HIGH LUMINOSITY LHC OPTICS FEASIBILITY STUDIES FOR: ATLAS, ALICE, AND LHCb*

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Properties of proton trajectories along the High Luminosity LHC beamline in the vicinity of ATLAS, ALICE, and LHCb interaction points are discussed. Based on this, possible locations of forward proton detectors in the vicinity of these experiments were identified. Finally, studies of geometric and mass acceptances were performed.

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1. Introduction

Close to 40% of proton–proton collisions occurring at the High Luminosity Large Hadron Collider (HL-LHC) [1] will be diffractive. Analyses of the HL-LHC data are expected to significantly advance measurements of the Standard Model [2–5] and searches for beyond the Standard Model phenomena [6–9]. In these cases, an important class of processes predicts the forward scattering of incident protons: $pp \to pXp$.

Theoretical frameworks usually describe diffraction as a process involving the exchange of vacuum quantum numbers. In the case of electromagnetic interaction, the force carrier is a photon. For the strong force, it is the so-called Pomeron. Experimentally, diffractive events may be identified by the presence of the so-called rapidity gaps: a space in the rapidity devoid of reconstructed objects. Unfortunately, in the HL-LHC environment, the gaps will be populated by particles originating from pile-up — other pp collisions happening during the same bunch crossing. Therefore, a direct proton measurement, possible with the use of dedicated detectors, remains the only way to study such events.

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The HL-LHC aims at a significant increase in the luminosity. This requires a redesign of the machine layout resulting in changes of its optics [10, 11]. The optics and magnet layout used for the presented studies is HL-LHC V1.5 [12] which assumes the centre-of-mass energy $\sqrt{s} = 14$ TeV and beam emittance of 2.5 μm $\times$ rad.

2. ATLAS

The ATLAS [13] experiment already has forward detectors for proton tagging: the ATLAS Roman pots (ARP). The ARP detectors include ALFA [14] and AFP [15]. The ALFA (Absolute Luminosity For ATLAS) system consists of four detector stations at 237 m and 241/245 m (LHC Run 1/ Runs 2–3) on either side of the Interaction Point 1 (IP1). The detectors are installed in the Roman pot devices and can move vertically. The AFP (ATLAS Forward Proton) detector has four horizontally moving stations situated symmetrically with the ATLAS IP at roughly 205 and 217 m. ARP successfully participated in data collection campaigns since Run 1 (ALFA) and Run 2 (AFP).

Due to the complete redesign of the HL-LHC structure in the vicinity of IP1, the first step in exploring the feasibility of incorporating forward proton detectors is to evaluate suitable installation places. This assessment is essential given the constraint space due to the presence of various elements, including magnets, collimators, or beam monitors.

According to the V1.5 layout, only a few locations are possible for the insertion of Roman pots around IP1. They are listed in Table 1. An important setting is the crossing-angle plane [10]. Due to the overall stability of the accelerator optics, it should differ by 90° between ATLAS and CMS IPs. In Runs 1–3, ATLAS has a vertical crossing angle. For HL-LH, a horizontal crossing pointing outside of the ring ($\phi = 0$) is planned at IP1.

Table 1. Possible locations of Roman pots in the vicinity of IP1 at HL-LHC.

RP1	RP2	RP3	RP4
RP1A at 195.5 m	RP2A at 217.0 m	RP3A at 234.0 m	RP4 at 418.8 m
RP1B at 198.0 m	RP2B at 219.5 m	RP3B at 237.0 m	
		RP3C at 245.0 m	

Studies of the scattered proton trajectory in the vicinity of IP1 were done, see Fig. 1. Following the usual convention (*cf.* Ref. [10]), the trajectories were defined in a curvilinear, right-handed coordinate system denoted (x, y, s), with the ATLAS collision point located at $(0, 0, 0)$. The thick, solid, red line at $x = 0$ denotes the 7 TeV beam — the nominal proton trajectory. Protons that lost a fraction of the energy, $\xi = 1 - E_{\mathrm{proton}}/E_{\mathrm{beam}}$, are drawn as various black $\rightarrow$ red dashed/dotted lines. The HL-LHC magnets are highlighted as lightly shadowed blue areas, while the beam pipe aperture is depicted by light red/grey lines at the top and bottom of the figure.

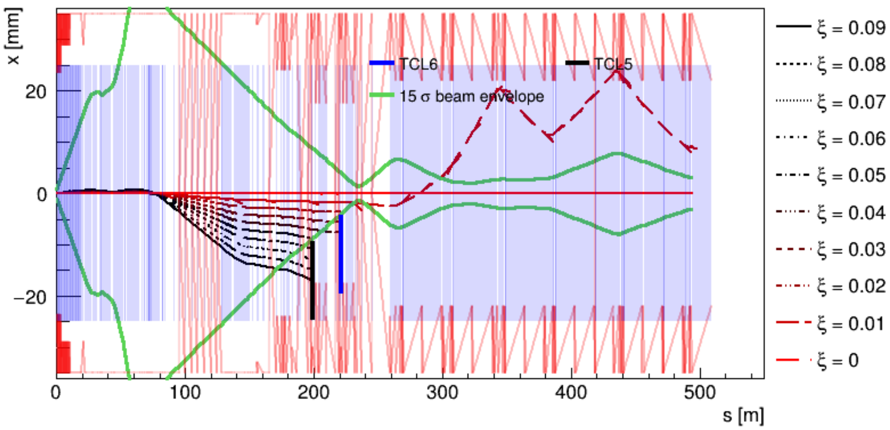

Fig. 1. (Colour on-line) Proton trajectories around the ATLAS collision point $(x, s) = (0, 0)$. For a detailed description see the text.

Figure 1 shows trajectories of protons with ξ ranging from 1% to 10%. The more energy is lost by the proton, the larger its deflection from the nominal trajectory is. At one point, such protons will be stopped by the beam pipe aperture or collimators. The latter are shown with the thick vertical lines in black and blue. These collimators are close to 16.4σ, where σ is the nominal beam size at the given location. The thick, green/grey lines mark the 15σ beam envelope — the usual limit to which Roman pots can approach. It should be noted that the negative x values are outside the HL-LHC ring, whereas positive ones mean that protons are scattered in between the beam pipes.

Figure 2 shows the geometric acceptances[1] as a function of ξ and p_{T} for detectors located at 195.5 and 418.8 m. Detectors located closer to the IP1 offer higher acceptance for ξ, thereby facilitating the detection of higher masses within the central system. Conversely, detectors positioned at 418.8 m provide acceptance for lower-ξ values, enabling access to lower masses. For the optimistic detector beam distance of 11σ and taking into account the dead edge of about 0.8 mm, the RP1A station allows for accessing protons with $0.2 < \xi < 0.35$, whereas the RP4 one shows the acceptance within $0.003 < \xi < 0.02$.

[1] Geometric acceptance is defined as the ratio of protons with a given ξ and p_{T} reaching the detector to the total number of dispersed protons with ξ and p_{T}.

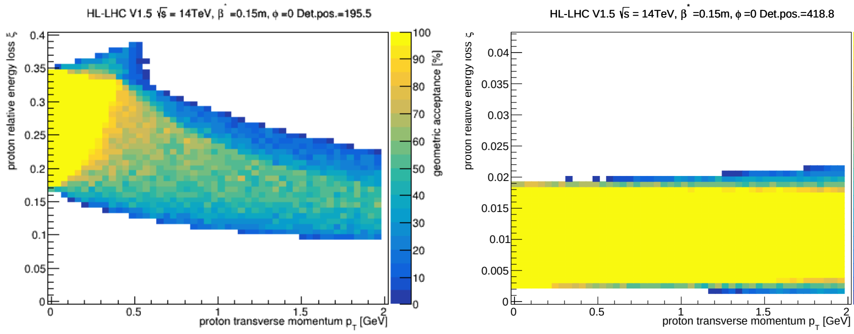

Fig. 2. Geometric acceptance for stations near IP1 and the horizontal crossing angle ($\phi = 0$) for two possible locations: RP1A at 195.5 m (left) and RP4 at 418.8 m (right).

A single set of stations limits the accessible acceptance region. Therefore, a scenario of multiple Roman pots was considered. This is seen in Fig. 3, when the mass acceptance, computed as $M = \sqrt{s\,\xi_1\,\xi_2}$, is shown. RP**X** denotes the combination of two stations, RP**X**A and RP**X**B, situated on both sides of the IP, with a proton tagged in all of them. When referring to RP**X**+RP**Y**, a configuration where the proton is tagged (RP**X**A and RP**X**B) or (RP**Y**A and RP**Y**B) on both sides of ATLAS is considered.

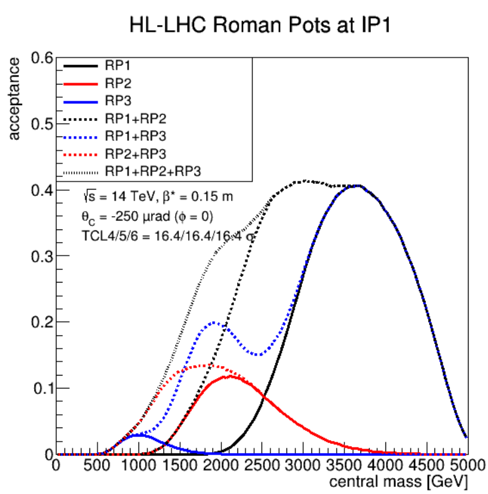

Fig. 3. Mass acceptance for various combinations of stations near IP1.

Based on the above results, the idea of having Roman pots around IP1 was considered by the ATLAS Collaboration [16]. Contrary to CMS [17], the decision was to not install such devices for Run 4, with an open possibility for Run 5 and beyond.

3. ALICE

Similar studies were conducted for the ALICE experiment (IP2). The crossing angle was assumed to be 270 μrad (vertical plane) and β^* was set to 10 m [11]. Figure 4 (left) depicts the proton trajectories up to 500 m from IP2. It should be noted that here the region with negative values of x is in between beam pipes. Similarly to IP1, the low-ξ region is accessible for detectors located around 400 m. For the high-ξ studies, the best location for the Roman pots is around 150 m. Corresponding geometric acceptance is shown in Fig. 4 (right). For the detector–beam distance of 15σ, the station at 150 m allows access to a proton with $0.04 < \xi < 0.13$.

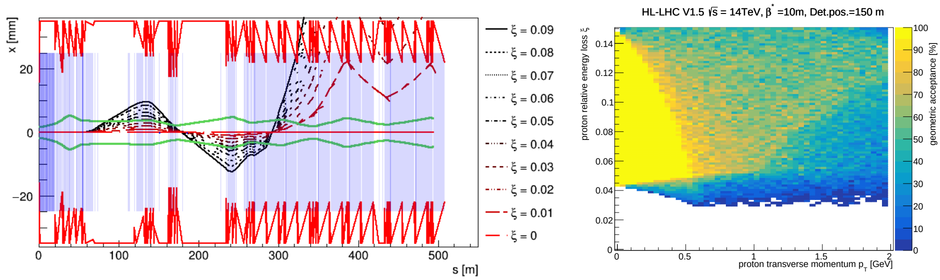

Fig. 4. Left: proton trajectories in the vicinity of the ALICE collision point (IP2). Right: geometric acceptance for pots located at 150 m from IP2.

4. LHCb

A study considering the LHCb case (IP*) is described in detail in [18]. Three potential locations for forward proton detectors were identified: 150, 180, and 430 m. Geometric acceptances above 80% were found for $0.05 < \xi < 0.1$, $0.025 < \xi < 0.1$, and $0.003 < \xi < 0.013$, respectively. In addition, a discussion of the impact of asymmetrical acceptance of the "central" LHCb detector (boost of the central system) was held.

5. Summary

The HL-LHC layout has been established. Among all large LHC Collaborations, only the CMS experiment will be equipped with a dedicated set of forward proton detectors installed for Run 4. The ATLAS, ALICE, and LHCb cases are still open for Run 5 and beyond. It should be stressed that understanding of the acceptance of the forward protons at the potential detector locations serves as an initial step for conducting feasibility studies essential for constructing the physics case.

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