The Search for Feebly-Interacting Particles with SHADOWS at CERN

Gaia Lanfranchi – LNF-INFN

Mainz, Excellence Cluster – 14 December 2022

1. A few words about me..

My Curriculum

Name: Gaia Lanfranchi,

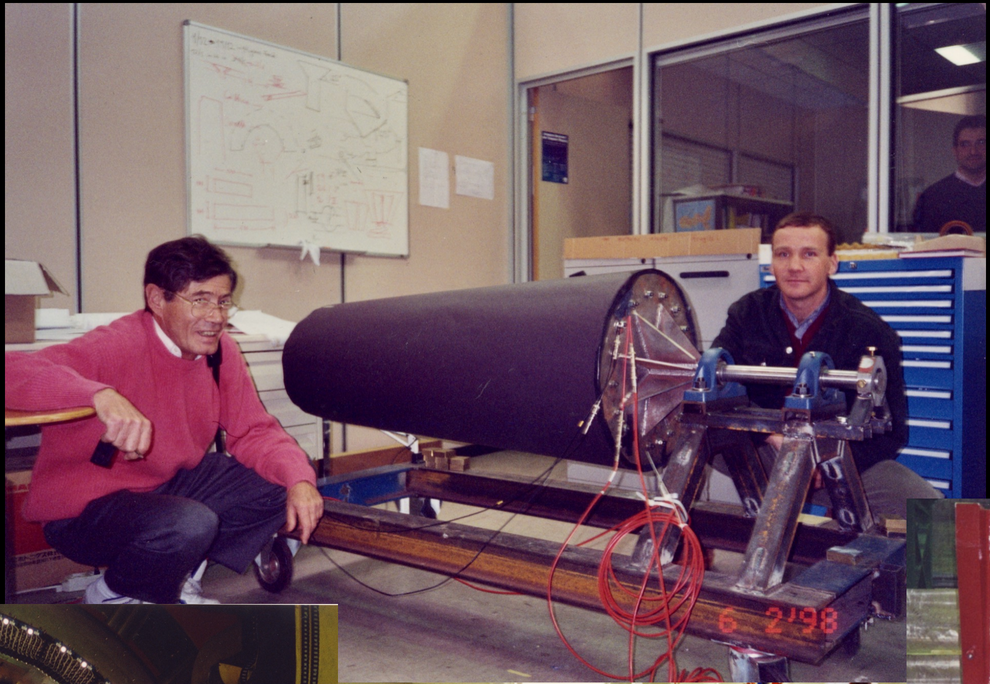
Position: Senior Physicist at Istituto Nazionale di Fisica Nucleare (Italy), based at CERN since 2007.

I come from a family of lawyers, I received a classical education (latin & ancient greek), but developed a genuine curiosity for physics since I was very young…

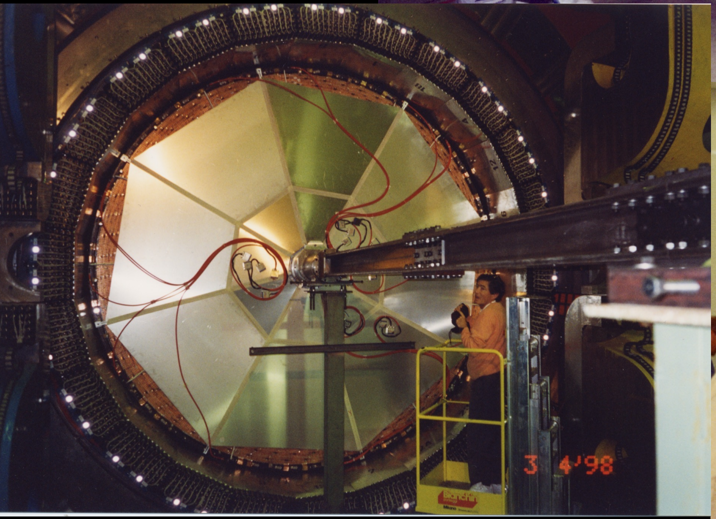
- ✓ **Degree at University of Rome "La Sapienza" (Italy) In Particle Physics**
- ✓ **Ph.D at University of Rome in Particle Physics.**
- ✓ **Fellowship at Laboratori Nazionali di Frascati**
- ✓ **Limited Duration contract at INFN**
- ✓ **Limited Duration contract at CERN**
- ✓ **Permanent position as researcher at INFN**
- ✓ **Scientific Associate at CERN (twice)**
- ✓ **Permanent position as Senior Physicist at LNF**

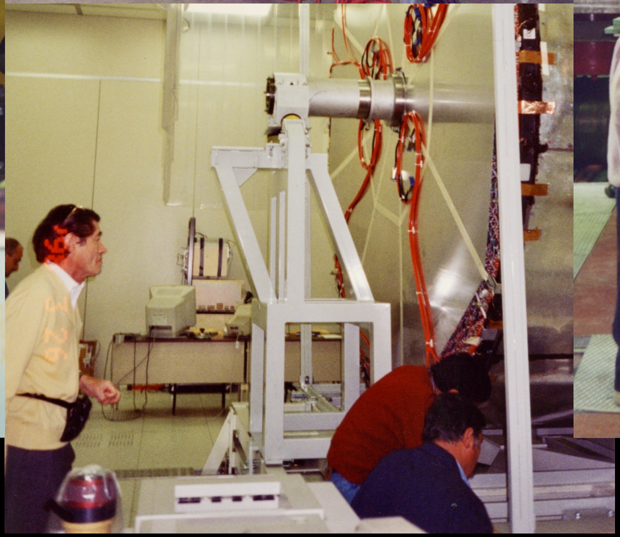
1992-2002

1992-2002: KLOE Experiment in Frascati, precision flavor physics with Kaons

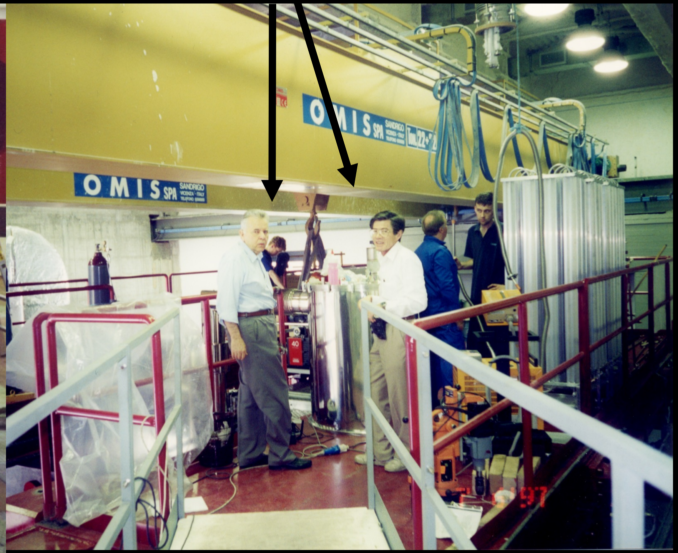


My mentor and tutor: Prof. Paolo Franzini
One of the best physicists I met in my life
I have learned from him that there is no
Experimental or Theoretical physics but only Physics…





Paolo Franzini with Nicola Cabibbo

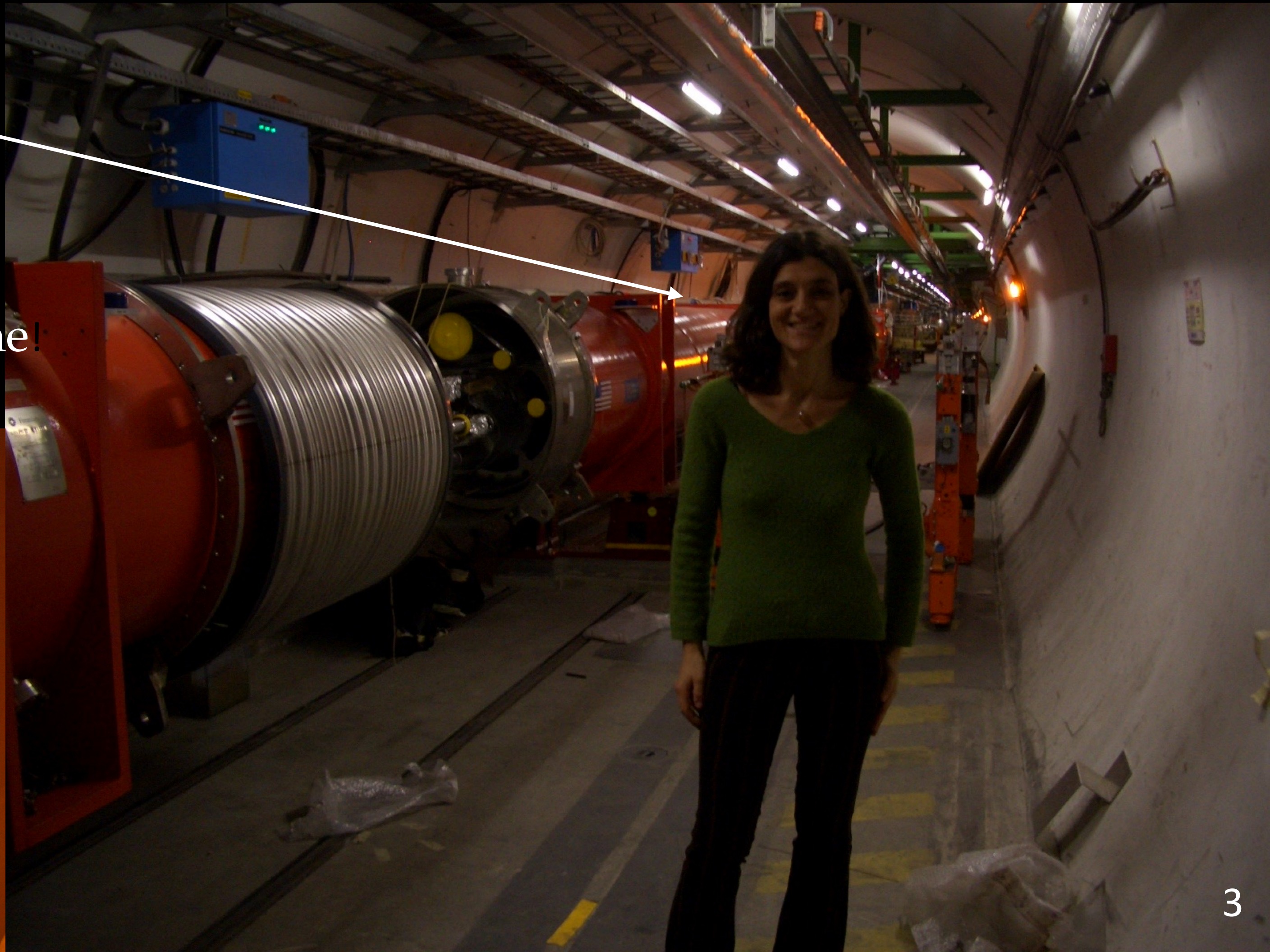


2002-2010

2002-2018: LHCb experiment at CERN: precision flavor physics with B

I joined CERN in 2002 to work in LHCb well before the accelerator was ready to start…

In the LHC tunnel



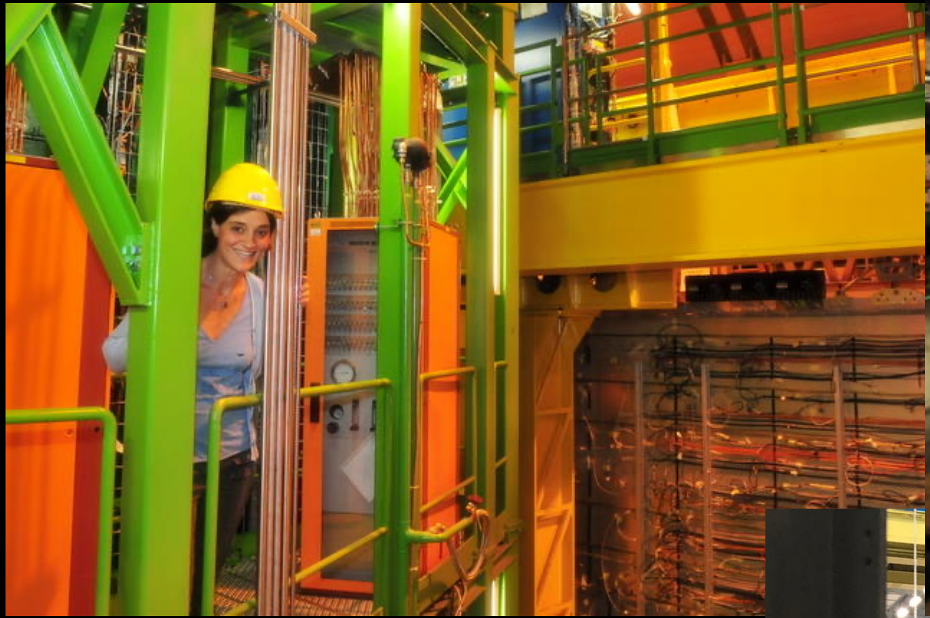
.. I also managed to bring my son Marco with me!

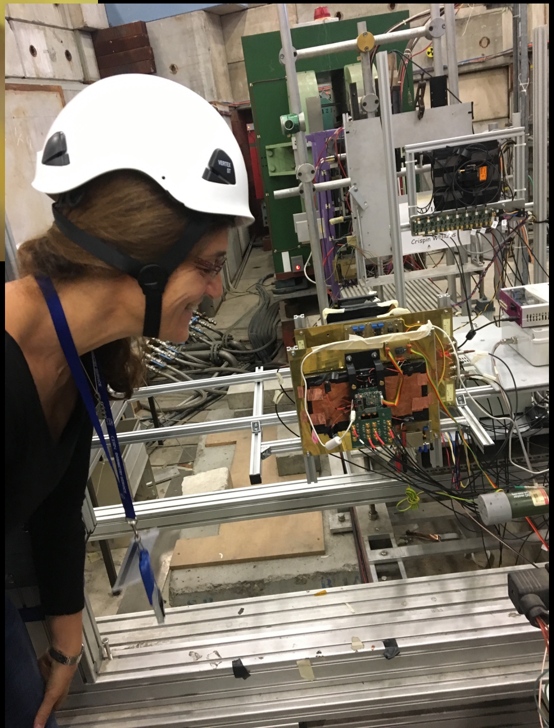
2006

2002-2010

My activity in LHCb: 2002 – 2010:

R&D, construction, installation, and calibration of the LHCb Muon System (based on multi-wire proportional chambers)





« You cannot do any physics if you do not know in depth your detector …»
P. Franzini.

March 2010

And then (finally) in 2010 the LHC was ready …

… the day of the first collisions!

2010-2012

My activity in LHCb: 2010 – 2013:

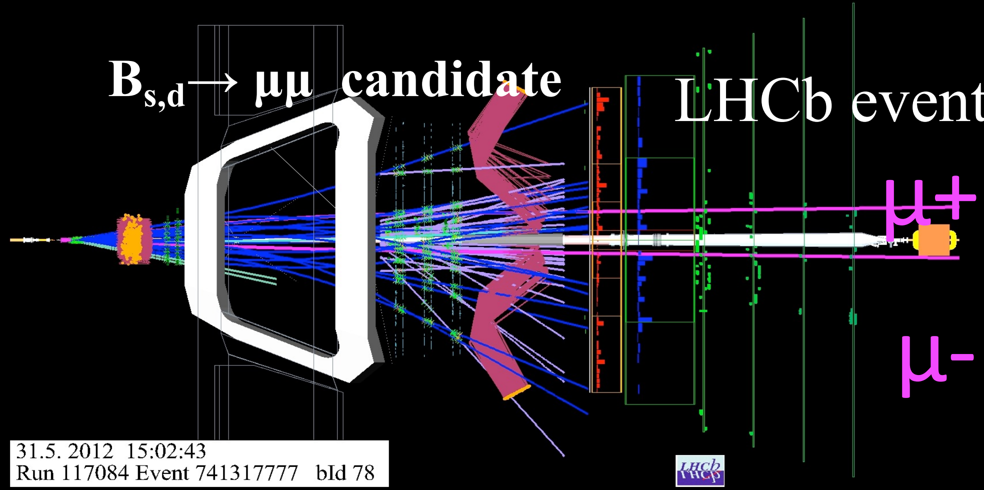
The search for the ultra-rare decay $B_s \rightarrow \mu\mu$

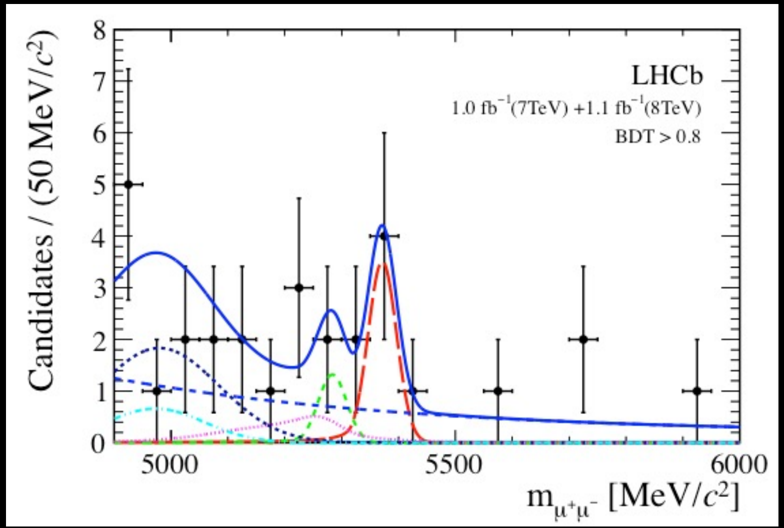
In 2010 the only results available were from Tevatron experiments (CDF and D0) and was 40 times above the SM predictions.
Since then a big race between LHCb and CMS started to find this decay…. In 2 years we published 4 papers on the subject:

- March 2011: - *Phys.Lett.B* 699 (2011) 330-340 e-Print: 1103.2465 (135 cits)
- December 2011: *Phys.Lett.B* 708 (2012) 55-67 e-Print: 1112.1600 (71 cits)
- March 2012: *Phys.Rev.Lett.* 108 (2012) 231801 e-Print: 1203.4493 (298 cits)

November 2012: First Evidence for the Decay Bs0→μ+μ−Bs0→μ+μ,
Phys.Rev.Lett. 110 (2013) 2, 021801. e-Print: 1211.2674 (557 cits)

And we won the race!





2012-2015

Since then we all had a bright period: many many invited talks all over the world, awards, etc.
I was appointed as convener of the large « Rare B decays group » in LHCb and
as member of the prestigious SPS Committee at CERN.

Invited talk at Lepton Photon Conference

SPS Committee Visit at NA62…

BUT…….

2012-2015

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I was appointed as convener of the large « Rare B decays group » in LHCb and as member of the prestigious SPS Committee at CERN.

Invited talk at Lepton Photon Conference

SPS Committee Visit at ECN3…

BUT…….

- **All the LHCb measurements were in agreement with the SM**
- **All the Higgs couplings were in agreement with the SM,**
- **ATLAS/CMS did not find any sign of NP at the TeV scale…**

?

How about New Physics at the TeV scale?

How about New Physics at the TeV scale?

(a comic version of a serious crisis)

2. The Search for Feebly-Interacting Particles @ CERN

2015

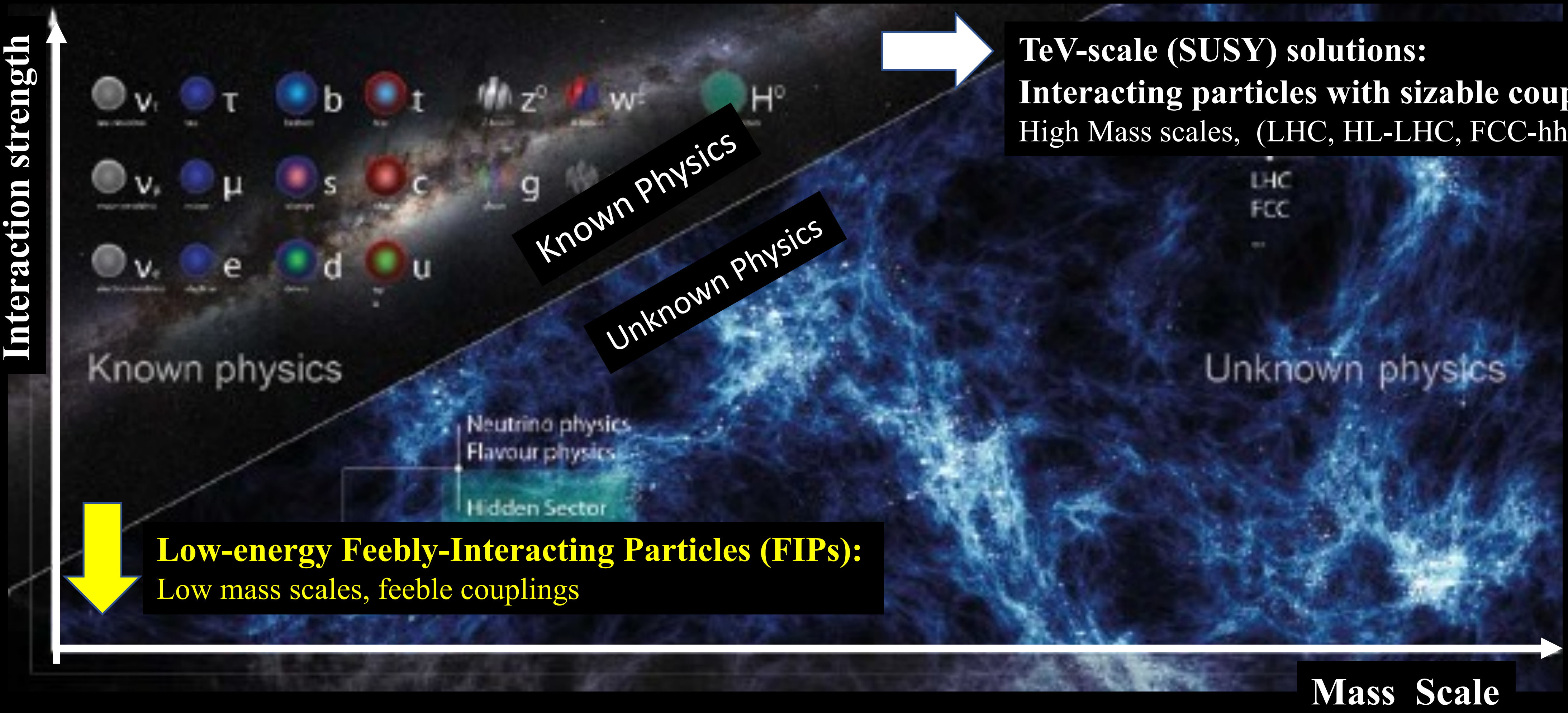
Maxim Pospelov's Seminar:

"Today particle physics faces the challenge of explaining the mystery of dark matter, the origin of matter over anti-matter in the Universe, the apparent fine-tuning of the electro-weak scale, and many other aspects of fundamental physics..."

Maxim Pospelov, Perimeter Institute & Minnesota University

"Perhaps the most striking frontier to emerge in the search for answers involves New Physics at mass scales comparable to familiar matter (MeV-GeV) and with very feeble interaction strength…."

New Physics can be light and feebly-interacting



…A change of paradigm….

What are Feebly-Interacting Particles (FIPs)?

<u>Very roughly:</u>

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)]

<u>Fully complementary to high-energy searches.</u>

Naturally long-lived.

What FIPs can provide us:

1) Thermal DM candidates that extend the WIMP paradigm in the MeV-GeV range
2) Ultra-light non thermal DM candidates;
3) The simplest theories to explain the origin of CP-symmetry in strong interactions
4) Candidates to explain the origin of neutrino masses and the matter/anti-matter asymmetry in the Universe;

and:

Candidates to address the electro-weak hierarchy problem, possible answers to the flavor puzzle, answers to many astrophysical anomalies,…..

What FIPs can provide us: A notable example

1) Thermal DM candidates that extend the WIMP paradigm in the MeV-GeV range
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and:

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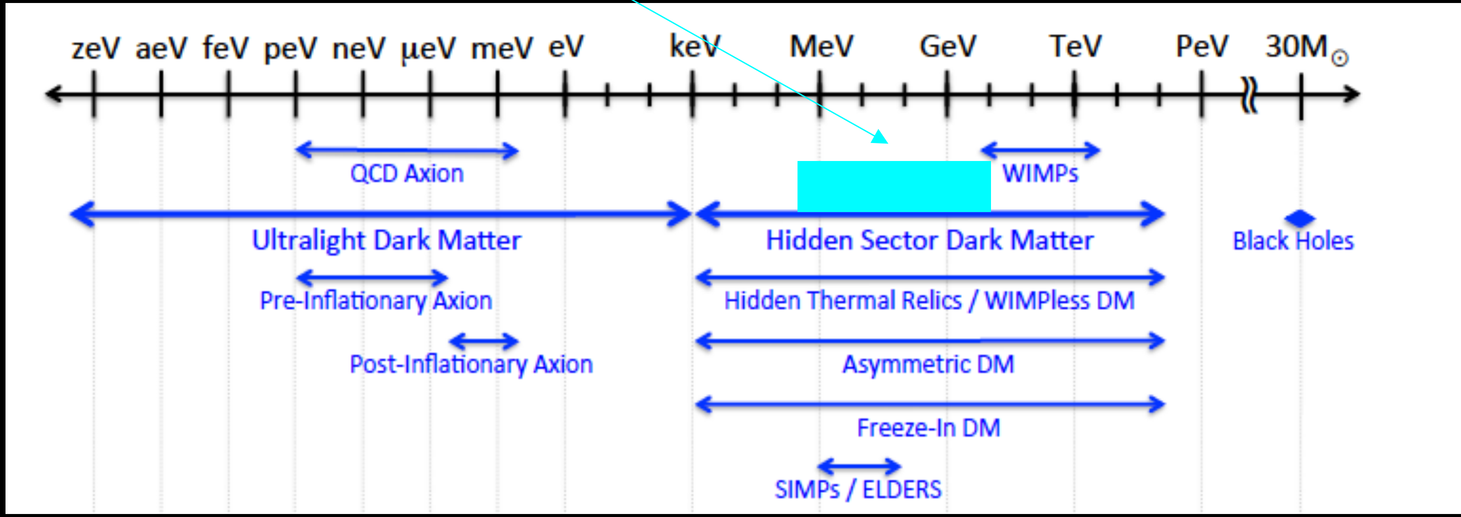
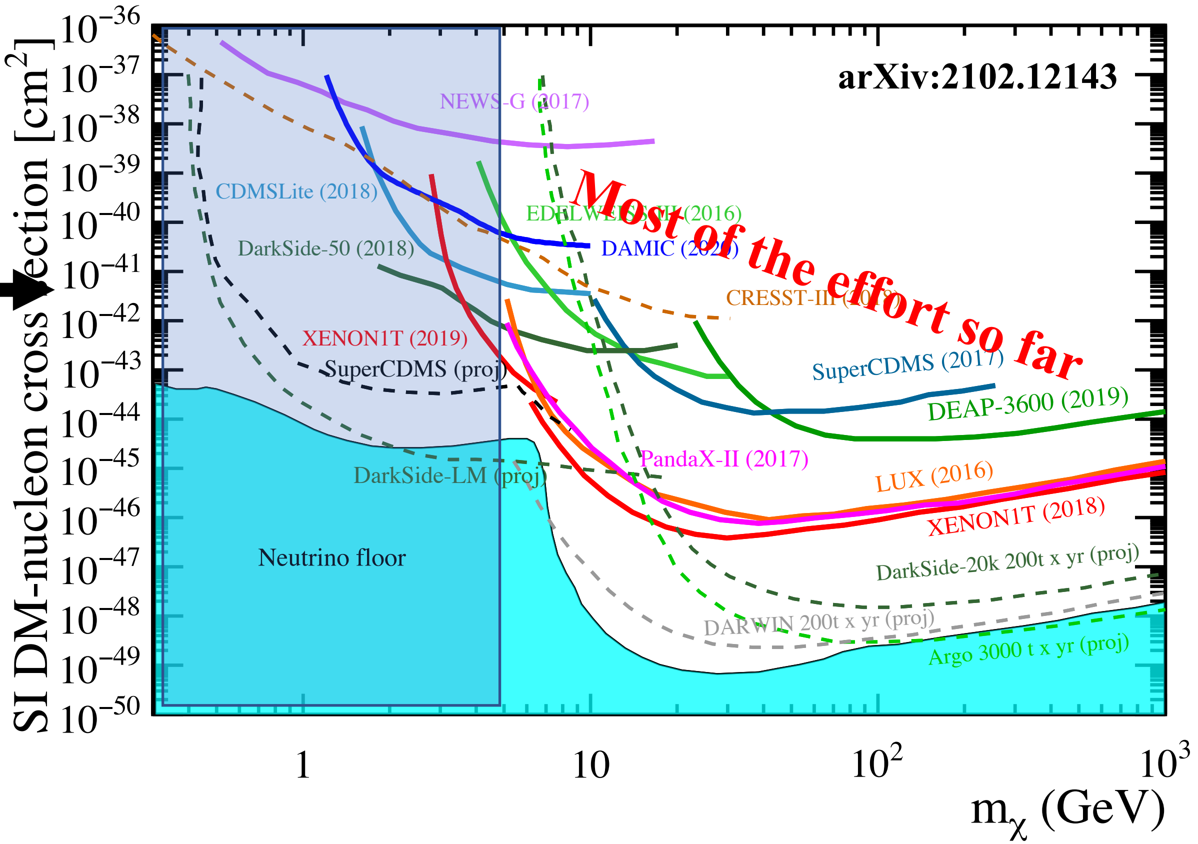
DM available mass range
~ 80 orders of magnitude..



Cosmic Visions, arXiv:1707.04591

Direct Detection DM searches below a few GeV: A vibrant field.

DM in the MeV-GeV range: a blooming field



DM direct detection experiments are pushing the exploration down to the neutrino floor in the MeV-GeV range

MeV-GeV range is accessible also by accelerator-based experiments.

Light DM with thermal origin with a new light Vector Mediator

(with new forces/interactions the Lee-Weinberg bound can be evaded)

Accelerator-based experiments

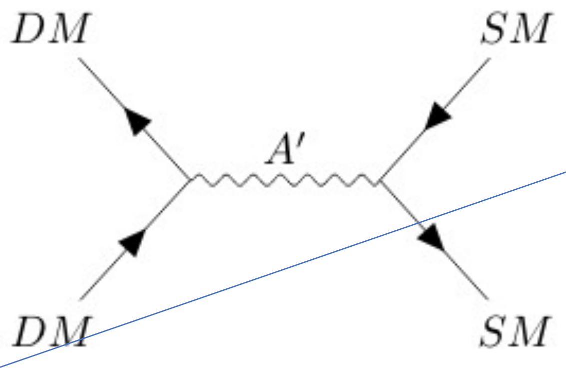
Production of DM at accelerators
(via SM (electron/proton/..) particles)

$$< \sigma v > \sim \alpha_D \varepsilon^2 \alpha \times \frac{m_{\mathrm{DM}}^2}{m_{A'}^4} \times m_{\mathrm{DM}}^2 \times \frac{1}{m_{\mathrm{DM}}^2}$$

y variable

DM Direct detection experiments

DM scattering with e/protons



$$\sigma(DMe^- \to DMe^-) \sim 3.7 \cdot 10^{-27}\mathrm{cm}^2 \times \left(\frac{10\ \mathrm{MeV}}{m_{\mathrm{DM}}}\right)^4 \times y$$

Astroparticle, cosmology

$$\Omega_{\mathrm{DM}} h^2 \sim \frac{10^9\ \mathrm{GeV}^{-1}}{M_{\mathrm{pl}}} \frac{1}{\langle \sigma v \rangle}$$

Direct DM annihilation
(main process to get the thermal relic abundance)

January 2017

In 2017 Maxim and I joined the Physics Beyond Colliders study group put in place by the newly elected CERN General Director Fabiola Gianotti….

Physics Beyond Colliders

Physics Beyond Colliders (PBC) and its mission in 2017-2019

"The PBC is an exploratory study aimed at exploiting the full scientific potential of CERN's accelerator complex and its scientific infrastructure through projects complementary to the LHC, HL-LHC and other possible future colliders. These projects would target fundamental physics questions that are similar in spirit to those addressed by high-energy colliders, but that require different types of beams and experiments"

The PBC allowed us to perform a systematic investigation of the potential of CERN accelerator complex for feebly interacting particles beyond the LHC.

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..

PBC-BSM Report, 1901.09966, J. Phys. G47 (2020) 1

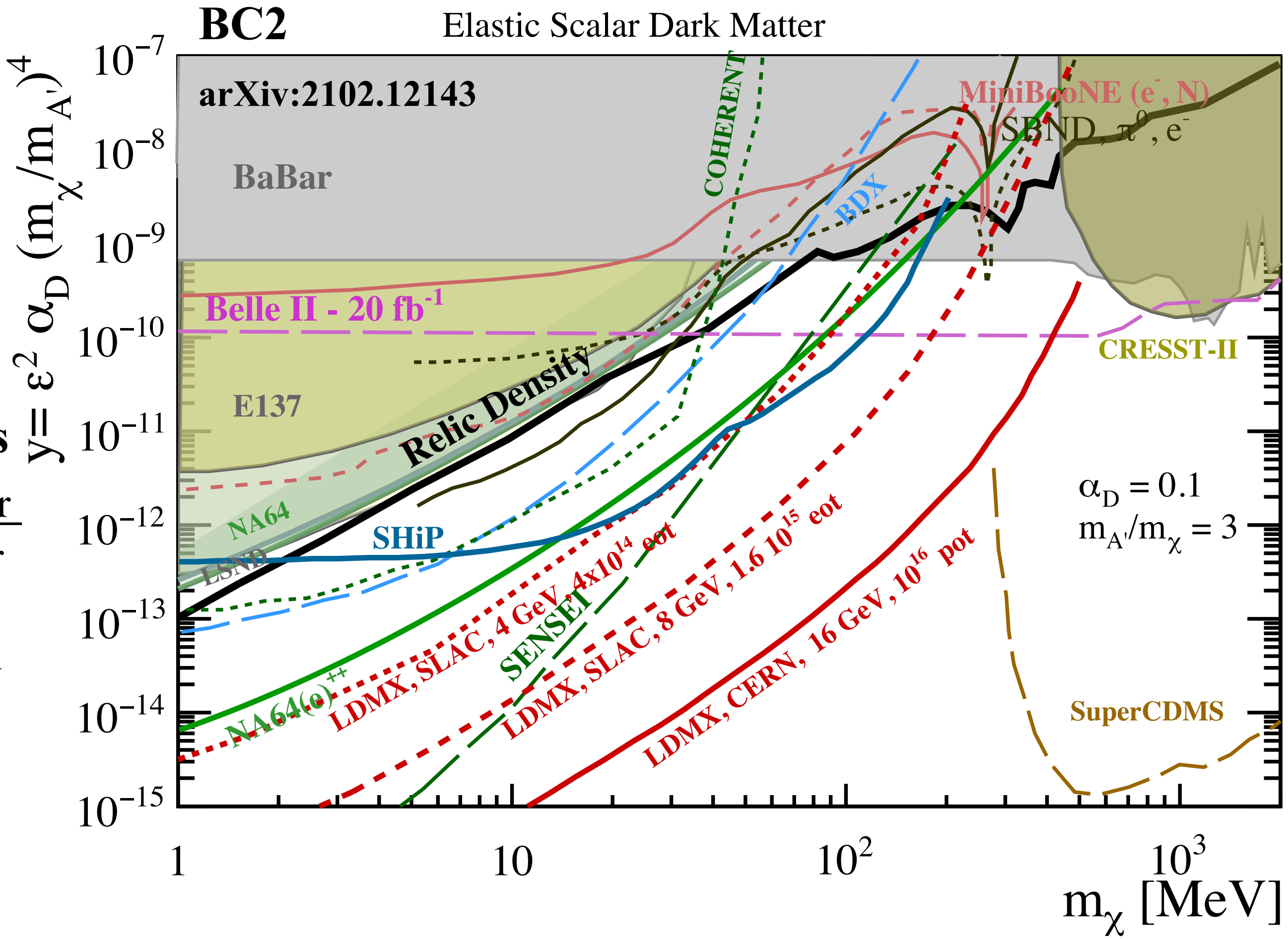
Portal	Coupling
Dark Photon, A_μ	$-\frac{\epsilon}{2\cos\theta_W} F'_{\mu\nu} B^{\mu\nu}$
Dark Higgs, S	$(\mu S + \lambda S^2) H^\dagger H$
Axion, a	$\frac{a}{f_a} F_{\mu\nu} \tilde{F}^{\mu\nu}$, $\frac{a}{f_a} G_{i,\mu\nu} \tilde{G}_i^{\mu\nu}$, $\frac{\delta_\mu a}{f_a} \overline{\psi} \gamma^\mu \gamma^5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

The full set of allowed renormalizable interactions for dark sector with SM, consistent with SM Gauge invariance (plus one notable generalization)

They are representative of broad classes of models:
Each may predict distinct texture of New Physics interactions:
From the portals, the PBC picked up 11 notable benchmark models now widely used

Light DM with thermal origin with a new light Vector Mediator

(with new forces/interactions the Lee-Weinberg bound can be evaded)



CMB-safe annihilations

If the DM is Elastic Scalar the annihilation via vector mediator is in p-wave and the CMB bound is evaded

CERN projects:

NA64^{++}(e), NA64(μ), NA62,…

Worldwide landscape:

- Accelerator-based:
  Belle-II, BDX, SBND, MiniBooNE, LDMX,…
- Direct Detection:
  CRESST-II, SuperCDMS, SENSEI..

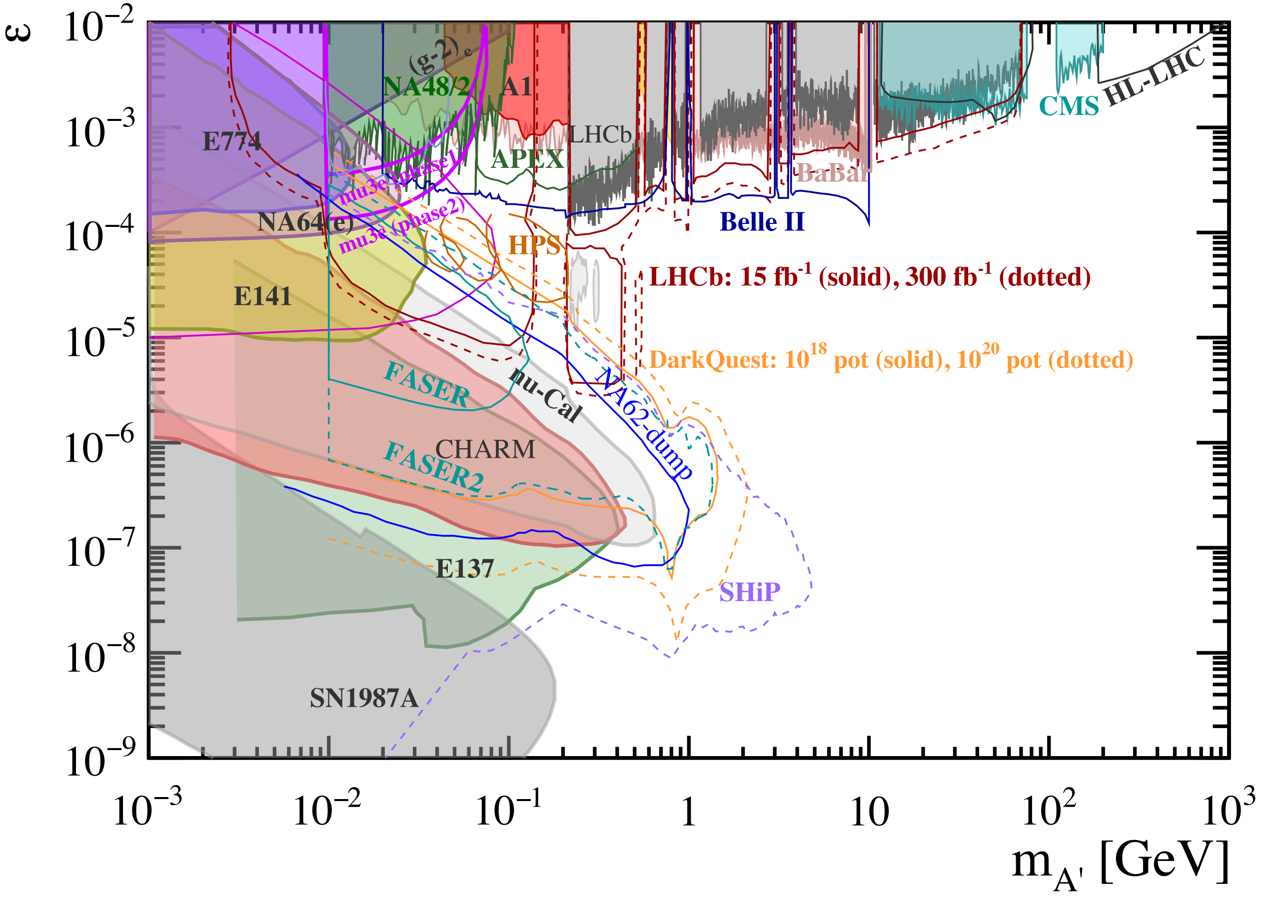
Major Labs involved:

CERN, KEK, JLAB, FNAL, SLAC, SNOLAB, Gran Sasso,…

Within this model accelerator-based results can be directly compared with DD:
Natural synergy between accelerator-based and direct detection experiments.

Light DM with thermal origin with a new light Vector Mediator (if the M(med) < 2 M(DM))

BC1

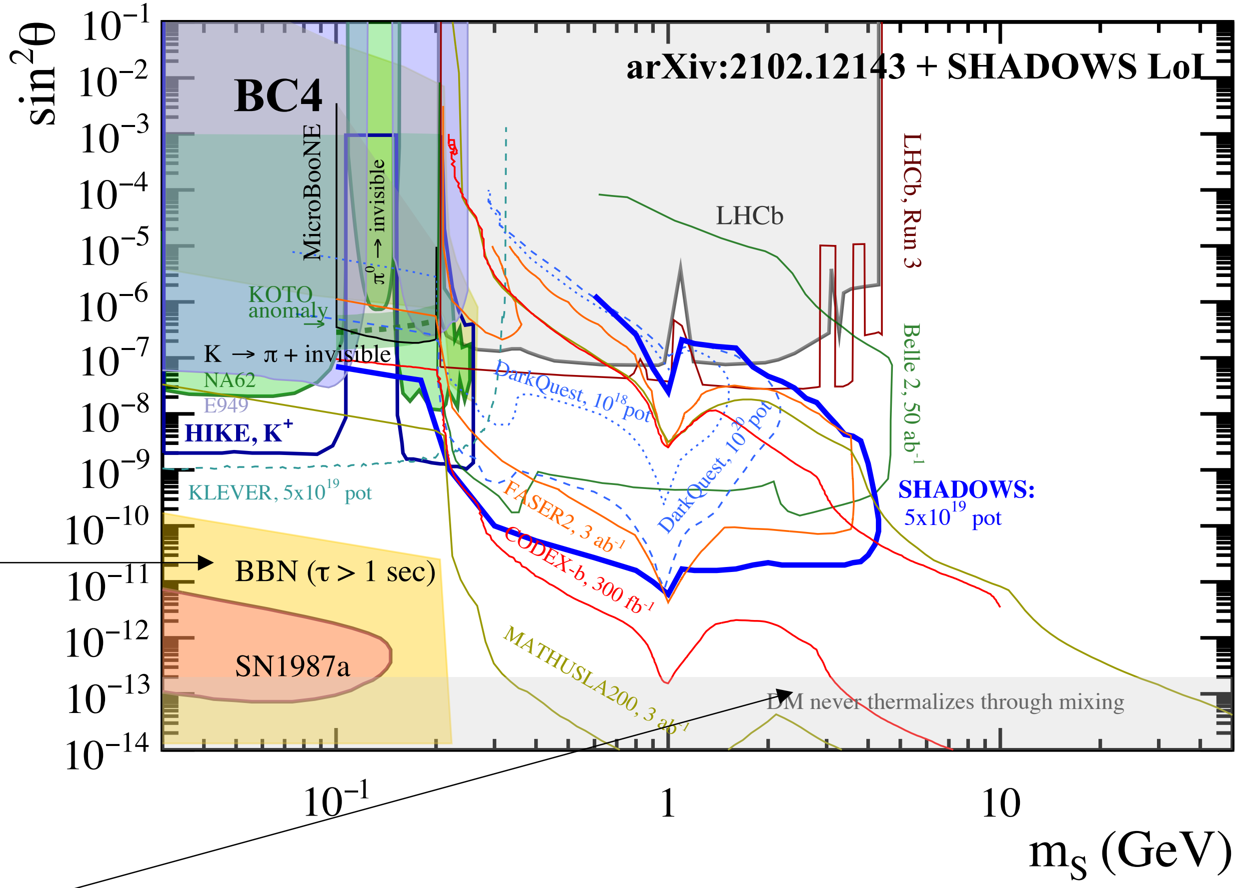


If M(mediator) < 2 M(DM) then the mediator goes back to SM particles:

An example: Light DM as a product of secluded annihilation via light feebly-interacting scalars

a simple but UV complete model, fully compliant with astroparticle & cosmology

The process $\chi\chi \rightarrow$ h1 h1 $\rightarrow$ SM SM SM SM is allowed
(even if the connection with the thermal relic density is lost).



Astroparticle,
Cosmology
(SN 1987A, BBN)

Lower bound in coupling strength if DM is a thermal relic….

CERN projects:

SHADOWS, HIKE, FASER2, LHCb, CODEX-b, SHiP, MATHUSLA,..

Worldwide landscape:

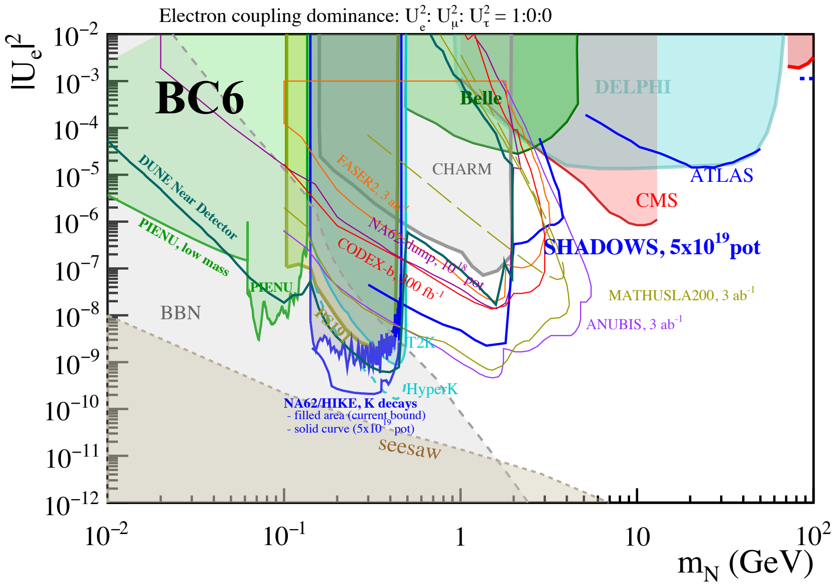
MicroBooNE, KOTO, DarkQuest, Belle-II, …

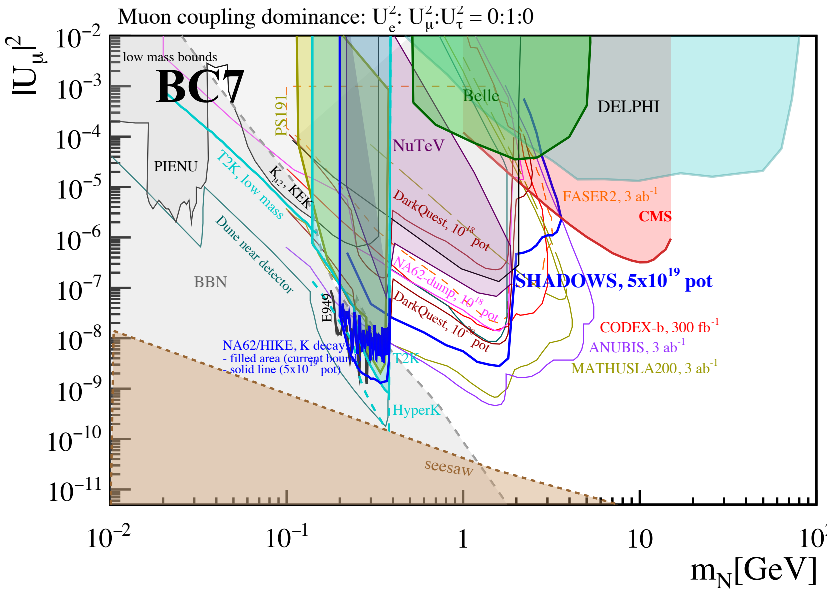
Main LABs involved:

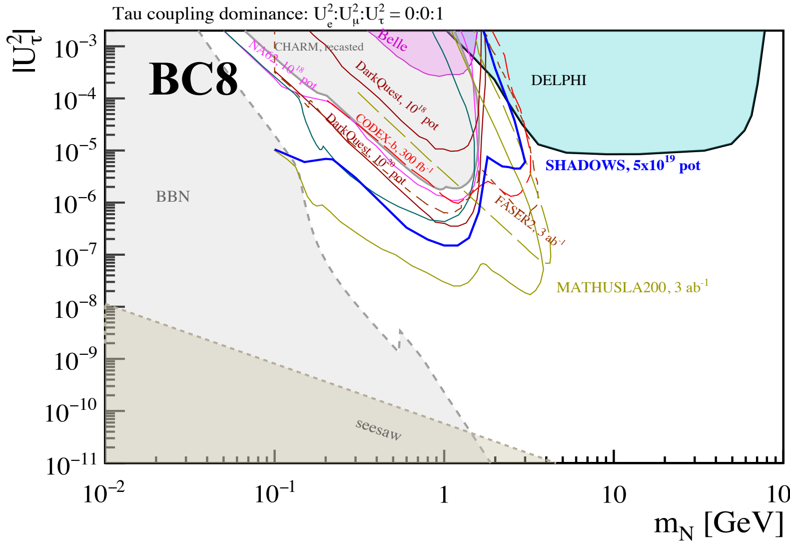
CERN, KEK, JPARC, FNAL,…

Another example: Heavy Neutral Leptons as Heavy Neutrinos?

current worldwide experimental status - couplings to the three lepton generations







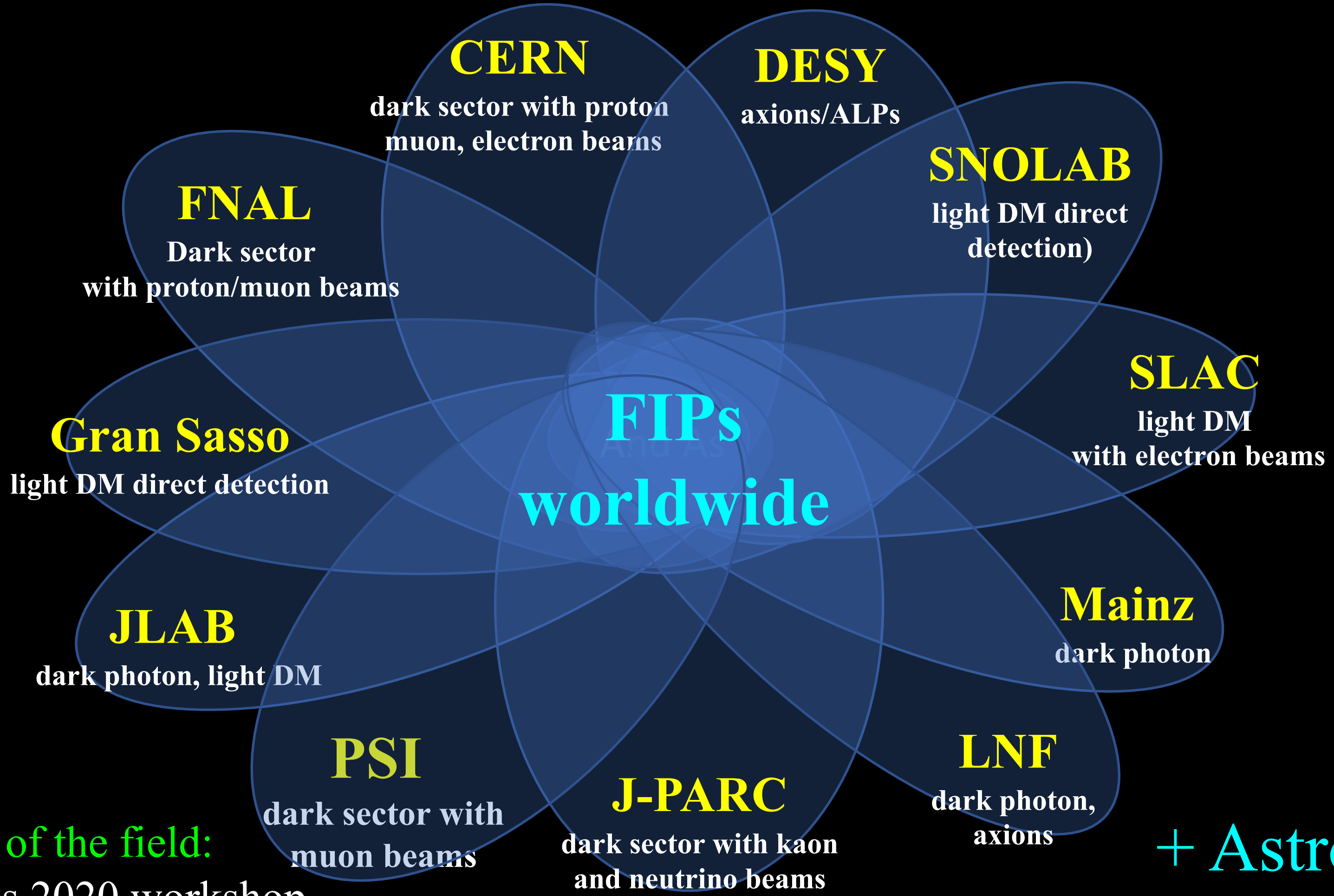
CERN experiments/projects: CODEX-b, FASER(2), MATHUSLA, SHiP, NA62/HIKE, SHADOWS, LHCb, ATLAS, CMS, …

Worldwide landscape: T2K, Belle-II, DarkQuest, DUNE near detectors, …

Labs involved: CERN, KEK, JPARC, FNAL, …

Systematizing models also focused experimental activity, and allowed to obtain new results using old data, + incorporated brand new experimental results…

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



+ Astroparticle, cosmology

For a recent overview of the field:

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

December 2018

The Physics Beyond Colliders BSM WG Report

arXiv:1901.009966, *J.Phys.G* 47 (2020) 1, 010501
372 citations to date (1 citation every 3 days since 3 years):

A report containing the results and future perspectives for searching for FIPs in the coming decade was prepared and submitted to the ESPP. →

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

Physics Beyond Colliders

CERN-PBC-REPORT-2018-007

arXiv:1901.09966v2 [hep-ex] 2 Mar 2019

Physics Beyond Colliders at CERN
Beyond the Standard Model Working Group Report

J. Beacham[1], C. Burrage[2,*], D. Curtin[3], A. De Roeck[4], J. Evans[5], J. L. Feng[6], C. Gatto[7], S. Gninenko[8], A. Hartin[9], I. Irastorza[10], J. Jaeckel[11], K. Jungmann[12,*], K. Kirch[13,*], F. Kling[6], S. Knapen[14], M. Lamont[4], G. Lanfranchi[4,15,*,**], C. Lazzeroni[16], A. Lindner[17], F. Martinez-Vidal[18], M. Moulson[15], N. Neri[19], M. Papucci[4,20], I. Pedraza[21], K. Petridis[22], M. Pospelov[23,*], A. Rozanov[24,*], G. Ruoso[25,*], P. Schuster[26], Y. Semertzidis[27], T. Spadaro[15], C. Vallée[24], and G. Wilkinson[28].

Abstract: The Physics Beyond Colliders initiative is an exploratory study aimed at exploiting the full scientific potential of the CERN's accelerator complex and scientific infrastructures through projects complementary to the LHC and other possible future colliders. These projects will target fundamental physics questions in modern particle physics. This document presents the status of the proposals presented in the framework of the Beyond Standard Model physics working group, and explore their physics reach and the impact that CERN could have in the next 10-20 years on the international landscape.

* PBC-BSM Coordinators and Editors of this Report
** Corresponding Author: Gaia.Lanfranchi@lnf.infn.it

The impact of this Report was immediate: after 3 weeks I was invited by Gian Giudice (CERN TH Head) to join the BSM group for the preparation of the Physics Documents for the upcoming European Strategy for Particle Physics.

May 2019

The BSM group at the Granada Symposium of the ESPP, May 2019

October 2019

The Briefing Book of the European Strategy

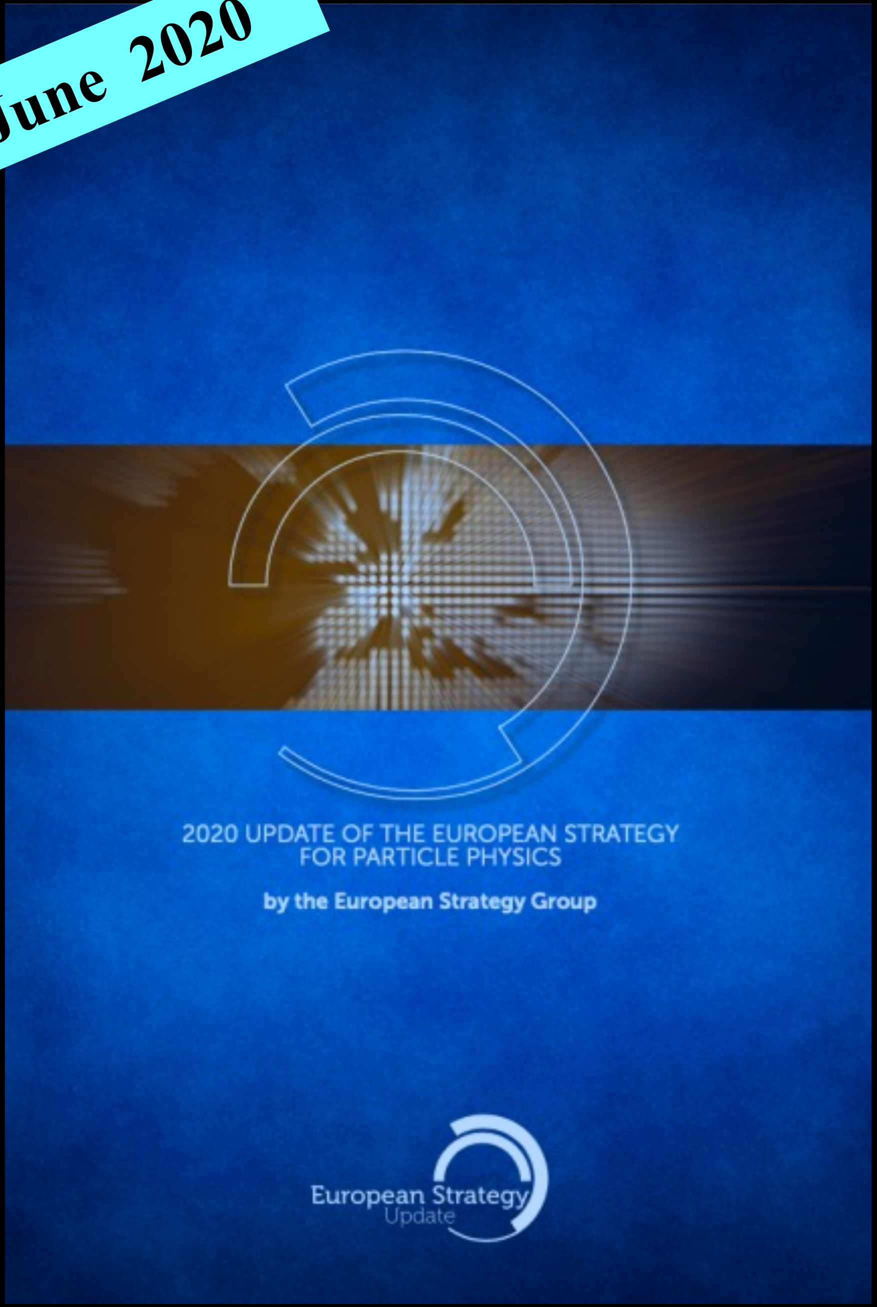
arXiv:1910.11775 , BSM Chapter, p.141

" The absence, so far, of unambiguous signals of new physics from direct searches at the LHC, indirect searches in flavour physics and direct DM detection experiments invigorates the need for broadening the experimental effort in the quest for new physics and in exploring ranges of interaction strengths and masses different from those already covered by existing or planned projects.

While exploration of the high-mass frontier remains an essential target, other research directions have valid theoretical motivations and deserve equal attention.

Feebly-interacting particles (FIPs) represent an alternative paradigm with respect to the traditional BSM physics explored at the LHC. The full investigation of this paradigm over a large range of couplings and masses requires a great variety of experimental facilities."

June 2020



European Strategy for Particle Physics 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

January 2021

Physics Beyond Colliders

General PBC coordinators:
Claude Vallee
Gianluigi Arduini
Joerg Jaeckel

GL & M. Pospelov

ltech/ESA/CXC/STScI

Website: http://cern.ch/pbc

FIP
Physics Centre

Daniel Boer,
Jan Pawlowski,
Gunar Schnell

QCD
Working Group

BSM
Working Group

A. Rozanov,
C. Rembser
F. Kahlhoefer,

Beam Dump Facility

Conventional Beams

LHC – Fixed Target

Technology

PBC-A&T
Committee

Accelerator Complex
Capabilities

Forward Physics Facility

Gamma Factory

Prototype EDM Storage Ring

Civil Eng., Integration,
Radiation Protection

Physics Beyond Colliders

Mikhail Shaposhnikov (HNL)

Gian Francesco Giudice (Head of CERN-TH)

Stefania Gori (Snowmass)

Yevgeni Stadnik (ultra-light FIPs)

Marco Drewes (HNL)

Philip Schuster (extracted beams in US)

Torben Ferber (Belle II)

Albert De Roeck (LLP @ LHC)

Maurizio Giannotti (stars)

FIP Physics Centre

Joerg Jaeckel (axions)

Martin Bauer (ALPs

Silvia Pascoli (HNL)

Gordan Krnjaic (light DM)

Contacts: Maxim Pospelov & GL

Pilar Hernandez (HNL)

Stefan Ulmer (ultra-light FIPs)

Joshua Ruderman (astroparticle

Jocelyn Monroe (DM DD)

James Beacham (LLP @ LHC)

Igor Irastorza (axion physics)

Jessie Shelton (astroparticle)

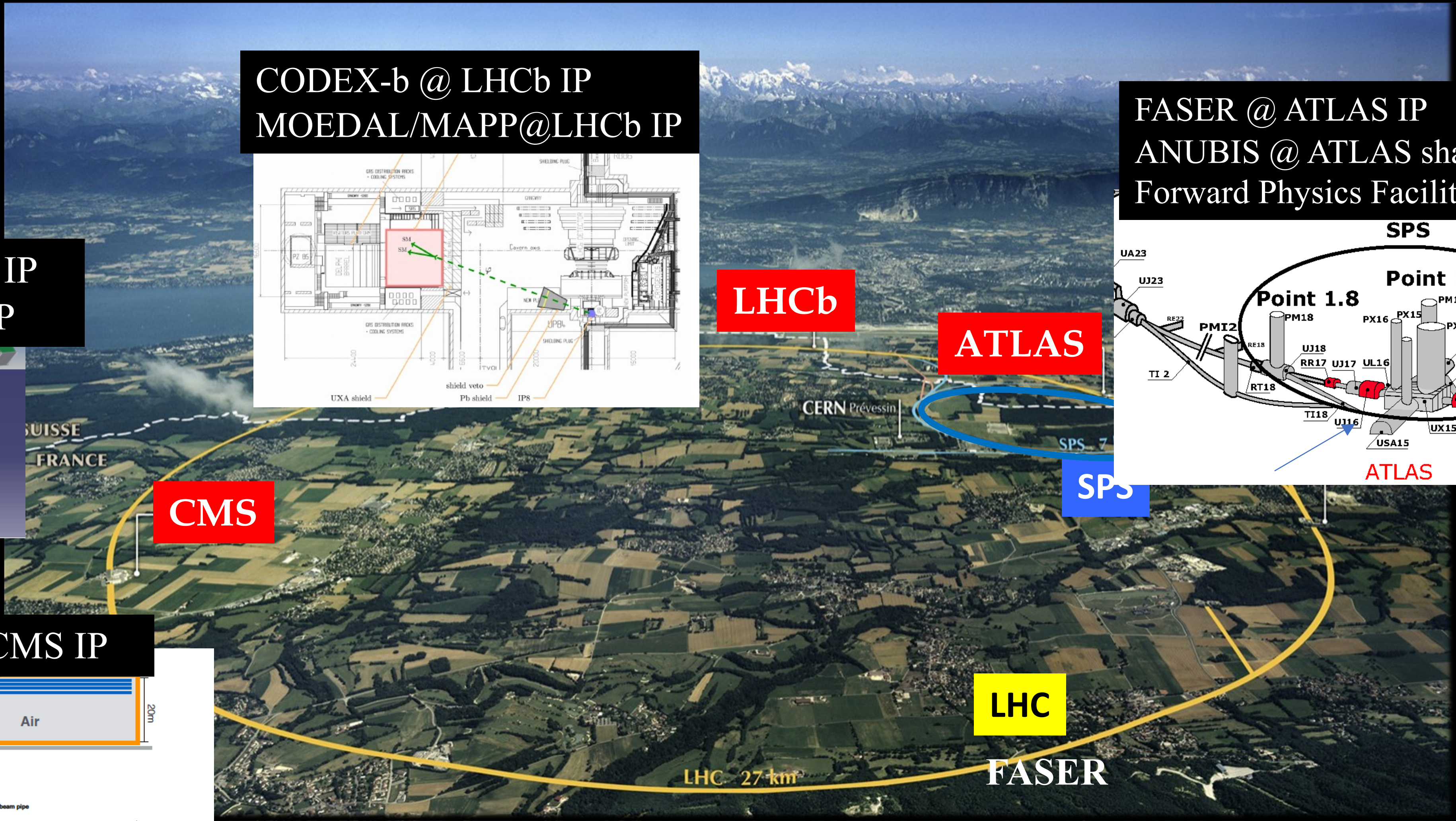
Jacobo Lopez-Pavon (HNL)

Philip Harris (DM LHC WG)

Felix Kahlhoefer (Axions,ALPs,..)

+ one representative per PBC experiment related to FIP physics

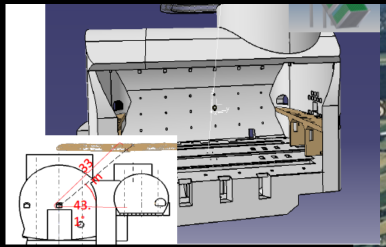
FIPs @ CERN –The Long-Lived Particle detectors at the LHC IPs



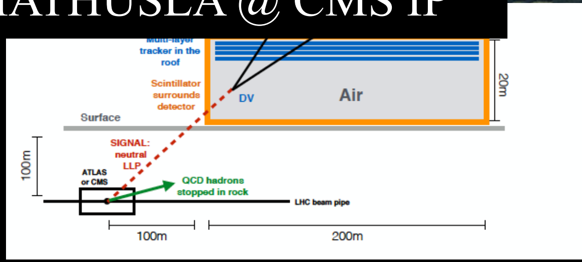
CODEX-b @ LHCb IP
MOEDAL/MAPP@LHCb IP

FASER @ ATLAS IP
ANUBIS @ ATLAS shaft
Forward Physics Facility @ ATLAS IP

MilliQan @ CMS IP
FACET @ CMS IP



MATHUSLA @ CMS IP

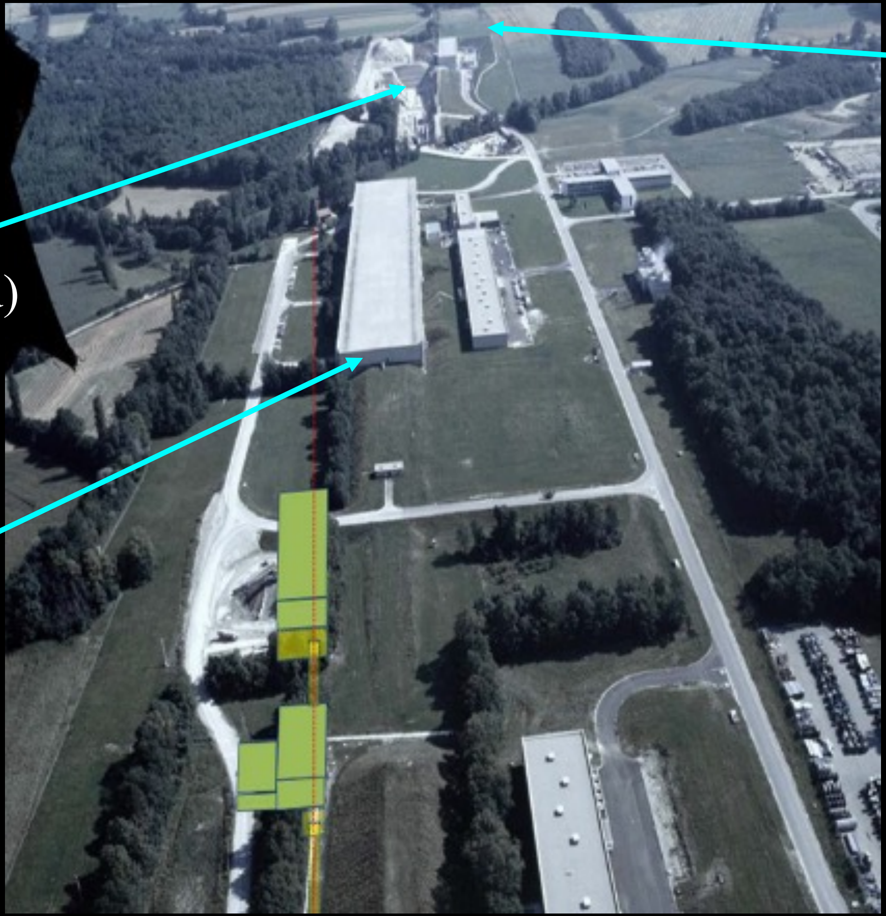


+ an active LLP community inside ATLAS, CMS, and LHCb collaborations

FIPs @ CERN – The North Area: a unique infrastructure…

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

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



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

… to search for FIPs at extracted beam lines

A Hidden Sector Campus.

Physics Beyond Colliders

Experiments/proposals related to FIPs in PBC

FIPs @ CERN

SPS
(MeV- few GeV)

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

SHiP

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

SHADOWS
FIPs @ proton beam dump

Gamma-factory
(mostly ALPs)

(Baby-)IAXO
solar axions

Axions/Dark Photons
(< meV)

VMB
Vacuum birifrangence

proton-EDM

LHC
(few GeV – TeV)

CODEX-b
FIPs @ LHCb IP

ANUBIS
(FIPs @ ATLAS shaft)

MATHUSLA
FIPs @ CMS IP

Forward Physics Facility (FASER2, …)

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

AION
FIPs with atom interferometer

nTOF

Nuclear astrophysics

ISOLDE

AD
FIPs @ anti-proton decelerator

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

Jan-Dec 2022

3. The SHADOWS experiment at CERN

Design, physics reach, challenges, technology options, status, and next steps.

Expression of Interest - CERN-SPSC-2022-006 ; SPSC-EOI-022 and arXiv:2110.080025
Letter of Intent – CERN-SPSC-2022-030; SPSC-I-256

What is SHADOWS?

[Search for Hidden And Dark Objects With the SPS]

SHADOWS is a newly proposed proton beam dump experiment
to search for feebly-interacting particles (FIPs)
emerging from charm and beauty decays.

Where is SHADOWS?

the CERN North Area (Prevessin zone)

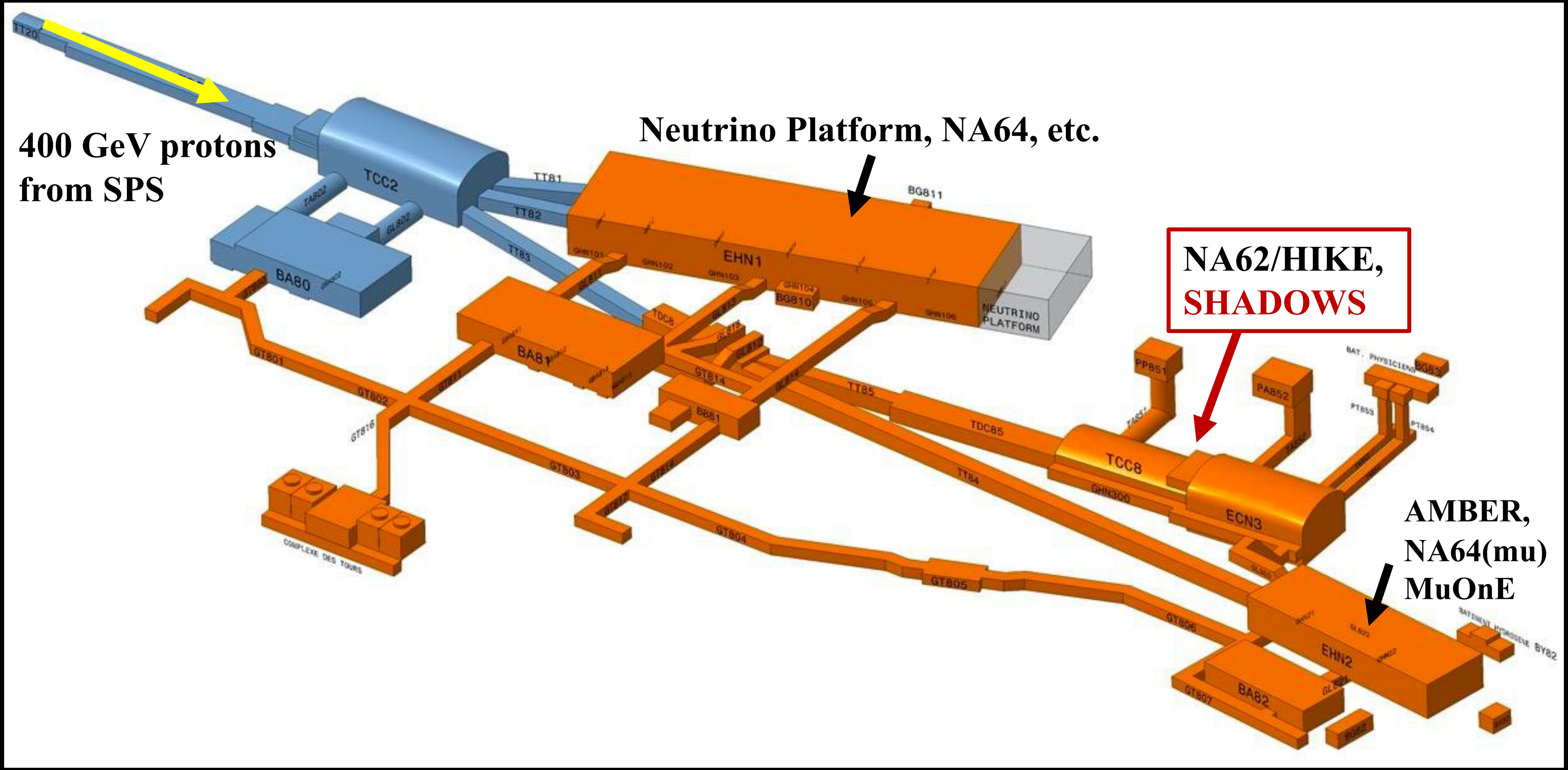
ECN3:
P42/K12: 400 GeV p beam
up to 3x10^{18} pot/year (now)
→ **NA62**
up to ~1.2 x 10^{19} pot/year
→ **HIKE, SHADOWS, SHiP**

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

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

Where is SHADOWS?

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 3×10^{12} ppp with 3.3s pulse duration: ~ 10^{12} pot/sec, up to 2×10^{18} pot/year

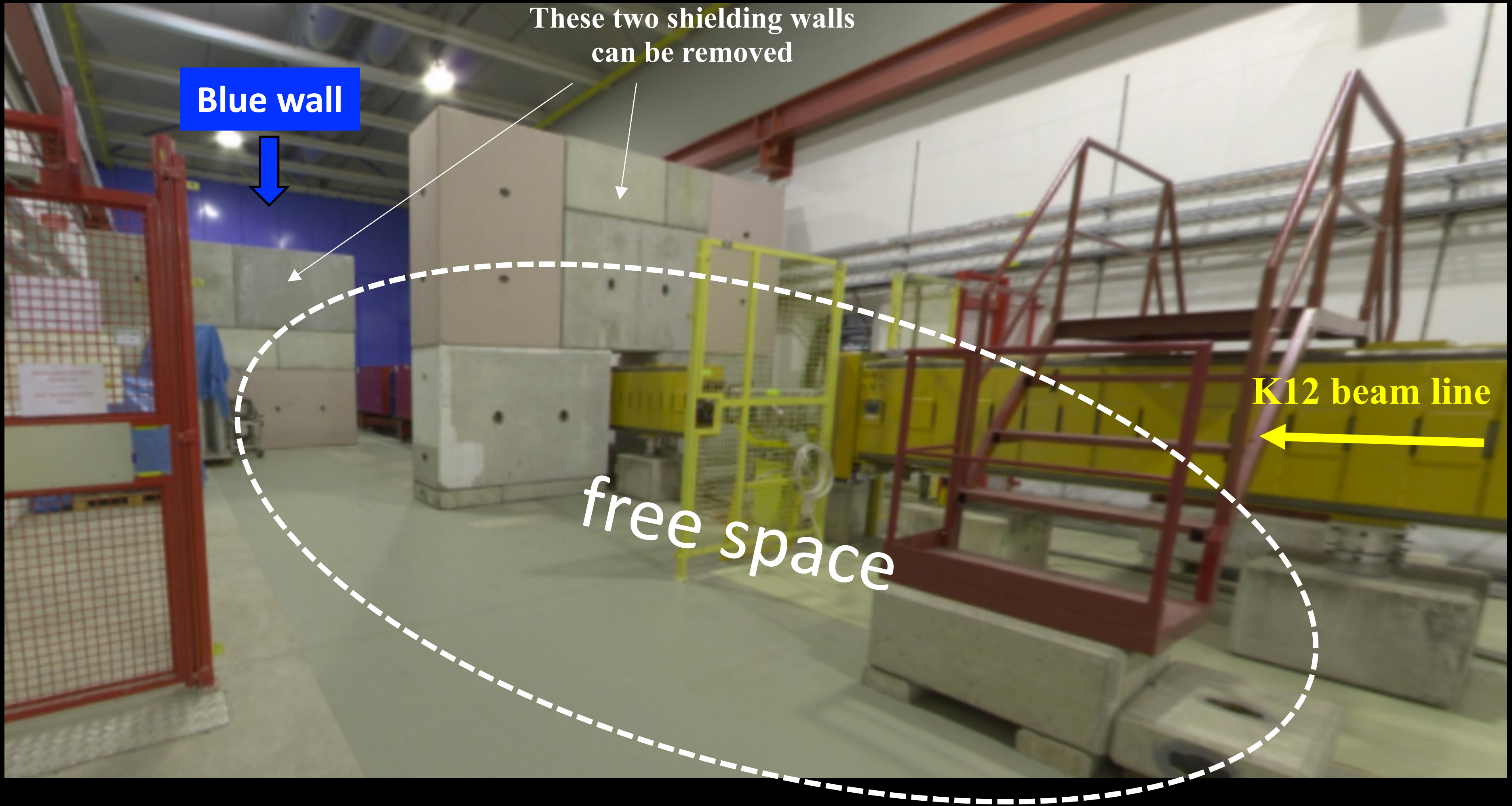
- ✓ **K12 beam intensity proposed to be increased by a factor x 7**
  - for high intensity K beams, NA62-DUMP and SHADOWS → up to $1.2 * 10^{19}$ pot/year

SHADOWS can collect 5×10^{19} protons on target in ~4 years of data taking

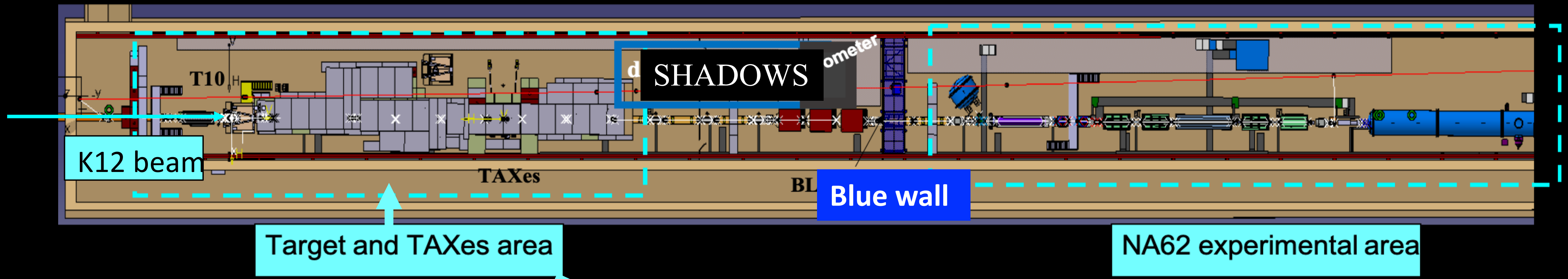

NA62 in ECN3
Blue wall
Beam
~ 150 m

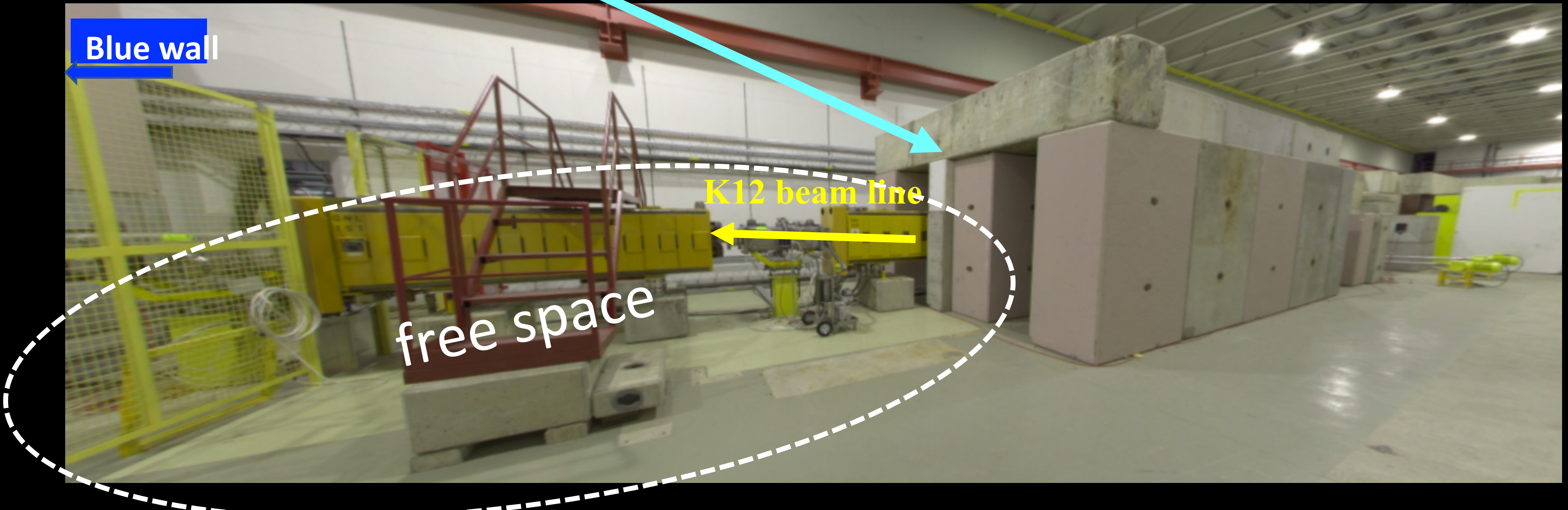
SHADOWS in ECN3

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

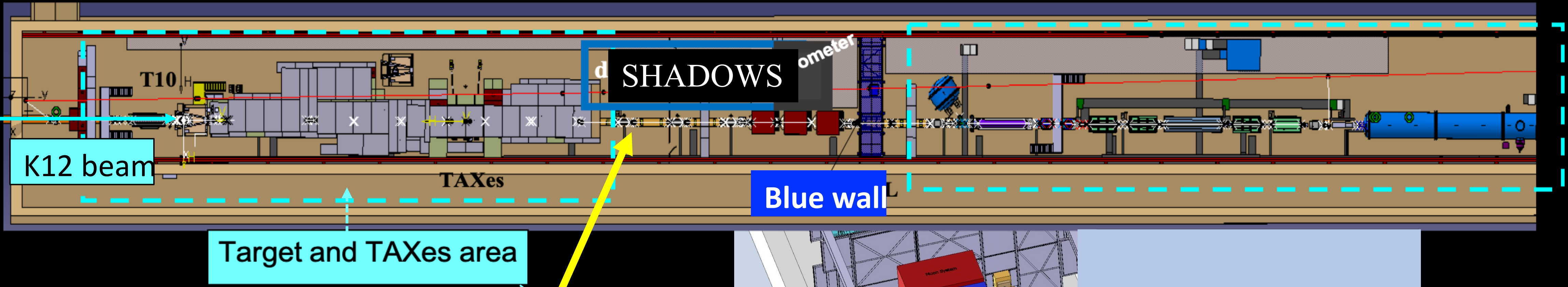


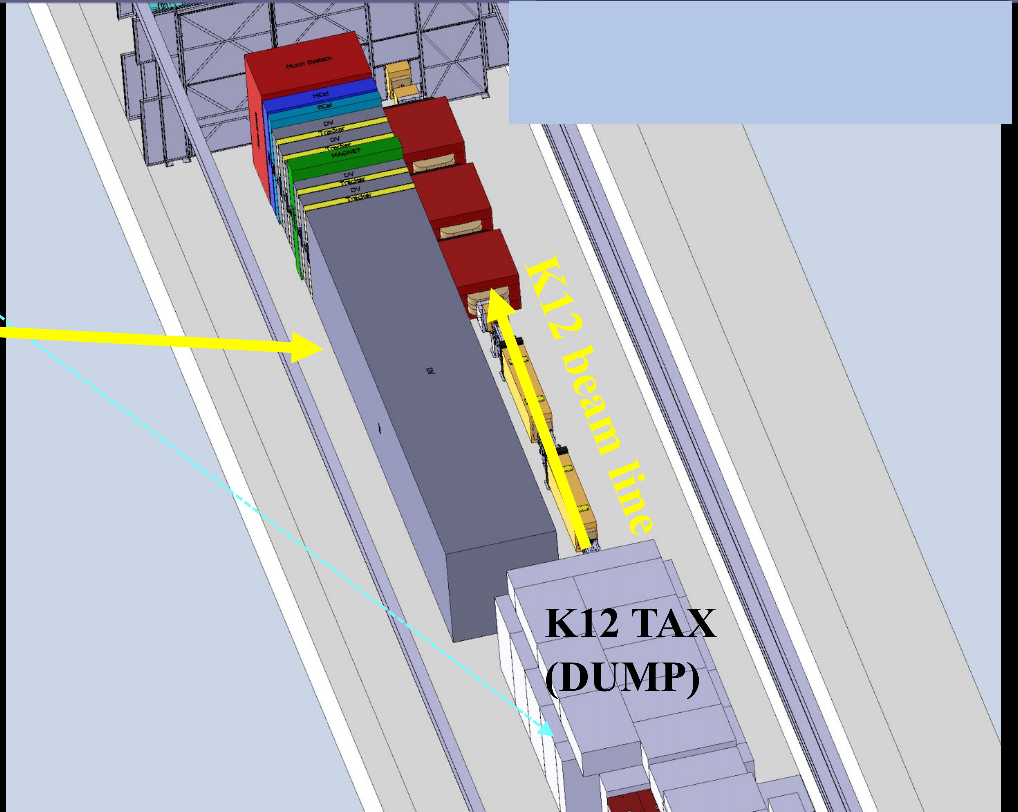
SHADOWS in ECN3





SHADOWS in ECN3

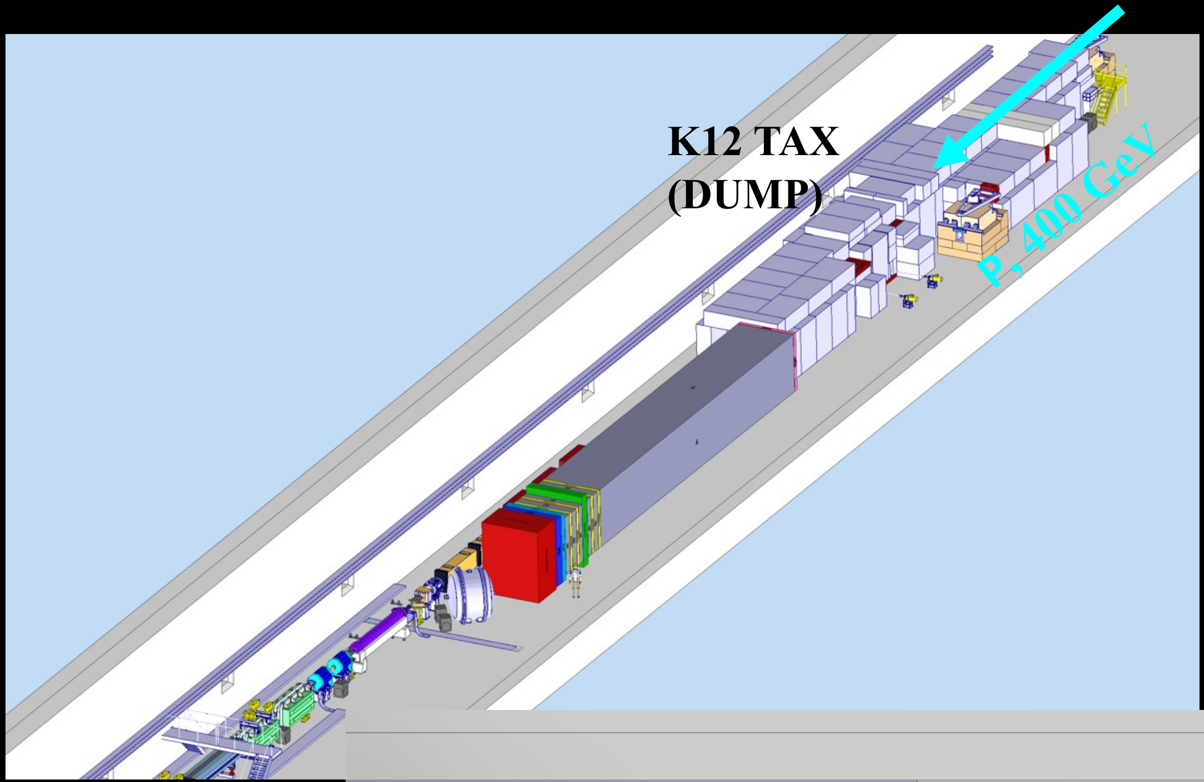




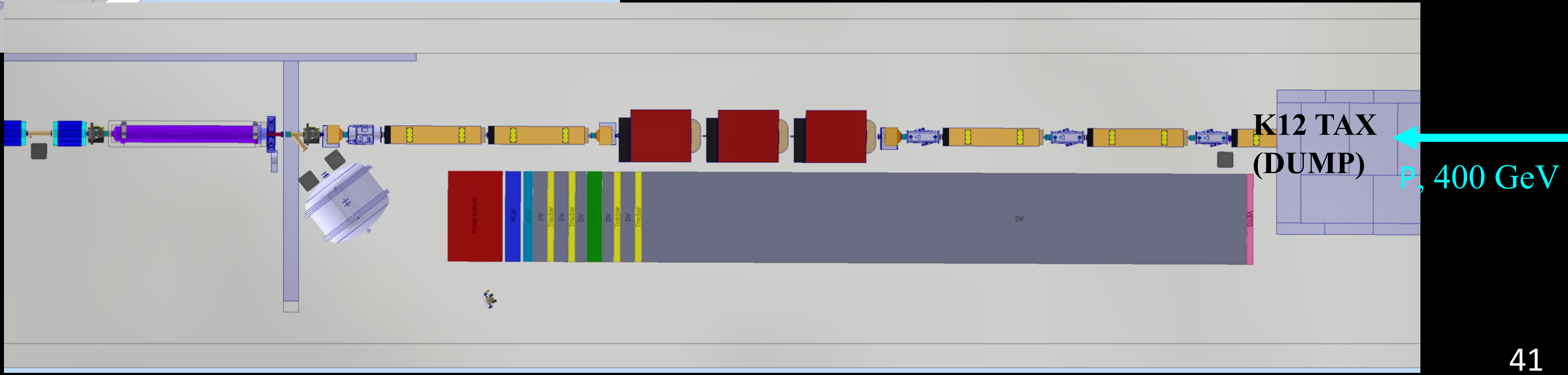
<u>Preliminary Conceptual Layout</u>

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

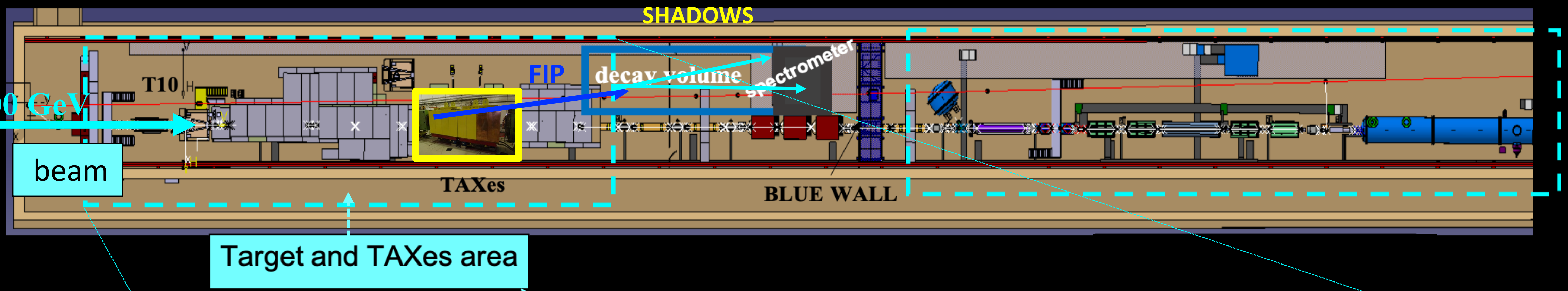
SHADOWS in ECN3



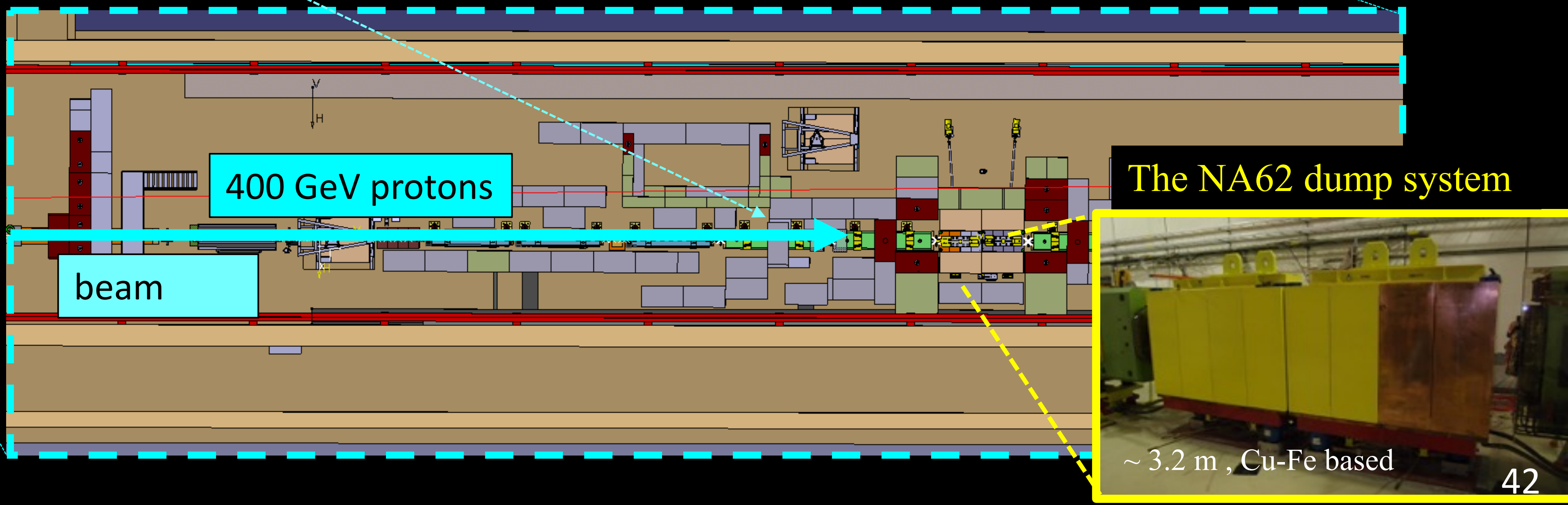
<u>SHADOWS detector components:</u>
20 m long, in vacuum decay volume,
Muon Veto, Tracking System with a (warm) dipole magnet,
Timing layer, Electro-magnetic calorimeter,
Iron filter and four Muon Stations.
Transversal size: 2.5x2.5 m^2.



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

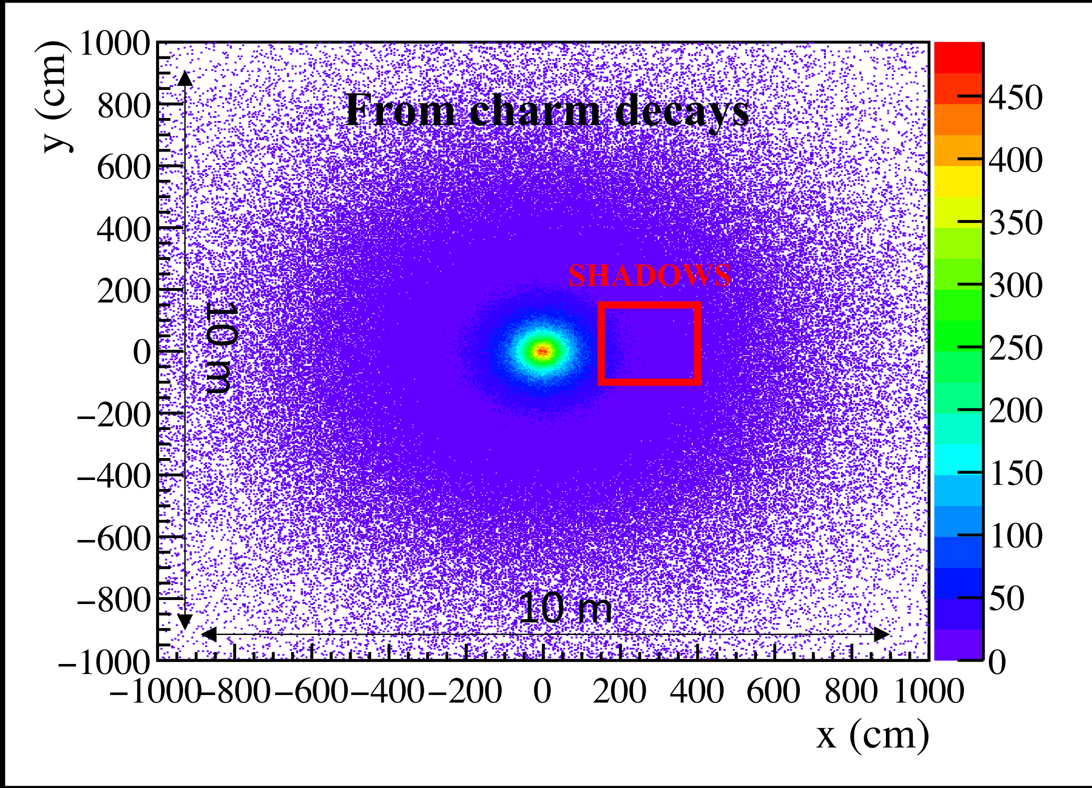


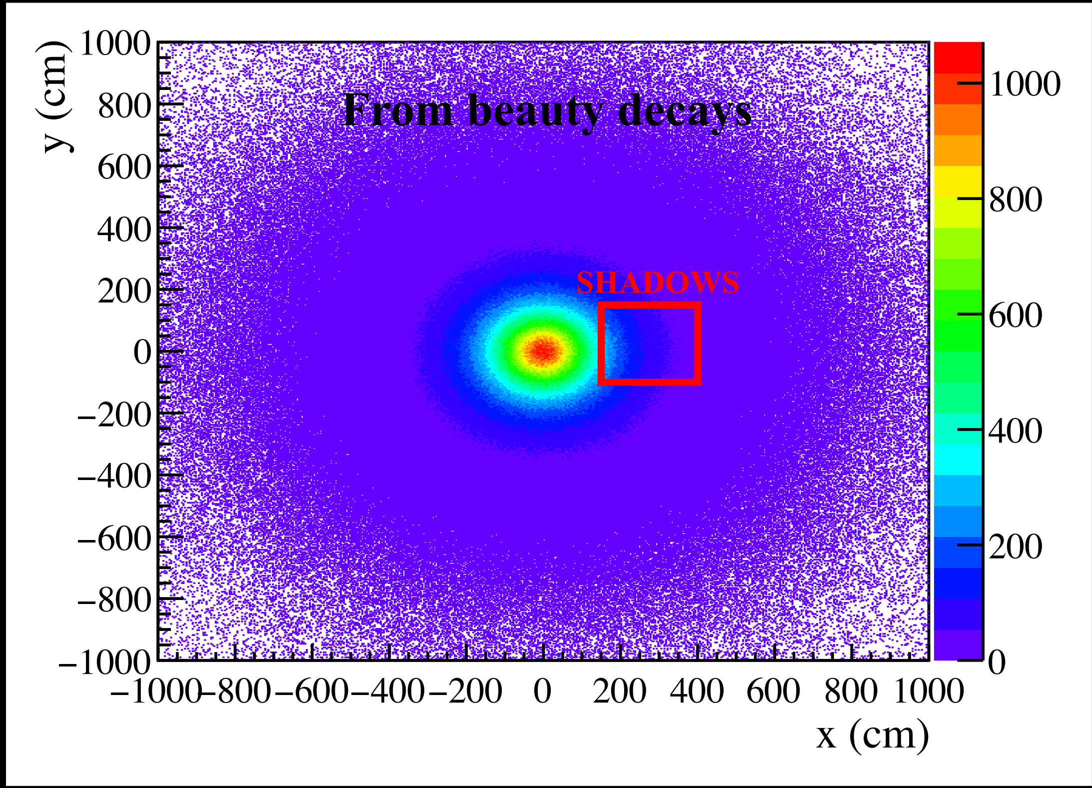
T10 target is lifted and the 400 GeV primary p beam is sent onto the dump



Why "off-axis" works: Signal

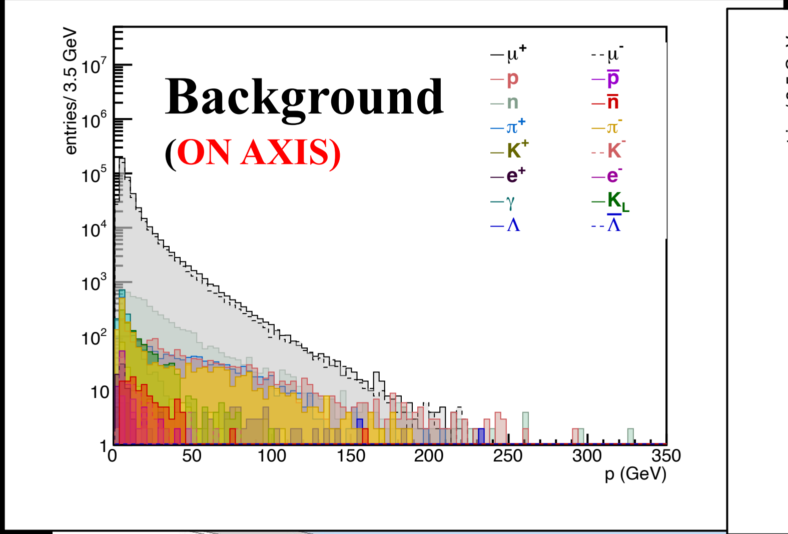
HNL→ **πμ** illumination @ first SHADOWS tracking station

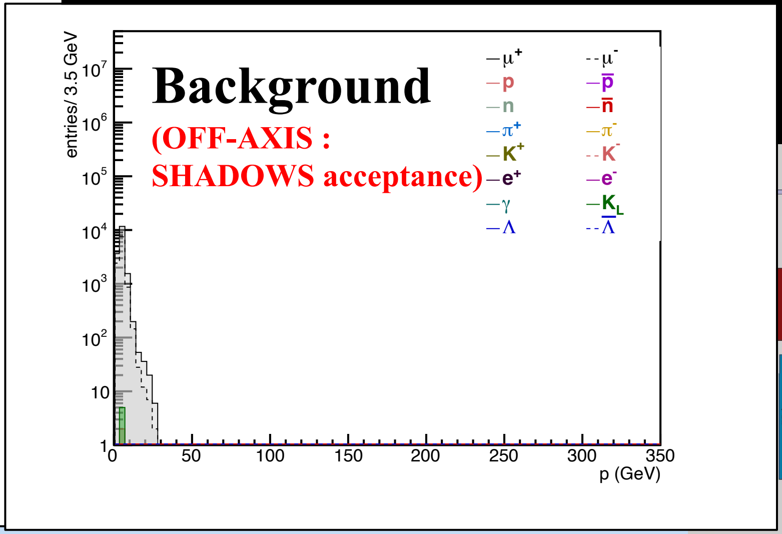


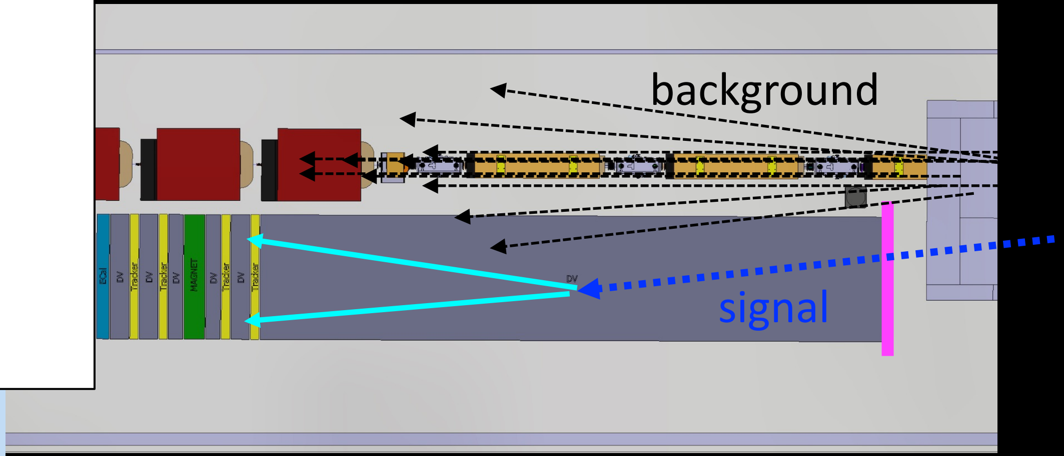


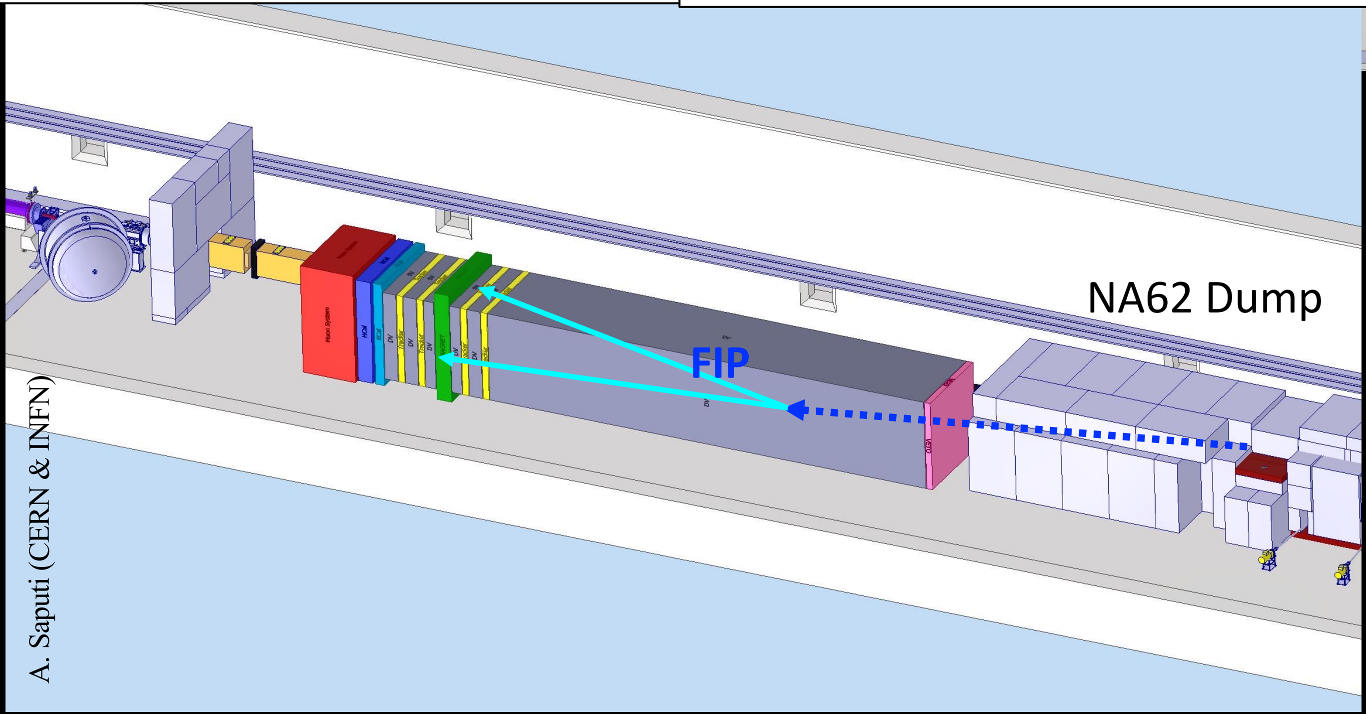
FIPs emerging from charm and beauty decays (HNLs, dark scalars, ALPs,…)
at the SPS energy are produced with a large polar angle

Why "off-axis" works: Background









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

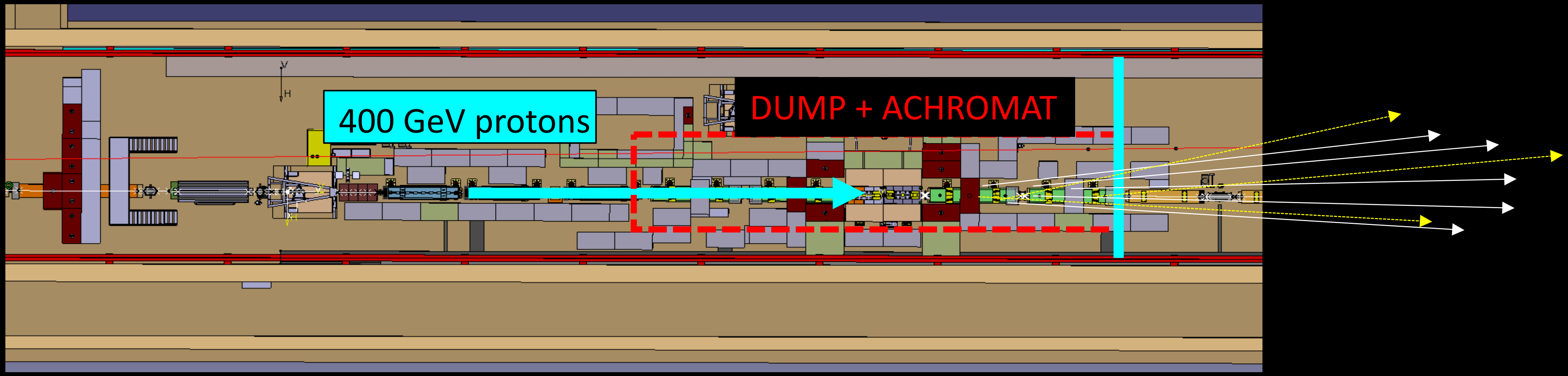
SHADOWS Main Idea: Stay close & stay off-axis!

- Stay close to the dump:
  to maximise acceptance for signals with a relatively small detector

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

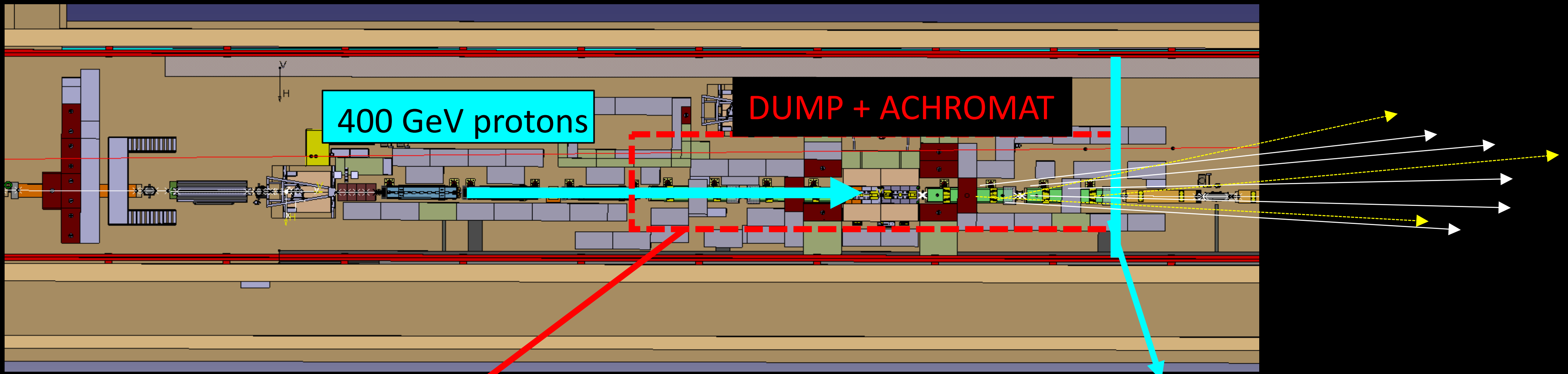
The beam-induced background:
the name of the game

Beam-induced background after the dump



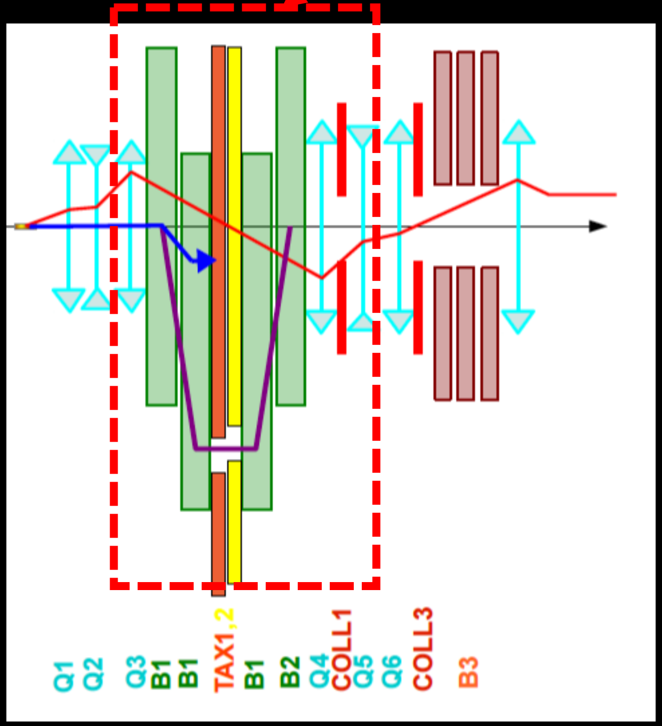
- Muons
- neutrinos

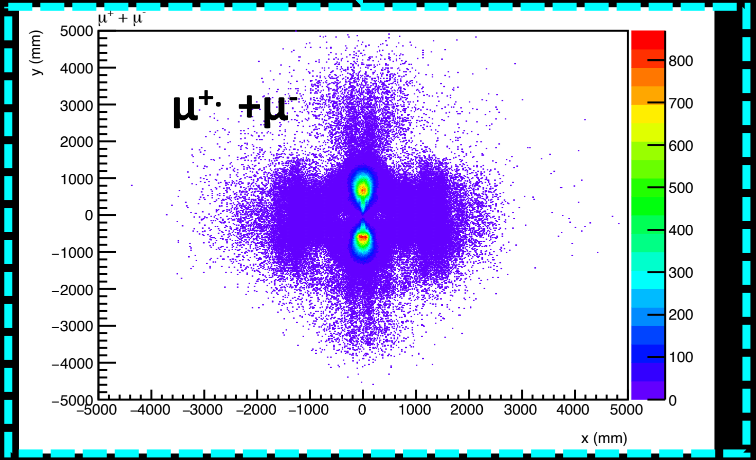
Beam-induced background after the dump



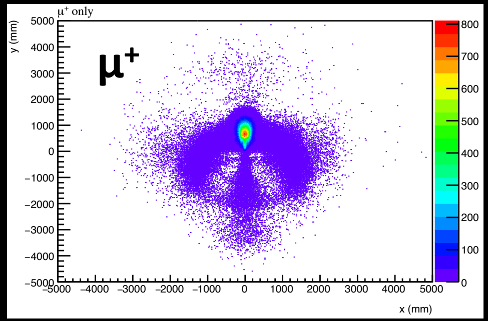
- Muons
- neutrinos

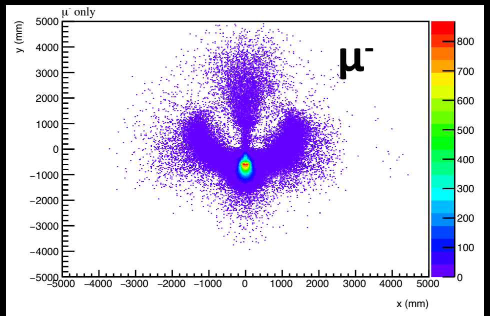
Layout of the beamline around the dump



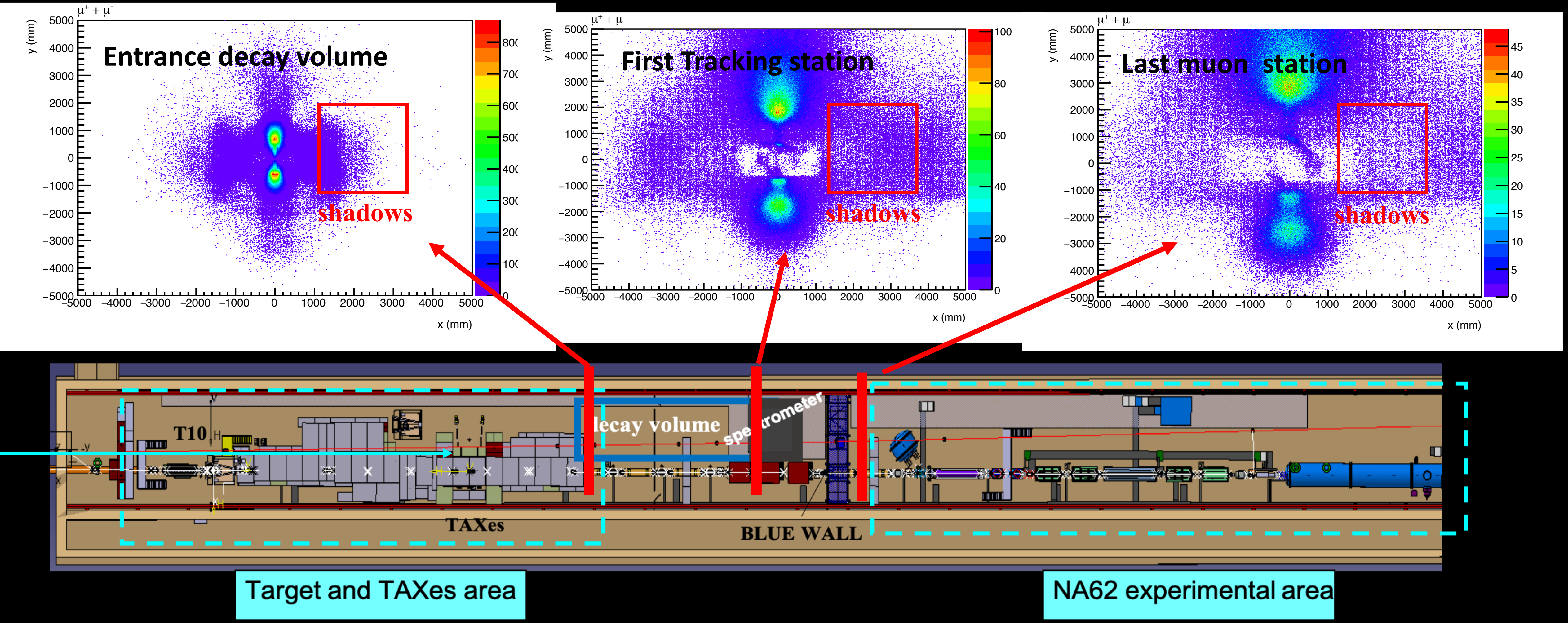


Muon illumination after the dump

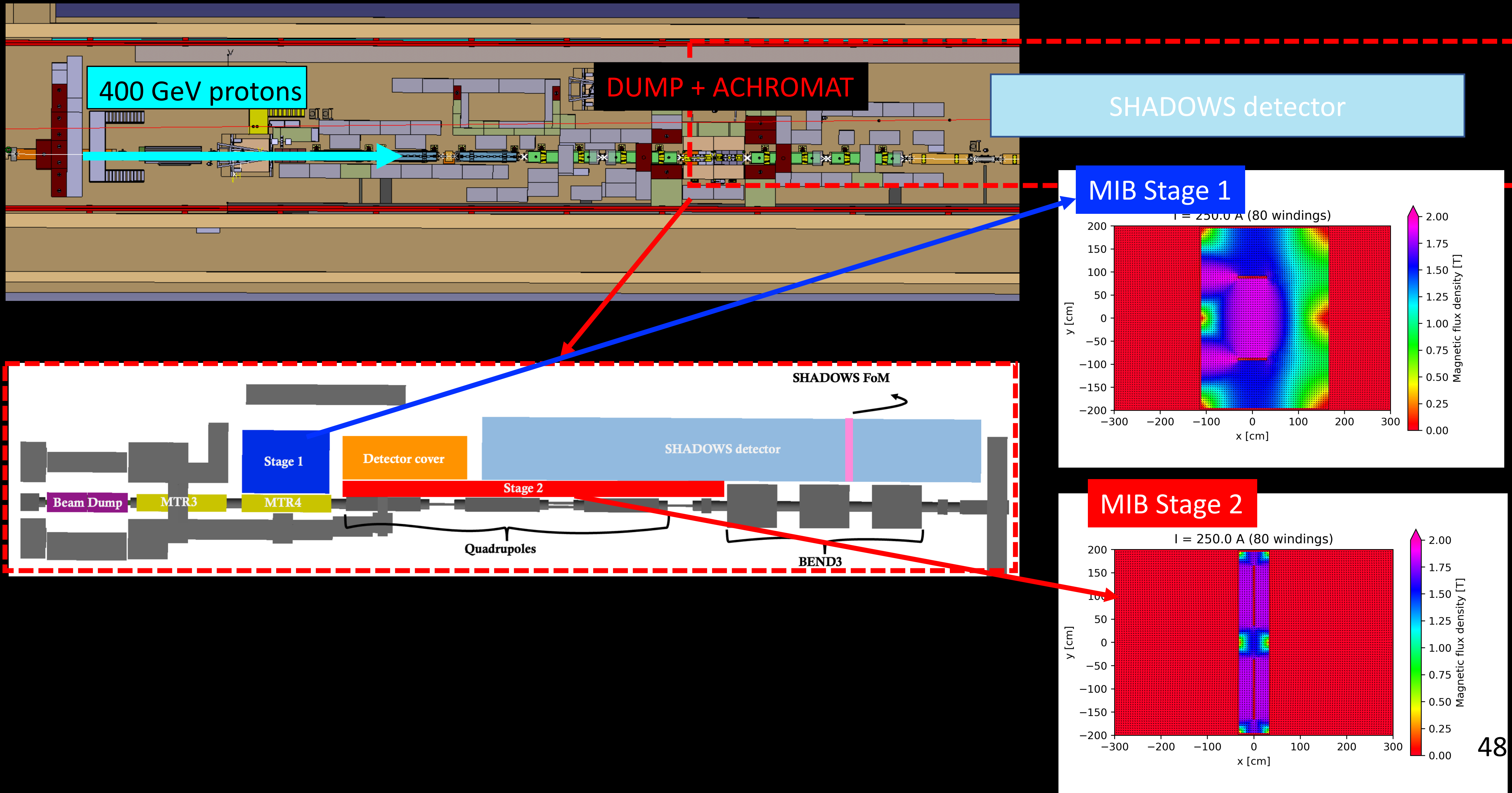




Muon illumination as a function of the position along the beamline

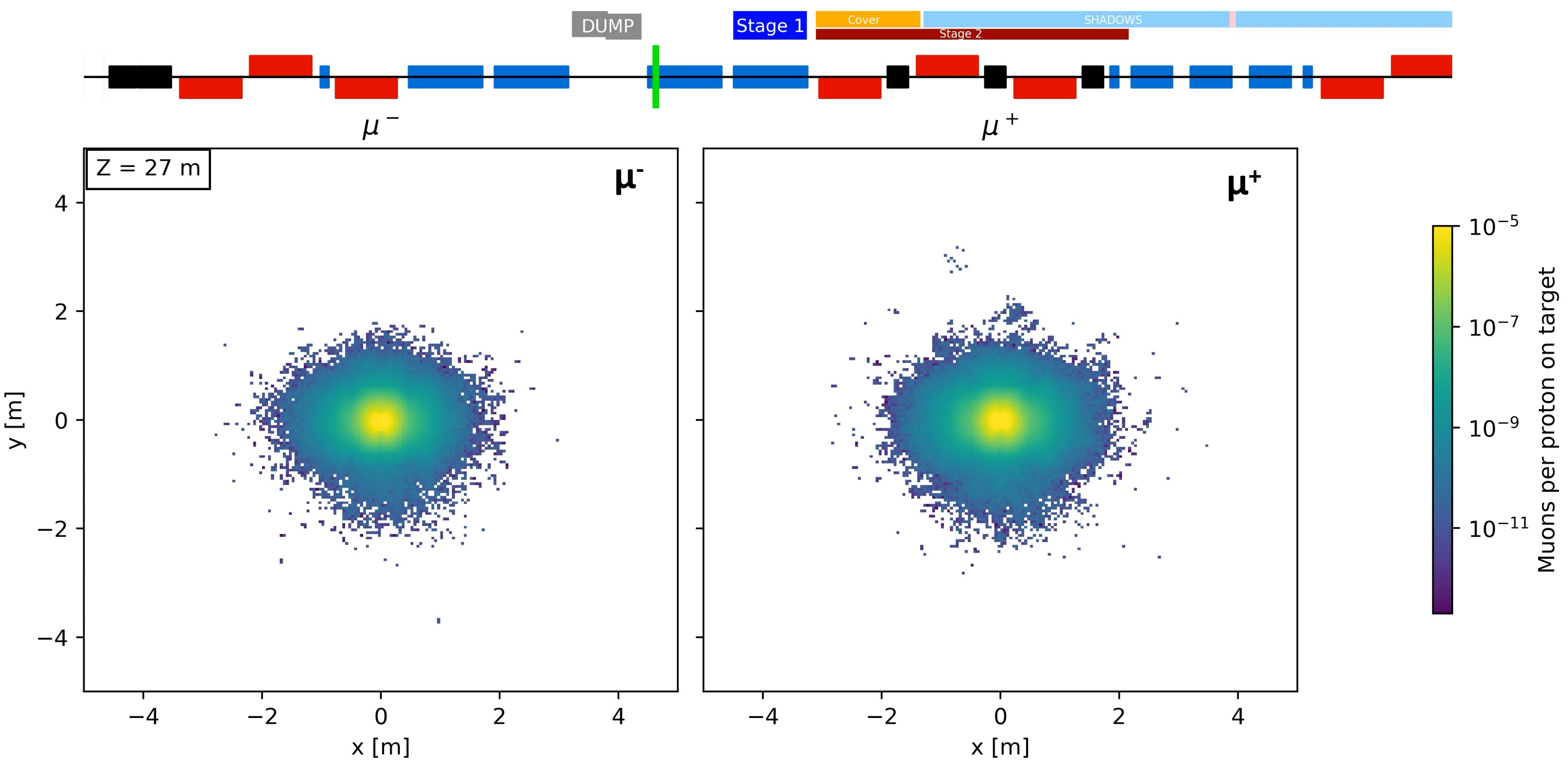


The sweeping system: the Magnetized Iron Blocks (MIB)



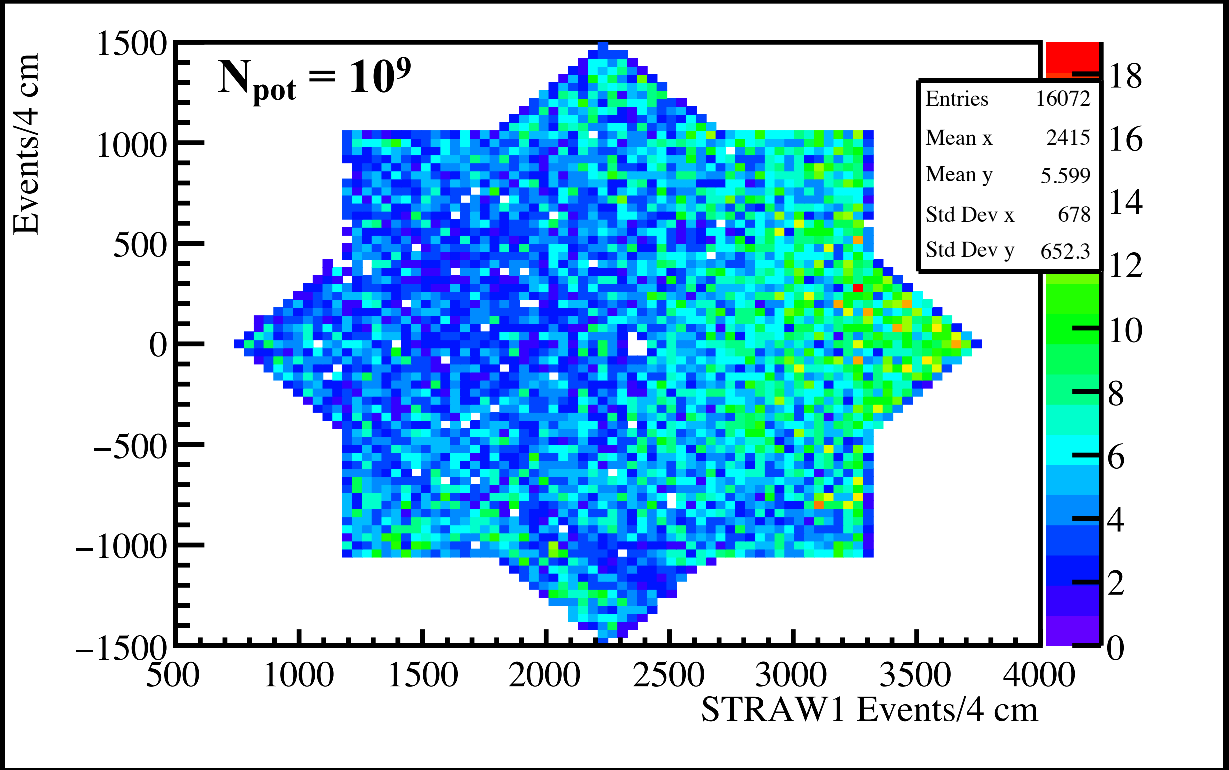
Muon Illumination with the sweeping system (MIB)

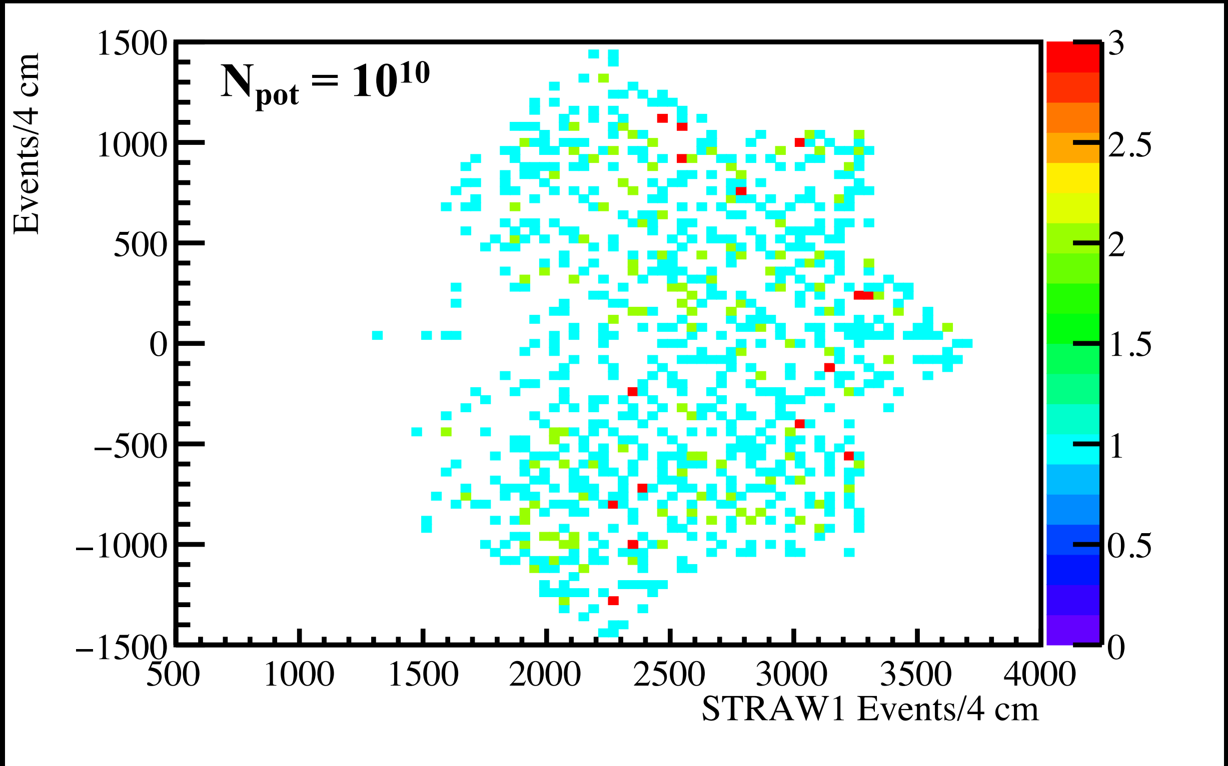
$N_{pot} = 10^{12}$



Muon Illumination with the Sweeping System (MIB) at first tracking chamber

	$\mu^+ + \mu^-$	μ^+	μ^-
rate before MIB	100 MHz	50 MHz	50 MHz
MIB reduction factor	~ 120	~ 110	~ 150
rate after MIB	0.8 MHz	0.5 MHz	0.3 MHz

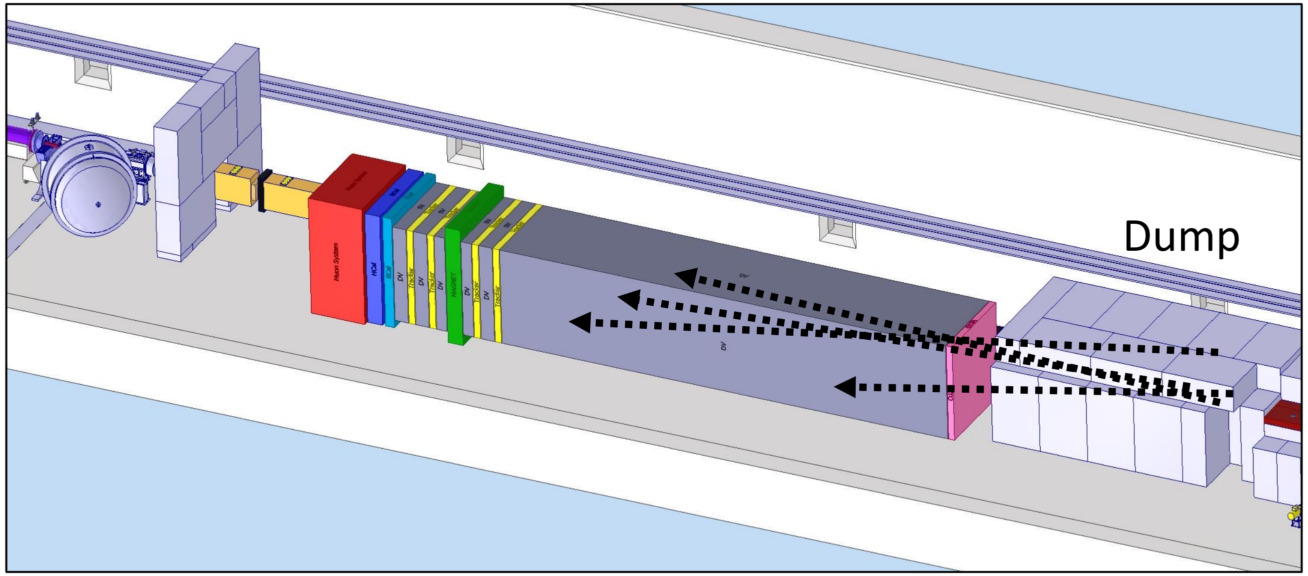


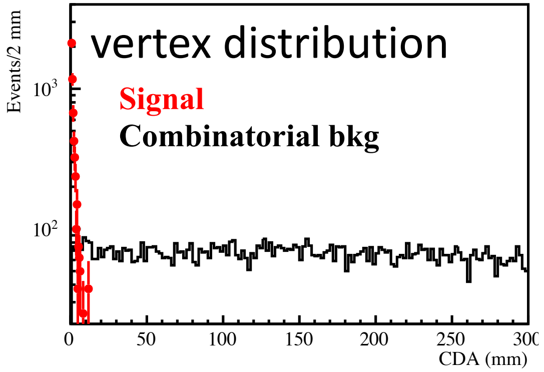


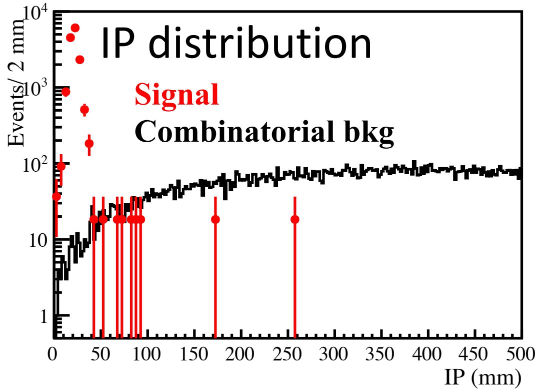
1. Background: Muon Combinatorial

Muon rate without MIB: 100 MHz in acceptance from NA62 data and MC.
MIB reduces it to 0.8 MHz (0.5 MHz μ^+ ad 0.3 MHz μ^-)

$N_{\mu\mu}$/spill	requirement
480	timing (T)
$1.2 \cdot 10^{-2}$	UV
$2.4 \cdot 10^{-5}$	CDA<10 mm
$2.4 \cdot 10^{-7}$	IP<30 mm
$N_{\mu\mu}/5 \cdot 10^{19}$ pot	
0.7 events	T & UV & CDA & IP





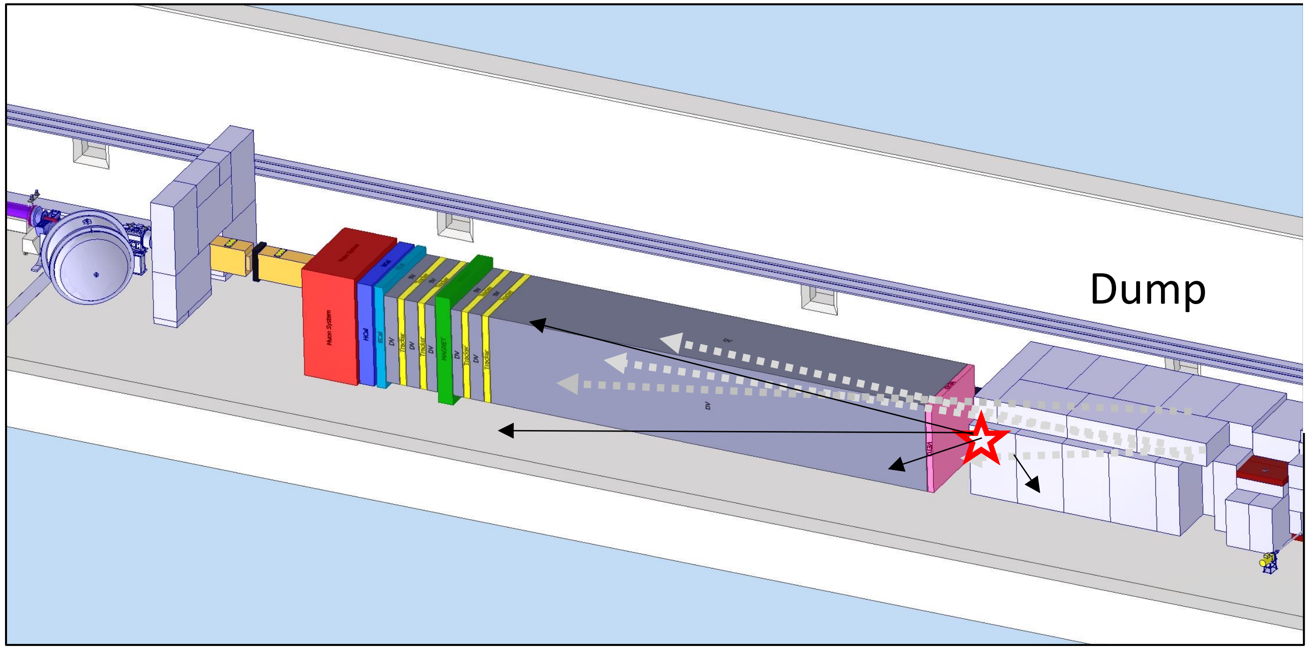


N(μμ) = 0.7 events in 5x10^{19} pot

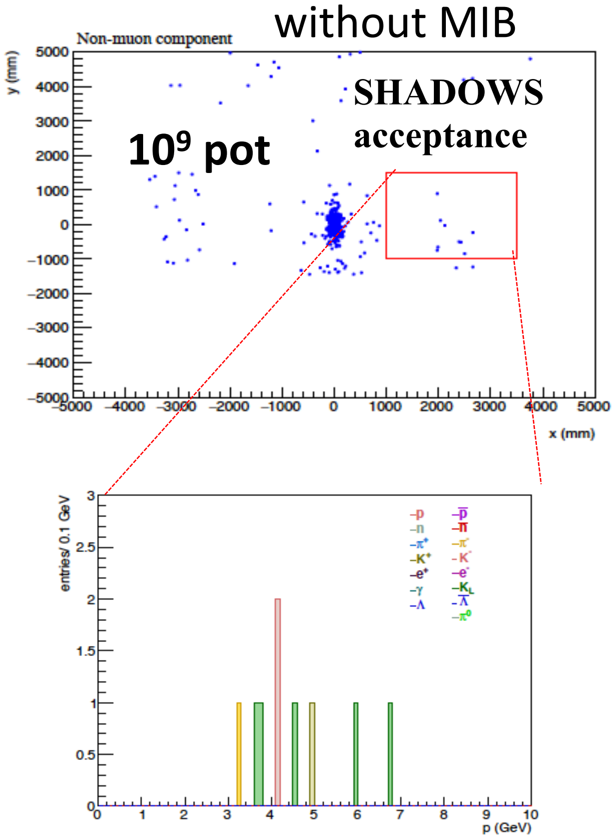
2. Background: Muon inelastic interactions in dump, MIB and beamline elements

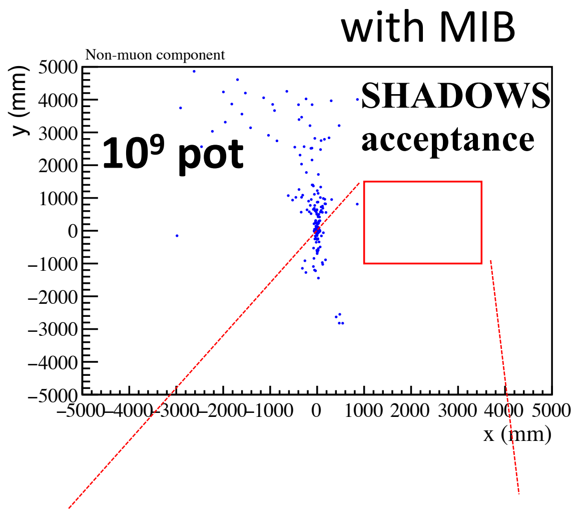
These interactions give signal in the Upstream Veto (UV), form a vertex very close to the boundaries of Decay Volume and do not point back to the impinging point of the proton beam onto the dump.

This will not be the dominant background….



Non muon background in front of decay vessel





with MIB: zero events in a sample of 10^9 pot

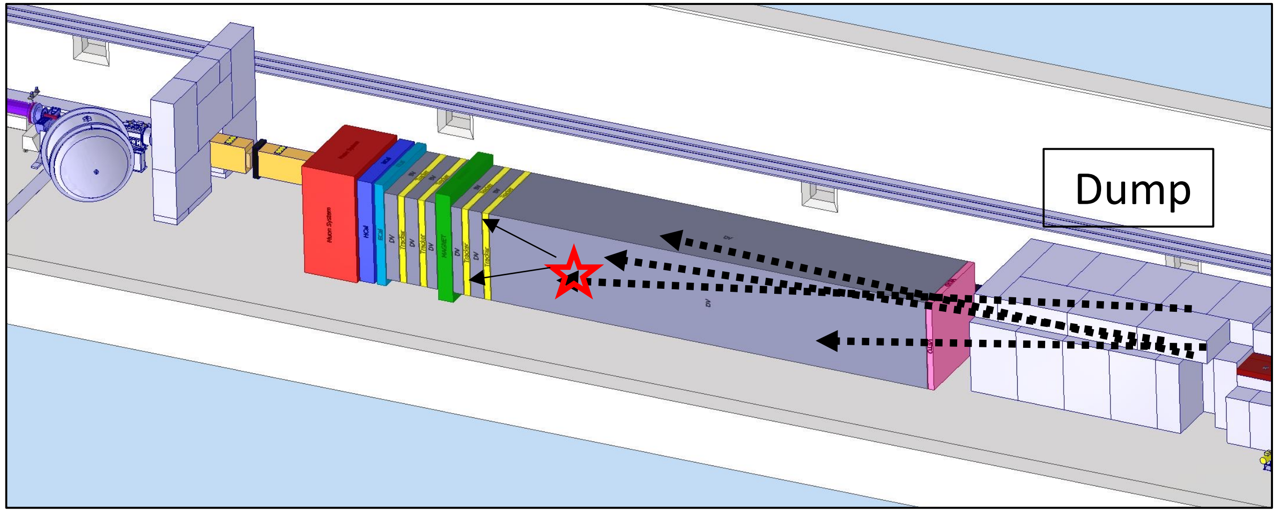
N(μ inel. Int.) = no event in acceptance in 10^9 pot

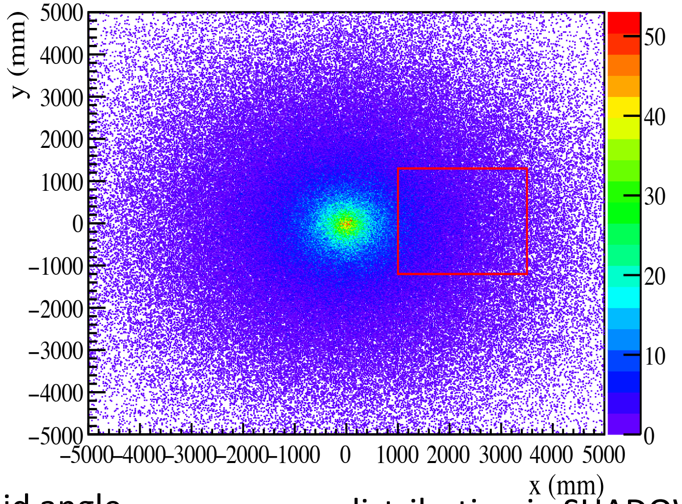
3. Background: Neutrino inelastic interactions in decay volume

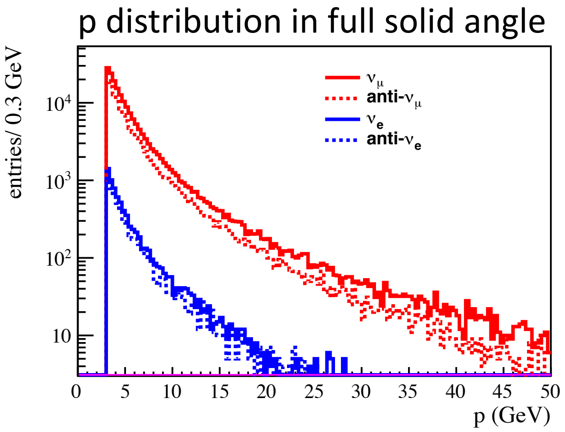
Number of inelastic interactions in 20 m long decay volume filled by air at atmospheric pressure, for $< E_\nu > \sim 5$ GeV:

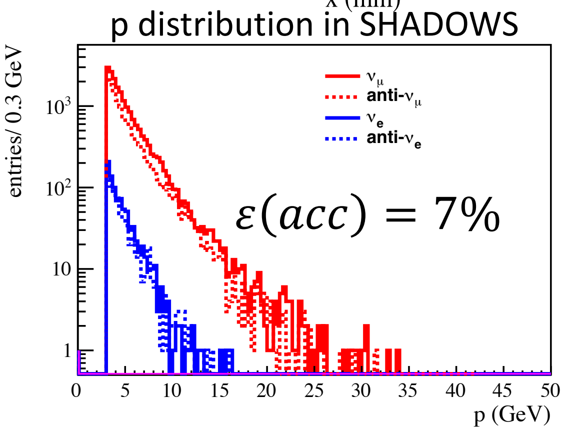
$$N_{\nu,\overline{\nu}\ \mathrm{inel.int.}}(N_{\mathrm{pot}} = 5 \times 10^{19}) = N_{\nu,\overline{\nu}} \times \varepsilon_{acc} \times P_{\mathrm{inel.int.}} \sim 1.5 \cdot 10^{16} \times 2 \cdot 10^{-15} \sim 30$$

1 mbar vacuum reduces them to < 1 event in 5x10^{19} pot









$N(\nu + vbar, inel.\,int.\,in\,decay\,volume)$ < 1 event in 5x10^{19} pot

NB: Neutrino DIS with detector+beamline material still to be evaluated.

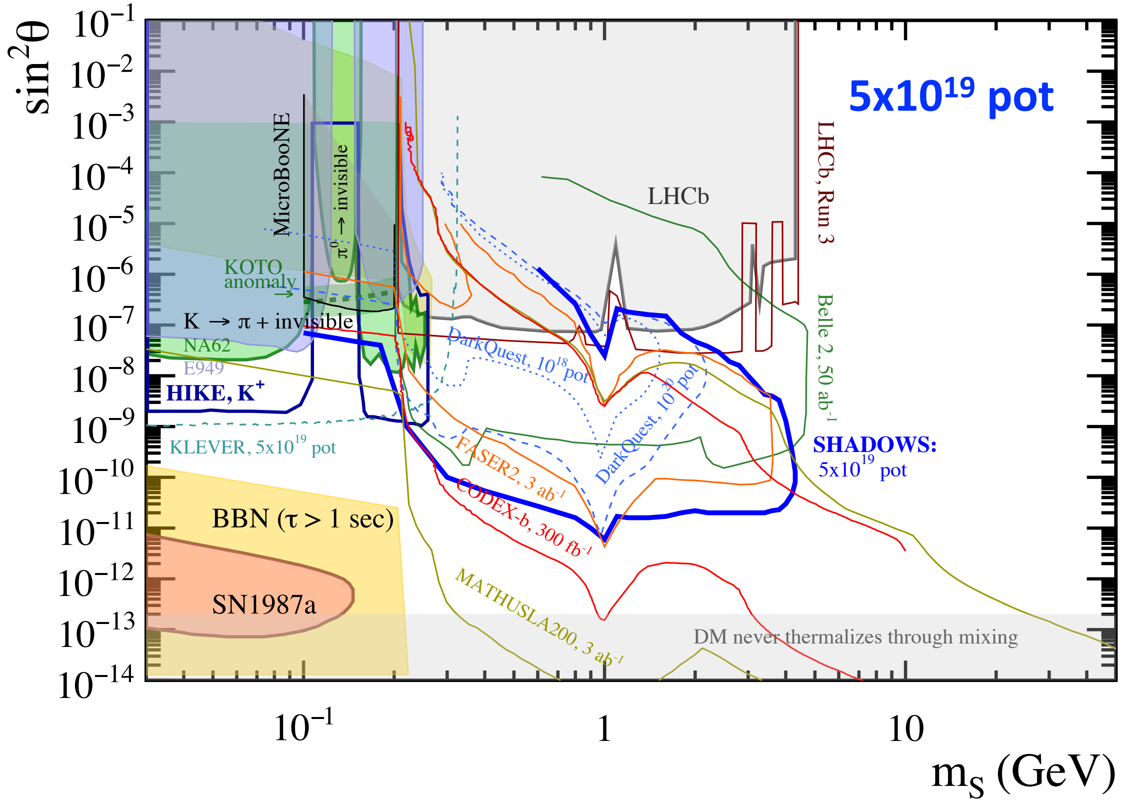
SHADOWS physics sensitivity for some standard PBC benchmarks

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

SHADOWS sensitivity to standard PBC benchmarks

(PBC benchmarks: J. Phys.G47 (2020) 1, 010501, e-Print: 1901.09966, section 9)

Light Dark Scalar mixing with the Higgs (BC4)



SHADOWS covers about 4 orders of magnitude in coupling in the mass range 2 M_{μ} -M_b

(Interesting synergy with HIKE-K^+ which dominates below K threshold)

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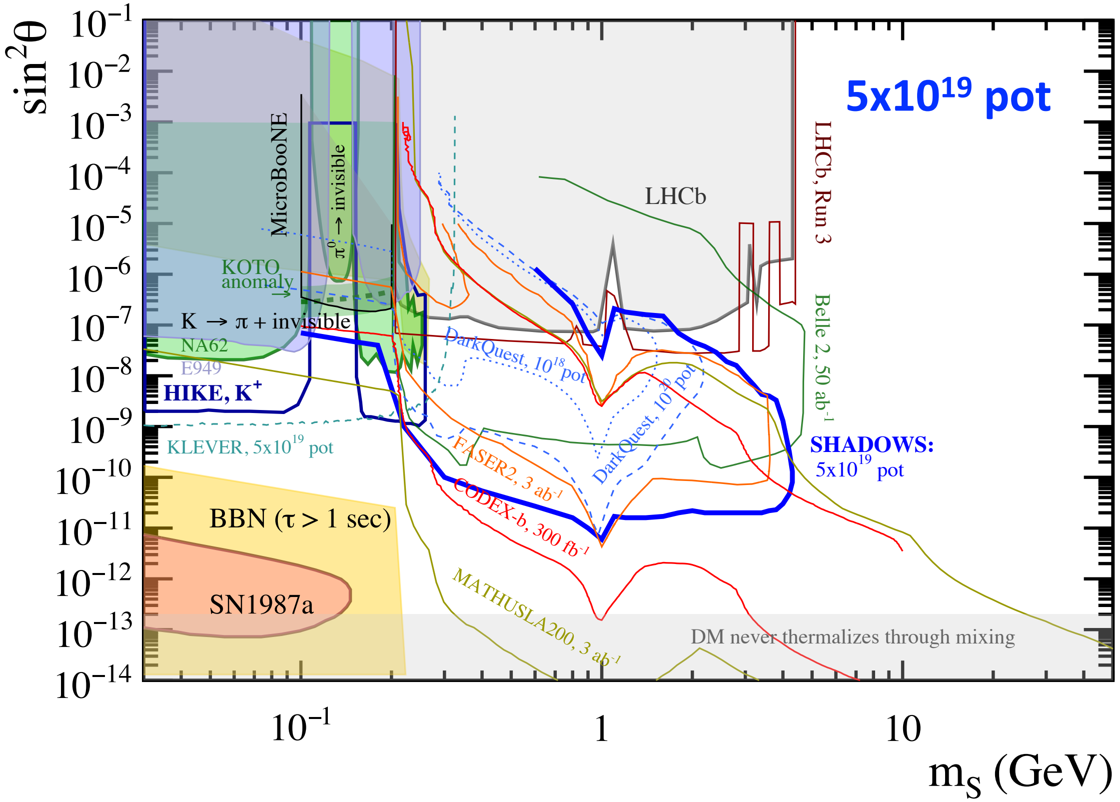

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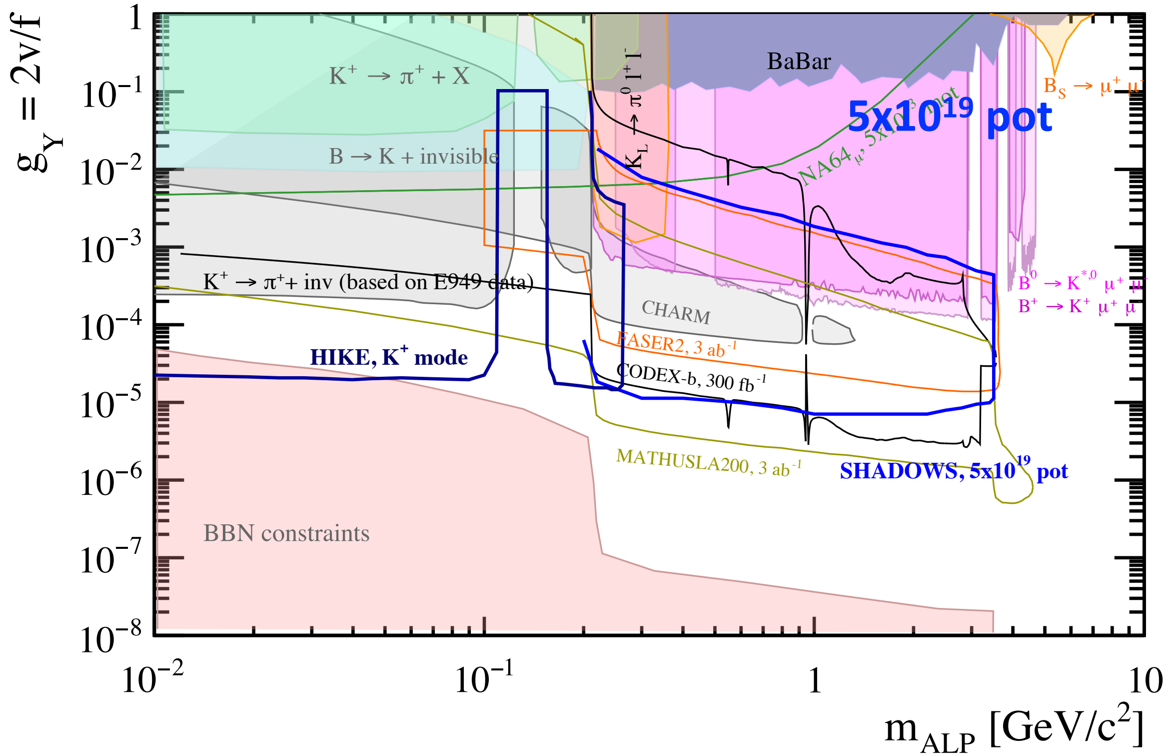
ALPs with fermion couplings (BC10)



SHADOWS (5×10^{19} pot) better than FASER2 (3 ab^{-1}), and comparable to CODEX-b (300 fb^{-1}).

(Interesting synergy with HIKE-K^+ which dominates below K threshold)

SHADOWS sensitivity to standard PBC benchmarks

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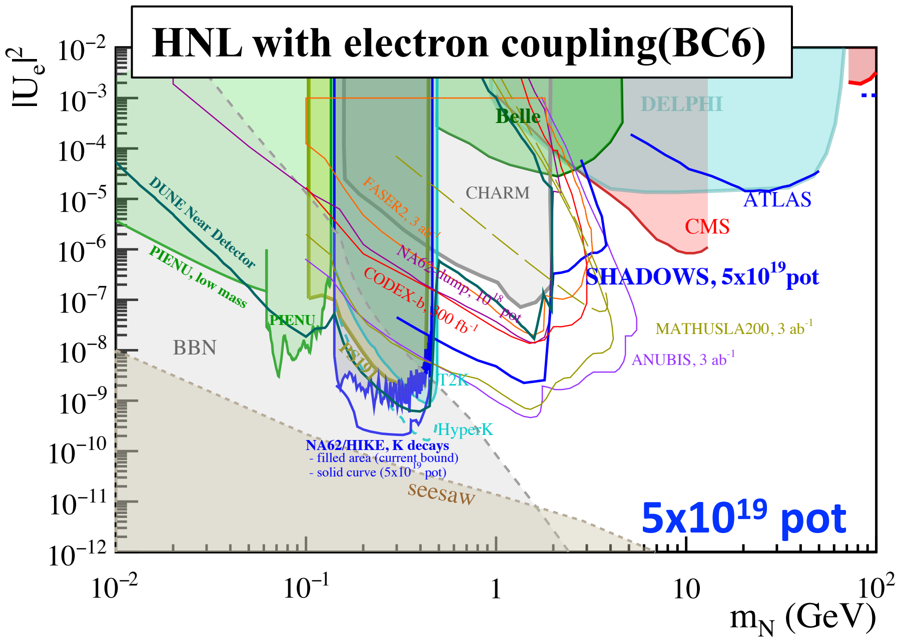

HNL – single lepton dominance:

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

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

Interesting synergy with HIKE-K+ that dominates below K-mass and with HIKE-dump that covers the part forward.

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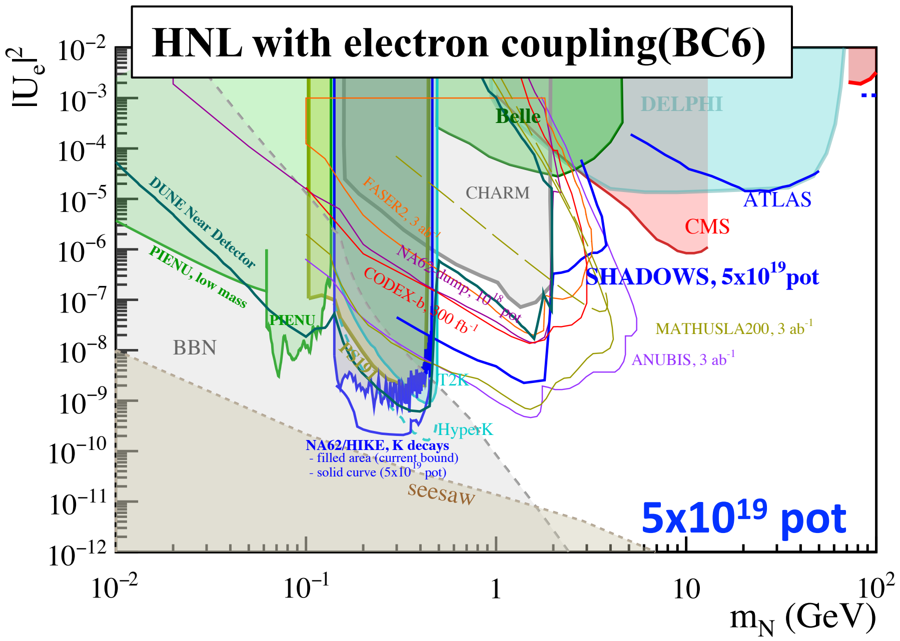

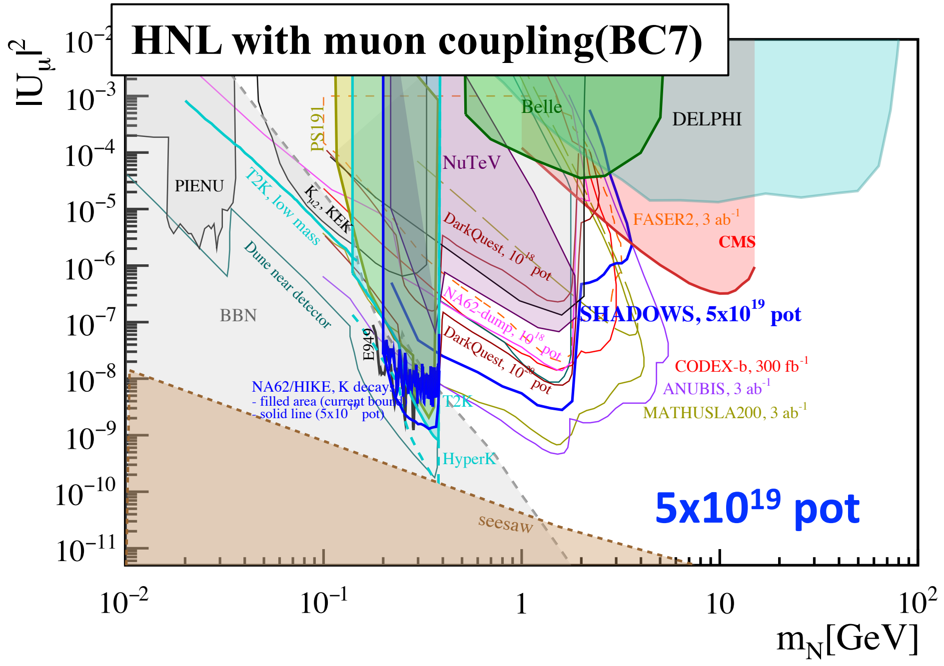

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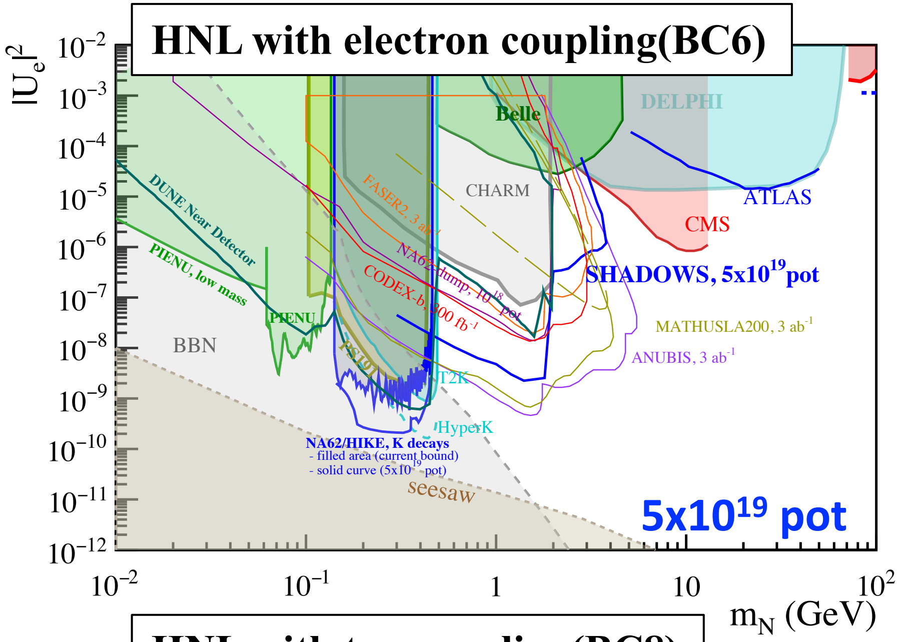

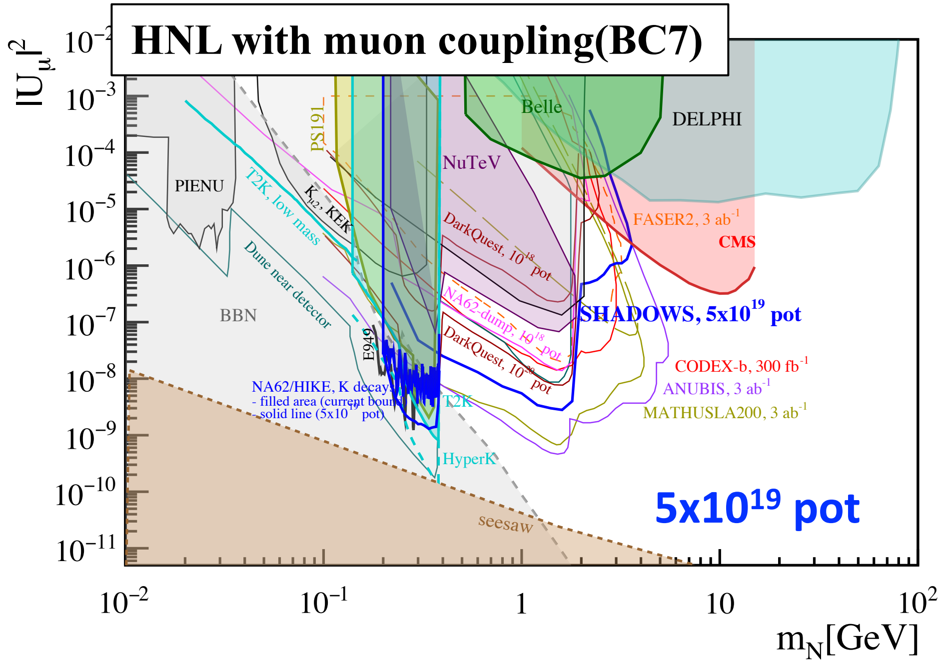

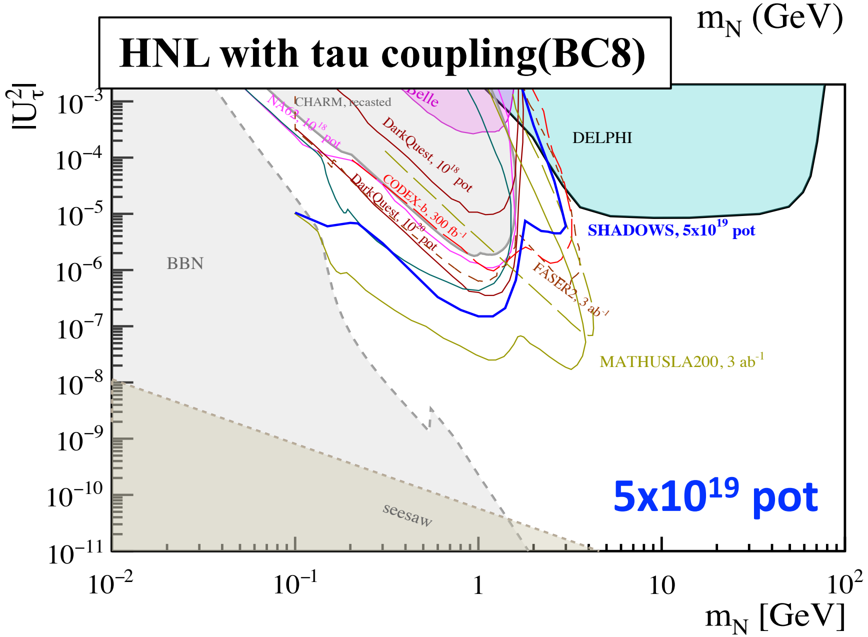

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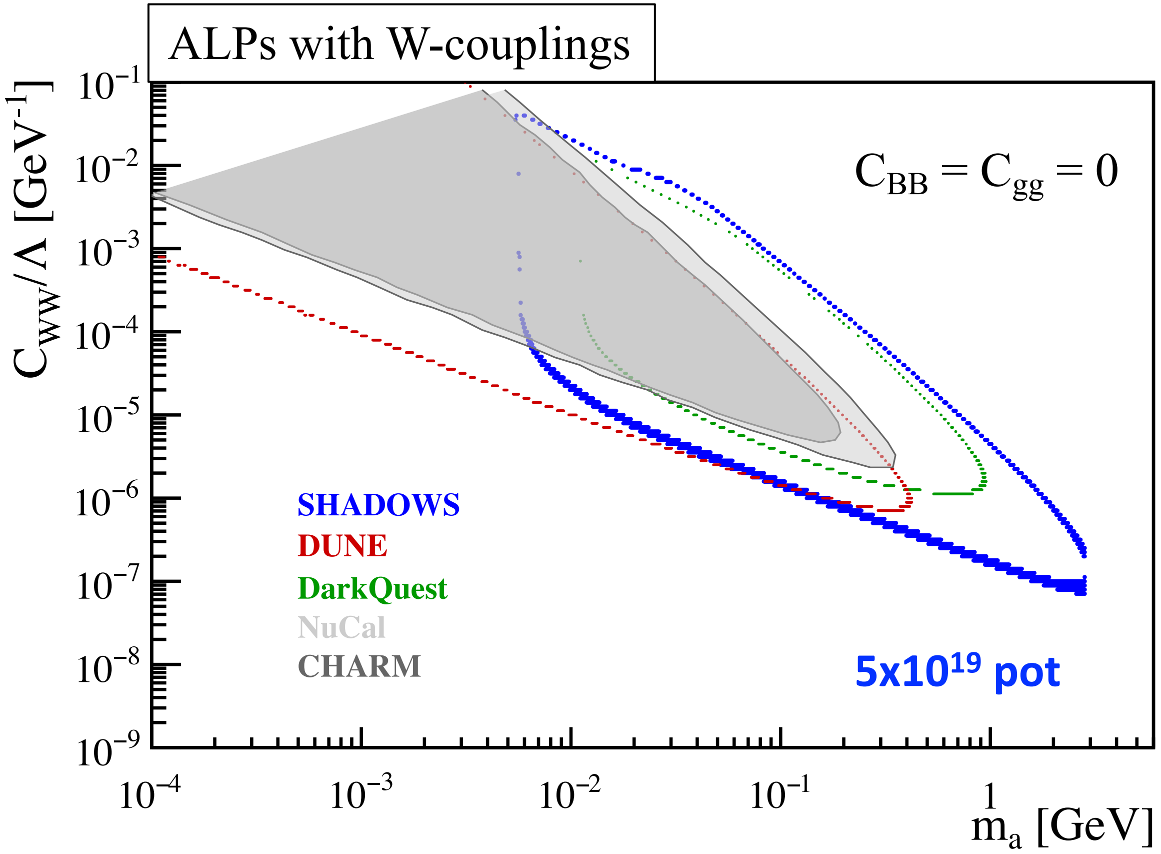
Derived from F. Kahlhoefer et al, 2201.05170 (only fixed target/beam dump experiments considered).



SHADOWS (5x10^{19} pot) competitive with DUNE for small couplings and extends the mass range towards heavier ALPs and larger couplings.

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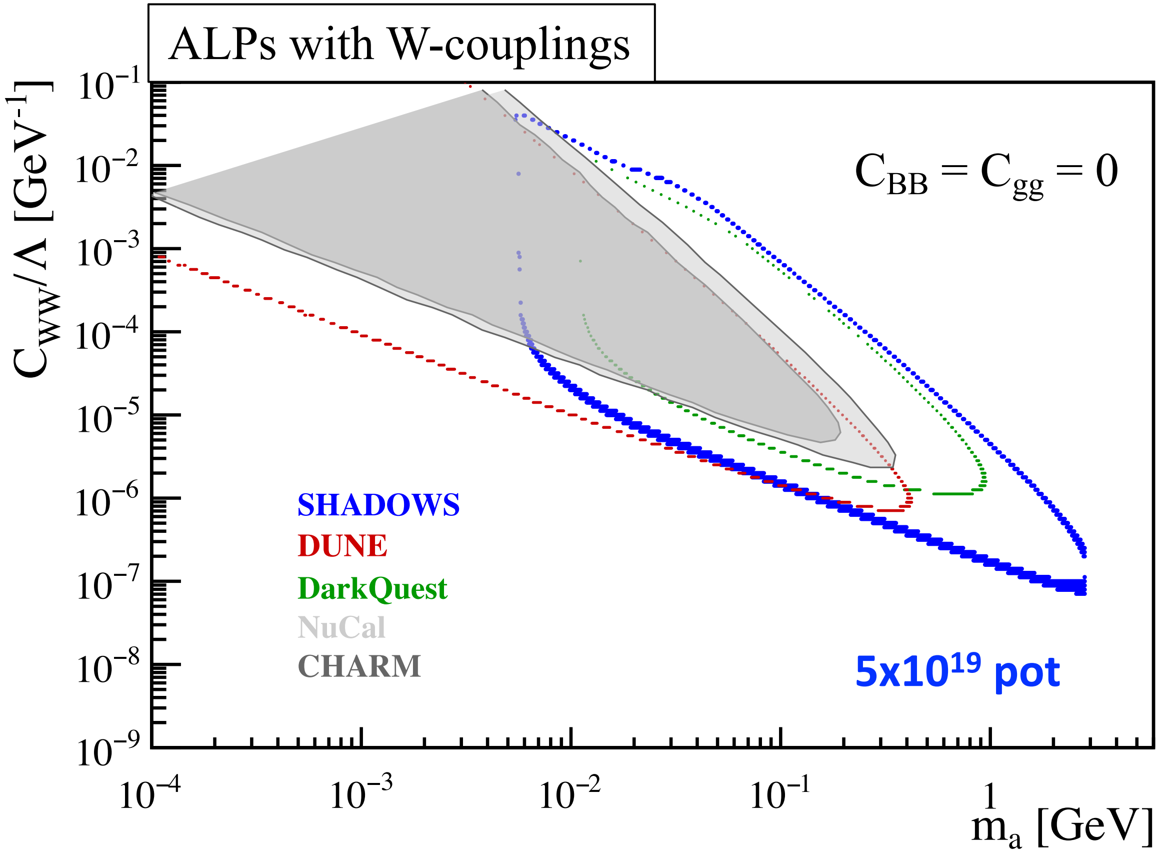

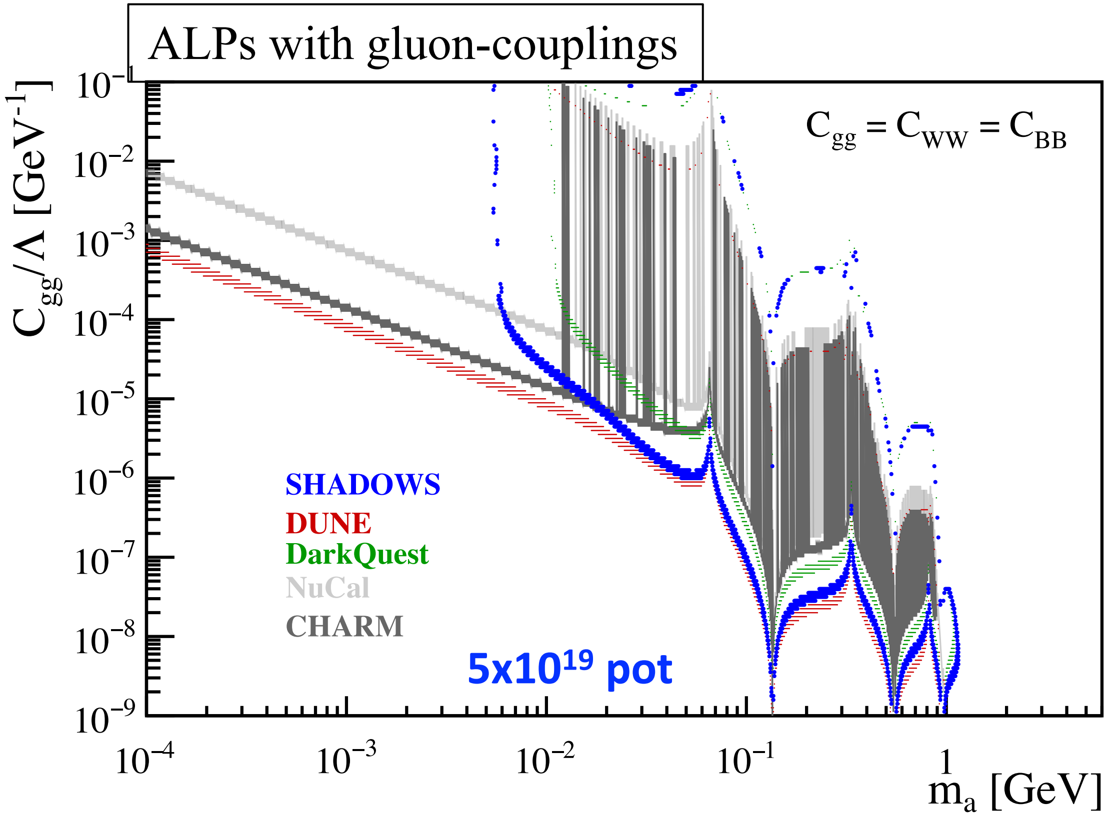

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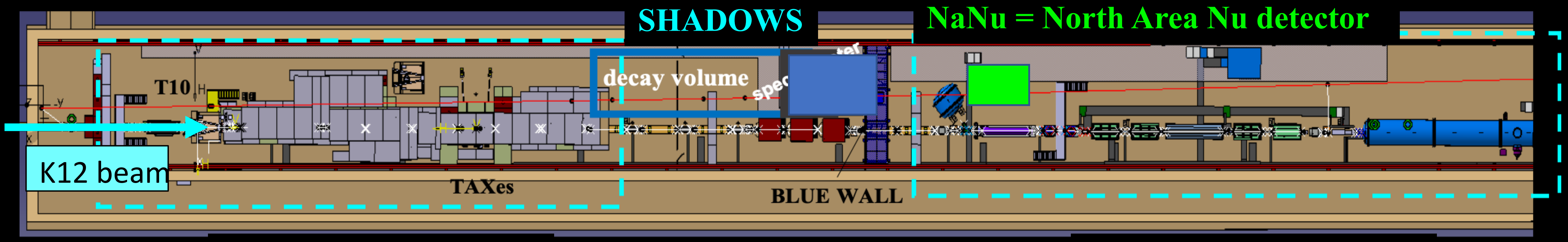
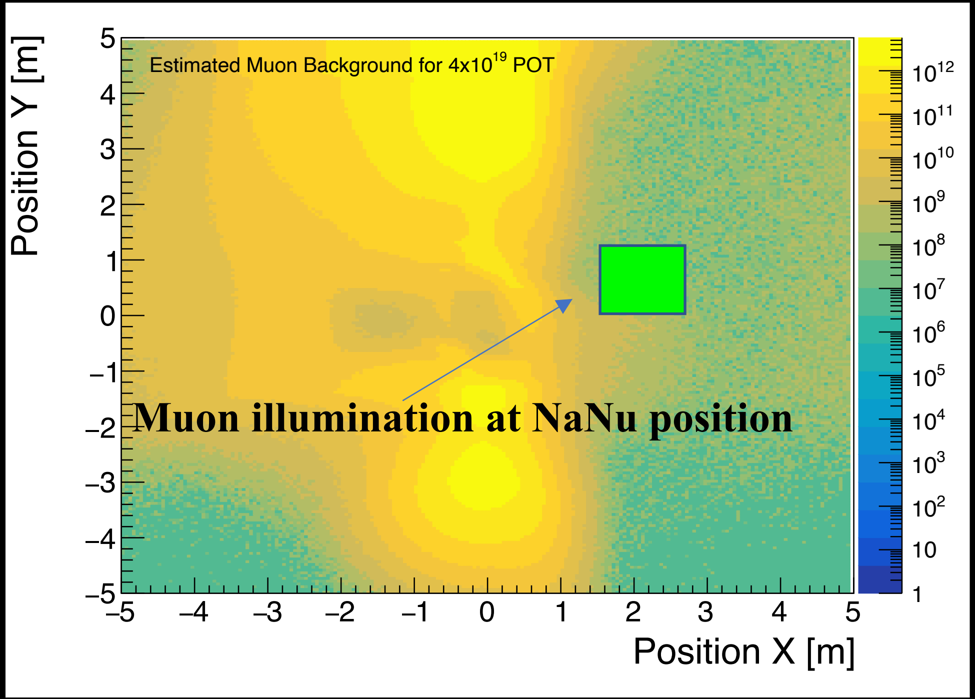
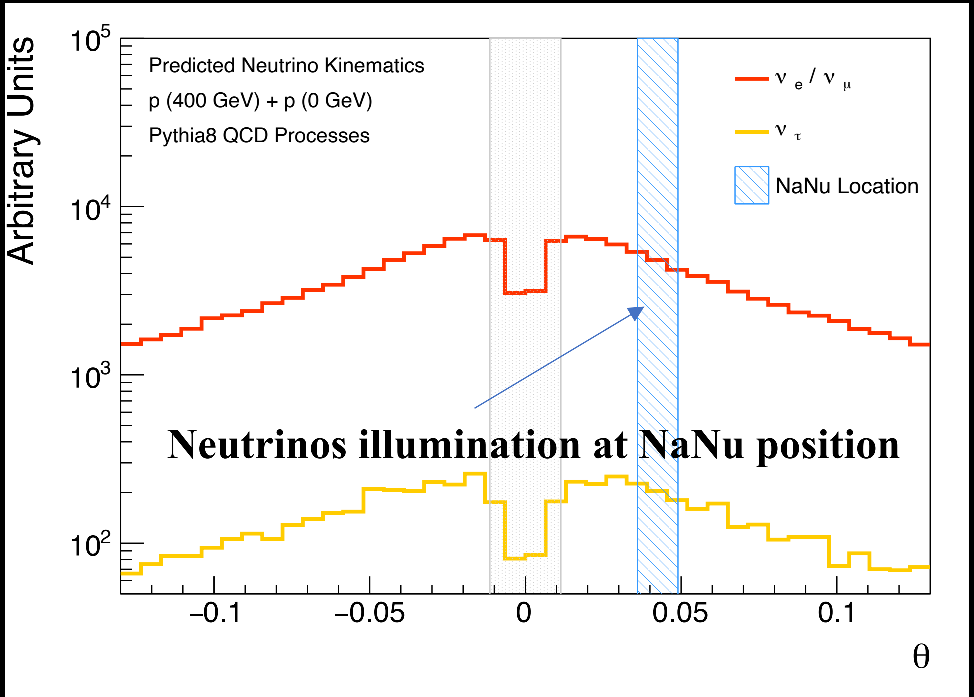
Not only FIPs @ SHADOWS… but also neutrino physics with NaNu @SHADOWS!

(Matthias Schott, Friedemann Neuhaus)







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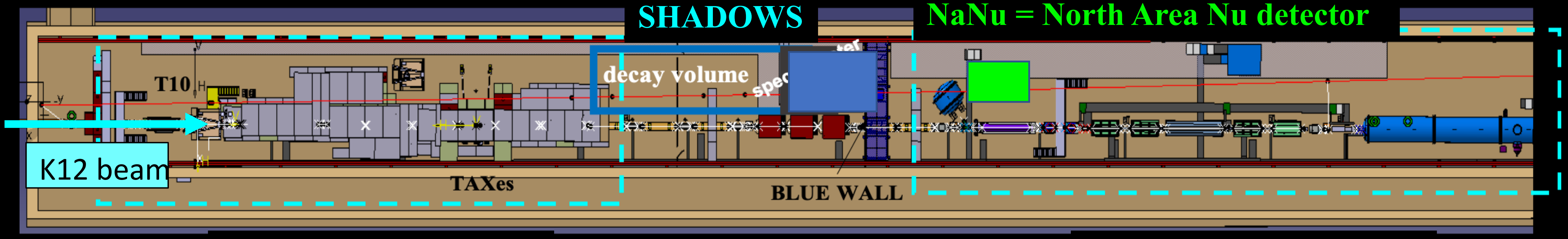
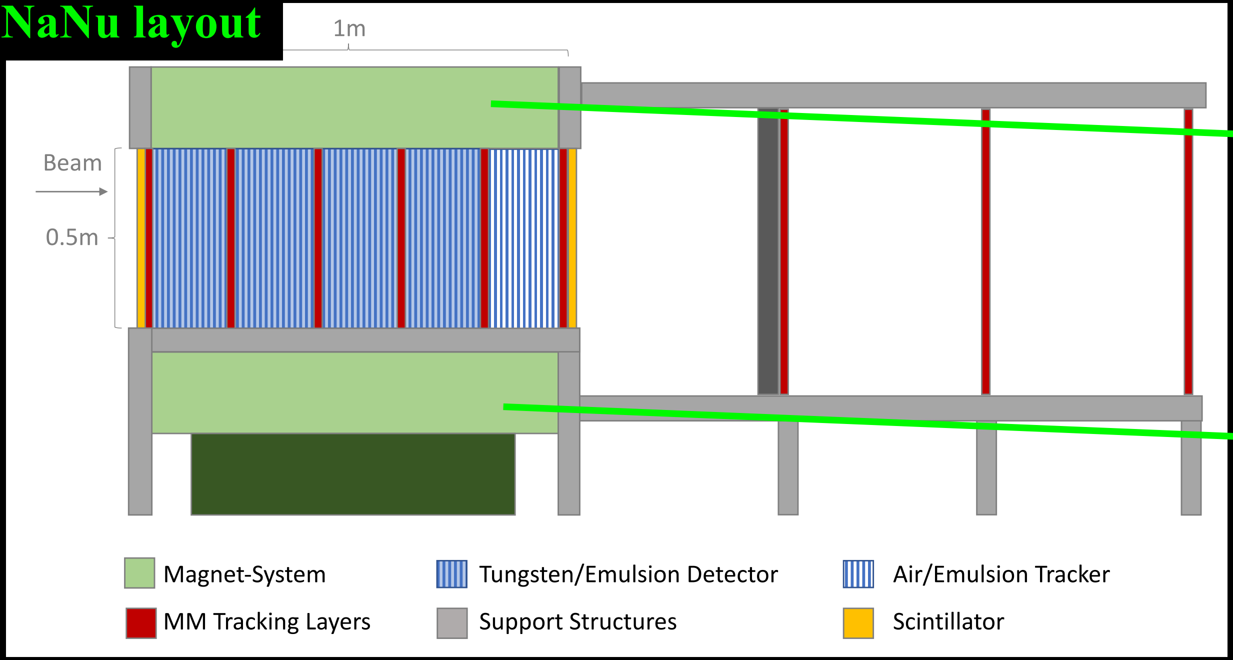


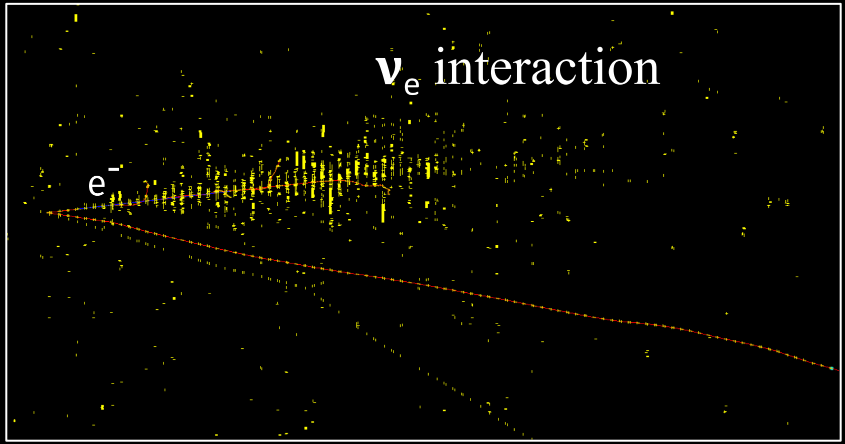
NaNu layout

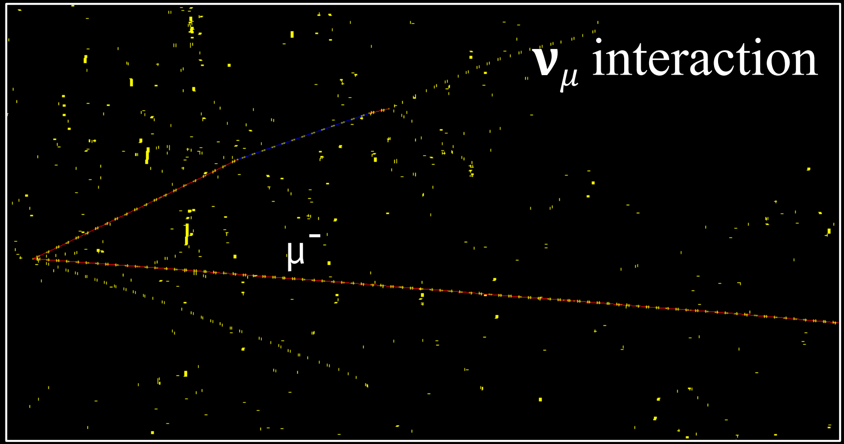


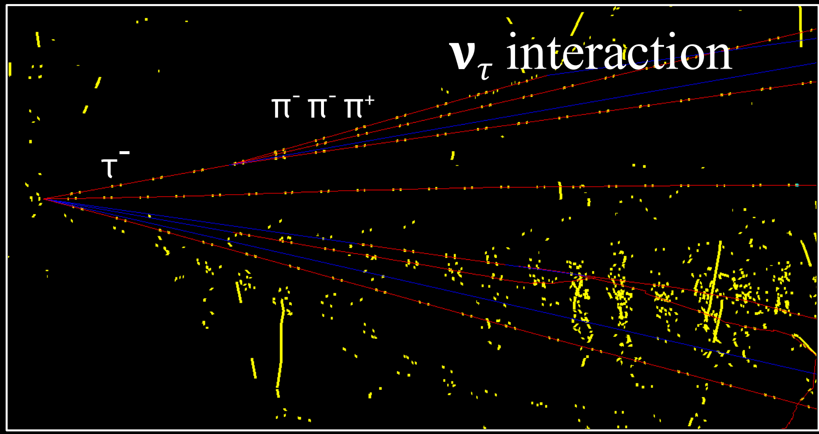
Not only FIPs @ SHADOWS… but also neutrino physics with NaNu @SHADOWS!

ν_τ interaction events in NaNu (including BRs and efficiencies)

	$\tau \to e$	$\tau \to \mu$	$\tau \to h(\pi^\pm)$	$\tau \to 3h(3\pi^\pm)$	$\bar{\tau} \to e$	$\bar{\tau} \to \mu$	$\bar{\tau} \to h(\pi^\pm)$	$\bar{\tau} \to 3h(3\pi^\pm)$
BR	0.17	0.18	0.46	0.12	0.17	0.18	0.46	0.12
Geometrical	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
Decay search	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6
PID	1.0	0.8	0.9	0.9	1.0	0.8	0.9	0.9
Total Events	50	50	150	40	30	30	100	30



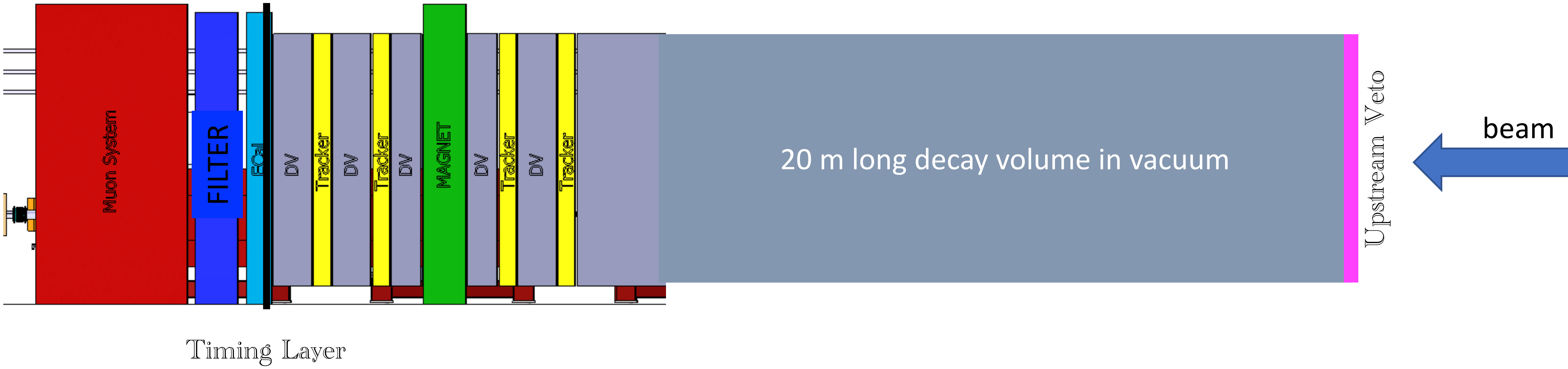




Geant4 simulated ν-interactions in NaNu

Detector design:
requirements & survey of technology options

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



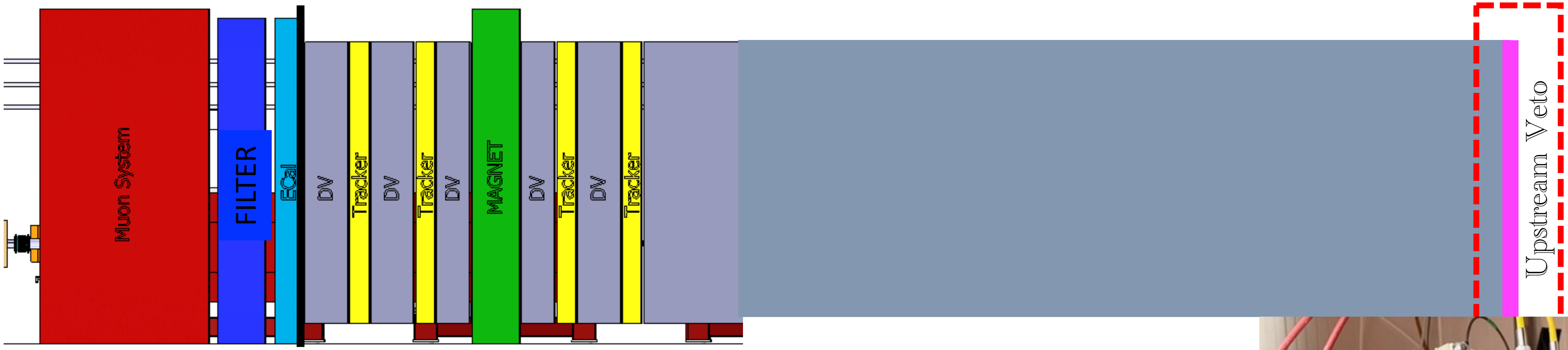
<u>SHADOWS detector components:</u>

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.

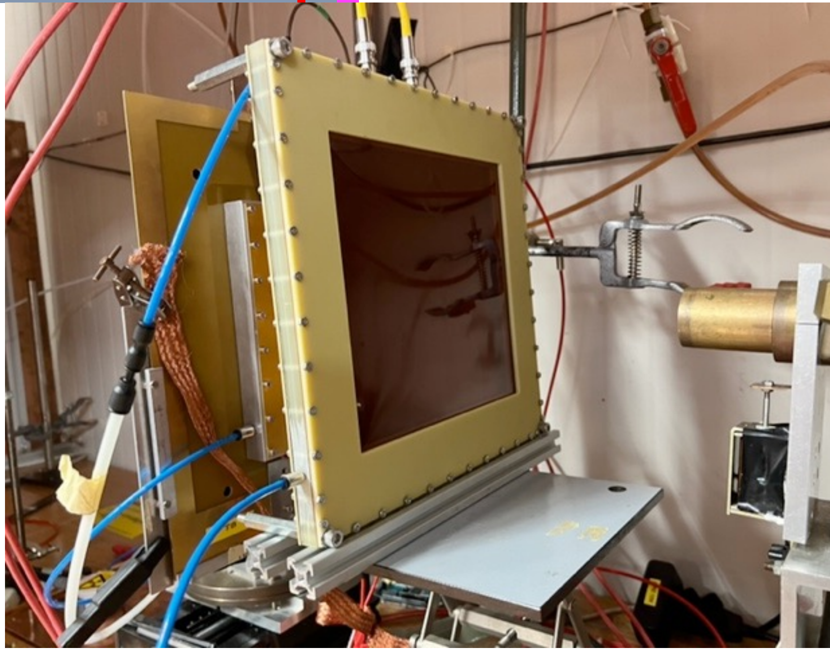
SHADOWS Upstream (Muon) Veto: MicroMegas

INFN Napoli, Roma3,…



Requirements:

1. efficiency: 99.5%
2. time resolution: o(10 ns) (to allow matching with the other detectors)
3. position resolution: o(cm) (match the backward extrapolation of tracks)
4. rate capability: up to several kHz/cm^2

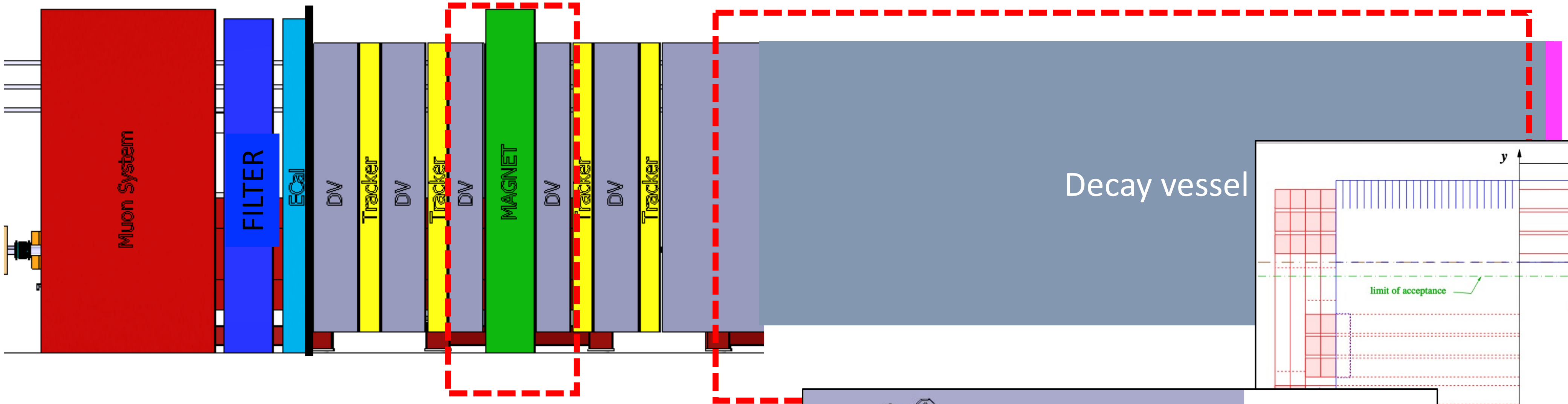


Proposal: **double layer of MicroMegas.**

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

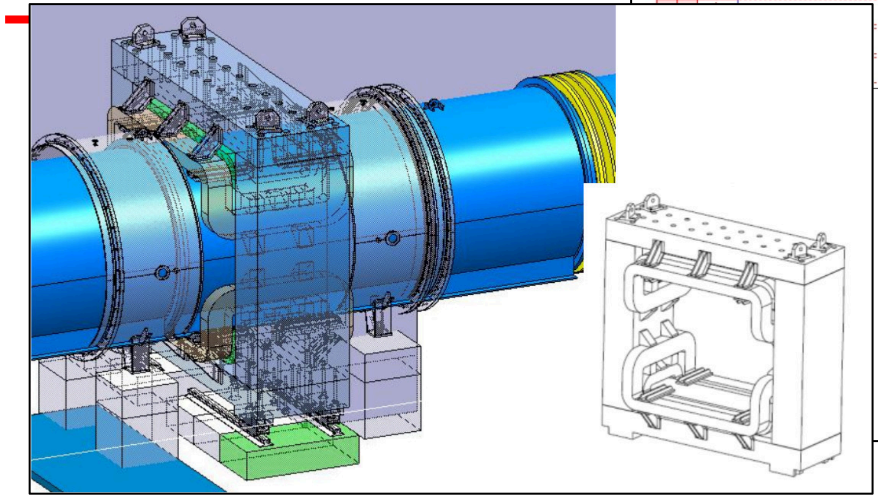
CERN, INFN-Ferrara…

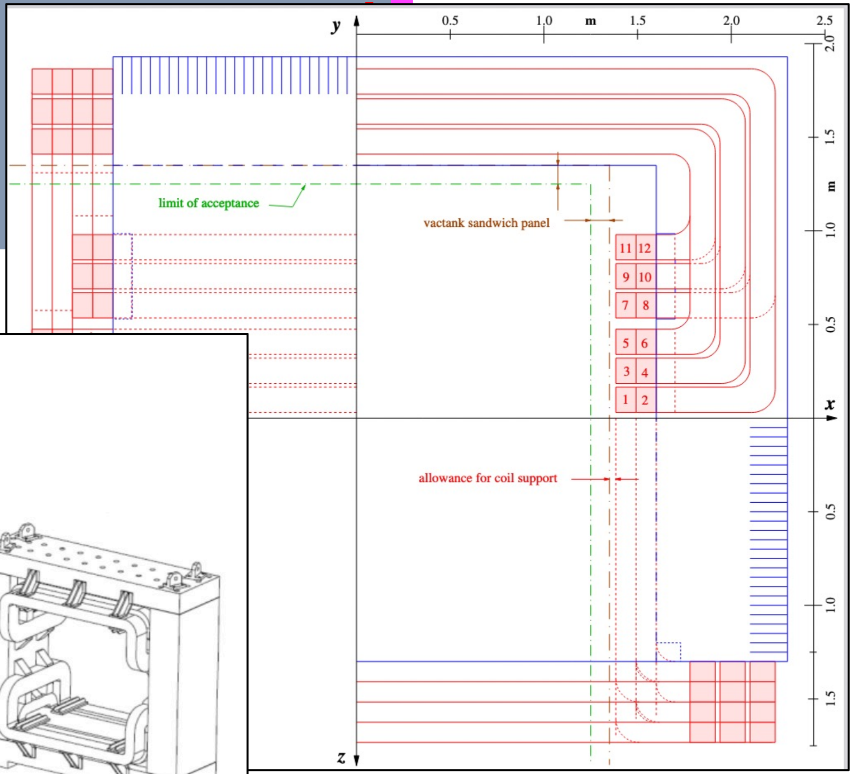
SHADOWS Dipole Magnet and Decay Vessel:



Requirements:

- **Dipole Magnet: about 1 Tm (warm)**
- **Decay vessel: 125 m^3 in vacuum (1 mbar)**



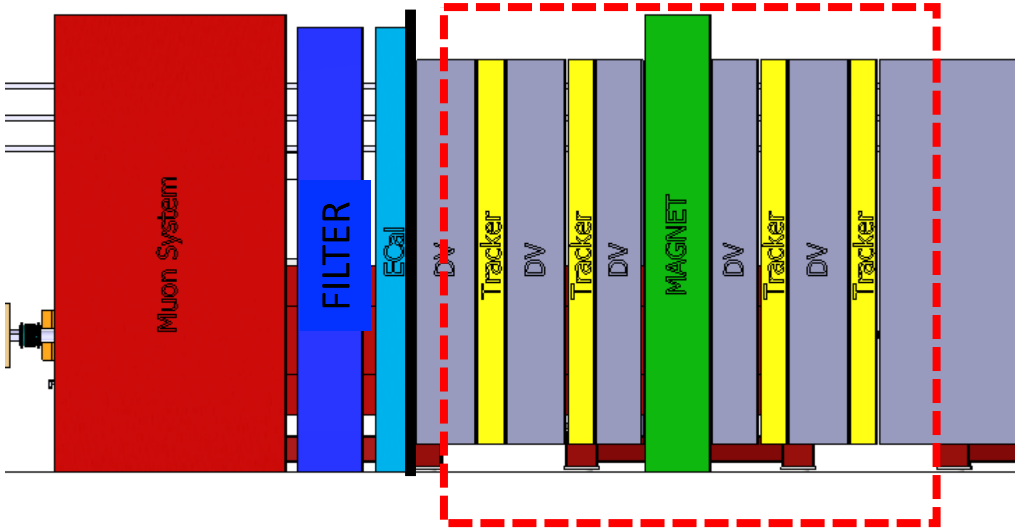


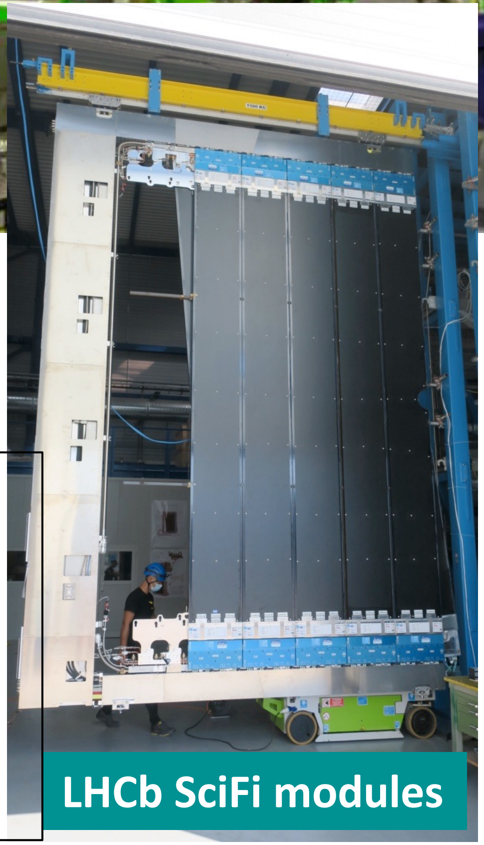
Dipole Magnet design quite advanced.
NA62 magnet-like but:

- Bending power increased by x2
- Power consumption decreased by x10.

Dipole Magnet and Decay Vessel being designed at CERN (CERN –DT) (**P. Wertelaers**, **Burkhard Schmidt**, and **CERN-DT department**). Overall detector integration responsibility: **Alessandro Saputi** (INFN-Ferrara)

SHADOWS Tracker: NA62 straws or SciFi





Requirements:

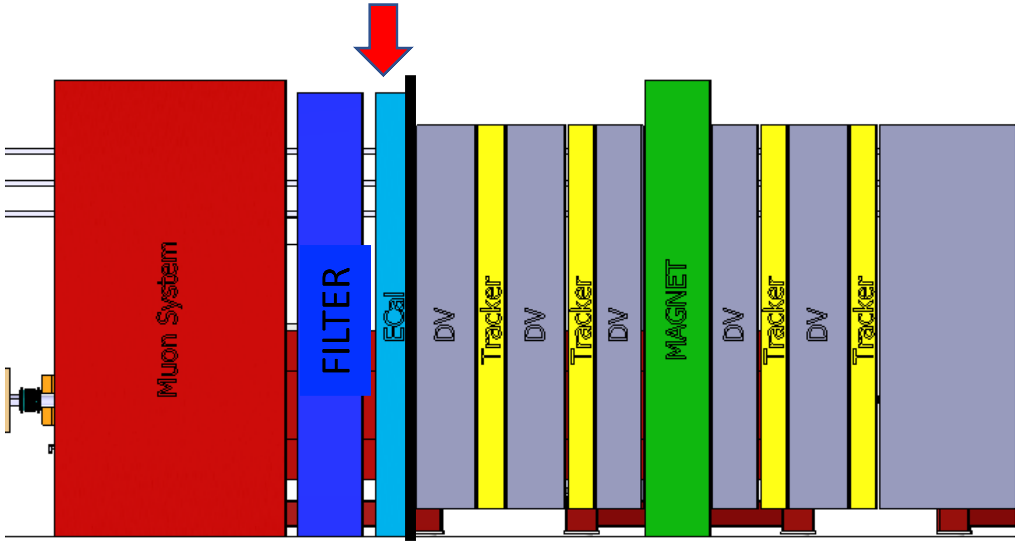
- vertex resolution over 20 m long decay volume: sigma_xy ~ 1 cm
- impact parameter resolution at o(30) m distance: sigma(IP) < few cm
- must operate in vacuum (1 mbar or so).

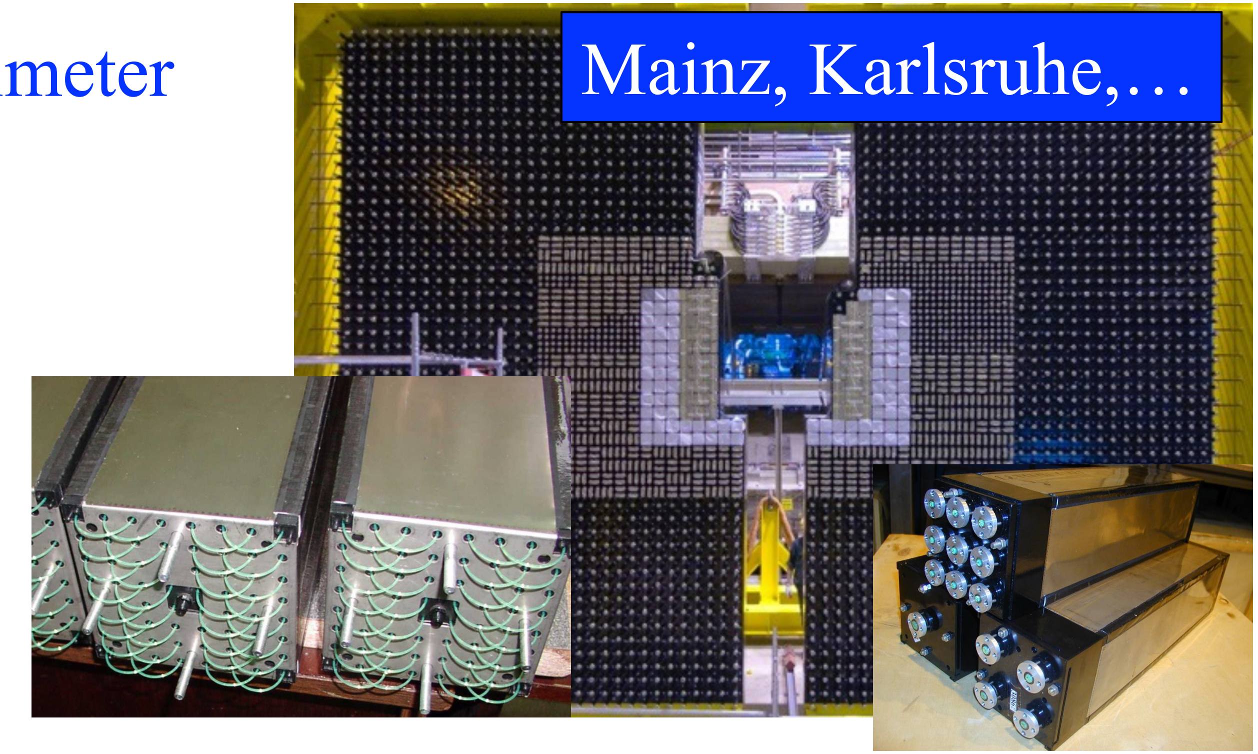
Two options under scrutiny:

1. NA62 STRAW tubes
2. Fibre Tracker (LHCb)

[**Hans Danielsson** (CERN, **Project leader of the NA62 Straws**) and Prof. **Ulrich Uwer** (Heidelberg, **Project leader of LHCb SciFi**) are in SHADOWS

SHADOWS: Electromagnetic calorimeter





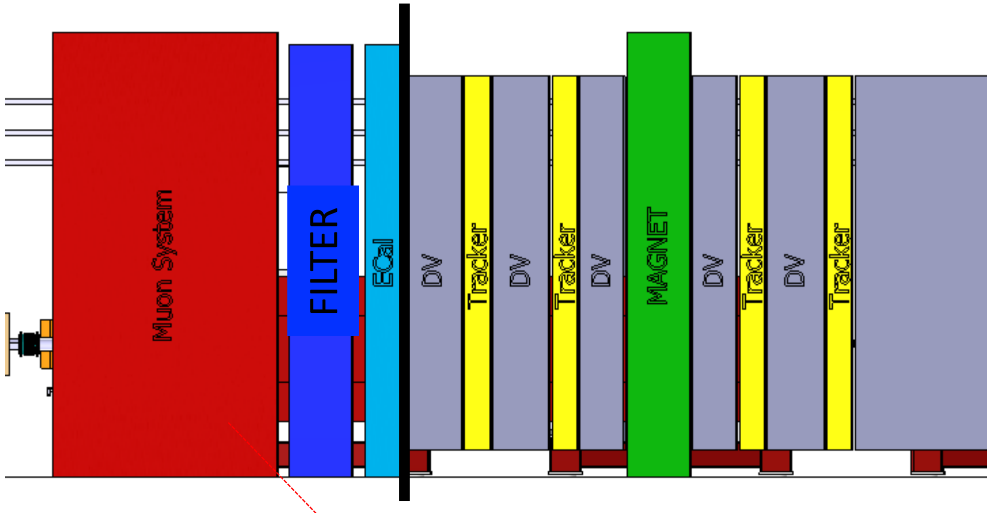
Requirements:

- must identify electrons/photons against muons/hadrons
- π^0 reconstruction (eg: HNL $\rightarrow$ e rho$\rightarrow$ e $\pi^+\pi^0$)
- photon directionality: Important for ALP$\rightarrow\gamma\gamma$
- mild energy resolution: <10% or so for E=0.5-100 GeV
- granularity defined by the minimum distance of two gammas from π^0 decays: o(5-10) cm

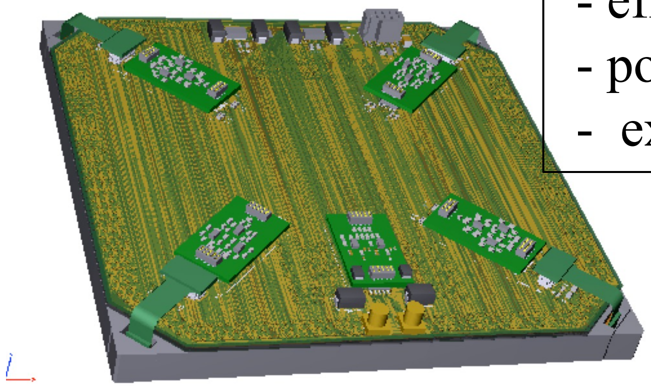
Options under scrutiny: Shashlik, PbWO4 (from CMS), CALICE, SplitCal

SHADOWS: Muon Detector

INFN (Frascati, Bologna, Ferrara, Roma1), ..

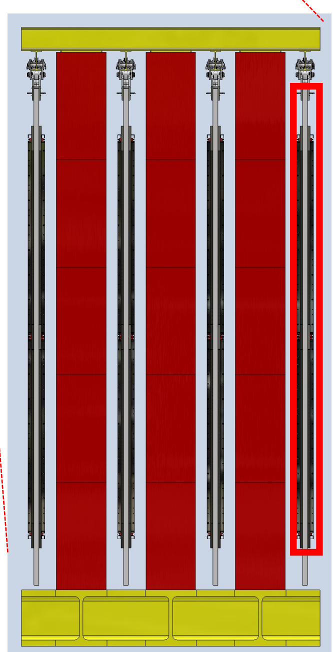


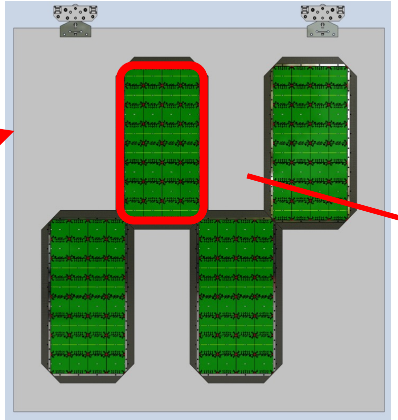
1 tile = 15x15 cm2,
Direct SiPM readout at the corners
One analog output per tile



Requirements:

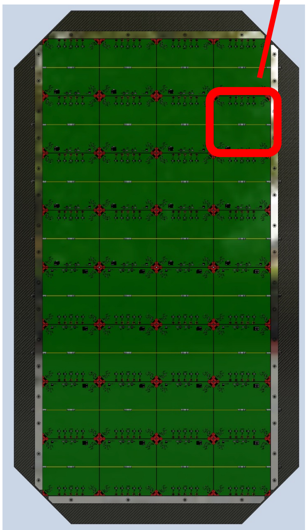
- time resolution: o(150) ps or less
- efficiency: <99% per station
- position resolution: o(few cm).
- expected rates: < 100 Hz/cm2



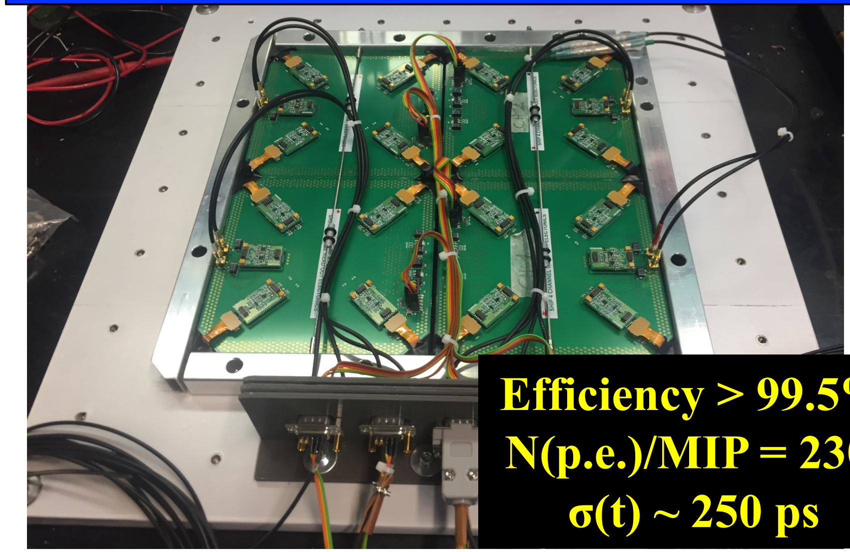


1 station = 8 modules
[same pattern staggered
on the other side of the wall]

1 module = 16/32 tiles



4-tile prototype built in INFN Bologna/LNF



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

Project Status, Cost & Timeline

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

Expression of Interest, 15 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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(3) *CERN*
(4) *INFN, Sezione di Bologna, Bologna, Italy*
(5) *University of Lancaster, Lancaster, UK*
(6) *University of Mainz, Germany*
(7) *Royal Holloway, University of London, UK*

CERN-SPSC-2022-006 / SPSC-EOI-022
15/01/2022

→

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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(11) *University of Mainz, Germany*
(12) *Royal Holloway, University of London, UK*
(13) *PARTREC and University of Groningen, Groningen, The Netherland*
(14) *University of Bologna, Bologna, Italy*

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

The Collaboration has doubled in a few months

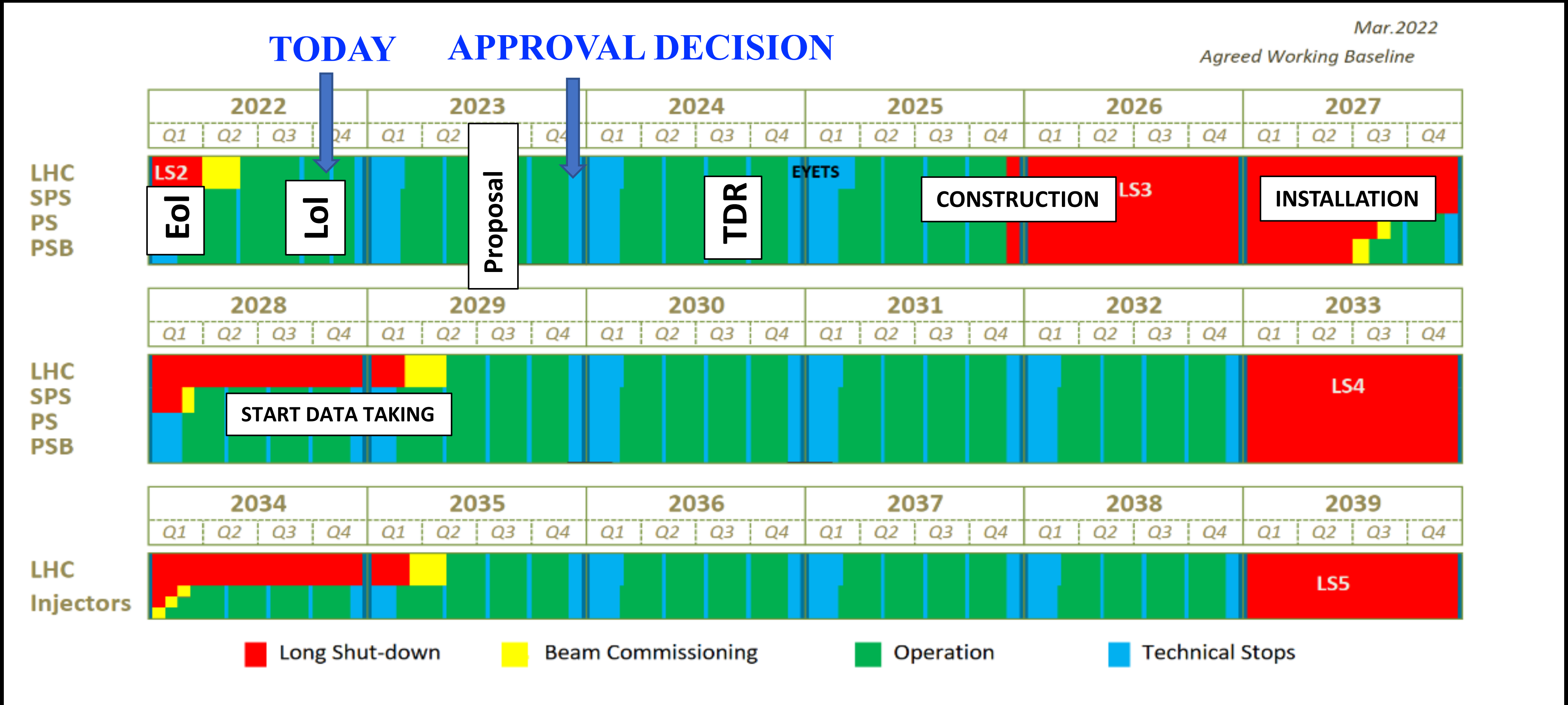
SHADOWS: TENTATIVE COST

(to be updated when the detector technologies will be frozen)

Sub-detectors	Possible Technology	very preliminary) cost
Upstream Veto	Micromegas	0.3 M€
Decay Vessel	in vacuum	1 M€
Dipole Magnet	warm	4-5 M€
Tracker	SciFi	4 M€
Timing Layer	small scintillating tiles	0.1-0.2 M€
ECAL	Shashlik	2-3 M€
Muon	scintillating tiles	0.4-0.5 M€
TDAQ & offline	NA62-based	o(1-2) M€
Total SHADOWS		**12.4-15.5 M€**
Total NaNu		**1.960 €**

NB: the cost estimate is based on prices pre-Ukraine war

SHADOWS: TENTATIVE TIME SCHEDULE



- ✓ Jan 2022: SHADOWS EoI to SPSC
- ✓ Nov 2022: SHADOWS LoI to SPSC
- ✓ March 2023: decision about high-intensity beamline upgrade
- ➢ Sept-Oct 2023: SHADOWS Proposal
- ➢ End 2023: Decision about SHADOWS.

Conclusions

✓ FIP physics is in full swing at CERN and worldwide.

✓ SHADOWS is a proposed proton beam dump experiment for FIP physics that can be built in ECN3 and take data concurrently to HIKE (operated in beam-dump mode).

✓ SHADOWS (5×10^{19} pot) has similar/better sensitivity than CODEX-b ($300\ fb^{-1}$) and FASER2 ($3\ ab^{-1}$) for FIPs from charm/beauty:
⇨ It naturally complements HIKE-dump that is mostly sensitive to very forward objects, and HIKE-K that is mostly sensitive to FIPs below the K-mass.

✓ NaNu@SHADOWS can enrich the physics programme with active neutrino physics
⇨ it naturally complements FASERnu@LHC and SND@LHC covering a different region in phase space.

✓ **ECN3 with SHADOWS+HIKE can become a "hot spot" on worldwide scale for FIP physics in 4-5 years from now.**