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The SHiP experiment at CERN

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Abstract. The discovery of the Higgs boson has fully confirmed the Standard Model of particles and fields. Nevertheless, fundamental phenomena like the existence of dark matter and the baryon asymmetry of the Universe still deserve an explanation that could come from the discovery of new particles. The SHiP experiment proposal at CERN is meant to search for particles in the few GeV mass domain, very weakly coupled with ordinary particles. The existence of such particles, foreseen in Beyond Standard Models, 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. 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.

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 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] 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. 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. Beauty particle decays are relevant for masses above 2 GeV. D_s mesons, copiously produced among charmed hadrons, are a source of tau neutrinos through their fully leptonic decay. Therefore,

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the SHiP facility is ideal also to study the physics of tau neutrinos, the less known particle in the Standard Model.

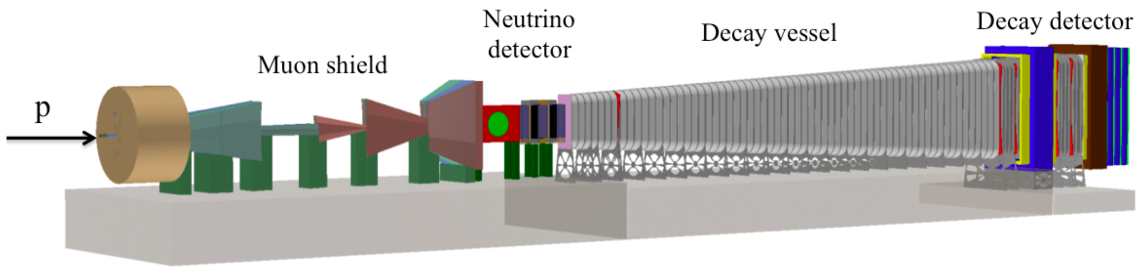

Figure 1. The beam dump facility and the SHiP detector. The total length is about 100 m and the scheme is to scale.

2. The SHiP detector and facility

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. 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. 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 [3].

The neutrino detector is located downstream of the muon shield, followed by the decay vessel and the detector for hidden particles. The Collaboration will prepare a document for the European Strategy by the end of 2018 and a Comprehensive Design Report by 2019, in the framework of the Physics Beyond Colliders working group, launched in 2016 at CERN. The construction and installation of the detector will start in 2021 and last until the end of the third LHC long shutdown such that the data taking is assumed to start in 2026.

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 both the neutrino target and a particle spectrometer. 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. This detector is suitable for the measurement of 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 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. 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.

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

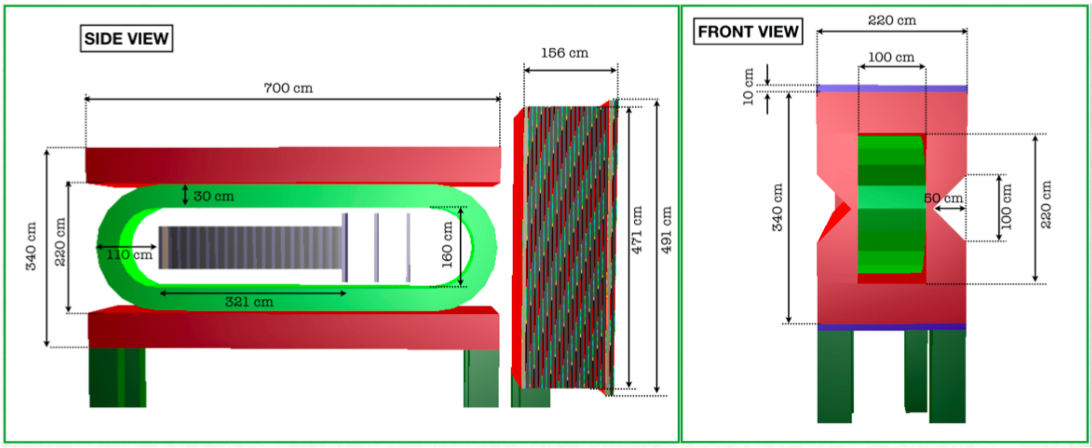

Figure 2. The neutrino detector upstream of the decay vessel in different views.

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 negligible background from neutrino interactions with the air in the vessel over five years sets the pressure below the mbar level. 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 vessel would be surrounded 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. A timing detector complements the apparatus to reject vertices produced by random coincidences.

3. 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 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 the left plot of Figure 3 the sensitivity to heavy neutral leptons, when only the muon coupling U_μ is considered [5]. For an overview of the sensitivity to different Portals and corresponding particles, we refer to Refs. [1, 2].

4. Physics with the neutrino detector

The observation of tau neutrinos was confirmed by the DONUT experiment only in 2008 when nine candidates events were reported [6]. The OPERA experiment [4] has detected ten tau neutrino candidate events [7, 8, 9, 10, 11, 12], leading to the discovery of tau neutrino appearance from muon-neutrino oscillations [11, 12]. The only leptonic decay observed by OPERA [9] shows negative charge as expected from a ν_τ interaction. Therefore, so far there is no direct evidence for tau anti-neutrinos. 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% [13]. Experiments based on electron detectors identify charmed hadrons

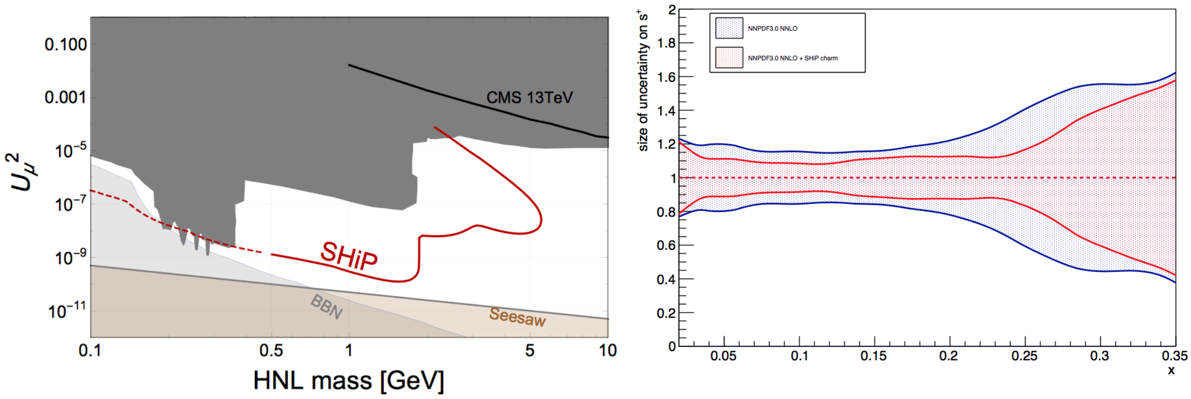

Figure 3. Left: SHiP sensitivity to heavy neutral leptons [5]. Right: Improvement of the accuracy on s^+ with SHiP (red) compared to the present status (blue) in the $0.02 < x < 0.35$ range.

only in their muonic decay channel, when two opposite-sign muons are produced in the final state, since the other channel would have a too large background. 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, which strongly suppress the background. 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 [13]. Indeed, 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 right plot of Figure 3 in terms of $s^+ = s(x) + \bar{s}(x)$ in the $0.02 < x < 0.35$ range, where $s(x)$ represents the strange work content of the nucleon as a function of the Bjorken x.

5. Charm cross-section measurement

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 the charmed hadron yield is increased by a factor of 2.3 from the cascade production [14]. Charmed hadrons are produced either directly from the interactions of primary protons or from the subsequent interactions of the particles produced in the hadronic cascade showers, including the protons after a primary elastic collision. The only available measurement of the charm production per nucleon at the energy of 400 GeV in the laboratory frame, $\sigma_{c\bar{c}} = 18.1 \pm 1.7\ \mu b$, [15], was indeed obtained with a thin target where the secondary production is negligible.

The SHiP Collaboration has proposed the SHiP-charm project [16], 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 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

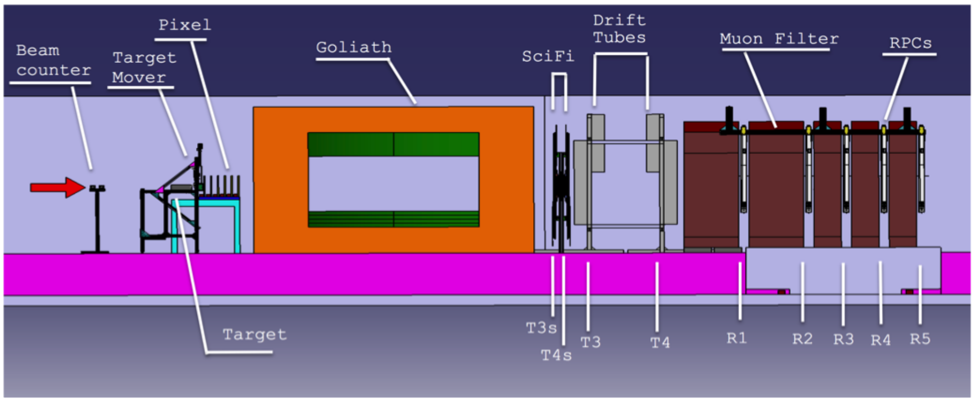

Figure 4. Setup of the charm measurement experiment including the downstream muon filter based on the RPC technology.

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 Figure 4 allows a full kinematical reconstruction of the event. An optimization run was approved at CERN for July 2018[1], meant to integrate more than 10^6 protons on target that would correspond to about 100 fully reconstructed charmed pairs. 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. This final run will provide also the double differential cross-section on top of the cascade effect.

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[1] The run was actually carried out in July 2018 and data are under analysis.