Search for Feebly-Interacting Particles (FIPs) with NA62/HIKE and SHADOWS experiments

Gaia Lanfranchi
INFN-LNF

FPCapri, June 2022

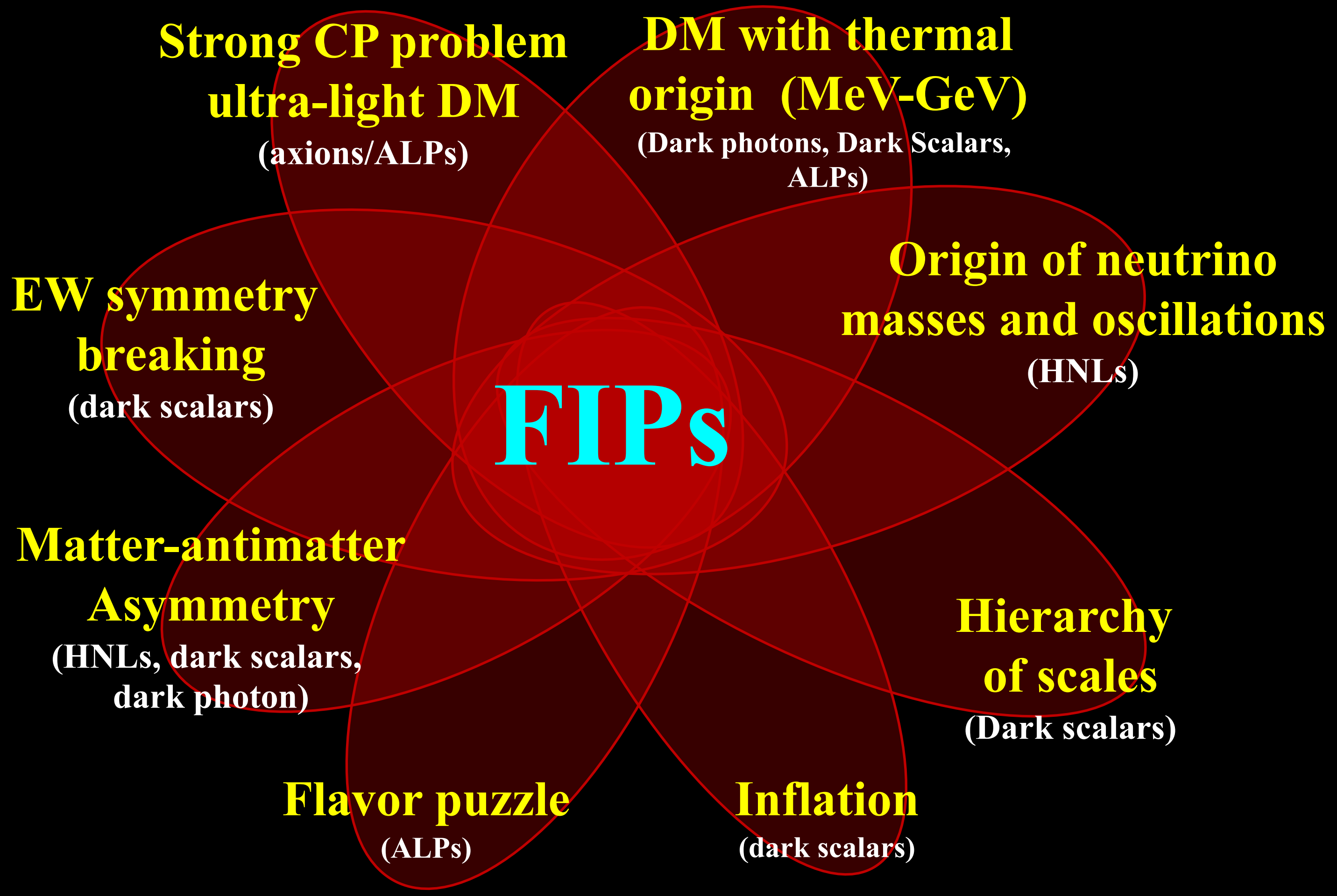
What are Feebly-Interacting Particles (FIPs)?

Very roughly:
any NP with (dimensional or dimensionless) effective couplings $\ll 1$
possibly neutral under SM symmetries

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

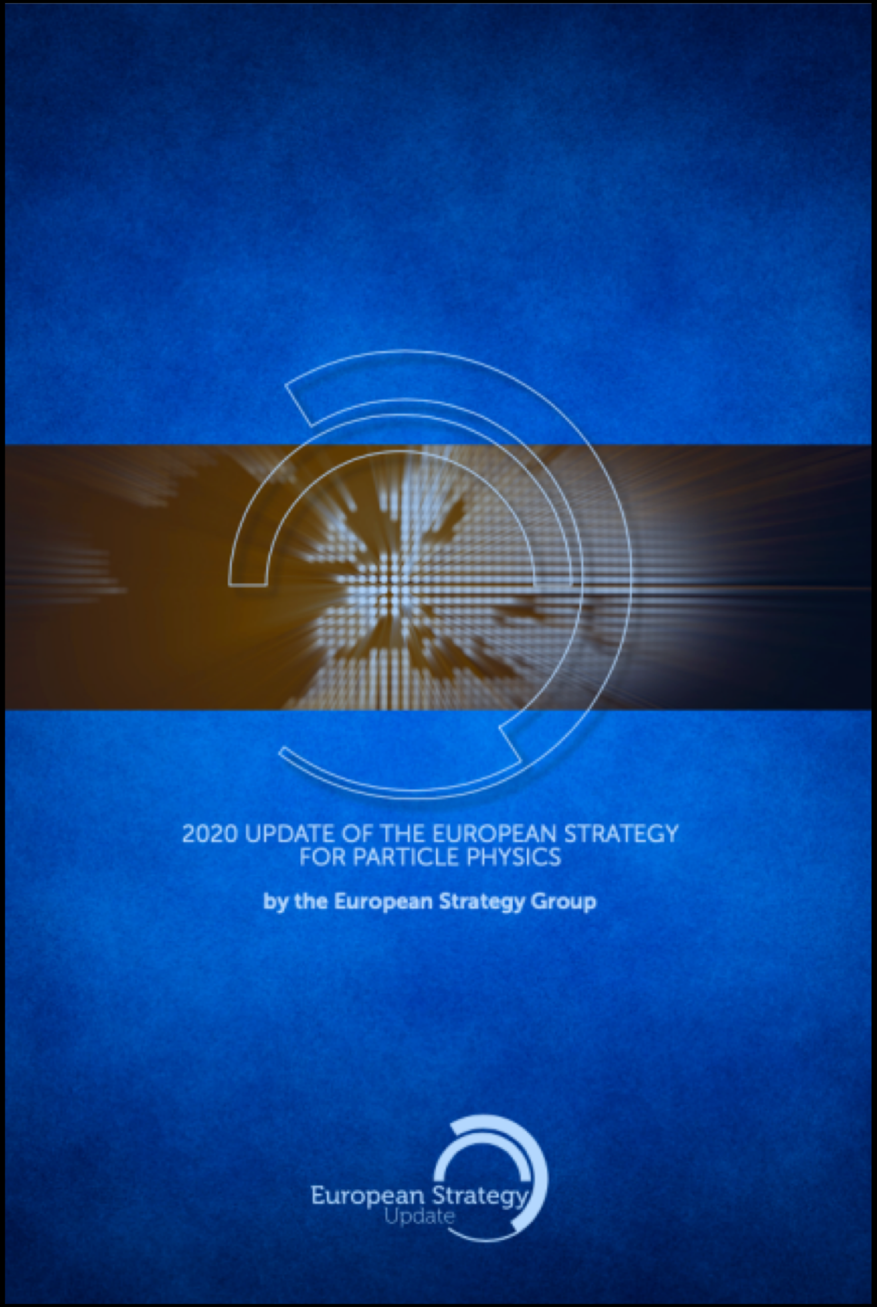
Fully complementary to high-energy searches.
Naturally long-lived.

FIPs might provide answers to fundamental physics questions…



For a general introduction (not too technical):

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



ESPP Recommendations

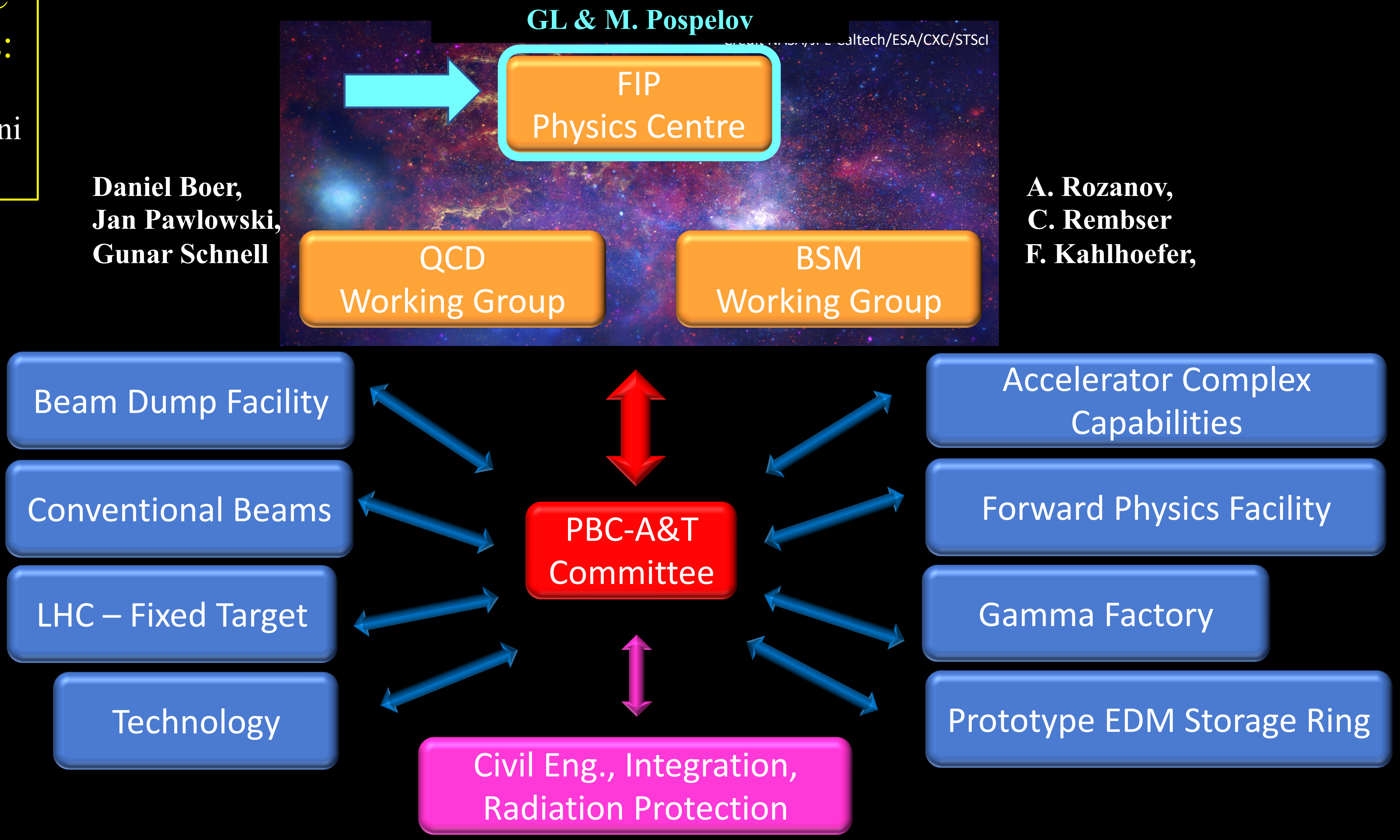
- "*4. Other essential scientific activities for particle physics:*
- *a) The quest for dark matter and the exploration of flavour and fundamental symmetries are crucial components of the search for new physics.*
- *This search can be done in many ways, for example through precision measurements of flavour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

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

Physics Beyond Colliders @ CERN

https://pbc.web.cern.ch

General PBC coordinators:
Claude Vallee
Gianluigi Arduini
Joerg Jaeckel



Physics Beyond Colliders

FIP Physics Centre

Composition

(contacts: M. Pospelov & GL)

https://pbc.web.cern.ch/fpc-mandate

Mikhail Shaposhnikov (HNLs)

Gian Francesco Giudice (Head of CERN-TH)

Stefania Gori (light DM)

Yevgeni Stadnik (ultra-light FIPs)

Maurizio Giannotti (astroparticle)

Philip Schuster (light DM, SLAC)

Torben Ferber (Belle II)

Albert De Roeck (LLP @ LHC)

Marco Drewes (HNLs)

Martin Bauer (ALPs)

Joerg Jaeckel (axions/ALPs)

Silvia Pascoli (HNL)

Gordan Krnjaic (light DM, FNAL)

Pilar Hernandez (HNL)

Stefan Ulmer (ultra-light FIPs, CERN AD)

Matheus Hostert (non-minimal HNLs)

Jocelyn Monroe (DM direct detection, Gran Sasso)

James Beacham (LLP @ LHC)

Igor Irastorza (axion physics, DESY)

Jessie Shelton (astroparticle)

Jacobo Lopez-Pavon (HNL)

Philip Harris (DM LHC WG)

Felix Kahlhoefer (Axions,ALPs,..)

Experimentalists

Theorists

+ CERN experiments' representatives

Physics Beyond Colliders

Experiments/proposals related to FIPs in PBC

FIPs @ CERN

SPS
(MeV- few GeV)

NA62/HIKE
FIPs with kaons/proton beam dump

SHiP

SHADOWS
FIPs @ proton beam dump

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

(Baby-)IAXO
solar axions

Axions/Dark Photons/etc.
(< meV)

VMB
Vacuum birifrangence

Gamma-factory
(mostly ALPs)

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, …)

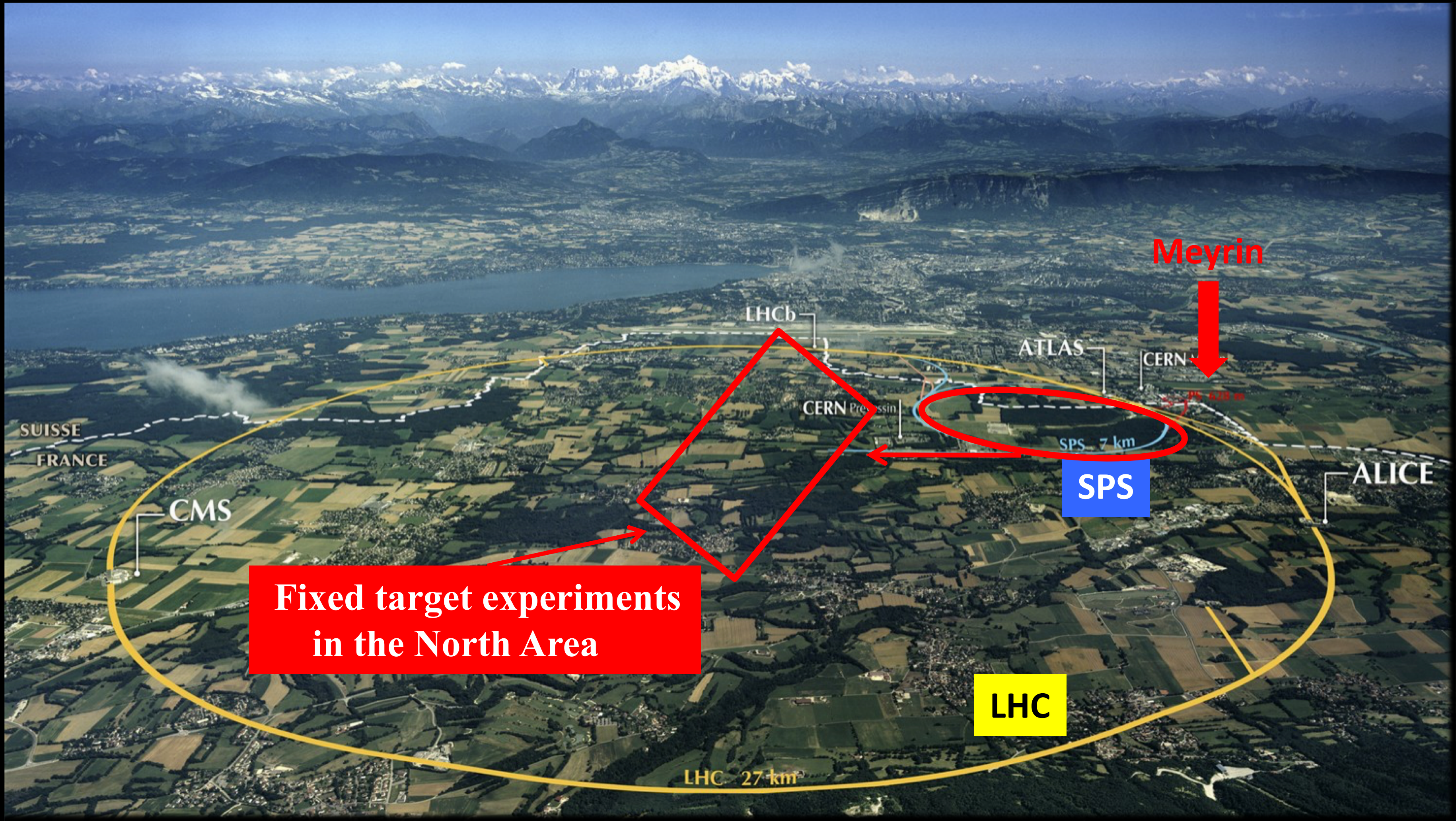
ISOLDE

AD
FIPs @ anti-proton decelerator

Nuclear astrophysics

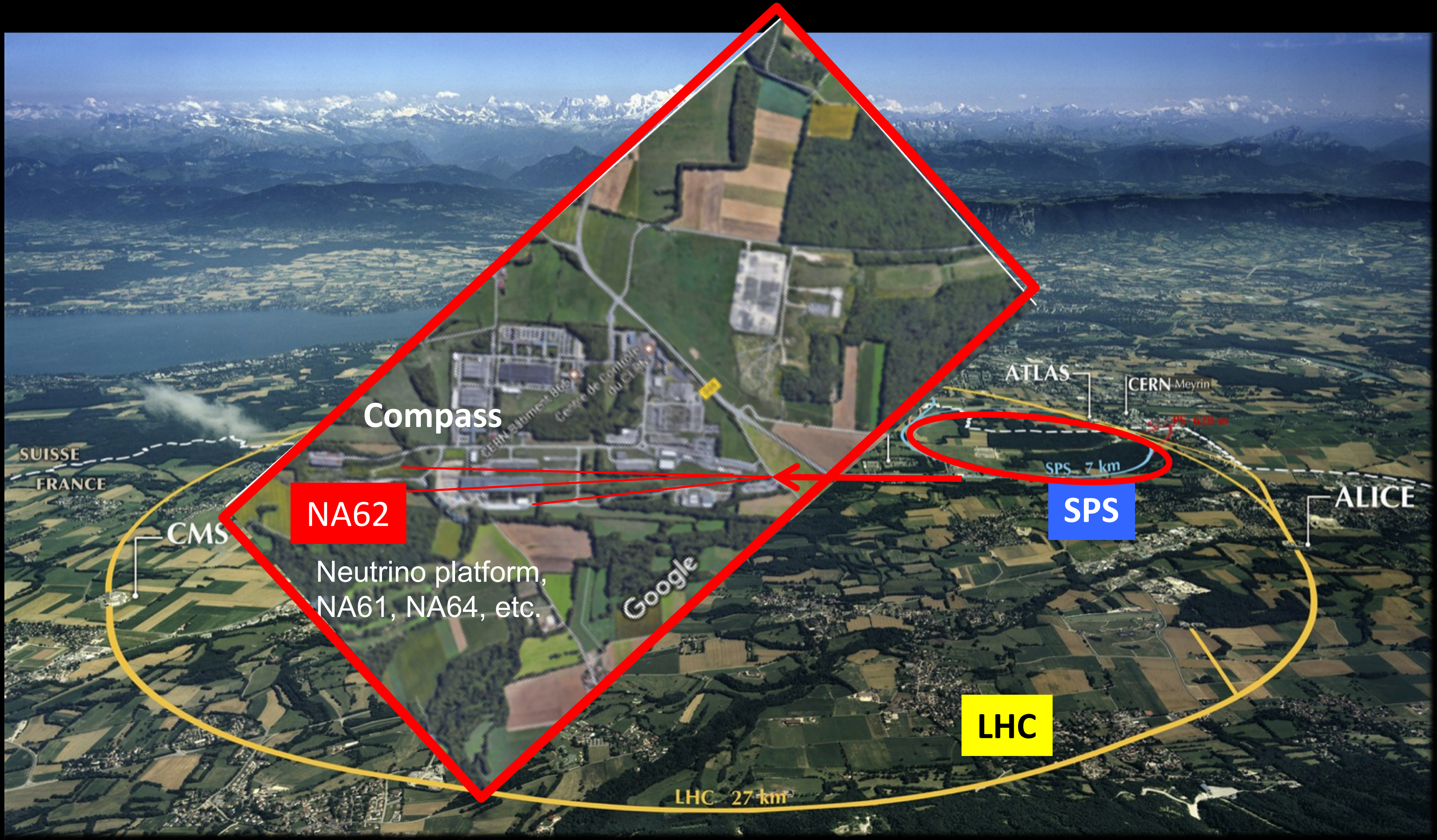
Ultra-light FIPs
(via quantum sensors, atomic clocks and the likes)

Where are NA62/HIKE and SHADOWS?



The CERN accelerator complex

Where are NA62/HIKE and SHADOWS?



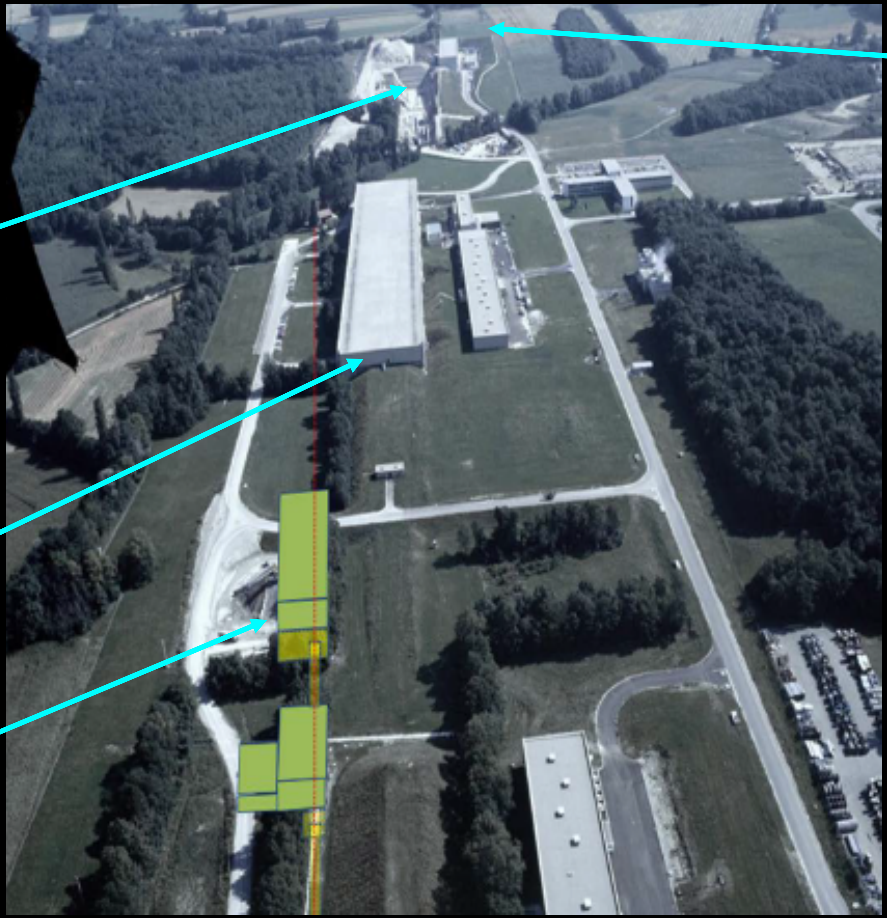
2015: 2-3 10^{19} pot delivered to the North Area.
Highest energy proton beam delivered for fixed target experiments in the world

Where are NA62/HIKE and SHADOWS?

ECN3:
P42/K12: 400 GeV p beam
up to 3x10^{18} pot/year (now)
→ **NA62**
up to ~10^{19} pot/year
→ **HIKE, SHADOWS**

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

Medium-long term projects:
SHiP@ BDF, etc



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

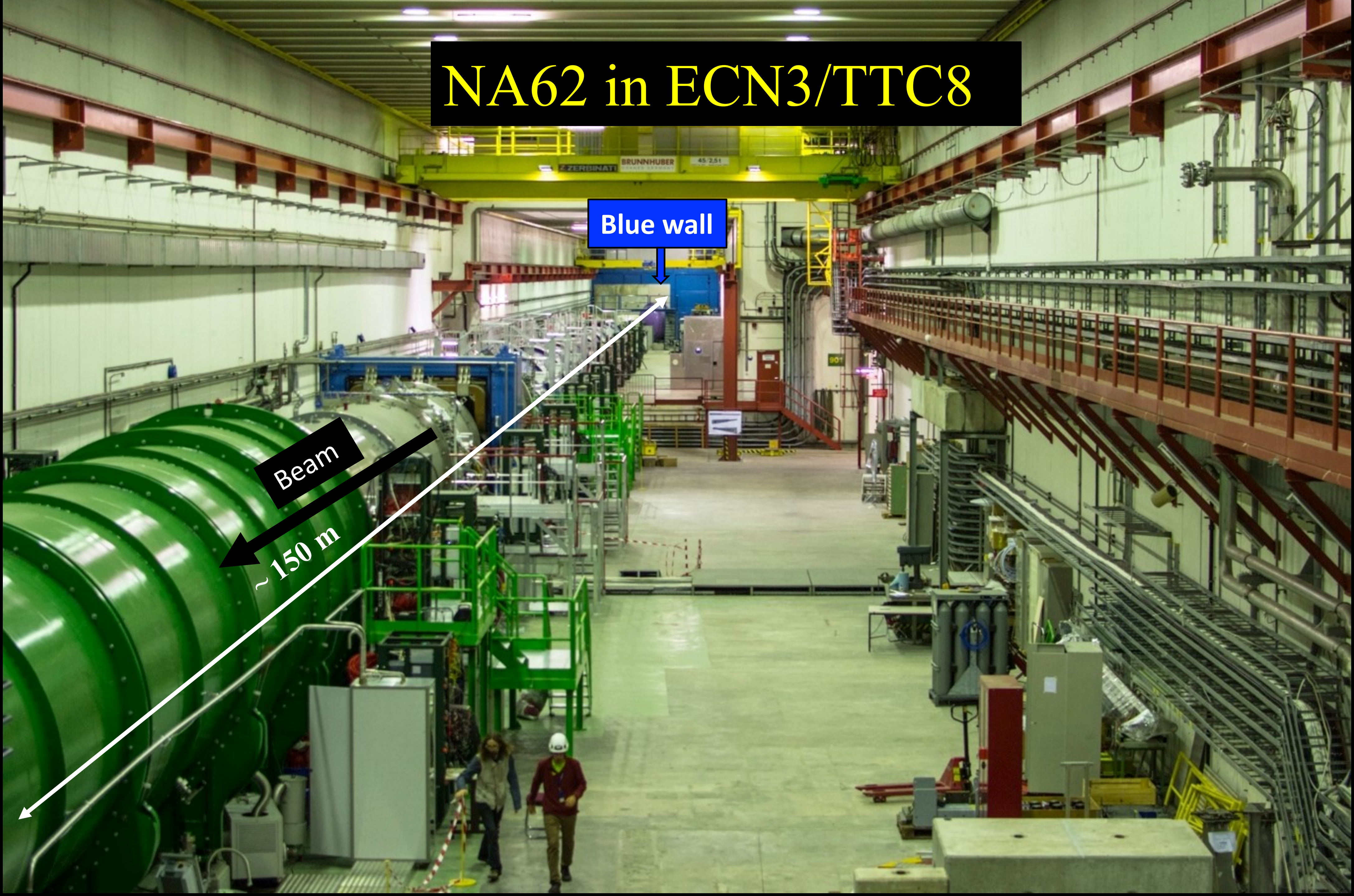
Aerial view of the CERN North Area (Prevessin zone)

Why in ECN3 area ?

- ✓ Because ECN3/TCC8 has the best 400 GeV primary extracted proton beam line at CERN (and worldwide) and a plethora of hidden sector particles can emerge from interactions of a high-energy proton beam with a dump
  - NA62 nominal intensity is $3x10^{12}$ ppp with 4.8s pulse duration: ~ 10^{12} pot/sec, up to $2x10^{18}$ pot/year
- ✓ The proton beam intensity proposed to be increased by a factor x6-7
  - for high intensity K beams and proton beam dump → up to $1.2*10^{19}$ pot/year

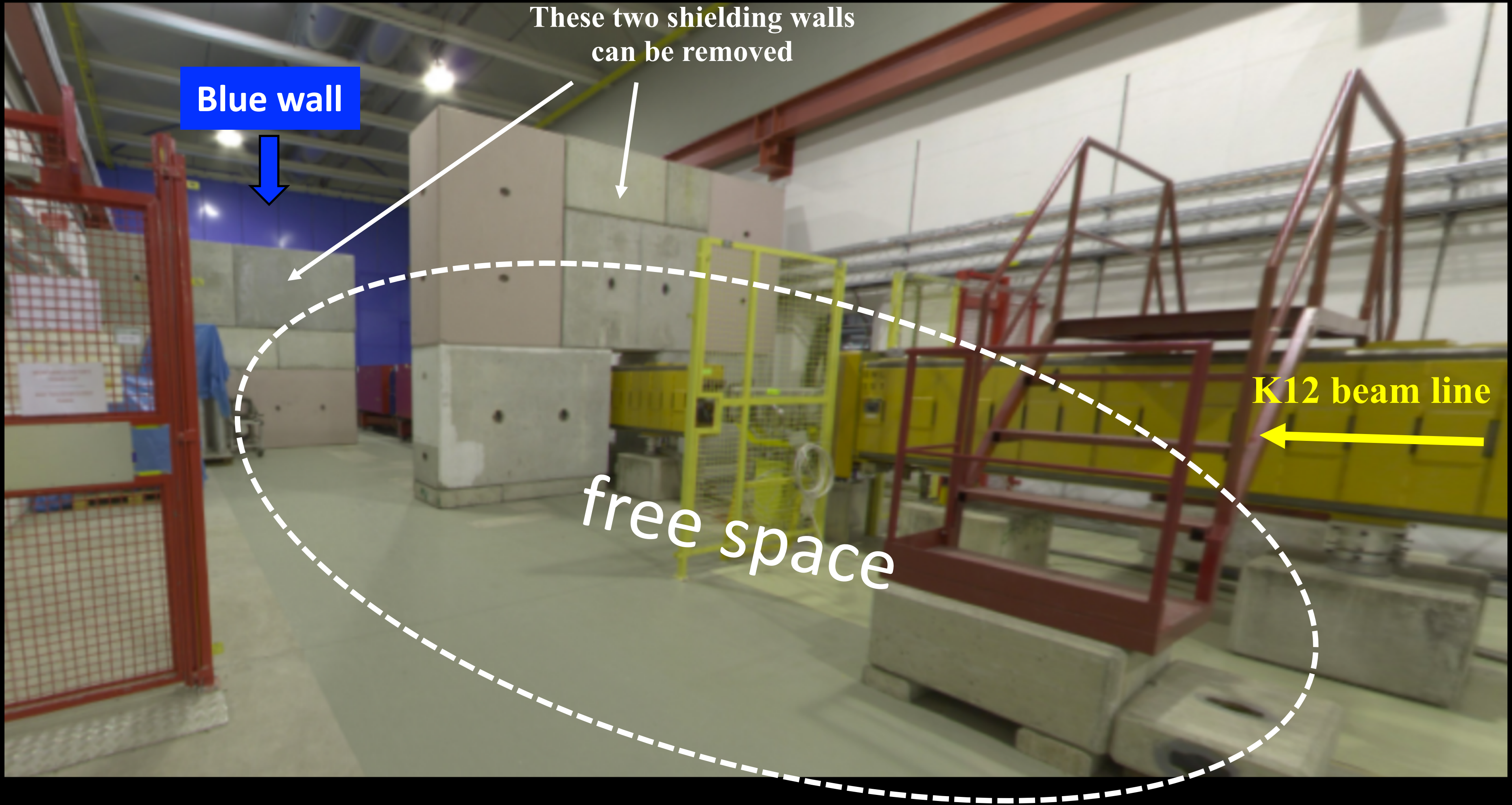
HIKE/SHADOWS can collect about 10^{19} pot per year of data taking starting after LS3

NA62 in ECN3/TTC8



SHADOWS in ECN3/TTC8

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



https://cds.cern.ch/record/2799412/files/SPSC-EOI-022.pdf

SHADOWS in ECN3/TTC8

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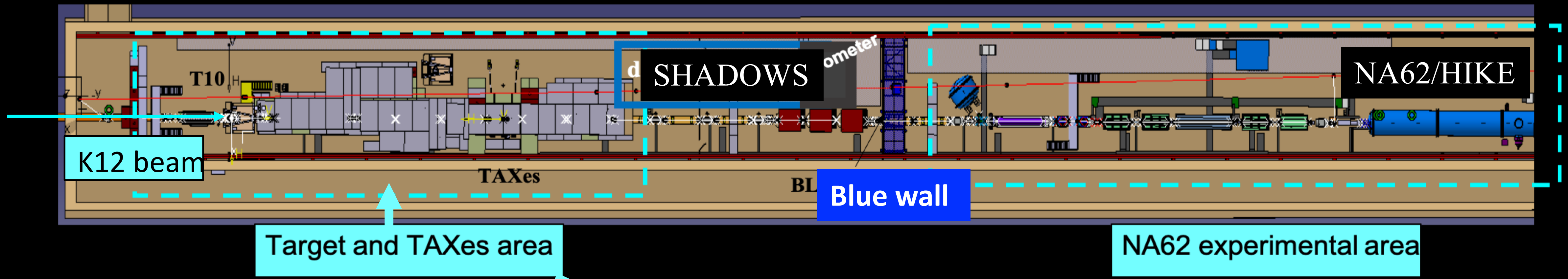

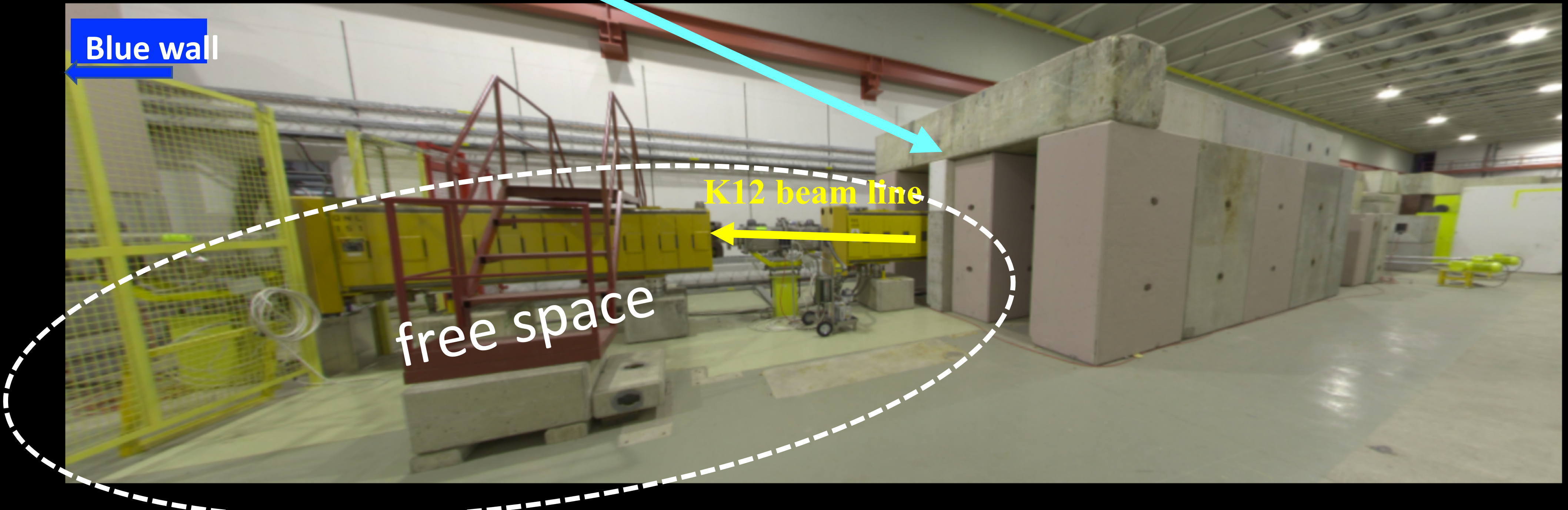

SHADOWS in ECN3/TTC8

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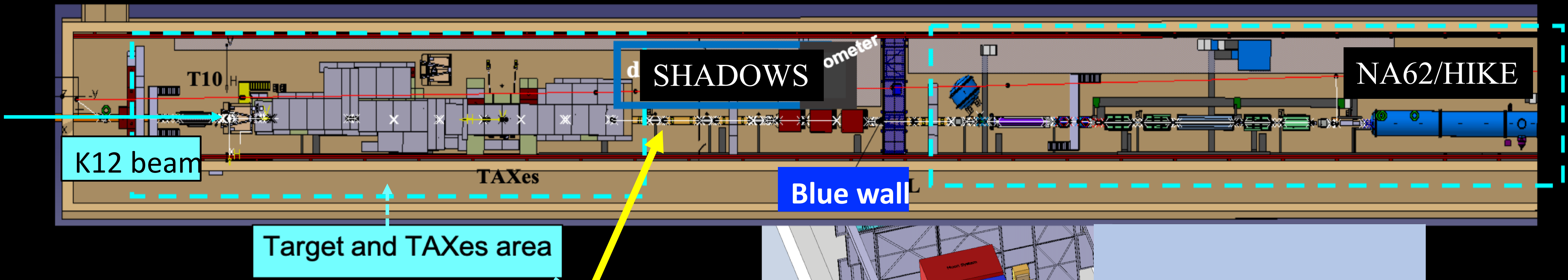
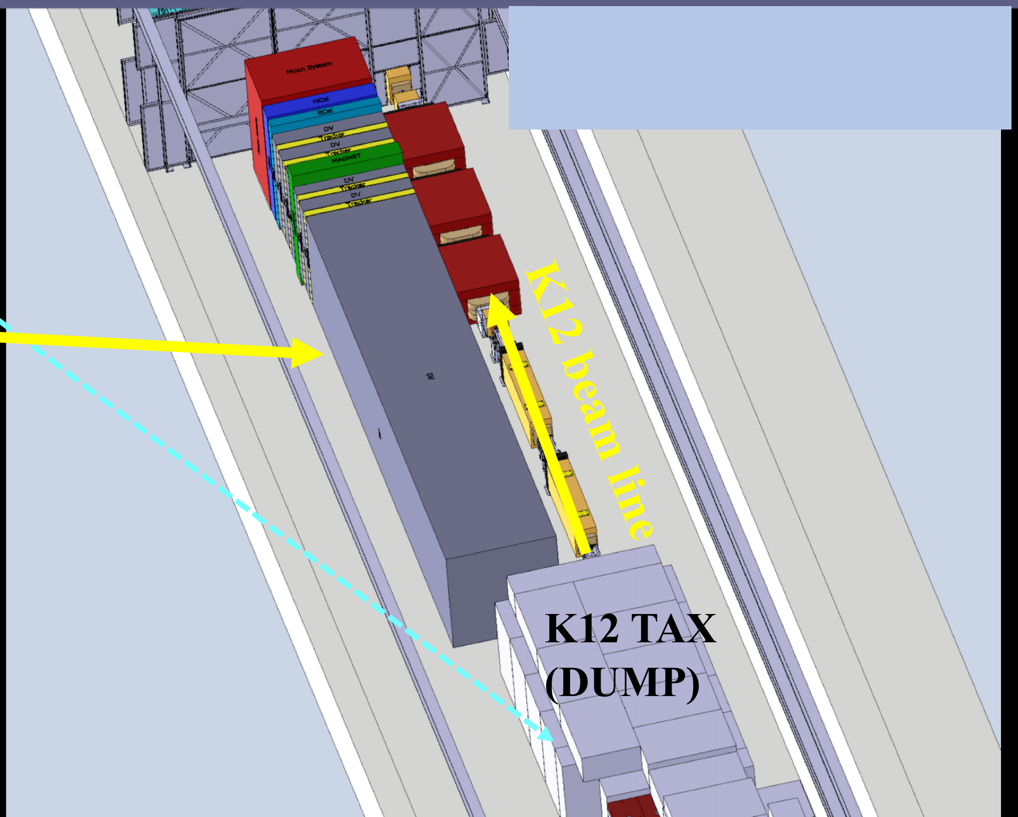
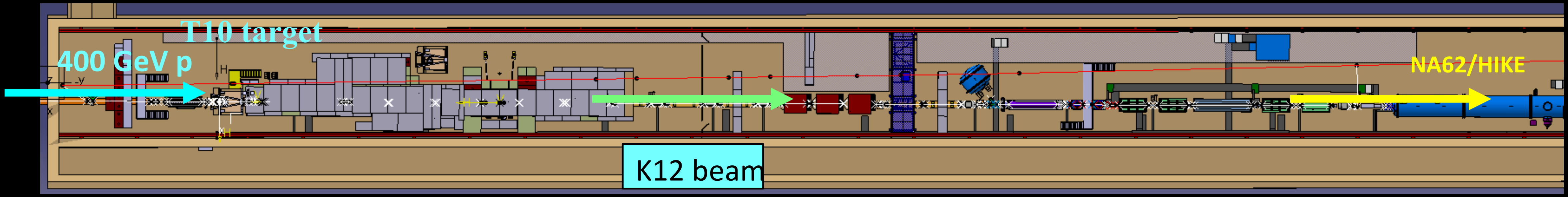




<u>Preliminary Conceptual Layout</u>

A spectrometer of about 2.5x 2.5 m^2 transverse area
~1 m off-axis from beam line
20 m long decay volume,
starting ~10 m downstream of the K12-dump (TAXes)

NA62/HIKE: K^+-mode operation



SPS protons
400 GeV/c

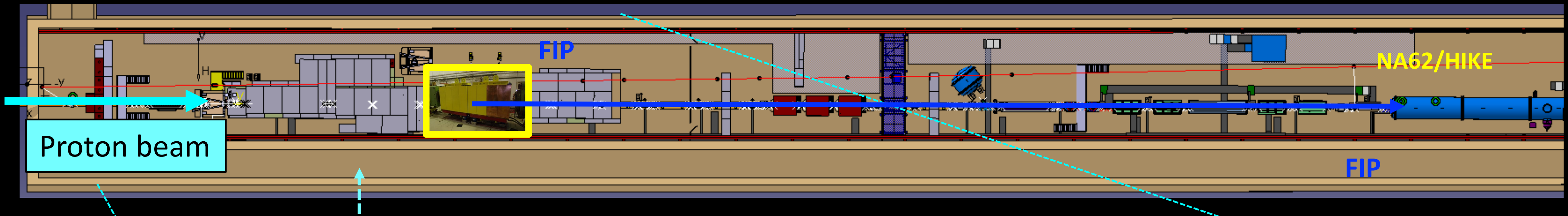
NA62: 10^{12} p/sec,
HIKE: 2×10^{13} p /sec
4.8 sec spill

Secondary beam
K(6%),π(70%),p(23%)
Total rate: 750 MHz
$\delta p/p \sim 1\%$

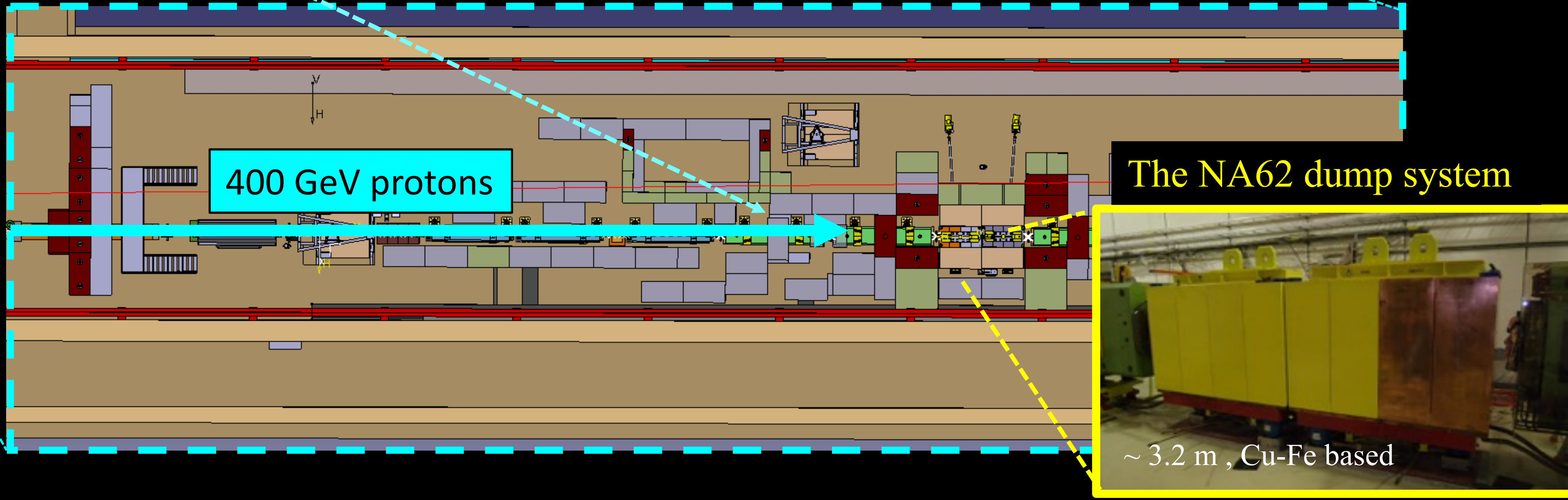
Kaon decays
~ 5 MHz
4.5×10^{12}/year

CAVEAT: HIKE aims at having multiple phases (K^+, K_L, K_S,..). Today we discuss only the first phase (K^+ beam).

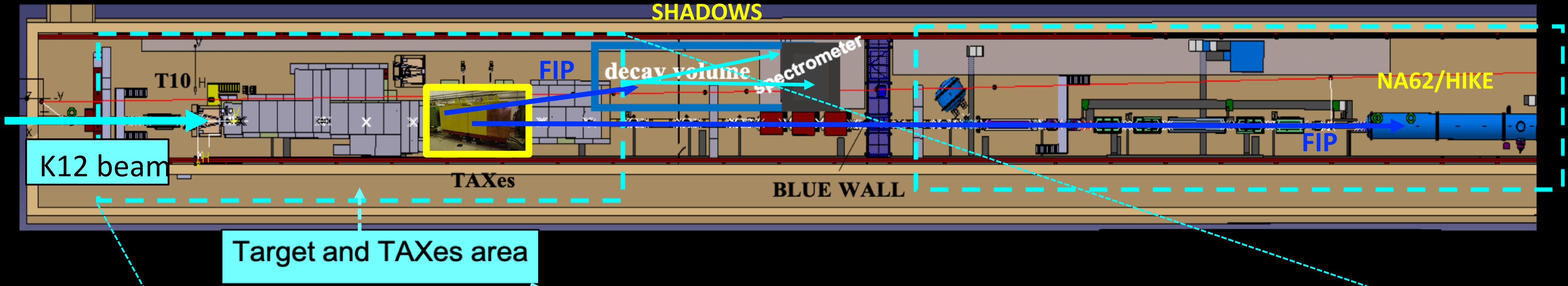
NA62/HIKE in dump-mode



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



NA62/HIKE & SHADOWS in dump-mode



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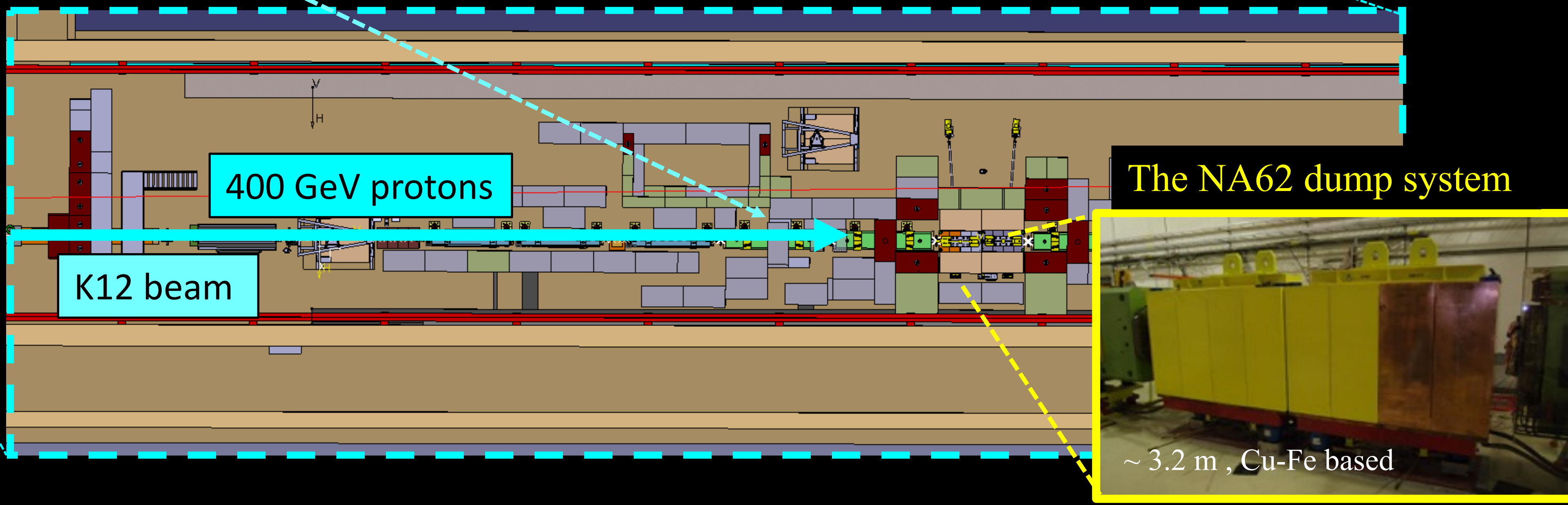
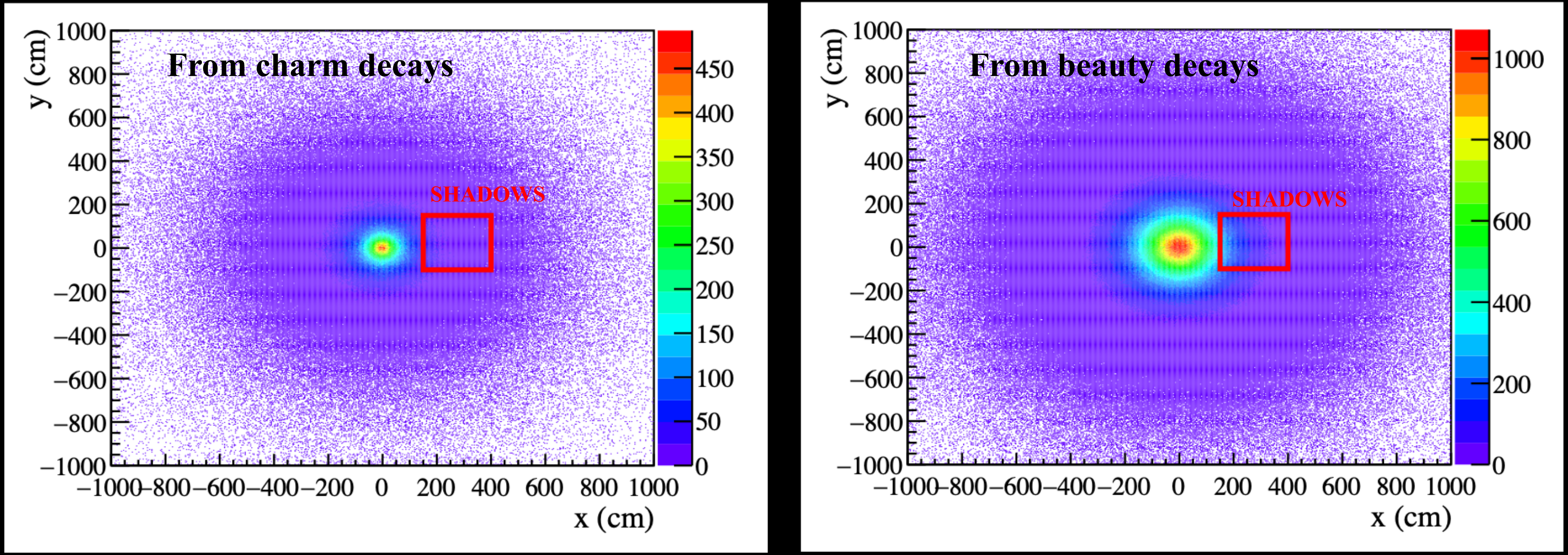


Why “off-axis” works: Signal

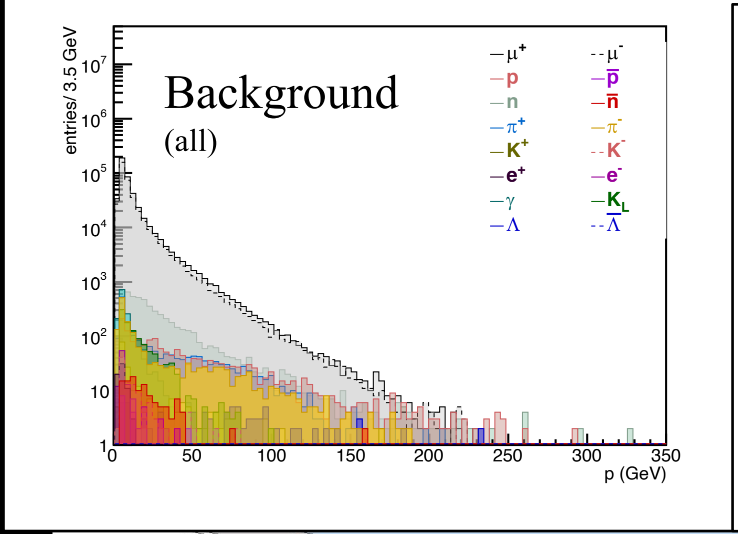
https://cds.cern.ch/record/2799412/files/SPSC-EOI-022.pdf

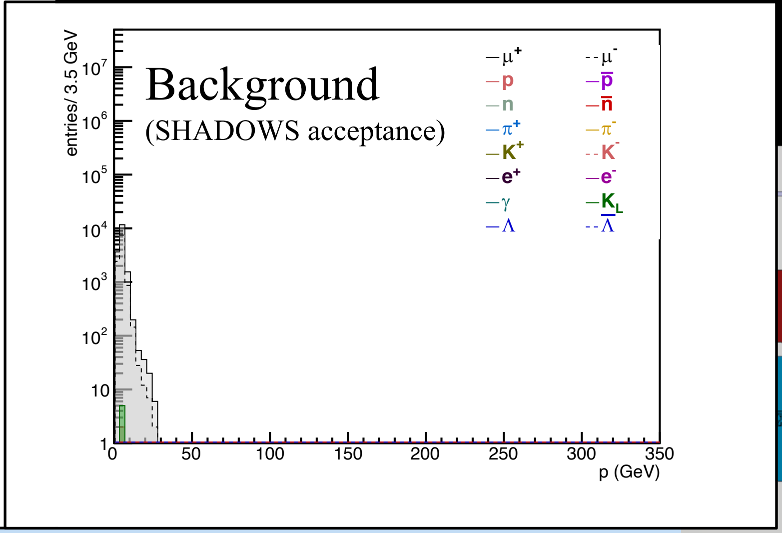
HNL→ **πμ** illumination @ D = 55 m (first SHADOWS tracking station)

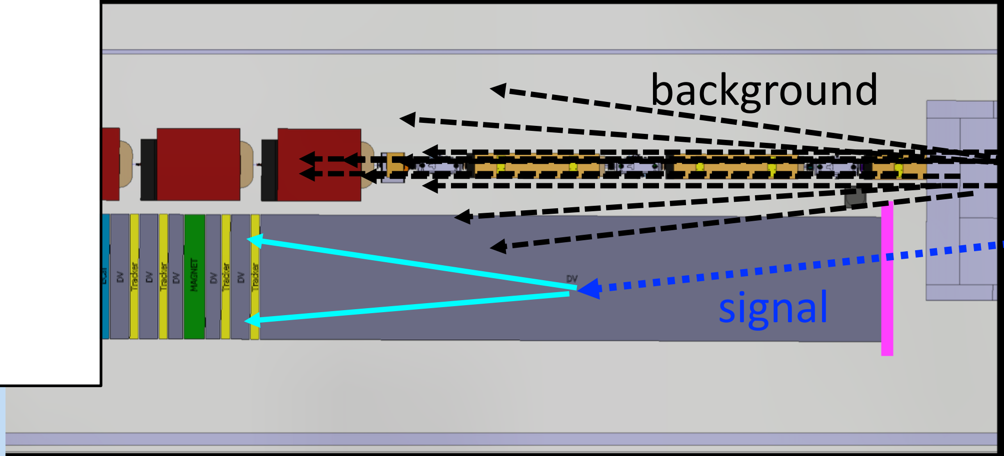


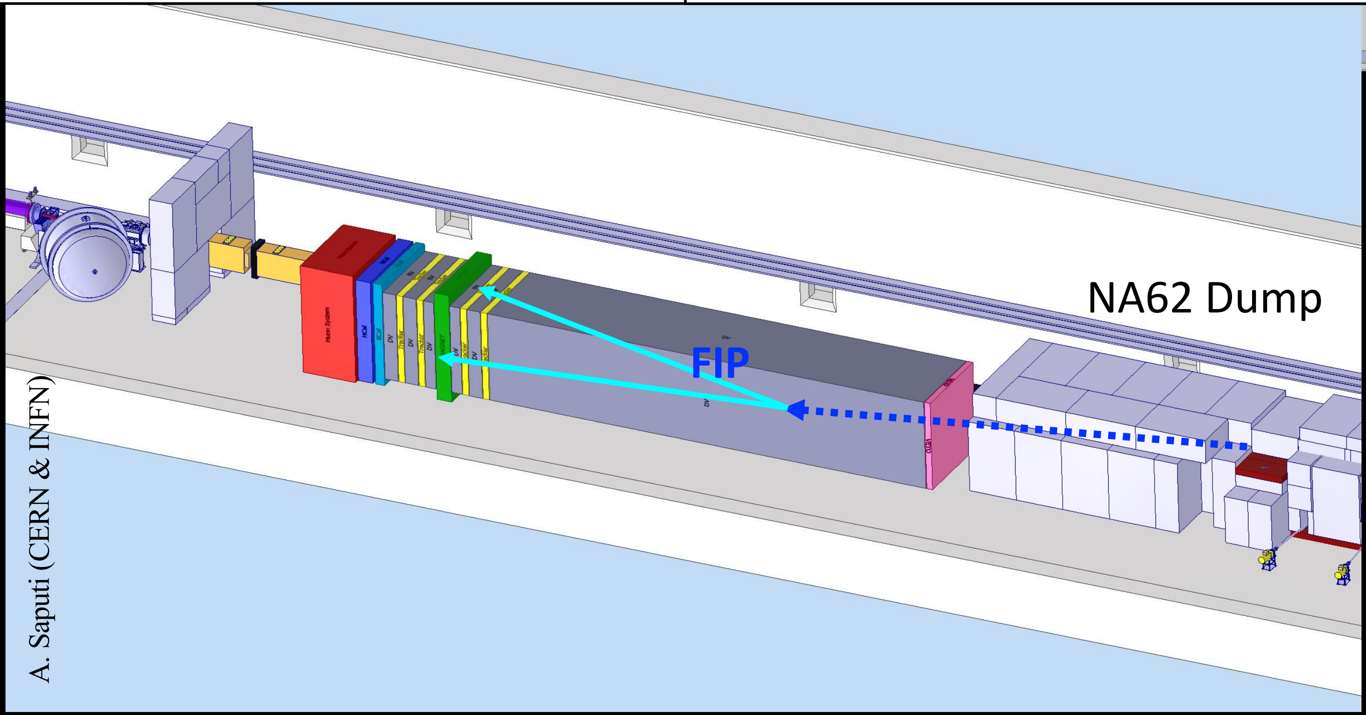
FIPs emerging from charm and beauty decays (HNLs, dark scalars, ALPs,…)
at the SPS energy are produced with a large polar angle

Why “off-axis” works: Background





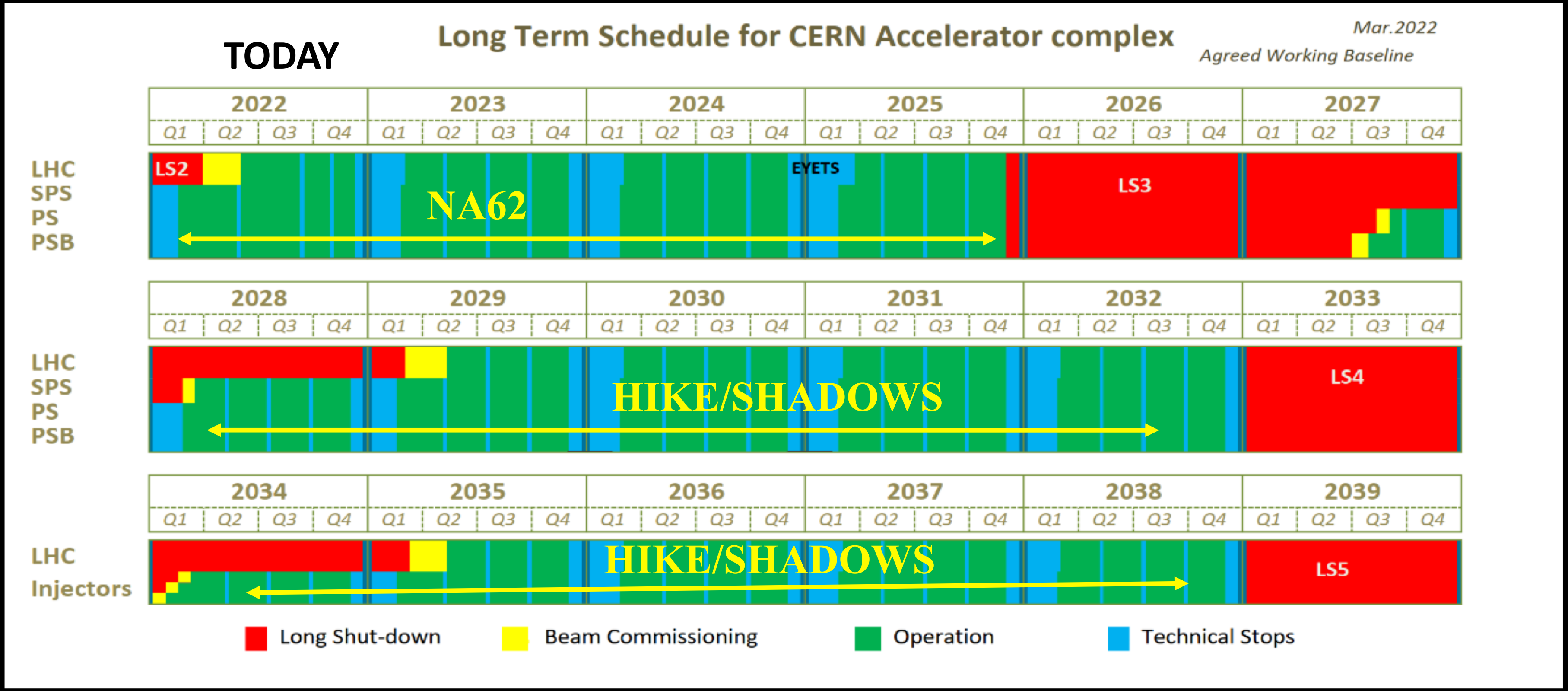




Most of the residual background emerging from TAXes are muons and neutrinos that are mostly produced forward (and miss SHADOWS acceptance).

Timescale & datasets

NA62/HIKE and SHADOWS: dataset & timescale



NA62 (2016-2025):

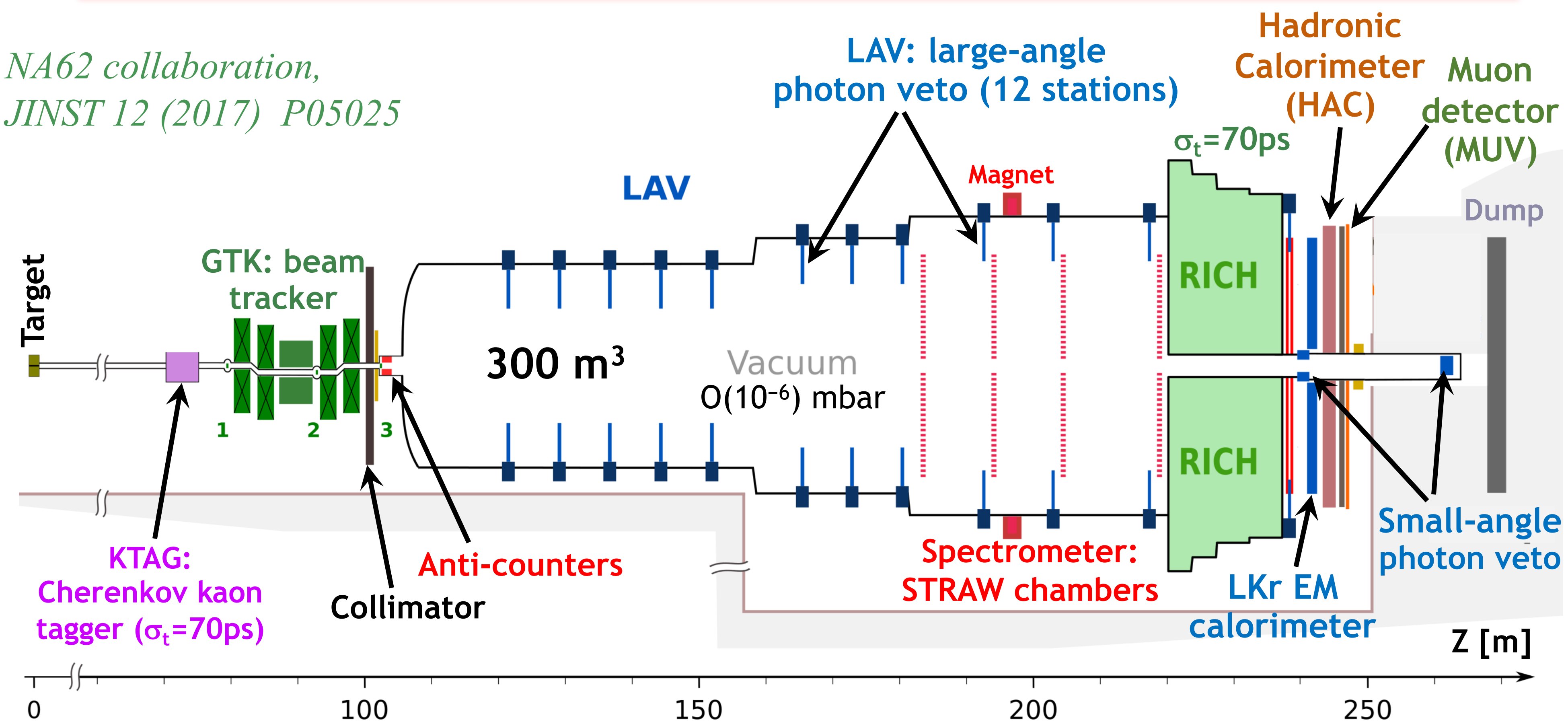
- Run1~2x10^{18} pot (6.2x10^{12} useful K^+ decays);
- Run 2 (2021–): in progress (~3×10^{12} ppp), approved till LS3.

HIKE/SHADOWS (2028-2042)

- 5x10^{19} pot (4 years) in dump mode by LS5 and ~8 years in K mode by 2042

The detectors

NA62 Detector



- ❖ Currently, 1 year of operation ≈ 10^{18} protons on target; 4×10^{12} K^+ decays.
- ❖ Single event sensitivities for K^+ decays: approaching $BR{\sim}10^{-12}$.
- ❖ Kinematic rejection factors: 1×10^{-3} for $K^+\to\pi^+\pi^0$, 3×10^{-4} for $K\to\mu^+\nu$.
- ❖ Hermetic photon veto: $\pi^0\to\gamma\gamma$ decay suppression (for $E_{\pi0}$>40 GeV) $\sim10^{-8}$.
- ❖ Particle ID (RICH+LKr+HAC+MUV): $\sim10^{-8}$ muon suppression.

HIKE in the K+ phase: an empowered NA62 detector

An in-flight $K^+ \to \pi^+ \nu\nu$ experiment at ×4 the NA62 beam intensity (the present SPS limit), aiming at ~5% precision.

- ✓ Challenge: 20–40 ps time resolution for key detectors to keep random veto under control, while maintaining all other NA62 specifications.
- ✓ Challenges aligned with HL-LHC projects and future flavour/dark matter exp.

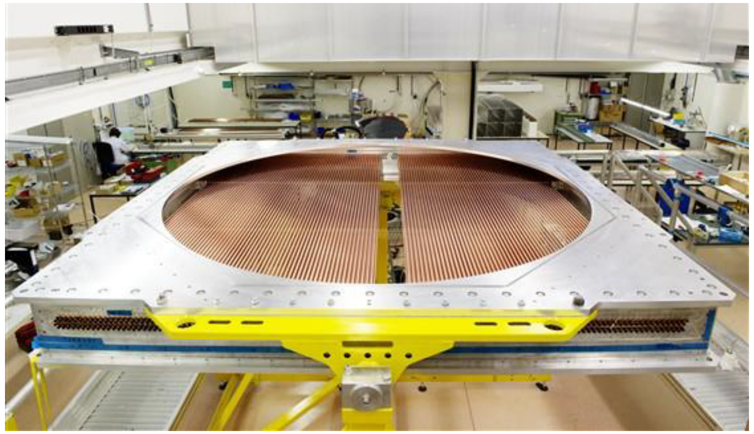
New pixel beam tracker (GTK):

time resolution: <50 ps per plane;
pixel size: <300×300 μm^2;
efficiency: >99% per plane (incl.fill factor);
material budget : 0.3–0.5% X_0;
beam intensity: 3 GHz on 30×60 mm^2;
peak intensity: 8.0 MHz/mm^2.

A current NA62 GTK station

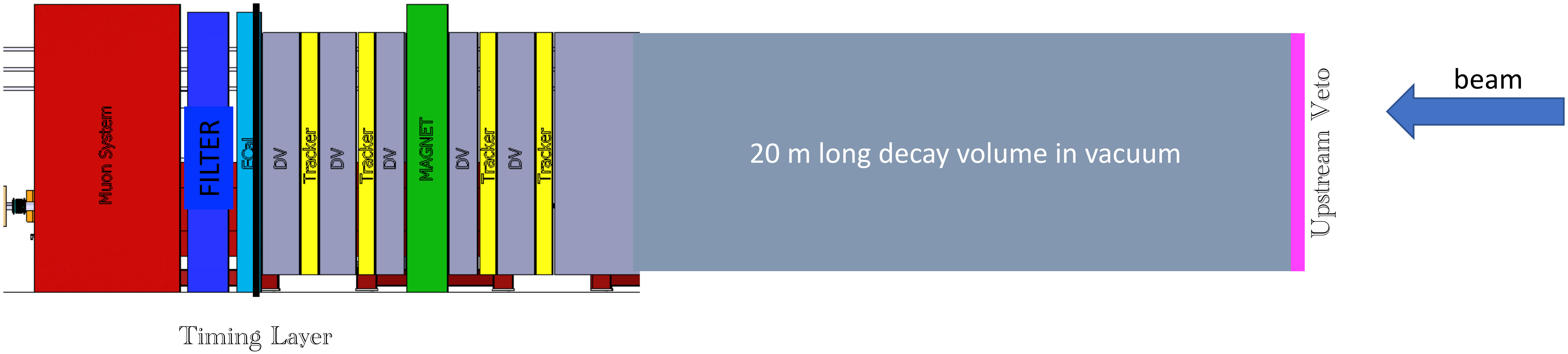
New STRAW spectrometer:

operation in vacuum;
straw diameter/length: 5 mm/2.2 m;
trailing time resolution: ~6 ns per straw;
maximum drift time: ~80 ns;
layout: ~21000 straws (4 chambers);
total material budget: 1.4% X_0.



A current NA62 STRAW chamber

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



<u>SHADOWS detector components:</u>

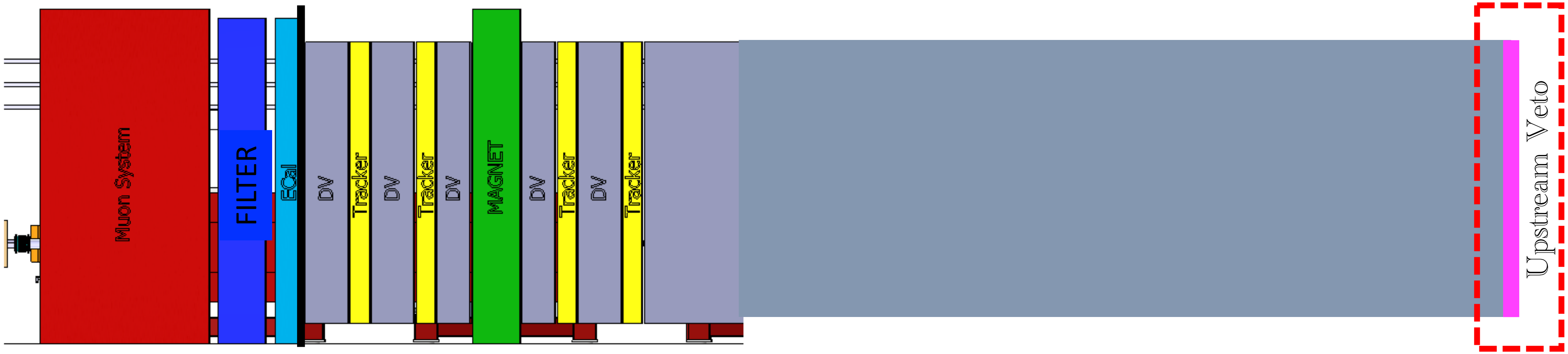
20 m long, in vacuum decay volume, an Upstream Veto, a Tracking System with a (warm) dipole magnet, Timing layer, Electro-magnetic calorimeter, a filter and four Muon Stations.

Transversal size: 2.5x2.5 m^2.

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

SHADOWS Detector: Upstream Veto

Possible interest: INFN-Roma 3, Napoli…



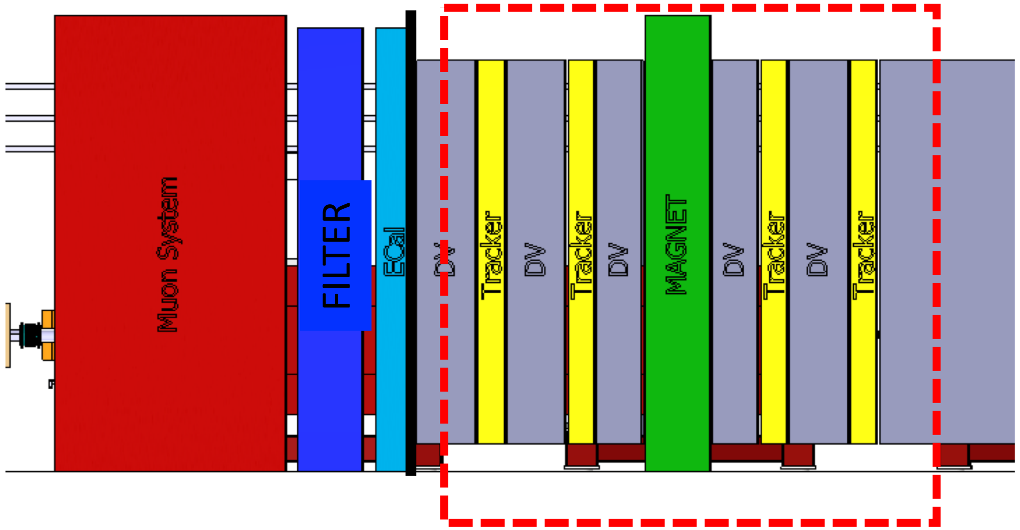
The only detector that has to stand to rates of o(10) kHz/cm^2.

Possible option: double layer of MicroMegas.

Study being performed by some of the **groups who built the ATLAS New Small Wheels**

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

SHADOWS Tracker:

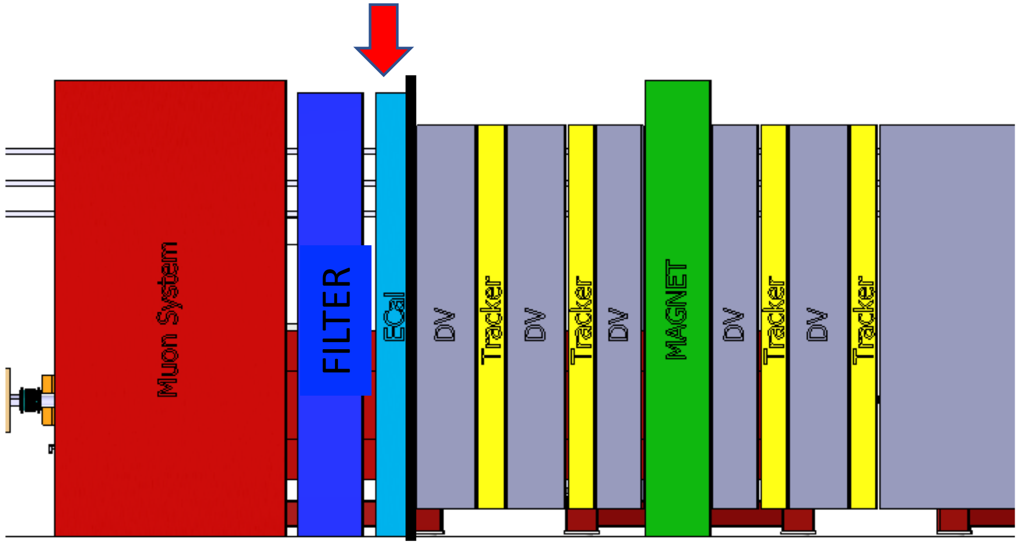


1. NA62 STRAW tubes: Ar(70%): CO_2 (30%), in vacuum, 10 mm diameter
One straw chamber is composed of four views (X, Y, U, V), one double-layer per view, 8 layers per station
Hit resolution better 400 um over most of the straw diameter per single layer. Warm dipole magnet with 0.9 Tm bending power.
3-4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

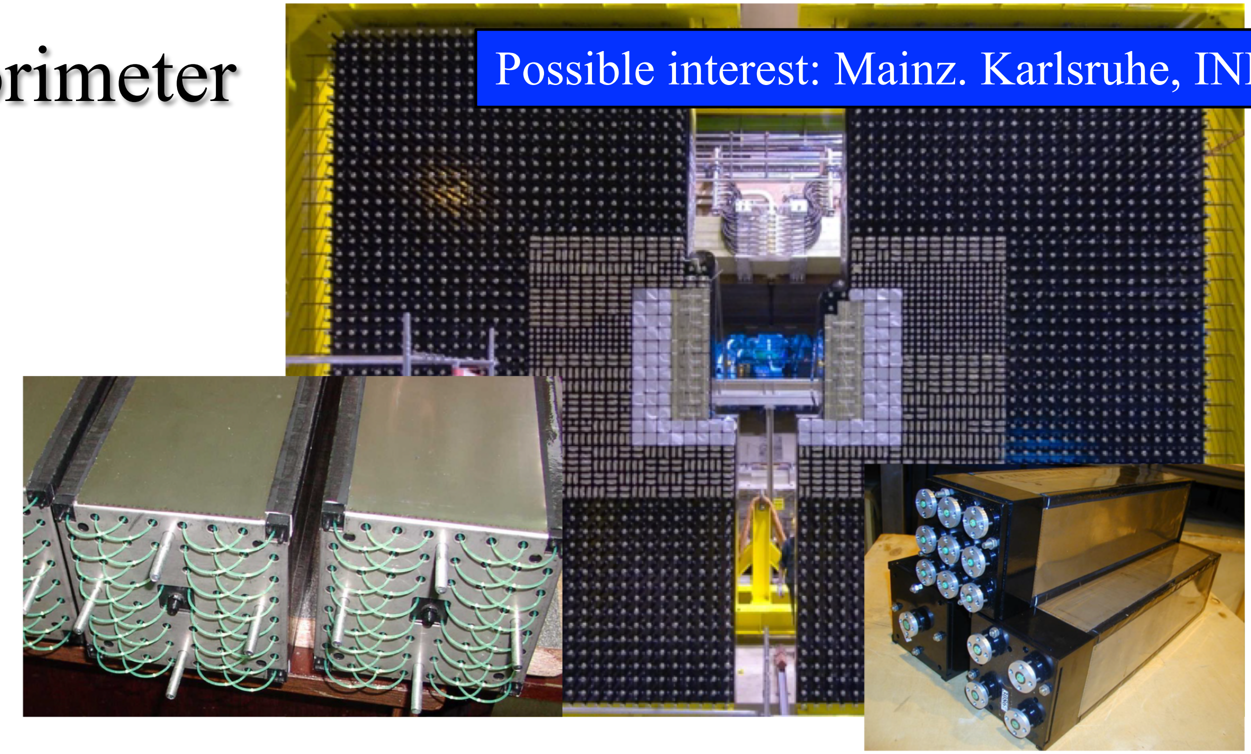
2. Fibre Tracker (LHCb): 250 um diameter, 2.5 m long scintillating fibres; three stations, six detection layers each.
Hit resolution per station < 80 um. 4 Tm bending magnet.

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

SHADOWS Electromagnetic calorimeter



Possible interest: Mainz. Karlsruhe, INR,…



Current situation:

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

Other options:

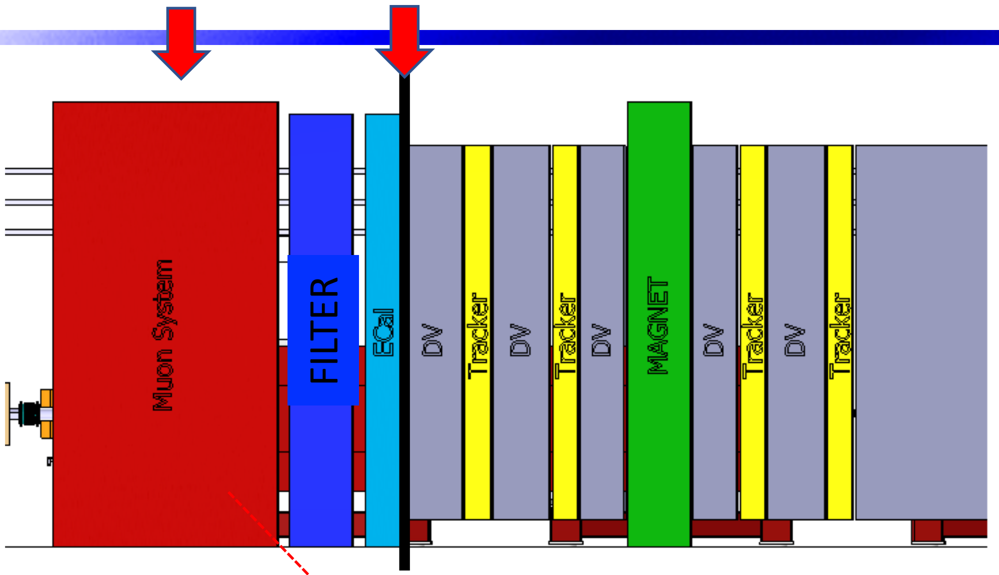
- **PbWO4 crystals from CMS ECAL endcaps** – will be removed during LS3. Some reconditioning will be needed but a large fraction of crystals could be ready to be used. Option viable if there are interested groups.

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

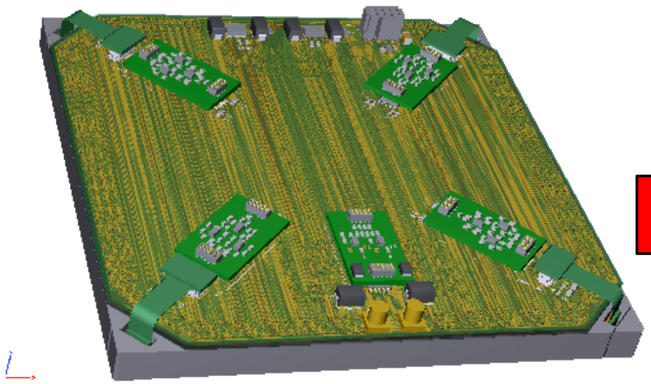
SHADOWS: Muon Detector

(same technology could be used for timing detector)

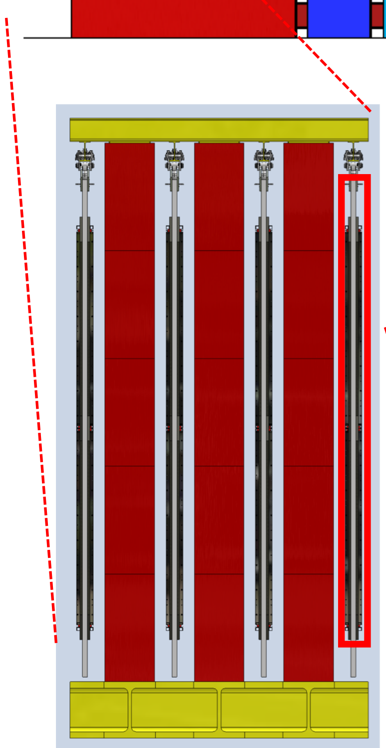
Possible interest: INFN (Frascati, Bologna, Ferrara), INR, ..

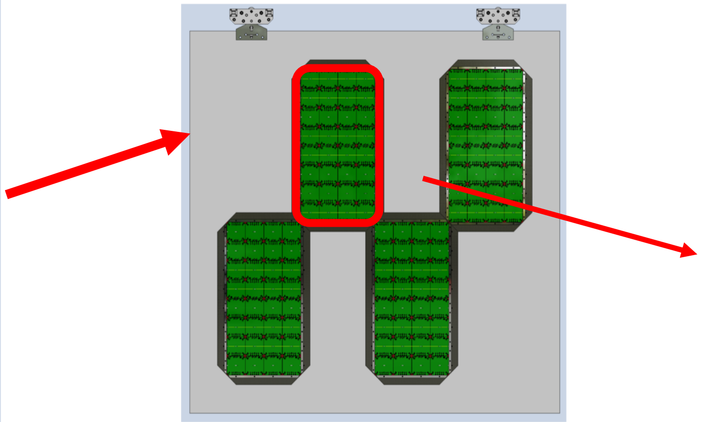


1 tile = 15x15 cm2,
Direct SiPM readout at the corners
One analog output per tile



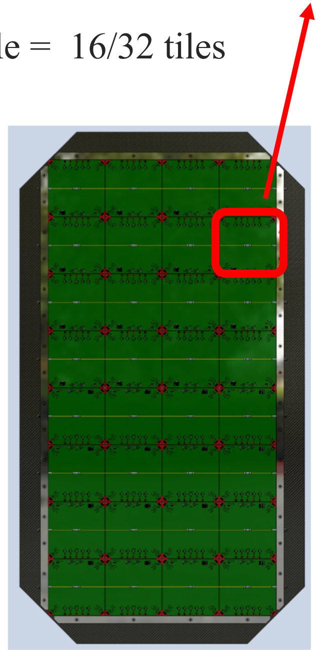
JINST 17 (2022) 01, P01038



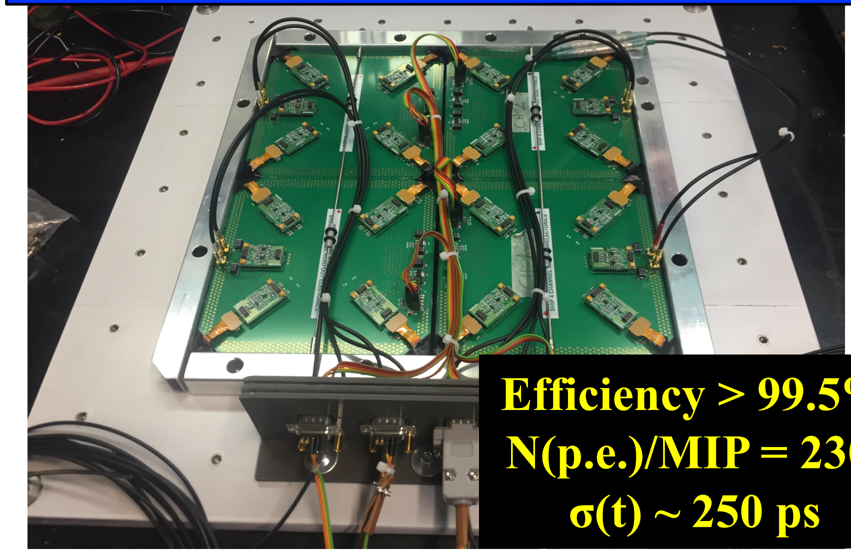


1 station = 8 modules
[same pattern staggered
on the other side of the wall]

1 module = 16/32 tiles



4-tile prototype built in INFN Bologna/LNF

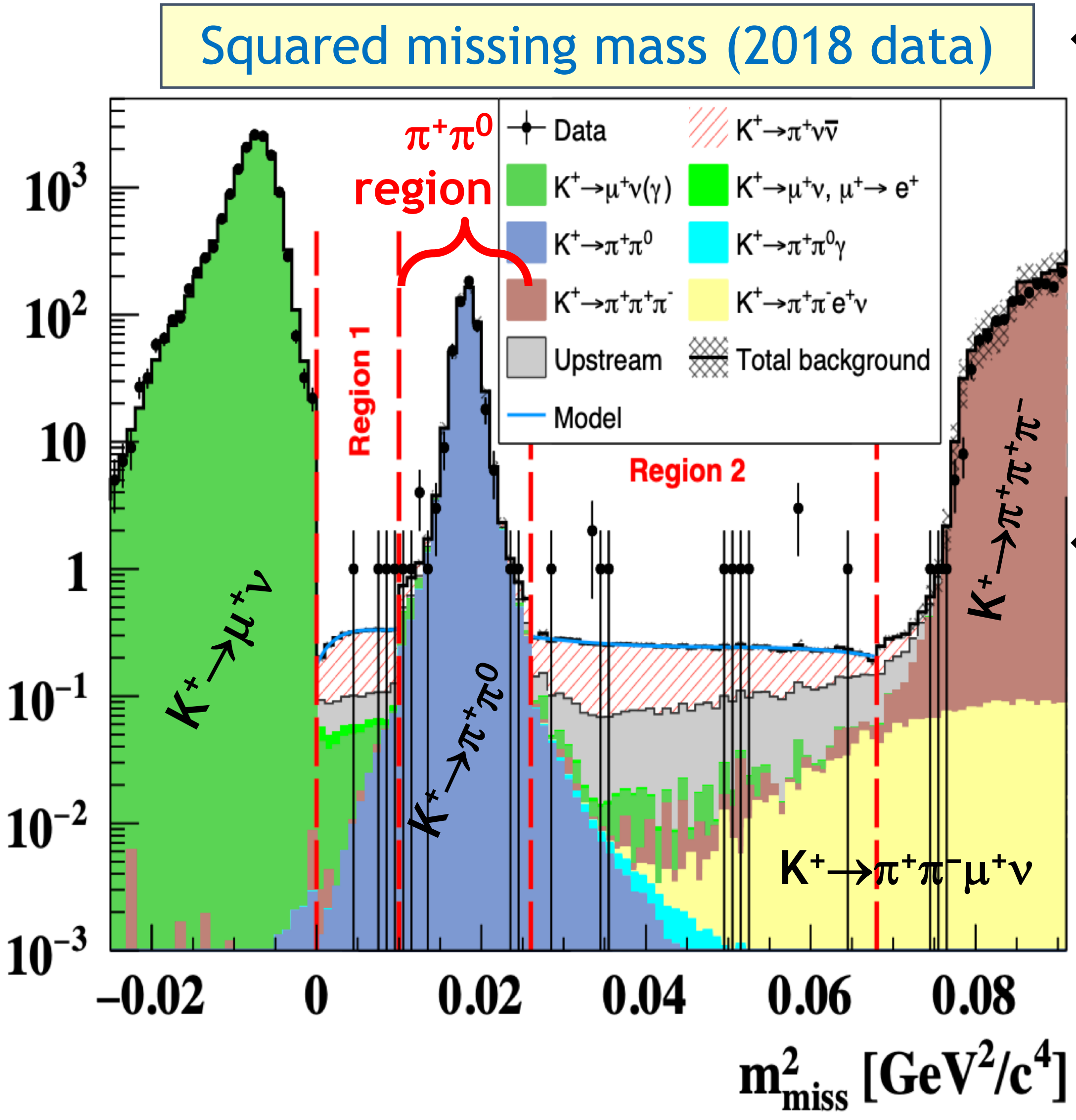


Efficiency > 99.5%
N(p.e.)/MIP = 230
$\sigma(t) \sim 250$ ps

The experimental techniques:

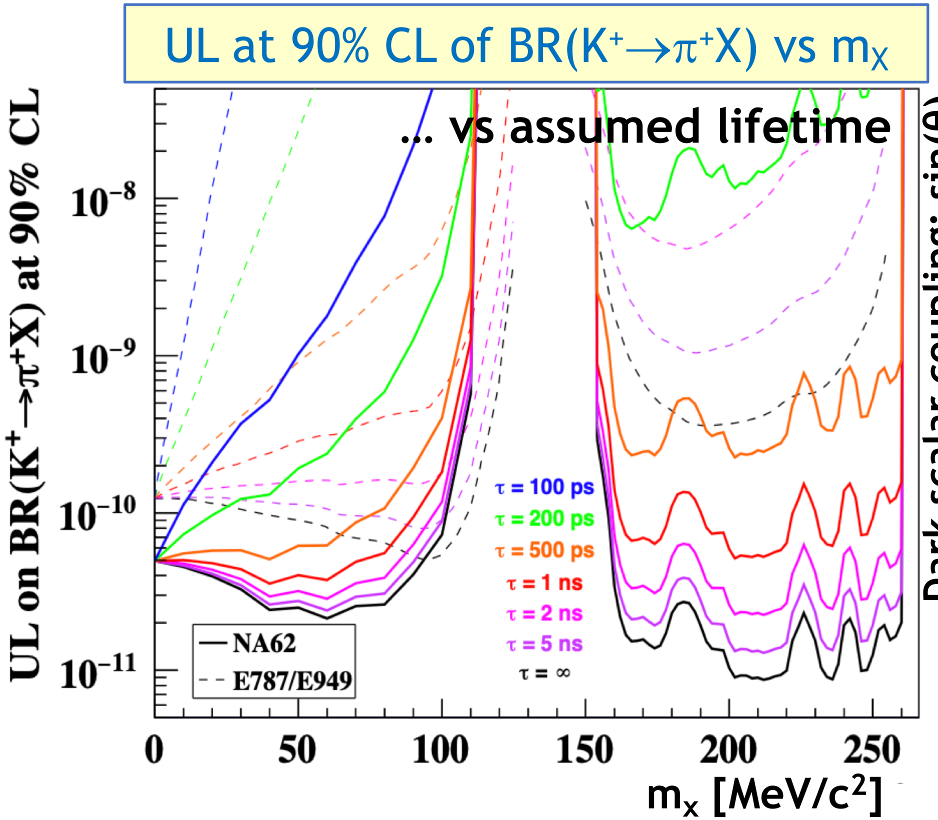
1. K-decays

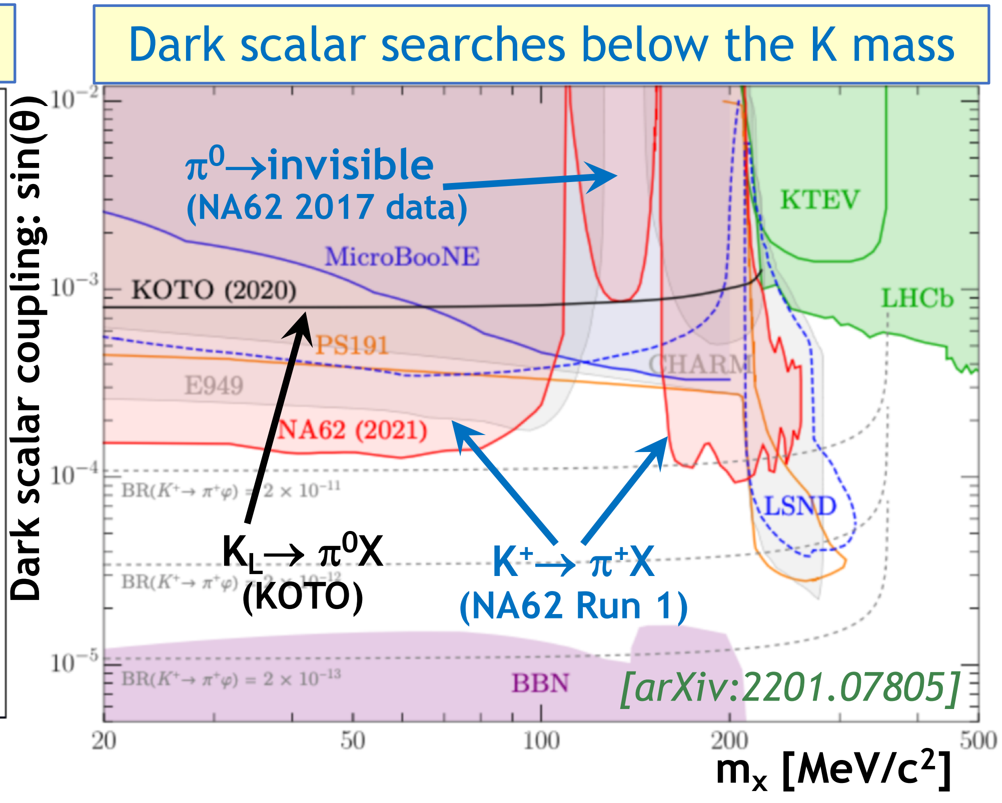
NA62: FIPs as by-product of $K^+ \to \pi^+ \nu\nu$



- Signal regions **R1**,**R2**: search for $K^+ \to \pi^+ X$ (X=invisible), $0 \le m_X \le 110$ MeV/c^2 and $154 \le m_X \le 260$ MeV/c^2.
  - ✓ Interpretation: dark scalar, ALP, QCD axion, axiflavon.
  - ✓ Main background: $K^+ \to \pi^+ \nu\nu$.
- The $\pi^+\pi^0$ region: search for $\pi^0 \to$ **invisible**.
  - ✓ SM rate: $BR(\pi^0 \to \nu\nu) \sim 10^{-24}$.
  - ✓ Observation = BSM physics.
  - ✓ Reduction of $\pi^0 \to \gamma\gamma$ background: optimised π^+ momentum range.
  - ✓ Interpretation as $K^+ \to \pi^+ X$, with m_X between R1 and R2.

NA62: Search for $K^+ \to \pi^+ X$ (Run 1)

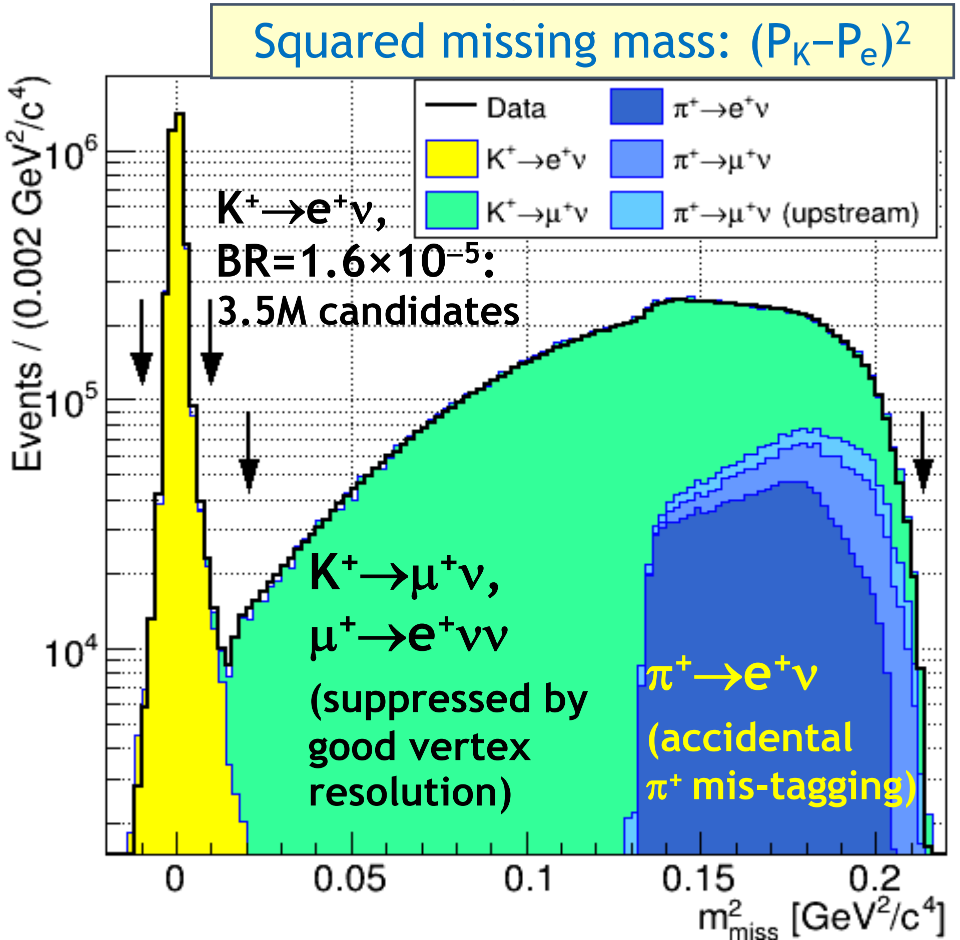


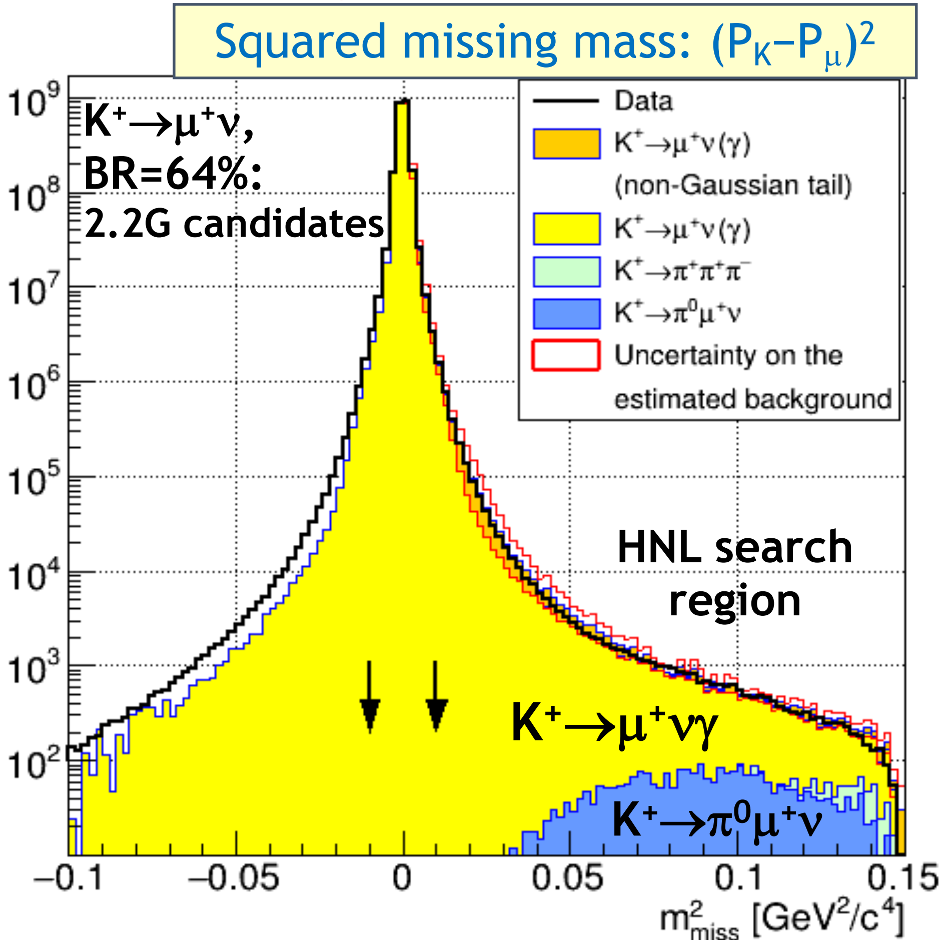


- Mass resolution improves with m_X and is $\delta m_x \sim 40$ MeV/c² at $m_X=0$.
- Upper limits of $BR(K^+ \to \pi^+ X)$ established depending on X mass and lifetime.
- Improvement on BNL-E949 *[PRD79 (2009) 092004]* over most of m_x range.
- Interpreted within the dark scalar and ALP (fermionic coupling) models *[EPJ C81 (2021) 1015; arXiv:2201.07805]*
- Note the **KOTO** result based on 2016−18 data. *[PRL125 (2021) 021801]*

NA62: HNL production search dataset

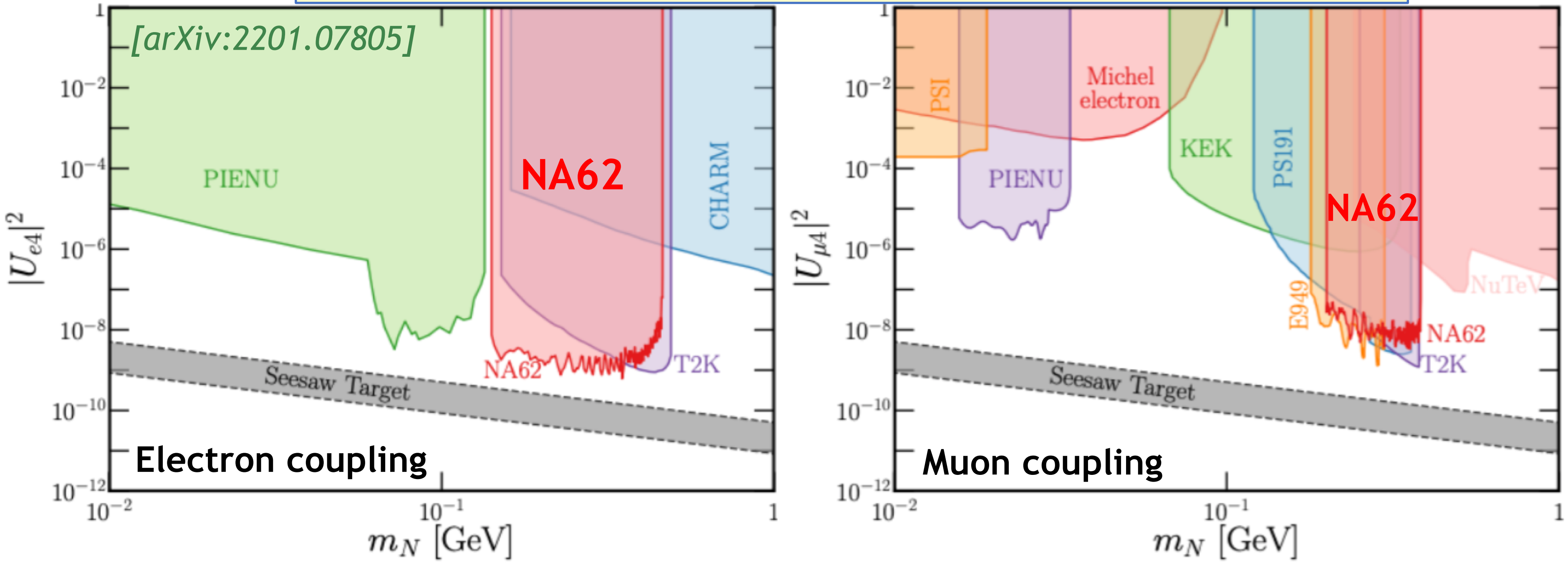
- Triggers used: **$K_{\pi\nu\nu}$** for **$K^+ \to e^+N$**; **Control/400** for **$K^+ \to \mu^+N$**.
- Numbers of **K^+** decays in fiducial volume:
  $N_K=(3.52\pm0.02)\times10^{12}$ in positron case; **$N_K=(4.29\pm0.02)\times10^9$** in muon case.
- Squared missing mass: **$m^2_{miss}=(P_K-P_\ell)^2$**, using STRAW and GTK trackers.
- HNL production signal: **a spike above continuous missing mass spectrum**.





NA62: HNL production search results

$|U_{\ell 4}|^2$ limits vs m_{HNL} from production & decay searches

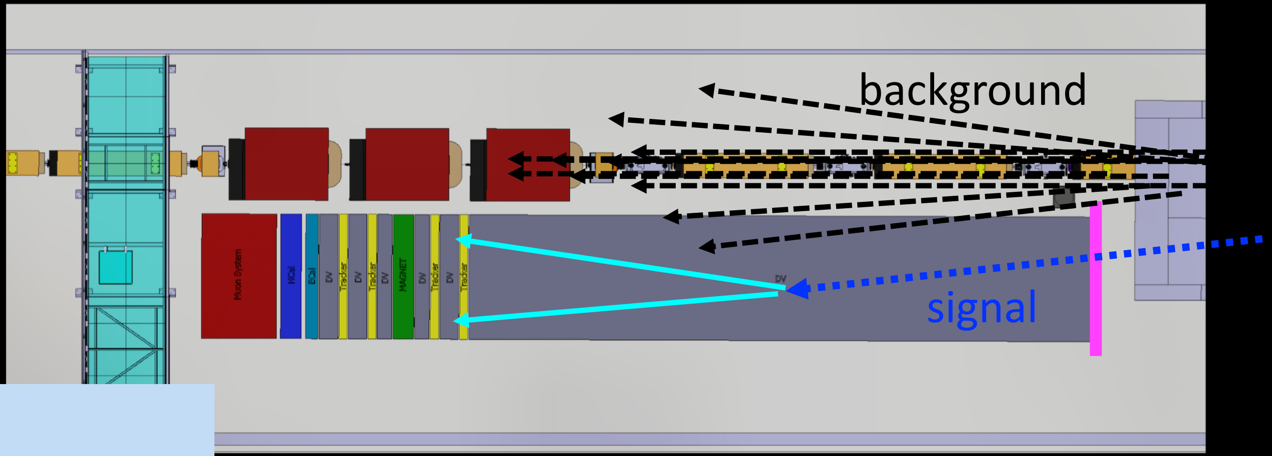


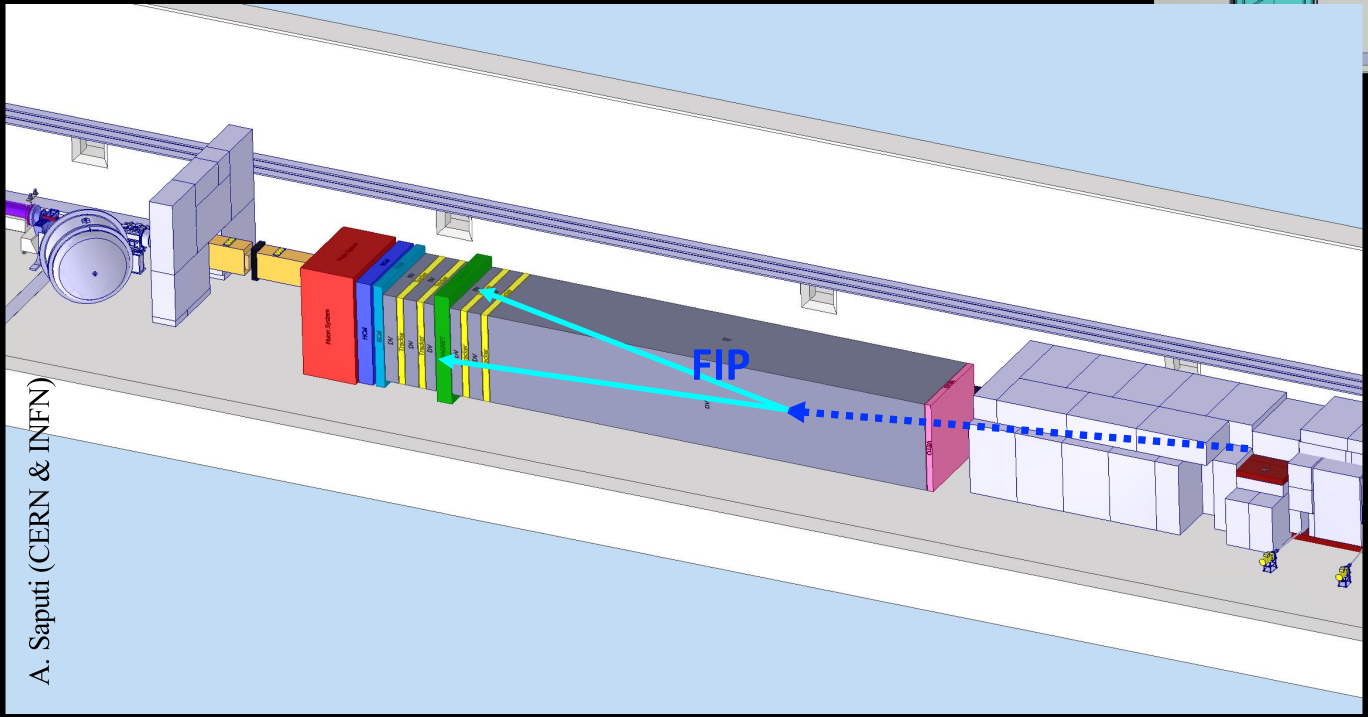
- For $|U_{e4}|^2$, complementary to search for $\pi^+ \to e^+ N$ at PIENU.
- For $|U_{\mu 4}|^2$, complementary to search for $K^+ \to \mu^+ N$ at BNL-E949.
- In both cases, complementary to HNL *decay* searches at T2K.

[PLB 807 (2020) 135599; PLB 816 (2021) 136259]

The experimental technique:
2. Beam - dump

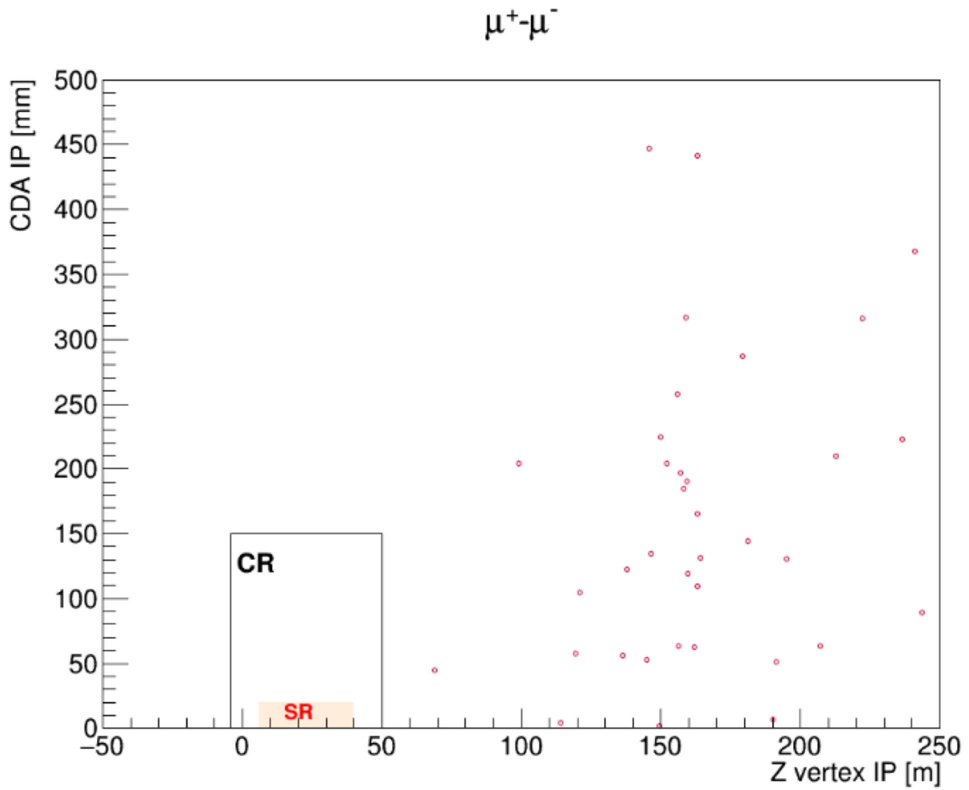
Search for a displaced vertex in long decay volumes…





Here the background is the name of the game

Beam-induced Muon Background in NA62/HIKE



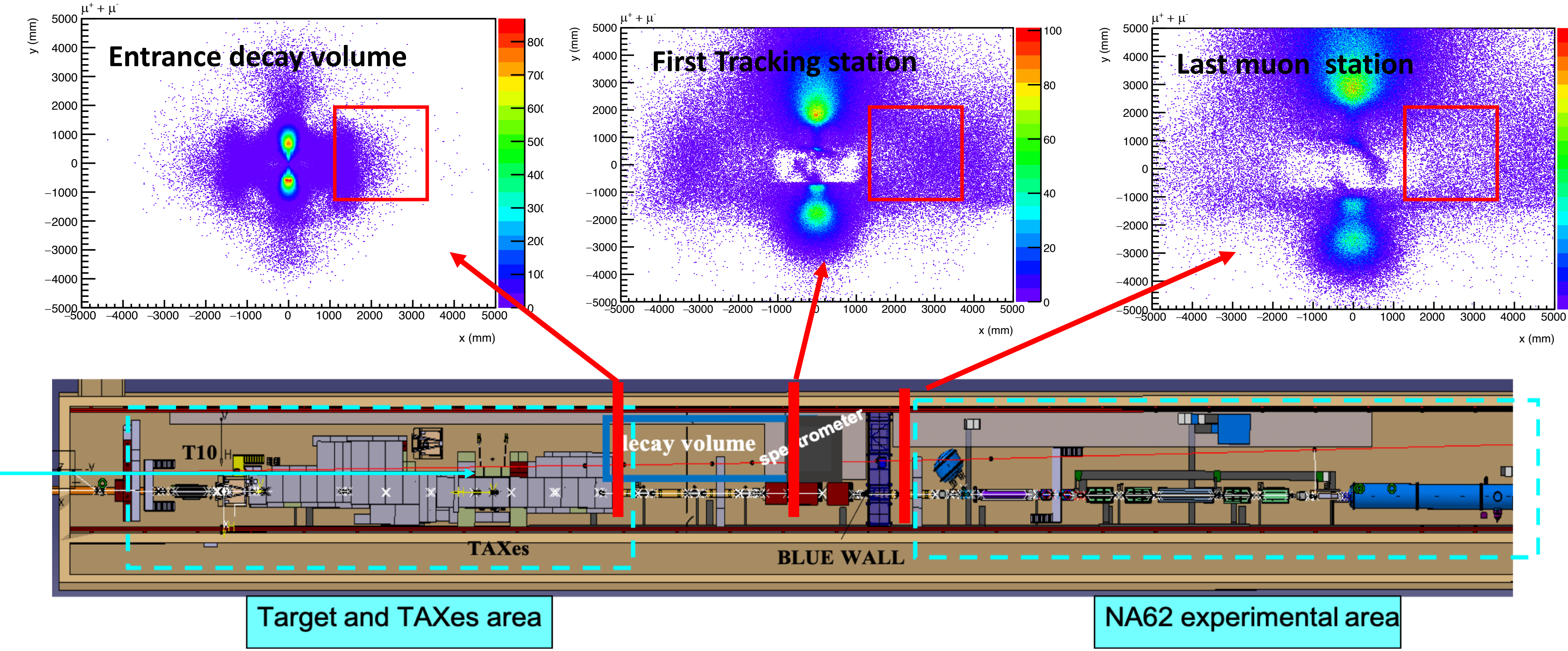
Based on 1.3x10^{17} pot taken in dump mode in November 2021

Observed muon background extremely small.

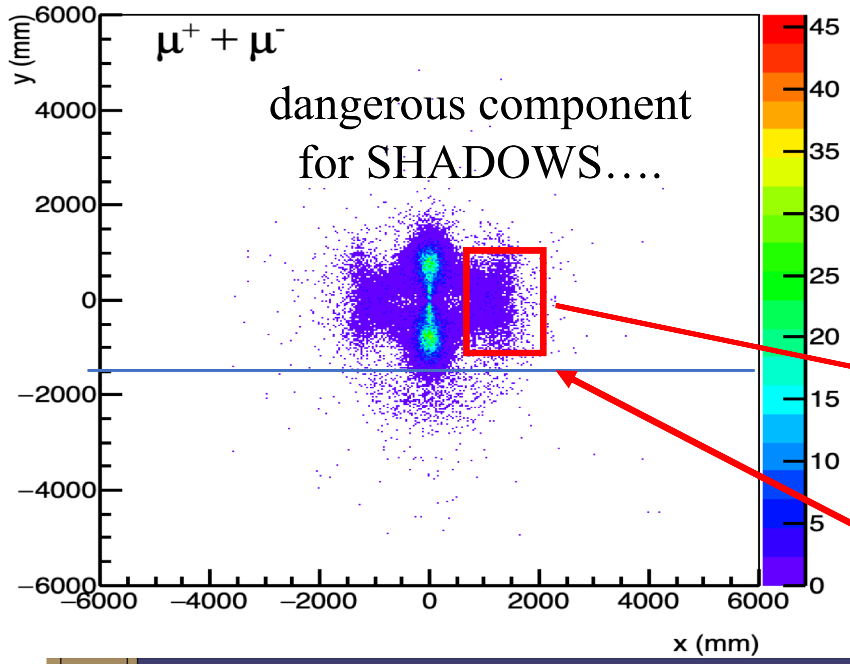
Neutrino inelastic interactions in the decay volume fully negligible (vacuum: 10^{-6} mbar)

Beam-induced muon Background in SHADOWS

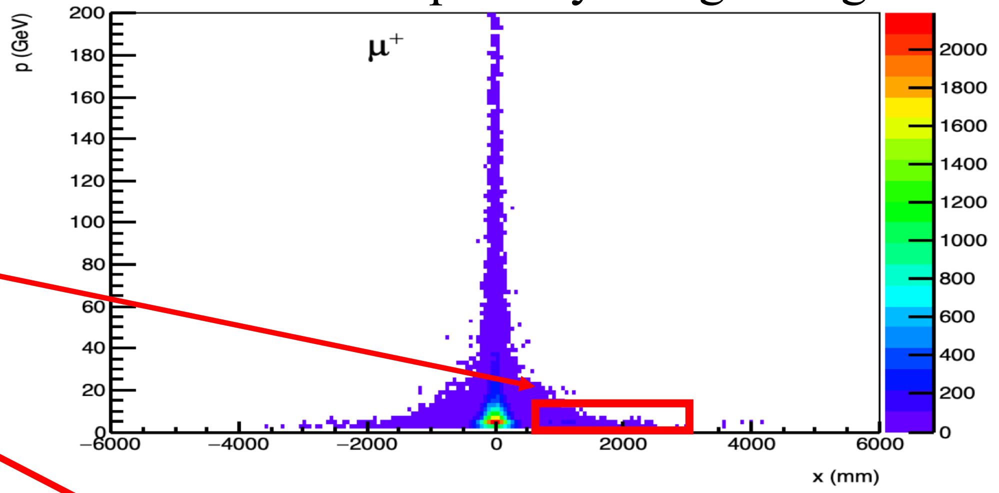
Muon illumination as a function of the position along the line

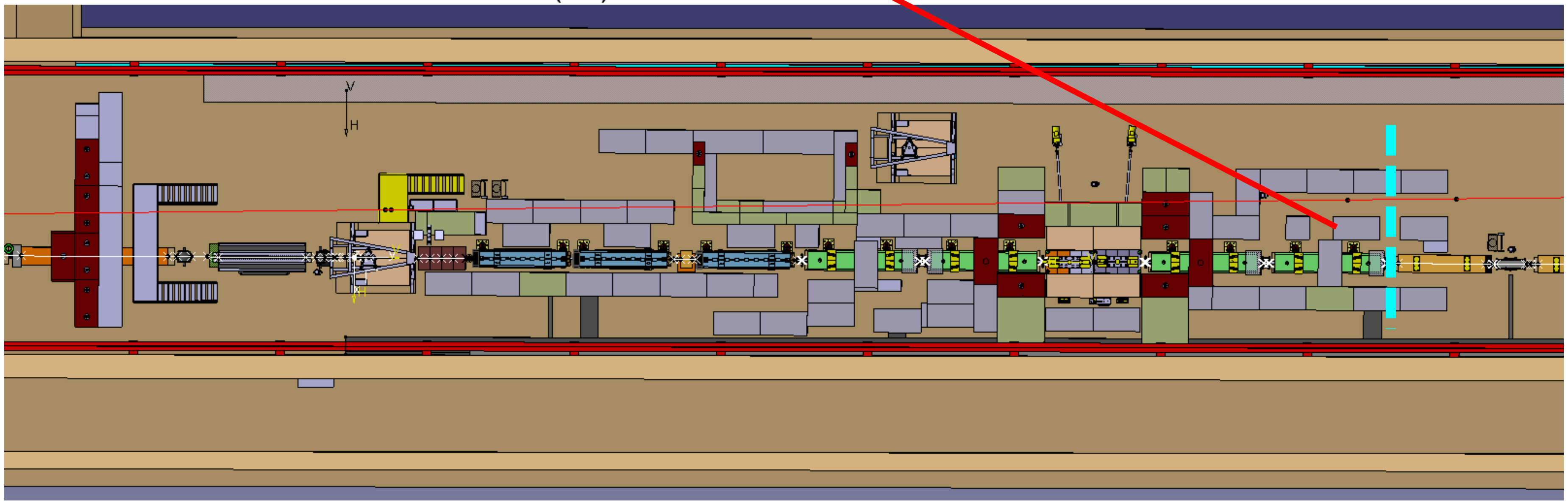


Muon illumination after the second dipole of the Achromat

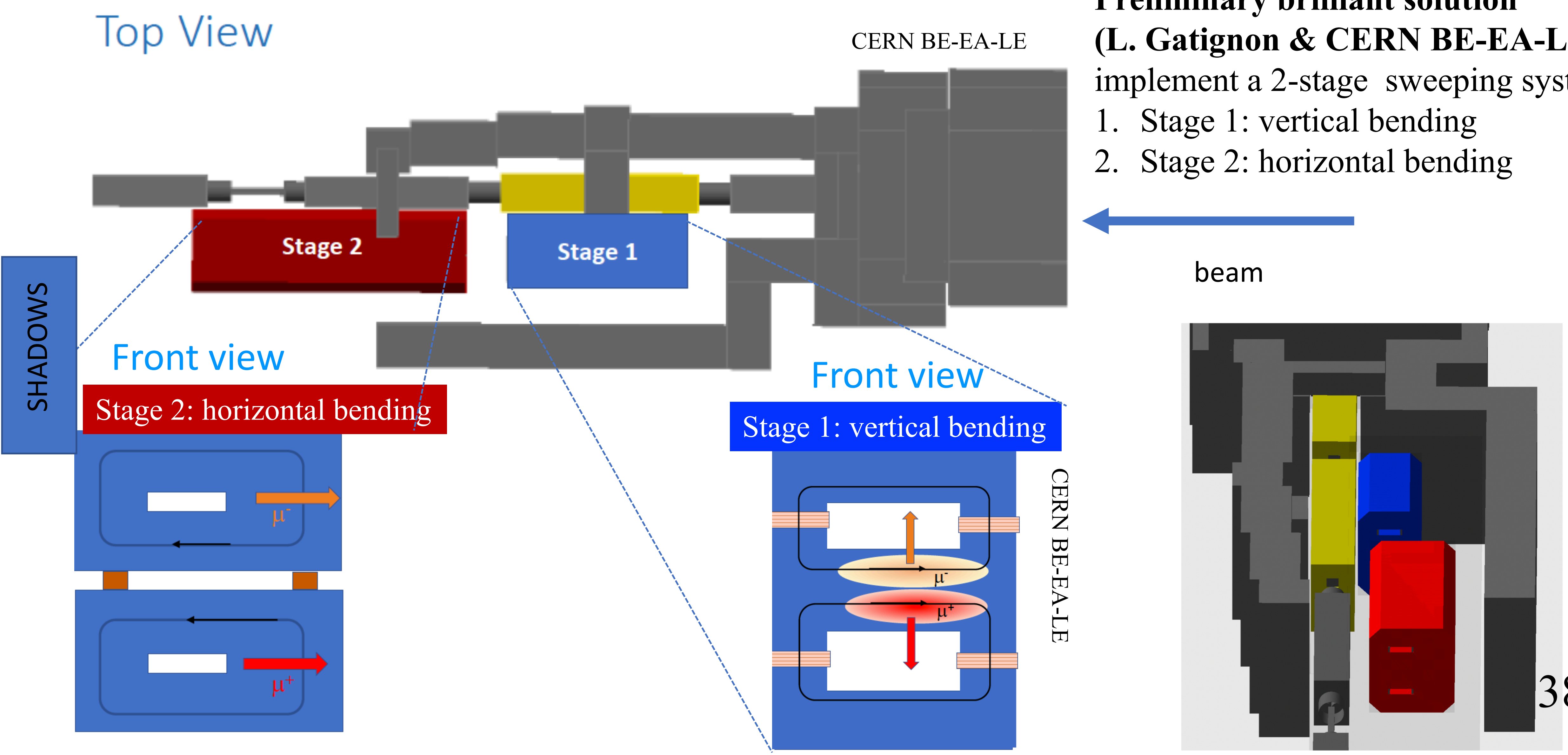


…But it is made of low-p (< 15 GeV) muons
that can be swept away using a magnetized iron block!





SHADOWS Muon Sweeper: a system of Magnetized Iron Blocks



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

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

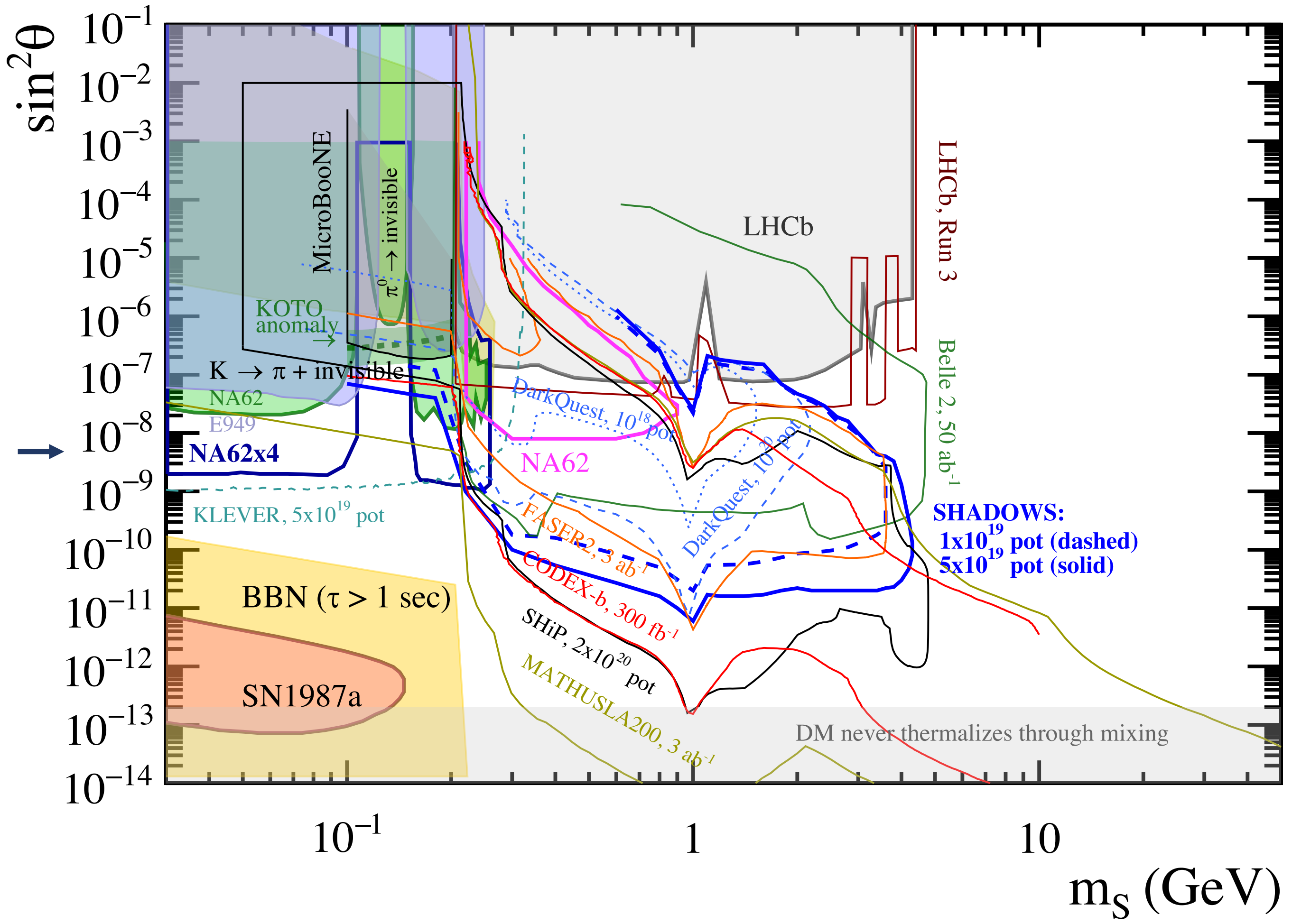
NA62/HIKE & SHADOWS physics sensitivity for standard PBC benchmarks

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

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

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

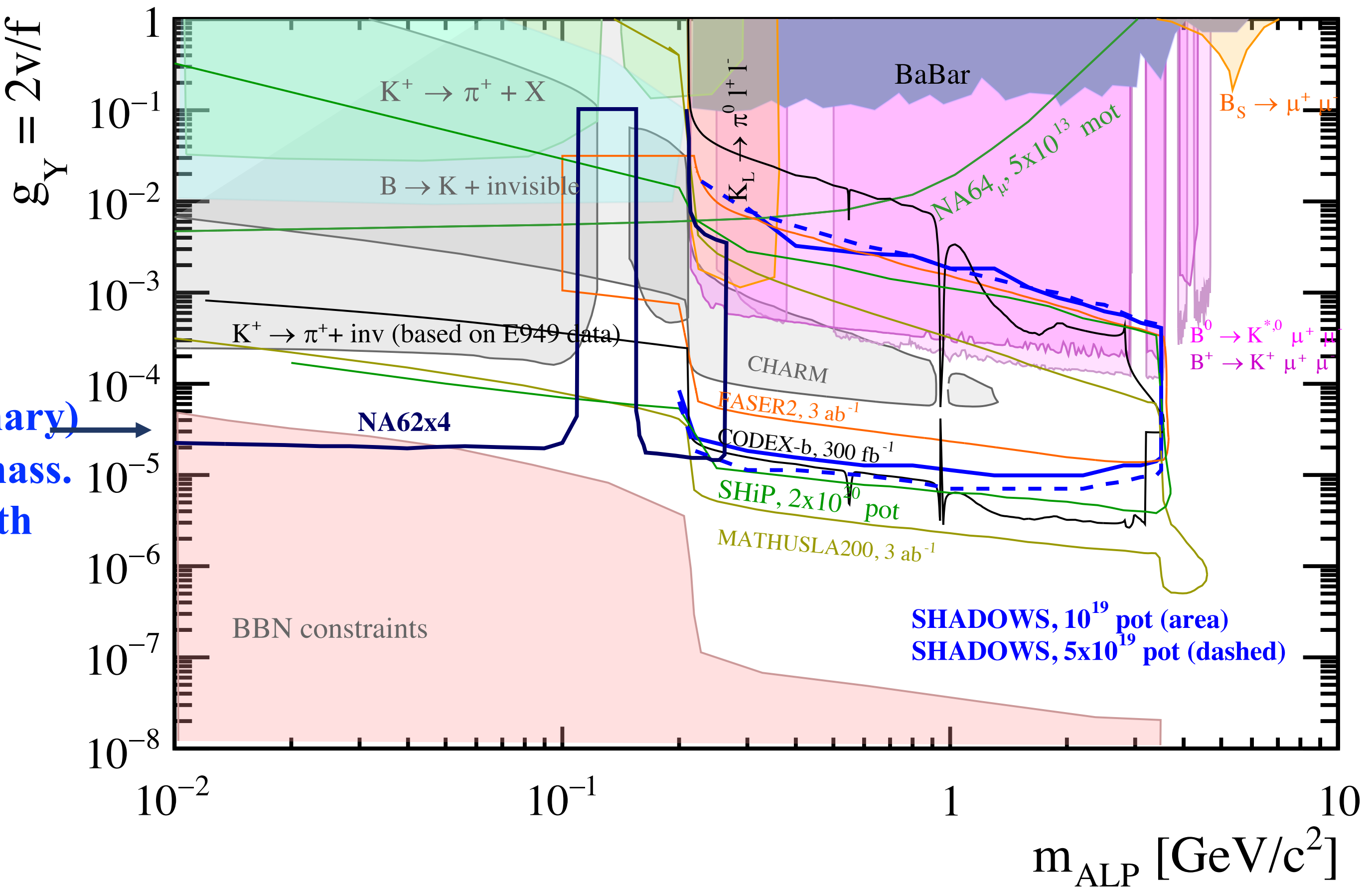
HIKE in K-mode (preliminary) covers the range below K-mass. Strong complementarity with SHADOWS.



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

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

HIKE in K-mode (preliminary) covers the range below K-mass. Strong complementarity with SHADOWS.

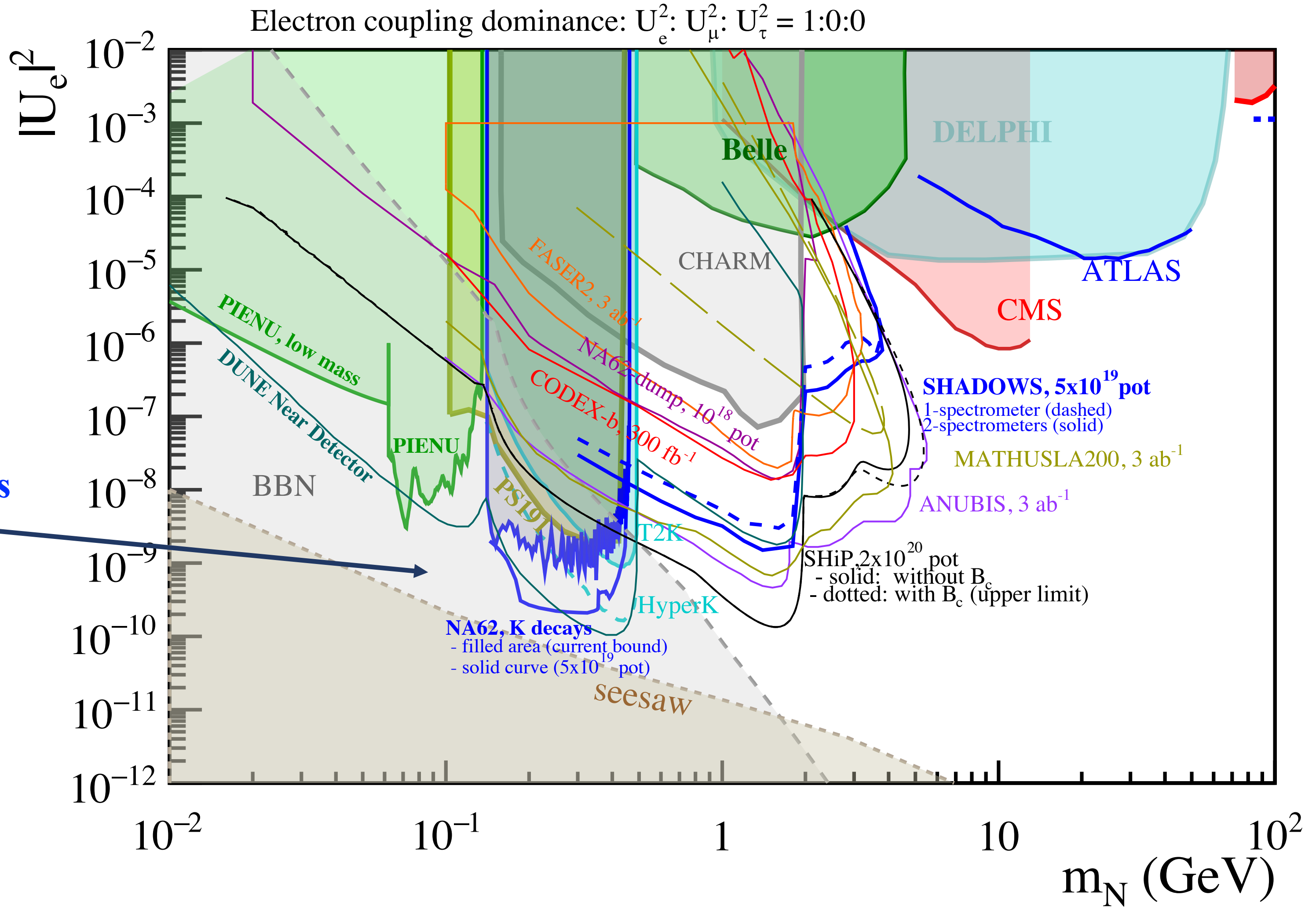


SHADOWS with 5x10^{19} pot is better than FASER2 with 3 ab^{-1}, and comparable to CODEX-b (with 300 fb^{-1}) and SHiP (with 2x10^{20} pot).

Heavy Neutral Leptons (with electron coupling)

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

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

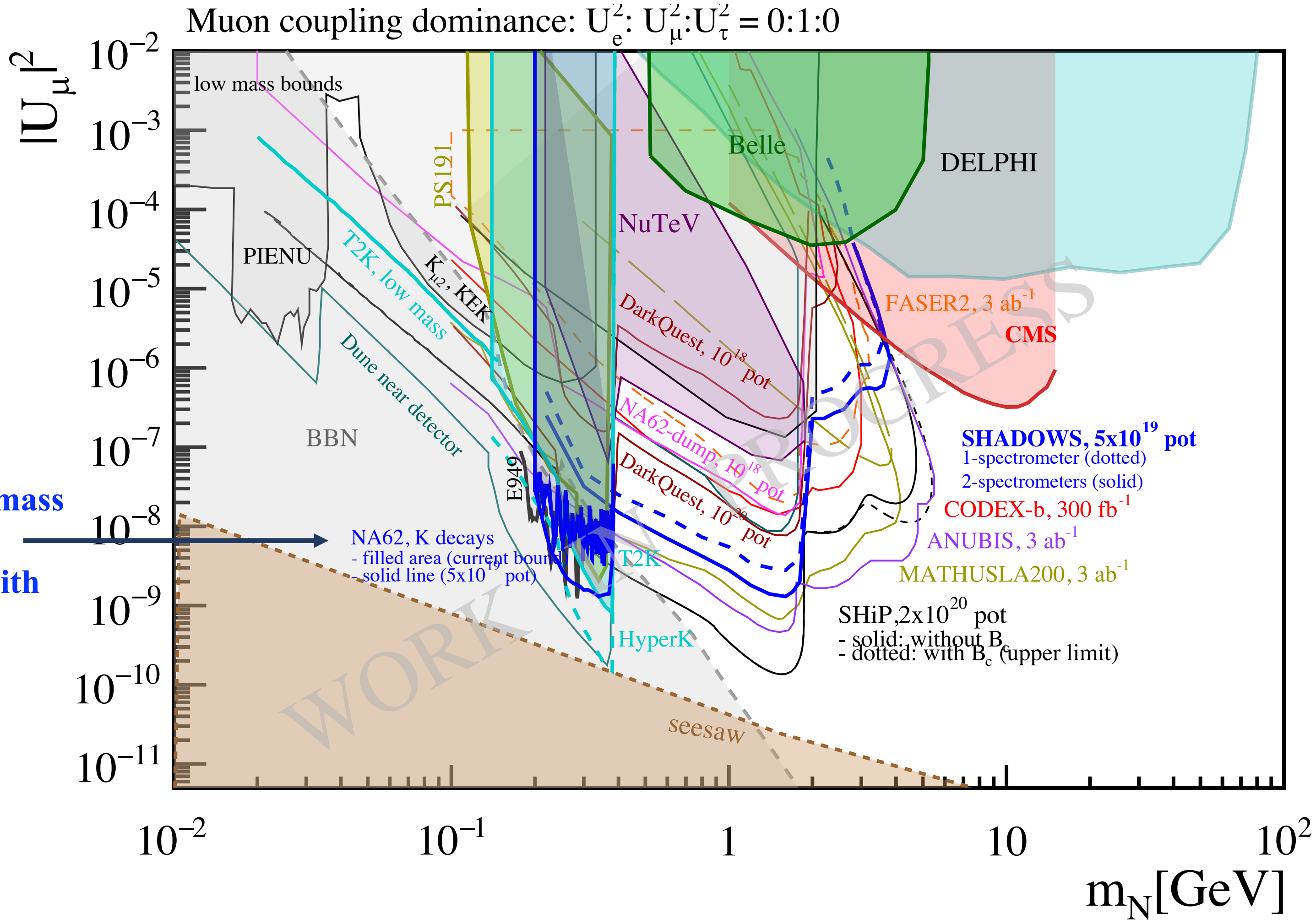


Between K and D: SHADOWS is (much) better than CODEX-b and FASER2 with full dataset.

Between D and B: SHADOWS expands by two-three orders of magnitude wrt current bounds (Belle)

Heavy Neutral Leptons (with muon coupling)

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



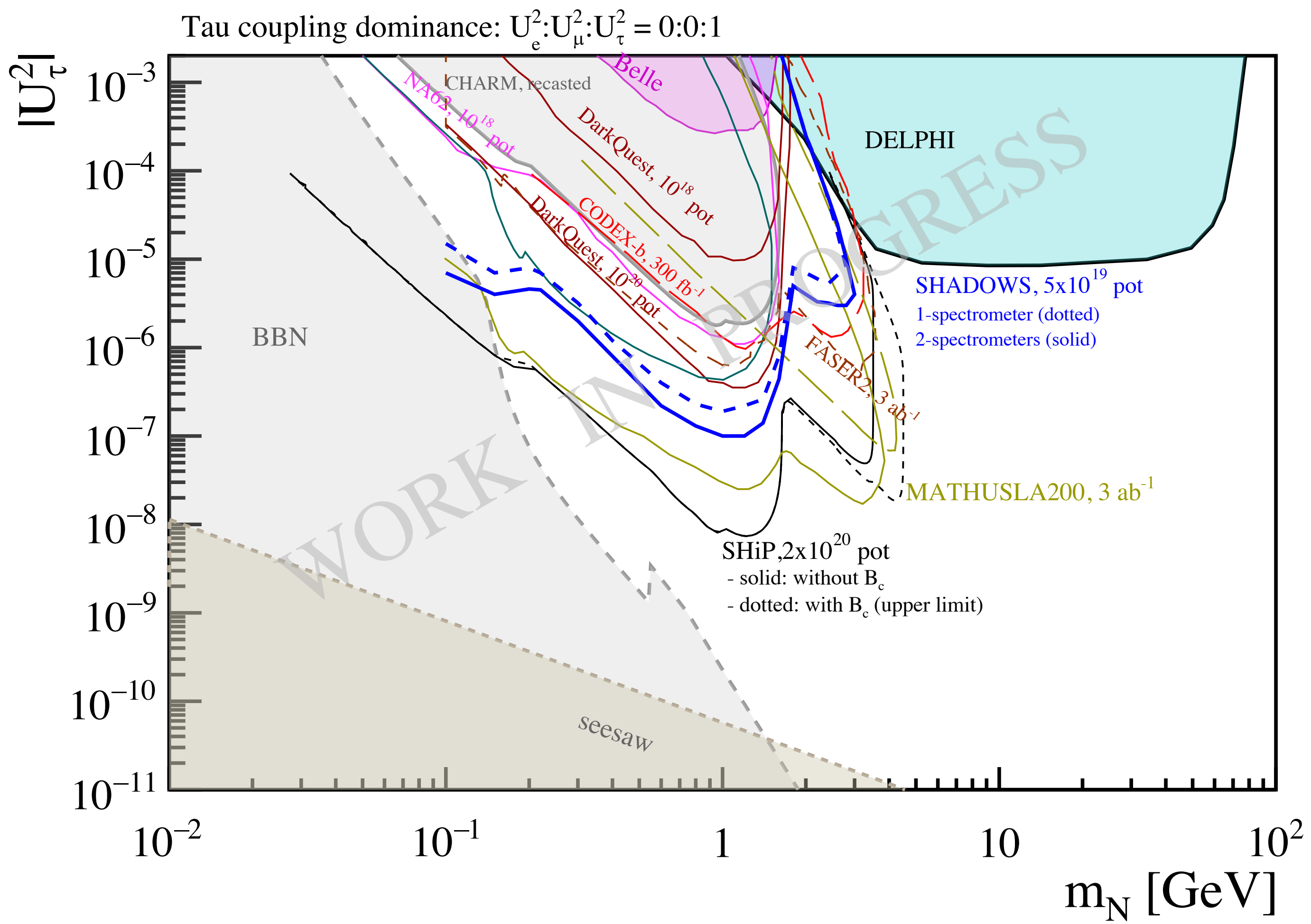
NA62 in K-mode covers the range below K-mass down to the seesaw limit. Strong complementarity with SHADOWS.

Between K and D: SHADOWS is (much) better than CODEX-b and FASER2 with full dataset.

Between D and B: SHADOWS expands by ~two-three orders of magnitude wrt current bounds

Heavy Neutral Leptons (with tau coupling)

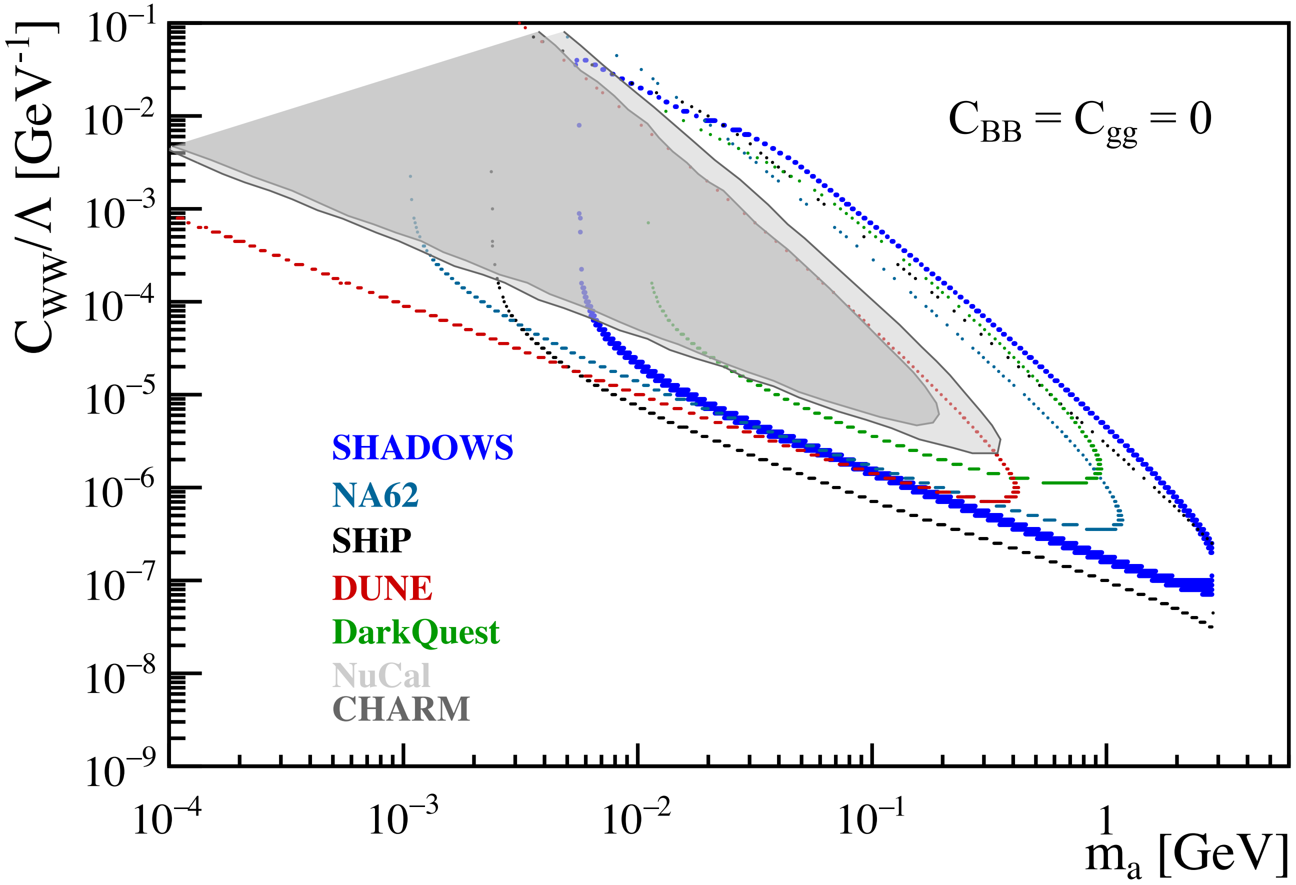
(origin of neutrino masses and oscillation, baryogenesis through leptogenesis)



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

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

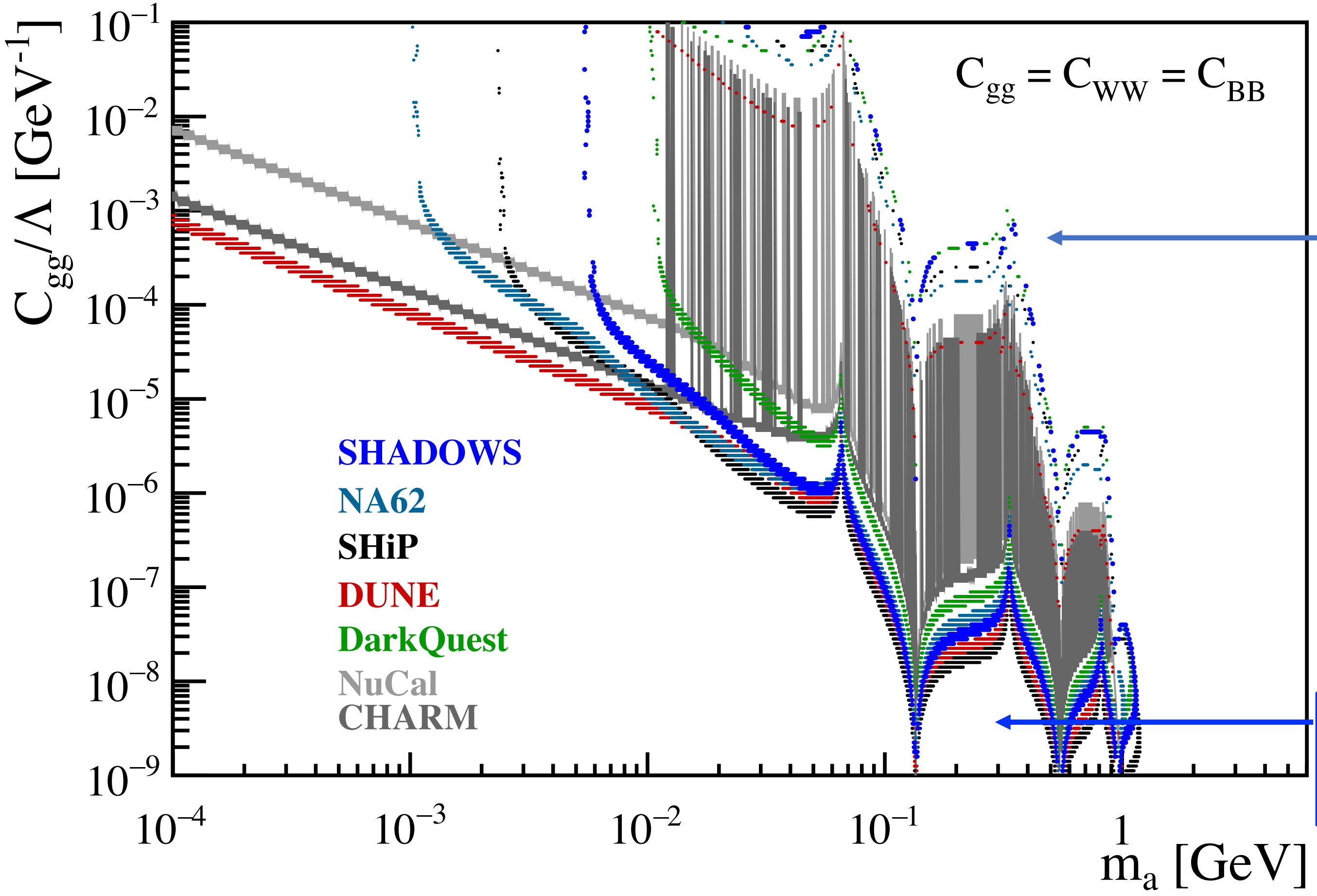
F. Kahlhoefer et al, 2201.05170 (only fixed target/beam dump experiments considered)



SHADOWS with 5×10^{19} pot is competitive with DUNE and SHiP@BDF

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

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

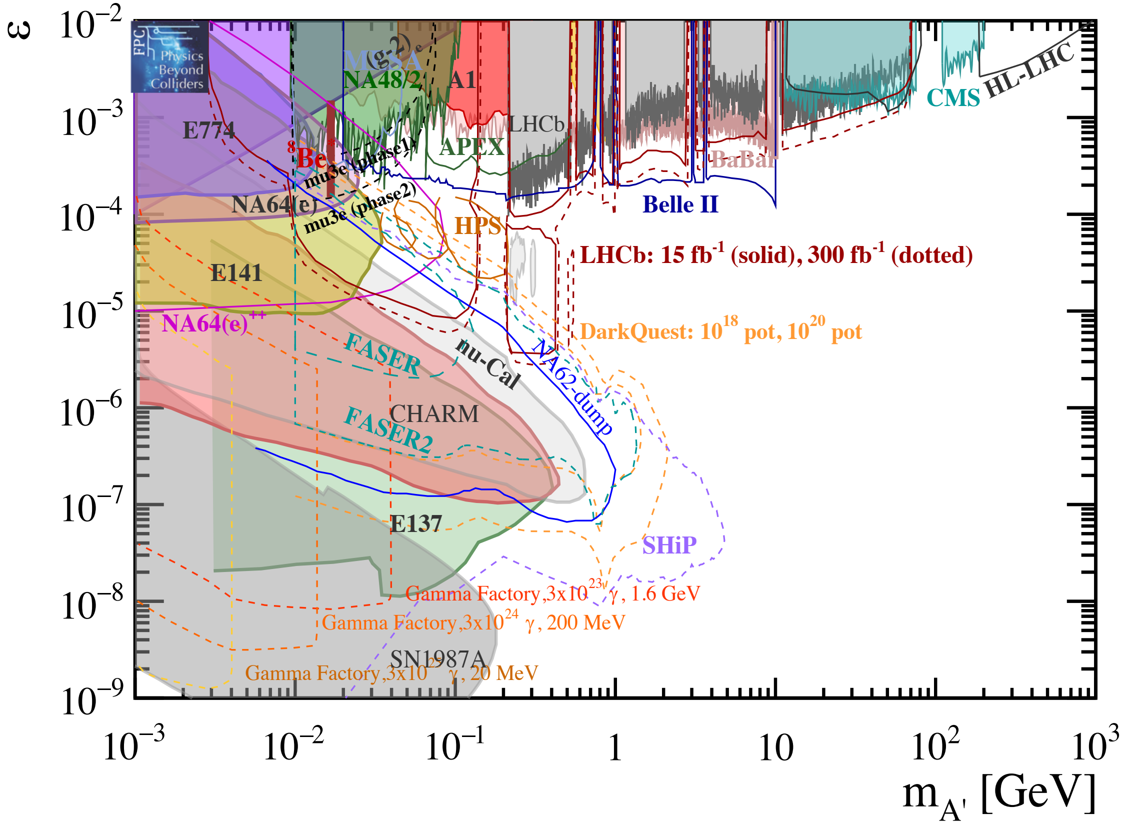


Here SHADOWS is the best

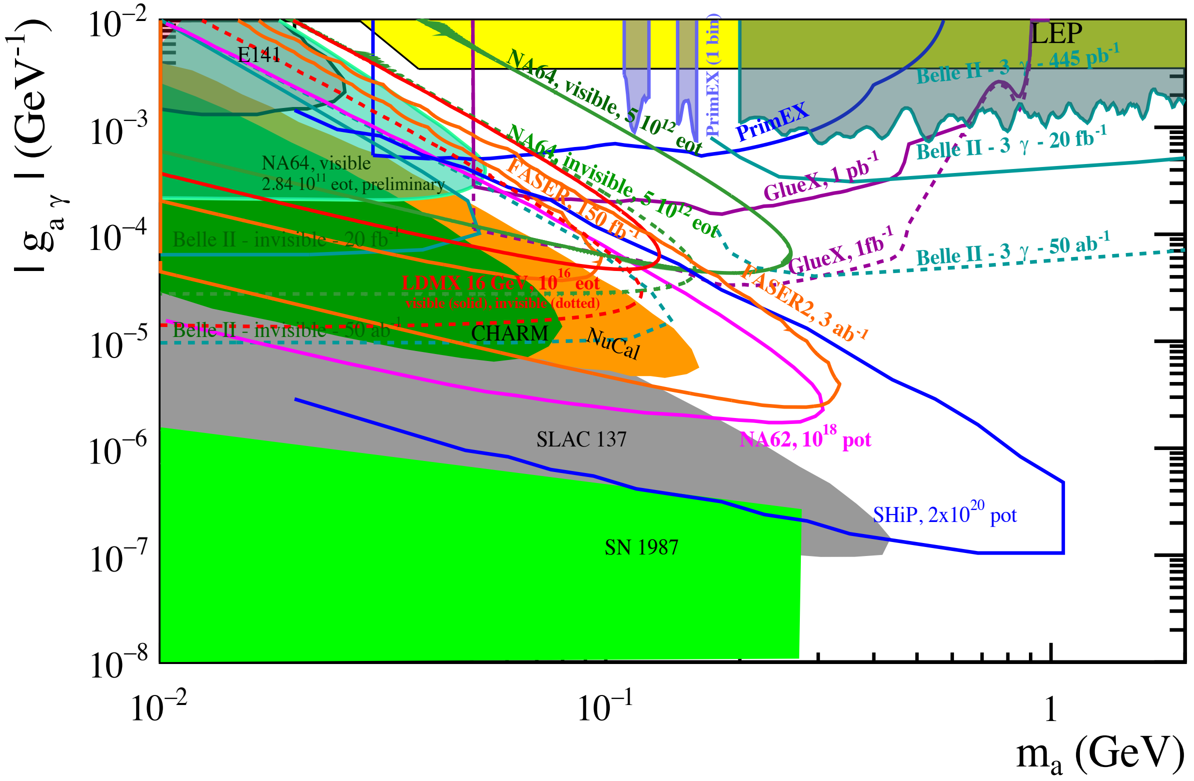
Here SHADOWS is slightly worse only of DUNE & SHiP @ BDF.

Dark Photon and ALPs with photon couplings

Dark Photon minimal models



ALPs with photon-coupling only

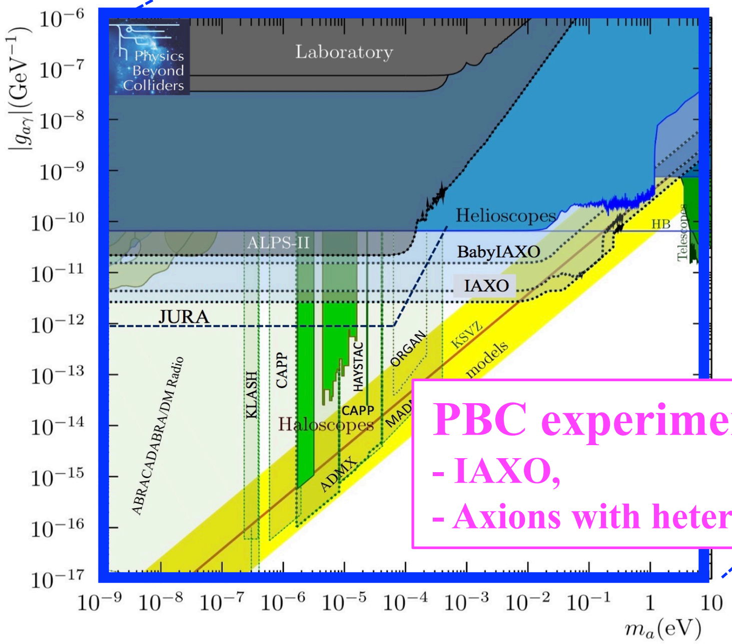


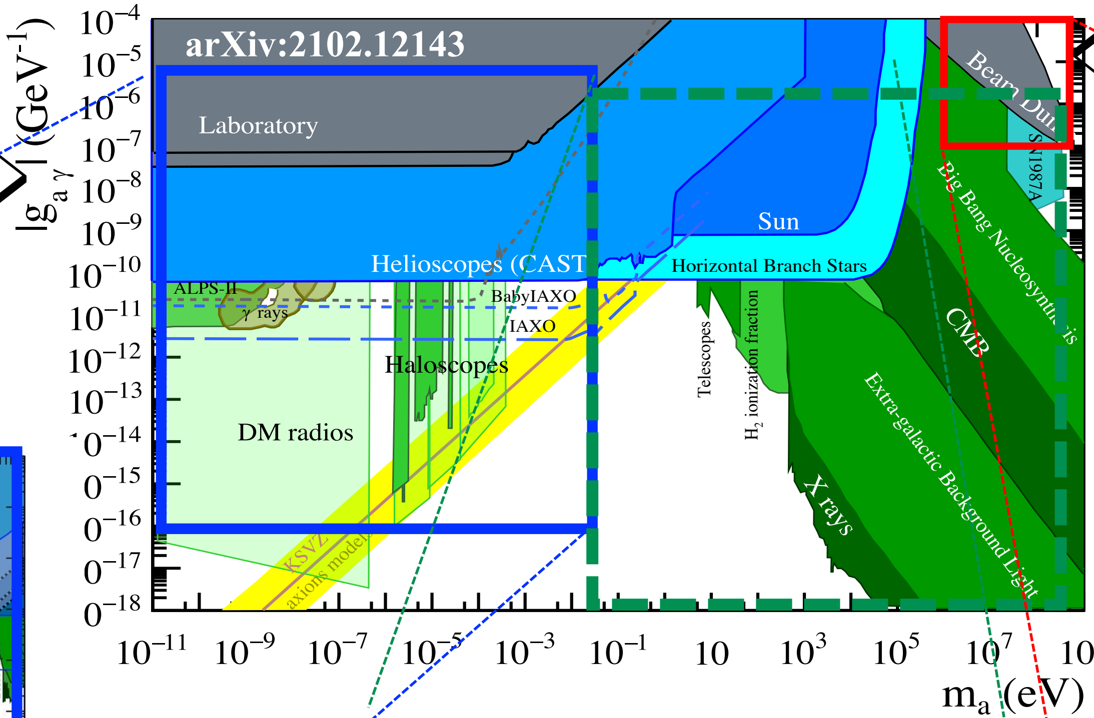
NA62 projections only for 10^{18} pot. HIKE projections with 5×10^{19} pot are being computed

An axion/ALP from 10^{-11} eV to the QCD scale (~GeV): 20 orders of magnitude

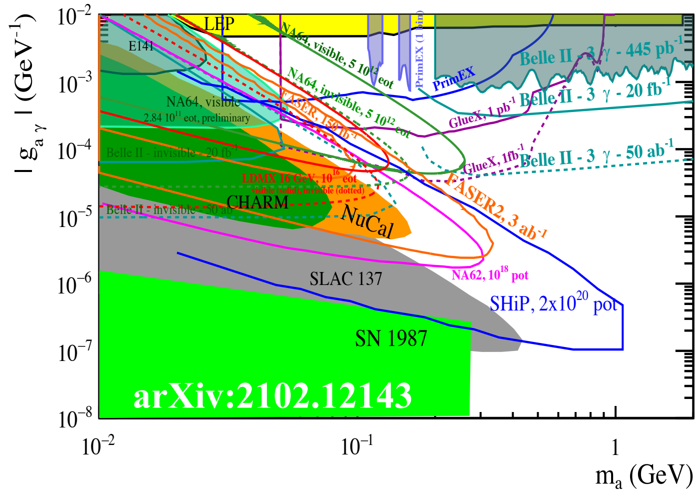
sub-eV range accessible at **helioscopes and haloscopes**

Here axion/ALP can be DM





MeV-10 GeV range accessible at **accelerator based experiments**



Astroparticle realm:
BBN, CMB, X-rays, SN1987, Solar lifetime, etc..

PBC experiments:
- **IAXO,**
- **Axions with heterodyne detection**

PBC experiments/projects: NA64(e), FASER(2), NA62(dump),…

Worldwide landscape: Belle II, ATLAS,CMS,…

https://indico.cern.ch/e/FIPs2022

FIPs 2022

Workshop on
Feebly-Interacting Particles

17-21 October 2022
CERN
Main Auditorium

Preliminary programme already posted on the web. Registrations are open.

We look forward to welcoming you at the Workshop!

Conclusions (1/2)

✓ NA62 Run 1 (2016-18) K+ decay dataset: world leading results on:
- HNL prodiction [PLB807 (2020) 135599; PLB816 (2021) 136259]
- Dark scalar production (JHEP 02 (2021) 201, JHEP 06 (2021) 93
- Invisible dark photon production [JHEP 05 (2019) 182]

✓ Broad programme of hidden-sector searches in K decays

Beyond the PBC benchmark scenarios: arXiv:2201.07805

✓ HIKE K+ phase: [2027--]
- significant advances expected. Solid projections based on experience with NA62 data.

Conclusions (2/2)

- ✓ SHADOWS is a proposed proton beam dump experiment for FIPs physics that can be built in ECN3 and take data concurrently to NA62 when NA62 is operated in beam-dump mode:
  - ⇨ SHADOWS can be built now: (almost) all the infrastructure is in place.
  - ⇨ Proposal ready by early 2023.

- ✓ SHADOWS (5x10^{19} pot) has similar/better sensitivity than CODEX-b (300 fb^{-1}) and FASER2 (3 ab^{-1}) and for specific benchmarks as SHiP (2x10^{20} pot) for FIPs from charm/beauty:
  - ⇨ It naturally complements NA62-dump that is mostly sensitive to very forward objects, and NA62-K that is mostly sensitive to FIPs below the K-mass.

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  - ⇨ It naturally complements NA62-dump that is mostly sensitive to very forward objects, and NA62-K that is mostly sensitive to FIPs below the K-mass.

A broad and synergistic programme for FIPs can be done in ECN3 with NA62/HIKE and SHADOWS:
Together can provide an unprecedented physics reach in the international landscape.

SPARES

Physics Beyond Colliders

The FIP Physics Center – Structure

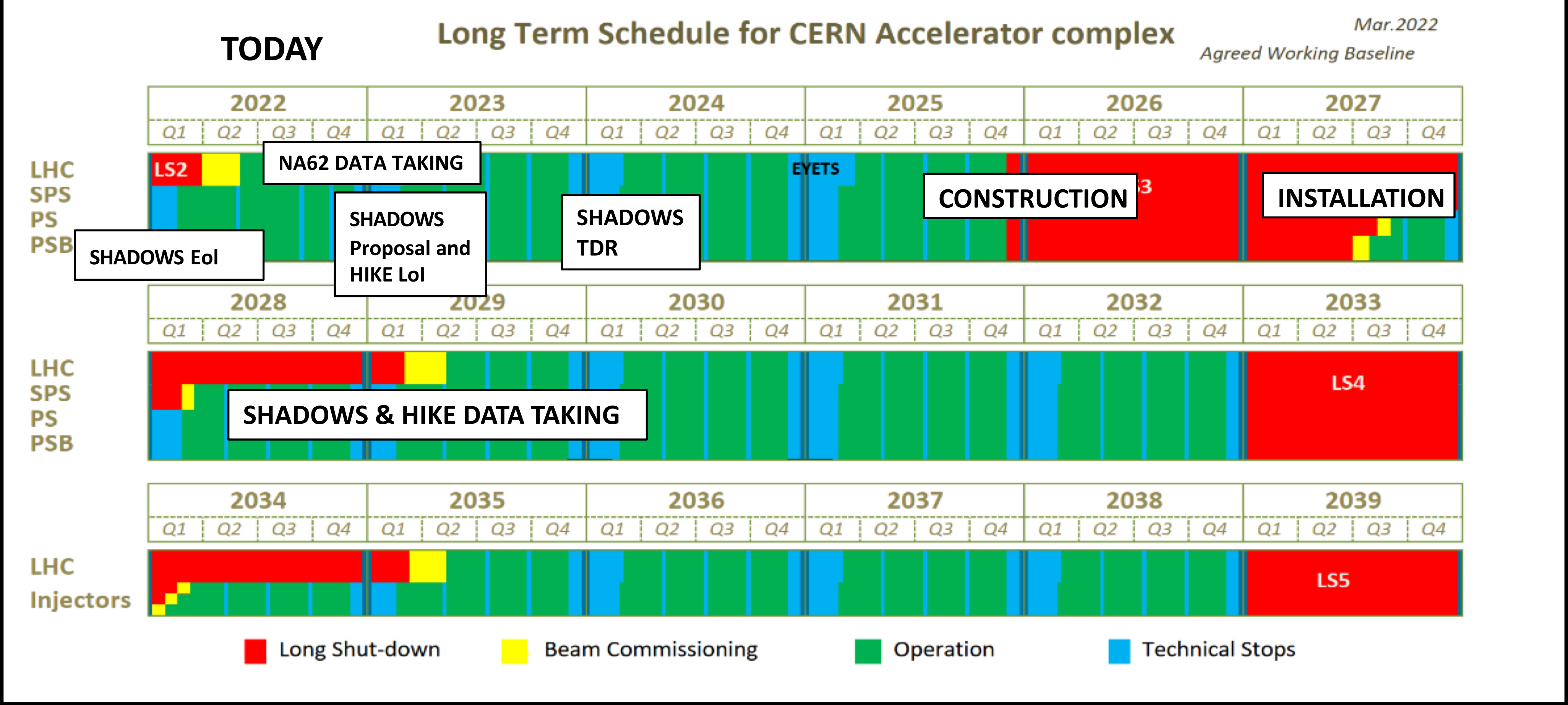
PHYSICS WORKING GROUPS

WG1:
FIPs and light (MeV-GeV) DM:
theory models,
Interplay between accelerator-based & direct detection experiments;
Astroparticle, cosmology.

WG2
Ultra-light FIPs (including Axions/ALPs)
Forefront theoretical progress
Experimental searches from 10^{-11} eV to the EW scale

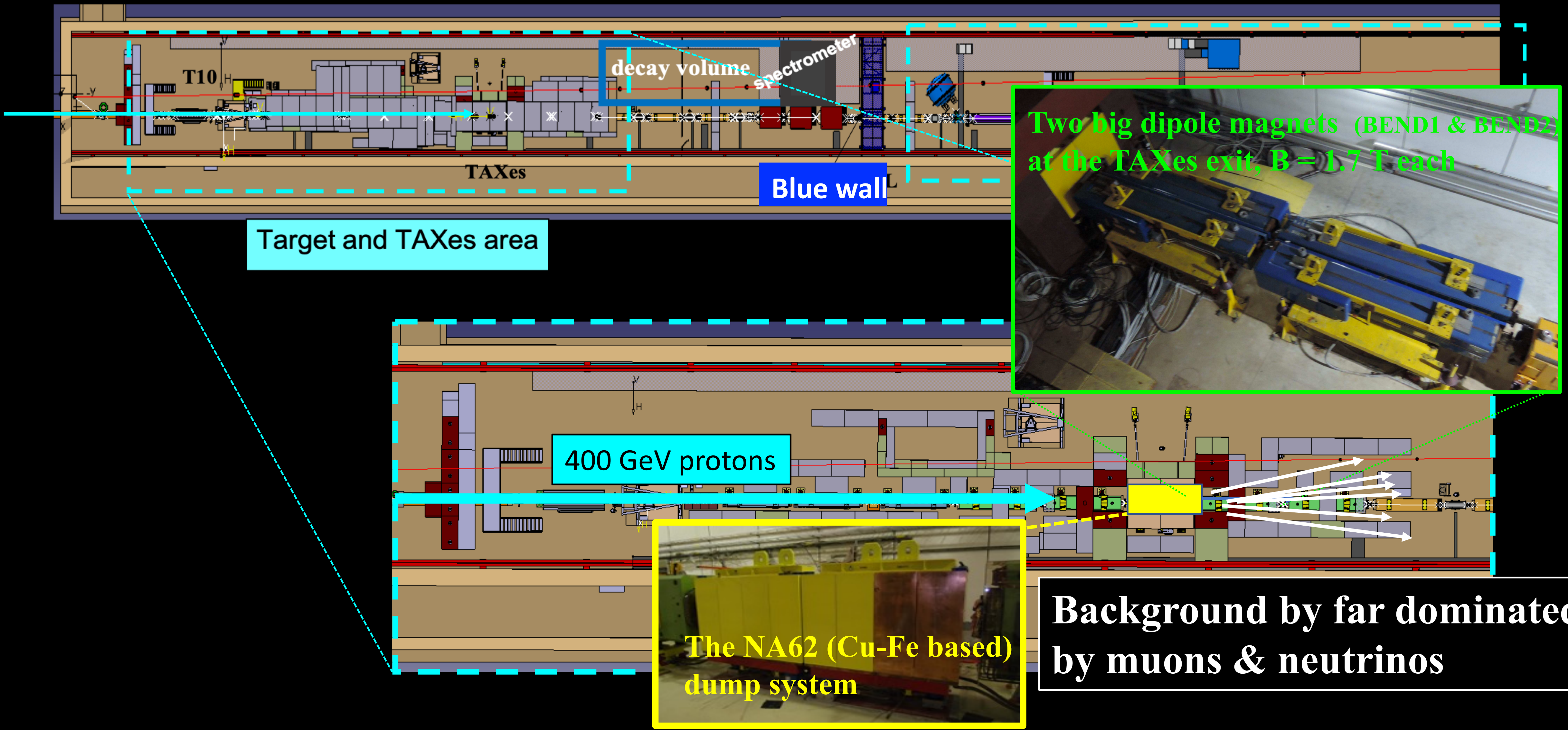
WG3
HNLs and neutrino mass generation:
- astroparticle, cosmology
- light neutrino physics
- Searches at extracted beams, and colliders.

SHADOWS & HIKE: TENTATIVE TIME SCHEDULE



The beam-induced background in dump mode:
the name of the game

The beam-induced background:



Background by far dominated by muons & neutrinos

Background for the dump mode (HIKE-dump and SHADOWS)

Three main backgrounds:

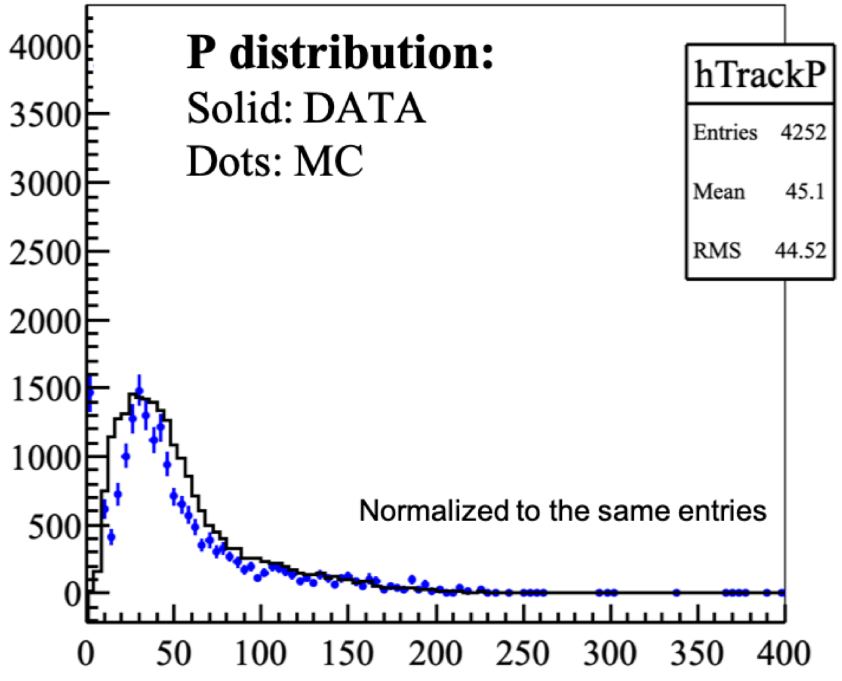
1. Muon combinatorial

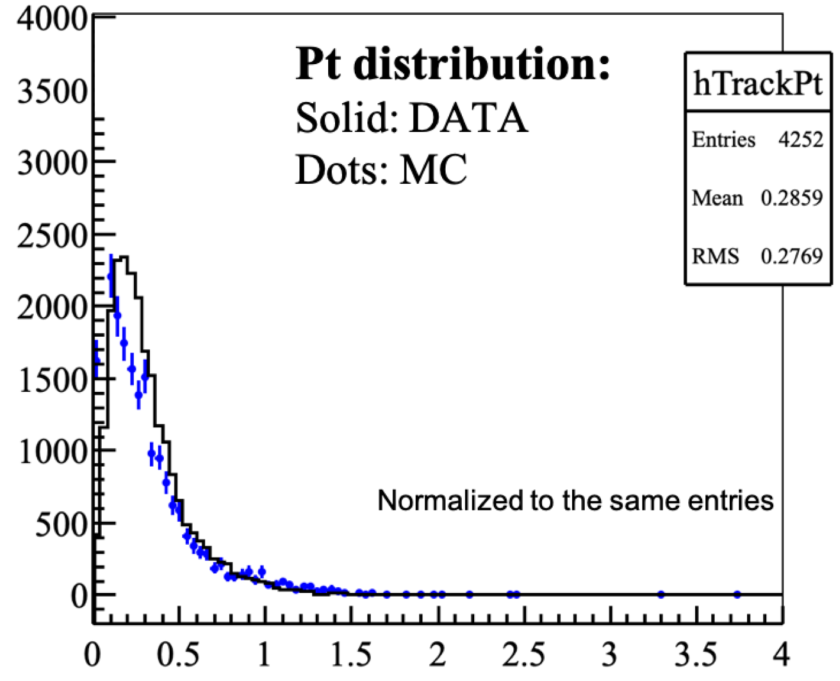
2. Neutrinos inelastic interactions with the air in the decay volume

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

Background: (Preliminary) Validation of muon background simulation

NA62 has collected about 1.7 x10^{17} pot in dump in November 2021

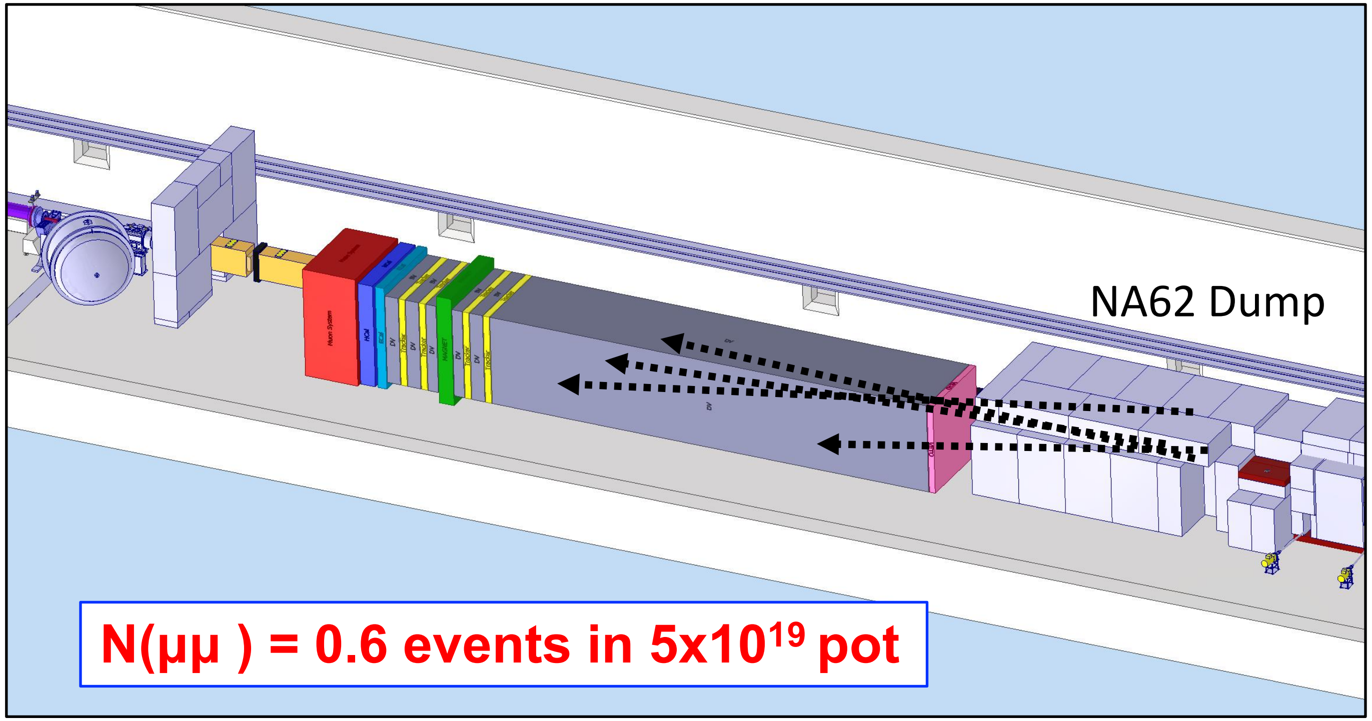




This data set allows to validate the output of the MC simulation (based on BDSim package, GEANT4).
Shapes of distributions are reasonably well reproduced,
Simulated rates are under-estimated by a factor 3 in the momentum range of interest for SHADOWS.

1. SHADOWS Background: Muon Combinatorial

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



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

N(μμ) initial = 4×10^{6} /spill

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

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

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

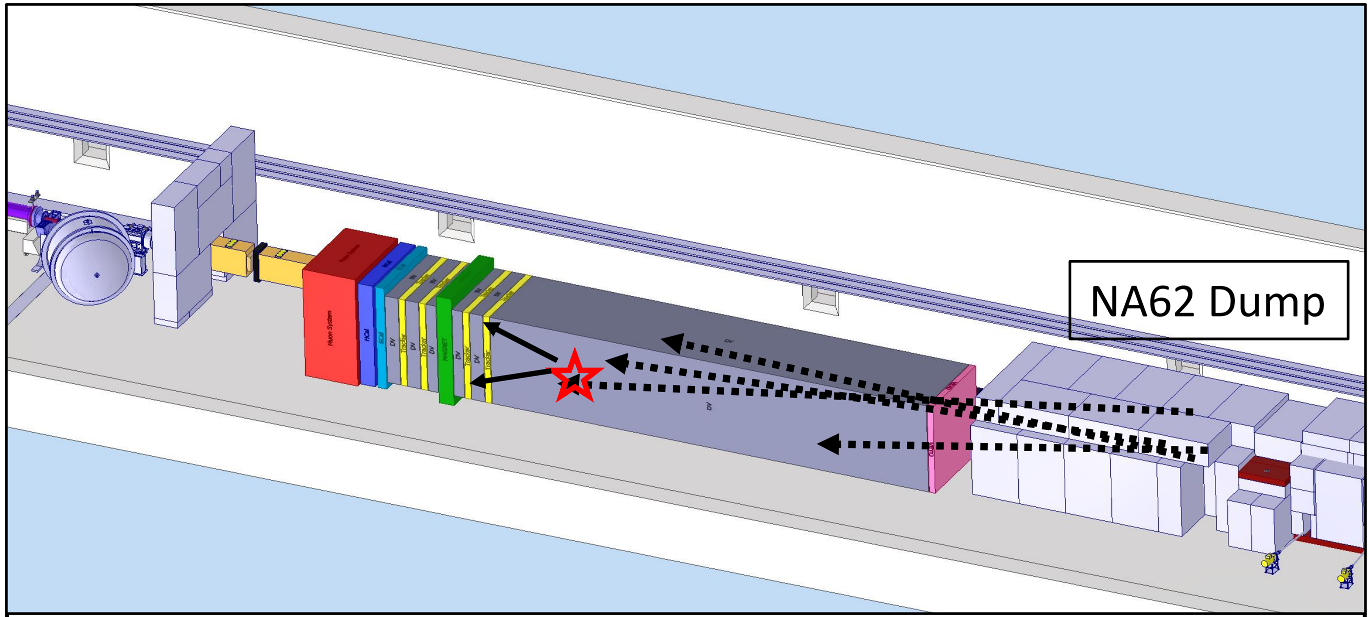
4) Pointing: Probability to point back to impinging point of protons onto the dump: 10^{-3}

ALL IN ALL : 2×10^{-7} μμ /spill, 3×10^{6} spills in 5×10^{19} pot
N(μμ) final = 0.6 events in 5×10^{19} pot

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

Number of neutrinos in SHADOWS acceptance:

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



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

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

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

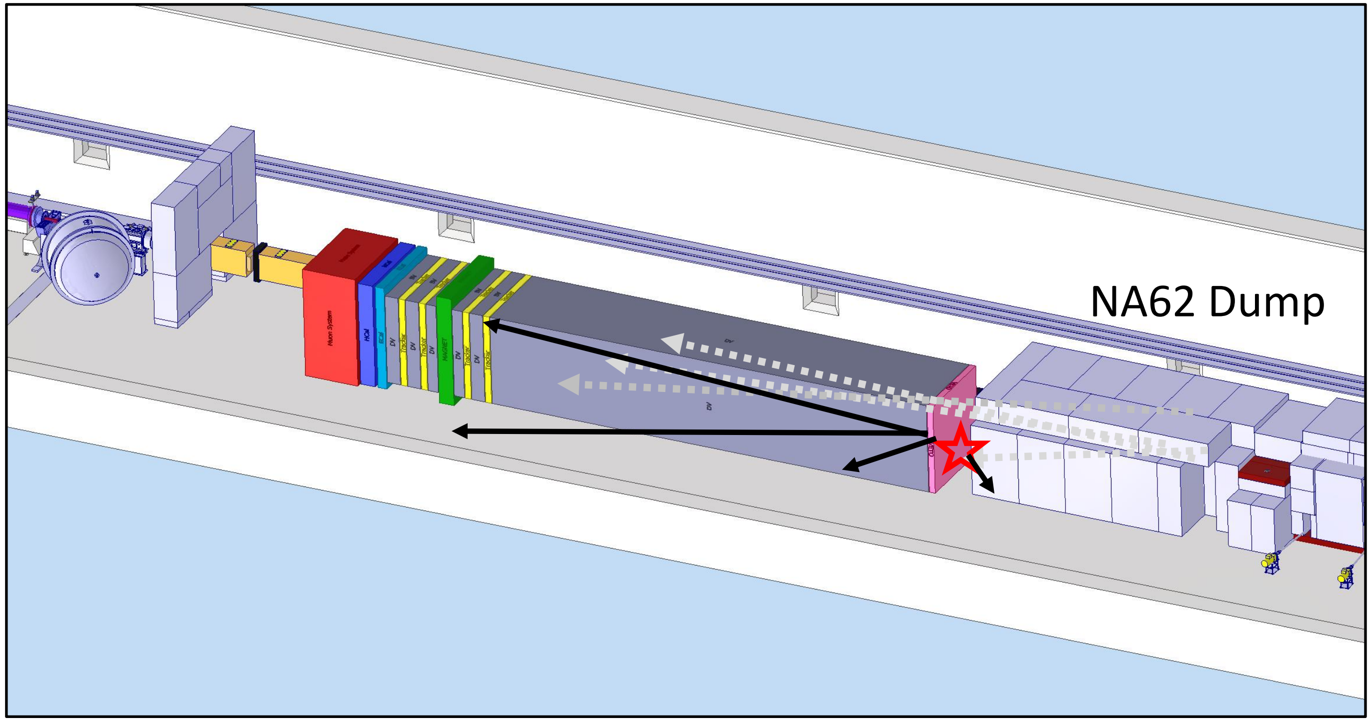
1 mbar vacuum reduces this number to 0.6 events in $5\text{x}10^{19}$ pot

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

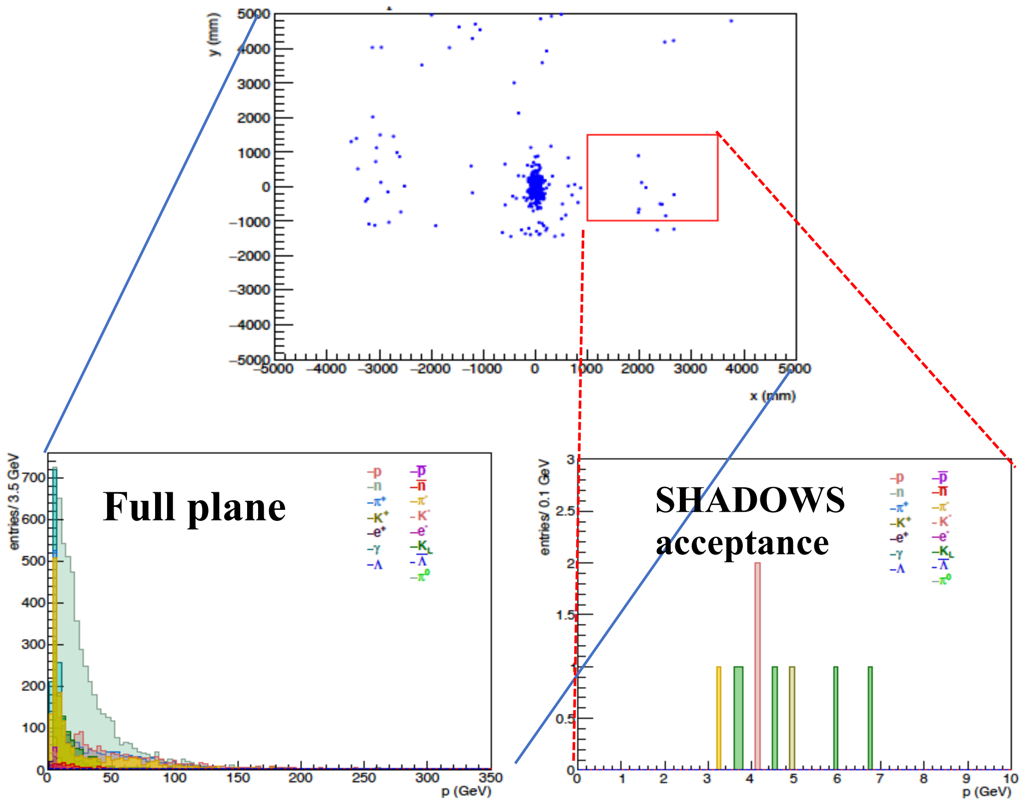
3. SHADOWS Background: Neutrino & Muon inelastic interactions in Upstream Veto

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

This will not be the dominant background….



Non muon background downstream of TAXes



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