SHADOWS

Search for **H**idden **A**nd **D**ark **O**bjects **W**ith the **S**PS

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[11] *University of Freiburg, Freiburg, Germany*
[12] *Charles University, Prague, Czech Republic*
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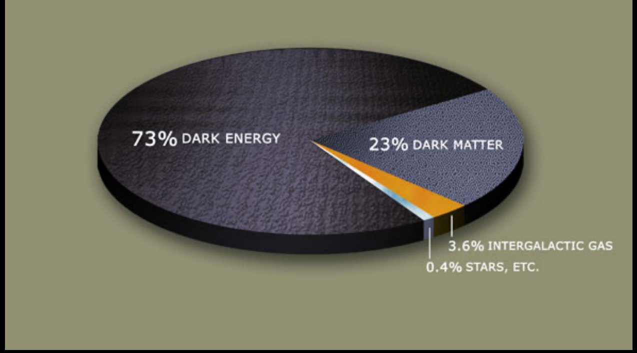
+ the invaluable support of the CBWG, ECN3 Task Force, NA-CONS team, and CERN EP-DT Group.

ECFA meeting – 17 November 2023

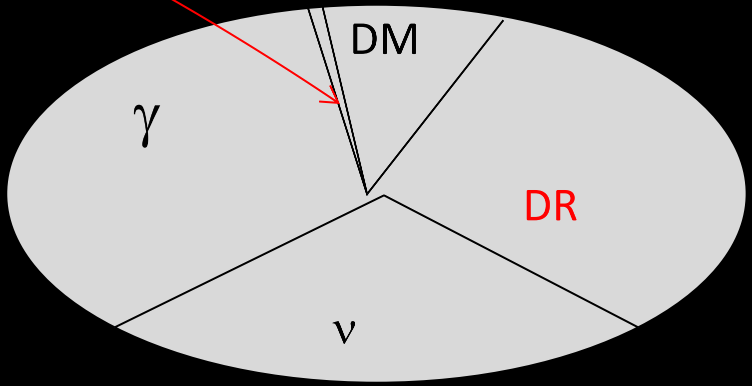
Evidence for New Physics



Atoms

In Energy chart they are 4%.

In number density chart ~ 5×10^{-10} relative to γ



We have no idea about DM number densities. (WIMPs ~ 10^{-8} cm^{-3}; axions ~ 10^{9} cm^{-3}. Dark Radiation, Dark Forces – Who knows!).

Lack of precise knowledge about nature of dark matter leaves a lot of room for existence of dark radiation, and dark forces – dark sector in general.

New IR degrees of freedom = light (e.g. sub-GeV) BSM states

Typical BSM model-independent approach is to include all possible BSM operators once very heavy new physics is integrated out:

$L_{SM+BSM} = - m_H^2\ (H^+_{SM} H_{SM})$ + all dim 4 terms $(A_{SM},\ y_{SM},\ H_{SM})$ +
(W.coeff. $/L^2$) × Dim 6 etc $(A_{SM},\ y_{SM},\ H_{SM})$ + …
all lowest dimension portals $(A_{SM},\ y_{SM},\ H,\ A_{DS},\ y_{DS},\ H_{DS})$ × portal couplings
+ dark sector interactions $(A_{DS},\ y_{DS},\ H_{DS})$

SM = Standard Model
DS – Dark Sector

Golden rule of any EFT approach: first look at low-dim operators !

The Portal Framework

Expand the SM with the minimal set of operators of lowest dimension gauge-invariant and renormalizable (all but the pseudo-scalar). This guarantees that the theoretical structure of the SM is preserved and any NP is just a simple (natural?) extension of what we already know..

Portal	Coupling
Dark Photon, A_μ	$-\frac{\epsilon}{2\cos\theta_W}F'_{\mu\nu}B^{\mu\nu}$
Dark Higgs, S	$(\mu S + \lambda S^2)H^\dagger H$
Axion, a	$\frac{a}{f_a}F_{\mu\nu}\tilde{F}^{\mu\nu}$, $\frac{a}{f_a}G_{i,\mu\nu}\tilde{G}_i^{\mu\nu}$, $\frac{\delta_\mu a}{f_a}\overline{\psi}\gamma^\mu\gamma^5\psi$
Sterile Neutrino, N	$y_N LHN$

They are representative of broad classes of models:
Each may predict distinct texture of New Physics interactions:

What are Feebly-Interacting Particles (FIPs)?

Very roughly:

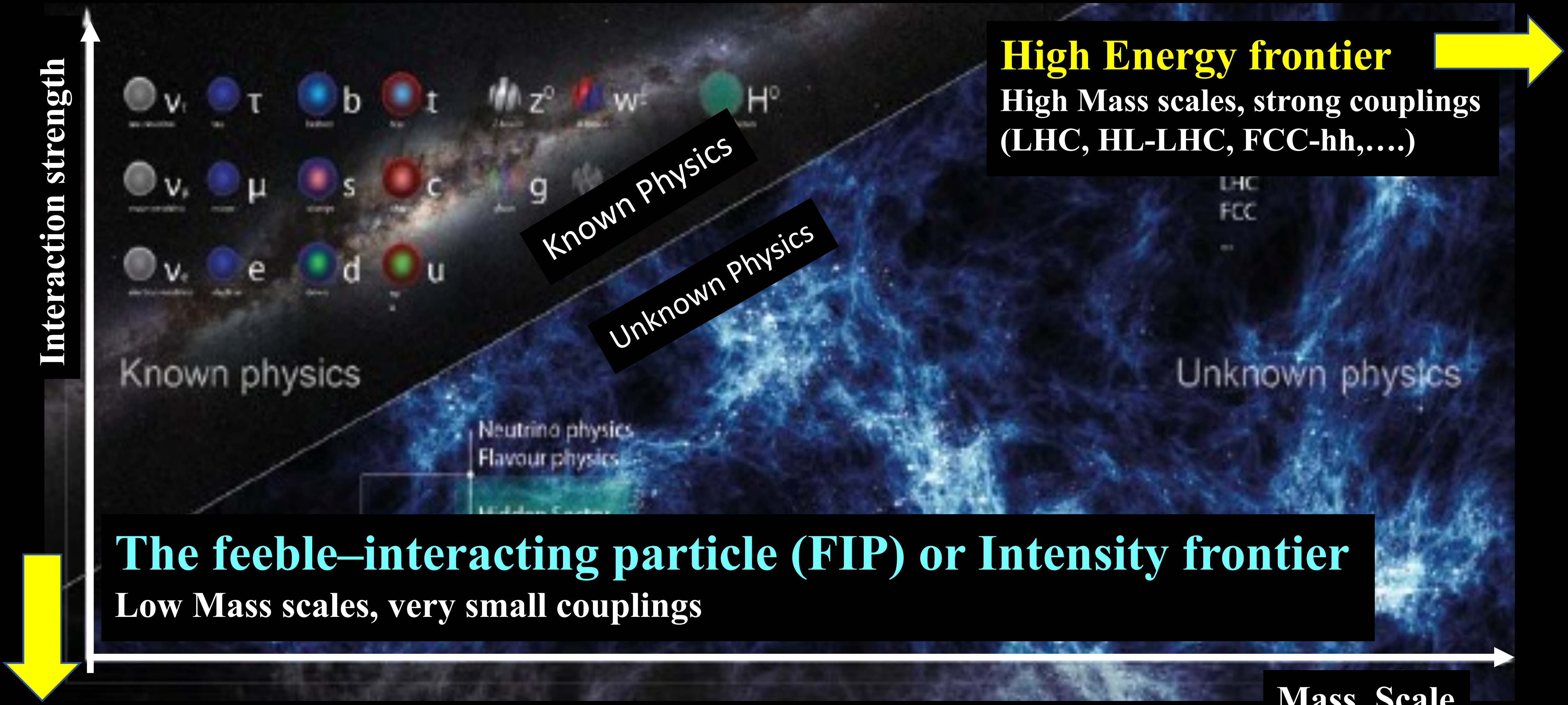
any NP with (dimensional or dimensionless) effective couplings $\ll 1$

[The smallness of the couplings can be generated by an approximate symmetry almost unbroken, and/or a large mass hierarchy between particles (as data seem to suggest)]

Fully complementary to high-energy searches.

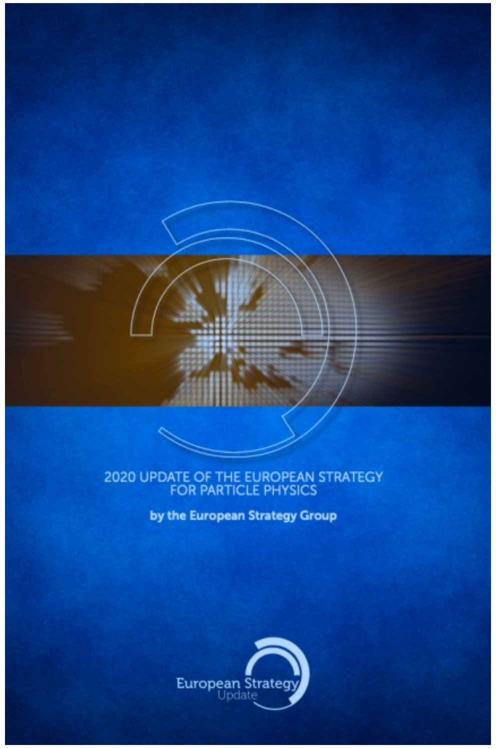
Naturally long-lived.

The Quest for New Physics



European Strategy for Particle Physics recommendations

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



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.*

SHADOWS and HIKE can explore simultaneously
the multi-TeV region via precision measurements and low-mass NP with very feeble couplings
becoming main players in the future CERN diversity programme.

SHADOWS: 20 very intense (and exciting) months..

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

Expression of Interest, 6 January 2022

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], N. Charitonidis[3], A. Ceccucci[3], V. Cicero[4], P. Ciambrone[2], H. Danielsson[3], A. De Roeck[3], F. Duval[3], G. D'Alessandro[3], G. Felici[2], L. Foggetta[2], L. Gatignon[5], A. Gerbershagen[3], V. Giordano[4], G. Lanfranchi[2], I. Lax[4], A. Montanari[4], R. Murphy[3], T. Napolitano[2], A. Paoloni[2], G. Papalino[2], T. Rovelli[4], A. Saputi[2], S. Schuchmann[6], F. Stummer[7], G. Torromeo[4], N. Tosi[4], A. Vannozzi[2].

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CERN-SPSC-2022-009 / SPSC-EOI-023
12/01/2022

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

Letter of Intent, 4 November 2022

SHADOWS

Search for Hidden And Dark Objects With the SPS

Letter of Intent

M. Alviggi[1], S. Bachmann[2], W. Baldini[3], A. Balla[4], M. Biglietti[8], V. Büscher[11], A. Calcaterra[4], V. Cafaro[5], N. Charitonidis[6], A. Ceccucci[6], V. Cicero[5], P. Ciambrone[4], H. Danielsson[6], M. Dellapietra[1], A. De Roeck[6], F. Duval[6], G. Felici[4], T. Ferber[7], L. Foggetta[4], M. Gatta[4], A. Gerbershagen[13], V. Giordano[5], S. Hansmann-Menzemer[2], P. Iengo[1], M. Iodice[8], K. Jakobs[9] M. Klute[7], K. Köneke[9], M. Koval[10], G. Lanfranchi[4], A. Laudrain[11], I. Lax[5], B. Leverington[2], P. Lichard[6], K. Massri[6], A. Montanari[5], R. Murphy[6,12], T. Napolitano[4], F. Neuhaus[11], L. J. Nevay[6], A. Paoloni[4], G. Papalino[4], U. Parzefall[9], S. Ritter[11], T. Rovelli[5,14], A. Saputi[3], B. Schmidt[6], M. Schott[11], H.C. Schultz-Coulon[2], G. Sekhniaidze[1], F. Stummer[6,12], G. Torromeo[5], N. Tosi[5], U. Uwer[2], M. van Dijk[6], A. Vannozzi[4], R. Wanke[11], C. Weiser[9], P. Wertelaers[6], T. Zickler[6]

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CERN-SPSC-2022-030 / SPSC-I-256
04/11/2022

Technical Proposal, 18 August 2023

SHADOWS

Search for Hidden And Dark Objects With the SPS

Technical Proposal

M. Alviggi[1], S. Bachmann[2], W. Baldini[3], A. Balla[4], M. Barth[2], M. Biglietti[1], V. Büscher[6], A. Calcaterra[4], V. Cafaro[7], M. Cavallina[3], A. Ceccucci[8], D. Chouhan[6], V. Cicero[7], P. Ciambrone[4], H. Danielsson[8], M. Della Pietra[1], C. Delogu[6], A. De Roeck[8], L. Dittmann[2], F. Duval[8], G. Felici[4], T. Ferber[9], L. Foggetta[4], E. Gamberini[8], M. Gatta[4], A. Gerbershagen[10], V. Giordano[7], T. Gross[2], S. Hansmann-Menzemer[2], P. Iengo[5], M. Iodice(5), K. Jakobs[11], J. Kieseler[9], M. Klute[9], K. Köneke[11], M. Koval[13], C. Langenbruch[2], G. Lanfranchi[4], A. Laudrain[6], I. Lax[8], T. M. Leeflang[2], G. Lehmann Miotto[8], B. Leverington[2], P. Lichard[8], K. Massri[8,16], A. Montanari[7], T. Napolitano[4], A. Paoloni[4], G. Papalino[4], U. Parzefall[11], B. Ponzio[4], B. Regnery[9], S. Ritter[6], S. Rosati[14], T. Rovelli[15,7], S. Roy[2], A. Saputi[3], B. Schmidt[8], M. Schott[6], D. Schub[2], H.C. Schultz-Coulon[2], G. Sekhniaidze[1], R. Stamen[2], G. Torromeo[7], N. Tosi[7], N. Trevisani[6], U. Uwer[2], A. Vannozzi[4], C. Wang[6], R. Wanke[6], J. Webb[11], C. Weiser[11], C. Welschoff[2], P. Wertelaers[8]

Abstract

We propose a new proton 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 copper-iron based 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. SHADOWS will take data off-axis concurrently to the HIKE experiment when the P42 beamline is operated in beam-dump mode and aims to accumulate up to 5×10^{19} protons on target in about 4 integrated years of operation.

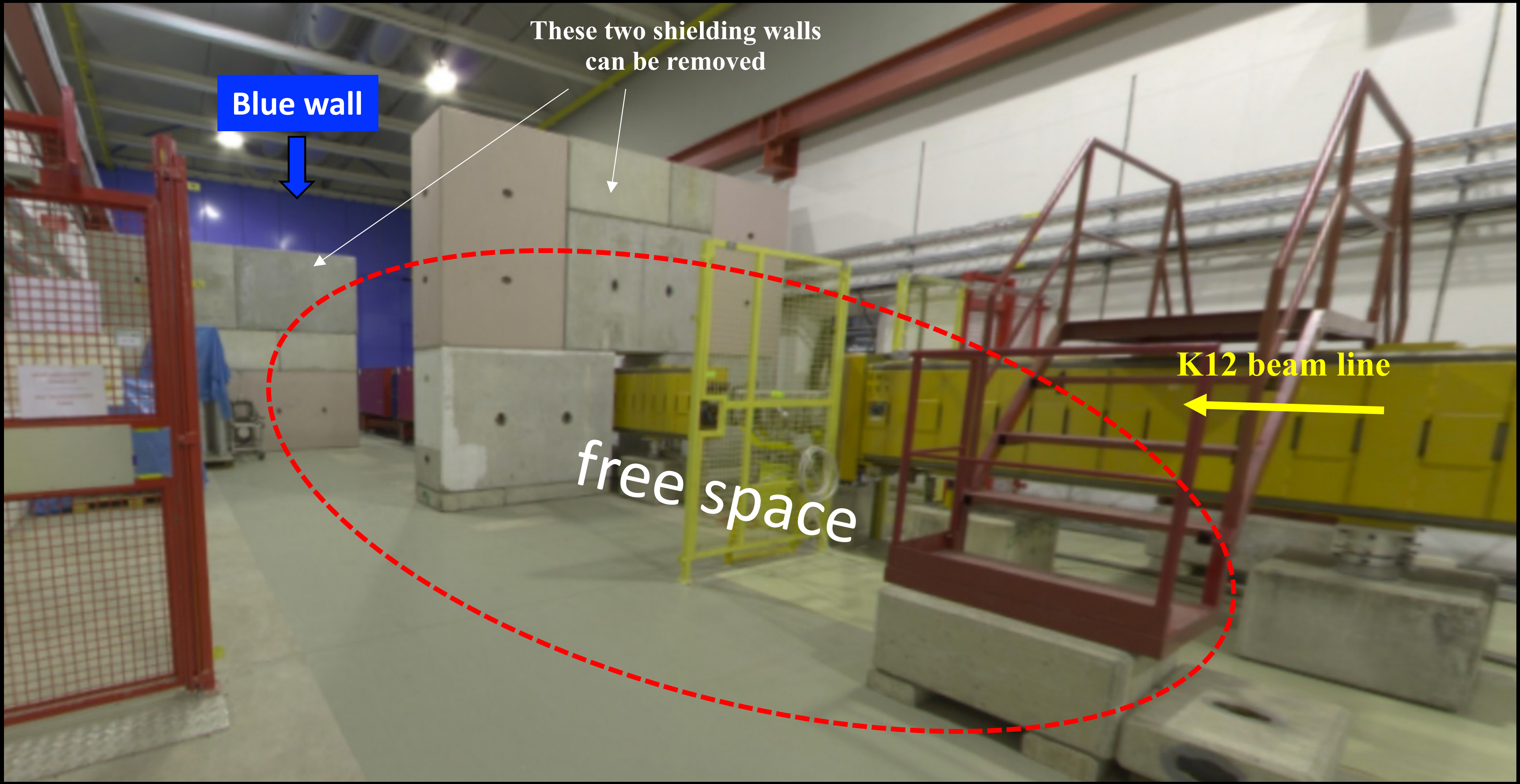
CERN-SPSC-2023-029 / SPSC-P-367
30/10/2023

From the Expression of Interest (Jan 22) ⟶ Proposal (Aug. 23)
the collaboration almost tripled (about 80 collaborators, 16 institutions)

NA62 in ECN3/TTC8

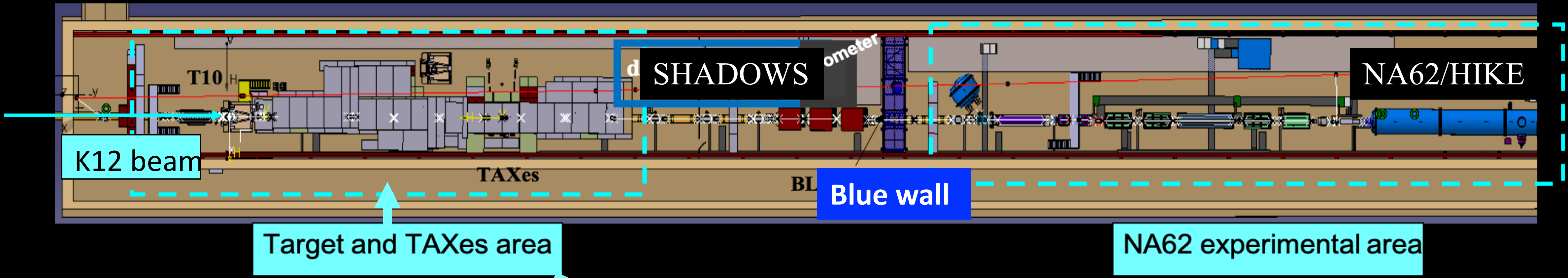
....where everything began....

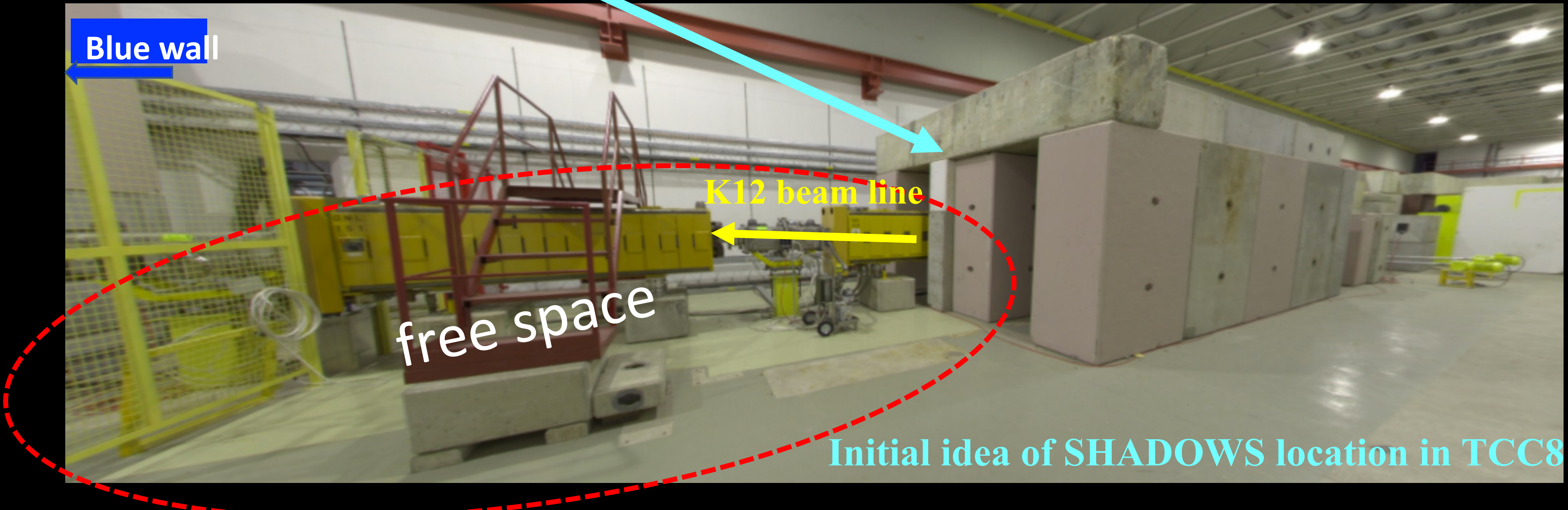
From the first idea (Jan 2022)….



Initial idea of SHADOWS location in TCC8

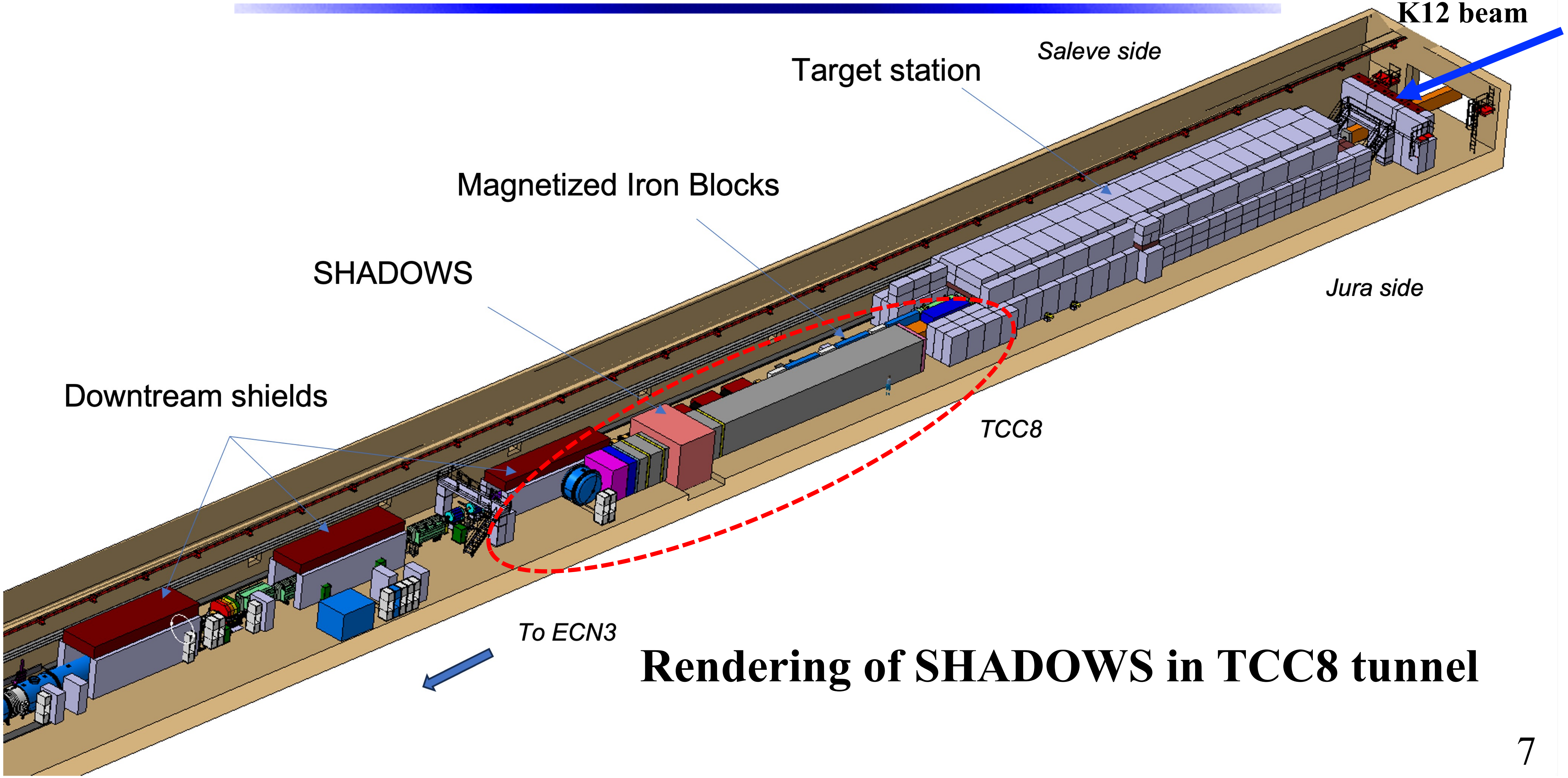
From the first idea (Jan 2022)….





Initial idea of SHADOWS location in TCC8

.. to a preliminary but complete project…



Rendering of SHADOWS in TCC8 tunnel

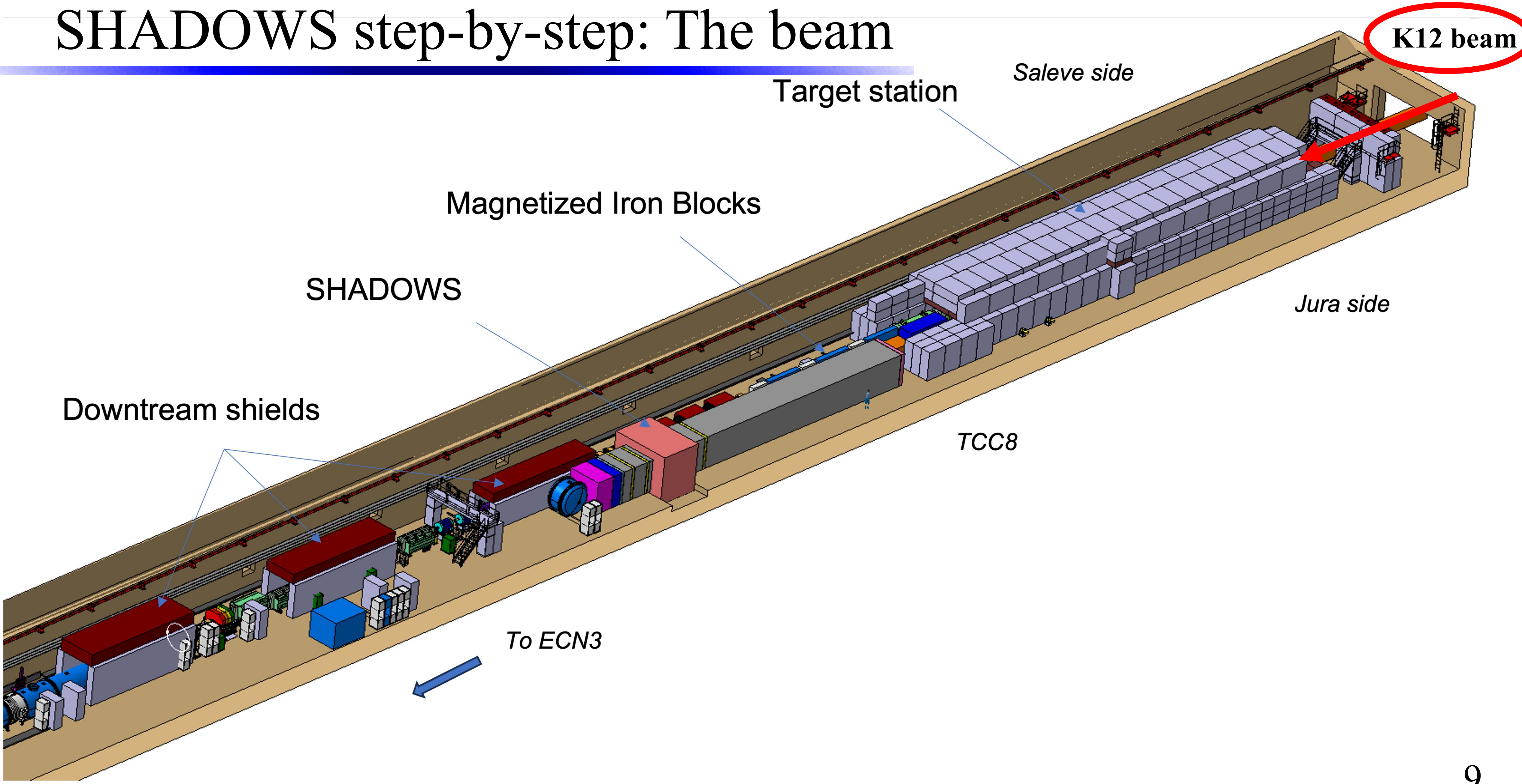
… documented in 223 pages of the Technical Proposal (Aug. 23)

Contents

Submitted to the SPSC the 18 August 2023.

https://cds.cern.ch/record/2878470/files/SPSC-P-367.pdf

SHADOWS step-by-step: The beam

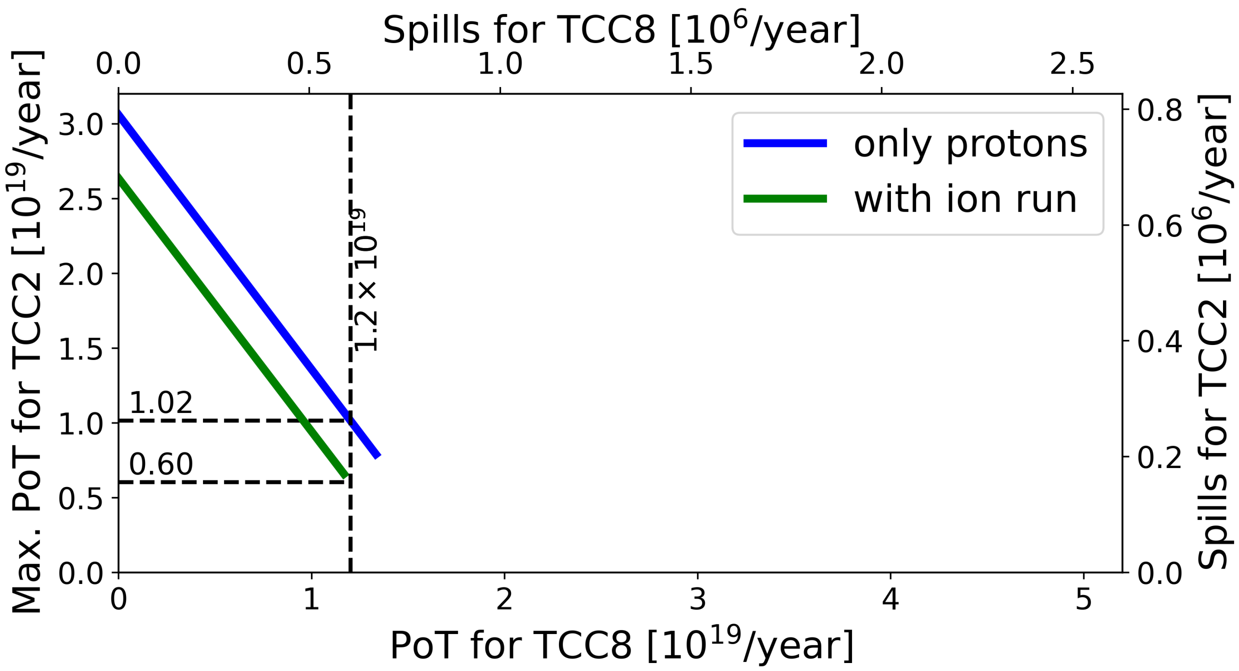


The high-intensity K12 beam line

Intensity to TCC8 [p/spill]	(PoT/year)	Spill Length [s]	Fastest Repetition Period [s]
up to 2.0×10^{13}	up to 1.2×10^{19}	≥ 4.5	14.4

Table 1. Experimental requirements for HIKE/SHADOWS.

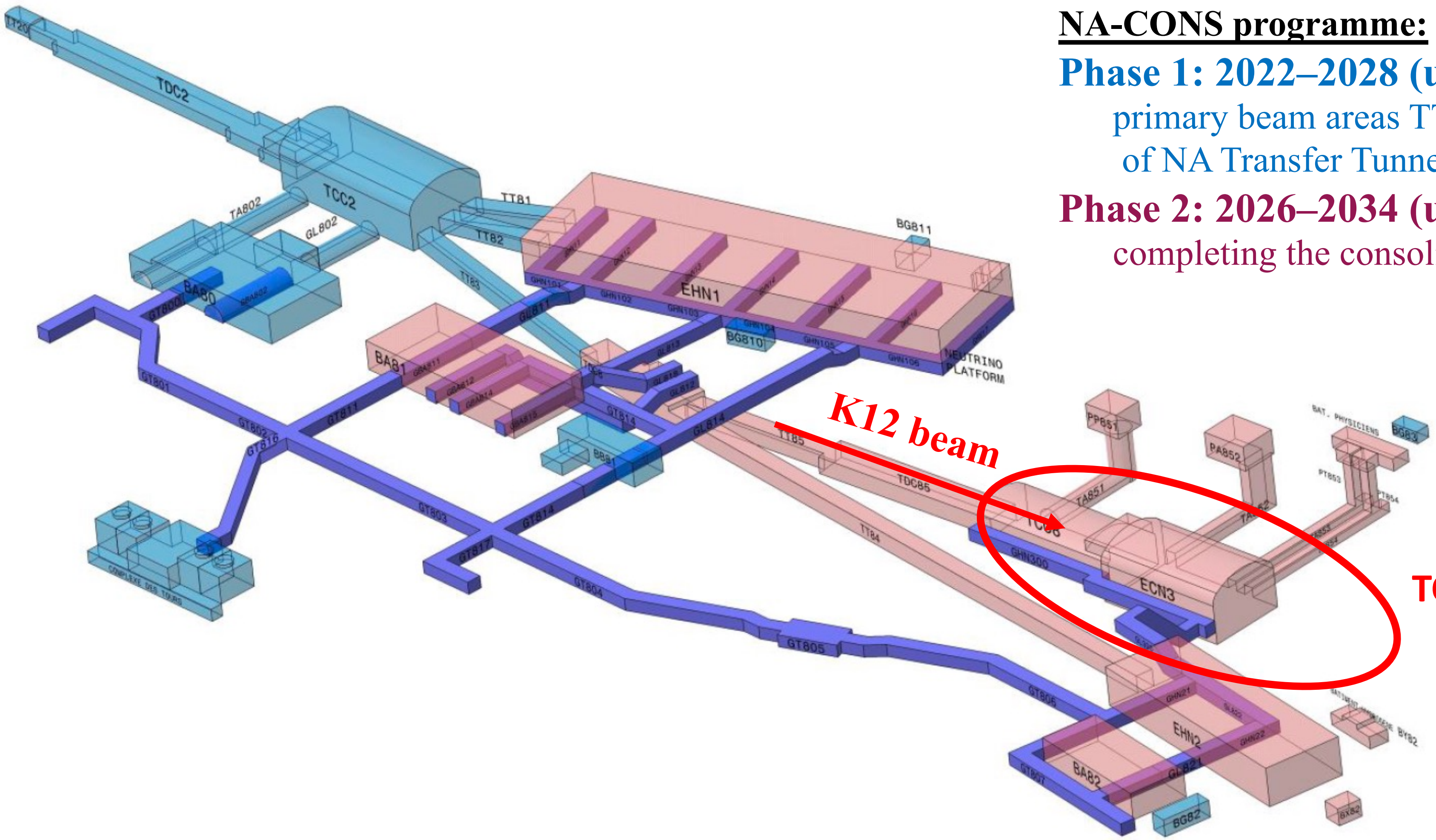
Up to a factor 7 more than the current intensity



5×10^{19} protons-on-target (pot), with 4.8 sec long spills, can be delivered to ECN3 in 4 integrated years with a dedicated beam delivery for ECN3, and shared cycles to EHN1 and EHN2. This annual yield is **fully compatible with the current North Area operation.**

The high-intensity K12 beam line

Fully compatible and synergistic with the (already funded) North-Area Consolidation Programme:

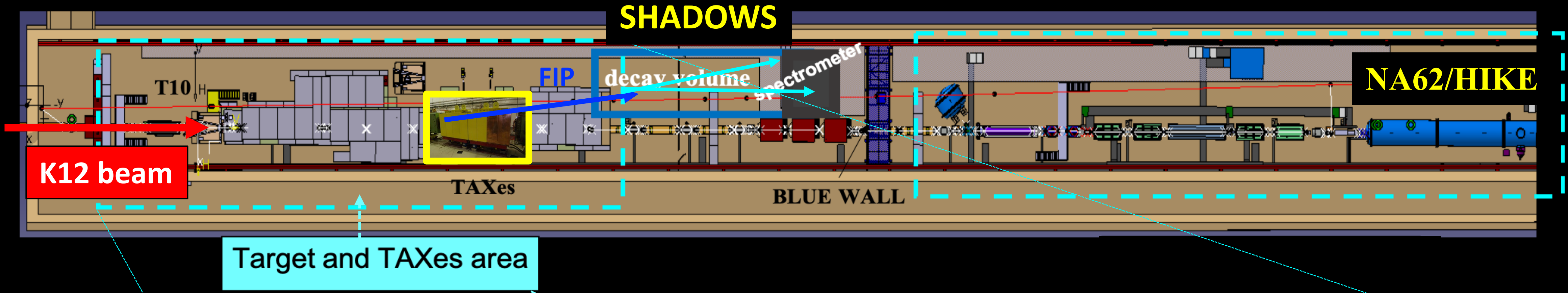


NA-CONS programme:

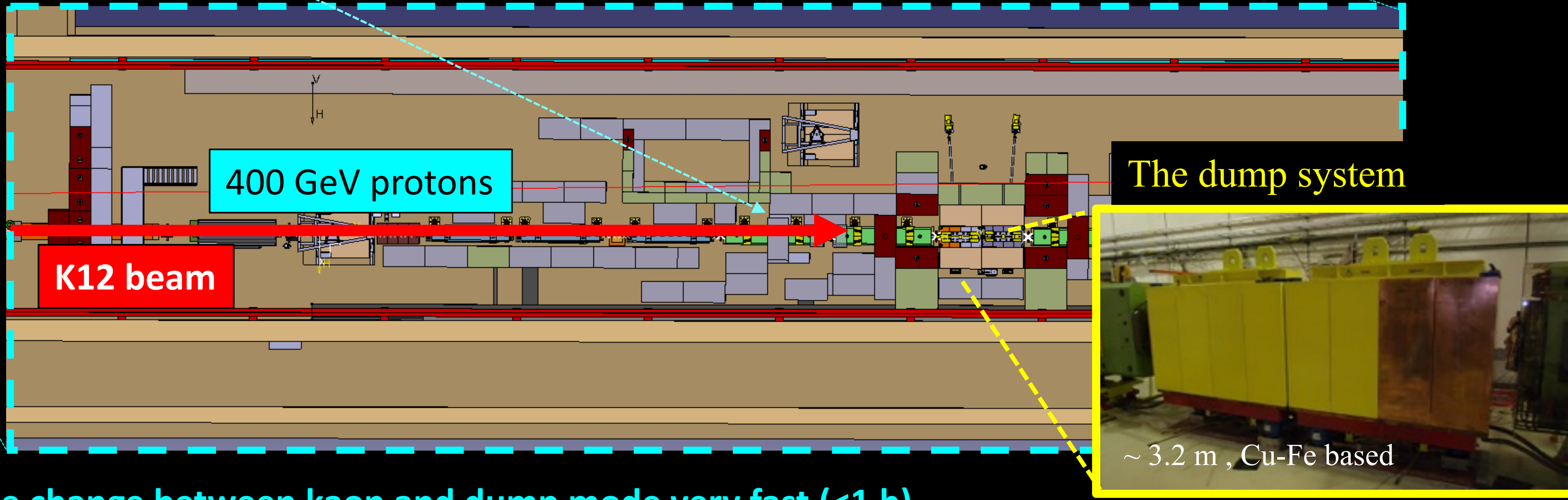
Phase 1: 2022–2028 (up to end LS3),
primary beam areas TT20, TDC2, TCC2 and initial section of NA Transfer Tunnels.

Phase 2: 2026–2034 (up to end LS4),
completing the consolidation of the secondary beam areas.

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



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

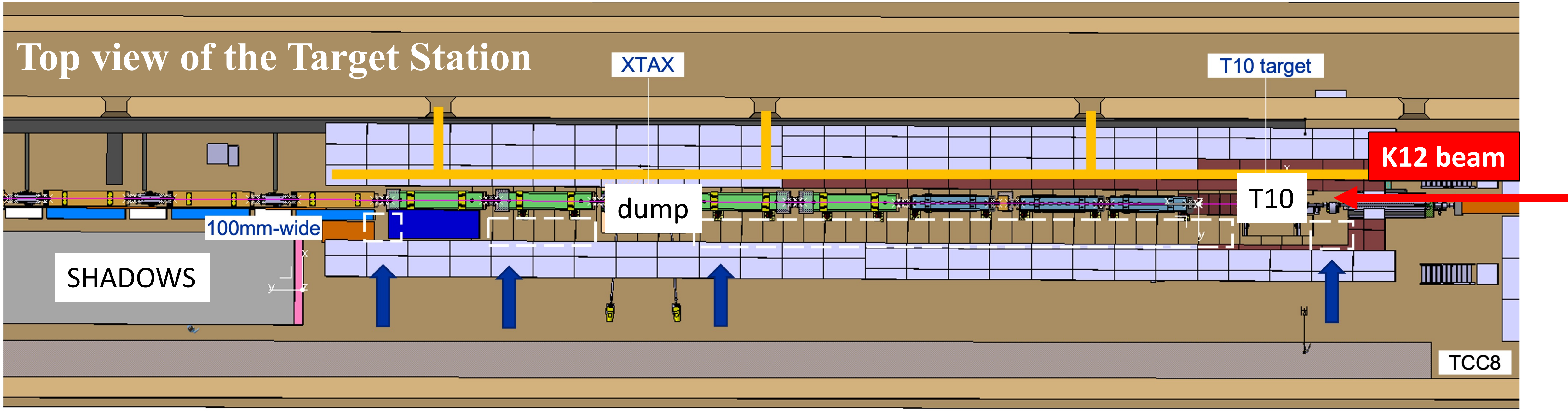


The change between kaon and dump mode very fast (<1 h)

The Target Station: New design

M. Calviani, J.L. Grenard et al.
CERN PBC ECN3 Task Force

The instantaneous and integrated beam intensities requested by HIKE/SHADOWS require the installation of a new target complex, associated cooling and ventilation systems,and shielding in TCC8.



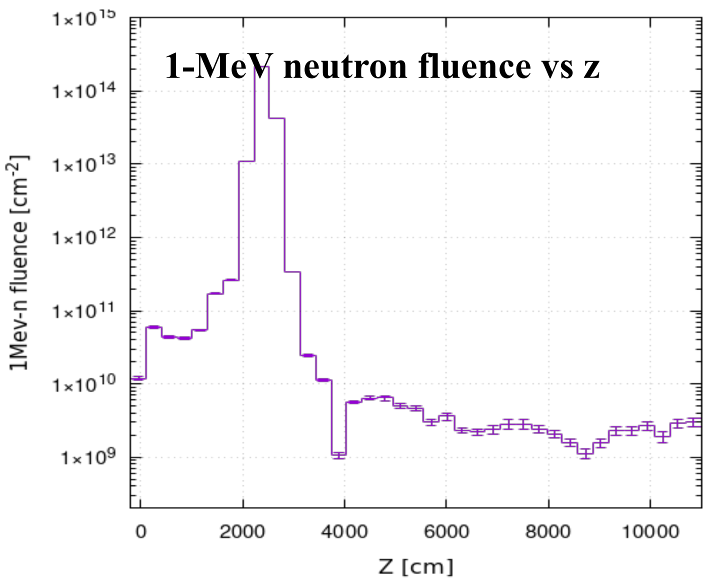
- **Significant shielding improvement with respect to the current NA62 target system:** optimised to reduce the prompt radiation above ground to comply with a Non-designated Area.
- **A new TAX Cu-Fe based system needed**: along with upgraded cooling and maintenance capabilities.
- **Change from Kaon mode to beam dump mode very fast**: mostly dominated by different magnet settings

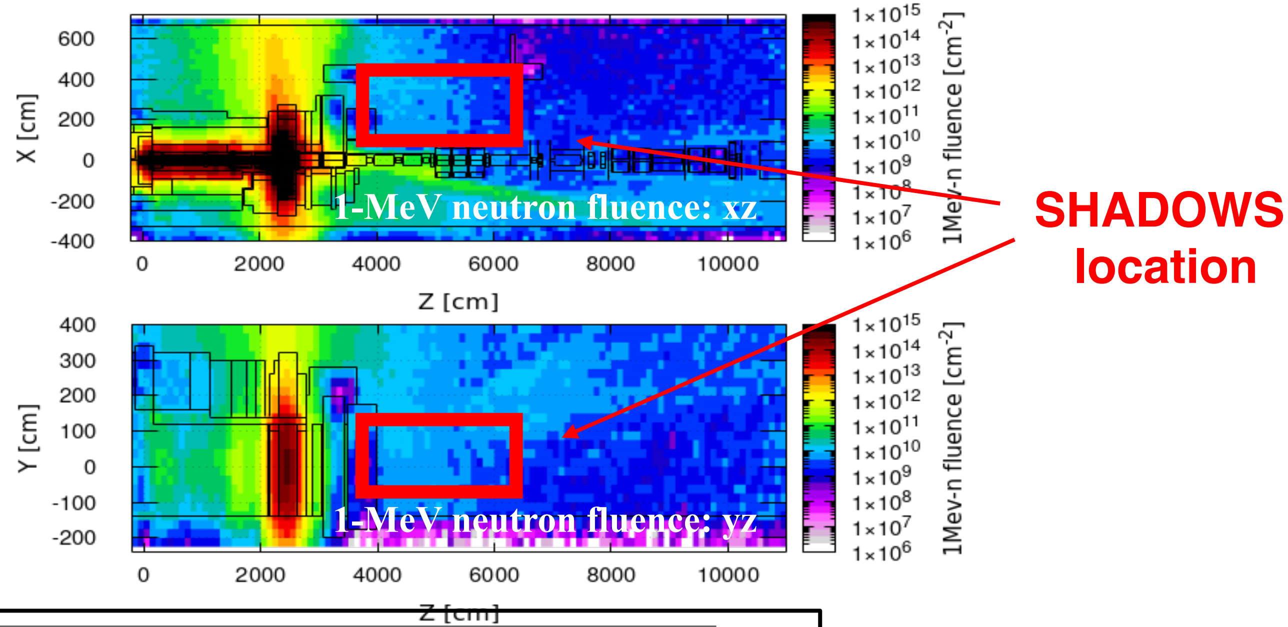
SHADOWS

Target station: Radiation Levels

C. Ahdida, L. Esposito, S. Niang, E. Nowack
CERN PBC ECN3 Task Force

1-MeV equivalent neutron fluence, high energy hadron fluence and thermal neutron fluence evaluated with a detailed FLUKA simulation in SHADOWS area



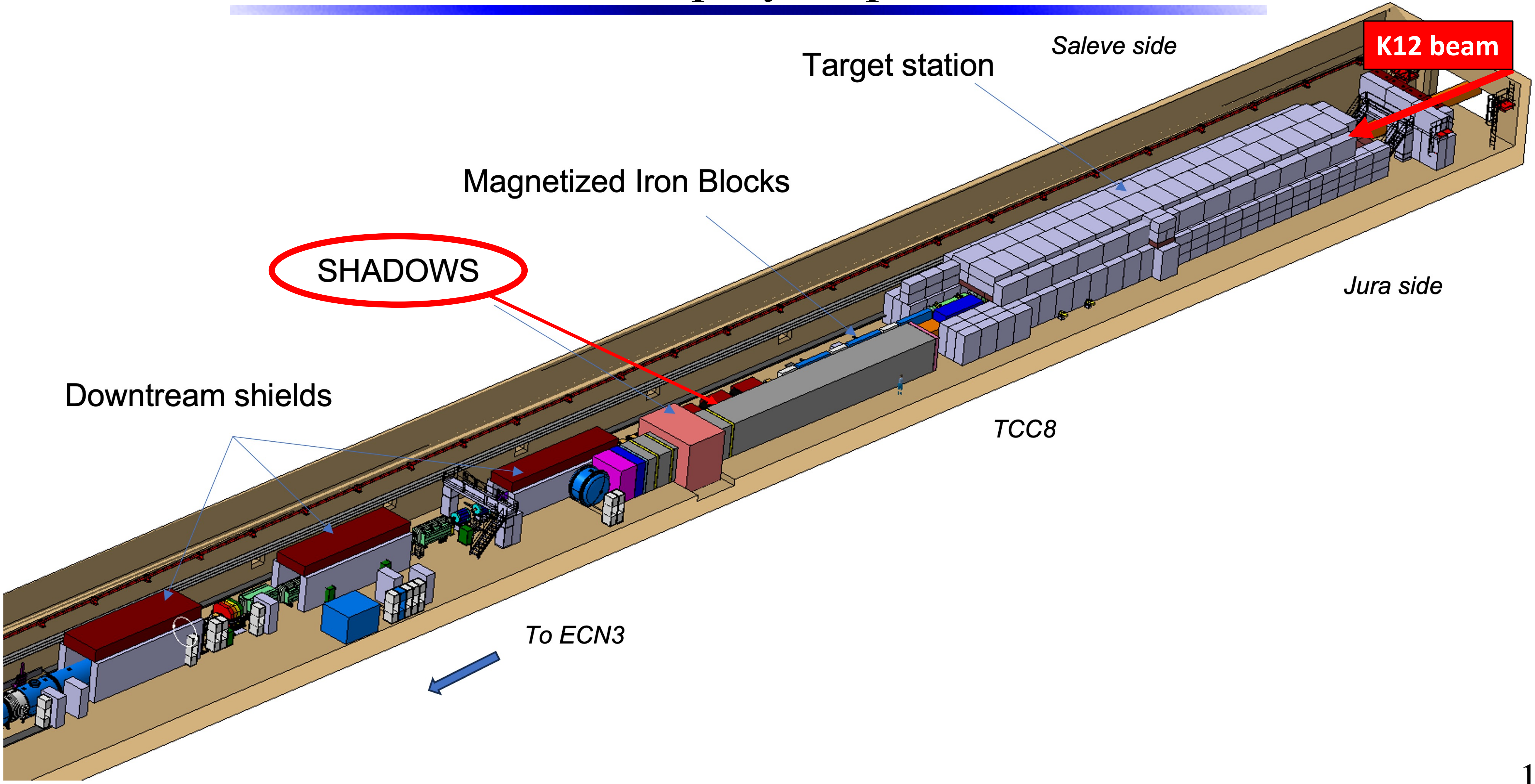


Quantity	Detector location	R2E safe
Total Ionising Dose (Gy)	0.1-1 per year	< 10
1-MeV neutron equivalent fluence (cm^{-2})	10^{9-10} per year	$< 10^{11}$
High-Energy Hadron eq. fluence ($cm^{-2}year^{-1}$)	few 10^9	$< 3 \times 10^6$
Th. neutron eq. fluence ($cm^{-2}year^{-1}$)	$< 5 \times 10^{10}$	$< 3 \times 10^7$

Radiation levels are not a show-stopper in the very-close-to-dump SHADOWS location

Radiation- tolerant electronics will have to be used in proximity of the SHADOWS detector
Dedicated alchoves with iron/concrete shielding far from the dump for the off-detector electronics.

SHADOWS step-by-step: The Detector



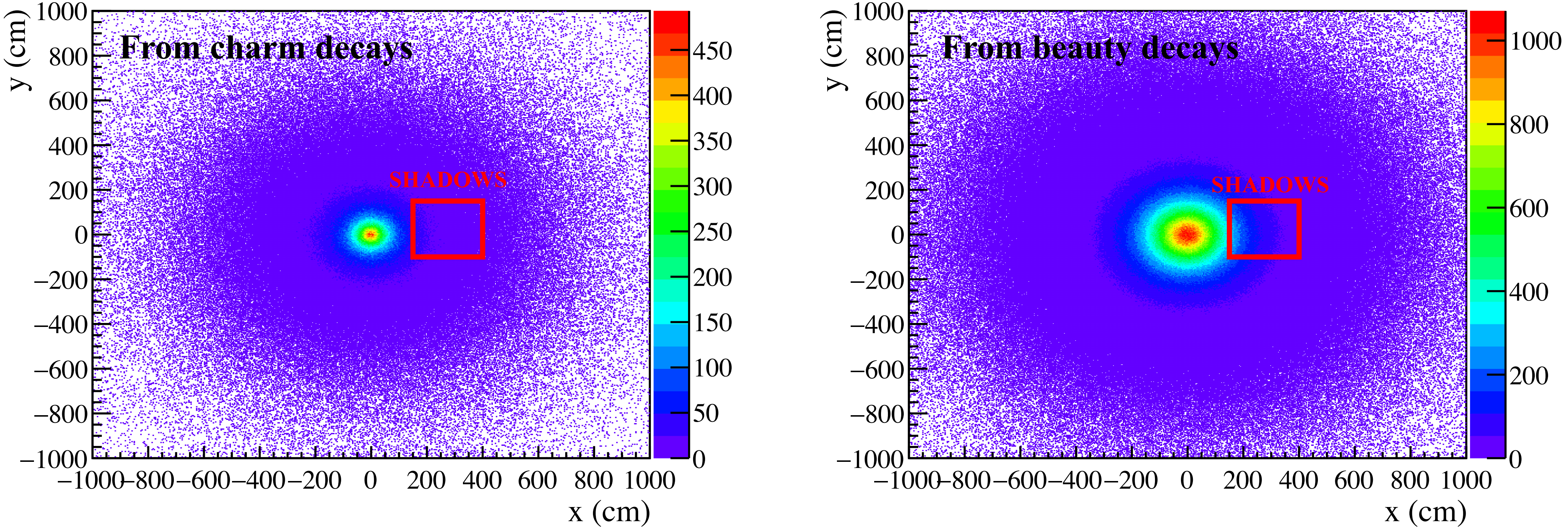
SHADOWS Main idea: Stay close & stay off-axis!

- **Stay close to the dump:**
  to maximise acceptance for signals with a relatively small detector
  for FIPs emerging from beauty and charm hadron decays

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

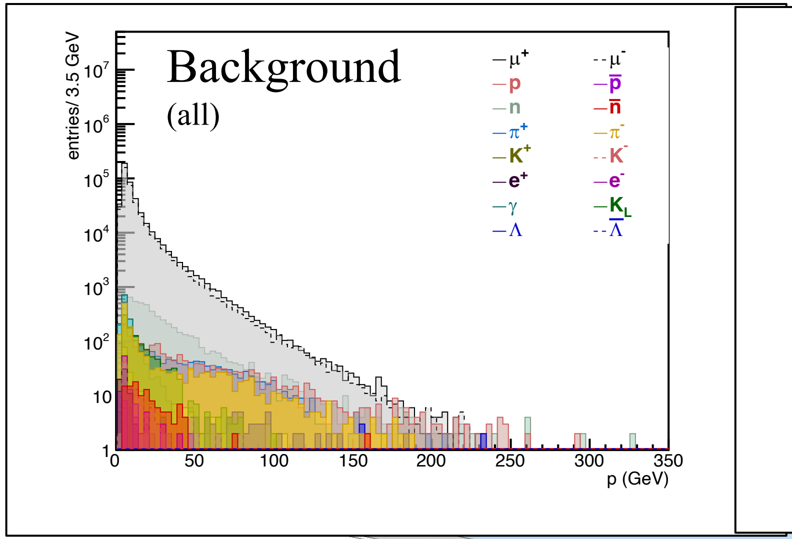
Why "off-axis" works: Signal (stay close!)

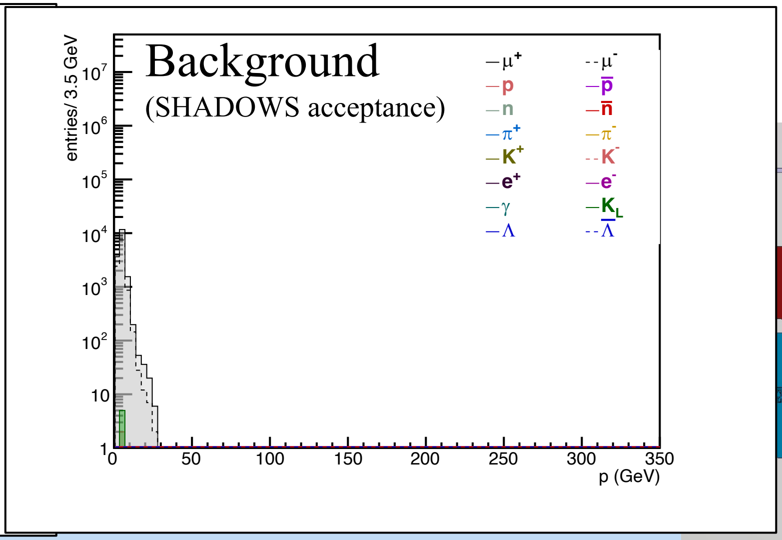
HNL→ **πμ** illumination @ first SHADOWS tracking station

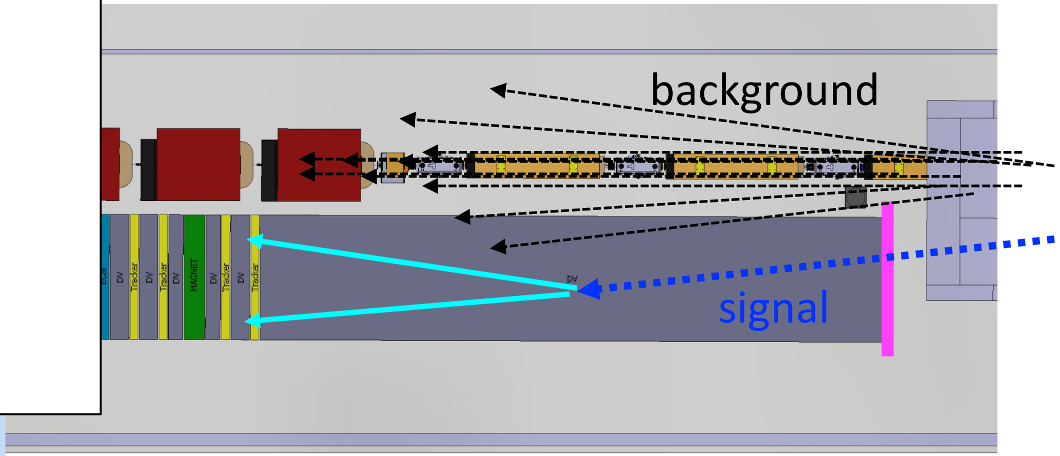


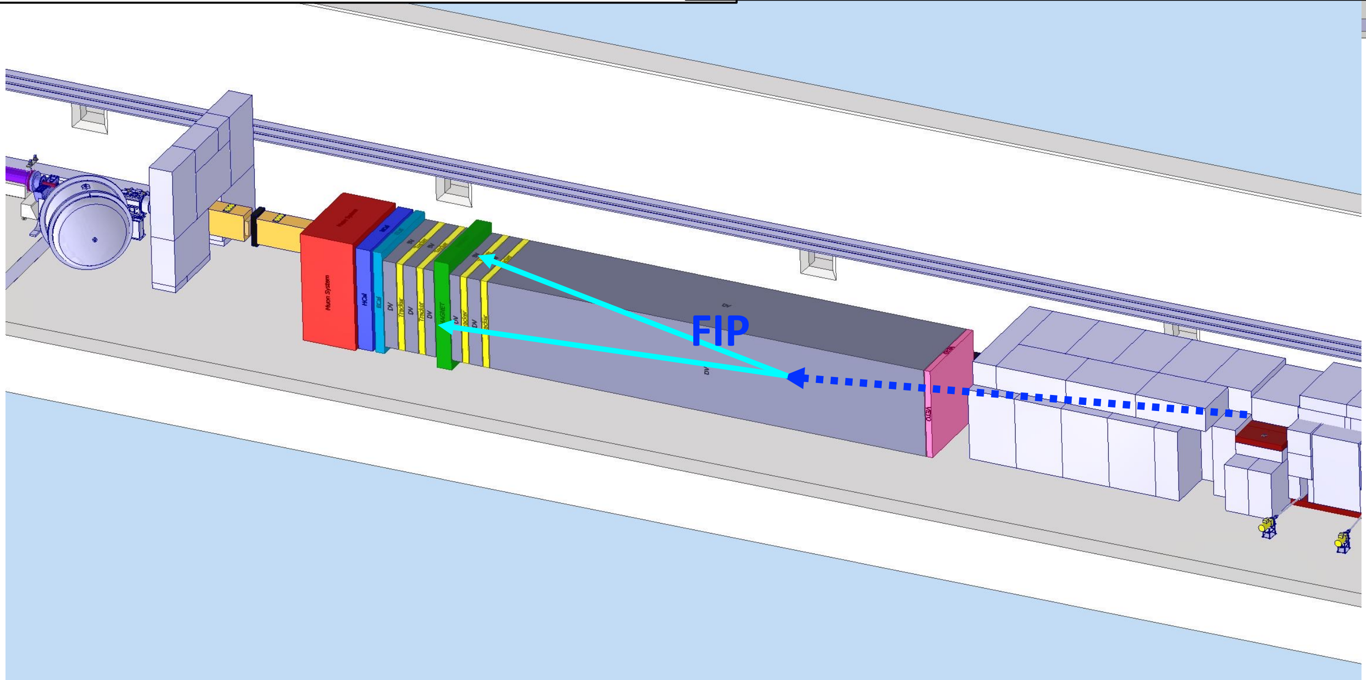
The closer you go the more you get.

Why “off-axis” works: Background (stay off-axis!)





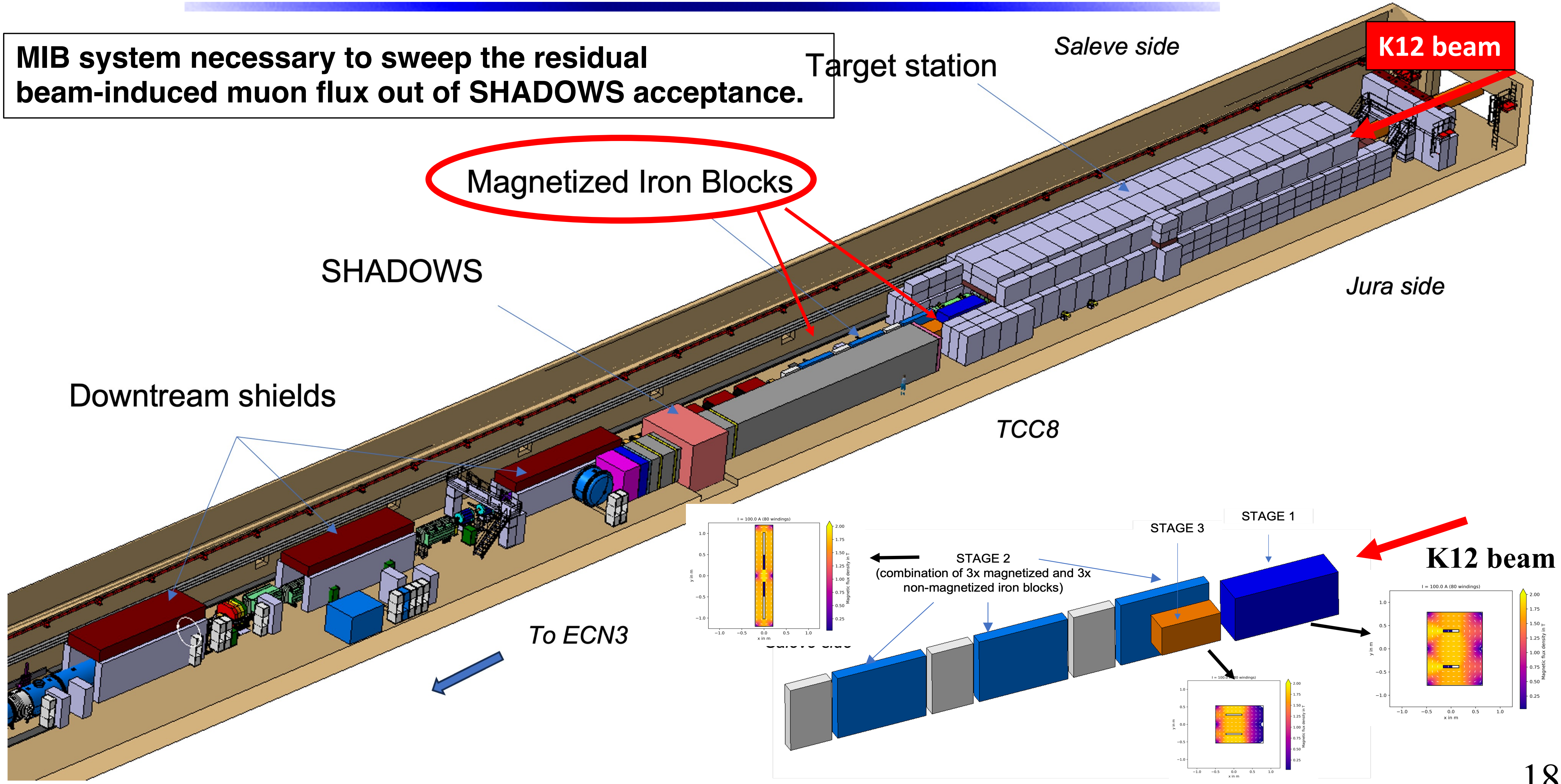




Most of the residual background emerging from TAXes are muons and neutrinos that are mostly produced forward (and miss SHADOWS acceptance).

SHADOWS step-by-step: The Magnetized Iron Blocks

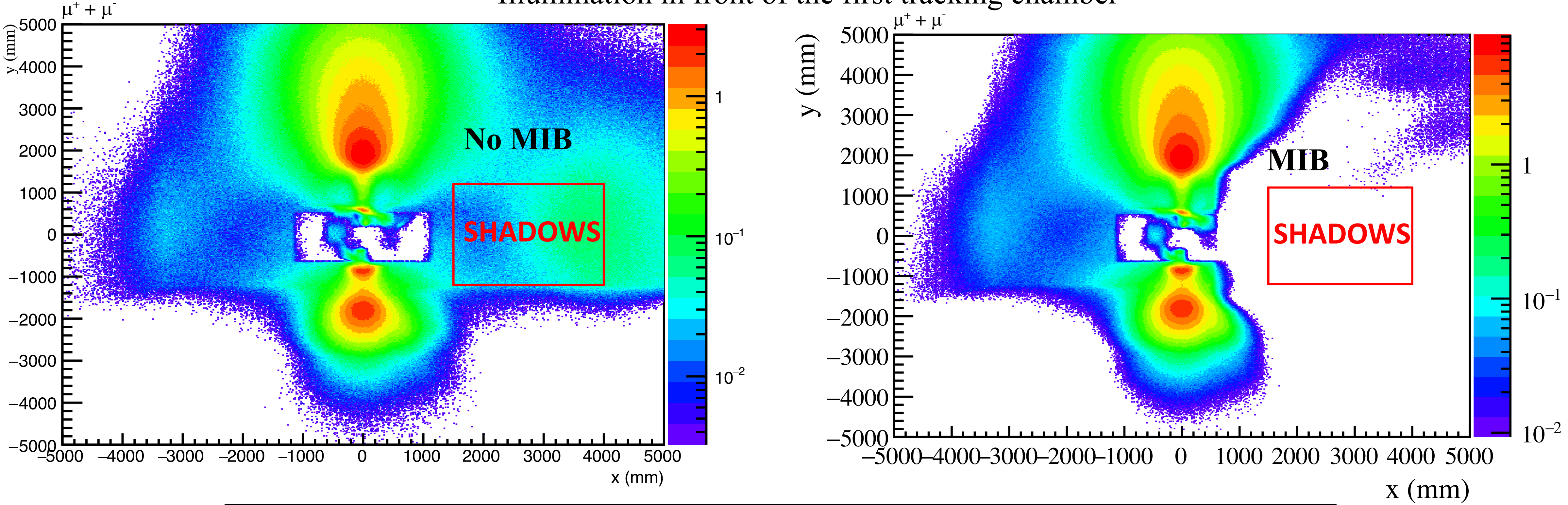
MIB system necessary to sweep the residual beam-induced muon flux out of SHADOWS acceptance.



The MIB muon sweeping system: Performance

Design by Florian Stummer
CERN BE-EA-LE group

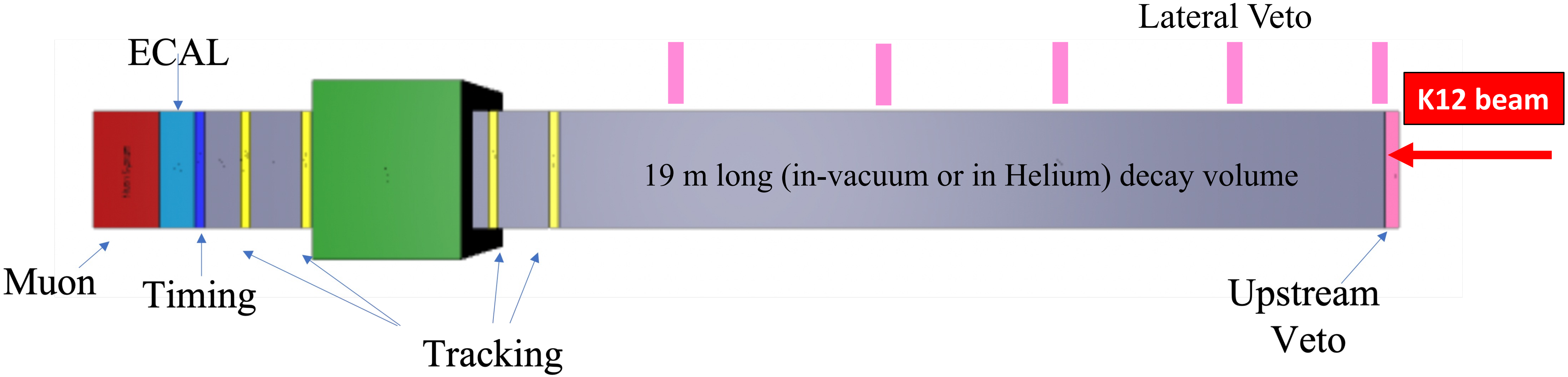
Illumination in front of the first tracking chamber



Muon flux reduction in SHADOWS acceptance from 150 MHz → 2 MHz

	$\mu^+ + \mu^-$	μ^+	μ^-
rate without MIB	147 MHz	81 MHz	66 MHz
MIB reduction factor	~ 70	~ 58	~ 94
rate with MIB	2.1 MHz	1.4 MHz	0.7 MHz

The Detector

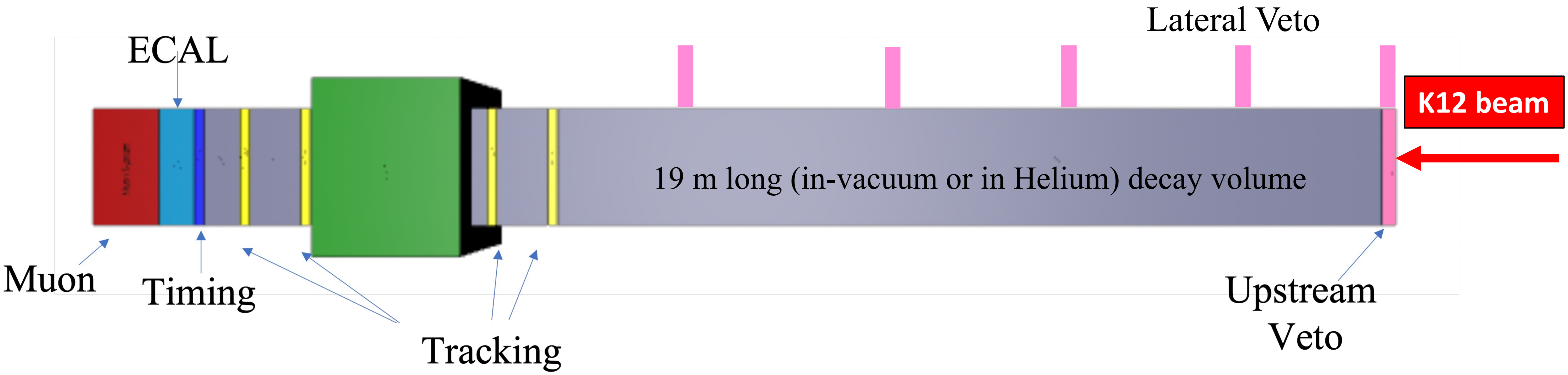


SHADOWS must be able to reconstruct and identify most of the visible final states of FIPs decays

Scalar portal	$\ell^+\ell^-$, $\pi^+\pi^-$, K^+K^-
Pseudo-scalar portal	$\ell^+\ell^-$, $\gamma\gamma$, $\pi^+\pi^-$, K^+K^-
Vector portal	$\ell^+\ell^-, \pi^+\pi^-, K^+K^-$
Fermion (neutrino) portal	$\ell^\pm\pi^\mp, \ell^\pm K^\mp, \ell^\pm\rho^\mp(\rho^\mp \to \pi^\pm\pi^0), \ell^+\ell^-\nu$

Standard spectrometer, with 19m long in-vacuum decay volume, 2.5x2.5m2 transverse area
excellent tracking system, high resolution timing layer, ECAL with pointing capability, muon system and efficient vetoes

The Detector



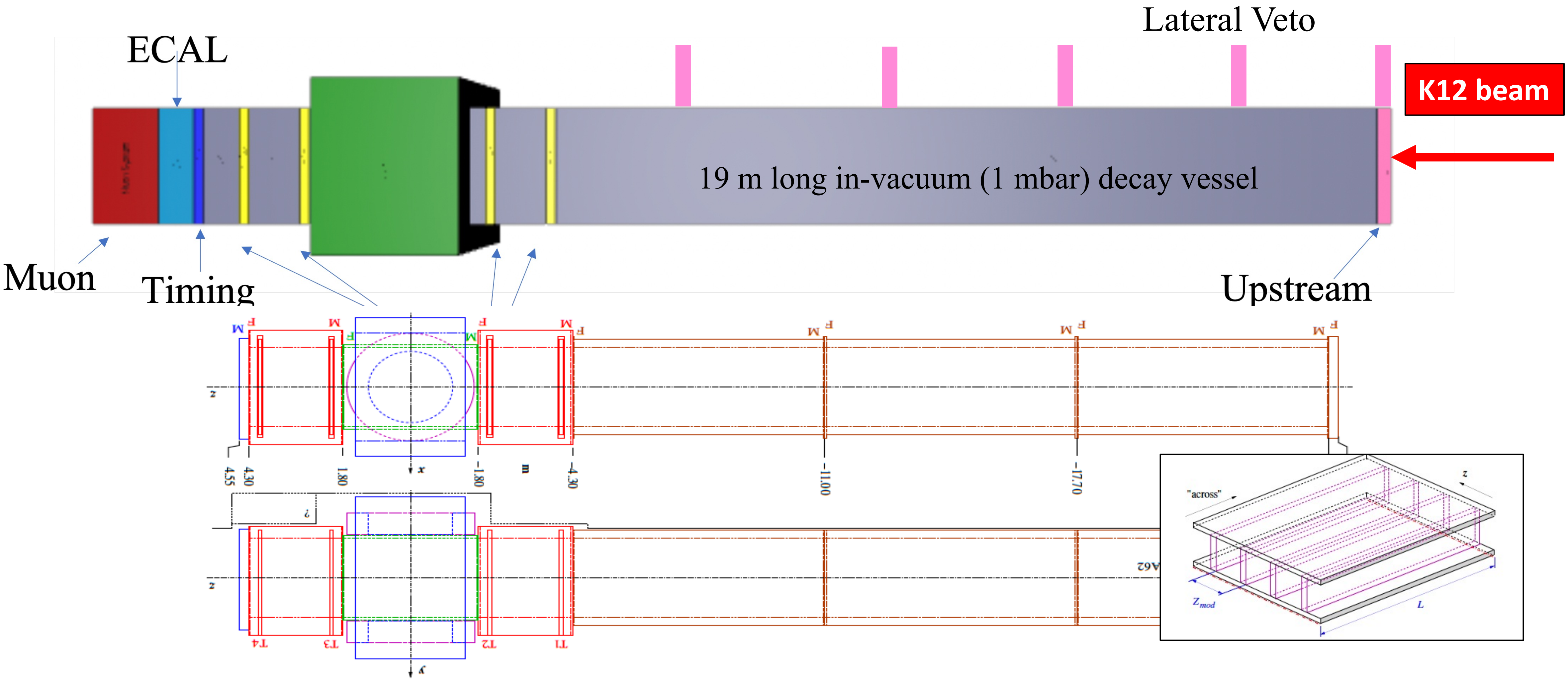
<u>Important Remark:</u>

- SHADOWS detectors are based on **well known** and **established technologies**.
- The detector readiness leverages on the **long-standing expertise of the groups involved**.
- Most of the groups have already **built and operated prototypes or even full-size detectors, mostly at the LHC**.

➢ **All these elements guarantee the readiness of the detector for data taking in 2030.**

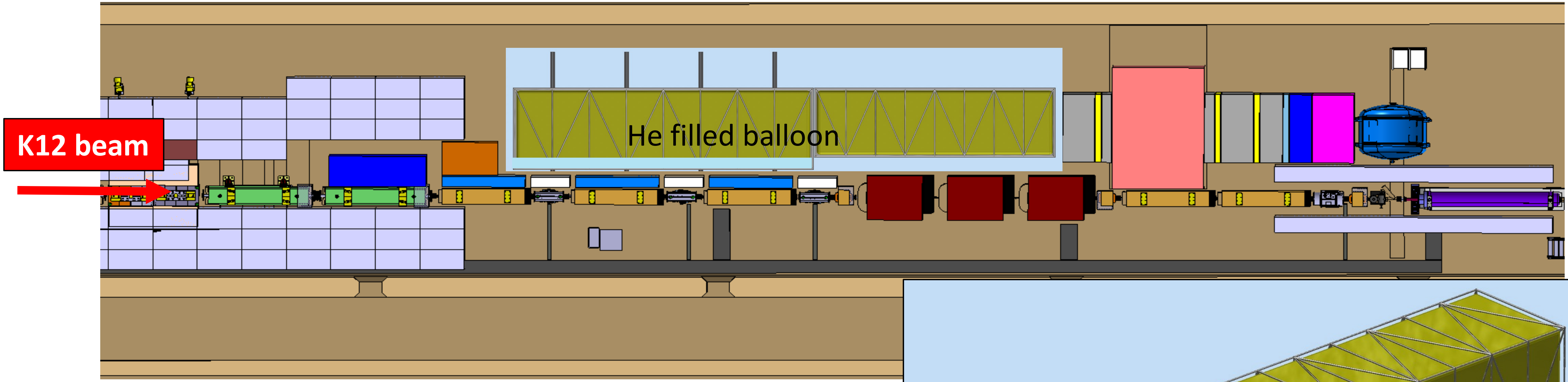
The decay vessel: in-vacuum option

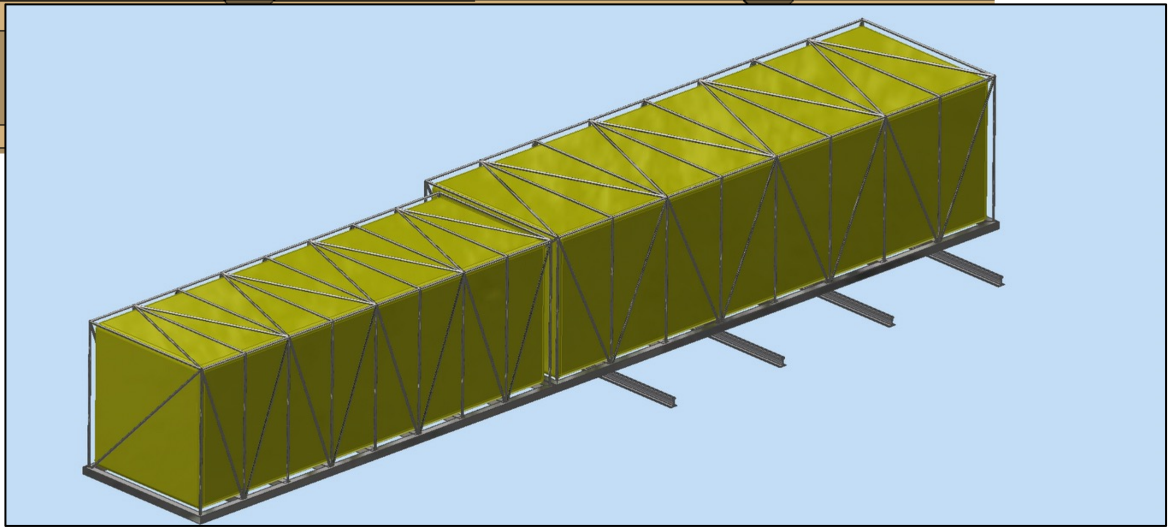
Design by Piet Wertelaers
CERN EP-DT group



Fully engineered, modular, transportable, stainless-steal based, in-vacuum decay vessel anchored to the dipole magnet and containing the 4 tracking stations.

The decay vessel: Helium balloon



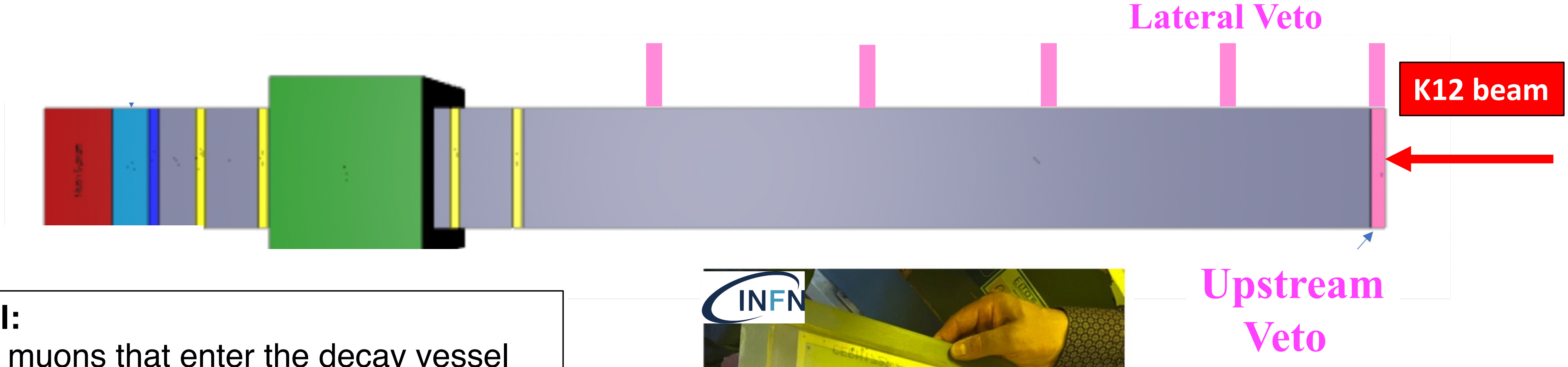


Several advantages:
- recover part of the acceptance while remaining compliant with the integration constraints.
- reduce to zero the inelastic interactions with the vessel
- reduce the cost..

This layout will be the baseline for the TDR phase

The Detector: Upstream & Lateral Veto

Institutes:
INFN-Roma3, INFN-Naples
Expertise:
ATLAS new small wheels.



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

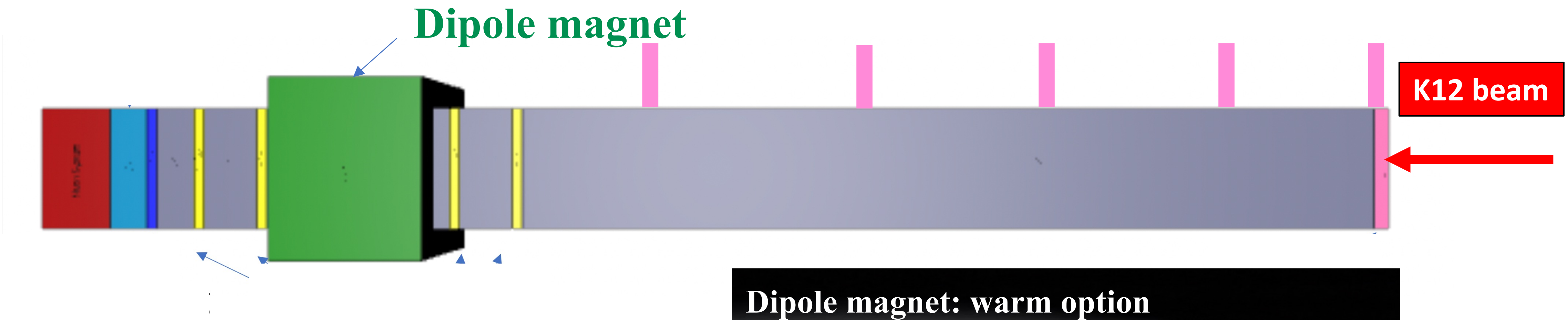
Technology:
Double layer of micromegas detectors:
- efficiency > 99.8%
- space resolution: o(1) mm
- time resolution: o(10) ns
- rate capability: up to 10 MHz /cm^2

Requirements fully satisfied.

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

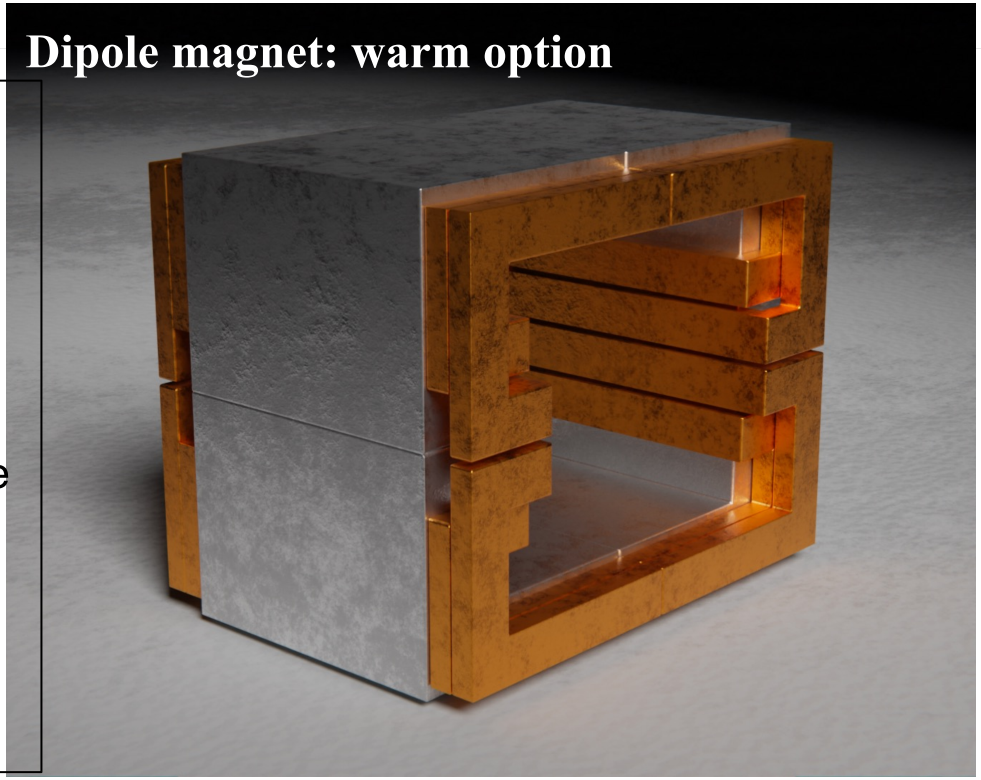
The Detector: Dipole Magnet

Design by Piet Wertelaers
CERN EP-DT group



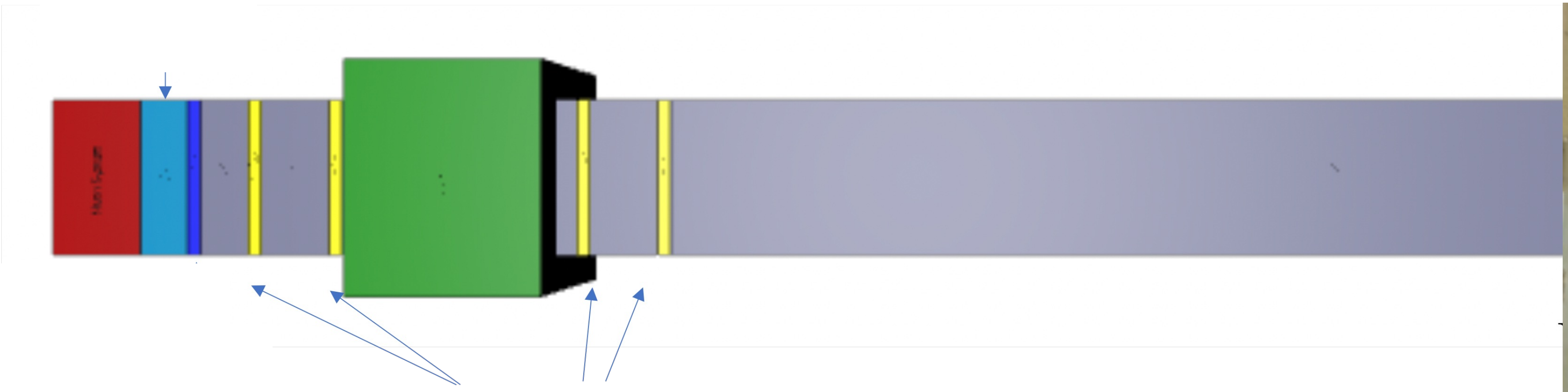
Requirements:
- field integral ~1 Tm (similar to NA62 dipole magnet MNP33)
- low power consumption
- 2.7x2.7 m aperture

Two solutions:
- *warm option (baseline):*
  - dissipated power: 287 kW, 10x less than MNP33 NA62 dipole
  - copper-based coil, iron-based yoke
- *superconducting option*
  - compelling & innovative, will be studied for the TDR
  (collaboration between CERN-EP and ATS sector
  being put in place for experiment-oriented SC magnets)



The Detector: Tracking Stations

Institutes: University of Heidelberg, CERN
Expertise: LHCb Outer Tracker,
LHCb SciFi Tracker, NA62 straw tracker

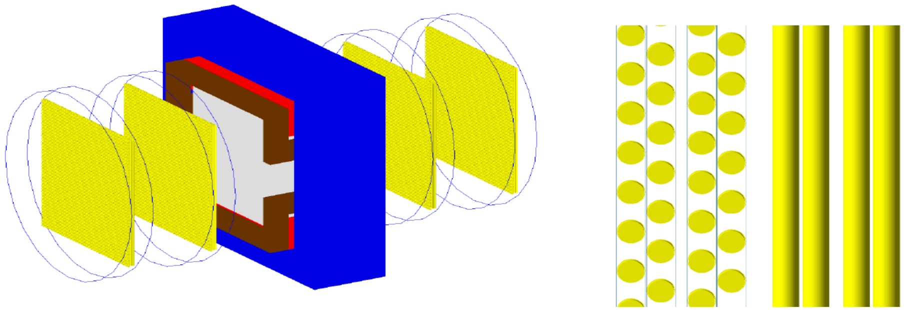


Main goal:
Reconstruct signals & reject background with at least 2 tracks

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

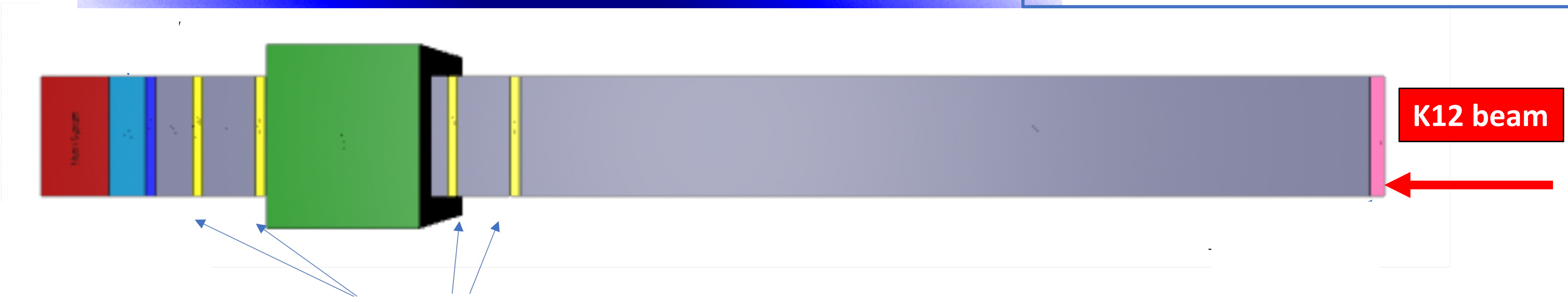
Baseline technology:
Straw Tubes in vacuum (NA62-like)
(Scintillating fibres technology under consideration)
Four stations, 2 views each, 4 layers per view

Technology Requirements	
Single hit resolution	$< 150\,\mu m$
Single hit efficiency	$> 98\%$
Material per stereo-layer	$< 0.1\%\, X_0$
Rate capability (hot spot)	$200\,Hz/cm^2$
Rate capability (total)	4 MHz

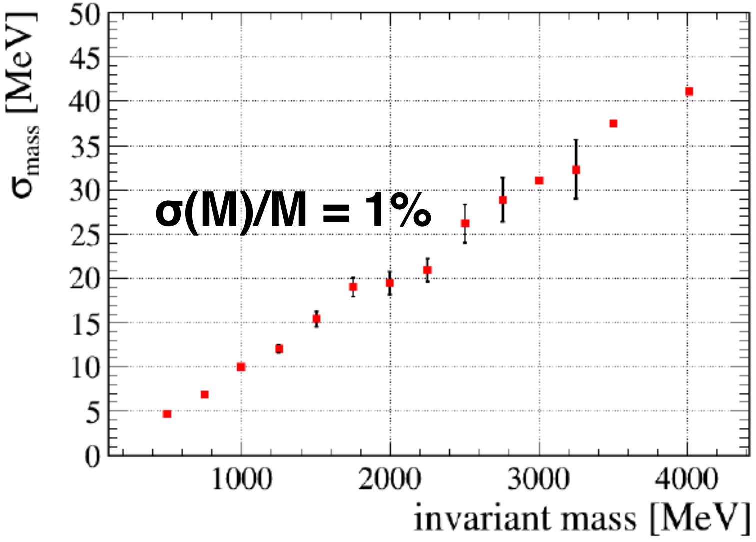


The Detector: Tracking Performance

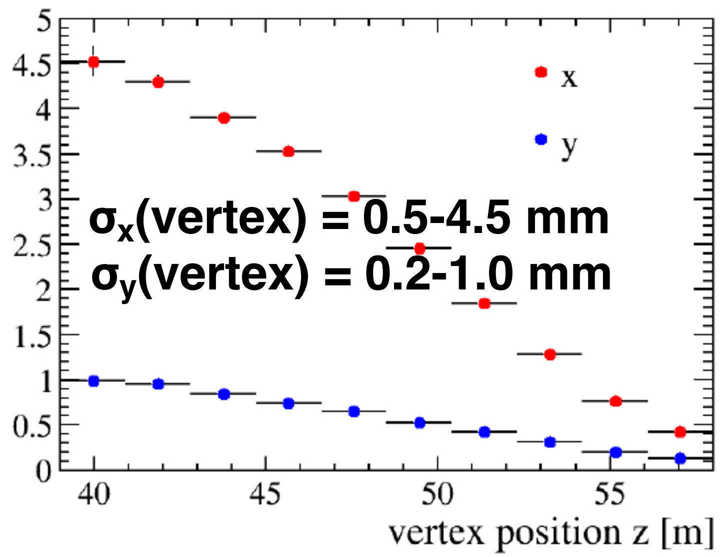
Institutes: University of Heidelberg, CERN
Expertise: LHCb Outer Tracker,
LHCb SciFi Tracker, NA62 straw tracker



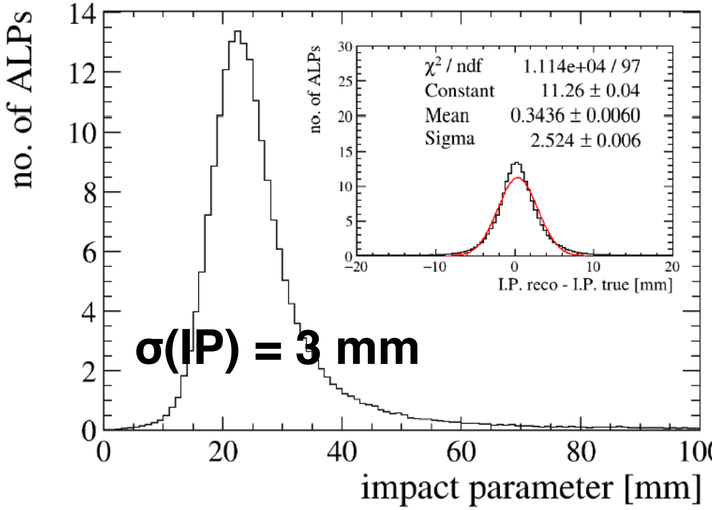
Mass resolution



Vertex resolution



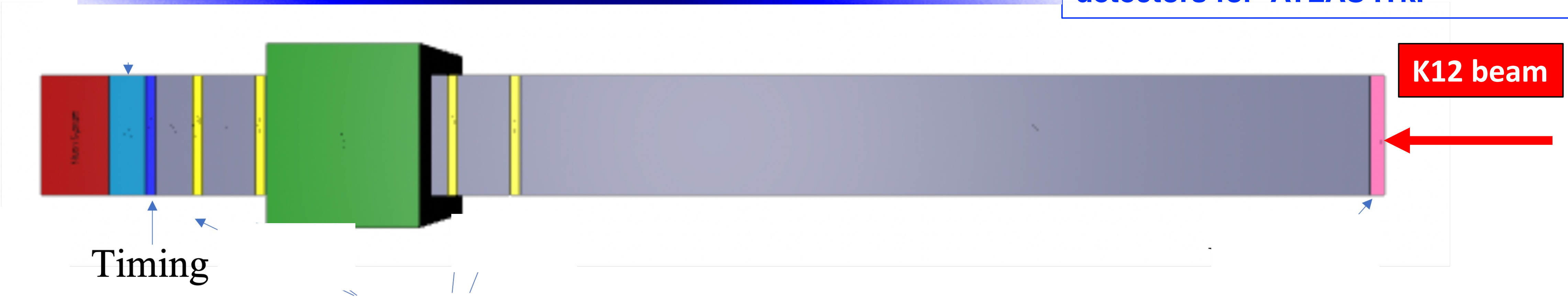
Impact parameter resolution



Requirements fully satisfied.

The Detector: Timing layer

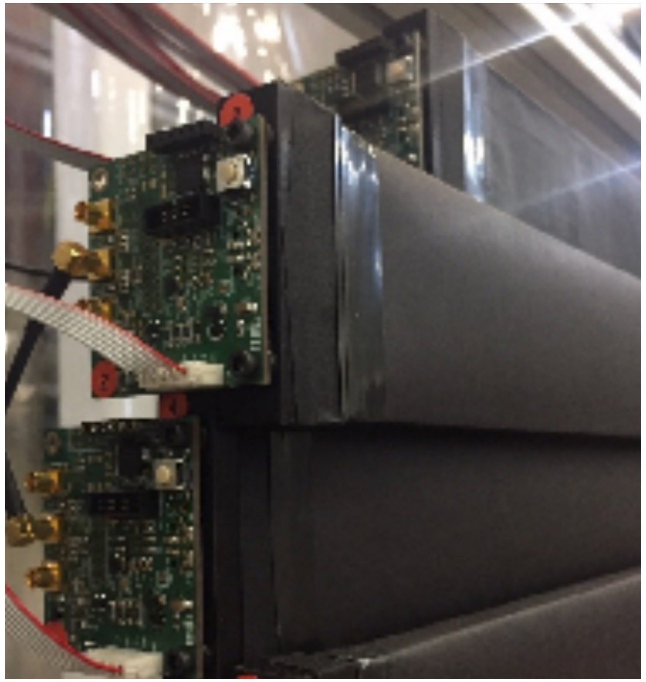
Institutes: University of Freiburg
Expertise: fast timing silicon-based detectors for ATLAS ITk.



Goals:
reject muon combinatorial background requiring fast time coincidence

Requirements:
Time resolution of o(100) ps

Baseline solution:
plastic scintillating bars with direct sipm readout
about 1 cm thickness, 6 cm width, 1.26 m length, thereby covering half of the 2.5 x 2.5 m^2 acceptance.
Proved to reach < 100 ps time resolution.



Requirements fully satisfied.

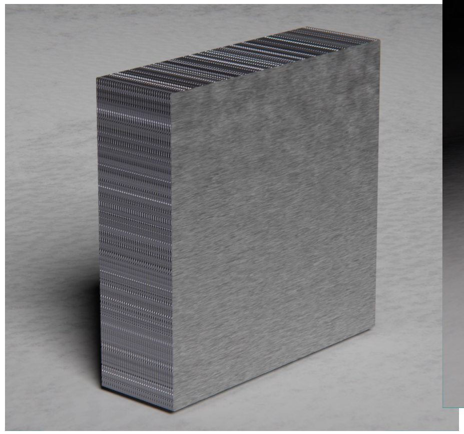
The Detector: ECAL

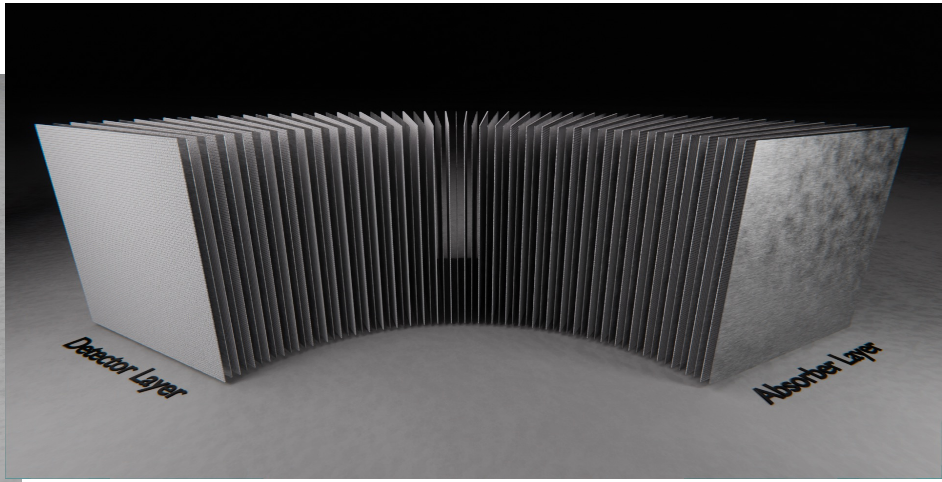
Groups: Mainz cluster of excellence, Karlsruhe Institute of Technology; ASIC developed by Heidelberg.
Expertise: NA62 hadron calorimeter, CMS ECAL.

Render of the GEANT4 geometry of the SHADOWS ECAL.

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

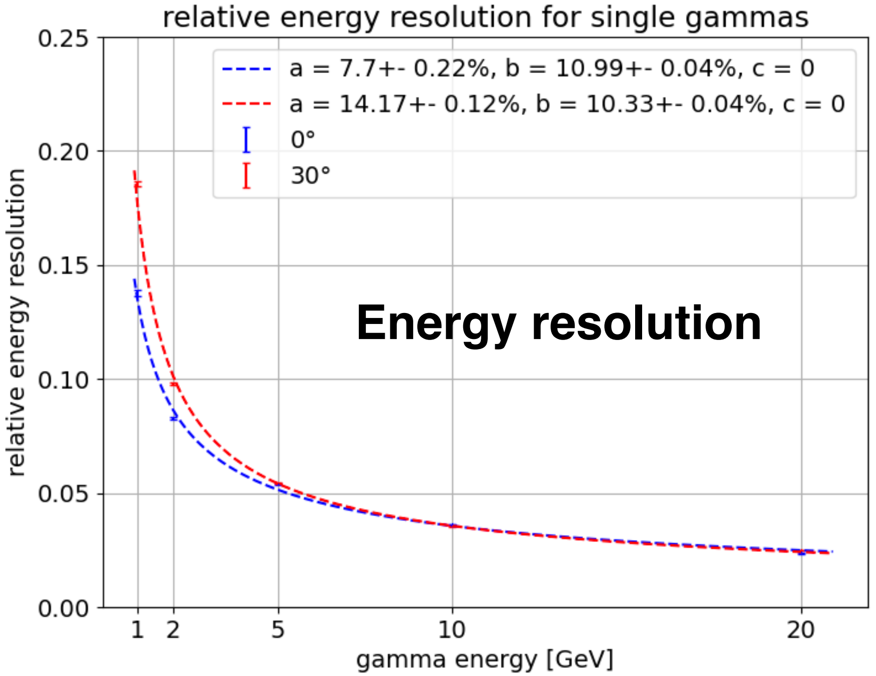
Baseline solution:
StripCAL: 2.5 m long, 1cm wide, 1 cm thick
strips in x,y directions read out with WLS fibres+sipms
Alternating with iron layers, 9 mm thick.
20 X_0 total depth to avoid shower leakage

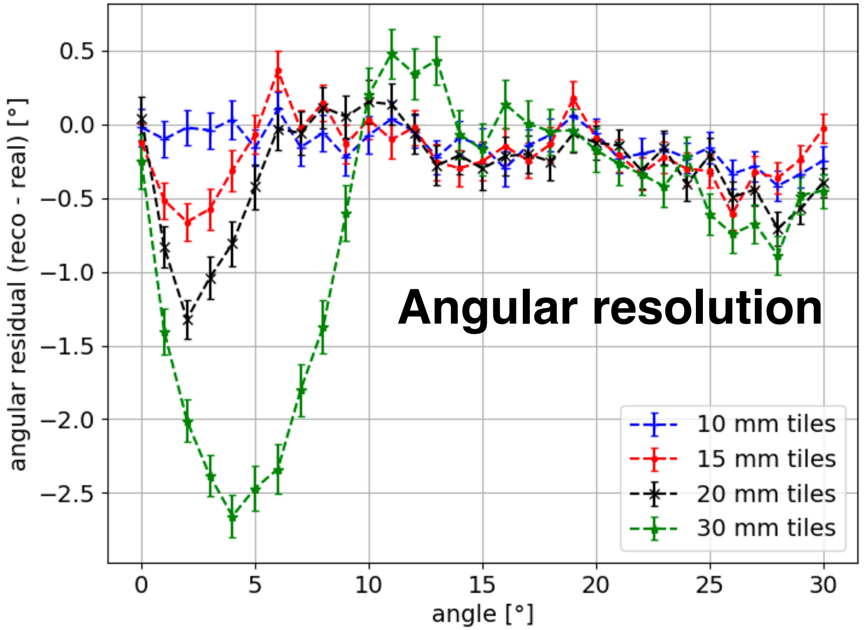




The Detector: ECAL - performance

Groups: Mainz cluster of excellence, Karlsruhe Institute of Technology; ASIC developed by Heidelberg.
Expertise: NA62 hadron calorimeter, CMS ECAL.

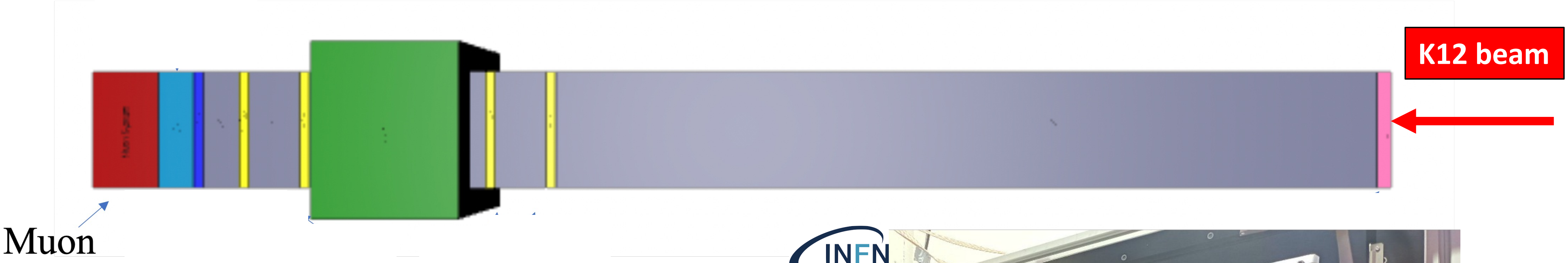




Requirements fully satisfied.

The Detector: Muon System

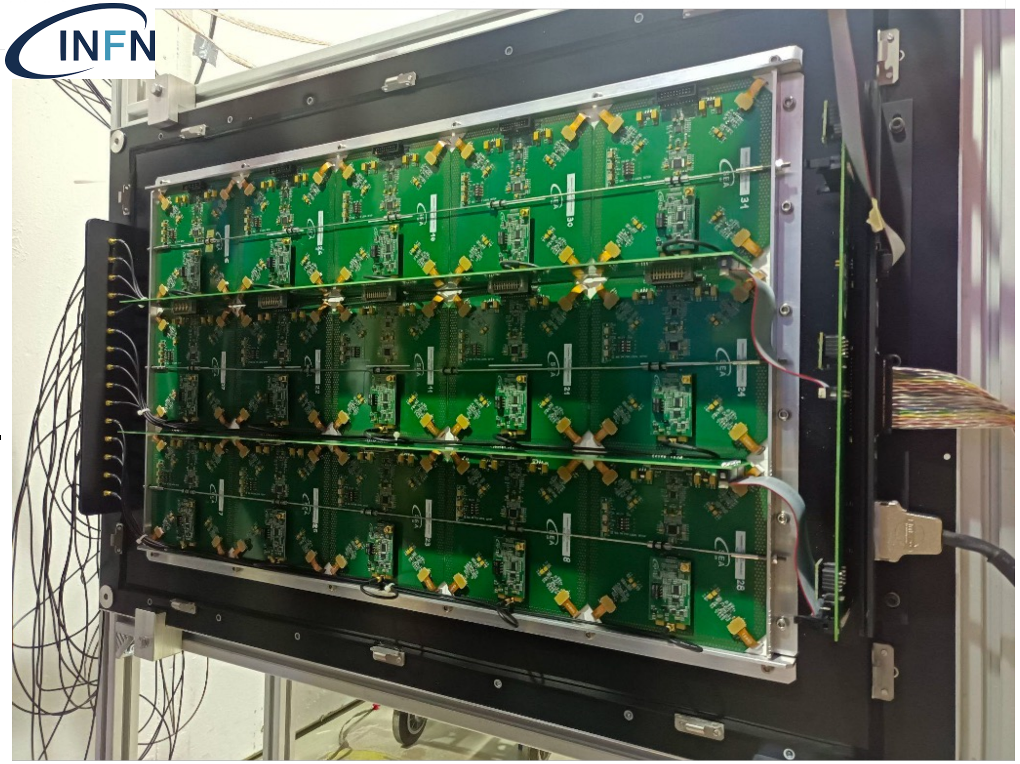
Groups: INFN-LNF, INFN-Bologna, INFN-Ferrara
Expertise: LHCb muon system, CMS muon system



Goal:
identify muons and reduce muon combinatorial background via timing measurement.

Technology:
3 stations of scintillating tiles with direct sipm readout
Interleaved by iron filters. Measured 250 ps resolution per station.

Two full-size modules already funded by INFN in 2023 and used to measure the off-axis muon flux in ECN3 during the June 2023 campaign (see later).

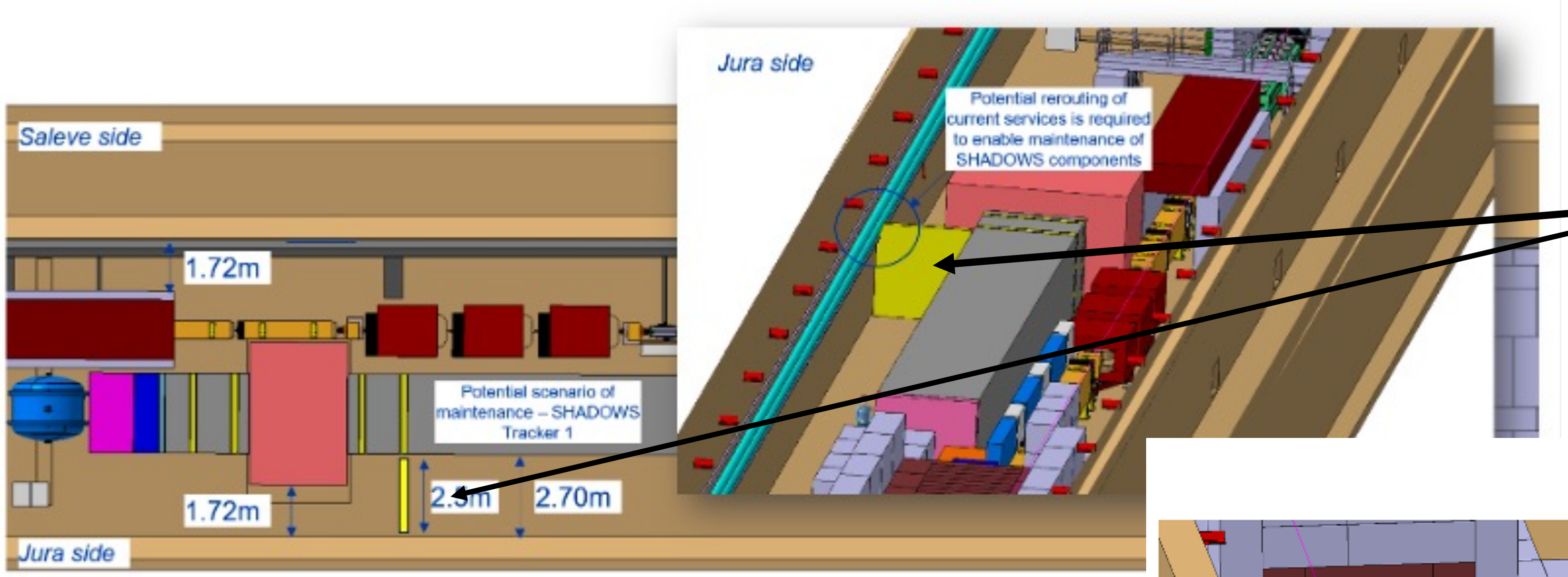


Requirements fully satisfied.

The Detector: Integration

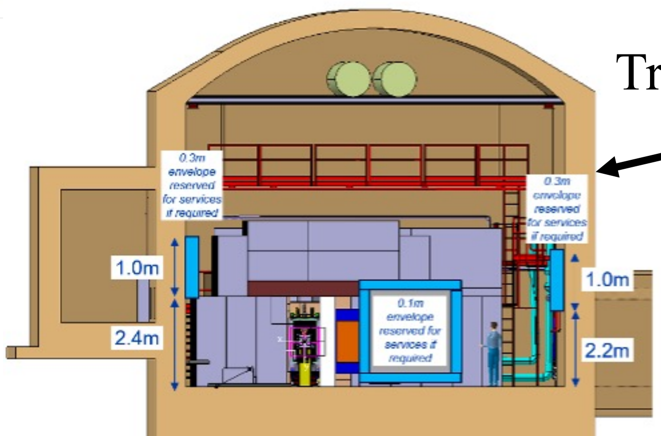
Lukasz Krzempek
PBC-ECN3 task force

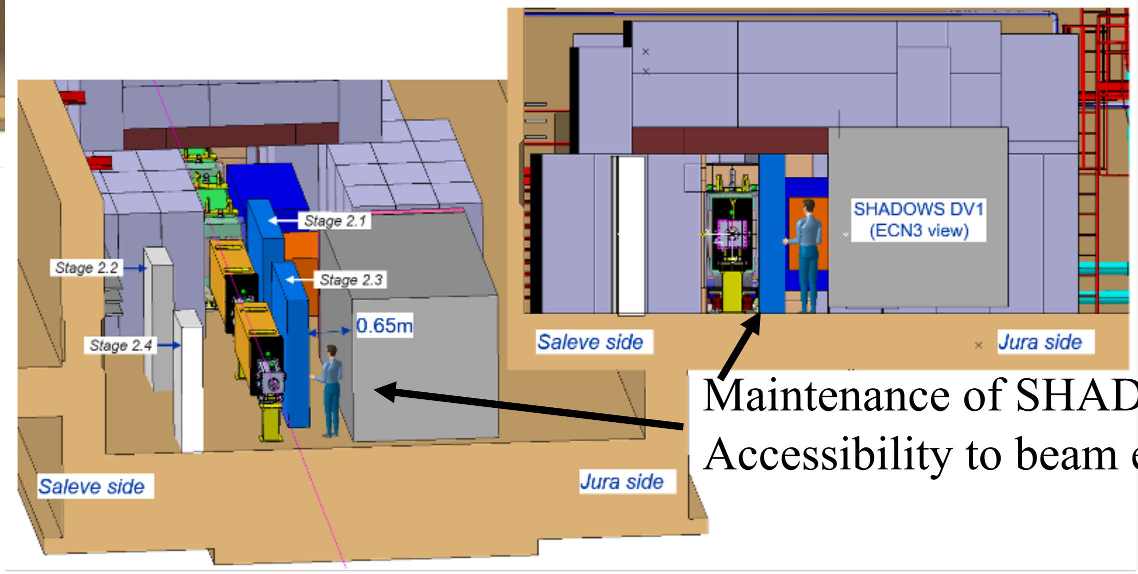
Detector integrated in the area, including civil engineering, transport and handling, and services



Installation & Maintenance of SHADOWS components

Transport & handling





Maintenance of SHADOWS MIBs
Accessibility to beam elements

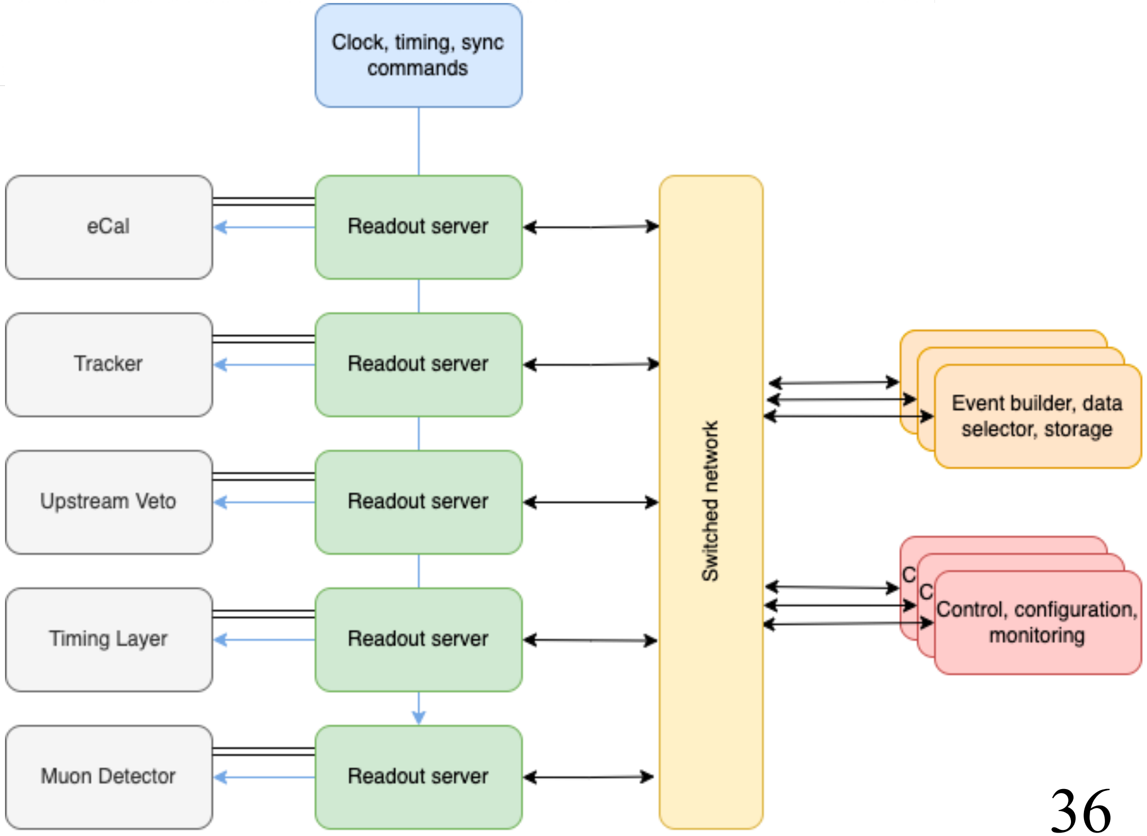
The Detector: TDAQ system

Design by E. Gamberini, et al.
CERN EP-DT-DI department

Trigger-less approach: data filtering mostly at high-level-trigger level. stream all (zero suppressed) raw data directly from the on-detector electronics towards the TDAQ.

Use lpGBT (Low Power Gigabit Transceiver) technology developed for the HL-LHC experiments, which offers data Rates of 8.96 Gb/s.

Joint project with HIKE to maximise expertise sharing & development effort.

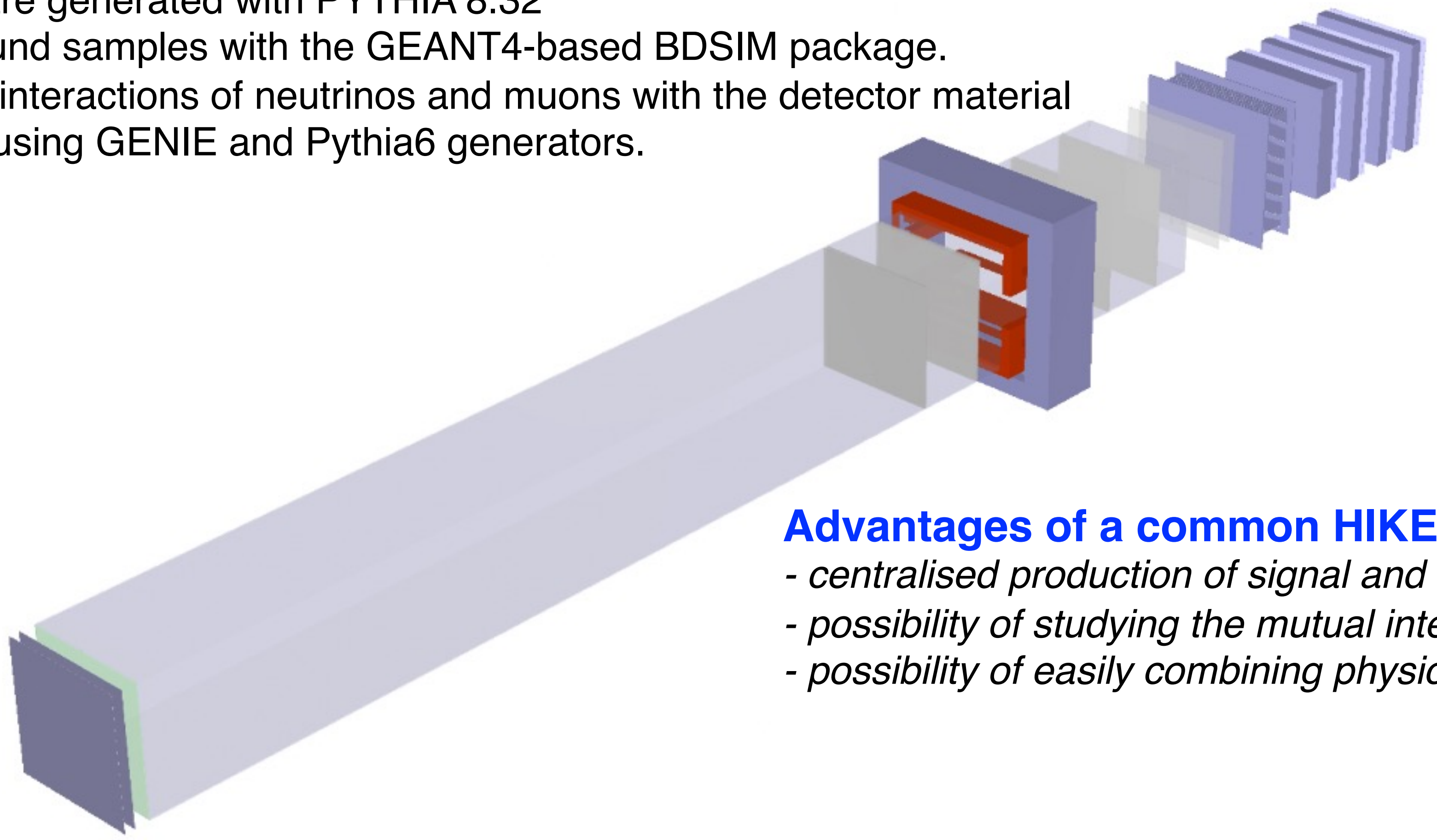


The Detector: Full simulation

Groups: INFN-Rome1 INFN-LNF, Mainz, Heidelberg, Prague

SHADOWS full Monte Carlo simulation is part of the general NA62/HIKE Monte Carlo framework and is a C++, GEANT4-based code.

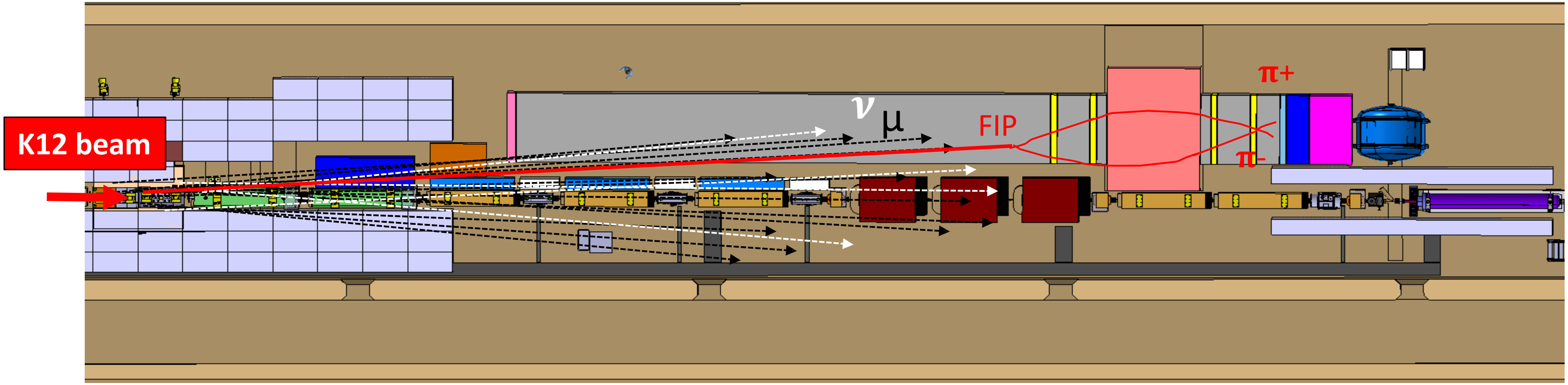
- The beamline simulation is done using the Geant4-based BDSIM package.
- The signals are generated with PYTHIA 8.32
- The background samples with the GEANT4-based BDSIM package.
- The inelastic interactions of neutrinos and muons with the detector material are simulated using GENIE and Pythia6 generators.



Advantages of a common HIKE+SHADOWS framework

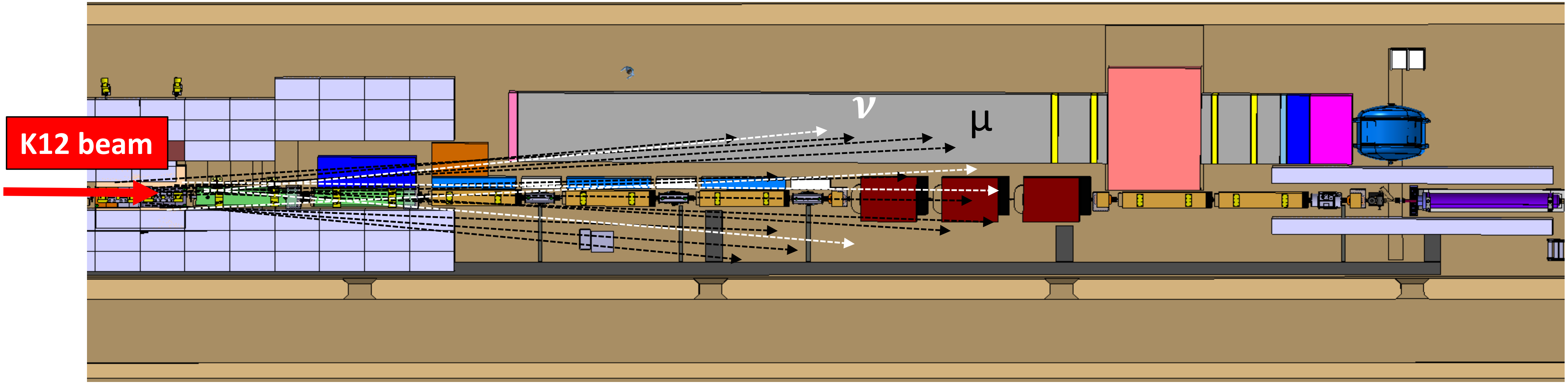
- centralised production of signal and MC samples
- possibility of studying the mutual interference
- possibility of easily combining physics results

Background: The name of the game



Main background arise from muons and neutrinos emerging from the dump.
An off-axis setup is much less affected by background than an on-axis one,
as muons and neutrinos are mostly emitted in the forward direction.

Background: The name of the game



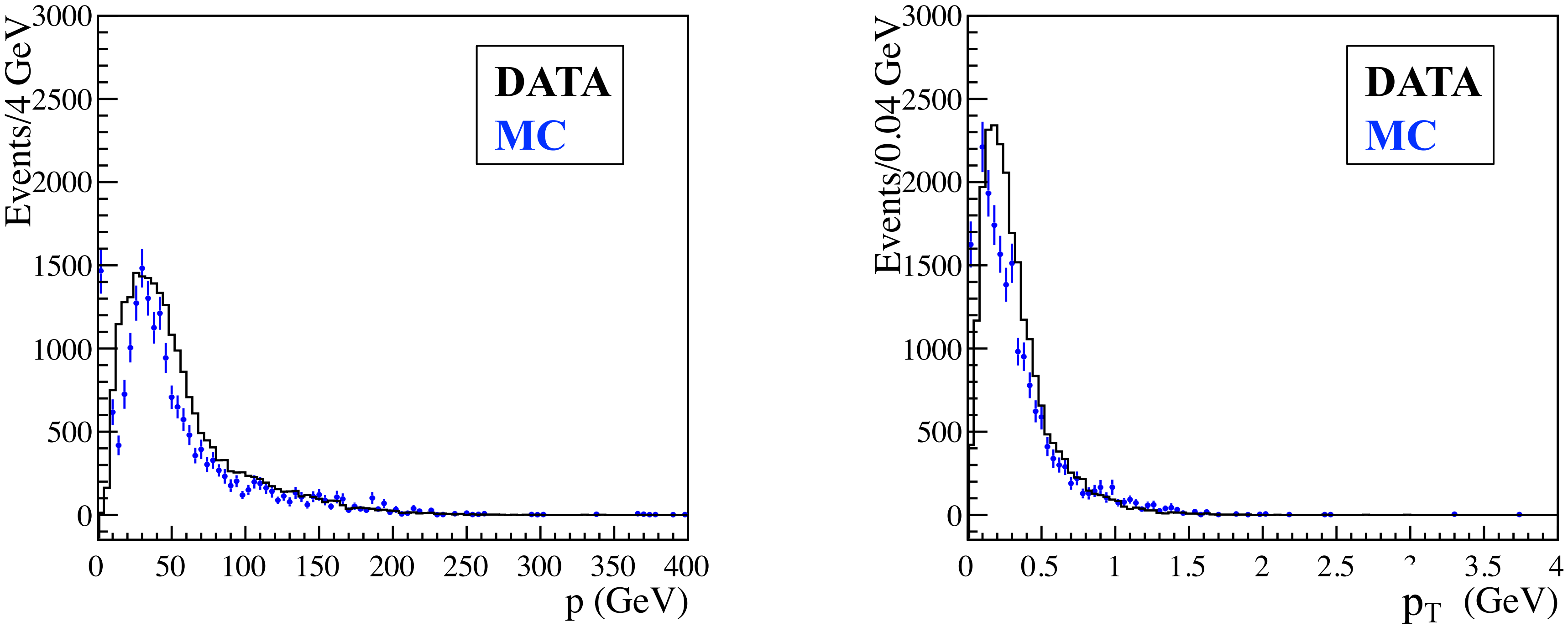
Three important backgrounds to be considered:

1. **Muon combinatorial** background
2. **Muon inelastic interactions** with the decay vessel
3. **Neutrino inelastic interactions** with the decay vessel & residual air in the decay volume

For the first two backgrounds the knowledge of the muon flux is paramount.

Validation of the simulated *on-axis* muon flux *with NA62 data*

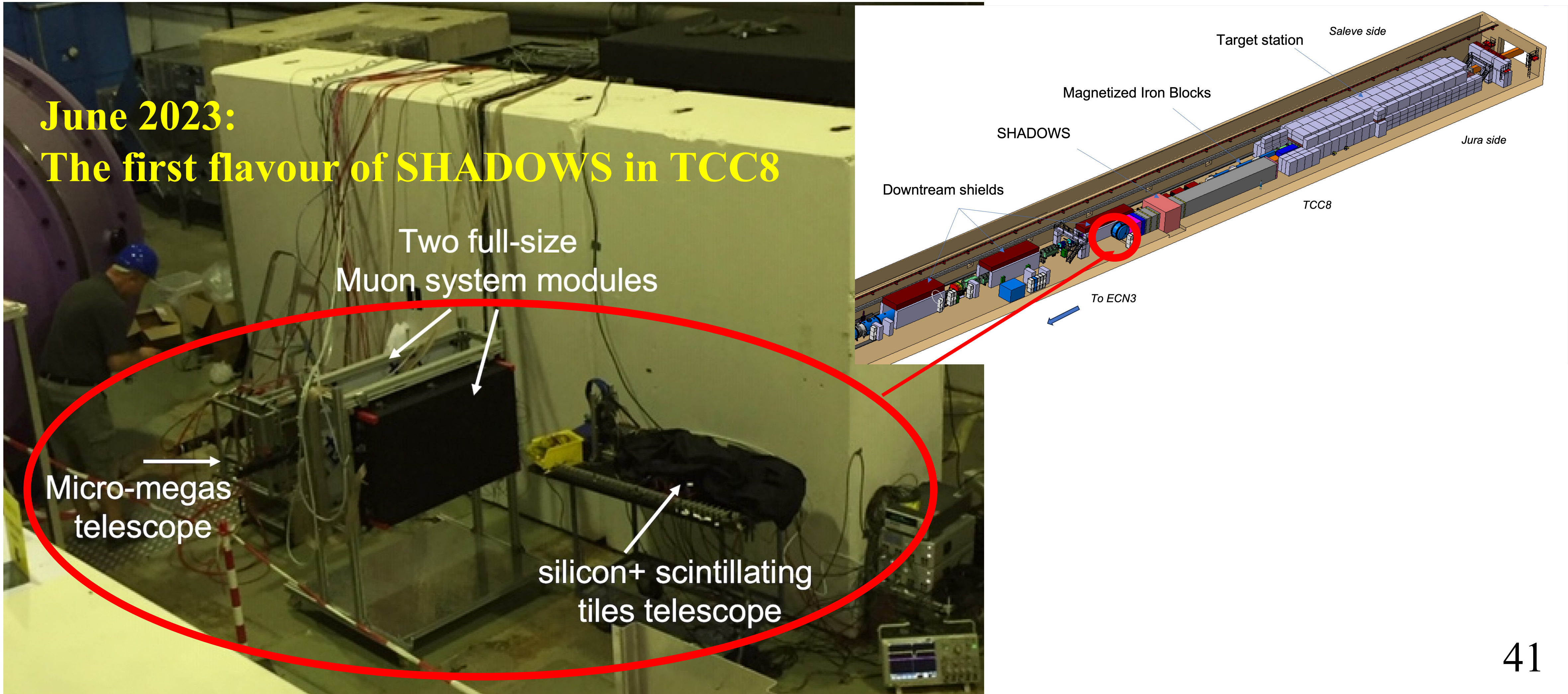
Monte Carlo simulation has been compared against data collected by NA62 in October 2021, when the experiment was successfully operated in beam-dump mode for about 1 week at about 150% the nominal NA62 beam intensity. In this period NA62 collected about 1.5 $\times 10^{17}$ pot



Excellent agreement in shape, the MC rate is about 3 times less than data as expected. MC rates corrected by this factor.

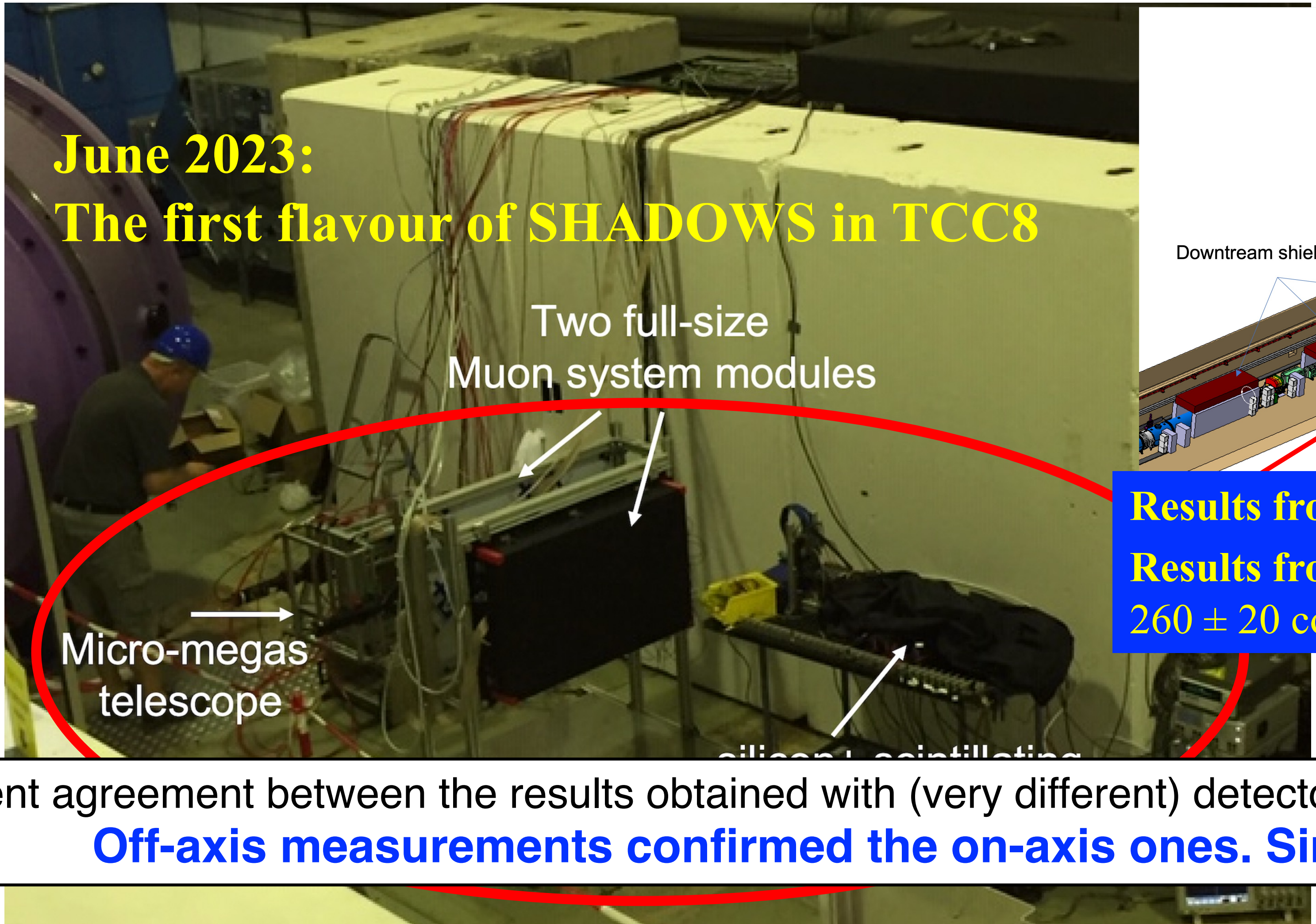
Validation of the simulated *off-axis* muon flux ***with SHADOWS prototypes***

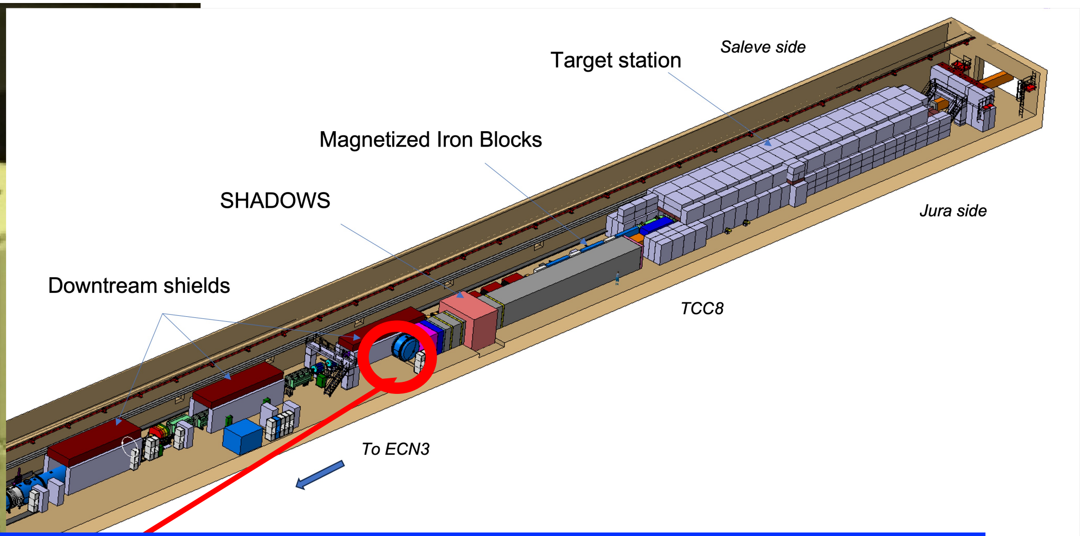
Measurement performed in June 2023 with NA62 operated in beam-dump mode at nominal beam intensity.
Effort partially funded via EUROLABS European Grant.



Validation of the simulated *off-axis* muon flux ***with SHADOWS prototypes***

Measurement performed in June 2023 with NA62 operated in beam-dump mode at nominal beam intensity.
Effort partially funded via EUROLABS European Grant.





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

Results from simulation (rescaled):
260 ± 20 counts/cm2/10^{12} pot

Excellent agreement between the results obtained with (very different) detectors gives reliability of the measurement.
Off-axis measurements confirmed the on-axis ones. Simulation fully validated.

The SHADOWS teams at work in TCC8

A big thanks to the NA62 Collaboration for the support and help

Background: Results

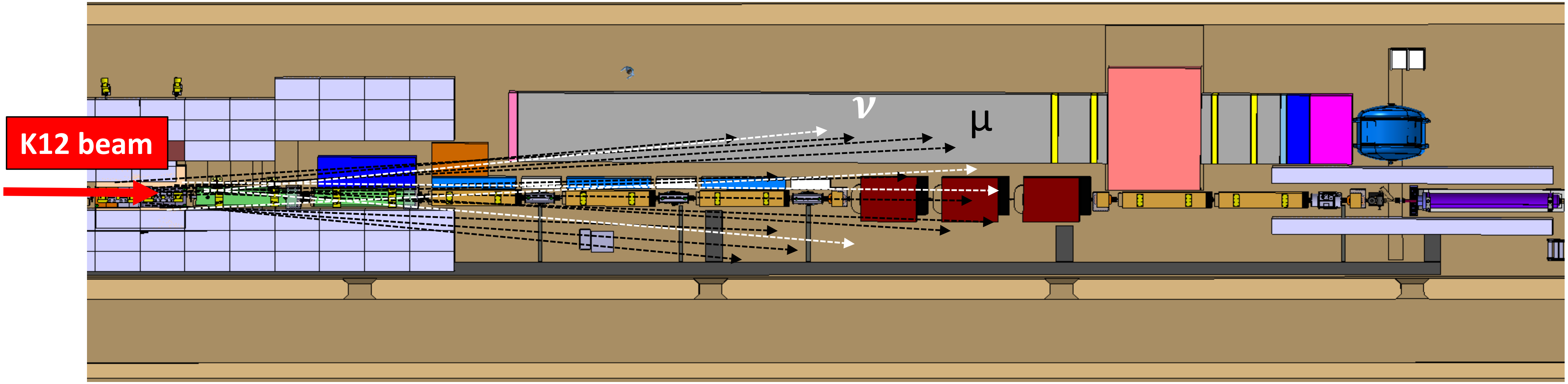


Table 31. Estimated background events in 5×10^{19} pot. For muon-induced background events the factor 3 difference between data and monte carlo simulation discussed in Section 8.7 has been taken into account.

background type	fully reconstructed	partially reconstructed
combinatorial di-muon	10^{-3}	0.7
muon inelastic interactions	$< 2.5 \cdot 10^{-2}$	< 0.90
neutrino inelastic interactions	< 0.01	< 0.01

All the background sources are very small and well under control.

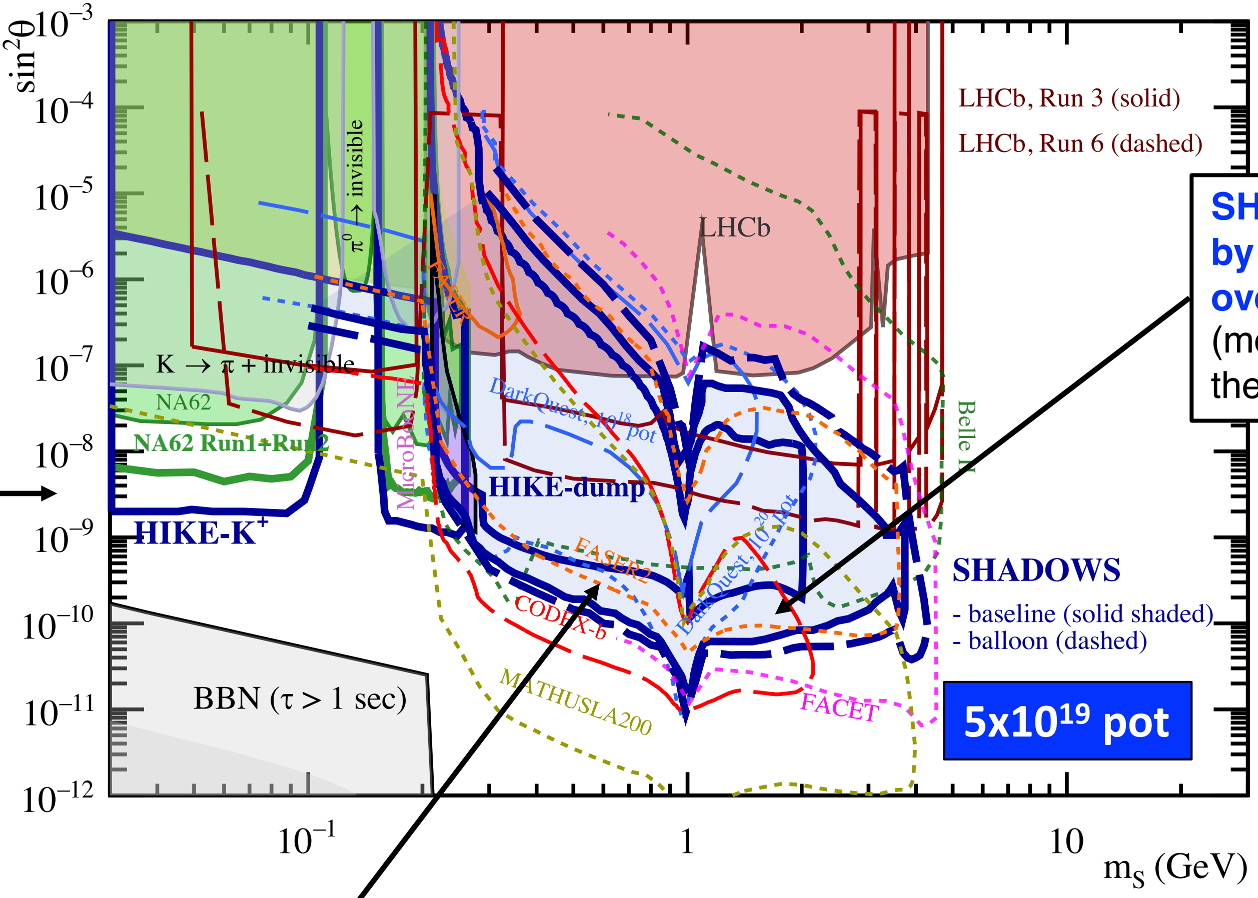
SHADOWS FIP Physics Reach with $5x10^{19}$ pot

SHADOWS

Physics sensitivity: Light Dark Scalar mixing with the Higgs

(mediator of sub-GeV DM interacting with SM particles; candidate for relaxion mechanism, etc.)

SHADOWS is fully complementary to HIKE-phase 1 in kaon mode, that improves by about one order of magnitude below the kaon mass.



SHADOWS can improve by three orders of magnitude over the existing bounds (mostly from LHCb) between the di-muon threshold and ~4 GeV.

Given the extremely low background, **the contour plot can be interpreted as discovery plot.**

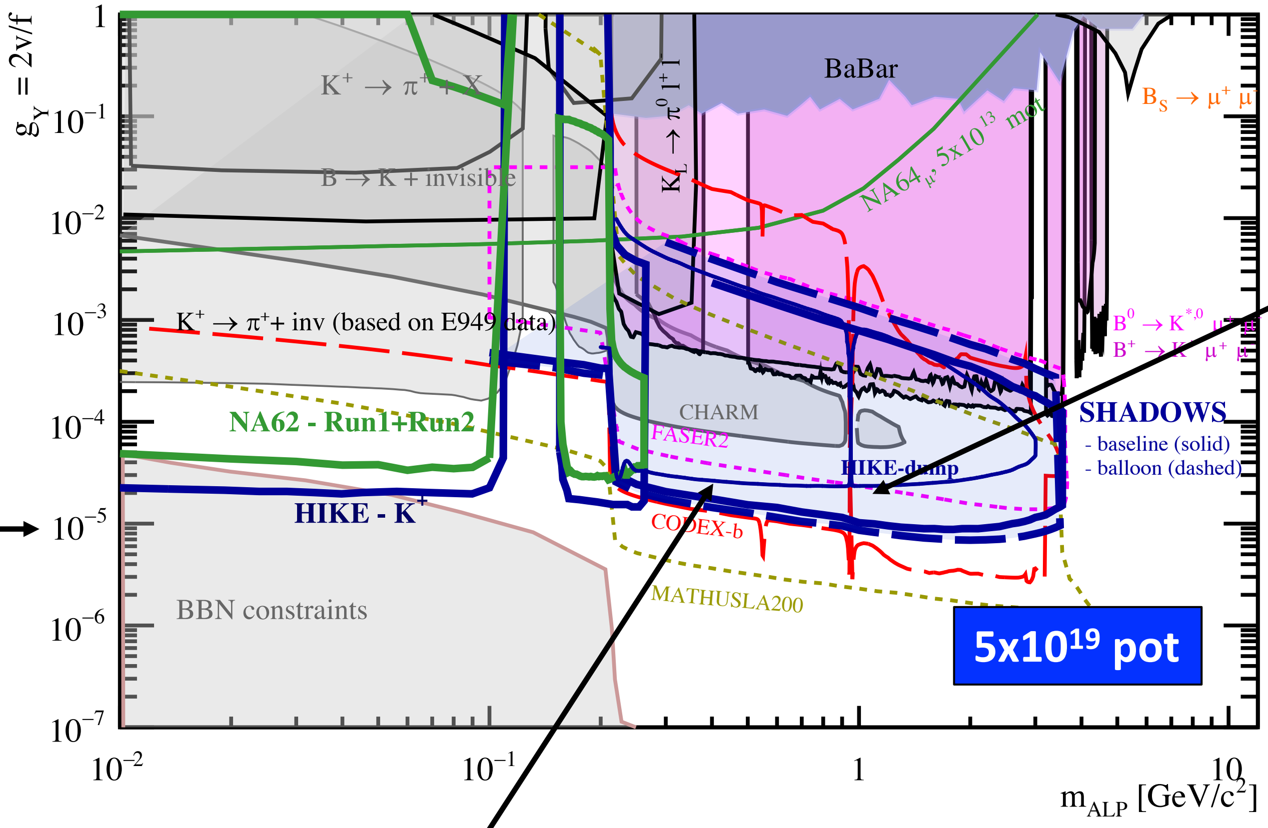
SHADOWS can cover a larger area in the (still uncharted) parameter space **than: DarkQuest; LHCb Run3 & Run 4 (upgrade 1); LHCb Run 6 (upgrade 2); CODEX-b; FASER2** at the Forward Physics Facility.

Worldwide landscape from FIPs2022 Proceedings, arXiv:2305.01715

Physics sensitivity: ALPs with fermion couplings

Axions/ALPs in the MeV-GeV range are possible solution to the strong-CP problem

SHADOWS is complementary to HIKE-phase 1 in kaon mode, that can improve by about one order of magnitude the current bound below the K mass, and fill the gap down to BBN.



SHADOWS can improve by two orders of magnitude over the existing experimental bounds (LHCb) between the di-muon threshold and ~ 4 GeV.

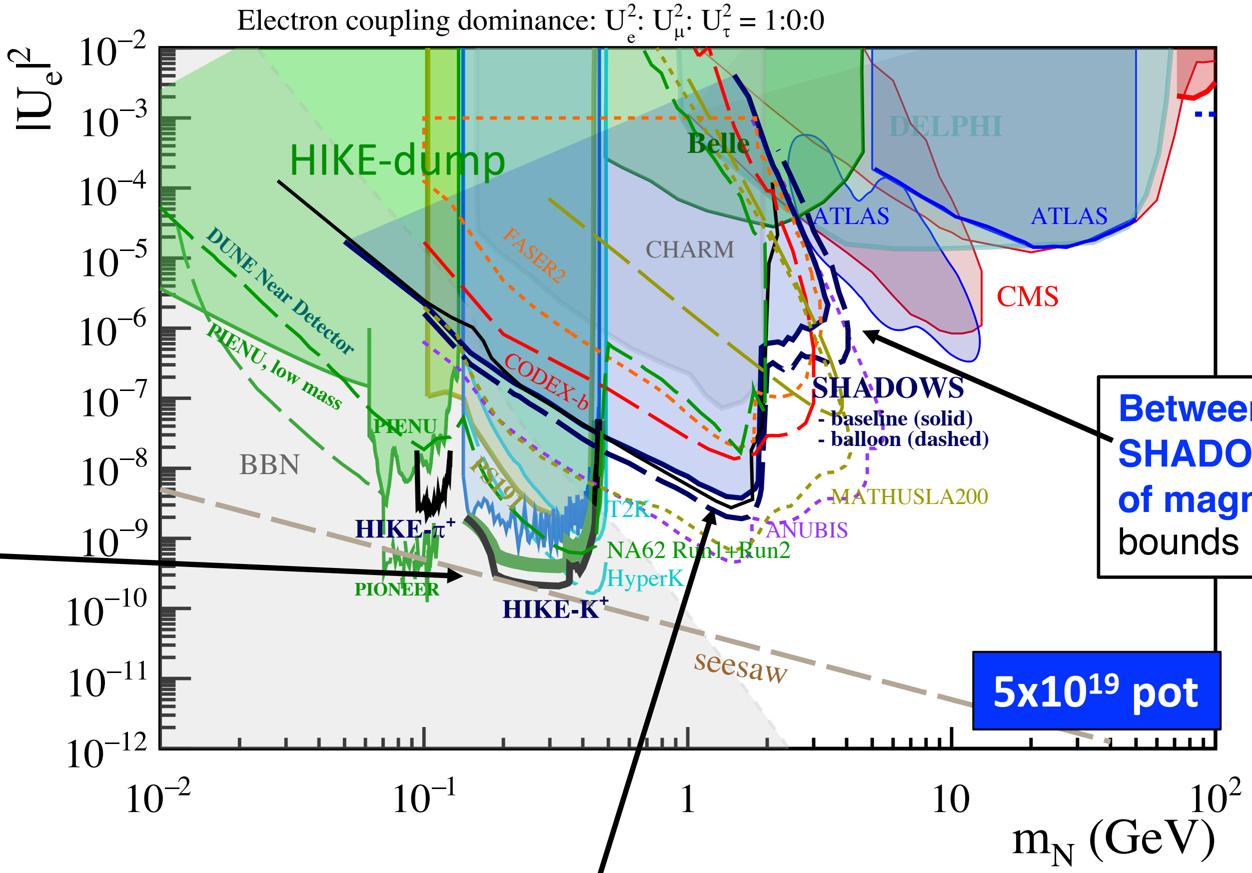
Given the extremely low background, **the contour plot can be interpreted as discovery plot.**

SHADOWS can cover a larger area than:
FASER2 at the Forward Physics Facility; and is very similar to CODEXb with the full data set at the end of the HL-LHC (3 ab^{-1}).

Worldwide landscape from FIPs2022 Proceedings, arXiv:2305.01715

Physics sensitivity: HNL with electron couplings

Possible solution to the origin of the neutrino masses and matter-antimatter asymmetry



Fully complementary with HIKE phase 1 and BD
Below the K and above the B threshold. Synergistic Between K and D thresholds.

Between D and B thresholds SHADOWS improves by about one order of magnitude over the existing experimental bounds (Belle & CMS)

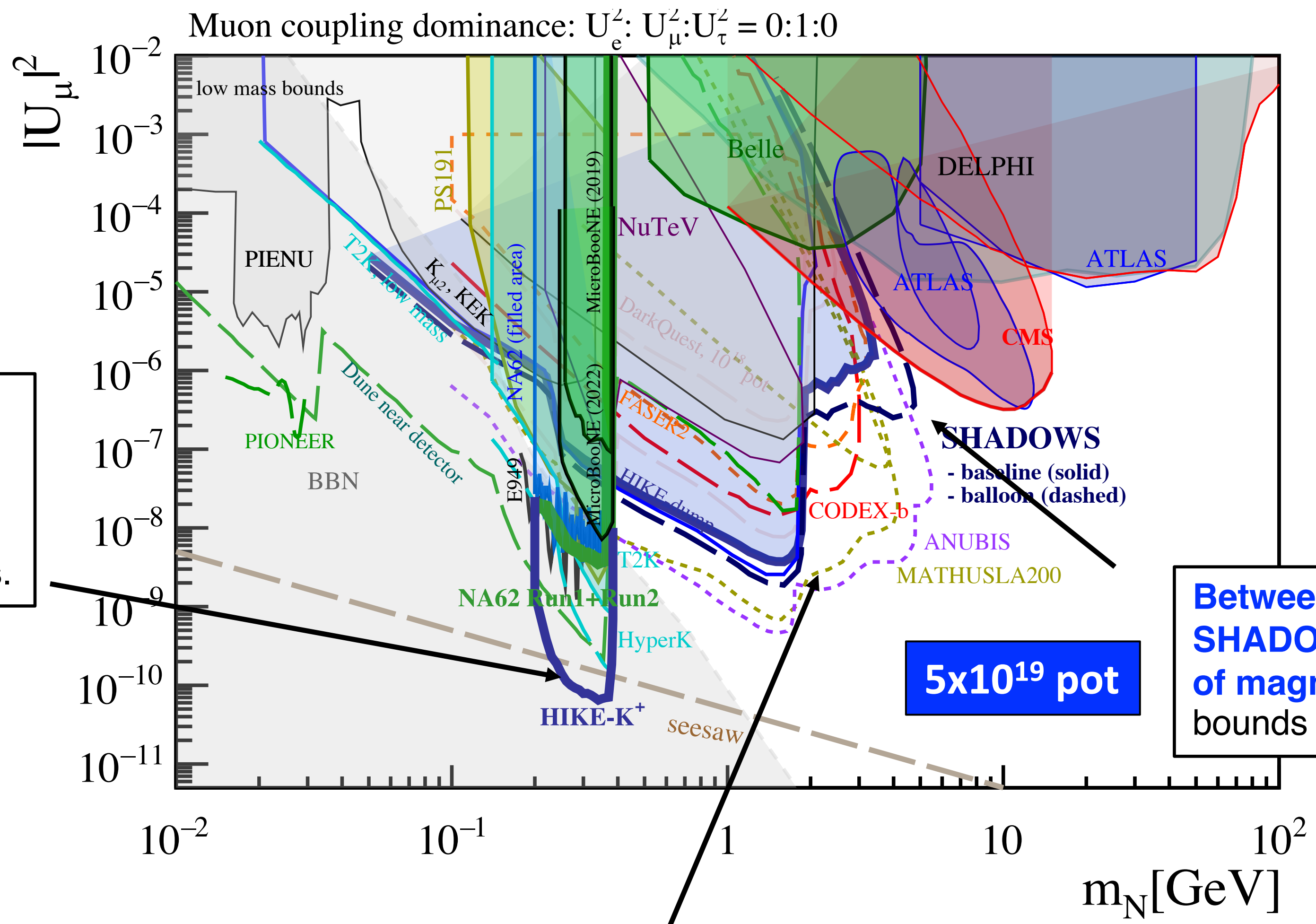
Given the extremely low background, **the contour plot can be interpreted as discovery plot.**

Between K and D thresholds SHADOWS improves by about four orders of magnitude over the existing experimental bounds (Belle)

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

Physics sensitivity: HNL with muon couplings

Possible solution to the origin of the neutrino masses and matter-antimatter asymmetry



Fully complementary with **HIKE phase 1** and BD below the K and above the B threshold. Synergistic between K and D thresholds.

Between D and B thresholds SHADOWS improves by about one order of magnitude over the existing experimental bounds (CMS)

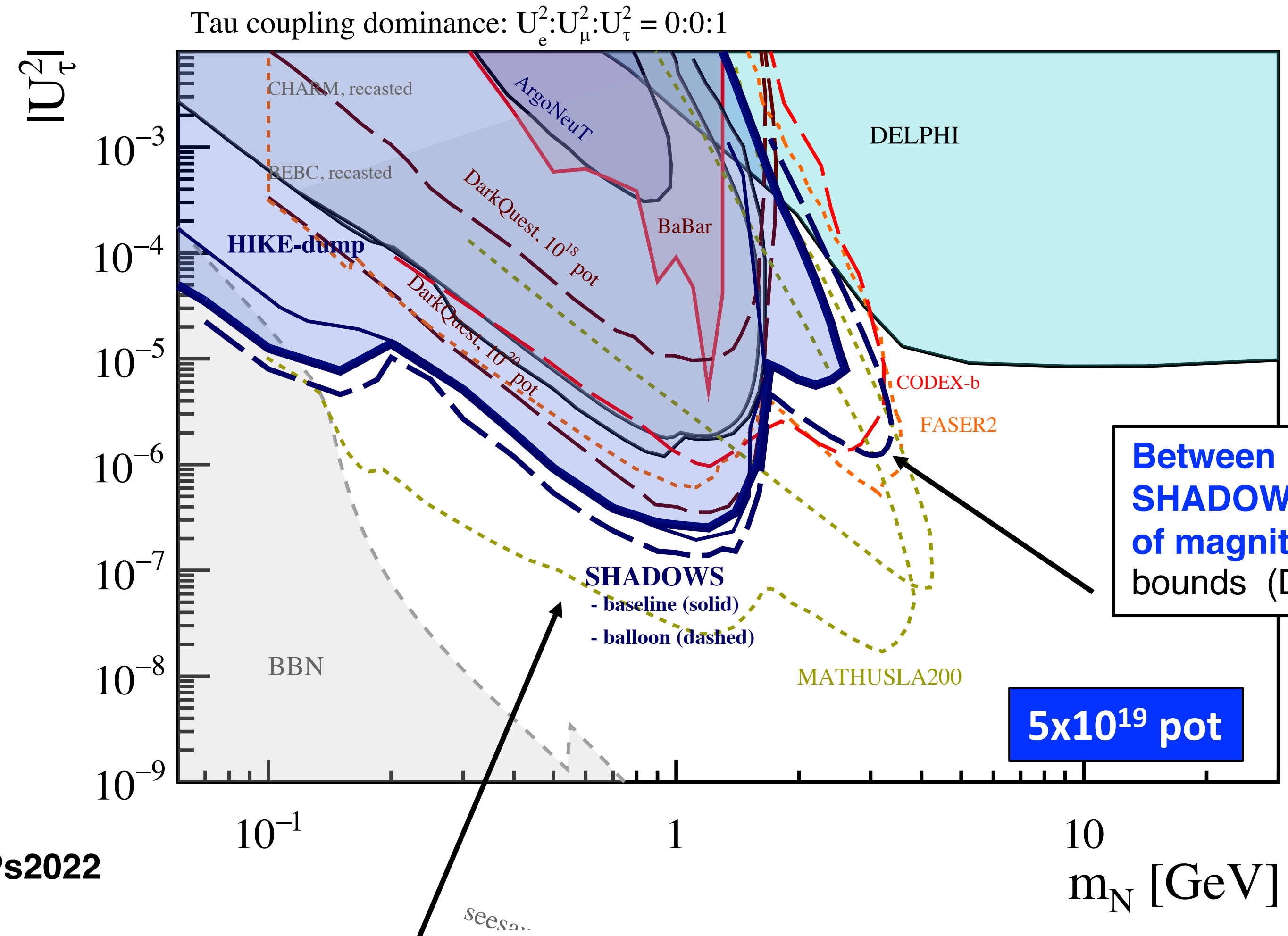
Given the extremely low background, **the contour plot can be interpreted as discovery plot.**

Between K and D thresholds SHADOWS improves by about one order of magnitude over the existing experimental bounds (NuTeV)

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

Physics sensitivity: HNL with tau couplings

Possible solution to the origin of the neutrino masses and matter-antimatter asymmetry



Between D and B thresholds SHADOWS improves by two orders of magnitude over the existing experimental bounds (DELPHI)

Given the extremely low background, **the contour plot can be interpreted as discovery plot.**

Worldwide landscape from FIPs2022 Proceedings, arXiv:2305.01715

Up to D threshold SHADOWS improves by two-four orders of magnitude over the existing experimental bounds (ArgoNeut & BaBar) and is better than DarkQuest, CODEX-b and FASER2.

Assume now that a hint of New Physics in any of the portals is found…

..and perhaps it is worth to push the run in dump as much as possible…

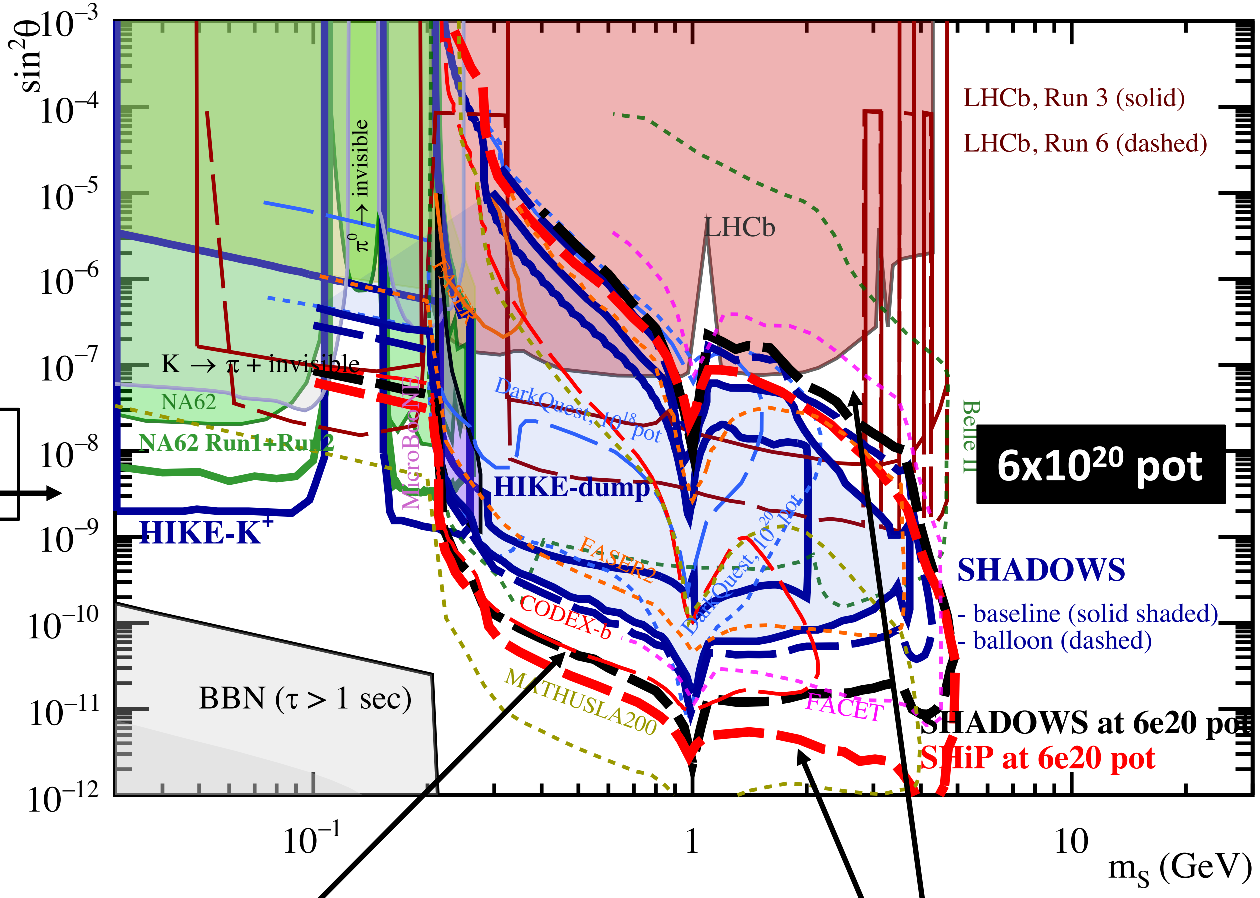
Which is the SHADOWS physics reach for $6x10^{20}$ pot ?

Physics sensitivity: Light Dark Scalar mixing with the Higgs

(mediator of sub-GeV DM interacting with SM particles; candidate for relaxion mechanism, etc.)

HIKE provides the world-best limits below the Kaon mass

HIKE Proposal
SPSC-P-368



SHiP Proposal
SPSC-P-369

SHADOWS & SHiP are very similar below 1 GeV

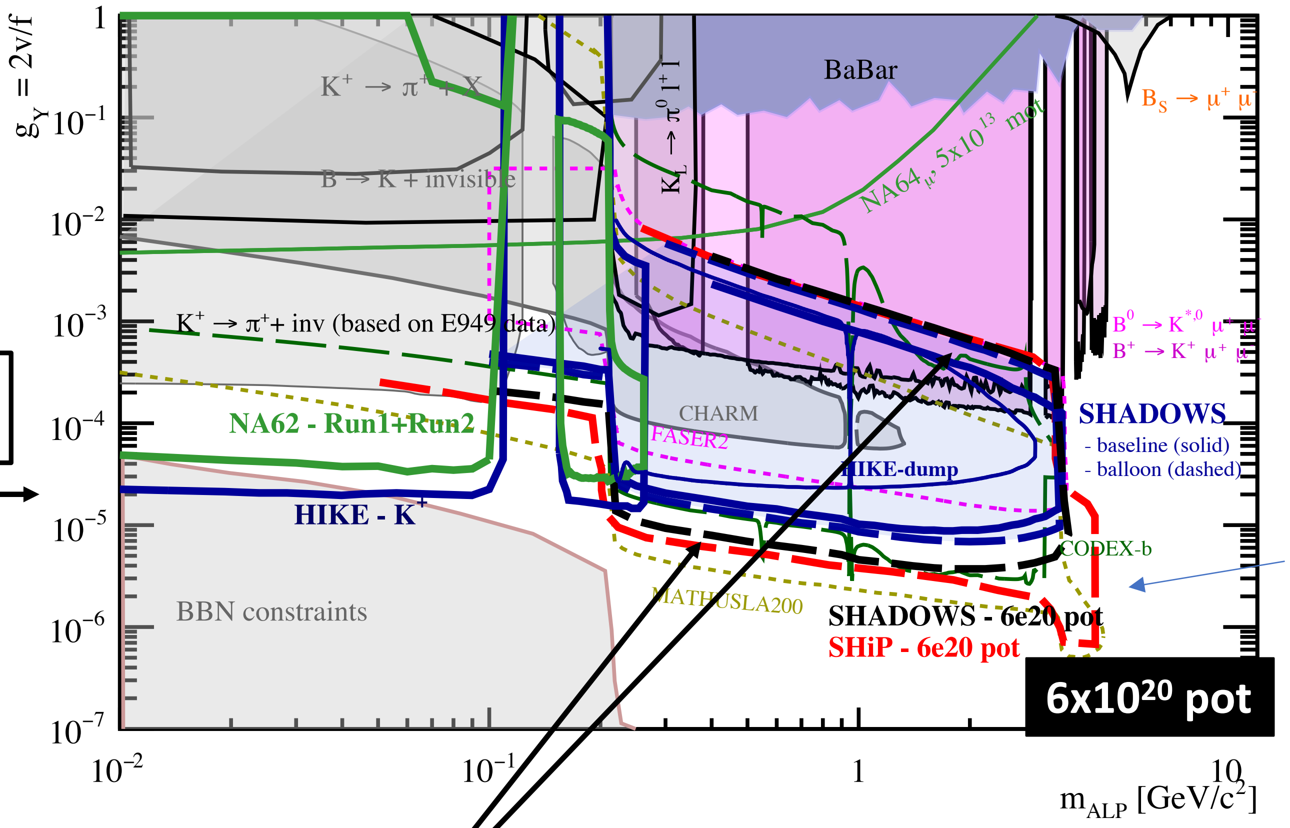
Above 1 GeV:
- **SHiP is better than SHADOWS for low couplings.**
- **SHADOWS is better than SHiP for large couplings**

Physics sensitivity: ALPs with fermion couplings

Axions/ALPs in the MeV-GeV range are possible solution to the strong-CP problem

HIKE-phase 1 in kaon mode, Sets the world best limit

HIKE Proposal
SPSC-P-368



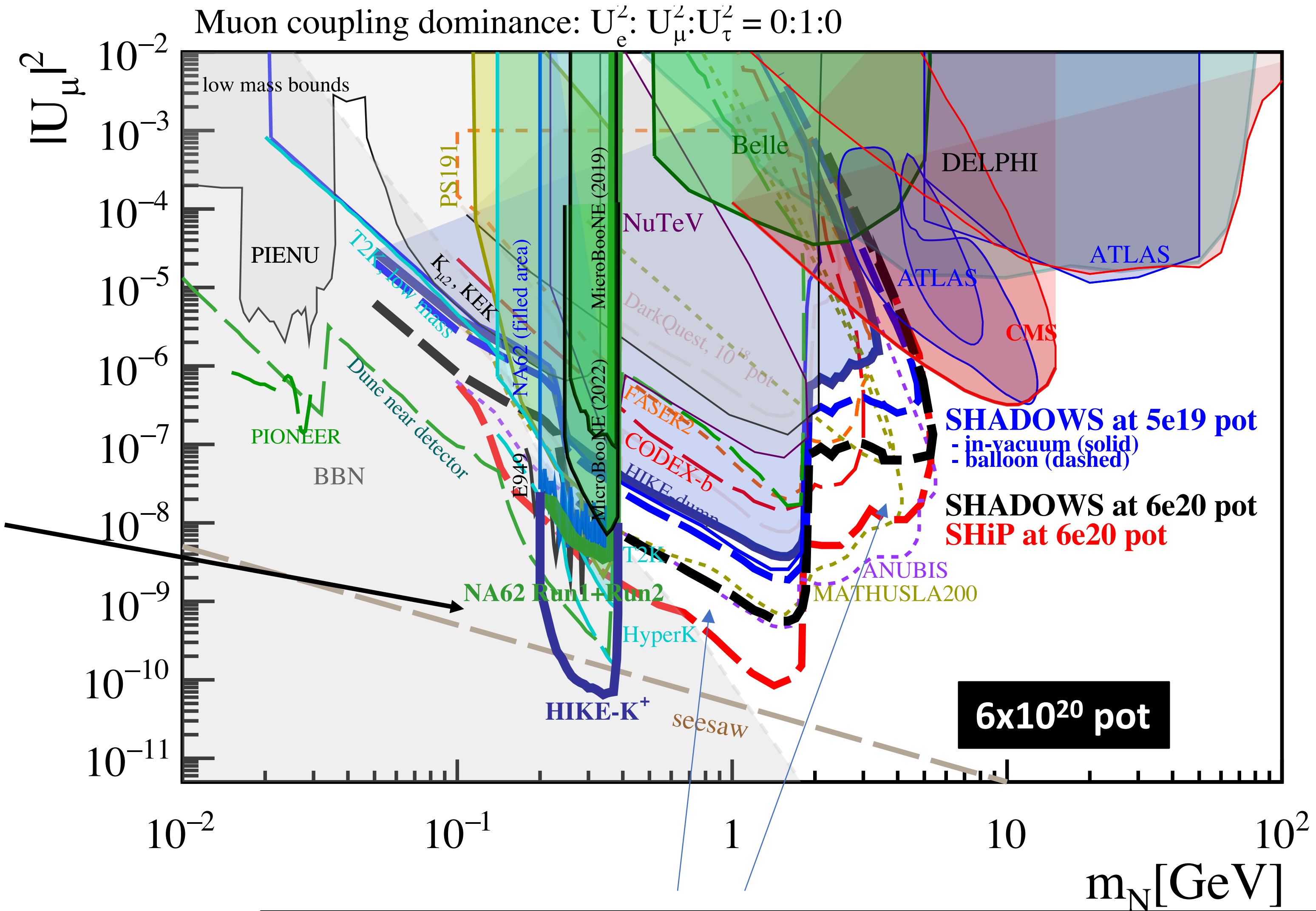
SHiP Proposal
SPSC-P-369

The difference at large masses
Is due to the fact that SHADOWS
did not yet include the tau-tau
final state in the computations.

SHADOWS very similar to SHiP above the di-muon threshold either for low and for large couplings

Physics sensitivity: HNL with muon couplings

Possible solution to the origin of the neutrino masses and matter-antimatter asymmetry



HIKE phase 1 sets the world best limit below the K threshold

HIKE Proposal
SPSC-P-368

SHiP Proposal
SPSC-P-369

Above the Kaon mass, the difference between SHADOWS & SHiP
Is greatly reduced when compared with the same number of pot

All in all:

SHADOWS very competitive with an on-axis detector for the same number of pot

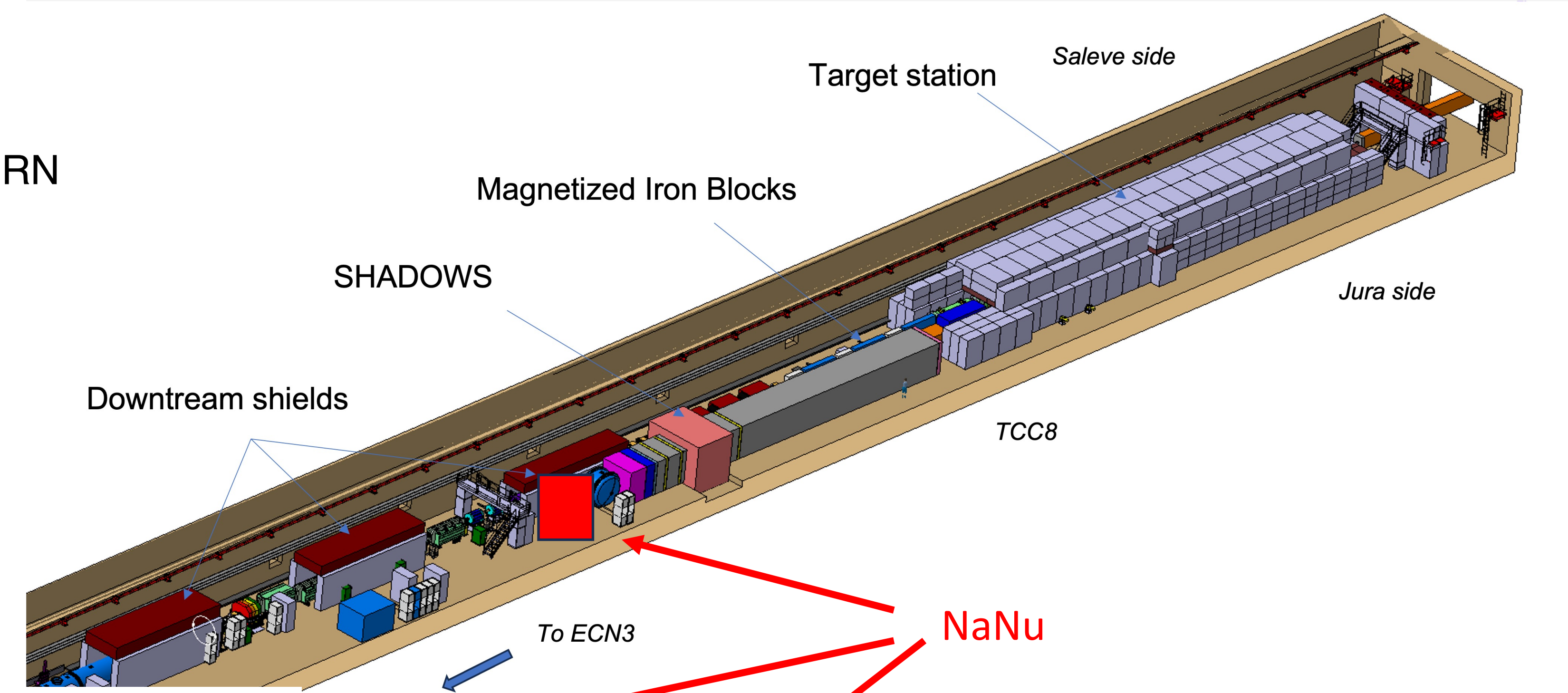
With the following (important) advantages:

1) ***SHADOWS's cost is much less (1/5 wrt SHiP);***
2) ***SHADOWS (+HIKE) layout is flexible:***
Priority for Kaon or FIP physics can be decided along the way…

SHADOWS

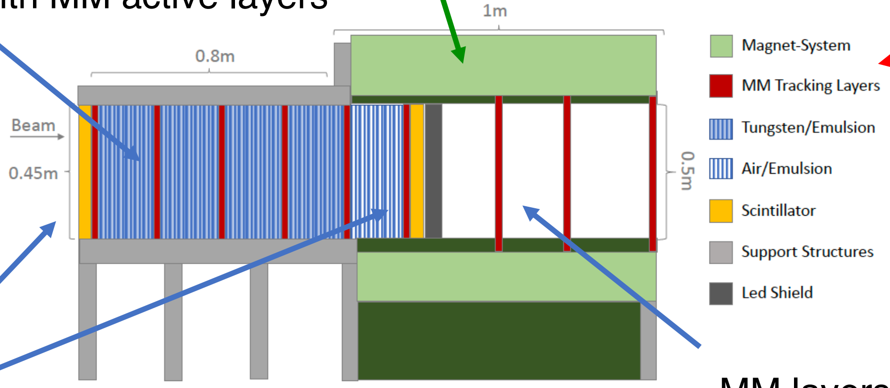
The North Area Neutrino Detector (NaNu@SHADOWS)

NaNu magnet already available at CERN



NaNu

Tungsten-emulsion detector
Interleaved with MM active layers

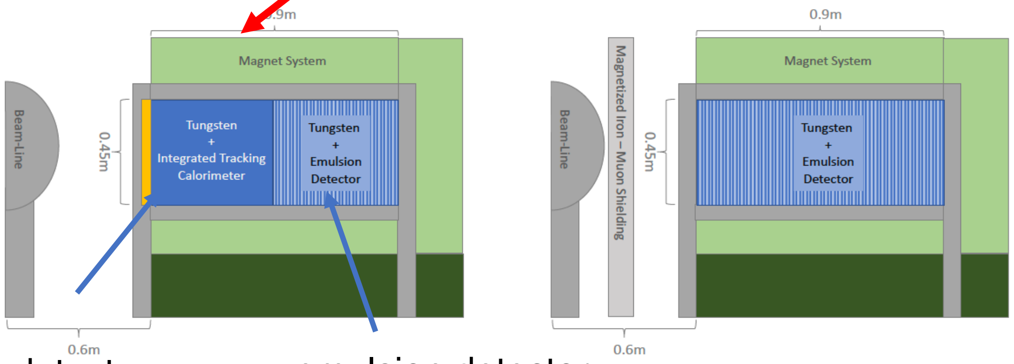


Scintillator-based vetoes

Lateral view

MM layers

Super-NaNu



active detector

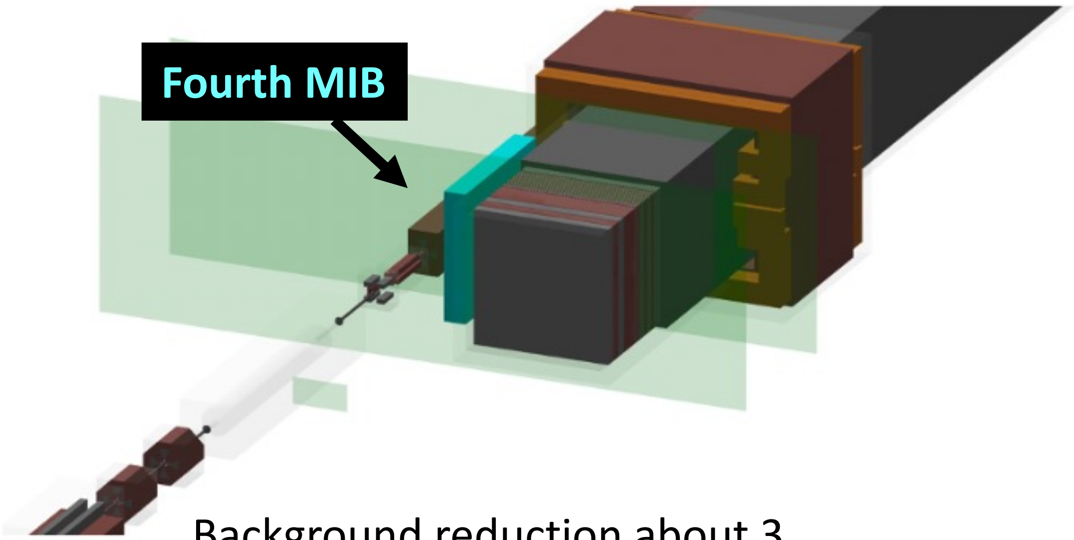
emulsion detector

Front view

Background reduction for neutrino physics

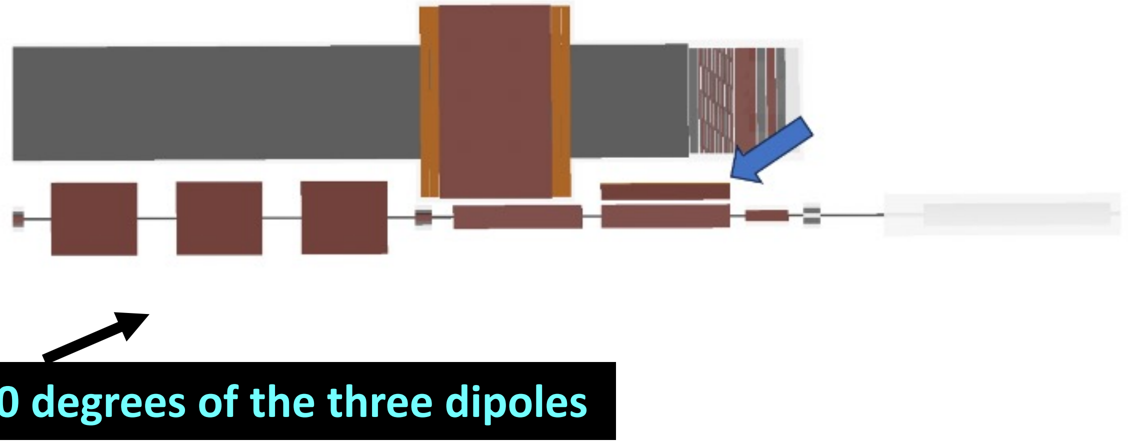
Background reduction in NaNu zone possible by:

1. Addition of a fourth MIB
2. Rotation by 90 degrees of the three BEND3 dipoles to sweep the muon flux up-down



Background reduction about 3

Background reduction about 45



Full emulsion instrumentation (Super-NaNu layout) possible since day 1

Neutrino Physics with Super-NaNu ($5x10^{19}$ pot)

Expected **number of detectable neutrino interactions** within the NaNu detector for 5 $x10^{19}$ POT for NaNu and Super-NaNu.

Experimental Setup	NaNu	Super-NaNu
ν_e	4.1×10^3	20×10^3
$\bar{\nu}_e$	1.0×10^3	4.5×10^3
ν_μ	40×10^3	40×10^3
$\bar{\nu}_\mu$	9×10^3	9×10^3
ν_τ	0.12×10^3	0.72×10^3
$\bar{\nu}_\tau$	0.07×10^3	0.41×10^3

Overview of various **tau decay channels** including their branching ratio (BR) together with the efficiencies of various selection and identification criteria

Decay-Channel	$\tau \to e$	$\tau \to \mu$	$\tau \to h(\pi^\pm)$	$\tau \to 3h(3\pi^\pm)$
BR	0.17	0.18	0.46	0.12
Geometrical	0.9	0.9	0.9	0.9
Decay search	0.6	0.6	0.6	0.6
PID	1.0	0.9	0.9	0.9
Total Events (NaNu)	10	10	30	10
Total Events (Super-NaNu)	60	60	180	45
Decay-Channel	$\bar{\tau} \to e$	$\bar{\tau} \to \mu$	$\bar{\tau} \to h(\pi^\pm)$	$\bar{\tau} \to 3h(3\pi^\pm)$
BR	0.17	0.18	0.46	0.12
Geometrical	0.9	0.9	0.9	0.9
Decay search	0.6	0.6	0.6	0.6
PID	1.0	0.9	0.9	0.9
Total Events (NaNu)	7	7	20	5
Total Events (Super-NaNu)	40	40	115	30

ν(τ)

anti-ν(τ)

Physics programme

- **Deep inelastic scattering of ν(μ) with 5-10% precision**, measurement of charm production sensitive to s-quark content in nucleons (important for W mass measurement).
- **First observation of anti- ν(τ)**
- **measurement of ν(τ) and anti- ν (τ) inclusive cross-sectio**n at 10% (5%) at NaNu (superNaNu), with possible observation of F4 and F5 structure function effects.
- **study of ν(τ) (anomalous) magnetic moment**

Project Schedule

2023	2024	2025	2026	2027	2028	2029	2030	2031
NA62 Run			LS3	LS3	LS3	ECN3/HI Installation/ commissionin g	ECN3/HI Installation/ commissioning	ECN3/HI run
Proposal	TDR	TDR	TDR/PRR	Production	Production	Production/ Installation	Installation/ Pilot Run	SHADOWS run

2032	2033	2034	2035	2036	2037	2038	2039	2040
ECN3/HI run	LS4		ECN3/HI Run				LS5	
SHADOWS run	consolidation	SHADOWS run	SHADOWS run	SHADOWS run	SHADOWS run	SHADOWS run	consolidation	SHADOWS run

SPSC review process ended two days ago. Expect decision at the CERN Research Board December 6th.
If approved, SHADOWS will start data taking in 2030 and collect 5×10^{19} (or more) pot by 2040.

Project Organization: preliminary groups interest

Table 41. Preliminary group interests for SHADOWS sub-detectors and activities.

Item	Technology	Interested groups
MIB system	magnetized iron blocks	CERN, LNF-INFN
Upstream Veto	Micromegas	INFN (Rome3, Naples)
Decay Vessel	in-vacuum	CERN
Dipole Magnet	warm	CERN
Tracker	Straws	Heidelberg
Timing Layer	scintillating bars	Freiburg
ECAL	StripCal	Mainz, KIT
Muon	scintillating tiles	INFN (LNF,Ferrara, Bologna)
Software		INFN-Rome 1, Prague
TDAQ		CERN
NaNu		Mainz/Bonn

All detectors/activities have groups involved. Still a lot of room for new groups/collaborators.

Project Organization: preliminary cost estimate

Table 40. Preliminary cost estimate of SHADOWS sub-detectors and magnets. The cost of the NaNu experiment is reported in the last row.

Item	Technology	Cost (M€)
MIB system	magnetized	
	iron blocks	0.992
Upstream Veto	Micromegas	0.860
Decay Vessel	in-vacuum	1.0
Dipole Magnet	warm	2.57
Tracker	Straws	1.624
Timing Layer	scintillating bars	0.180
ECAL	StripCal	0.980
Muon	scintillating tiles	1.111
TDAQ		0.250
Total SHADOWS		**9.567**
Total NaNu		**2.840**

Cost uncertainty C3 class:
(-(10-20)%, +(10-30)%)

The relative small-medium size (and cost) makes SHADOWS feasible and realistic in the short timescale
(start production in three years from now, production lasting only two years)

Conclusions

✓ **SHADOWS and HIKE** running simultaneously and covering complementary ranges in the FIP parameter space, *above* and *below* the kaon mass, **will become a hot spot for FIP physics in the worldwide landscape.**

✓ The possibility of **exploring new light and feebly-interacting phenomena** and, simultaneously, **very high-scale masses through precision measurements** in the kaon sector, **makes the combined SHADOWS + HIKE system unique worldwide.**

✓ The upgrade in intensity of the K12 beamline would allow CERN to have ***a* world-class facility with** several experiments running concurrently and covering **a broad and diverse spectrum of physics topics, which is crucial, we think, for the future of particle physics**.

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Thanks for your attention.