EPJ Web of Conferences **234**, 01003 (2020) https://doi.org/10.1051/epjconf/202023401003
FCCP2019

The SHiP physics program at CERN

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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, the neutrino masses 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 is proposed to search for very weakly coupled particles in the few GeV mass domain where the existence of such particles 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 very intense source of neutrinos and, in particular, of tau neutrinos, the less known particle in the Standard Model. We report the physics potential of such an experiment. An ancillary measurement of the charm cross-section was carried out in July 2018 and the data are under analysis and we report preliminary results. Moreover, a prototype of the neutrino detector is being designed to possibly take data at the LHC in its Run3 of operation. We describe the proposed detector and the physics case.

1 Introduction

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 there is new physics 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 consists 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), was proposed in 2015 [1], designed to operate at a beam dump facility to be built at CERN in the North Area and to search for weakly coupled particles in the few GeV mass range. The physics case for such an experiment is widely discussed in Ref. [2]. 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 decays. 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 at CERN: downstream of the target, the hadron absorber filters out all hadrons, therefore only muons and neutrinos are left. An active muon shield [3] 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 $\sim 10^5$ muons 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 experimental facility is described in Ref. [4].

The neutrino detector is located downstream of the muon shield, followed by the decay vessel and the detector for hidden particles. The Collaboration submitted a document to the European Strategy at the end of 2018 and is preparing a Comprehensive Design Report to be submitted to the SPS Committee by 2019, in the framework of the Physics Beyond Colliders working group, launched in 2016 at CERN. The schedule for construction and installation of the detector will be clearly defined in 2020. Data

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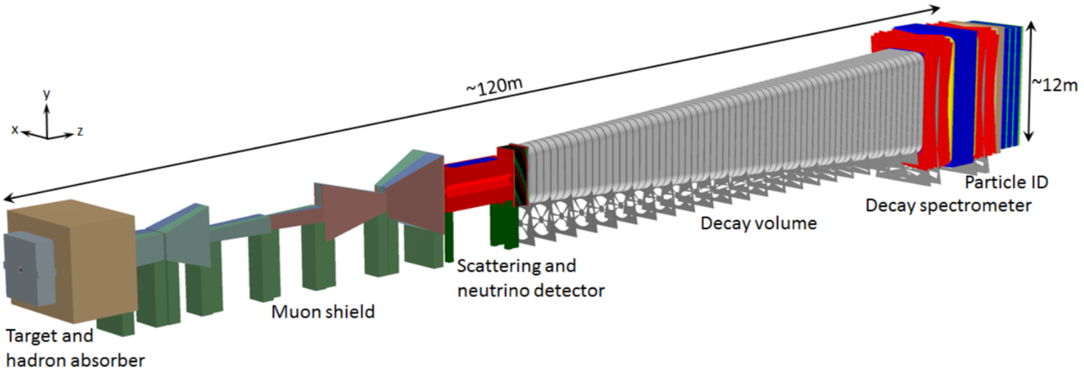

Figure 1. Layout of the SHiP facility.

taking is expected after the Long Shutdown 3 of the machine.

The neutrino detector is made of a magnetised region, followed by a muon identification system, as shown in Figure 2. The magnetised region will host the neutrino target, a target tracker station and a charged particle spectrometer. The magnet of the neutrino detector is shown in Figure 3 and its design is reported in Ref. [5]. The neutrino target is based on the emulsion cloud chamber technology successfully employed by the OPERA experiment [6], with a compact emulsion spectrometer, made of a sequence of very low density plates and emulsion films to measure the charge and momentum of hadrons in magnetic field. A first prototype of this compact emulsion spectrometer was developed in 2008 [7] measuring momenta below 4 GeV/c. Its functionality is being extended to measurements of momenta up to about 10 GeV/c: a first attempt is shown in figure 4, showing a charge misidentification at the percent level. Indeed, the measurement of the charge 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 inside the magnetic field to provide the time stamp to the event, connect muon tracks from the target to the muon system and measure the charge and momentum for particles (mostly muons) with momenta above 10 GeV/c. A muon system is located downstream of the magnet. It is based on alternating 20 cm thick iron slabs with Resistive Plate Chambers (RPC), providing the tracking within the slabs. The muon system will also act as upstream veto tagger for background processes to the hidden particle search. Two stations developed according to the technique of the multi-gap glass RPC [8] will act as a veto tagger with about 300ps timing resolution. The good timing performance is needed in order to avoid spoiling the signal efficiency with opening a longer gate around possible candidates in the hidden sector spectrometer.

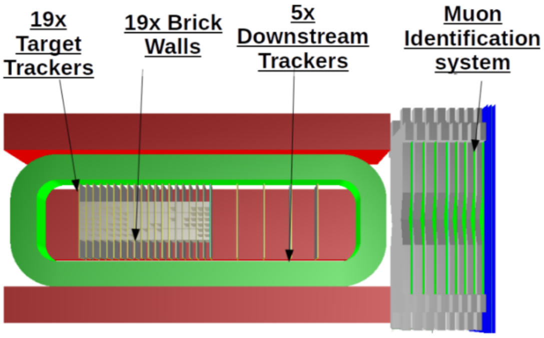

Figure 2. The neutrino detector upstream of the decay vessel.

The emulsion target will also act as the target of dark matter as well as of any feebly interacting particle produced in 400 GeV proton-target collisions, 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 the time-of-flight measurement.

The detector for hidden particles is located in the downstream part of a 60 m long evacuated decay vessel, with a conical shape and an elliptical transverse section at the very downstream end of 5×10 m^2, the longer axis being vertical. 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

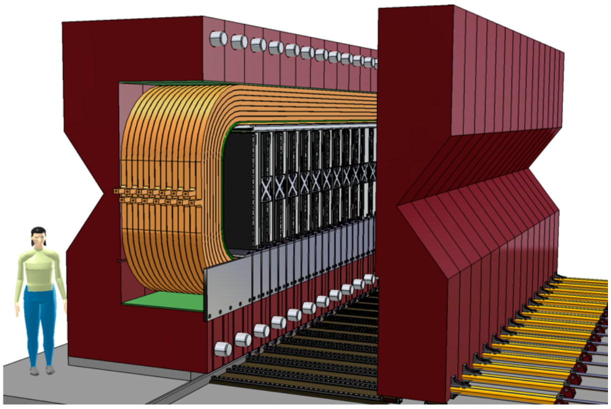

Figure 3. The magnet hosting the scattering and neutrino detector.

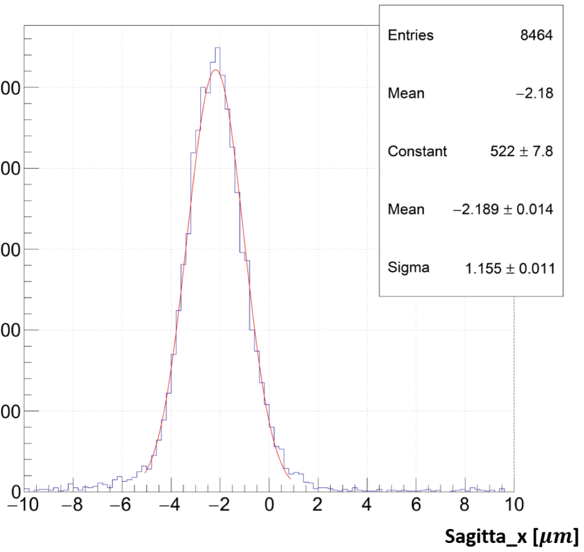

Figure 4. First measurement of 10 GeV/c pion momentum with a compact emulsion spectrometer: the sagitta is shown with its sign.

position resolution of 120 μm per straw, with 8 hits per station on average. This gives a momentum resolution of about 1%. The vessel will be surrounded by a liquid scintillator layer to tag charged particles coming from outside. Downstream of the spectrometer, an hadronic and electromagnetic calorimeter and a muon filter are used to identify particles. A timing detector with a resolution better than 100ps complements the apparatus to reject vertices produced by the chance coincidence of two tracks.

2 Search for hidden particles and physics searches with the neutrino detector

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 composite operators (so-called Portals) of the Standard Model. The SHiP detector has the potentiality to discover very weakly interacting and long lived particles in a wide unexplored range of their masses and couplings, within these Portals. As an example, we report in Figure 5 the sensitivity to heavy neutral leptons, when only the muon coupling U_μ is considered [9]. For an overview of the sensitivity to different portals and corresponding particles, we refer to [1, 2].

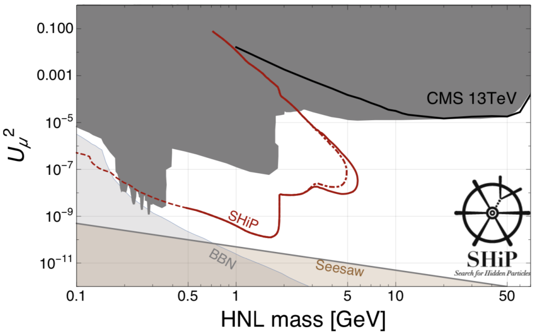

Figure 5. SHiP sensitivity to heavy neutral leptons [9].

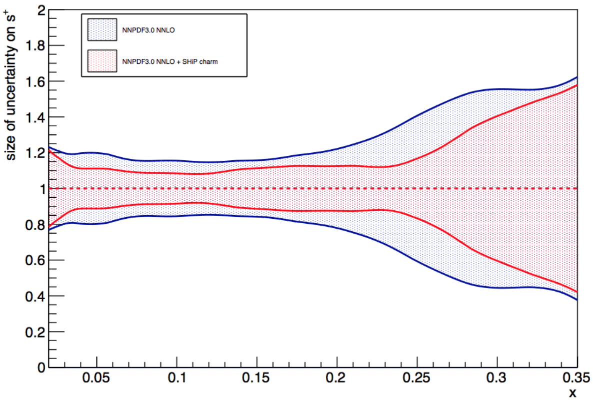

Figure 6. Improvement of the accuracy on s^+ with SHiP (red) compared to the present status (blue) in the $0.02 < x < 0.35$ range.

The observation of tau neutrinos was confirmed by the DONUT experiment only in 2008 when 9 candidates events were reported [10]. The OPERA experiment [6] has detected ten tau neutrinos [11–16], leading to the discovery of tau neutrino appearance from muon neutrino oscillations [15, 16]. The only leptonic decay observed by OPERA [13] shows negative charge as expected from a ν_τ interaction. Therefore, so far there is no direct evidence for tau anti-neutrino scattering. The SHiP facility is a ν_τ factory, with 6.6×10^{15} tau neutrinos produced in primary proton collisions, 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.

Charmed hadrons are produced in neutrino and anti-neutrino charged-current interactions at the level of about 5% [17]. 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 [17]. Indeed, SHiP will integrate about 10^5 charm candidates induced by neutrino interactions, more than one order of magnitude larger than the present statistics [18–20], 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 Figure 6 in terms of $s^+ = s(x) + \bar{s}(x)$ in the $0.02 < x < 0.35$ range.

The neutrino detector is also very efficient in the detection of the scattering of any neutral and feebly interacting particle with the atoms (electrons or nucleons) of the emulsion detector. Hence the name of Scattering and Neutrino Detector (SND). Indeed we have studied the sensitivity to a dark matter produced in the decay of a dark photon. The widely used minimal framework foresees a (fermion or scalar) DM particle, χ, coupled to the SM via a dark photon mediator A'. Such an extension and its interactions are fully described by four parameters: coupling constant α_D between A' and χ, mixing parameter ϵ between the A' and the SM photon, and the masses of the two new particles m_χ and $m_{A'}$. With these parameters at hand, one can compare the reach of accelerator-based searches looking for a particle escaping detection ("missing energy" technique) with those looking for the direct scattering of a DM particle off the target atoms. Figure 7 shows the sensitivity of the SHiP experiment to a light (below 500 MeV) mass χ particle in the coupling and mass plane. It is clearly visible that the reach extends well beyond the relic density curves for a large part of the parameter space and much beyond current existing limits (grey region).

2.1 The charm cross-section measurement

The tau neutrino yield as well as the yield of any hidden particle produced by charm decays are affected by a large uncertainty: indeed, simulation studies of proton interactions in heavy and thick targets show that the charmed hadron yield is increased by a factor of 2.3 from the cascade production [21]. 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, including in particular the protons after a primary elastic collision. The available measurement of the associated charm production per nucleon $\sigma_{c\bar{c}} = 18.1 \pm 1.7$ μbarn [22] was indeed obtained with a thin target where the secondary production is negligible.

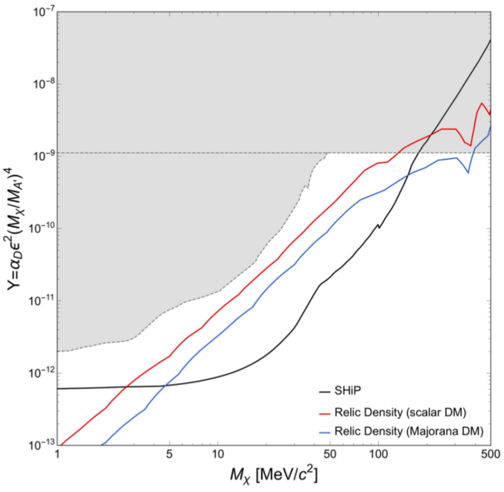

Figure 7. Sensitivity to the dark matter search.

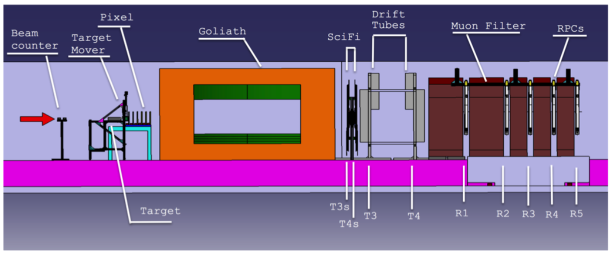

Figure 8. Setup of the charm measurement experiment built in 2018.

The SHiP Collaboration proposed the SHiP-charm project [23], aiming at measuring the associated charm production by employing the SPS 400 GeV/c proton beam. This proposal was approved by the SPSC and the Collaboration took data in 2018. The study of the cascade effect was carried out by using the ECC technique, i.e. slabs of a replica of the SHiP target [1] interleaved with emulsion films. The detector was hybrid, combining the emulsion technique with electronic detectors to provide the charge and momentum measurement of charmed hadron decay daughters and the muon identification. The setup shown in Figure 8 allows a full kinematical reconstruction of the event. The emulsion detector was constructed according to the emulsion cloud chamber technology alternating 1mm thick lead plates with emulsion films of about 300 μm thickness. The emulsion chamber was placed on a moving table in order to ensure a uniform distribution of the proton beam over the whole emulsion surface of 12.5×10 cm^2. Downstream of the emulsion chamber a magnetic spectrometer was made of four tracking stations, two upstream and two downstream of the magnet. The two downstream (denoted as pixel in Figure 8) were required to be highly segmented and withstand a high occupancy. For these two stations we used a hybrid silicon pixel detectors, of the same kind as currently successfully used in the Insertable B-Layer (IBL [24]) of the upgraded ATLAS detector. Each pixel module consists of a planar sensor and two custom developed large FE-I4 front-end chips [25] with a sophisticated readout architecture. The sensors are 200 μm thick with an inactive edge width of less than 450 μm, translating into a geometrical acceptance of 97.8%. The pixel tracking station cover a transverse area of about 33.6×37 mm^2, sufficient to contain the beam spot and the products of the interactions in the lead-emulsion target.

For the two downstream stations, denoted as T3 and T4 in Figure 8, a combination of two different technologies was used: Scintillating Fibre trackers (SciFi) with 250 μm diameter in the central 40×40 cm^2 region, where the density of tracks is higher, and drift tubes in the outer region. Two modules per station were used for the SciFi, each consisting of two planes, in such a way to provide XU and YU coordinates, where U has a stereo angle of about 2° with respect to X and Y, respectively. While the SciFi were built on purpose, the drift tube chambers were adapted from the modules built for the OPERA experiment [26].

The muon tagger is the most downstream detector in the apparatus. It has the task of identifying muons with high purity to tag the muonic decay channel of charmed hadrons. At the same time, it has to reconstruct the muon track slope to match the corresponding track reconstructed in the upstream magnetic spectrometer (made of the four tracking stations described above) and assign the momentum to the muon track. The layout of the muon tagger is made of five concrete slabs, two 80 cm-thick and three 40 cm-thick, acting as hadron absorber, interleaved by five RPC planes, acting as trackers. The transverse size of the RPC planes is 195×125 cm^2. The muon identification is done on the basis of the number of crossed layers in the detector. The RPC chambers were designed and constructed on purpose. The RPCs were designed to operate in avalanche mode, with a time resolution of about 1 ns. Two orthogonal sets of strips, 1cm thick, were used for 2D measurements with a position resolution of about 3 mm in both directions.

An optimisation run was performed at the H4 beamline of the CERN SPS in July 2018 with an integrated number of protons on target of about 1.5×10^6. Data are under analysis. Figure 9 shows one of the double charm candidate events found in the analysis. The event shows three vertices: the most upstream is the proton interaction vertex. There are two additional vertices: one shows a 2 prong topology without any charged parent particle while the other one shows a kink topology. Therefore, the first one is a D^0 candidate while the other is most likely either a D or a D_s meson. The flight lengths of the neutral and charged charm candidates are 2.1 mm and 12.7 mm, respectively. The impact parameter of the D^0 daughter tracks with respect to the primary proton vertex are 250 and 590 μm. The kink of the charged charm candidate is 31mrad and the impact parameter of the daughter particle to the primary proton vertex is 390 μm. From the measured flight length and average decay angle, one can infer an estimate of the lifetime of the particle [27]: this gives 1.4×10^{-12}s for the neutral candidate and 1.3×10^{-12}s for the charged one, both consistent with the hypothesis of charmed hadron decays.

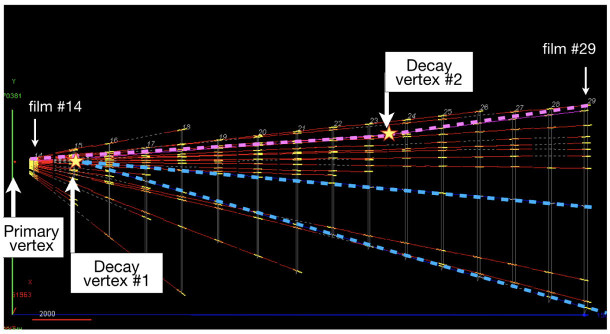

Figure 9. A double charm candidate event produced in proton collisions with the lead target.

The measurement with larger statistics 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 1000 fully reconstructed interactions.

2.2 The SND detector at LHC

Neutrino interactions provide precise tests of the SM [17, 28–30], probes of new physics [31–33], and windows to otherwise veiled regions of the Universe [34]. They have been extensively investigated only for neutrino energies below 350 GeV, and mostly for muon neutrinos only. The IceCube Collaboration recently reported a few tens of events with energies from about 10TeV to 1PeV [35]. A collection of all the available cross-section measurements is given in Ref. [36] which includes the IceCube shower events. The region between 350 GeV and about 10 TeV is totally unexplored. Recently, it was pointed out that LHC is an intense source of high-energy (about 1 TeV) neutrinos of all kinds and a proper location was looked for, by measuring the background in different caverns underground with an emulsion detector [37]. The TI18 cavern was identified as the most suitable location in terms of environmental and machine-induced background [37].

One of the challenges of the SND apparatus is the reconstruction of neutrino interactions in an environment where the muon flux is relatively high. In particular, the replacement frequency of the emulsion films depends on the capability to withstand the muon flux without spoiling the efficiency in the neutrino event reconstruction. These conditions can be well reproduced in the LHC environment, in the TI18 cavern. Therefore, a prototype of the SND detector is being designed to be possibly exposed in TI18, during the Run3 of the LHC operation. The detector consists of a target region, instrumented with nuclear emulsions and SciFi planes. Upstream of the target region, a plane of scintillator bars will act as a veto for charged particles. A muon identification system is located downstream of the target. It will consist of passive material slabs interleaved with planes of scintillating bars [38]. This detector placed in TI18 might test the above-mentioned experimental challenges of the SHiP SND and measure for the first time the process $pp \rightarrow \nu X$ at the LHC.

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