SHADOWS

Search for Hidden And Dark Objects With the SPS

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

SHADOWS PROPONENTS

INFN-LNF,

INFN-Ferrara, INFN-Bologna,

CERN

University of Lancaster,

Royal Holloway London

University of Mainz (excellence cluster)

University of Heidelberg, KIT University of Karlsruhe,

University of Freiburg,

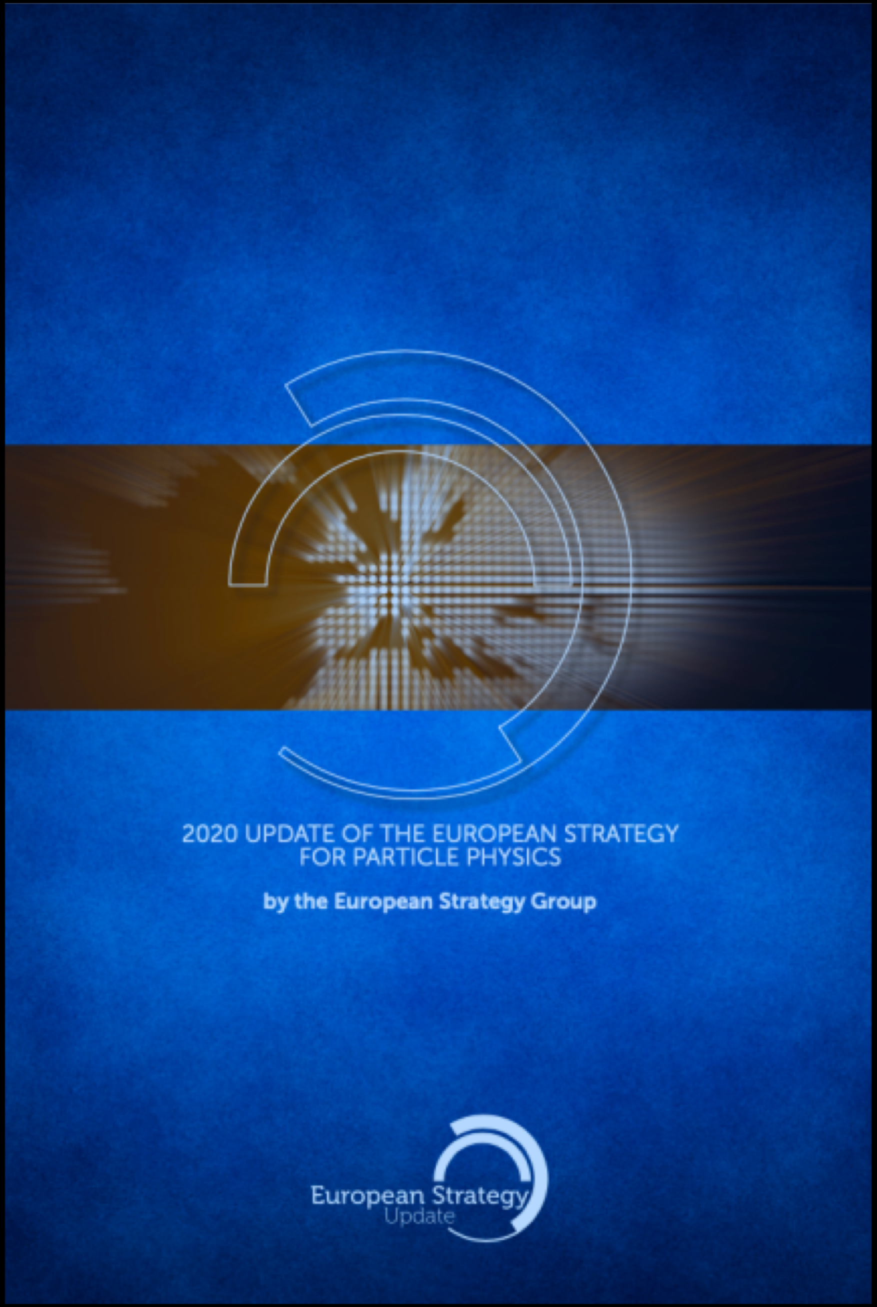
INR-Moscow , INFN-Naples, INFN- Rome3,…..

LNF - Consiglio dei Laboratori, 6 July 2022

LNF SHADOWS TEAM:

from SHiP ….to SHADOWS ….passing by AIDA-Innova!

The Context

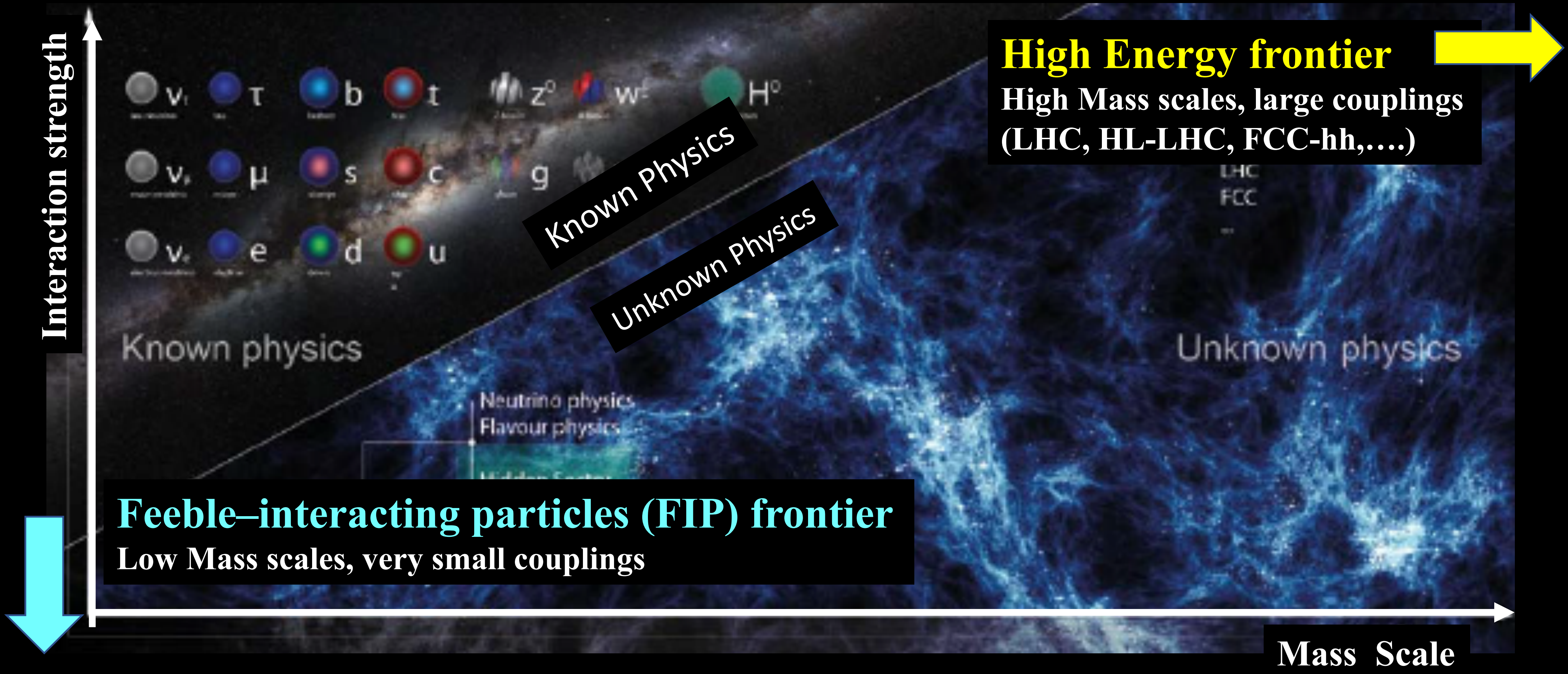


ESPP Recommendations

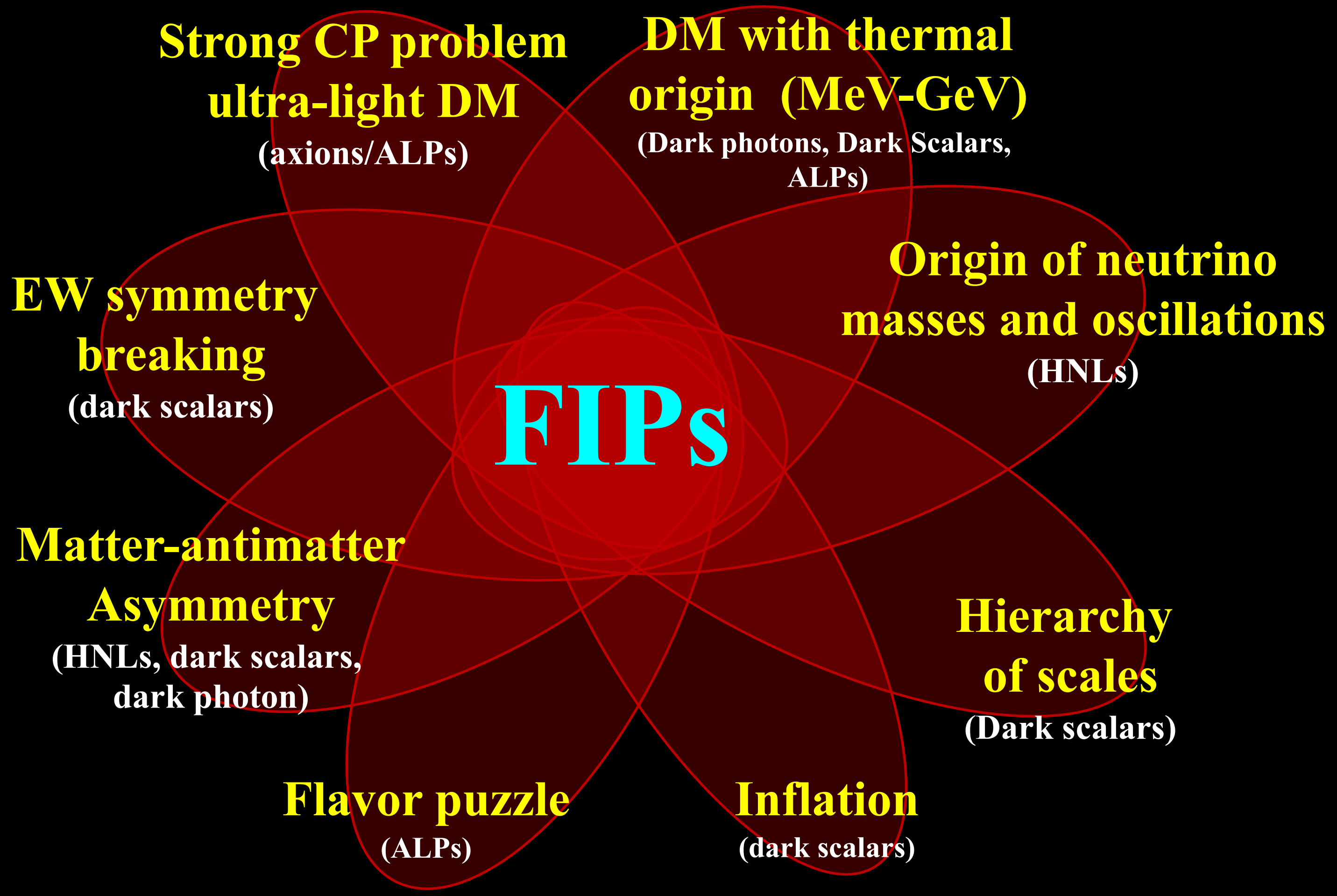
- *"4. Other essential scientific activities for particle physics:*
- *a) The quest for dark matter and the exploration of flavour and fundamental symmetries are crucial components of the search for new physics.*
- *This search can be done in many ways, for example through precision measurements of flavour physics and electric or magnetic dipole moments, and searches for axions, dark sector candidates and feebly interacting particles.*
- *There are many options to address such physics topics including energy-frontier colliders, accelerator and non-accelerator experiments. A diverse programme that is complementary to the energy frontier is an essential part of the European particle physics Strategy.*

https://cds.cern.ch/record/2721370/files/CERN-ESU-015 2020%20Update%20European%20Strategy.pdf

FIPs: a change in perspective….



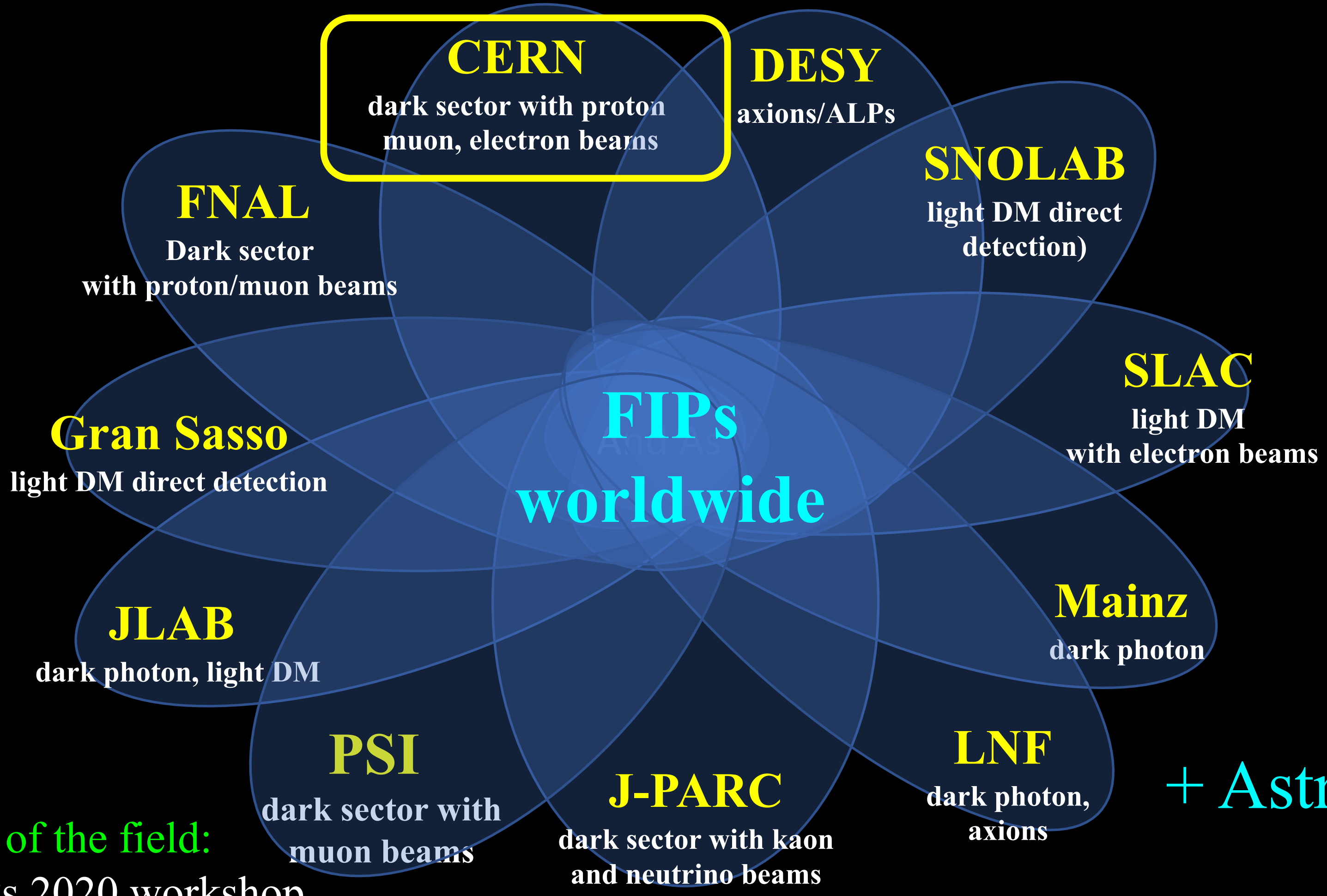
... that might provide answers to fundamental physics questions…



For a general introduction (not too technical):

M. Pospelov, P. Schuster and GL *The Search for Feebly-interacting particles,*
Ann.Rev.Nucl.Part.Sci. 71 (2021) 279-313: 2011.02157

The Search for Feebly-Interacting Particles:
A lively multi-community effort



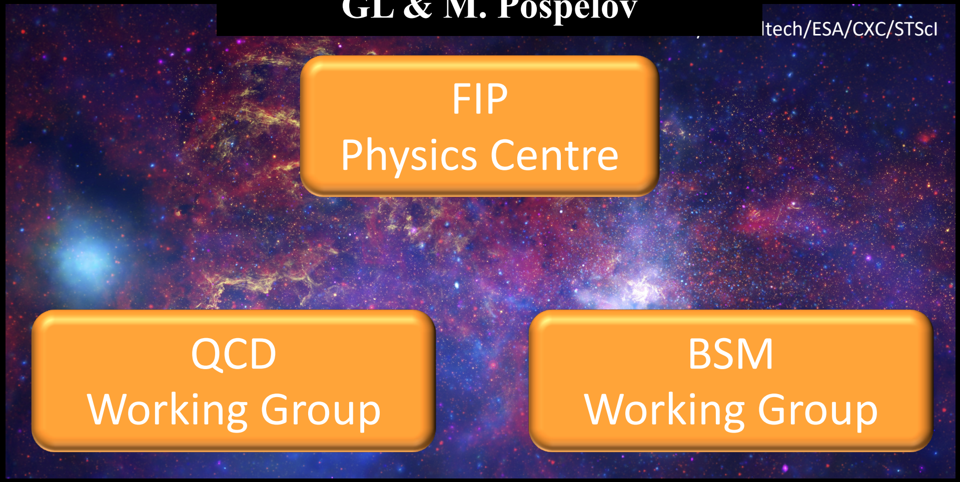
+ Astroparticle, cosmology

For a recent overview of the field:

- Proceedings of FIPs 2020 workshop,
- *Eur.Phys.J.C* 81 (2021) 11, 1015
- e-Print: 2102.12143 [hep-ph]

Physics Beyond Colliders @ CERN

GL & M. Pospelov



https://pbc.web.cern.ch/

General PBC coordinators:
Claude Vallee
Gianluigi Arduini
Joerg Jaeckel

Daniel Boer,
Jan Pawlowski,
Gunar Schnell

A. Rozanov,
C. Rembser
F. Kahlhoefer,

- Beam Dump Facility
- Conventional Beams
- LHC – Fixed Target
- Technology

PBC-A&T Committee

Civil Eng., Integration, Radiation Protection

- Accelerator Complex Capabilities
- Forward Physics Facility
- Gamma Factory
- Prototype EDM Storage Ring

Physics Beyond Colliders

Experiments/proposals related to FIPs in PBC

See also next ECFA meeting, CERN, 21-22 July 2022

FIPs @ CERN

SPS
(MeV- few GeV)

HIKE (NA62-successor)
FIPs with kaons/proton beam dump

SHiP

NA64-e/mu/h
Light DM with e/mu beams

SHADOWS
FIPs @ proton beam dump

Gamma-factory
(mostly ALPs)

Axions/Dark Photons
(< meV)

(Baby-)IAXO
solar axions

VMB
Vacuum birifrangence

proton-EDM

LHC
(few GeV – TeV)

CODEX-b
FIPs @ LHCb IP

ANUBIS
(FIPs @ ATLAS shaft)

MATHUSLA
FIPs @ CMS IP

Forward Physics Facility (FASER2, …)

Gravitational Waves
via atom interferometry
(10^{-20} eV)

AION
FIPs with atom interferometer

nTOF

Nuclear astrophysics

ISOLDE

AD
FIPs @ anti-proton decelerator

Ultra-light FIPs
(atomic clocks, quantum sensors and the likes)

SHADOWS

Search for Hidden And Dark Objects With the SPS

What is SHADOWS?

SHADOWS is a newly proposed proton beam dump experiment placed off-axis in the ECN3/TCC8 experimental cavern in North Area 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 FIP Physics program can be performed with HIKE (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

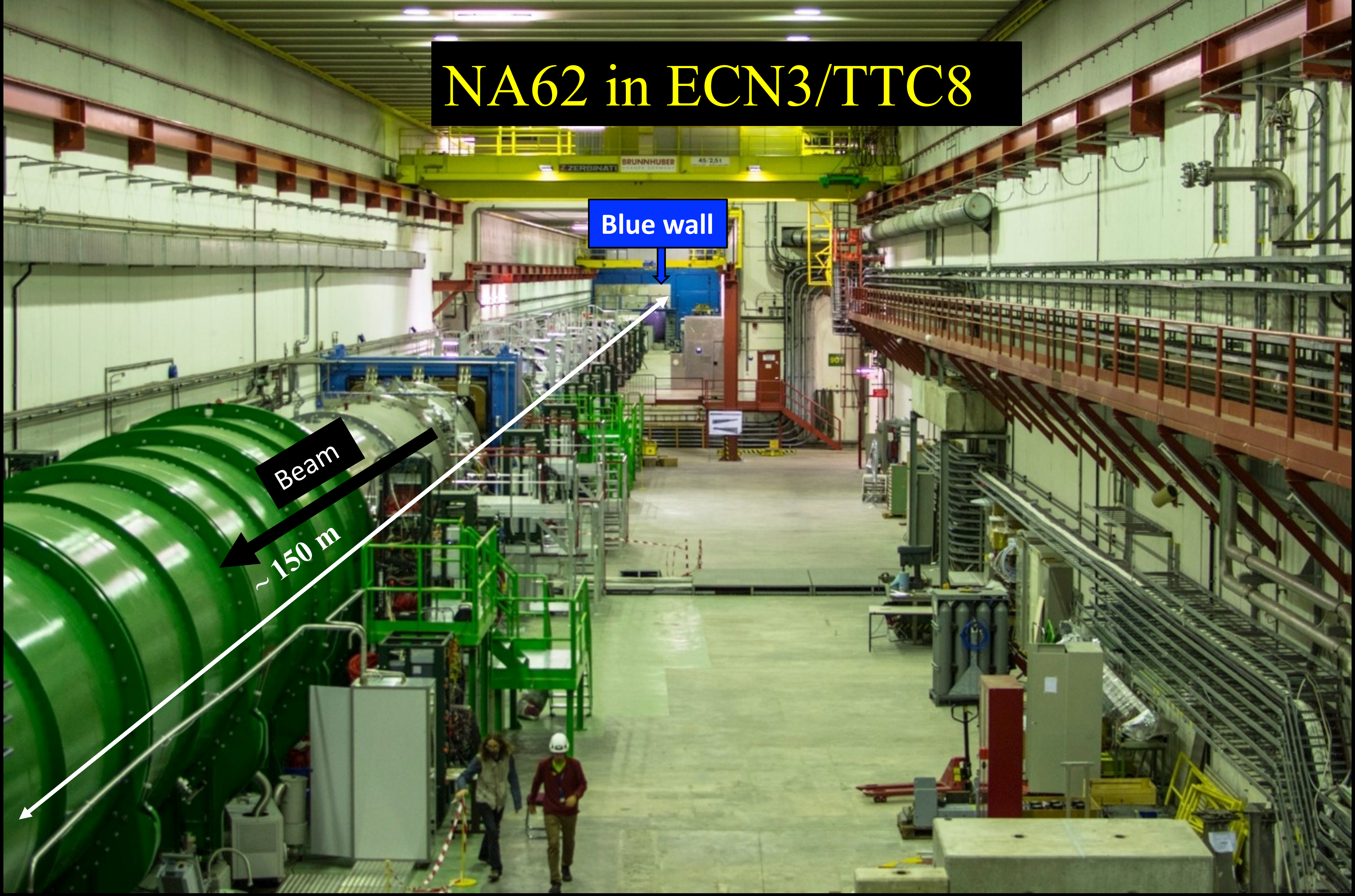
- NA62 nominal intensity is $3x10^{12}$ ppp with 3.3s pulse duration: ~ 10^{12} pot/sec, up to $2x10^{18}$ pot/year

✓ K12 beam intensity proposed to be increased by a factor x6-7

- for high intensity K beams and SHADOWS → up to $1.2*10^{19}$ pot/year

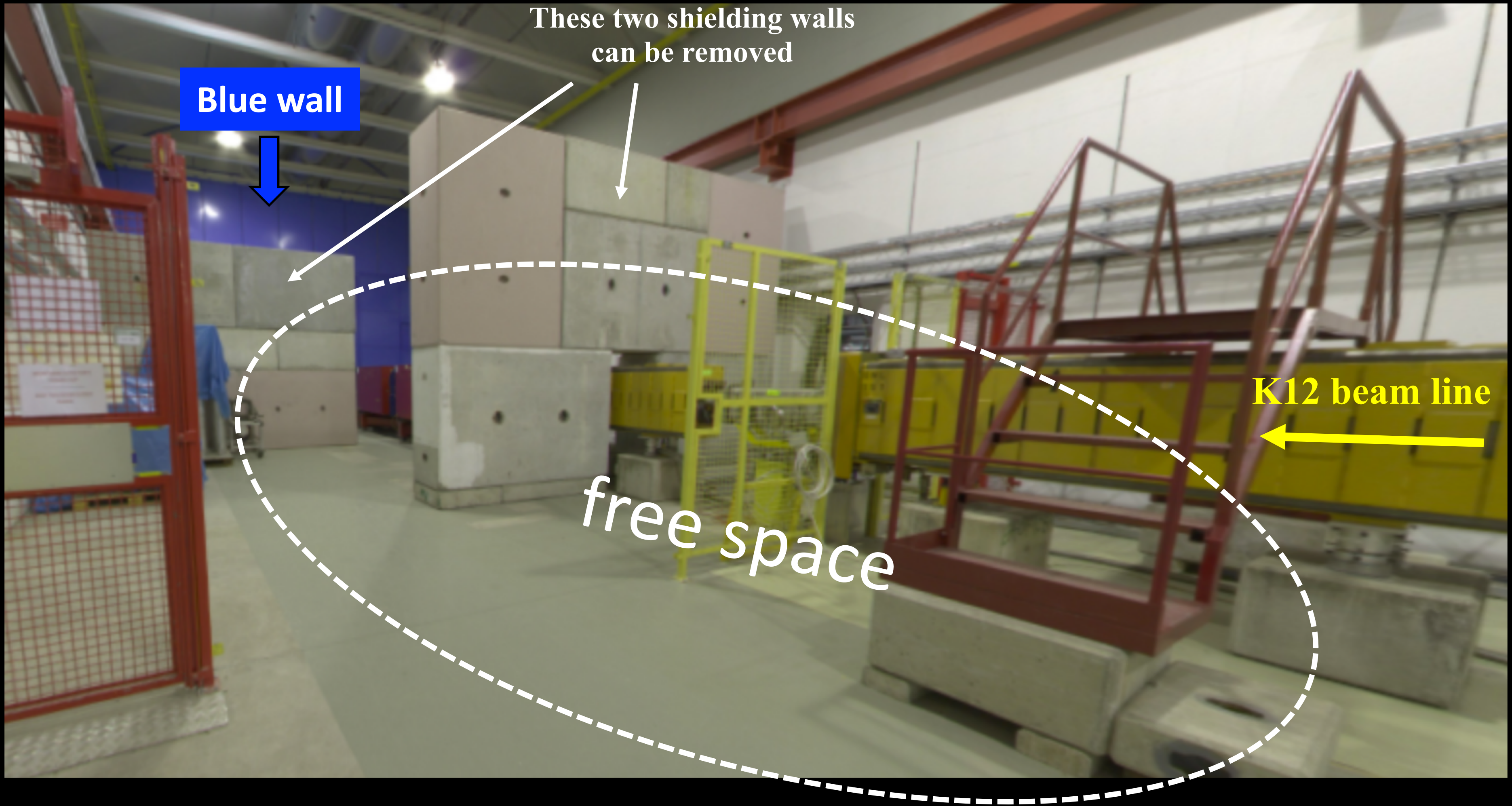
SHADOWS can collect $5x10^{19}$ pot in ~4 years of data taking starting after LS3 (~2028)

NA62 in ECN3/TTC8

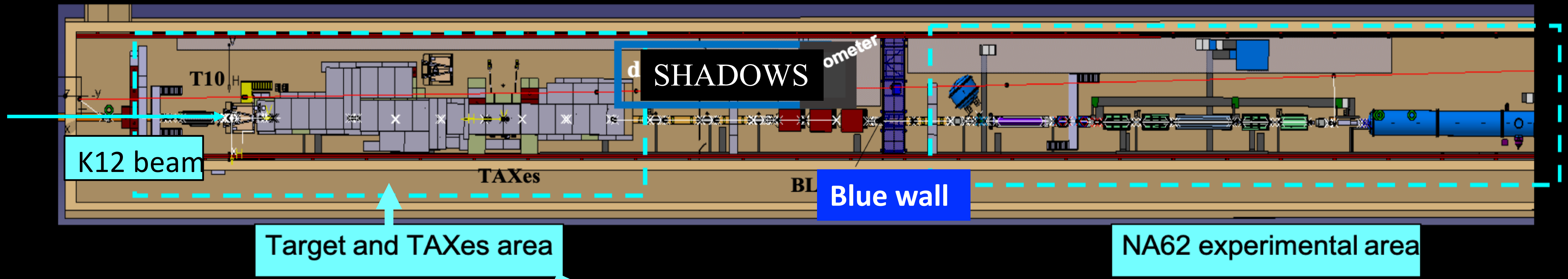


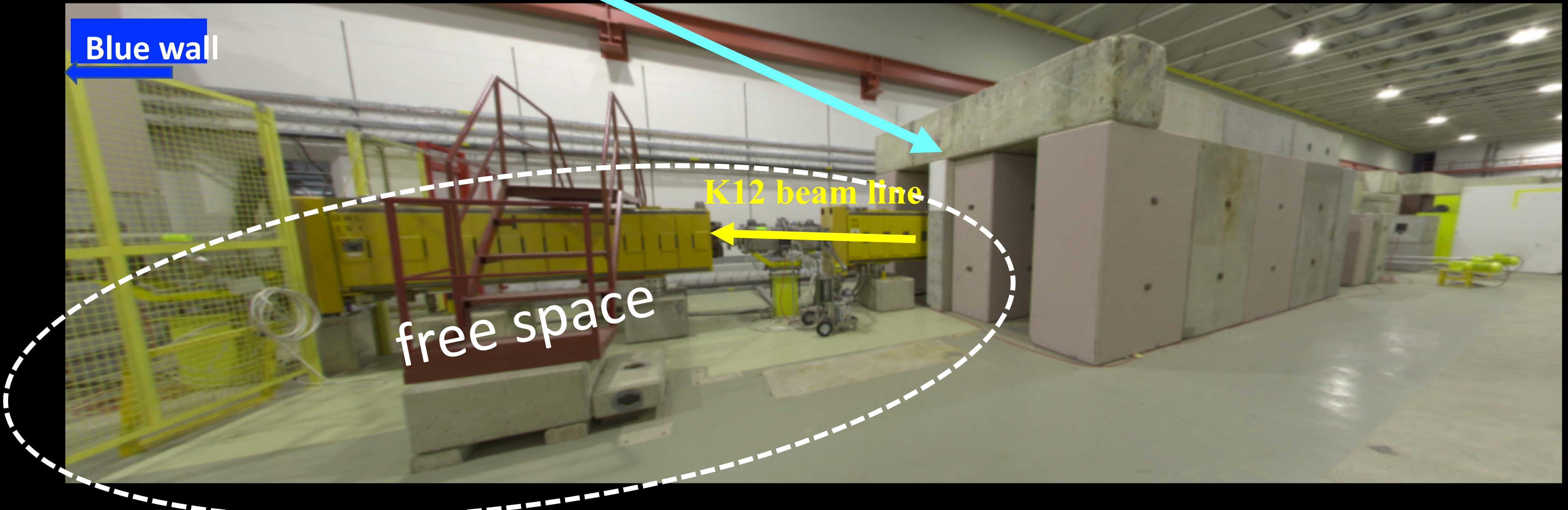
SHADOWS in ECN3/TTC8

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

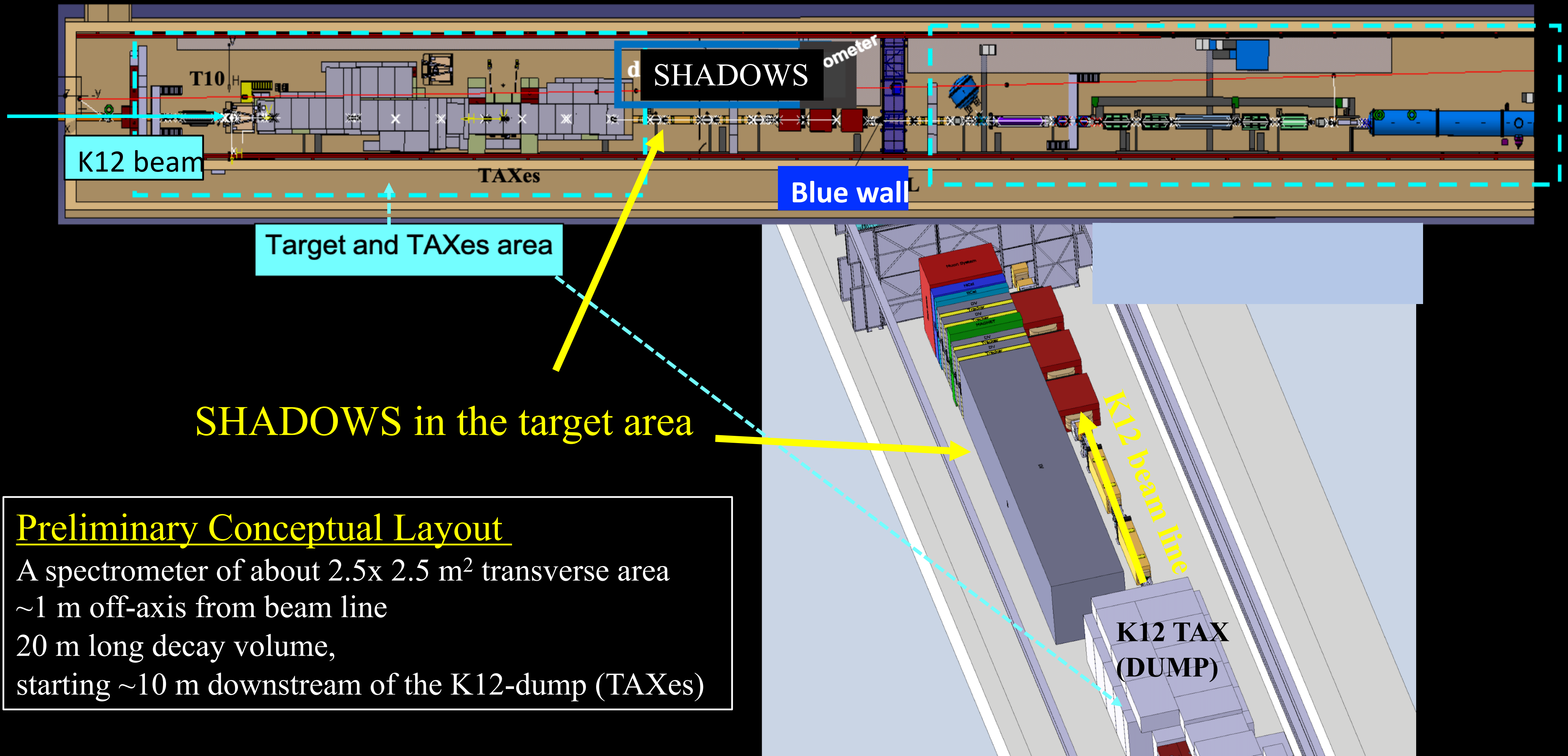


SHADOWS in ECN3/TTC8





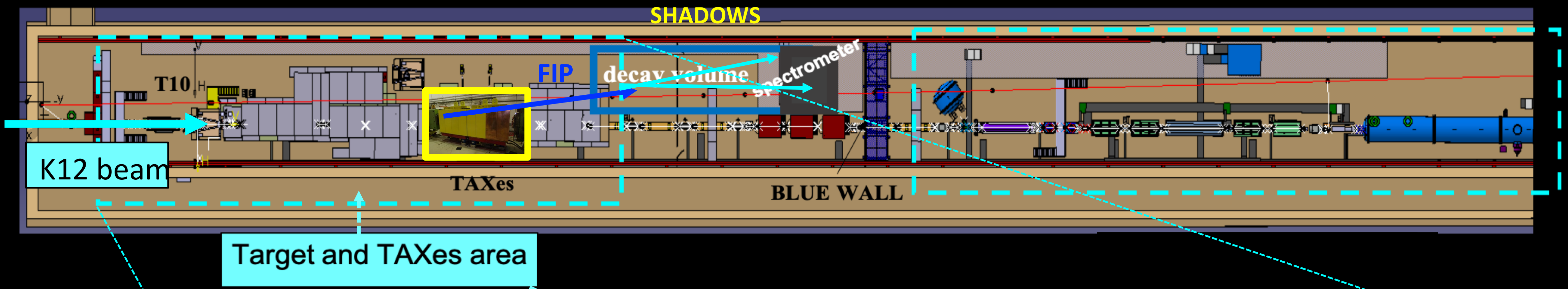
SHADOWS in ECN3/TTC8



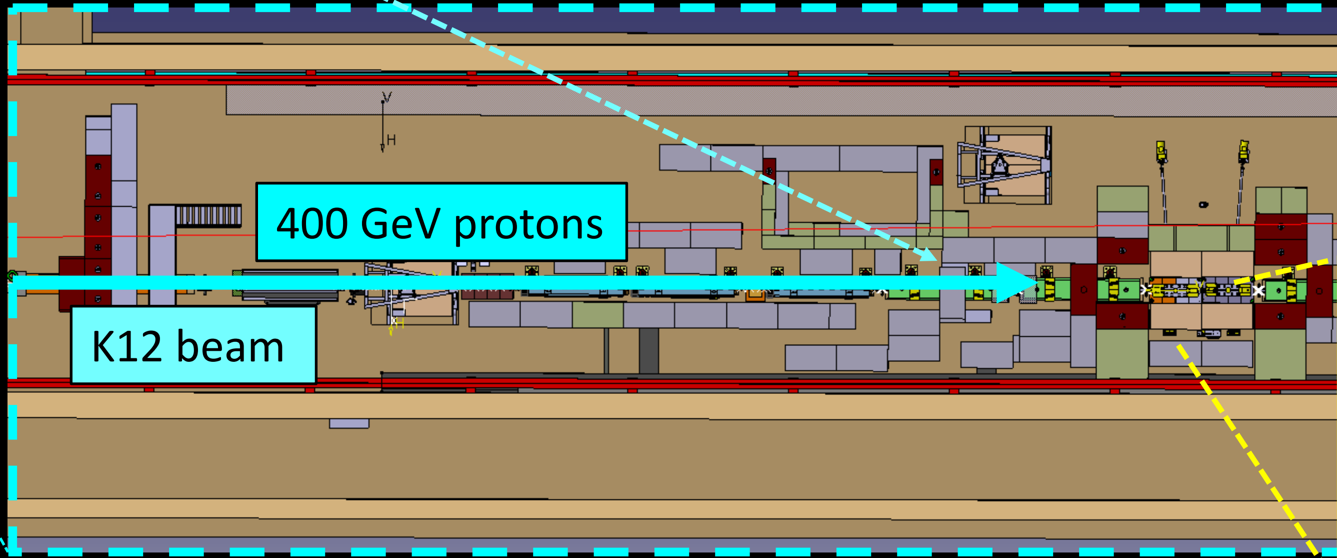
<u>Preliminary Conceptual Layout</u>

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)

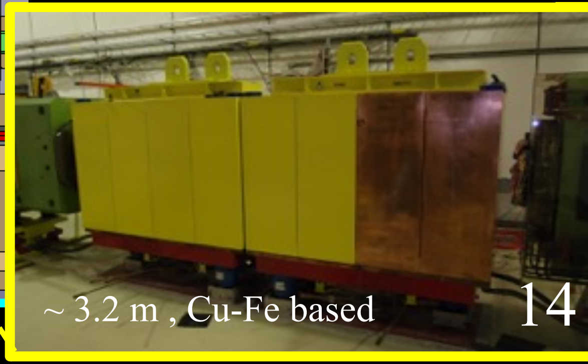
SHADOWS can operate when K12 beam line runs in dump-mode



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

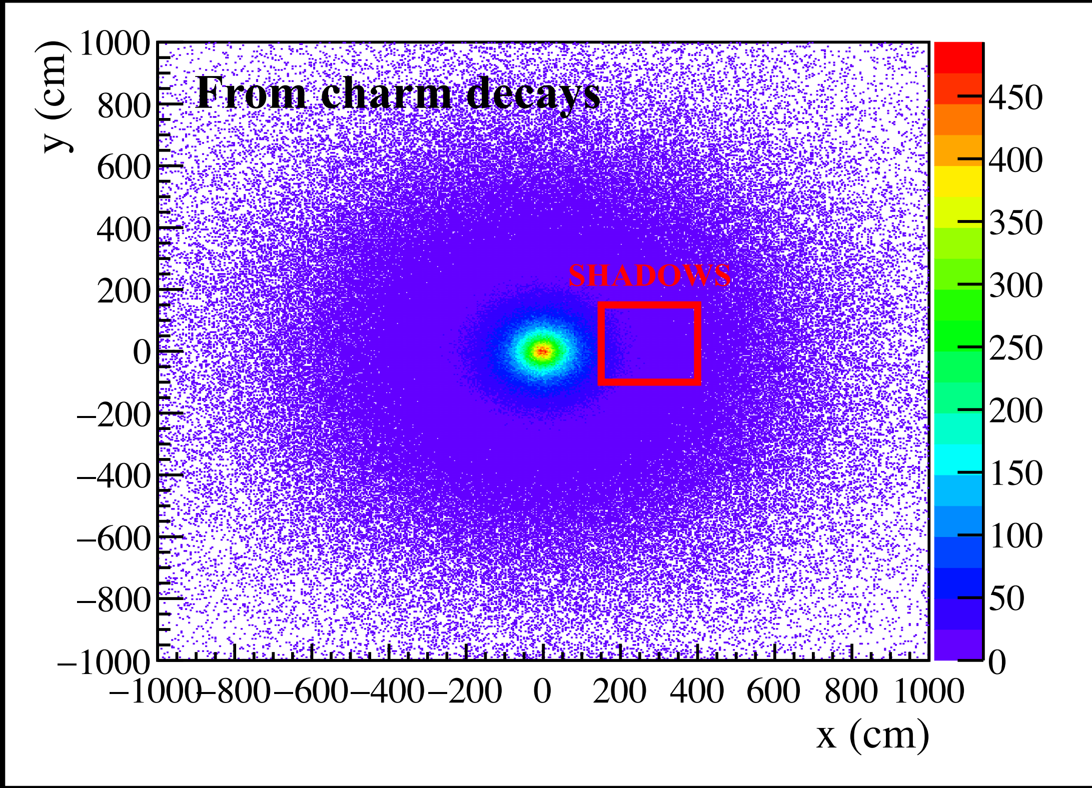


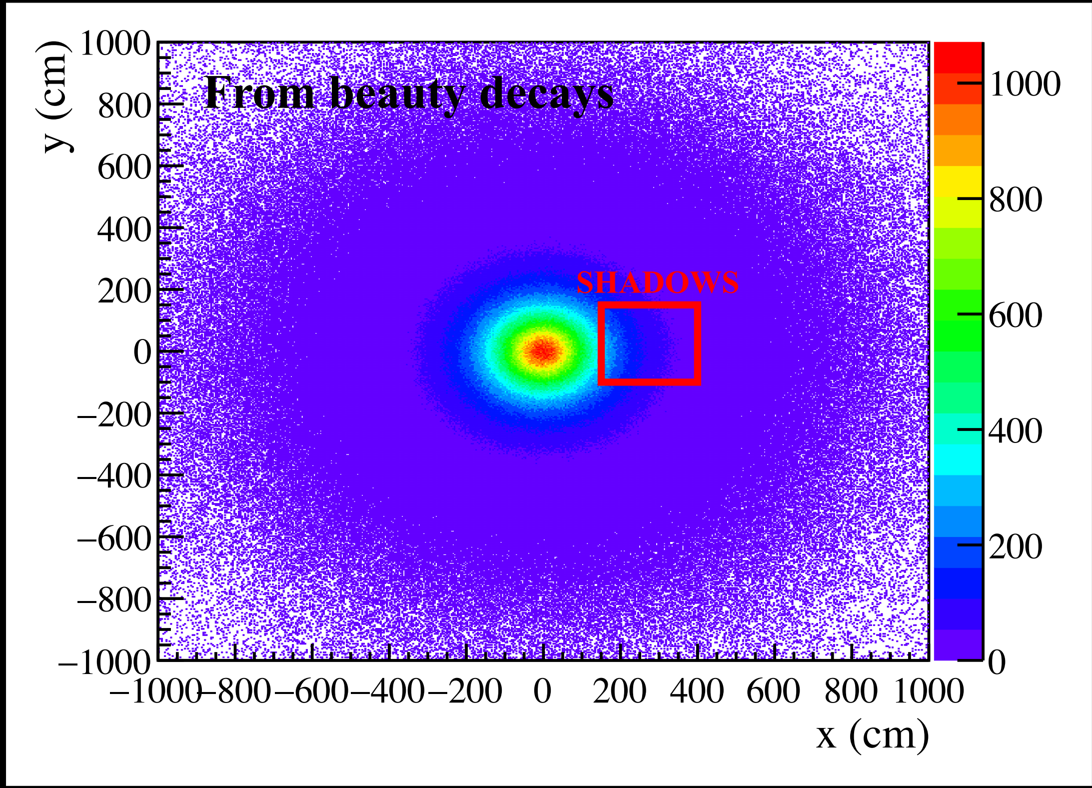
The NA62 dump system



Why "off-axis" works: Signal

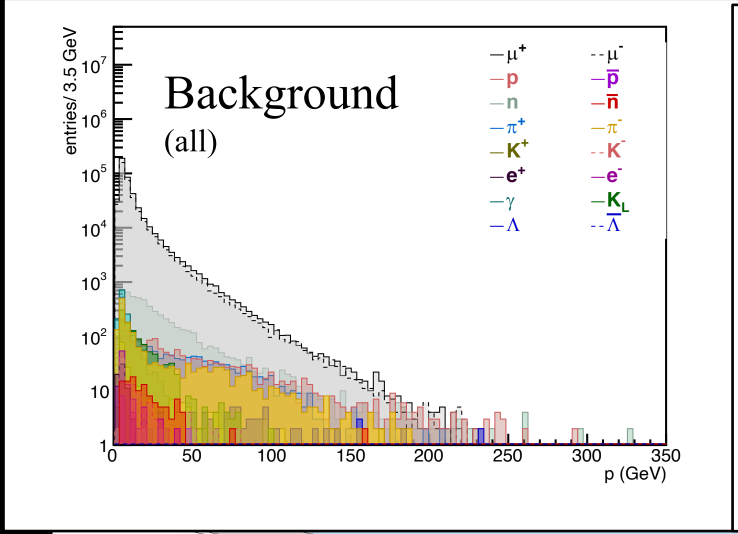
HNL→ **πμ** illumination @ D = 55 m (first SHADOWS tracking station)

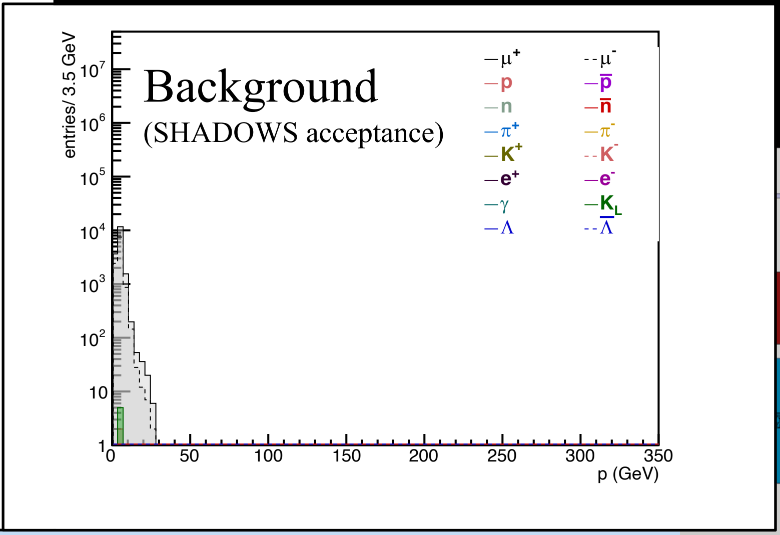


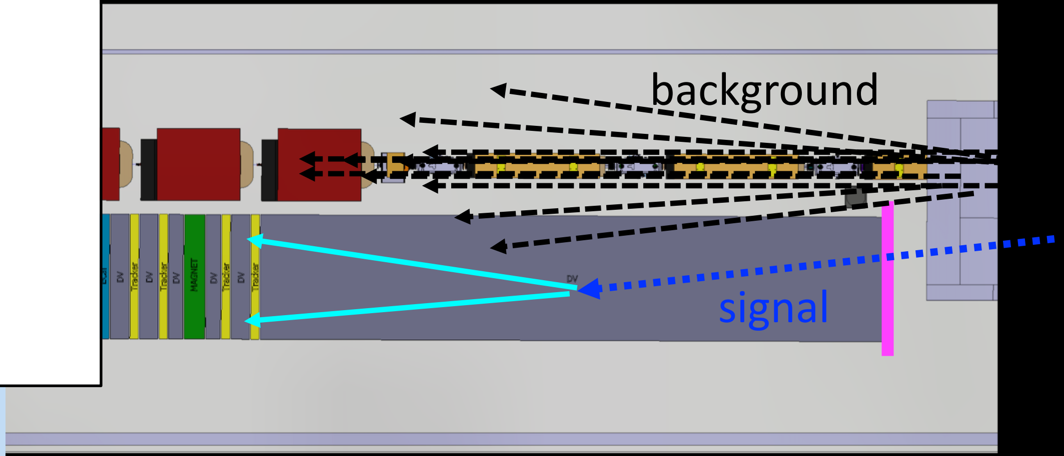


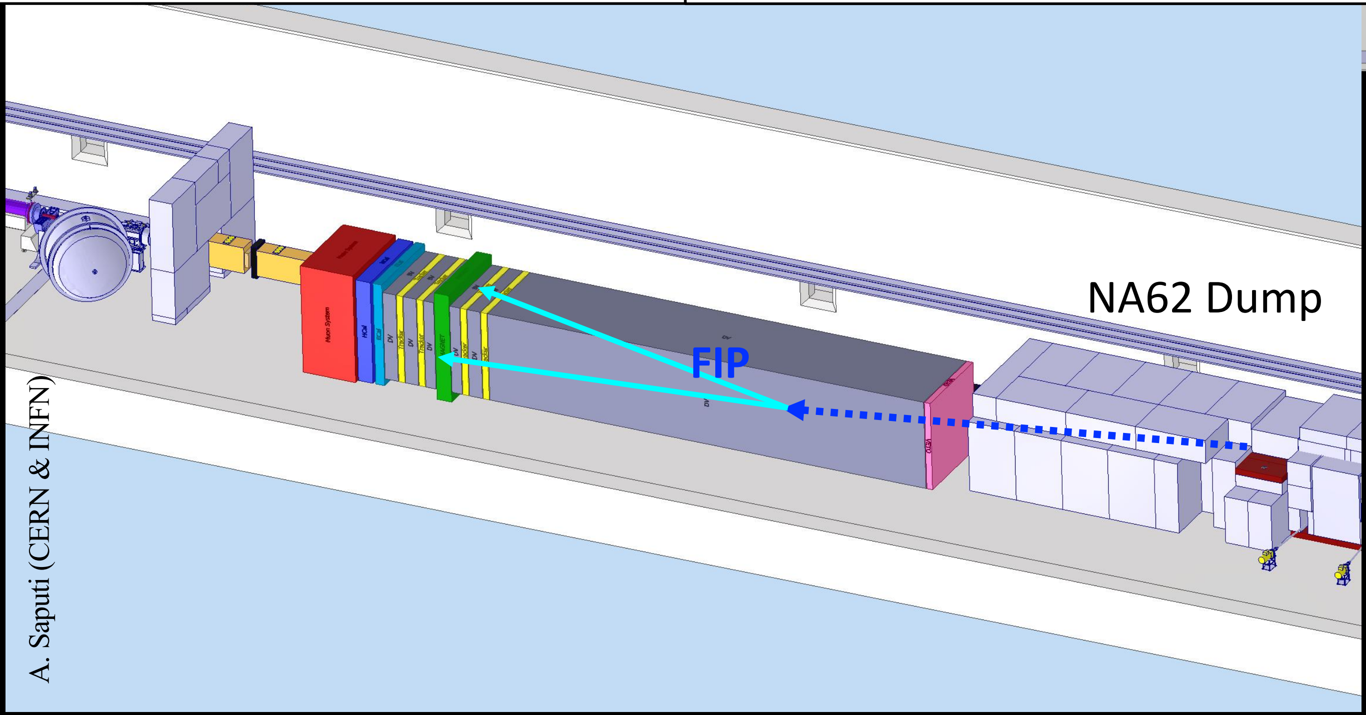
FIPs emerging from charm and beauty decays (HNLs, dark scalars, ALPs,…)
at the SPS energy are produced with a large polar angle

Why “off-axis” works: Background









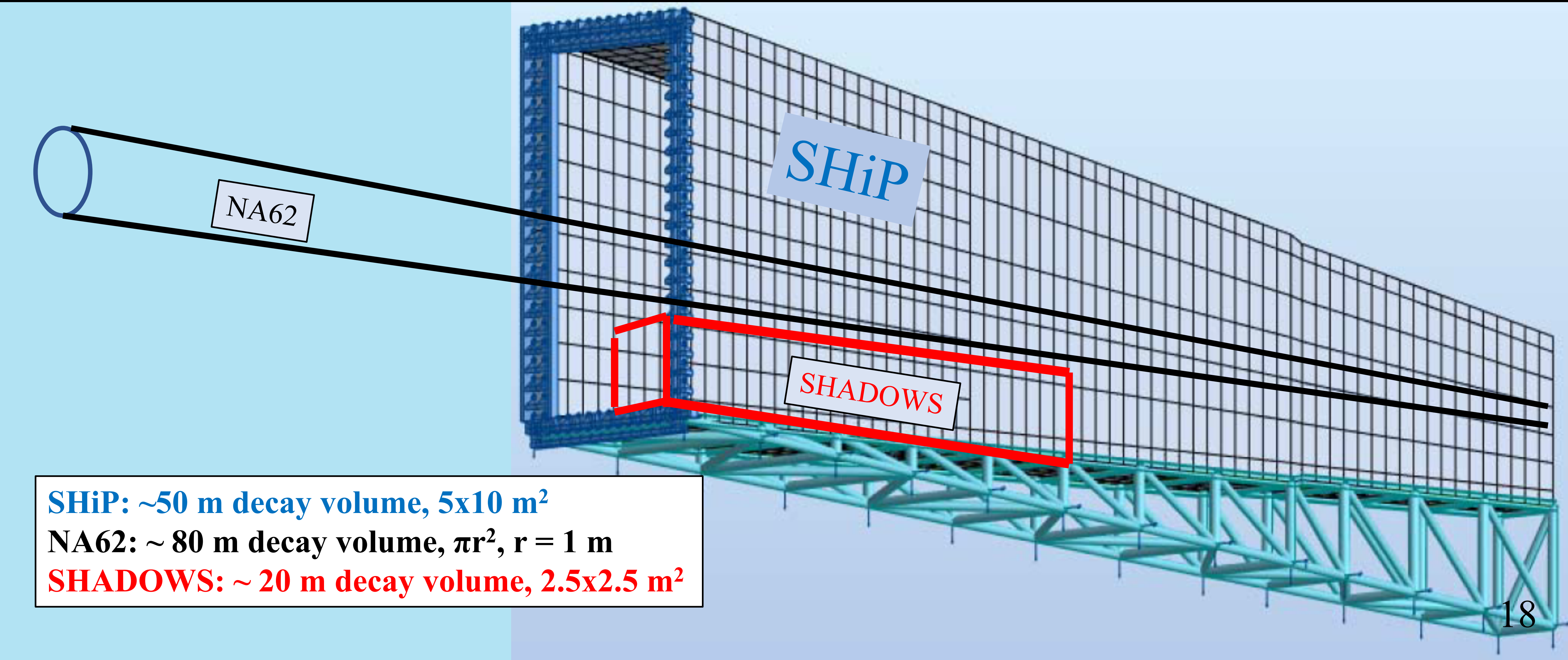
Most of the residual background emerging from TAXes are muons and neutrinos that are mostly produced forward (and miss SHADOWS acceptance).

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

- Stay close to the dump:
  to maximize 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)



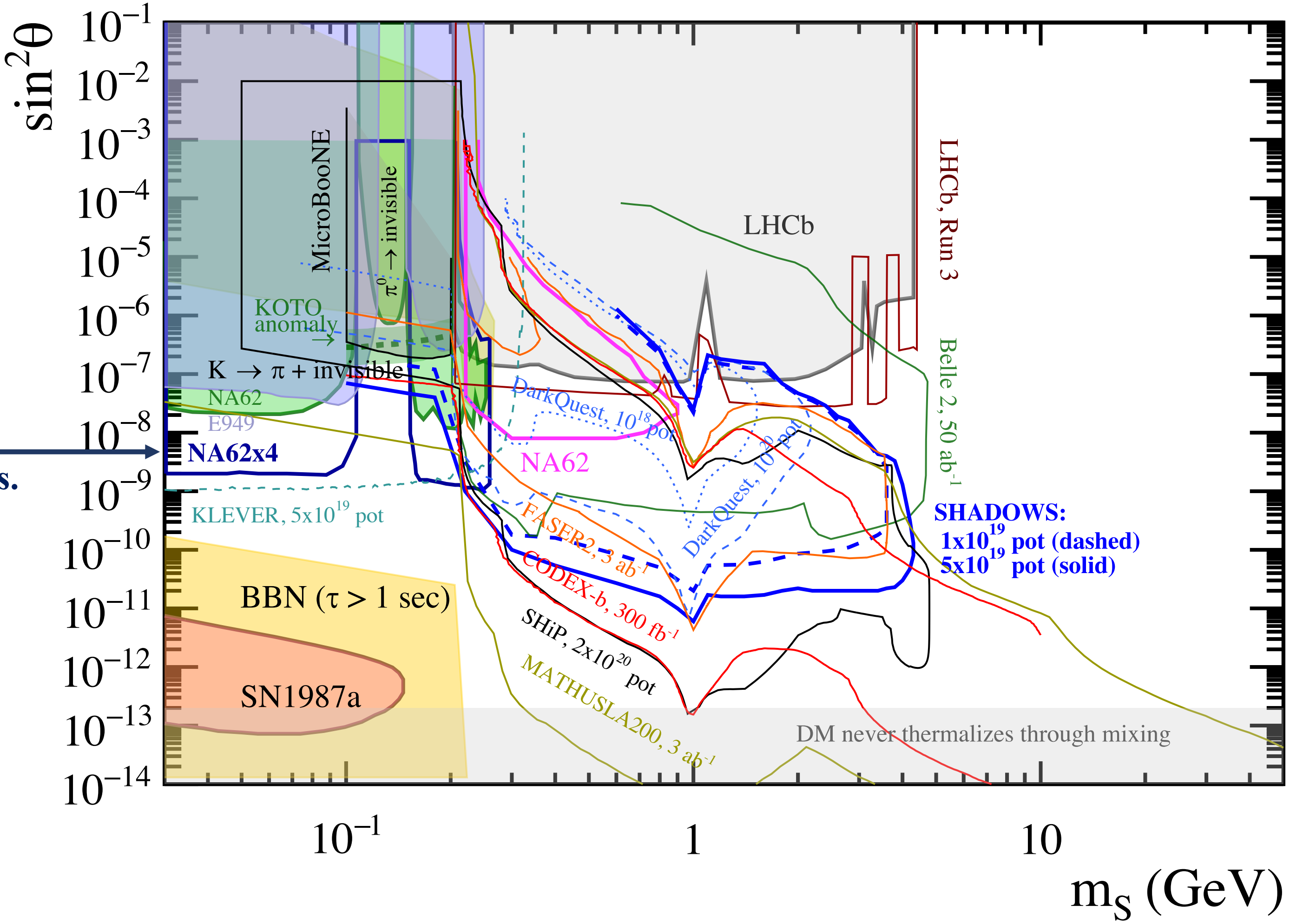
SHiP: ~50 m decay volume, 5x10 m^2
NA62: ~ 80 m decay volume, πr^2, r = 1 m
SHADOWS: ~ 20 m decay volume, 2.5x2.5 m^2

SHADOWS physics sensitivity for some 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)

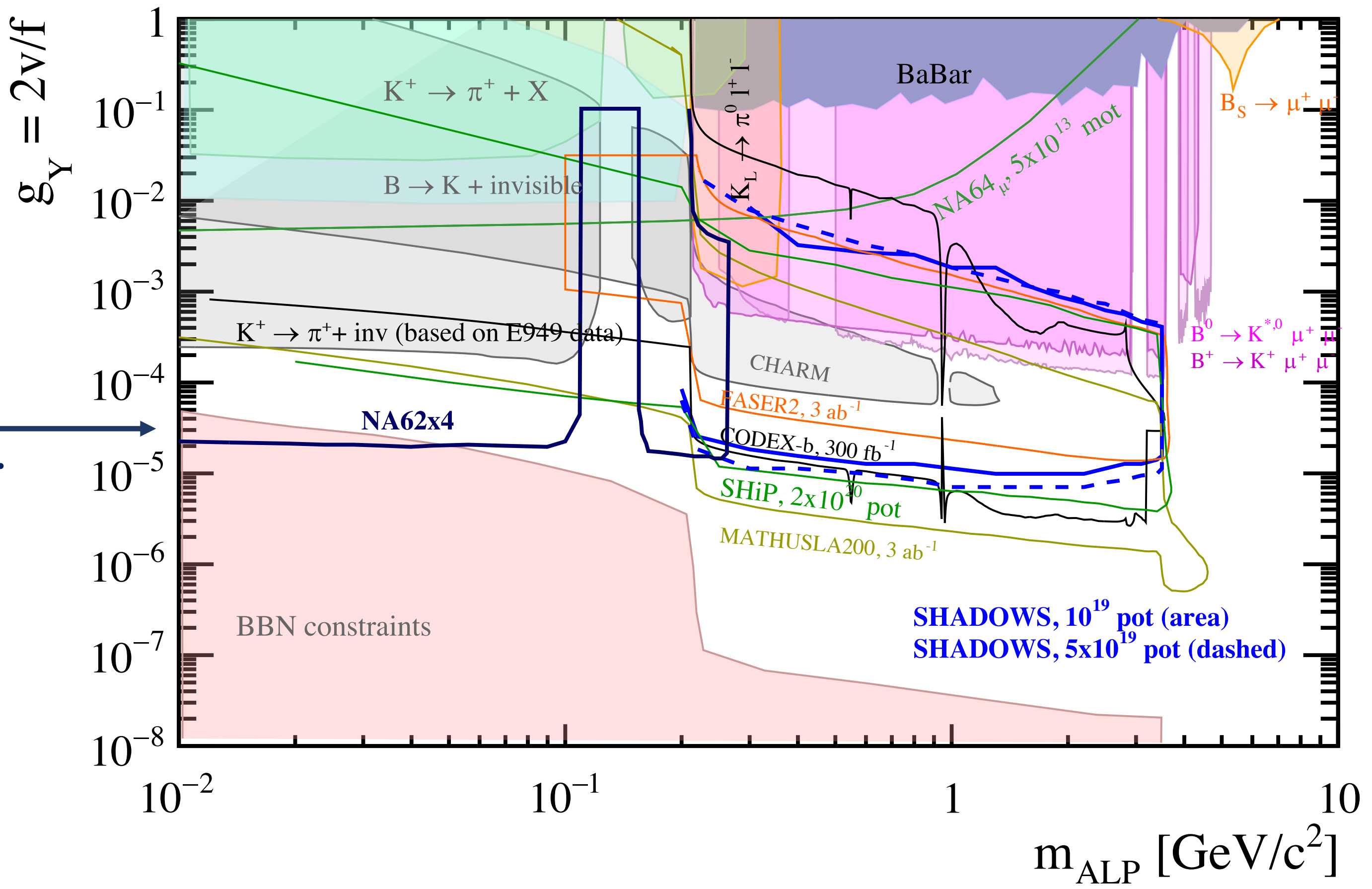


NB: NA62 in K-mode covers the range below K-mass. Strong complementarity with SHADOWS.

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

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

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

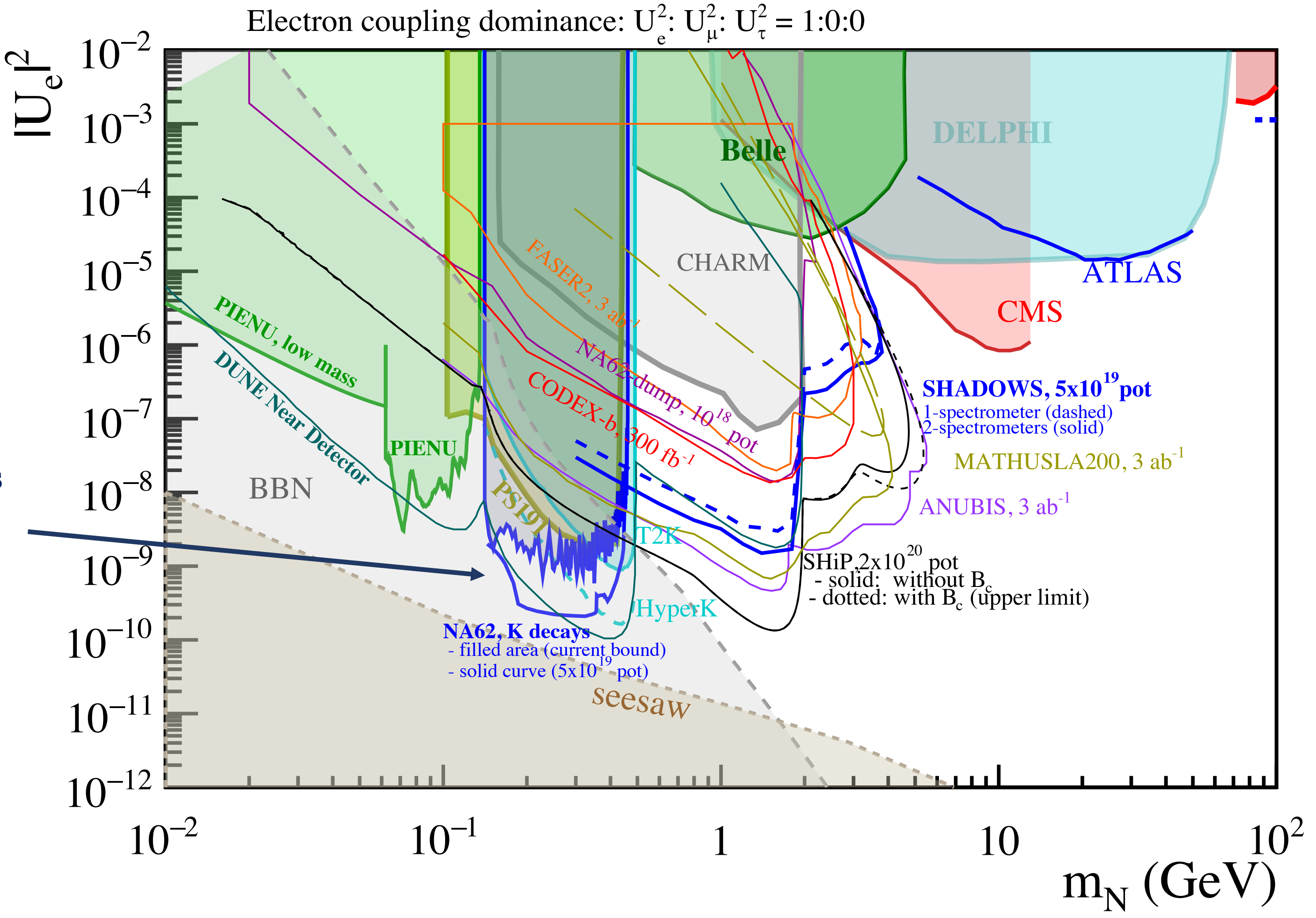


SHADOWS with 5x10^{19} pot is better than FASER2 with 3 ab^{-1}, and comparable to CODEX-b (with 300 fb^{-1}) and SHiP (with 2x10^{20} pot).

Heavy Neutral Leptons (with electron coupling)

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

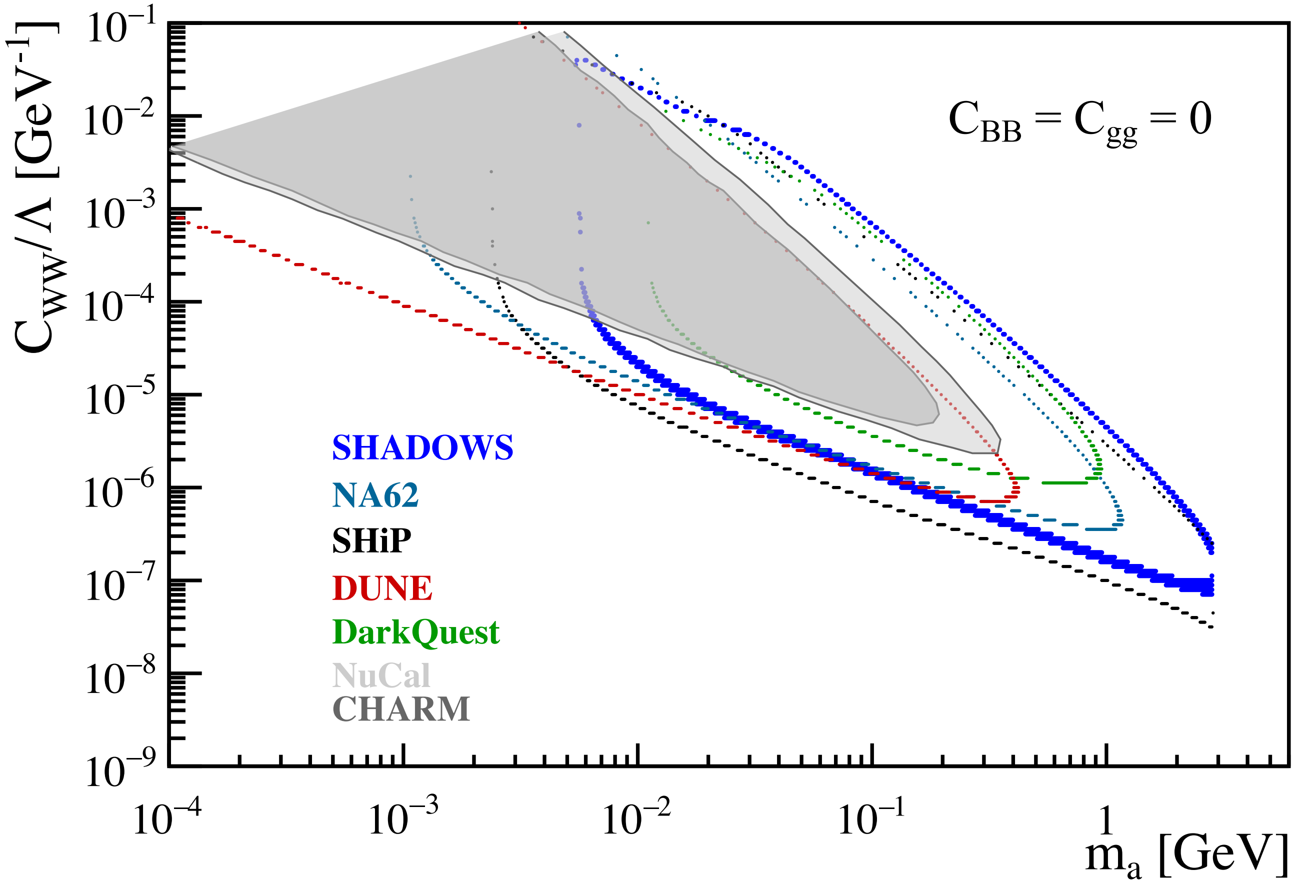
NB: NA62 in K-mode covers the range below K-mass down to the seesaw limit. Strong complementarity with SHADOWS.



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)

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

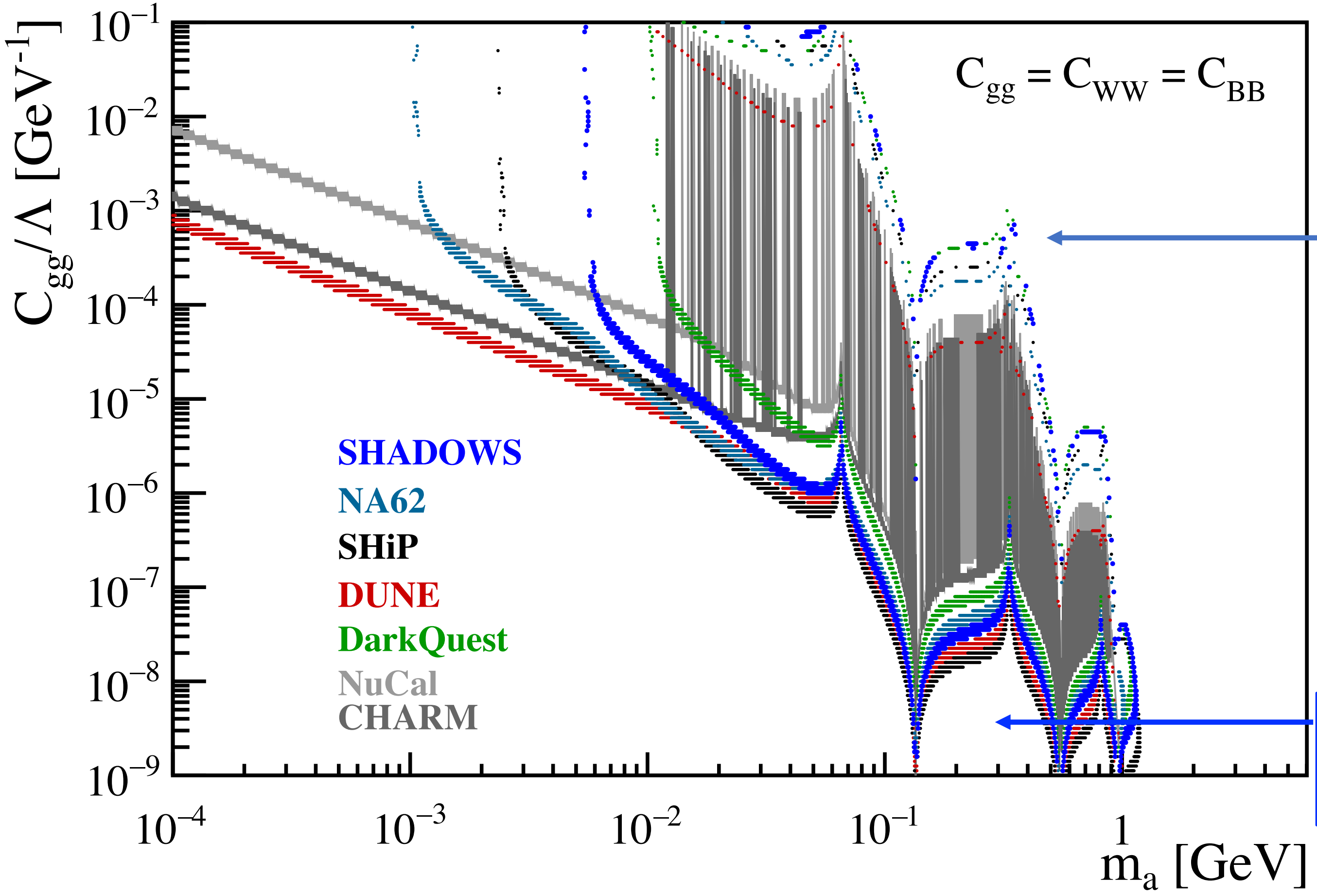
F. Kahlhoefer et al, 2201.05170 (only fixed target/beam dump experiments considered)



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

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

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

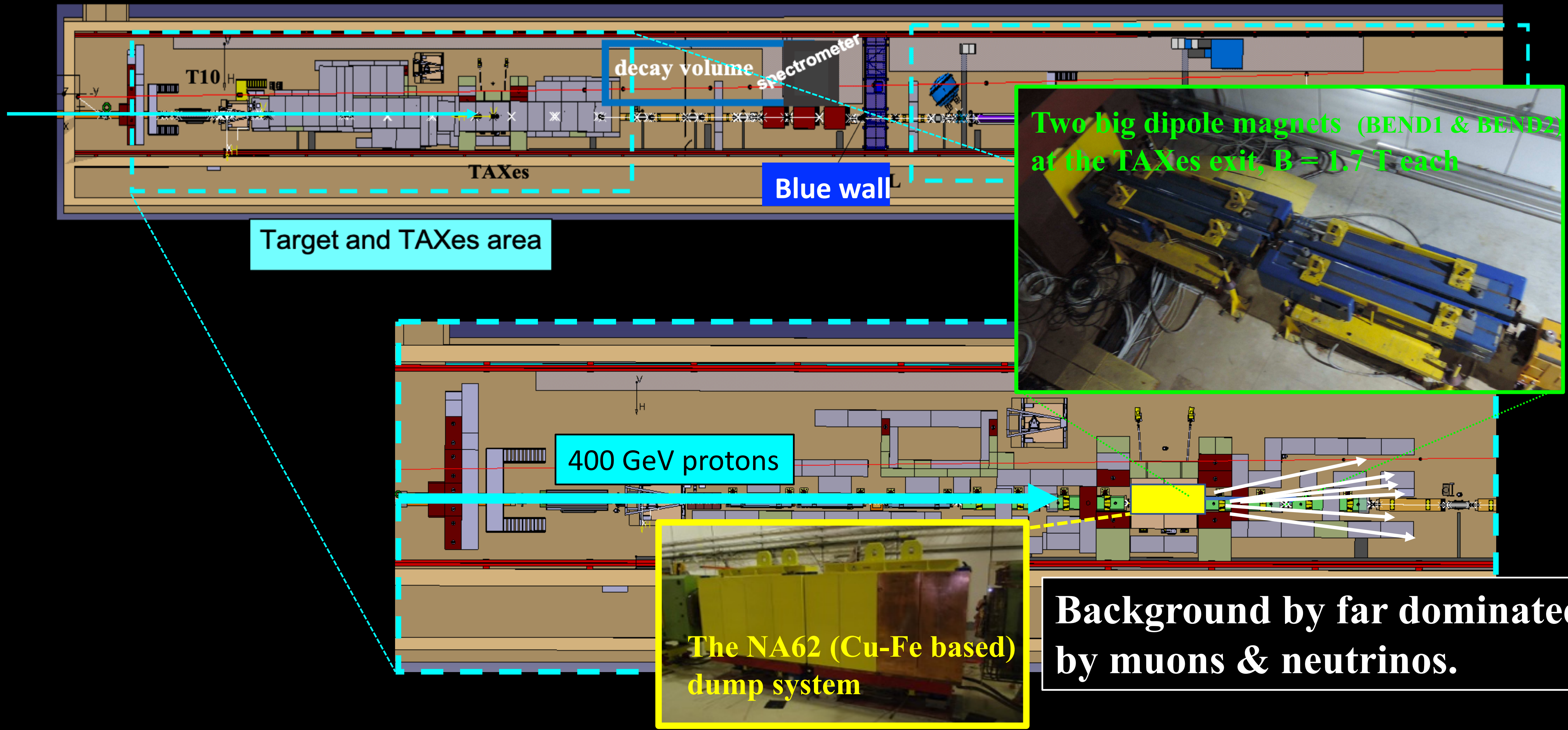


Here SHADOWS is the best

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

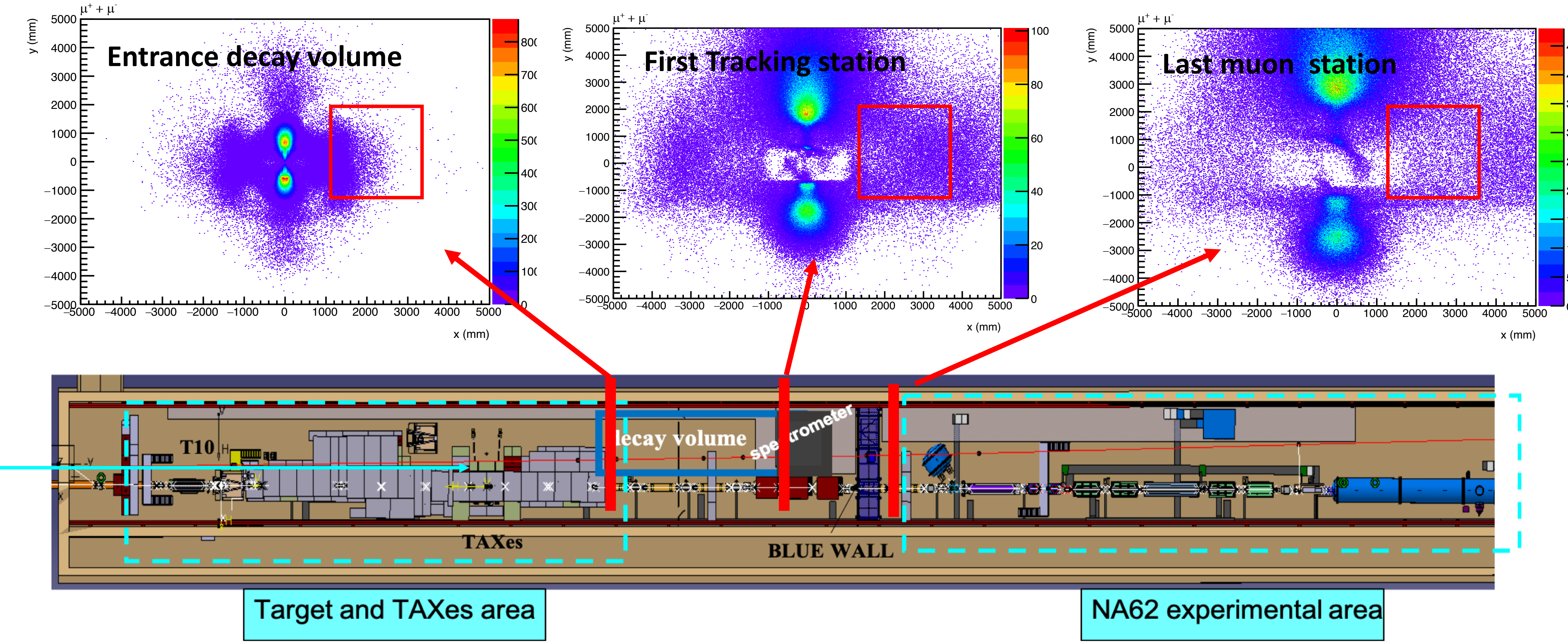
The beam-induced background:
the name of the game

The beam-induced background:



Background by far dominated by muons & neutrinos.

Muon illumination as a function of the position along the line

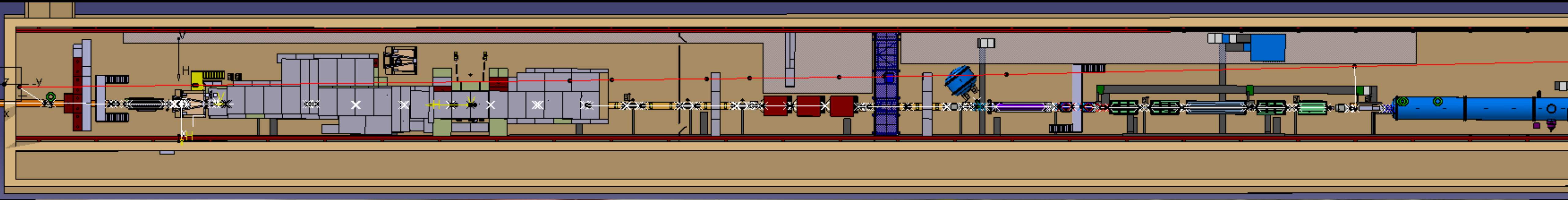


SHADOWS Muon Sweeping system:

CERN, LNF Accelerator Division,…

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

(currently studied in CERN BE-EA-LE group and LNF Accelerator Division)

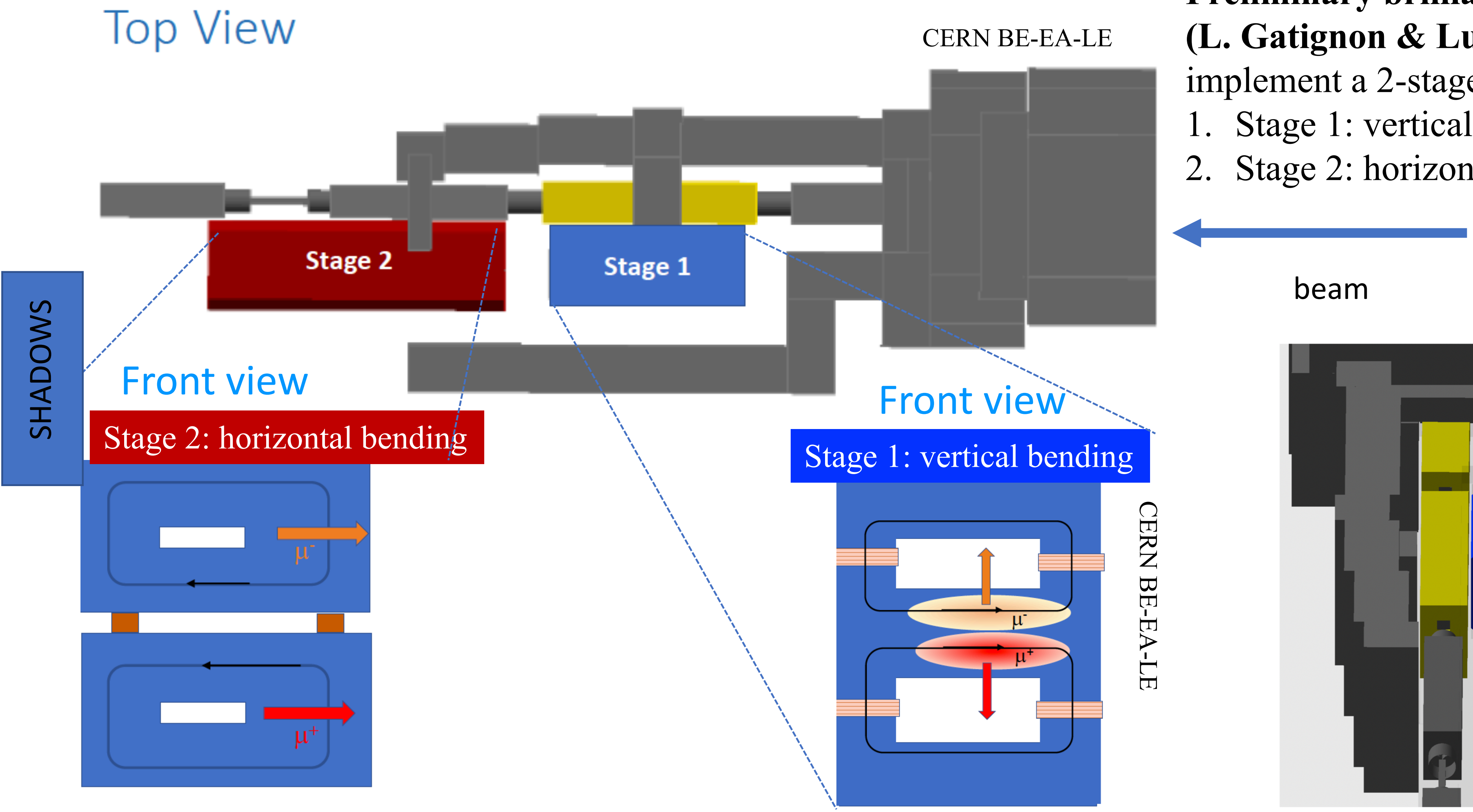


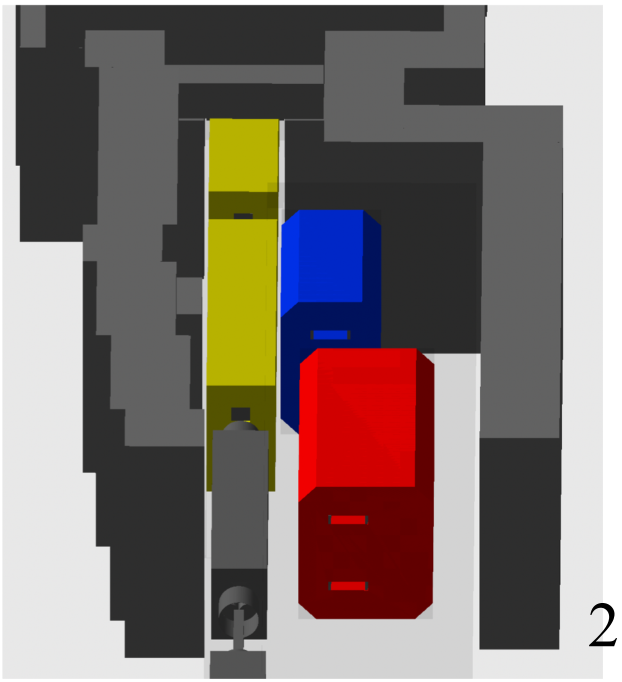
An example exists in M2

SHADOWS Muon Sweeper: a system of Magnetized Iron Blocks

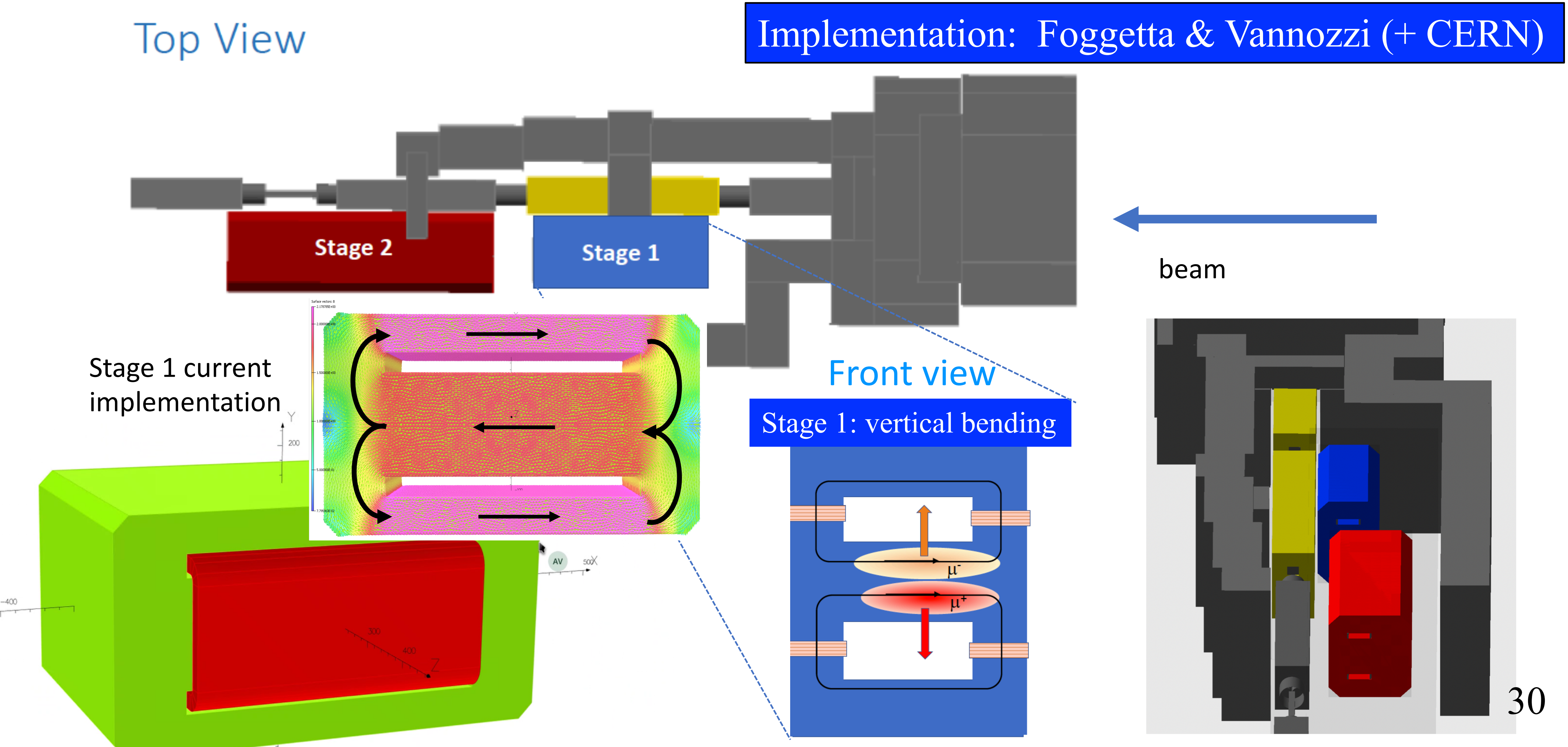
Preliminary brilliant solution (L. Gatignon & Luca Foggetta):
implement a 2-stage sweeping system:

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





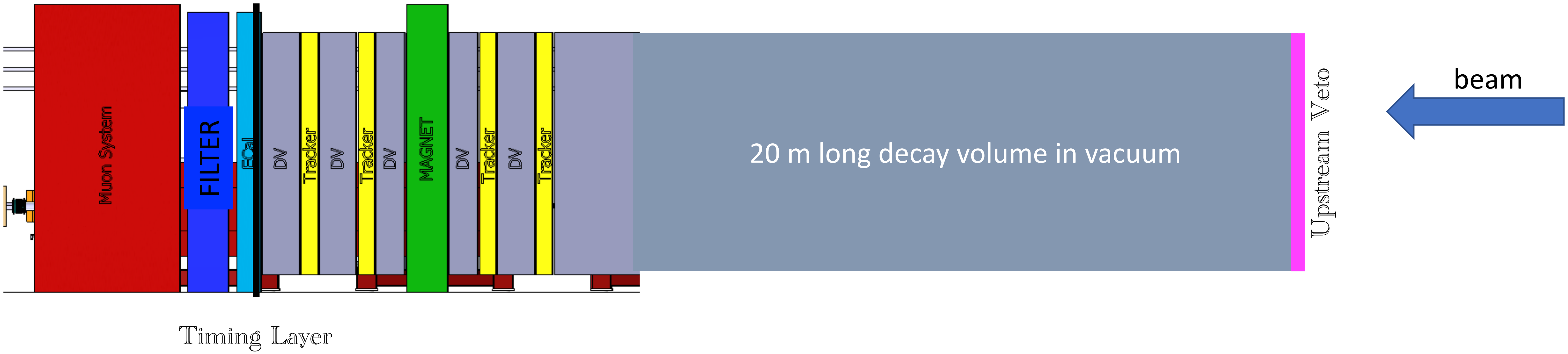
SHADOWS Muon Sweeper: a system of Magnetized Iron Blocks



Detector design: survey of technology options

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

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

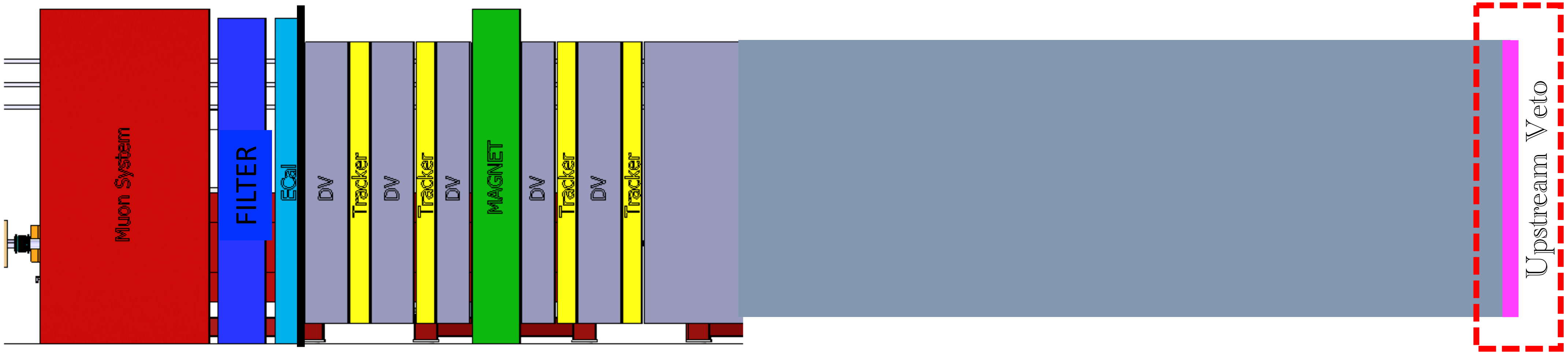


<u>SHADOWS detector components:</u>
20 m long, in vacuum decay volume, an Upstream Veto, a Tracking System with a (warm) dipole magnet, Timing layer, Electro-magnetic calorimeter, a filter and four Muon Stations.
Transversal size: 2.5x2.5 m^2.

<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.

Naples, Rome3,…

SHADOWS Upstream Veto: MicroMegas



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

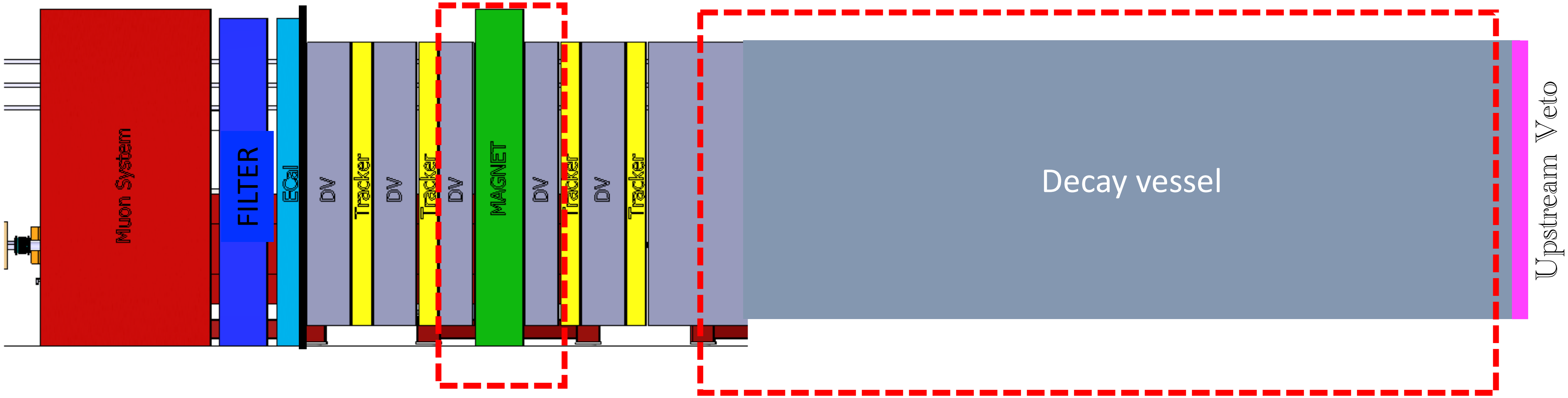
Upstream Veto: double layer of MicroMegas.

Interest from groups who built the ATLAS New Small Wheels (P. Iengo & M. Iodice)

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

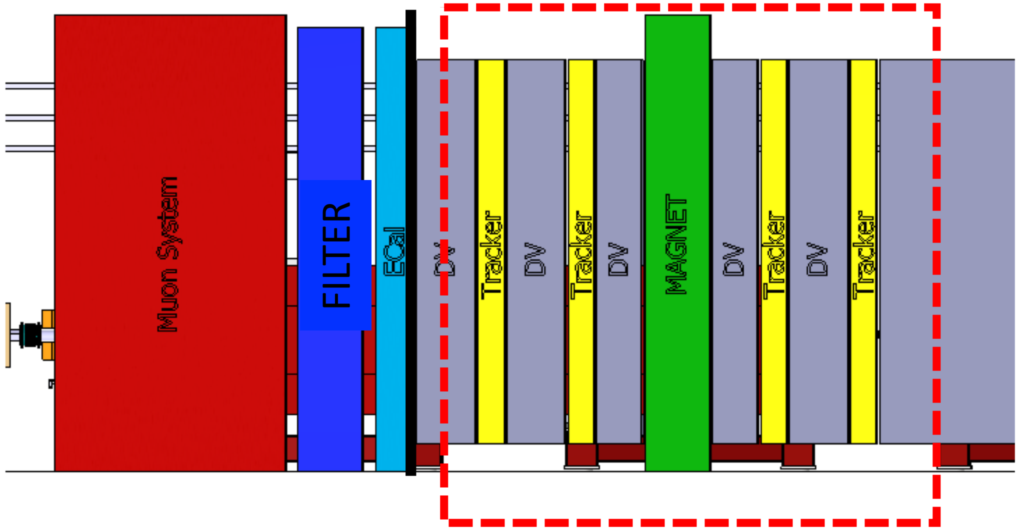
CERN, INFN-Ferrara…

SHADOWS Dipole Magnet and Decay Vessel:



Dipole Magnet of the Tracking System and in-vacuum Decay Vessel being designed at CERN (**P. Wertelaers**, **Burkhard Schmidt**, and **CERN-DT department**).
Overall detector integration responsibility: **Alessandro Saputi** (Ferrara)

SHADOWS Tracker: NA62 straws or SciFi

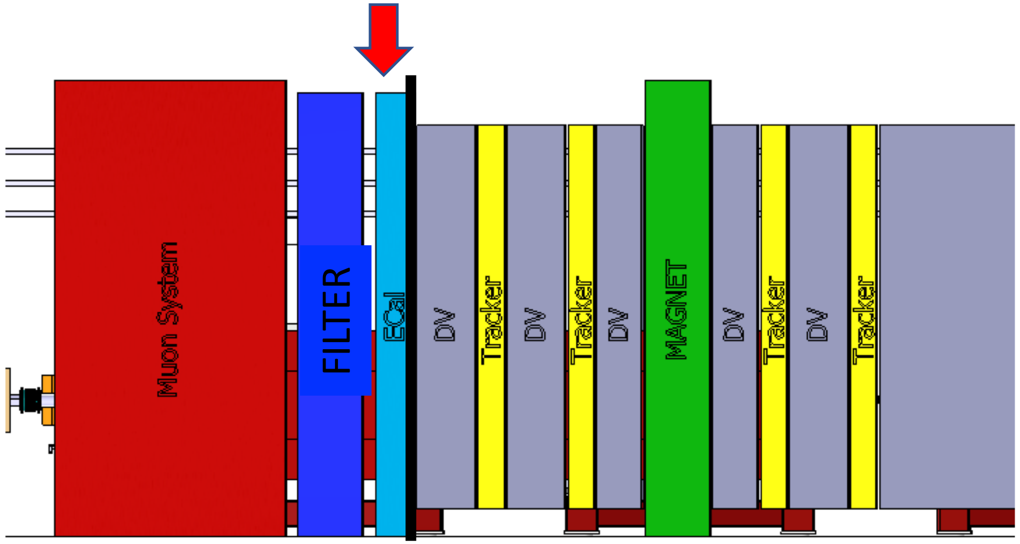


1. **NA62 STRAW tubes:** Ar(70%): CO_2 (30%), in vacuum, 10 mm diameter
One straw chamber is composed of four views (X, Y, U, V), one double-layer per view, 8 layers per station
Hit resolution better 400 um over most of the straw diameter per single layer. Warm dipole magnet with 0.9 Tm bending power.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

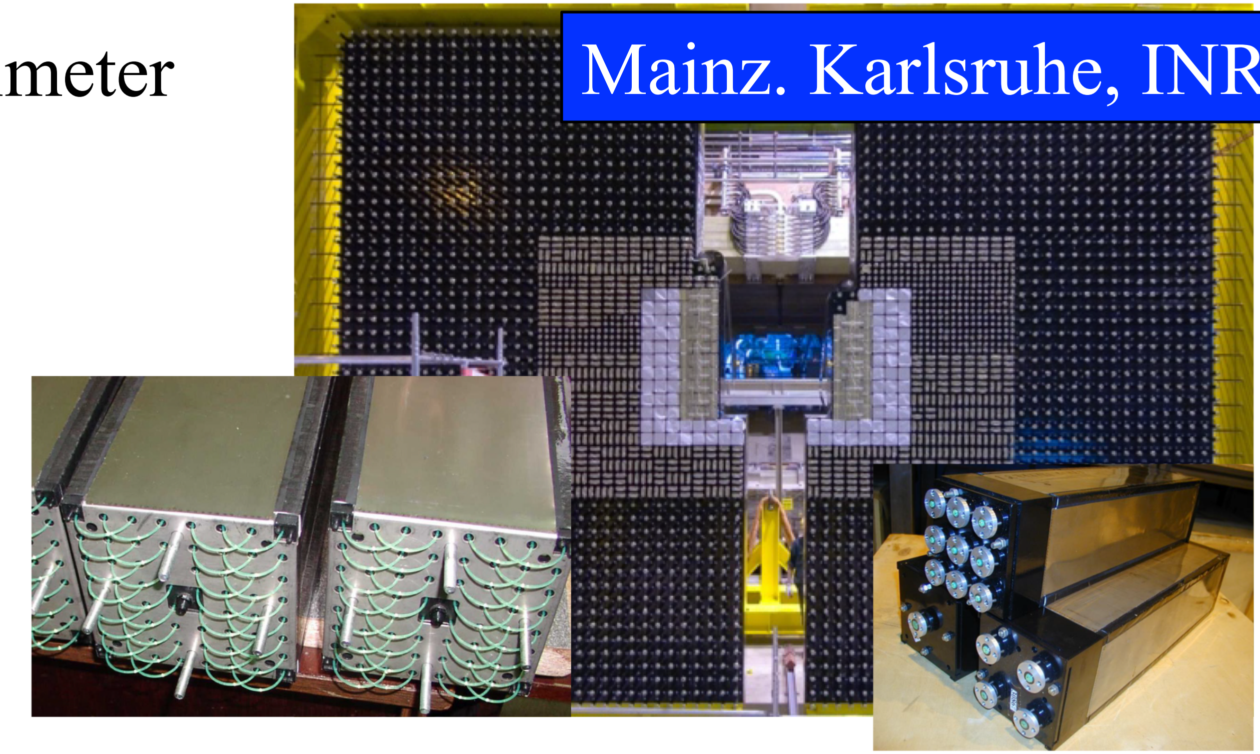
2. **Fibre Tracker (LHCb):** 250 um diameter, 2.5 m long scintillating fibres; three stations, six detection layers each.
Hit resolution per station < 80 um. 4 Tm bending magnet.

[**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



Mainz. Karlsruhe, INR,…



Current situation:

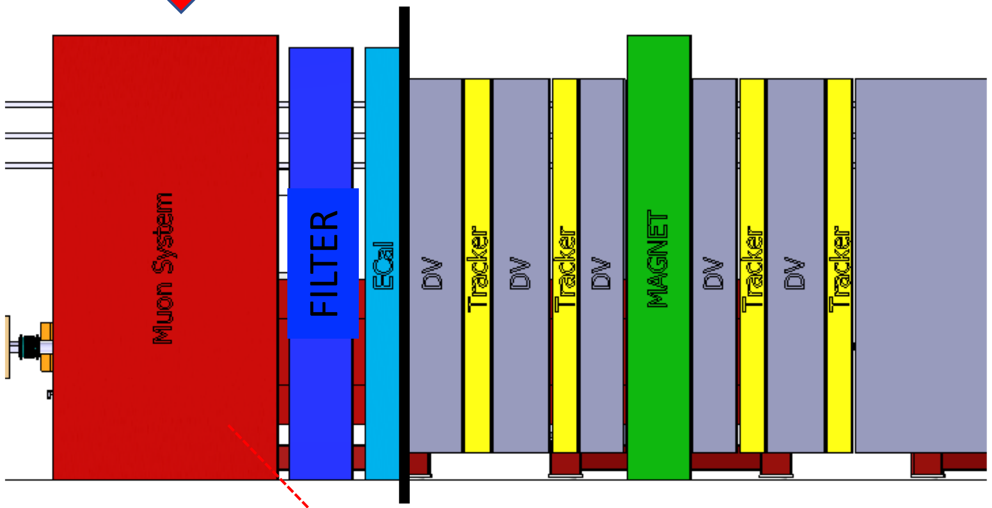
176 Shashlik of LHCb-ECAL modules could become available at LS3 (as proposed in the LHCb FTDR): can be used to instrument an area of 160 x 160 cm^2. The o(200) modules missing could be built at **INR**.

Mainz (prof. R. Wanke) also interested in this topic.

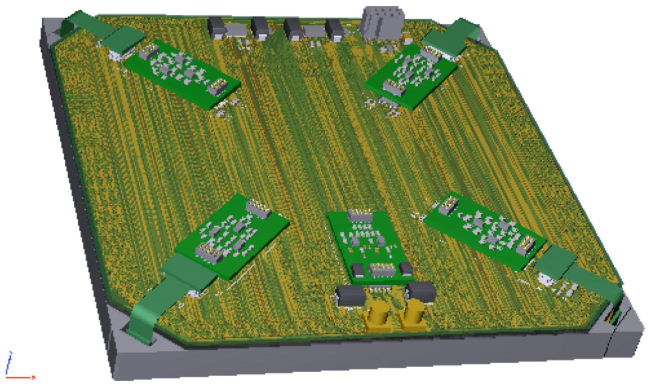
Karlsruhe (Prof. Klute and Prof. Ferben) interested to study the option of a tracking calorimeter (important for di-photon final states) (eg: **CMS-HGCal/CALICE or recover PbWO4 crystals from CMS endcaps)**

SHADOWS: Muon Detector

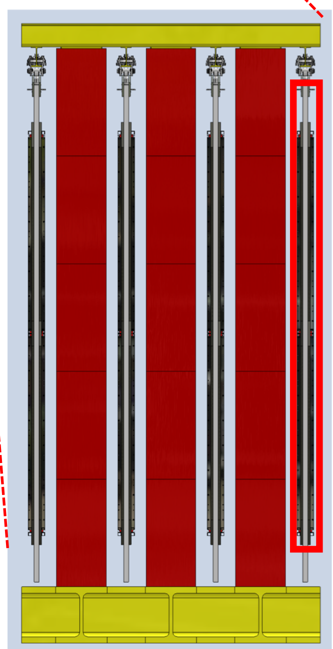
INFN (Frascati, Bologna, Ferrara), INR, ..

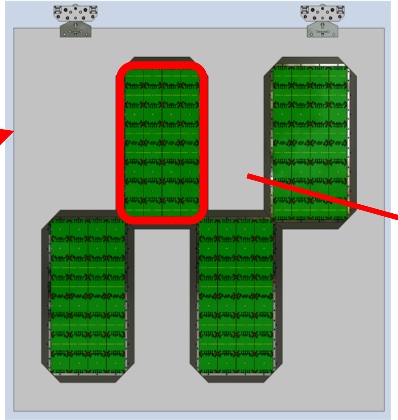


1 tile = 15x15 cm2,
Direct SiPM readout at the corners
One analog output per tile

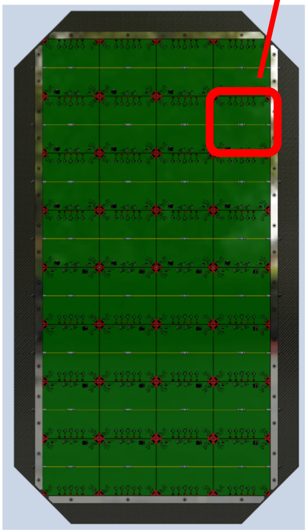


1 module = 16/32 tiles

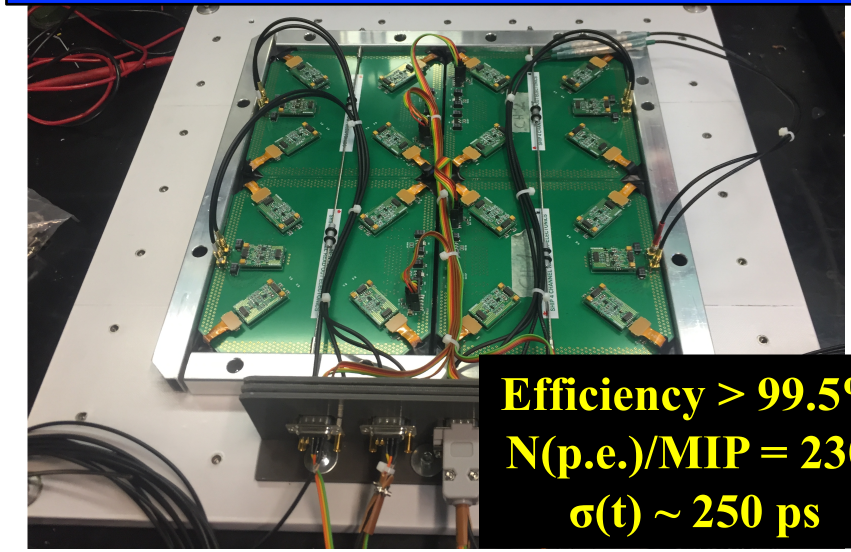




1 station = 8 modules
[same pattern staggered
on the other side of the wall]

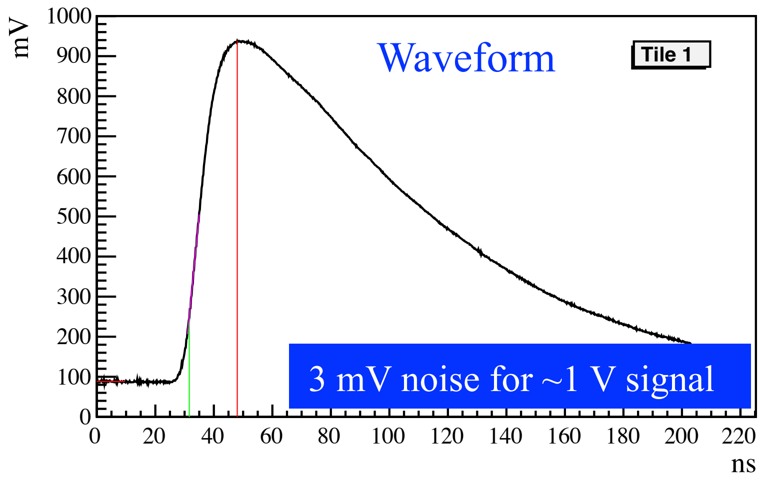


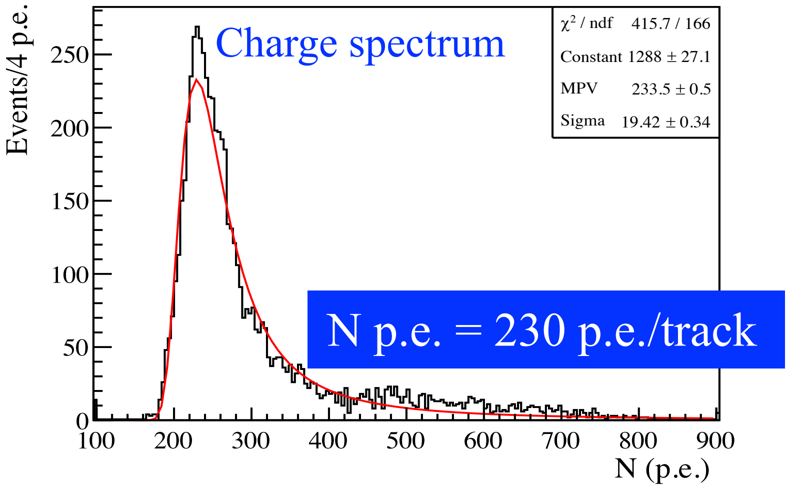
4-tile prototype built in INFN Bologna/LNF

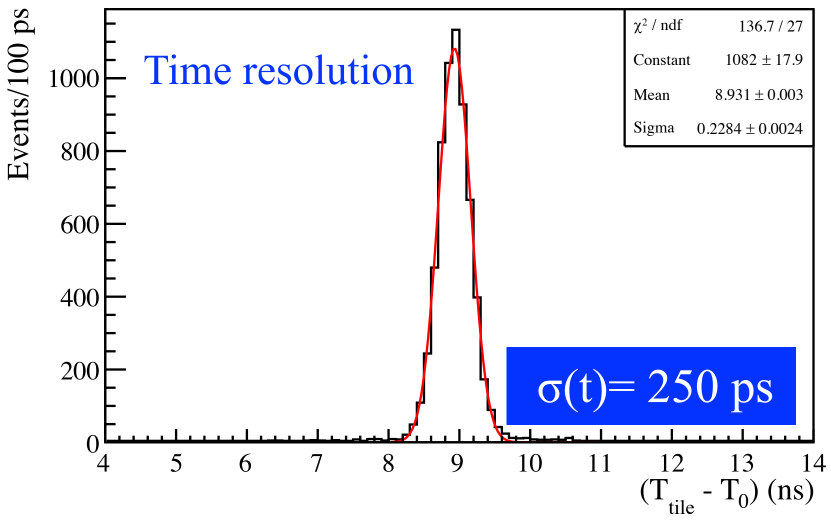


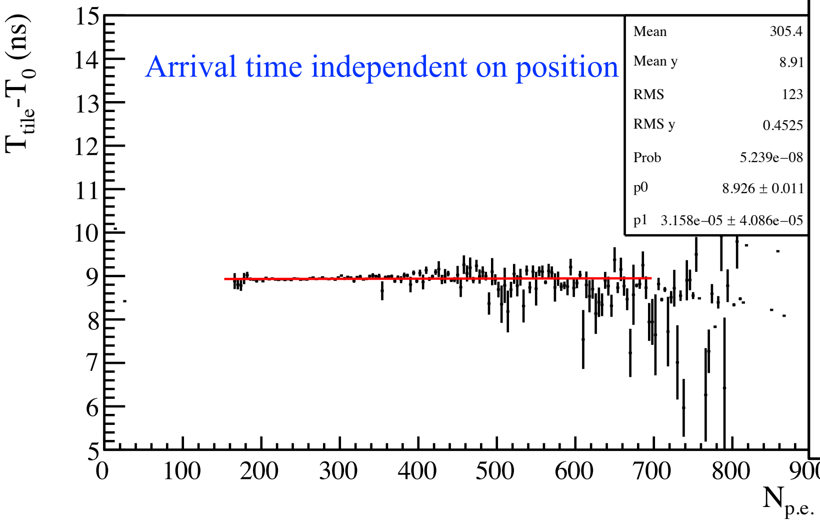
Efficiency > 99.5%
N(p.e.)/MIP = 230
σ(t) ~ 250 ps

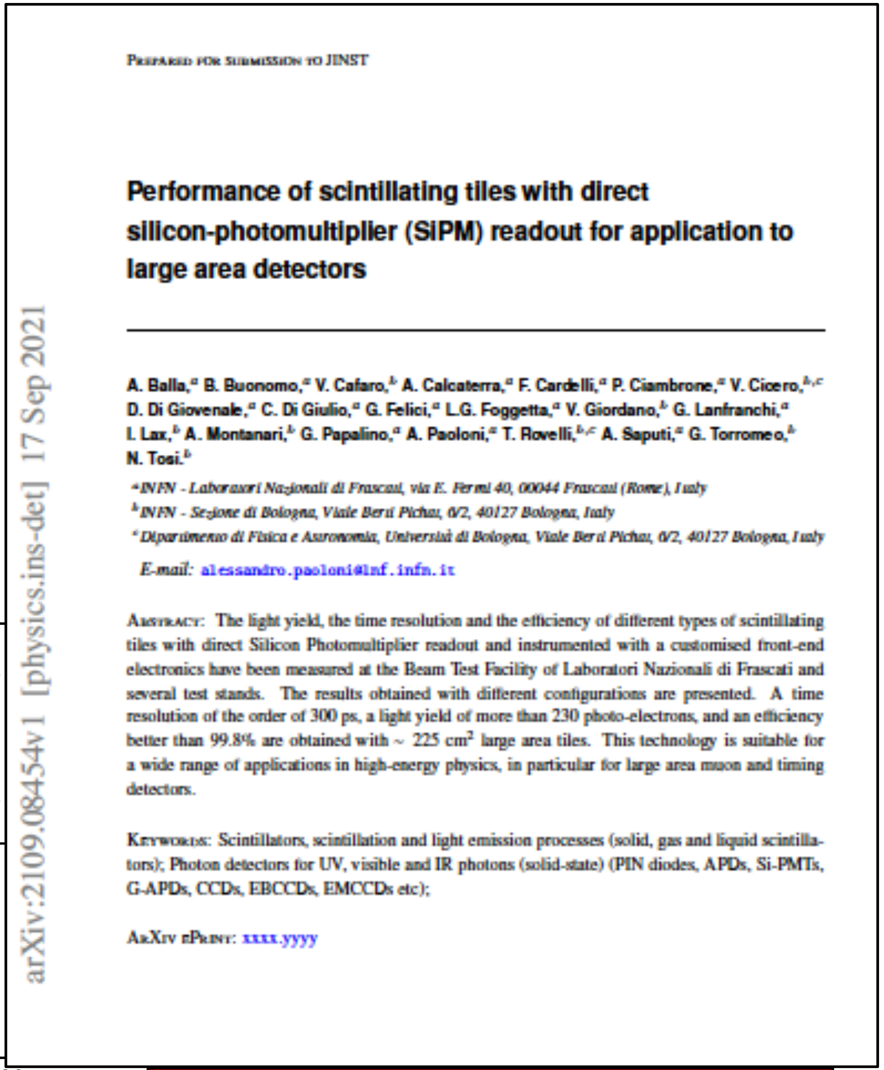
SHADOWS: The Muon Detector











Prepared for submission to JINST

Performance of scintillating tiles with direct silicon-photomultiplier (SiPM) readout for application to large area detectors

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Abstract: The light yield, the time resolution and the efficiency of different types of scintillating tiles with direct Silicon Photomultiplier readout and instrumented with a customised front-end electronics have been measured at the Beam Test Facility of Laboratori Nazionali di Frascati and several test stands. The results obtained with different configurations are presented. A time resolution of the order of 300 ps, a light yield of more than 230 photo-electrons, and an efficiency better than 99.8% are obtained with ~ 225 cm² large area tiles. This technology is suitable for a wide range of applications in high-energy physics, in particular for large area muon and timing detectors.

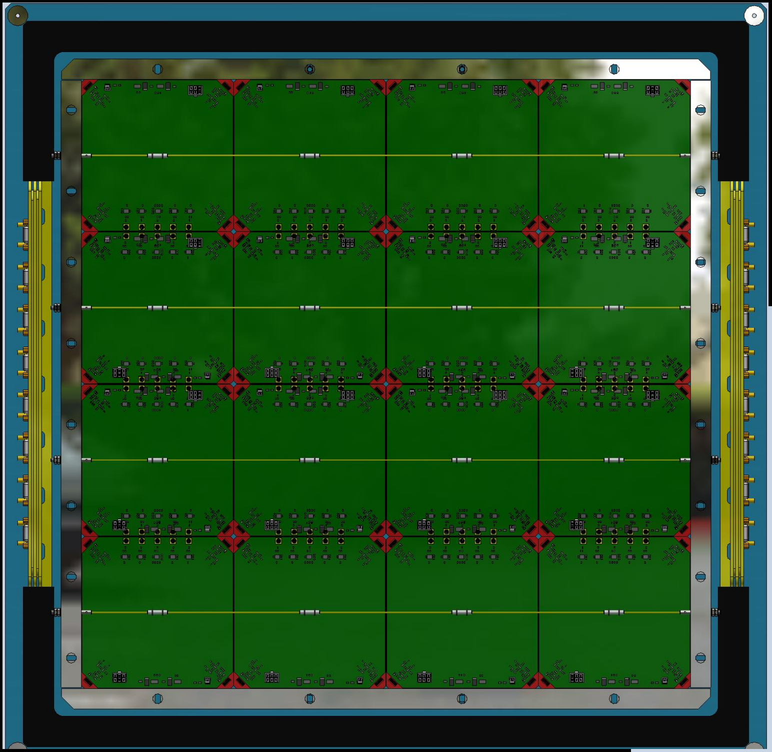
Keywords: Scintillators, scintillation and light emission processes (solid, gas and liquid scintillators); Photon detectors for UV, visible and IR photons (solid-state) (PIN diodes, APDs, Si-PMTs, G-APDs, CCDs, EBCCDs, EMCCDs etc);

ArXiv ePrint: xxxx.yyyy

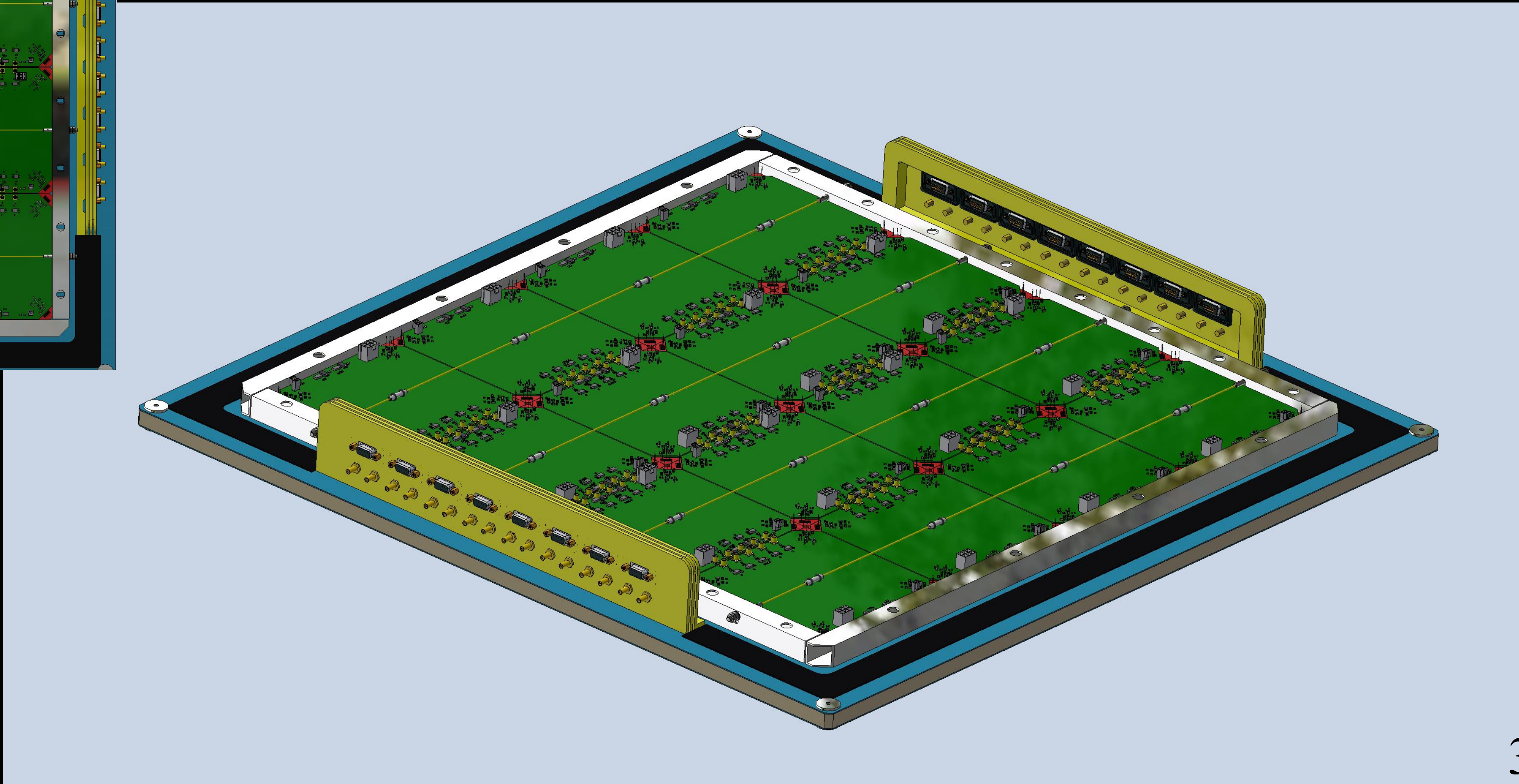
arXiv:2109.08454v1 [physics.ins-det] 17 Sep 2021

JINST 17 (2022) 01, P01038

Two big modules: funded by INFN within AIDA-Innova, Task 8.3.2



Currently developing two full size modules.



Alessandro Saputi (INFN & CERN)

People, Timescale, Cost, Next Steps

SHADOWS PROPONENTS (SO FAR)

INFN-LNF: Gaia, G. Felici, P. Ciambrone (Elect. Dept. Head), A. Paoloni, A. Calcaterra, L. Foggetta, A. Vannozzi

INFN-Ferrara: Alessandro Saputi (Mech. Workshop Head), Wander Baldini,….

INFN-Bologna: A. Montanari, N. Tosi, T. Rovelli, V. Cicero, I. Lax, G. Torromeo (Electr. Dept. Head)

CERN: A. Ceccucci, H. Danielsson (NA62 Tech. Coord.) , A. De Roeck, B. Schmidt (DT Dept. Head), F. Duval, P. Wertelaers. Beam people: J. Bernhard, R. Murphy M. Brugger, etc.

University of Lancaster: L. Gatignon

Royal Holloway London: F. Stummer

University of Mainz (excellence cluster): Rainer Wanke, prof. M. Schott, and several postDocs.

University of Heidelberg: Prof. S. Hansmann Menzemer, prof. U. Uwer (SciFi project leader), Prof. Hans. Chrstian, Shultz-Coulon, + postDocs + PhDs

KIT University of Karlsruhe: prof. T. Ferben, prof. M. Klute, + postDocs..

University of Freiburg: prof. M. Schumann, Prof. H. Fischer , Prof Parzifal, prof. K. Jakobs (+ postDocs)

INR-Moscow: prof. Y. Kudenko and his group (5-6 people)

INFN-Naples: P. Iengo, ….

INFN- Rome3: M. Iodice,…..

SHADOWS LNF ACTIVITY IN 2022-2023

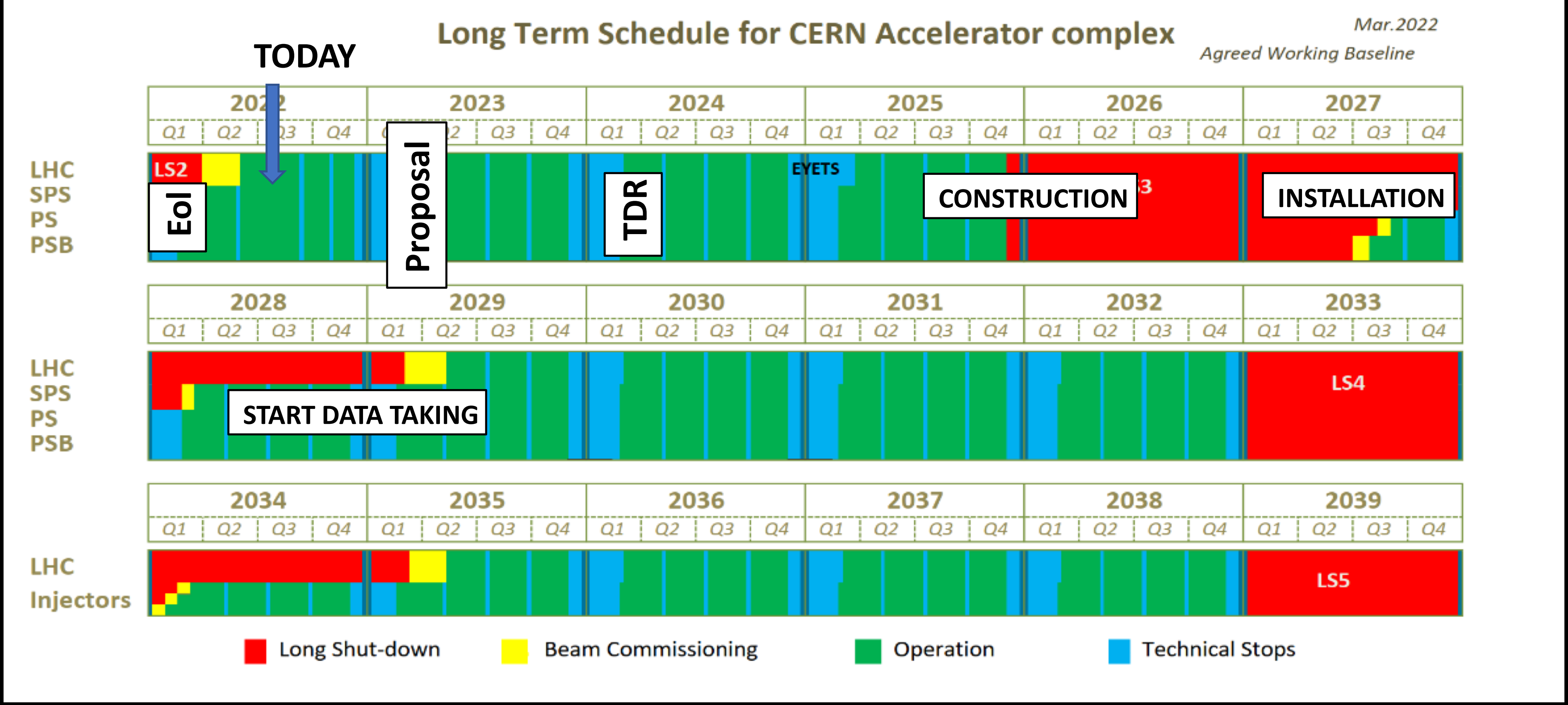
- PEOPLE: Gaia, Giulietto, Ale Paoloni, Sandro Calcaterra, Paolo Ciambrone, A. Vannozzi, L. Foggetta.

- ACTIVITY:
  - Deliver the full size modules for AIDA-Innova (including test beam at BTF in January)
  - Write Proposal (this is a major effort…)

- MISSIONI:
  - 2 meetings/persona/anno, 2gg/meeting, 0.5 kE/meeting: 1 kE/persona, 7 kE
  - 2 kE per Gaia che gira come una trottola
  - 2 kE: gettone conferenza per uno del Gruppo

- CONSUMI:
- 2.5 kE: 2nd version of the FEE mother board
- 2.5 kE: slow control master board
- 2.5 kE: slow control distribution

SHADOWS: TENTATIVE TIME SCHEDULE



Next step: Prepare a Proposal by end 2022 - early 2023

Approval (or not): spring 2023.

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
INFN →	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
INFN →	Muon	scintillating tiles	0.4-0.5 MCHF
	TDAQ & offline		o(1-2) MCHF
	Total		$\sim 11.6 - 14.9$ MCHF

SHADOWS Next events:

1. July 22: Presentation in all involved INFN sections/labs and in Gruppo1 next week in Pisa.
2. October 22: talk at the FIPs 2022 workshop at CERN: https://indico.cern.ch/event/1119695/
3. November 22: talk at the General PBC workshop at CERN: https://indico.cern.ch/event/1137276/
4. Jan-Feb 23: delivery full size muon modules for AIDA-Innova
5. March (at latest) 23: Proposal submitted to SPSC
6. April 23: feedback from the SPSC.

If positive feedback: start to prepare TDR….

Conclusions

- ✓ 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 (5x10^{19} pot) has similar/better sensitivity than CODEX-b (300 fb^{-1}) and FASER2 (3 ab^{-1}) and for specific benchmarks as SHiP (2x10^{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+HIKE can become a "hot spot" on worldwide scale for FIP physics after LS3.

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

SPARES

Background: Preliminary considerations

Three main backgrounds:

1. Muon combinatorial

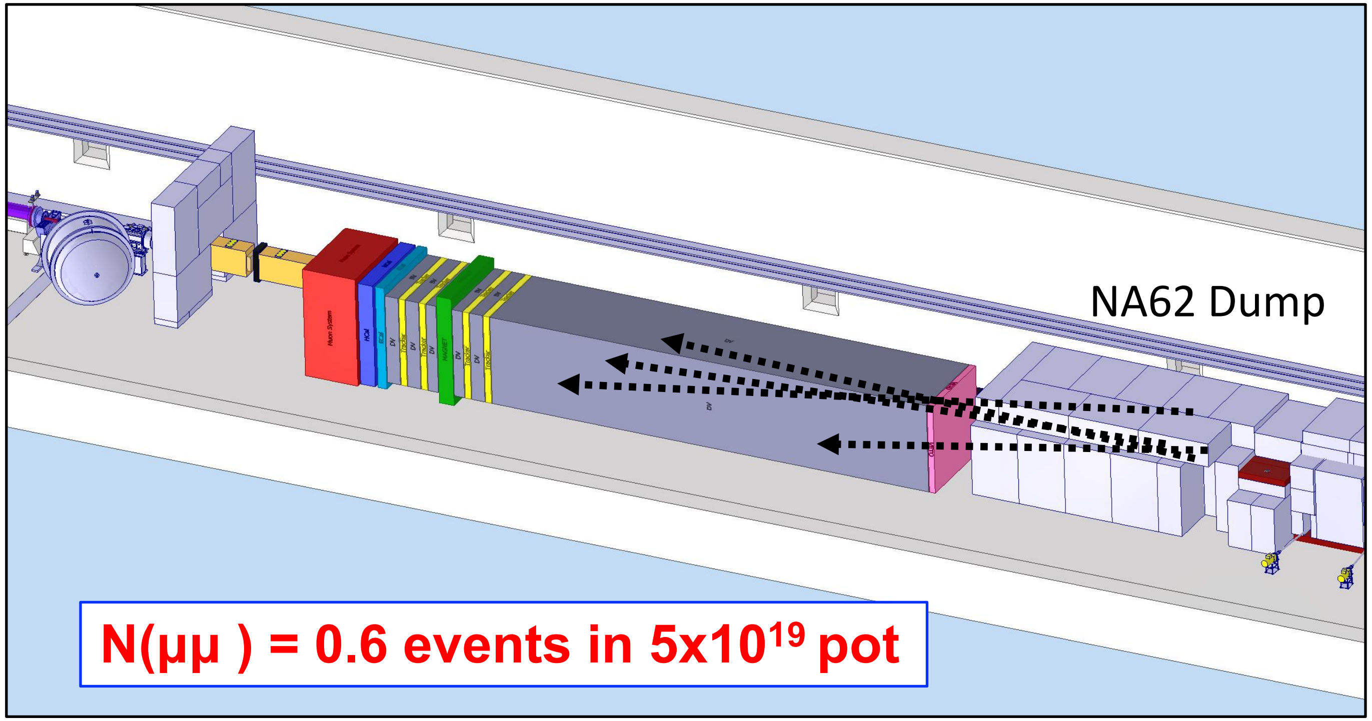
2. Neutrinos inelastic interactions with the air in the decay volume

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 $\times 10^9$ pot on dump.
A detailed study of the background will be done for the Proposal.

1. Background: Muon Combinatorial

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.



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

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}

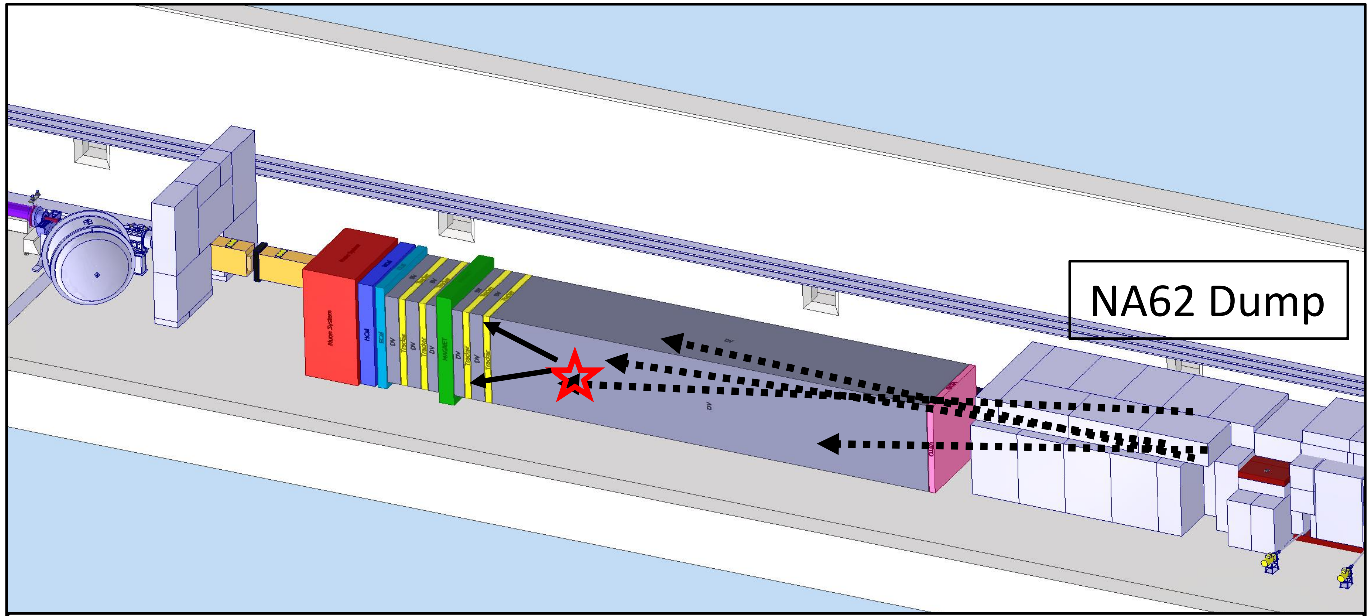
4) Pointing: Probability to point back to impinging point of protons onto the dump: 10^{-3}

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

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

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 = 5×10^{19} pot)



N(ν inel. interactions in DV, 1 mbar) = 0.6 events in 5×10^{19} pot

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

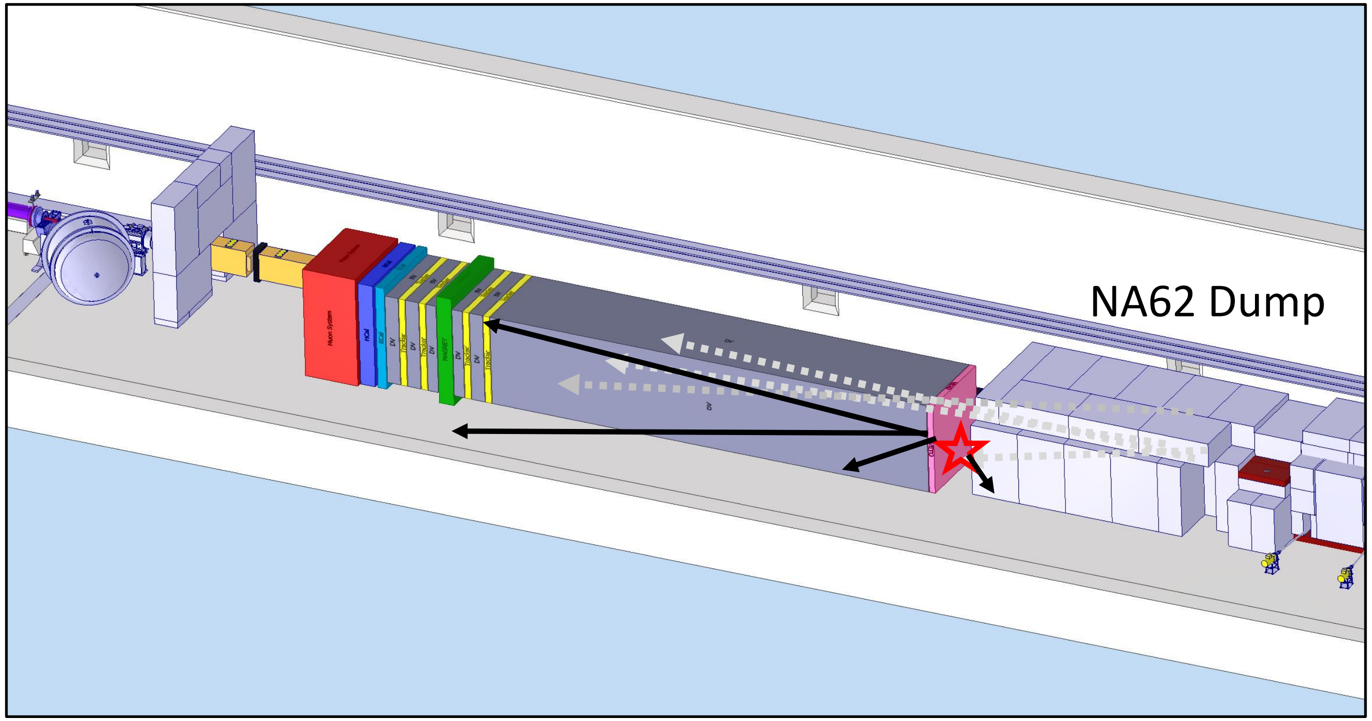
$$N_{\nu\ \text{inelastic int.}} = N_\nu \times 10^{-13} = 6 \cdot 10^{15} \times 10^{-13} = 600$$

1 mbar vacuum reduces this number to 0.6 events in 5×10^{19} pot

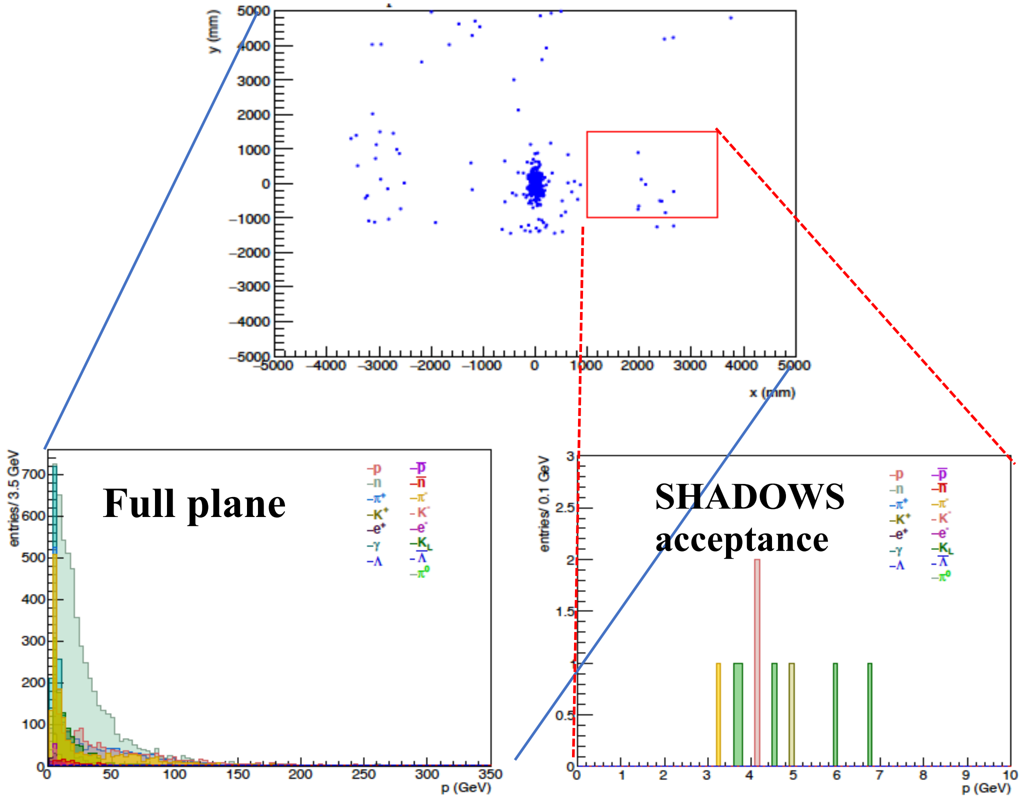
NB: A detailed evaluation will be done for the Proposal.

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

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….

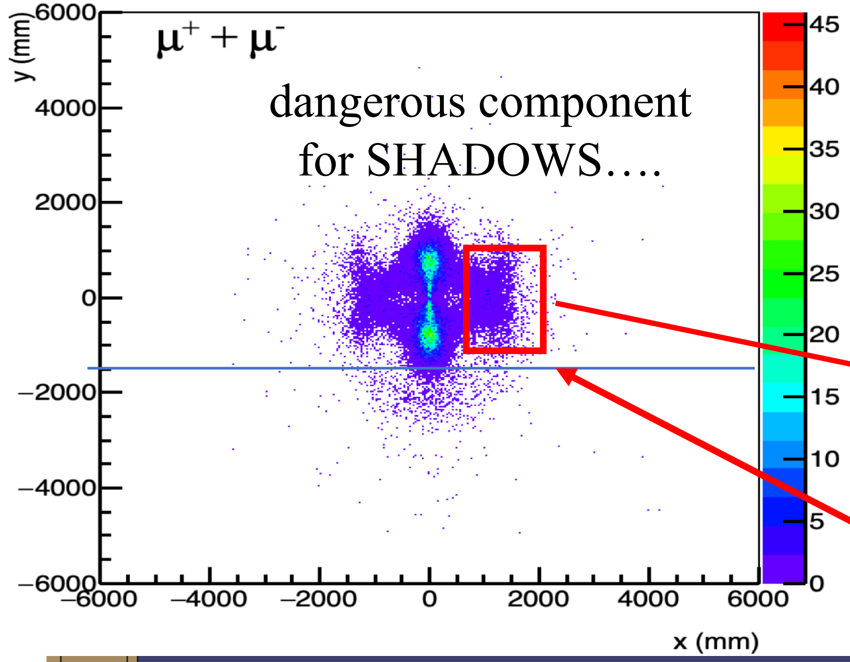


Non muon background downstream of TAXes



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

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!