PROCEEDINGS OF SCIENCE

Neutrino physics with the SHiP experiment at CERN

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On behalf of the SHiP Collaboration

The SHiP Collaboration has proposed a general-purpose experimental facility operating in beam dump mode at the CERN SPS accelerator with the aim of searching for light, long-lived exotic particles of Hidden Sector models. The SHiP experiment incorporates a muon shield based on magnetic sweeping and two complementary apparatuses. The detector immediately downstream of the muon shield is optimised both for recoil signatures of light dark matter scattering and for tau neutrino physics, and consists of a spectrometer magnet housing a layered detector system with heavy target plates, emulsion film technology and electronic high precision tracking. The second detector system aims at measuring the visible decays of hidden sector particles to both fully reconstructible final states and to partially reconstructible final states with neutrinos, in a nearly background free environment. The detector consists of a 50 m long decay volume under vacuum followed by a spectrometer and particle identification with a rectangular acceptance of 5 m in width and 12 m in height. Using the high-intensity beam of 400 GeV protons, the experiment is capable of integrating 2×10^{20} protons in five years, which allows probing dark photons, dark scalars and pseudo-scalars, and heavy neutrinos with GeV-scale masses at sensitivities that exceed those of existing and projected experiments. The sensitivity to heavy neutrinos will allow for the first time to probe, in the mass range between the kaon and the charm meson mass, a coupling range for which baryogenesis and active neutrino masses can be explained. The sensitivity to light dark matter reaches well below the elastic scalar dark matter relic density limits in the range from a few MeV/c^2 up to 200 MeV/c^2. The tau neutrino deep-inelastic scattering cross-sections will be measured with a statistics a thousand times larger than currently available data, with the extraction of the F4 and F5 structure functions, never measured so far, and allow for new tests of lepton non-universality with sensitivity to BSM physics. Following the review of the Technical Proposal, the CERN SPS Committee recommended in 2016 that the experiment and the beam dump facility studies proceed to a Comprehensive Design Study phase. These studies have resulted in a mature proposal submitted to the European Strategy for Particle Physics Update.

The 21st international workshop on neutrinos from accelerators (NuFact2019)
August 26 - August 31, 2019
Daegu, Korea

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1. Introduction

The SHiP (Search for Hidden Particles) [1, 2, 3] is a newly proposed fixed target experiment at CERN aiming at searching for hidden particles which are feebly interacting long-lived particles with mass from sub-GeV up to $O(10)$ GeV/c^2. This experiment will cover the "cosmological interesting region" of the parameter space near the super-weak coupling down to 10^{-10}.

These light, long-lived exotic particles of Hidden Sector models [2] such as heavy neutral leptons, dark photons, dark scalars and axion-like particles would be produced from decay of charm or beauty particles using the high intensity 400 GeV proton beam at the SPS beam dump facility. In addition, the SHiP can perform unprecedented measurements with tau neutrinos and anti-tau neutrinos. It can also probe the existence of light dark matter (LDM) through the observation of its scattering off electrons in the Emulsion target.

The SHiP detector is sensitive both to decay and scattering signatures of these particles. The detector (total length is about 120m) consists of Scattering and Neutrino detector (SND) including the Emulsion target, long evacuated Decay volume ($\sim$50m vacuum vessel) and the Hidden Sector decay spectrometer (5 m in width and 12 m in height) including Calorimeter and Muon detector in order to allow full reconstruction and particle identification, as shown in Figure 1.

2. Tau Neutrino Physics

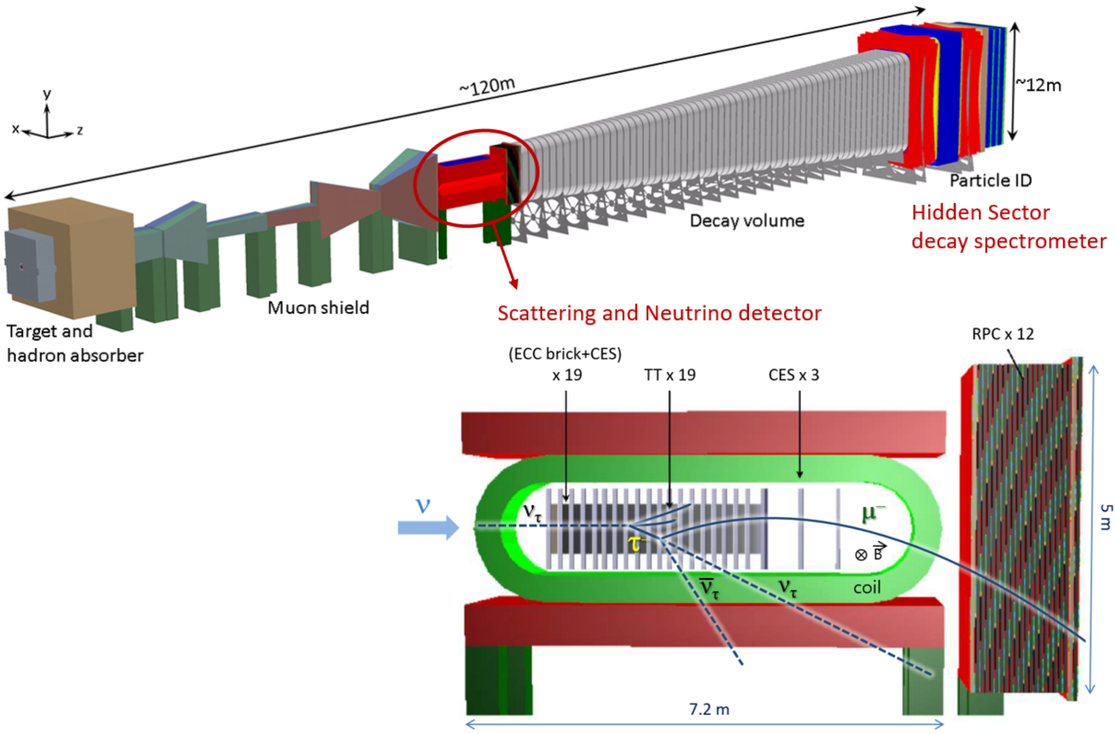

Figure 1: The SHiP main detector (up) and the Scattering and Neutrino detector (down).

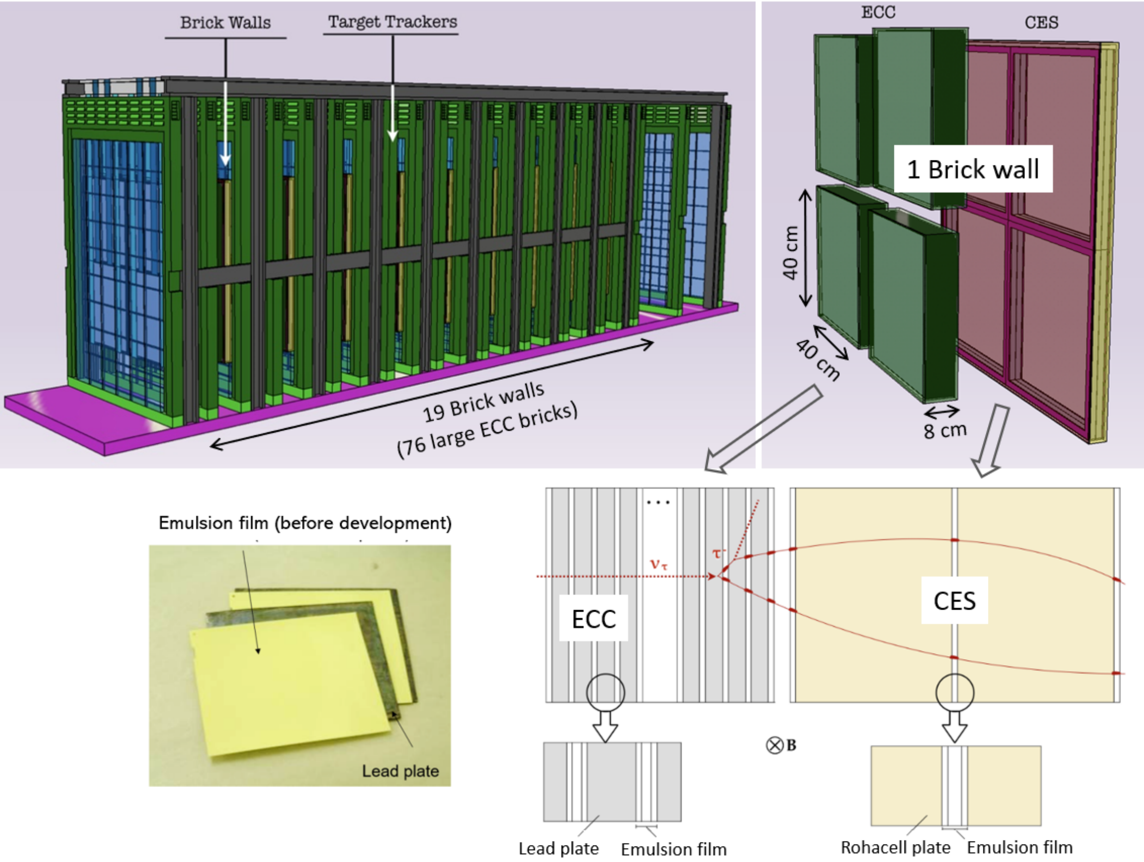

Figure 2: Layout of the Emulsion target and closeup view of one Emulsion brick wall of four cells, each containing an ECC and a CES.

In order to detect ν_τ and $\bar{\nu}_\tau$, the Nuclear emulsion will be used as both target and detector. It has micrometric accuracy for τ lepton identification ($c\tau \sim 87\mu$m) and has been proven a suitable ν_τ detector in the OPERA experiment.

The Emulsion target, placed inside magnet (1.25T) of the SND, is made of 19 Emulsion brick walls and 19 Target tracker (TT) planes. The brick walls are divided in 2×2 cells, each with a transverse size of 40×40 cm^2, containing an Emulsion Cloud Chamber (ECC) and a Compact Emulsion Spectrometer (CES) as illustrated in Figure 2. The ECC brick is made of 36 Emulsion films interleaved with 1 mm thick tungsten alloy layers. The thickness and weight of one brick are about 5 cm (corresponding to $\sim$10 X_0 which can contain the electromagnetic shower) and about 100 kg, respectively. The overall target weight with 19 walls is about 8 tonnes [3].

The charge determination of decay products of τ lepton is essential to separate ν_τ and $\bar{\nu}_\tau$. The charge can be measured by curvature of the τ decay tracks such as muon and hadrons using the CES under magnetic field. The TT can provide information on the precise positions and angles of outgoing tracks and also provide the time stamp. The RPCs are used as muon identification system. A pilot production of five RPC detectors (size 2×1.25 m^2) was made and successfully operated for the muon flux and charm production measurements in 2018 at the CERN H4 beam line.

The number of the observed ν_τ so far is 19, among them 9 events are from DONuT and

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10 events from OPERA experiment. Given the ECC target, the neutrino flux, the geometrical acceptance of the detector and the Standard Model cross section, unprecedented samples of about 6000 ν_τ and 5000 $\bar{\nu}_\tau$ events are expected to be observed with an integrated 2×10^{20} protons on target (PoT) during 5 years, as reported in Table 1. The $\tau \to e$ decay channel is currently not considered for the discrimination of ν_τ and $\bar{\nu}_\tau$ because the electron charge is not measurable. The anti-tau neutrinos can be observed for the first time.

With a statistics a thousand times larger than currently available data, the scattering cross sections and magnetic moments of ν_τ and $\bar{\nu}_\tau$ can be determined. The structure functions F4 and F5 of the ν_τ ($\bar{\nu}_\tau$) differential cross section, not accessible with other neutrinos, will be extracted. And the SHiP will be able to study neutrino-induced charm production from all flavours with a data expected more than 2×10^5 charmed hadrons. Using these data, the uncertainty on the strange quark content in the nucleon can be reduced significantly in the Bjorken x range between 0.02 and 0.35.

3. Light Dark Matter Search

Given the proton beam energy, the LDM (χ) with GeV and sub-GeV mass range would be copiously produced at a beam dump facility via the decay of a dark photon $A' \to \chi\bar{\chi}$. The LDM particles can be observed through its scattering off the electrons in the ECC target of the SND; $\chi e^- \to \chi e^-$. The signature of the LDM signal is an isolated electromagnetic cascade shower due to relativistic electron recoil from the LDM-electron elastic scattering. Neutrino events with only one reconstructed outgoing electron at the primary vertex constitute background in the LDM searches.

The micrometric accuracy of the Nuclear emulsion is crucial for detecting any associated activity at the origin of the electromagnetic shower in order to discriminate the LDM signal from neutrino-induced background events In addition, the ECC bricks, interleaved with the TT planes, act as sampling calorimeters with five active layers per radiation length, X_0, and a total depth of 10 X_0. The configuration is possible to reconstruct the cascade shower produced by the electron recoil to determine the particle energy and angle. Correlation between the electron energy and the scattering angle is shown in Figure 3 (Left) for 1 GeV/c^2 dark photons produced in the decay of mesons and decaying into LDM with a benchmark mass $M_\chi = M_{A'}/3$.

Table 1: Expected number of ν_τ and $\bar{\nu}_\tau$ signal events observed in the different τ decay channels, except for the $\tau \to e$ where the lepton number cannot be determined.

Decay channel	ν_τ	$\bar{\nu}_\tau$
$\tau \to \mu$	1200	1000
$\tau \to h$	4000	3000
$\tau \to 3h$	1000	700
Total	6200	4700

Table 2: Estimate of the neutrino backgrounds in the LDM search with the SND for an integrated proton yield of 2×10^{20} PoT.

Background	ν_e	$\bar{\nu}_e$	ν_μ	$\bar{\nu}_\mu$	all
Elastic Scattering	81	45	56	35	217
Quasi-elastic Scattering	245	236	-	-	481
Resonant Scattering	8	126	-	-	134
Deep Inelastic Scattering	-	14	-	-	14
Total	334	421	56	35	846

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The resulting background estimate for the different categories of neutrino interactions for 2×10^{20} PoT is reported in Table 2. The dominant background contribution arises from ν_e quasi-elastic scattering ($\nu_e n \to e^- p$, with the soft proton unidentified) and from topologically irreducible sources, i.e. $\nu_e(\bar{\nu}_e)$ elastic and $\bar{\nu}_e$ quasi-elastic scattering ($\bar{\nu}_e p \to e^+ n$).

The expected sensitivity to LDM for 2×10^{20} PoT, taking into account the geometrical acceptance and the selection criteria, is shown in Figure 3 (Right) in the parameter space (M_χ, Y), where $Y = \varepsilon^2 \alpha_D (M_\chi/M_{A'})^4$, M_χ is the LDM mass, $M_{A'}$ is the mass of dark photon as LDM parent and ε is the dark photon coupling. This plot is drawn for $M_\chi = M_{A'}/3$ and $\alpha_D = 0.1$. In this Figure, the SHiP sensitivity is compared with the current experimental constraints and the thermal relic abundances, showing an excursion of about one order of magnitude, and competitive limits in the considered region. The ultimate SHiP sensitivity for zero background is also shown [3]. The Signal/background discrimination for LDM search is currently being studied using Machine Learning.

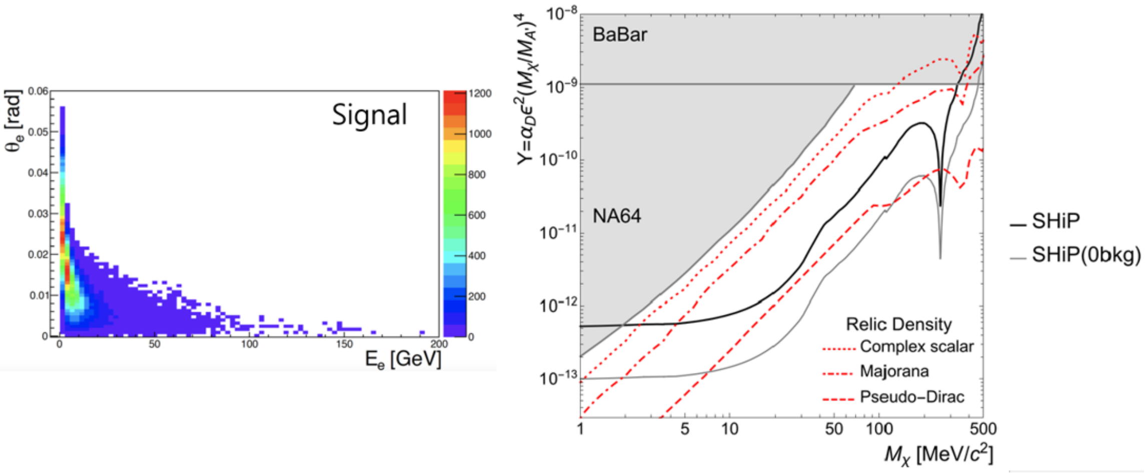

Figure 3: (Left) Energy–angle correlation of electron recoils for LDM signal, (Right) SHiP exclusion limits at 90% CL as a function of the LDM mass M_χ, compared to the current experimental limits by NA64 and BaBar (grey shaded area) and the predicted thermal relic abundances. The coupling is provided as $Y = \varepsilon^2 \alpha_D (M_\chi/M_{A'})^4$.

Acknowledgements

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (No. 2018R1A2B2007757).

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