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Neutrino physics with the SHiP experiment at CERN

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SHiP (*Search for Hidden Particles*) is a general purpose experimental facility recently proposed at CERN. It will be operated in beam dump mode at the CERN SPS accelerator with the aim of searching for long-lived particles of Hidden Sector models in the GeV mass range. The SHiP beam dump will be a copious source of hidden particles together with active neutrinos of all flavours. The SHiP Scattering and Neutrino Detector (*SND*), based on the Emulsion Cloud Chamber technique, has been specifically designed to perform precision studies of neutrino and anti-neutrino interactions. In five years, the integrated statistics of 2×10^{20} protons on target will provide the first direct observation of tau anti-neutrinos. The ν_τ and $\bar{\nu_\tau}$ deep-inelastic scattering cross-sections will be measured with statistics a thousand times larger than currently available, allowing for the extraction of the F_4 and F_5 structure functions, never measured so far. Charm physics studies will also be performed with improved accuracy with respect to past experiments, thus providing good sensitivity to the strange quark distribution in the nucleon.
In this paper, focus will be given to the physics potential of the SHiP SND, including its sensitivity to light dark matter searches.

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1. Introduction

The Standard Model of Particle Physics represents our best current understanding of the constituents of matter and of how they interact. Its predictions have been successfully tested by many experiments, the latest of them being the discovery of the Higgs boson at the LHC in 2012 [1], [2]. Nevertheless, the Standard Model cannot account for a number of well-established observational phenomena. Non-zero neutrino masses, dark matter signatures, the baryon asymmetry of the Universe are examples of experimental facts that cannot be explained with the known particles alone and push the search for new physics.
The current results in theoretical and experimental particle physics, cosmology and astrophysics still leave the parameters of new physics largely undetermined. No convincing signs of new particles have been found so far, likely due to very heavy masses, hardly or definitively not accessible with the present-day accelerators, or to very weak couplings with the ordinary matter. Searches for new phenomena occurring at the *energy frontier* are being carried out at the LHC, while complementary searches for very weakly coupled long lived particles require to be investigated at the *intensity frontier* with a beam dump facility.
The recently proposed Search for Hidden Particles (SHiP) beam dump experiment [3] at the CERN Super Proton Synchrotron (SPS) accelerator has been designed to investigate, in the GeV mass range, the existence of such *hidden* particles, coupled to the *visible sector* through gauge-singles operators (portals). Those unknown particles are expected to be predominantly accessible through the decays of heavy hadrons. A dedicated experimental facility, the BDF (*Beam Dump Facility*) [4], has been proposed by the SHiP Collaboration in order to maximise the hidden particles production while providing an extremely clean background environment. At BDF, an abundant production of neutrinos from charmed hadron decays is also expected, allowing neutrino and anti-neutrino physics studies at unprecedented precision.
In the following, we will describe the SHiP facility and the experimental apparatus, focussing on the neutrino physics potential of the project.

2. The SHiP facility

The CERN-based BDF [4], specifically designed for the SHiP experiment, will be located on a new beam extraction line which branches off from the CERN SPS transfer line to the North Area. Its layout foresees a high density proton target followed by an iron absorber and a muon shield.
The high intensity 400 GeV/c SPS proton beam will be dumped on a molybdenum-tungsten target. In five years run, 2×10^{20} protons on target will be delivered leading to a copious production of heavy mesons ($\mathscr{O}(10^{18})$ charmed mesons, $\mathscr{O}(10^{14})$ beauty mesons). Hidden, long-lived particles in the GeV mass range will be produced either in beam proton interactions or in decay processes of the secondary mesons. The target will be followed by an hadron absorber in order to strongly reduce the huge flux of Standard Model particles emerging from the dump while the active muon shield will sweeps muons produced in the beam dump out of acceptance of the downstream detectors. Apart from residual muons, the only remaining particles are electron, muon and neutrinos on top of hidden particles. As a consequence, SHiP will have a dual detector system: a *Hidden Sector* detector (HS) devoted to search for new, weakly coupled, long lived particles from the Hidden

Sector and a *Scattering and Neutrino Detector* (SND) designed for neutrino physics and Light Dark Matter searches. The HS will be made up of a 50 m long cylindrical decay vessel, evacuated down to a pressure of $\mathcal{O}(10^{-3})$ bar and surrounded by a veto system in order to ensure efficient suppression of the backgrounds. A magnetic spectrometer and a particle identification system will be located downstream the decay vessel, being essential to fully reconstruct hidden particle decays and discriminate between the very wide range of Hidden Sector models. Figure 1 shows a schematic overview of the SHiP facility, from the proton target to the end of the Hidden Sector detector.

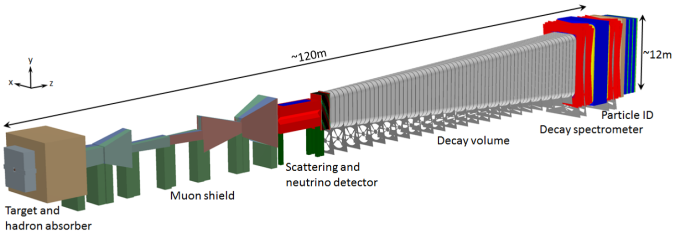

Figure 1: Schematic layout of the Beam Dump Facility and of the SHiP detectors.

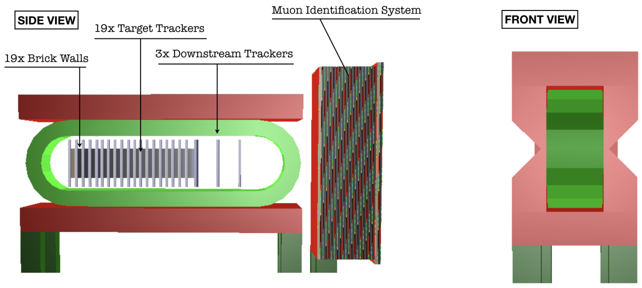

Figure 2: Schematic layout of the SHiP Scattering and Neutrino Detector.

2.1 The Scattering and Neutrino Detector

The SND has been designed to perform neutrino physics studies and search for light dark matter signatures. The detector layout, shown in figure 2, foresees a $(3.6 \times 7.2 \times 2.2)m^3$ magnetised region followed by a muon identification system. The magnetised region will host a neutrino target followed by a particle spectrometer. They are both immersed in a 1.2 T horizontal magnetic field. The neutrino target is a hybrid detector consisting of 19 "Brick Walls" (walls of *Emulsion Targets*) alternated to Target Tracker planes. The Emulsion Target has a modular structure: the unit cell consists of a (40 $\times$ 40) cm^2 Emulsion Cloud Chamber (ECC) brick made of 1 mm - thick absorber plates (tungsten or lead) interleaved with 300 μm - thick nuclear emulsion films. Each brick will be followed by a Compact Emulsion Spectrometer (CES), a sequence of very low density material and nuclear emulsion films. Four ECC bricks, together with the corresponding CES, are disposed in a 2×2 matrix to fill one Emulsion Target. The absorber mass totals about 8 tons.

The Emulsion Cloud Chamber technology was successfully exploited in past years in the OPERA experiment [5] to reconstruct neutrino interactions with micrometric resolution. Here is combined with the CES detector that allows measuring charge and momentum of hadrons produced in the reconstructed ν interactions up to 12 GeV. This feature makes possible to discriminate between tau neutrinos and anti-neutrinos, also in the hadronic decay channels of the tau lepton.

The Emulsion Target is complemented by SciFi Target Trackers, tracking chambers with spatial resolution better than 50 μm that provide the timestamp to the event and link muon tracks from the target to the muon system. Three additional Target Tracker planes (the *Downstream Trackers*), separated by 50 cm air gaps, will be mounted after the neutrino target in order to measure the charge and momentum of muons exiting the target region, thus extending significantly the detectable momentum range of the CES and improving the connection between the ECC bricks and the muon identification system placed downstream. The combination of the nuclear emulsion technology with the information provided by the muon identification system makes it possible to distinguish different neutrino flavors identifying the primary charged lepton produced in neutrino charged-current interactions. The lepton identification is also used to classify the tracks produced in the τ decay and, therefore, to identify the τ decay channel.

The neutrino target design is currently undergoing an optimisation phase that concerns the target material choice, the sampling frequency of the ECC and the timing performances of the Target Trackers, that would enable the separation between neutrinos and heavy particles based on time-of-flight measurements.

The SND Muon Identification System is made of a sequence of iron filters and RPC planes with sensitive area of $\sim 2 \times 4$ m^2, totalling about two metres in length. The RPCs, to be operated in avalanche mode, have been specifically designed for SHiP SND and are characterised by large gas gap dimensions ($\sim 2 \times 1$ m^2) with respect to those usually employed in HEP. The muon identification efficiency of the system has been evaluated to be about 97% while the hadrons mis-identidication probability is expected to be at the level of 1.5%. A first prototype of the system has been built and successfully operated for a campain of measurement realised at SPS in order to evaluate the SHiP muon flux [6] and the charm production cross-section, including the contribution of cascade processes [7].

The Muon Identification System will also act as upstream veto tagger for background processes to the hidden particle search, which motivates a high sampling choice, still under optimisation.

3. Physics with the SND

At SHiP BDF, a huge flux of neutrinos and anti-neutrinos of all flavours is expected. These particles will originate from the decay of heavy and light mesons produced at the beam dump. Mainly due to geometrical acceptance, only a few percent of them reaches the SND, interacting within the target. Nevertheless, in five years run, the number of neutrino and anti-neutrino interactions suitable for ν physics studies at the SHiP SND is still high, representing a unique opportunity to report the first ever direct observation of $\overline{\nu}_\tau$, perform precision studies on different neutrino and anti-neutrino flavours and on high statistics neutrino induced charm production as well. Moreover,

the SND will be also able to detect dark matter candidates in the GeV mass range.
In the following we will detail the SND physics potentials for neutrino, charm and dark matter physics.

3.1 Neutrino physics

At SHiP BDF tau neutrinos are copiously produced by D_s mesons through their fully leptonic decay, while a high rate of electron and muon neutrinos originates from the decay of soft pions and kaons. Table 1 shows the expected number of charged-current deep-inelastic (anti-)neutrino interactions in the SND Emulsion Target during the whole data taking, together with the $\nu(\overline{\nu})$ mean energy.

	<E> [GeV]	CC DIS int.
ν_e	59	$1.1 \cdot 10^6$
ν_μ	42	$2.7 \cdot 10^6$
ν_τ	52	$3.2 \cdot 10^4$
$\overline{\nu}_e$	46	$2.6 \cdot 10^5$
$\overline{\nu}_\mu$	36	$6.0 \cdot 10^5$
$\overline{\nu}_\tau$	70	$2.1 \cdot 10^4$

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

The expected number of ν_τ and $\overline{\nu}_\tau$ charged current interactions are about 32000 and 21000, respectively. Compared to the status of the art, where still there is no direct evidence for tau anti-neutrinos and the observation of tau neutrinos was confirmed by the DONUT experiment only in 2008 when nine candidates events were reported [8] while its appearance from muon-neutrino oscillations was discovered by the OPERA experiment [5] following the detection of ten tau neutrino candidate events [9], the SND will be able to make the first direct observation of the $\overline{\nu}_\tau$ and, thanks to the expected unprecedented statistics of both tau neutrinos and anti-neutrinos it will also be able to precisely study their properties and their cross-section.
The full expression for the neutrino differential deep-inelastic scattering cross-section on a nucleon is expressed in terms of five structure functions F_i, $i \in 1,...,5$, which in the Parton Model can be interpreted as a measure of the partonic structure of the hadrons. The structure functions F_4 and F_5, unlike the others, are proportional to the mass of the charged lepton associated to the flavour of the interacting neutrino and therefore they are not negligible only in case of ν_τ. At SHiP SND will be possible to make a first measure of F_4 and F_5. At leading order, in the limit of massless quarks and target hadrons, F_4 is null and $2xF_5 = F_2$, where x is the Bjorken-x variable [10]. Calculations at NLO show that the F_4 contribution to this cross-section is about 1% [11]. As a matter of fact, a non null value of F_4 and F_5 affects the cross-section which increases with respect to the hypothesis of both the structure function equal to zero, especially at lower neutrino energies. Simulations have shown that SHiP can probe a non-zero value of F_4 and F_5 by observing more than 300 expected events with $E < 38$ GeV if only the $\overline{\nu}_\tau$ dataset is considered.

3.2 Charm physics

At SHiP, in 2×10^{20} protons on target, more than $\sim2\times10^{5}$ charged current deep inelastic scattering neutrino induced charmed hadrons are expected. The use of nuclear emulsion films allows charmed hadrons identification on topological basis, given their capability to reconstruct with micrometric accuracy both the neutrino interaction vertex and the charmed hadron decay vertex occurring after about one millimetre. All the decay channels of the charmed hadrons, not only di-lepton events, turn out to be accessible without any kinematical cut. As a consequence, the available statistics exceed by more than one order of magnitude that of previous experiments, with a large ($\sim$ 30%) contribution from anti-neutrinos. This will improve the current results on charm physics performed with neutrino interactions and will let accessible some decay channels never studied before. As an example, none charm candidate from ν_e interactions was ever reported up to now.
Charmed hadrons produced in neutrino interactions are also important to investigate the strange quark content of the nucleon. As shown in figure 3, SHiP will improve significantly the uncertainty on the strange quark distribution in the nucleon in terms of $s^{+} = s(x) + \bar{s}(x)$ in the $0.03 < x < 0.35$ range, where s(x) represents the strange quark content of the nucleon as a function of the Bjorken x.

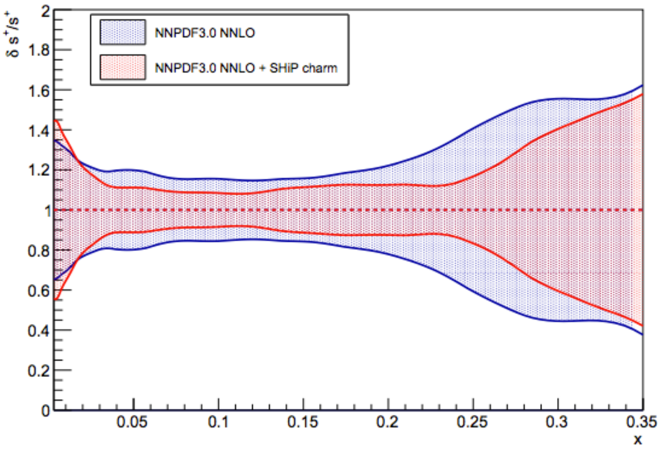

Figure 3: Present NNLO estimates (blue line)[12] and future (red line) knowledge of parton distribution functions of $s(x) + \bar{s}(x)$, for Bjorken x spanning from 0.03 to 0.35 in a Q^2 region between 3 GeV^2 and 80 GeV^2.

3.3 Light Dark Matter searches

The SHiP SND is an ideal laboratory to look for Light Dark Matter scattering signatures, too. A Light Dark Matter (LDM) candidate χ, eventually produced in a dark photon decay and undergoing elastic scattering on the atomic electrons of the Emulsion Target, produces an isolated electromagnetic shower originating from the recoil electron. The ECC bricks act as fine sampling calorimeters with a total thickness of 10 X0, allowing an accurate measurement of both the energy of the recoil electron and the incident angle. Neutrino and anti-neutrino interactions with only one reconstructed electron at the interaction vertex constitute the main source of background to the LDM search. Therefore the discrimination of LDM signal from the (anti-)neutrino induced

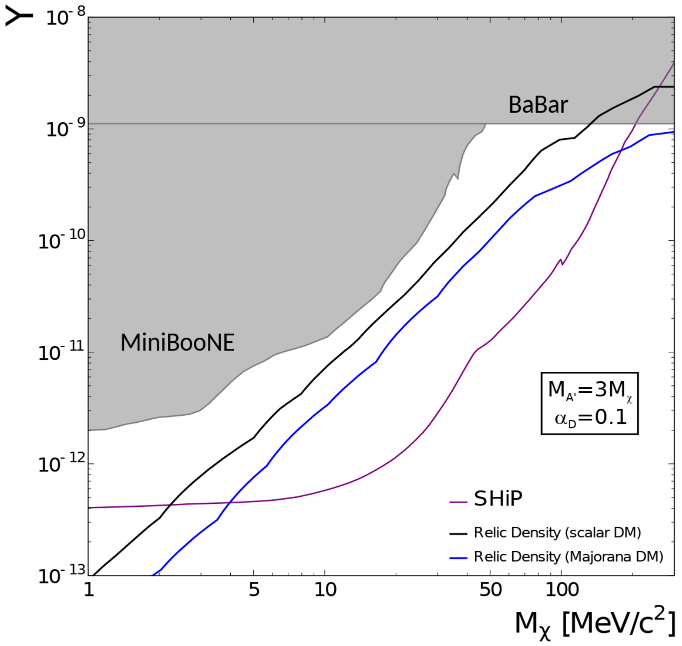

Figure 4: SHiP sensitivity to LDM produced in dark photon decays. The grey shaded regions represent the parameter space which has been already ruled out by the searches at the BaBar [13] and the MiniBooNE [14] experiments.

background strongly relies on the nuclear emulsion micrometric accuracy with which is possible to detect any additional visible activity accompanying the recoil electron in the Emulsion Target. An other important contribution to the background comes from (anti-)neutrino events with elastic scattering topology similar to the LDM signal. The signal is thus selected evaluating the kinematic correlations between the electron energy and the angle with respect to the neutrino direction. Figure 4 shows the expected sensitivity for SHiP to LDM searches in the parameter space (m$_\chi$,Y), where $Y = \varepsilon^2\alpha'_D(m_\chi/m_{A'})^4$. For 2×10^{20} pot, taking into account geometrical acceptance and selection criteria, in the mass region from a few MeV up to ~200 MeV the SHiP sensitivity reaches below the limit which gives the correct relic abundance of dark matter. The current estimate is conservative since at the moment only meson decays and Drell-Yan production have been considered as a source of dark photons decaying to LDM.

4. Conclusions

The SHiP experiment has been proposed to probe the existence of new, very weakly interacting particles in the GeV mass range at the intensity frontier. It offers also a unique opportunity for precision neutrino physics programme and LDM searches. Currently, the Collaboration is concluding the Comprehensive Design phase, moving forward to produce TDRs by 2021-2022.

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