SHiP-LNF: 2018 Status Report

M. Anelli (Tecn.), G. Bencivenni, M. Bertani, A. Calcaterra,
P. Ciambrone, G. Felici, G. Lanfranchi (Resp.), A. Saputi (Tecn.), F. Angeloni (Tech.), G. Papalino (Tech.)
with the external participation of: A. Paoloni, M. Poli-Lener, G. Morello and M. Giovannetti

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 2018 are:

- **SHiP inputs to the ESPP**
  The SHiP collaboration has prepared for the ESPP two extensive documents, one about the status of the experiment, the *Comprehensive Design Study Status Report*, and one about the status of the Beam Dump Facility (BDF). These documents are listed below in the *SHiP Publication list, n.1 and n.2.* A much longer and detailed report ($\sim$ 500 pages) on the BDF will be published as a CERN Yellow Report. SHiP has also actively contributed to the preparation of the *Summary Report of the BSM Working Group of the Physics Beyond Colliders activity* (*Publication list, n.3*, G. Lanfranchi main author), where the SHiP physics performance have been compared to the physics performance of a multitude of existing or proposed experiments aiming at searching feebly-interacting long-lived particles at CERN or elsewhere in the world. G. Lanfranchi has been invited to be part of the *Physics Preparatory Group for the ESPP Symposium in Granada*, as experimental expert of feebly-interacting long-lived particles.

- **The SHiP Comprehensive Design Study (CDS)**
  The published *SHiP Comprehensive Design Study Status Report* is an intermediate step towards a more complete document, *The SHiP Comprehensive Design Study (CDS)* which will describe in detail the SHiP detector design, including involved institutions, project planning and cost. The CDS document has been requested by the SPS Committee and it must be ready by the end of 2019. To this aim, the SHiP collaboration has performed a thorough R&D during 2018 and the LNF group has actively participated to it, as described below.

2 Activities of the LNF group

In 2018 the Frascati group continued to work along the directions presented in the 2016 and 2017 SHiP LNF Status Reports, namely:

1. R&D of the muon system and related electronics;
2. R&D of a high-spatial resolution tracker based on μ-RWELL technology for the tau neutrino detector;
3. Design and engineering of the two systems.

For each item we report here below a short description of the 2018 activity.

R&D of Muon System and related electronics

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

The Muon System is described in Section 4.11 of the SHiP Technical Proposal [1] and comprises four stations of active layers interleaved by three muon filters 6 m wide and 12 m high. In 2017 we decided to choose as baseline technology *scintillating tiles with direct SiPM readout* instead of the *extruded plastic scintillator strips with wavelength shifter fibers and SiPM readout* that was discussed in the *2016 SHiP LNF Status Report* and summarized in a JINST paper [2].

The advantages of using tiles instead of strips are manyfold, as listed below:
1. factor of 3 or higher improvement in time resolution (due to the removal of the WLS fibers);
2. direct determination of the x, y coordinate with a single layer;
3. larger tolerance againsts hit rate variations;
4. easier construction and assembly.

Motivation of enhancing the muon system time resolution

The main source of background in SHiP are halo muons emerging from the target which are not swept out from the active filter. Random combinations of muons which enter the vacuum vessel, either by back-scattering in the surrounding cavern walls or due to imperfection of the muon shield, may mimic signal events. SHiP simulation shows that $\sim$26 kHz of muons are expected to enter the decay vessel during a single spill, which corresponds to about 8.5×10^{15} accidental muon pairs in 5 years of data taking. These muons are (almost) uniformly spread over the spill duration (1 sec). Hence the requirement to have muons in time within a tight time window is the major handle to reduce this rate. The muon detector with a combined time resolution of $\sim$ 200 ps can provide a suppression factor of 10^{10} on muons with increased robustness against low-energy hits (due to a 3-4 fold AND of stations) and already at the online level.

Prototypes of scintillating tiles with direct SiPM readout and test beam results

The first prototypes with scintillating tiles technology were built at LNF and Bologna already in 2017, as reported in the *"2017 SHiP LNF Status Report"*. They were tested during a 2-weeks long test beam performed at the T10 area of the CERN PS in the period 18-31 October 2017. The smaller tile ($7 \times 7 \times 0.6$ cm^3) showed an excellent time resolution of $\sim$ 200 ps, well beyond expectations. However the results obtained with the bigger tile ($7 \times 24 \times 1$ cm^3), whose size was more matching the requirements for the muon detector, were not conclusive. Therefore an extended R&D was planned for 2018 and two weeks of test beam at the T10 area of the CERN PS in October 2018 were granted by the SPS Committee. The 2018 test beam was also used to test different solutions for the front-end electronics.

The prototypes built in 2018 in Frascati and Bologna and tested at the 2018 test beam are:

1. a rectangular scintillating tile of $(10 \times 20 \times 0.8)$ cm^3 made of EJ200 scintillator (Eljen technology) and wrapped by aluminized Mylar (Figure 1). This tile is read out by 6 SiPMs, (4×4) mm^2 area, 50 μm pixels size, Hamamatsu, S14160, that serve as input to a customized ASIC chip (MUSIC chip, built by the Barcelona CCUB group) which provides amplified analog output for each single SiPM signal and for the analog sum of the 6 SiPMs. The waveforms of the analog ouputs (both for individual SiPMs and the analog sum) were then recorded using a 5 GS CAEN digitizer.

2. a set of squared scintillating tiles with various wrapping/coating material and different types

and position of the sipms. The two bigger tiles $(150 \times 150 \times 10)$ mm^3, with Teflon tape wrap, were read out by SiPMs mounted in two/four corners: ($2\times$ S13360 Hamamatsu 6×6 mm^2 and $4\times$ S13360 Hamamatsu 3×3 mm^2). These tiles were read out by a custom, single-channel fast (~ 1 GHz bandwidth) amplifier with custom design and by the SAMPIC digitizer developed at LAL-Orsay, operated at 3.2 GS/sec.

All tiles were exposed simultaneously to the beam on a moving frame (Figure 2) to study the time response as a function of the beam impinging point. The T_0 was provided by a pair of fast scintillators equipped with fast PMTs, with an intrinsic time resolution better than 100 ps. The time response of the rectangular tile for a beam impinging on a central position of the tile is shown in Figure 4 (left): after the subtraction of the T_0 time jitter, we find an intrinsic time resolution of ~ 280 ps, essentially with no dependence on the signal amplitude (Figure 4, right). The time resolution integrated on the central part of one of the two halves of the rectangular tile is shown in Figure 4: the excellent resolution of ~ 330 ps is due to the convolution of the intrinsic time resolution (larger component) and the time drift of the average of the distributions with the impinging point position.

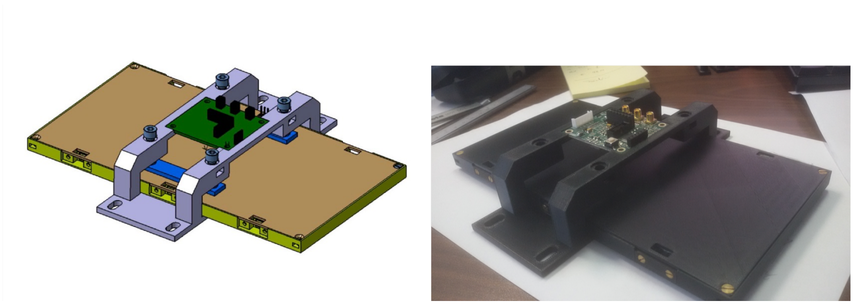

Figure 1: Design and realization of the $(10 \times 20 \times 0.8)$ cm^3 rectangular tile read out by 6 SiPM (6×6) mm^2 and the ASIC chip MUSIC, housed in the tile support.

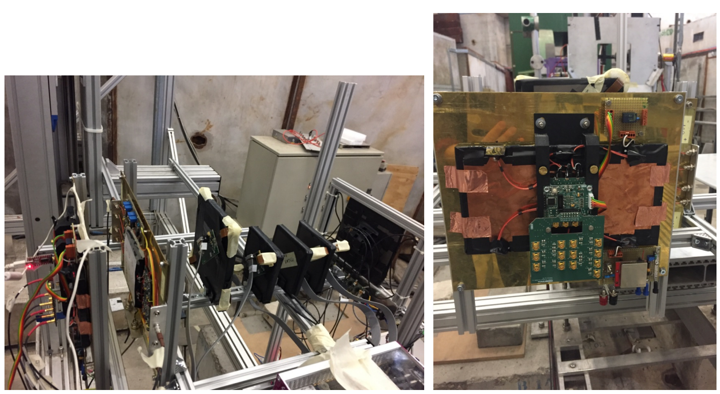

Figure 2: Left: all tiles designed and built at LNF/Bologna exposed simultaneously to the beam on a moving frame in the T10 area of the CERN PS, October 2018. Right: rectangular tile mounted on the moving frame.

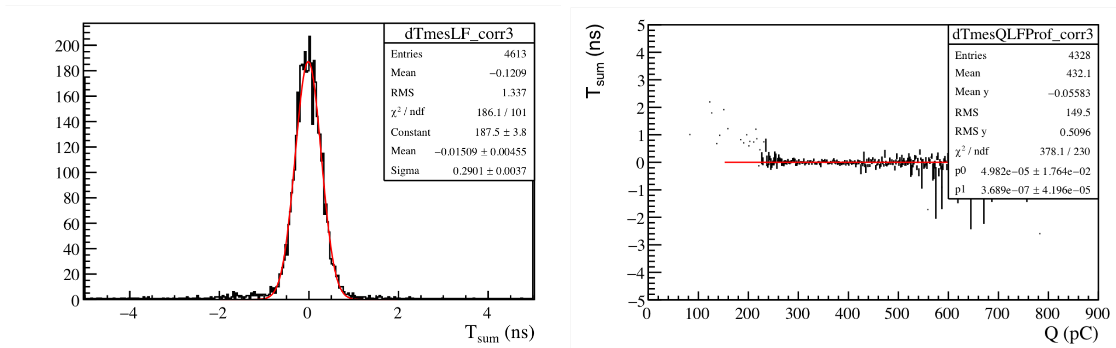

Figure 3: Intrinsic time response of the rectangular tile for a beam impinging on a central position of the tile (left) and time response dependence with the signal amplitude (right). After the subtraction of the T_0 time jitter, the rectangular tile has an excellent intrinsic time resolution of ~ 280 ps, with essentially no dependence on the signal amplitude.

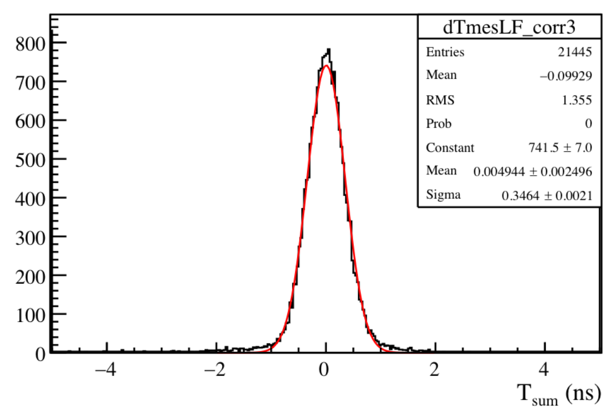

Figure 4: Time response of the rectangular tile averaged over the central points of one of the two halves of the tile. The time resolution is the convolution of the intrinsic response of the tile and the time-drift of time response distribution with the impinging point of the beam. After the subtraction of the T_0 time jitter, the rectangular tile has an excellent average time resolution of ~ 320 ps.

R&D of μ-RWELLS for the SHiP Target Tracker

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), Lebedev Institute (Russia), NRC KI (Russia), Gwangju (Korea), *LNF for the μ-RWELLS option.*

The Target Tracker (TT) is described in Section 4.2.2 of the Technical Proposal [1]. 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 detector 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 triple-GEM option was considered in 2015-2016 and the results discussed in the *SHiP LNF Status Report* in 2016 and recorded in a JINST paper published in 2017 [3]. However, given the request of large area detectors, the solution proposed in 2017 for the TT by the LNF group was based on the μ-RWELL [4] technology, (see *SHiPLNF Status Report 2017*) and a test beam was performed at the H8 area of the CERN SPS. In 2018 the analysis of the 2017 test beam was finalized with the aim of assessing the performance of the μ-RWELLS in magnetic field and with tracks with large impinging angle.

For tracks orthogonal to the detector the spatial resolution of a μ-RWELL, equipped with 400 μm strip pitch readout board, determined with the Charge Centroid (CC) method shows a minimum of about 50 μm for a DLC surface resistivity of about 100 MΩ/cm^2 [4].

The CC mode use the charge-weighted strip centroid, to reconstruct the track position on the anode readout. The micro-TPC mode is an alternative readout approach for MPGDs, firstly introduced by the ATLAS MicroMegas (MM) community [5], that exploits the combined measurement of the time of arrival and the amplitude of the induced signals on the strip readout. It improves resolution for particles with an incident angle to the detector greater than a few degrees.

In addition, when a magnetic field is present, the direction of ionization electrons inside the gas drift volume changes and the Lorentz force biases coordinate measurements and deteriorates resolutions. This effect is common to all MPGDs such as GEMs, rWells or MicroMegas, and can be corrected according to Montecarlo studies of the behaviour of the drift electron subject to the Lorentz angle.

$\mu-$RWELLS for SHiP Target Tracker: test beam results

Since one of the most stringent requirement for the TT in SHiP is a spatial resolution better than 100 μm on each coordinate up to angles as large as 1 rad, a combined test beam of μ-RWELLs operated in micro-TPC mode and a set of emulsion bricks was for the first time assembled and exposed to the muon beam of the H8-SPS at CERN. The $\mu-$RWELLS prototype coupled to the emulsion brick in the H8 area of CERN SPS is shown in Figure 5.

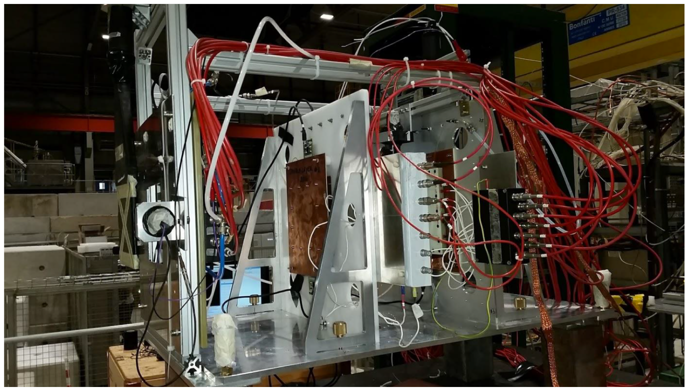

Figure 5: The $\mu-$RWELLS prototype coupled to the emulsion brick mounted in the H8 area of CERN SPS.

The experimental setup was made of:
1. two scintillators with PMT readout for triggering: S1 upstream and S2 downstream;
2. two tracking stations, G1 and G2 respectively about 0.5 m upstream and downstream w.r.t. the emulsion-bricks/μ-RWELL sandwich;
3. each tracking station consists of one triple-GEM chambers equipped with 650 μm 2-D (XY) pitch strip readout board;
4. two μ-RWELL were placed on a rotating platform at the center of the set-up to perform exposures at different angles. Each -RWELL was equipped with 400 μm 1-D pitch strip readout board, while the drift gaps were 6 mm wide.

During the combined data taking the two μ-RWELL have been sandwiched with two emulsion stacks. The two $\mu-$RWELLs have been operated in two different configurations:
1. with the two strip readout patterns parallel one to each other (parallel mode);
2. with the two strip readout patterns orthogonal one to each other, thus emulating a 2D (X-Y) readout (orthogonal mode).

The parallel mode has been used to perform the preliminary calibration of the detector measuring the spatial resolution in one view with both CC and micro-TPC mode calculating the difference of the track position reconstructed by the two prototypes. The orthogonal mode allowing the 2D reconstruction of the particle impact point has been exploited for the combined test with the emulsions. The emulsion detectors, characterized by a spatial resolution at level of few microns, have been used to finely extrapolate the particle impact position on the $\mu-$RWELLs by a global fitting the clusters inside the two emulsion stacks. The position reconstructed by the $\mu-$RWELL is determined by both CC and micro-TPC mode introducing in this case a T_0 signal needed for the correct positioning of reconstructed track segment in the drift gap.

Figure 6 shows the spatial resolution as a function of the track incidence angle, obtained in parallel mode operating the detectors with a the drift field $E_d = 0.5$ kV/cm. The black curve shows the results obtained with the CC method; the blue one the spatial resolution in micro-TPC mode while the red curve is a convolution of both methods. The CC-mode gives good results for orthogonal tracks (90°) while the micro-TPC as expected gives high performance for non-orthogonal tracks ($0° < \theta \leq 5°$). *Combining the two methods a spatial resolution of less than 60 μm could be achieved. This is an excellent result.*

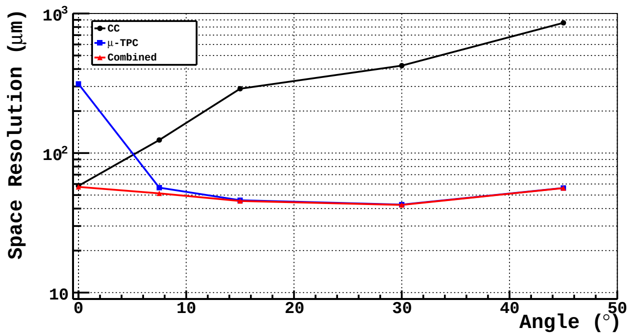

Figure 6: Spatial resolution of the μ-RWELL as function of the track incidence angle.

3 Talks and Publications

SHiP-LNF Talks

1. *Long-lived particles beyond colliders*, invited talk, LLP at the LHC workshop, Amsterdam, the Netherlands, November 2018.
2. *The Physics Beyond Colliders activity at CERN and the SHiP experiment*, invited talk at Particle Physics Advisory Committee of STFC, Birmingham, UK, October 2018.
3. *The SHiP experiment at CERN*, Dark Matter conference, plenary talk, Santander (Spain), June 2018
4. *Overview of the Physics Beyond Colliders BSM landscape*, Physics Beyond Colliders workshop, plenary talk, CERN, June 2018.
5. *Search for Hidden and Dark Objects with the SPS*, Voyages Beyond the Standard Model, invited talk, Raiatea (French Polynesia), February 2018.

SHiP-LNF Publications

1. SHiP collaboration (C. Ahdida *et al.*), *SHiP Experiment - Progress Report*, CERN-SPSC-2019-010, SPSC-SR-248.
2. SHiP collaboration (C. Ahdida *et al.*), *The experimental facility for the Search for Hidden Particles at the CERN SPS*, arXiv:1810.06880 [physics.ins-det], accepted by JINST.
3. Beacham *et al.*, *Physics Beyond Colliders: BSM Summary Report*, CERN-PBC-REPORT-2018-007, arXiv:1901.09966.
4. SHiP collaboration (C. Ahdida *et al.*), *Sensitivity of the SHiP experiment to Heavy Neutral Leptons*, arXiv:1811.00930 [hep-ph], submitted to JHEP.
5. SHiP collaboration, *The SHiP experiment and the RPC technology*, arXiv:1806.03890 [physics.ins-det], submitted to JINST.
6. SHiP collaboration, *Studies for the electro-magnetic calorimeter SplitCal for the SHiP experiment at CERN with shower direction reconstruction capability*, JINST **13** (2018) no.02, C02041.

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. W. Baldini, A. Blondel, A. Calcaterra, R. Jacobsson, A. Khotjantsev, Y. Kudenko, V. Kurochka, G. Lanfranchi, A. Mefodiev, O. Mineev, A. Montanari, N. Tosi, A. Saputi, E. Noah Messomo, *Measurement of parameters of scintillating bars with wavelength-shifting fibres and silicon photomultiplier readout for the SHiP Muon Detector*, *JINST* **12** (2017) no.03, P03005, e-Print: arXiv:1612.01125.

3. A. Alexandrov, G. Bencivenni, M. Bertani, A. Buonaura, C. Capoccia, G. Cibinetto, A. Calcaterra, G. De Lellis, E. De Lucia, A. Di Crescenzo, D. Domenici, R. Farinelli, G. Felici, N. Kitagawa, M. Komatsu, G. Morello, K. Morishima, M. Poli Lener, and V. Tioukov, *JINST* **12** (2017) no.09, P09001, e-Print: arXiv:1705.06635 [physics.ins-det].

4. G. Bencivenni *et al.*, *Performance of μ-RWELL detector vs resistivity of the resistive stage*, Nucl. Inst. Meth. A 886 (2018) 36-39, DOI: 10.1016/j.nima.2017.12.037 on-line version on http://authors.elsevier.com/sd/article/S0168900217314274.

5. T. Alexopoulos *et al.*, *Development of large size Micromegas detector for the upgrade of the ATLAS Muon system*, Nucl. Instrum. Meth. A 617 (2010) 161