PROCEEDINGS OF SCIENCE

The SHADOWS experiment at the CERN SPS

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SHADOWS (Search for Hidden And Dark Objects With the SPS) is a proposed proton beam-dump experiment for the search of a large variety of feebly-interacting particles (FIPs) at the CERN SPS. It will exploit the potential for searches and discoveries at the intensity frontier offered by the upgrade of the ECN3 beam line. SHADOWS will be located off-axis, which allows the suppression of the background, and will collect data from up to 5×10^{19} protons of 400 GeV on target in 4 years of operations. The conceived detector, with a transversal size of 2.5×2.5 m^2 and a length of 34 m, offers excellent tracking and timing performances for the identification and reconstruction of most of the visible final states of FIP decays. SHADOWS allows to explore a large region in parameter space of many FIPs, like light dark scalars, axion-like particles and heavy neutral leptons, with masses ranging between 0.1 and 5 GeV. It will be possibly complemented by a dedicated neutrino experiment (NaNu@SHADOWS) to further extend the physics reach, in particular for the study of tau-neutrino events. This article reports about the status and overview of the SHADOWS experiment.

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PoS(EPS-HEP2023)465

1. Introduction

Feebly-interacting particles (FIPs) with masses below the electro-weak (EW) scale, potentially part of a rich dark sector, offer a complementary approach to traditional Beyond the Standard Model (SM) physics explored at the LHC. They may address various open questions in modern particle physics, including the baryon asymmetry of the Universe, the nature of dark matter (DM), the origin of neutrino masses and oscillations, cosmological inflation, and the strong CP problem.

The goal of the SHADOWS experiment is to search for FIPs in the MeV to a few GeV mass range, utilizing CERN's existing infrastructure, the 400 GeV proton beam line P42, extracted from the SPS and the ECN3/TCC8 complex in the CERN North area (shown in Figure 1). This area currently accommodates the NA62 experiment and will host, if approved, the future HIKE experiment [1]. The fundamental concept is to reconstruct FIPs originating from B and D decays which in turn are produced from the interaction of protons with the beam dump. Most of the FIPs travel over considerable distances, and decay into detectable SM particles.

2. SHADOWS location, beamline and target area

The ECN3/TCC8 complex is shown in Figure 2. As a baseline scenario, SHADOWS aims to run in parallel with HIKE when the K12 beam-line is operated in Beam Dump mode. SHADOWS will be installed off-axis on the Jura side (i.e. left-hand side looking in beam direction) of the K12 beam line. With the proposed increase in the K12 beam intensity by a factor of six, SHADOWS will collect 5×10^{19} protons on target (pots) in this location in just 4 years of operation [2].

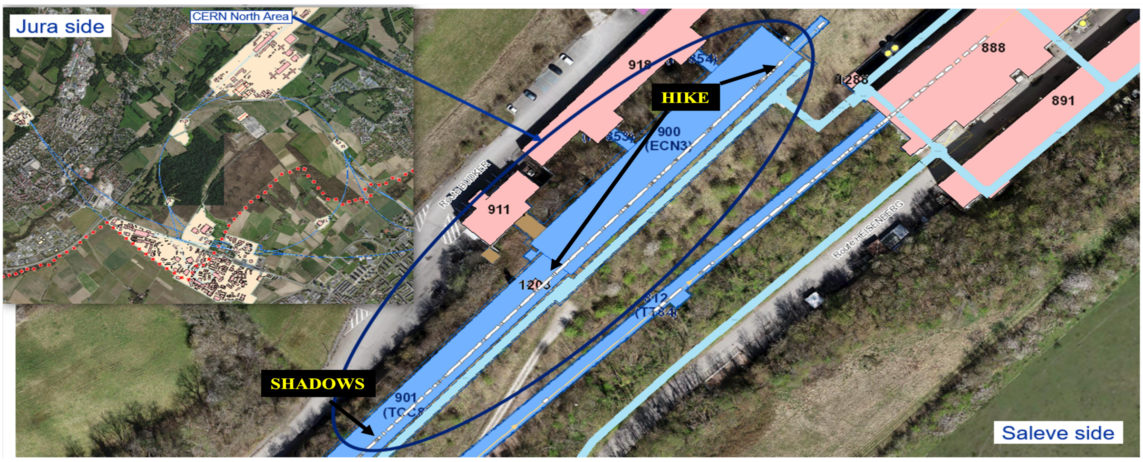

Figure 1: Aerial view of the ECN3/TCC8 complex and indicative positions of SHADOWS and HIKE.

3. SHADOWS : muon sweeping system

SHADOWS uses an off-axis detector for two main reasons: to take advantage of the available space upstream of NA62, and to minimize background interference, which is vital for detecting rare events. In contrast to other background particles generated from proton-beam interactions with the dump, muons pass through the material without being stopped, making them the main source of

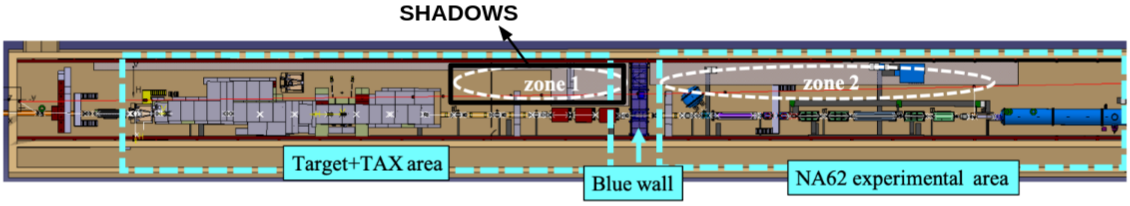

Figure 2: Schematics of the TCC8 tunnel comprising the target area and a fraction of the NA62 zone. The SHADOWS experiment is planned to be placed in zone 1. The beam direction is from left to right.

background for SHADOWS. Simulations estimate a background muon rate of 150 MHz over the active SHADOWS cross-section of 2.5×2.5 m^2, originating from the beam dump. To mitigate this, SHADOWS employs a muon sweeping system using dense magnetized iron blocks (MIBs). This system operates in two stages: Stage 1 separates positively and negatively charged muons, while Stage 2 and Stage 3 effectively sweep the separated muons off-axis. This two-step process is found to be the most efficient for background mitigation and significantly reduces the background muon rate to 2.1 MHz.

4. SHADOWS detector

SHADOWS detector requirements are determined by the characteristics of FIPs originating from interactions of a 400 GeV proton beam with the beam dump. An off-axis detector is essential due to wide polar angles of FIPs from the decays of charmed and beauty hadrons. The detector's distance is a compromise between maximizing the FIP flux and the likelihood of FIP decay inside the decay vessel. The SHADOWS detector has a total length of 34 m along beam axis (z direction) and covers an area of 2.5 × 2.5 m^2 transverse to the beam axis (in x/y direction). A sketch of the detector is shown in Figure 3. It consists of the following components:

1. **Vacuum tank :** The vacuum tank is a 19 m long vacuum vessel at an absolute pressure of about 1 mbar. It contains the dipole magnet and the tracking system.
2. **Dipole magnet :** It has an integrated B field strength of 1 Tm and a rectangular aperture of 2.7×2.7 m^2 with options for both warm and superconducting configurations.
3. **Upstream and lateral veto systems :** They employ resistive pad micromegas detector [3–5] with rate handling capabilities of up to 10 MHz/cm^2 and are used to tag the muons surviving the MIB.
4. **High-precision tracking system :** The tracking system consists of four stations, each with x and y layers. It is optimized to determine the mass, the decay vertex and the impact parameter of FIP decays with at least two charged tracks in the final state. Straw tubes are the baseline technology for the tracking stations [6], with scintillating fibers also under consideration.
5. **Timing detector :** The timing detector utilizes bars of plastic scintillators with Silicon Photo-Multipliers (SiPMs) mounted on both ends of a bar to reduce the combinatorial background.
6. **Electromagnetic calorimeter :** Featuring longitudinal segmentation, the baseline design comprises an iron-scintillator sandwich calorimeter having a depth of 20 radiation lengths (20 X_0) to accurately reconstruct ALP to two photons decays.

7. **Muon detector :** The muon detector uses plastic scintillator tiles [7], each read out by four SiPMs, for positively charged muon identification.

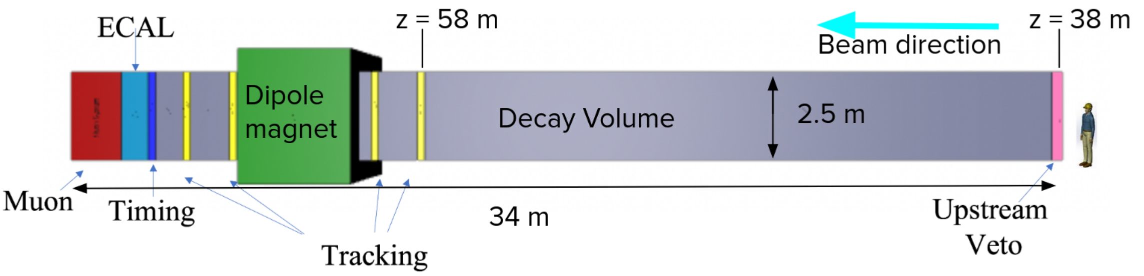

Figure 3: SHADOWS detector layout (lateral view). The grey area is the vacuum vessel. The green block is the dipole magnet placed between four tracking stations (yellow)

5. Tracking performance : Monte Carlo simulation

In tracking system performance studies, signal reconstruction and selection efficiencies for a FIP decaying into a two-track final state are determined using simulated decays of Axion Like Particle (ALP) to $\mu\mu$ final state (masses 500 MeV to 4.0 GeV) using GEANT4. All muon hits in the straws (resolution of 150 μm per station) are used for a χ^2-minimization based track fit, separately in the x-z and y-z planes of the tracking system. Multiple scattering is not taken into account in the track fit.

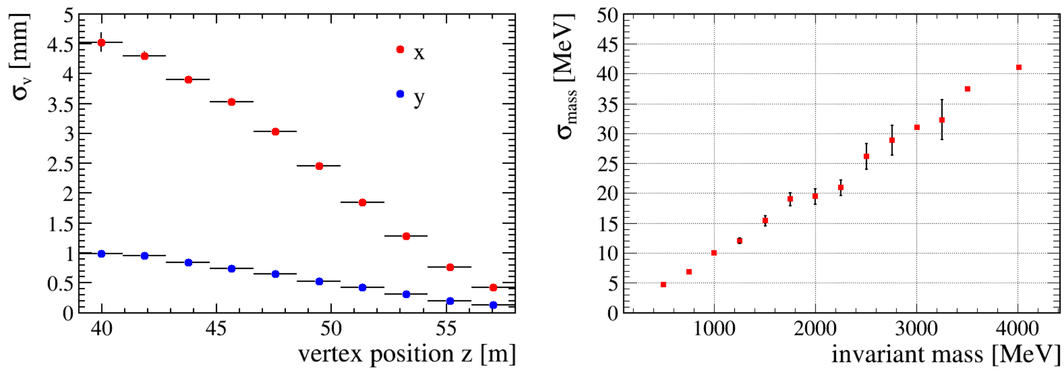

Figure 4: Left: Vertex resolution of the SHADOWS tracking system as a function of the z position of the ALP decay vertex. The red markers are the vertex resolution in x direction and the blue markers are the vertex resolution in y direction. Right: Mass resolution as a function of ALP mass.

5.1 Momentum resolution and vertex resolution

The angular resolution (σ_θ) of the tracking system at momenta larger than 10 GeV is ~0.1 mrad for x-z and ~0.04 mrad for y-z tracks, respectively. The relative momentum resolution σ_p/p comprises a flat offset of 0.3% at low momenta due to multiple scattering and rises linearly with the

transverse momentum. The current detector setup provides a relative momentum resolution better than 2% in the relevant momentum range of 2-40 GeV.
The vertex resolution is best for decays close to the tracking system. It is better in the non-bending plane y-z(0.1-1.0 mm) than in the bending plane x-z(0.5-4.5 mm). The ALP candidate's path is extended toward the beam dump to reconstruct the impact parameter (IP) which is reconstructed closely to the true IP and has an impact parameter resolution of ∼ 3 mm.
Figure 4 displays the vertex resolution for ALP candidates with a mass of 600 MeV decaying into two muons as a function of the z decay position along with the mass resolution as a function of ALP masses. The mass resolution is roughly 1% for ALP masses spanning from 500 MeV to 4 GeV, respectively.

5.2 Reconstruction and efficiency

The tracking efficiency ranges from 92% at low momenta to a plateau of 98-99% for momenta exceeding 10 GeV, with an average reconstruction efficiency (ϵ_{track}) of 98% per track. The vertex reconstruction efficiency (ϵ_{vertex}) is constant at 89.2% along the z coordinate within the decay volume, while the impact parameter requirement exhibits an efficiency (ϵ_{IP}) of 96.6%. The total ALP reconstruction efficiency within the acceptance is given by:

$$\epsilon_{ALP} = \epsilon_{track} * \epsilon_{track} * \epsilon_{vertex} * \epsilon_{IP}.$$

It is equal to 83.9 ± 2.4 %. The efficiencies are evaluated applying the same selection criteria which are described for the background rejection in the following section.

6. Combinatorial background estimation

The dominant background in the SHADOWS acceptance consists of muons. This background is calculated from a simulated sample statistically equivalent to of 3×10^{13} pot for muon combinatorial studies and to 2×10^{21} pot for muon inelastic interaction studies. The muon rate at the first tracking chamber, without the MIB is on average ∼ 150 MHz. The residual muon flux after the MIB is 2.1 MHz. The timing detector requires the muon pairs to fall within a time window of $\delta T = 3\sigma_t$, where σ_t is about 100 ps which further reduces the background. The probability of not-vetoing (using upstream and lateral vetoes) two muon tracks emerging from the dump is $(1 - \varepsilon)^2 = (0.2 \cdot 10^{-2})^2 = 4 \cdot 10^{-6}$. In addition, the closest distance of approach (CDA) of both the muons is required to be within $5 \cdot \sigma$, with $\sigma = \sqrt{\sigma_x^2 + \sigma_y^2}$, where $\sigma_{\mathrm{x,y}}$ is the vertex resolution in the x and y direction, respectively. An $IP < 6$ cm cut is also applied. Table 1 summarises the expected number of events. Given an average of 6.0×10^{-10} (3×10^{-7}) di-muon background events per spill and $2.4 \cdot 10^6$ spills in the SHADOWS lifetime, about 0.001 (0.7) combinatorial di-muon background events are expected for fully (partially) reconstructed final states after the selection.

7. SHADOWS physics reach

SHADOWS sensitivities to dark scalars and ALPs with fermion couplings are shown in Figure 5. The results are established using a sample of 5×10^{19} pots with the current baseline SHADOWS geometry and placement in the TCC8 tunnel. HIKE-phase 1 and SHADOWS can significantly

PoS(EPS-HEP2023)465

Table 1: Number of dimuon events per spill after applying selection requirements consecutively. This assumes to have initially 1.4 MHz of negative muons and 0.7 MHz of positive muons over 4.8-sec spill length in the SHADOWS acceptance.

$N_{\mu\mu}$/spill	requirement
3000	timing (T)
$1.2 \cdot 10^{-2}$	vetoes (UV)
$6.0 \cdot 10^{-6}$	vertex requirements (CDA)
$6.0 \cdot 10^{-10}/3.0 \cdot 10^{-7}$ (fully/partially rec. events)	IP requirements (IP)
$N_{\mu\mu}/5 \cdot 10^{19}$ pot	
0.001/0.7 events (fully/partially rec.)	T & UV & CDA & IP

enhance existing limits by one to three orders of magnitude, spanning below and above the kaon mass up to the *B* mass, depending on the model and scenario. The possibility of exploring new light and feebly-interacting phenomena and, simultaneously, very high-scale masses through precision measurements in the kaon sector, makes the combined SHADOWS + HIKE system unique.

If the SHADOWS technical proposal [8] is approved by early 2024, the aim is to begin construction in 2027, with a first pilot run anticipated by the end of 2030 or early 2031. Over the following eight years, data collection will take place, with the beam alternating between kaon mode (HIKE Phase I) and beam-dump mode (HIKE and SHADOWS).

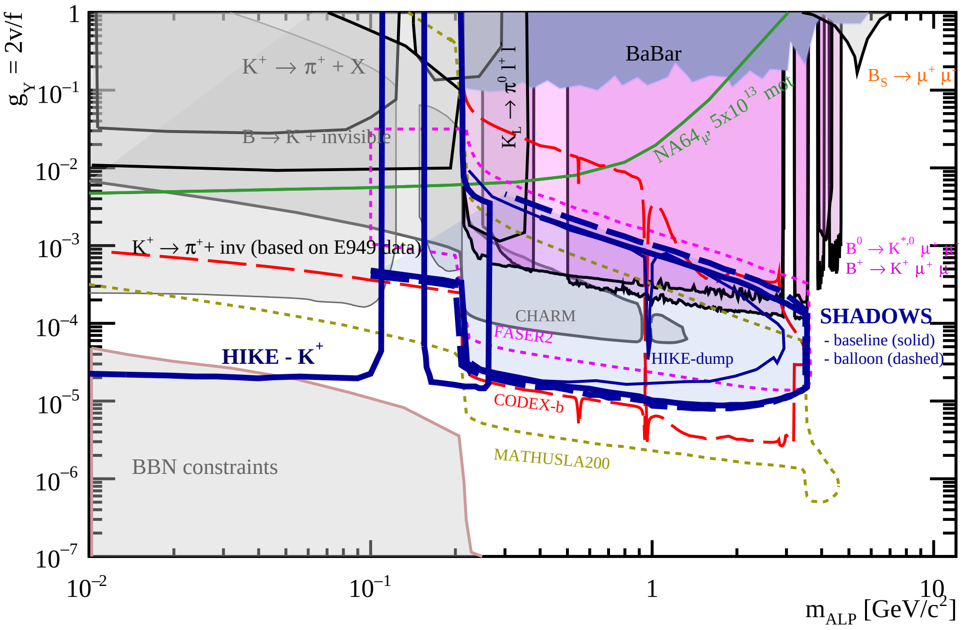

Figure 5: SHADOWS sensitivity to ALPs with fermion couplings at 90% CL exclusion limit (solid thick blue curve with shaded light blue area). HIKE-phase1 sensitivity at 90% exclusion limit (solid thick blue curve with no shaded area).

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PoS(EPS-HEP2023)465