Experiment at the CERN Super Proton Synchrotron to search for Hidden Particles

Scientific part of the proposal submitted to the Swiss National Science Foundation by

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1 Summary

The Search for Hidden Particles (SHiP) experiment is a new general-purpose fixed target facility at the Super Proton Synchrotron (SPS) to search for hidden particles, as predicted by a large number of models, providing an explanation for dark matter, neutrino oscillations, and the origin of the baryon asymmetry in the Universe. The experiment is aimed at searching for very weakly interacting long-lived particles including Heavy Neutral Leptons (right-handed partners of neutrinos), light supersymmetric particles, dark photons, etc. Prof. M. Shaposhnikov is one of the proponents of the theoretical context of the experiment and one of the founding members of SHiP. The University of Zurich (Prof. Nicola Serra) also participates in the SHiP experiment.

An initial detector concept was presented at the CERN SPS and PS experiments committee (SPSC) in an expression of interest (EOI) [1, 2]. The SPSC recognized the physics potential and gave an endorsement to proceed towards a technical proposal, which is now in preparation. Subsequently, the SHiP collaboration intends to carry out the required R&D with the preparation of a Technical Design Report (TDR) by the end of 2017.


We ask SNSF to support the above-mentioned activity at EPFL through the salary of one postdoc and travel expenses.
2 Research plan

2.1 Current state of research in the field

2.1.1 Theoretical motivation

The discovery of the Higgs boson of the Standard Model (SM) with a mass of about 126GeV suggests that the SM maybe a self-consistent, weakly coupled effective field theory up to the Planck scale without the addition of new particles [3, 4]. Although the SM is consistent with all observations at the LHC, it is clear that it is incomplete. The baryon asymmetry of the Universe (BAU), the presence of dark matter and the mixing of neutrinos are all unexplained by the SM. The most economical theory extension that can solve simultaneously these three shortcomings is the neutrino minimal Standard Model (νMSM) [5, 6]. Three new heavy neutral leptons (HNLs) are predicted, which are right-handed Majorana fundamental particles. The lightest HNL $N_1$ with a mass in the order of 10keV provides the dark matter candidate. Recent observations from two independent groups [7, 8] show a hint for an unidentified line at 7keV in the X-ray spectra of galaxy clusters, which can be explained by the dark matter candidate decay $N_1 \rightarrow \nu\gamma$. On the other hand these results have to be taken with a strong caveat given the difficulties to estimate the background, see [9] for instance. The heavier HNLs $N_{2,3}$, with nearly degenerate masses in the few GeV region, give masses to the active neutrinos via the seesaw mechanism and produce the BAU via leptogenesis. Cosmological and experimental constraints on the lifetime $\tau$, the integral mixing angle with the active neutrinos $U^2$, and the mass of $N_{2,3}$ are shown in Fig. 1. Previous experiments lack the

![Figure 1: Constraints on the lifetime (left) and the integral mixing angle (right) of the degenerate HNLs $N_{2,3}$ for normal mass hierarchy of the active neutrinos. The allowed region of the parameter space is shown in white. The constraints come from cosmological considerations (the Big Bang Nucleosynthesis (BBN) and the BAU), from neutrino mixing (via the seesaw mechanism) and previous experimental searches. The solid and dashed lines indicate the dependence of these regions on the pattern of HNL mixing with the electron, muon and tau-neutrino). Figures taken from Ref. [10].](image-url)
sensitivity in the majority of the parameter space allowed by cosmological constraints.

The production and the decay of the HNLs in the $\nu$MSM proceeds through the mixing with active neutrinos. In a direct experimental search, the HNL-neutrino mixing occurs at both production and decay, thus the signal yields depend on $U^4$. For masses below the charm threshold, the HNLs are most abundantly produced in the charm meson decays $D_s \to \mu N_{2,3}$ and $D \to \pi \mu N_{2,3}$, with expected branching fractions of $10^{-8}$–$10^{-12}$. The most favourable two-body HNL decay modes are $N \to l^\pm \pi^\mp$ and $N \to l^\pm \rho^\mp$ with $l = e, \mu$ and predicted branching fractions between 0.1% and 50%. An interesting three-body decay is $N \to \nu l_1^\mp l_2^\pm$ with a branching fraction of 1–10%, which depends on the individual mixing angles with the active neutrinos. The cleanest experimental signature is obtained in the $\mu\pi$ final state, while the other channels can be used to extend the sensitivity and provide additional constraints. Preliminary experimental design studies were reported in Ref. [11].

2.1.2 SHiP experiment overview

An initial detector concept was presented at the SPS and PS experiments committee (SPSC) in an expression of interest (EOI) [1, 2]. The SPSC recognized the physics potential and gave an endorsement to proceed towards a technical proposal. A dedicated task force, formed by the CERN management, has published a report on the required infrastructure and resources [12]. Research is currently in progress in view of a Technical Proposal for the SHiP experiment, which is to be completed by March 2015. Two workshops have been organised [13], where the physics case of the experiment and the detector requirements and technologies were explored. Working groups were formed that will provide a conceptual design of the experimental facility and the detector, and a detailed evaluation of the physics reach.

The SHiP experiment requires a 400GeV proton beam from the SPS with a total of $2 \times 10^{20}$ protons on target. The experimental setup consists of a target, a hadron absorber and a muon shield followed by a detector complex. The SHiP detector includes two decay volumes, each followed by a magnetic spectrometer, a calorimeter and a muon detector as shown in Fig. 2. This design allows for full reconstruction and particle identification, which are needed to reach the best sensitivity possible in a variety of decay modes. A detector based on an emulsion target will be placed before the upstream decay volume and will be used for the study of neutrino interactions.

This facility, which will make use of the copious production of charm mesons, is ideal for searches of light long-lived (very weakly interacting) hidden particles such as the HNLs. Several such portals to physics beyond the Standard Model are explored in
Figure 2: Three-dimensional sketch of the decay volume and the detector arrangement according to the initial design. The hybrid neutrino detector is upstream (to the left) of the decay volume and is not shown. Figure taken from Ref. [1].

recent theoretical works: a Higgs portal with dark scalars, a vector portal with dark or secluded photons, axion portals related to pseudo-Nambu-Goldstone bosons, and light SUSY particle portals (see, e.g. Refs. [14, 15, 16, 17, 18, 19].) The proposed experiment will cover a significant fraction of the cosmologically allowed region below 2GeV, improving on the sensitivity of previous searches by four orders of magnitude. This approach is complementary to new particle searches at colliders, which are sensitive to high masses and large couplings.

The setup is also ideal for the study of neutrino interactions. Tau neutrinos with similar kinematics as HNLs are produced in $D_s$ decays. Scaling from the DONUT experiment [20], about 3400 $\nu_\tau$ charged current events are expected in an emulsion target of six tons. The broad physics case for tau neutrinos includes the first observation of the tau anti-neutrino, cross-section measurement and searches for new physics [21]. Moreover, various measurements of neutrino-induced charm hadron production can be made in the emulsion based detector, including nucleon structure functions, associated charm production, charm fragmentation fractions. Electron neutrino interaction studies at energies above 10GeV can provide a normalization of the charmed hadron production in the target, which is an important input for the HNL search.
2.1.3 SHiP detectors

The general detector configuration consists of a 40m long decay volume, followed by a 10m long magnetic spectrometer, a calorimeter and a muon detector as shown in Fig. 2. The use of an additional detector element increases the geometric acceptance by 70%, thus two almost identical detector elements are envisaged, resulting in a total length of about 110m. The background caused by muon and neutrino interactions with the air inside the decay volume needs to be reduced to a negligible level by operating inside a 50m long and 5m wide cylindrical vacuum vessel at a pressure of less than $10^{-2}$ mbar. Backgrounds from charged particles entering the fiducial volume will be rejected by veto detectors at the beginning of each decay vessel. The spectrometer includes a 4m long dipole magnet with a field integral of about 0.5Tm, and four low material tracking stations (two upstream and two downstream of the magnet). The current design is based on straw tube technology developed for the NA62 experiment [22]. Investigations are required in order to adapt the design to the requirements of SHiP, e.g. the length of the straws, the layer orientations, the resolution in time. The electromagnetic calorimeter is located behind each vacuum vessel. A good energy resolution and a sufficiently high granularity is required for $\pi^0$ reconstruction and lepton identification. The Shashlik technology, demonstrated in many experiments (e.g. LHCb [23] and HERA-B [24]), provides a good energy resolution, matching the spectrometer momentum resolution in the 10–20GeV range. A careful optimization of the design parameters is needed to achieve the best possible electron and photon identification as well as pion/muon discrimination. Two options are considered for the tracking stations of the muon detector: scintillating strips with SiPM readout (e.g. NA62 and SuperB experiments) or resistive plate chambers.

The neutrino detector is located on the beam axis, following the muon filter and before the decay volumes. The detector is based on the so called Emulsion Cloud Chamber (ECC) technique [25], which consist of a lead neutrino target interleaved with nuclear emulsion layers, which act as micrometer resolution trackers. The technology leads to an increase of the interaction rate and allows resolving both the neutrino interaction and the tau decay vertices. The excellent precision of the technique relies on having up to about 300 interactions per ECC brick. It is estimated that the bricks need to be exchanged every $2 \times 10^{19}$ protons on target (i.e. ten times). A compact emulsion spectrometer (CES) [26] following each brick can provide measurement of the total charge of the tau decay products and thus provide the ability to tag the tau neutrino helicity. A high resolution (100µm) and high efficiency ($\sim 100\%$) tracker station following each wall of bricks will provide matching with the emulsion tracks. Two options exist, a
tracker based on scintillating fibres (as developed for the LHCb upgrade [27]) or a gas electron multiplier (GEM) detector (as envisaged for LHC experiments upgrades). The charge and momentum of muons will be measured by a muon spectrometer following the neutrino target region. As the energetic forward muons can be detected in the hidden particle detector, it is important to focus on the low energy muons and a large angular acceptance. A high muon identification efficiency is needed to separate tau neutrino interactions from charmed-particle production in muon neutrino interactions.

2.1.4 Background

The main sources of background to HNL decays are due to the neutrino flux from the target region or due to the residual muon flux. The backgrounds can be classified as being caused by: inelastic interactions with the residual gas in the decay volume; decays of strange hadrons produced from interactions in the last interaction lengths before the fiducial volume; random muon pair combinations (false decay vertices).

The background level due to the residual gas in the vacuum vessel is estimated to be negligible. If proven necessary, the pressure can be reduced to $10^{-4}$ mbar. Neutral current neutrino interactions in the material before the fiducial volume produce $K^0$ and $\Lambda$ mesons. Two-prong vertices in the first 5m of the decay volume are mainly from $K^0_S$ and $\Lambda$ decays, while in the remaining 35m 95% of two-prong vertices are from $K^0_L$ decays. A few hundred $K^0_L$ decay vertices are expected in $2 \times 10^{20}$ protons on target. The feasibility of tagging neutral current interactions by instrumenting the last interaction lengths will be considered. Charged current neutrino interactions in the material before the fiducial volume can be rejected by the veto detectors with high efficiency.

Studies following the EOI have shown that a sufficient reduction of the initial muon flux ($10^{11}\mu$/spill) is challenging. A promising alternative to the baseline passive muon shield, which consists of about 100t of tungsten and 2000t of lead, is a combination of an active and a passive shielding. The active shielding consists of conventional iron-filled dipole magnets, with a field integral of about 30Tm, capable of deflecting muons with momenta up to about 350GeV. Low momentum muons, which are bent back by the return field, have to be stopped by a passive (iron) shield. A significant research effort is required for the simulation and optimization of the magnetic field configuration and the passive shielding, while minimizing the cost and respecting the radiological aspects. In addition, a reliable knowledge of the residual muon flux entering the decay volumes is essential for estimating the background to hidden particle searches.

A residual muon flux of $10^5$ muons for a 1s spill seems achievable. Assuming a time resolution of a few ns, a total of $10^7$–$10^8$ two-muon coincidences are expected for the full
data taking period and about 1% form a vertex. The invariant mass of the muon pairs lies in the 0.2–1.2GeV region and a fraction of the pairs are pointing to the target, mimicking HNL decays. To reduce this background and to enable the positive identification of the HNL $\mu\pi$ decay mode, it is crucial to have the best possible pion/muon discrimination. Moreover, as several hidden sector theories predict decays to $\mu\mu(\nu)$, precise particle identification will reduce background and increase sensitivity. Therefore, a detailed study and optimization of the combined performance of the calorimeter and the muon detector is needed.

2.2 Current state of our own research

The Laboratoire de Physique des Hautes Energies (LPHE) of EPFL has expertise in the research and development of detectors and in data analysis. Past and present experiments with significant LPHE contributions are L3, NOMAD and LHCb at CERN, HyperCP at Fermilab, USA, and BELLE at KEK, Japan.

In particular, in LHCb we had major detector construction responsibilities, including the development, construction and installation of the so-called TELL1 common readout boards [28], of the transmission electronics for the silicon vertex detector VELO [29], and of the silicon Inner Tracker stations [30]. We have also contributed to the development of trigger algorithms and general software, to the optimization of the physics performance and to the detector calibration.

During the past few years we undertook new R&D activities for an upgraded LHCb tracking based on scintillating fibers (SciFi) and Silicon Photomultipliers (SiPM) [27]. Several simulations (based on GEANT [31] and FLUKA [32]) were written by members of the lab and validated by measurements. Under our guidance, new 128-channel SiPMs have been developed in collaboration with Hamamatsu Photonics. Currently, LPHE is in charge of the quality assurance of the SiPMs, which will equip the LHCb SciFi tracker. This expertise will be very valuable in the design of the SHiP subdetectors, triggers, and DAQ electronics.

In SHiP, SiPMs are foreseen to read out the muon detector scintillating strips and the SciFi tracker option for the neutrino detector. LPHE is equipped with all the tools needed to characterize such devices. This includes an inverted microscope for the injection of photons on a tiny area of the device and an automatized optical bench for the measurement of the photon detection efficiency (PDE) as function of the light wavelength. A dark room is also available for single photon sensitivity studies when large structures (full detector size) are to be tested.

For the SciFi tracker option of the neutrino detector 15 planes of $\sim 3\text{m}^2$ are foreseen
in the present design. For the needs of the LHCb upgrade, the LPHE is now installing a lab for the production of such components, including a winding machine capable of producing 3m long SciFi mats. This installation will be available in a short term (middle 2015) for the construction of prototypes but also for the mass production of the SHiP subdetector (foreseen to start in 2018, beyond the LHCb production period in 2015–2017).

In conclusion, LPHE has the potential to contribute to SHiP in a significant way, exploiting the already existing know-how and infrastructure.

2.3 Detailed research plan

During the period covered by this request the main emphasis will be on the simulation of the detector. We propose to contribute to this effort with one scientist who has experience with GEANT and FLUKA. He will receive the support of LPHE physicists and he will work in close collaboration with experts and engineers from CERN and also from the Rutherford Appleton Laboratory. The EPFL high energy theory group will provide the necessary input for particle physics models and physical process signatures. Note that the participation of Master and PhD students is also foreseen, mainly with contributions to the detector R&D for SiPM and SciFi.

With the goal to make a significant contribution to the TDR preparation, the objectives for the period covered by this request should be the following:

Simulation and optimization of the muon shield.
Detailed simulation (GEANT and FLUKA) of the muon flux through the active and passive shielding. Optimization of the magnetic field configuration and the geometry of the passive shielding.

Simulation and optimization of the calorimeter and the muon detector.

Estimation of the achievable background levels. Estimation of the experimental sensitivity to various decay modes of hidden particles.
2.4 Schedule and milestones

A preliminary schedule is reported in Ref. [12] (see Table 1). The work on a technical proposal has already been started. The most important interim milestones concerning the detector are:

**Q2 2015**  Delivery and approval of the technical proposal.


**2018 – 2021**  Production of the detector.

**2021 – 2022**  Installation of the detector.

**2022 – 2023**  Commissioning and start of data taking.

The postdoctoral researcher will join the SHiP collaboration and will participate in the research and development phase needed for the Technical Design Report.

2.5 Relevance and impact

The energy scale of new physics is not known. If it exists at energies above the Fermi scale (examples include supersymmetry, large or warped extra dimensions, models with dynamical electroweak symmetry breaking), the search for new particles can be carried out in direct experiments, such as ATLAS and CMS at LHC. In addition, new hypothetical heavy particles inevitably appear as virtual states, leading to different rare processes, absent in the SM. These effects can be found at experiments such as LHCb and are competitive with the direct searches. If no new physics is found at the LHC, this may indicate the absence of new physics all the way between the Fermi and Planck scales.

Quite paradoxically, the up to now largely unexplored domain of energies, where the new physics can be hidden, is related to physics below the Fermi scale. If the new particles are light and weakly interacting then the search for rare processes is superior to high energy experiments. It provides a unique possibility for discovery of new physics, not accessible by any of the LHC experiments. Moreover, this new physics can be responsible for neutrino masses, baryon asymmetry of the Universe, and dark matter.

The SHiP experiment is optimised for searches of hidden particles such as heavy neutral leptons, dark photons, light scalars and pseudo-scalars, and light SUSY particles with the planned sensitivity exceeding by four orders of magnitude (with HNL as an
example) the previous experiments such as CHARM or NuTeV. If the searches for new physics are concerned, the importance of the discovery of new particles is impossible to overestimate. At the same time, the negative results would limit the domain where new physics can hide itself.

In conclusion, SHiP has the potential to make fundamental discoveries about some of the most intriguing puzzles of nature: the substance of dark matter, the predominance of matter over antimatter, and the mixing of neutrinos. The resulting knowledge will determine our representation of the Universe, with a strong cultural impact.

The technologies envisaged for this experiment are an excellent training ground for master students, PhD students and postdocs in experimental particle physics.

All the physics results of our research will be publicly available. They will be published in international peer-reviewed journals and presented at international conferences on high-energy physics or more specialized topics. An outreach effort, in which we participate, is being put in place within the Swiss Institute of Particle Physics (CHIPP).
Table 1: Preliminary schedule of the SHiP facility. Table taken from Ref. [12].

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Figure 39: The timeline for the SHiP installation
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