HIKE AND SHADOWS

High **I**ntensity **K**aon **E**xperiment(s) **&**
Search for **H**idden **A**nd **D**ark **O**bjects **W**ith the **S**PS

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

Cluster of Excellence PRISMA+
Precision Physics, Fundamental Interactions and Structure of Matter

Rainer Wanke

Terascale Detector Workshop
Mainz

Feb 22nd, 2024

HIKE & SHADOWS

HIKE (High Intensity Kaon Experiments):

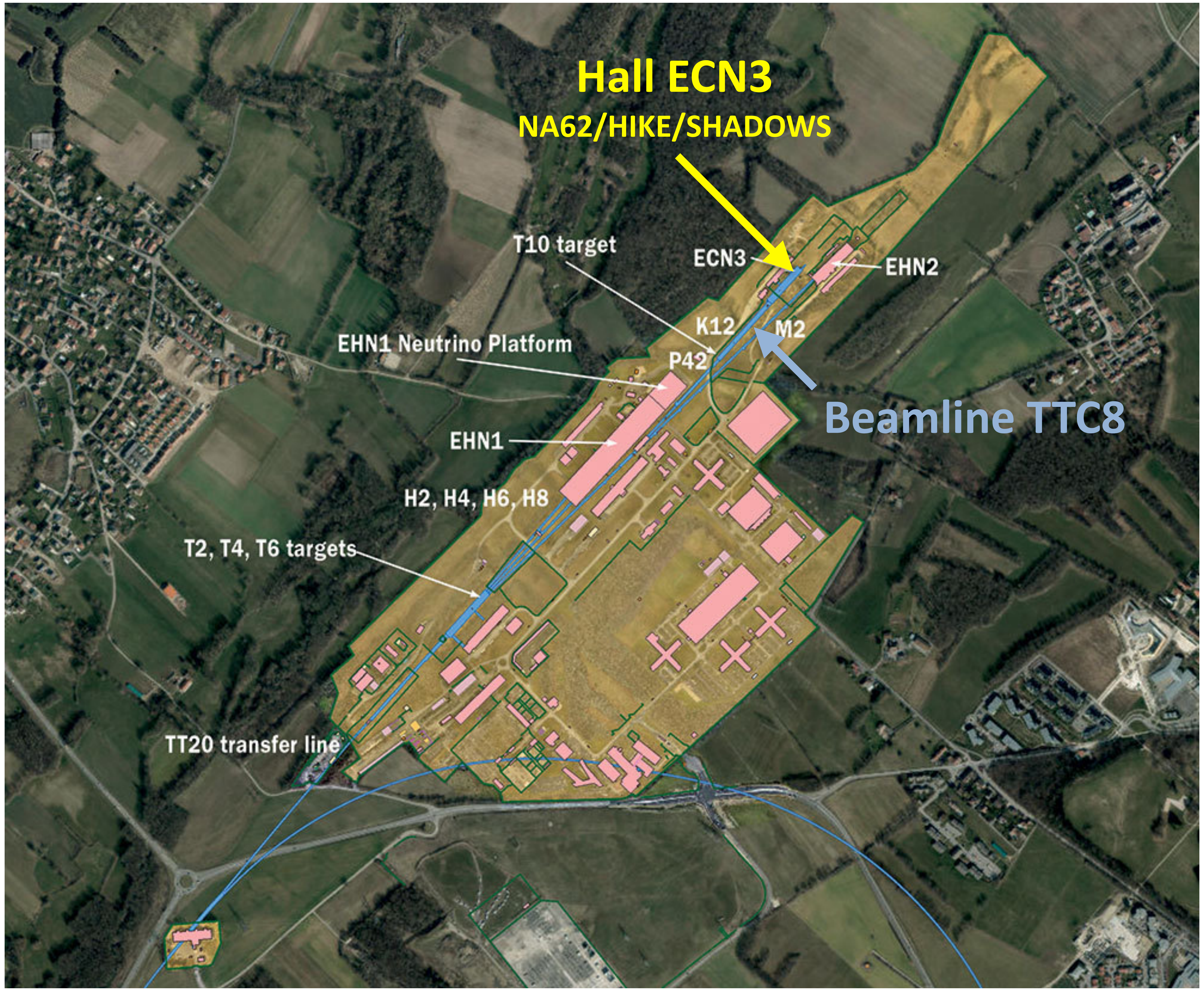
- **Successor** of existing **NA62 experiment** to measure the ultra-rare decay $K^+ \to \pi^+ \nu\bar{\nu}$ to ~ **5%** (Br($K^+ \to \pi^+ \nu\bar{\nu}$) ≈ 10^{-10}!).
  - ➜ **4 × increase in intensity**
  - ➜ **Upgraded NA62 detector and beam-line.**

SHADOWS (Search for Hidden And Dark Objects With the SPS):

- **New experiment** in the NA62/HIKE beamline to search for **long-lived, weakly-interacting, neutral, and massive particles** *(ALPs, HNLs, Dark photons, …)*.
- Runs alternately with HIKE Kaon Physics in **„Beamdump Mode“**.

Hall ECN3 in the CERN North Area

CERN North Area receives a **high-intensity 400 GeV/*c* proton beam from the SPS** and hosts several **fixed-target experiments.**



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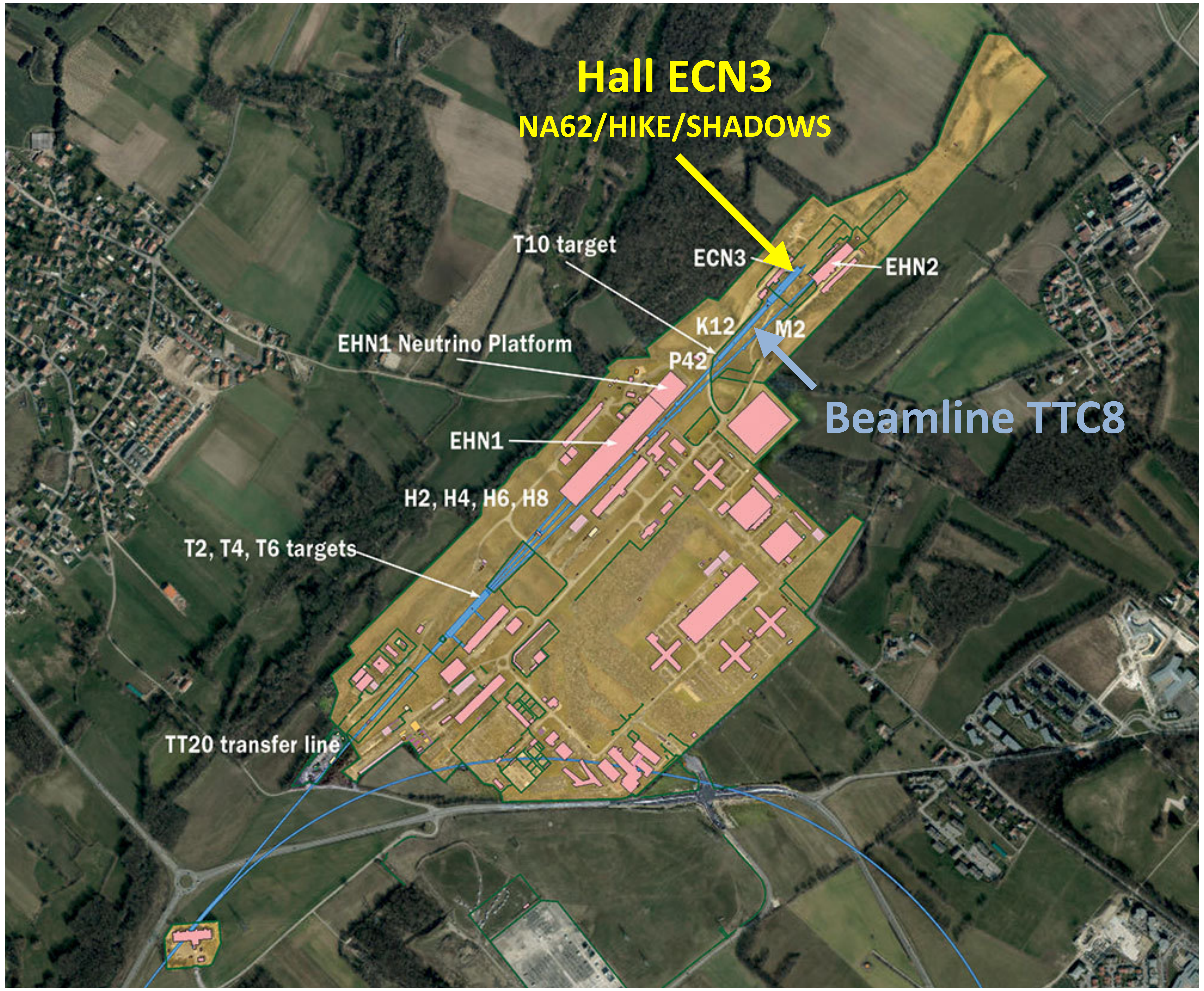
- Home of the **NA62 experiment** until Long Shutdown 3 in 2026.
- **Two proposals for Run 4 after LS3:**
  - NA62 Successor **HIKE** + Beamdump experiment **SHADOWS**
  - Large beamdump experiment **SHiP**.



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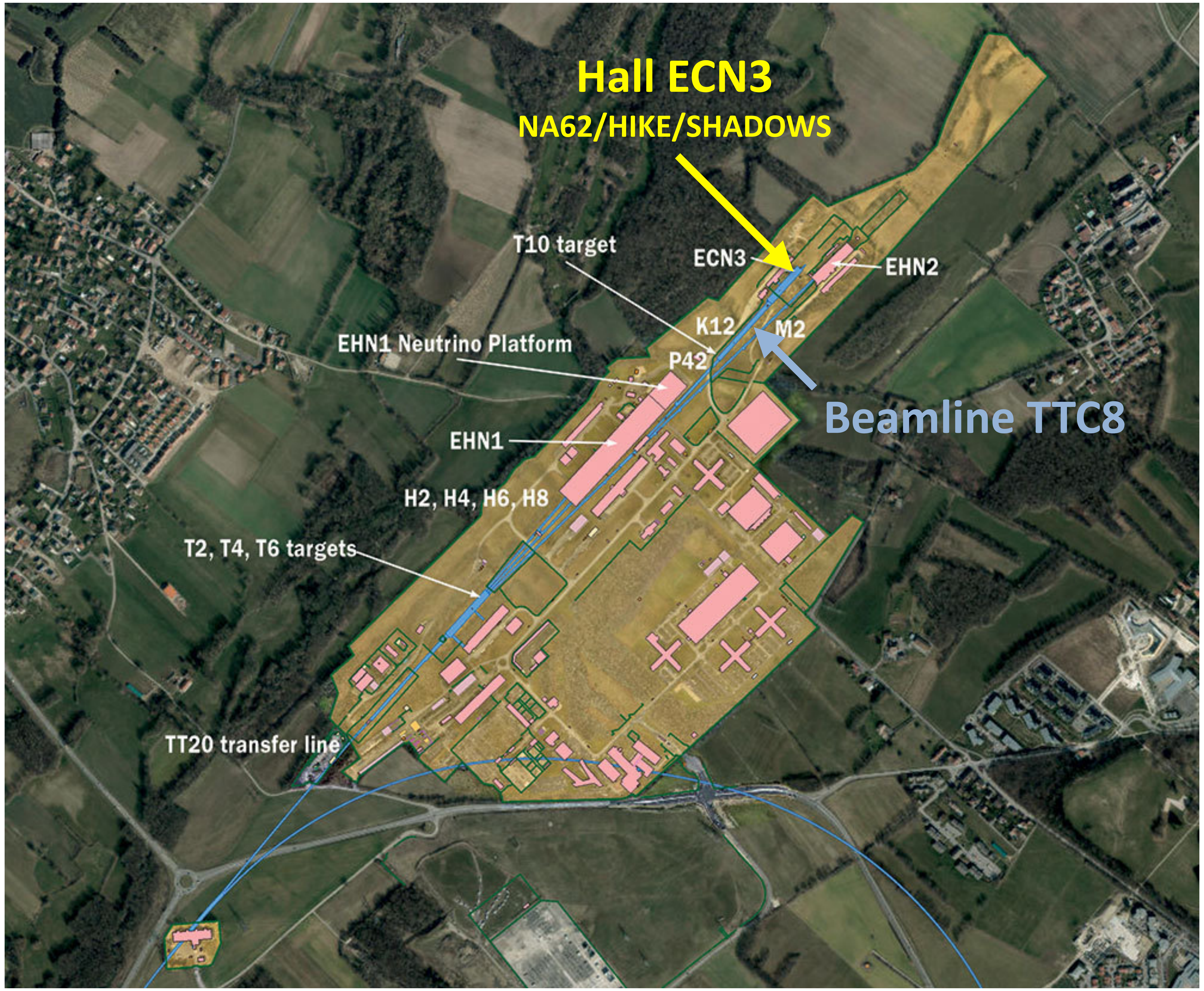
This talk



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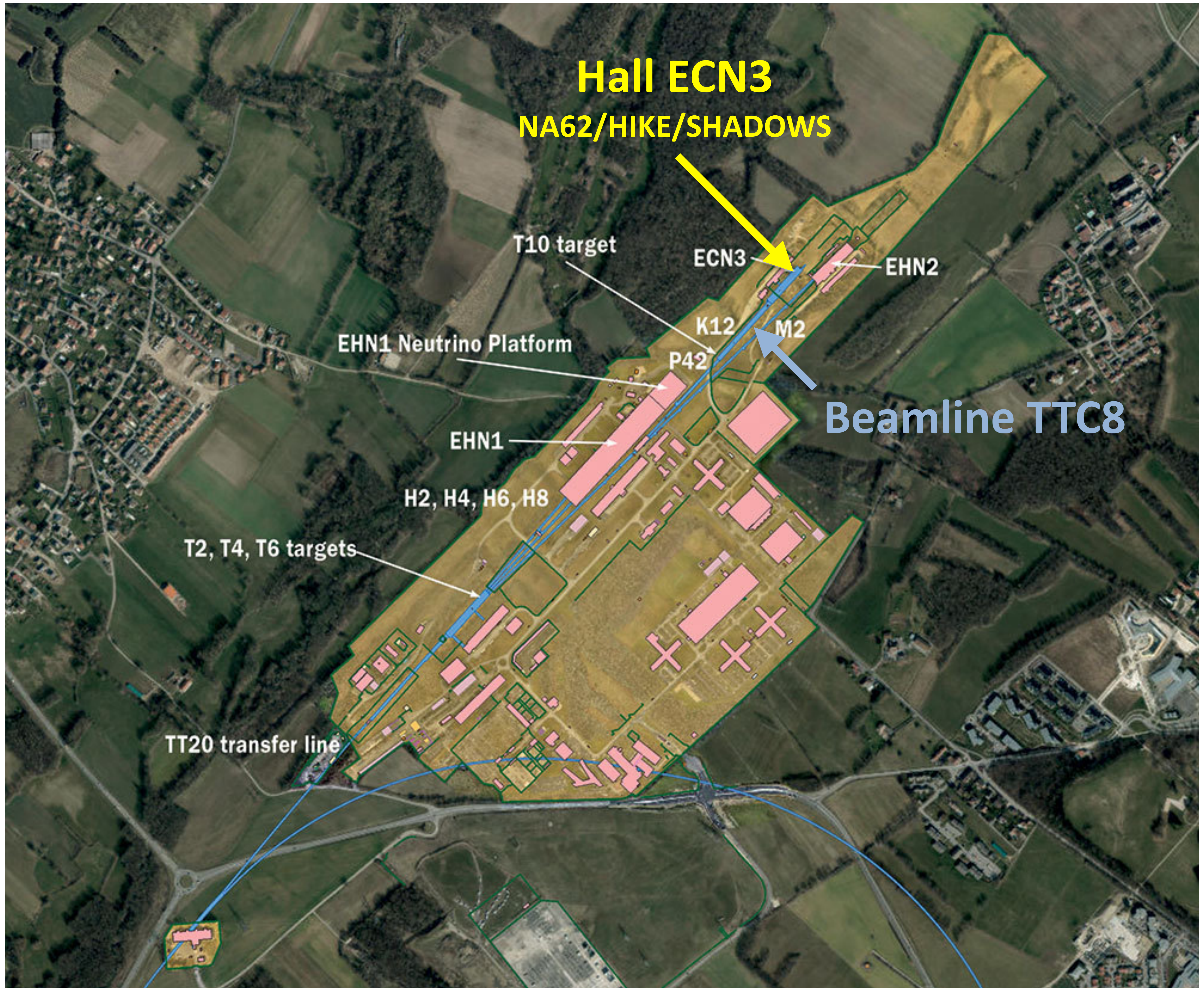
This talk
- NA62 Successor **HIKE** + Beamdump experiment **SHADOWS**

Next talk
- Large beamdump experiment **SHiP**.



Hall ECN3


Hall ECN3
NA62/HIKE
100 m
Secondary beam
Beamline TTC8
SHADOWS
Target T10
SPS protons

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100 m
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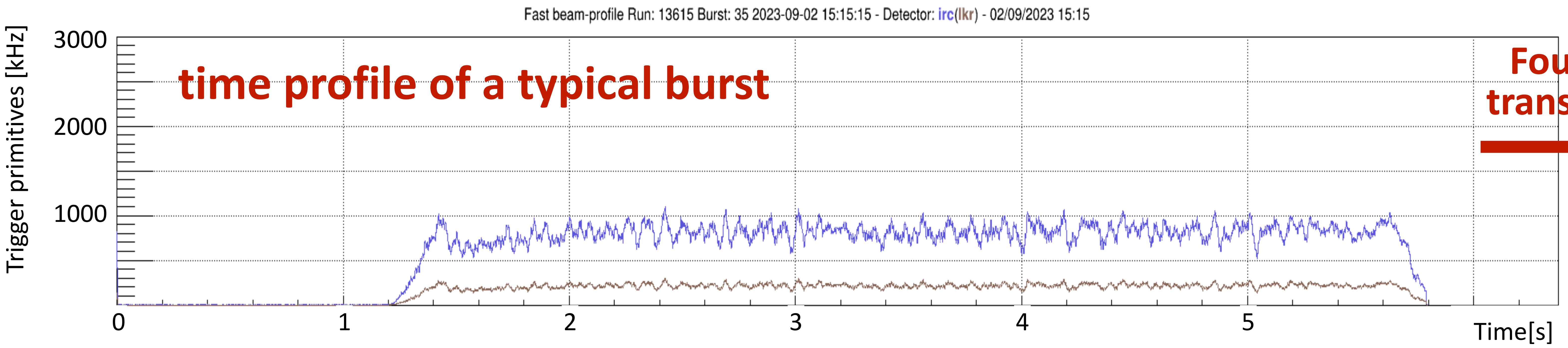
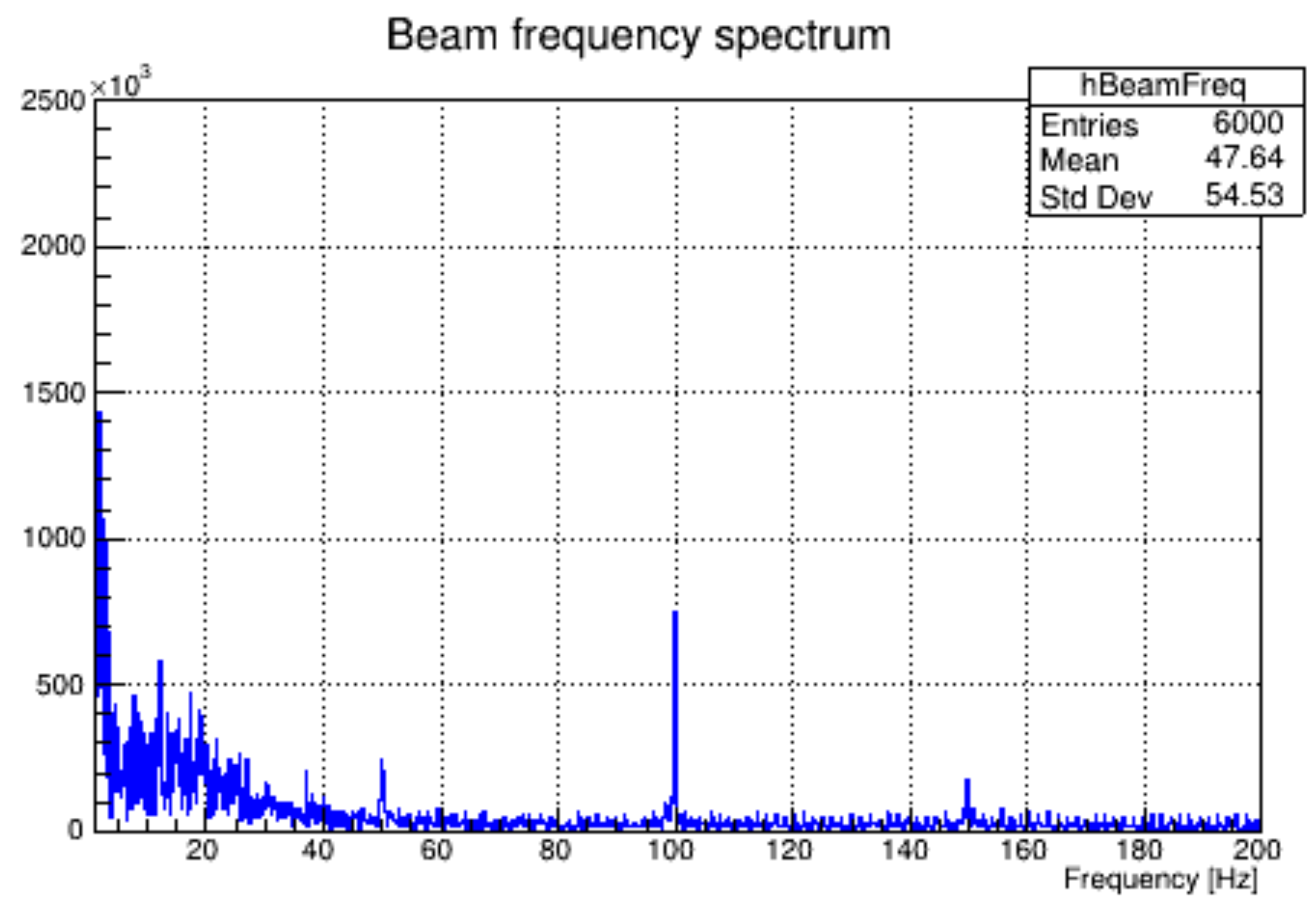
SPS protons

Particles come in Bursts

- „Slow extraction" of 400 GeV SPS proton beam.
  - ➜ **Spill/burst** with „flat top" of typically **4.8 sec** every 14.4 sec (or less often).
  - ➜ **2×10^{13} particles per pulse *(ppp)*** (4 × NA62 intensity).
- Flat top everything else than „flat":
  - Usually **strong intensity fluctuations**, e.g. with 50 or 100 Hz, depending on SPS performance.



Fourier transform ➜



Particles come in Bursts

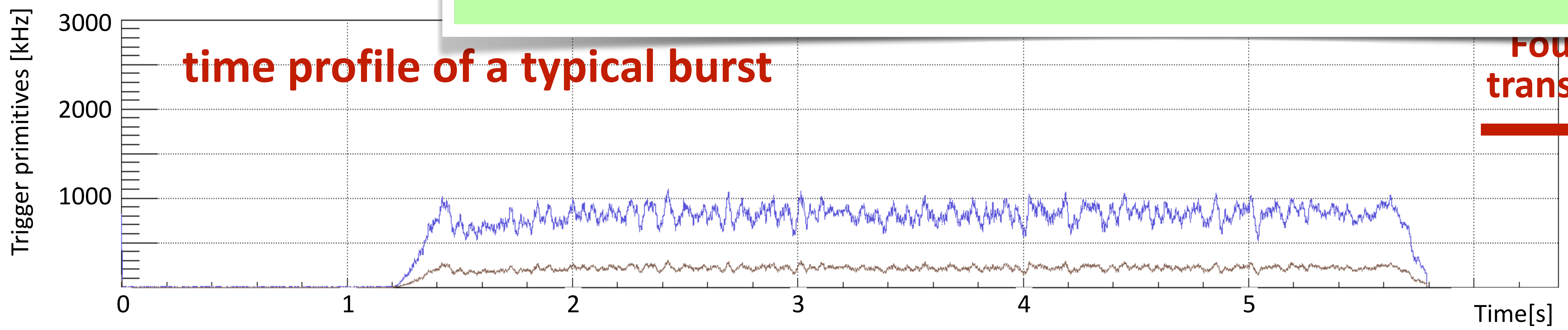
- „Slow extraction“ of 400 GeV SPS proton beam.
  - ➜ **Spill/burst** often).
  - ➜ **2×10^{13} pa**
- Flat top every
  - Usually **str**
    depending

Very different triggering and data-taking scheme compared to colliders:

Events may come at any time, not only during bunch-crossings.

➜ **Detector dead-time** as small as possible.

➜ **Very precise timing** to avoid overlapping events.



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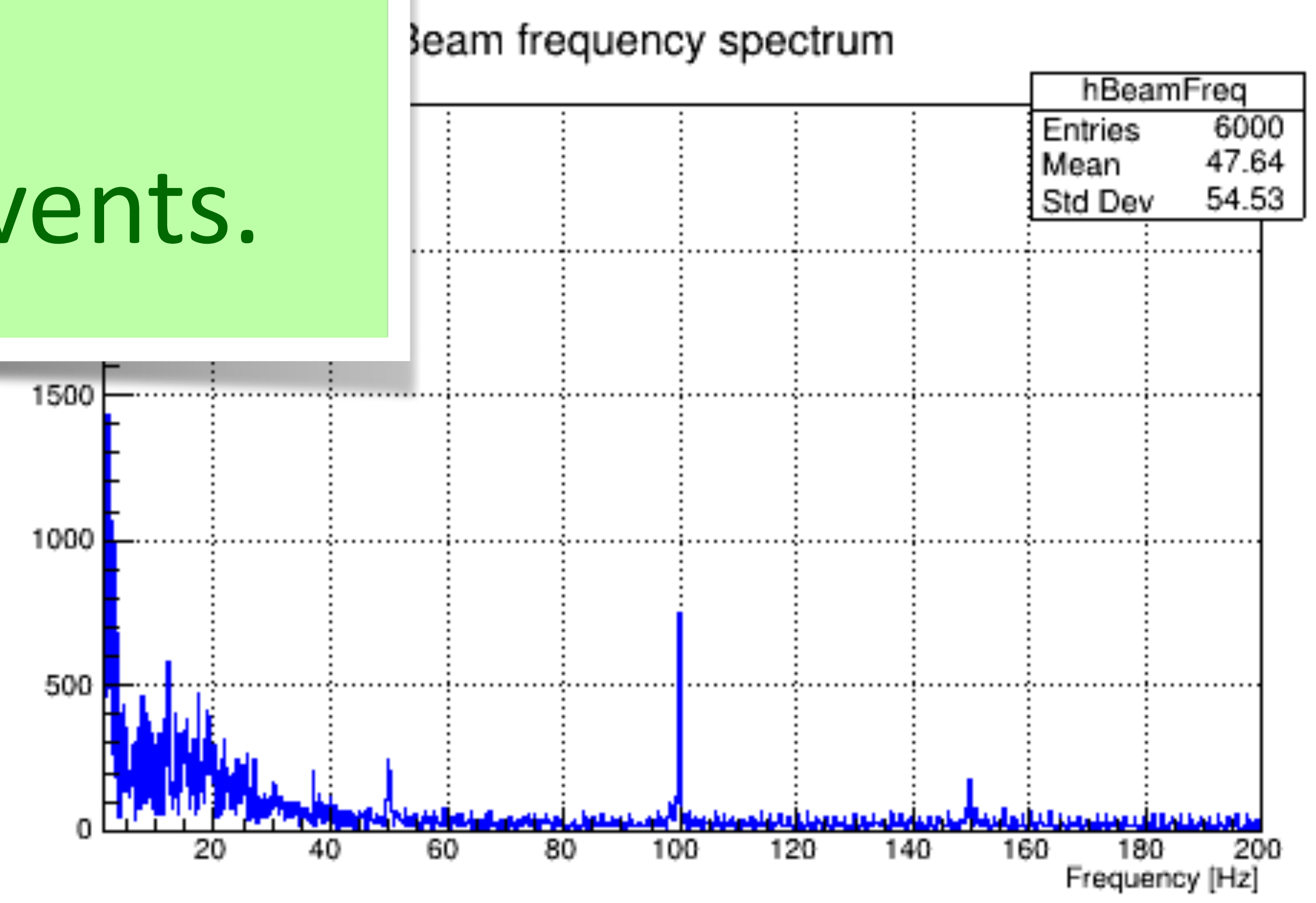
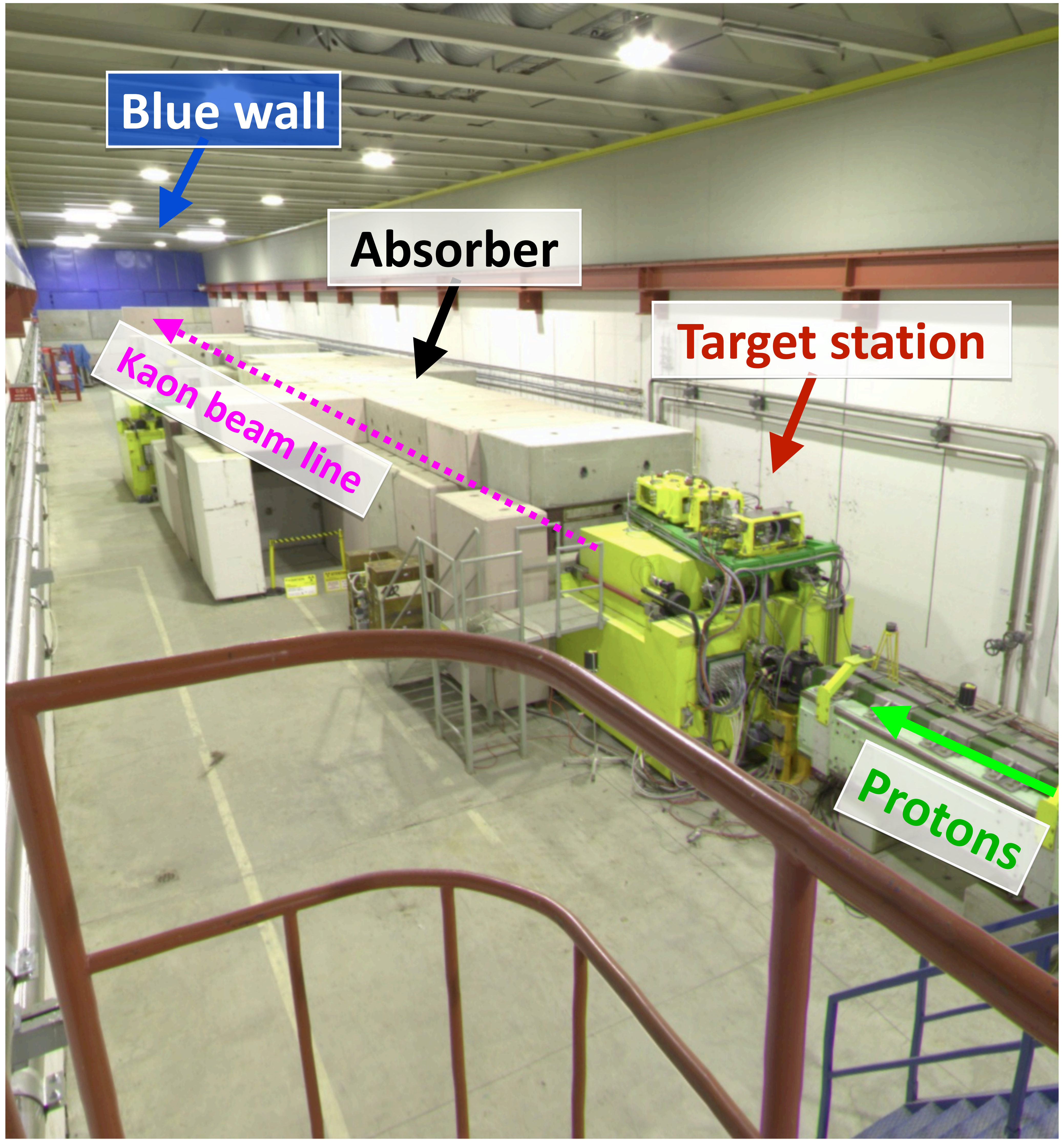
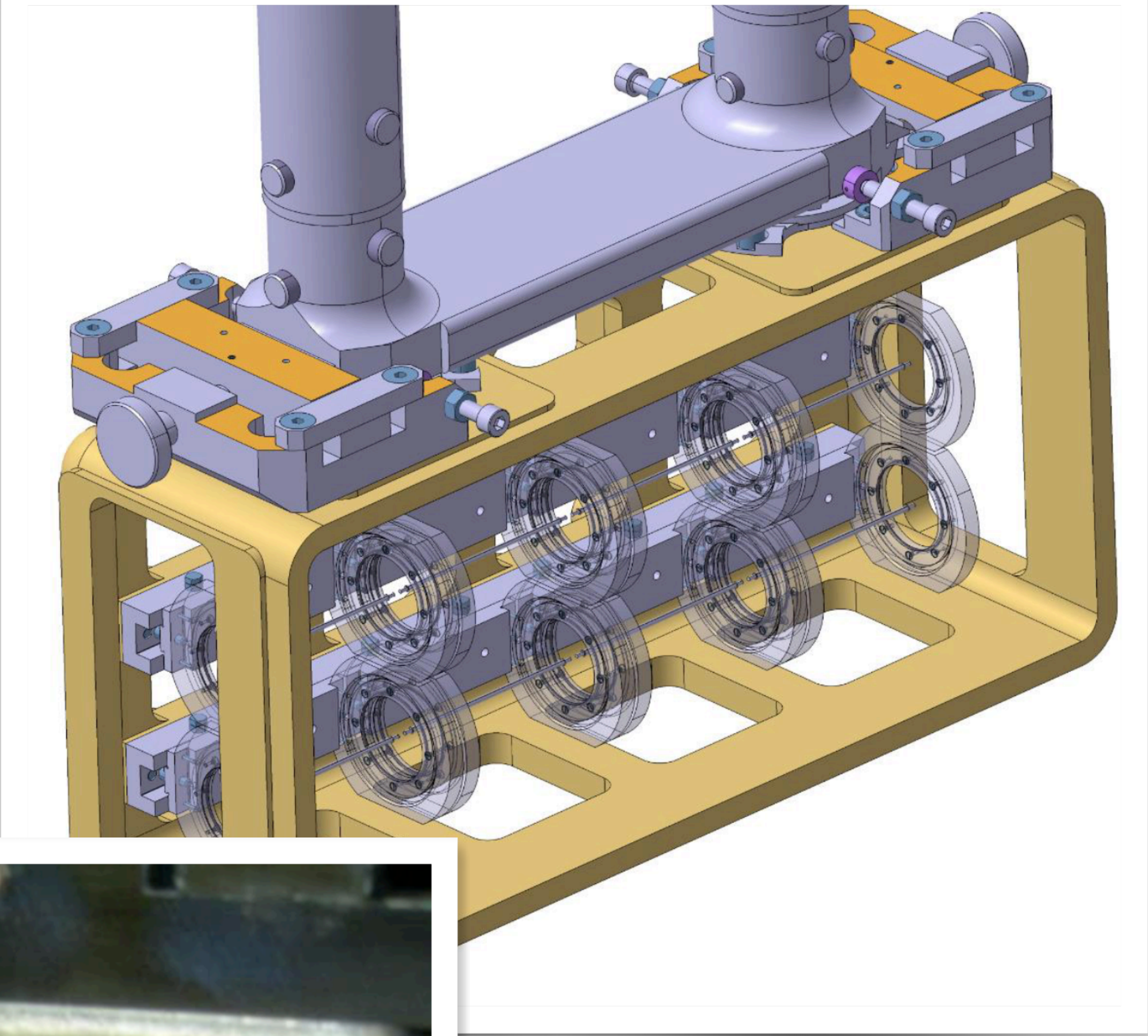
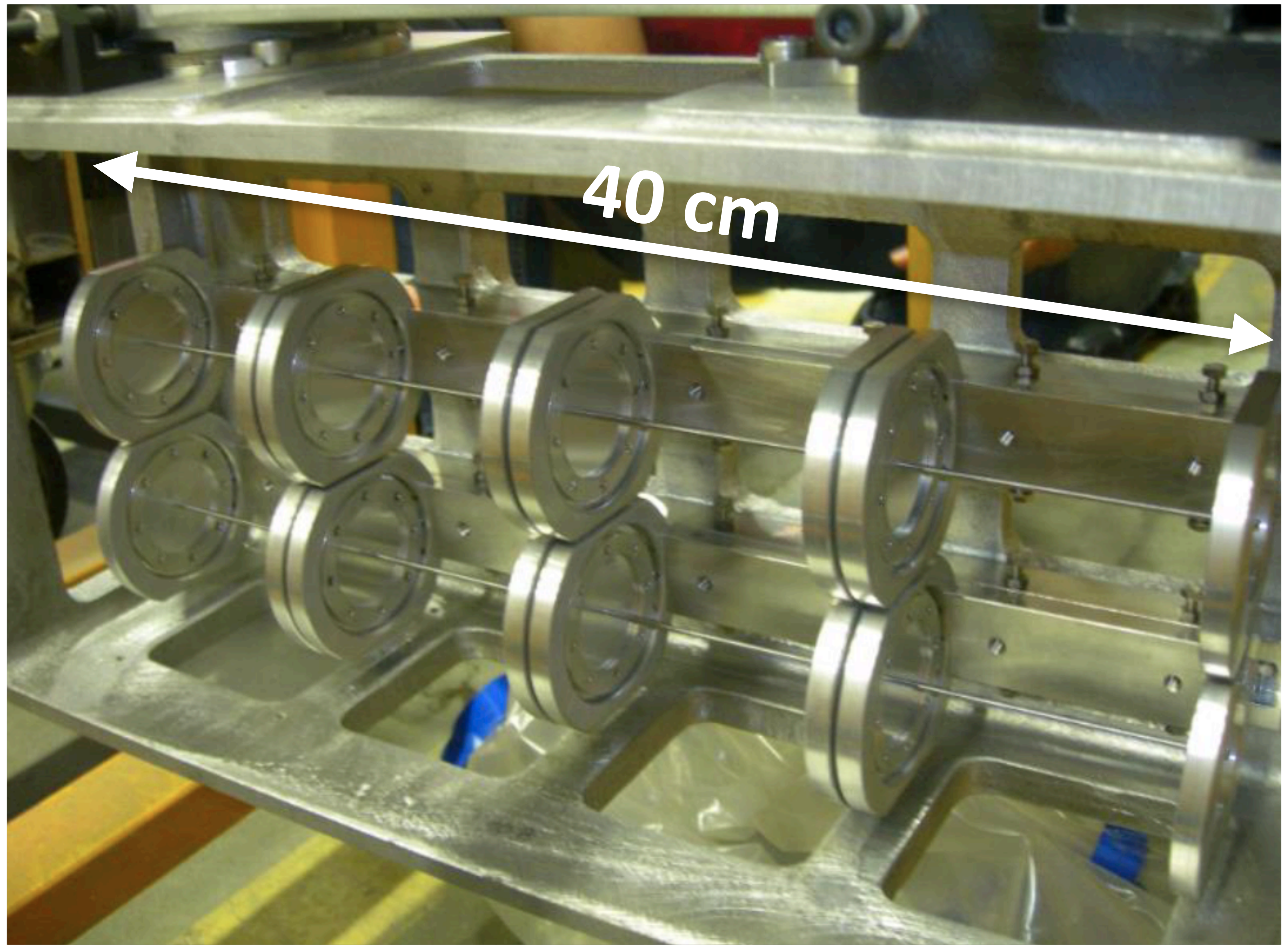


HIKE Target



- Beryllium rod of 40 cm length and 2 mm diameter.





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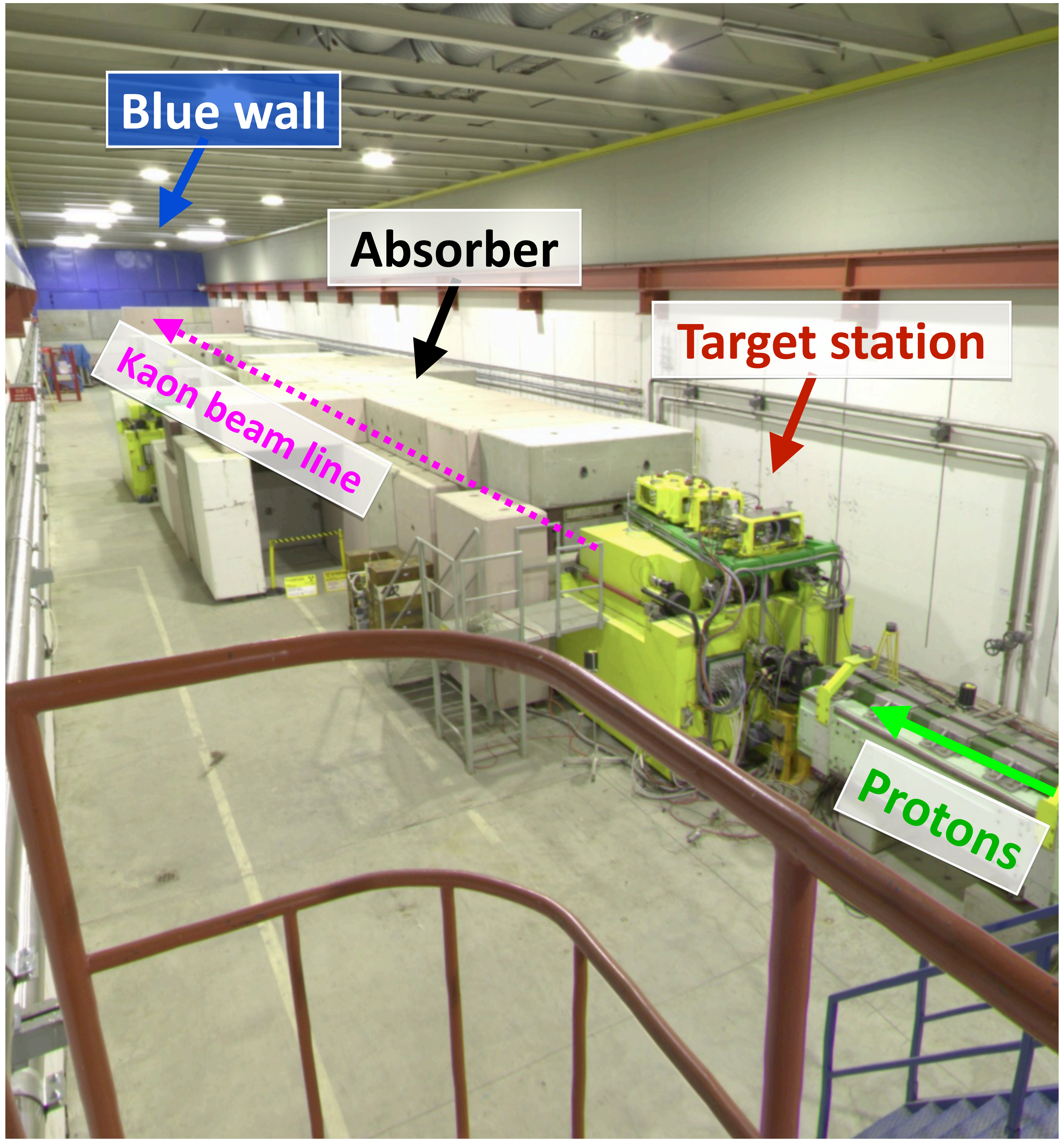
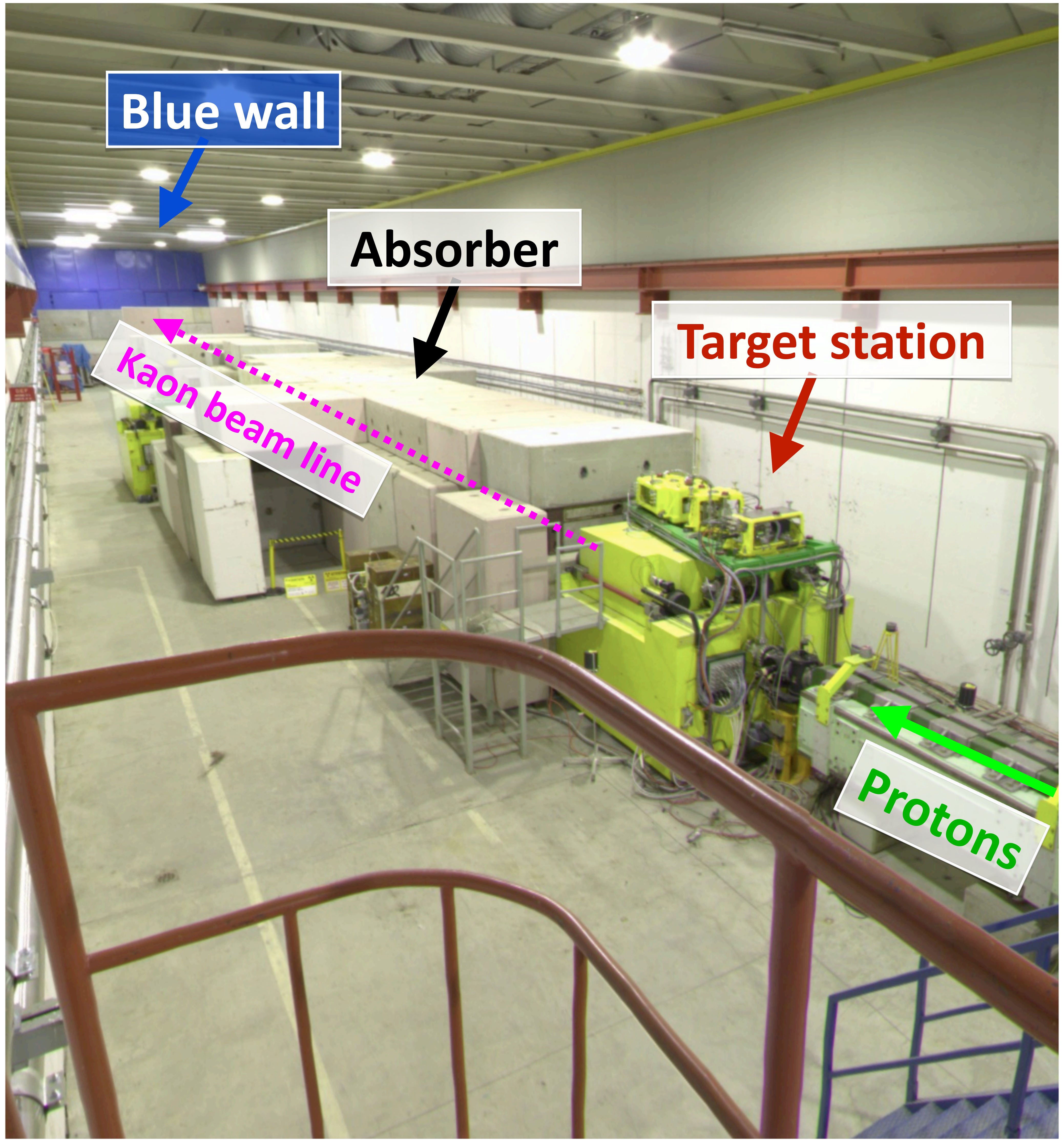


Total number of protons on target (p.o.t.) in HIKE:

- **5×10^{19} p.o.t.** in 5 years of running.

HIKE Target



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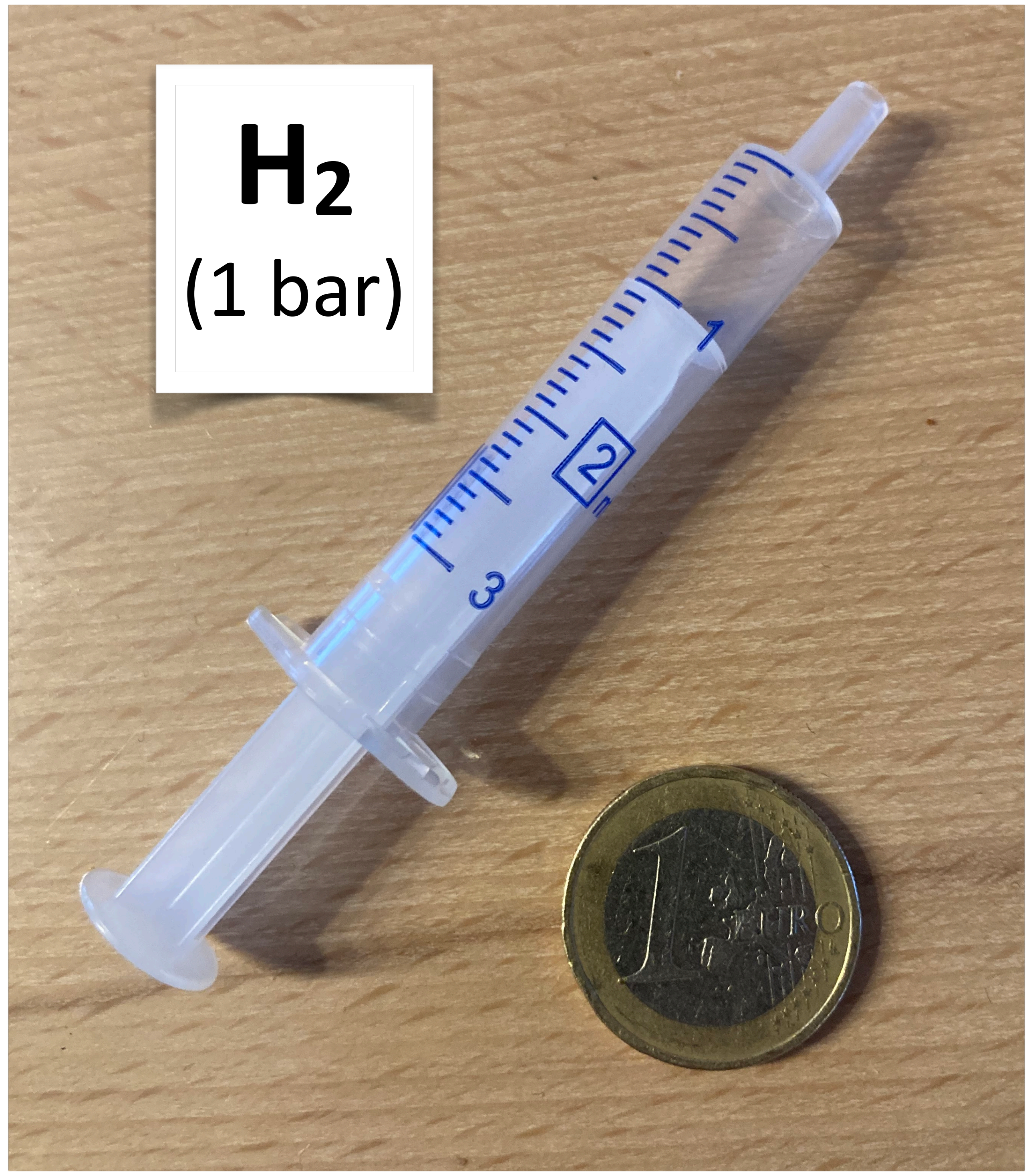
Sounds a lot?

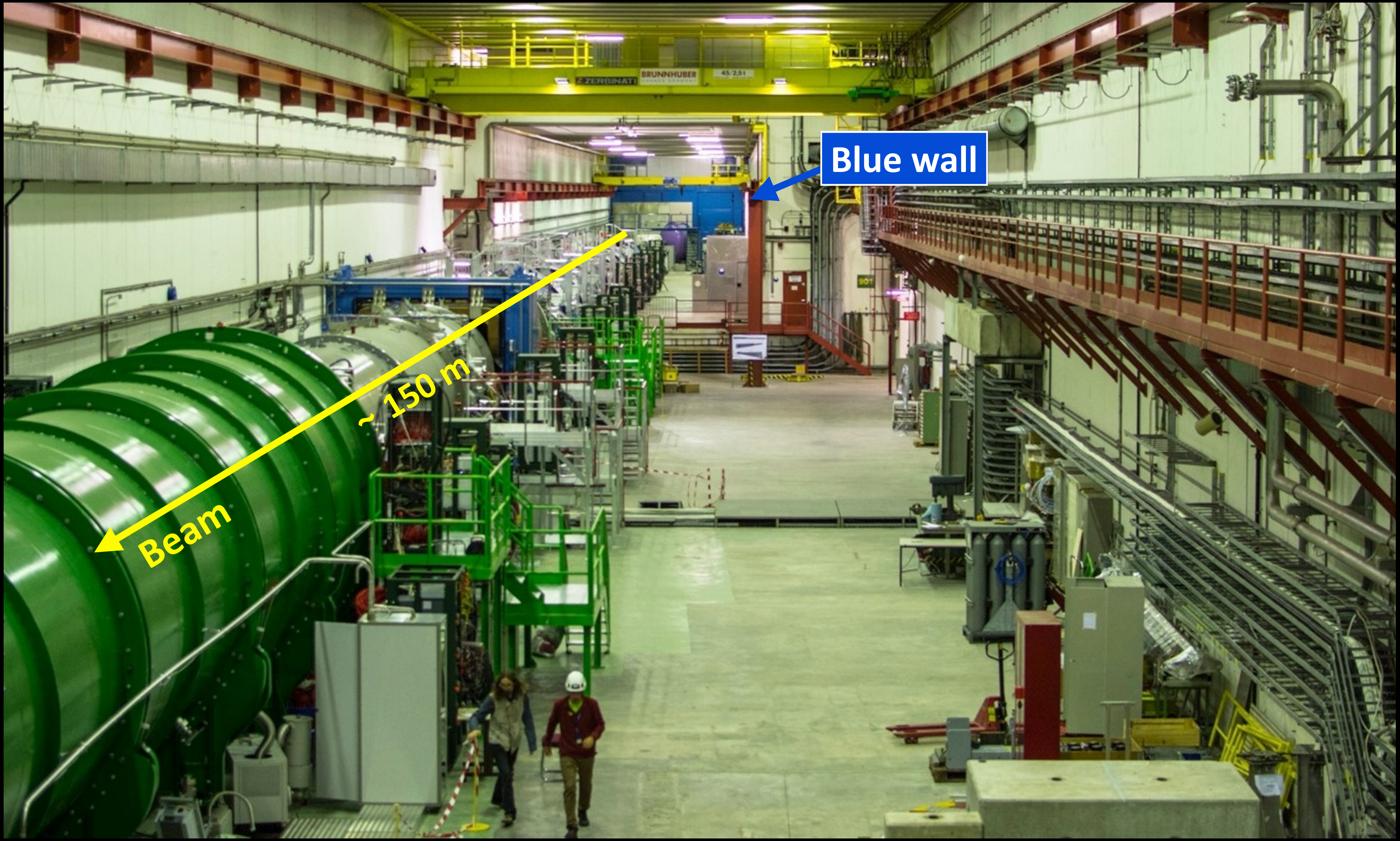
It is a lot!



Hall ECN3

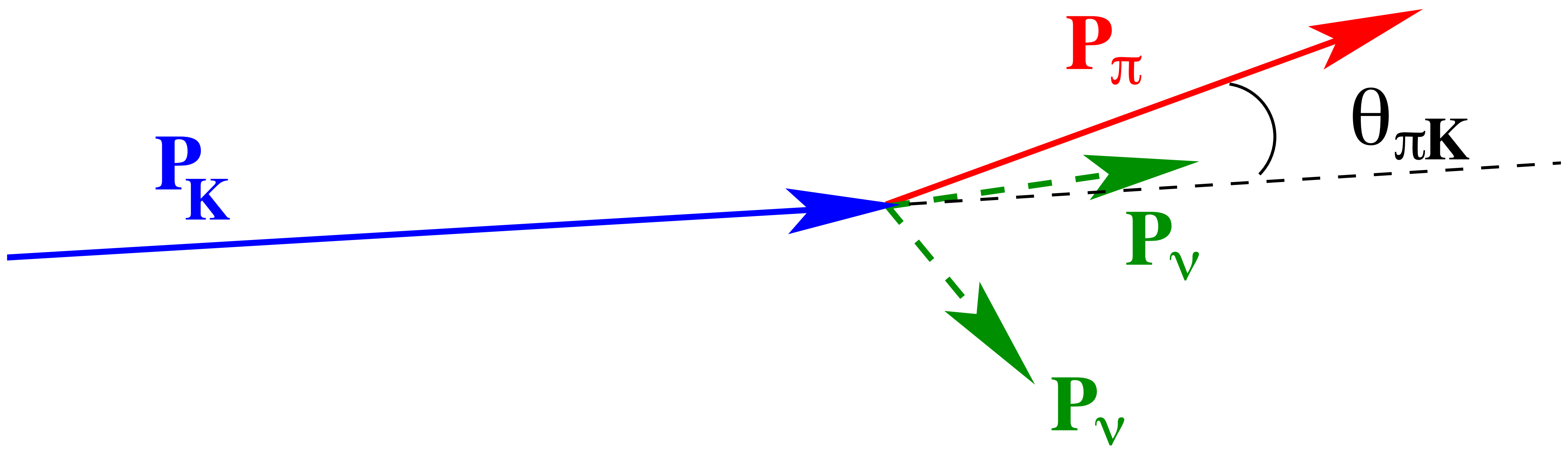

Hall ECN3
NA62/HIKE
100 m
Secondary beam
Beamline TTC8
SHADOWS
Target T10
SPS protons

A Look into ECN3 with NA62



How to measure $K^+ \to \pi^+ \nu \bar{\nu}$?

- Charge particles with high momentum ➜ **Kaon decay in flight.**
- Signal signature: K^+ track + π^+ track + nothing else.
- Trigger: 1 track + μ/γ veto



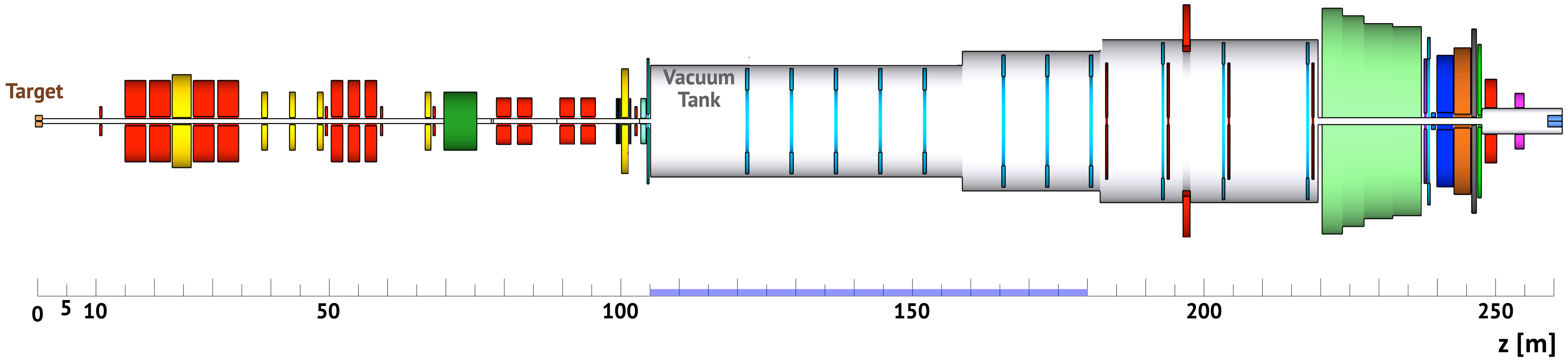
- Signal reconstruction by measurement of *(missing mass)*^{2} = $(p^\mu_K - p^\mu_\pi)^2$:

$$m^2_{miss} \approx m^2_K \left(1 - \frac{p_\pi}{p_K}\right) + m^2_\pi \left(1 - \frac{p_K}{p_\pi}\right) - p_K\, p_\pi\, \vartheta^2_{\pi K}$$

➡

- K^+ momentum
- π^+ momentum
- K^+ identification
- π^+ identification
- Bkg suppression

The HIKE Detector



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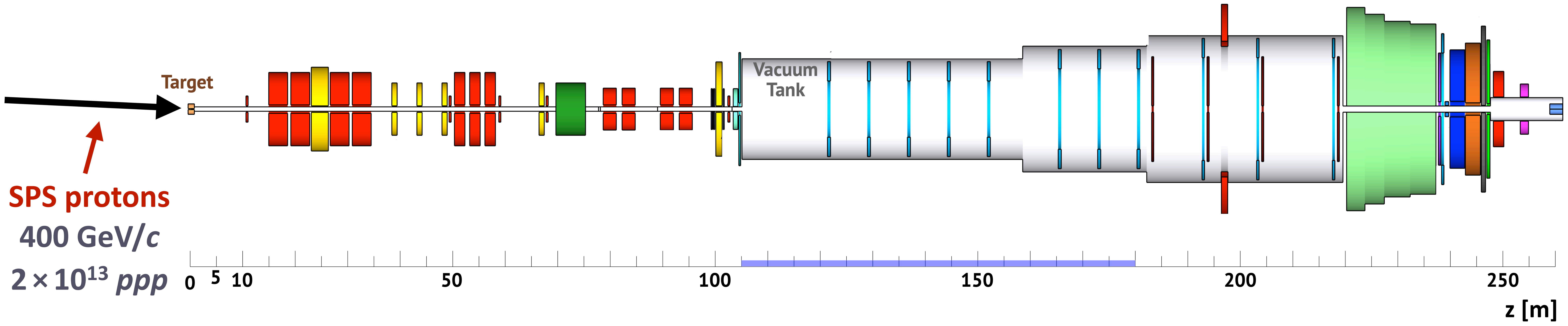

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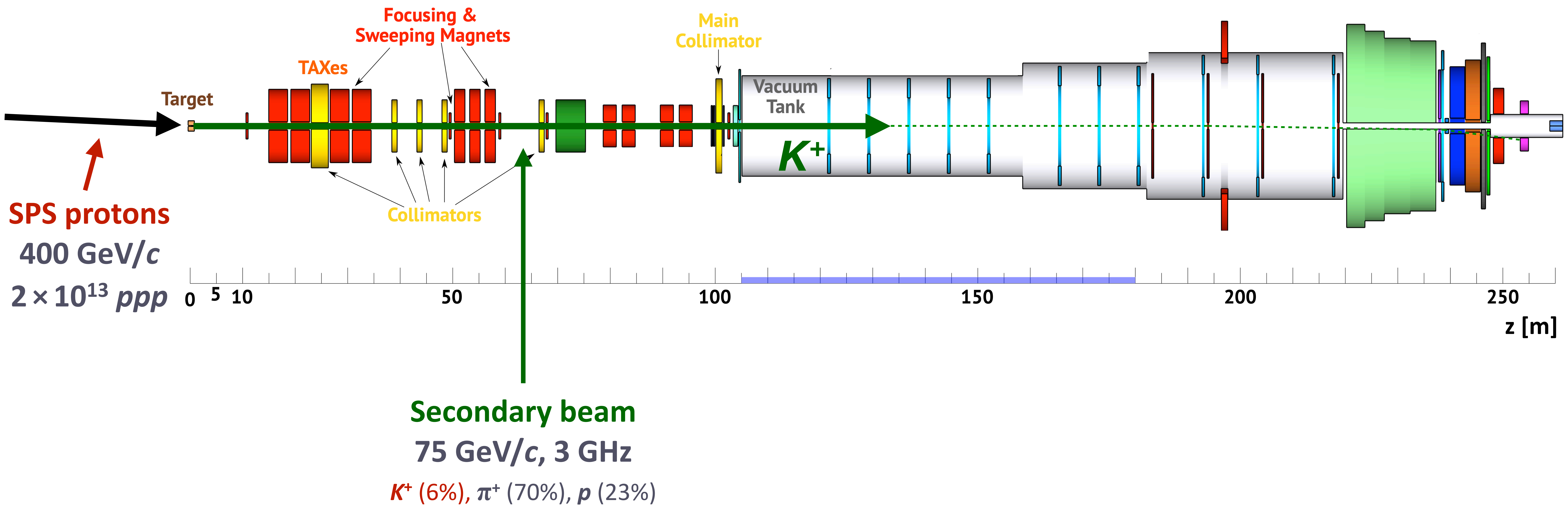
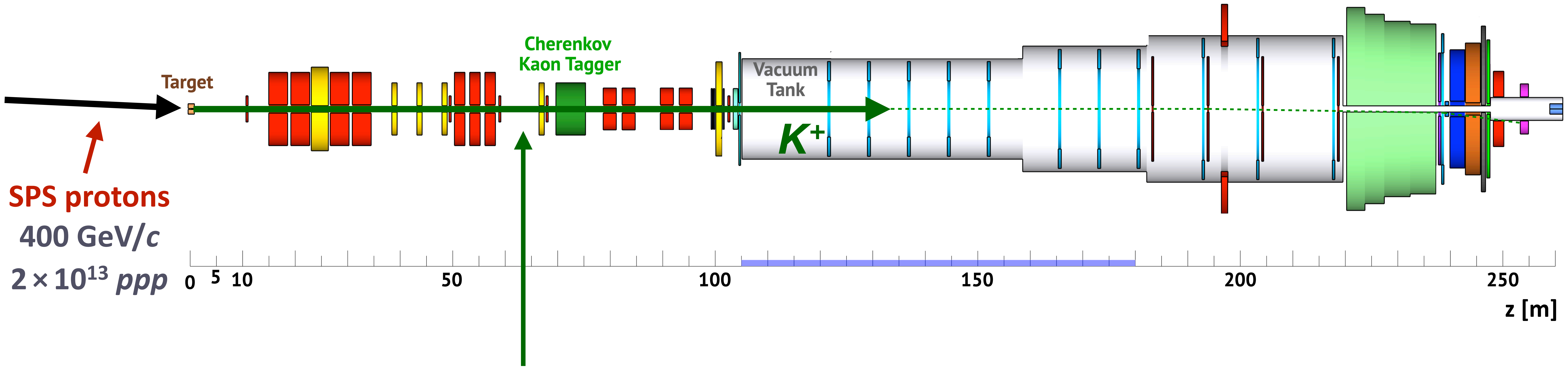


The HIKE Detector

Detectors for Secondary Beam
- Cedar for Kaon ID

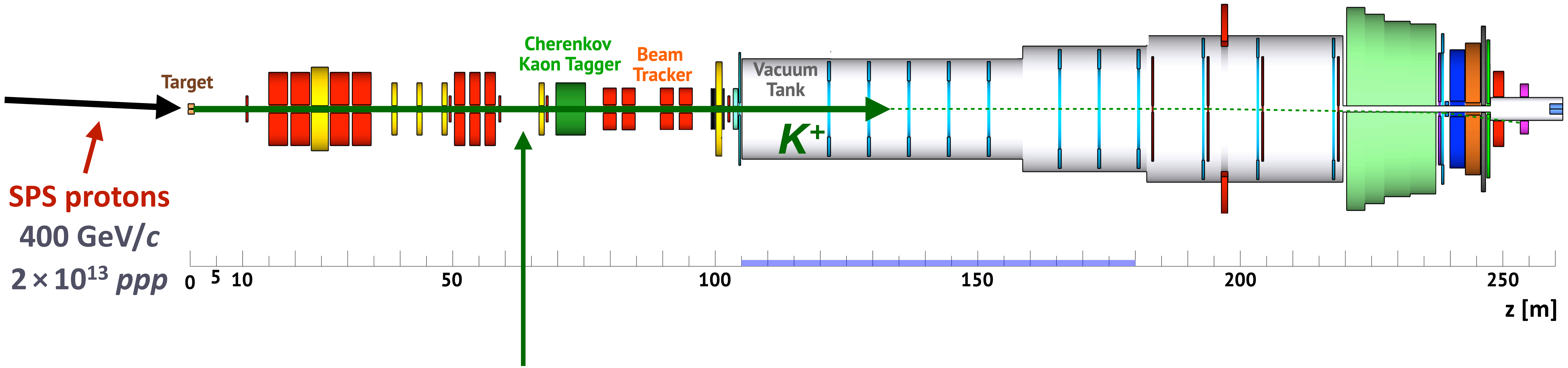


SPS protons
400 GeV/c
2×10^{13} *ppp*

Secondary beam
75 GeV/c, 3 GHz
K^+ (6%), π^+ (70%), p (23%)

The HIKE Detector

Detectors for Secondary Beam
- Cedar for Kaon ID
- Beam Tracker



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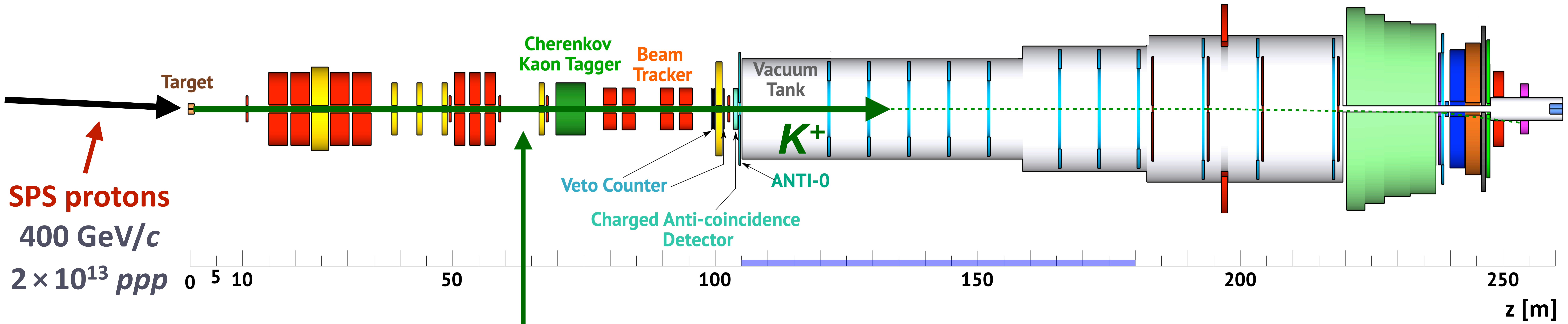

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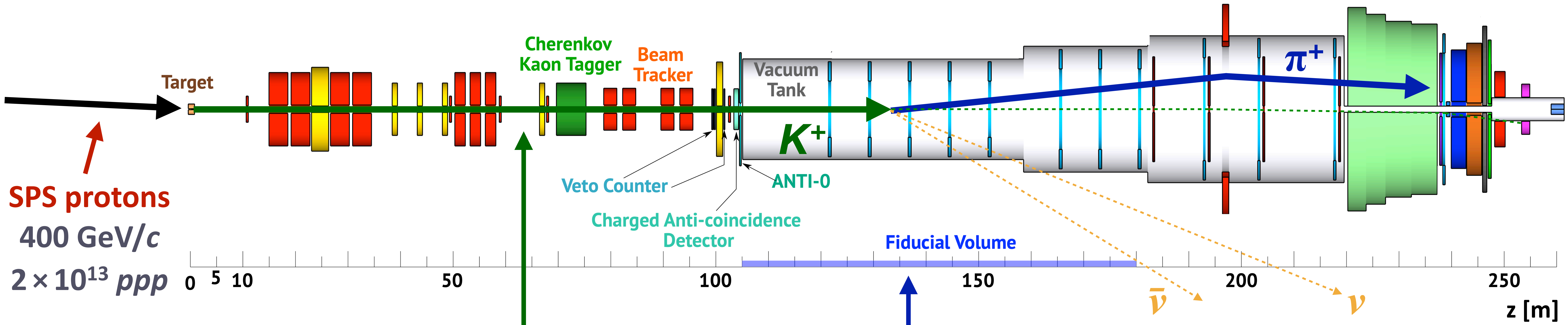

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K^+ decay
75 m long
~ 10 MHz

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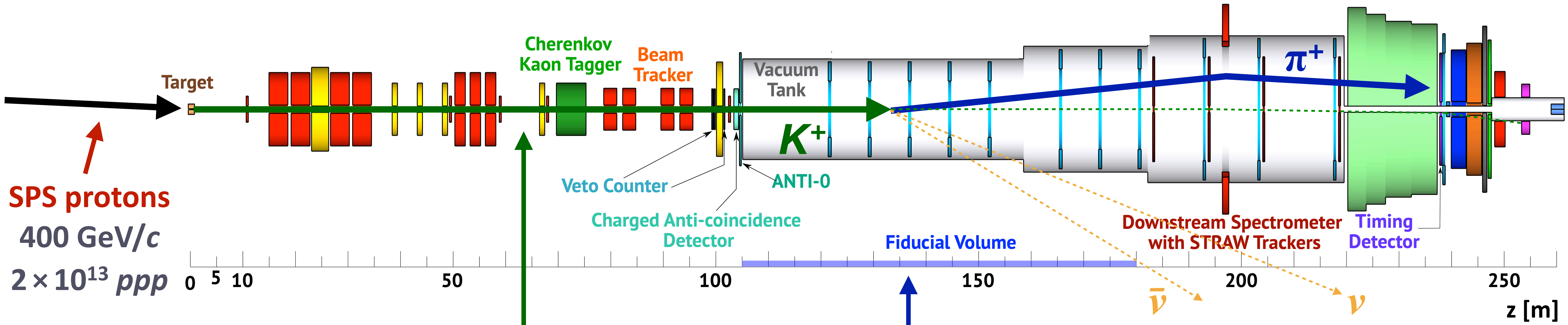

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Detectors for Decay Products
- Charged Particle Tracking & Timing

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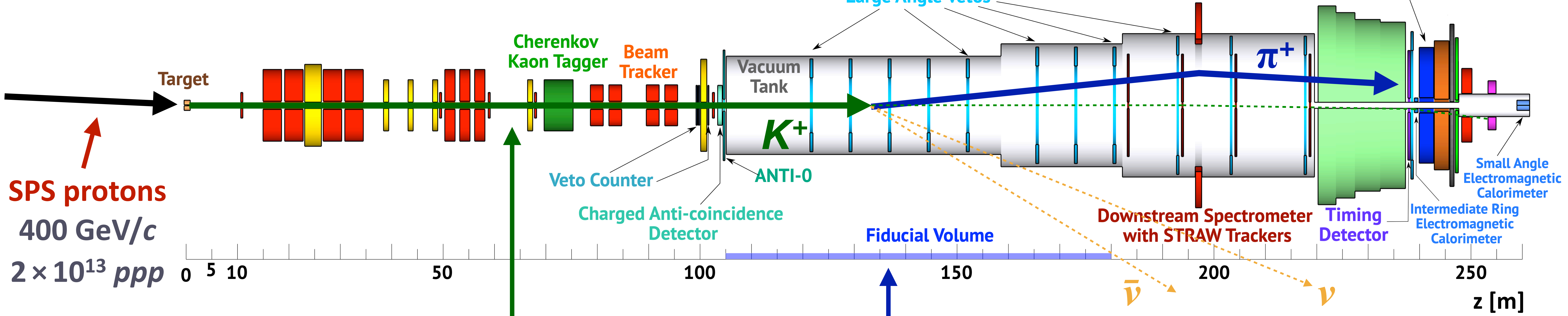
Detectors for Secondary Beam
- Cedar for Kaon ID
- Beam Tracker
- Beam guard veto counter



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Detectors for Decay Products
- Charged Particle Tracking & Timing
- Photon Detection

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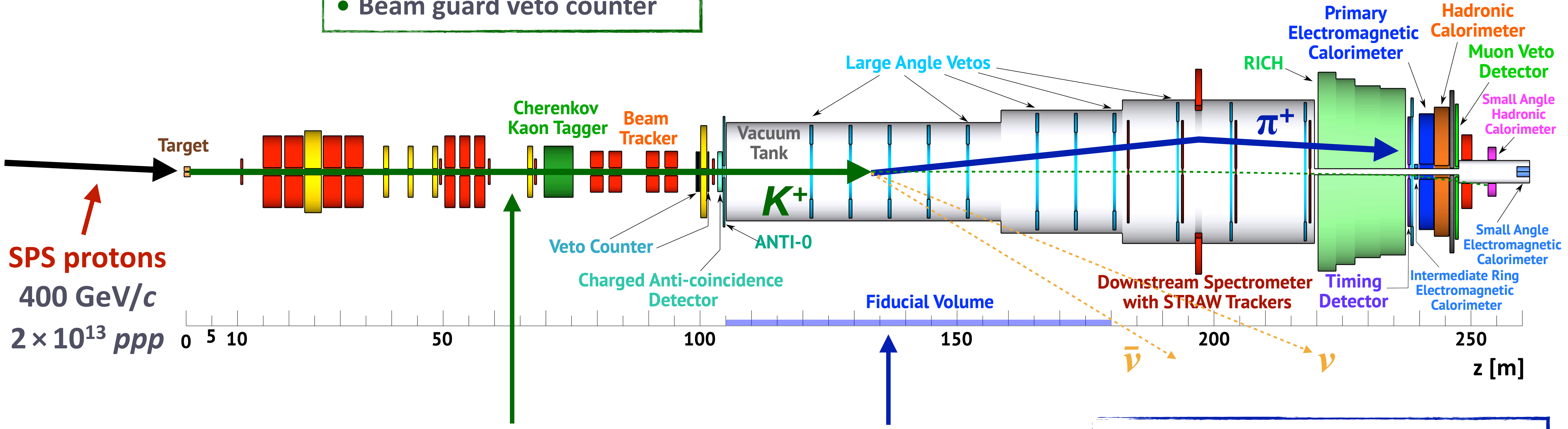

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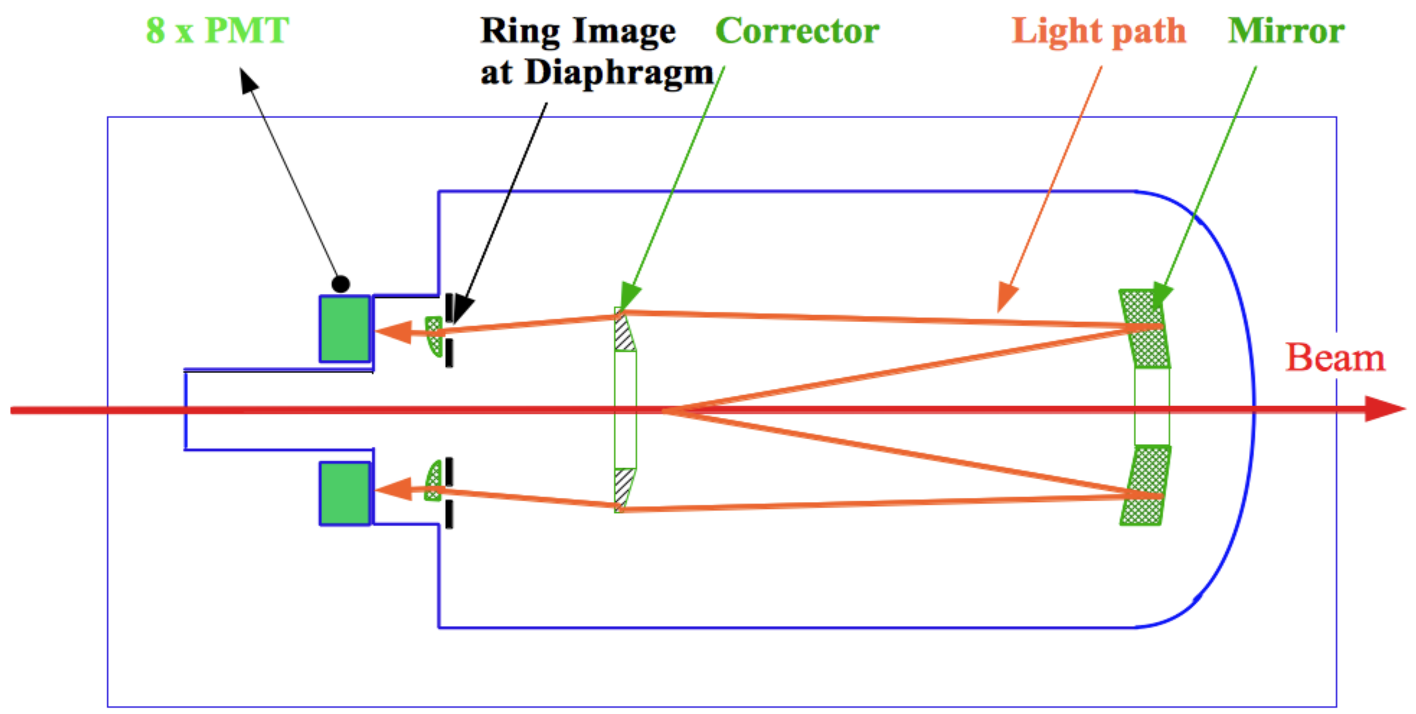
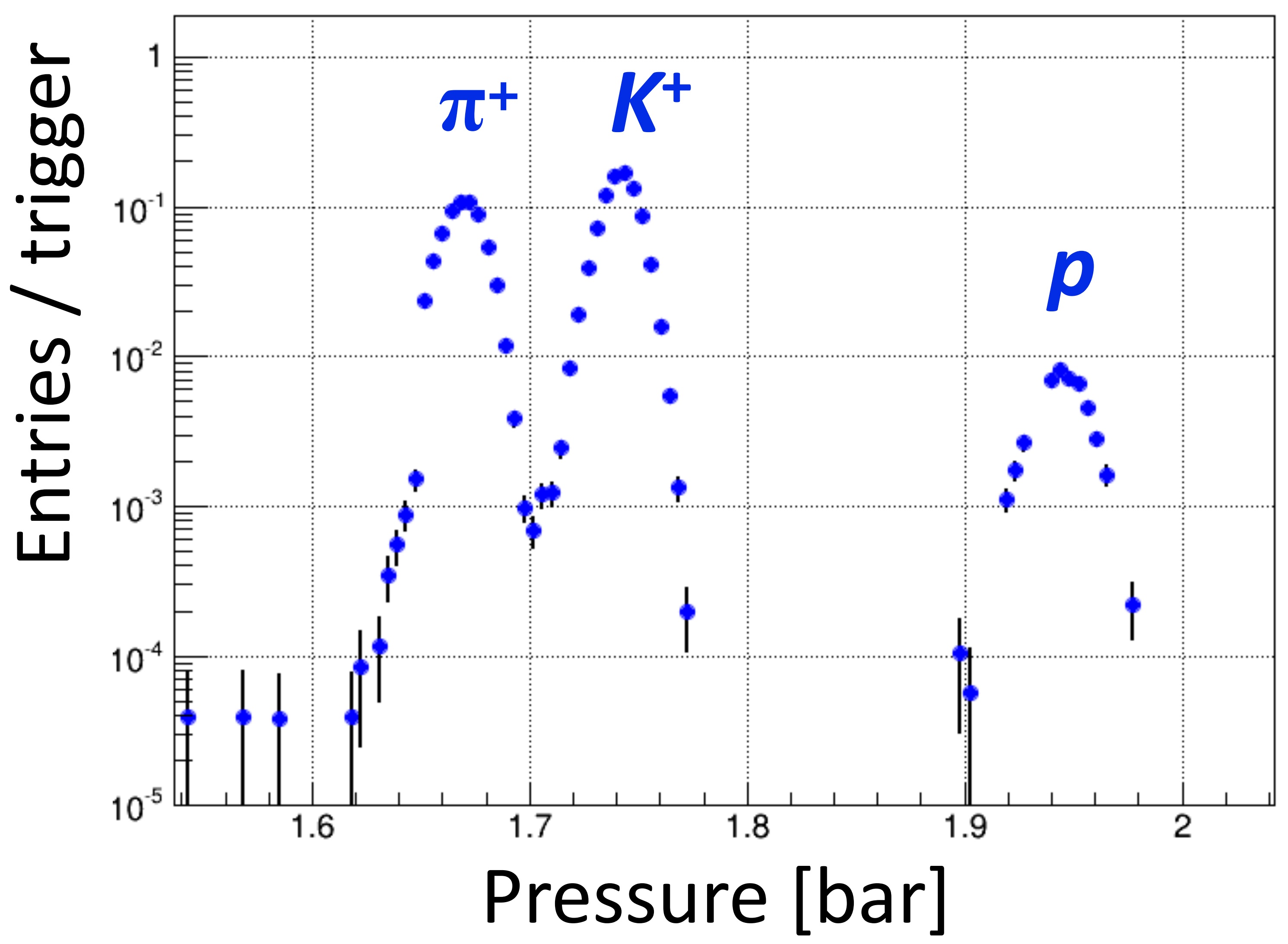
Detectors for Decay Products
- Charged Particle Tracking & Timing
- Photon Detection
- Particle ID

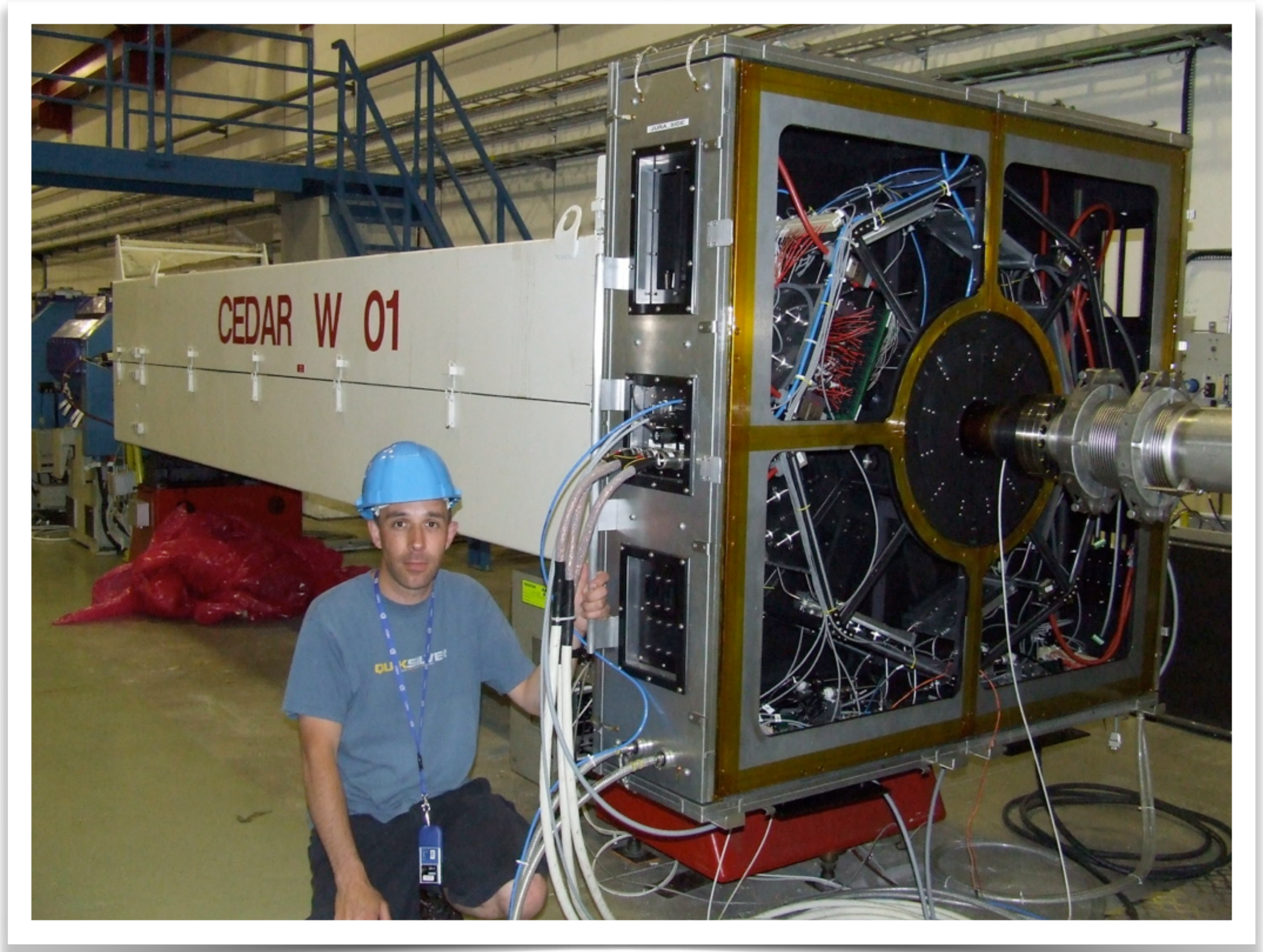
K^+ Identification

CEDAR Counter:

- K^+ have lower velocity than π^+
  ➜ Identification with a **Threshold Cherenkov counter.**
- Cherenkov light is reflected to 8 PMT arrays with 48 PMTs each.







K^+ Momentum Measurement

Beam Tracker:

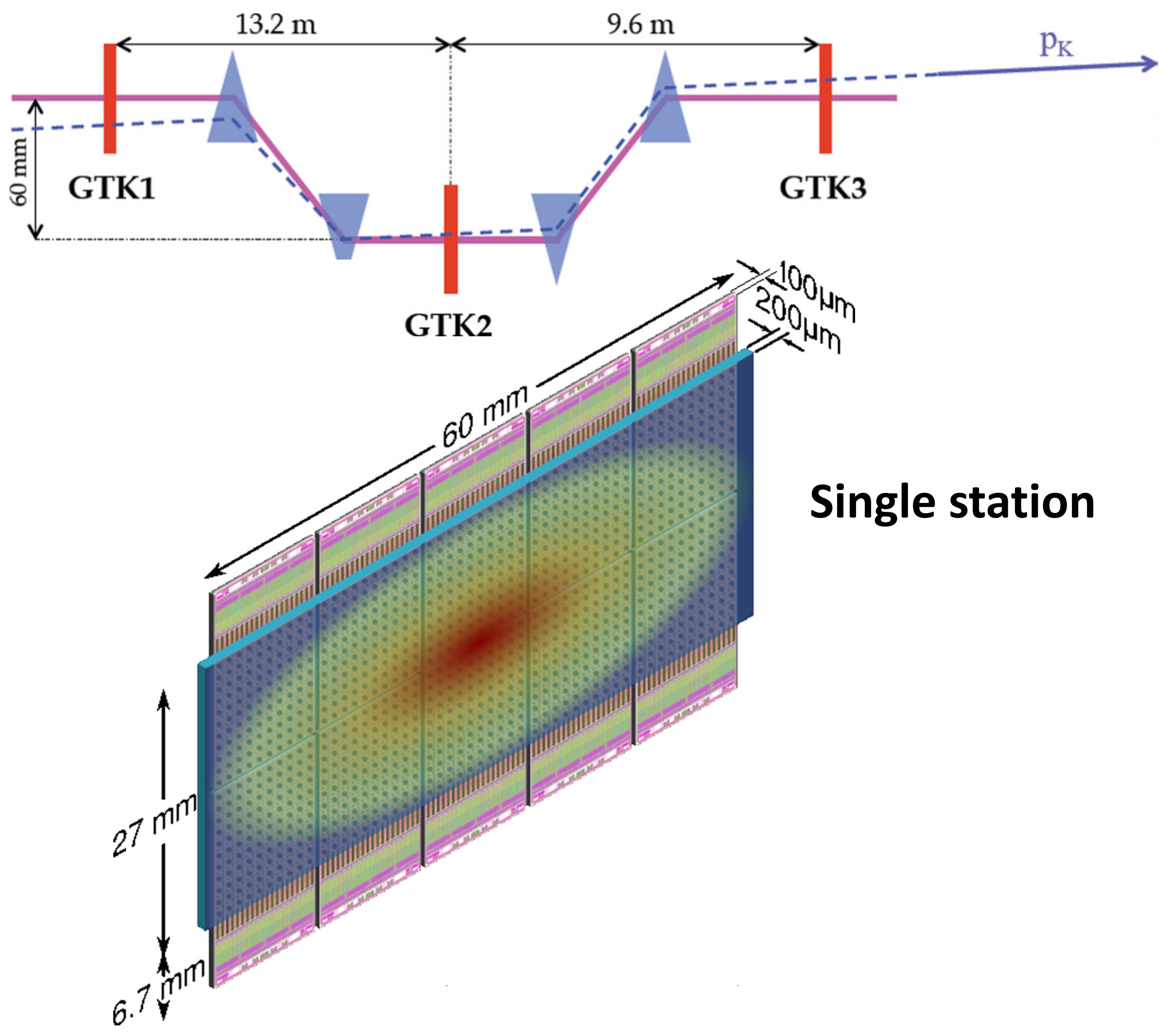
- Four Si-Pixel stations in 3 GHz beam.
- **Similar requirements as NA62 GigaTracker**
  - On-sensor TDC with micro channel cooling
  - X/X_0 **< 0.5%** / station
  - **Momentum resolution ~ 0.2%** (± 0.15 GeV/*c*)

but:

» **4 × time resolution** (200 ps ➞ 50 ps).

» **4 × radiation hardness.**

NA62 GigaTracker



Single station

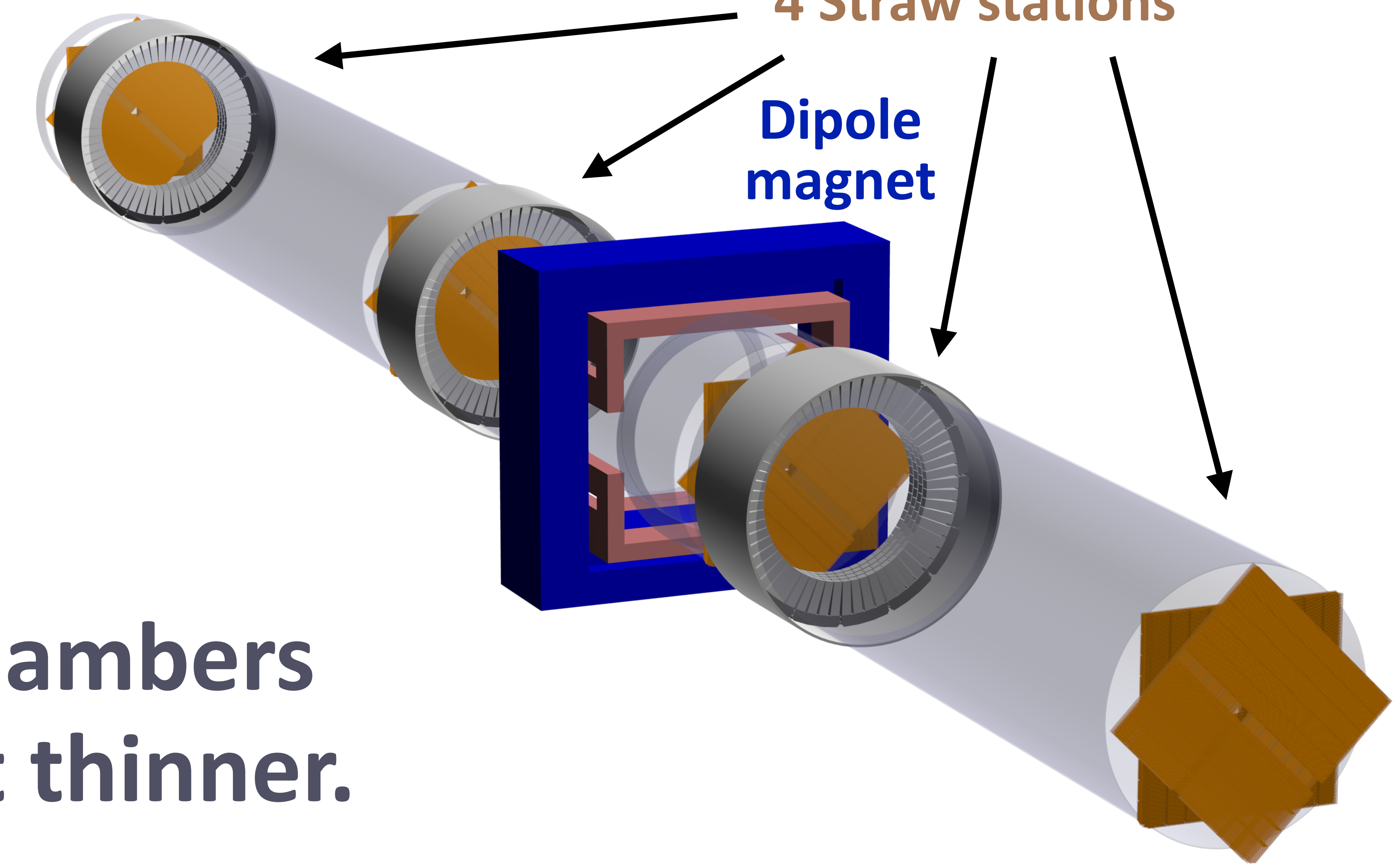
	NA62 GigaTracker	New beam tracker
Single hit time resolution	< 200 ps	< 50 ps
Track time resolution	< 100 ps	< 25 ps
Peak hit rate	2 MHz/mm^2	8 MHz/mm^2

π^+ Momentum Measurement

Straw Spectrometer

- Main requirements:
  - » **Low material budget**
  - » **Very good timing**

➜ **Similar as NA62 Straw Chambers** (straw tubes in vacuum), **but thinner.**



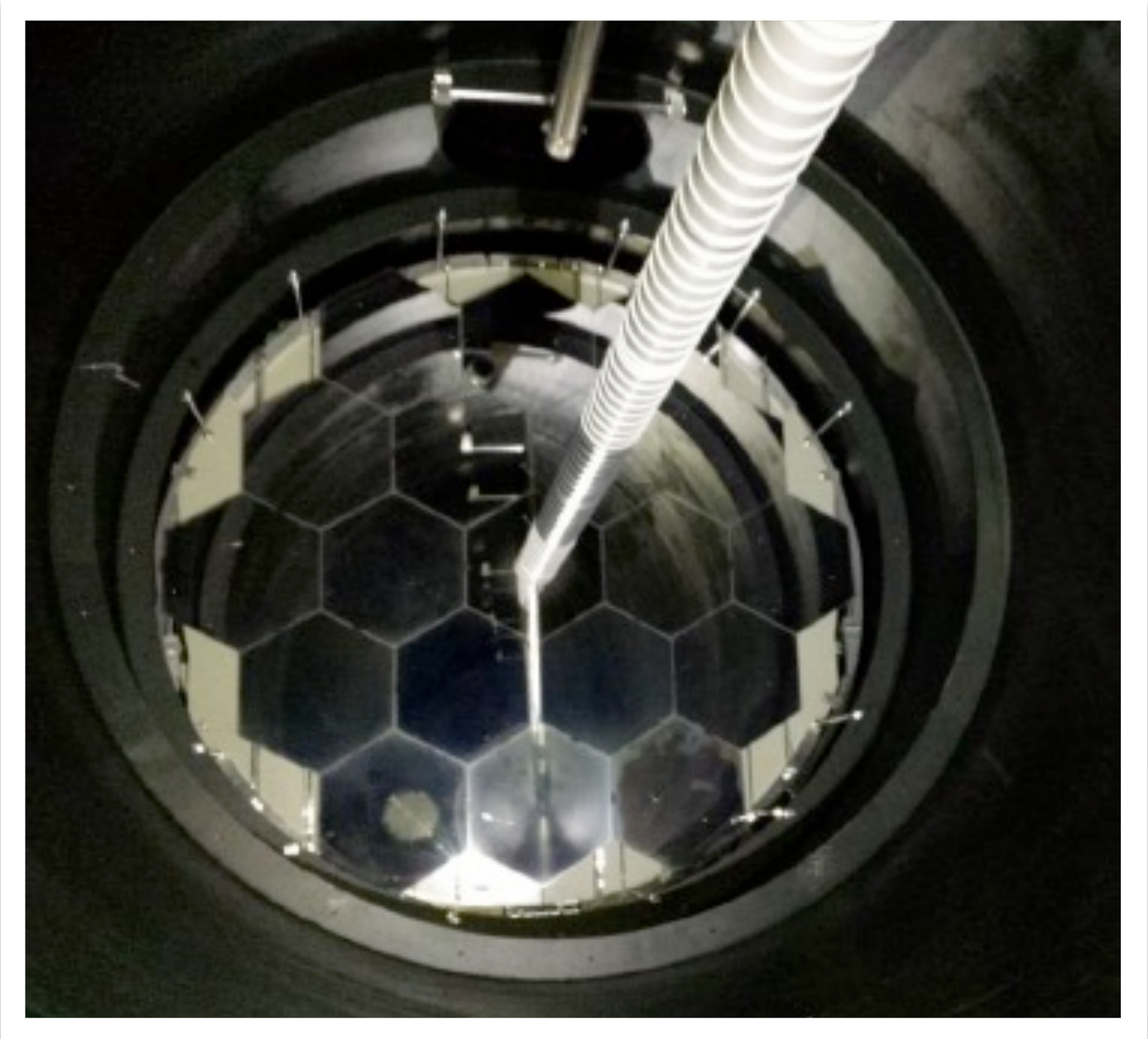
NA62 Straw Station

	Current NA62 spectrometer	HIKE spectrometer
Straw diameter	9.82 mm	4.82 mm
Straw length	2100 mm	2100 mm
Planes per view	4	8
Straws per plane	112	~160
Straws per chamber	1792	~5200
Mylar thickness	36 μm	(12 or 19) μm
Anode wire diameter	30 μm	(20 or 30) μm
Total material budget	1.7% X_0	(1.0 – 1.5)% X_0
Maximum drift time	~150 ns	~80 ns
Hit leading time resolution	(3 – 4) ns	(1 – 4) ns
Hit trailing time resolution	~30 ns	~6 ns
Average number of hits hits per view	2.2	3.1

π^+ Identification (1)

RICH Detector:

- **NA62 RICH** will be kept, but **PMTs → SiPMs.**

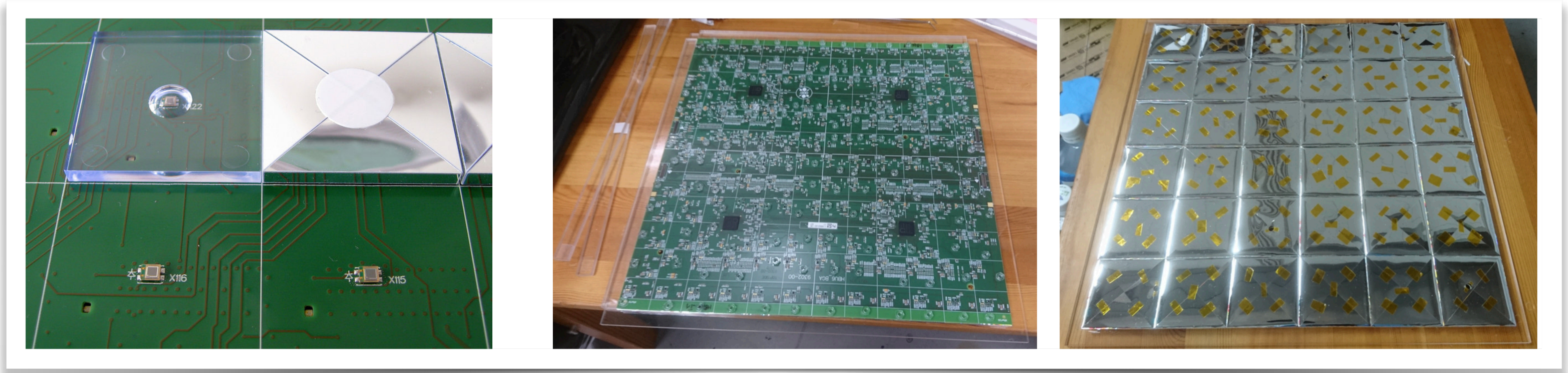


π^+ Identification (2)

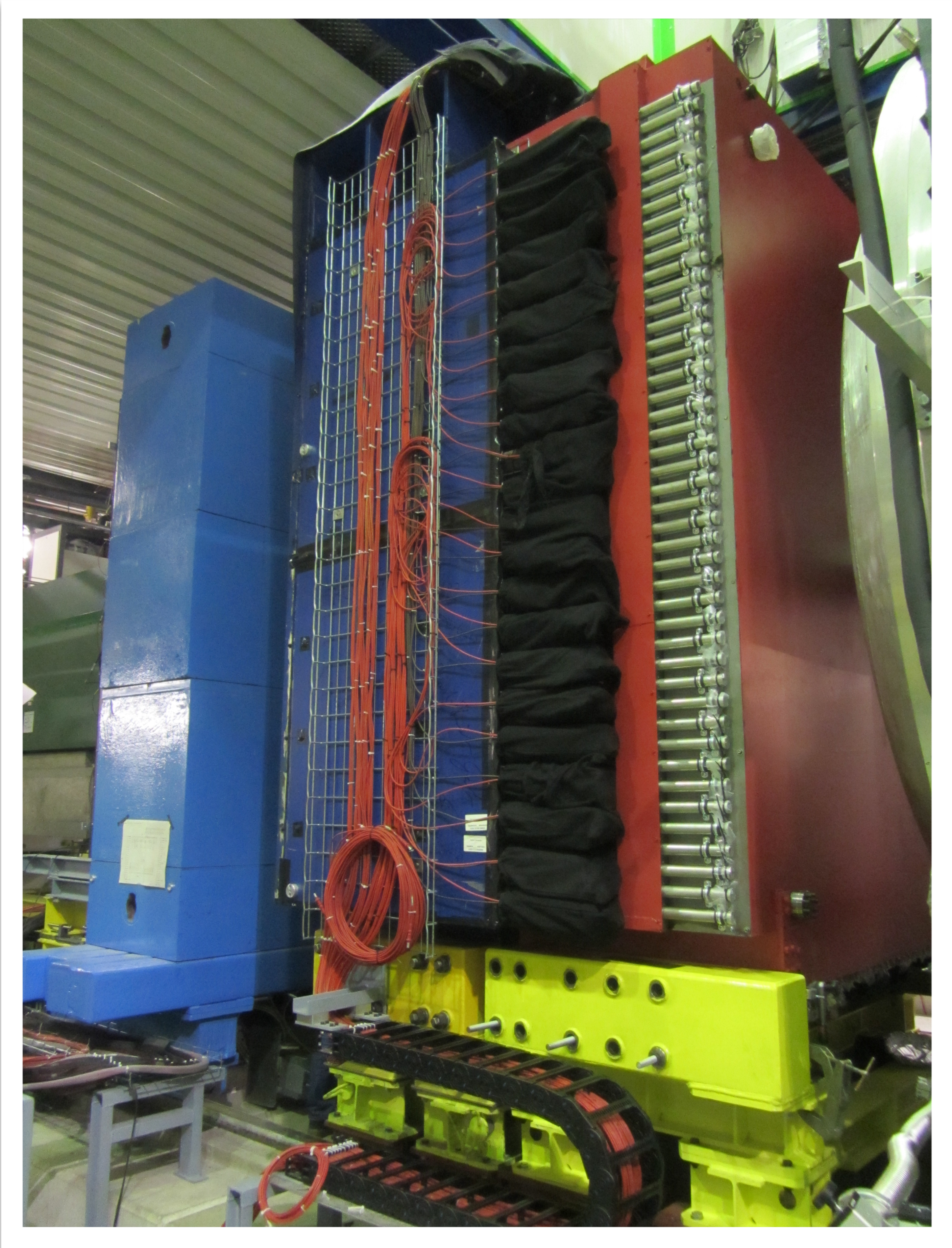
Hadron Calorimeter (HCAL):

- **Iron-scintillator sandwich calorimeter,** but granularity needs to be small because of **high particle rate** (→ *precise timing & small dead-time*).
- **Tile-design** as for ILC calorimeters.

CALICE Analog Hadron Calorimeter



NA62 Hadron Calorimeter



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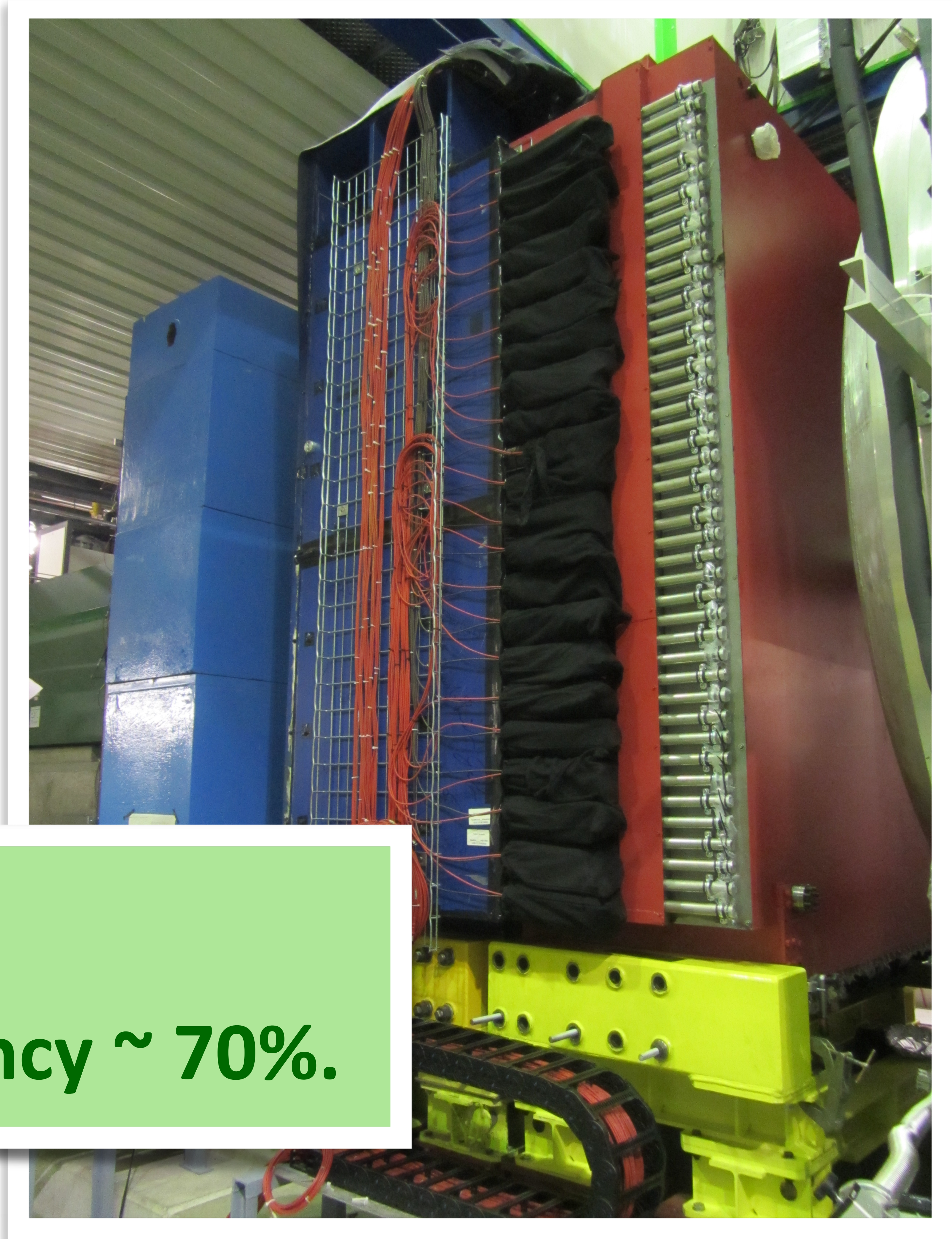
NA62 Hadron Calorimeter



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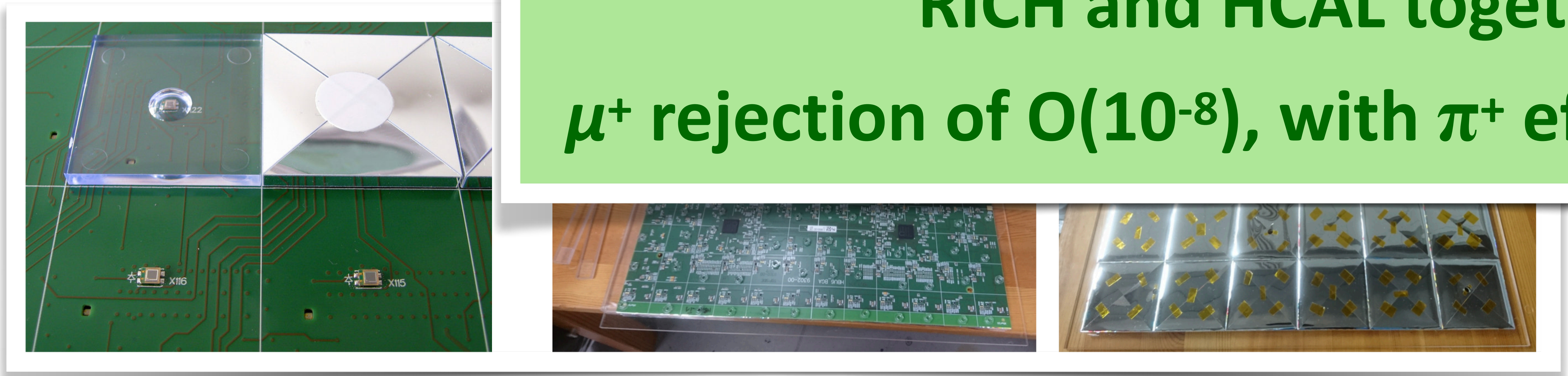


RICH and HCAL together:

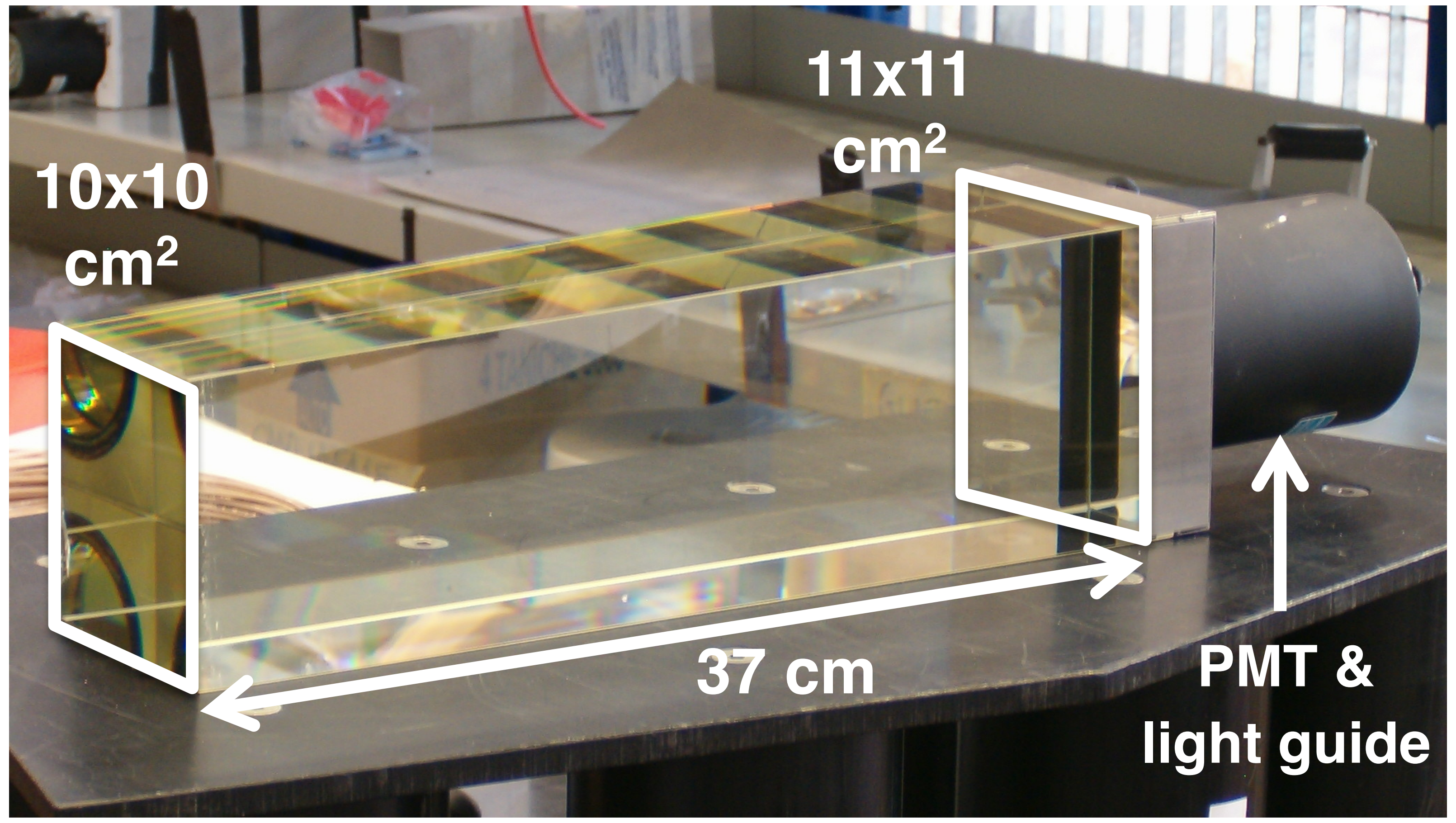
μ^+ rejection of O(10^{-8}), with π^+ efficiency ~ 70%.

Photon Vetoes

Surrounding Large Angle Vetoes:

- **Existing NA62 vetoes,** but a handful of new stations with faster read-out.

OPAL lead glasses



Station 1

Station 12

Photon Vetoes

Electromagnetic Calorimeter

- **Liquid-Krypton (LKr) calorimeter (NA62)** fine, but **time resolution** not excellent.

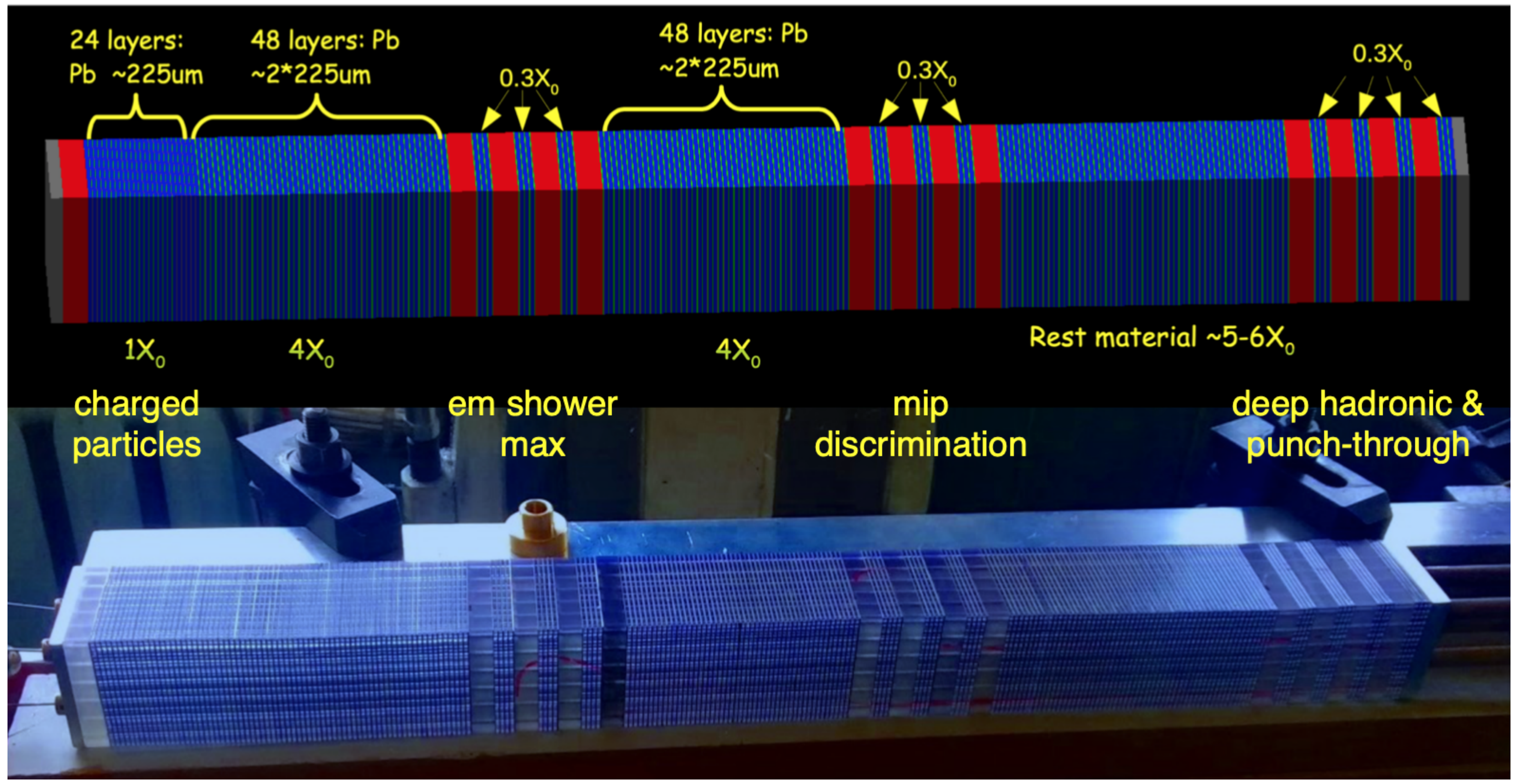
$$\frac{\sigma_E}{E} = 0.0042 \oplus \frac{0.032}{\sqrt{E(\text{GeV})}} \oplus \frac{0.09}{E(\text{GeV})},$$

$$\sigma_{x,y} = 0.06\ \text{cm} \oplus \frac{0.42\ \text{cm}}{\sqrt{E(\text{GeV})}},$$

$$\sigma_t = \frac{2.5\ \text{ns}}{\sqrt{E(\text{GeV})}}.$$

- Feasibility being investigated.

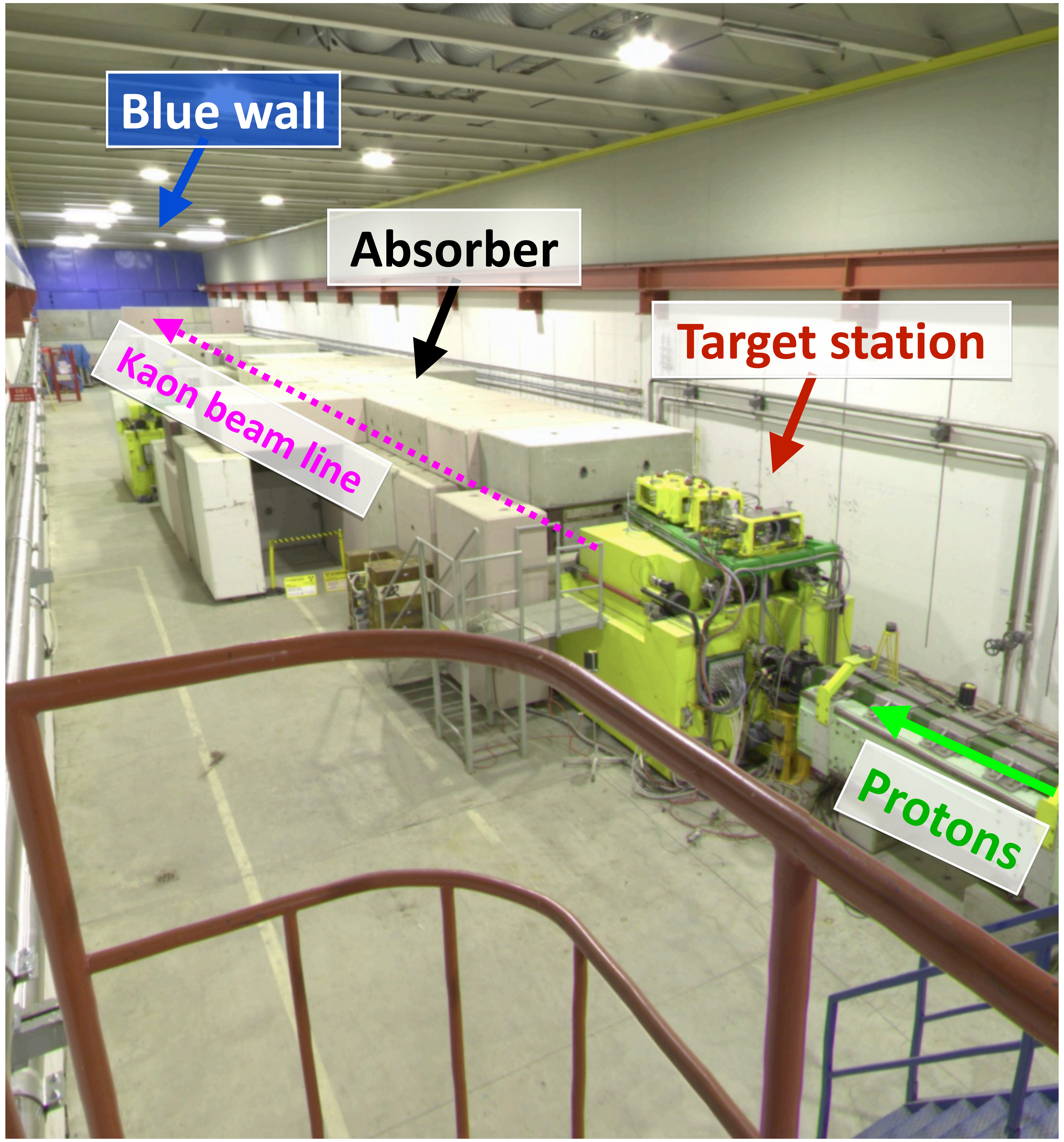
- **Other option:** Development of a **shashlyk calorimeter** in KOPIO/PANDA design.



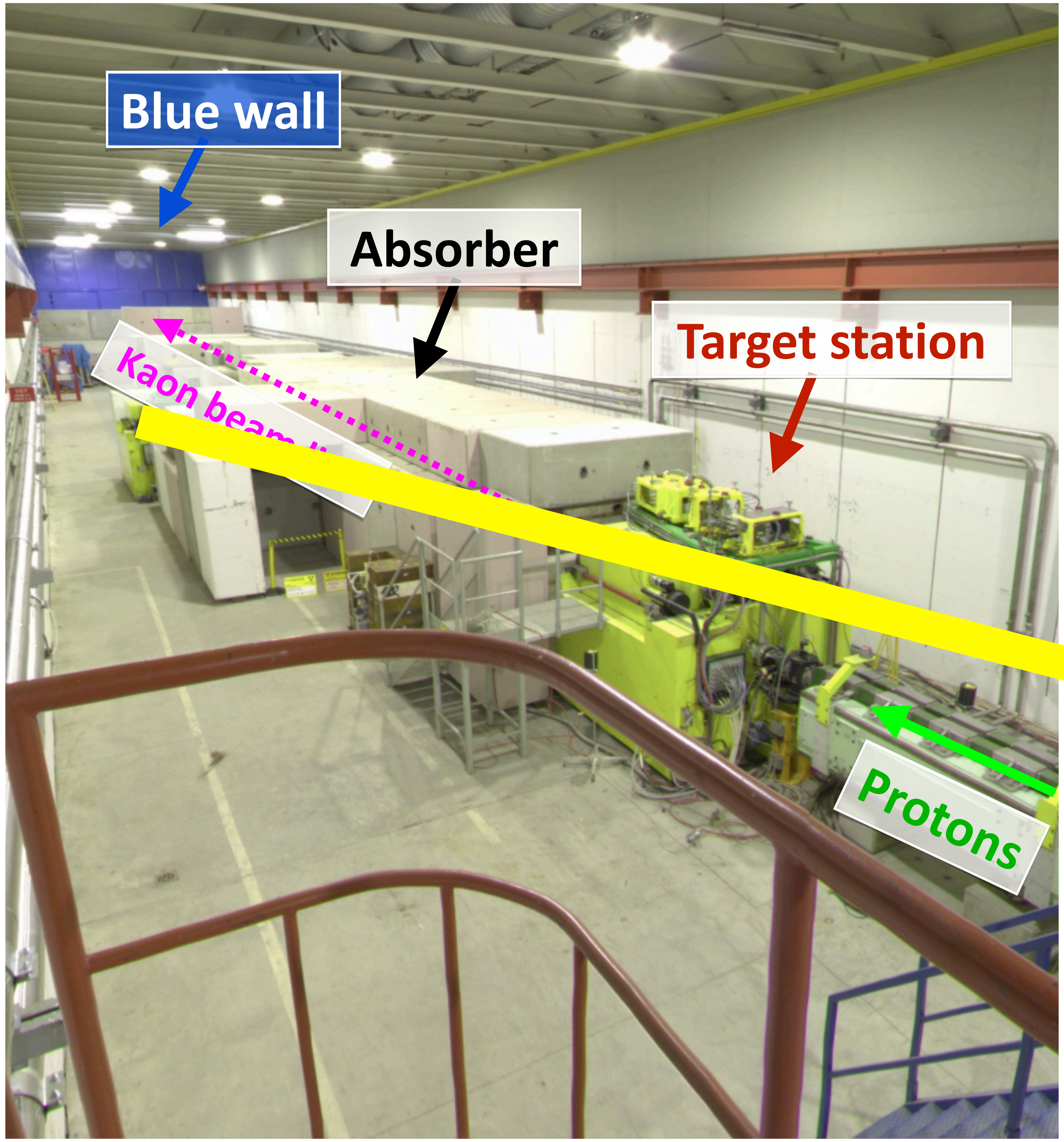
Hall ECN3

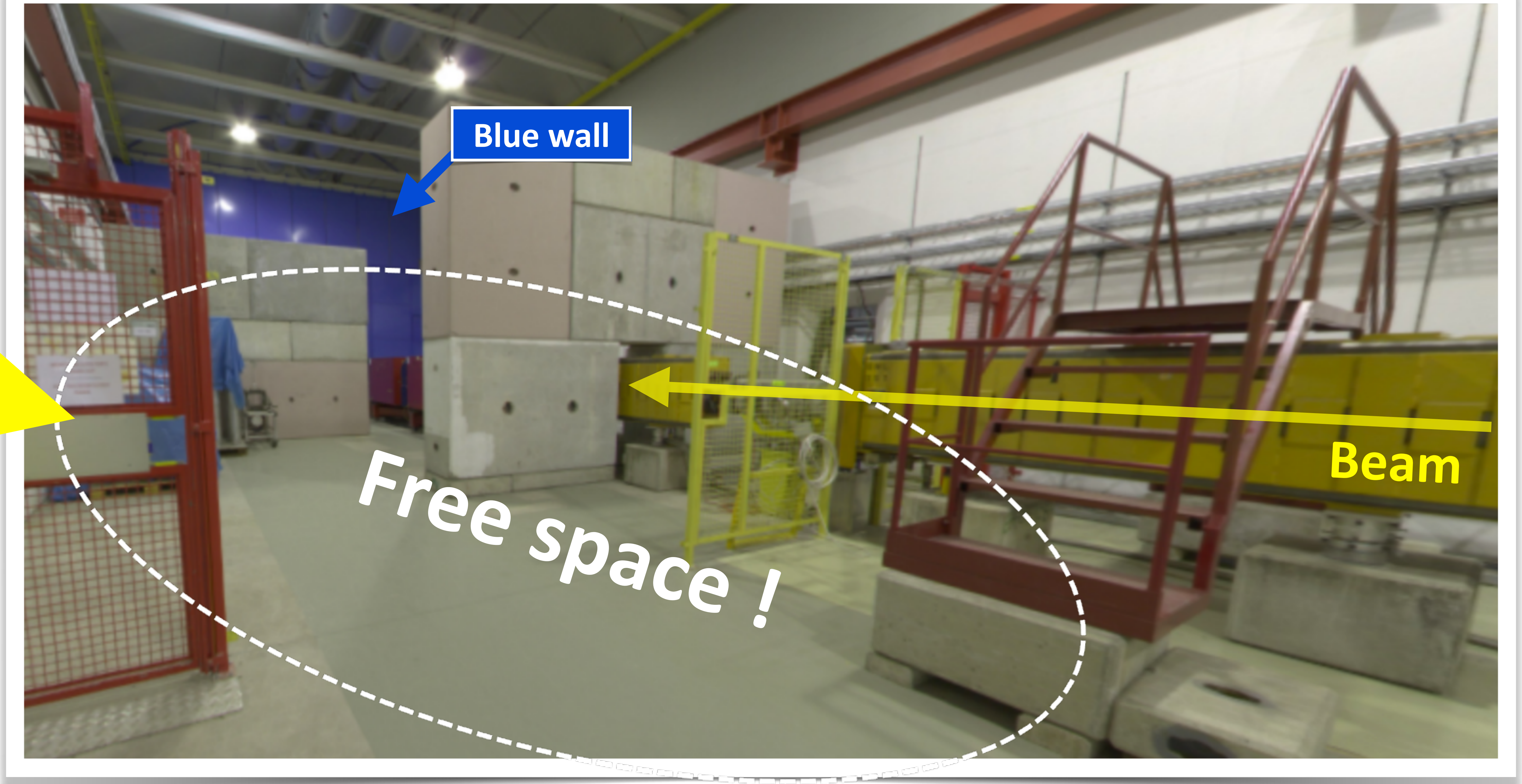

Hall ECN3
NA62/HIKE
100 m
Secondary beam
Beamline TTC8
SHADOWS
Target T10
SPS protons
900
(ECN3)
901
888
891
918
947
978
910
970
971
972
909
912

SHADOWS in HIKE Beam Line



SHADOWS in HIKE Beam Line





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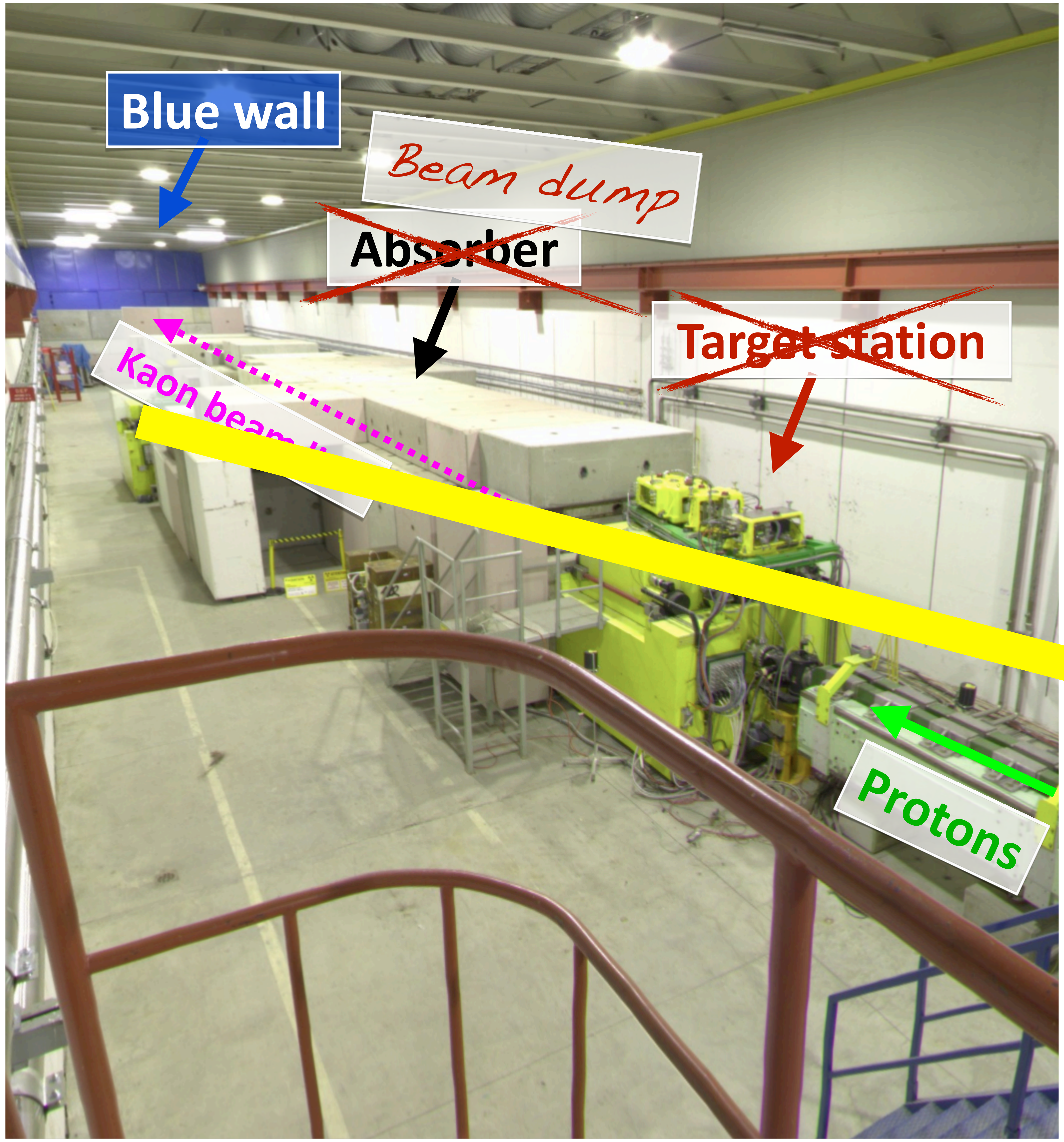
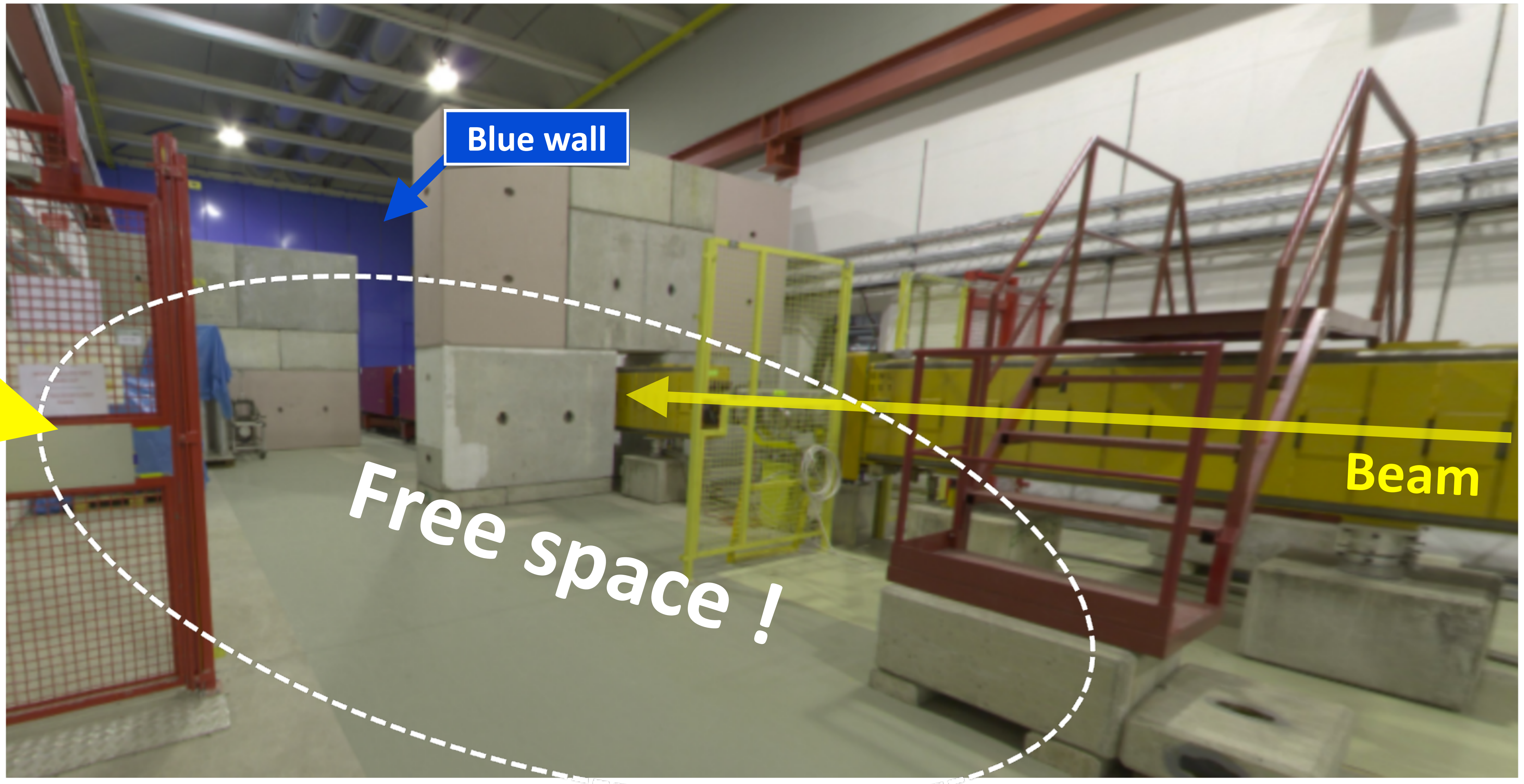
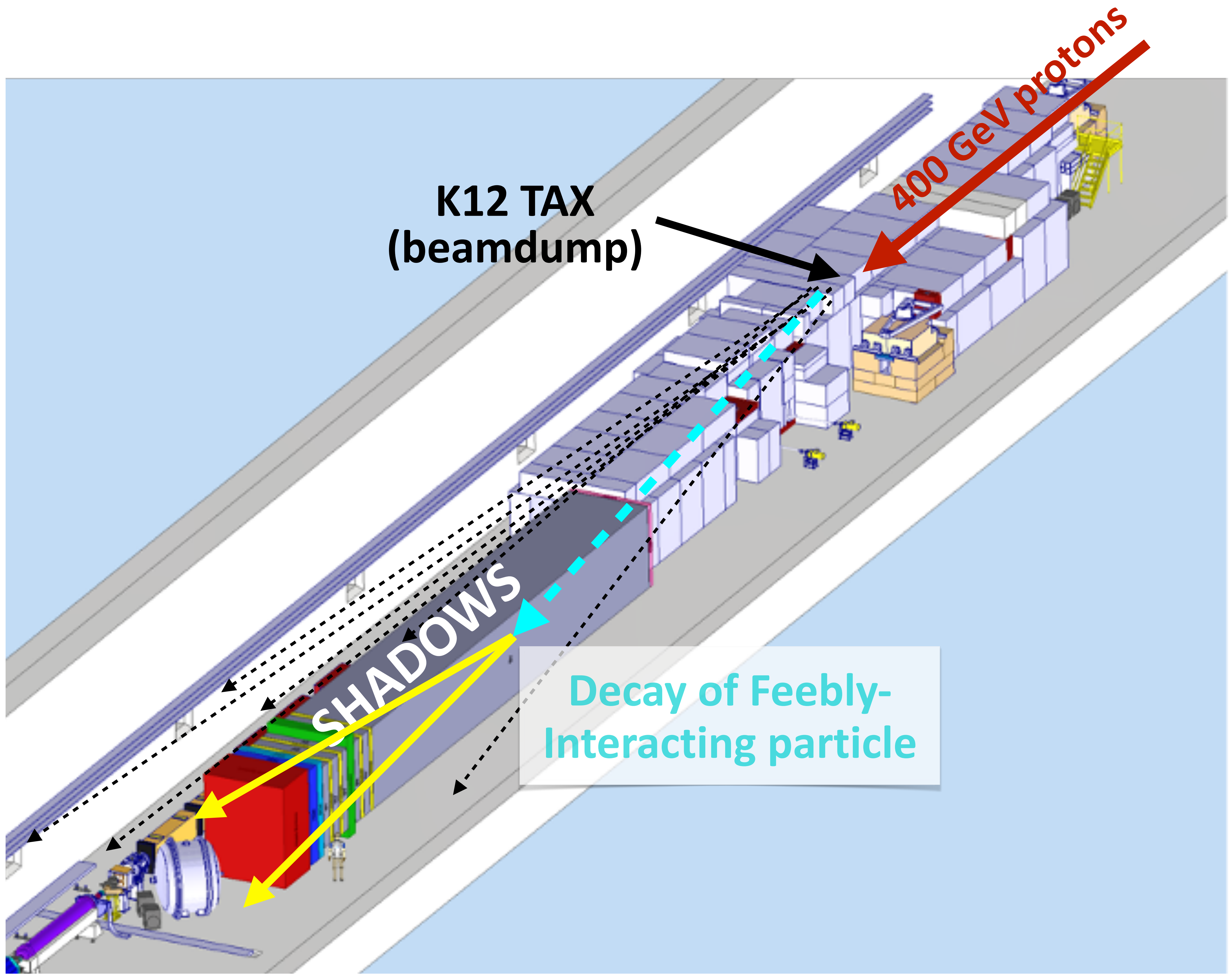


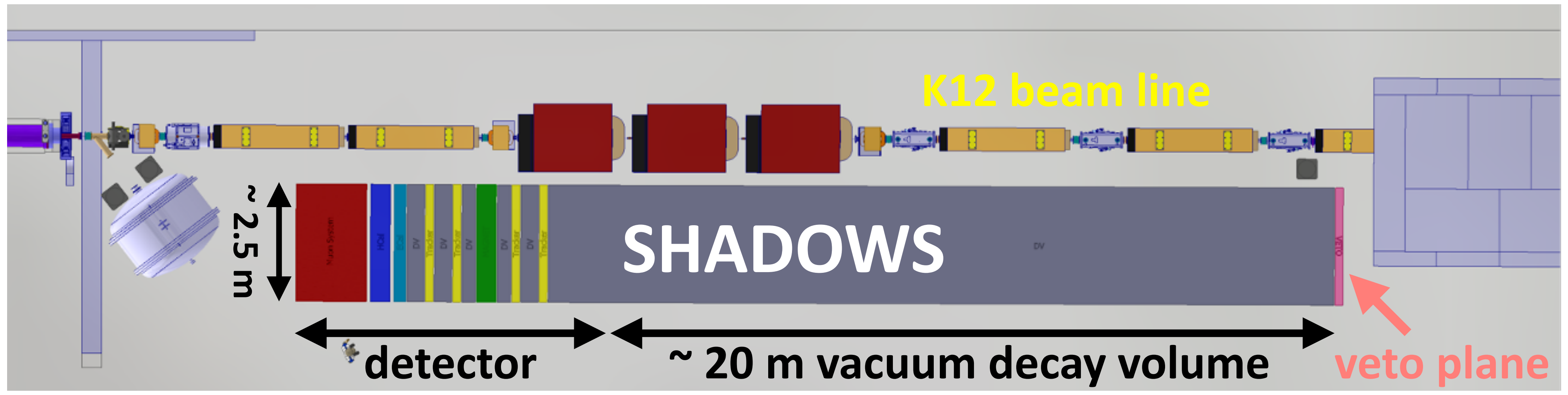


SHADOWS

SHADOWS main ideas:

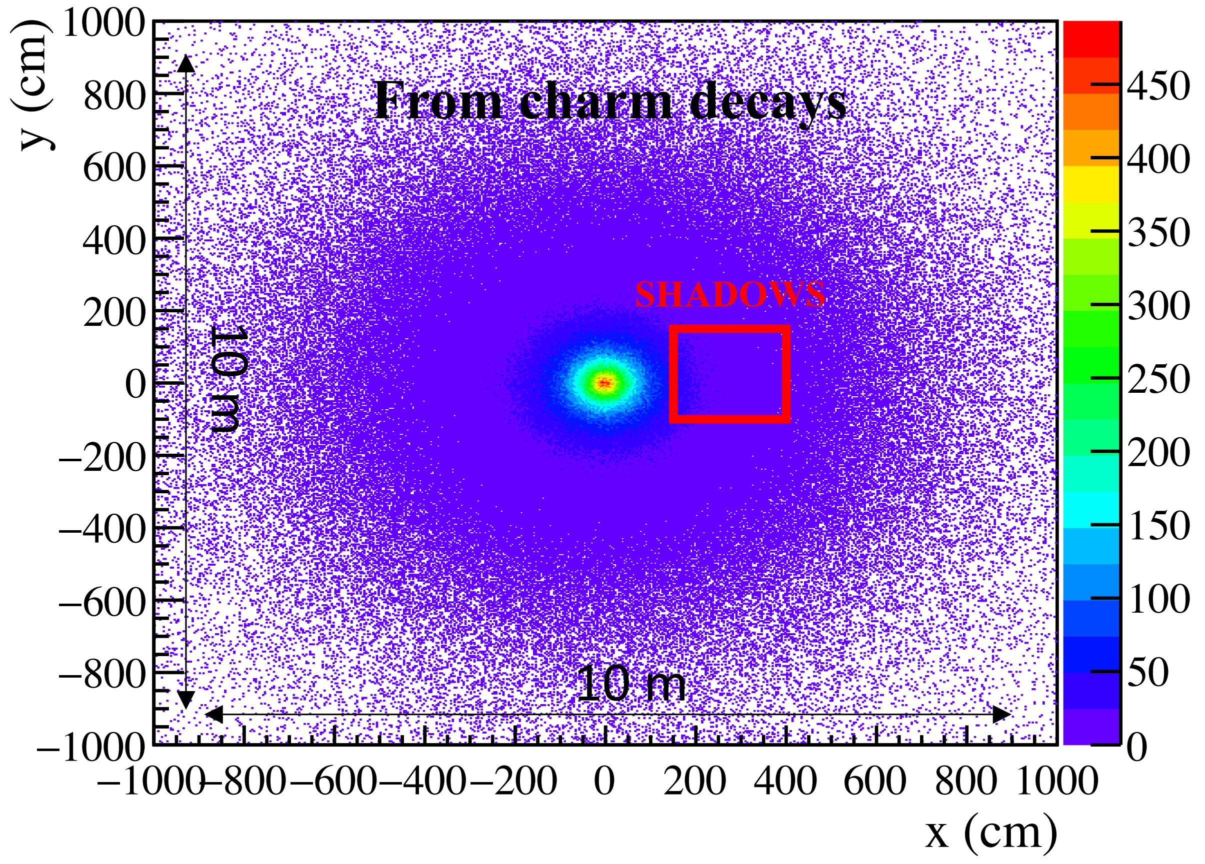
- **Stay close to the dump:**
  ➜ **maximize acceptance for signals** with a relatively small detector.
- **Stay off-axis with respect to the beam line:**
  ➜ **minimize acceptance for background** (mostly peaked forward).
- **Main feature** (w.r.t. other beamdump exp's)**:**
  ➜ **1 m off-axis** w.r.t. main beam-line.

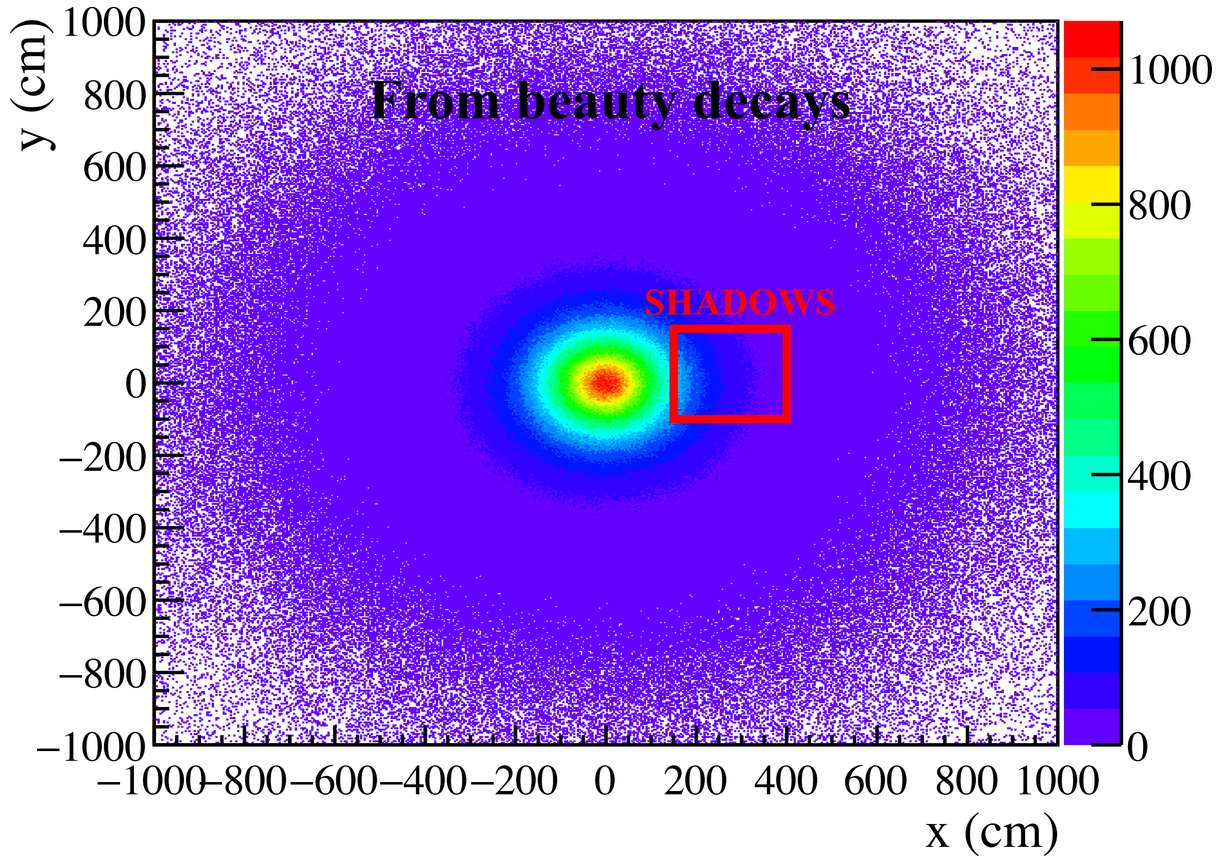




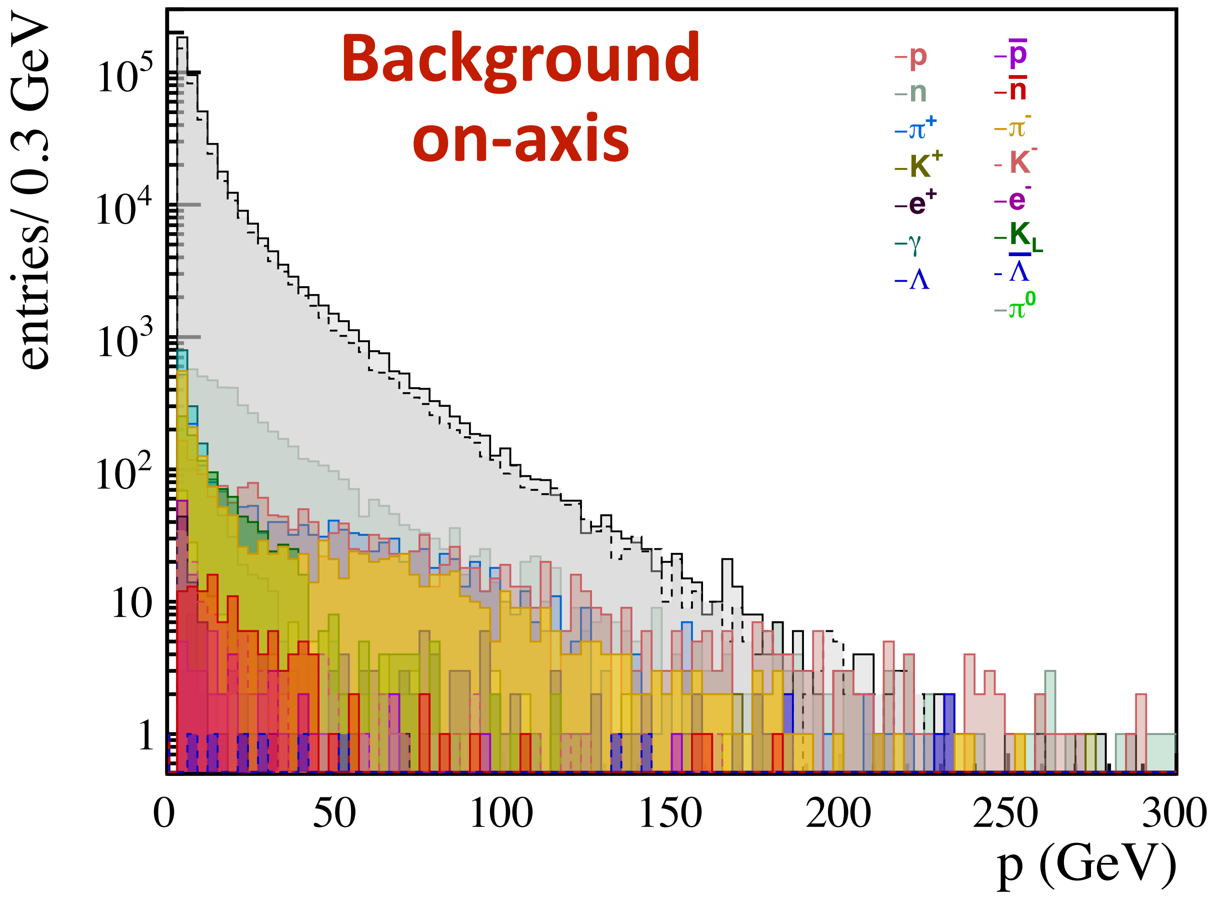
Why „off-axis“ works

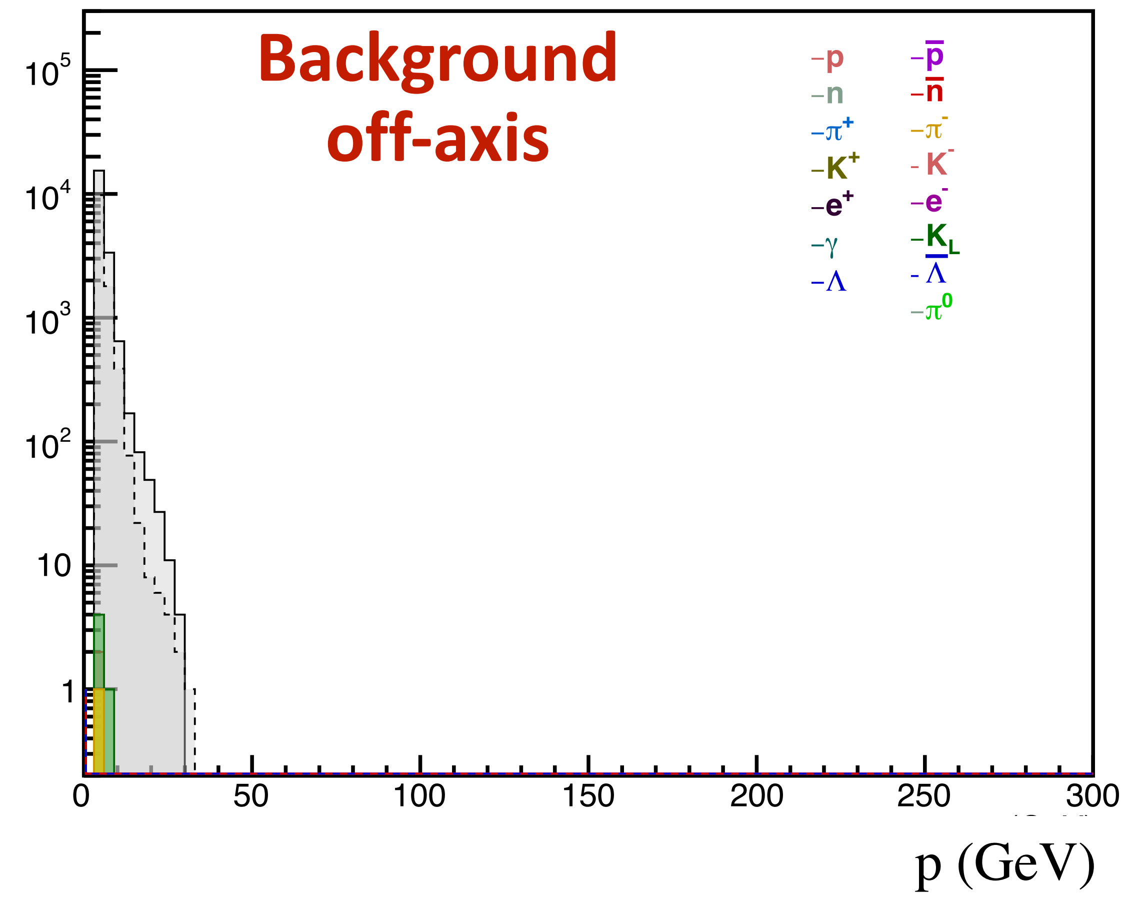
- **FIPs from charm and beauty decays** (HNLs, dark scalars, ALPs,…) are produced with a significant polar angle at the SPS energy.





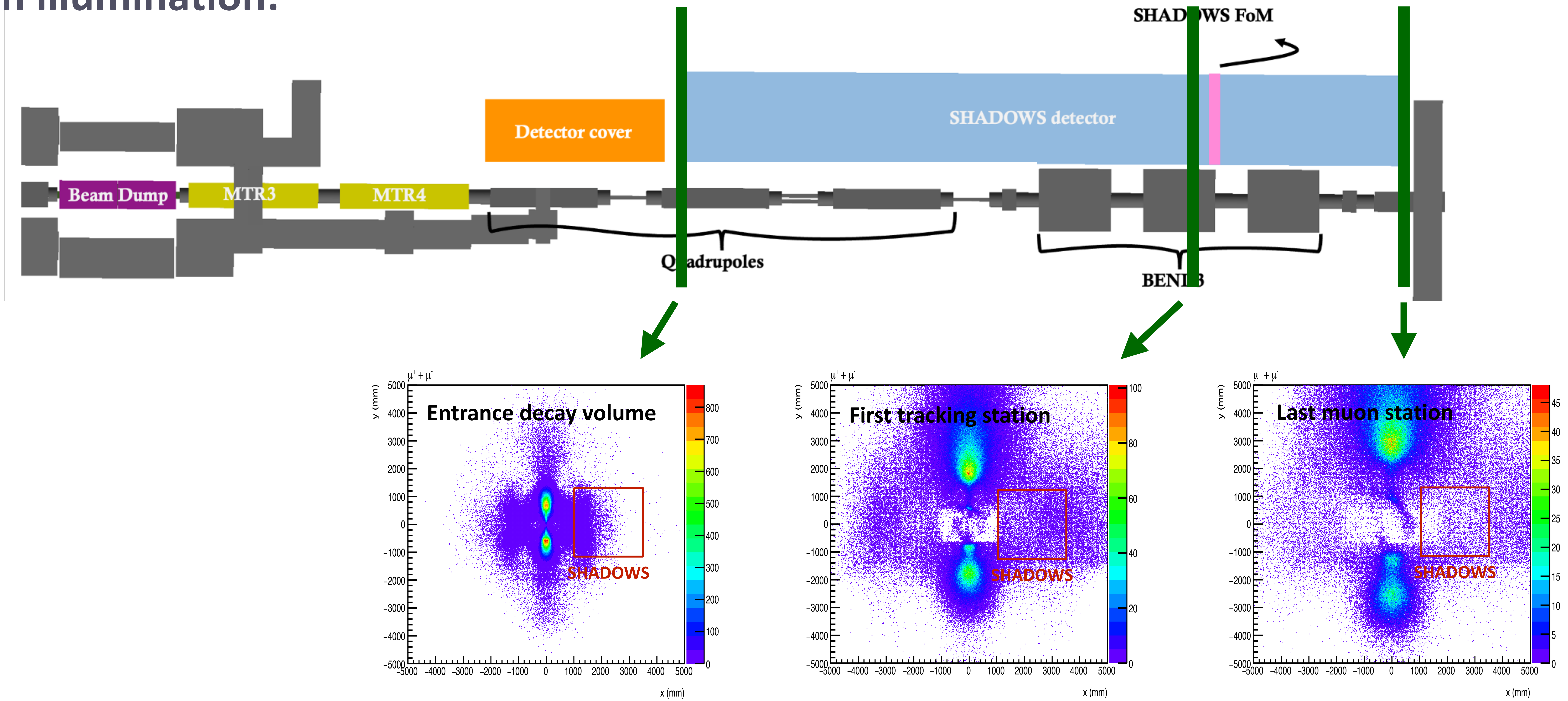
- **Most of the residual background** from the target are muons & neutrinos that are produced in forward direction (and miss SHADOWS acceptance!).



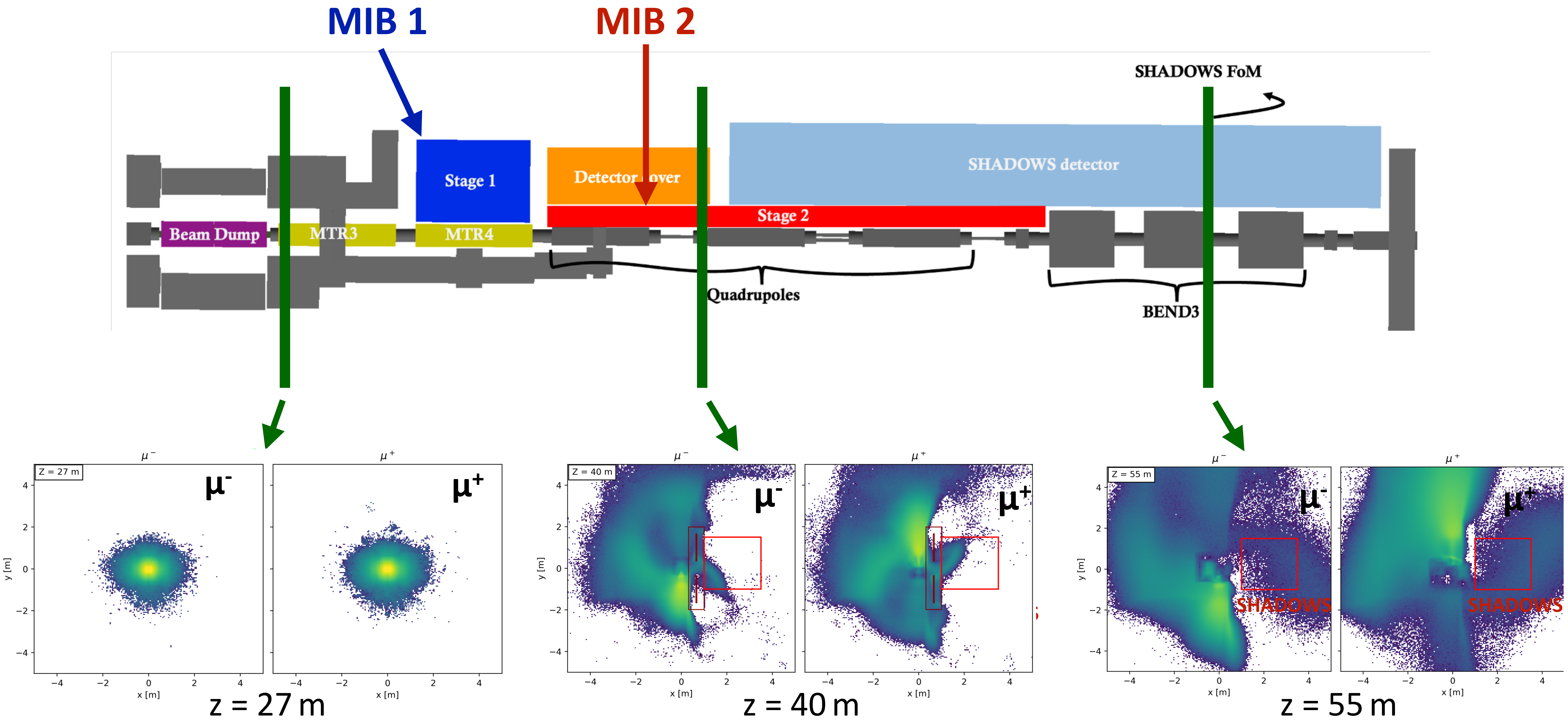


Main Issue is Background Reduction

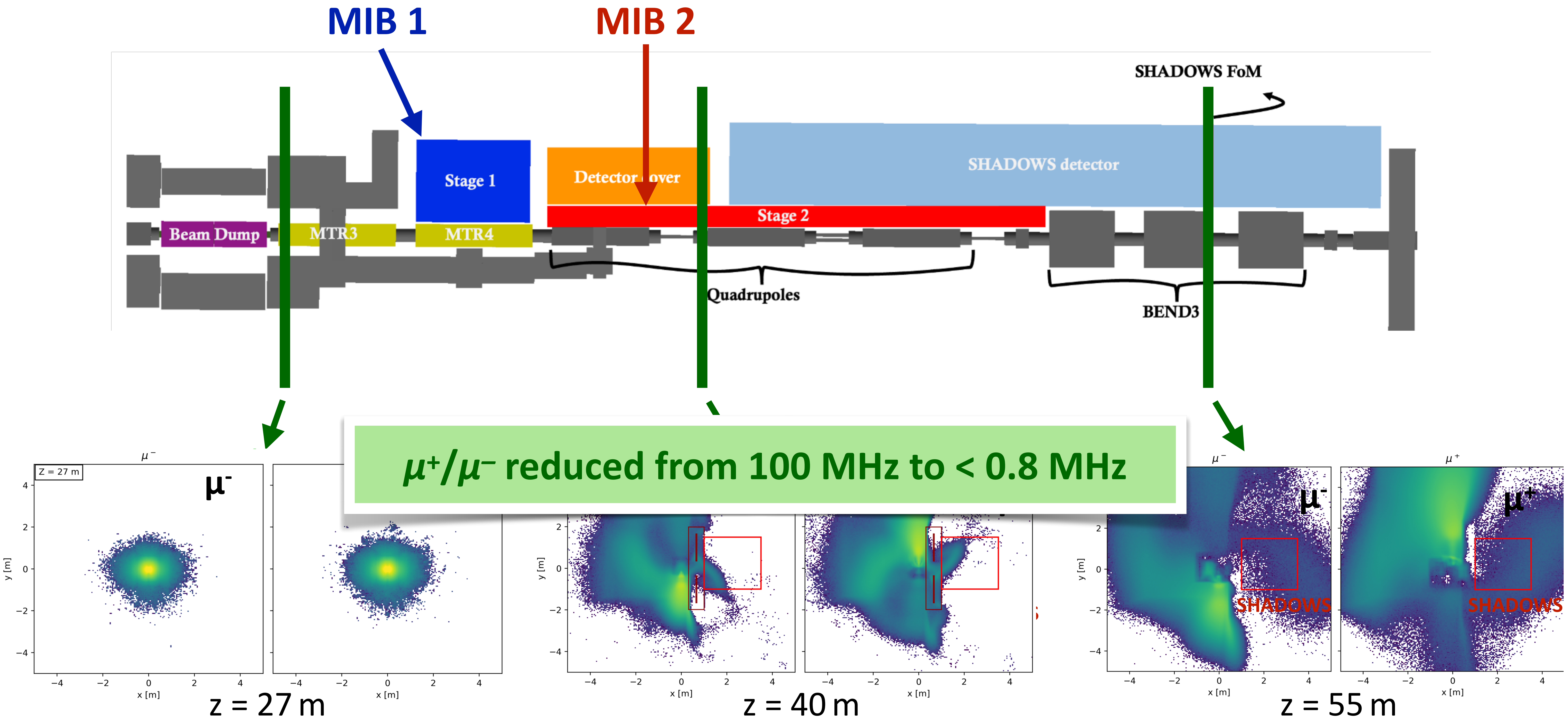
Muon illumination:



Muon Sweeping by two Magnetized Iron Blocks (MIBs)

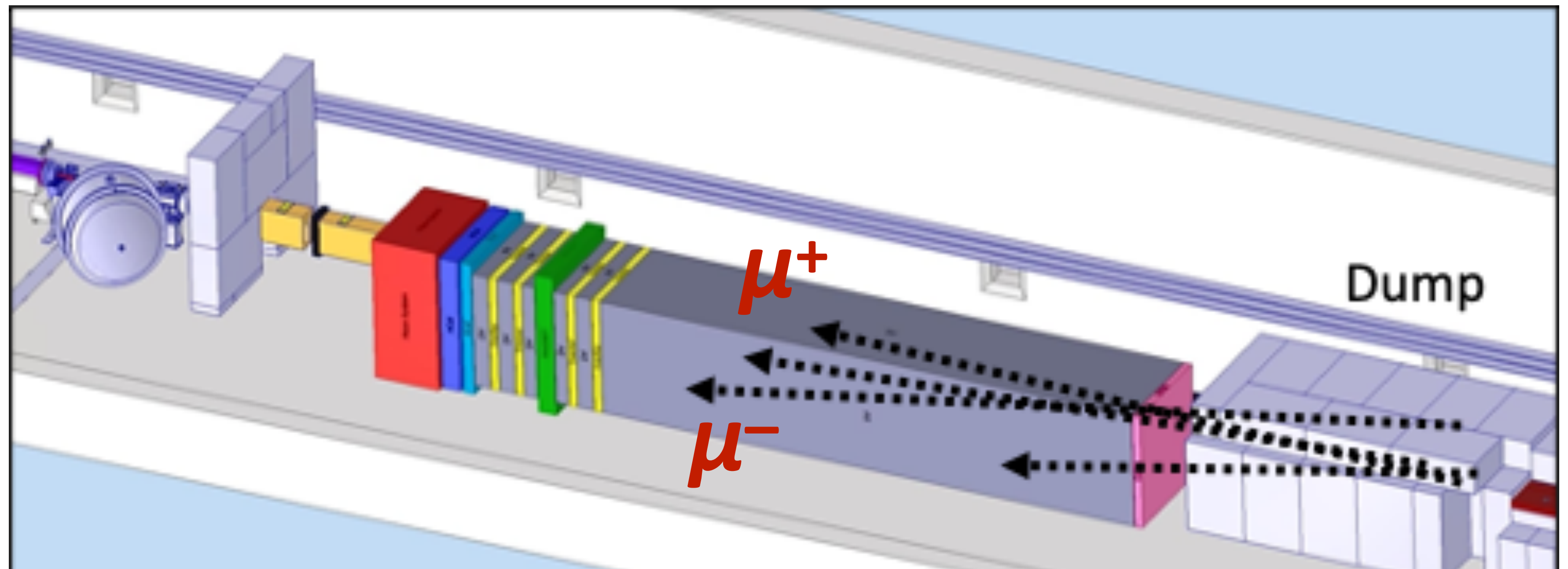


Muon Sweeping by two Magnetized Iron Blocks (MIBs)

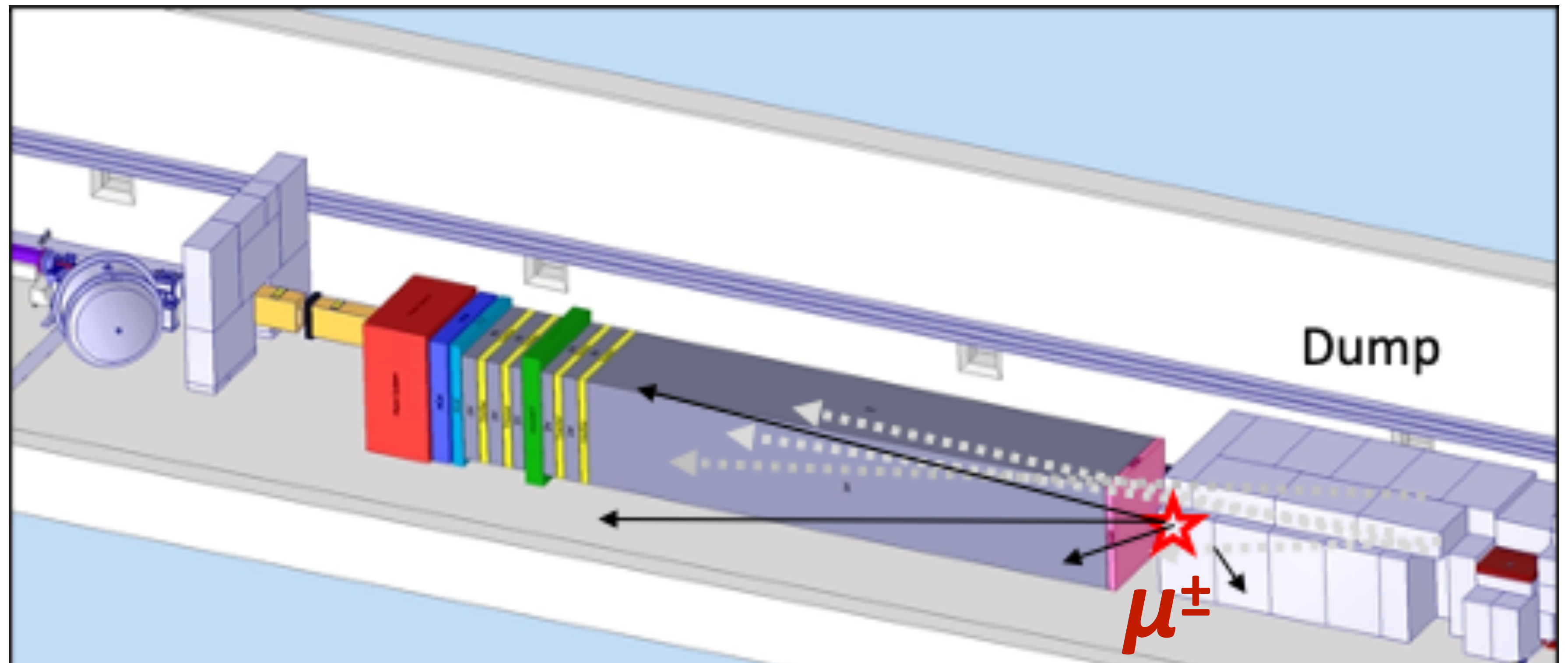


Backgrounds

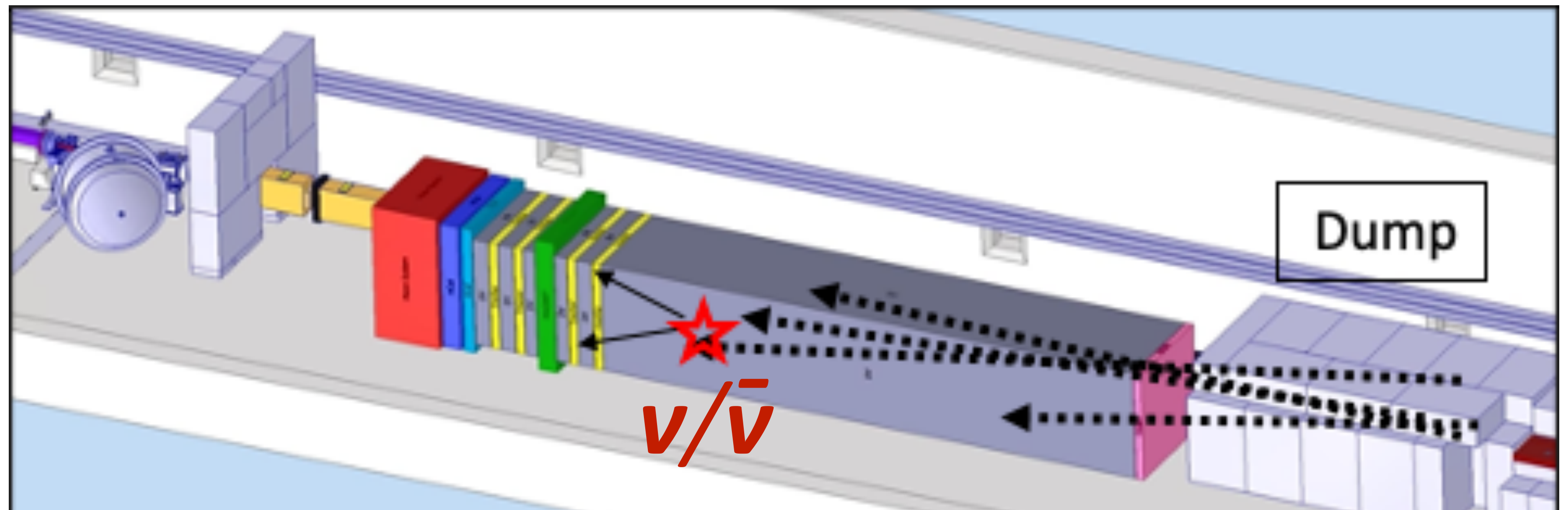
- **Muon combinatorial background** from in-time $\mu^+\mu^-$ **pairs.**
  - MHz rate → **10^{13} $\mu^\pm$** in SHADOWS lifetime!
  - But: Rate of coincidences small.
  - ➜ **$N_{\mu\mu}$ = 0.7 events for 5×10^{19} pot**
- **Muon inelastic interactions** in dump, MIB, and beamline elements.
  - ➜ **$N_{\mu(\text{inelast. int.})} = 0$ for 10^9 pot**
- **Neutrino inelastic interactions** in decay volume.
  - ➜ **$N_{\nu/\bar{\nu}\,(\text{inelast. int.})} \leq 1$ event for 5×10^{19} pot**



In-time $\mu^+\mu^-$ pair



Inelastic $\mu^\pm$ interaction



Inelastic $\nu,\bar{\nu}$ interaction

Backgrounds

- **Muon combinatorial background** from in-time $\mu^+\mu^-$ **pairs.**
  - MHz rate → **10^{13} $\mu^\pm$** in SHADOWS lifetime!
  - But: Rate of coincidences small.
  - ➜ **$N_{\mu\mu}$ = 0.7 events for 5×10^{19} pot**
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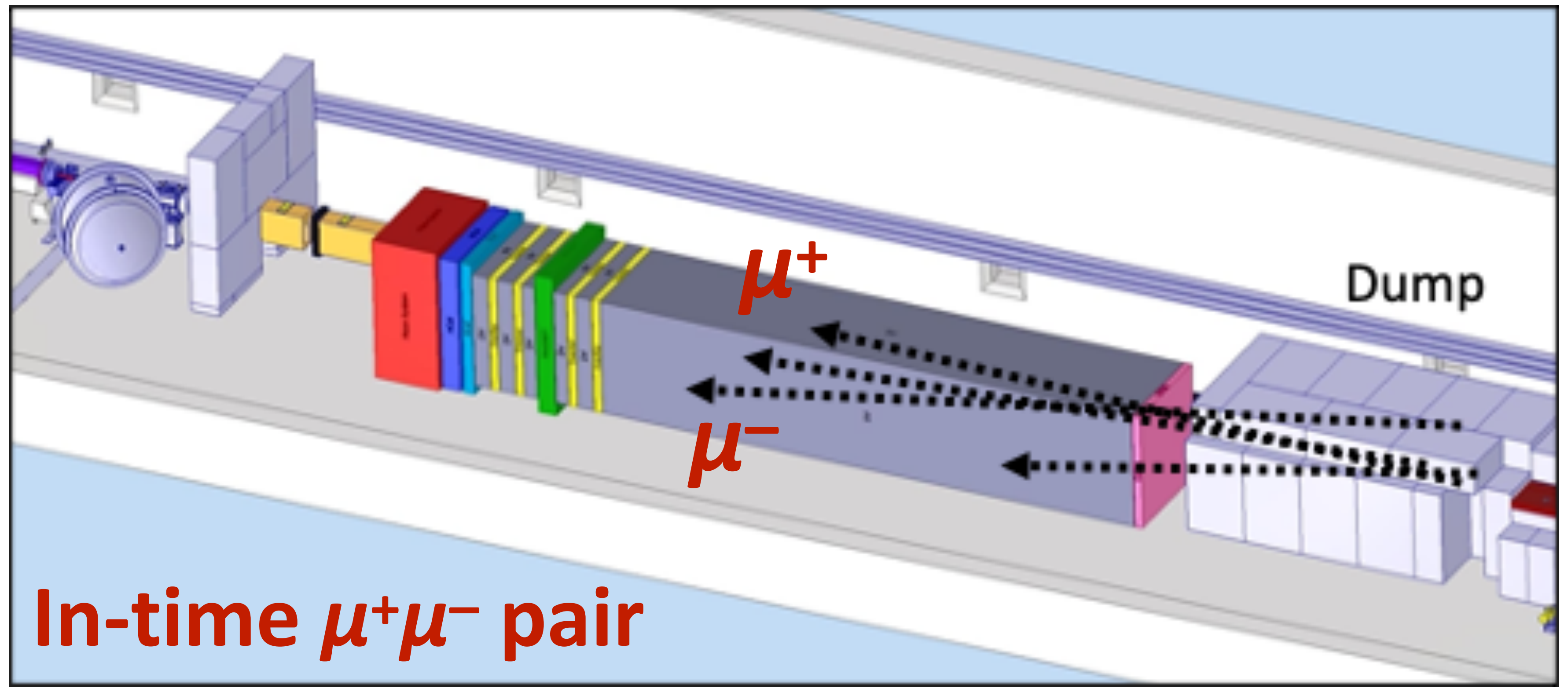
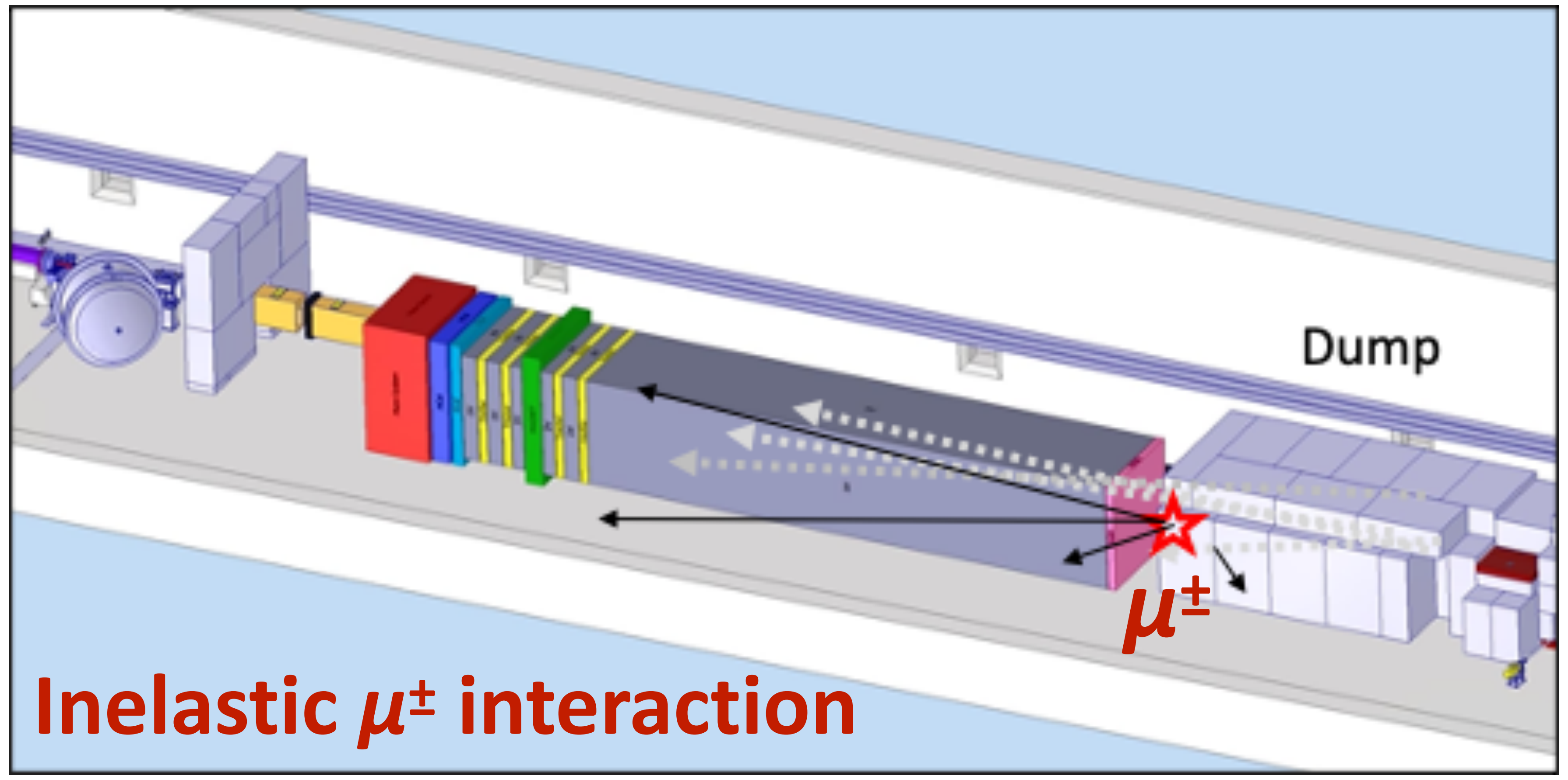
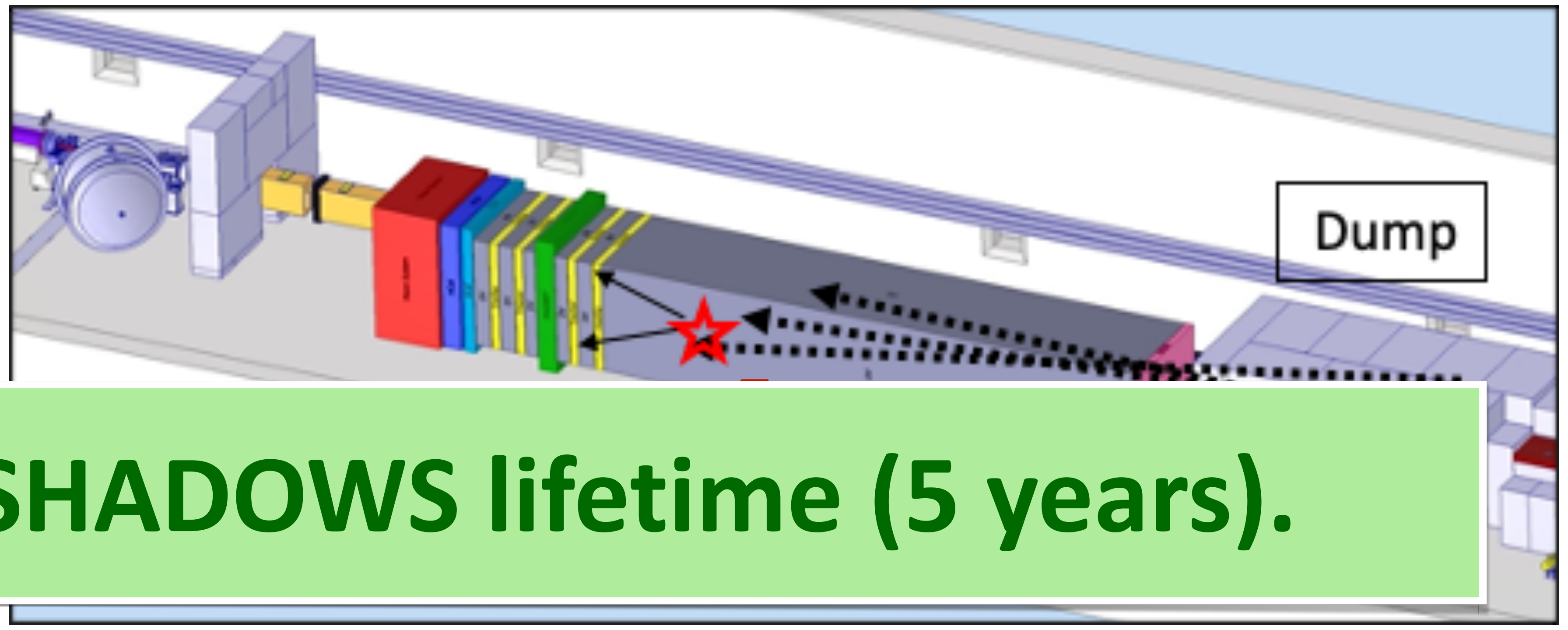
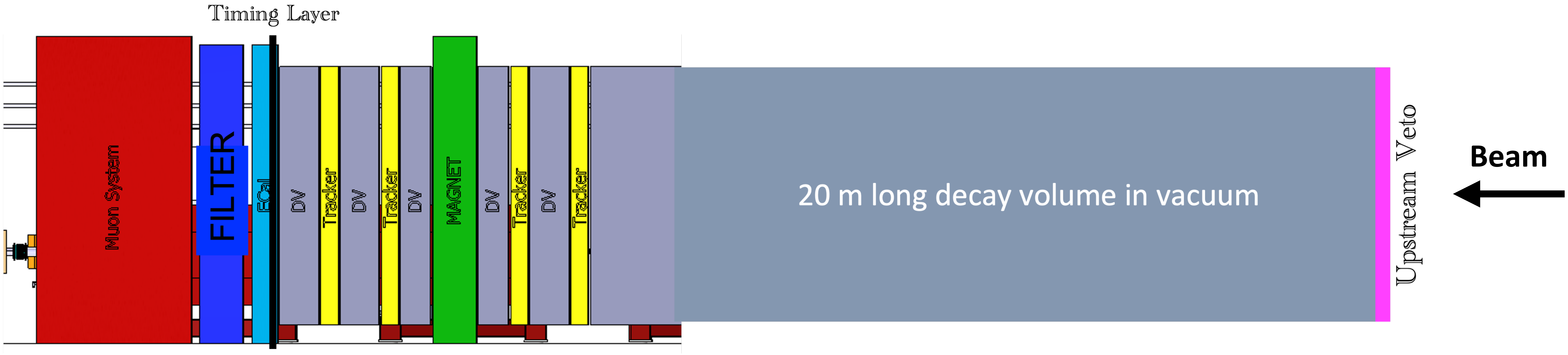




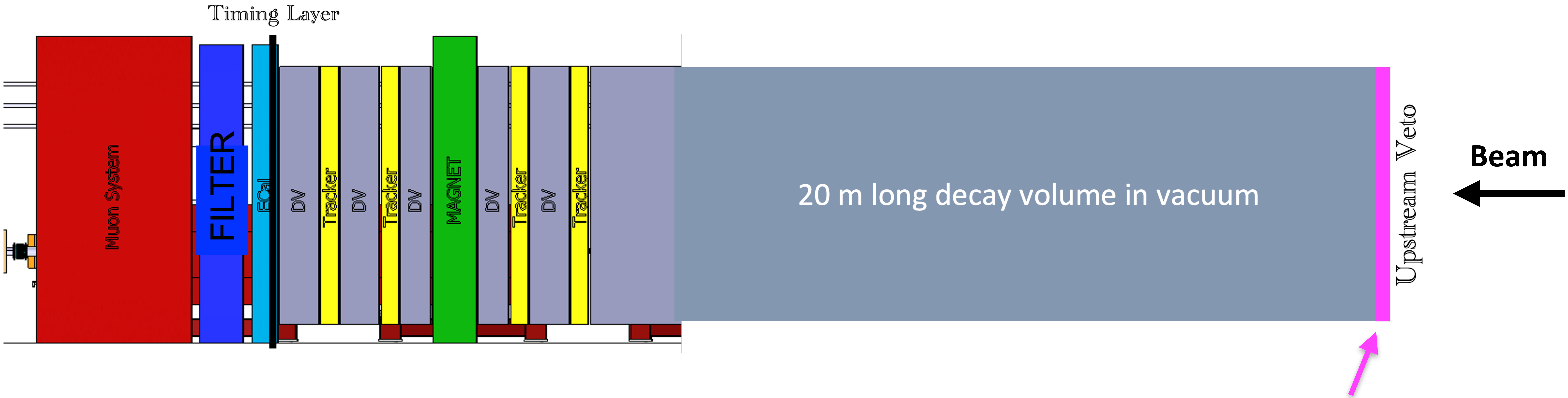


Background estimation: ~ 1 event for whole SHADOWS lifetime (5 years).

The SHADOWS Detector



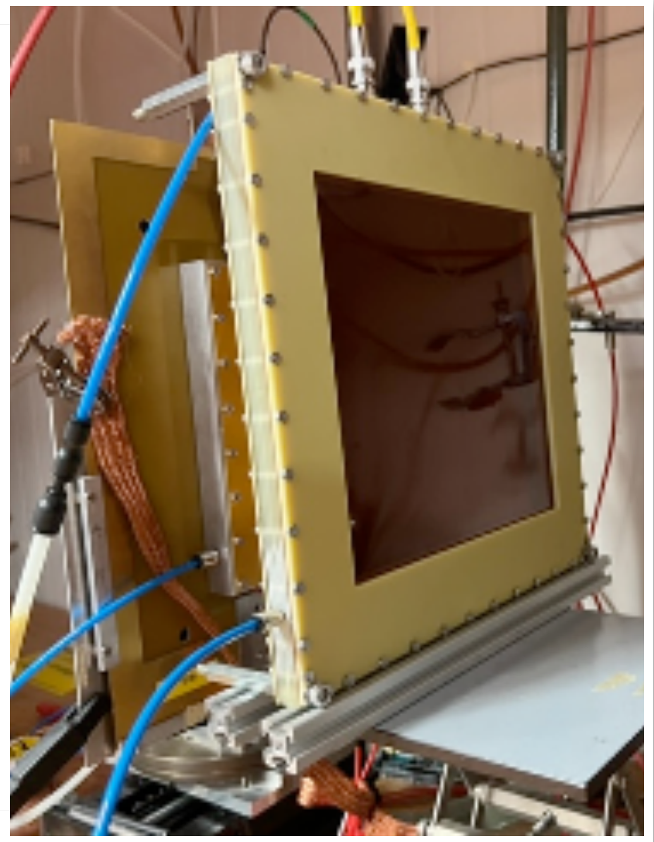
The SHADOWS Detector



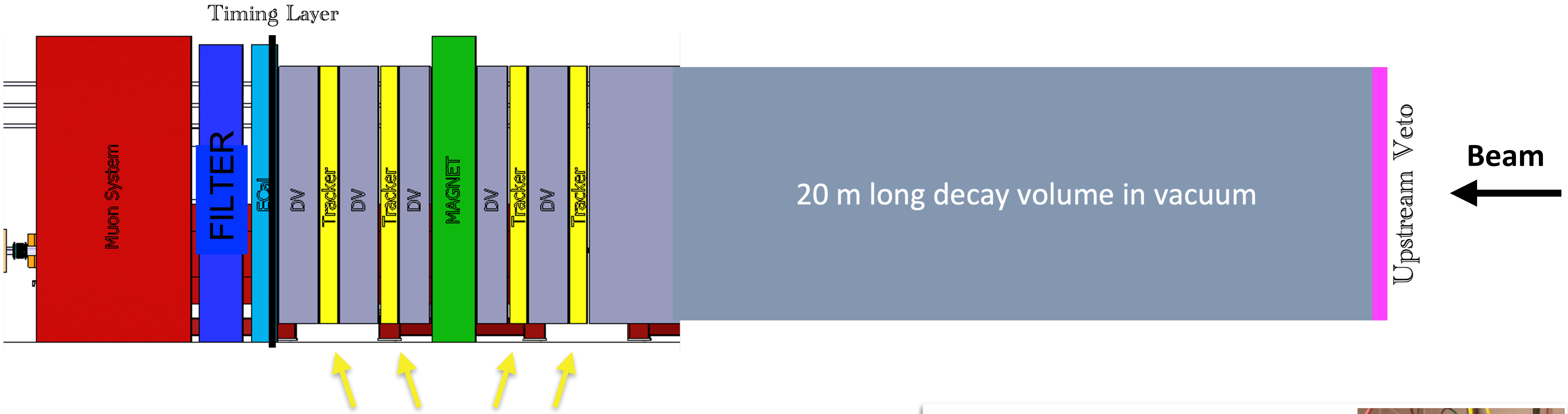
Upstream veto:

- Efficiency: 99.5%
- Time resolution: $\mathcal{O}$(10 ns)
- Position resolution: $\mathcal{O}$(cm)

Proposal: MicroMegas



The SHADOWS Detector



Spectrometer:

- Vertex resolution: $\mathcal{O}(1\ \text{cm})$
- To be operated in vacuum

Proposals:

Straws, SciFis

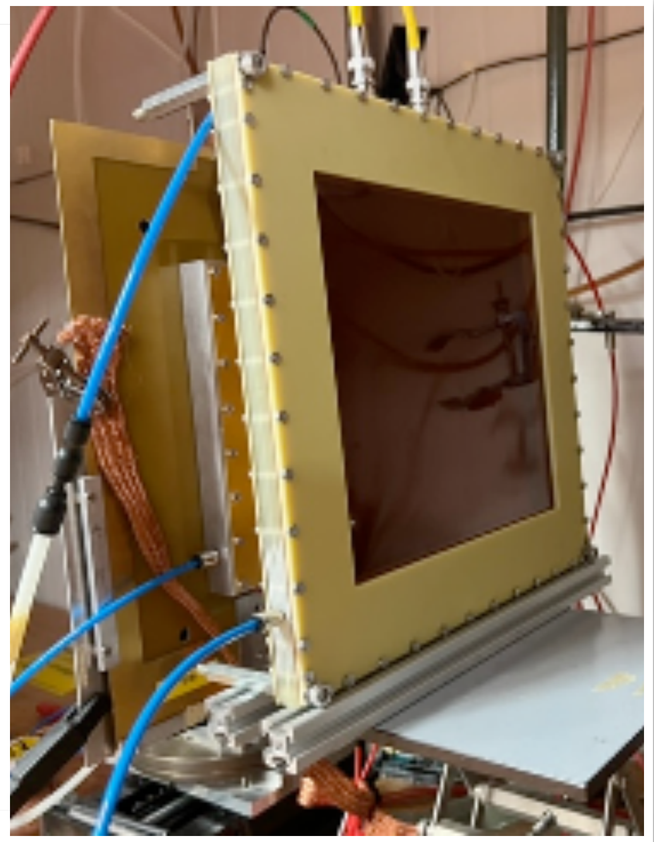
eam veto:

ficiency: 99.5%

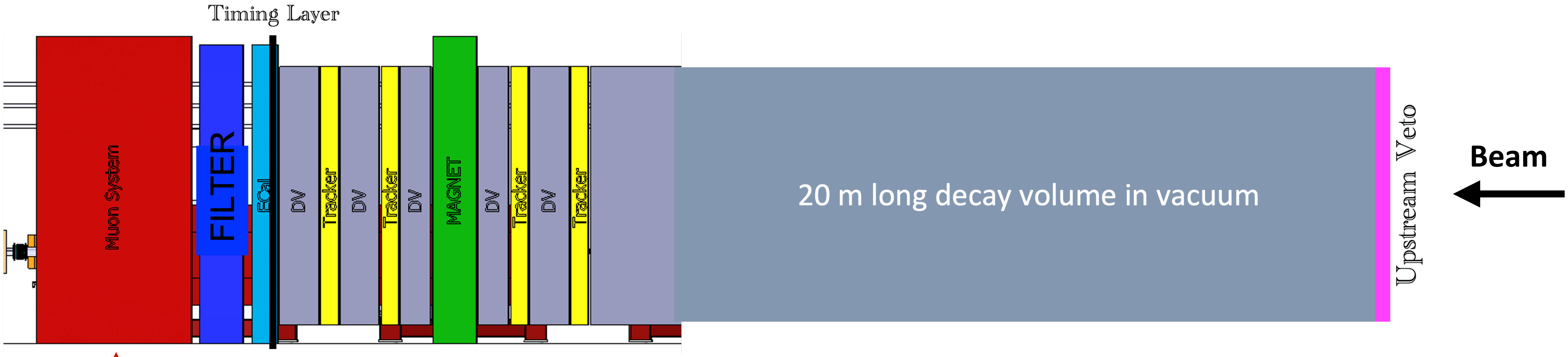
me resolution: $\mathcal{O}(10\ \text{ns})$

sition resolution: $\mathcal{O}(\text{cm})$

sal: MicroMegas



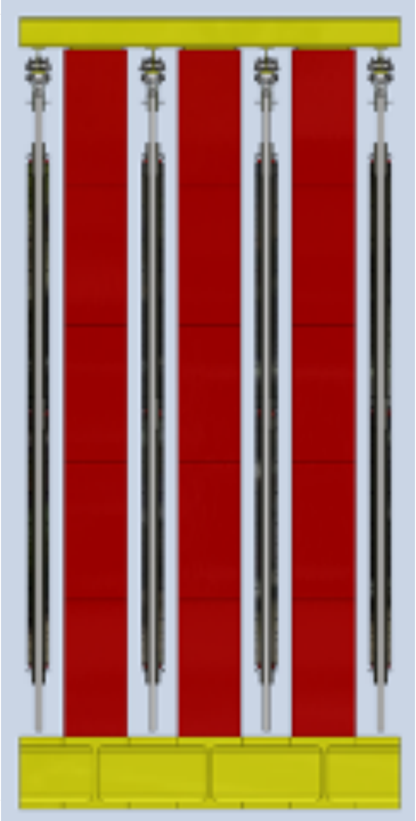
The SHADOWS Detector



Muon system:

- Efficiency: 99%
- Time resolution: $\mathcal{O}$(150 ps)
- Position resolution: $\mathcal{O}$(few cm)

Proposal: Scintillating tiles



r:

ution: $\mathcal{O}$(1 cm)

ted in vacuum

iFis

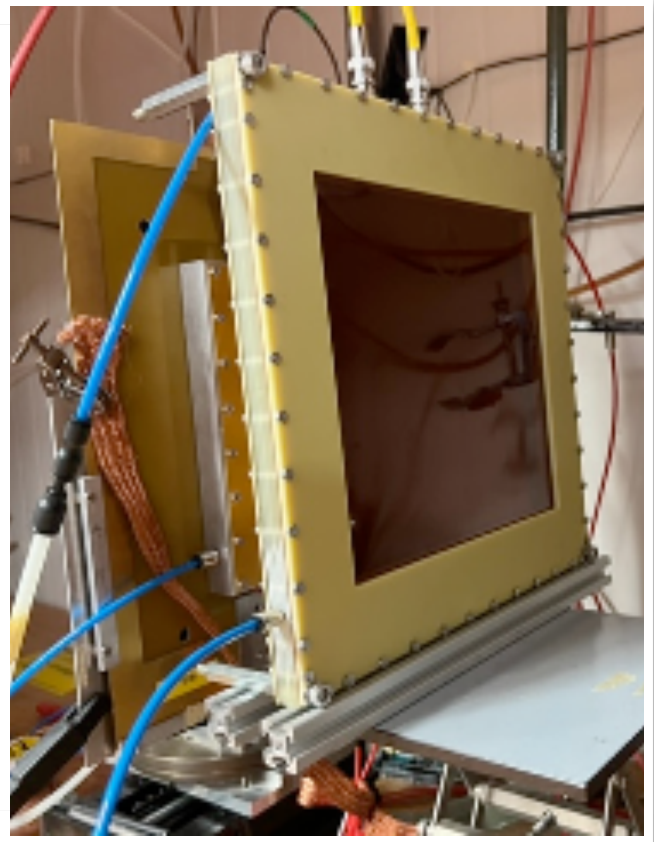
eam veto:

ficiency: 99.5%

me resolution: $\mathcal{O}$(10 ns)

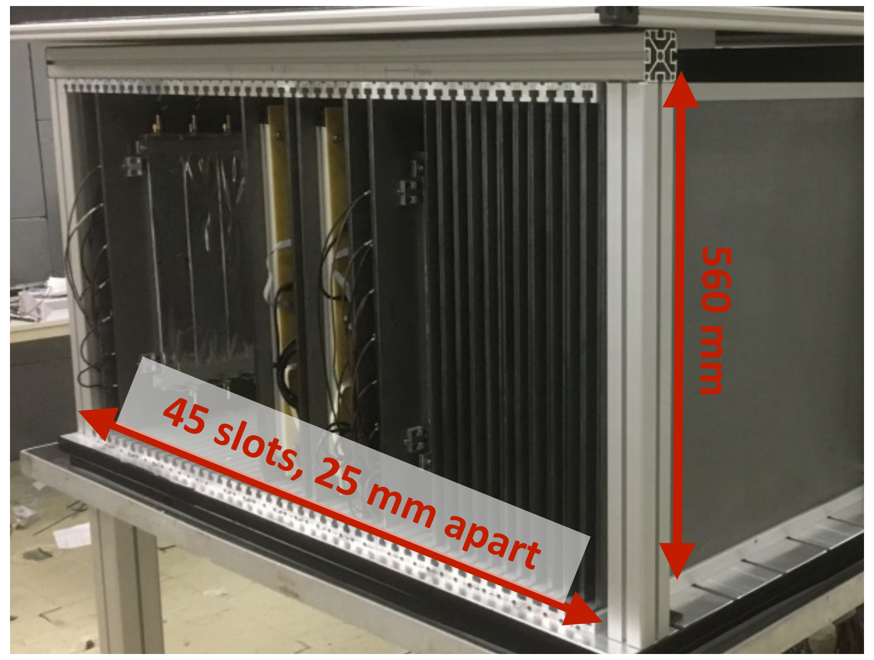
sition resolution: $\mathcal{O}$(cm)

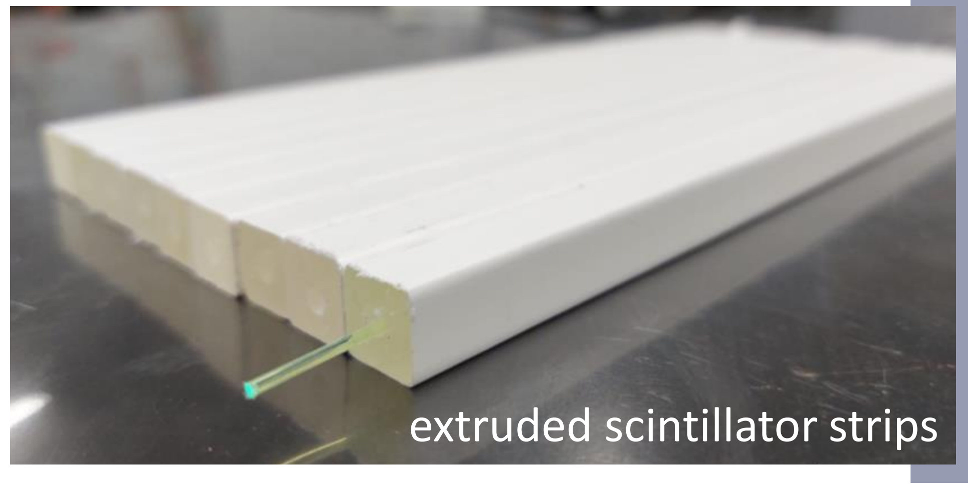
sal: MicroMegas

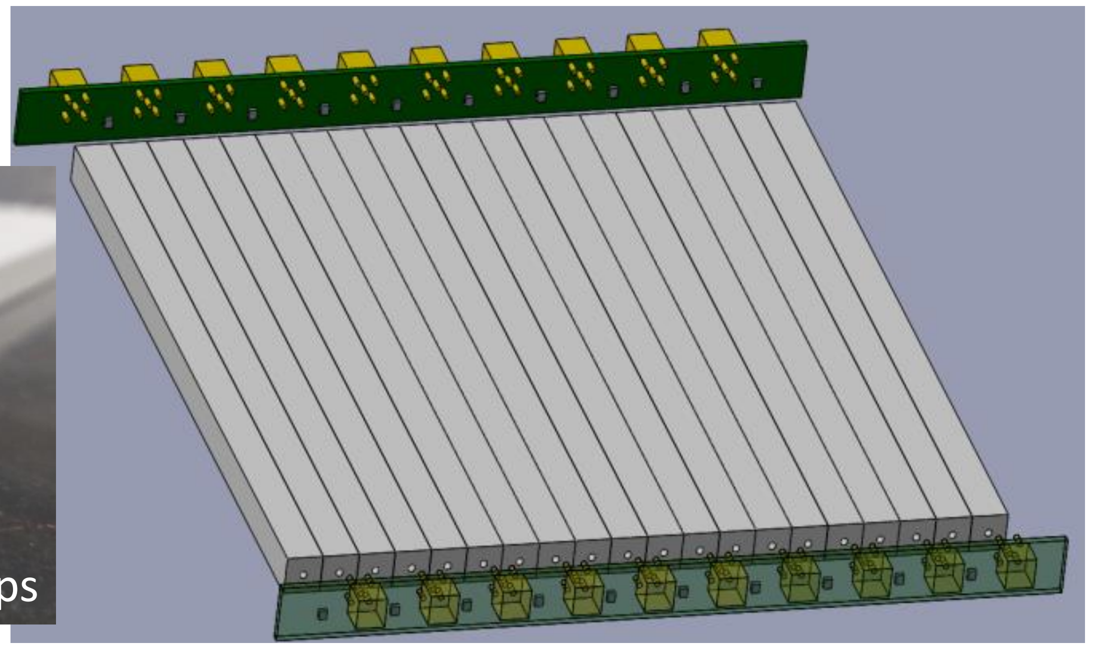


Electromagnetic Calorimeter

- **Several options investigated:** Shashlik, $PbWO_4$ (from CMS), CALICE TileCal, SplitCal, …
- Now: **Pointing calorimeter** with **1 cm wide scintillator strips** and **WLS fibres**.
  - ➜ Possibility to reconstruct ***ALP*** **→ γγ decays** without a track vertex.

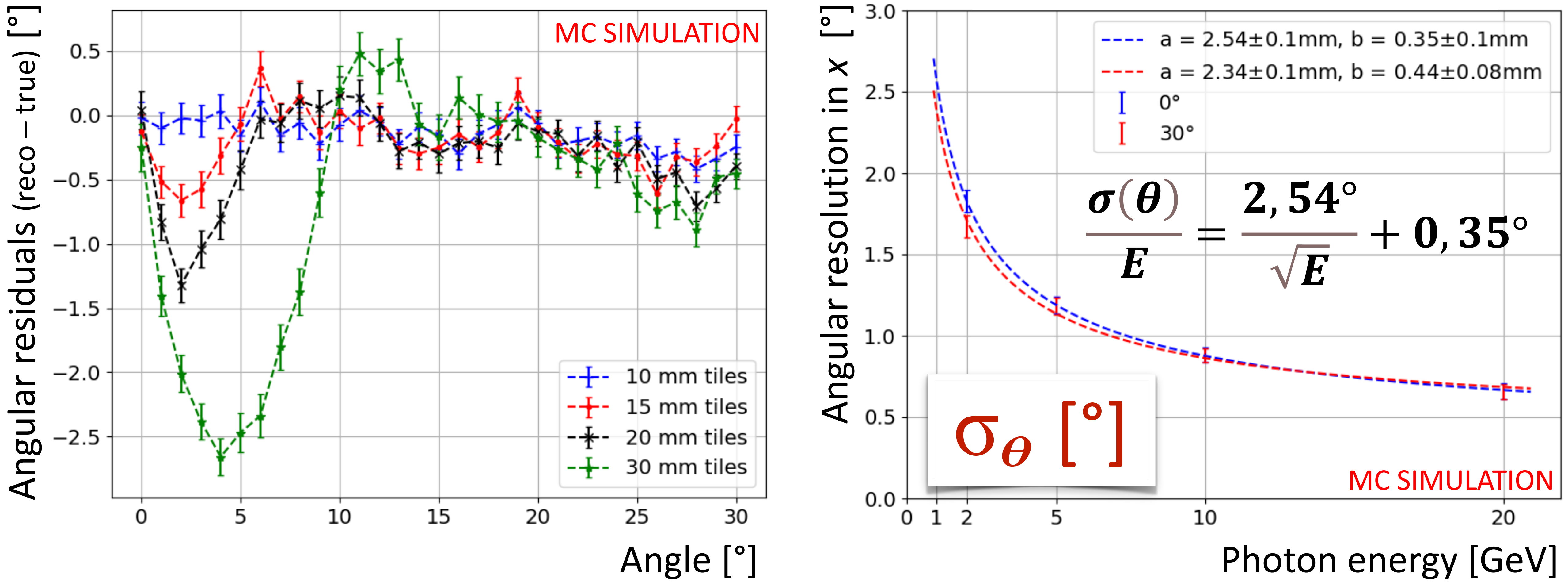






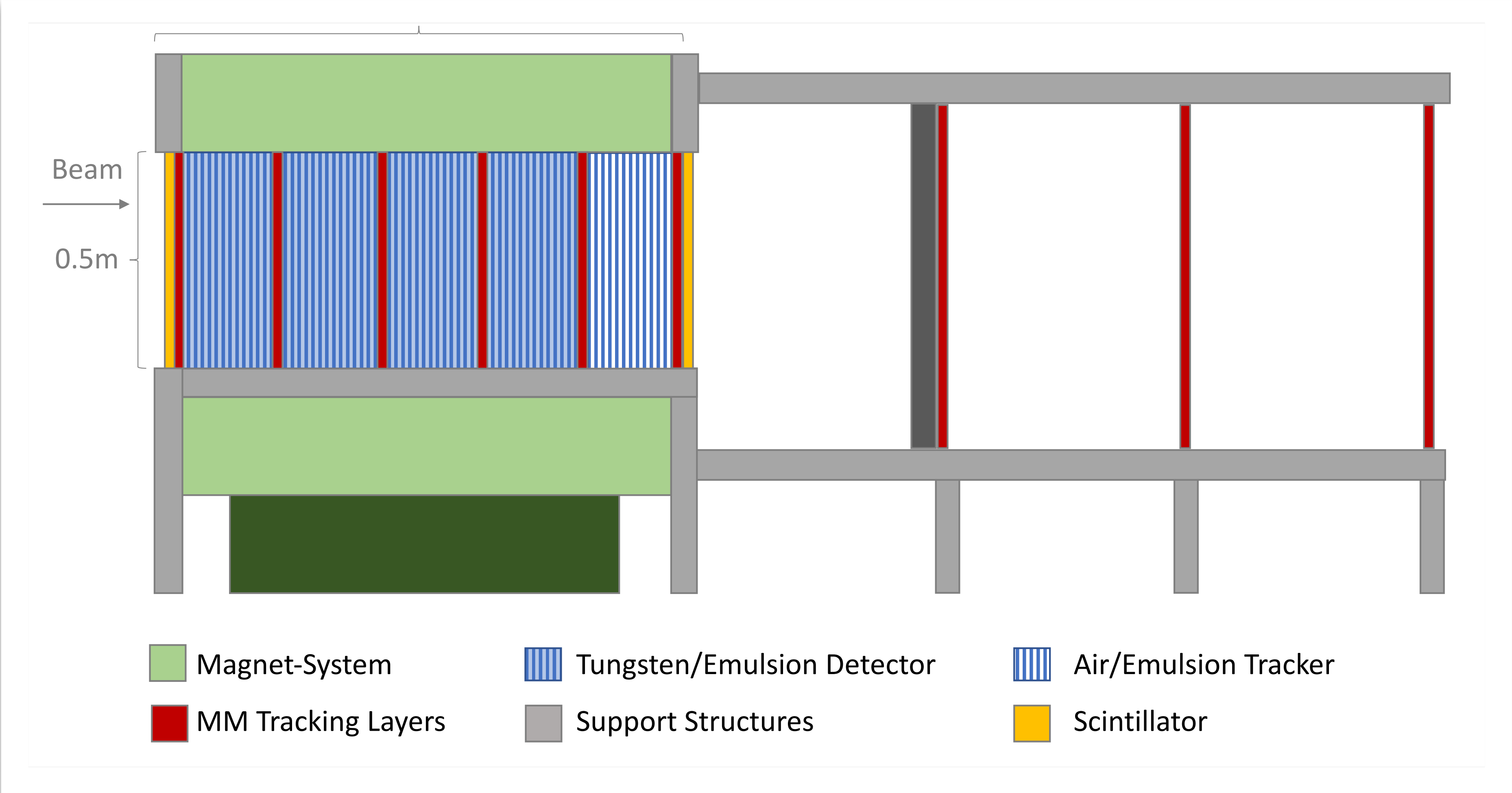
SHADOWS ECAL prototype

Reconstruction of photon shower directions



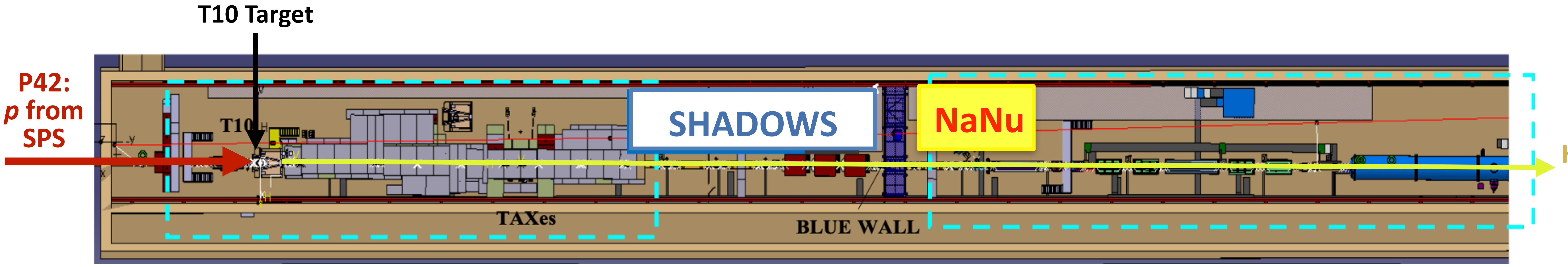
That’s it?

That's it?



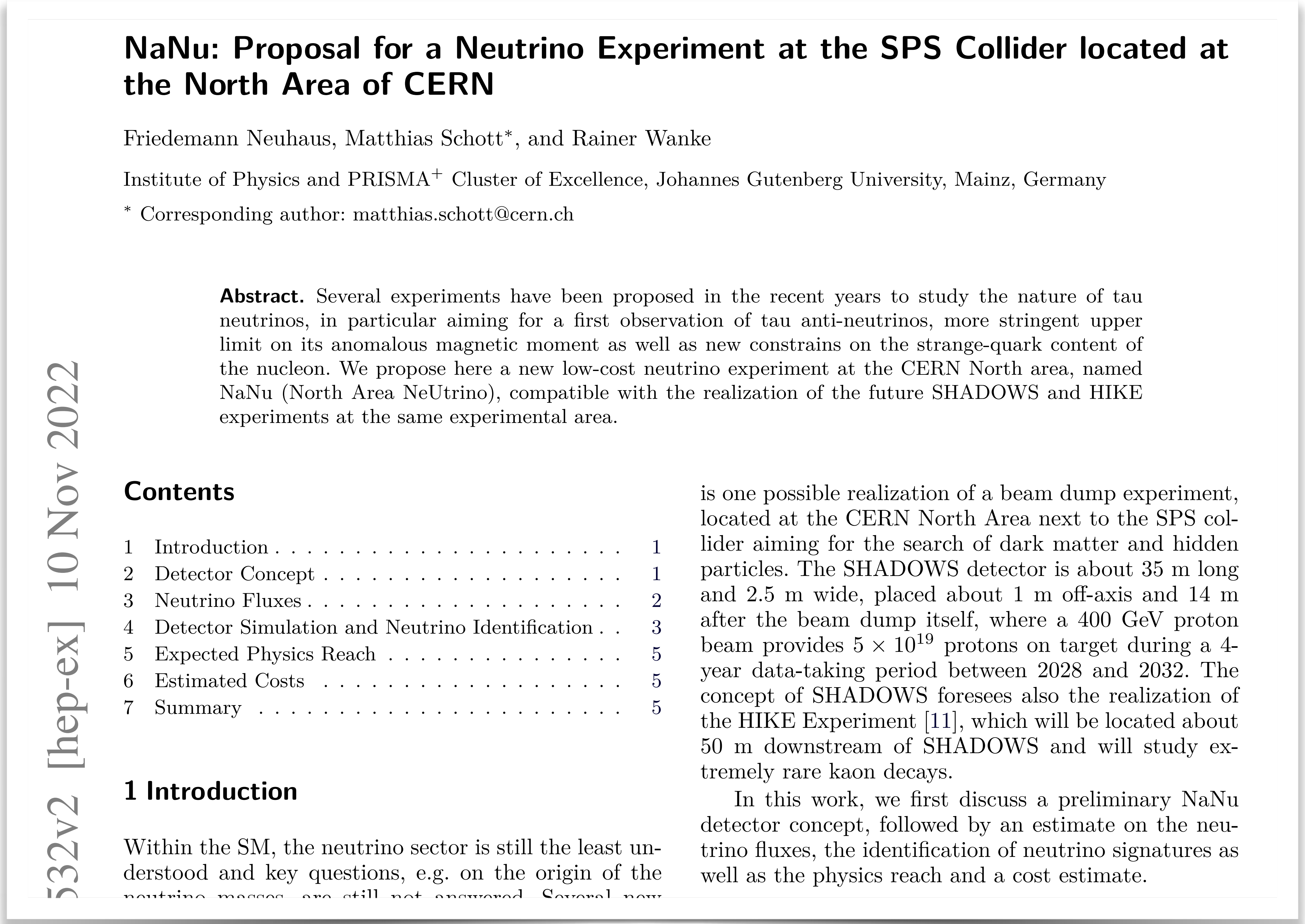
NaNu?!

NaNu: Option for Tau and Anti-Tau Neutrino Detection



- Charm production at the beamdump
  ➜ Lot's of **$D_s \to \tau \nu_\tau$ decays.**
- **τ neutrinos** can be detected with a massive detector with **τ reconstruction.**

➜ **NaNu:** Special detector behind SHADOWS for **τ neutrino** detection.



NaNu: Proposal for a Neutrino Experiment at the SPS Collider located at the North Area of CERN

Friedemann Neuhaus, Matthias Schott*, and Rainer Wanke

Institute of Physics and PRISMA+ Cluster of Excellence, Johannes Gutenberg University, Mainz, Germany

* Corresponding author: matthias.schott@cern.ch

Abstract. Several experiments have been proposed in the recent years to study the nature of tau neutrinos, in particular aiming for a first observation of tau anti-neutrinos, more stringent upper limit on its anomalous magnetic moment as well as new constrains on the strange-quark content of the nucleon. We propose here a new low-cost neutrino experiment at the CERN North area, named NaNu (North Area NeUtrino), compatible with the realization of the future SHADOWS and HIKE experiments at the same experimental area.

[...]532v2 [hep-ex] 10 Nov 2022

Contents

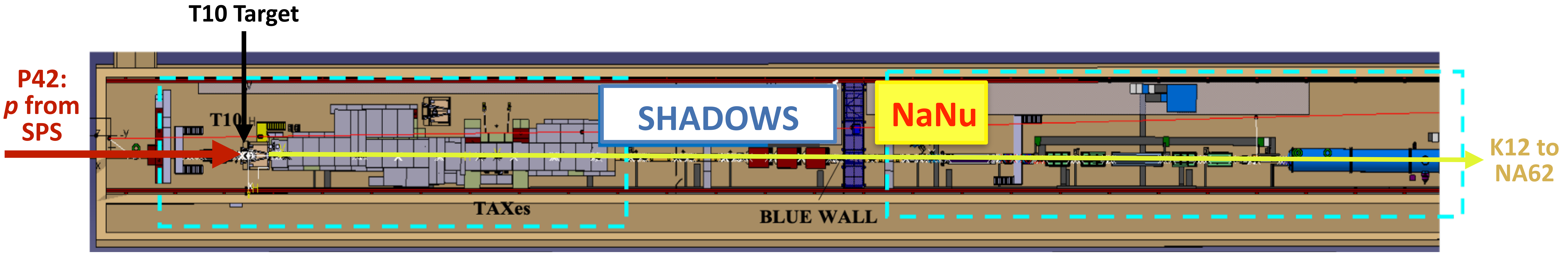
1 Introduction

Within the SM, the neutrino sector is still the least understood and key questions, e.g. on the origin of the [...]

is one possible realization of a beam dump experiment, located at the CERN North Area next to the SPS collider aiming for the search of dark matter and hidden particles. The SHADOWS detector is about 35 m long and 2.5 m wide, placed about 1 m off-axis and 14 m after the beam dump itself, where a 400 GeV proton beam provides 5×10^{19} protons on target during a 4-year data-taking period between 2028 and 2032. The concept of SHADOWS foresees also the realization of the HIKE Experiment [11], which will be located about 50 m downstream of SHADOWS and will study extremely rare kaon decays.

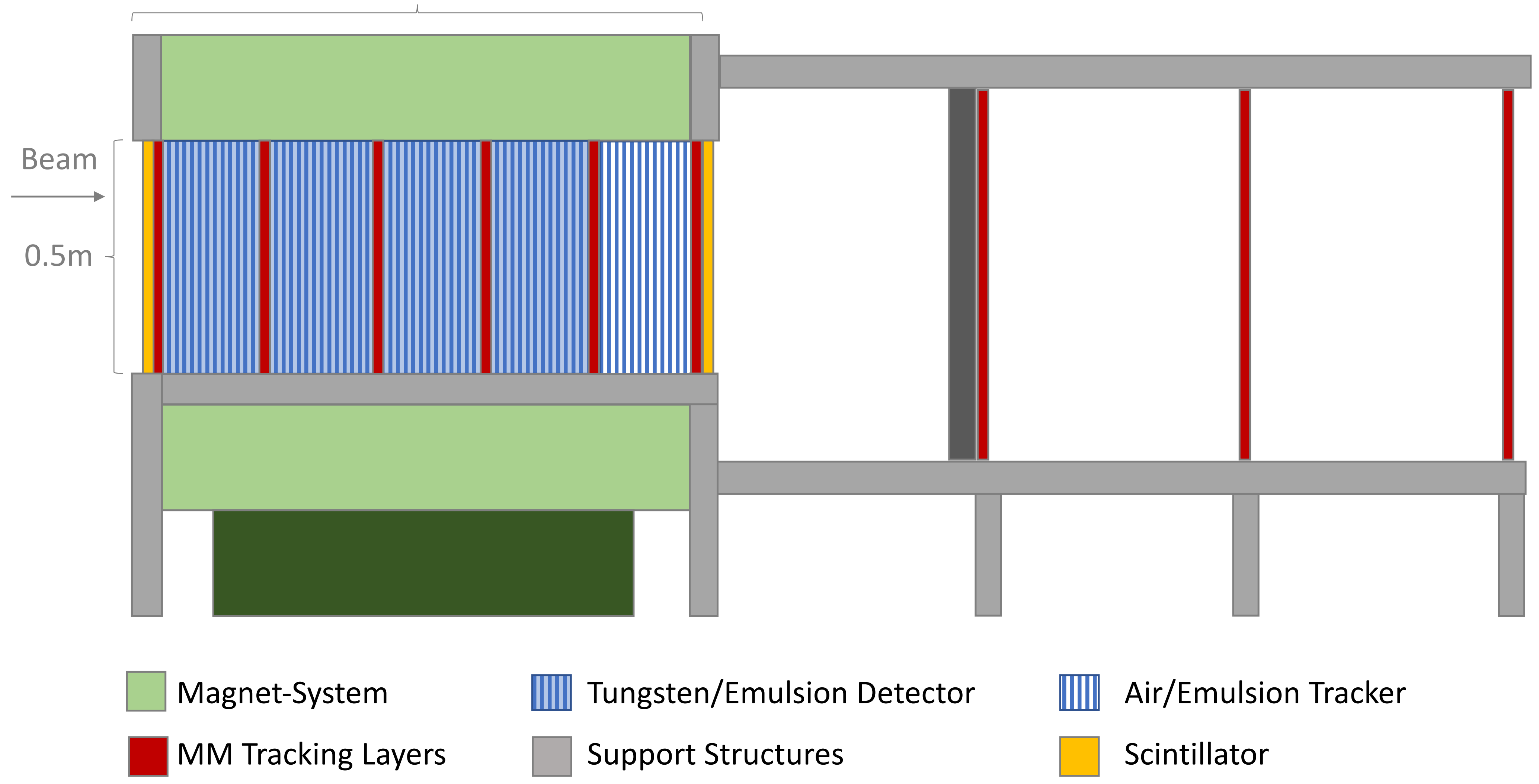
In this work, we first discuss a preliminary NaNu detector concept, followed by an estimate on the neutrino fluxes, the identification of neutrino signatures as well as the physics reach and a cost estimate.

NaNu: Option for Tau and Anti-Tau Neutrino Detection



NaNu: (Anti-)Tau Neutrino Detection

- Separate, self-sustained detector.
- Emulsion-based with track spectrometer (magnet available at CERN).
- Further tracking with MicroMegas planes,



HIKE & SHADOWS Schedule

- **North Area Consolidation** planned for **Long Shutdown 3 (2026-30 for ECN3):** Construction/Installation of experiment(s).
- **2031 → LS 5 (2040?): Data taking.**

ECN3 High Intensity - Indicative Schedule & Constraints

Machine/Facility/Experiments	Comments	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035
LHC	priority on available resources esp. (EL, CV, HE, BI, STI, etc.)				LS3			Commission.				LS4		
SPS					LS3							LS4		
EHN1+2 NA-CONS (baseline)	BA80 and general Infr. Focus				LS3		Commissioning + Operation					LS4		
ECN3 HI TT20/TCC2/TDC2/TTs	critical equipment & servics (limited work in TCC2)				LS3		Commissioning					LS4		
ECN3 HI TCC8 Target Complex	HL-LHC + NA-CONS overlapping resources/schedule	PreStudy -> Approval	TDR	TDR	TDR/PRR	Preparation, Dismantling	Procurement / Assembly	Procurement /Installation	Installation/ Commission.			LS4		
HIKE Experiment	Modifications and upgrades of detectors as required	Proposal	TDR	PRR	Upgrades and Installation		Detector Commissioning		Det./Beam Comm. (tbc)			LS4		
SHADOWS Experiment	Approval on critical path for TDR phase to be launched/financed	Proposal	TDR	TDR	PRR	Production/ Area preparation	Construction /Installation	Installation/Commissioning				LS4		

Many thanks

Spares

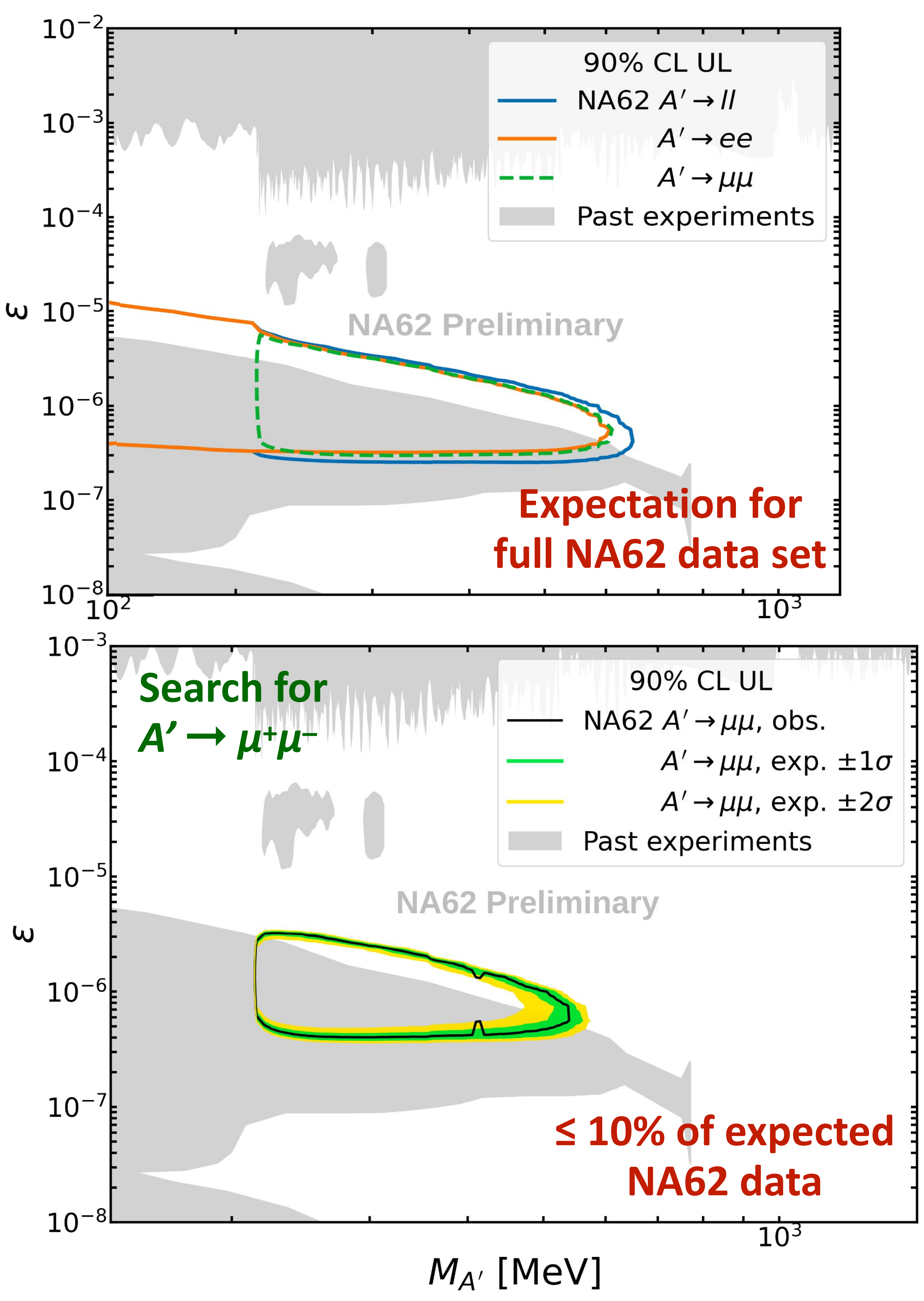
NA62: Beamdump Mode

Running in „**Beamdump Mode**“ by closing defining collimator ➞ acts as beamdump.

(➞ Presentation of Heiko Lacker)

- **Search for long-lived, neutral particles**
  (as also proposed for SHiP or SHADOWS).
- Long distance to detector, narrow detector
  ➜ **Sensitivity in different phase space region.**
- **2021:** 10-day beamdump run **1.4×10^{17} pot**
  –2025: ≥ 10 × more planned **~ 2×10^{18} pot**
  (**background-free** in e.g. $\mu^+\mu^-$ up to at least **10^{18} pot)**

Search for Dark Photon $A' \rightarrow \mu^+\mu^-$

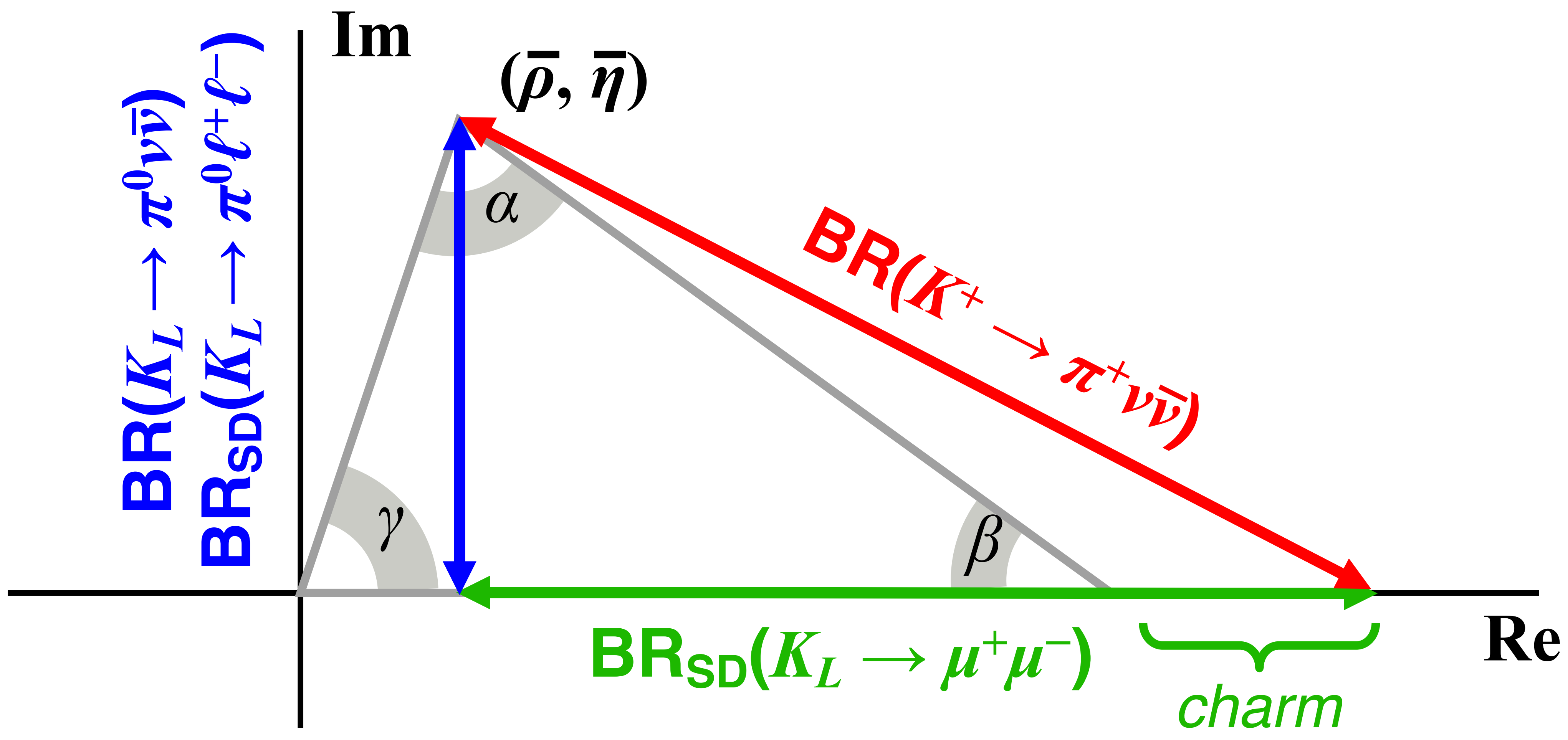


The region enclosed by the contour shown is excluded

Rare Kaon Decays beyond 2026

Interest in many ultra-rare Kaon decays:

- **Flavor-changing processes** with varying contributions from short-distance amplitudes.
- **Highly suppressed** in the SM.
  - ➜ Sensitivity to New Physics at energy scales beyond collider energies.
- Rates related to **CKM matrix elements** with minimal parametric uncertainty



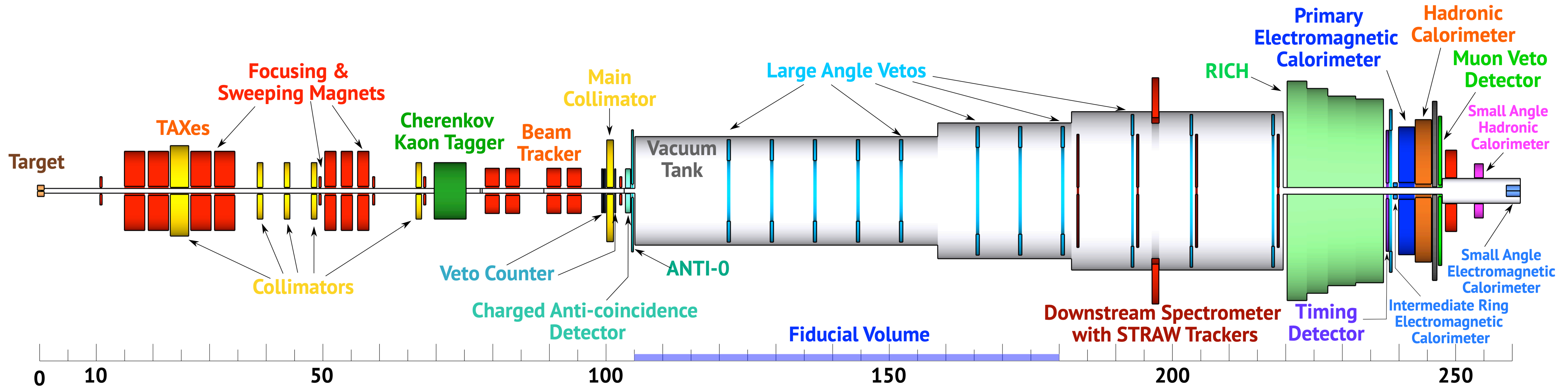
Decay	Γ_{SD}/Γ	Theory err.*	SM BR × 10^{11}	Exp. BR × 10^{11} (Oct 2022)
$K_L \to \mu^+\mu^-$	10%	30%	79 ± 12 (SD)	684 ± 11
$K_L \to \pi^0 e^+ e^-$	40%	10%	3.2 ± 1.0	$< 28^\dagger$
$K_L \to \pi^0 \mu^+\mu^-$	30%	15%	1.5 ± 0.3	$< 38^\dagger$
$K^+ \to \pi^+ \nu\bar{\nu}$	90%	4%	8.6 ± 0.4	11 ± 4
$K_L \to \pi^0 \nu\bar{\nu}$	>99%	2%	2.9 ± 0.2	$< 300^\dagger$

*Approx. error on LD-subtracted rate excluding parametric contributions †90% CL

HIKE Phase 1 → HIKE Phase 2

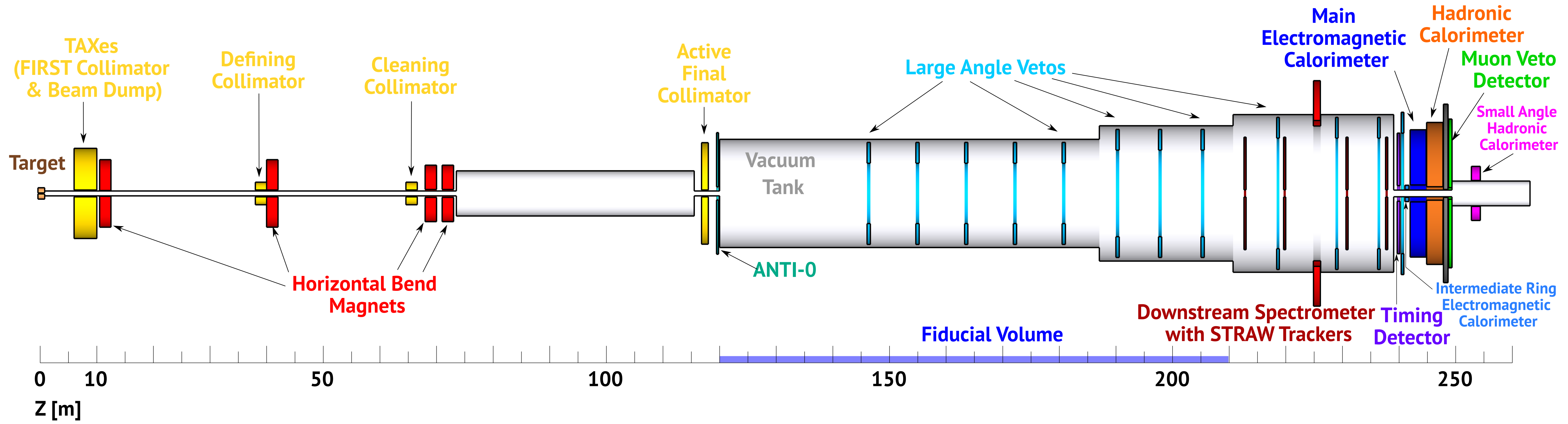
Phase 1:

- **$\mathrm{Br}(K^+ \to \pi^+ \nu\bar{\nu})$ to ~ 5%.**
- $K \to e\nu / K \to \mu\nu$, $K^+ \to \pi^+ ll$, $K^+ \to \pi^- l^+ l^+$, radiative decays, precision measurements, …



Phase 2: Same intensity, K_L beam.

- **Rare K_L decays:** $K_L \to \pi^0 l^+ l^-$, $K_L \to \mu^+\mu^-$, …



During phase 1&2:

- **Beamdump mode with 5×10^{19} pot.**

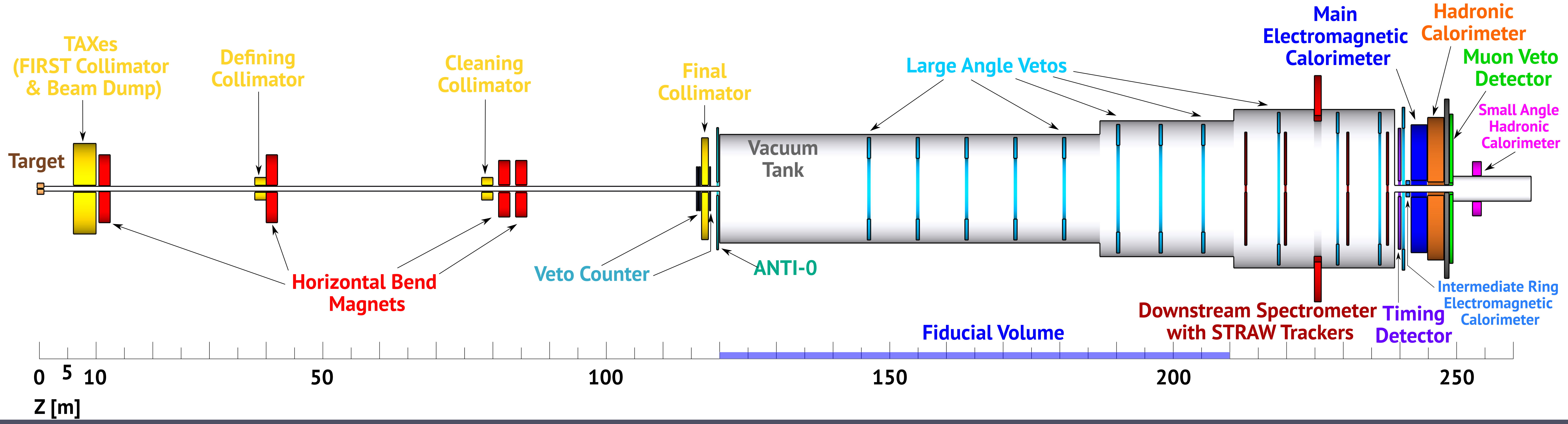
Phase 2: Rare K_L decays

Similar proton-on-target intensity (pot) as Phase 1

- **New neutral beamline**
  (similar to original NA48 experiment).
- **Some new or modified detectors,**
  but most to be used from Phase 1.

Physics reach HIKE Phase 2:

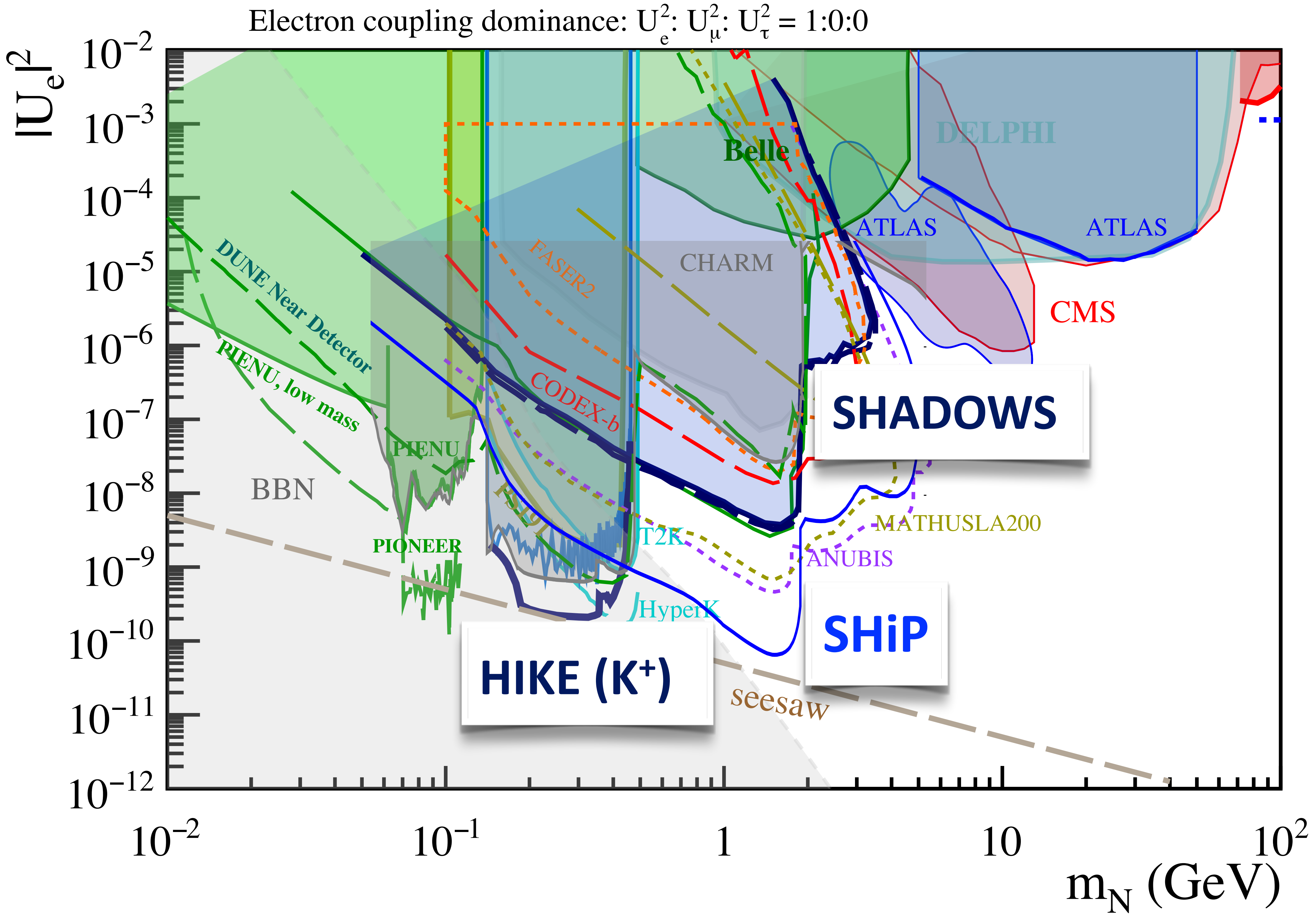
Mode	Assumed branching ratio	Acceptance	Signal yield in five years
$K_L \to \pi^0 e^+ e^-$	3.5×10^{-11}	2.1%	140
$K_L \to \pi^0 \mu^+ \mu^-$	1.4×10^{-11}	6.0%	160
$K_L \to \mu^+ \mu^-$	7×10^{-9}	17%	2.3×10^5
$K_L \to \mu^\pm e^\mp$	–	16%	–



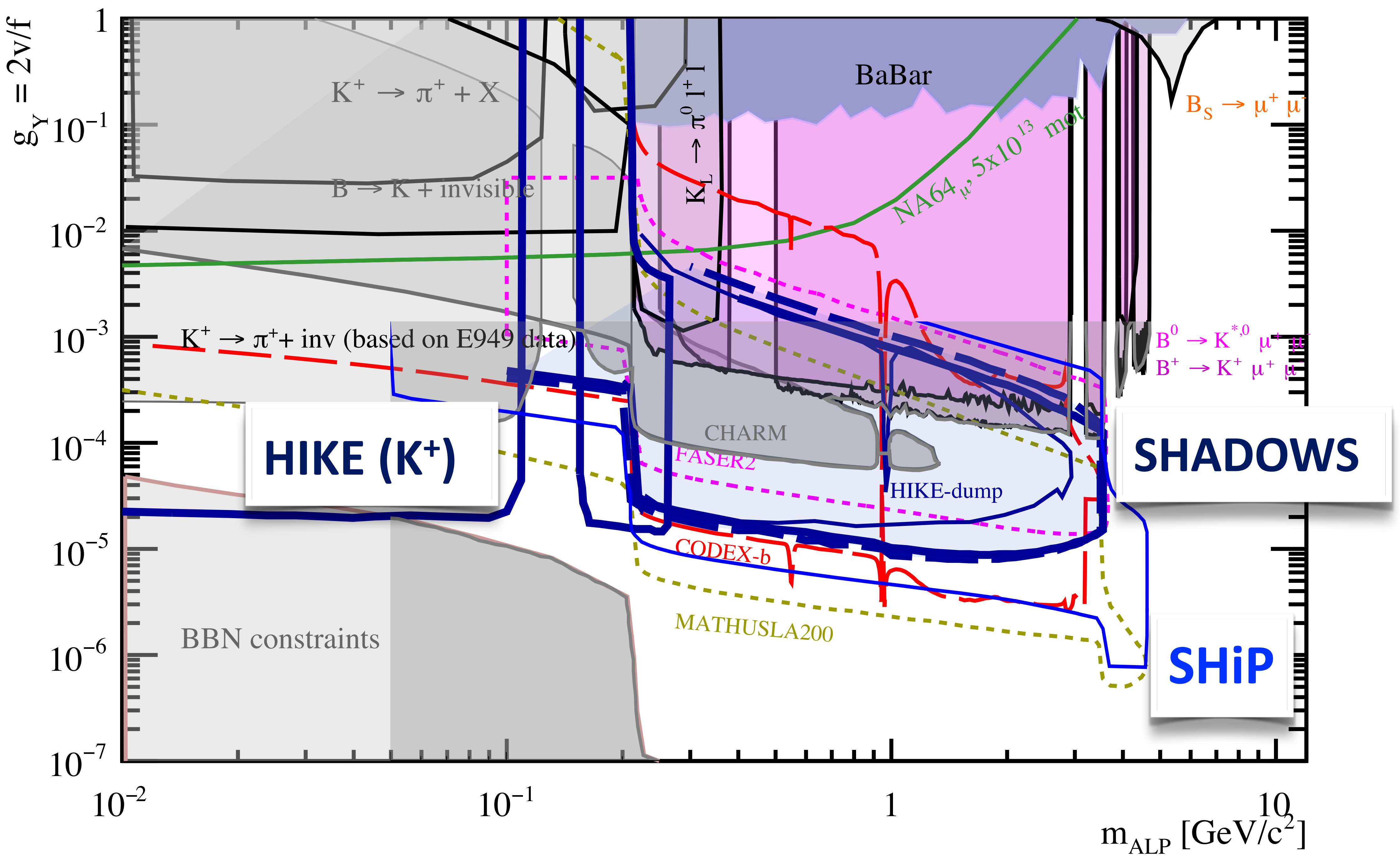
Reach of SHADOWS/HIKE

- **Multi-purpose experiments: Searches for HNLs, ALPs, Dark Photons, Scalars, …**
  Just two examples:

Electron coupled HNLs



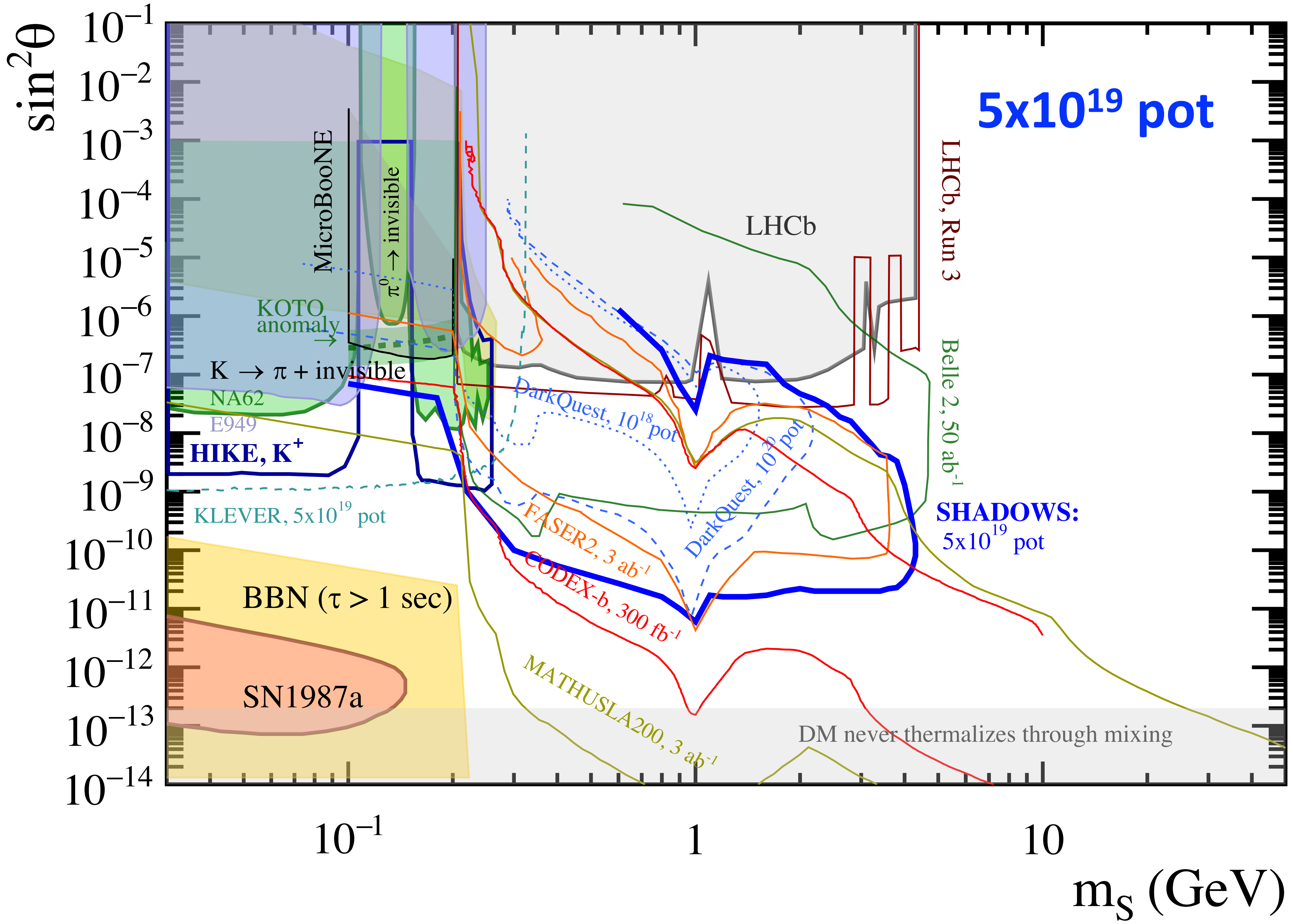
Fermion coupled ALPs



SHADOWS sensitivity to standard PBC benchmarks

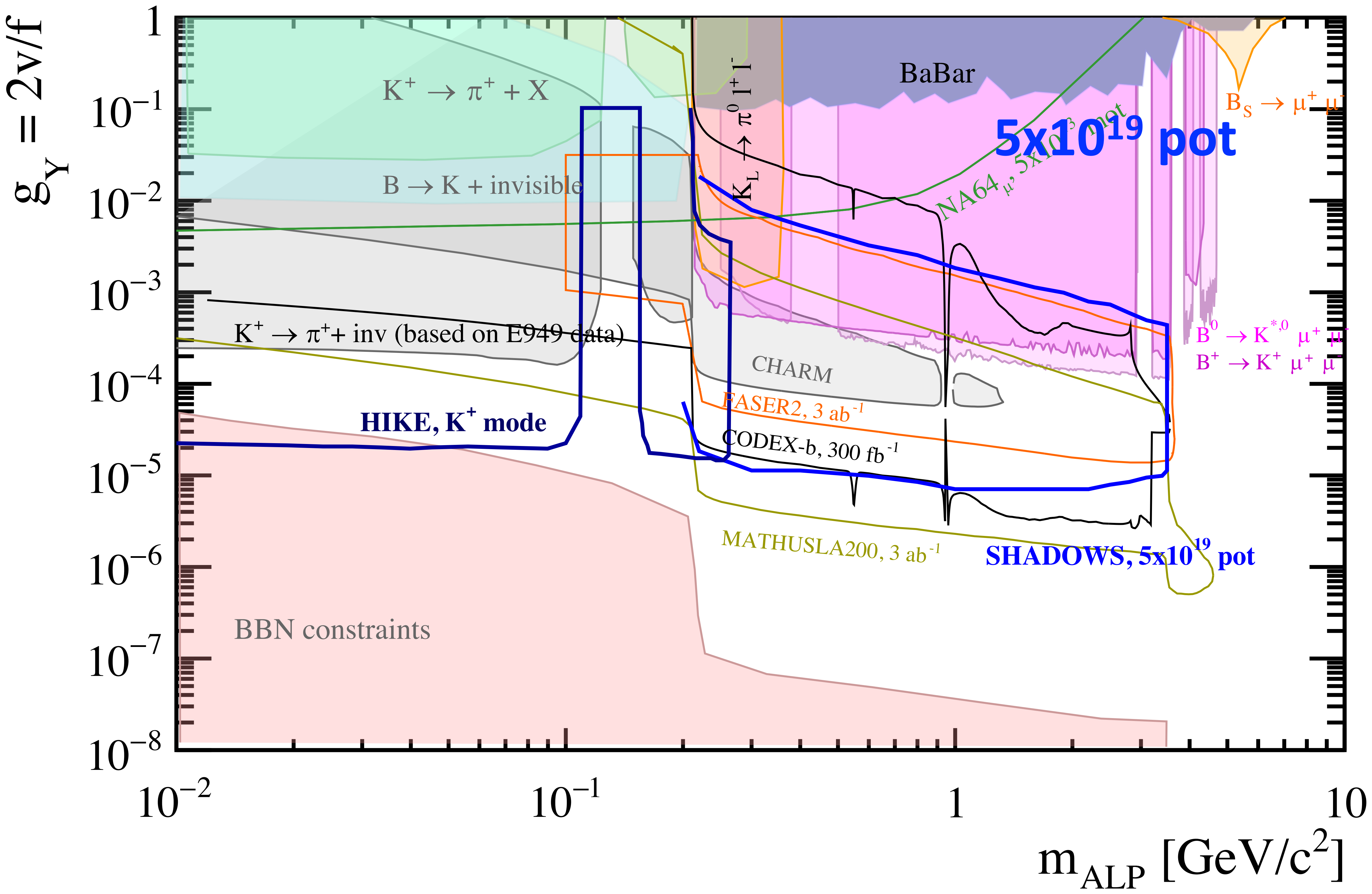
(PBC benchmarks: J. Phys.G47 (2020) 1, 010501, e-Print: 1901.09966, section 9)

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

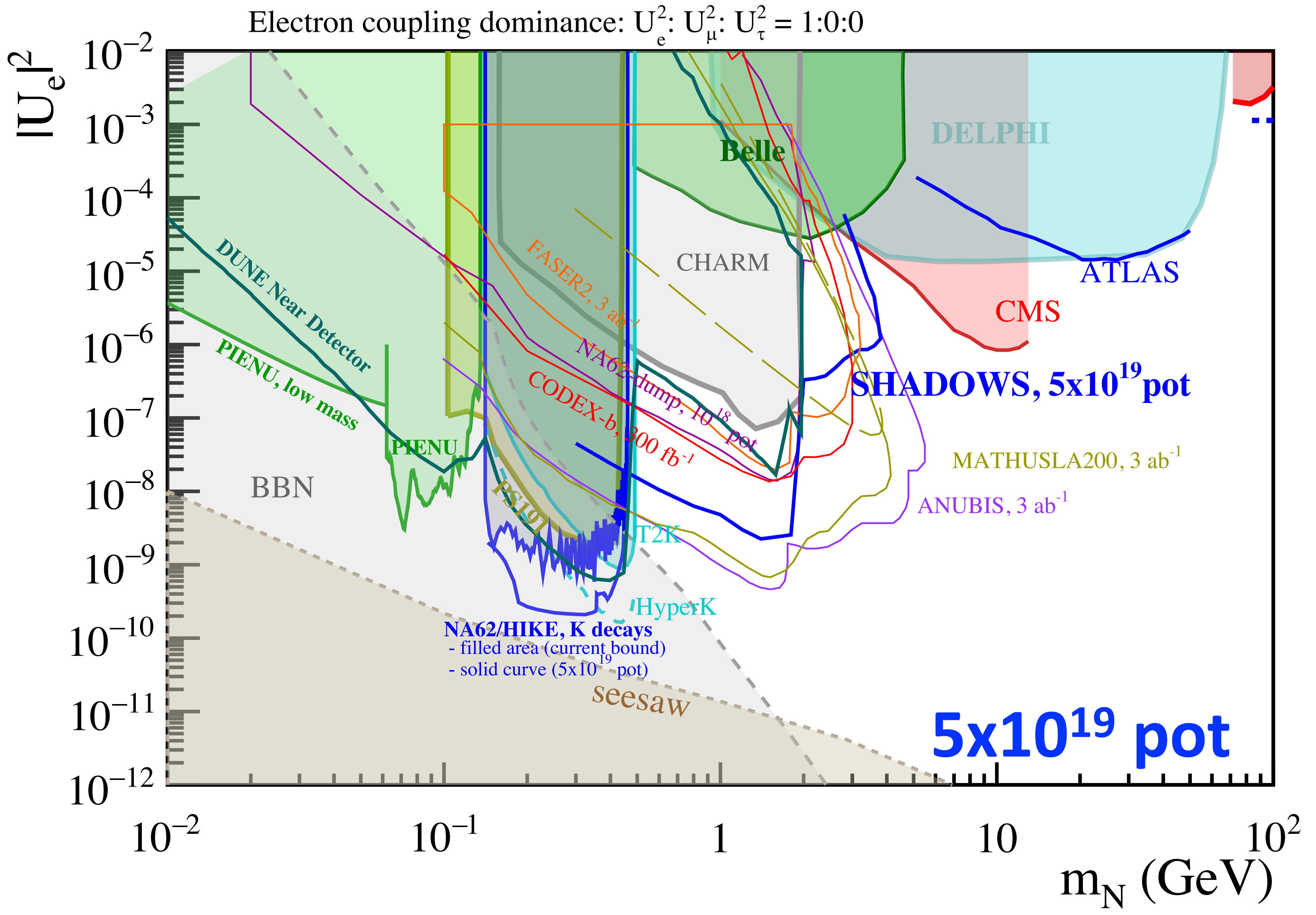
ALPs with fermion couplings (BC10)

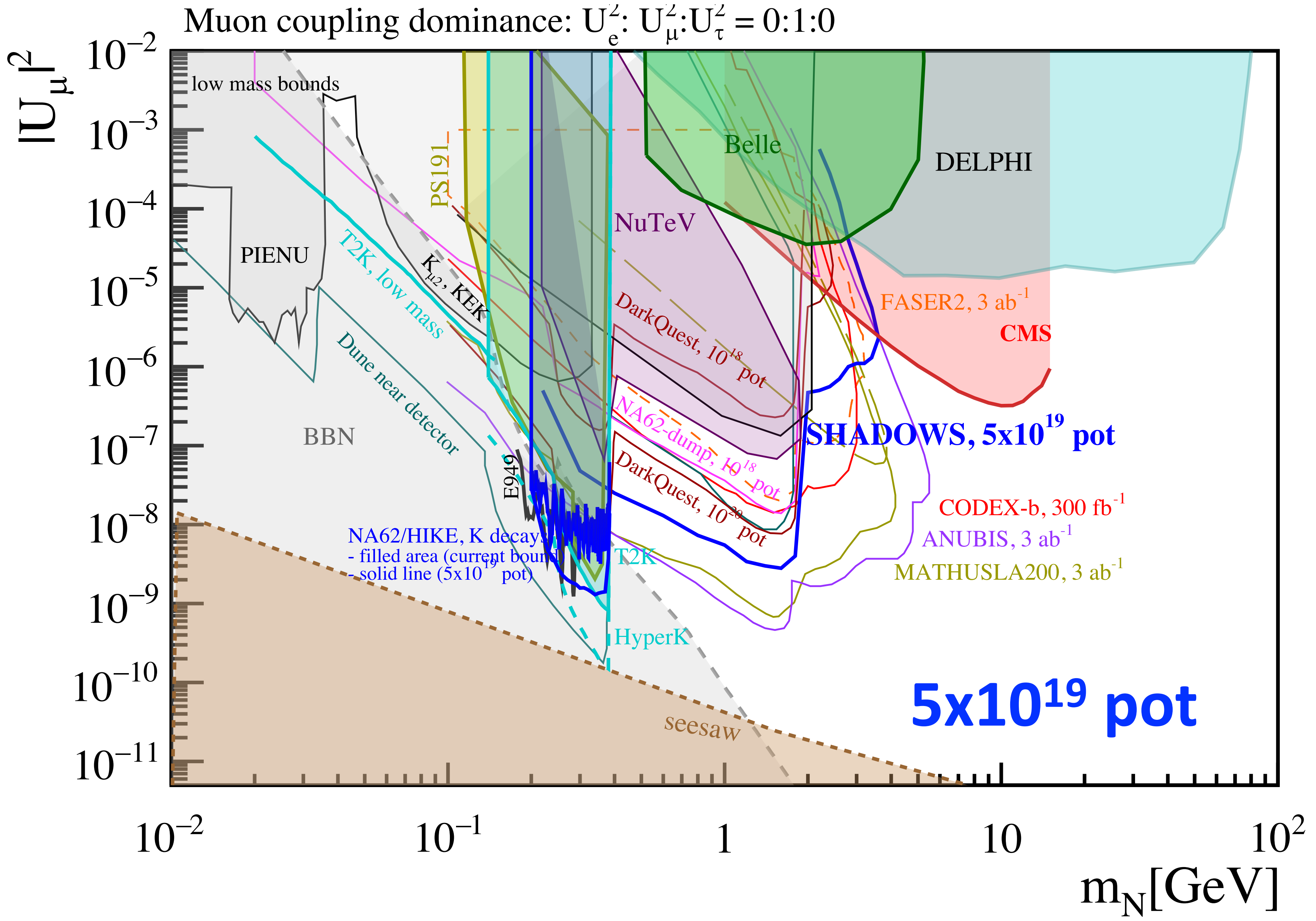


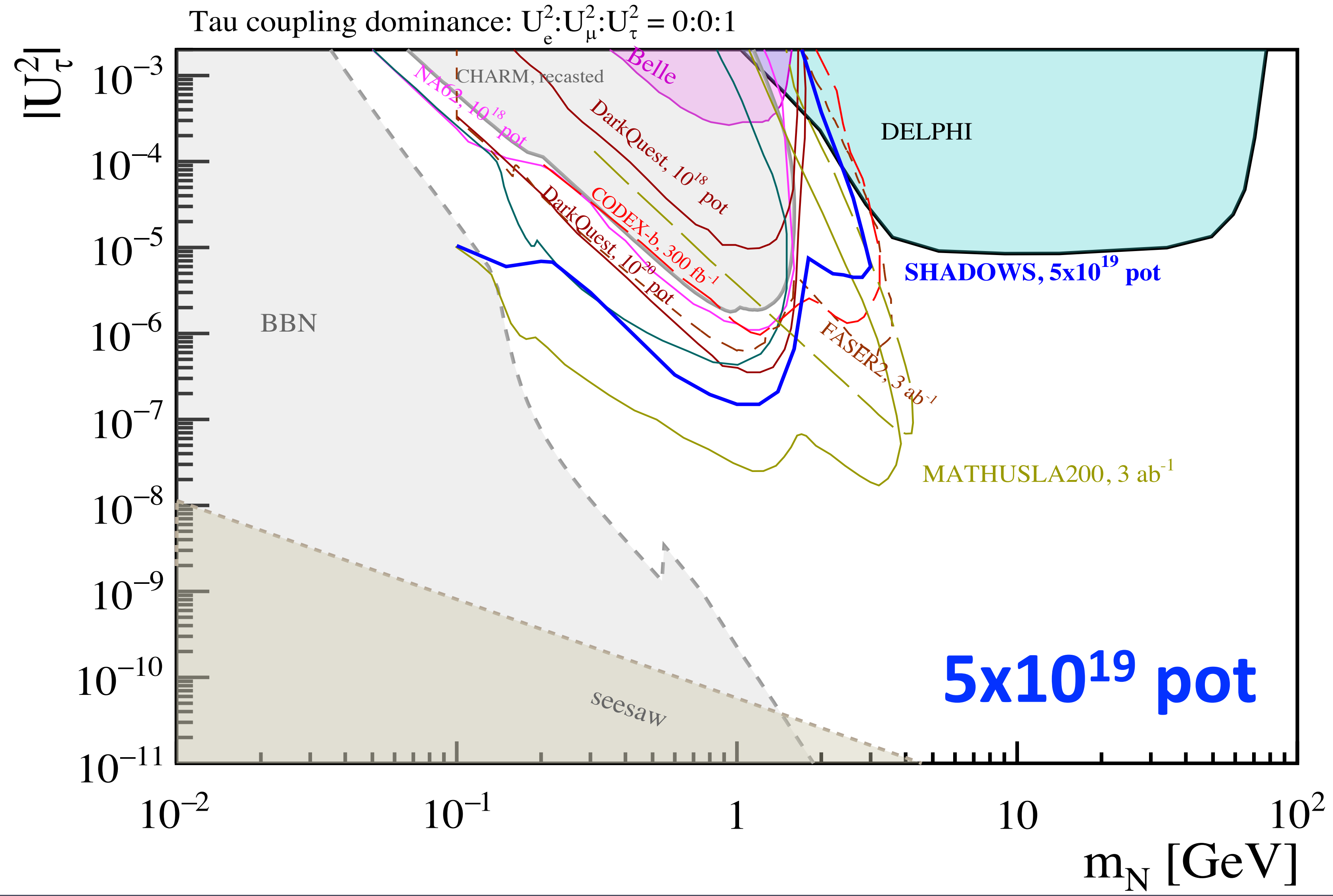
SHADOWS ($5x10^{19}$ pot) better than FASER2 (3 ab^{-1}), and comparable to CODEX-b (300 fb^{-1}).

SHADOWS sensitivity to standard PBC benchmarks

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







HNL – single lepton dominance:

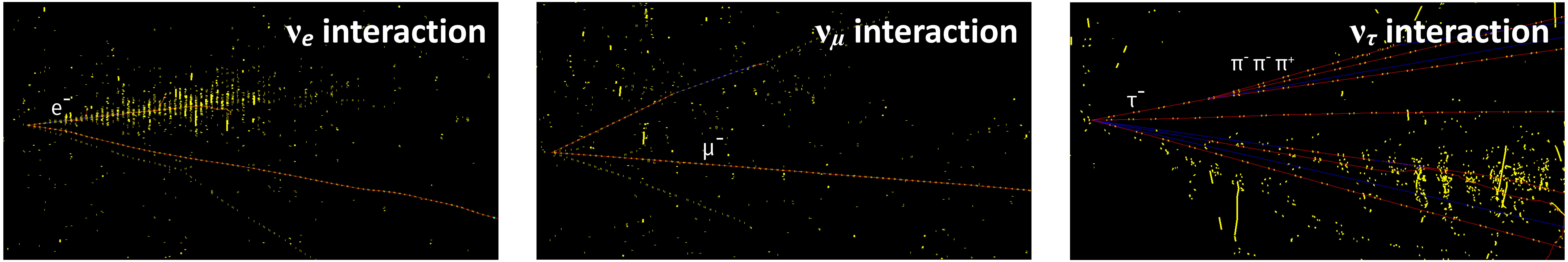
Between K and D: SHADOWS is better than CODEX-b and FASER2 with their full dataset.

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.

NaNu: Option for Tau and Anti-Tau Neutrino Detection

GEANT4 Simulation:



Reconstructed $\nu_\tau/\bar{\nu}_\tau$ events in NaNu:

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

290 reconstructed ν_τ interactions **190 reconstructed $\bar{\nu}_\tau$ interactions**