9 Particle Physics with SHiP

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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 allow one to probe a variety of models with light long-lived exotic particles with masses below $\mathcal{O}(10\ \text{GeV/c}^2)$. Active neutrino cross-sections and angular distributions will also be studied, thanks to a dedicated detector placed between the target and the downstream 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 can 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]. Since then, we played a leading role by taking responsibility of the physics programme (Nicola Serra is convener for the SHiP physics performance group) and of part of the detector design and R&D (Barbara Storaci is convener for the upstream veto and timing detectors).

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

9.1 SHiP detector

A dedicated beam line extracted from the SPS will convey a 400 GeV/c proton beam at the SHiP facility [1,3]. Figure 9.1 shows an overview of the setup.. The beam will be stopped in a Molybdenum and Tungsten target, at a center-of-mass energy $E_{CM} = \sqrt{2E_b m_p} \simeq 27$ GeV. Approximately 2×10^{20} proton-target collisions are foreseen in 5 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 measurement and identification of charged particles produced in charged current neutrino interactions. An upstream tagger will help to detect and veto charged particles produced in front of the main decay volume, which is contained in a 50 m long cylindrical vacuum vessel with elliptical section, of semi-axes 2.5 m and 5 m, at about 64 m from the target. 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, whose 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 4 stations in a magnetic field of 1 T; 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.

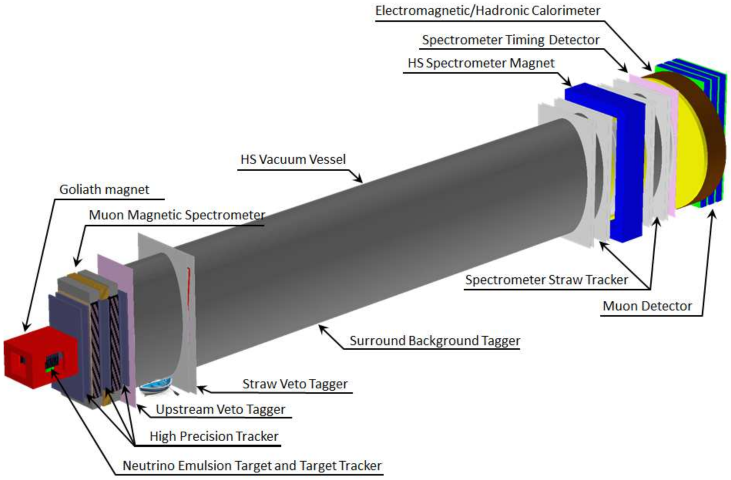

FIG. 9.1 – Overview of the SHiP detector.

[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).

Our group has also lead the optimization studies for the shape of the vacuum vessel containing the HS decay volume. The length of the decay volume is obtained by maximizing the acceptance to the hidden particle decay products given the transversal size, fixed by the muon sweeping power of the upstream magnet.

9.1.1 Timing detector

C. Betancourt, I. Bezshyiko, N. Serra and B. Storaci

Background muons crossing the decay volume represent a significant source of combinatorial background. It can be removed by requiring that the two tracks mimicking a genuine signal event are coincident in time. This requires a time resolution equal to, or even smaller than, 100 ps. For this reason, a dedicated timing detector, placed in front of the calorimeter system, is required.

Two technologies are considered for the timing detector: plastic scintillating bars and multi-gap resistive plate chambers (MRPC). Both technologies can be based on existing and well-studied designs and reach the desired time resolution of 100 ps [3]. Our group is involved in studies of scintillating bars read by Silicon Photomultiplier (SiPM) arrays. We are presently conducting tests in the laboratory to measure the time resolution for different geometry and configurations of SiPM arrays.

[3] M. Anelli *et al.*, [SHiP Collab.], arXiv: .CERN-SPSC-2015-016.

9.2 SHiP physics performance

At the energy accessible at the SPS, the hidden particles are predominantly produced in decays of hadrons, in particular in decays of charmed and beauty hadrons above the kaon mass, and in proton bremsstrahlung. In comparison with the couplings between the particles of the SM, the hidden sector couplings with SM particles are very suppressed, leading to expected production rates of $\mathcal{O}(10^{-10})$ or less. The principal background to the hidden particle decay signal originates from the inelastic scattering of neutrinos and muons in the vicinity of the detector, producing long-lived V^0 particles. Another source of background comes from random combinations of tracks in the fiducial volume from the residual muon flux, or other charged particles from interactions in the proximity, which enter the decay volume and together mimic signal events. The contribution of cosmic muons to both types of background is expected to be small [3].

Since our group leads the studies about the SHiP physics performance, we have conducted a thorough study of the neutrino-induced background and coordinated the analyses of the other background sources. With our statistical power, no evidence of any irreducible background was found.

9.2.1 Background studies

I. Bezshyiko, N. Chételat, E. Graverini, N. Serra and B. Storaci

The neutrino flux is estimated to be 10^{11} neutrinos per spill, with an energy spectrum ranging from 2 GeV to about 100 GeV. A sample of neutrino interactions with the detector material was simulated, corresponding to five years of SHiP operation. Neutrino interactions were found to take place mainly in the muon magnetic spectrometer of the tau neutrino detector, in the entrance window of the vacuum vessel and in the surrounding walls of the vacuum vessel. The probability that neutrinos interact with the residual gas inside the decay volume is negligible if the vacuum pressure is set to 10^{-6} bar. A more sophisticated analysis showed that many of these background events can be rejected by making use of the surrounding veto tagger and topological cuts, which would relax the requirements on the vacuum pressure.

The topology of the products of the neutrino interactions is such that relatively loose selection requirements allow efficient rejection. 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. The requirement of having two tracks with a reduced χ^2 below 5, forming a vertex with a maximum width of 30 cm, and with an impact parameter with respect to the proton target below 5 m rejects 99.4% of the reconstructed background-induced candidates. At the level of online selection, the requirement of having at least one veto detector with a positive response, together with a loose requirement on the pointing of the interaction products to the target, rejects about 99.5% of tracks coming from neutrino interactions.

The combination of veto detectors and offline selections reduces the neutrino induced background to zero expected events in five years of running. The set of selections applied is highly redundant and can be trimmed down to study specific channels. Tab. 9.1 shows the effect of three sets of selections on two exotic decays (HNLs and dark photons) and on neutrino-induced background. Events with multiple reconstructed candidates are discarded, as well as those with vertices and tracks not fully contained in the fiducial decay volume. High quality tracks and vertices are then selected, and candidates not pointing back to the target or with activity registered in the background-tagging detectors are discarded.

Tab. 9.1 –
Efficiency of the selection requirements for the HNL and dark photon decays, and for neutrino-induced background.

Sample	Vertex Isolation	Fiducial Volume	Event Selection
$HNL \to \pi\mu$	97.5 %	76.1 %	82.0 %
$\gamma' \to \mu\mu$	99.6 %	85.2 %	88.4 %
ν bkg.	79.1 %	21.0 %	0.0 %

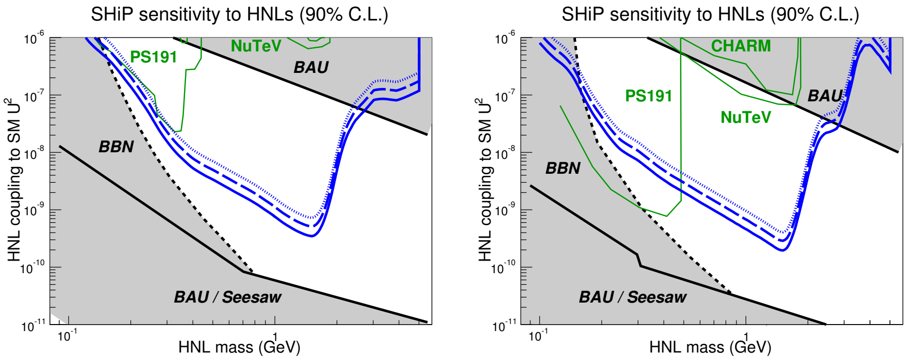

FIG. 9.2 – SHiP's sensitivity to HNLs assuming normal (left) or inverted (right) hierarchy of SM neutrino masses. The parameter space of the νMSM is superimposed. The solid blue curve represents the 90% C.L. upper limit assuming 0.1 background events in 2×10^{20} proton-target collisions. The dashed blue curve assumes 10 background events. The dotted blue curve assumes a 60% systematic uncertainty on the level of background, i.e. 10 ± 6 background events.

9.2.2 SHiP sensitivity

I. Bezshyiko, E. Graverini, N. Serra and B. Storaci

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, to the development of which our group contributed substantially, and of a fast Monte Carlo simulation developed by Elena Graverini 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 5 years of SHiP operation is calculated. 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 using the full simulation outcomes as a function of the mass of the HNL, for two body and three body decays. SHiP's sensitivity to HNLs as a function of their mass and couplings, for normal and inverted hierarchy of SM neutrinos, is shown in Fig. 9.2.

A very similar method, analogous the one used by the authors of [4], was used to estimate SHiP's sensitivity to dark photons (see Fig. 9.3). To derive the limits, the results of the three channels identified earlier (meson decays, bremsstrahlung, and direct QCD production) were used. Bremsstrahlung production must be accompanied by a form factor suppression, if the mass of the dark photon is above the typical QCD scale.

Several other models with hidden particles can be studied at SHiP and are described in Ref. [5].

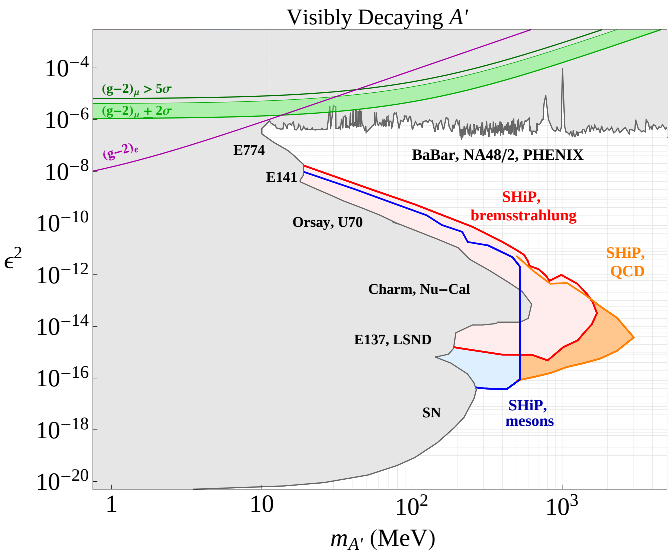

FIG. 9.3 – SHiP's sensitivity to dark photons. Previous searches, as well as limits from cosmological observations, are superimposed. The projected SHiP sensitivity contour is derived using three modes of production: mesons, bremsstrahlung, and QCD production.

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

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