

# SHiP: a new facility to search for heavy neutrinos and study $\nu_\tau$ properties

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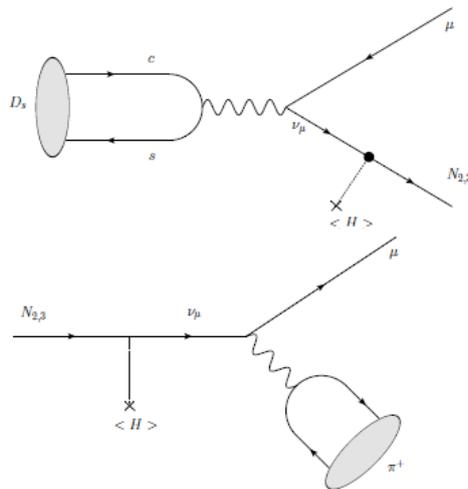
**Abstract.** SHiP (Search for Hidden Particles) is a newly designed fixed target facility, proposed at the CERN SPS accelerator, with the aim of complementing searches for New Physics at LHC by searching for light long-lived exotic particles with masses below a few  $\text{GeV}/c^2$ . The sensitivity to Heavy Neutrinos will allow for the first time probing a region of the parameter space where Baryogenesis and active neutrino masses and oscillation could also be explained. A dedicated detector, based on OPERA-like bricks, will provide the first observation of the tau anti-neutrino. Moreover,  $\nu_\tau$  and  $\bar{\nu}_\tau$  cross-sections will be measured with a statistics 1000 times larger than currently available data and will allow extracting the F4 and F5 structure functions, never measured so far. Charm physics studies will be performed with significantly improved accuracy with respect to past experiments.

## 1. Introduction

The Standard Model (SM) provides a consistent description of the fundamental constituents of matter and their interactions. Although successfully tested by many experiments, it cannot be regarded as the ultimate theory of Nature, since it cannot account for a number of established experimental facts, such as neutrino masses and oscillation, the excess of matter over antimatter in the Universe and the existence of the dark matter. New, yet unknown particles and/or interactions should exist.

The SHiP project (Search for Hidden Particles, [1]), recently proposed at CERN, aims at investigating the presence of *hidden* particles with masses in the GeV range, not directly interacting with SM particles and coupled to the *visible sector* through gauge-singles operators (portals). Complementary to LHC experiments, searching for massive particles with ordinary couplings to matter, SHiP will investigate a largely unexplored domain where lighter particles with very weak couplings to SM particles could be hiding. A rich physics program [2], including also the investigation of the vector, scalar and axion portals, is envisaged. In this paper, focus will be given to the neutrino portal, namely to the search for Heavy Neutral Leptons, right-handed partners of the active neutrinos, in the framework of the Neutrino Minimal Standard Model ( $\nu\text{MSM}$ , [3]). Since an abundant production of neutrinos from charmed hadron decays is expected at the designed facility, SHiP foresees to perform also  $\nu$  and anti- $\nu$  physics studies with unprecedented sensitivities. In particular, the first observation of the  $\bar{\nu}_\tau$  and the measurement of  $\nu_\tau$  and  $\bar{\nu}_\tau$  cross-sections are among the primary goals of the proposed experiment.





**Figure 1.** Example of production (top) and decay (bottom) of  $N_{2,3}$ .

## 2. The neutrino portal

The oscillation mechanism among active neutrinos has been unambiguously confirmed after several decades of experimental searches, using both artificial [4, 5, 6, 7, 8] and natural [9, 10] sources of neutrinos. The existence of such process implies a non-zero  $\nu$  mass and is thus an indication of *New Physics*, neutrinos being massless particles in the SM. In order to embed  $\nu$  masses in the theory, gauge-singlet fermions  $N_I$  ( $I = 1, 2, \dots, n$ ) can be introduced, extending the SM Lagrangian  $L_{SM}$  as follows:

$$L' = i \bar{N}_I \partial_\mu \gamma^\mu N_I - Y_{I\alpha} \bar{N}_I^c \tilde{H} L_\alpha - M_I \bar{N}_I^c N_I + \text{h.c.} + L_{SM}$$

where the second term is the Yukawa term describing the mixing between gauge singlets and active neutrinos and the third term is the Majorana mass term.

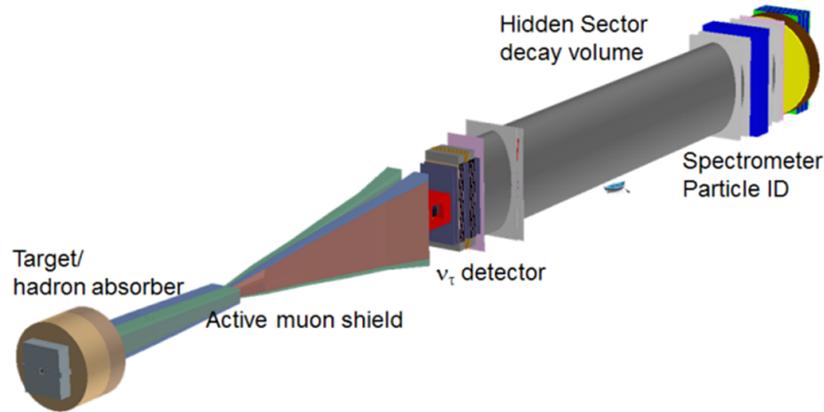
$L'$  is the most general renormalizable Lagrangian, allowing for the generation of  $\nu$  masses through the see-saw mechanism.

In the  $\nu$ MSM,  $n = 3$  and  $N_{1,2,3}$  represent three sterile right-handed massive neutrinos, referred to as *Heavy Neutral Leptons* (HNL). Such particles are Majorana partners of the active neutrinos with masses below the electroweak scale. The particle  $N_1$ , with a mass in the keV region, is found to be a possible dark matter candidate;  $N_2$  and  $N_3$ , with masses  $O(\text{GeV}/c^2)$ , could explain the oscillation mechanism as well as the observed baryon asymmetry.

$N_2$  and  $N_3$  could be produced in the semi-leptonic decays of sufficiently heavy mesons (Fig. 1). Due to very tiny coupling to active neutrinos, they are long-lived particles with flight lengths  $O(\text{km})$ . The experimental search for  $N_2$  and  $N_3$  requires the construction of a dedicated beam dump facility with a high density proton target followed by a hadron stopper and a properly designed muon shield reducing the background from prompt particles down to a reasonable level.

## 3. The SHiP facility

SHiP aims at searching for HNLs produced in the decays of charmed mesons by detecting their decays to SM particles, e.g.  $N_{2,3} \rightarrow \mu \pi$  (Fig. 1). The detection of such a rare process requires the  $\nu$  flux from pions and kaons to be minimised, as well as an effective shield against hadrons, electromagnetic showers and muons. Figure 2 shows the layout of the SHiP facility to be build



**Figure 2.** Layout of the SHiP facility.

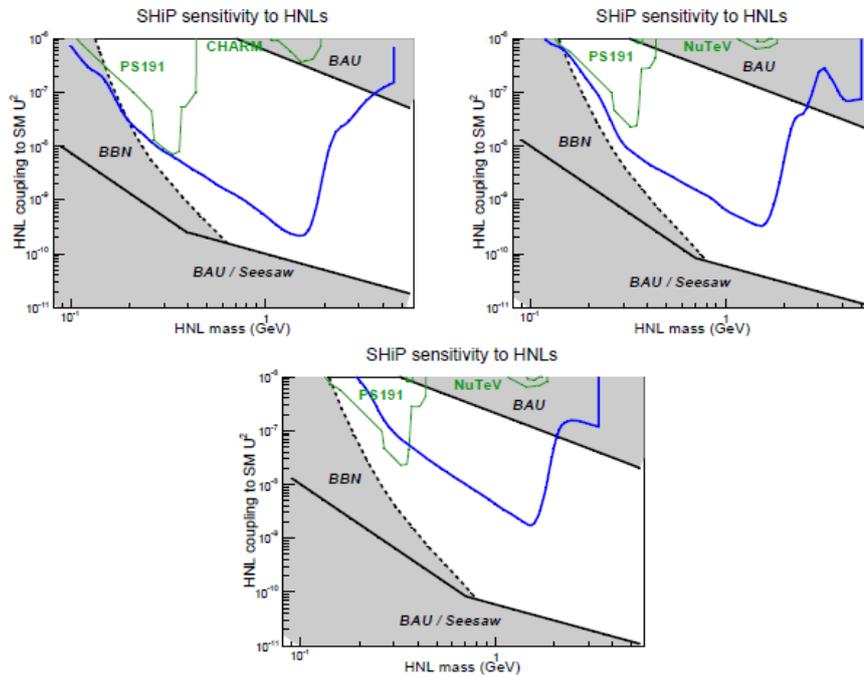
at CERN in the North Area.

A high intensity 400 GeV proton beam from SPS will be delivered onto a dense hybrid target with a total length of 116 cm, consisting of blocks of titanium-zirconium doped molybdenum alloy followed by pure tungsten. The foreseen integrated intensity is  $2 \times 10^{20}$  protons on target over five years of data-taking. Downstream of the target, an iron absorber stopping the hadrons and the electromagnetic component and a compact active muon filter bending out a large fraction of the muons emerging from the target are located.

The HNL detector consists of a 50 m long evacuated vessel, acting as a decay tunnel, surrounded by a veto system to suppress neutrino and residual muon interactions, followed by a magnetic spectrometer, electromagnetic and hadronic calorimeters and a muon detector. The use of high resolution ( $\sim 100$  ps) timing detectors is foreseen in order to suppress the muon combinatorial background below 0.1 events.

Since an abundant production of neutrinos from charmed hadron decays is expected, SHiP is ideally suited for studying also  $\nu$  physics with high statistics, the main goals being the first experimental observation of the  $\bar{\nu}_\tau$  and the measurement of  $\nu_\tau$  and  $\bar{\nu}_\tau$  cross-sections. Indeed,  $\nu_\tau$ s are among the less known particles in the SM. Only a handful of  $\nu_\tau$  CC interactions have been detected so far by DONUT [11] and, more recently, by OPERA [12, 13, 14, 15, 16]. At SPS energies, the  $D_s$  meson decays are the main source of tauonic neutrinos. Muon and electron neutrinos will be produced as well in the decays of charmed hadrons. SHiP will be thus able to study neutrino induced charm production, the expected charm yield exceeding by more than one order of magnitude the overall statistics from previous experiments.

A dedicated neutrino detector, located immediately upstream of the HNL decay vessel, has been designed. It consists of a target segmented into OPERA-like bricks, made of lead plates and thin nuclear emulsion foils, followed by a muon spectrometer. Electronic trackers are placed in between target walls to provide the time stamp. This layout has already proven to have the unique capability of efficiently detecting all active  $\nu$  flavors in OPERA. The foreseen installation of the target in a magnetised region and the use of Compact Emulsion Spectrometers [17] will provide the additional capability of measuring the electric charge of hadrons, thus allowing to separate tau neutrinos and anti-neutrinos through their decays in the hadronic channels as well as in the muonic channel.



**Figure 3.** SHiP sensitivity regions to HNLs for three scenarios where  $U_e^2$  (top left),  $U_\mu^2$  (top right) and  $U_\tau^2$  (bottom) dominate respectively.

#### 4. Expected performance

Fig. 3 shows SHiP sensitivity to HNLs (blue curve) for three different scenarios where the couplings  $U_e^2$ ,  $U_\mu^2$  and  $U_\tau^2$  dominate respectively. The plots have been computed assuming five years of data-taking. In case no signal is found, SHiP will be able to scan a largely unexplored region of the parameter space above kaon mass, thus significantly improving present limits. Assuming a level of background of 0.1 events, the curves of Figure 5.19 can be interpreted as  $3\sigma$  evidences if two events are observed.

Table 1 summarises the expected numbers,  $N^{exp}$ , of  $\nu_\tau$  and  $\bar{\nu}_\tau$  CC interactions with the  $\tau$  lepton in the final state decaying into muon, single hadron and three hadrons. The corresponding numbers of background events,  $N^{bg}$ , mainly due to  $\nu$ -induced charm production with unidentified primary lepton, and the values of the signal to noise ratio,  $R$ , are also reported. About 1800  $\nu_\tau$  and 900  $\bar{\nu}_\tau$  detected interactions are expected in five years run assuming a target mass of 9.6 tons.

With the above statistics, SHiP will have the unique capability of measuring the F4 and F5 structure functions which are negligible in  $\nu_\mu$  and  $\nu_e$  interactions because of a suppression factor proportional to the square of the charged lepton mass. The hypothesis of  $F4 = F5 = 0$  would result in an increase of the  $\nu_\tau$  and  $\bar{\nu}_\tau$  deep-inelastic cross-sections with respect to the SM prediction, the ratio  $r$  between the two being higher for lower neutrino energy. As an example, the evidence for a non-zero value of F4 and F5 with a significance of  $3\sigma$  would require  $r > 1.6$  which corresponds to  $E_{\bar{\nu}_\tau} < 38\text{GeV}$  where about 300  $\bar{\nu}_\tau$  interactions are expected.

In five years run, more than  $10^5$   $\nu$ -induced charmed hadrons will be detected. Detailed studies on charm physics will be thus performed with significantly improved accuracy with respect to past experiments. Charm production in anti-neutrino interactions is particularly

**Table 1.** Expected numbers of  $\nu_\tau$  and  $\bar{\nu}_\tau$  signal ( $N^{exp}$ ) and background ( $N^{bg}$ ) events for different  $\tau$  decay channels. The signal to noise ratio  $R$  is also reported.

Decay channel	$\nu_\tau$			$\bar{\nu}_\tau$		
	$N^{exp}$	$N^{bg}$	$R$	$N^{exp}$	$N^{bg}$	$R$
$\tau \rightarrow \mu$	570	30	19	290	140	2
$\tau \rightarrow h$	990	80	12	500	380	1.3
$\tau \rightarrow 3h$	210	30	7	110	140	0.8
total	1770	140	13	900	660	1.4

interesting since it allows probing the strange-quark content of the nucleon, unlike neutrino scattering where the presence of valence quarks favours the d-quark as neutrino target. Defining  $s^\pm = s(x) \pm \bar{s}(x)$ , an improvement on the accuracy of almost a factor of two is expected in the range of the Bjorken variable  $x$  between 0.03 and 0.35 for  $s^+$  and between 0.08 and 0.30 for  $s^-$ .

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