PROCEEDINGS OF SCIENCE

# The BDF/SHiP experiment at the ECN3 high-intensity beam facility at the CERN SPS

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The BDF/SHiP experiment is a general purpose intensity-frontier experiment for the search of feebly interacting GeV-scale particles and to perform neutrino physics measurements at the HI-ECN3 (high-intensity) beam facility at the CERN SPS, operated in beam-dump mode, taking full advantage of the available $4 \times 10^{19}$ protons per year at 400 GeV. CERN recently decided in favour of BDF/SHiP for the future programme of this facility. The setup consists of two complementary detector systems downstream an active muon shield. The former, the scattering and neutrino detector (SND), consists of a light dark matter (LDM)/neutrino target with vertexing capability. The latter, the hidden sector decay spectrometer (HSDS), consists of a 50 m long decay volume followed by a spectrometer, timing detector, and a PID system. BDF/SHiP offers an unprecedented sensitivity to decay and scattering signatures of variegated new physics models and tau neutrino physics.

*12th Large Hadron Collider Physics Conference (LHCP2024)*
*3-7 June 2024*
*Boston, USA*

*Speaker



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PoS(LHCP2024)093

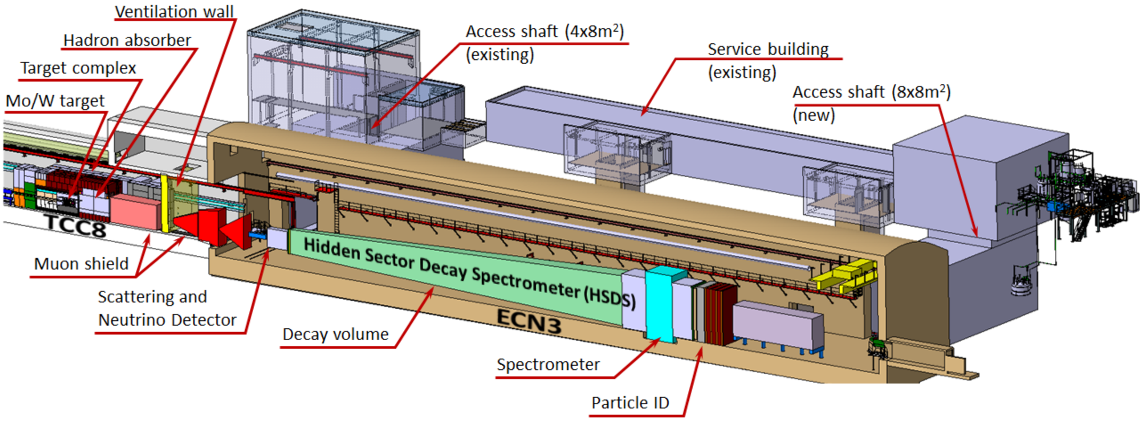


**Figure 1:** Layout of the BDF/SHiP facility, taken from Ref. [3].

## 1. Introduction

While the LHC has found the last missing piece of the Standard Model, and is measuring it ever more precisely, many mysteries remain, for instance the nature of dark matter, the origin of neutrino masses and the baryon asymmetry of the universe. All of these mysteries could be solved by models predicting additional particles below the electroweak scale, which interact too feebly for detection at current and planned experiments, see for example Ref. [1]. These particles would constitute feebly interacting or long-lived particles which could be visible at dedicated experiments. Their production and interactions vary widely, but can be categorised according to their coupling term to the Standard Model, which can be enumerated, leading to the PBC benchmark channels [2].

Many of these channels remain largely unconstrained, with large areas of mass-coupling space beyond the reach of current and proposed experiments. The Search for Hidden Particles (SHiP) experiment is aiming at exploring these blank spots on the map, by fully exploiting the intensity available at the HI-ECN3 beam facility with its two specialised detectors.

## 2. Experimental design

The layout of the BDF/SHiP facility can be seen in Figure 1. The Beam Dump Facility (BDF) that hosts the SHiP experiment is located at the HI-ECN3 beam facility at the CERN's SPS. It provides $4 \times 10^{19}$ protons-on-target (PoT) at an energy of 400 GeV per year, directed onto a TZM and tungsten target with a length of twelve interaction lengths. The annual yield of approximately $2 \times 10^{17}$ charmed hadrons, $1.4 \times 10^{13}$ beauty hadrons, $2 \times 10^{15}$ tau leptons and $\mathcal{O}\left(10^{20}\right)$ photons above 100 MeV gives SHiP access to a broad range of production mechanisms of feebly interacting particles, as well as unprecedented sample of $\nu_\tau$. These yields benefit from a hadronic cascade in the dense target. Following the target, a hadron absorber stops all particles but muons and neutrinos. It is magnetised to support the muon shield in the deflection of the muon flux.

An active muon shield comprising two magnet systems follows the absorbers. Its role is the deflection of muons resulting in a reduction of the muon flux by about six orders of magnitude. Since the original Comprehensive Design Study (CDS) of SHiP, which foresaw a fully warm muon

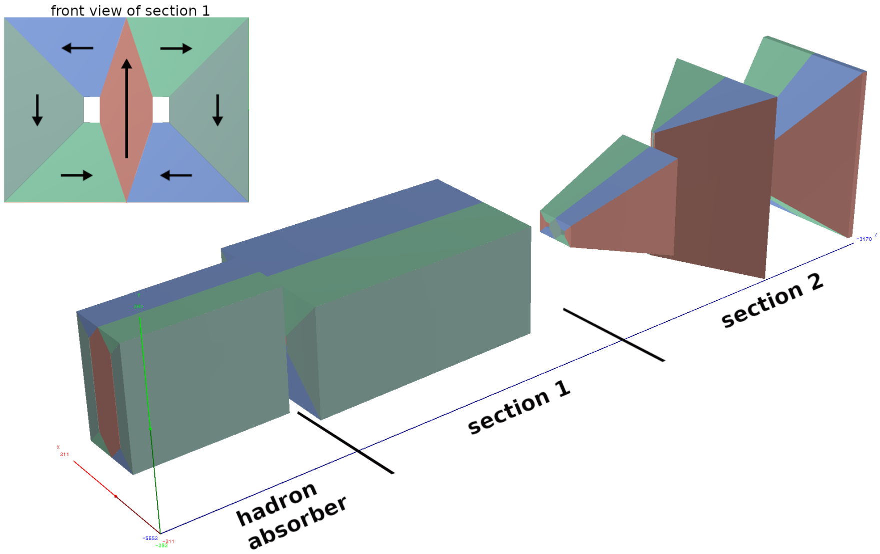


**Figure 2:** Components of the muon shield. In the baseline, Section 1 is superconducting while Section 2 consists of warm electromagnets. Taken from Ref. [3].

shield, as described in detail in Ref. [4], the option of using a superconducting magnet for the first section of the muon shield has become feasible and attractive: The higher field results in a shorter muon shield, resulting in a higher experimental acceptance, while also reducing the power use. The resulting new baseline option is shown in Figure 2. A fully warm option based on the CDS design of SHiP is kept as a backup option while the Technical Design of the muon shield is finalised.

As the muon shield is crucial to guaranteeing the zero-background conditions necessary for the physics programme of SHiP, the optimisation of the final design is of highest importance. To give us confidence in its design, it is optimised with full simulation, validated with a dedicated experiment performed in 2018 with a replica of the target [5]. As the simulation is computationally extremely challenging, several optimisation techniques based on machine-learning techniques have been studied, including Bayesian Optimisation [4], Local Generative-Surrogate Optimisation [6] and a reinforcement-learning-based approach [7]. For now, Bayesian Optimisation is the baseline optimisation algorithm, and calculation of field-maps on the fly during the optimisation is under study.

The last section of the SHiP muon shield will host the Scattering and Neutrino Detector (SND), which is optimised to study the scattering of neutrinos of all flavours and of light dark matter. Originally foreseen to use the same technology as the SND@LHC experiment [8], emulsion cloud chambers, a fully electronic option is currently under study, in close collaboration with the proposed AdvSND upgrade [9] of the SND@LHC experiment for Run 4 of the LHC, which aims to replace nuclear emulsions with silicon trackers. Its integration into the muon shield allows it to reduce the length of the experiment while also obviating the need for an additional stand-alone magnet for charge-separation and momentum measurement. Nuclear emulsions and electronic detectors offer complementary challenges and unique benefits: The tracking and vertex resolution of nuclear emulsions is unparalleled with electronic detectors allowing reliable reconstruction of displaced vertices of tau-lepton and charm decays. However, in the high-intensity environment of SHiP, the expected

| Background source | Expected events in 15 years |
|---|---|
| Neutrino DIS | $< 0.1$ (fully)/$< 0.3$ (partially) |
| Muon DIS (factorisation) | $< 5 \times 10^{-3}$ (fully) / $< 0.2$ (partially) |
| Muon combinatorial | $(1.3 \pm 2.1) \times 10^{-4}$ |

**Table 1:** Expected background yield over 15 years for the dominant backgrounds with a common, minimal selection.



background occupancy is at the limit of what is currently achievable with a reasonable replacement schedule. Electronic detectors such as silicon-strip or scintillation fibre detectors, both under study, deal with the occupancy with easy, but can not resolve the displaced vertices directly, necessitating the development of sophisticated machine-learning techniques for the reliable reconstruction and identification of the expected neutrino and beyond Standard Model signatures.

Following the muon shield and SND, the Hidden Sector Decay Spectrometer (HSDS) offers unique sensitivity to long-lived particles: A helium-filled decay-volume with upstream and surrounding background taggers provides a fiducial volume for the decay of beyond Standard Model particles with negligible background, followed by a magnetic spectrometer, a timing detector and PID detectors to identify and precisely measure their decay products.

For more details on the experimental layout, see the BDF/SHiP Proposal [3].

## 3. Physics performance

For the study of experimental backgrounds, full simulation using the FairShip framework is used. It is based on the FairRoot toolkit which integrates Geant4 and many other tools. Pythia8 is used to generate prompt processes, while Pythia6 is used for the hadronic cascade and the simulation of muon deep-inelastic scattering (DIS) and GENIE is used to generate neutrino interactions.

To augment the simulation statistics of rare processes, the rates of rare muon processes are enhanced, and interactions are forced for muon DIS and neutrino DIS. The collaboration has also studied the use of generative-adversarial networks to improve muon statistics for the study of muon induced backgrounds [10].

With a minimal selection, common to all signal channels for the Proposal phase, the backgrounds can be reduced to negligible levels, even for partially reconstructed signatures, as show in Table **??**. Now, more targeted selections are being developed per channel to improve the signal efficiencies while still rejecting all backgrounds reliably.

Sensitivities to feebly interacting particles are by default calculated using the SensCalc [11] tool, which is in excellent agreement with the previous implementations of signal channels using Pythia8 in full simulation. An evolution of SensCalc called EventCalc has now been integrated in FairShip and will allow detailed study numerous signal channels in full simulation.

A selection of sensitivities to feebly interacting particles are shown in Figure 3. For additional sensitivities, please see Ref. [3]. All sensitivities are given for 15 years of data taking.

In addition to beyond Standard Model searches, SHiP is uniquely suited for precision neutrino studies in a parameter range complementary to other experiments, especially to those at the HL-

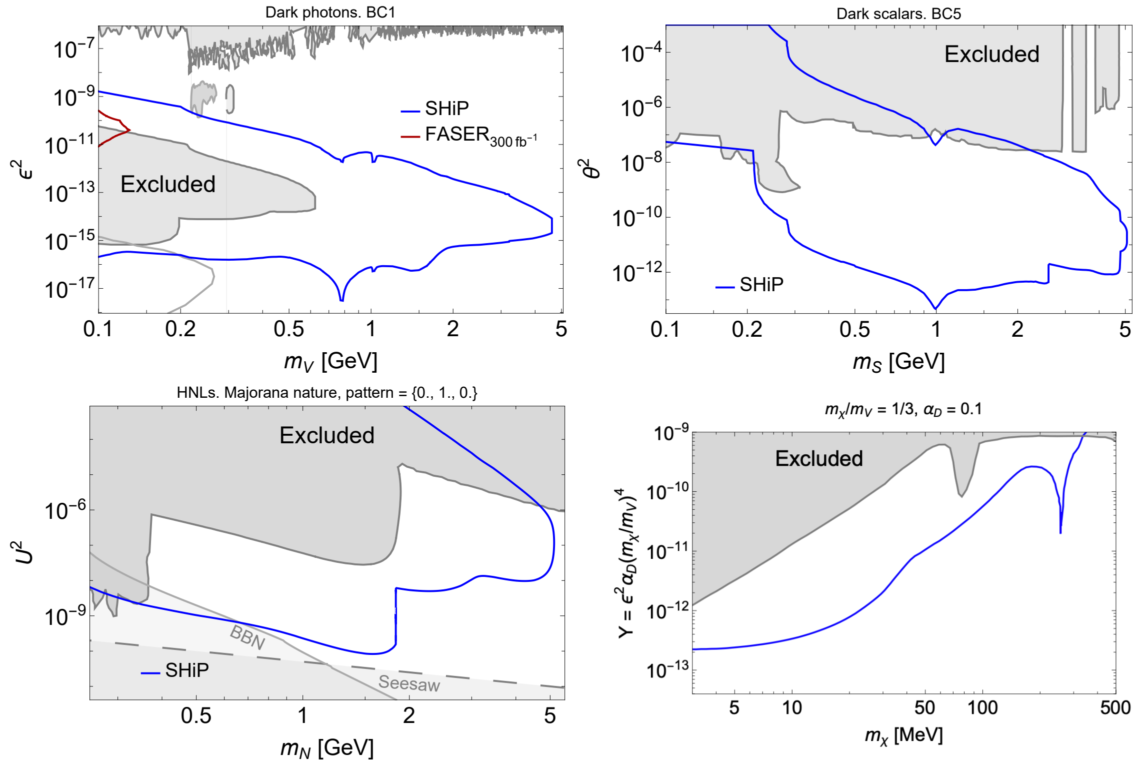


**Figure 3:** SHiP sensitivities (from top left to bottom right) for a selection of PBC benchmark models [2] BC1, BC5, BC7, and light dark matter scattering on electrons. Please see Ref. [3] for the remaining benchmark channels. Sensitivities are given for 15 years of data taking.

LHC. The BDF provides large yields of (anti-)neutrinos at lower energies and boost to SHiP's SND detector, which is designed to be capable to distinguish all flavours and determine the charge in leptonic channels. With an expected yield of approximately $10^6$ $\nu_e$, $10^7$ $\nu_\mu$, $10^5$ $\nu_\tau$, many planned studies would be no longer statistically limited.

## 4. Conclusion

After the selection of SHiP as the experiment to be hosted at the HI-ECN3 beam facility, it is entering the TDR stage to finalise the design and prove the technical feasibility. At the new location, the physics performance is as good or even better than at the previously considered purpose-built facility, with SHiP projected to beat current-exclusion limits by orders of magnitude across a variety of feebly interacting particle models, while also offering unique potential for precision measurements of neutrinos.

In addition to SHiP, the BDF facility at HI-ECN3 could host additional experiments and facilities, such as an irradiation facility for material science and radiation-hard electronics development, a downstream liquid-argon experiment to complement SHiP for scattering signatures, or an upstream tau-lepton flavour violation experiment [3].

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