The SHiP experiment at CERN

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Abstract

The current status of the proposed SHiP experiment at the CERN Beam Dump Facility is presented. SHiP is a general-purpose fixed-target experiment. The 400 GeV/c proton beam extracted from the SPS will be dumped on a heavy target to integrate $2 \times 10^{20}$ protons on target in five years. The detector, based on a long vacuum tank followed by a spectrometer and particle identification detectors, will allow to probe a variety of models with light long-lived exotic particles and masses below $\mathcal{O}(10)$ GeV/c$^2$. The main focus will be the physics of the so-called hidden portals, i.e. the search for dark photons, light scalars and pseudo-scalars, and heavy neutrinos. The sensitivity to heavy neutrinos will allow to probe, in the mass range between the kaon and the charm meson mass, a coupling range for which baryogenesis and active neutrino masses could also be explained. A second dedicated detector will study neutrinos and explore light dark matter.

1 Introduction

SHiP is a general-purpose beam-dump experiment designed to use the high-intensity 400 GeV/c beam of protons available from the CERN SPS accelerator in order to search for hidden particles. The proposal of the experiment evolved from a first idea [1] to search for Heavy Neutral Leptons (HNLs), whose existence is predicted in the $\nu$MSM model [2, 3] with guidance described in Ref. [4], to a more comprehensive programme of new physics searches at the intensity frontier [5], including the option of producing and studying a large sample of $\nu_\tau$ neutrinos [6], that lead to the SHiP technical proposal [7]. Since then, the detector layout has been continuously optimised and expanded. The most recent results were documented in a progress report [8] and the comprehensive design study report [9].

2 Motivation

While the Higgs boson discovery at the Large Hadron Collider in 2012 marks the triumph of the Standard Model (SM), there are still several shortcomings in particle physics that are waiting to be explained. The SM particles cannot account for the observed matter in the Universe, as there is convincing evidence of dark matter (DM), with unknown mass and couplings. The predominance of matter over antimatter in the Universe calls for additional sources of $CP$ violation, beyond what is known in the SM. The tiny, but non-zero masses of the neutrinos, causing oscillations, could be explained via the see-saw mechanism with right-handed neutrinos with Yukawa couplings to the...
Higgs boson and SM leptons. There are also aesthetic shortcomings, like the strong $CP$ problem or the hierarchy/fine-tuning problem of the Higgs mass.

It is thus important to probe new physics beyond the SM in different directions. At the intensity frontier the paradigm is that low-energy, high-intensity experiments could uncover new interactions and particles with very feeble couplings. Popular extensions of the SM proceed through so-called portals, that are generally categorized according to the nature of the mediator: scalar, vector, pseudo-scalar or fermion. Examples for these categories are Dark Higgs, Dark Photon, Axion Like Particles (ALPs), and HNLs, respectively.

3 The SHiP detector at the Beam Dump Facility

The SHiP detector is planned to be installed in the North Area at the CERN SPS 400 GeV/$c$ beam, taking advantage of the Beam Dump Facility (BDF). It features two main sub-detector systems, pursuing complementary physics goals. The hidden sector (HS) decay spectrometer aims at measuring visible decays of HS particles and will reconstruct their decay vertices in a large decay volume. The scattering and neutrino detector (SND) is dedicated to neutrino physics and the search for light dark matter (LDM). The design of the detector underwent several optimisation steps and its current implementation is shown in Figure 1. In particular, there has been a large effort to re-optimize the muon magnetic shield configuration and, as a consequence, the detector layout.

![Figure 1: Drawing of the current outline of the SHiP detector [9].](image)

3.1 Beam Dump Facility

The proposed BDF is foreseen to be located at the North Area of the CERN SPS. It is designed to be able to serve both, beam-dump like and fixed-target experiments. The full exploitation of the SPS would allow the delivery of an annual yield of up to $4 \times 10^{19}$ 400 GeV/$c$ protons on target (pot) while delivering protons to the HL-LHC and the existing SPS facilities. Slow extraction of a de-bunched beam with good uniformity is required to keep the combinatorial background under control and to dilute the large beam power in the proton target. The proposed implementation of the beam dump experimental facility is based on a minimal modification to the SPS complex and maximal use of the existing beamlines. The BDF is described in detail in Ref. [10].

3.2 Target

The SHiP target [11] is designed to maximise the production of hidden sector particles, mainly through the decay of flavoured hadrons produced in the target through primary and secondary (cascade) interactions. At the same time, the target material and density are chosen such to reduce the production of other particles. The longitudinally segmented hybrid target consists of four nuclear interaction
lengths ($\lambda_{\text{INT}}$) of TZM (titanium-zirconium doped molybdenum) alloy, followed by $6\lambda_{\text{INT}}$ of tungsten, and is interleaved with water cooling spaces, for a cross section of $30 \times 30 \text{cm}^2$ and a total length of more than 120 cm. Cooling will be essential, as the peak power of the beam during a spill will be 2.56 MW. The target complex will be housed in a 440 m$^3$ bunker made of remotely handled iron bricks and is additionally cooled, underpressurized, and shielded. A 5 m thick iron shield absorbs hadrons behind the target.

### 3.3 Active muon shield

After the hadron absorber, penetrating muons are a possible source of undesired occupancy. From simulation, it is expected that $10^{11}$ muons/s are produced in the collisions of the proton beam on the beam-dump target from the decay of pions, kaons, and other light and charmed mesons. A magnetic muon shield [12] will deflect muons of both polarities and a wide range of transverse momenta and significantly reduce this muon flux. Since the produced hidden sector particles typically exhibit large transverse momenta, the muon shield has to be as compact as possible. The original design has been revised using a Bayesian optimisation algorithm [13], resulting in a total length of 34 m, a weight of 1.5 kt, and a magnetic field of up to 1.8 T. The first part aims at separating muons of opposite polarities and also acts as a hadron absorber, while the rest of the series of magnets is designed to also remove the lower momentum muons that re-enter the acceptance due to the return fields. The muon flux will be reduced to $10^5$ muons/s after the muon shield.

### 3.4 Scattering and neutrino detector

Downstream of the muon shield a detector system consisting of emulsion cloud chamber (ECC) bricks made of lead plates and nuclear emulsion films, interleaved with electronic trackers and followed by a compact emulsion spectrometer (CES) with low-density material, will be immersed in a 1.2 T magnetic field. Behind the magnet, a muon identification system, consisting of several 10 cm thick iron filters and RPC tracking planes, aims at identifying the muons produced in neutrino interactions and $\tau$-decays occurring in the emulsion target. The ECC bricks are composed of stacks of alternating 1 mm lead plates, acting as neutrino targets, and 300 $\mu$m emulsion films, where $\nu_\tau$ interactions and $\tau$-lepton decay vertices can be reconstructed. The CES, a light structure with a long lever arm, will be essential to measure the charge of the $\tau$-lepton daughters. The electronic tracker technologies under study include scintillating fibres (SciFi), and micro-pattern gaseous detectors ($\mu$-RWELL).

### 3.5 Hidden sector decay volume

The SHiP decay volume has a pyramidal frustum shape with rectangular bases of $2.4 \times 4.5 \text{m}^2$ at the entrance and $5 \times 10 \text{m}^2$ at the exit, for a length of 50 m. It has to be sufficiently evacuated from residual air to suppress muon and neutrino interactions. The complete volume is enclosed by the surrounding background tagger (SBT), a veto detector, based on 480 t of linear alkylbenzene liquid scintillators, which will help to identify activity from outside of the detector, like cosmic rays or cavern background. The liquid scintillator is coupled to 3500 wavelength-shifting optical modules (WOM), already proposed to be used in an extension of the IceCube detector.

### 3.6 Spectrometer and particle identification

The HS decay volume is followed by a spectrometer with an acceptance of $5 \times 10 \text{m}^2$. The first sub-detector is the spectrometer straw tracker, designed to accurately reconstruct the momenta and the decay vertex, mass and impact parameter of the hidden particle trajectory at the proton target. The spectrometer dipole magnet is a conventional magnet with a total field integral of 0.65 Tm. The SplitCal electromagnetic calorimeter employs the sampling technology with lead/scintillator planes. To accurately measure the shower transverse profile, the SplitCal is longitudinally segmented and
will contain high-precision layers of MicroMegas chambers, similar to those developed for the ATLAS muon upgrade. This will be important for the reconstruction of decays of axion-like particles to two photons. The muon system consists of four stations interleaved by three muon filters. To reject random crossings, a dedicated timing detector made of scintillator bars is placed at the end of the detector and will match the arrival times of the particles forming vertex candidates with a precision of 100 ps.

4 Physics performance

The SHiP experiment is a unique discovery tool for HS particles. Present constraints on various channels will be improved by several orders of magnitude. SHiP will also distinguish among different models, and measure parameters relevant for cosmology and model building, in a large part of the parameter space. Together with the direct search for LDM and neutrino physics, SHiP is a wide scope general-purpose fixed-target experiment.

The HS detector is designed to fully reconstruct a wide range of decay modes, and identify the particles, to ensure a model-independent search for hidden particles. The SND detector is optimised for scattering signatures of LDM and neutrinos. The sensitivity of the SHiP experiment heavily relies on redundant background suppression. The SHiP physics case was presented in Ref. [5].

4.1 Background studies

Large samples of simulated events have been produced to accurately determined the level of backgrounds, including from the floor, ceiling, walls and detector supports, using Geant4 [14] and the FairRoot framework [15]. Samples of muons produced in $10^{12}$ pot have been fully simulated. In order to claim discovery of a HS particle, it is of paramount importance to suppress the backgrounds that would mimic the same final states to a negligible level. Signal events feature a vertex pointing back to the target, consisting of at least two charged particles and possibly additional invisible particles.

Three sources of background can mimic the HS signature: random muon combinatorial, muon inelastic scattering and neutrino deep-inelastic scattering. The background from cosmics has been found to be negligible. The three sources of background are reduced by requirements on the track momentum, vertex position and impact parameter with respect to the target. To avoid irreducible background from neutrinos interacting with the air molecules inside the vessel, a level of vacuum below $10^{-2}$ bar is necessary. The background from neutrino scattering in the floor and the walls of the cavern was studied and found to be negligible. Additionally, information from the timing detector and veto information from the SBT will reduce the backgrounds to less than 0.3 events during the five-year data-taking. Thus, SHiP can be considered a zero-background experiment with a high level of redundancy to efficiently suppress the background for a broad spectrum of searches.

4.2 Signal sensitivities

Hidden sector

To illustrate the physics potential of SHiP to hidden sector particles the sensitivities to HNLs, dark scalars, dark photons and ALPs coupling to photons are shown in Figures 2 and 3. More details can be found in the report of the Physics Beyond Colliders study group [16].

In the case of a discovery, SHiP is capable of measuring parameters and identifying the underlying models. For instance, SHiP may distinguish between Majorana-type and Dirac-type HNLs in a significant fraction of the parameter space by detecting lepton number violating or conserving decays [17], as shown in Figure 2. If the mass splitting between the HNLs is small, it may also be possible to resolve HNL oscillations as a direct measurement of the mass splitting between HNLs.
The muon shield and the SHiP detector systems are housed in an experimental hall at a depth of 150 m to reduce long-lived neutral particles, cosmic rays and other backgrounds. Two detector systems provide a complementary search. The HS detector aims to perform a model-independent search for hidden particles. The SND system is optimised for scattering experiments, and to photons (bottom-right). References to the current constraints provided by GENIE. The expected number of CC DIS in the target of the SND detector is reported in the neutrino target is evaluated by convoluting the generated neutrino spectrum with the cross-section at the POI. Neutrino flavour is determined through the flavour of the primary charged lepton produced in neutrino interactions observed in the different detectors (left). It could smear out fast decay products. The charge of hadrons and muons is measured by the Compact muon system makes it possible to identify the three different neutrino flavours in the SND detector.

### 2.4 Neutrino physics at SHiP

The physics performance of the SHiP experiment is anchored in an extremely efficient and redundant background suppression. Two detector systems provide a complementary search. The HS detector aims to perform a model-independent search for hidden particles. The SND system is optimised for scattering experiments, and to photons (bottom-right). References to the current constraints provided by GENIE. The expected number of CC DIS in the target of the SND detector is reported in the neutrino target is evaluated by convoluting the generated neutrino spectrum with the cross-section at the POI. Neutrino flavour is determined through the flavour of the primary charged lepton produced in neutrino interactions observed in the different detectors (left). It could smear out fast decay products. The charge of hadrons and muons is measured by the Compact muon system makes it possible to identify the three different neutrino flavours in the SND detector.

The muon shield and the SHiP detector systems are housed in an experimental hall at a depth of 150 m to reduce long-lived neutral particles, cosmic rays and other backgrounds. Two detector systems provide a complementary search. The HS detector aims to perform a model-independent search for hidden particles. The SND system is optimised for scattering experiments, and to photons (bottom-right). References to the current constraints provided by GENIE. The expected number of CC DIS in the target of the SND detector is reported in the neutrino target is evaluated by convoluting the generated neutrino spectrum with the cross-section at the POI. Neutrino flavour is determined through the flavour of the primary charged lepton produced in neutrino interactions observed in the different detectors (left). It could smear out fast decay products. The charge of hadrons and muons is measured by the Compact muon system makes it possible to identify the three different neutrino flavours in the SND detector.

Figure 2: Left: Sensitivity to HNL for the mixing with muon flavour [18]. The dark grey area and the solid line indicate the excluded regions by previous experiments. The solid and dashed-dotted red lines indicate the uncertainty related to the production of $B_c$ mesons. Right: SHiP sensitivity to lepton number violation (thick dashed curve) compared to exclusions by previous experiments (coloured areas). The thin dashed grey lines show the number of fully reconstructible events [17].

Figure 3: Sensitivity of SHiP to dark scalar [9], dark photon, ALPs [16] and LDM signals [9], compared to existing (coloured or grey areas) and projected (lines) exclusion limits.
Light Dark Matter

If LDM particles undergo elastic scattering ($\chi e^- \rightarrow \chi e^-$) in the SND detector material, the electromagnetic shower induced by the recoil electron can be detected in the SND, which would act as a sampling calorimeter. A sufficient portion of the shower can be reconstructed in order to determine the particle angle and energy. The high accuracy of the nuclear emulsions will provide topological discrimination against neutrino-induced background. Figure 3 shows the SHiP sensitivity as a function of the LDM mass $M_{\chi}$, along with existing constraints and the thermal relic abundance, for a benchmark scenario with a dark coupling $\alpha_D = 0.1$.

Neutrino physics

The SND detector will be able to determine the neutrino flavour by measuring the flavour of the charged lepton produced in the neutrino charged-current interactions. About $10^4 \tau$-neutrinos will be detected and the tracking capabilities in the SND will allow distinguishing, for the first time, between $\nu_\tau$ and $\bar{\nu}_\tau$. In addition, the large sample of neutrino-induced charm production will allow for unprecedented studies in this domain, as for instance double-charmed production or the strange-quark content of nucleons. The samples available at SHiP will also allow to significantly constrain the $\nu_\tau$ magnetic moment and test lepton flavour violation in the neutrino sector.

5 Measurements

5.1 Muon flux normalisation

In order to validate the Monte-Carlo simulation (Pythia, Geant4) that is being used for the sensitivity studies, the muon flux was measured in a test-beam setup at the CERN SPS [19]. Protons of 400 GeV/$c$ were directed onto a SHiP target replica with full length. Behind an iron hadron absorber the emanated muons were measured with a spectrometer setup using scintillators, OPERA drift-tubes stations, the Goliath magnet and an RPC-based muon tagger. In three weeks during 2018, about 327 billion pot were recorded, corresponding to 1% of a nominal SHiP spill. Events with muons were recorded at a rate of one in 710.

The relevant physics processes for muon production are foremost the decays of pions and kaons, the production and decay of charm particles and low-mass resonances, and the transportation of the muons through the iron absorber. Data and simulation agree remarkably well (Figure 4), with maximal differences in the absolute rate of 30% for large transverse momenta at high muon momenta.

5.2 Charm production cross-section

The production of charmed hadrons in 400 GeV/$c$ protons on the SHiP target is expected to be increased by a factor of more than two with respect to the direct production due to the interactions of particles produced in the hadronic cascade showers. The exact normalisation is an important input and will be measured by the SHiP-charm experiment at the CERN SPS [20].

An optimisation run was performed in 2018, collecting about 1.5 million pot, directly after the muon flux measurement, thus using the same magnet, the scintillators, drift tubes and RPCs. To precisely measure the charm production vertices and the tracks, emulsion films were used, along with a tracker built with ATLAS pixel modules and LHCb SciFi. To keep the occupancy to manageable levels, the emulsion detector was moving horizontally during a spill at 2 cm/s and vertically in between spills. This makes the alignment and matching of tracks between the detectors challenging. Preliminary results show that more than 50% of the tracks associated with reconstructed vertices can be matched. Several runs were taken with varying amounts of target material in front of the emulsion detector, to probe the charm content of the different parts of the shower development. Figure 4 shows an event display of a charm candidate in the emulsion detector.
Table 1 Simulation samples made for SHiP background studies. $\chi$ is the number of POT. For simulated data, some individual sources are highlighted, muons from charm (green), from dimuon decays of low-mass resonances in Pythia8 (cyan), in Geant4 (turquoise), photon conversion (blue), and Positron annihilation (brown). In data, the most important individual sources in simulation are shown, along with the total prediction. Right: A double-charm candidate event produced in proton collisions with the tungsten target recorded at the H4 charm-production measurement [9].

6 Conclusions

With the current status of SHiP and the mature understanding of the continued detector developments, the SHiP project is ready to commence the Technical Design Report phase. First prototypes of all subsystems can be constructed and tested within the next three years. It is estimated that the detector production will require two to three years and that the detector assembly and installation, including infrastructure, will require another two years. The installation of the facility and the SHiP detector could be performed in the Long Shutdown 3, allowing commissioning and starting data-taking early in Run 4.

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