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MUON BACKGROUND STUDIES FOR BEAM DUMP OPERATION OF THE K12 BEAM LINE AT CERN

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Abstract

In the scope of the Physics Beyond Colliders study at CERN a future operation of the NA62 experiment in beam dump mode is discussed, enabling the search for dark sector particles, e.g. heavy neutral leptons, dark photons and axions. For this purpose, the 400 GeV/c primary proton beam, extracted from the SPS, will be dumped on a massive dump collimator located in the front end of the K12 beam line. Muons originating from interactions and decays form a potential background for this kind of experiment. To reduce this background, magnetic sweeping within the beam line is employed. In this contribution, the muon production and transport has been investigated with the simulation framework G4beamline. The high computational expense of the muon production has been reduced by implementing sampling methods and parametrizations to estimate the amount of high-energy muons and efficiently study optimizations of the magnetic field configuration. These methods have been benchmarked with measured data, showing a good qualitative agreement. Finally, first studies to reduce the muon background by adapting the magnetic field configuration are presented, promising a potential background reduction by a factor four.

INTRODUCTION

The North Area at the Super Proton Synchrotron (SPS) at CERN has a long history of fixed target experiments and R&D studies. Extracted from the SPS, a 400 GeV/c proton beam is directed via transfer lines to two experimental halls (EHN1, EHN2) and an underground cavern (ECN3) located at the CERN Prévessin site. In ECN3, a high-intensity secondary hadron beam, that has been created at a beryllium target, is transported via the K12 beam line towards the NA62 experiment [1]. This experiment aims to measure the branching ratio of the very rare decay $K^+ \rightarrow \pi^+ \nu \bar{\nu}$. First results of this operation have been presented recently [2]. Besides the main measurement program, a future proposal for NA62 suggests the search for dark sector particles such as heavy neutral leptons, dark photons and axions in "dedicated dump runs" [3]. For this purpose, the beryllium target will be removed and the primary proton beam will be dumped on a 3.2 m long massive dump collimator (TAX) in order to create the hypothetical dark sector particles. The decay of these particles into Standard Model particles, e.g. muons in the final state, might be observable by the NA62 experiment. The implementation of this proposal is studied by the the Conventional Beams Working Group (CBWG) within the Physics Beyond Colliders (PBC) framework. Muons directly produced in the primary interactions within the TAX pose an crucial background for this kind of experiment, e.g. through random spatiotemporal track combinations of muons and antimuons. Studies to understand the trajectories of this muon background are essential to further optimize the magnetic sweeping of the K12 beam line, when operated in beam dump mode. To investigate and reduce this muon background, the optimisation of the magnetic sweeping along the K12 beam line is performed. Monte Carlo studies based on the program G4beamline [4] have been combined with analytical parametrisations of the muon distributions to reduce the computational demands. In this contribution, benchmarking results with recorded data as well as first results from the optimization studies are shown.

THE K12 BEAM LINE MODEL

The simulation of production and transport of the muon background is computationally highly expensive and requires the precise knowledge of the magnetic field maps in the entire K12 beam line. A G4beamline model, including a simplified model of the NA62 experiment, has been developed to investigate the particle production, transport and decay of the particles in the beam line. It is illustrated in Fig. 1. The 400 GeV/c protons with a nominal intensity of 3×10^{12} protons per burst impinge on a 400 mm-long beryllium target (T10), which corresponds to about one nuclear

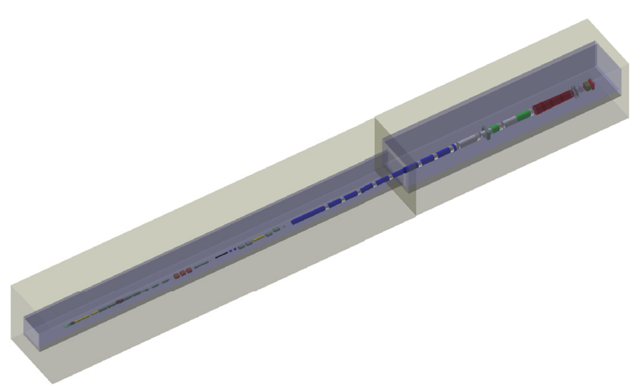

Figure 1: The G4Beamline model of the K12 beam line and NA62 experiment.

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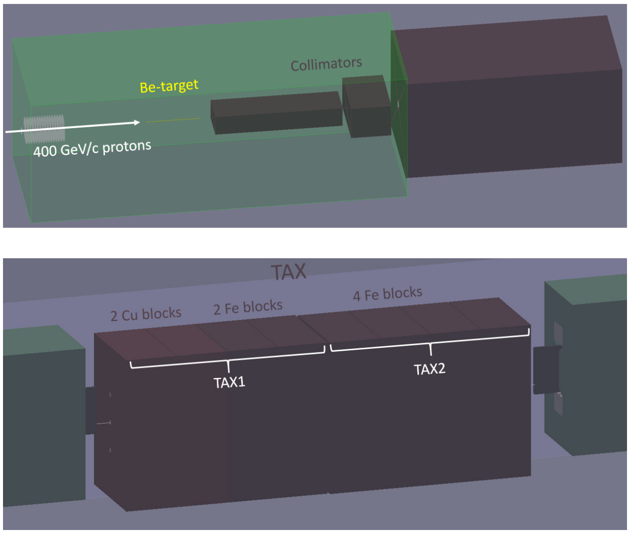

Figure 2: Model of the T10 target region (up) and TAX (down). The 400 GeV/c proton beam enters from the left in the upper figure. The green volume illustrates an air volume, in which an upstream monitor, the T10 target and two collimators are located. The TAX consists of 2 copper and 2+4 iron blocks with bores for the beam passage.

interaction length. The target is followed by a set of collimators and a small-aperture, radiation-hard quadrupole triplet defining the maximum acceptance of the secondary beam, mostly consisting of pions, protons and kaons. To maximize the number of signal events in the fiducial decay volume of the NA62 experiment, the beam line optics is tuned for a transfer of positively charged particles with a momentum of 75 GeV/c [5]. Behind the quadrupole triplet, a momentum selection is performed, mainly by a 3.2 m long massive dump collimator (TAX) centered in a four bend achromat. The model of the target region and the TAX are shown in Fig. 2. The first pair of bends of the achromat induces a vertical deflection to the charged particle beam, which amounts to -110 mm for the 75 GeV/c-beam fraction, allowing it to pass the 1-cm diameter bores in the TAX and being returned to the central axis by the second pair of bends. Other momentum slices, especially the non-interacting primary 400 GeV/c protons, are dumped on the TAX with different vertical offsets, i.e. -20.625 mm for the primary protons. Muons mainly created in pion and kaon decays upstream of the TAX are not stopped and form a halo around the selected hadron beam. Various magnetic elements, i.e. muon sweeping dipole magnets with a field-free region for the hadron beam passage and scraping magnets with a toroidal field around the axis are employed to reduce this halo before the beam enters the decay volume of the NA62 experiment at about 102 m downstream the production target. The detailed study of muon halo requires the simulation of the magnetic fields within the magnet apertures but also in the iron yokes in the entire beam line. For the current version of the model these field distributions have been extracted from existing measurements and simulations previously implemented in the simulation tool HALO [6]. Within the experiment, several detector components are employed to identify the particles leaving the decay volume, i.e. four straw spectrometer stations for track reconstruction and momentum identification, two charged particle hodoscopes and a muon veto system at the end of the line. A more detailed description of the beam line and the various sub-detectors can be found in Ref. [1].

Nominal Configuration

The current implementation of geometry has been validated with a simulation based on nominal beam optics for the current NA62 operation. Figure 3 illustrates the distribution of the pion momentum in front of the decay volume. It is centered around 75 GeV/c with a momentum spread of 1.15 %. The latter can be further adjusted by additional momentum-selection collimators within the beam line. Similar shapes are observed for kaons and protons. The corresponding particle rates (Table 1) obtained with the FTFP_BERT physics list of Geant4 were compared to the reference values estimated in Ref. [1] using the HALO software together with the Atherton formula for particle production [7]. Both estimates yield pion and kaon rates in very good agreement within a few percent, while a slightly enhanced proton rate

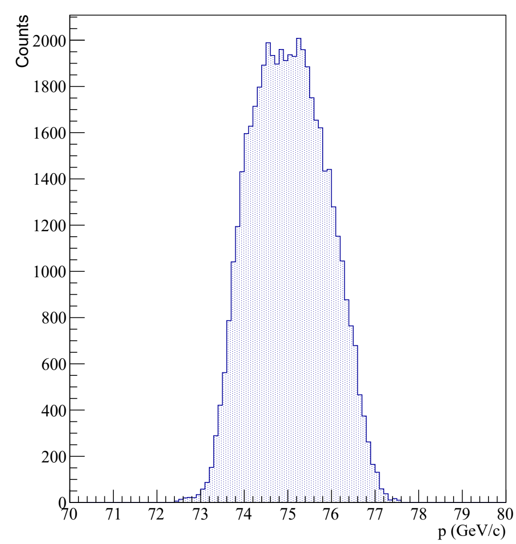

Figure 3: Simulated pion momentum distribution at z = 102 m for 10^8 protons on target. The nominal beam is centered around 75 GeV/c with a momentum spread of 1.15%.

Table 1: Fluxes at 102 m After Target per 1.1×10^{12} Incident Protons per Second

Particle	Reference [1] (MHz)	G4beamline (MHz)
Pions	525	547
Protons	173	308
Kaons	45	45

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is observed in the Geant4 based simulation with respect to the reference estimate.

Beam Dump Configuration

In dedicated beam dump configuration, the beryllium target is removed from the beam line to reduce the muon halo background originating from the production and decay of pions and kaons upstream of the TAX. The residual material budget in the target region is reduced to about 1% compared to the nominal setup including the beryllium target [8]. The remaining material is modeled by the vacuum windows, beam instrumentation elements and the surrounding air in the target region, as shown in Fig. 2. After passing this region, the primary proton beam passes the quadrupole triplet and is dumped directly on the TAX. The two independently moveable parts of the TAX (TAX1+TAX2) are vertically displaced with respect to each other to prevent the passage for any particle coming from the upstream direction of the beam line. The muon background investigated in this study is composed from the contributions of upstream decays and the production within the TAX.

MUON SIMULATION ALGORITHMS

The simulated muon spectrum and spatial distribution obtained directly after the TAX is depicted in Fig. 4. It shows the concentration around the proton impact point, that is vertically shifted due to the first two bends of the first achromat. The radial symmetry is slightly broken due to the existing tungsten inserts around the bores, which are located above and below the proton impact point. Furthermore, a rate decrease with increasing momentum of several orders of magnitude is observable, drastically limiting the statistics

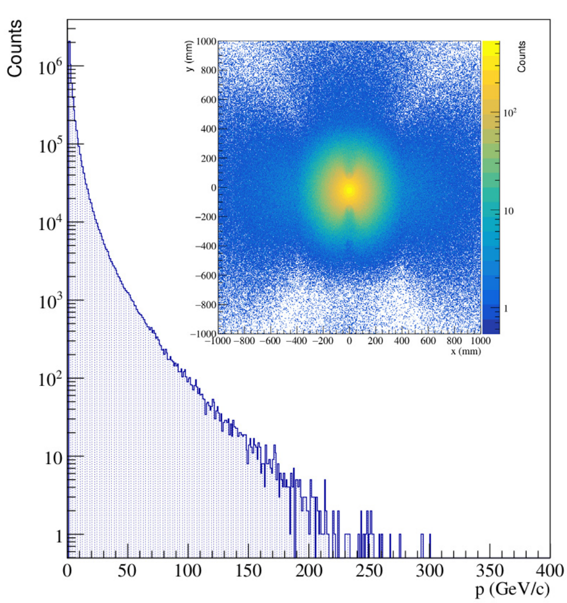

Figure 4: Simulated muon spatial distribution and spectrum after the TAX obtained for 10^9 incident protons.

for high-energy muons. Since the dump simulation of the 400 GeV/c protons is computationally highly expensive (currently ~10 protons per second for an illustrated sample of 10^9 incident protons), an increase of the number of incident protons for the study of multiple magnetic configurations is not reasonable. Instead, two methods based on the recorded particle information directly after the TAX have been employed to reduce the computational effort and increase the statistics for higher momenta.

Method 1: Sampling

In the first method, the recorded particles behind the TAX are binned according to position, momentum and type. From the number of particles in each multi-dimensional bin a probability distribution is deduced to generate new and individually-sized samples representing the particle distribution after the TAX. These samples are employed to study the particle transport starting after the TAX removing the computationally expensive simulations of the interacting protons in the TAX. The limiting factor of this method is the underlying particle sample. Due to the low statistics for higher momenta as shown in Fig. 4, the calculated probability distribution is not representing the full phase-space for these particles. Thus, certain momenta appear only at similar locations or are entirely missing.

Method 2: Parametrization

A second method has been implemented in order to reduce the variance for higher momenta. For that purpose, the muons and antimuons created in and recorded directly after the TAX are first sorted in bins of different longitudinal momenta. The horizontal and vertical phase space of each bin can be parametrized by a two dimensional Gaussian distributions in each bin, respectively. This is shown exemplary in Fig. 5 for a longitudinal momentum of $p_z = 25\,\mathrm{GeV}/c$ and the horizontal phase space. The evolution of the parameters describing the Gaussian distributions can be illustrated with respect to the longitudinal momentum, as depicted exemplary for the horizontal width of the antimuon distribution in Fig. 5. This evolution is further parametrized by analytical functions up to a longitudinal momentum of 80 GeV/c and extrapolated for momenta up to 350 GeV/c to estimate the high-momenta muon distribution, where the statistics of the underlying sample is limited. To additionally increase the statistics of the high-momenta muons, the new samples are created uniformly distributed in momentum, but a weighting factor representing the probability of appearance is assigned. This allows for a re-normalization of the simulated muons recorded in the NA62 detectors, after the tracking through the K12 beam line elements downstream of the TAX is performed. Bases on this method, samples representing the major contributions of the muon background are created.

Comparison

To validate the algorithms, the generated samples have been compared with each other. Figure 6 depicts the momentum spectrum and vertical distribution of antimuons

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directly after the TAX obtained with both methods and with similar number of particles in the samples. The momentum spectrum is very well represented in both methods, but for the second method the variations at higher momenta could be drastically reduced. Simultaneously, also the vertical distribution, the core below 200 mm is in very good agreement between both methods, while larger relative differences are only observable at bigger distances. A similar effect is observable in the horizontal distribution. Overall, a satisfactory agreement between both methods could be shown. Due to the reduced computational expenses and a better representation of the high-momenta muons, the second method is used in the muon background studies described in the following.

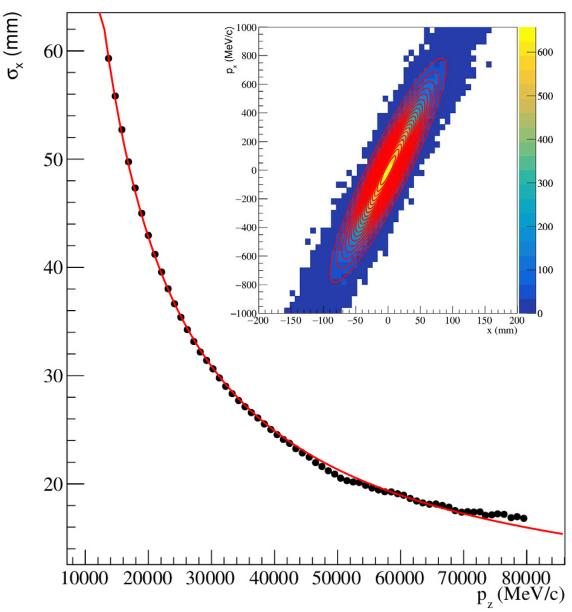

Figure 5: Parametrization of the transversal width σ_x for different longitudinal momenta p_z.

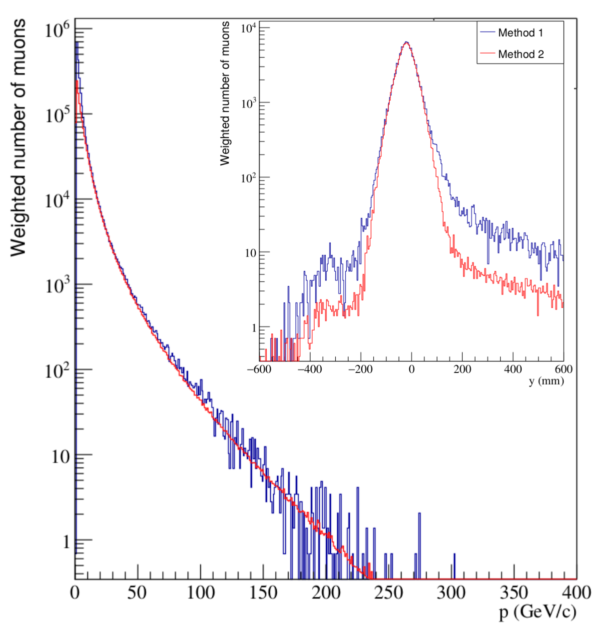

Figure 6: Simulated antimuon momentum spectrum and vertical distribution after the TAX for both methods. The distributions are normalized to 10^9 incident protons.

COMPARISON TO MEASURED RATES

Based on the previously described method, a comparison to measured data from the NA62 experiment has been performed. For this purpose, recorded data taken in short runs in beam dump mode has been used. The trigger selection

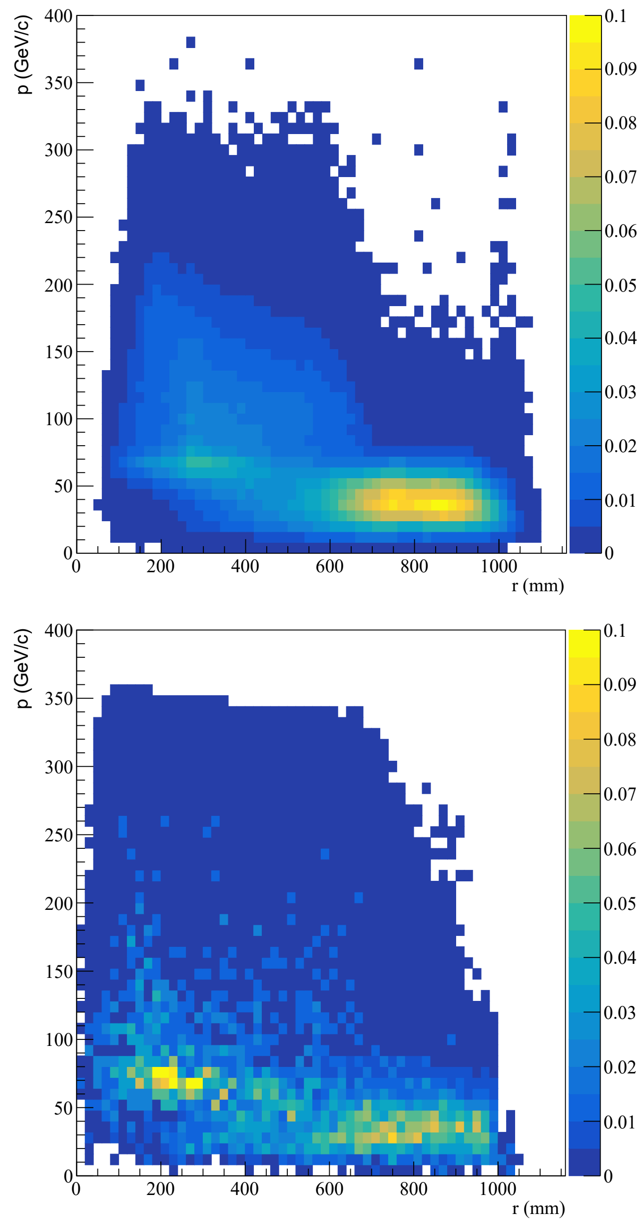

Figure 7: Comparison of measured (up) and simulated distributions (down) of positively charged muons in beam dump configuration reconstructed at 180 m, close to the first straw chamber of NA62. The color scale represents the number of tracks per 10^9 incident protons and bin. The measured data is downscaled by a factor five.

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required at least one hit in the charged particle hodoscope (CHOD) of NA62. The charged particle tracks were reconstructed using the information of the straw detector chambers, yielding the momentum, the charge, and the position at the first straw chamber. These information were used to compare the spatial distributions and spectra of positive and negative tracks between recorded data and simulation. Since the simulation currently focuses on the study of muons, a time-associated hit in the muon veto detector MUV3 was requested for the reconstructed tracks. Figure 7 depicts the radius $r = \sqrt{x^2 + y^2}$ and momentum of the positive charged tracks obtained in measurement and simulation at 180 m, close the first straw chamber of NA62. Both distributions feature two accumulations in similar regions. In separate studies of the muon distribution originating in upstream decays, the accumulation at about 75 GeV/c and a radius of 250 mm could be associated to the muon production before the TAX, while the large accumulation at lower momenta and larger radii at about 800 mm originates from processes occuring within the TAX. The good qualitative agreement validates the implementation of the magnetic configuration in the G4beamline model. Quantitatively, the calculated muon rates in the data sample are a factor five larger than observed in the present simulation, showing an enhanced contribution from muons originating from the TAX region in the recorded data. This excess is investigated in present studies.

FIRST RESULTS OF OPTIMIZATION STUDIES

To further reduce the muon background in beam dump operation, optimization studies of the magnetic layout of the beam line have been performed. For this purpose, the muon distribution at the MUV3 detector at the end of the NA62 experiment $z \approx 247$ m has been investigated. The simulated muon momentum spectrum at the MUV3 detector plane using this configuration is illustrated in Fig. 8. A similar spectrum for muons and antimuons is observed in the present nominal beam dump configuration. The extrapolation boundary for higher momenta leads to the hard cut at 350 GeV/c. Figure 9 depicts the spatial distribution on the MUV3 detector plane in initial configuration.

The entire sensitive region of the MUV3 detector is populated by muons. The accumulation in the vicinity of the beam pipe is dominated by a contribution of muons with a slightly lower momentum than 75 GeV/c. This is related to the beam optics optimization for 75 GeV/c in the nominal configuration, leading to a favored transport of positively charged muons in this momentum region. Energy losses slightly reduce the final momentum by a few GeV/c.

First studies aim for a reduction of the muon background at the MUV3 plane applying only a minimal amount of changes to the existing beam line. To eliminate the 75 GeV/c-component observed from the muons in upstream decays, the first quadrupole triplet is optimized for the transport of the 400 GeV/c protons and the quadrupoles downstream of

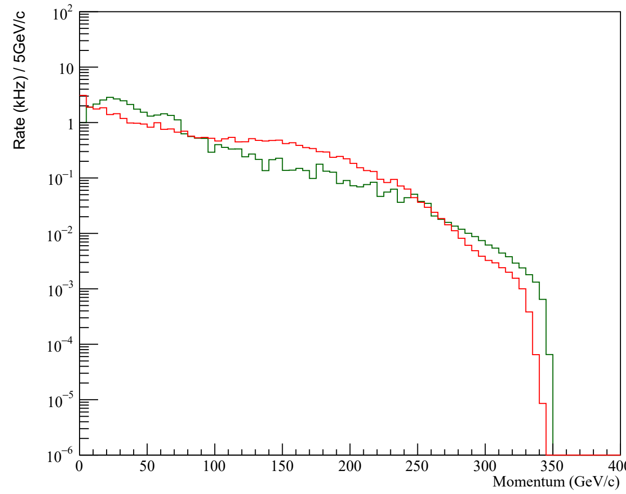

Figure 8: Simulated momentum spectrum of muons (red) and antimuons (green) at the MUV3 detector for the initial configuration in beam dump mode. The rate is normalized to 1.1×10^{12} protons per eff. second. A cutoff at 350 GeV/c is applied.

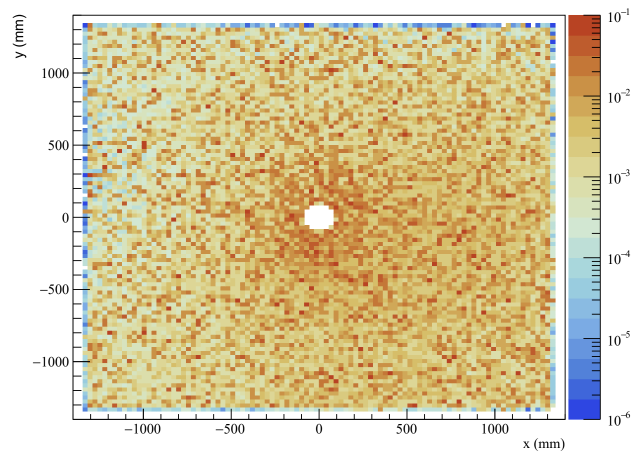

Figure 9: Simulated muon spatial distribution at the MUV3 detector for the initial configuration in beam dump mode. The color scale represents the number of hits per 10^9 incident protons and bin.

the TAX are turned off. Additionally, a deflection close to the production location in the TAX is preferable to further improve the muon sweeping. For that purpose, the magnetic setup of the first achromat surrounding the TAX is investigated. The first two bending magnets are turned off, letting the proton beam impinge centrally on the TAX. The magnetic field of the second two dipoles is scanned to study the influence on the remaining muon rate with respect to the initial nominal configuration in beam dump mode. The results are shown in Fig. 10. The highest rate is observed for disabled sweeping within the first achromat. In this case, the muon flux is increased by a factor five. Operating the magnets with same strengths but opposite sign shows a general enhancement of the muon rates, since the angular deflection of the consecutive magnets cancels each other. For same sign, the muon rates are reduced by increasing the

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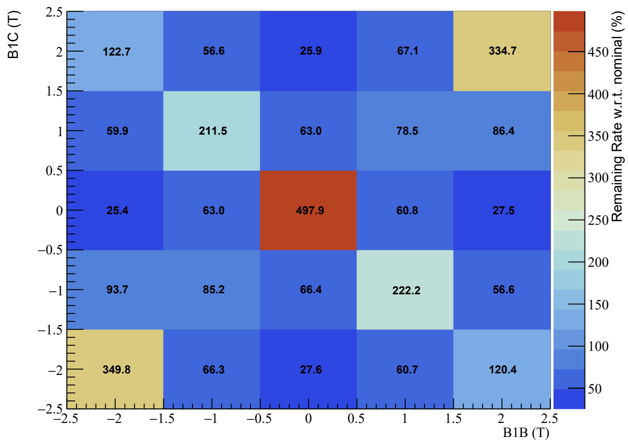

Figure 10: Remaining muon rate with respect to the initial configuration in beam dump mode. The two bending magnets after the TAX (B1B,B1C) have been scanned in steps of 1 T field strength in the center of the gap.

field strengths up to a certain point. At this point, the deflection for low momenta muons in the first bend is sufficiently strong to let them reach the iron yokes of the second bend. Thus, the return field of the second bend deflects them back towards the sensitive part of the muon veto detector. This significantly enhances the rate due to the large amount of low-momenta muons. For maximum field of the the first magnet at -1.82 T, an optimum for the second magnet is found at about -0.3 T. The spatial distribution for this particular setting is depicted in Fig. 11.

The accumulation close to the beam pipe disappeared due to the change of the magnetic configuration. The observable horizontal deflection arises from the three muon sweepers with vertical magnetic field, while the left-right asymmetry is related to the optimized sweeping of positive muons in the nominal setup using a muon scraper with toroidal field that is located downstream in the K12 beam line. Overall, the total simulated muon flux is reduced by a factor four in this setting compared to the nominal dump configuration. Taking

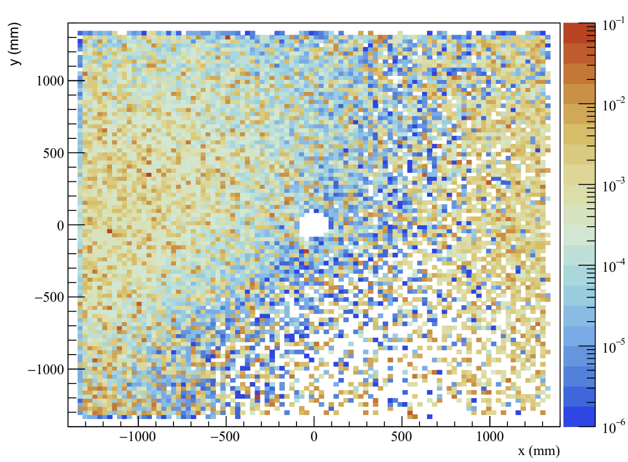

Figure 11: Simulated muon spatial distribution at the MUV3 detector for the optimized configuration of the first achromat. The color scale represents the number of hits per 10^9 incident protons and bin.

only muons above a threshold of 15 GeV$/c$ into account, the reduction can be further maximized by operating the two last bending magnets of the first achromat at their maximum field of -1.82 T. In this configuration the simulated muon rate above 15 GeV$/c$ is reduced by a factor 20, but the rate of low-momenta muons is enhanced simultaneously, as explained above.

CONCLUSION & OUTLOOK

The study of the muon background in beam dump operation of the NA62 experiment required the development of a new model of the K12 beam line that transports the beam to this experiment. Using the available magnetic field maps, this model has been implemented in the G4beamline software framework, which allows for investigation of the production, transport and decay of particles. The production of the initial muon population created by the dumped 400 GeV$/c$ proton beam is strongly suppressed and hence requires a substantial amount of computational power. Consequently, methods reducing the computational time by estimates of the distribution at higher momenta have been successfully implemented. Benchmarking of the simulated muon background distribution with already measured data showed a promising qualitative agreement. A further reduction by a factor four could be achieved by small changes to the beam line, mainly by the optimization of the first two bending magnets behind the TAX. These results will be further used to quantify the benefit of bigger upgrades of the K12 beam line for an operation of the NA62 experiment in beam dump configuration.

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