SHiP-LNF: 2019 Status Report

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1 Status of the SHiP project

The SHiP Project is one of the main medium-size projects proposed at CERN for the current update of the European Strategy for Particle Physics (ESPP). The main novelties in 2019 are summarized here below.

1.1 SHiP and the European Strategy for Particle Physics

The SHiP physics case comprises a wide variery of hidden sector models and has been fully recognized in the Briefing Book of the current European Strategy Update for Particle Physics [1], co-authored by one of the SHiP-LNF members (G. Lanfranchi).

In the Introduction of the Briefing Book, p.8, the Beam Dump Facility (BDF) serving the SHiP experiment, is explicitely mentioned as a possible way to explore dark matter paradigms complementary to the standard WIMP searches:

"Europe has the opportunity to play a leading role in the searches for DM by fully exploiting the opportunities offered by the CERN facilities, such as the SPS, the potential Beam Dump Facility (BDF), and the LHC itself, and by supporting the programme of searches for axions to be hosted at other European institutions. The preparatory study of the BDF facility is now mature and a decision should be taken on its implementation following this Strategy update; its potential sensitivity to new physics should be compared to that of competing proposals, such as long-lived particle searches at the LHC, to inform this decision."

The Briefing Book, again in the same Introduction at p.10, outlines the importance of developping at CERN a *"Diversity Programme"* complementary to the programme exploited at colliders, and elaborated in the Physics Beyond Colliders effort [2], where SHiP is one of the main players.

Hidden sector with feebly-interacting particles is an emerging field which is getting a lot of interest, as demonstrated by the fact that a large fraction of Chapters of the Briefing Book mention it as an important direction to pursue. *No other topic has been so widely represented in the Briefing Book across all the Chapters.*

- **Chapter 5, Flavour Physics, Section 5.4 and 5.6:**
  "From both the experimental and the theory side, a novel synergy between the searches for flavour violating decays and that for feebly interacting and dark particles is emerging. Searching for exotic signatures in flavour violating decays may have profound implications for our understanding of the Universe, and should be part of any broad program of searches for dark sectors. High-energy colliders will explore a large number of signatures and cover a large fraction of the parameter space for the high-mass range (above 10 GeV). Nevertheless fixed-target smaller-scale experiments, LHC projects dedicated to long-lived particles and beam-dump facilities may provide complementary information to explore a lower mass range (1 MeV - 10 GeV) and open new interesting research lines".
- **Chapter 6, Neutrino Physics, Section 6.5.2**
  "SHiP is a beam-dump experiment designed and optimised to search for Hidden Particles. It

will take advantage of the high-intensity proton beam of the Beam-Dump Facility [425] (BDF) under study in the context of the Physics Beyond Collider activity, that would allow starting data taking in the LHC Run 4 of the CERN accelerator schedule. SHiP will accumulate the full statistics of NA62++ every few days, thanks to the larger acceptance and beam intensity (2×10^{20} *POT in 5 years).*

- **Chapter 8, Beyond the Standard Model, Section 8.6**
  This section shows in an extensive way the complementarity between future colliders and beam dump experiments for the search for feebly-interacting particles (FIPs). The Physics Beyond Colliders plots have been extended to include also the sensitivity of e^+e^-, ep and pp colliders for fermion, scalar, pseudo-scalar and vector FIPs. The importance of this research direction if clearly outlined in the Conclusions of this Chapter.
  "The absence, so far, of unambiguous signals of new physics from direct searches at the LHC, indirect searches in flavour physics and direct DM detection experiments invigorates the need for broadening the experimental effort in the quest for new physics and in exploring ranges of interaction strengths and masses different from those already covered by existing or planned projects. While exploration of the high-mass frontier remains an essential target, other research directions have valid theoretical motivations and deserve equal attention. Feebly-interacting particles (see Sect. 8.6) represent an alternative paradigm with respect to the traditional BSM physics explored at the LHC. The full investigation of this paradigm over a large range of couplings and masses requires a great variety of experimental facilities. In this context, the physics reach of experiments at future colliders is complemented by beam-dump facilities which typically cover the range of low masses and extremely feeble couplings".

- **Chapter 9, Dark Matter and Dark Sector**.
  The entire Section 9.4, *Dark Matter and Dark Sector at beam-dump and fixed target experiments* is dedicated to the study of hidden sector at accelerator-based (non collider) experiments. The case of sub-GeV Dark Matter with thermal origin and related light, feebly-interacting mediators, is presented with all details and all experimental techniques are listed. SHiP at the BDF is clearly mentioned as an outstanding way of probing this class of models.

1.2 The Beam Dump Facility Comprehensive Design Study

The Beam Dump Facility (BDF) team has submitted a Comprehensive Design Study in December 2019 [3]. Following the first evaluation of the BDF in 2014-2016, CERN management launched a Comprehensive Design Study over three years for the facility. The BDF study team has since executed an in-depth feasibility study of proton delivery to target, the target complex,and the underground experimental area, including prototyping of key sub-systems and evaluations of the radiological aspects and safety. A first iteration of detailed integration and civil engineering studies has been performed in order to produce a realistic schedule and cost. This document gives a detailed overview of the proposed facility together with theresults of the studies, and draws up a possible road map for a three-year Technical Design Report phase, followed by a 5 to 6 year construction phase.

1.3 The SHiP Comprehensive Design Study

The experiment counter part of the BFD Comprehensive Design Study has been, as anticipated last year, the *SHiP Comprehensive Design Study* (*n.1 of Publication List).* This document summarises the status of the physics and the detector and outlines a three-year design and development plan towards Technical Design Reports. The document concludes with an overall road map and updated costs for the detector R&D and construction. With the submission and review of this document, together with the *SHiP Progress Report* [4] and the BDF Comprehensive Design Study, the SHiP Collaboration is ready to proceed with the preparation of Technical Design Reports, pending approval.

2 Activities of the LNF group

The 2019 activity of SHiP-LNF has been focussed on the R&D and project planning of the muon detector which has been included in the Comprehensive Design Study.

R&D and project planning of Muon System

Groups involved: INFN-Bologna, INFN-Cagliari, INFN-LNF, INR, MEPHY; LAL-Orsay (France) and Barcelona-CCUB (Spain) for Electronics.
Project Leaders: G. Lanfranchi (LNF-INFN) and Y. Kudenko (INR, Russia)

The Muon System is described in Section 4.11 of the SHiP Technical Proposal [5] and comprises four stations of active layers interleaved by three muon filters 6 m wide and 12 m high. The baseline technology is *scintillating tiles with direct SiPM readout*, as described in details in the 2018 SHiP-LNF Report.

The work performed in 2019 has been mostly focused on the following topics:

- *Finalization of the definition of the tile characteristics, both in terms of scintillating material, tile size and shape, photodetector type and coupling to the tile, and coating material.*

  Baseline solution: square tile made of EJ200 scintillator, coated with high reflectivity paint, of dimensions $(15 \times 15 \times 1)$ cm^3, with SiPMs placed at the corners and connected with optical glue to the tile. Alternative solutions: tiles with different shape (rectangular), type of scintillator (UNIPLAST, Vladimir, Russia) and painted with a diffusive paint (such as EJ510) are currently under test.

  Comparative tests of scintillator performance (EJ200 versus UNIPLAST) performed in Frascati in 2019 have shown that a rectangular tile made of EJ200 scintillator produces almost twice the light emitted by an identical tile built with UNIPLAST. A new (square) scintillating tile produced by UNIPLAST with a new scintillator chemical composition, will be tested in 2020.

  The hardware R&D activity is being complemented by a detailed FLUKA simulation of the combined response of the tile and photo-sensor to a minimum ionizing particle. A square 15×15 cm^2 tile, made of EJ200 scintillator and read by four (6×6)mm^2 SiPM Hamamatsu at the corners has been simulated. The EJ200 scintillator properties (attenuation length, scintillation efficiency, emission spectrum, raise/decay time) and the photo-detection efficiency versus wavelength of the different SiPM types used during tests have been implemented. The output signal is obtained by adding all four SiPMs output signal waveforms. Figure 1 shows the time response of the tile as a function of the impinging point of the muon on the tile itself. The response is quite uniform for the large majority of the area, as confirmed by the measurements.

- *Choice of large area SiPMs with high PDE and good time resolution, and search for the SiPM operating conditions for optimal matching with the light pulse emitted by the chosen scintillator.*

  Baseline solution: SiPM, Hamamatsu, S14160-6050HS, 6×6 mm^2 active area, 50 μm cell.

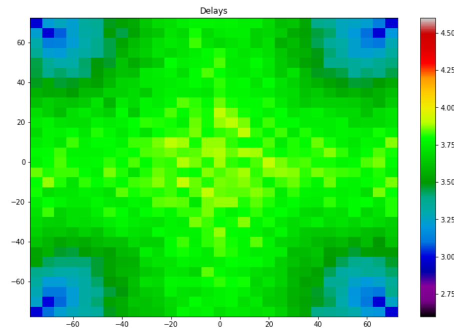

Figure 1: FLUKA simulation: time response of the analog sum as a function of different impinging points of a particle on a square 15×15 cm^2 tile.

Alternative solution: SiPM produced by the *Fondazione Bruno Kessler* (FBK), with 5×5-6×6 mm^2 active area, to be developed in collaboration with FBK. An Expression of Interest for a grant within the forthcoming European programme *AIDA-Innova* has been submitted (and currently retained) with the aim of developing with FBK a large area (6×6 mm^2) SiPM with comparable performance and cost with the Hamamatsu S14160-6050HS. The R&D of large area, high PDE SiPMs with the FBK will occur in next 2-3 years in parallel to the other activities.

- *Development of a readout electronics able to cope with a large sensor capacitance and to extract the required time information from the signal.*

  Baseline solution: customized discrete-component board hosting four amplifiers directly connected to the SiPMs and a common adding point with single analog output. This board has been designed and built (see Figure 2) and its response to scintillating light will be fully characterised in 2020. Preliminary tests show that the level of noise of the new electronics designed and built in Frascati is much lower (almost half) than the noise of the MUSIC chip used in the 2018 test beam.

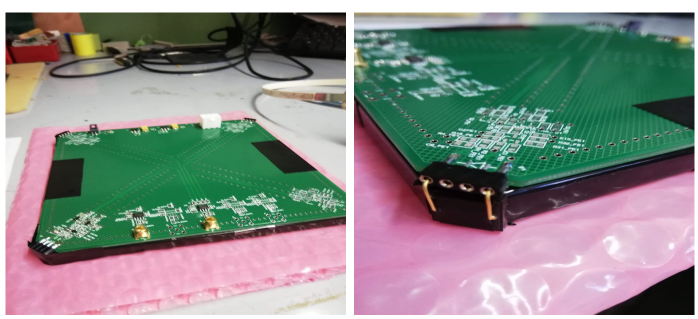

Figure 2: Left: prototype of the customized readout board for a $(15 \times 15 \times 1)$ cm^3 square tile with four SiPMs at the corners. Right: detail of the board connection to the SiPMs.

- *Construction and test of a module-0 (32 tiles) of the muon system equipped with the final front-end and prototype digitizer board.*

The construction and test of a 32-tile module-0 (Figure 3, left) will be the main goal for the TDR. A 32-tile fully equipped module-0 built with the final tile basic unit will be tested in one of the CERN beam line with the final front-end electronics and the first working prototype of the middle-end electronics. This test will not only fully characterize the overall performance of the system, but will allow the mechanical design to be finalized, and the electronics/optical cross-talk to be assessed. Construction and test of a fully equipped Module-0 will be done by 2022- early 2023. This year we built a first full-size mock-up of the module 0 (Figure 3, right) in order to study the mechanical structure, and its interplay with the FE electronics which is being designed at LNF.

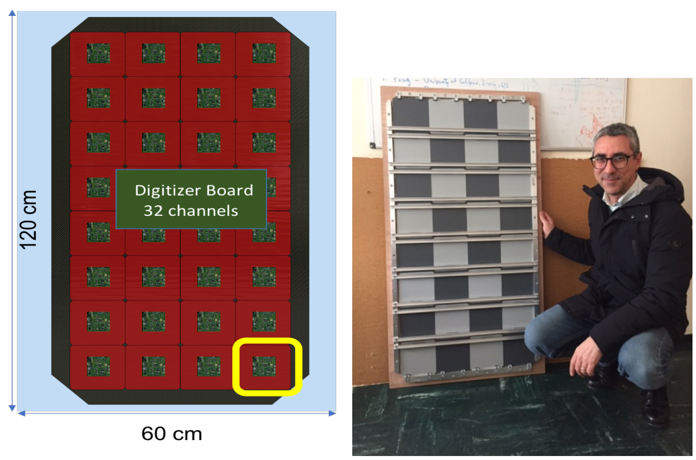

Figure 3: Left: schematic layout of a 32-tile module 0 of the muon system. Right: full-size mock-up of a module 0.

- *Development of a prototype Digitizer board*

  A 32-channel board hosting two SAMPICs will be developed to read out a module and some initial thoughts have been done in collaboration with the SHiP Electronics group led by Dominique Breton (LAL). This board will be managed by a small FPGA interfacing the SAMPICs and other features with the DAQ, timing and control link with the common SHiP electronics backend. The prototype will also feature a standalone mode to be used for characterization and test beams. The Digitizer board will provide all required services to the front-end boards, including regulated low voltage and SiPM bias voltage.

- *Integration of the readout electronics into the overall SHiP electronics and TDAQ framework*

  This activity is evolving in parallel to the other activities in strict collaboration with the Electronics and TDAQ SHiP groups and will involve mainly the groups related to the design of the Digitizer board. The SHiP Electronics group has begun the process of defining a common digital link format between subdetector electronics and common back-end system. A medium speed four-lane copper link will provide clock, synchronization and configuration commands to the on-detector subdetector board, and receive data and monitoring information. The usable data bandwidth will be between 100 and 300 Mbps, which exceeds the requirement of the muon detector by a large margin. On or near the detector, multiple copper links will be aggregated into higher speed optical links connecting to the DAQ farm, the TFC, and the slow control infrastructure.

- *Engineering of the detector layout and its integration with the other detectors in the experimental hall.*
  This activity is already ongoing and it will evolve in strict coordination with the rest of the detector. A preliminary design of the support structures of the muon stations is shown in Figure 4.

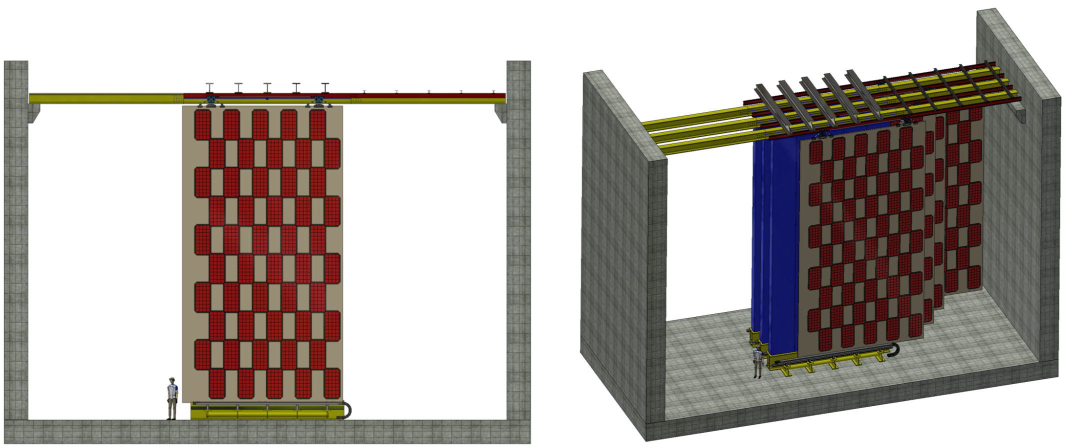

Figure 4: Left: Front view of one station of the HS muon system. Each station is made of 100 modules, 32-tile each, disposed in a chess structure staggered on both sides of a supporting wall. Right: 3D view of the HS muon system, with four active stations and three iron filters. The stations are designed to slide on rails in order to ease the access to the modules.

- *Simulation of the overall detector performance integrated in the general FairSHiP framework.*
  The code for the simulation of the muon detector, for the digitization of the Geant hits and for the reconstruction of muon tracks has been integrated into the general FairSHiP framework. The software is flexible and allows both to change the size of the tiles separately for each individual station, to tune the width of the filters and change the number of stations. The simulation of the HS muon system is being developed in coordination with the overall SHiP simulation framework.

3 SHiP-related Talks given by LNF people

1. *Experimental searches for Heavy Neutral Leptons*, invited seminar, 22 November 2019, CERN cross-talk neutrino physics series, https://indico.cern.ch/event/850455/
2. *Feebly interacting particles: experimental landscape*, invited talk, KAON2019 International Conference, Perugia, 10-13 September 2019.
3. *Feebly-interacting particles: experimental prospects at accelerator-based experiments*, invited review talk, 15th PATRAS workshop on Axions, WIMPs and WISPs, Freiburg (Germany), June 2019.
4. *Search for very weakly coupled particles: sensitivity for beam dump experiments*, CERN Faculty Meeting for CERN senior staff, 14 June 2019, https://indico.cern.ch/event/796152/.
5. *Feebly Interacting Particles: what can we learn from experiments* Granada Symposium for the European Strategy for Particle Physics update, May 2019, invited talk, Granada, Spain.
6. *Search for New Physics at the High Intensity Frontier: Physics Beyond Colliders activity* invited talk, Workshop on Light scalars: origin, cosmology, astrophysics and experimental probes, April 2019, Benasque (Spain).
7. *Round table for the 40th anniversary of the CERN North Area*, G. Lanfranchi, Terry Sloan Lyn Evans, Niels Doble, Claude Vallee and John Dainton, CERN, Main auditorium, 3 April 2019.
8. *The Physics Beyond Colliders activity*, invited talk, Aspen Conference, March 2019, Colorado, US
9. *Search for New Physics at the High Intensity Frontier: the Physics Beyond Colliders activity*, I2FEST, INFN-IHEP Workshop, invited talk, Torino, Italy, February 2019.
10. *Search for Hidden Particles at CERN*, Zurich Phenomenology Workshop, invited talk, January 2019, Zurich, Switzerland.
11. *The SHiP experiment at the Beam Dump Facility*, Invited Seminar, Heidelberg University, Germany, January 2019.

4 SHiP-LNF Publications in 2019

1. SHiP collaboration, *SHiP Experiment - Comprehensive Design Study report*, CERN-SPSC-2019-049 ; SPSC-SR-263.
2. SHiP collaboration, *Fast simulation of muons produced at the SHiP experiment using Generative Adversarial Networks*, JINST **14** (2019) P11028.
3. SHiP collaboration, *The downstream Muon detector of the SHiP experiment*, Nucl. Instrum. Meth. **A936** (2019) 263-265.
4. SHiP collaboration, *Sensitivity of the SHiP experiment to Heavy Neutral Leptons*, JHEP **04** (2019) 077.
5. SHiP collaboration, *The experimental facility for the Search for Hidden Particles at the CERN SPS*, JINST **14** (2019) no.03, P03025.
6. SHiP collaboration, *The SHiP experiment and the RPC technology*, JINST **14** (2019) no.06, C06009.

References

1. R. K. Ellis *et al.*, *Physics Briefing Book : Input for the European Strategy for Particle Physics Update 2020*, arXiv:1910.11775.

2. J. Beacham *et al.*, *Physics Beyond Colliders at CERN: Beyond the Standard Model Working Group Report*, arXiv:1901.09966, J.Phys. **G47** (2020) no.1, 010501.

3. C. C. Ahdida *et al.*, *SPS Beam Dump Facility - Comprehensive Design Study*, arXiv:1912.06356.

4. SHiP collaboration *SHiP Experiment Progress Report*, CERN-SPSC-2019-010, SPSC-SR-248.

5. M. Anelli *et al.* (SHiP collaboration), *Technical Proposal: A facility to Search for Hidden Particles (SHiP) at the CERN SPS*, CERN-SPSC-2015-016, SPSC-P-350,arXiv:1504.04956 [physics.ins-det].