SHADOWS

Search for Hidden And Dark Objects With the SPS

INFN-LNF
INFN-Ferrara
INFN-Bologna
University of Bologna
CERN
Royal Holloway London
University of Mainz (excellence cluster)
University of Heidelberg
Karlsruhe Institute of Technology
University of Freiburg
INFN-Naples
INFN- Rome3
Charles University, Prague
University of Groningen, The Netherland

+ the invaluable support of the CBWG, NACONS team, and CERN-DT Depart.

SPSC Open Session – November 2022

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

Expression of Interest, 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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12/01/2022
CERN-SPSC-2022-006 / SPSC-EOI-023

→

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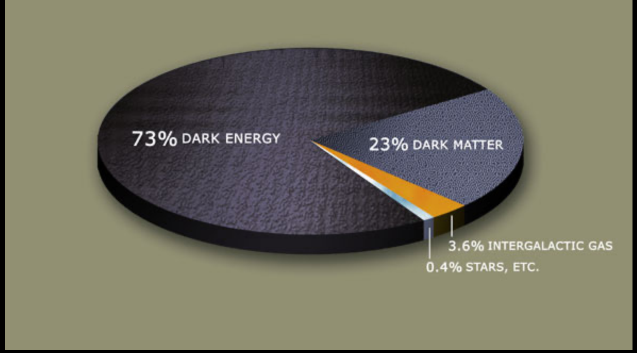
CERN-SPSC-2022-030 / SPSC-I-256
04/11/2022

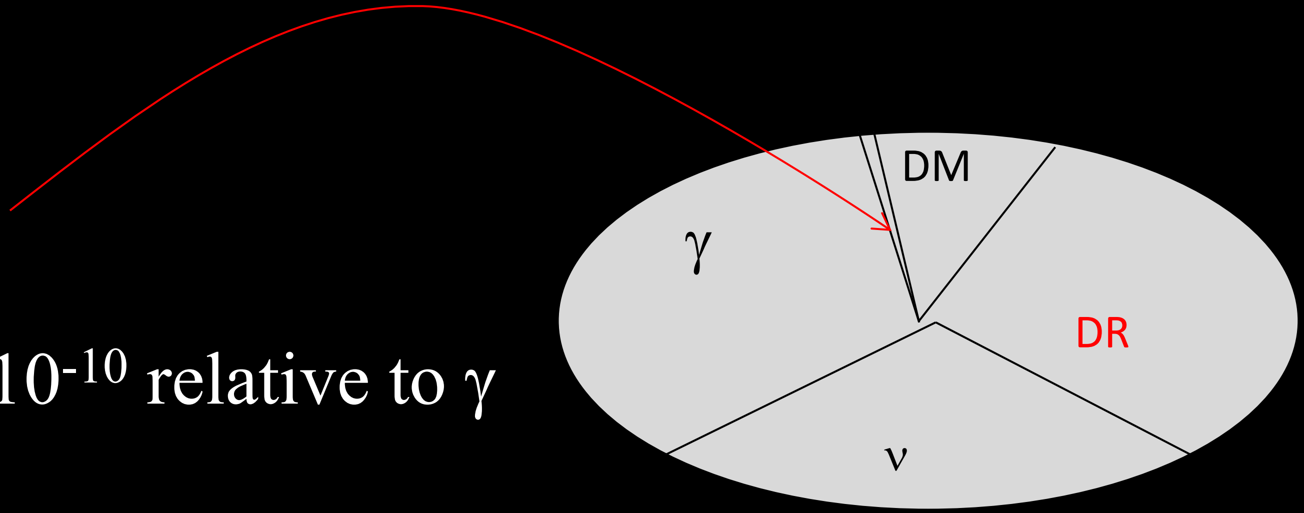
The Collaboration has doubled in a few months

PS: since the submission (4 Nov) one more group joined: INFN-Roma1

Introduction to the Physics Case



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.

- The Search for Feebly Interacting Particles,, Pospelov, Schuster, GL, *Ann.Rev.Nucl.Part.Sci.* 71 (2021) 279-313 e-Print: 2011.02157 [hep-ph]

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..

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

•Physics Beyond Colliders at CERN: Beyond the Standard Model Working Group Report, .*Phys.G* 47 (2020) 1, 010501 e-Print: 1901.09966 [hep-ex]

What are Feebly-Interacting Particles (FIPs)?

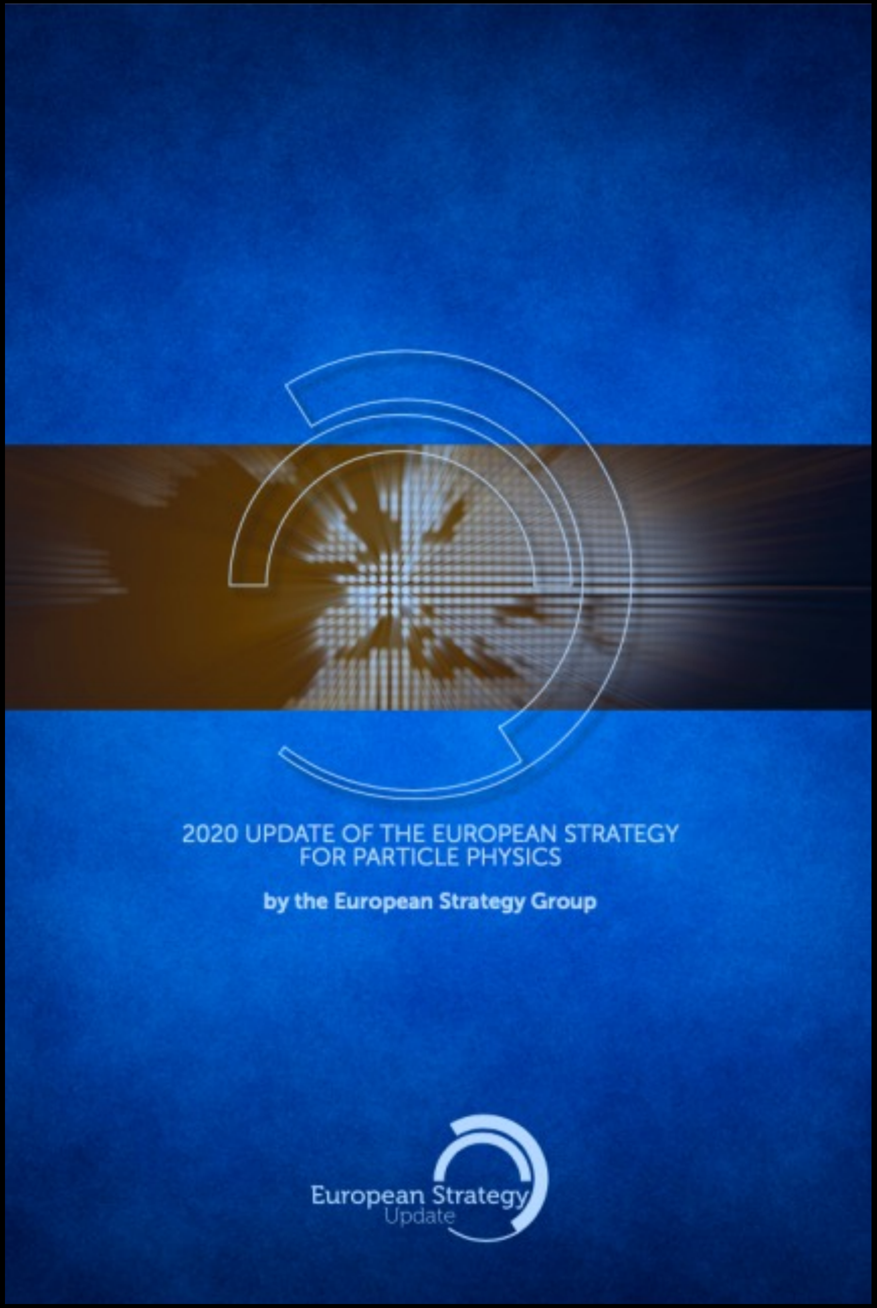
<u>Very roughly:</u>

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.



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

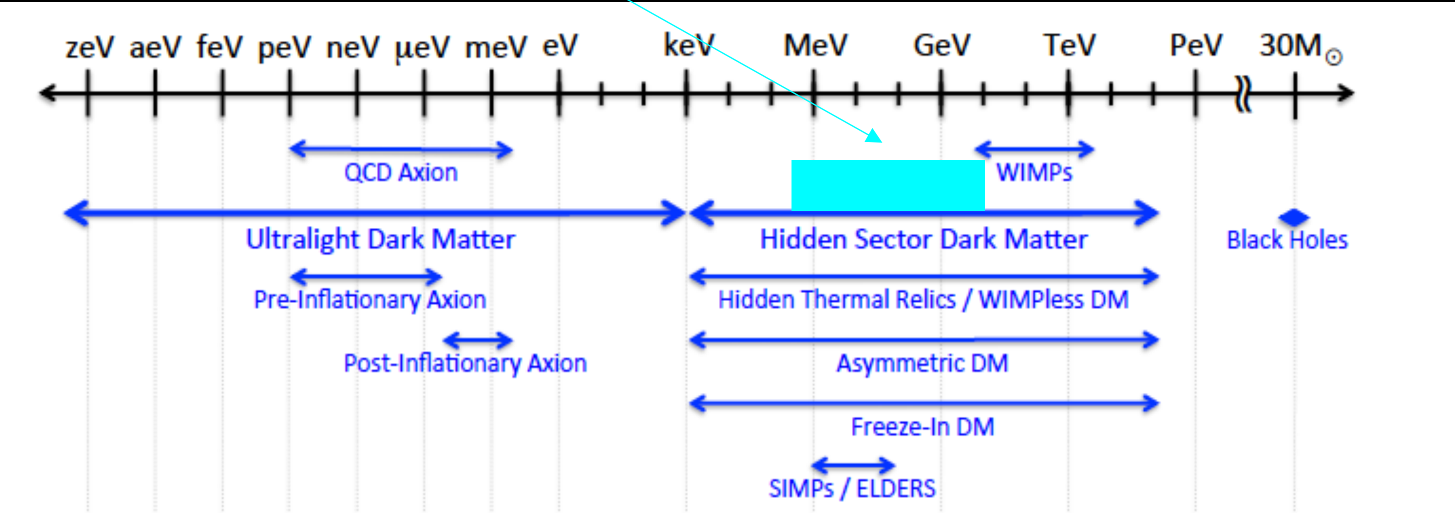
What FIPs can provide us: A notable example

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,…..

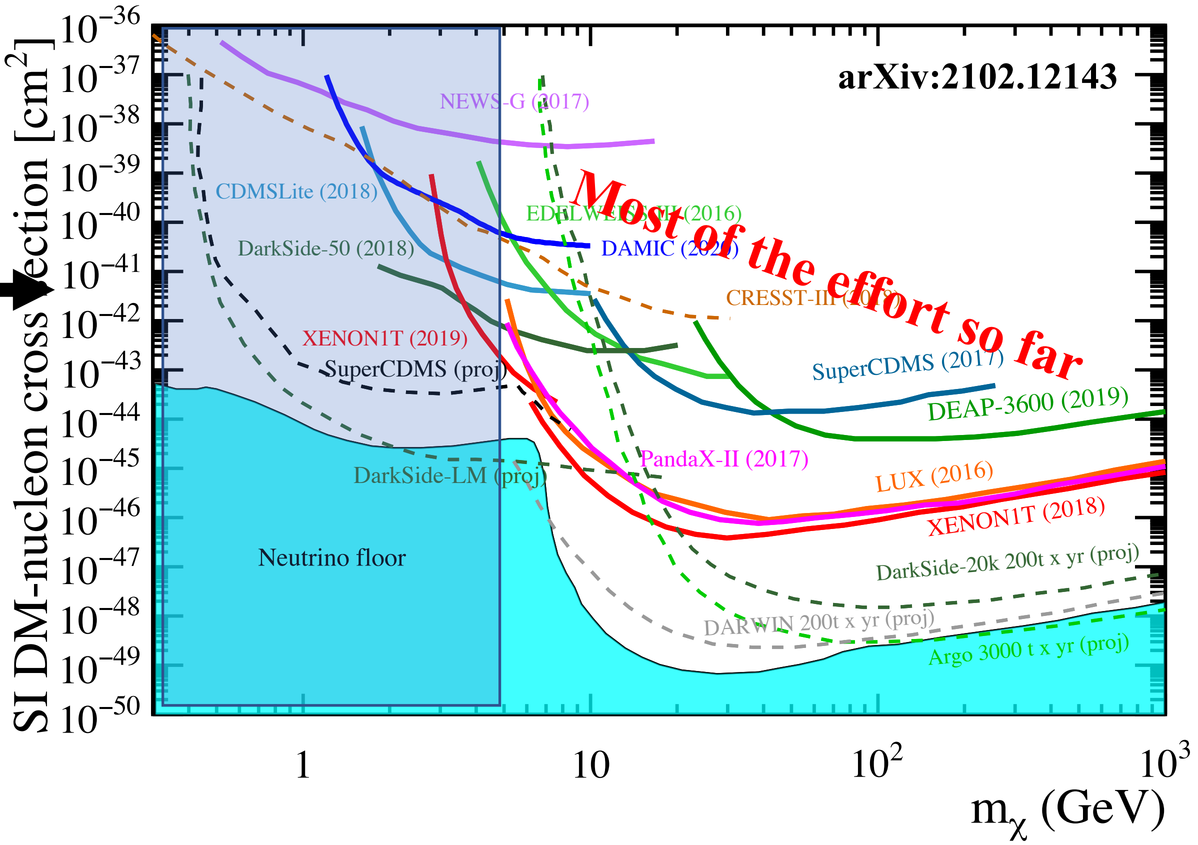
DM available mass range
~ 80 orders of magnitude..



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)

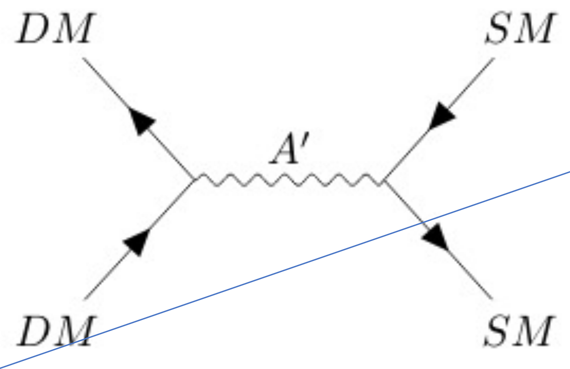
$$< \sigma v > \sim \alpha_D \varepsilon^2 \alpha \times \frac{m_{\rm DM}^2}{m_{A'}^4} \times m_{\rm DM}^2 \times \frac{1}{m_{\rm DM}^2}$$

y variable

DM Direct detection experiments

DM scattering with e/protons

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



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

Astroparticle, cosmology

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

Physics Beyond Colliders

PBC Experiments/projects

https://indico.cern.ch/event/1089151/contributions/4620414/attachments/2358602/4025863/FPC-Dec2021-Lanfranchi.pdf

Experiment	Dataset assumed for sensitivities, beams	Tentative Timescale	References	Benchmarks	Comments
NA64-e	3x10^{12} eot, electrons, 100 GeV	< LS3 (2025) (approved)	CERN-SPSC-2018-004 ; SPSC-P-348-ADD-2.	BC1, BC2, BC9	Extrapolation from data
FASER	150 fb^{-1}, pp@13 TeV	< LS3 (2025) (approved)	arXiv:1812.09139 ; CERN-LHCC-2018-036	BC1, BC9, BC9, BC11	Full simulation ? Bkg included?
NA62-dump	10^{18} pot, protons 400 GeV	< LS3 (2025) (approved)	CERN-SPSC-2019-039 ; SPSC-P-326-ADD-1	BC1, BC4, BC5, BC6, BC7, BC8, BC9, BC10, BC11	Full simulation, bkg from data
milliQan	3 ab^{-1}	First run: 2022		BC3	
nTOF	6x10^{17} pot, protons, 20 GeV	2022-2023	INTC-I_233	BC1	New experiment
NA64-mu	Up to 2x10^{13} mot, muons, 160 GeV ~10^{7} μ/spill	LS3 (2026) < run < LS4 (2031) Pilot run 11/2021	CERN-SPSC-2019-002 ; SPSC-P-359, CERN-SPSC-2018-024 ; SPSC-P-348-ADD-3 1903.07899, 2110.15111	BC2	Full simulation, Bkg included.
SHADOWS	Phase1: 10^{19} pot, protons , 400 GeV Phase2: 5 10^{19}, protons, 400 GeV	LS3 < run < LS4 (2031) LS4 < run < LS5 (2035)	EoI: 2110.08025	BC4, BC5, BC6, BC7, BC8, BC10, BC11	Fast simulation, bkg being estimated using dump data in ECN3

In green: already approved
In black: under consideration

PBC Experiments/projects

Experiment	Dataset assumed for sensitivities, beams	Tentative Timescale	References	Benchmarks	Comments
SHiP	2×10^{20} pot, 400 GeV protons	2037+ ?	CDS: CERN-SPSC-2019-049 ; SPSC-SR-263 Progress Report: CERN-SPSC-2019-010	BC1, BC2, BC4, BC5, BC6, BC7, BC8, BC9, BC10, BC11	Full simulation, bkg included Based on MC sample: 1.8×10^{9} pot, with p>1 GeV from Progress Report, p. 24, CERN-SPSC-2019-010 ; SPSC-SR-248)
KLEVER/NA62 high intensity	A few 10^{19} pot/year	After LS4 ?	1901.03199	BC4, BC9, ….	Full simulation, bkg evaluated but not included in results?
CODEX-b	300 fb^{-1}, pp@14 TeV	2038 (end of HiLumi) CODEX-beta could start after LS3	EOI: 1911.00481 Background: 1912.03846	BC4, BC5, BC6, BC7, BC8, BC10, BC11	Fast simulation, background evaluated but not included in results?
MATHUSLA	3 ab^{-1}	2038 (end of HiLumi)	Physics case: 1806.07396 LoI: 1811.00927	BC4, BC5, BC6, BC7, BC8, BC10, BC11	Fast simulation, no bkg (bkg being evaluated with data)
FLArE@FPF	3 ab^{-1}	2038 (end of HiLumi)	2109.10905	DM via scattering (BC2)	Fast simulation, no bkg
FASER-2@FPF	3 ab^{-1}	2038 (end of HiLumi)	2109.10905	BC1, BC4, BC5, BC6, BC7, BC8, BC9, BC10, BC11	Fast simulation, no bkg
FORMOSA@FPF	3 ab^{-1}	2038 (end of HiLumi)	2109.10905, 2010.07941	BC3	Fast simulation, no bkg
Gamma Factory	Laser on stripped ions (LHC)	Still undefined.. PoP crucial to understand.	2105.10289 (DP)	BC1, BC6	Fast simulation, no bkg

FIP related experiments/projects @ accelerators beyond PBC

All approved experiments

Experiment	LAB	Dataset assumed for sensitivities, beam	Timescale	Benchmarks	Comments
DarkQUEST	FNAL	10^{18} pot, protons, 120 GeV	2022-2023	BC1, BC4, BC5	Depends on the situation of SpinQUEST (QCD)
LDMX	SLAC	4×10^{14} eot, electrons 4 GeV 1.6×10^{15} eot, electrons 8 GeV	2024-2031	Mostly BC2	Full simulation
SUBMET	JPARC	10^{22} pot, T2K beam, 30 GeV, protons	First run: 2022-2023	BC3	0.5 M$ already secured from KOREA; status of simulation?
LUXE	DESY	XFEL, 16.5 GeV e-, 1.5×10^{9} e-/burst; 40 (350) TW optical laser	2025-2026	BC1, BC9, BC10	Fast simulation, no bkg
mu3e	PSI	Muons, 29 MeV, 10^{8} μ/sec (10^{10} μ/sec)	Phase-1: 2023 Phase-2: 2029	BC1, ….	Phase-I and phase-II
PADME	LNF	e+, 500 MeV	running	BC1, BC2, BC9	data
Belle II	KEK	$e^+ e^-$ @ Y(4S); 220 fb^{-1} collected, 1 ab^{-1} by 2024, 50 ab^{-1} by 2031++	running	BC1, BC2, BC64, BC5, BC6, BC7, BC8, BC9, BC10	data
T2K ND280	KEK	30 GeV proton beam	running	BC6, BC7, BC8	data
microBooNE	FNAL	Protons, 8 GeV, 10^{21} pot	running	BC2 (DM scattering),others?	data
Dark MESA	Mainz	e-, 155 MeV, 150 uA	2031^{++}?	BC1,…	Full simulation?

Physics Beyond Colliders

All (but FACET) approved experiments

FIP related experiments/projects @ accelerators: beyond PBC

Experiment	LAB	Dataset assumed for sensitivities, beam	Timescale	Benchmarks	Comments
LHCb	CERN	50 fb^{-1} (phase I), 300 fb^{-1} (phase II)	< 2031 (phaseI) < 2038 (phaseII)	BC1, BC4, BC5	Mass range: 2m(mu) – B (mass). Sensitive mostly to large couplings.
ATLAS/CMS	CERN	Up to 3 ab^{-1}	Now – 2038++	BC1, BC4, BC5, BC6, BC7, BC7, BC9, BC10	Mostly sensitive above 10 GeV and large couplings. Below 10 GeV very limited sensitivity.
Moedal/MAPP	CERN	Up to 3 ab^{-1}	Now – 2038++		
FACET	CERN	Up to 3 ab-1	HiLumi		Under consideration within CMS
HyperK near detectors	KEK		??	BC6, BC7, BC8	As T2K-ND280 but larger sample
DUNE near detectors	FNAL	10^{22} pot (11 years of data taking)	2040++	BC6, BC7, BC8	Several estimates done by theorists.

UNDER CONSTRUCTION

- **Proceedings of the 2020 edition (FIPs 2020) :**

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

Back to SHADOWS…..

Why the 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 4.8s pulse duration: ~ 10^{12} pot/sec, up to 2×10^{18} pot/year

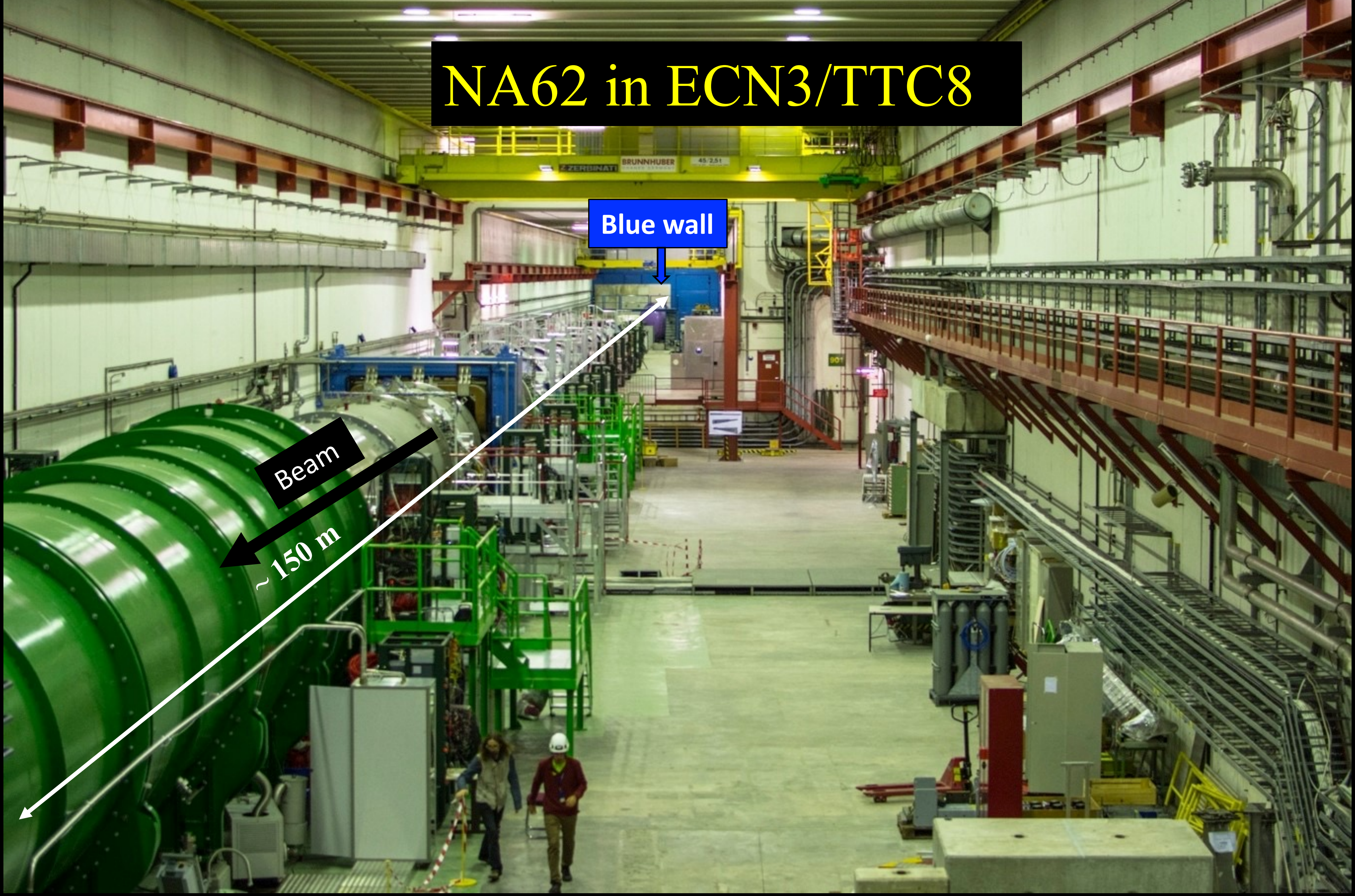
- ✓ K12 beam intensity proposed to be increased by a factor x6-7
  - for high intensity K beams and SHADOWS → up to 1.2×10^{19} pot/year

Physics Experiment	Proton Momentum	[1]SPS Cycle [s]	Proton / pulse	[2]Pulses / day	Days / year	POT/year
HIKE–Phase1			$1.2\ 10^{13}$			$0.72\ 10^{19}$
HIKE–Phase2	400 Gev/c	4.8 / 14.4	$2.0\ 10^{13}$	3000	200	$1.2\ 10^{19}$
HIKE–Phase3			$2.0\ 10^{13}$			$1.2\ 10^{19}$
HIKE-Dump Mode	400 Gev/c	4.8 / 14.4	[3]2-4 10^{13}	3000	200	[4]5.0 10^{19}
SHADOWS	400 Gev/c	4.8 / 14.4	$2.0\ 10^{13}$	3000	200	$1.2\ 10^{19}$
BDF/SHiP	400 Gev/c	1.2 / 7.2	$4.0\ 10^{13}$	5000	200	$4.0\ 10^{19}$

EDMS-2791543
(in preparation)

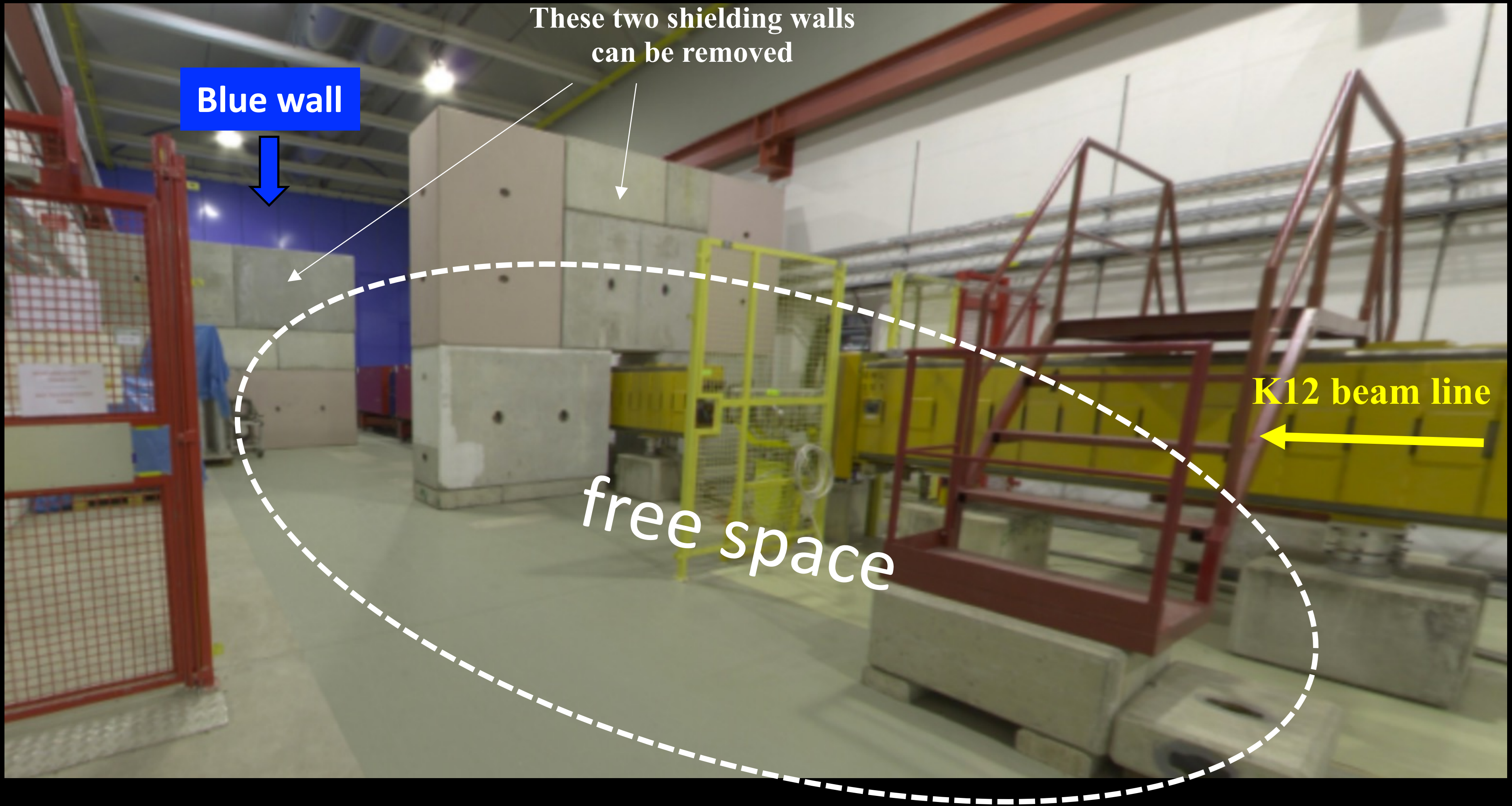
SHADOWS can collect 5×10^{19} pot in ~4 years of data taking starting after LS3 (~2028)

NA62 in ECN3/TTC8

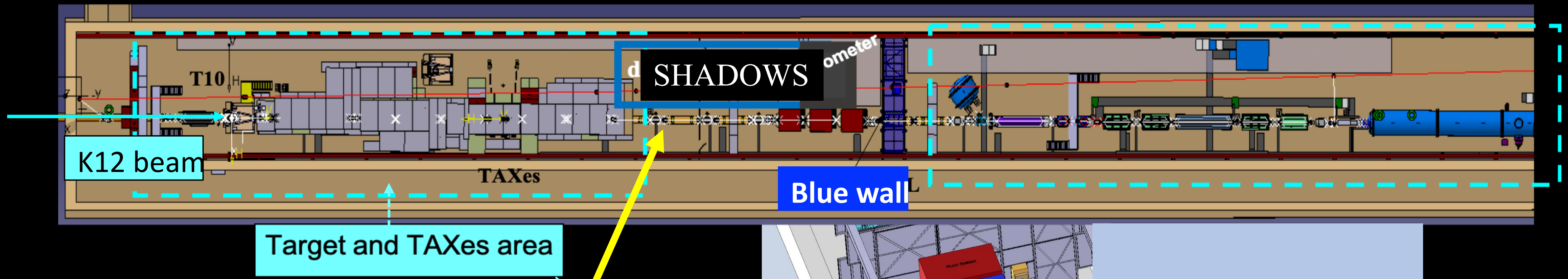


SHADOWS in TTC8/ECN3

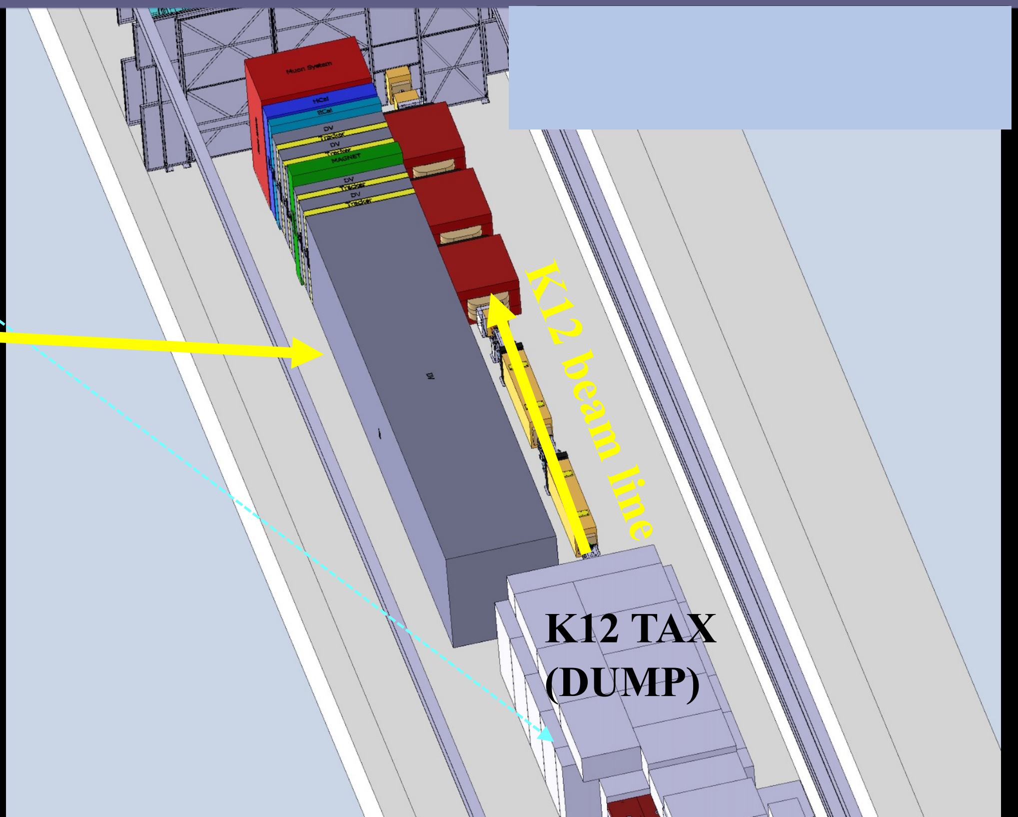
On the other side of the NA62 blue wall – in the target area (supervised zone)



SHADOWS in TTC8/ECN3



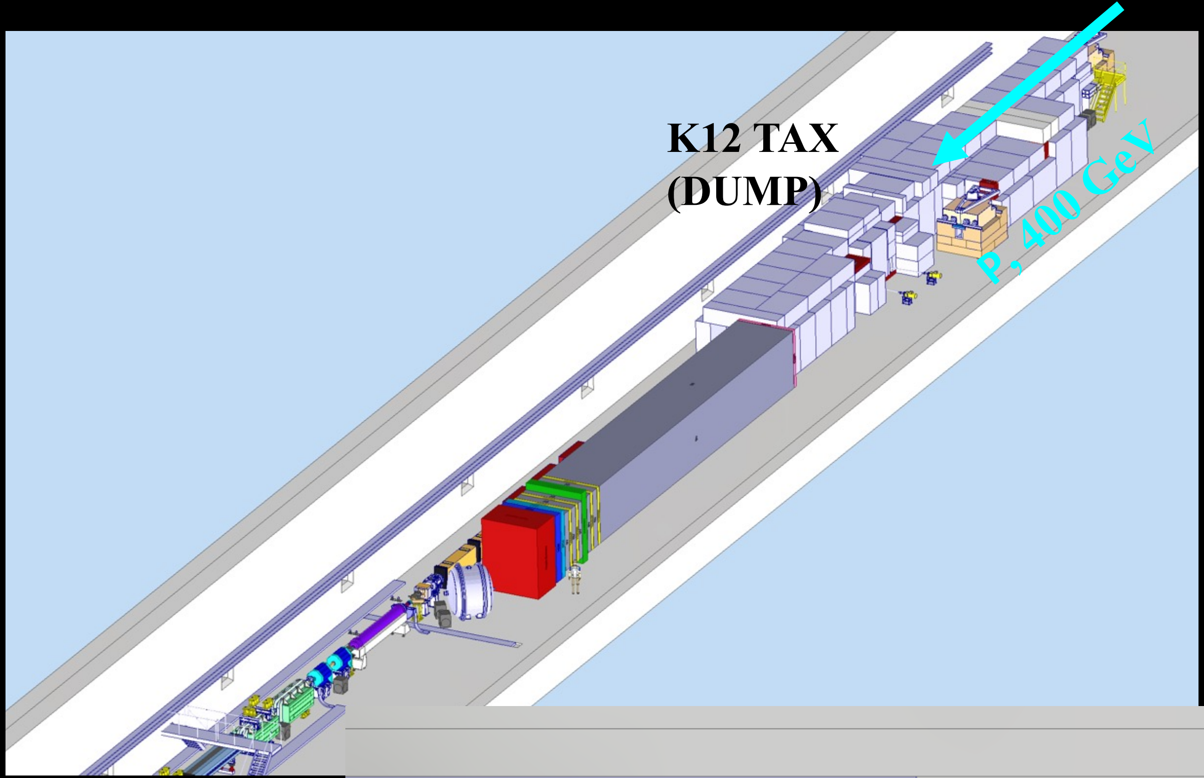
SHADOWS in the target area



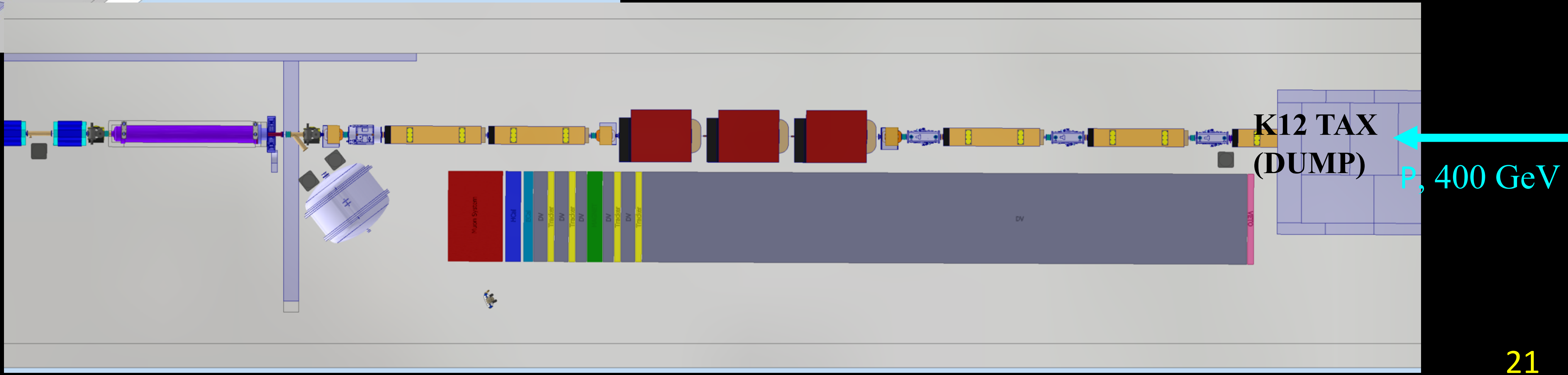
Preliminary Conceptual Layout

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)

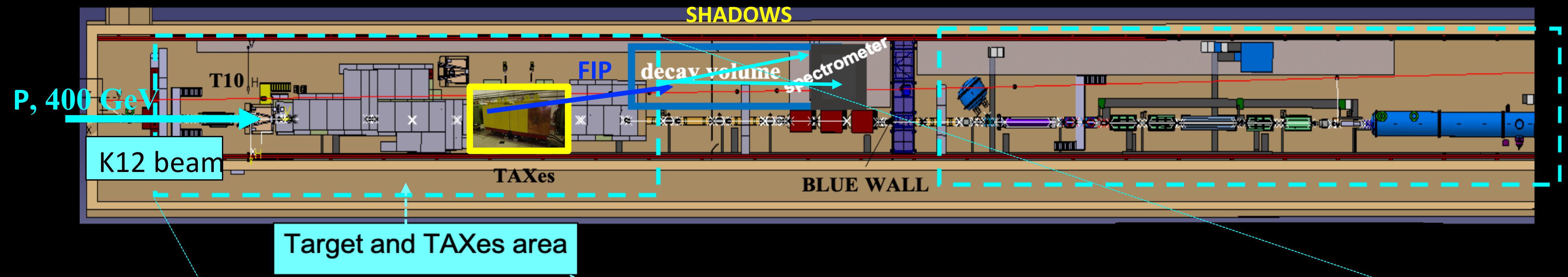
SHADOWS in ECN3/TTC8



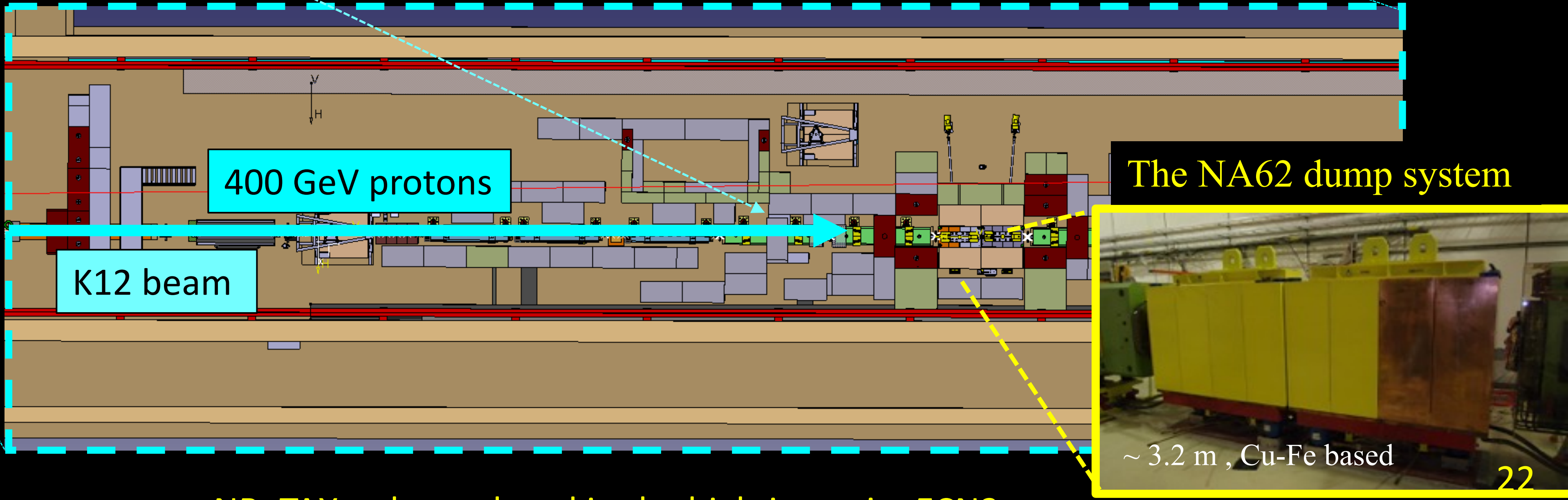
SHADOWS detector components:
20 m long, in vacuum decay volume,
Muon Veto, Tracking System with a (warm) dipole magnet,
Timing layer, Electro-magnetic calorimeter,
Iron filter and four Muon Stations.
Transversal size: 2.5x2.5 m^2.



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



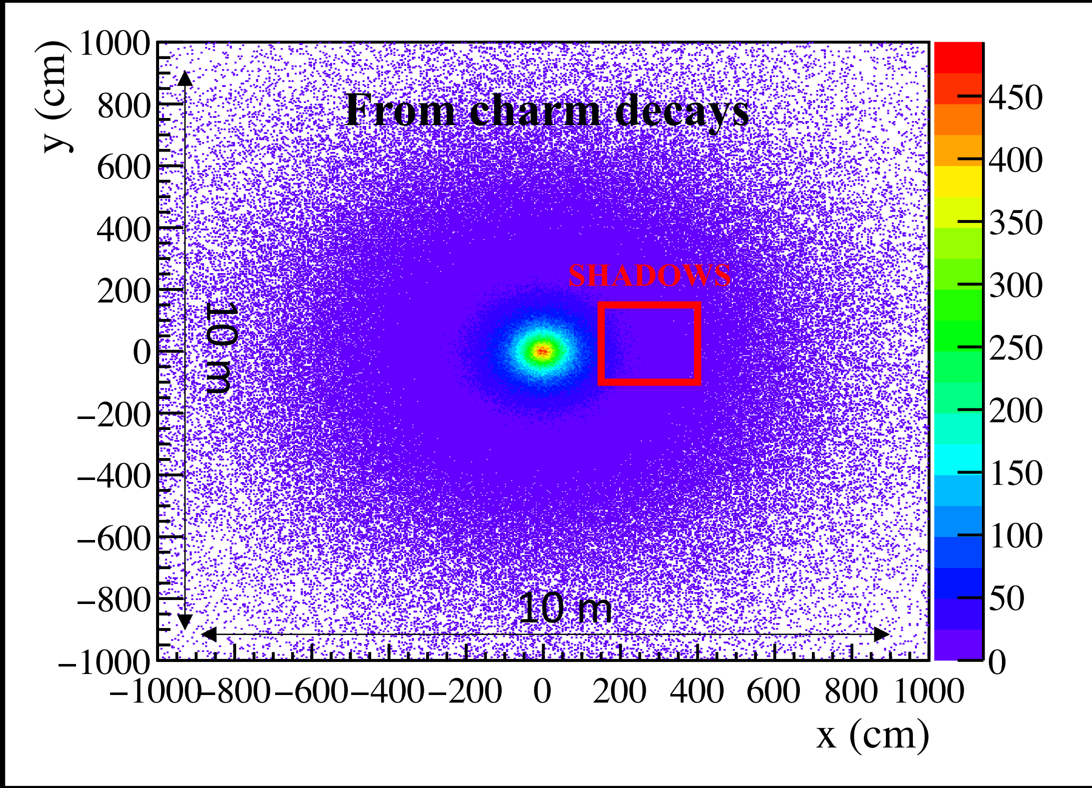
T10 target is lifted and the 400 GeV primary p beam is sent onto the dump

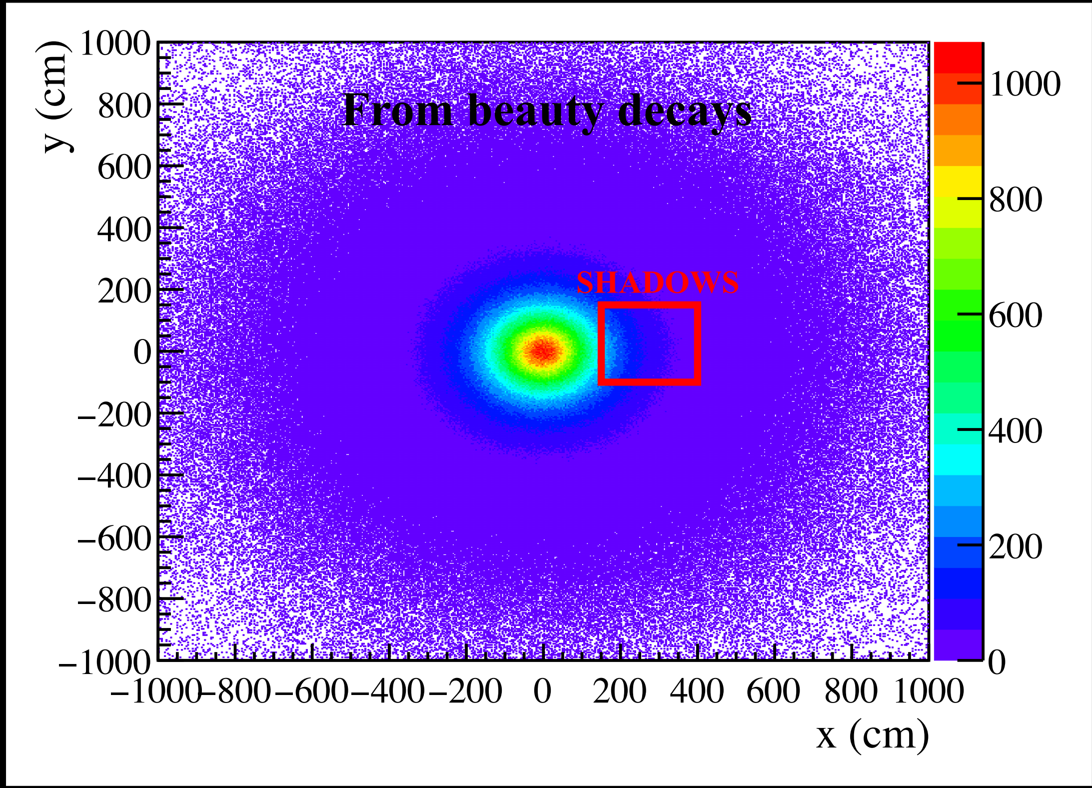


NB: TAX to be replaced in the high-intensity ECN3 era

Why “off-axis” works: Signal

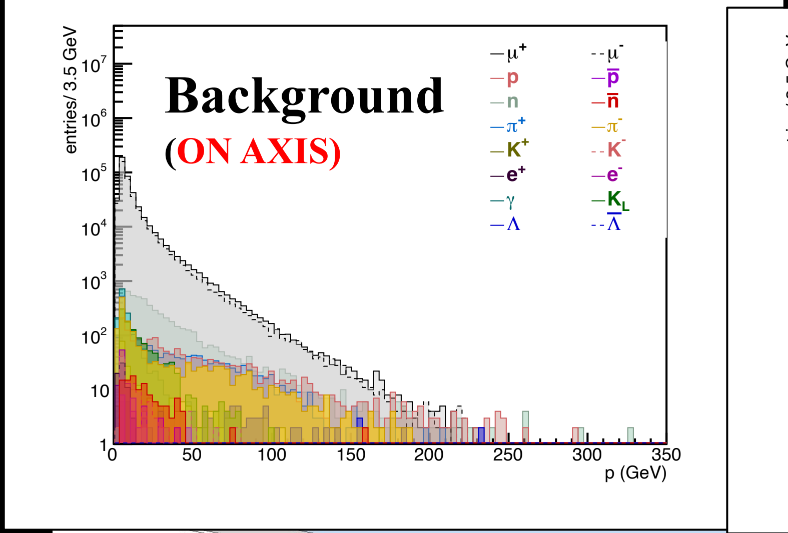
HNL→ **πμ** illumination @ first SHADOWS tracking station

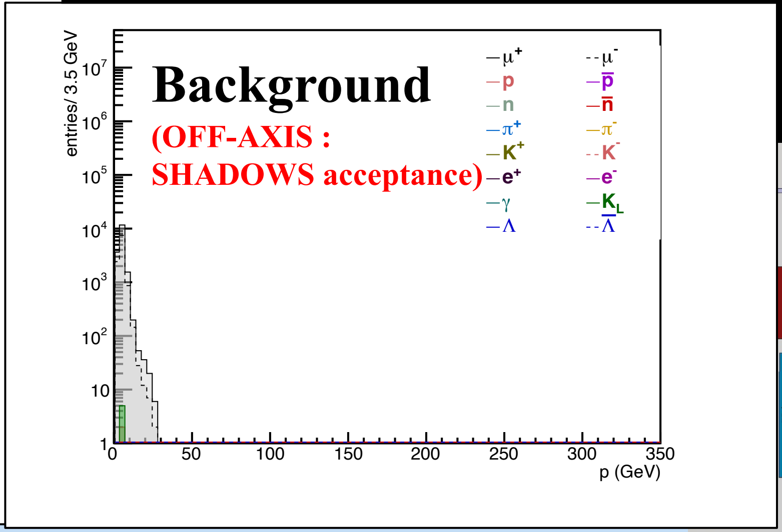


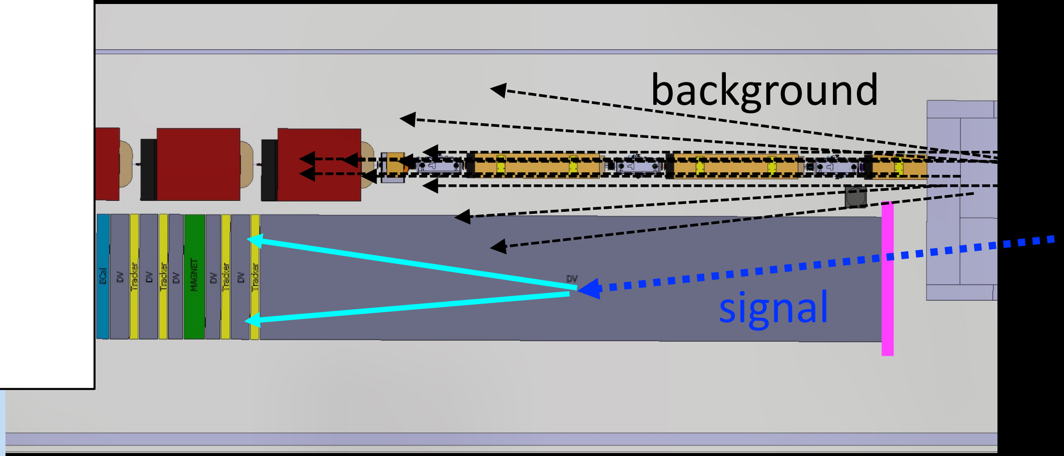


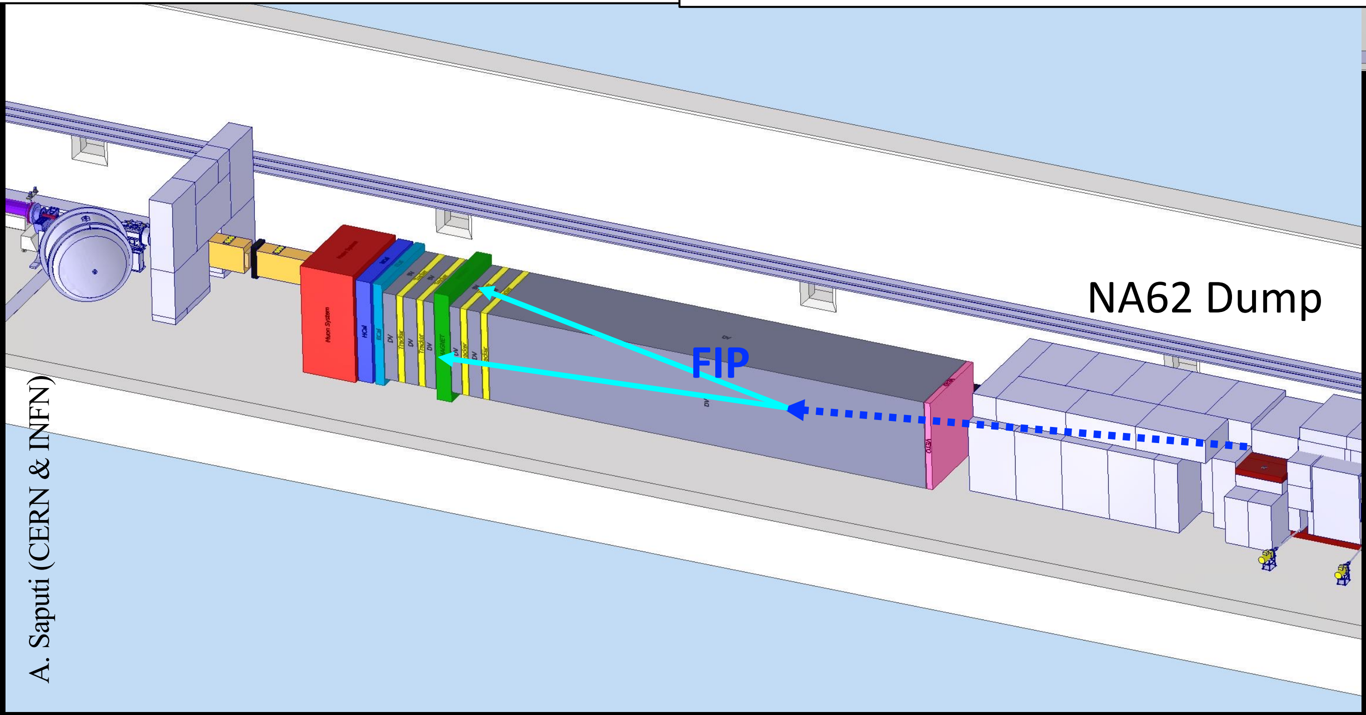
FIPs emerging from charm and beauty decays (HNLs, dark scalars, ALPs,…)
at the SPS energy are produced with a large polar angle

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).

NB: muon deep-inelastic scattering IS simulated in SHADOWS MC

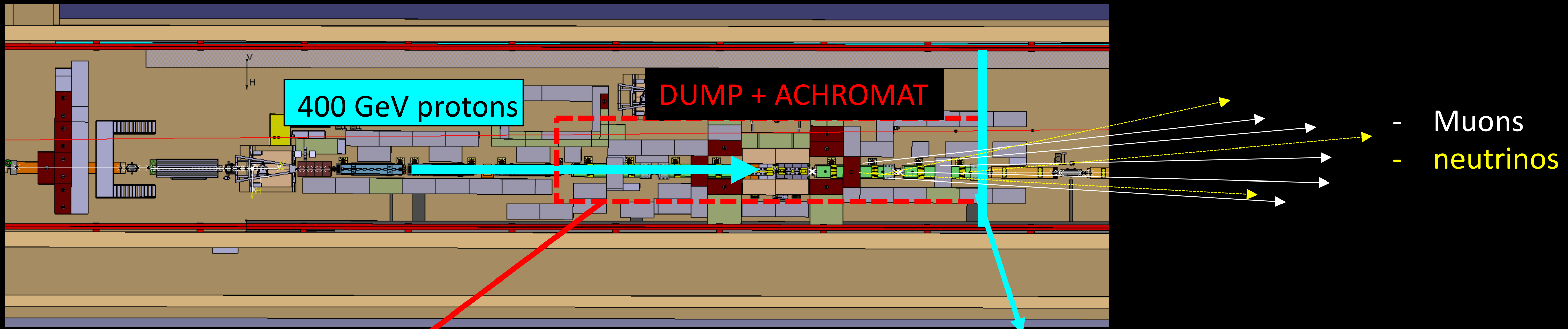
SHADOWS Main Idea: Stay close & stay off-axis!

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

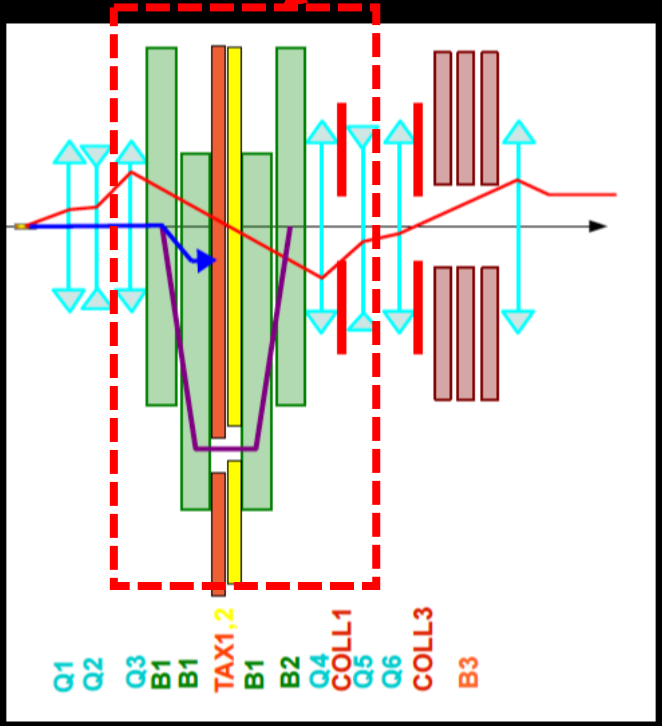
- Stay off-axis with respect to the beam line:
  to minimize acceptance for backgrounds (mostly peaked forward)

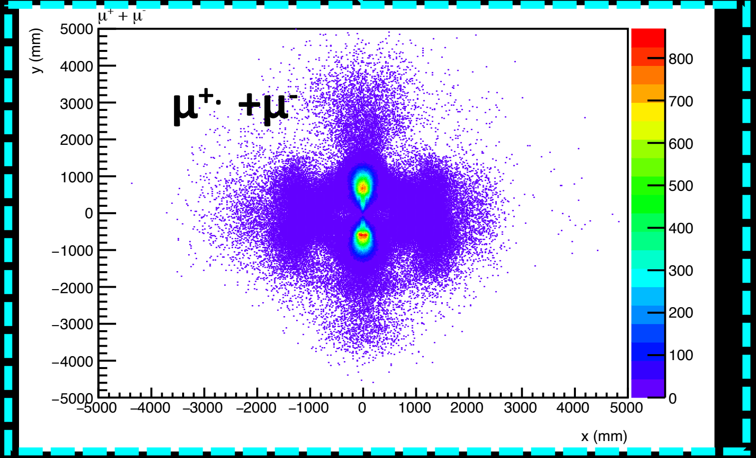
The beam-induced background: the name of the game

Beam-induced background after the dump

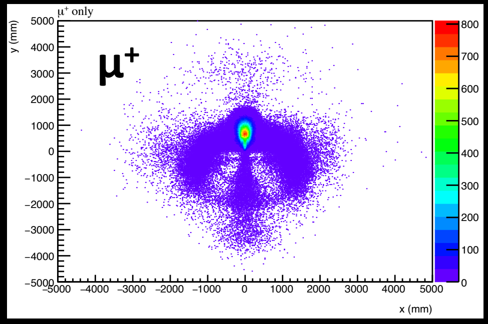


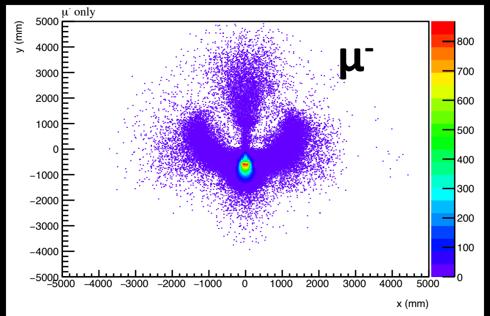
Layout of the K12 beamline around the dump



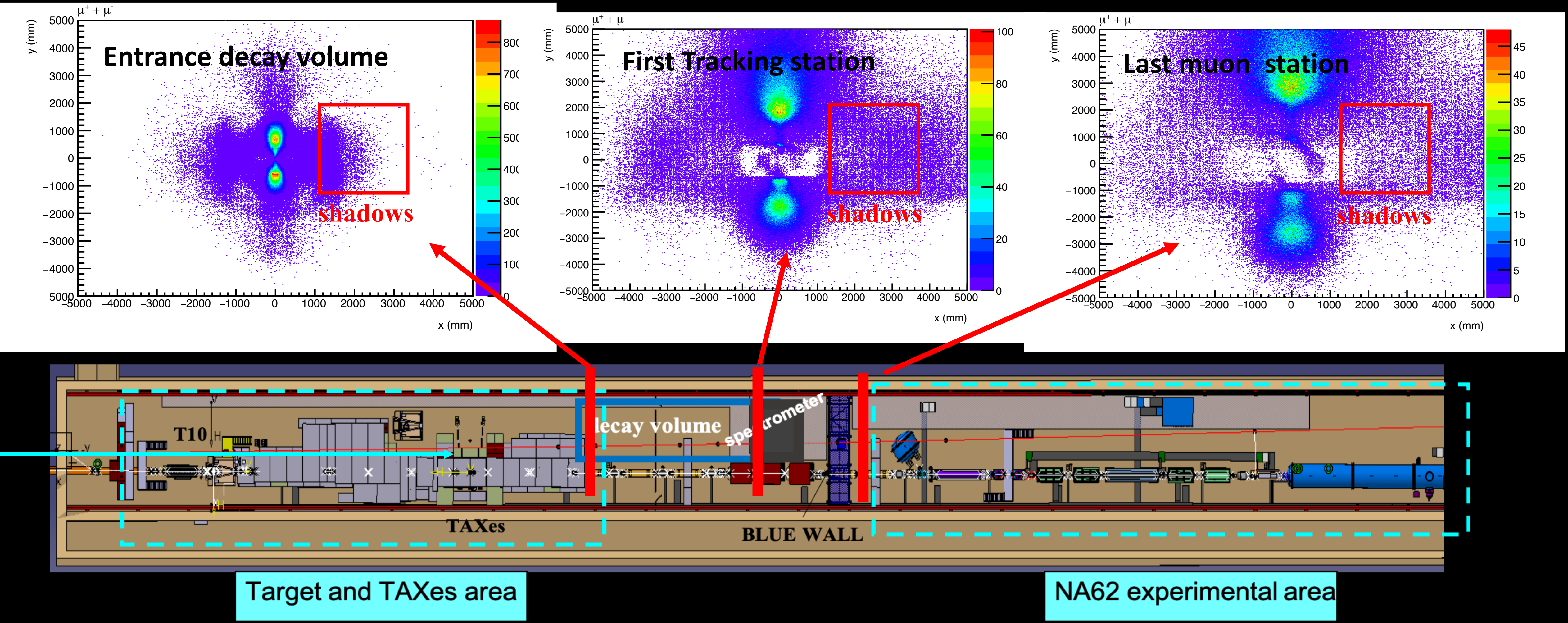


Muon illumination after the dump

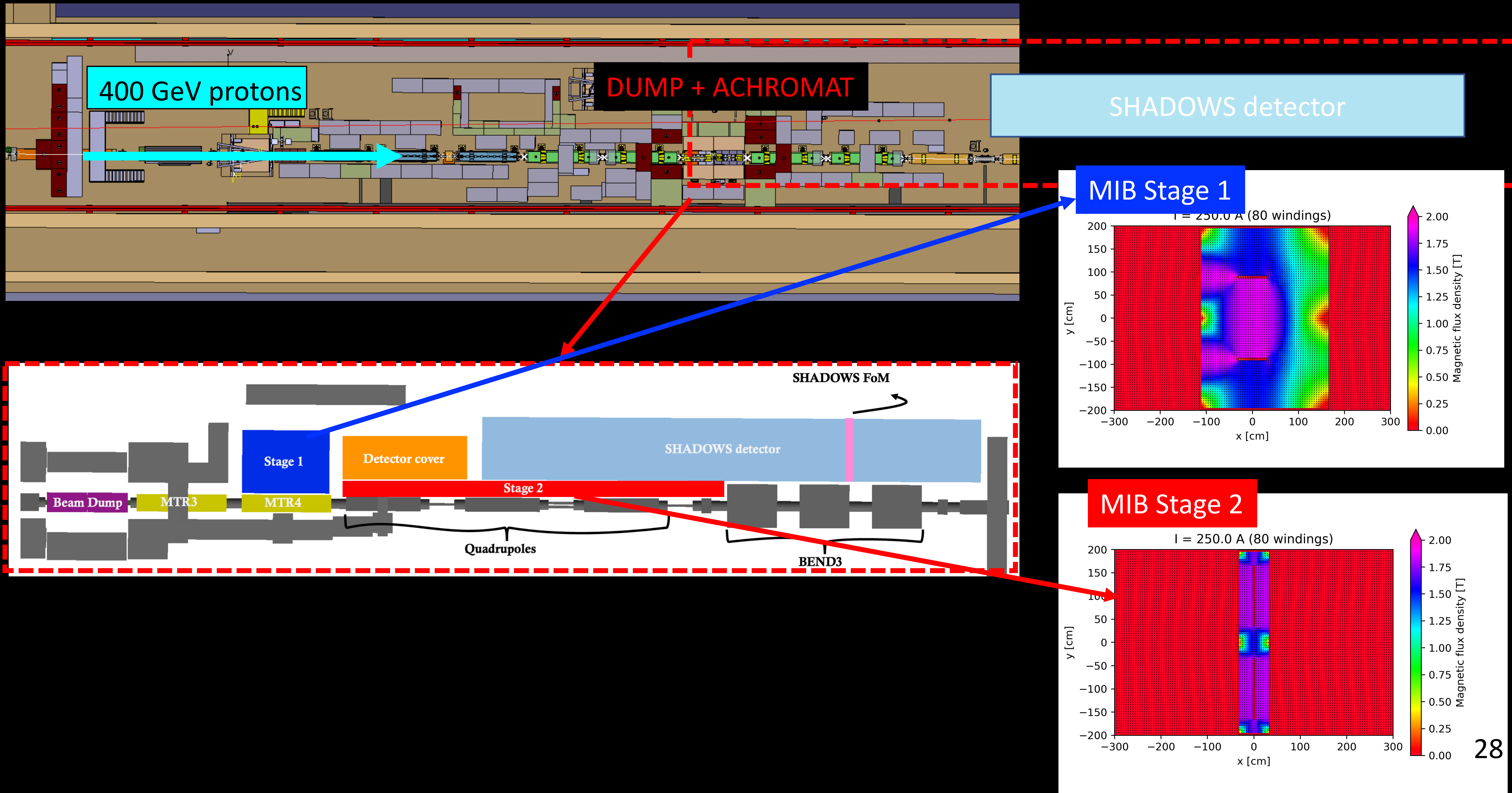




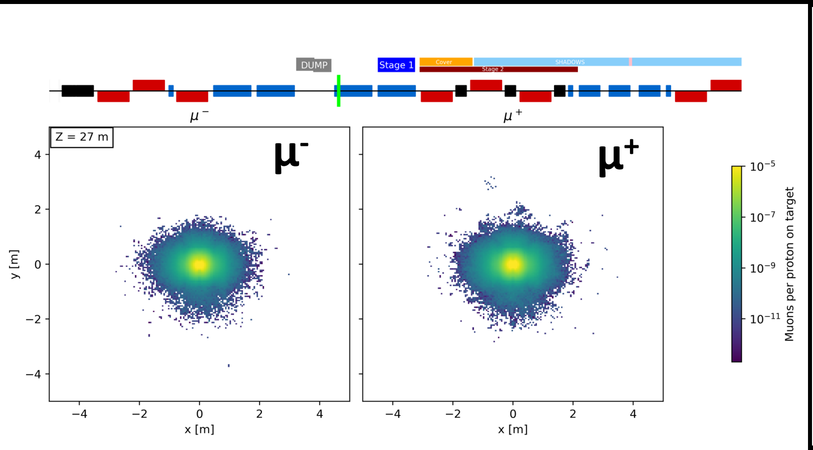
Muon illumination as a function of the position along the beamline

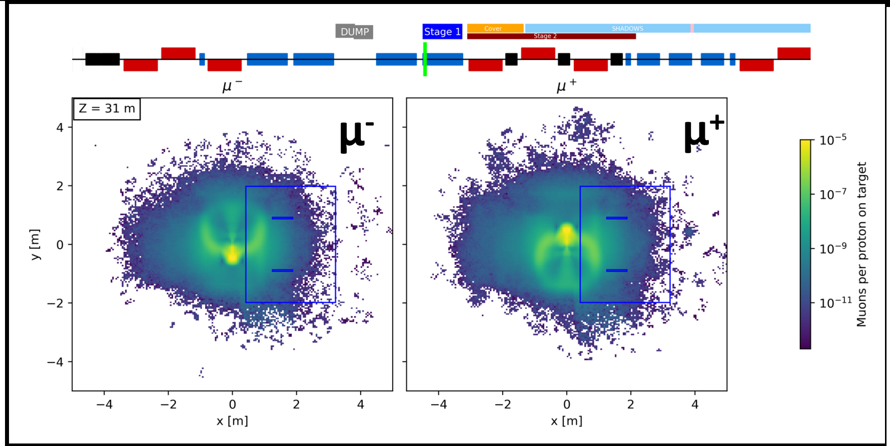


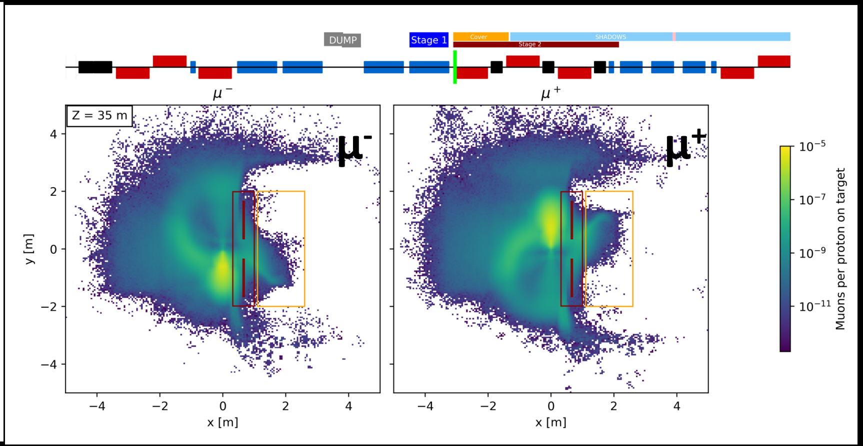
The sweeping system: the Magnetized Iron Blocks (MIB)

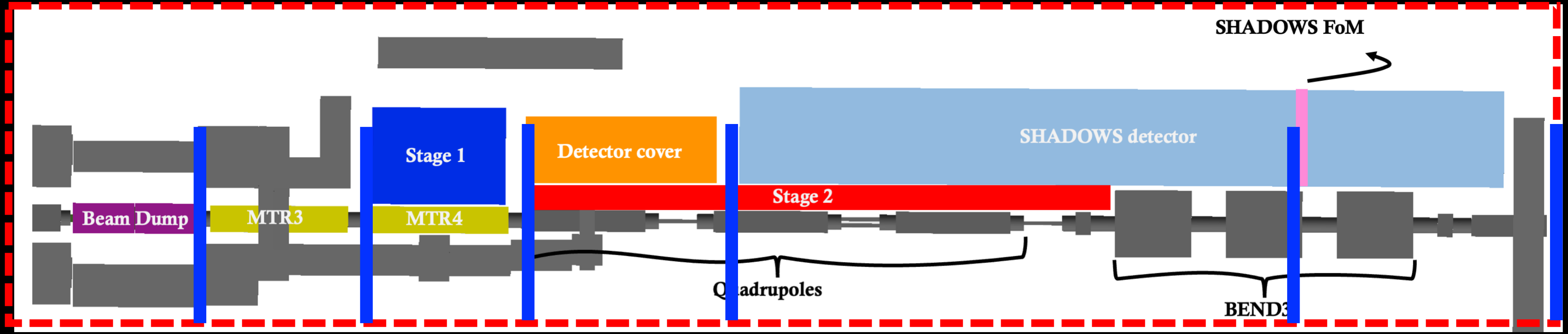


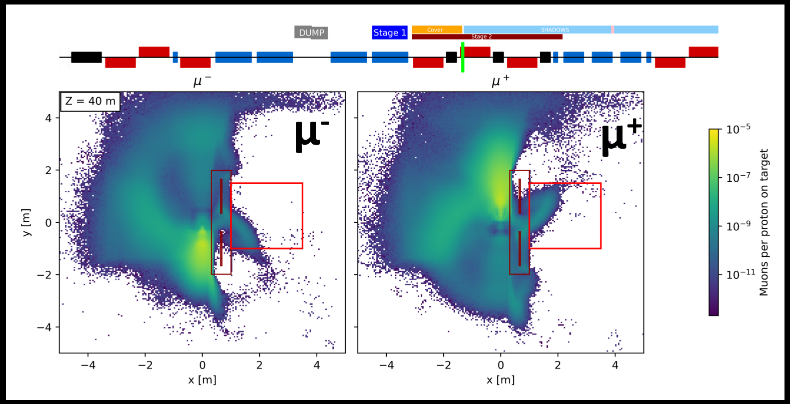
Muon Illumination with the Sweeping System (MIB)

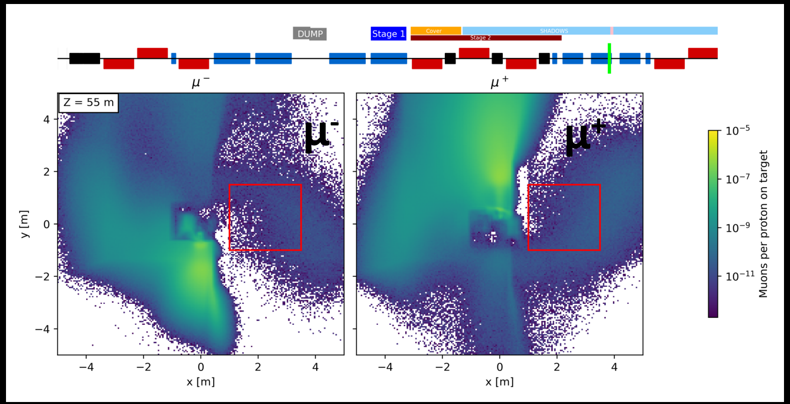


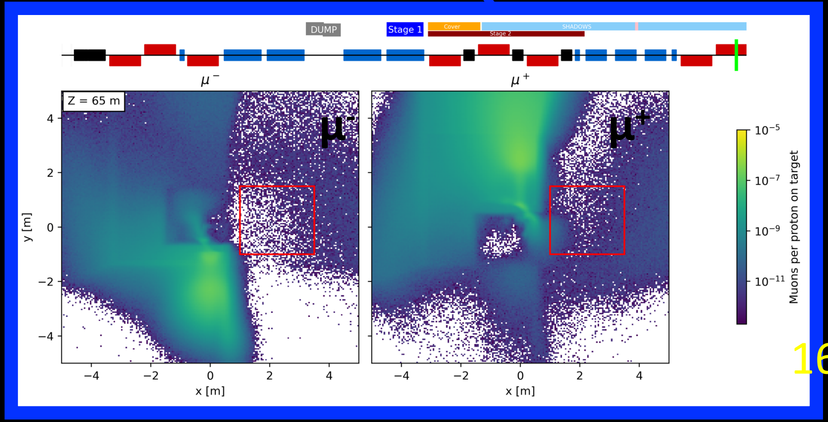






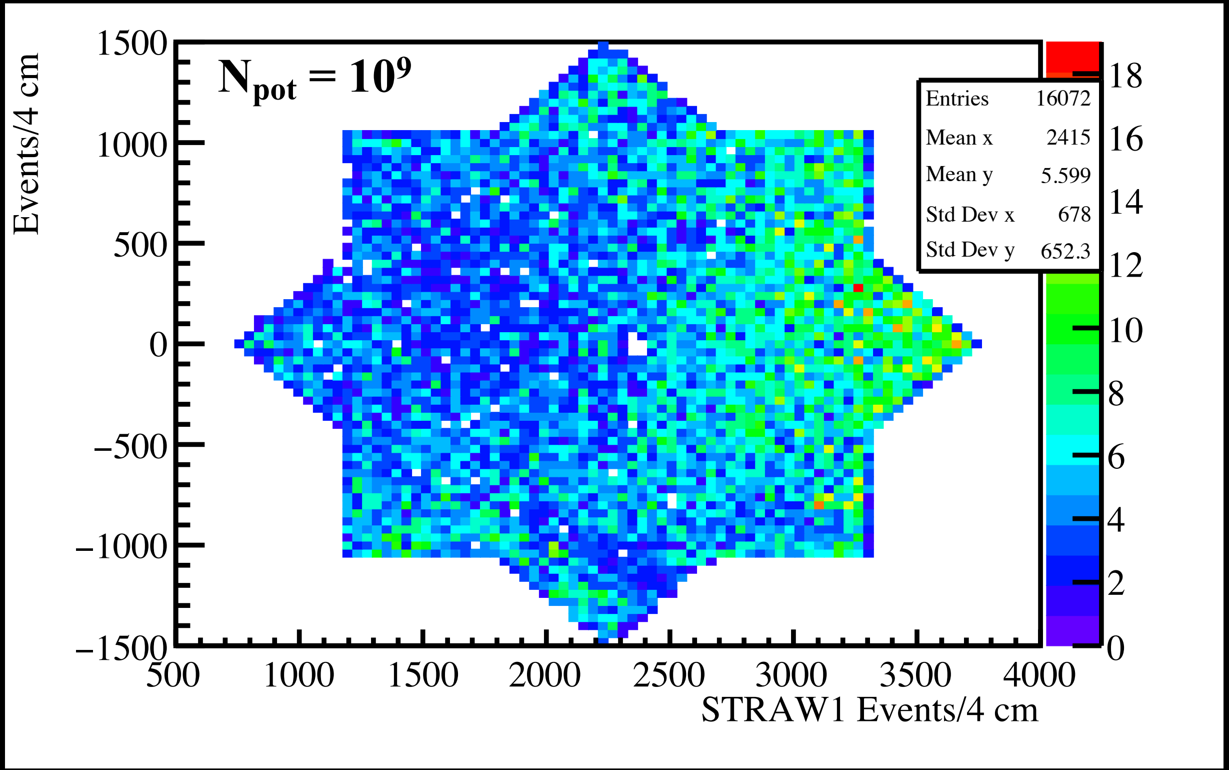


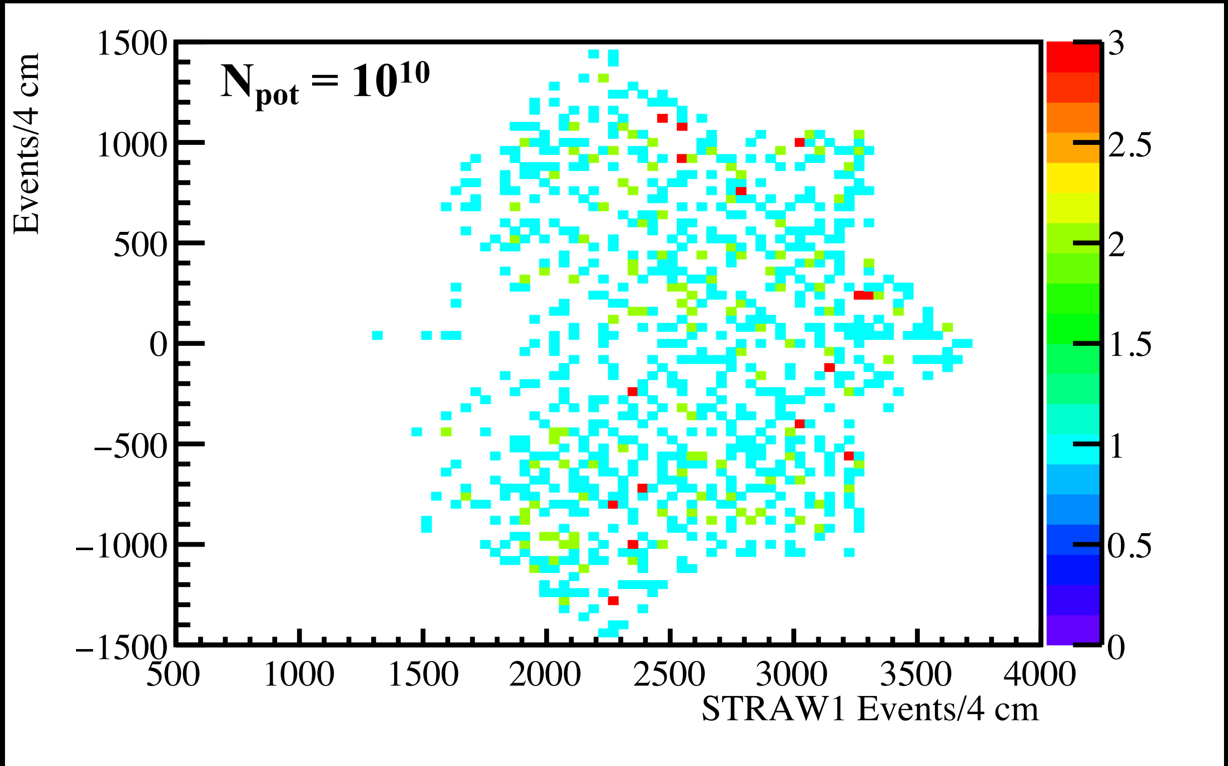




Muon Illumination with the Sweeping System (MIB) at first tracking chamber

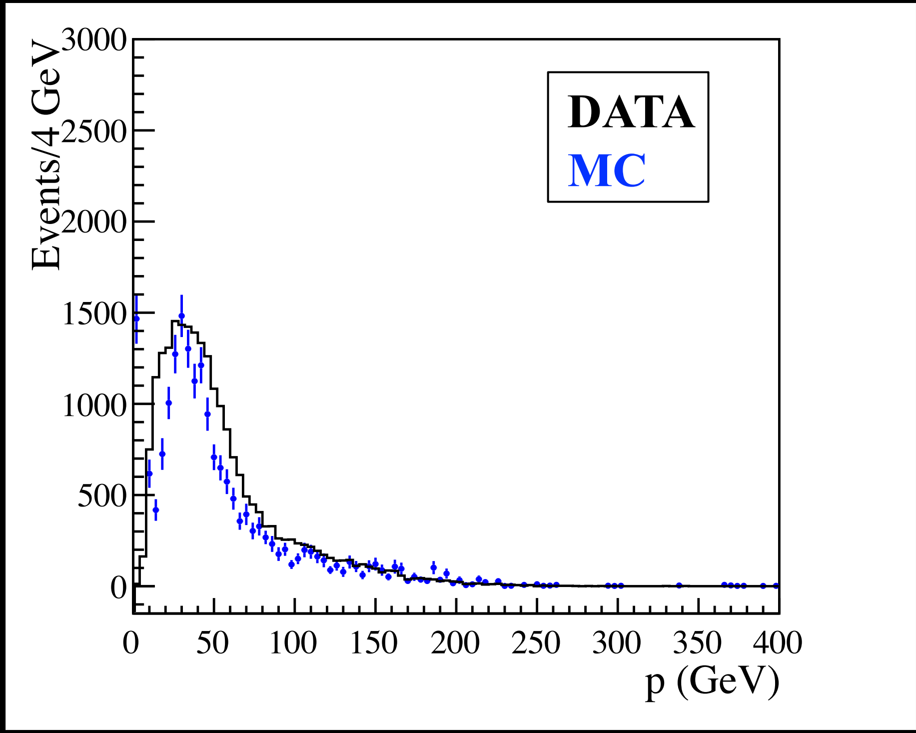
	$\mu^+ + \mu^-$	μ^+	μ^-
rate before MIB	100 MHz	50 MHz	50 MHz
MIB reduction factor	~ 120	~ 110	~ 150
rate after MIB	0.8 MHz	0.5 MHz	0.3 MHz

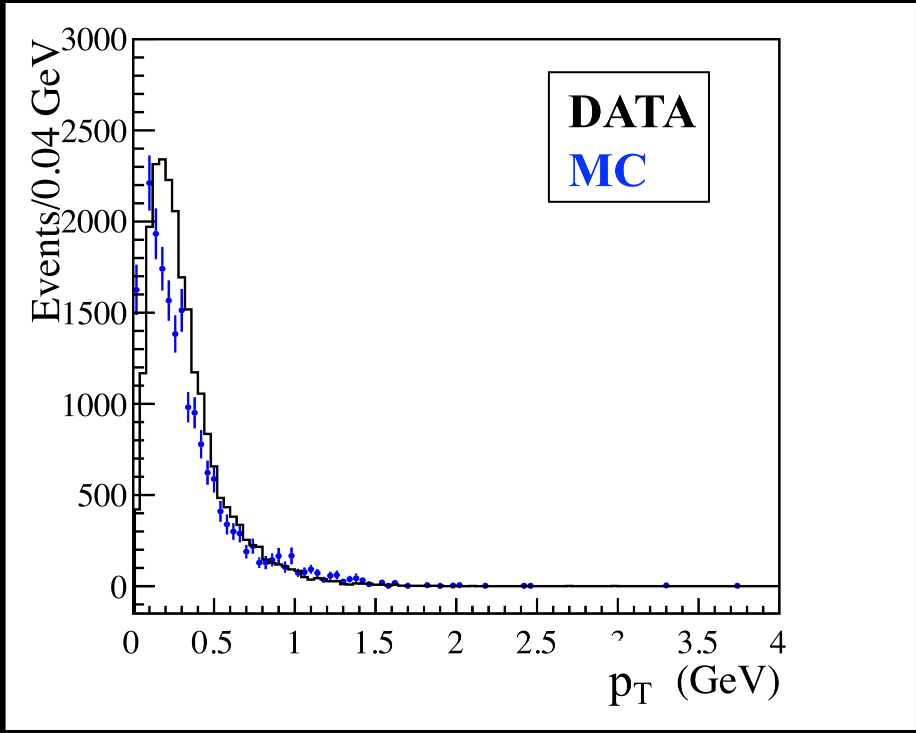




Validation of the simulated muon flux with NA62 data

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 x10^{17} pot



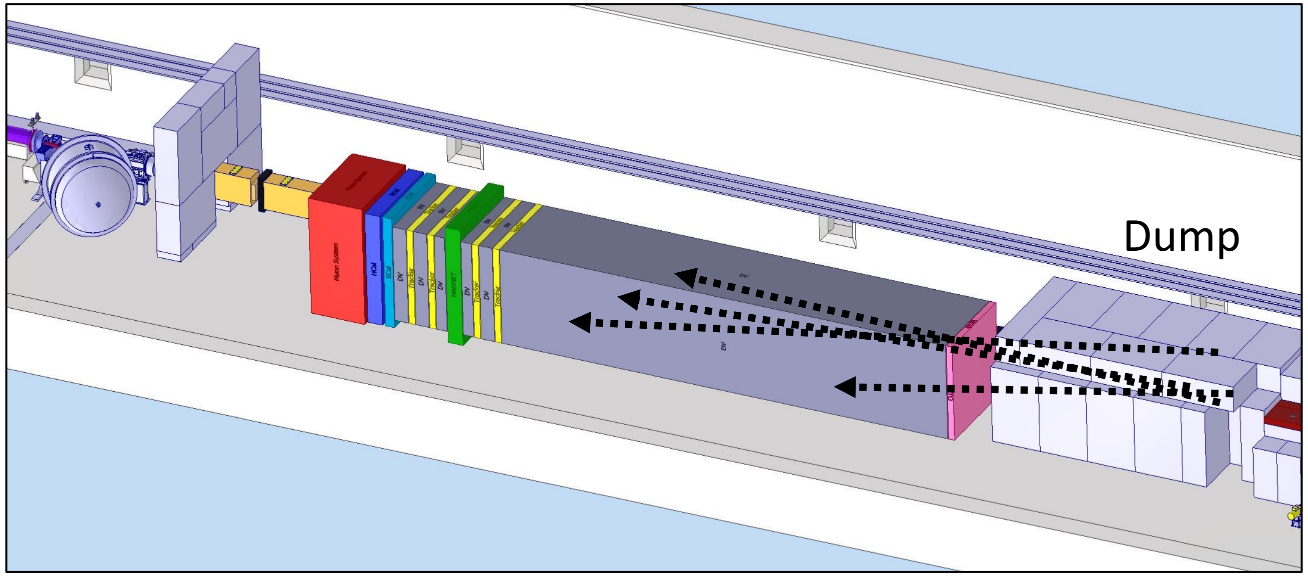


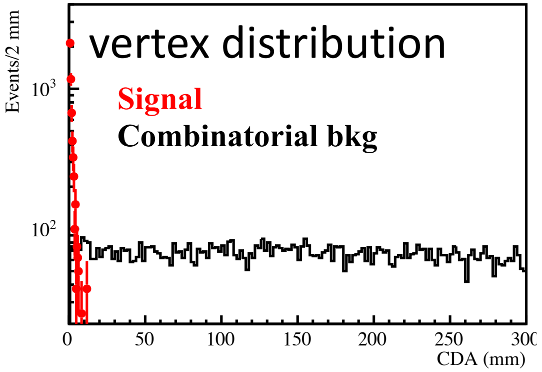
Excellent agreement in shape, the rate is about 3 times lower in MC than in data.
MC rates corrected by this factor.

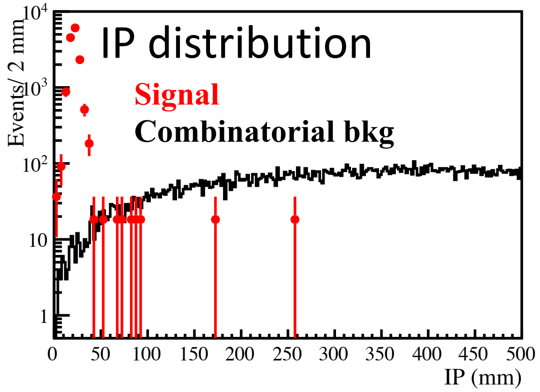
1. Background: Muon Combinatorial

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





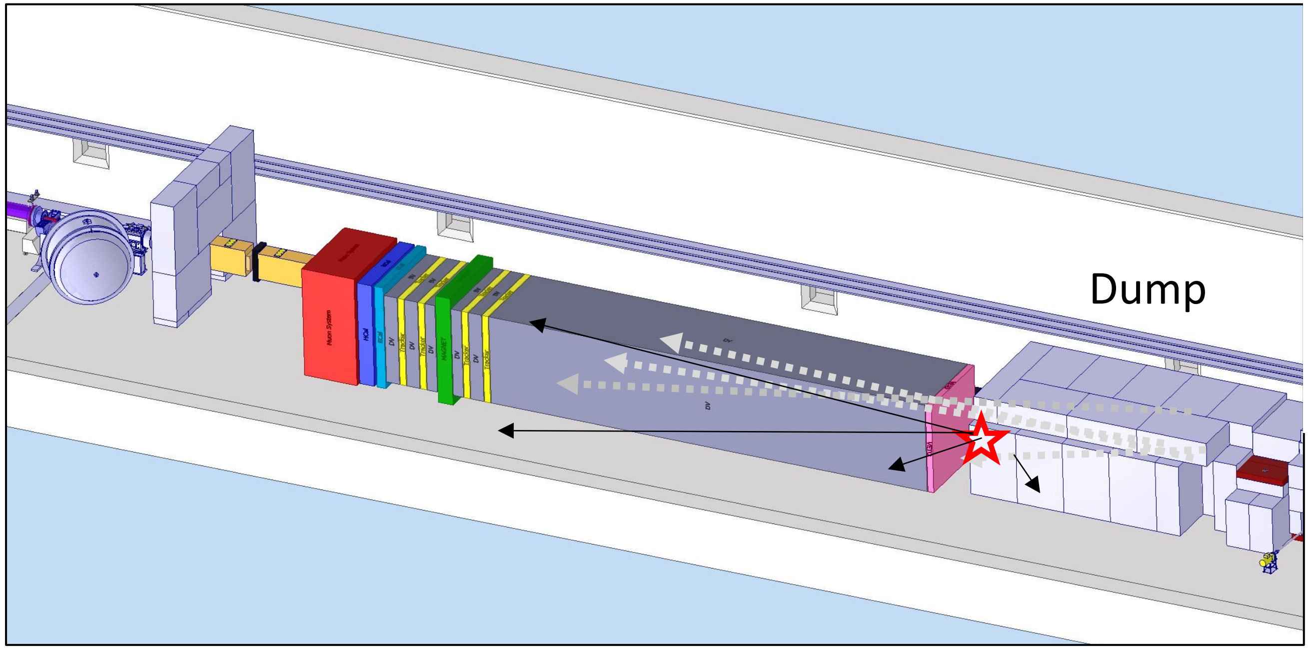


N(μμ) = 0.7 events in 5x10^{19} pot

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

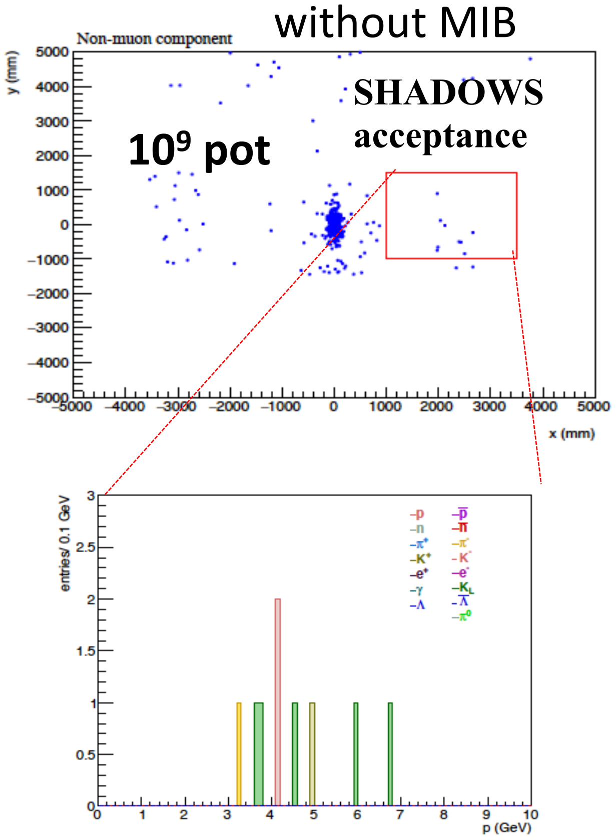
These interactions give signal in the Upstream Veto (UV), form a vertex very close to the boundaries of Decay Volume and do not point back to the impinging point of the proton beam onto the dump.

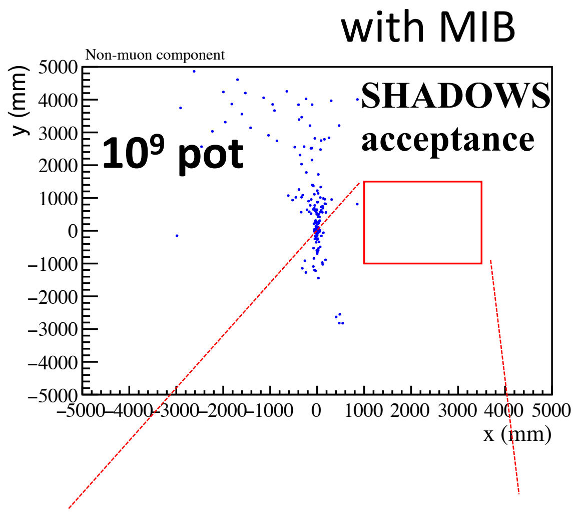
This will not be the dominant background….



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

Non muon background in front of decay vessel





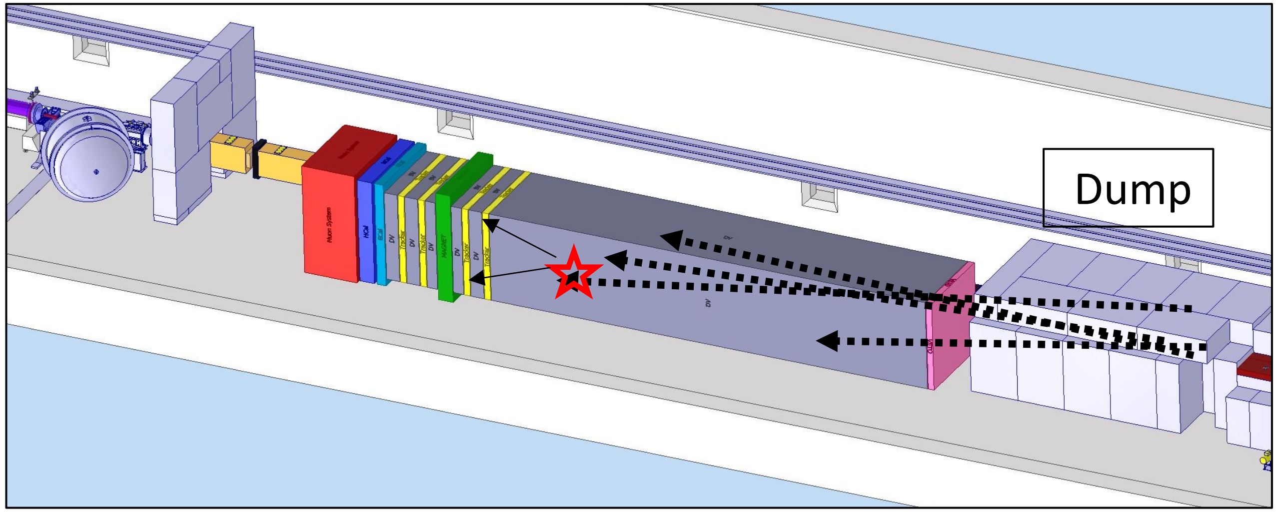
with MIB: zero events in a sample of 10^9 pot

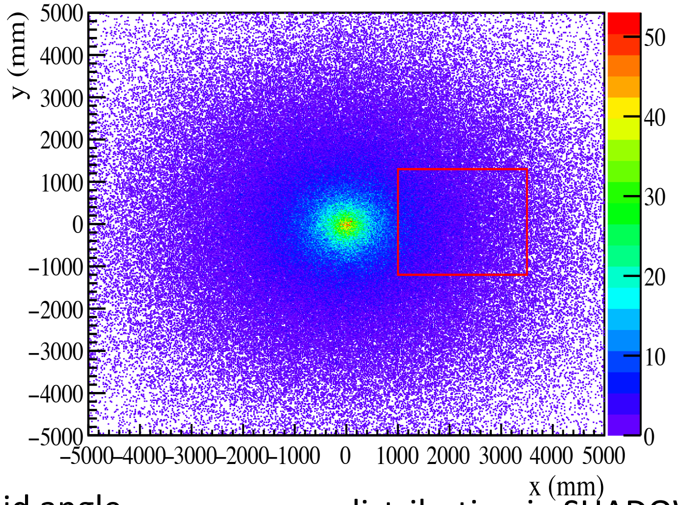
3. Background: Neutrino inelastic interactions in decay volume

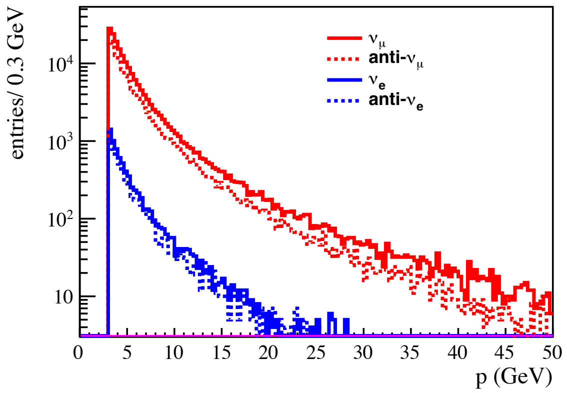
Number of inelastic interactions in 20 m long decay volume filled by air at atmospheric pressure, for $< E_\nu > \sim 5$ GeV:

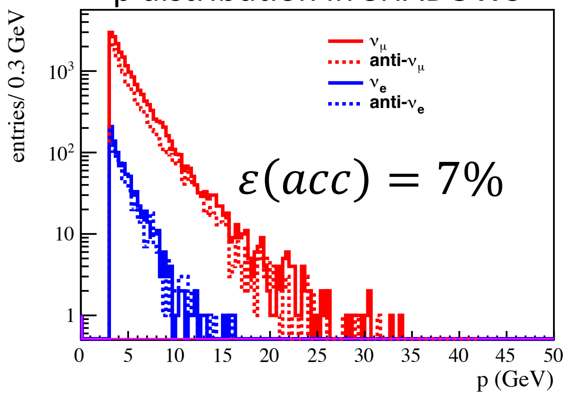
$$N_{\nu,\overline{\nu}\ \mathrm{inel.int.}}(N_{\mathrm{pot}} = 5 \times 10^{19}) = N_{\nu,\overline{\nu}} \times \varepsilon_{acc} \times P_{\mathrm{inel.int.}} \sim 1.5 \cdot 10^{16} \times 2 \cdot 10^{-15} \sim 30$$

1 mbar vacuum reduces them to < 1 event in $5\mathrm{x}10^{19}$ pot









N($v + vbar$, inel. int. in decay volume) < 1 event in $5\mathrm{x}10^{19}$ pot

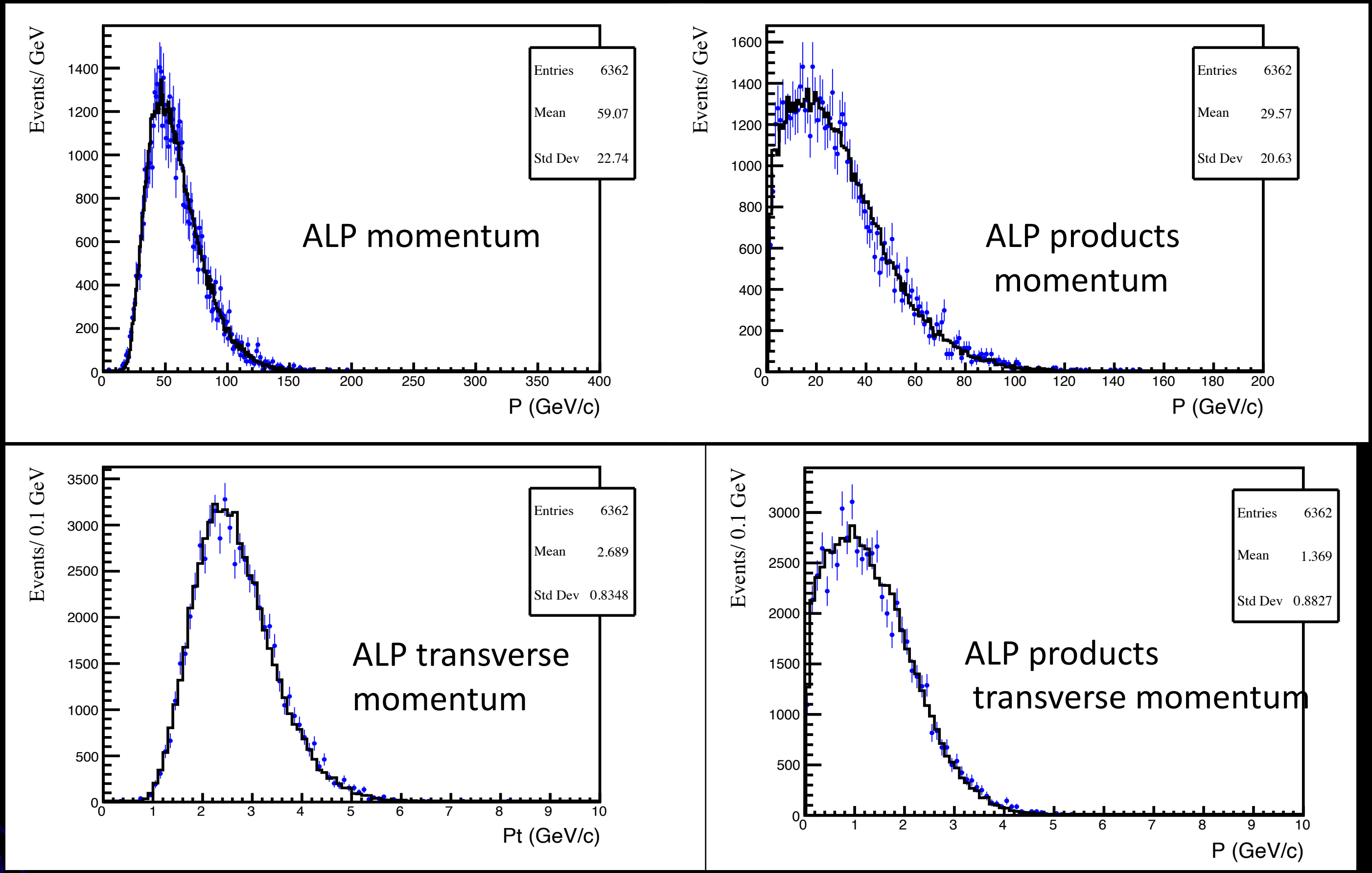
NB: Neutrino DIS with detector+beamline material still to be evaluated.

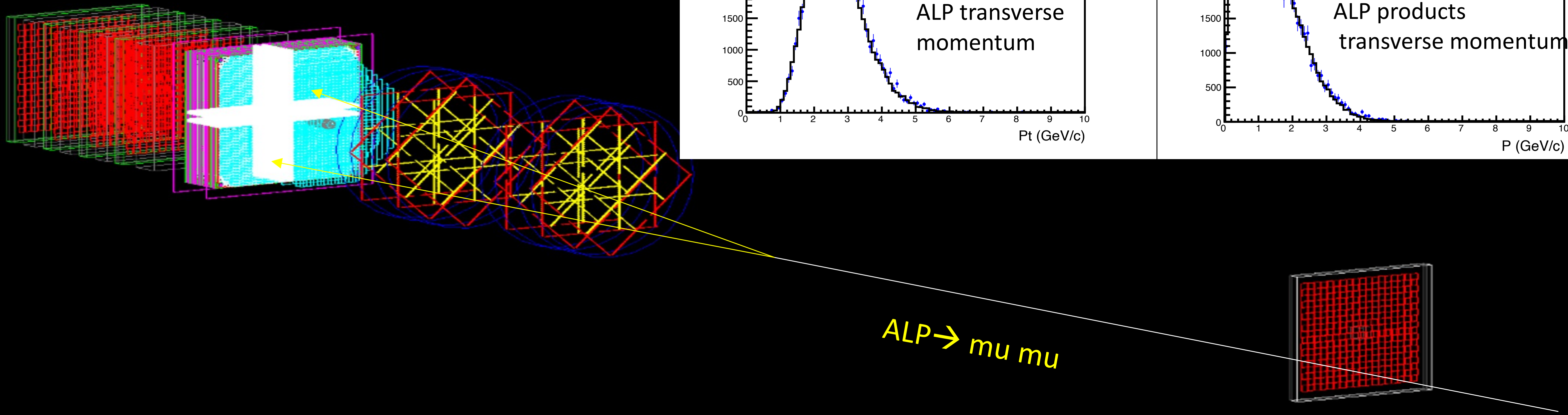
SHADOWS physics sensitivity
for some standard PBC benchmarks

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

SHADOWS Geant4-based Monte Carlo

Validation of toy kinematic distributions
with SHADOWS full MC
(only Geant hit now, no reconstruction yet)

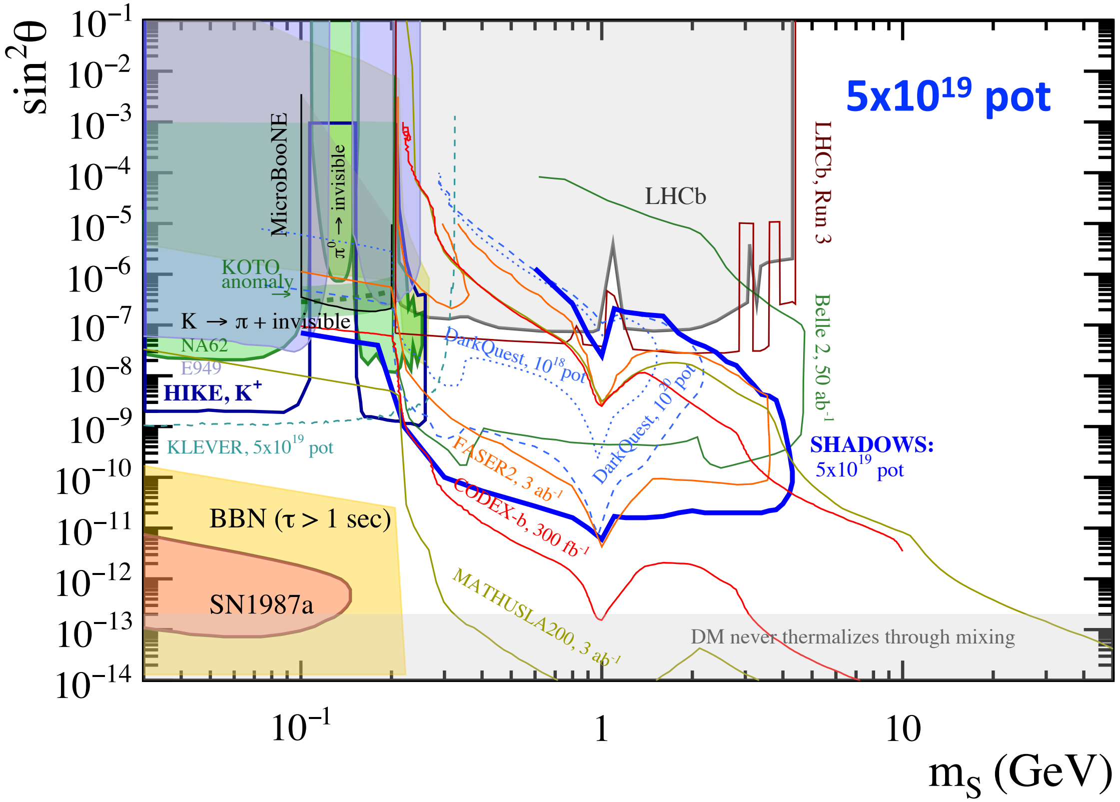




SHADOWS sensitivity to standard PBC benchmarks

(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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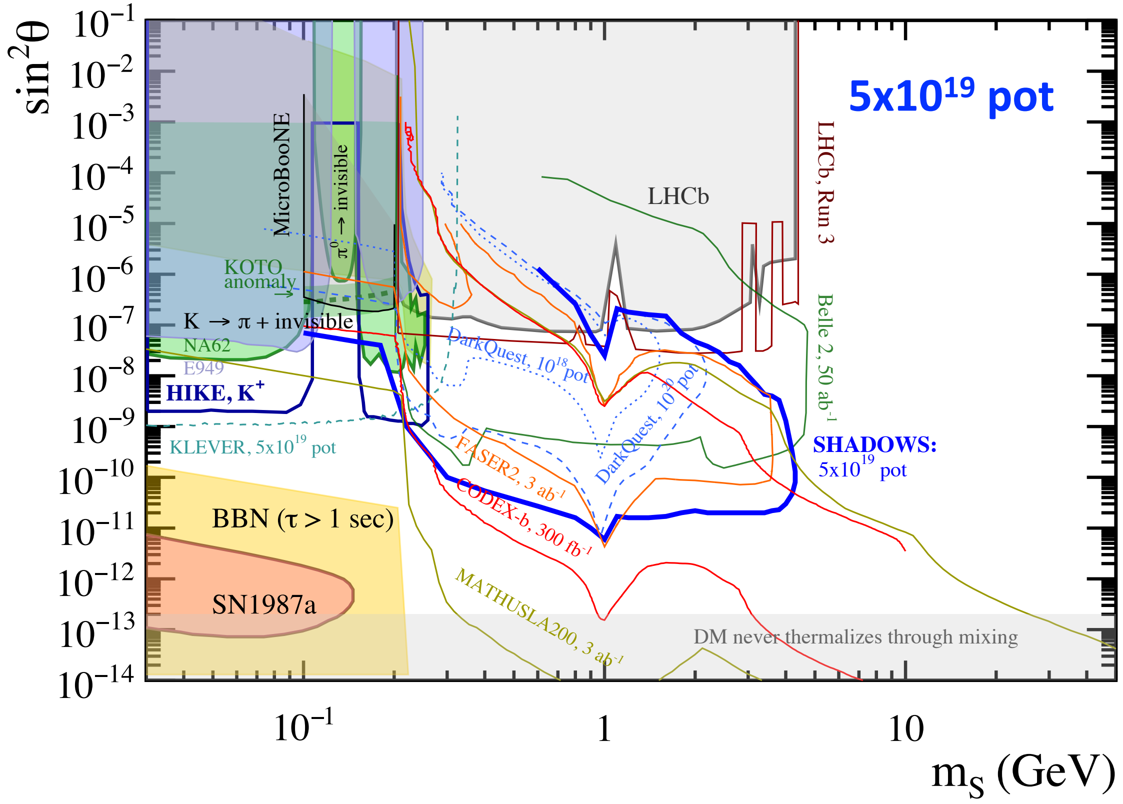

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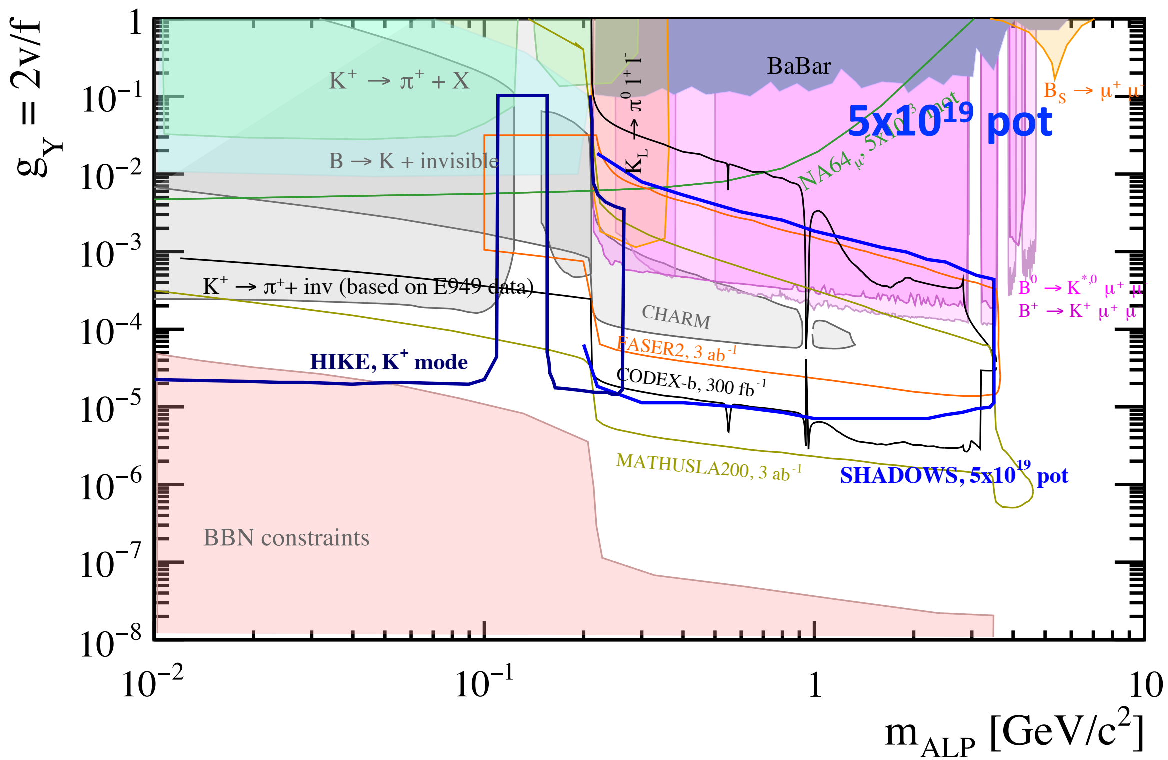
ALPs with fermion couplings (BC10)

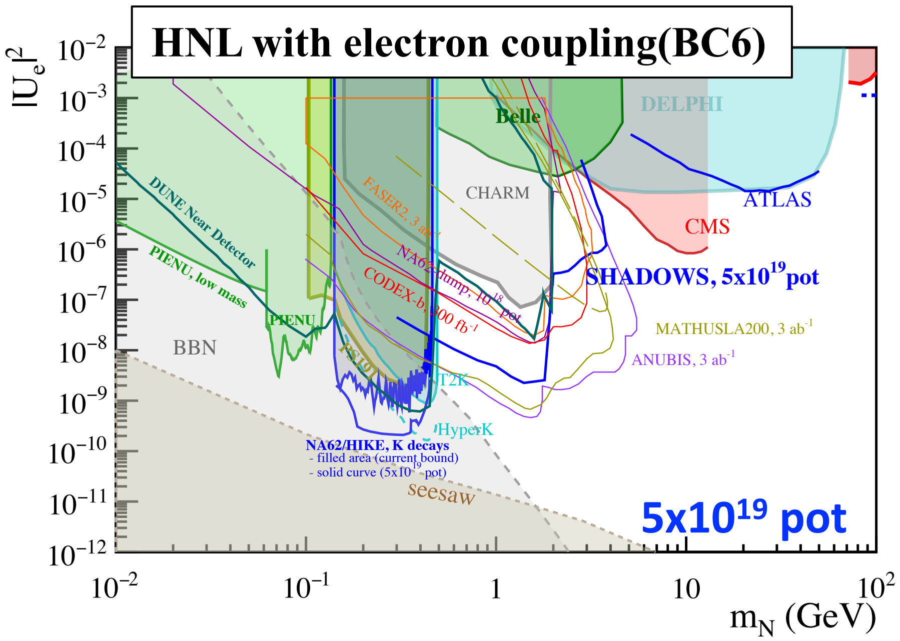


SHADOWS ($5x10^{19}$ pot) better than FASER2 (3 ab^{-1}), and comparable to CODEX-b (300 fb^{-1}).

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

SHADOWS sensitivity to standard PBC benchmarks

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



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.

SHADOWS sensitivity to standard PBC benchmarks

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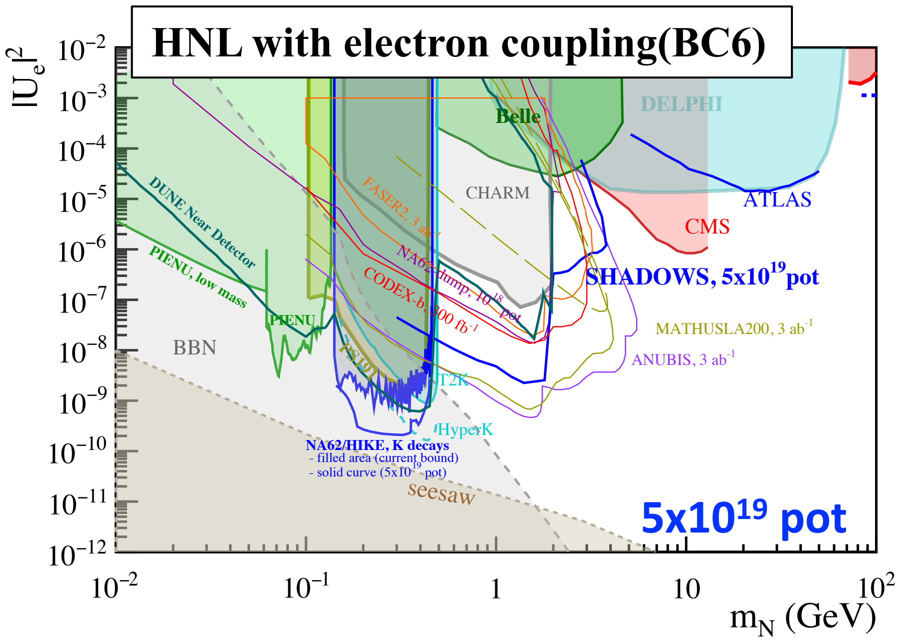

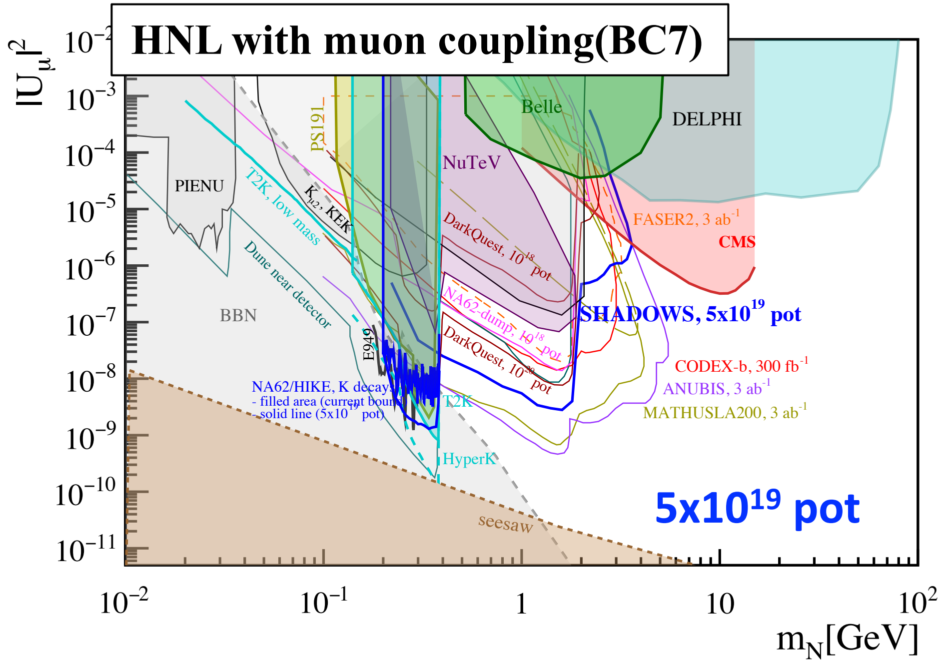

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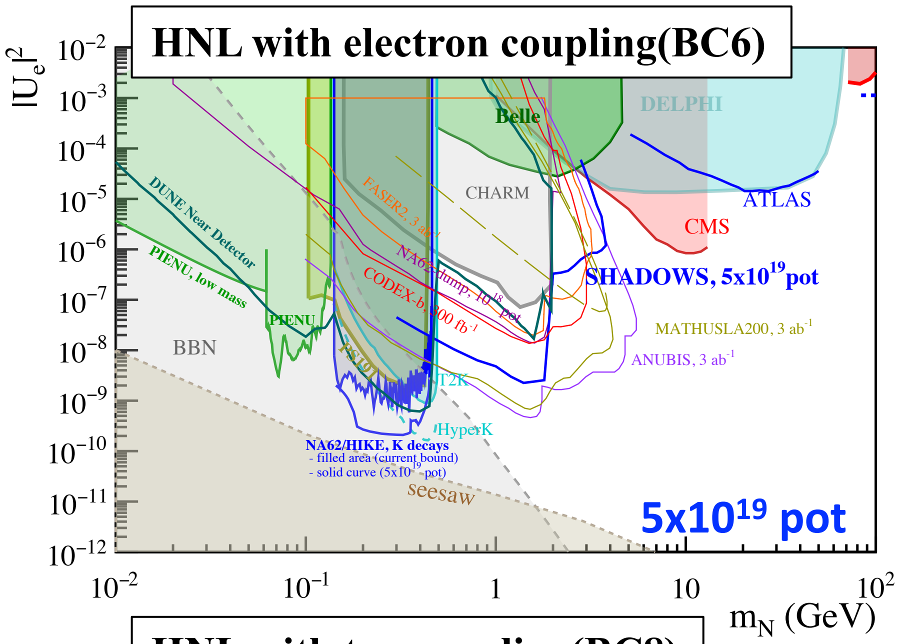

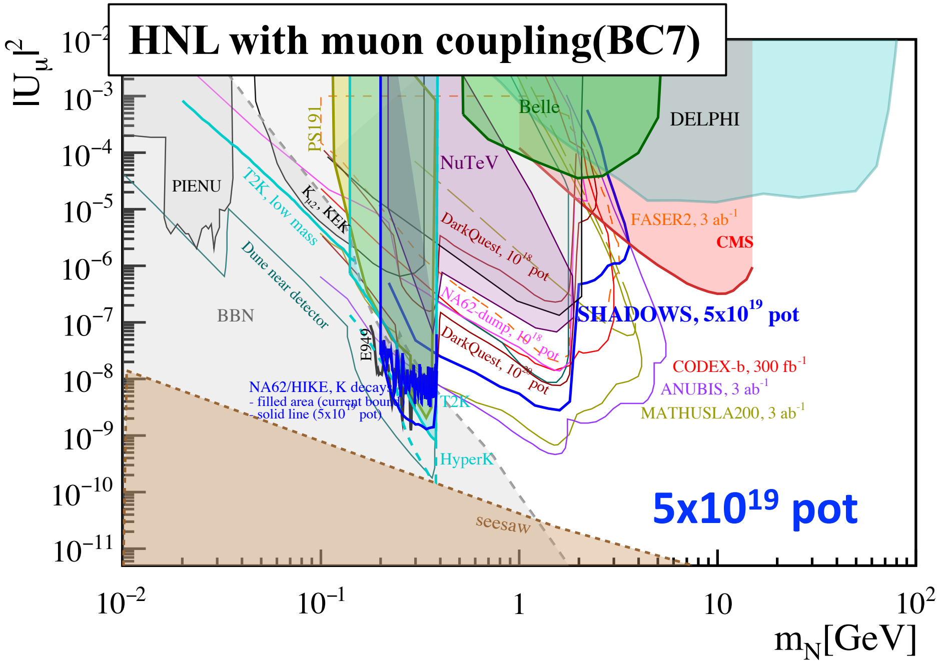

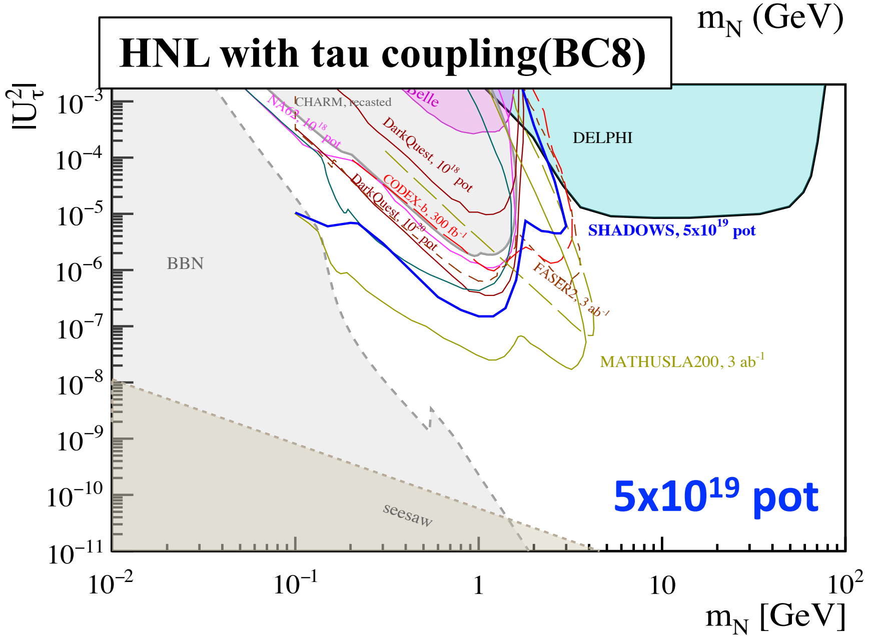

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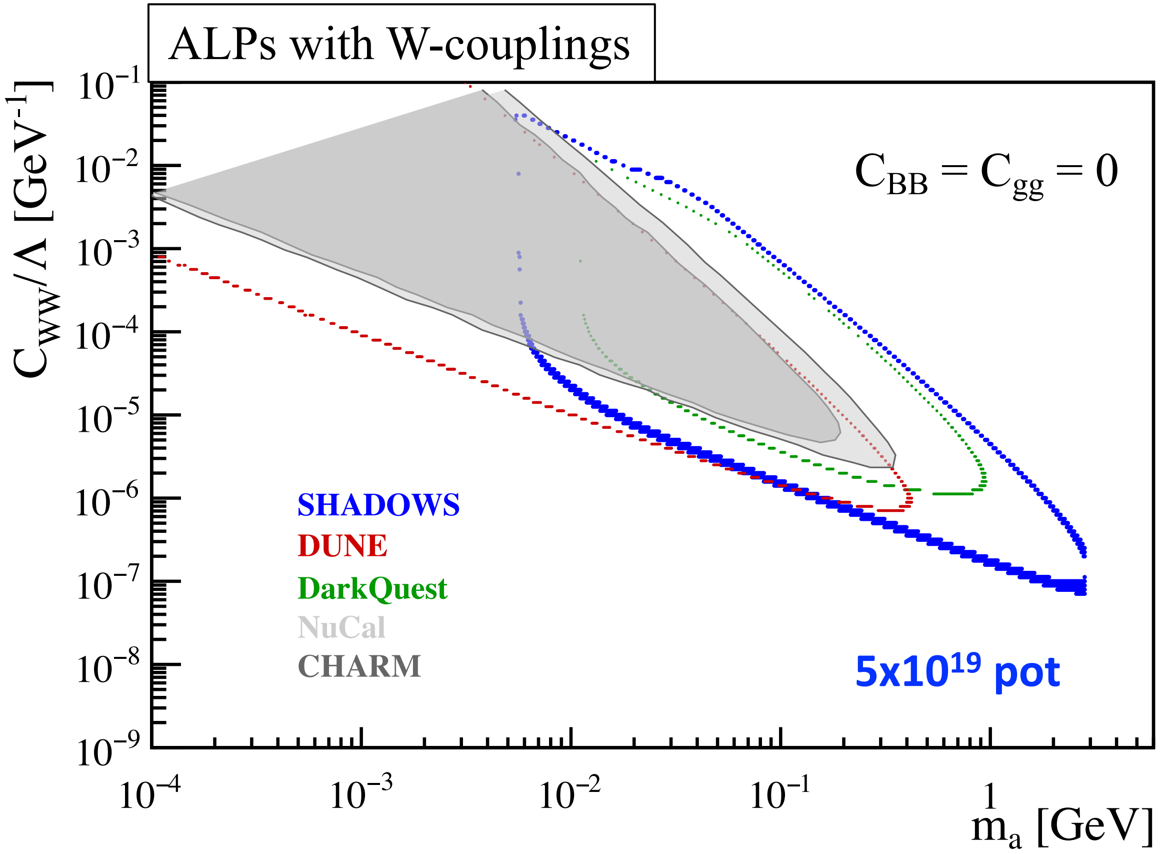
Derived from F. Kahlhoefer et al, 2201.05170 (only fixed target/beam dump experiments considered).



SHADOWS (5×10^{19} pot) competitive with DUNE for small couplings and extends the mass range towards heavier ALPs and larger couplings.

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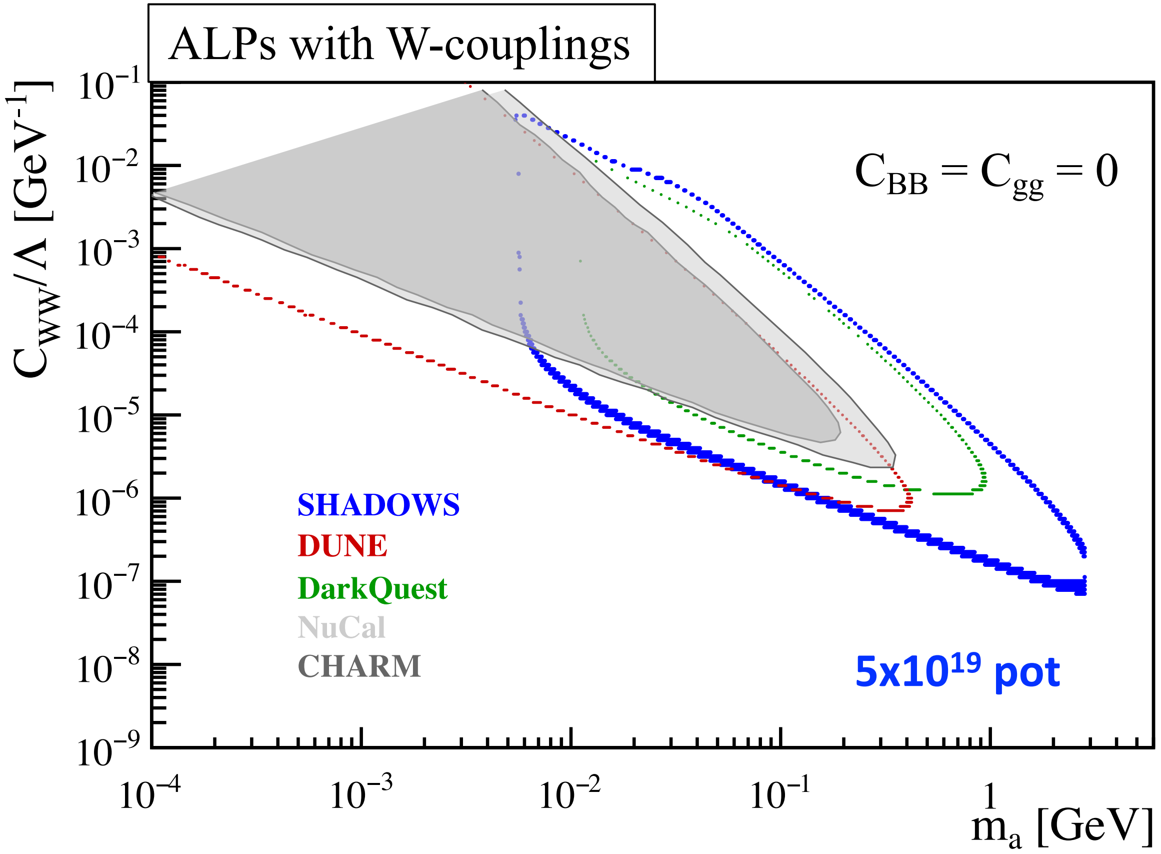

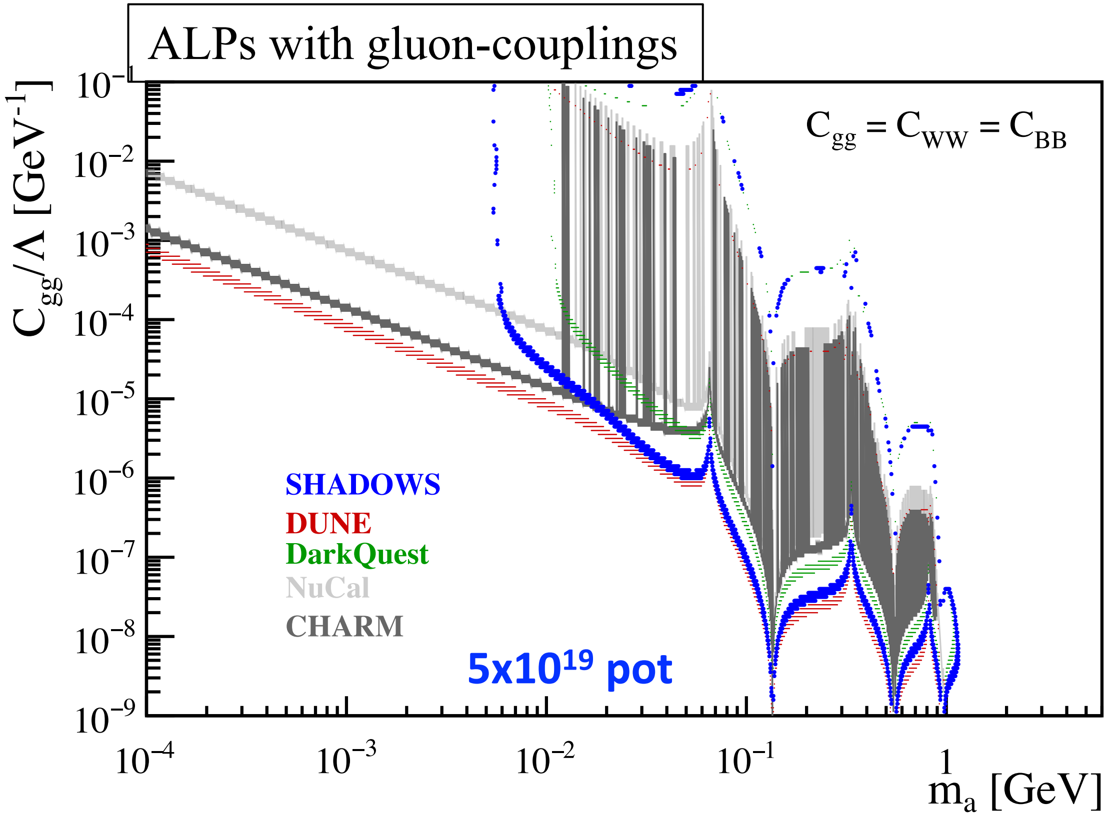

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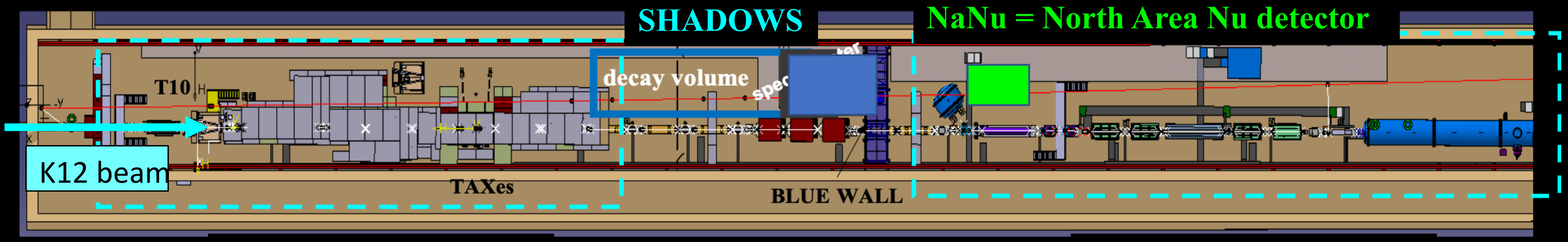
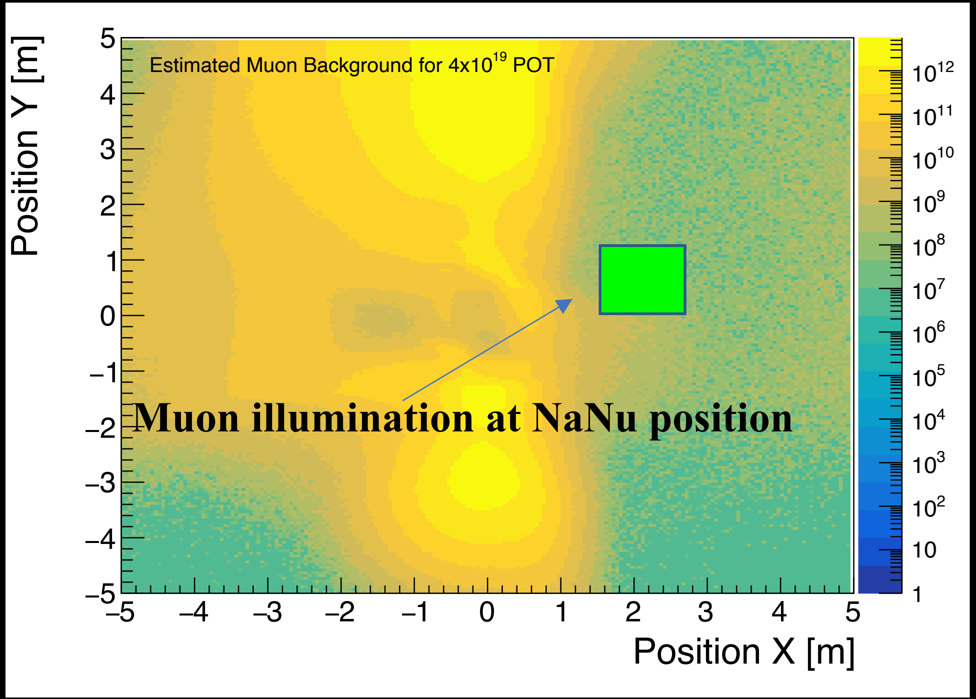
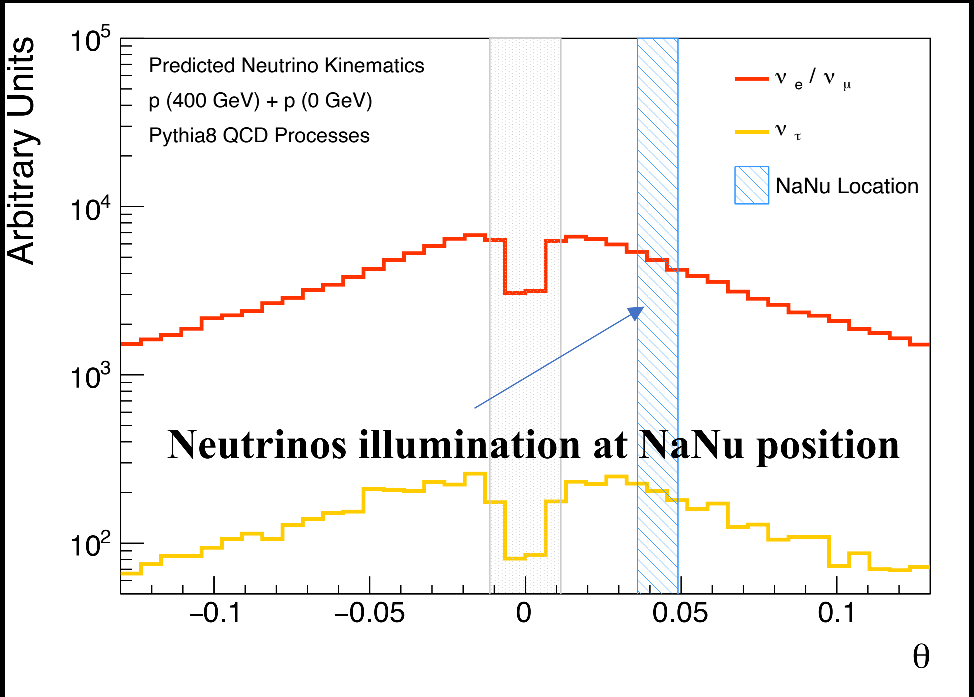
Not only FIPs @ SHADOWS… but also neutrino physics with NaNu @SHADOWS!







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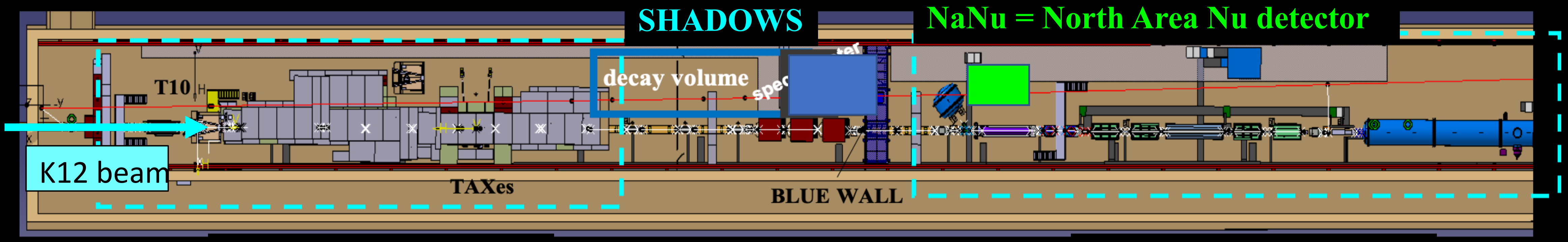
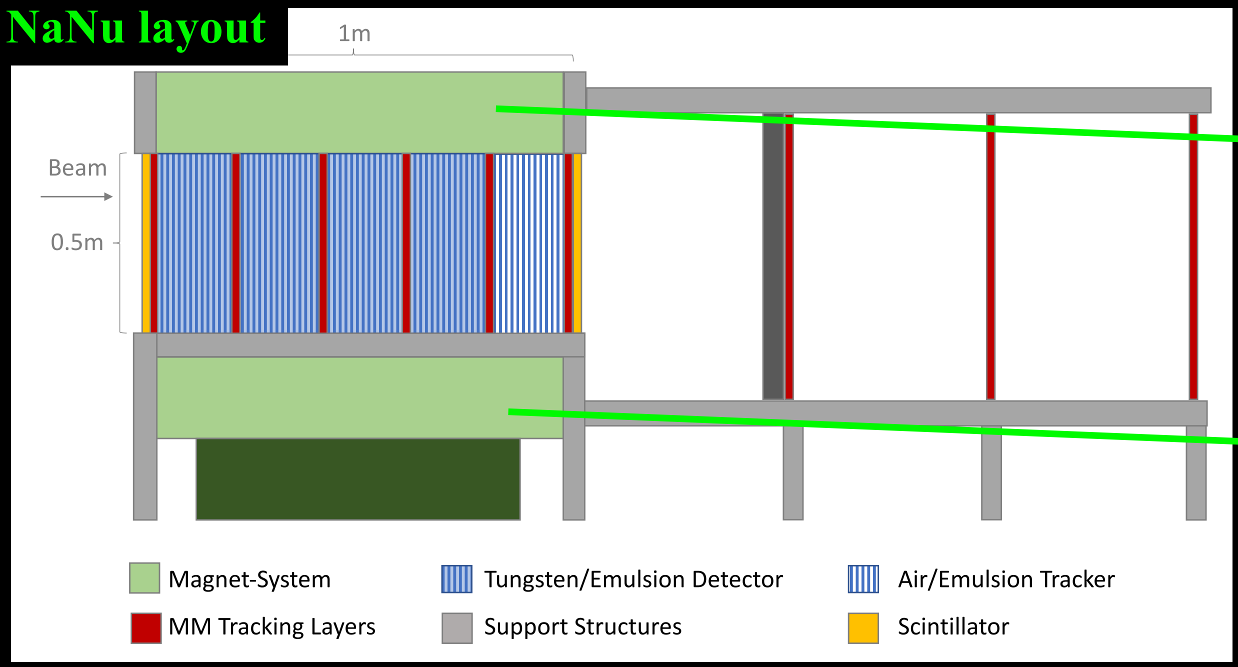
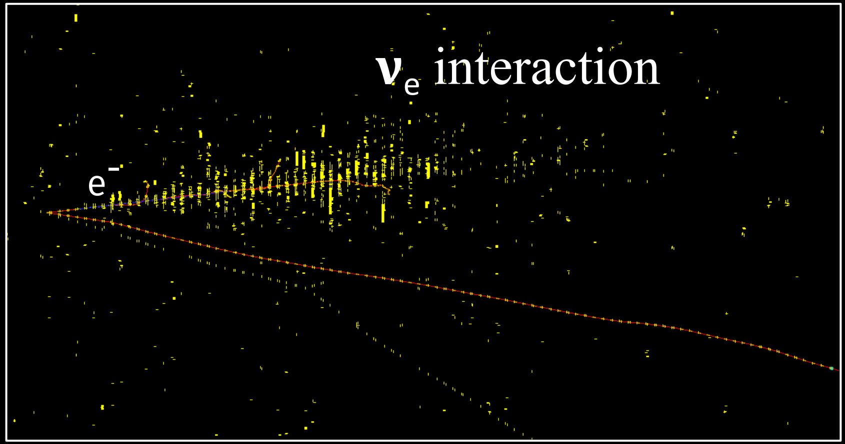


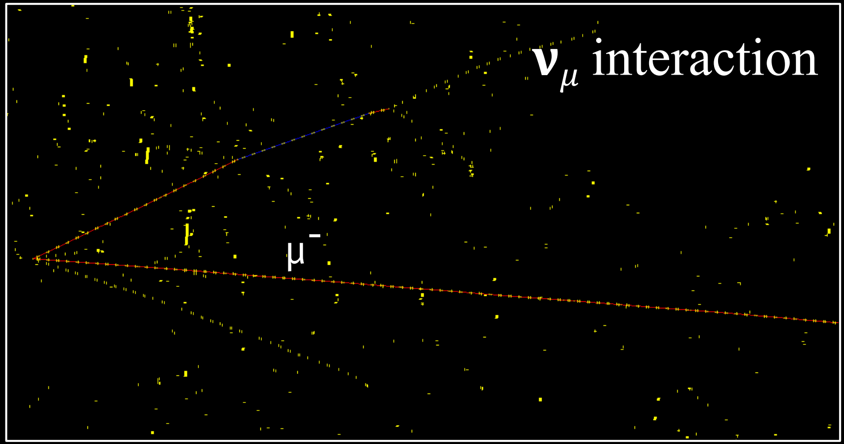


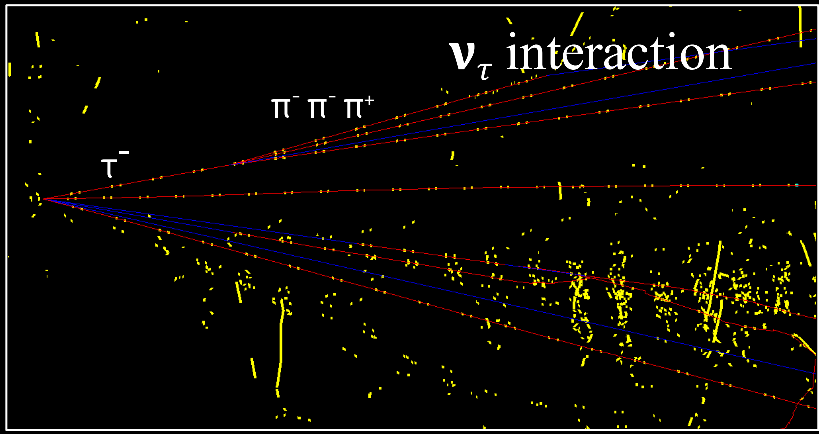
Not only FIPs @ SHADOWS… but also neutrino physics with NaNu @SHADOWS!

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



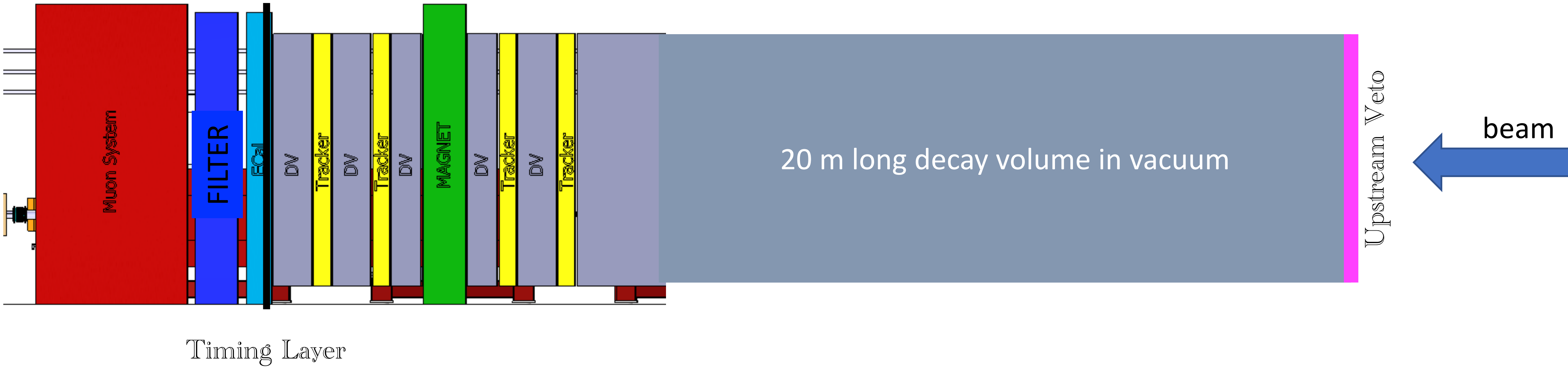




Geant4 simulated ν-interactions in NaNu

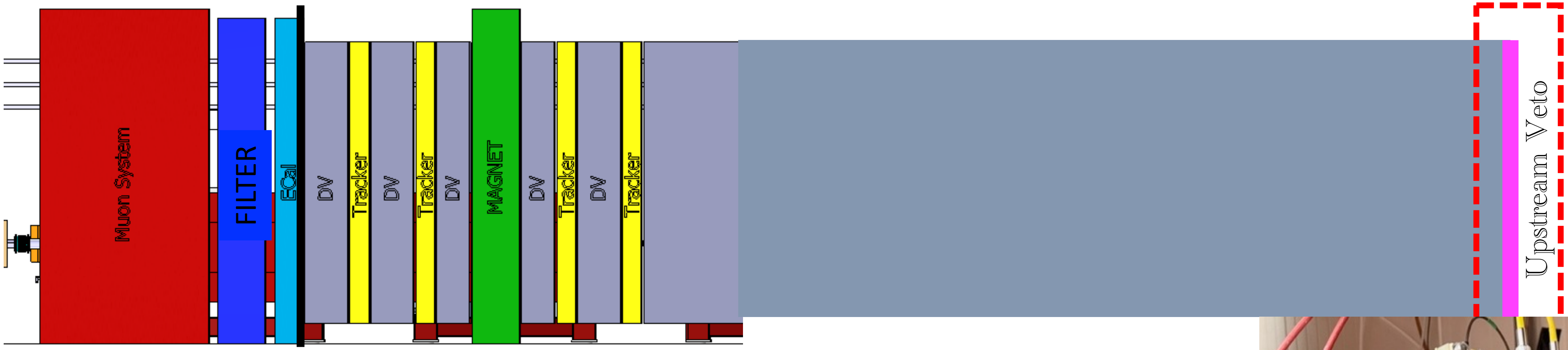
Detector design:
requirements & survey of technology options

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



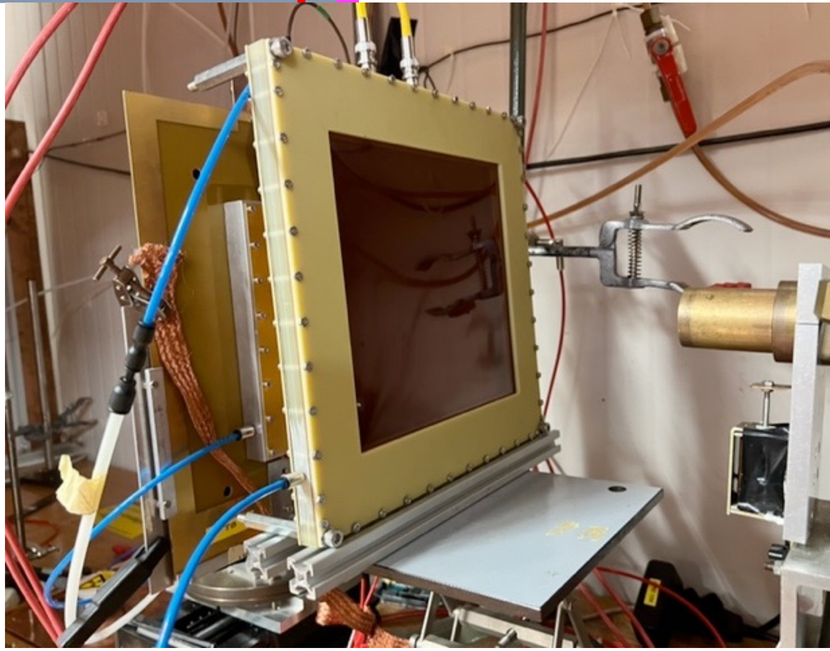
SHADOWS detector components:
20 m long, in vacuum decay volume, an Upstream Veto, a Tracking System with a (warm) dipole magnet, Timing layer, Electro-magnetic calorimeter, a filter and four Muon Stations.
Transversal size: 2.5x2.5 m^2.

SHADOWS Upstream (Muon) Veto: MicroMegas



Requirements:

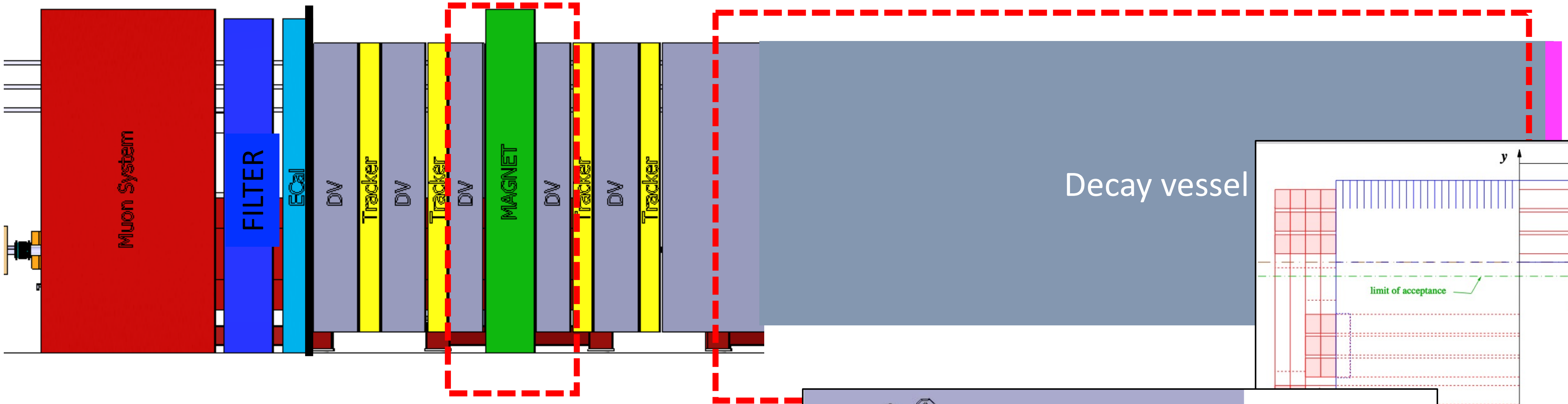
1. efficiency: 99.5%
2. time resolution: o(10 ns) (to allow matching with the other detectors)
3. position resolution: o(cm) (match the backward extrapolation of tracks)
4. rate capability: up to several kHz/cm^2

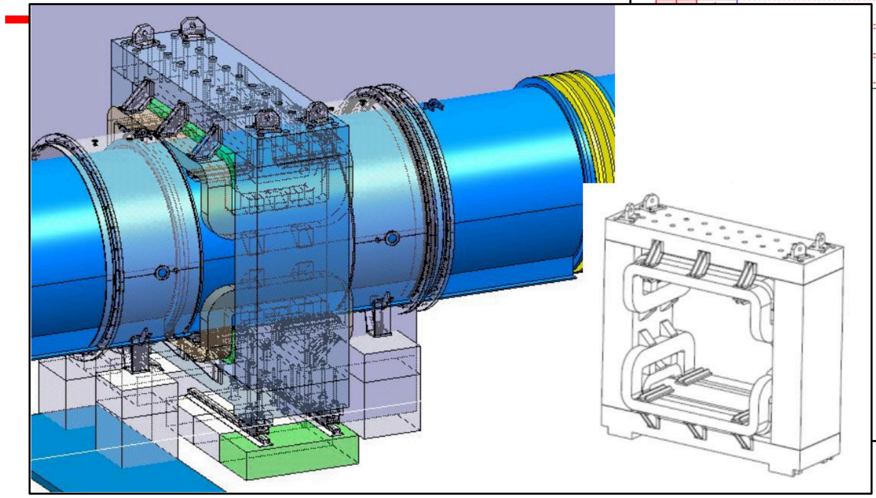


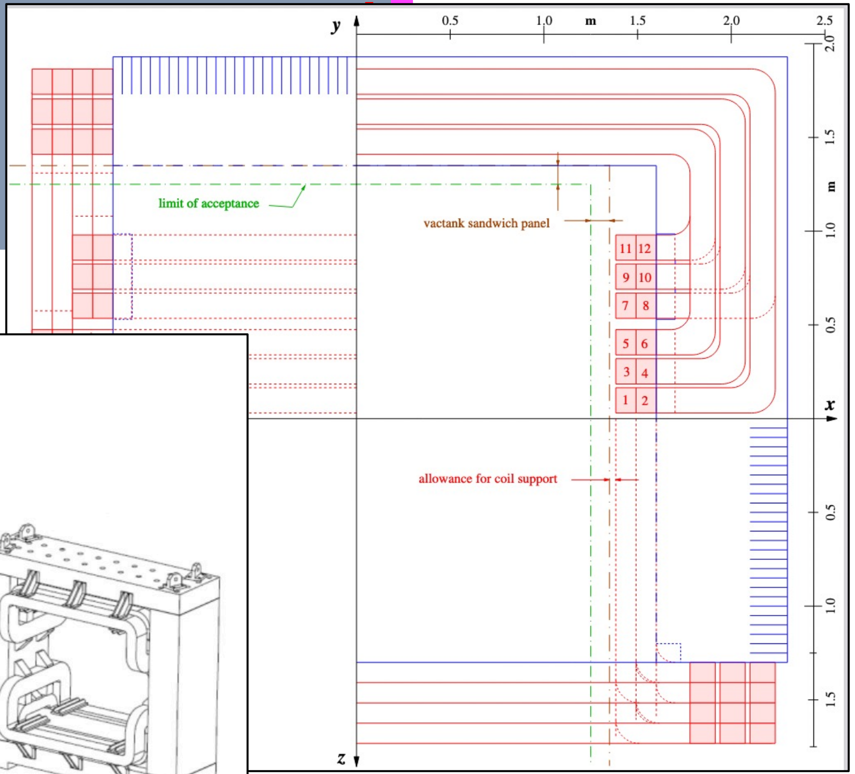
Proposal: **double layer of MicroMegas.**
Interest from groups who built the ATLAS New Small Wheels (P. Iengo, M. Iodice, & collaborators)

SHADOWS Dipole Magnet and Decay Vessel:

CERN, INFN-Ferrara…





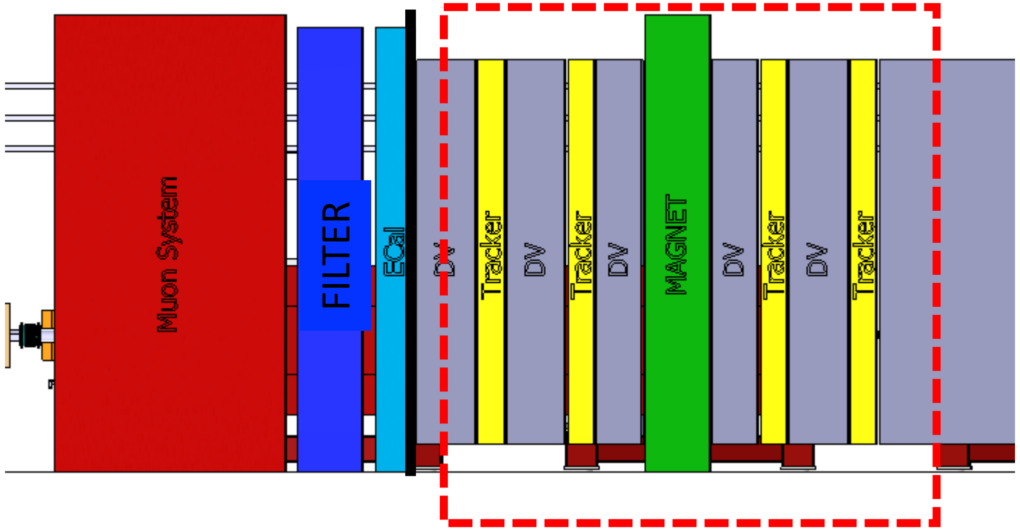


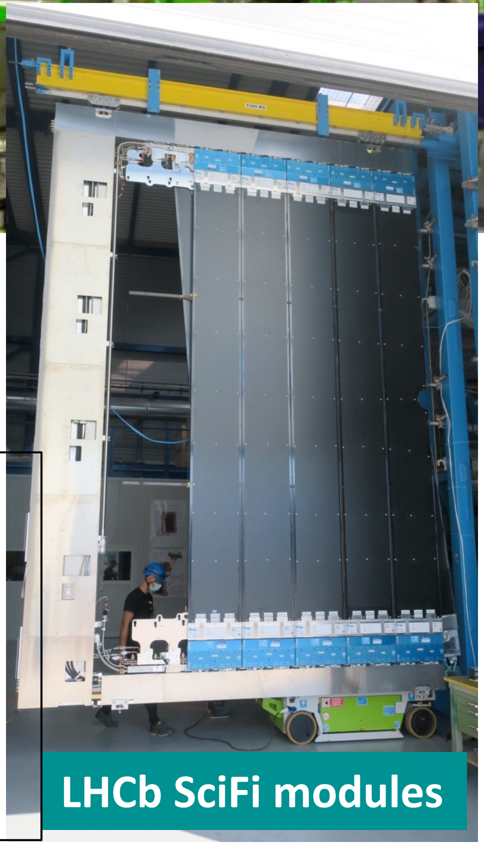
Requirements:
- Dipole Magnet: about 1 Tm (warm)
- Decay vessel: 125 m^3 in vacuum (1 mbar)

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:

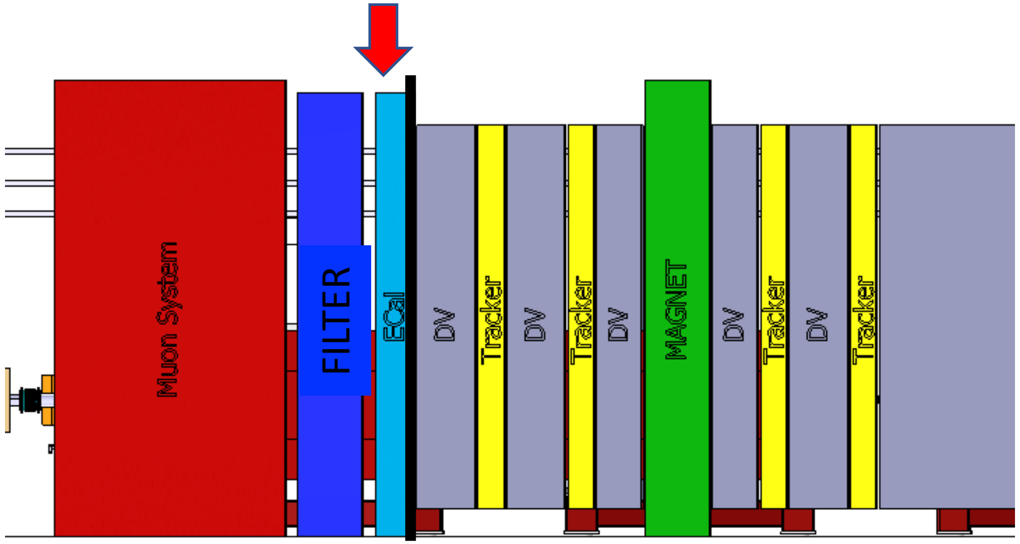
- vertex resolution over 20 m long decay volume: sigma_xy ~ 1 cm
- impact parameter resolution at o(30) m distance: sigma(IP) < few cm
- must operate in vacuum (1 mbar or so).

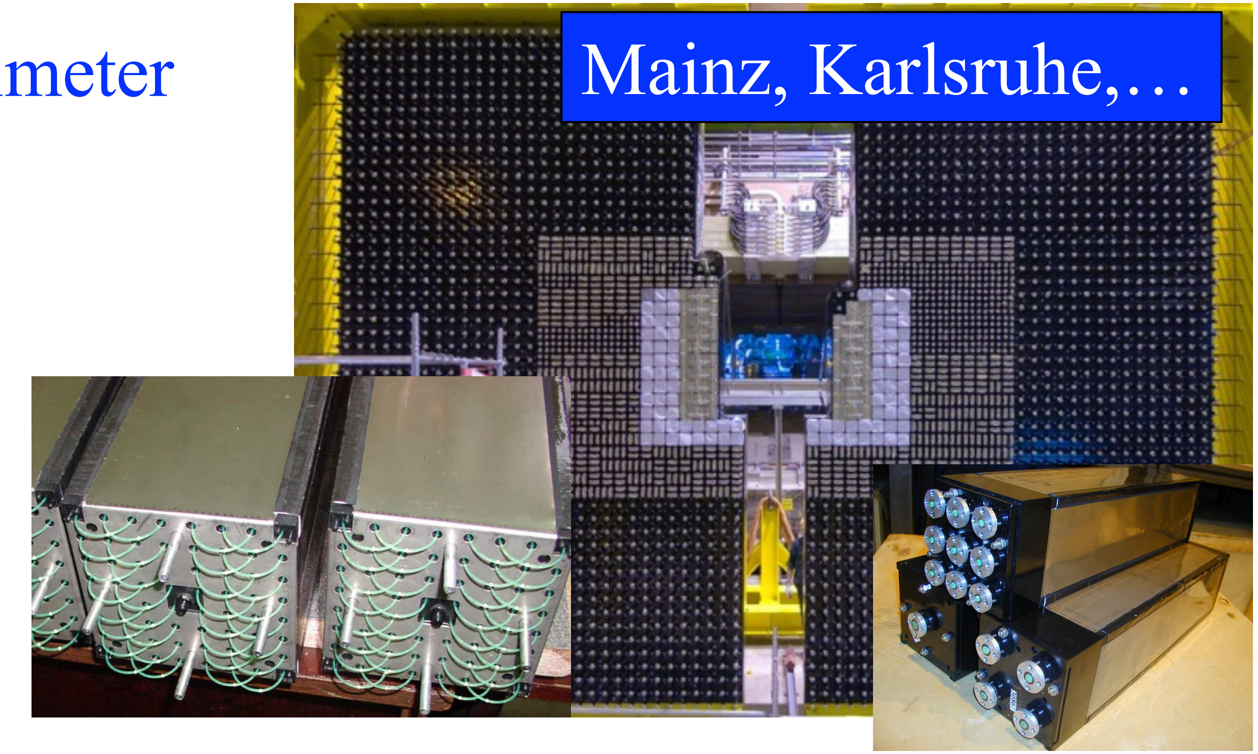
Two options under scrutiny:

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





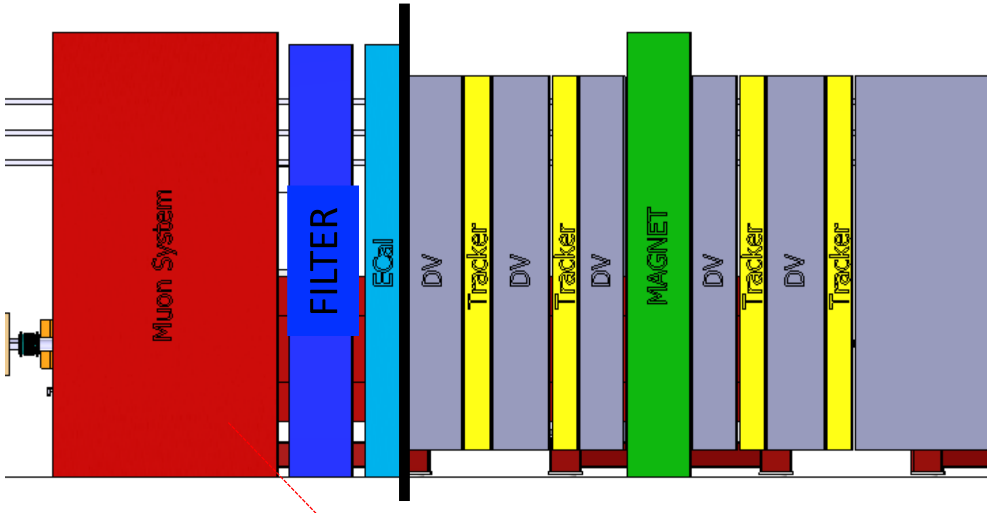
Requirements:

- must identify electrons/photons against muons/hadrons
- π^0 reconstruction (eg: HNL → e rho→ e $\pi^+\pi^0$)
- photon directionality: Important for ALP→$\gamma\gamma$
- 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

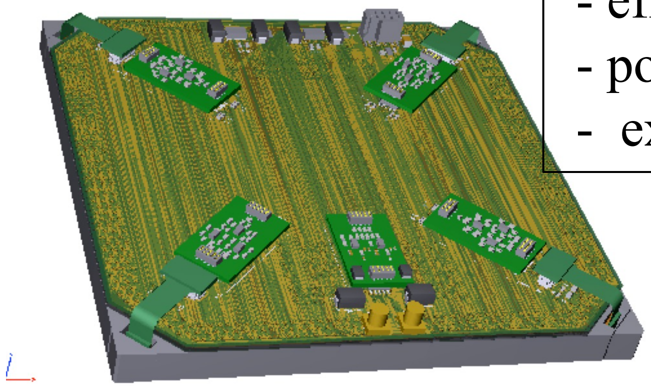
Options under scrutiny: Shashlik, PbWO4 (from CMS), CALICE, SplitCal

SHADOWS: Muon Detector

INFN (Frascati, Bologna, Ferrara), ..

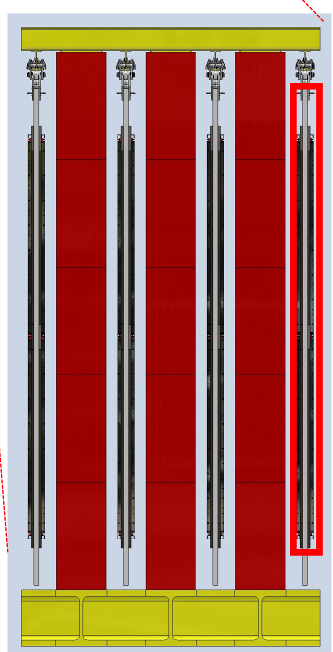


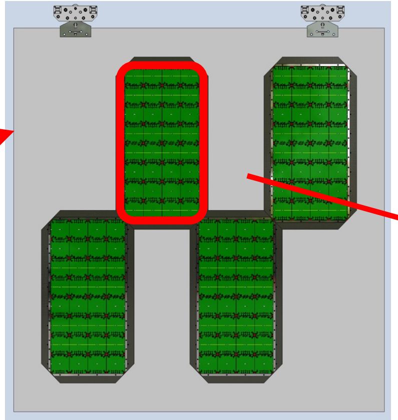
1 tile = 15x15 cm2,
Direct SiPM readout at the corners
One analog output per tile



Requirements:

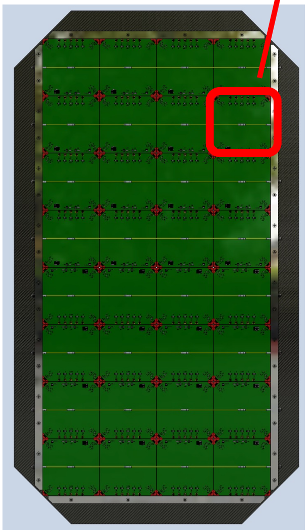
- time resolution: o(150) ps or less
- efficiency: <99% per station
- position resolution: o(few cm).
- expected rates: < 100 Hz/cm2



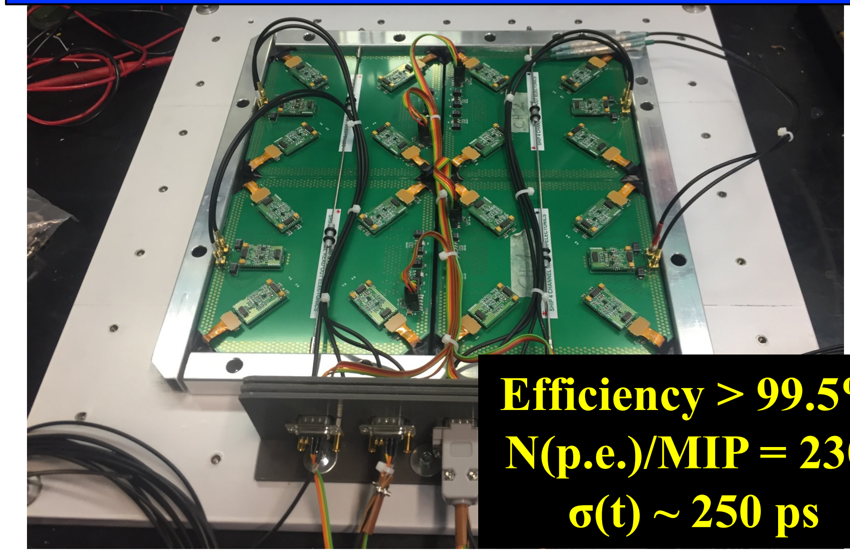


1 station = 8 modules
[same pattern staggered
on the other side of the wall]

1 module = 16/32 tiles



4-tile prototype built in INFN Bologna/LNF



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

Preliminary COST & TIMELINE

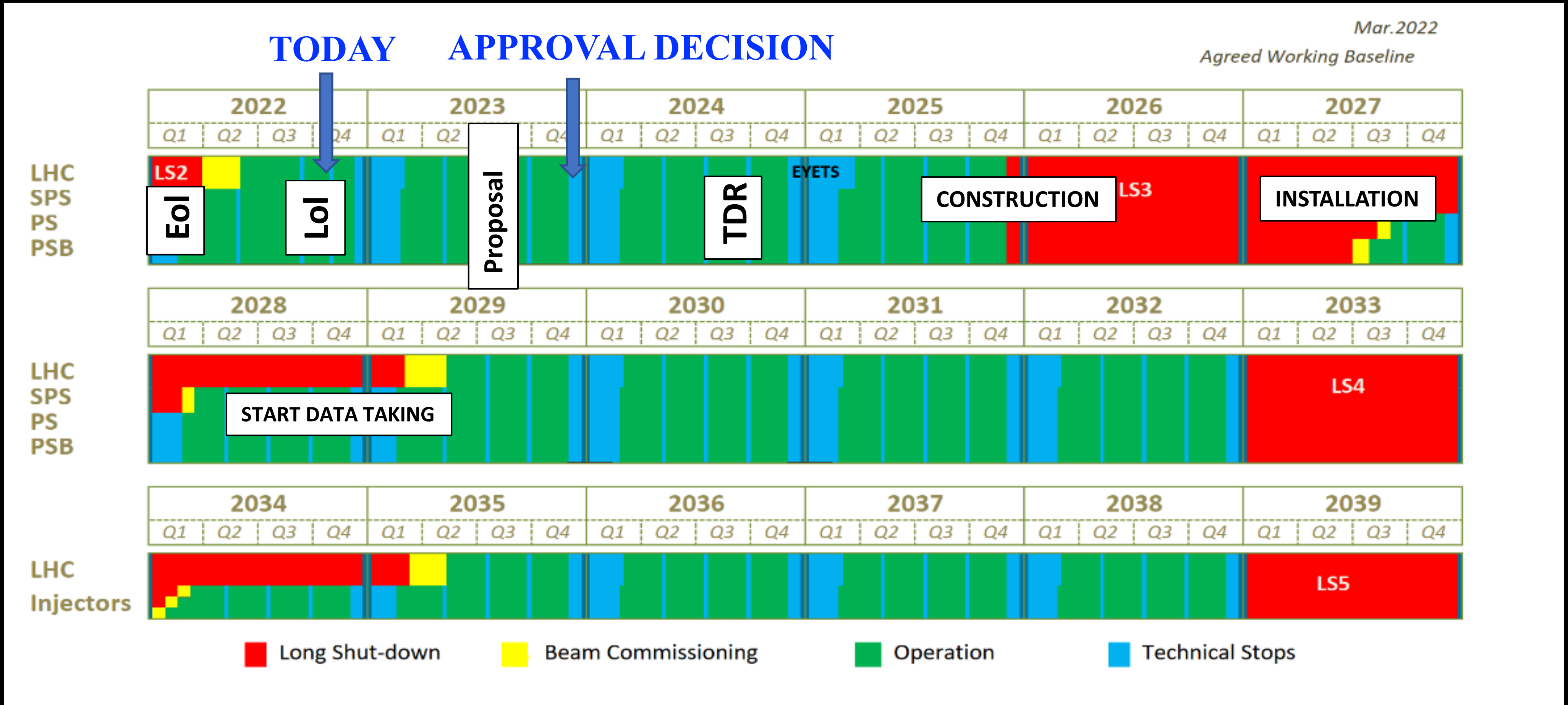
SHADOWS: TENTATIVE COST

(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

✓ 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.

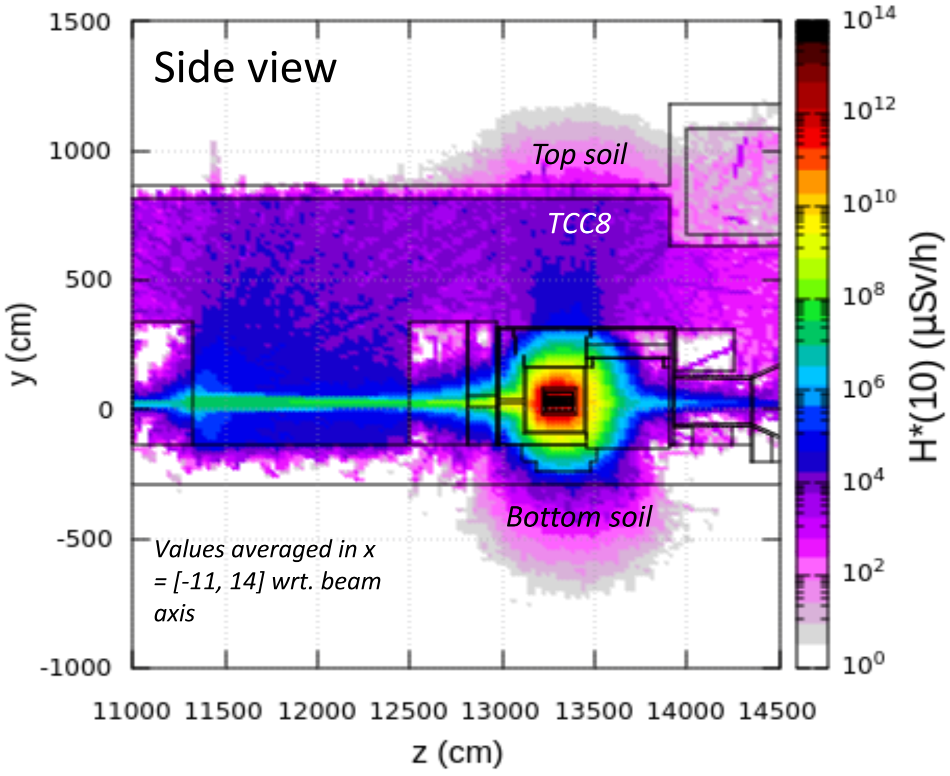
✓ ECN3 with SHADOWS+HIKE can become a "hot spot" on worldwide scale for FIP physics after LS3, fully compatible with a superb flavor programme in ECN3.

SPARES

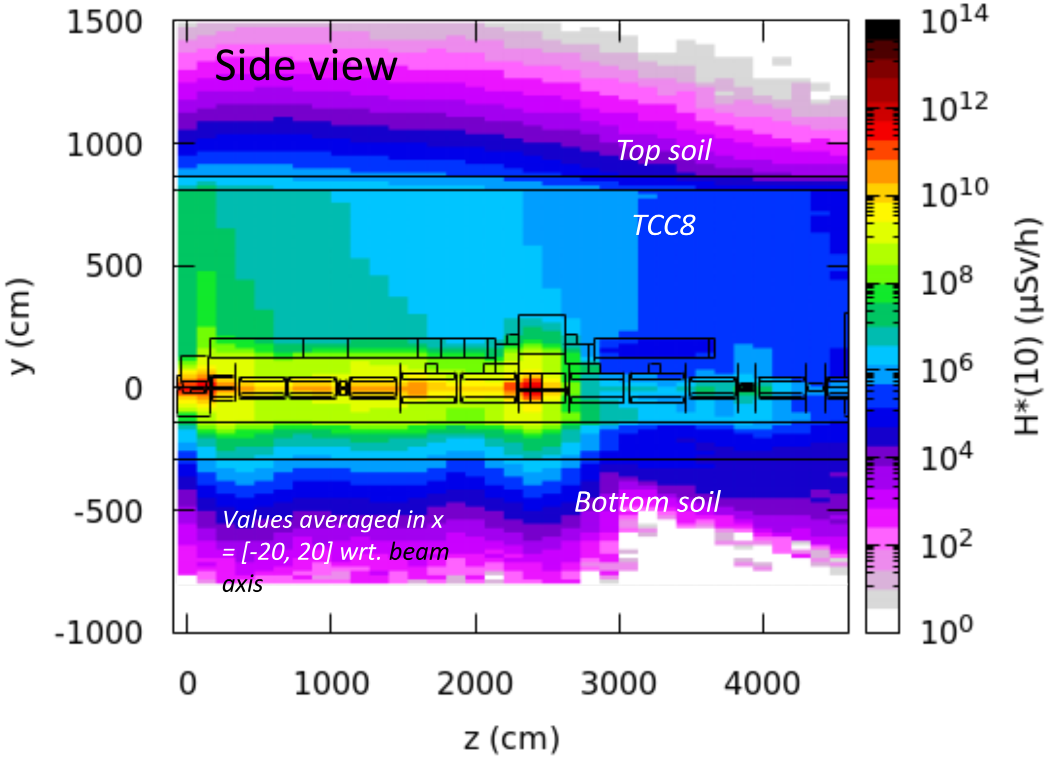
Preliminary BDF and HIKE prompt dose rates

T6: $1.4*10^{13}$ p/spill every 14.4 s (63 kW) (~$3.1*10^{18}$ POT 2021/22)
T10: $3.5*10^{12}$ p/spill every 14.4s (16 kW) (~$1.1*10^{18}$ POT 2021/22)

BDF
$4*10^{13}$ p/spill every 7.2 s (355 kW)



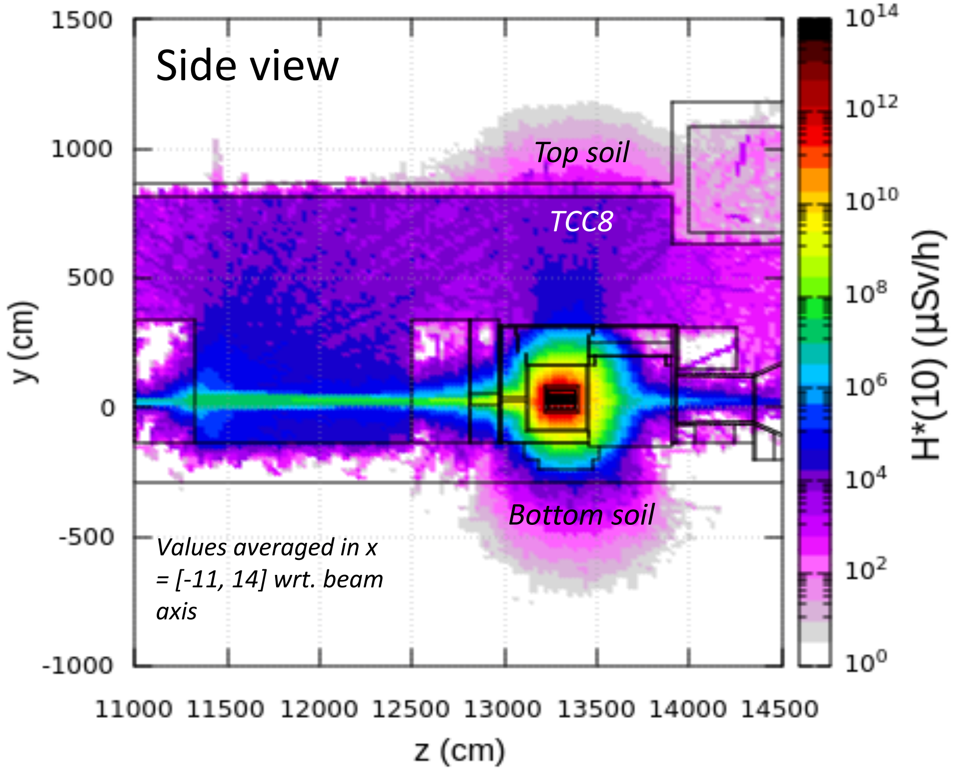
HIKE* w/ NA62 shielding
$2*10^{13}$ p/spill every 14.4 s (90 kW)



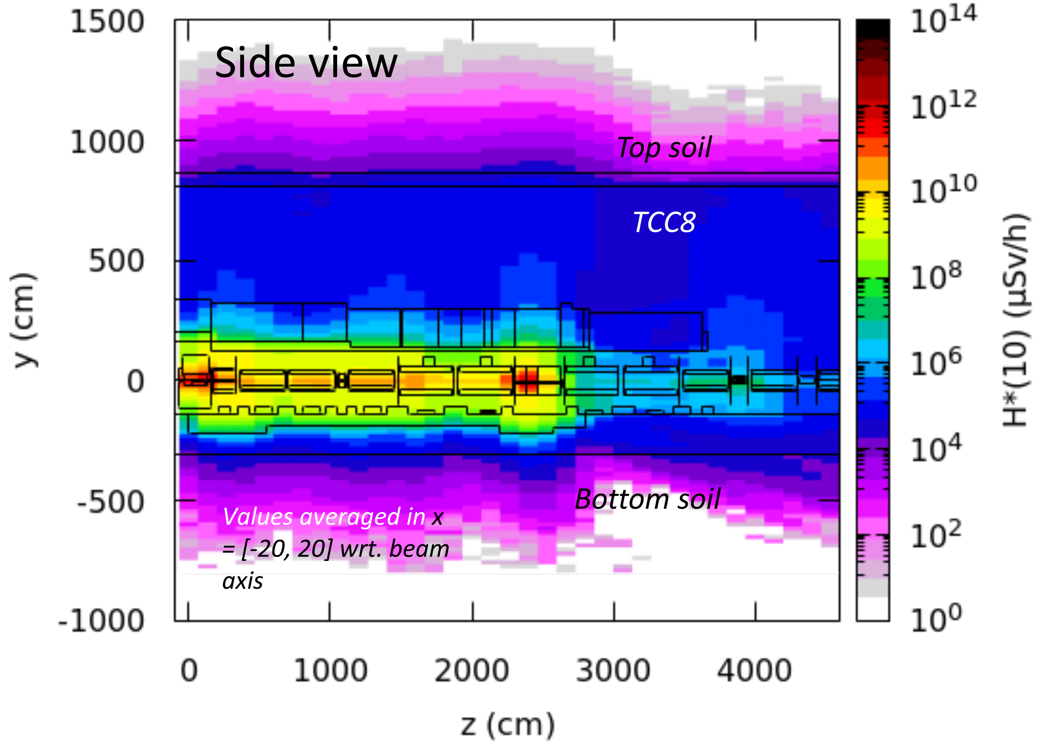
***With current NA62 shielding**

Preliminary BDF and HIKE prompt dose rates

BDF
$4*10^{13}$ p/spill every 7.2 s (355 kW)



HIKE* w/ additional shielding
$2*10^{13}$ p/spill every 14.4 s (90 kW)



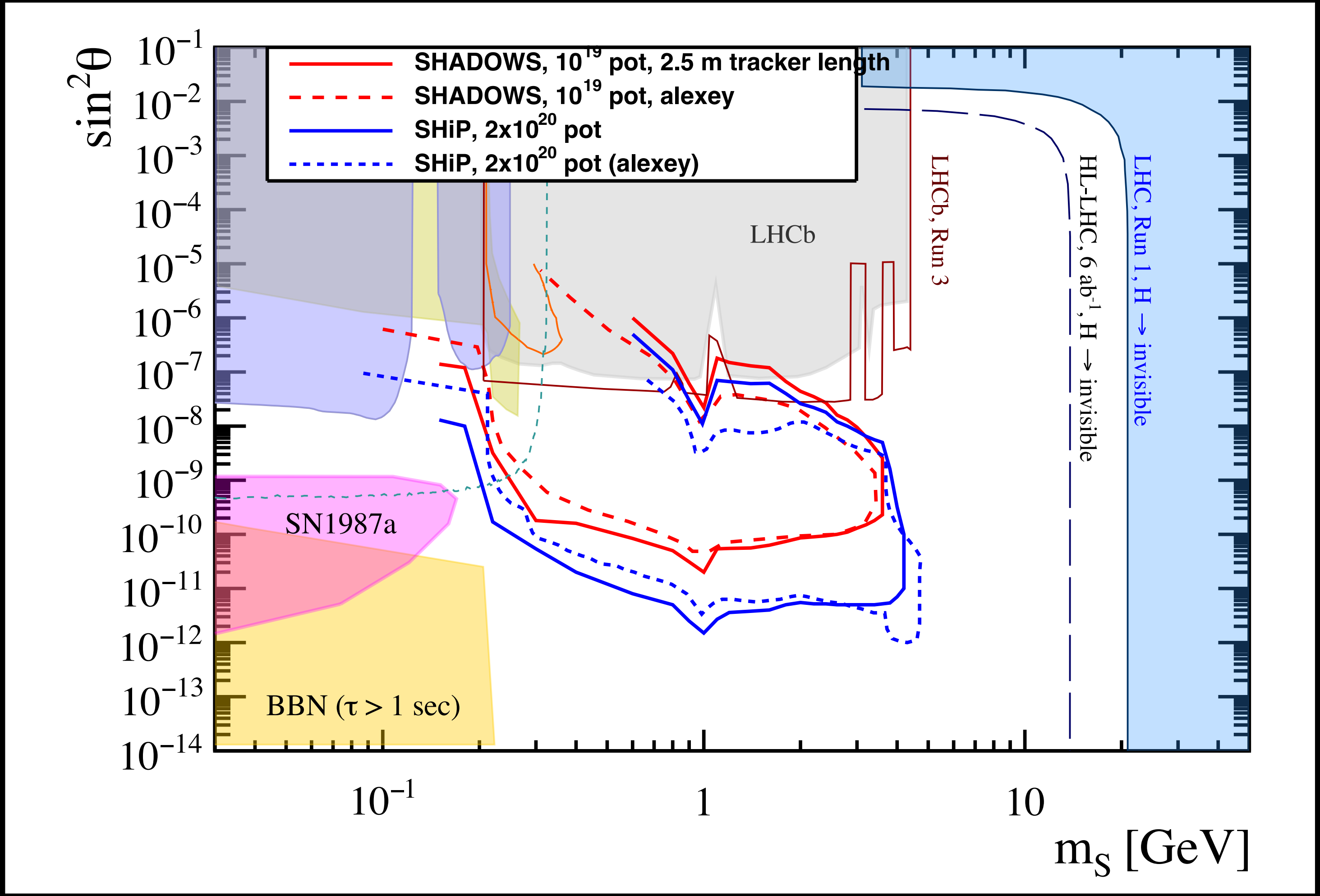
With preliminary shielding design as presented at PBC Annual Workshop

The Dark Scalar:
SHADOWS vs SHiP

SHADOWS meeting with SHiP people May 2021

https://indico.cern.ch/event/1038458/contributions/4361009/attachments/2247315/3811799/SHADOWS_19May2021.pdf

Comparison of sensitivity: SHADOWS (10^{19} pot, 1 year) vs SHiP ($2x10^{20}$ pot, 5 years)



Comparison between Alexey's and Gaia's estimate: the lower bounds agree within a factor of 2

(some difference due to Alexey's bounds at 95% CL and Gaia's bounds at 90% CL)

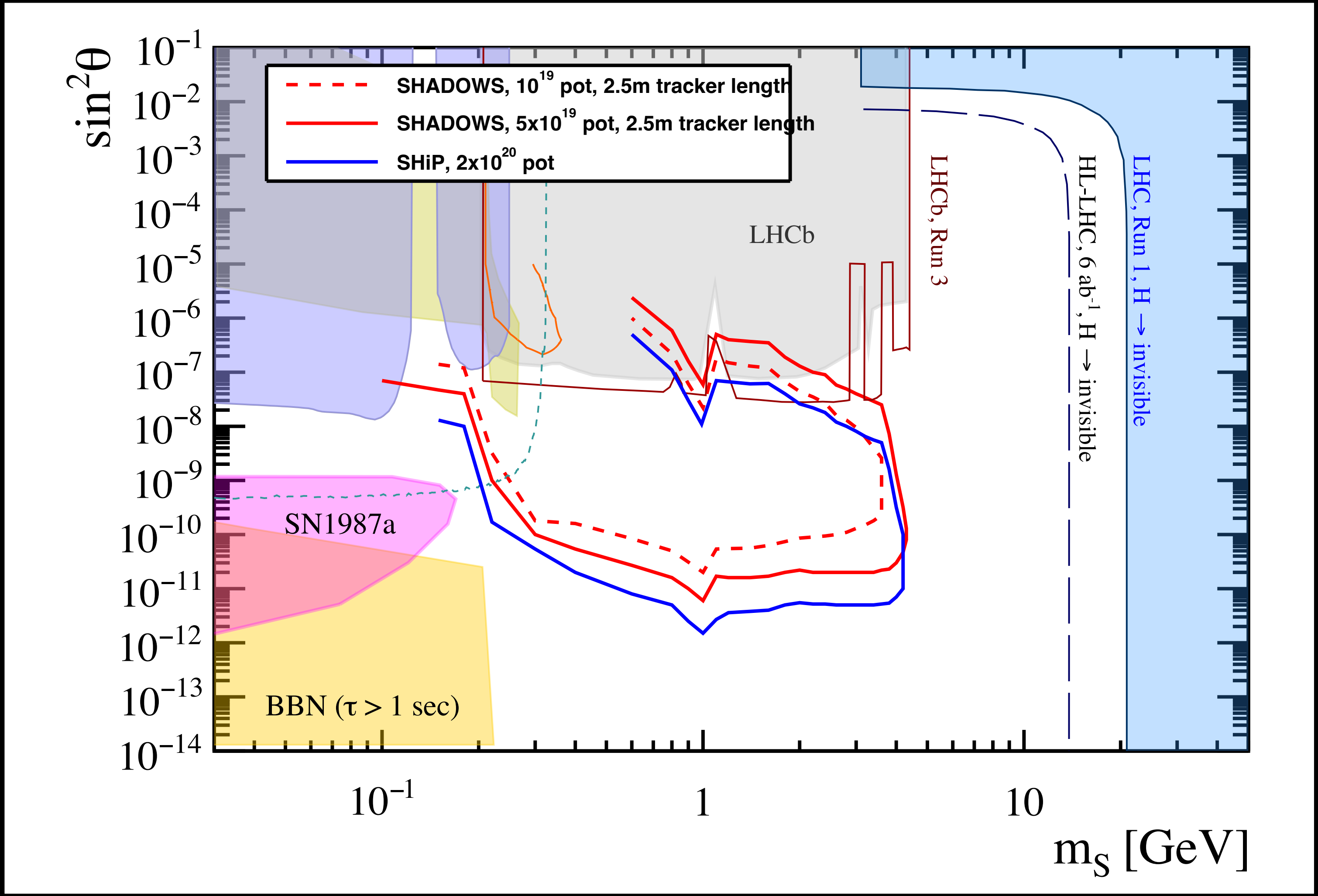
Still some mismatch in the upper bound between 1 and 2 GeV to be cross-checked.

(This region will be covered anyhow by LHCb well before SHiP/SHADOWS)

SHADOWS meeting with SHiP people May 2021

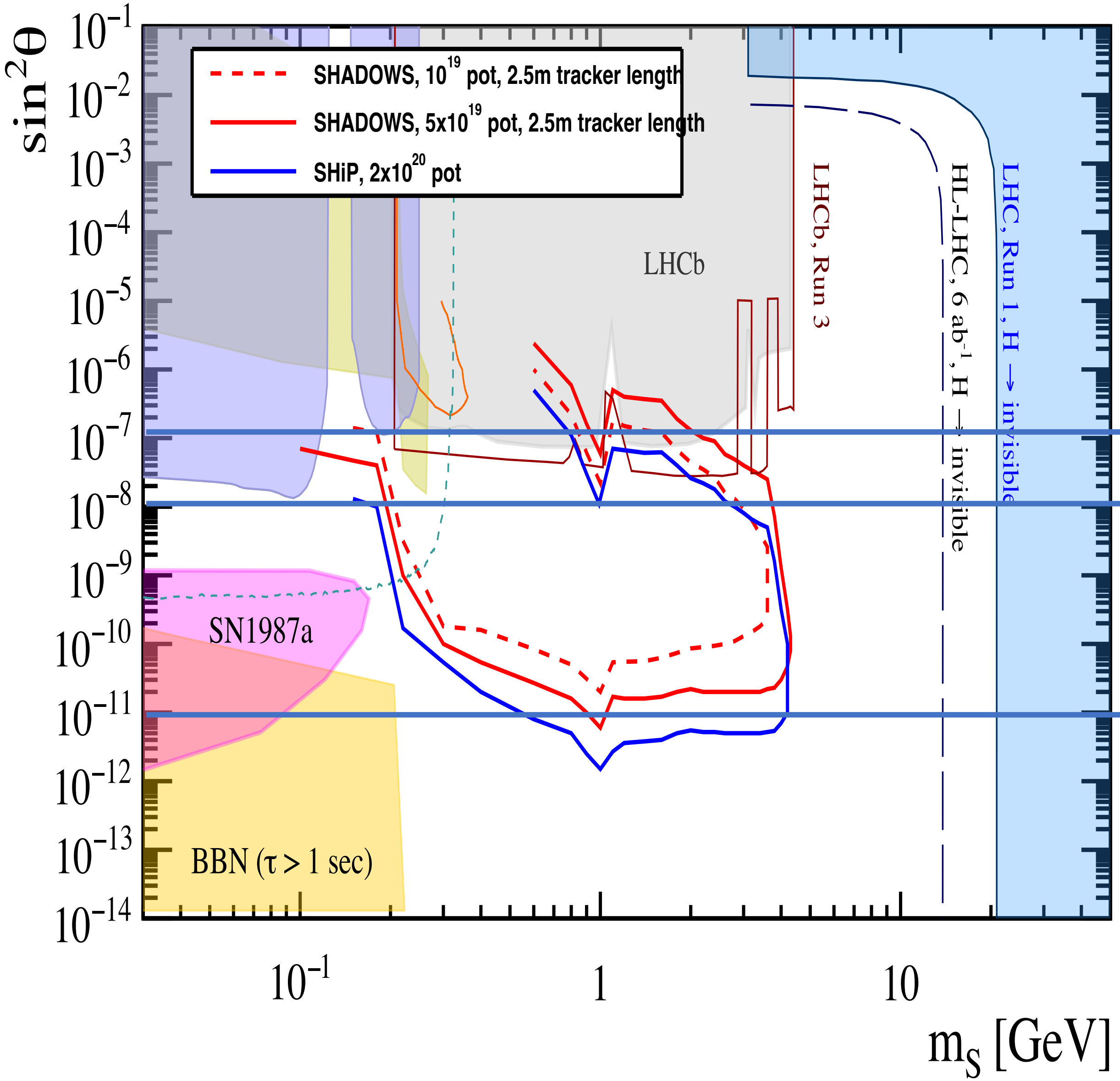
https://indico.cern.ch/event/1038458/contributions/4361009/attachments/2247315/3811799/SHADOWS_19May2021.pdf

Comparison of sensitivity: SHADOWS ($5x10^{19}$ pot, 5 years) vs SHiP ($2x10^{20}$ pot, 5 years)

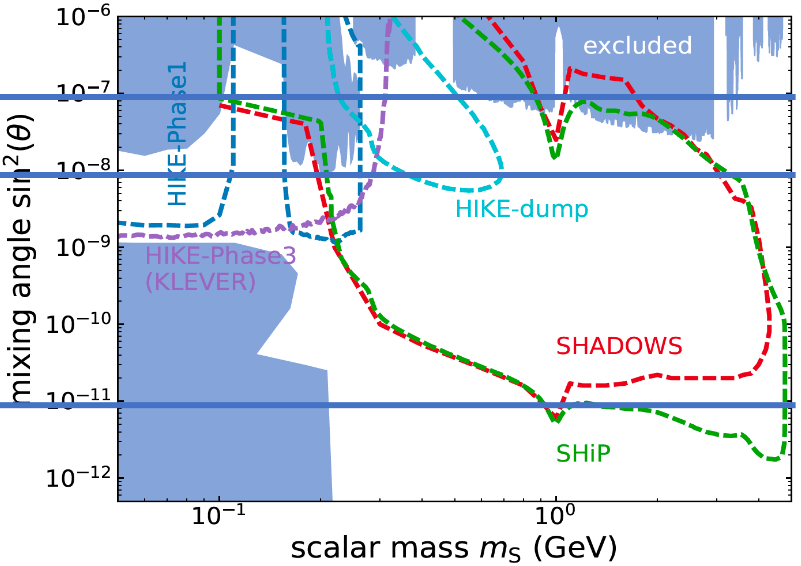


SHADOWS vs SHiP: similar area covered, just shifted.

Comparison of sensitivity: SHADOWs ($5x10^{19}$ pot, 5 years) vs SHiP ($2x10^{20}$ pot, 5 years)



PBC workshop, Nov. 2022.



SHiP sensitivity is dramatically changed wrt the past.

Sensitivity depends upon:

1. Underlying theory model
(for light dark scalars, there are large non-perturbative effects in the lifetime computation that affect the sensitivity);

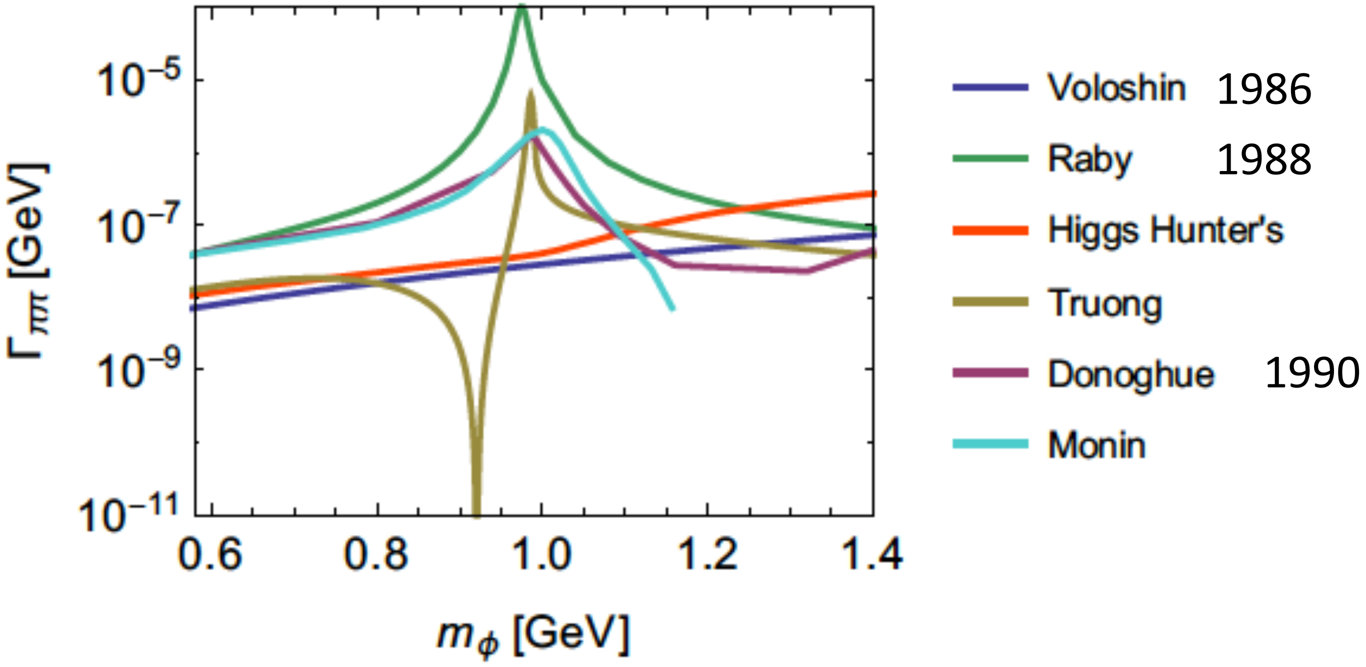
2. Geometry

3. Number of protons-on-dump.

Dark Scalars: Branching Fractions

Dark Scalar hadronic widths: a longstanding (non-perturbative) theoretical problem

Winkler, 1809.01876 and references therein (see also Boyarsky et al., 1904.10447)

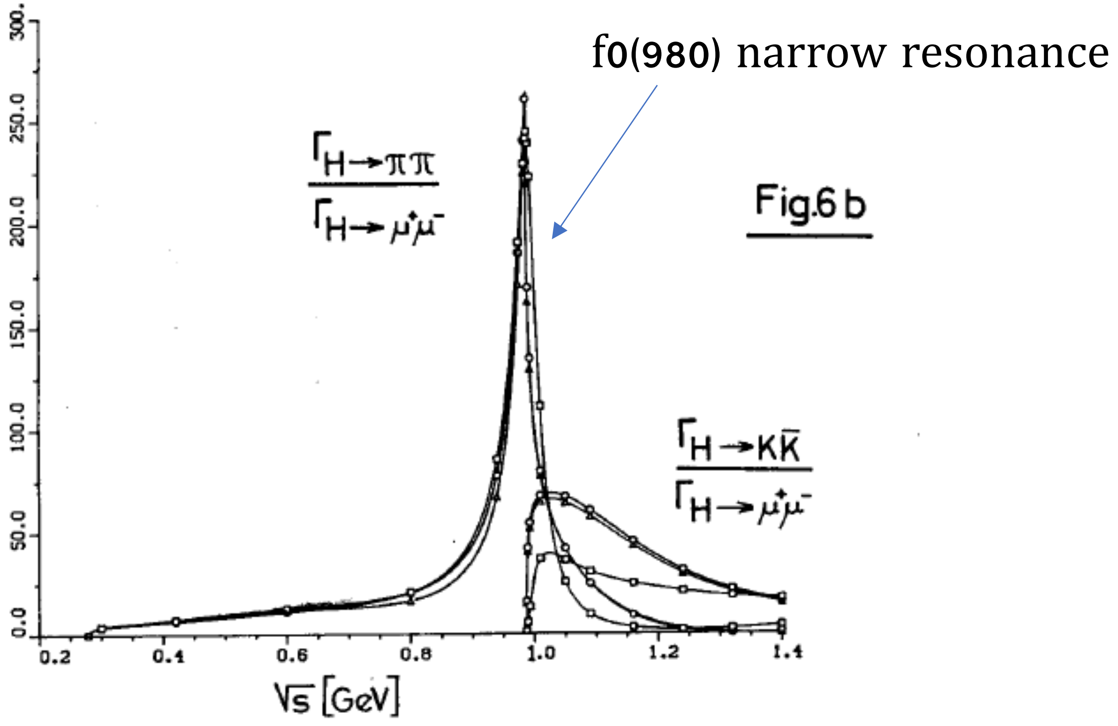


For Scalar, hadronic decays are dominant immediately above the 2 m(pi) threshold.
Non-perturbative resonance effects around 1 GeV due to interference with 4 pi channel

Dark Scalars: Branching Fractions

PBC recommendation: use the Donoghue et al. computation

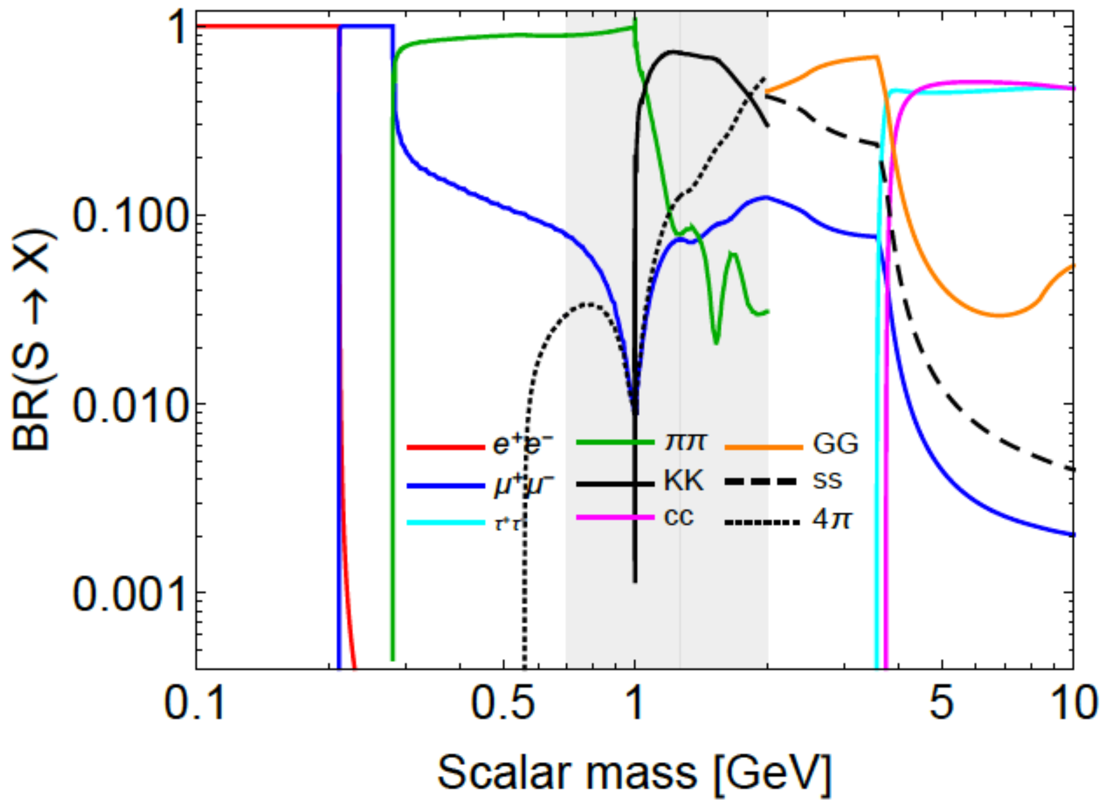
Donoghue, Gassler and Lewwyler, 90'



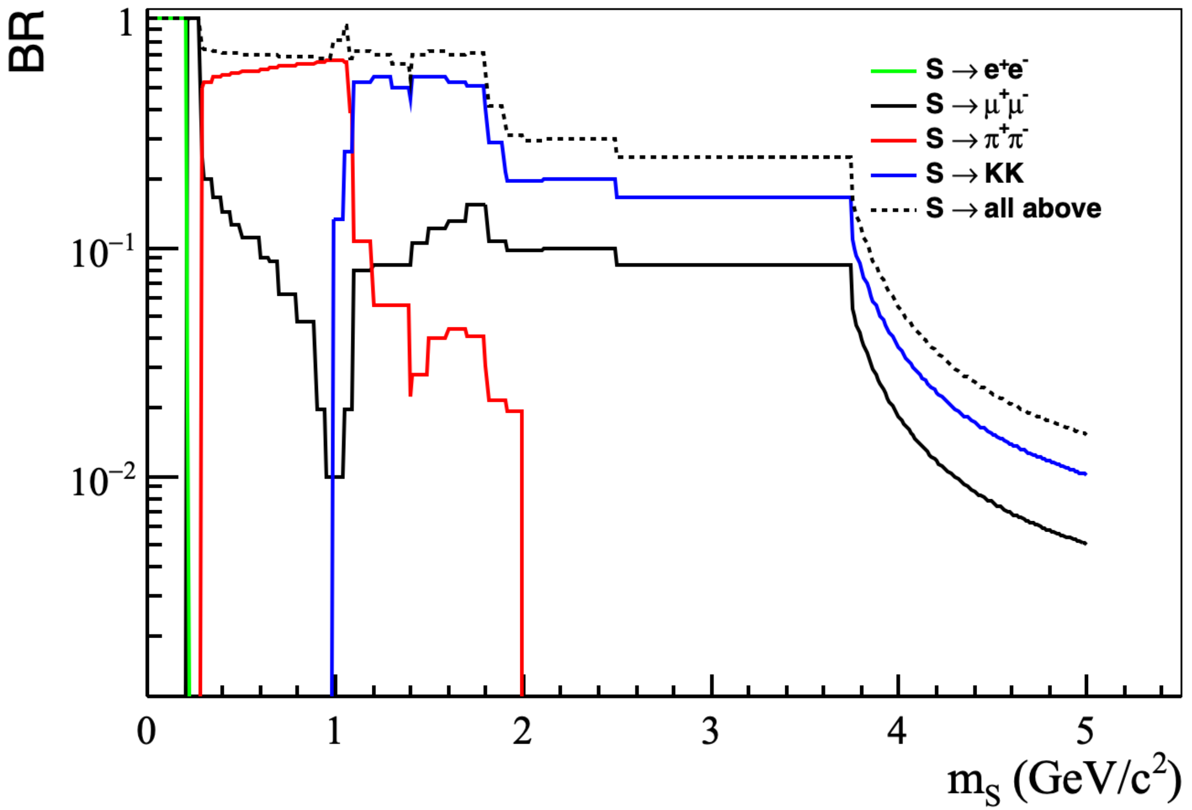
This peak affects the lifetime that around 1 GeV becomes very short

Dark Scalars: Branching Fractions

Boyarsky et al., 1904.10447



My simulation

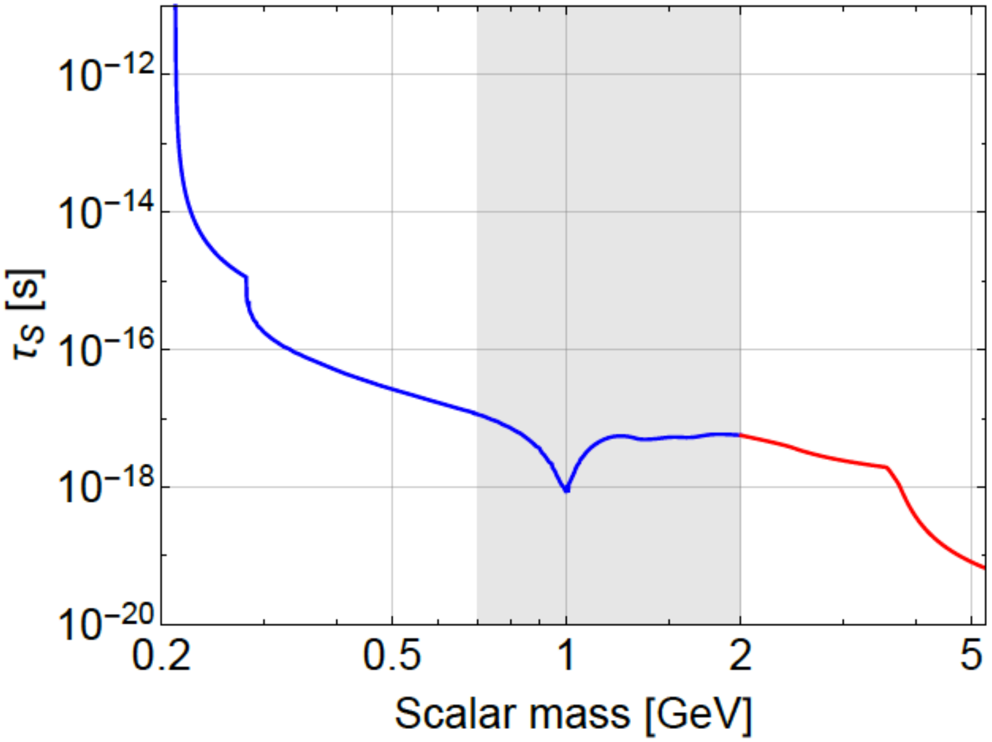


I did not attempt to repeat the non-perturbative calculations (of course!) but I used their findings numerically.
I am not considering the S → **ττ** channel for the time being.

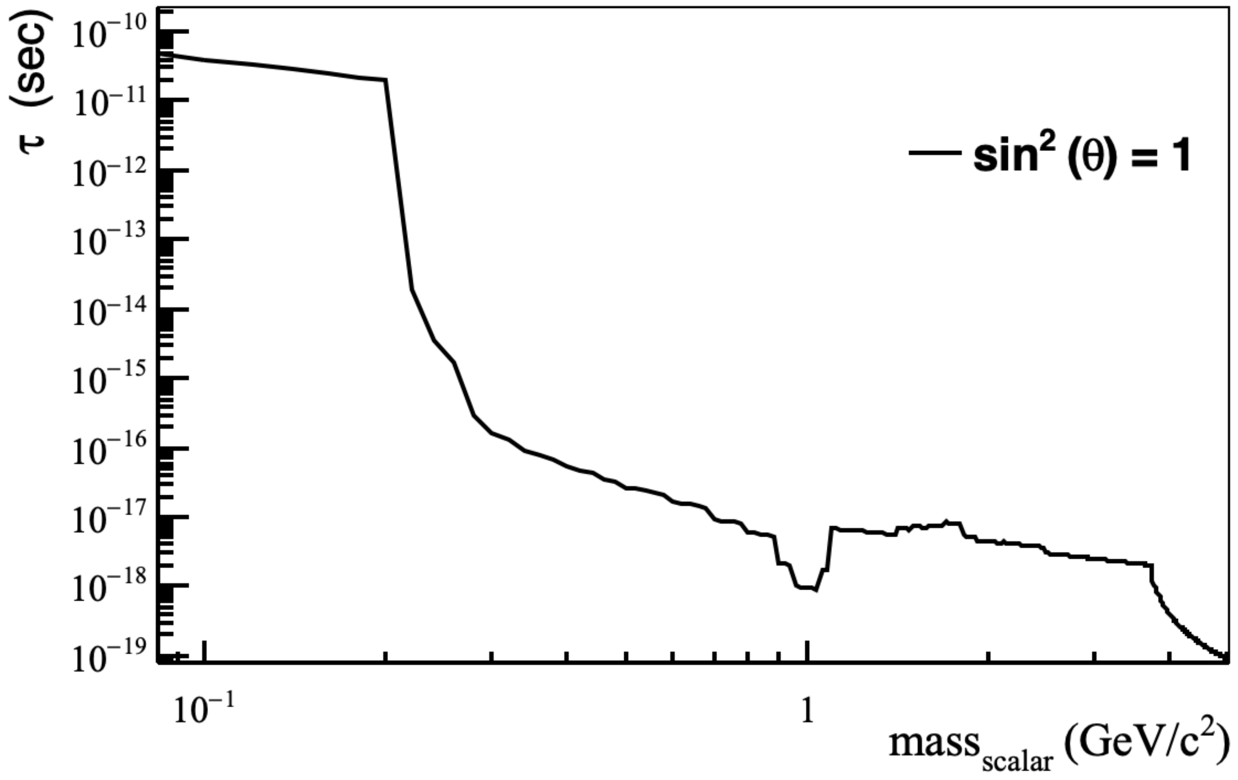
Dark Scalars: Lifetime

Plugging together all the partial decay widths I can evaluate the lifetime…

Boyarsky et al, 1904.10447



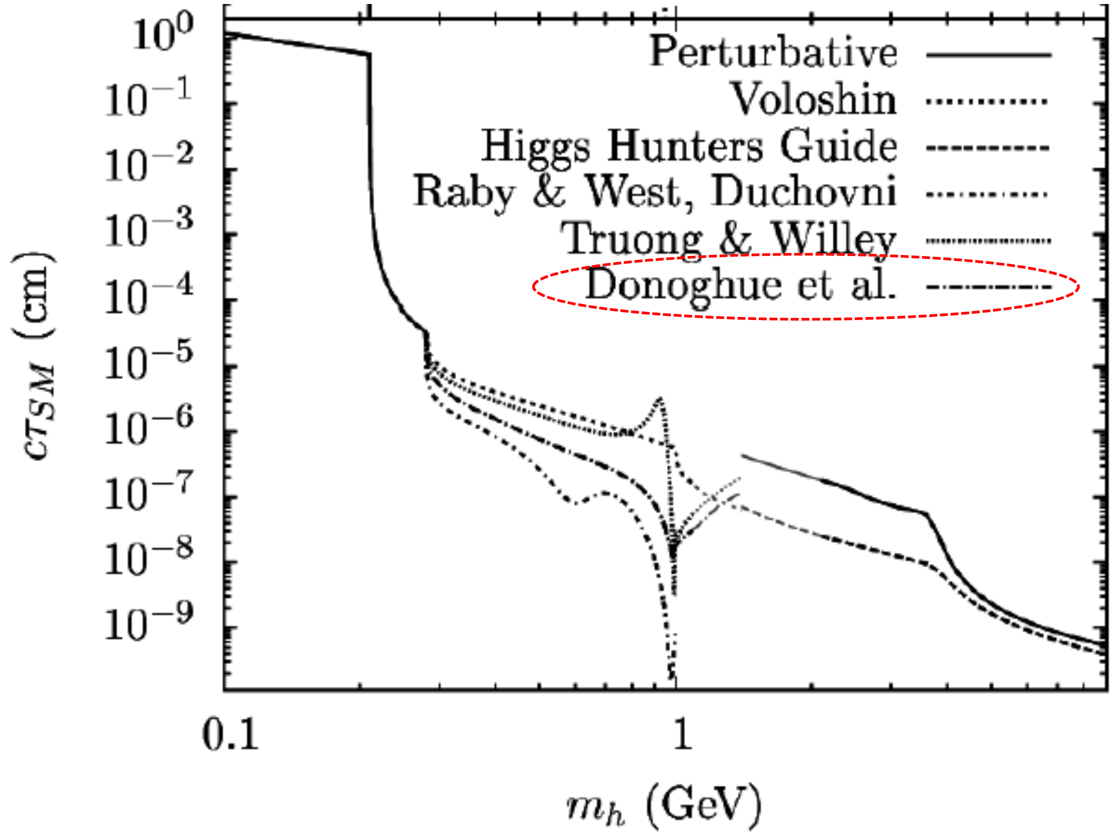
My simulation



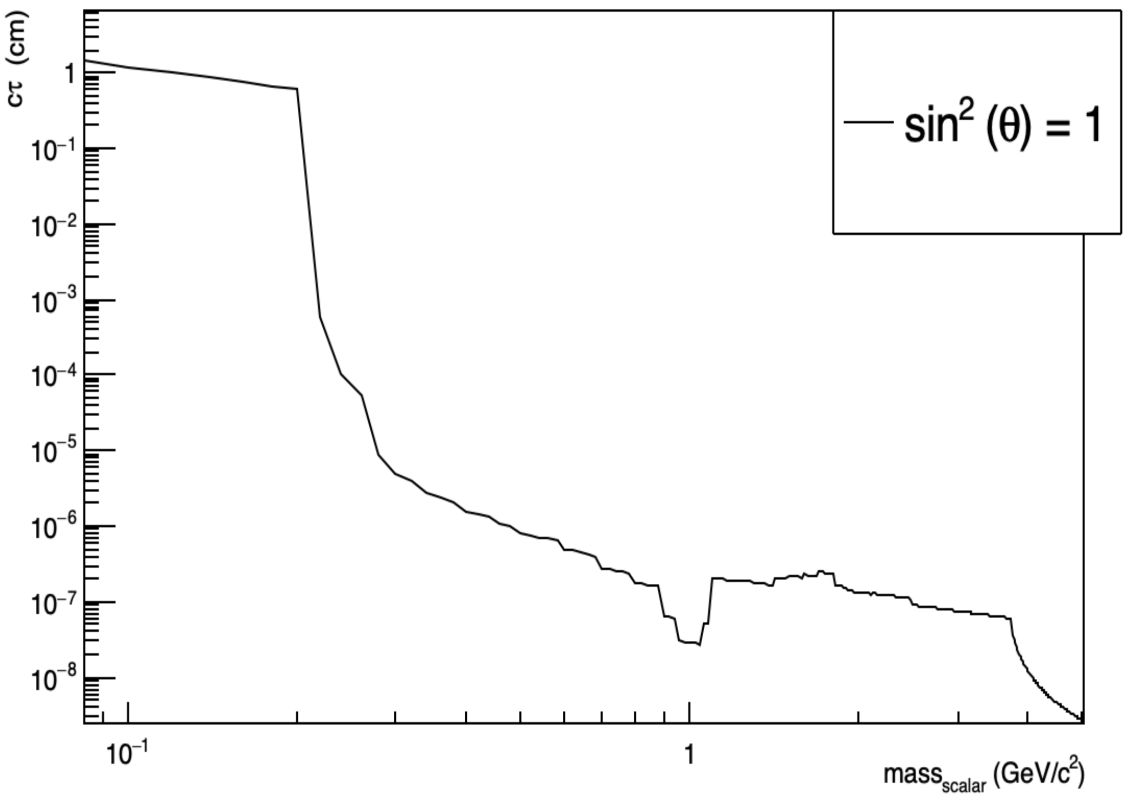
... and I can recover Alexey's computations…

Dark Scalars: Lifetime

1310.8042



My simulation



…and I can recover Donoghue's computations too..

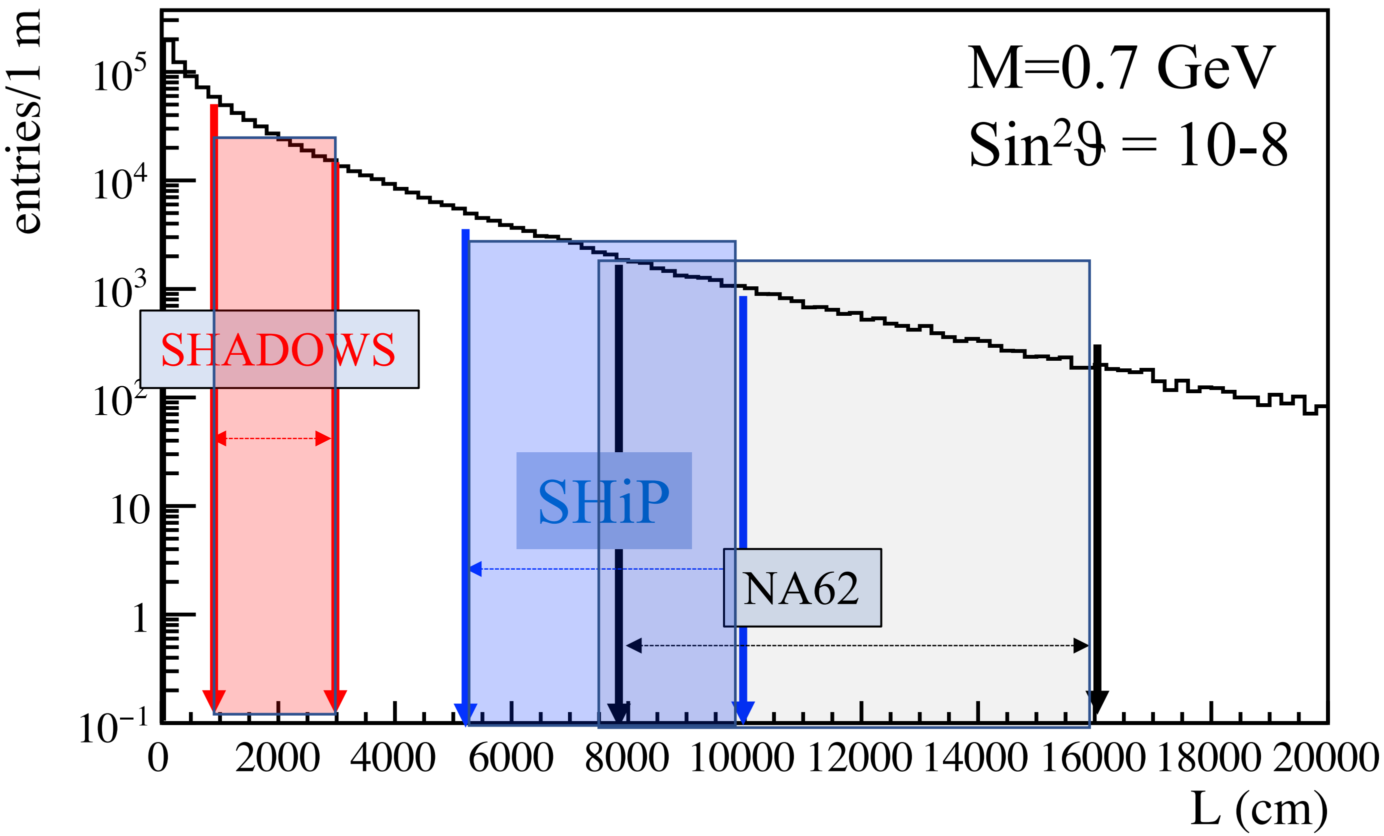
Sensitivity depends upon:

1. Underlying theory model
(for light dark scalars, there are large non-perturbative effects in the lifetime computation that affect the sensitivity);

2. Geometry

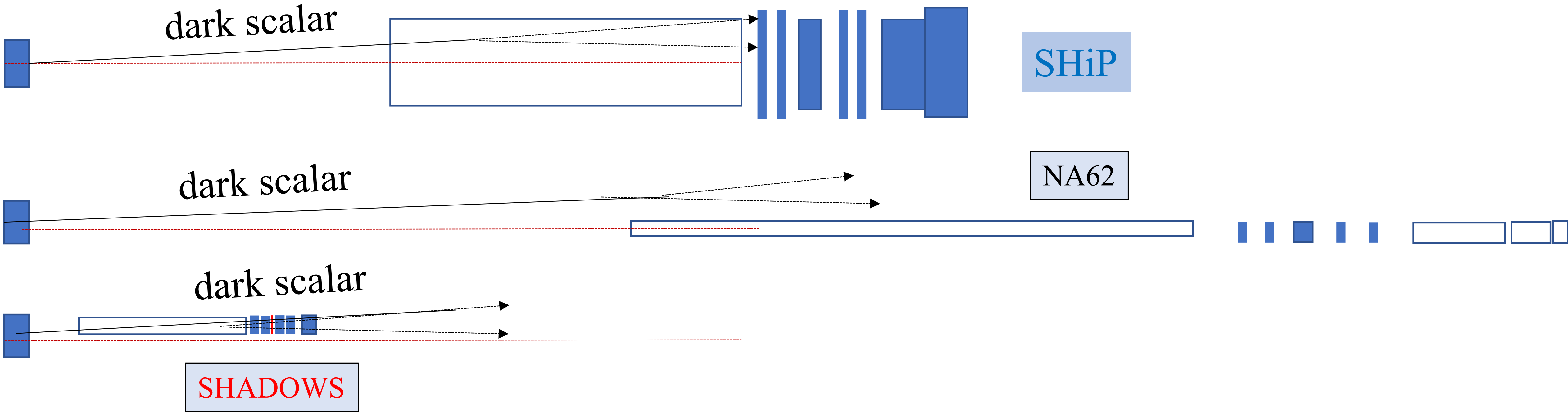
3. Number of protons-on-dump.

An example of lifetime for a light scalar



For a (relatively) short lived dark scalar, the closer to the dump you go, the more you get.

Lateral view (almost to scale): including distance from the dump



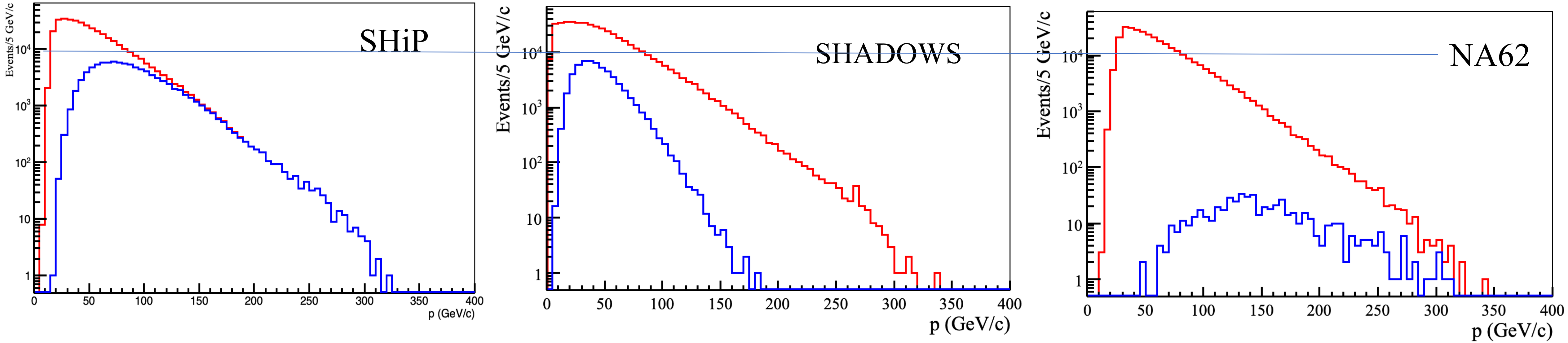
Not only because we sample the lifetime at the very beginning
but because we intercept more flux…

Momentum distribution of a light dark scalar

M=0.7 GeV
Sin²ϑ = 10-8

Red: light dark scalar decays between z_{min} and z_{max}

Blue: Red + at least two charged tracks in acceptance

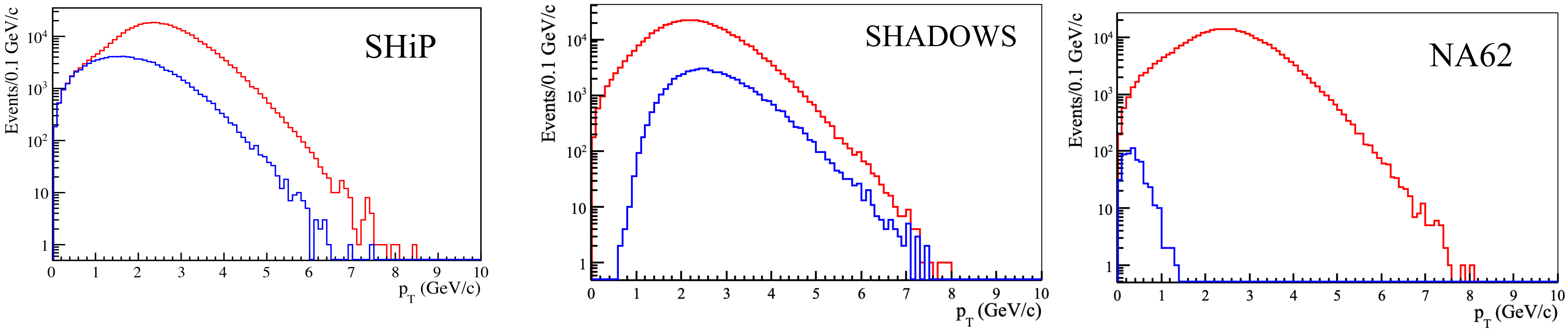


SHADOWS acceptance selects low-p candidates, NA62 acceptance high-p (very boosted) candidates

Transverse Momentum distribution of a light dark scalar

M=0.7 GeV
$Sin^2\vartheta$ = 10-8

Red: light dark scalar decays between z_{min} and z_{max}
Blue: Red + at least two charged tracks in acceptance



SHADOWS acceptance selects high-pT candidates (off-axis), NA62 acceptance low-pT candidates (on-axis & far away)