BACKGROUND MITIGATION CONCEPTS FOR SUPER-NaNu*

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Abstract

Super-NaNu is a proposed neutrino experiment as part of the SHADOWS proposal for the high intensity facility ECN3 in CERN's North Area. It aims to detect neutrino interactions downstream of a beam-dump that is exposed to a 400 GeV/c high intensity proton beam from the SPS. The experiment would have run in parallel to the HIKE and SHADOWS experiments, taking data with an emulsion detector. Simulations show that various types of muon backgrounds pose the most stringent constraint on NaNu operation. As muons will leave tracks in the emulsion detector, their flux at the detector location is directly related to the required frequency of emulation exchange and therefore with the cost and operability of the experiment. Finding ways of mitigating the muon background as much as possible is therefore essential. In this paper, we present a possible mitigation strategy for muon backgrounds.

THE NANU EXPERIMENT

From all the particles in the Standard Model (SM) the tau neutrino is still the one that is least understood. So far the tau anti-neutrino remains the only SM-particle that has never been experimentally confirmed and the origin of the neutrino masses also has yet to be unveiled. Several ideas were developed to address this issue by using particle accelerators and are pursued by collaborations such as DUNE [1], FASER [2] or SND [3]. For all of them the Neutrino Platform hosted in CERN's North Area [4] plays a crucial role in developing and testing the necessary detector technologies.

While FASER and SND focus on studying neutrinos from particle collisions at the LHC, fixed-target experiments with their high interaction rate will be complementary to their search by creating a huge amount of tau and anti-tau neutrinos from the $D_S^{\pm} \rightarrow \tau \nu_\tau$ decay. To generate vast numbers of $D_S^{\pm}$-mesons high energy collisions are needed and the 400 GeV/c proton beam from the SPS that is available in CERN's North Area presents an excellent candidate for it.

The NaNu experiment is a proposed beam-dump experiment [5] that wants to take on this task. Once the NA62 experiment finishes its measurement at the end of CERN's Run 3, its experimental complex ECN3 will receive a High-Intensity upgrade [6–8] making it the perfect location for NaNu. Together with the proposed kaon experiment HIKE [9] and the Dark Matter detector of SHADOWS [10], NaNu would share the experimental hall. An alternative proposal to the three experiments already mentioned is the SHiP experiment [11], a detector that specialises on the search for Dark Matter and as well on unraveling neutrino physics. All proposed experiments were studied in detail with the help of the Conventional Beams Working Group [12] and the Physics Beyond Colliders initiative [13]. Both proposed paths can serve the particle physics community by providing a strong and diverse physics program with the next generation of fixed-target experiments.

The setup from the beam-dump onwards can be seen in Fig. 1. The K12 beamline would serve the kaon measurements of HIKE, but the beamline could also be switched to beam-dump mode allowing HIKE and SHADOWS to search for feebly-interacting particles while NaNu studies neutrinos. HIKE would be placed on-axis, while SHADOWS and NaNu would be placed off-axis, alongside the K12 beamline allowing them to be much closer to the beam-dump while still having only moderate muon backgrounds as most muons would be created in forward direction [14].

The NaNu detector design largely resembles that of FASERν [15] which uses an emulsion detector — an interleaved scheme of emulsion films and tungsten plates — to store the information of the particle tracks. With modern reconstruction algorithms of emulsion detectors NaNu can store up to 10^6 tracks per cm^2 before the emulsion films need to be exchanged in one of the possible maximum weekly interventions during user changeovers and Machine Development Sessions. The main driver of the emulsion exchange

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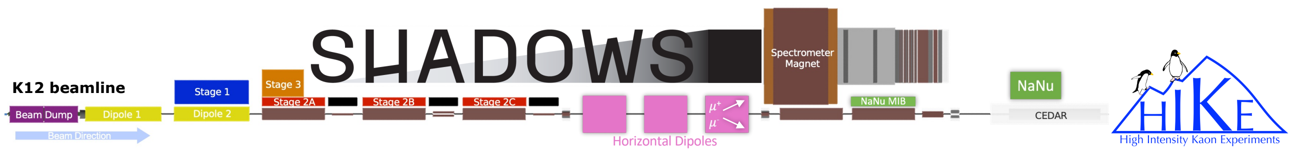

Figure 1: Experiment setup from the beam-dump (purple) downstream (beam direction left to right). The NaNu setup is shown in green and the horizontal dipoles relevant for the muon background are pink.

rate is the muon background as each muon passing through the NaNu detector would leave a track. The neutrino flux and the neutrino energies increase if the detector is moved closer to the beamline, but so is the muon flux. Because of that, for NaNu the detector position was optimised by moving as close to the beam axis as possible without having to change the emulsions more than twice every year to keep the experiment cost effective and the frequency of interventions low.

In the context of the experiment proposals in ECN3, studies were carried out to investigate options for mitigating the off-axis muon background of NaNu in order to move the detector closer to the beam axis without increasing the emulsion exchange rate. As the lower muon rate not only reduces the emulsion exchange rate but also allows for other additional upgrades in the detector design, the proton rate and hence the neutrino flux seen by the detector could be significantly enhanced. Because of that, the experiment playfully calls this option ”Super-NaNu” (hence the title). This paper presents the result of these studies.

By the time of writing this paper, SHiP has been selected for the future of ECN3. Because of that, the muon mitigation studies will be continued in the context of SHiP.

MUON BACKGROUND SUPPRESSION

Discussion of the Muon Background

The vast majority of the muons reaching the NaNu setup originate from proton interactions within the beam-dump. Immediately downstream of the beam-dump the muons are deflected by a vertical sweeping system made of dipole magnets. The muon component that gets deflected off-axis by the return yokes of these dipoles in the direction of the SHADOWS and NaNu setup is then mitigated with the SHADOWS muon sweeping system meaning that this component is successfully eradicated already upstream [16]. However, the muons that have high enough momenta to still stay close to the beam axis will continue to move ahead to a second sweeping system that is dedicated to mitigating the remaining on-axis background for HIKE. As another vertical sweeping system will pose a threat in terms of radiation protection as more radiation would point to the surface, this sweeping system must act in horizontal direction. The setup for this sweeping system has already been optimised and was studied in detail [14, 17].

As these dipole magnets are alongside the tracking system of SHADOWS, the component that is pushed off-axis horizontally does not pose a threat to the SHADOWS experiment anymore, as SHADOWS will discard any signal that does not enter the first tracking station. Nonetheless, as the proposed NaNu detector location is downstream of the SHADOWS detector, NaNu will see this component and in fact simulations show that this component makes up for the majority of the background seen at the NaNu location.

Due to the fact that the horizontal sweeping will push positively charged muons towards NaNu and negatively charged muons to the opposite side, away from the detector, the muon background mainly consists of muons with positive charge as can be seen in Fig. 2.

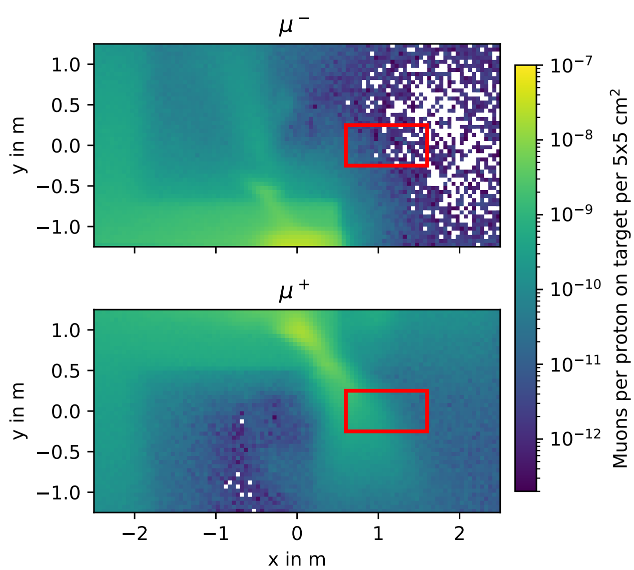

Figure 2: Simulated muon flux at the NaNu detector (red) without the NaNu MIB. Dominant component: μ^+

Mitigation Concept

The obvious solution to the problem for NaNu would be to simply rotate the dipole magnets from horizontal to vertical sweeping. In fact, simulations show that this would reduce the background at the NaNu location by a factor of 45, and would therefore solve the problem entirely. Note that this also shows that the majority of the background is coming from these dipoles. Nevertheless, as this poses a problem for radiation protection [18] and potentially for HIKE as this would result in a redesign of the K12 beamline downstream of the sweeping dipoles, this is not an option.

Instead we propose the installation of a magnetic shielding that consists of magnetised iron blocks (MIBs). MIBs consist of a yoke made of iron that have a coil winded around it that induces a magnetic field inside of the yoke. They are able to mitigate the muon background actively with the magnetic field and passively with the stopping power of the dense materials that they are made of. Because of that, MIBs can serve as a cost effective solution for shielding against muons. A number of them are already installed in the M2 and K12 beamlines of CERN's North Area [19].

To put such a MIB alongside the K12 beamline to mitigate the background for NaNu, integration requirements for installing it in the experimental hall need to be considered such as its location, weight, the space available and the cost. A good location for the MIB was found to be next to the second quadrupole magnet downstream of the horizontal sweeping dipoles as shown in Fig. 1. These considerations lead to the following design limitations:

- The current must be lower than 250 A to match the constraints given by the power converters.
- As the quadrupole must be accessible from the front and the back for maintenance reasons, the length must not exceed 3 m. Also its width is restricted and must not be larger than 40 cm ensure a save passage between the MIB and the SHADOWS detector.
- The beamline is located 1.2 m above the floor, limiting the maximal height of the MIB to 2.4 m if we consider the MIB being symmetrical along the beam axis.
- The weight must not exceed the crane limit of 30 t.

With these limitations in mind it is possible to start the design optimisation of the NaNu MIB.

DESIGN OPTIMISATION

The design of the NaNu MIB is optimal if the effect of the magnetic field and the stopping power maximally reduce the muon background at the NaNu location. As the stopping power only depends on the length of the magnet, which we can fix to the maximum of 3 m, the main focus of the optimisation lies in the magnetic field. With the muon background only consisting of one charge, a figure-0-shaped design is the best choice. As can be seen in Fig. 3 the polarity of the MIB can be chosen so that the magnetic field pushes all particles of positive charge away from the center of the MIB to divert the muons from the detector downstream. The dimensions of this MIB must be optimised.

To facilitate that, a dataset of magnetic fields for figure-0-shaped MIBs was established using the finite-element-method simulation software FEMM [20]. Furthermore, the Geant4-based simulation software BDSIM [21, 22] was used to evaluate the energy-weighted muon flux at the MIB location using the model of the K12 beamline [14, 23] including the variance reduction methods established by NA62 [24]. This muon flux at the MIB location was filtered to only include muons that also hit the NaNu detector. Each field is then combined with the muon distribution to receive a measure of how effective each magnetic field would act on the flux at hand.

To improve the design further, a deep neural network (DNN) was trained to predict the effectiveness of a given MIB design so that not only the magnets in the dataset are covered, but also any possible designs in the parameter space in between The DNN was then plugged into an optimiser to find the best MIB design given the design limitations.

The optimised MIB design can be seen in Fig. 3 and its design parameters can be found in Table 1.

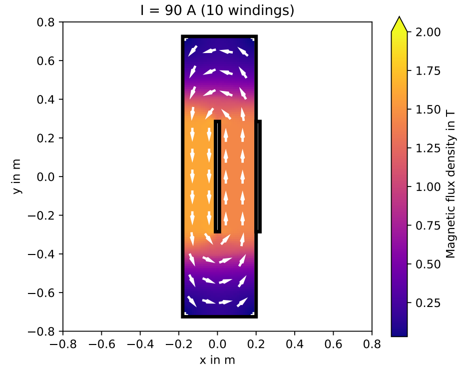

Figure 3: NaNu MIB with optimised design. The beam axis would be at the left.

Table 1: Magnet Specifications

Property	**Value**
yoke (width/height)	36 cm / 145 cm
coil (width/height)	2 cm / 57 cm
left leg	17 cm
length	3.0 m
current	90.0 A
windings	10
weight	14 t

Enhanced Background Mitigation

The optimised NaNu MIB including its magnetic field was then added to the BDSIM model of the setup to evaluate its impact on the muon background. A comparison of the muon background with and without the MIB shows that the MIB can reduce the muon background at the detector location by 55%. This is equivalent to saying that due to the MIB the frequency of emulsion changes can be halved making the experiment more cost effective. If the experiment wants to keep the emulsion change frequency at twice per year, they can now instead choose to move closer to the beam axis and pursue Super-NaNu.

CONCLUSION

The muon background is the main limitation for enhancing the neutrino signal yield at the proposed NaNu experiment. A magnetic muon shield was designed which allows NaNu to reduce the muon background by 55% allowing the experiment to speed up their search for new neutrino physics. The studies will be continued in the context of SHiP.

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