7 Particle Physics with the SHiP experiment

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The full SHiP collaboration consists of 52 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 experiment 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 [1, 2]. After the target there is a hadron stopper, followed by a system of shielding magnets to sweep muons away from the fiducial decay volume. This is followed by a neutrino detector which has a modular structure and employs the Emulsion Cloud Chamber technology. The main unit of the detector is the brick where lead plates acting as passive material for neutrino interactions are interleaved with emulsion films which are tracking devices with micrometric resolution. The main purpose of the neutrino detector is to perform the first direct observation of the tau anti-neutrino, hence it is placed in a magnetic field so to allow the reconstruction of the charge of the τ lepton daughters and hence discriminate ν_τs from $\bar{\nu}_\tau$s. The neutrino detector is followed by a magnetic spectrometer, contained in a 50 m long vessel of pyramidal frustum shape, to measure the charge and the momentum of muons produced in charged current muon neutrino interactions or in $\tau \rightarrow \mu$ decays. 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 4 stations in a magnetic field of 1 Tm; 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.

Several models with Hidden Particles can be tested at the SHiP experiment. In particular, Sterile Neutrinos at the GeV scale can solve several open problems of the Standard Mode, including the asymmetry between matter and anti-matter [3]. These particles can be produced by heavy mesons decays (charmed and beauty mesons). The SHiP sensitivity to Heavy Neutral Leptons (HNLs) are shown in Fig. 7.1 for two different coupling schemes. These studies have been conducted by E. Graverini and N. Serra. 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].

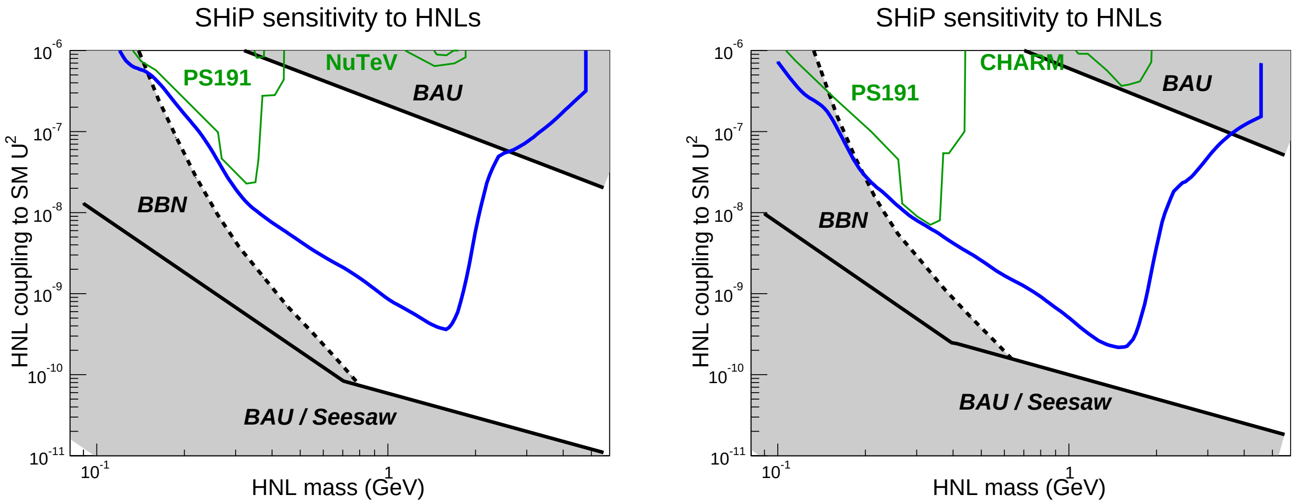

FIG. 7.1 – SHiP's sensitivity to HNLs assuming normal (left) or inverted (right) hierarchy of SM neutrino masses. The parameter space of the νMSM is superimposed.

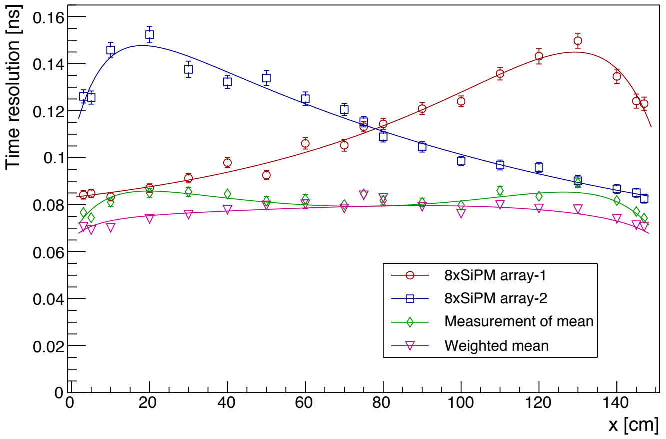

FIG. 7.2 – Time resolution as a function of position along a plastic EJ-200 scintillating bar with dimensions 150 × 6 × 1 cm^3 and read out on both ends with an array of 8 SiPMs.

Our group is taking a leading role in the design and construction of the SHiP veto timing detector. This detector is vital to reject combinatorial di-muon background by requiring events be coincidence in time within 100 ps or less. We have been one of the main proponents of a plastic scintillator based detector read out by arrays of silicon photomultipliers (SiPMs) [4,5].

Preliminary tests conducted at UZH involved characterisation of several SiPM devices. Tests compared the breakdown voltage, single photon timing resolution, dark count rate, cross talk probability and gain of different type of devices. A comparison of similar devices from different manufacturers was also performed. Measurements of the time resolution of single plastic scintillating bars read out on both ends by an array of SiPMs was also investigated using a radioactive source.

Test-beam measurements at CERN were carried out in June and October 2017 on bars of different types and geometries read out by SiPM arrays. The main results of these studies was the measurements of a time resolution 80 ps along a bar of dimensions 150 × 6 × 1 cm^3 read out on both ends by arrays of 8 SiPMs, as shown in Fig. 7.2. These results were extrapolated to a bar with a length of 170 cm, close to the final proposed bar geometry, indicating a resolution of 85 ps along the bar. Additionally, a custom designed ASIC for read out of SiPM arrays, called MUSIC and developed by the University of Barcelona, was tested for the first time during these test-beams. These measurements paved the way for the design of a timing detector prototype. The prototype will consist of 20 scintillating bars of dimensions 168 × 6 × 1 cm^3, read out on both ends by an array of 8 SiPMs. The data acquisition system will consist of MUSIC boards and SAMPIC waveform digitisers.

Since the Technical Proposal was submitted in 2015, the optimisation phase of the SHiP detector has started.

In preparation for the Technical Design Report, the idea to gain acceptance for Hidden Particle searches by placing the decay volume closer to the beam dump has been explored. Our group gave a crucial contribution proposing to use a conical vacuum vessel, with a shape reproducing the development of the muon free region along the beam axis, thus allowing to gain efficiency and reduce muon induced background.

After the feasibility of such a shaped decay vessel was confirmed by engineers, the subsequent step in the optimisation phase was to study how to shorten the muon shield. The aim of these studies was the optimisation of the shield in order to reduce the amount of iron used, hereby reducing cost while maintaining the same level of muon flux reduction. New methods have been developed for the simulation and the optimisation of shielding magnets taking into account the total mass of the magnets as well as the muon hits in the spectrometer. Our group played a major role in the optimisation of the active muon shield. We showed that is possible to reduce the muon rate to the level of $3{\times}10^5$ muons/spill, which is considered to be sufficiently low even though the muon shield was shortened from 53 m to 34 m. This allowed to increase the acceptance for hidden sector particles at the same time reducing the iron by more than 1000 ton (from 2896 to 1845 tons) with respect to the Technical Proposal. These studies are documented in Ref. [6]. The reoptimized SHiP detector is shown in Fig. 7.3.

Aiming the SHiP experiment to be a zero-background experiment, possible background sources to hidden particle searches have to be studied carefully. One of the most dangerous background in searches for hidden particles consists of neutrino interactions. The flux of neutrinos is estimated to be 10^{11} neutrinos per spill, inducing around 7 millions interactions in the proximity of the fiducial volume for 2×10^{20} PoTs.

We simulated a large sample of neutrino interactions and studied the background as a function of the pressure in the vacuum vessel, showing that a pressure of 10^{-3} mbar is sufficient to reduce to a negligible level the number of neutrino interactions in the air. We also studied background rejections by using kinematic selection and veto systems, demonstrating the possibility to reduce the background level to < 0.1 events for 5 nominal years of running.

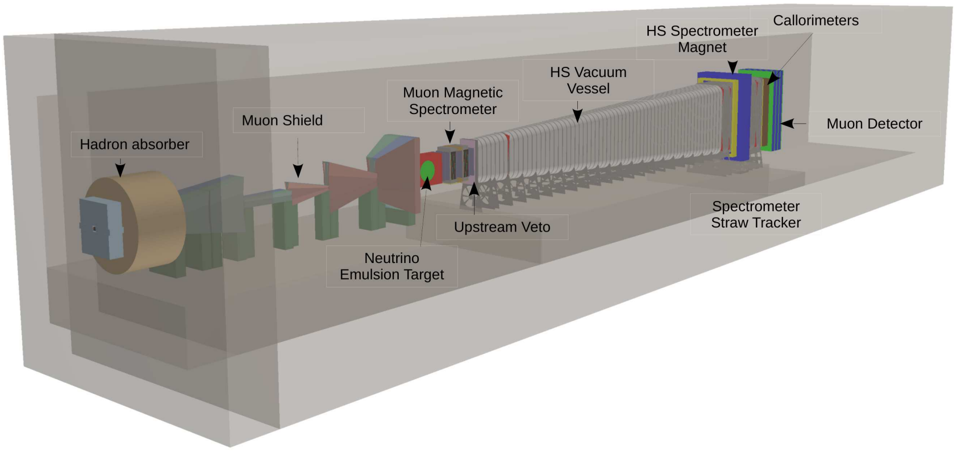

FIG. 7.3 – Overview of the SHiP detector. From left to right: the target, followed by the hadron stopper, the muon shield, the neutrino and Light-Dark-Matter detector (emulsion detector and muon magnetic spectrometer), the Hidden Sector vacuum vessel and the Hidden Sector spectrometer. The latter consists of straw tube tracking stations, a dipole magnet, a veto-timing detector, a calorimeter system and a muon system.

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[6] A. Akmete *et al.*, The SHiP Collaboration,
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