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SHiP: a new multipurpose beam-dump experiment at the SPS

H.B. Dijkstra[1,a]

[1] *CERN, Geneva, Switzerland*

Abstract. SHiP is an experiment to look for very weakly interacting particles at a new to be constructed beam-dump facility at the CERN SPS. The SHiP Technical Proposal has been submitted to the CERN SPS Committee in April 2015. The 400 GeV/c proton beam extracted from the SPS will be dumped on a heavy target with the aim of integrating 2×10^{20} proton on target in five years. A 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 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 Neutral Leptons (HNL). The sensitivity to HNL 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. Integrated in SHiP is an Emulsion Cloud Chamber, already used in the OPERA experiment, which will allow to study active neutrino cross-sections and angular distributions. In particular SHiP can distinguish between ν_τ and $\bar{\nu}_\tau$, and their deep inelastic scattering cross sections will be measured with statistics three orders of magnitude larger than currently available.

1 Introduction

With the discovery of the Higgs boson[1][2] all the constituents of the Standard Model (SM) have now been observed. The data indicates that the SM provides a phenomenological description of electroweak and strong interactions at the Fermi scale, including the Higgs sector of electroweak symmetry breaking. Nature has chosen masses for the Higgs boson and the top quark such that the lifetime of the SM vacuum greatly exceeds the lifetime of the Universe[3]. In addition, the Landau pole in the Higgs self-interaction potential, which indicates when the theory would become unphysical, suggests this will be well above the Planck scale[4]. Hence, the SM could be an effective, weakly-coupled field theory all the way up to the Planck scale. However, experimental observations like neutrino oscillations, the existence of dark matter (DM) and the baryon asymmetry of the Universe (BAU) prove that the SM is an incomplete description of nature. While this necessitates the extension of the theory, neither experiment nor theory provide guidance on the mass scale of physics beyond the SM (BSM), nor on the coupling strength of any new particles to the SM particles.

Over the next decades the Fermi-mass scale and even beyond will be comprehensively explored either directly by ATLAS and CMS at the LHC and possibly at a FCC facility, or indirectly assuming generic couplings at experiments like LHCb, Belle2 and NA62. Hidden particles, which interact very

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[a] e-mail: Hans.Dijkstra@cern.ch

weakly with the SM particles, are predicted in many theoretical models capable of explaining the known shortcomings of the SM. A large part of their accessible parameter space remains hitherto unexplored.

The goal of the proposed Search for Hidden Particles (SHiP) experiment is to extend the search for BSM physics by searching directly for these very weakly interacting particles. Models with no new physics between the Fermi and Planck scales try to extend the SM using the smallest possible set of fields and renormalizable interactions. For example this "*Minimality principle*" motivates νMSM[5][6] which attempts to explain the pattern of neutrino masses, DM and the observed BAU by introducing three, new, right-handed Majorana Heavy Neutral Leptons (HNL). The lightest of these, N_1, provides the DM candidate, while $N_{2,3}$ are responsible for the baryon asymmetry. Through the seesaw mechanism[7] these HNLs also allow the pattern of neutrino masses and oscillations to be explained. This paper will concentrate on the search for these HNL particles. The full physics programme of SHiP is elaborated in the SHiP Physics Proposal[8].

The next section will present the experiments with the best sensitivity to date. The best limits are obtained for hidden particles with couplings to active neutrinos, which can be produced in semi-leptonic decays of strange or charmed particles. A new general purpose fixed target facility at the CERN SPS accelerator would provide an unique combination of intensity and energy capable of producing the large yields required, combined with the most favourable experimental conditions. With SPS performance equivalent to what was achieved for the CNGS[9] programme, the charm yield with a 400 GeV/c beam-dump will provide almost two orders of magnitude more charm than what can be obtained at the high luminosity LHC. Section 3 describes all aspects of the required new beam line, its dump and the SPS operational scenario. The SHiP facility does not interfere with approved SPS experiments.

The detectors for the hidden particle search are described in section 4, which includes a discussion of backgrounds and gives the expected sensitivity reach for HNLs.

Active neutrinos can be considered as the previous generation of hidden particles, and they are produced copiously at the SHiP facility. Hence, in addition to a hidden particles spectrometer, the SHiP experiment contains an emulsion based detector which will allow studying the properties of ν_τ and $\bar{\nu}_\tau$ independently. Section 5 will show that SHiP will increase the ν_τ statistics by almost three orders of magnitude compared to all previous experiments combined.

2 Past Experiments

Previous experiments have made essential contributions to constraining the parameter space for HNLs. The most significant limits below the charm mass [1] have been obtained in the fixed target experiments PS191, CHARM and NuTeV, shown in Figure 1.

The pioneer experiment, PS191, was specifically designed to search for HNLs at the CERN PS. No signal candidates survived rigorous visual tests at the final stage of the event selection leading to the limits on their coupling strength U_μ^2 to ν_μ shown in Figure 1. With $\sqrt{s} = 6$ GeV/c^2 no charm is produced, and hence the results of PS191 are limited to masses below 450 MeV/c^2. The high energies available at the CERN SPS and the FNAL accelerators allowed extending the searches for HNLs to higher masses using the HNL production via mixing to active neutrinos from charmed decays. CHARM searched for HNL decays in the $e^+e^-\nu$, $\mu^+\mu^-\nu$ and $e\mu\nu$ final states. No signal candidate was found resulting in limits on U_e^2 and U_μ^2, as shown in Figure 1 for U_μ^2. NuTeV searched for events with a muon and a charged track originating from a common decay vertex in their helium volume.

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[1] Searches in B and Z^0 decays are in general sensitive to larger masses, but they only cover orders of magnitude larger couplings.

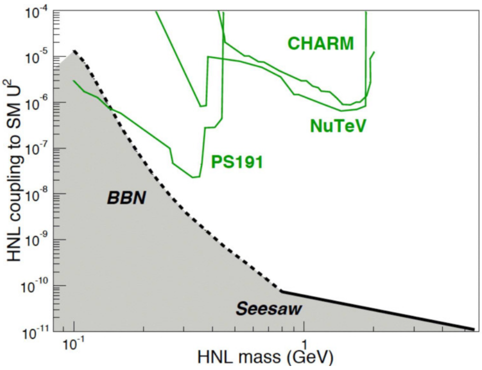

Figure 1. Sensitivity contours for the HNL coupling to active neutrino, $U^2 = U_e^2 + U_\mu^2 + U_\tau^2$ as function of the HNL mass assuming $U_e^2 : U_\mu^2 : U_\tau^2 = 1 : 16 : 3.8$. Experiments are discussed in the text.

No signal events passed the selection criteria which is consistent with the expected background of 0.57±0.15 events originating mainly from active neutrino interactions within the decay volume and in its vicinity. The corresponding NuTeV limit on U_μ^2 is also shown in Figure 1.

Table 1 lists the relevant parameters of these three experiments, in comparison with those planned for SHiP. SHiP can obtain about four orders of magnitude more yield for the same coupling by a combination of increasing the number of protons on target (p.o.t.), moving closer to the target, and increasing the fiducial decay volume.

Table 1. Comparison of the experimental conditions of HNL search experiments.

Experiment Reference	PS191 [10]	NuTev [11]	CHARM [?]	SHiP [13]
Proton energy (GeV/c)	19.2	800	400	400
p.o.t. ($\times 10^{19}$)	0.86	0.25	0.24	20
Decay volume (m^3)	360	1100	315	1780
Decay volume pressure (bar)	1, He	1, He	1, Air	10^{-6}
Distance to target (m)	128	1400	480	120
Angle to beam (mrad)	40	0	10	0

3 The SHiP Facility at the SPS

The SHiP experiment requires a total of 2×10^{20} p.o.t. over a period of about five years. The CERN management set up a task force of the CERN accelerator sector and the occupational health and safety and environmental protection unit to study an implementation of a 400 GeV/c proton beam for SHiP with minimal modifications to the SPS complex, and maximum use of existing transfer lines. Figure 2 shows the location of the proposed facility in the SPS accelerator complex. The location is ideally suited since it allows a full integration on CERN land with almost no impact on the existing facilities.

The SHiP facility shares the TT20 transfer line with the other North Area facilities, allowing switching on a cycle-by-cycle basis with other North Area beam destinations. Contrary to the beam extraction used for the CNGS programme, SHiP requires a spill of about one second to reduce background from muon pile-up. Taking into account that 20 % of the SPS time will be used for injecting protons into the LHC, and the number of protons required for the other targets in the North Area, leads to a SPS cycle with 4×10^{13} p.o.t. per 1 s spill, and 10^6 spills per year.

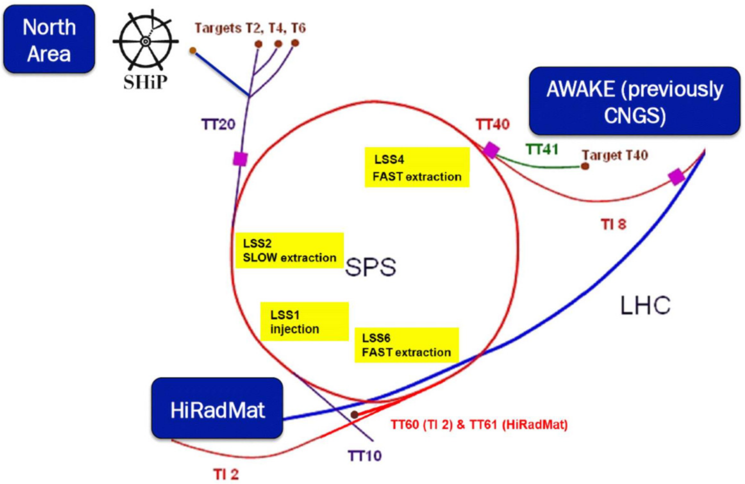

Figure 2. Overview of the SPS accelerator complex. The SHiP facility is located in the North Area and shares the TT20 transfer line with the fixed target programmes.

In order to maximize the production of heavy mesons and minimize the production of neutrinos and muons, the target must be designed with a material of the shortest possible nuclear interaction length and with dimensions to contain the proton shower. Consequently, the SHiP production target is one of the most challenging aspects of the facility due to the very high average beam power (up to 350 kW) deposited on the target. The peak power during the spill amounts to 2.56 MW. For this reason, the design of the target relies on the energy dilution produced by the large beam spot and the beam sweep produced at the beginning of the SHiP beam line. The required performance is achieved with a longitudinally segmented hybrid target consisting of blocks of four interaction lengths of titanium-zirconium doped molybdenum (TZM) alloy (58 cm) in the core of the shower followed by six interaction lengths of pure tungsten (58 cm). The target is embedded in a massive cast iron bunker (440 m^3), which acts as additional hadron absorber.

4 Hidden Particle Spectrometer

HNLs couple to the standard model active neutrinos, albeit with a very small coupling strength, and can hitherto replace neutrinos in any semi-leptonic decay if kinematically allowed. A 400 GeV/c proton on the Mo target produces $\sim$ 0.008 D-hadrons. HNLs produced from a semileptonic charm decay have a relatively large opening angle to the beam direction, hence the spectrometer should be placed as close to the target as possible. The small coupling results in a long lifetime, typically $c\tau = 50$ km, requiring a long decay volume. The spectrometer has been optimised to detect the decay of HNLs to $l^{\pm}l^{\mp}\nu$ and $l^{\pm}h^{\mp}$, with $h = \pi,\ \rho$. The protons that impinge on the target produce $\sim 10^{10}$ muons/s. To maximize the sensitivity of the experiment, this muon flux has to be reduced to less than $\sim 10^5$/s to avoid mimicking the signal due to μ-interactions, or pile-up of muons.

Figure 3 shows an overview of the spectrometer, with a total length of ~130 m. On the left is the target complex followed by the hadron absorber. This is followed by a 48 m long complex of warm magnets to sweep the muon flux out of the acceptance of the spectrometer. After this muon shield, the first 10 m is used for the ν_τ detector, and this is followed by a large vacuum vessel with a magnetic spectrometer.

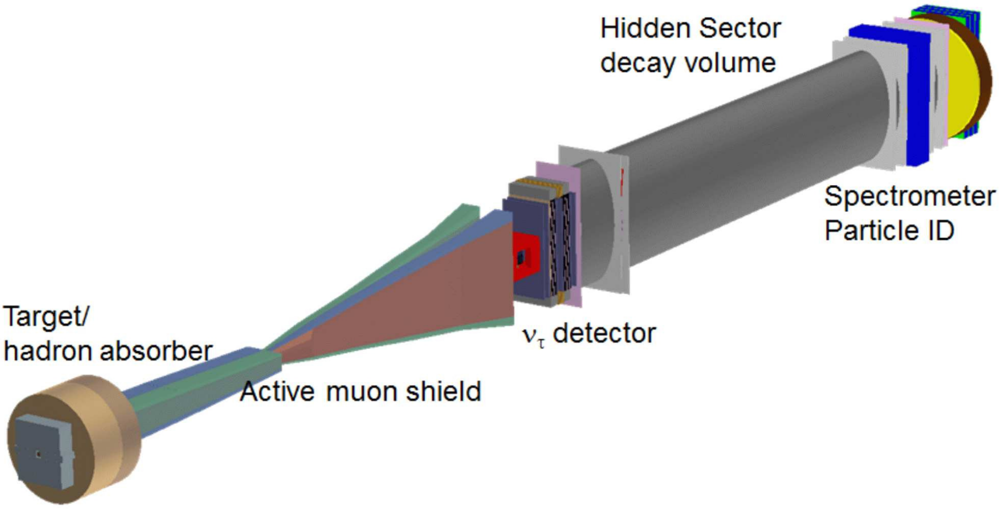

Figure 3. Overview of the SHiP spectrometer.

Large momentum muons are predominately produced in decay of η, ρ and ϕ-mesons. Their rate up to 350 GeV/c is prohibitively large, hence the muon shield needs a total $\int B_y \mathrm{d}l \approx 85$ Tm to bend these particles out of the acceptance of the spectrometer. Figure 4 shows on the left side the trajectory of muons with an initial momentum of 350 GeV/c through 48 m of warm Fe-magnets with a field of 1.8 T. Large momentum muons with an angle which is not too large in the opposite direction from the magnetic bending direction are swept out far enough to miss the contour of the HNL decay-vessel. However, as is shown in the right panel of Figure 4, the return field bends back lower momentum muons back towards the detector. To prevent this, the first section of field $0 < z < 19$ m is used to separate μ^+ and μ^- to either side of the beam direction. This separation creates enough room to place the return field for the subsequent magnets $19 < z < 48$ m in the central region, where there are no charged particles. Hence, particles bend back into the acceptance of the spectrometer will encounter the field again and will be swept back out. With this configuration of magnets, the total number of muons above 3 GeV/c in the spectrometer is less than 10 kHz.

The spectrometer to detect the HNL decay products consists of a $\sim$ 60 m long evacuated (10^{-6} bar) vessel. At the end of the vessel a 0.65 Tm spectrometer magnet surrounded by four straw stations allows to determine the momentum of the decay products with $\Delta p/p < 1$ %. The vessel is followed by an electromagnetic calorimeter to provide e, γ and π identification, and a hadron calorimeter to provide π/μ discrimination especially at low momenta. Larger momentum muons are identified with the muon

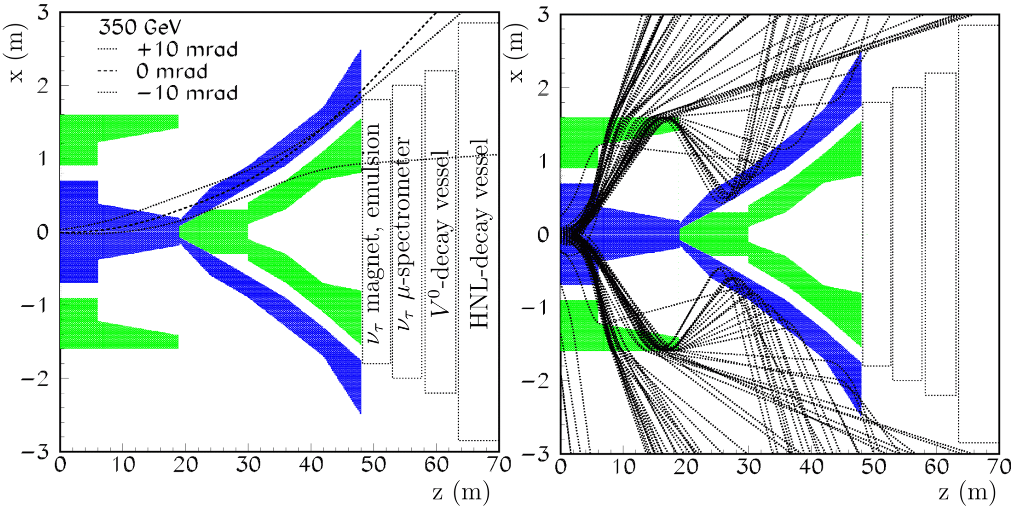

Figure 4. A horizontal cut of the active muon shield. The blue and green show the regions of field and return-field respectively, both are oriented perpendicular to this view. Also sketched are the outlines of the various detector elements. On the left the trajectory of three 350 GeV/c muons with a range of initial angles. On the right the shield is overlayed with a selection of low momentum muon trajectories.

spectrometer downstream of the calorimeters. While the spectrometer has moderate requirements, the real challenge is to tag all the possible background sources, such as:

- Neutrino- and muon-induced backgrounds: neutrinos and muons coming from hadron decays produced in the proton interactions can interact inelastically with the material surrounding the decay volume. These interactions can generate particles that enter the decay volume and mimic signal events.
- Random combination of tracks in the fiducial volume from muons, or other charged particles from interactions in the proximity of the detector, which enter the decay volume and together fake decay vertices which resemble signal events.
- Cosmic muons entering the decay volume can create background in the same way as the previous two classes.

To tag these backgrounds, the vessel is surrounded by:

- The entrance window is covered by a large array of scintillators detecting with high efficiency any charged particle which enters the vessel.
- 5 m after the entrance window, inside the vessel, a thin straw chamber detects in addition the decay products of V^0-particles which have entered the vessel.
- The entire vessel is surrounded by liquid scintillator read by $\sim$ 1700 photo-detectors.
- Just after the exit window of the vessel, a large array of scintillators form a TOF detector with a resolution of $\sim$ 100 ps to reduce the random combination of tracks.

SHiP has simulated all backgrounds with effective statistics larger than expected in 2×10^{20} p.o.t., and has not found any background events which could mimic a HNL decay. For the sensitivity contours 0.1 background events will be assumed.

The HNL yield depends on the hierarchy of the active neutrino masses and on the relative strength of the HNL couplings to the three SM flavours U_e^2, U_μ^2, U_τ^2. Figure 5 shows two scenarios which conform to existing theoretical studies[16], $U_e^2 : U_\mu^2 : U_\tau^2 \sim 52 : 1 : 1$ and inverted hierarchy of active neutrino masses, and $U_e^2 : U_\mu^2 : U_\tau^2 \sim 1 : 16 : 3.8$ and normal hierarchy of active neutrino masses.

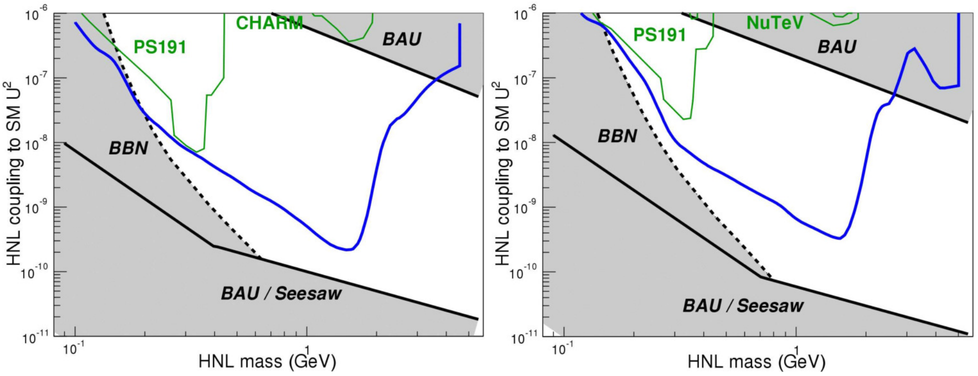

Figure 5. Sensitivity regions in the parameter space of νMSM, for two scenarios where U_e^2(left) and U_μ^2(right) dominate. The blue curves can be interpreted as 3σ evidence if two events are observed in SHiP. In the region below BAU, the observed Baryogenesis can be generated via oscillations of the two heaviest HNLs. The regions below the "seesaw" and "BBN" lines are excluded by neutrino oscillations experiments and Big Bang Nucleosynthesis respectively.

5 Active ν Physics

The tau neutrino detector shown in Figure 3 is located immediately downstream of the muon shield. It consists of a neutrino emulsion target in a magnetic field of 1 T, followed by a Muon Magnetic Spectrometer (MMS). The emulsion target is made of Opera-type modules which employ the Emulsion Cloud Chamber (ECC) technology. The charges of the hadrons produced in the neutrino interactions are identified using a tracker consisting of active planes which interleave the ECC modules. Muons are identified by the MMS which consists of a warm iron dipole magnet instrumented with active layers based on the Opera Resistive Plate Chambers and the Opera Drift Tube Tracker.

With this addition, the SHIP detector will have the unique potential to explore the physics of tau neutrinos. Whereas DONUT at Fermilab observed nine tau neutrino candidates[14] and OPERA at LNGS five candidates from oscillations[15], the SHiP experiment will collect $\sim$ 3000 reconstructed tau neutrino interactions during the above mentioned data-taking period. Both the ν_τ and $\bar{\nu}_\tau$ cross sections will be measured independently for the first time! SHiP is unique in its capability to accumulate large statistics of all the three active neutrino and anti-neutrino flavours. The ν_e cross-section will be studied at high energies, and since its production is dominated by charm decays, this measurement will also provide the normalization for the search for hidden particles. In addition the strange-quark content of the nucleon will be measured by means of the charmed hadron production in anti-neutrino interactions and the collection of a few million muon neutrinos will contribute to the studies of structure functions and to the measurement of the Weinberg angle.

6 Conclusion

SHiP intends to search for very weakly interacting particles in a hitherto unexplored region of parameter space. The covered region is particularly promising, since if such particles are found, the νMSM model[5][6] can link these particles to active neutrino mixing and Baryogenesis. In addition SHiP will measure ν_τ and $\bar{\nu}_\tau$ cross sections independently and with unprecedented statistics.

The discovery of a very weakly interacting hidden sector would lead to a dramatic breakthrough in our fundamental understanding of particle physics. In addition, it would open up a new field of experimental particle physics, which would benefit from accelerators capable of exceeding the already unique performance of the SPS.

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