SHADOWS

Search for Hidden And Dark Objects With the SPS

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On behalf of the SHADOWS team
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LLPX Workshop, 9 November 2021

Physics Beyond Colliders

Experiments/proposals related to FIPs in PBC

SPS
(MeV- few GeV)

NA62x4/ KLEVER
FIPs with kaons/proton beam dump

SHiP

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

(Baby-)IAXO
solar axions

Axions/Dark Photons
(< meV)

SHADOWS
FIPs @ proton beam dump

Gamma-factory
(mostly ALPs)

VMB
Vacuum birifrangence

FIPs @ CERN (within PBC)

CODEX-b
FIPs @ LHCb IP

proton-EDM

ANUBIS
(FIPs @ ATLAS shaft)

AION
FIPs with atom interferometer

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

LHC
(few GeV – TeV)

MATHUSLA
FIPs @ CMS IP

nTOF

Forward Physics Facility (FASER2, …)

ISOLDE

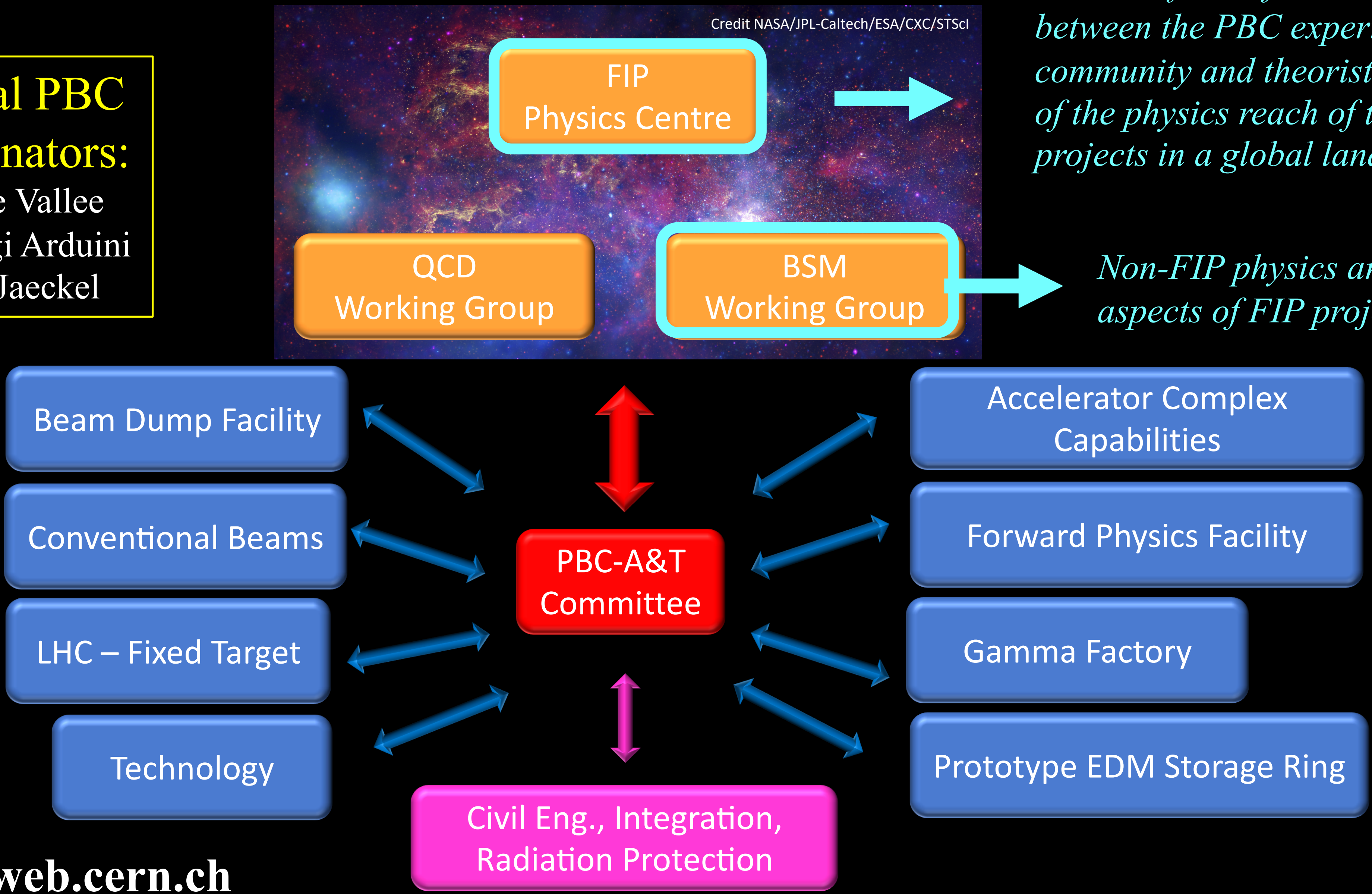
AD
FIPs @ anti-proton decelerator

Nuclear astrophysics

Ultra-light FIPs
(via atomic clocks and the likes)

The Physics Beyond Colliders structure

General PBC coordinators:
Claude Vallee
Gianluigi Arduini
Joerg Jaeckel



“Central forum for exchanges between the PBC experimental community and theorists for assessment of the physics reach of the proposed projects in a global landscape”

Non-FIP physics and experimental aspects of FIP projects

https://pbc.web.cern.ch

September 2021

The Physics Beyond Colliders budget

CERN Medium Term Plan 2022-2026

CERN/SPC/1158/Rev.
CERN/FC/6491/Rev.
CERN/3575
Original: English
2 June 2021

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Action to be taken		Voting procedure
For recommendation to the Council	SCIENTIFIC POLICY COMMITTEE 323rd Meeting 14-15 June 2021	—
For recommendation to the Council	FINANCE COMMITTEE 377th Meeting 16 June 2021	Chapters I and IV.1: Simple majority of Member States represented and voting (abstentions are not counted) and 70% of the contributions of the Member States represented and present for the voting (abstentions are counted as votes against) and at least 51% of the contributions of all Member States. Chapter III: Two-thirds majority of Member States represented and voting (abstentions are not counted) and 70% of the contributions of the Member States represented and present for the voting (abstentions are counted as vote against) and at least 51% of the contributions of all Member States.
For decision	RESTRICTED COUNCIL 203rd Session 17-18 June 2021	Chapters I and IV.1: Simple majority of Member States represented and voting (abstentions are not counted). Chapter III: Two-thirds majority of Member States represented and voting (abstentions are not counted).

Medium-Term Plan for the period 2022-2026 and Draft Budget of the Organization for the sixty-eighth financial year 2022

GENEVA, June 2021

- *…….A diverse scientific programme is strongly supported by the 2020 Strategy update, which also recognised the role of the Physics Beyond Colliders (PBC) study group as the focal point for promoting and channelling new research initiatives.……*
- *………Given the importance of a diverse scientific programme to addressing the outstanding questions in particle physics in a way complementary to high-energy colliders PBC activities are funded with an increased budget of ~3.5 MCHF/year in this MTP (up from 1 MCHF/year)*

Scientific projects	**284.8**	**341.0**	**330.1**	**318.2**	**272.6**	**209.9**	**1 757**
LHC upgrades	**212.1**	**234.0**	**228.7**	**218.4**	**184.5**	**137.3**	**1 215**
LHC injectors upgrade (LIU)	*7.4*						*7*
HL-LHC upgrade	*162.9*	*159.7*	*156.6*	*150.5*	*131.7*	*98.0*	*860*
LHC detectors upgrades (Phase I) and consolidation	*7.9*	*3.8*	*2.0*	*2.0*	*1.0*	*2.2*	*19*
LHC detectors upgrades (Phase II) and R&D	*33.9*	*70.5*	*70.1*	*65.8*	*51.8*	*37.1*	*329*
Future colliders studies	**18.6**	**27.5**	**33.0**	**31.3**	**22.9**	**19.8**	**153**
Linear collider	*5.4*	*5.1*	*4.7*	*4.2*	*4.1*		*23*
Future Circular Collider	*11.7*	*20.2*	*26.3*	*25.1*	*16.8*		*100*
Muon colliders	*1.5*	*2.3*	*2.0*	*2.0*	*1.9*		*10*
High-energy frontier						*19.8*	*20*
Accelerator technologies and R&D	**26.8**	**35.5**	**31.5**	**28.6**	**31.3**	**28.2**	**182**
R&D for future detectors	**7.5**	**8.0**	**7.7**	**7.3**	**4.1**	**4.1**	**39**
Scientific diversity projects	**19.7**	**36.1**	**29.3**	**32.6**	**29.9**	**20.5**	**168**
Neutrino Platform	*8.8*	*23.0*	*17.1*	*20.0*	*18.4*	*9.0*	*96*
Physics Beyond Colliders	*2.3*	*4.2*	*3.7*	*3.5*	*3.3*	*3.3*	*20*
EU supported computing R&D, support to external facilities	*8.7*	*8.9*	*8.5*	*9.1*	*8.2*	*8.2*	*51*

FIP Physics Center

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Yevgeni Stadnik

Stefan Ulmer

Philip Harris

+ one representative per PBC experiment related to FIP physics

What is SHADOWS?

SHADOWS is a new off-axis experiment in the ECN3/TCC8 experimental cavern
currently hosting the NA62 experiment
to search for feebly-interacting particles (FIPs)
emerging from charm and beauty decays.

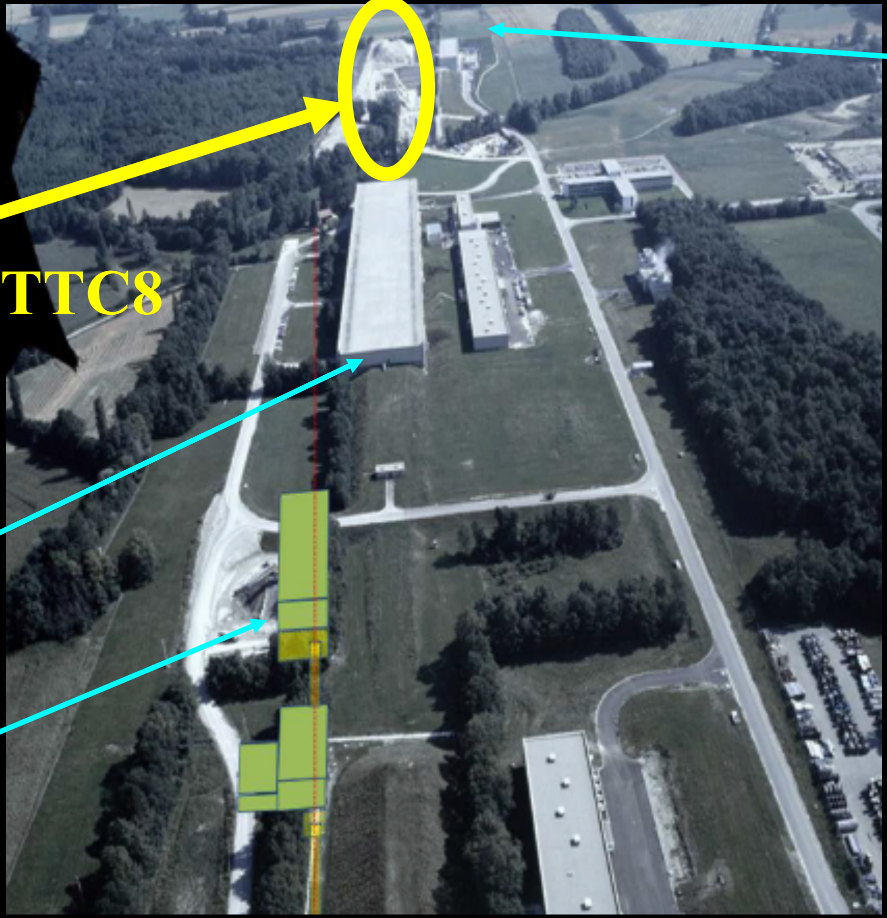
SHADOWS can take data
when the beam line is operated in beam-dump mode.

A synergistic and broad FIPs Physics program can be performed with NA62
when NA62 is operated in dump-mode..

Where is SHADOWS?

ECN3:
P42/K12: 400 GeV p beam
up to 3×10^{18} pot/year (now)
→ **NA62 (and its upgrades)**

→ **SHADOWS in ECN3/TTC8 (CERN North Area)**



EHN2:
M2: 100-160 GeV, mu beam
up to 10^{13} μ/year
→ **$NA64^{++}$ (mu)**

EHN1:
H4: 100 GeV e- beam
up to 5×10^{12} eot/year
→ **$NA64^{++}$ (e), $NA64^{++}$(hadrons)**

Long term projects:
SHiP@ BDF, etc

Why in ECN3 area ?

✓ Because ECN3/TCC8 has the best 400 GeV primary extracted proton beam line at CERN (and worldwide) (P42 primary proton beam line) and a plethora of hidden sector particles can emerge from interactions of a high-energy proton beam with a dump

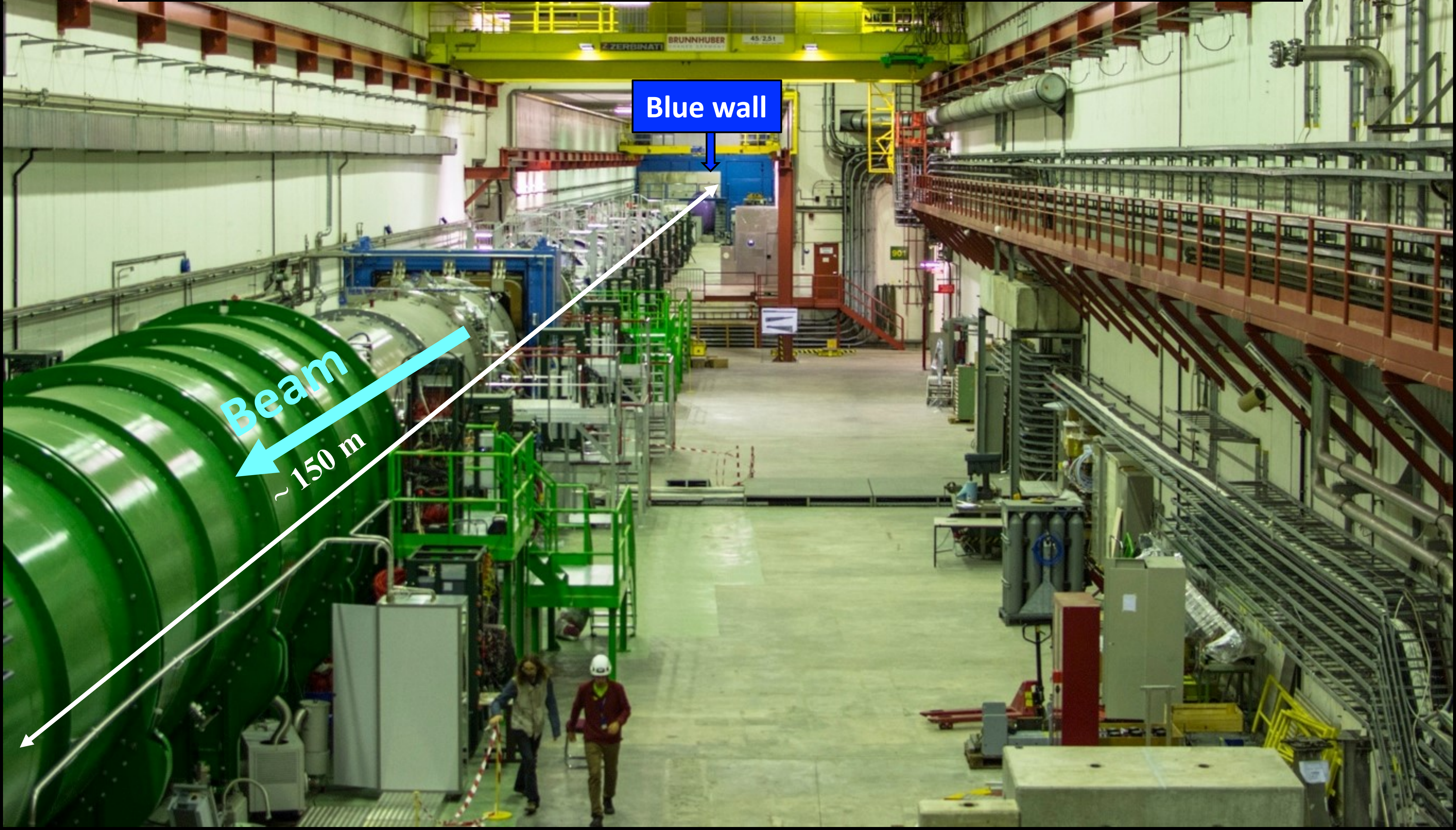
- P42 nominal intensity is 3×10^{12} ppp with 3.3s pulse duration: ~ 10^{12} pot/sec, up to 3×10^{18} pot/year

✓ Beam intensity can be increased by a factor up to 6 (and be compatible with the rest of the current North Area programme):

x 4 (for the high-intensity K^+ beam, NA62x4 project) → up to 10^{19} pot/year

x 6-7 (for high intensity K_L beam , KLEVER project) → up to a 1.5 10^{19} pot/year

The ECN3 Hall (and the NA62 experiment)

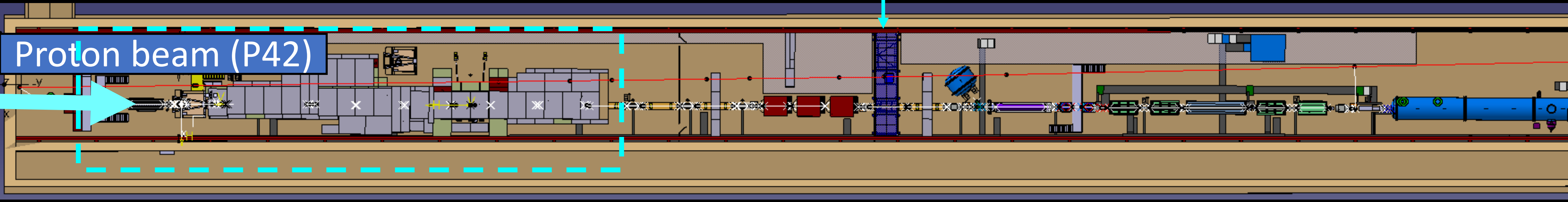


TCC8 + ECN3 hall - zoom out

TCC8: Behind the blue wall
(target and dump complex)

Blue wall

TCC8/ECN3: In front of the blue wall
(NA62 hall)



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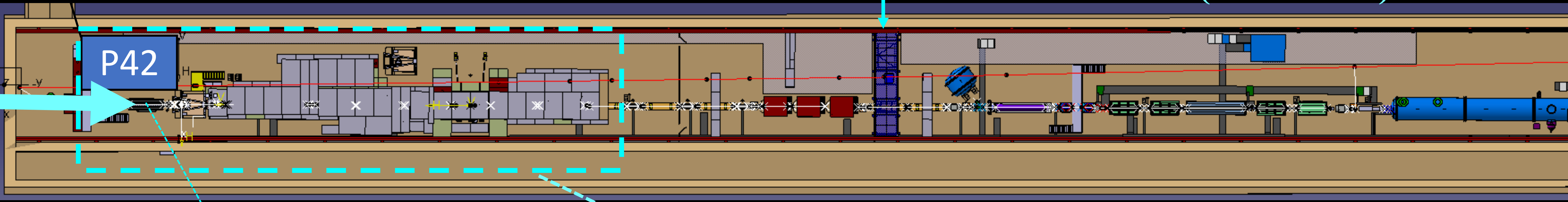
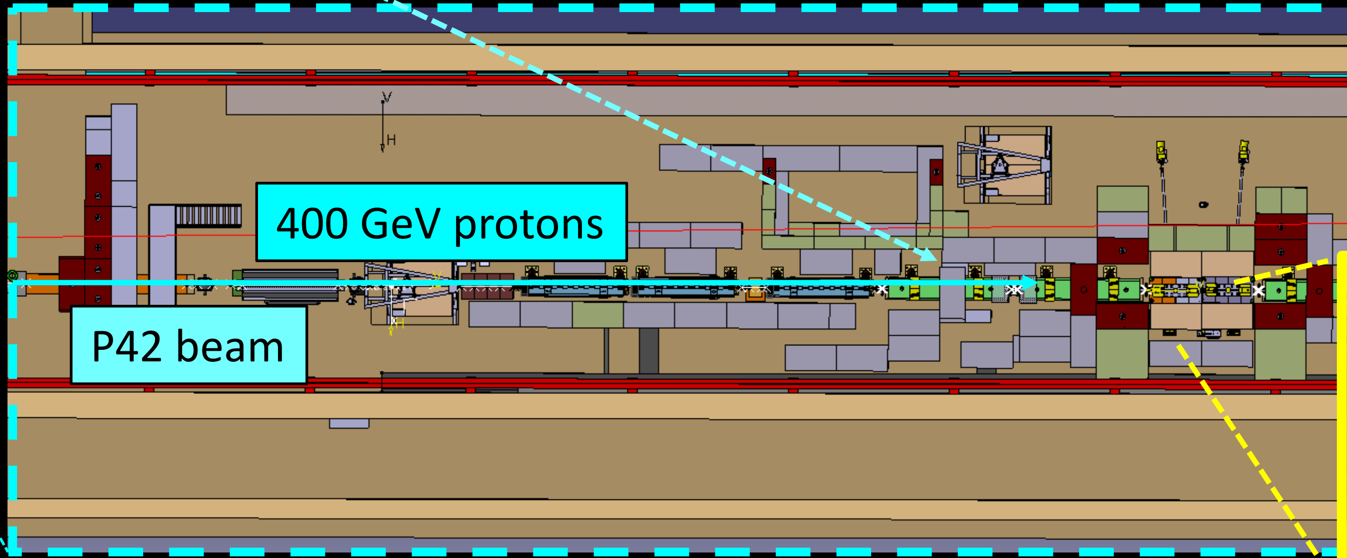
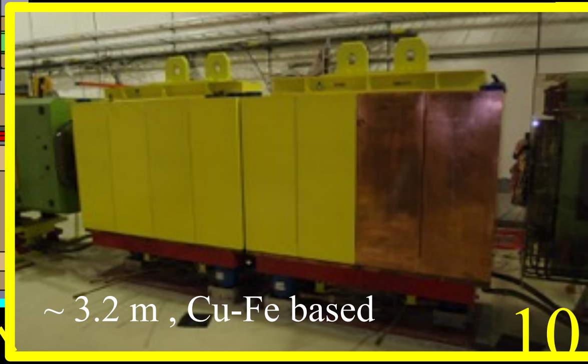


T10 target is lifted and the 400 GeV primary proton beam is sent onto the dump



The NA62 dump system



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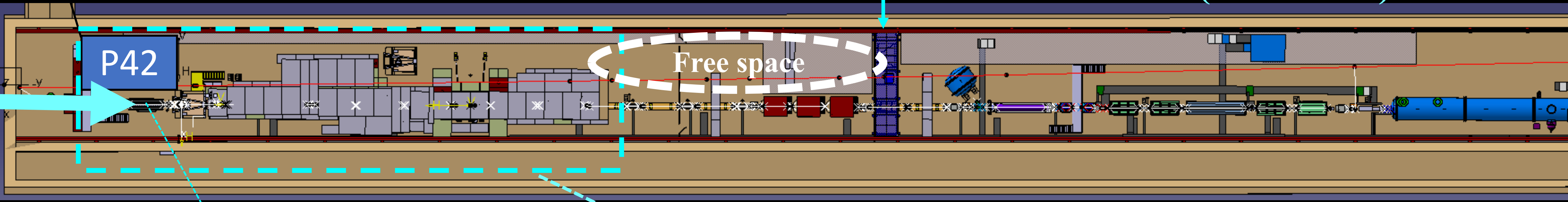

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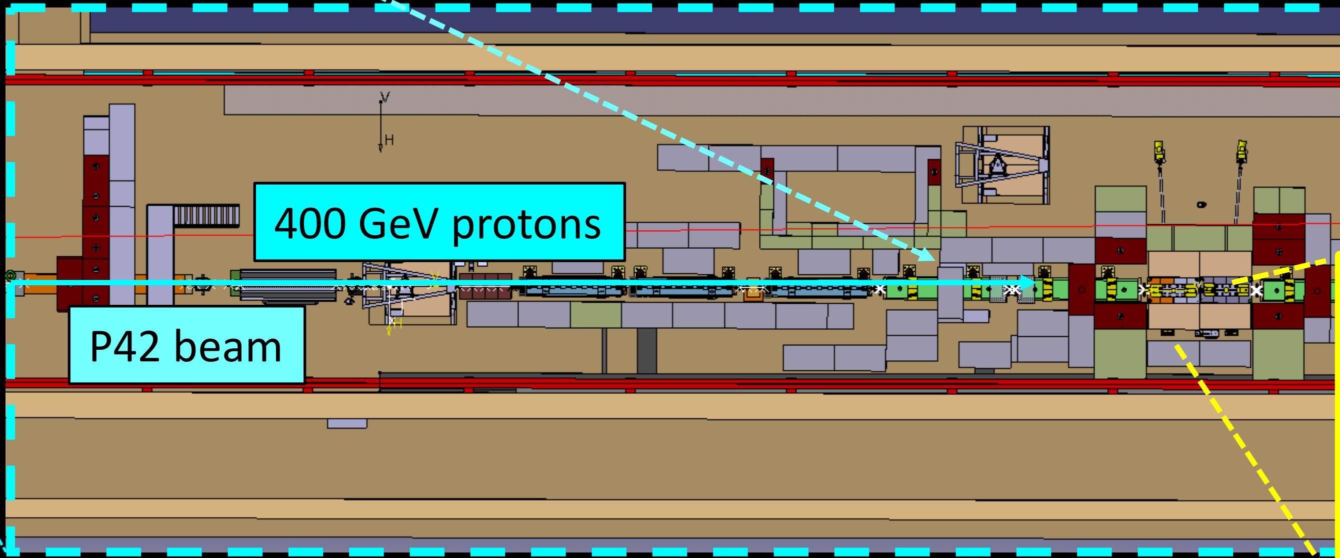

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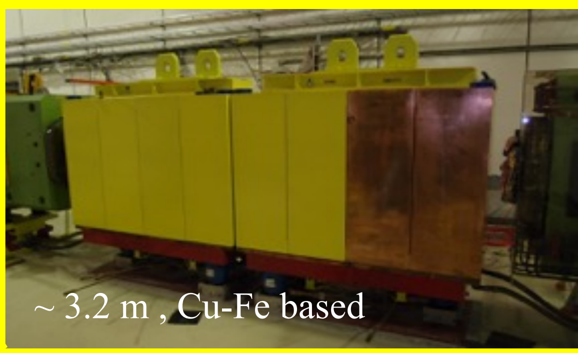

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Blue wall

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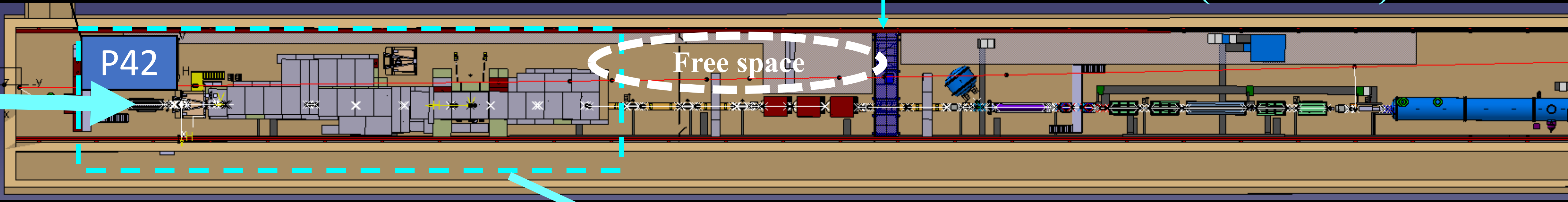
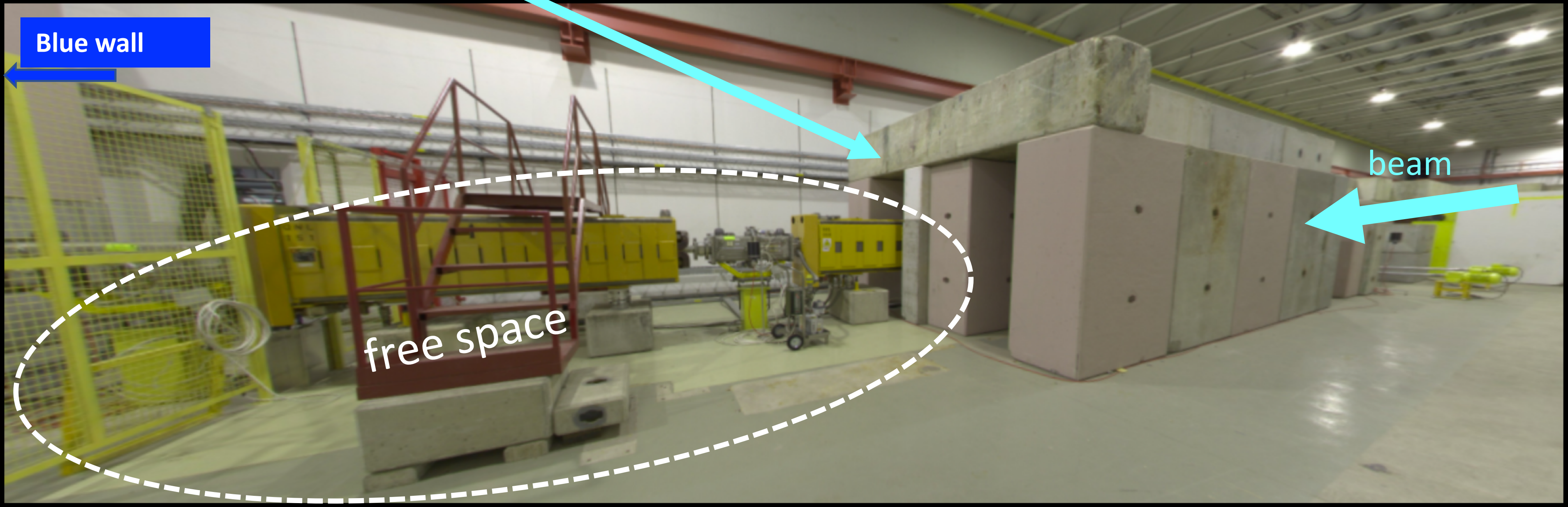
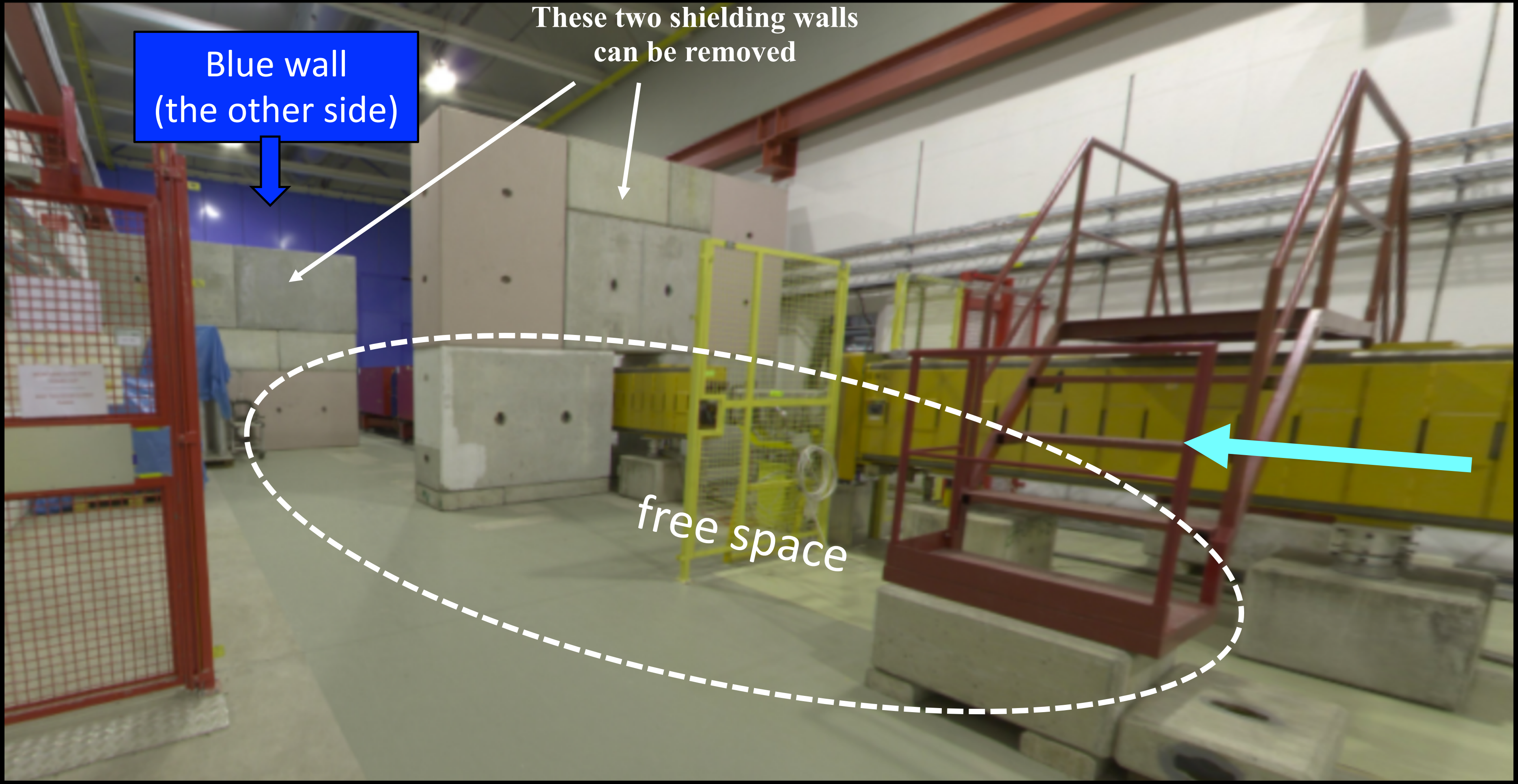


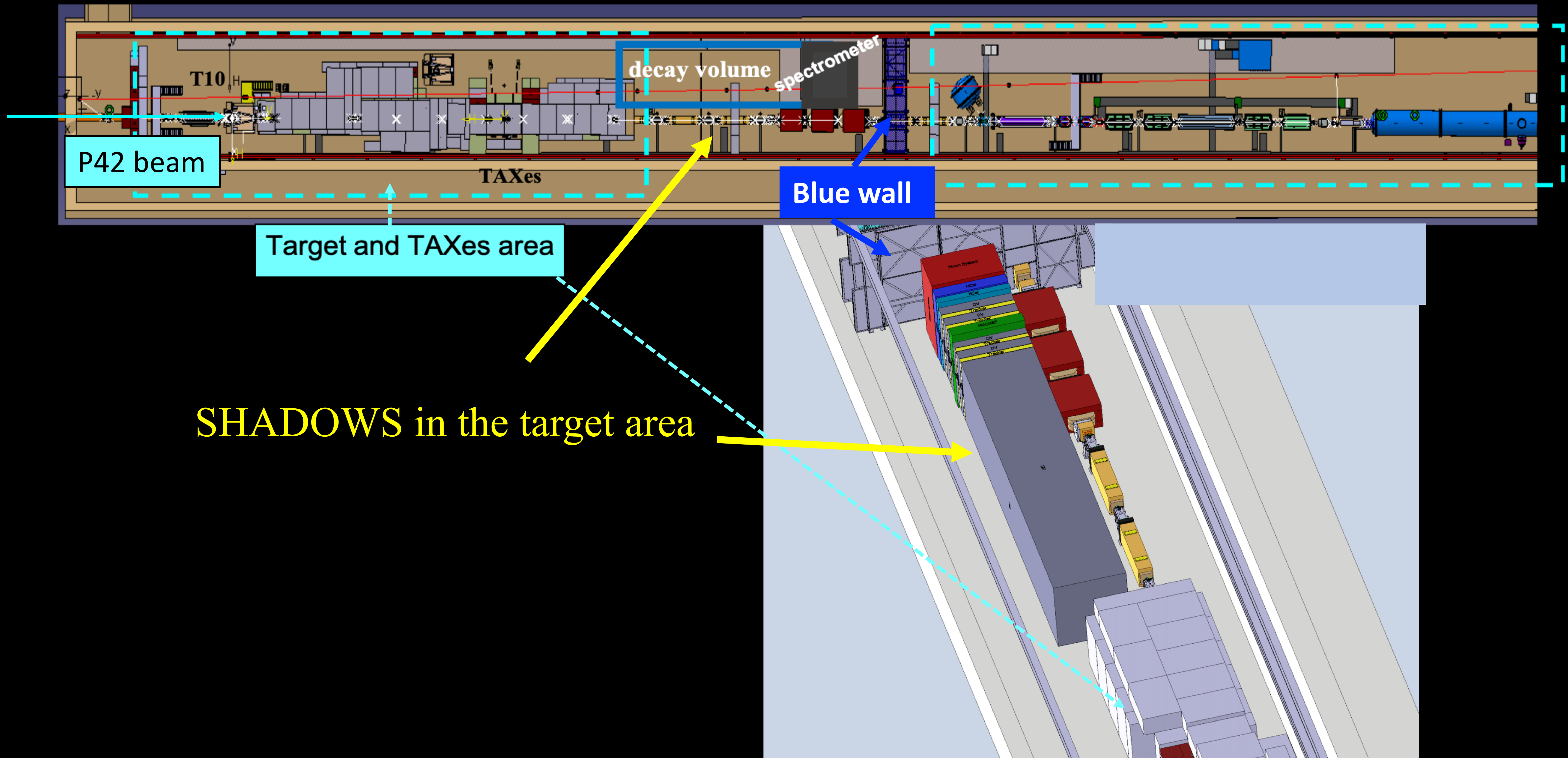


SHADOWS in ECN3/TTC8

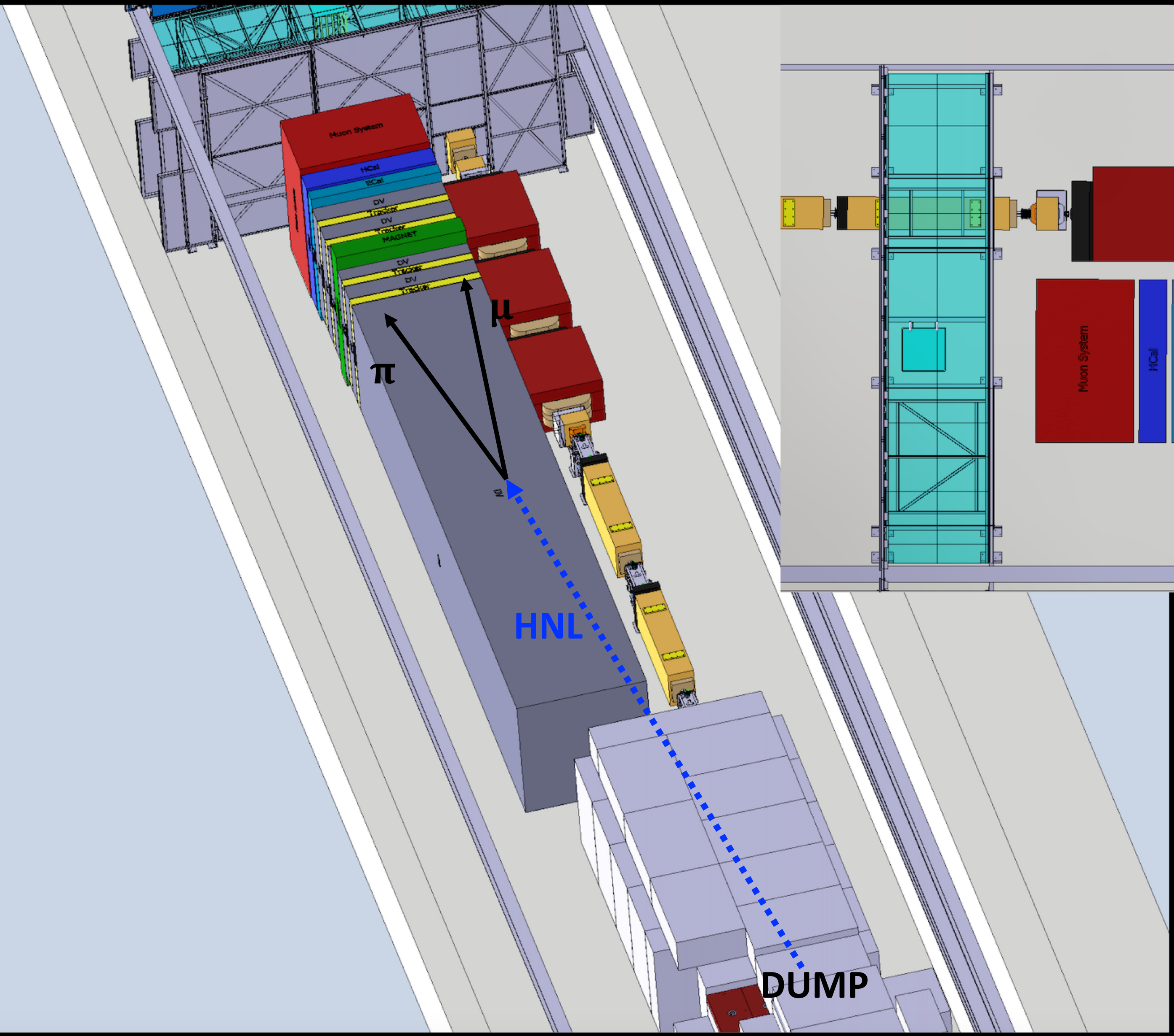
On the other side of the NA62 blue wall – in the target area

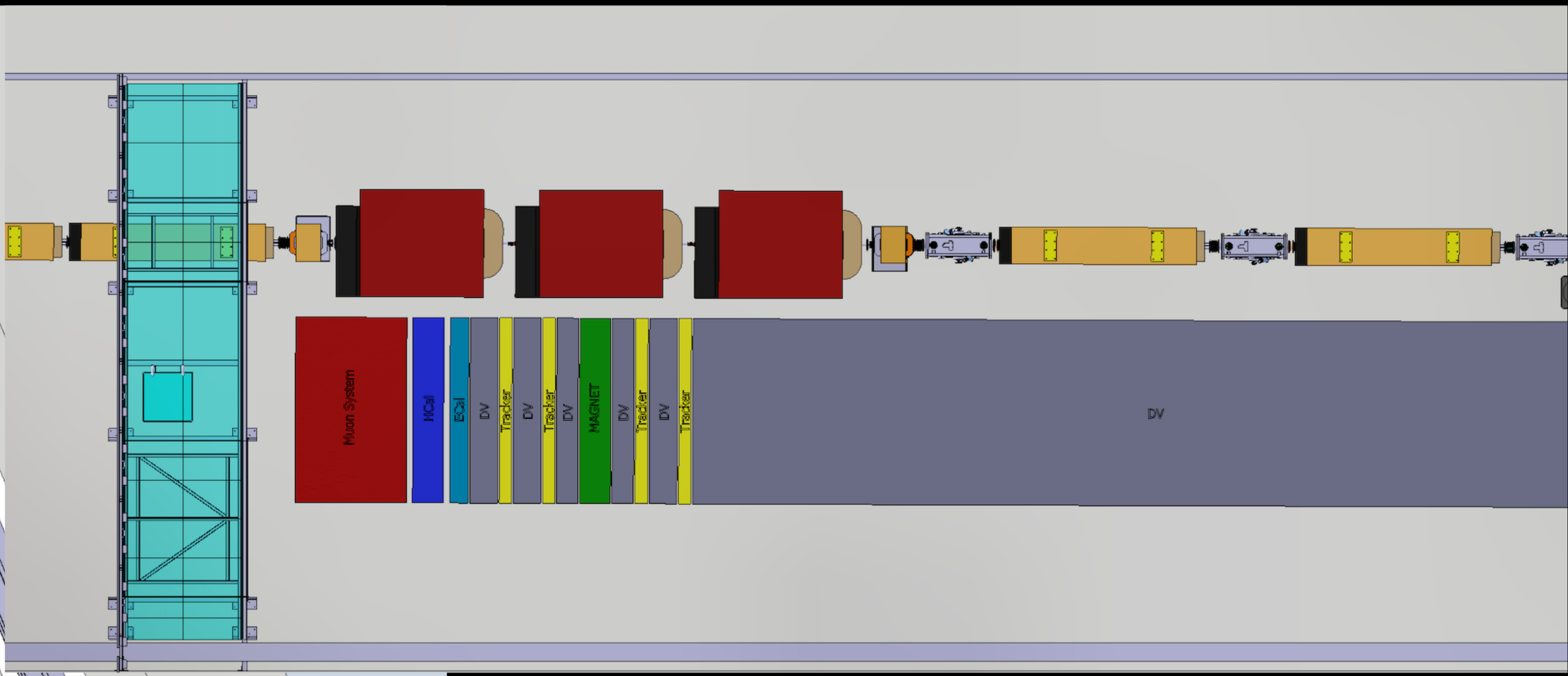


SHADOWS in ECN3/TTC8: an off-axis spectrometer



SHADOWS in ECN3/TTC8: an off-axis spectrometer





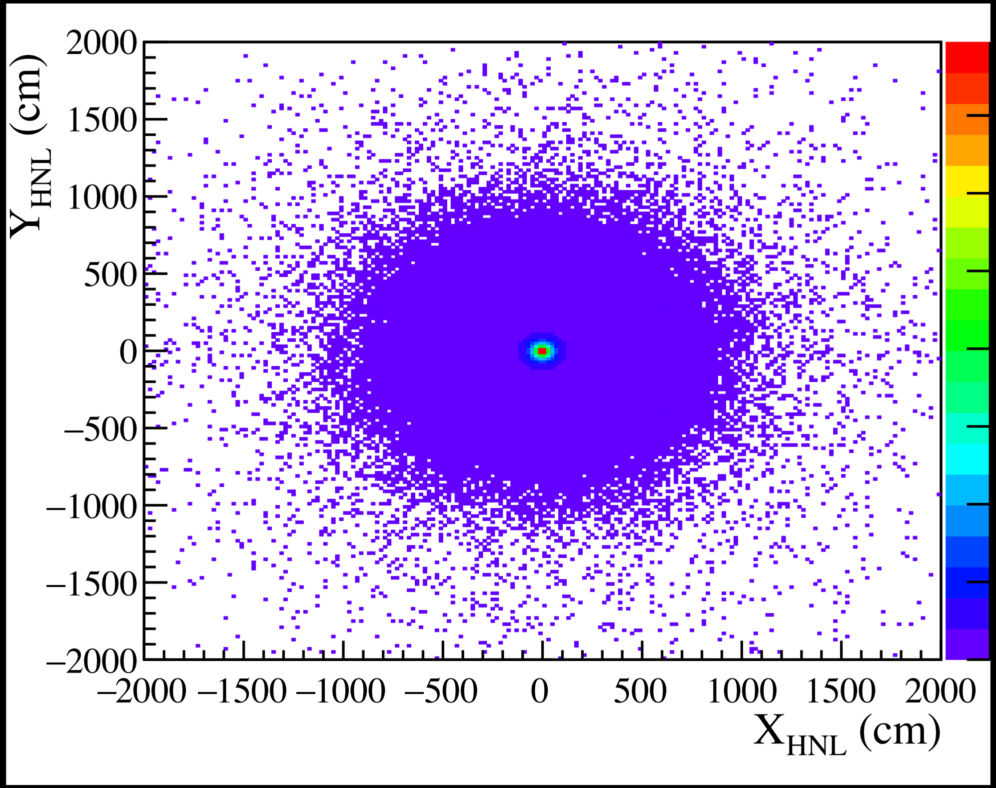
__Preliminary Conceptual Layout__

A spectrometer of about 2.5x 2.5 m^2 transverse area starting at ~1-1.5 m off-axis from beam line

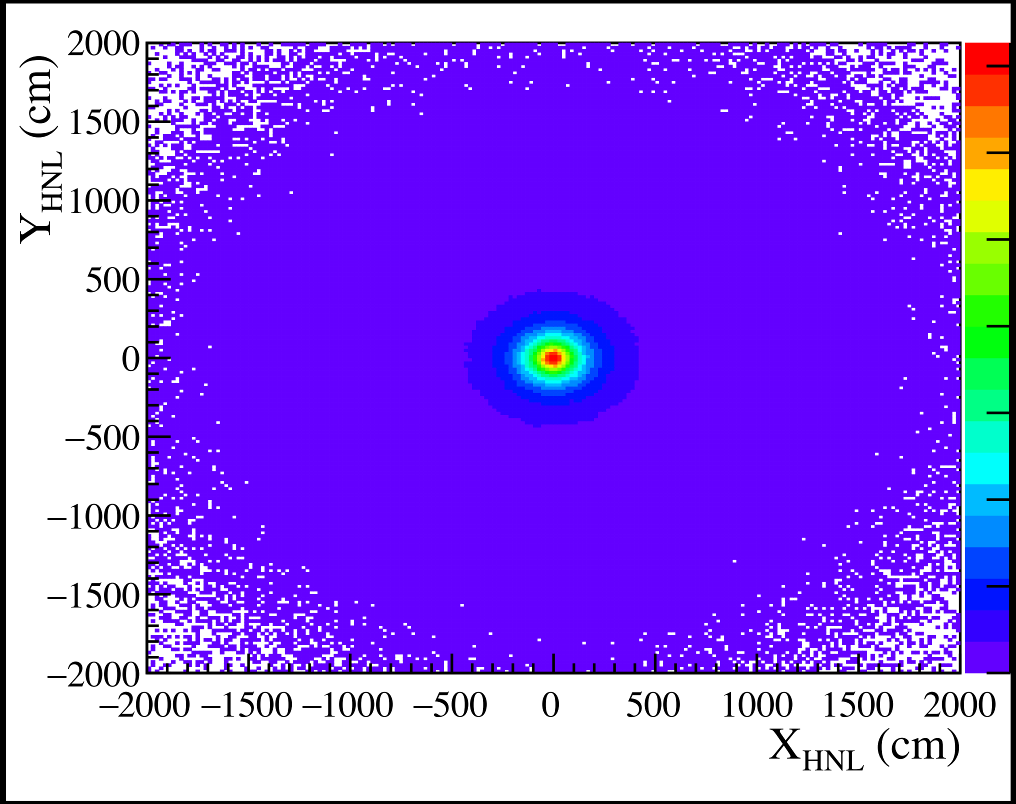
20 m long decay volume, starting ~10 m downstream of the NA62-dump (TAXes) .

Why "off-axis" works

HNL illumination @ D_{min} = 10 m from dump



HNL illumination at D = 80 m from dump

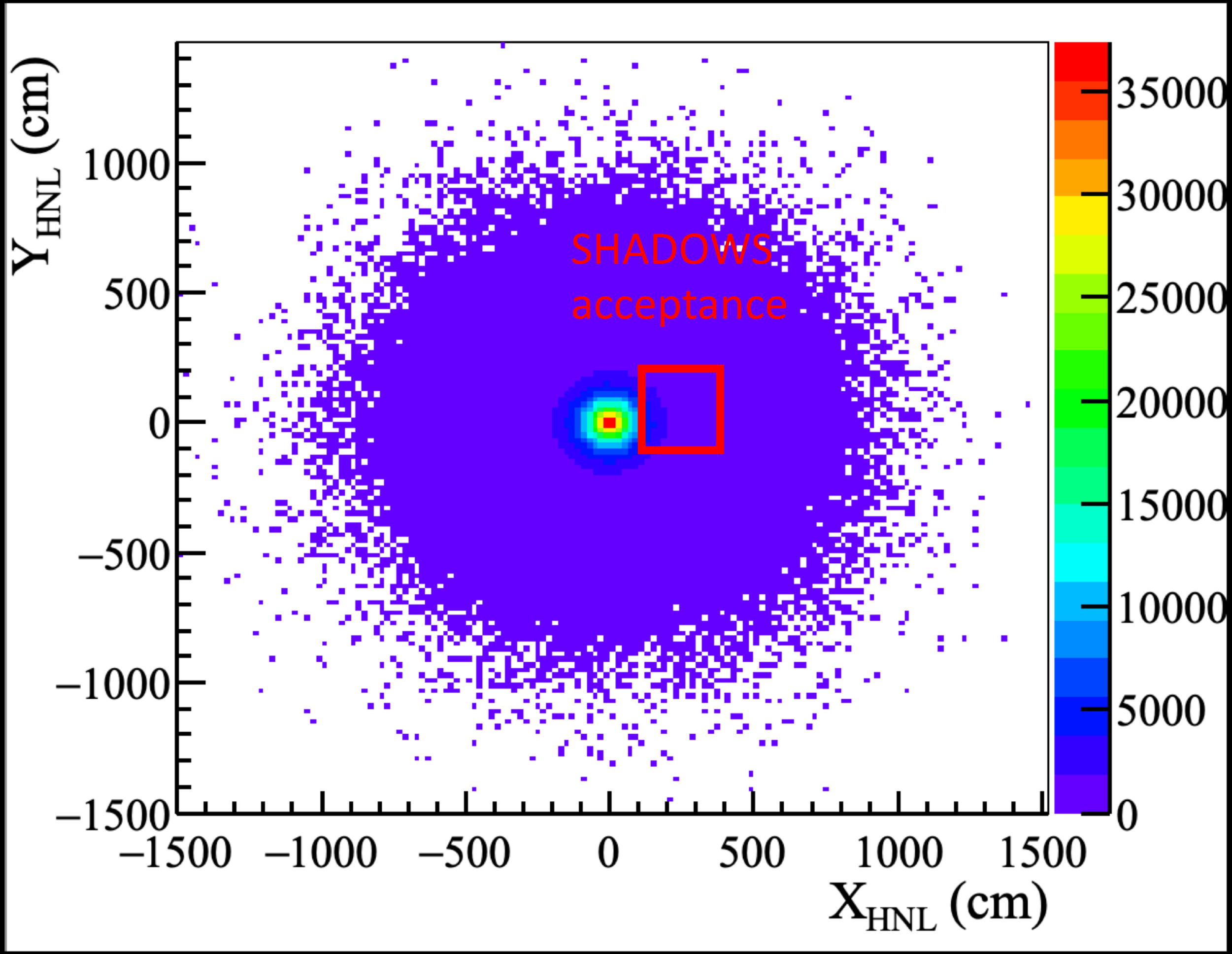


FIPs emerging from charm and beauty decays (HNLs, dark scalars, ALPs) are produced with a large polar angle.

The closer you go to the dump the better…..

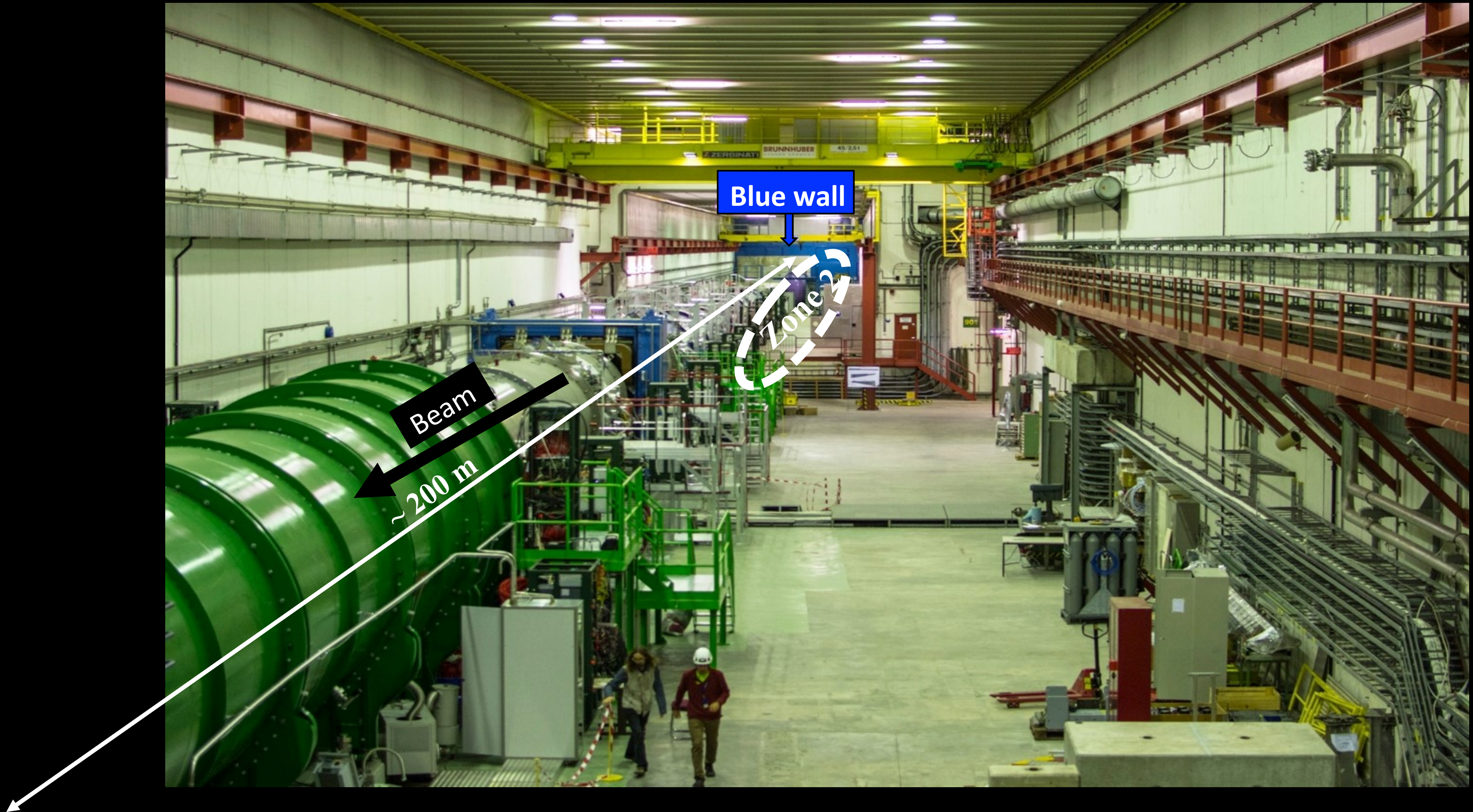
Why "off-axis" works

Heavy Neutral Lepton illumination at the SHADOWS tracking plane

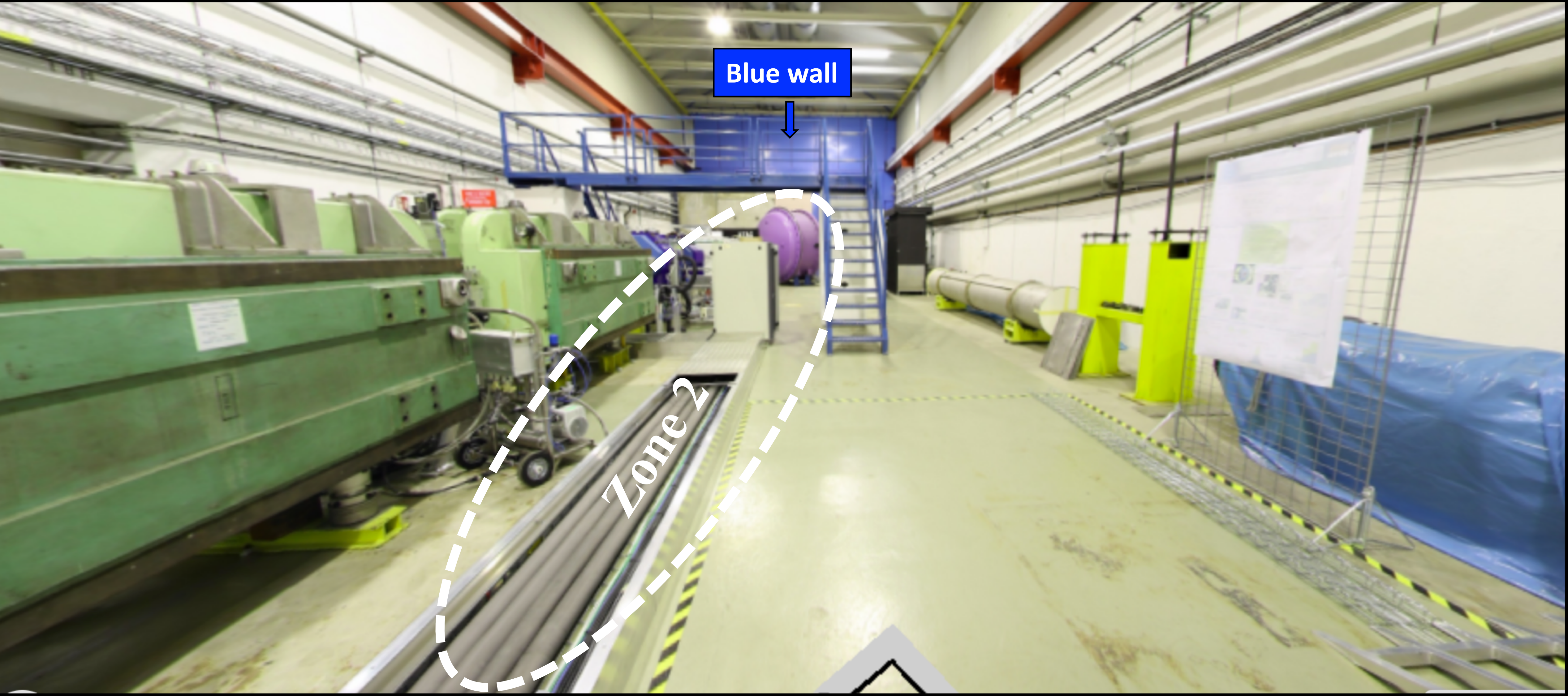


SHADOWS position is a compromise between maximal acceptance and minimum background

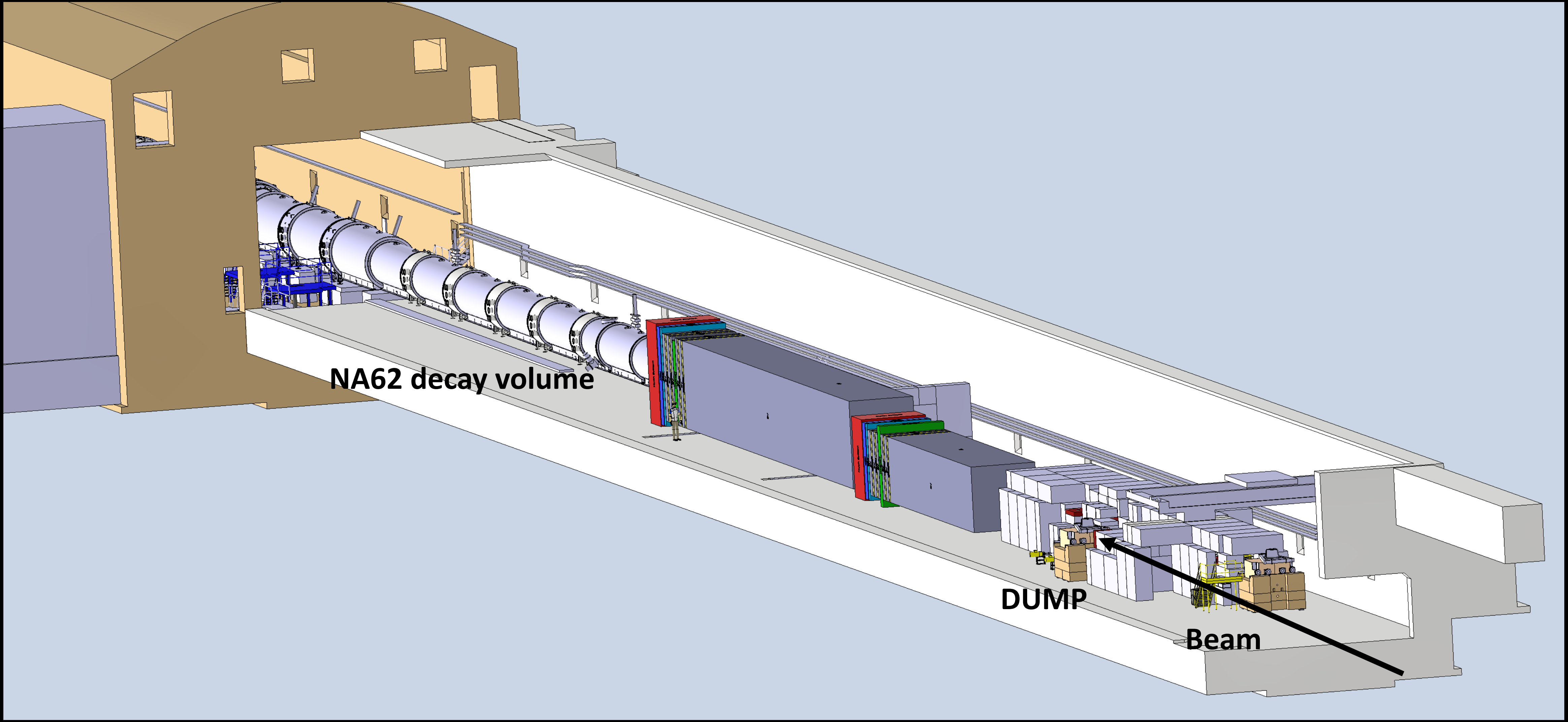
SHADOWS in ECN3/TTC8: possible extension for future upgrades



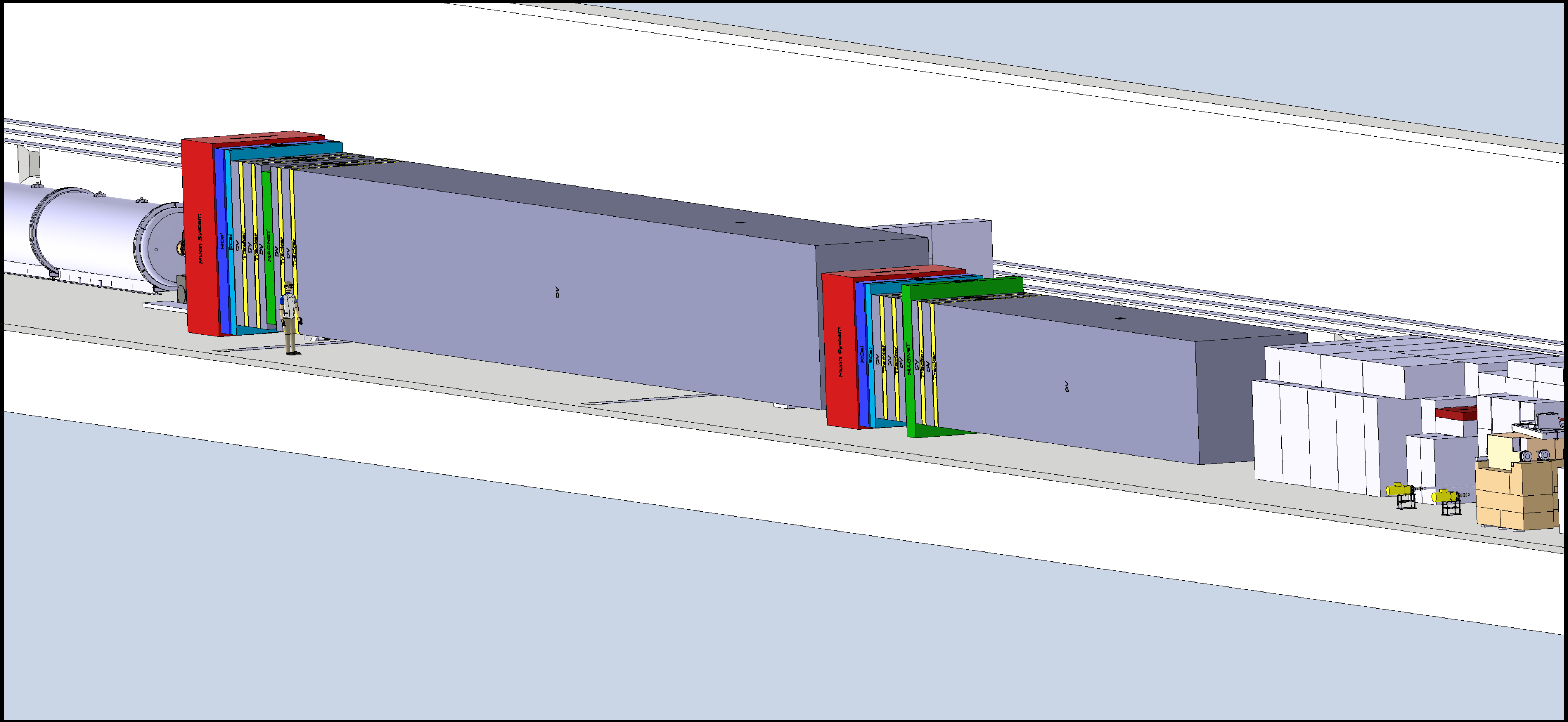
SHADOWS in ECN3/TTC8: possible extension for future upgrades



Possible extension – longer timescale
(exact position still to be defined)

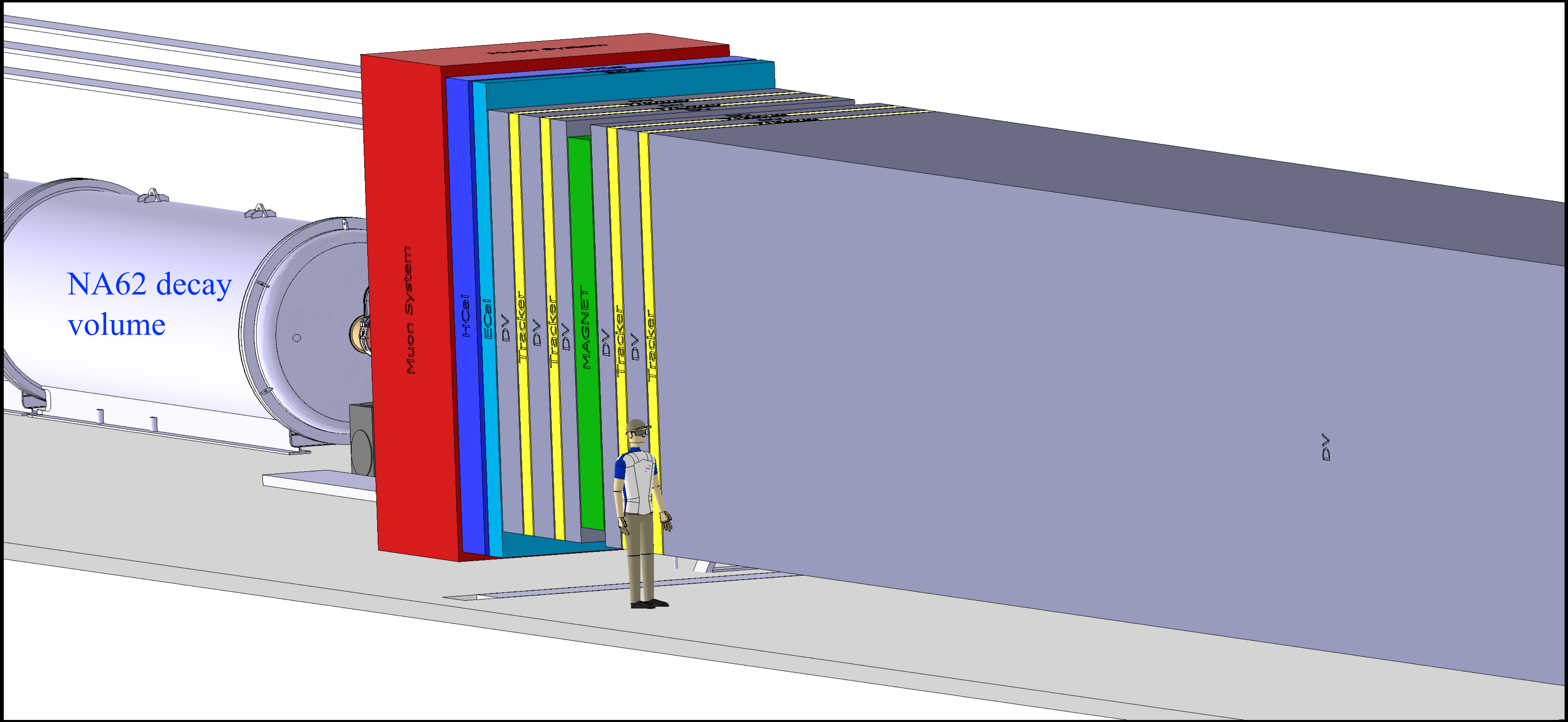


The second shadows spectrometer could have 30 m long decay volume and 3x4 m^2 transverse dimensions



The addition of a second spectrometer is equivalent to multiply the beam intensity by x5-6.

The second spectrometer must end before the beginning of the NA62 decay volume

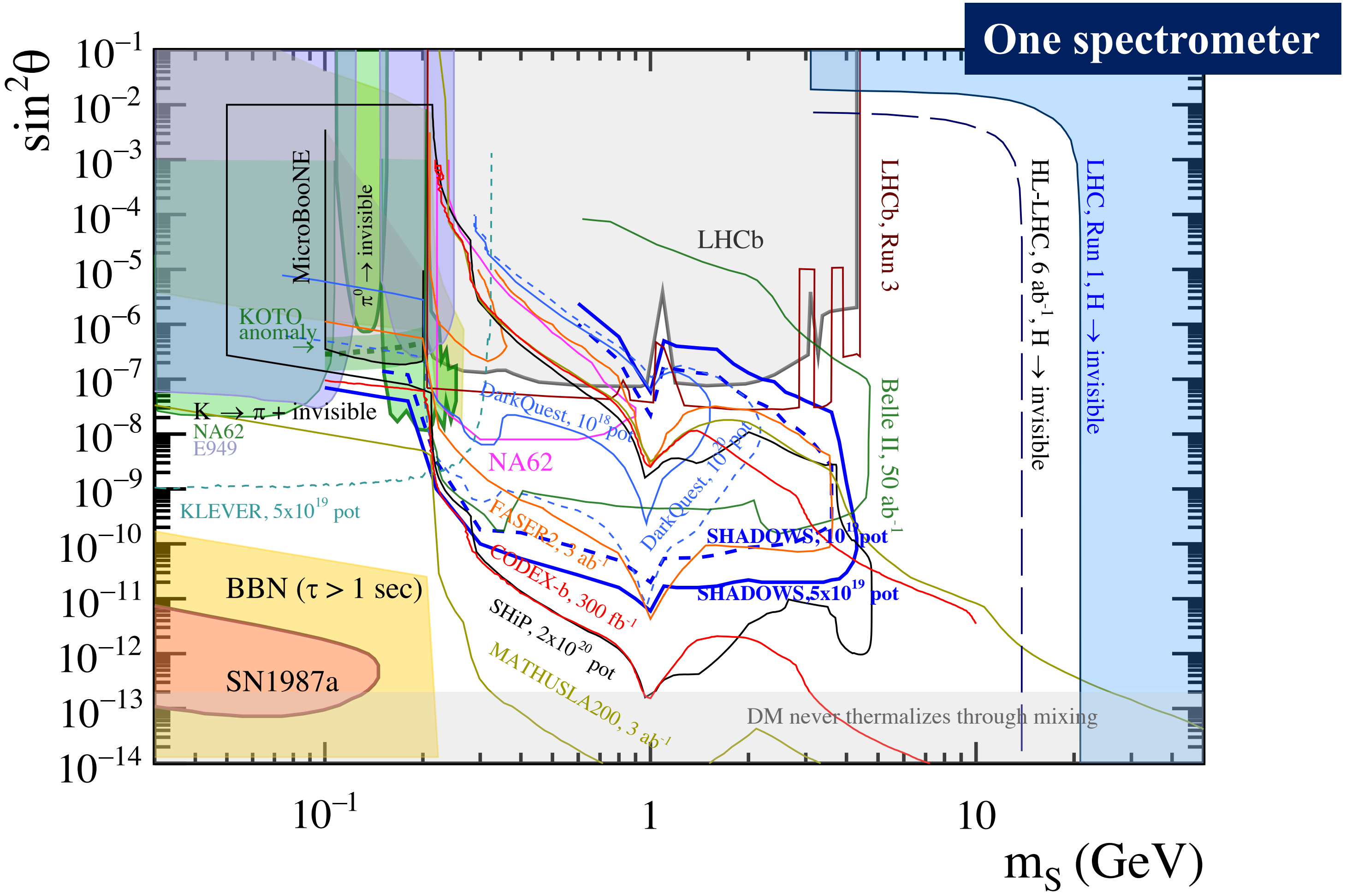


SHADOWS physics sensitivity for some PBC benchmark models

Two scenarios considered:

1) Scenario 1: 10^{19} pot (1 year at x4 intensity or 3 years at nominal NA62 intensity)
2) Scenario 2: 5×10^{19} pot (5 years at x4 intensity or 3 years at x6)

Sensitivity to feebly-interacting Dark Scalars
(SHADOWS with 10^{19} and $5x10^{19}$ pot)

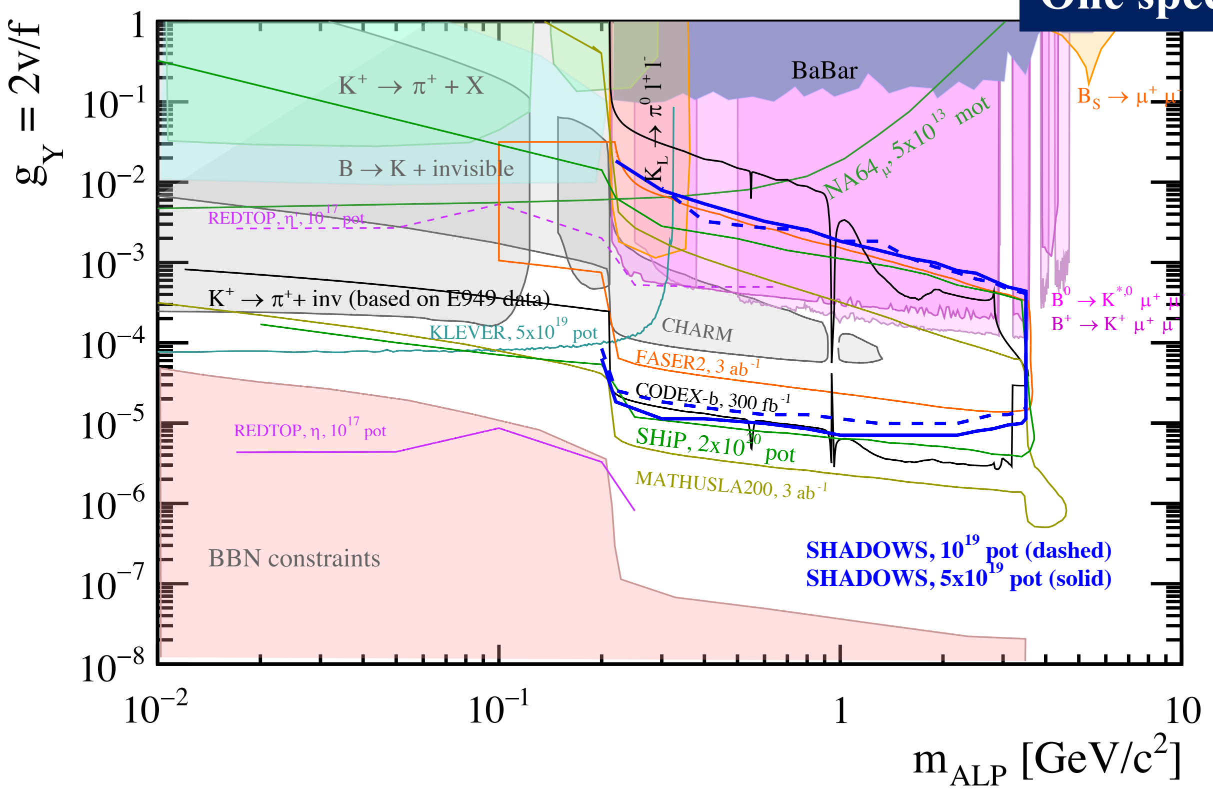


With $5x10^{19}$ pot SHADOWS sensitivity is better than FASER2 ($3ab^{-1}$) and competitive with CODEX-b (300 fb^{-1}) below the B mass and SHiP ($2x10^{20}$ pot)

Sensitivity to feebly-interacting ALPs with fermion coupling

(SHADOWS at 10^{19} and $5x10^{19}$ pot)

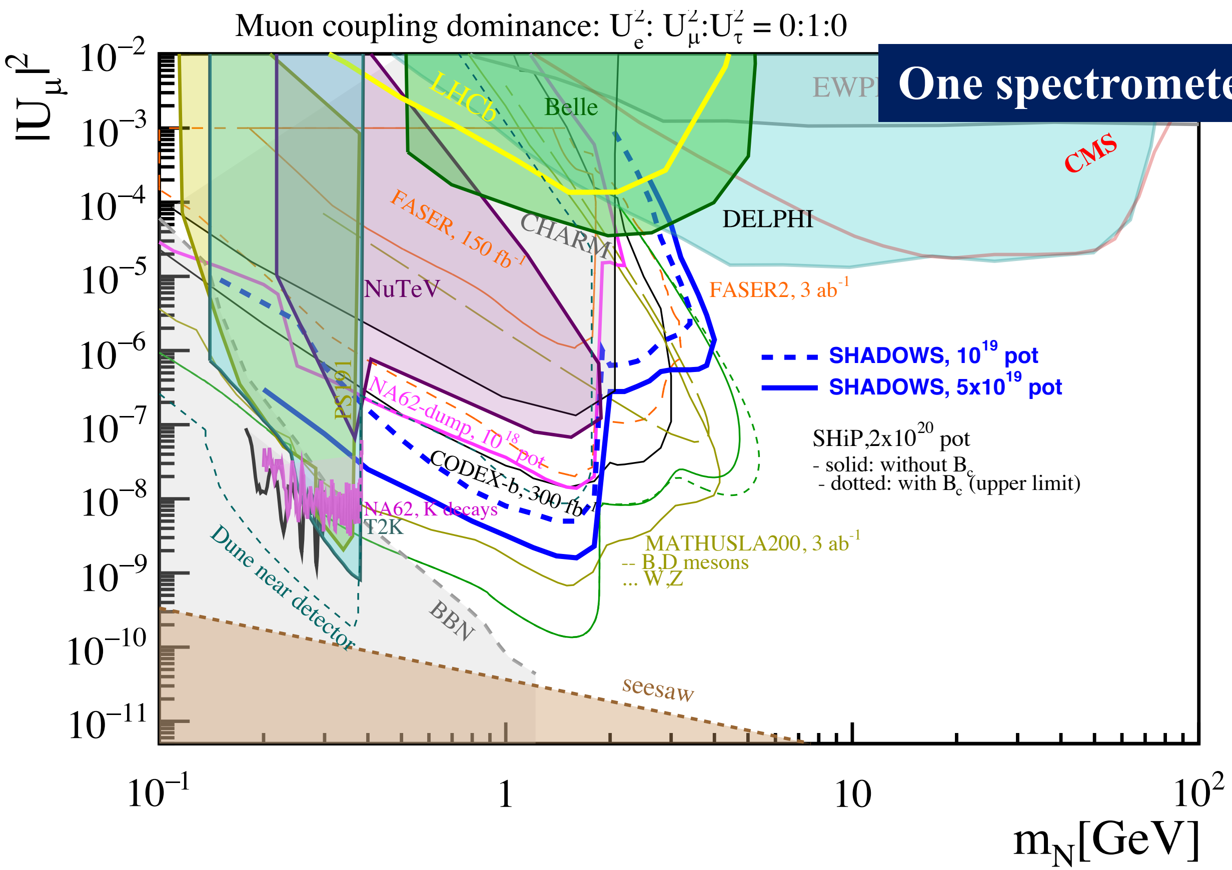
One spectrometer

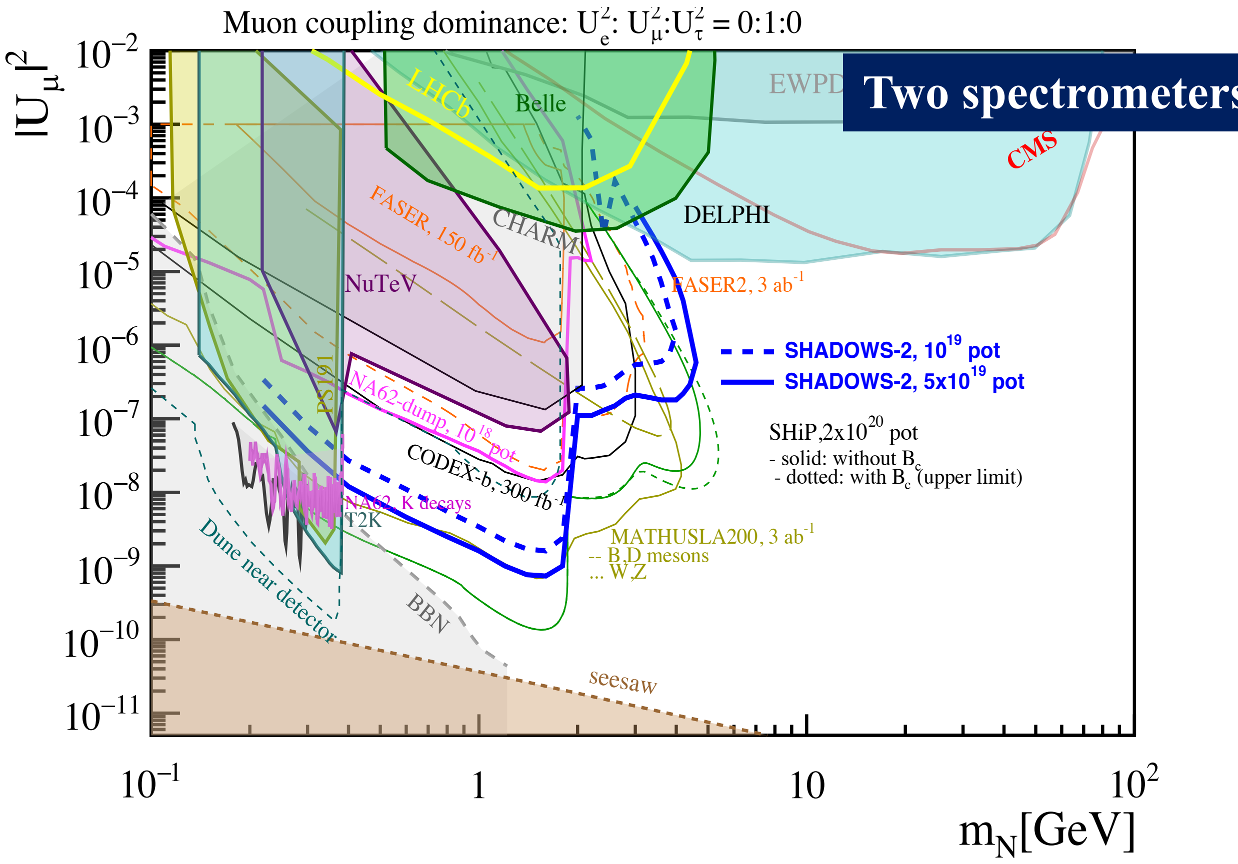


SHADOWS sensitivity is similar to FASER2 (3 ab^{-1}) and CODEX-b (300 fb^{-1}) and for this specific benchmark to SHiP (2x10^{20} pot)

Sensitivity to Heavy Neutral Leptons – coupling to the second lepton generation

(SHADOWS at 10^{19} and $5\text{x}10^{19}$ pot)

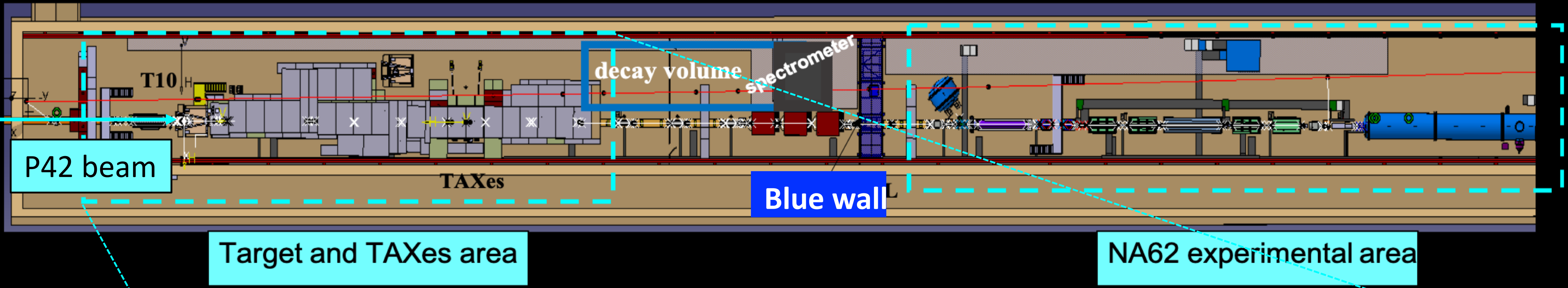


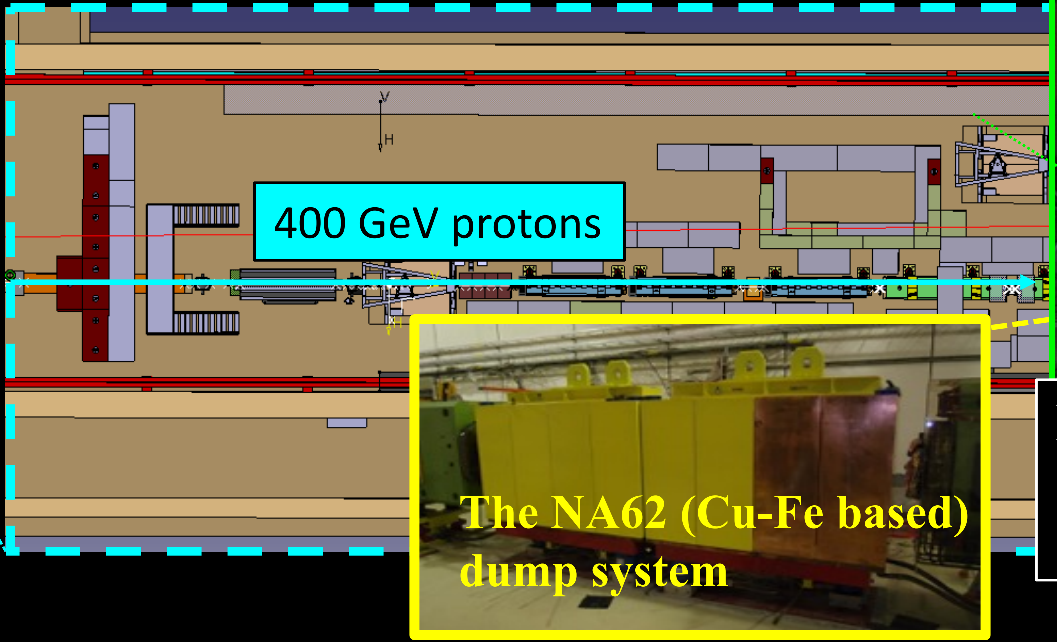


Below the charm threshold, SHADOWS-1 is better than any existing or proposed experiment in same mass range apart MATHUSLA and SHiP. Above the charm threshold and below the b-mass, SHADOWS with one (two) spectrometer(s) allows us to improve the current bounds by 2.0 (2.5) orders of magnitude.

The beam-induced background:
the name of the game

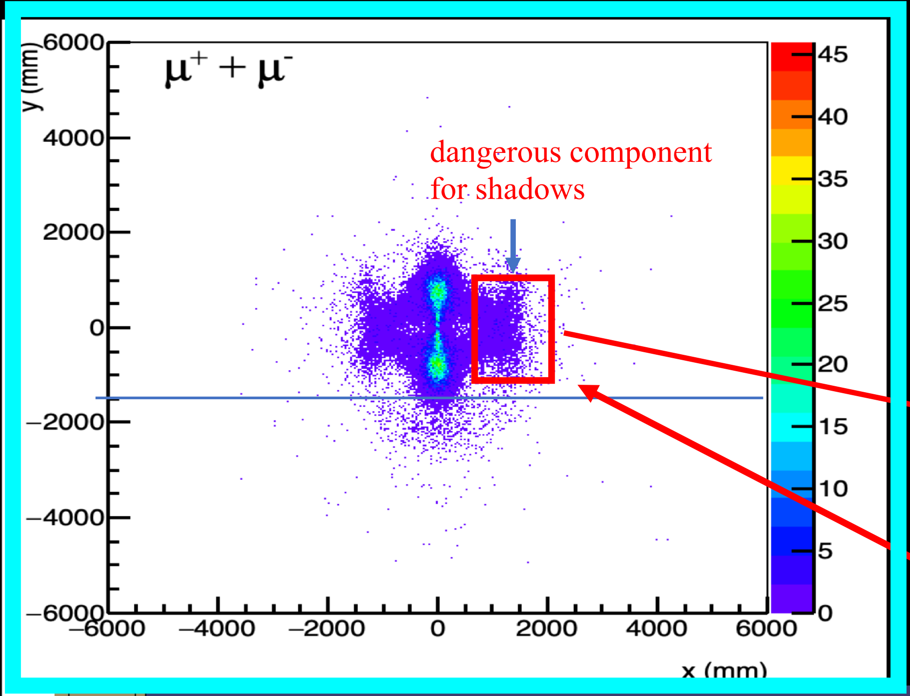
The beam-induced background:

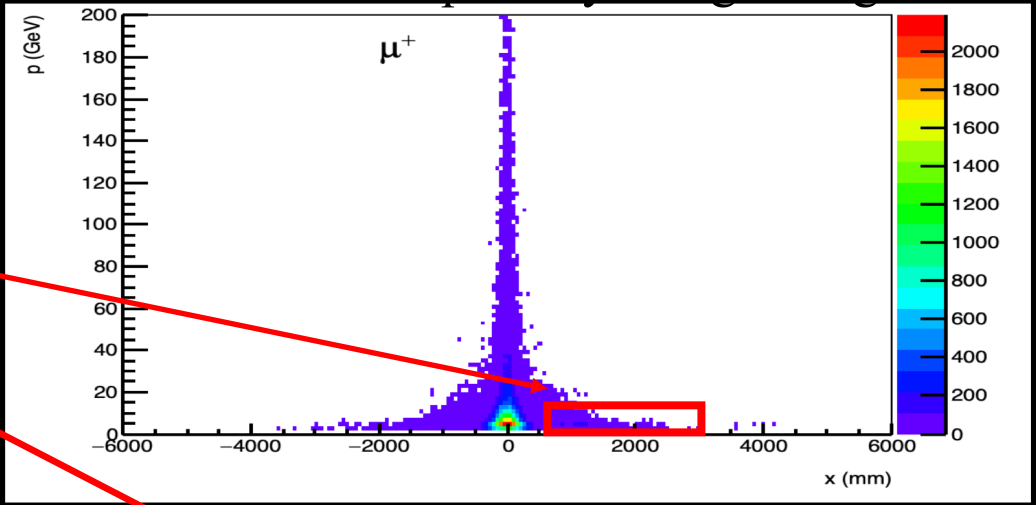


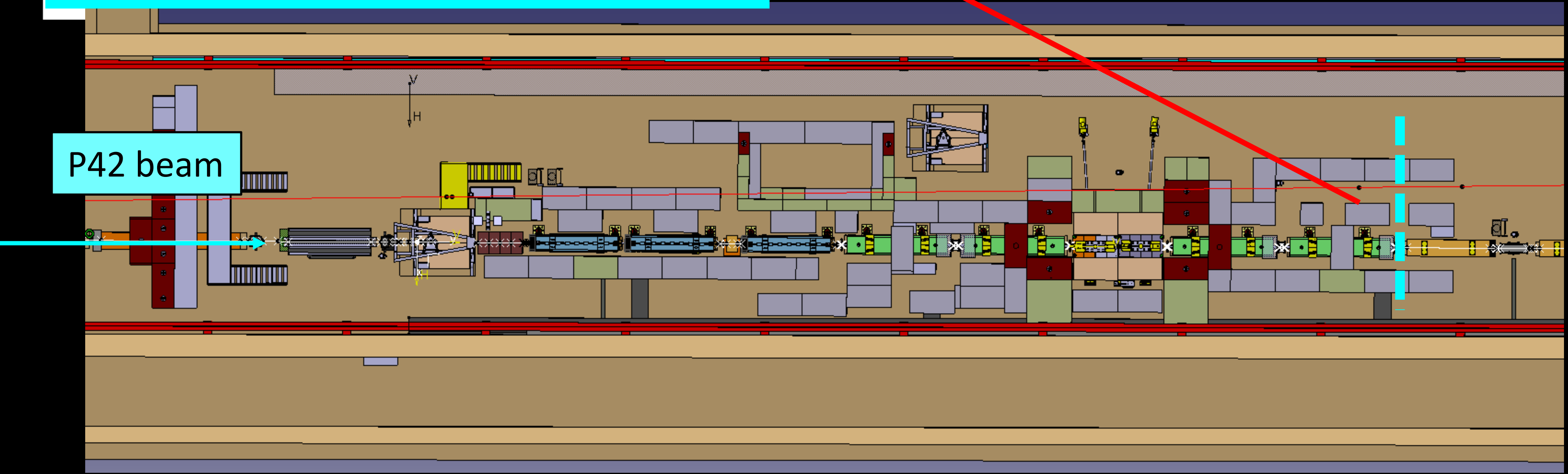


Background by far dominated by muons (neutrinos not a problem for an off-axis detector)

Simulated muon background illumination



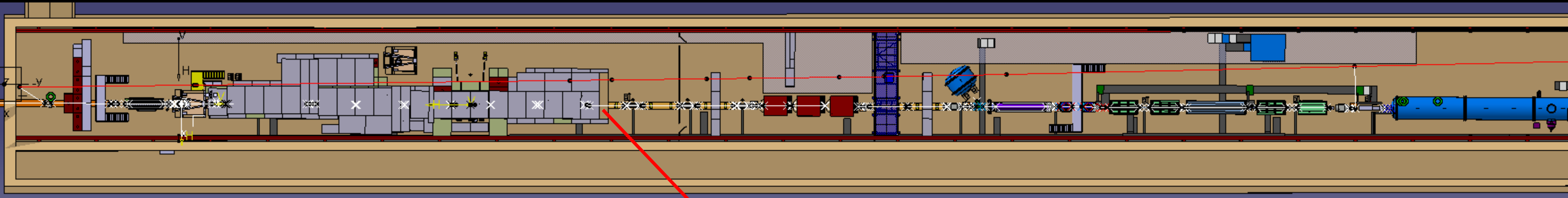


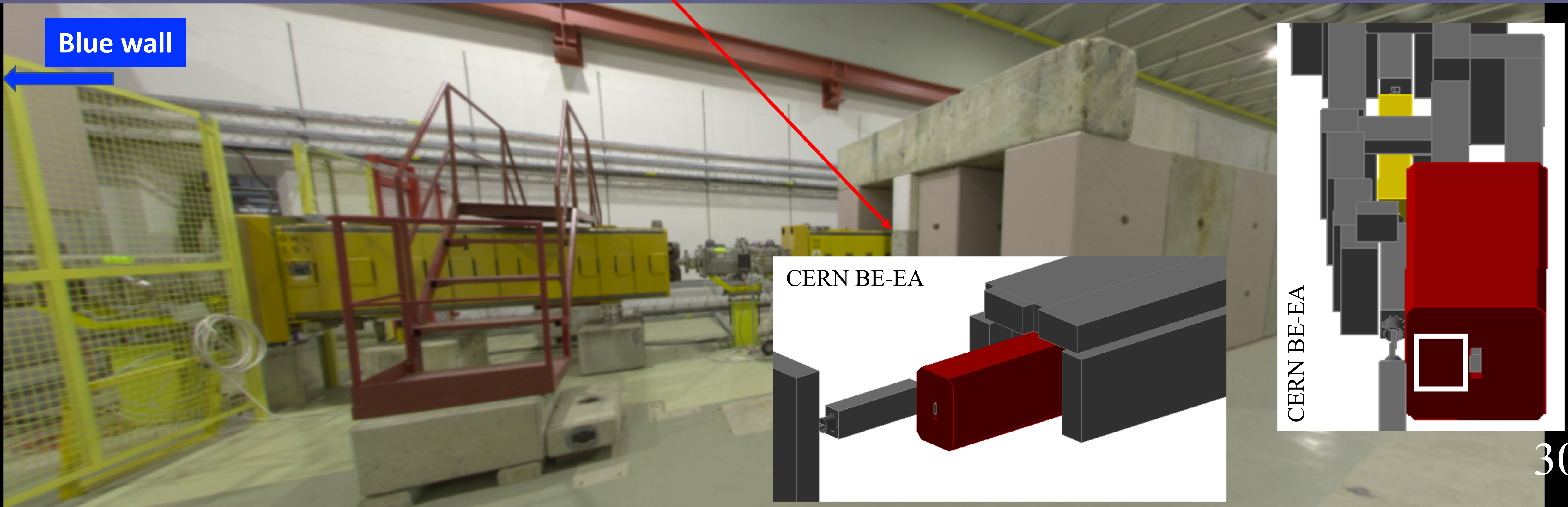


SHADOWS muon sweeping system:

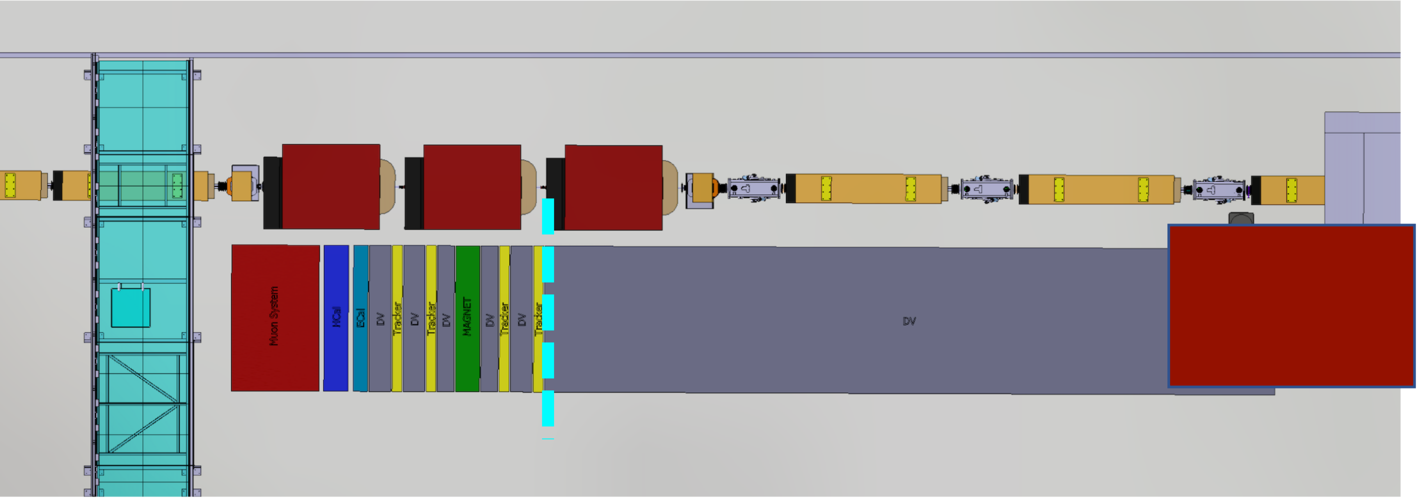
A magnetized iron block as part of the TAX shielding structure

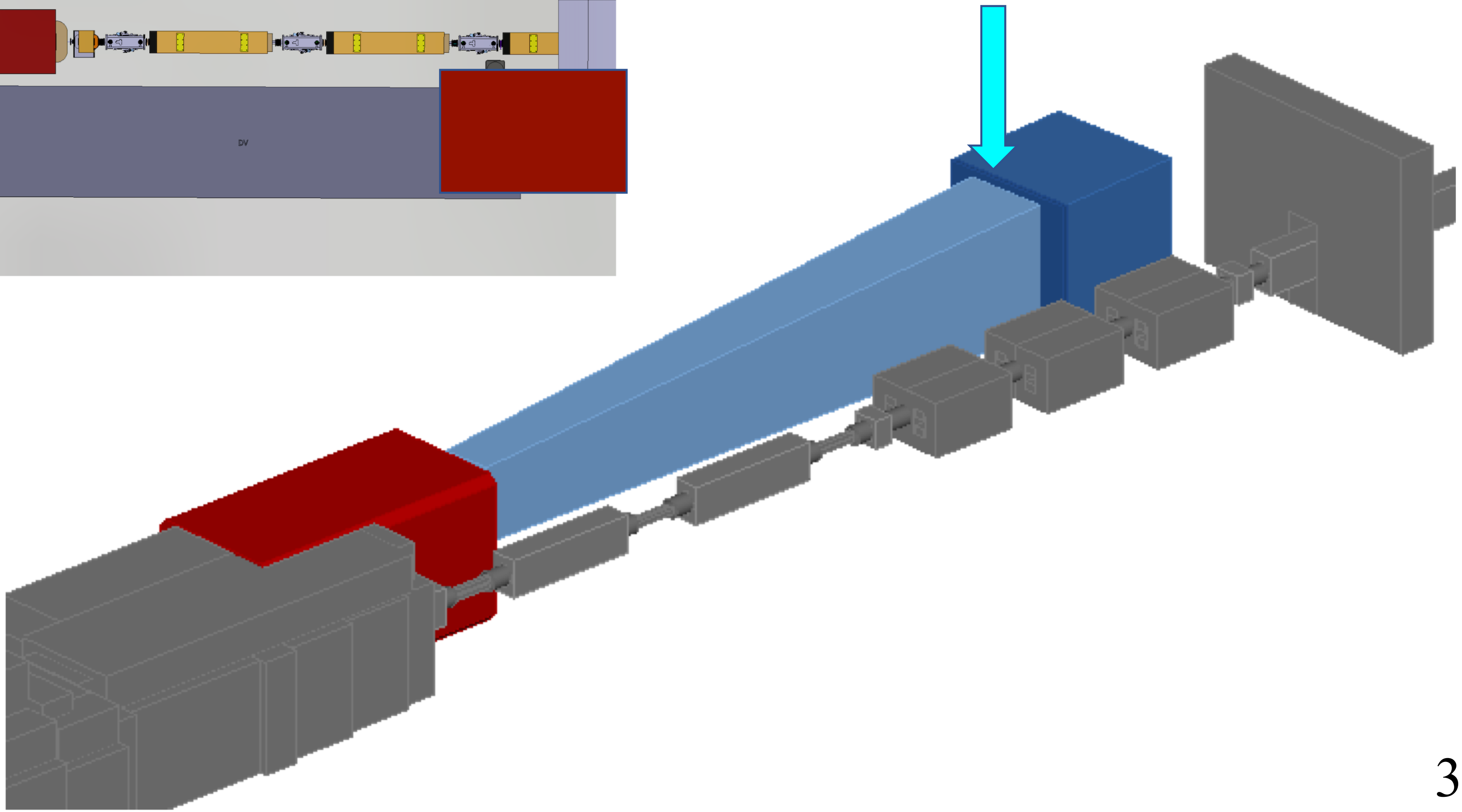
(currently studied in CERN BE-EA-LE group)





Background illumination at the SHADOWS spectrometer





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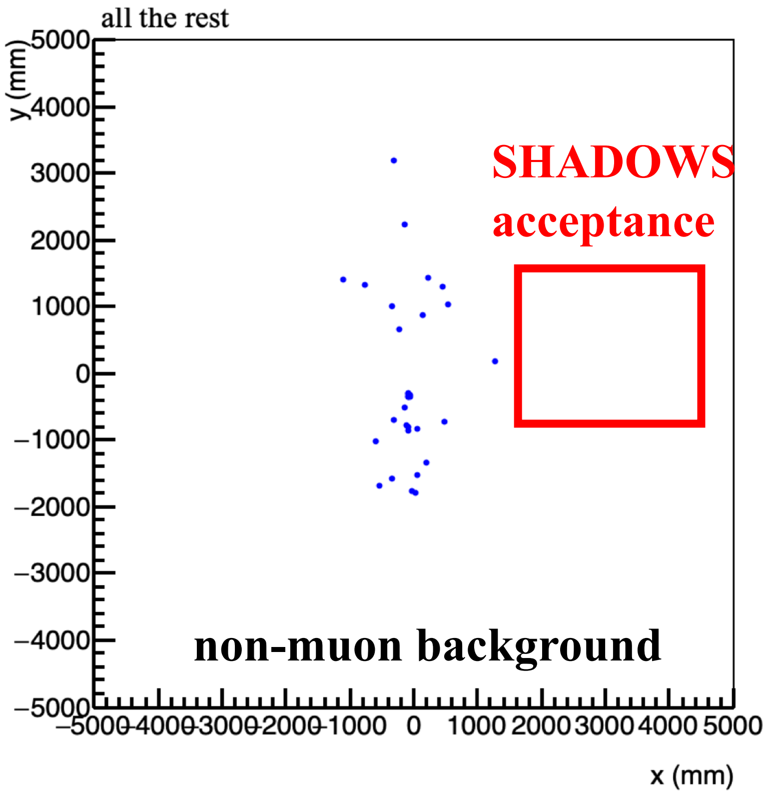
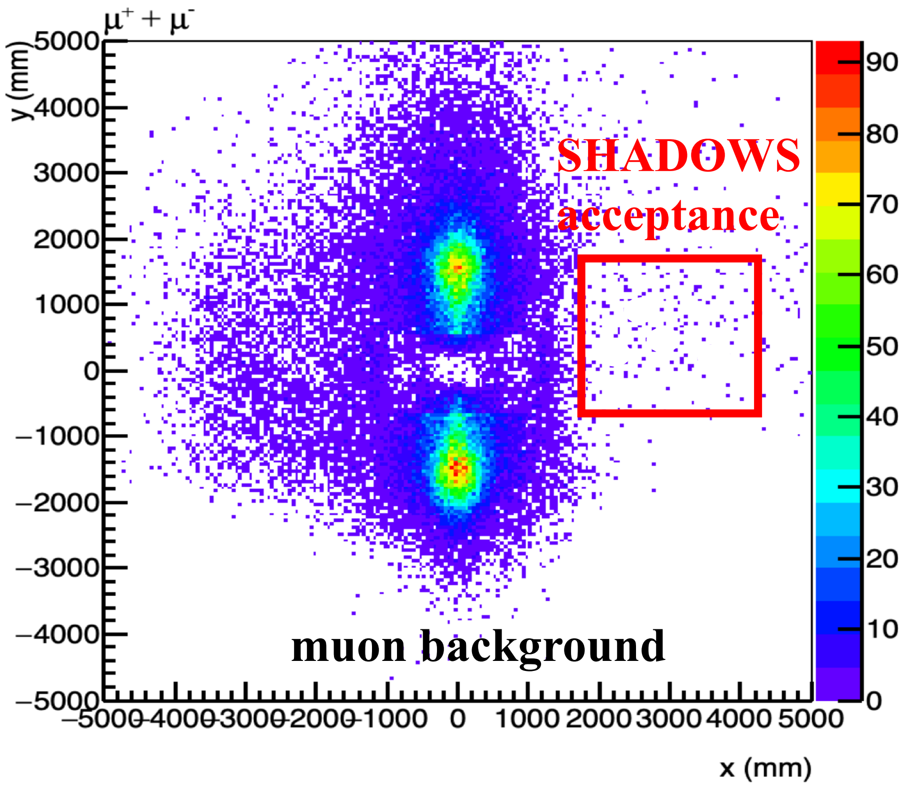
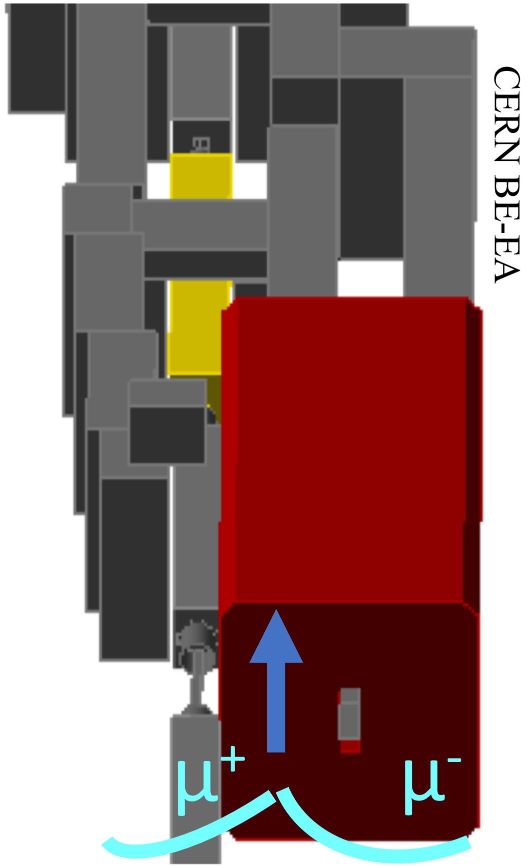


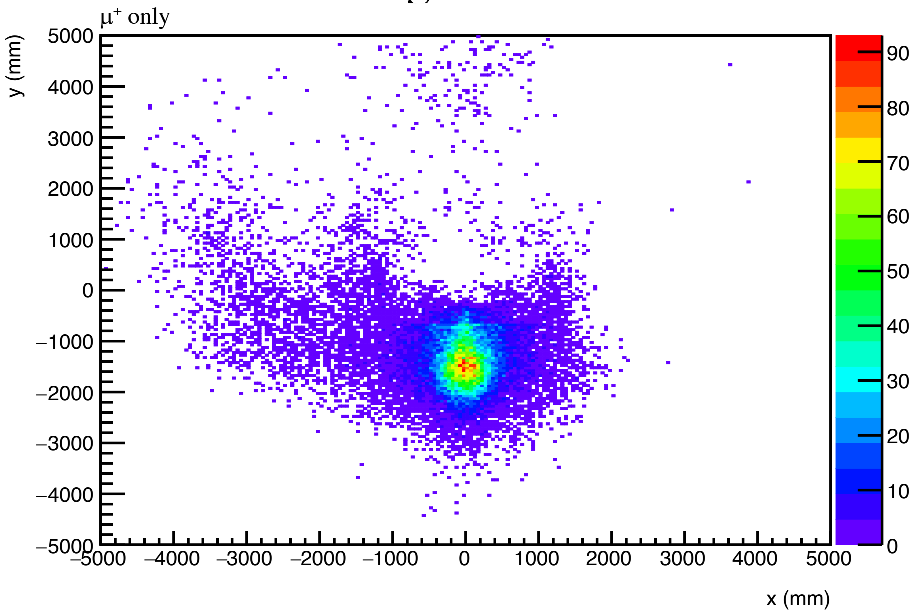


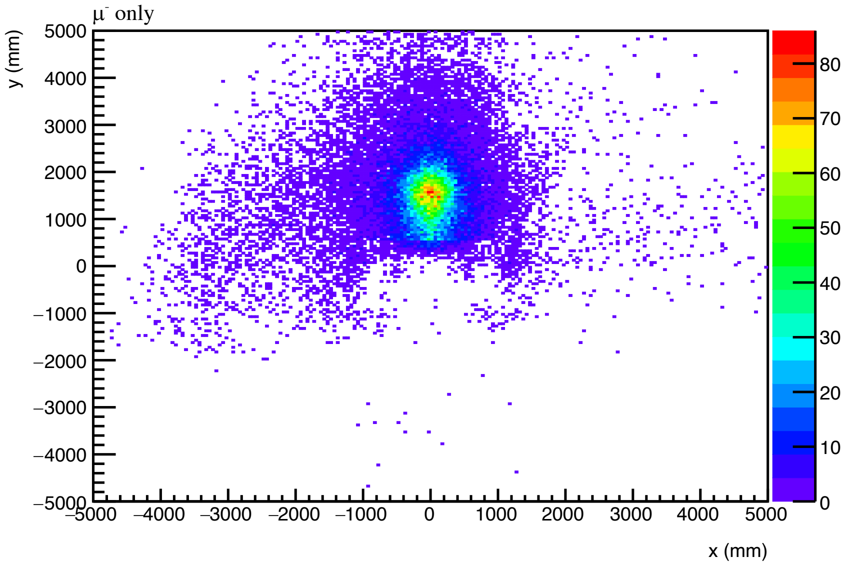


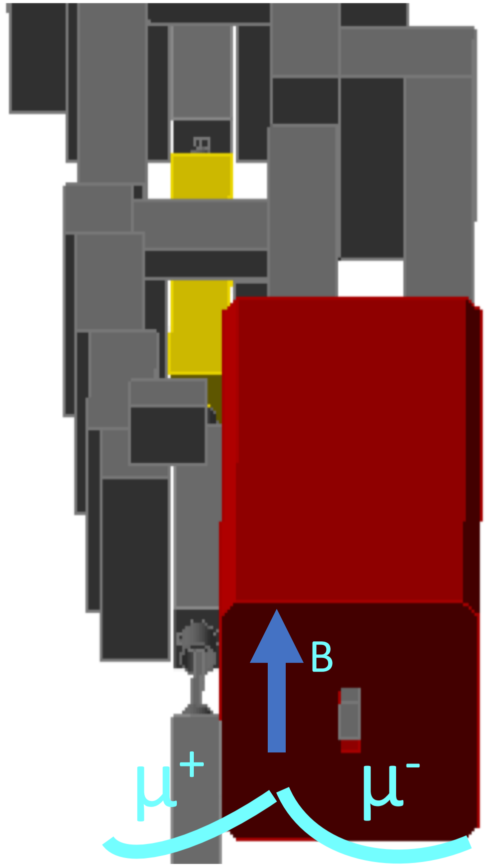
- ➢ All background components found negligible but the muon one.
- ➢ The muon background is reduced by already an order of magnitude in a first attempt by the magnetized iron block, Work in progress to further reduce it.

SHADOWS muon sweeping system: The Magnetized Iron Block (MIB)

Background illumination at the SHADOWS spectrometer

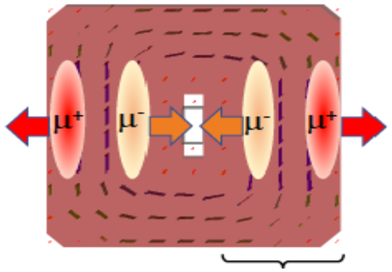






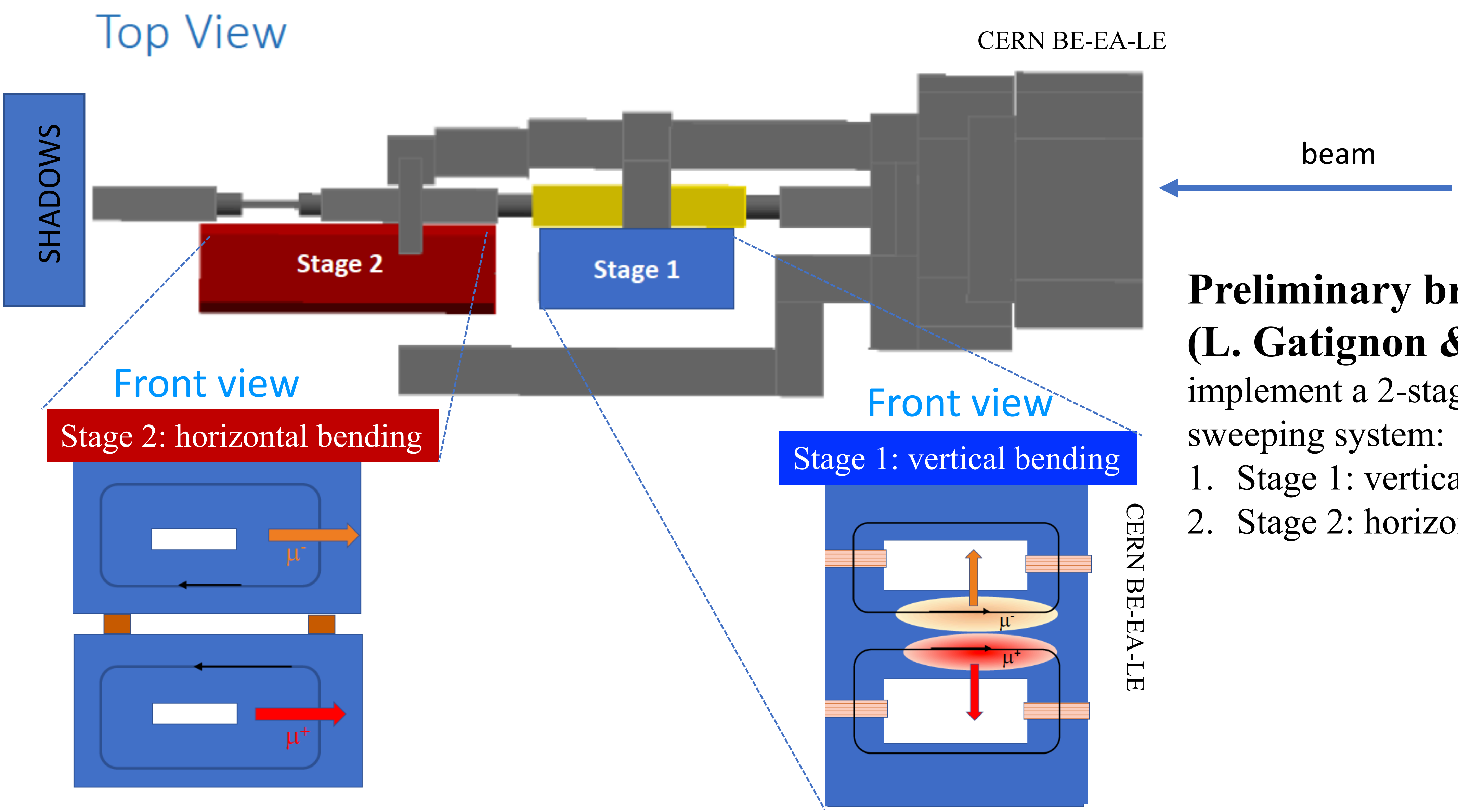
CERN BE-EA-LE

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

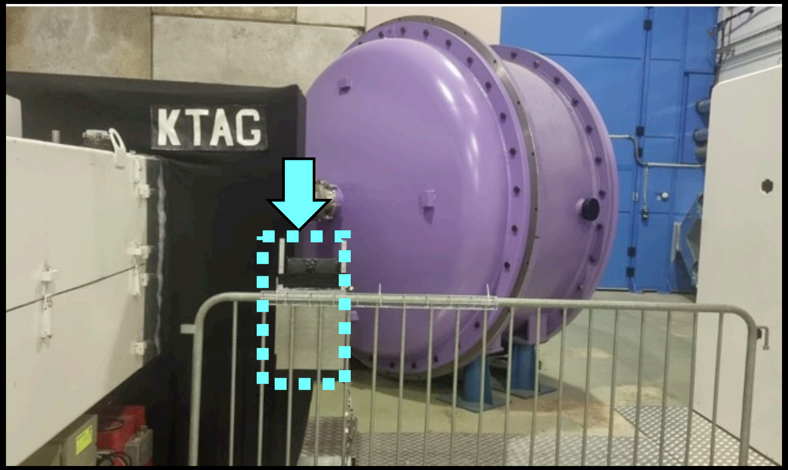
SHADOWS muon sweeping system: The Magnetized Iron Block (MIB)

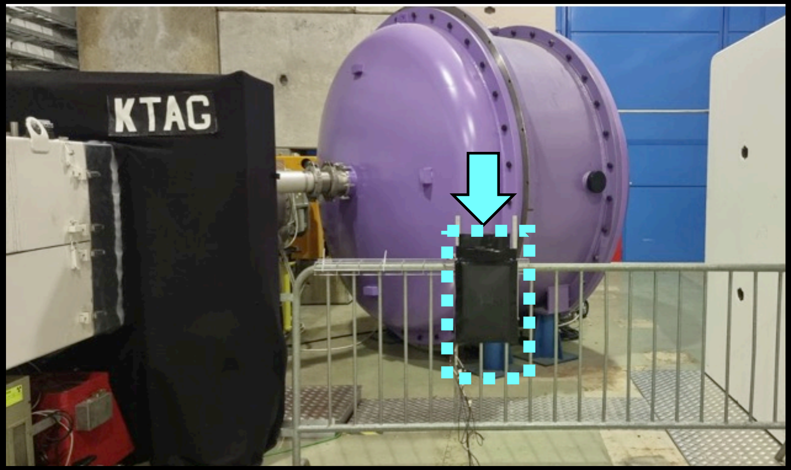


Preliminary brilliant solution (L. Gatignon & BE-EA-LE):
implement a 2-stage sweeping system:

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

First campaign of measurements off-axis during the 1-week long NA62 run in dump done in October. ...



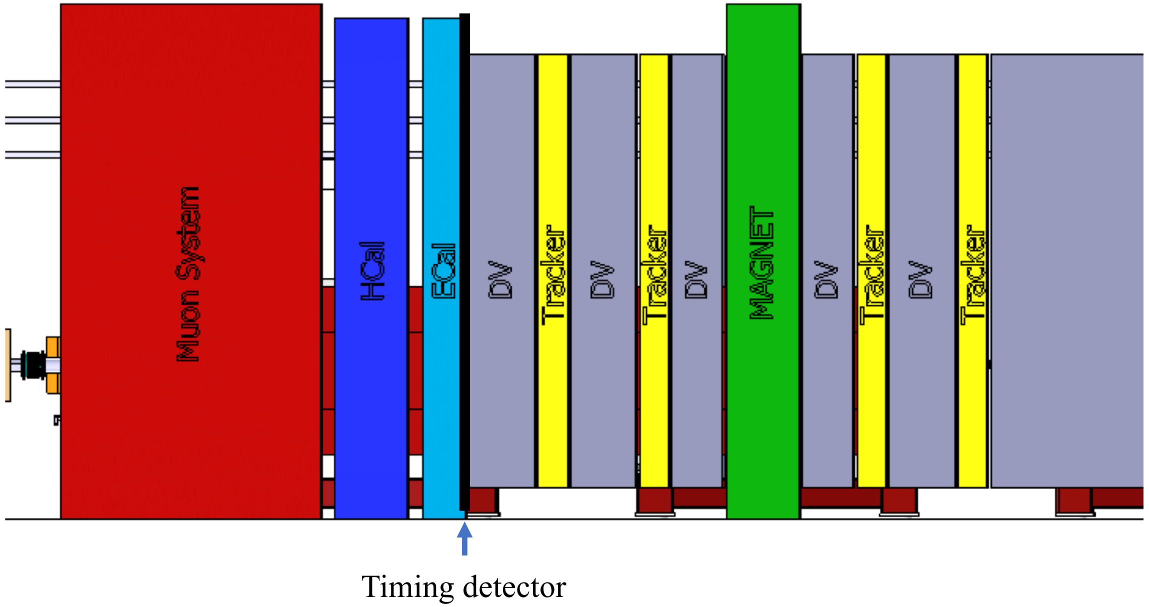


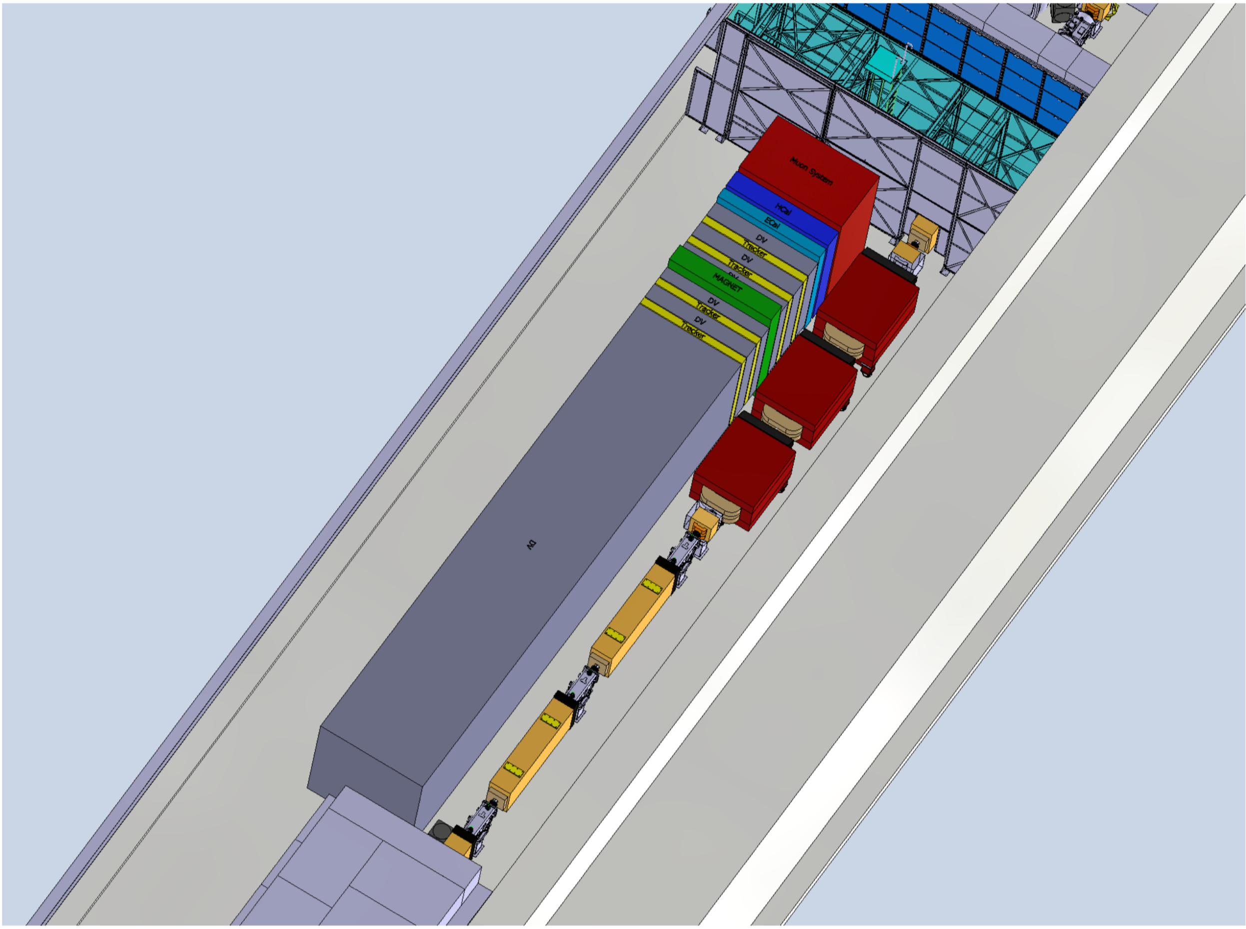
Position (from beam center to tile center) [cm]	Run	Bursts & Burst number	POT/burst	Pot (total)
100	11092	136 (from 1 to 136)	6.4×10^{12}	8.7×10^{14}
220	11094	117 (from 258 to 375)	6.4×10^{12}	7.5×10^{15}
340	11092	1364 (from 136 to 1500)	6.4×10^{12}	8.7×10^{15}

…Useful to cross-check simulation..

The detector

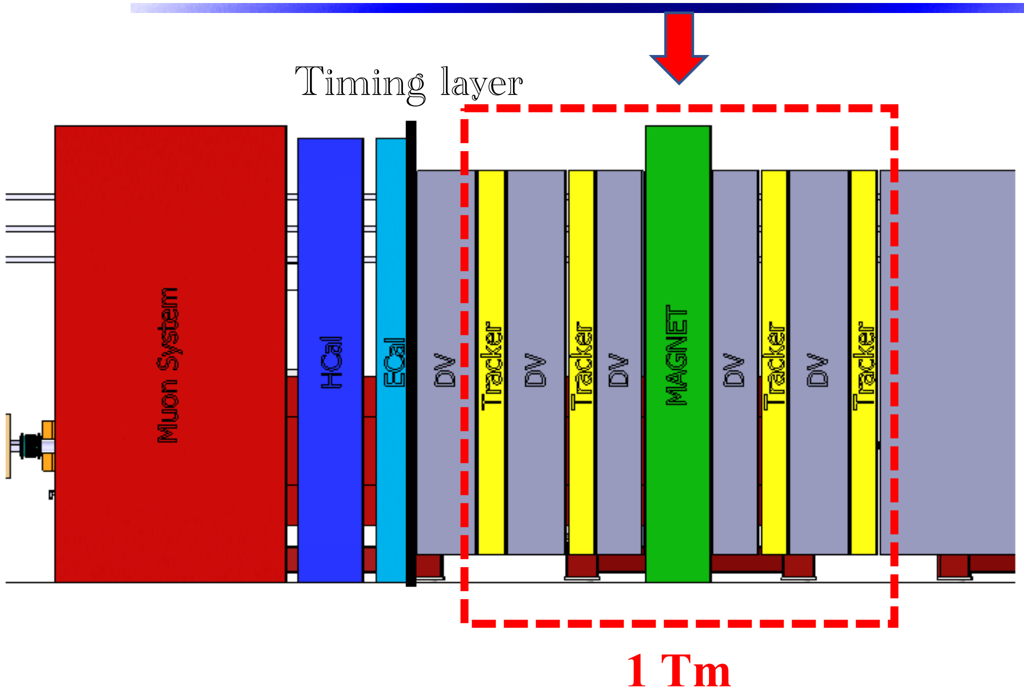
SHADOWS: A standard spectrometer



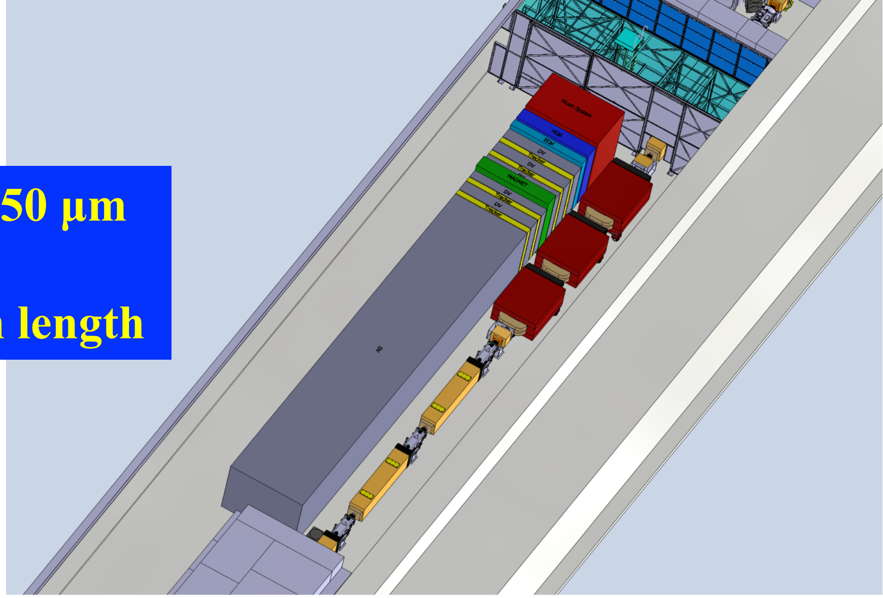


<u>Important message:</u> SHADOWS can be built with <u>existing technologies.</u>
R&D on new technologies is welcome but is not absolutely needed
More than one option per subdetector is already available on the market.
Preliminary contacts with many groups ongoing.

SHADOWS Tracker: requirements & layout



single plane resolution: 250 µm
vertex resolution:
σ (x,y) ~ 1 cm over 20 m length



Dipole magnet and Tracker : design driven by resolution on decay vertex

p [GeV]	Vxy [mm]	Vz [mm]	ro (m)	theta (rad)	σp/p [%]
1	10.6	500.0	3.33	0.46677	0.2
2	10.6	500.0	6.67	0.22694	0.4
5	10.6	500.0	16.67	0.09012	1.1
10	10.6	500.0	33.33	0.04502	2.2
20	10.6	500.0	66.67	0.02250	4.4
50	10.6	500.0	166.67	0.00900	11.1
100	10.6	500.0	333.33	0.00450	22.2
200	10.6	500.0	666.67	0.00225	44.4

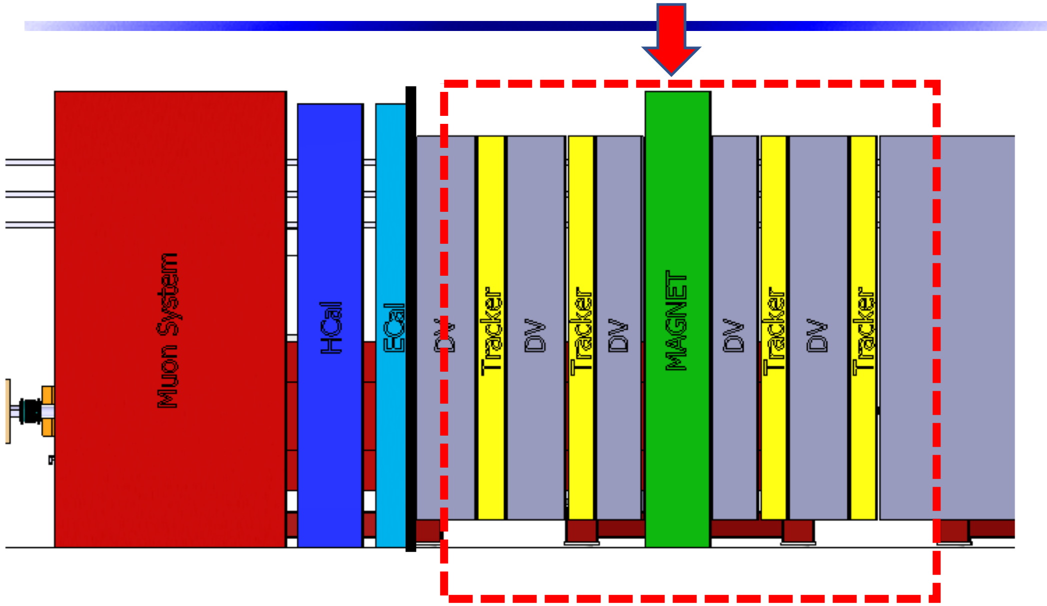
Notes:

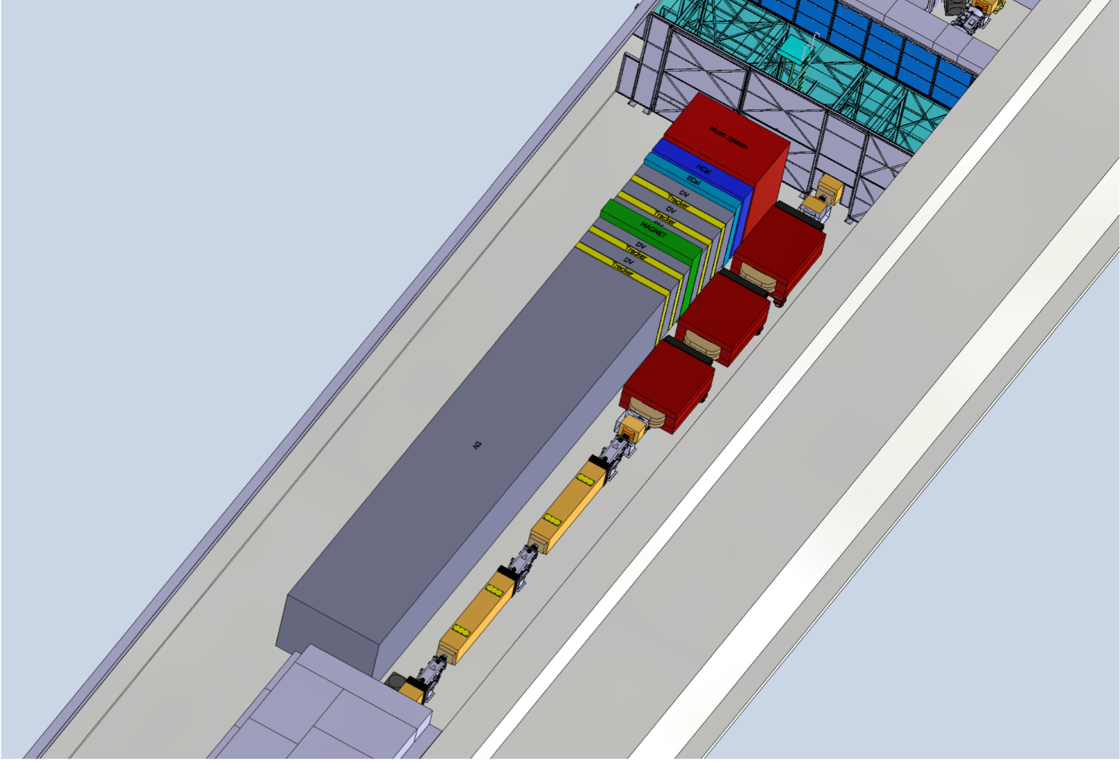
Vxy	Vertex X and Y resolution at the far end of Decay Volume
Vz	Vertex Z resolution at the far end of Decay Volume
ro	Curvature radius inside B field
theta	Angle of curvature inside B field (Result inaccurate for theta >~ 0.1)
σp/p	Relative momentum resolution

Assumptions:
B field uniform in L2 gap
L1 == L3, outside of field
No scattering
Valid for small angles only

Key Parameters:		
B field	1	T
Single plane resolution	0.25	mm
L1/L3	500	mm
L2	1500	mm
Decay Volume (before L1)	15000	mm
Average track angle w.r.t. z-axis	15	mrad

SHADOWS Tracker: possible technologies





Possible options:

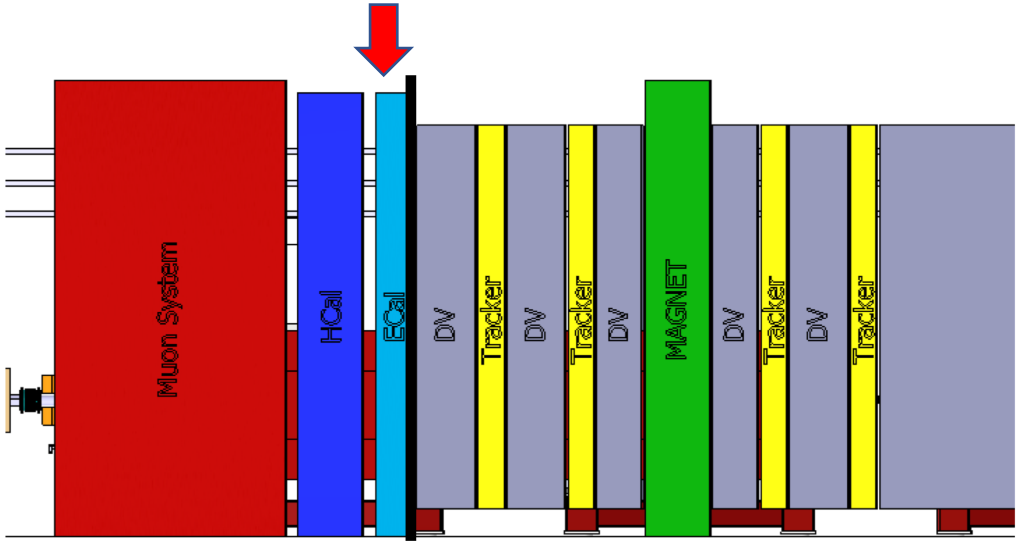
1. NA62 STRAW tubes: Ar(70%): CO_2 (30%), in vacuum, 5mm diameter; Single plane resolution:
One straw chamber is composed of four views (X, Y, U, V), one double-layer per view. Hit resolution better 400 um over Most of the straw diameter per single layer, 8 layers per tracking station. Warm dipole magnet 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 length.

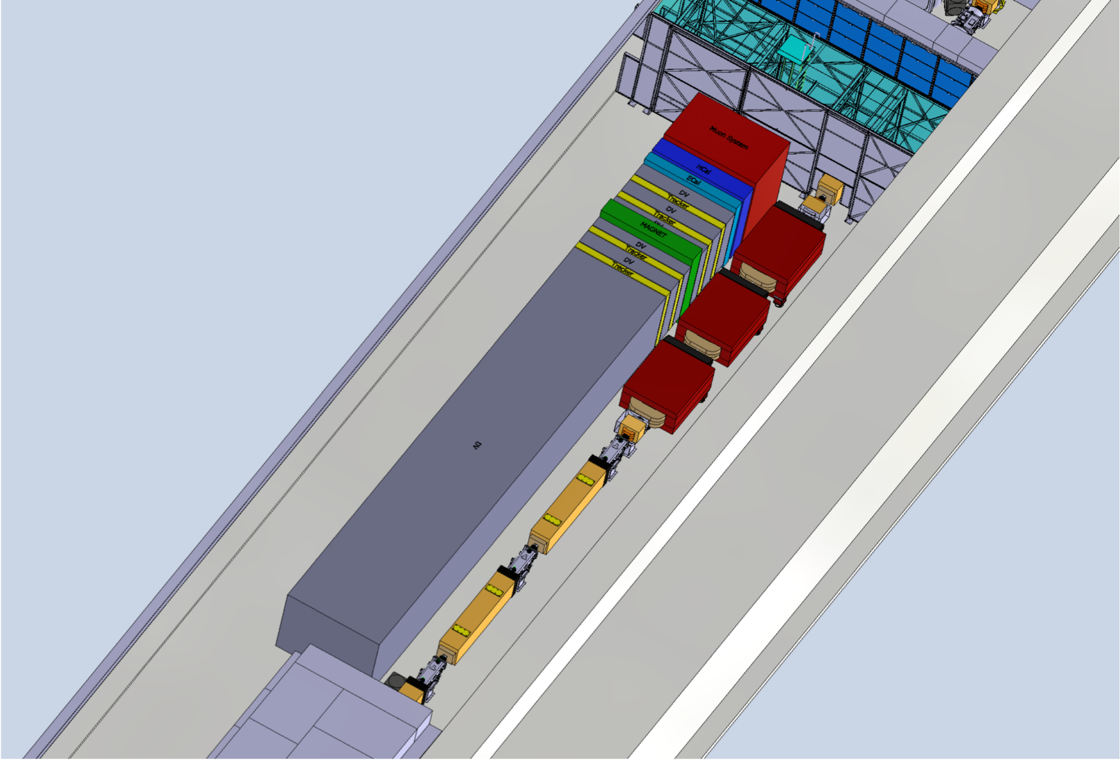
2. LHCb Outer Tracker - like gas-tight straw-tube modules. Ar(70%): CO_2 (30%).
Each module contains two staggered layers of drift-tubes with inner diameters of 4.9 mm.
Drift-coordinate resolution (200μm). 4 Tm bending magnet.

3. Fibre Tracker (LHCb upgrade phase 1): 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.

4. Micromegas…

SHADOWS: Electromagnetic calorimeter





Possible options:

1. Shashlik LHCb ECAL modules: maybe option to recuperate 172 LHCb ECAL modules to be replaced at LS3.

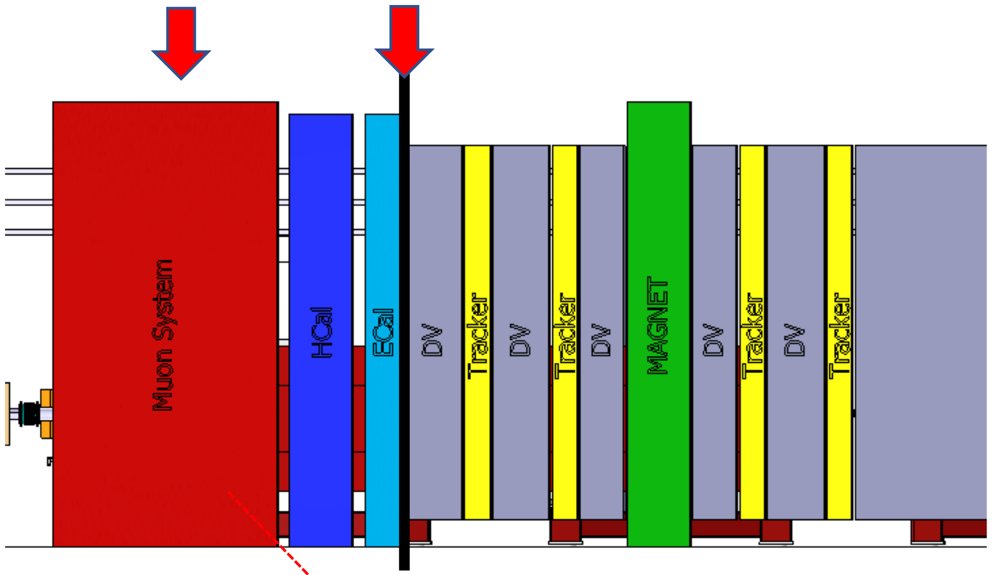
2. PbWO4 crystals from CMS ECAL endcaps – will be removed during LS3. Some reconditioning will be needed but a large fraction of crystals could be ready to be used.

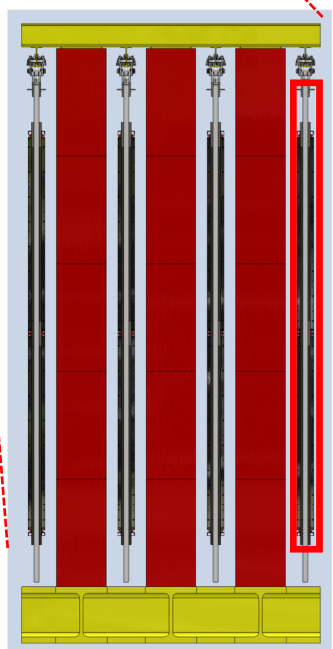
3. SHiP EM calorimeter – SplitCal concept. longitudinally segmented lead sampling calorimeter with a total sampling depth of $20X_0$. Sampling layers are scintillating plastic bars read-out by WLS fibres with a relatively coarse spatial segmentation. Three sampling layers (located at the depth of the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

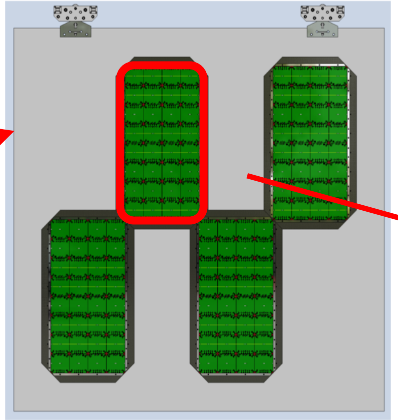
SHADOWS: The Muon Detector (& perhaps timing layer)

INFN (Frascati, Bologna, Ferrara)

Baseline: scintillating tiles with direct SiPM readout.
Advantages: modular, cost-effective, high-efficiency, large light yield, high time resolution.

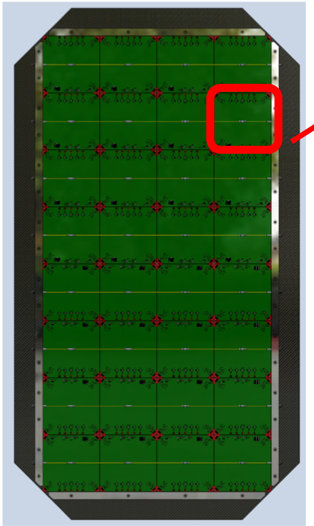


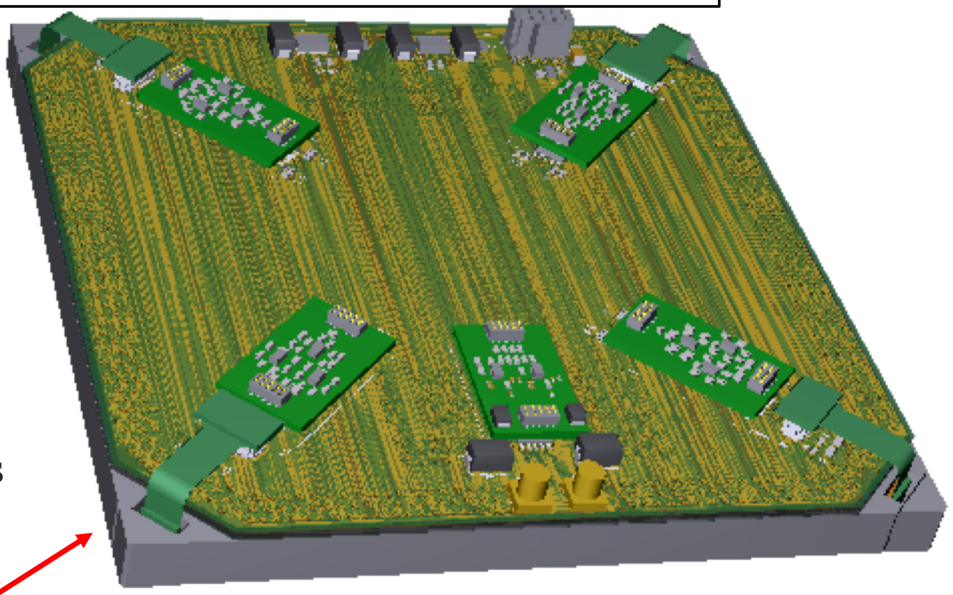




1 station = 8 modules
[same pattern staggered
on the other side of the wall]

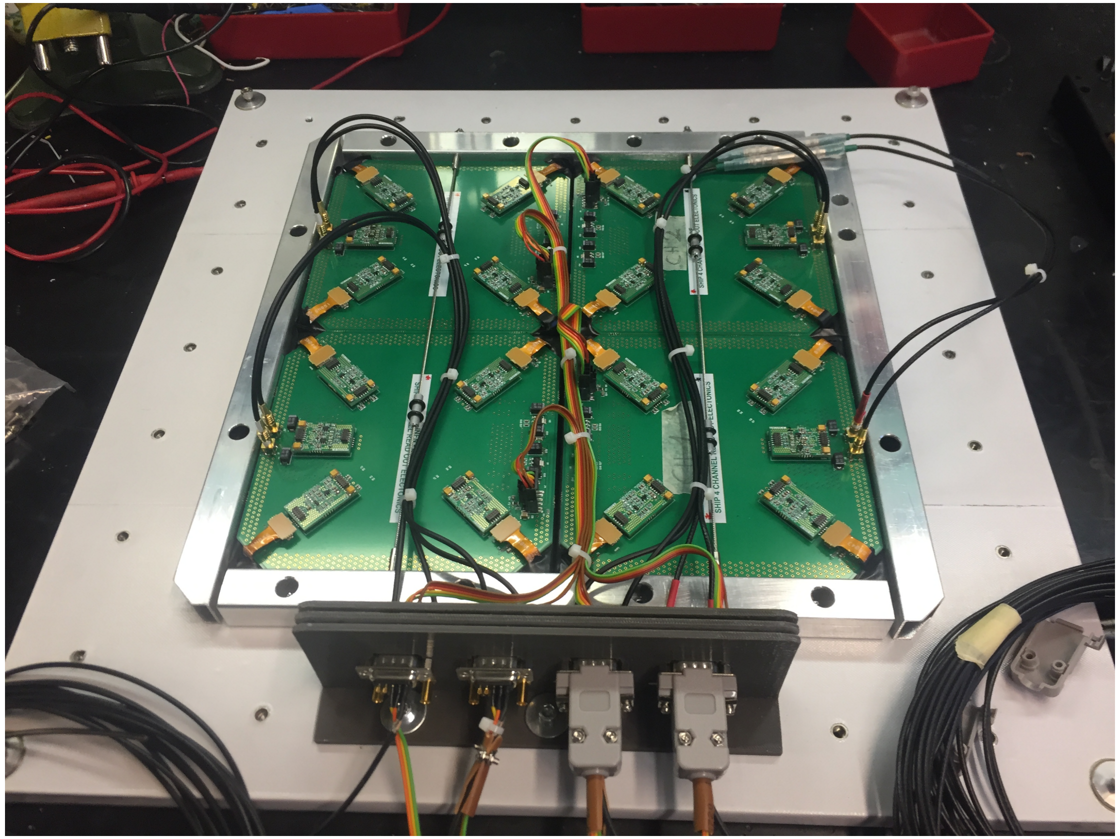
1 module = 32 tiles





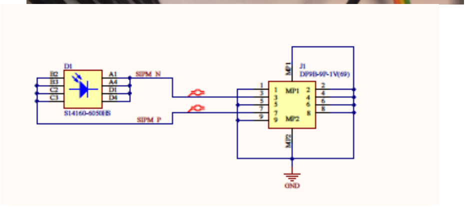
1 tile = 15x15 cm2,
Direct SiPM readout at the corners
One analog output per tile

SHADOWS: The Muon Detector (& perhaps timing layer)



4-tile prototype built in INFN Bologna/LNF

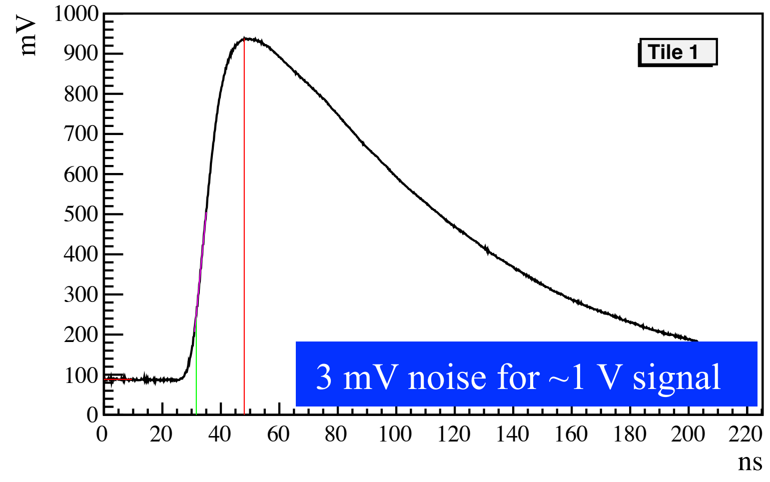
Efficiency > 99.5%
N(p.e.)/MIP = 250
σ(t) ~ 290 ps



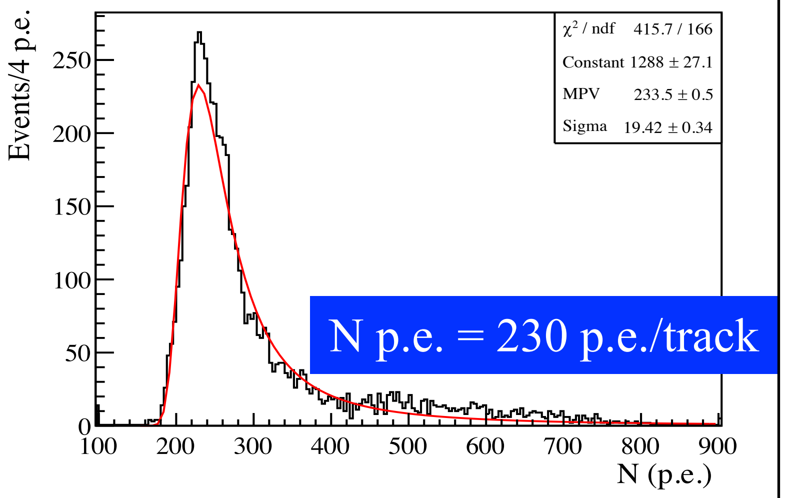
- Optic glue refractive index matches matches well with EJ200 scintillator.
- SiPM slot is still slightly visible in Russian scintillator.

SHADOWS: The Muon Detector

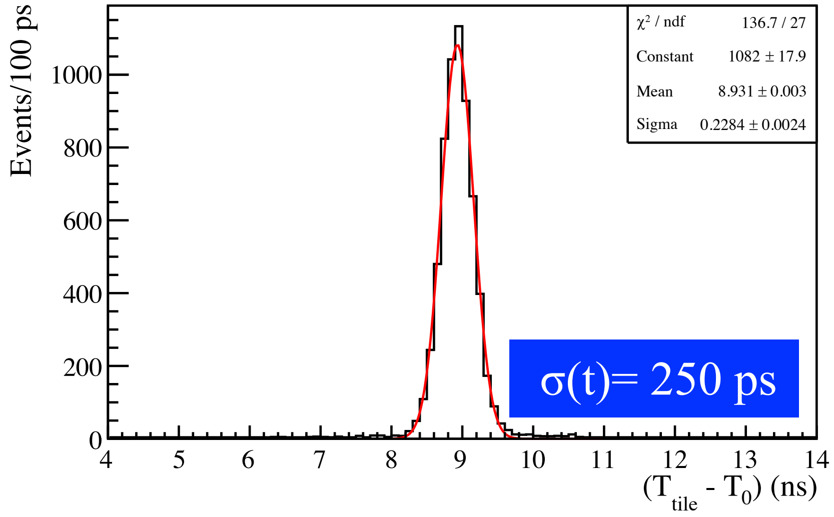
Waveform



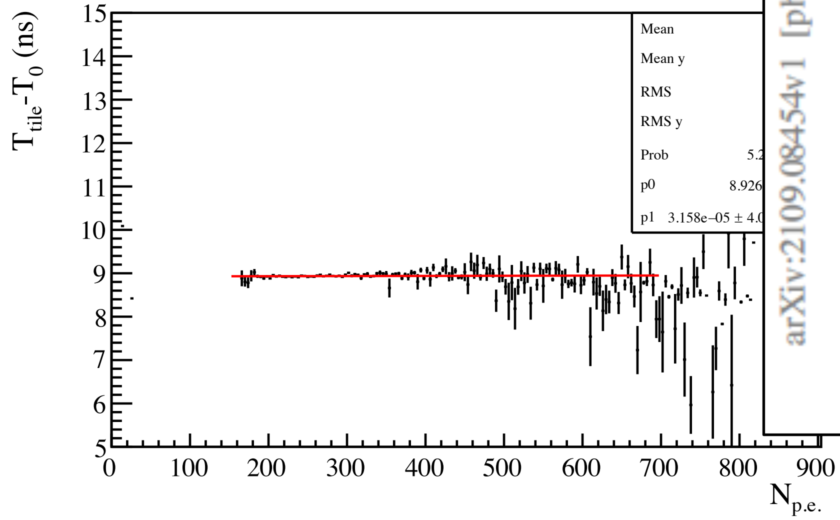
Charge spectrum



Time resolution



Arrival time independent on position



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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[b] INFN - Sezione di Bologna, Viale Berti Pichat, 6/2, 40127 Bologna, Italy
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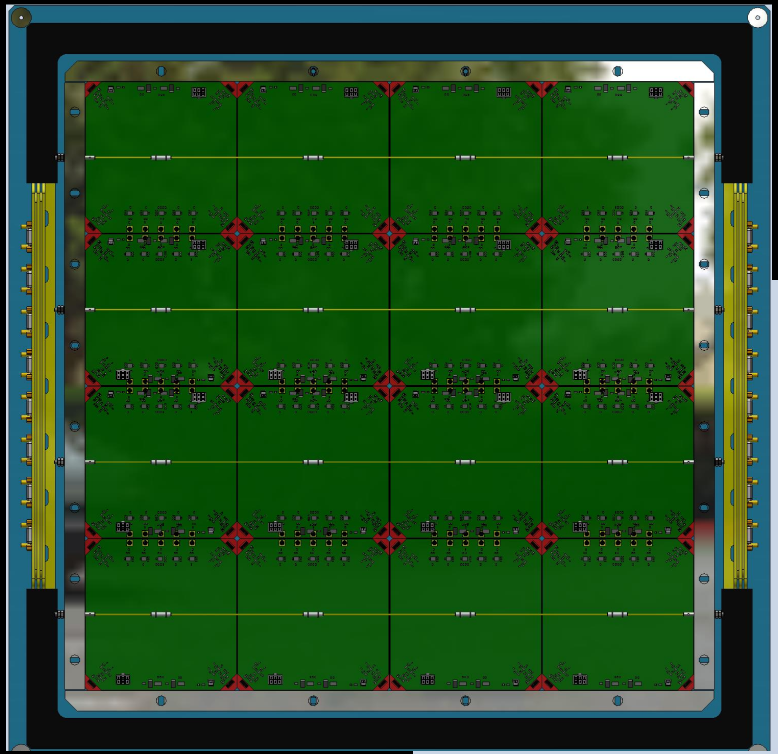
Abstract: The light yield, the time resolution and the efficiency of different types of scintillating tiles with direct Silicon Photomultiplier readout and instrumented with a customised front-end electronics have been measured at the Beam Test Facility of Laboratori Nazionali di Frascati and several 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

SHADOWS MUON: Full scale module

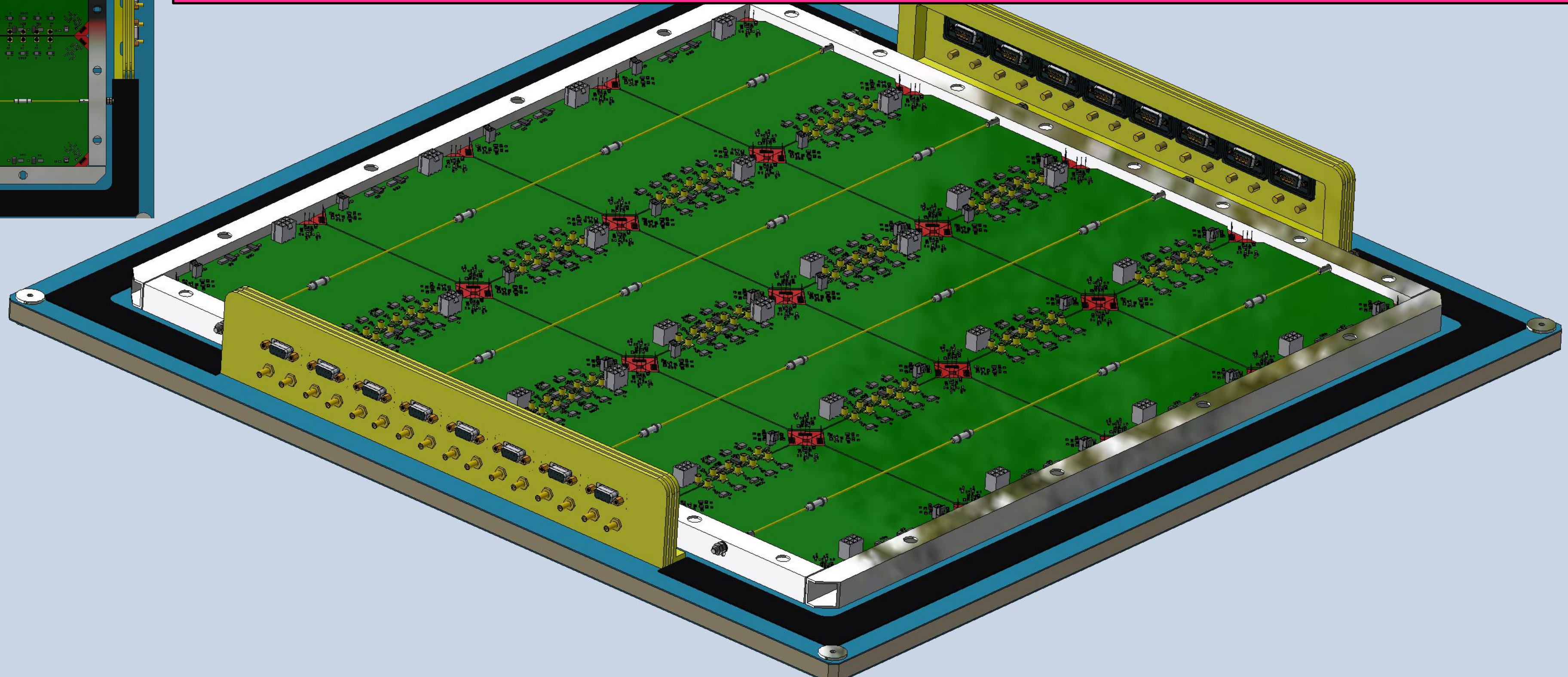


AIDA-Innova (task 8.3.2)
Large area scintillator detectors

Goal: build, instrument, and test a 16 tile module equipped with front-end and middle-end electronics

Asked 52 kEuro to INFN, ~20 kEuro already granted in 2021, the rest in 2022

LNF, Bologna, Ferrara, Resp.: A. Montanari (Bologna)



SHADOWS Expression of Interest

(arXiv:2110.08025, to appear on CERN CDS)

SHADOWS Proponents so far

W. Baldini, A. Balla, J. Bernhard, A. Calcaterra, V. Cafaro, A. Ceccucci,V. Cicero, P. Ciambrone, H. Danielsson, G. D'Alessandro, G. Felici, L. Gatignon, A. Gerbershagen, V. Giordano, G. Lanfranchi, A. Montanari, A. Paoloni, G. Papalino, T. Rovelli, A. Saputi, S. Schuchmann, F. Stummer, N. Tosi.

CERN, INFN-LNF, INFN-Bologna, INFN-Ferrara, Mainz U. (D), Vienna U. (A), CERN, Lancaster U (UK).

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

SHADOWS

Search for Hidden And Dark Objects With the SPS

Expression of Interest

W. Baldini[(1)], A. Balla[(2)], J. Bernhard[(3)], A. Calcaterra[(2)], V. Cafaro[(4)], A. Ceccucci[(3)], V. Cicero[(4)], P. Ciambrone[(2)], H. Danielsson[(3)], G. D'Alessandro[(3)], G. Felici[(2)], L. Gatignon[(5)], A. Gerbershagen[(3)], V. Giordano[(4)], G. Lanfranchi[(2)], A. Montanari[(4)], A. Paoloni[(2)], G. Papalino[(2)], T. Rovelli[(4)], A. Saputi[(2)], S. Schuchmann[(6)], F. Stummer[(7)], N. Tosi[(4)]

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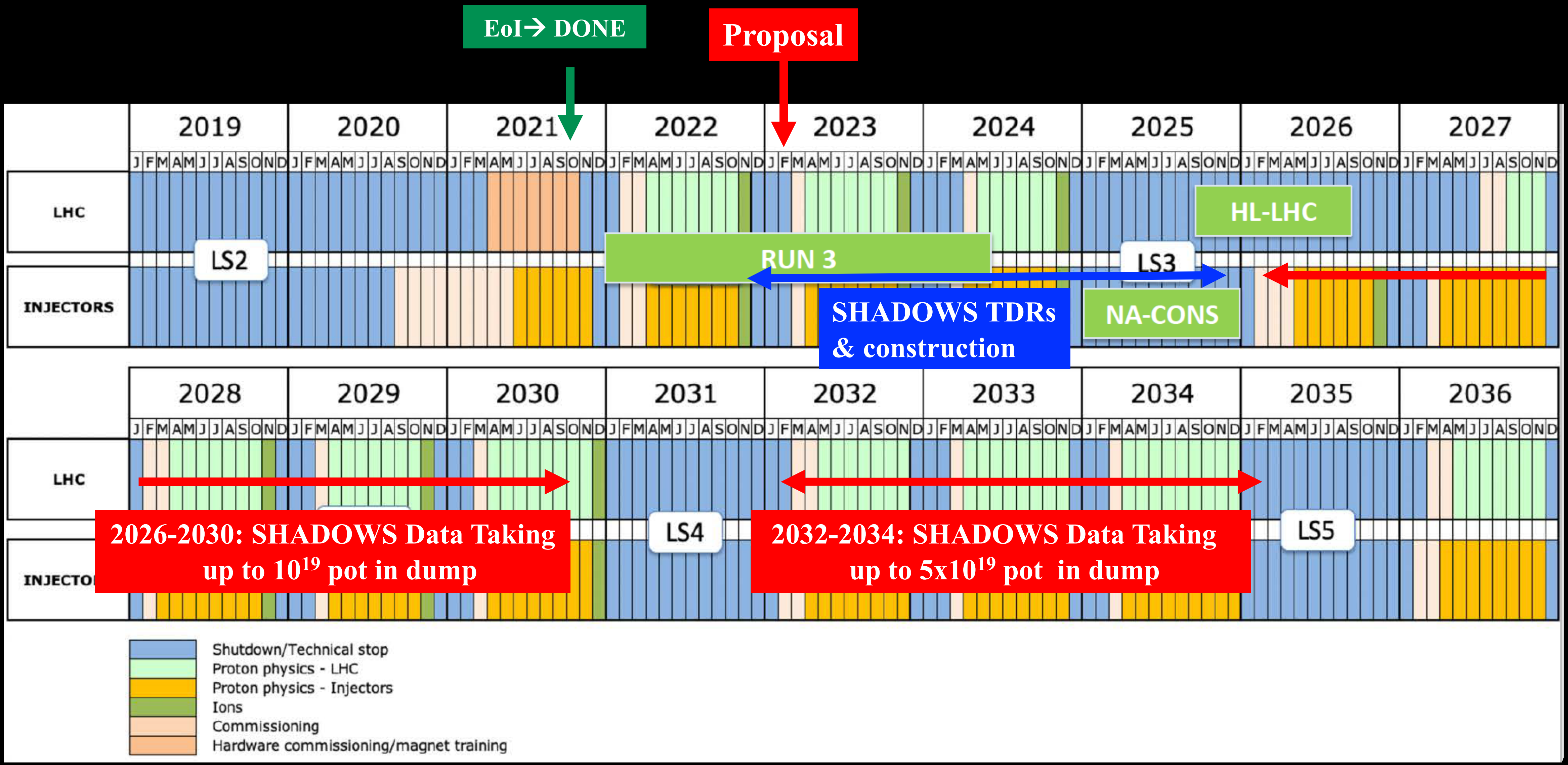
[(3)] *CERN*
[(4)] *INFN, Sezione di Bologna, Bologna, Italy*
[(5)] *University of Lancaster, Lancaster, UK*
[(6)] *University of Mainz, Germany*
[(7)] *University of Vienna, Austria*

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 $\sim 2 \cdot 10^{19}$ 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.

SHADOWS: Tentative Schedule



Conclusions

✓ FIP Physics is literally exploding worldwide:

⇨ A lively theoretical activity is complementing novel ideas for experiments in all major labs

⇨ In the PBC Currently moving from an "exploratory phase" to a more "mature phase".

✓ SHADOWS aims to become a major player for FIP Physics in this decade:

⇨ SHADOWS can be built now using existing technologies.

⇨ SHADOWS has similar sensitivity as CODEX-b (300 fb^{-1}) and FASER2 (3 ab^{-1}) and for specific benchmarks as SHiP ($2x10^{20}$ pot) for FIPs from charm/beauty decays.

✓ The EoI has been submitted to PBC and arXiv. Plan to have the Proposal ready by end of next year and to start construction in 2024 to be ready for Run 4.