

Status and Physics of the SHiP experiment at CERN

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Abstract. SHiP is a new general purpose fixed target facility, whose Technical Proposal has been recently reviewed by the CERN SPS Committee and by the CERN Research Board. The two boards recommended that the experiment proceeds further to a Comprehensive Design phase in the context of the new CERN Working group "Physics Beyond Colliders", aiming at presenting a CERN strategy for the European Strategy meeting of 2019. 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, 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 $\mathcal{O}(10)$ GeV/ c^2 . The main focus will be the physics of the so-called Hidden Portals, i.e. search for Dark Photons, Light scalars and pseudo-scalars, and Heavy Neutrinos. The sensitivity to Heavy Neutrinos will allow for the first time to probe, in the mass range between the kaon and the charm meson mass, a coupling range for which Baryogenesis and active neutrino masses could also be explained. Another dedicated detector will allow the study of neutrino cross-sections and angular distributions. ν_τ deep inelastic scattering cross sections will be measured with a statistics 1000 times larger than currently available, with the extraction of the F_4 and F_5 structure functions, never measured so far and allow for new tests of lepton non-universality with sensitivity to BSM physics.

1. Introduction

Despite the great success of the Standard Model, there are a number of phenomena still unexplained in current particle physics and thus strong evidence for *Beyond the Standard Model* (BSM) physics. Among others, the origin of neutrino masses and oscillations, the nature of non-baryonic dark matter, the excess of matter over antimatter or the cosmic inflation remain unexplained by the SM. Furthermore there is a shortcoming of theory when it comes to explaining the gap between Fermi and Planck scales, dark energy or the connection of gravity to the SM. To account for these phenomena, novel or extended models are needed, which predict a variety of new particles. Whereas current experiments, e.g. at the LHC, search for new particles at the *energy frontier*, the recently proposed SHiP (Search for Hidden Particles) experiment aims to explore a sector of very weakly interacting, long lived particles at the *intensity frontier*.

Such particles in the GeV range are hoped to be produced at a new beam dump facility at CERN made of a high density proton target followed by a hadron stopper and a muon shield. The detector comprises a vacuum decay chamber followed by detectors for particle tracking and identification.

Besides possible hidden particles, such a facility also produces a high intensity neutrino flux. A dedicated detector between the muon shield and the decay vessel is anticipated to investigate



Table 1. Final states for different BSM models

Models	Final States
Neutrino portal, HNL, SUSY neutralino	$\ell^\pm \pi^\mp, \ell^\pm K^\mp, \ell^\pm \rho^\mp$
Vector, scalar, axion portals, SUSY sgoldstino	$e^+ e^-, \mu^+ \mu^-$
Vector, scalar, axion portals, SUSY sgoldstino	$\pi^+ \pi^-, K^+ K^-$
Neutrino portal, HNL, SUSY neutralino, axino	$\ell^+ \ell^- \nu$

interactions of these neutrinos, in particular of the ν_τ and $\bar{\nu}_\tau$. This detector is also suited for the detection of light dark matter through scattering off atomic electrons in the target.

2. The Hidden Sector

SHiP can investigate a wide number of models introducing BSM physics. A broad overview of the SHiP physics potential is presented in [1]. These models have in common that there is generally a portal which mediates between the standard model and one or more hidden particles. An overview of a selection of models and their final states is shown in Tab. 1. Note that when coupling with the SM, each of the presented models ends up with two charged particles in the final state.

A promising example of hidden sector particles are Heavy Neutral Leptons (HNLs) predicted by the neutrino minimal standard model ν MSM [2]. It is an extension to the SM where each of the left-handed neutrinos has a heavy right-handed partner. This would introduce three new particles N_1 , N_2 and N_3 , where N_1 is in the order of $\mathcal{O}(10 \text{ keV})$ and would be a candidate for dark matter. N_2 and N_3 are in the order of $\mathcal{O}(1 \text{ GeV})$ and mix with the active neutrinos, thus effectively coupling them to the SM. They can explain neutrino masses via the see-saw mechanism and account for the baryon asymmetry of the universe via leptogenesis. Such particles could be produced in heavy flavor decays and decay back to visible final states as depicted in Fig. 1.

3. The SHiP Facility

The SHiP facility is a new beam dump facility at the SPS in the CERN North Area, recently proposed to the SPSC committee [3]. The setup of the facility is shown in Fig. 2. 400 GeV protons are aimed onto a heavy target made of tungsten and molybdenum of $12\lambda_{\text{int}}$ interaction lengths, optimized for heavy flavor production. It is followed by an iron hadron absorber. An active muon shield reduces the muon flux of approximately 10^{10} muons per spill by five orders of magnitude. It is followed by an emulsion spectrometer mainly designed for SM physics. An evacuated decay volume, equipped with detectors for tracking and particle identification then follows. 4×10^{13} protons are extracted in each spill of 1 second duration. In five years of running, the facility will accumulate a total of 2×10^{20} protons on target.

The detection principle is simple, a hidden particle enters the decay volume and decays in the vacuum. The decay products can then be observed by the installed detectors. To reject background, it is essential to have a precise track reconstruction and to ensure that the detected particles originate from the same vertex inside the vacuum.

To ensure sensitivity to very weakly coupled new physics it is essential to maximize the intensity while minimizing backgrounds. SHiP aims to be a zero-background experiment for the visible decay signature in the hidden sector spectrometer.

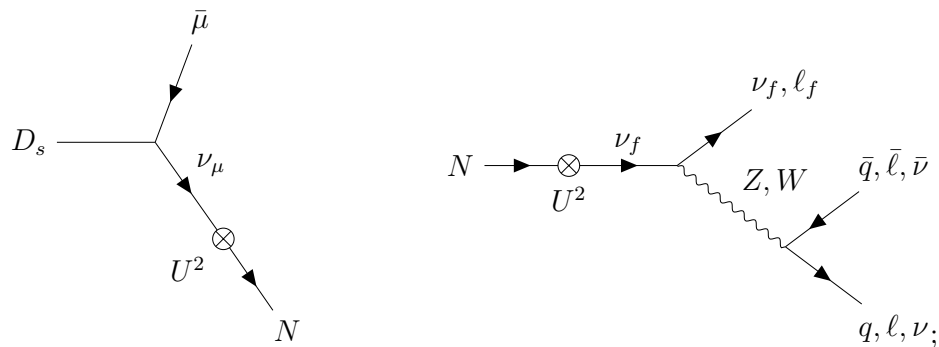


Figure 1. Production and decay of a heavy neutral lepton N .

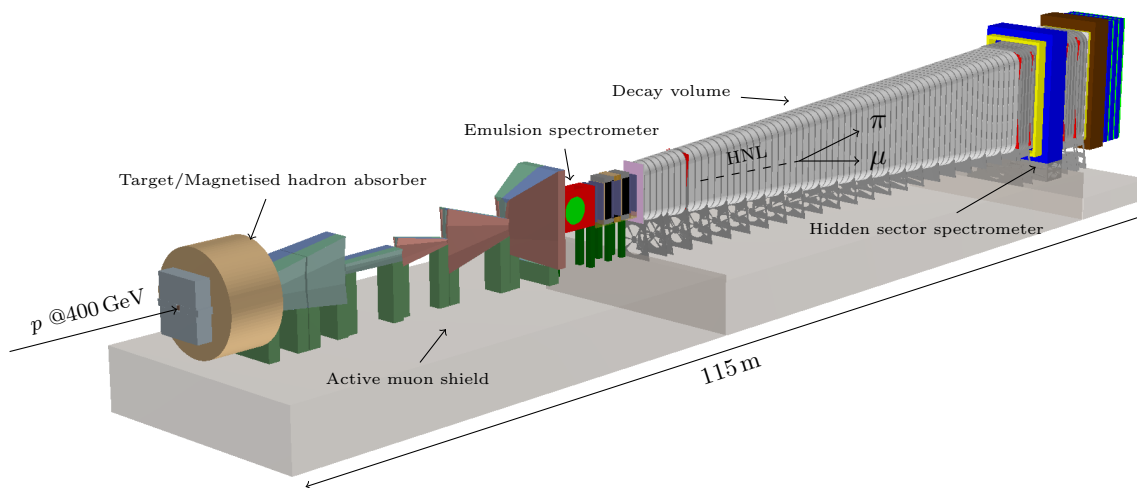


Figure 2. The SHiP Facility. 400 GeV protons are aimed at a target followed by a magnetized hadron absorber and an active muon shield. An emulsion spectrometer follows. Behind is the long evacuated decay volume with detectors for particle tracking and identification at the end.

3.1. Performance of the Hidden Sector Detector

SHiP can test many models. Among others there are promising models introducing dark photons coupling through a vector portal, dark scalars or the above mentioned HNLs. The sensitivities of SHiP for a selection of models are as follows:

3.1.1. Dark Photons: Dark photons can be produced directly from proton interactions with the target and in decays of π^0 , η , ω or η' . They then may decay into dark matter particles or, if no lighter hidden particle exists, into final states of two oppositely charged fermions. Fig. 3 shows the exclusion limit set by SHiP in case no signal is found for a dark photon.

3.1.2. Dark Scalars: SHiP will cover a large fraction of the parameter space in the search of dark scalars, as can be seen in Fig. 4, complementary to other (B -) experiments which are sensitive only to smaller lifetimes.

3.1.3. HNLs: Fig. 5 shows exemplarily the sensitivity to HNLs. SHiP will scan most of the cosmologically allowed region below the charm mass. In five years of running, 210 events are expected for $m_{2,3} = 1 \text{ GeV}$.

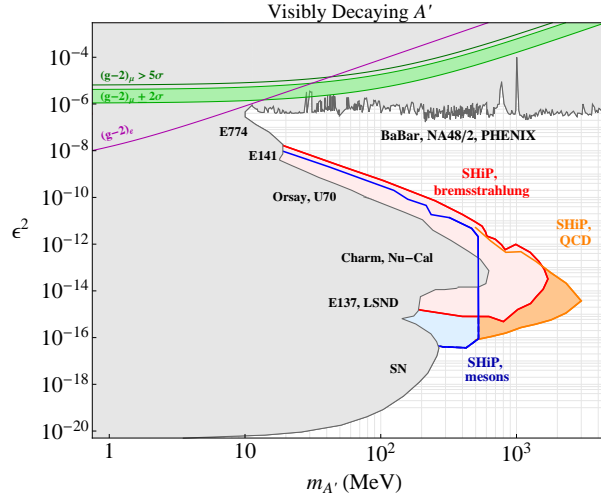


Figure 3. Dark photon sensitivity at SHiP as presented in [1]

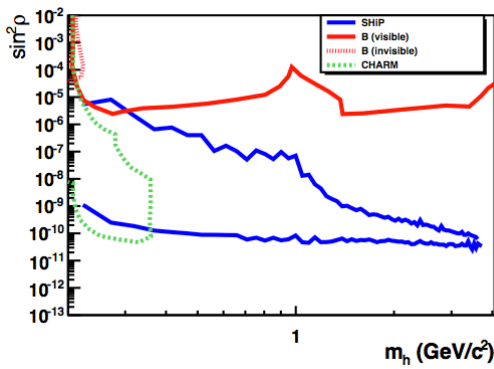


Figure 4. Sensitivity for the dark scalar portal. SHiP (blue line) covers a complementary region with respect to other experiments due to its ability to observe longer lifetimes.

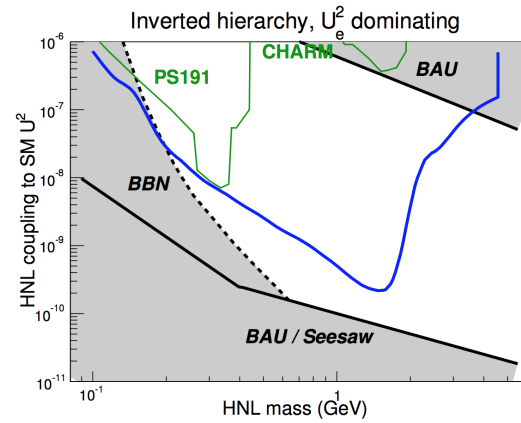


Figure 5. Sensitivity (blue line) of SHiP to HNLs with U_e dominating. SHiP will scan most of the cosmologically allowed region below the charm mass.

3.2. The Emulsion Spectrometer

Besides possible unknown weakly interacting particles, a huge amount of neutrinos of all flavors will be produced in the target. For example, τ -neutrinos are produced in the decay of D_S mesons, where the expected number $N_{\nu_\tau + \bar{\nu}_\tau}$ to be produced is given by:

$$N_{\nu_\tau + \bar{\nu}_\tau} = 4N_p \frac{\sigma_{c\bar{c}}}{\sigma_{pN}} f_{D_S} Br(D_S \rightarrow \tau) = 6.6 \times 10^{15},$$

with $N_p = 2 \times 10^{20}$ the number of interacting protons, $\sigma_{c\bar{c}}$ the cross-section of the associated charm production and σ_{pN} the hadronic cross-section per nucleon in the target, f_{D_S} the fraction of D_S mesons produced and $Br(D_S \rightarrow \tau)$ the branching ratio for their decay into a τ .

Behind the muon shield, these neutrinos will be detected by a dedicated neutrino detector, which is based on the OPERA concept [4].

This detector will consist of a magnetized target based on the emulsion cloud chamber (ECC) technique. Neutrinos will interact in lead plates interleaved with nuclear emulsion

for the detection of charged particles. Additionally, each ECC unit is followed by a compact emulsion spectrometer (CES), made of emulsion films interleaved with a low density material such as rohacell, to measure charge and momentum of charged particles emerging from neutrino interactions in the magnetic target and thus allowing for a separation between neutrinos and antineutrinos. The target will fit 1155 bricks, which have to be completely exchanged every six months of running for scanning. Assuming a 9.6 tons neutrino target and taking into account the geometrical acceptance, the number of neutrino interactions can then be estimated using the standard model cross-section. A number of $\mathcal{O}(10000)$ ν_τ and $\bar{\nu}_\tau$ interactions are expected.

This large number of neutrino interactions allows for several interesting studies. The τ -neutrino is the least known particle in the standard model: So far, only a few candidates have been experimentally observed by DONUT and OPERA. SHiP will bring great improvement to the determination of the ν_τ charged current cross-section, including the possibility of the measurement of the F_4 and F_5 structure functions. The ability to separate ν_τ from $\bar{\nu}_\tau$ interactions allows to experimentally observe the anti-tau-neutrino for the first time ever.

In about 5% of the neutrino and anti-neutrino interactions, charmed hadrons are produced—a process which is extremely sensitive to the strange quark content of the nucleon. These charmed hadrons can be identified topologically in the nuclear emulsions by detecting their decay vertex. SHiP will integrate about 10^5 charm events, exceeding current statistics by an order of magnitude and will thus be able to significantly improve knowledge of the strange quark content of the nucleon.

4. Conclusions

The SHiP facility offers a great opportunity for a wide range of new physics. It can cover many different regions of so far unexplored parameter spaces for numerous models. A Technical Proposal [3] was presented in 2015. The detector design is now being optimized. The collaboration has been requested by the SPSC committee to present a comprehensive design report by 2018. This will also serve as an input for the update of the High Energy panel of the European Strategy in 2019/2020. Construction and installation will last until the third long shutdown of the LHC so that the facility will start data taking in 2026.

References

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