# SHADOWS

Search for Hidden And Dark Objects With the SPS

Gaia Lanfranchi (LNF-INFN)
On behalf of the SHADOWS Proponents

Based on the EoI - CERN-SPSC-2022-006 ; SPSC-EOI-022 and arXiv:2110.080025

SPS Committee Open Session, 12 April 2022

This talk is in memory of Paolo Franzini who passed away on January 27th, 2022

# SHADOWS Expression of Interest

Submitted to the PBC and to arXiv in October, and to the SPSC in January

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

CERN-SPSC-2022-006 / SPSC-EOI-022
12/01/2022

## SHADOWS

Search for Hidden And Dark Objects With the SPS

*Expression of Interest*

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### 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 $\sim (1-2)\cdot 10^{19}$ 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.

Contents



New since January: four new groups have expressed interest in joining the Project: Mainz, Heidelberg, Karlsruhe, INR

# What is SHADOWS?

SHADOWS is a newly proposed proton beam dump experiment placed off-axis in the ECN3/TCC8 experimental cavern to search for feebly-interacting particles (FIPs) emerging from charm and beauty decays.

SHADOWS can take data when the P42/K12 beam line is operated in beam-dump mode.

A synergistic and broad FIPs Physics program can be performed with NA62-successor.

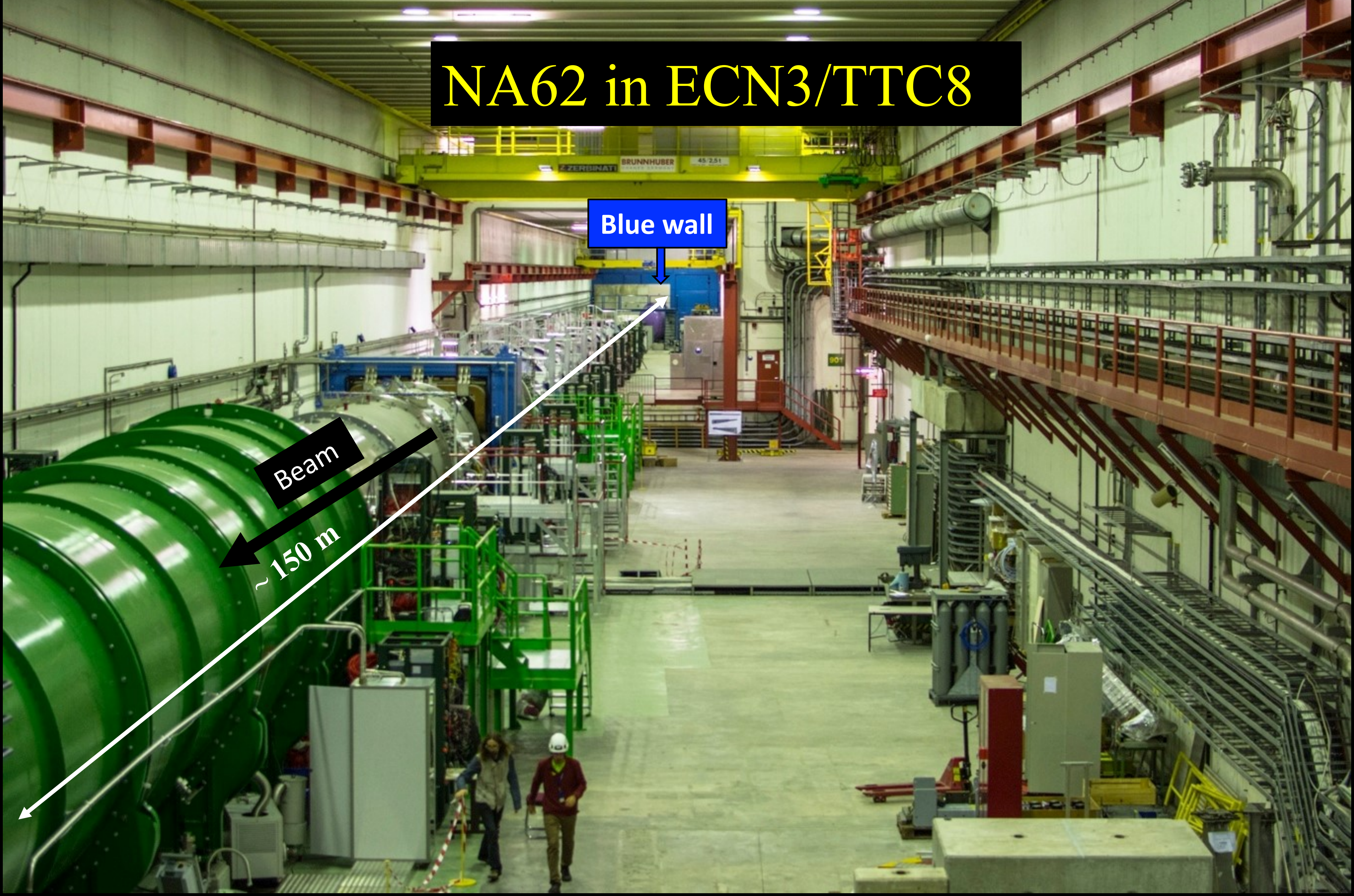
# Why in ECN3 area ?

- ✓ Because ECN3/TCC8 has the best 400 GeV primary extracted proton beam line at CERN (and worldwide) and a plethora of hidden sector particles can emerge from interactions of a high-energy proton beam with a dump
  - NA62 nominal intensity is $3x10^{12}$ ppp with 3.3s pulse duration: ~ $10^{12}$ pot/sec, up to $2x10^{18}$ pot/year

- ✓ K12 beam intensity proposed to be increased by a factor x6-7
  - for high intensity K beams, NA62-DUMP and SHADOWS → up to $1.2*10^{19}$ pot/year

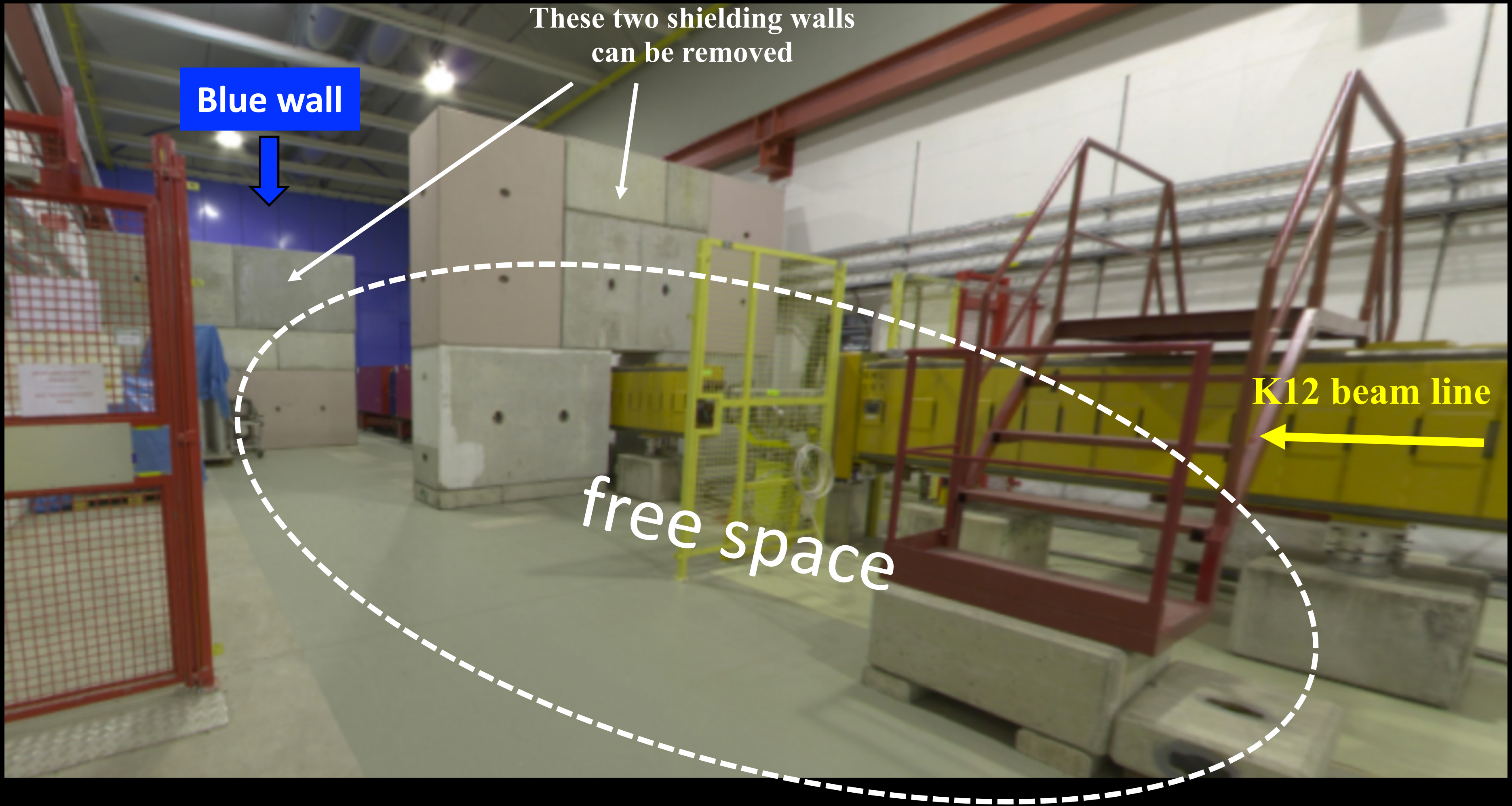
**SHADOWS can collect $5x10^{19}$ pot in ~4 years of data taking starting after LS3**

# NA62 in ECN3/TTC8

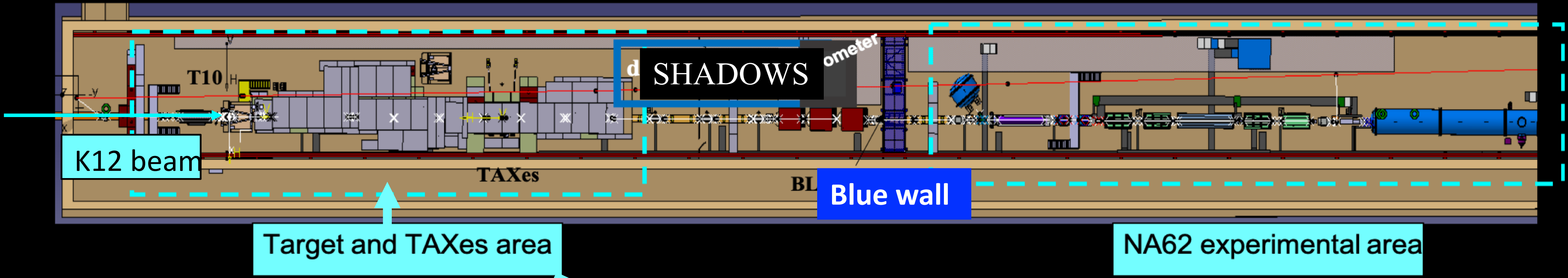


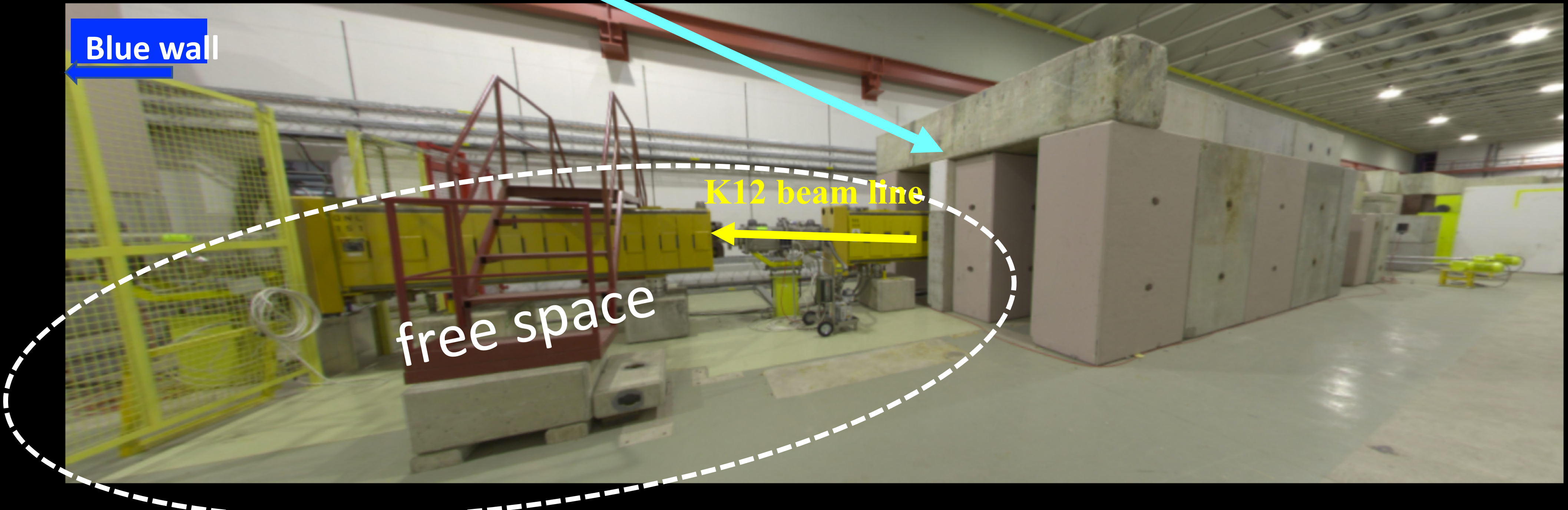
# SHADOWS in ECN3/TTC8

On the other side of the NA62 blue wall – in the target area (supervised zone)

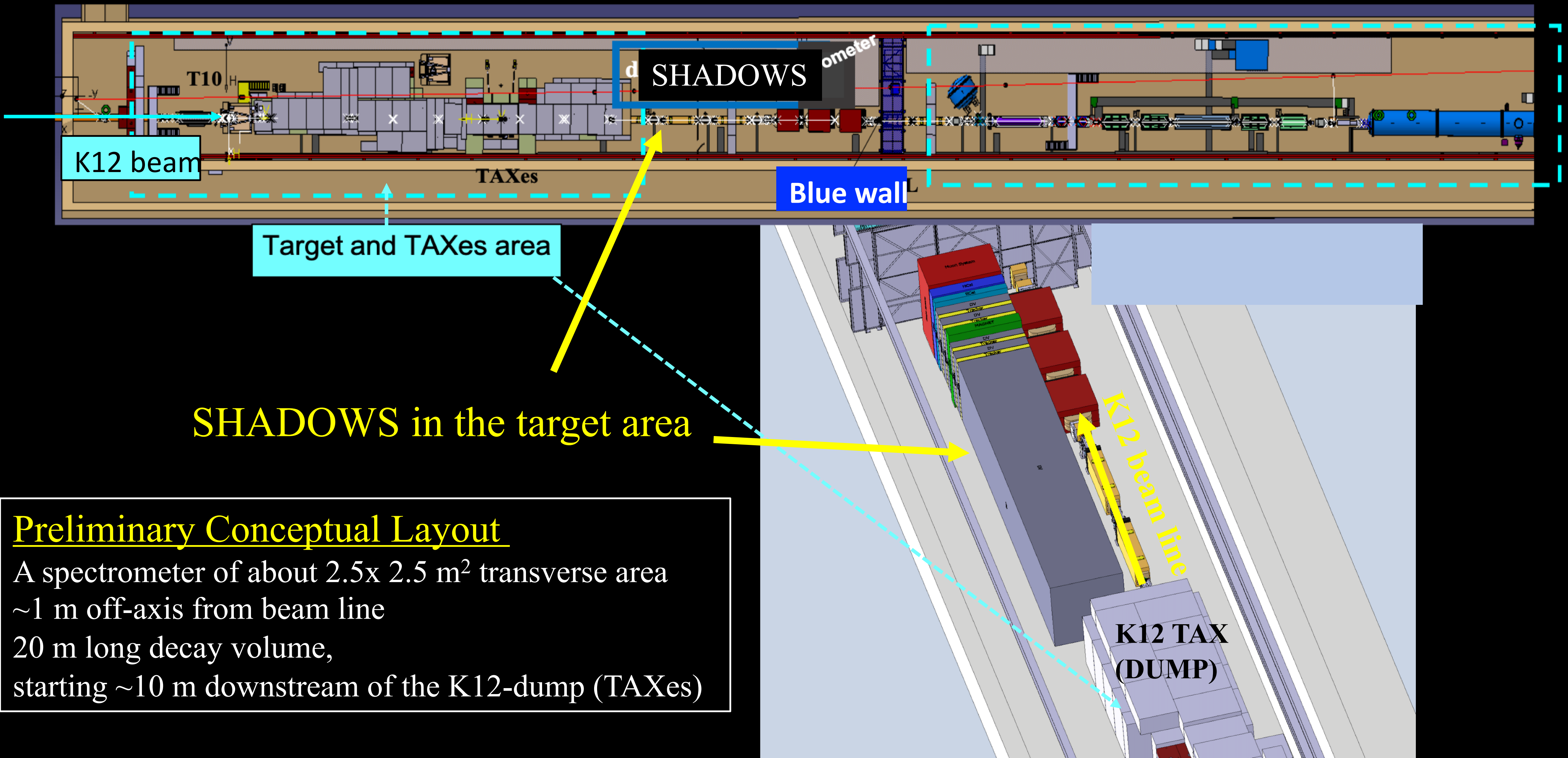


# SHADOWS in ECN3/TTC8



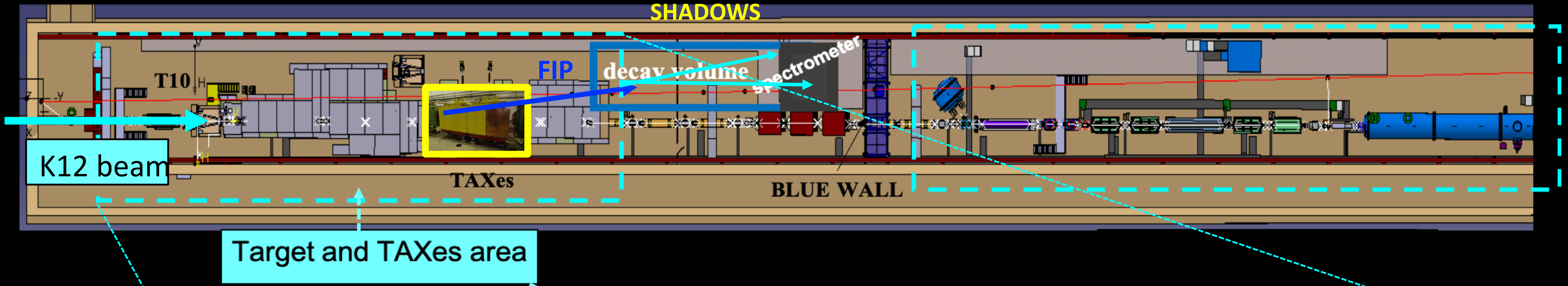
# SHADOWS in ECN3/TTC8



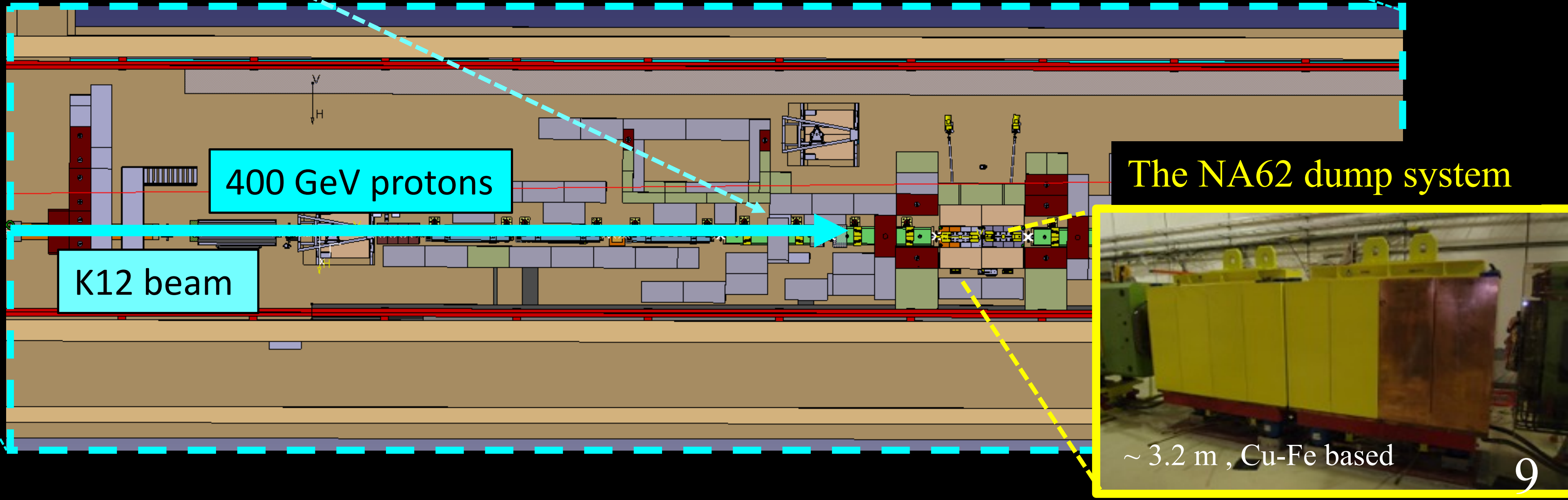

**Preliminary Conceptual Layout**

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)

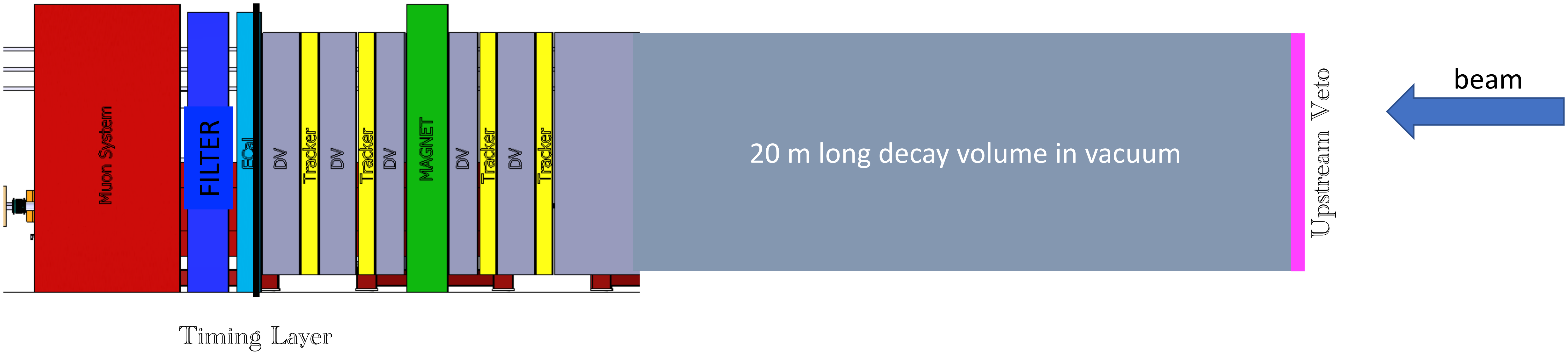
# SHADOWS can operate when K12 beam line runs in dump-mode




**T10 target is lifted and the 400 GeV primary p beam is sent onto the dump**



# SHADOWS Conceptual Design: a standard spectrometer (NA62-like)




<u>SHADOWS detector components:</u>

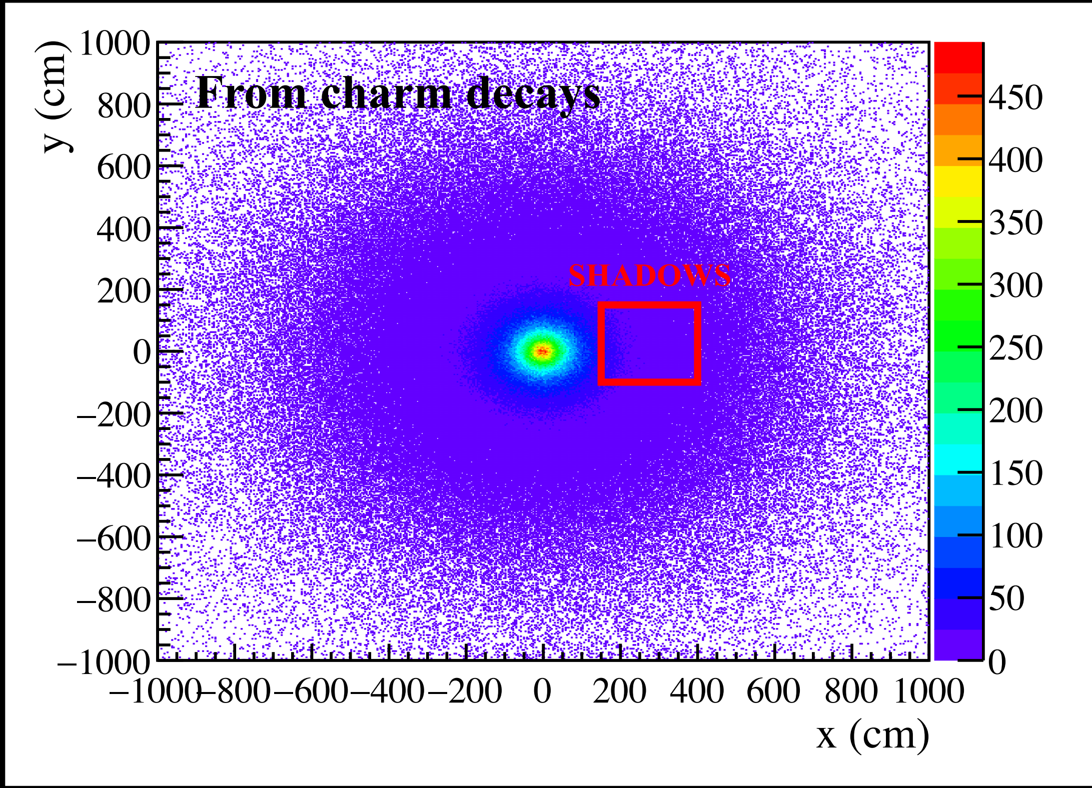
20 m long, in vacuum decay volume, an Upstream Veto, a Tracking System with a (warm) dipole magnet, Timing layer, Electro-magnetic calorimeter, a filter and four Muon Stations.

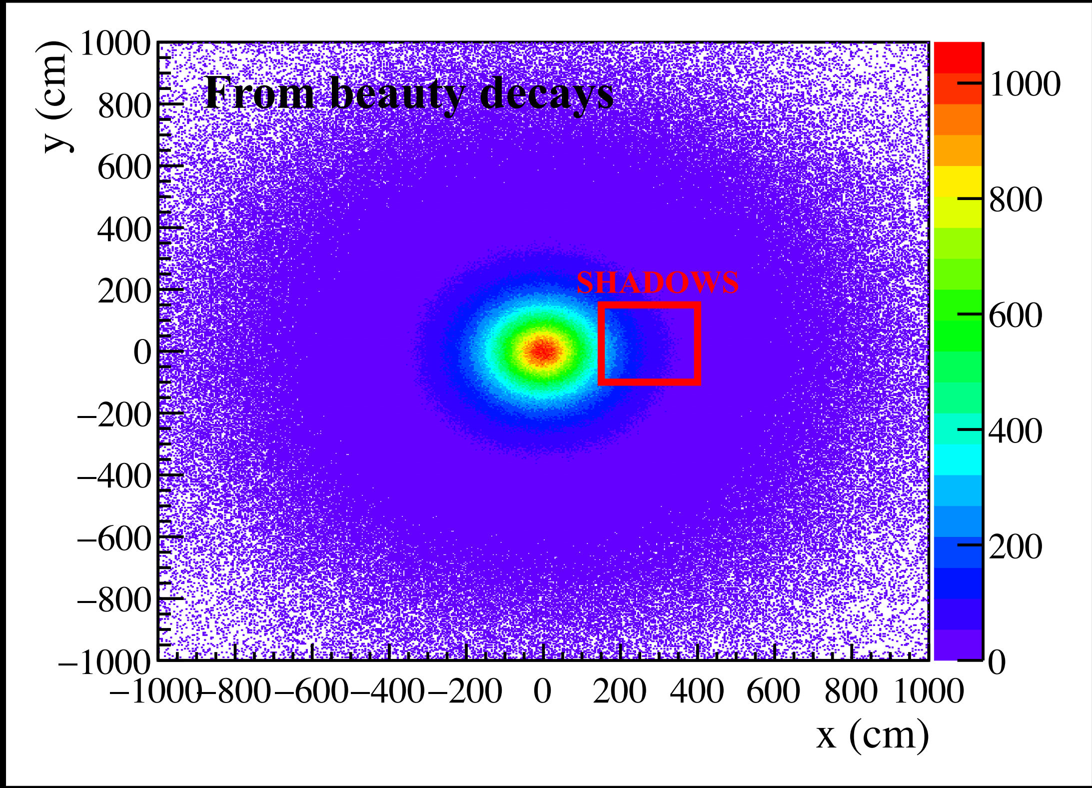
Transversal size: 2.5x2.5 $m^2$.

**<u>Important message:</u>** SHADOWS can be built with <u>existing technologies.</u>
No intense R&D is needed, more than one option per detector is already available on the market.

# Why “off-axis” works: Signal

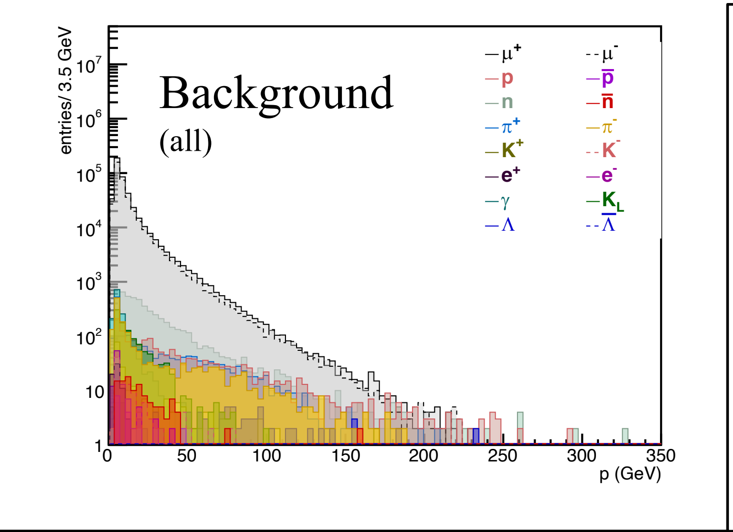
HNL→ **πμ** illumination @ D = 55 m  (first SHADOWS tracking station)

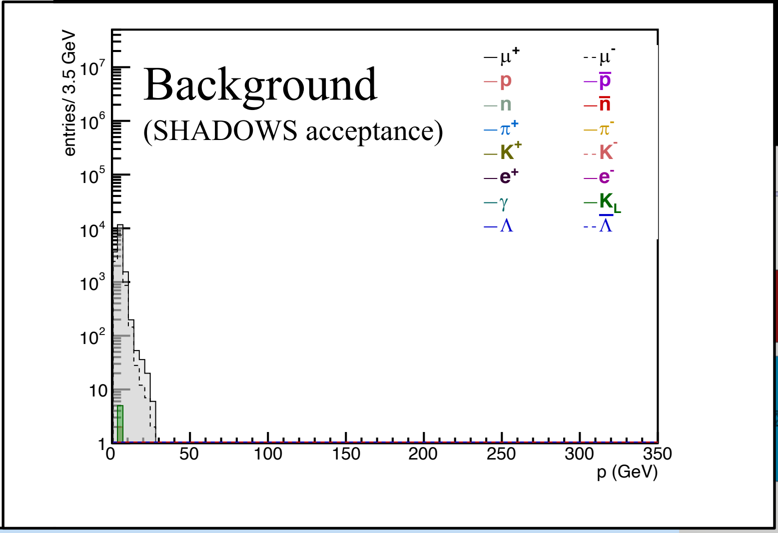


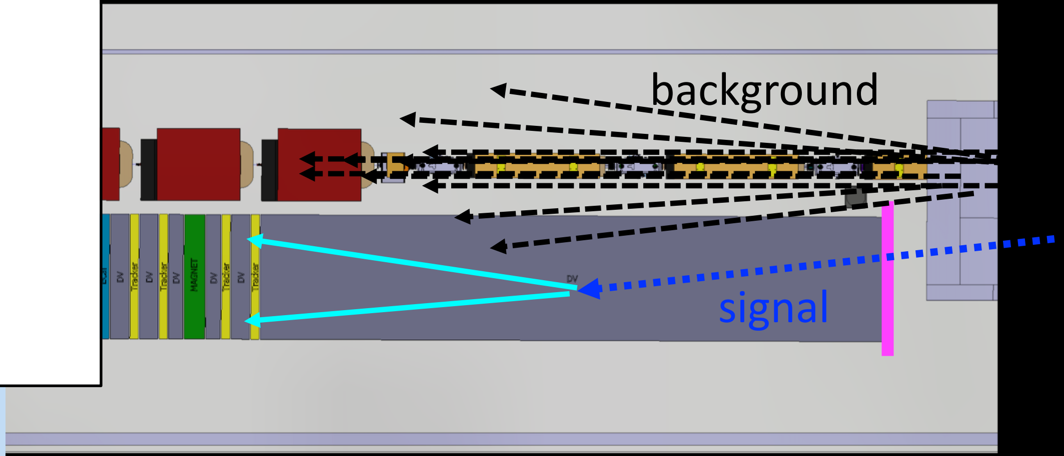



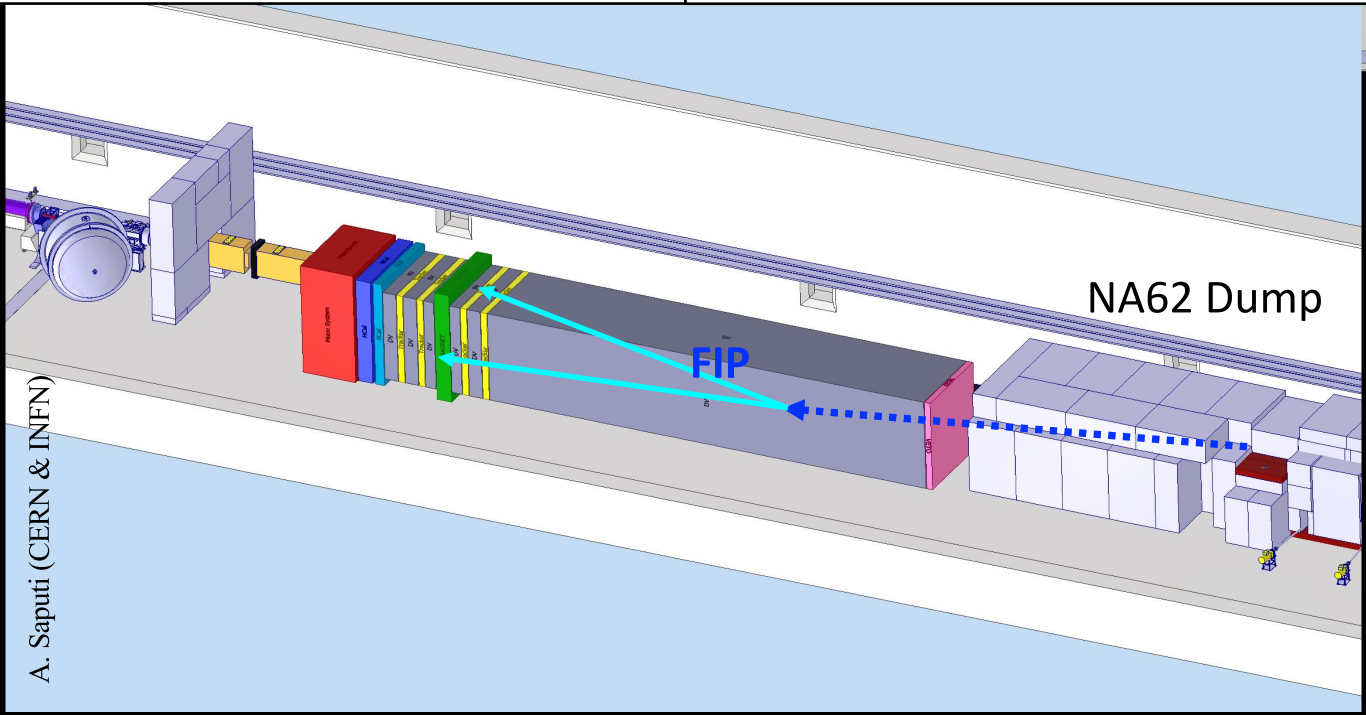

FIPs emerging from charm and beauty decays (HNLs, dark scalars, ALPs,…)
at the SPS energy are produced with a large polar angle

# Why “off-axis” works: Background



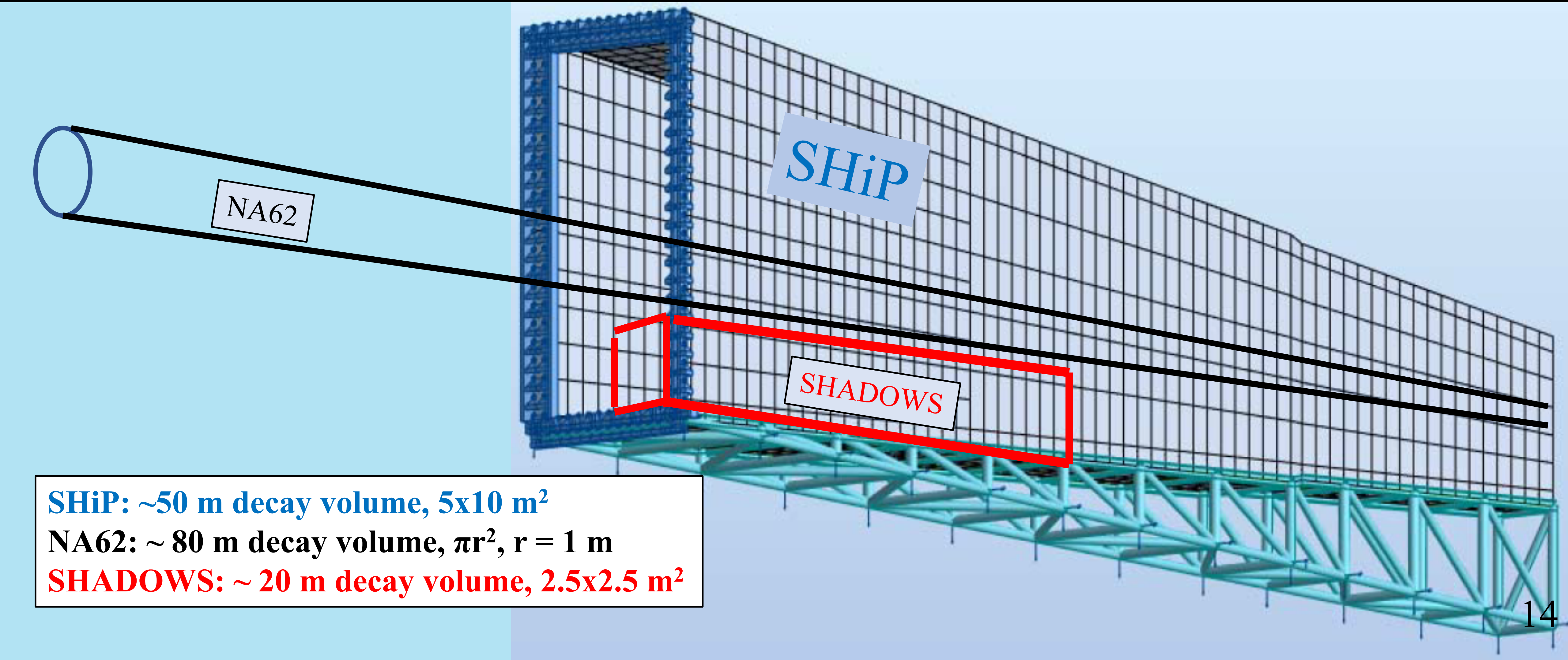

Most of the residual background emerging from TAXes are muons and neutrinos that are mostly produced forward (and miss SHADOWS acceptance).

# SHADOWS Main idea: Stay close & stay off-axis!

- Stay close to the dump:
  to maximise acceptance for signals with a relatively small detector

- Stay off-axis with respect to the beam line:
  to minimize acceptance for backgrounds (mostly peaked forward)

# SHiP/NA62/SHADOWS comparison: Tentative 3D view (almost to scale)




**SHiP: ~50 m decay volume, 5x10 m$^2$**
**NA62: ~ 80 m decay volume, $\pi r^2$, r = 1 m**
**SHADOWS: ~ 20 m decay volume, 2.5x2.5 m$^2$**

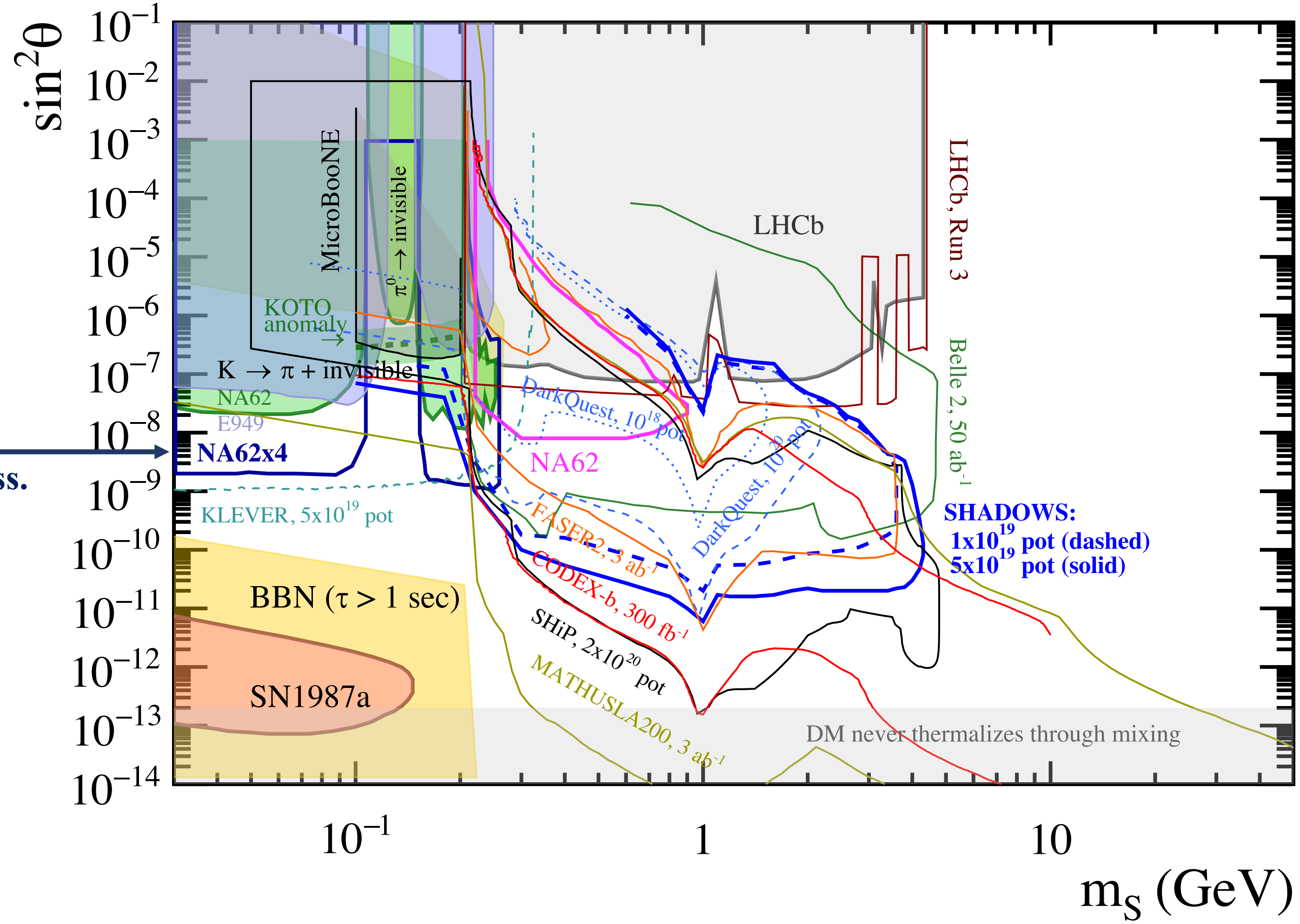
# SHADOWS physics sensitivity for standard PBC benchmarks

Standard PBC benchmarks: J. Phys.G 47 (2020) 1, 010501, e-Print: 1901.09966, section 9

# Light Dark Scalar mixing with the Higgs going to visible final states

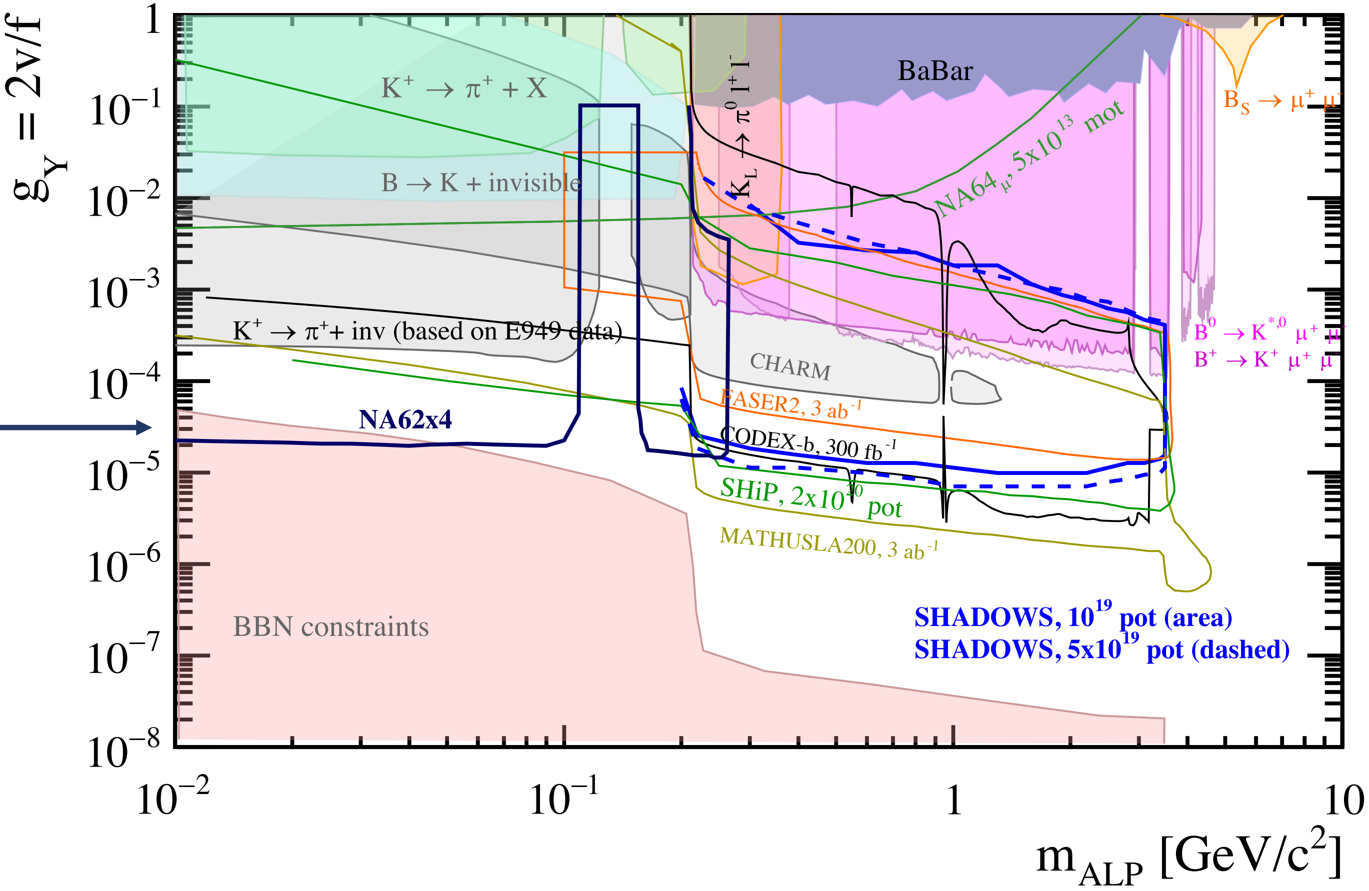
(light dark scalar enters in models related to light DM, inflation, Higgs stability, EW symmetry breaking phase transition, etc)

**NB: NA62 in K-mode covers the range below K-mass. Strong complementarity with SHADOWS.**




**SHADOWS covers about 4 orders of magnitude in coupling in the mass range 2 $M_\mu$ -$M_b$ where dark scalar can be a mediator SM-thermal relic DM.**

# Axion-like Particle (ALP) at the QCD scale: fermion couplings



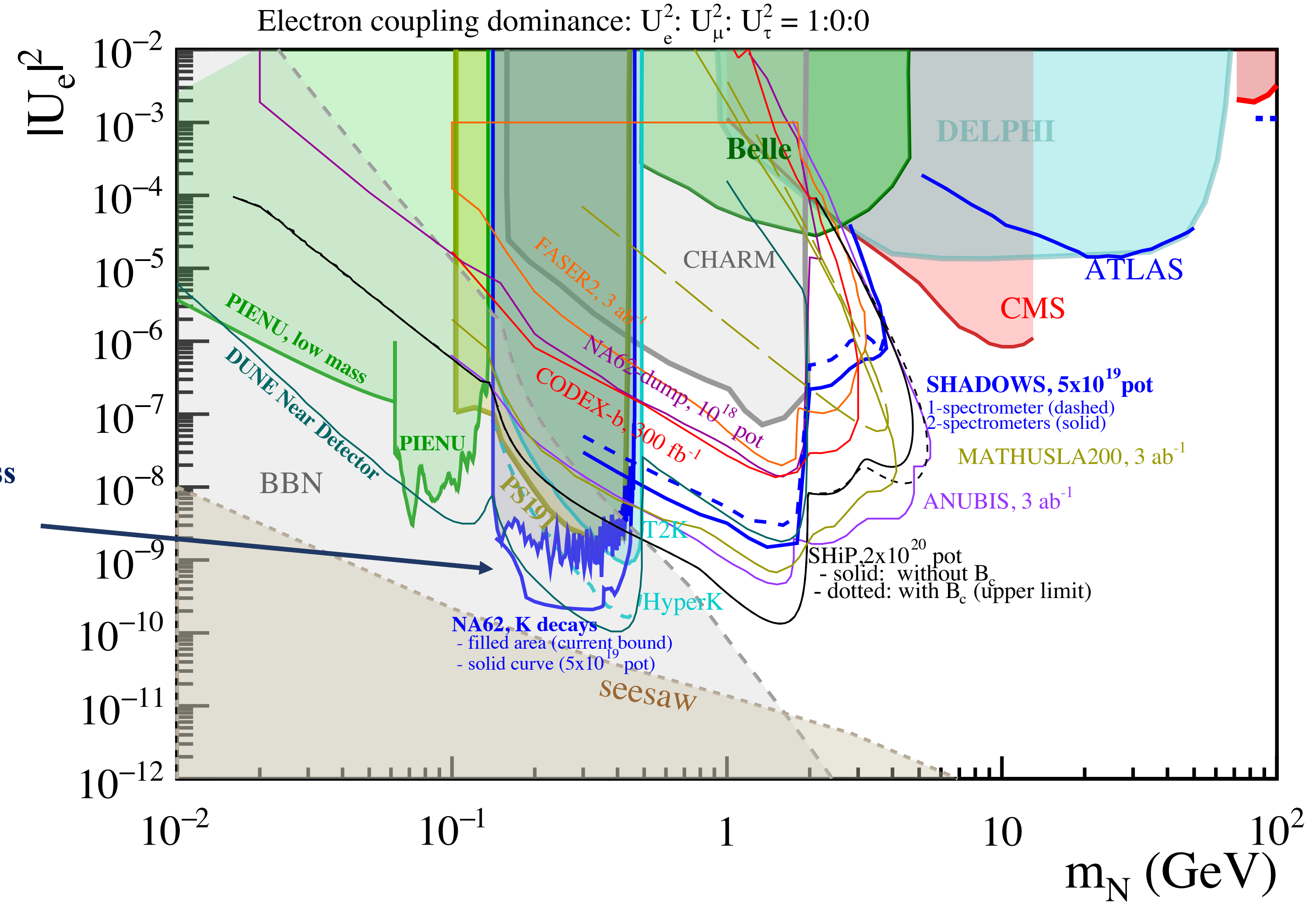

**NB: NA62 in K-mode covers the range below K-mass. Strong complementarity with SHADOWS.**

**SHADOWS with 5x10$^{19}$ pot is better than FASER2 with 3 ab$^{-1}$, and comparable to CODEX-b (with 300 fb$^{-1}$) and SHiP (with 2x10$^{20}$ pot).**

# Heavy Neutral Leptons (with electron coupling)

## (origin of neutrino masses and oscillation, baryogenesis through leptogenesis)

**NB: NA62 in K-mode covers the range below K-mass down to the seesaw limit. Strong complementarity with SHADOWS.**

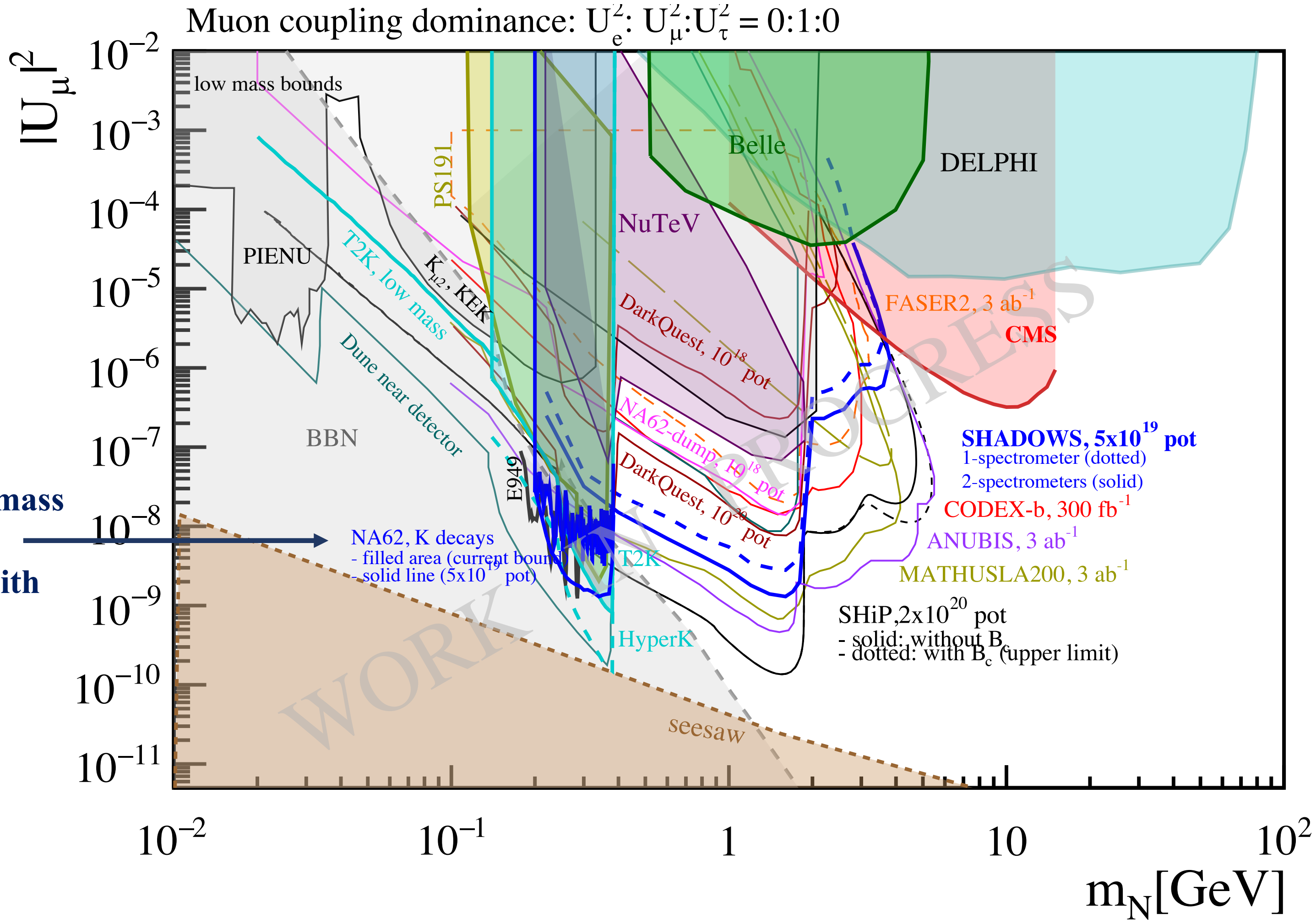



**Between K and D:** SHADOWS is (much) better than CODEX-b and FASER2 with full dataset.
**Between D and B:** SHADOWS expands by two-three orders of magnitude wrt current bounds (Belle)

# Heavy Neutral Leptons (with muon coupling)

(origin of neutrino masses and oscillation, baryogenesis through leptogenesis)

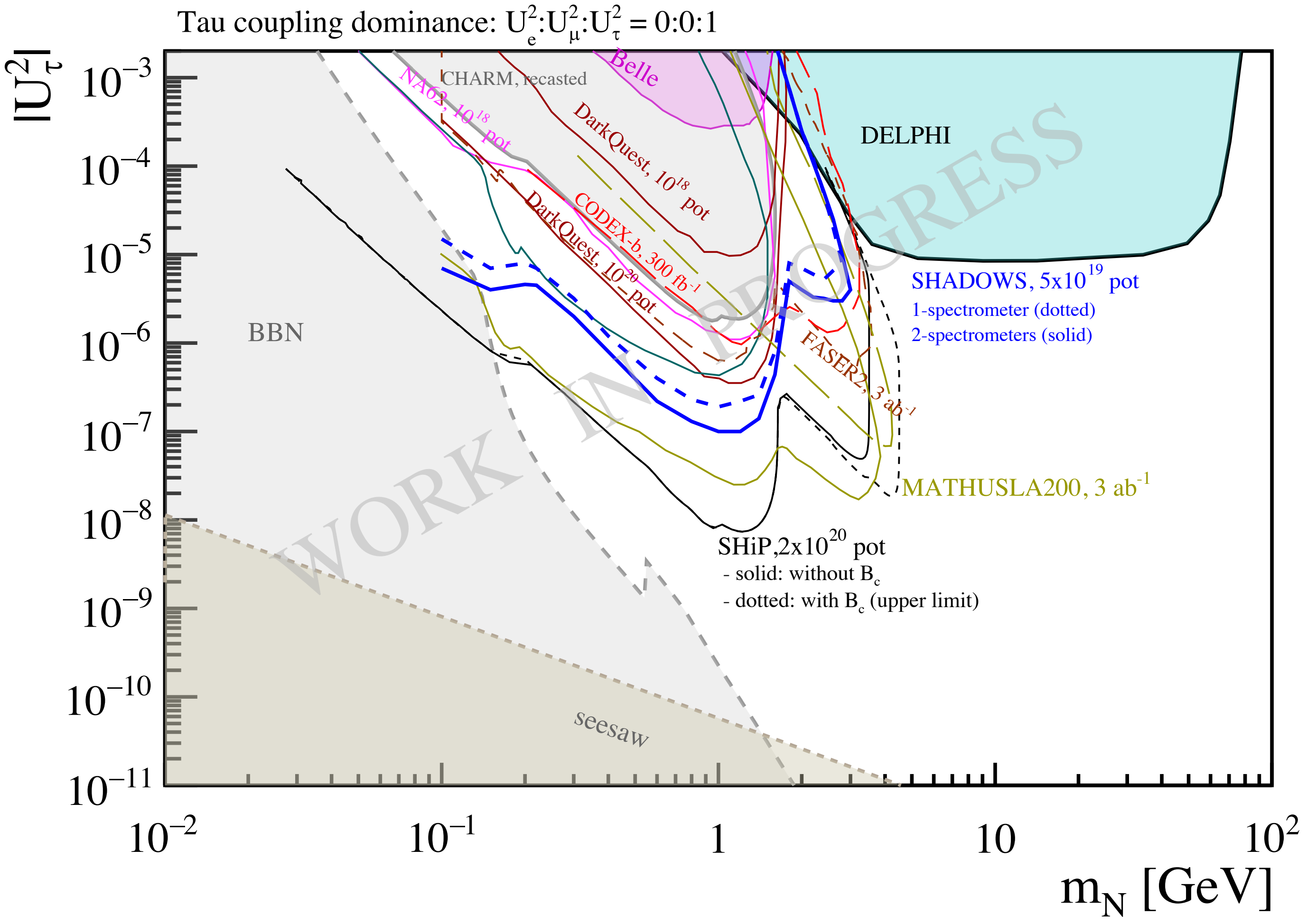
**NB: NA62 in K-mode covers the range below K-mass down to the seesaw limit. Strong complementarity with SHADOWS.**




**Between K and D:** SHADOWS is (much) better than CODEX-b and FASER2 with full dataset.
**Between D and B:** SHADOWS expands by ~two-three orders of magnitude wrt current bounds

# Heavy Neutral Leptons (with tau coupling)

(origin of neutrino masses and oscillation, baryogenesis through leptogenesis)

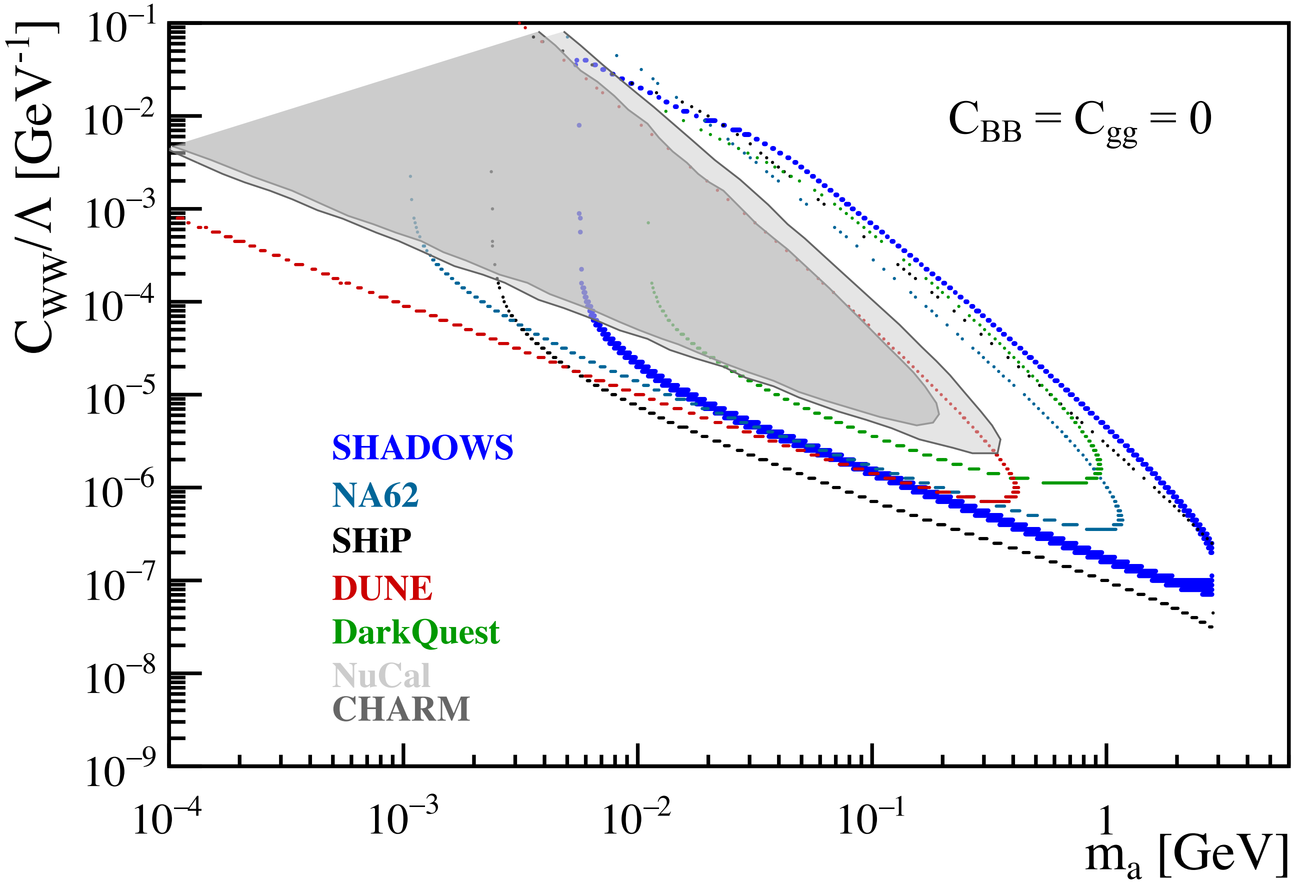



**Between K and D:** SHADOWS is (much) better than CODEX-b and FASER2 with full dataset.
**Between D and B: SHADOWS** expand by two orders of magnitude wrt current bounds

# Axion-like Particle (ALP) at the QCD scale: W couplings

NEW wrt EoI

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

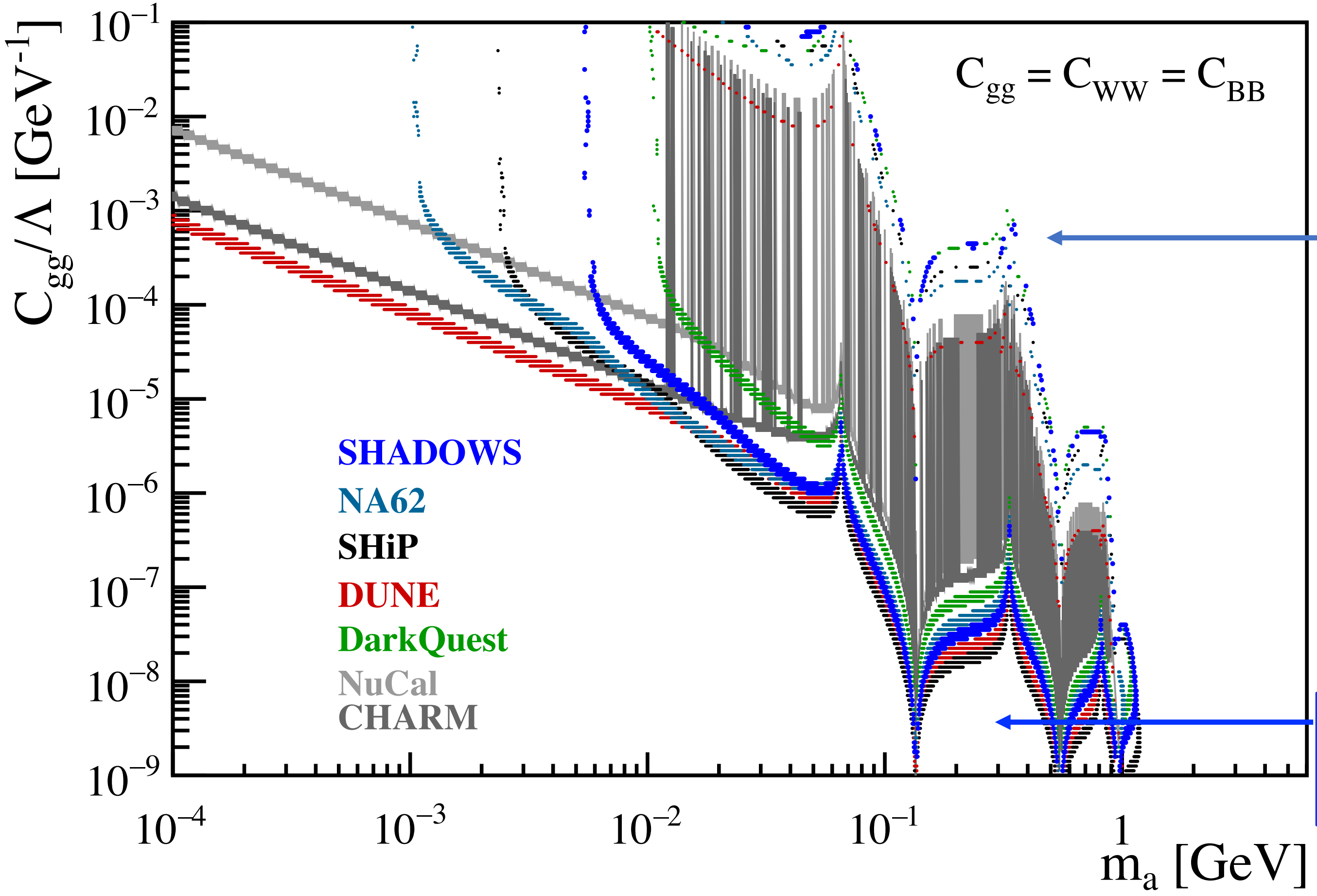



**SHADOWS with $5x10^{19}$ pot is competitive with DUNE and SHiP@BDF**

# Axion-like Particle (ALP) at the QCD scale: gluon couplings

NEW wrt EoI

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

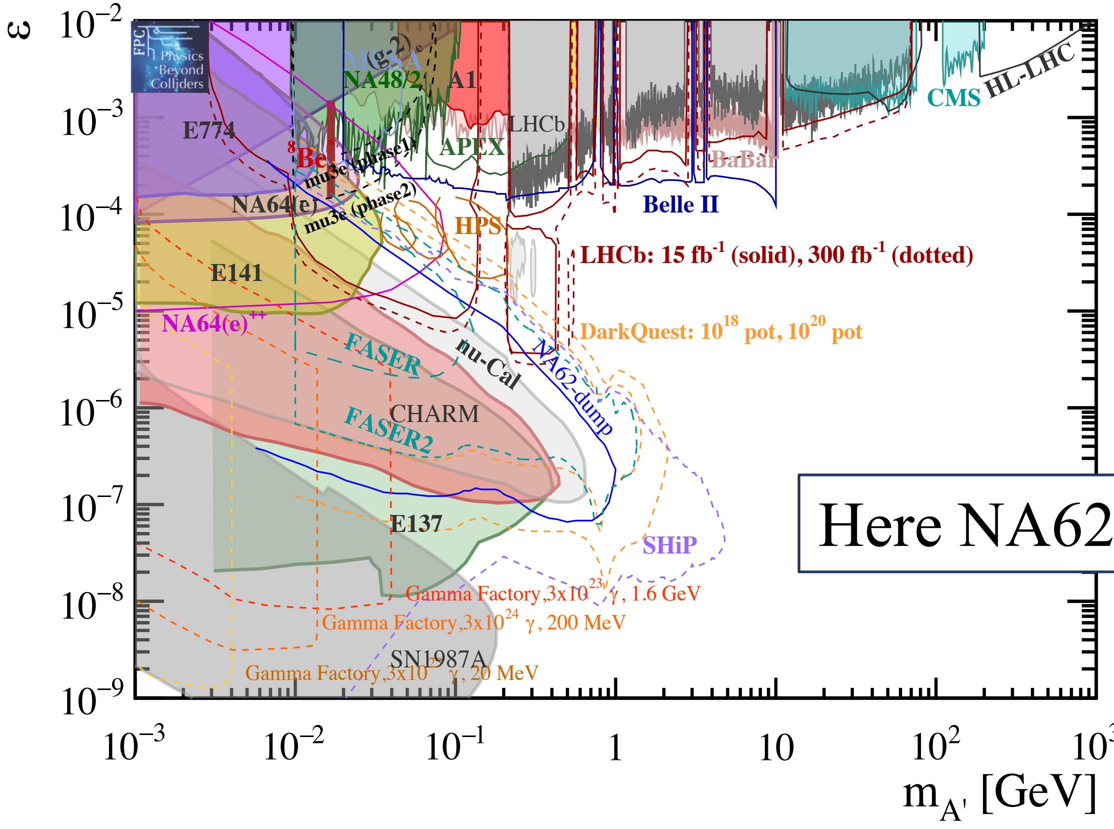



Here SHADOWS is the best

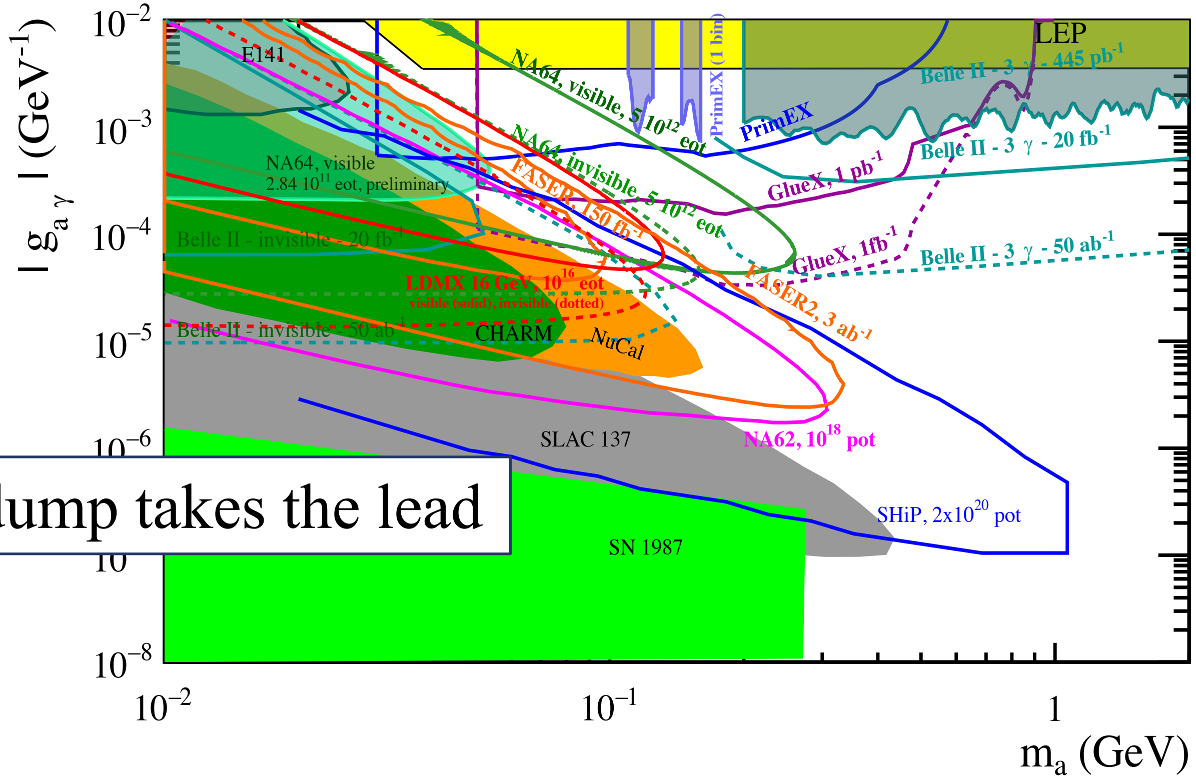
Here SHADOWS is slightly worse only of DUNE & SHiP @ BDF.

# Where SHADOWS is NOT sensitive: FIPs produced very forward

**Dark Photon minimal models**




**ALPs with photon-coupling only**

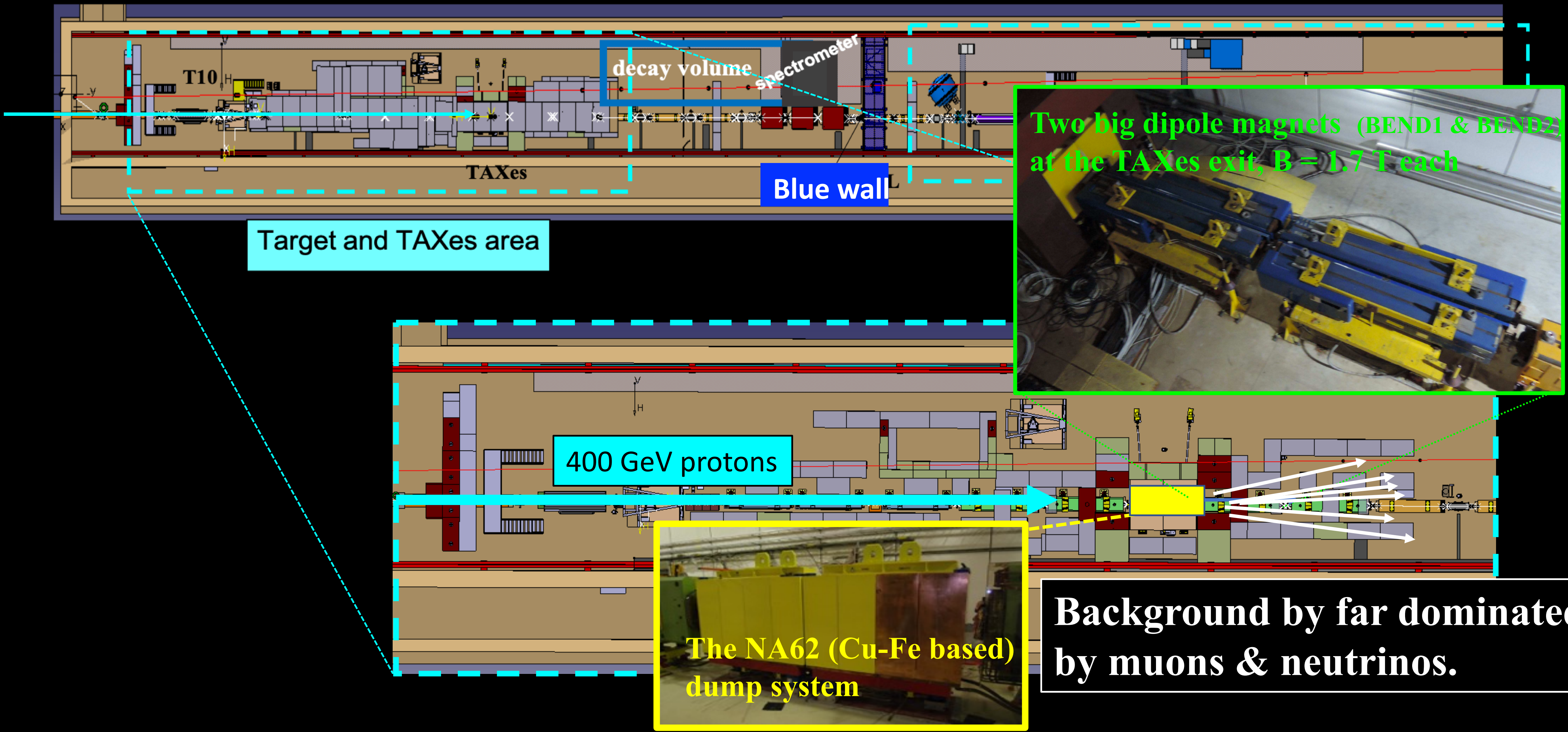



Here NA62-dump takes the lead

A broad and synergistic programme for FIPs
can be done in ECN3 with NA62-K, NA62-dump and SHADOWS.
Together can provide an unprecedented physics reach in the international landscape.

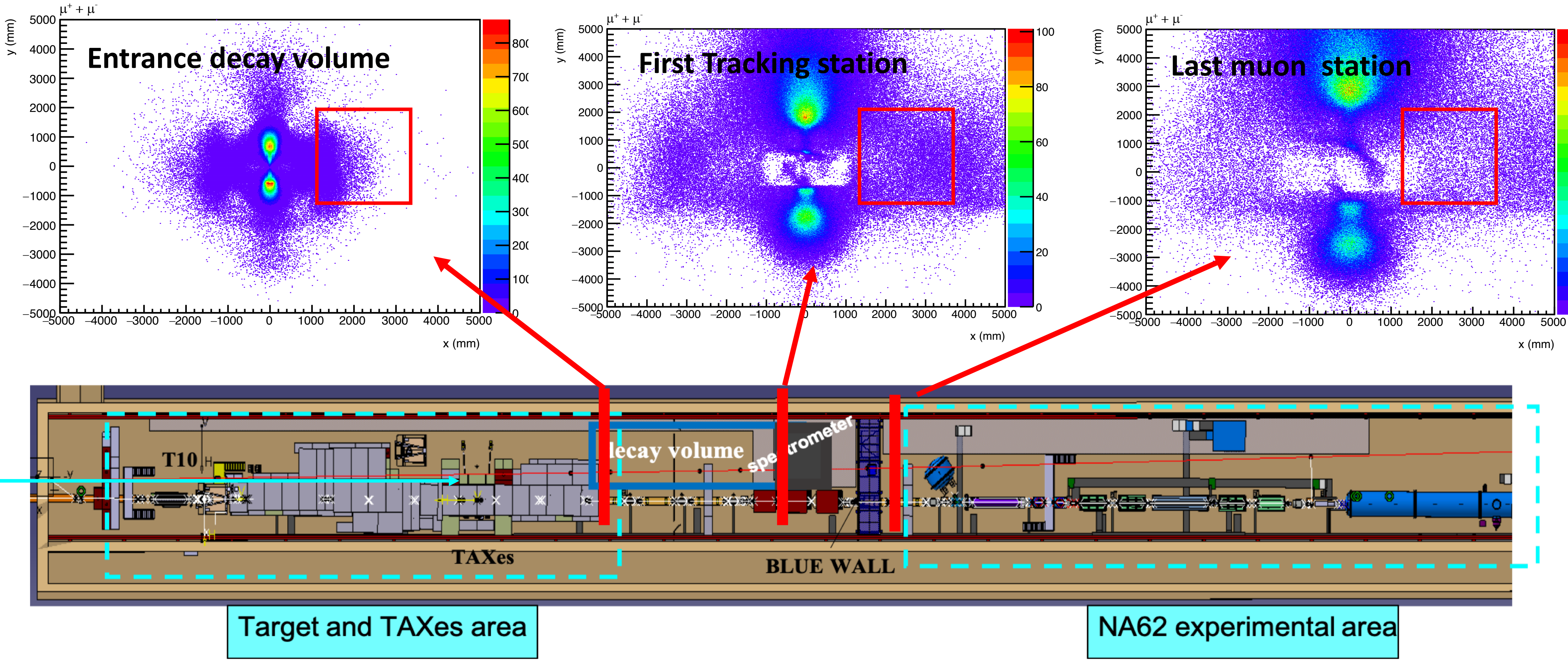
# The beam-induced background:
# the name of the game

# The beam-induced background:

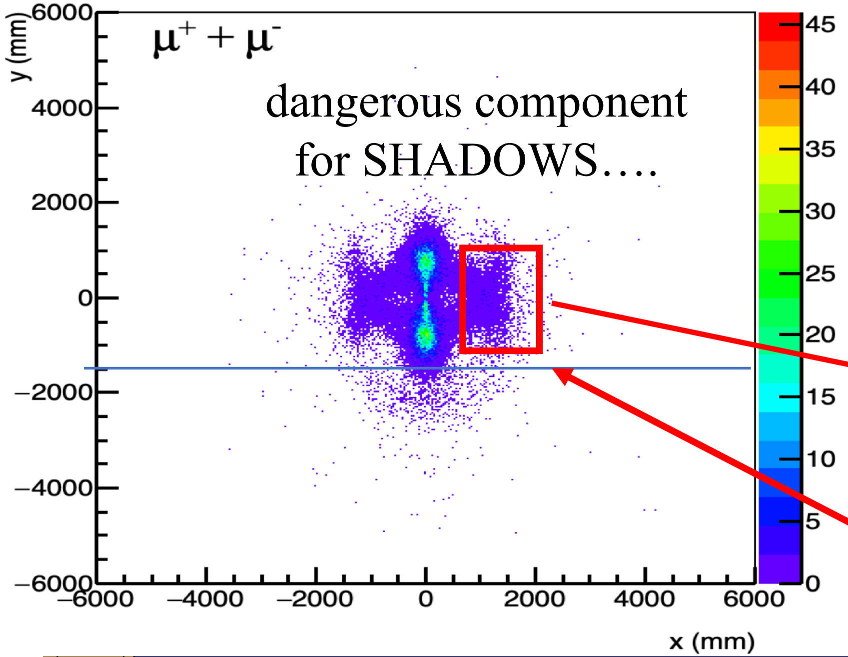



**Background by far dominated by muons & neutrinos.**

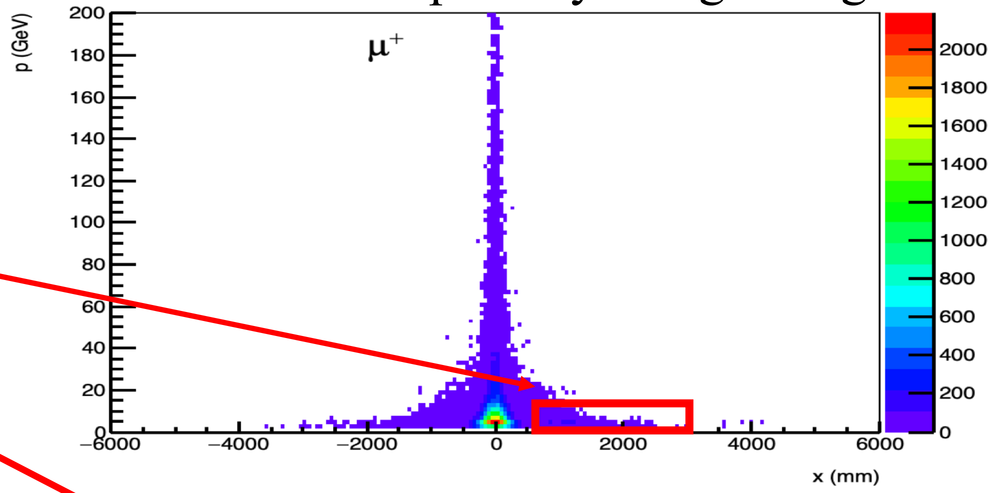
# Muon illumination as a function of the position along the line

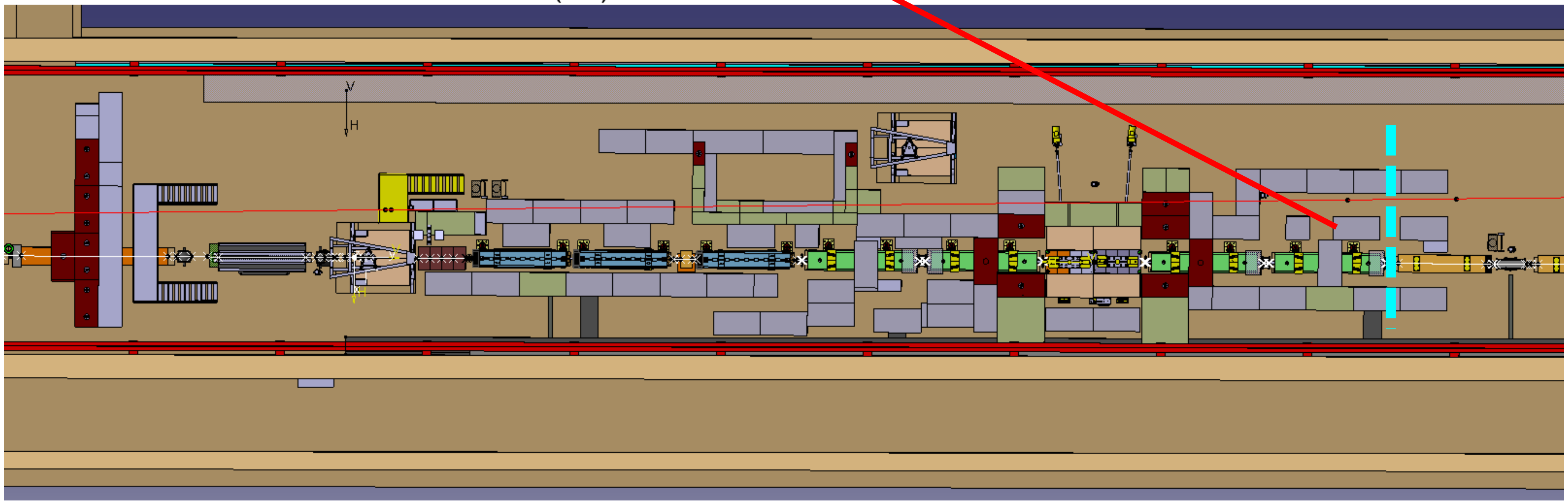


# Muon illumination after the second dipole of the Achromat




…But it is made of low-p (< 15 GeV) muons
that can be swept away using a magnetized iron block!

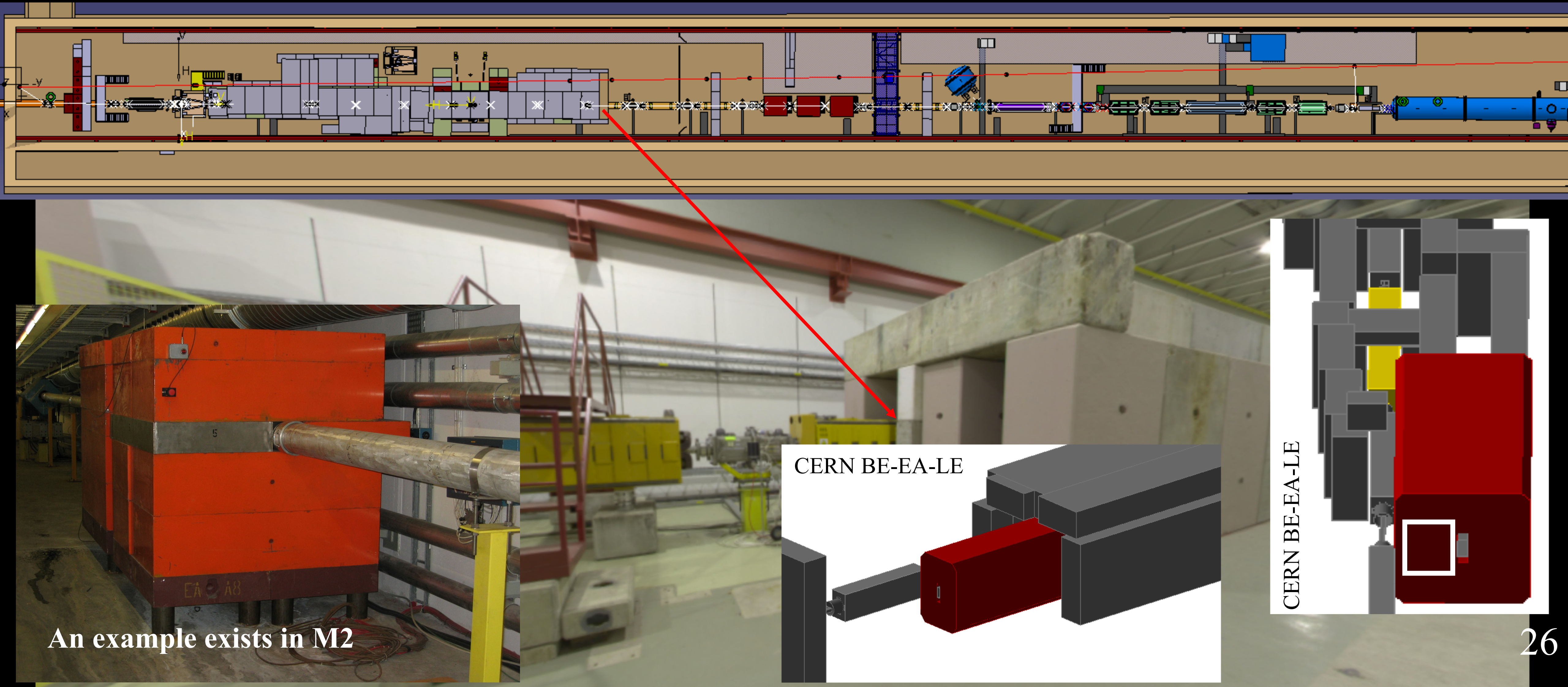


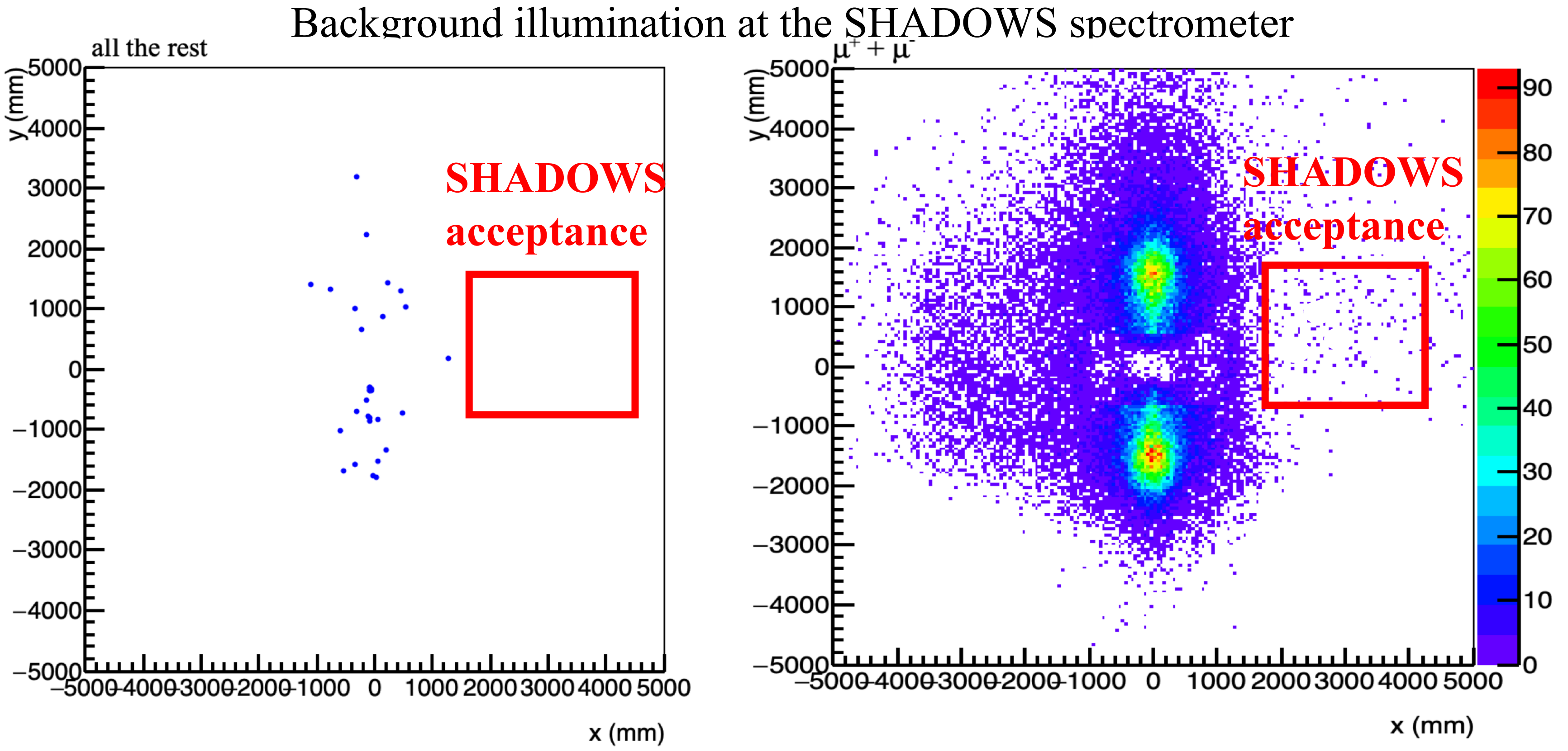
# SHADOWS Muon Sweeping system:

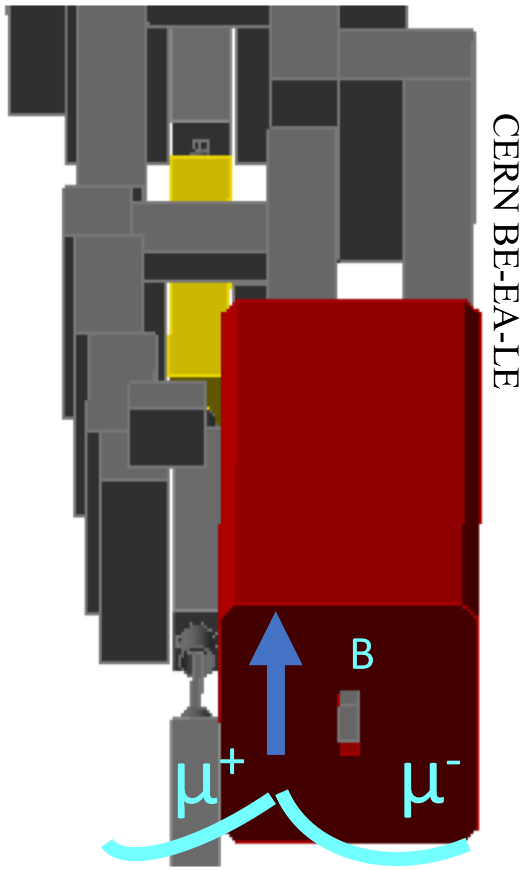
## A Magnetized Iron Block (MIB) as part of the TAX shielding structure

(currently studied in CERN BE-EA-LE group)



# SHADOWS Muon Sweeping System: MIB results in the EoI



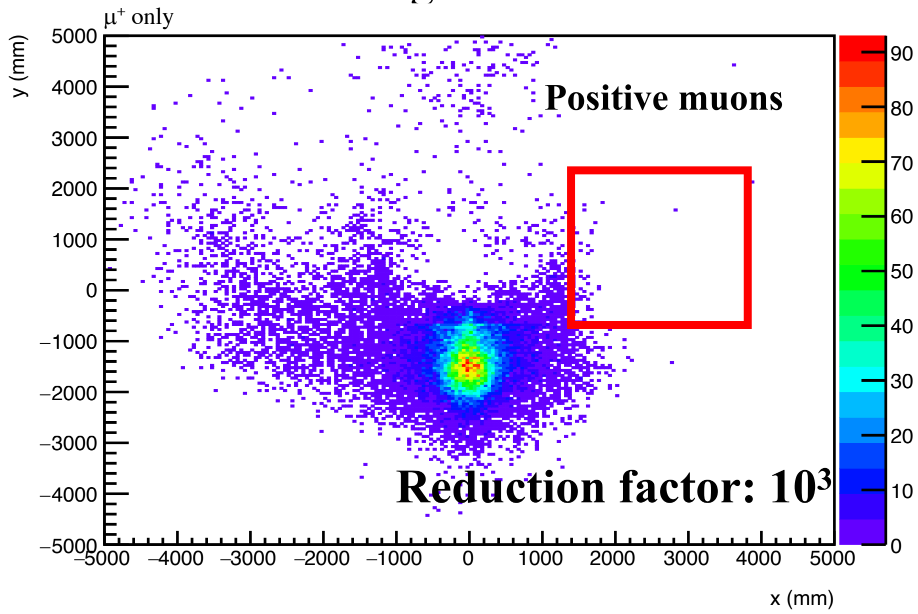



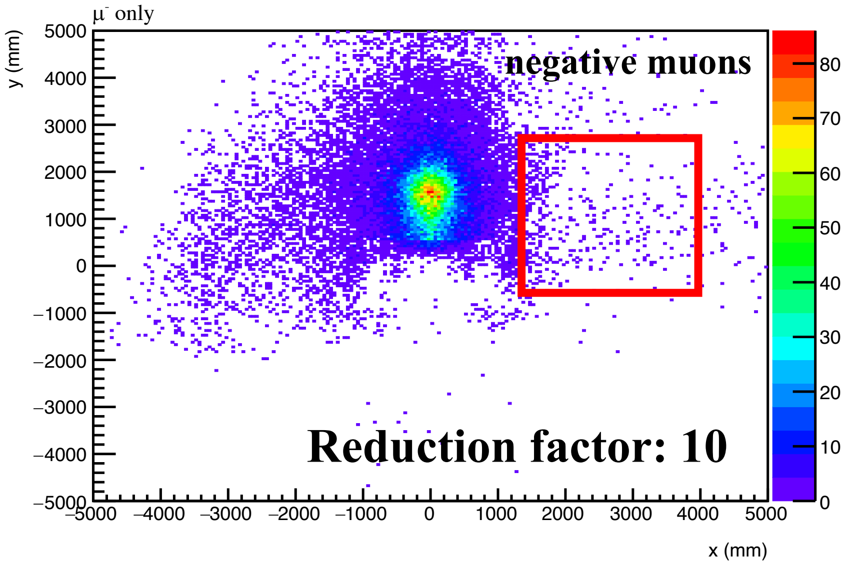

**non-muon background:**
**fully negligible.**

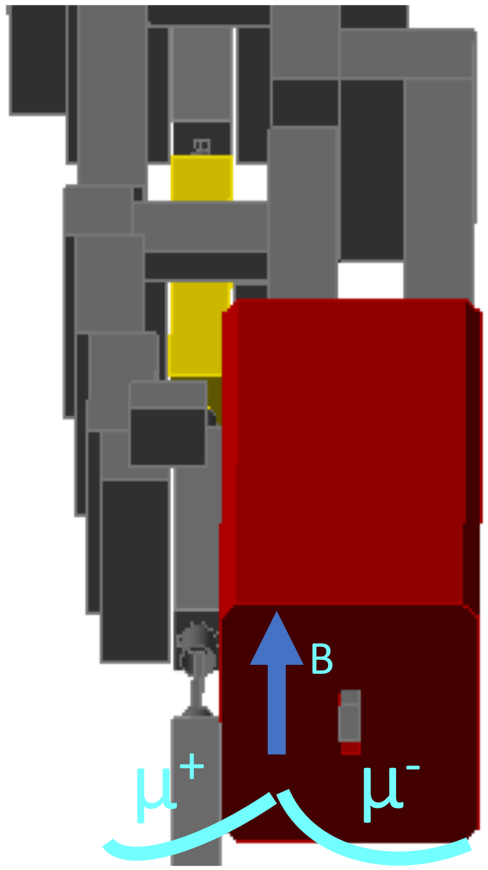
**muon background:**
**reduced by a factor ~10 at the first attempt**

# SHADOWS Muon Sweeping System: MIB results in the EoI

Background illumination at the SHADOWS spectrometer

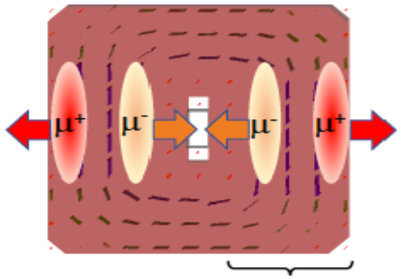



CERN BE-EA-LE

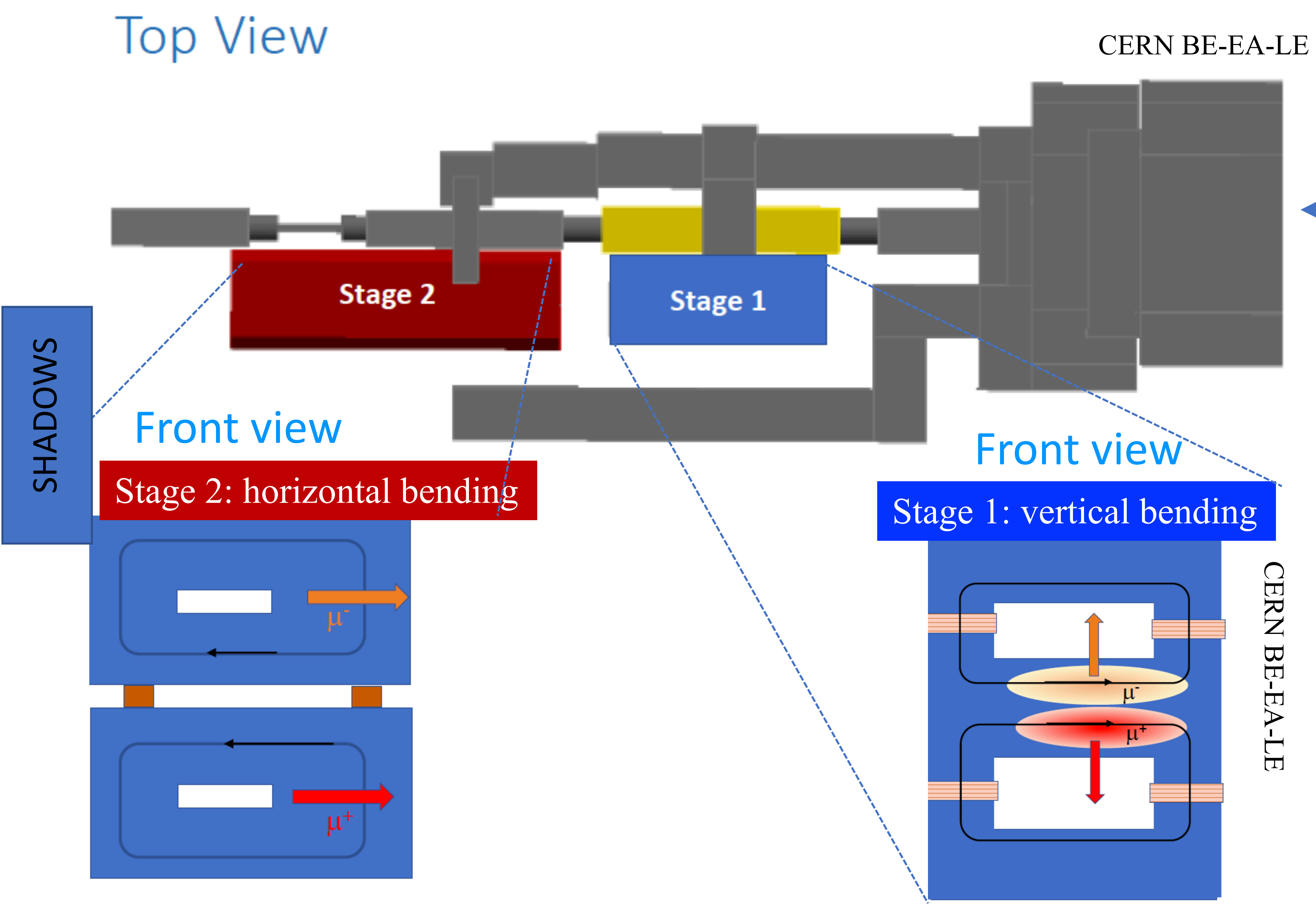
**Residual background fully dominated by negative charged muons bent back from the "wrong" B field polarity…**




Second half of the sweeping magnet works against us

# New conceptual MIB design: work ongoing…

NEW wrt EoI




**Preliminary brilliant solution (L. Gatignon & BE-EA-LE):** implement a 2-stage sweeping system:

1. Stage 1: vertical bending
2. Stage 2: horizontal bending

**Potential interest also of the LNF Accelerator Division** (1 beam physicist and 1 engineer expert in magnet design).

# Background: Preliminary considerations

Three main backgrounds:

1. Muon combinatorial

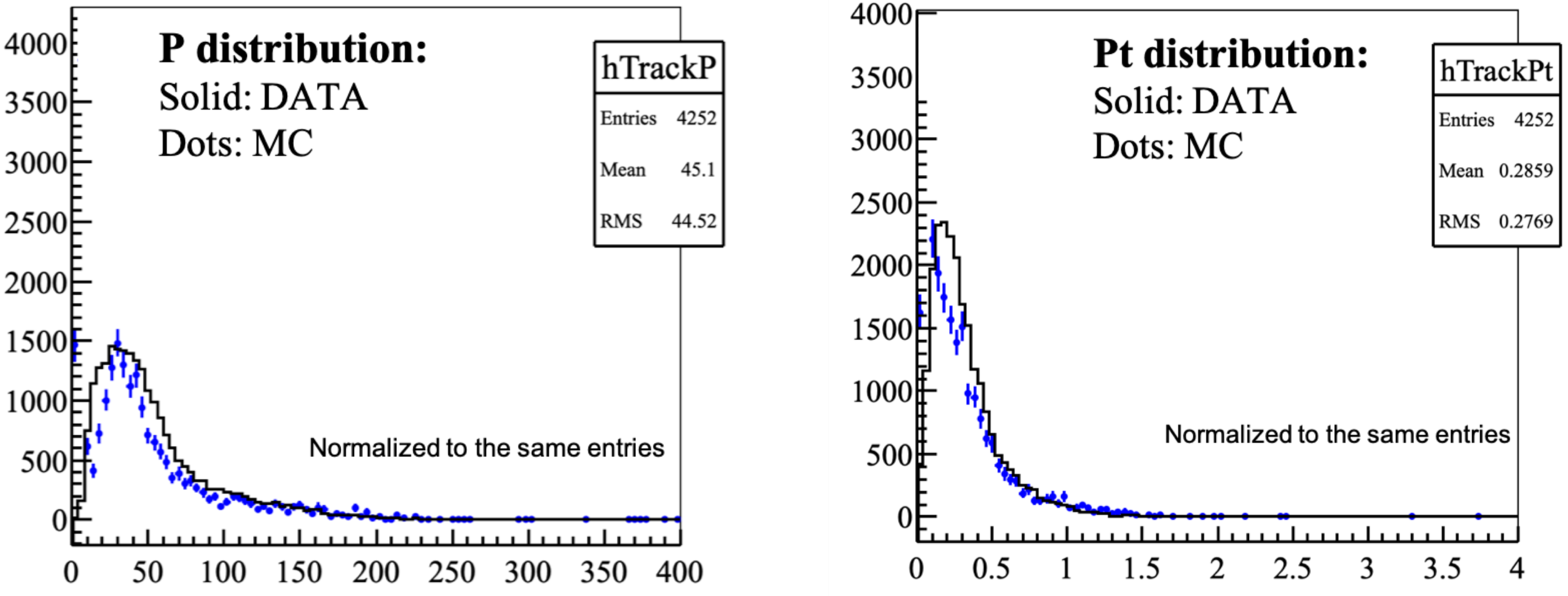
2. Neutrinos inelastic interactions with the air in the decay volume

3. Muon and neutrino inelastic interactions in the material at the entrance of the vessel

MIB still to be designed and full MC of the detector still to be implemented.
Today preliminary considerations based on the MC truth of a simulated sample of 1.3 $x10^9$ pot on dump.
A detailed study of the background will be done for the Proposal.

# Background: (Preliminary) Validation of muon background simulation

**NA62 has collected about 1.7 x$10^{17}$ pot in dump in November 2021**

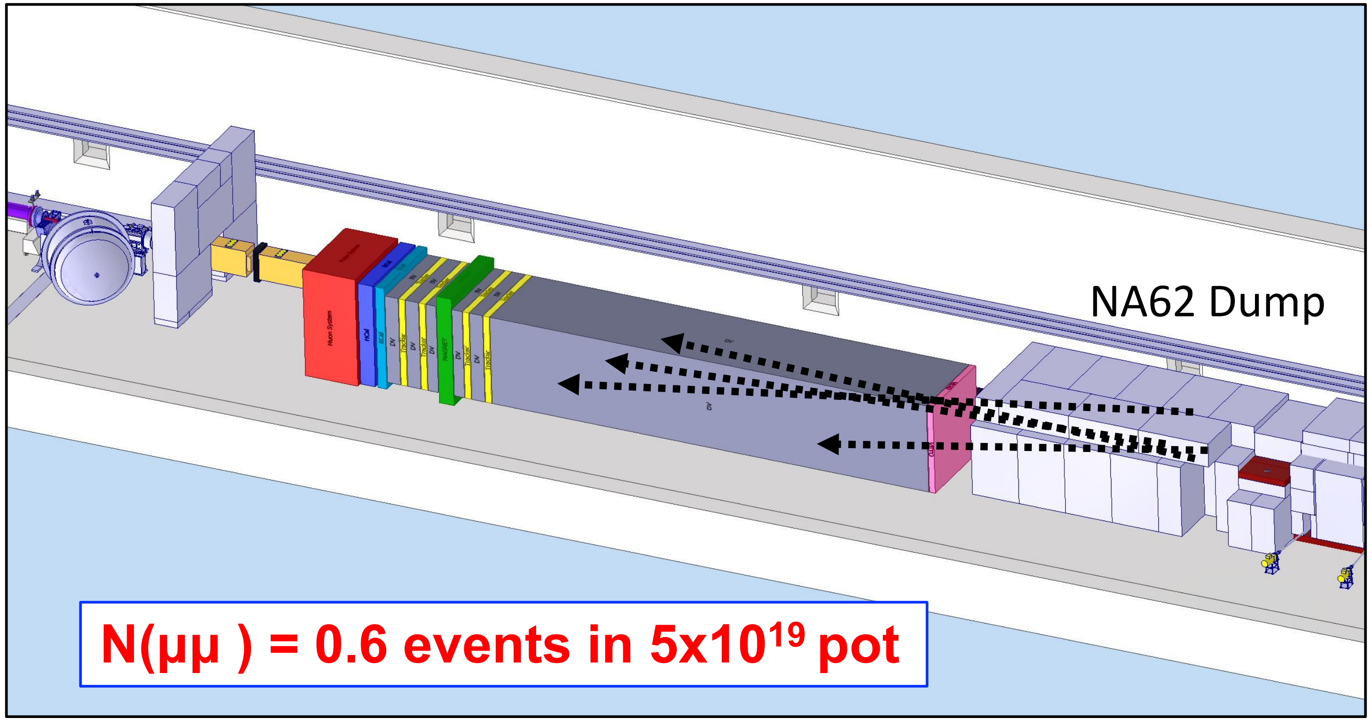



This data set allows to validate the output of the MC simulation (based on BDSim package, GEANT4).
**Shapes of distributions are reasonably well reproduced**,
**Simulated rates are under-estimated by a factor 3** in the momentum range of interest for SHADOWS.

# 1. Background: Muon Combinatorial

NEW wrt EoI

Muon rate without MIB: 100 MHz in acceptance from NA62 data and MC.
Assume MIB reduces it to 1 MHz , we have 4 Mevents/spill, 4-sec long.
CAVEAT: we assume that kinematic properties of muons with/without MIB are the same.




**N(μμ) initial = $4x10^6$ /spill**

**1) timing:** Require 2 muons in 3 sigma window of the Timing layer N(μμ): 2400/spill

**2) Upstream Veto:** assume eff = 99.5%.
Probability of non-vetoing two tracks: 2.5 $10^{-5}$

**3) Vertex in FV:** Probability to have a vertex in FV: 3 $10^{-3}$

**4) Pointing:** Probability to point back to impinging point of protons onto the dump: $10^{-3}$

ALL IN ALL : $2x10^{-7}$ μμ /spill, $3x10^6$ spills in $5x10^{19}$ pot
**N(μμ ) final = 0.6 events in $5x10^{19}$ pot**

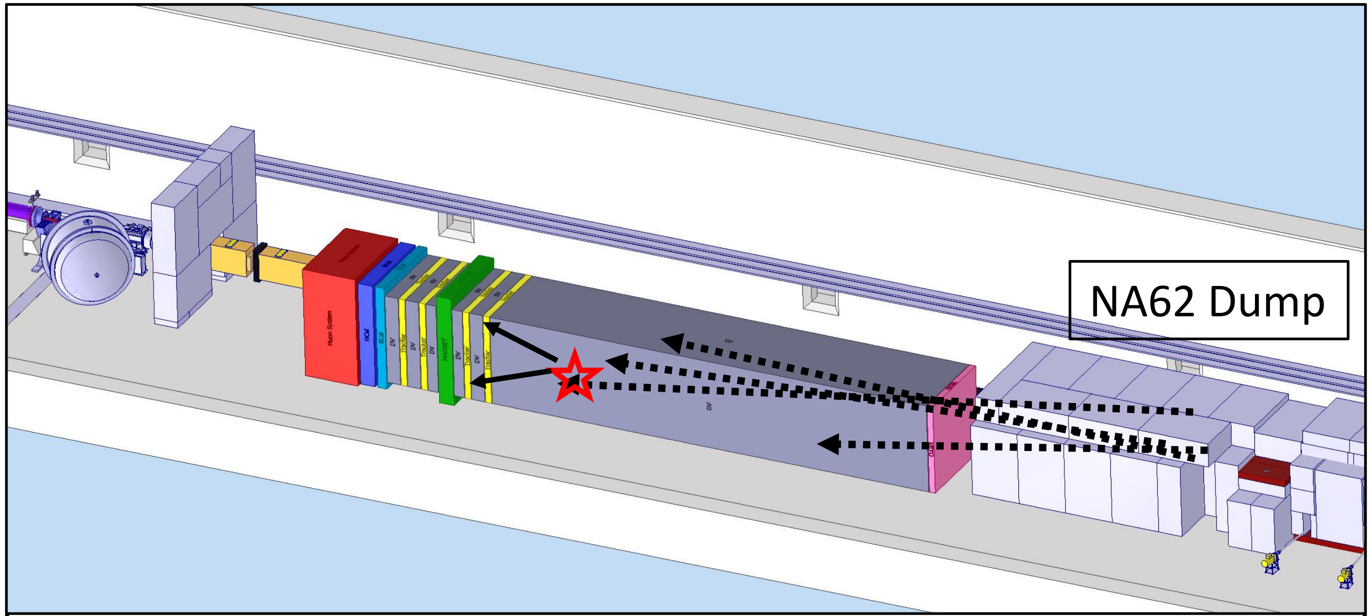
**NB: A detailed evaluation will be done for the Proposal.**

# 2. Background: Neutrino inelastic interactions in air of decay volume

NEW wrt EoI

Number of neutrinos in SHADOWS acceptance:

$$N_\nu = N \times 2 \cdot \chi_{c\bar{c}} \times 2 \cdot BR(c \to e/\mu X) \times \epsilon_{acc} \sim 6 \cdot 10^{15}$$ (for N = $5 \times 10^{19}$ pot)




**N($\nu$ inel. interactions in DV, 1 mbar ) = 0.6 events in $5 \times 10^{19}$ pot**

Number of inelastic interactions in 20 m long decay volume filled by air at atmospheric pressure, for E$\nu$ ~ 10 GeV:

$$N_{\nu \text{ inelastic int.}} = N_\nu \times 10^{-13} = 6 \cdot 10^{15} \times 10^{-13} = 600$$

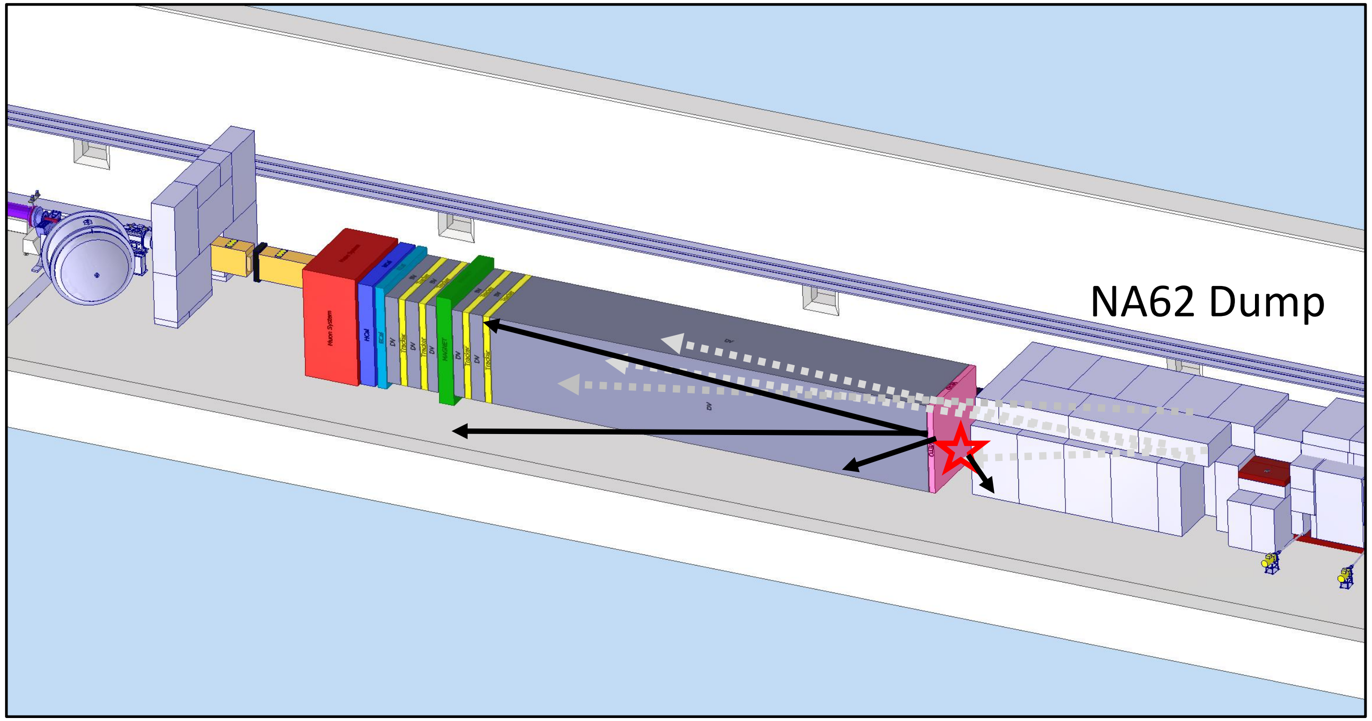
**1 mbar vacuum reduces this number to 0.6 events in $5 \times 10^{19}$ pot**

**NB: A detailed evaluation will be done for the Proposal.**

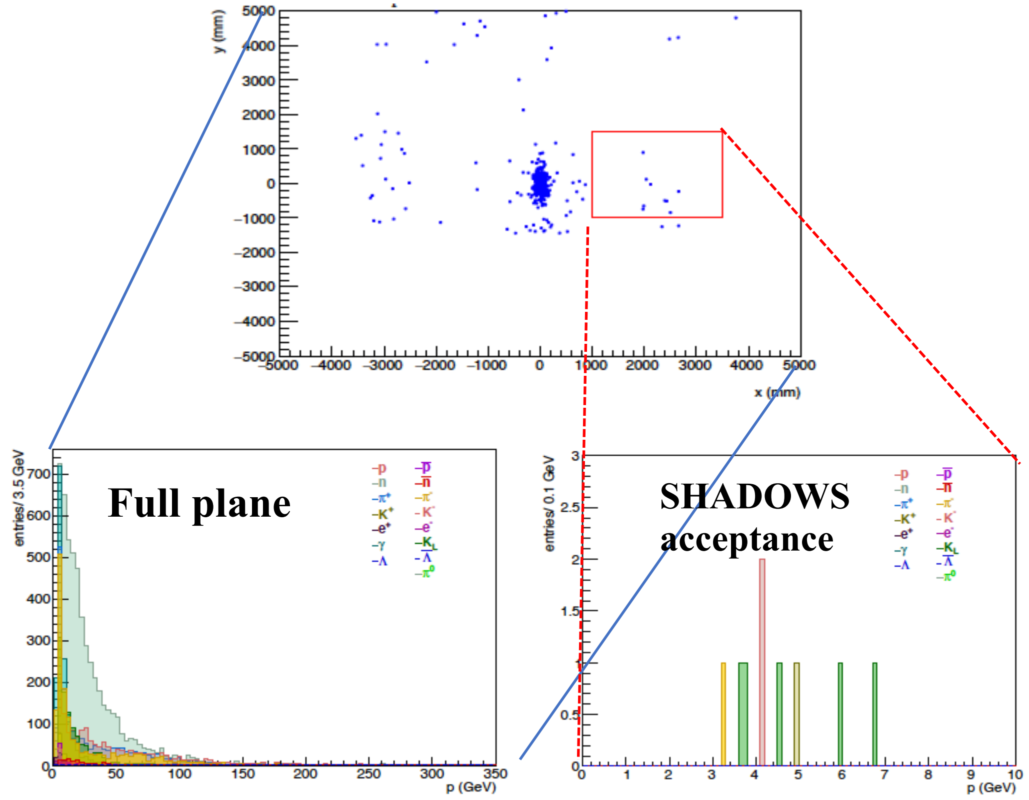
# 3. Background: Neutrino & Muon inelastic interactions in Upstream Veto

NEW wrt EoI

These interactions give signal in the Upstream Veto (UV), form a vertex very close to the boundaries of Decay Volume and do not point back to the impinging point of the proton beam onto the dump.
**This will not be the dominant background**….




**Non muon background downstream of TAXes**

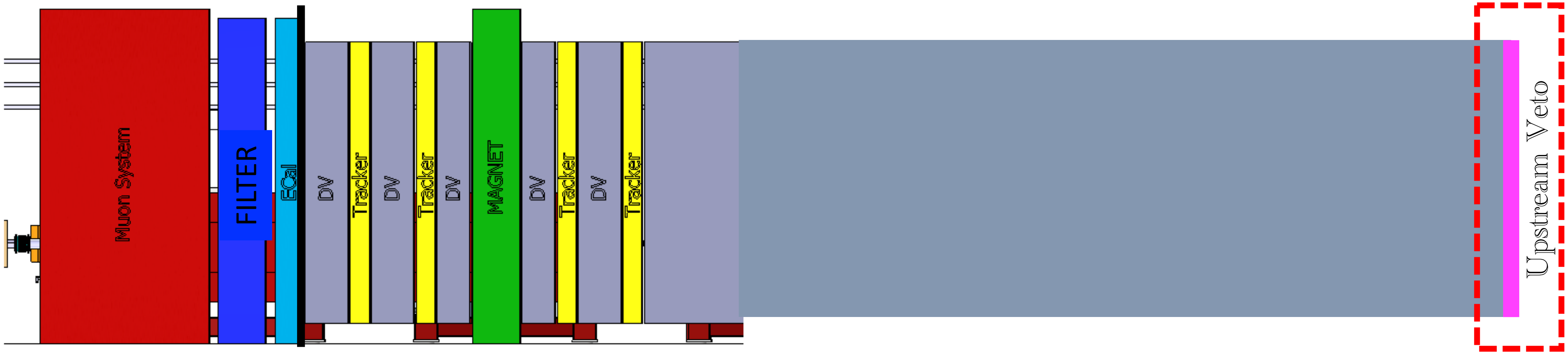



**NB: A detailed evaluation will be done for the Proposal.**

# Detector design: survey of technology options

a. Upstream Veto
b. Magnetic Spectrometer
c. Electromagnetic Calorimeter
d. Timing layer
e. Muon Detector

# SHADOWS Upstream Veto: MicroMegas



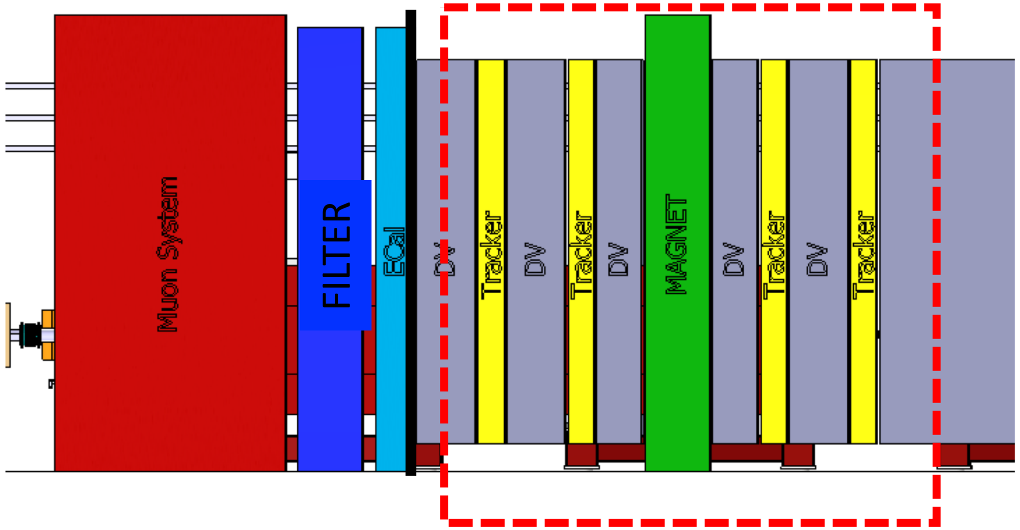

The only detector that has to stand to rates of o(10) kHz/cm$^2$.

Possible option: double layer of MicroMegas.

Discussions ongoing with some of the **groups who built the ATLAS New Small Wheels**

[M.Alviggi et al., Construction and test of a small-pad resistive Micromegas prototype, JINST 13 P11019, 201]

# SHADOWS Tracker: NA62 straws or SciFi



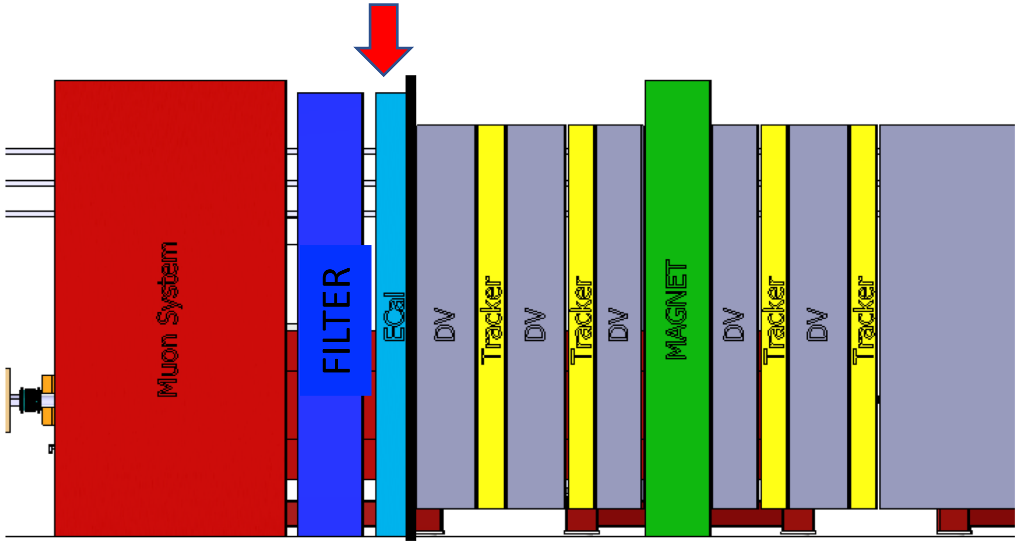


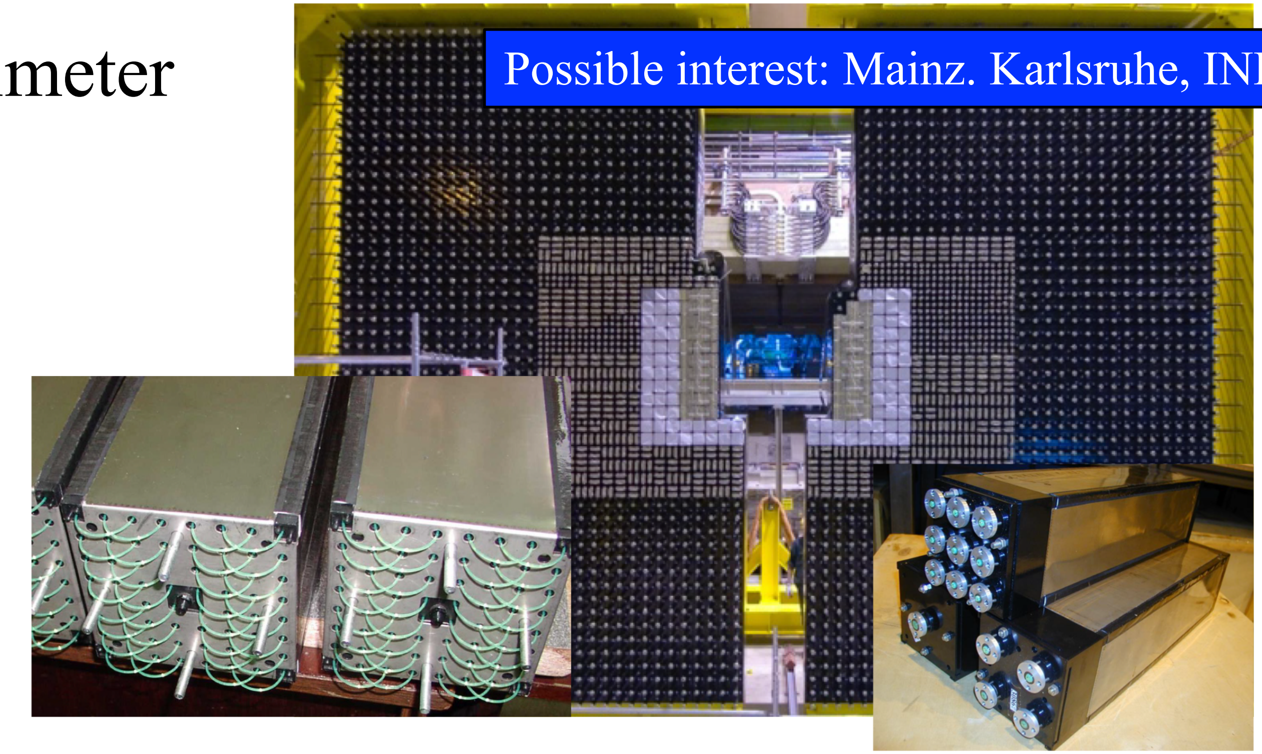

**1. NA62 STRAW tubes:** Ar(70%): $CO_2$ (30%), in vacuum, 10 mm diameter
One straw chamber is composed of four views (X, Y, U, V), one double-layer per view, 8 layers per station
Hit resolution better 400 um over most of the straw diameter per single layer. Warm dipole magnet with 0.9 Tm bending power.
3-4 MeV mass resolution for HNL -> pi mu final states. Impact parameter resolution < 1 cm over 180 m distance.

**2. Fibre Tracker (LHCb):** 250 um diameter, 2.5 m long scintillating fibres; three stations, six detection layers each.
Hit resolution per station < 80 um. 4 Tm bending magnet.

**Heidelberg** and **CERN** interested in studying the tracker.
[**Hans Danielsson** (CERN, **Project leader of the NA62 Straws**) and **Ulrich Uwer**
(Heidelberg, **Project leader of LHCb SciFi**) are part of the SHADOWS proto-collaboration].

# SHADOWS: Electromagnetic calorimeter




## Current situation:

176 Shashlik of **LHCb-ECAL** modules could become available at LS3 (as proposed in the LHCb FTDR): can be used to instrument an area of 160 x 160 $cm^2$. The o(200) modules missing could be built at **INR**. **Mainz** also interested in this topic. **Karlsruhe** (Prof. Klute and Prof. Ferben) interested to study the option of a tracking calorimeter (important for di-photon final states) (eg: **CMS-HGCal/CALICE**).

## Other options listed in the EoI:

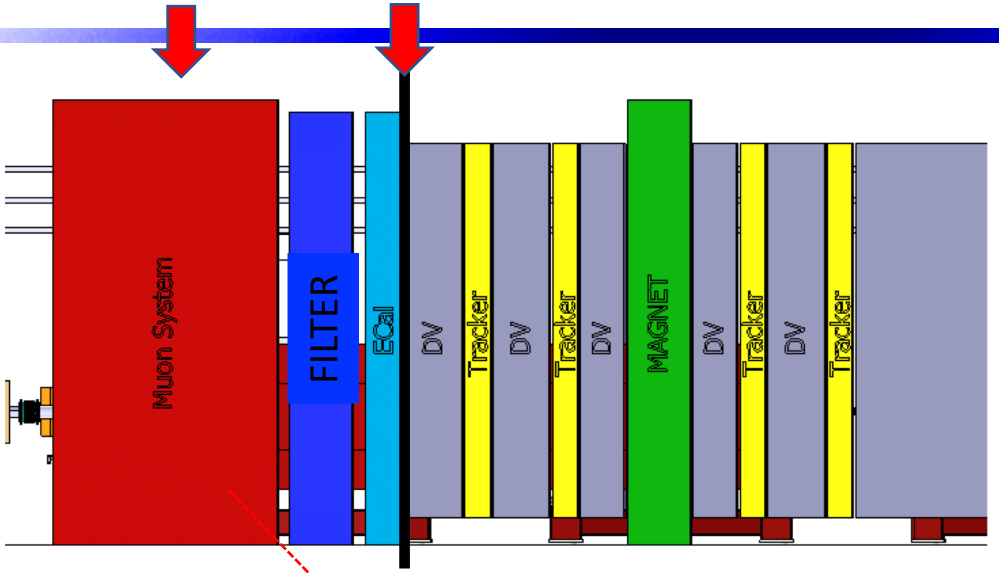
- **PbWO4 crystals from CMS ECAL endcaps** – will be removed during LS3. Some reconditioning will be needed but a large fraction of crystals could be ready to be used. Option viable if there are interested groups.

- **SHiP EM calorimeter – SplitCal concept.** longitudinally segmented lead sampling calorimeter with a total sampling depth of $20X_0$. Sampling layers are scintillating plastic bars read-out by WLS fibres. Three sampling layers (located at the depth of the shower maximum) with high resolution detectors (μRWELLS) providing a spatial segmentation of 200 μm for pointing measurements.

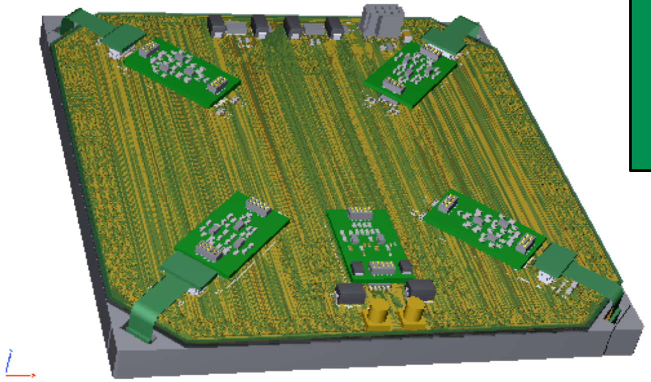
# SHADOWS: Muon Detector

(same technology could be used for timing detector)

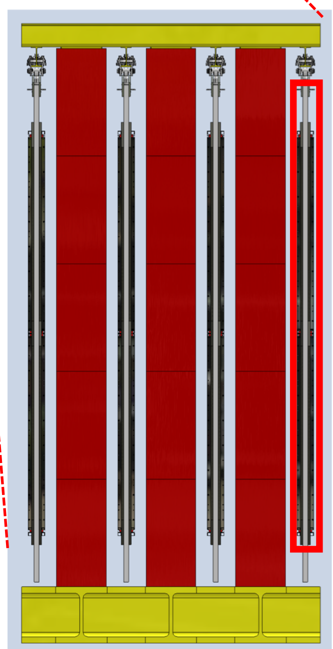
Possible interest: INFN (Frascati, Bologna, Ferrara), INR, ..

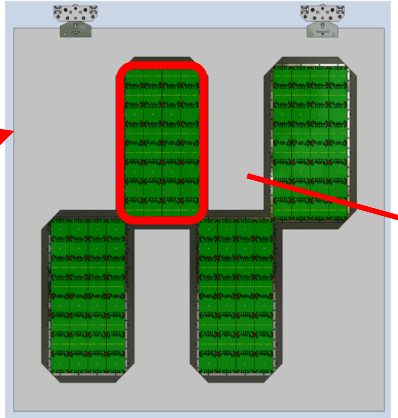



1 tile = 15x15 cm2,
Direct SiPM readout at the corners
One analog output per tile



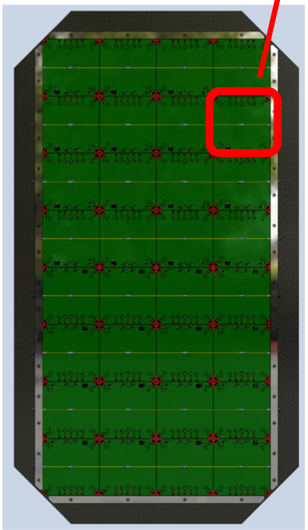
**Received o(50) kEuro from INFN/AIDA-innova for development of first full size prototype**



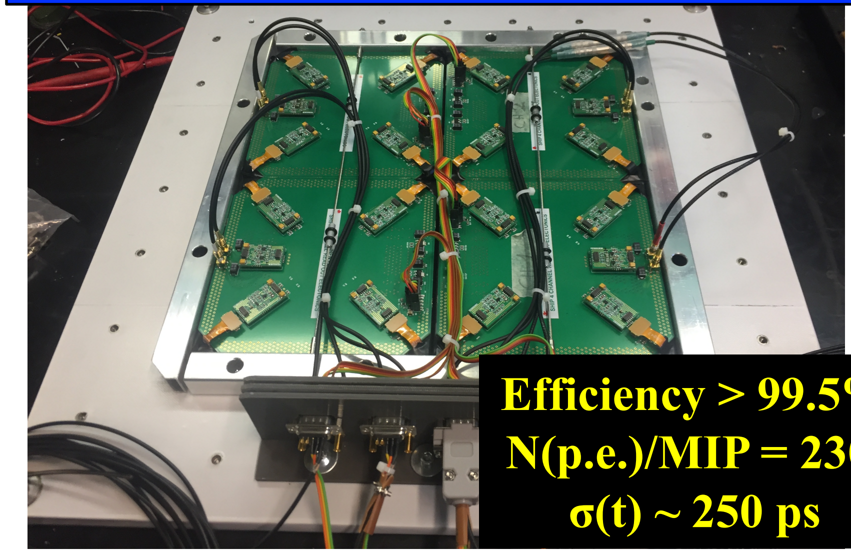


1 station = 8 modules
[same pattern staggered on the other side of the wall]

1 module = 16/32 tiles

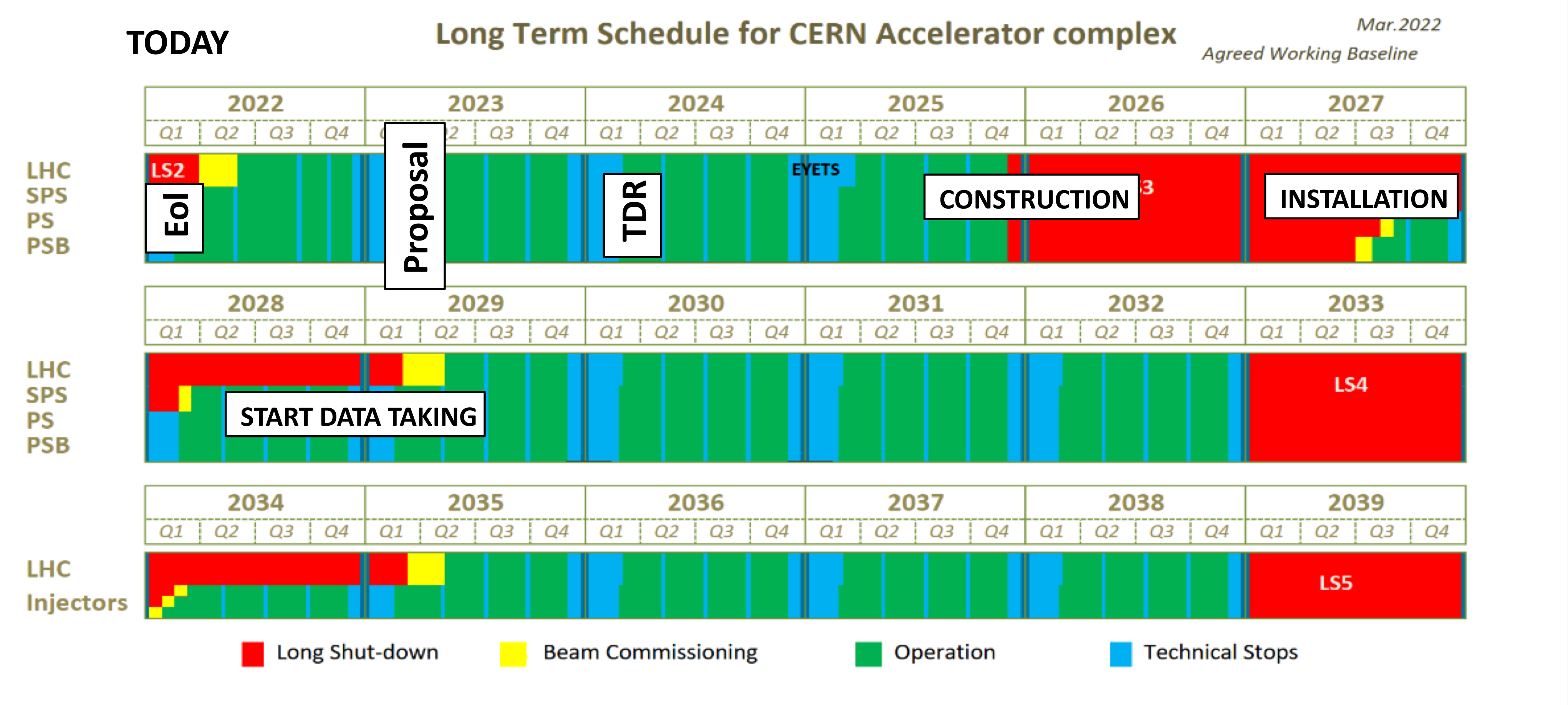


4-tile prototype built in INFN Bologna/LNF



**Efficiency > 99.5%**
**N(p.e.)/MIP = 230**
**σ(t) ~ 250 ps**

# SHADOWS: TENTATIVE TIME SCHEDULE




Next step: if positive recommendation from SPSC: Prepare a Proposal by early 2023.

# Conclusions & Next steps

- ✓ SHADOWS is a proposed proton beam dump experiment for FIPs physics that can be built in ECN3 and take data concurrently to NA62 when NA62 is operated in beam-dump mode:
  ⇨ SHADOWS can be built now: (almost) all the infrastructure is in place.

- ✓ SHADOWS ($5 \times 10^{19}$ pot) has similar/better sensitivity than CODEX-b (300 $fb^{-1}$) and FASER2 (3 $ab^{-1}$) and for specific benchmarks as SHiP ($2 \times 10^{20}$ pot) for FIPs from charm/beauty:
  ⇨ It naturally complements NA62-dump that is mostly sensitive to very forward objects, and NA62-K that is mostly sensitive to FIPs below the K-mass.

- ✓ ECN3 with SHADOWS+NA62-K+NA62-dump can become a "hot spot" on worldwide scale for FIPs physics after LS3:
  ⇨ A timely NA consolidation programme is paramount to ensure stable and reliable operation.

- ✓ SHADOWS Next step:
  ⇨ Preparation of the Proposal by early 2023.

# SPARES

# SHADOWS: TENTATIVE COST

(to be updated when the detector technologies will be decided)

**Table 2.** Very preliminary cost estimate of SHADOWS sub-detectors.

| Sub-detectors | Possible Technology | very preliminary) cost |
|---|---|---|
| Upstream Veto | Micromegas | 0.2 MCHF |
| Decay Vessel | in vacuum | 1 MCHF |
| Dipole Magnet | warm | 4-5 MCHF |
| Tracker | NA62 Straws or SciFi | 3 MCHF |
| Timing Layer | small scintillating tiles | 0.1-0.2 MCHF |
| ECAL | Shashlik | 2-3 MCHF |
| Muon | scintillating tiles | 0.4-0.5 MCHF |
| TDAQ & offline | | o(1-2) MCHF |
| Total | | $\sim 11.6 - 14.9$ MCHF |

# SHADOWS: CRITICAL ITEMS

**Critical items in beam line/infrastructure:**

1. MIB (design and realization) as part of the K12 TAX shielding (largely in common with NA62);
2. New TAX system (both K12 and P42 TAXes) (able to stand $\times$ 6 intensity) (in common with NA62);
3. Integration studies for SHADOWS detector in ECN3/TTC8.
4. Radiation Protection studies for beam intensity $\times 6$ (in common with NA62);
5. Refurbishment of the electrical infrastructure of the area, power converters for MIB, tracker dipole.

**Critical items for SHADOWS:**

1. Dipole magnet of the tracker;
2. Decay vessel.