Neutrino physics with the SHiP experiment at CERN

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Abstract. The SHiP (Search for Hidden Particles) experiment has been recently proposed at CERN to be operated in beam dump mode at the SPS, with the aim of investigating the Hidden Sector searching for long-lived particles in the GeV mass range. The beam dump will be a copious source of hidden particles, together with active neutrinos of all flavours. The SHiP detector is designed to detect feebly interacting particles and to perform precision studies of neutrino and anti-neutrino interactions, too. In five years run $2 \times 10^{20}$ protons on target will be delivered, leading to the first direct observation of tau anti-neutrinos. The $\bar{\nu}_\tau$ and $\nu_\tau$ deep-inelastic scattering cross-sections will be evaluated with a statistics a thousand times larger than currently available. The $F_4$ and $F_5$ structure functions, never measured so far, will be also extracted and charm physics studies will be realised with improved accuracy with respect to the past, thus improving the sensitivity to the $s$ quark distribution in the nucleon. This paper will focus on the neutrino physics potential of the SHiP experiment, including its sensitivity to Heavy Neutral Leptons searches.

1. Introduction

Many experiments have successfully tested the Standard Model (SM) predictions, the latest of them with the Higgs boson discovery at the LHC in 2012 [1, 2]. Nonetheless, the SM cannot account for a number of established experimental evidences such as non zero neutrino masses, dark matter and the baryon asymmetry of the Universe that push forward the search for New Physics.

Current results in experimental and theoretical particle physics, astrophysics and cosmology leave the parameters of this new physics largely undetermined. New particles may be currently hidden due to their very heavy mass or to their very weak couplings with SM particles. Searches for very feebly interacting particles have to be pursued at the intensity frontier, with a beam dump facility. The Search for Hidden Particles (SHiP) beam dump experiment has been recently proposed at the CERN SPS accelerator and has been designed to investigate the existence of such hidden particles in the GeV mass range. They are expected to be predominantly produced through the decays of heavy flavoured hadrons. The SHiP-related Beam Dump Facility (BDF) [3] will allow to maximize the hidden particles production while providing an extremely clean background environment. An abundant production of neutrinos from meson decays is also expected, allowing neutrino and anti-neutrino physics studies with unprecedented precision.

In the following, the BDF facility and the SHiP experimental apparatus will be described, focusing on the overall neutrino physics potential of the project.
2. The SHiP facility

The CERN-based BDF [3] will be located on a new extraction line branching off from the CERN SPS transfer line to the North Area. Its main components will be a dense proton target, followed by a 5m-thick iron absorber and an active muon shield.

The high intensity and high energy 400 GeV/c SPS proton beam will be dumped on a target made up by a titanium-zirconium doped molybdenum alloy. In five years run $2 \times 10^{20}$ protons will be delivered on the target, leading to a copious production of heavy flavoured mesons ($O(10^{18})$ charmed mesons, $O(10^{14})$ beauty mesons). Hidden long-lived particles in the GeV mass range will arise either from proton beam interactions or from the decay of the secondary mesons. The target will be followed by the iron hadron absorber which has to strongly reduce the huge flux of SM particles emerging from the dump. The active muon shield will sweep the muons produced in the upstream region out of the acceptance of the downstream detectors. Apart from the residual muon flux, the only remaining particles on top of hidden particles are neutrinos. SHiP will therefore have a dual detector system: the Scattering and Neutrino Detector (SND) optimised for neutrino physics and Light Dark Matter searches and the Hidden Sector detector (HS) designed to look for feebly interacting particles from the Hidden Sector. Figure 1 shows a schematic overview of the SHiP facility, from the proton target to the end of the Hidden Sector detector.

![Figure 1. Layout of the Beam Dump Facility and the SHiP detectors.](image)

2.1. The Scattering and Neutrino Detector

The SND, shown in figure 2, will consist in a $(3.6 \times 7.2 \times 2.2)\text{m}^3$ magnetised region followed
by a $\mu$ identification system. The magnetised region ($B = 1.2$ T) will host the $\nu$ target followed by a particle spectrometer.

The $\nu$ target will be a hybrid detector. It will consist of 19 "Brick Walls" (walls of *Emulsion Targets*), alternated to SciFi Target Tracker planes. Each Emulsion Target is designed as a $2 \times 2$ matrix of $(40 \times 40) \text{cm}^2$ Emulsion Cloud Chamber (ECC) brick followed by a Compact Emulsion Spectrometer (CES). The ECC brick is made of 1 mm - thick tungsten plates alternated to 300 $\mu$m - thick nuclear emulsion films. A Compact Emulsion Spectrometer (CES) is a sequence of a few nuclear emulsion films air-separated. The total absorber mass is about 8 tons.

The ECC technology is the optimal choice to reconstruct neutrino interactions and short-lived particle decays with micrometric resolution and was successfully exploited in the past by the OPERA Collaboration [4]. Here will be complemented by the CES detector, that will allow to measure charge and momentum of hadrons produced in $\nu$ interactions or secondary short-lived particle decays. This is a key feature to discriminate tau neutrinos from anti-neutrinos also in case the $\tau$ lepton produced in charged-current (CC) $\nu_\tau$ interactions will decay in hadron(s).

The SciFi Target Trackers will have spatial resolution better than 50 $\mu$m. Their main goal is to provide event timestamp and link $\mu$ tracks from the target to the muon identification system. The informations provided by the ECC together with the muon identification system makes it possible to distinguish $\nu$ flavors, identifying the primary charged lepton produced in CC $\nu$ interactions.

The SND Muon Identification System consists of iron filters alternated with HPL Resistive Plate Chambers (RPCs). Its sensitive area is about $2 \times 4 \text{m}^2$, while the overall length is about two metres. The $\mu$ identification efficiency of the system has been evaluated to be about 97%. The hadron mis-identification probability is expected to be around 1.5%. Three additional multi-gap RPCs planes will act as veto to tag background processes to the search for hidden particle.

### 2.2. The Hidden Sector Detector

The HS has the aim to precisely reconstruct hidden particles decays in SM particles, ensuring an efficient suppression of different backgrounds. The 50 m long frustum-shaped decay vessel, with a total volume of 2040 $\text{m}^3$, will be maintained at a pressure of $O(10^{-3})$ bar in order to suppress the background produced by those neutrinos eventually interacting in the decay volume. The vessel will be surrounded by 480 ton of liquid scintillator to ensure an efficient suppression of the residual background induced by neutrinos and muons. As shown in figure 1 a large magnetic spectrometer and a particle identification system will be located downstream with respect to the decay vessel. They are needed to precisely reconstruct feeblly interacting particles decays and discriminate between the wide range of HS models.

The magnetic Straw Tracker Spectrometer (SST) consists of a large conventional dipole magnet ($B_{x,max} = 0.14$ T) and a pair of tracking stations made of straws at each side of the magnet. The straw hit spatial resolution is about 120 $\mu$m and the efficiency is greater than 99%. The start time to the SST will be given by a dedicated timing detector with timing resolution better than 100 ps. The particle identification system is made up by an electromagnetic calorimeter (SplitCAL) and a muon system. The first sub-detector is a $(6 \times 12)m^2 \times 20X_0$ sampling lead/scintillator calorimeter with, in addition, a few MicroMegas chambers as precision layers to measure shower transverse profile at different depth of its evolution and assure a good backward pointing resolution. The muon system consists of 4 active stations equipped with scintillating tiles alternated by iron filters $3\lambda_f$ thick. A time resolution better than 300 ps per tile is needed in order to get an overall time resolution at the level of 100 ps.
3. Neutrino Physics with the SND

At BDF a huge flux of $\nu$ and anti-$\nu$, originating from the decay of mesons produced at the beam dump, is expected. Due to geometrical acceptance only a few percent of them reaches the SND and interacts within the magnetised target. In five years run the total number of expected interactions, suitable for $\nu$ physics studies, will be anyhow still high and represents a unique opportunity to perform precision studies on (anti-)neutrinos of all flavours, improving the actual knowledge in this field and, moreover, reporting the first ever direct observation of $\nu_{\tau}$.

The main source of tau neutrinos at the SHiP beam dump are $D_s$ mesons, through their fully leptonic decay. A high rate of muon and electron neutrinos originates from $\pi$ and K decay. The expected number of CC DIS (anti-)neutrino interactions in the SND Target during the whole data taking is shown in table 1 together with the neutrino mean energy.

Table 1. Expected neutrino CC deep inelastic interactions in the SHiP SND. 2×10^{20} protons delivered on SHiP target are assumed.

| $\nu_e$  | 59 | 1.1 · 10^6 |
| $\nu_\mu$ | 42 | 2.7 · 10^6 |
| $\nu_\tau$ | 52 | 3.2 · 10^4 |
| $\bar{\nu}_e$ | 46 | 2.6 · 10^5 |
| $\bar{\nu}_\mu$ | 36 | 6.0 · 10^5 |
| $\bar{\nu}_\tau$ | 70 | 2.1 · 10^4 |

Table 1 shows that the number of $\nu_\tau$ and $\bar{\nu}_\tau$ charged current interactions expected at SHiP SND is at least three order of magnitude greater than what reported by past experiments. Moreover, at the state of the art, there is still no direct evidence for tau anti-neutrinos. The observation of tau neutrinos was confirmed by the DONUT experiment in 2008 when 9 candidate events were reported [5]; its appearance from muon-neutrino oscillations was discovered by the OPERA Collaboration [4] who reported in 2018 the detection of 10 $\nu_\tau$ candidate events [6]. SHiP will be able to make the first ever direct observation of the $\nu_\tau$ and, given the unprecedented statistics of $\nu$ CC DIS expected, it will also precisely study their properties and cross-section.

As an example, at SHiP SND will be possible to evaluate the structure functions $F_4$ and $F_5$. The neutrino differential deep-inelastic scattering cross-section on a nucleon is indeed expressed in terms of structure functions $F_i$, $i \in 1,...,5$, which represent a measure of the partonic structure of hadrons. $F_4$ and $F_5$ are the only structure functions proportional to the mass of the charged lepton associated to the flavour of the interacting $\nu$. They are not negligible only in case of $\nu_\tau$. In the limit of massless quarks and target hadrons, at leading order, $F_4 = 0$ and $2xF_5 = F_2$, where the x variable is the Bjorken-x [7]. At NLO the contribution of $F_4$ to the cross-section is about 1% [8]. A non null value for $F_4$ and $F_5$ would affect the cross-section which, especially at low E, will increase with respect to the hypothesis of $F_4 = F_5 = 0$. Simulations show that SHiP can probe a non-zero value of $F_4$ and $F_5$ on a statistical basis, by observing a number of $\nu_\tau$ events with E < 38 GeV greater than the expected value of 300.

In 5 years run, ∼2×10^5 CC DIS neutrino induced charmed hadrons are expected at SHiP SND. Thanks to the use of ECC technique it will be possible to identify charmed hadrons with micrometric accuracy on a topological basis without any kinematical cut. The expectations show that the available statistics will exceed by more than one order of magnitude those reported by previous experiments and that a contribution of ∼30% will come from anti-neutrinos. Current results on charm physics with $\nu$ interactions will be improved in terms of both reduction of...
uncertainties and assessment of decay channels never studied before.

The study of charmed hadrons produced in $\nu$ interactions will also contribute to investigate the s-quark content of the nucleon. Figure 3 shows how SHiP will significantly improve the uncertainty on the $s^+$ distribution in the $0.03 < x < 0.35$ range, where $s^+ = s(x) + \tilde{s}(x)$ and $s(x)$ is the s-quark content of the nucleon as a function of the Bjorken $x$.

Figure 3. Present NNLO estimates (blue line)[9] and future (red line) knowledge of parton distribution functions of $s(x) + \tilde{s}(x)$, for Bjorken $x$ spanning from 0.03 to 0.35 in a $Q^2$ region between 3 GeV$^2$ and 80 GeV$^2$.

4. Heavy Neutral Lepton searches with the HS

SHiP will have an unprecedented sensitivity to a multiplicity of Hidden Sector models based on (new) particles interacting very feebly with ordinary matter.

Heavy Neutral Leptons (HNLs) are hidden particle candidates at the base of neutrino portals. The Neutrino Minimal Standard Model ($\nu$MSM) is one of the simplest extension of the SM, in which 3 right-handed Heavy Neutral Leptons ($N_1$, $N_2$ and $N_3$) are added to the SM leptons as gauge-singlet counterpart of the well-known active neutrinos. In this model, $N_1$ is a light long-lived particle with mass of the order of KeV/c$^2$ and constitutes a good dark matter candidate. $N_2$ and $N_3$ are heavier long-lived particles with mass of the order of GeV/c$^2$ and their existence could explain non-zero neutrino masses (via see-saw mechanism) and the origin of BAU [10][11]. At SHiP, the most probable production processes for HNLs are weak decays of flavoured mesons emerging from the target: basically D and B mesons with a not negligible contribution of $B_c$ in case of HNL masses greater than 3 GeV/c$^2$. HNLs are then expected to decay in SM particles, mainly in the 2-body decay $HNL \rightarrow \mu \pi$, inside the SHiP decay vessel. This peculiar topology constitutes the signature of a HNLs decay, to be looked at the HS detector. In 5 years run, the number of expected visible HNLs decays will be of the order of $1 \times 10^4$. Figure 4 shows the sensitivity curve for HNLs and the significant contribution SHiP can give to the overall physics landscape, with the assumption that the ratio between the HNLs mixing angles is $U_{e2}^2 : U_{\mu2}^2 : U_{\tau2}^2 = 0 : 1 : 0$. More details on the sensitivity of SHiP to HNL can be found in [12].

5. Conclusions

The SHiP experiment has been proposed at CERN to search for New Physics at the intensity frontier probing the existence of currently hidden, feebly interacting particles in the GeV mass range. Thanks to the huge amount of (anti-)neutrino produced at BDF, SHiP offers a unique
Figure 4. Parameter space for HNLs and potential reach of the SHiP experiment for muon coupling dominance.

opportunity to significantly improve the present knowledge in SM neutrino physics and, at the same time, to perform Heavy Neutral Leptons searches.

Currently, the R&D and prototyping activities are on-going and in a good shape. The Collaboration has finalized the Comprehensive Design Study at the end of 2019, and now is looking forward to the TDR phase.

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