SHADOWS

[Search for Hidden And Dark Objects With the SPS]

Searching for Feebly-Interacting Particles at CERN

Gaia Lanfranchi

LNF-INFN

Laboratori Nazionali di Frascati – 10 June 2021

What is SHADOWS?

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

SHADOWS can take data concurrently with NA62
when NA62 is operated in beam-dump mode.

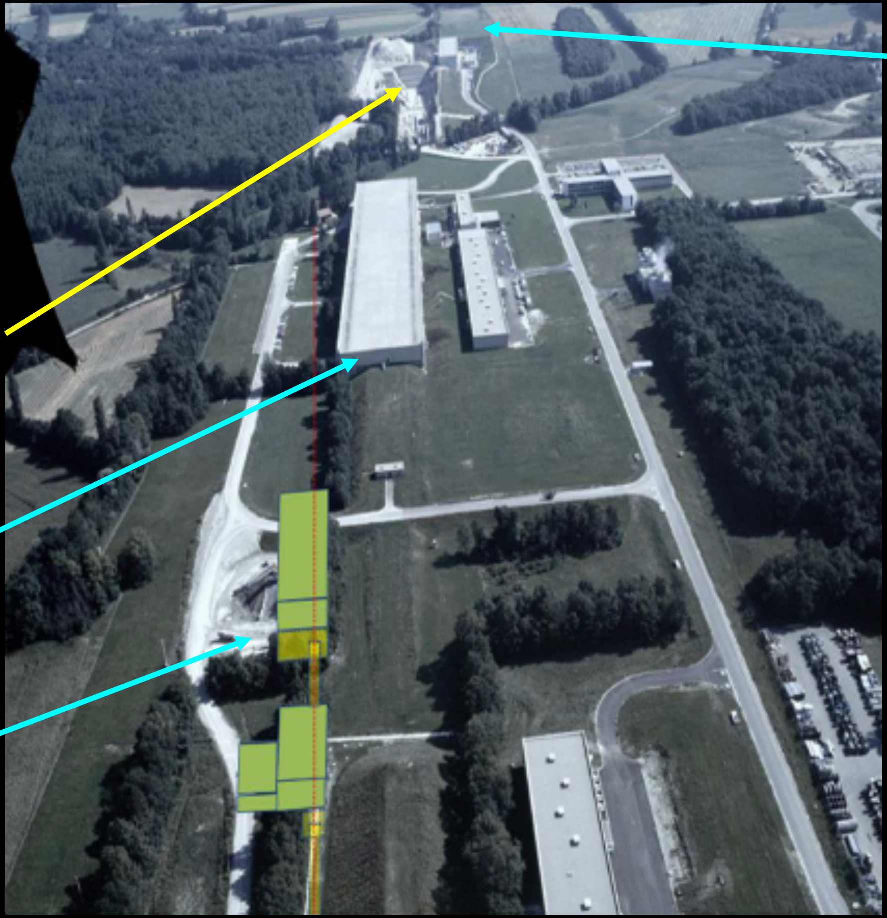
A synergistic and broad FIP physics program can be performed with NA62.

Where to install SHADOWS?

ECN3/TCC8
P42/K12: 400 GeV p beam
up to $3x10^{18}$ pot/year (now)
→ **NA62 (NA62-dump)**
up to a few 10^{19} pot/year
NA62x4, KLEVER ,
→ SHADOWS in ECN3

EHN1:
H4: 100 GeV e- beam
up to $5x10^{12}$ eot/year
→ **$NA64^{++}$ (e), $NA64^{++}$(hadrons)**

SHiP @ BDF
(medium/long term)



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

Why in ECN3 area ?

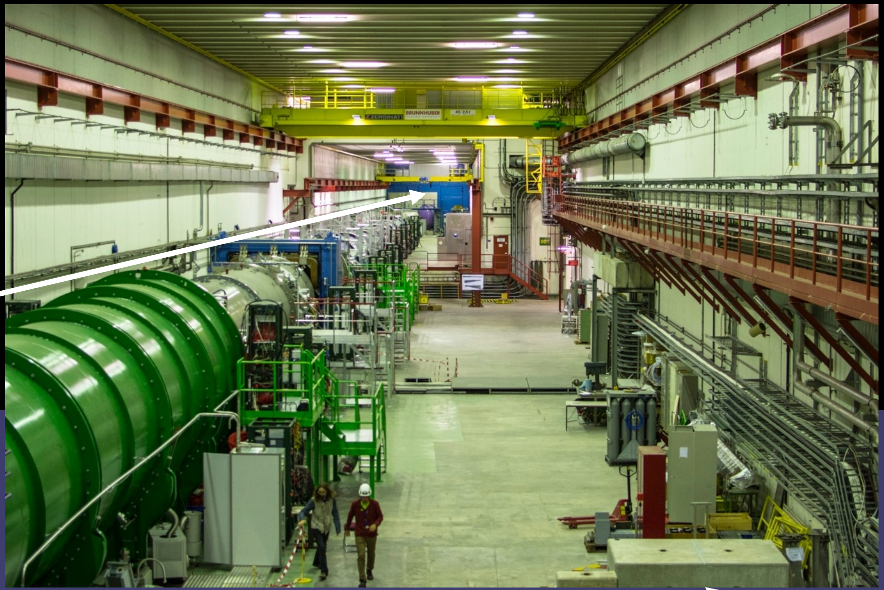
- ✓ Because ECN3/TCC8 has the best 400 GeV primary extracted proton beam line at CERN (and worldwide) and a plethora of hidden sector particles can emerge from interactions of a high-energy proton beam with a dump
  - NA62 nominal intensity is 3×10^{12} ppp with 3.3s pulse duration: ~ 10^{12} pot/sec,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

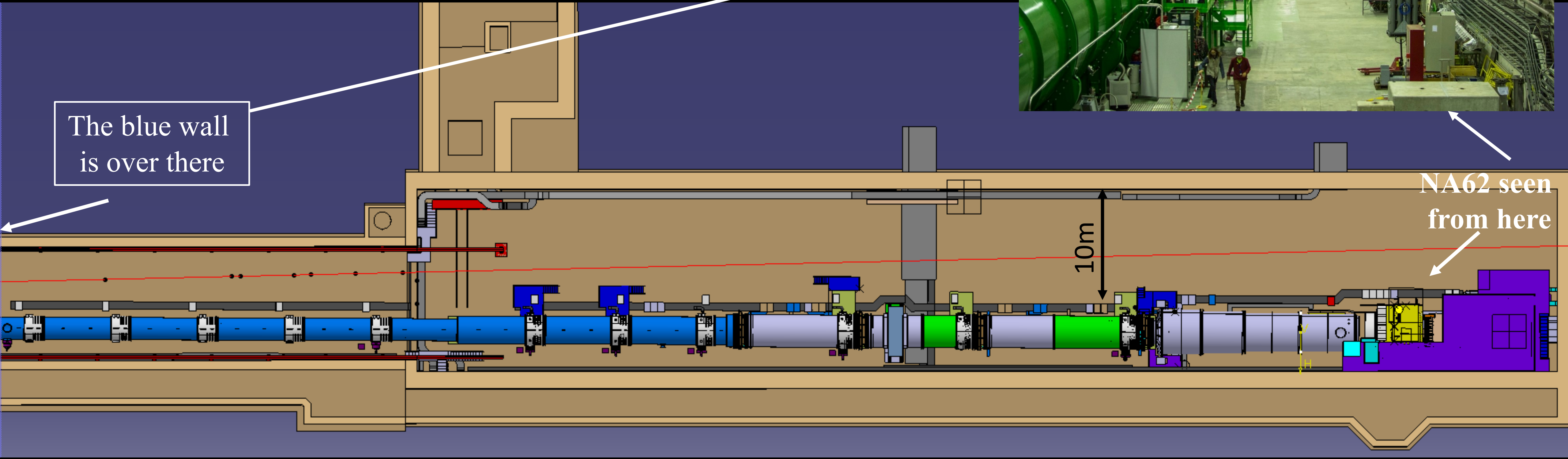
- ✓ NA62 beam intensity proposed to be increased by a factor:
  - x 4 (for the high-intensity K^+ beam, NA62x4 project) → up to 10^{19} pot/year
  - x 6-7 (for high intensity K_L beam , KLEVER project) → up to a 1.5 10^{19} pot/year

- ✓ Which implies a new target/TAXes (dump)/RP studies:
  - (as presented in previous talk)

NA62 in the ECN3 Hall

ECN3 Hall – zoom out



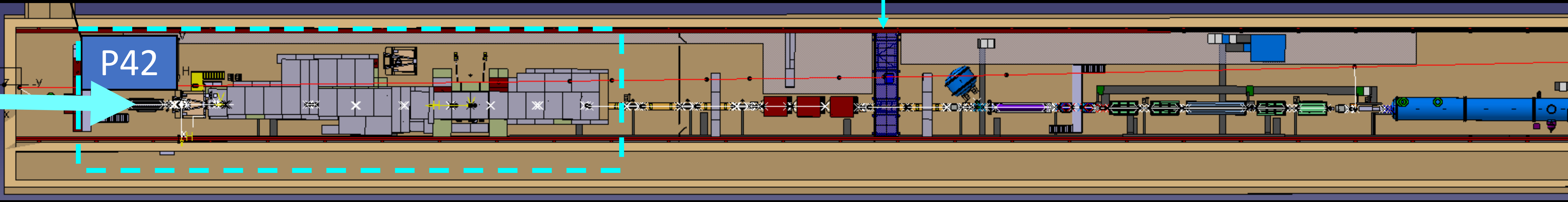


TCC8 + ECN3 hall - zoom out

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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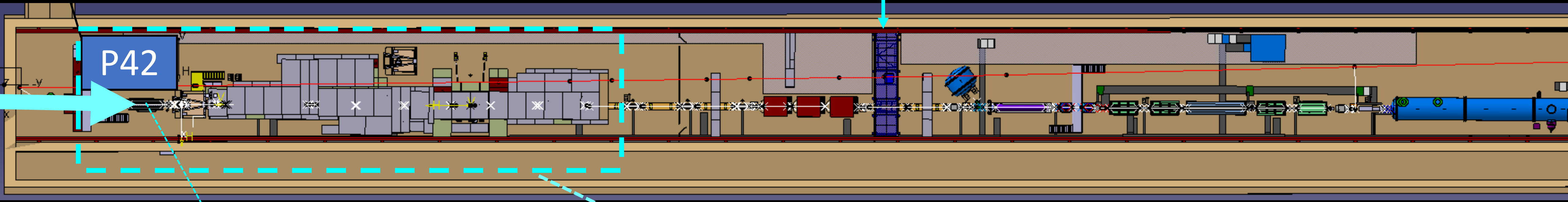
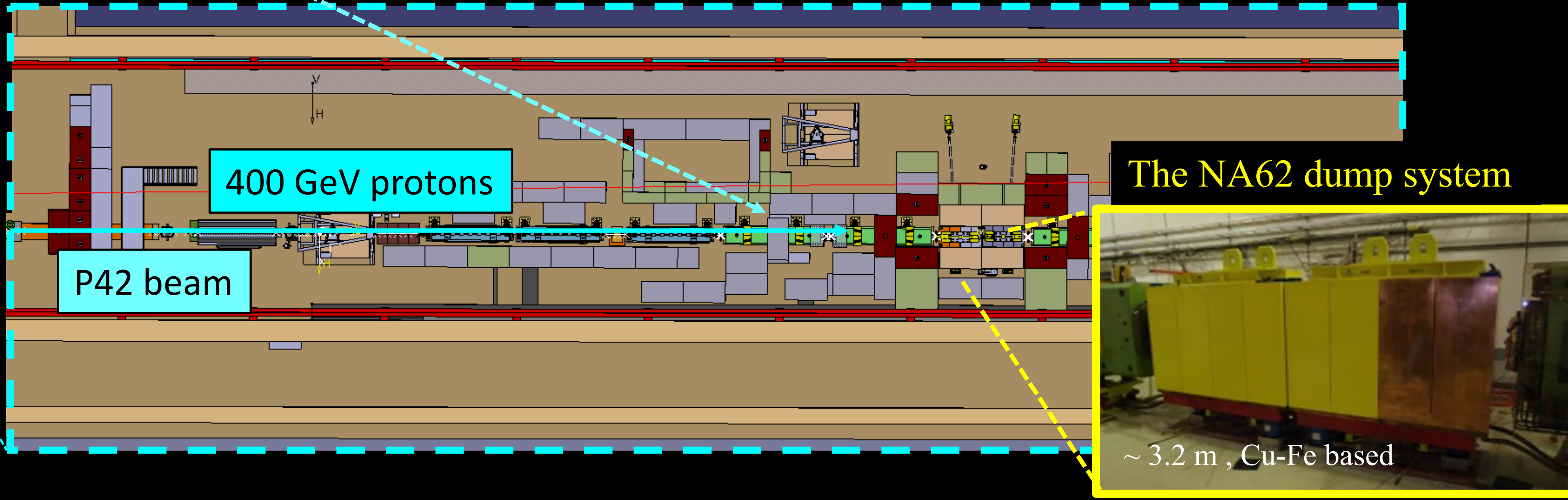


T10 target is moved to empty target head and the 400 GeV primary proton beam is sent onto the dump



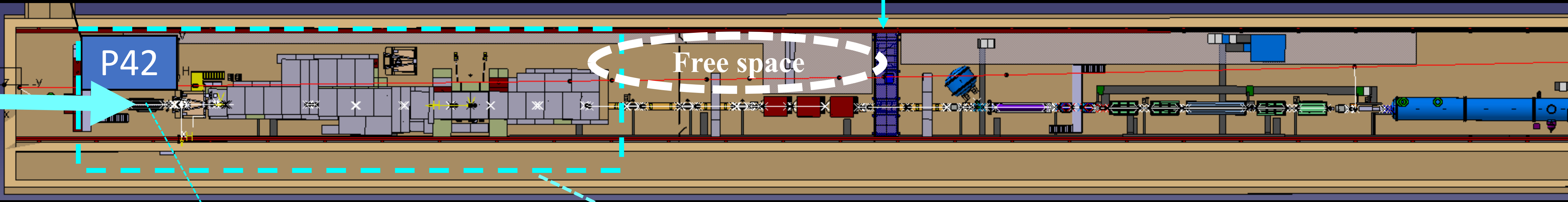
The NA62 dump system

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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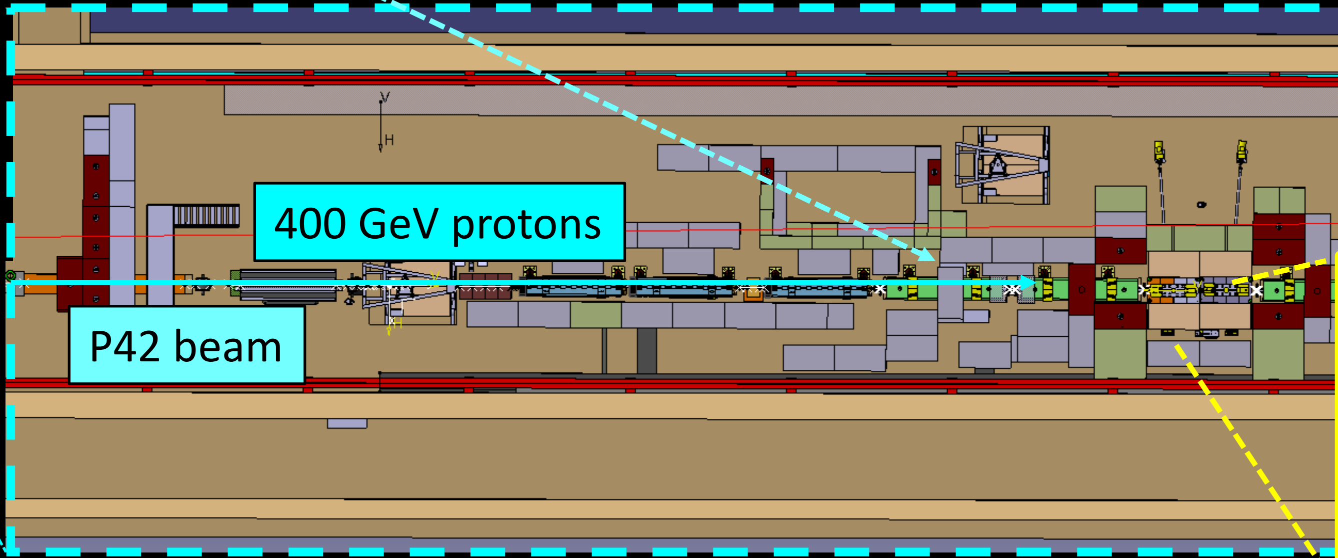
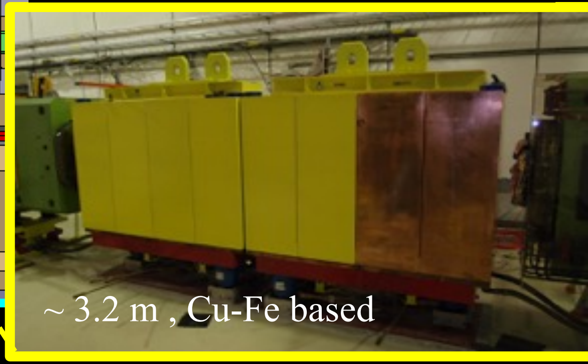
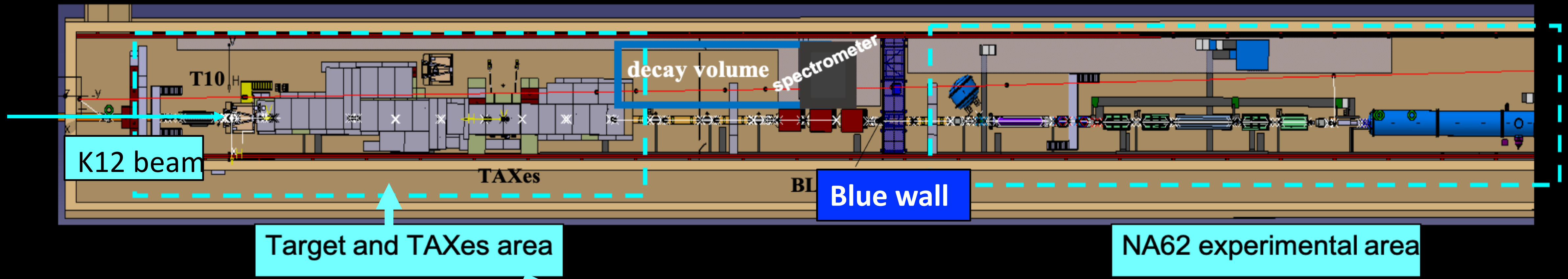
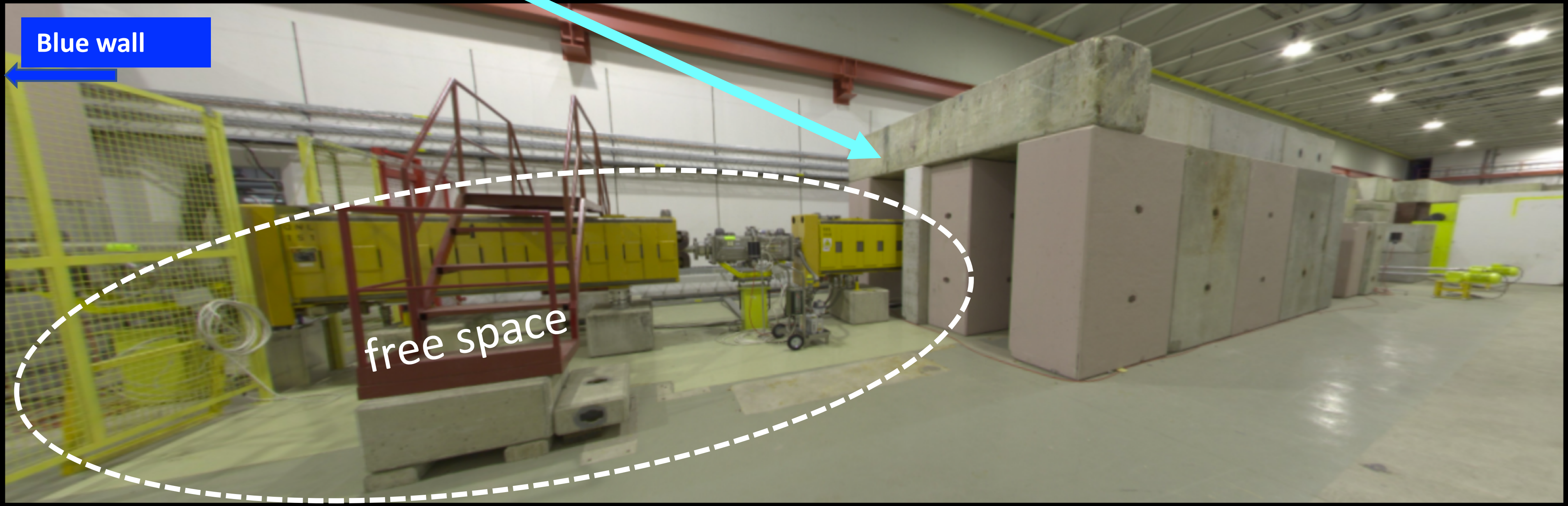


The NA62 dump system



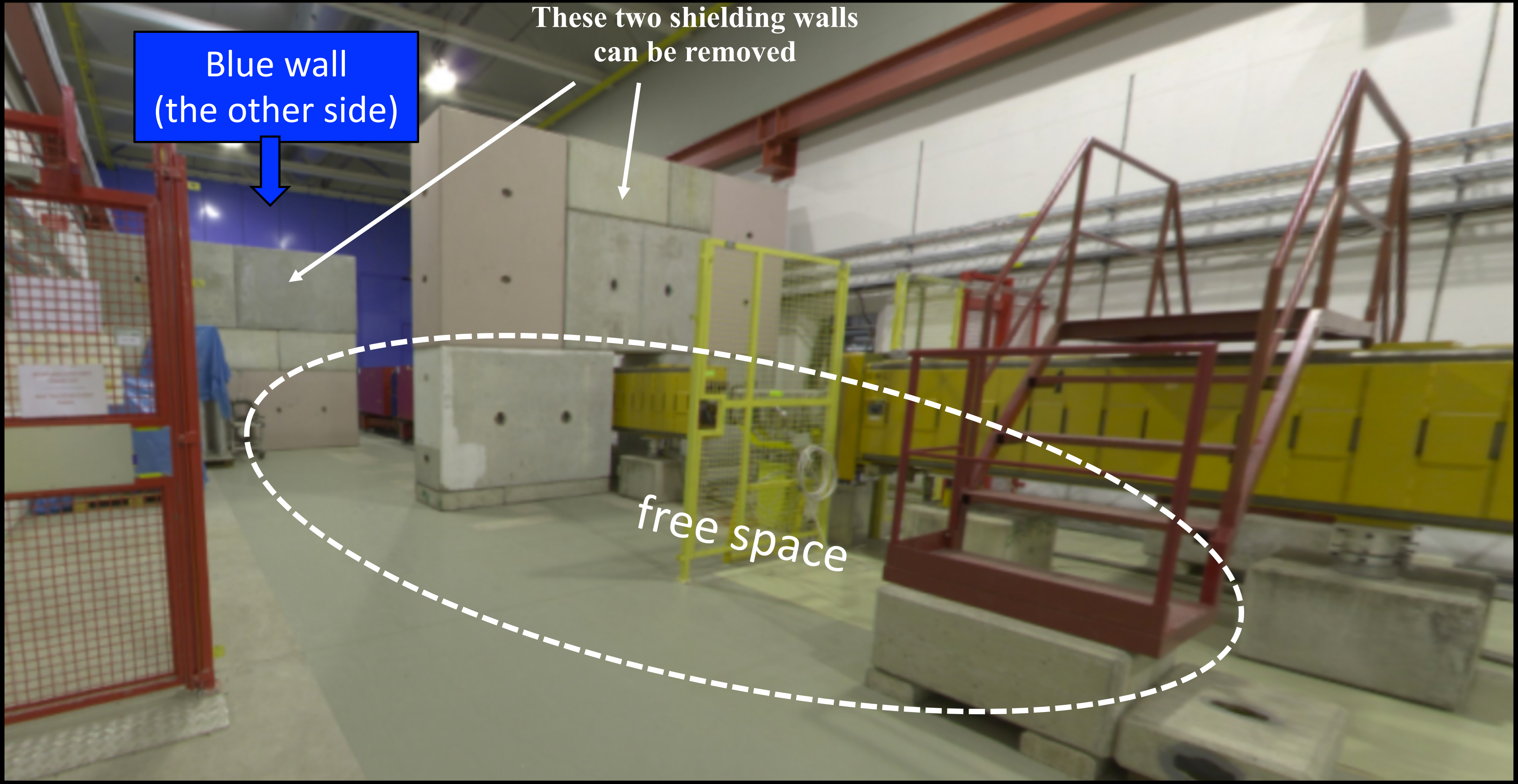
SHADOWS in ECN3/TTC8



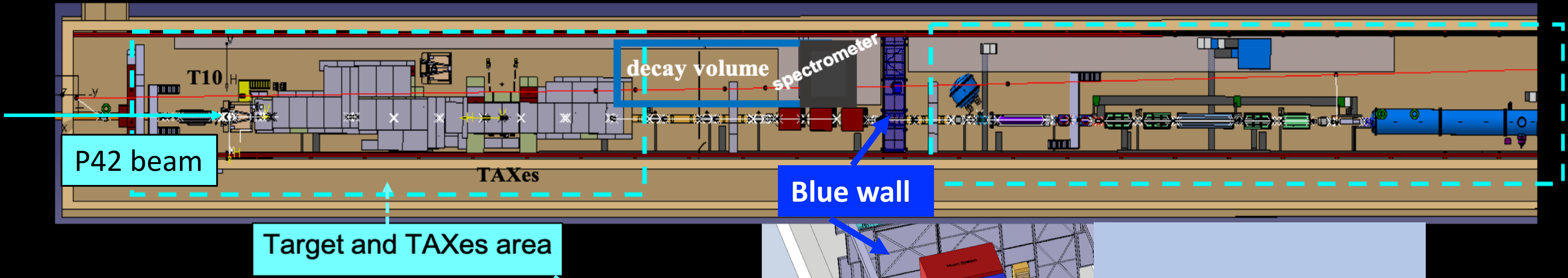


SHADOWS in ECN3/TTC8

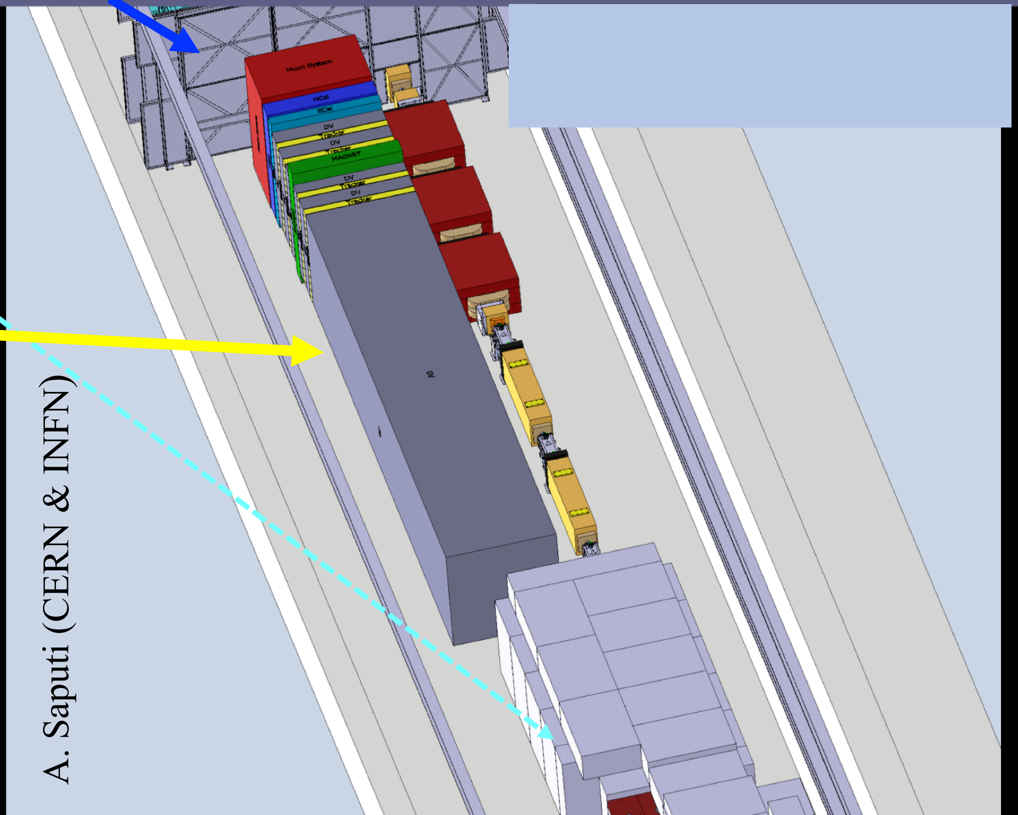
On the other side of the NA62 blue wall – in the target area



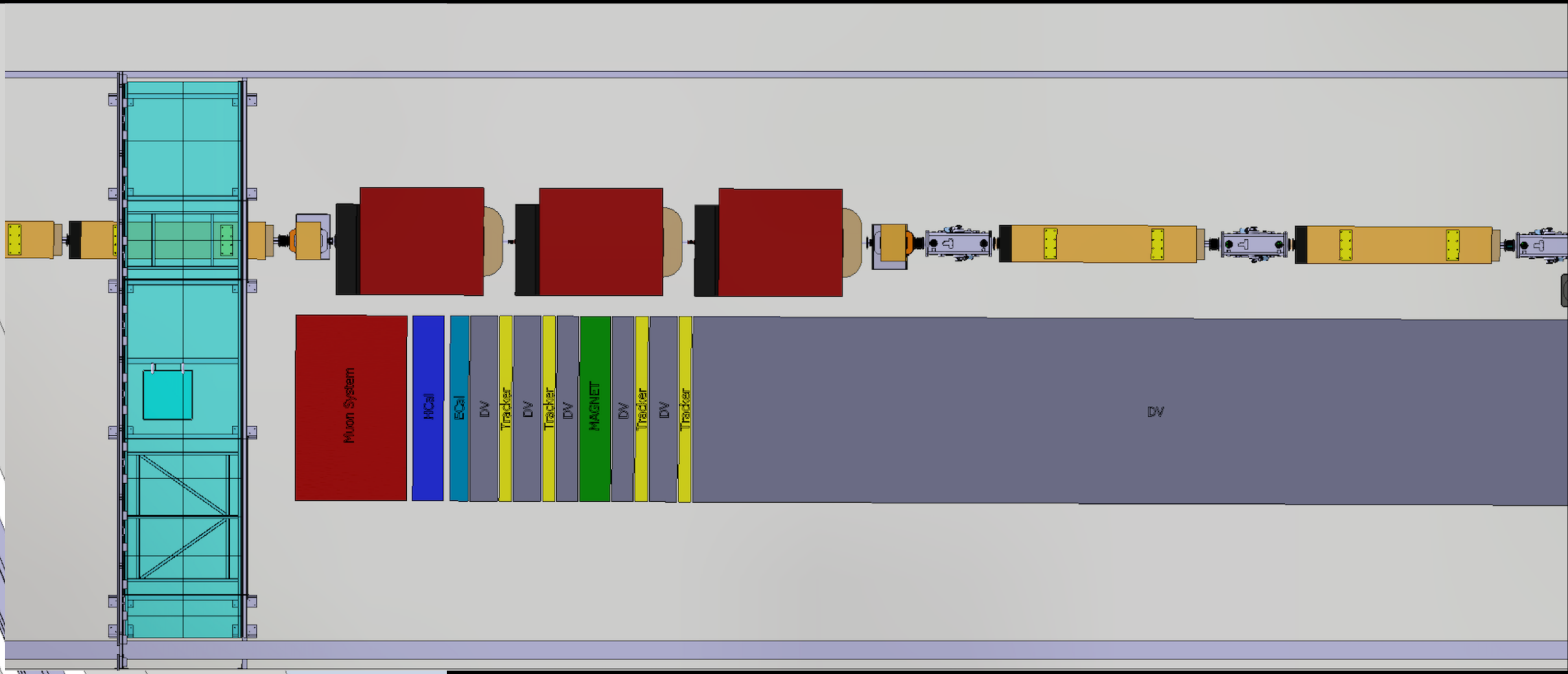
SHADOWS in ECN3/TTC8



SHADOWS in the target area



SHADOWS in ECN3/TTC8



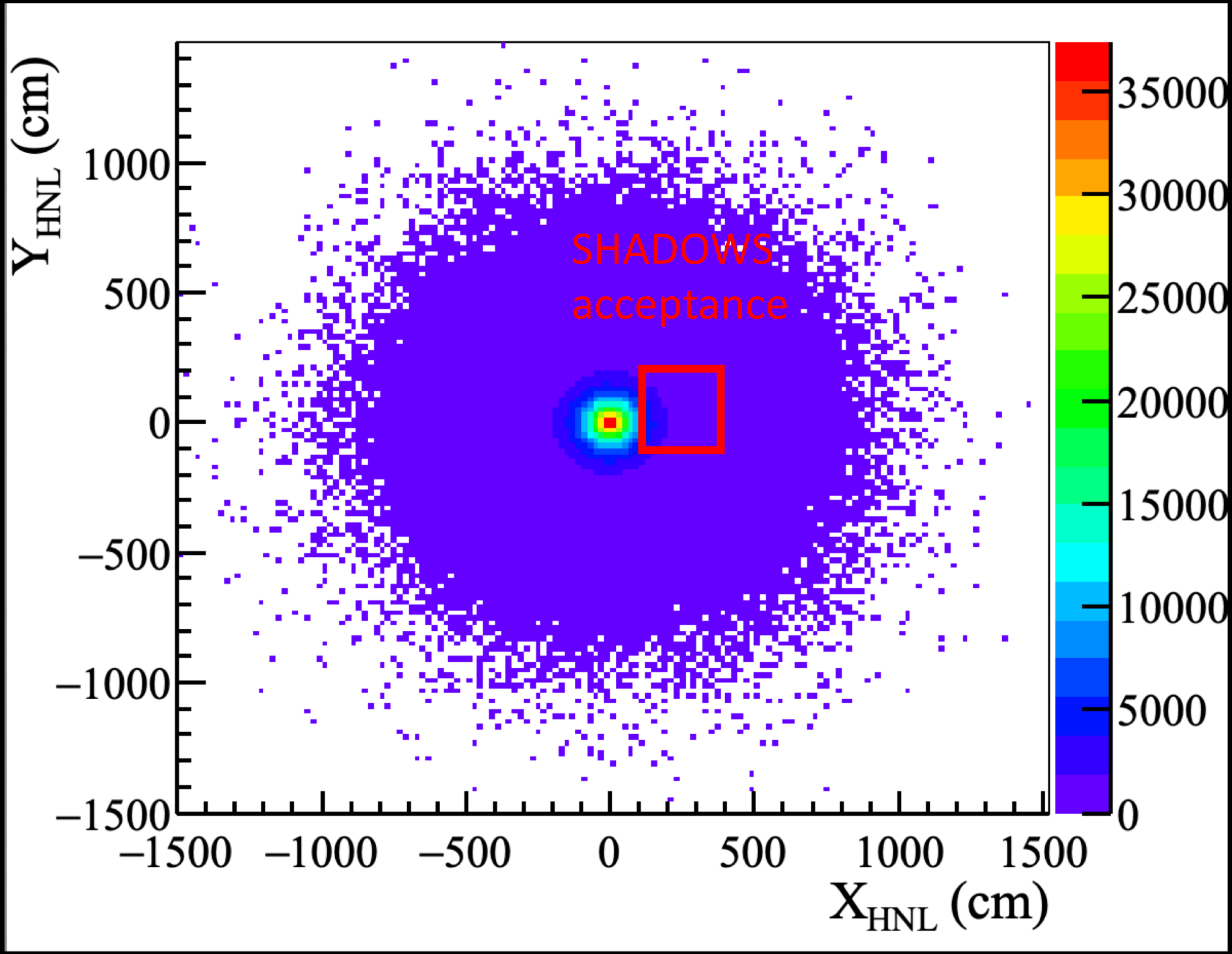
<u>Preliminary Conceptual Layout</u>

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) .

A. Saputi (CERN & INFN)

Why "off-axis" works

Heavy Neutral Lepton illumination at the SHADOWS tracking plane



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

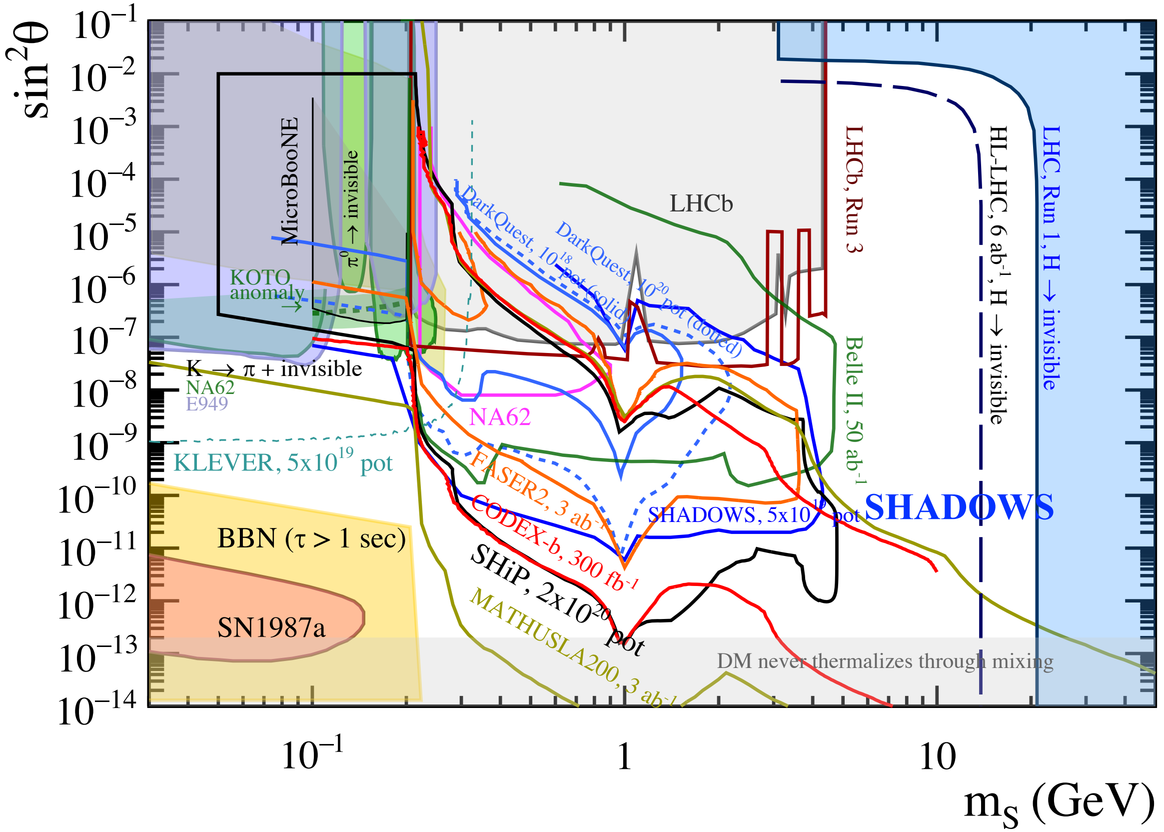
SHADOWS physics sensitivity for some PBC benchmark models

Two scenarios considered:

1) Scenario 1: 10^{19} protons-on-target collected in Run 4 (2027-2030)
2) Scenario 2: 5×10^{19} protons-on-target collected in Run 5 (2032++)

Sensitivity to feebly-interacting Dark Scalars

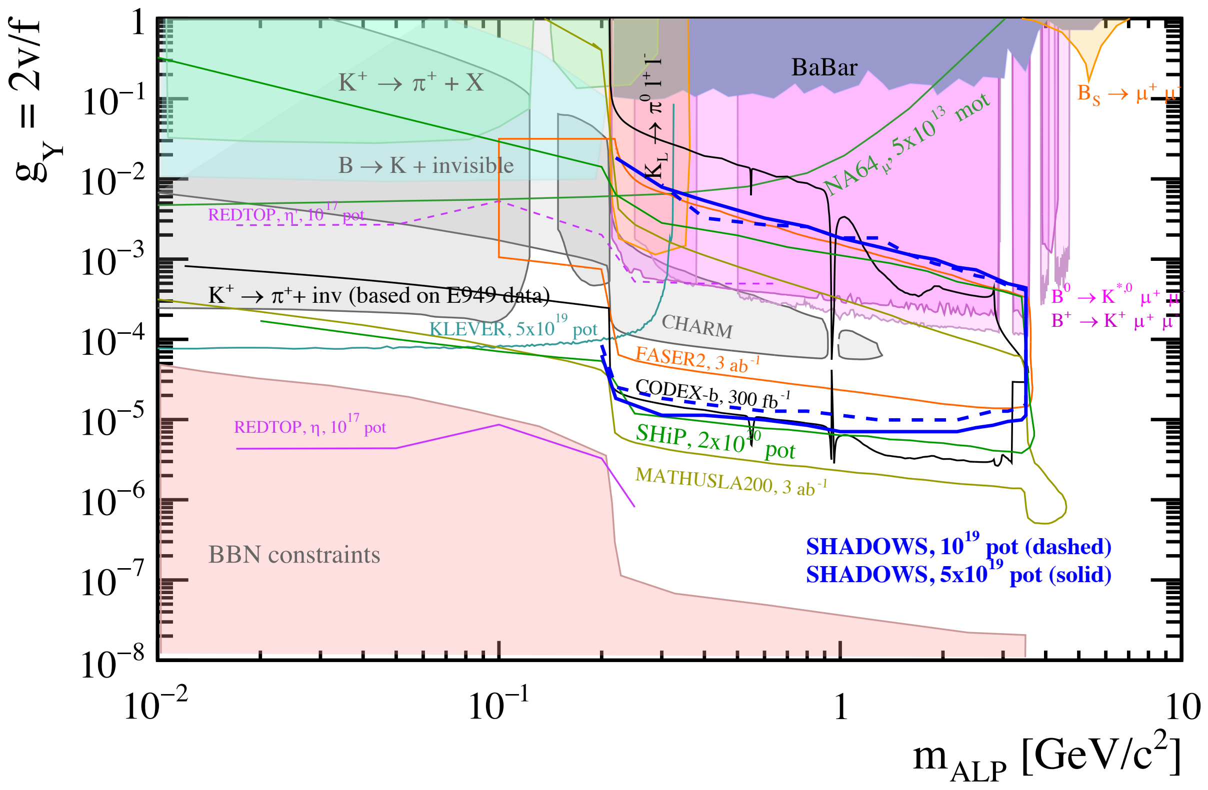
(SHADOWS at 10^{19} and 5×10^{19} pot)



With 5×10^{19} pot SHADOWS sensitivity is better than FASER2 (3ab^{-1}) and competitive with CODEX-b (300 fb^{-1}) below the B mass and SHiP (2×10^{20} pot)

Sensitivity to feebly-interacting ALPs with fermion coupling

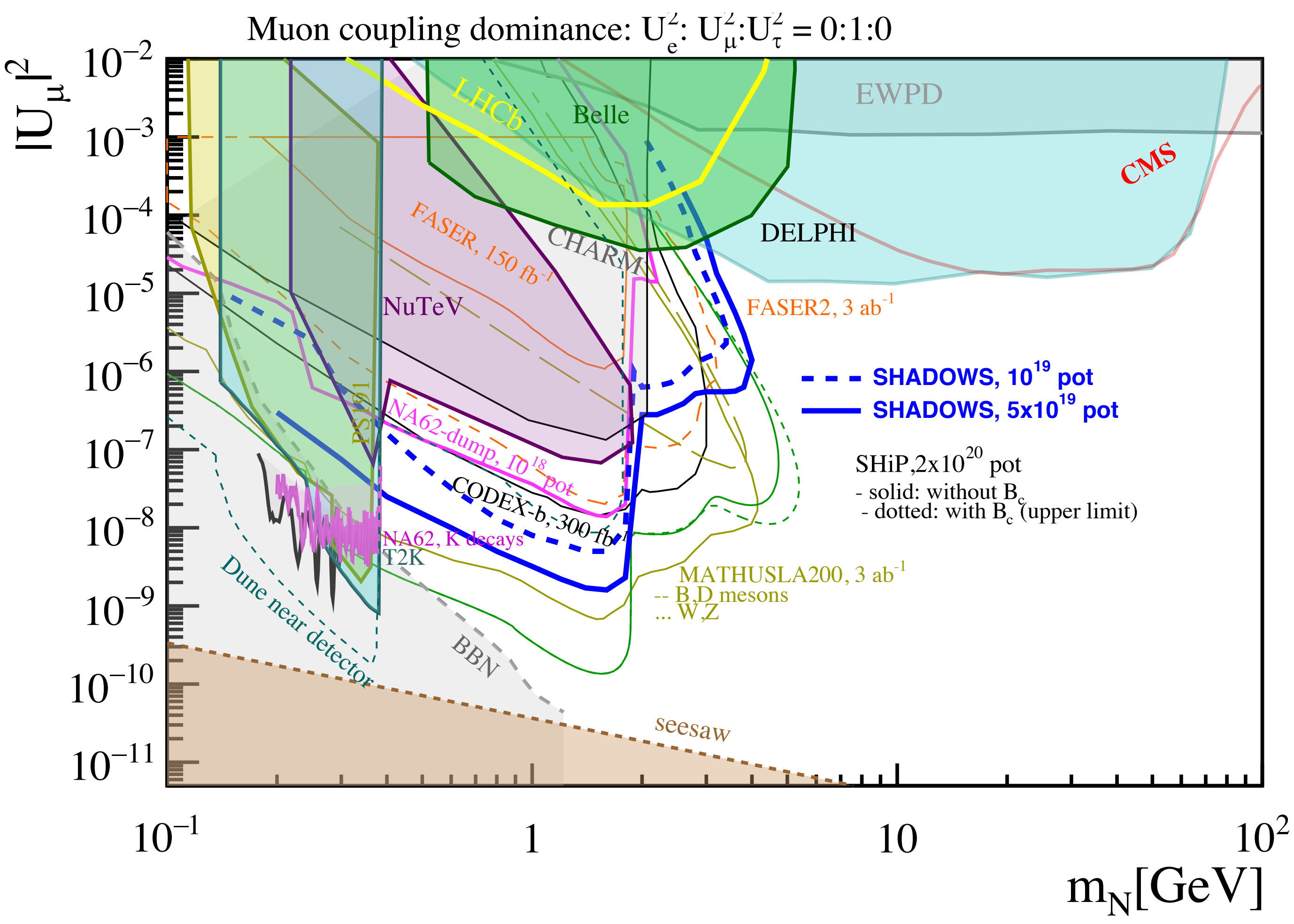
(SHADOWS at 10^{19} and $5\text{x}10^{19}$ pot)



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

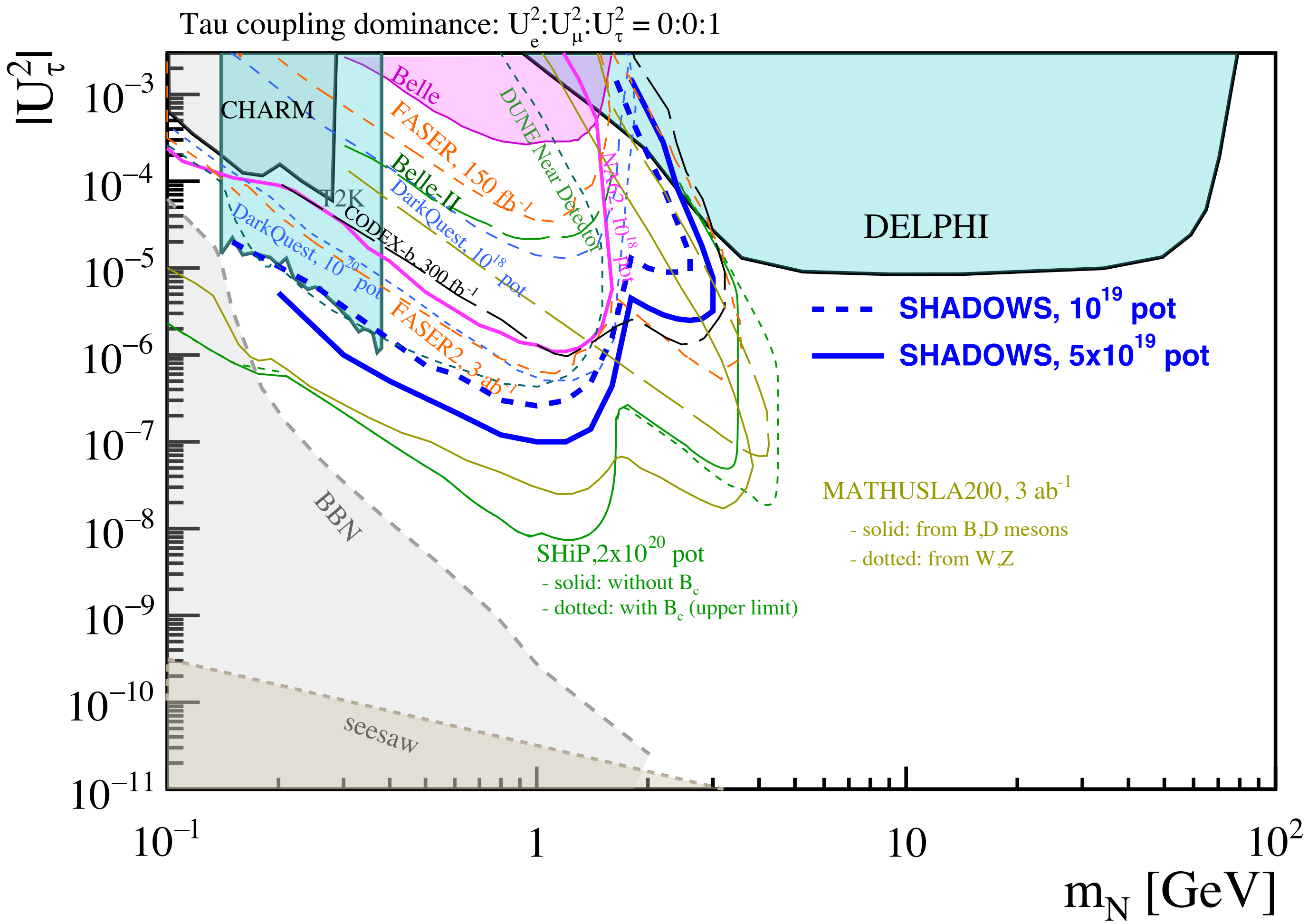
(SHADOWS at 10^{19} and 5×10^{19} pot)



SHADOWS is competitive with CODEX-b (300 fb^{-1}) ad FASER2 (3 ab^{-1})

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

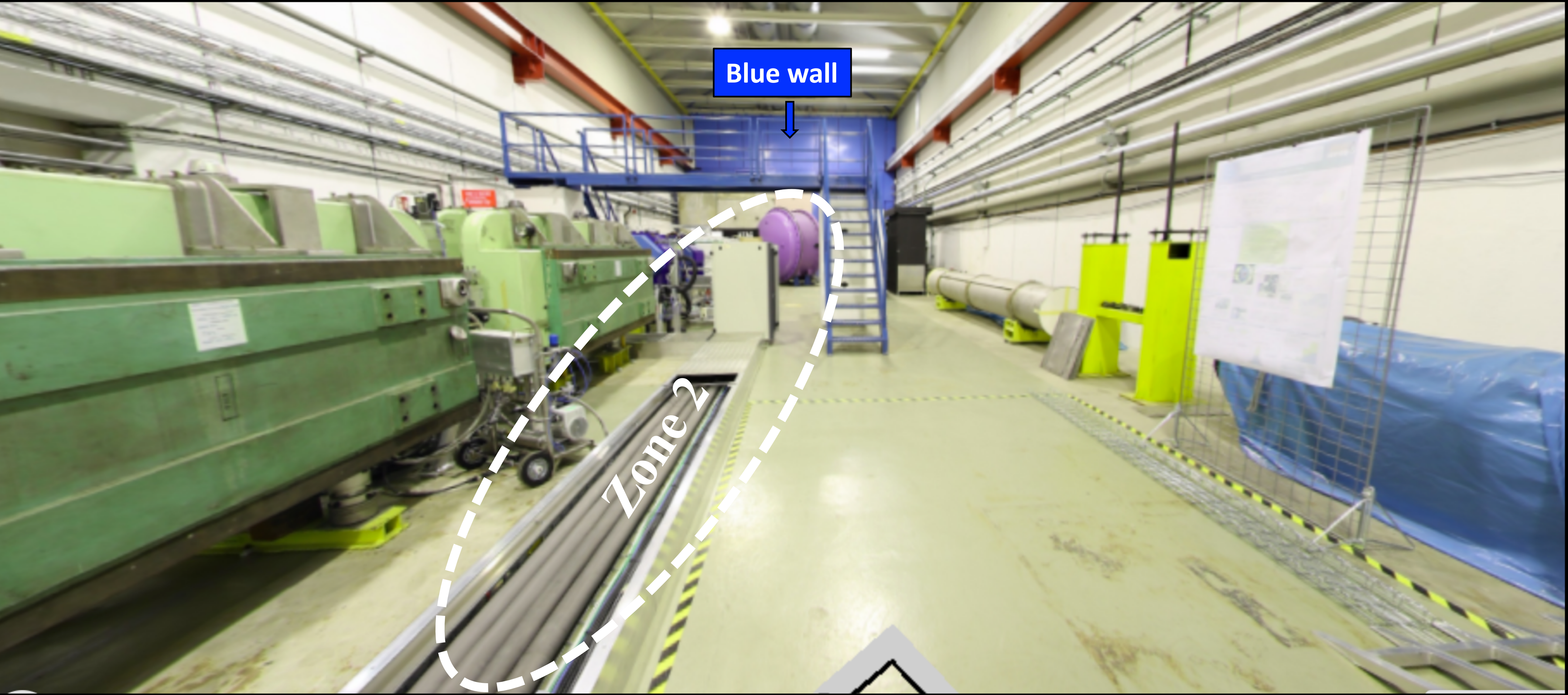
(SHADOWS at 10^{19} and 5×10^{19} pot)



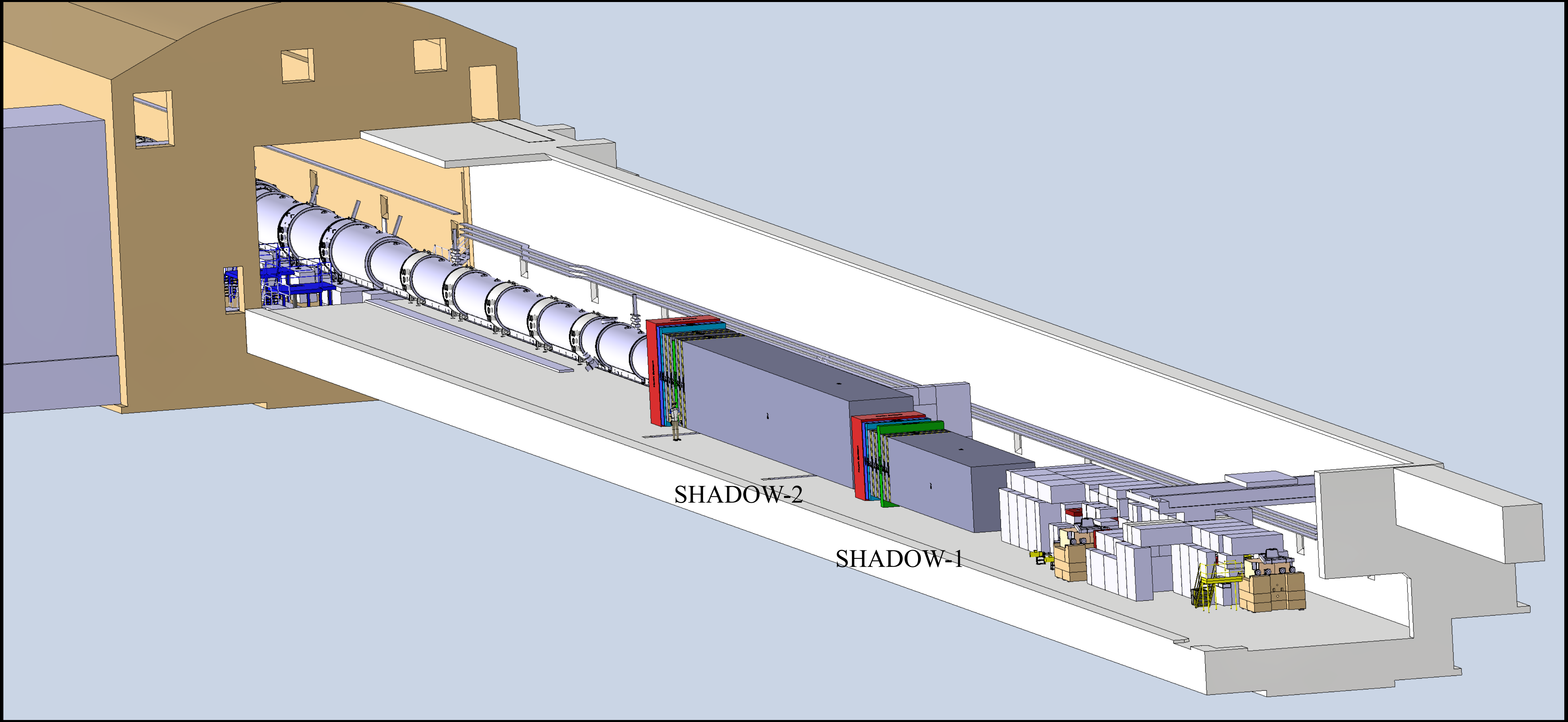
SHADOWS with $O(10^{19})$ pot is three orders of magnitude better than Belle II, better than FASER2 (3 ab^{-1}) and CODEX-b (300 fb^{-1})

How to improve SHADOWs sensitivity for HNLs ?

Blue wall
Zone 2
Beam
~ 200 m

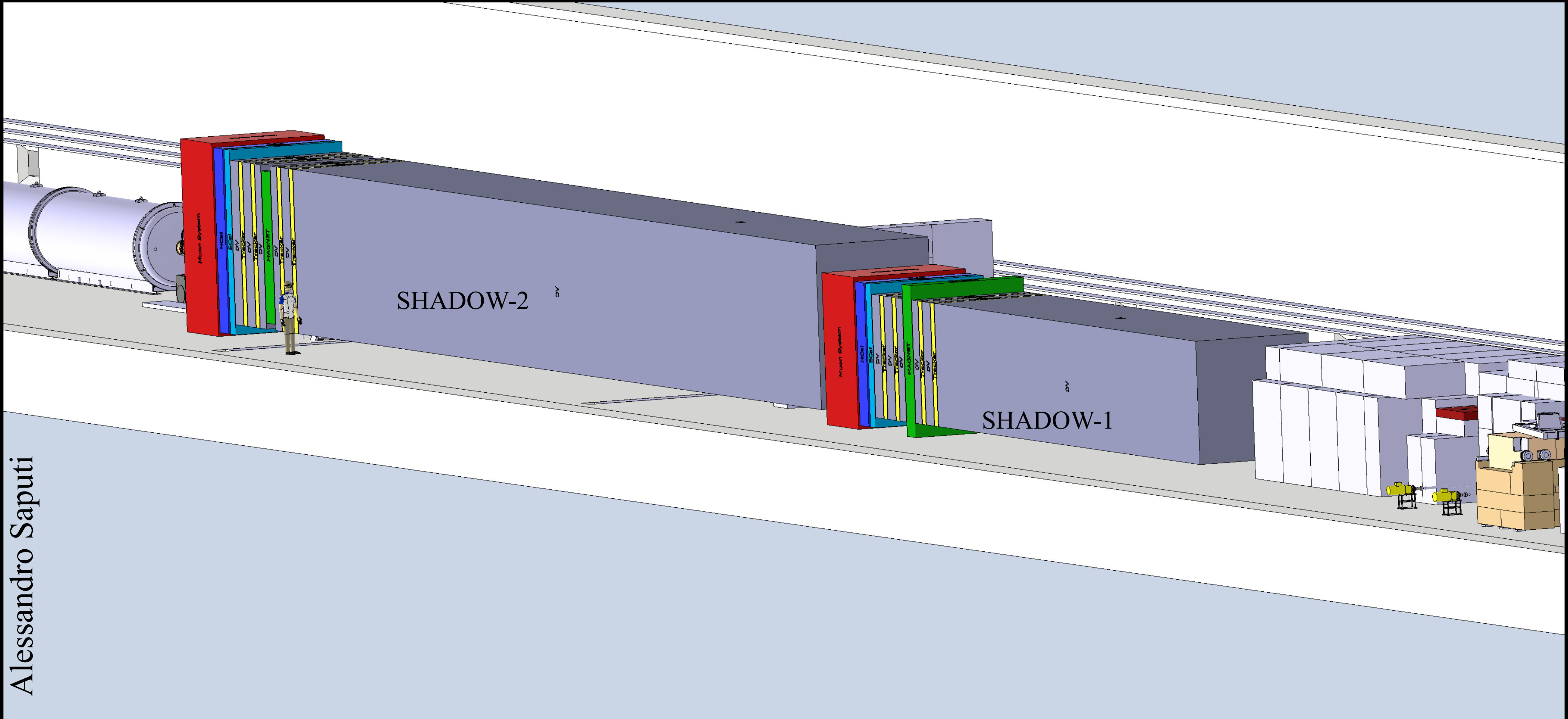

Blue wall
Zone 2

Add a second spectrometer (SHADOW-2) in the free space in TCC8
(exact position is still to be defined)

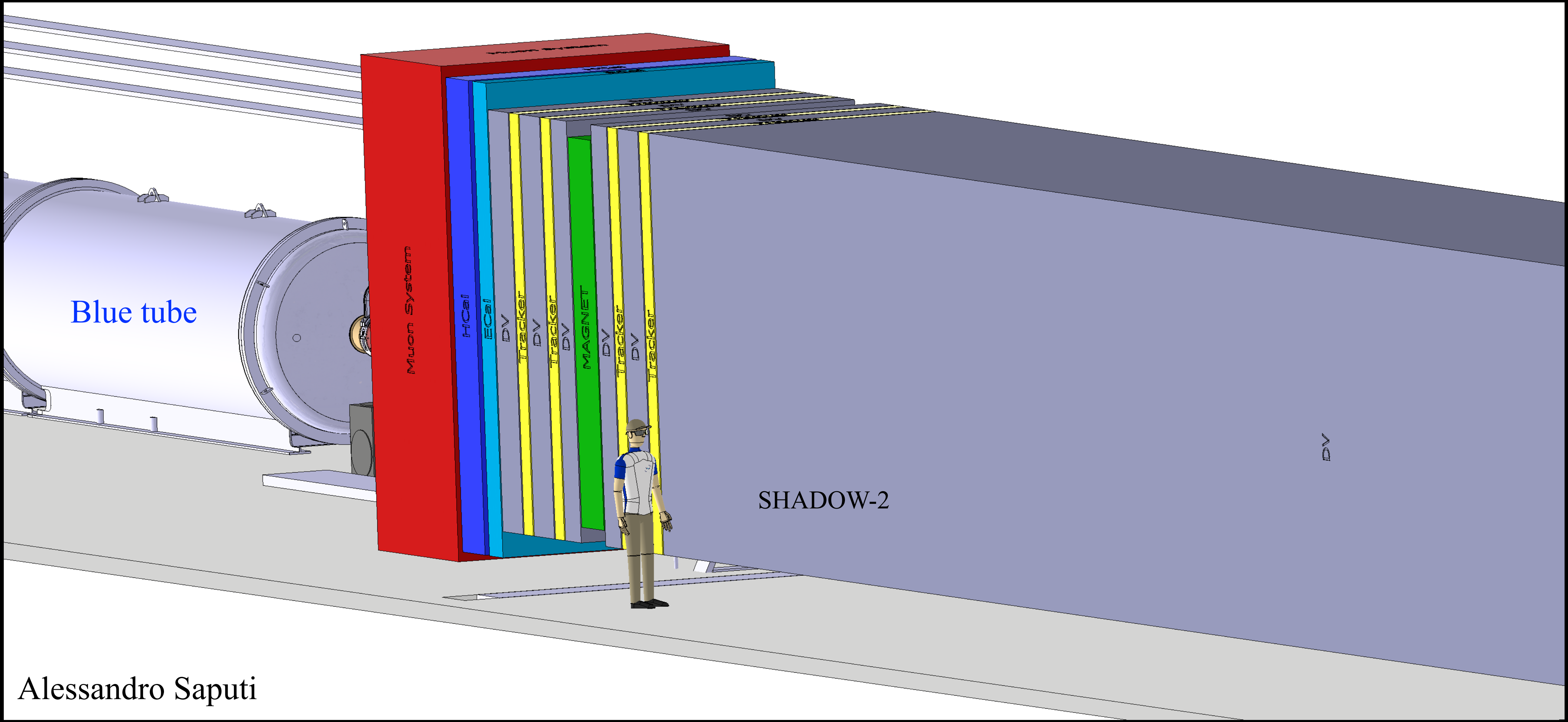


Alessandro Saputi

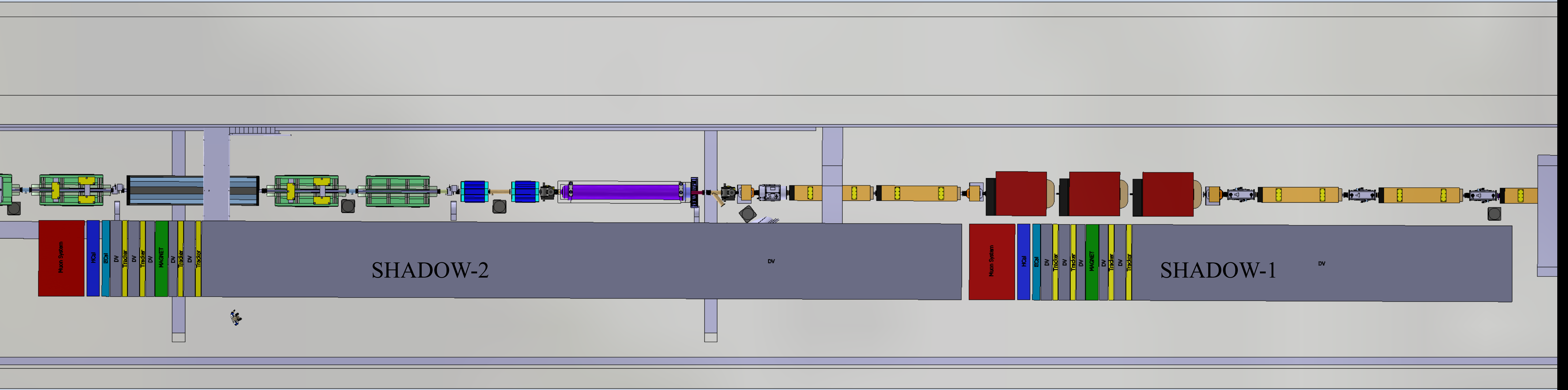
The second shadows spectrometer could have 30 m long decay volume and 3x4 m^2 transverse dimensions



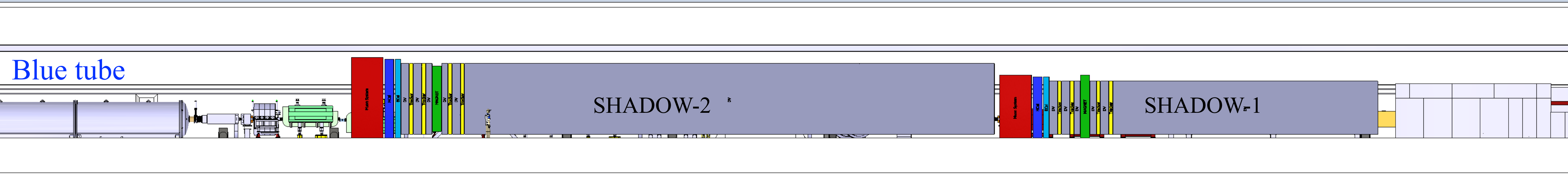
The second spectrometer must end before the beginning of the blue tube



The two “SHADOWS”: Top view

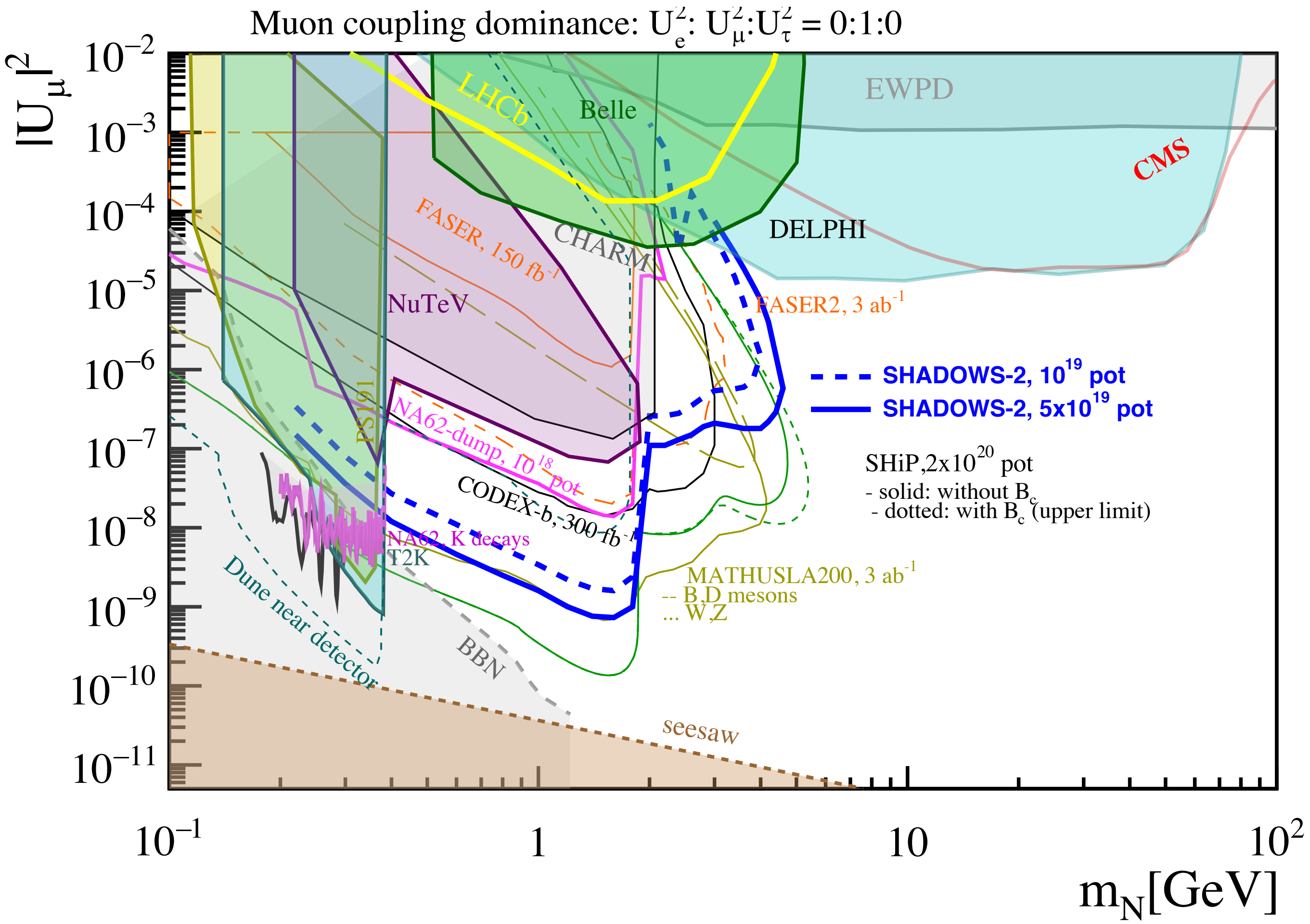


The two "SHADOWS": Lateral view



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

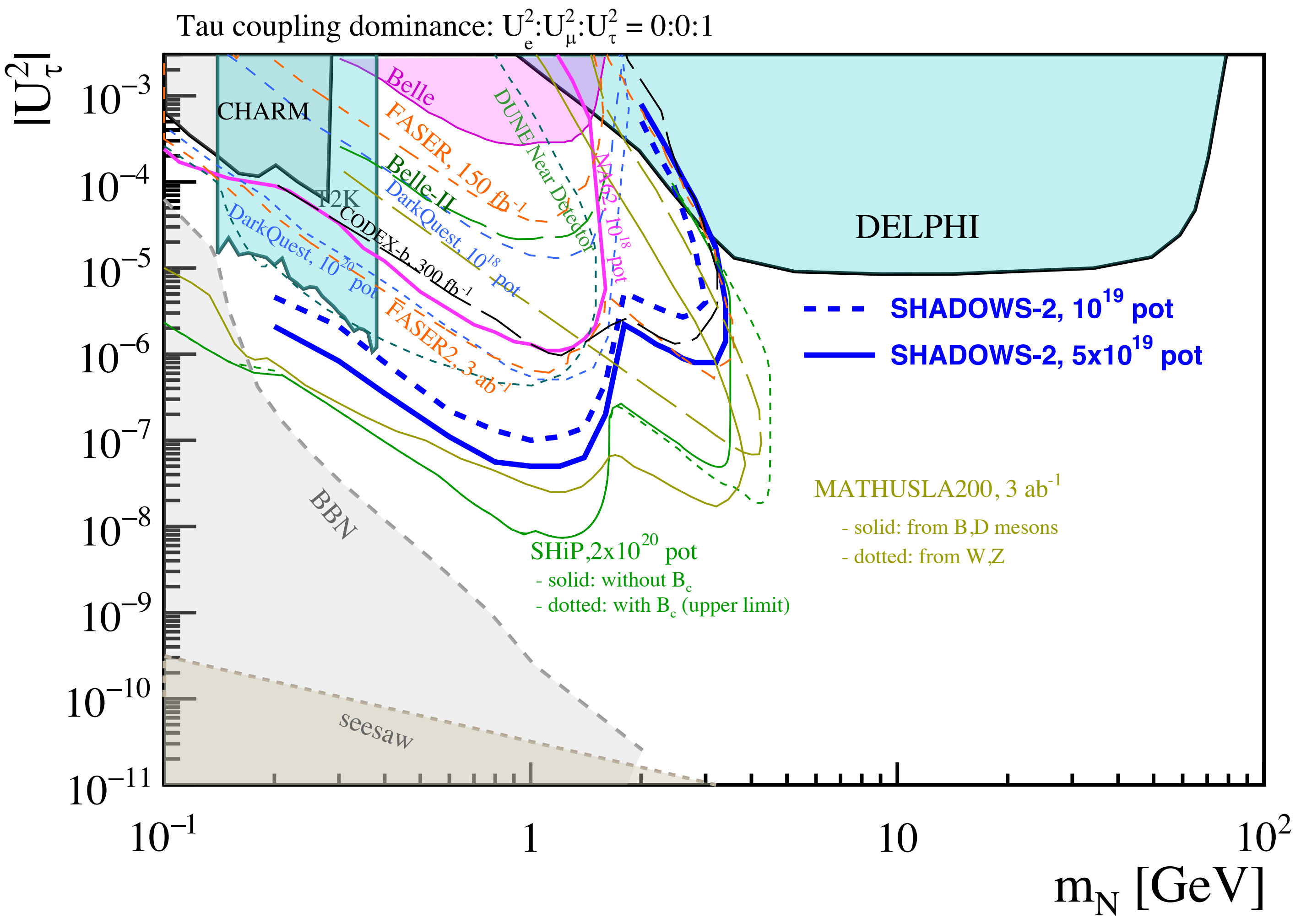
(SHADOWS-2 at 10^{19} and 5×10^{19} pot)



The addition of a second spectrometer allows us to increase the HNL flux by 6.
Competitive with MATHUSLA below the charm mass.

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

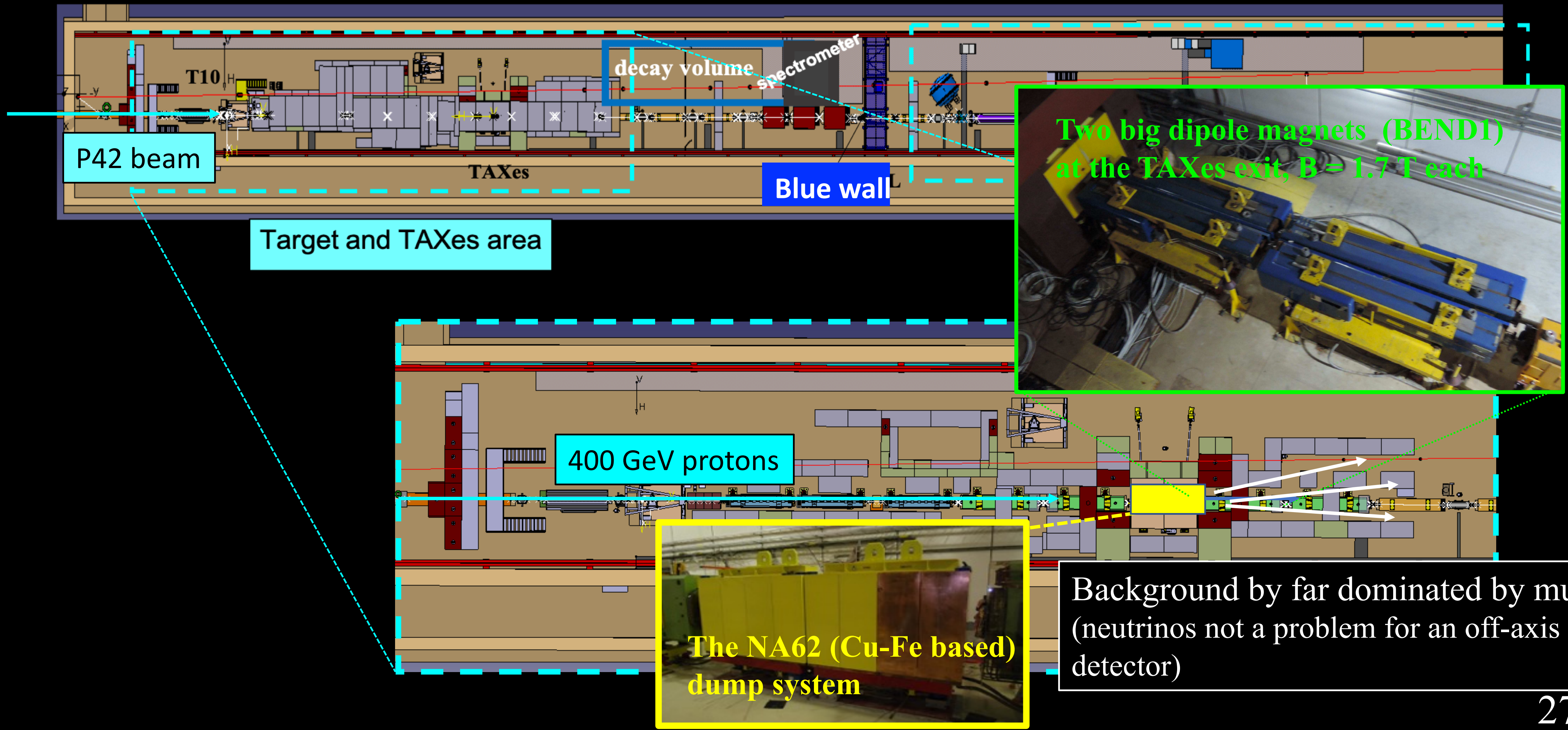
(SHADOWS-2 at 10^{19} and $5\text{x}10^{19}$ pot)



SHADOWS-2 sensitivity is the better than anyone else except SHiP and MATHUSLA

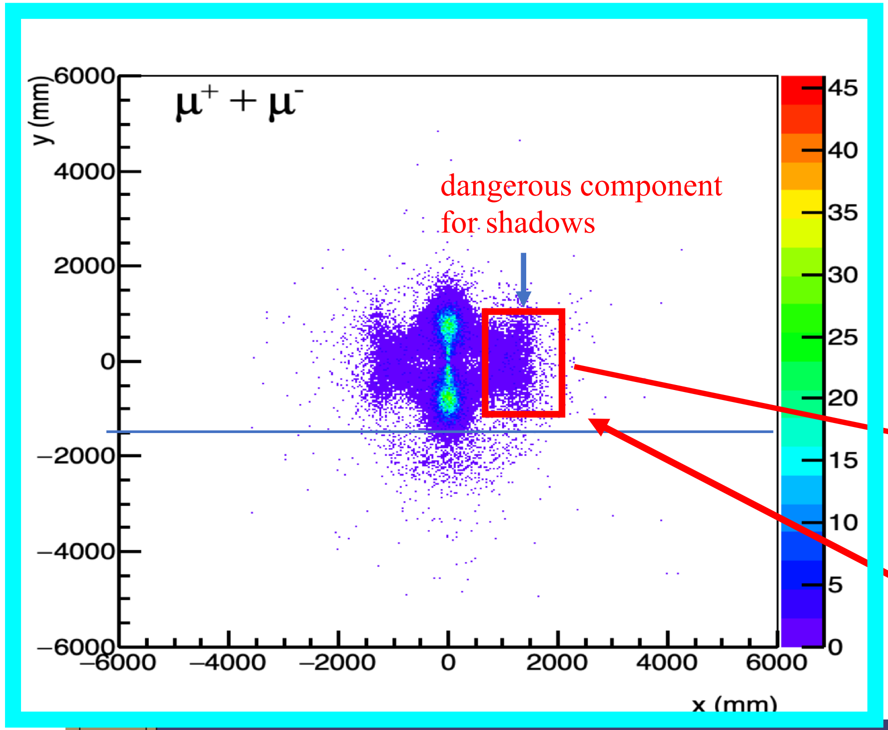
The beam-induced background:
the name of the game

The beam-induced background:

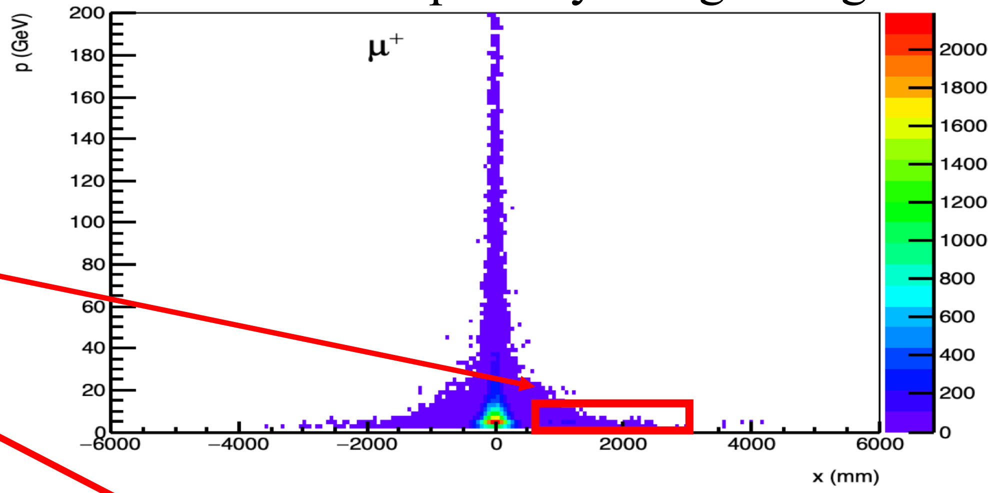


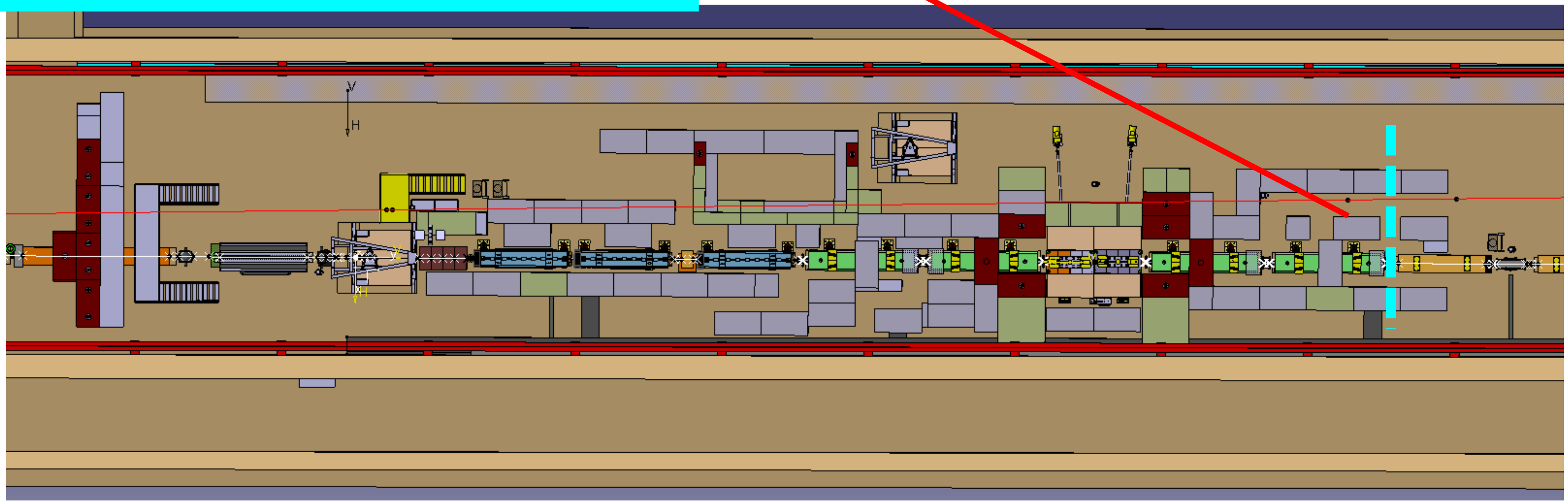
Background by far dominated by muons (neutrinos not a problem for an off-axis detector)

Muon illumination after the second dipole



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

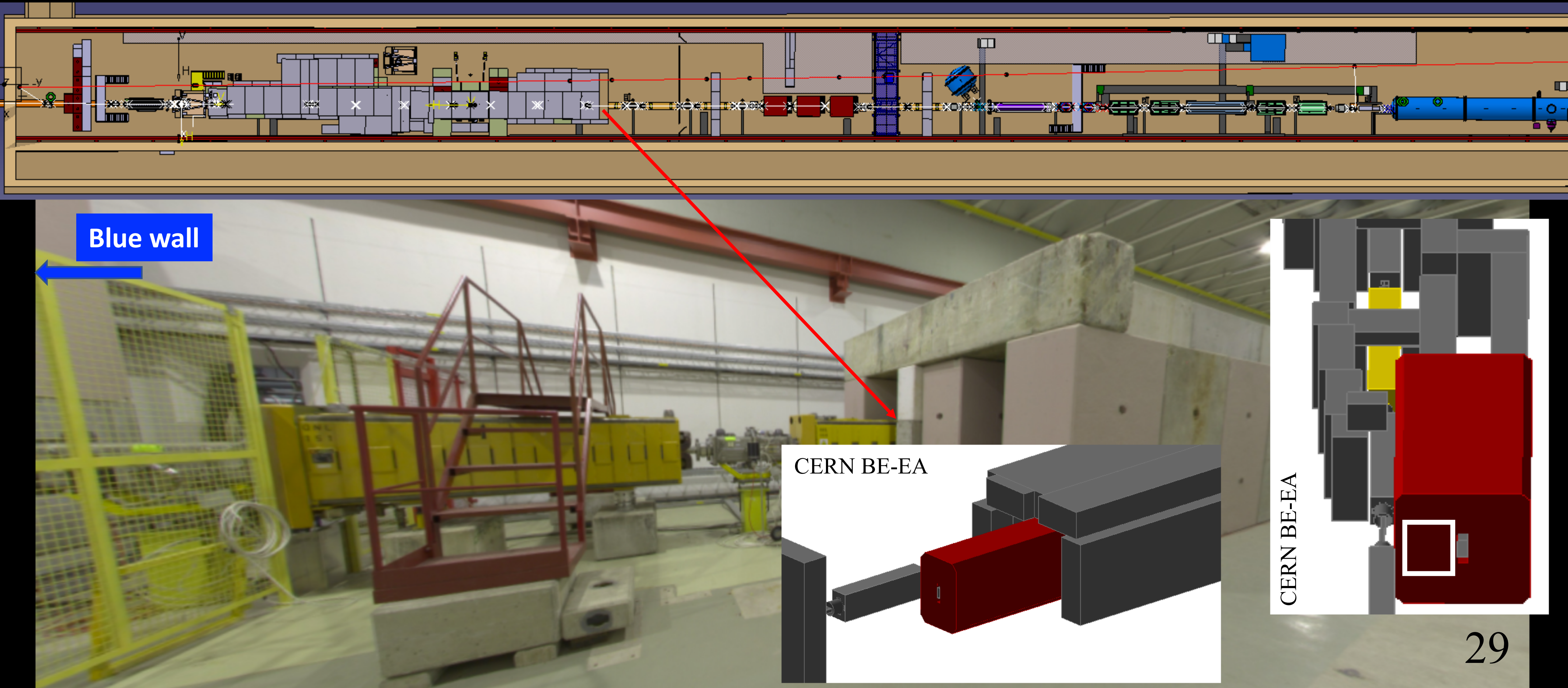




SHADOWS muon sweeping system:

A magnetized iron block as part of the TAX shielding structure

(currently studied in CERN BE-EA group)



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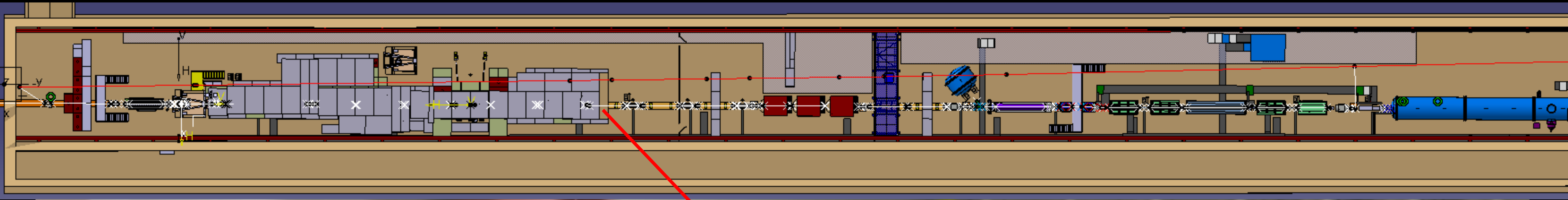
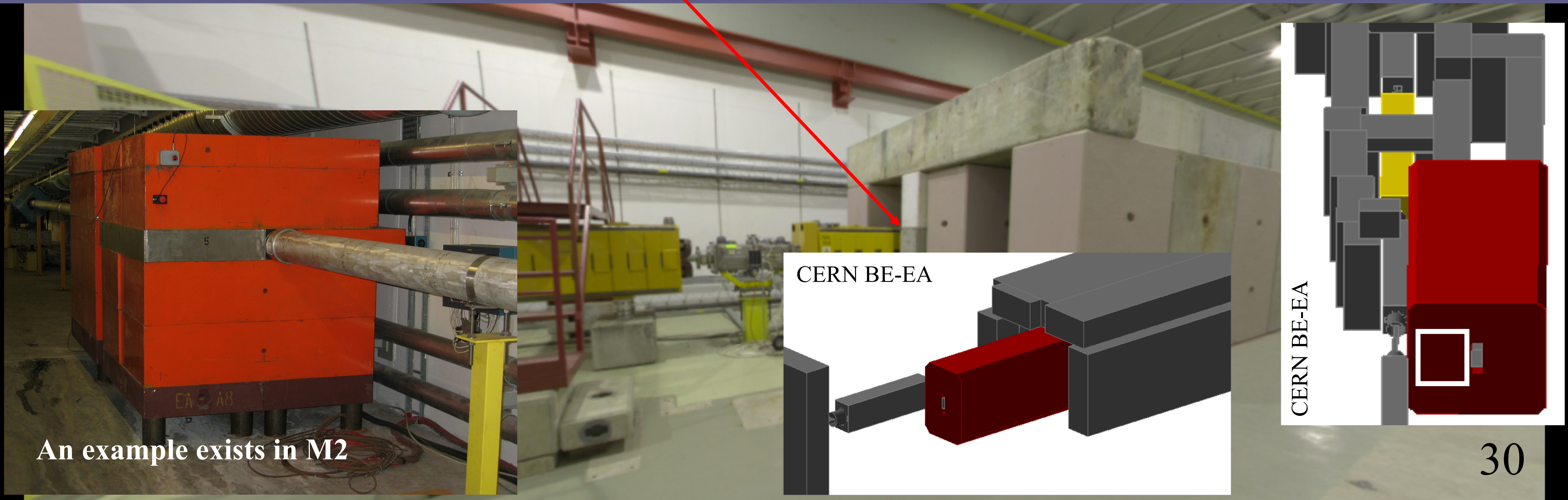
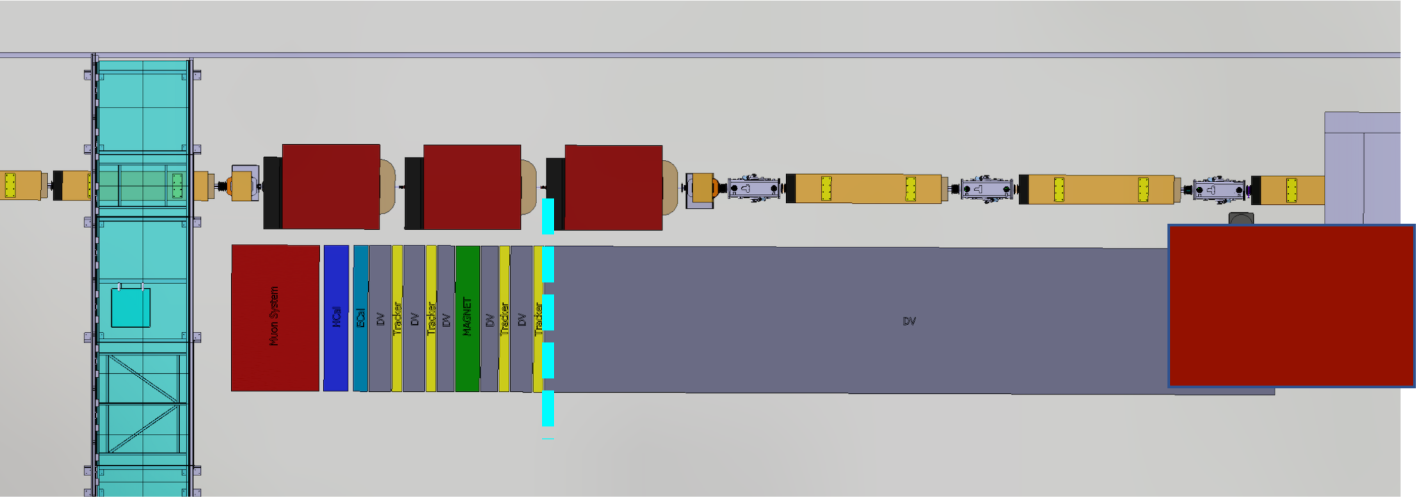
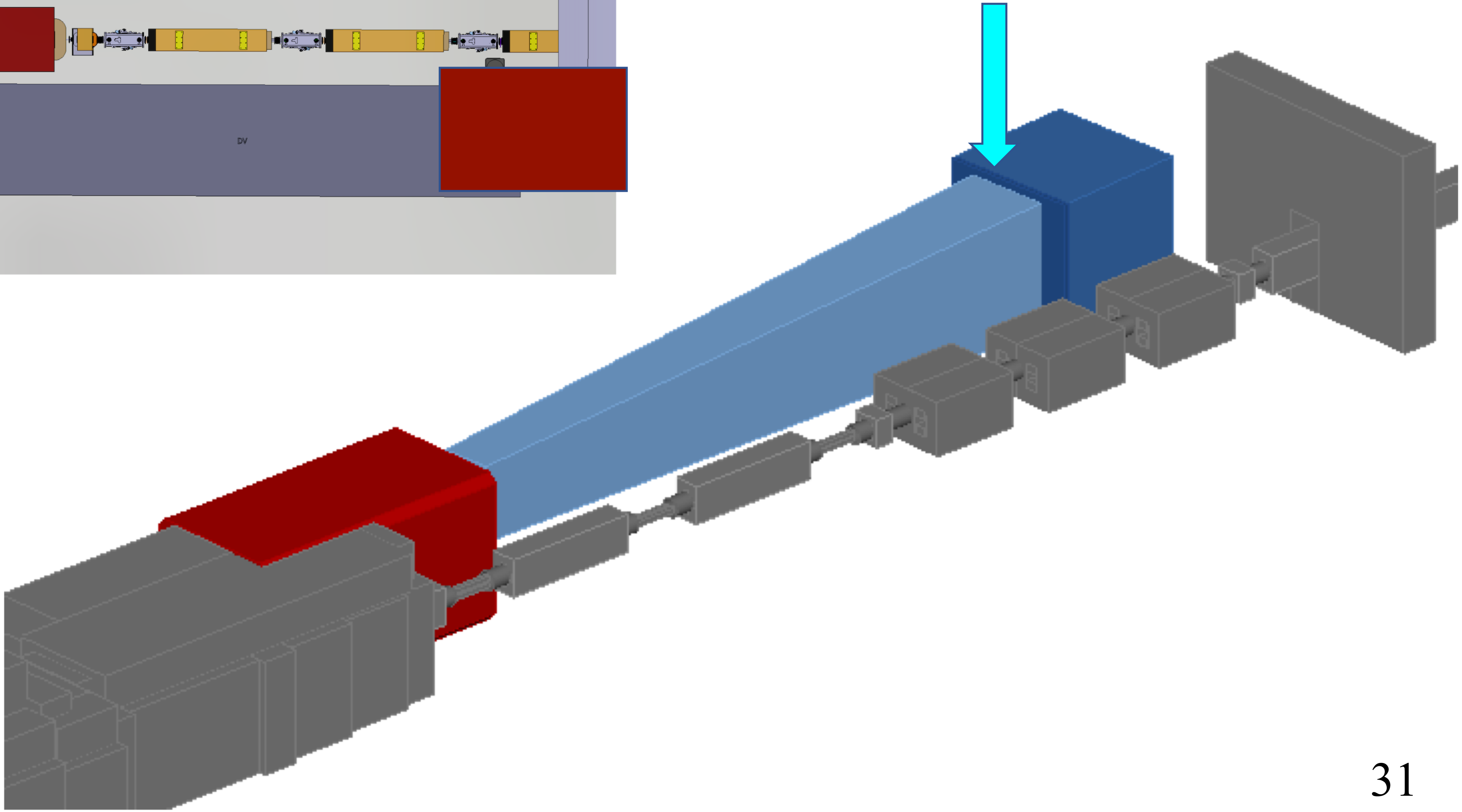




Background illumination at the SHADOWS spectrometer





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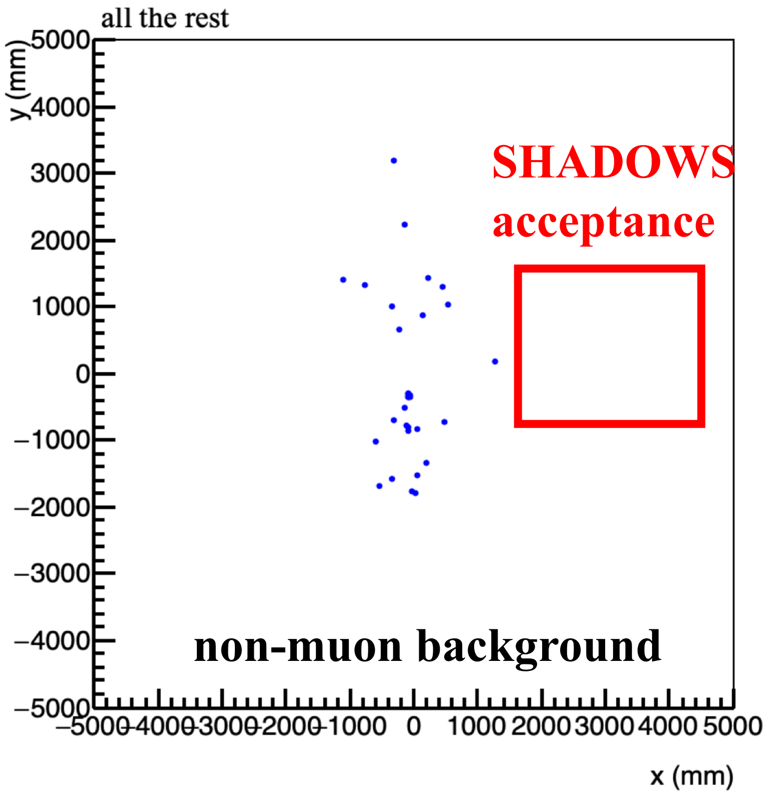
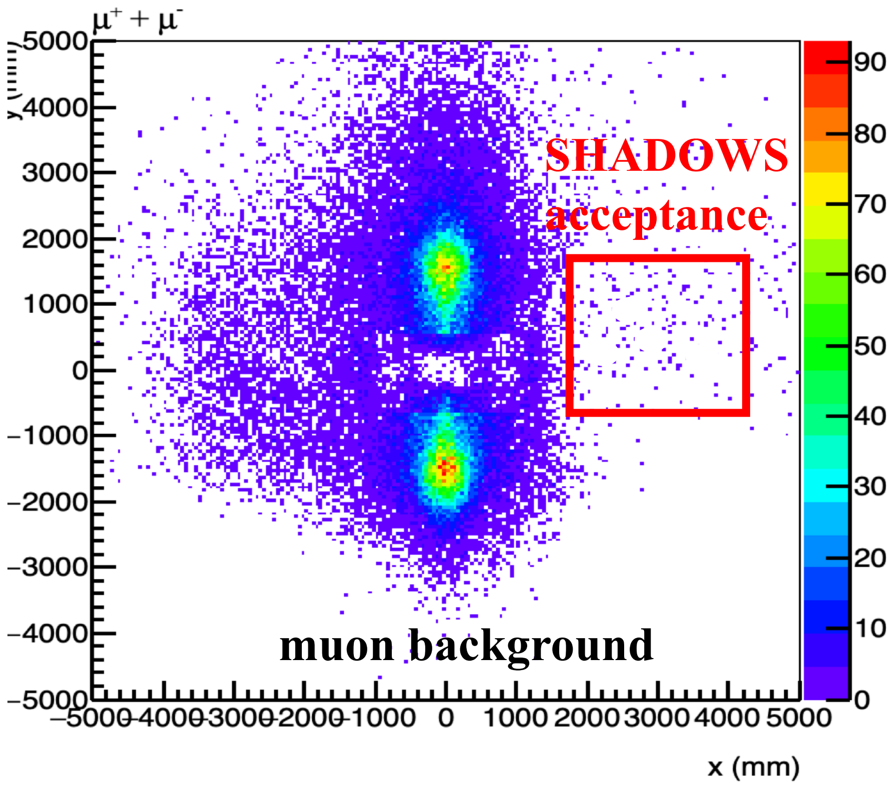
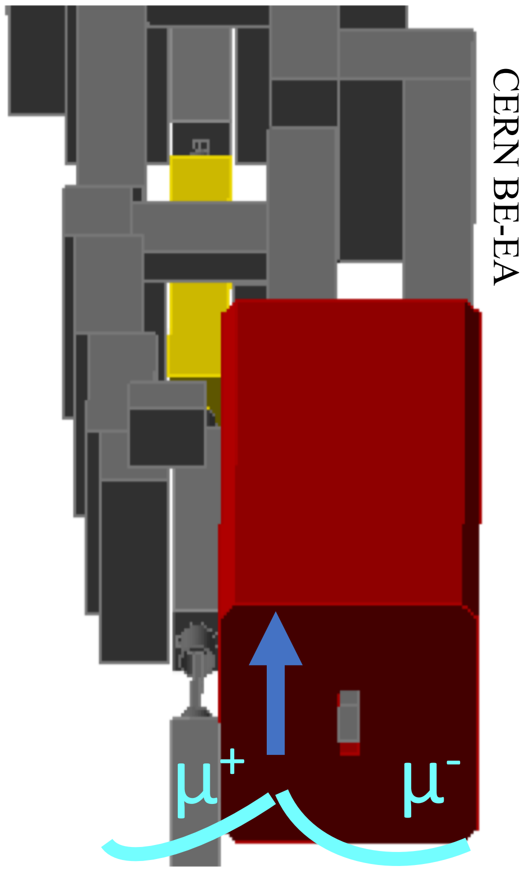




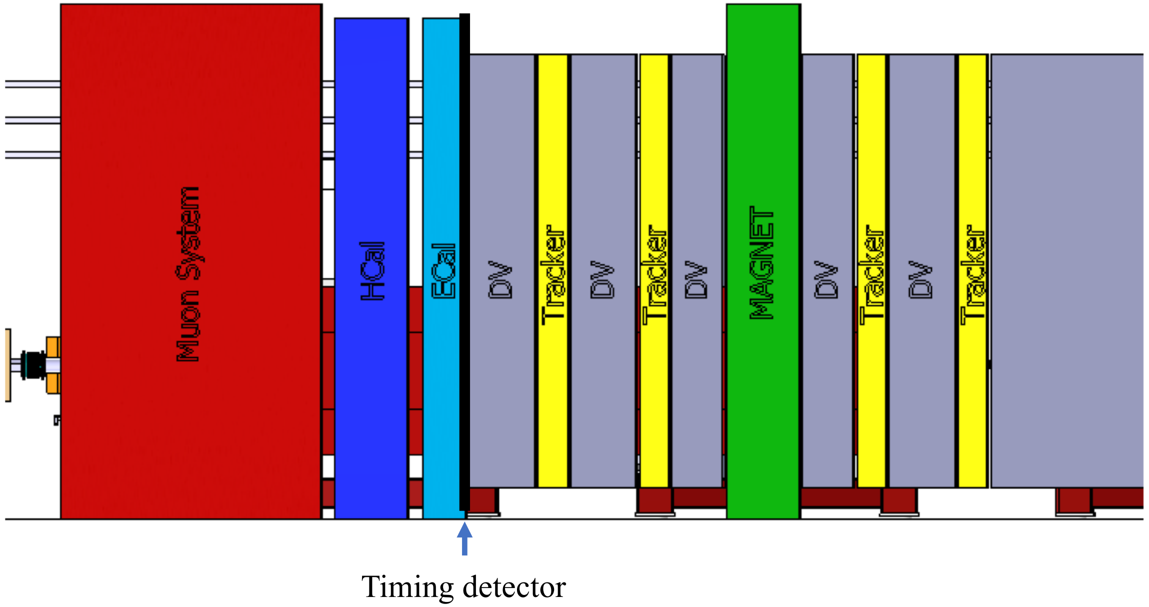


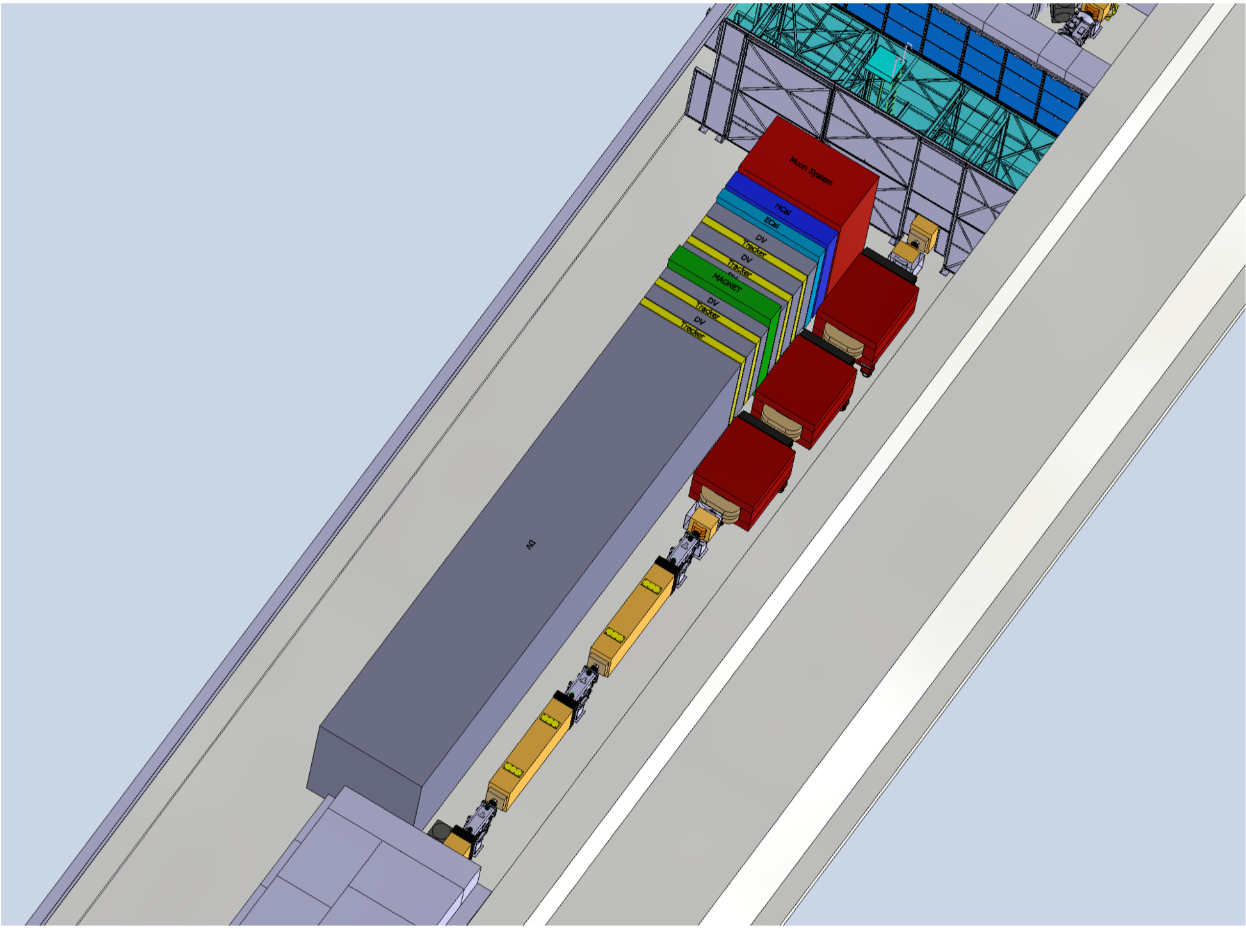
- All background components found negligible but the muon one.
- The muon background is reduced by already an order of magnitude in a first attempt by the magnetized iron block, Work in progress to further reduce it.

The detector

SHADOWS: A standard spectrometer

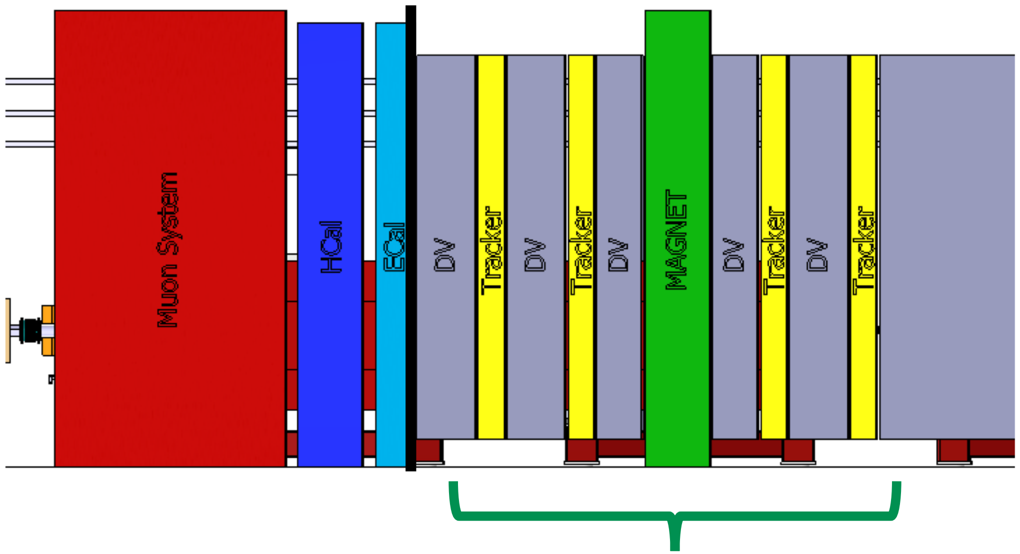
(we do not reinvent the wheel…)



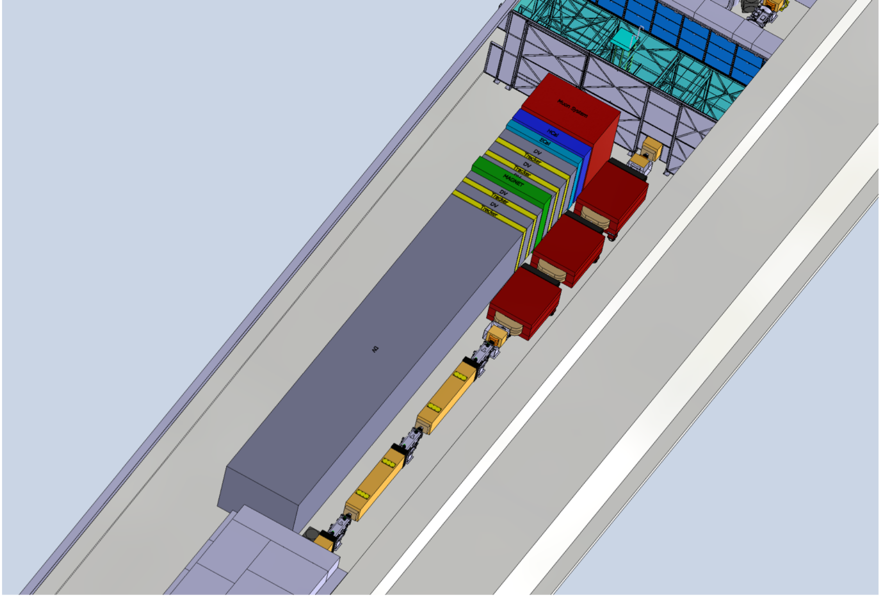


<u>Important message:</u> SHADOWS can be built with <u>existing technologies.</u>
R&D on new technologies is welcome but is not absolutely needed
More than one option per subdetector is already available on the market.
Preliminary contacts with many groups ongoing.

SHADOWS Tracker: requirements & layout



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



Dipole Magnet could be built at CERN-DT

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

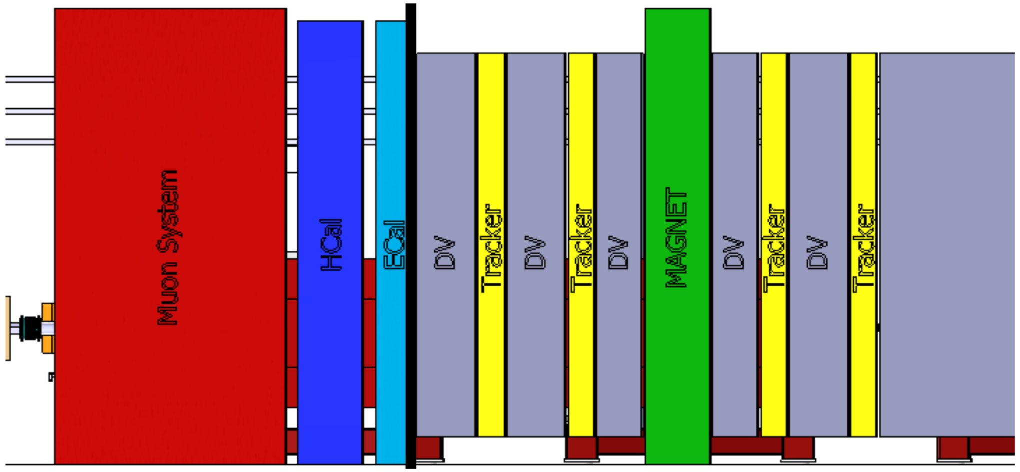
Notes:

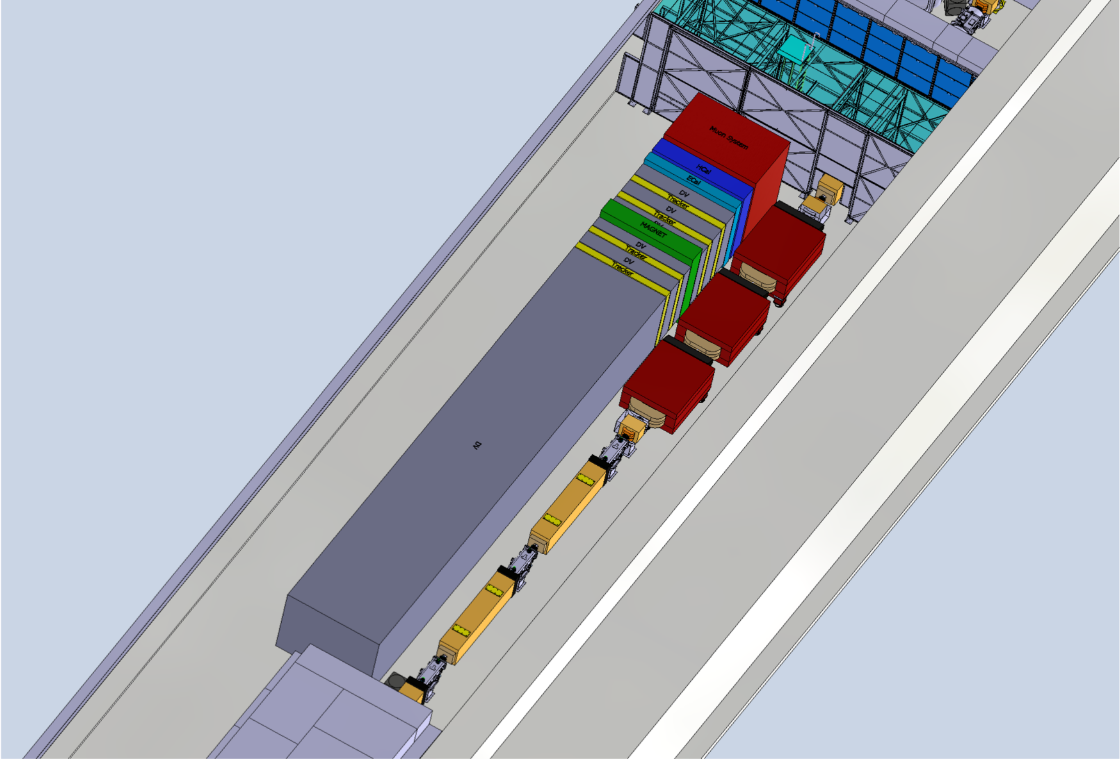
Vxy	Vertex X and Y resolution at the far end of Decay Volume
Vz	Vertex Z resolution at the far end of Decay Volume
ro	Curvature radius inside B field
theta	Angle of curvature inside B field (Result inaccurate for theta >~ 0.1)
σp/p	Relative momentum resolution

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





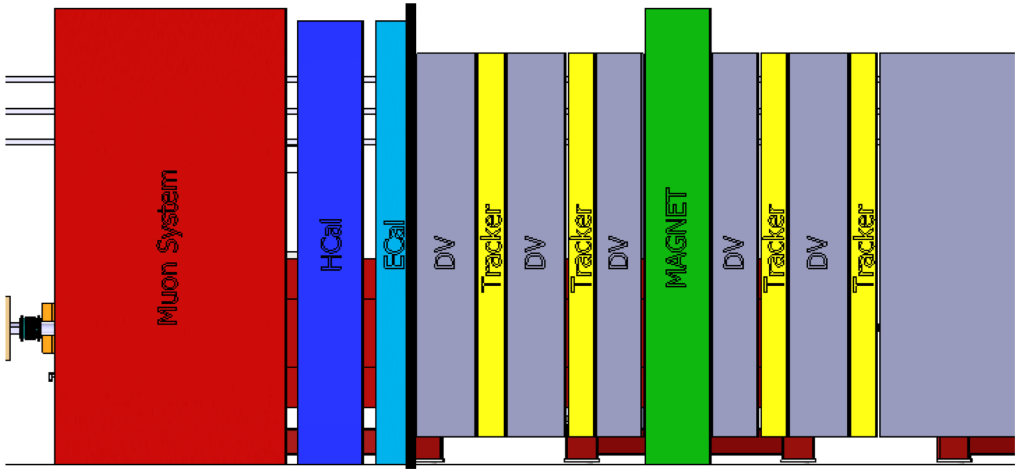
Possible options:

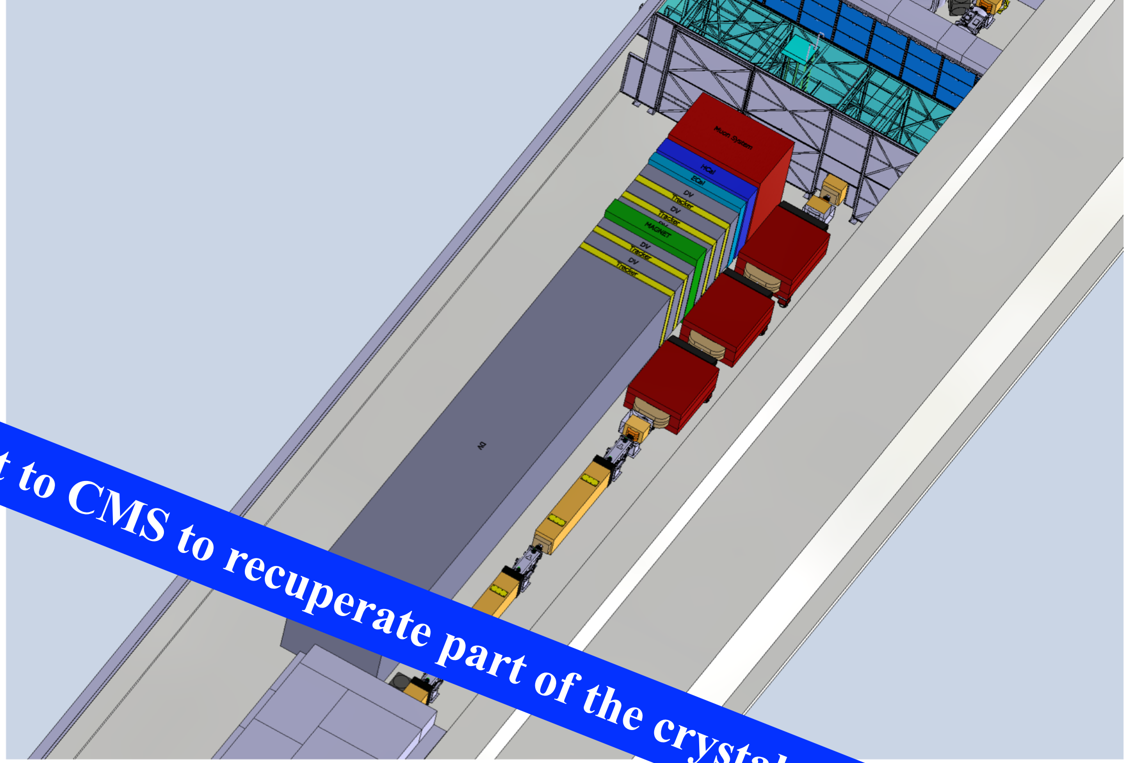
1. NA62 STRAW tubes: Ar(70%): CO_2 (30%), in vacuum, 5mm diameter; Single plane resolution:
One straw chamber is composed of four views (X, Y, U, V), one double-layer per view. Hit resolution better 400 um over
Most of the straw diameter per single layer, 8 layers per tracking station. Warm dipole magnet with 0.9 Tm bending power.
3-4 MeV mass resolution for HNL -> pi mu final states. Impact parameter resolution < 1 cm over 200 m length.

2. LHCb Outer Tracker: 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.

SHADOWS: Electromagnetic calorimeter





Request to CMS to recuperate part of the crystals during LS3

Possible options:

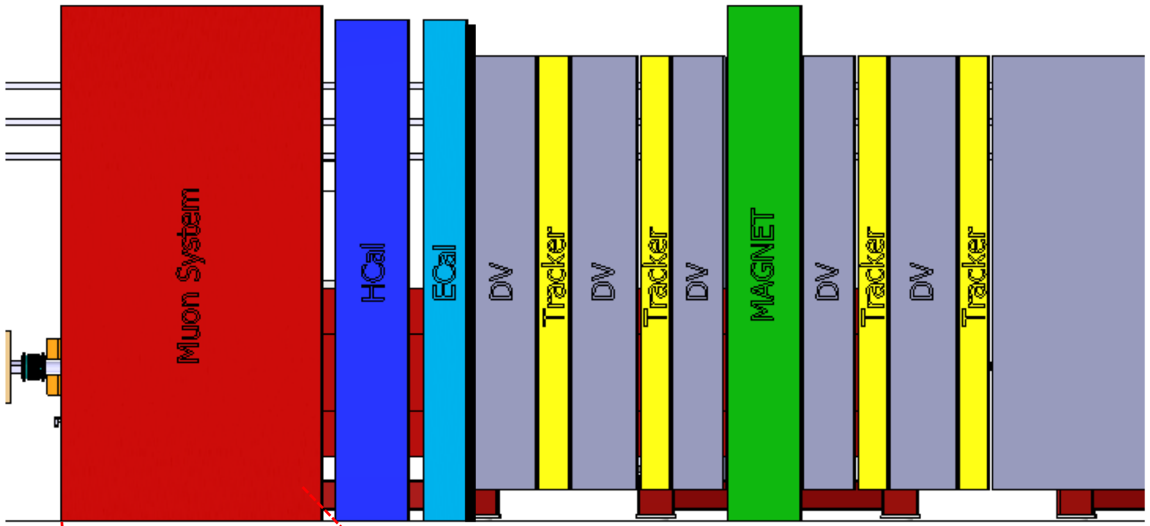
1. **PbWO4 crystals from CMS ECAL endcaps** – will be removed during LS3. Some reconditioning will be needed but a large fraction of crystals could be ready to be used.

2. **SHiP EM calorimeter – SplitCal concept.** longitudinally segmented lead sampling calorimeter with a total sampling depth of 20X0. 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.

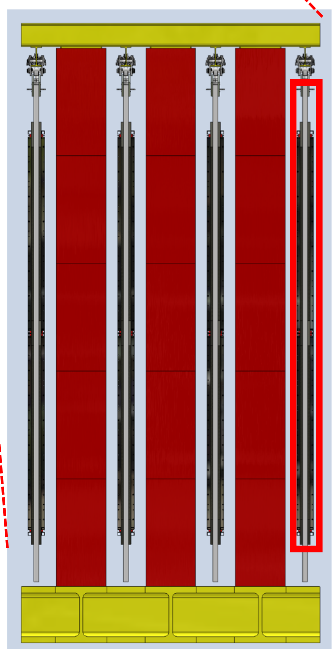
3. Other options certainly possible…

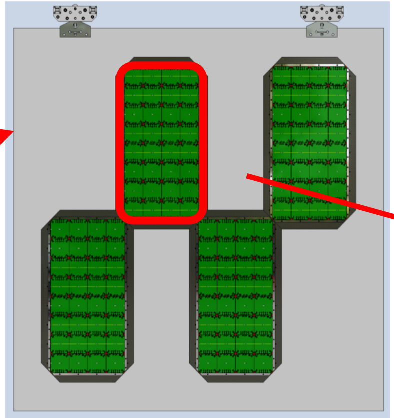
SHADOWS: The Muon Detector

INFN-LNF and INFN-Bologna



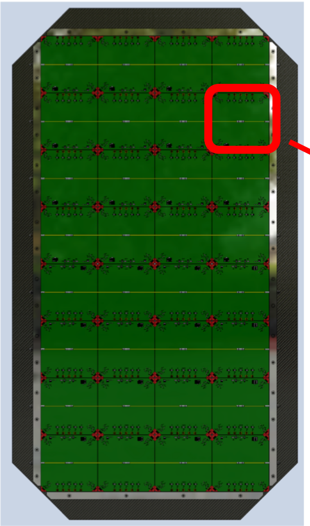
Baseline: scintillating tiles with direct SiPM readout.
Advantages: modular, cost-effective, high-efficiency, large light yield, high time resolution.



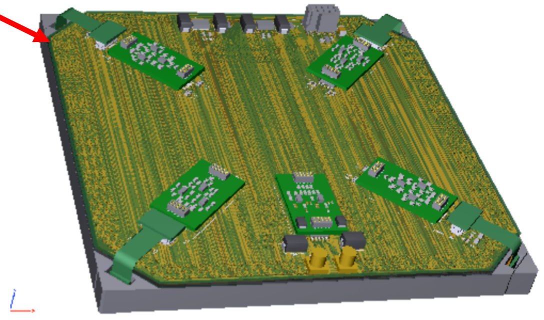


1 station = 8 modules
[same pattern staggered
on the other side of the wall]

1 module = 32 tiles



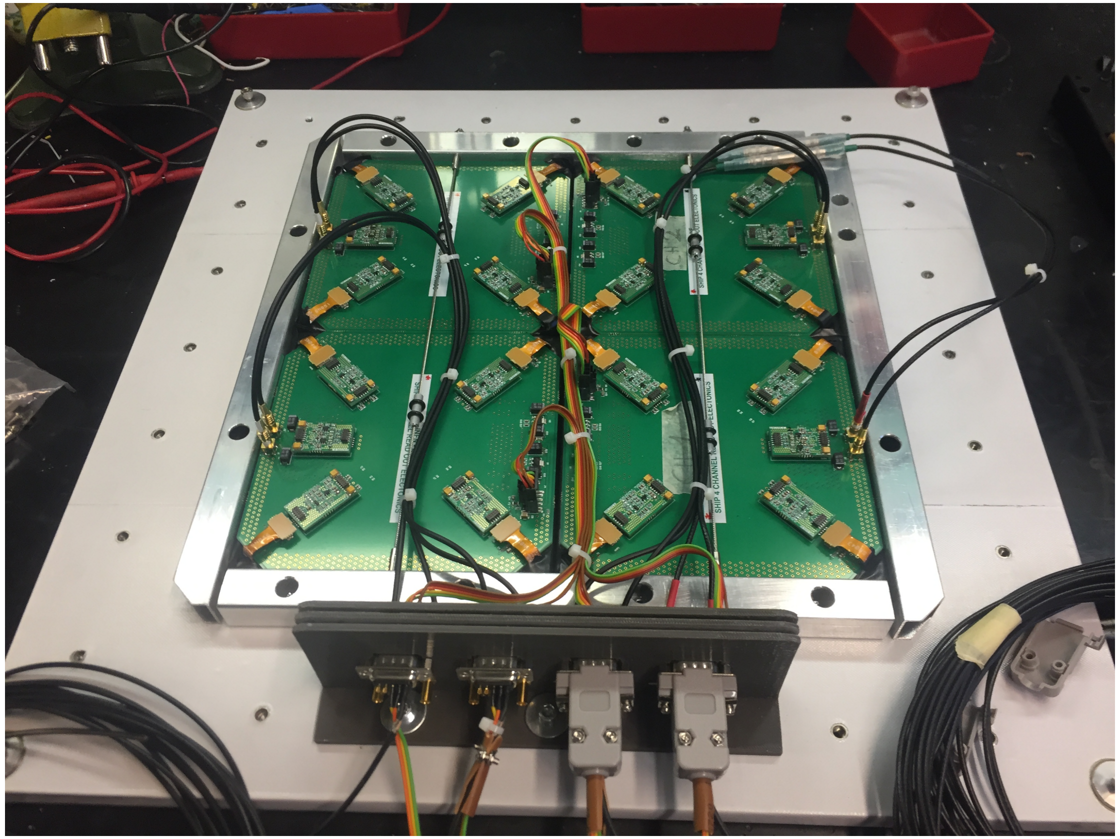
1 tile = 15x15 cm2,
Direct SiPM readout at the corners
One analog output per tile

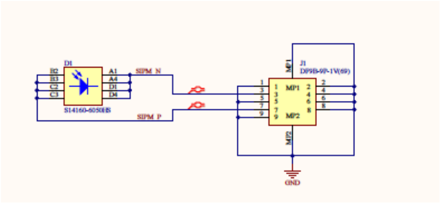


SHADOWS: The Muon Detector

4-tile prototype built in INFN Bologna/LNF

Electronics done by:
A. Balla, P. Ciambrone, G. Felici, G. Papalino & SEA team



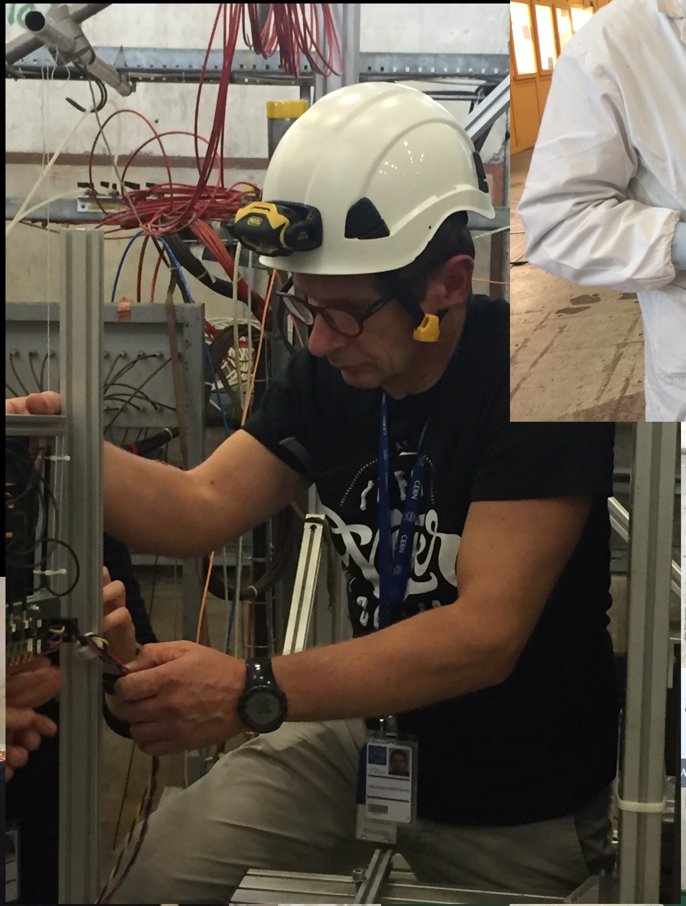


- Optic glue refractive index matches matches well with EJ200 scintillator.
- SiPM slot is still slightly visible in Russian scintillator.

SHADOWS Muon Detector: Test beam at BTF in January

Many many thanks to the BTF crew!

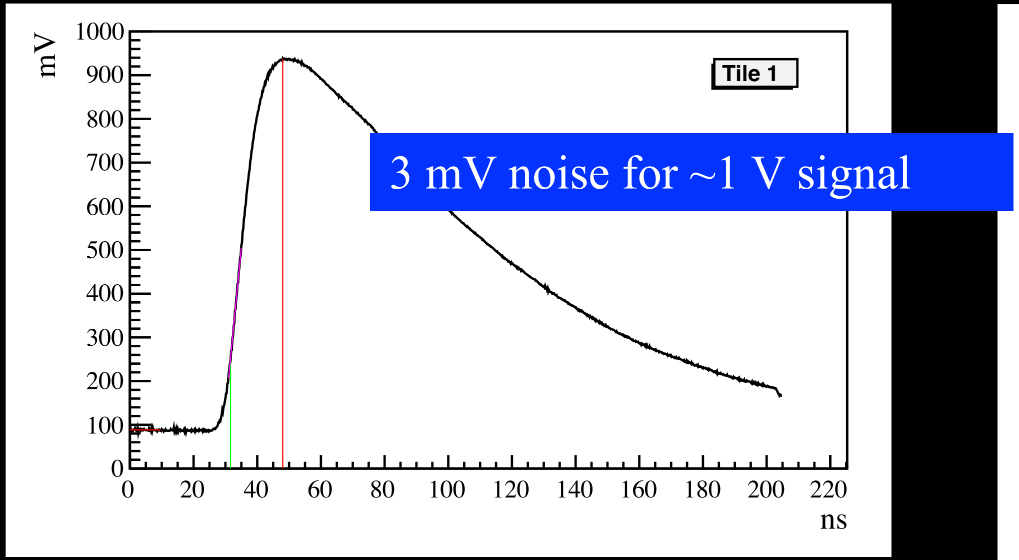
.. But this was just the last of a long series of test beams….



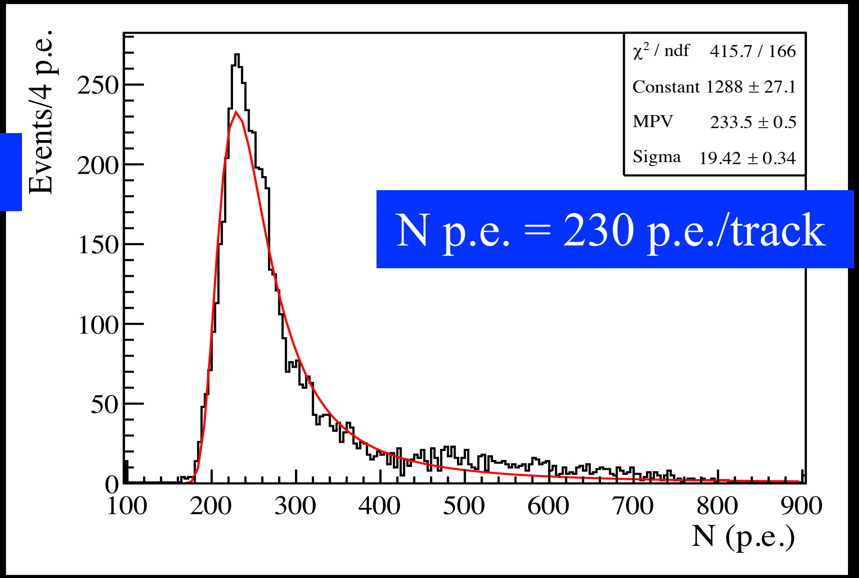
…..A beautiful team…

… for beautiful results!

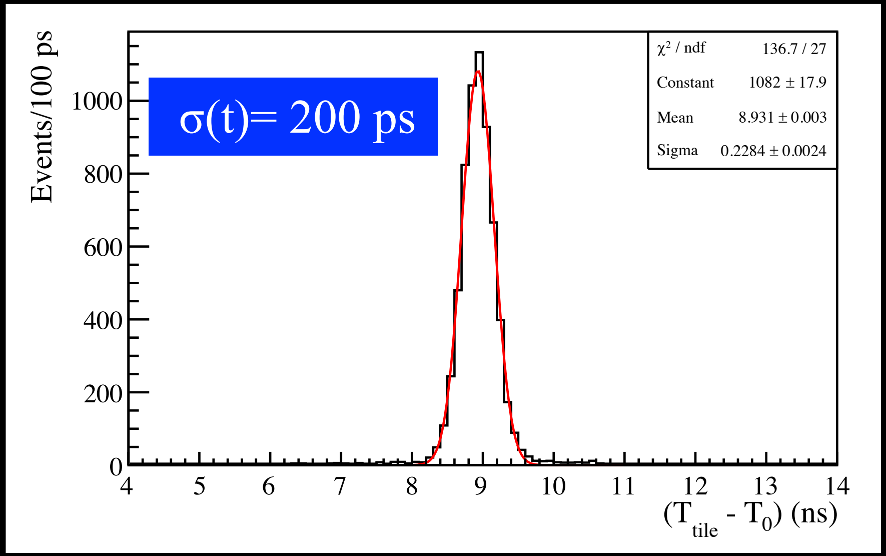
Waveform

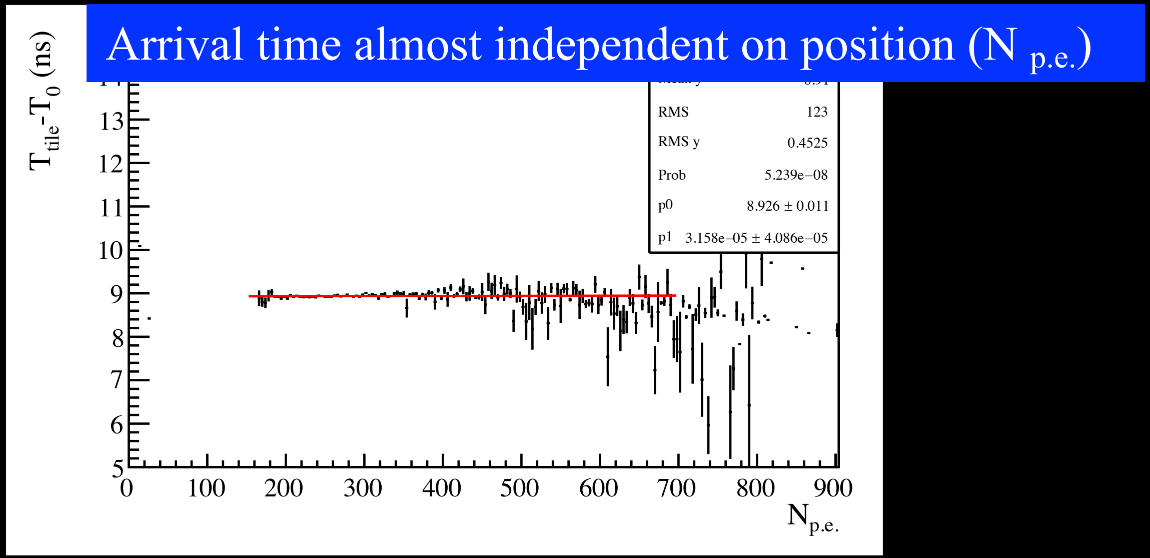


Charge spectrum



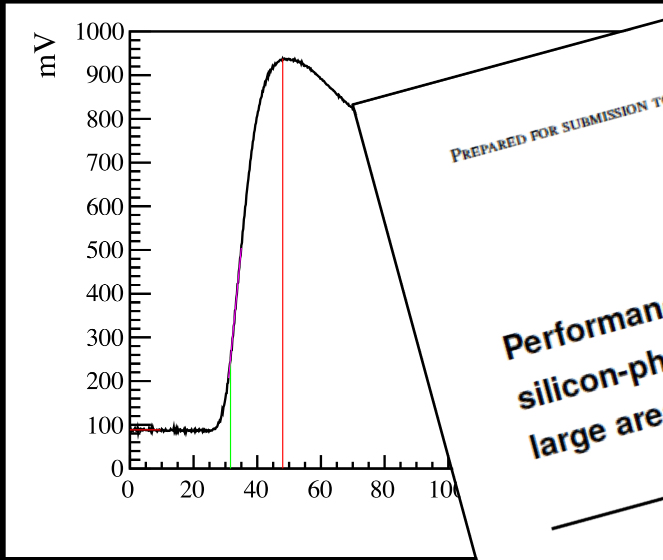
Time resolution

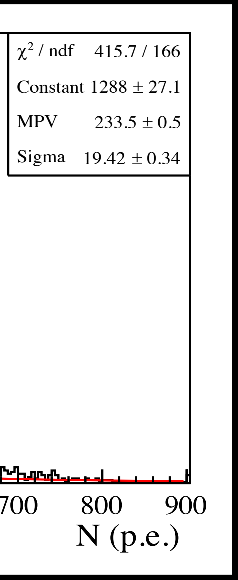




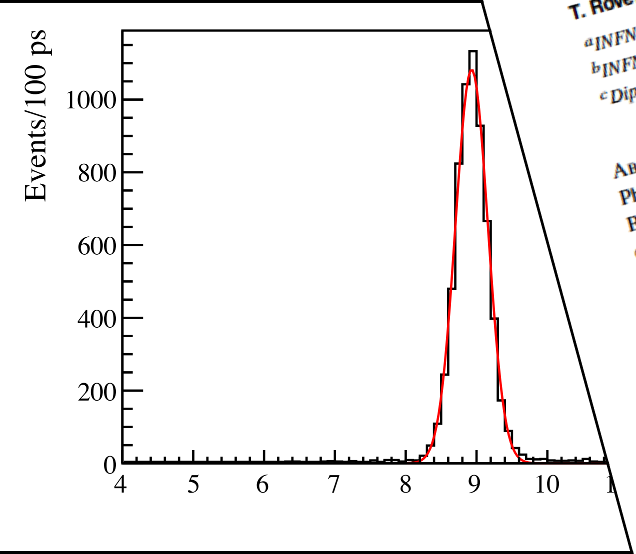
… for beautiful results!

Waveform

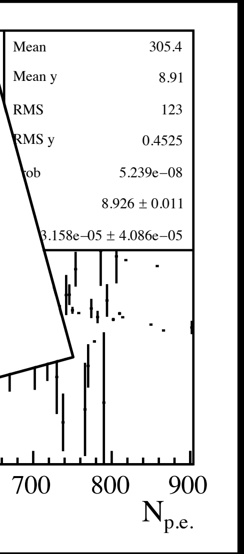


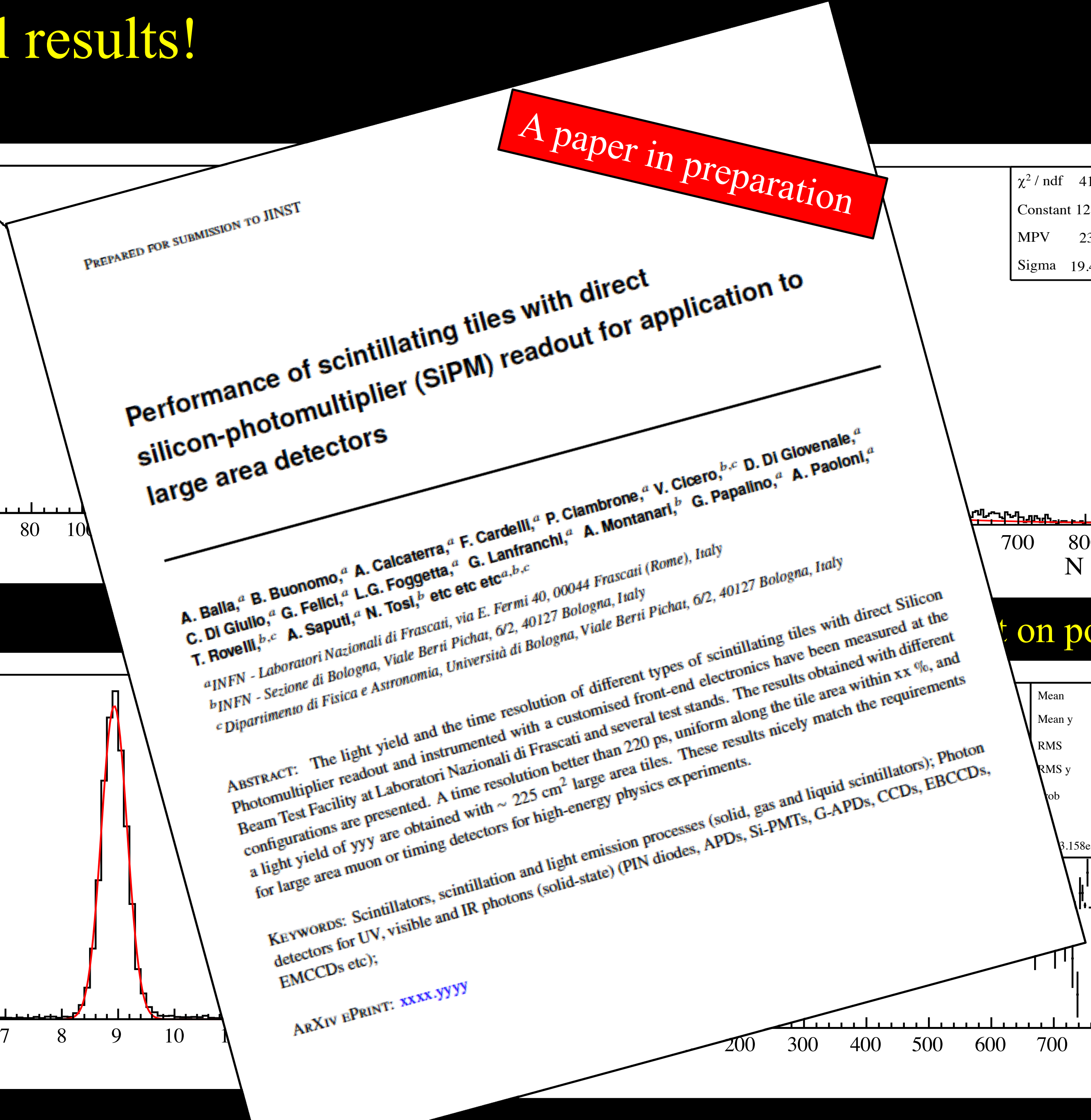


Time resolution



t on position ($N_{p.e.}$)





A paper in preparation

PREPARED FOR SUBMISSION TO JINST

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

A. Balla,[a] B. Buonomo,[a] A. Calcaterra,[a] F. Cardelli,[a] P. Ciambrone,[a] V. Cicero,[b,c] D. Di Giovenale,[a] C. Di Giulio,[a] G. Felici,[a] L.G. Foggetta,[a] G. Lanfranchi,[a] A. Montanari,[b] G. Papalino,[a] A. Paoloni,[a] T. Rovelli,[b,c] A. Saputi,[a] N. Tosi,[b] etc etc etc[a,b,c]

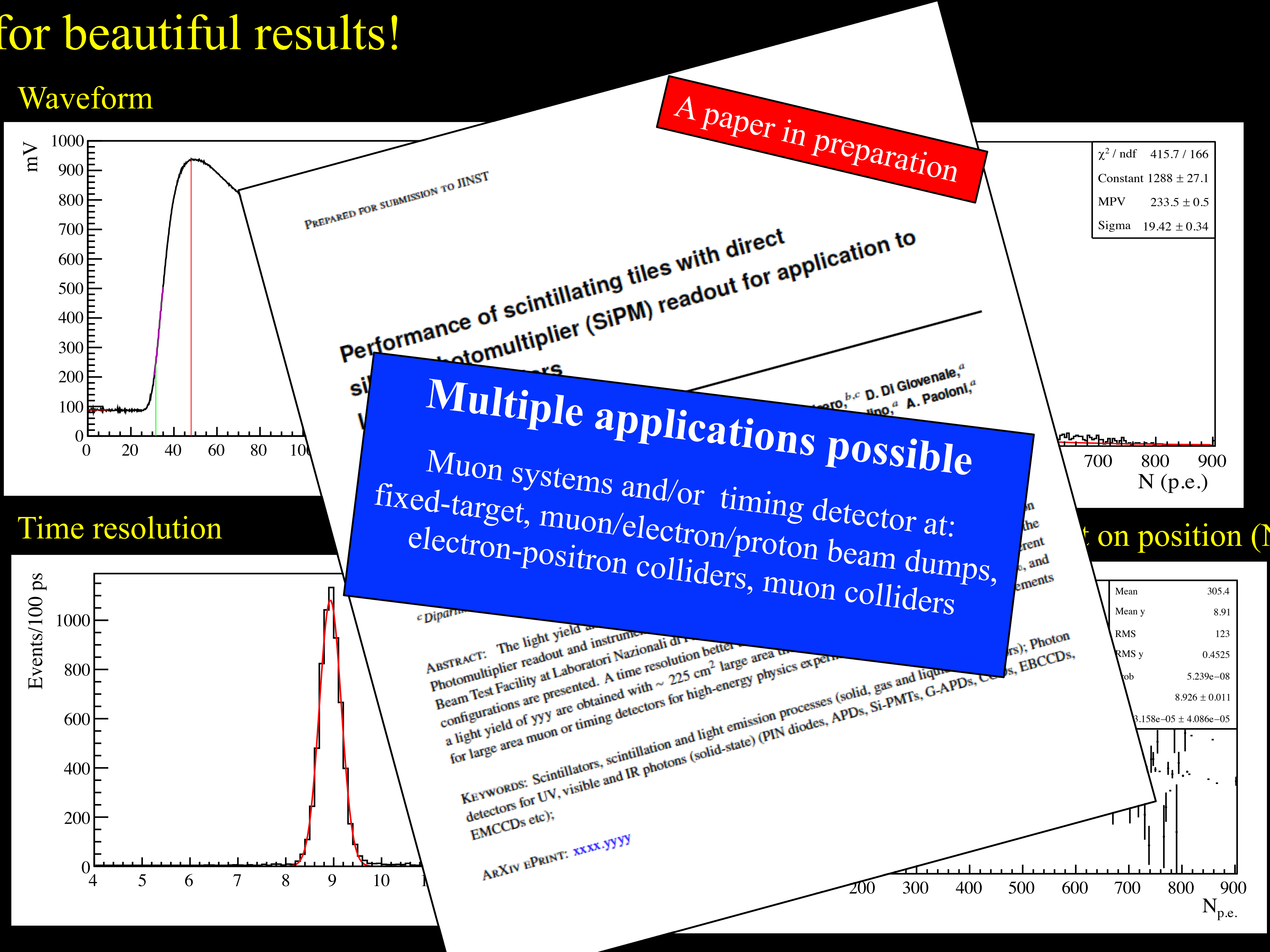
[a] INFN - Laboratori Nazionali di Frascati, via E. Fermi 40, 00044 Frascati (Rome), Italy
[b] INFN - Sezione di Bologna, Viale Berti Pichat, 6/2, 40127 Bologna, Italy
[c] Dipartimento di Fisica e Astronomia, Università di Bologna, Viale Berti Pichat, 6/2, 40127 Bologna, Italy

ABSTRACT: The light yield and the time resolution 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 at Laboratori Nazionali di Frascati and several test stands. The results obtained with different configurations are presented. A time resolution better than 220 ps, uniform along the tile area within xx %, and a light yield of yyy are obtained with ~ 225 cm^2 large area tiles. These results nicely match the requirements for large area muon or timing detectors for high-energy physics experiments.

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);

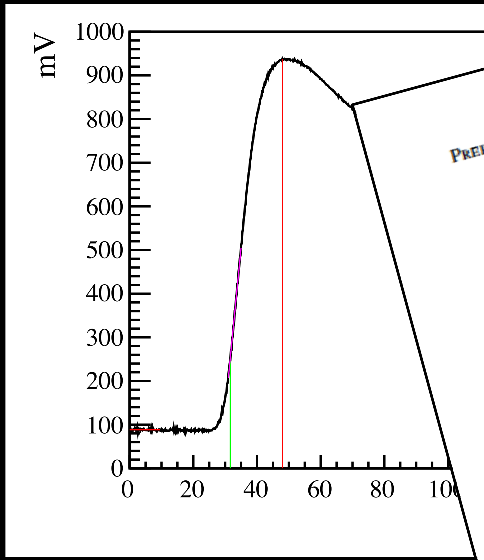
ARXIV EPRINT: xxxx.yyyy

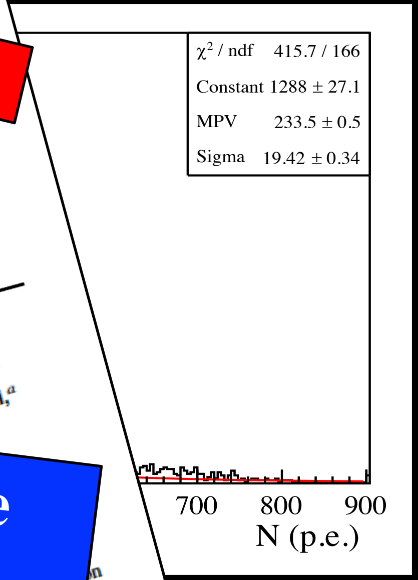
… for beautiful results!



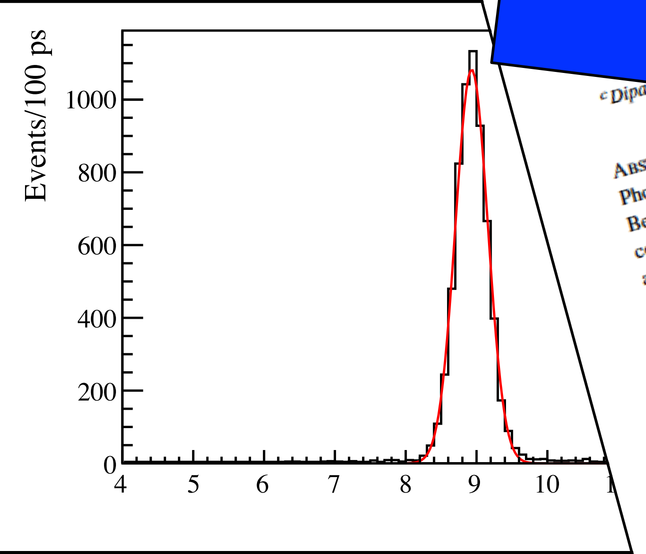
… for beautiful results!

Waveform

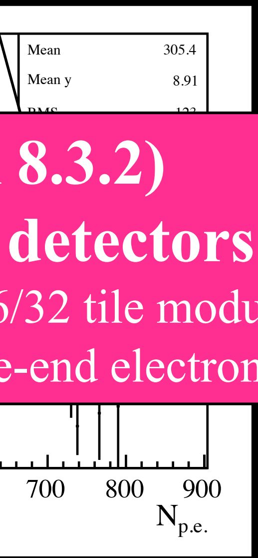


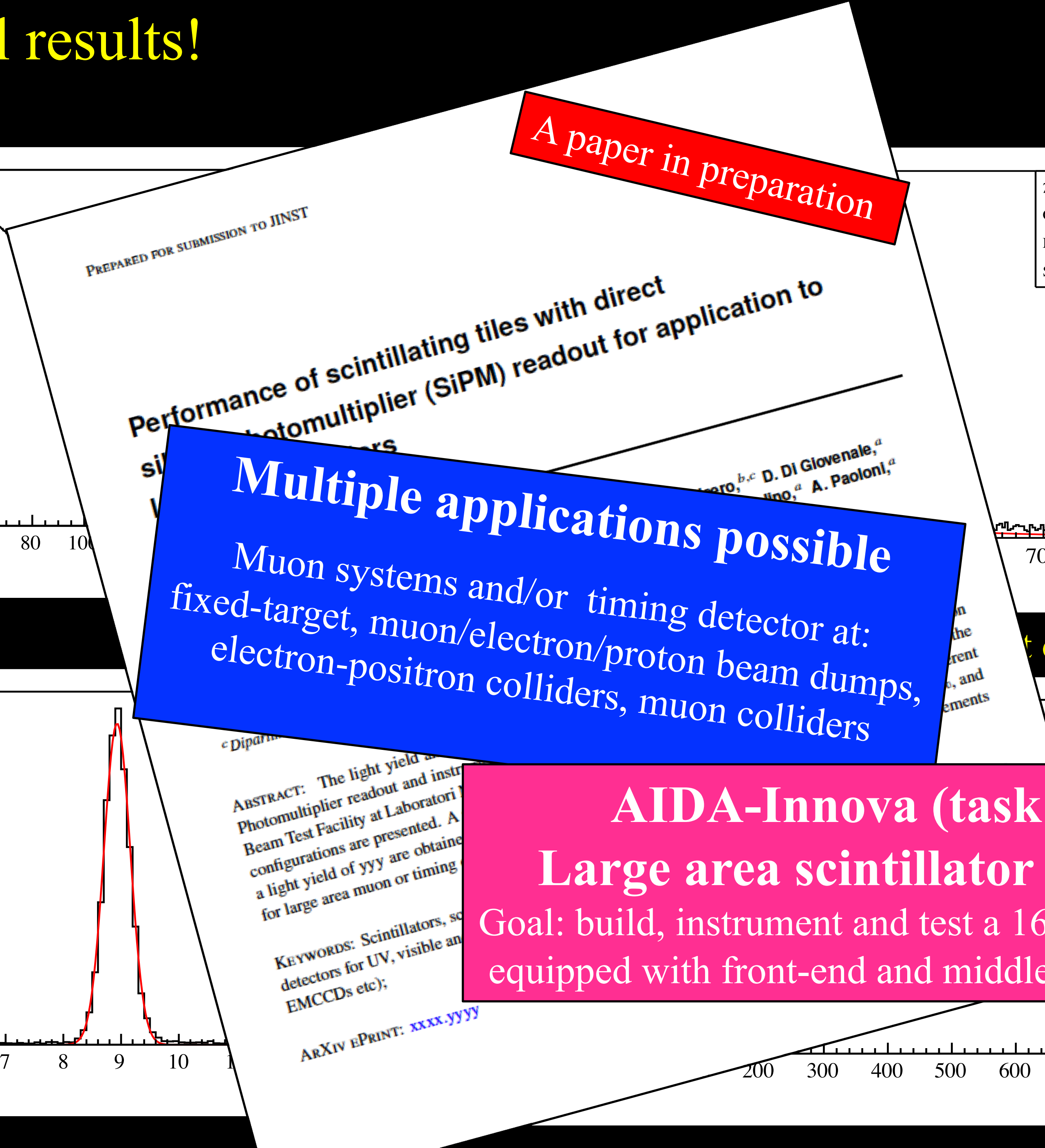


Time resolution



on position (N p.e.)





A paper in preparation

Multiple applications possible

Muon systems and/or timing detector at:
fixed-target, muon/electron/proton beam dumps,
electron-positron colliders, muon colliders

AIDA-Innova (task 8.3.2)
Large area scintillator detectors

Goal: build, instrument and test a 16/32 tile module equipped with front-end and middle-end electronics

SHADOWS Expression of Interest

SHADOWS Study Group (as presented at the PBC in March)
J. Bernhard, A. Calcaterra, V. Cafaro,
V. Cicero, P. Ciambrone, G. D'alessandro, F. Fabbri, 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.

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

Recently: A. Ceccucci joined the effort.

Discussions ongoing with other groups/individuals.

Finalize list of authors for submission of the EoI to the arXiv
and to SPSC.

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

SHADOWS

Search for Hidden and Dark Objects With the SPS

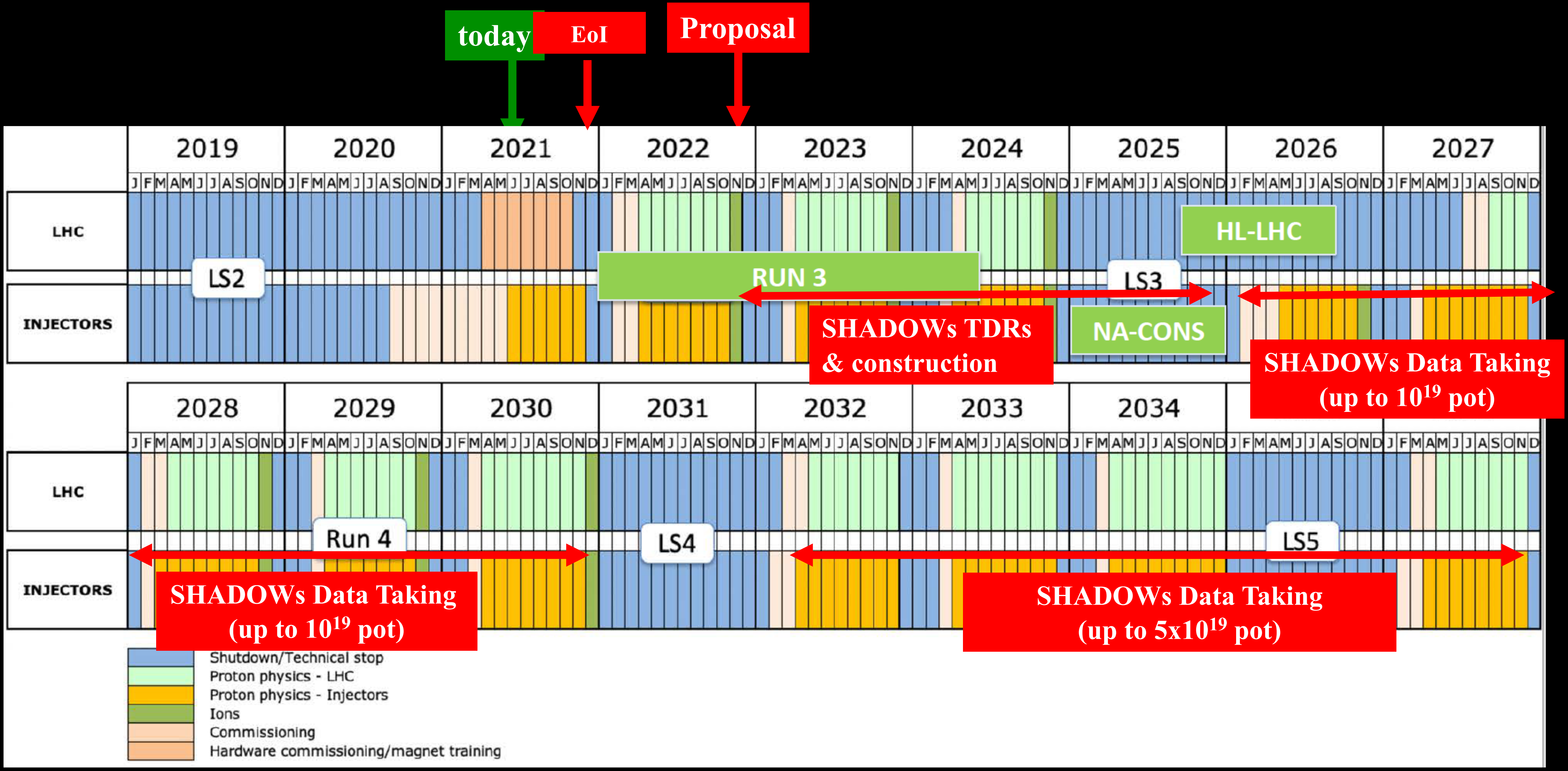
Expression of Interest

The authors

Executive Summary

We propose a new beam-dump experiment, SHADOWS, to search for a large variety of feebly-interacting particles (FIPs) 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 running concurrently to NA62 when NA62 is operated in beam-dump mode. SHADOWS can accumulate up to a few 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 which is allowed by cosmological and astrophysical observations. 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 mass 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



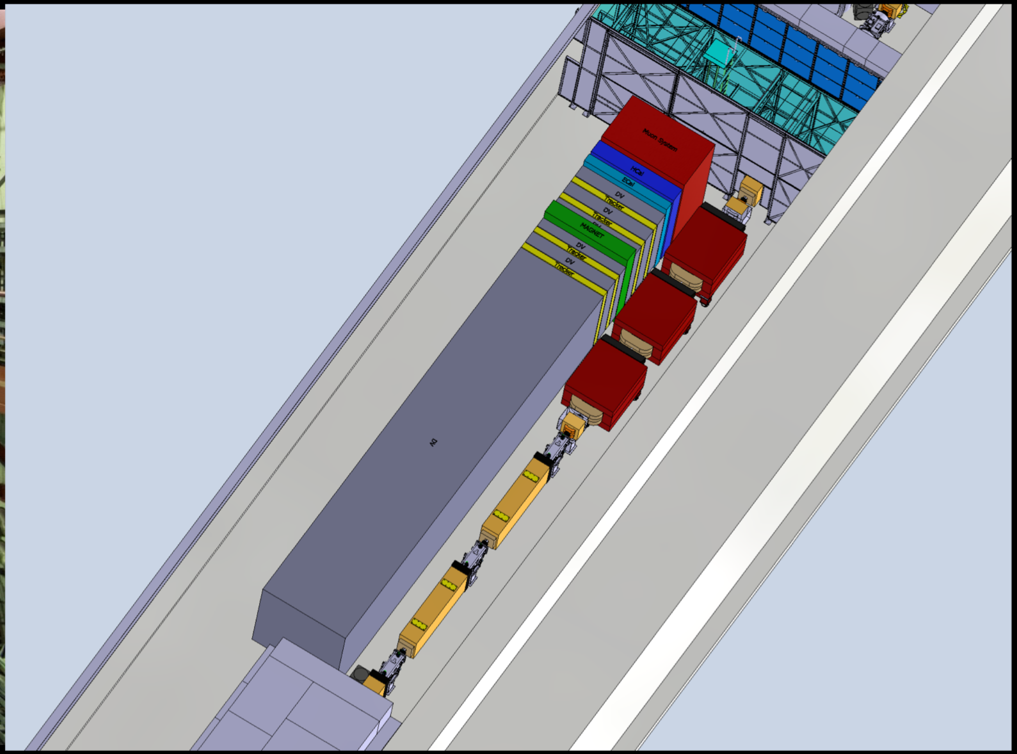
Conclusions

✓ SHADOWS is an off-axis experiment for FIPs physics that can be built in the ECN3 hall and take data concurrently to NA62/NA62x4/KLEVER when operated in beam-dump mode:
⇨ 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:
⇨ It naturally complements kaon experiments in dump-mode that are mostly sensitive to very forward objects (ALPs from Primakoff, Dark Photons from light resonances, etc.)

✓ Currently preparing the EoI to be sent in the fall to the SPSC and Snowmass

One beam, two experiments……:



… NA62 (NA62x4/KLEVER) and its "SHADOWS".

(to follow up updates on this programme, freely subscribe to **shadows-news@cern.ch**

Thanks for your attention!