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SHiP: a new facility with a dedicated detector to search for new long-lived neutral particles and study tau neutrino properties

Antonia DI CRESCENZO[*]
[†]
University e INFN, Napoli (IT)
E-mail: antonia.di.crescenzo@cern.ch

SHiP (Search for Hidden Particles) is a new general purpose fixed target facility, proposed at the CERN SPS accelerator. In its initial phase the 400 GeV protons beam will be dumped on a heavy target with the aim of integrating 2×10^{20} protons on target in five years. A dedicated detector downstream of the target will allow us to probe a variety of models with the light long-lived exotic particles and masses below O(10) GeV/c^2. Another dedicated detector will allow the study of active neutrino cross-sections and angular distributions. In particular, the neutrino deep-inelastic cross-sections will be performed with a statistics 1000 times larger than currently available, with the extraction of the F_4 and F_5 structure functions, never measured so far. Tau neutrinos will be distinguished by anti-neutrinos, thus providing the first observation of the tau anti-neutrino. With muon neutrinos it will be possible to study the strangeness content of the nucleon.

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[*] Speaker.

[†] on behalf of the SHiP Collaboration.

1. Introduction

The Standard Model of elementary particle physics has provided a consistent description of Nature's fundamental constituents and their interactions. Its predictions have been tested and confirmed by numerous experiments. With the discovery of the Higgs boson [1, 2], all the predicted constituents of the SM have now been observed. At the same time, no significant deviations from the Standard Model were found in direct or in indirect searches for new physics.
For the particular value of the Higgs mass it is possible that the Standard Model remains mathematically consistent and valid as an effective field theory up to a very high energy scale, possibly all the way to the scale of quantum gravity, the Planck scale [3, 4, 5].
However, it is clear that the SM is not a complete theory. It fails to explain a number of observed phenomena in particle physics, astrophysics and cosmology. The major unsolved challenges are: the non-zero neutrino mass, the existence of dark matter, and the baryon asymmetry of the universe. Some yet unknown particles or interactions would be needed to explain these puzzles and to answer these questions. The hypothetical new particles can be searched for either at the energy and at the intensity frontier.
The high energy frontier will be comprehensively investigated in the next few decades, while the searches for alternative low mass *beyond Standard Model* physics at the intensity frontier have been neglected in recent years. Light new particles may have remained undetected by previous experiments because of the very small couplings involved. New data at the intensity frontier will therefore be particularly useful in exploring portal models with light new physics, and in searching for Majorana neutrinos. A new intensity frontier experiment, SHiP, is consequently very timely for direct searches for very weakly interacting new physics.

2. The detector for hidden particles

The main physics goal of the SHiP experiment consists in exploring hidden portals and extensions of the Standard Model (SM) which incorporate long-lived and very weakly interacting particles through the direct detection of their decays to SM particles. For this purpose, the 400 GeV proton beam of the SPS will be dumped on a heavy target. Over five years of data taking, 2×10^{20} protons on target are expected.
Hidden particles are predominantly produced in decays of hadrons, in particular in decays of charmed and beauty hadrons above the kaon mass. They have very small coupling with SM particles and are therefore very long-lived. In order to maximise their production, the target is made of molybdenum and tungsten, these materials being characterized by a very short interaction length. The target is followed by an iron absorber, aiming at stopping the hadrons and the electromagnetic radiation emerging from the target. In order to reduce the large flux of muons produced in the decay of pions and kaons, a 48 m long active muon shield based on magnetic deflection is located immediately downstream of the target.
The Hidden Sector (HS) detector is made by a cylindrical 50 m long decay volume. It is under vacuum and surrounded by a veto system. The full reconstruction of the hidden particle decays is performed by a magnetic spectrometer and a system for particle identification at the end of the decay volume. Figure 1 shows a schematic overview of the SHiP facility from the proton target to

the end of the Hidden Sector detector.

The SHiP experiment can probe an interesting parameter space for a number of BSM models describing interactions between new particles and different *portals* (scalars, vectors, fermions or axion-like particles), as described in detail in the Technical Proposal [6]. In the following section we will focus on the Neutrino Portal.

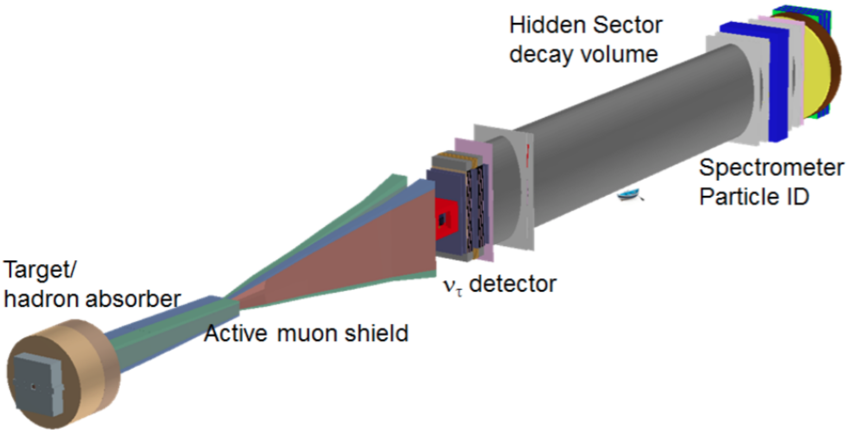

Figure 1: Overview of the SHiP facility.

2.1 Neutrino Portal

Models with right-handed Majorana neutrinos or heavy neutral leptons (HNLs) can give a simultaneous explanation to neutrino masses and mixings, baryon-antibaryon asymmetry and dark matter. The most promising of these models is the ν Minimal Standard Model (νMSM). In this model the lightest of these neutrinos (N_1), has a mass in the keV region and it is sufficiently stable to play the role of dark matter candidate. The other two neutrinos ($N_{2,3}$) are almost degenerate in mass (in the GeV region) and are responsible for neutrino oscillations and baryon-antibaryon asymmetry in the Universe.

The states N_2 and N_3 could be produced in the decay of sufficiently massive particles like charmed hadrons. The states produced in this way would be long lived particles that in turn could decay, for example, into a μ and a π. Therefore, by measuring the invariant mass of the μ and π system, one would expect a peak to show up. It is worth noticing that there are more cosmological than terrestrial experimental constraints in the mass region around 1 GeV. Charmed hadrons are the ideal parents of such heavy neutral leptons if their mass is around 1 GeV. Indeed, with kaon decays one is sensitive only to masses lower than 400 MeV, while the cross-section for the production of beauty hadrons is a factor of 20 to 100 lower. Moreover, given that beauty hadrons decay to charmed hadrons, the explored mass range would only extend from 2 to 3 GeV. As we have shown in the previous section, a proton beam dump facility is the ideal source of charmed hadrons and to search for heavy neutral leptons of this mass and lifetime (10^{-5}s) range.

Figure 2 shows the experimental and cosmological bounds on the search for heavy neutral leptons. It also reports superimposed the exclusion limits SHiP could set in case no signal is found. The left plot assumes the model reported in Ref. [7] with normal hierarchy and a dominant muon coupling, $U_e^2 : U_\mu^2 : U_\tau^2 = 1 : 16 : 3.8$, while the right plot refers to the model in Ref. [8] for inverted hierarchy and a dominant electron coupling, $U_e^2 : U_\mu^2 : U_\tau^2 = 46 : 1 : 1$. The parameter space explored by SHiP extends in the cosmologically relevant region that is experimentally unexplored.

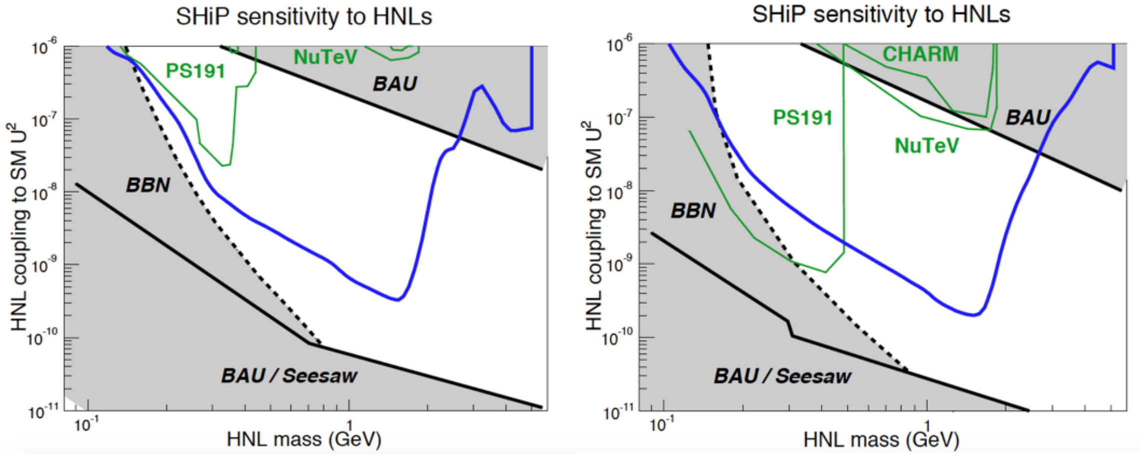

Figure 2: Exclusion limits sets by the SHiP experiment in case no signal is found. Left: normal hierarchy with U_μ^2 dominating according to Ref. [7]. Right: inverted hierarchy with U_e^2 dominating according to Ref. [8].

3. The neutrino detector

The tau neutrino detector shown in Figure 3 is located immediately downstream of the active muon shield. It consists of the Neutrino Target in a magnetic field followed by a Muon Magnetic Spectrometer. The Neutrino Target is made of Opera-type modules which employ the Emulsion Cloud Chamber (ECC) technology. The charges of the hadrons produced in the neutrino interactions are identified using the Target Tracker (TT) consisting of active planes which interleave the ECC modules. The magnetic field is provided by the Goliath magnet. The Muon Magnetic Spectrometer of the tau neutrino detector consists of a warm iron dipole magnet instrumented with active layers based on the Opera Resistive Plate Chambers and the Drift Tube Tracker.

The Emulsion Cloud Chamber (ECC) structure used in the Neutrino Detector is made of a sequence of passive material plates interleaved with emulsion films. The target is modular and its units are made of two parts as shown in Figure 4: the brick and the Compact Emulsion Spectrometer (CES). The brick, using lead as passive material, combines the micrometric tracking accuracy of nuclear emulsions and the high lead density as required to maximise the number of neutrino interactions in a compact detector. The CES is made of a sandwich of light material plates (e.g. Rohacell) and emulsion films. It is designed to distinguish ν_τ and $\overline{\nu}_\tau$ by performing the electric charge measurement of the τ decay products.

So far only DONUT [9] and OPERA [10] experiments succeeded in detecting a few ν_τ interactions. The ECC structure is well suited for the measurement of charged particles momenta [11] and for electron identification [12], as largely exploited with the OPERA experiment. The momentum is measured by the multiple coulomb scattering in the lead plates; electrons can be identified by detecting the electromagnetic showers. The ν_τ and $\overline{\nu}_\tau$ interactions are identified through the detection of the τ lepton production and decay. The τ decay channels investigated are the electron ($BR = 17.8\%$), muon ($BR = 17.7\%$), single-hadron ($BR = 49.5\%$) and three-hadron ($BR = 15.0\%$) channels.

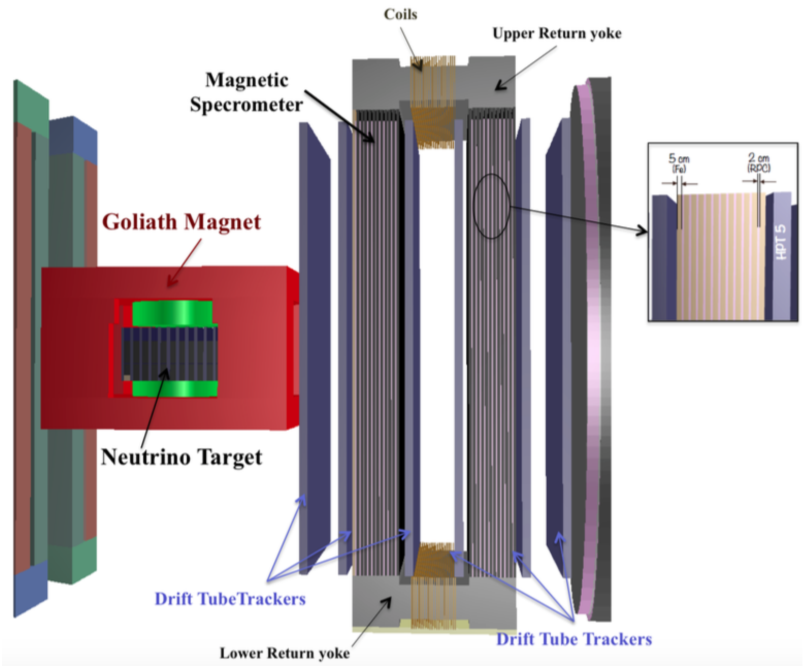

Figure 3: Overview of the tau neutrino detector.

4. Tau neutrino physics

The neutrino detector has the unique capability of detecting all three neutrino flavors and of distinguishing neutrinos from anti-neutrinos. The expected number of charged-current deep-inelastic neutrino interactions in a 9.6 ton detector in 5 years run is reported in Table 1: the energy spectra are shown in Figure 5.

	<E> (GeV)	Interactions
N_{ν_e}	46	2.5×10^5
N_{ν_μ}	29	1.7×10^6
N_{ν_τ}	59	7.4×10^3
$N_{\overline{\nu}_e}$	46	9.0×10^4
$N_{\overline{\nu}_\mu}$	28	6.7×10^5
$N_{\overline{\nu}_\tau}$	58	3.7×10^3

Table 1: Charged-current deep-inelastic neutrino interactions integrated in the target in five years run.

The charged-current ν_τ ($\overline{\nu}_\tau$) differential cross-section is represented by a standard set of five struc-

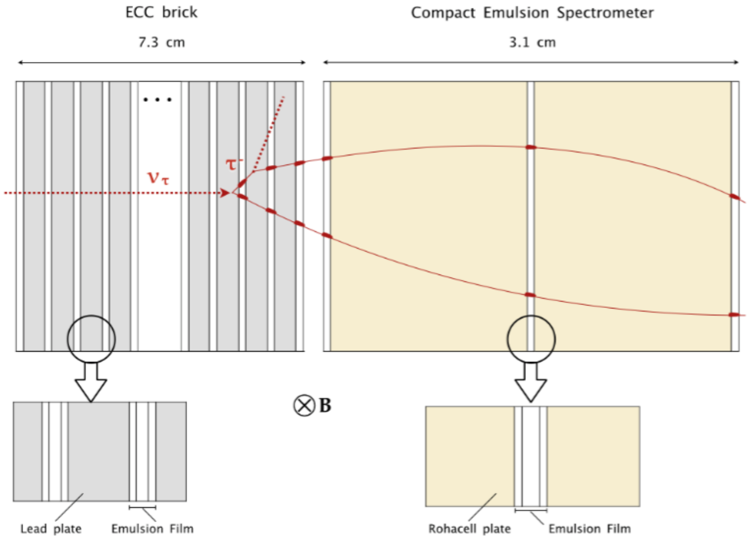

Figure 4: Schematic representation of the neutrino detector unitary cell.

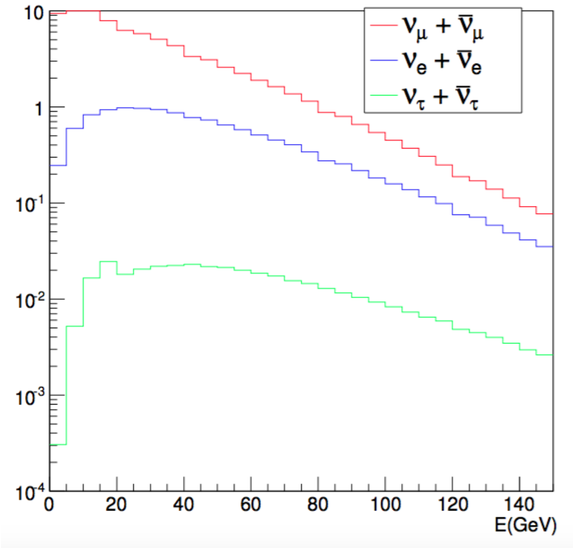

Figure 5: Energy spectrum of the different neutrino flavors interacting in the neutrino detector. A 0.5 GeV cut is applied for ν_μ and ν_e. The total number of neutrinos is normalized to 100.

ture functions:

$$\frac{d^2\sigma^{\nu(\bar{\nu})}}{dxdy} = \frac{G_F^2 M E_\nu}{\pi(1+Q^2/M_W^2)^2}\Bigg((y^2x+\frac{m_\tau^2 y}{2E_\nu M})F_1+\left[(1-\frac{m_\tau^2}{4E_\nu^2})-(1+\frac{Mx}{2E_\nu})\right]F_2$$
$$\pm\left[xy(1-\frac{y}{2})-\frac{m_\tau^2 y}{4E_\nu M}\right]F_3+\frac{m_\tau^2(m_\tau^2+Q^2)}{4E_\nu^2 M^2 x}F_4-\frac{m_\tau^2}{E_\nu M}F_5\Bigg),$$

where $\{x, y, Q^2\}$ are the standard Deep Inelastic Scattering (DIS) kinematic variables related through $Q^2 = 2M_N E_\nu xy$.

The structure functions F_4 and F_5, pointed out by Albright and Jarlskog in Ref. [13], are neglected in muon neutrino interactions because of a suppression factor depending on the square of the charged lepton mass divided by the nucleon mass times neutrino energy. Given the higher mass value of the τ lepton, F_4 and F_5 structure functions contribute, instead, to the tau neutrino cross section. At leading order, in the limit of massless quarks and target hadrons, $F_4 = 0$ and $2xF_5 = F_2$, where x is the Bjorken-x variable (Albright-Jarlskog relations). Calculations at NLO show that F_4 is about 1% of F_5 [14].

With the statistics of tau neutrino interactions collected in five years run, the SHiP experiment will have the unique capability of being sensitive to F_4 and F_5. The hypothesis of $F_4 = F_5 = 0$ would result in an increase of the ν_τ and $\overline{\nu}_\tau$ charged-current deep-inelastic cross sections and consequently, of the number of expected ν_τ and $\overline{\nu}_\tau$ interactions.

The difference between the cross sections in the $F_4 = F_5 = 0$ hypothesis and the SM one is larger for lower neutrino energies. This behavior is reflected in the energy dependence of the variable r, defined as the ratio between the cross section in the two hypotheses: it is higher for lower neutrino energies, where the discrepancy of the two curves is larger, and decreases, tending to one, for higher energies, where the contribution of F_4 and F_5 becomes negligible.

The ratio r is reported for $\overline{\nu}_\tau$ in the left plot of Fig. 6. To have evidence of a non-zero value of F_4 and F_5, the ratio r is required to be larger than 3σ, with σ being the uncertainty on the incoming neutrino flux, amounting to 20%. This condition is satisfied for $E_{\overline{\nu}_\tau} < 38$ GeV, where we expect to observe about 300 $\overline{\nu}_\tau$ interactions.

The ratio r was estimated also for the sum of ν_τ and $\overline{\nu}_\tau$. The right plot of Fig. 6 shows that in this case $r > 3\sigma$ for neutrino energies below 20 GeV, where the number of observed $\nu_\tau + \overline{\nu}_\tau$ interactions, not requiring the leptonic number to be measured, is expected to be about 420 .

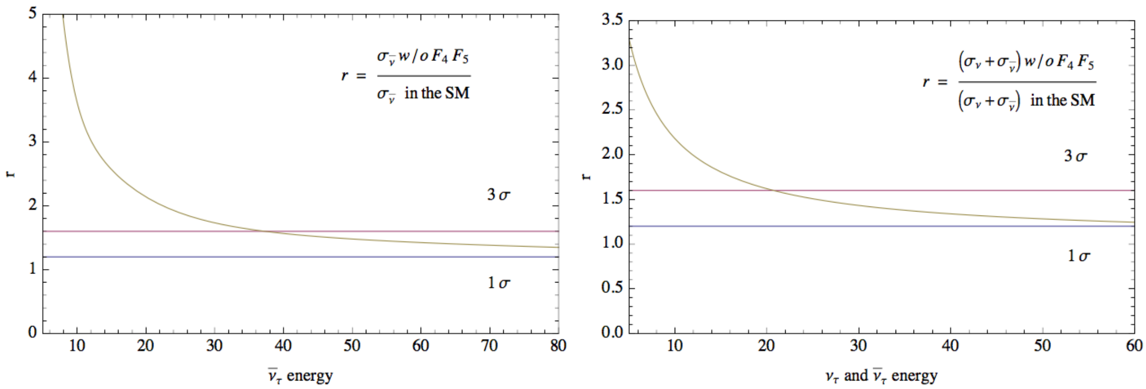

Figure 6: Energy dependence of the ratio r between the DIS cross section in the $F_4 = F_5 = 0$ hypothesis and the SM prediction, for $\overline{\nu}_\tau$ (left) and for the sum of ν_τ and $\overline{\nu}_\tau$ (right).

5. Charmed hadron physics

The SHiP experiment is suitable also to perform studies of charmed hadron production. The relative charm production yield in muon and electron neutrino and anti-neutrino interactions expected at SHiP energy amounts to 4% and 6%, respectively. In five years run, more than 10^5

neutrino induced charmed hadrons are expected, thus largely exceeding the statistics available in previous experiments by more than one order of magnitude. Therefore all the studies on charm physics performed with neutrino interactions will be revised with improved accuracy and some channels inaccessible in the past will be explored.

Unlike neutrino scattering where the presence of valence quarks favours the d-quark as neutrino target thus compensating the large suppression provided by the Cabibbo angle, charmed hadron production in anti-neutrino interactions selects anti-strange quark in the nucleon. Precise knowledge of the strangeness is an important information for many precision tests of the SM as well as for BSM searches at the LHC.

The potential impact of simulated charm data was assessed by adding them to the NNPDF3.0 NNLO fit [15]. The constraining power of the SHiP pseudodata is shown in Figure 7 (left) for the s^+ variable defined as $s+ = s(x) + \bar{s}(x)$. The vertical axis reports $1 + \Delta s^+/s^+$ where Δs^+ is the accuracy on s^+, in such a way that the difference to unity indicates the accuracy. The horizontal axis is the Bjorken variable x. A significant improvement on this variable is achieved in the x range between 0.03 and 0.35. Figure 7 (right) shows the improvement achieved on the variable $s- = s(x) - \bar{s}(x)$. versus the x variable. The vertical axis reports $1 + \Delta s^-/s^-$. A significant gain with SHiP data is obtained in the x range between 0.08 and 0.30.

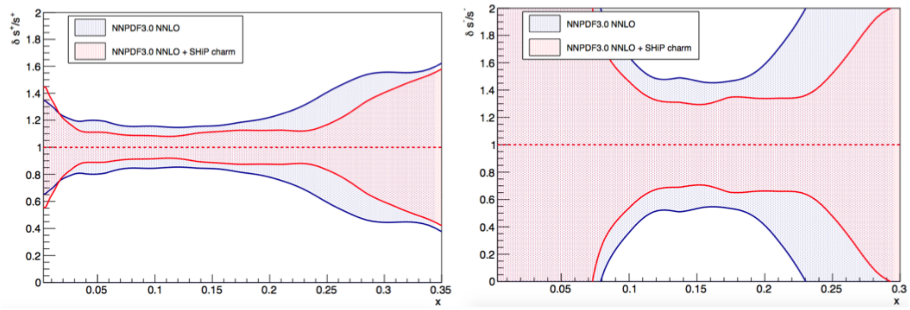

Figure 7: The blue line shows the present accuracy in the distribution of $s^+ = s + \bar{s}$ (left) $s^- = s - \bar{s}$ (right) as a function of x. The red contour shows the improvement obtained with SHiP.

6. Search for light dark matter

The neutrino detector is well suited to perform search for dark matter in the low mass region (sub GeV), still not accessible with direct detection experiments. This region can be explored by accelerator experiments, where the target recoils gain enough energy to be detected.

In a proton dump, light DM particles can be produced via the decay of the dark photon ([16], [17], [18], [19]) and the neutrino detector can identify them through the scattering off electrons. Background sources for this search are neutral current ν_μ and ν_e scattering on electrons, and charged current elastic, resonant and deep inelastic ν_e scattering off nuclei. The main variables to separate signal from background are the electron energy and the angle with respect to the neutrino direction and the number of detectable particles at the neutrino interaction vertex. Preliminary studies have shown that the sensitivity that the SHiP neutrino detector can achieve is considerably extending the reach of previous experiments.

7. Conclusions

The SHiP experiment is a new general-purpose fixed target facility at the CERN SPS to search for hidden particles as predicted by a very large of recently elaborated models of Hidden Sectors which can explain dark matter, neutrino oscillations and the baryon asymmetry in the Universe. The SHiP experiment is also suited to perform active neutrino physics with high statistics. It will have the opportunity observe for the first time the tau anti-neutrino and to perform tau neutrino and tau anti-neutrino cross-section measurements, with the extraction of F_4 and F_5, never measured so far. The large flux of muon and electron neutrino will allow the study of the charmed hadron production with high statistics and the estimation of the strangeness content of the nucleon.

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