The SHADOWS Experiment

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ON BEHALF OF THE SHADOWS COLLABORATION

VIENNA CONFERENCE OF INSTRUMENTATION 21-25 FEB 2022

What is SHADOWS?

SHADOWS *(**S**earch for **H**idden **A**nd **D**ark **O**bjects **W**ith the **S**PS)* is a new experiment proposed at CERN within the Physics Beyond Colliders Program to search for a large variety of Feebly interacting Particles (FIPs) produced in the interaction of a proton beam with a dump.

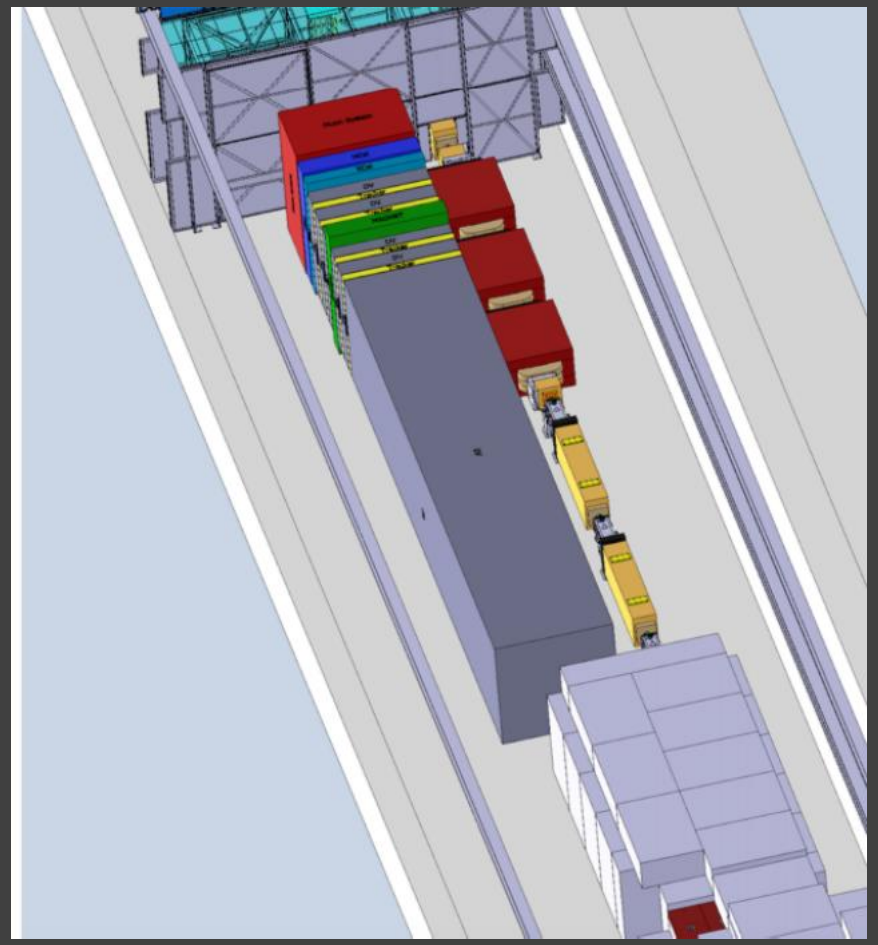
FIPs are neutral particles (scalar, vector…) with effective couplings << 1.
Prominent examples are:

- *Axions* and *Axion-like* particles;
- *Heavy Neutral Leptons*;
- *Light dark scalars.*

These particles can be originated from the decay of Beauty, Charm and Strange hadrons, and from photons produced in the interaction of protons with a target.

- FIPs coupling to SM particles is very suppressed -> expected production rates of 10^-10 or less
- Charm and Beauty cross-section steeply increase with energy

→ a high energy and high intensity proton beam, such as the CERN SPS proton beam, is required to improve over the current results.



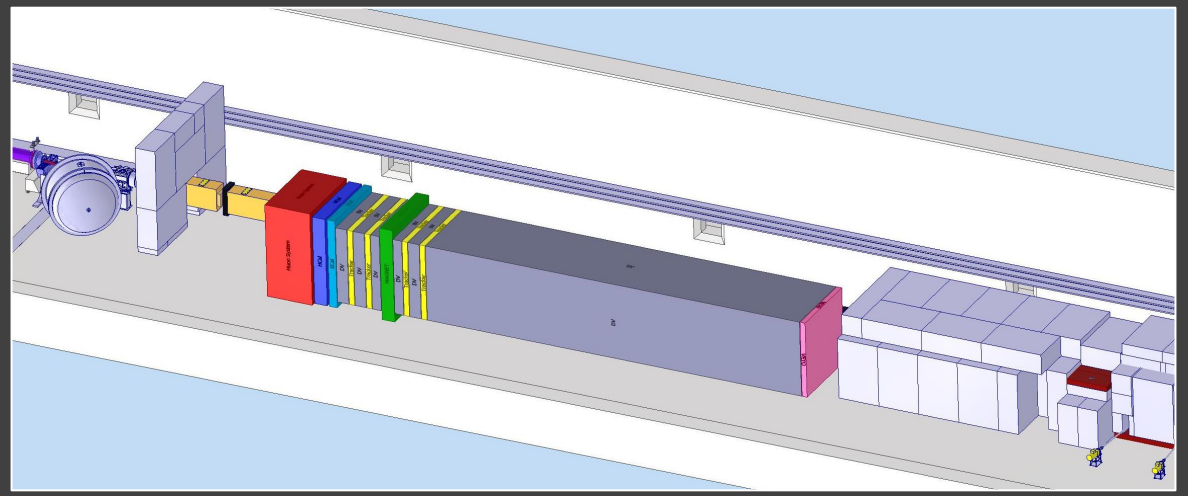
the SHADOWS experiment

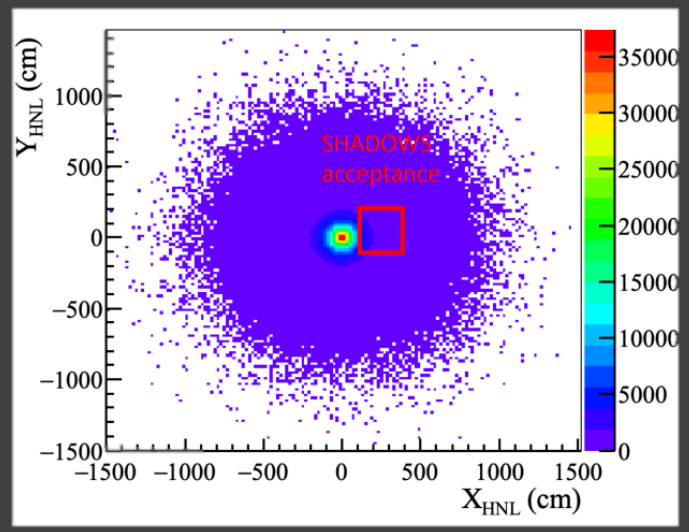
Detector concept

Due to their very small couplings, FIPs are naturally long-lived.
The optimal detector for FIPs at a proton beam dump is made of a series of spectrometers, each preceded by an empty decay volume whose length is a function of the spectrometer transverse dimension.

At the SPS center of mass energy hadrons are produced with a small boost. Therefore, FIPs emerging from their decays can have a large polar angle.
If the series of spectrometers is placed off-axis the loss in acceptance is mitigated by a large background reduction with respect to an on-axis setup.

Preliminary Conceptual Layout: A spectrometer of about 2.5x 2.5 m2 transverse area starting at ~1-1.5 m off-axis from beam line 20 m long decay volume, starting ~10 m downstream of the NA62-dump.





Heavy Neutral Lepton illumination at the SHADOWS tracking plane

TCC8/ECN3 experimental area

This feature opens up the possibility of installing SHADOWS off-axis in the TCC8/ECN3 experimental area at CERN where the NA62 experiment is hosted, and taking data concurrently with the latter during its operation in beam-dump mode.

Background reduction

It is critical to have very low (or no) background in such an experiment.

The magnetic muon sweeping system:

Off-axis muons are typically made of low-momentum (<20 GeV) tracks. Low-p muons can be swept away using a magnetic field in a magnetized iron block after the dump, where they are still concentrated in a small area.

Magnetized iron block for muon background sweeping
maximum field value of 1.7 T/m, ~5m length

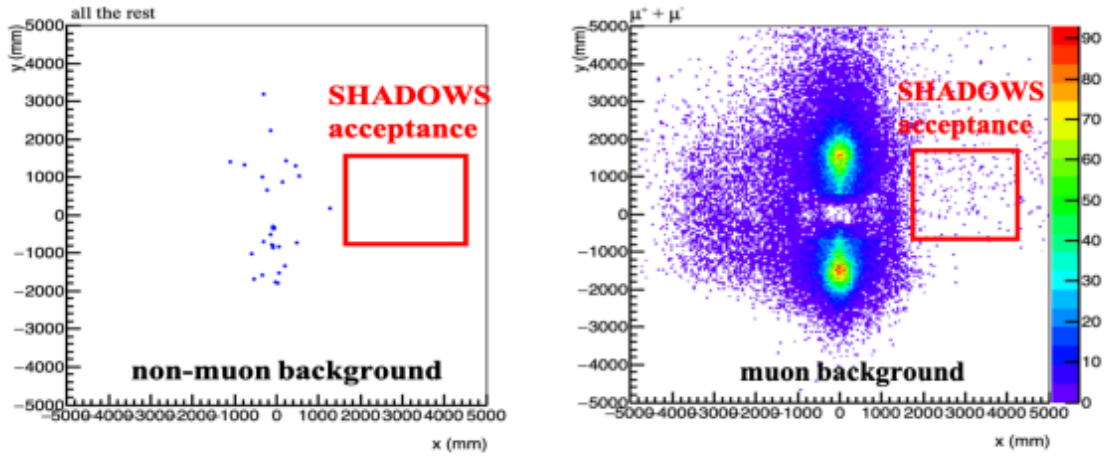


Figure 28. Residual background at z=55.3 m (position of the first tracking station). Left: non-muon background; Right: muon background. In the SHADOWS acceptance the non muon background is fully negligible and the muon one is reduced by more than an order of magnitude with respect to the one without sweeping system.

Detector-based methods:

Backgrounds from inelastic interactions of the residual muon flux hitting the detector material and from combinatorial mixing of two (or more) muon tracks are expected to have the following characteristics:

1. The total momentum of tracks when extrapolated backward to the dump does not point to the position of the proton beam impinging point;
2. combinatorial tracks form rarely a fake vertex in the 20 m long fiducial volume;
3. combinatorial tracks are mostly non-coincident in time.

Physics reach

SHADOWS has the potential to discover FIPs if they have a mass between the kaon and the beauty mass, a region in which the existing experimental boundaries are relatively
weak.

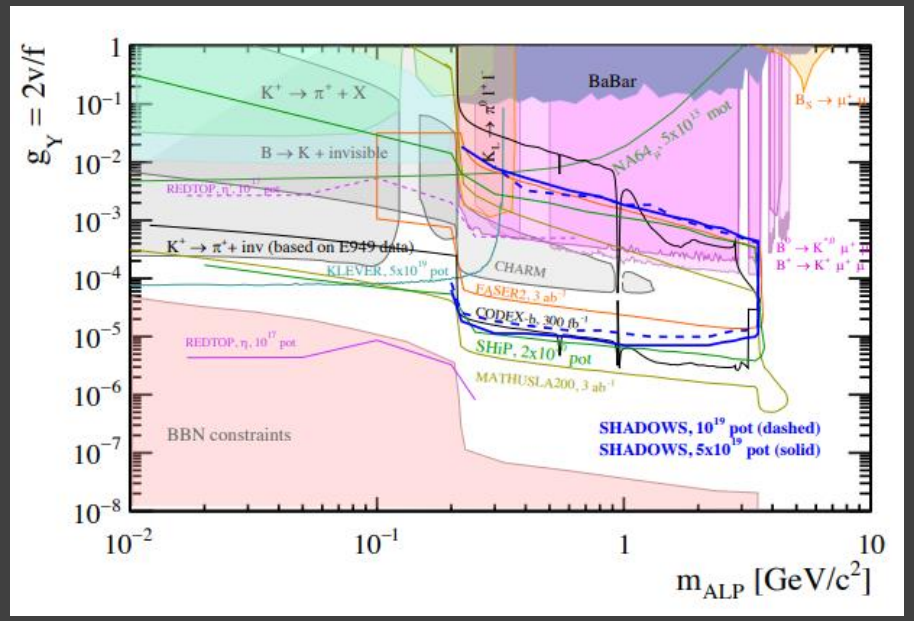
If no signal is found, SHADOWS will push the limits on FIP couplings with SM particles between one and four orders of magnitude in the same mass range, depending on the model and scenario, opening new directions in model building.

Two scenarios considered in the simulation:

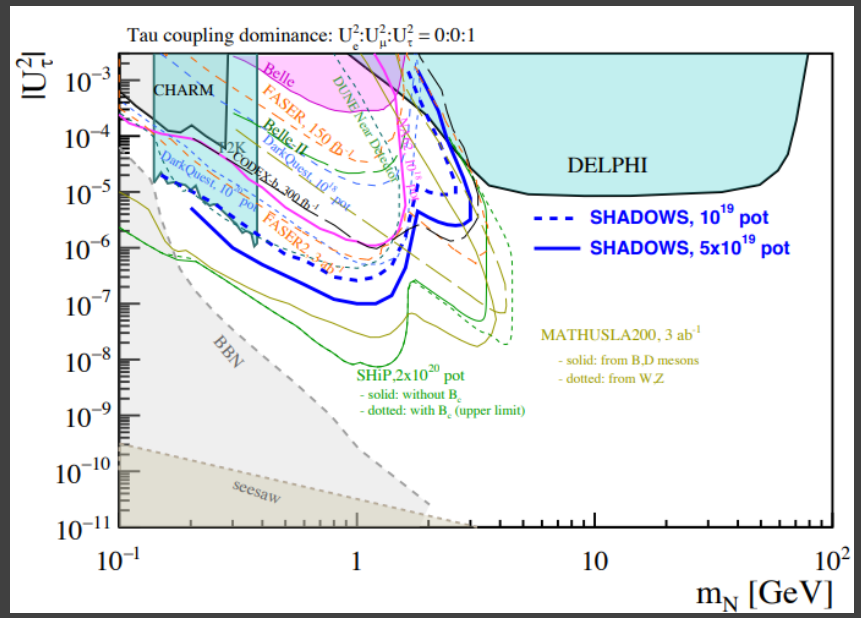
1) Scenario 1: 10^19 protons-on-target (~one year of data taking)
2) Scenario 2: 5x10^19 protons-on-target (~4-5 years if data taking)

Start of data taking: 2028 (after Long Shutdown 3)

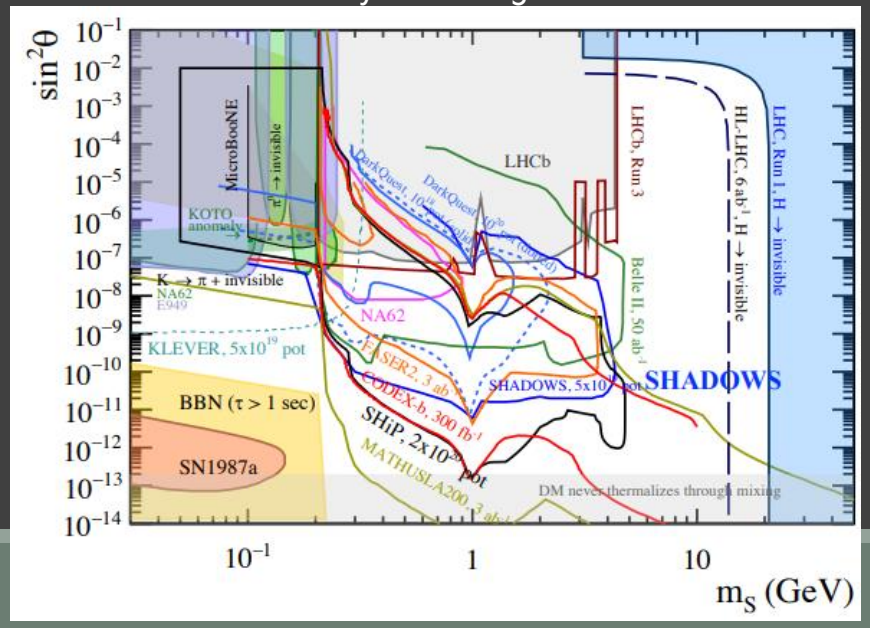
ALPs



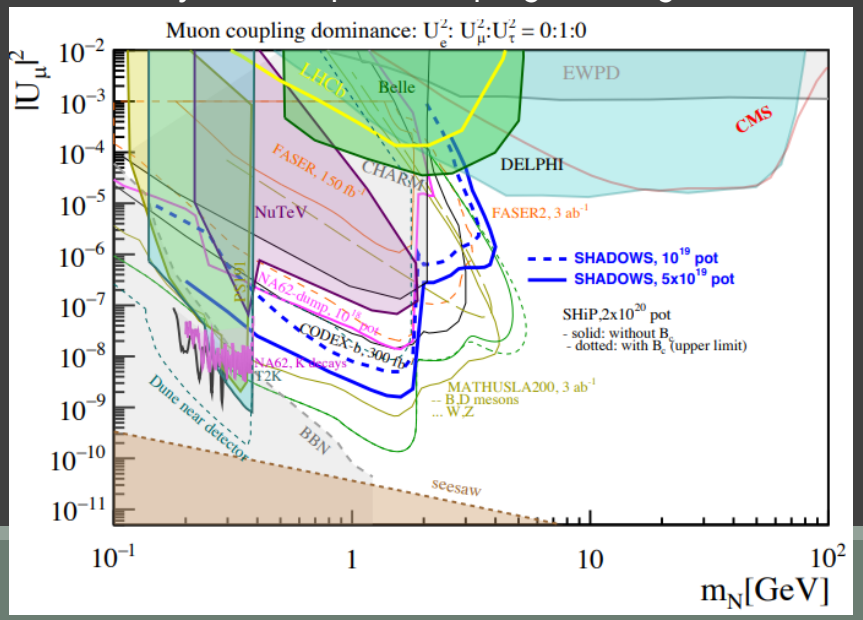
Heavy neutral leptons, coupling third generation



Feebly interacting dark scalars

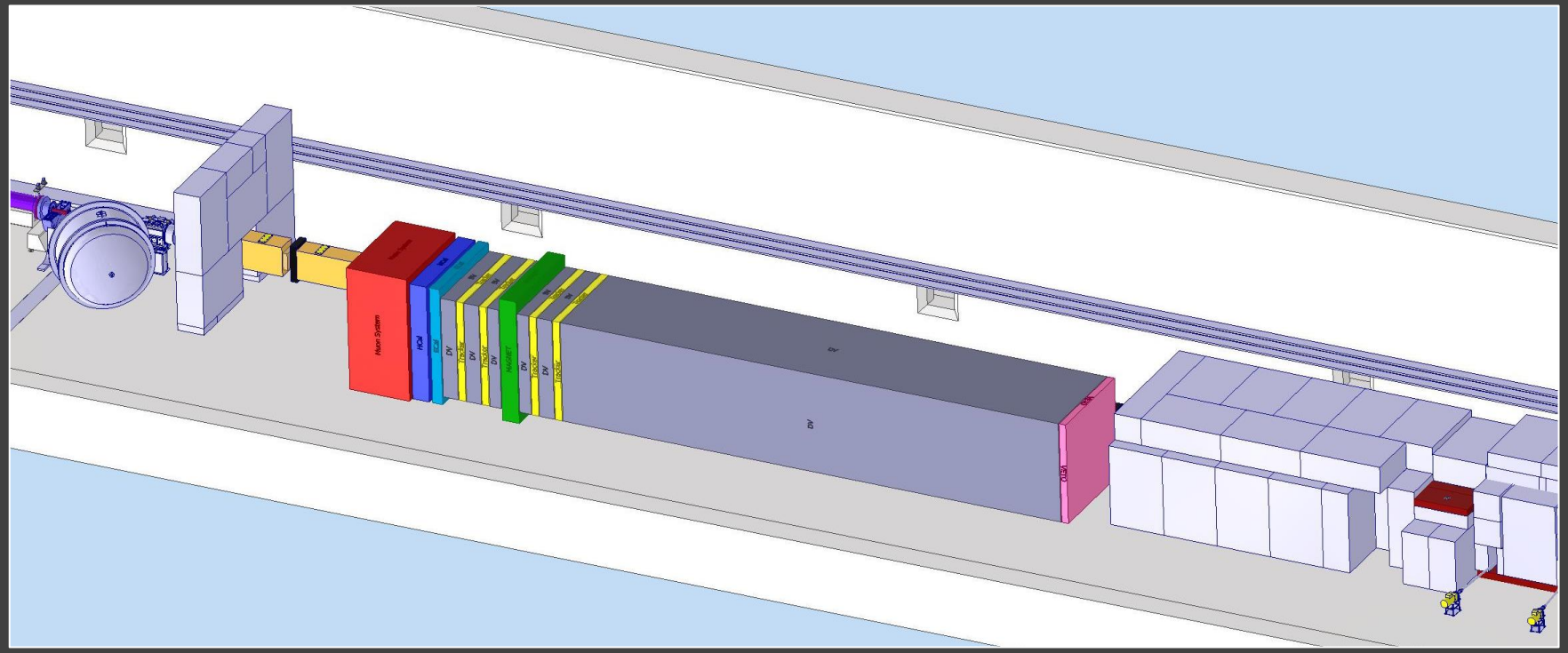


Heavy neutral leptons, coupling second generation

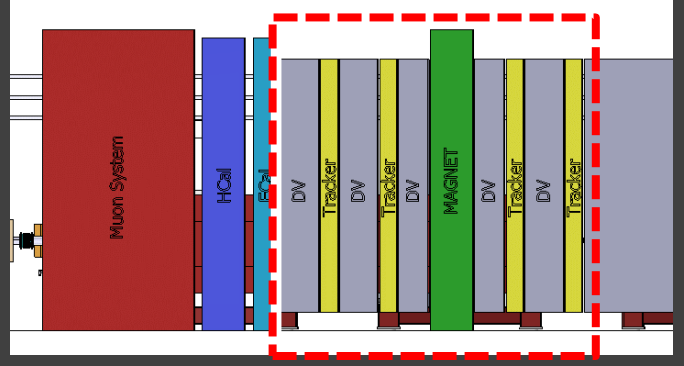


The SHADOWS detector

The SHADOWS detector must be able to reconstruct and identify most of the visible final states of FIPs decays. The experimental signature will be two (or more) charged tracks (e, μ, π) and/or photons originating from the same point in the decay volume.
To this aim a spectrometer with excellent tracking and timing performance and some particle identification capability is required. Given the relatively low rate and low energies involved, few radiation issues are expected.



Tracking system



Requirements:

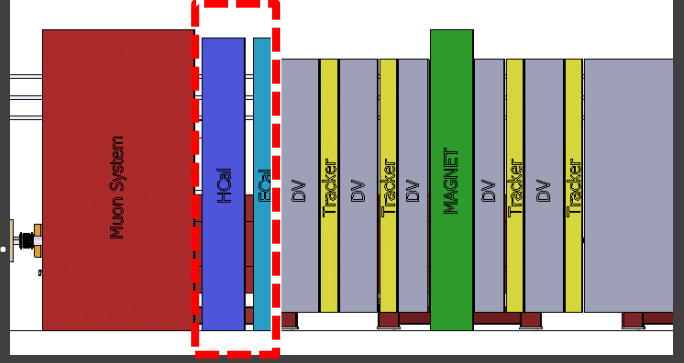
- Mass resolution of a few MeV for masses of the order of a few GeV;
- Vertex resolution of 1 cm in the transverse plane over a volume length of 20 m;
- Impact parameter resolution of 1 cm for FIP decays into two charged tracks when the total momentum is extrapolated backward toward the target.

Possible technologies:

- *NA62 STRAW tubes*: Ar(70%): CO2 (30%), in vacuum, 5mm diameter.
  One straw chamber is composed of four views (X, Y, U, V), one double-layer per view. Hit resolution better 400 µm over most of the straw diameter per single layer, 8 layers per tracking station. Warm dipole magnet with 0.9 Tm bending power. 3-4 MeV mass resolution for HNL -> πµ final states. Impact parameter resolution < 1 cm over 180 m length.
- *Fibre Tracker (LHCb upgrade phase 1)*: 250 µm diameter, 2.5 m long scintillating fibres; three stations, six detection layers each. Hit resolution per station < 80 um. 4 Tm bending magnet.

LHCb Fibre tracker module

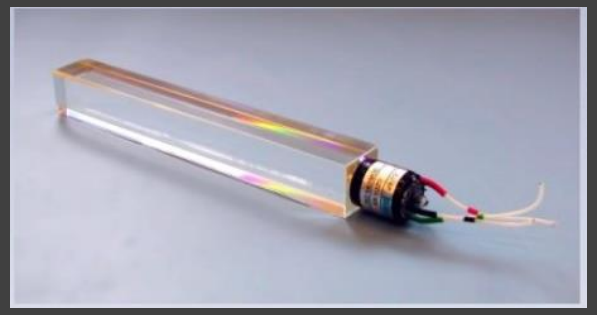
Electromagnetic Calorimeter



Reconstruct energy, position and (possibly) the direction of photons coming from FIP decays.
No radiation issues expected (low rate and energies involved).

Possible technologies:

- PbWO4 crystals (CMS electromagnetic calorimeter)
- Shashlik technology (LHCb) ECAL



PbWO4 crystal read out by vacuum photomultiplier

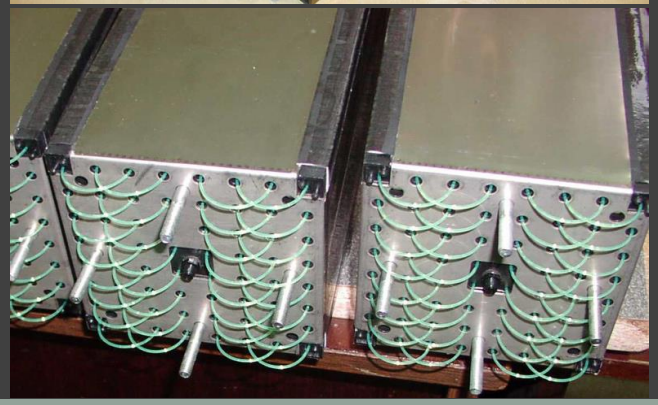
LHCb ECAL Basic module:
4 mm thick scintillator tiles and 2 mm thick lead plates
66 lead plates and 67 scintillator layers, ≈ 40 cm deep, ~25 X0 (1.1 λI)
Molière radius: ≈ 35 mm
Module size: 12 x 12 cm2
Performance:

Energy resolution:

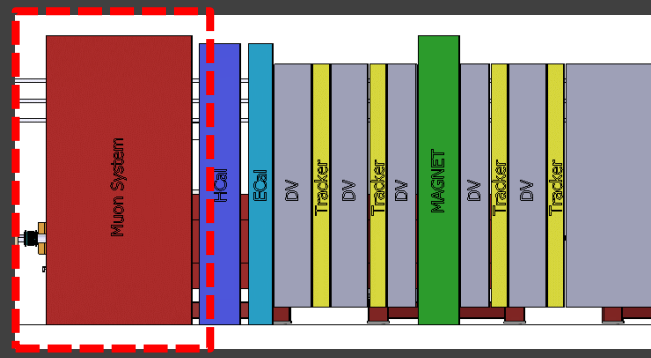
$$\frac{\sigma_E}{E} = \frac{(8 \div 10)\%}{\sqrt{E(GeV)}} \oplus (0.8 \div 0.9)\%$$

Photoelectron yield (with HAMAMATSU R7899-20): ≈ 3000 ph.el. / GeV

Time resolution ~ 80 ps @ 5 GeV



Muon Detector



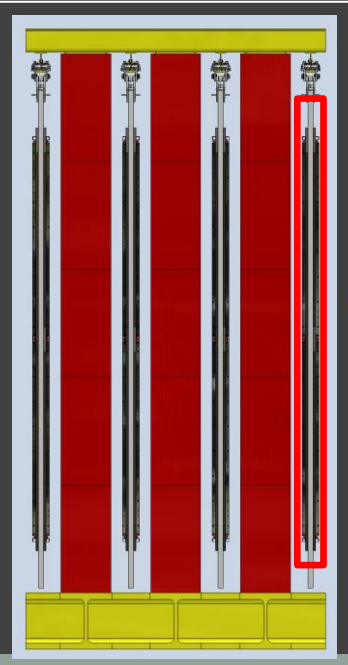
Requirements:

- Identify muons with high efficiency (>95%),
- Reduce the hadron contamination to less than 1% in a momentum range between 5-100 GeV/c;
- timing capabilities to reinforce the rejection of the combinatorial muon background in combination with the timing detector (< 3 · σt , σt ~ 150 ps).

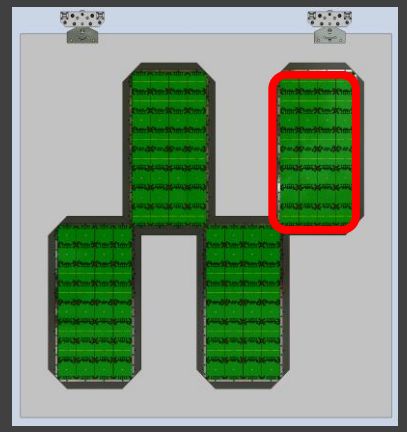
Baseline design:

4 active stations of scintillating tiles with direct SiPM readout, interleaved with passive iron filters (~ 3.0λI thick)

Advantages: modular, cost-effective, high-efficiency, large light yield, high time resolution.

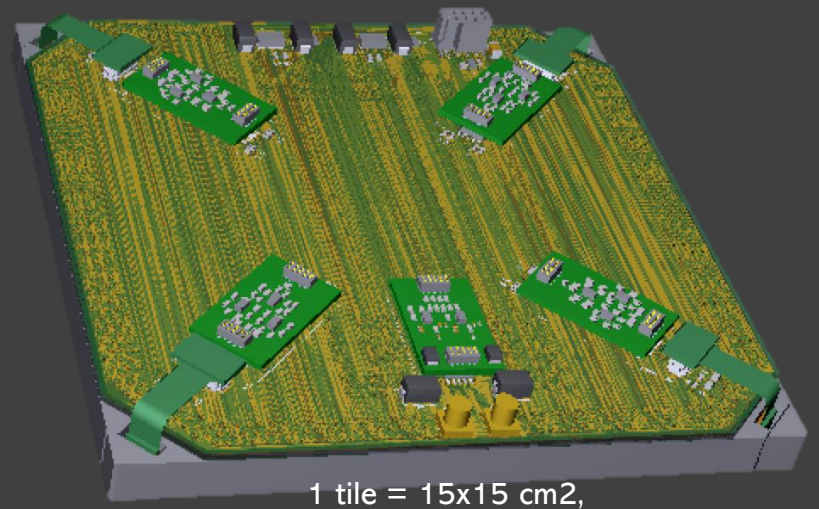


(2.5 × 2.5) m2 transverse area



1 station = 8 modules
(same pattern staggered
on the other side of the wall)

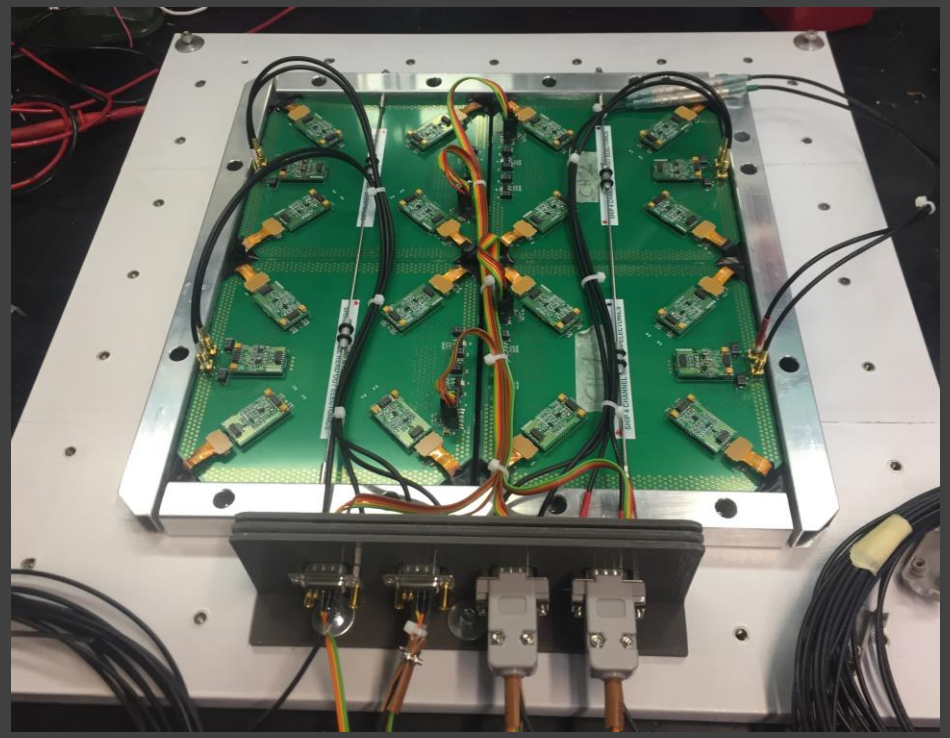
1 module = 32 tiles

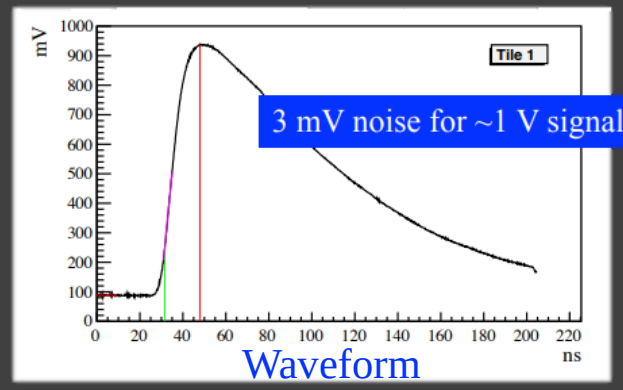


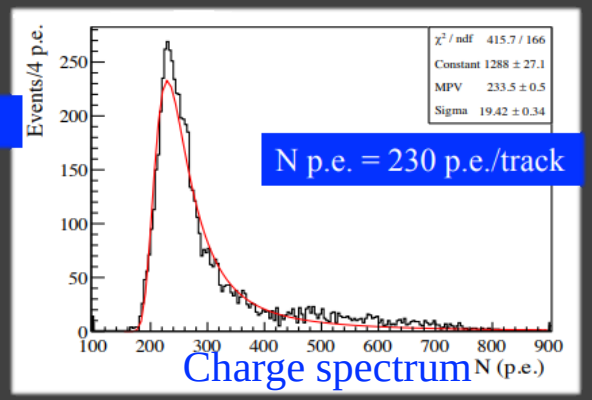
1 tile = 15x15 cm2,
Direct SiPM readout at the corners
One analog output per tile

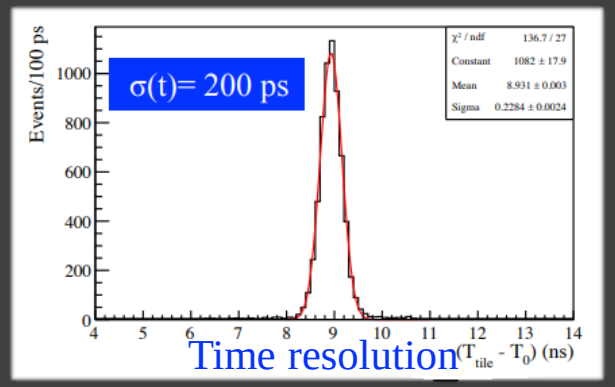
Muon Detector prototype

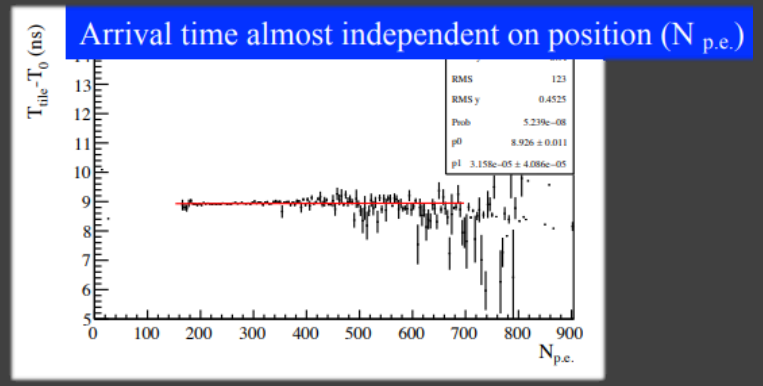
4-tile prototype built in INFN Bologna/LNF
Tested different types of scintillators, tile coatings and custom electronic readouts











Efficiency > 99.5%
N(p.e.)/MIP = 250
σ(t) ~ 290 ps

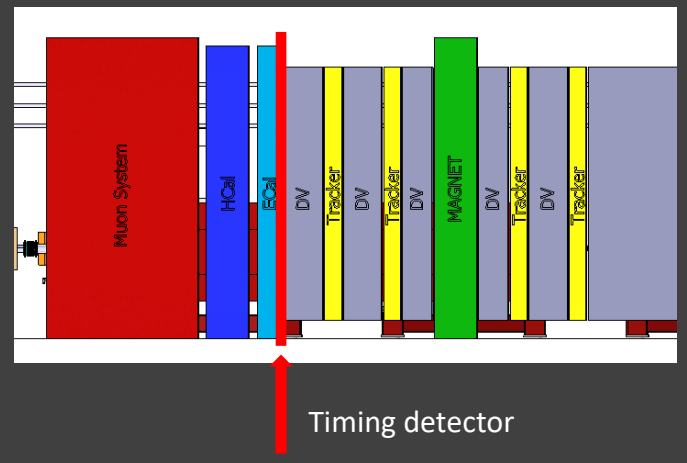
Balla et Al. "Performance of scintillating tiles with direct siliconphotomultiplier (SiPM) readout for application to large area detectors"
2022 JINST 17 P01038

Timing detector

Requirement:
o(100-150) ps timing resolution to reject combinatorial background.

Possible technologies:

- Scintillating bars: 168 cm×6 cm×1 cm scintillating bars read out by array of silicon photomultipliers. ~ 80 ps time resolution achieved;
- Multigap Resistive Plate Chambers (MRPC) with a Sealed Glass Stack (SGS). ~ 60 ps time resolution measured on prototypes;
- Scintillating pad detectors (muon detector technology, smaller tiles).

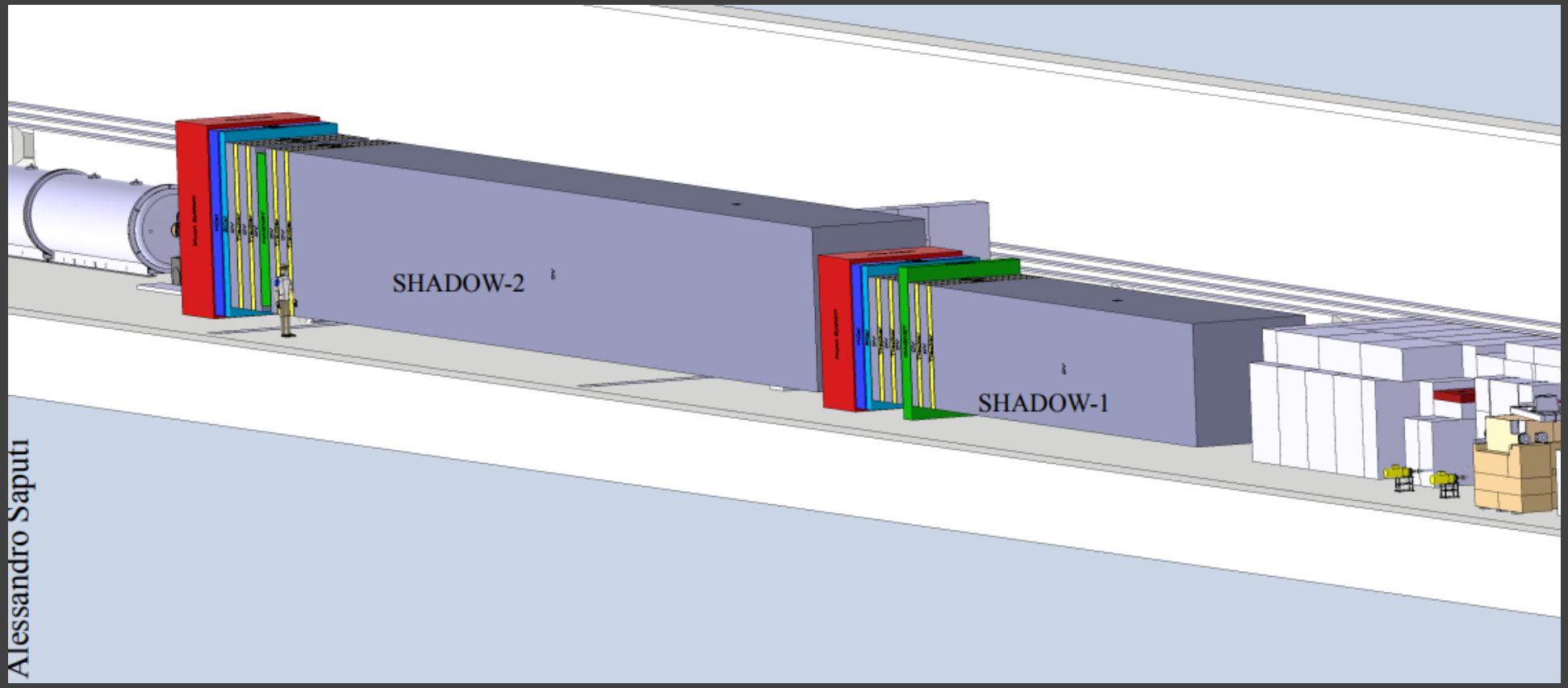


Upstream veto

An upstream veto should be installed in the front face of the decay volume to tag the muon background.
Possible technologies are micro-megas or μRWELLs.

Further developments:

To further improve SHADOWS sensitivity to Heavy Neutral Leptons, it is possible to add a second module in the free space of the TCC8 experimental area.
The second shadows spectrometer could have 30 m long decay volume and 3x4 m2 transverse dimensions.



Expression of interest and Tentative schedule

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

SHADOWS

Search for Hidden And Dark Objects With the SPS

Expression of Interest

W. Baldini[1], A. Balla[2], J. Bernhard[3], A. Calcaterra[2], V. Cafaro[4], A. Cecucci[3], V. Cicero[4], P. Ciambrone[2], H. Danielsson[3], G. D'Alessandro[3], G. Felici[2], L. Gatignon[5], A. Gerbershagen[3], V. Giordano[4], G. Lanfranchi[2], A. Montanari[4], A. Paoloni[2], G. Papalino[2], T. Rovelli[4], A. Saputi[2], S. Schuchmann[6], F. Stummer[7], N. Tosi[4]

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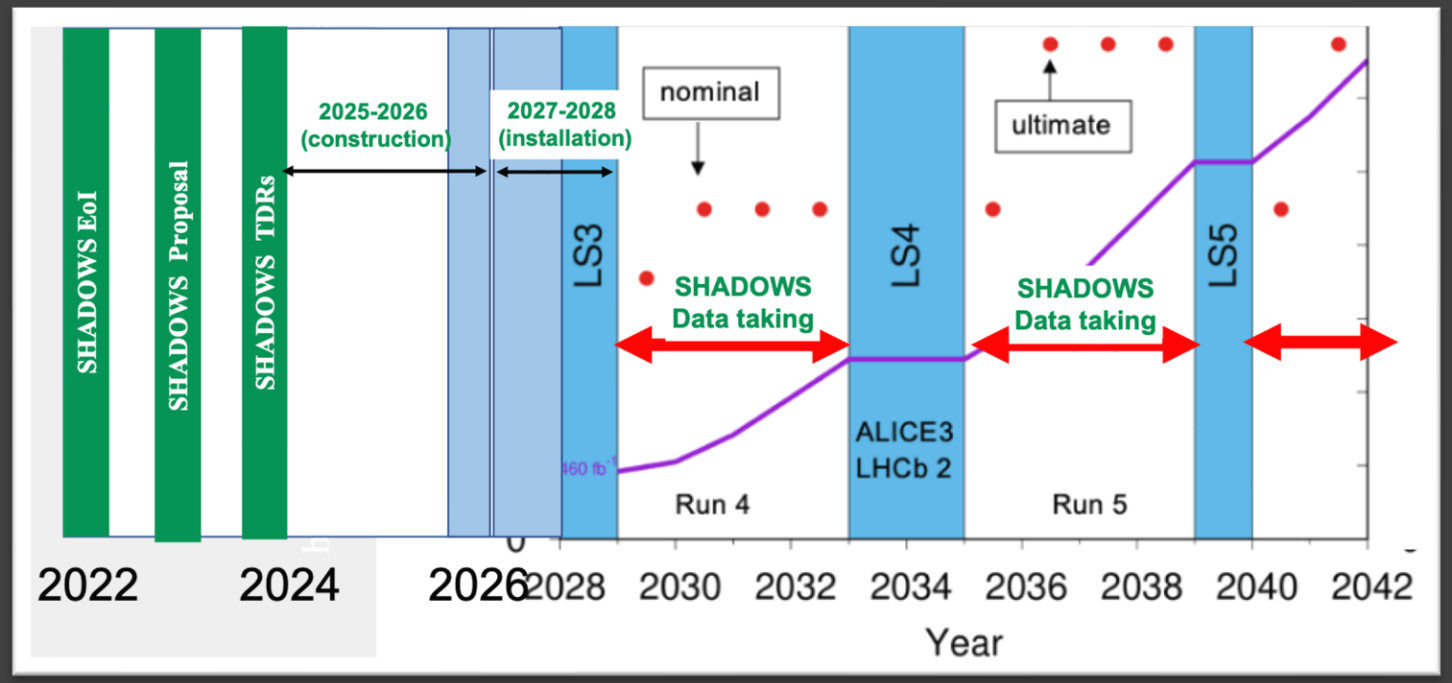
arXiv:2110.08025v1 [hep-ex] 15 Oct 2021

Executive Summary

We propose a new beam-dump experiment, SHADOWS, to search for a large variety of feebly-interacting particles possibly produced in the interactions of a 400 GeV proton beam with a high-Z material dump. SHADOWS will use the 400 GeV primary proton beam extracted from the CERN SPS currently serving the NA62 experiment in the CERN North area and will take data off-axis when the P42 beam line is operated in beam-dump mode. SHADOWS can accumulate up to a $\sim 2 \cdot 10^{19}$ protons on target per year and expand the exploration for a large variety of FIPs well beyond the state-of-the-art in the mass range of MeV-GeV in a parameter space that is allowed by cosmological and astrophysical observations. So far the strongest bounds on the interaction strength of new feebly-interacting light particles with Standard Model particles exist up to the kaon mass; above this threshold 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.

SHADOWS Expression of Interest arXiv: 2110.080025, submitted to Snowmass and **SPS Committee at CERN** (CERN-SPSC-2022-006 ; SPSC-EOI-022). Review process started.

SHADOWS can be built now using existing technologies and start data taking in Run 4



Conclusions

Feebly-interacting particles (FIPs) may provide an answer to many open questions in particle physics, astrophysics, and cosmology.
In the coming years a wealth of experimental results for FIPs are expected from all the major laboratories in the world.

SHADOWS will be a major player for FIP Physics in this decade:

- ⇨ SHADOWS can be built now using existing technologies.
- ⇨ SHADOWS sensitivity is comparable to CODEX-b (300 fb-1) and FASER2 (3 ab-1) and, for specific benchmarks, to SHiP (2x10^20 pot) for FIPs from charm/beauty decays.

The experiment design is under active development.

Groups or individuals interested in contributing to the SHADOWS physics case and/or to the SHADOWS detector can contact: Gaia.Lanfranchi@lnf.infn.it, Augusto.Ceccucci@cern.ch

References

[1] **W. Baldini et al.**, *SHADOWS (Search for Hidden And Dark Objects With the SPS)* (2021) [2110.08025]

[2] **J. Beacham et al.**, Physics Beyond Colliders at CERN: Beyond the Standard Model Working Group Report, J. Phys. G 47 (2020) 010501, [1901.09966].

[3] **A. Balla et al.**, *Performance of scintillating tiles with direct silicon-photomultiplier (SiPM) readout for application to large area detectors*, (2022) JINST 17 P01038 ,[2109.08454].