9 Particle Physics with the proposed SHiP experiment

N. Chételat (since March 2015), E. Graverini, B. Kilminster, 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)

Apart from the observed neutrino oscillations the Standard Model (SM) describes all known microscopic physics phenomena with great precision. The existence of Dark Matter and the matter-antimatter asymmetry in the Universe give additional evidence that the SM is not a complete theory. All these deficiencies could be addressed by adding (at least three) right-handed neutrinos to the SM particle content, particles also known as sterile or Majorana neutrinos or Heavy Neutral Leptons (HNLs).

SHiP is a newly proposed general purpose fixed target experiment at the CERN SPS accelerator with as primary goal the search for HNLs in the mass region below 5 GeV, improving by roughly four orders of magnitude the present experimental sensitivities. SHiP would operate with a beam energy of 400 GeV dumped into a heavy target. A total of 2×10^{20} Proton on Target (PoT) would be studied during 5 years of data taking.

In addition to the search for HNLs, for which the experiment was optimized, SHiP can test several other models of physics beyond the SM, involving very weakly interacting long-lived particles. A detailed description of the SHiP physics case can be found in Ref. [1].

Our group has been active in SHiP since the submission of the Expression of Interest in 2013 [2]. We play a leading role by taking responsibility of the physics programme (Nicola Serra is the physics convener) and of part of the detector design and R&D (Barbara Storaci is convener for the upstream veto and timing detectors).

9.1 the SHiP detector

A dedicated beam line extracted from the SPS will convey a 400 GeV/c proton beam at the SHiP facility [2, 3]. 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. Figure 9.1 shows an overview of the setup. The target will be followed by a hadron stopper and by a system of sweeping magnets primarily to keep 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 to detect charged particles produced in charged current neutrino interactions. An upstream tagger will help to veto charged particles entering the main decay volume, defined by a 60 m long vacuum vessel of elliptical cross section with semi-axes 2.5 m and 5 m. A straw tagger is placed 5 m downstream of the entrance window of the vessel. A liquid-scintillator background tagger surrounds the fiducial decay volume.

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

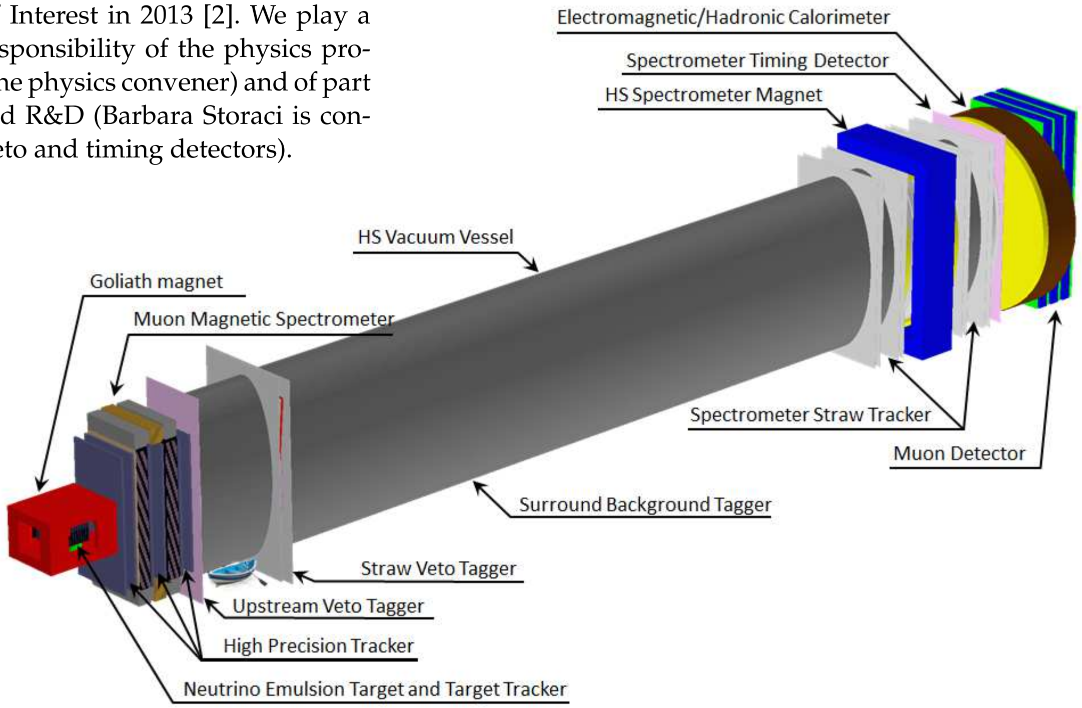

FIG. 9.1 – Ship overview.

a magnetic field of 1 Tm, a precision timing detector, a particle identification system featuring electromagnetic and hadronic calorimeters and, finally, a muon system consisting of four active layers interlaced with iron.

Our group has lead the optimization studies for the shape of the vacuum vessel. The length of the decay volume was obtained by maximizing the acceptance to the hidden particle decay products given the transvers dimensions, dictated by the upstream sweeping magnet.

9.1.1 Upstream Veto and Timing detector

E. Graverini, B. Kilminster, N. Serra and B. Storaci

A potential background source is associated with neutral kaons produced by neutrino and muon interactions upstream of the vacuum vessel, in the passive material of the tau-neutrino detector. The muon spectrometer that follows the tau-neutrino detector is not optimized to act as veto, and does not cover the full acceptance of the decay volume. An upstream veto tagger will reduce this background to negligible levels, and ensure a good level of redundancy of veto systems.

Muons crossing the decay volume represent a dangerous source of combinatorial background which can be removed by requiring that the two tracks mimicking a genuine signal event are coincident in time. A time resolution ≤ 100 ps is required for which a dedicated timing detector is needed.

Two technologies are considered: plastic scintillating bars and multi-gap resistive plate chambers (MRPC). For both technologies well-studied designs are available [3]. In collaboration with the group of the University of Geneva we are the main proponent of a veto timing detector with plastic scintillating bars, read out with silicon photomultipliers. This technology would profit from synergy for R&D and production since the same technology is considered for the muon detector and for the timing detector.

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 highly suppressed, resulting in 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].

9.2.1 Background studies

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

Our group has conducted a thorough study of the neutrino-induced background and coordinated the analyses of the other background sources. Studies conducted with the full SHiP Monte Carlo simulation indicate that a level of background of 0.1 events for 5 years of data taking is achievable with making use of appropriate veto systems. The flux of neutrinos is estimated to be 1.0×10^{11} neutrinos per spill, with an energy spectrum ranging from 2 GeV to about 100 GeV. A large sample of neutrino interactions with the detector material was simulated, corresponding to expectations during the full five years of SHiP operation. Neutrino interactions were found to take place mainly in the muon magnetic spectrometer of the tau neutrino detector, and in the entrance window and the surrounding walls of the vacuum vessel. Neutrino interactions with the residual gas in the decay volume are negligible if the vacuum pressure is below 10^{-6} bar. Preliminary studies show that the background can be suppressed further by simple selection criteria, which would allow to relax the requirements on the vacuum pressure. In general the interaction products do not point at 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 (see Fig. 9.2) allows rejects 99.4% of the

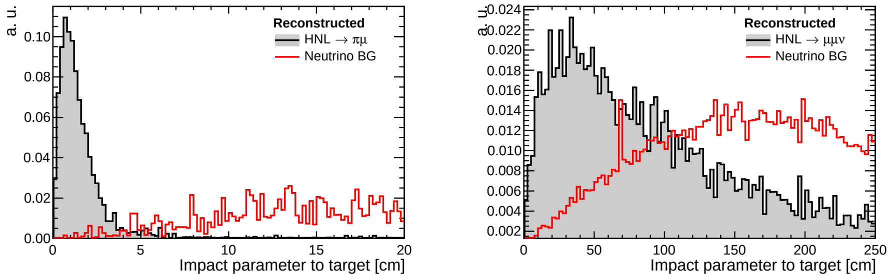

FIG. 9.2 – Simulated distributions of the impact parameter with respect to the proton target of reconstructed HNL events decaying into $\pi\mu$ (left) and $\mu\mu\nu$ (right) with the neutrino-induced backgrounds superimposed.

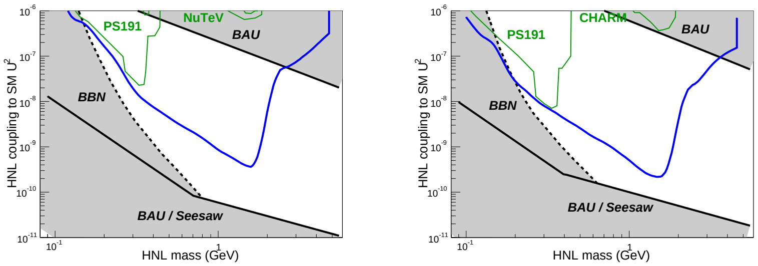

FIG. 9.3 –
SHiP's sensitivity to HNLs assuming normal (left) or inverted (right) hierarchy of standard neutrino masses. The parameter space of the νMSM is shown as well.

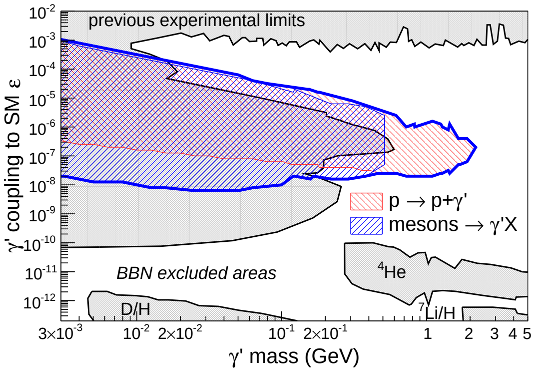

FIG. 9.4 –
SHiP's sensitivity to dark photons superimposed on present limits including those from cosmological observations.

reconstructed background-induced candidate events. 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 events originating in neutrino interactions.

Together, the combination of veto detectors and offline selections allows to reduce the neutrino induced background to zero. The set of selections applied is highly redundant and can be trimmed down to study specific channels.

9.2.2 SHiP sensitivity

E. Graverini, N. Serra and B. Storaci

Our group has been responsible for studying the SHiP sensitivity to HNLs and for dark photons. The latter are gauge bosons of a minimalistic theory based on the breaking of a $U(1)$ symmetry in the hidden sector (for theoretical details see [1]).

The SHiP physics sensitivities are evaluated using the FAIRSHIP package which is based on the FAIRROOT [4] package, a lightweight software framework based on ROOT. Our group contributed substantially to the development of FAIRSHIP. In addition, we developed a fast simulation to interpolate the results of the full simulation.

The FAIRSHIP simulation makes use of the package GEANT4 to simulate the interaction between stable particles and the material and is therefore relatively high CPU consuming. The fast simulation has been validated with the full simulation and corrected for the reconstruction efficiency. The use of the fast simulation allows to scan a large set in the models phase space of the various. The sensitivity to HNLs as a function of their mass and couplings, for normal and inverted hierarchy of SM neutrinos, is shown in Fig. 9.3.

A very similar method, analogous the one used by the authors of [5], was used to estimate SHiP sensitivity to dark photons, shown in Fig. 9.4.

[1] S. Alekhin *et al.*,
A facility to Search for Hidden Particles at the CERN SPS: the SHiP physics case, arXiv:1504.04855.

[2] W. Bonivento *et al.*,
Proposal to Search for Heavy Neutral Leptons at the SPS, arXiv:1310.1762.

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

[4] Al-Turany *et al.*, J. Phys. Conf. Ser. 396 (2012) 022001.

[5] J. Blümlein and J. Brunner, Phys. Lett. **B** (2014) 731.