INVESTIGATING THE IMPACT OF ALTERNATIVE LHC OPTICS ON ACCELERATOR BACKGROUNDS AT FASER USING BDSIM

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Abstract

Alternative configurations around the ATLAS experiment are investigated aiming to reduce muon rates at forward physics experiments such as FASER and SND@LHC. The Geant4 toolkit BDSIM is used to propagate muons through a model of a section of the LHC and the TI12 tunnel, where the FASER experiment is located. We compare the muon rates in BDSIM with FASER data collected during dedicated tests in the LHC. Results show a significant worsening of the background with the non-nominal polarity configuration of the triplet quadrupoles, used in 2024. The horizontal crossing angle further increased the background, however a partial mitigation of approximately 10% was found using a set of orbit corrector magnets. Additionally, nominal triplet polarity was favorable for both vertical and horizontal crossing angles. This work served as benchmark of simulations that will be used to validate future configurations.

MOTIVATION

Inside the Large Hadron Collider (LHC) at CERN, at the heart of the ATLAS experiment, protons collide with each other at centre-of-mass energies of 13.6 TeV. The resulting flux of secondary particles provides valuable research towards fundamental physics problems. However, the collision products and ionizing radiation generated by the pp-collisions also cause damage to critical machine components. To extend the life-span of the LHC, the polarity of the quadrupole triplet nearest to ATLAS is flipped periodically. The crossing angle at ATLAS must also be reversed to preserve the beam dynamics. Between 2023 and 2024, the inner quadrupole polarity and therefore the vertical crossing at ATLAS was flipped (from -160 rad to $+160$ rad). Consequently, a large increase in muon backgrounds was observed at the Forward Search Experiment (FASER) [1].

The FASER detector is preceded by the FASERν emulsion box. The films within this box record charged tracks from neutrino interactions with great precision, but must be replaced routinely to avoid track saturation. The increased muon background disproportionally accelerates the saturation of these films, leading to less neutrinos being recorded per box. As the emulsion films are in limited supply and the LHC must be stopped during exchanges, this results in substantial data losses.

In this paper, an LHC backgrounds study using Beam Delivery Simulation (BDSIM) software is presented [2]. The objective is to identify machine configurations that yield more favorable muon backgrounds at the FASER location.

MODEL AND SIMULATION

The muon flux at FASER is significantly influenced by LHC magnet settings along the ~ 400 m of beamline between the detector and ATLAS. An additional ~ 100 m of concrete separating the experiments, absorbs muons with $E_K < 50$ GeV originating from ATLAS. Transversely, the FASER magnet aperture (used for comparison with BDSIM) is closely aligned with ATLAS collisions line-of-sight (LOS). Figure 1 illustrates the layout through the BDSIM model visualization.

Muon fluxes are simulated by propagating secondary particles through an LHC model in BDSIM v1.7.7 (v1.7.5 for the 2023 sample). BDSIM is a Geant4 (v10.7) toolkit capable of machine interaction simulations [2, 3]. ATLAS collision products are generated from 13.6 TeV pp-collisions with the `SIBYLL2.3d` model in the Cosmic-Ray Monte-Carlo package [4, 5]. Only products exiting the collision in the forward direction ($p_z/p > 0.9$) are introduced into the model. Muons with $E_K < 10$ GeV are killed to reduce simulation runtime. These muons would be stopped within the concrete, or are trivial to identify during experimental analysis.

The LHC model encompasses machine components, a cryogenic pipe and LHC tunnels ranging from ATLAS to the FASER detector location [6]. The tunnels are surrounded by a ~ 20 m layer of soil to include muons that scatter towards FASER from outside the LHC. Custom geometry for tunnel segments, shielding elements and the ATLAS endcap improves simulation accuracy. Dipole and quadrupole field maps have been provided by the CERN Magnet Group and the soil composition is taken from a geological survey of the area [7]. The 2023 and 2024 machine settings, including apertures and magnet strengths, are taken from LHC optics files on AFS [8] ($\beta^* = 60$ cm is assumed). Model validation includes removing geometry overlaps, visualizing magnet field maps and matching proton trajectory optics to reference parameters obtained in MAD-X [9].

The Geant4 high energy physics list `FTFP_BERT` is used in conjunction with processes: `GammaToMuons`, `PositronToMuons`, `MuonNuclear`, `GammaNuclear`, `PositronToHadrons` and `NeutrinoActivation`.

To minimize CPU time, muon production is boosted with two biasing methods: muon splitting and cross-section biasing. During muon splitting, muons with a parent kinetic energy $E_K > 50$ GeV are independently re-sampled five times. Furthermore, muons with $E_K > 500$ GeV parents are re-sampled thirty times. Cross-sectional biasing increases the likelihood of muon production via e^+e^- annihilation, and $\pi^\pm$ or $K^\pm$ decays. After simulation, both biases are reversed with statistical weights.

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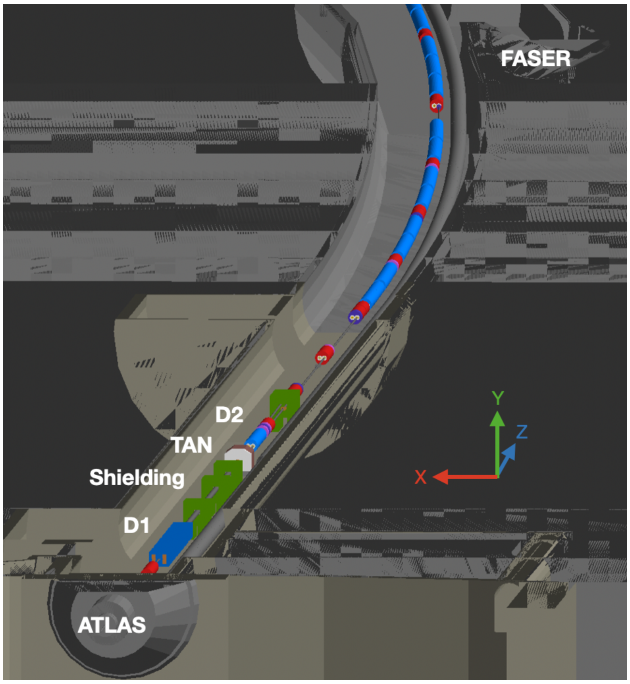

Figure 1: Model visualization with a cutaway plane along $y = 1$ m. Dipoles, quadrupoles and shielding elements are blue, red and green, respectively.

2023 AND 2024 COMPARISON

The primary difference between the 2023 and 2024 LHC magnet settings is the reversal of the three quadrupoles closest to ATLAS. Additionally, the 4th quadrupole is turned off. Finally, the half-gap of the TCL.6L1.B2 collimator is widened from 1 mm to 1.6 mm. The respective LHC settings were incorporated in the 2023 and 2024 BDSIM samples. Each sample contained the outcomes of 80M pp-collisions, recorded through a 1×1 m^2 transverse sampler located at $z = 473$ m (in front of FASER). The energy spectra of muons crossing these samplers (see Fig. 2) showed a factor of two increase in overall flux relative to 2023 (corroborated by experimental observation). The high energy flux at the detector increased by a further factor of $2 - 3$. The latter change was particularly problematic, as FASER dark matter signals most often involve higher energy particles [10, 11].

In BDSIM, the primary muon sources were the TAN and TCL.6L1.B2 elements. Within these dense shielding elements a significant portion of forward collision products were stopped, preventing heating and damage of downstream magnets. Hence frequent energetic $\pi^{\pm}$ and $K^{\pm}$ decays occurred, resulting in highly collimated muons. In the 2024 sample, 52% of the $E_K < 1TeV$ background was composed of μ^- deflected towards FASER in the arc section of the LHC (peaks at $z = 340$ m and $z = 420$ m in Fig. 3). A trajectory inspection showed that muons entering LHC dipole yokes were focused towards FASER. These dipoles must bend two opposite-circulating beams in the same direction, therefore the two magnet apertures must have opposite polarity fields.

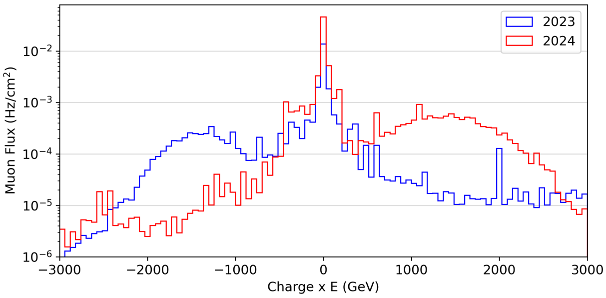

Figure 2: BDSIM predictions for the muon energy spectra at FASER. The high energy bump in the distribution has grown and changed sign between 2023 and 2024.

As evidenced in Fig. 4, the resulting yoke field focused particles towards its center. To reduce high energy FASER backgrounds, muons produced before the LHC dipoles ($z < 270$ m) had to be deflected beyond the 27 cm radius of the dipole yokes. MAD-X matching showed that dipole corrector magnets MCBYH.4L1.B2, MCBYV.A4L1.B2 and MCBYV.B4L1.B2 could feasibly achieve strong enough kicks, whilst preserving the desired proton optics before and beyond these kickers. Elements MCBCH.5L1.B2, MCBCH.7L1.B2, MCBYV.A4L1.B2 and MCBCV.6L1.B2 were also considered, but were rejected due to the low density of muons crossing their strong field regions.

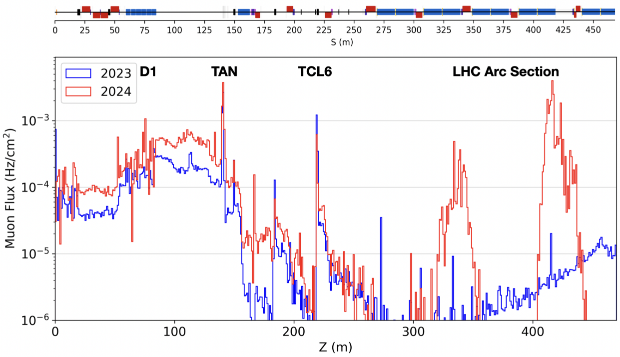

Figure 3: Z origin of muons reaching the FASER sampler in BDSIM. Muons are primarily produced in the TAN and TCL.6L1.B2 elements, where secondary $\pi^{\pm}$ and $K^{\pm}$ decay. A corresponding beam-line diagram is shown above the histogram, with dipoles in blue, quadrupoles in red, and shielding elements in black and gray.

ORBIT CORRECTOR KICKS

Four modes for muon sweeping were investigated after verifying their feasibility with MAD-X. These included positive and negative horizontal kicks by MCBCH.5L1.B2, a joint positive vertical kick by MCBYV.A4L1.B2 and MCBYV.B4L1.B2, and combined negative horizontal and positive vertical kicks (where a horizontal positive kick directs μ^+ towards the center of the machine).

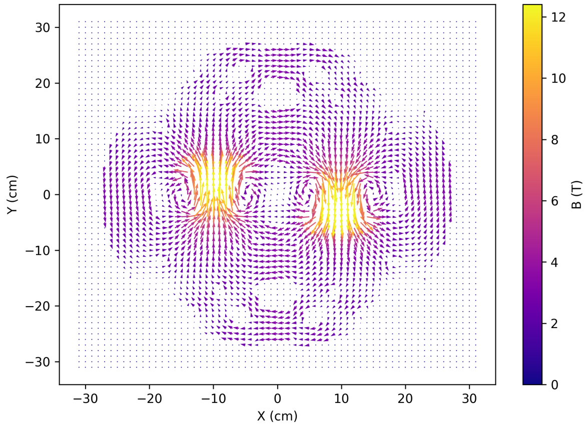

Figure 4: LHC main dipole field map, such that the center of the LHC is in the negative x direction. Each arrow length is proportional to the field strength taken at the tail-end of the arrow. The yoke field extends up to a radius of 30 cm and has a focusing effect for positive particles traveling towards FASER (into the page).

For each mode, MAD-X optics were matched with 2024 operations settings (−160 rad vertical half-crossing with reversed quadrupole polarities near ATLAS). For better comparison with data, BDSIM fluxes were measured through a 10 cm radius circular sampler centred on LOS (approximately matching the size and location of the FASER magnet aperture). The alternative settings were tested during a dedicated experiment (15/10/2024), when the FASER detector recorded background fluxes (see Fig. 5). Backgrounds were minimized with a negative horizontal kick, as confirmed by the experiment. BDSIM showed a 25% reduction, whereas FASER observed a smaller reduction of 10% in comparison to the 2024 nominal optics. BDSIM notably underestimates fluxes in settings that involved horizontal kicks. This trend has not yet been fully understood and warrants further study. Potential causes include generator model uncertainties, biasing methods and tunnel geometry clipping.

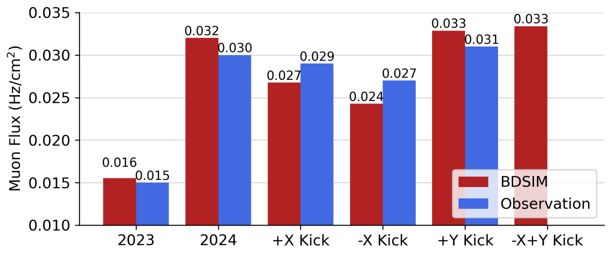

Figure 5: Muon flux comparison between FASER observations and BDSIM predictions, for different trajectory kicks.

ALTERNATIVE IP1 CROSSINGS

Changes to the ATLAS crossing were also examined, such as inverting the vertical crossing angle or shifting to a horizontal mode.

In each case, magnet strengths were obtained by matching optics in MAD-X assuming a half-crossing angle of 160 rad and the removal of the 4th quadrupole near ATLAS. Background fluxes for these configurations were measured by the FASER detector during a dedicated experiment (20/08/2024), as shown in Fig. 6. No favorable setting was found, as background fluxes dramatically increased for all crossing angles considered. Data and simulation showed that the optimal setting was a negative vertical crossing with all 4 quadrupoles nearest to ATLAS operational. The individual impact of the TCL.6L1.B2 half-gap on the muon flux at FASER has not yet been assessed.

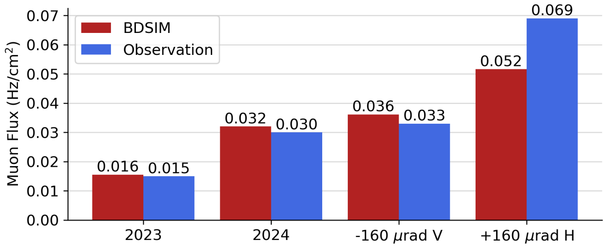

Figure 6: Muon flux comparison between FASER observations and BDSIM predictions, for different collision half-crossing angles.

CONCLUSION

BDSIM was used to find favorable machine settings for forward experiments near ATLAS. Within the extent of the study, the most optimal mode was found to be a negative horizontal muon sweep induced by orbit corrector MCBCH.5L1.B2. The projected flux was reduced by 25% in comparison to 2024 settings. However, measurements during dedicated experiments showed that, in reality, the flux reduction was approximately 10%. Changing the positive vertical crossing angle, without flipping the triplet polarity, showed no benefits in simulation or data. Results were presented to the LHC Backgrounds Group and LHC Programme Coordination, where it was decided to revert back to 2023 optics for ATLAS and instead reverse the polarity in CMS. The decision was primarily taken by prioritizing radiation safety and due to further background studies potentially exceeding time constraints. Nevertheless, this work served as a benchmark for future machine configuration studies and demonstrated the utility of BDSIM for such studies.

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