SHiP-LNF: 2016 Status Report

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1 Status of the SHiP project

The main achievements in 2016 of the overall SHiP project are the following:

1. the CERN Research Board in March 2016 recommended the SHiP Collaboration to proceed towards a Comprehensive Design Study to be used as input of the European Strategy Group in 2019-2020;
2. the SHiP Project has been recognized as official CERN project and it is now officially represented in the CERN greybook;
3. the SHiP beam line, target, experimental hall and related infrastructure is now considered as a project stand-alone, called Beam Dump Facility (BDF), under CERN responsibility. This project is now separated from the SHiP Detector that is under responsibility of the SHiP Collaboration.
4. the CERN Medium Term Plan 2017-2021 allocated resources for the R&D of the BDF: about ~ 4 MCHF and ~ 10 FTE, currently increasing with additional CERN fellows;
5. the SHiP project is one of the major projects currently discussed in the framework of the Physics Beyond Colliders working group, setup by the CERN Director General for studying physics opportunities at the CERN accelerator complex beyond the physics topics that can be studied at colliders, see http://pbc.web.cern.ch. G. Lanfranchi is one of the permanent members of the Beyond Standard Model physics working group of the Physics Beyond Colliders activity.

2 Activities of the LNF group

The Frascati group in 2016 continued to work along the directions presented in the 2015 activity report:

1. physics and simulation;
2. R&D of the muon system and related electronics;
3. R&D of a high-spatial resolution tracker based on GEM/μ-RWELL technology for the tau neutrino detector;
4. tests of the OPERA RPCs, for a possible their re-use in the muon system of the tau neutrino detector.

For each item we report here below a short description of the 2016 activity.

2.1 Physics and Simulation

The study of the hidden scalar sector has been documented in Section 5.2.5 of the Technical Proposal [1] and in Section 3 of the Physics Proposal [2]. This work has been done by LNF authors together with some theorists and has been described in the 2015 activity report.

The work performed in 2016 has been mostly focused on 1) the optimization of the SHiP geometry with the goal of maximizing the acceptance for light scalar particles; 2) the impact of the background on the SHiP sensitivity. The main results of this study have been summarized in the SHiP Public note CERN-SHiP-NOTE-2017-001 and are reported briefly here below.

The SHiP experiment has a large potential to discover (or set exclusion limits for) a light scalar particle mixing with the Higgs in a still poorly covered region of the parameters space. In 5-years of operation with $2 \cdot 10^{20}$ protons on target, SHiP can improve by few orders of magnitude over the LHCb results between the $2m_\mu$ threshold and ~ 5 GeV. In 2016, the dependence of the sensitivity as a function of the distance of the vessel from the target and as a function of the decay vessel length has been studied. The results can be summarized as follows: 1) no sizeable change in sensitivity is expected by reducing the vessel length from 60 m to 40 m (see Figure 1, left), while a gain in sensitivity up to a factor of two is achieved when the distance between the target and the vessel is reduced from 68.8 m to 20 m (see Figure 1, right).

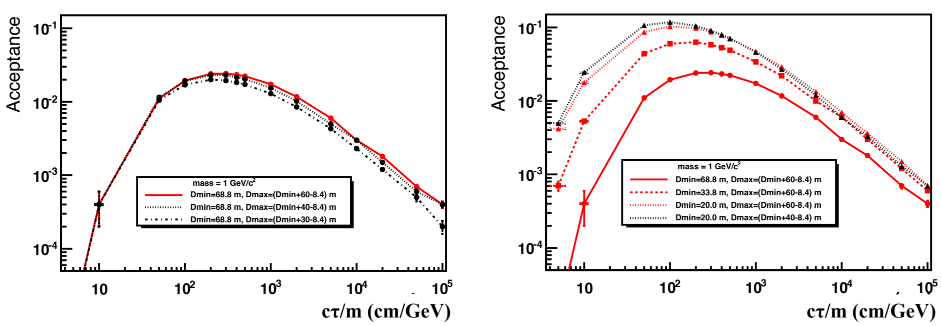

Figure 1: Left: acceptance as a function of $c\tau/m$ for three different values of the vessel length, L=60, 40, and 30 m. Right: acceptance as a function of $c\tau/m$ for different distances of the decay vessel from the target, $D_{\rm min}$ = 68.8, 33.8 and 20 m and for the nominal length of the vessel $L = 60$ m. For $D_{\rm min} = 20$ m the acceptance is computed also for $L = 40$ m.

While SHiP has being designed to be a *zero background* experiment, the impact of a hypothetical background on the sensitivity has been studied. For 2-track final states, 200 background events uniformly distributed in the full mass range reduce the 90% CL exclusion limit to up to 40%, and the 3σ sensitivity curve by up to a factor of two, depending on the values of the mass and coupling parameter. Figure 2 shows the SHiP sensitivity in absence of background (right) and in presence of 200 background events uniformly distributed in the mass range 200-4800 MeV/c^2 (left).

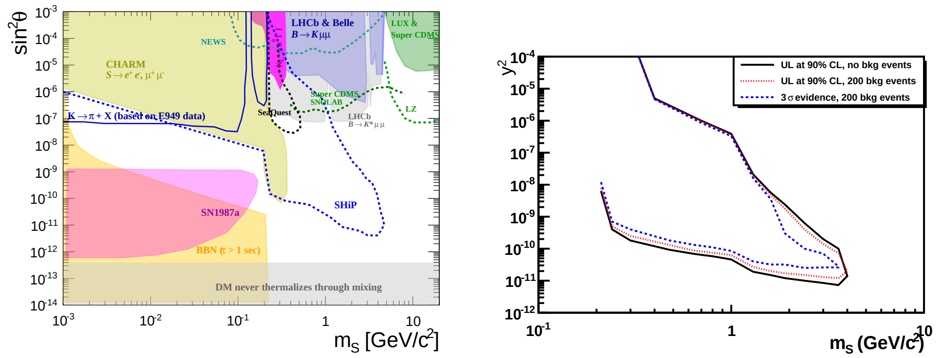

Figure 2: Left: Sensitivity contours for a light scalar particle mixing with the Higgs in the plane $\sin^2\theta$ versus mass. Shaded areas are already excluded parameters regions by past experiments, dotted lines are sensitivities of planned experiments. The SHiP sensitivity corresponding to $N_{\mathrm{pot}} = 2 \cdot 10^{20}$ is shown as the blue dotted line. Right: 90% CL upper limit in absence of background (black solid line), 90% CL upper limit with 200 background events (red dotted line), $3\,\sigma$ evidence with 200 background events uniformely distributed in the mass range 200 - 4800 MeV/c^2 (blue dashed line).

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

Groups involved: INFN-Bologna, INFN-Ferrara, INFN-Cagliari, LNF, INR, MEPhY;
G. Lanfranchi co-Project Leader (with Yuri Kudenko, INR)

The Muon System is described in Section 4.11 of the SHiP Technical Proposal. 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.

A two-weeks long test beam has been performed at the T9 area of the CERN PS in 14-28 October 2015. The analysis of the data was performed in 2016 and a paper summarizing the results has been accepted by JINST for publication in January 2017. Here below we summarize the main results.

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). Table 1 and Table 2 show the main parameters of scintillating bars from NICADD and Uniplast manufacturers, respectively. The results obtained at the test beam can be summarized as follows:

- *Light yield:* the total light yield for the three 3m-long bars from NICADD company goes from ~ 50 p.e. for bar 3m-long, 1cm-thick with 1.2 mm diameter fiber, to more than 150 p.e. for a bar 3 m long, 2cm thick and instrumented with 2mm diameter fibers. The light yield for 3m-long bars from the Uniplast company is more than 60 p.e. for 3m-long, 0.7cm thick and 3 cm wide bars and more than 50 p.e. for 3m-long, 0.7cm thick and 5 cm wide bars.

- *Efficiency:* an efficiency $\epsilon > 99.5\%$ has been measured for 3m long, 0.7 cm thick and 5 cm wide bars.

- *Time resolution:* a time resolution of ∼800 ps, constant along the bar length has been measured for the best NICADD bar, (3m long, 2cm thick and 5cm wide); similar results have been found for the best Uniplast bar, (3m long, 0.7cm thick and 3cm wide).

In general all the results are very good and fully compliant with the Technical Proposal specifications. A new test beam is scheduled for October this year at the T10 area of the CERN PS to test more configurations.

Table 1: Prototypes of extruded scintillator bars from NICADD manufacturer. All the bars were instrumented with fibres Kuraray WLS Y11(200) S-type except the S2 bar that has been instrumented with fibres from the Saint Gobain company (BCF92). The fibres in the L1, L2 and L4 bars were read out at both ends. The fibres in the S1, S2, S5 and S8 bars were read out only at one end.

	Bar dimensions (h × w × l) mm^3	number of fibres/bar	fibre diameter [mm]	SiPM model (AdvanSiD company)
L1	(10 × 45 × 3000) mm^3	1 fibre in 1 groove	2	ASD-NUV3S-P
L2	(20 × 40 × 3000) mm^3	1 fibre in 1 groove	2	ASD-NUV3S-P
L4	(20 × 40 × 3000) mm^3	1 fibre in 1 groove	1.2	ASD-NUV1S-P
S1	(10 × 45 × 250) mm^3	2 fibres in 1 groove	1.2	ASD-NUV3S-P
S2	(10 × 45 × 250) mm^3	2 fibres in 1 groove	1.2	ASD-NUV3S-P
S5	(20 × 40 × 250) mm^3	2 fibres in 1 groove	1.2	ASD-NUV3S-P
S8	(20 × 40 × 250) mm^3	1 fibre in 1 hole	2	ASD-NUV3S-P

Table 2: Prototypes of extruded scintillating bars from UNIPLAST manufacturer. All the bars were instrumented with fibres Kuraray WLS Y11(200) S-type. In the bars U1, U2 and U3 the fibres were read out at both ends, in the U4 bar the two fibres were read out just at one end, opposite with respect to each other.

	Bar dimensions (h × w × l) mm^3	number of fibres/bar	fibre diameter [mm]	SiPM model (Hamamatsu company)
U1	(7 × 30 × 3000) mm^3	1 fibre in 1 groove	1	MPPC S13081-050CS
U2	(7 × 50 × 3000) mm^3	1 fibre in 1 groove	1	MPPC S13081-050CS
U3	(7 × 100 × 3000) mm^3	2 fibres in 2 grooves	1	MPPC S13081-050CS
U4	(7 × 100 × 3000) mm^3	2 fibres in 2 grooves	1	MPPC S13081-050CS

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

Groups involved: INFN-Napoli, INFN-Bari, INFN - Gran Sasso, LNF(IT), INFN-Rome, Nagoya University (Japan) , Nihon University (Japan), Aichi University (Japan), Kobe University (Japan), Toho University (Japan), MSU (Russia), Lededev Institute (Russia), NRC KI (Russia), Gwangju (Korea), **LNF for the GEM/rWELLS option.**

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 spatial resolution on both coordinates (also considering the coupling with the emulsions) and high efficiency ($> 99\%$) for angles up to 1 rad.

The combined test of the detector composed by emulsion films and triple-GEM prototype was performed in October 2015 at the CERN SPS on the H4 beam line. A picture of the detector installed on the H4 line is shown in Figure 3.

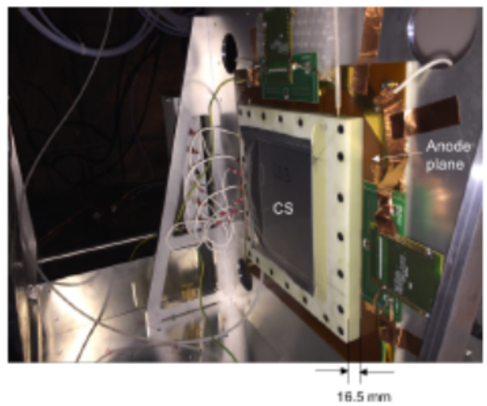

Figure 3: *GEM and emulsion foils (CS) detector installed on the H4 test beam area .*

The GEM-Emulsion detector was exposed to 150 GeV/c muons produced mainly by the decay of pions coming from the interaction of a 400 GeV/c primary proton beam extracted from the SPS onto the T2 primary beryllium target. The spatial resolution of the GEM chamber was measured as a function of the angle with respect to the beam and of the magnetic field polarity. The required field of 1 T strength was supplied by the Goliath Magnet, located inside PPE134 zone. A triple GEM was placed inside the magnet cavity on a rotating platform to perform exposures at different angles. At 16.5 mm from the GEM anode, on its upstream surface, an emulsion doublet was attached, as shown in Figure 3.

In total three sets of exposures were made: one at B = 0 T, one at B = 1 T and one at B = -1 T. In each exposure the GEM-Emulsion detector was rotated so to meet the muon beam at different angles: $0°$, $7.5°$, $15°$, $30°$, $45°$. This allowed to test the matching between the emulsion and the GEM detector in different experimental conditions. Given the micrometric accuracy of the emulsion detector, the resolution of the GEM-Emulsion detector is fully dominated by the GEM resolution.

The measured GEM spatial resolution ranges from $\sigma = (54 \pm 2)$ μm at zero angle in absence of magnetic field up to $\sigma = (369 \pm 36)$ μm at $\phi = 15°$ with negative polarity of the field (B = -1 T). As expected, the best result is obtained without magnetic field and with a zero incident angle of the beam on the detector. In absence of magnetic field, with inclined tracks, the spatial resolution degrades of a factor 2 every $\sim 10°$. Instead, when introducing the magnetic field, the resolution degrades of a factor 2 every $\sim 5°$, hence a factor 2 faster. When inverting the field polarity, there is a partial compensation of the Lorentz angle that becomes complete at $15°$ where the resolution is compatible with the one obtained with perpendicular tracks and no magnetic field. However, for incident angles larger than $15°$, a significant degradation is observed reaching $\sigma = (320 \pm 40) \mu$m at $\phi = 45°$. The resolution at $\phi = 0°$ and B =0 T complies with the needs of the SHiP experiment. The degradation of the resolution for inclined tracks spoils significantly the performances of the GEM detector. Nevertheless the implementation of micro-TPC mode algorithm for the reconstruction of tracks in the GEM detector is expected to improve considerably the spatial resolution also for inclined tracks and in presence of magnetic field. *A paper summarizing the results is in preparation.*

2.4 Test of the OPERA RPCs

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

In the SHiP TP [1] we proposed to re-use one of the OPERA spectrometers (magnet and RPCs) assuming a muon rate originated from the dump of 3-4 kHz/m^2.

The OPERA RPCs (bakelite resistivity $> 5 \cdot 10^{11} \Omega \cdot$ cm) were operated in streamer mode in a low rate environment (20 Hz/m^2) inside the OPERA Magnets (sandwich of iron slabs and RPCs). In order to operate the chambers at surface level, a new electronics was developed in BARI for the NESSiE experiment able to cope with a rate of $\sim$1 kHz/m^2. A modified version (SHiP-like) of this electronics has been used for our tests at LNF. The goal of this activity is to test RPCs dismounted from OPERA, validate their functionality and study their performance in streamer mode with a particle rate of 3-4 kHz/m^2. For this last study a test-beam at the CERN GIF is foreseen.

Test of RPCs dismounted from the OPERA detector

A full RPC layer (21 chambers) dismounted from OPERA has been tested @LNF in October 2016: 11 chambers showed mechanical damages (broken gas inlets) likely produced during dismounting. Of the remaining 10, 8 have been tested at LNF with cosmic rays: the efficiency plot is shown in Figure 4, left. Three RPCs (out of eight) showed a global efficiency lower than 95% at plateau, the inefficiency being localized in few regions.

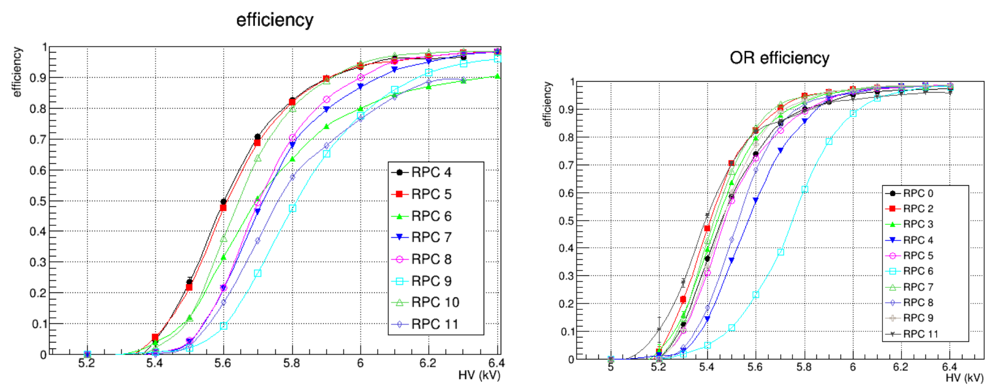

Figure 4: *Efficiency of the RPCs dismounted from the OPERA experiment (left) and efficiency of the spare RPCs of the OPERA experiment tested in the LNF test stand .*

Test of "spare" RPCs from OPERA production

Twenty out of about 200 chambers not installed in OPERA, have been also tested at LNF. In this case no mechanical damage has been observed. In principle they would be sufficient to build the SHiP spectrometer in the final configuration. On this set of chambers a good efficiency has been measured in LNF test stand, as shown in Figure 4, right.

However, the initial counting rate (muons) expected used in the TP was of 4-5 kHz/m^2. The update of the simulation brought this value up to 100 kHz/m^2; in addition the neutrino-tau detector is currently expected to be placed closer to the target than originally thought, therefore the rate is expected to further increase. This means that there is no way to re-use OPERA RPCs if operated in *streamer mode*. A possibility could be to re-use the OPERA RPCs in *avalanche mode*, and for this purpose a test is foreseen in 2017 at the GIF++ facility at CERN (in collaboration with the CMS Bari RPC group). Two chambers 10×10 cm^2 wide with resistivity OPERA-like have been assembled at LNF for this reason, as shown in Figure 5.

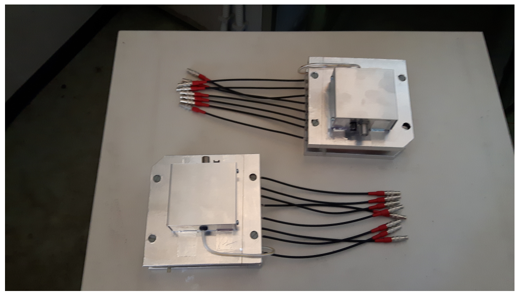

Figure 5: *Small RPC prototypes with the same resistivity as the OPERA RPCs built at LNF and ready to be tested at the GIF++ .*

3 Talks and Publications

Talks:

- A. Paoloni, *Gas mixture studies for streamer operated RPCs*, XIII Workshop on Resistive Plate Chambers and Related Detectors (RPC 2016), Ghent, February 22-26 2016;
- A. Paoloni, *L'esperimento SHiP all'SPS del CERN*, IFAE, Genova, March 2016
- G. Lanfranchi, *SHiP sensitivity to Dark Photons decaying to visible final states*, Dark Sector Workshop, SLAC, 28-30 April 2016.

Publications:

- J. Alexander et al. (G. Lanfranchi among the authors), *Dark Sectors 2016 Workshop: Community Report*, arXiv:1608.08632, proceedings of the SLAC 2016 Dark Sector Workshop.
- W. Baldini, A. Blondel, A. Calcaterra, R. Jacobsson, A. Khotjantsev, Yu. Kudenko, V. Kurochka, G. Lanfranchi, A. Mefodiev, O. Mineev, A. Montanari, E. Noah Messomo, A. Saputi, N. Tosi, *Measurement of parameters of scintillating bars with wavelength-shifting fibres and silicon photomultiplier readout for the SHiP Muon Detector*, arXiv:1612.01125, accepted by JINST for publication;
- A. Paoloni, A. Longhin, A. Mengucci, F. Pupilli, and M. Ventura, *Gas mixture studies for streamer operated RPCs*, Journal of Instrumentation vol.11 (2016) C06001 (proceedings of RPC 2016);
- A. Paoloni, *L'esperimento SHiP all'SPS del CERN*, proceedings di IFAE, to appear on Nuovo Cimento.

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