The SHiP experiment at the SPS Beam Dump Facility

COMPREHENSIVE OVERVIEW

SHiP Collaboration

Abstract

The SHiP Collaboration has proposed a general purpose experimental facility at the CERN SPS accelerator to search for feebly interacting GeV-scale particles. SHiP complements the world-wide program of New Physics searches by covering a large region of parameter space which cannot be addressed by other experiments. The SHiP detector is sensitive both to decay and scattering signatures of models with heavy neutral leptons, dark photons, dark scalars, light dark matter and other super-weakly interacting particles. In addition, SHiP can perform unprecedented measurements with tau neutrinos and neutrino-induced charm production. Following the continued development since the Technical Proposal submitted in 2015, this paper is a comprehensive overview of the re-optimized SHiP spectrometers and the improved physics performance.

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1 Introduction

SHiP is a beam dump experiment aiming at searching for hidden particles by using the high-intensity beam of $400\,\mathrm{GeV}/c$ protons available from the CERN SPS accelerator. An Expression of Interest [1] was submitted to the SPS committee (SPSC) in 2013. The subsequently formed collaboration submitted the Technical Proposal [2, 3] and the Physics Proposal [4] to the SPSC in 2015. Since then the experiment has been further optimized and the physics cases extended. The present paper provides a comprehensive overview of the design, and shows the improved physics performance of the proposed experiment. The description of the proton delivery and the experimental facility is the subject of a separate paper [6] submitted to the EPPSU.

2 Physics motivation

The discovery of the Higgs boson at the LHC in 2012 made the Standard Model (SM) of elementary particles complete - all the particles predicted by the model have been found, and their interactions, tested at the LHC till now, are consistent with those predicted by the SM. The triumph of the SM in particle physics is accompanied by the success of the standard cosmological model (ΛCDM) based on Einstein's General Relativity, allowing to describe the structure of the Universe by a small number of parameters.

The era of guaranteed discoveries in particle physics has come to the end with the detection of the Higgs boson: for the particular value of the Higgs mass revealed by the LHC, the SM remains mathematically consistent and valid as an effective field theory up to a very high energy scale, possibly all the way up to the Planck scale.

The quest for new particles has however not ended. We are certain that the SM does not represent the full picture. Several well-established observational phenomena – neutrino masses and oscillations, dark matter, and baryon asymmetry of the Universe – cannot be explained with known particles alone and clearly indicate that New Physics (NP) should exist. Unfortunately, we do not have a definitive prediction where to find NP, nor do we have experimental clues on the masses, spins, and coupling constants of the associated new particles.

The first ever LHC run with proton-proton collisions at a centre-of-mass energy of 13 TeV has uncovered no significant deviations from the SM. Nor did other searches for NP at particle physics laboratories worldwide. A few anomalies remain to be addressed by future experiments. Namely, intriguing hints of lepton flavour universality violation in semi-leptonic B decays have been reported in recent years by BaBar, Belle and LHCb. The measurements of the muon anomalous magnetic moment at BNL show a tension with the Standard Model prediction. Even if these hints are confirmed, it will not be possible to determine the scale of NP with certainty.

Significant efforts in neutrino physics in recent years did not improve our knowledge about the mass scale of the new particles that could be the origin of the neutrino masses and oscillations. In particular, taking aside different unconfirmed signals of eV scale neutrino states, all the oscillation signatures can be explained by the SM extended by two additional sterile neutrinos of essentially any mass ranging from a fraction of an eV to very high masses.

With regard to Dark Matter, the absence of detections in direct and indirect search experiments for weakly interacting massive particles (WIMPs) in the GeV-TeV mass range has stimulated growing interest in light dark matter (LDM) candidates: sterile neutrinos, axions, WIMP-like particles but with lower (sub-GeV) masses. This has led to a significant increase of the corresponding experimental efforts in both direct searches and at accelerators. A similar trend is revealed in cosmological studies where models of structure formation, as well as systematic searches for various signatures of such particles in cosmological and astrophysical observations, have been investigated. As a result, the "cosmologically interesting" region of the parameter space of hidden particles, which can be tested at SHiP and the LHC, was pinned down with much better accuracy.

In summary, the current results in theoretical and experimental particle physics, cosmology and astrophysics still leave the parameters of NP largely undetermined. The fact that no convincing signs of new particles have been found so far suggests that they are either heavier than the reach of present-day accelerators or interact very weakly. The current experimental situation thus defines three main and fully complementary directions for the development of particle physics:

- The direct searches for NP, namely the search for new phenomena occurring at high energies, such as the production of new types of massive particles (*energy frontier*).
- The indirect searches for NP, namely the search for possible departures from the SM predictions when performing high-precision experiments at any energy scale (*precision frontier*).
- The direct searches for feebly interacting, relatively light particles (*intensity frontier*).

While the energy frontier is investigated at the LHC and the precision frontier is pursued at LHCb, Belle II and elsewhere, the intensity frontier remains under-explored. It is the main goal of the SHiP experiment to make a break-through in this direction. In particular, SHiP will explore the domain of particle masses and couplings that are not accessible to the energy and precision frontier experiments, and potentially find the particles that lead to neutrino masses and oscillations, explain baryon asymmetry of the Universe, and shed new light on the properties of dark matter.

New particles with masses much lighter than the electroweak scale can couple to the SM fields via renormalisable interactions with small dimensionless coupling constants. These, so called "portals", can mediate interactions between the SM and "Hidden Sectors". Depending on the spin of the mediator, there are three classes of portals mixing with the SM particles: scalar portal (spin 0, coupling coefficient $\sin^2\theta$), neutrino portal (spin 1/2, coupling coefficient U^2) and vector portal (spin 1, coupling coefficient ϵ). SHiP is sensitive to all these portals, and moreover to a special case of non-renormalizable models predicting axion-like particles (ALP) decaying to photons, gluons and fermions (coupling coefficients $g_{a\gamma\gamma}$, g_{agg} and g_{aff}, respectively). SHiP can also probe the existence of LDM through the observation of its scattering off electrons and nuclei in the detector material. In addition to the exploration of the Hidden Sector, the SHiP physics program includes a rich program of tau neutrino physics and measurements of neutrino-induced charm production.

SHiP has received a large amount of attention from the particle physics community in recent years. The SHiP physics paper [4] has been cited over 300 times since its publication in 2015, and many groups continue to explore the scientific potential of the experiment, making detailed predictions for models of feebly interacting particles. Searches for heavy neutral leptons (HNL), dark photons, dark scalars, light dark matter and other super-weakly interacting light particles have recently been included in the scientific goals of many presently running experiments, and several intensity frontier experiments have been proposed in the last few years.

3 Overview of the SHiP detector and simulation

SHiP is a unique, dedicated experiment capable of reconstructing the decay vertex of a Hidden Sector (HS) particle, measuring its invariant mass and providing particle identification of the decay products in a nearly zero level background environment. Moreover SHiP is also optimized to search for LDM scattering and for tau neutrino physics.

The SHiP detector will be served by a new, short, dedicated beam line branched off the splitter section of the SPS transfer line to the CERN North Area. The Comprehensive Design Study for the experimental Beam Dump Facility (BDF) [5–7], consisting in a preliminary design of the main components of the proton delivery, the target system and the target complex, and the experimental area, has been carried out in the context of the Physics Beyond Colliders (PBC) study group [8] at CERN.

At the SPS, the optimal experimental conditions for SHiP are obtained with a proton beam energy of around $400\,\mathrm{GeV}$. A nominal beam intensity of 4×10^{13} protons on target per spill is assumed for the

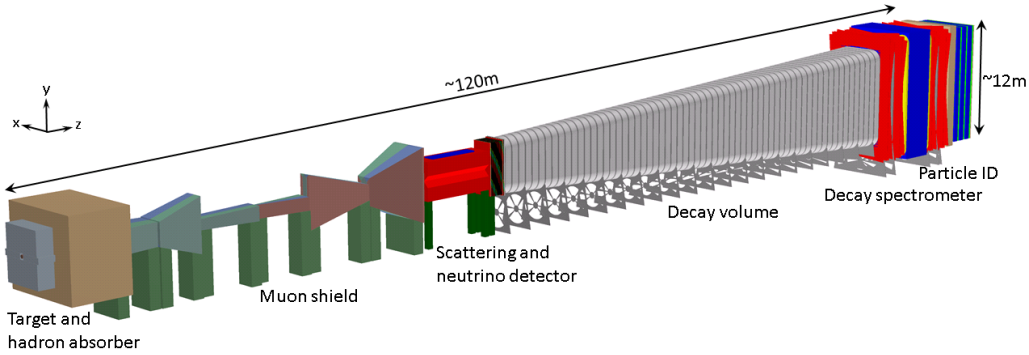

Figure 1: Overview of the SHiP experimental setup.

design of the BDF and the SHiP detector. In the baseline scenario for SHiP, the beam sharing delivers an annual yield of 4×10^{19} protons to the BDF and a total of 10^{19} protons to the other physics programs at the CERN North Area, while respecting the beam delivery required by the HL-LHC . The physics sensitivities are based on acquiring a total of 2×10^{20} protons on target, which may thus be achieved in five years of nominal operation.

The SHiP detector

The current layout of the SHiP experimental setup is shown in Fig. 1. The setup consists of a high-density proton target, followed by a hadron stopper and an active muon shield [9], which sweeps away the muons produced in the beam dump in order to reduce the initial flux by six orders of magnitude in the detector acceptance. The target is made of blocks of a titanium-zirconium doped molybdenum alloy (TZM) in the core of the proton shower, followed by blocks of pure tungsten. The total target depth is twelve interaction lengths. The five metres long hadron stopper of iron absorbs hadrons and electromagnetic radiation emerging from the target. The hadron absorber is equipped with a coil which magnetizes the iron shielding blocks to serve as the first section of the active muon shield. The rest of the muon shield consists of 35 m of free-standing warm magnets located in the underground experimental hall, totalling 1400 tonnes of magnetic mass.

The SHiP detector consists of two complementary apparatuses, the Scattering and Neutrino Detector (SND) and the Hidden Sector (HS) decay spectrometer. The SND will search for LDM scattering and perform neutrino physics. It also provides normalisation of the yield for the hidden particle search. It consists of an emulsion spectrometer located inside a single long magnet with a field of 1.2 T, followed by a muon identification detector. The emulsion spectrometer is a hybrid detector composed of modules with alternating layers of absorber, nuclear emulsion films and fast electronic trackers. The absorber mass totals $\sim$10 tonnes.

The HS decay spectrometer aims at measuring the visible decays of HS particles by reconstructing their decay vertices in a 50 m long decay volume of a pyramidal frustum shape. In order to eliminate the background from neutrinos interacting in the decay volume, it is maintained at a pressure of $\sim$ 1 mbar. The decay volume is followed by a large spectrometer with a rectangular acceptance of 5 m width and 10 m height. The main element of the spectrometer is the straw tracker designed to accurately reconstruct the decay vertex, the mass, and the impact parameter of the hidden particle trajectory at the proton target. The spectrometer dipole magnet is a warm magnet with a total field integral of about 0.5 Tm.

An electromagnetic calorimeter (ECAL) and a muon detector provide particle identification which is essential in discriminating between the very wide range of HS models. The ECAL is a lead sampling calorimeter, consisting of two parts which are mechanically separated in the longitudinal direction, each

part being equipped with a high spatial resolution layer to reconstruct ALP$\rightarrow \gamma\gamma$ decays. The muon system consists of four stations interleaved by three muon filters.

The key feature of the HS decay spectrometer design is to ensure efficient suppression of the different backgrounds. A dedicated timing detector with $\sim$100 ps resolution provides a measure of time coincidence in order to reject the combinatorial background. The decay volume is surrounded by the background taggers: the upstream muon detector of the SND, and the surround background tagger (SBT) which instruments the decay volume walls. The taggers identify neutrino and muon inelastic interactions in the material of the SND detector and in the decay volume walls, which may produce long-lived neutral particles, V^0s, decaying in the decay volume and mimicking HS signal events.

The muon shield and the SHiP detector systems are housed in an $\sim$120 m long underground experimental hall at a depth of $\sim$15 m. To minimize the background induced by the flux of muons and neutrinos interacting with material in the vicinity of the detector, no infrastructure is located on the sides of the detector, and the hall is 20 m wide along its entire length.

Simulation

The SHiP software framework is based on the FairRoot package and is called FairShip. The framework incorporates GEANT4 to trace particles through the target and the experimental setup, PYTHIA8 for the primary proton fixed-target interaction, PYTHIA6 for muon deep inelastic scattering, and the GENIE MC generator for interactions of neutrinos. Some rare processes which produce muons with relatively high momenta, such as decays of light vector mesons, γ-conversions and positron annihilation, are disabled by default in GEANT4. These have been enabled and their rates artificially boosted by a factor of 100.

The production and decays of the various Hidden Sector particles have been implemented in FairShip. PYTHIA8 is predominantly used to generate the different signal processes. For HS particles produced from the decays of charm and beauty hadrons, the effect of cascade production of charm and beauty from secondary hadrons is accounted for. This increases the expected yield for HNLs for instance, by a factor of more than two. For decays to hadronic final states fragmentation is handled by PYTHIA8.

In total, 6.5×10^{10} protons on target have been simulated with an energy cut for transporting particles after the hadron absorber of $10\,\mathrm{GeV}$, and 1.8×10^9 protons on target with an energy cut of $1\,\mathrm{GeV}$. The samples produced with charm and beauty hadrons correspond to about 10^{11} protons on target.

The validity of the FairShip prediction of the particle fluxes has been verified by comparing to the data from the CHARM beam dump experiment at CERN. The FairShip description of multiple scattering and catastrophic energy losses, which is crucial for the muon shield performance, has also been found in good agreement with existing data. The most realistic cross-check of FairShip has been performed in summer 2018 in a dedicated experiment at the CERN SPS (Fig. 2) which has directly measured the rate and momentum of muons produced by $400\,\mathrm{GeV}/c$ protons dumped on a replica of the SHiP target. The analysis of the collected 6×10^{11} protons on target is ongoing.

4 Physics performance

The physics performance of the SHiP experiment is anchored in the emphasis on an extremely efficient and redundant background suppression, and a detector which is sensitive to as many decay modes as possible to ensure a model independent search for hidden particles. A set of common benchmark models is used below to illustrate the physics sensitivity.

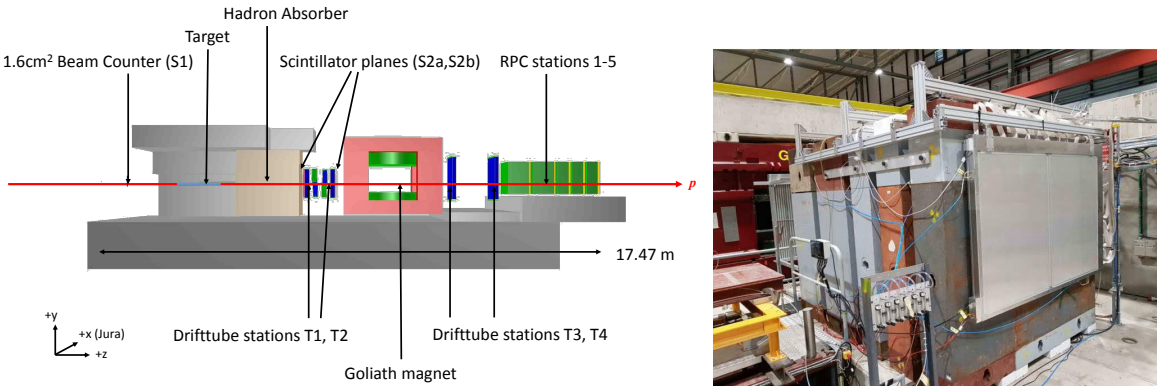

Figure 2: Layout of the spectrometer to measure the muon flux produced in the replica of the SHiP target, and a photo of the setup in the CERN H4 beam-line seen from the back.

Sensitivity to Hidden Sector particle decays

All benchmark HS models predict a signature with an isolated vertex in the HS spectrometer. Hence, HS signal candidates are required to form an isolated vertex in the fiducial volume. Table 1 summarizes the selection criteria used to estimate the signal sensitivity for the HS benchmark models. For fully reconstructed signal decays, where all particles coming from the decaying hidden particle are reconstructed in the spectrometer, it is required that the impact parameter (IP) to the target is less than 10 cm. This selection cut is very powerful in rejecting all background sources. Partially reconstructed final states (with one or more missing particles, e.g. $N \to \mu^+\mu^-\nu$) point back more loosely to the target. These final states are therefore more challenging to discriminate from the background. The signal candidates are required to have IP < 250 cm and, in addition, no associated activity in the SBT.

Cut	Value
Track momentum	$> 1.0\,\mathrm{GeV}/c$
Dimuon distance of closest approach	< 1 cm
Dimuon vertex position	(> 5 cm from inner wall)
IP w.r.t. target (fully reconstructed)	< 10 cm
IP w.r.t. target (partially reconstructed)	< 250 cm

Table 1: Selection criteria used for the sensitivity estimate and background rejection in the analysis of Hidden Sector particle decays.

The background to the searches for hidden particles includes three main classes: neutrino and muon induced backgrounds resulting from inelastic interactions in the material of the detector, and combinatorial muon background resulting from residual muons reconstructed as charged tracks in the SHiP decay spectrometer. As it was demonstrated in the SHiP Technical Proposal, backgrounds originating from cosmic muons can be reduced to a negligible level.

Large samples of neutrino and muon inelastic backgrounds, corresponding to about ten years and five years of SHiP operation, respectively, have been generated using FairShip, forcing all produced neutrinos and muons to interact with the material. The interaction points were distributed along the neutrino and muon trajectories according to the material density.

The dominant source of neutrino induced background comes from neutrino interactions in the upstream muon detector of the SND and in the walls of the decay volume. The expected number of background events with at least two reconstructed tracks of opposite charge amounts to 5×10^5 events per 2×10^{20} protons on target, to be compared with only 10^{-2} neutrino interactions inside the decay volume at $\sim$1 mbar pressure. In total, two events originating from photon conversions in the entrance of

the decay volume remain after the selection criteria for partially reconstructed final states and the veto criteria in the SBT. These type of events are rejected by an additional requirement on the decay opening angle.

The muon inelastic background is completely dominated by the muon deep inelastic scattering (DIS) in the walls of the decay volume. These background events have a high multiplicity leaving a signal in the SBT. The requirement that the SBT is not fired brings the muon inelastic background to zero. Assuming no correlation between the veto criterion based on detecting the incoming muon or the products resulting from the interaction, and the pointing requirement for the decay vertex, an upper limit on the residual background can be set as low as 6×10^{-4} and 2×10^{-5} events (at 90% CL) for partially and fully reconstructed final states, respectively.

The combinatorial muon background has been estimated using fully reconstructed muons which pass the muon shield and enter the HS spectrometer with a rate of about 25 kHz during a spill. The simulated statistics correspond to a complete spill. Unique pairs of tracks, formed out of those muons, have been subjected to the criteria listed in Table 1, and the veto criteria from the SBT and the upstream muon system of the SND. The final requirement, specifically designed to suppress combinatorial background, is the use of the timing veto detector. Applying a time window, corresponding to three times the resolution of the timing detector, a large suppression factor can be achieved by using timing information alone. Combining the criteria, the muon combinatorial background is reduced to 1.2×10^{-2} events.

In summary, Table 2 shows the upper limits for the main classes of backgrounds which can be set with the currently available simulation data samples. Simulation of neutrino background is ongoing to increase the data sample by an order of magnitude, and machine learning techniques are used to generate a larger sample of muons which enter the detector acceptance for further studies of the muon combinatorial background.

Background source	Expected events
Neutrino background	< 1
Muon DIS (factorisation)	$< 6 \times 10^{-4}$
Muon Combinatorial	4.2×10^{-2}

Table 2: Expected background to the HS particle search at 90% CL for 2×10^{20} protons on target.

All signal sensitivity curves are obtained using the FairShip simulation framework. The 90% confidence region is defined as the region in the parameter space where on average $\bar{N}_{\text{events}} \geq 2.3$ reconstructed signal events are expected in the whole mass range, corresponding to a discovery threshold with an expected background level of 0.1 events.

The HNL signal events were simulated for various masses and mixing angles $U^2_{e,\mu,\tau}$ with the SM electron, muon and tau neutrinos as the input parameters. The decays of HNLs to a large number of final states, that contain at least two charged particles, were simulated using the HNL branching fractions from [10]. The sensitivity to various HNL benchmark models was estimated by applying the selection criteria in Table 1 with the loose pointing requirements on the two body system. Fig. 3 presents the sensitivity curve for HNLs, with the benchmark assumption that the ratio between the three HNL mixing angles corresponds to ($U^2_e : U^2_\mu : U^2_\tau = 1 : 0 : 0$). For completeness, both the conservative and the optimistic sensitivity contours are shown for $f_{b\to B_c} = 0$ and $f_{b\to B_c} = 2.6 \times 10^{-3}$, respectively.

Three different mechanisms of dark photon production have been studied for estimating the sensitivity, considering at the moment only the primary proton interactions. The contribution from cascade production, which is included for the HNL and the dark scalar, is not currently taken into account for the dark photon. Dark photons with masses below $0.9\,\text{GeV}/c^2$ can mix with photons from neutral meson decays ($\pi^0 \to \gamma\gamma$, $\eta \to \gamma\gamma$, $\omega \to \pi^0\gamma$, $\eta' \to \gamma\gamma$) that are produced in non-diffractive interactions. PYTHIA8 is used to obtain an estimate of the neutral meson production rate. The proton interaction can also lead to the radiation of a dark photon via a bremsstrahlung process. This mechanism dominates

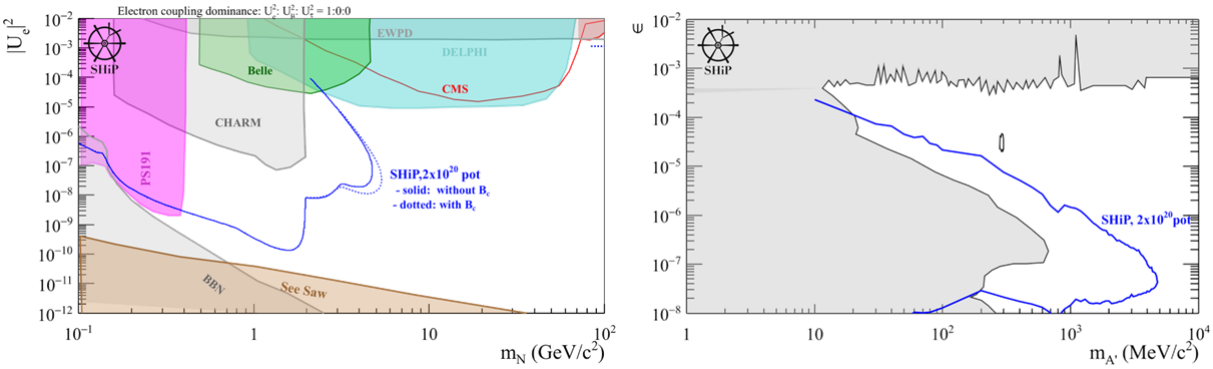

Figure 3: (Left) Sensitivity of the SHiP experiment to HNLs. The dotted curve show the contribution from B_c mesons, when the fragmentation fraction is taken equal to that at LHC energies: $f_{b\to B_c} = 2.6 \times 10^{-3}$. The solid curve does not include contributions from B_c. Below a mass of $0.5\,\mathrm{GeV}/c^2$ only production from D and B mesons is included. (Right) Sensitivity of SHiP to dark photons adding up the three production mechanisms, as described in the text. Both plots are based on 2×10^{20} protons on target (pot). The exclusion contours from existing experimental constraints are overlaid.

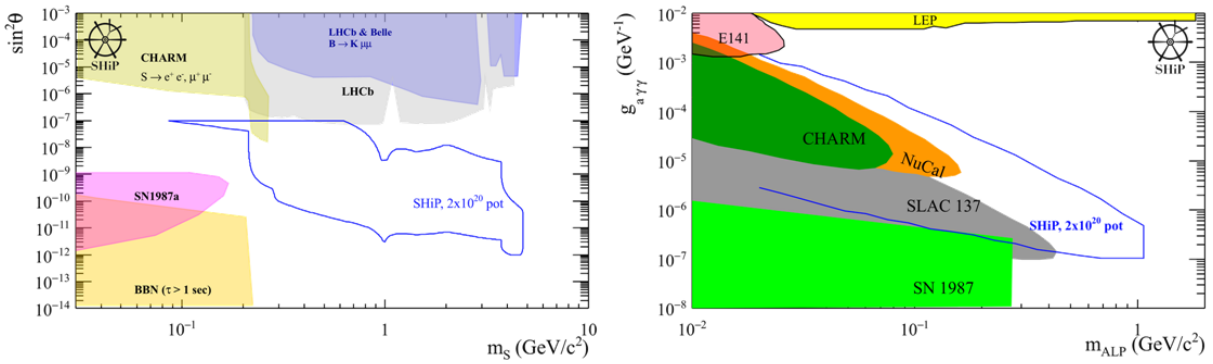

Figure 4: (Left) Sensitivity to dark scalars. Only contribution from B mesons is taken into account. (Right) SHiP sensitivity to ALP decaying to two photons. Both plots are based on 2×10^{20} protons on target (pot). The exclusion contours from existing experimental constraints are overlaid.

for dark photon masses in the range 0.4–1.3 GeV/c^2. Above $1.3\,\mathrm{GeV}/c^2$, the predominant production mechanism is quark-quark annihilation into dark photons. This process is simulated using a generic resonance that couples both to SM fermion pairs and hidden particles, as implemented in PYTHIA8 for the "HiddenValley" Z' model. The native cross section from PYTHIA8 is used for the normalisation of the process. The 90% CL exclusion contour is shown in Fig. 3 (right) adding up the three production modes studied.

The sensitivity to dark scalars is shown in Fig. 4 (left). Inclusive decays of dark scalars are considered using the inclusive $b \to SX_s$ branching fraction given in [11].

For the sensitivity to ALPs, SHiP has used the model with an exclusive coupling to photons as benchmark channel ($ALP \to \gamma\gamma$). This channel requires the ambitious angular resolution of the ECAL to cope with background from electromagnetic processes and background from neutrino interactions in the ECAL itself. Fig.4 (right) shows the SHiP sensitivity to ALPs decaying to two photons. SHiP has a unique sensitivity in the mass range between $200\,\mathrm{MeV}/c^2$ and $1\,\mathrm{GeV}/c^2$. Although it has not been studied up to now, SHiP should also have a unique sensitivity to ALPs with coupling to gluons.

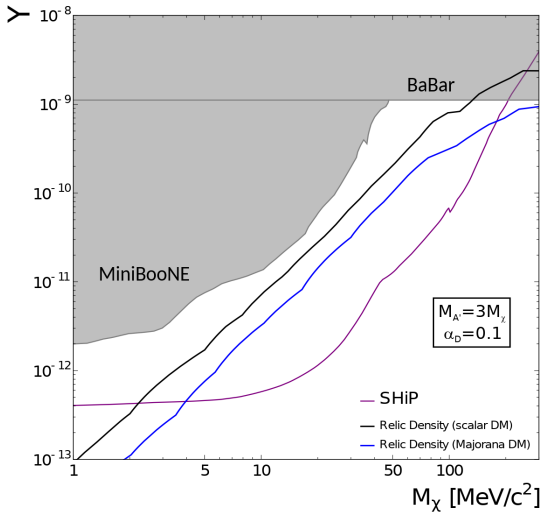

Figure 5: SHiP sensitivity to LDM produced in dark photon decays. The coupling is given as $Y = \epsilon^2 \alpha'_D (m_\chi / m_{A'})^4$. Only meson decays and Drell-Yan processes are considered here as production mechanisms for the dark photons. The grey shaded regions represent the parameter space which has been already ruled out by the searches at the BaBar and the MiniBooNE experiments.

Sensitivity to light dark matter

LDM scattering in the emulsion spectrometer produces an isolated electromagnetic shower originating from the recoil electron. The modules of the emulsion spectrometer act as fine sampling calorimeters with more than five active layers per radiation length X_0 over a total thickness of ten X_0, allowing the electron energy and incident angle to be measured accurately. The micrometric accuracy of the emulsion is crucial for detecting any associated activity at the origin of the electromagnetic shower in order to discriminate the LDM signal from background induced by neutrino interactions.

The background to the LDM search, which comes primarily from neutrino interactions with only one reconstructed electron at the interaction vertex, has been simulated with the help of GENIE. A neutrino scattering event is tagged as background if the interaction vertex is within the geometrical acceptance, and if the electron is accompanied by additional visible activity, such as charged tracks or photons. At the final stage of the selection, the LDM signal is discriminated from neutrino events with the same LDM elastic scattering topology, using the kinematic correlation between the energy and the azimuthal angle of the scattered electron.

The resulting estimate of the background levels for 2×10^{20} protons on target is shown in Table 3 for the various classes of neutrino interactions. The main source of background is due to elastic and quasi-elastic scattering events from ν_e and $\bar{\nu}_e$.

Background	ν_e	$\bar{\nu_e}$	ν_μ	$\bar{\nu_\mu}$	all
Elastic Scattering on e^-	81	45	56	35	217
Quasi-elastic Scattering	245	236	-	-	481
Resonant Scattering	8	77	-	-	85
Deep Inelastic Scattering	-	14	-	-	14
Total	334	372	56	35	797

Table 3: Number of background events in the LDM search after the selection for 2×10^{20} protons on target.

The expected SHiP sensitivity, taking into account the geometrical acceptance and the selection criteria, is shown in Fig. 5. In the region from a few MeV/c^2 to $\sim 200\,\mathrm{MeV}/c^2$ the SHiP sensitivity

reaches below the limit which gives the correct relic abundance of dark matter. The current estimate is conservative since at the moment only meson decays and Drell-Yan production have been considered as a source of dark photons decaying to LDM.

Physics with neutrinos

The neutrino fluxes produced at the beam dump were estimated with FairShip including the contribution from cascade production in the target. The integrated yield for five years of nominal operation is shown in the left column of Table 4. The number of charged-current (CC) deep-inelastic interactions in the neutrino target is evaluated by convoluting the generated neutrino spectrum with the cross section provided by GENIE. The expected number of CC DIS charm events in the target of the SND detector is reported in the right column of Table 4.

	<E>[GeV]	CC DIS interactions	<E>[GeV]	CC DIS charm prod.
N_{ν_e}	59	1.1×10^6	66	6.0×10^4
N_{ν_μ}	42	2.7×10^6	55	1.3×10^5
N_{ν_τ}	52	3.2×10^4		
$N_{\overline{\nu}_e}$	46	2.6×10^5	57	1.3×10^4
$N_{\overline{\nu}_\mu}$	36	6.0×10^5	49	2.5×10^4
$N_{\overline{\nu}_\tau}$	70	2.1×10^4		

Table 4: Left column: Expected yield of neutrino CC deep-inelastic interactions in the SND for the different neutrino flavours. Right column: Expected neutrino-induced charm production for all species except for tau neutrinos (under evaluation). 2×10^{20} protons on target are assumed.

The SND has the unique capability of detecting all three neutrino flavours and of distinguishing neutrinos from anti-neutrinos. The unprecedented yields of ν_τ and $\overline{\nu}_\tau$ interactions, shown in Table 4, provide a unique capability to make a measurement of the ν_τ ($\overline{\nu}_\tau$) differential cross-section, which in turn is sensitive to the F_4 and F_5 structure functions. Lepton flavour universality will be further tested in the neutrino sector, including an exploration of the ν_τ anomalous magnetic moment down to $1.3 \times 10^{-7} \mu_B$.

The total charm yield expected in the CC DIS interactions exceeds the statistics available in previous experiments by more than an order of magnitude. It is worth noting that the emulsion experiment with the largest neutrino flux was the CHORUS experiment at CERN, where only 2013 charm candidates coming from ν_μ, and 32 charm candidates coming from $\overline{\nu}_\mu$ interactions, were reported. No charm candidate from electron and tau neutrino interactions has ever been reported. Therefore all the studies on charm physics performed with neutrino interactions will be updated with improved accuracy, and some channels inaccessible in the past will be explored. This includes the double charm production cross-section and the search for pentaquarks with charm quark content. Charmed hadrons produced in neutrino interactions are also important to investigate the strange quark content of the nucleon. The statistics available in SHiP will have a significant impact on the knowledge of the nucleon strangeness.

5 Detector challenges and project plan

All of SHiP's sub-systems have undertaken genuine programs of prototyping to validate their performance with beam tests of small scale prototypes [12]. The results have been used in the simulation of the expected physics performance. The next level of prototyping is ongoing and consists in the preparation of larger-scale prototypes aiming to measure their global performance in beam tests in 2021, and corroborating the manufacturing techniques. This ensures validating the detector concepts in time for the Technical Design Reports in 2022, and also serves as the basis for the cost and planning of the

experiment. The engineering of the muon shield and the straw tracker, and the design of the calorimeter with the required angular resolution for the ALP$\rightarrow \gamma\gamma$ reconstruction, are considered to be particularly challenging projects.

The proposed schedule for both the SHiP experiment and the Beam Dump Facility is largely driven by the CERN long-term accelerator schedule and the unique opportunity to fully exploit the current SPS in the LHC Run 4 and Run 5. Most of the experimental facility can be constructed in parallel to operating all of the current beam facilities. However, to minimize the impact on the availability of beam in the CERN North Area during the connection of the facility to the existing beam line, and to fully profit from the operation of the accelerators in the LHC Run 4, the last phase of civil engineering and installation of the facility and the SHiP detector is planned for the Long Shutdown 3 with start of commissioning and data taking early in Run 4. The schedule is elaborated in more detail in SHiP's status report [12] and in the BDF Comprehensive Design Study report [7] submitted as supporting documents to the EPPSU.

6 Status of the SHiP collaboration

SHiP is currently a collaboration of 50 institutes and 4 associated institutes from 18 countries, CERN and JINR. The formal organisation of SHiP, which has been adopted for the Comprehensive Design Study phase, consists of a Country Representative Board (CRB), Interim Spokesperson, Technical Coordinator and Physics Coordinator, and the group of Project Conveners as elected and ratified by the CRB.

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