SHiP-LNF: 2015 Status Report

M. Anelli (Tecn.), G. Bencivenni, M. Bertani, A. Calcaterra,
C. Capoccia (Tecn.), A. Cecchetti (Tecn.), P. Ciambrone, D. Domenici,
G. Felici, G. Lanfranchi (Resp.), A. Paoloni, A. Saputi (Tecn.).

1 Introduction

As this is the first SHiP status report, the following introduction aims at introducing SHiP and put it into context.

Particle physics today is in a very peculiar situation: all the particles of the Standard Model have been observed and the measured masses of the Higgs boson and top quark fall into a narrow region of parameters, where consistency of the Standard Model (SM) does not require new particles up to a very high energy scale, possibly up to the Planck mass.

However, it is clear that the Standard Model is not a complete theory. Some yet unknown particles or interactions are required to explain a number of observed phenomena in particle physics, astrophysics and cosmology as the neutrino masses and oscillations, the baryon asymmetry of the universe, the dark matter, the cosmological inflation and the dark energy.

While direct searches at the LHC are exploring the energies up to few TeV, the experimental results in flavour physics, searches for charged lepton flavour violation, and electric dipole moment of the electron indicate that there might be no new physics with a direct and sizeable coupling to the SM particles up to energies $\sim 10^3$ TeV unless specific flavour structures/symmetries are postulated.

On the other hand, it is possible that we did not observe new particles not because they are too heavy but because they interact very feebly with the SM particles and so far escaped the detection. Hidden sector theories postulate the presence of light and weakly-interacting particles which are singlet under SM gauge interactions and mix with SM portal fields which do not carry electromagnetic charge (the Higgs and the Z bosons, the photon and the neutrinos).

A new general purpose fixed target facility is proposed at the CERN SPS accelerator which is aimed at exploring the domain of hidden particles and make measurements with tau neutrinos. The high intensity of the SPS 400 GeV proton beam allows probing a wide variety of models containing light long-lived exotic particles with masses below ~ 5 GeV/c^2, including very weakly interacting low-energy SUSY states. Under nominal conditions the current SPS is capable of providing an integrated total of 2×10^{20} protons on target in five years of operation. This allows access to a significant fraction of the unexplored parameter space for the Hidden Sector with sensitivities which are several orders of magnitude better than previous experiments. The associated tau neutrino detector will allow performing a number of unique measurements with tau neutrinos, including a first direct experimental observation of the anti-tau neutrino interactions.

The SHiP collaboration currently consists of almost 250 members from 47 institutes in 15 countries. The SHiP Technical Proposal [1], signed-up also by the LNF authors, has been submitted to the CERN SPS and PS experiments Committee (SPSC) in April 2015. The SHiP physics case has been studied and elaborated by a collaboration of more than 80 theorists in the SHiP Physics Proposal [2]. Some LNF authors who contributed substantially to the Physics Proposal have been acknowledged explicitely in the document (p.6 of the Physics Proposal). The SHiP physics case has been also widely discussed in the framework of the INFN *What Next* activity and some LNF authors are among the proponents of the *White Paper* [3] elaborated by the INFN-CSN1. An Addendum [4] to the Technical Proposal containing the answers to the main questions raised by the SPSC during the review process has been published in October 2015.

The SPSC has recently completed the review of the SHiP Technical and Physics Proposal, and it recommended the SHiP collaboration to proceed towards the Comprehensive Design Report, which will provide input into the next update of the European Strategy for Particle Physics, in 2018/2019.

2 Activity of the LNF group

The LNF group has been one of the first groups joining the project and has been involved since the beginning in the global design of the detector as well as in the simulation and sensitivity studies. The activity of the group in 2015 has been focussed mainly along four lines:

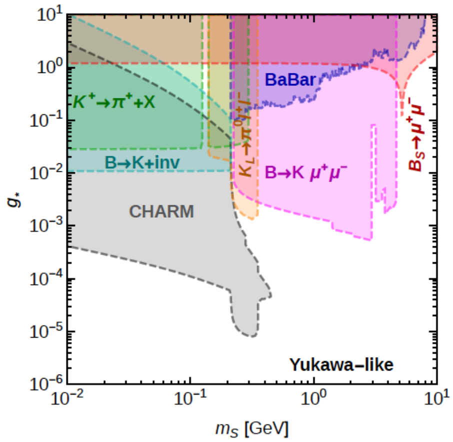
1. sensitivity studies for a specific hidden sector portal, the *Dark Scalar*, in collaboration with some theorists (C. Grosjean, B. Batell and R. Essig);
2. R&D of the muon system for the hidden sector detector and related electronics;
3. R&D of a high-spatial resolution tracker based on GEM/μ-RWELL technology for the tau neutrino detector;
4. test at high rate of the OPERA RPCs, for a possible their re-use in the muon system of the tau neutrino detector. This activity will end in the first half of 2016.

For each item we report here below a short description of the 2015 activity.

2.1 Sensitivity studies for the scalar sector

The study of the hidden scalar sector has been documented in Section 5.2.5 of the Technical Proposal and in Section 3 of the Physics Proposal. This work has been done by LNF authors together with some theorists. Additional scalars are required to exist in various extensions of the SM. Speculations regarding a possible Higgs portal coupling to new, weakly-coupled *hidden* scalar particles have intensified after the discovery of the Higgs boson. The SHiP experiment has the potential to probe this portal provided that the new states connected to it are light with masses of $\sim$ GeV/c^2.

The sensitivity of the SHiP experiment to light-hidden scalars has been evaluated with toy Monte Carlo assuming the nominal beam intensity of the SHiP facility and the geometry described in the Technical Proposal. The current limits in the coupling of the dark scalar to the Higgs vs mass plane are shown in Fig. 1 (left). The sensitivity of the SHiP experiment corresponding to five years of data taking is shown in Fig. 1 (right). An impressive improvement of two orders of magnitude in the limit of the dark scalar coupling to the Higgs is expected.



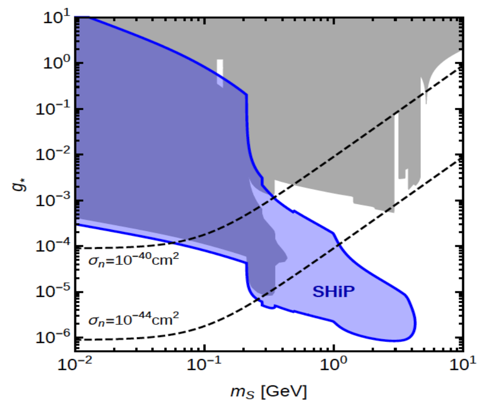


Figure 1: *Existing limits on the coupling versus mass plane for a hidden scalar (left) and sensitivity of the SHiP experiment corresponding to five years of data taking (right) .*

2.2 R&D of muon system for the hidden sector detector and related electronics

Groups involved: INFN-Bologna, INFN-Ferrara, INFN-LNF (G. Lanfranchi project leader), INR (Moscow, Russia).

The muon system of the hidden sector detector is described in details in Section 4.11 of the Technical Proposal. It is designed primarily to identify with high efficiency muons from signal channels as $N \to \pi^+\mu^-, \mu^+\mu^-\nu$ in the neutrino portal, $V \to \mu^+\mu^-$ or $S \to \mu^+\mu^-$ in the vector and scalar portals, respectively, and to separate them from $\nu-$ and $\mu-$ induced backgrounds and from combinatorial beam-induced muon background. To reject the latter, a time resolution better than 1 ns is required.

The muon detector comprises four stations of active layers interleaved by three muon filters 6 m wide and 12 m high. The baseline technology chosen for the active layers is extruded plastic scintillator strips with wavelength shifter fibers (WLS) and SiPM readout.

This technology is straightforward to operate, as no high voltage or inflammable gases are employed, has high efficiency and good time resolution. Other reasons for such a choice are: simple transverse segmentation, simple and robust construction, potential for distributed production, long-term stability, low maintenance, high reliability and cost effectiveness, all important aspects for building a large area detector.

The scintillating strips in the SHiP muon detector will be 5 or 10 cm wide, 3 m long and 1 or 2 cm thick. Crossings of horizontal and vertical strips can provide the x, y view in each muon station with a readout granularity of 5 or 10 cm. Figure 2 shows the layout of horizontal and vertical strips for each muon station. Figure 3 shows how the strips will be attached to the supporting walls. All the drawings have been done by the LNF group. About 480 vertical strips and 480 horizontal strips 5 cm wide are needed to instrument one muon station in the two views, 3840 strips for the entire system readout at both ends by 7680 electronic channels.

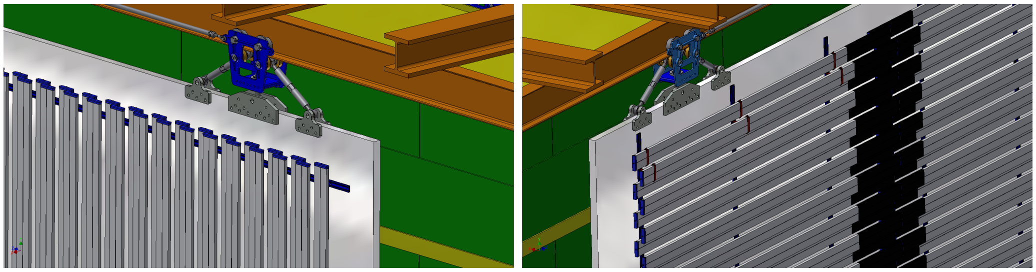


Figure 2: *Layout of the scintillating strips*

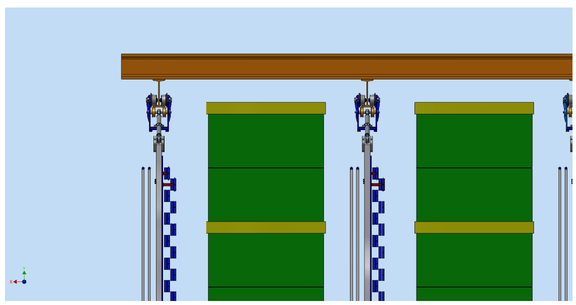


Figure 3: *Strips attached to the supporting wall .*

The R&D towards the final design of the detector aims at maximizing the light yield and the time resolution of the scintillating bars. This comprises the following items:

- optimization of the final dimensions of the scintillating bars;
- choice of the manufacturer of the scintillating bars;
- definition of the number and layout of the WLS fibers;
- choice of the manufacturer of the WLS fibers;
- test of the SiPMs present on the market;
- design and test of prototypes of the front-end electronics.

A two-weeks long test beam has been performed at the T9 area of the CERN PS in 14-28 October 2015. The test beam has been funded by a grant obtained in the framework of the AIDA-2020 EU programme. Several scintillating bars of two different companies (NICADD at FNAL, US and Uniplast at Vladimir, Russia) have been tested. The bars have been instrumented with different types of WLS fibers (Kuraray Y11 and Bicron BCF-92) of different diameter (1 mm, 1.2 mm and 2 mm) and readout with different SiPM (Hamamatsu MPPC S13081-050CS and Advansid - ASD-NUV3S-P). The bars were assembled in Bologna and in Moscow.

The results were excellent and exceeded our expectations: we measured light yields up to 150 photo-electrons for beam impinging at the center of a bar 3 m long and readout at both ends and a time resolution of 800 ps constant along the bar length. The results of the test beam have been reported in the last SHiP general meeting (10-12 February 2016)[1]. A paper summarizing these results is in preparation.

A very preliminary scheme of the readout electronics has been drawn for the Technical Proposal. The main tasks required to the front-end electronics are:

- to allow a fine biasing of the SiPM;
- to extract, to amplify and to shape the detector signal preserving its time information;
- to measure the arrival time of each signal with respect to a master clock;
- to format and to transmit the zero-suppressed data to the FARM;
- to interface with the TFC and ECS systems.

The conceptual block diagram has been developed at LNF and is shown in Fig. 4. The R&D of the muon readout electronics will be shared between LNF and Bologna in close contact with the SHiP TDAQ group.

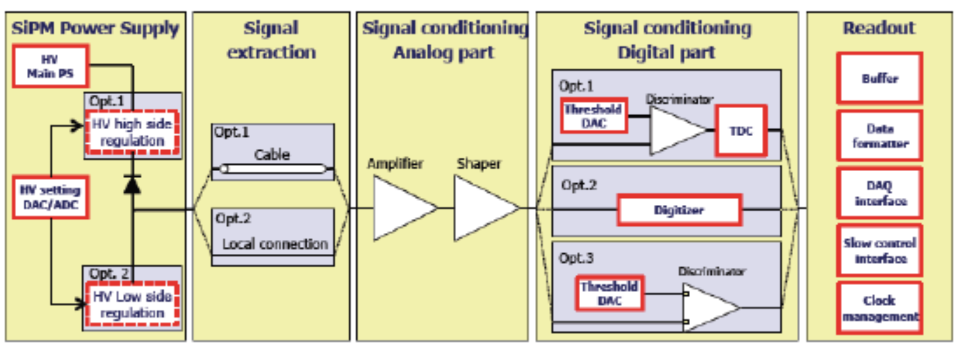


Figure 4: *Muon readout block diagram.*

[1]See https://indico.cern.ch/event/482695/timetable/#20160211.detailed, talks by G. Lanfranchi and A. Montanari.

2.3 R&D of the target tracker for the tau neutrino detector

Groups involved: LNF for the triple-GEM/μ-RWELL option (G. Bencivenni project leader).

The target tracker is described in Section 4.2.2 of the Technical Proposal. It provides the time stamp to the events reconstructed in the emulsion bricks and predicts the target unit where the neutrino interaction occurred. The neutrino emulsion target is made of 11 walls, each interleaved with a Target Tracker (TT) plane of a transverse size of about (2×1) m^2, with the longest side being horizontal. The physics performance, to be obtained in a magnetic field with a strength between 1.0 and 1.5 Tesla, are: 100 μm position resolution on both coordinates (also considering the coupling with the emulsions) and high efficiency ($> 99\%$) for angles up to 1 rad.

Three basic options for the target tracker are considered: scintillating fibers (mostly driven by the Kurchatov Institute), Micromegas (French groups) and triple GEM/μ-RWELL detectors (LNF, in synergy with BES-III and the CMS phase II R&D) . The final choice of the technology for the target tracker will be done for the Comprehensive Design Report.

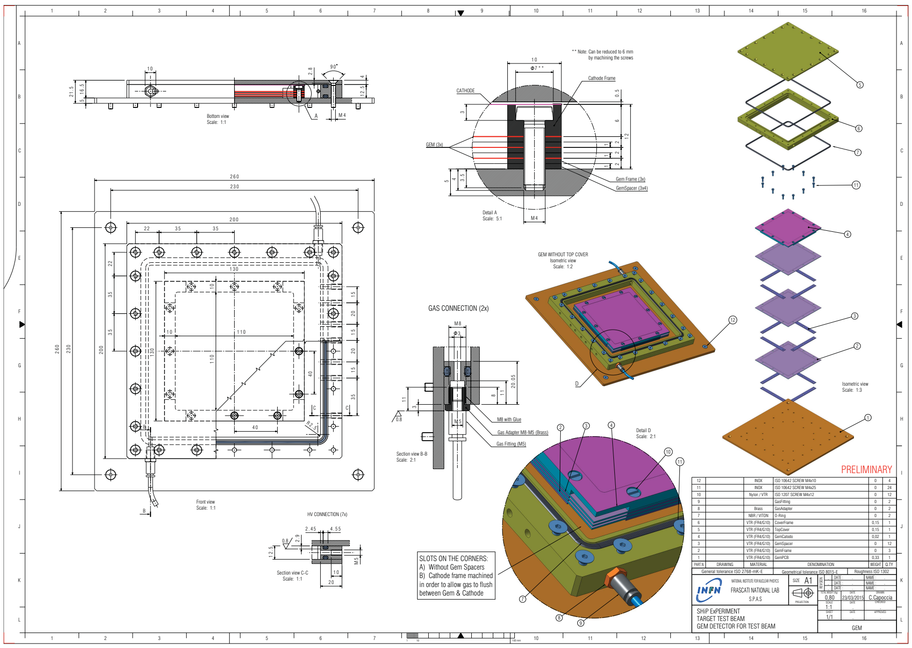
A triple GEM prototype has been built at LNF in spring 2015 (Fig. 5, top) to be tested at a test beam at the H4 line of the CERN SPS between October 24^{th} and November 4^{th} 2015. A rotating support able to change the detector orientation with respect to the impinging beam up to 60 degrees and hosting together the GEM detector and the emulsion films has been designed at LNF explicitely for the test beam (Fig. 5, bottom). The test beam has been funded by a second grant obtained in the framework of the AIDA2020 EU programme.

The results of the test beam have been presented at the SHiP general meeting (10-12 February 2016)[2] and can be summarized as follow:

- the triple-GEM option, for $\theta < 15°$ and $B = 0, \pm 1$T shows $100\ \mu m < \sigma < 400\ \mu m$ and $97 < \epsilon < 99\%$. Improvement of space resolution (large angle and high B) can be achieved using the μ-TPC approach currently developed in collaboration with the Ferrara BES-III group. However building a large size detector seems to be an issue for assembly complexity and costs.

- The μ-RWELL detector, for $\theta = 0°$ and $0 < B < 1$ T shows a spatial resolution $\sigma < 180\ \mu$m and $98\% < \epsilon < 98.5\%$. This is a very promising technology and allows for the most simple and cost-effective large area MPGD solution. More tests will be needed in the future that will be performed in the framework of the R&D of the CMS phase-II muon detector.

[2] See https://indico.cern.ch/event/482695/timetable/#20160211.detailed, talks by G. Bencivenni and V. Tioukov.



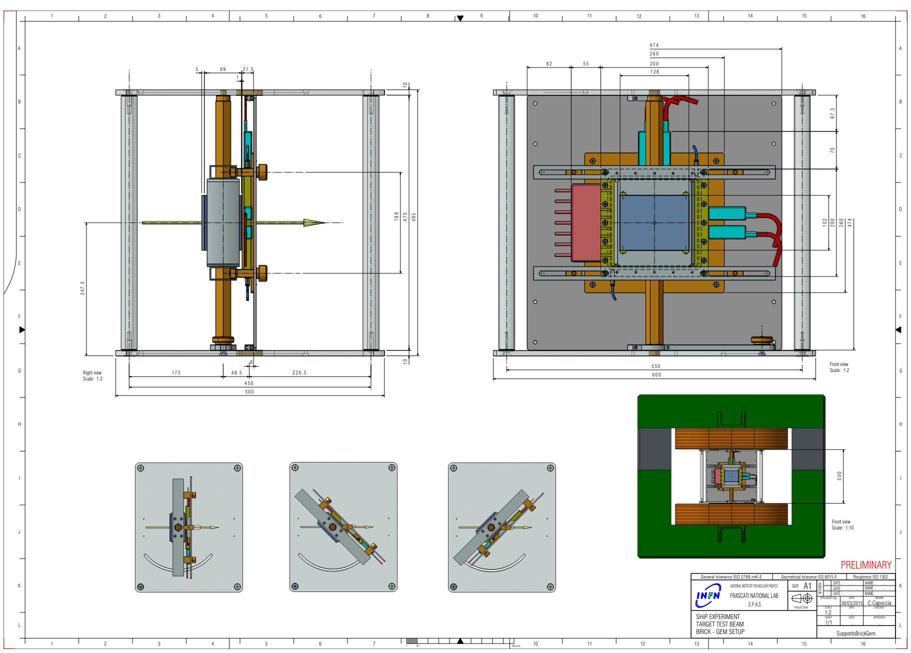


Figure 5: *Mechanical drawings of the GEM prototype (top) and the rotating mechanical support (bottom) designed at LNF for the SHiP-GEM test beam.*

Figure 6: *Small RPC chambers with the same resistivity as the OPERA RPCs ready to be tested at the LNF irradiation facility .*

2.4 Test at high-rate of the OPERA RPCs

Groups involved: INFN-Napoli, INFN-Bari, Laboratori Nazionali del Gran Sasso, LNF.

The muon magnetic spectrometer of the tau-neutrino detector is described in Section 4.3 of the Technical Proposal. The SHiP collaboration is currently evaluating the possibility to reuse one of the two OPERA magnetic spectrometers that will be dismounted in 2016. These are based on magnetized iron and RPCs. However the SHiP RPCs have to operate in a muon flux of $\sim$4 kHz/m^2, which is almost two orders of magnitude higher than the typical counting rate in OPERA. Hence a "high-rate" test of these chambers is mandatory.

The LNF group in 2015 has built new small RPC chambers, (10×10) cm^2 wide: two OPERA-like chambers (electrodes 2 mm thick of resistivity $> 5 \cdot 10^{11}$ Ω cm) and four chambers with electrodes 1 mm thick and low resistivity ($5 \cdot 10^{10}\Omega$cm), developed for high rate applications. These chambers, shown in Figure 6, will be tested in the brand new irradiation facility at LNF as soon as the gas system is finalized (March 2016). After the end of the CNGS run, the flushing of the OPERA RPCs with pure Nitrogen at 30% relative humidity started aiming at recovering the original resistivity value. A few OPERA RPCs are expected to be tested at LNF in 2016 after being dismounted. In case they would turn to be not adequate to the muon rates, new chambers with lower resistivity will be possibly developed in Naples/Bari.

3 List of Conference Talks by LNF Authors

No talks were given this year by LNF authors.

References

1. 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].

2. S. Alekhin *et al.*, *A facility to Search for Hidden Particles at the CERN SPS: the SHiP physics case*, CERN-SPSC-2015-017, arXiv:1504.04855 [hep-ph].

3. A. Andreazza *et al.*, *What Next: White Paper of the INFN-CSN1*, Frascati Phys. Ser. 60 (2015) 1-302, (2015-05-29).

4. M. Anelli *et al.* (SHiP collaboration), *Addendum to the Technical Proposal*, CERN-SPSC-2015-016, SPSC-P-350-ADD-2.