MITIGATION OF MUON BACKGROUNDS AT LHC FORWARD-PHYSICS EXPERIMENTS THROUGH ORBIT BUMPS[*]

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Abstract

The Scattering and Neutron Detector at the LHC (SND@LHC) and the Forward Search Experiment (FASER) are located at the CERN Large Hadron Collider, 480 m from the ATLAS experiment on opposite sides. They study high-energy neutrinos and dark matter candidates produced in the proton-proton collisions at ATLAS. A key challenge for both experiments is the muon background, produced in the collisions and by nearby proton losses in the LHC ring. In 2024, a reversal of the magnet polarity of the final-focus system in IR1 caused a substantial increase in muon background at both experiments. Although nominal triplet polarity was restored in 2025, background levels remained significantly higher than in 2023. To mitigate the losses in cell 11, considered the origin of the main contribution to the background, orbit bumps were designed to displace the losses away. The bumps were designed using both conventional techniques and a novel Xsuite-based matching method employing beam losses as the optimisation observable. Experimental tests done in 2025 confirmed a background reduction in SND and FASER when activating the bumps. This study demonstrates that the proposed strategy is a viable operational solution for reducing muon backgrounds in future physics operations.

INTRODUCTION

The production of forward particles in proton-proton collisions at the Large Hadron Collider (LHC) [1] offers a unique opportunity to explore physics processes at energies never seen before. The Scattering and Neutron Detector (SND@LHC) [2] and the Forward Search Experiment (FASER) [3], located on opposite sides of the interaction point 1 (IP1) near ATLAS [4] (see Fig. 1), are dedicated to such studies. Their physics programmes aim to measure high-energy neutrinos and to search for particles potentially linked to dark matter.

A major challenge for SND and FASER operation is the background induced by high-energy muons emerging from the collisions or nearby proton losses on the machine aperture. These muons can penetrate a substantial amount of material and reach the experiments, potentially contaminating the emulsion detectors requiring more frequent replacements, which need to be minimised to limit LHC downtime. Understanding and minimising these backgrounds is therefore crucial for ensuring good performance and smooth operation of both experiments.

During the 2024 LHC operation, an inversion of the inner triplet magnet polarity in insertion region 1 (IR1) modified the secondary particle flux toward FASER and SND, resulting in a significant increase in the observed muon rates. Although the nominal polarity configuration was restored in 2025, background measurements remained noticeably higher than those recorded in 2023 (see Fig. 2 and Table 1). Dedicated FLUKA [5] studies for the radiation transport of the particles coming out of the collisions at IP1, combined with wide-angle tracking detectors data in SND, revealed that collisional proton losses in the dispersion suppressor (DS) region downstream of IP1 (cell 11) constituted the main source of excess background. The increase of losses in cell 11 was shown to be caused by a change of crossing plane from vertical in 2023-2024 to horizontal in 2025.

In this context, operational mitigation strategies were considered necessary to reduce this background. To do so, orbit bumps were developed to locally displace the collisional proton losses away from the cell 11. This article presents the development, including novel matching concepts based on beam losses, as well as the measured background during experimental tests of these bumps in the LHC, which were considered for deployment in the LHC 2026 run.

Table 1: Relative Measured Muon Rates Normalised to 2023 [6]

	2023	2024	2025
FASER	1	1.95	1.11
SND	1	2.07	1.43

LOSS ORIGIN ANALYSIS AND STEERING WITH ORBIT BUMPS

Among the multiple magnet families in the LHC, the orbit corrector dipoles (MCB) enable localised beam steering adjustments without affecting the global machine configuration. To mitigate the cell 11 losses, dedicated strengths were determined for the MCB correctors between IP1 and this cell (~400 m downstream of ATLAS) to produce two different bumps (see Fig. 3): the first approach looks to displace the losses downstream (Bump 1), while the second upstream (Bump 2). Horizontal bumps are most effective in modifying dispersive losses in cell 11, whereas such bumps can be generated using correctors between cell 5 and 17 (mcbch.5/7/9/13/15/17.r1.b1).

To carry out the matching of both bumps, it was first needed to simulate the losses produced from IP1 due to the proton-proton collisions. These particles were produced with the DPMJET-III [7] event generator included in FLUKA [8–10], which has recently been included in

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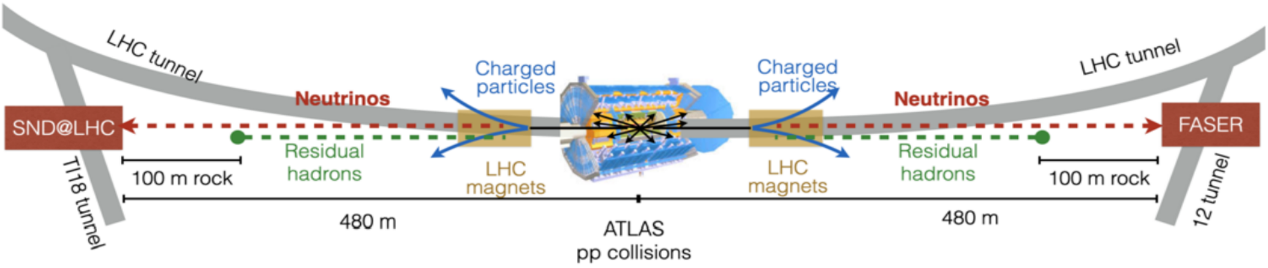

Figure 1: SND and FASER experiments with respect to the ATLAS detector.

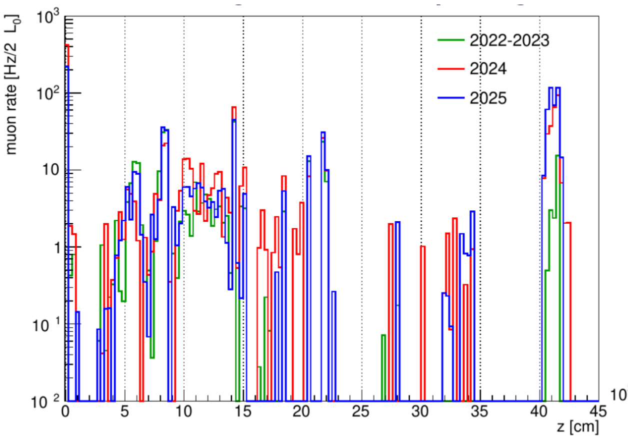

Figure 2: Simulated origin of muon impact in SND. Courtesy of S. Illieva and A.-G. Serban.

Xsuite [11, 12]. Following this, two different orbit bumps were produced. Bump 1 was designed to displace the losses further downstream, and the orbit correctors upstream of cell 11 were matched to create an orbit excursion in cell 11. The dispersive protons can then pass through the cell 11 without impacting the aperture. For Bump 2 a numerical minimisation of the losses in cell 11 was instead done, while a constraint was added to increase the losses in the cells upstream. This was done using the optimisation method in Xsuite, which allows user-defined functions to be used as optimisation targets in a flexible manner, in this case tracking of particles and counting the number of losses per cell. For both bumps it was ensured that the bump would close downstream of cell 11. A constraint was also added to ensure that the physical aperture remains sufficiently large, i.e., by limiting the maximum orbit excursion. The resulting bumps are shown, compared to the nominal orbit, in Fig. 4, while the simulated losses are shown in Fig. 5.

Bump 2, manages to deviate about 60 % of the losses in cell 11 upstream, where they should not contribute significantly to the SND background according to preliminary studies [5].

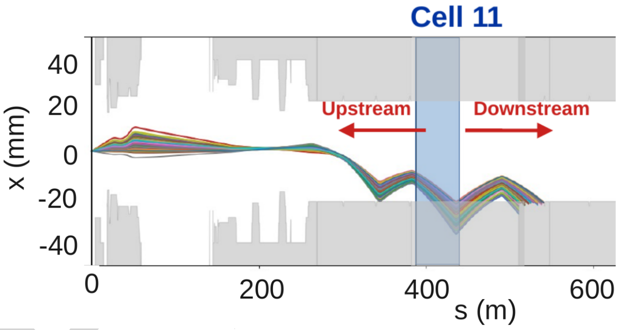

Figure 3: Various particles produced in IP1 ending up in cell 11. The bumps are expected to transfer the particles upstream or downstream.

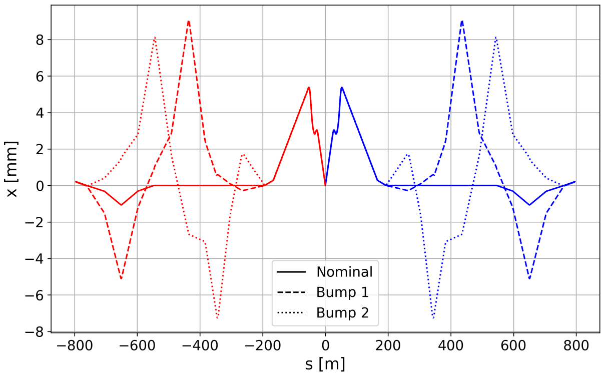

Figure 4: Beam 1 (in blue) and Beam 2 (in red) horizontal closed-orbit for Nominal and both proposed bumps.

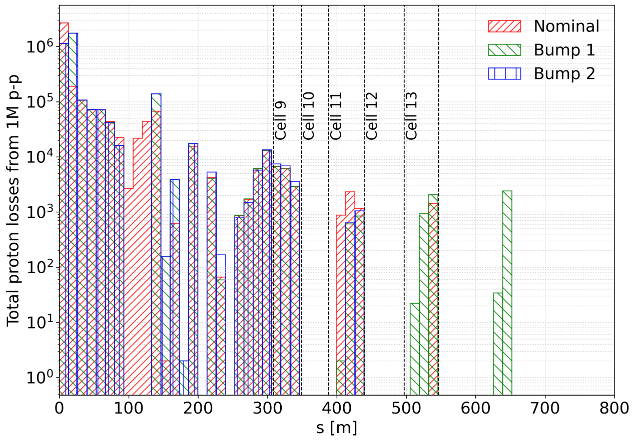

Figure 5: Losses comparison between Nominal, Bump 1 and Bump 2 in the region of interest.

In addition to these results, FLUKA simulations were performed to simulate the full radiation shower and estimate the muon background in the experiments [5]. The results of these simulations showed a reduction of ≈ 20-25 % of the total background in SND.

2025 BEAM TESTS AND 2026 RUN

These studies motivated dedicated beam tests to quantify the effect on background of the proposed bumps in machine operation. Two beam tests were scheduled: the first targeting only SND (on 07.09.2025) and the second one (on 02.11.2025) for both forward experiments. Only the latter is presented here, although more details related to the first test are available in Ref. [13].

2nd November 2025 Bumps Test

The test assessed the application of both of these bumps and measured the muon rate for both experiments. Since there was still interest in understanding also the impact of using Bump 1 at 30 % of its amplitude, three configurations were finally tested: 60 % Bump 1, 30 % Bump 1, and Bump 2.

Figure 6 shows the SND measurements for the cases mentioned above. These measurements show the muon tracks observed in the SND detectors, depending on the angle of incidence. One can see that the bumps effectively cure the excess losses at large incident angles. Table 2 shows the overall muon rate for nominal optics and the three bumps considered for both SND and FASER, normalised by the values in 2023.

Bump 1 reduces the background by around 20 % for both experiments at full strength or about 10–15 % at half strength for FASER and SND. Bump 2, moving the losses upstream, shows a reduction of 15 % for both experiments. Compared to 2023, there are only 10-20 % higher losses in SND and a reduction of 5-10 % in FASER.

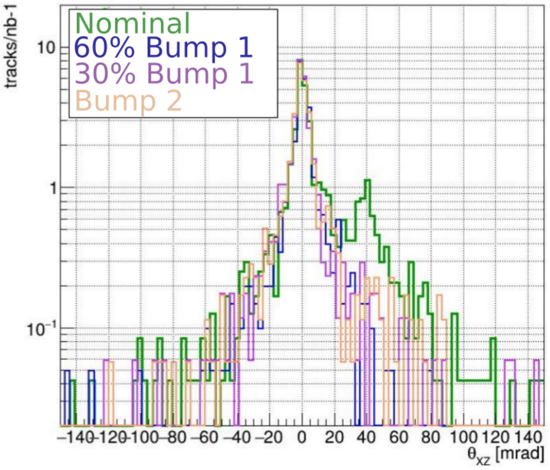

Figure 6: SND muon tracks vs. incidence angle for nominal optics and tested bumps. Courtesy of S. Ilieva.

Table 2: Muon Rate Normalised by 2023 Nominal Optics for Proposed Bumps

Configuration	**SND [μ rate]**	**FASER [μ rate]**
No Bump	1.43	1.11
Bump 1 (60 %)	1.11	0.88
Bump 1 (30 %)	1.20	0.99
Bump 2	1.21	0.94

Perspectives 2026 Run and Beyond

Discussions took place ahead of the LHC run in 2026 to decide on the operational deployment [14,15] . Bump 1 turns out not to be suitable for operational deployment since the displacement of losses to cells 13 and 15 causes radiation-to-electronics (R2E) concerns in the area [16], requiring upgrades to more radiation-hard electronics. Bump 2 does not have such issues since the electronics in cells 8-9 is already radiation-hard. While improvements in background reduction and related gains for SND emulsion data quality and reconstruction were identified, these were not deemed sufficient to justify changes to the operational baseline for a short run period. Nevertheless, the experience accumulated for experimental techniques, and the benchmark of simulations is an important asset for future optimisations.

For High-Luminosity LHC in Run 4, SND plans to upgrade from emulsion detectors to silicon strips [14], removing sensitivity to muon-induced background. FASER may follow a similar approach if emulsion backgrounds prove challenging, as indicated by previous studies [17]. Whether additional muon background mitigation will be required for FASER in Run 4 remains an open question, depending on ongoing studies.

CONCLUSIONS AND OUTLOOK

The studies presented in this work demonstrate in simulations and measurements that local orbit manipulations provide an effective handle to reduce muon background in forward experiments at the LHC. By combining precise tracking of collision products with experimental measurements from SND and FASER, proton losses in the IR1 dispersion suppressor, in particular around cell 11, were identified as the dominant source of the excess background following the optics changes.

Orbit bumps designed with Xsuite were shown to displace these losses away from this critical region, leading to a measurable reduction of the muon flux at the detectors during machine tests in 2025. The simulations were in good agreement with measurements in the machine, demonstrating the effectiveness of the approach. These results provide a validated framework for loss localisation and background mitigation, and may contribute to maintaining the viability of emulsion-based detector concepts for FASER in the HL-LHC era.

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