8 Particle Physics with SHiP

C. Betancourt, I. Bezshyiko, E. Graverini, P. Owen, N. Serra, B. Storaci

The full SHiP collaboration consists of 45 institutes from Bulgaria, Chile, Denmark, France, Germany, Italy, Japan, Russia, Sweden, Switzerland, Turkey, Ukraine, the United Kingdom and the United States of America.

(SHiP Collaboration)

SHiP is a newly proposed general purpose fixed target facility at the CERN SPS accelerator. A 400 GeV proton beam will be dumped on a heavy target in order to produce 2×10^{20} proton-target interactions in five years. A dedicated detector downstream of the target will probe a variety of models with light long-lived exotic particles with masses below $\mathcal{O}(10\,\mathrm{GeV/c^2})$. Active neutrino cross-sections and angular distributions will also be studied, thanks to a dedicated detector placed between the target and the hidden sector detector [1].

SHiP's flagship goal is to use decays of charm and beauty mesons to search for Heavy Neutral Leptons (HNLs), which are right-handed partners of the Standard Model (SM) neutrinos. The existence of such particles is strongly motivated by theory, as they can simultaneously solve multiple problems left open by the SM. In the Neutrino Minimal Standard Model (νMSM), HNLs allow to explain the baryon asymmetry of the Universe, account for the pattern of neutrino masses and oscillations and provide a dark matter candidate [2].

Our group was one of the founding groups since the Expression of Interest submitted in 2013 [1]. We continue to play a leading role by taking charge of the physics programme (Nicola Serra is convener for the SHiP physics performance) and of part of the detector design and R&D (Barbara Storaci is convener for the upstream veto and timing detectors).

The experiment has recently been positively reviewed by the relevant scientific committee at CERN (SPSC), who requested the preparation of a Comprehensive Design Report (CDR). The CDR will be incorporated into the European Strategy Document of CERN which will be prepared by the year 2019.

[1] W. Bonivento *et al.*, arXiv:1310.1762, SPSC-EOI-010.

[2] A. Takehiko, S. Blanchet and M. Shaposhnikov, Phys. Lett. B631 151-156 (2005)

8.1 SHiP detector

A dedicated beam line extracted from the SPS will convey a 400 GeV/c proton beam at the SHiP facility [3, 4]. The beam will be stopped in a Molybdenum and Tungsten target, at a center-of-mass energy of about 27 GeV. Approximately 2×10^{20} proton-target collisions (PoT) are foreseen in five years of operation. The target will be followed by a hadron stopper and a system of shielding magnets to sweep muons away from the fiducial decay volume. A neutrino detector consisting of OPERA-like bricks of laminated lead and emulsions, followed by a tracker and a muon spectrometer, will allow for measurement and identification of charged particles produced in charged current neutrino interactions. An upstream tagger will help detect and veto charged particles produced in front of the main decay volume, contained in a 50 m long cylindrical vacuum vessel with elliptical section. A straw tagger is placed in vacuum 5 m downstream of the entrance lid of the vessel. An additional background tagger surrounds the fiducial decay volume. Its walls enclose 30 cm of liquid scintillator. The Hidden Sector (HS) detector will comprise: a tracking system placed in vacuum at the end of the vessel, made of 5 m long straw tubes organized in four stations in a 1 Tm magnetic field; a high-accuracy timing detector; and a particle identification system featuring electromagnetic and hadronic calorimeters followed by a muon system made of four active layers interlaced with iron.

Recently, we played a leading role in studying the reoptimization of the SHiP detector. In order to get closer to the target, thereby increasing the acceptance, the vacuum vessel was redesigned with a conical shape. In addition, the sweeping magnet was also reoptimized. The layout of the SHiP experiment after the reoptimization is shown in Fig. 8.1.

[3] W. Bonivento *et al.*, arXiv:1310.1762, SPSC-EOI-010.

[4] M. Anelli *et al.*, [SHiP Collab.], arXiv:1504.04956.

8.2 SHiP studies

8.2.1 SHiP magnet studies

I. Bezshyiko

A muon flux of 10^{11}/spill is expected in SHiP. These muons could incur background, and hence their flux has to be reduced by several orders of magnitude over the shortest possible distance to achieve the largest possible acceptance for HNLs. SHiP adopted the use of a series of magnets to deflect the muons out of the acceptance of the spectrometer. The muon shield had the strict requirement to sweep muons out of the (x,y)=(5,10) m area at the

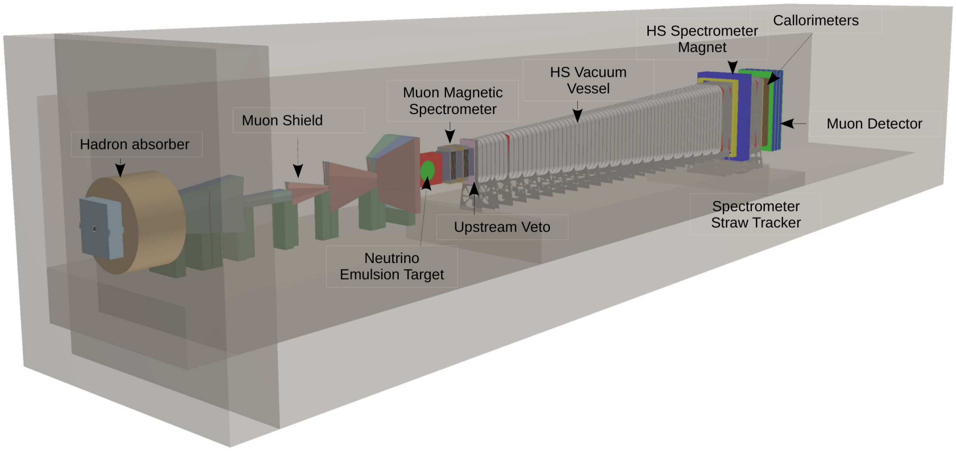

FIG. 8.1 – Overview of the SHiP detector. From left to right we have: the target, followed by the hadron stopper, the muon shield, the neutrino and Light-Dark-Matter detector (emulsion detector and muon magnetic spectrometer), the Hidden Sector vacuum vessel and the Hidden Sector spectrometer. The latter consists of straw tube tracking stations, a dipole magnet, a veto-timing detector, a calorimeter system and a muon system.

beginning of the decay vessel in the configuration of the technical proposal. SHIP now moved to a conical vessel design, which relaxes the requirement of the shield, having to clear only 5x10 m at the position of the last tracking station.

Our group took a major role in the optimization of the active muon shield for the new SHiP geometry configuration. The optimization had the goal to reduce the amount of used iron, but maintain a decent muon reduction. New procedures were developed for simulation and optimization of the shield magnets taking into account the total mass of the magnets and the background level from muons in the spectrometer. A special function was written in the FAIRROOT framework to configure the magnets taking into account the necessary space for their coils and shaping their armature to reduce their magnetic reluctance. The total mass of iron for the muon shield was reduced from 2896 to 1845 tons while keeping the background level from muons at an acceptable level [5].

[5] I. Bezshyiko, H. Dijkstra, "The Active Muon Shield", CERN-SHiP-NOTE-2016-005.

8.2.2 Timing detector

C. Betencourt, R. Bründler, N. Serra and B. Storaci

Background muons, mostly backscattered from the surrounding walls, can enter the decay vessel and can be reconstructed as fake signals. This combinatorial di-muon background is randomly distributed in time along the whole length of a spill, so an effective rejection of these events would be a coincidence timing requirement. In order to reduce this background to an acceptable level, a dedicated timing detector located between the spectrometer and the calorimeters with a timing resolution of 100 ps or less is required [6].

Our group is studying one option for such a detector consisting of rows of plastic scintillating bars, readout on either end by Silicon Photomultipliers. Such a technology has already been shown to resolve signals on the sub 100 ps range [7]. Effort is ongoing to optimize the geometry and electronic readout of such a set-up as would be appropriate for SHiP. Initial studies indicate that a resolution down to 50 ps is possible [8].

[6] M. Anelli *et al.*, [SHiP Collab.], arXiv:1504.04956.

[7] P. Cattaneo *et al.*,
IEEE Trans. Nucl. Sci. 61, 2657, (2014).

[8] C. Betancourt *et al.*, JINST 12, (2017).

8.2.3 Background studies

I. Bezshyiko, and N. Serra

The flux of neutrinos is estimated to be 10^{11} neutrinos per spill, with an energy spectrum ranging from 2 GeV to about 350 GeV. A large statistic sample of neutrino interactions with the detector material was simulated, corresponding to the amount of neutrino interactions expected in five years of SHiP operation. Neutrino interactions were found to mainly take place in the muon magnetic spectrometer of the tau neutrino detector, in the entrance window of the vacuum vessel and in its surrounding walls. The probability that neutrinos interact with the residual gas inside the decay volume is negligible if the vacuum pressure is 10^{-6} bar. A more detailed analysis showed that many of these background events can be rejected by using the veto tagger and requiring that the reconstructed candidate points back to the primary target [9]. This would allow to relax the requirements on the vacuum pressure.

The topology of the products of the neutrino interactions is such that relatively loose selection cuts allow efficient rejection. Table 8.1 shows that no HNL candidates were found which satisfy all the selection cuts. Less than 0.1 background events were found for non-pointing events without using the information from the surround veto tagger. Detailed investigation

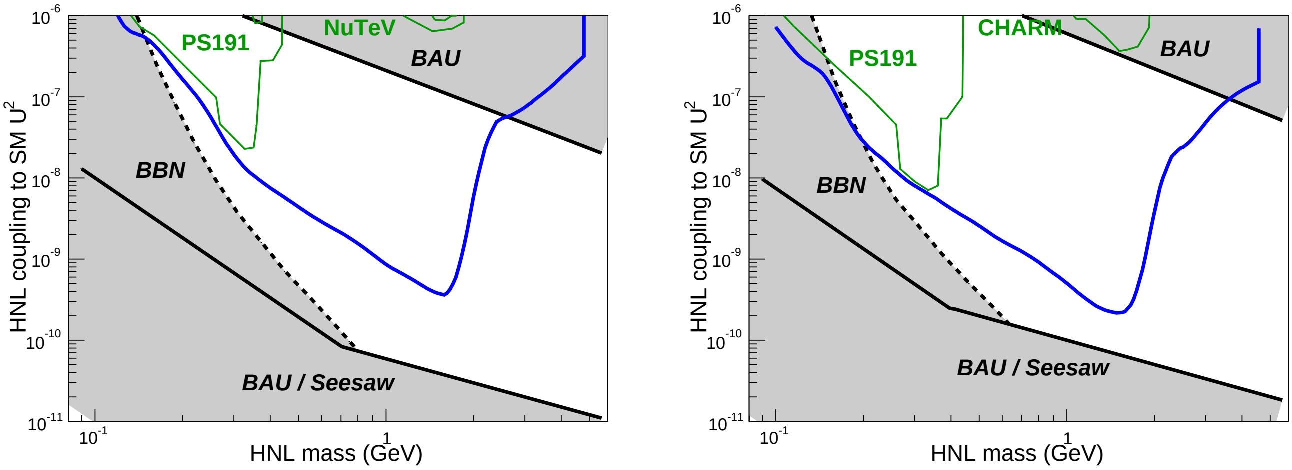

FIG. 8.2 – SHiP's sensitivity to HNLs assuming normal (left) or inverted (right) hierarchy of the SM neutrino masses. The parameter space of the νMSM is superimposed.

of these events revealed a strong correlation between the reconstructed vertex and the geometrical position of the closest hit in the vacuum tagger, which allows to make the selection based on only part of the tagger. In general the interaction products do not point to the target, do not have a reconstructed vertex inside the decay volume, and have very poor track quality.

TAB. 8.1 – Expected neutrino background in 5 years

Selection type	HNL cand.
Pointed events, with veto system	0
Pointed events, no veto system	0
Non-pointed events, with veto system	0
Non-pointed events, no veto system	<0.1

[9] M. Anelli *et al.*, [SHiP Collab.], arXiv:1504.04956.

8.2.4 SHiP sensitivity

E. Graverini, N. Serra and P. Owen

Our group has provided the official SHiP sensitivity estimates for the νMSM, the SHiP flagship theory, and for dark photons, the gauge bosons of a minimalistic theory based on the breaking of a $U(1)$ symmetry in the HS.

The SHiP physics sensitivities are evaluated on the basis of the official simulation and reconstruction package, called FAIRSHIP, the development of which our group contributed substantially, and of a fast Monte Carlo simulation developed in order to determine both the rate of HNLs produced at the target and the acceptance of the HNL decay products. From these estimates, the expected number of events in five years of SHiP operation is calculated. SHiP's sensitivity to HNLs assuming normal or inverted hierarchy of the SM neutrino masses is shown in Fig. 8.2.

The official software and the fast simulation were compared and validated against each other. The official software, that contains a full GEANT4 description of the material and detector geometry, was used to devise offline selections able to suppress the background while maintaining a large signal acceptance. To assess the impact of the reconstruction and selection on the signal, a correction to the fast simulation is applied as a function of the mass of the HNL, based on the outcome of the full simulation, separately for two body and three body decays.

A very similar method, analogous the one used by the authors of [10], was used to estimate SHiP's sensitivity to dark photons. SHiP's sensitivity is shown in Fig. 8.3. Several other models with hidden particles can be studied at SHiP and are described in Ref. [11].

[10] J. Blümlein and J. Brunner,
Phys. Lett. B731 (2014).

[11] S. Alekhin et al.,
arXiv:1504.04855, CERN-SPSC-2015-017.

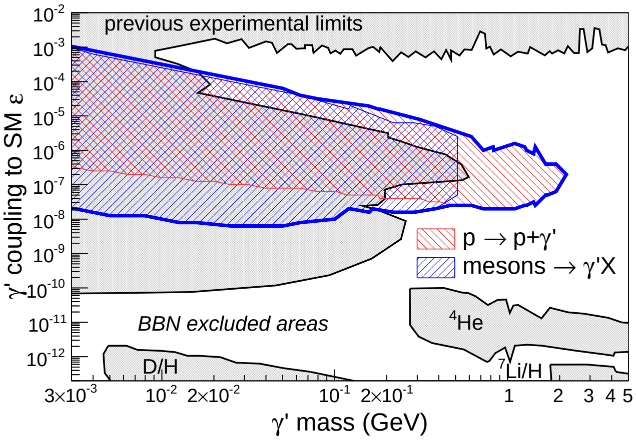

FIG. 8.3 – SHiP's sensitivity to dark photons. Previous searches, as well as limits from cosmological observations, are superimposed.