The SHADOWS experiment at the CERN SPS

V. Cicero on behalf of the SHADOWS Collaboration

28/09/2023 16th Topical Seminar on Innovative Particle and Radiation Detectors

SHADOWS

- The European Particle Physics Strategy's update highlights the importance of studying the Physics of Feebly-Interacting Particles in the next decade.
- SHADOWS is a newly proposed beam dump experiment to search for FIPs in the range from MeV to few GeV, emerging from charm and beauty decays
- Collaboration steadily growing (82 collaborators, 16 institutions)
- Technical proposal submitted to SPS Committee.
- If project approval by end of 2023, SHADOWS can start data taking in 2030

Technical Proposal, 18 August 2023

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

SHADOWS

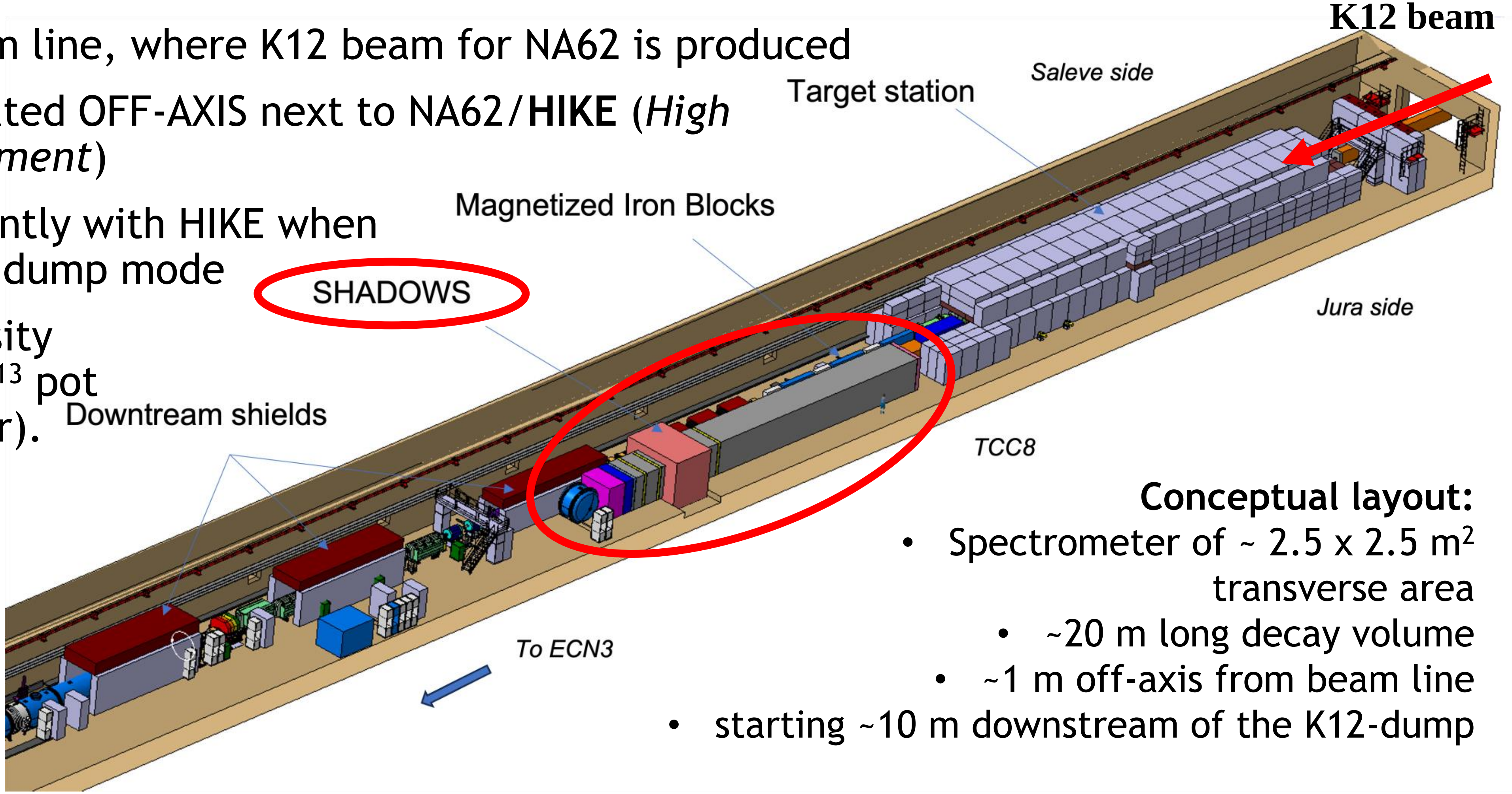
Search for Hidden And Dark Objects With the SPS

Technical Proposal

M. Alviggi[1], S. Bachmann[2], W. Baldini[3], A. Balla[4], M. Barth[2], M. Biglietti[5], V. Büscher[6], A. Calcaterra[4], V. Cafaro[7], M. Cavallina[3], A. Ceccucci[8], D. Chouhan[6], V. Cicero[7], P. Ciambrone[4], H. Danielsson[8], M. Della Pietra[1], C. Delogu[6], A. De Roeck[8], L. Dittmann[2], F. Duval[8], G. Felici[4], T. Ferber[9], L. Foggetta[4], E. Gamberini[8], M. Gatta[4], A. Gerbershagen[10], V. Giordano[7], S. Hansmann-Menzemer[2], P. Iengo[11], M. Iodice[11], K. Jakobs[12], J. Kieseler[9], M. Klute[9], K. Köneke[12], M. Koval[13], G. Lanfranchi[4], A. Laudrain[6], I. Lax[87, T. M. Leeflang[2], G. Lehmann Miotto[8], B. Leverington[2], P. Lichard[8], K. Massri[8], A. Montanari[7], T. Napolitano[4], A. Paoloni[4], G. Papalino[4], U. Parzefall[12], B. Ponzio[4], B. Regnery[9], S. Ritter[6], S. Rosati[15], T. Rovelli[16,7], S. Roy[2], A. Saputi[3], B. Schmidt[8], M. Schott[6], D. Schub[2], H.C. Schultz-Coulon[2], G. Sekhniaidze[1], R. Stamen[2], G. Torromeo[7], N. Tosi[7], N. Trevisani[6], U. Uwer[2], A. Vannozzi[4], C. Wang[6], R. Wanke[6], C. Weiser[12], C. Welschoff[2], P. Wertelaers[8]

SHADOWS

- The SHADOWS experiment is designed to be located in TCC8/ECN3 at CERN North Area
- 400 GeV primary beam line, where K12 beam for NA62 is produced
- SHADOWS will be located OFF-AXIS next to NA62/**HIKE** (*High Intensity Kaon Experiment*)
- Can operate concurrently with HIKE when the beam line runs in dump mode
- Proposed beam intensity upgrade (x7) to $2x10^{13}$ pot ($1.2x10^{19}$ pot in a year).

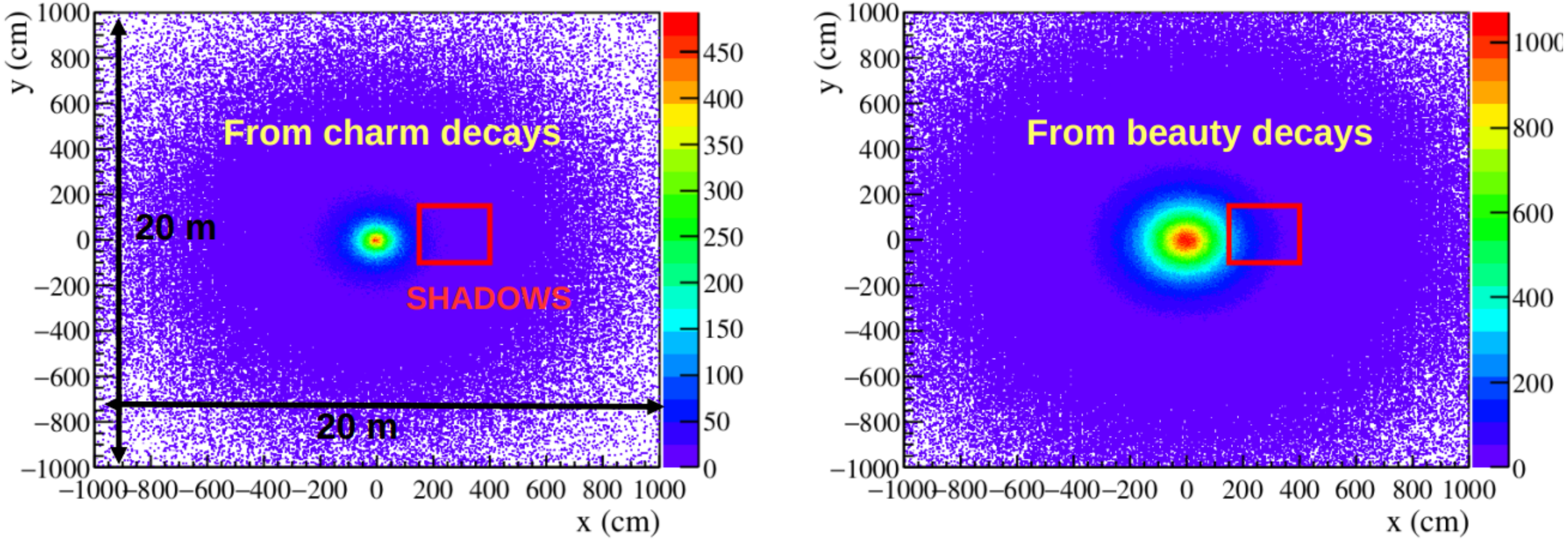


Conceptual layout:

- Spectrometer of ~ 2.5 x 2.5 m^2 transverse area
- ~20 m long decay volume
- ~1 m off-axis from beam line
- starting ~10 m downstream of the K12-dump

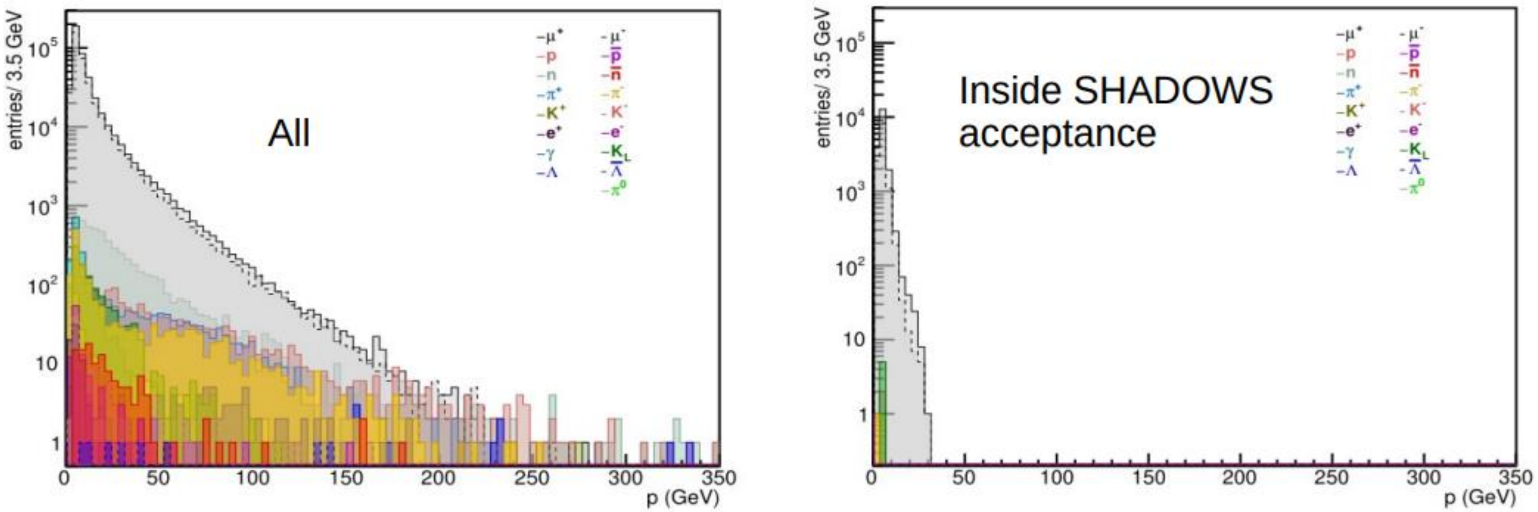
WHY OFF-AXIS?

HNL → μπ illumination @ first SHADOWS tracker station

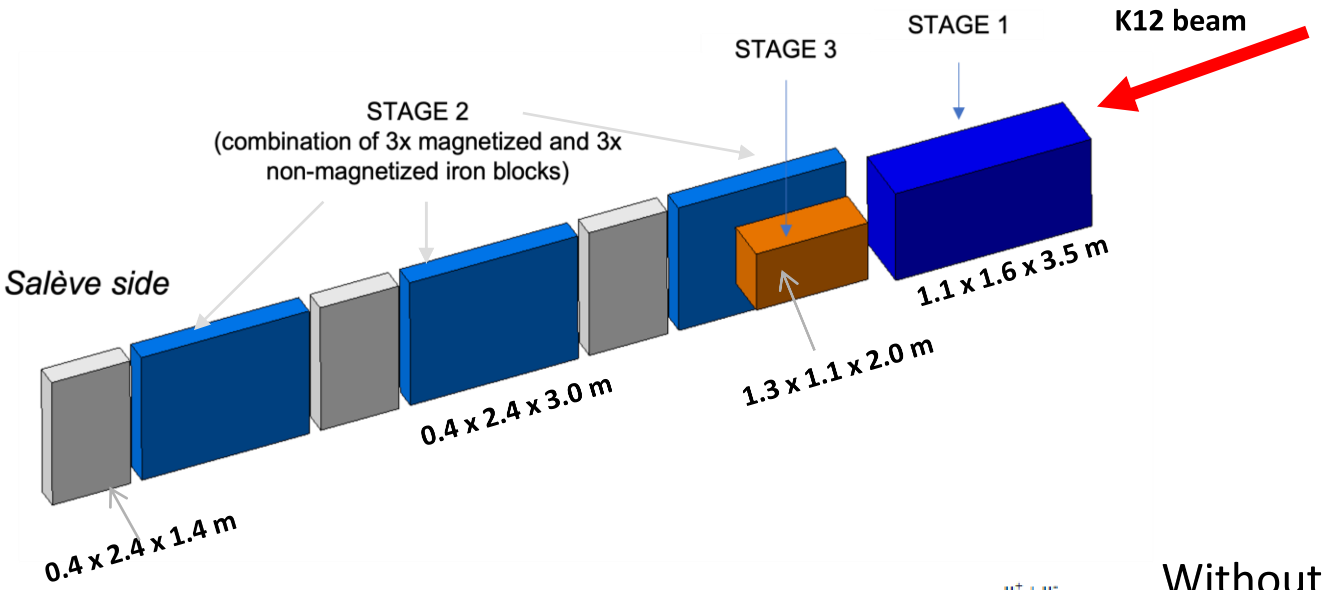


- at SPS $\sqrt{s}$ ~ 28 GeV heavy hadrons produced with small boost
- FIPs emerging from charm and beauty decays are produced at large polar angle

- Beam background (μ, ν) is concentrated in the forward region
- Inside SHADOWS acceptance, muons have low-p (up to 30 GeV) and can be mostly swept away.



MAGNETIZED IRON BLOCK SYSTEM



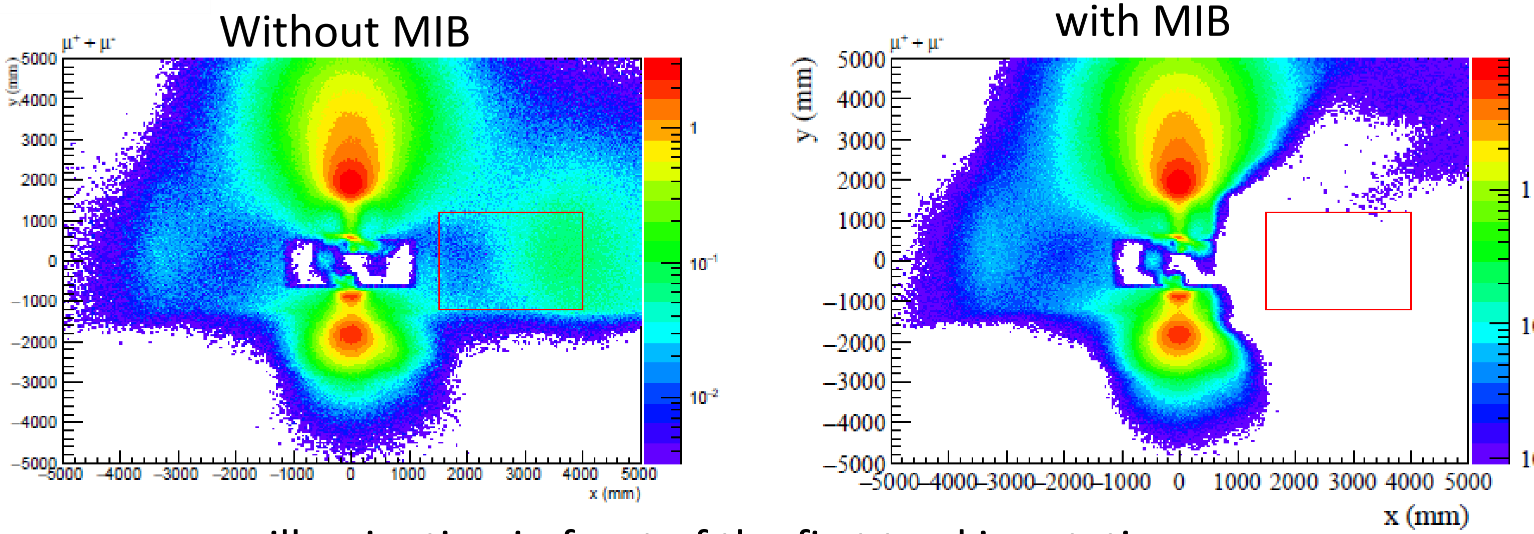
Magnetized Iron Block (MIB) system necessary to sweep the beam-induced muon flux out of the SHADOWS acceptance.

- 3 stages of active and passive mitigation
- Stage current = 100 A

μ+μ- rates in SHADOWS acceptance:

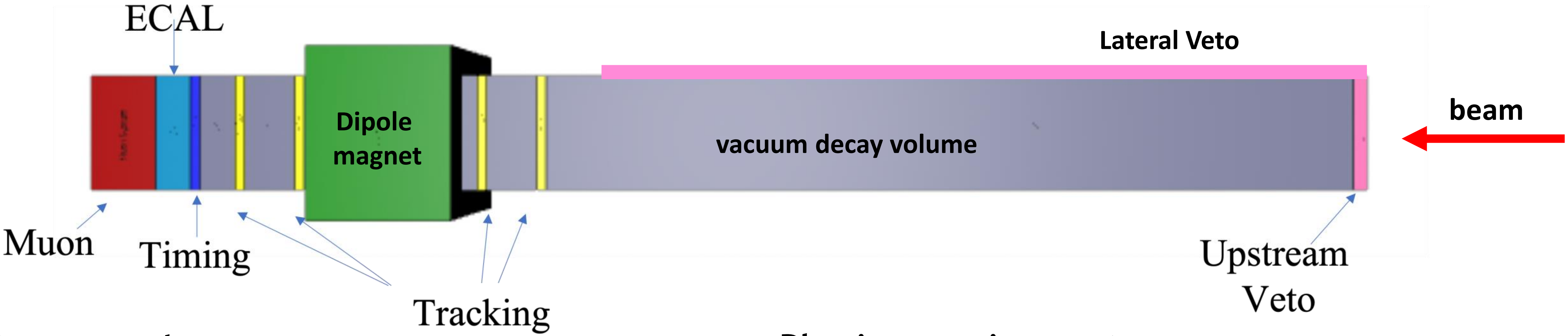
- Without MIB: 147 MHz
- With MIB: 2.1 MHz

→ MIB reduction factor ~ 70



μ illumination in front of the first tracking station

DETECTOR CONCEPT and REQUIREMENTS



Detector elements:

- 19 m long in-vacuum decay vessel
- Upstream and lateral vetoes
- Tracking system with dipole magnet
- Timing layer
- Electromagnetic calorimeter
- Muon filter and 4 muon stations

Physics requirements:

- reconstruct and identify most of the visible final states of FIPs decays.
- reject background coming mostly from combinatorial muons that can mimick FIP decays vertexes

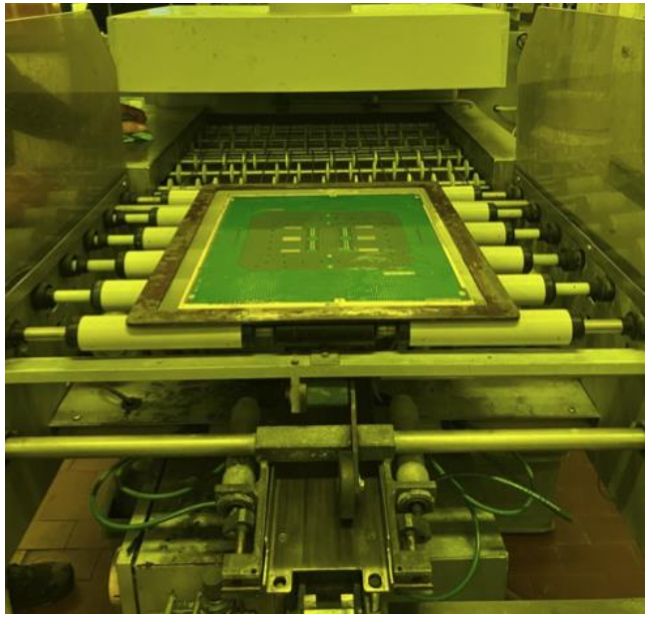
  - timing resolution $\sigma_t \sim 100$ ps
  - Veto efficiency > 99.0 %
  - Vertex resolution : ~ 1 cm inside decay vessel

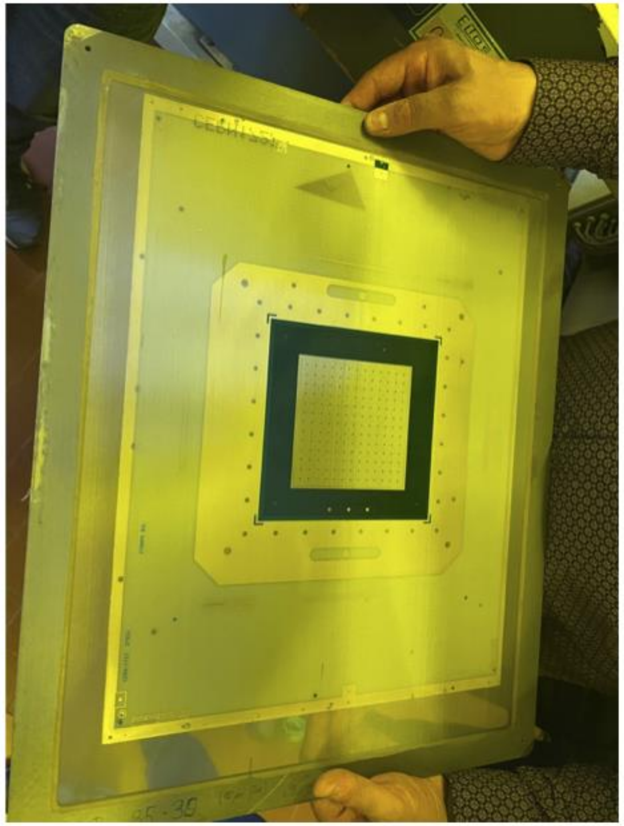
UPSTREAM and LATERAL VETO

Goal:
veto muons that enter the decay vessel escaping the MIB system

Technology:
Double layer of micromegas detectors

- efficiency > 99.8%
- space resolution: o(1) mm
- time resolution: o(10) ns
- rate capability: up to 10 MHz /cm^2

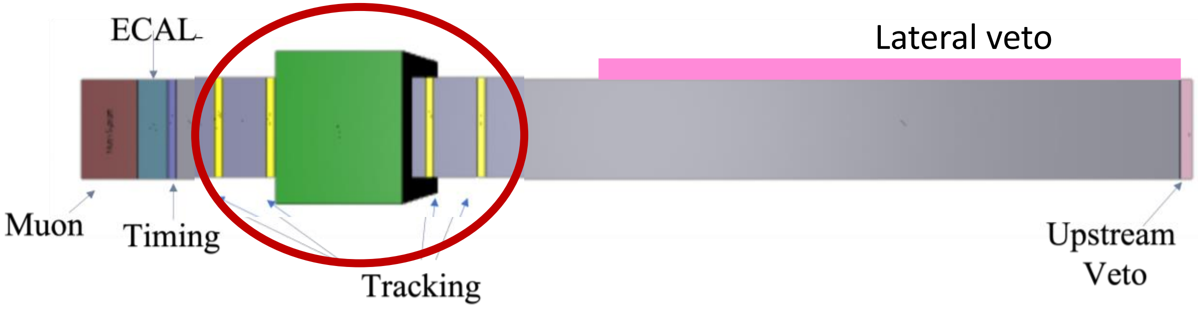




First small prototype funded by INFN in 2023
A large size prototype will be prepared in 2024

talk by M.T. Camerlingo: High Granularity Resistive Micromegas for Tracking Detectors in Future Experiments

TRACKING STATIONS

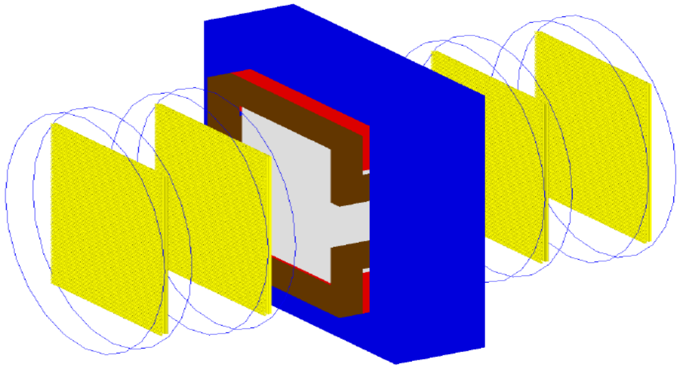


Goal:

Reconstruct signals and reject background with at least 2 tracks

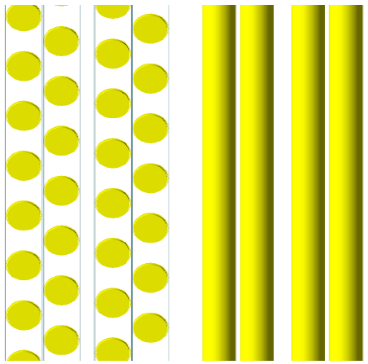
Requirements:

- Vertex resolution o(1) cm over 20 m
- IP resolution o(1) cm from 35 m distance
- Mass resolution: 1-2% mass

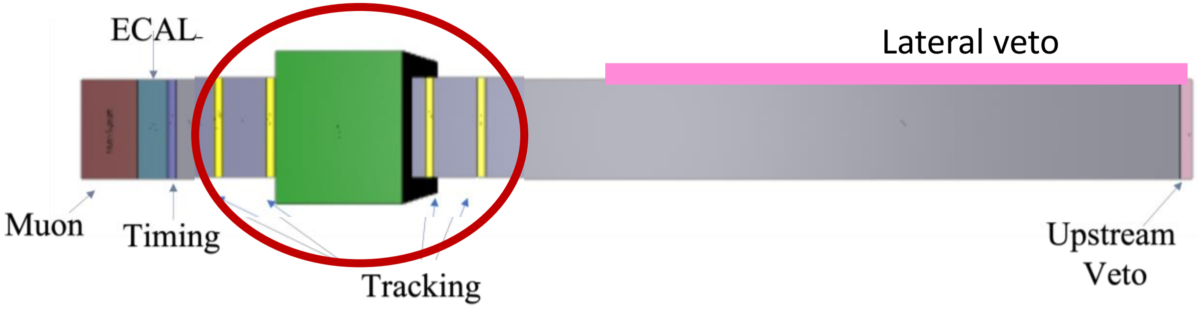


Baseline technology:

- Straw Tubes in vacuum (NA62-like)
  - Four stations, 2 views each, 4 layers per view
- Scintillating fibres technology under consideration



DIPOLE MAGNET

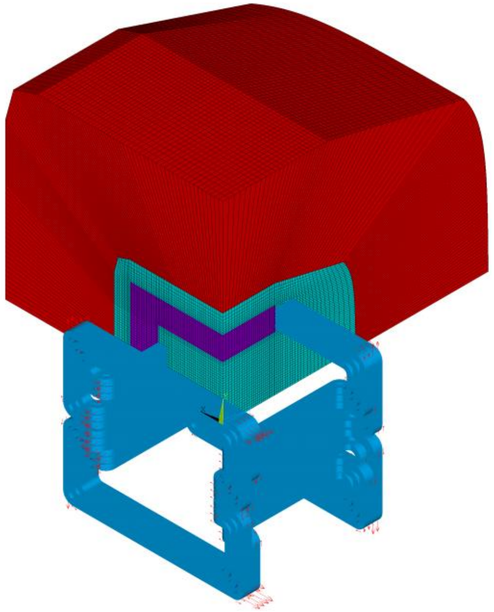


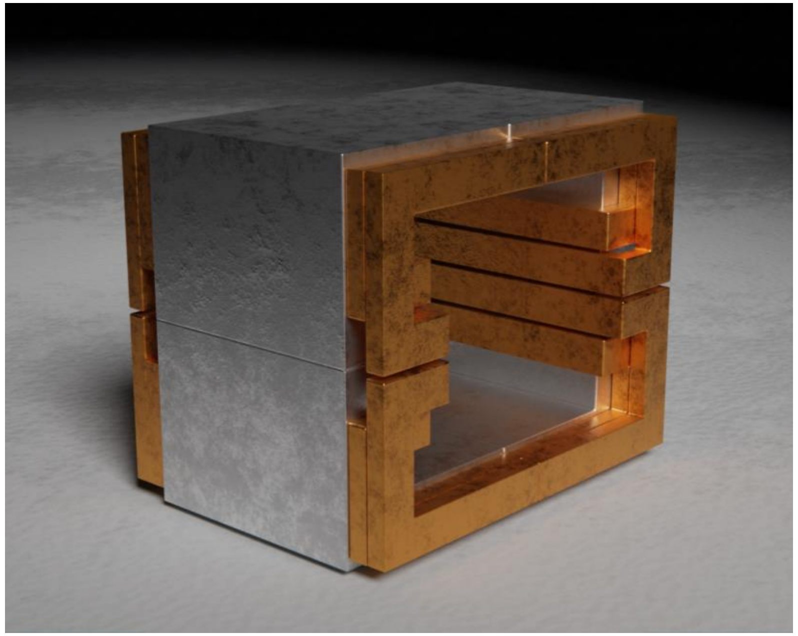
Requirements:

- field integral ~1 Tm
- low power consumption
- 2.7 x 2.7 m aperture

Baseline technology:

- warm magnet :
  - dissipated power: 287 kW
  - copper-based coil, iron-based yoke
- superconducting magnet under study

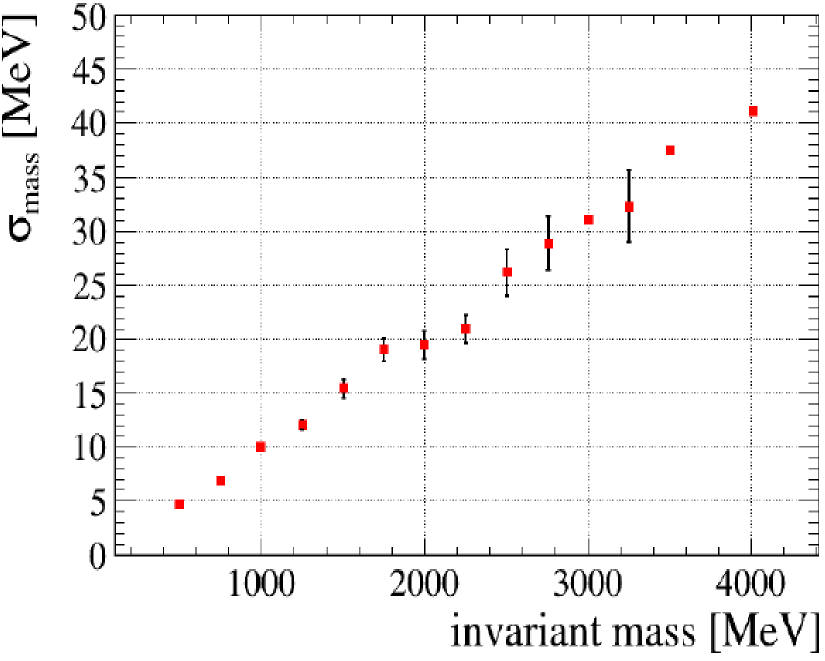




TRACKING PERFORMANCE

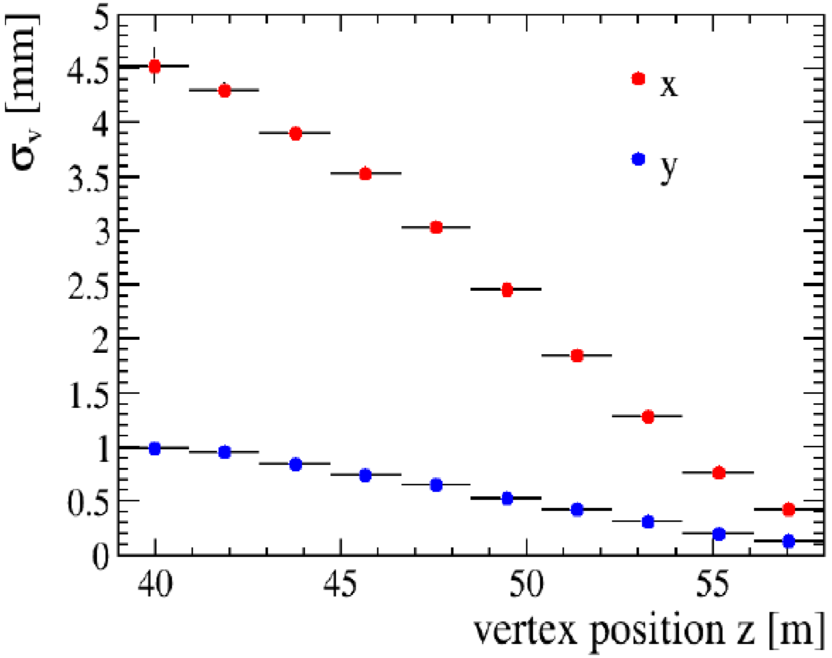
Reconstruction performance evaluated with Monte Carlo simulations of ALP particles with E = 600 MeV decaying into two muons

Mass resolution



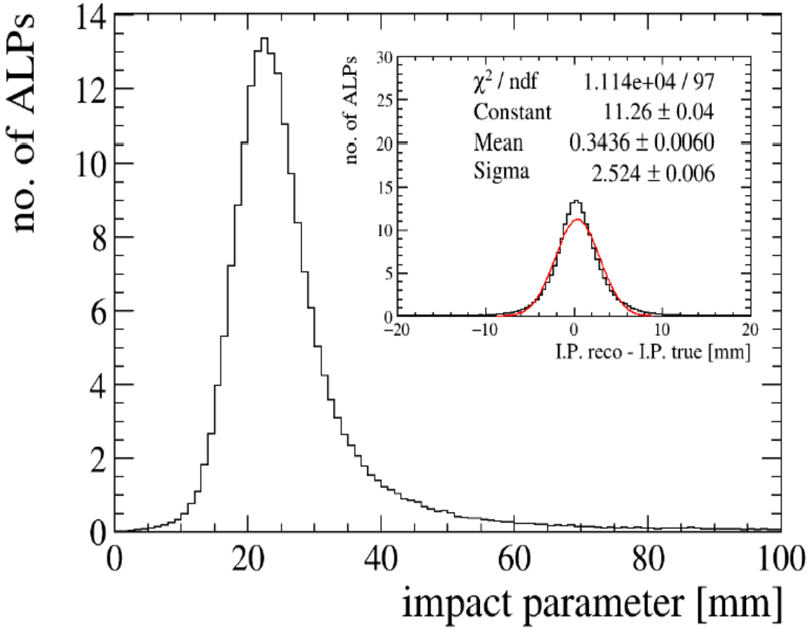
$\sigma(M)/M = 1\%$

Vertex resolution



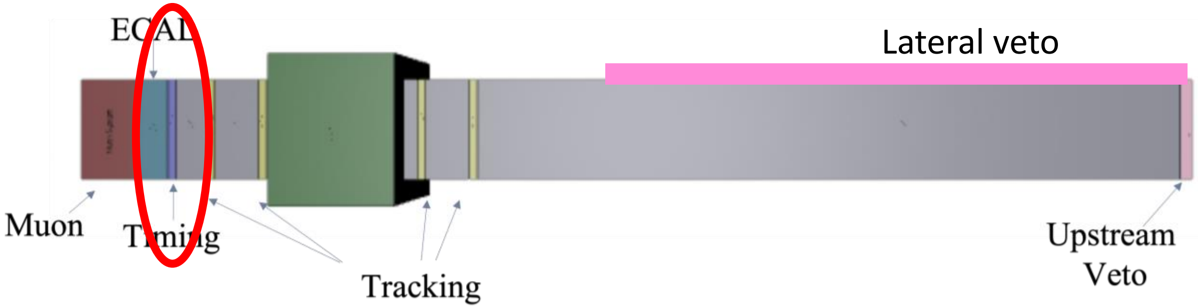
σ_x(vertex) = 0.5-4.5 mm
σ_y(vertex) = 0.2-1.0 mm

Impact parameter resolution



$\sigma(IP) = 3$ mm

TIMING LAYER



Goals:
reject muon combinatorial background requiring fast time coincidence

Requirements:
Time resolution of o(100) ps

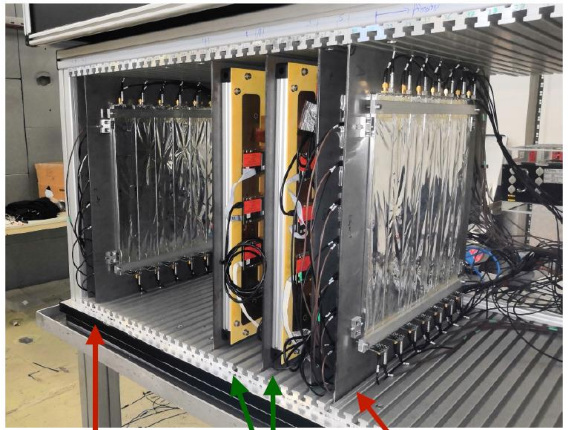
Baseline technology:
plastic scintillating bars with direct SiPM readout

- about 1 cm thickness, 6 cm width, 1.26 m length
- covering half of the 2.5 x 2.5 m^2 acceptance.
- Proved to reach < 100 ps time resolution.

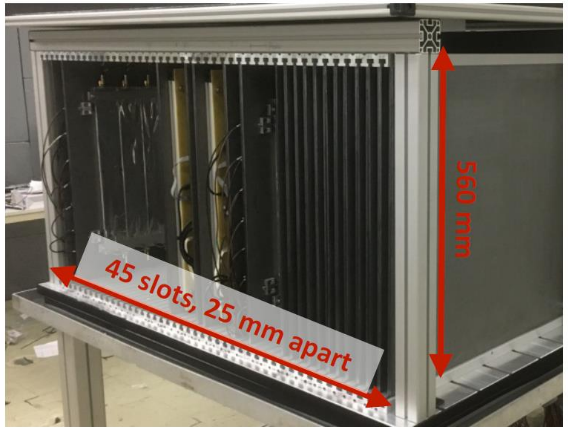
ECAL

Requirements:

- Moderate energy resolution: 10-15% / $\sqrt{E(GeV)}$
- Particle ID via E/p measurement
- Pointing capability for fully neutral final state (eg: ALP → gg)
- Time resolution : o(1) ns.

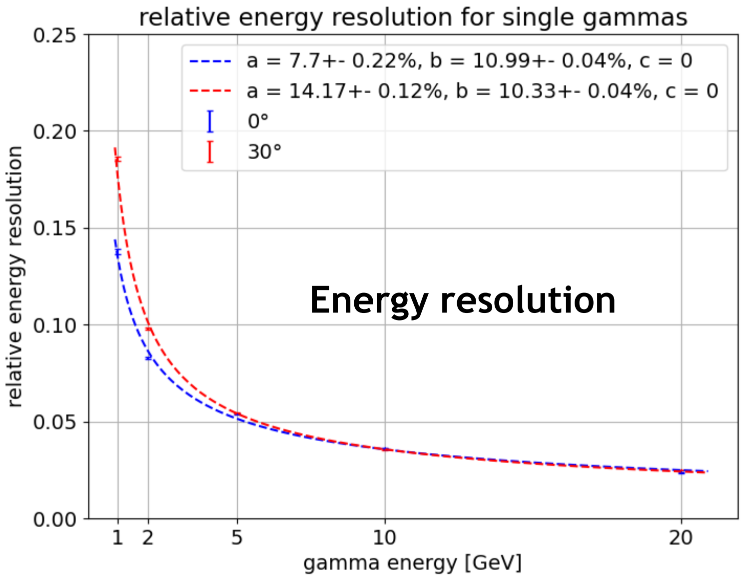


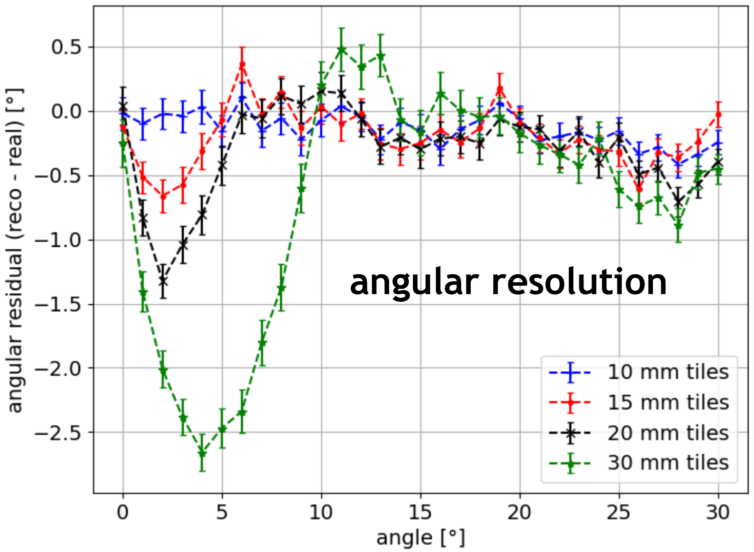
2 scintillator layers (*x* & *y*) | 2 Micro-Megas | 2 scintillator layers (*x* & *y*)



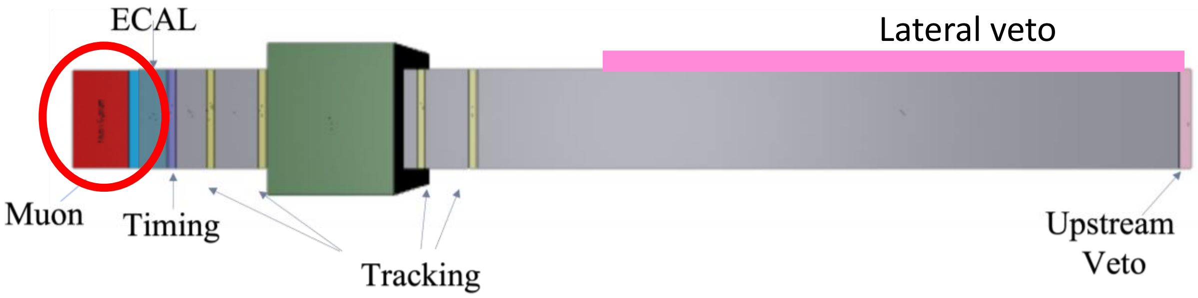
Baseline technology: StripCAL

- 2.5 m long, 1cm wide, 1 cm thick strips in x,y directions with WLS fibres + SiPMs read-out
- alternating with iron layers, 9 mm thick.
- 20 X_0 total depth to avoid shower leakage





MUON SYSTEM



Goal:

- identify muons and reduce muon combinatorial background via timing measurement.

Technology:

- 3 stations of scintillating tiles with direct SiPM readout interleaved by iron filters.
- 15 x 15 cm tiles
- Measured 250 ps resolution per station.

Two full-size modules already built in 2023.

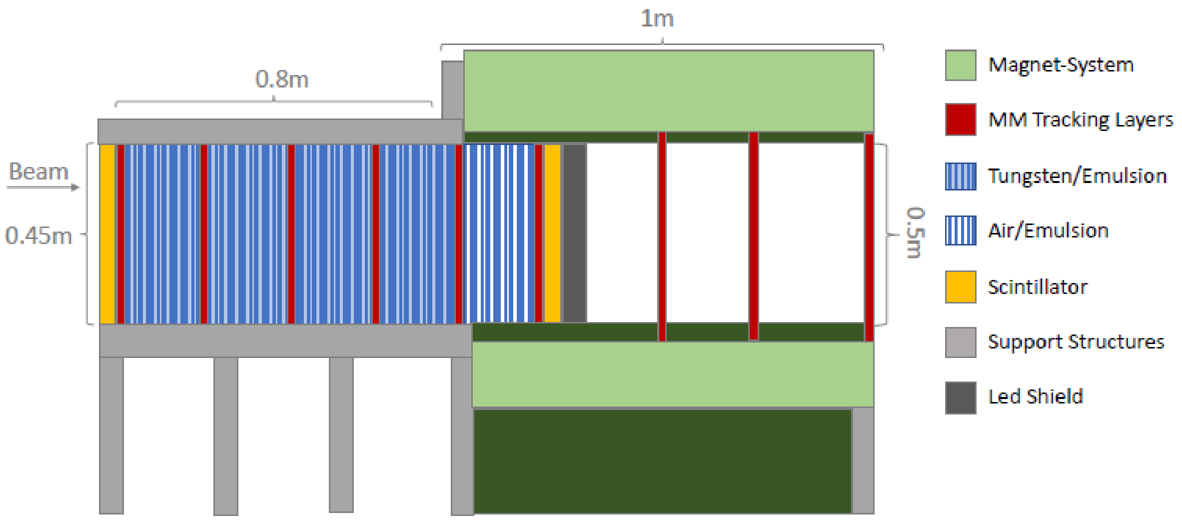
NaNu DETECTOR

NaNu (North Area Neutrino Detector) placed 50 m from the beam dump, immediately downstream of SHADOWS detector.

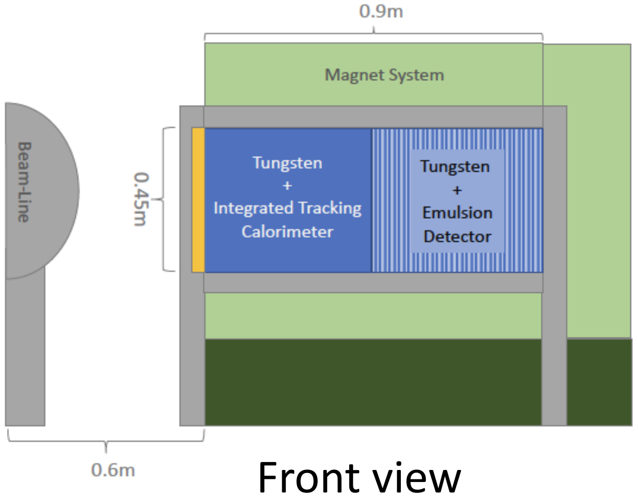
- Two main detector components of 45 x 45 x 100 cm^3
- Emulsion detector:
  - Emulsion films of silver bromide crystals, 70 µm layers
  - Interleaved with 1 mm tungsten plates, 560 total
  - 50 to 100 nm spatial resolution
- Micro-Megas based tracking detector to complement emulsions with timing information

- Active detector: tungsten plates interleaved with plastic scintillators with SiPM read-out

- Dipole magnet with 1.4 T field (already existing)



Side view



Front view

OUTLOOK

- SHADOWS is a proposed proton beam dump experiment for FIPs physics that can be built in ECN3 and take data concurrently to HIKE
- SHADOWS and HIKE running simultaneously to cover complementary ranges in the FIP parameter space, *above* and *below* the kaon mass, will play a major role for FIP physics in the incoming years
- In addition to the FIP programme, a neutrino programme can be pursued with NaNu.
- SHADOWS Technical proposal submitted in August 2023
- Expected decision of SPS Committee for approval: December 2023

BACKUP SLIDES

COMBINATORIAL MUON BACKGROUND

Random combination of opposite charge muons entering the decay vessel can mimick a decay vertex in the fiducial volume.

With MIB muon flux reduction system, we have ~ 10 Mevents/spill

Background can be further mitigated using event properties:

1. Timing : $\pm 3\ \sigma_t$ ($\sigma_t \sim 100$ ps) → rate of accidentals ~ 3000/spill
2. Veto efficiency 99.8 %: probability of not vetoing each of the two $P(\text{Veto}) = 4\text{x}10^{-6}$
3. Vertex reconstruction in fiducial volume requirements: $P(\text{Vertex}) = 5 \times 10^{-4}$
4. Pointing to proton dump : $P(\text{IP} < 6\text{cm}) = 1 \times 10^{-4}$

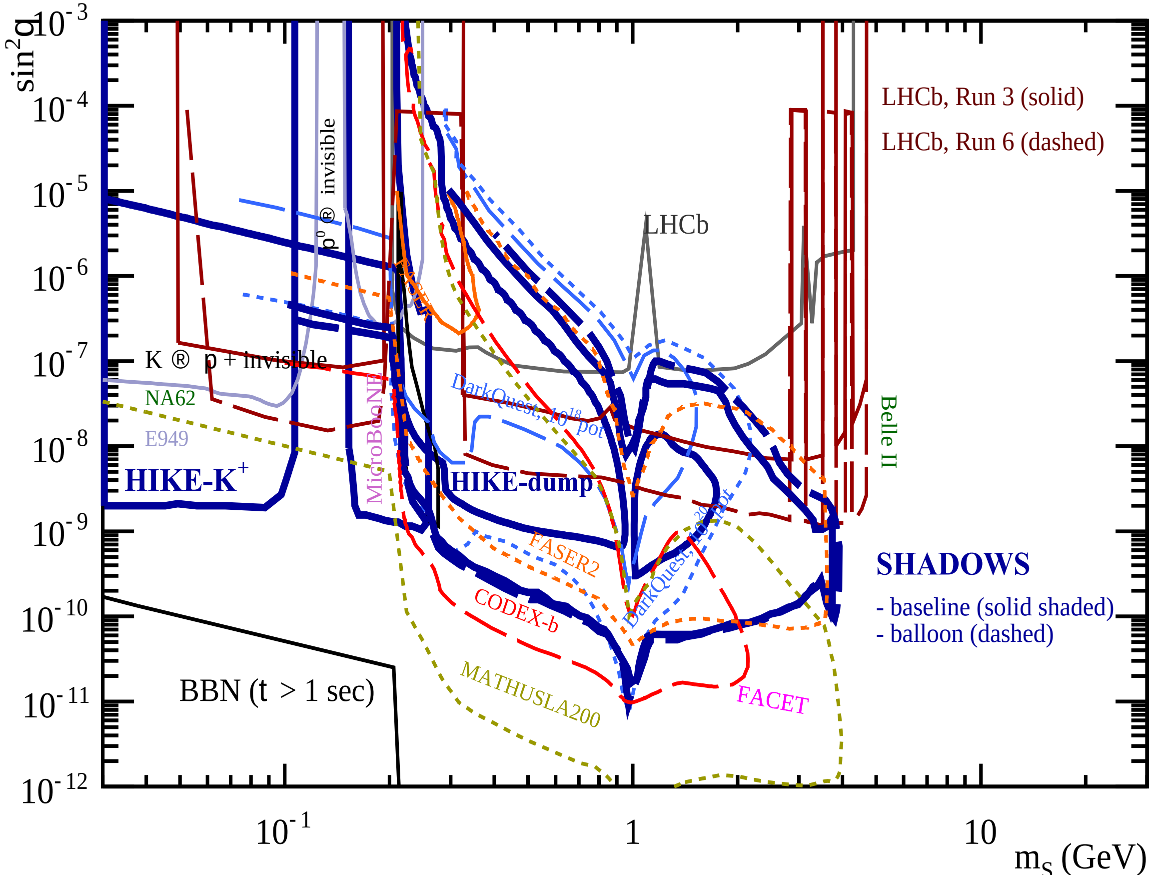
$N(\mu^+\mu^-)$ flux = Timing events x P(Veto) x P (Vertex) x P (Pointing direction)   events/Spill

Expected background events on experiment lifetime = 0.7 Events

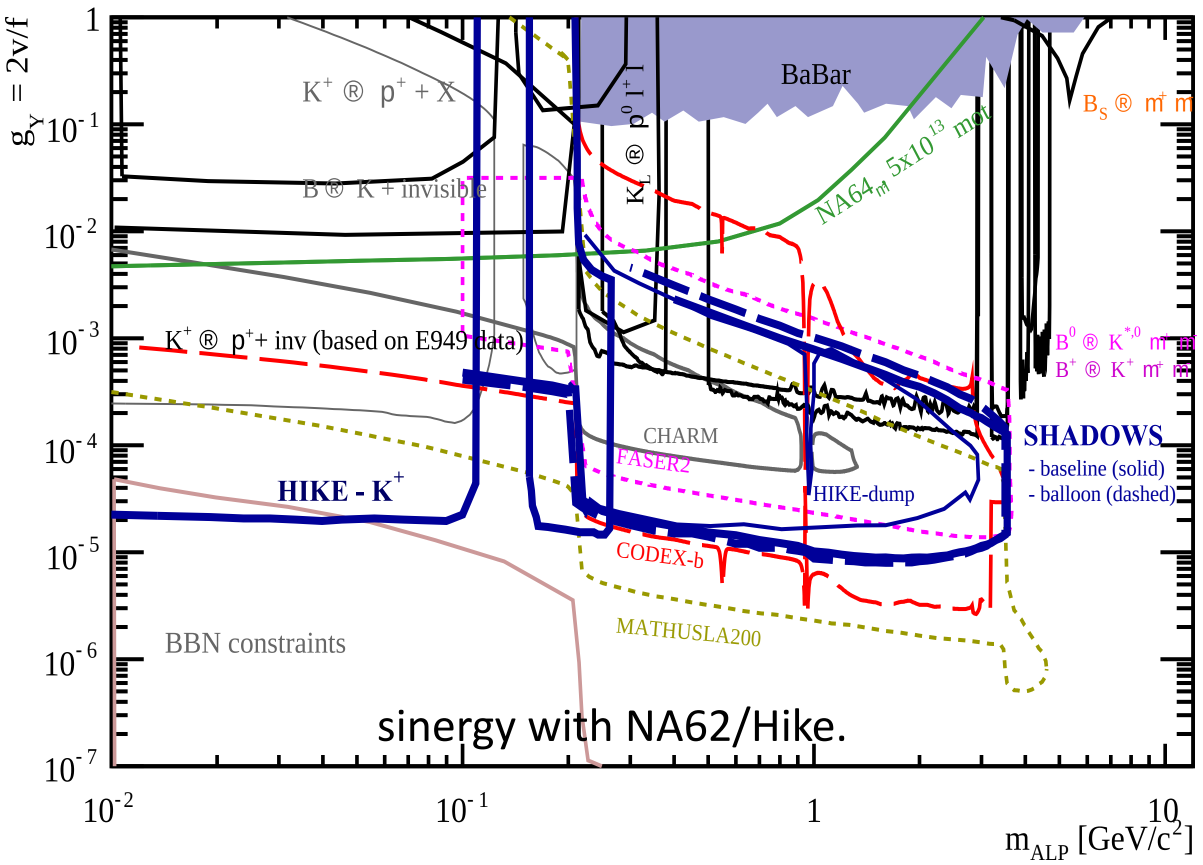
+ Other backgrounds: muon inelastic interactions (0.9 events in SHADOWS lifetime),
neutrino interactions (0.01 events).

SENSITIVITY to standard PBC benchmarks

Light dark scalar mixing with Higgs boson



Axion-like Particle (ALP) at QCD scale

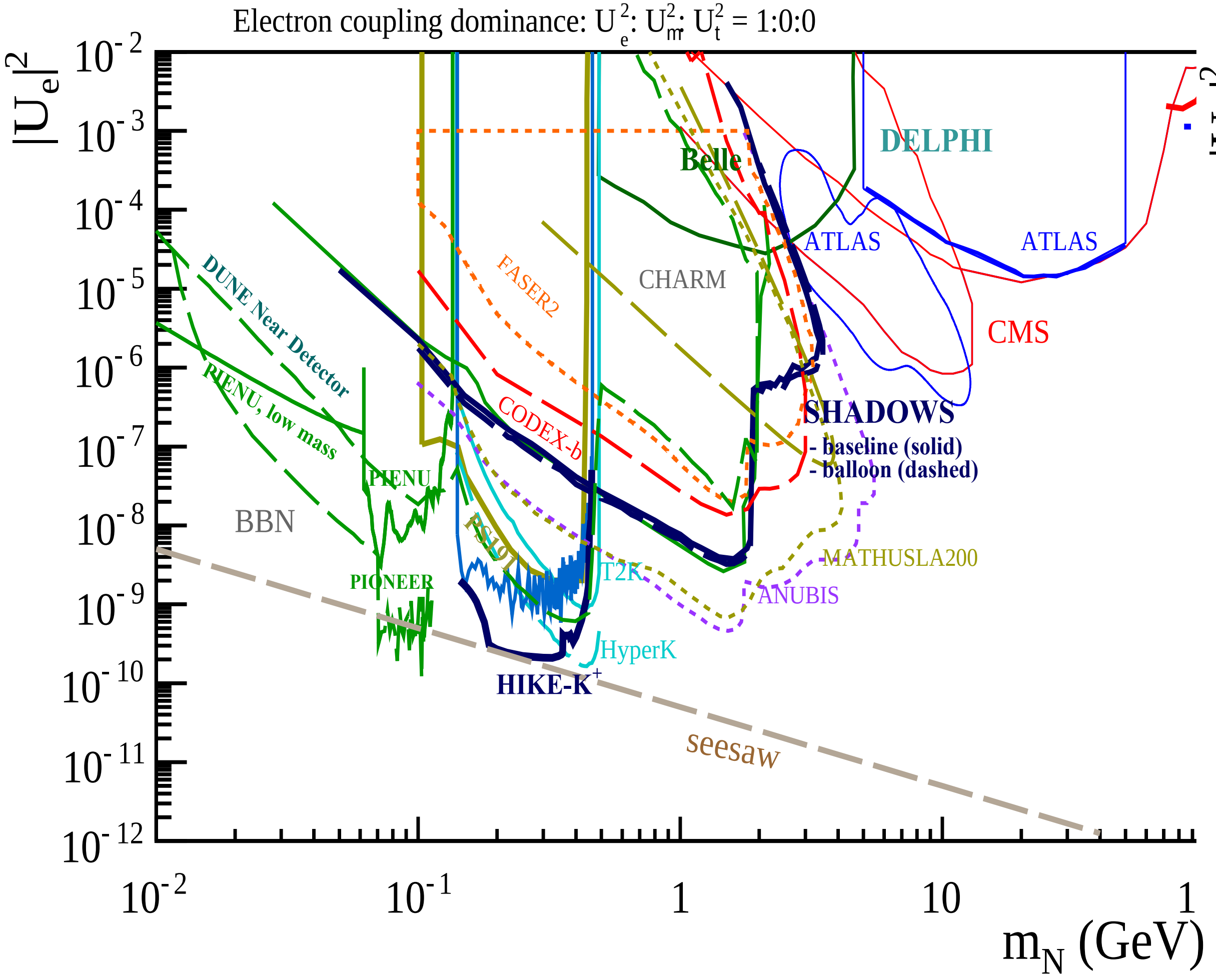


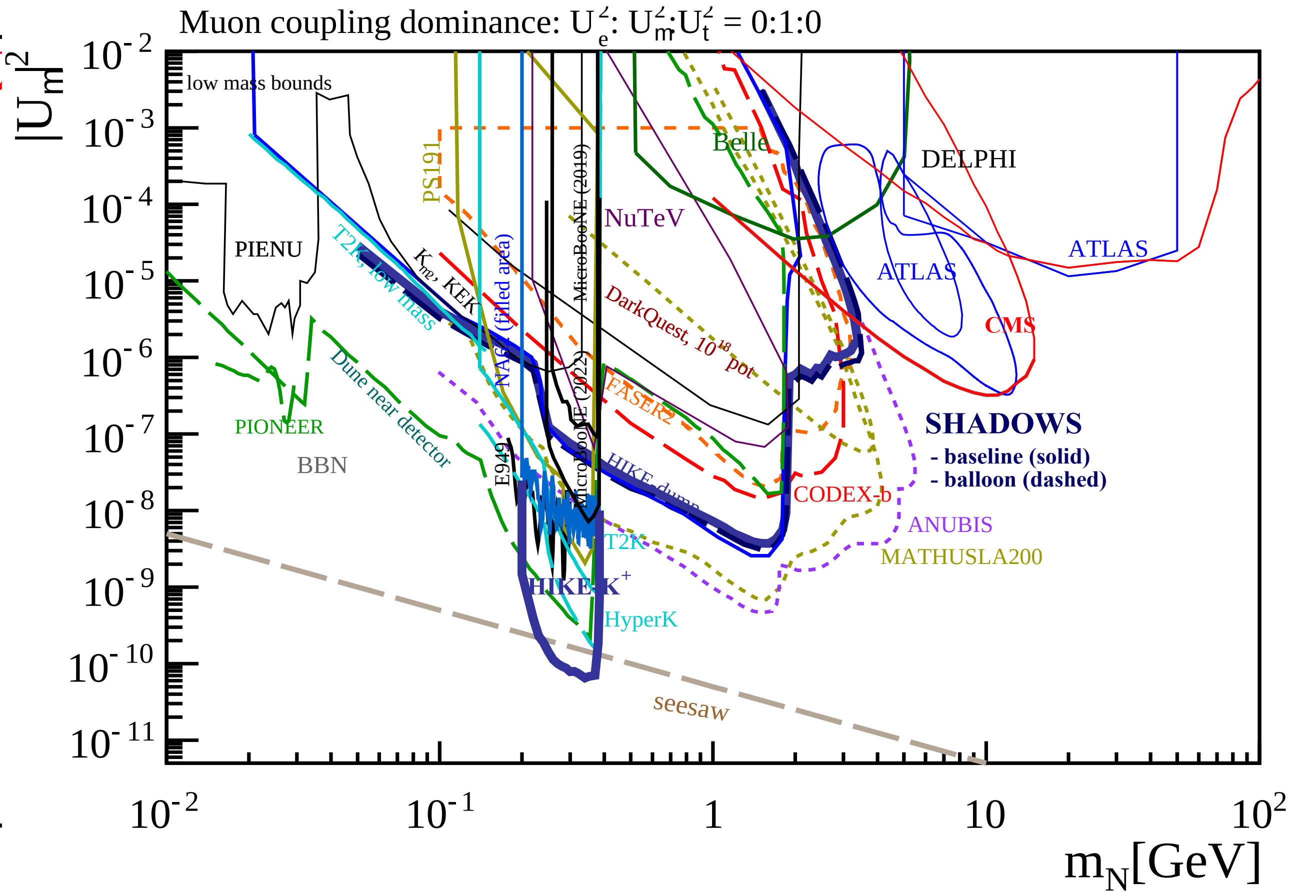
- Improvement of 2 (Light scalar mixing) or 3 (ALP) order of magnitudes over existing experimental bounds.
- Synergy with HIKE experiment

Worldwide landscape from FIPs2022 Proceedings, arXiv:2305.01715, accepted by EPJC

SENSITIVITY to standard PBC benchmarks

Heavy Neutral Leptons (single lepton dominance)

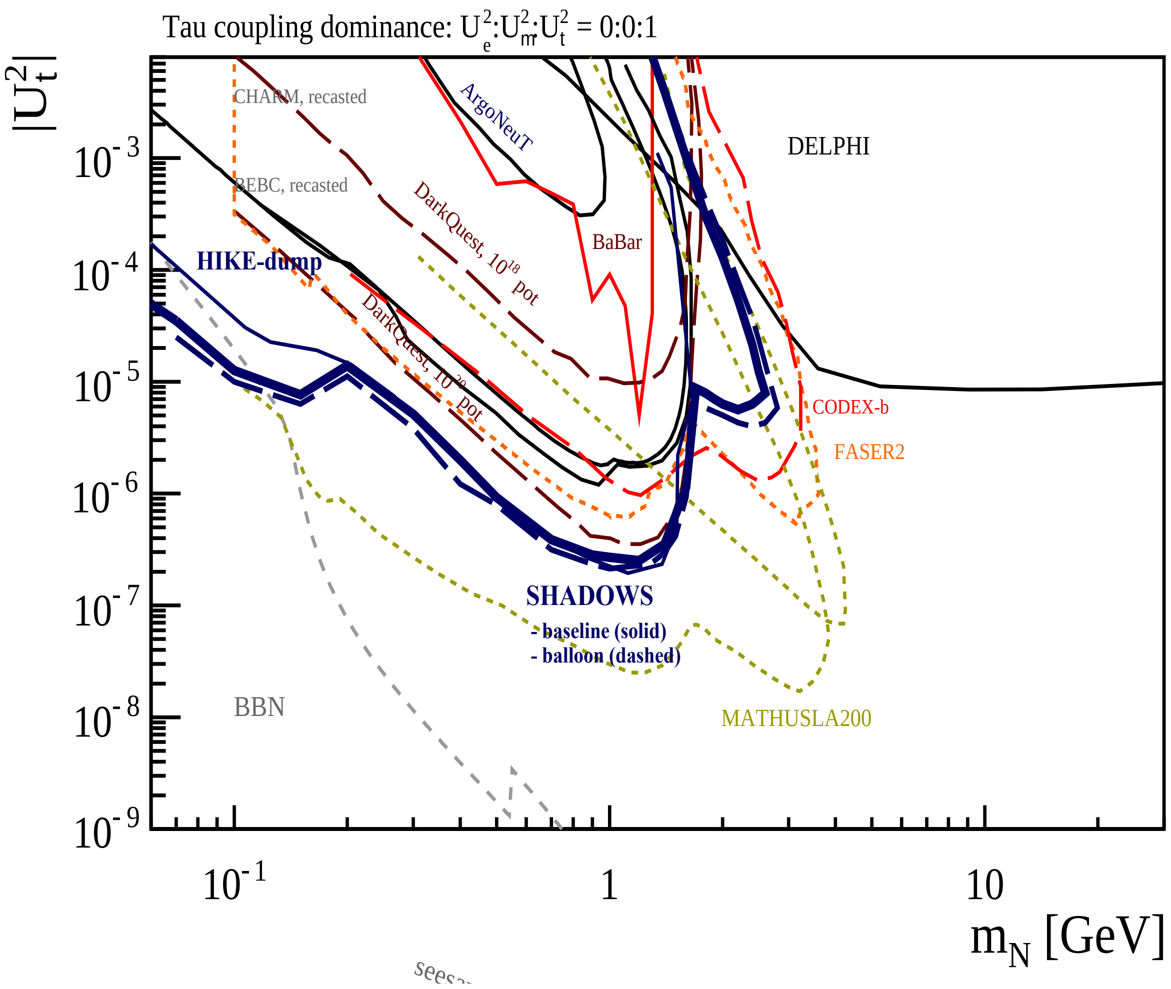




Worldwide landscape from FIPs2022 Proceedings, arXiv:2305.01715, accepted by EPJC

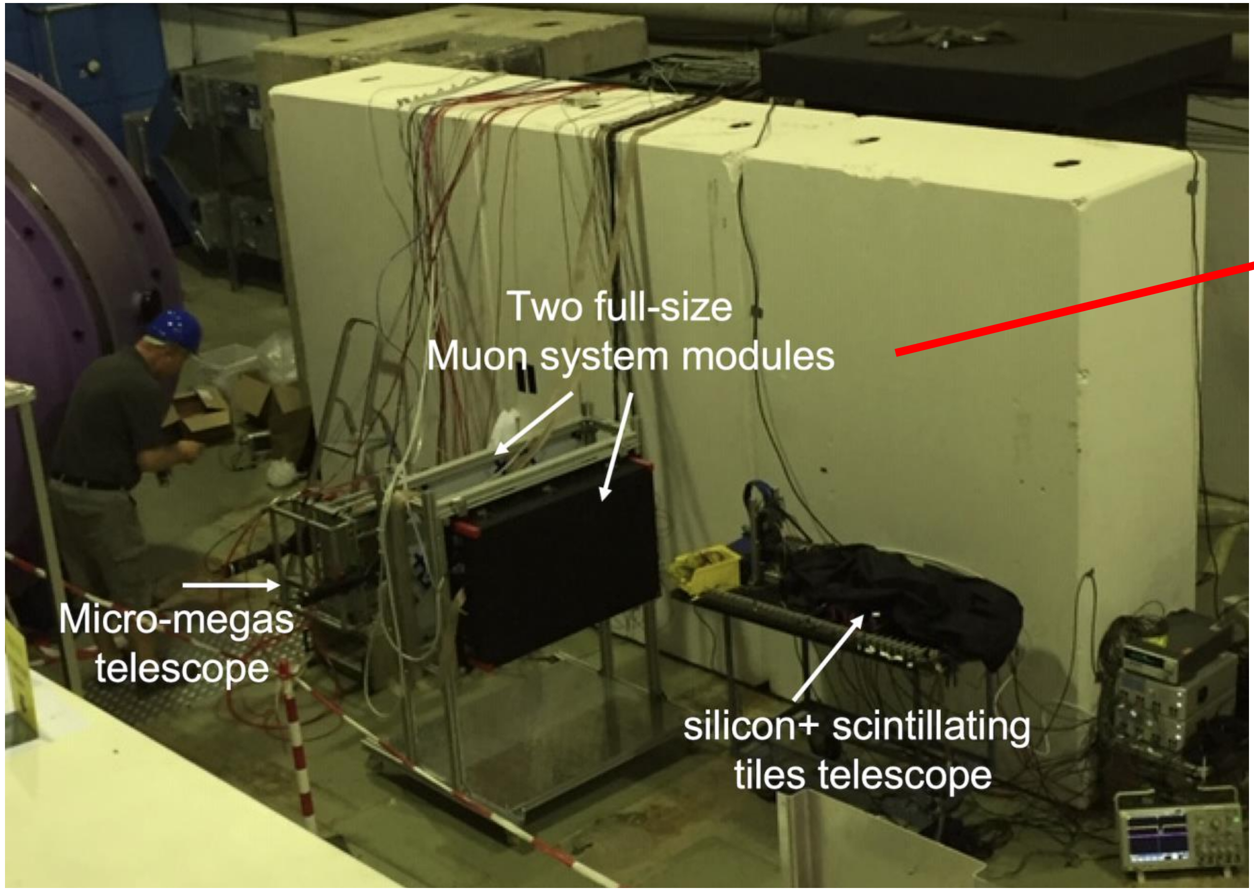
SENSITIVITY to standard PBC benchmarks

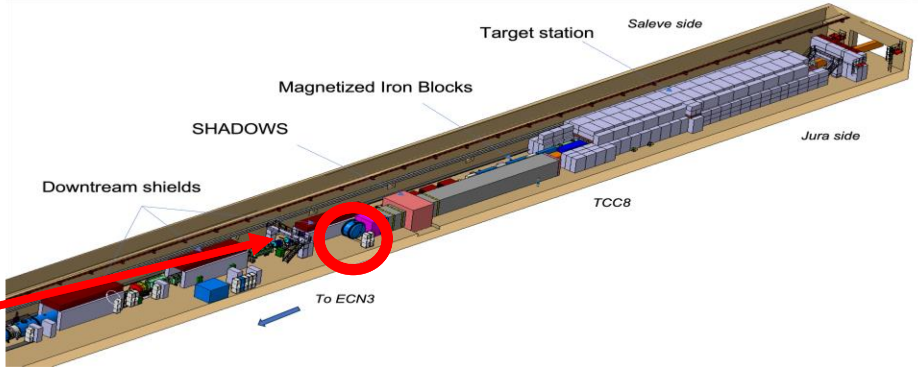
Heavy Neutral Leptons (single lepton dominance)



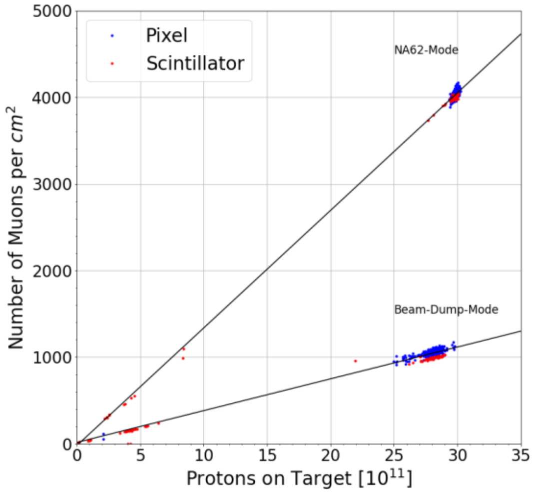
Worldwide landscape from FIPs2022 Proceedings, arXiv:2305.01715, accepted by EPJC

SHADOWS PROTOTYPES AT WORK





Measurements perfomed in June 2023 with NA62 operating in beam-dump mode at nominal beam intensity, for validation of the simulated off-axis muon flux



Results from data:
250-300 counts/cm^2/10^{12} pot

Results from simulation :
260 $\pm$ 20 counts/cm2/10^{12} pot