SHADOWS project at CERN: status and prospects

A. Paoloni on behalf of SHADOWS collaboration

FIPs 2022 workshop

CERN 17-21 October 2022

SHADOWS is a newly proposed experiment to search for FIPs emerging from charm and beauty decays.

EOI - CERN-SPSC-2022-006 ; SPSC-EOI-022
and arXiv:2110.080025

SHADOWS Letter Of Intent

will be submitted to the SPSC in 2 weeks time

Proto-collaboration growing day by day…

Special thanks to BE-EA-LE CERN accelerator division for their work and support

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

SHADOWS

Search for Hidden And Dark Objects With the SPS

Letter of Intent

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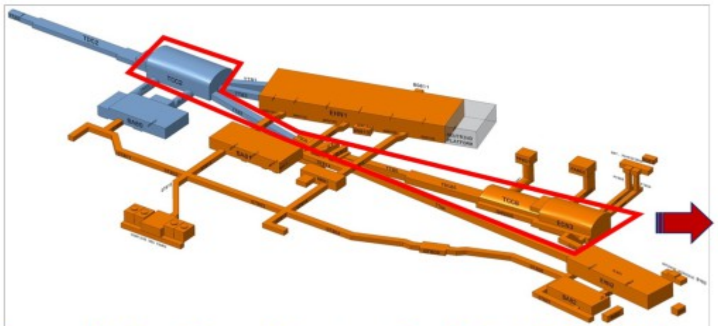
Executive Summary

We propose a new proton 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. SHADOWS will take data off-axis concurrently to the HIKE experiment when the P42 beam line is operated in beam-dump mode to accumulate up to $5 \cdot 10^{19}$ protons on target in 4 years of operation. This document describes the main achievements with respect to the Expression of Interest and represents an intermediate step towards the Proposal.

We were cited in the highlights of the September Council Session reported by the DG during last Monday Directorate Meeting (https://indico.cern.ch/event/1205151/)....

Future opportunities for scientific diversity programme: example

Consolidation Phase 1 (funded): 2019 – 2027



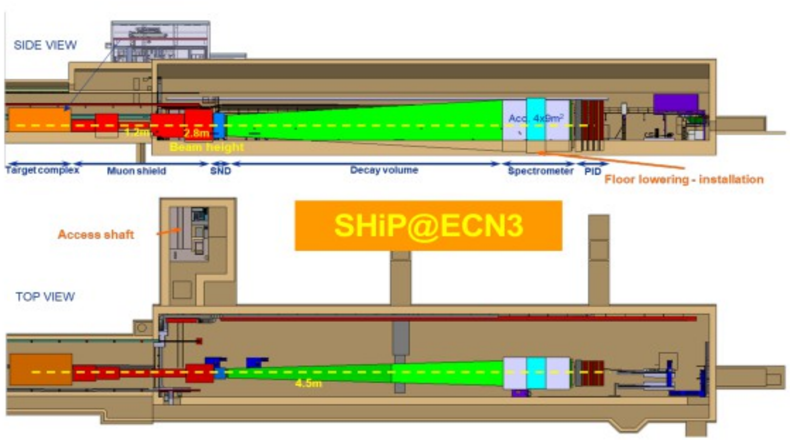
Consolidation Phase 2 (not yet funded): 2028 – 2033

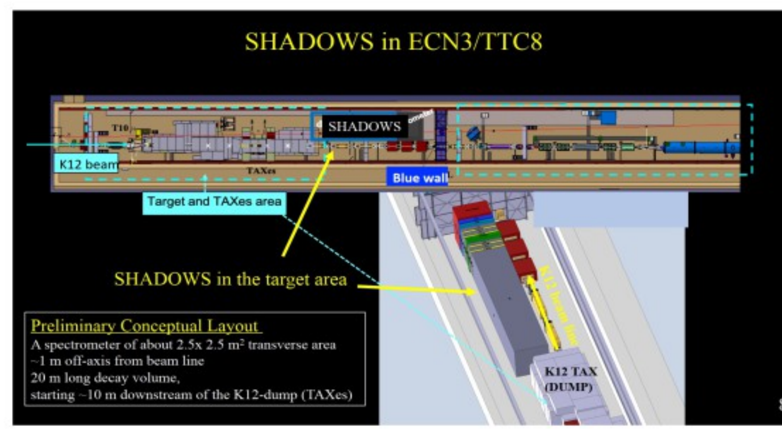
Areas concerned with high intensity beams

North Area upgrade to higher-intensity beams:

up to ~ 4 x 10^{19} POT/year (slow extraction) post-LS3 (exp. request: 6-20x today's perf.)
Current interest: kaon physics (HIKE), beam dump experiments for dark sector and other studies (SHADOW, SHiP), lepton-flavor violation through τ → 3μ (TauFV), …
If work done during LS3 → operation can start ~ 2029

Two "task forces" established to assess physics case (SPSC) and technical aspects
→ Funding may be secured in 2023 MTP and experiment(s) may be selected by end 2023





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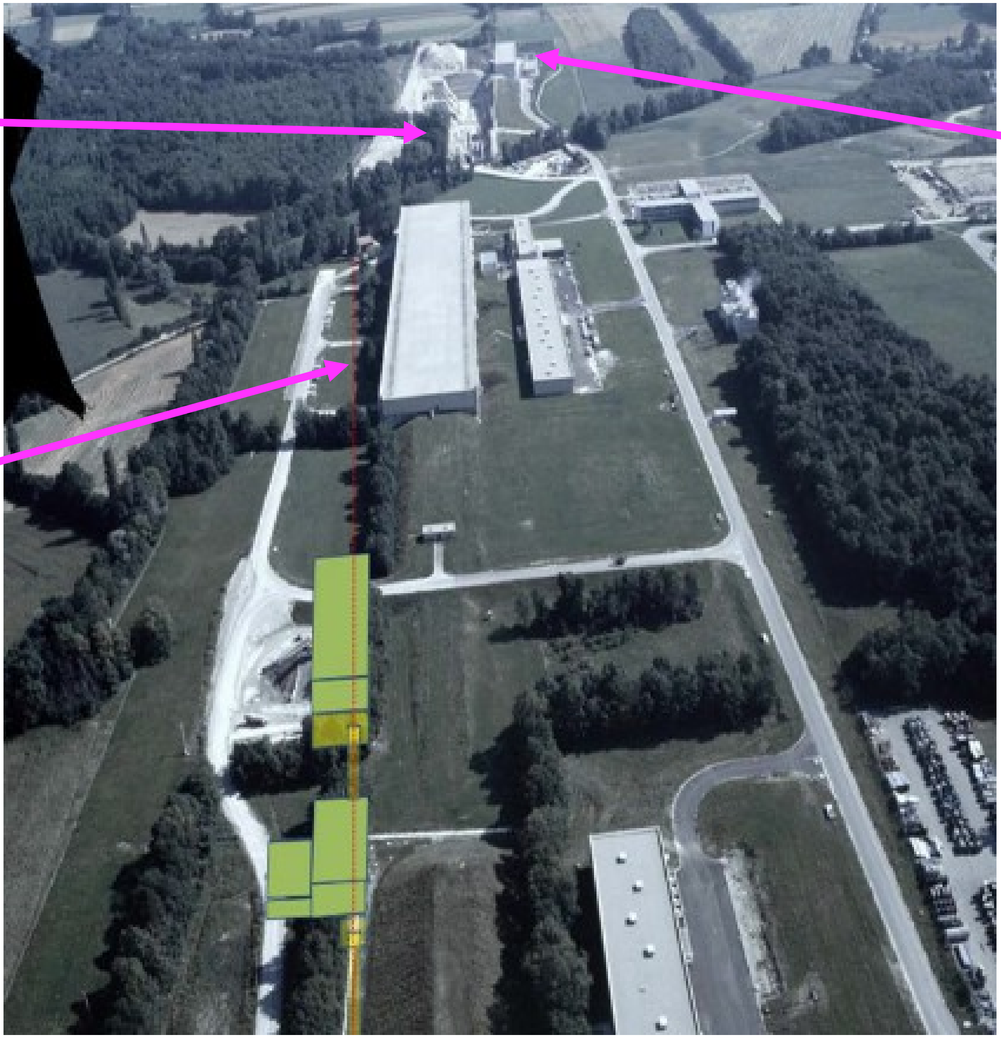
North area upgrade:
Two task forces at work to assess beam and physics (SPSC) case.
Project approval by end 2023.

North Area @CERN

TCC8/ECN3 :

P42 400 GeV proton beam

SHADOWS



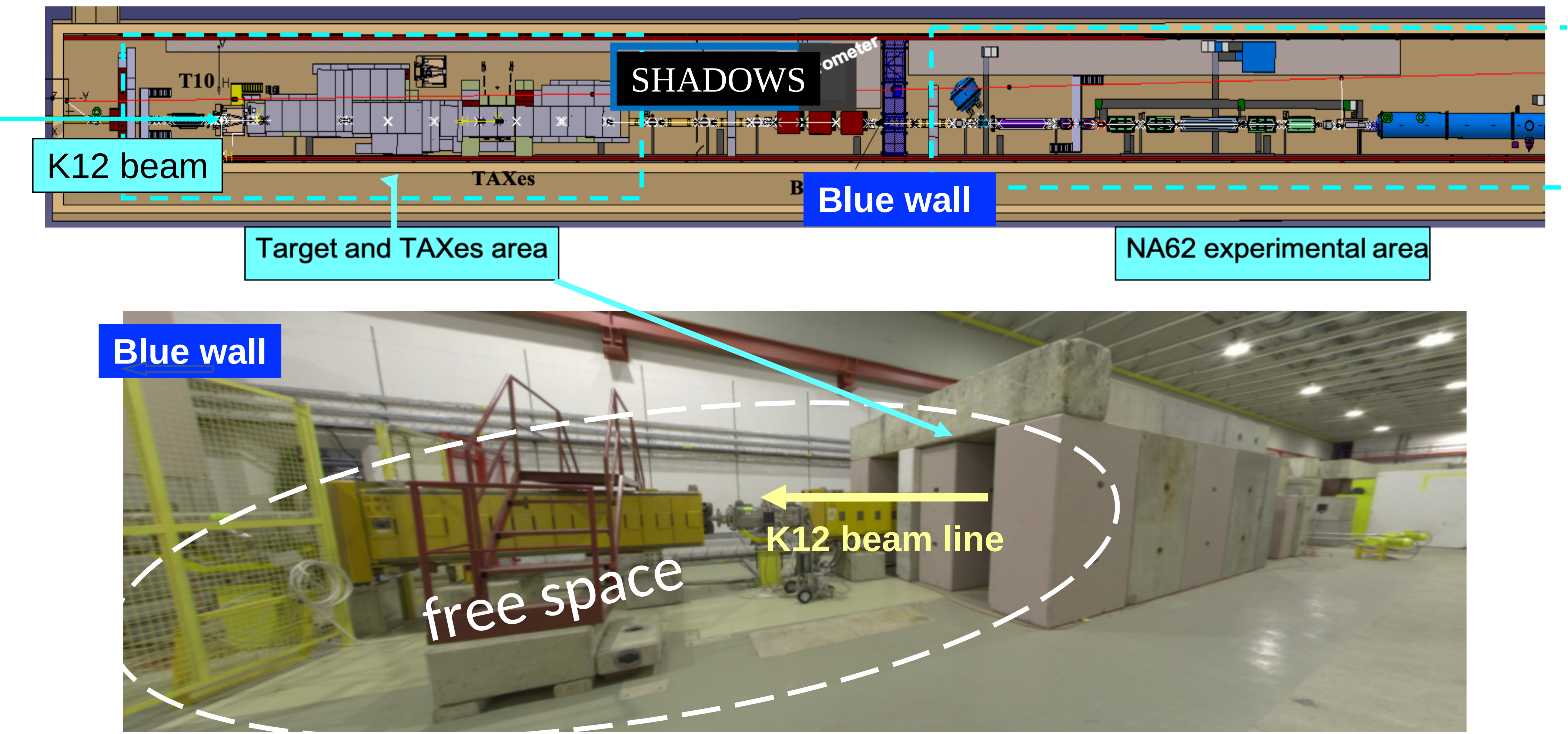
EHN2

EHN1

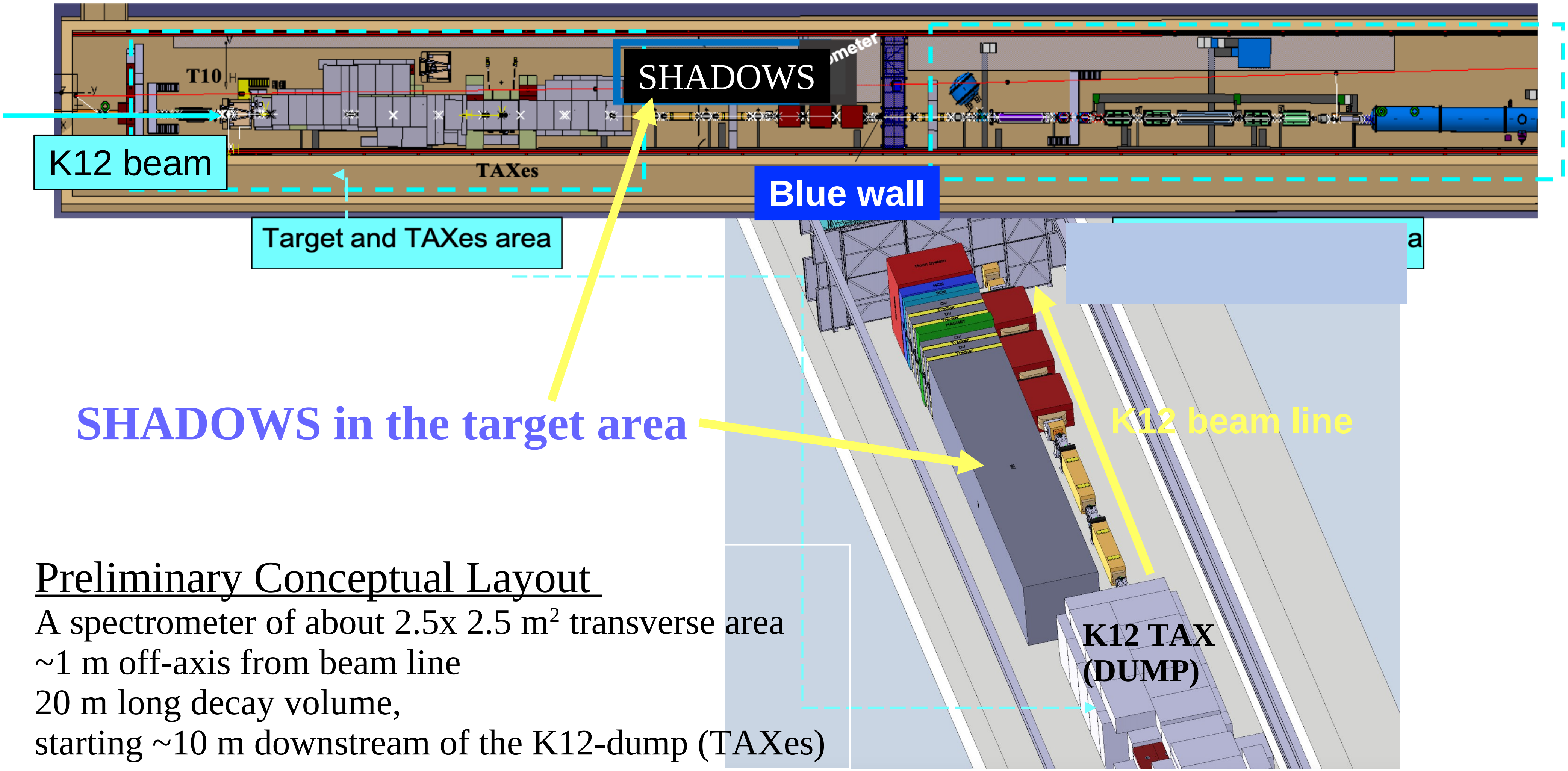
Highest energy/intensity proton, hadron, electrons, positron, and muon extracted beams in the world delivered for fixed target experiments and test beams.

SHADOWS in TCC8/ECN3

SHADOWS experiment is designed to be located in TCC8/ECN3, served by a 400 GeV proton primary beam line, where K12 beam for NA62 is produced.
SHADOWS can operate when K12 beam line runs in dump mode (i.e. 400 GeV protons are dumped on TAXes) concurrently with HIKE.
Proposed beam intensity upgrade (x7) to 2×10^{13} pot in 4.8 sec spills (1.2×10^{19} pot in a year).



SHADOWS in TCC8/ECN3

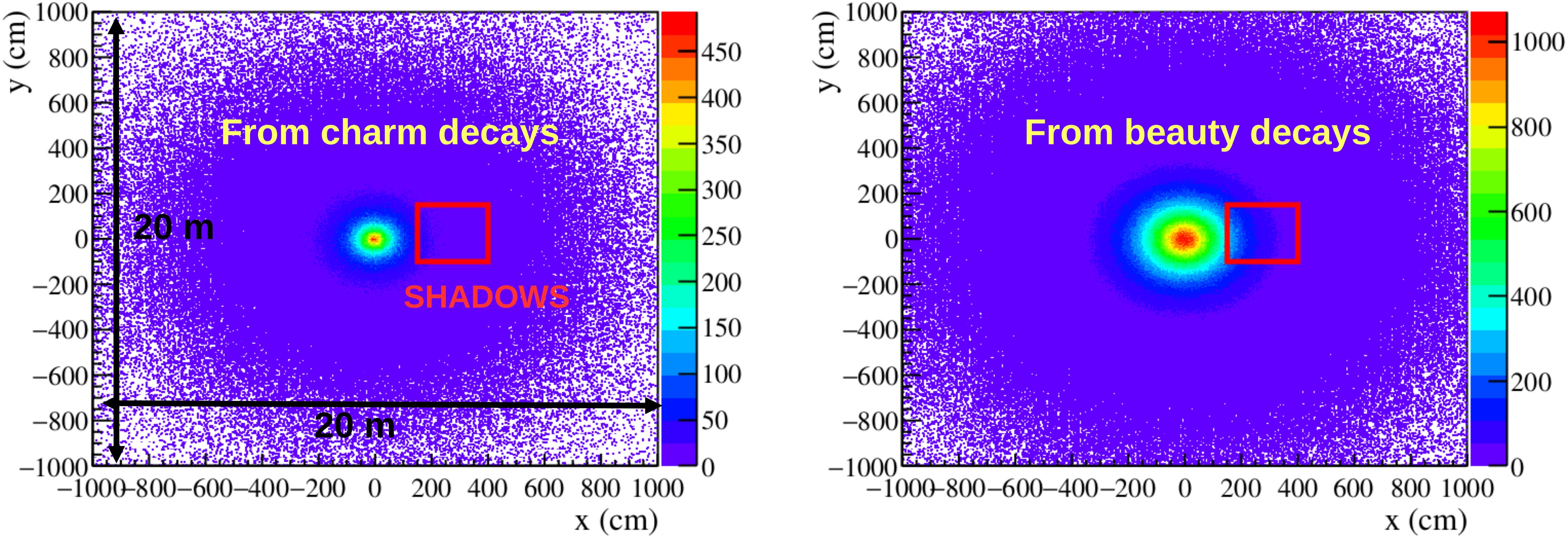


<u>Preliminary Conceptual Layout</u>

A spectrometer of about 2.5x 2.5 m^2 transverse area
~1 m off-axis from beam line
20 m long decay volume,
starting ~10 m downstream of the K12-dump (TAXes)

Why off-axis works

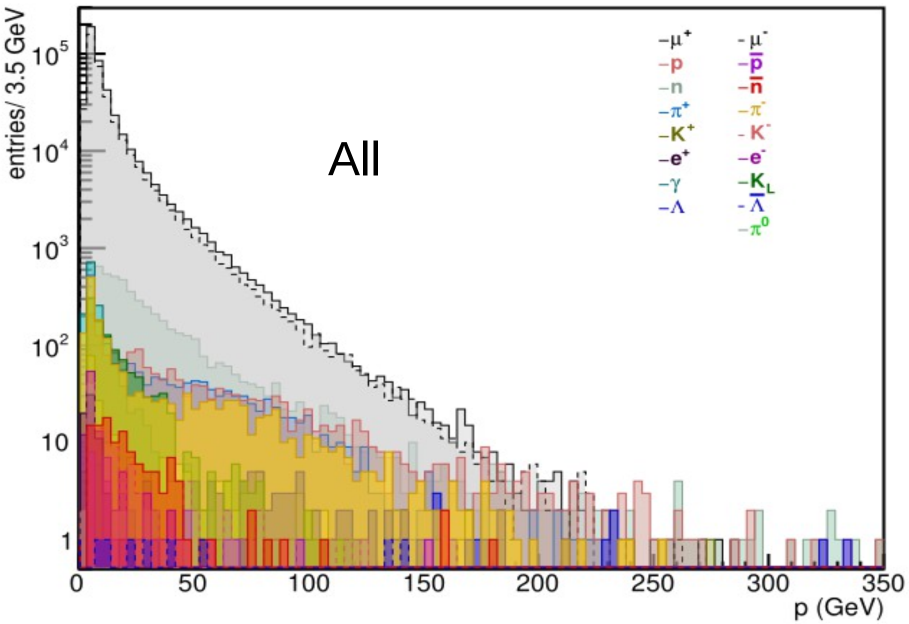
HNL → πμ illumination @ first SHADOWS tracker station

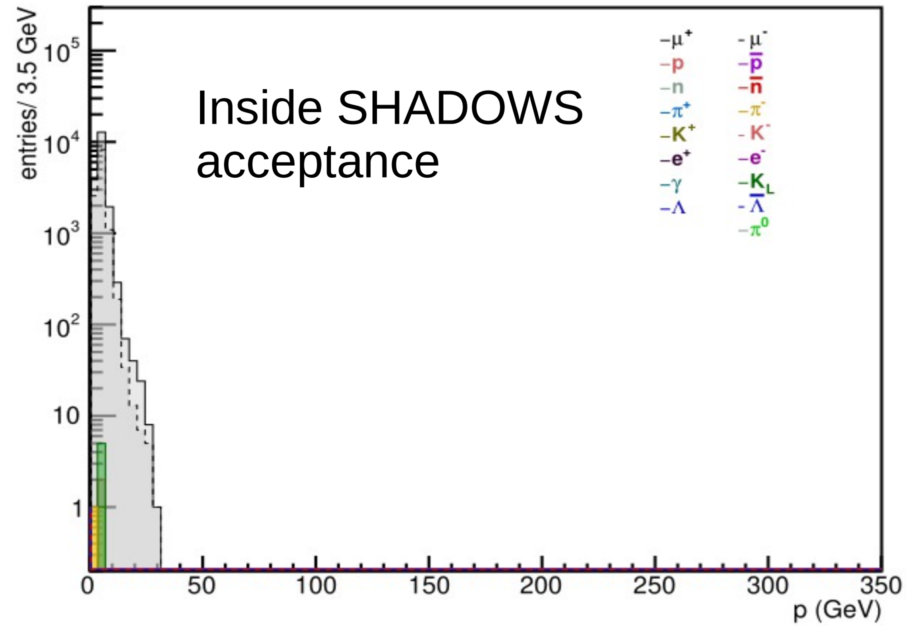


FIPs emerging from charm and beauty decays are produced at high P_T even at SPS energy.

Why off-axis works (2)

Beam background spectra in front of decay vessel (1.3x10^9 pot)





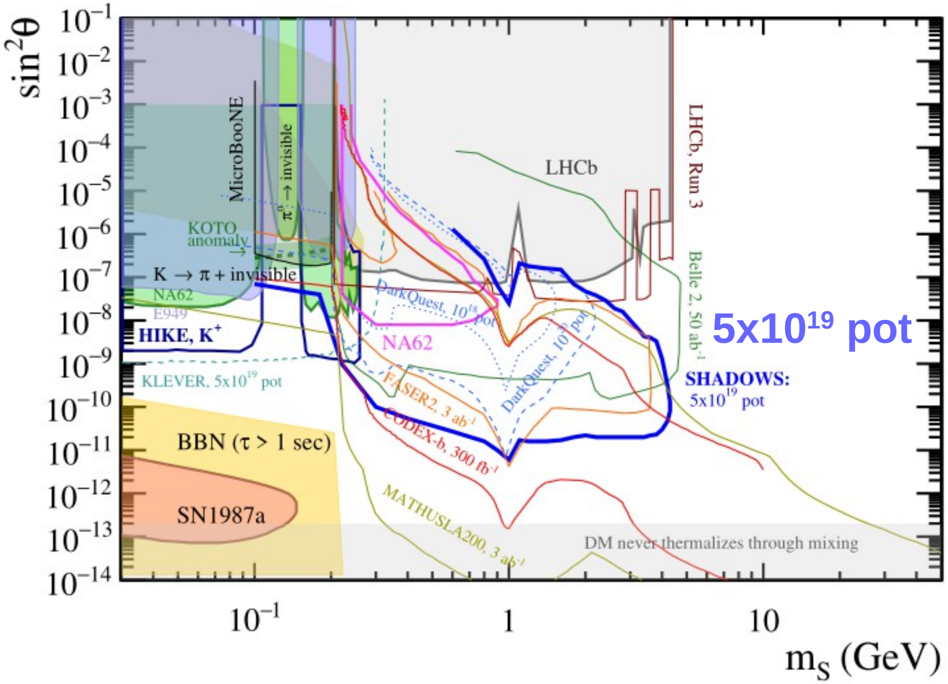
Most of the residual backgrounds emerging from dump (muons and neutrinos) are produced forward (missing SHADOWS acceptance).
Inside SHADOWS acceptance, muons have low-p (up to 30 GeV) and can be mostly swept away.

SHADOWS sensitivity to standard PBC benchmarks

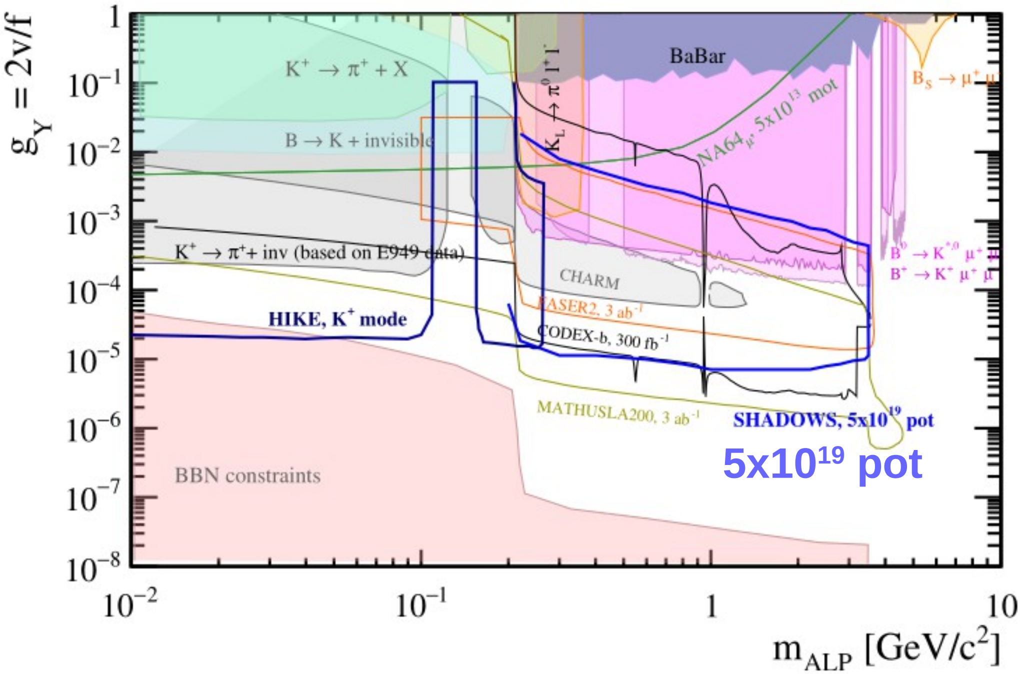
(PBC benchmarks: J. Phys.G47 (2020) 1, 010501, e-Print: 1901.09966, section 9)

SHADOWS sensible to FIPs produced in heavy quarks decay.
Interesting sinergy with NA62/Hike.

Light dark scalar mixing with Higgs boson



Axion-like Particle (ALP) at QCD scale (fermion coupling)

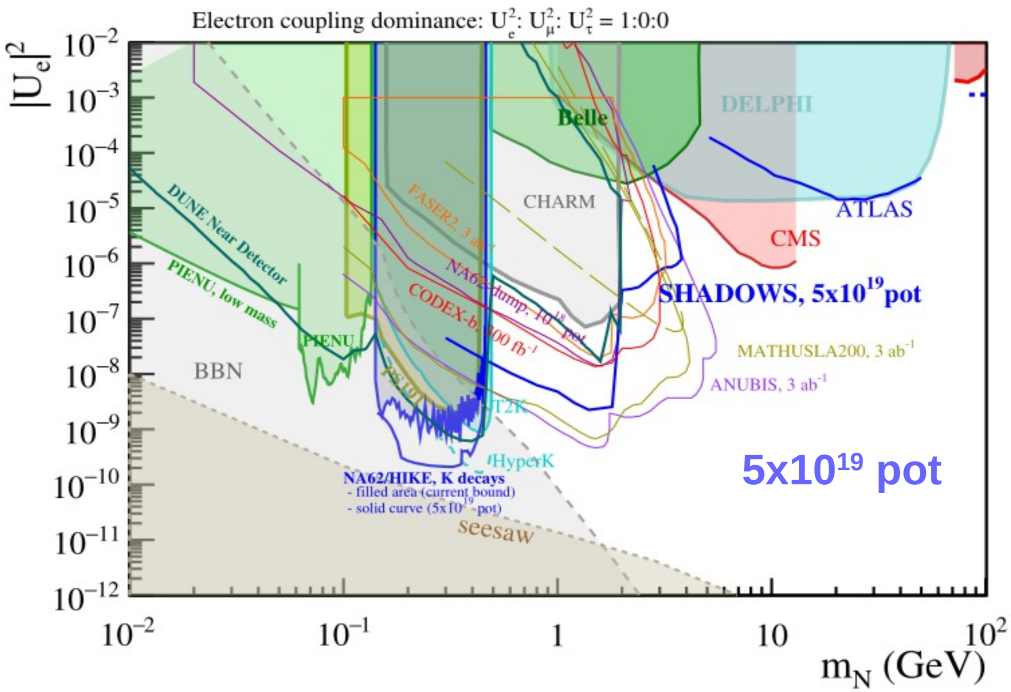


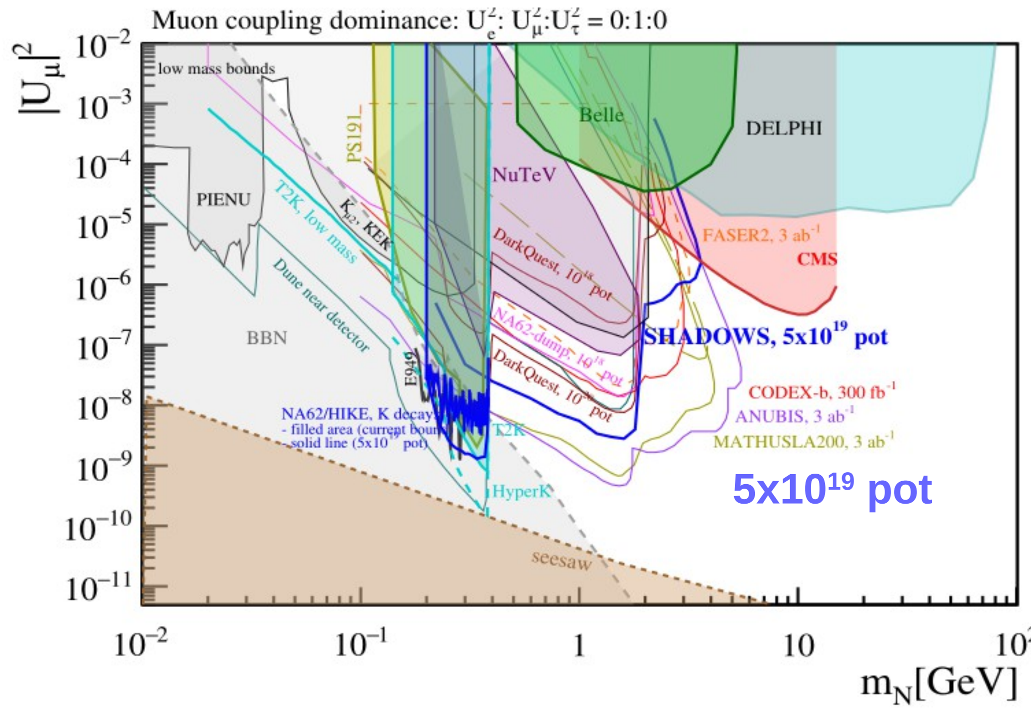
SHADOWS covers 4 orders of magnitude in coupling in the mass range ($2m_\mu$-m_b).

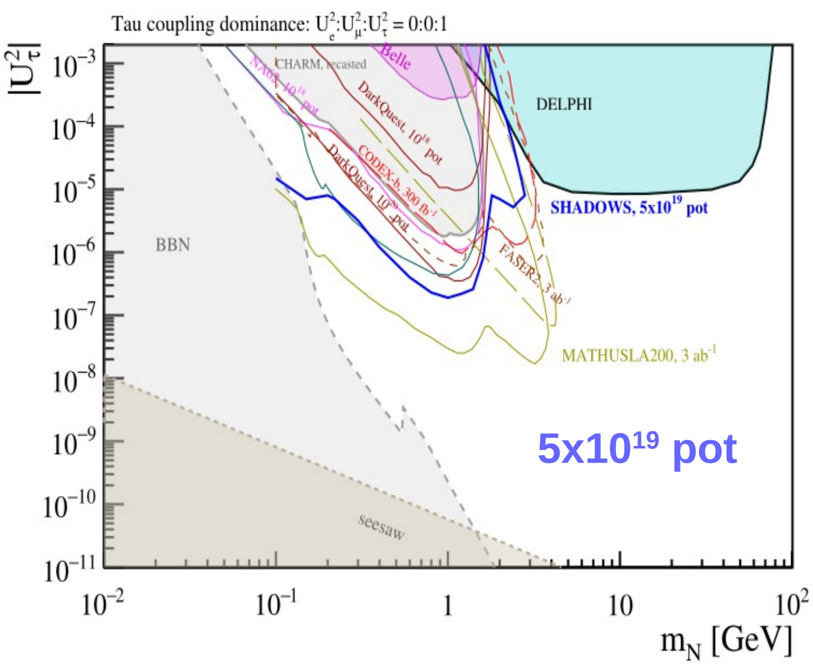
SHADOWS (5×10^{19} pot) better than FASER2 (3 ab^{-1}), comparable to CODEX-b (300 fb^{-1}).

SHADOWS sensitivity to standard PBC benchmarks

(PBC benchmarks: J. Phys.G47 (2020) 1, 010501, e-Print: 1901.09966, section 9)







Heavy Neutral Leptons (single lepton dominance)

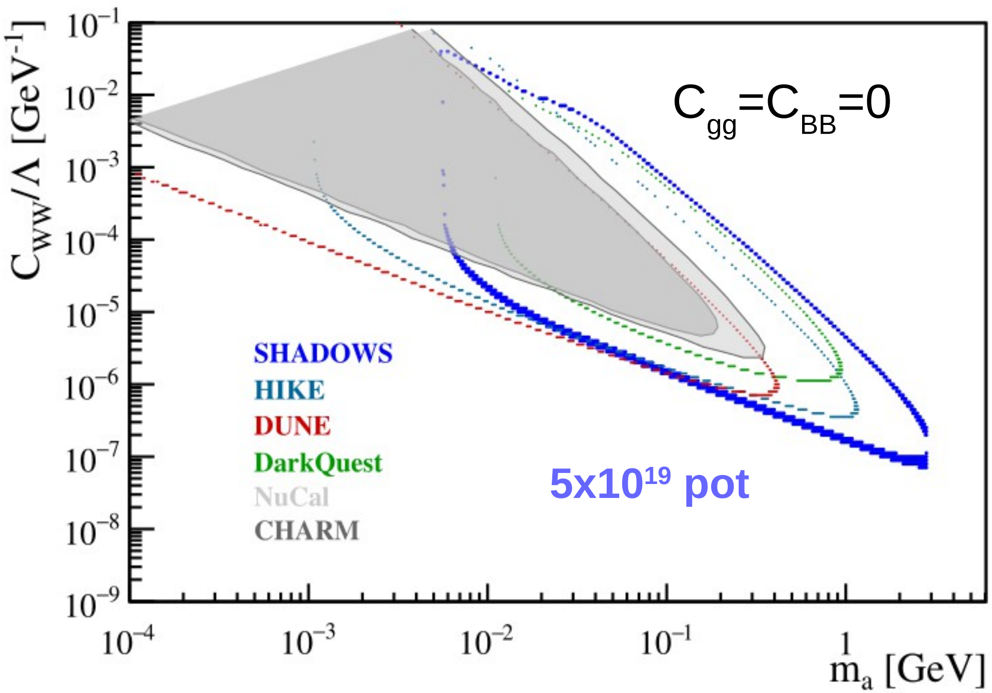
In the mass range (m_K-m_D) SHADOWS is (much) better than Codex-b and FASER2 (full dataset).
In the mass range (m_D-m_B) SHADOWS extends of 2-3 orders of magnitude the explored range for mixing matrix elements.

SHADOWS sensitivity to standard PBC benchmarks

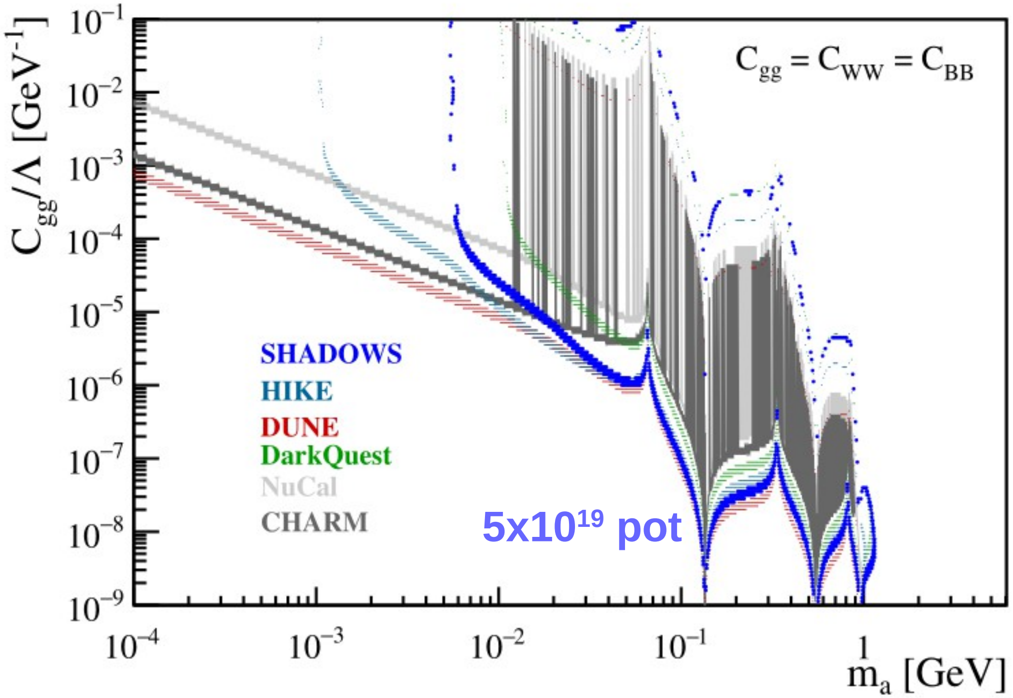
(PBC benchmarks: J. Phys.G47 (2020) 1, 010501, e-Print: 1901.09966, section 9)

Derived from
F. Kahlhoefer et al, 2201.05170 (only fixed target/beam dump experiments considered).

ALPs @QCD scale (W coupling)



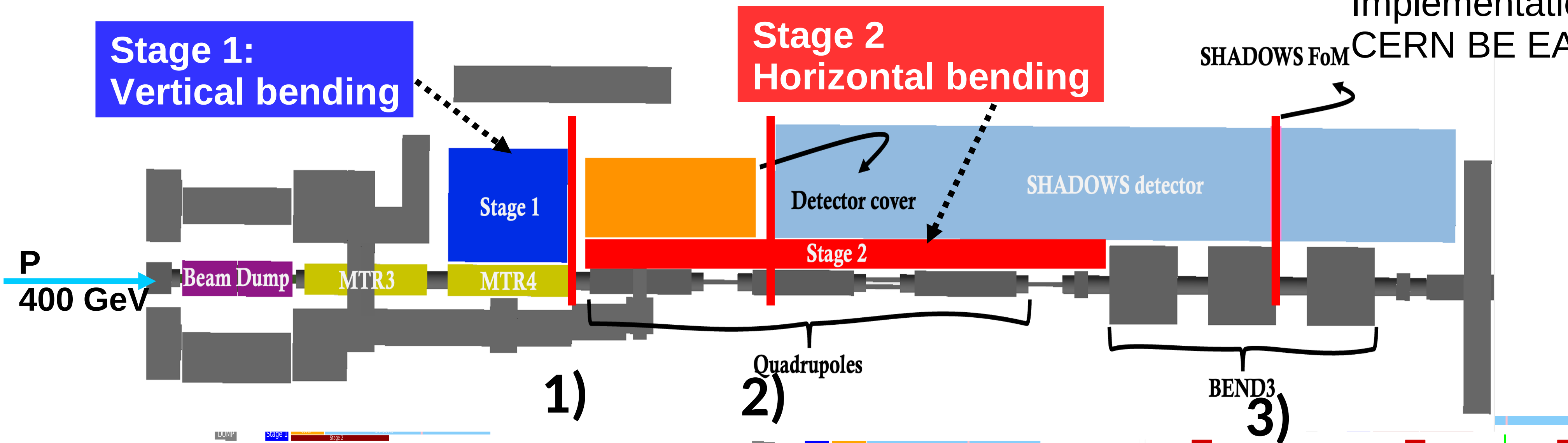
ALPs @QCD scale (gluon coupling)

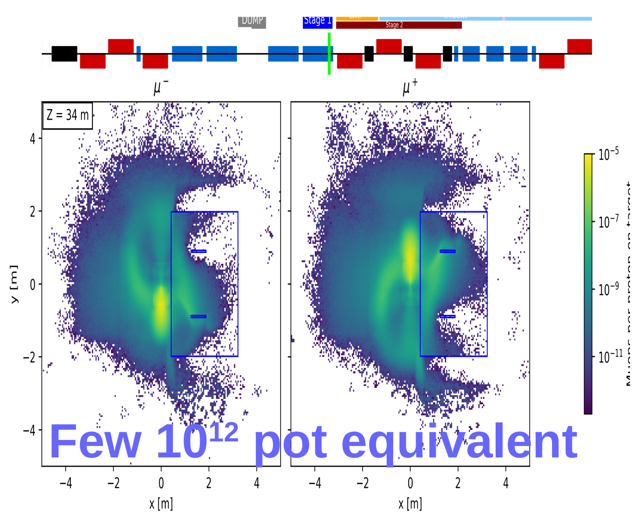


SHADOWS (5×10^{19} pot) competitive with DUNE for small couplings and extends the mass range towards heavier ALPs and larger couplings.

SHADOWS Muon Sweeper: a system of Magnetized Iron Blocks

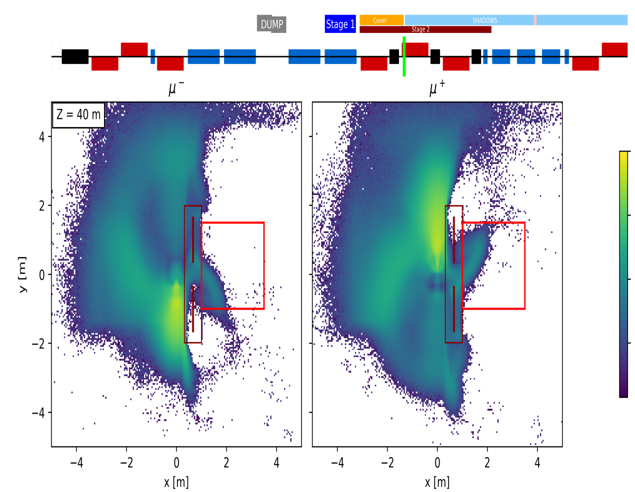
Implementation:
CERN BE EA LE



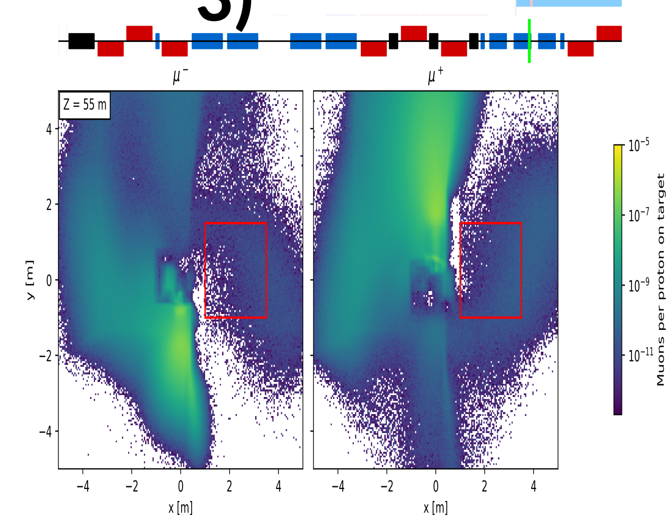


Few 10^{12} pot equivalent

1. End of MIB Stage1



2. Upstream Veto



3. First Tracking Station

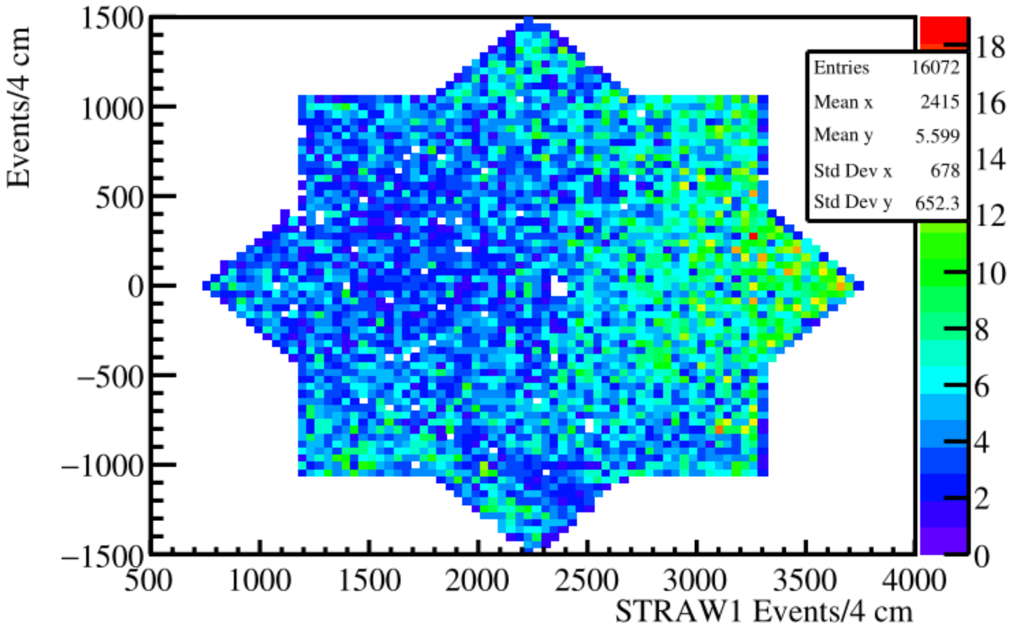
	$\mu^+ + \mu^-$	μ^+	μ^-
rate before MIB	100 MHz	50 MHz	50 MHz
MIB reduction factor	$\sim$ 120	$\sim$ 110	$\sim$ 150
rate after MIB	0.8 MHz	0.5 MHz	0.3 MHz

Muon rate in SHADOWS acceptance

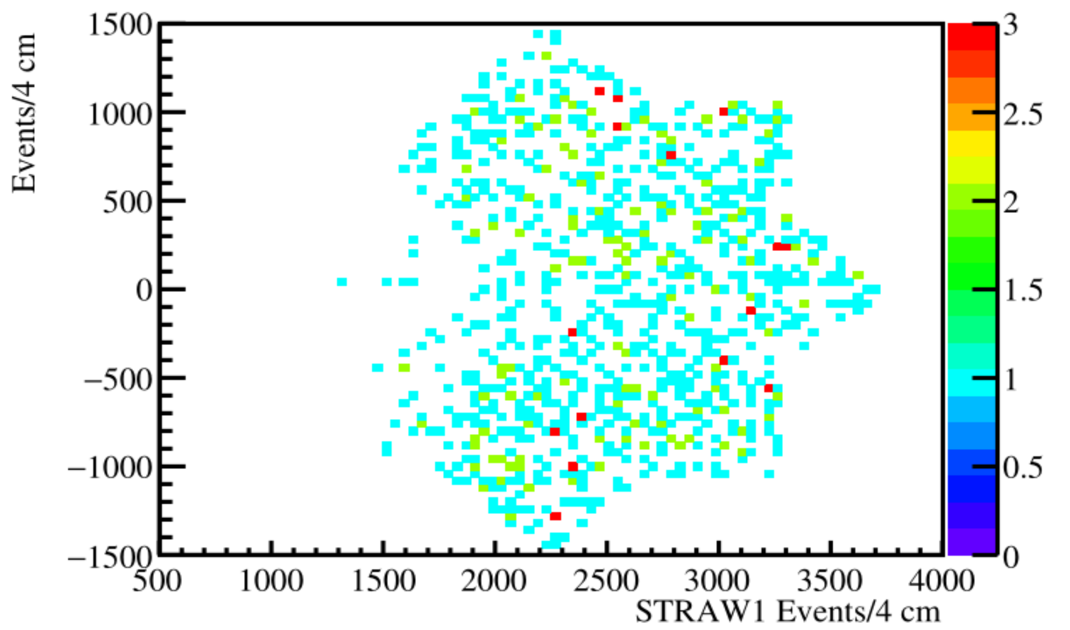
Expected combinatorial background: 0.6 events for 5×10^{19} pot

Magnetized Iron Block (MIB)

First tracker station muon illumination (using SHADOWS detector simulation)



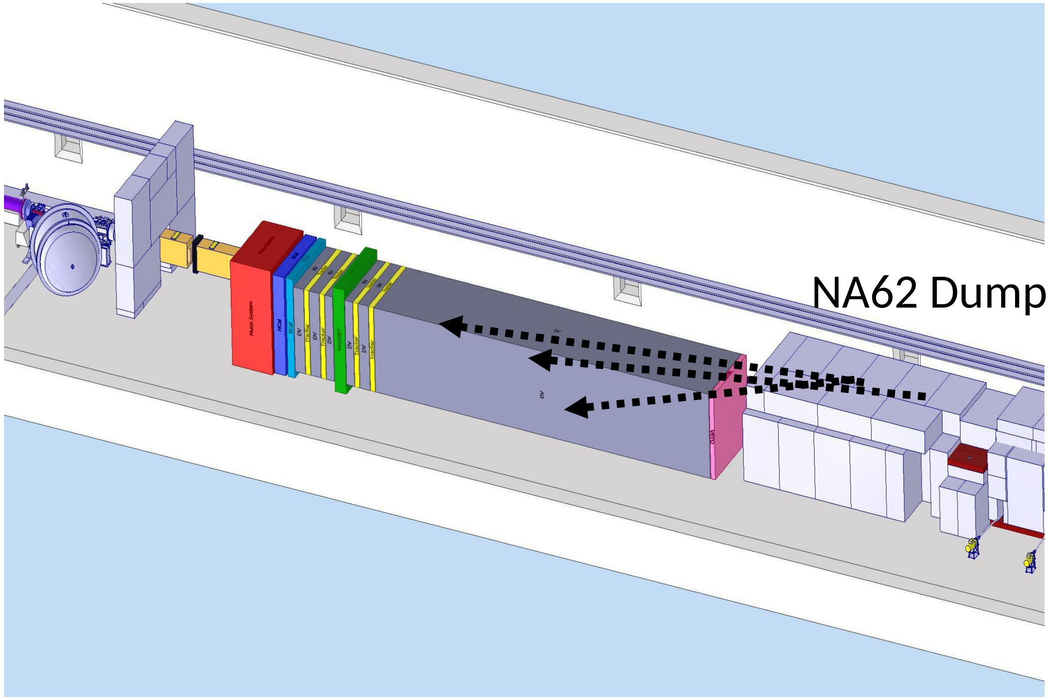
Without MIB (1.3x10^{9} pot simulation)



With MIB (10^{10} pot simulation)
120 attenuation factor
(still margin for improvement)

Combinatorial muon background

Most dangerous background: random combination of opposite charge muons, entering the decay vessel and mimicking a decay vertex in the fiducial volume.
Muon rate without MIB: 100 MHz in acceptance from NA62 data and MC.
Assume MIB reduces it to 0.8 MHz , we have ~4 Mevents/spill, 4-sec long.



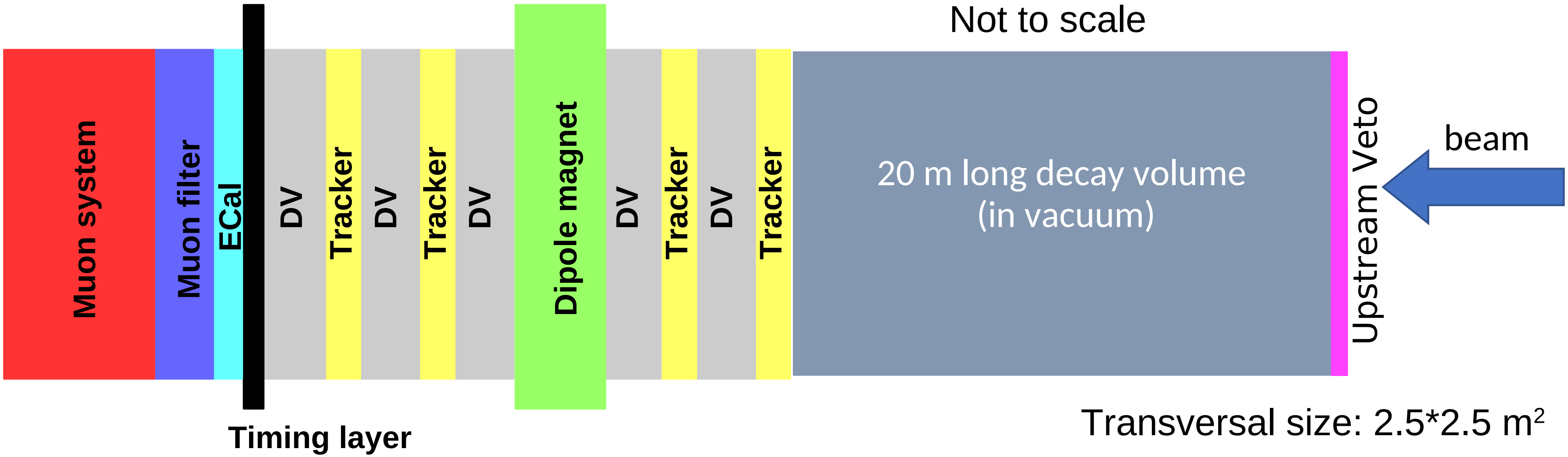
Background mitigation using event properties:
1) Timing:$\pm 3\sigma_t$ (σ_t~100 ps)coincidence:430/spill
2) VETO efficiency (99.5%): probability of not vetoing each of the two=2.5×10^{-5}
3) Vertex reconstruction in Fiducial Volume (s~cm) probability=2×10^{-3}
4) Pointing to proton dump (10^{-2} attenuation)

$N(\mu^+\mu^-)=430\times2.5\times10^{-5}\times2\times10^{-3}\times10^{-2} \sim 10^{-7}$/spill
Expected bkg events on experiment lifetime (3×10^6 spill) = 0.6

Other sub-dominant backgrounds under investigation:
Neutrino inelastic interactions with the air of the decay volume (mitigated with low pressure)
Muon inelastic interactions upstream or inside decay vessel producing V^0 mimicking signal

Detailed evaluation ongoing (still room for optimization).

Detector concept/requirements

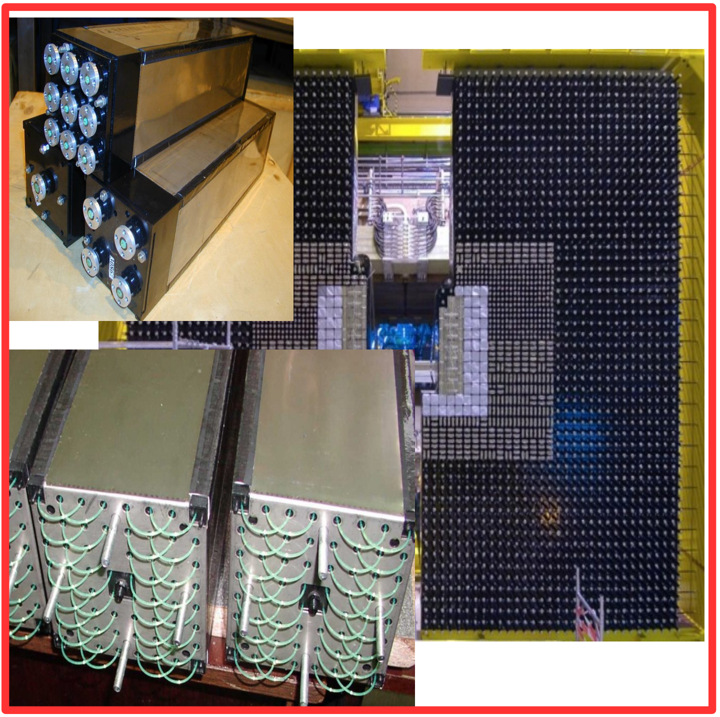


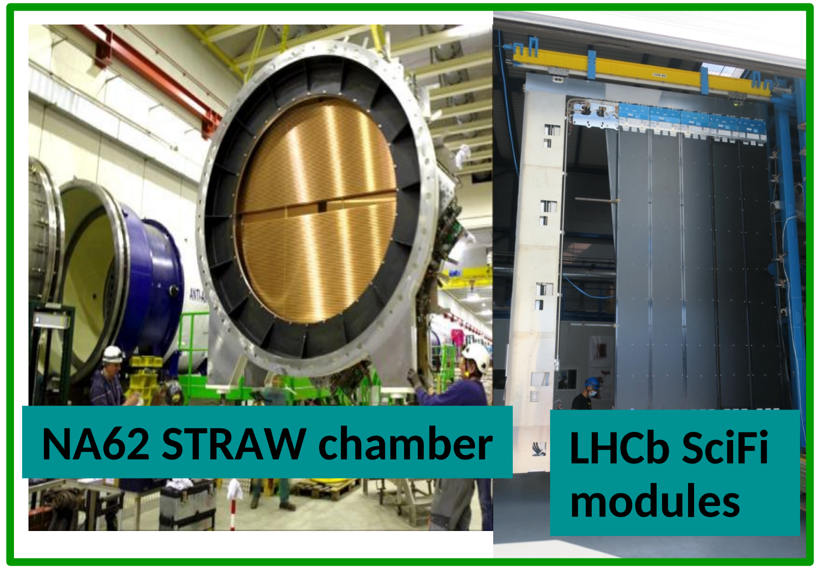
SHADOWS detectors and requirements:

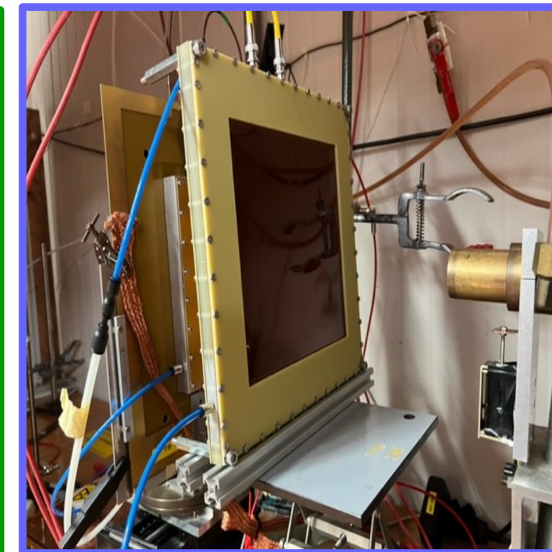
- **Upstream Veto (99.5% efficiency, 1 ns time resolution, 1 cm space resolution, several kHz/cm^2 rate capability)**
- **20 m long in vacuum decay vessel (1 mbar pressure to minimize interactions)**
- **Tracking system with a (warm) dipole magnet (vacuum operation, cm resolution on vertexes inside decay vessel)**
- **Timing layer (99.5% efficiency, 100 ps time resolution, 1 cm space resolution, 100 Hz/cm^2 rate capability)**
- **Electromagnetic calorimeter (e/γ vs μ/h identification, 10% σ_E up to 100 GeV, few cm granularity)**
- **Muon filter and four Muon Stations (99% efficiency, 150 ps time resolution, 100 Hz/cm^2 rate capability)**

SHADOWS can be built with existing technologies (more than one option/detector considered).

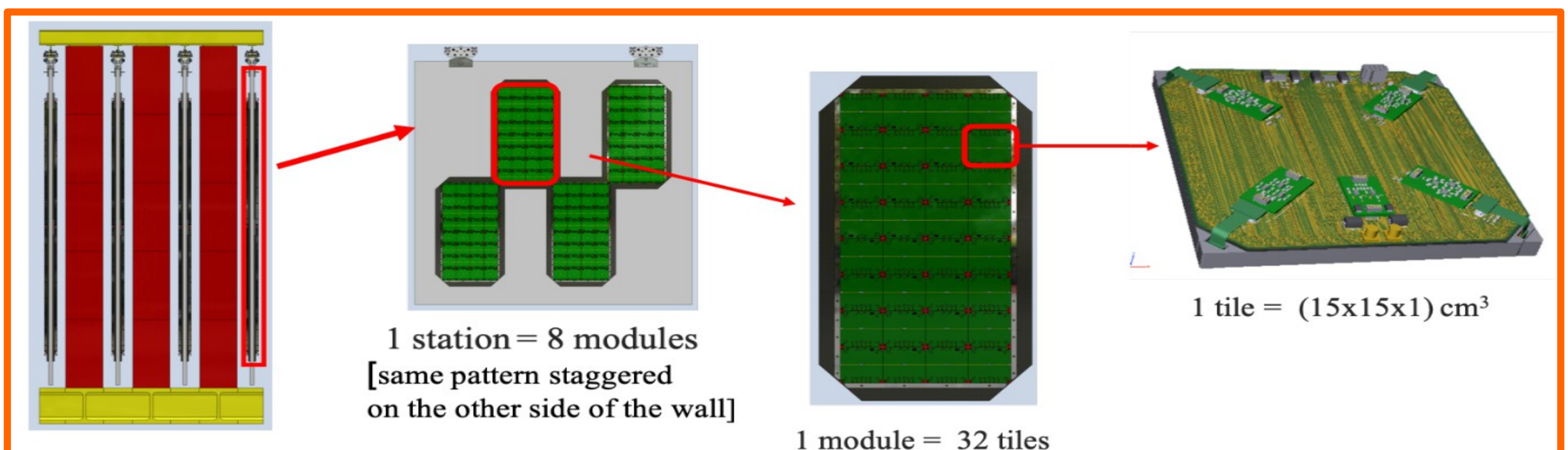
SHADOWS detectors



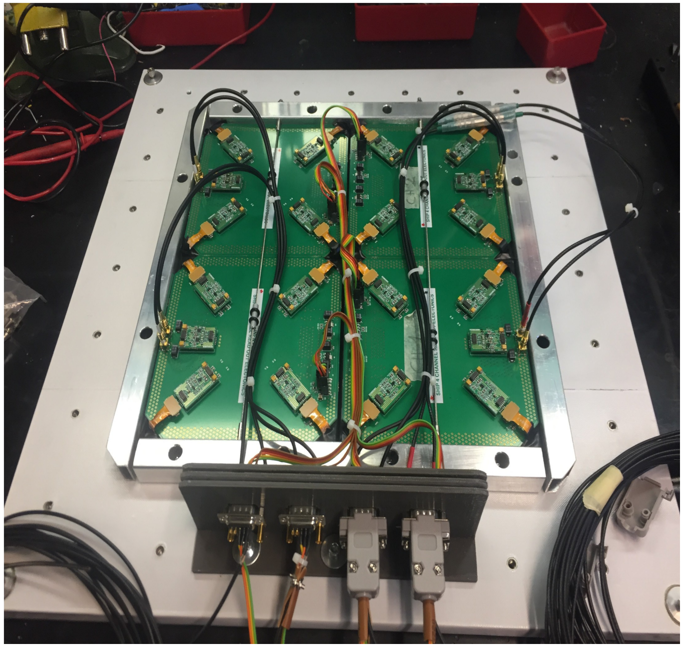




Upstream Veto: double layer of MicroMegas (INFN Napoli-Roma3)
Decay vessel and warm dipole magnet (CERN DT)
Tracking system: Straw tubes/Fibre tracker (Heidelberg/CERN)
Timing layer: scintillating bars, glass RPCs, MCPs
Electromagnetic calorimeter: Shashlik, $PbWO_4$ crystals, tracking calorimeter (Karlsruhe/Mainz)
Muon System: iron walls/scintillator tiles with direct SiPM readout (INFN Bologna-Ferrara-Frascati)



Muon detector - prototypes

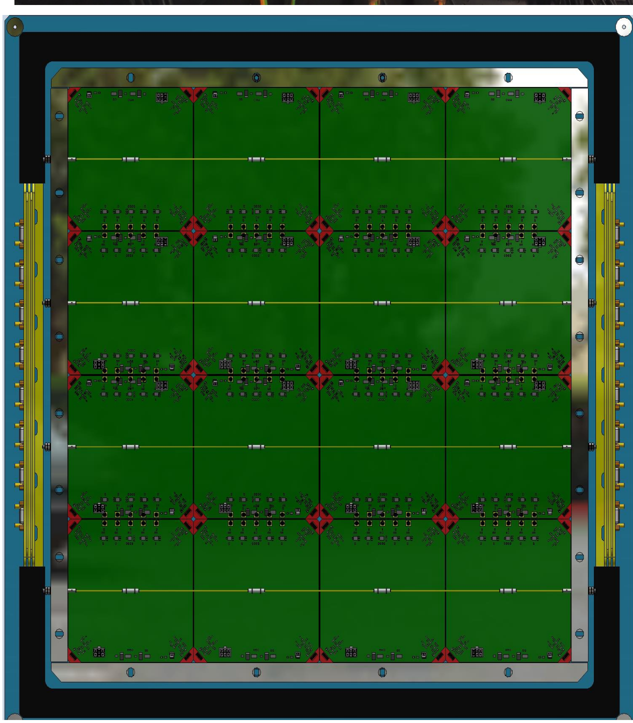


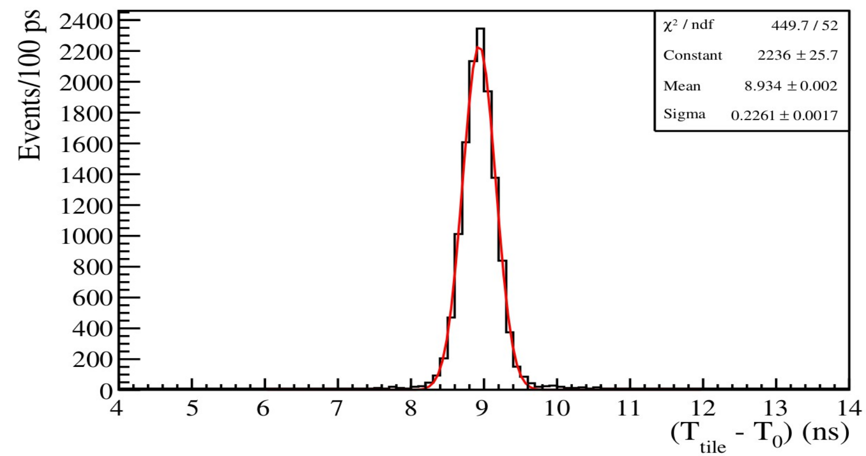
4 tiles prototype assembled at INFN Bologna and LNF.
Different construction techniques and FE electronics tested.
Tested @BTF and with cosmic rays:

- Efficiency > 99.5%
- N(pe)/Mip ~ 230
- σ_t ~ 250 ps/tile

JINST 17 (2022) 01, P01038

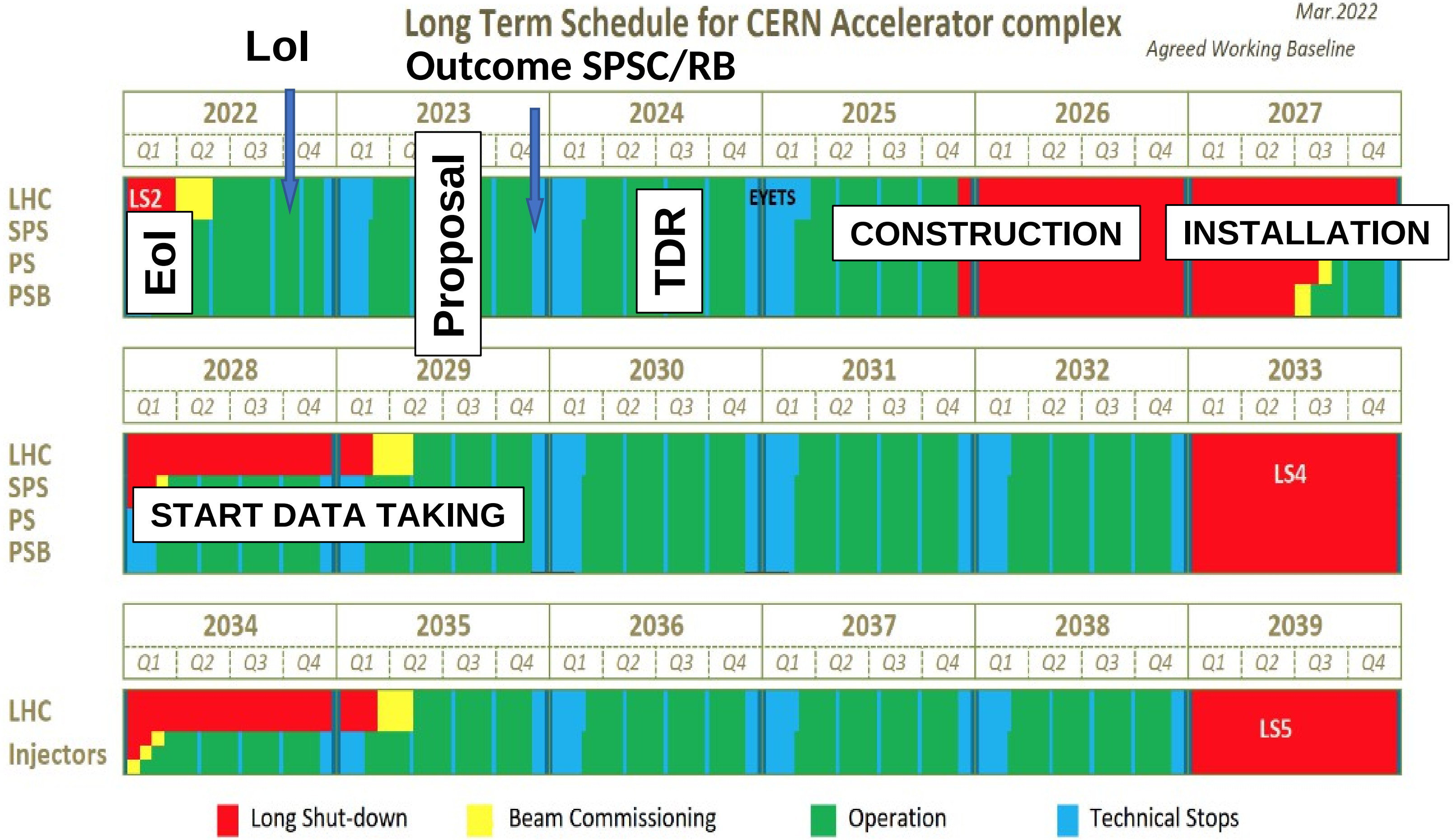
Geant4 simulation also developed for performance evaluation.





Two big modules funded by INFN (under AIDA-Innova, Task 8.3.2)
Full size prototype under development (AIDA-Innova milestone early 2023)

Time schedule and milestones



Jan 2022: EoI submission to the SPSC.
Jan-April 2022: Review process with SPSC Referees.
April 2022: Presentation to SPSC Open Session & positive outcome from the SPSC.
November 2022: LoI submission to SPSC.
October 2023: Proposal submission to SPSC.
End 2023: recommendation of the SPSC.

Conclusions

SHADOWS is a proposed proton beam dump experiment for FIPs physics that can be built in ECN3 and take data concurrently to HIKE (operated in beam-dump mode):

⇨ SHADOWS can be built now: (almost) all the infrastructure is in place.

SHADOWS ($5x10^{19}$ pot) has similar/better sensitivity than CODEX-b (300 fb^{-1}) and FASER2 (3 ab^{-1}) for FIPs from charm/beauty:

⇨ It naturally complements HIKE-dump that is mostly sensitive to very forward objects, and HIKE-K that is mostly sensitive to FIPs below the K-mass.

ECN3 with SHADOWS+HIKE can become a "hot spot" on worldwide scale for FIP physics after LS3, fully compatible with a superb flavor programme in ECN3.

Next steps:

- LoI Submission to SPSC (November 2022).
- Proposal submission to SPSC (October 2023).
- Decision by CERN expected 2nd half 2023.