IL NUOVO CIMENTO **39 C** (2016) 226
DOI 10.1393/ncc/i2016-16226-9

Colloquia: IFAE 2015

The SHiP experiment at CERN SPS

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received 7 January 2016

Summary. — SHiP is a new general purpose fixed target facility, whose Technical Proposal has been recently submitted to the CERN SPS Committee. In its initial phase, the 400 GeV proton beam extracted from the SPS will be dumped on a heavy target with the aim of integrating 2×10^{20} pot in 5 years. A dedicated detector located downstream of the target, based on a long vacuum tank followed by a spectrometer and particle identification detectors, will allow probing a variety of models with light long-lived exotic particles and masses below a few GeV/c^2. The beam dump is also an ideal source of tau neutrinos, the less known particle in the Standard Model. Another dedicated detector, based on the Emulsion Cloud Chamber technology already used in the OPERA experiment, will allow to perform for the first time measurements of the tau neutrino deep inelastic scattering cross section. Tau neutrinos will be distinguished from tau anti-neutrinos, thus providing the first observation of the tau anti-neutrino.

1. – Introduction

The recent discovery of the Higgs boson [1, 2] is a big triumph of the Standard Model. For the particular value of the Higgs mass it is possible that the Standard Model is an effective field theory up to a very high energy scale, possibly to Planck scale [3-5].

Nevertheless, there are several things 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 that the new physics is there and presumably several new particles have still to be discovered.

The hypothetical new particles can be searched for either at the energy and at the intensity frontier. While the high energy frontier is being investigated with accelerator experiments, possible low mass particles Beyond Standard Model (BSM) may have remained undetected 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.

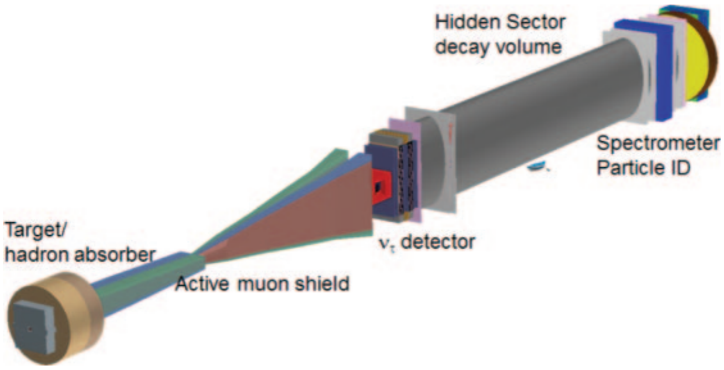

Fig. 1. – Overview of the SHiP facility.

2. – The detector for hidden particles

The main physics goal of the SHiP experiment consists in exploring hidden portals and extensions of the Standard Model (SM) which incorporate long-lived and very weakly interacting particles through the direct detection of their decays to SM particles. For this purpose, the 400 GeV protons beam of the SPS will be dumped on a heavy target. Over five years of data taking, 2×10^{20} protons on target are expected.

Hidden particles are predominantly produced in decays of hadrons, in particular in decays of charmed and beauty hadrons above the kaon mass. They have very small coupling with SM particles and are therefore very long-lived. In order to maximise their production, the target is made of molybdenum and tungsten, being these materials characterized by a very short interaction length. The target is followed by an iron absorber, aiming at stopping the hadrons and the electromagnetic radiation emerging from the target. In order to reduce the large flux of muons produced in the decay of pions and kaons, a 48 m long active muon shield based on magnetic deflection is located immediately downstream of the target.

The Hidden Sector (HS) detector is made by a cylindrical 50 m long decay volume. It is under vacuum and surrounded by a veto system. The full reconstruction of the hidden particle decays is performed by a magnetic spectrometer and a system for particle identification at the end of the decay volume. Figure 1 shows a schematic overview of the SHiP facility from the proton target to the end of the Hidden Sector detector.

The SHiP experiment can probe an interesting parameter space for a number of BSM models describing interactions between new particles and different *portals* (scalars, vectors, fermions or axion-like particles), as described in detail in the Technical Proposal [6]. In the following section we will focus on the Neutrino Portal.

2˙1. *Neutrino portal.* – Models with right-handed Majorana neutrinos or heavy neutral leptons (HNLs) can give a simultaneous explanation to neutrino masses and mixings, baryon-antibaryon asymmetry and dark matter. The most promising of these models is the ν Minimal Standard Model (νMSM). In this model the lightest of these neutrinos (N_1), has a mass in the keV region and it is sufficiently stable to play the role of dark matter candidate. The other two neutrinos ($N_{2,3}$) are almost degenerate in mass (in the GeV region) and are responsible for neutrino oscillations and baryon-antibaryon asymmetry in the Universe.

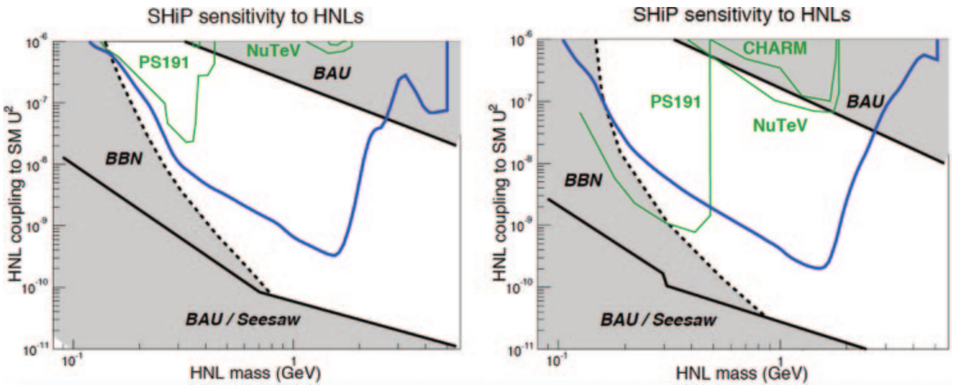

Fig. 2. – Exclusion limits sets by the SHiP experiment in case no signal is found. Left: normal hierarchy with U_μ^2 dominating according to ref. [7]. Right: inverted hierarchy with U_e^2 dominating according to ref. [8].

The states N_2 and N_3 could be produced in the decay of sufficiently massive particles like charmed hadrons. The states produced in this way would be long lived particles that in turn could decay, for example, into a μ and a π. Therefore, by measuring the invariant mass of the μ and π system, one would expect a peak to show up. It is worth noticing that there are more cosmological than experimental constraints in the mass region around 1 GeV. Charmed hadrons are the ideal parents of such heavy neutral leptons if their mass is around 1 GeV. Indeed, with kaon decays one is sensitive only to masses lower than 400 MeV, while the cross-section for the production of beauty hadrons is a factor of 20 to 100 lower. Moreover, given that beauty hadrons decay to charmed hadrons, the explored mass range would only extend from 2 to 3 GeV. As we have shown in the previous section, a proton beam dump facility is the ideal place where to produce charmed hadrons and search for heavy neutral leptons of this mass and lifetime (10^{-5} s) range.

Figure 2 shows the experimental and cosmological bounds on the search for heavy neutral leptons. It also reports superimposed the exclusion limits SHiP could set in case no signal is found. The left plot assumes the model reported in ref. [7] with normal hierarchy and a dominant muon coupling, $U_e^2 : U_\mu^2 : U_\tau^2 = 1 : 16 : 3.8$, while the right plot refers to the model in ref. [8] for inverted hierarchy and a dominant electron coupling, $U_e^2 : U_\mu^2 : U_\tau^2 = 46 : 1 : 1$. The parameter space explored by SHiP extends in the cosmologically relevant region that is experimentally unexplored.

3. – The detector for tau neutrinos

Tau neutrino is the less known particle in the Standard Model. So far only DONUT [9] and OPERA [10] experiments succeeded in detecting a few ν_τ interactions. The OPERA experiment observed for the first time the $\nu_\mu \to \nu_\tau$ oscillation in appearance mode, by detecting the decay of the τ lepton produced in ν_τ charged current interactions.

The proton beam dump facility provides a powerful source of tau neutrinos. Tau neutrinos and antineutrinos are equally produced, essentially via D_s decays. The facility will therefore host a 10 m long tau neutrino detector, located between the active muon shield and the decay volume of the HS detector. It is made of a neutrino target region

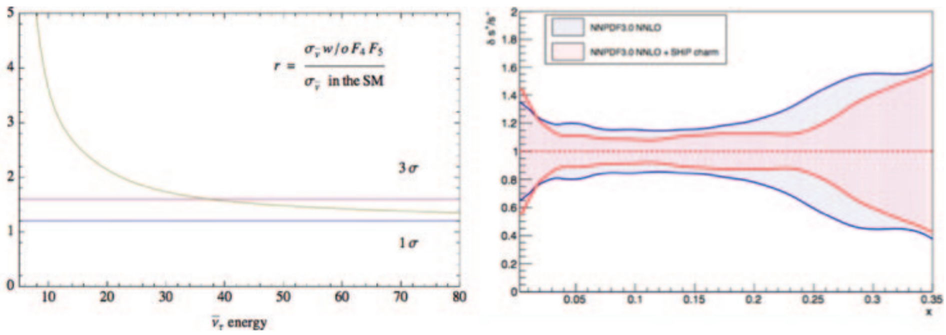

Fig. 3. – Left: energy dependence of the ratio r between the DIS cross section in the $F_4 = F_5 = 0$ hypothesis and the SM prediction, for $\overline{\nu}_\tau$. Right: the blue line shows the present accuracy in the distribution of $s^+ = s + \overline{s}$ as a function of x. The red contour shows the improvement obtained with SHiP.

followed by a muon spectrometer. The neutrino target is made of Opera-type modules which employ the Emulsion Cloud Chamber (ECC) technology. The magnetic field is provided by the Goliath magnet. The ECC structure is made of a sequence of passive material plates interleaved with emulsion films. The target is modular and its units are made of two parts: the brick and the Compact Emulsion Spectrometer (CES). The brick, using lead as passive material, combines the micrometric tracking accuracy of nuclear emulsions and the high lead density as required to maximise the number of neutrino interactions in a compact detector. The CES is made of a sandwich of light material plates (*e.g.* Rohacell) and emulsion films. It is designed to distinguish ν_τ and $\overline{\nu}_\tau$ by performing the electric charge measurement of the τ decay products through their curvature in magnetic field. The target is complemented by planes of electronic detectors to provide the time stamp of the event and to identify the target unit where the neutrino interaction occurred.

3˙1. *Tau neutrino physics*. – The neutrino detector has the unique capability distinguishing tau neutrinos from tau anti-neutrinos. In the present design, about 1800 ν_τ and 900 $\overline{\nu}_\tau$ interactions are expected to be located in the bricks. This data sample will allow to perform the first observation of $\overline{\nu}_\tau$, to study the cross-section of ν_τ and $\overline{\nu}_\tau$ and to evaluate the nuclear structure functions with ν_τ scattering.

The SHiP experiment will have the unique capability of being sensitive to F_4 and F_5, being them accesible only in tau neutrino interactions. The hypothesis of $F_4 = F_5 = 0$ would result in an increase of the ν_τ and $\overline{\nu}_\tau$ charged-current deep-inelastic cross sections and consequently, of the number of expected ν_τ and $\overline{\nu}_\tau$ interactions.

The difference between the cross sections in the $F_4 = F_5 = 0$ hypothesis and the SM one is larger for lower neutrino energies. This behavior reflects in the energy dependence of the variable r, defined as the ratio between the cross section in the two hypotheses: it is higher for lower neutrino energies, where the discrepancy of the two curves is larger, and decreases, tending to one, for higher energies, where the contribution of F_4 and F_5 becomes negligible. The ratio r is reported for $\overline{\nu}_\tau$ in the left plot of fig. 3. To have evidence of a non-zero value of F_4 and F_5, the ratio r is required to be larger than 3σ, being σ the uncertainty on the incoming neutrino flux. This condition is satisfied for $E_{\overline{\nu}_\tau} < 38\,\mathrm{GeV}$, where we expect to observe about 300 $\overline{\nu}_\tau$ interactions.

3˙2. *Charmed hadron physics.* – The SHiP experiment is suitable also to perform studies of charmed hadron production. In five years run, more than 10^5 neutrino induced charmed hadrons are expected, thus largely exceeding the statistics available in previous experiments by more than one order of magnitude. Therefore all the studies on charm physics performed with neutrino interactions will be revised with improved accuracy and some channels inaccessible in the past will be explored.

Unlike neutrino scattering where the presence of valence quarks favours the d-quark as neutrino target thus compensating the large suppression provided by the Cabibbo angle, charmed hadron production in anti-neutrino interactions selects anti-strange quark in the nucleon.

The SHiP experiment can improve the knowledge of the strangeness content of the nucleon. The constraining power is shown in the right panel of fig. 3 for the s^+ variable, defined as $s+ = s(x) + \overline{s}(x)$. A significant improvement on this variable is achieved in the x-Bjorken range between 0.03 and 0.35.

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