PROCEEDINGS OF SCIENCE

Neutrino physics with the SHiP experiment at CERN

Marilisa De Serio[a,1,*]

[a] *University of Bari & INFN Bari, I-70126, Bari, Italy*

E-mail: Marilisa.Deserio@ba.infn.it

The SHiP experiment at CERN has been proposed to search for New Physics at the so-called intensity frontier by probing the existence of very fleebly coupled particles, predicted in several theoretical models, in the few GeV/c^2 mass range. Such *hidden* particles would be produced in the decays of heavy hadrons from 400 GeV/c proton interactions on a high density target at the Beam Dump Facility to be located in the CERN SPS North Area.
Among hidden particles, the search for Heavy Neutral Leptons is very strongly motivated by theory, as they would explain simultaneously the baryon asymmetry of the Universe and the observed neutrino masses. The expected copious production of Ds mesons at the beam dump, producing tau neutrinos through fully leptonic decays, makes SHiP also ideal to study tau neutrino physics with unprecedented sensitivity.
The current status of the experiment, recently summarised in the Comprehensive Design Study Report, is presented.

40th International Conference on High Energy physics - ICHEP2020
July 28 - August 6, 2020
Prague, Czech Republic (virtual meeting)

[1]For the SHiP Collaboration.
[*]Speaker

PoS(ICHEP2020)123

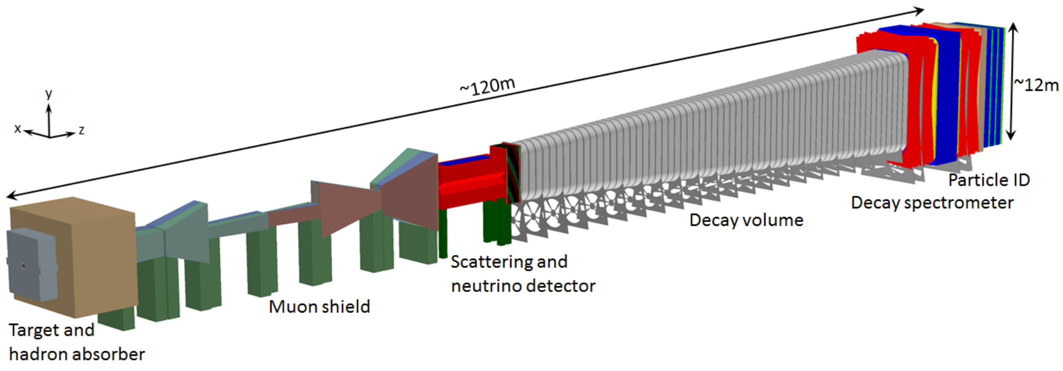

Figure 1: Layout of the SHiP facility.

1. Introduction

In the current picture of High Energy Physics, showing at the same time the triumph of the Standar Model (SM) and evidence for the existence of physics beyond the SM, two complementary approaches can be exploited to search for new physics: probe the energy frontier, as HL-LHC and future colliders, or investigate the intensity frontier to look for *light* long-lived particles with very feeble couplings to SM particles.

SHiP (*Search for Hidden Particles*, [1]) is a proton beam dump experiment designed to operate at the Beam Dump Facility (BDF, [2]) to be located in the CERN SPS North Area. The main goals, widely discussed in [3], are the search for the so-called *hidden particles* with masses at the GeV/c^2 scale as well as neutrino physics with special emphasis on tau neutrino physics.

Following the recommandation from the SPSC and the CERN Research Board, at the end of 2019 the Collaboration has finalised the Comprehensive Design Study Report [4], including improved physics performance and significant progress in the detector design.

2. The SHiP facility

Figure 1 shows the current layout of the SHiP facility: 400 GeV/c protons will impinge on a high density target in spills of 1 sec. A total of 4×10^{13} protons will be extracted in each spill.

The target will be made of blocks of titanium-zirconium-molybdenum alloy followed by blocks of pure tungsten with a total thickness of about 12 interaction lengths. The structure has been specifically optimised for heavy meson production while minimising the flux of neutrinos coming from π / K decays. The target is followed by a hadron stopper filtering out hadrons and the electromagnetic component emerging from the target and a magnetised muon shield [5] with the task of bending beam-related muons out of the detector acceptance, reducing their flux by about 6 orders of magnitude.

In order to validate the Monte-Carlo simulation used to compute the experiment sensitivity, the muon flux produced in a small replica of the SHiP target, exposed to the CERN H4 proton beam line, was measured in 2018. The analysis of collected data, corresponding to about 3×10^{11} protons on target, shows a remarkable agreement with simulation with differences in the absolute rate of the order of 30% for large transverse momenta at high muon momenta [6].

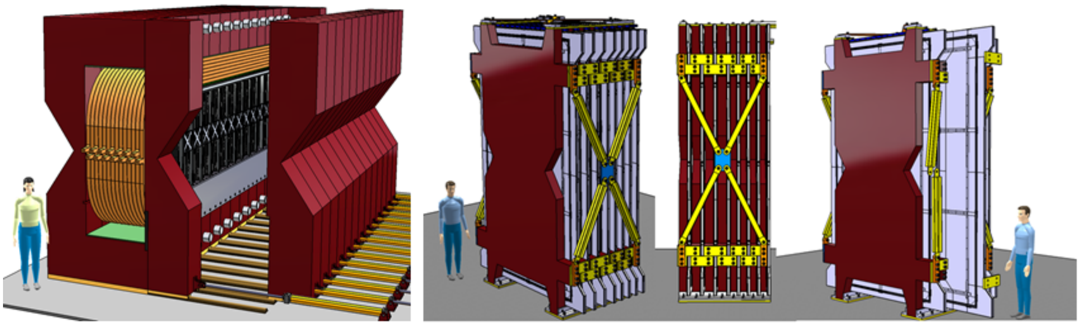

Figure 2: Details of the design of the SND: magnet surrounding the target (left); mechanical structure of the Muon System (right).

Hidden particles in the few GeV/c^2 mass range would be mostly produced in the decays of heavy hadrons from proton interactions. Among those, Ds mesons are also a copious source of tau neutrinos through their fully leptonic decays. Therefore, the SHiP facility is ideal to study tau neutrino physics with unprecedented sensitivity. This motivated the design of two main sub-detector systems, the *Scattering and Neutrino Detector* (SND) and the *Hidden Sector spectrometer*.

The SND, specifically dedicated to neutrino physics and to the search for light dark matter [7], consists of a magnetised target made of emulsion - tungsten *bricks*, interleaved with planes of scintillating fibre trackers. The sub-micrometric space resolution of nuclear emulsions allows the tau lepton decays, typically occurring a few hundred μm downstream of the primary vertex, to be reconstructed. The magnetic field allows for the measurement of the sign of the charge of the tau daughter particles, thus making it possible to distinguish τ neutrinos from anti-neutrinos.

The SND magnet [8], enclosing a volume of about $10\,\mathrm{m}^3$ kept at a temperature of 18 °C with a magnetic field of 1.2 T and a stray field outside at ‰ level, is shown in Figure 2 (left). A special opening mechanism has been designed to access the inner volume for detector installation and fast maintenance during operation.

A Muon Identification System instrumented with RPCs [9] and iron filters is located downstream of the magnet. Figure 2 (right) shows the mechanical structure with the RPCs hanging from top and sliding on upper trays for insertion and extraction. Two additional stations using multi-gap glass RPCs will act as a veto tagger for the downstream HS spectrometer providing a time resolution of about 300 ps.

The HS detector has been designed to seach for visible decays of possible hidden particles occurring in a 50m-long evacuated decay vessel located immediately downstream of the SND. The vessel has a pyramidal frustum shape and is surrounded by a veto system based on liquid scintillator to efficiently suppress the background. The HS spectrometer includes a straw tracker with a space accuracy of $120\,\mu$m, a timing detector with a resolution better than 100 ps required to suppress the combinatorial background, an electromagnetic calorimeter and a muon system equipped with scintillating tiles read out by SiPM.

In five years of data-taking, corresponding to an integrated intensity of 2×10^{20} protons on target, more than 10^{18} heavy mesons and more than 10^{16} τ neutrinos are expected to be produced at the beam dump.

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

Table 1: Expected numbers of detectable ν_τ and $\overline{\nu}_\tau$ interactions in 5 years of data-taking.

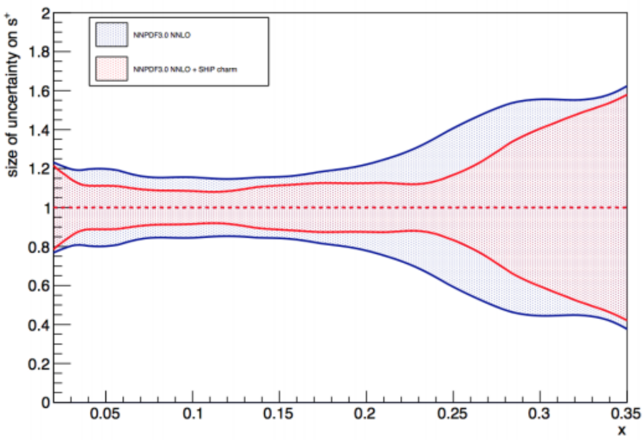

Figure 3: Improvement of the accuracy on s^+ (red) as compared to the present status (blue) as a function of the Bjorken variable x.

3. Physics performance

3.1 Neutrino physics

Table 1 shows the expected numbers of detectable ν_τ and $\overline{\nu}_\tau$ interactions according to the different τ decay channels. Overall, in 5 years of data-taking, assuming a neutrino target mass of about 8 tons, SHiP will be able to collect about 10,000 events, a sample a factor of 1000 larger with respect to available data from the DONUT experiment [10] providing the only measurement so far of ν_τ cross-section based on a sample of 9 events. Ten tau neutrinos have been detected by the OPERA experiment [11], leading to the discovery of muon to tau neutrino oscillations in appearance mode ([12] - [17]). There is no direct evidence so far for tau anti-neutrino scattering.

The measurement of ν_τ and $\overline{\nu}_\tau$ interaction cross-sections also offers the unique capability of measuring the structure functions F_4 and F_5, typically not accessible through muon and electron neutrinos due to multiplying factors proportional to the squared mass of the charged lepton. Moreover, SHiP is expected to collect more than 200,000 charmed hadrons produced in neutrino-induced interactions with a large contribution from anti-neutrinos. This sample exceeds by more than one order of magnitude the available statistics from previous experiments. In addition, charm production in antineutrino-nucleon deep inelastic scattering can improve the knowledge of the flavour composition of the nucleon, allowing for studying its strange quark content with a significant reduction of the uncertainty on the s quark distribution, as shown in Figure 3 in terms of $s^+ = s(x) + \overline{s}(x)$.

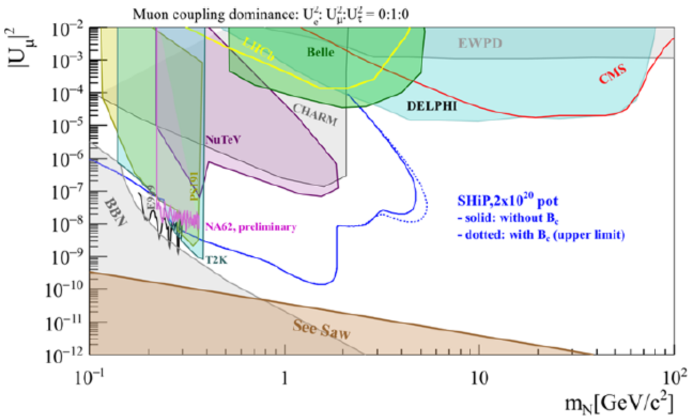

Figure 4: SHiP sensitivity to HNLs. Details can be found in [4], [20].

3.2 Search for Heavy Neutral Leptons

One of the main goals of the experiment is the search for Heavy Neutral Leptons (HNLs), i.e. right-handed sterile partners of the SM neutrinos predicted by the ν Minimal Standard Model [18, 19]. The existence of such particles is strongly motivated by theory, as they would explain simultaneously the baryon asymmetry of the Universe via leptogenesis, the observed neutrino masses and oscillation via the see-saw mechanism and would provide a dark matter candidate. Figure 4 shows the 90% C.L. exclusion limits under the hypothesis of zero background assuming that HNLs couple only to the second SM generation: a significant improvement in the few-GeV region probed by SHiP is expected.

4. Conclusions

SHiP is a proton beam dump experiment proposed at the CERN SPS to probe the so-called intensity frontier in the GeV/c^2 mass range and to study neutrino physics with unprecedented sensitivities. The SHiP detector has recently undertaken a major reoptimisation with an intense activity of prototyping and tests to validate its performance. The progress in the detector design and the improved physics performance have been presented in detail in the Comprehensive Design Study Report finalised at the end of 2019.

References

[1] M. Anelli *et al.* (SHiP Collaboration), *A facility to Search for Hidden Particles (SHiP) at the CERN SPS*, *CERN-SPSC-2015-016; SPSC-P-350* [arXiv: 1504.04956].

[2] C. Ahdida *et al.*, *SPS Beam Dump Facility - Comprehensive Design Study*, *CERN-PBC-REPORT-2019-005; CERN-2020-002* [arXiv:1912.06356].

[3] S. Alekhin *et al.*, *A facility to Search for Hidden Particles at the CERN SPS: the SHiP physics case*, *Rept. Prog. Phys.* **79** (2016) 124201.

[4] C. Ahdida *et al.* (SHiP Collaboration), *SHiP Experiment - Comprehensive Design Study report*, *Tech. Rep. CERN-SPSC-2019-049; SPSC-SR-263*.

[5] A. Akmete *et al.* (SHiP Collaboration), *The active muon shield in the SHiP experiment*, *JINST* **12** (2017) no. 05, P05011.

[6] C. Ahdida *et al.* (SHiP Collaboration), *Measurement of the muon flux from 400 GeV/c protons interacting in a thick molybdenum/tungsten target*, *Eur. Phys. J. C* **80** (2020) 284.

[7] C. Ahdida *et al.* (SHiP Collaboration), *Sensitivity of the SHiP experiment to light dark matter*, arXiv:2010.11057.

[8] C. Ahdida *et al.* (SHiP Collaboration), *The Magnet of the Scattering and Neutrino Detector for the SHiP experiment at CERN*, *JINST* **15** (2020) P01027.

[9] L. Congedo, *RPCs and readout system for the neutrino detector of the SHiP experiment*, *JINST* **15** (2020) C09014.

[10] K. Kodama *et al.* (DONUT Collaboration), *Final tau-neutrino results from the DONuT experiment*, *Phys. Rev. D* **78** (2008) 052002.

[11] N. Agafonova *et al.* (OPERA Collaboration), *The OPERA experiment in the CERN to Gran Sasso neutrino beam*, *JINST* **4** (2009) P04018.

[12] N. Agafonova *et al.* (OPERA Collaboration), *Observation of a first ν_τ candidate in the OPERA experiment in the CNGS beam*, *Phys. Lett. B* **691** (2010) 138.

[13] N. Agafonova *et al.* (OPERA Collaboration), *New results on $\nu_\mu \to \nu_\tau$ appearance with the OPERA experiment in the CNGS beam*, *JHEP* **1311** (2013) 036.

[14] N. Agafonova *et al.* (OPERA Collaboration), *Evidence for $\nu_\mu \to \nu_\tau$ appearance in the CNGS neutrino beam with the OPERA experiment*, *Phys. Rev. D* **89** (2014) 051102.

[15] N. Agafonova *et al.* (OPERA Collaboration), *Observation of tau neutrino appearance in the CNGS beam with the OPERA experiment*, *PTEP* **2014** (2014) 101C01.

[16] N. Agafonova *et al.* (OPERA Collaboration), *Discovery of τ neutrino appearance in the CNGS Neutrino Beam with the OPERA experiment*, *Phys. Rev. Lett.* **115** (2015) 121802.

[17] N. Agafonova *et al.* (OPERA Collaboration), *Final results of the OPERA experiment on ν_τ appearance in the CNGS beam*, *Phys. Rev. Lett.* **120** (2018) 211801.

[18] T. Asaka, S. Blanchet and M. Shaposhnikov, *The νMSM, dark matter and neutrino masses*, *Phys. Lett. B* **631** (2005) 151.

[19] T. Asaka and M. Shaposhnikov, *The νMSM, dark matter and baryon asymmetry of the universe*, *Phys. Lett. B* **620** (2005) 17.

[20] J. Beacham *et al.*, *Physics Beyond Colliders at CERN: Beyond the Standard Model Working Group Report*, arXiv:1901.09966.