OPEN ACCESS
10th International Conference on New Frontiers in Physics
(ICNFP 2020)
International Journal of Modern Physics: Conference Series
Vol. 51 (2023) 2360002 (6 pages)

DOI: 10.1142/S2010194523600029

Neutrino physics and dark matter search with SHiP at CERN

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Published 27 December 2023

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} pot in five years. A dedicated detector downstream the target will allow to probe a variety of models with the light long-lived exotic particles and masses below O(10) GeV/c^2. 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. We report the physics potential of such an experiment. We also describe an ancillary measurement of the charm cross-section carried out in July 2018.

Keywords: Neutrinos; dark matter.

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, 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. 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. The experiment has been proposed in 2015, with a submission of a Technical Proposal[1] and a Physics Paper.[2] Since 2016 it has been part of the Physics Beyond Colliders research group[3] and it is currently in the design phase.[4]

2. The SHiP Detector

The SHiP experiment looks for new long lived very weakly interacting particles, also knownas *Hidden Particles*, predicted by various Beyond the Standard Model theories. These particles can be produced from the interactions of 400 GeV protons, impinging on a fixed target. The experiment will be located at the North Area of the CERN SPS accelerator, in a new beam dump facility which will provide various research possibilities. A total of 2×10^{20} protons on target are expected to be collected, during a data taking period of 5 years. The overall structure of the SHiP experiment is shown in Fig. 1.

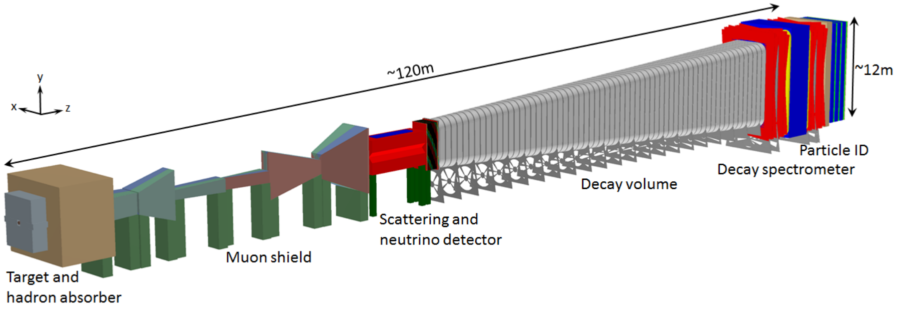

Fig. 1. Overall layout of the SHiP experiment.

The 400 GeV proton beam produced by the SPS accelerator complex, impinges on a 12 interaction length (λ_{int}) target made of Molybdenum and Tungsten, followed by a $30\lambda_{int}$ 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, area source of tau neutrinos through their fully leptonic decays. Therefore, the SHiP facility is ideal also to study the physics of tau neutrinos, the less known particle in the Standard Model. Downstream of the target, the hadron absorber filters out all hadrons, therefore only muons and neutrinos are left. An active muon shield[5] is designed with two sections with opposite polarity to maximize the muon flux reduction: it reduces the muon flux from $\sim 10^{10}$ down to $\sim 10^5$ per spill. 4×10^{13} protons are extracted in each spill, designed to be 1s long to reduce the detector occupancy. 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 detectorfor hidden particles.

3. The Scattering and Neutrino Detector

The neutrino detector consists of a magnet, hosting the neutrino target and a particle spectrometer, followed by a muon identification system, as shown in Fig. 2. The neutrino target is based on the emulsion cloud chamber technology employed by the OPERA experiment,[7] 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.

This detector is suitable for the measurement of muon and hadron momenta up to 12 GeV. 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 based on the SciFi technology to provide the time stamp to the event, connect muon tracks from the emulsion target to the muon system and measure the charge and momentum for particles with momenta above 10 GeV. The muon system is based on 23 iron slabs, 5 cm thick each, alternated with 24 RPCs providing the tracking within the slabs.

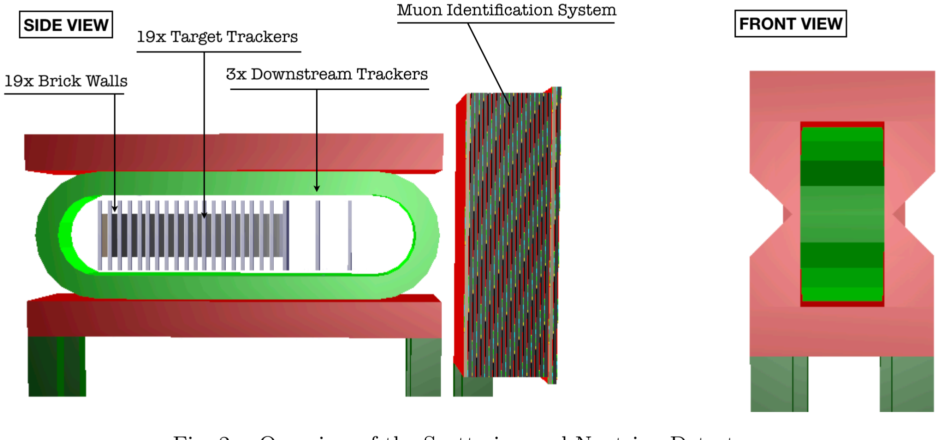

Fig. 2. Overview of the Scattering and Neutrino Detector.

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

The emulsion target will also act as the target of dark matter as well as of any very weakly interacting particle produced at the accelerator, when its mass is in the GeV range. The ongoing optimisation of this detector concerns 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 time-of-flight measurements.

4. Neutrino Physics and Dark Matter Search

The expected neutrino fluxes produced in the beam dump during the five years of data taking are reported in Table 1, along with the expected number of charged current Deep Inelastic Scattering (CC-DIS) events.

The nuclear emulsion technology combined with the information provided by the muon identification system makes it possible to identify the three different neutrino flavors in the SND detector. The neutrino flavour is determined through the flavour of 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. In addition, the target magnetisation will allow for the first time to distinguish between ν_τ from $\overline{\nu}_\tau$. The unprecedented statistics of about 6000 ν_τ and 5000 $\overline{\nu}_\tau$ detected interactions are expected for 2×10^{20} protons on target. The available statistics will allow to test lepton flavor violation in the neutrino sector.

Light Dark Matter (LDM) scattering in the emulsion spectrometer produces an isolated electromagnetic shower originating from the recoil electron. The modules of the emulsion spectrometer act as fine sampling calorimeters with more than five active layers per radiation length X_0 over a total thickness of ten X_0, allowing the electron energy and incident angle to be measured accurately. The micrometric accuracy of the emulsion is crucial for detecting any associated activity at the origin of the electromagnetic shower in order to discriminate the LDM signal from background induced by neutrino interactions. The background to the LDM search comes primarily from neutrino interactions with only one reconstructed electron at the interaction vertex. The LDM signal is discriminated from neutrino events with the same LDM elastic scattering topology, using the kinematic correlation between the energy and the azimuthal angle of the scattered electron. The estimated sensitivity is shown in Fig. 3

5. The SHiP-Charm Measurement

The SHiP Collaboration has proposed the SHiP-charm project,[6] aiming at measuring the associated charm production by employing the SPS 400 GeV proton beam. This proposal includes a study of the cascade effect to be carried out using

Table 1. Expected neutrino flux for different neutrino flavors at the beam dump (left) and charged-current deep-inelastic interactions in the Scattering Spectrometer (right). 2×10^{20} protons on target were assumed.

	<E>[GeV]	Beam dump	<E>[GeV]	CC DIS interactions
N_{ν_e}	4.1	2.8×10^{17}	59	1.1×10^6
N_{ν_μ}	1.5	4.2×10^{18}	42	2.7×10^6
N_{ν_τ}	7.4	1.4×10^{16}	52	3.2×10^4
$N_{\overline{\nu}_e}$	4.7	2.3×10^{17}	46	2.6×10^5
$N_{\overline{\nu}_\mu}$	1.6	2.7×10^{18}	36	6.0×10^5
$N_{\overline{\nu}_\tau}$	8.1	1.4×10^{16}	70	2.1×10^4

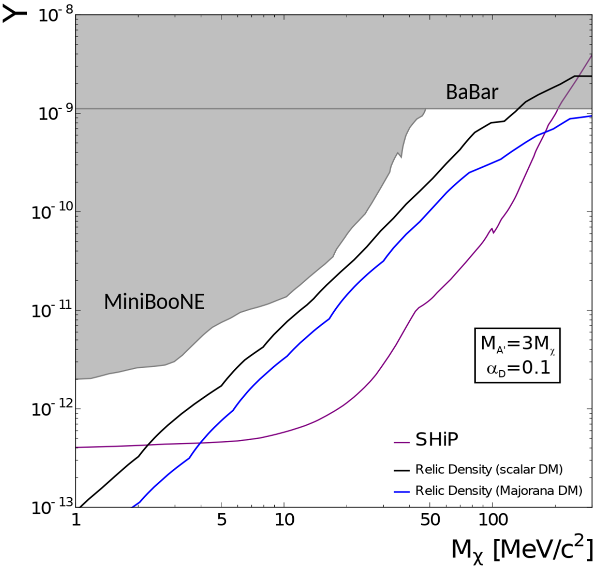

Fig. 3. Estimated sensitivity of the SHiP experiment to Light Dark Matter scattering.

the ECC technique, *i.e.* alternating slabs of a replica of the SHiP experiment target[1] 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 a muon identification system.The charge and momentum measurement of charmed hadron daughters is accomplished by dedicated tracking stations upstream and downstream of a magnet, so-called Goliath, in the H4 experimental hall at CERN, which provides an integrated field larger than 2 Tm. Pixel trackers are located upstream of Goliath while scintillating fibers and drift tubes instrument the downstream stations. The muon system is made of iron slabs interleaved with RPC chambers with two orthogonal sets of strips operated in avalanche mode. The setup shown in Fig. 4 allows a full kinematic reconstruction of the event. An optimization run was approved at CERN for July 2018, meant to integrate more than 10^6protons on target that would correspond to about 100 fully

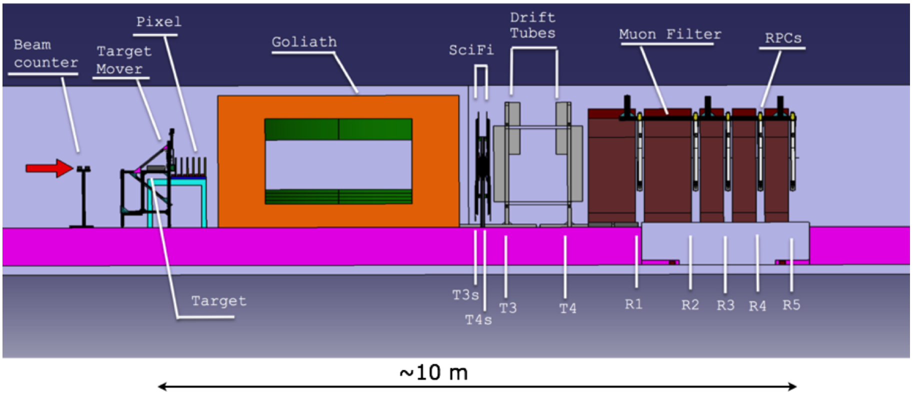

Fig. 4. Layout of the apparatus used to study the charm production yield in July 2018.

reconstructed charmed pairs. Analysis of the data collected is currently ongoing. The comparison of the results with the Monte Carlo predictions will provide in the next years important information for the optimization of the design of the SHiP experiment.

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