MONTE-CARLO SIMULATIONS OF BEAMLINE-INDUCED MUON BACKGROUNDS FOR THE SHiP EXPERIMENT

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Abstract

The Search for Hidden Particles (SHiP) experiment at the CERN SPS requires excellent control of muon backgrounds produced upstream of the detector. We present a first Monte-Carlo estimate of beamline-induced sources of muons from proton transport through the P42 beamline to the Beam Dump Facility (BDF) target. A detailed Beam Delivery Simulation (BDSIM) model is used to evaluate muon fluxes at a plane upstream of the BDF target complex, with particle rates and momentum spectra assessed within the transverse acceptance of the SHiP muon shield. In addition, a first mitigation study based on magnetised iron blocks in the approximately 100 m between the last magnet and the target was performed. The results provide input for the on-going optimisation of the P42 beamline design for SHiP.

INTRODUCTION

The SHiP (Search for Hidden Particles) experiment is an upcoming fixed-target facility at the CERN SPS aimed at probing physics beyond the Standard Model through the production and decay of feebly interacting particles [1–4]. The facility is designed to accumulate 4×10^{19} protons on target per year using the SPS 400 GeV/c proton beam [2, 5]. In current SHiP operating scenarios, this corresponds to slow-extracted 1 s spills of approximately 4×10^{13} protons, making beam-loss control along P42 a central design requirement [6, 7, 9, 10].

Delivering such beam intensities requires significant upgrades to the SPS North Area beam delivery chain for the future Beam Dump Facility (BDF) serving SHiP [4]. In particular, the P42 beamline, which transports the protons to the ECN3 cavern that will house the SHiP experiment, is being studied and upgraded in the context of CERN's High-Intensity ECN3 (HI-ECN3) project to transport such high-intensity proton beams while minimising losses and radiation levels [6, 8, 11].

SHiP is a beam-dump experiment in which the primary proton beam is absorbed in a massive target. Ref. [12] provides an overview of the full BDF/SHiP facility layout, including the target complex, muon shield, and detector region. This heavily shielded setup efficiently suppresses particles produced at the target, including off-axis hadrons. Muons, on the other hand, are far more penetrating at higher energies and can still traverse the shielding in large numbers, making them a particularly severe background source. SHiP therefore relies on an active magnetic muon shield to sweep target-produced muons away from the spectrometer acceptance [13, 14]. However, muons originating from upstream beamline interactions are not the primary design criterion of that shield and may enter the experimental acceptance from off-axis trajectories. Understanding beamline-induced contributions is therefore essential for validating the beam delivery design and assessing possible mitigation measures.

In this paper, we present the first Monte Carlo estimate of beamline-induced particle fluxes upstream of the BDF target, based on a detailed BDSIM model of the future P42 beamline for BDF/SHiP. The study quantifies the muon flux entering the target-complex region and provides a first evaluation of upstream mitigation using dedicated magnetised iron blocks.

BEAMLINE MODEL

The simulated beamline model ranges from the T4 target region to the BDF target complex, corresponding to 1 km of beam transport. The model used in this study corresponds to the latest design for the new P42 line. It is aimed at minimising beam losses, reducing beamline-induced backgrounds, and maximising proton transmission to the SHiP target.

The beam bypasses the T4 target, which is normally used for secondary beam generation, and enters the P42 beamline. The model includes the T4 target section including beam intercepting instrumentation matching into a FODO section with a new dedicated collimation system. This section runs parallel to the M2 muon beamline for 420 m and then is bent by 54 mrad into a separate tunnel towards the ECN3 cavern, where the SHiP experiment will be located. The final section will use a final focus scheme to prepare a beam size of $\sigma_{x,y} = 16$ mm at the BDF target and a series of four dipoles, included with time-dependent fields in the simulation, which sweep the beam in a circular pattern on the target at 4 Hz to spread the deposited energy over a larger area.

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Approximately 50 beamline magnets, together with the relevant beam intercepting devices, are included using detailed geometries and magnetic field maps generated with `eadevices`, a Python package for Experimental Area beamline studies with BDSIM/Geant4. Detailed aperture and material descriptions are used in the regions closest to the beam axis, where they are most important for realistic loss and background predictions. This provides a detailed but maintainable model across successive design iterations. The beamline vacuum level is assumed to be 10^{-3} mbar, consistent with present P42 primary-vacuum operation and used as a realistic baseline for residual-gas background estimates [6]. The main sections discussed above are indicated in the beam optics overview in Figure 1.

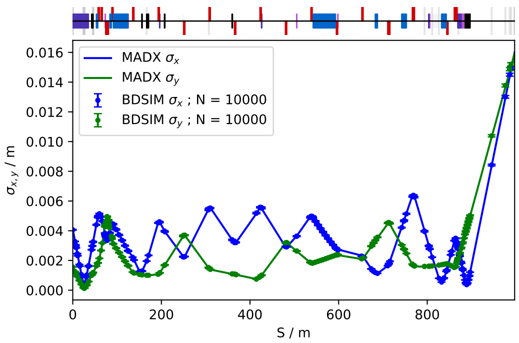

Figure 1: Comparison of the horizontal and vertical beam envelopes along the P42 beamline obtained from the detailed BDSIM model and the corresponding MAD-X optics model. The good agreement confirms the consistency of the Monte-Carlo beamline implementation with the reference optics.

SIMULATION SETUP

The beam transport and particle interactions were simulated with BDSIM (v1.7.7) [15], which combines accelerator tracking with Geant4 (v10.7.2.3) particle-matter interactions [16–18]. The simulation assumes slow extraction of 400 GeV protons with a momentum sweep from 399.7–400.3 GeV/c over a 1 s spill. A total of 1×10^7 primary protons were simulated and a kinetic-energy threshold of 10 GeV was applied to secondary particles in order to focus the simulation on the energy range most relevant. Muons with momenta lower than this are expected to be largely absorbed by the dense shielding of the BDF target complex.

To efficiently sample rare muon-producing processes, several variance reduction techniques were employed: proton inelastic cross-sections in the vacuum pipe were enhanced by a factor 5×10^5, pion decay probabilities were increased by a factor 10, and muon splitting with a factor 10 was applied by resampling muon-producing decays with appropriate statistical weights. These biasing techniques are implemented in BDSIM for the efficient simulation of rare processes such as beam-gas interactions [19]. All quoted uncertainties in this paper are statistical only and reflect the weighted event sample after biasing.

Particle fluxes were recorded at a plane located 8 m upstream of the BDF target. The results show the beamline-induced muon background entering the target-complex region rather than a full detector-background prediction. The simulation includes interactions along the full P42 beamline, including beam-gas interactions as well as interactions with apertures, collimators, and other material close to the beam. A $10 \times 10\,\mathrm{m}^2$ area was used to study the particle distribution at this plane with all kinematic variables. The magnetic muon shield has the potential to redirect off-axis muons that would miss SHiP towards the detector. Thus, the central $4 \times 4\,\mathrm{m}^2$ region corresponding to the lateral muon-shield acceptance, excluding the central area occupied by the BDF target, might be particularly sensitive and was used to evaluate particle spectra.

BEAMLINE-INDUCED MUON BACKGROUNDS AT THE BDF

Figure 2 shows the transverse distributions of muon rates at the plane upstream of the BDF target complex. The highest rates are observed close to the beam centre, reaching local peak values of about $55\,\mathrm{Hz\,cm^{-2}}$ for muons during a 1 s spill of 4×10^{13} protons. The muon rates decrease steeply with the transverse distance from the beam axis, as summarised in Table 1. The drop is most pronounced close to the beam centre, after which the decrease becomes more gradual at larger offsets. Both muon charges follow a very similar radial trend, indicating that the beam-induced muon background is strongly concentrated around the axis and falls off significantly towards the outer acceptance region.

Figure 3 shows the muon momentum spectra within the transverse SHiP muon-shield acceptance. The spectra rise strongly towards lower momentum within the considered energy range above the applied threshold. Relative to 10 GeV/c, the flux at 50, 100 and 200 GeV/c is suppressed by about two, three, and four orders of magnitude, respectively. The sharp cut-off at 10 GeV/c is a consequence of the kinetic-energy threshold applied in the simulation.

Table 1: Muon rates as a function of transverse position x along $y = 0$ m (beam centre).

x in m	μ^+-rate in $\mathrm{Hz\,cm^{-2}}$	μ^--rate in $\mathrm{Hz\,cm^{-2}}$
0.00	29.68 ± 0.78	24.86 ± 0.65
1.00	1.99 ± 0.17	1.31 ± 0.10
2.00	0.73 ± 0.11	0.72 ± 0.12
3.00	0.38 ± 0.06	0.39 ± 0.07

MUON MITIGATION USING MAGNETISED IRON BLOCKS

A mitigation study was performed using six magnetised iron blocks (MIBs) placed after the dilution system with a similar design as the ones currently being used in the CERN M2 beamline. Each block is 1.6 m long and generates a toroidal magnetic field of up to 1.6 T within the iron. The MIB yoke has an overall transverse size of $1.6 \times 1.6\,\mathrm{m}^2$, with a centred $20 \times 20\,\mathrm{cm}^2$ square aperture. The six blocks are installed within 15 m downstream of the dilution system and end about 100 m upstream of the BDF target.

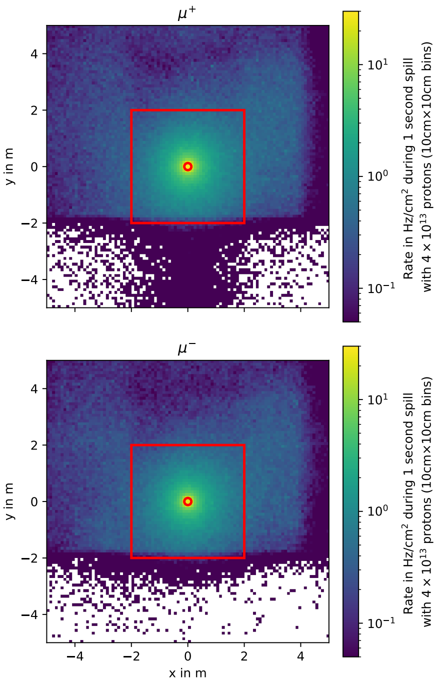

Figure 2: μ^+ and μ^- rate distributions at a plane located about 8 m upstream of the BDF target for a 1 s spill of 4×10^{13} protons, beam direction out of the page. The transverse sizes of the BDF target and SHiP muon shield are indicated in red. The surrounding tunnel and shielding geometry shape the transverse extent of the particle distribution.

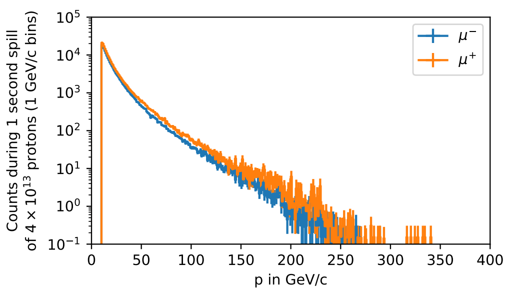

Figure 3: Muon momentum spectra per 1 s spill of 4×10^{13} protons in the SHiP muon-shield acceptance, defined as a $4 \times 4\,\mathrm{m}^2$ region at a plane 8 m upstream of the BDF target, excluding the central 12.5 cm target radius.

The toroidal field bends positive muons outward from the beam axis and negative muons inward (see Figure 4). Due to the 100 m drift between the last MIB and the BDF target, both bending directions can either decrease or increase the muon flux entering the BDF acceptance, depending on the muon's initial momentum and direction. For example, a 250 GeV/c muon traversing the full MIB system is deflected by 18 mrad, which corresponds to a transverse displacement of roughly 1.8 m after 100 m. This is sufficient to move a sizeable fraction of muons out of the muon shield acceptance. In addition, the iron provides passive shielding and can reduce the muon momentum by up to 15 GeV/c. Muons

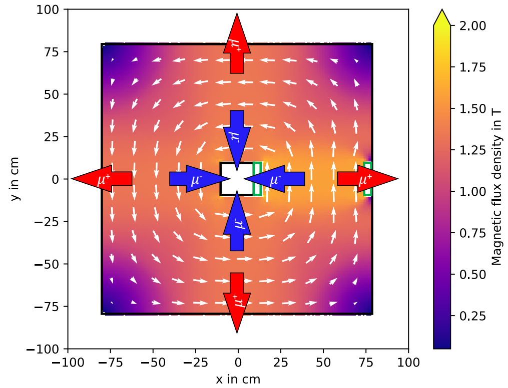

Figure 4: Toroidal magnetic field of a MIB redirecting traversing μ^+ away from and μ^- towards the beam centre.

passing close to the beam axis or laterally outside the transverse coverage of the MIB system are not affected.

For events in which the primary proton interacts upstream of the end of the MIB section and produces secondary particles, a comparison between simulations with and without MIBs shows that the μ^+ and μ^- flux within the muon shield acceptance region is reduced by (32 ± 1) % and (28 ± 1) %, respectively. Future studies will optimise the position, aperture, and transverse coverage of the MIB system to maximise its impact on the beamline-induced muon background.

CONCLUSION

A Monte-Carlo study of beamline-induced muon sources relevant for the SHiP experiment has been carried out using a detailed BDSIM model of the future P42 beamline. The results provide a first estimate of the magnitude and transverse distribution of the muon fluxes upstream of the BDF target complex, with the highest rates concentrated near the beam axis and a rapid fall-off with distance. Within the transverse acceptance of the SHiP muon shield, the muon spectrum is dominated by the low-momentum component.

A first mitigation study with generic magnetised iron blocks shows that upstream magnetic deflection can suppress the flux of muons originating upstream of the MIBs in the muon shield acceptance region by (32 ± 1) % for μ^+ and (28 ± 1) % for μ^- for the configuration studied. This initial layout mainly affects muons passing through the transverse region covered by the MIBs, motivating further optimisation of their position, aperture, and transverse coverage.

These results provide an initial estimate of beamline-induced source terms upstream of the BDF target and support ongoing optimisation of the P42 beamline design. Future work will extend the simulation to include the full BDF target complex, active muon shield, and detector geometry in order to evaluate the transport and residual impact of these backgrounds at detector level. Based on this, the MIB design will be further optimised and the need for additional mitigation systems, such as movable magnetic collimators will be evaluated.

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