efficiency in certain configurations of the bunch structure of the LHC beams. The dead time appears due to the prolongated effects on readout electronics caused by the charge deposited by the diffractive proton traversing the detector material. The signal amplitude may exceed the threshold value for over ≈300 ns (see: Figure 3, left), during which time no new trigger may be fired. The right panel of Figure 3 shows how the SiT trigger efficiency decreases for consecutive filled bunches, while during the empty bunches the SiT read-out is able to partially recover and an increase of its efficiency is recorded.

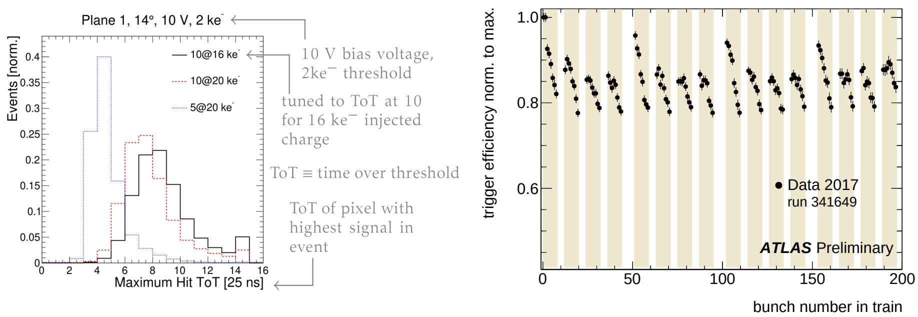

Figure 3: Left: Distribution of time over threshold (ToT) of the pixel with highest signal in an event for one of the silicon planes. With a peak at 8 clock cycles of 25 ns, a typical dead-time of ≈200 ns is expected (taken from [19]). Right: Relative SiT trigger efficiency (normalized to the highest) in dependence on the bunch structure. The efficiency decreases for consecutive filled bunches (8, shaded regions). Filled bunches (8) are separated by empty ones (4-8), during which an increase in efficiency is observed.

3.2 Particle showers created in SiT planes

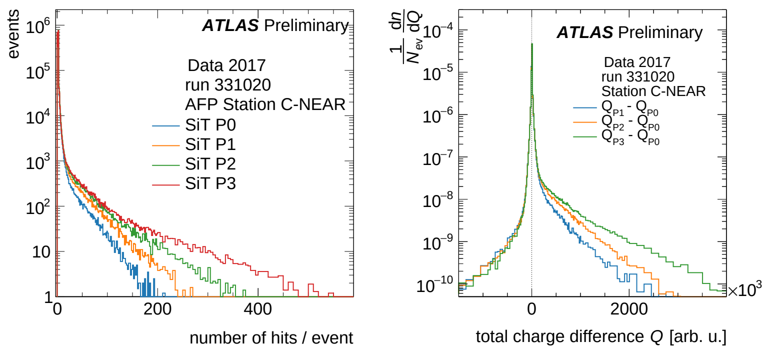

Figure 4: Distribution of the number of hits per event (left) and the difference of recorded charge for each of silicon planes in C-NEAR station. Secondary interactions with detector material results in higher number of hits and higher recorded charge for consecutive SiT planes.

Diffractive protons registered in AFP may interact with either silicon tracker, or the Roman Pot floor. Most of such interactions is of electromagnetic nature, leading to a production of δ-electrons. However, it is also possible that the proton interacts strongly, creating a high-multiplicity hadron showers. Particles originating from secondary interactions propagate downstream from the IP and may be recorded by subsequent layers of SiT. Thus, each consecutive layer registers on average a larger number of hits, as well as, a higher charge deposit (Figure 4).

4. Summary

ATLAS Forward Proton detectors provide a unique possibility to study diffractive physics with forward proton tagging and direct measurements of its kinematics. In 2017, the ATLAS Collaboration recorded a dedicated set of data in low luminosity conditions. Analysis of the data recorded in the special low-μ runs has been initiated and some of its interesting features were reported in this article, including the AFP SiT trigger efficiency dependence on bunch structure and the presence of particle showers. Continuation of physics analysis is planned for near future and even more data is to be collected during the LHC Run 3.

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