SHADOWS-LNF: 2021 Status Report

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1 Status of the SHADOWS project

The year 2021 has been a transitional year from SHiP to SHADOWS, a proposed beam dump experiment to be installed *off-axis* in the ECN3 experimental hall of the CERN North Area complex. SHADOWS will use the 400 GeV primary proton P42/K12 beam line currently serving the NA62 experiment. The LNF group (together with Bologna and Ferrara) aims to build the muon system, using the same technology developed for the SHiP muon system (eg: scintillating tiles with direct sipms readout).

Formally the SHADOWS group is still not officially recognized by the INFN (even if a dedicated presentation has been already done in CSN1[1]), still a lot of activity has been done in 2021, in part in synergy with the ongoing activity in AIDA-Innova (Task 8.3.2, "Large area scintillator detectors") and in part as a stand-alone activity finalized to the submission of the Expression of Interest to the CERN SPS Committee, submission finalized in January 2022. The details of the work done in 2021 are summarized below.

1.1 SHADOWS: Expression of Interest

The SHADOWS Expression of Interest (EoI) 1) has been finalized during 2021 and submitted to the arXiv in October 2021 and to the CERN SPS Committee in January 2022. The goal is now to prepare a Technical Proposal to be submitted to the SPSC in about a year.

About 32 people signed the EoI, coming from the following Institutions:
INFN, Sezione di Ferrara; INFN, Laboratori Nazionali di Frascati; INFN, Sezione di Bologna; University of Lancaster, Lancaster (UK); University of Mainz (D); Royal Holloway, University of London (UK); CERN.

The main physics case of the SHADOWS proposal is the search for feebly-interacting particles (FIPs) emerging from the interaction of a 400 GeV primary proton beam extracted from the SPS with the high-Z material of a dump. The FIP mass range that can be optimally explored with SHADOWS is the range of the "familiar" matter, MeV-GeV, that is a range particularly motivated by models of light (MeV-GeV) dark matter, low scale seesaw models, and models with light and feebly-interacting scalars and pseudo-scalar particles (ALPs).

In the range of MeV-GeV, the strongest bounds on the interaction strength of new light particles with SM particles exist up to the kaon mass; above this mass the bounds weaken significantly. SHADOWS can do an important step into this still poorly explored territory and has the potential to discover them if they have a mass between the kaon and the beauty mass. If no signal is found, SHADOWS will push the limits on their couplings with SM particles between one and four orders of magnitude in the same mass range, depending on the model and scenario, opening new directions in model building. Examples of SHADOWS sensitivity for a light dark scalar mixing with the Higgs and an Heavy Neutral Lepton (HNL) with electron coupling are shown in Figure 1.

[1] see G.Lanfranchi, CSN1, July 2021, https://agenda.infn.it/event/27425/

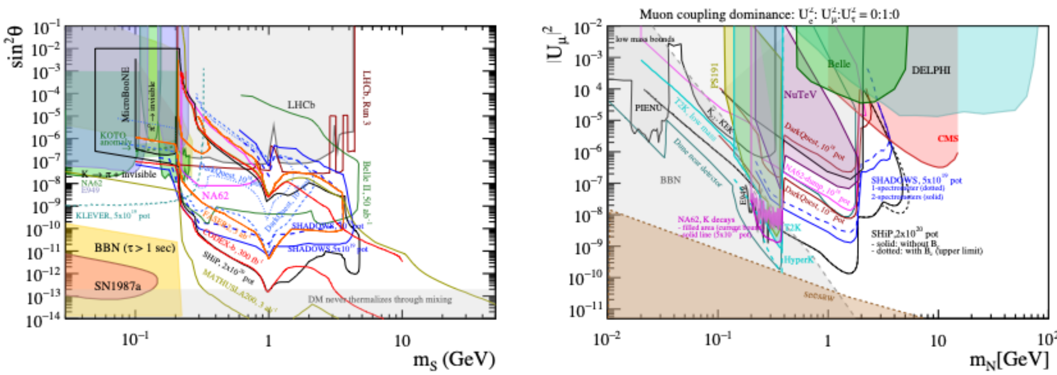

Figure 1: SHADOWS sensitivity for light dark scalar mixing with the Higgs (left) and HNL with electron coupling (right) compared to existing bounds (filled areas) and other proposed projects (solid curves).

A conceptual scheme of the SHADOWS detector is shown in Figure 2. It consists of a standard spectrometer, of 2.5×2.5 m^2 active area, placed off-axis with respect to the P42/K12 beam line and after 20 m in-vacuum decay volume which starts about 10 m downstream of the NA62 dump system (TAXes). The spectrometer comprises a tracking system, a timing detector, an electro-magnetic calorimeter, and a muon system. An upstream veto detector tags the residual beam-induced muon background in front of the decay volume.

The EoI presents a coincise summary of the proposed experiment. Section 2 explains why SHADOWS should be placed in the ECN3/TCC8 area currently hosting the NA62 experiment. Section 3 and Section 4 introduce the characteristics of the P42/K12 400 GeV proton beam line and the ECN3/TCC8 experimental complex, respectively. The main requirements for the detector are described in Section 5 and a description of the main detector components is provided along with suitable detector technologies in Section 8. The physics reach of the experiment for one and five integrated years of data taking is shown in Section 6 following the benchmarks proposed by the Physics Beyond Colliders BSM working group [2]. In Section 7 the most important beam-induced backgrounds are examined and a solution found for their reduction. A tentative schedule of the experiment is sketched in Section 9. Finally Section 10 draws the conclusions.

1.2 SHADOWS: synergy with AIDA-Innova, Task 8.3.2

The experimental activitiy of the LNF group within SHADOWS in 2021 has been carried on under the “umbrela” of AIDA-Innova, Task 8.3.2, *Large area scintillator detectors*, led by Alessandro Montanari (INFN-Bologna). This activity is carried on by LNF, Bologna, and Ferrara. LNF and Bologna received by AIDA-Innova about 27 kEuro in 2021 and almost the same amount is expected in 2022.

The main goal of the Task 8.3.2, is to build a full-size module of (15×15 cm^2) area scintillating tiles with direct silicon-photomultiplier (SiPM) readout for application to large area detectors with excellent ($\sim$250 ps) time resolution.

The main reasons for choosing organic scintillators are their fast response (short rise and decay times) and their high light yield. SiPMs provide advantageous properties such as good timing, compactness, and high photon detection efficiency. Hence: scintillating tiles with direct SiPM readout allows compact and cost effective detectors with high efficiency and excellent time

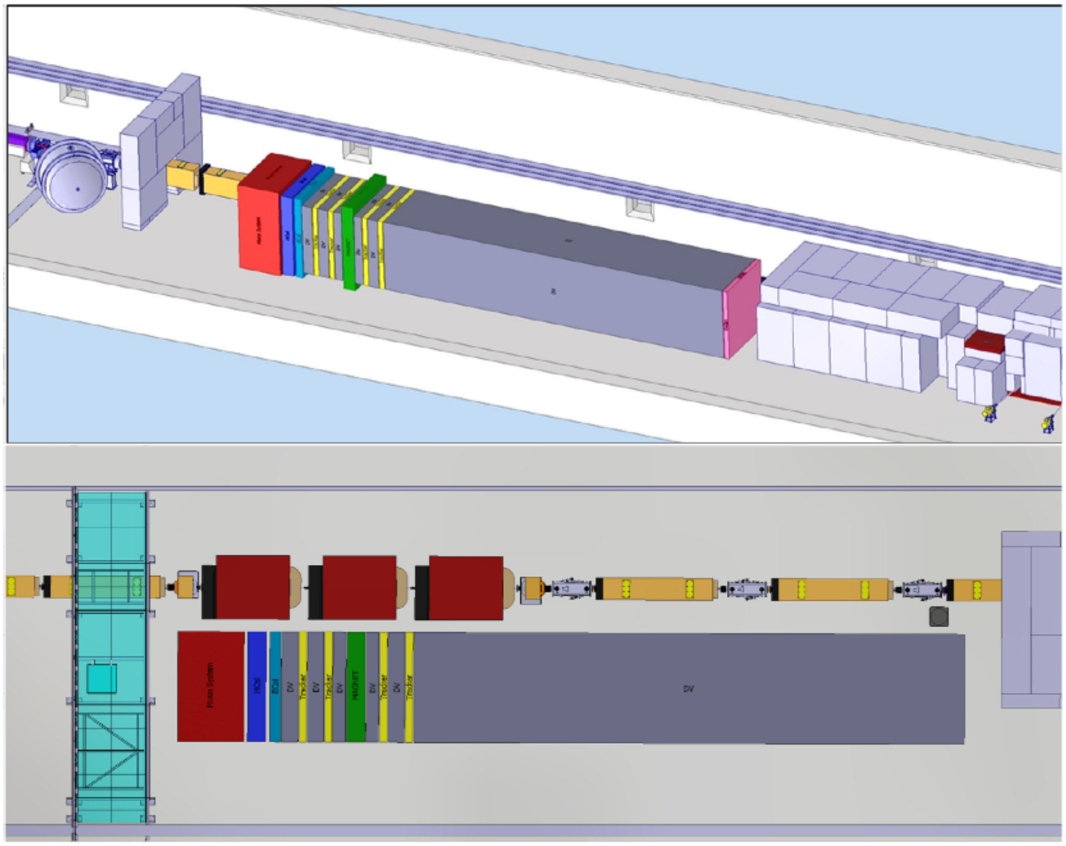

Figure 2: SHADOWS layout in the ECN3 experimental hall: 3D view (top) and top view (bottom).

resolution to be built.

A small prototype built in Bologna and Frascati consists of four tiles $(15 \times 15 \times 1)$ cm^3 of different types of scintillator (EJ200 or UNIPLAST) with four SiPMs (6×6 mm^2, S14160-6050HS Hamamatsu) engraved in slots at the four corners. The 4-tile small module is shown in Figure 4. The technical details of this prototype were discussed in the 2020 LNF Activity Report and will not be repeated here.

A customized front-end electronics (FEE) has been developed at LNF (Figure 3): the four SiPM are readout with individual preamplifiers followed by a common summing point. This is the best solution as it allows local SiPM signal amplification and the possibility of adjusting the readout chain shaping both at the input and at the summing point. The small module has been tested at a dedicated test beam held at the BTF in Frascati in January 2021. The data were throughly analysed during the first half of 2021 and the results, which fully satisfy the expectations, have been published on JINST, *A. Balla et al, JINST 17 (2022) 01, P01038, e-Print: 2109.08454 [physics.ins-det]*.

Levaraging on the good results obtained on the small module, with the money received in 2021 we are currently building two full scale modules, 16-tile each, with an improved FEE design and a new middle-end board, as interface between the FEE and the DAQ system. The technical layout of the full-size module is shown in Figure 5. Discussions are also ongoing between the

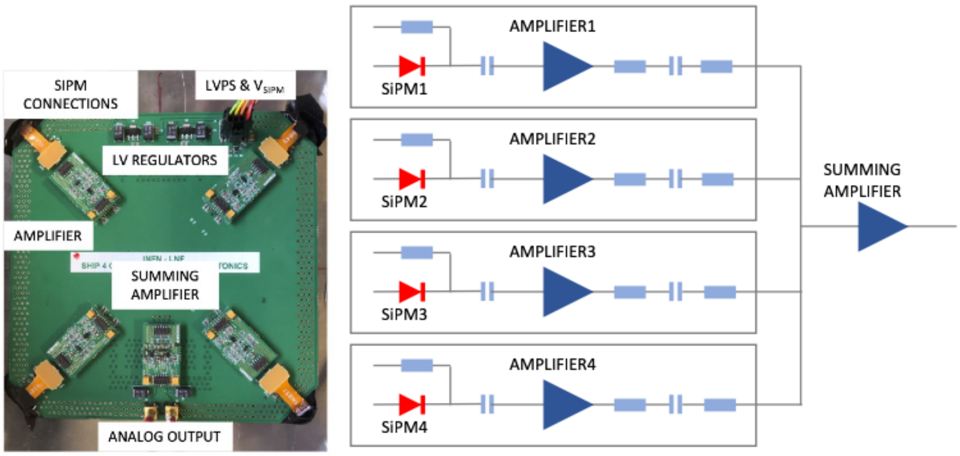

Figure 3: Picture of a fully instrumented tile (left) and its readout circuit block diagram (right).

electronic engineers in Frascati (Ciambrone, Felici) and Bologna (Lax and Torromeo) with the CERN group who will take care of designing and building the TDAQ system for SHADOWS to design the middle-end board in a way that can easily cope with the requirements of the overall TDAQ system of the experiment.

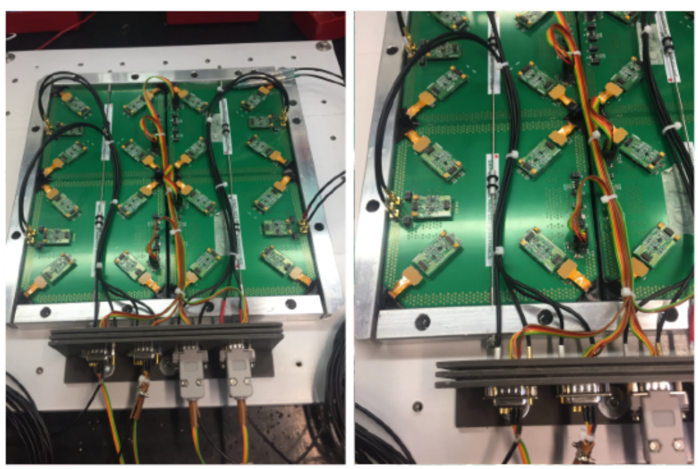

Figure 4: The minimodule: The four tiles tested at the test beam hosted in the light-tight supporting box that acts also as a Faraday cage.

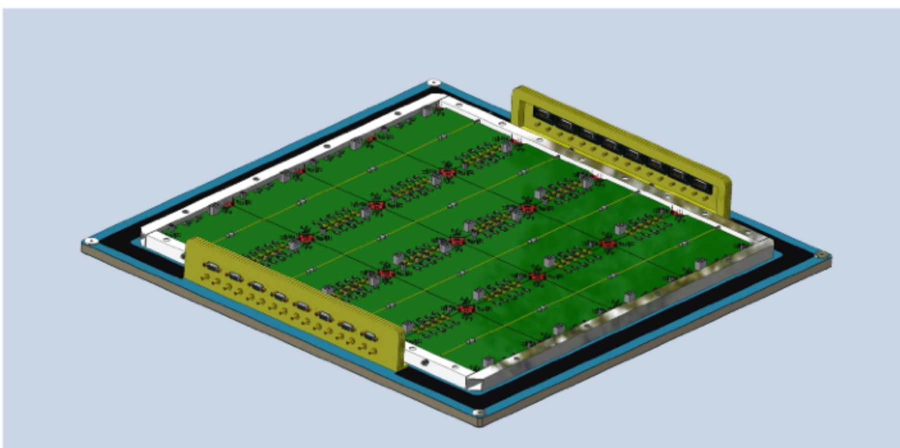

Figure 5: Layout of the full scale module under construction at LNF/Ferrara/Bologna.

1.3 SHADOWS: synergy with the LNF Accelerator Division

One of the most important issues in the SHADOWS project is the design of a magnetized iron block (MIB) able to sweeping away the beam induced muon background emerging from the dump. A preliminary study shows that with a super-simplified design (see Figure 6) the MIB can reduce the muon background at least of a factor of ten. A more refined design of the MIB is currently ongoing as a joint venture of CERN and LNF Accelerator Division people From LNF: Luca Foggetta and Alessandro Vannozzi from LNF have shown interest in participating to the study and initial discussiosn with the CERN people from the accelerator division have taken place in November 2021. More is expected in 2022.

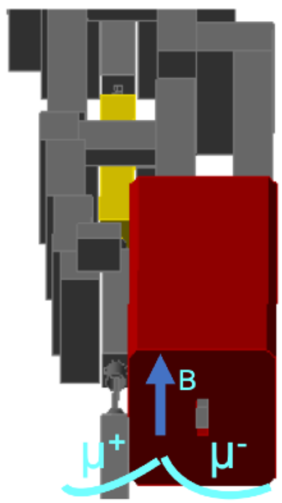

Figure 6: Preliminary Conceptual Layout of the Magnetized Iron Block.

2 Outlook

The work planned at LNF for 2022 consists of:

1. Construction and test of the two full-size modules for the muon system (with Bologna/Ferrara);
2. Optimization of the FEE and design of the first prototype of the middle-end board (with Bologna);
3. Optimization and design of the Magnetized Iron Block (MIB) (with CERN Accelerator Division);
4. Study of the beam-induced background in the SHADOWS area (data and Monte Carlo) (with Mainz, Royal Holloway, CERN, Lancaster);
5. Development of a full Monte Carlo package for the detector simulation (with Mainz group);
6. Finalization of the Proposal to be submitted to the SPSC by early 2023 (all groups).

3 SHADOWS-related Talks given by LNF people

1. *The SHADOWS project at CERN*, invited plenary talk, 10th Workshop of the LLP at LHC community, 9-12 Nov. 2021, CERN, virtual, https://indico.cern.ch/event/1042226/

2. *The Search for Feebly-Interacting particles: status and prospects*, invited Seminar, EPFL, Lausanne (Switzerland), October 28th, 2021. https://indico.cern.ch/event/1086046/.

3. *The SHADOWS project within the Physics Beyond Colliders activity at CERN*, invited Seminar, IJLab (Orsay, Paris) France, 18 October 2021, https://www.ijclab.in2p3.fr/en/seminaire/the-search-for-feebly-interacting-particles-with-the-shadows-project-within-the-physics-beyond-colliders-activity-at-cern-2/

4. *The SHADOWS project at the CERN SPS*, invited Seminar, University of Manchester, UK, 8 October 2021, https://indico.cern.ch/event/1053027/.

5. *Search for Dark Matter at accelerator-based experiments*, invited review talk, TAUP 2021, 31 August 3 September, 2021 Valencia (online), Spain, https://congresos.adeituv.es/TAUP2021/.

6. *Feebly-interacting particles: experimental landscape at accelerator-based experiments*, invited talk, XXI International Conference on High Energy Physics, Quarks-2020, Pereslavl Zalessky , Russia, (held online in June 2021), https://indico.quarks.ru/event/2020/overview.

7. *The search for feebly-interacting particles within the Physics Beyond Colliders activity at CERN*, LNF Seminar, 10 June 2021, https://agenda.infn.it/event/27261/

8. *The SHADOWS project to search for Feebly-Interacting Particles at CERN*, LNF seminar, 10 June 2021, https://agenda.infn.it/event/27261/

9. *The Search for Feebly-Interacting Particles in the new PBC activities*, Physics Beyond Colliders Annual Workshop, (online), plenary talk, 1-4 March 2021, https://indico.cern.ch/event/1002356/.

10. *The SHADOWS project*, Physics Beyond Colliders Annual Workshop, (online), invited talk, 1-4 March 2021, https://indico.cern.ch/event/1002356/.

11. *The Physics Beyond Colliders activity at CERN*, invited Colloquium at Lawrence Berkeley National Laboratory (LBNL) (Berkeley, US), June 17th (done online).

12. *The Search for Feebly-Interacting Particles: the landscape of particle physics and opportunities at SHADOWS and NA62* Invited Seminar at the CERN Beam Department, 23 March 2021, https://indico.cern.ch/event/1019523/

4 SHADOWS-related Workshops/Conferences organized by LNF people

- G. Lanfranchi has been in the Organizing Committee of the first Annual Workshop of iDMEu, Initiative for DM in Europe and beyond, online, 10-12 May 2021, https://indico.cern.ch/event/1016060/ (about 300 participants).

5 SHiP/SHADOWS-related publications in 2021

1. P. Agrawal *et al.*,*Feebly-interacting particles: FIPs 2020 workshop report* Eur.Phys.J.C 81 (2021) 11, 1015, e-Print: 2102.12143 [hep-ph]

2. C. Ahdida et al. (SHiP collaboration), *Track reconstruction and matching between emulsion and silicon pixel detectors for the SHiP-charm experiment*, e-Print: 2112.11754 [physics.ins-det]

3. C. Ahdida *et al.* (SHiP collaboration), *The SHiP experiment at the proposed CERN SPS Beam Dump Facility*, e-Print: 2112.01487 [physics.ins-det]

4. W. Baldini *et al.*, *SHADOWS (Search for Hidden And Dark Objects With the SPS): Expression of Interest*, e-Print: 2110.08025 [hep-ex],CERN-SPSC-2022-006 ; SPSC-EOI-022.

5. A. Balla *et al.*, *Performance of scintillating tiles with direct silicon-photomultiplier (SiPM) readout for application to large area detectors*, JINST 17 (2022) 01, P01038, e-Print: 2109.08454 [physics.ins-det]

6. C. Ahdida *et al.* (SHiP collaboration), *Sensitivity of the SHiP experiment to dark photons decaying to a pair of charged particles*, Eur.Phys.J.C 81 (2021) 5, 451 e-Print: 2011.05115 [hep-ex]

7. C. Ahdida *et al.* (SHiP collaboration) *Sensitivity of the SHiP experiment to light dark matter*, JHEP 04 (2021) 199, e-Print: 2010.11057 [hep-ex]

References

1. W. Baldini *et al.*, *SHADOWS (Search for Hidden And Dark Objects With the SPS)*, arXiv:2110.08025 [hep-ex]; CERN-SPSC-2022-006 ; SPSC-EOI-022; https://cds.cern.ch/record/2799412?ln=en.

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.