The SHiP experiment at CERN

A. Di Crescenzo(1)(2)(*)

(1) *INFN, Sezione di Napoli - Napoli, Italy*
(2) *Dipartimento di Fisica, Università di Napoli Federico II - Napoli, Italy*

Summary. — The SHiP experiment is a versatile facility operating at the intensity frontier at CERN, specifically designed to investigate physics beyond the Standard Model through the search for Feebly Interacting Particles (FIPs) in the GeV mass range. The experimental setup includes a multi-detector system capable of detecting both decay and scattering signatures associated with various FIP scenarios, such as dark-sector mediators, elastic and inelastic light dark matter candidates, and particles with fractional electric charge. In addition to its new physics program, SHiP will enable precision studies of Standard Model processes, particularly neutrino interactions. Notably, it will yield unprecedented samples of tau neutrinos and their antiparticles. The experiment is planned to be commissioned and begin data taking prior to the LHC's Long Shutdown 4, with an extensive 15-year scientific program. By probing otherwise inaccessible regions of the parameter space for GeV-scale FIPs, SHiP will serve as a complementary effort to LHC experiments and to future collider initiatives.

1. – Introduction

Although the LHC has successfully discovered the final missing component of the Standard Model and continues to refine its measurements with increasing precision, numerous fundamental questions remain unresolved. Among these are the nature of dark matter, the mechanism behind neutrino mass generation, and the source of the universe's baryon asymmetry. Various theoretical models propose additional particles with masses below the electroweak scale that interact very weakly, making them difficult to detect with current or planned experimental setups. Such particles, often referred to as feebly interacting or long-lived particles, could potentially be observed in experiments specifically designed for this purpose. Their production mechanisms and interaction signatures are diverse but can be systematically classified according to their coupling structures with the Standard Model. A significant portion of these parameter spaces remains unexplored, with large regions of mass and coupling strength beyond the sensitivity of existing

(*) on behalf of the SHiP Collaboration.

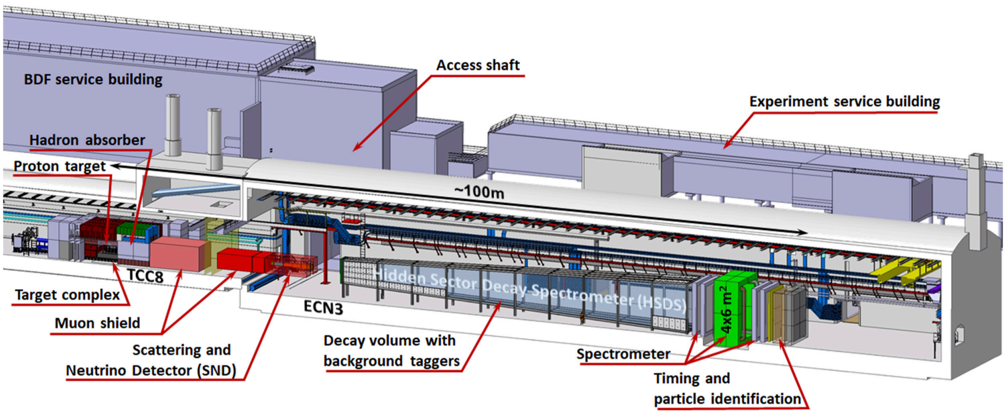

Fig. 1. – Overview of BDF/SHiP in ECN3 [3].

and forthcoming experiments. The SHiP experiment is designed to address these unexplored areas by harnessing the intense proton beam available at the HI-ECN3 facility and deploying two dedicated detectors optimized for this search.

2. – Experimental layout

The SHiP experiment is located at the Beam Dump Facility (BDF), within the HI-ECN3 area of CERN's Super Proton Synchrotron (SPS) (Figure 1). The facility is designed to handle an annual flux of 4×10^{19} protons-on-target (PoT) at 400 GeV, impacting a dense target, with a total depth equivalent to 12 nuclear interaction lengths. This configuration produces a high yield of secondary particles, including approximately $2\times10^{1}7$ charmed hadrons, $1.4\times10^{1}3$ beauty hadrons, 2×10^{15} tau leptons, and around 10^{20} photons above 100 MeV per year, enabling SHiP to explore a broad spectrum of production channels for feebly interacting particles (FIPs) and to collect an unmatched sample of tau neutrinos.

A hadron absorber positioned immediately downstream of the target stops all hadrons, leaving only muons and neutrinos. This section is magnetized to begin deflecting the intense muon flux, thus forming the first stage of SHiP's active muon shielding system. In the baseline design, the core of the target is made of water-cooled TZM blocks cladded in tantalum, followed by tantalum-coated tungsten. An alternative configuration under study envisions a fully tungsten target cooled with helium, which could further enhance performance.

The muon shield, extending over $\sim$25 m, combines the magnetized hadron absorber with a series of strategically arranged standalone magnets. It is engineered to suppress the muon flux—initially as high as 20 GHz for muons above 10 GeV, down to below 100 kHz in the acceptance region of the detectors.

The SHiP Scattering and Neutrino Detector (SND) is embedded within the downstream part of the muon shield (Figure 2). It is composed of alternating layers of tungsten and silicon sensors for precise vertex reconstruction in tau neutrino interactions and electromagnetic showers from electron neutrinos. A magnetized tracking calorime-

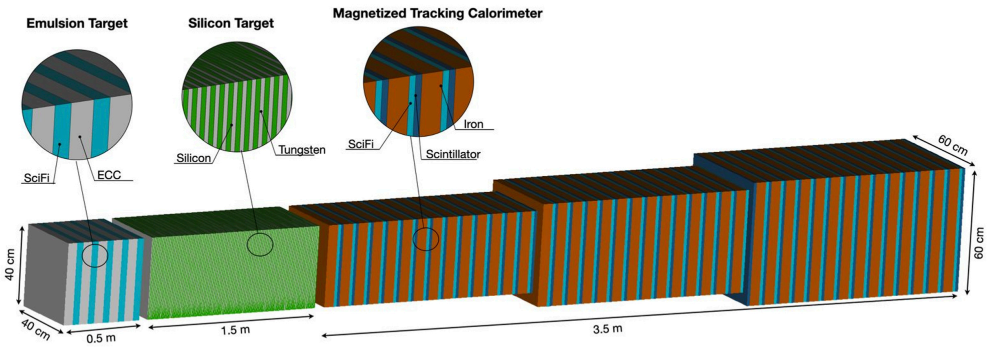

Fig. 2. – Schematic drawing of the SND detector [3].

ter (MTC), built with iron absorbers and active scintillating fiber and tile planes, follows the silicon tracker. The MTC is optimized for flavor identification of neutrinos, including tau neutrinos, through kinematic reconstruction.

Upstream of the MTC, an Emulsion Cloud Chamber (ECC) may be installed if the residual muon rate allows. The ECC uses tungsten plates interleaved with emulsion films, enhancing spatial resolution for vertex reconstruction.

SHiP's decay volume consists of a helium-filled gas vessel maintained at atmospheric pressure. It acts as the search region for long-lived FIP decays. It is surrounded by background tagger systems designed to veto incoming particles or interactions occurring near the detector walls. These systems include multi-gap resistive plate chambers (MRPCs), scintillating fibers, and liquid scintillator modules read out by wavelength-shifting devices.

A superconducting spectrometer magnet provides a field integral of 0.6–0.8 T·m over a 4×6 m^2 aperture, enabling precise momentum reconstruction. The magnetic field geometry and the arrangement of the four straw-based drift tracking stations—each only 0.5% of a radiation length—are carefully optimized to ensure excellent angular resolution within the decay volume.

Particle identification is completed by a high-granularity electromagnetic calorimeter (ECAL), capable of reconstructing electrons and photons and determining photon direction with enough precision to resolve decays such as ALP$\to \gamma\gamma$. A downstream hadronic calorimeter provides effective muon/hadron separation over a wide momentum range.

3. – Physics programme

3˙1. *Searches for FIPs through decay signatures.* – The discovery of long-lived feebly interacting particles (FIPs) would represent a major breakthrough in particle physics, offering a potential window into phenomena that lie beyond the Standard Model (SM). Many theoretically well-motivated extensions of the SM predict the existence of such particles, which may be linked to open fundamental questions, including the origin of neutrino masses, the nature of dark matter, and the baryon asymmetry of the Universe.

Leveraging the high-intensity proton beam of the SPS and a detector optimized for the reconstruction of complex final states, SHiP is specifically designed to conduct a broad, model-independent search for the decays of FIPs with very small couplings to SM particles. Among the most promising candidates are:

- Heavy Neutral Leptons (HNLs): Arising in seesaw-type models, HNLs naturally explain the smallness of neutrino masses and can account for the baryon asymmetry via leptogenesis.

- Dark Scalars and Dark Photons: Predicted in Higgs-portal and vector-portal scenarios, they offer a link between the visible and hidden sectors and may contribute to dark matter or inflationary dynamics.

- Axion-like Particles (ALPs): Common in many BSM frameworks, ALPs can serve as dark matter candidates or mediators of new interactions, often tied to UV completions through non-renormalizable operators.

- Inelastic Dark Matter: Appears in scenarios where dark matter has excited states, allowing unique signatures at fixed-target experiments.

- Supersymmetric Particles: Depending on the SUSY breaking scale, neutralinos and other superpartners could have masses in the GeV range, making SHiP sensitive to new physics at scales far beyond direct reach.

One of the key features of SHiP is its ability to probe extremely small couplings, reaching sensitivity several orders of magnitude below current experimental limits. In benchmark scenarios, SHiP is expected to improve coupling limits by 2–4 orders of magnitude and explore mass ranges broader by 1–2 orders compared to existing bounds, as shown in Figure 3. For some models, this translates into thousands of detectable events within the accessible parameter space, enabling not just discovery but also detailed characterization.

To achieve this, SHiP employs a multilayered strategy for background suppression. The dense target and hadron absorber minimize backgrounds from pion and kaon decays in flight, while a powerful muon shield drastically reduces the flux of muons reaching the decay volume. Surrounding the helium-filled decay region, high-efficiency background taggers, precise tracking, timing systems, and particle ID layers help discriminate genuine FIP signals from background processes.

The main sources of background are neutrino-induced interactions and residual muons. Neutrinos produced in the beam dump can interact in detector materials and mimic signal-like topologies. Muons, in turn, can lead to fake vertices through deep inelastic scattering or random coincidences. These are mitigated by the underground location of SHiP, reducing cosmic ray contributions to negligible levels, and by the use of high-resolution timing and tagging.

3·2. *Neutrino physics*. – The interaction of protons with the BDF target gives rise to an intense and broad-spectrum neutrino flux, comprising all three flavours. Energy spectra of neutrinos interacting in SND are shown in Figure 4.

Thanks to the target's considerable length and density, light mesons with longer lifetimes are more likely to undergo further interactions before decaying. This suppresses neutrino production from pion and kaon decays and instead enhances the contribution from charm and beauty hadron decays. As a result, SHiP benefits from an enriched

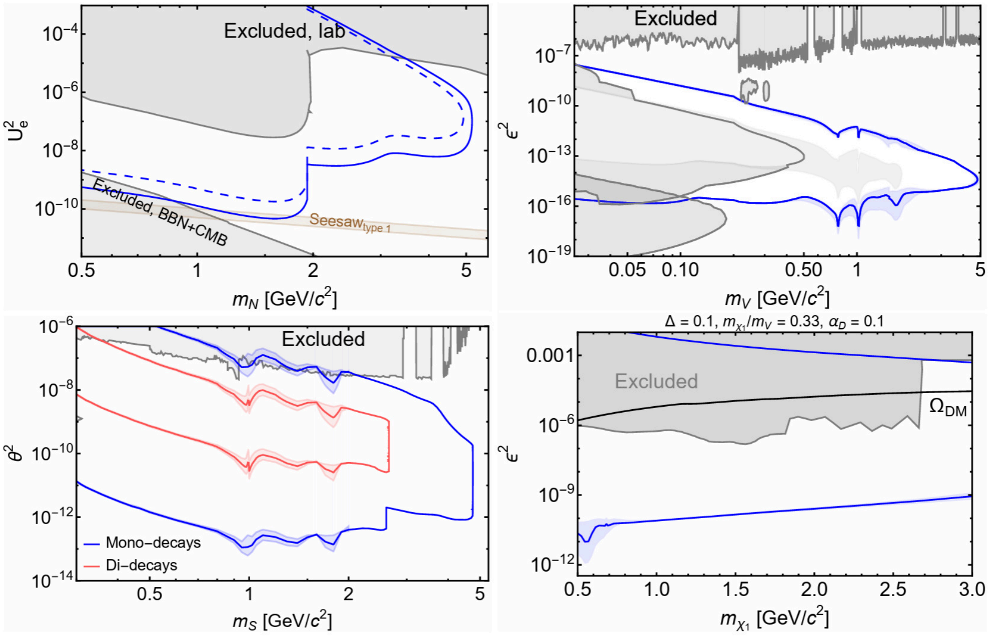

Fig. 3. – Sensitivity of SHiP to various new physics particles: Heavy Neutral Leptonsor HNLs(top left), dark photons (top right), Higgs-like scalars (bottom left), and inelastic dark matter coupled via dark photons (bottom right). The solid blue lines show the sensitivities per 15-year running time of SHiP [**?**].

sample of tau and electron neutrinos compared to the typically dominant muon neutrinos, enabling rare studies of their interaction dynamics.

With 15 years of data-taking and a 3-tonne neutrino detector, SHiP will accumulate a substantial number of neutrino interactions. One of its key objectives is the first unambiguous detection of tau anti-neutrinos, which remain undetected so far. SHiP's use of a high-intensity proton beam and a magnetised detection system will make it possible to distinguish between tau neutrinos and anti-neutrinos, allowing for statistically robust measurements of both species.

This capability will yield the first high-precision measurement of ν_τ cross-sections, significantly advancing our understanding of neutrino-nucleon interactions in the energy range between 10 and 100 GeV. In addition to total cross-section measurements, SHiP will investigate deep inelastic scattering (DIS) processes with tau neutrinos, targeting the structure functions F_4 and F_5, which are expected to play a unique role in such interactions and remain unmeasured experimentally. These studies will contribute crucial input to theoretical models used in current and future neutrino oscillation experiments.

A further unique opportunity at SHiP lies in the detailed study of charm production in neutrino interactions. This process is highly sensitive to the strange-quark content of nucleons and offers a complementary probe of the nucleon's internal structure. The high event rate will also permit a more accurate determination of the CKM matrix

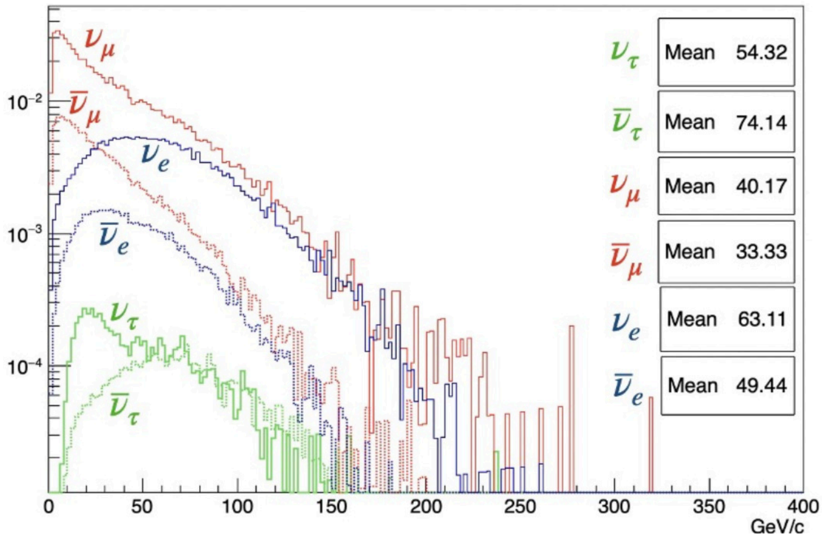

Fig. 4. – Energy spectra of neutrinos interacting in SND [3].

element $|V_{cd}|$, whose current uncertainty is limited by our knowledge of charm production dynamics.

REFERENCES

[1] SHiP Collaboration, Tech. Rep. CERN-SPSC-2015-016, SPSC-P-350.
[2] SHiP Collaboration, Tech. Rep. CERN-SPSC-2023-033, SPSC-P-369.
[3] SHiP Collaboration, arXiv:2504.06692v1.
[4] S. Alekin et al., Rept. Prog. Phys. 79(12) (2016) 124201.
[5] SND@LHC Collaboration, JINST 19 (2024) P05067.
[6] SND@LHC Collaboration, Tech. Rep. CERN-LHCC-2021-003, LHCC-P-016
[7] SND@LHC Collaboration, Tech. Rep. CERN-LHCC-2025-004, LHCC-P-026.