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# Search for new physics with the SHiP experiment at CERN

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The SHiP Collaboration has proposed a general-purpose experimental facility operating in beam dump mode at the CERN SPS accelerator with the aim of searching for light, long-lived exotic particles of Hidden Sector models. The SHiP experiment incorporates a muon shield based on magnetic sweeping and two complementary apparatuses. The detector immediately downstream of the muon shield is optimised both for recoil signatures of light dark matter scattering and for tau neutrino physics, and consists of a spectrometer magnet housing a layered detector system with heavy target plates, emulsion film technology and electronic high precision tracking. The second detector system aims at measuring the visible decays of hidden sector particles to both fully reconstructible final states and to partially reconstructible final states with neutrinos, in a nearly background free environment. The detector consists of a 50 m long decay volume under vacuum followed by a spectrometer and particle identification with a rectangular acceptance of 5 m in width and 10 m in height. Using the high-intensity beam of 400 GeV protons, the experiment is capable of integrating $2 \cdot 10^{20}$ protons in five years, which allows probing dark photons, dark scalars and pseudo-scalars, and heavy neutrinos with GeV-scale masses at sensitivities that exceed those of existing and projected experiments. The sensitivity to heavy neutrinos will allow for the first time to probe, in the mass range between the kaon and the charm meson mass, a coupling range for which baryogenesis and active neutrino masses can be explained. The sensitivity to light dark matter reaches well below the elastic scalar Dark Matter relic density limits in the range from a few MeV/$c^2$ up to 200 MeV/$c^2$. Following the review of the Technical Proposal, the CERN SPS Committee recommended in 2016 that the experiment and the beam dump facility studies proceed to a Comprehensive Design Study phase. These studies have resulted in a mature proposal submitted to the European Strategy for Particle Physics Update.

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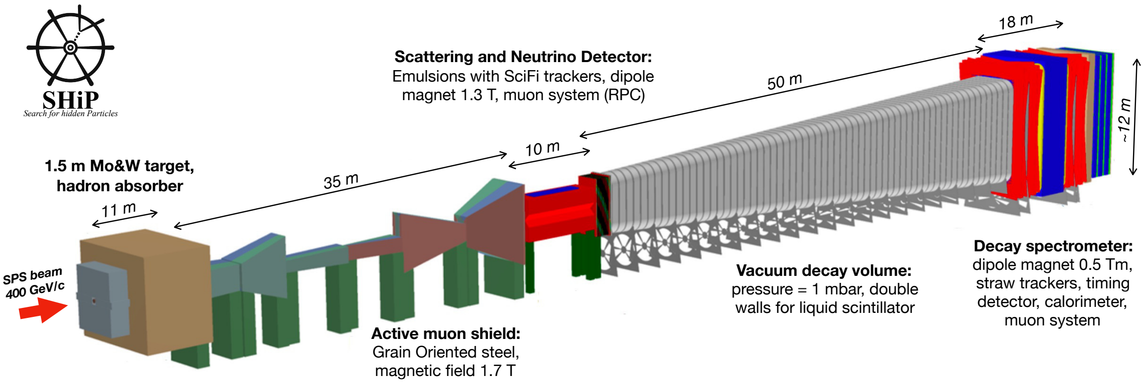


**Figure 1:** Experimental setup which includes (from left to right) the target bunker, the active muon shield, the scattering and neutrino detector and the hidden sector detector of SHiP [1, 3].

## 1. Introduction

A general-purpose experiment to search for hidden particles (SHiP) is proposed to be installed in the North Area of the CERN SPS. The experiment will use an intense beam of 400 GeV/$c$ protons and will be able to detect long lived particles in the masse range below $\mathcal{O}(10)$ GeV/$c^2$ and $c\tau$ of kilometres. The technical proposal [1] and description of physics case [2] were released by the SHiP collaboration in 2015. The latest study focusing on the detector optimisation and simulation, including beam tests results can be found in Ref. [3].

The physics programme of SHiP is aimed at searching for very weakly interacting long lived particles. SHiP will explore the so-called 'intensity frontier', i.e. looking for particles with a very low coupling to normal matter. This programme is complementary to the collider 'energy frontier' research. Low mass 'hidden sector' particles can be accessible in SHiP via their coupling to the standard model (SM) sector via renormalizable interactions with small dimensionless coupling constants, so called 'portals' [2]. Thus one can discover Heavy Neutral Leptons (right-handed partners of the SM neutrinos), dark photons (vector portal) or dark Higgs (scalar portal). Furthermore, one can check predictions of models with higher dimensional non-renormalizable couplings of new particles to the SM operators, e.g. pseudo-scalar axion-like particles.

## 2. Experimental setup

The experimental setup of SHiP consists of a target bunker, active muon shield, scattering and neutrino detector, hidden sector detector which includes the vacuum decay vessel and magnetic spectrometer as shown in Fig. 1.

A new junction cavern and extraction tunnel are proposed to be built in the North Area of CERN to house the new beam-line leading protons to the *Beam Dump Facility* (BDF) complex [4]. A 1.5 m long production target will be located inside the radiation protecting bunker at about 15 metres below ground level. The choice of the target material is driven by the requirement of maximising the relative production of charm and beauty hadrons. High-Z materials, molybdenum and tungsten, assure the re-absorption of pions and kaons, thus reduce the flux of muons and the associated muon neutrinos. The target will have to sustain an intensity of $4.2 \times 10^{13}$ protons per spill which corresponds to the beam power on target during spill of 2.56 MW. In order to prevent melting, an active water cooling will be provided. At such intensity a flux of $1.6 \cdot 10^{12}$ $\nu$ and $\bar{\nu}$ per spill is expected within the angular acceptance of the SHiP detector.

The area downstream of the target is occupied by 4.5 m long stainless-steel blocks with a magnetic coil on top to provide a field of 1.6 T. It represents the first stage of the *active shielding* which sweeps muons produced in the target away from the detector acceptance to reduce experimental SM backgrounds. The order of $10^{11}$ $\mu$/spill still exit the target bunker. It motivates an additional series of free-standing magnets of about 35 m long to deflect the muons [5]. The magnets are build of grain-oriented steel providing up to 1.7 T field in the critical regions. As a result, the muon flux is reduced by 6 orders of magnitude at the entrance point to the SHiP detector.

The SHiP detector incorporates two complementary apparatuses which will search for hidden particles through both visible decays and through scattering signatures from recoil of electrons or nuclei. A sensitivity to many decay modes will be important for a model-independent study. The *scattering and neutrino detector* (SND) is located downstream of the muon shield. The core of the detector is a 10 ton emulsion-based target located inside a 7 m long dipole magnet. This setup is complemented with a muon identification system assembled of iron filter and RPC planes. The nuclear emulsion technology makes possible to identify the three (anti-)neutrino flavours: $\nu_e$, $\nu_\mu$, $\nu_\tau$. The programme of SND is largely dedicated to the SM physics [6]. It is expected to reconstruct $10^4$ $\tau$ (anti-)neutrino vertices within 5 years of data-taking. One will also study a neutrino-induced charm production and nuclear effects by measuring the structure functions. Furthermore, the SND has a capability to register recoil signatures of light dark matter (DM) particles.

The second *HS detector* aims at measuring the decay vertices of hidden sector particles. The fiducial volume is represented by a 50 m long decay vessel. In order to suppress neutrino-induced background events inside the volume, the vacuum vessel will be maintained at a pressure of 1 mbar. The wall structure of the vessel is composed of 2–3 cm thick steel sheets welded in such a way as to form compartments. These compartments will be filled with a liquid scintillator which will act as a tagger [7] for background processes as decays of neutral mesons or neutrino interactions. The decay vessel ends with a magnetic spectrometer which is designed to fully reconstruct the exclusive decay vertices of hidden sector particles. The dipole magnet with the field integral of about 0.5 Tm bends charged particle trajectories in a vertical plane. Two stations of straw trackers are located up- and two stations downstream of the magnet. They provide a spatial resolution on a level of 120 $\mu$m. A dedicated timing detector provides the start time for the straw tubes and suppresses the combinatorial background by tagging tracks belonging to a single vertex with a temporal resolution of 100 ps [8, 9]. Particle identification is provided by SplitCal and muon systems.

SplitCal is a modified version of electromagnetic calorimeter. It is a $25X_0$ long sampling calorimeter assembled of 40 layers of lead and plastic scintillator which are spread out in space by about 2 m. Furthermore, SplitCal contains three tracking layers. They will serve to determine the direction of a shower, thus makes possible to provide a few mrad angular resolution for photon trajectories. The muon system is located downstream of the calorimeter and is built of four stations of plastic scintillator layers (tiles or bars) interleaved by the three muon filters (iron or concrete walls). It will identify muons in the momentum range of few – 100 GeV/$c$.



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## 3. Sensitivity study for hidden sector particles

A sensitivity of SHiP to the hidden sector particle as well as comparison to other experiments is presented in Figs 2-4. The statistic estimate is based on the assumption of using a similar fraction of beam time as the past CERN Neutrinos to Gran Sasso (CNGS) programme, i.e. an annual yield of $4 \times 10^{19}$ protons to the SHiP experimental facility and a total of $10^{19}$ to the other physics programmes at the CERN North Area, while respecting the beam delivery required by the HL-LHC. The physics sensitivities are thus calculated assuming a total of $2 \cdot 10^{20}$ protons on target (POT), which will be achieved in 5 years of nominal operation.

The search for a new particle requires efficient and redundant background suppression. A reconstructed isolated vertex in the HS spectrometer is an input to the analysis procedure [3]. One can distinguish three main contributions to the background searches. (I) muon combinatorial background: two muon tracks can be occasionally close in space, thus can mimic a decay vertex. Using the timing detector information this contribution can be reduced to $4.2 \cdot 10^{-2}$ for 5 years of operation. (II) inelastic interaction of muons in the material of the detector and the cavern walls. Neutral long-lived SM particles produced in these interactions can decay inside the fiducial volume. With proper selection cuts this contribution can be reduced down to $6 \cdot 10^{-4}$. (III) inelastic interaction of neutrinos which happens in the inner part of the vacuum vessel. It is the dominant source of background which can be suppressed only down to 0.1 level for 5 years of operation.

It was demonstrated in the $\nu$MSM model that by adding just three HNLs to the Standard Model one can explain neutrino oscillations, the origin of the baryon asymmetry of the Universe and also provide a dark matter candidate [11]. Two of the HNLs should have masses in the GeV range, thus can be detected by SHiP as originated from the charm or beauty decays. The sensitivity curves for *HNL*s mixing to only one SM flavour are shown in Fig. 2. Due to the fact that the $b$-quark fragmentation function $f(b \to B_c)$ is unknown at SHiP energies, two estimates are presented: the optimistic one for which $f(b \to B_c)$ is taken from the LHC measurements and the pessimistic estimate where $B_c$ mesons are not included at all [10].

*Dark photons* (DP) represent a vector field of gauge bosons which appears in an extension of SM with a U(1) gauge group. Only primary proton-proton interactions were considered in the sensitivity estimate. Three different production modes were investigated: mixing with photons from neutral meson decays, radiation via bremsstrahlung and quark-quark annihilation. Only visible decays of the DP into pairs of fermions were taken into account. The parameter space for DP attainable for SHiP is shown in Fig. 3 (left). The sensitivity region for long-lived DM, *WIMP*, that couple to electromagnetic current via DP is shown in Fig. 3 (right). WIMPs can be detected in SND as an isolated electromagnetic shower originating from the recoil electron.

In order to solve the strong CP problem in QCD, a pseudo Nambu-Goldstone bosons, axion, with a mass of about $10^{-5}$ eV was introduced. The SHiP experiment is not sensitive to the QCD axions. However an extension of the axion model into the MeV-GeV mass range gives rise to another hypothetical pseudo-scalar particle known as *axion-like particle* (ALP). Thanks to the longitudinal segmentation of the SHiP calorimeter, one can measure the trajectory of photons originated from the $ALP \to \gamma\gamma$ decays with angular precision of 5 mrad. The parameter space for the coupling of ALPs with photons is shown in Fig. 4 (left). Plots presenting the ALP coupling with fermions and gluons can be found in Ref. [12].



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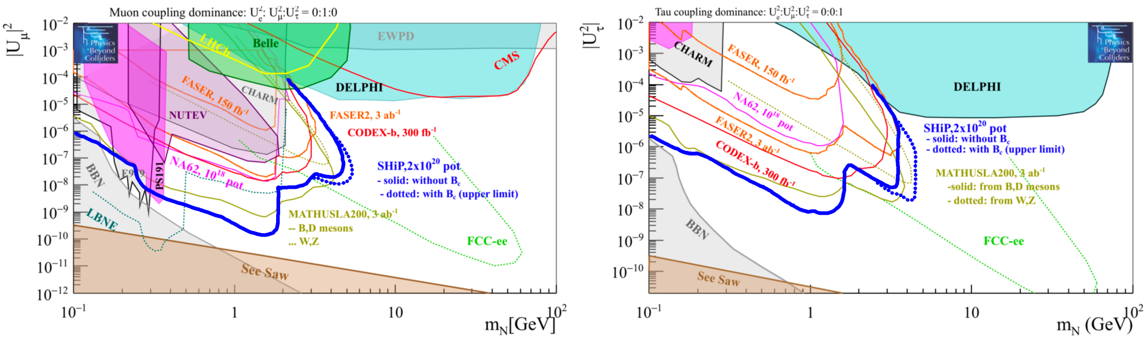


**Figure 2:** Sensitivity regions for Heavy Neutral Leptons assuming the exclusive coupling to muon (left) and tau (right). For the coupling to electron see Ref. [10, 12].

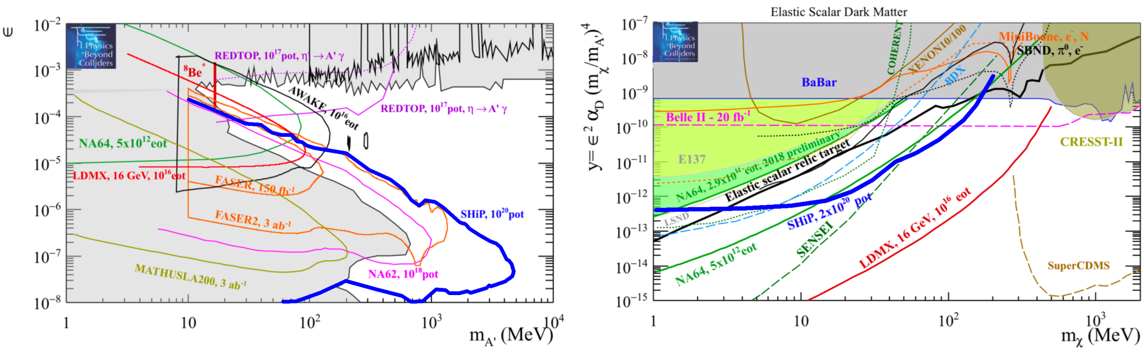


**Figure 3:** Sensitivity regions for dark photons (left) and light dark matter (right) [12].

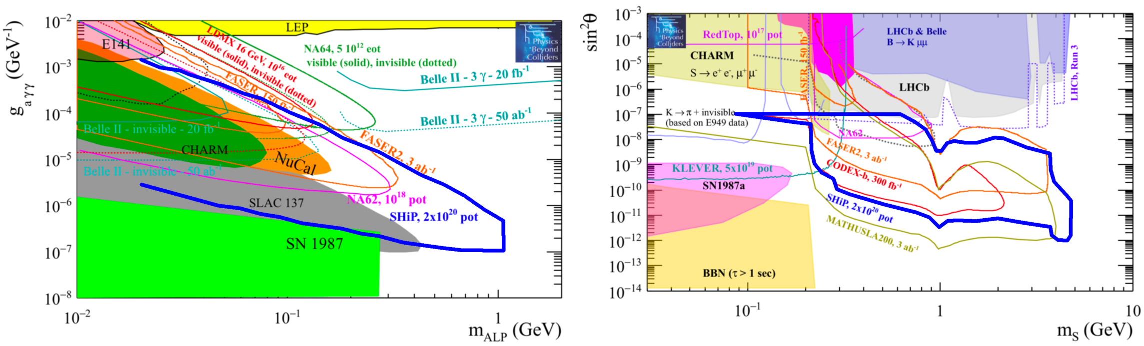


**Figure 4:** Sensitivity regions for axions-like particles (left) and dark scalars (right) [12].

Neutral gauge-singlet scalers can couple to the SM Higgs field. The presence of such states is predicted in many extensions of SM Higgs sector. Dark scalars are produced in decays of kaons, D and B mesons. Decays of scalars into pair of leptons or mesons can be detected. The sensitivity of SHiP to dark scalars is shown in Fig. 4 (right).

## 4. Conclusions

The SHiP experiment is proposed to explore the intensity frontier in the framework of study of new physics beyond the standard model. The experiment will require a new infrastructure in the North Area of the CERN SPS: extraction tunnel, target complex, experimental area. The detector is designed to fully reconstruct exclusive decays of the hidden sector particles and to reject the background down to below 0.1 events in the sample of $2 \cdot 10^{20}$ POT for the five years of operation. The schedule for the SHiP experiment is largely driven by the CERN long-term accelerator schedule. The comprehensive design report (CDR) will be submitted by the collaboration in 2020 and the technical design report (TDR) will be prepared by 2022. After the phase of civil engineering work and installation of the facility, the start of data-taking is planned for the LHC Run 4 (currently 2027-2029).

## References


[1] SHIP collaboration, M. Anelli et al., *A facility to Search for Hidden Particles (SHiP) at the CERN SPS*, 1504.04956.

[2] S. Alekhin et al., *A facility to Search for Hidden Particles at the CERN SPS: the SHiP physics case*, *Rept. Prog. Phys.* **79** (2016) 124201, [1504.04855].

[3] SHIP COLLABORATION collaboration, C. Ahdida et al., *SHiP Experiment - Progress Report*, Tech. Rep. CERN-SPSC-2019-010. SPSC-SR-248, CERN, Geneva, Jan, 2019.

[4] K. Kershaw et al., *Design Development for the Beam Dump Facility Target Complex at CERN*, *JINST* **13** (2018) P10011, [1806.05920].

[5] SHIP collaboration, A. Akmete et al., *The active muon shield in the SHiP experiment*, *JINST* **12** (2017) P05011, [1703.03612].

[6] A. Pastore, *Neutrino physics with the SHiP experiment at CERN*, *Proceedings, EPS-HEP2019: Ghent, Belgium, July 10-17, 2019* .

[7] M. Ehlert et al., *Proof-of-principle measurements with a liquid-scintillator detector using wavelength-shifting optical modules*, *JINST* **14** (2019) P03021, [1812.06460].

[8] A. Korzenev et al., *Plastic scintillator detector with the readout based on an array of large-area SiPMs for the ND280/T2K upgrade and SHiP experiments*, in *International Workshop on New Photon Detectors (PD18) Tokyo, Japan, November 27-29, 2018*, 2019, 1901.07785.

[9] C. Betancourt et al., *Application of large area SiPMs for the readout of a plastic scintillator based timing detector*, *JINST* **12** (2017) P11023, [1709.08972].

[10] SHIP collaboration, C. Ahdida et al., *Sensitivity of the SHiP experiment to Heavy Neutral Leptons*, *JHEP* **04** (2019) 077, [1811.00930].

[11] T. Asaka and M. Shaposhnikov, *The nuMSM, dark matter and baryon asymmetry of the universe*, *Phys. Lett.* **B620** (2005) 17–26, [hep-ph/0505013].

[12] J. Beacham et al., *Physics Beyond Colliders at CERN: Beyond the Standard Model Working Group Report*, 1901.09966.


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