The SHiP physics program

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Abstract. The discovery of the Higgs boson has fully confirmed the Standard Model of particles and fields. Nevertheless, there are still fundamental phenomena, like the existence of dark matter and the baryon asymmetry of the Universe, which deserve an explanation that could come from the discovery of new particles. The SHiP experiment at CERN meant to search for very weakly coupled particles in the few GeV mass domain has been recently proposed. The existence of such particles, foreseen in different theoretical models beyond the Standard Model, is largely unexplored. A beam dump facility using high intensity 400 GeV protons is a copious source of such unknown particles in the GeV mass range. The beam dump is also a copious source of neutrinos and in particular it is an ideal source of tau neutrinos, the less known particle in the Standard Model. Indeed, tau anti-neutrinos have not been directly observed so far. We report the physics potential of such an experiment including the tau neutrino magnetic moment.

1 The SHiP experiment

The discovery of the Higgs boson is certainly a big triumph of the Standard Model. In particular, given its mass, it could well be that the Standard Model is an effective theory working all the way up to the Planck scale. Nevertheless, there are several phenomena deserving an explanation that the Standard Model is unable to provide: the existence of dark matter and its nature, the baryonic asymmetry of the Universe and neutrino masses. It is therefore clear the new physics is there and presumably several new particles have still to be discovered.

Searches for new physics with accelerators are being carried out at the LHC, especially suited to look for high mass particles with ordinary couplings to matter. Complementary searches for very weakly coupled and therefore long-lived particles require a beam dump facility. Such a facility is made of a high density proton target, followed by a hadron stopper and a muon shield. Apart from residual muons, the only remaining particles are electron, muon and tau neutrinos on top of hidden, long-lived particles produced either in proton interactions or in secondary particle decays.

A new experiment, Search for Hidden Particles (SHiP), has been proposed [1], designed to operate at a beam dump facility to be built at CERN and to search for weakly coupled particles in the few GeV mass range. Since a high intensity tau neutrino flux is produced by such a facility from Ds decays, the experimental apparatus foresees a neutrino detector to study the tau neutrino cross-section and discover the tau anti-neutrino. This detector would also be suited to detect dark matter through the scattering off the atoms of its target. The physics case for such an experiment is widely discussed in Ref. [2]. We will review here the physics potential of this experiment for a selection of physics channels, including the tau neutrino magnetic moment.

In five years, the facility will integrate 2×10^{20} 400 GeV protons, produced by the SPS accelerator complex, impinging on a 12 interaction length (λ_{int}) target made of Molybdenum and Tungsten, followed by a 30 λ_{int} iron hadron absorber. Hidden particles in the GeV mass range would be produced mostly by the decay of charmed hadrons produced in proton interactions. D_s mesons, copiously produced among charmed hadrons, are a source of tau neutrinos through their fully leptonic decay. Therefore, the SHiP facility is ideal also to study the physics of tau neutrinos, the less known particle in the Standard Model.

Figure 1 shows the SHiP facility to be placed in the North Area: downstream of the target, the hadron absorber filters out all hadrons, therefore only muons and neutrinos are left. An active muon shield is designed with two sections with opposite polarity to maximize the muon flux reduction: it reduces the muon flux from 10^{10} down to 10^5 muons per spill. 4×10^{13} protons are extracted in each spill, designed to be 1s long to reduce the detector occupancy [3]. A first successful test of the SPS cycle with a 1s long spill was performed in April 2015.

The neutrino detector is located downstream of the muon shield, followed by the decay vessel and the detector for hidden particles. The Collaboration has been requested by the SPSC Committee to prepare a Comprehensive Design Report by 2018, in the framework of the Physics Beyond Colliders working group, launched in 2016 at CERN. This working group is meant to prepare proposals as input

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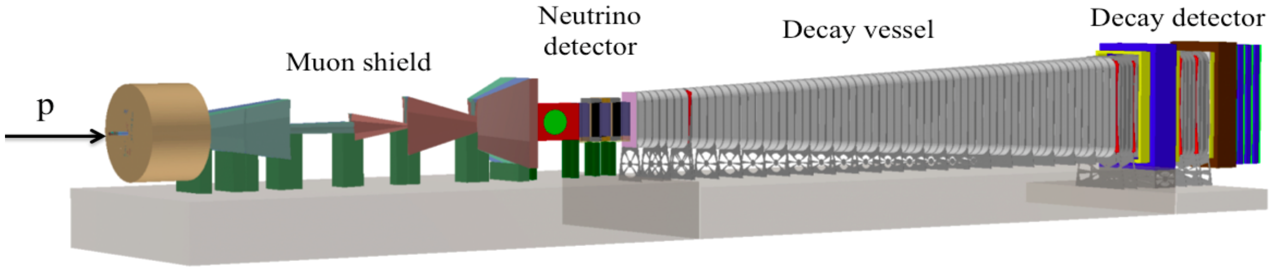

Figure 1. The beam dump facility and the SHiP detector.

for the High Energy panel of the European Strategy to be held in 2020, that will recommend about the approval of the experiment. The construction and installation will last until the third long shutdown of the LHC and the data taking is assumed to start in 2026.

The neutrino detector is made of a magnetised target region, followed by a muon spectrometer, as shown in Figure 2. The neutrino target is based on the emulsion cloud chamber technology employed by the OPERA experiment [4], with a compact emulsion spectrometer, made of a sequence of very low density material and emulsion films to measure the charge and momentum of hadrons in magnetic field. Indeed, this feature would allow to discriminate between tau neutrinos and anti-neutrinos also in the hadronic decay channels of the tau lepton. The emulsion target is complemented by high resolution tracking chambers to provide the time stamp to the event and connect muon tracks from the target to the muon spectrometer. The muon spectrometer is based on the concept developed for the OPERA apparatus: a dipolar iron magnet where drift tubes provide the momentum and resistive plate chambers provide the tracking within the iron slabs.

The emulsion target will also act as the target of dark matter as well as of any very weakly in- teracting particle produced at the accelerator, when its mass is in the GeV range. The detector is being optimised to search for interactions with the atoms (both electrons and nuclei) of very weakly interacting particles. The optimisation concerns e.g. the target material, the sampling frequency of the emulsion cloud chamber and the timing performances of the target tracker that would enable the separation between neutrinos and heavy particles based on the time of fligth measurement.

The detector for hidden particles is located in the downstream part of a 60 m long evacuated decay vessel, with an elliptical transverse section of 5×10 m^2, with the longer axis vertically. The hidden particles are supposed to decay within the vessel. The requirement to have less than 1 neutrino interaction in the vessel over five years sets the pressure to about 10^{-3} mbar. A magnetic spectrometer is located downstream of the vessel: it is made of straw tubes with a material budget of 0.5% X_0 per station, achieving a position resolution of 120 μm per straw, with 8 hits per station on average. This gives a momentum resolution of about 1%. The challenge is to build 5m long straw tubes and the large vacuum vessel. The vessel would be sorrounded by a liquid scintillator layer to tag particles coming from outside. Downstream of the spectrometer, an hadronic and electromagnetic calorimeter and a muon filter are used to identify particles.

2 Search for hidden particles

Extensions of the Standard Model in the low mass region foresee the existence of particles as singlets with respect to the Standard Model gauge group. These particles couple to different singlet compos- ite operators (so-called Portals) of the Standard Model. The neutrino can be considered as the first example of a hidden particle: it was postulated in 1930 to explain the puzzle of the beta decay, it is very light and extremely weakly interacting. The SHiP detector located immediately downstream of a beam dump has the potentiality to discover all of them, since it is sensitive to very weakly interacting and long lived particles in a wide unexplored range of their masses and couplings. We describe in the following its sensitivity to heavy neutral leptons, as an example. For the sensitivity to the other portals, we refer to Ref. [1].

2.1 Search for heavy neutral leptons

Neutrino masses are usually explained by the see-saw mechanism with a lagrangian term given by

$$L = \imath \bar{N}_I \partial_\mu \gamma^\mu N_I - Y_{I\alpha} \bar{N}_I^C \tilde{H} L_\alpha - M_I \bar{N}_I^C N_I + h.c. \quad (1)$$

where 3 right-handed heavy neutrinos N_I are introduced. The mass of active neutrinos is given by $m_\nu \simeq m_D^2/M_I$ where $m_D \simeq Y_{I\alpha} v$ and $v \simeq 246$ GeV is the Higgs vacuum expectation value. A massive neutrino with M_I of the order of 1 GeV and Yukawa couplings $Y_{I\alpha}$ of the order of 10^{-7} would account for an active neutrino mass $m_\nu \simeq 0.05$ eV, as measured by neutrino oscillation experiments.

If several conditions are satisfied, among which CP is not conserved, these right-handed neutrinos could also explain the leptogenesis and therein the baryogenesis [5, 6]. Such models do not pretend to explain also dark matter: a dark matter candidate could be provided by a fourth right-handed neutrino or an axion. Moreover they do not require

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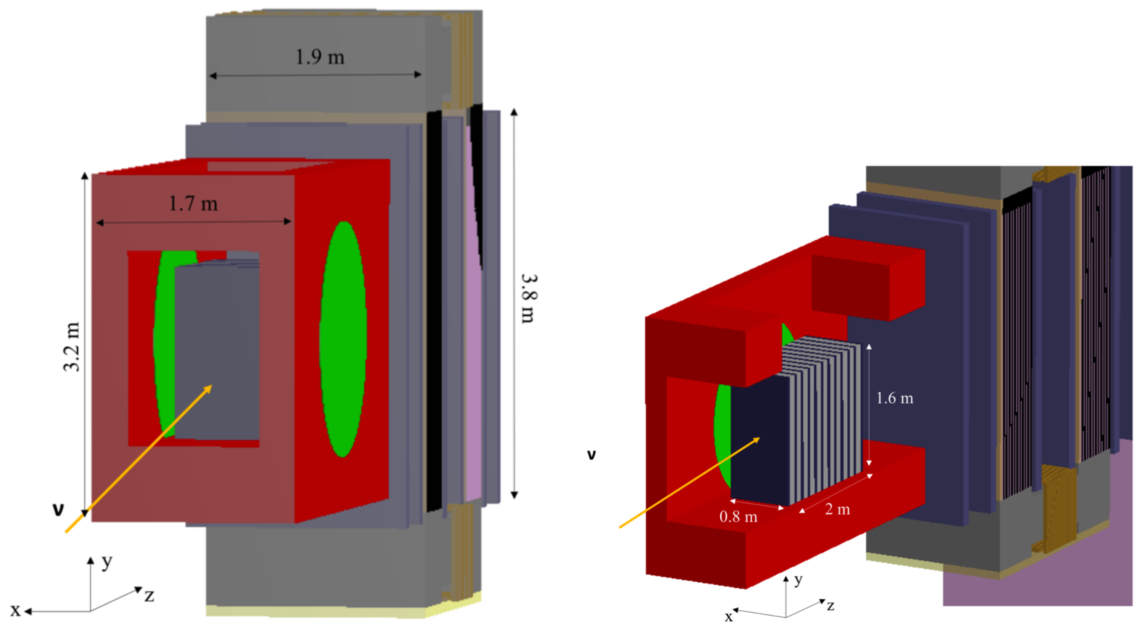

Figure 2. The neutrino detector upstream of the decay vessel in different views.

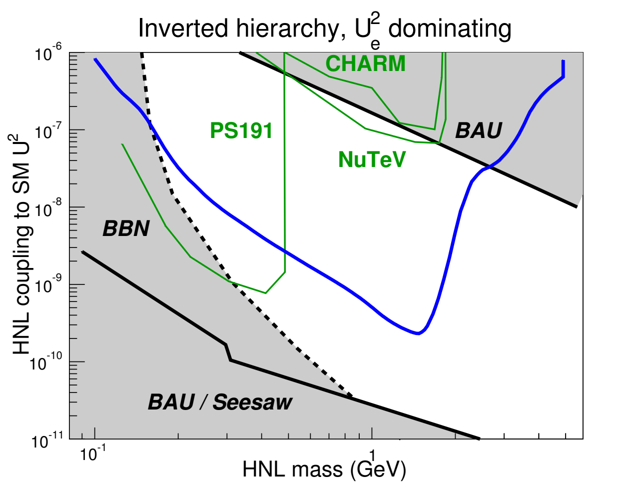

Figure 3. Exclusion limits at 90% C.L. set for inverted hierarchy with U_e^2 dominating, according to Ref. [10].

two of the three heavy neutrinos to be quasi-degenerate because CP violation does not need to be enhanced by mass degeneracy.

In the attempt of explaining also dark matter with three heavy neutrinos, it was first introduced in 2005 the so-called νMSM [7, 8], later followed by refined versions [9]. The role of the three right-handed neutrinos is different as well as their mass: M_1 could be a dark matter candidate with the mass of several keV while M_2 and M_3 should be states with a mass of about 1 GeV and quasi-degenerate to provide the baryon asymmetry of the Universe.

The states N_2 and N_3 could be produced in the decay of sufficiently massive particles like charmed hadrons. These states would be long lived particles that in turn could decay, for example, into $\pi\,\mu$.

Figure 3 shows the experimental and cosmological bounds on the search for heavy neutral leptons. It also reports superimposed the exclusion limits at 90% C.L. SHiP could set in case no signal is found, assuming the model reported in Ref. [10] with inverted hierarchy and a dominant electron coupling, $U_e^2 : U_\mu^2 : U_\tau^2 = 48 : 1 : 1$. The parameter space explored by SHiP extends in the cosmologically relevant region that is experimentally unexplored.

3 Physics with the neutrino detector

The tau neutrino is the less known particle in the Standard Model. Four candidates were firstly reported in 2001 by the DONUT experiment [11] and the observation of this particle was finally confirmed in 2008 when 9 candidates events were reported with an estimated background of 1.5 [12]. In the same paper they reported, for the first time, the tau neutrino cross-section where the constant term was measured to be $\sigma_{\nu_\tau}^{const} = (0.39 \pm 0.13 \pm 0.13) \times 10^{-38} cm^2 GeV^{-1}$. The large uncertainty is due to the poor statistical sample and to the rather scarce knowledge of the incoming flux. On top of the large uncertainty, DONUT could not separate tau neutrinos from anti-neutrinos. The OPERA experiment [4] has detected five tau neutrinos [13–17], leading to the discovery of tau neutrino appearance from muon neutrino oscillations [17]. The only leptonic decay observed by OPERA [15] shows negative charge as expected from a ν_τ interaction. Therefore, so far there is no direct evidence for tau anti-neutrinos.

The number of ν_τ and $\bar{\nu}_\tau$ emerging from the molybdenum target can be estimated as:

$$N_{\nu_\tau+\bar{\nu}_\tau} = 4N_p \frac{\sigma_{c\bar{c}}}{\sigma_{pN}} f_{D_s} Br(D_s \to \tau) = 6.6 \times 10^{15} \quad (2)$$

where N_p is the number of interacting protons (all incoming ones); $\sigma_{c\bar{c}} = 18.1 \pm 1.7$ μbarn [18] the associated charm production per nucleon; $\sigma_{pN} = 10.7$ mbarn the hadronic cross-section per nucleon in a Mo target. The inelastic cross-section pA shows the $A^{0.71}$ dependence [19]; $f_{D_s} = (8.8 \pm 0.6^{+0.5}_{-0.9})\%$ [20] is the fraction of D_s mesons produced; $Br(D_s \to \tau) = (5.54 \pm 0.24)\%$ [21] is the D_s branching ratio into τ; the factor 4 accounts for the charm pair production and for the two ν_τ produced per D_s decay. The SHiP facility is therefore a ν_τ factory, with 6.6×10^{15} tau neutrinos produced, equally divided in neutrinos and anti-neutrinos. Given the neutrino target mass of about 10 tons, one expects more than 10000 interactions of tau neutrinos and anti-neutrinos.

The prediction of the tau neutrino yield is affected by a large uncertainty: indeed, simulation studies of proton interactions in heavy and thick targets show that a sizeable contribution (about a factor of 2) to the charmed hadron yield comes from the cascade production [22]. Charmed hadrons are produced either directly from interactions of the primary protons or from subsequent interactions of the particles produced in the hadronic cascade showers. The SHiP Collaboration has proposed the SHiP-charm project [23], aiming at measuring the associated charm production by employing the SPS 400 GeV/c proton beam. This proposal includes a study of the cascade effect to be carried out using ECC techniques, i.e. slabs consisting of a replica of the SHiP experiment target [1] interleaved with emulsion films. The detector is hybrid, combining the emulsion technique with electronic detectors to provide the charge and momentum measurement of charmed hadron decay daughters and the muon identification. This allows a full kinematical reconstruction required by the double-differential cross- section measurement. According to the simulation performed, the delivery of 2×10^7 protons on target would allow the detection of about 1000 fully reconstructed charmed hadron pairs. An optimisation run is scheduled for 2018 and the full measurement is planned after the long shutdown LS2 of the CERN accelerator complex, with 5×10^7 protons on target and a charm yield of about 2500 fully reconstructed interactions.

The charged-current ν_τ ($\overline{\nu}_\tau$) differential cross-section is given by five structure functions. The contribution to the cross-section of F_4 and F_5 structure functions, introduced by Albright and Jarlskog [24], is negligible in muon and electron neutrino interactions due to the light charged lepton mass. On the contrary, given the non-negligible mass of the τ lepton, tau neutrino scattering is sensitive to their contribution. Indeed, the hypothesis of $F_4 = F_5 = 0$ would significantly increase the ν_τ and $\overline{\nu}_\tau$ charged-current deep-inelastic cross sections and the corresponding number of expected ν_τ and $\overline{\nu}_\tau$ interactions. The region of the energy spectrum below 40 GeV is highly sensitive to the non-zero values of these structure functions.

In the Standard Model, neutrinos may interact with a photon through second order diagrams giving a magnetic moment proportional to the neutrino mass and therefore totally negligible and undetectable. Beyond standard model theories predict a neutrino magnetic moment many orders of magnitude higher. Testing the neutrino magnetic moment is therefore a test of possible physics beyond the standard model. Limits on the magnetic moment of muon and electron neutrinos are rather stringent while the one of tau neutrinos is practically unconstrained. An anomalous magnetic moment of the tau neutrino would result in tau neutrino interactions with electrons. Quasi-elastic electron neutrino interactions where the final state proton is undetected constitute the main background. An upper limit $\mu_\nu < 1.3 \times 10^{-7}\mu_B$ can be achieved with the SHiP experiment in case no excess is observed.

3.1 Strange parton distribution

Charmed hadrons are produced in neutrino and anti-neutrino charged-current interactions at the level of about 5%. Experiments based on calorimetric technology identify charmed hadrons only in their muonic decay channel, when two opposite sign muons are produced in the final state. A cut of 5 GeV is applied to muons in order to suppress the background due to punch-through pions. The nuclear emulsion technology, instead, identifies topologically the charmed hadron by detecting its decay vertex. Energy cuts are therefore much looser, thus providing a better sensitivity to the charm quark mass. Moroever, a large statistical gain is provided by the use of hadronic decay modes [25]. Indeed, despite the fact that 1.280.000 ν_μ and 270.000 $\bar{\nu}_\mu$ charged-current interactions were collected by the NuTeV/CCFR Collaboration, only 5102 ν_μ and 1458 $\bar{\nu}_\mu$ events were identified as charm production induced by neutrino charged-current interactions. The largest number of events in an emulsion experiment was collected by CHORUS with 2013 charm candidates from ν_μ and only 32 from $\bar{\nu}_\mu$ [26]. SHiP will integrate about 10^5 charm candidates, more than one order of magnitude larger than the present statistics, with a large ($\sim$ 30%) contribution from anti-neutrinos. Charm production in neutrino scattering is extremely sensitive to the strange quark content of the nucleon, especially with anti-neutrinos where the s-quark is dominant. SHiP will improve significantly the uncertainty on the strange quark distribution in the nucleon as shown in the left plot of Figure 4 in terms of $s^+ = s(x) + \bar{s}(x)$ in the $0.02 < x < 0.35$ range.

3.2 Dark Matter search

The dark matter at an accelerator can be produced through the decay of a dark photon and it can thus be copiously produced at a beam dump facility. Given the proton energy, a dark matter in the GeV and sub-GeV mass range can be produced at SHiP. Direct searches performed in the underground laboratories rely on the observation of nuclear recoils induced by the scattering of galactic dark

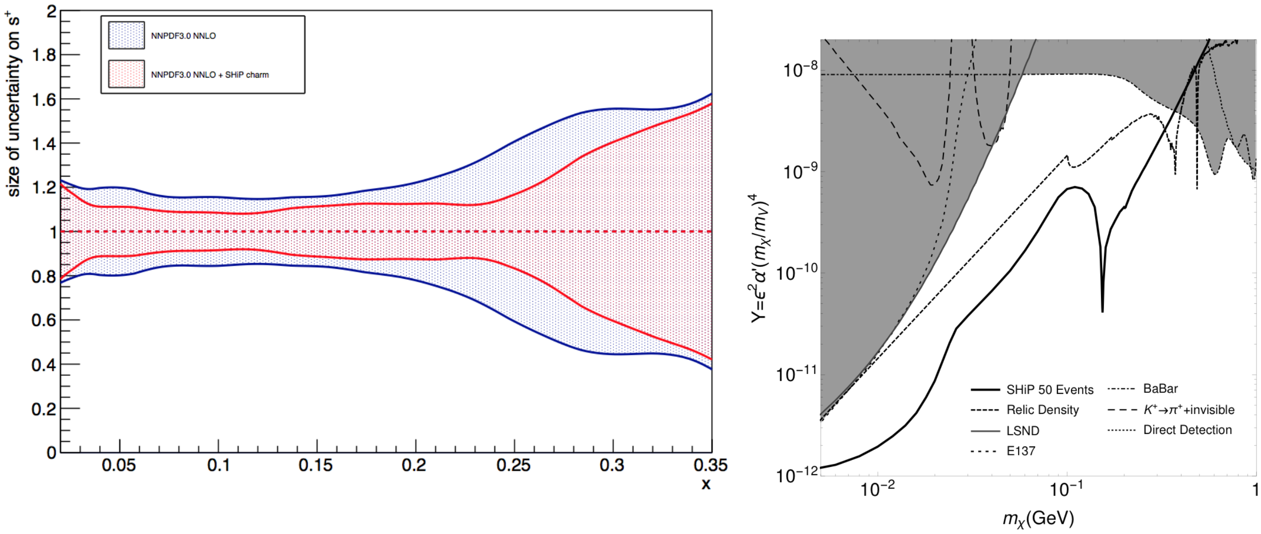

Figure 4. Left: Improvement of the accuracy on s^+ with SHiP (red) compared to the present status (blue) in the $0.02 < x < 0.35$ range. Right: SHiP sensitivity to light dark matter in the (m_χ, Y) plane.

matter. Given the non-relativistic nature of galactic dark matter, induced recoils show a kinetic energy of the keV order if the dark matter mass is around 1 GeV. This makes the search for dark matter at around 1 GeV or below extremely difficult. The sensitivity of current experiments in that range is therefore limited by the capability of observing such low energy recoils. At the accelerator, on the contrary, the dark matter would be ultra-relativistic and it could be observed through its scattering off the electrons of the lead-emulsion target of the neutrino detector. The elastic interaction of dark matter particles with electrons produces one electron in the final state, thus mimiking elastic interaction of neutrinos that constitute the main background for this search. In Ref. [1] we have estimated the total background. Following the approach described in Ref. [27], the right plot of Fig. 4 shows the SHiP sensitivity to light dark matter in the plane (m_χ, Y) where m_χ is the dark matter mass, $Y = \varepsilon^2 \alpha' \frac{m_\chi^4}{m_V^4}$, m_V the mass of the dark photon as dark matter parent, ε the coupling. This plot is drawn for the fixed ratio $\frac{m_V}{m_\chi} = 5$ and $\alpha' = 0.5$. The deep peak at around 150 MeV is due to the ρ/ω resonances in the dark photon production. The slope change around 27 MeV is due to π^0 production. The sensitivity to light dark matter turns out to be very competitive with all the planned experiments in the next decade.

The neutrino detector is in general sensitive to the search for very weakly interacting particles when they interact with the atoms of the emulsion target.

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