Search for mu->e conversion with Muons at J-PARC

@ Y. Uchida

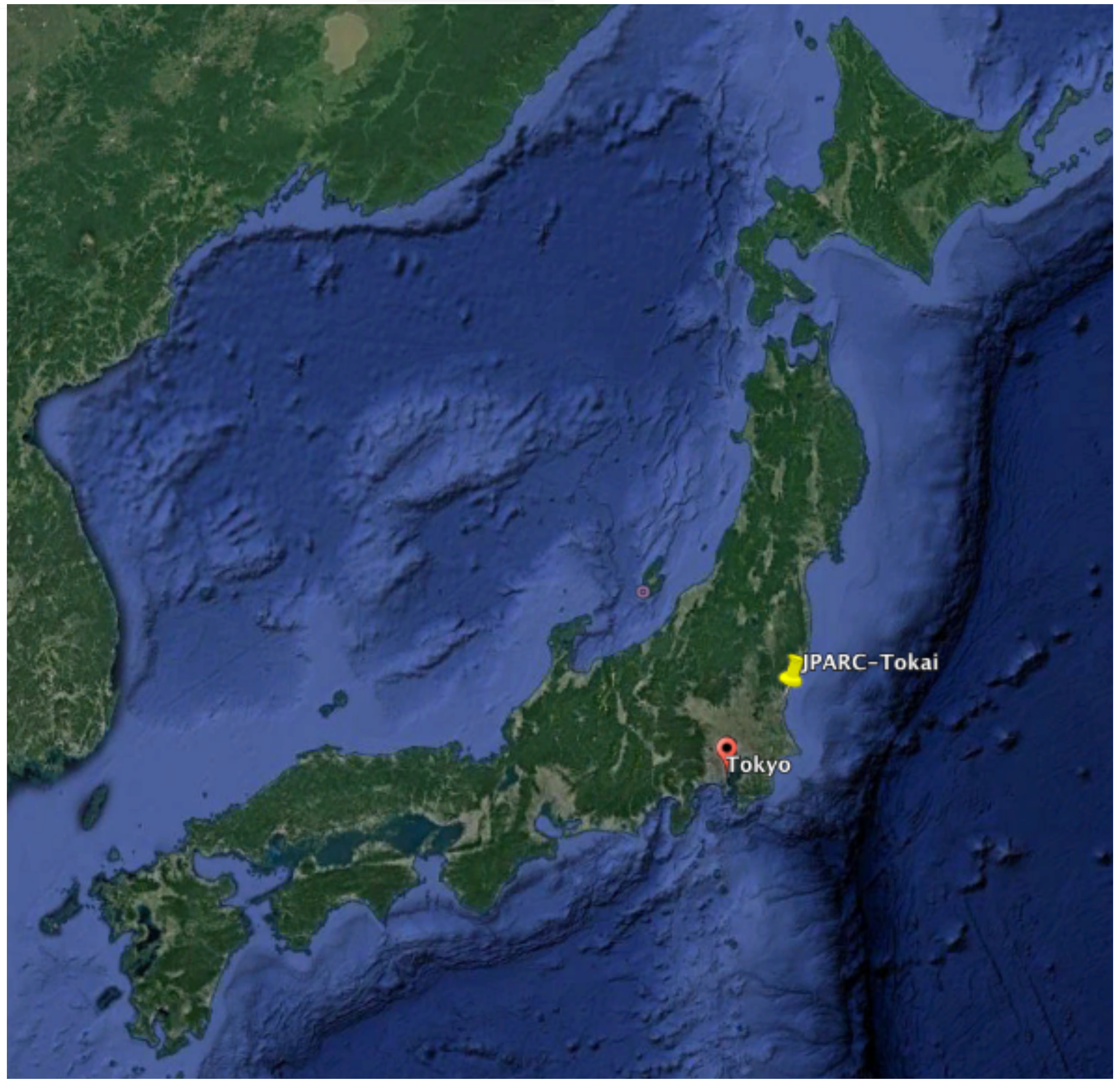
COMET

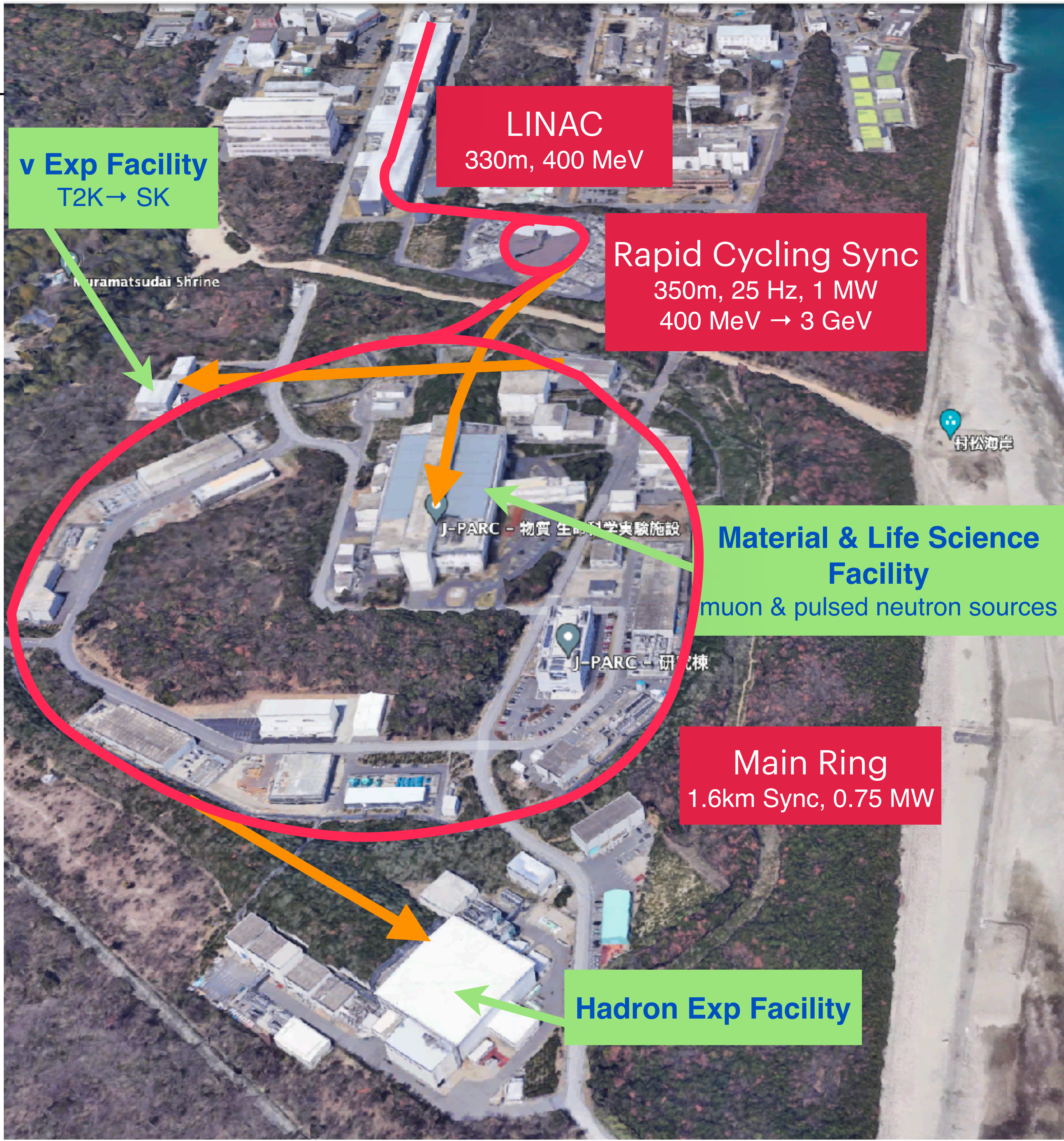
大強度陽子加速器施設
J-PARC
Japan Proton Accelerator Research Complex

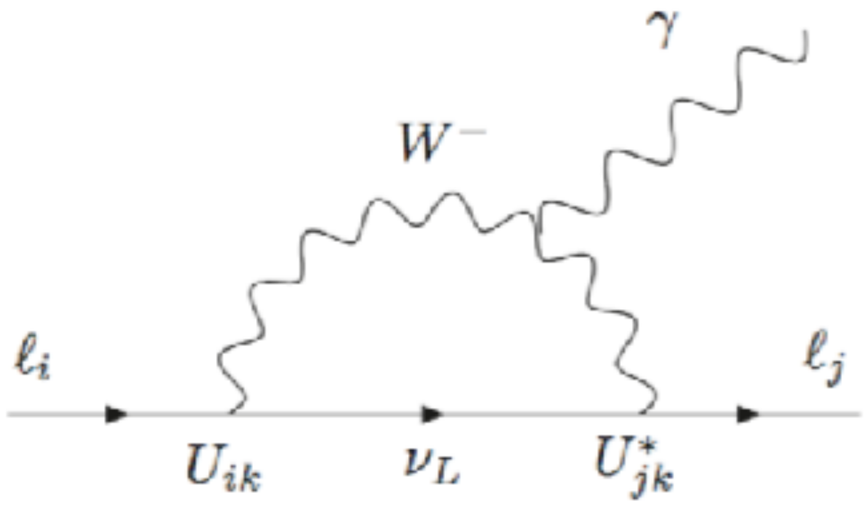
C Cârloganu
LPC/IN2P3/CNRS

COMET @JParc Facility (KEK/JAEA)

43 institutes,18 countries



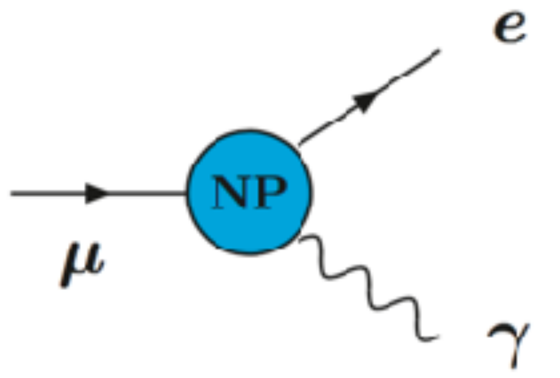




SM with $m_\nu > 0$

$$\mathrm{BR}(\mu \to e\gamma) \propto \left| \sum U^*_{\mu i} U_{ei} \frac{m^2_{\nu_i}}{M^2_W} \right|^2 \sim 10^{-54}$$

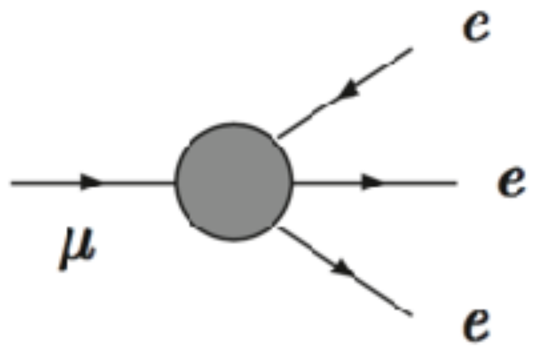
μ → e γ



Coincident
back-to-back e^+ - γ
$E_e = E_\gamma = m_\mu/2$ (~ 52.8 MeV)

BR(μ → eγ) 90% C.L.		
PSI/MEG	**2016**	**4.2×10^{-13}**
PSI MEG II		4×10^{-14}

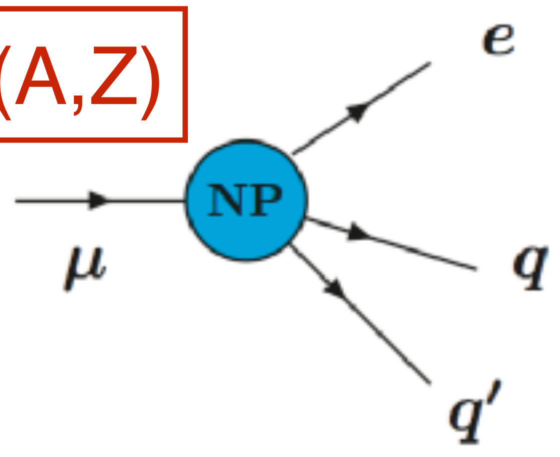
$\mu^+ \to e^+e^-e^+$



$\Sigma E = m$; $\Sigma \vec{P} = 0$
vertex; coincidence

BR(μ → eee) 90% C.L.		
PSI/SINDRUM	**1988**	**1.0×10^{-12}**
JINR	1991	3.6×10^{-11}
PSI/PSI/Mu3e		10^{-15} -

$\mu^- + (A,Z) \to e^- + (A,Z)$



E(Al, Pb, Ti) ≈100 MeV
single electron;
well defined energy
well defined time

$CR(\mu \to e, N), bound$		
4.3×10^{-12}	Ti	1993
4.6×10^{-11}	Pb	1996
7×10^{-13}	Au	2006

Improve by a factor 10^4 the present limit $R_{\mu e} < 7\ 10^{-13}$

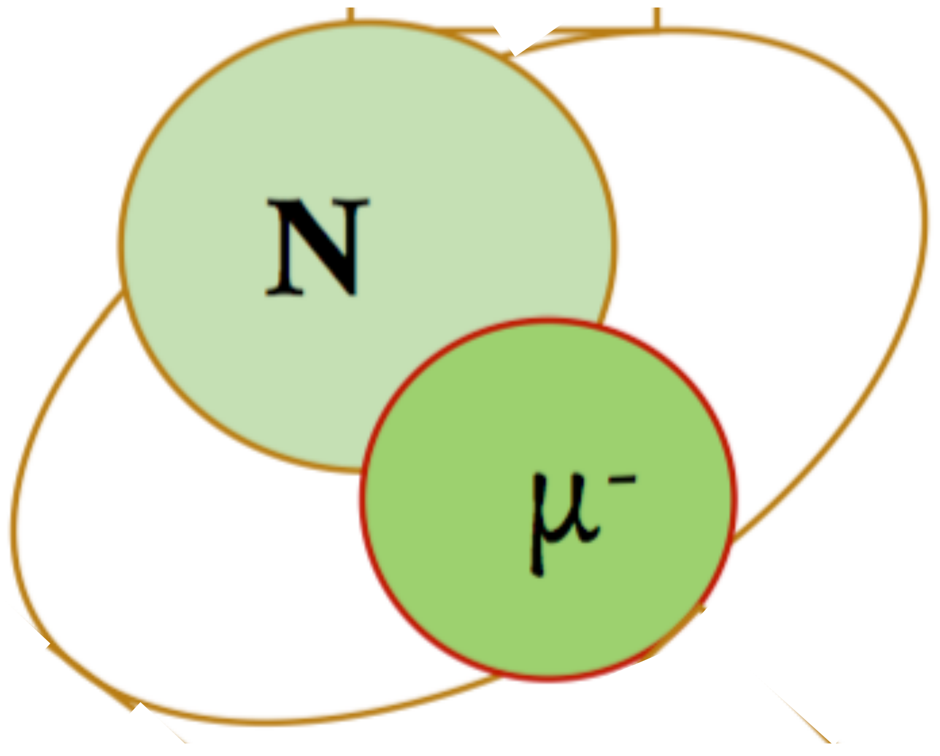
$$R_{\mu e} = \frac{\Gamma\left(\mu^- + N(A,Z) \rightarrow e^- + N(A,Z)\right)}{\Gamma\left(\mu^- + N(A,Z) \rightarrow \nu_\mu + N(A,Z-1)\right)}$$

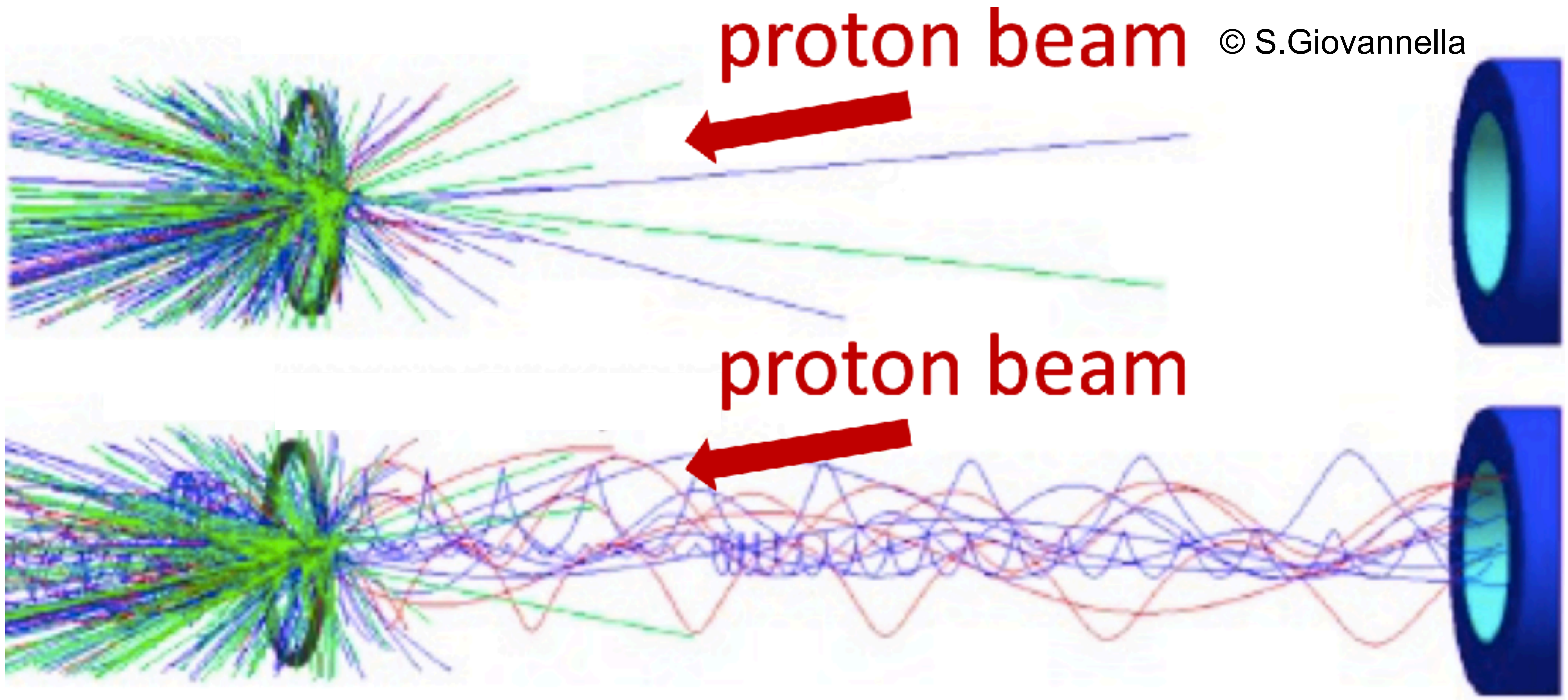
This requires:
- **10^{18} stopped muons**
- high background suppression ($N_{bckg} \ll 0.5$)

$CR(\mu \to e, N), bound$		
4.3 x 10^{-12}	Ti	1993
4.6 x 10^{-11}	Pb	1996
7 x 10^{-13}	Au	2006

Soft pions confined with solenoidal B field

Strong gradient to increase the yield through magnetic reflection





Proof of Principle : MuSIC @ RCNP, OSAKA University

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Delivering the world's most intense muon beam

S. Cook, R. D'Arcy, A. Edmonds, M. Fukuda, K. Hatanaka, Y. Hino, Y. Kuno, M. Lancaster, Y. Mori, T. Ogitsu, H. Sakamoto, A. Sato, N. H. Tran, N. M. Truong, M. Wing, A. Yamamoto, and M. Yoshida

Phys. Rev. Accel. Beams **20**, 030101 – Published 15 March 2017

3.5T and graphite proton target

MuSIC muon yields

μ^+ : 3×10^8/s with 400W

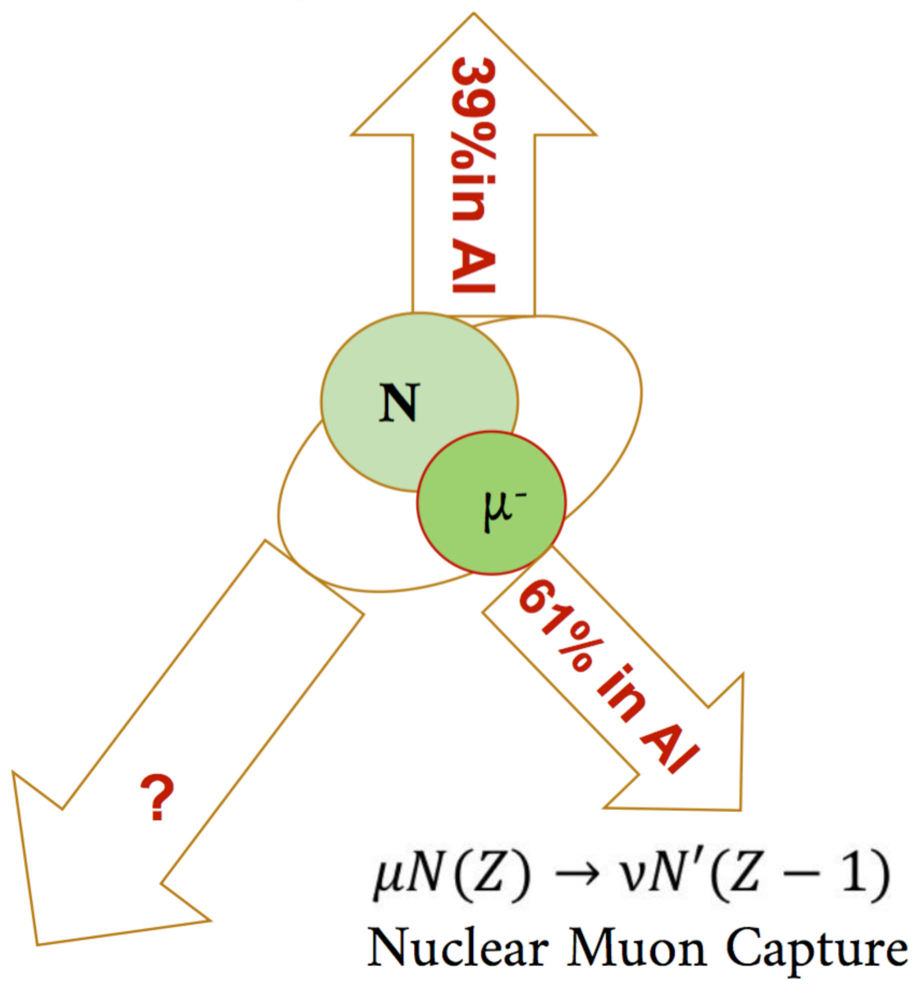
μ^- : 1×10^8/s with 400W

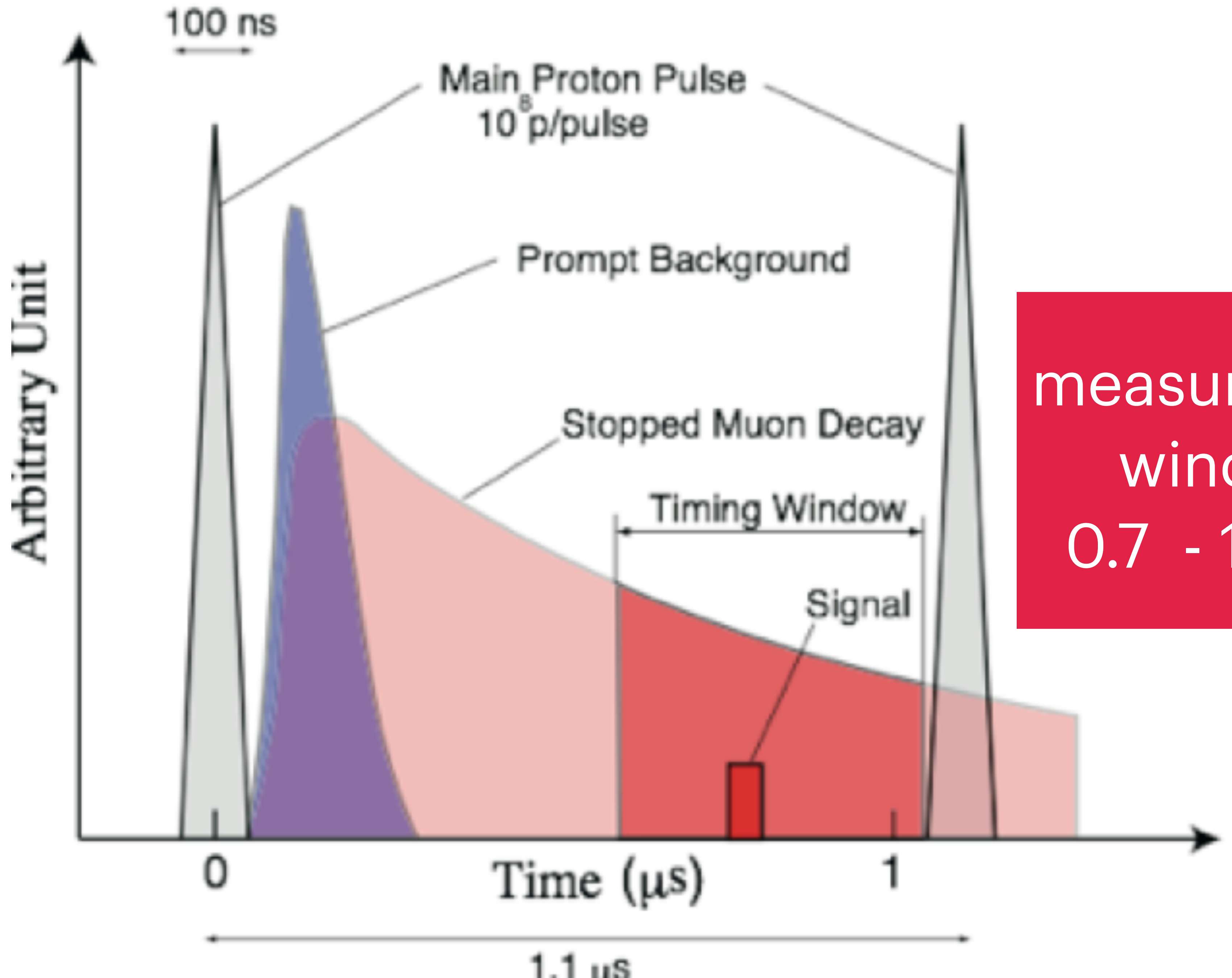
10^{11}/s with 50 kW, possible!

NUCLÉAIRE & PARTICULES

Decay In Orbit

$\mu N \to e\nu\bar{\nu}N$



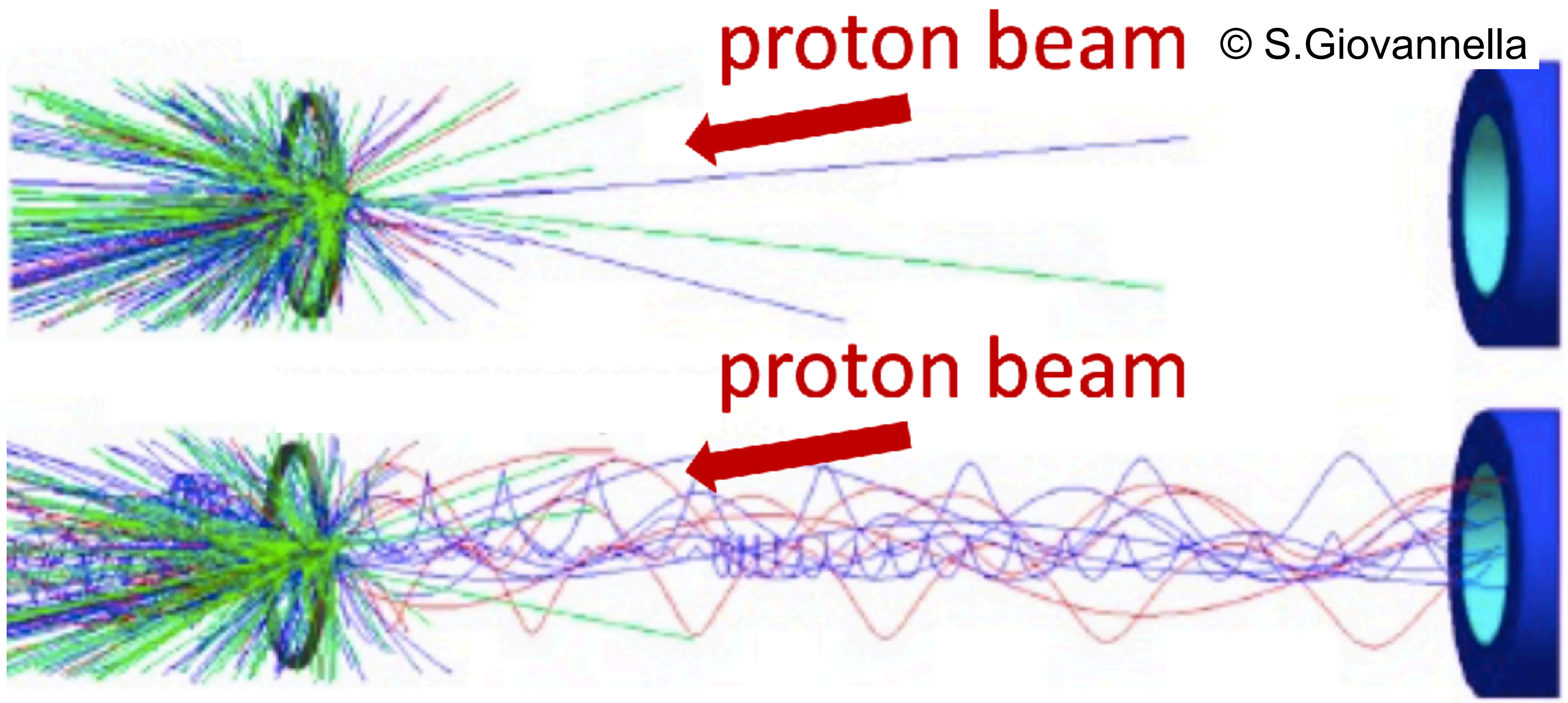


measurement window
0.7 - 1.17 μs

© Lobashev and Djilkibaev, MELC experiment [Sov.J.Nucl.Phys. 49, 384 (1989)]

Soft pions confined with solenoidal B field

Strong gradient to increase the yield through magnetic reflection



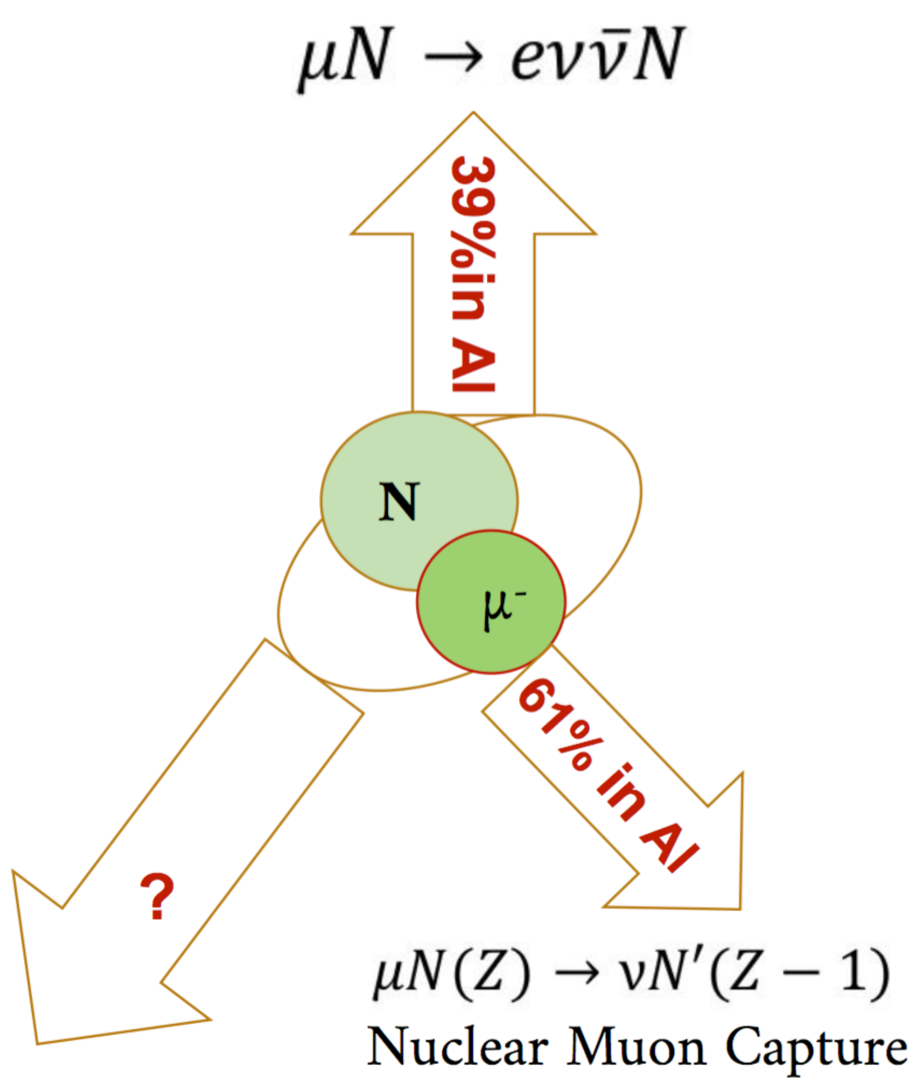
Delayed DAQ gate to suppress prompt backgrounds

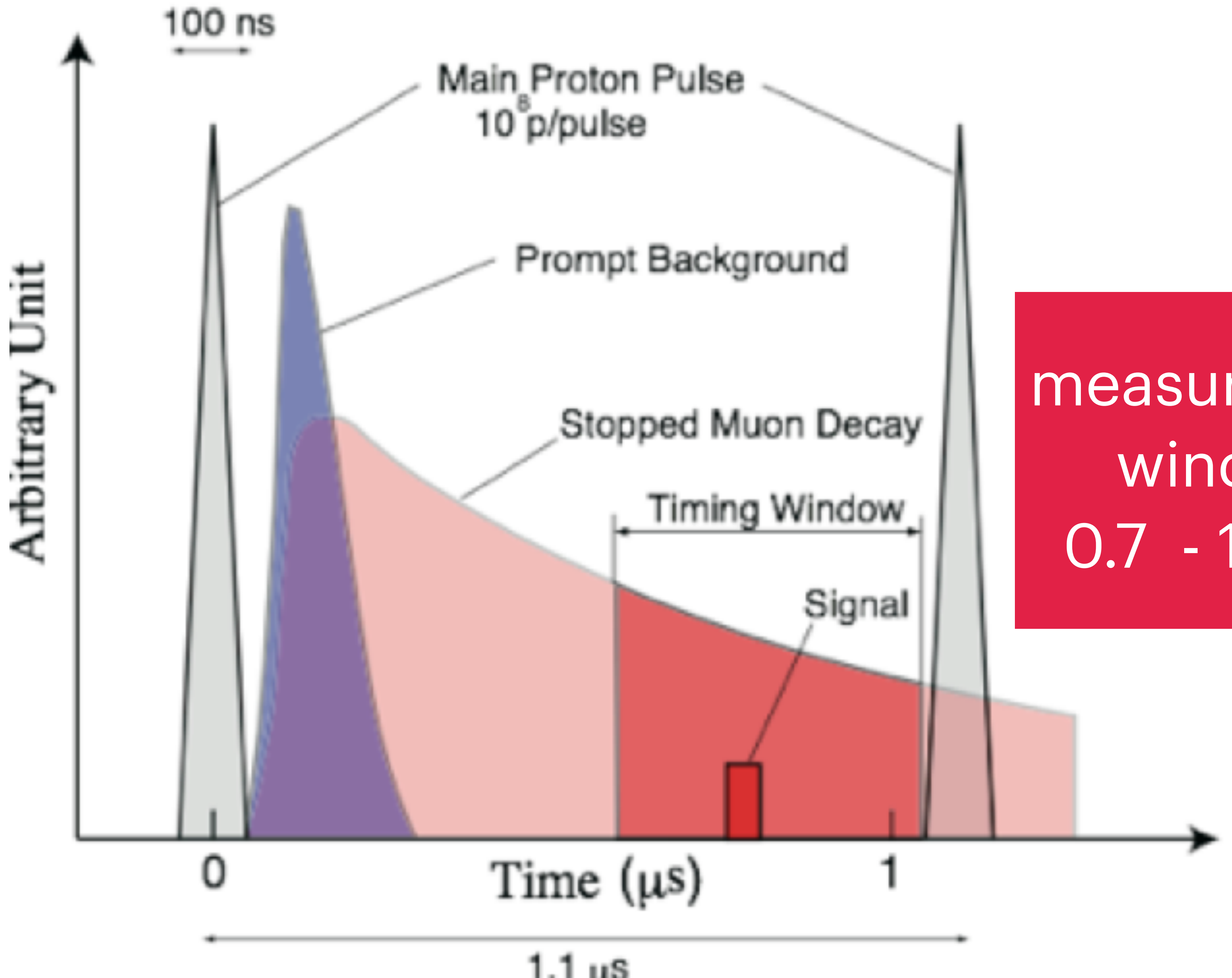
Narrow proton pulses

O(10^{10}) out-of-time protons suppression

Material target	Atomic number (Z)	Muonium lifetime (ns)
Aluminum	13	864
Titanium	22	330
Lead	82	74

Decay In Orbit





measurement window
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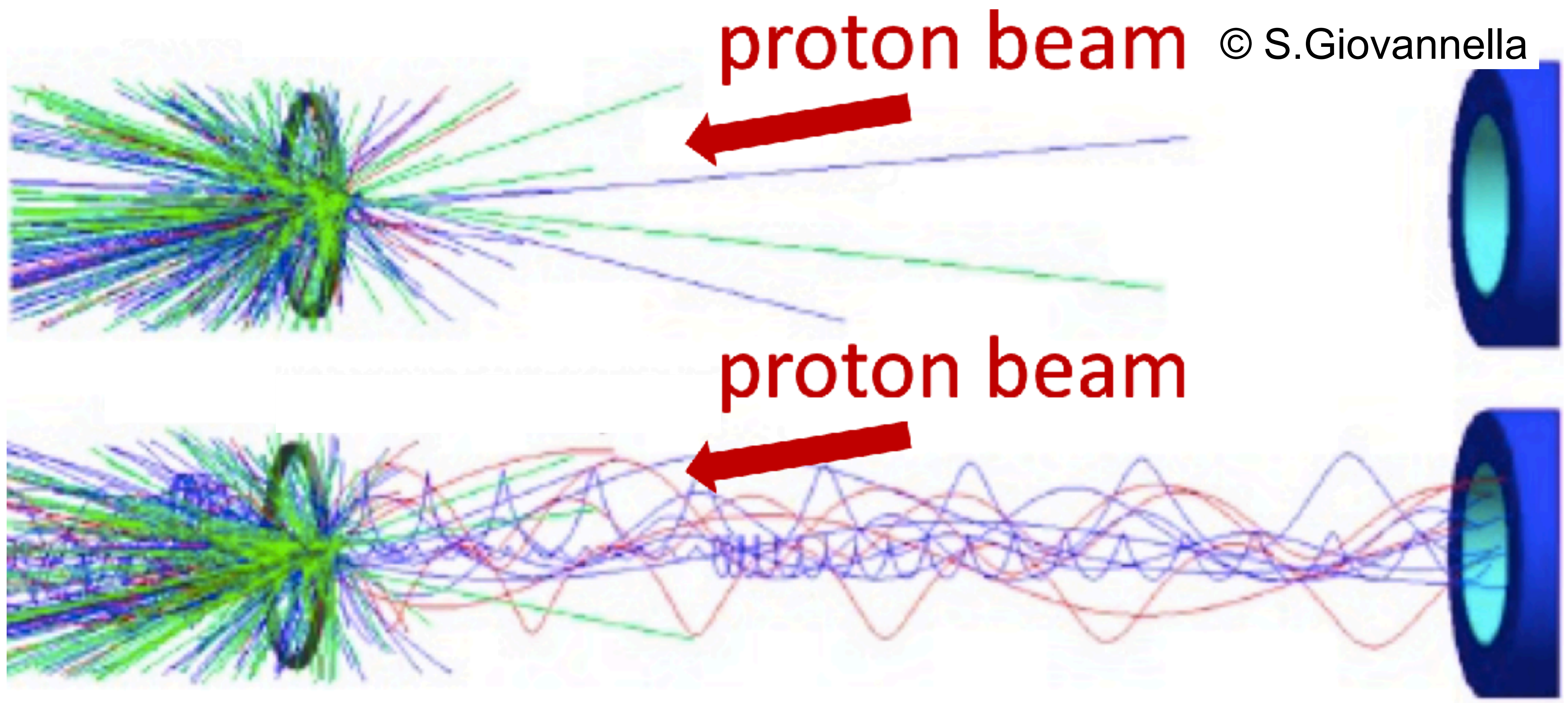
© Lobashev and Djilkibaev, MELC experiment [Sov.J.Nucl.Phys. 49, 384 (1989)]

Soft pions confined with solenoidal B field

Strong gradient to increase the yield through magnetic reflection

© S.Giovannella



Delayed DAQ gate to suppress prompt backgrounds

Narrow proton pulses

$O(10^{10})$ out-of-time protons suppression

Atmospheric muons can fake signal events

⇒ proportional to the running time

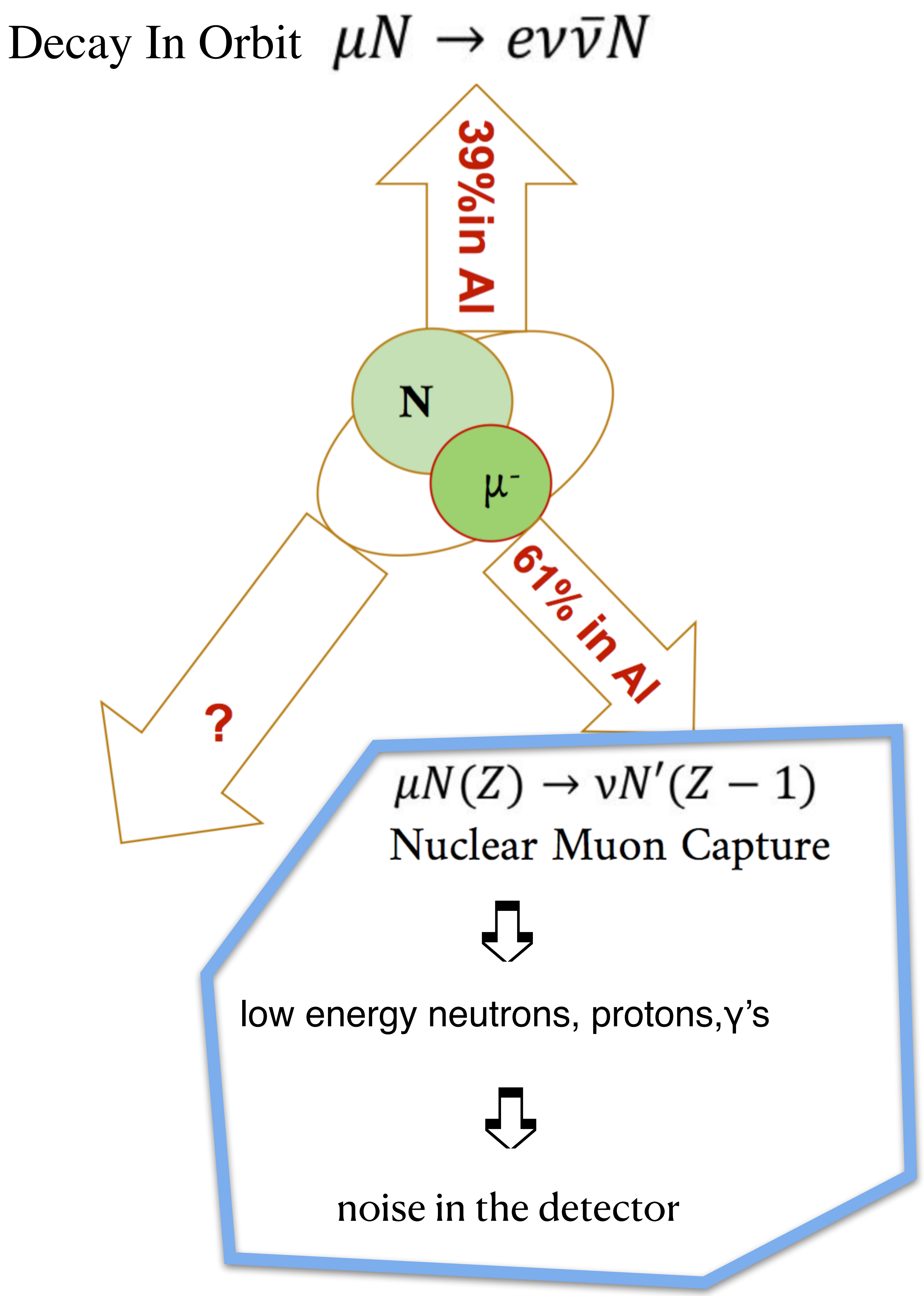
⇒ higher beam intensity is preferable

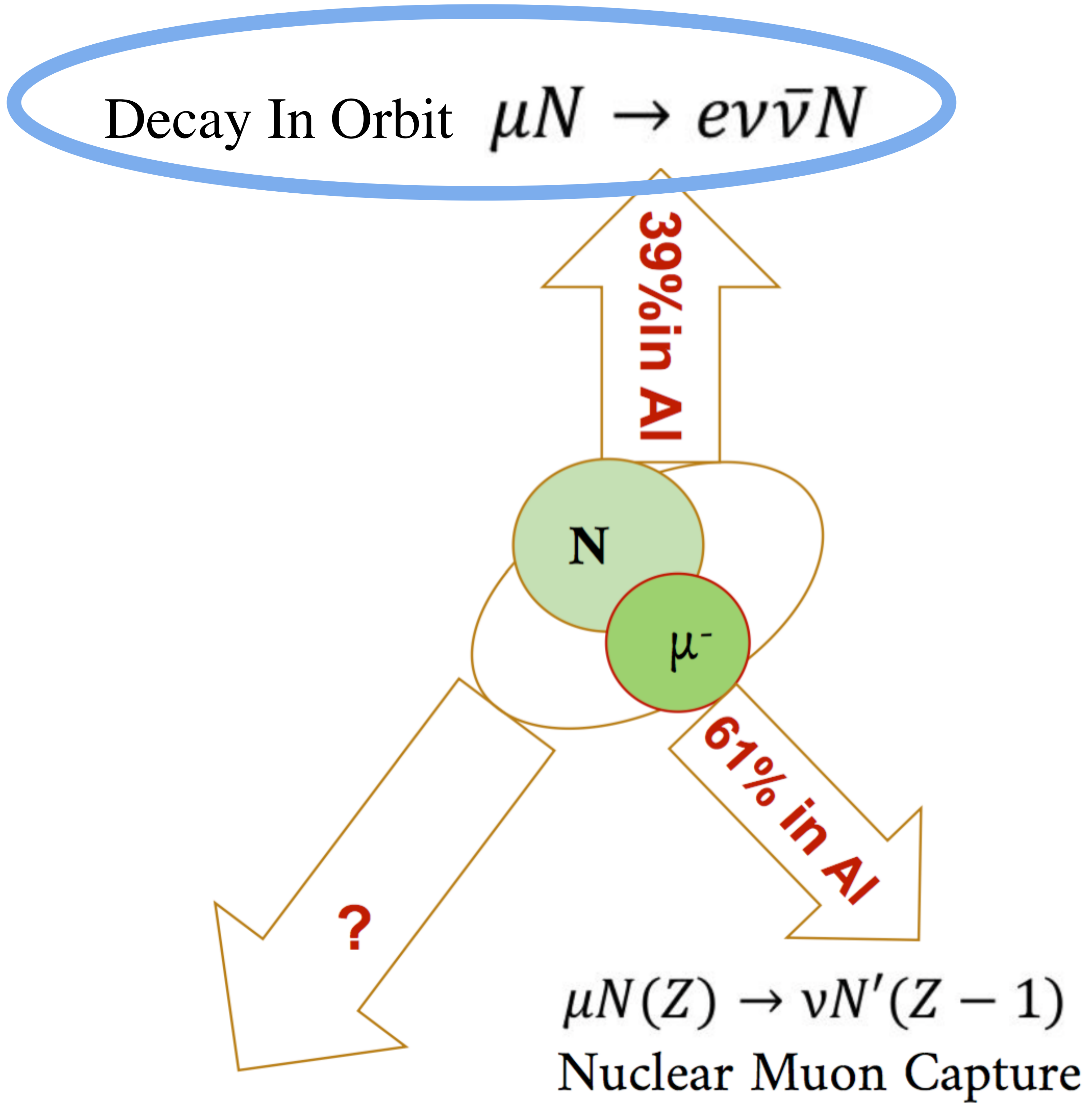
Muonic atoms

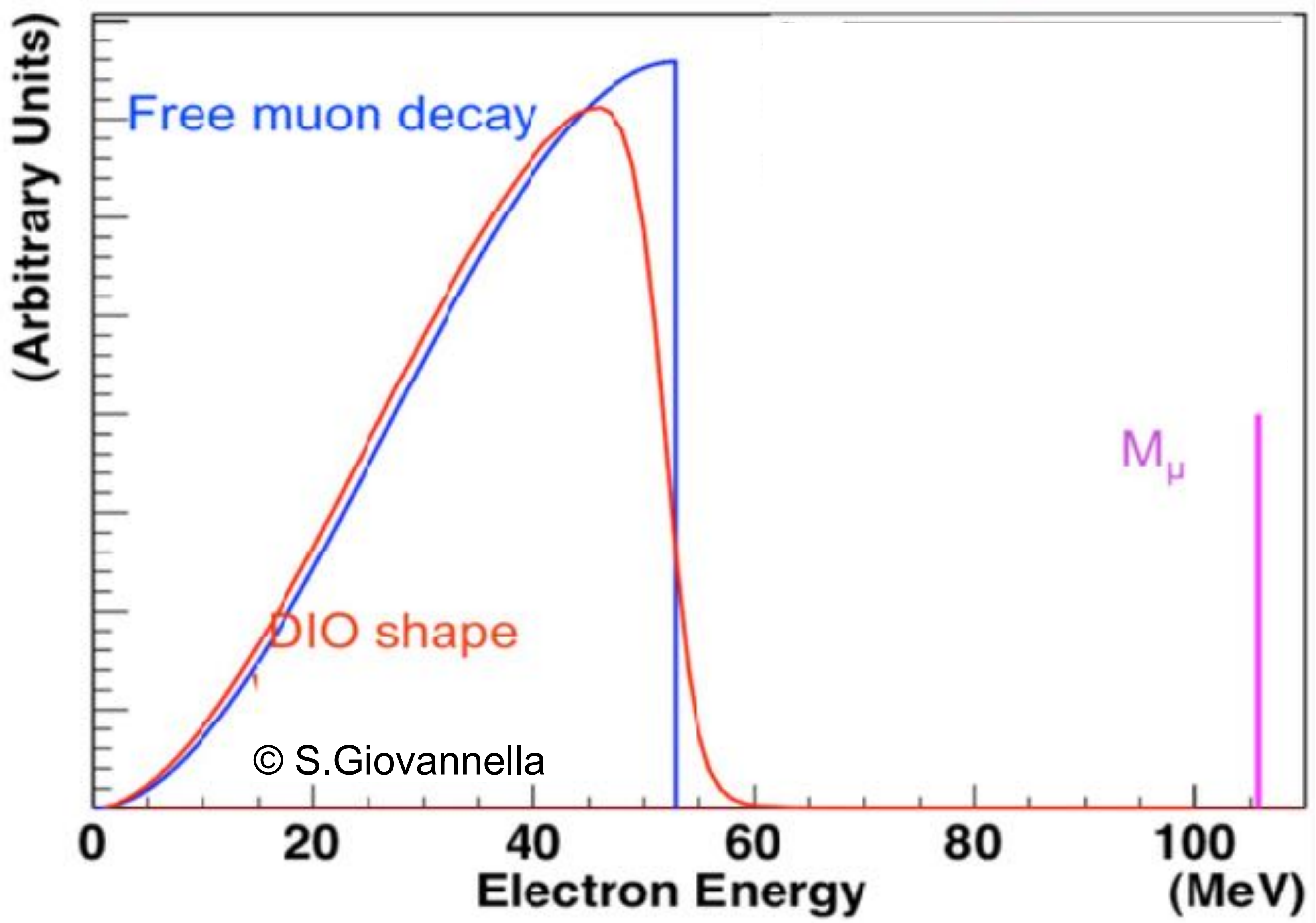
μ^- stopped in a target → 1s bound state

+

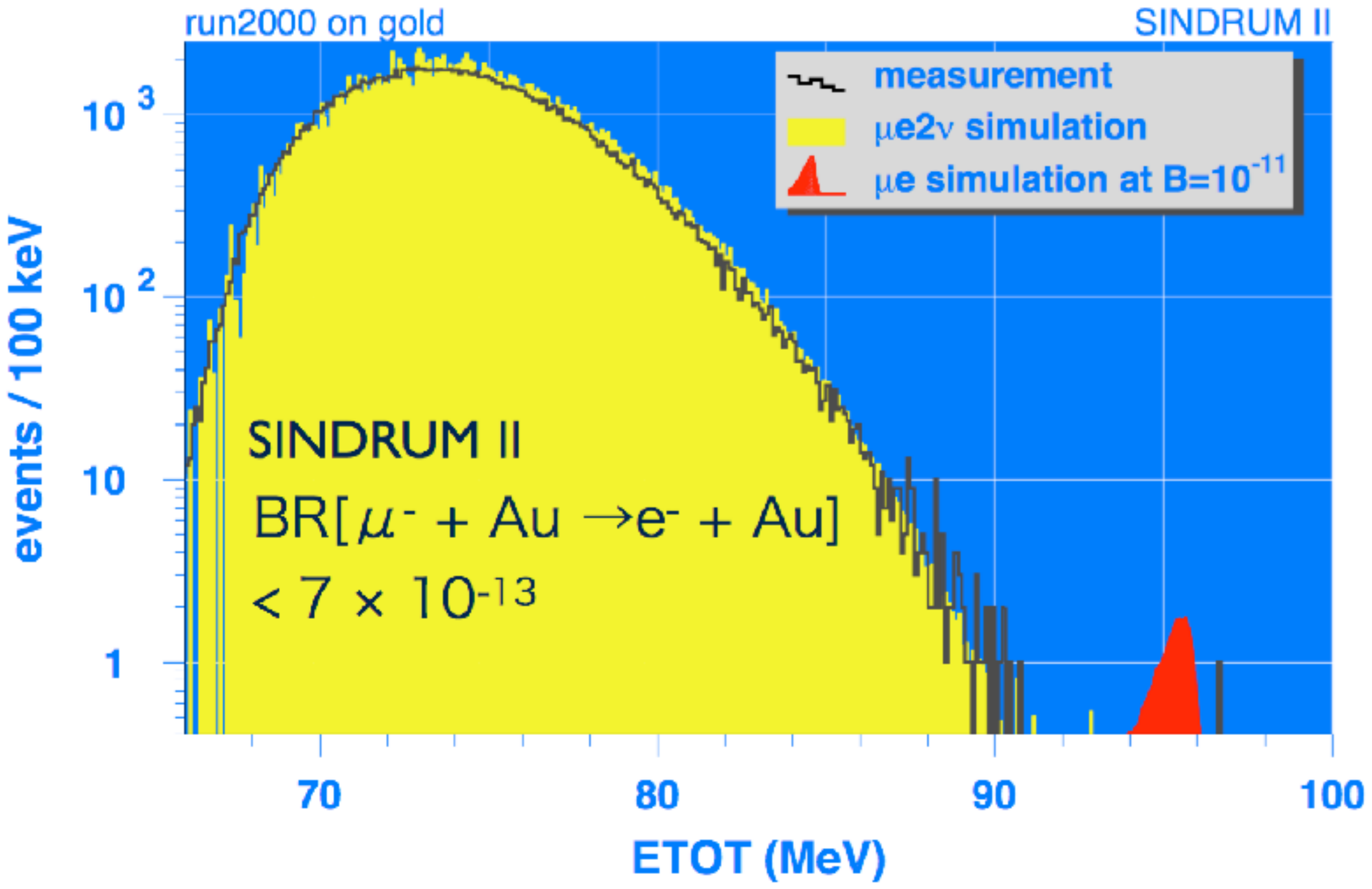
muonic X-Rays





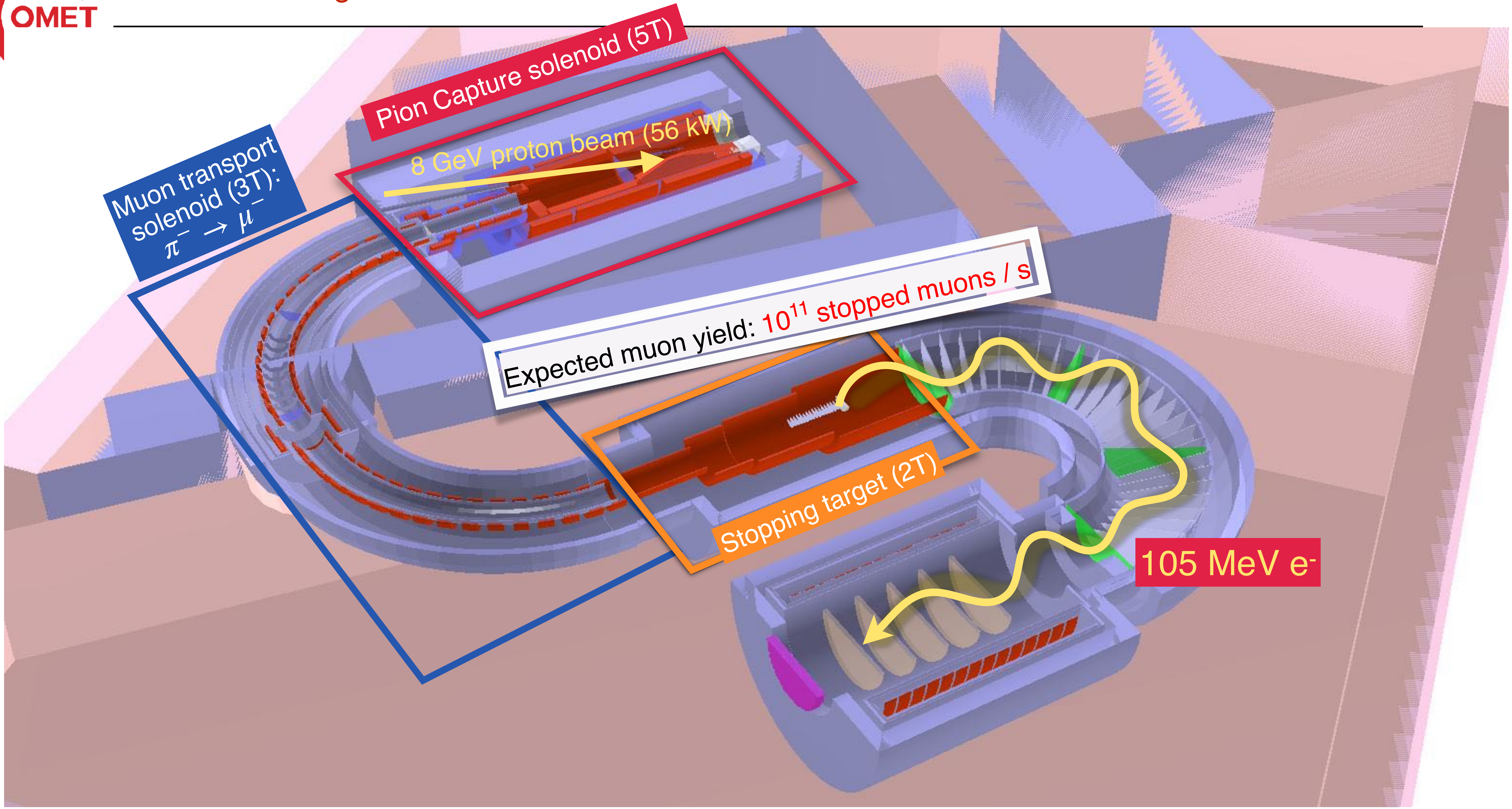


Required momentum resolution : better than 200 keV/c

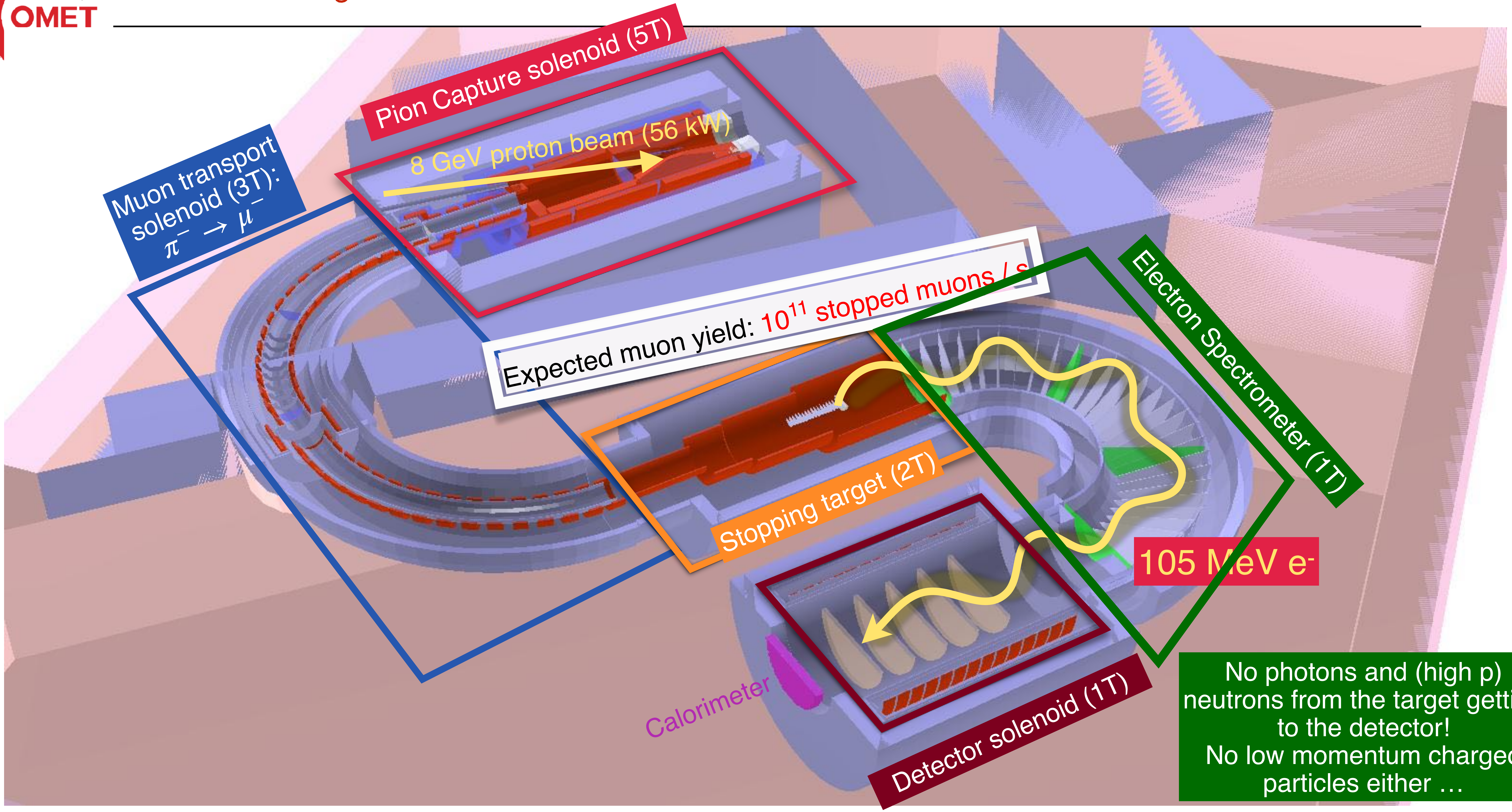


Improve the momentum resolution:
- minimise the multiple scattering : thin Al target, gas tracker

COMET design

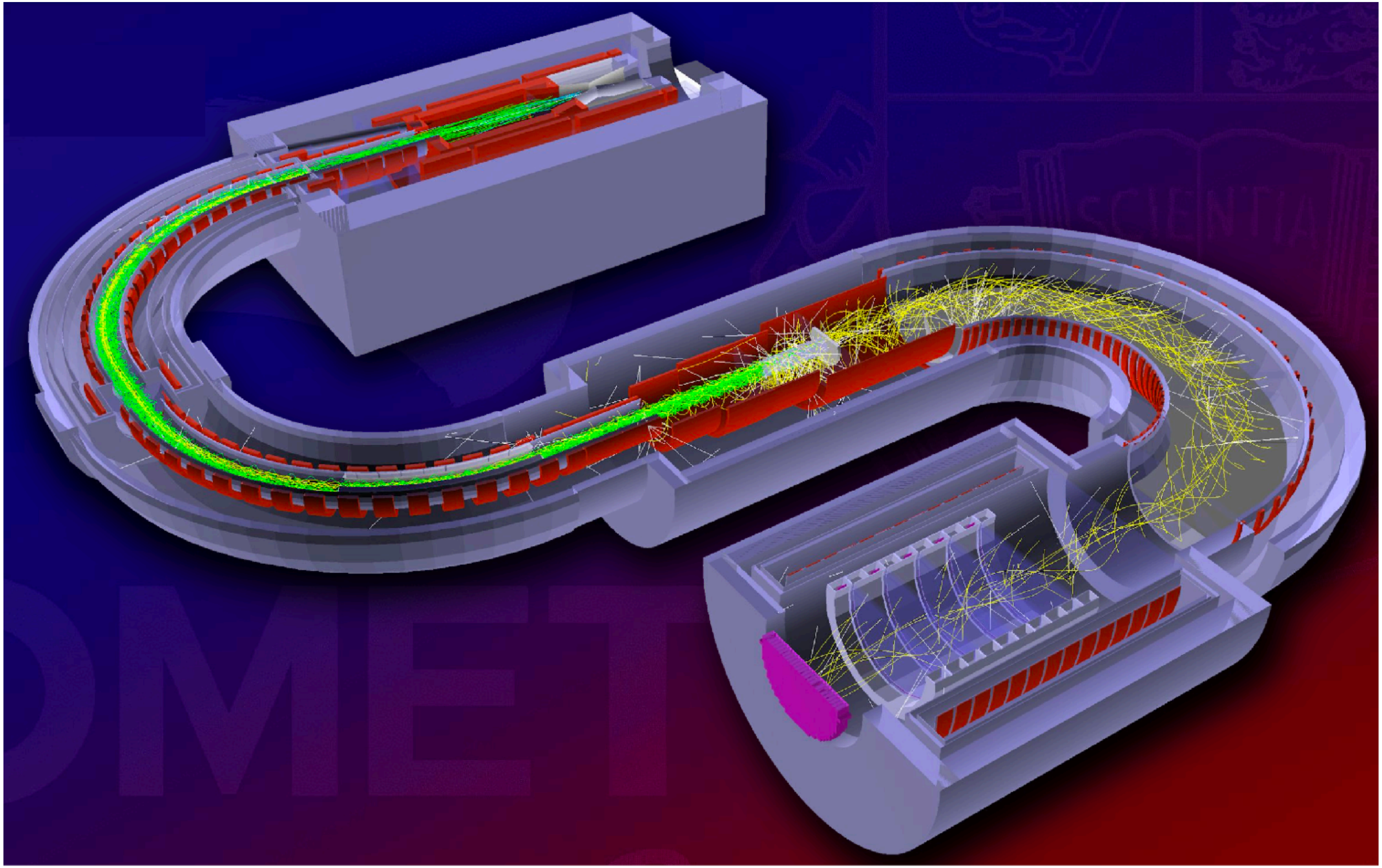


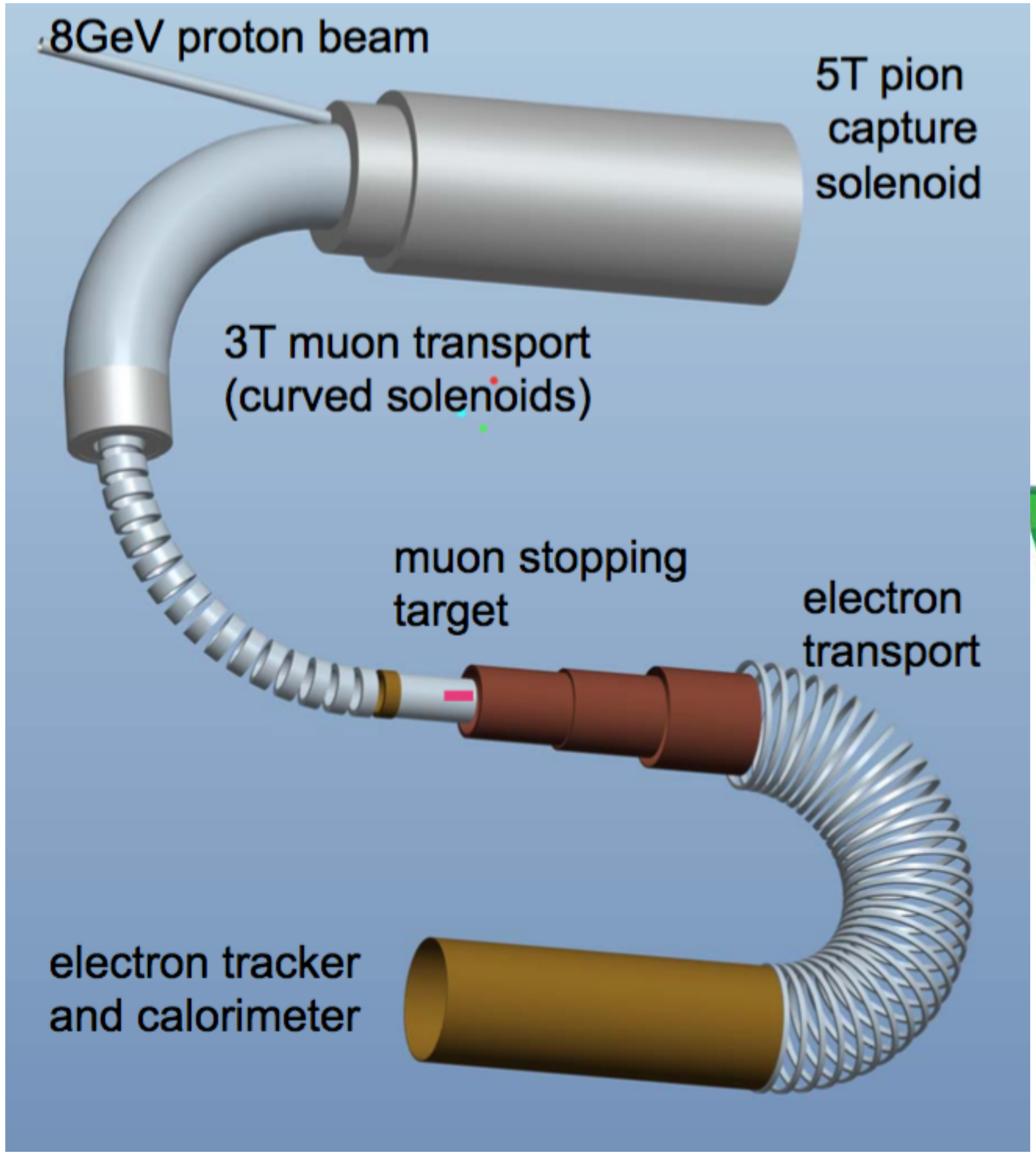
COMET design

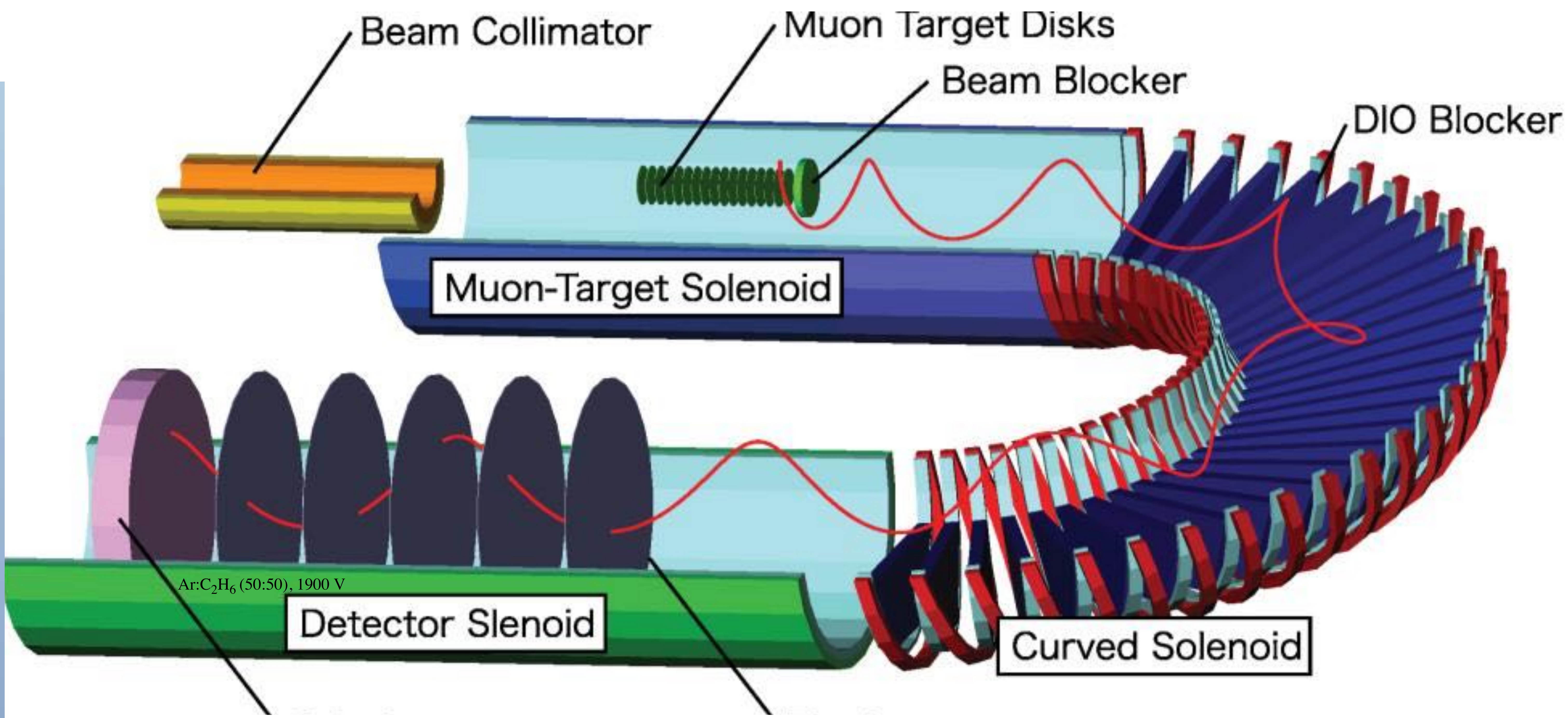


No photons and (high p) neutrons from the target getting to the detector!
No low momentum charged particles either …

A simulated COMET event







Electromagnetic calorimeter

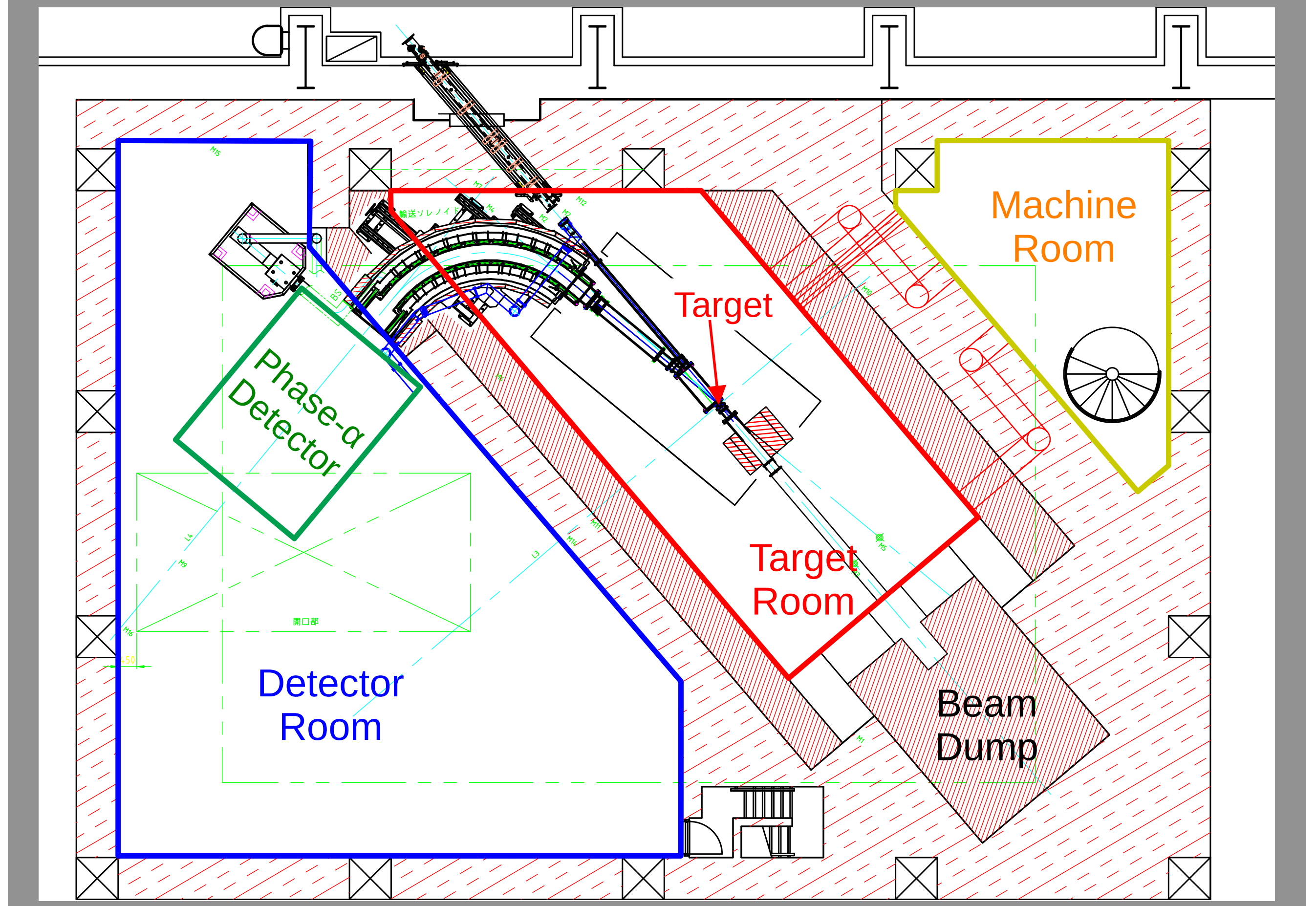
- trigger & timing: response time faster than 100 ns
- electron energy : $\Delta E/E < 5\%$ (@105 MeV)
- cluster position: σ_x<1 cm
- 50 cm of radius
- made of 1920 LYSO crystals $2\times2\times12$ cm^3 (10.5 X_0)
- read out by APDs (operates @ 1 T)

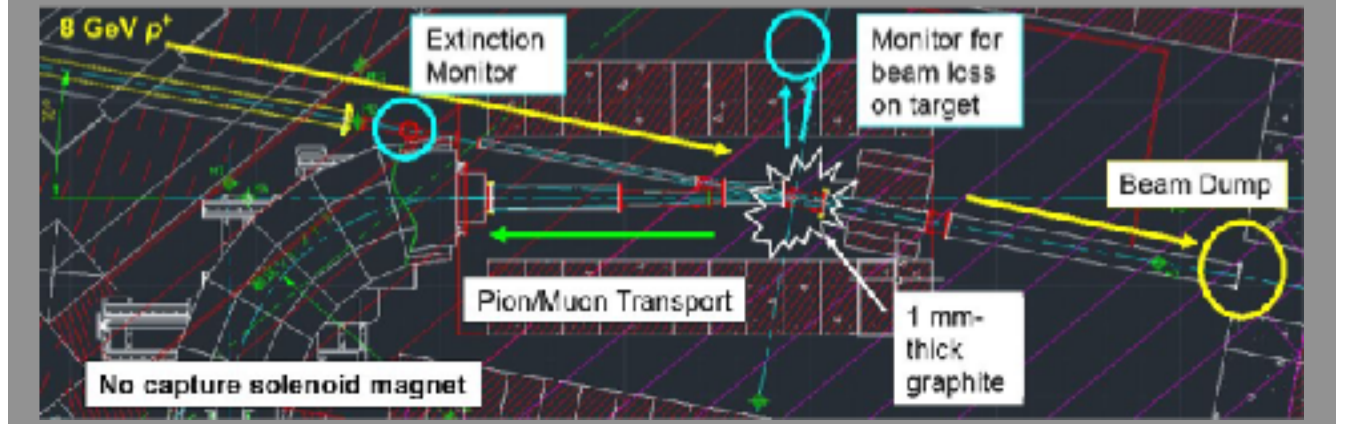
Straw tubes tracker

- operates in vacuum @ 1T
- Δp = 150~200 keV/c (@105 MeV/c)
- 12 µm thick, 5 mm diameter for Phase-II
- at least five stations

COMET, a 2-stage experiment (lately 2-> 2,5 ->3)

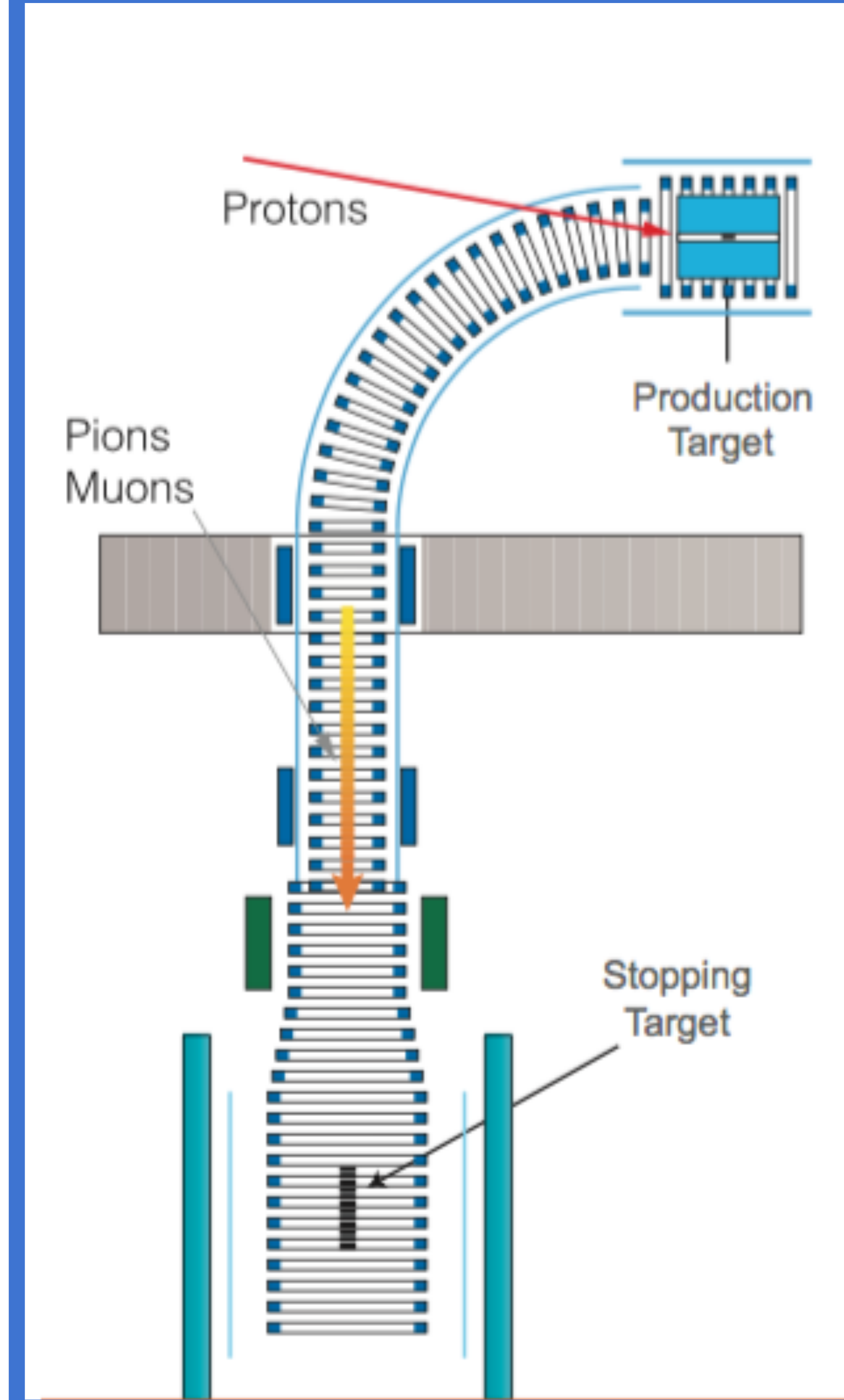
Phase α 2022





- Low intensity run (260 W) without Pion Capture Solenoid
- Thin graphite p-target
- Proton beam diagnostic detectors
- Secondary particle detectors

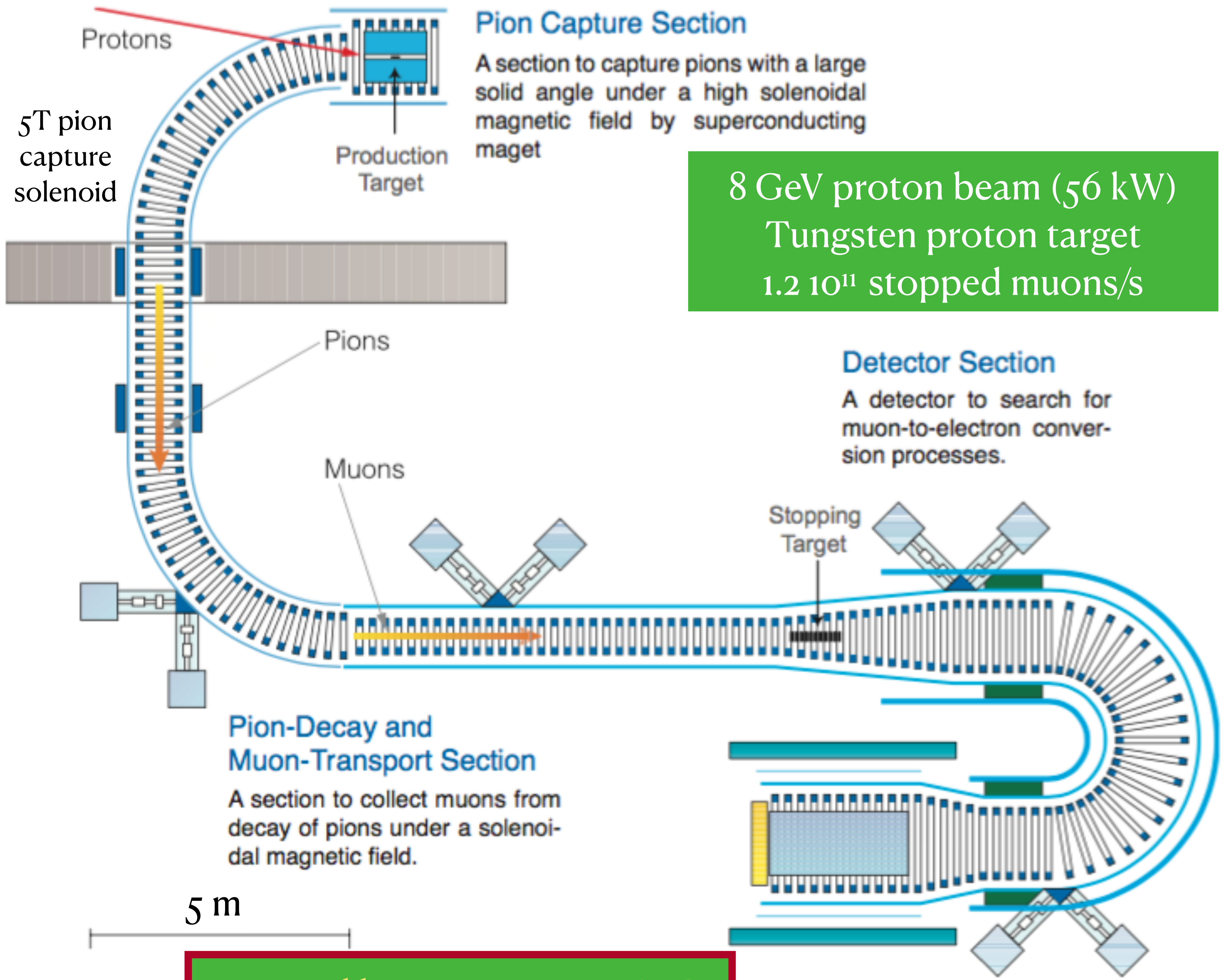
Phase I



8 GeV proton beam (3.2 kW)
Graphite proton target
1.2 10^{9} stopped muons/s

Expected limit : 7 10^{-15} @ 90% CL
Total background: 0.01 events
Running time: 0.4 yrs (1.2 10^{7} s)

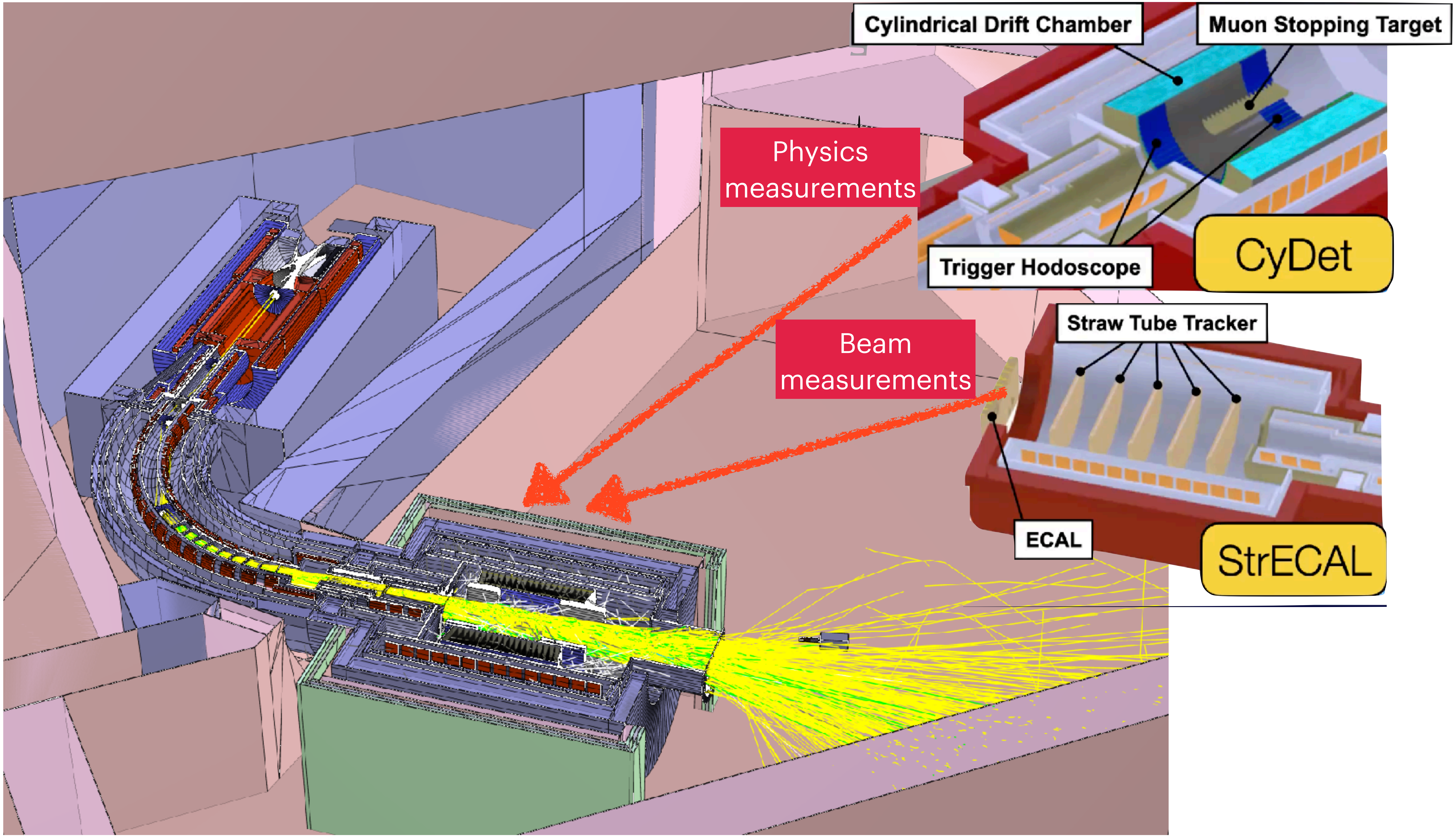
Phase II

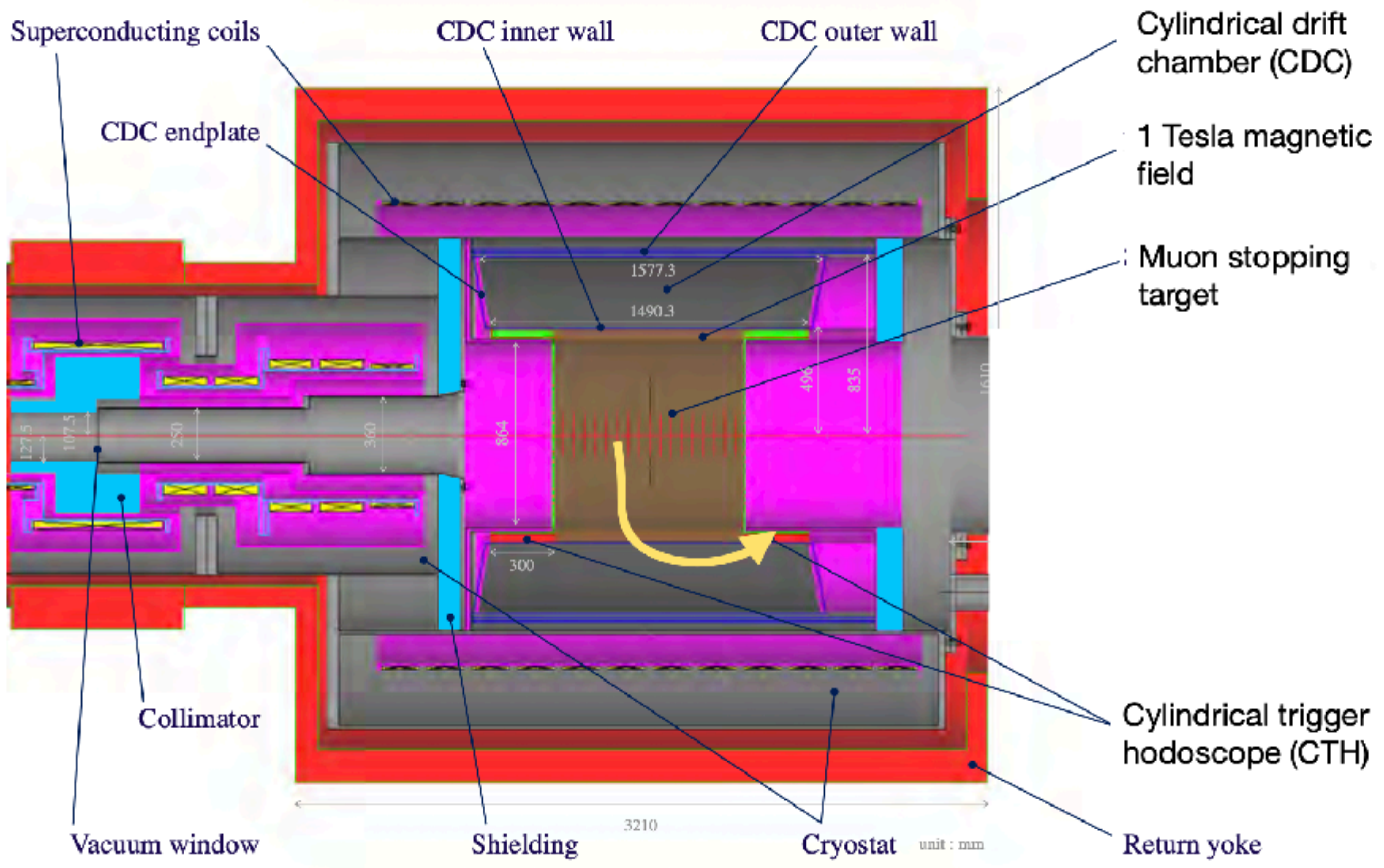


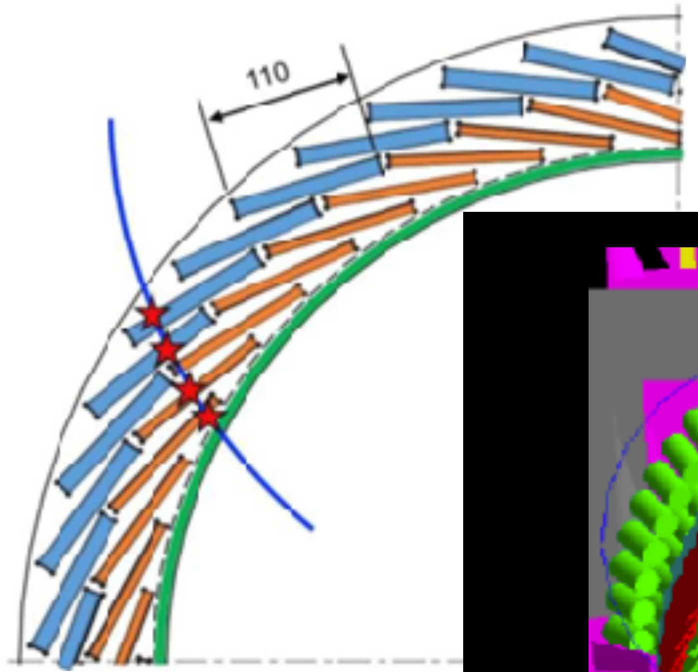
8 GeV proton beam (56 kW)
Tungsten proton target
1.2 10^{11} stopped muons/s

Expected limit : 7 10^{-17} @ 90% CL
Total background: 0.32 events
Running time: 1 yr (2 10^{7} s)

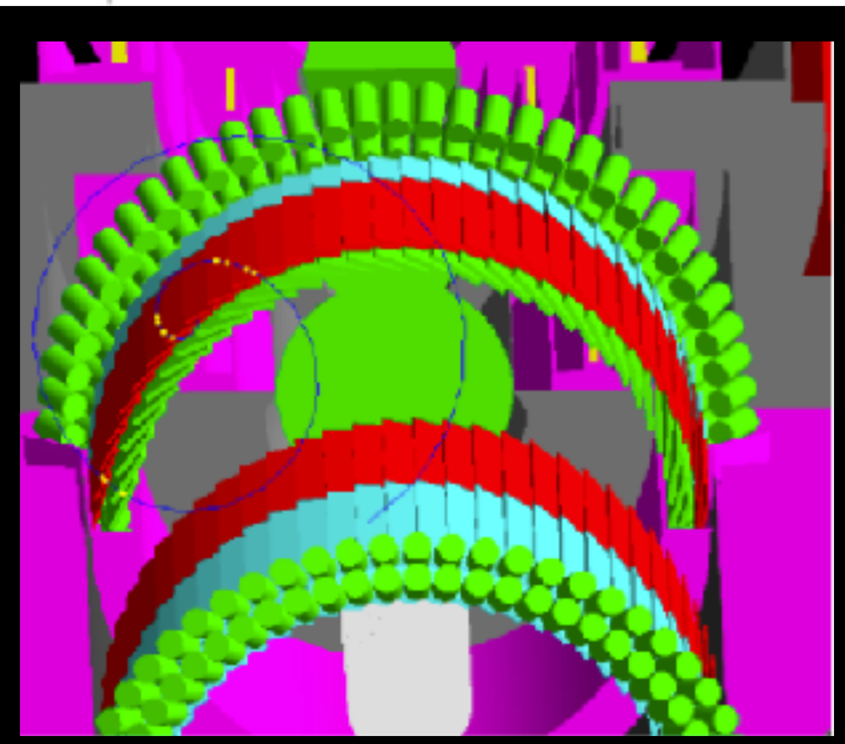
COMET Phase I



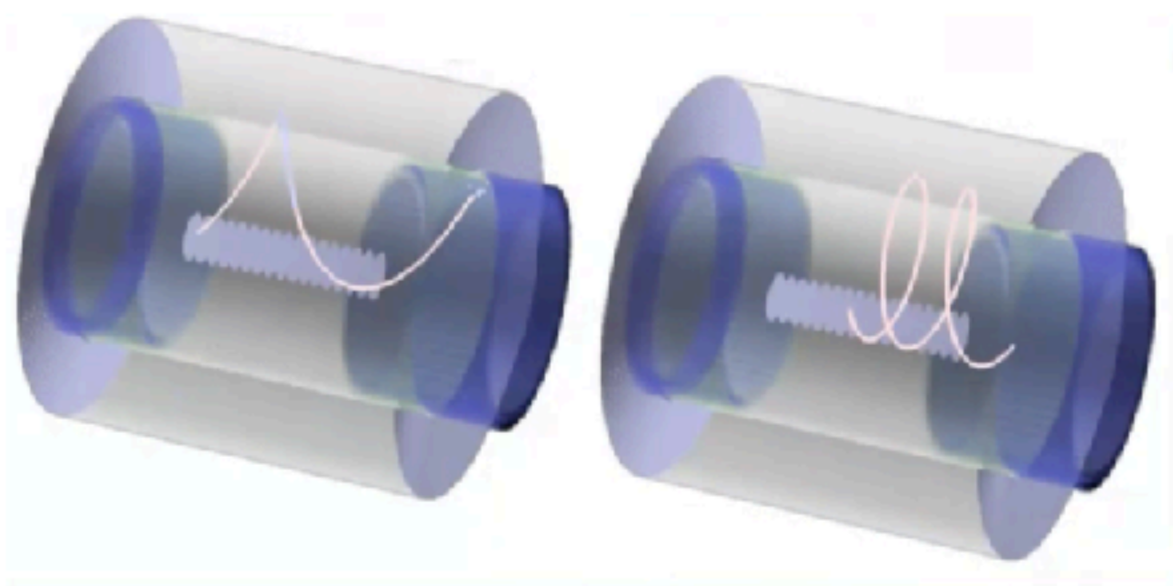


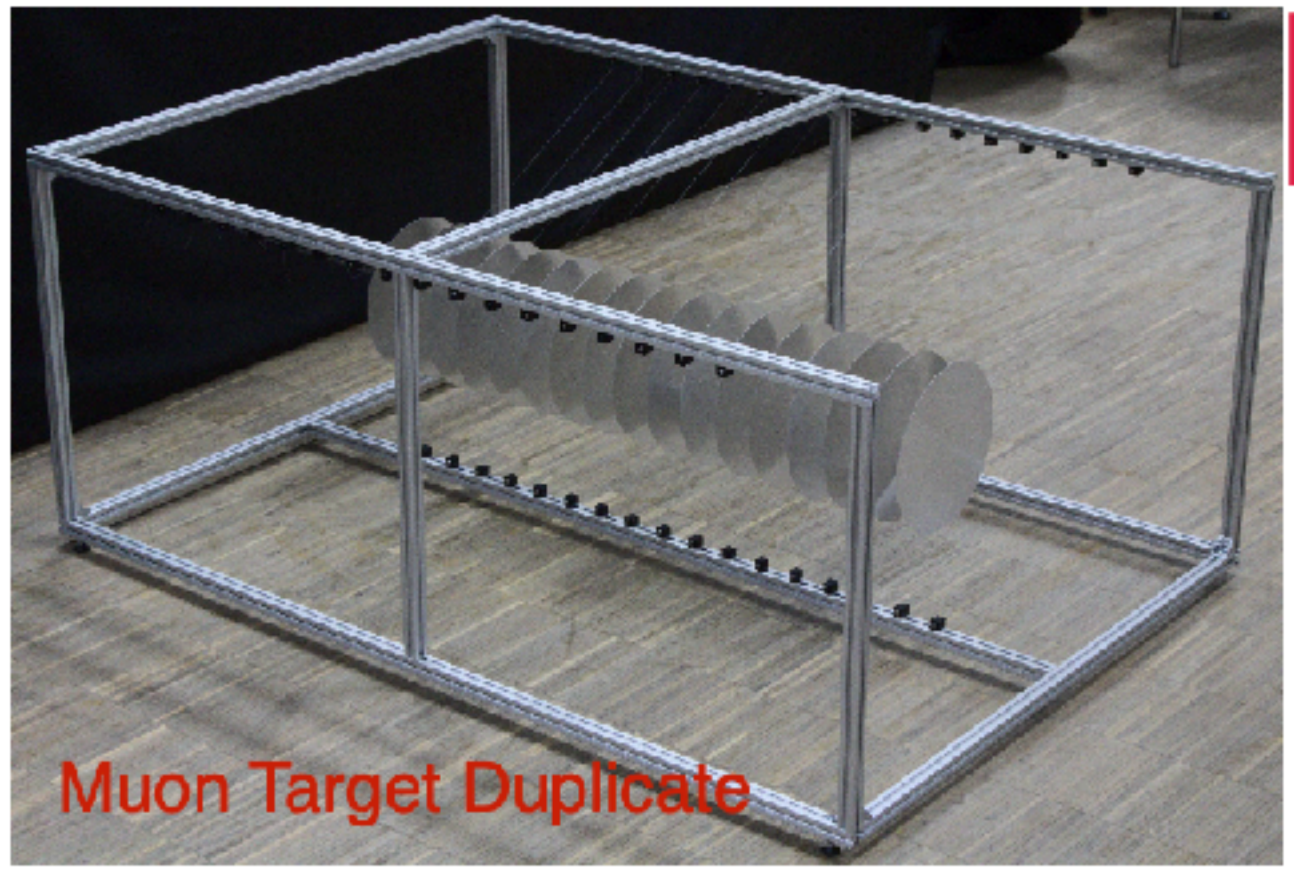


Four-hold coincidence provides trigger and PID

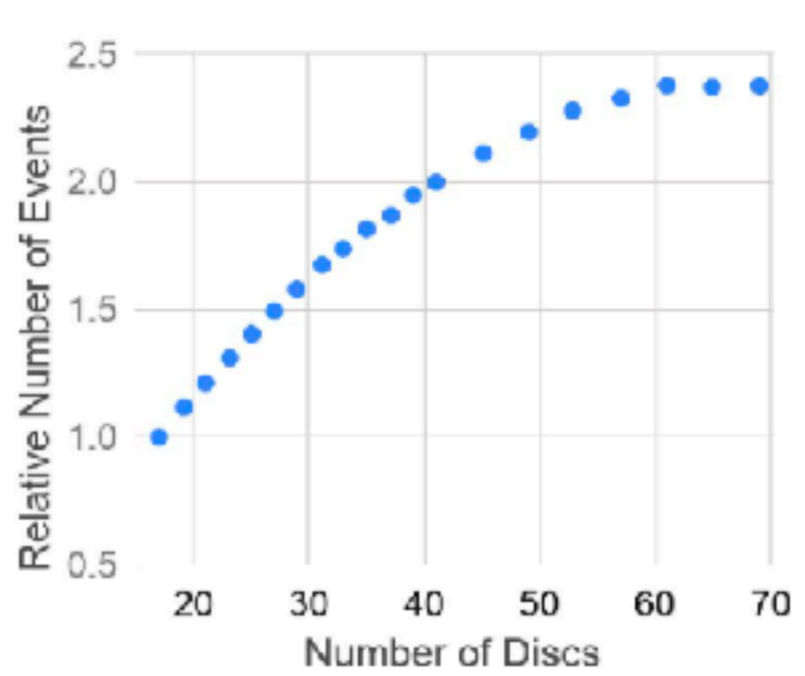


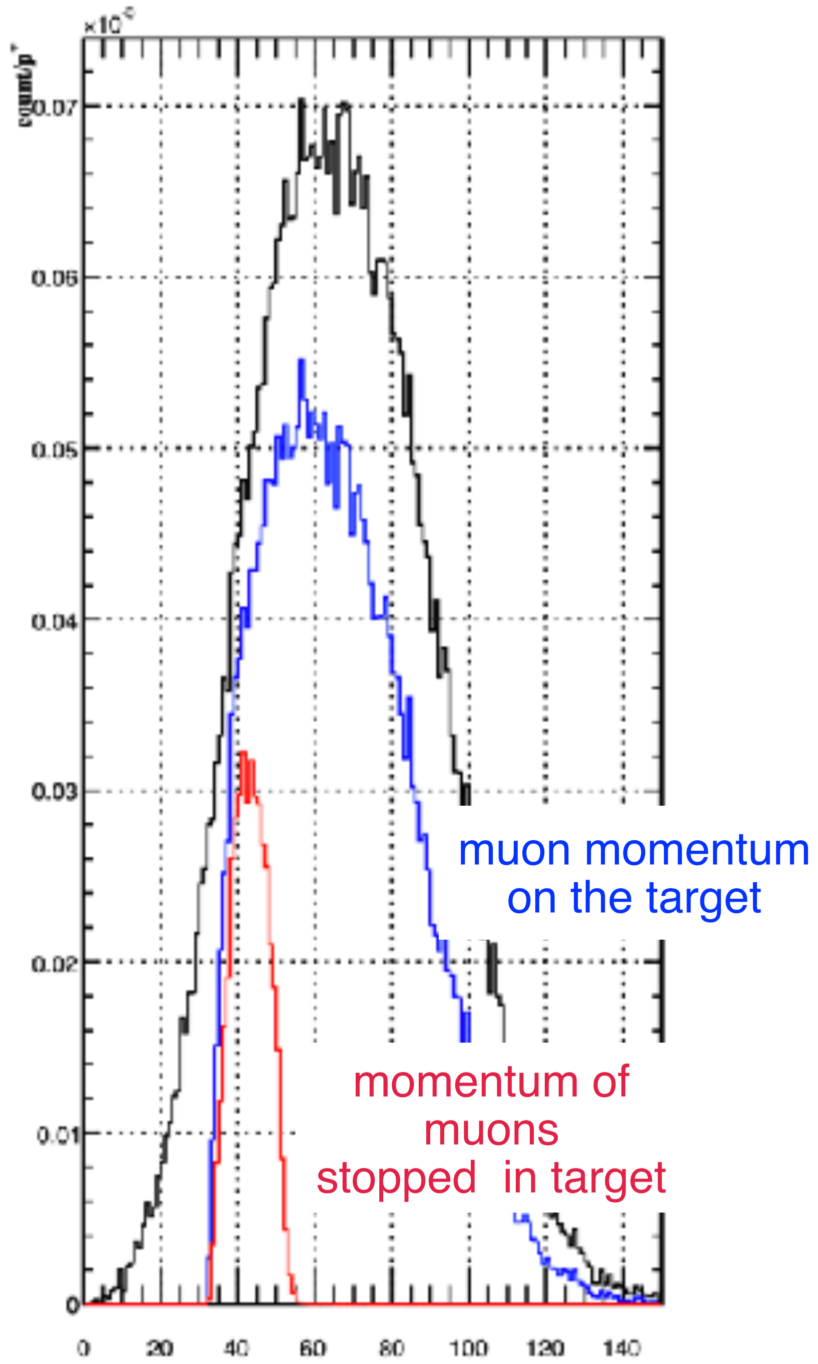
4-rings of ultra fast scintillators read by optical fibres and SiPMs



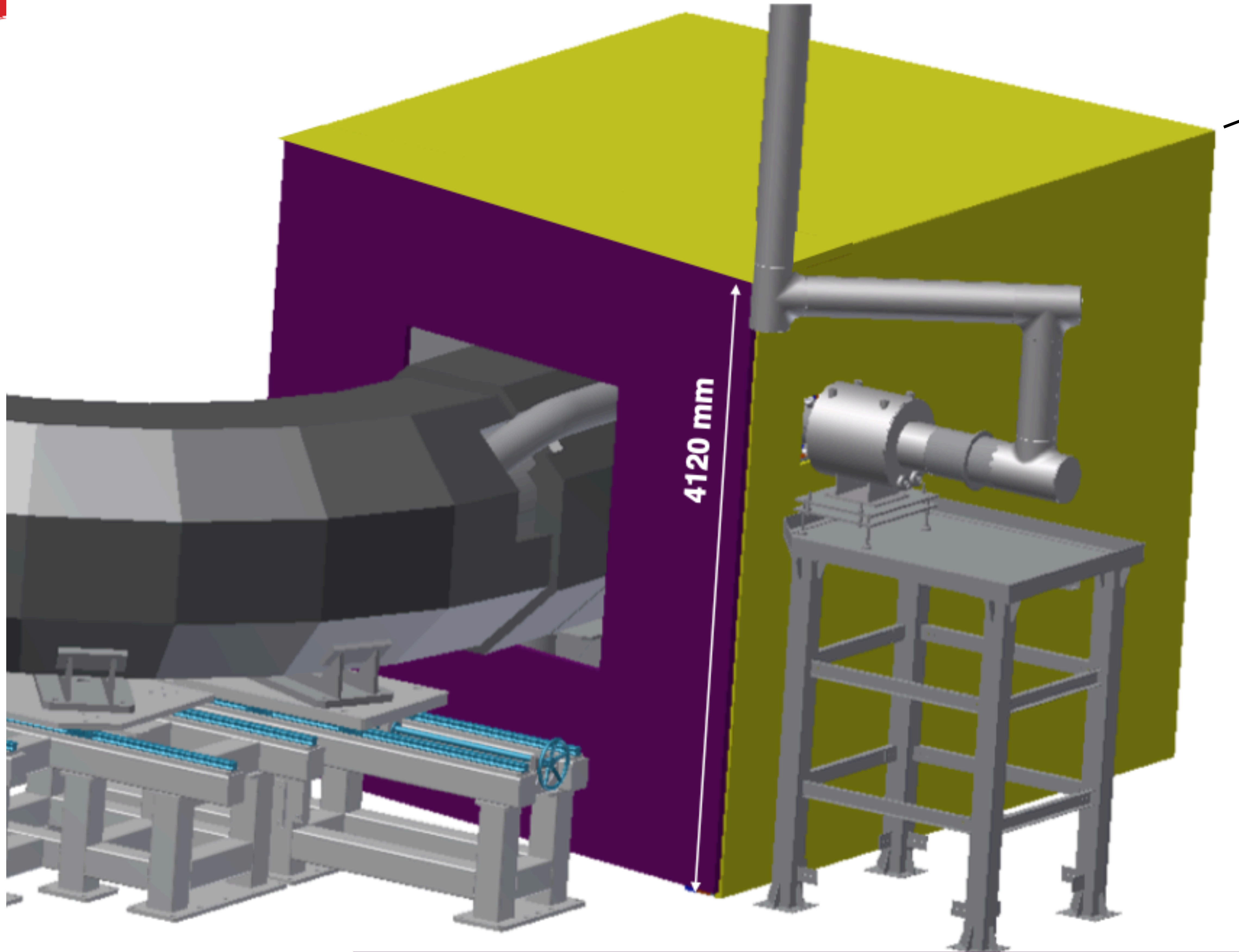


17 Al disks
100 mm radius, 200 µm thick

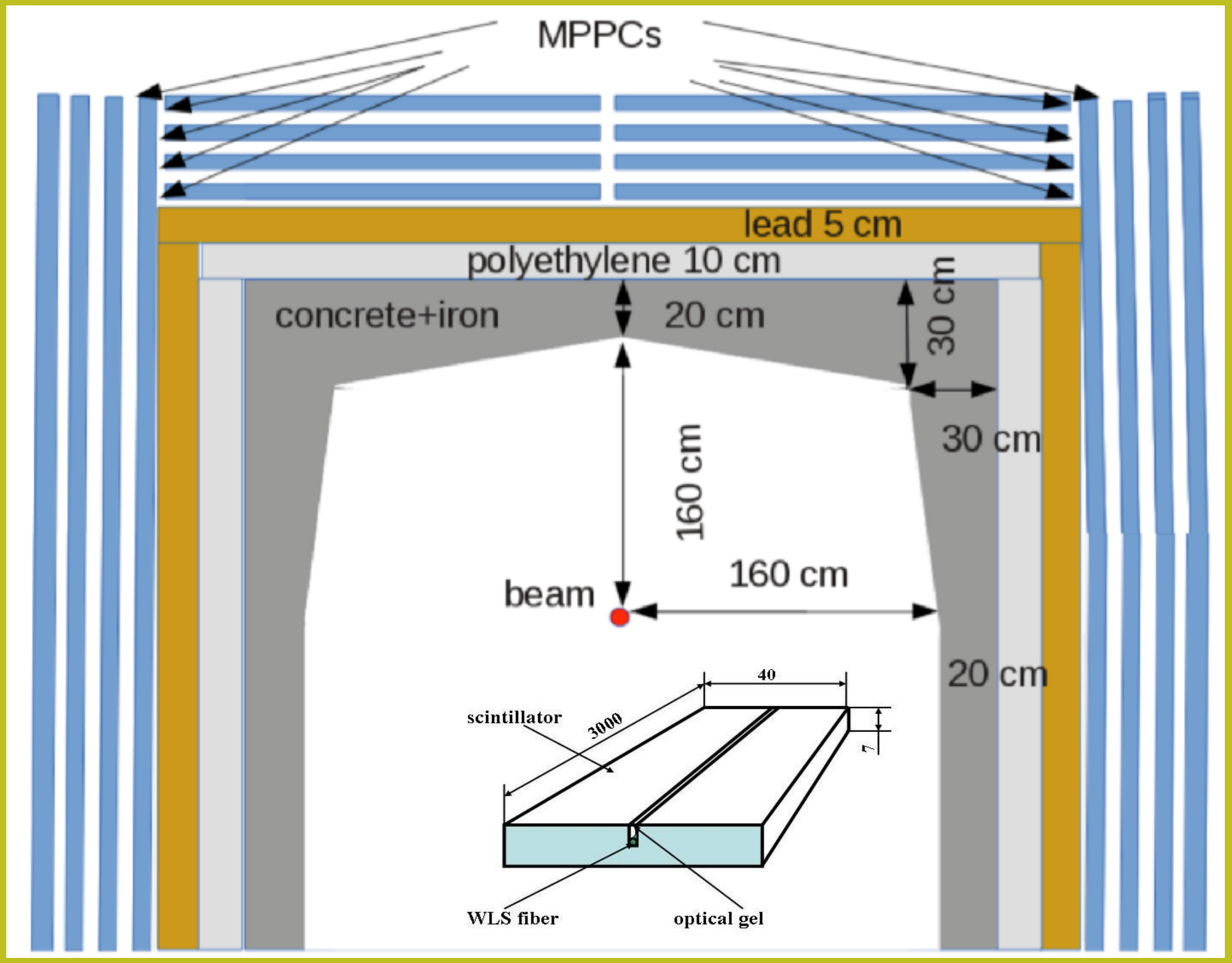




COMET Phase I :: a hybrid CRV



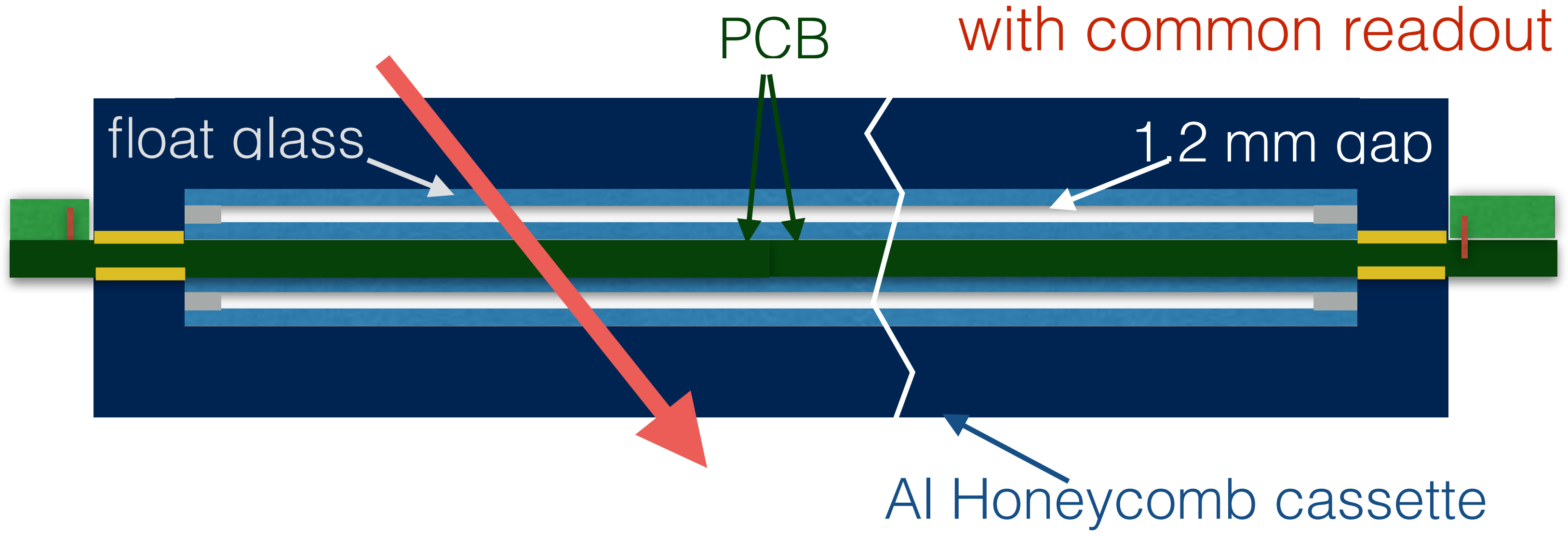
Scintillators CRV



GRPC CRV

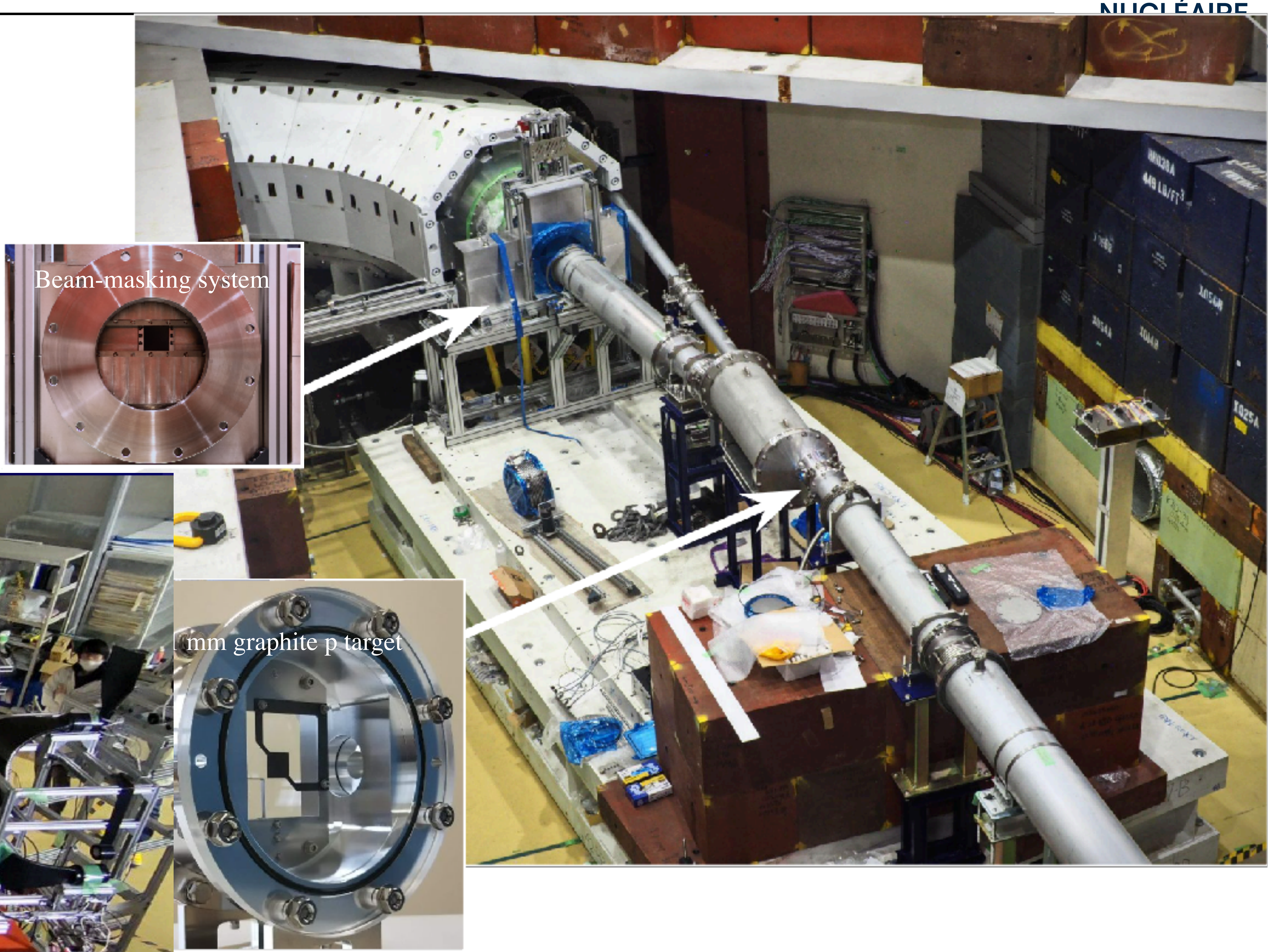
A tracker module: 5 detector modules (baseline)

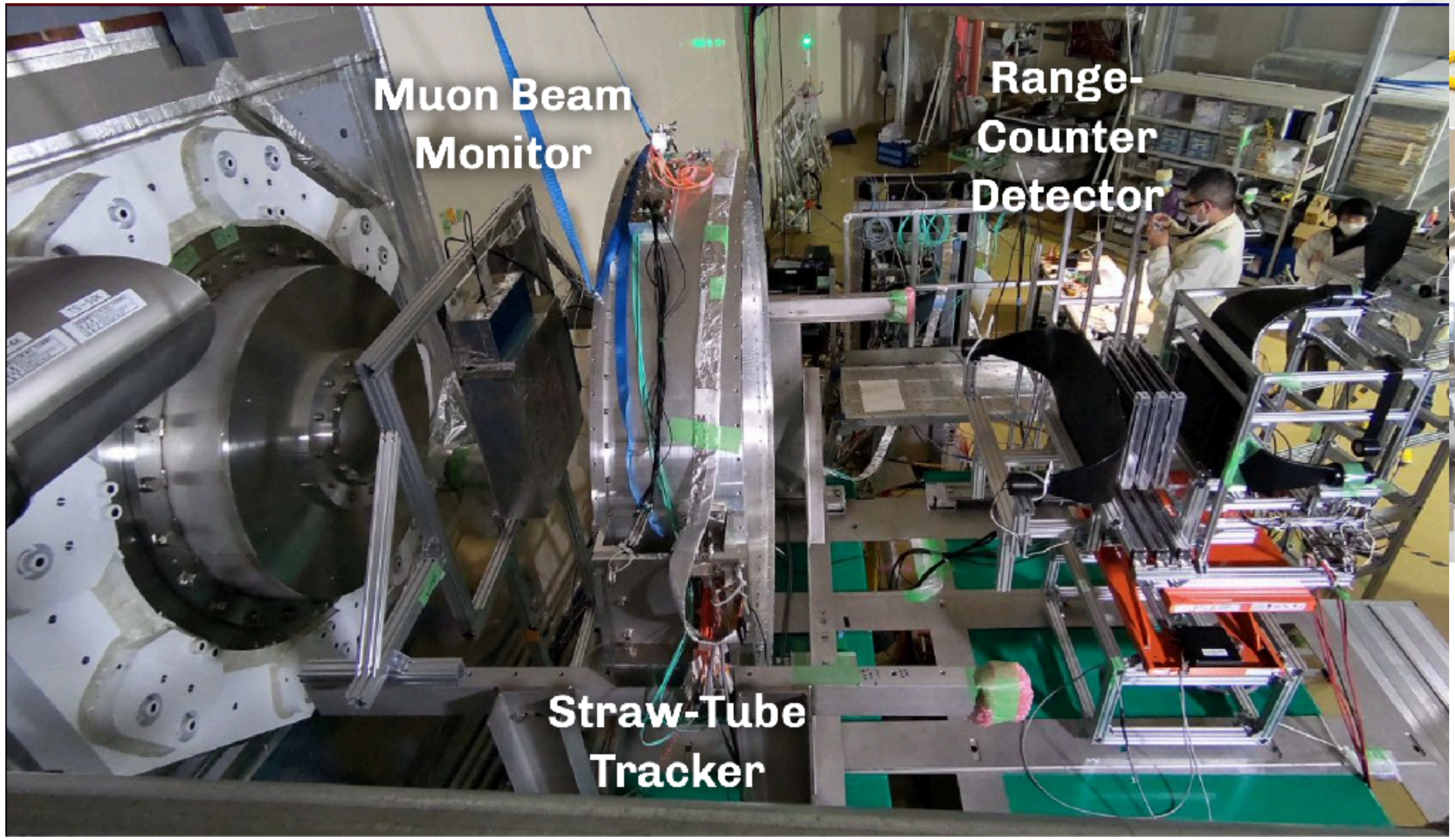
a module (1900x600 mm2):
two single-gap GRPCs
with common readout



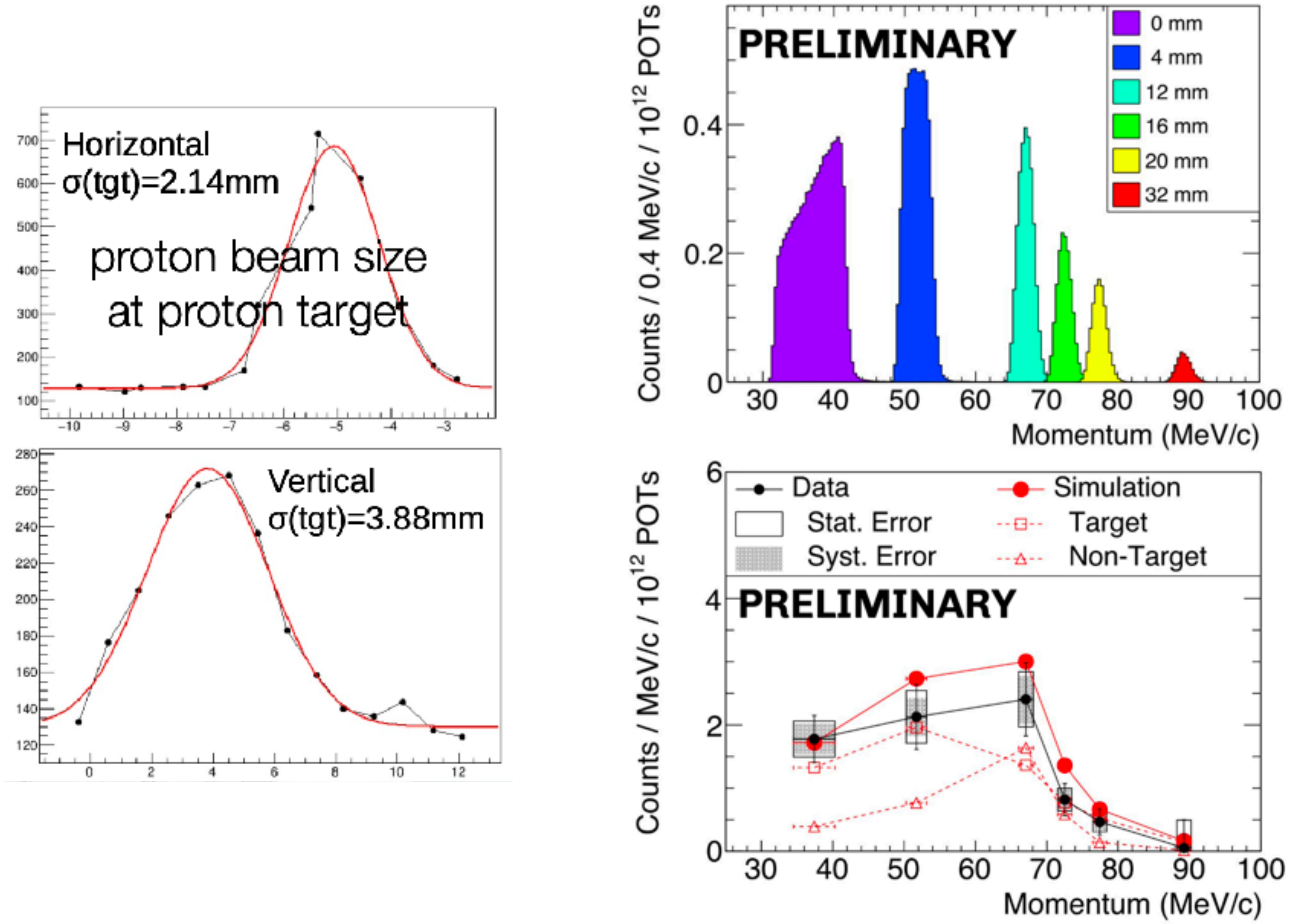
Phase-α : first proton beam in COMET Hall (Feb-March 2022)

- Low intensity run (260 W) without Pion Capture Solenoid
- Proton beam diagnostic detectors (time, intensity & xy distribution)
- Secondary particle detectors -> muon range distribution





Phase-α : first proton beam in COMET Hall (Feb-March 2022)



Pion Capture Solenoid at J-PARC since Nov 2024

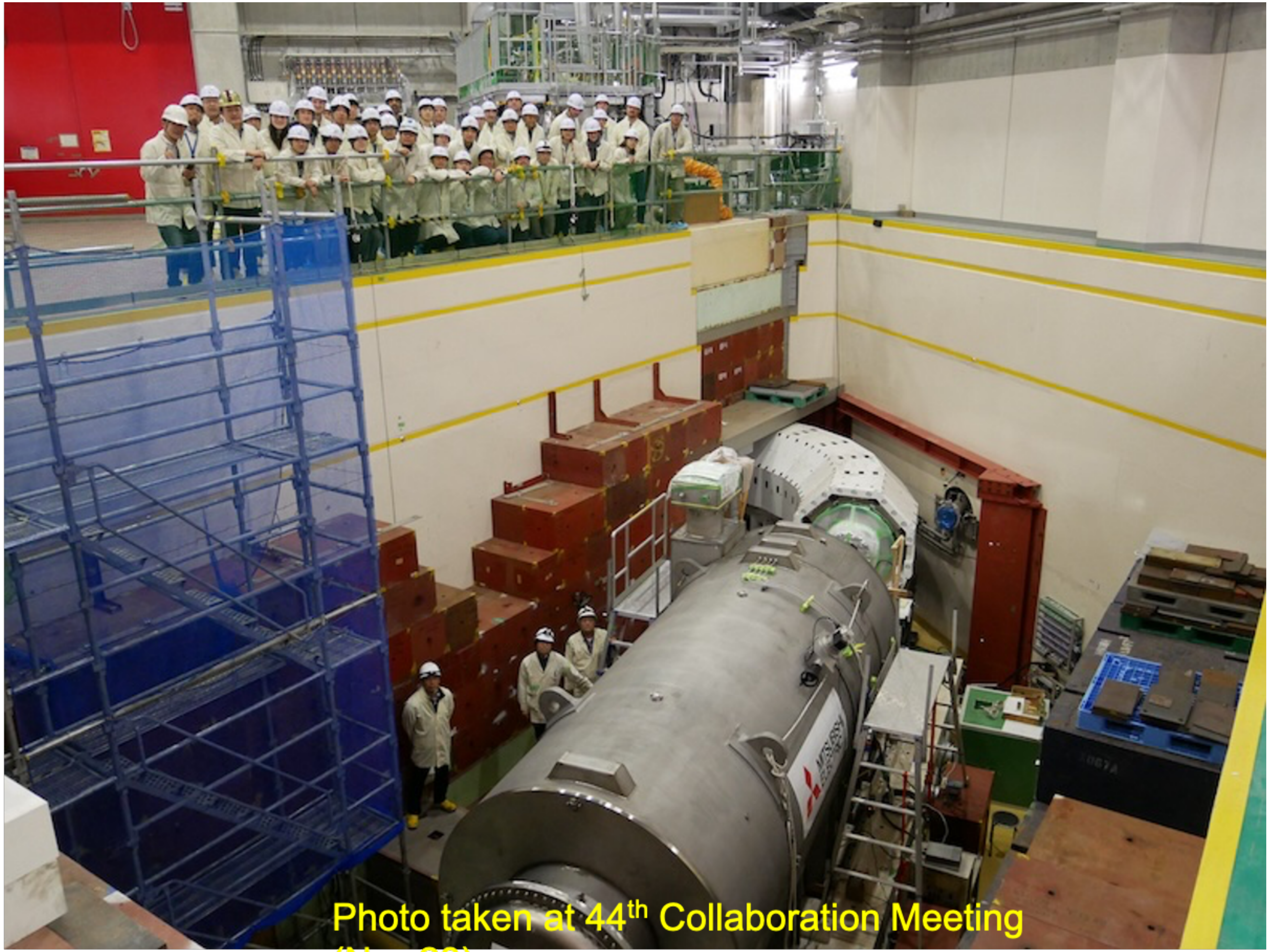
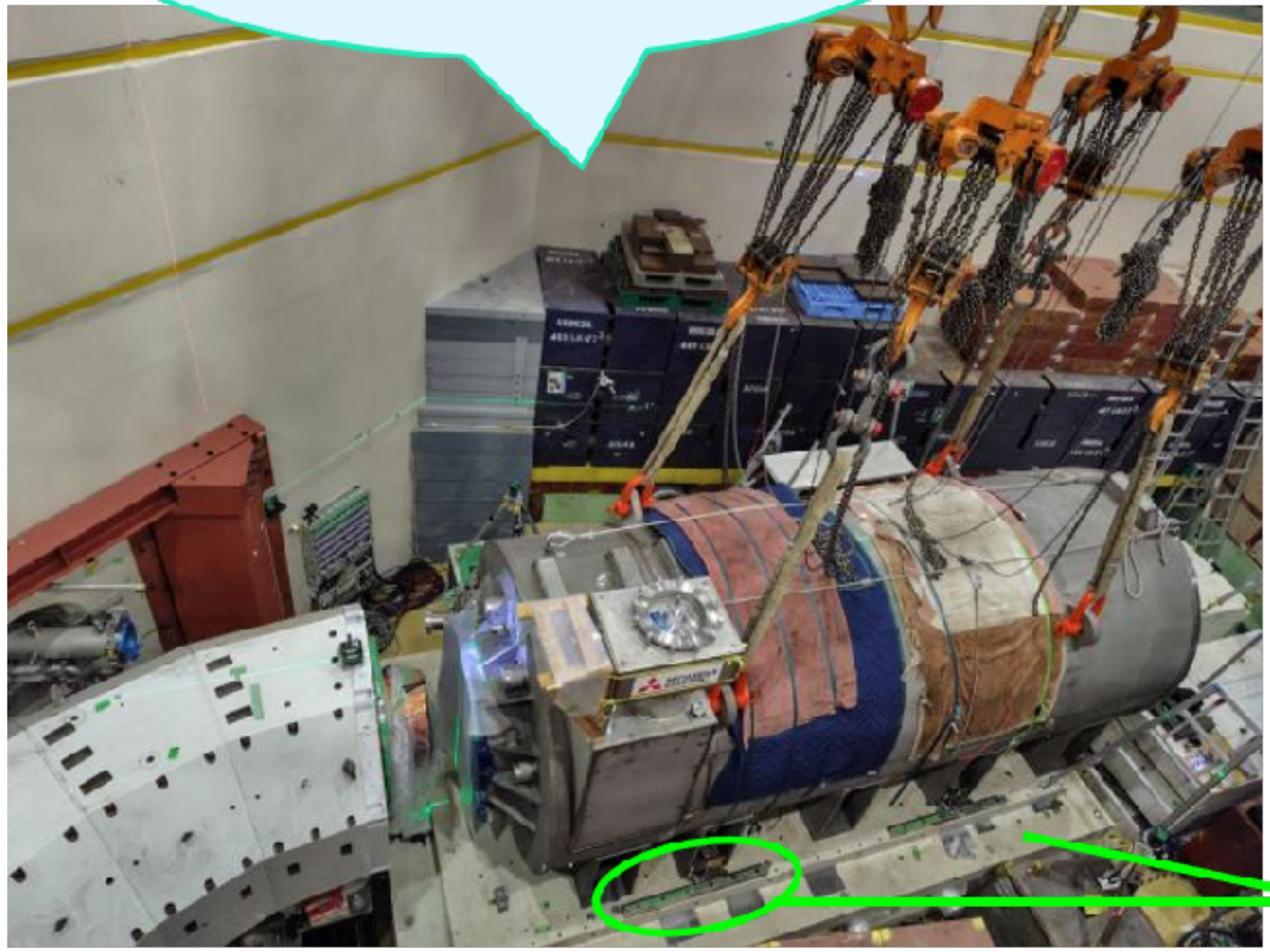


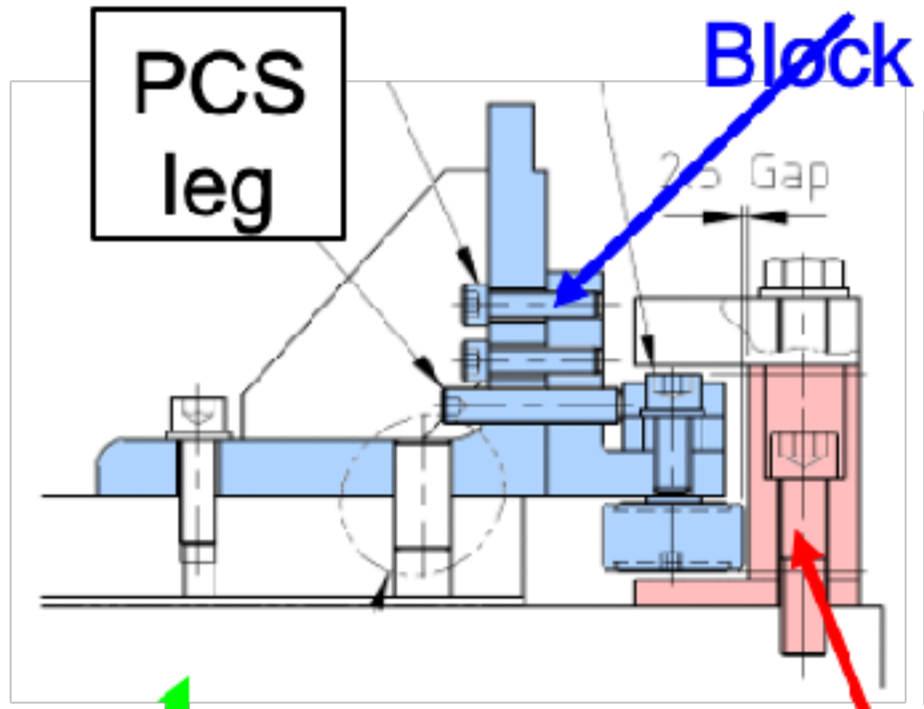
Photo taken at 44th Collaboration Meeting (Nov.28)

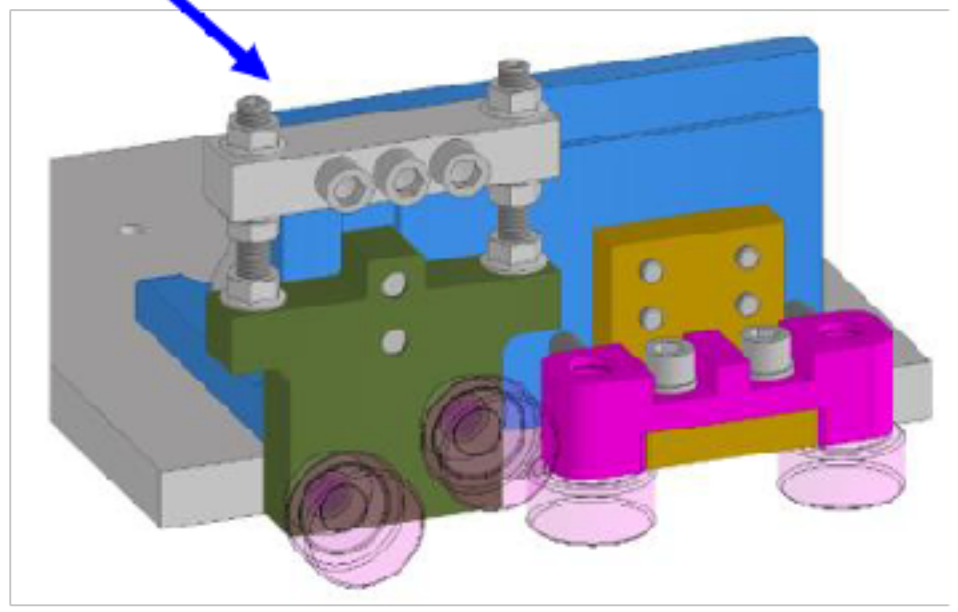
©Y Fukao, J-PARC PAC Jan 25

Aligned to beamline

Connected to Muon Transport Solenoid in December







Guide block and rail were utilized based on the preliminary test.

All magnets available - (almost) ready to use!

- DS was delivered at KEK Tsukuba in Sep. 2024.
- BS was delivered at J-PARC in Mar. 2022.

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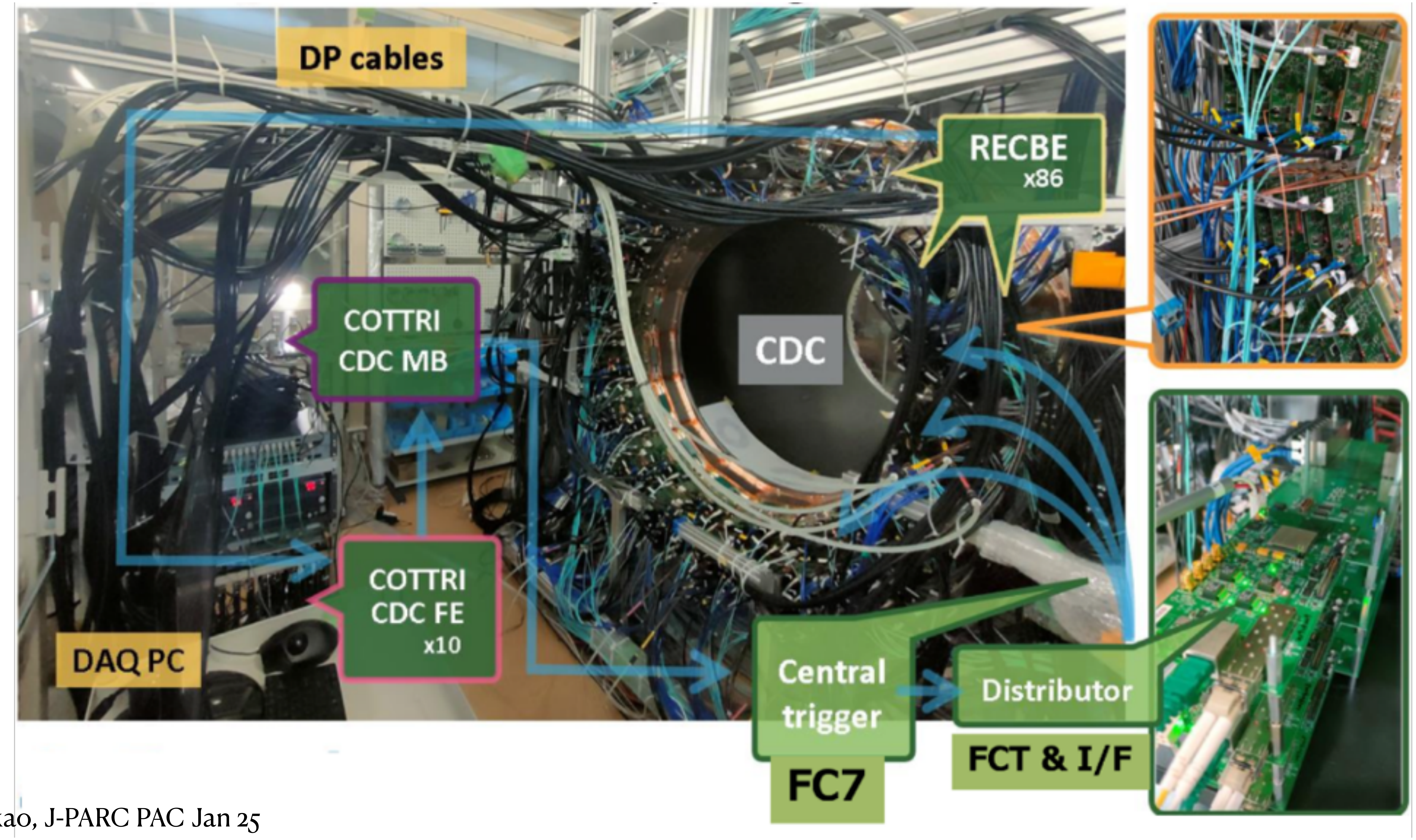
Oct. 2024



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Timeline

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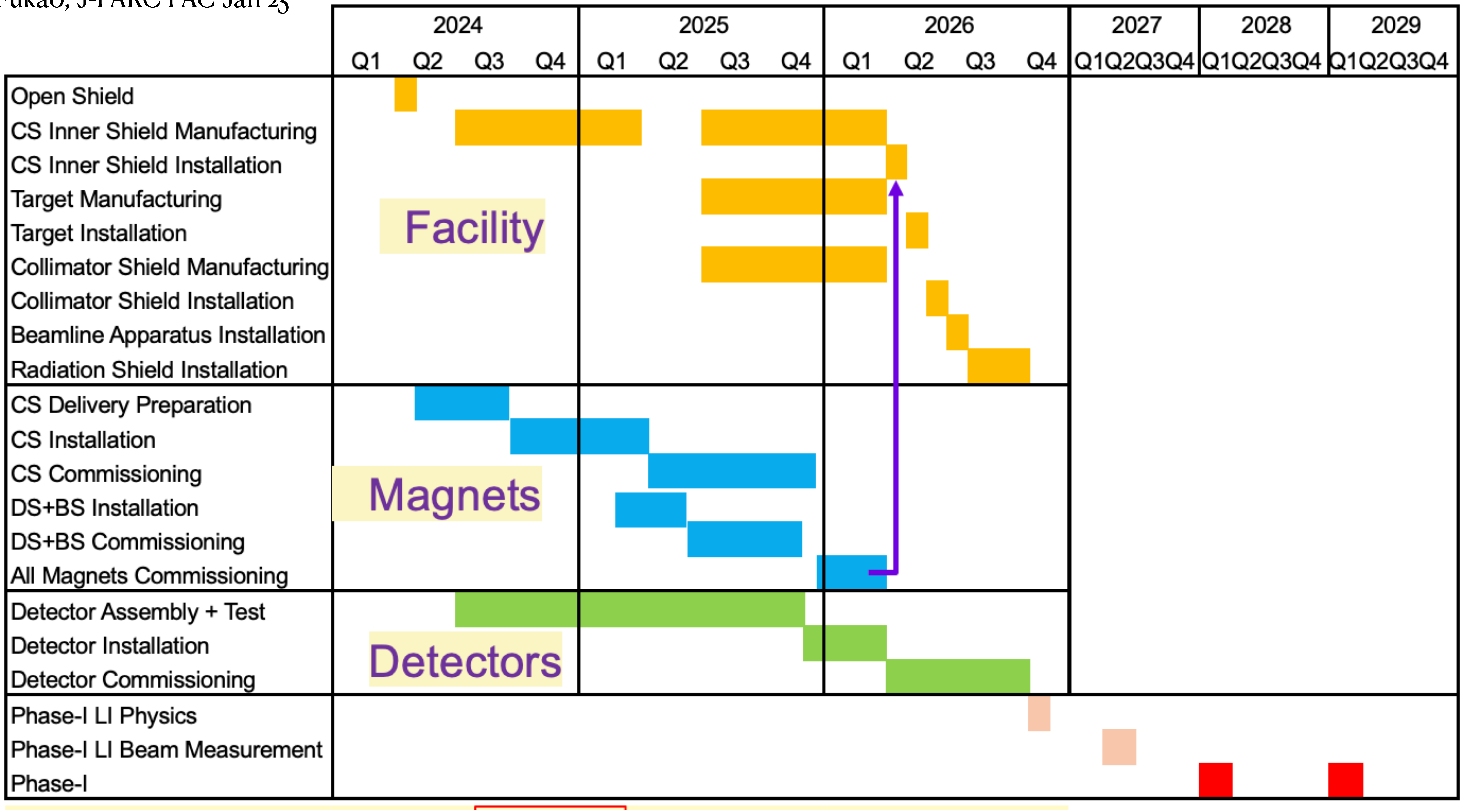


Each challenge is an opportunity

Physics Sensitivity for COMET phase-I

$$BR(\mu^- + Al \to e^- + Al) = 3.1\times 10^{-15}$$

$$BR(\mu^- + Al \to e^- + Al) \sim \frac{1}{N_\mu \cdot \boxed{f_{cap}} \cdot A_e}$$

8 GeV, 3.2 KW proton beam

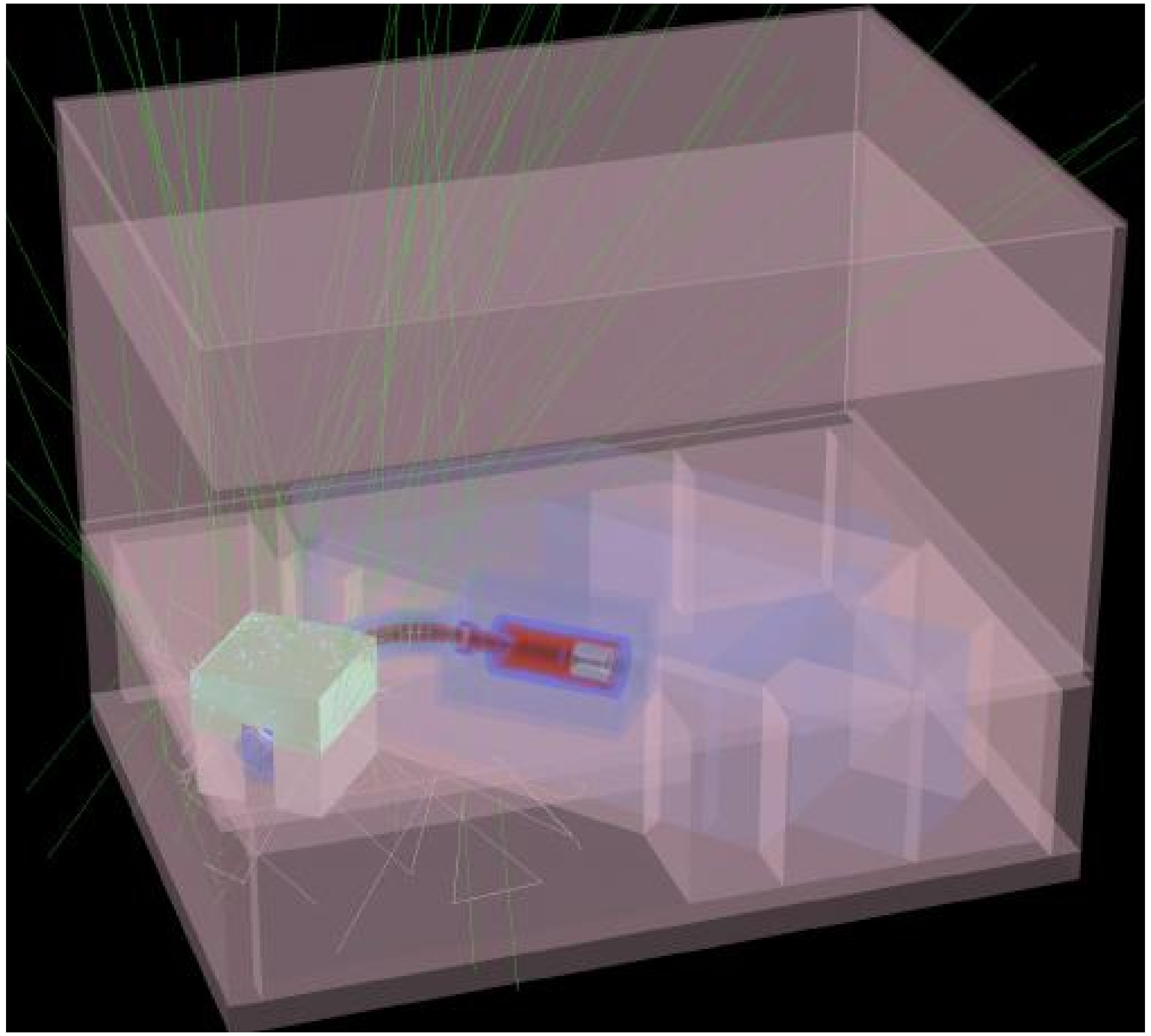
N_μ : # of stopping muons in the muon stopping target
f_{cap} : fraction of muon capture 0.6 for Al
A_e : detector acceptance = 0.04

$N_\mu = 1.5 \times 10^{16}$ number of stopped muons

Running time ~ 150 days

Type	Background	Estimated events
Physics	Muon decay in orbit	0.01
	Radiative muon capture	0.0019
	Neutron emission after muon capture	< 0.001
	Charged particle emission after muon capture	< 0.001
Prompt Beam	* Beam electrons	
	* Muon decay in flight	
	* Pion decay in flight	
	* Other beam particles	
	All (*) Combined	≤ 0.0038
	Radiative pion capture	0.0028
	Neutrons	$\sim 10^{-9}$
Delayed Beam	Beam electrons	~ 0
	Muon decay in flight	~ 0
	Pion decay in flight	~ 0
	Radiative pion capture	~ 0
	Antiproton-induced backgrounds	0.0012
Others	Cosmic rays†	< 0.01
Total		0.032

Summary of the estimated background events for a single-event sensitivity of 3×10^{-15}

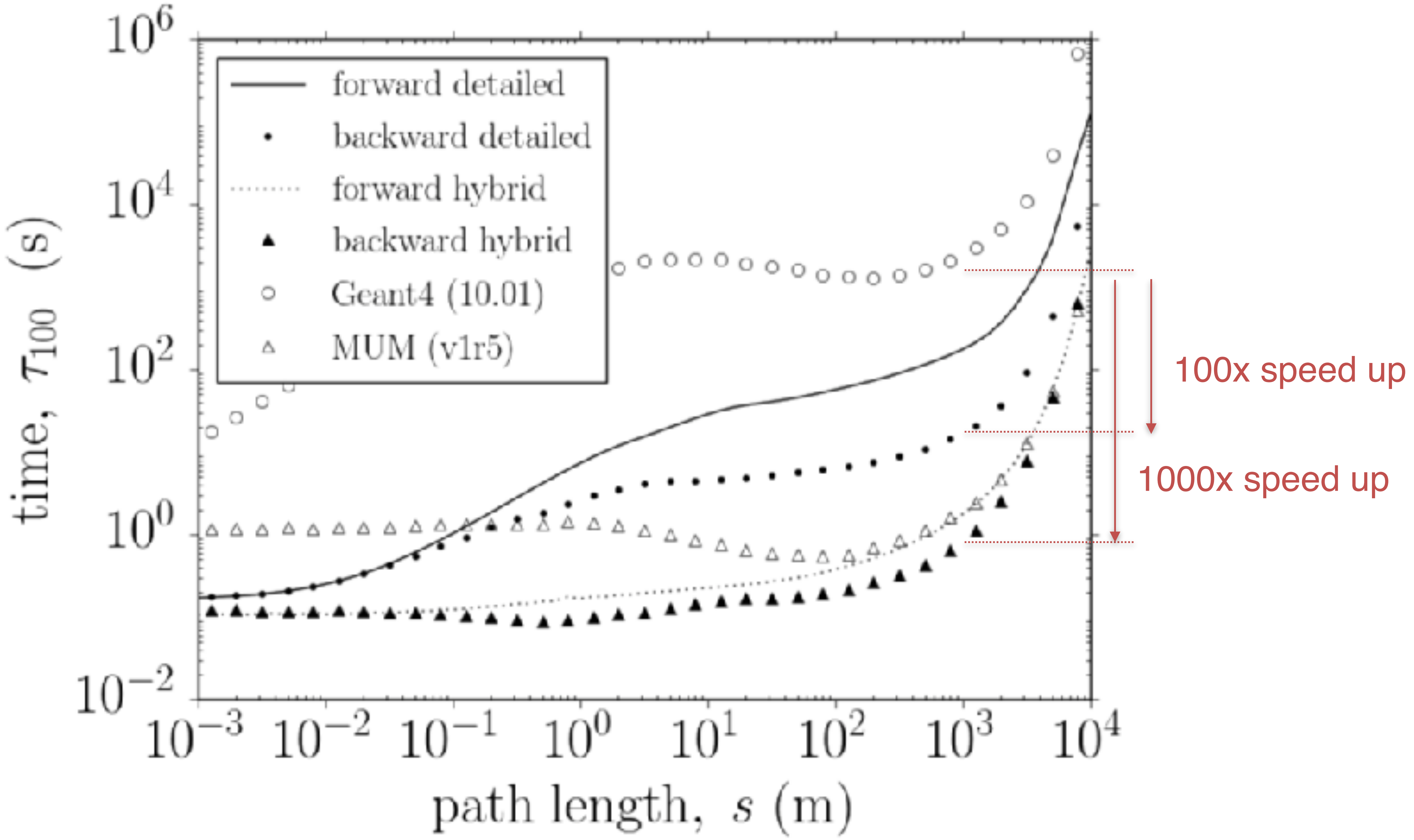


Rare muons and muon-induced electrons w/o CRV signals, undergoing high angle scattering before penetrating in the detection volume

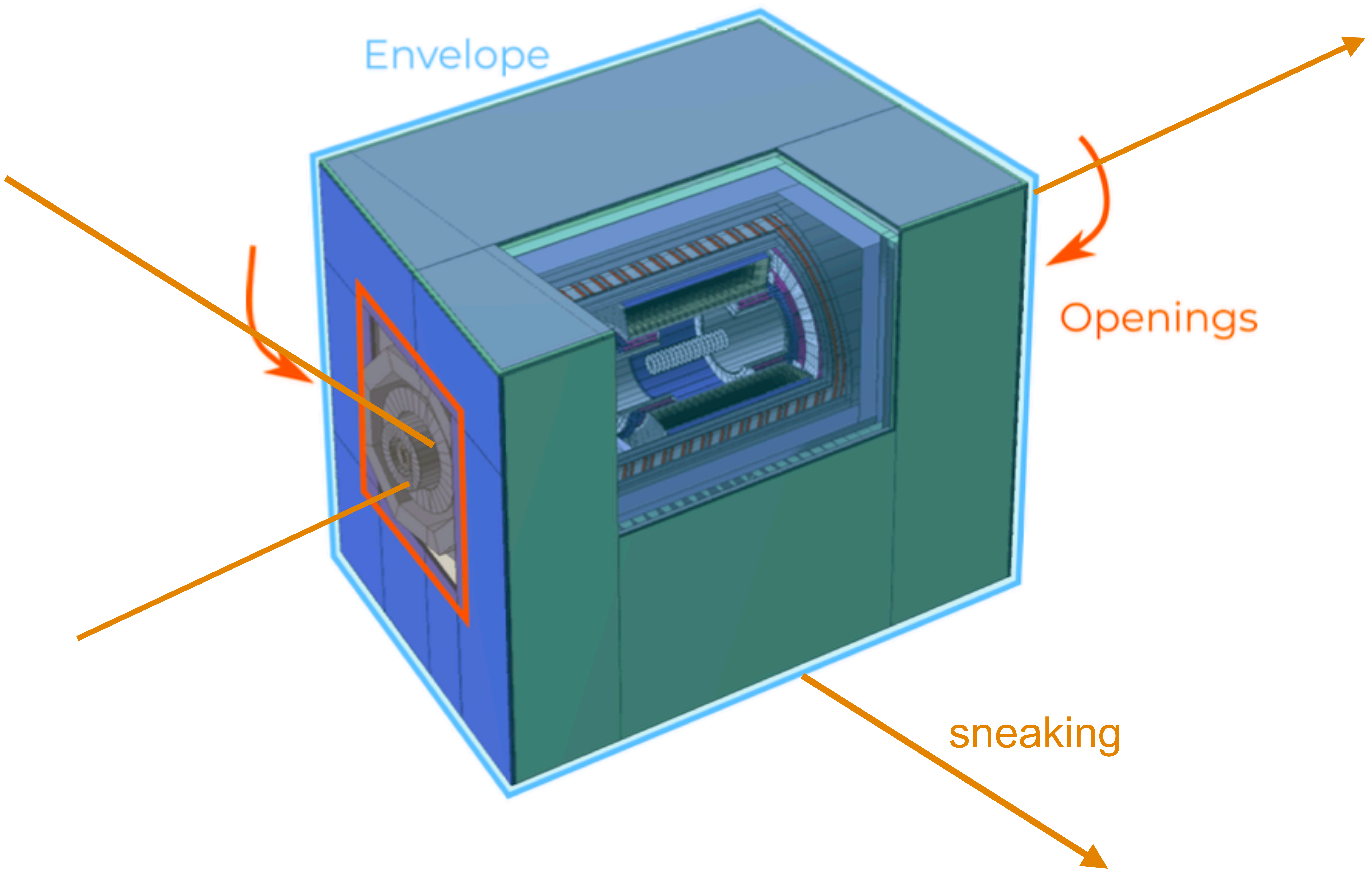
Very expensive to simulate with high accuracy with direct MC (G4),much better with a backward MC

V. Niess *et al*, CPC 2018, 229, pg 54

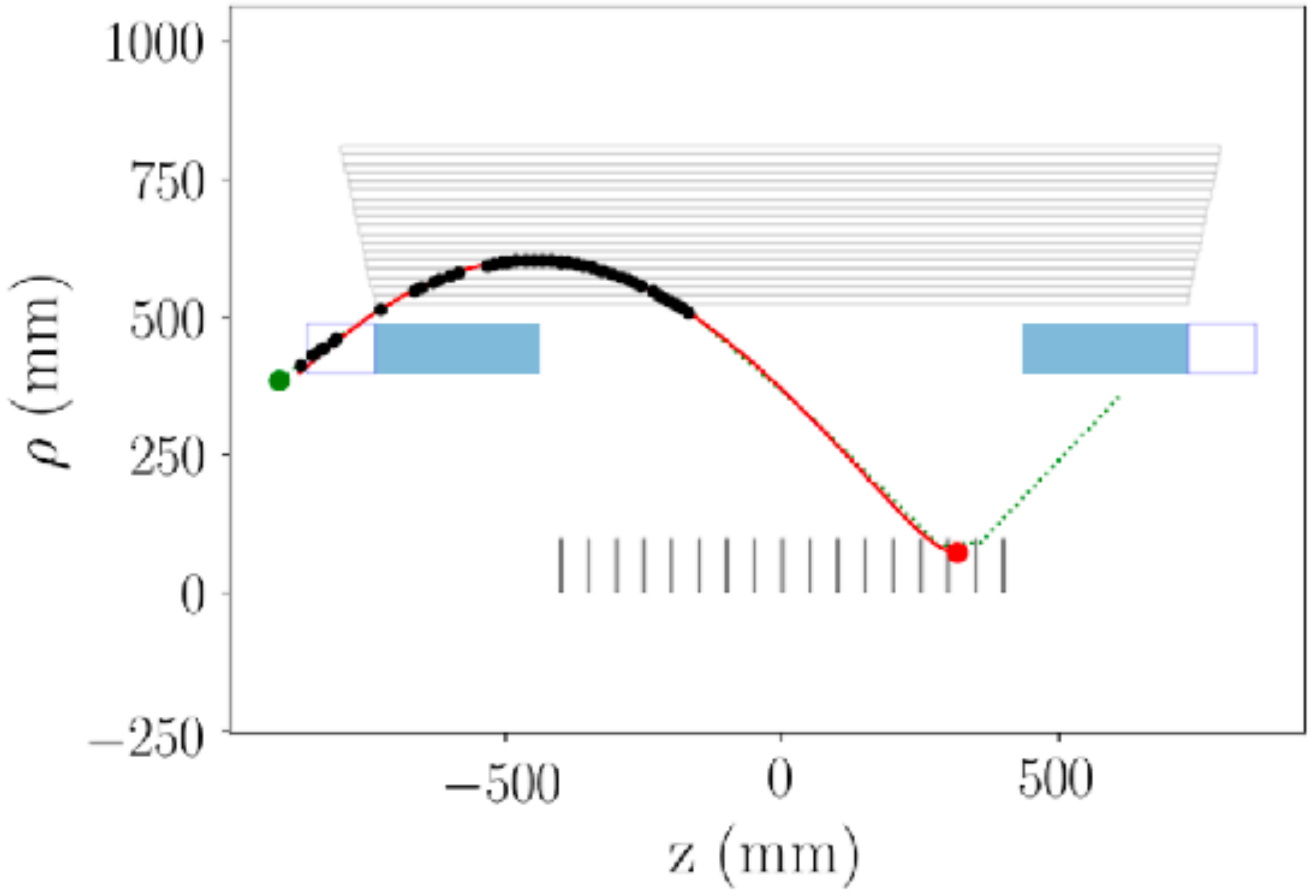
CPU time needed to simulate the transmitted flux with 1% accuracy

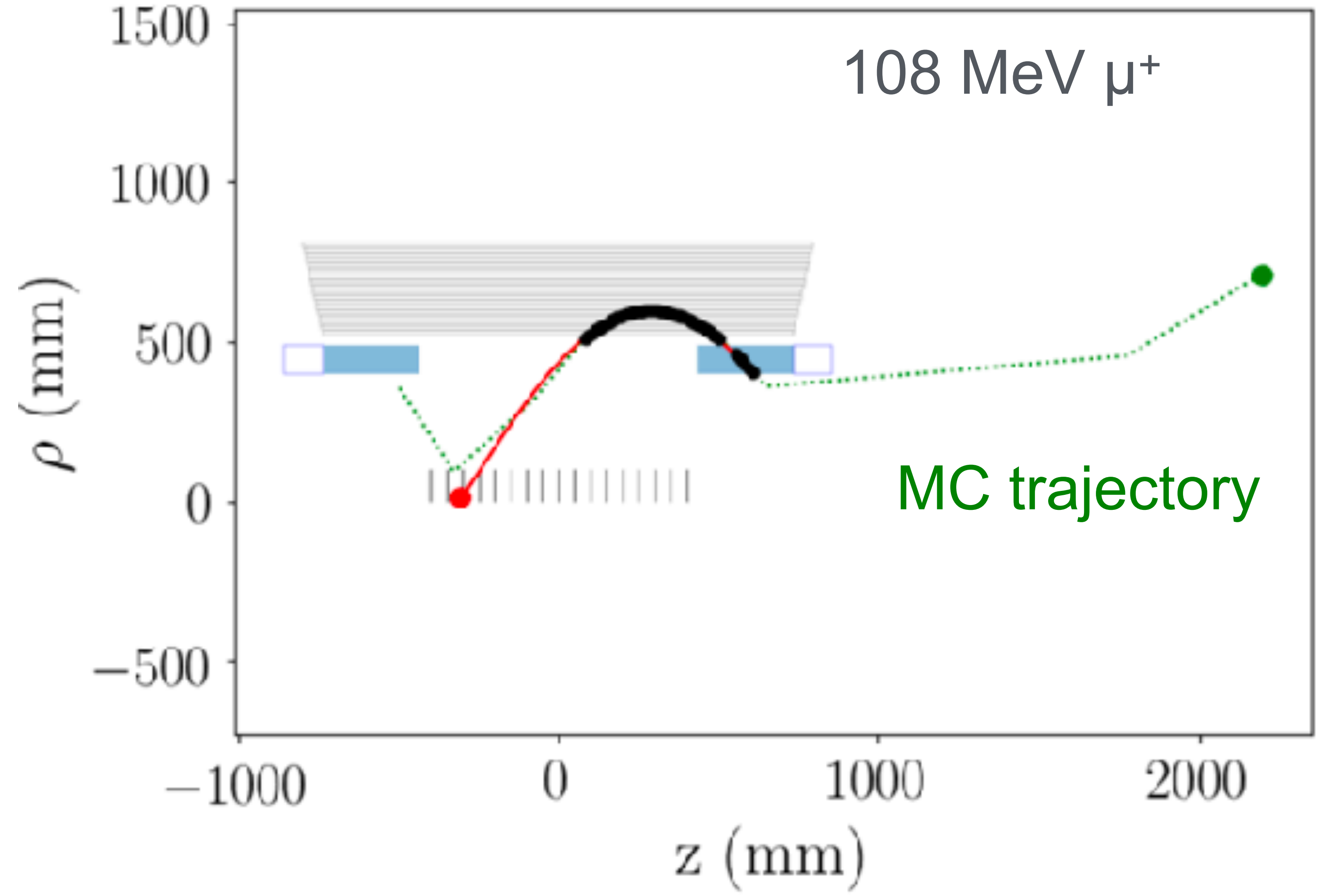


Non analog simulation using Importance Sampling and Backward Monte Carlo

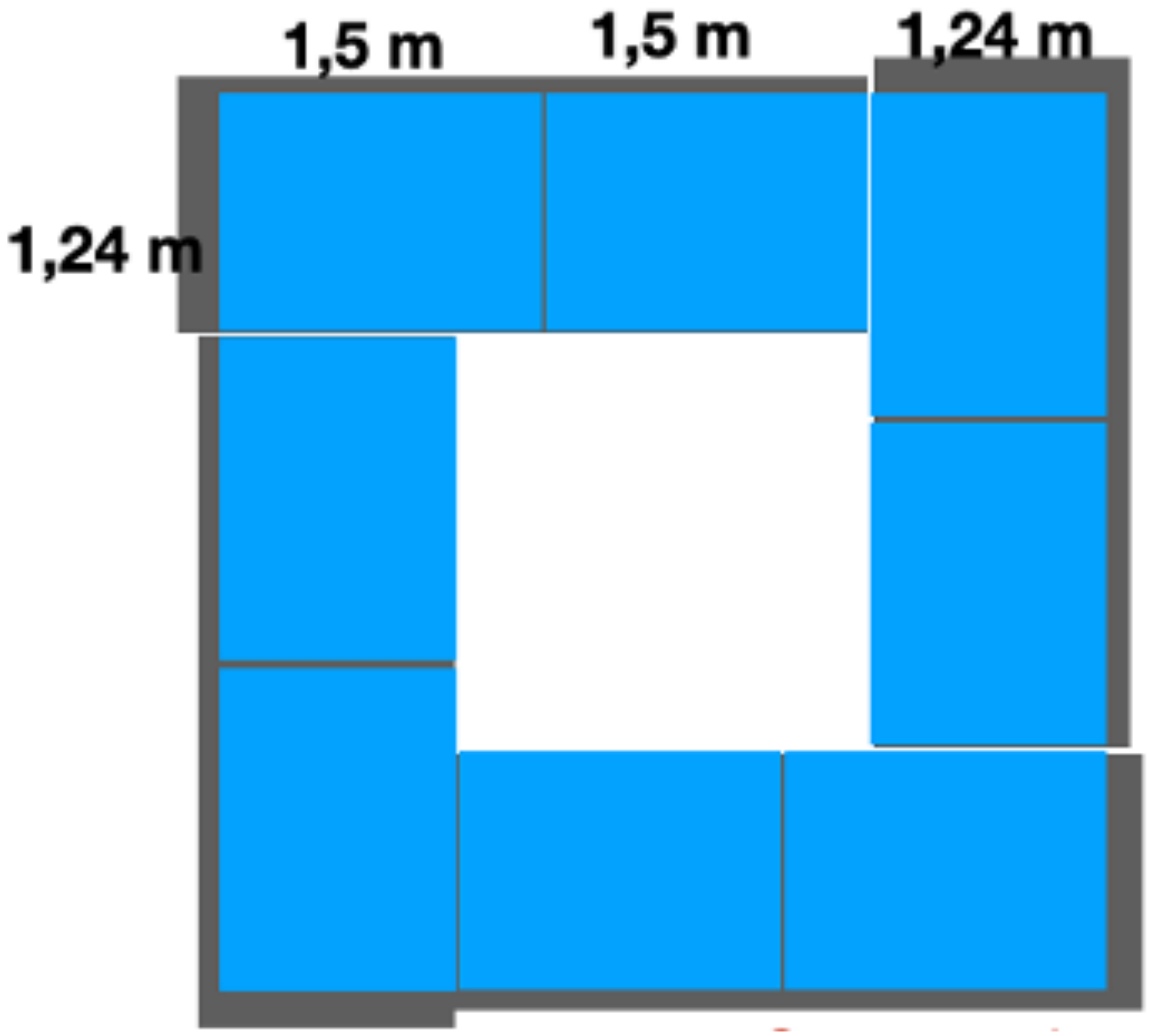


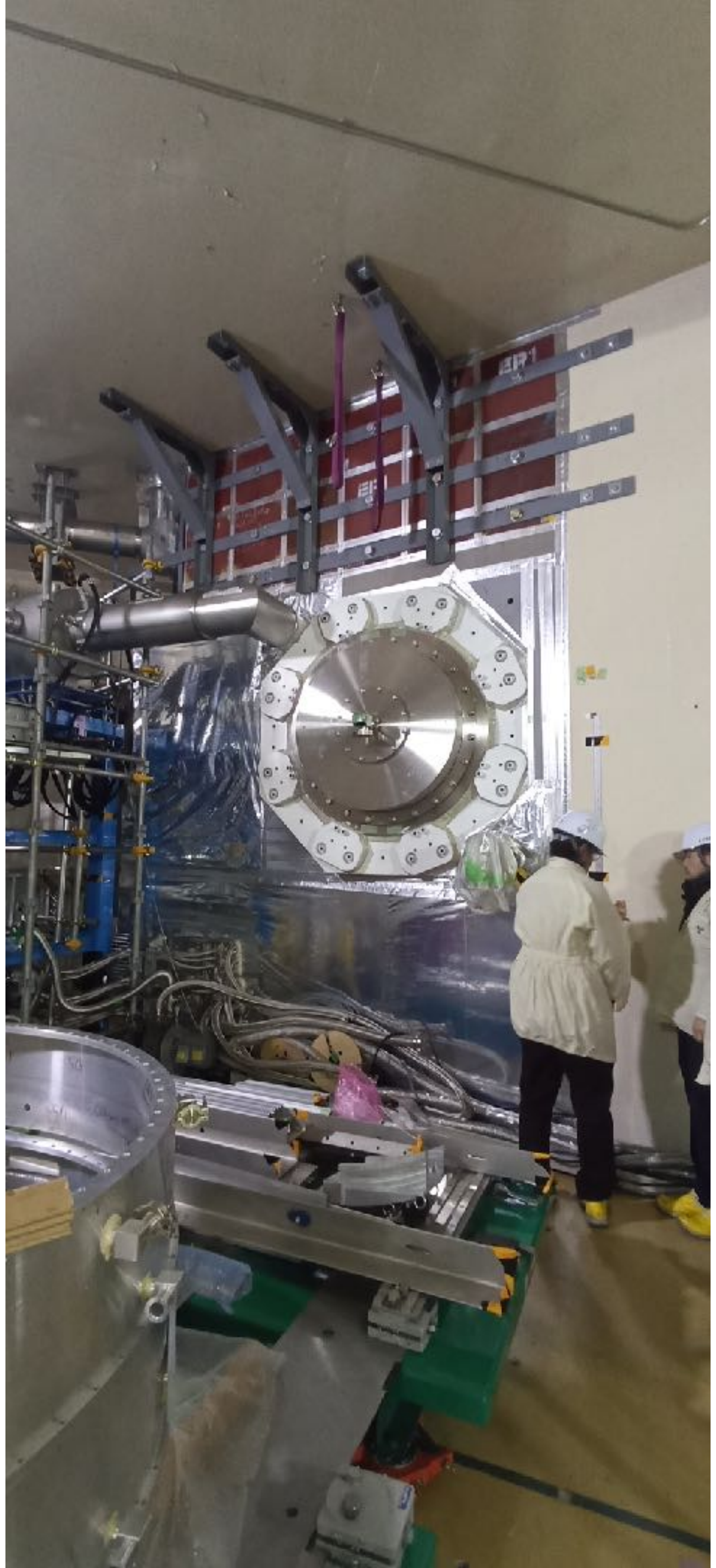
108 MeV sneaking e+ generated by the interaction of an atmospheric muon with the CTH support





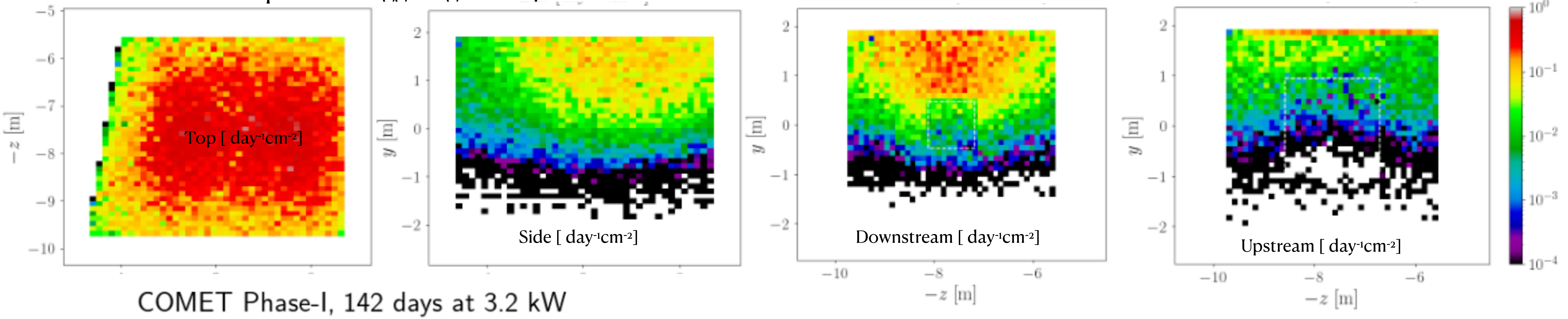
A tracker module: 5 modules

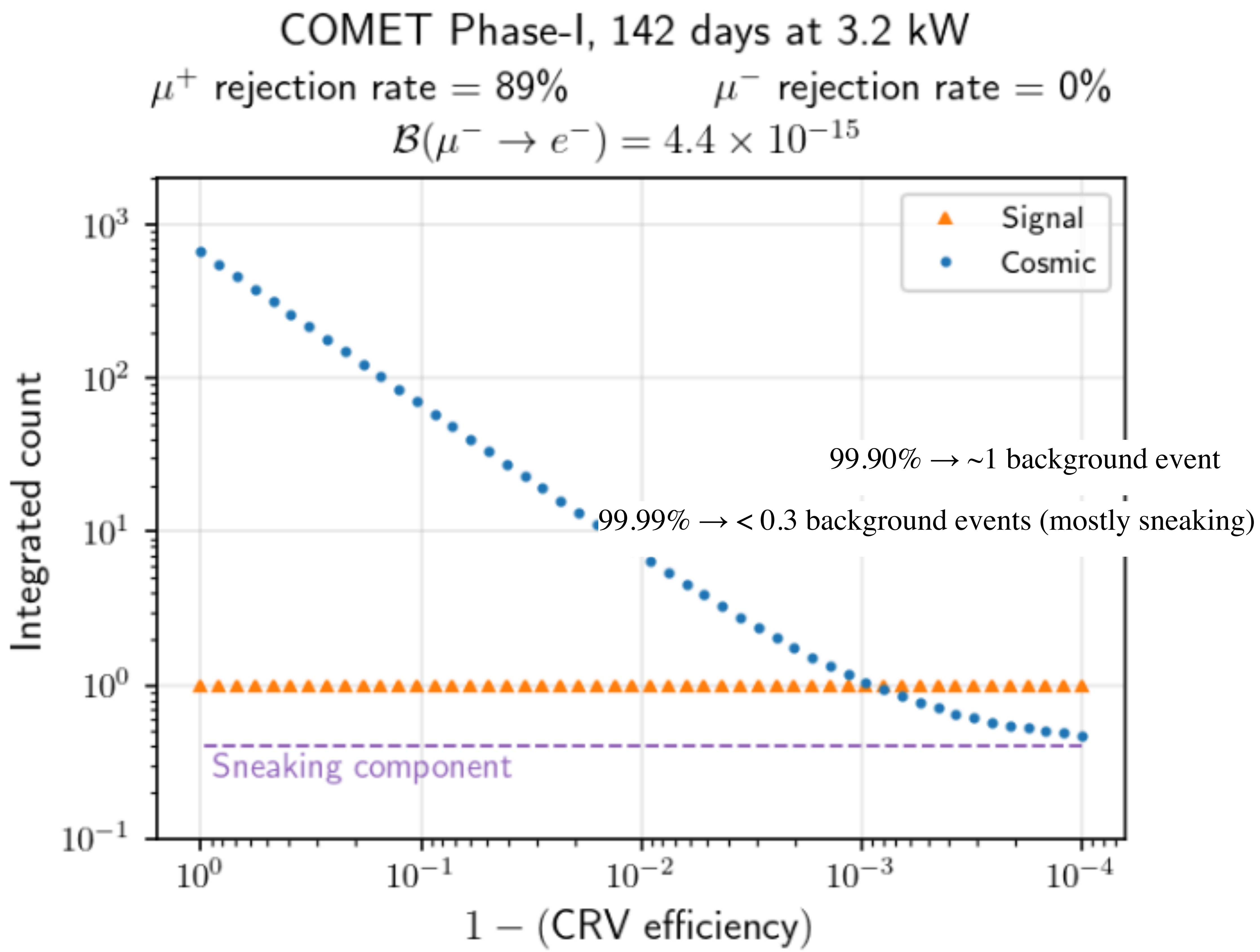


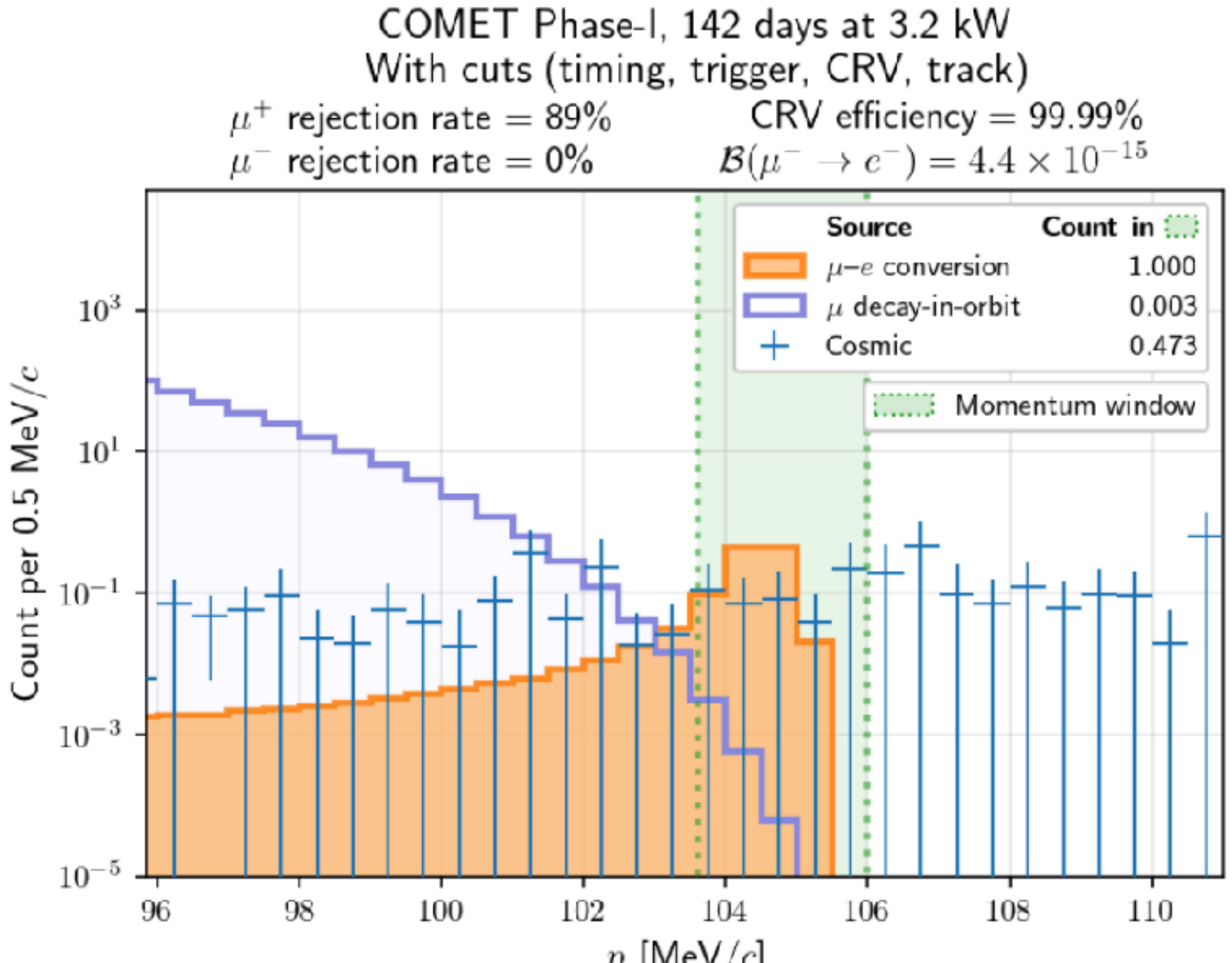


Characterisation of the Atmospheric Background

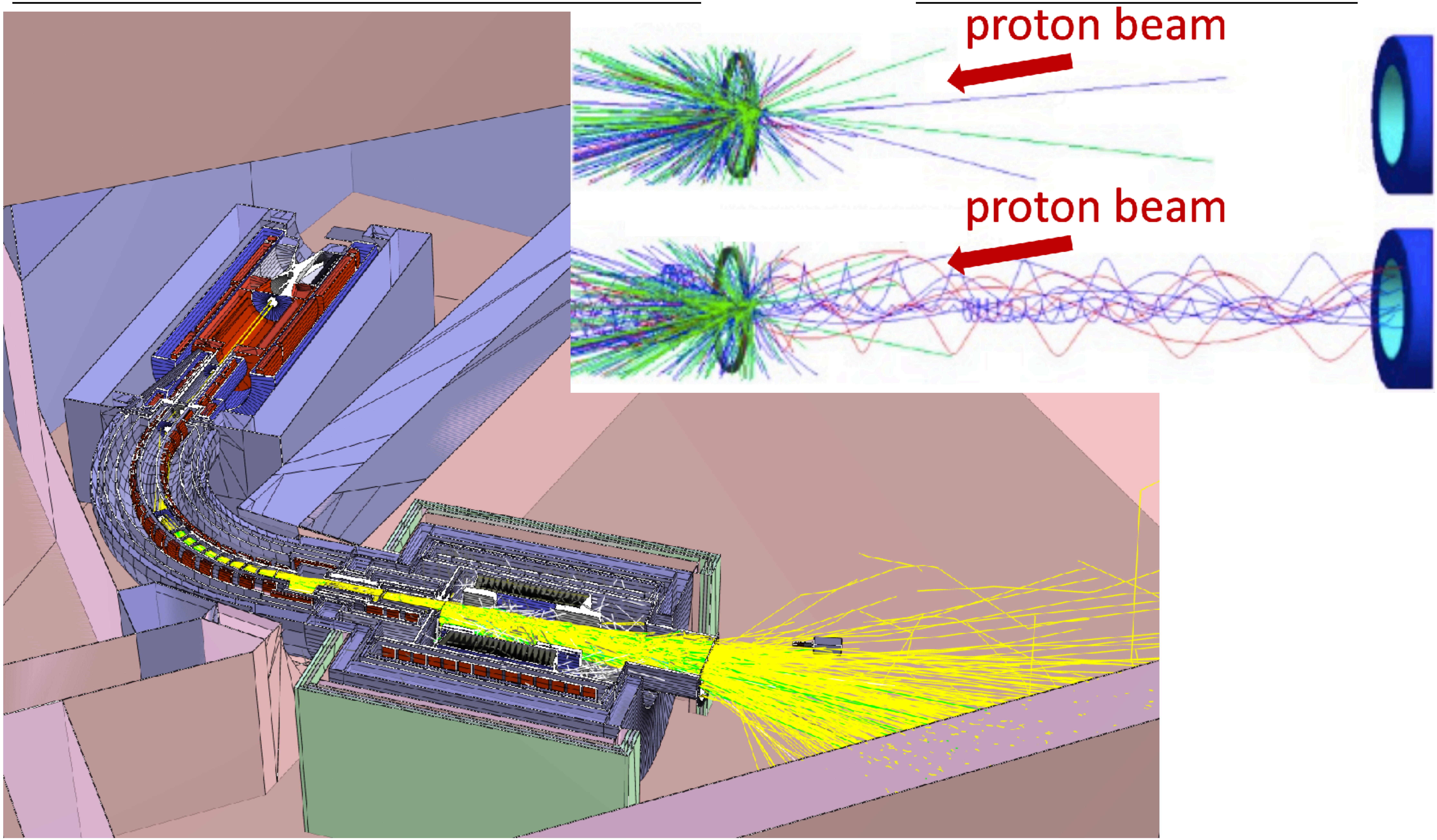
Maps of the triggering atmospheric muons



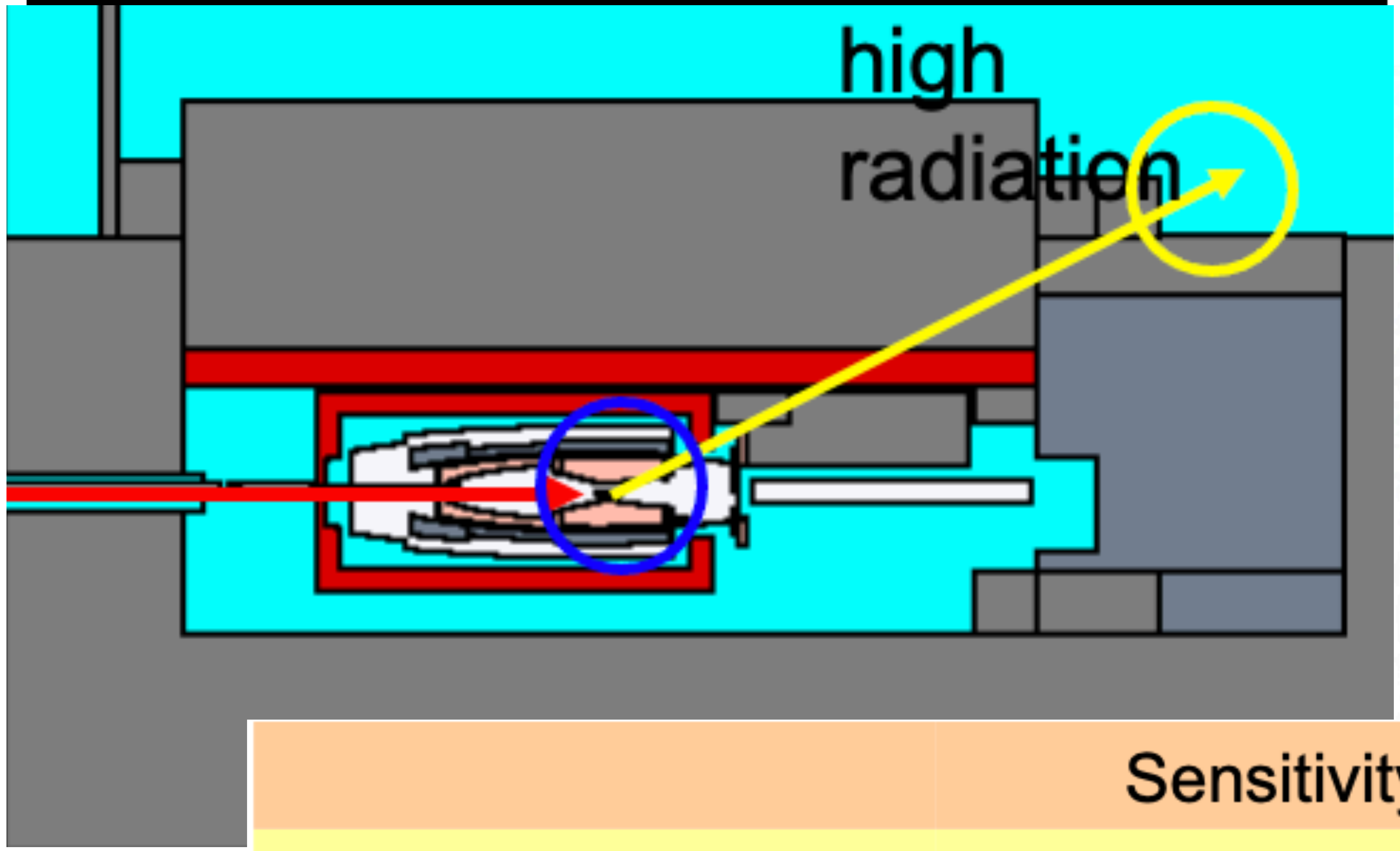


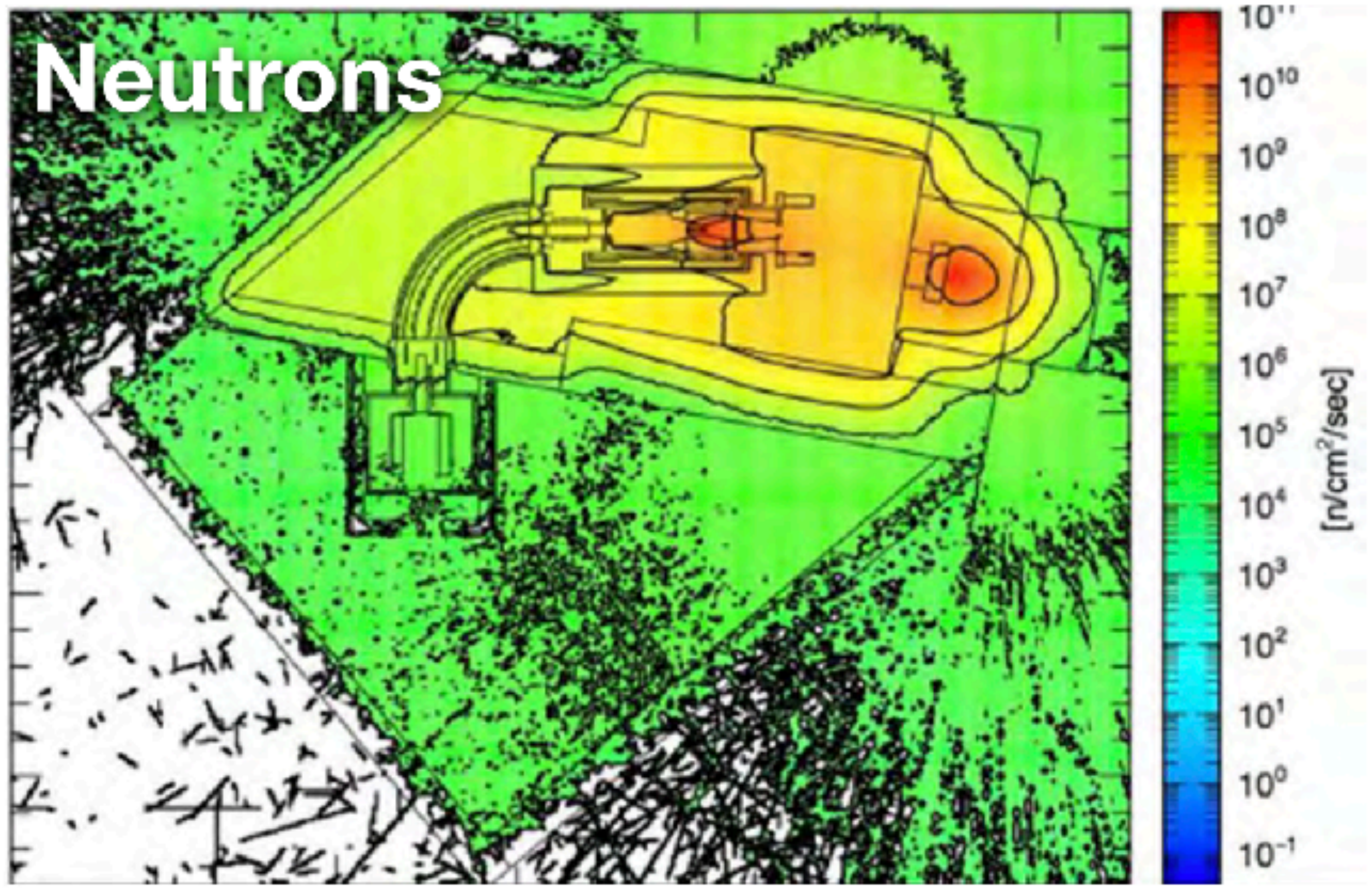


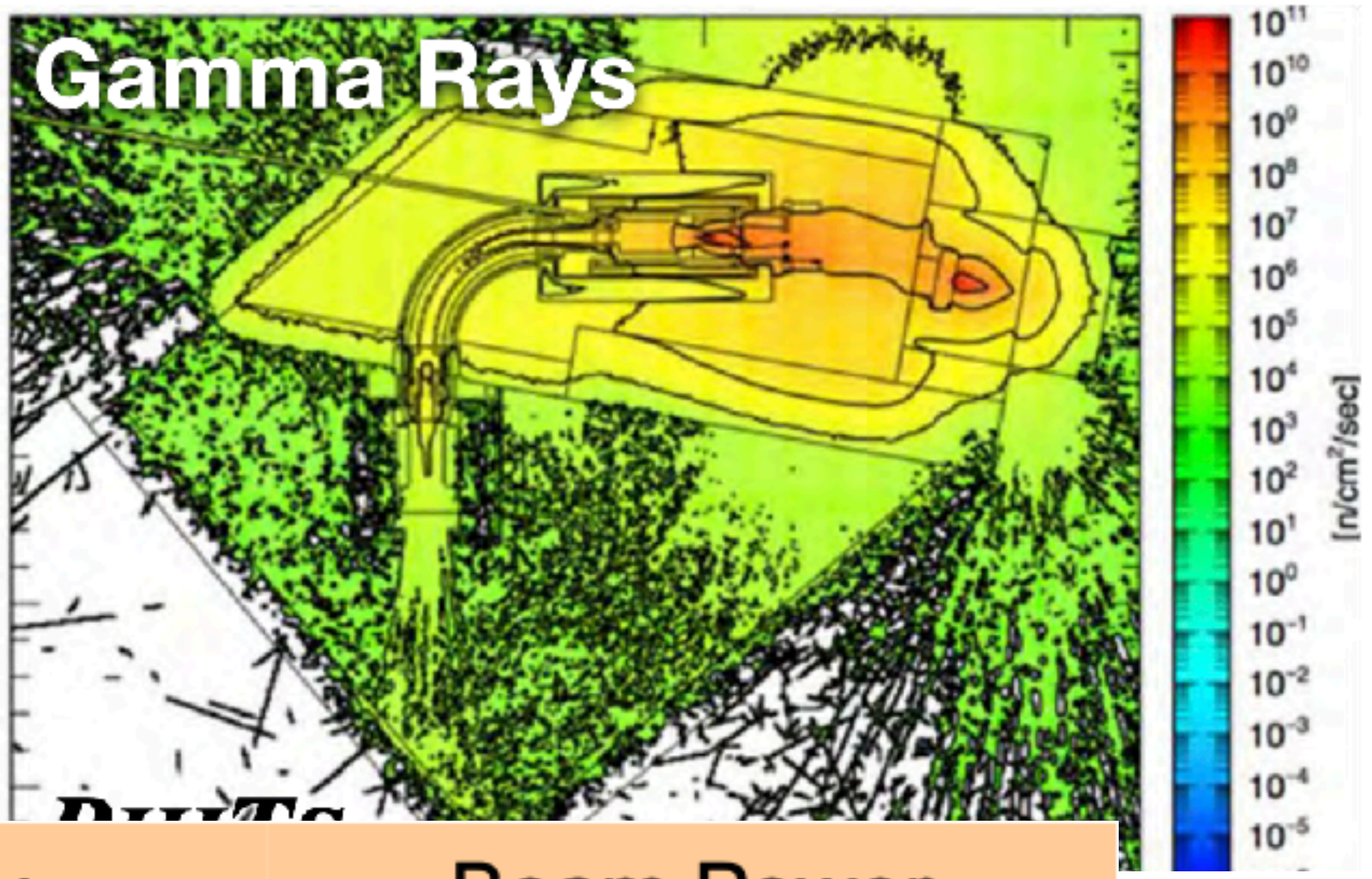
COMET Phase I



- Radiation levels for COMET Phase-I, studied by PHITS, MARS and Geant
- In the detector regions for 150 days, including margin of safety:
  - Neutrons: 10^{12} n/cm^2
  - Gamma rays: 2 kGy







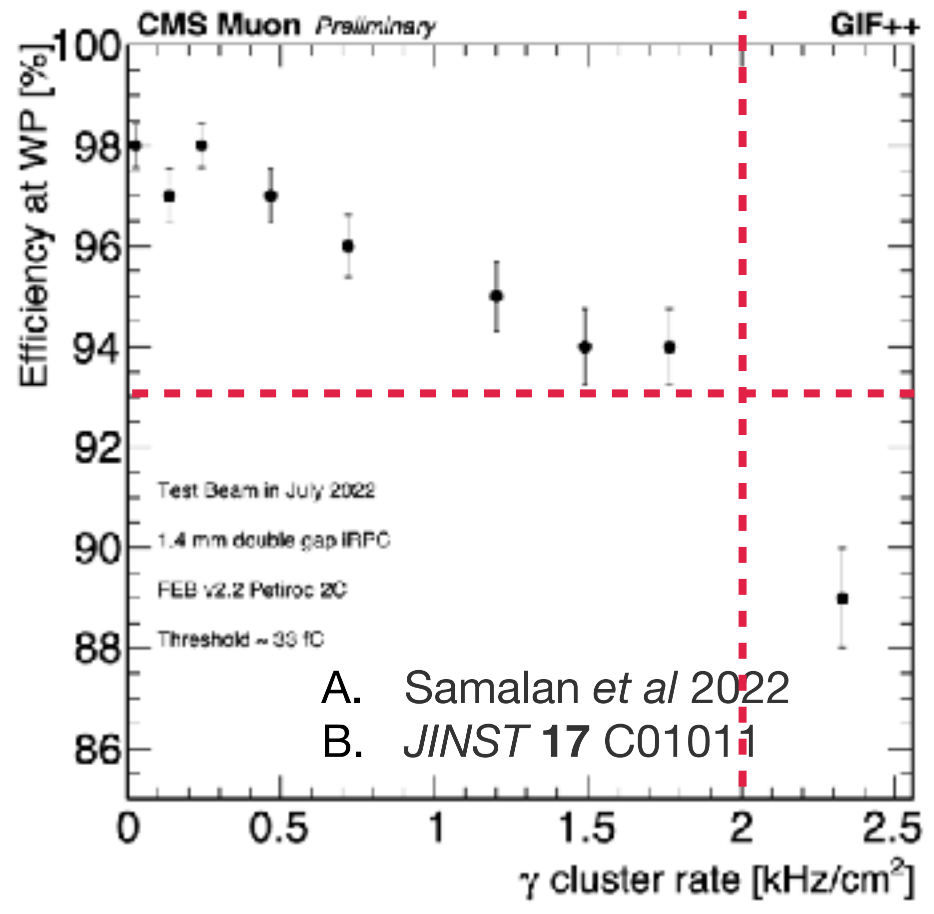
	Sensitivity	Beam Power
Phase-I LI (*)	3×10^{-13}	0.32kW
Phase-I	3×10^{-15}	3.2kW
Phase-II	$< 10^{-16}$	56kW

Very significant pileup::simulation under development

Upstream CRV

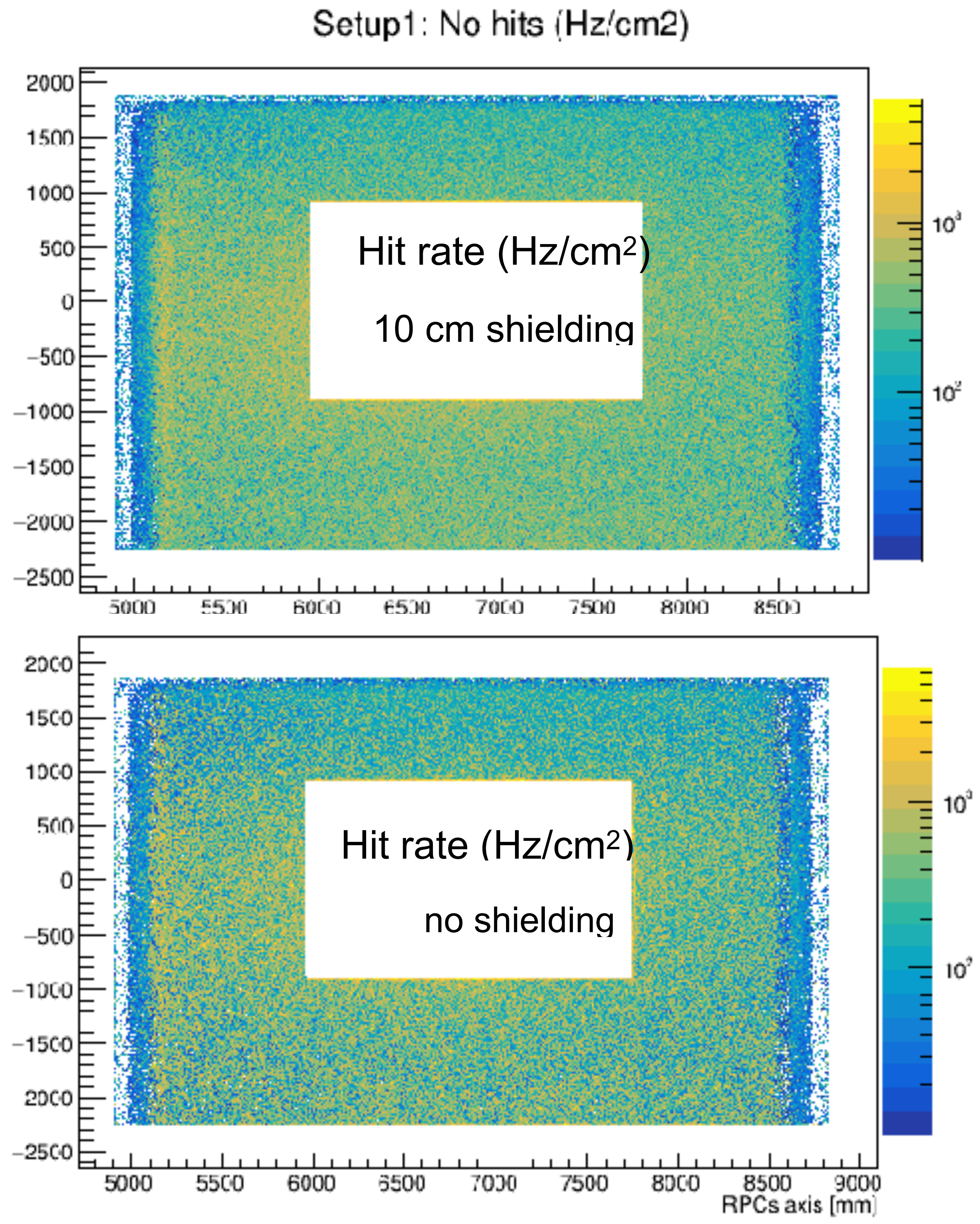
Fluence over full operation→ integrity of the detectors

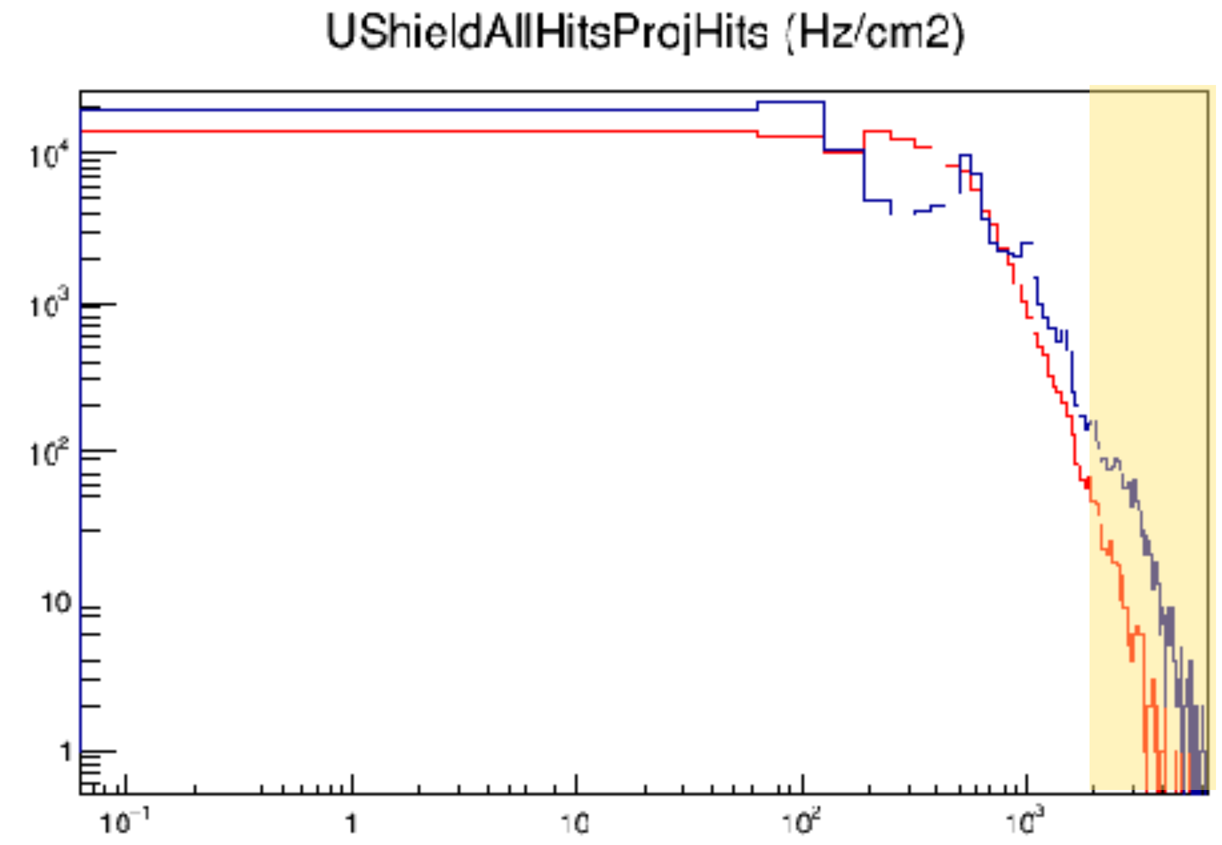
Instantaneous flux during operation → Rate of hits
→ significant loss of efficiency above 1.5 kHz/cm²
→ fake vetoes → dead time for COMET

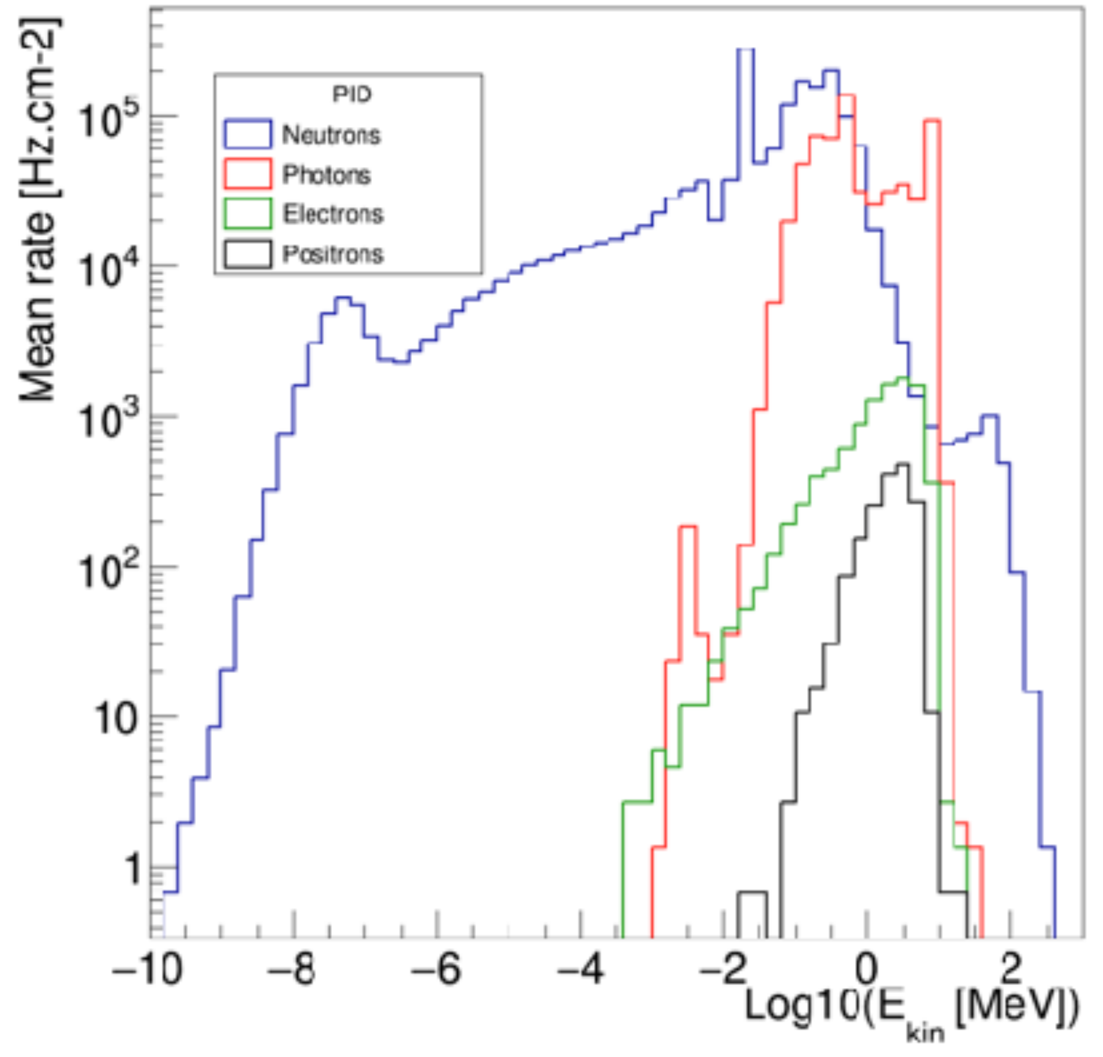


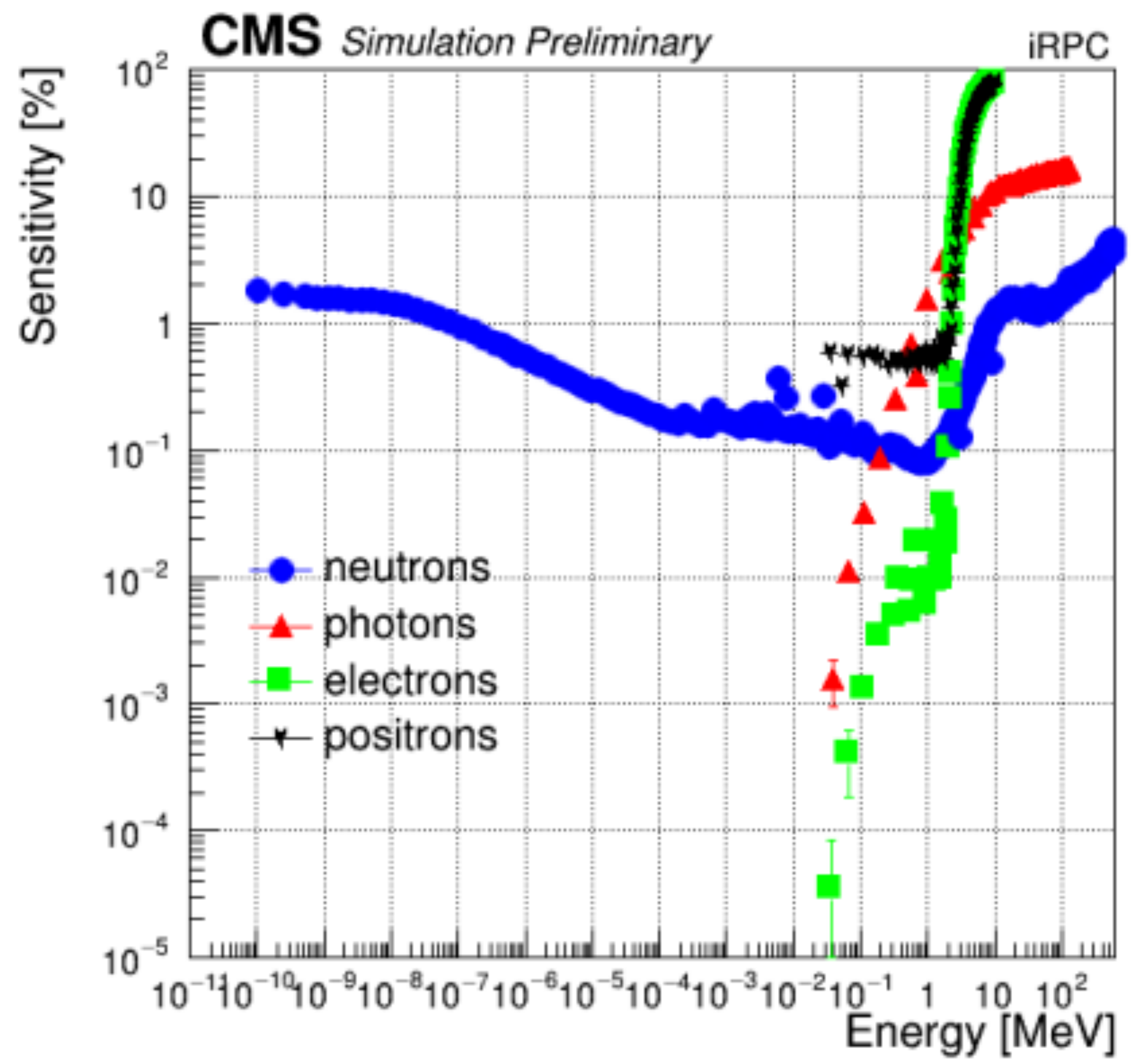
3 chambers in coincidence out of 5

eff chamber	93	95	98
ineff CRV	$3.1\ 10^{-3}$	$1.2\ 10^{-3}$	10^{-4}









Testing shielding no 1: 3.5 cm Mg(BH4)2 after the BS

$$Acc = Acc_{Geo} \bullet \varepsilon_{Trigger} \bullet \varepsilon_{DAQ} \bullet \varepsilon_{Finding} \bullet \varepsilon_{Tracking} \bullet \varepsilon_{quality} \bullet \varepsilon_{MomentumWindow} \bullet \varepsilon_{TimeWindow}$$

~20%

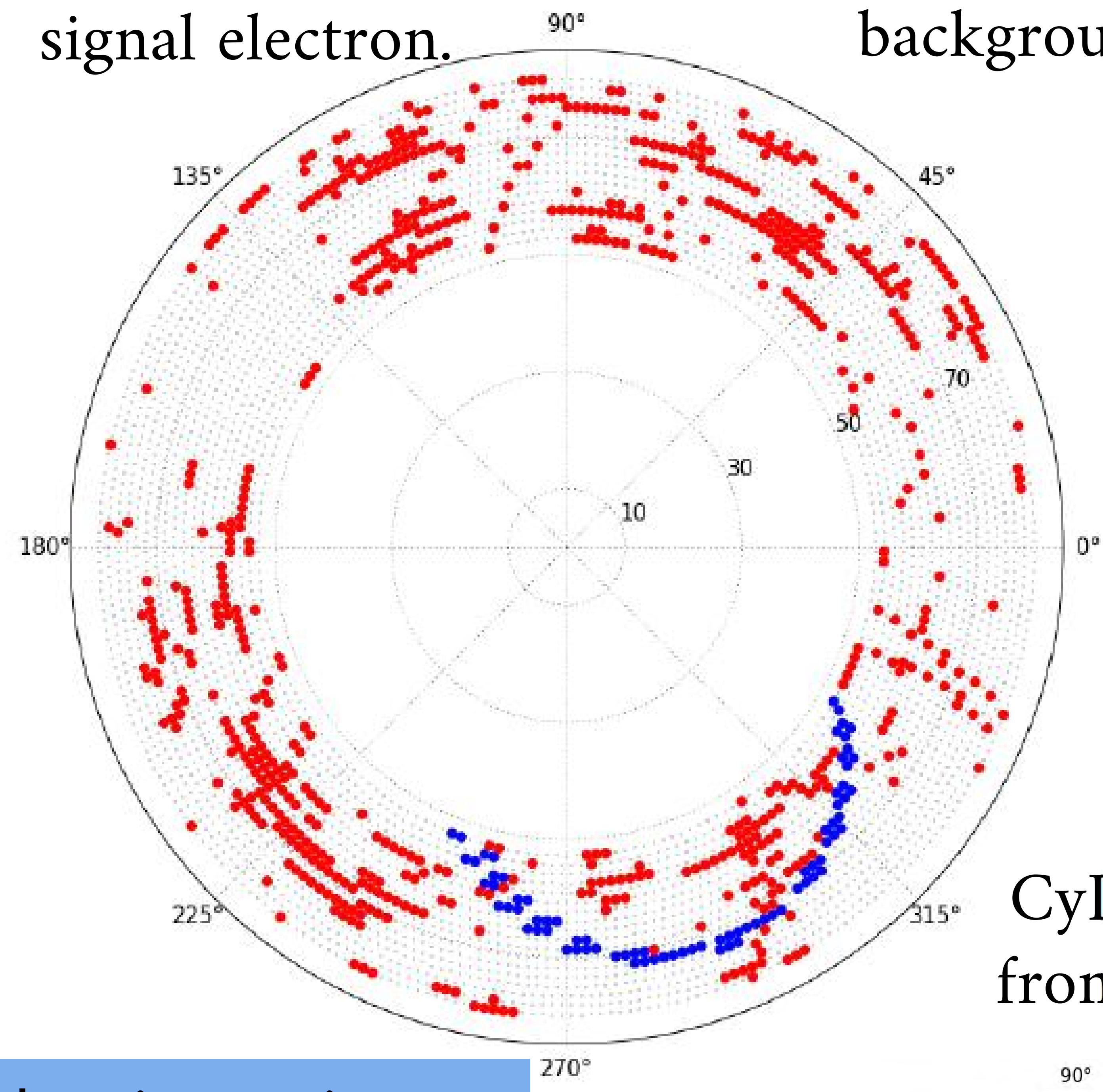
90%

99%

99%

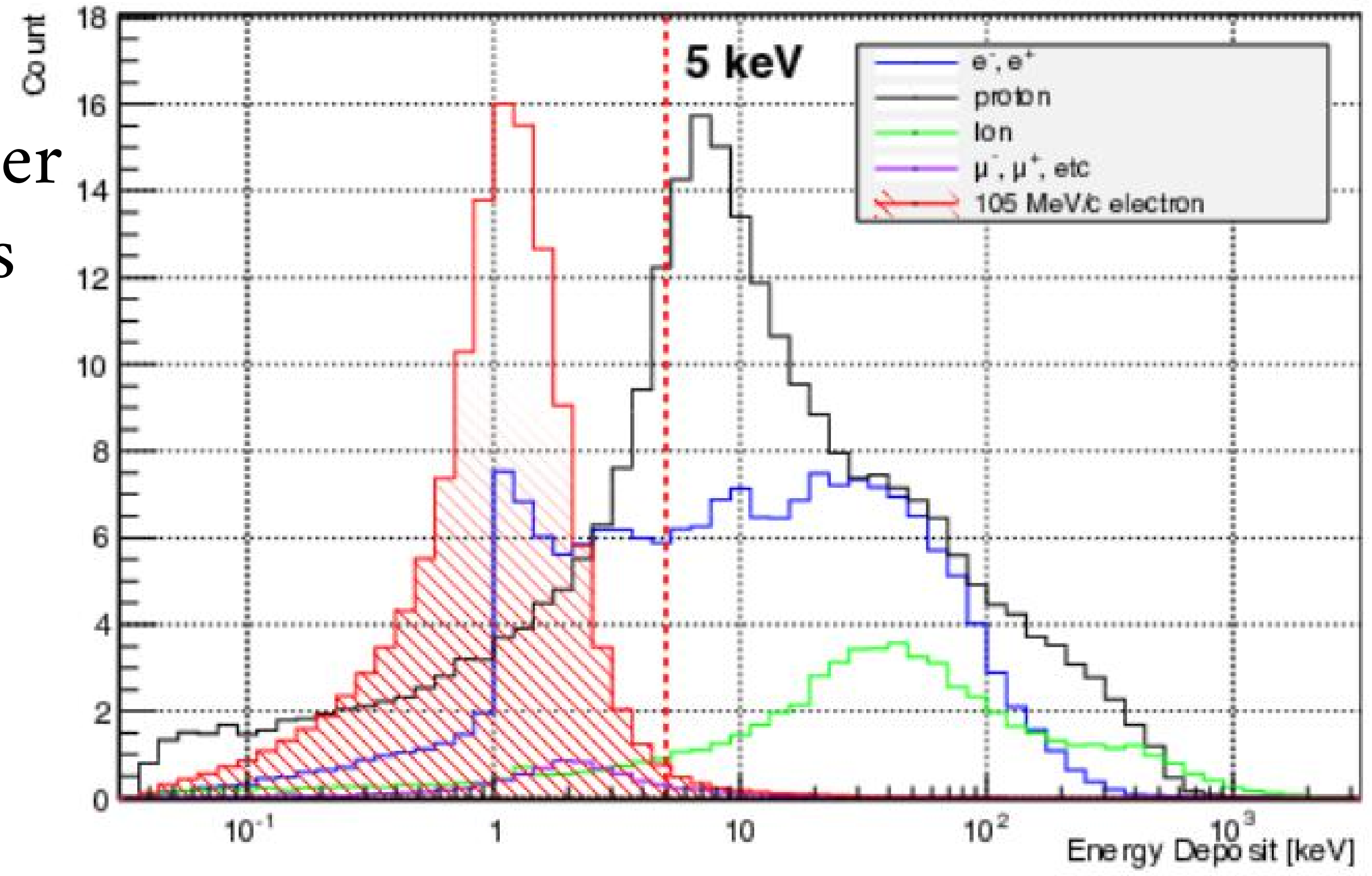
Blue hits correspond to the signal electron.

Red points are hits caused from background processes



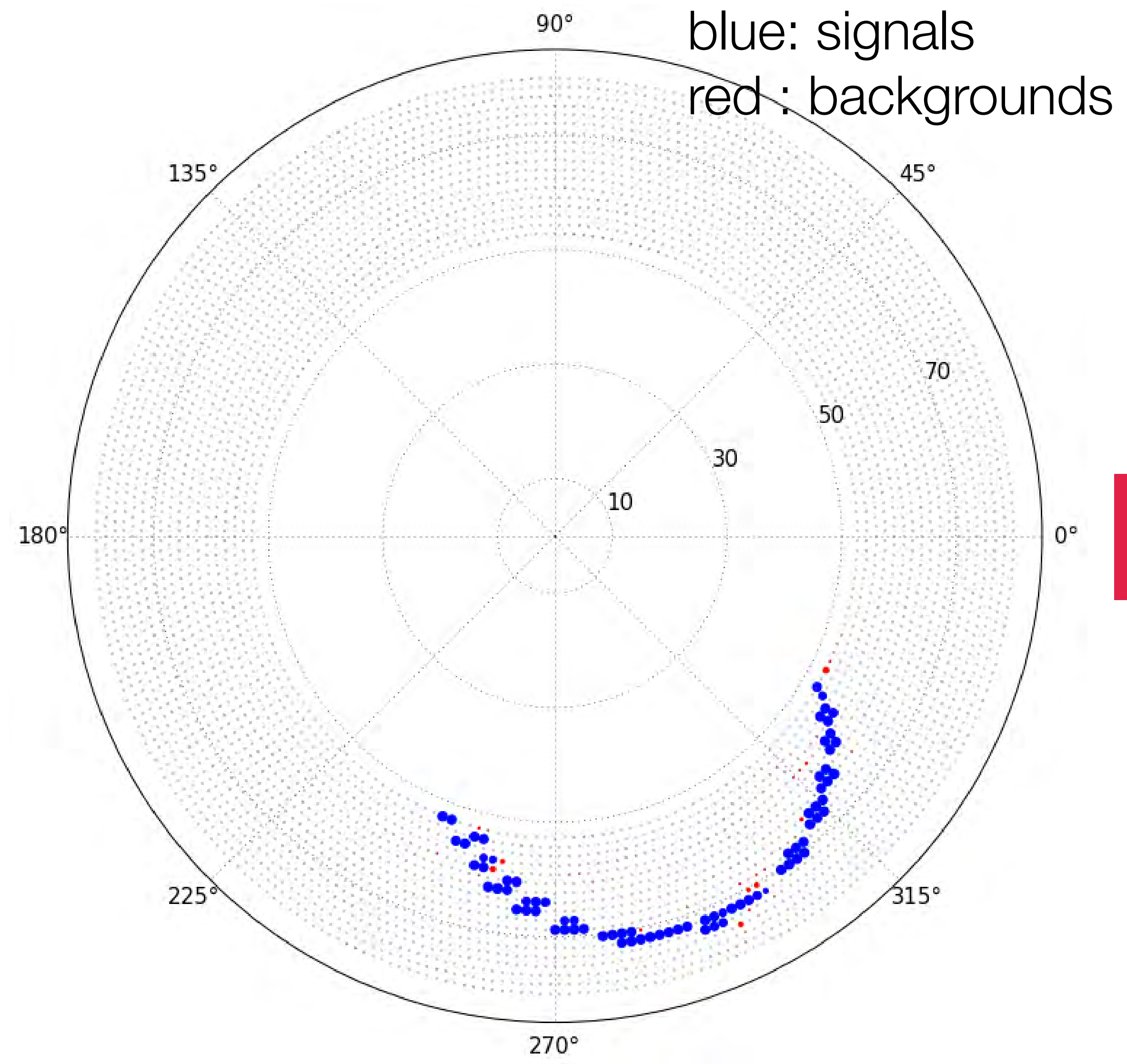
Most background hits are rejected based on timing, charge.

Total energy deposits per cell for signal electrons and noise hits



CyDet event. This is a projected view from the central plane of the detector

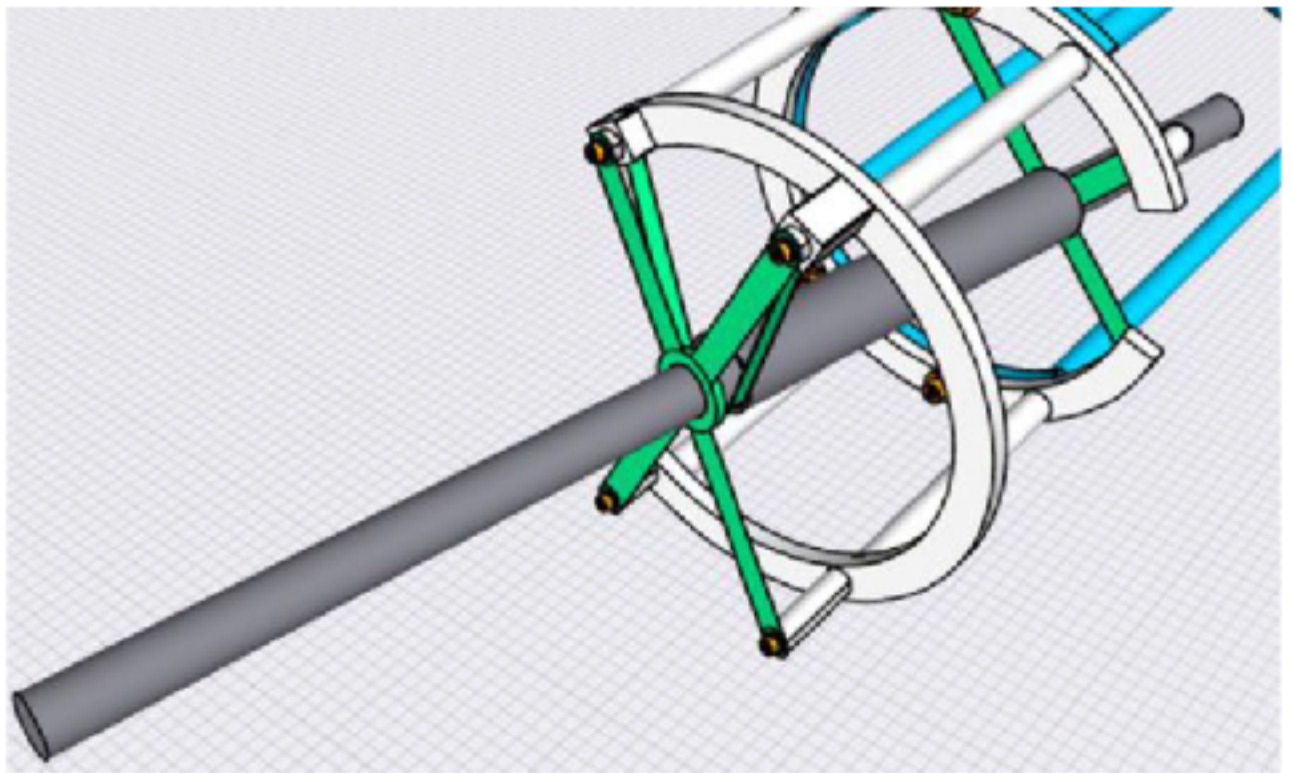
Hit selection using Gradient Boosted Decision Trees (GBDT) and Hough Transform

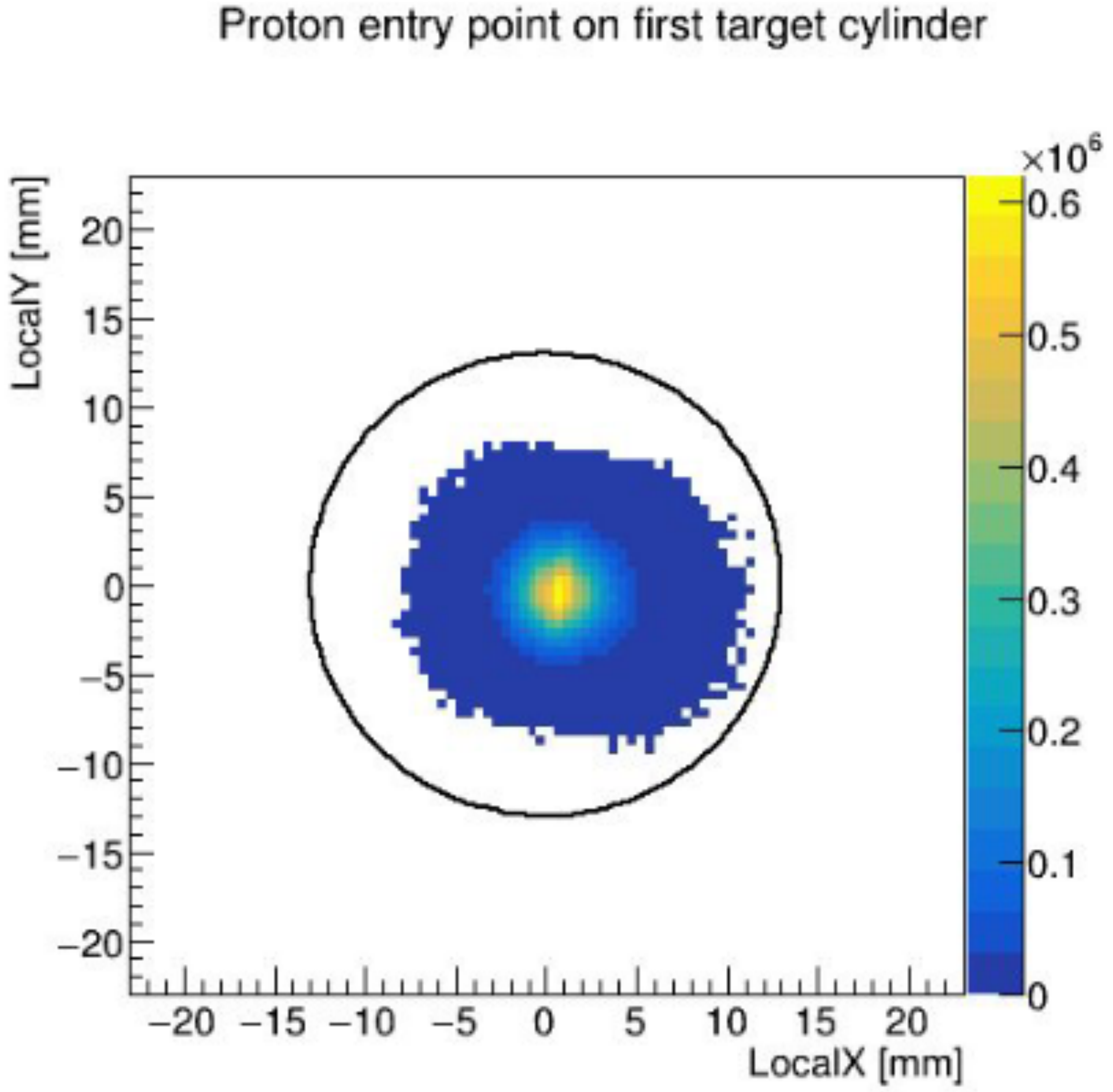


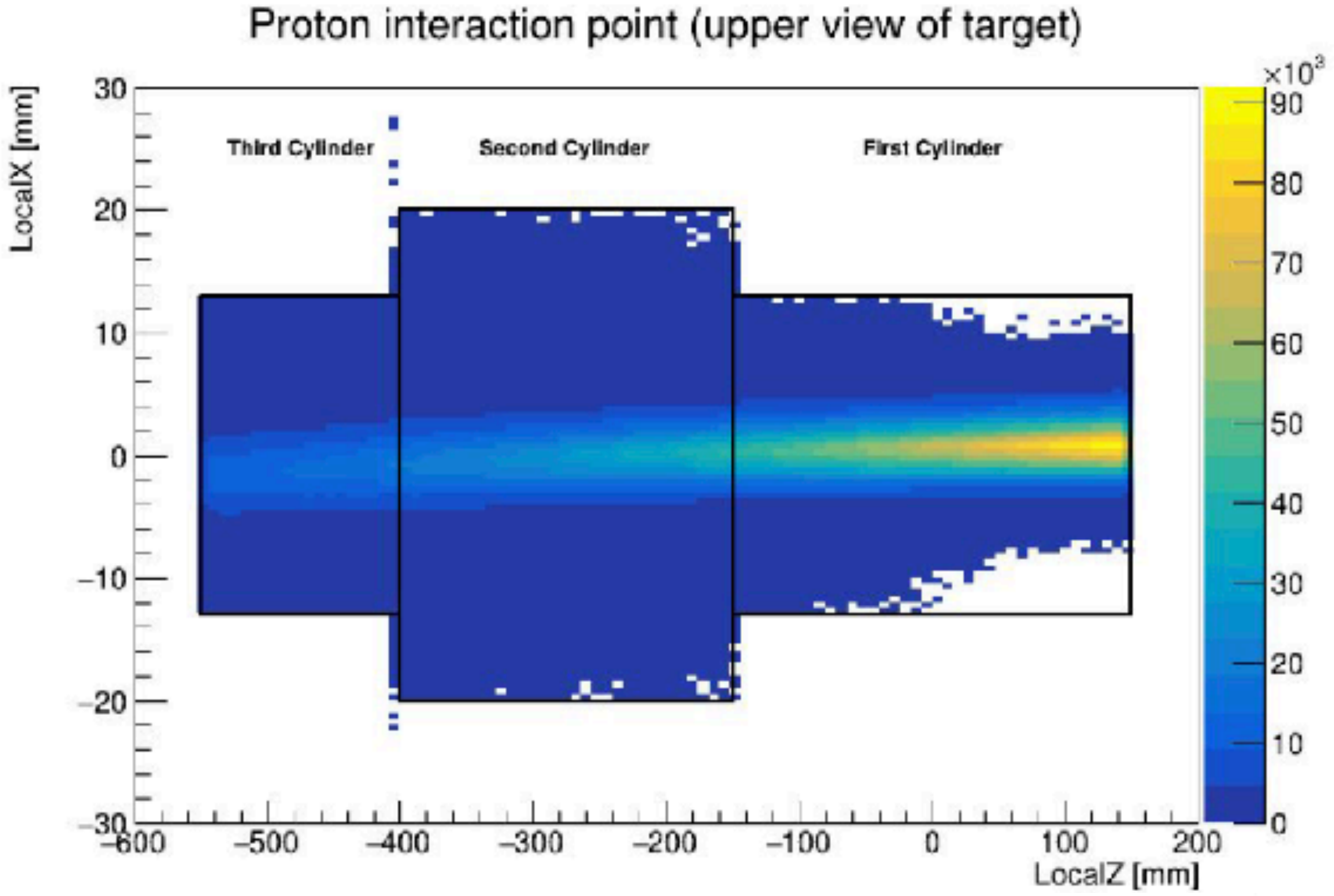
95% background rejection for 99% hit efficiency

Proton Target and Muon Transport

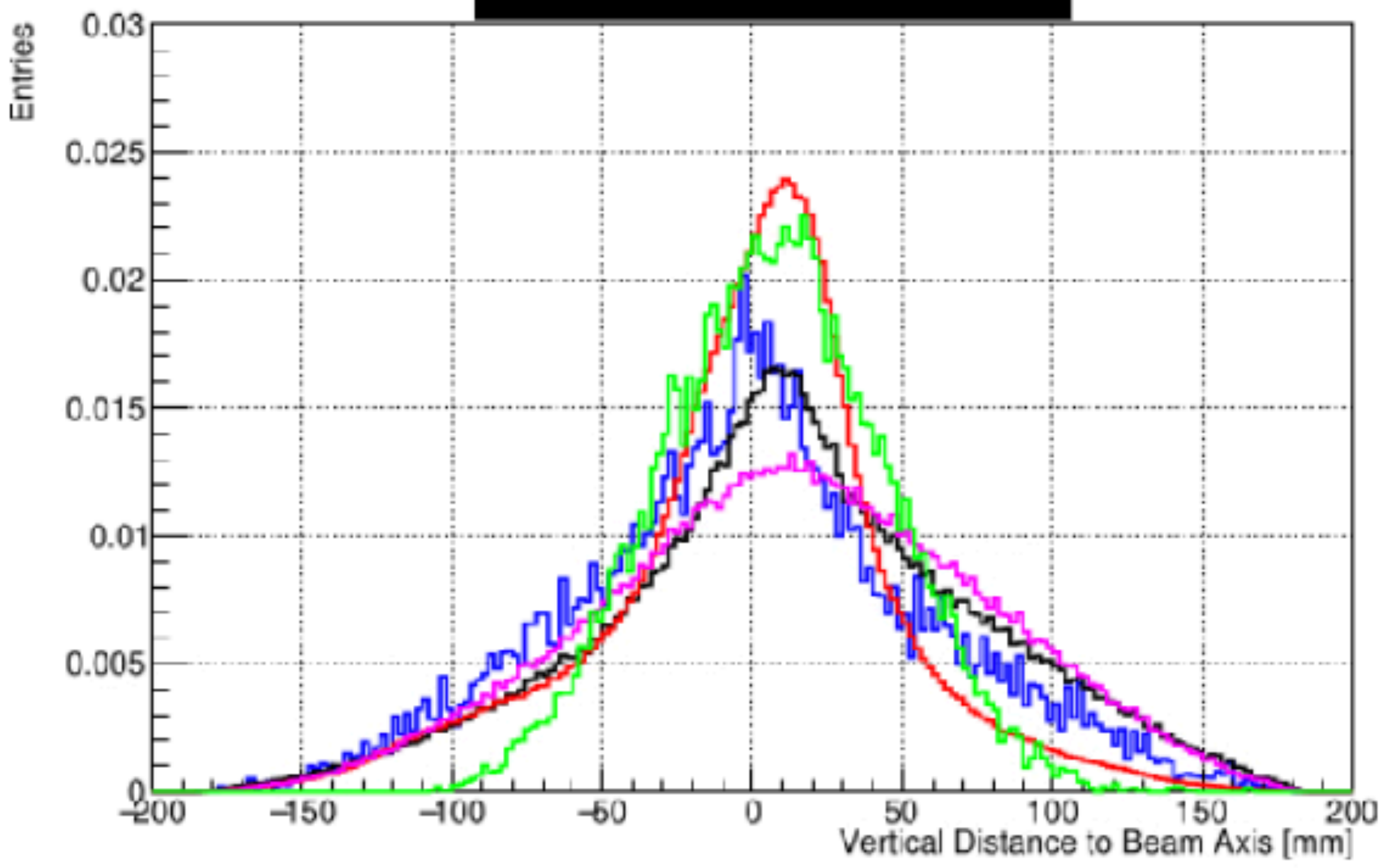
PCS 4.4T, 700 mm graphite target



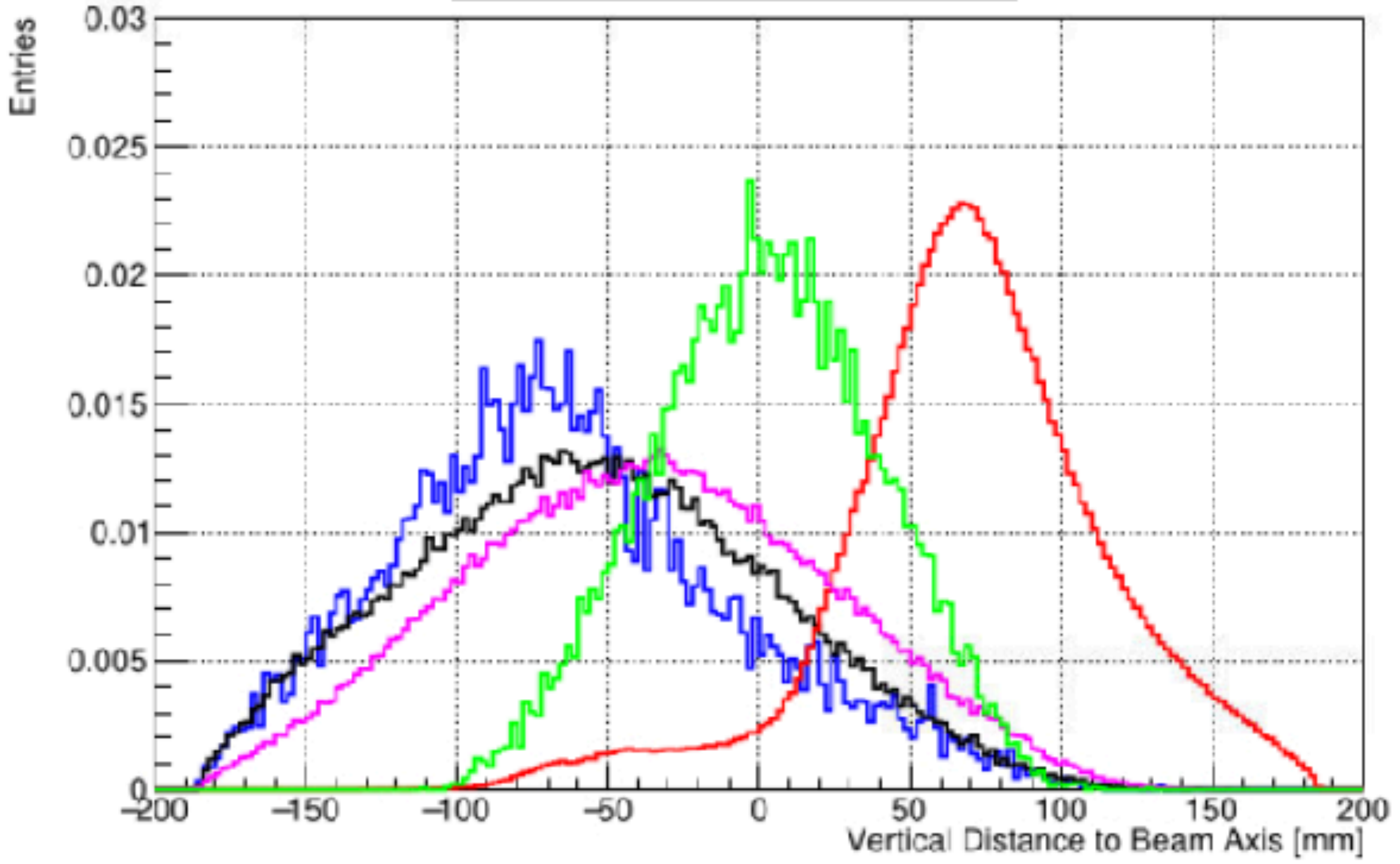




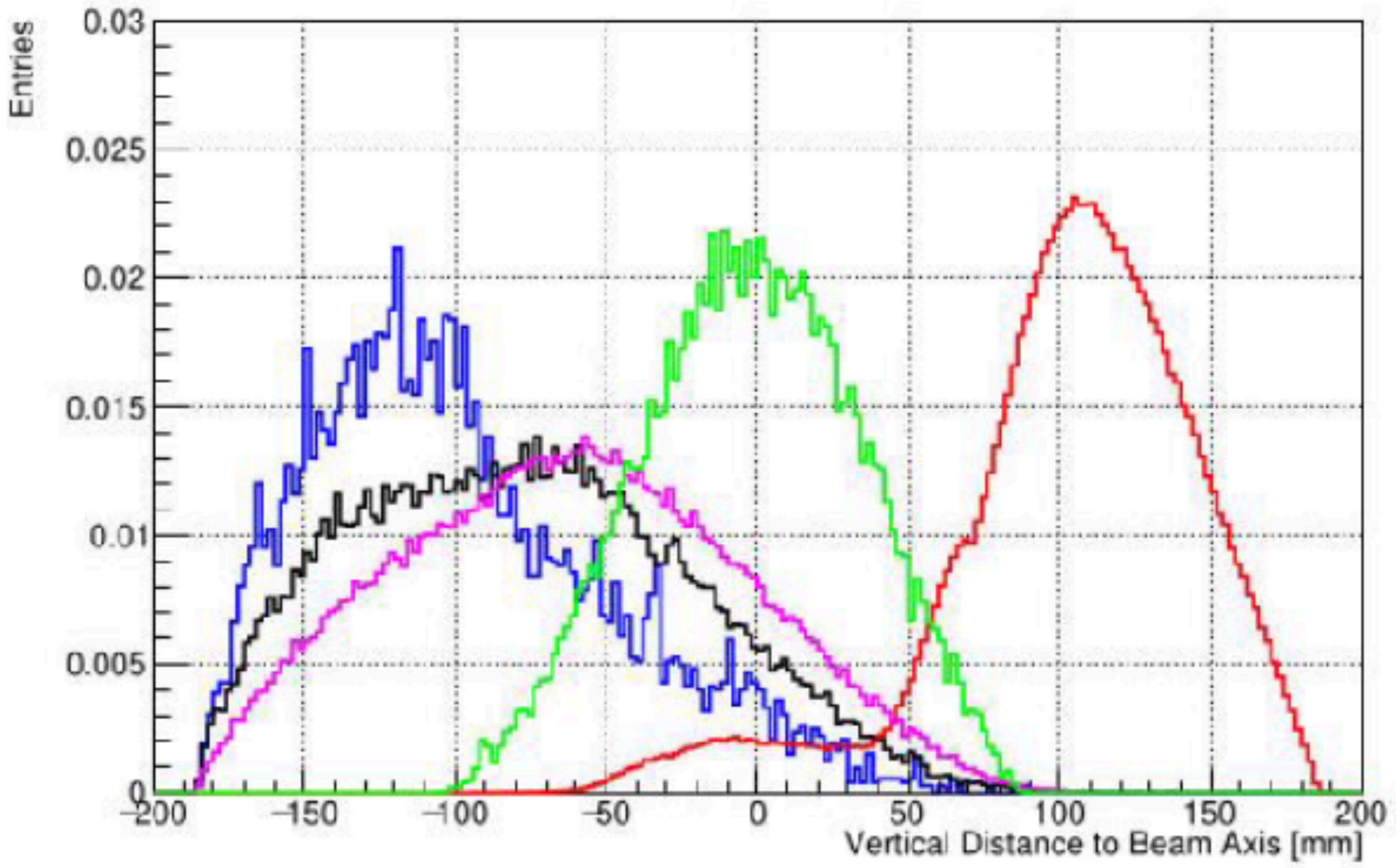
TS entrance



TS mid



TS exit

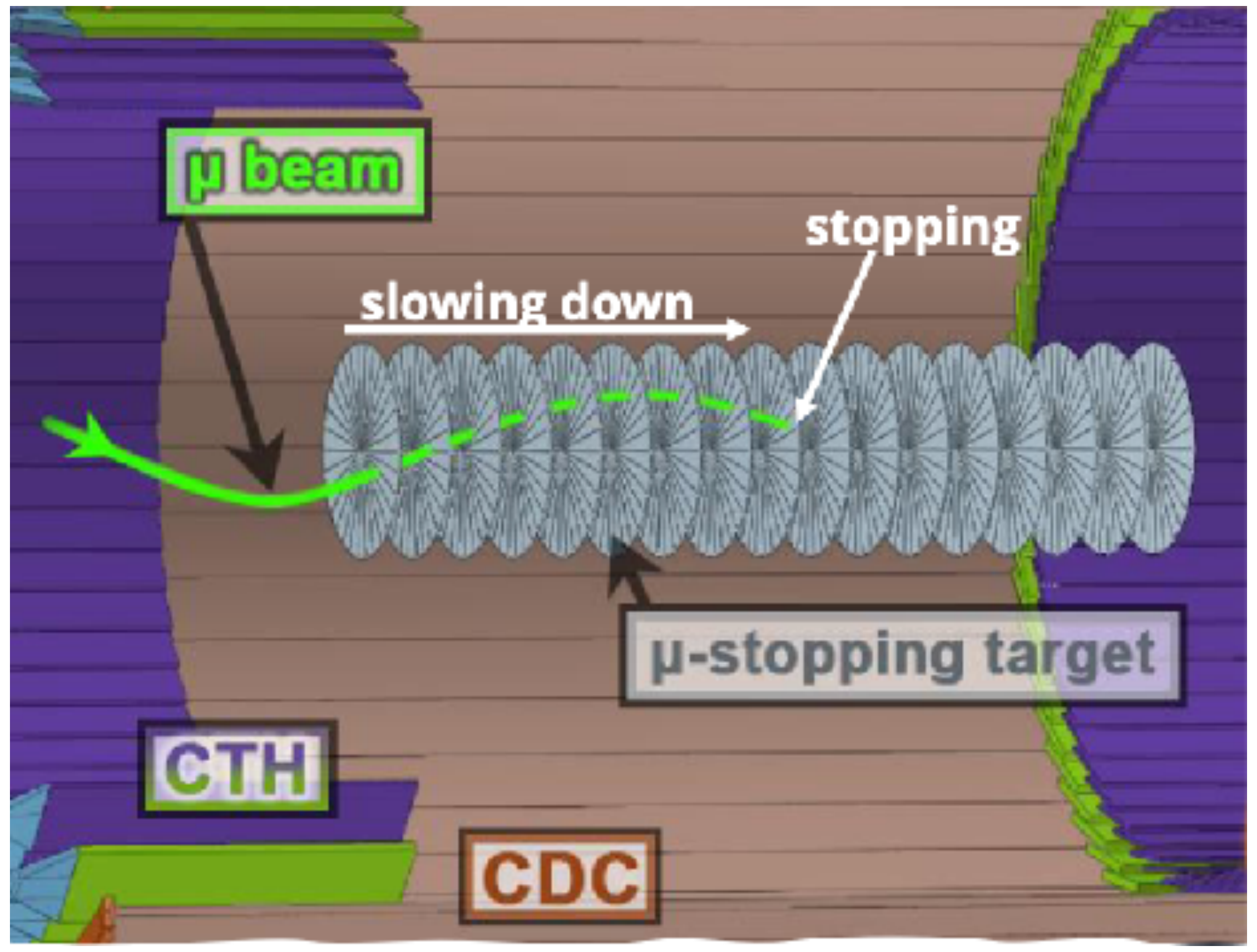


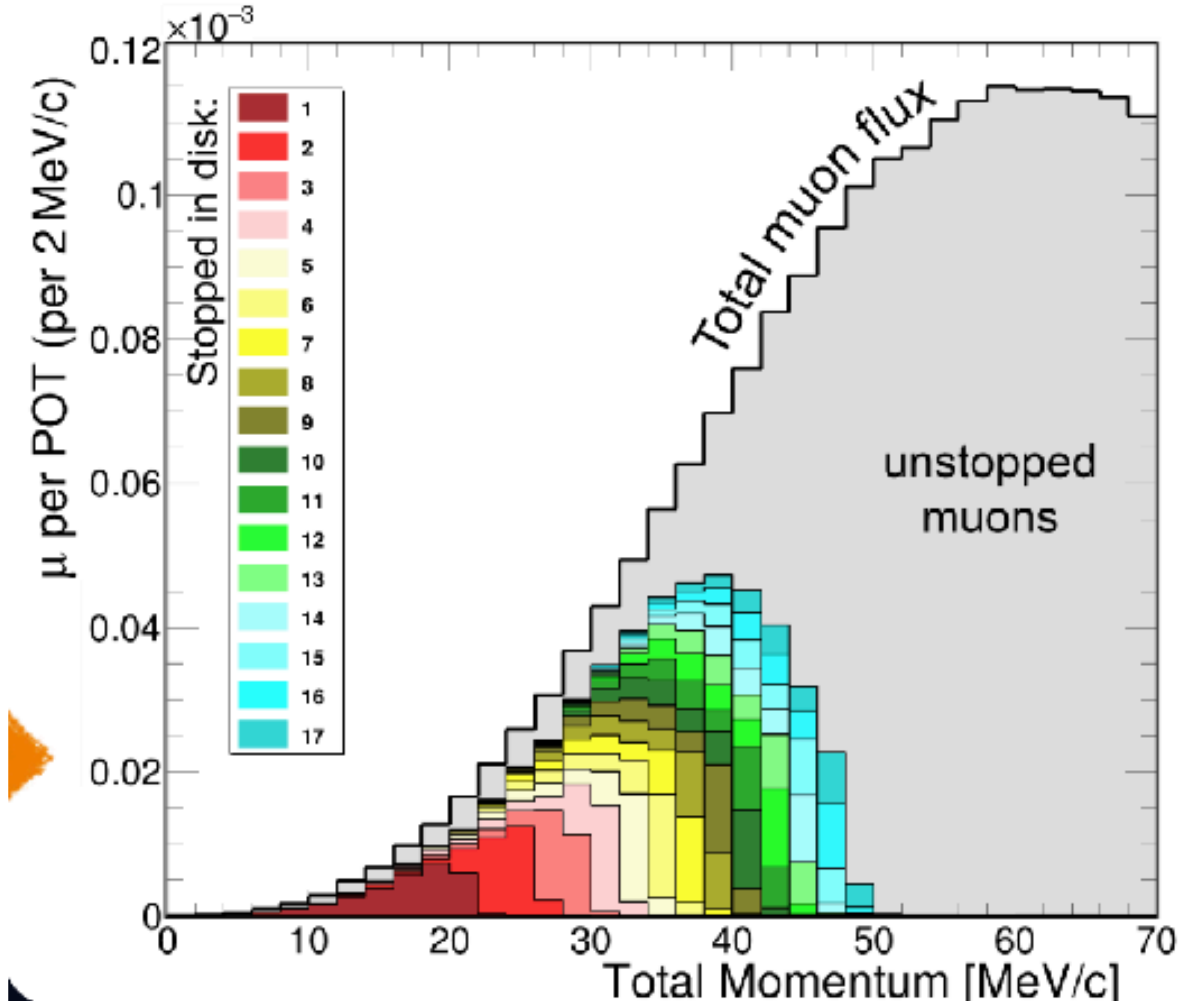
Red : p, $e+$, $\pi+$, $\mu+$, Magenta: $\mu-$, p > 70 MeV/c,

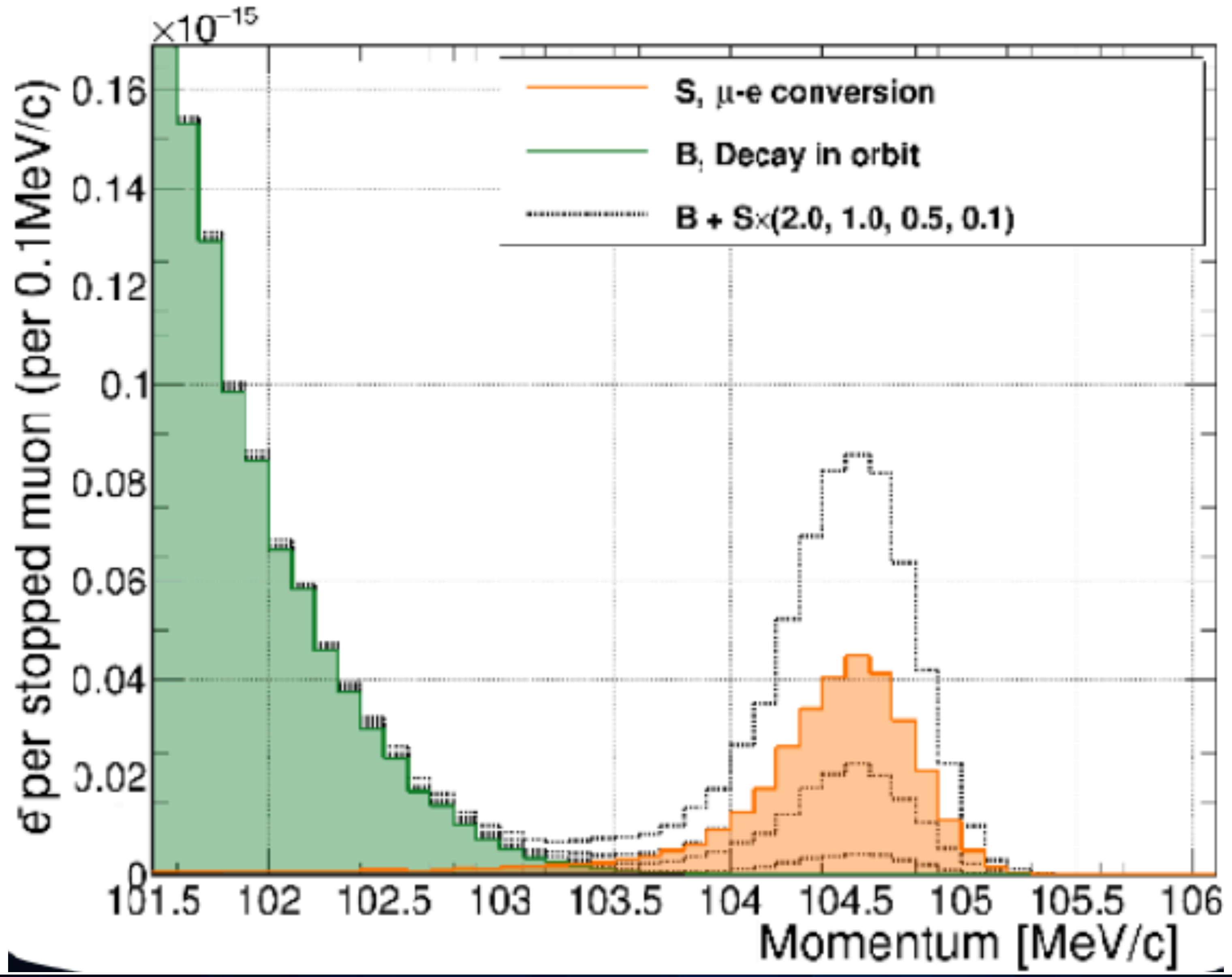
Black : $\pi-$, Blue: $e-$, p> 100 MeV/c , Green : Stopped μ

COMET
Aluminium Target

NUCLÉAIRE & PARTICULES







17 aluminium disks with...

100 mm radius

200 μm thickness

50 mm distance (total: 800 mm)