

# SHADOWS

Search for Hidden And Dark Objects With the SPS

INFN-LNF

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CERN

Royal Holloway London

University of Mainz (excellence cluster)

University of Heidelberg

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Charles University, Prague

University of Groningen, The Netherland

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

## Expression of Interest, January 2022

## SHADOWS

Search for Hidden And Dark Objects With the SPS*Expression of Interest*

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## Letter of Intent, 4 November 2022

## SHADOWS

Search for Hidden And Dark Objects With the SPS*Letter of Intent*

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# Why the ECN3 area ?

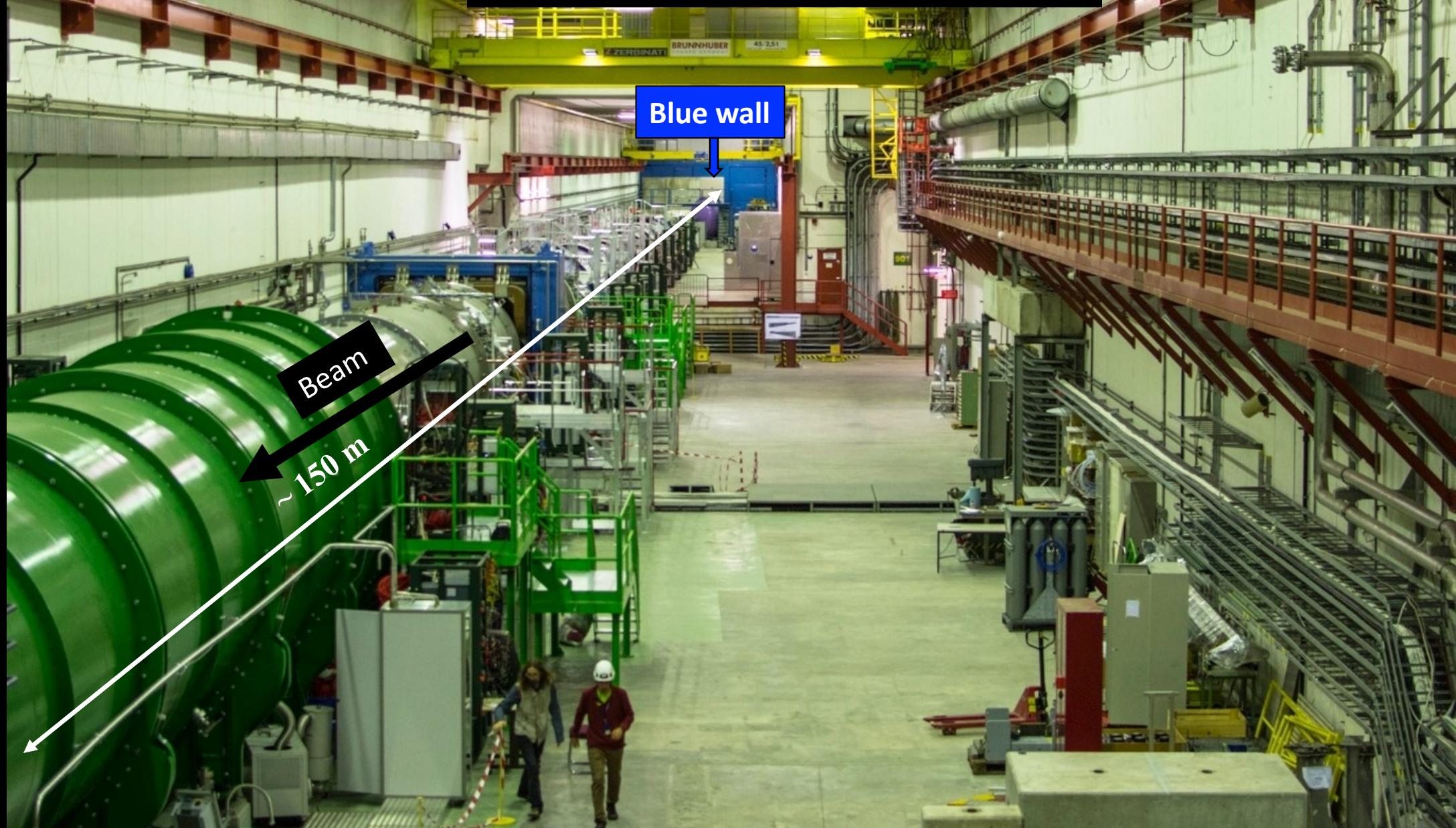
- ✓ Because ECN3/TCC8 has the best 400 GeV primary extracted proton beam line at CERN (and worldwide) and a plethora of hidden sector particles can emerge from interactions of a high-energy proton beam with a dump
  - NA62 nominal intensity is  $3 \times 10^{12}$  ppp with 4.8s pulse duration:  $\sim 10^{12}$  pot/sec, up to  $2 \times 10^{18}$  pot/year
- ✓ K12 beam intensity proposed to be increased by a factor x6-7
  - for high intensity K beams and SHADOWS → up to  $1.3 \times 10^{19}$  pot/year



Physics Experiment	Proton Momentum	SPS Cycle	Proton / pulse	Pulses / day	Days / year	POT/y
HIKE	400 Gev/c	4.8 s / 14.4 s	$2.1 \times 10^{13}$	3000	200	$1.3 \times 10^{19}$
SHADOWS	400 Gev/c	4.8 s / 14.4 s	$2.1 \times 10^{13}$	3000	200	$1.3 \times 10^{19}$
BDF/SHiP	400 Gev/c	1.2 s / 7.2 s	$4.2 \times 10^{13}$	6000	200	$4.0 \times 10^{19}$

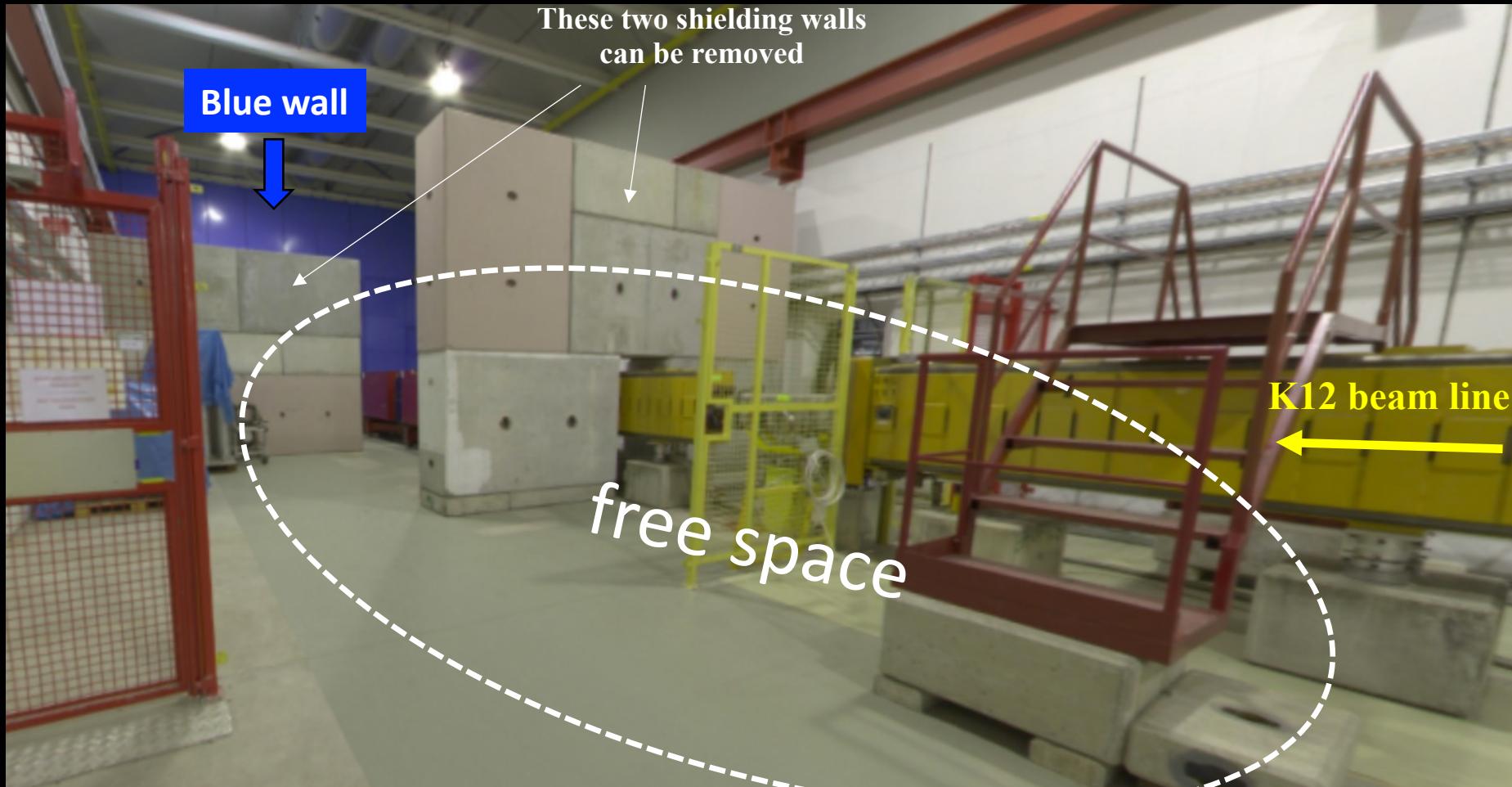
SHADOWS can collect  $5 \times 10^{19}$  pot in ~4 years of data taking starting after LS3 (~2028)

# NA62 in ECN3/TTC8

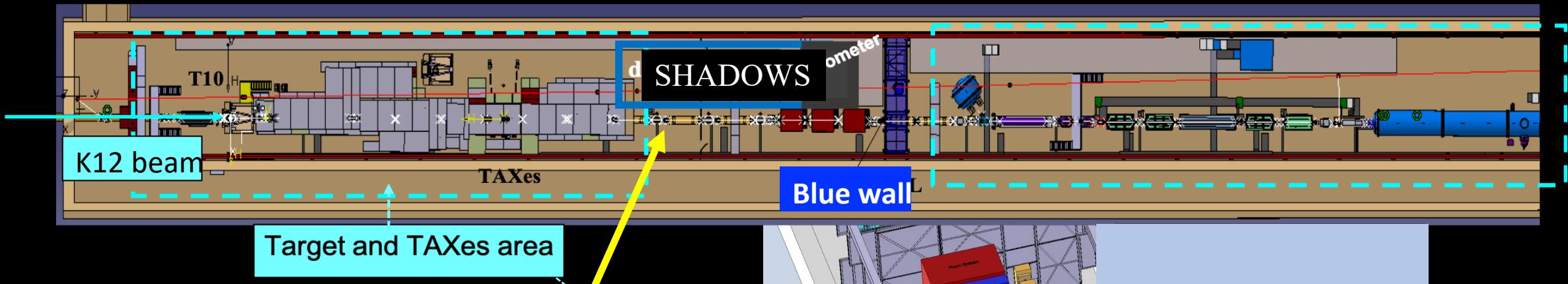


# SHADOWS in TTC8/ECN3

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



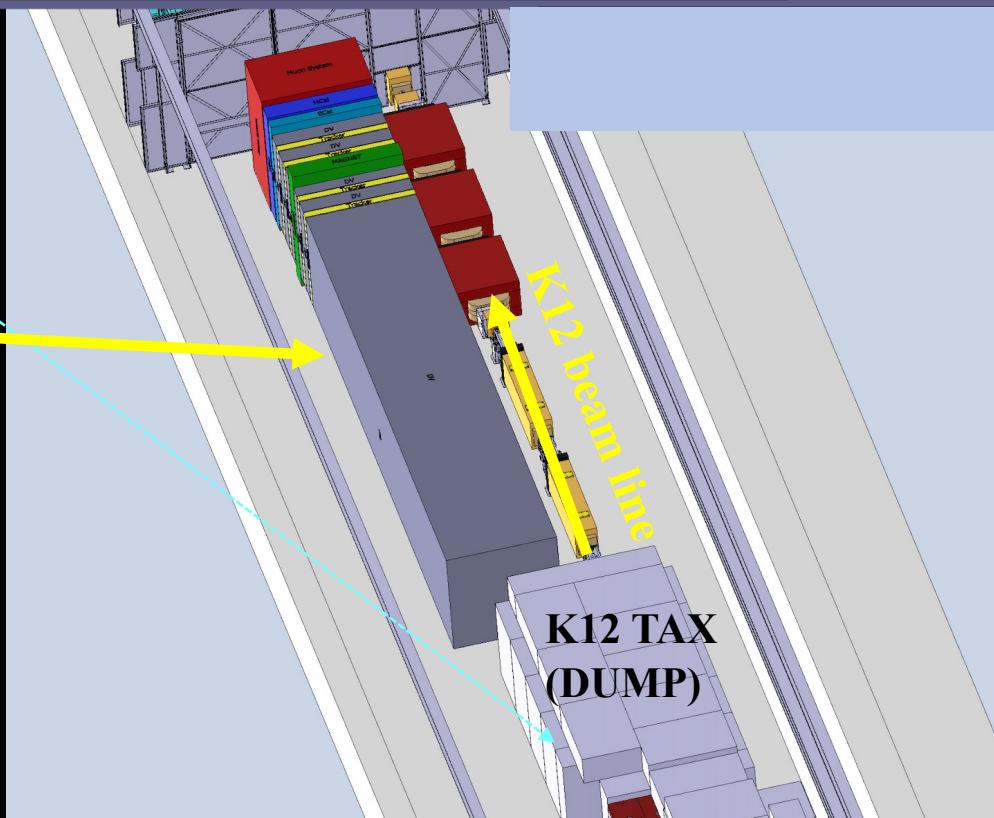
# SHADOWS in TTC8/ECN3



SHADOWS in the target area

## Preliminary Conceptual Layout

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



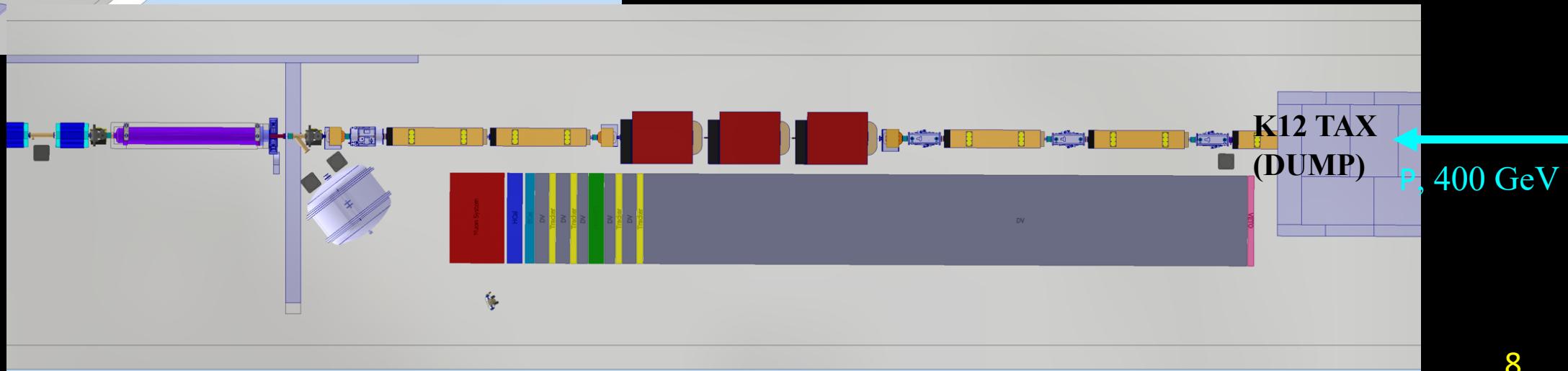
# SHADOWS in ECN3/TTC8



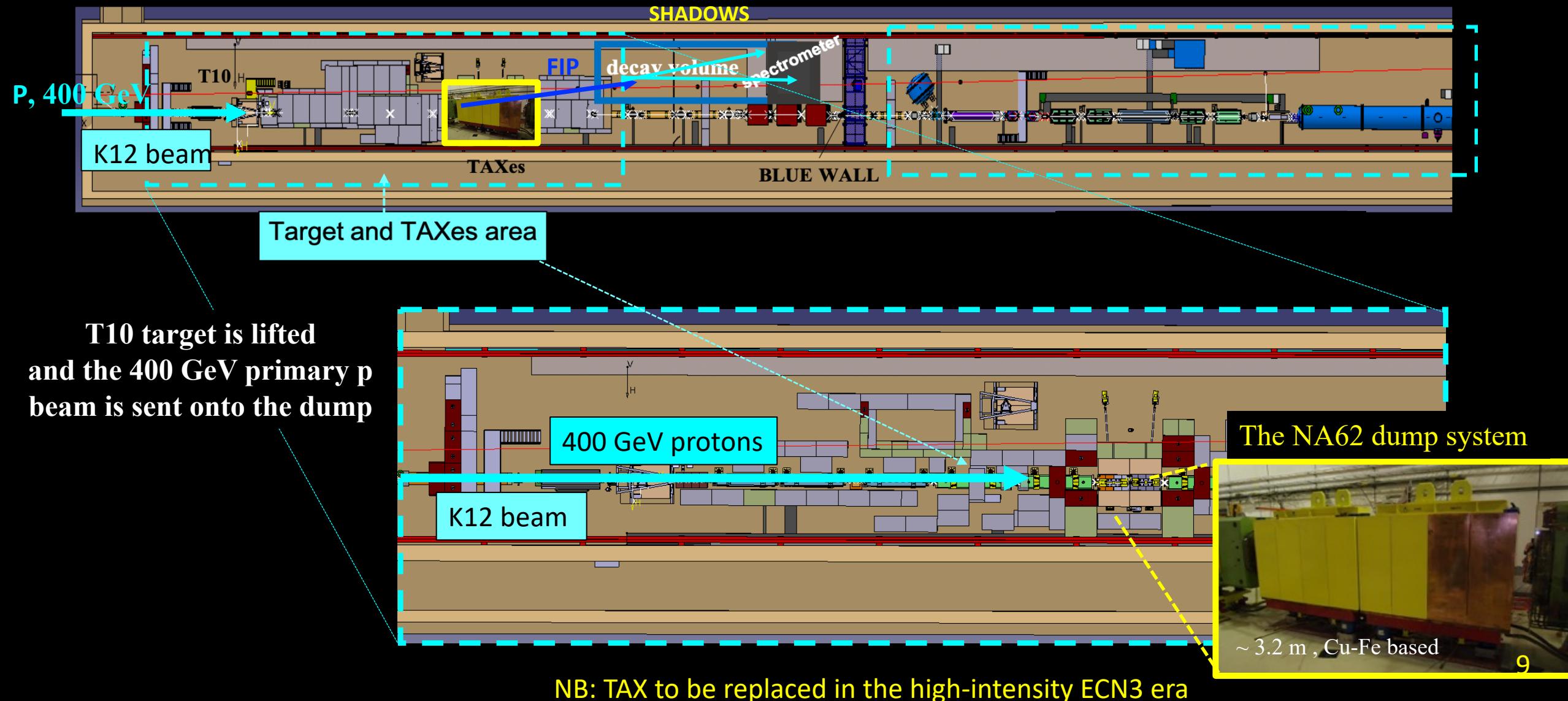
## SHADOWS detector components:

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:  $2.5 \times 2.5 \text{ m}^2$ .

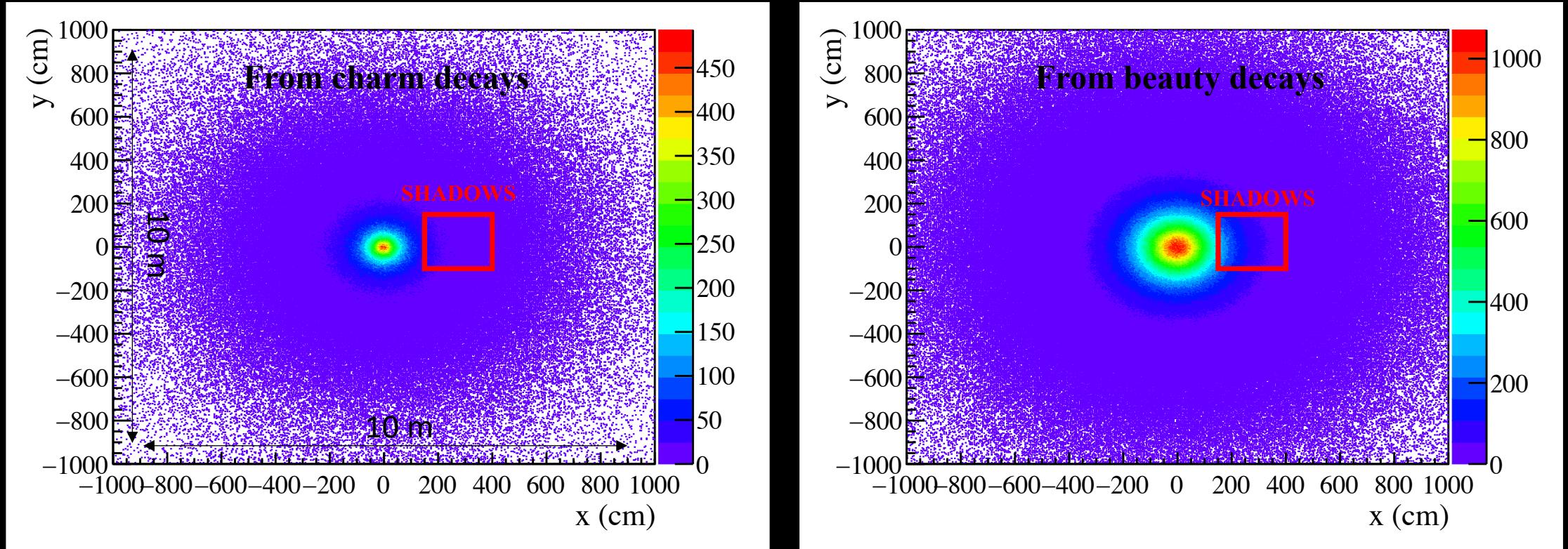


SHADOWS can operate when K12 beam line runs in dump-mode



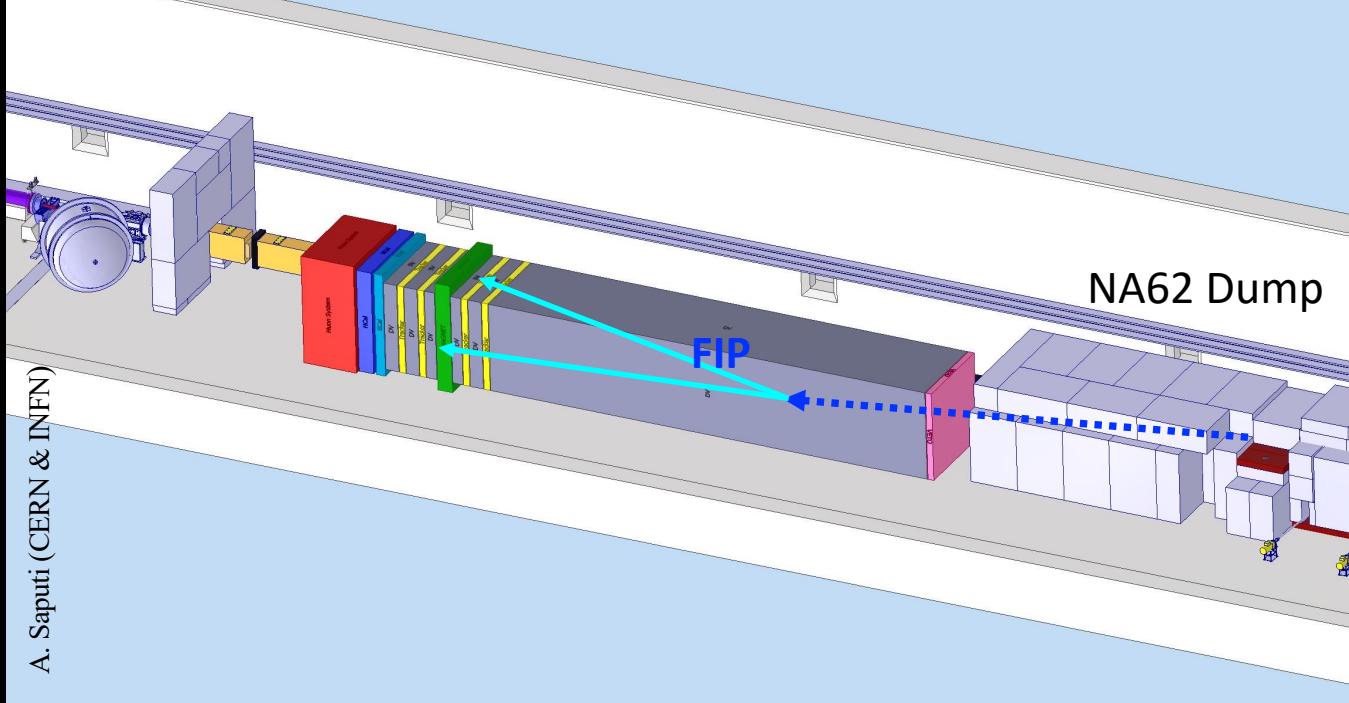
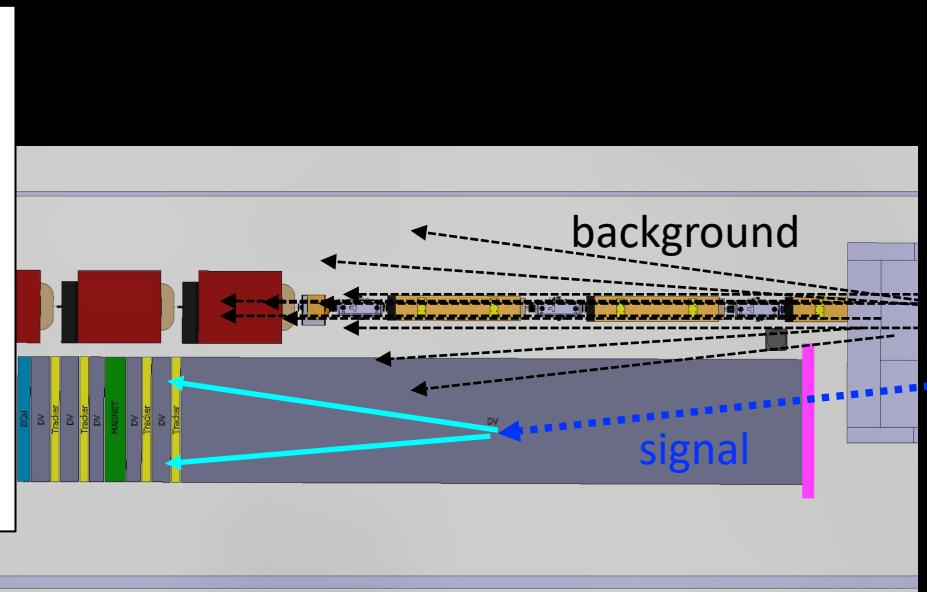
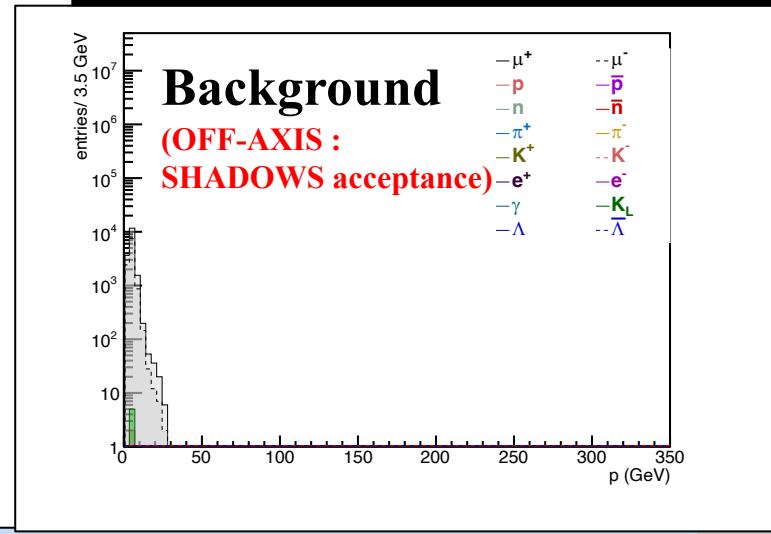
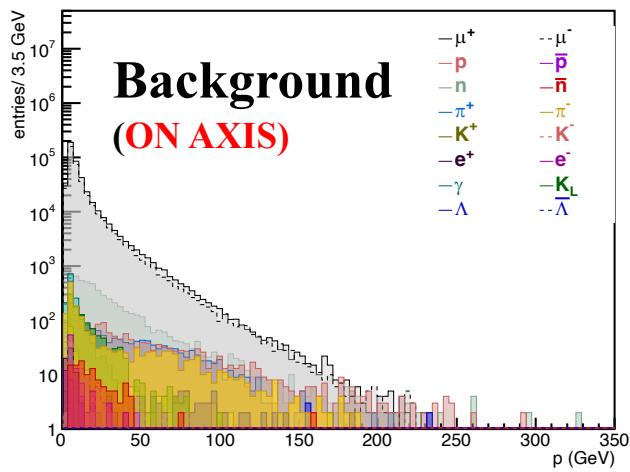
# Why “off-axis” works: Signal

$HNL \rightarrow \pi\mu$  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



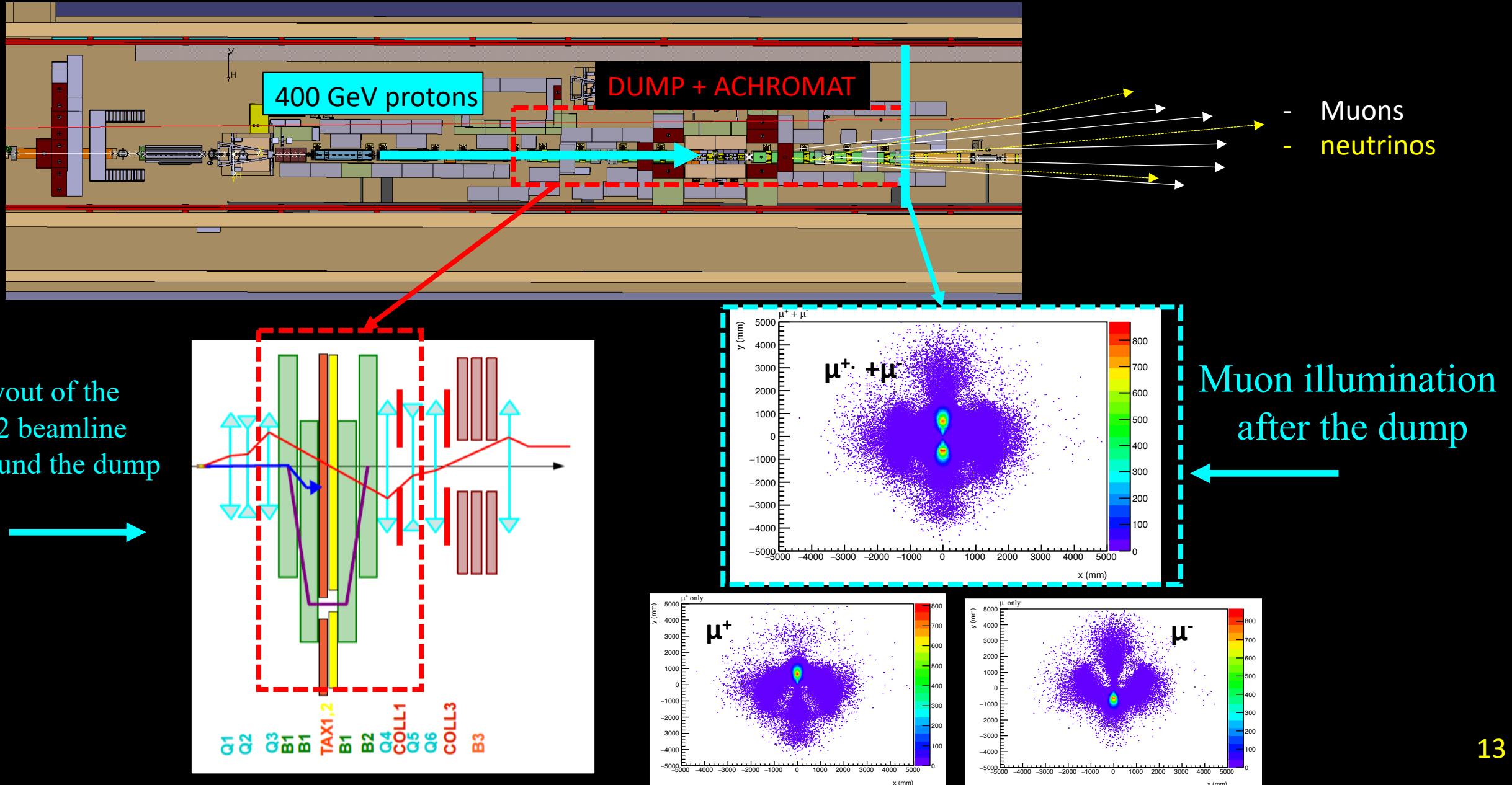
Most of the residual background emerging from TAXes are muons and neutrinos that are mostly produced forward (and miss SHADOWS acceptance).

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

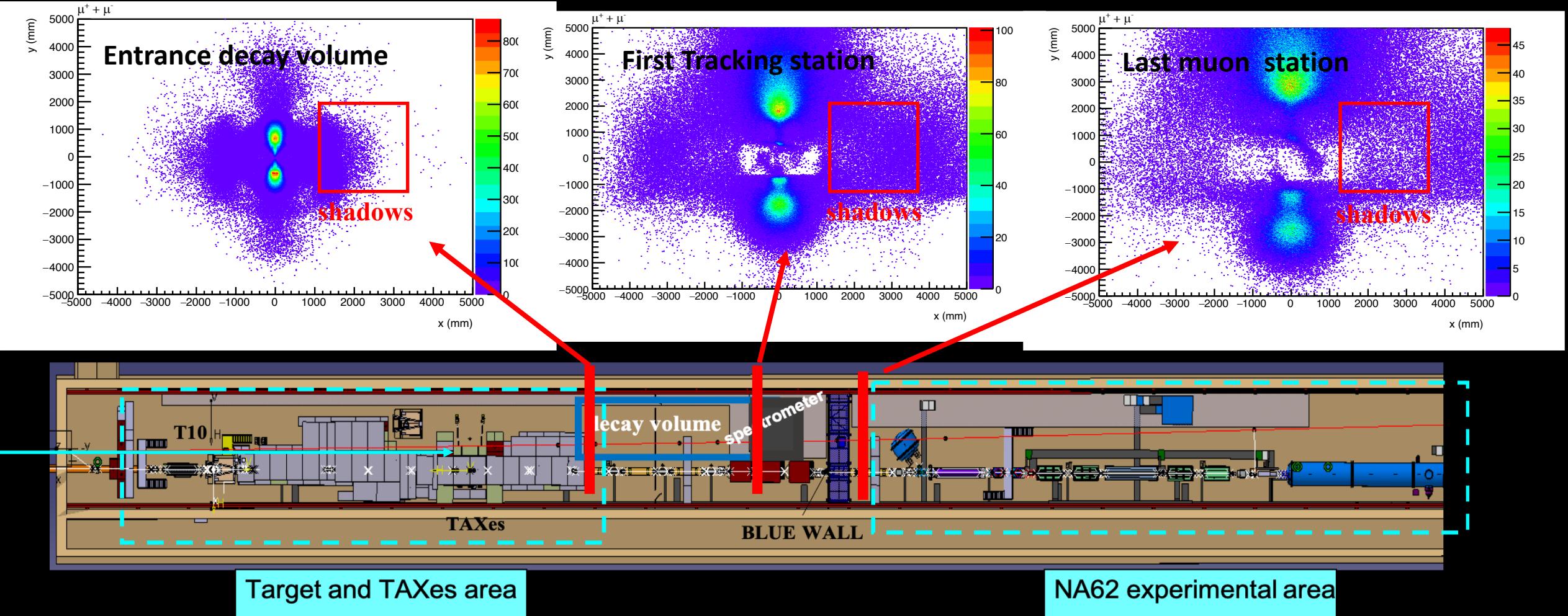
- Stay close to the dump:  
to maximise acceptance for signals with a relatively small detector
- Stay off-axis with respect to the beam line:  
to minimize acceptance for backgrounds (mostly peaked forward)

The beam-induced background:  
the name of the game

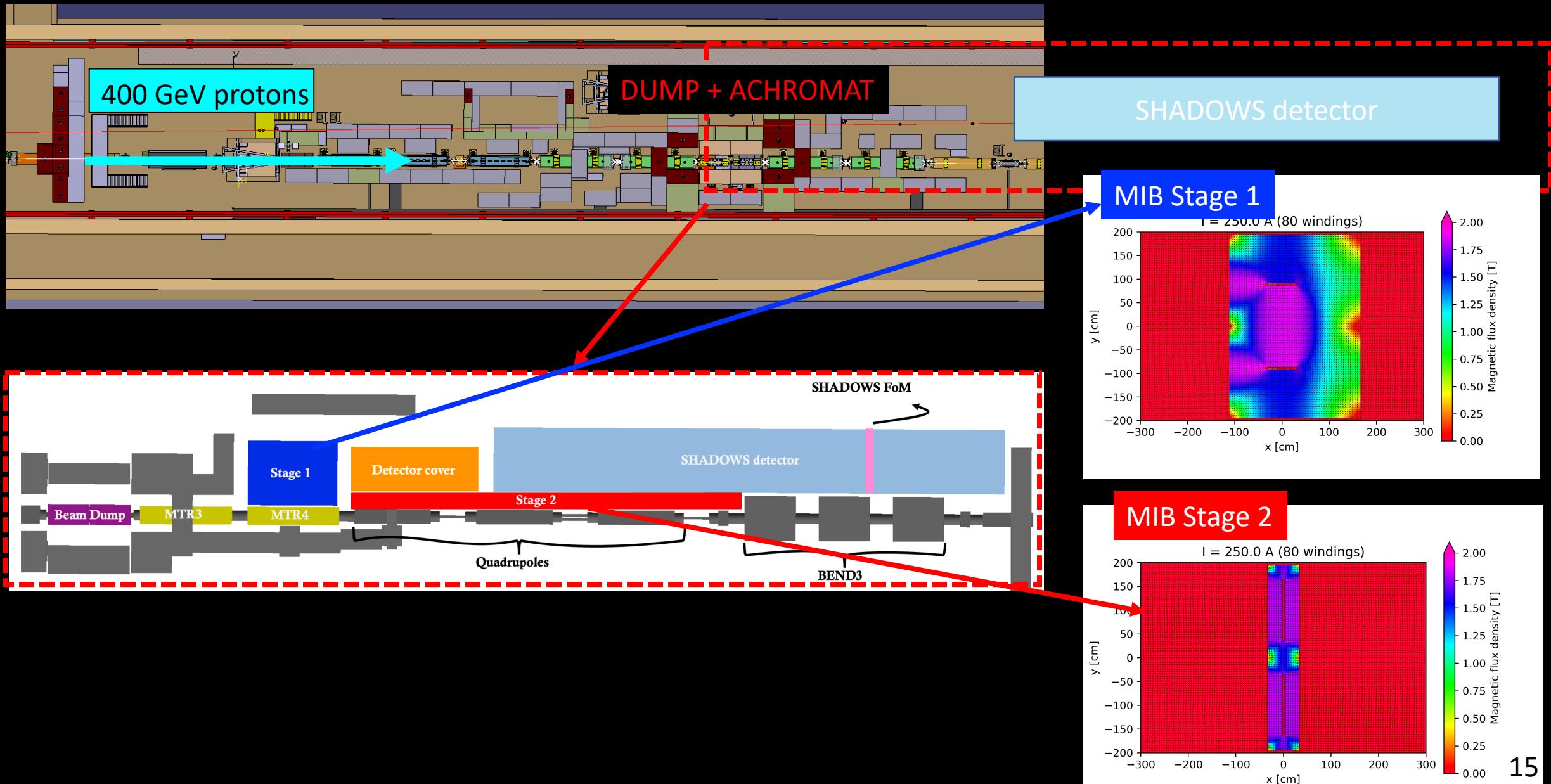
# Beam-induced background after the dump



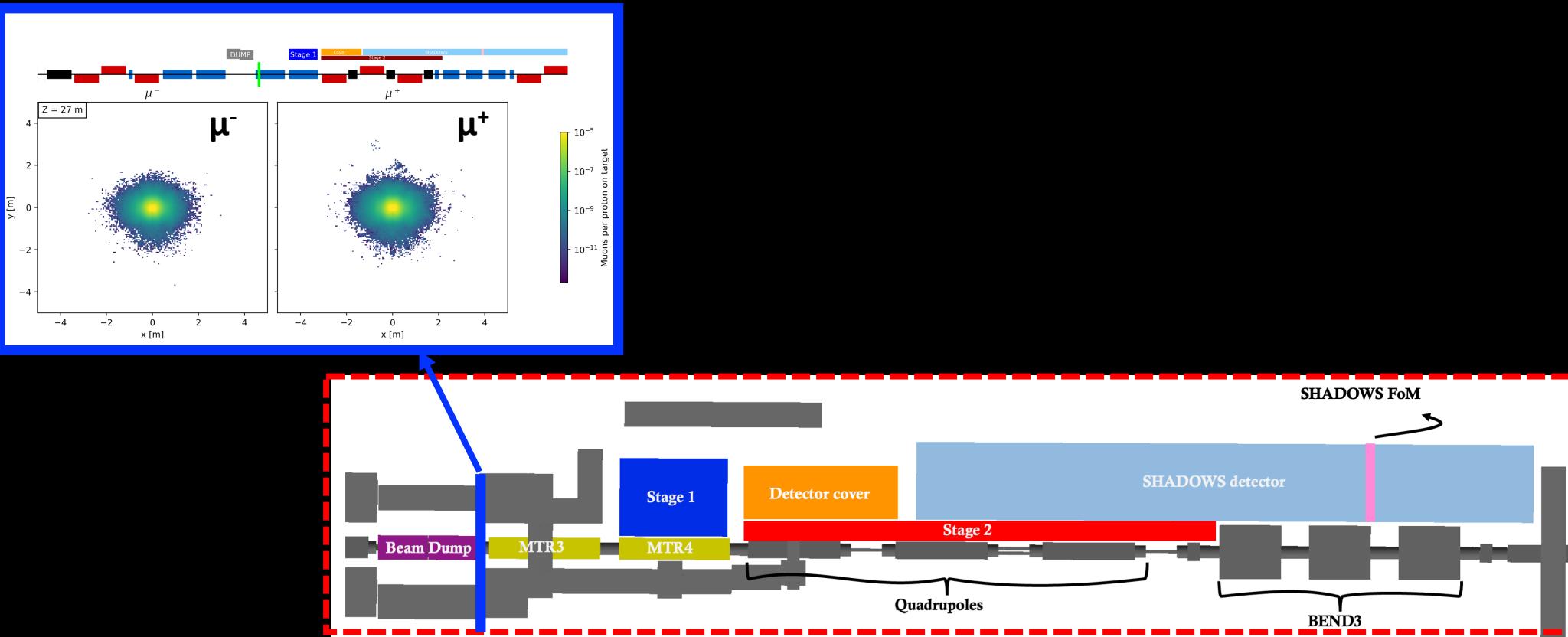
# Muon illumination as a function of the position along the beamline



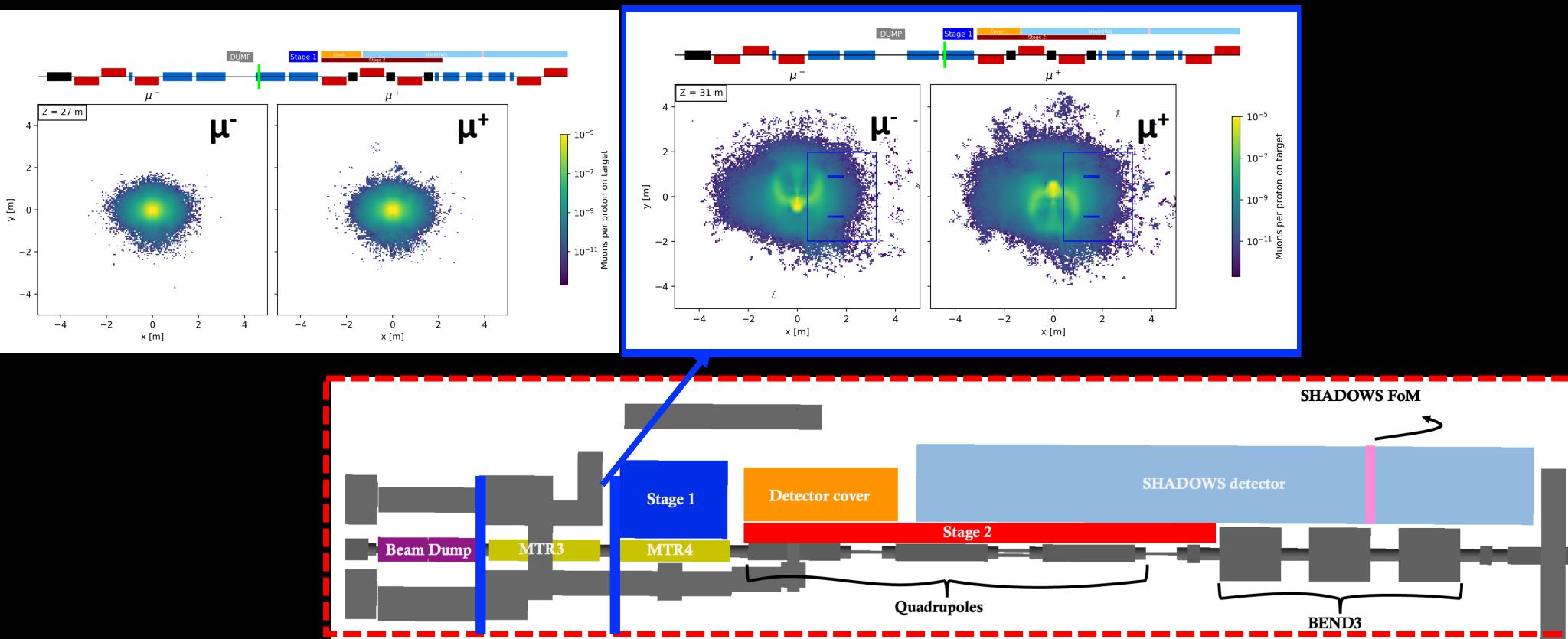
# The sweeping system: the Magnetized Iron Blocks (MIB)



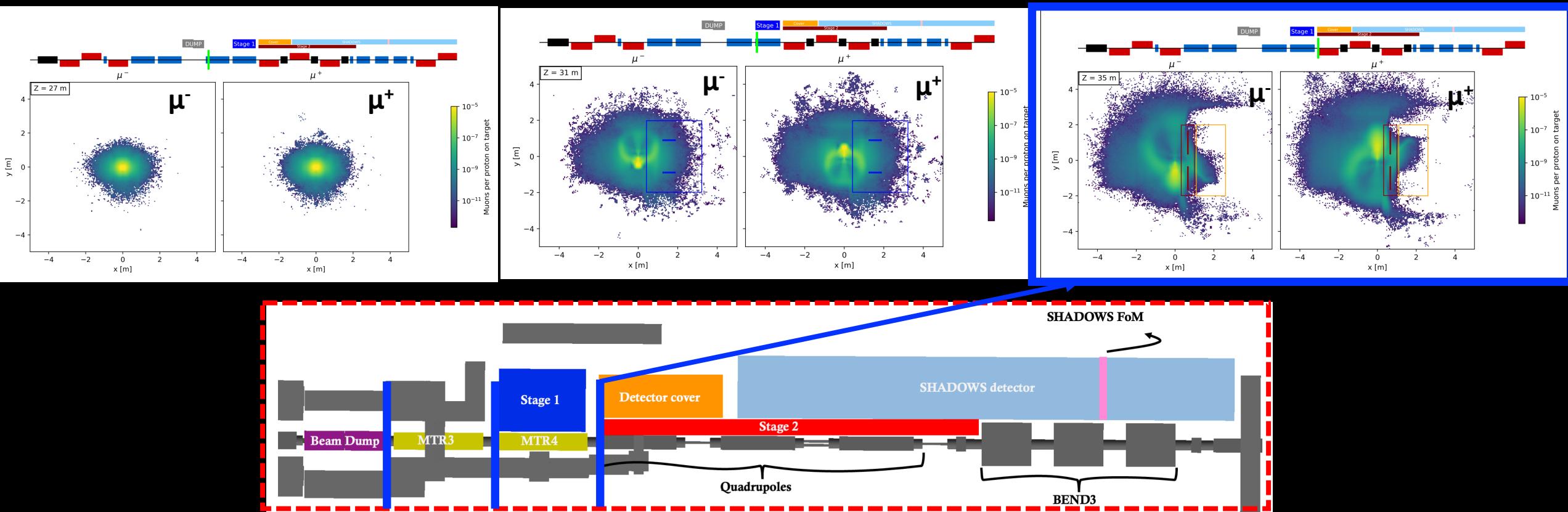
# Muon Illumination with the Sweeping System (MIB)



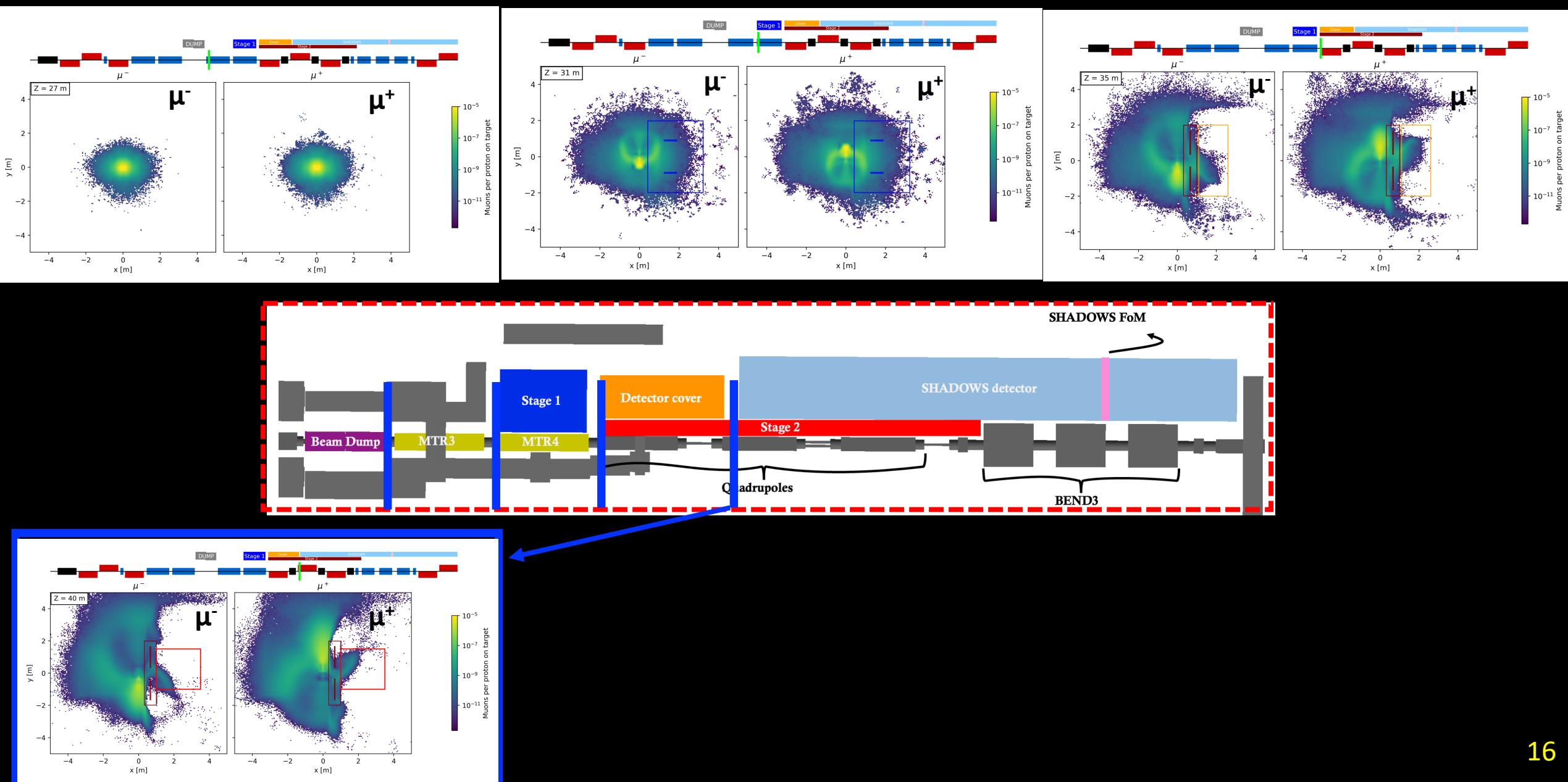
# Muon Illumination with the Sweeping System (MIB)



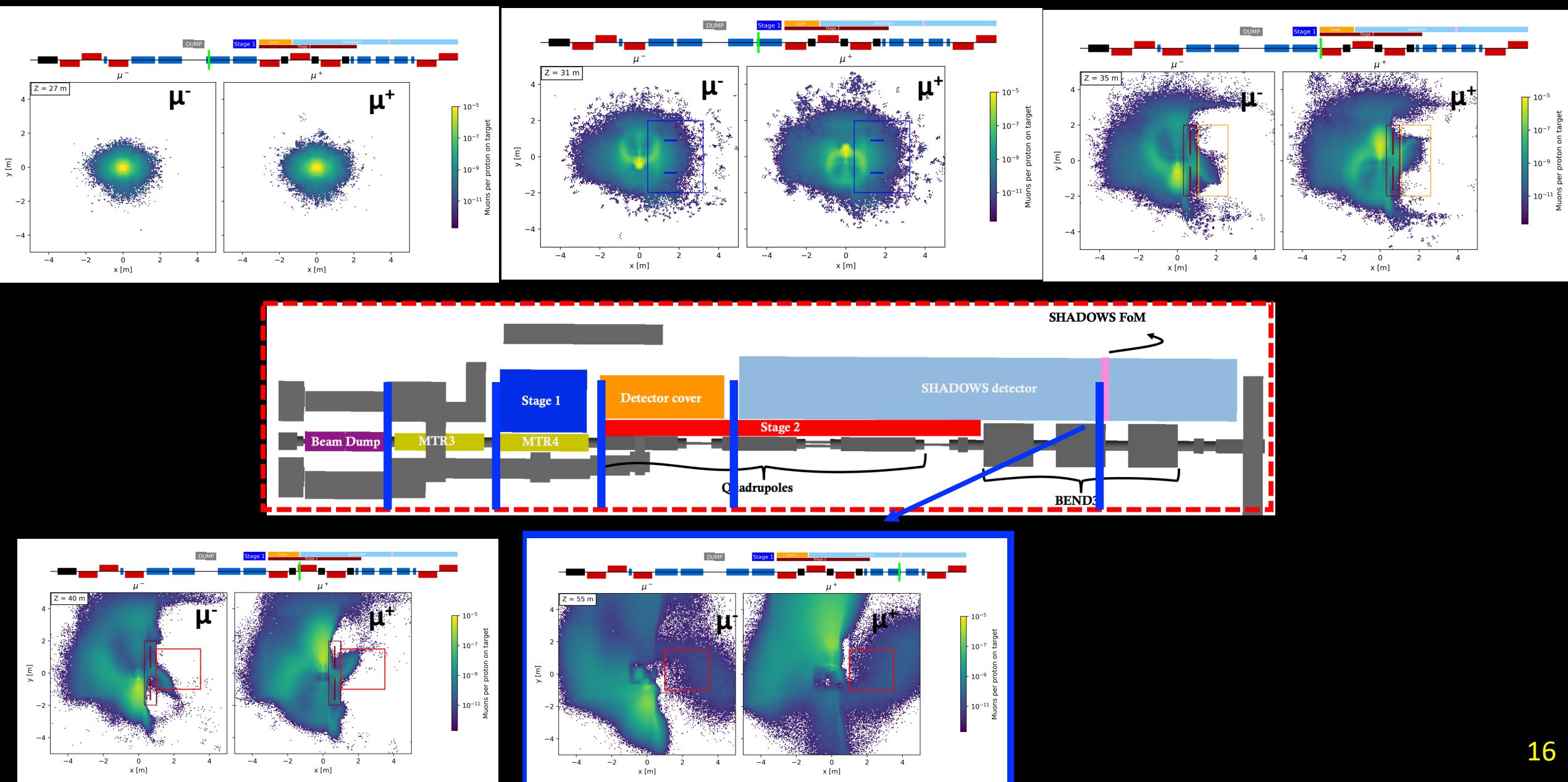
# Muon Illumination with the Sweeping System (MIB)



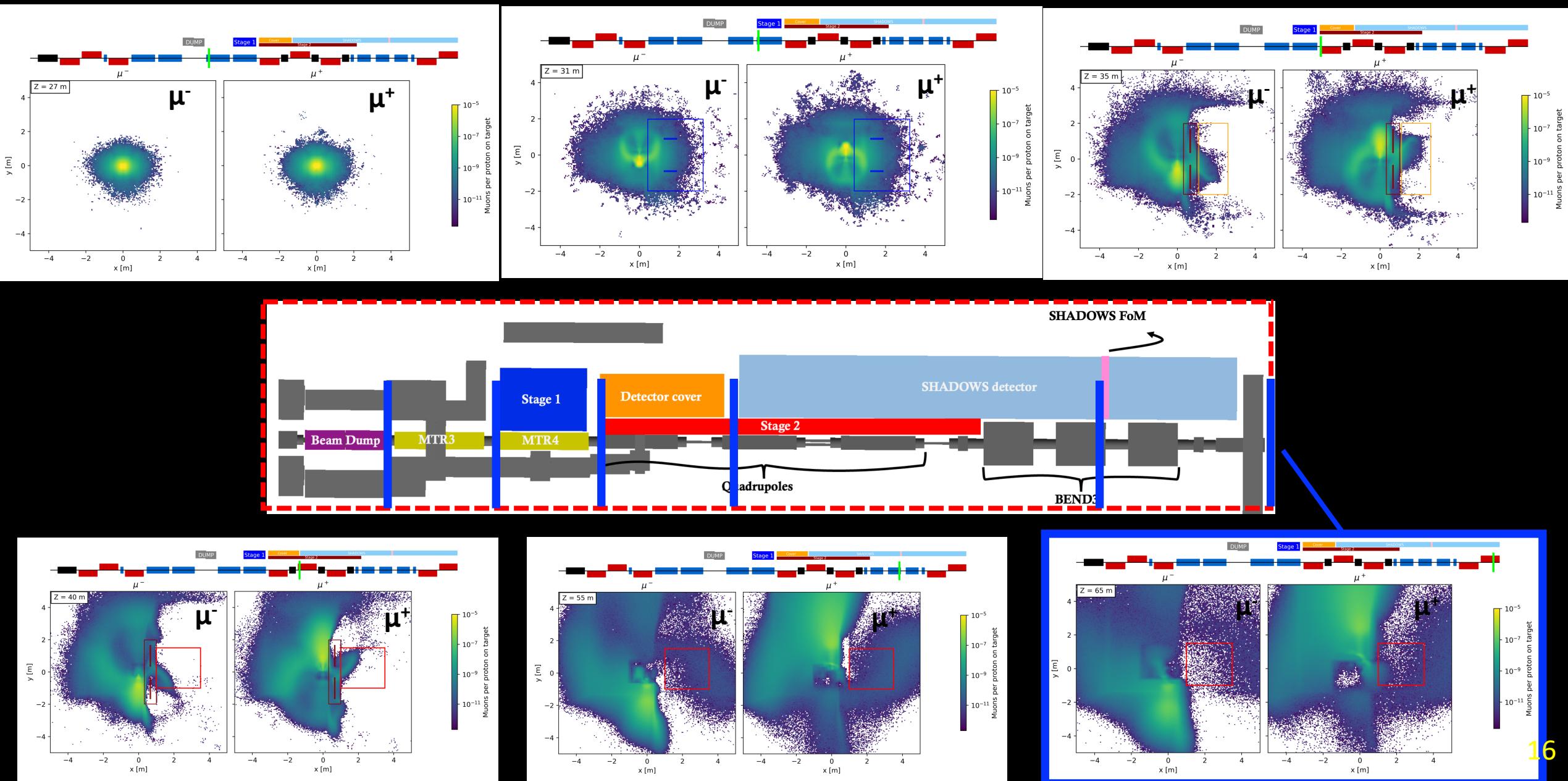
# Muon Illumination with the Sweeping System (MIB)



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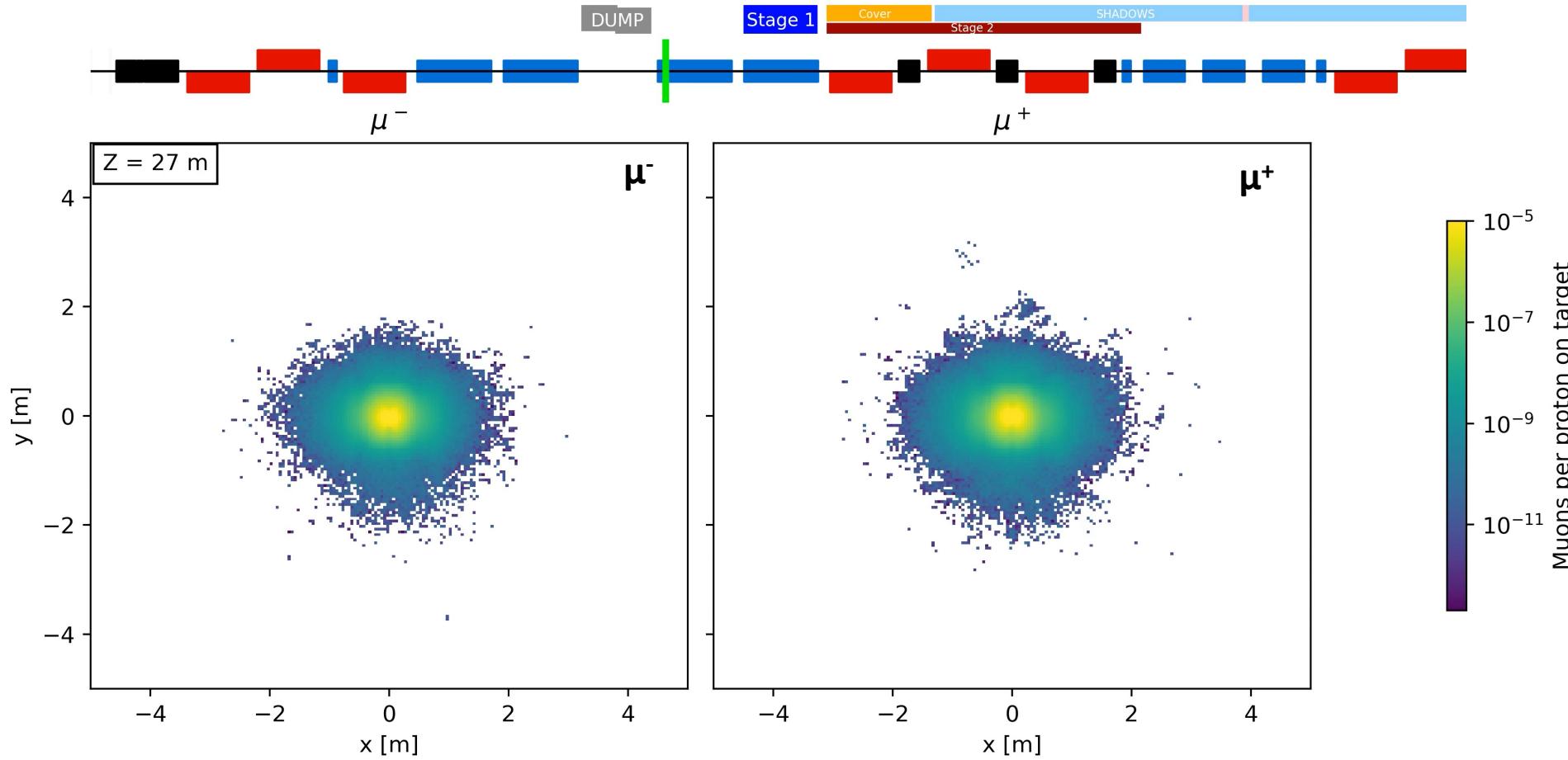


# Muon Illumination with the Sweeping System (MIB)



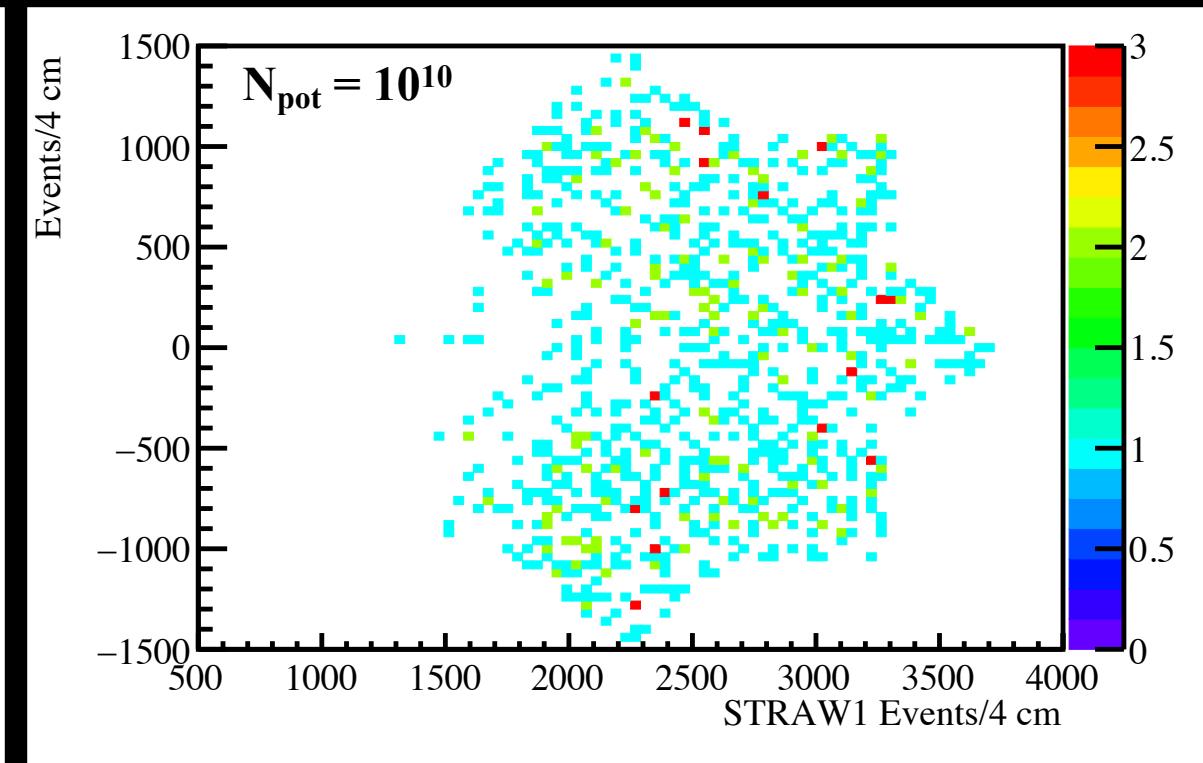
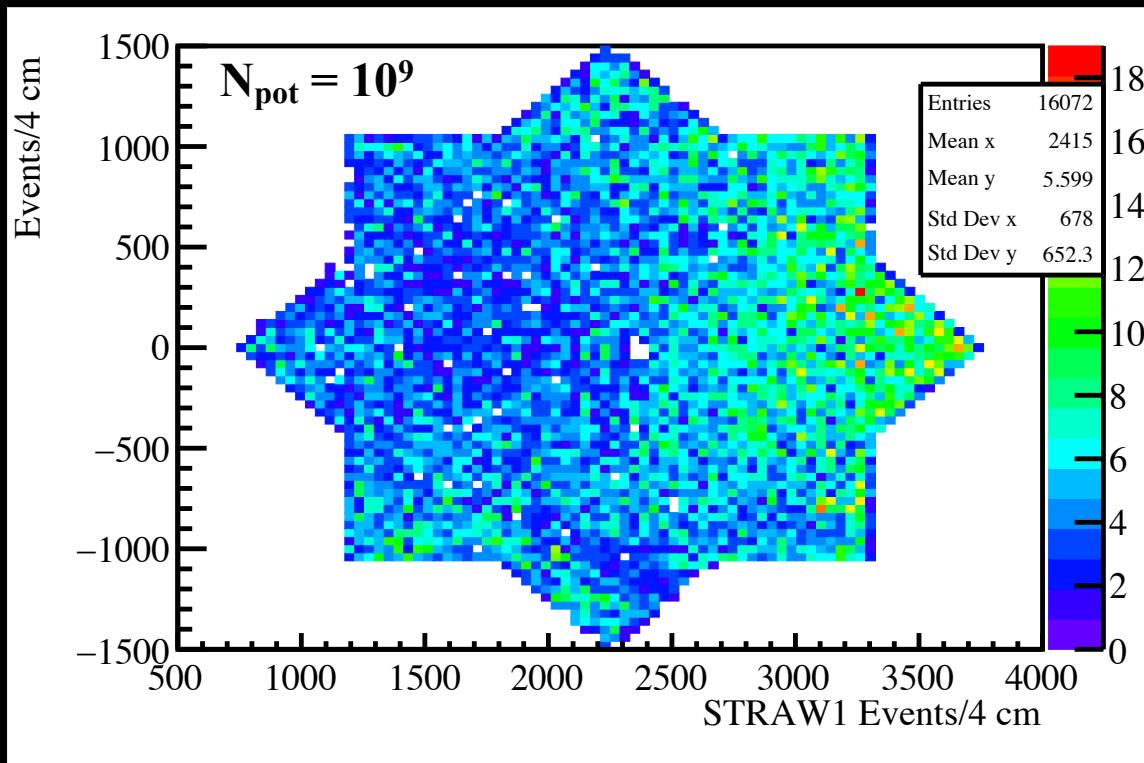
# Muon Illumination with the sweeping system (MIB)

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



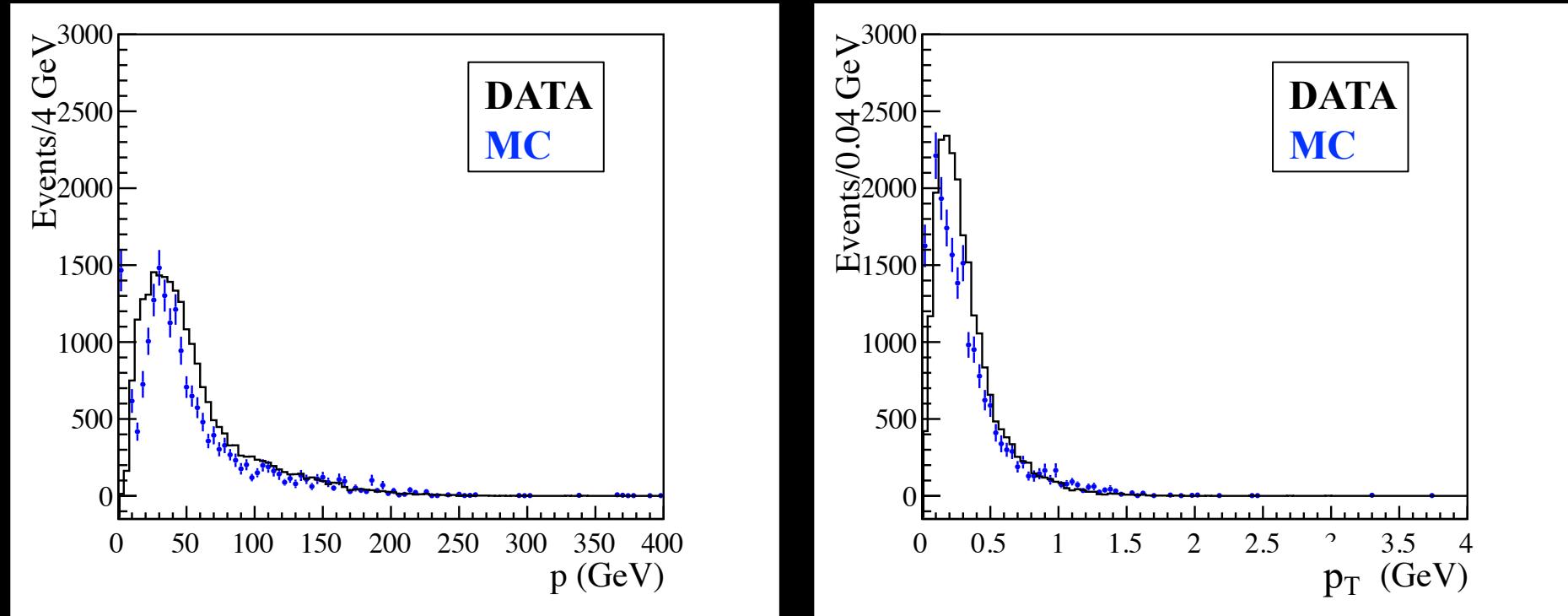
# Muon Illumination with the Sweeping System (MIB) at first tracking chamber

	$\mu^+ + \mu^-$	$\mu^+$	$\mu^-$
rate before MIB	100 MHz	50 MHz	50 MHz
MIB reduction factor	$\sim 120$	$\sim 110$	$\sim 150$
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  $1.5 \times 10^{17}$  pot

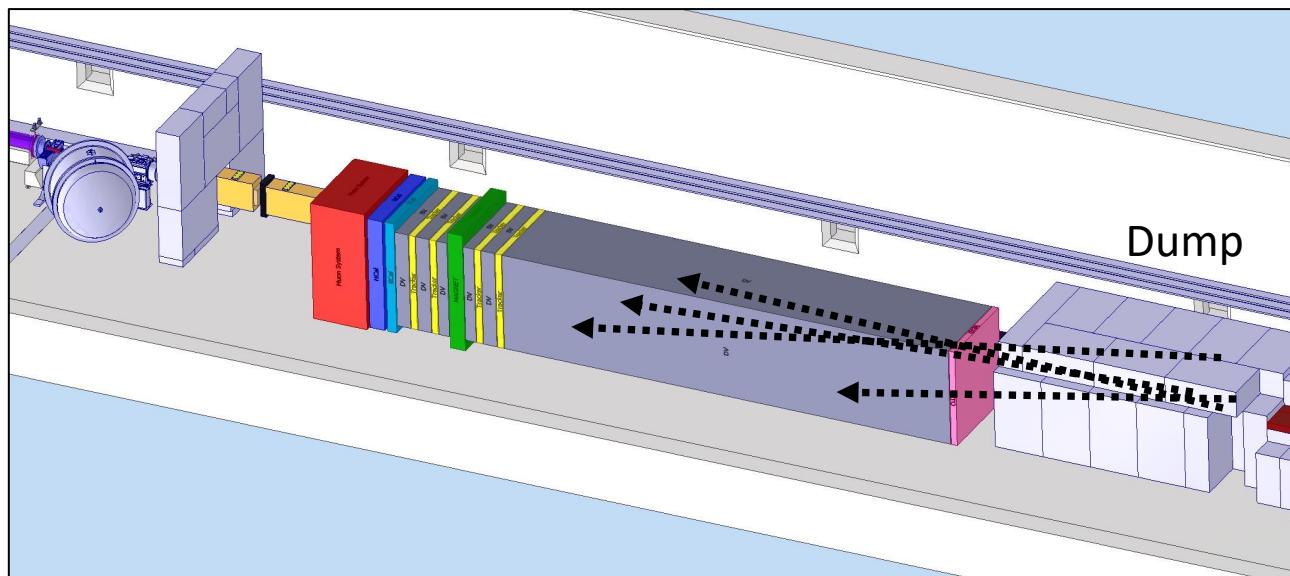


Excellent agreement in shape, the rate is about 3 times lower in MC than in data.  
MC rates corrected by this factor.

# 1. Background: Muon Combinatorial

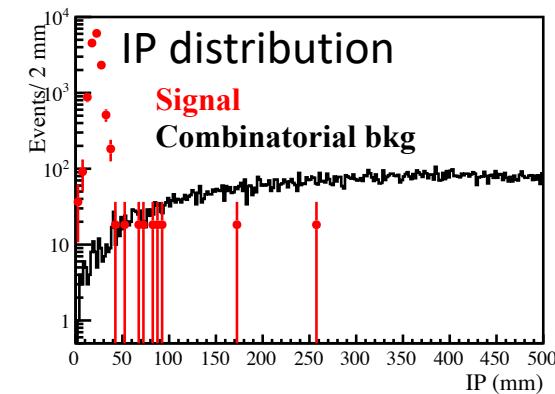
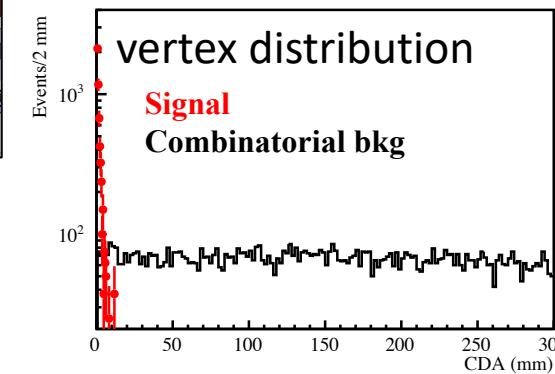
Muon rate without MIB: 100 MHz in acceptance from NA62 data and MC.

MIB reduces it to 0.8 MHz (0.5 MHz  $\mu^+$  ad 0.3 MHz  $\mu^-$ )



**$N(\mu\mu) = 0.7 \text{ events in } 5 \times 10^{19} \text{ pot}$**

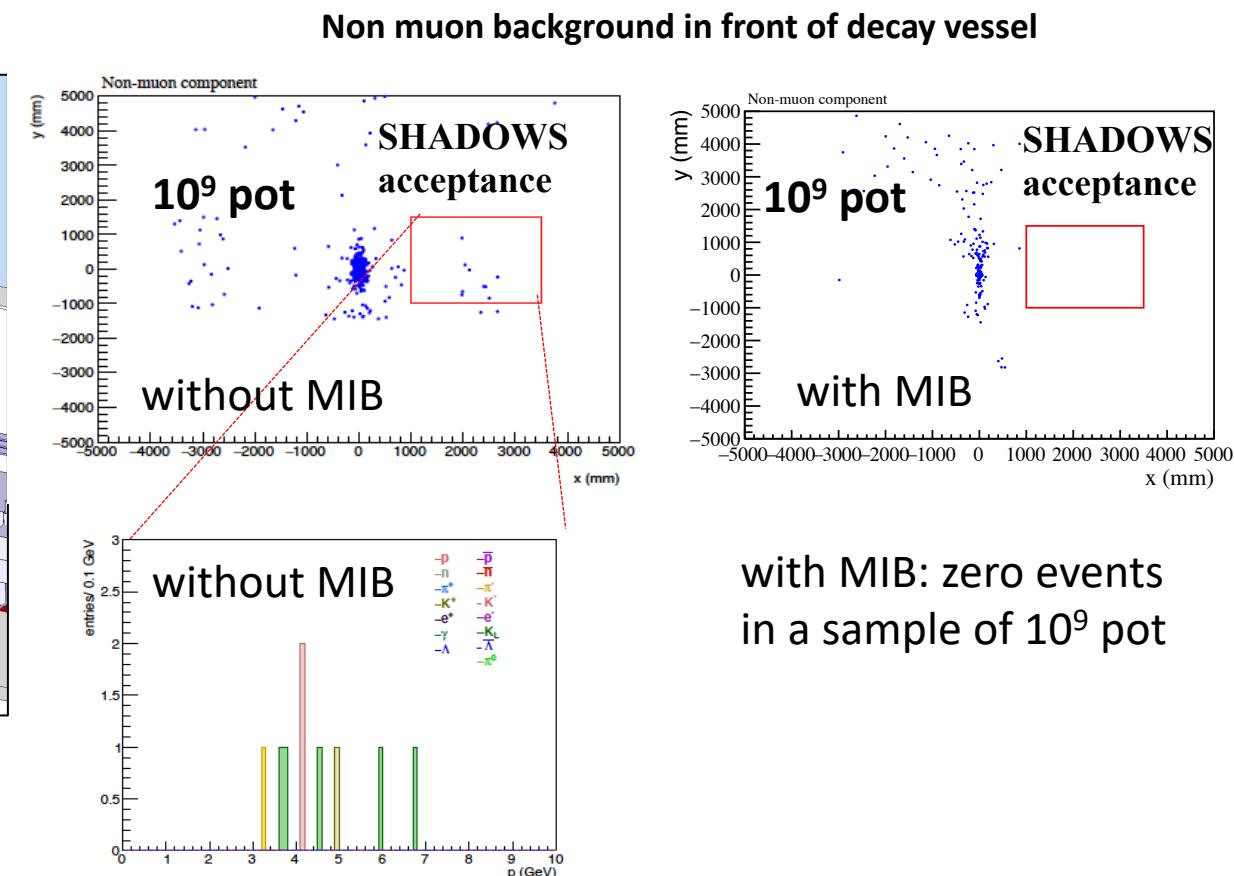
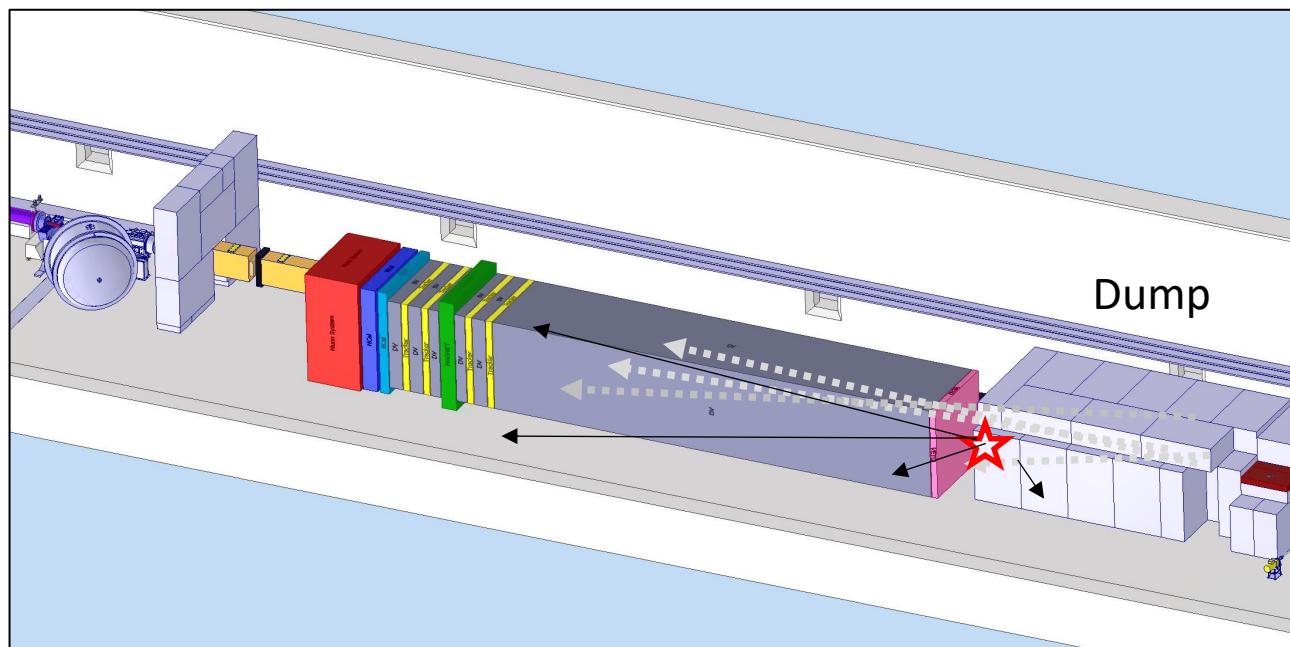
$N_{\mu\mu}/\text{spill}$	requirement
480	timing (T)
$1.2 \cdot 10^{-2}$	UV
$2.4 \cdot 10^{-5}$	CDA < 10 mm
$2.4 \cdot 10^{-7}$	IP < 30 mm
$N_{\mu\mu}/5 \cdot 10^{19} \text{ pot}$	
0.7 events	T & UV & CDA & IP



## 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....**



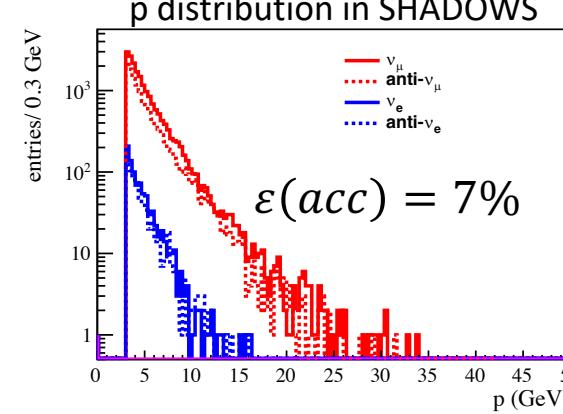
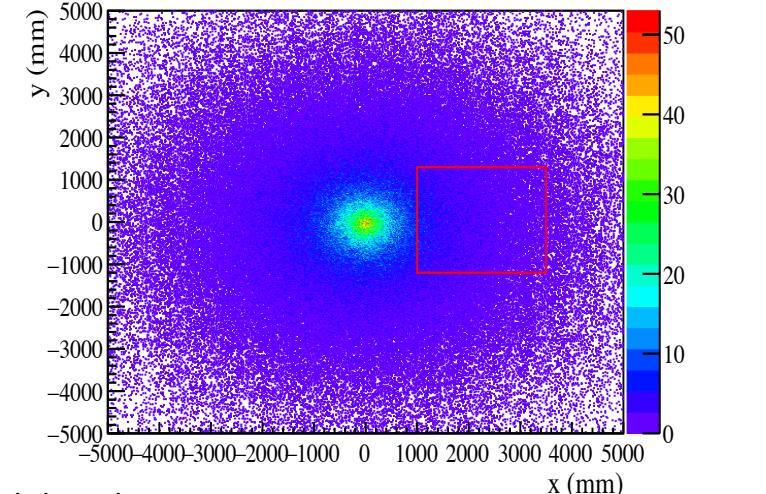
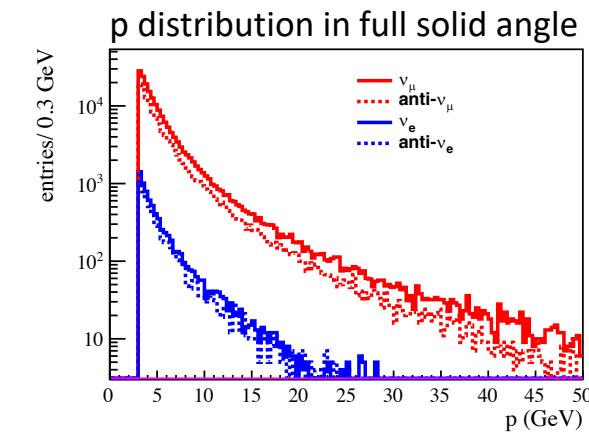
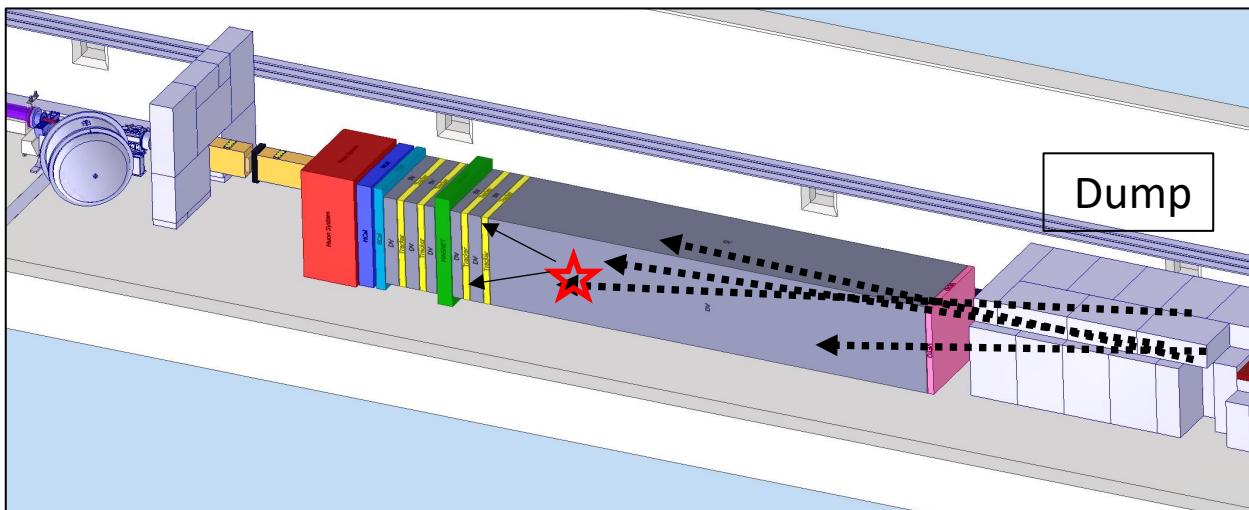
**N( $\mu$  inel. Int.) = no event in acceptance in 10<sup>9</sup> pot**

### 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  $\langle E_\nu \rangle \sim 5 \text{ GeV}$ :

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

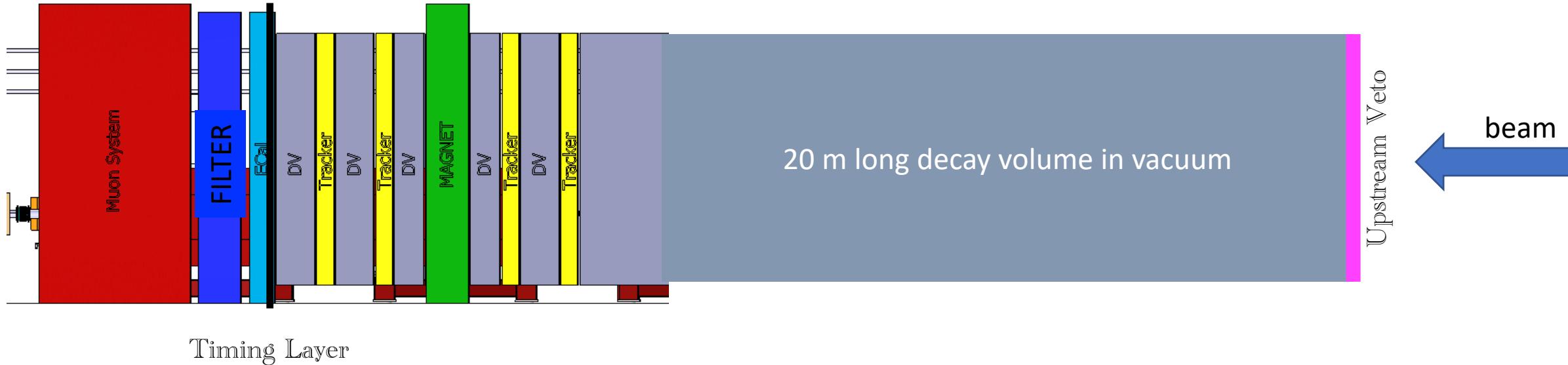
**1 mbar vacuum reduces them to < 1 event in  $5 \times 10^{19}$  pot**



**N( $\nu + \bar{\nu}$ , inel. int. in decay volume) < 1 event in  $5 \times 10^{19}$  pot**

# Detector design: requirements & survey of technology options

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

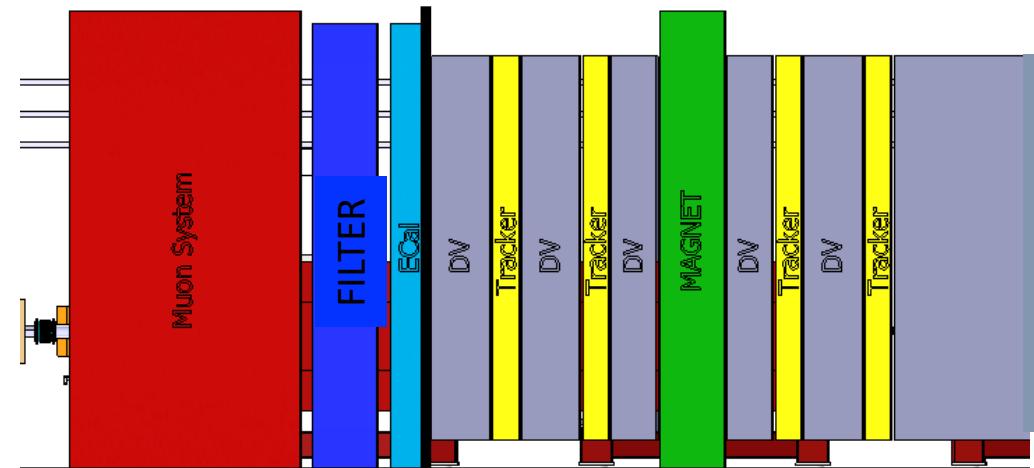


## SHADOWS detector components:

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:  $2.5 \times 2.5 \text{ m}^2$ .

# SHADOWS Upstream (Muon) Veto: MicroMegas

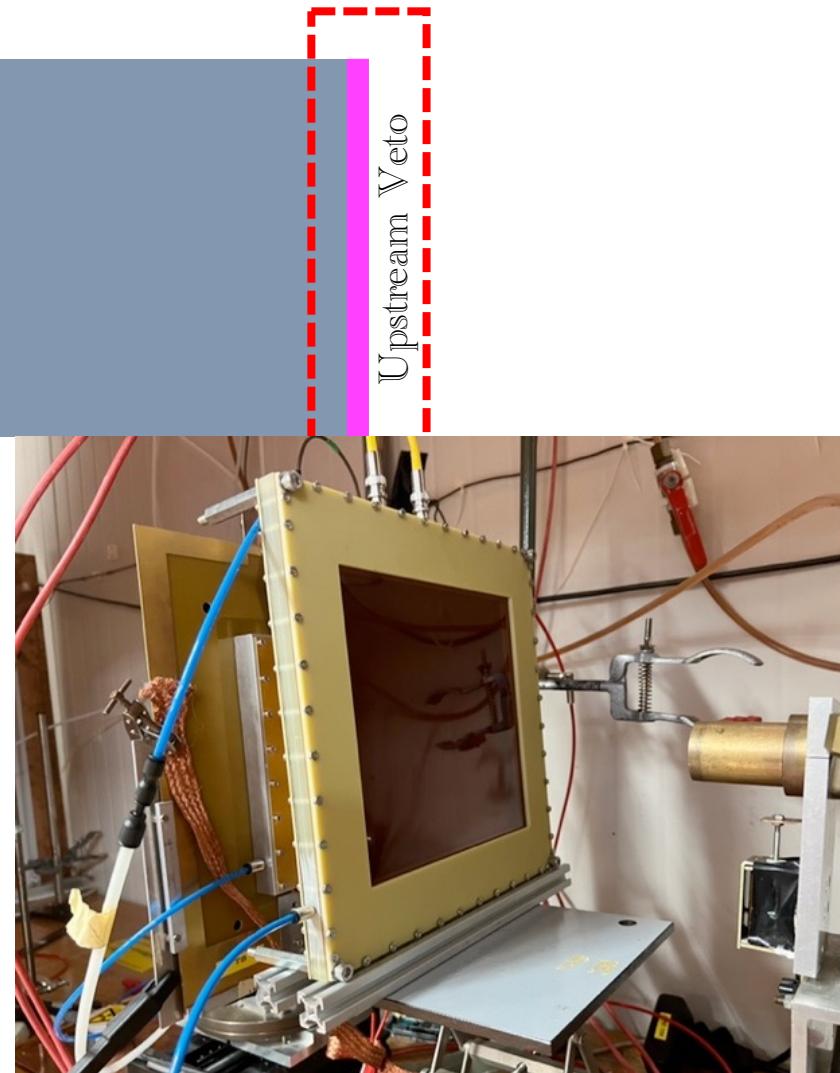


## Requirements:

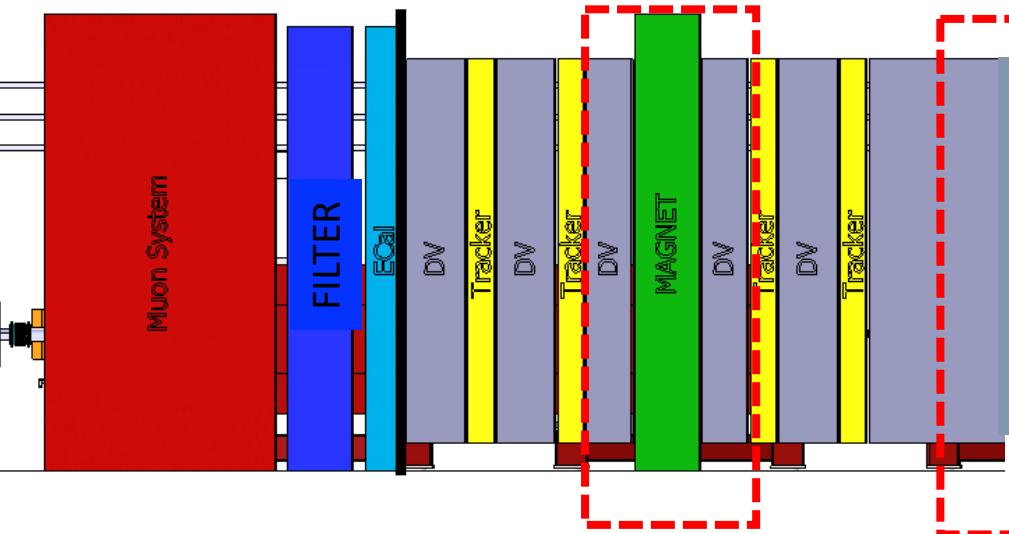
1. efficiency: 99.5%
2. time resolution:  $\text{o}(10 \text{ ns})$  (to allow matching with the other detectors)
3. position resolution:  $\text{o}(\text{cm})$  (match the backward extrapolation of tracks)
4. rate capability: up to several kHz/cm<sup>2</sup>

**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:



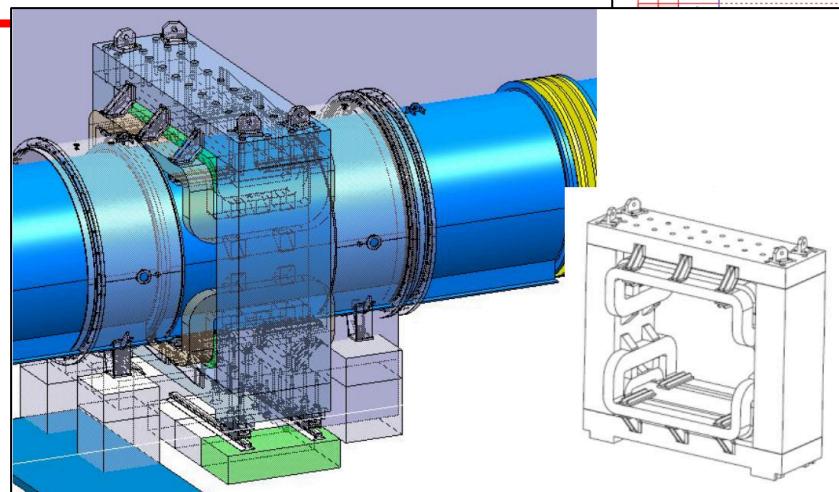
## Requirements:

- **Dipole Magnet: about 1 Tm (warm)**
- **Decay vessel: 125 m<sup>3</sup> in vacuum (1 mbar)**

**Dipole Magnet design quite advanced.**

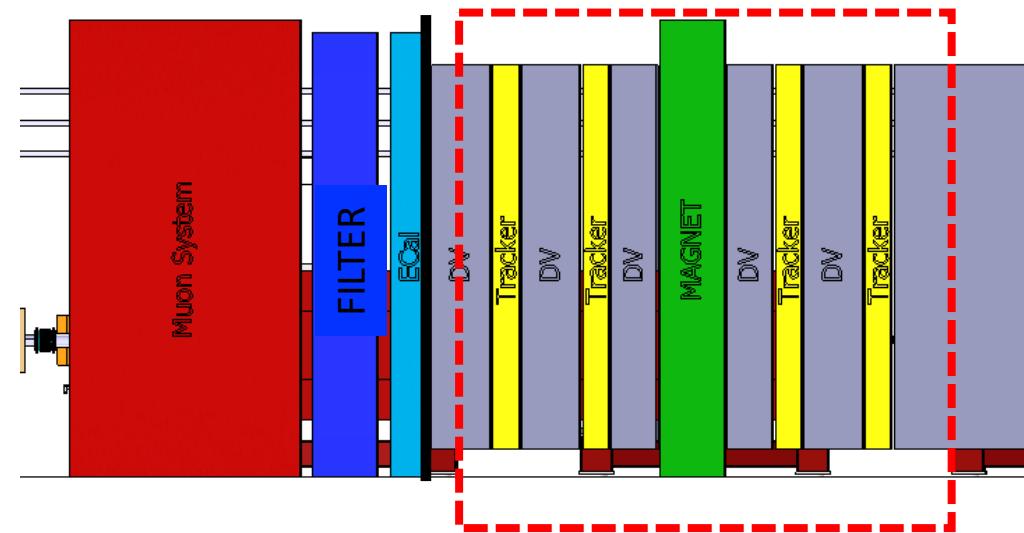
NA62 magnet-like but:

- 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



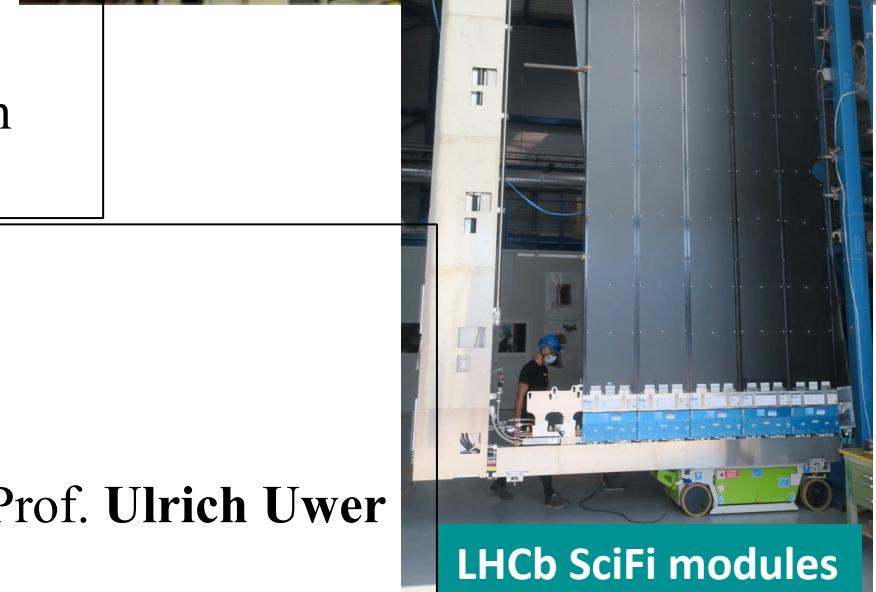
## Requirements:

- vertex resolution over 20 m long decay volume:  $\sigma_{xy} \sim 1$  cm
- impact parameter resolution at  $\approx 30$  m distance:  $\sigma(IP) < \text{few cm}$
- must operate in vacuum (1 mbar or so).

## Two options under scrutiny:

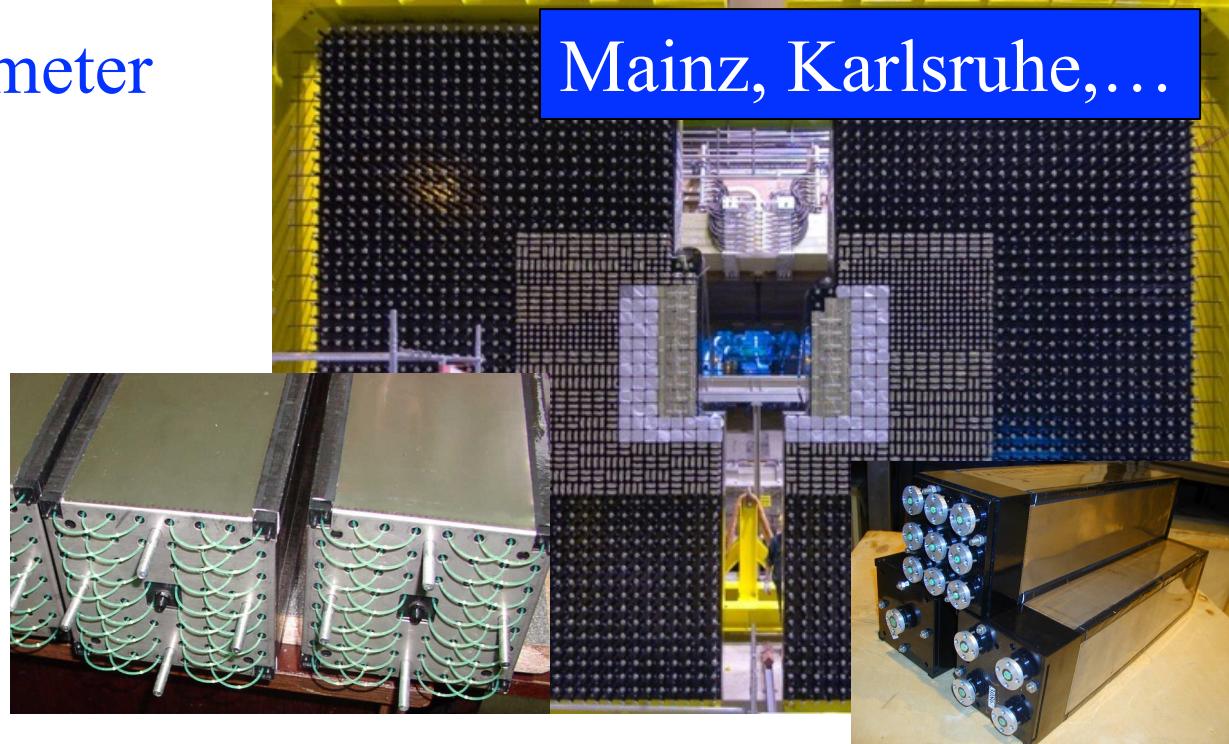
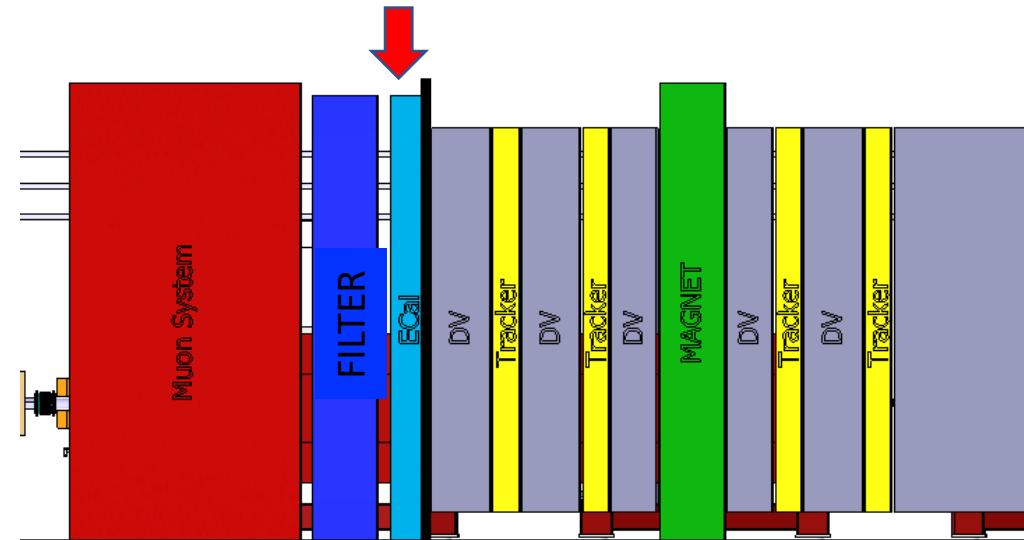
1. NA62 STRAW tubes
2. Fibre Tracker (LHCb)

[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

Mainz, Karlsruhe,...



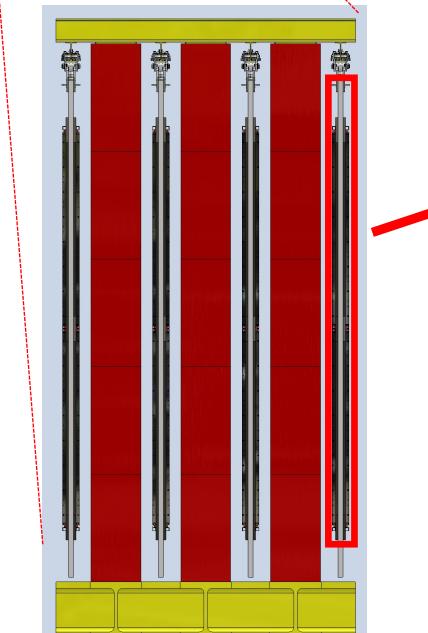
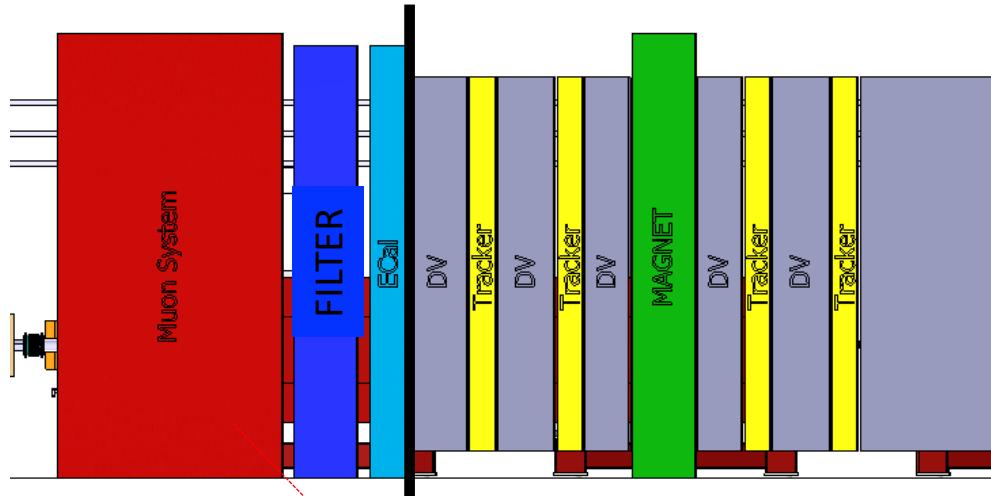
## Requirements:

- must identify electrons/photons against muons/hadrons
- $\pi^0$  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  $\pi^0$  decays: o(5-10) cm

Options under scrutiny: Shashlik, PbWO<sub>4</sub> (from CMS), CALICE, SplitCal

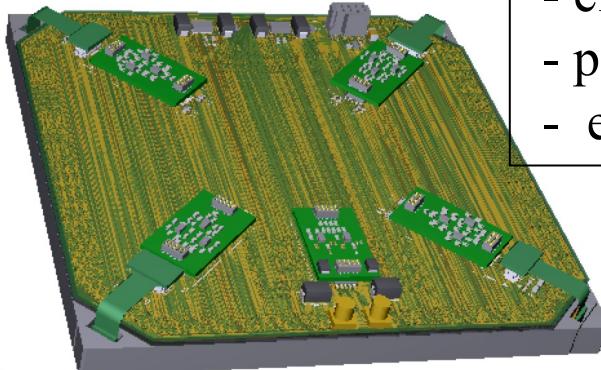
# SHADOWS: Muon Detector

INFN (Frascati, Bologna, Ferrara), ..

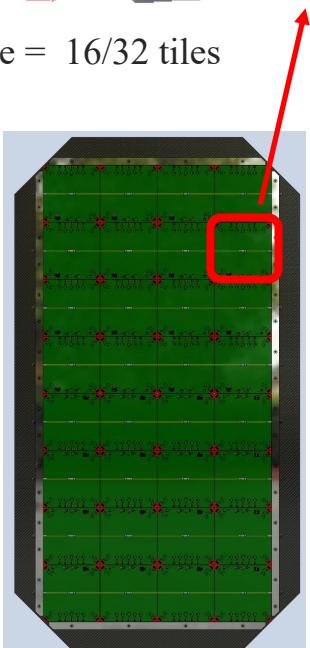


1 station = 8 modules  
[same pattern staggered  
on the other side of the wall]

1 tile = 15x15 cm<sup>2</sup>,  
Direct SiPM readout at the corners  
One analog output per tile



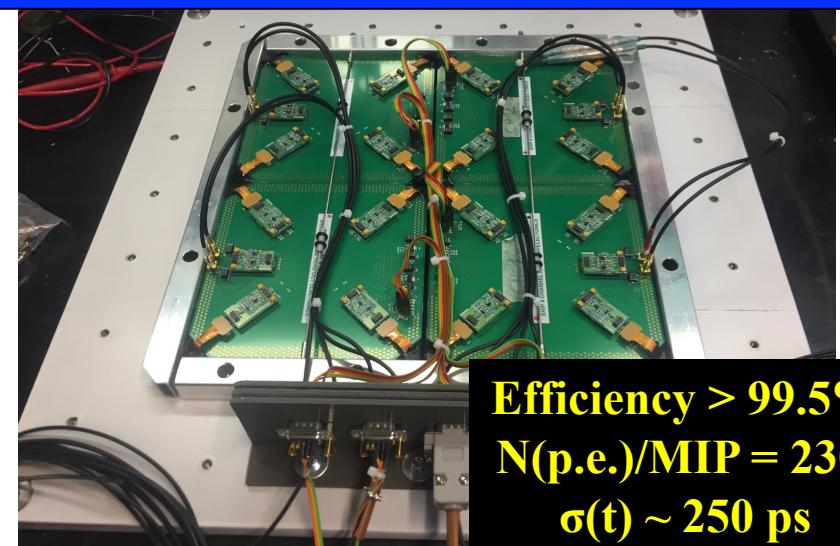
1 module = 16/32 tiles



## Requirements:

- time resolution:  $\sigma(150)$  ps or less
- efficiency: <99% per station
- position resolution:  $\sigma(\text{few cm})$ .
- expected rates: < 100 Hz/cm<sup>2</sup>

4-tile prototype built in INFN Bologna/LNF



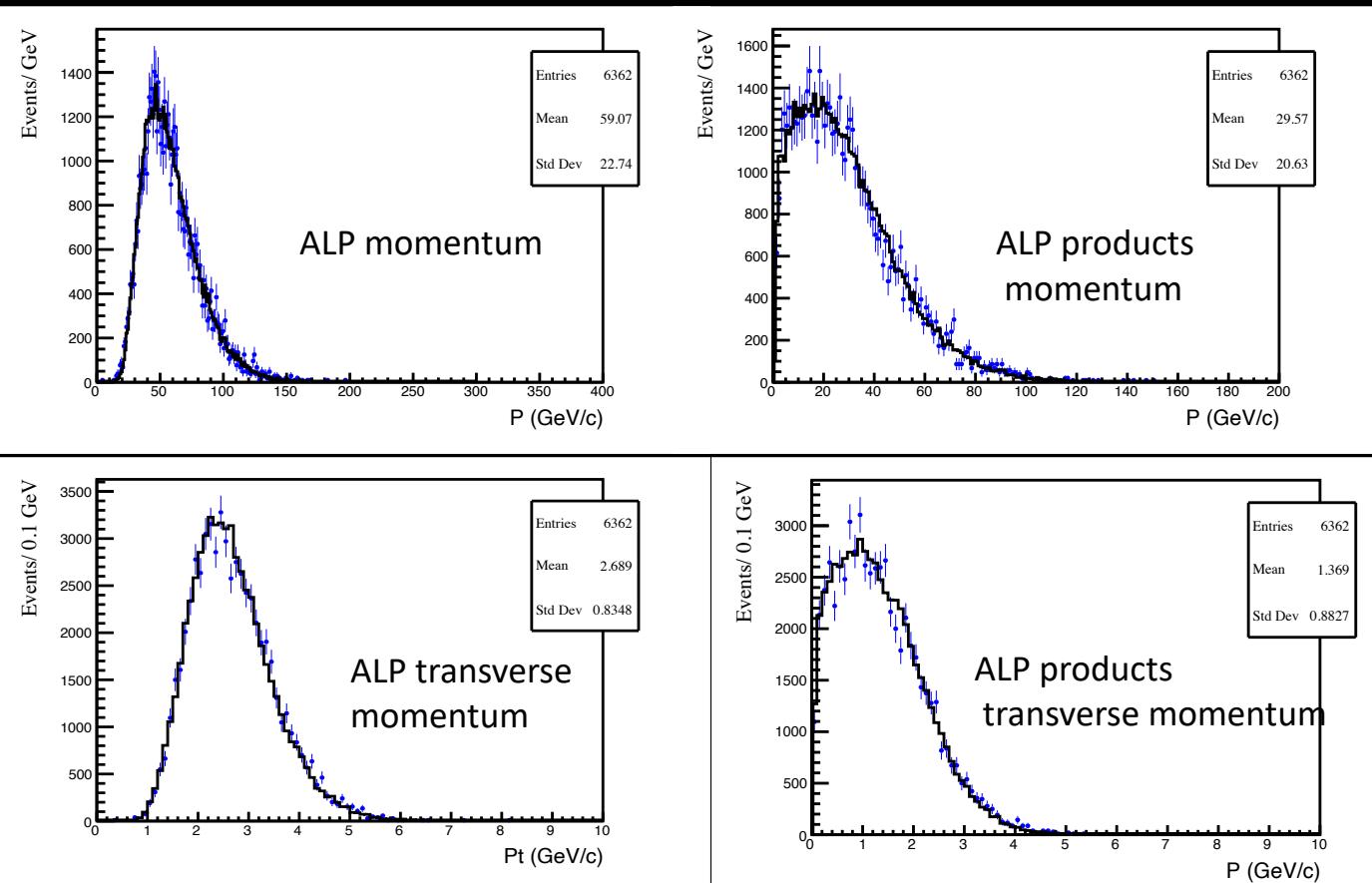
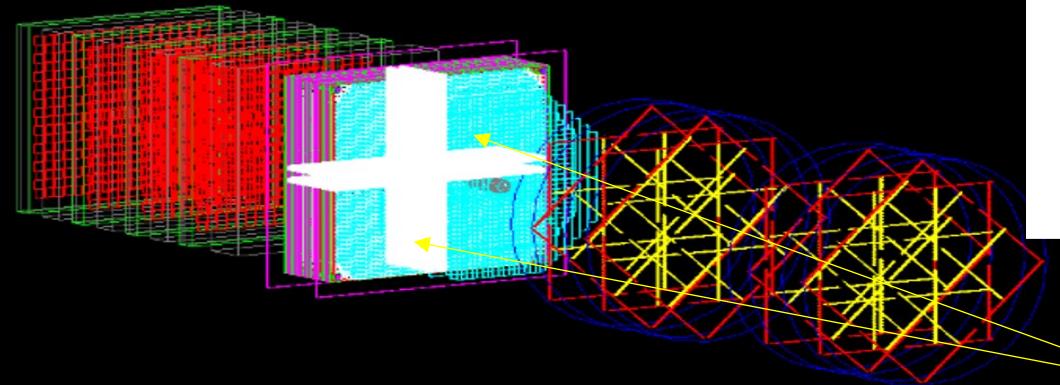
Efficiency > 99.5%  
 $N(\text{p.e.})/\text{MIP} = 230$   
 $\sigma(t) \sim 250$  ps

# SHADOWS physics sensitivity for some standard PBC benchmarks

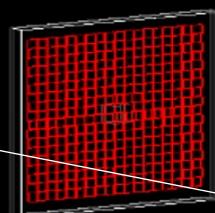
Standard PBC benchmarks: J. Phys.G 47 (2020) 1, 010501, e-Print: 1901.09966, section 9

# SHADOWS Geant4-based Monte Carlo

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



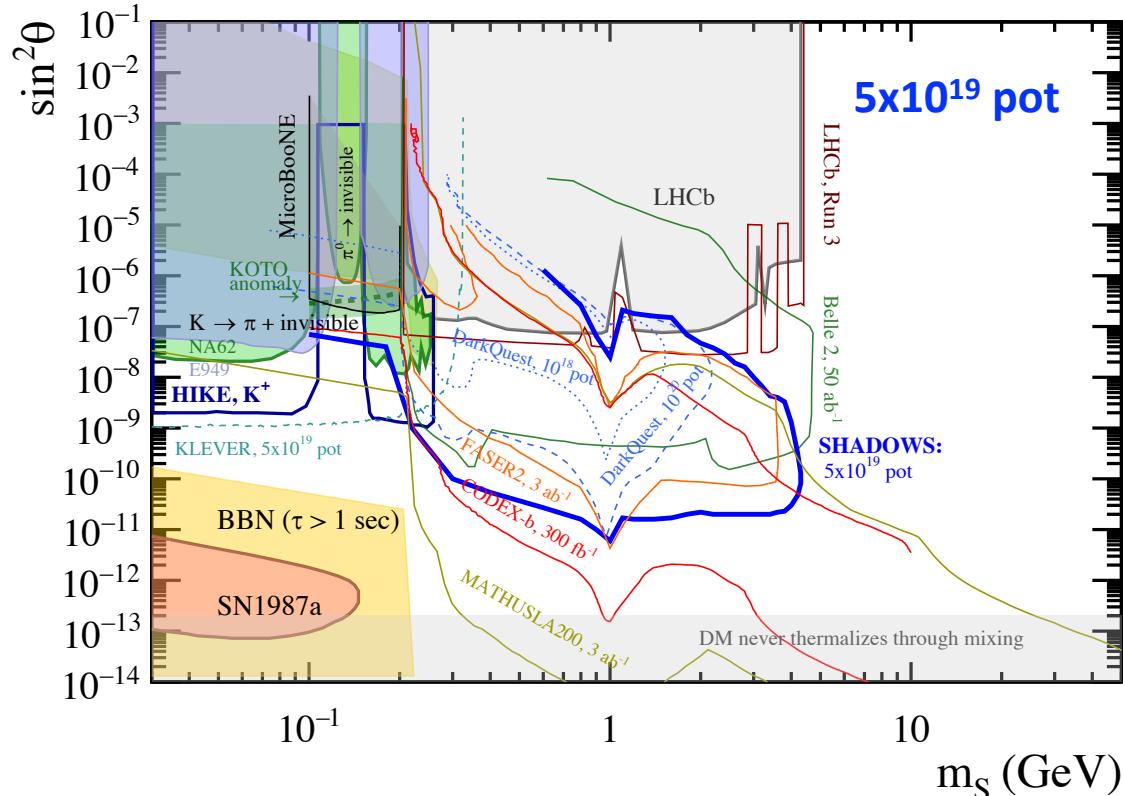
$ALP \rightarrow \mu\mu$



# SHADOWS sensitivity to standard PBC benchmarks

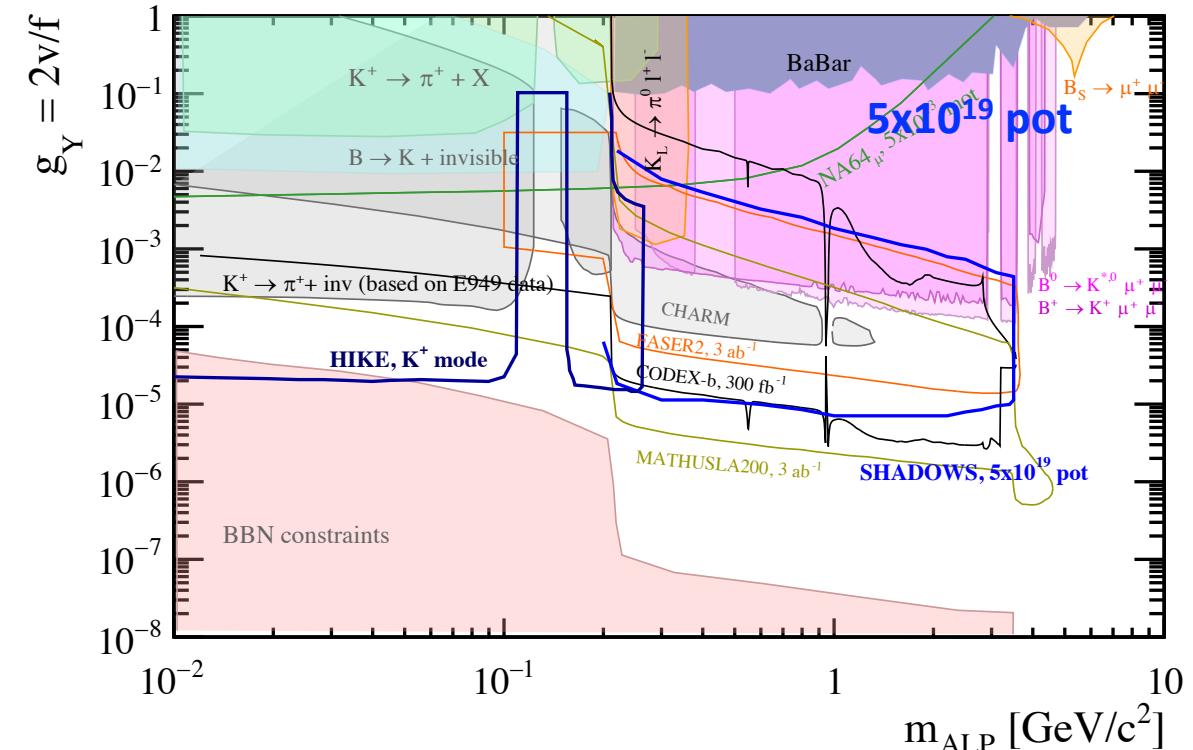
( PBC benchmarks: J. Phys.G47 (2020) 1, 010501, e-Print: 1901.09966, section 9 )

## Light Dark Scalar mixing with the Higgs (BC4)



SHADOWS covers about 4 orders of magnitude  
in coupling in the mass range  $2 M_\mu - M_b$

## ALPs with fermion couplings (BC10)

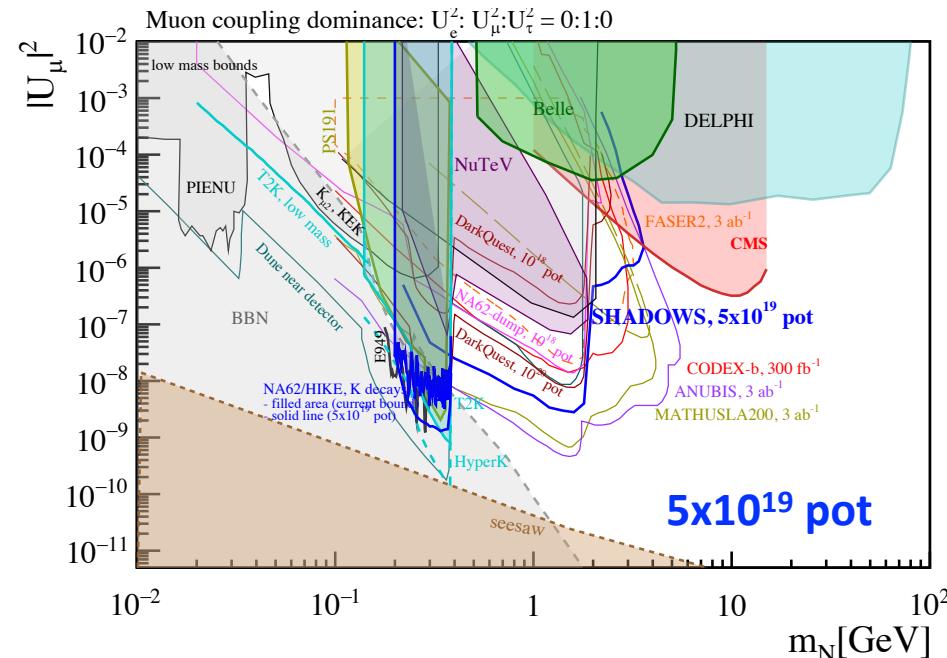
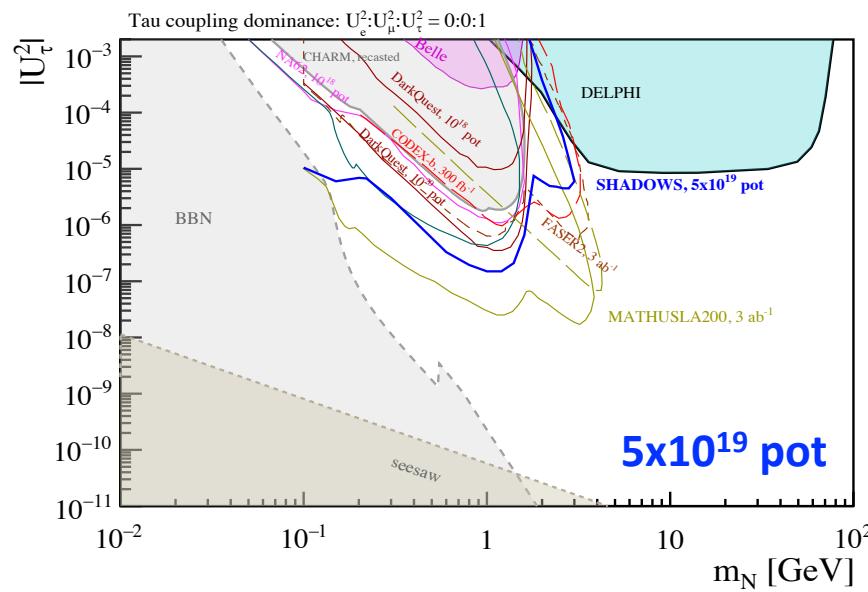
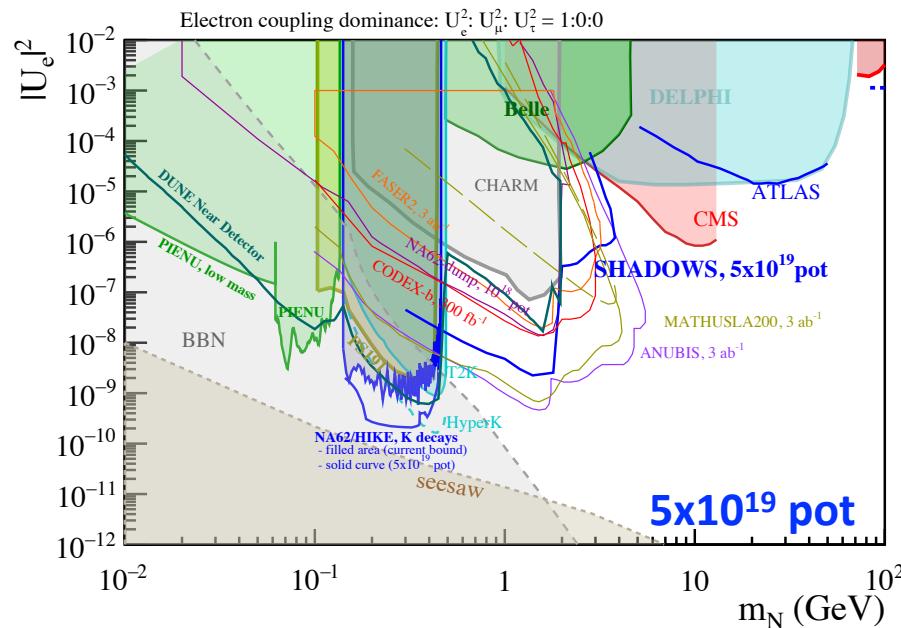


SHADOWS ( $5 \times 10^{19}$  pot) better than FASER2 ( $3 \text{ ab}^{-1}$ ),  
and comparable to CODEX-b ( $300 \text{ fb}^{-1}$ ).

(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.

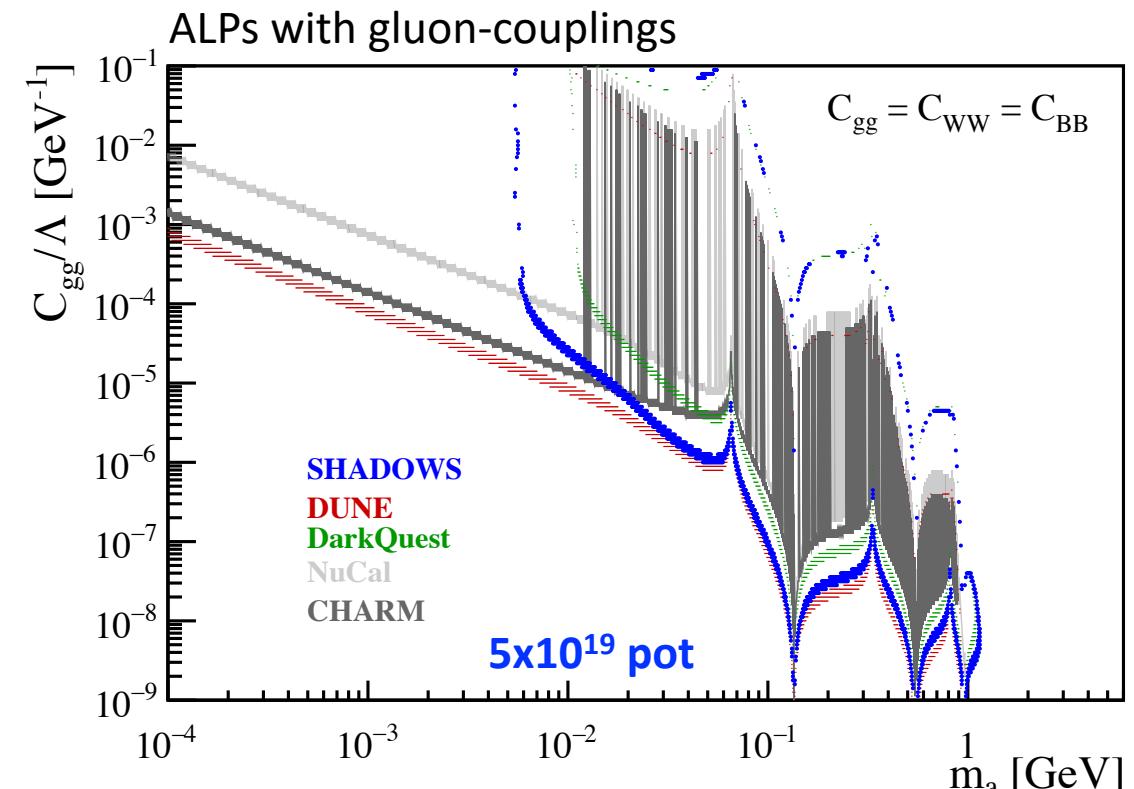
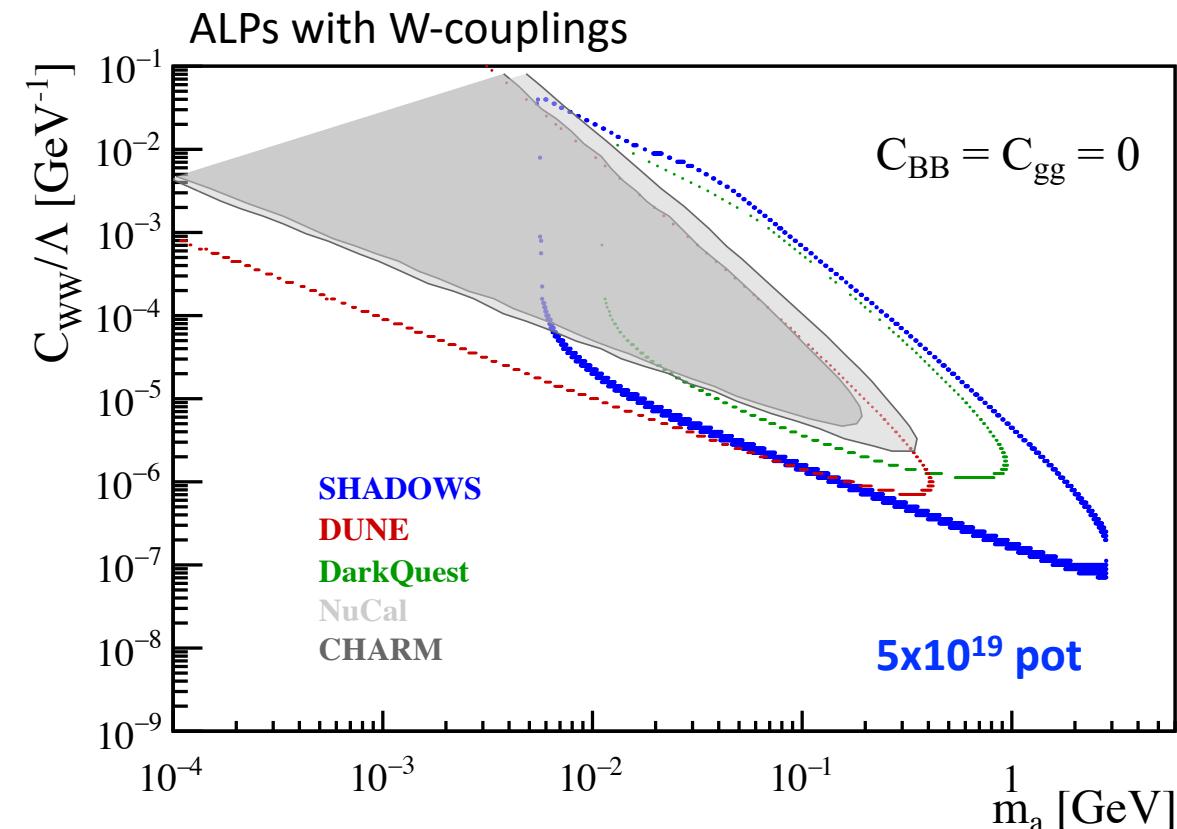
**Between D and B:** SHADOWS expands by two-three orders of magnitude wrt current bounds (Belle)

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

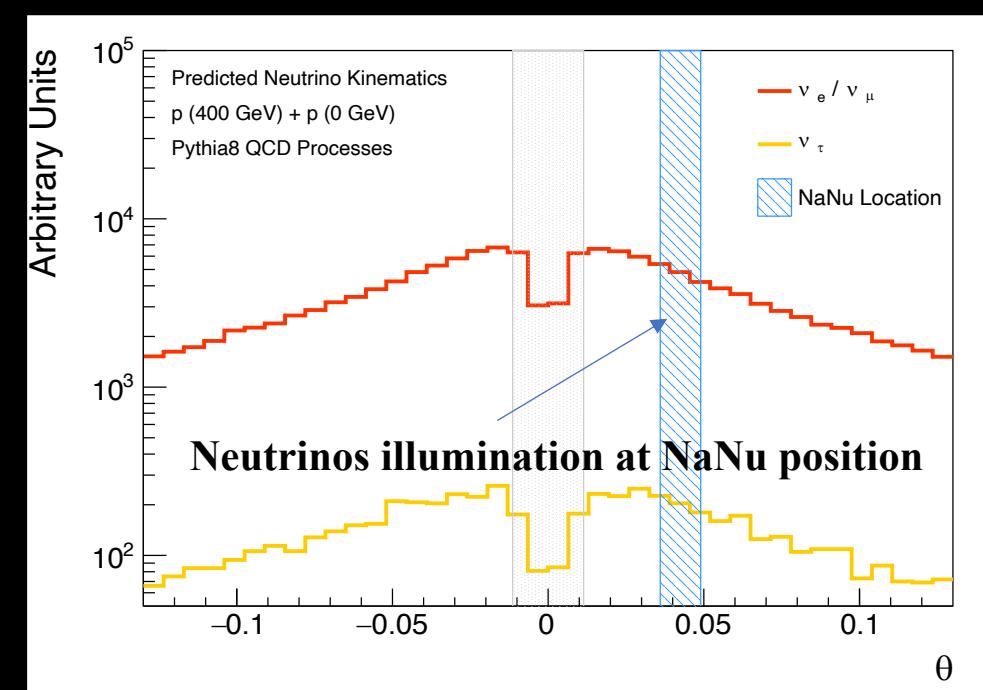
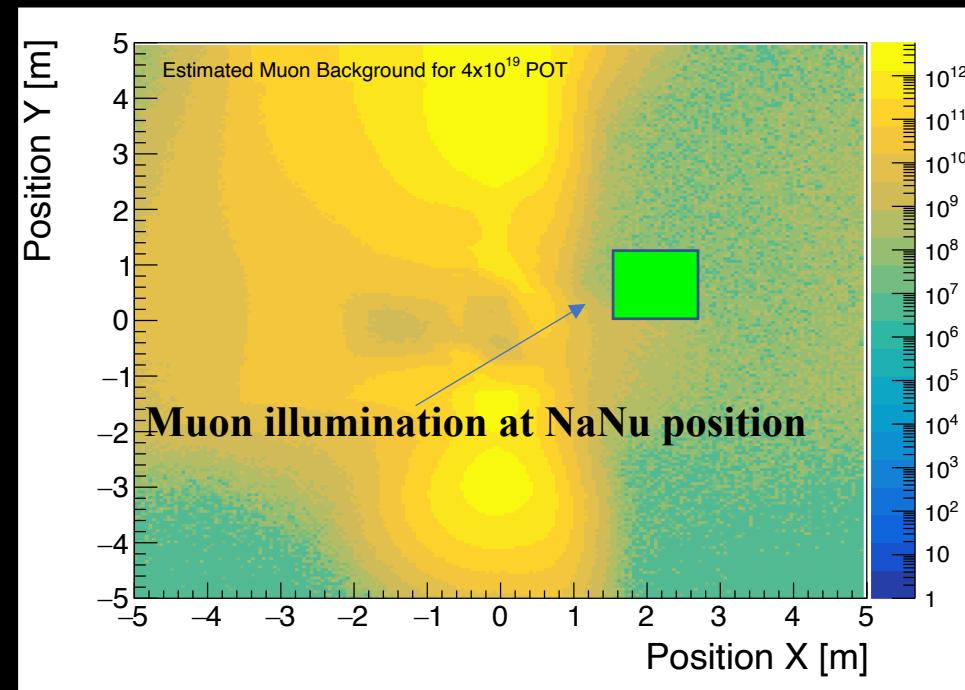
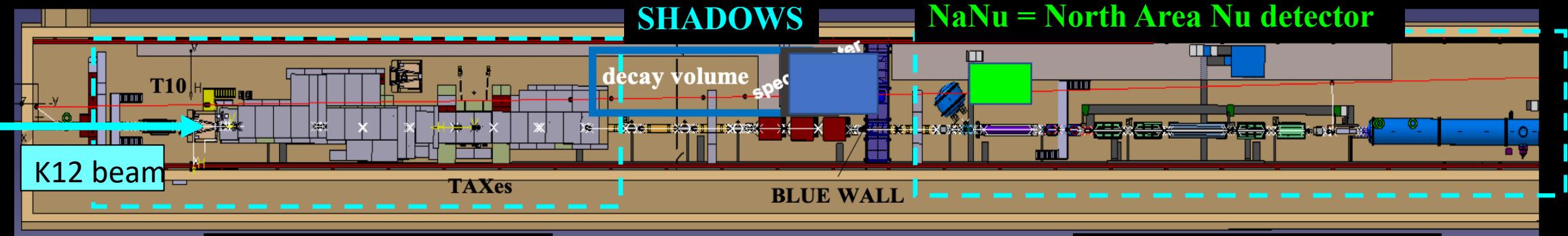
( PBC benchmarks: J. Phys.G47 (2020) 1, 010501, e-Print: 1901.09966, section 9 )

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

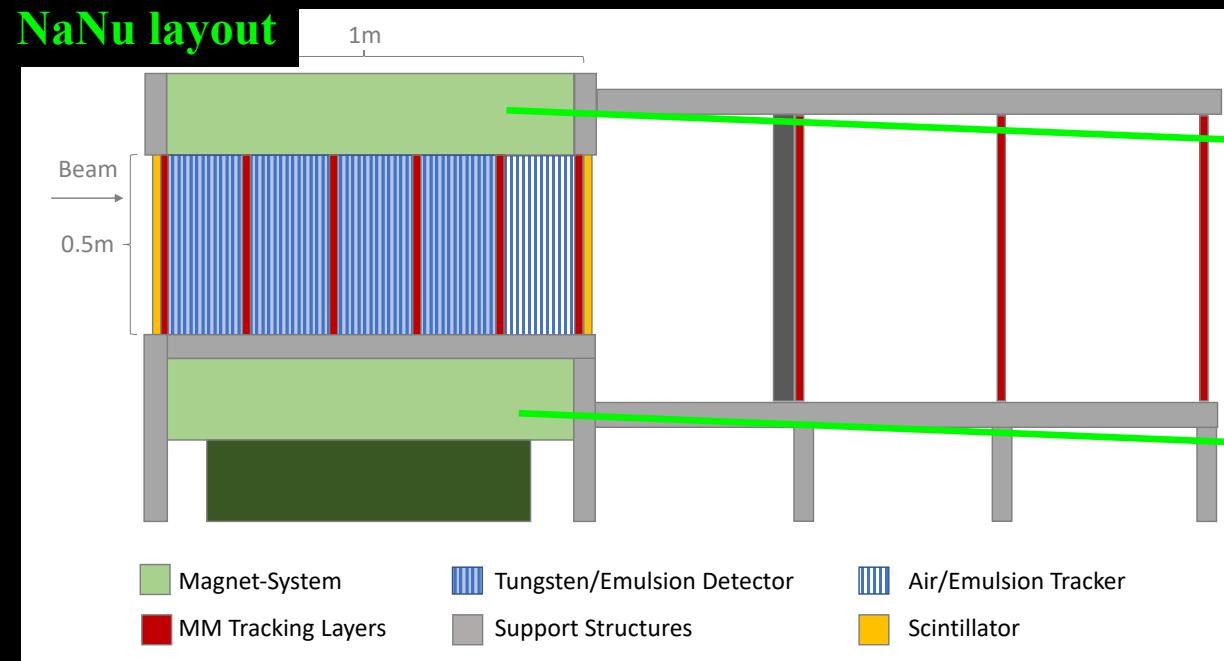
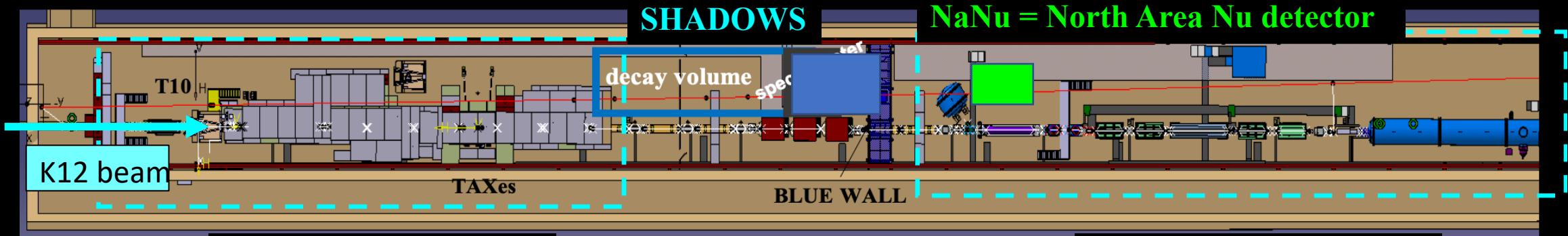


SHADOWS ( $5 \times 10^{19}$  pot) competitive with DUNE for small couplings and extends the mass range towards heavier ALPs and larger couplings.

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



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

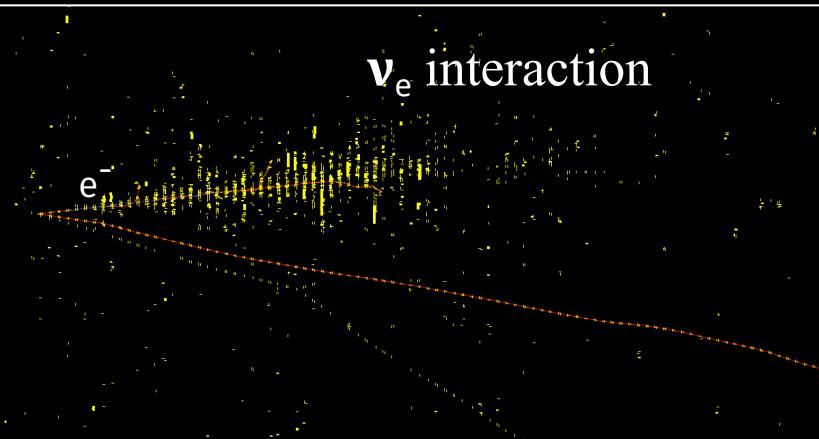


# Not only FIPs @ SHADOWS... but also neutrino physics with NaNu @SHADOWS!

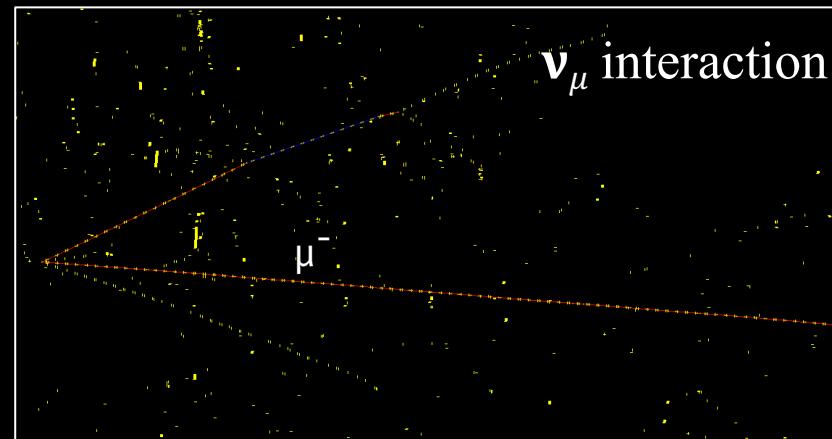
$\nu_\tau$  interaction events in NaNu (including BRs and efficiencies)

	$\tau \rightarrow e$	$\tau \rightarrow \mu$	$\tau \rightarrow h(\pi^\pm)$	$\tau \rightarrow 3h(3\pi^\pm)$	$\bar{\tau} \rightarrow e$	$\bar{\tau} \rightarrow \mu$	$\bar{\tau} \rightarrow h(\pi^\pm)$	$\bar{\tau} \rightarrow 3h(3\pi^\pm)$
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

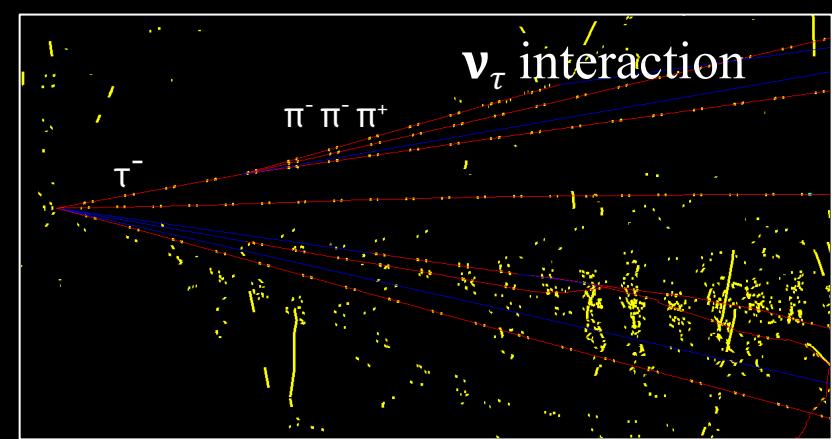
$\nu_e$  interaction



$\nu_\mu$  interaction



$\nu_\tau$  interaction



Geant4 simulated  $\nu$ -interactions in NaNu

# Preliminary COST & TIMELINE

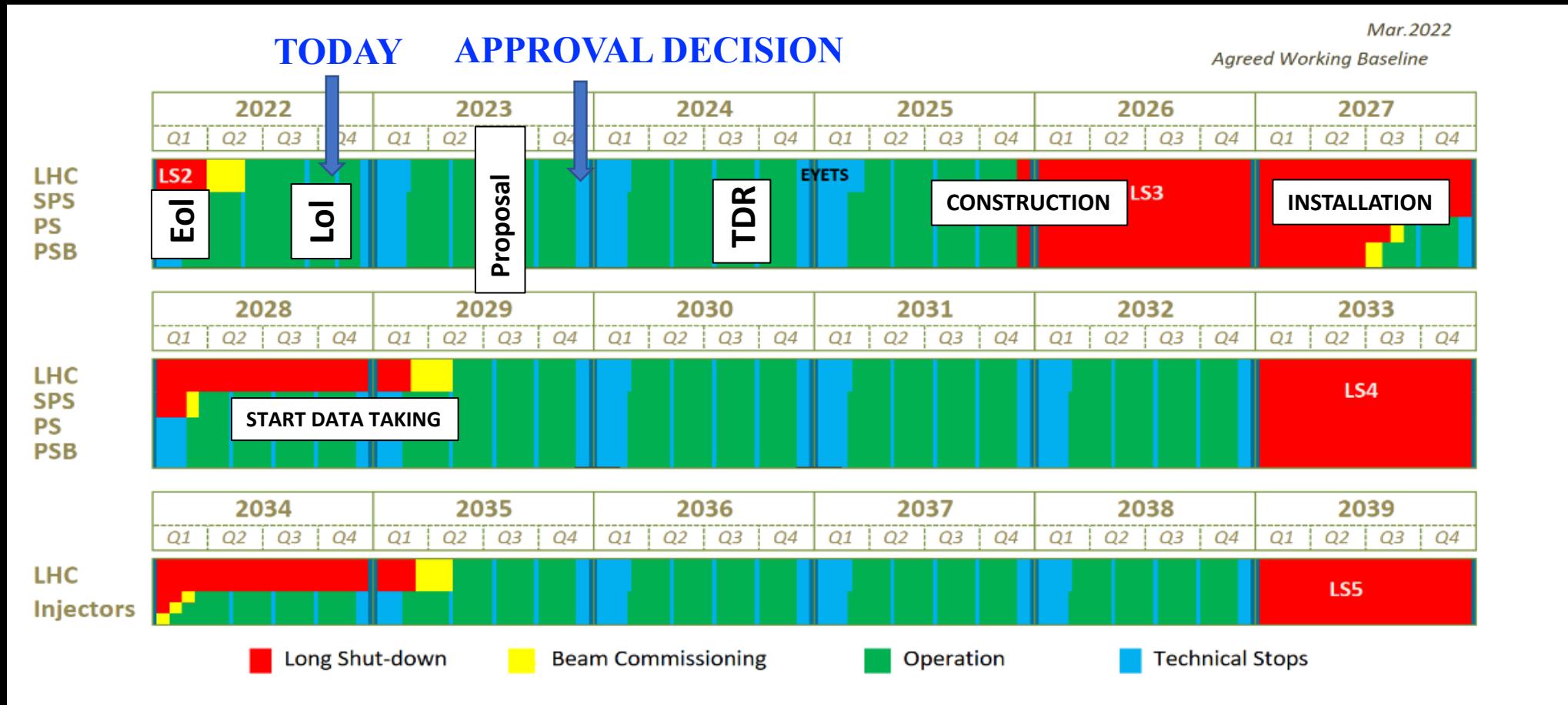
# SHADOWS: TENTATIVE COST

(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€
<b>Total SHADOWS</b>		<b>12.4-15.5 M€</b>
<b>Total NaNu</b>		<b>1.960 €</b>

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 (will be submitted in 2 days)
- March 2023: decision about high-intensity beamline upgrade
- Sept-Oct 2023: SHADOWS Proposal
- End 2023: Decision about SHADOWS.

# Conclusions

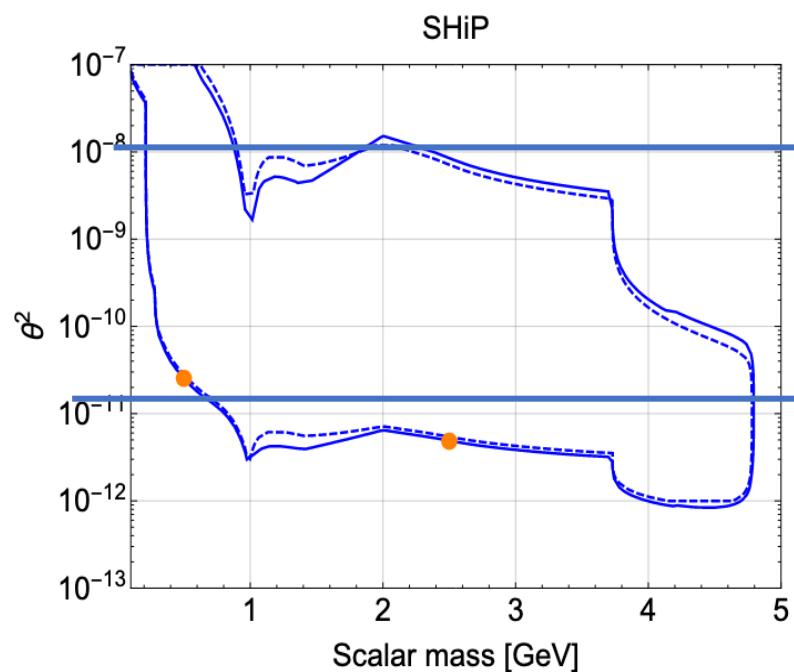
- ✓ SHADOWS is a proposed proton beam dump experiment for FIP physics that can be built in ECN3 and take data concurrently to HIKE (operated in beam-dump mode).
- ✓ SHADOWS ( $5 \times 10^{19}$  pot) has similar/better sensitivity than CODEX-b ( $300 \text{ fb}^{-1}$ ) and FASER2 ( $3 \text{ ab}^{-1}$ ) 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**

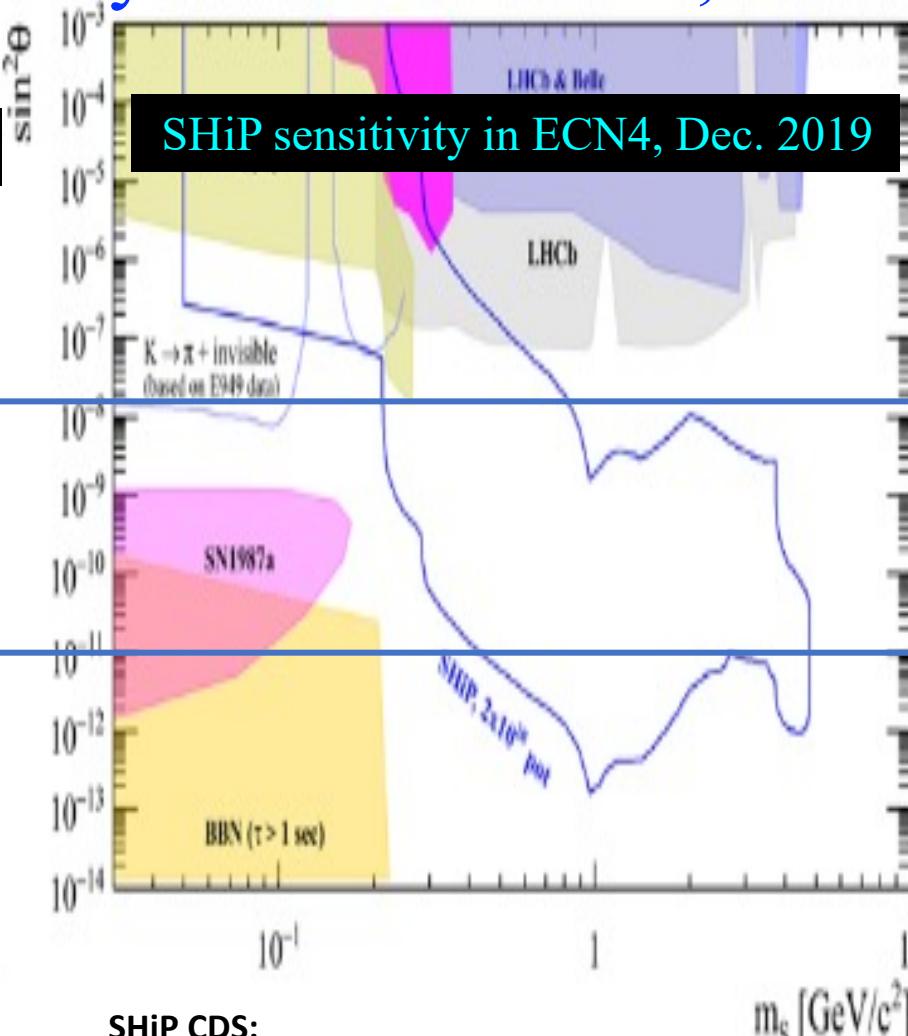
# The Dark Scalar: SHADOWS vs SHiP

# SHiP sensitivity for Dark Scalar, $2 \times 10^{20}$ pot, ECN4

SHiP sensitivity in ECN4, Feb 2019

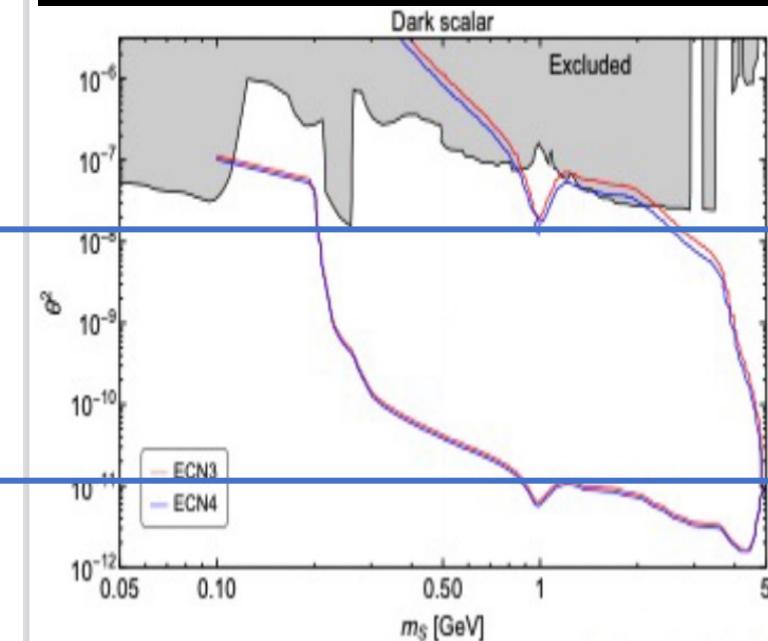


Alexey Boyarsky et al.  
<https://arxiv.org/pdf/1902.06240.pdf>.



SHiP CDS:  
<https://cds.cern.ch/record/2704147/files/SPSC-SR-263.pdf>

SHiP sensitivity in ECN4, Nov. 2022



A. Golutvin, FIPs 2022, Oct 2022  
<https://indico.cern.ch/event/1119695/>

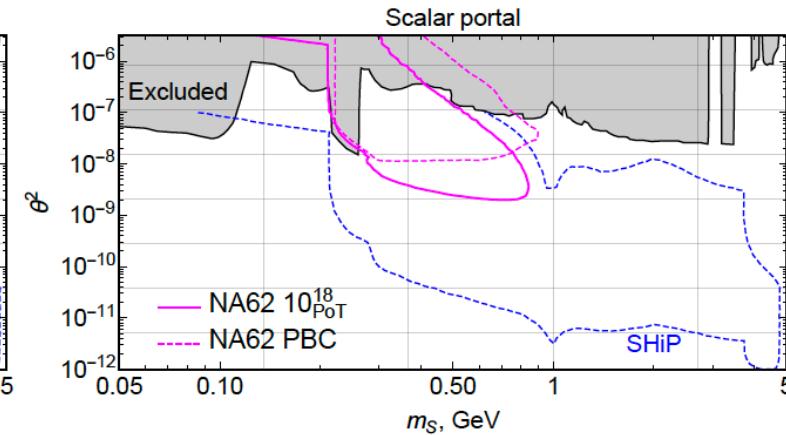
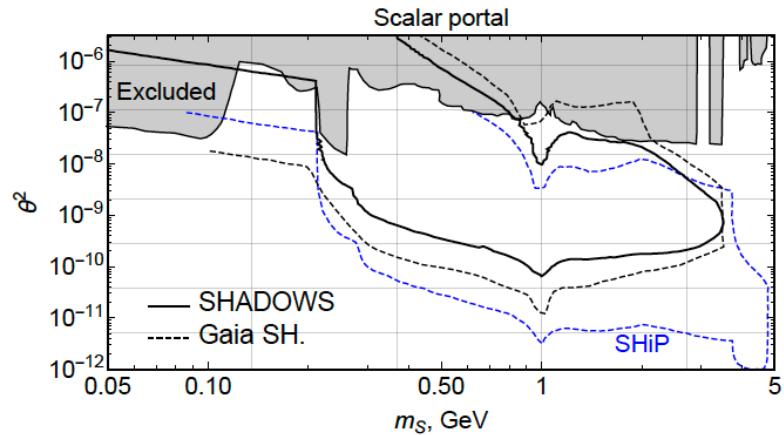
SHiP presented three different sensitivity curves for the same setup in ECN4: which is the correct one?

## SHADOWS sensitivity:

Gaia's sensitivity is for  $5 \times 10^{19}$  pot, 90% CL

Alexey's sensitivity is for  $10^{19}$  pot, 95% CL

### Sensitivity: scalars II



- Factor 5 discrepancy with Gaia for  $m_S \simeq 1$  GeV, factor 50 for  $m_S < 2m_\mu$
- One may try to recover Gaia's lower bound parametrizing the number of events by some acceptance  $\epsilon$ :

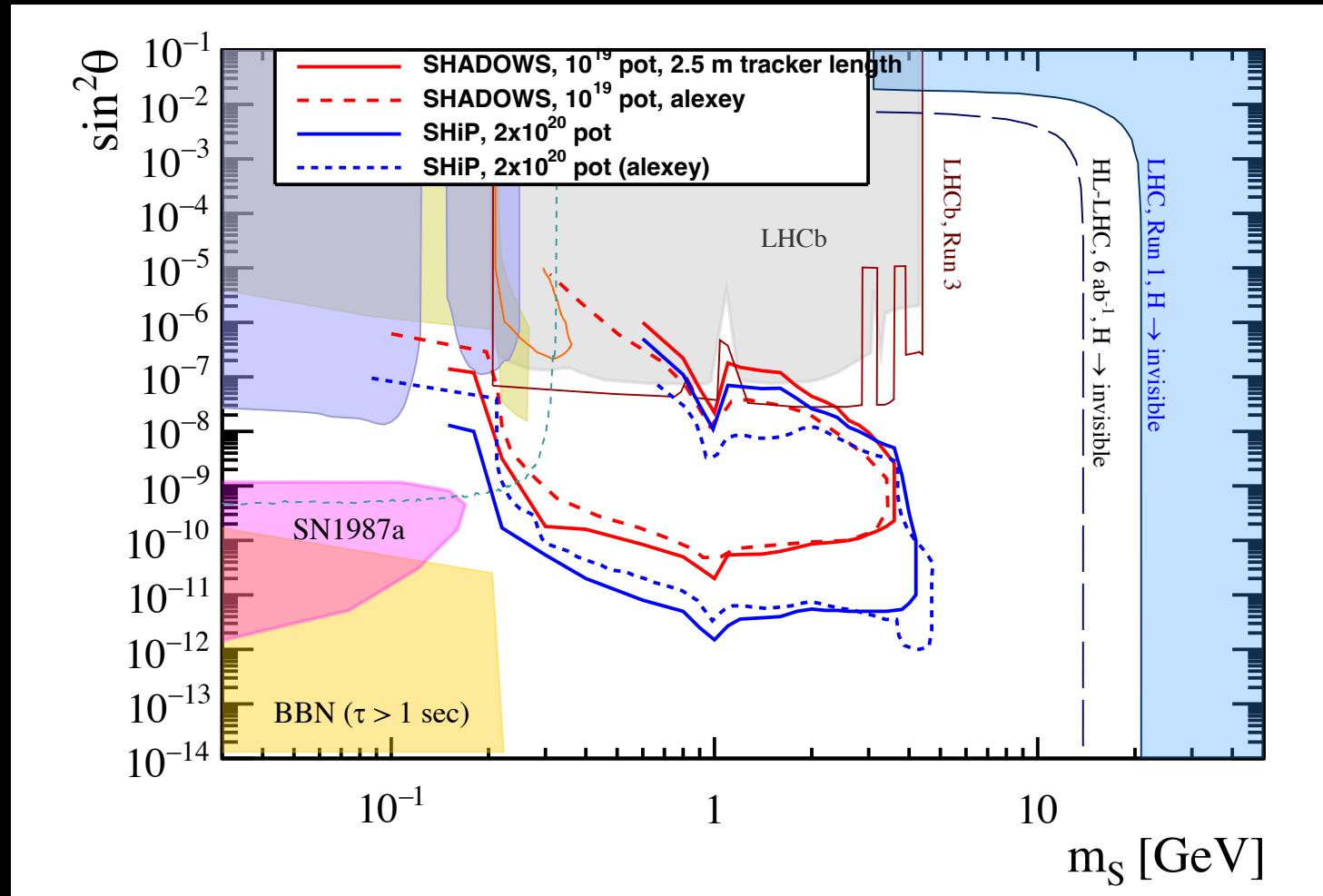
$$N_{\text{events}} = 2 \cdot N_{\text{PoT}} \cdot \chi_{b\bar{b}} \cdot \text{Br}_{b \rightarrow S} \cdot \epsilon \cdot \frac{\text{I}_{\max} - \text{I}_{\min}}{c\tau_S \langle p_S \rangle / m_S} \cdot \text{Br}_{\text{vis}} \quad (13)$$

- Approximating  $\langle p_S \rangle$  by  $40 - 60$  GeV, in dependence of mass, we find  $\epsilon \gg 1$  for  $m_S < 2m_\mu$  and  $\epsilon \simeq 0.3$  for higher masses

# SHADOWS meeting with SHiP people May 2021

[https://indico.cern.ch/event/1038458/contributions/4361009/attachments/2247315/3811799/SHADOWS\\_19May2021.pdf](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 ( $2 \times 10^{20}$  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)

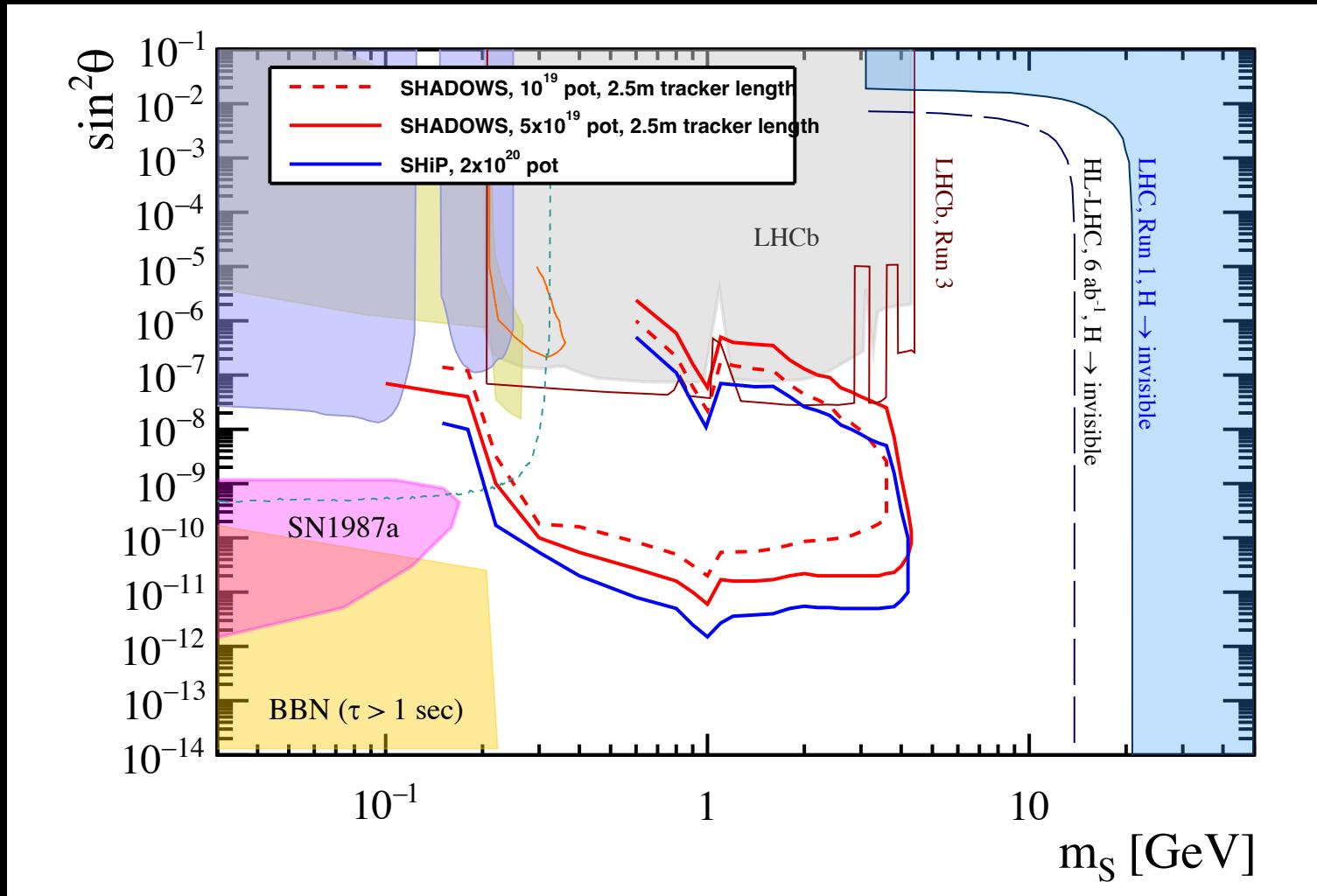
Still some mismatch in the upper bound between 1 and 2 GeV to be cross-checked.

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

# SHADOWS meeting with SHiP people May 2021

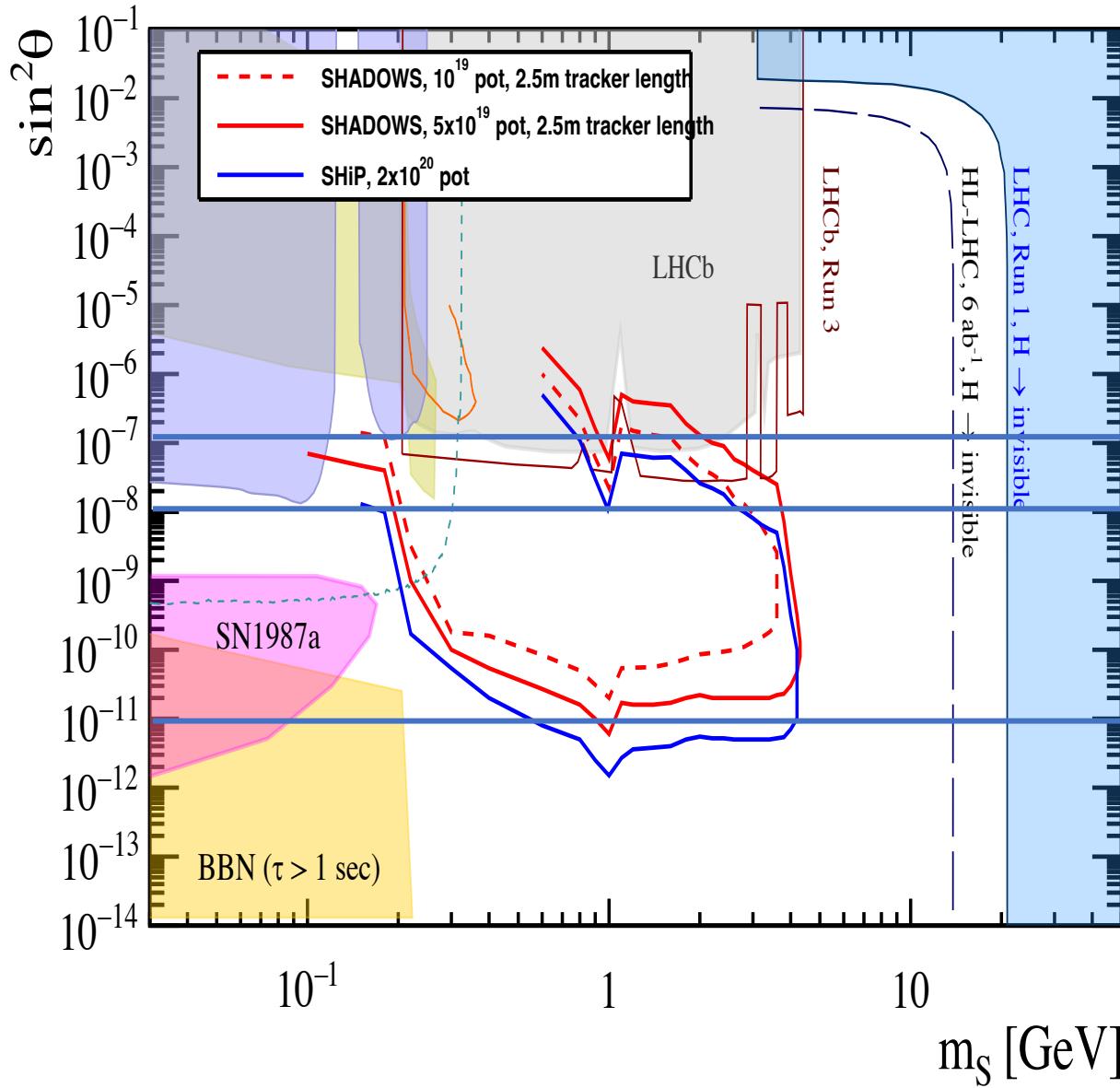
[https://indico.cern.ch/event/1038458/contributions/4361009/attachments/2247315/3811799/SHADOWS\\_19May2021.pdf](https://indico.cern.ch/event/1038458/contributions/4361009/attachments/2247315/3811799/SHADOWS_19May2021.pdf)

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

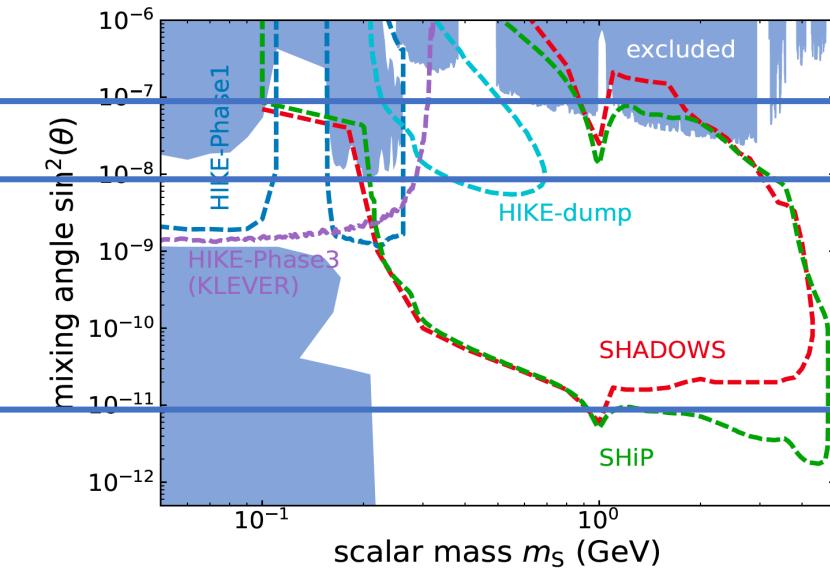


SHADOWS vs SHiP: similar area covered, just shifted.

# Comparison of sensitivity: SHADOWs ( $5 \times 10^{19}$ pot, 5 years) vs SHiP ( $2 \times 10^{20}$ pot, 5 years)



PBC workshop, Nov. 2022.



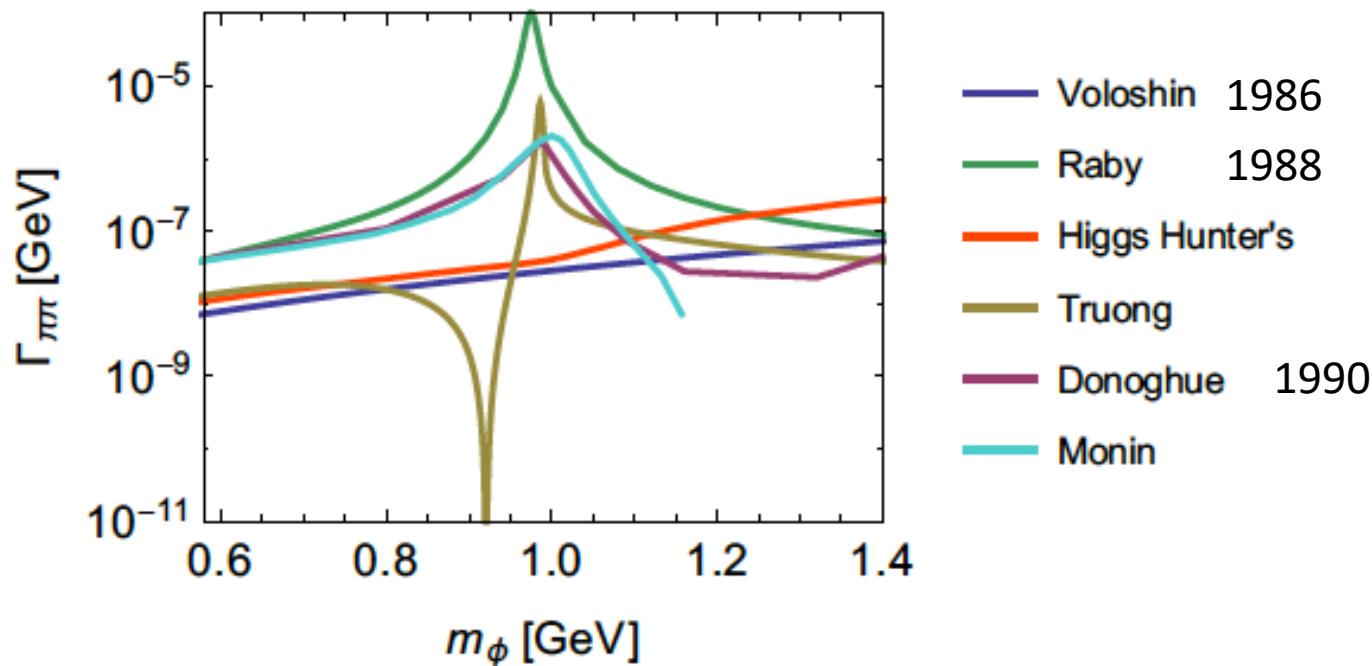
Sensitivity depends upon:

- 
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)

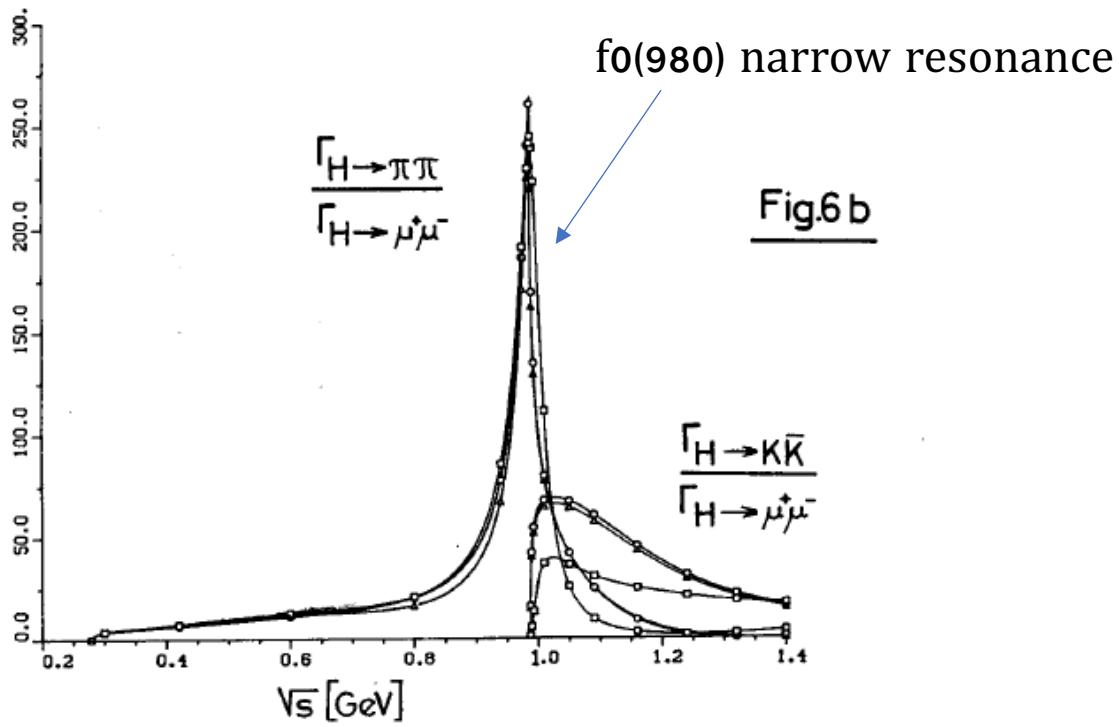


For Scalar, hadronic decays are dominant immediately above the  $2 m(\pi)$  threshold.  
Non-perturbative resonance effects around 1 GeV due to interference with 4 pi channel

# Dark Scalars: Branching Fractions

PBC recommendation: use the Donoghue et al. computation

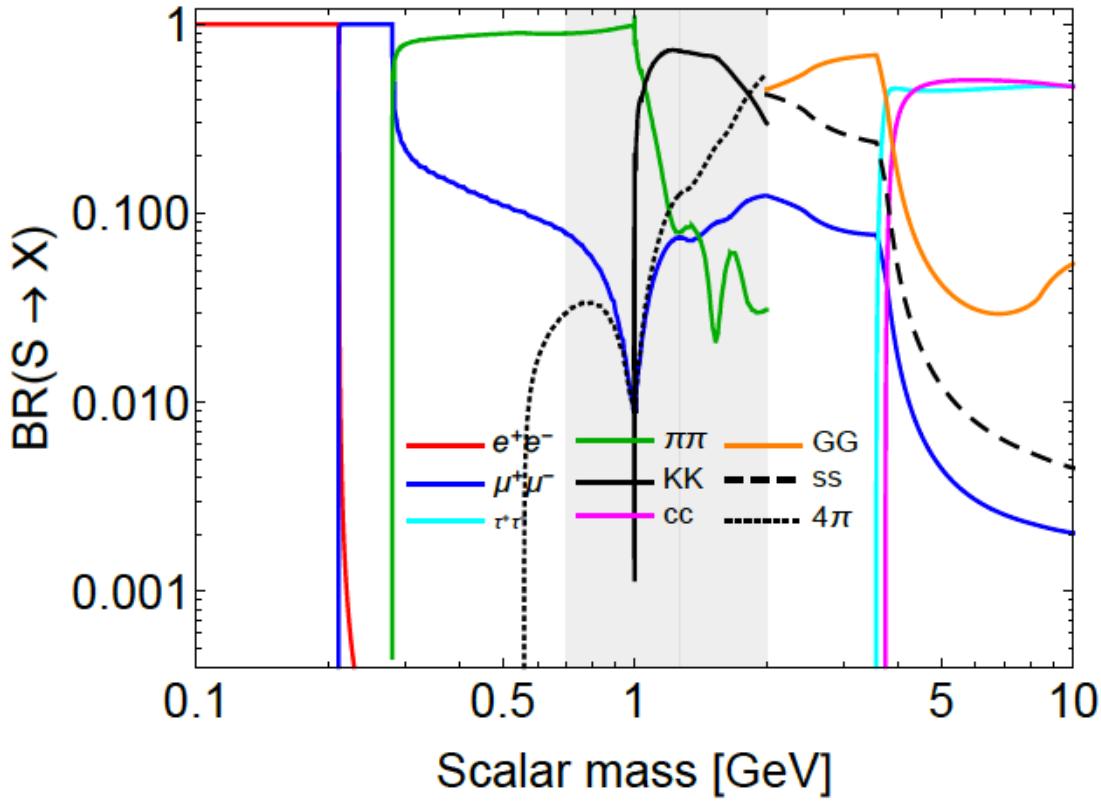
Donoghue, Gassler and Lewwyler, 90'



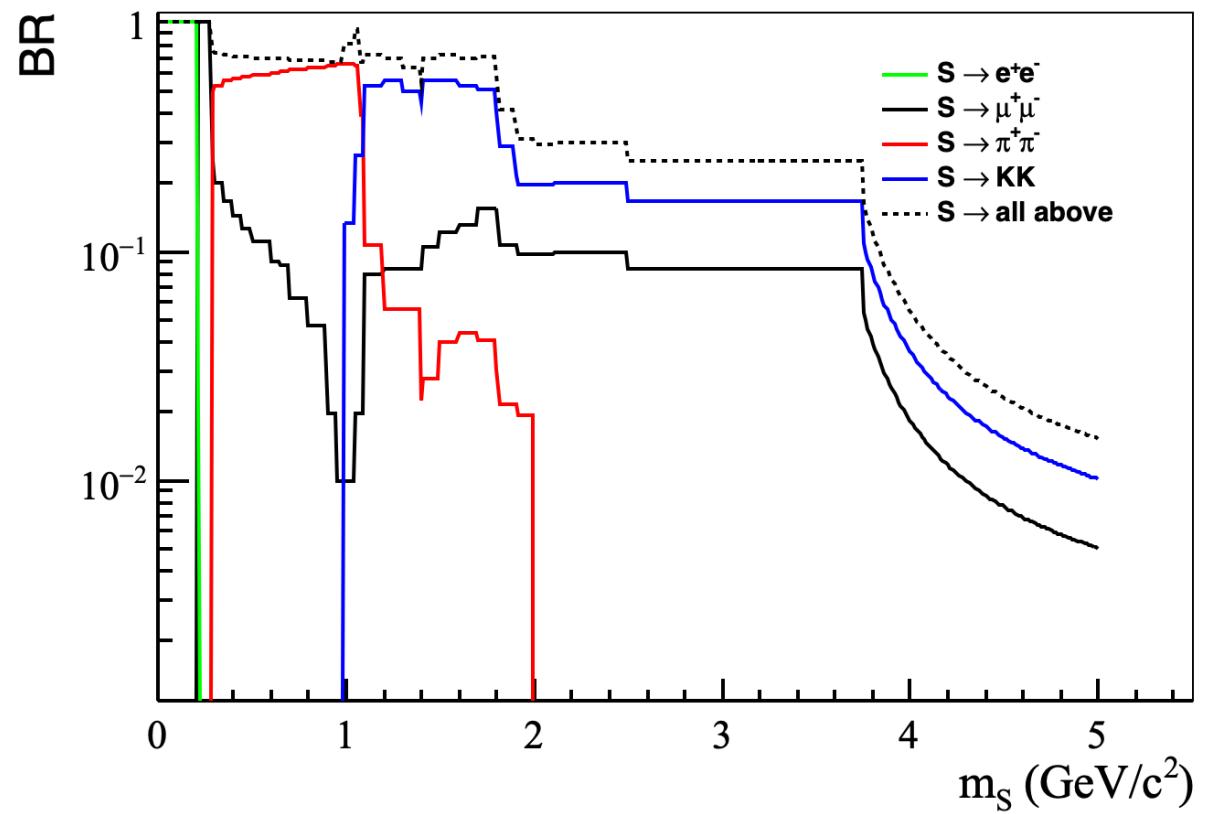
This peak affects the lifetime that around 1 GeV becomes very short

# Dark Scalars: Branching Fractions

Boyarsky et al., 1904.10447



My simulation

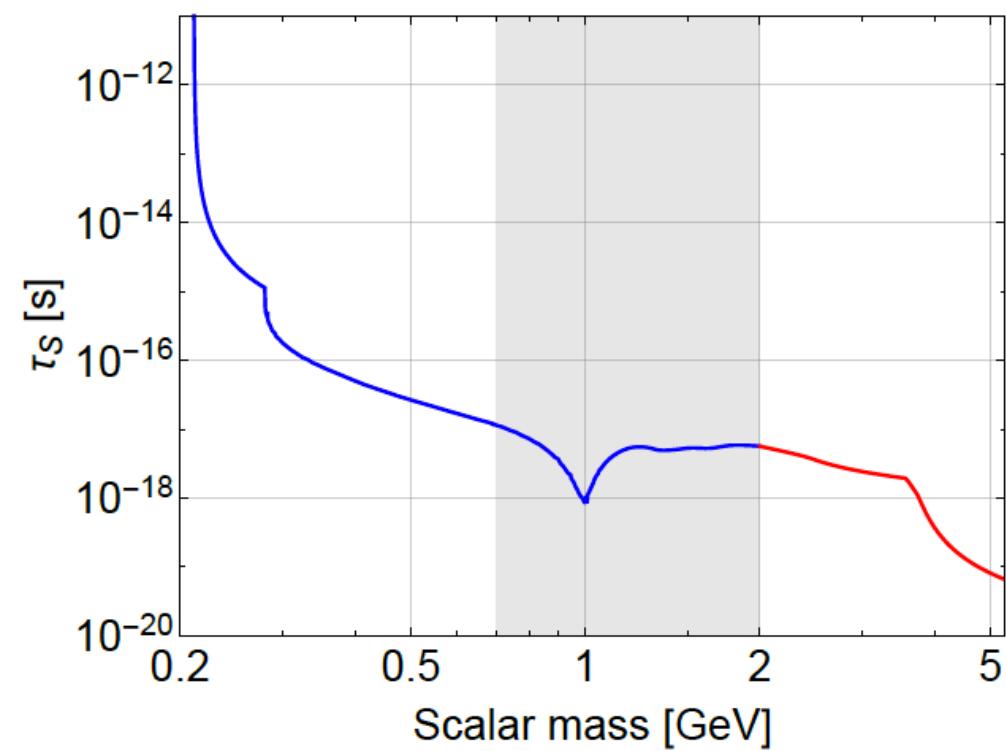


I did not attempt to repeat the non-perturbative calculations (of course!) but I used their findings numerically.  
I am not considering the  $S \rightarrow \tau\tau$  channel for the time being.

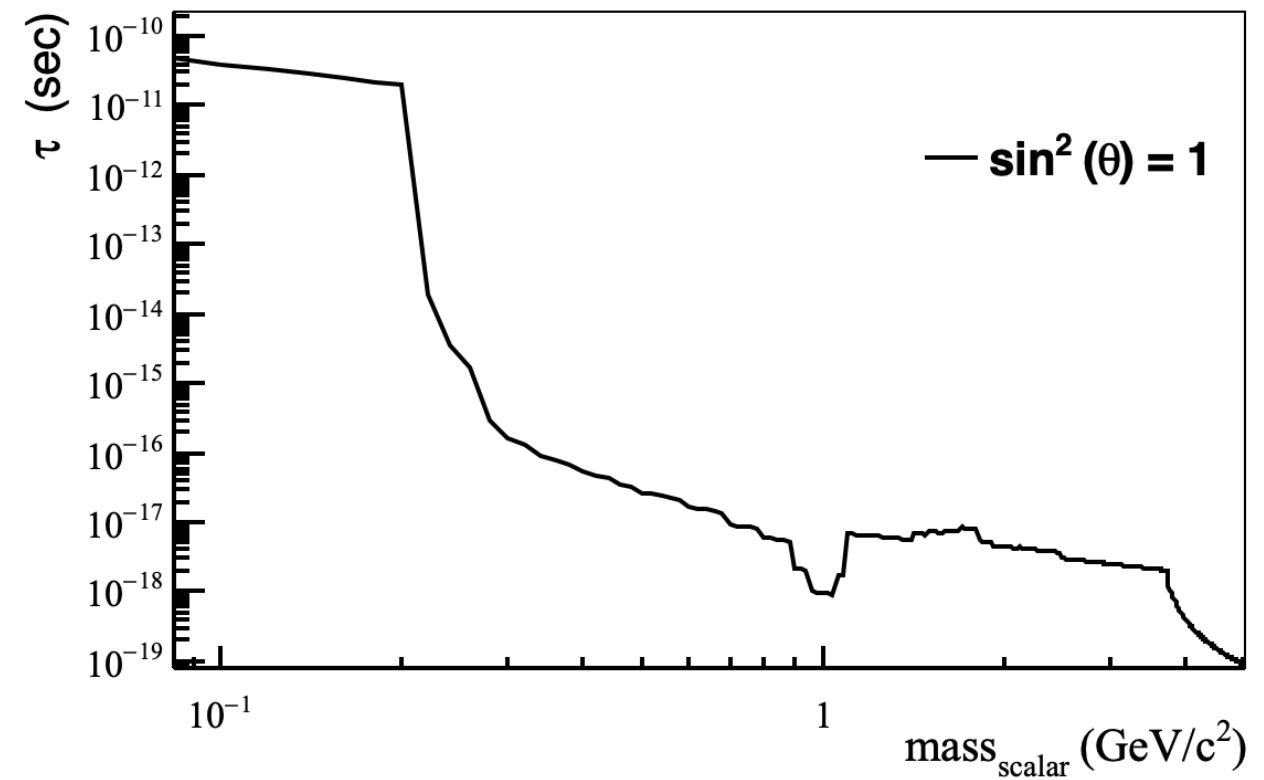
# Dark Scalars: Lifetime

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

Boyarsky et al, 1904.10447



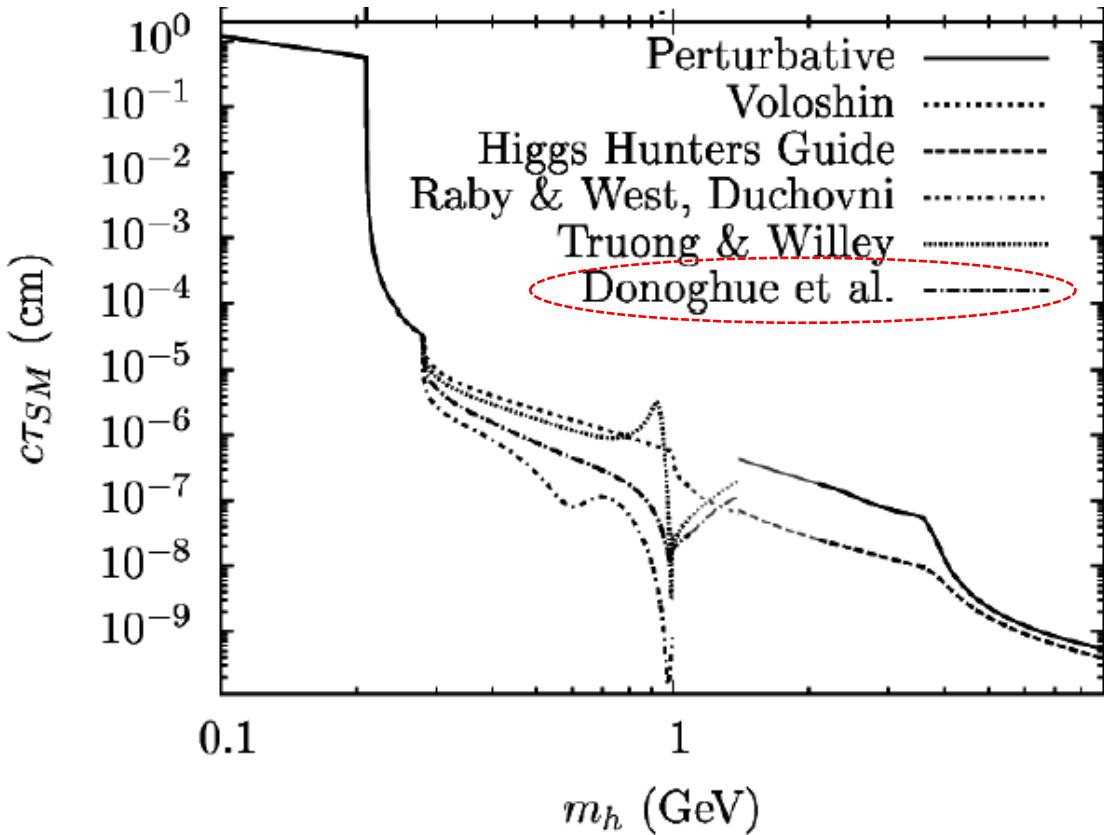
My simulation



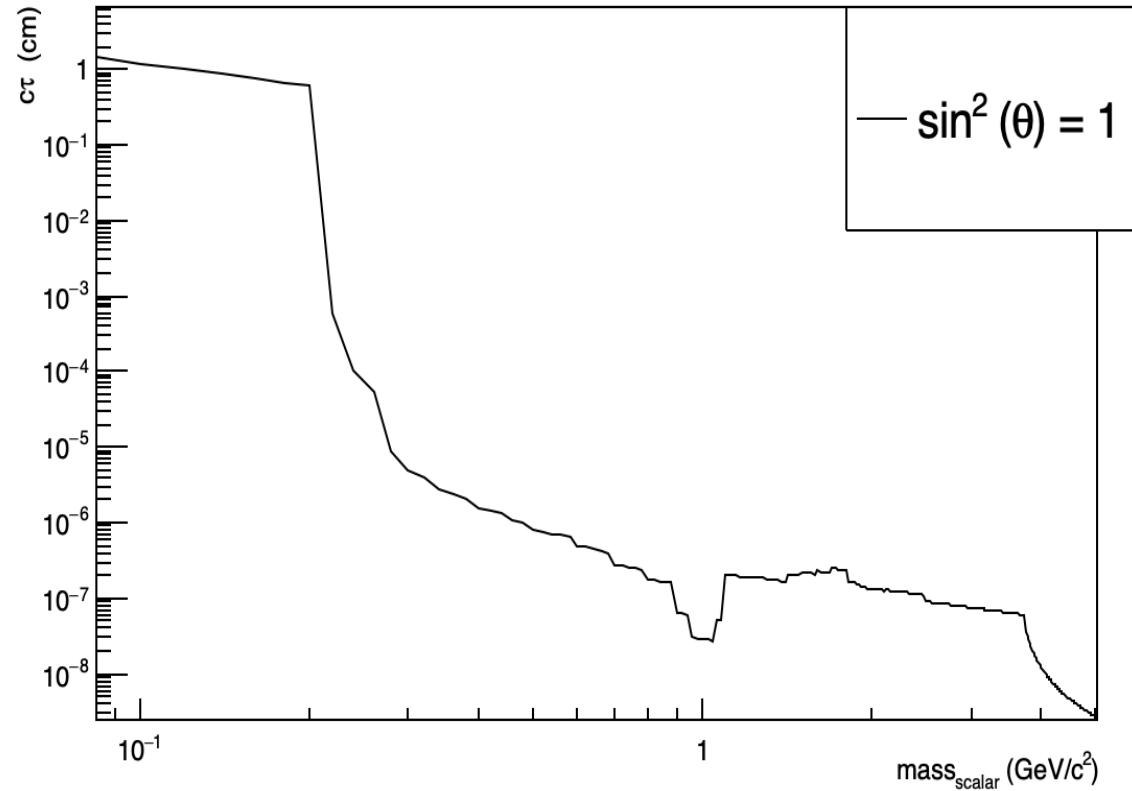
... and I can recover Alexey's computations...

# Dark Scalars: Lifetime

1310.8042



My simulation



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

Sensitivity depends upon:

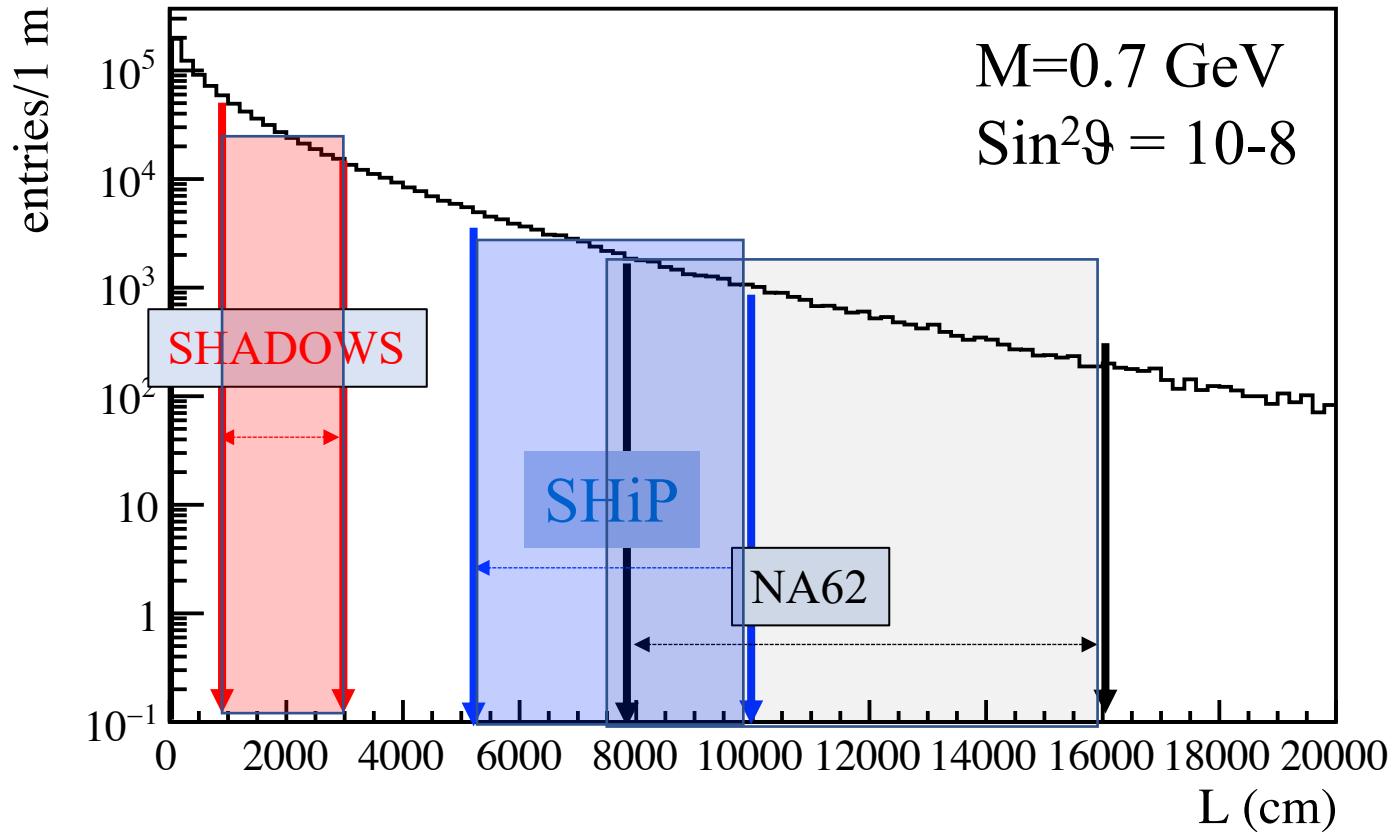
1. Underlying theory model

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

→ 2. Geometry

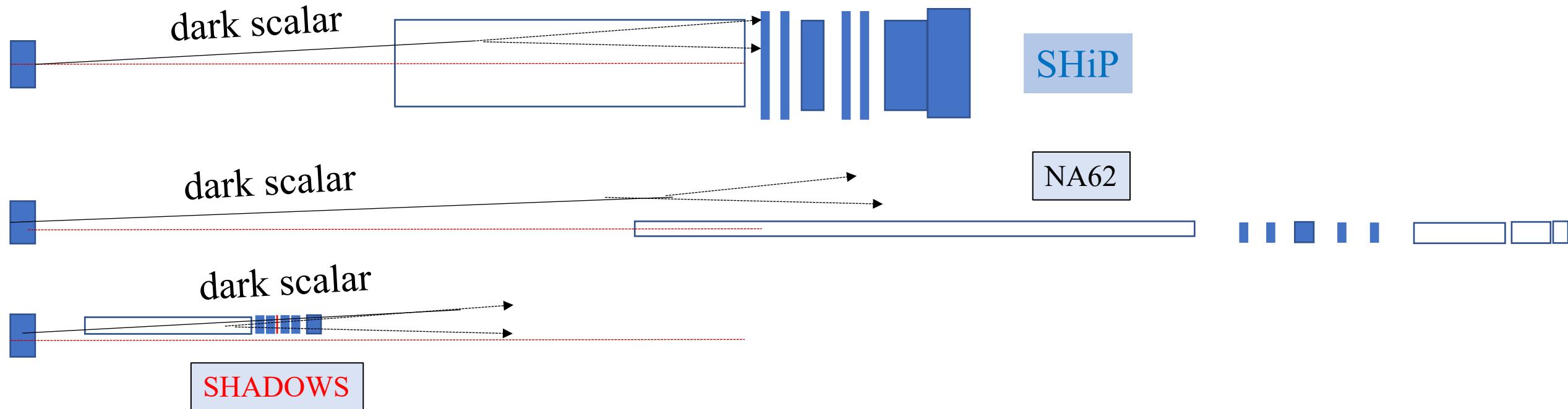
3. Number of protons-on-dump.

## 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

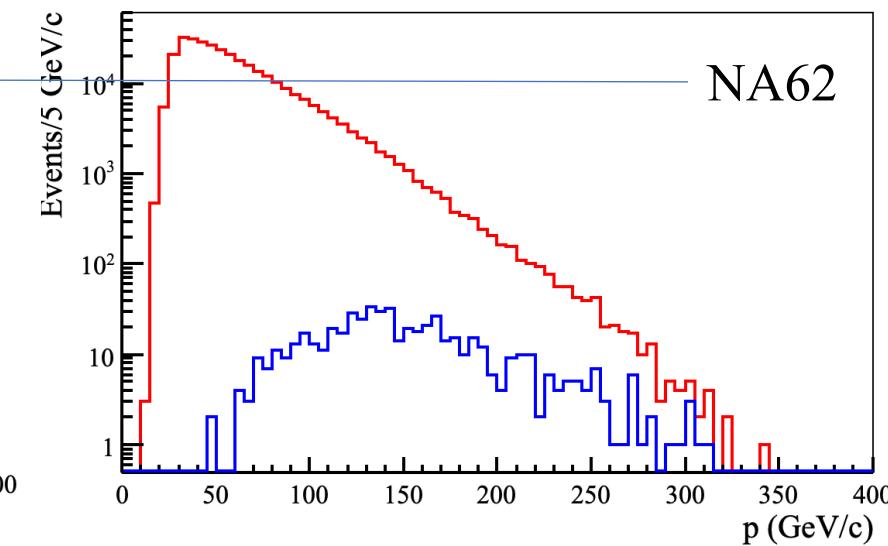
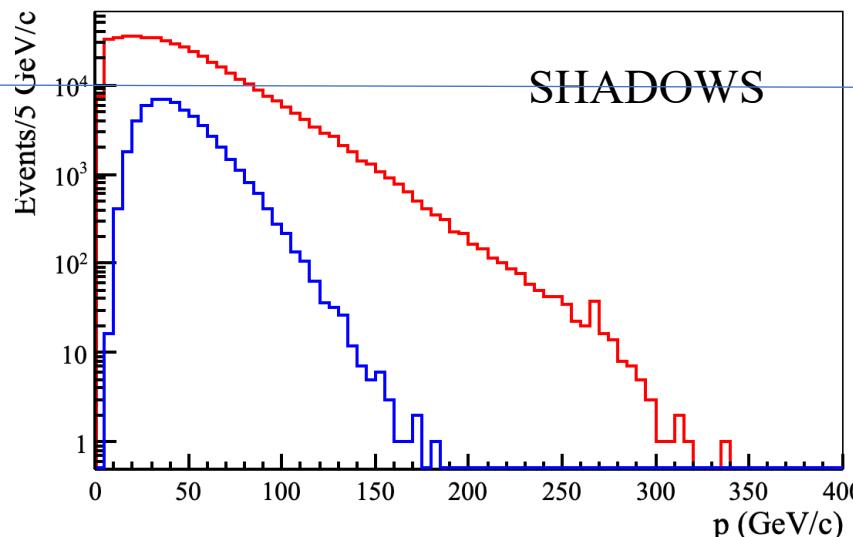
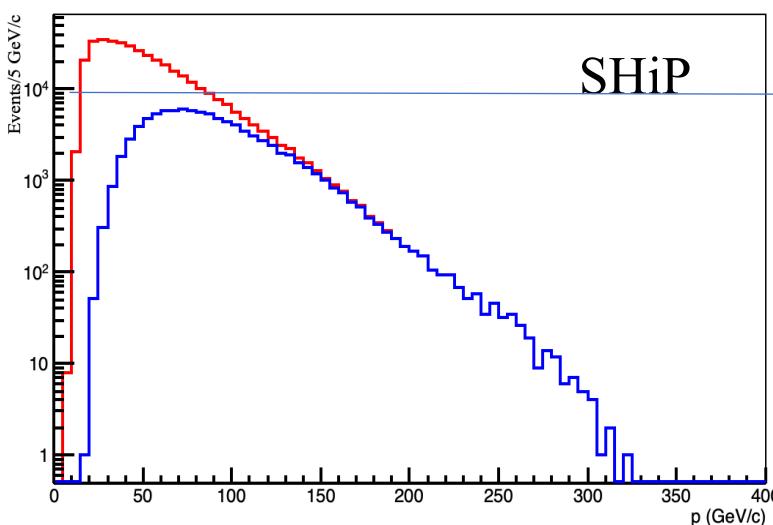


Not only because we sample the lifetime at the very beginning  
but because we intercept more flux...

# Momentum distribution of a light dark scalar

$M=0.7 \text{ GeV}$   
 $\sin^2\vartheta = 10^{-8}$

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

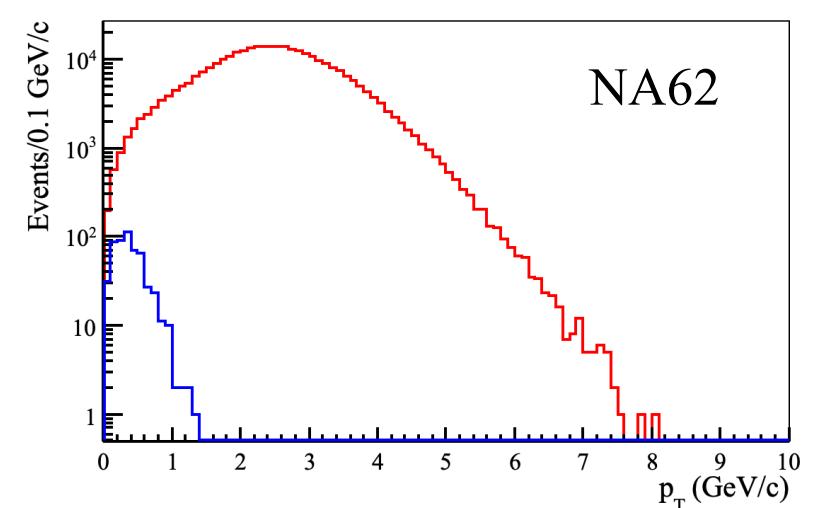
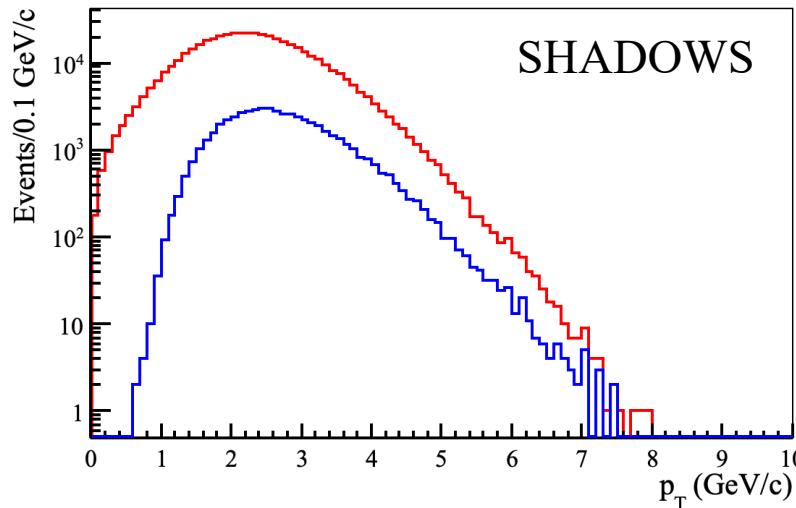
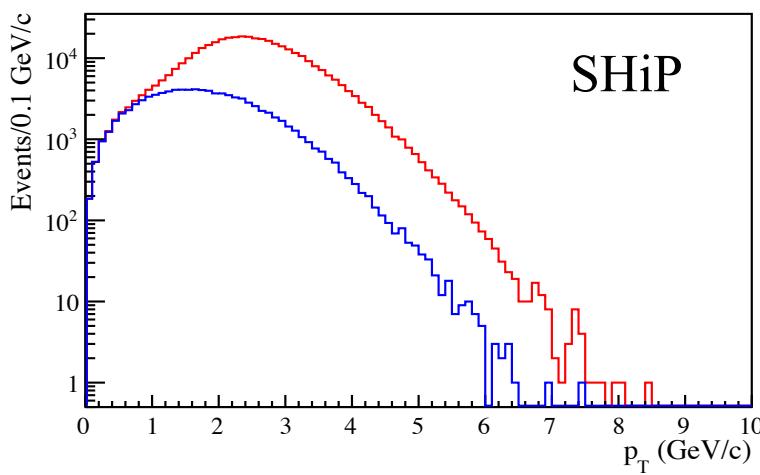


SHADOWS acceptance selects low-p candidates, NA62 acceptance high-p (very boosted) candidates

# 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)