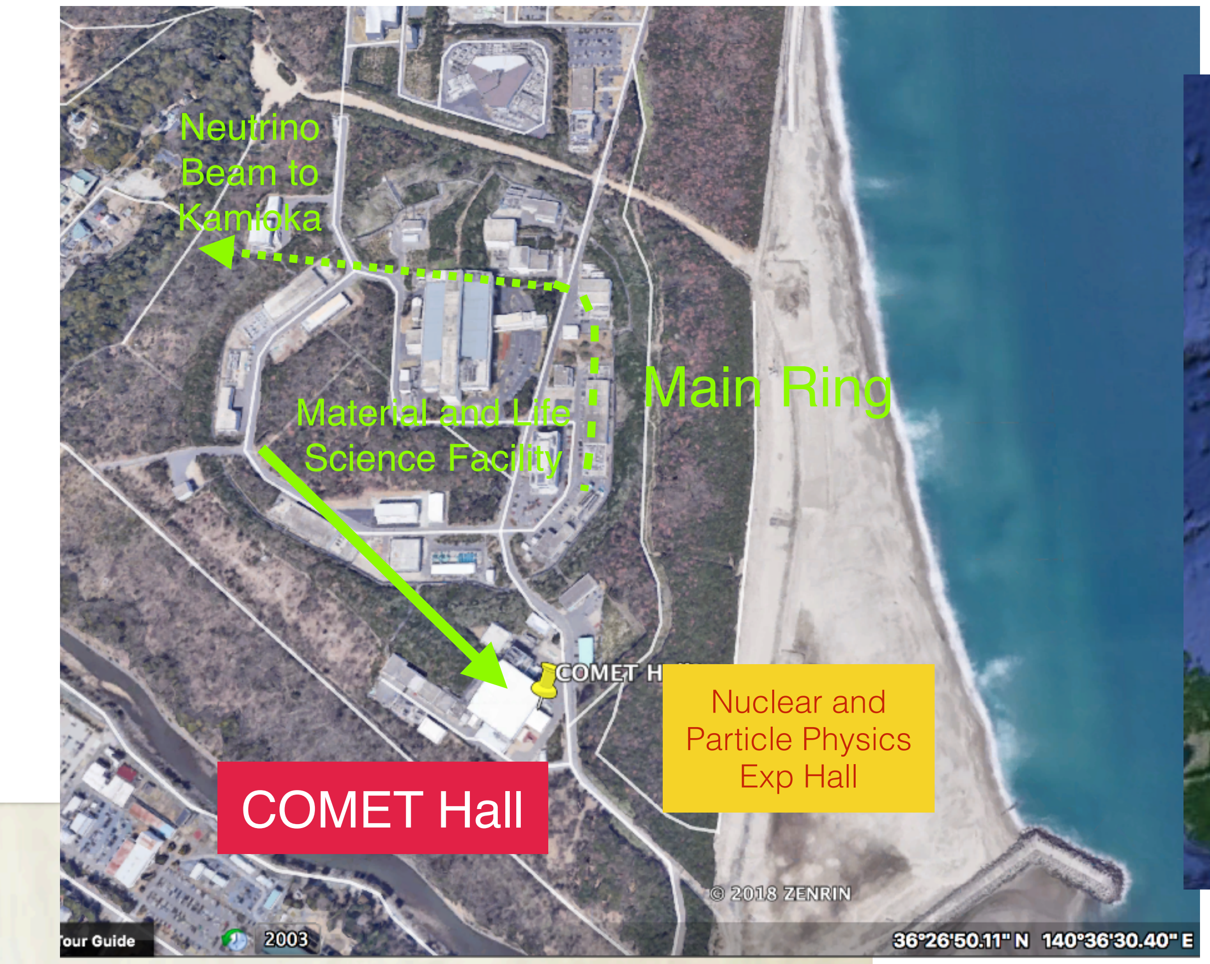
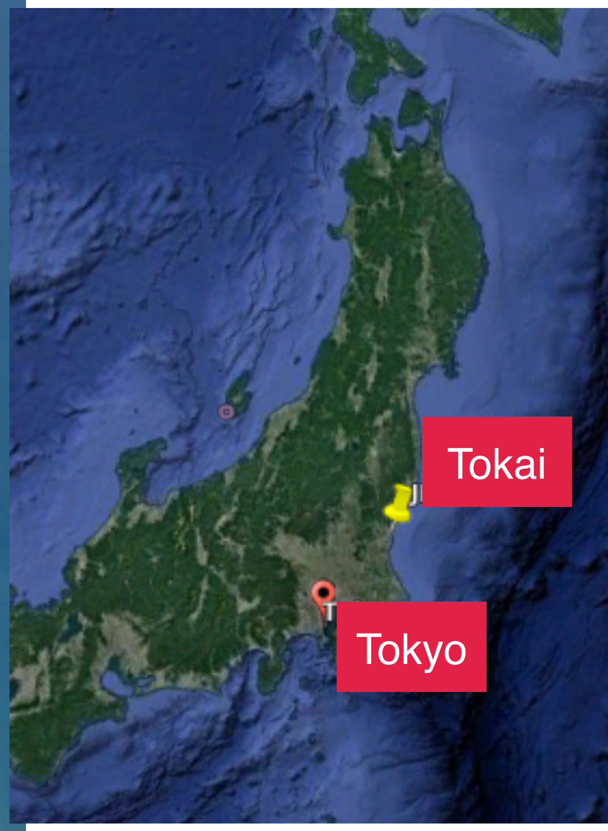




Patrice LEBRUN
Maxime GOUZEVITCH

Wilfried da SILVA
Luigi Del BUONO

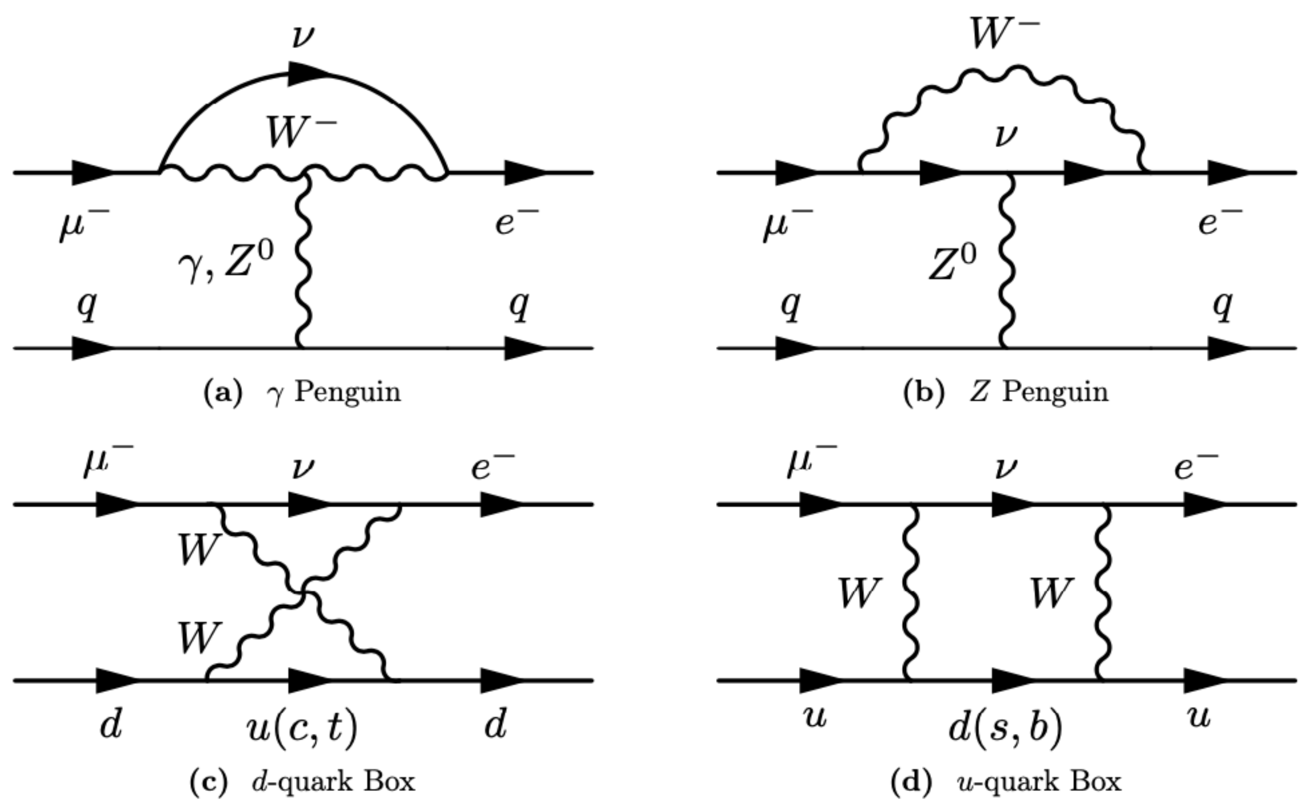
@ Y. Uchida

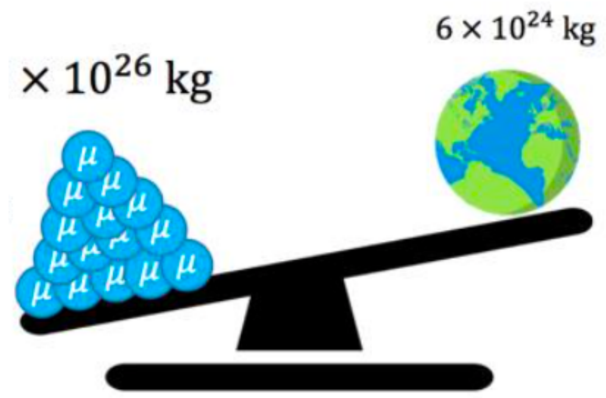
Jean-Claude ANGELIQUE
Gilles BAN

Cristina CÂRLOGANU
Nicolas CHADEAU (PhD)
Thomas CLOUVEL (PhD)
Geraldine FAURE
Ana M. TEIXERA (TH)

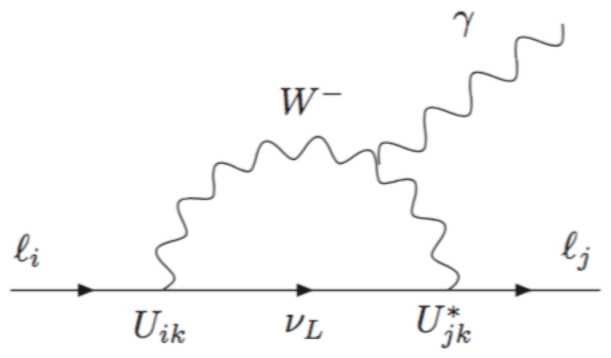
Fermion mixings in the SM

cLFV observed ⇒ New Physics in the lepton sector beyond minimally extended SM



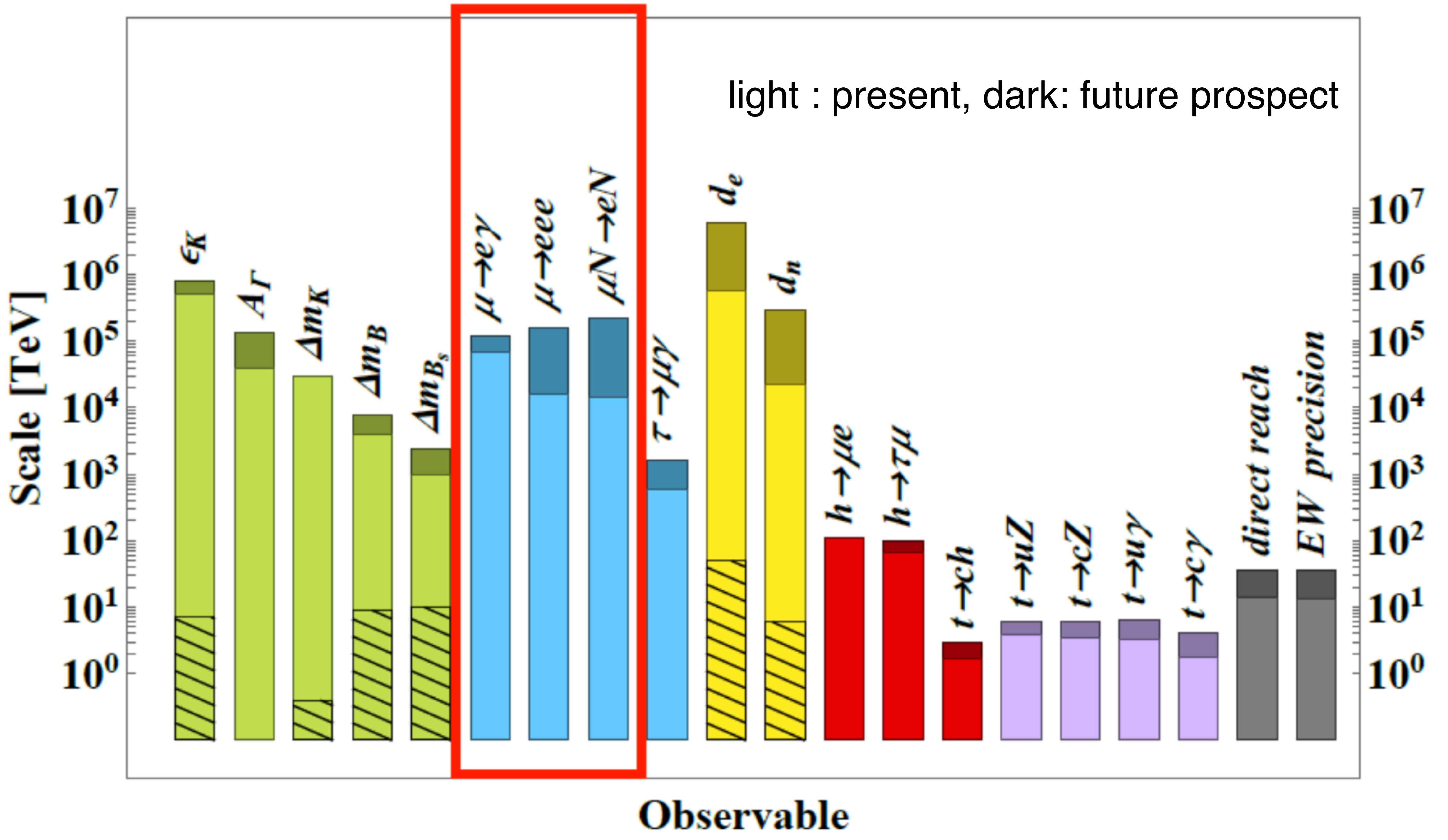


© MJ Lee



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

muon observables among the most sensitive to high scale new physics

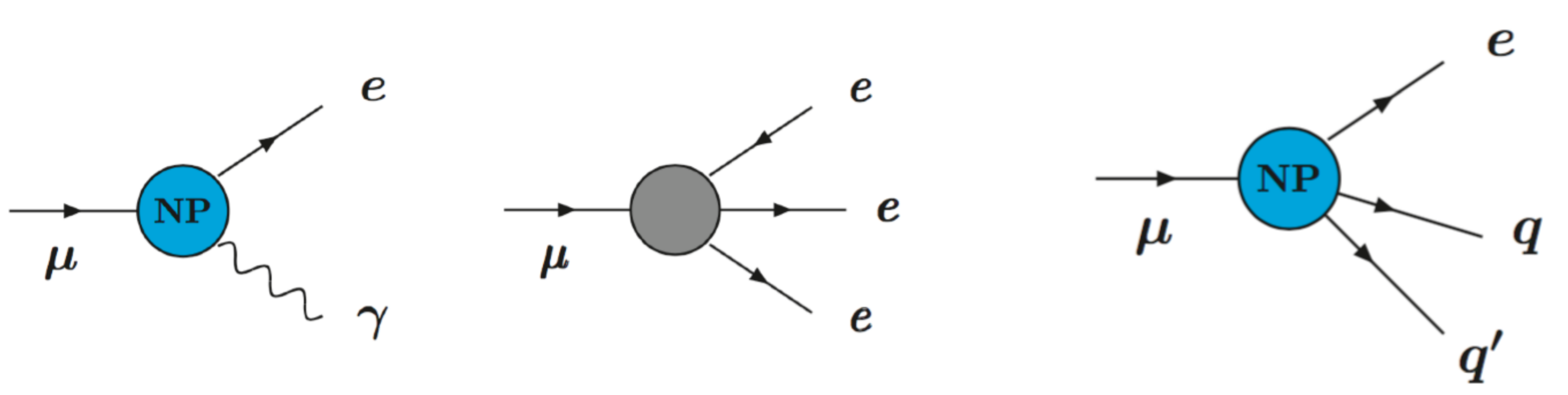


European Particle Physics Strategy Update (2019)

$\mu \to e\gamma$ / $\mu \to eee$ / $\mu N \to eN$ Complementarity

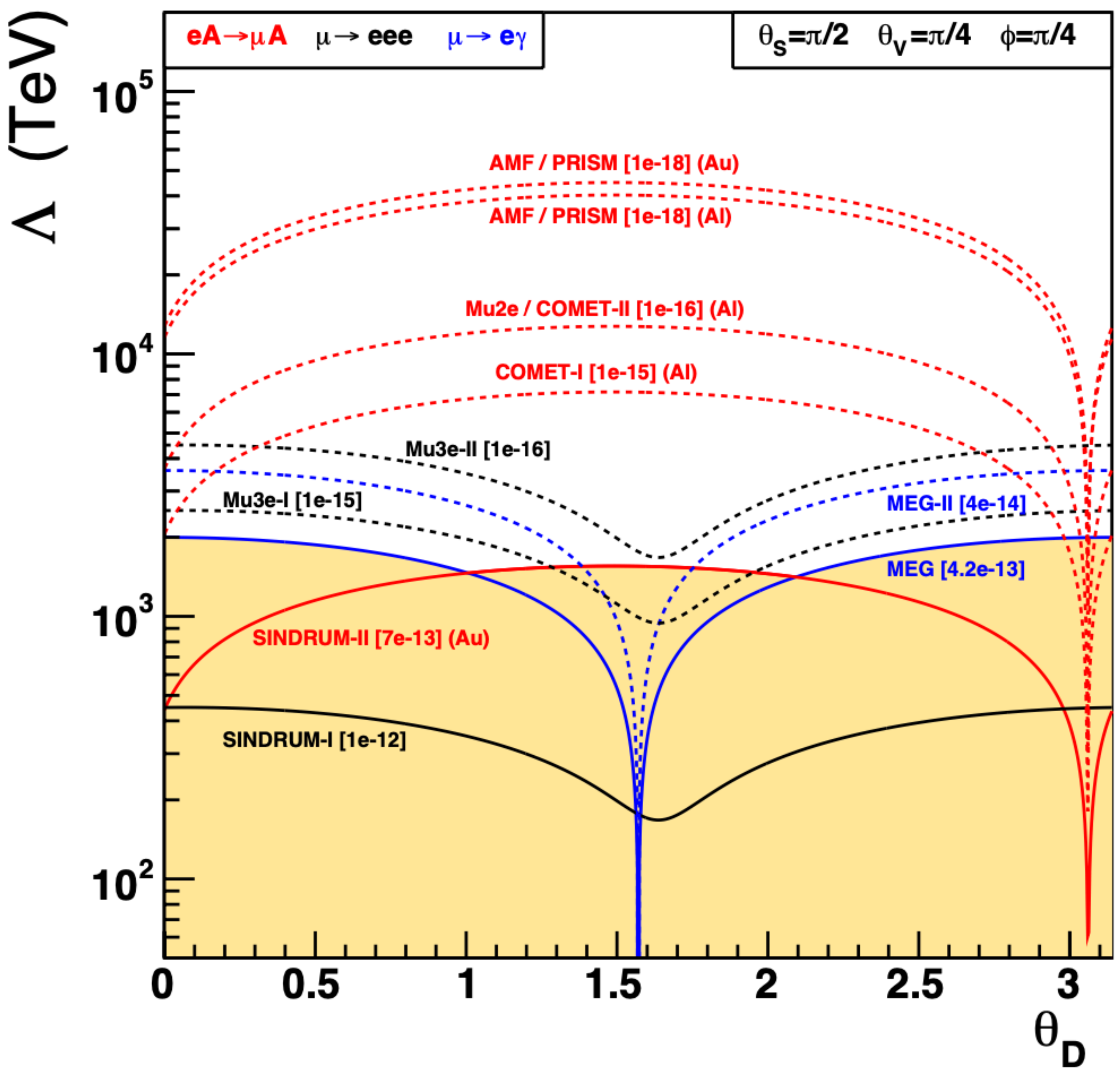
$$\delta\mathcal{L} = \frac{1}{\Lambda^2_{LFV}}\Big[m_\mu C_D(\bar{e}\sigma^{\alpha\beta}P_R\mu)F_{\alpha\beta} + C_S(\bar{e}P_R\mu)(\bar{e}P_Re) + C_{VR}(\bar{e}\gamma^\alpha P_L\mu)(\bar{e}\gamma_\alpha P_Re) + C_{VL}(\bar{e}\gamma^\alpha P_L\mu)(\bar{e}\gamma_\alpha P_Le) + C_{Alight}\mathcal{O}_{Alight} + C_{Aheavy\perp}\mathcal{O}_{Aheavy\perp}\Big]$$

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



	Collaboration	year	BR 90% C.L.
$\mu \to e\gamma$	**PSI/MEG+MEG2**	**2023**	**4.2×10^{-13}**
	PSI/MEG II	2026	*6×10^{-14}*
$\mu \to eee$	PSI/SINDRUM	**1988**	**1×10^{-12}**
	PSI/Mu3e	2026	10^{-15} - 10^{-16}
$\mu N \to eN$ (A,Z)	**PSI/SINDRUM**	**2006**	**7×10^{-12}**
	FNAL/Mu2e Run I/ Run 2	2028 / 2030	*6.2×10^{-16} / 3×10^{-17}*
	JParc/COMET Phase I / Phase II	2028 / 20XX	*5×10^{-15} / 7×10^{-17}*

S. Davidson, B.Echenard, Eur. Phys. J. C **82** (2022) no.9, 836



$$Rate \sim \frac{[\,]^2}{\Lambda^4}$$

Need to improve the SES by **10000** to reach **10** times higher in energy scale!

μ^- stopped in a target →

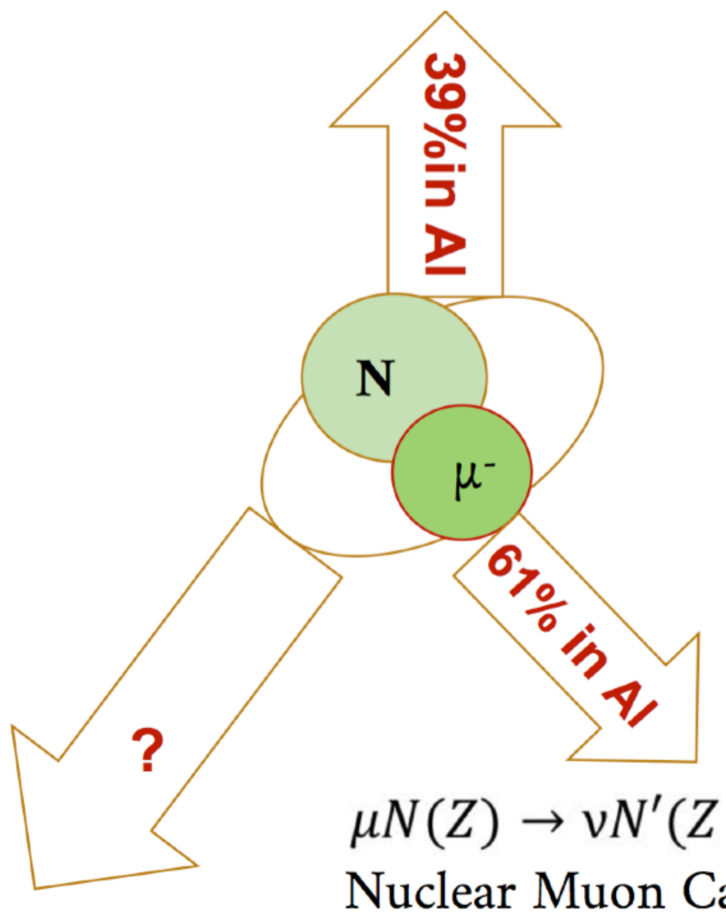
Muonic atom

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

This requires:
- 10^{18} **stopped muons**
- high background suppression

Decay In Orbit

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

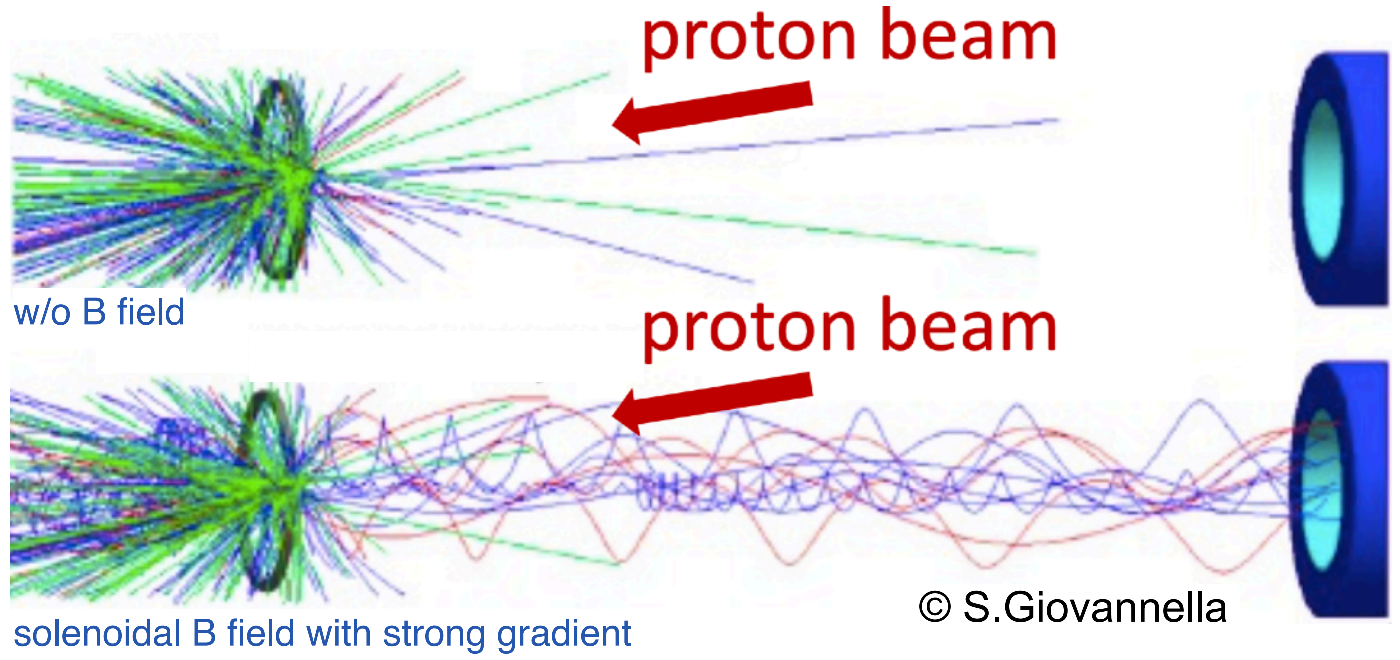


$\mu N(Z) \rightarrow \nu N'(Z-1)$

Nuclear Muon Capture

© Lobashev and Djilkibaev

MELC experiment [Sov.J.Nucl.Phys. 49, 384 (1989)]

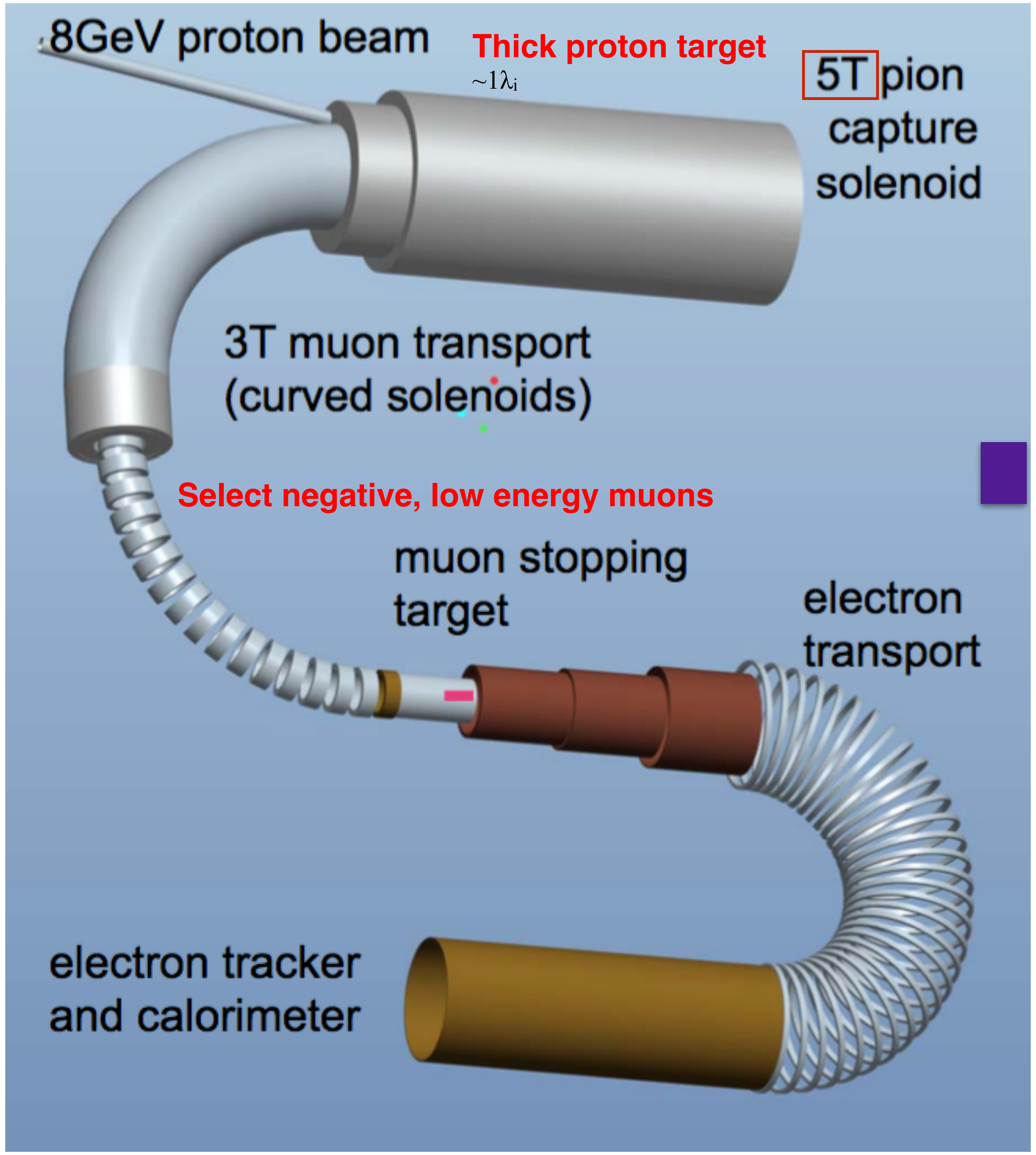


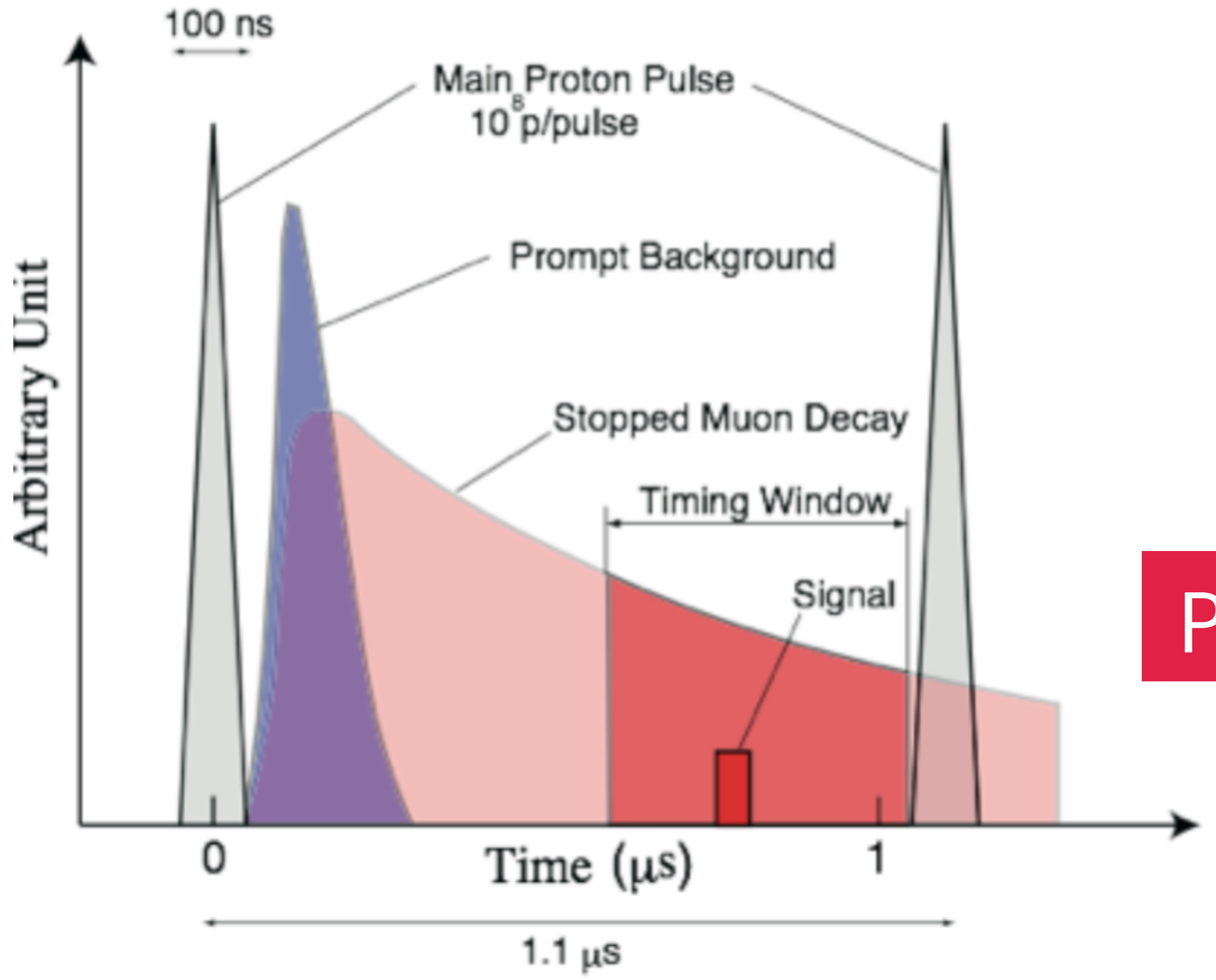
Muonic atom lifetime decreases with Z

Probability of the conversion increases with Z

⬇

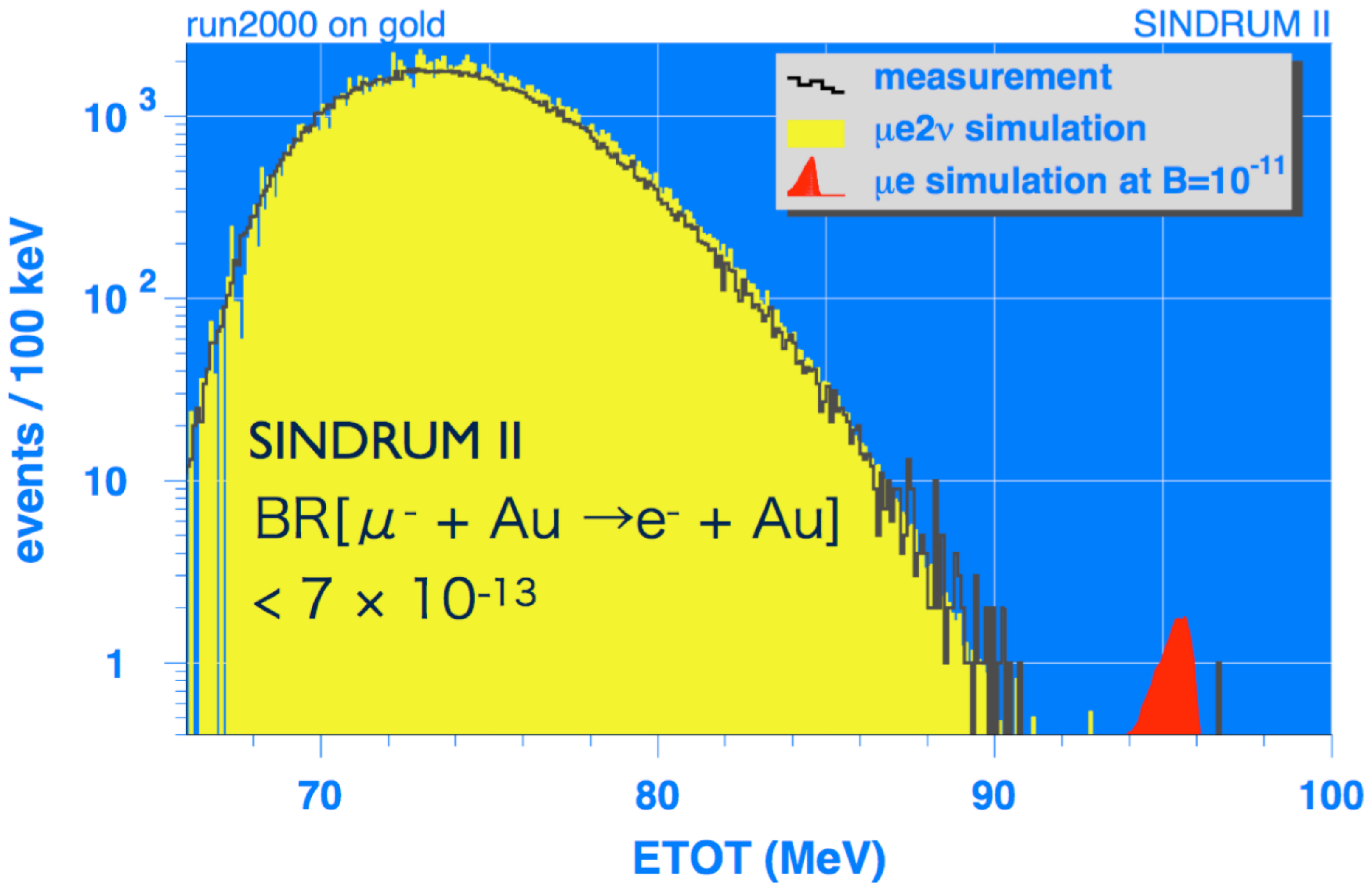
Aluminium (864 ns lifetime) is
a good experimental compromise





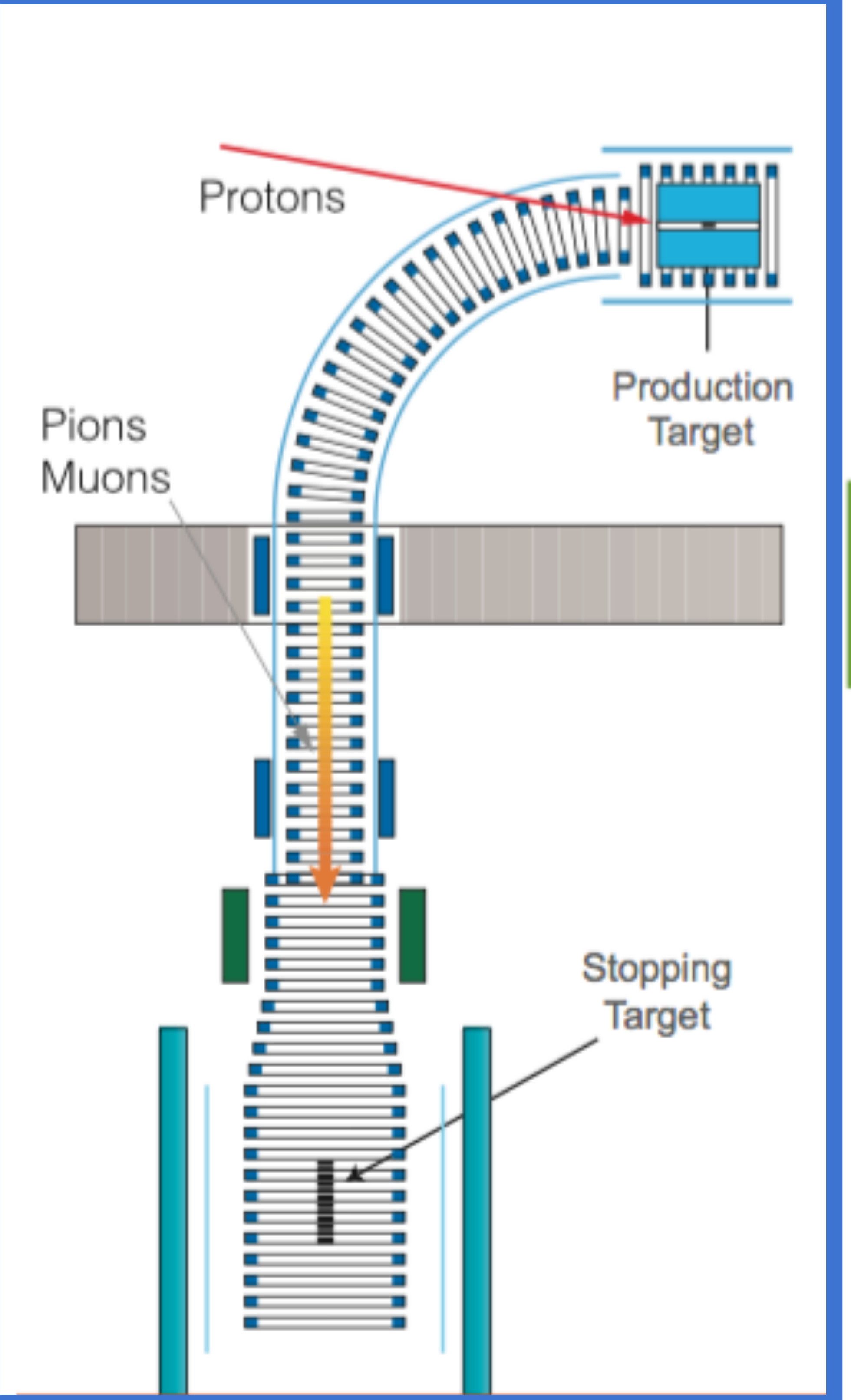
Pulsed beam

Required momentum resolution : better than 200 keV/c to control DIO



Atmospheric muons can fake signal events
⇒ proportional to the running time
⇒ higher beam intensity is preferrable

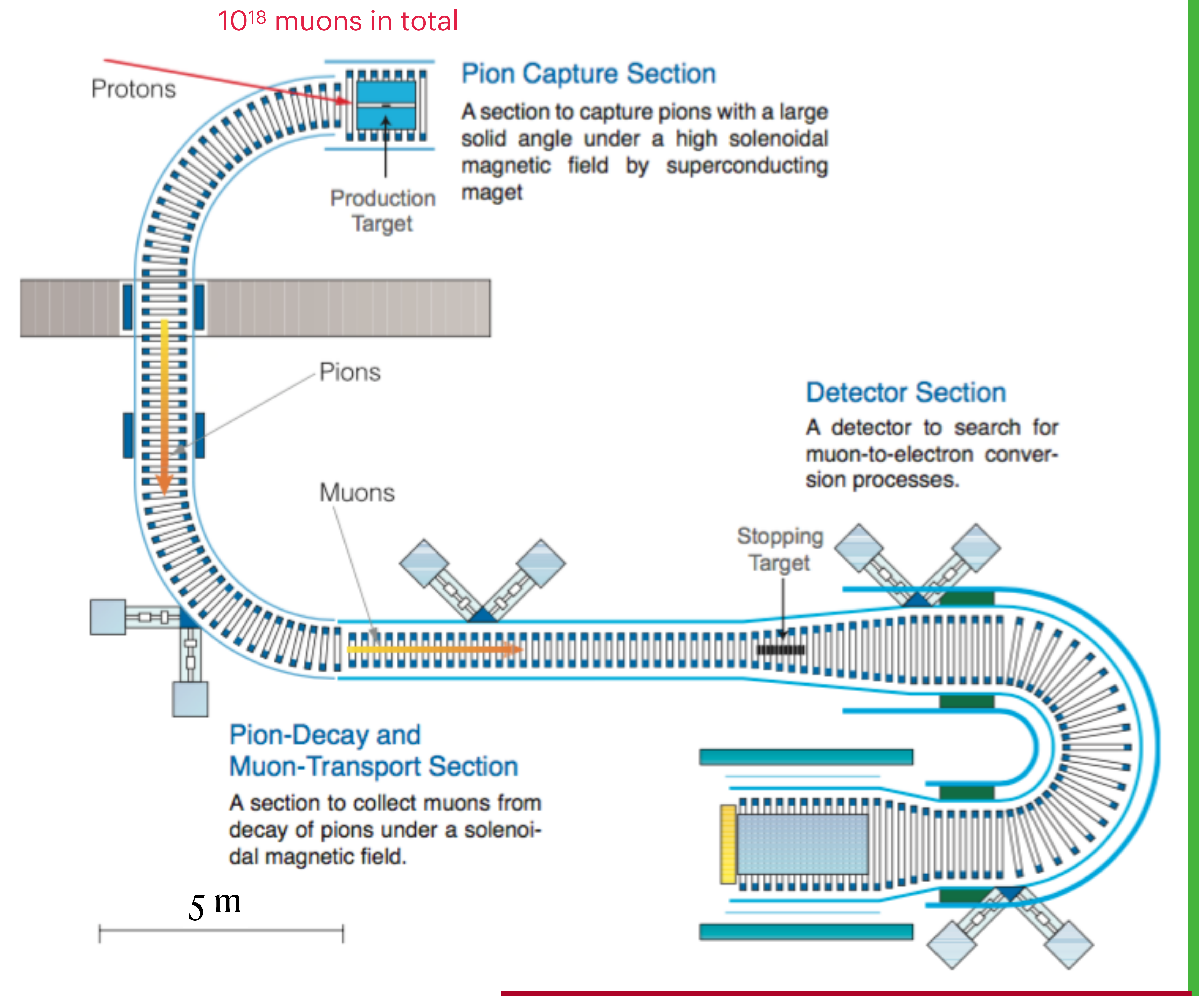
Phase I



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

SES : 2 10^{-15}
Expected limit : 5 10^{-15} @ 90% CL
Total background: 0.32 events
Running time: 0.4 yrs (1.2 10^7 s)

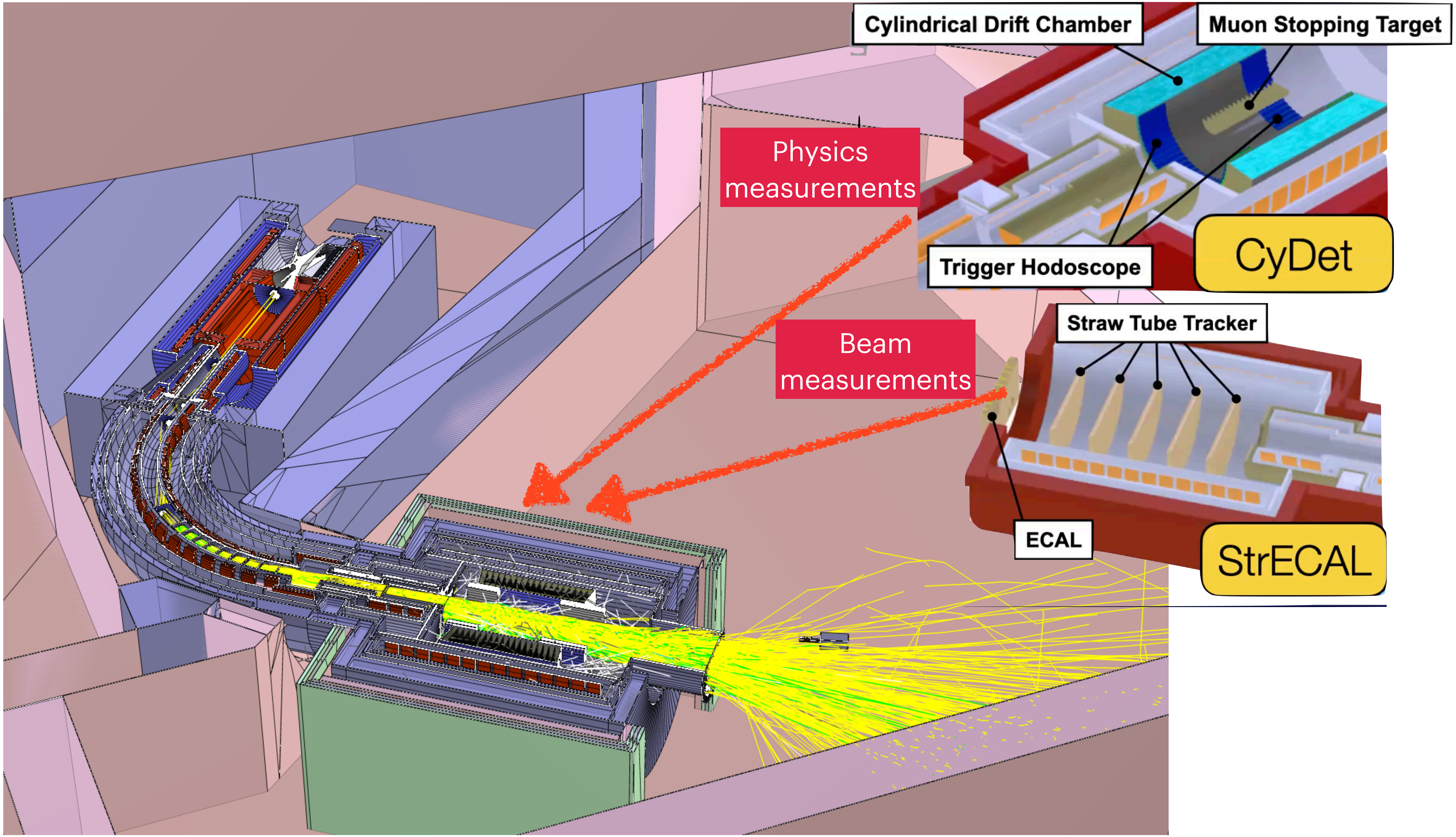
Phase II



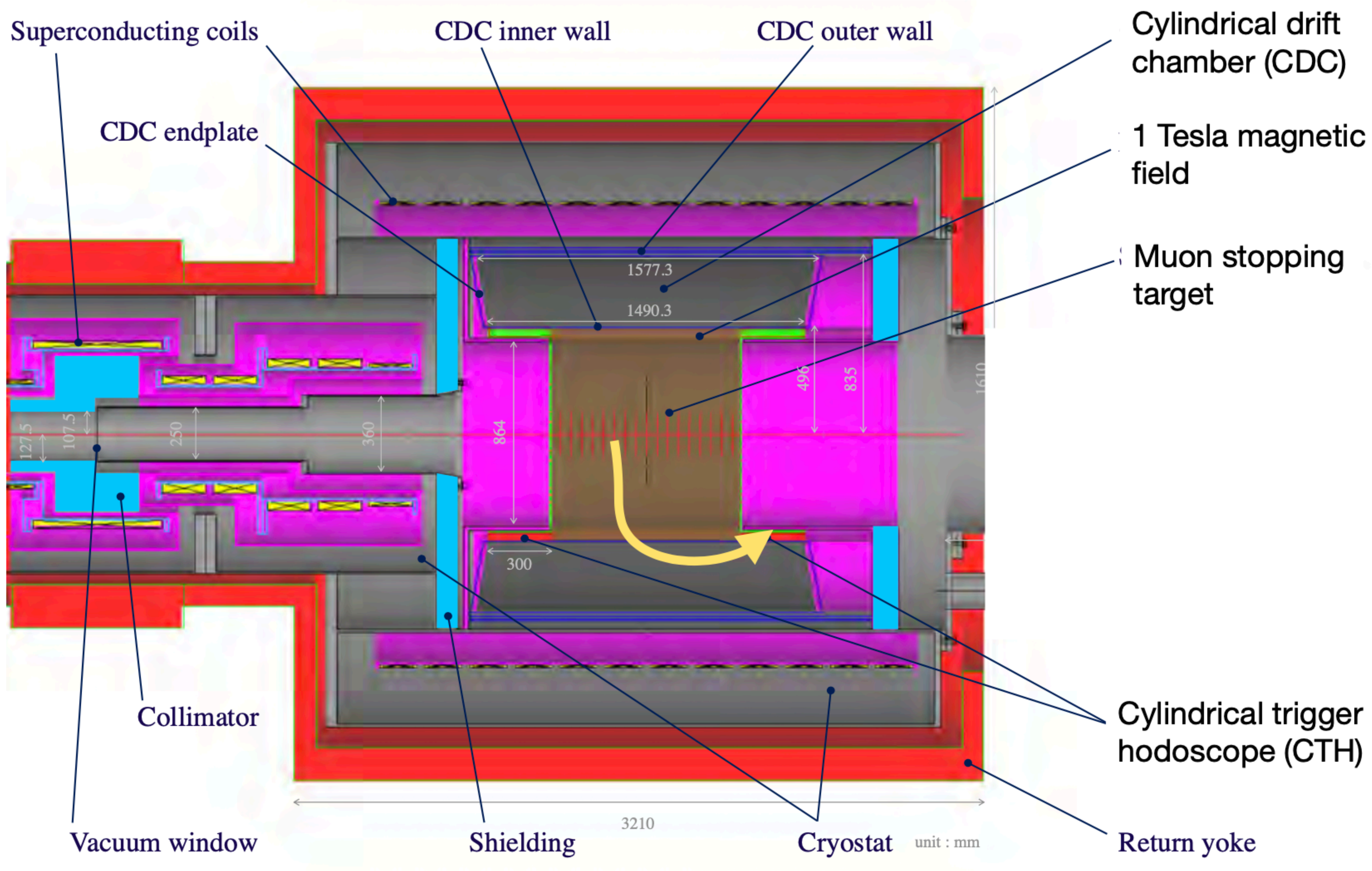
8 GeV proton beam (56 kW)
Tungsten proton target
1.2 10^{11} stopped muons/s

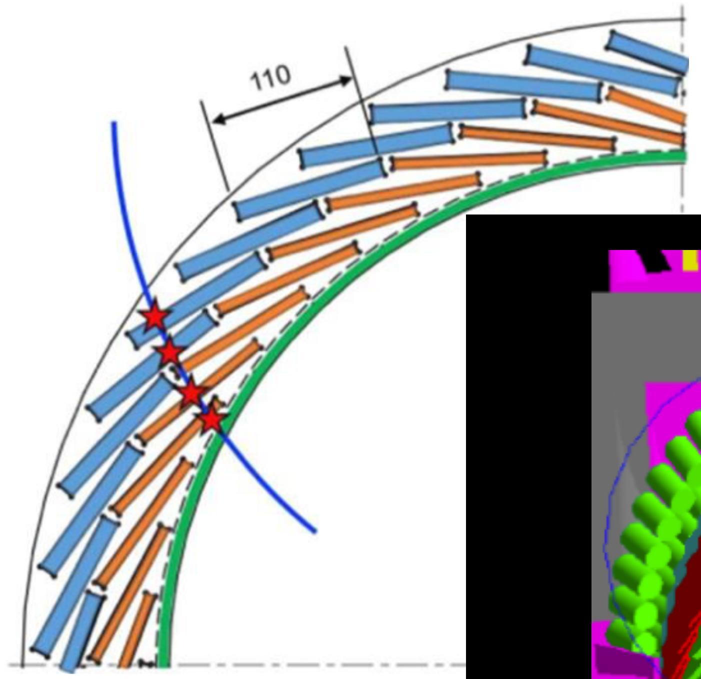
Expected limit : 7 10^{-17} @ 90% CL
Total background: 0.32 events
Running time: 1 yr (2 10^7 s)

COMET Phase I

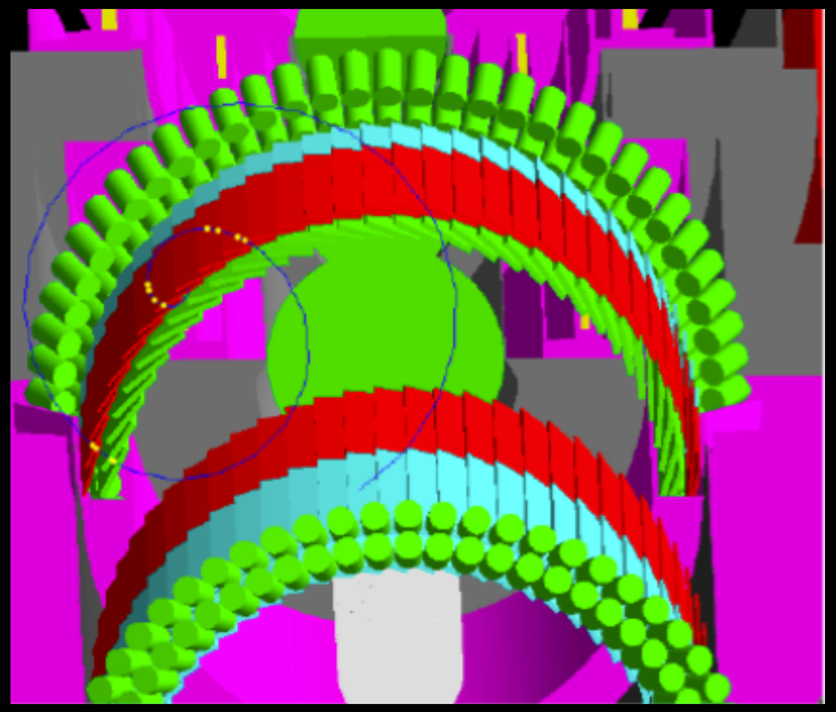


COMET Phase-I :: Electron Detectors (CyDet)

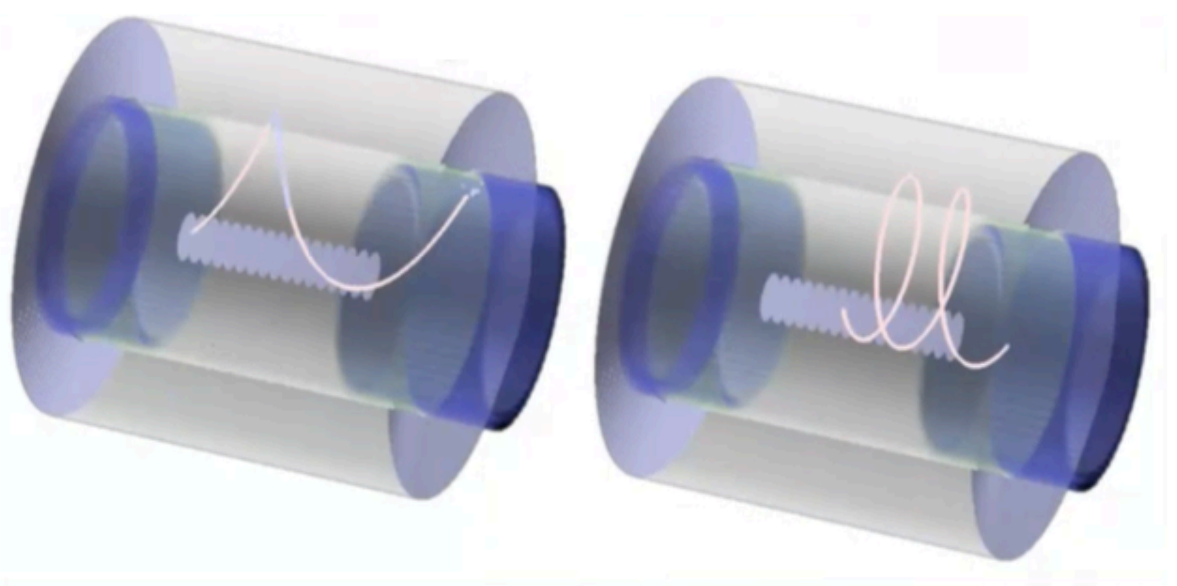


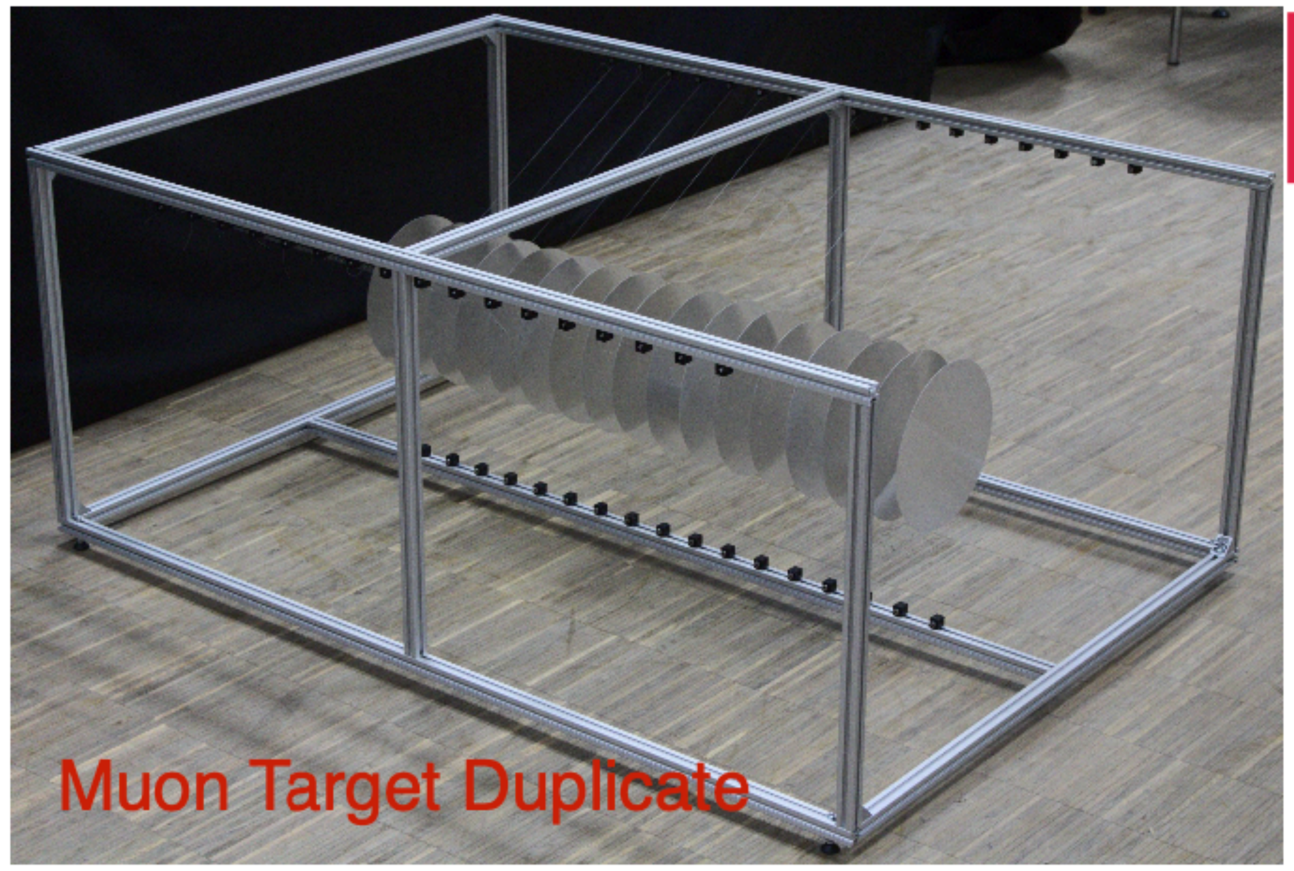


Four-hold coincidence provides trigger and PID

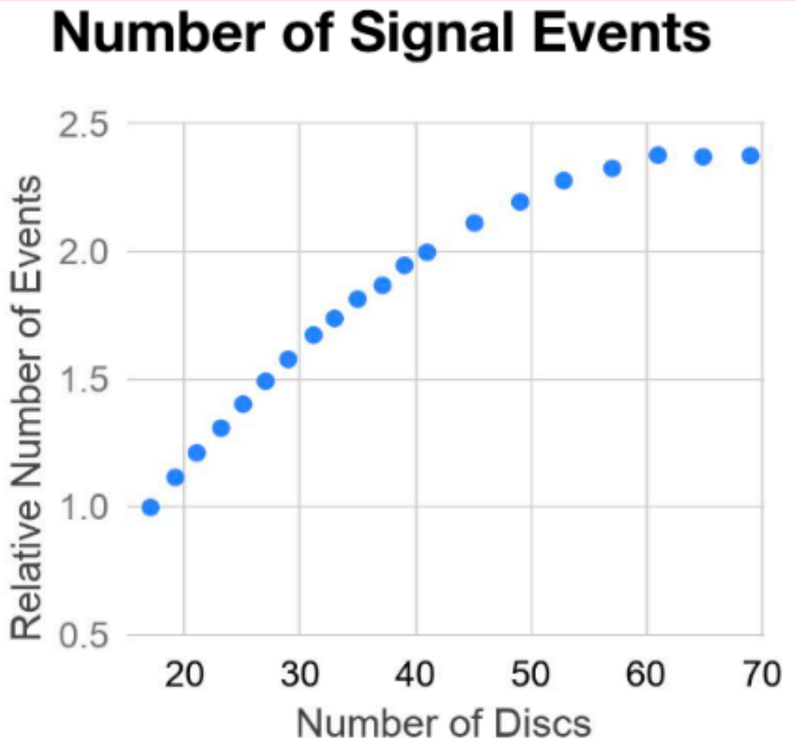


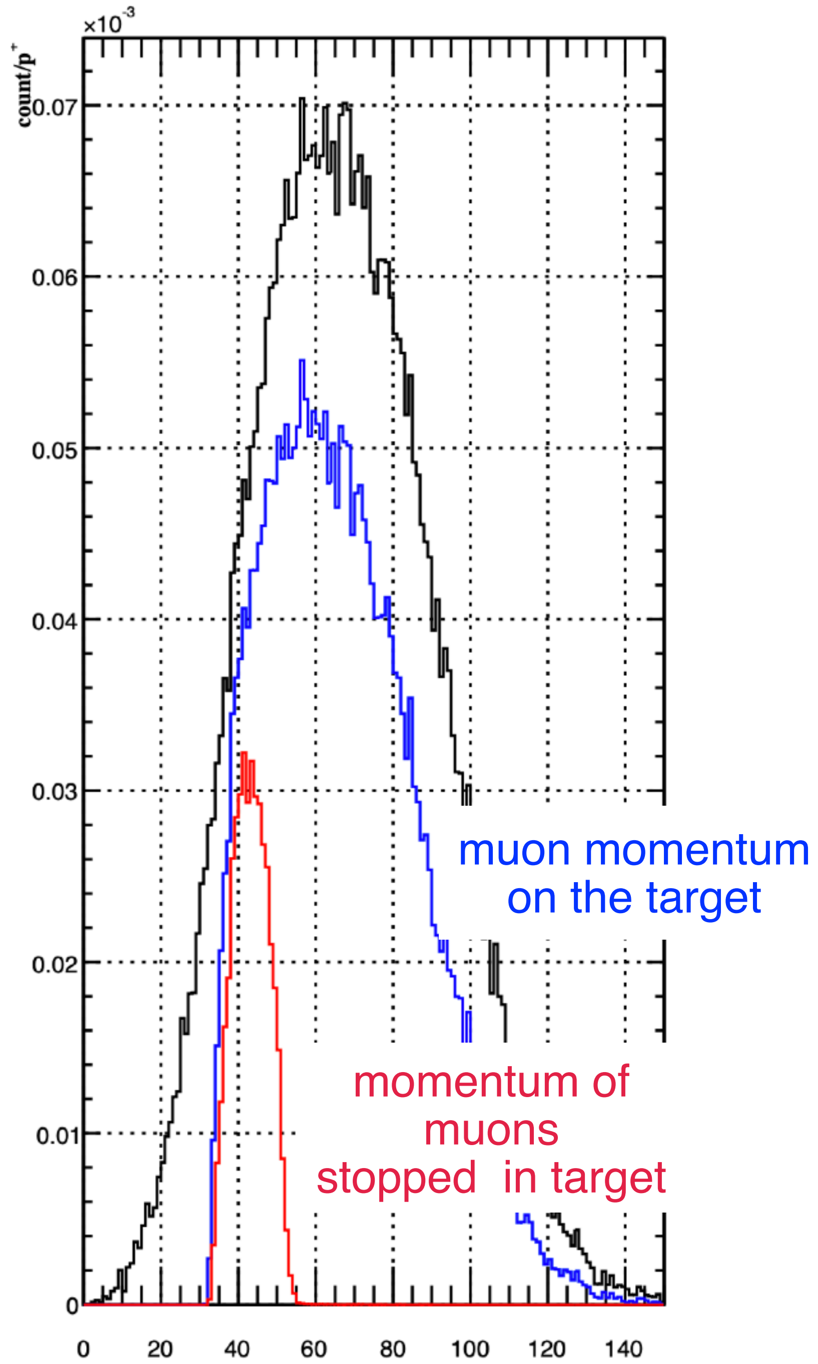
4-rings of ultra fast scintillators read by optical fibres and SiPMs



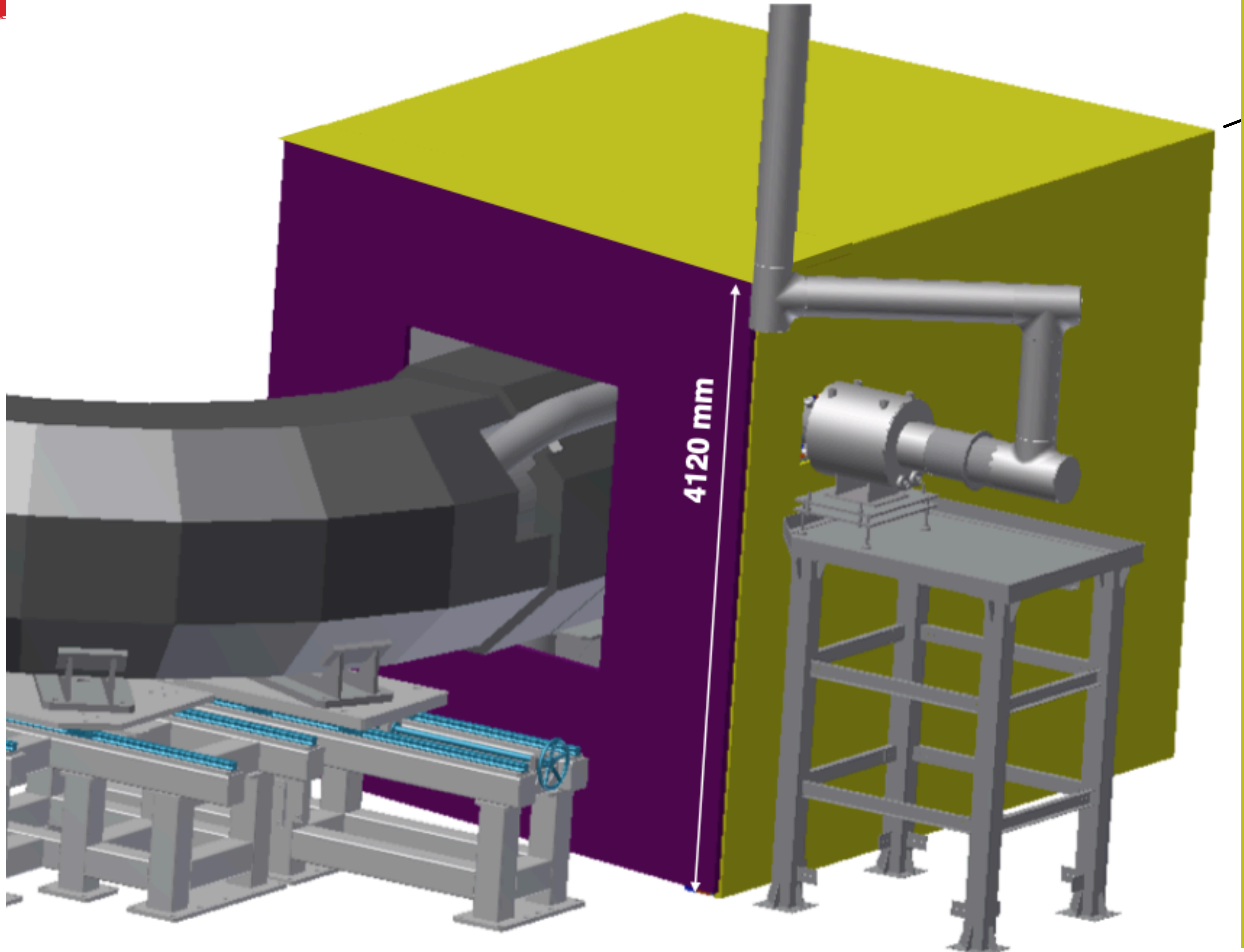


17 Al disks
100 mm radius, 200 µm thick

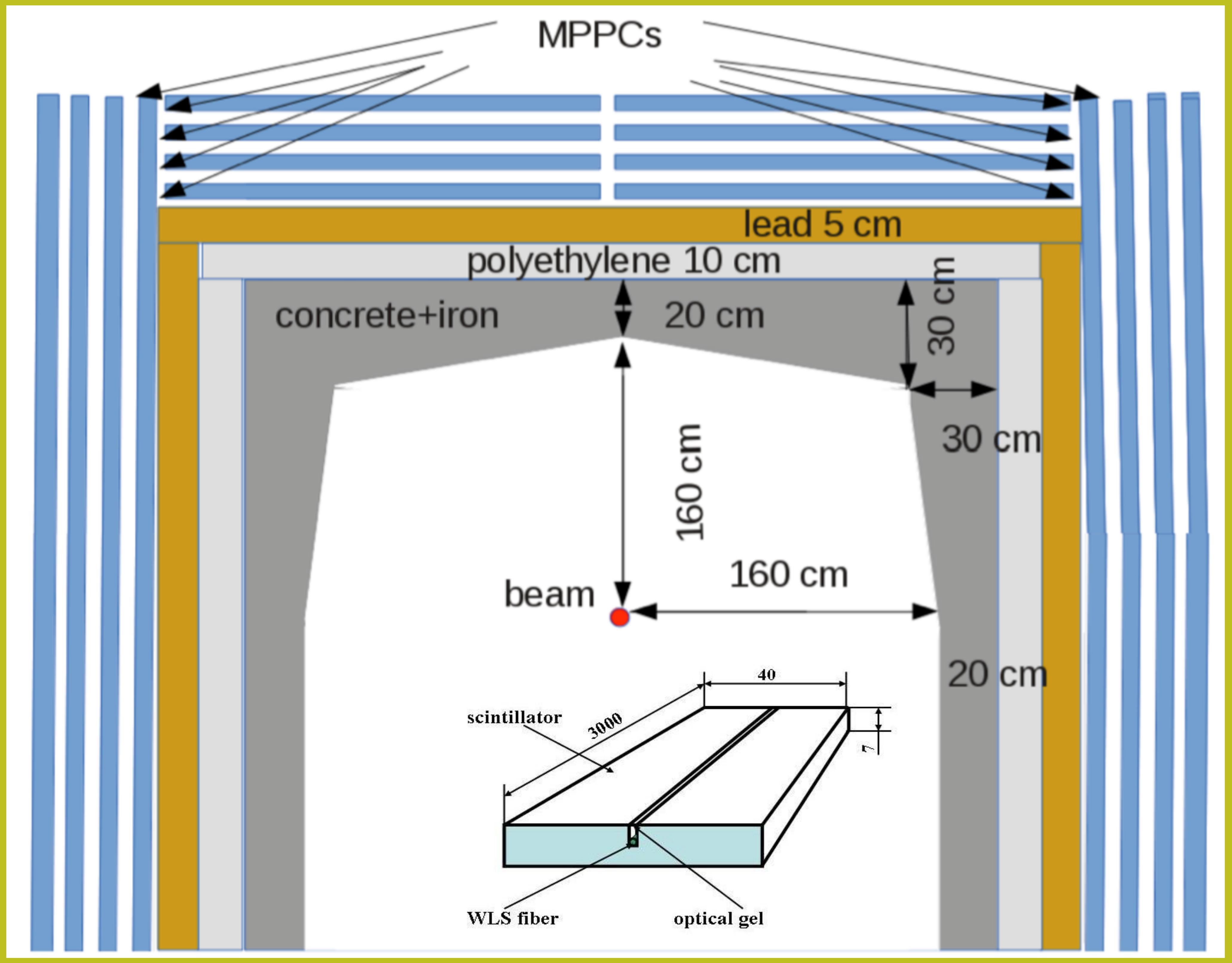




COMET Phase I :: a hybrid CRV



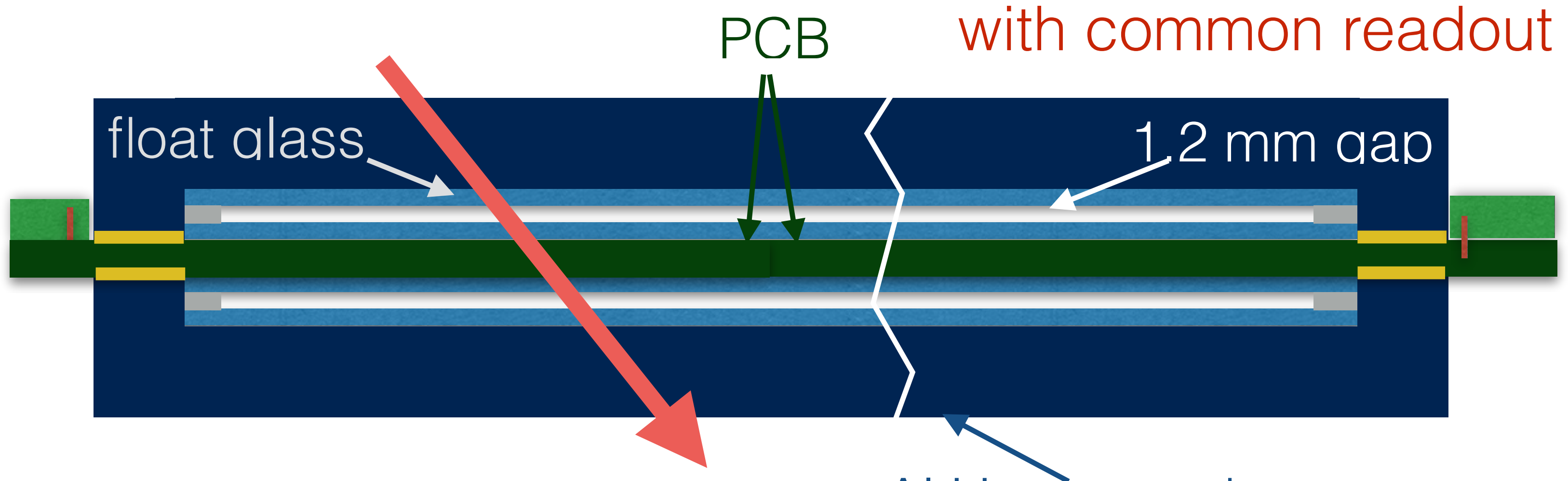
Scintillators CRV

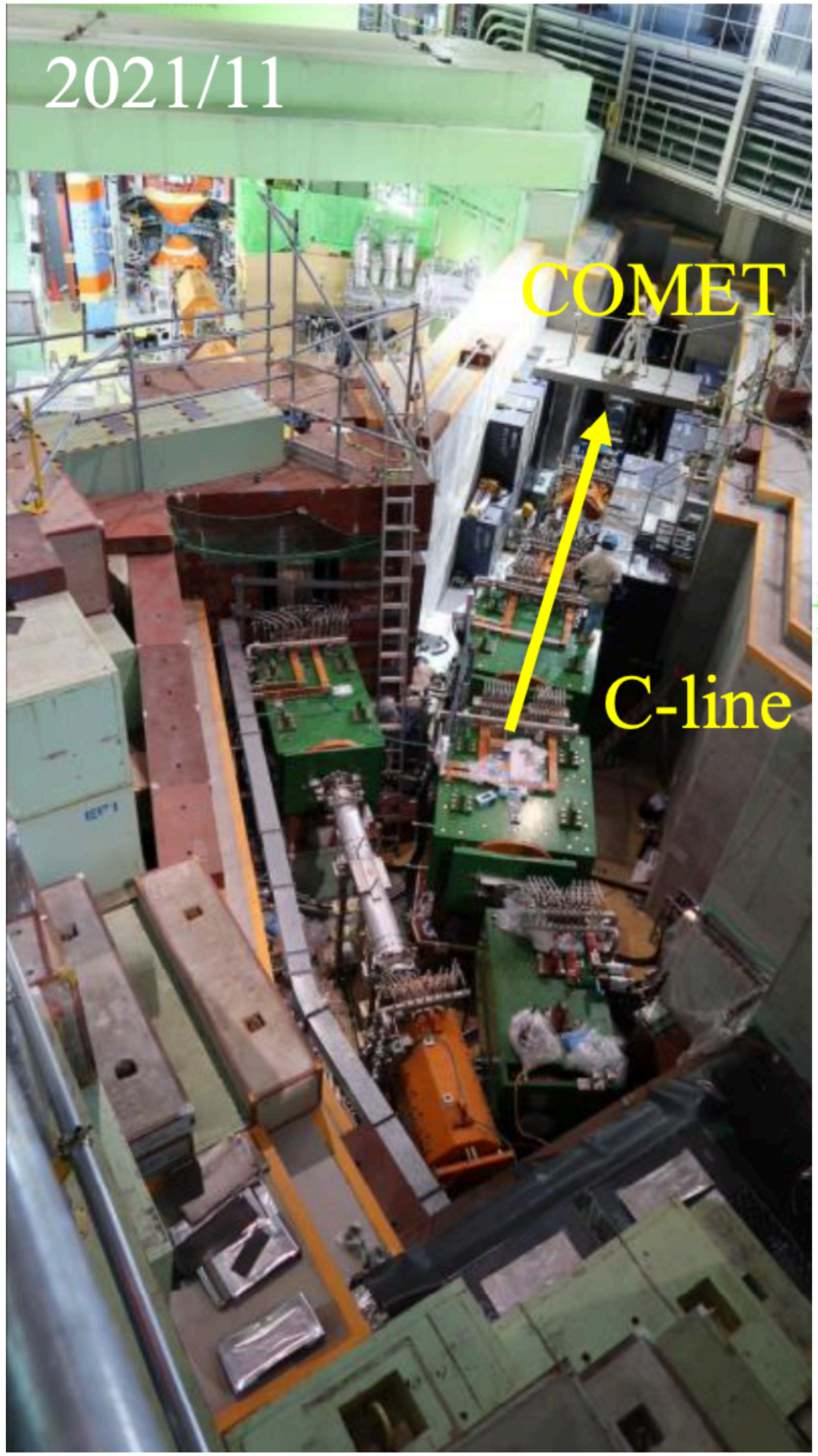


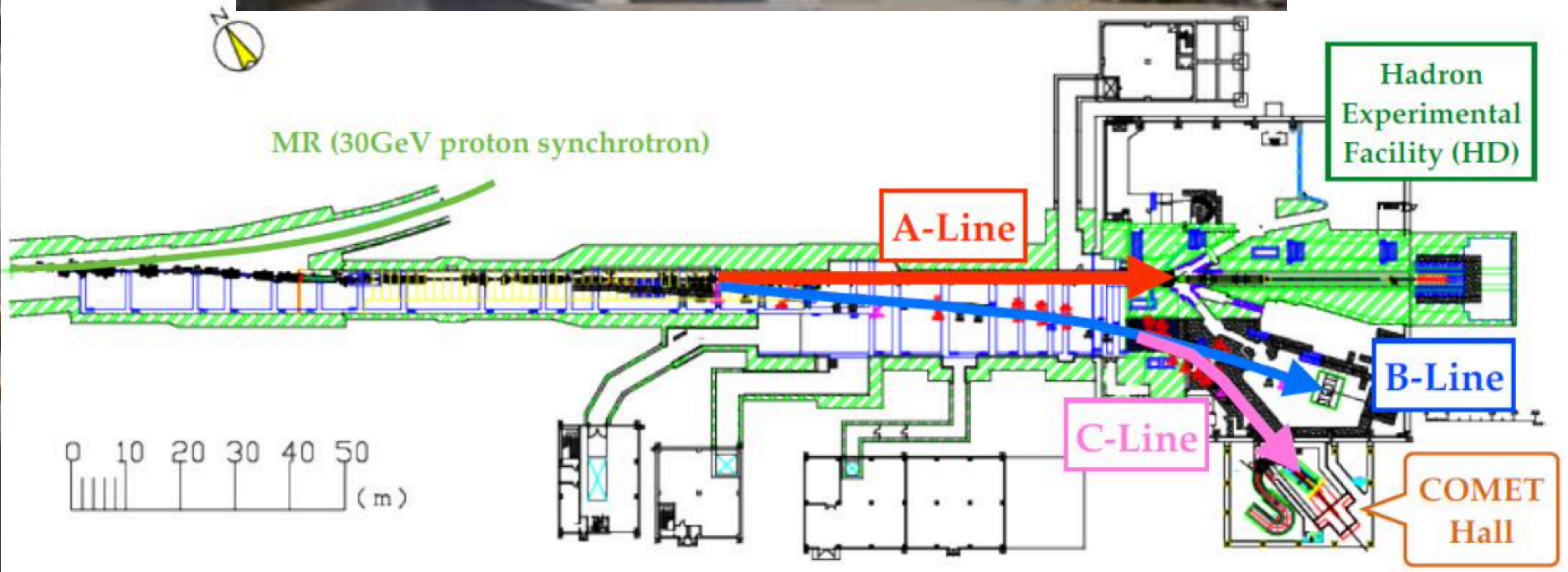
GRPC CRV

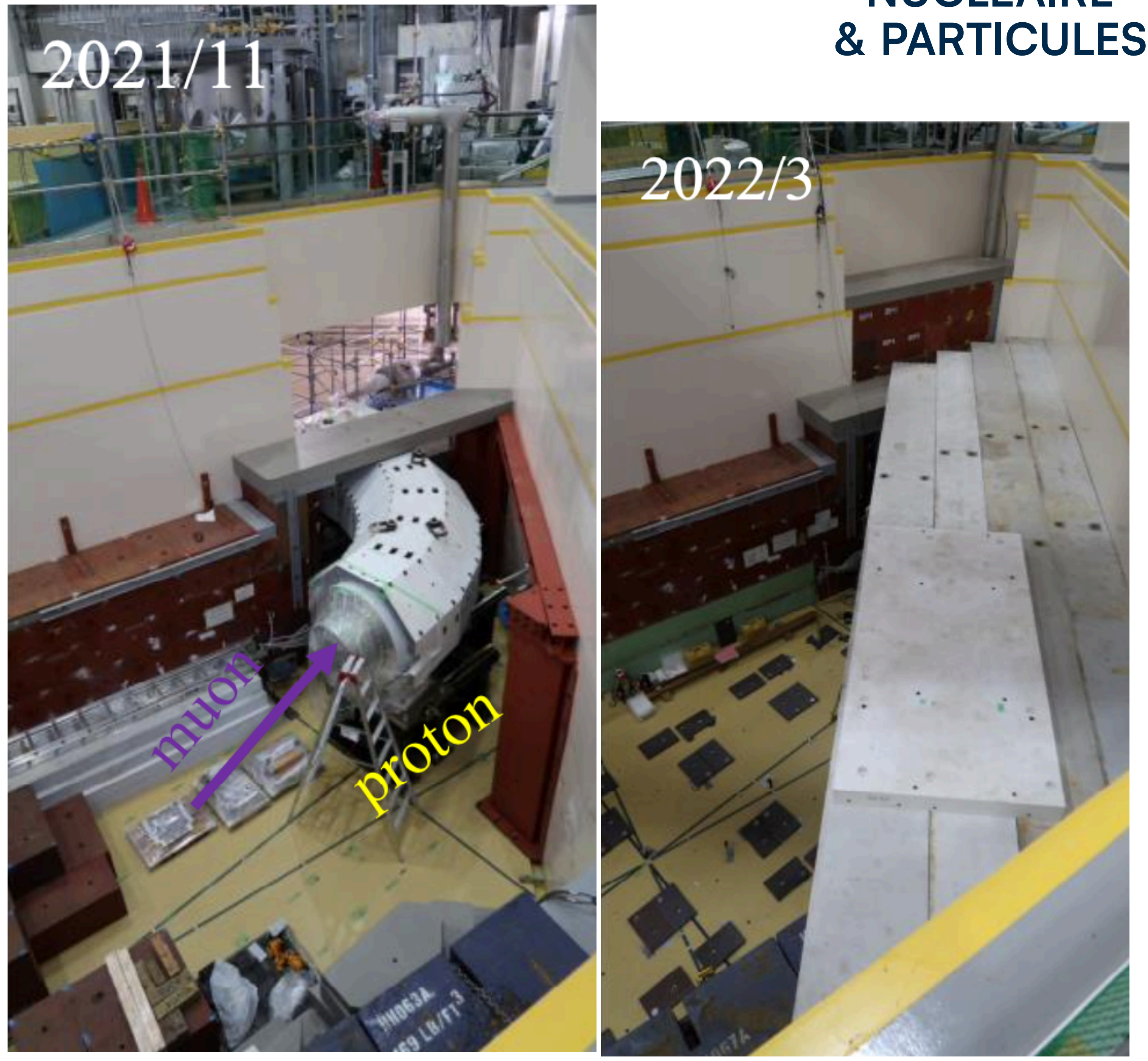
A tracker module: 5 detector modules (baseline)

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





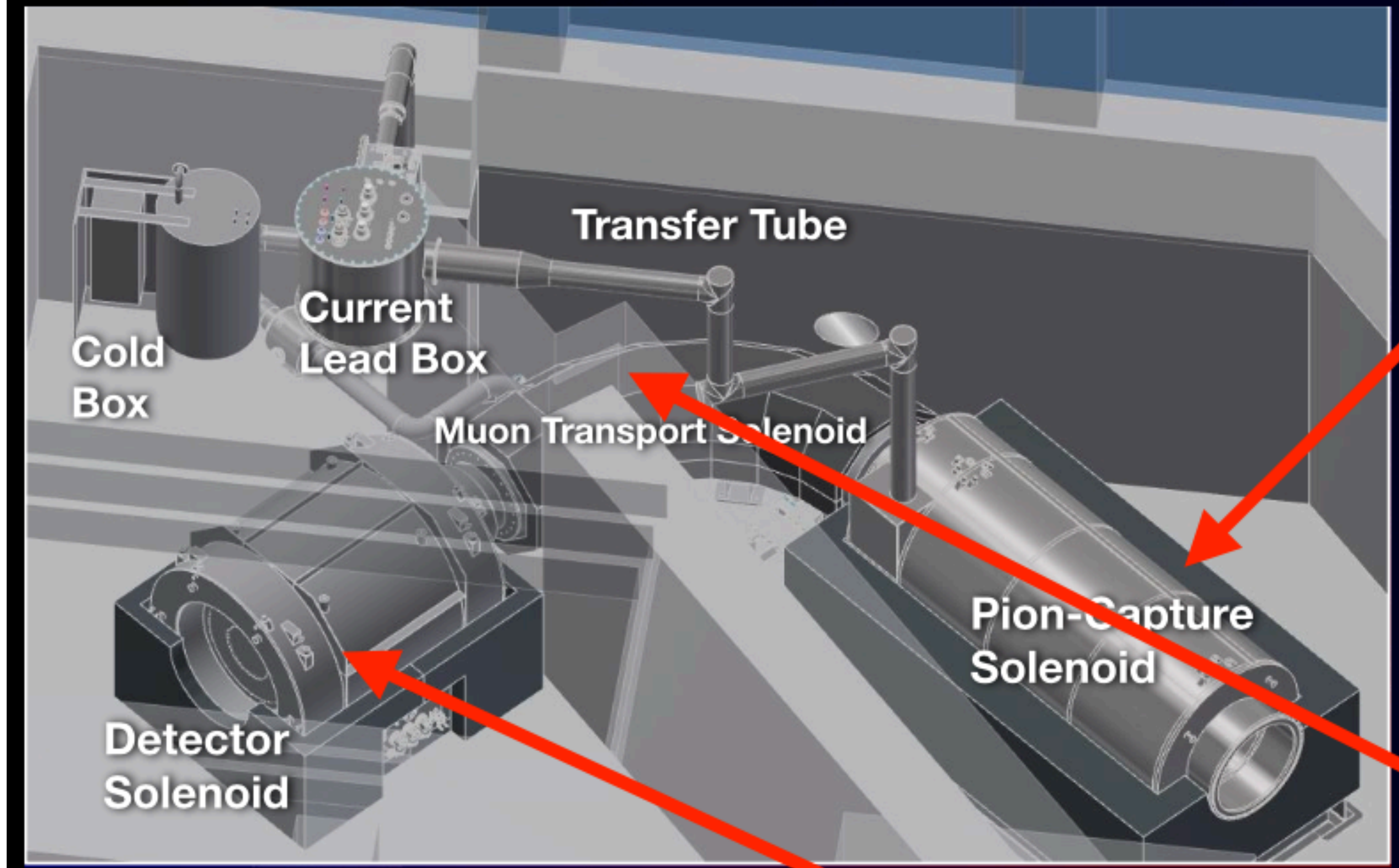


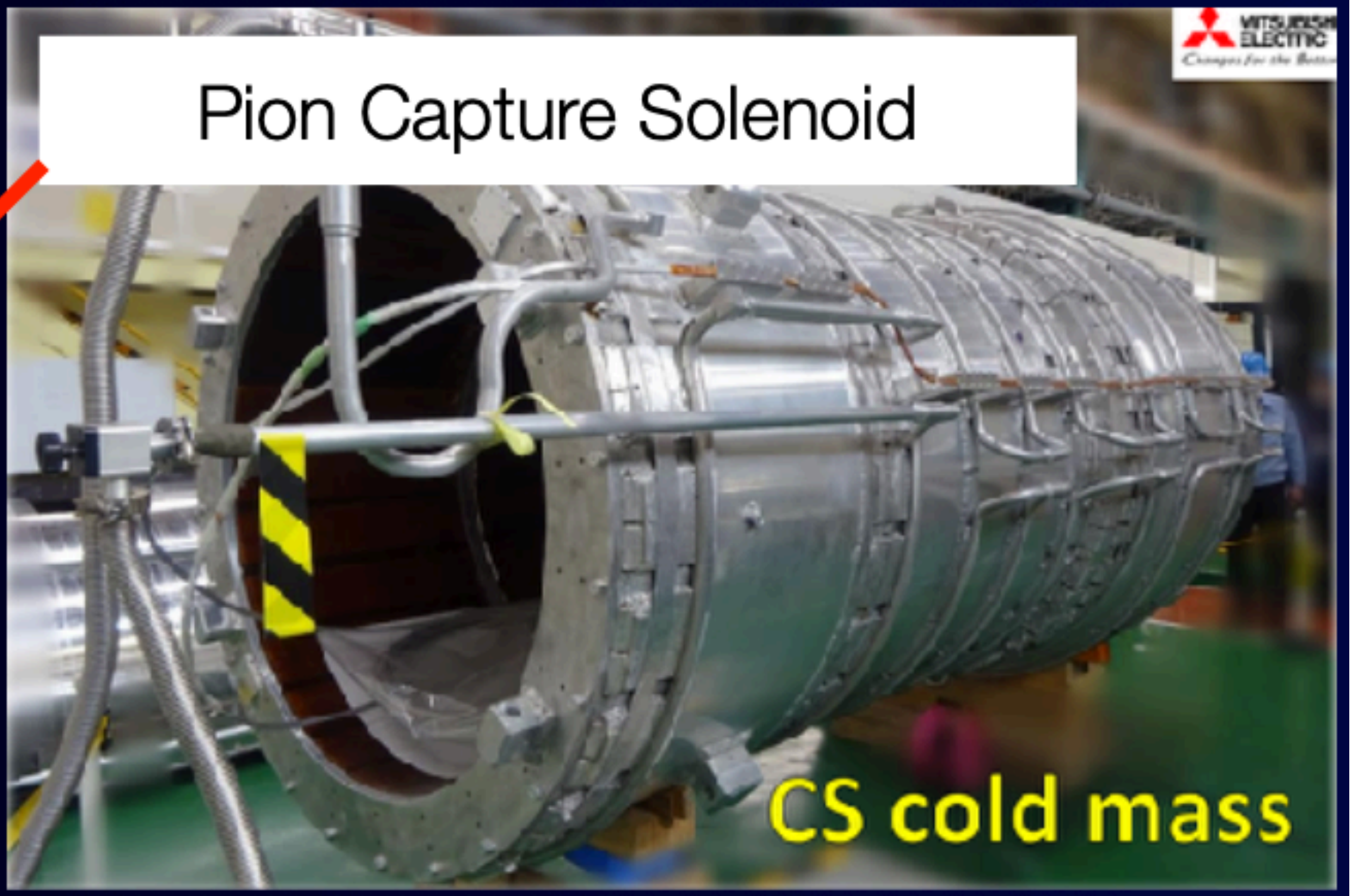


Muon Transport Solenoid

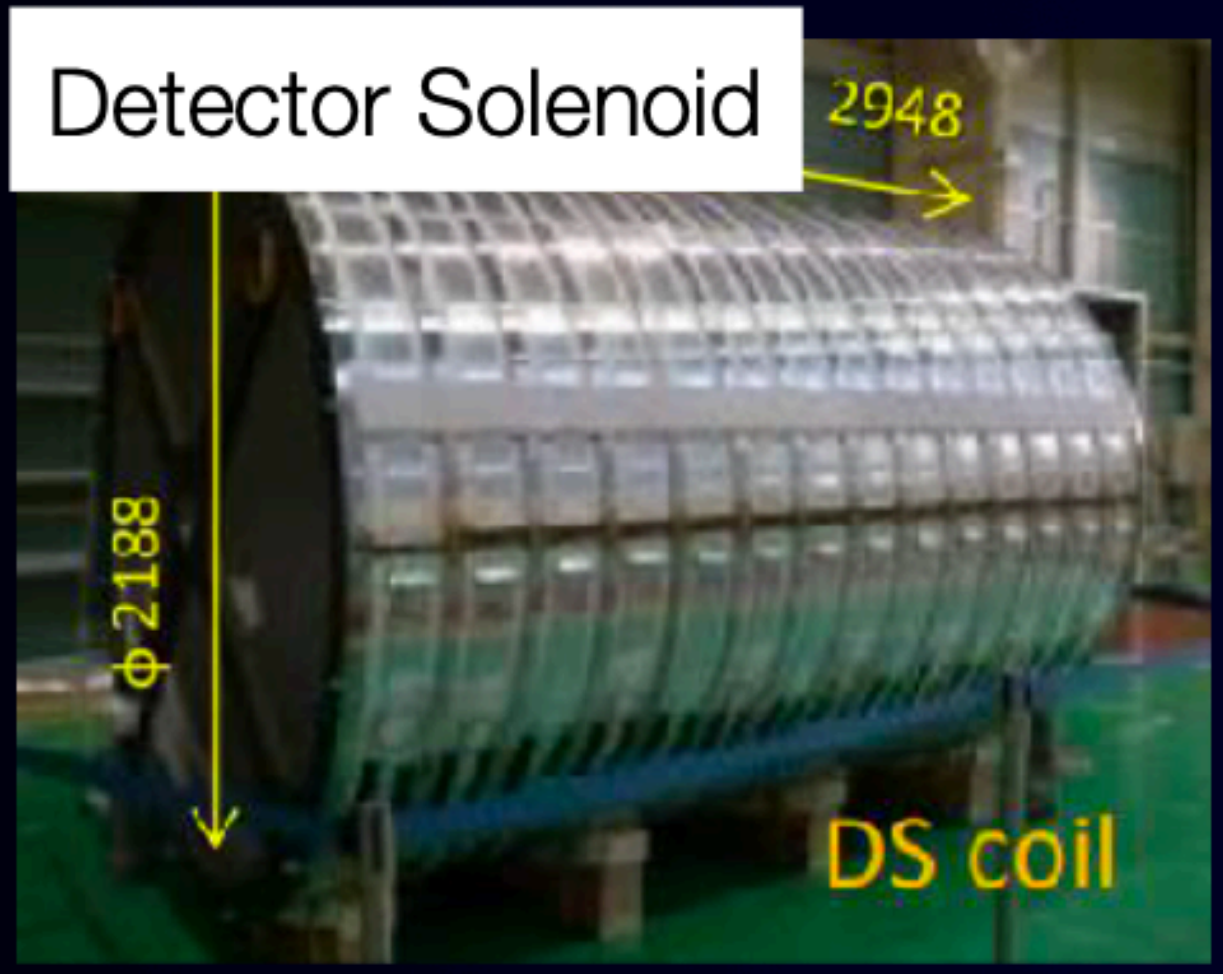
Detection area

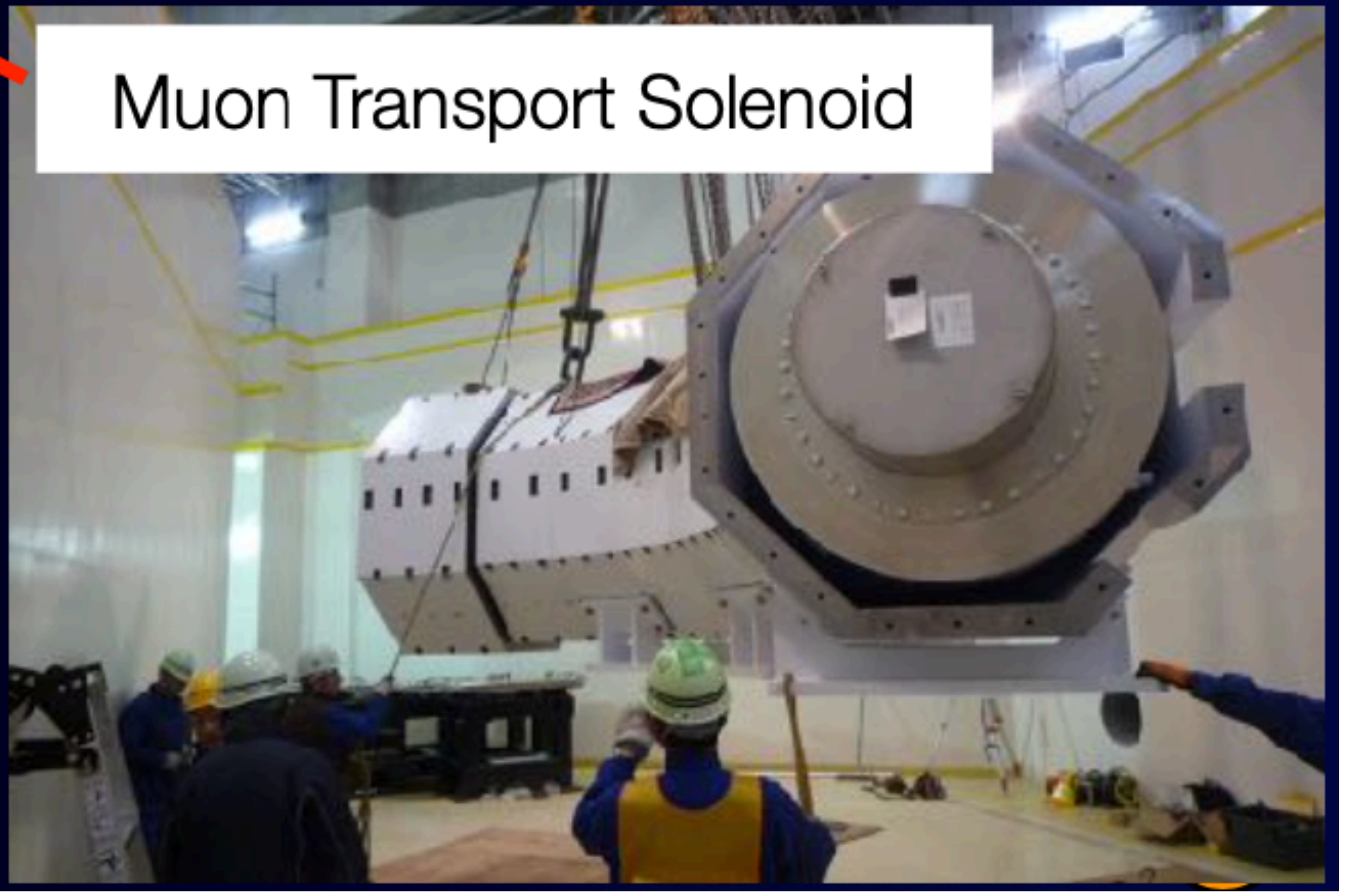
COMET (JParc E) Status :: Superconducting Solenoids

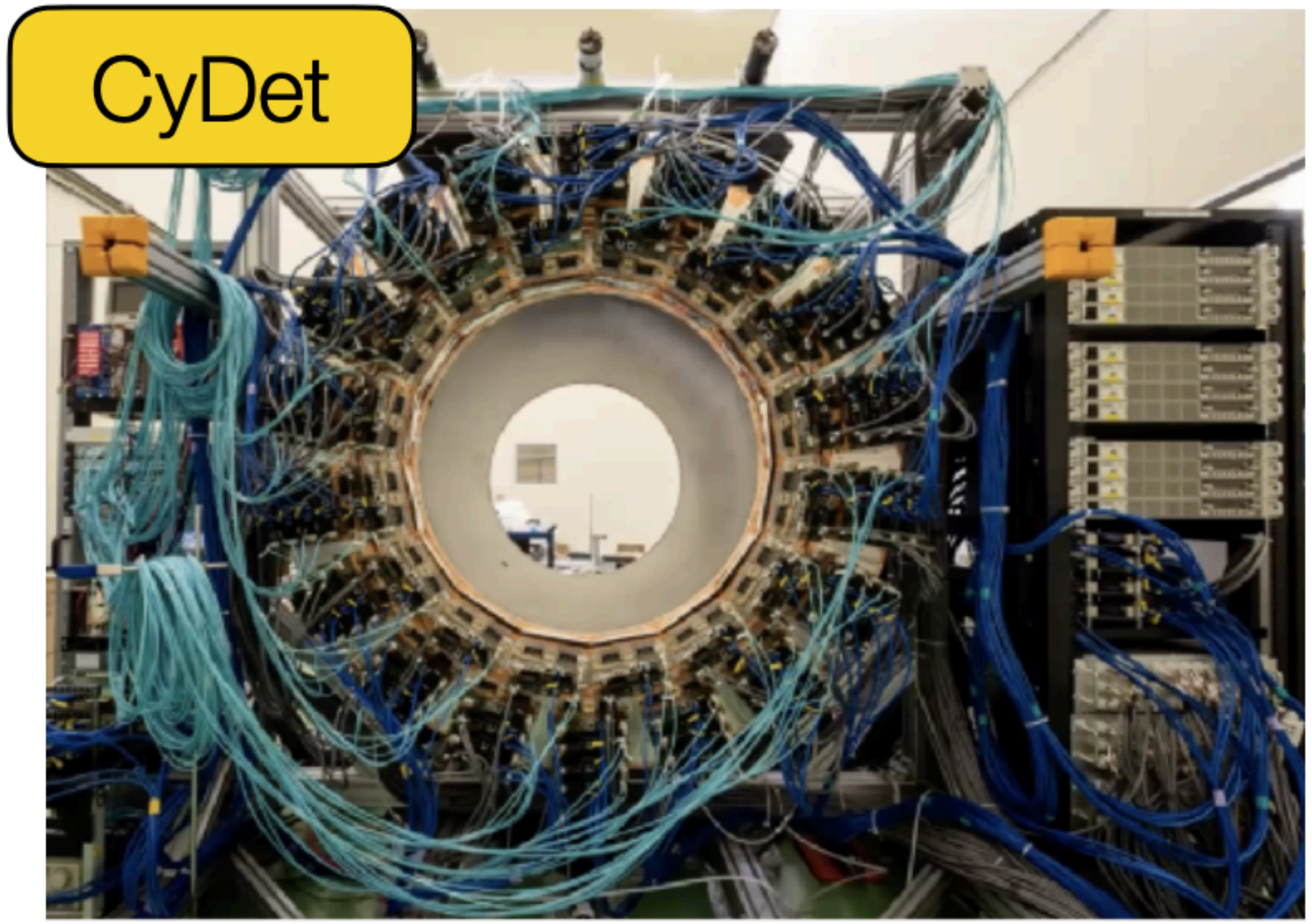


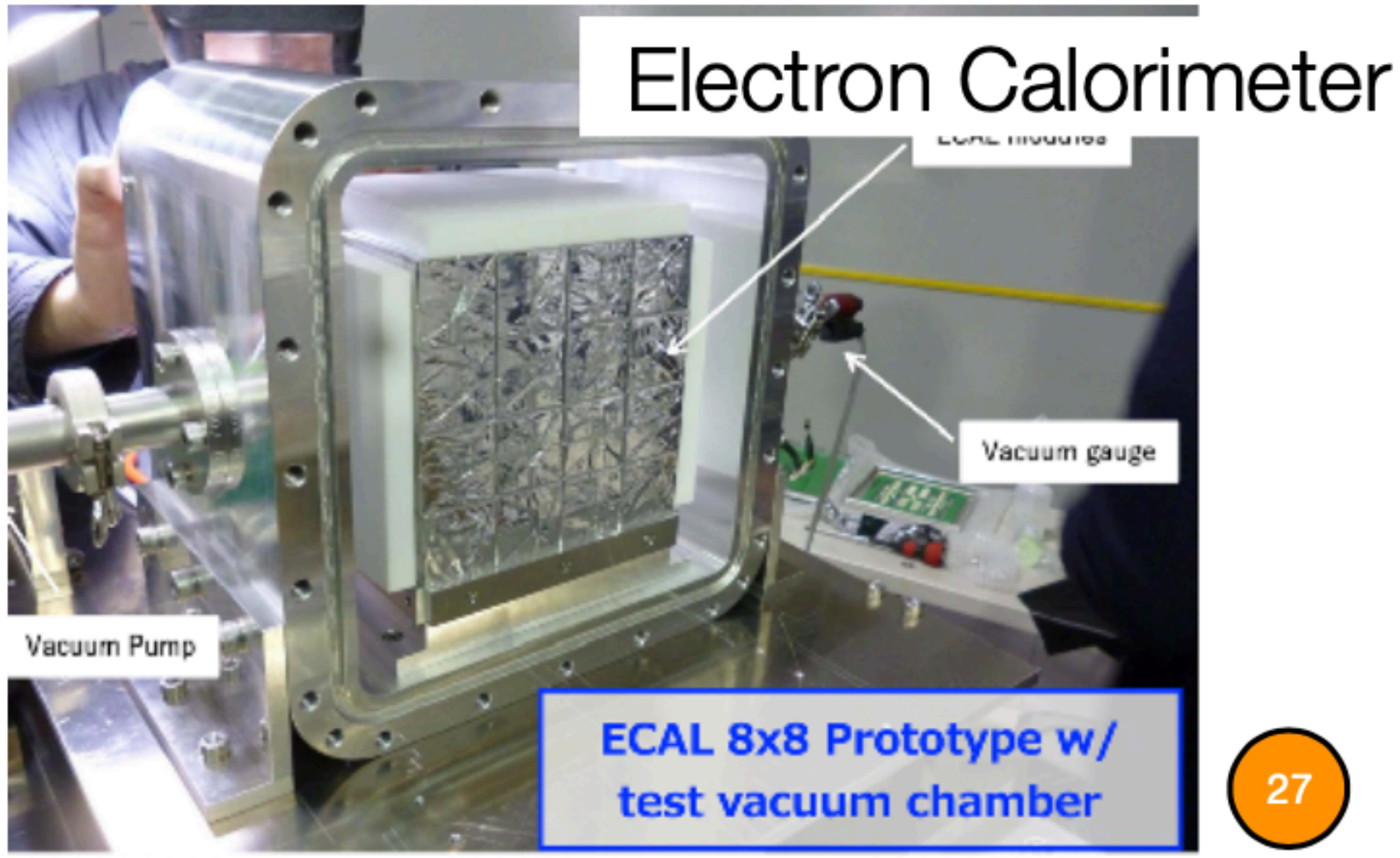


- MTS excitation completed in 2023
- PCS completed. Will be commissioned in 2025
- DS assemby to be completed in 2024

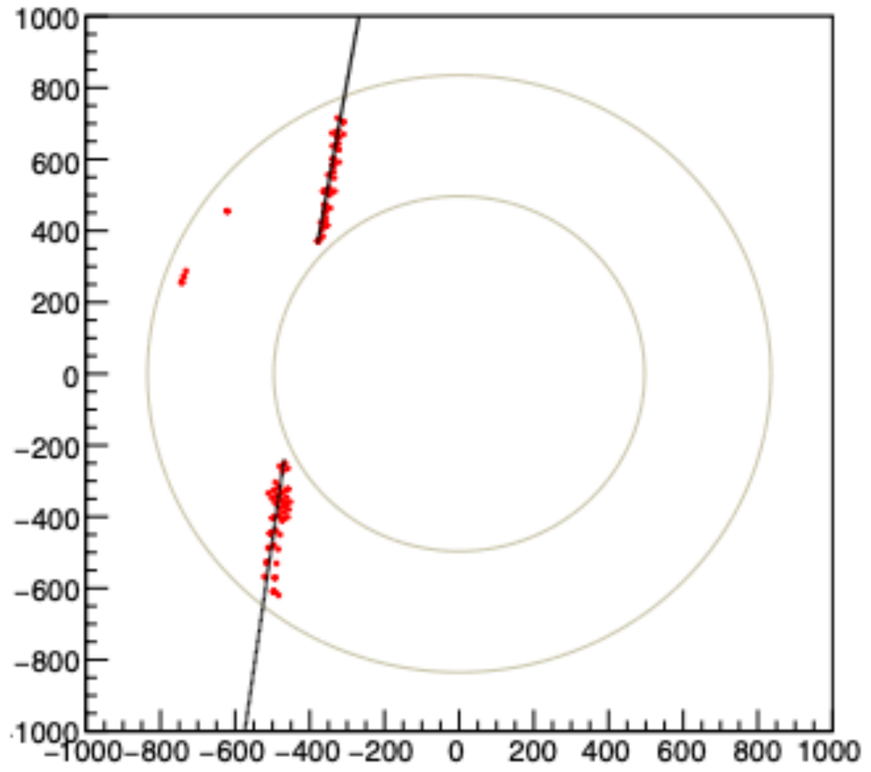






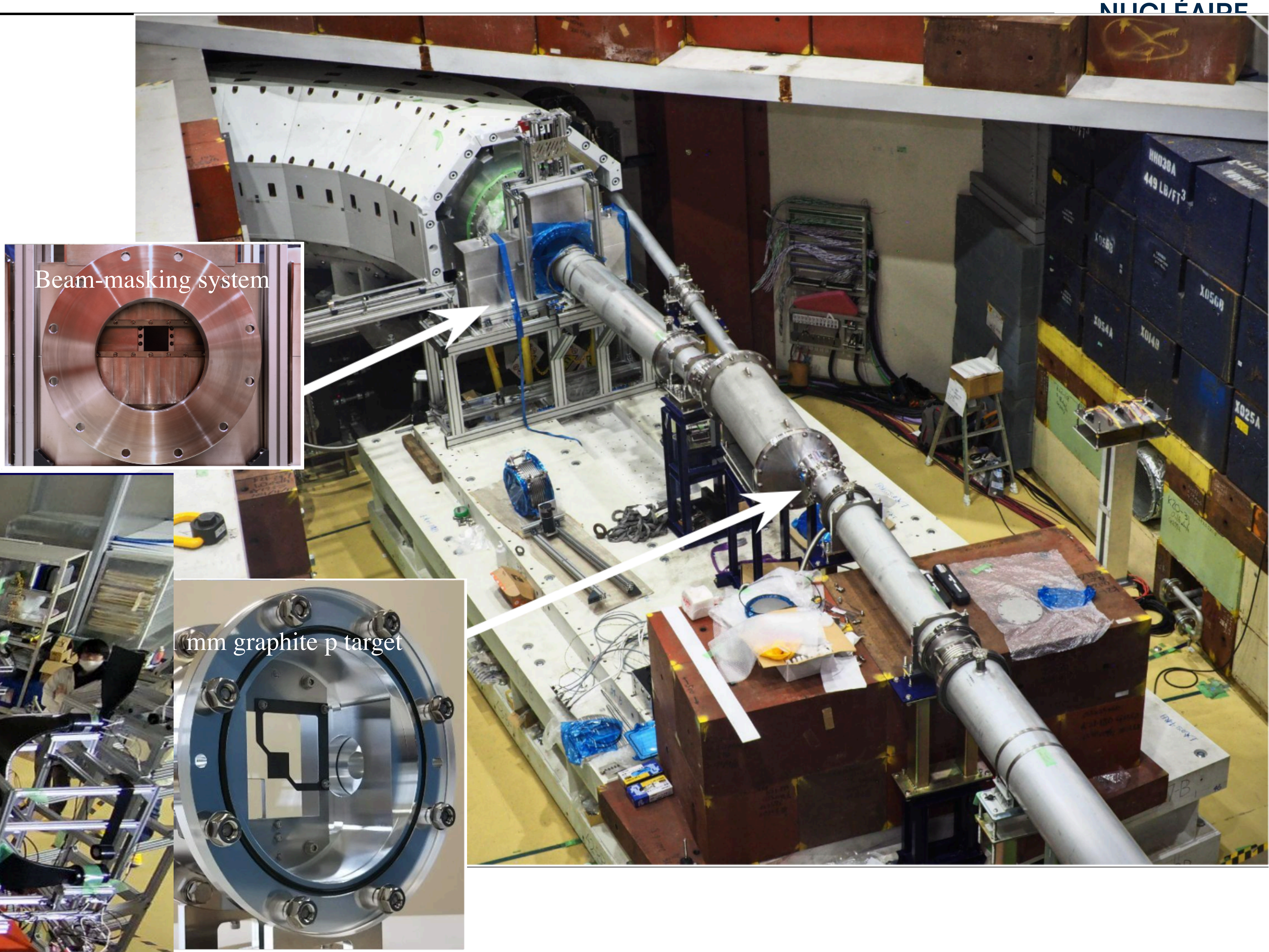


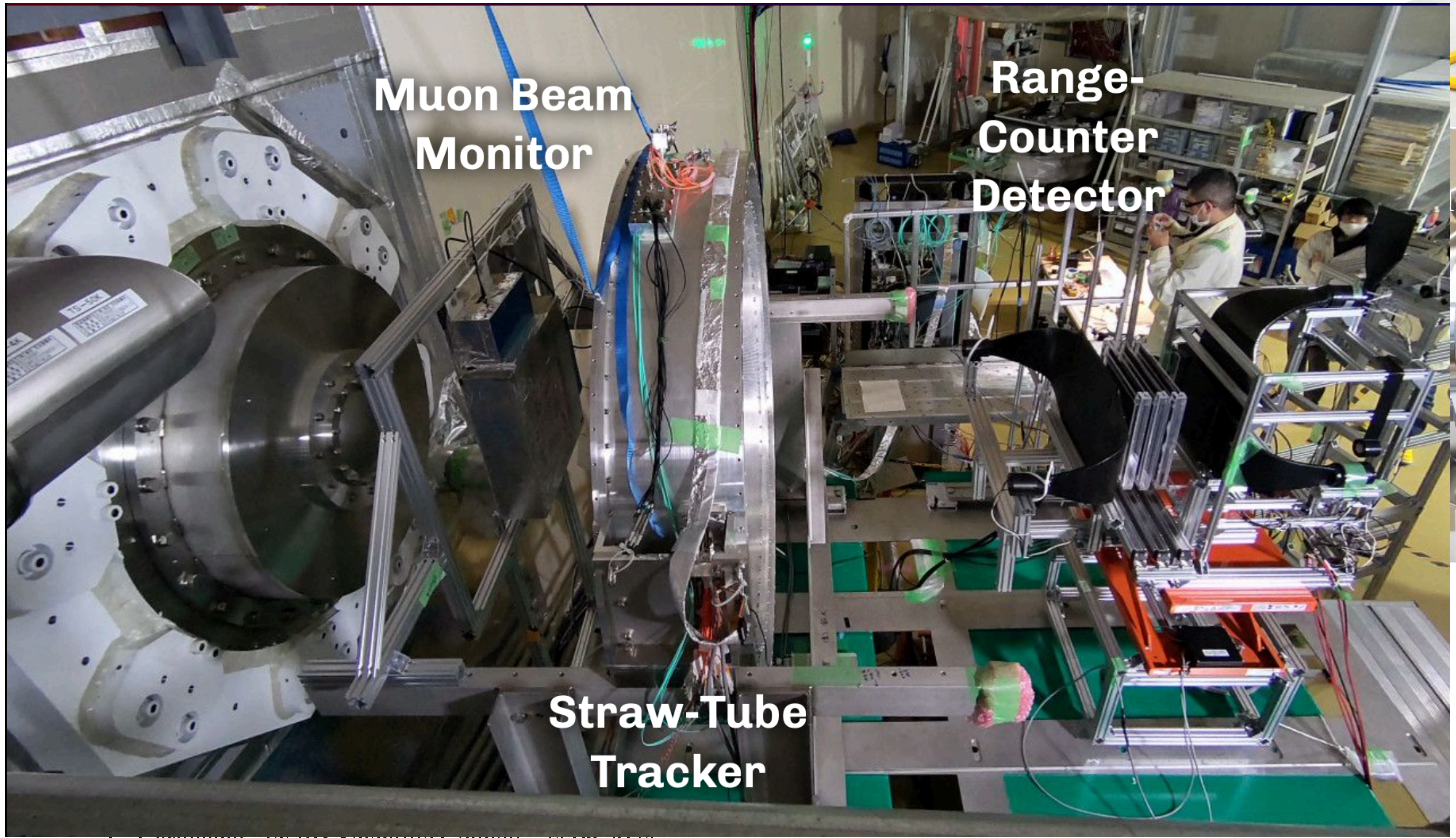
- CDC is currently taking cosmics at JParc
- 3 straw chamber modules already built
- Electron calorimeter prototype was successfully tested

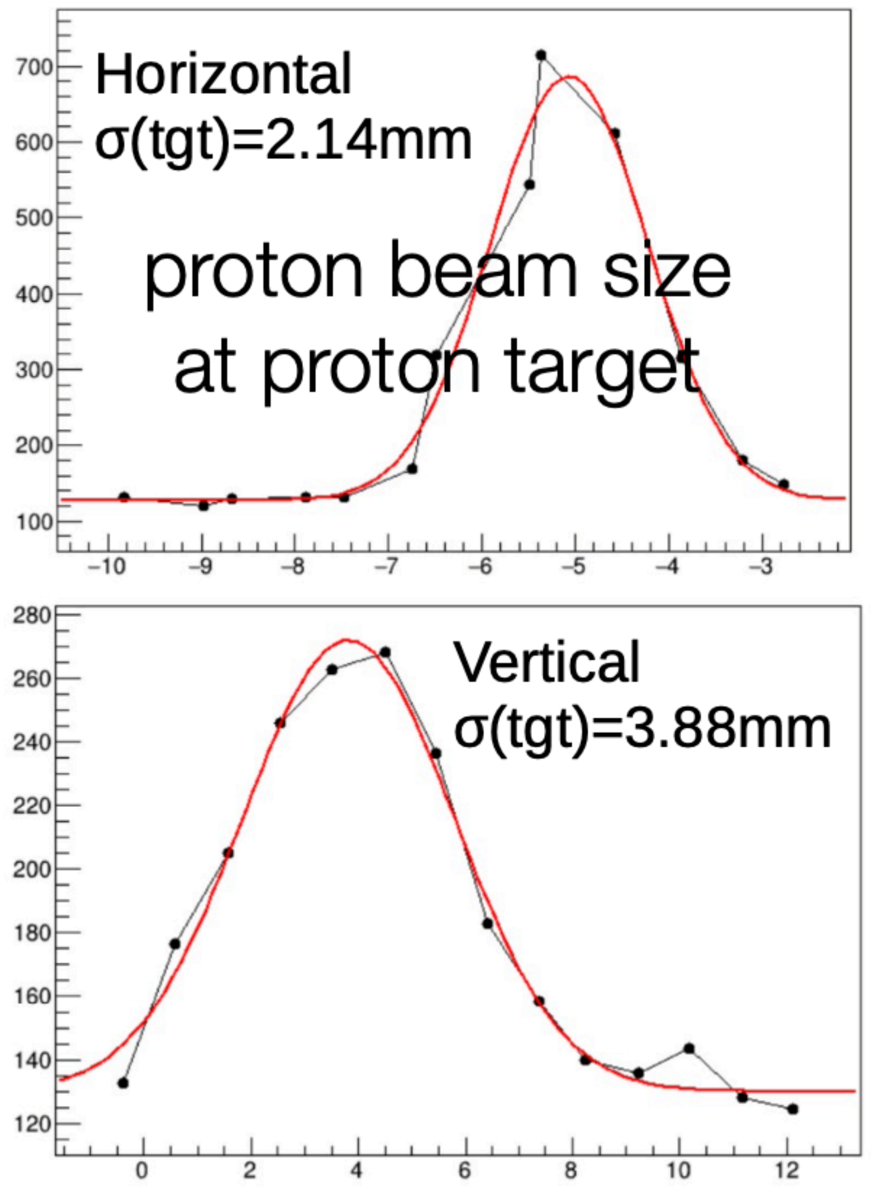


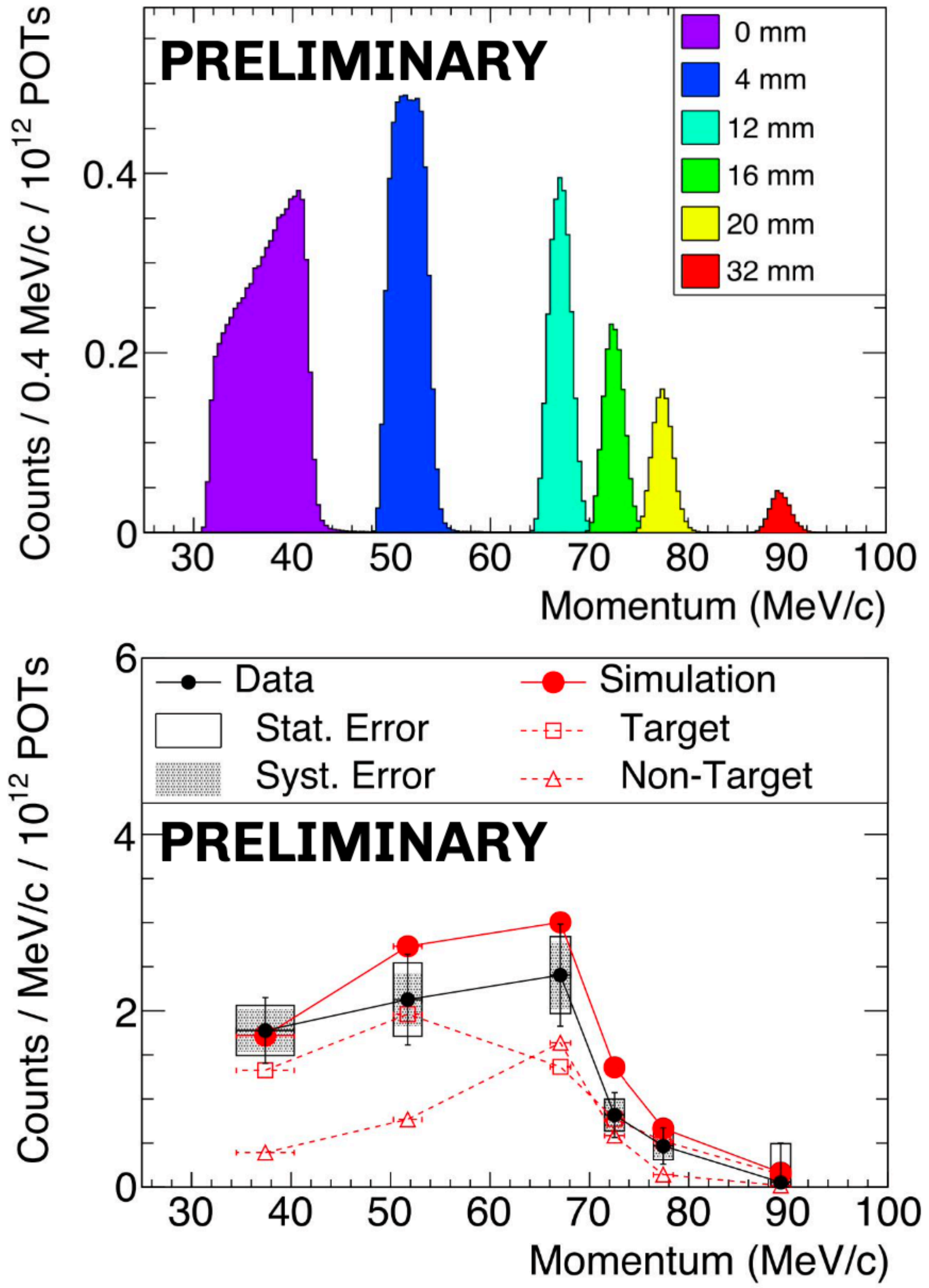
Phase-α : first proton beam in COMET Hall (Feb-March 2022)

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






Horizontal
σ(tgt)=2.14mm
proton beam size
at proton target
Vertical
σ(tgt)=3.88mm


PRELIMINARY
0 mm
4 mm
12 mm
16 mm
20 mm
32 mm
Counts / 0.4 MeV/c / 10^12 POTs
Momentum (MeV/c)
Data
Stat. Error
Syst. Error
Simulation
Target
Non-Target
PRELIMINARY
Counts / MeV/c / 10^12 POTs
Momentum (MeV/c)

COMET Phase I Timeline

French Contributions :: Computing @CCIN2P3

- CC-IN2P3 is the main MC data storage centre

- *KEK and CCIN2P3 are foreseen to be the main COMET centres for storing raw data, with replication at further locations for safety*

Year	Requested Hours*	Consumed Hours*	Consumed CPU*	Cores/year	Efficiency
2015	400 000	38 850	36 510	0	94 %
2016	12 000 000	10 318 205	8 901 264	94	86 %
2017	90 000 000	92 856 588	92 241 466	847	99 %
2018	140 000 000	58 994 582	52 069 092	538	88 %
2019	16 000 000	16 072 681	14 994 488	147	93 %
2020	180 000 000	34 716 729	29 360 699	317	85 %
2021	200 000 000	13 614 639	9 033 714	124	66 %
2022	140 000 000	2 844 466	2 157 021	26	76 %
2023	22 000 000	198 067 248	148 759 146	1 807	75 %
2024**	200 000 000	127 433 779	68 728 650	1 162	54 %
All	1 000 400 000	554 957 767	426 282 050	506	77 %

* in HS06.h.
** up to 21/04/2024

Significant increase of HTC CPU/h amount used by **comet.j-parc.jp VO** reported by the EGI Federation:
In 2022: 2 426 000 HS06.h
In 2023: 6 700 000 HS06.h

Type	Media	Occupied Space	Quota
HPSS/iRods	Tape	160 TiB	300 TiB
iRods	disk	159 TiB	-
SPS	disk	76 TiB	120 TiB
Xrootd	disk	824 GiB*	3.5 PiB
pbshome (permanent - backup)	disk	208 GiB	1470 GiB (default: 20 GiB/
pbsthrong (permanent - backup)	disk	81 GiB	120 GiB

P Lebrun (IP2I-Lyon)
W da Silva (LPNHE)
P. Warrin-Charpentier (LPNHE)

Snapshot comparison (first half of 2023)
Hadronic Physics at CCIN2P3:
Belle2 : 86.52%
COMET: 12.35%
… 4.35% of all HEP

- CC-IN2P3 provides additional services :
  - **Gitlab** : management of all official packages. Currently more than 41 projects and 75 members.
  - **Rocket.chat**
  - **iRods**
  - **JupyterLab**
  - **MariaDatabase**

Future needs:
- 200 M HS06.h per year
- number of GPU-equipped workstations needed for tracking under evaluation
- only slight increase in storage until arrival of data
- 260 TB of data expected from COMET Phase I

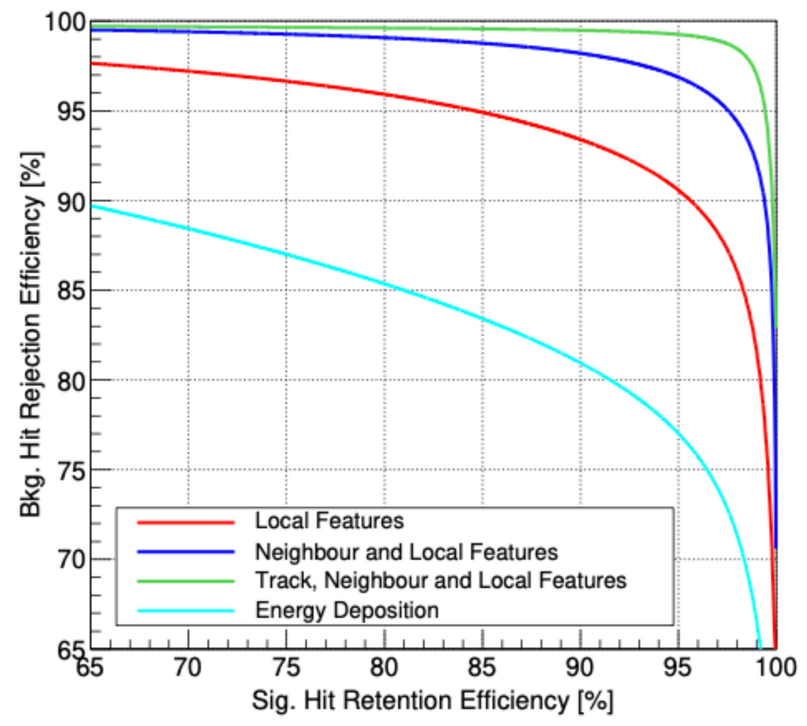
NUCLÉAIRE & PARTICULES

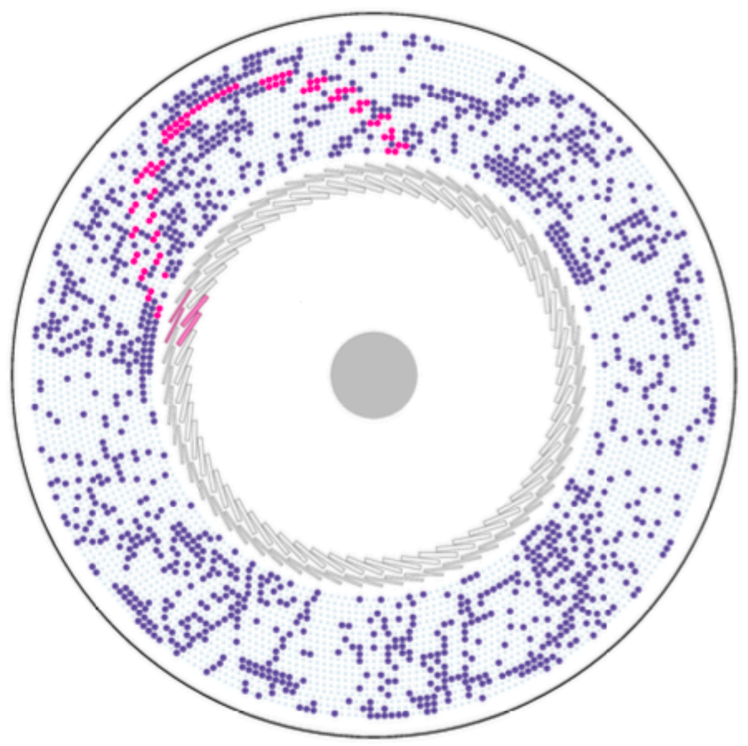
Project : Improved track finding performance in high occupancy and study of Julia language performance with GPUs at CC-IN2P3

Work by W da Silva (LPNHE)
P Lebrun (IP2I-Lyon)
JC Angélique (LPC Caen)
L Del Buono (LPNHE)
in collab. with IHEP (FCPPN/L), Osaka U, ICL

COMET (TDR) :

Track finding - occupancy 15 % (IC)



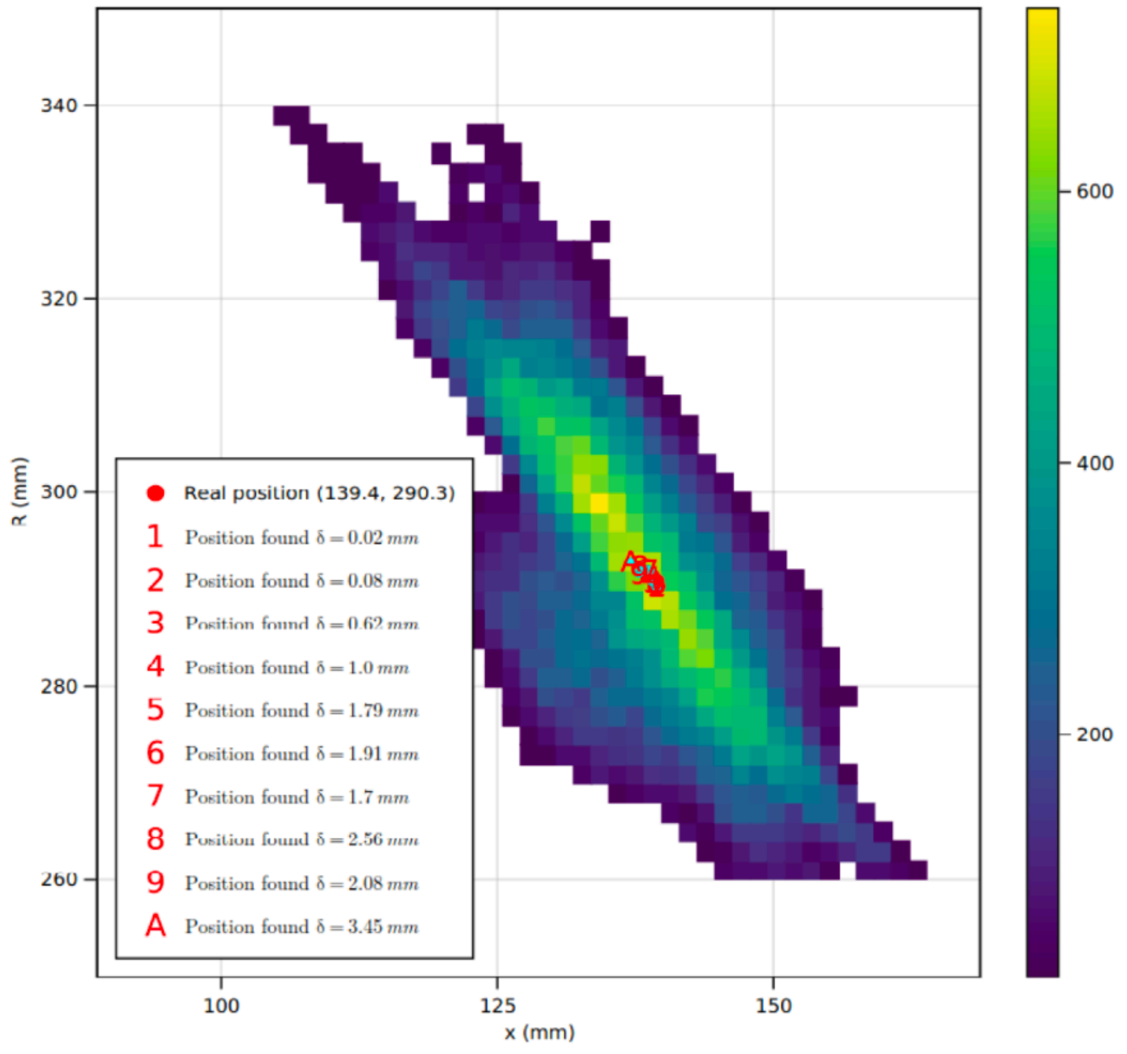


Reconstructed Drift Distance (Apollonius) ⇒ 4D Accumulator

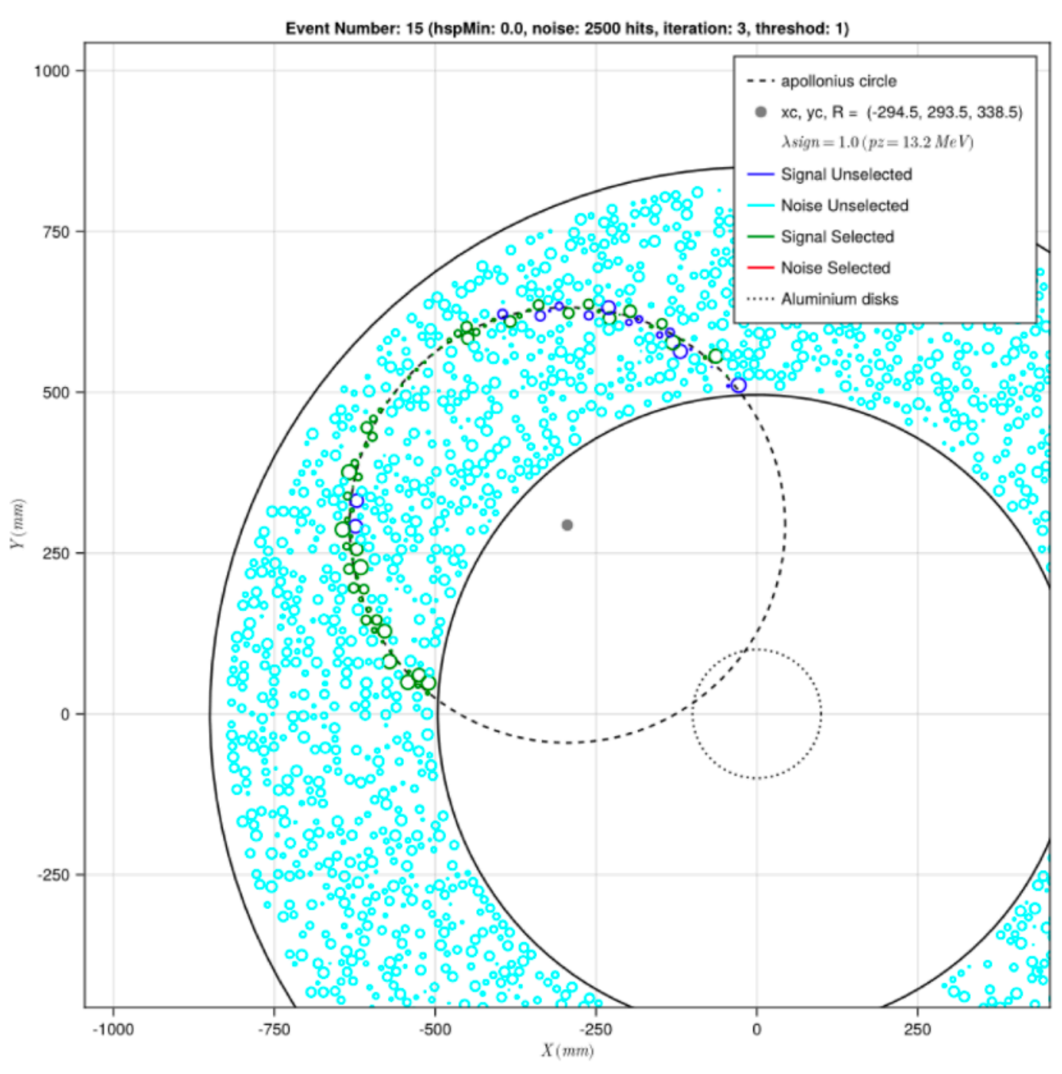
(counting using interval arithmetic and divide and conquer method)

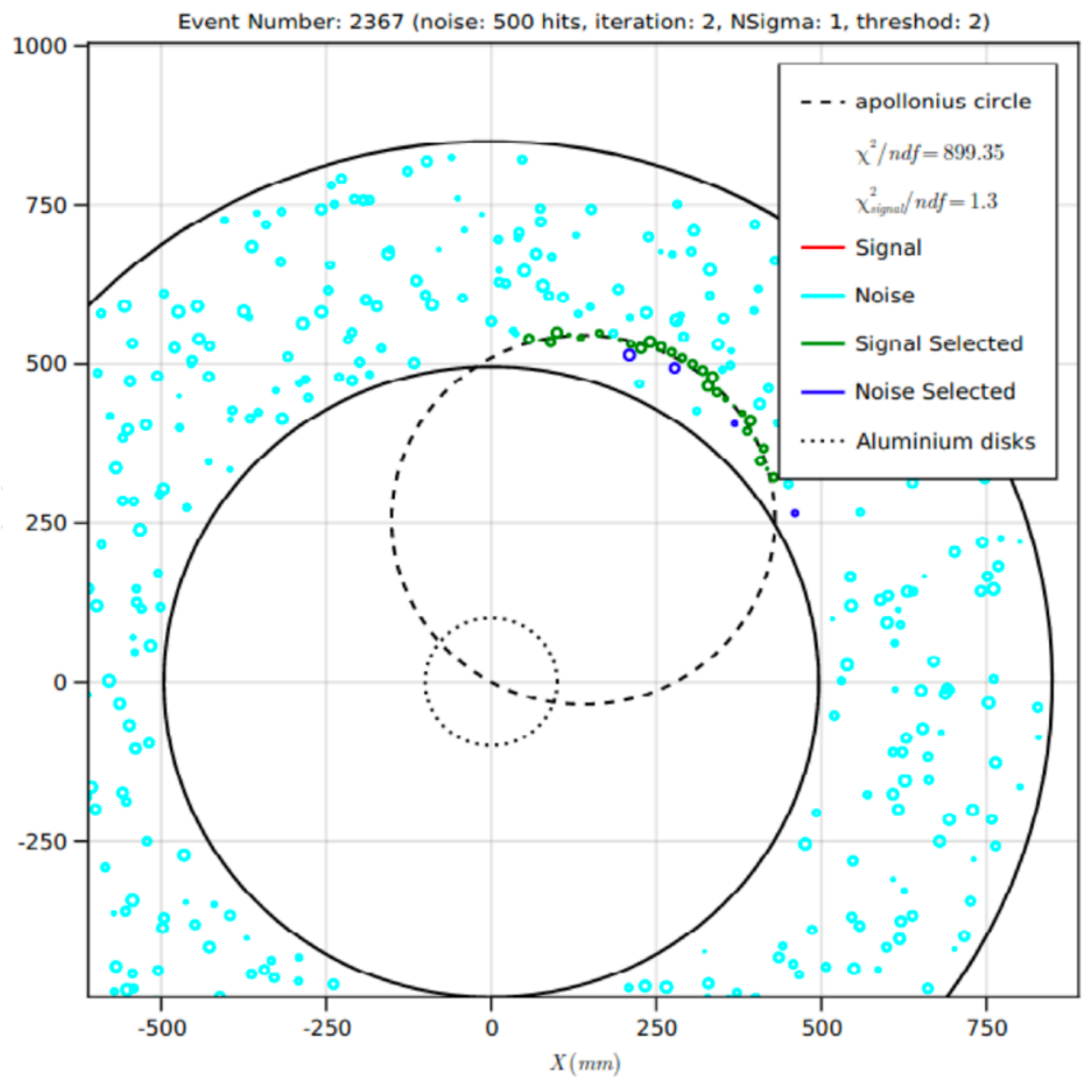
$$\left(x_i^{\mathrm{Ax.}} - x_c\right)^2 + \left(y_i^{\mathrm{Ax.}} - y_c\right)^2 - \left(R + \mathbf{d}_i^{\mathrm{Ax.}}\right)^2 = 0 \checkmark$$

$$\mathbf{d}_i^{\mathrm{Ax.}} = f^{\mathrm{Ax.}}\left(d_i^{\mathrm{St.}}, \tan\tau_i, n_i^{\mathrm{Turn}}, \cdots, x_c, y_c, R, z_0, \lambda\right) \checkmark$$



GPU-accelerated Interval Arithmetic to solve the Apollonius Problem applied to a Stereo Drift Chamber arXiv:2401.04576

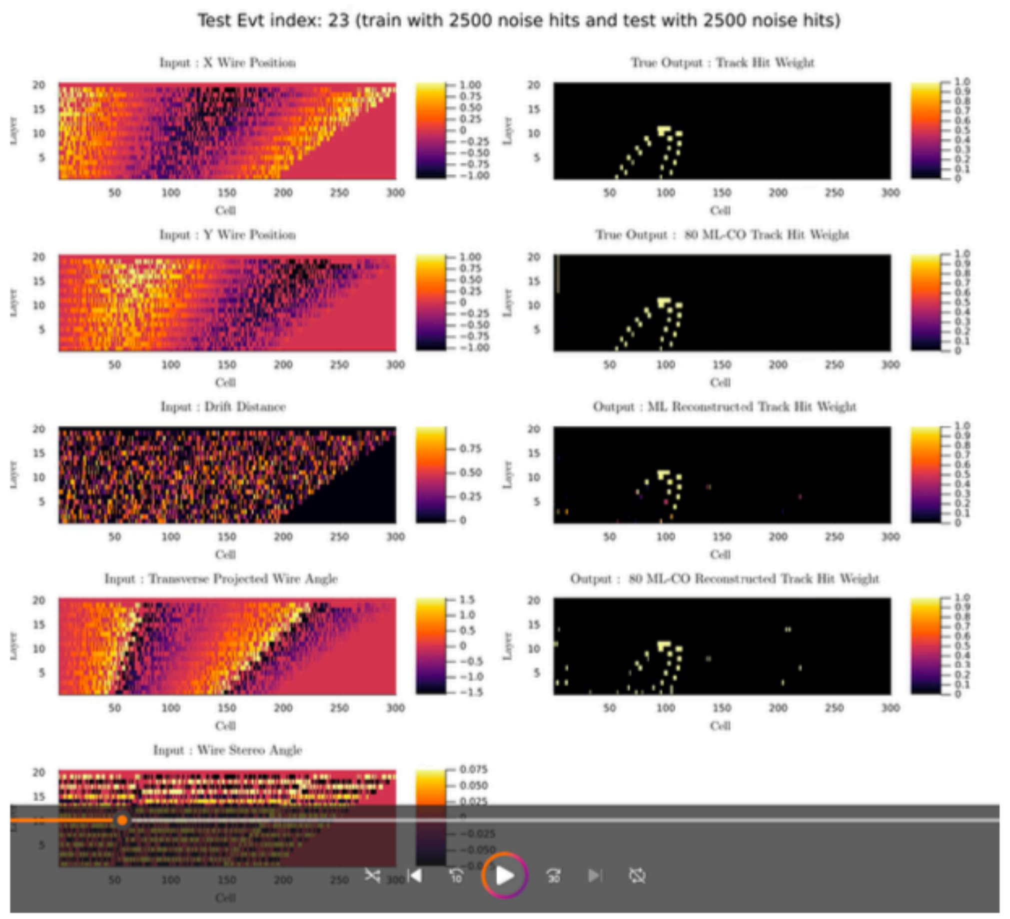


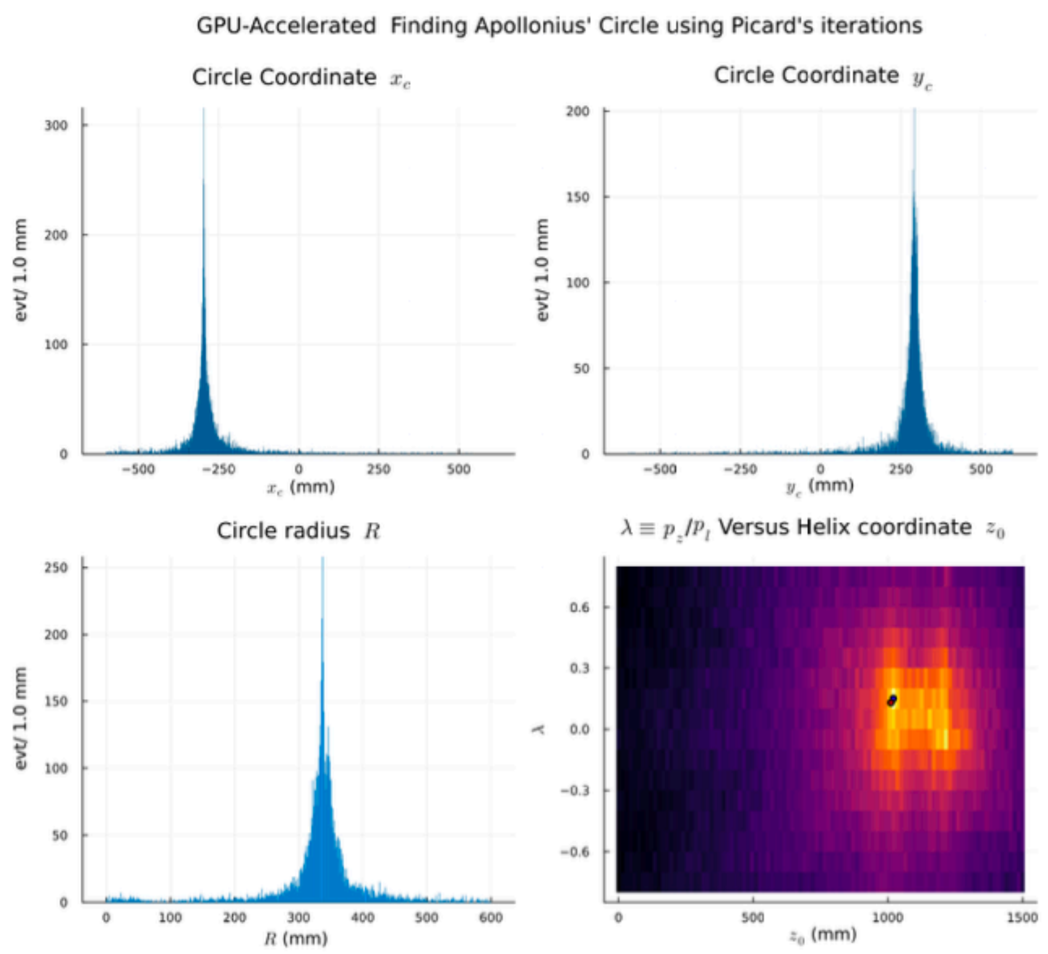


Ideal case : hit efficiency ~ 99 %, purity ~ 99 % – COMET : occupancy 50 % (study ongoing)

Coupling machine learning (studies ongoing) with :

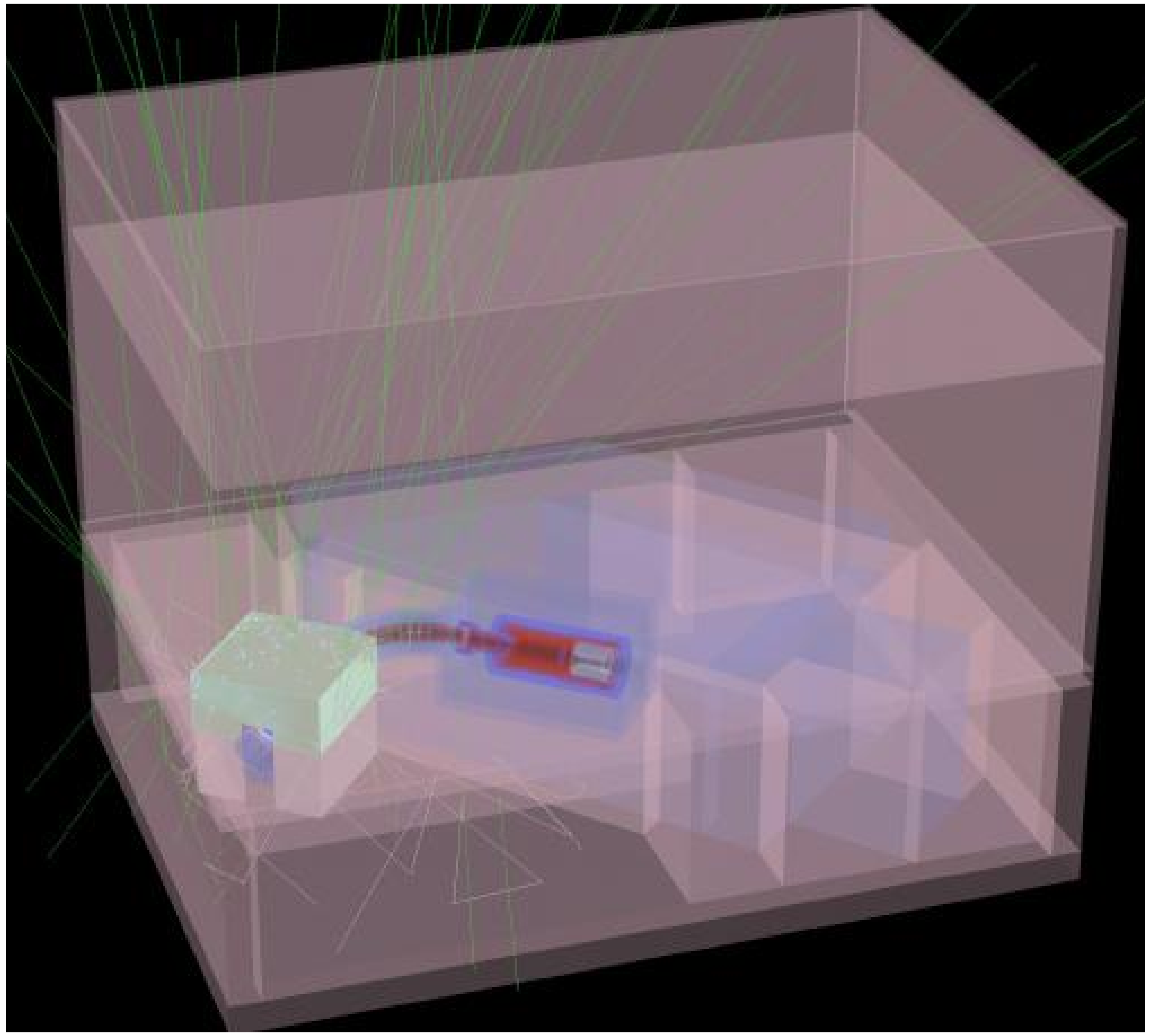
- Apollonius Method on GPUs
- Hough Transform on GPUs
- Fixed Point Iteration Method on GPUs
- Combinatorial Optimization
- Persistent Homology





Event (ResNet-18 + CO) Triplets (FPIM)

Embedding Julia language in ICEDUST (C++ COMET Software) in order to run our Julia tracking package Apollonius.jl with Julia as external package in ICEDUST (study ongoing)

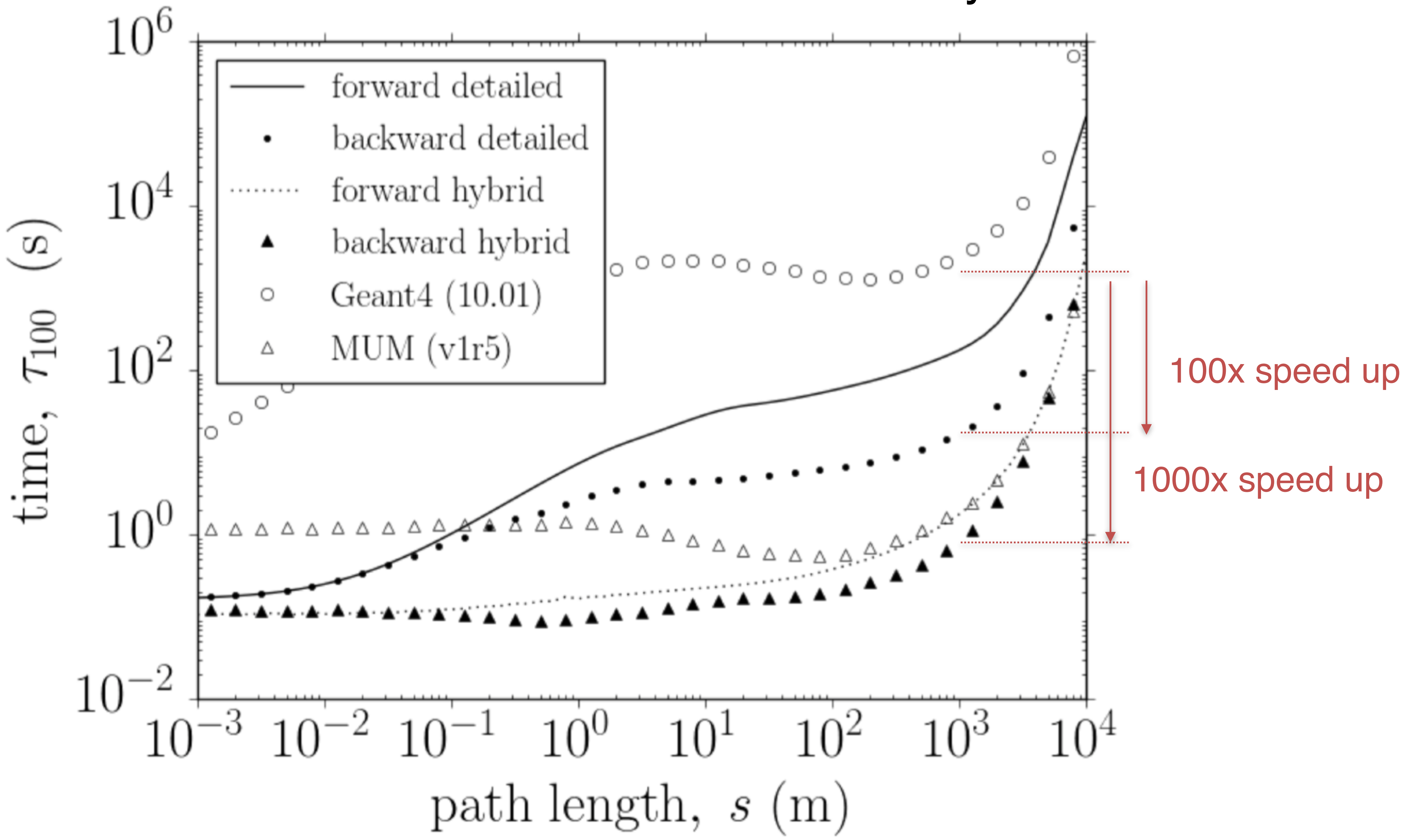


Rare muons and muon-induced electrons w/o CRV signals, undergoing high angle scattering before penetrating in the detection volume

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

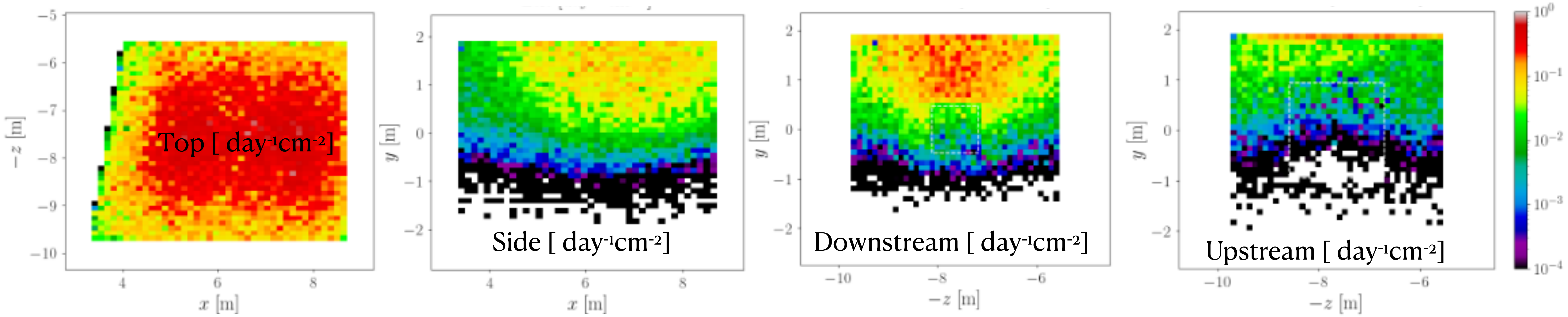
V. Niess *et al*, CPC 2018, 229, pg 54

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

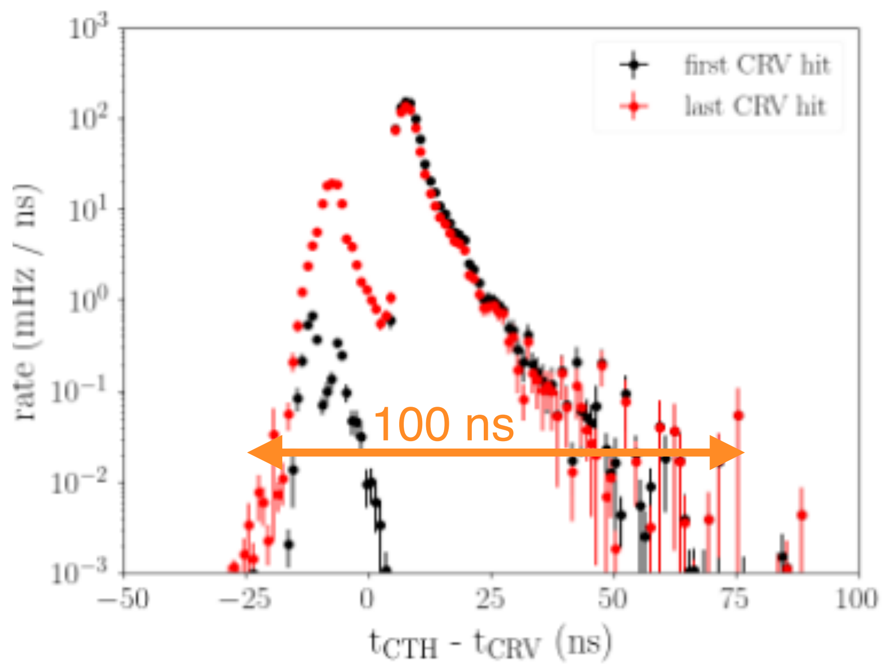


Non analog simulation using Importance Sampling and Backward Monte Carlo

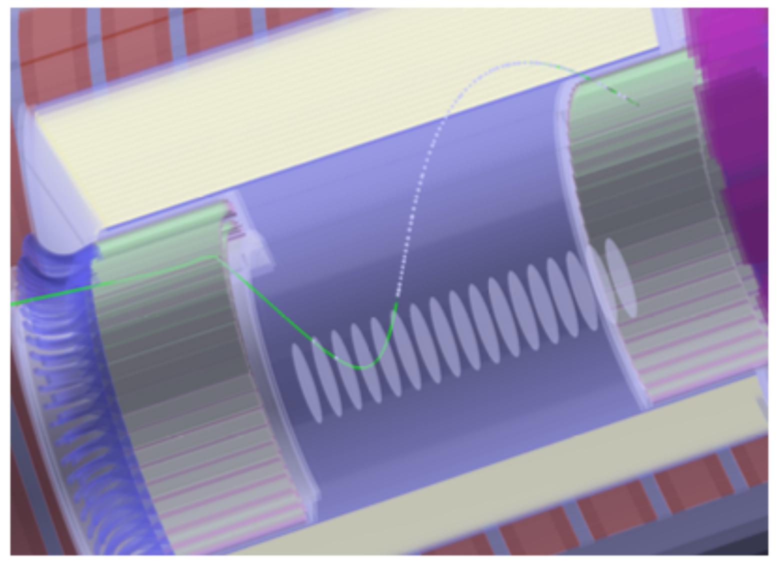
Maps of the triggering atmospheric muons

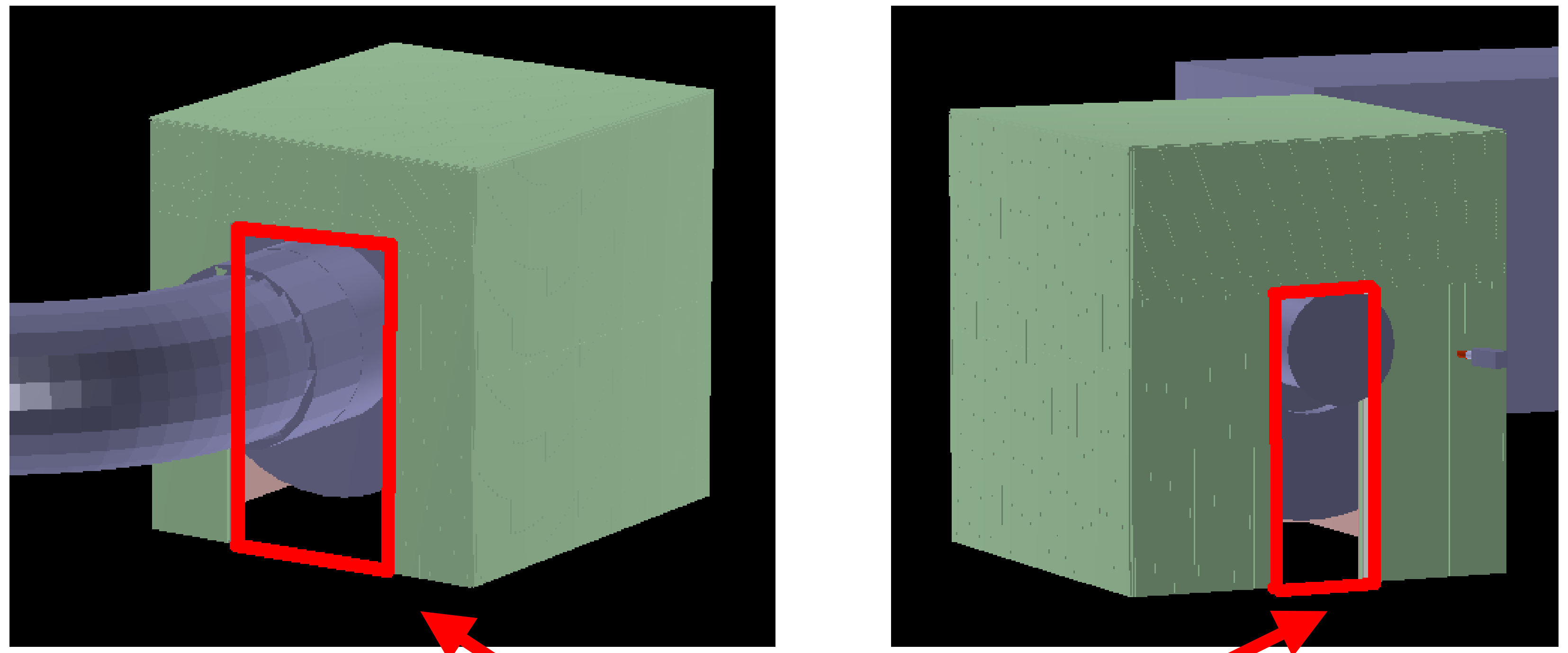


time distributions



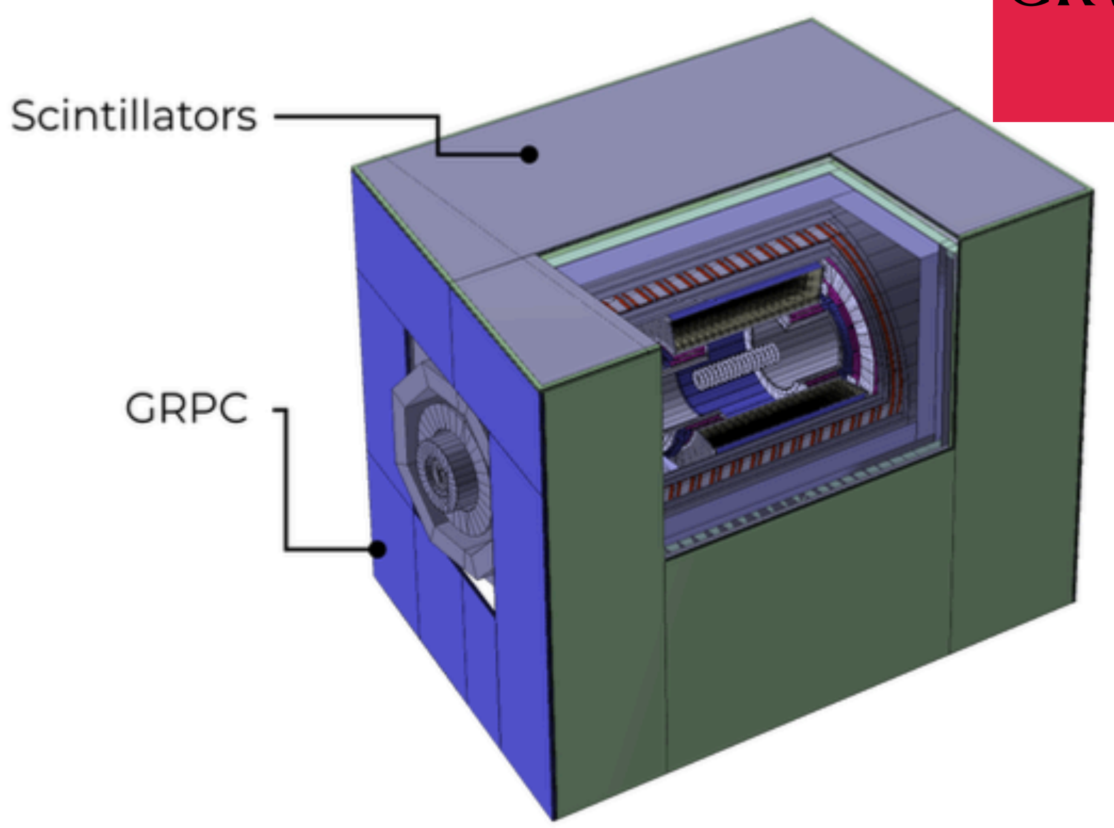
Sneaking μ^+ with p_{fit} = 101 MeV/c





Original beam openings

CRV modified in 2020

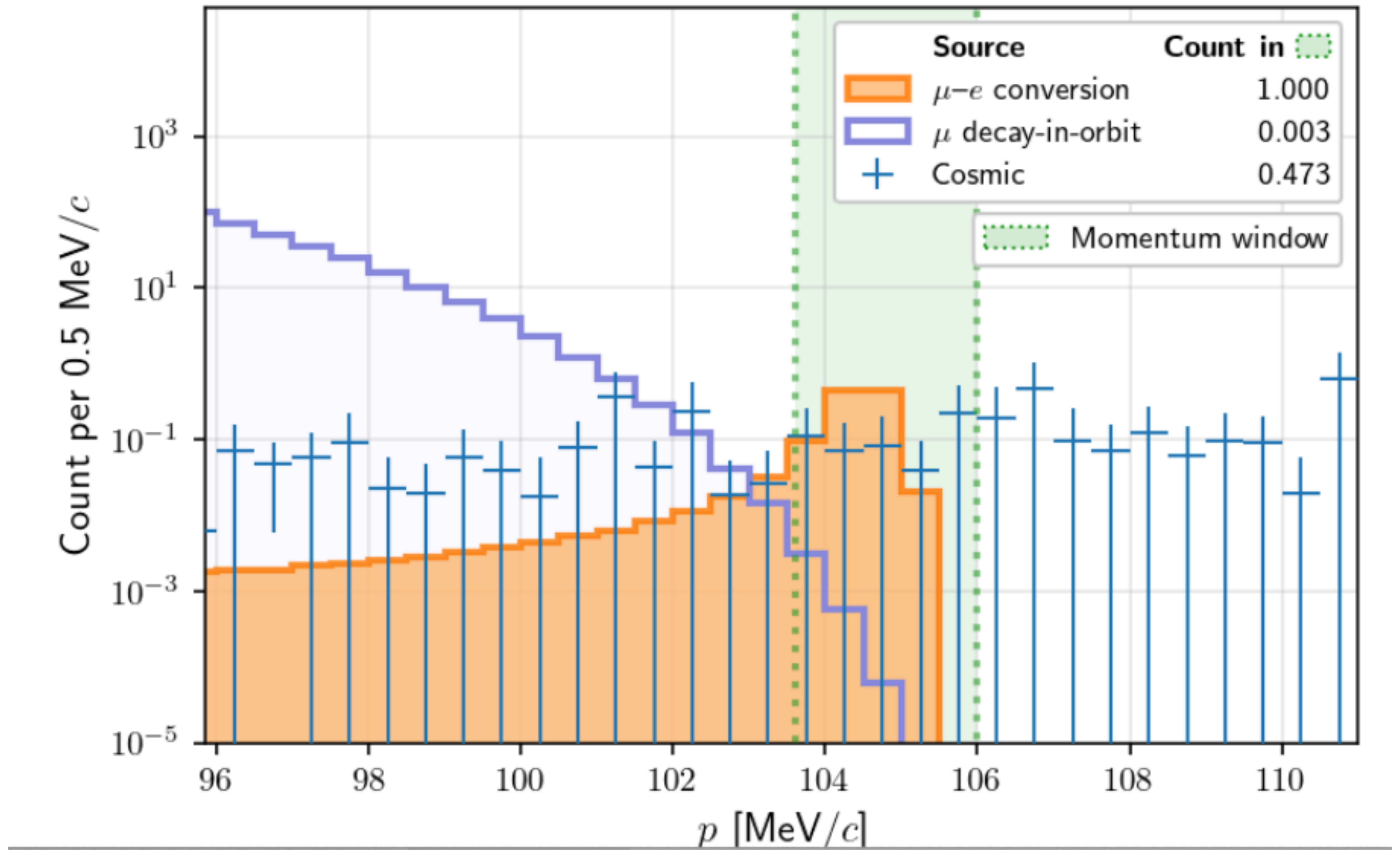


Statistics available

	Events	+ 4-fold + track(s)	$103.6 \leq p_{fit} \leq 106.0$
CRV envelope	1.0×10^9	7259	640
CRV openings	1.4×10^9	724	57

Work by V Niess (LPCA)
M Dubouchet (ICL)
N Chadeau and G Faure (LPCA)

COMET Phase-I, 142 days at 3.2 kW
With cuts (timing, trigger, CRV, track)
μ^+ rejection rate = 89% CRV efficiency = 99.99%
μ^- rejection rate = 0% $\mathcal{B}(\mu^- \to e^-) = 4.4 \times 10^{-15}$



COMET Phase-I, 142 days at 3.2 kW
μ^+ rejection rate = 89% μ^- rejection rate = 0%
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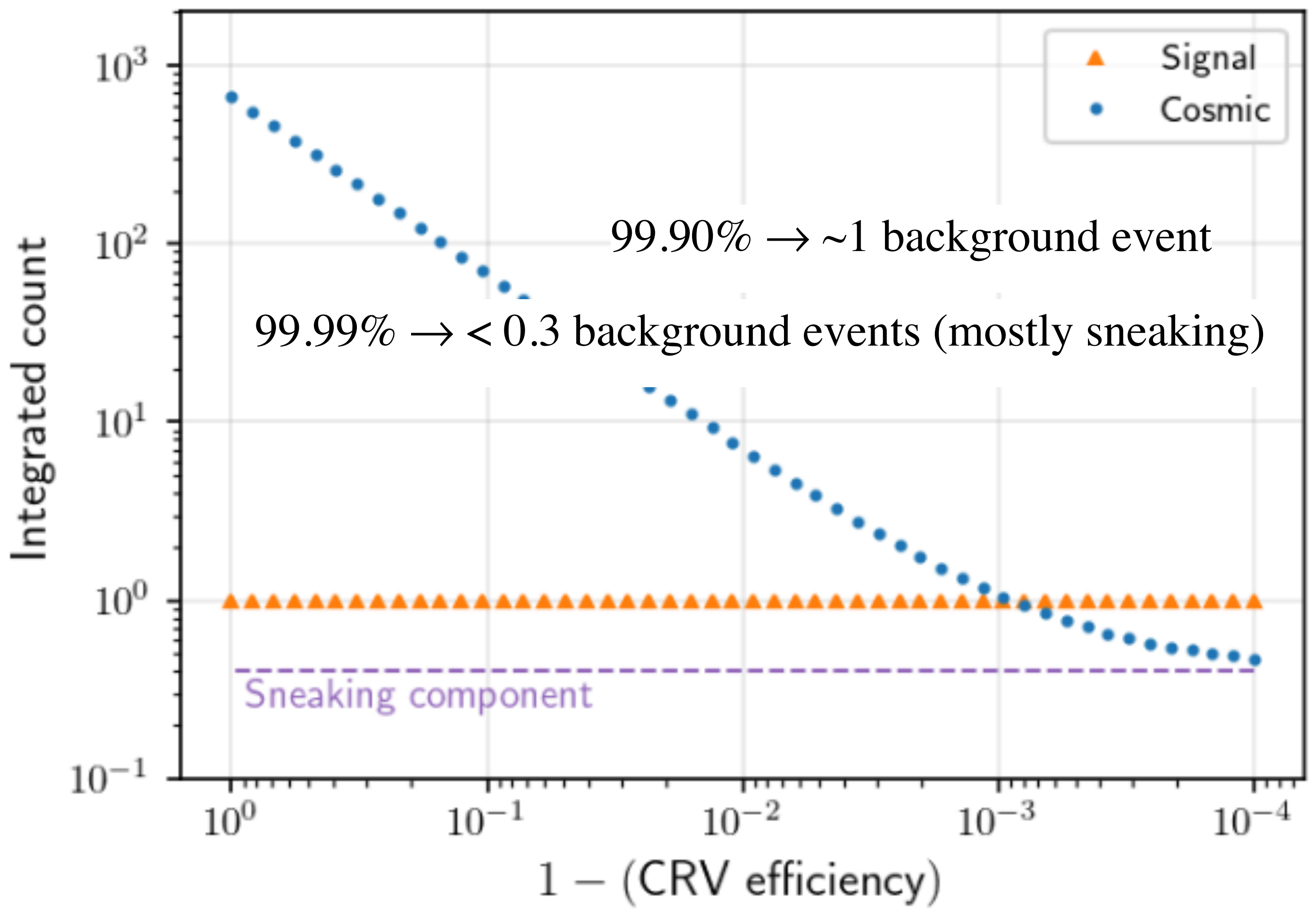


C.

(1) 105 MeV/c muons cannot be discriminated from electrons:
➔ Cosmic background > 2

(2) Only μ^+ can be discriminated from electrons:
➔ Cosmic background ~ 0.5

(3) Both μ^+ and μ^- can be identified with 99% efficiency:
➔ Cosmic background < 0.1

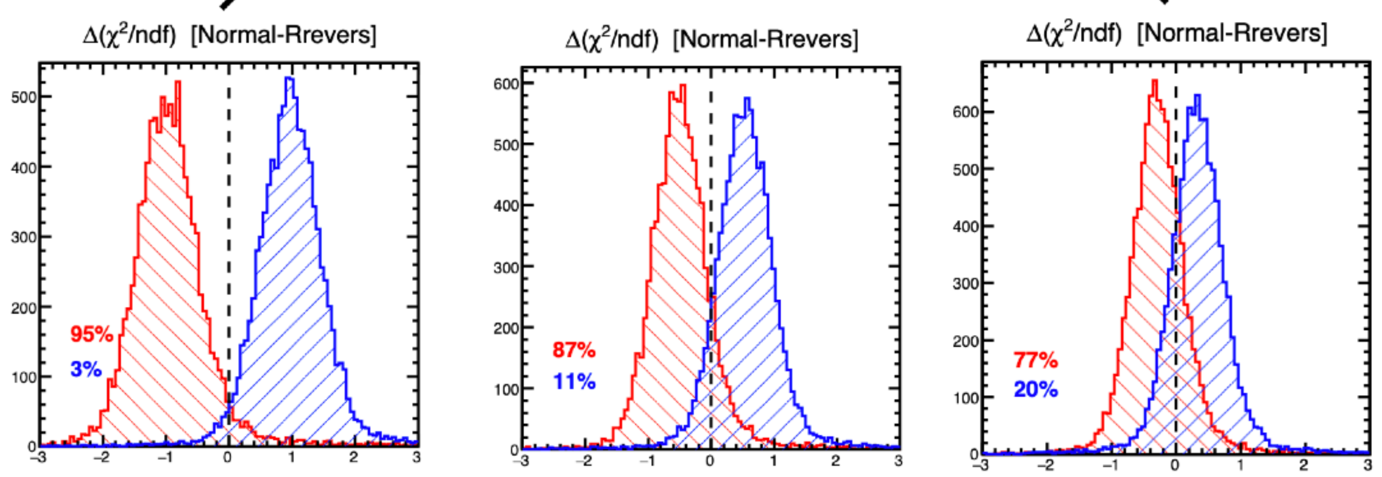
CTH is the key detector for μ/e discrimination

N. Chadeau (LPCA) works currently on the CTH dE/dx discrimination power
- full detector response
- CTH occupancy / pileup

- multiple-turns track, direction identified from momentum attenuation in-between turns
- single turn tracks:
  - t0 used for correcting the CDC drift time is estimated from the TOF between CTH and each CDC hit.
  - miscorrection of 9.7 ns for reverse μ^+ tracks

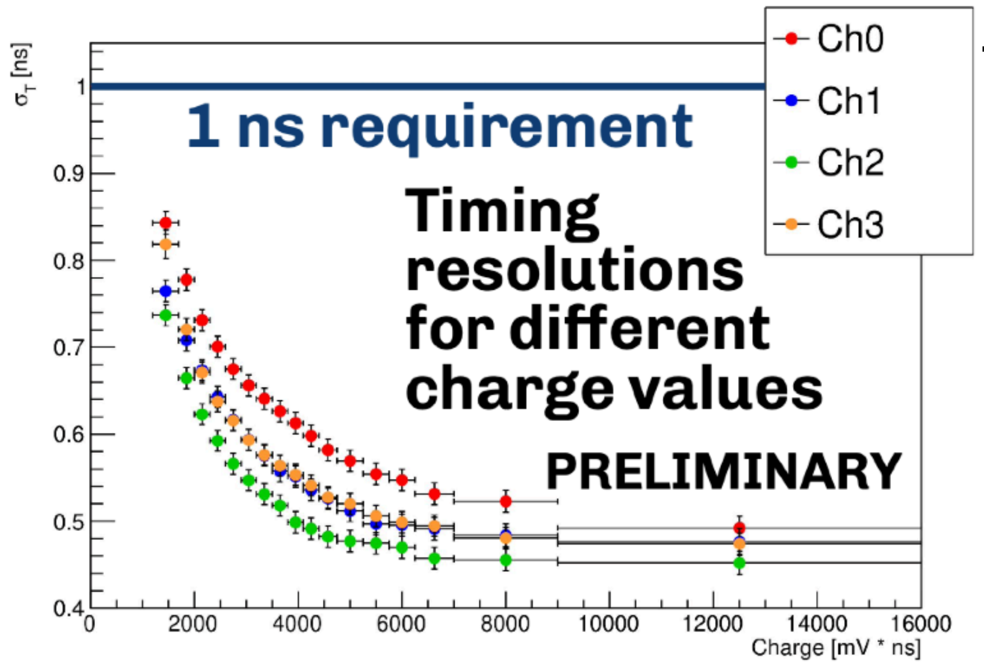
$\Delta(\chi^2/ndf) < 0$

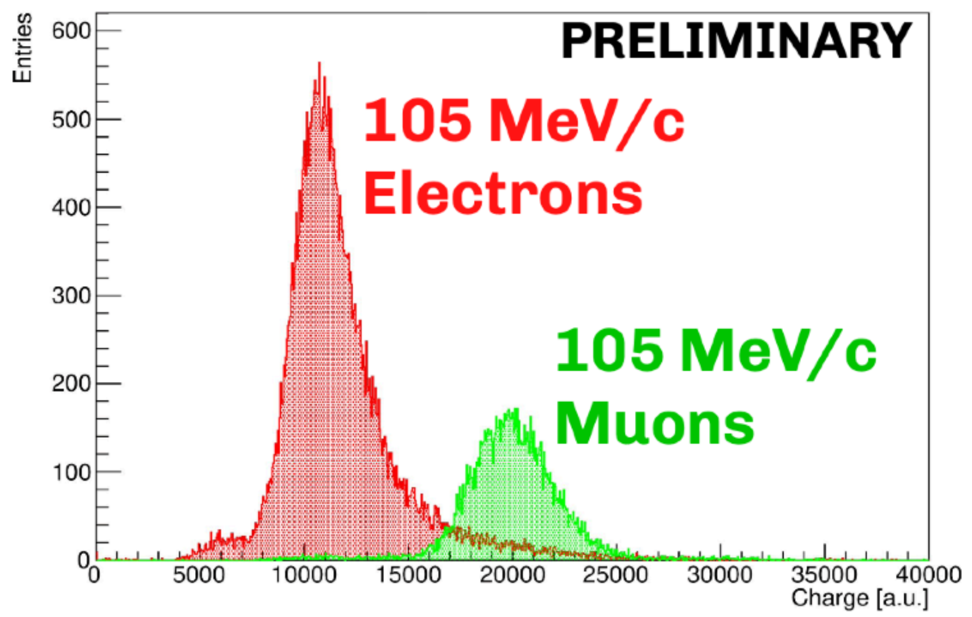
Spatial Resolution	100 μm	150 μm	200 μm
Signal Retention (e^-)	95%	87%	77%
Contamination (μ^+)	3%	11%	20%

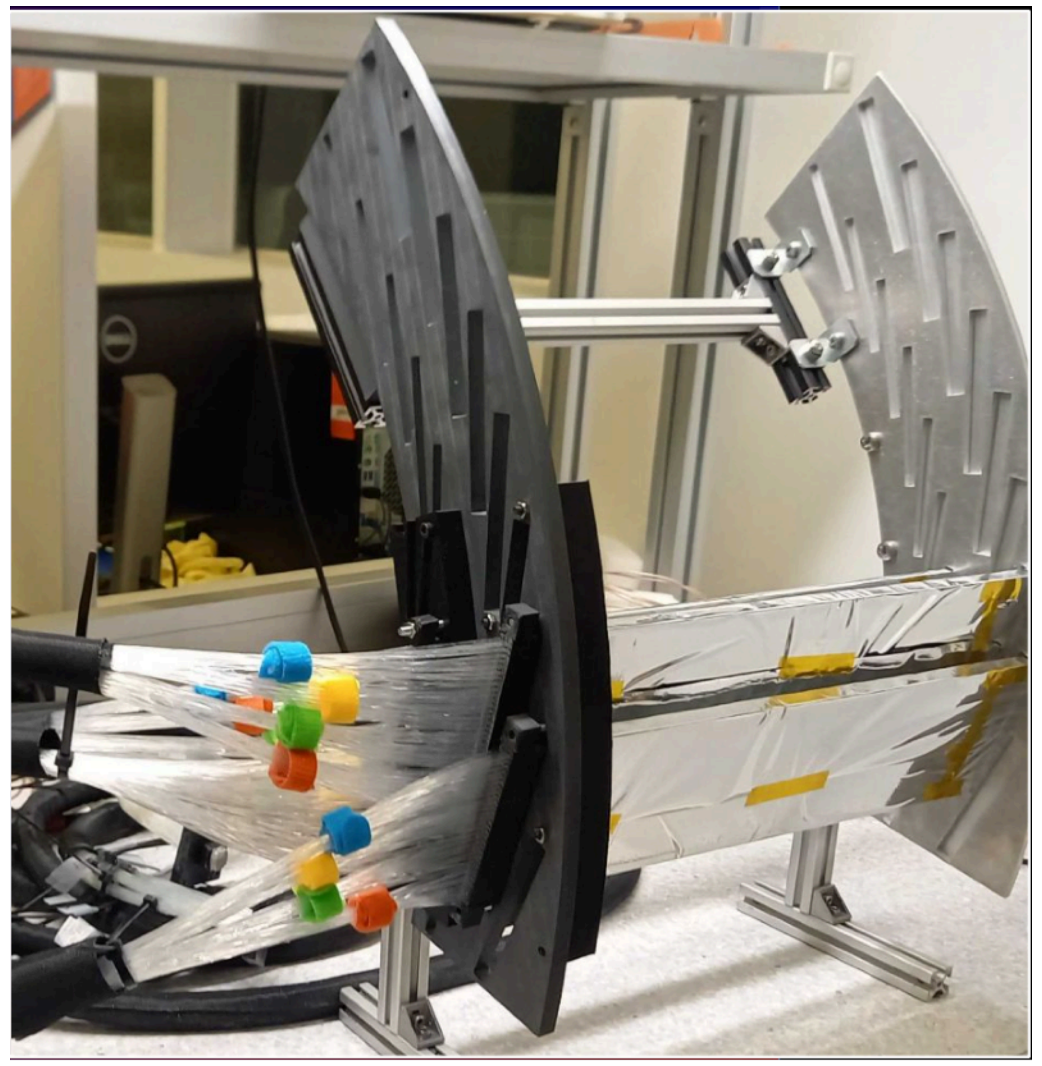


French Contribution :: CTH :: @Test Beam @ PSI PiM1 (Nov 2023)

- Phase-alpha detector efficiencies
- Cylindrical Triggering Hodoscope studies : response tested with electrons, muons and pions

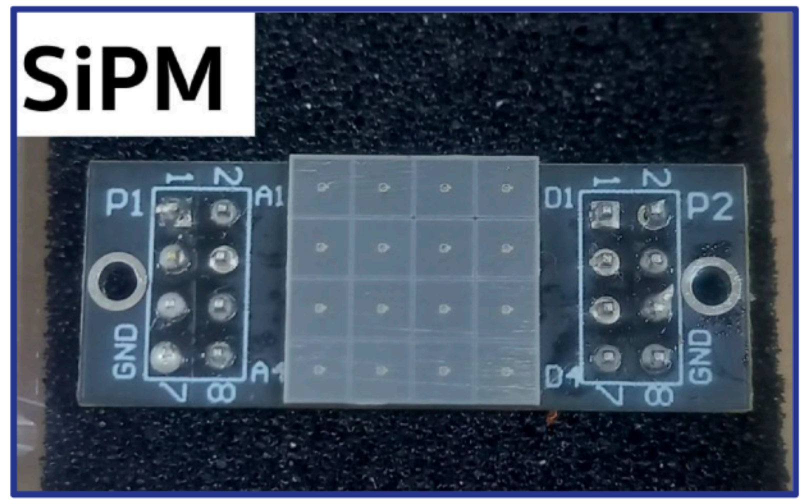


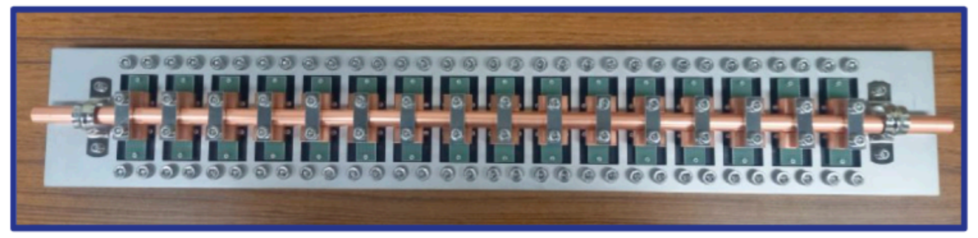


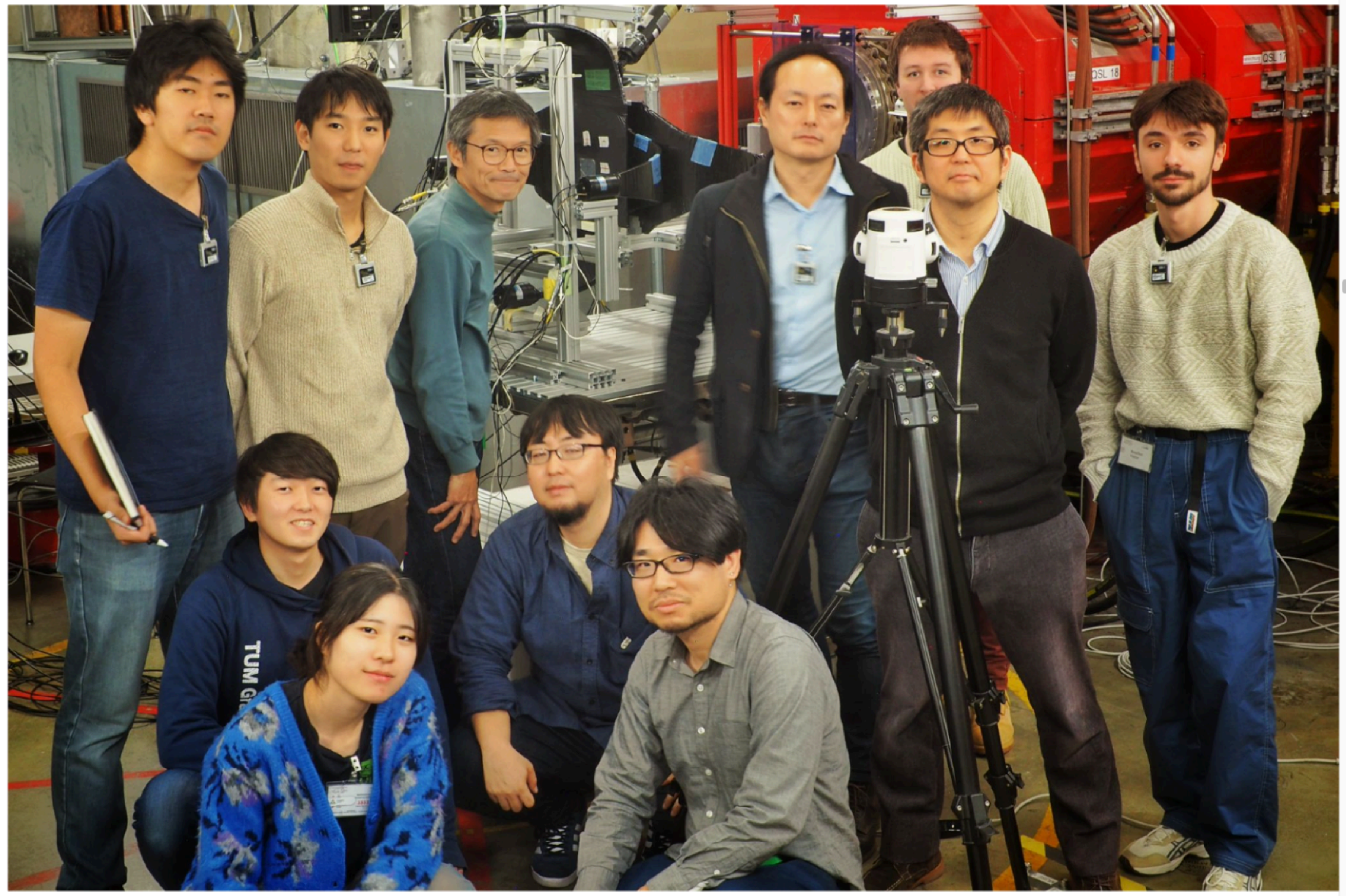


Work continues @ JParc for Thomas and Nicolas (June, July 24) !

Qualification of the SiPMs
Optimisation of their cooling system





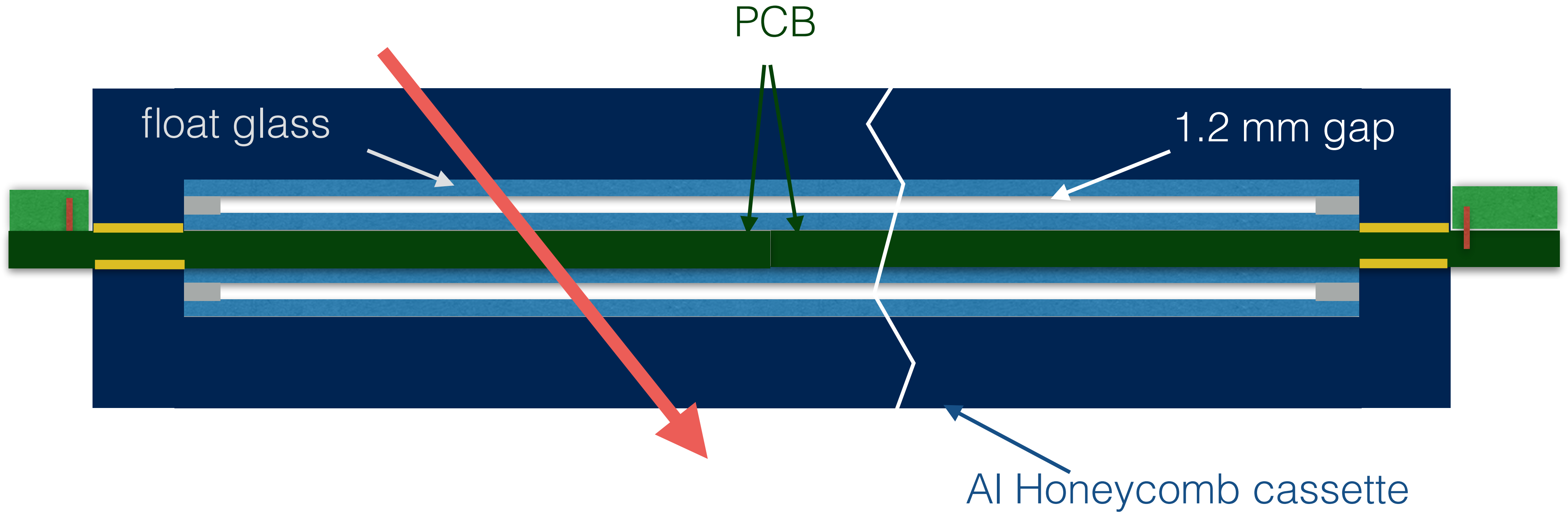


Single gap GRPC

- avalanche mode
- mm intrinsic segmentation
- ns intrinsic time resolution

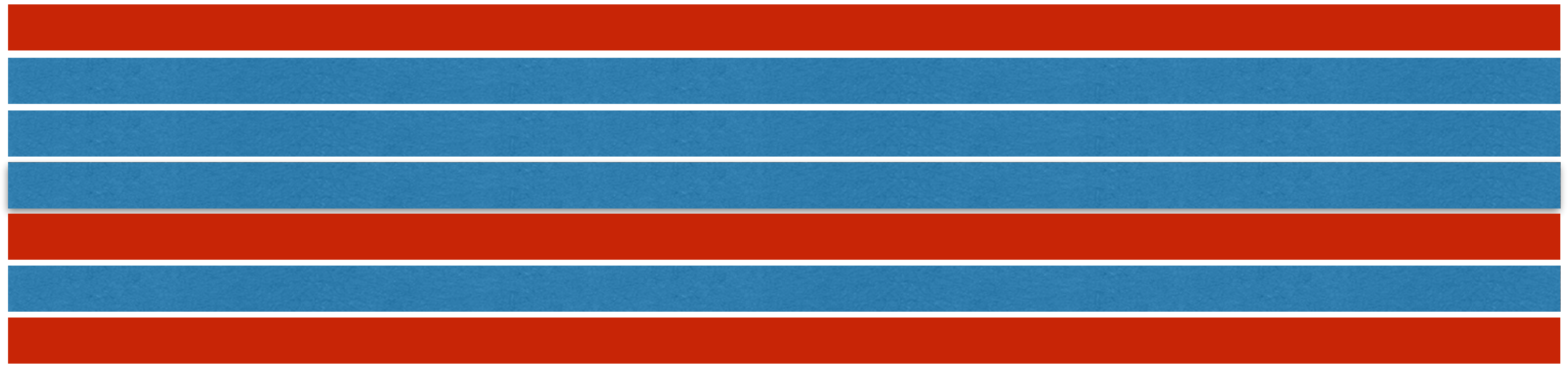
- ~90-95% efficiency
- gas: 98% TFE, 2% SF_6

A detector module: two single gap GRPCs with common readout



- layered PCB with x,y strips readout on opposite sides
- ~ 1,2 m / 1,5 m strips
- two GRPCs/ module
- <25 mm thick

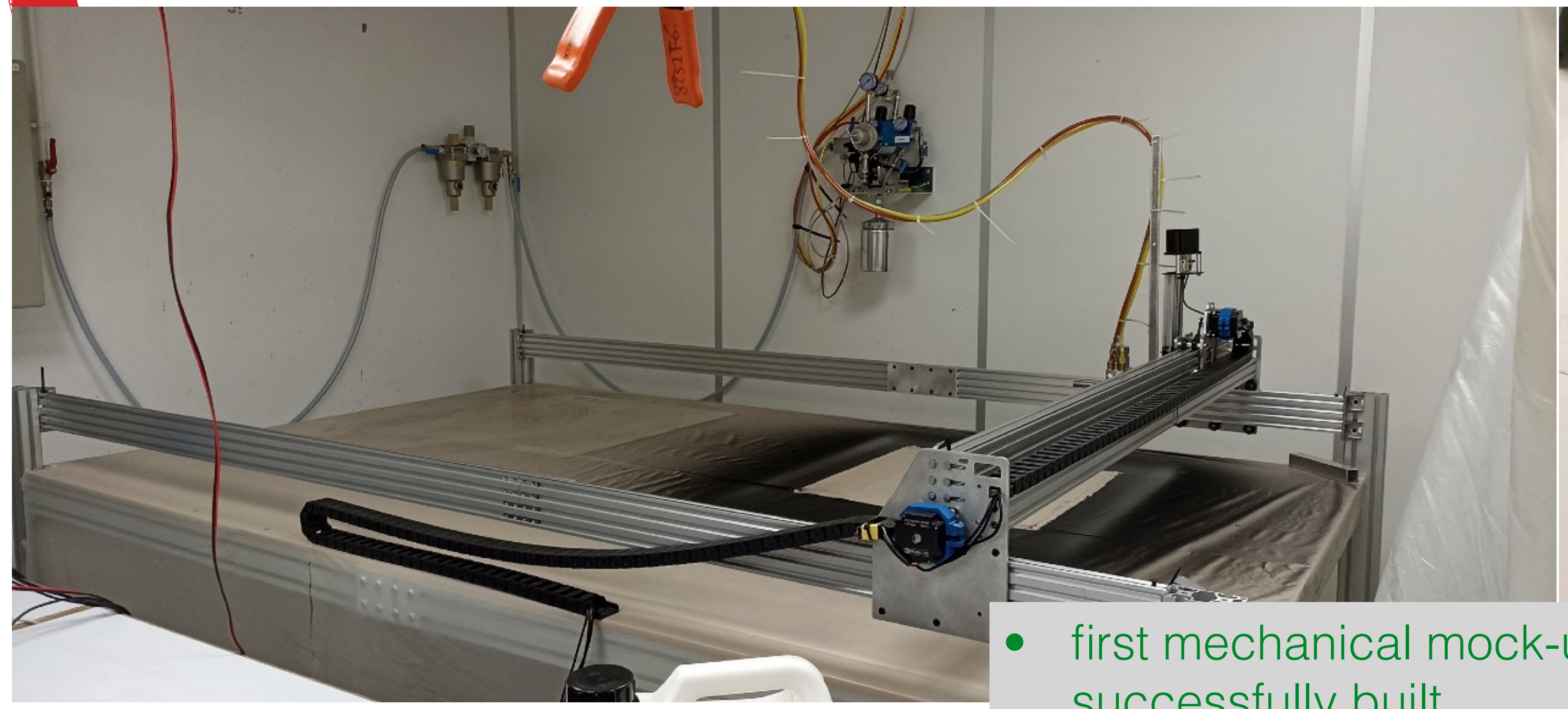
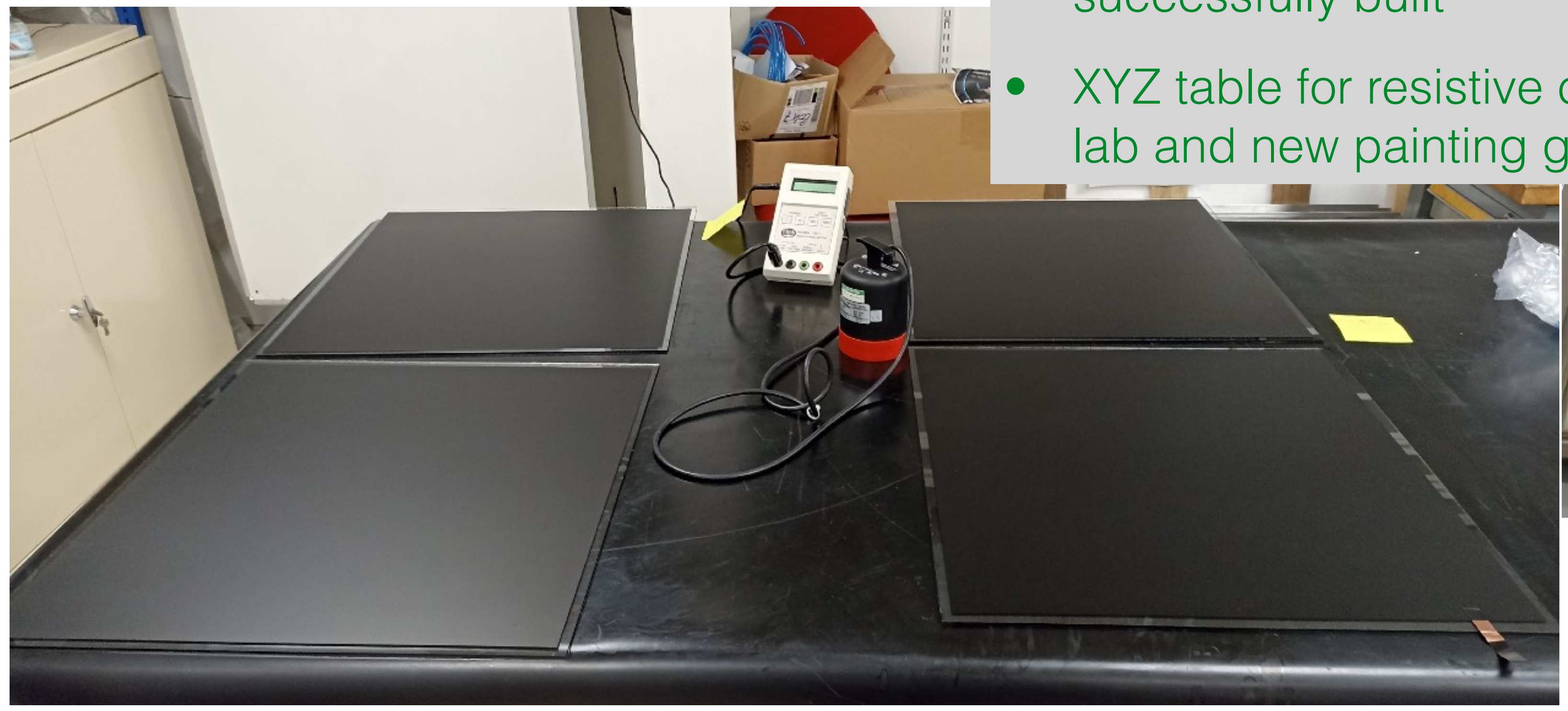
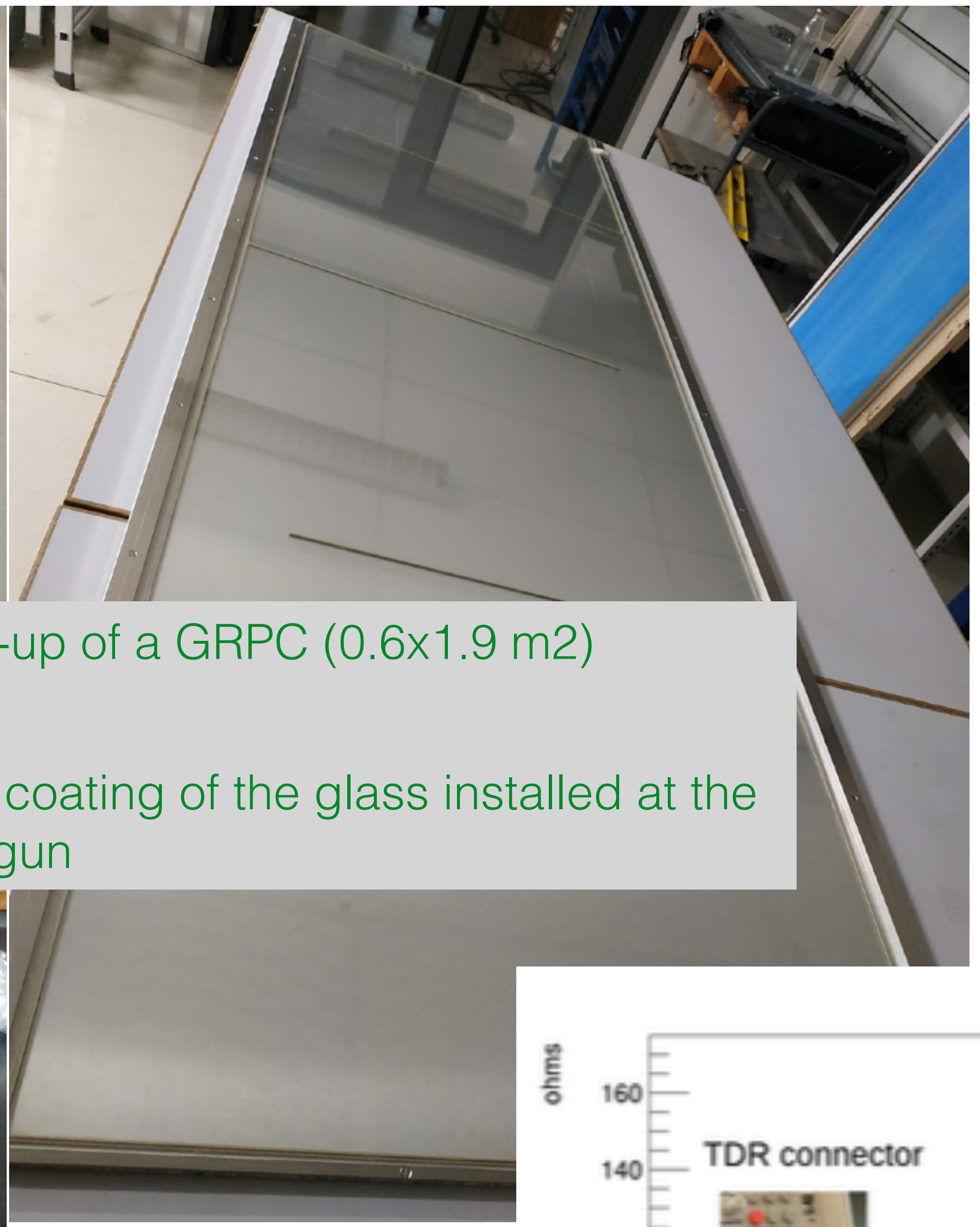
A tracker module: 5 to 7 detector modules



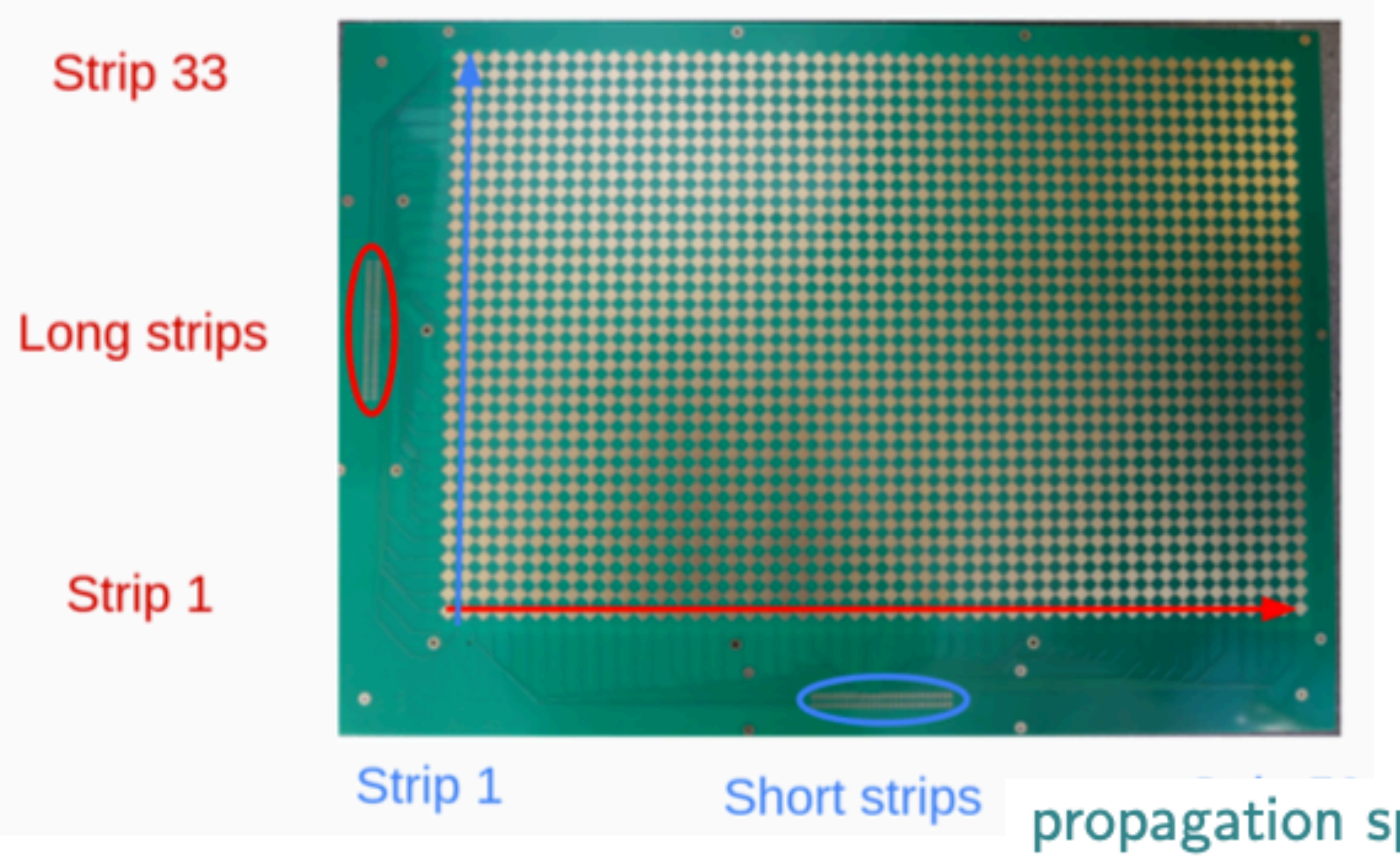
Segmentation and number of chambers to be defined by physics simulations & measured performance

ASIC	# ASIC/ module	# ASIC / CRV 5 layers	# ASIC / CRV 7 layers
PETIROC	144	720	1008
LIROC	40	200	280

Baseline: 10 mm pitch

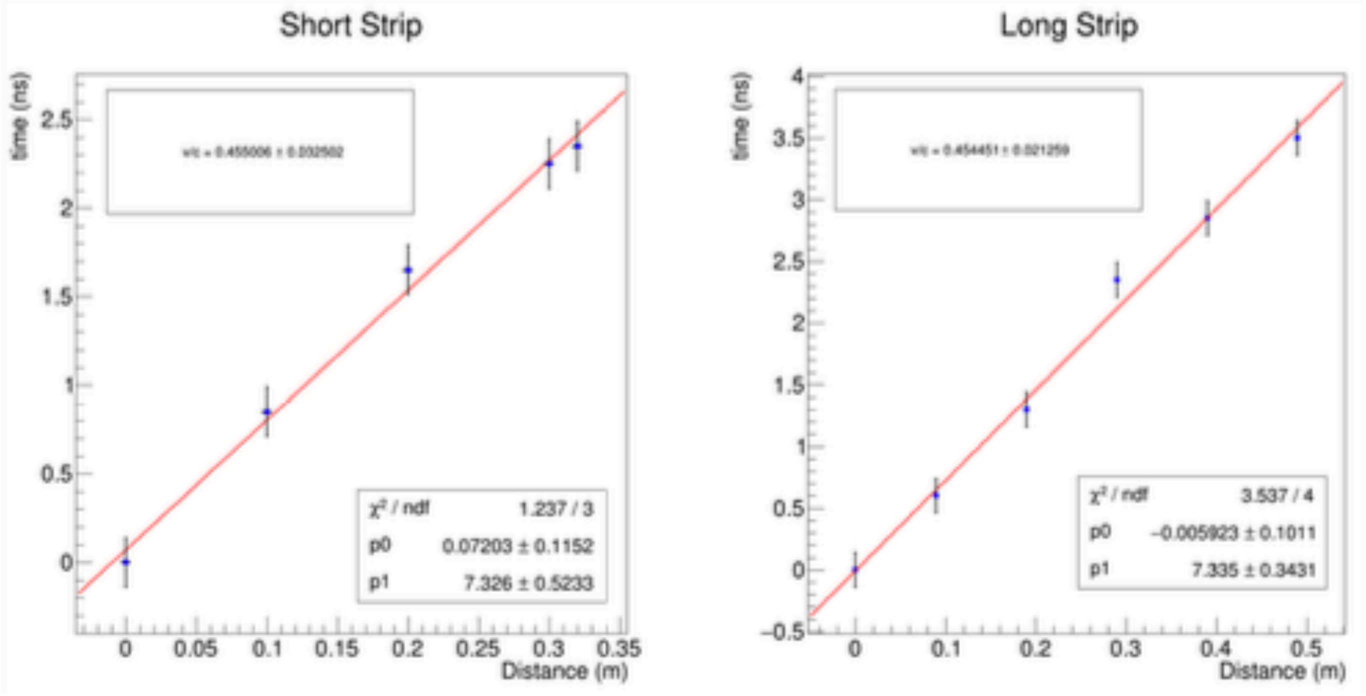




- first mechanical mock-up of a GRPC (0.6x1.9 m2) successfully built
- XYZ table for resistive coating of the glass installed at the lab and new painting gun

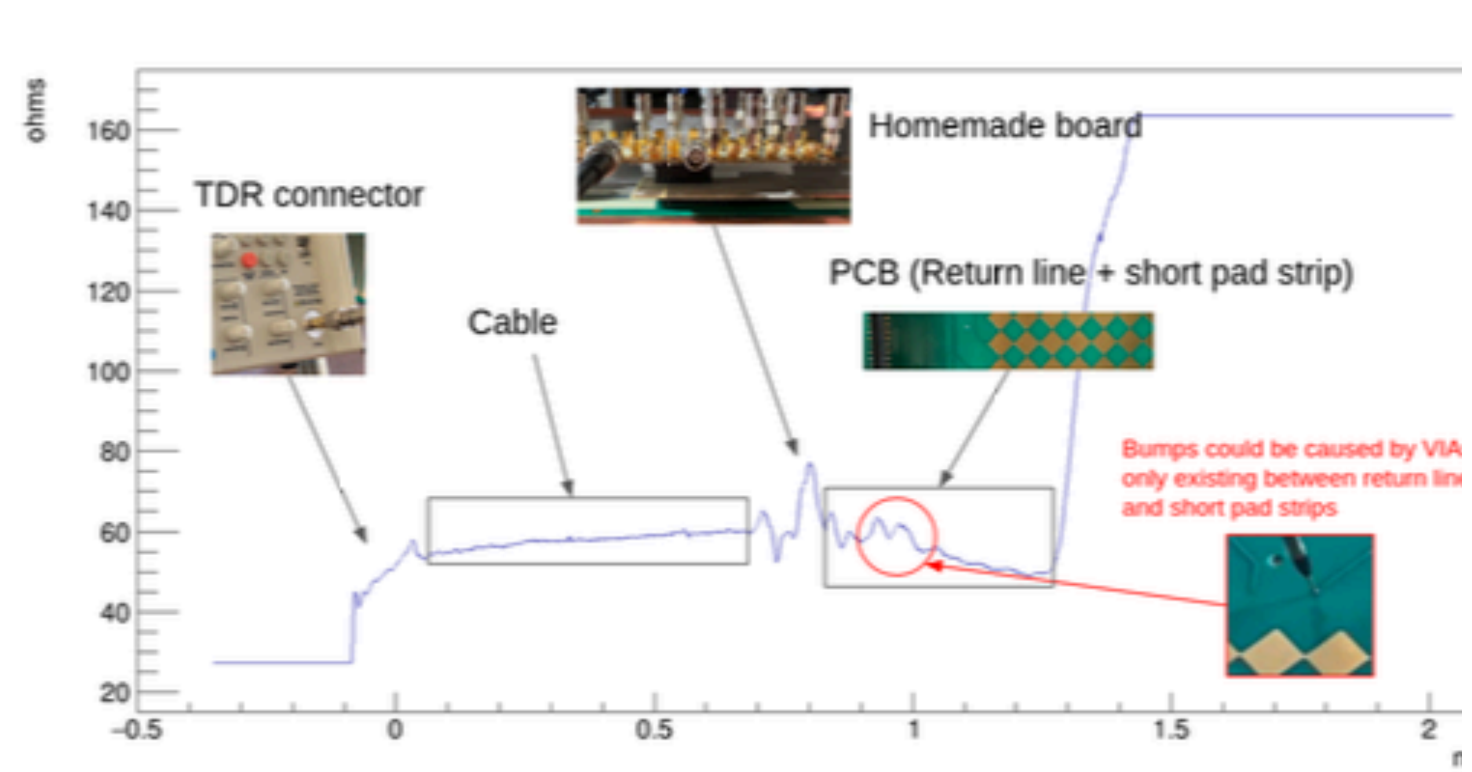


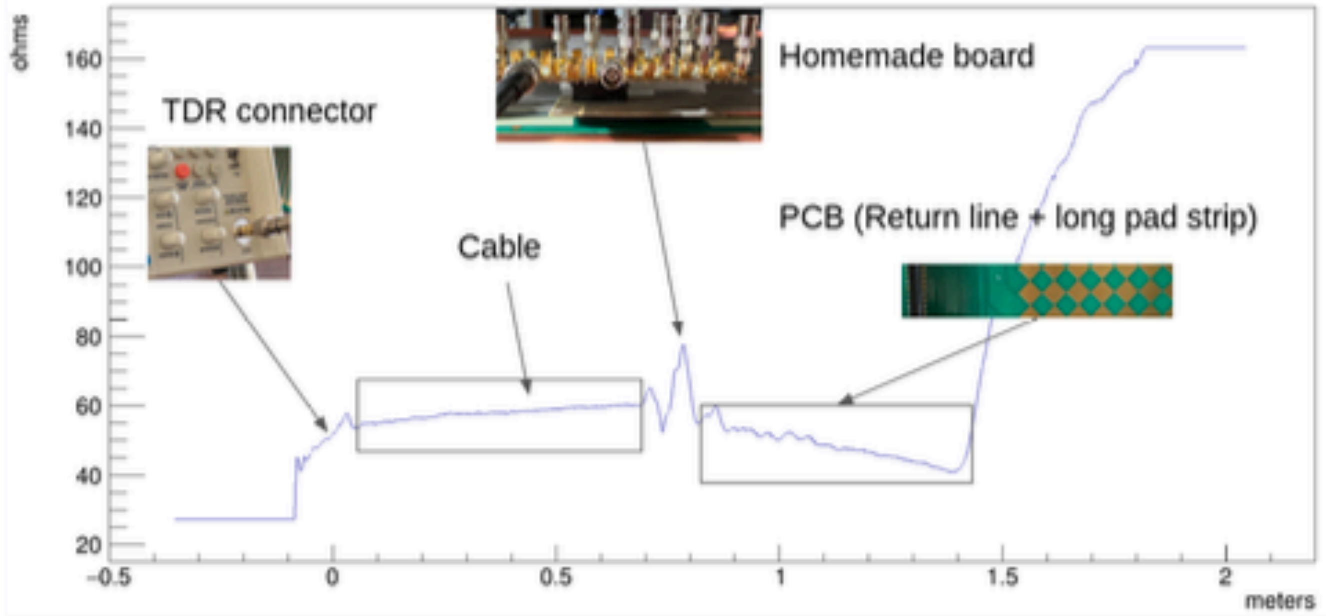
- Detection surface: 33x50 cm^2.
- Each side is dedicated to one direction (XY).

propagation speed of signals: $v/c \sim$ 45% .

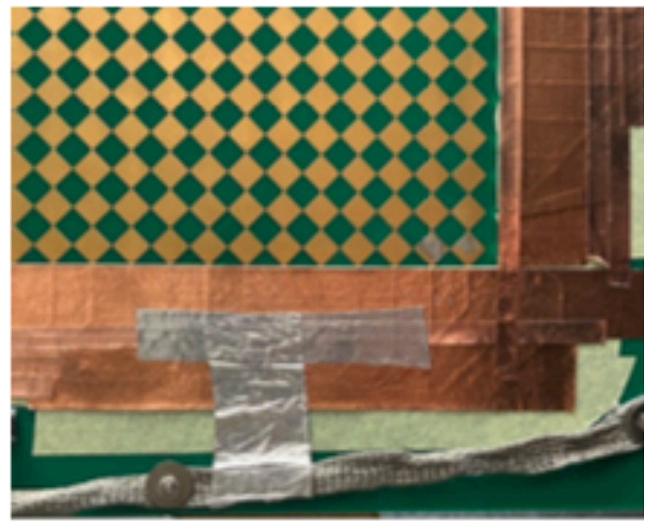


~10% amplitude signal loss expected





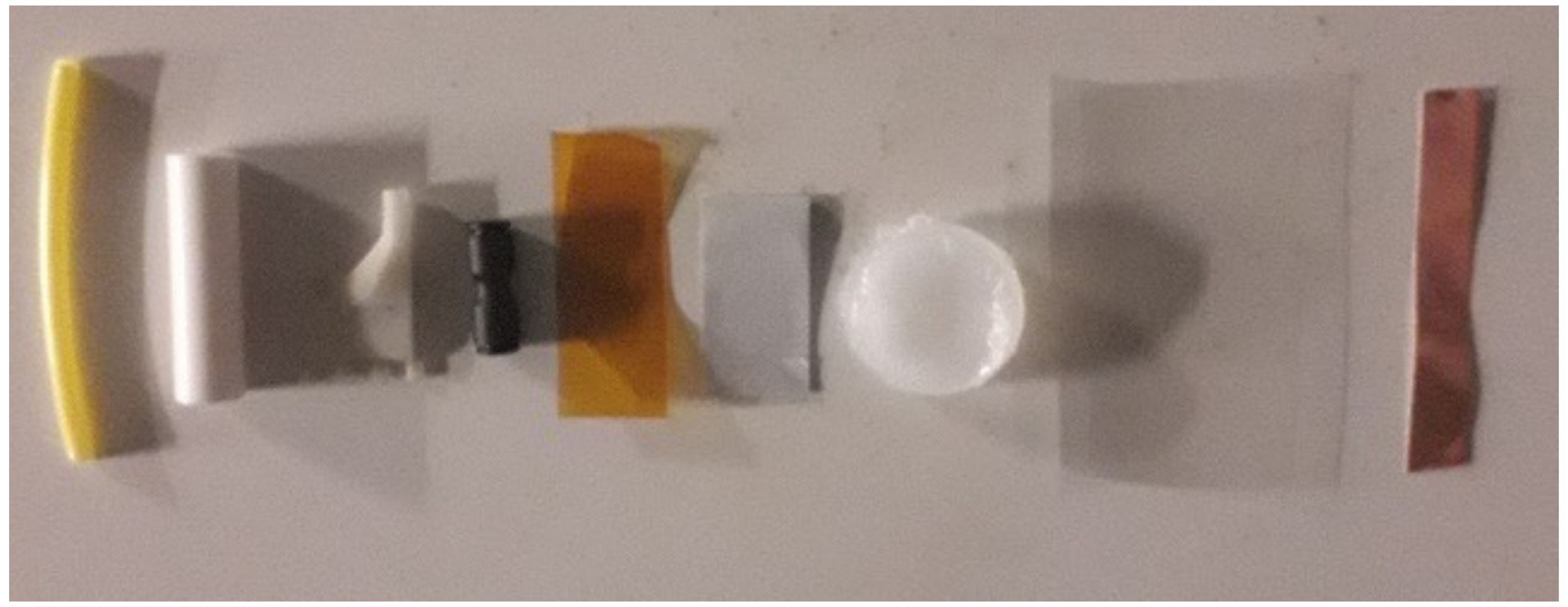
M Gouzevitch, G Garde, T Cluvel
March/April 2023

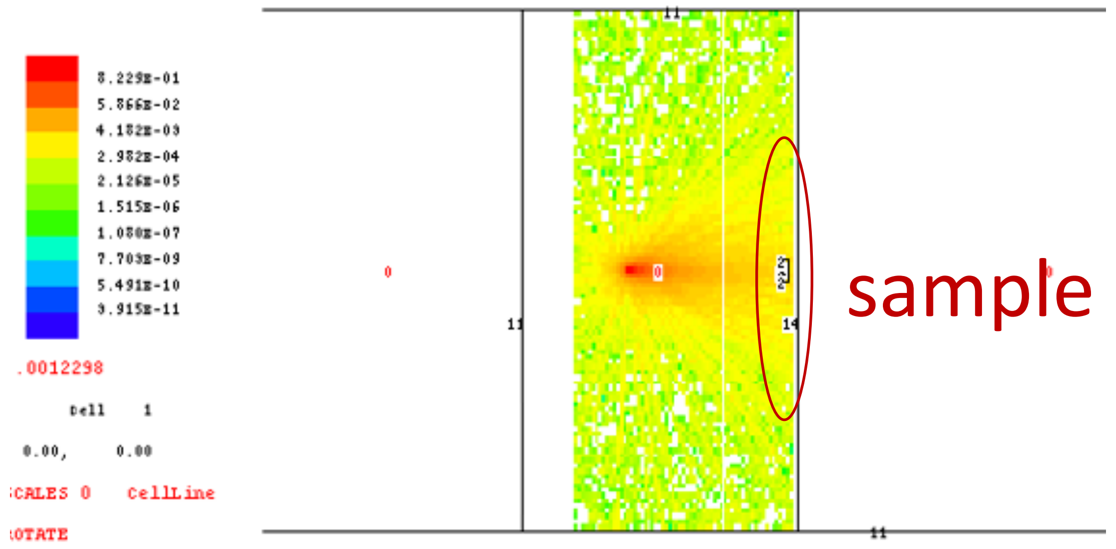



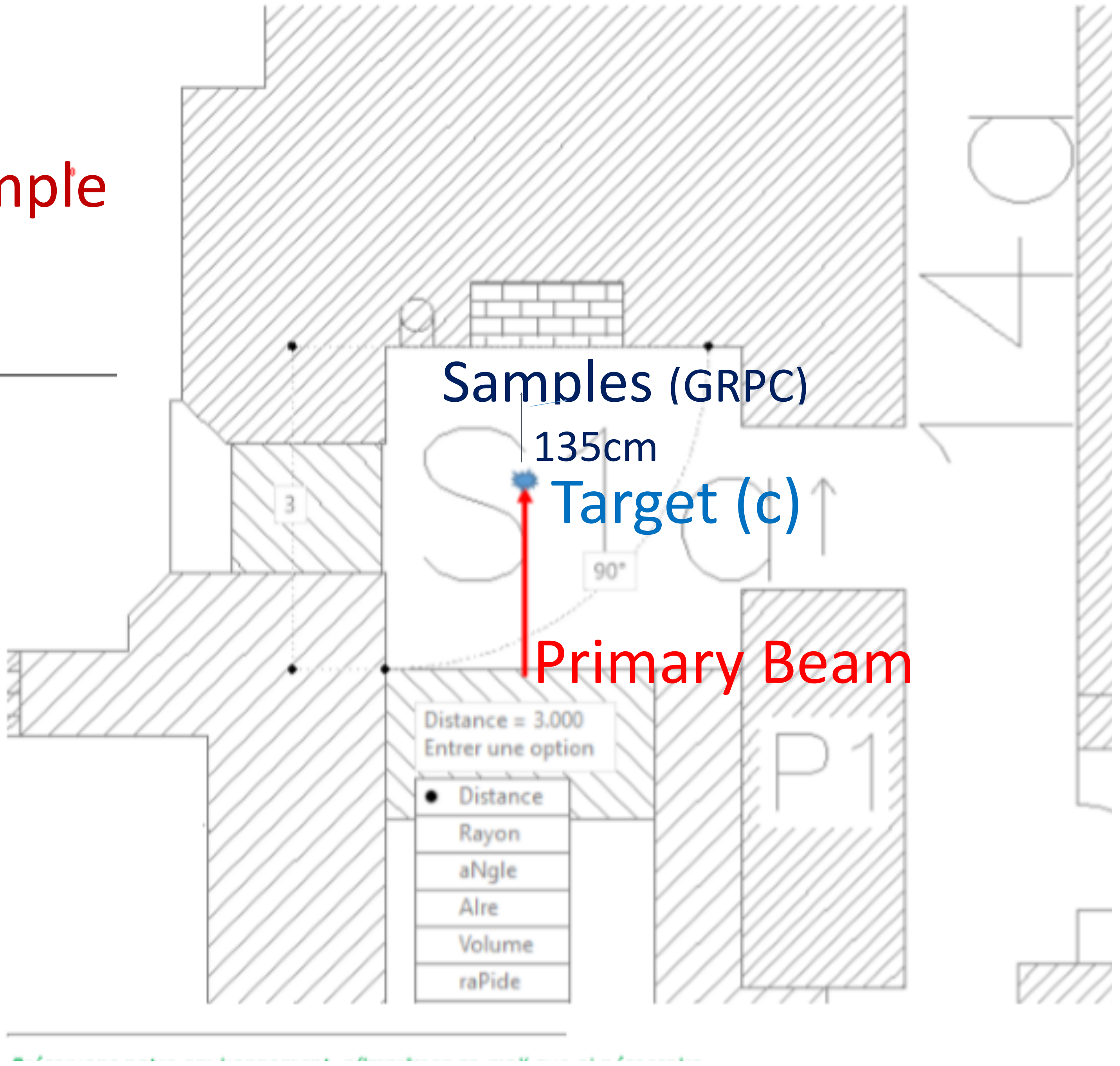
- Impedance bumps within the return lines and VIAs:

  → Need to remove the VIAs.

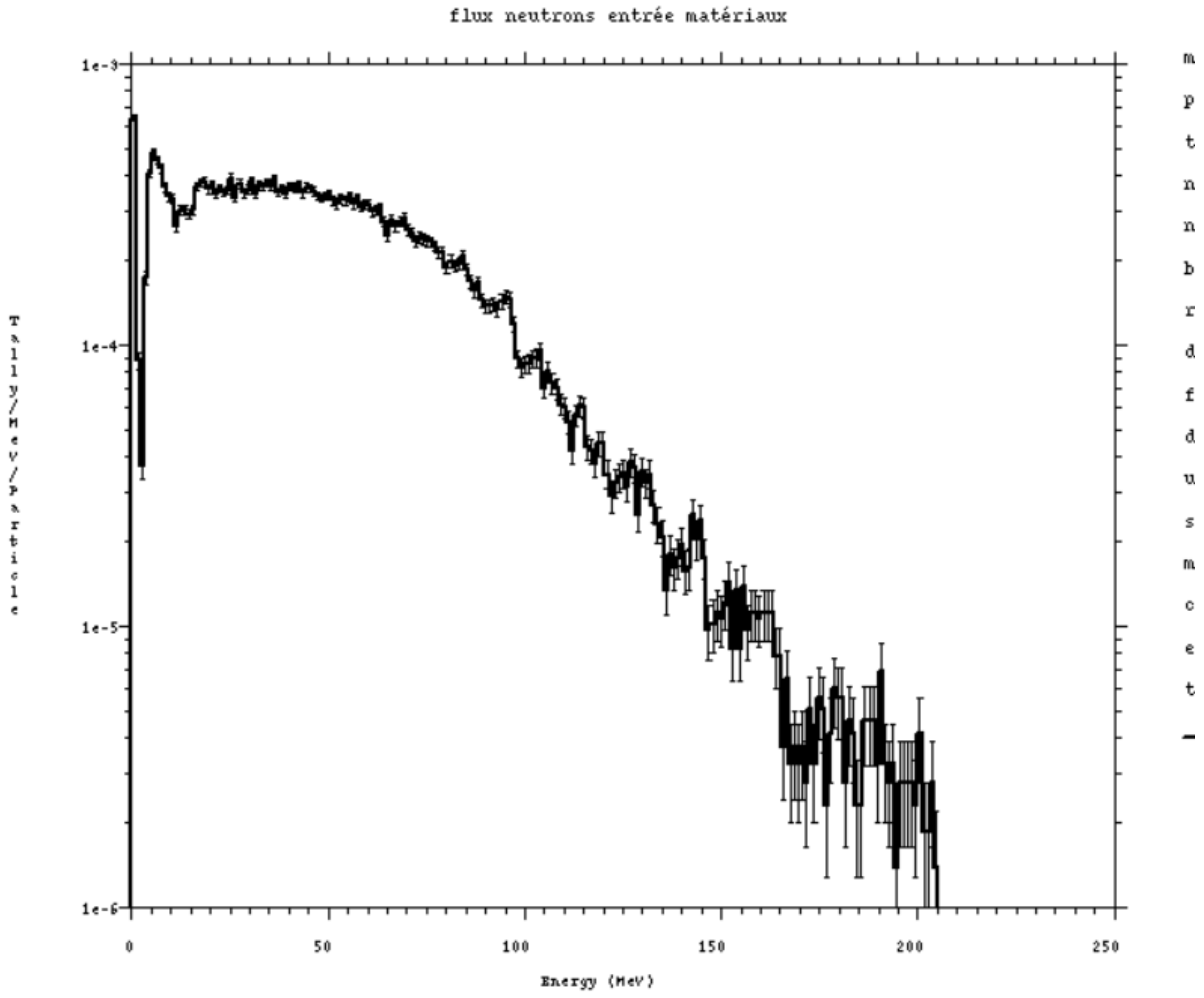
  → Need to add a ground plane on the return lines.

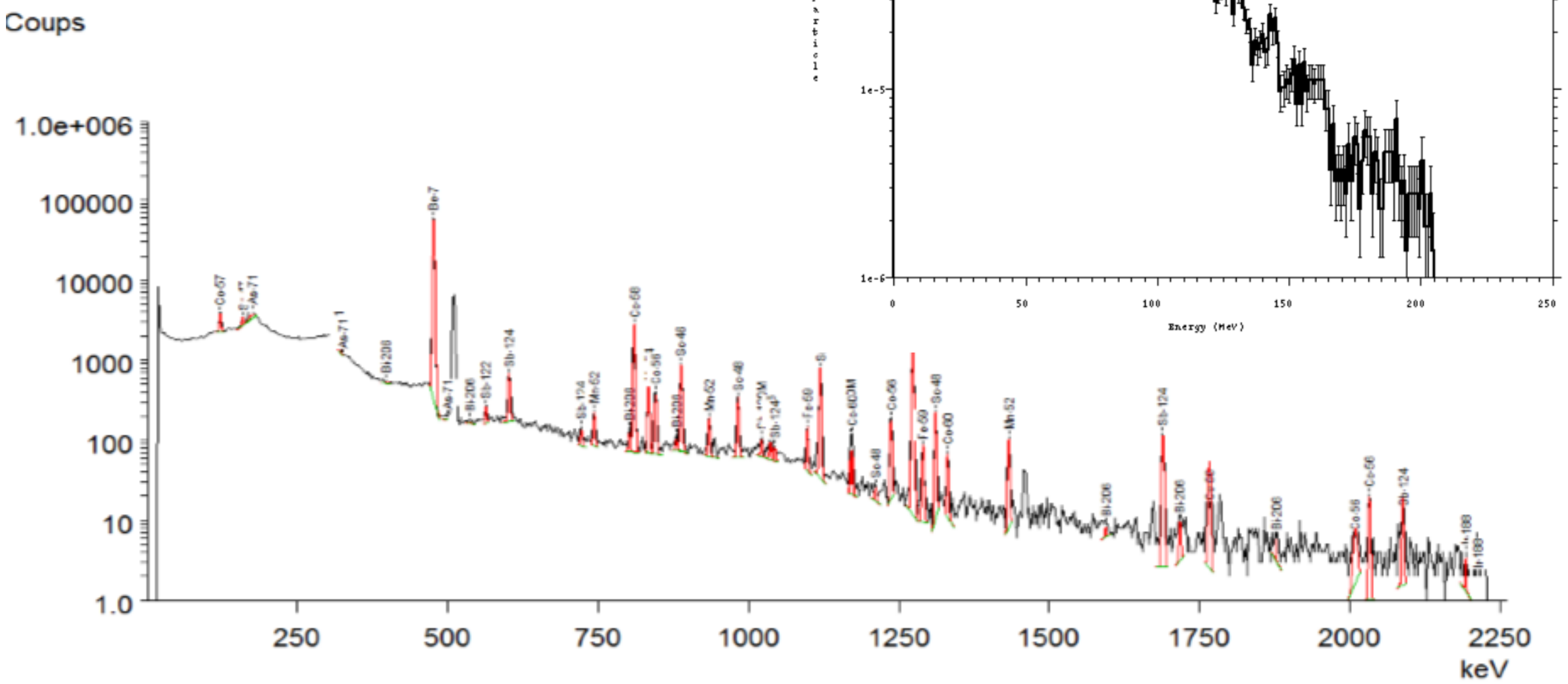






CRV Materials used for building the GRPC tested by JC Angélique at Ganil





Rate COMET Phase I :

Mars /Icedust : 8,64 10^{10} / 8 10^{9} neutrons

Beam	I(μA)	Total dose (μSv)	Total flux (n/cm2) in sample
$^{16}O^{8+}$	10	1.24 10^{14}	6.21 10^{13}
$^{40}Ca^{20+}$	4	10^{14}	5.02 10^{13}
$^{36}Ar^{18+}$	2	5.84 10^{14}	2.92 10^{13}

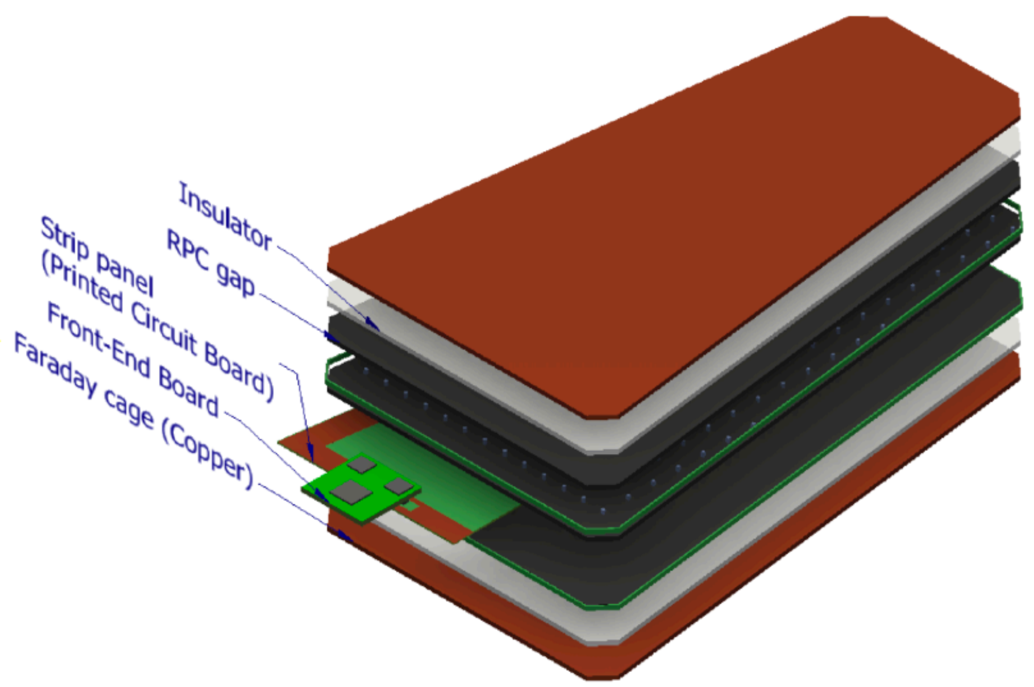
Proposal submitted in July 2023 to COMET, with caveats:

- the expected counting rate is consistent with the iRPCs
- we pre-validate the system in a pulsed testbeam configuration
- the CMS/Korean group agree to build the gaps
- financial support is secured from France and Japan

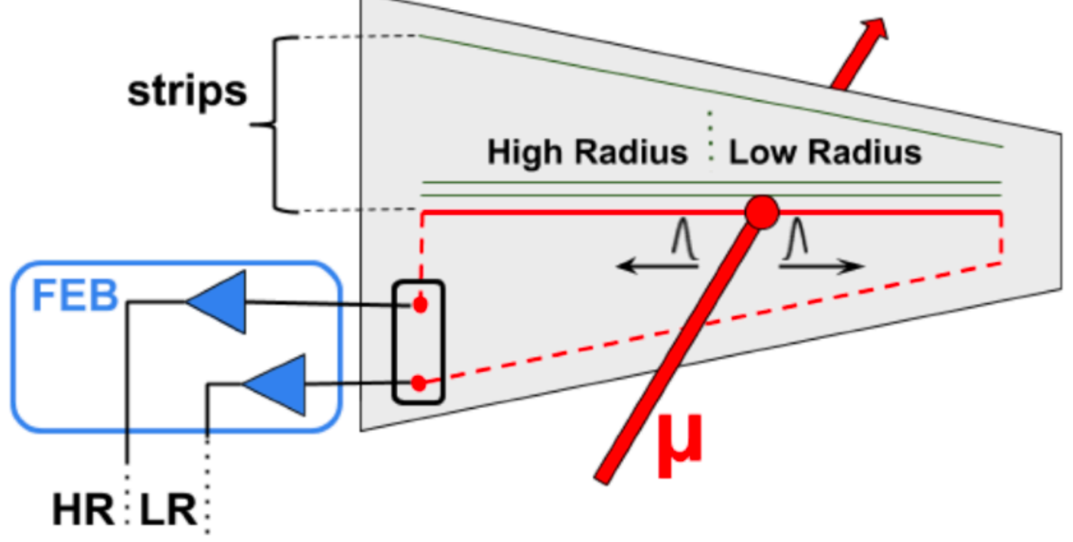
The RPC integration / qualification is expected to be done @Jparc (M. Gouzevitch, C Carloganu, Postdoc)

Additional technical support needed :

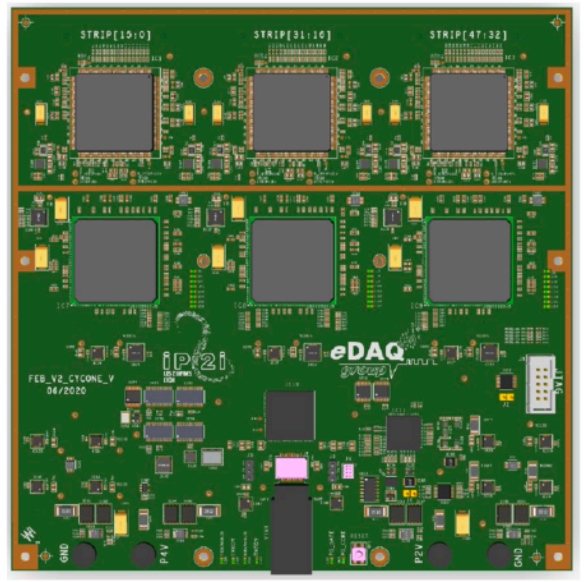
- IR mechanics for detector integration
- IR electronics to interface the CMS FEB with COMET DAQ, Trigger, SC

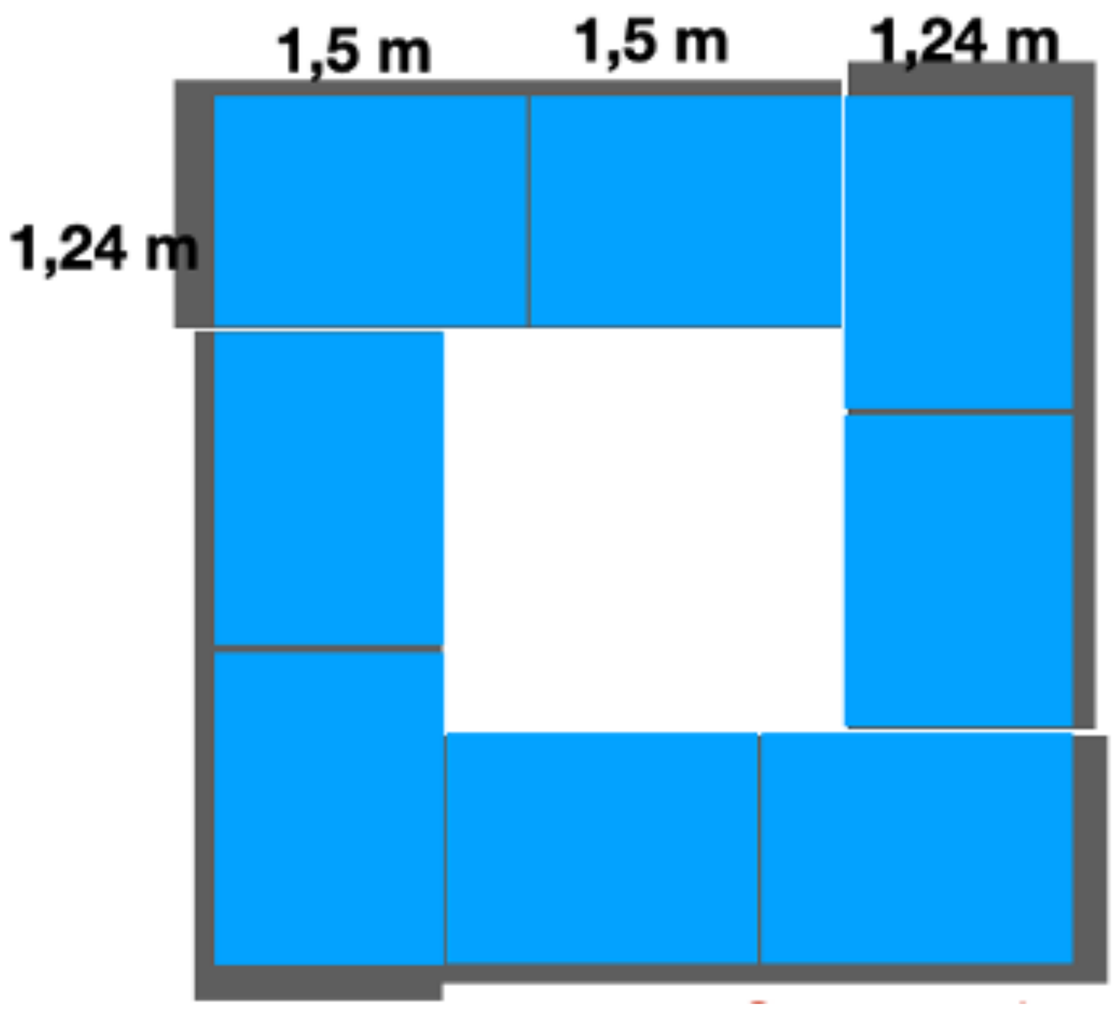


$$Y = \frac{L}{2} - \frac{v * (t_2 - t_1)}{2}$$



- Connected to both ends of a PCB strip through an internal return line (inside PCB): 2D signal readout
- PETIROC ASIC: preamplifier + discriminator (custom OMEGA).
- Time measurement with a TDC FPGA on board.
- FEB → Optical fiber → BackEnd

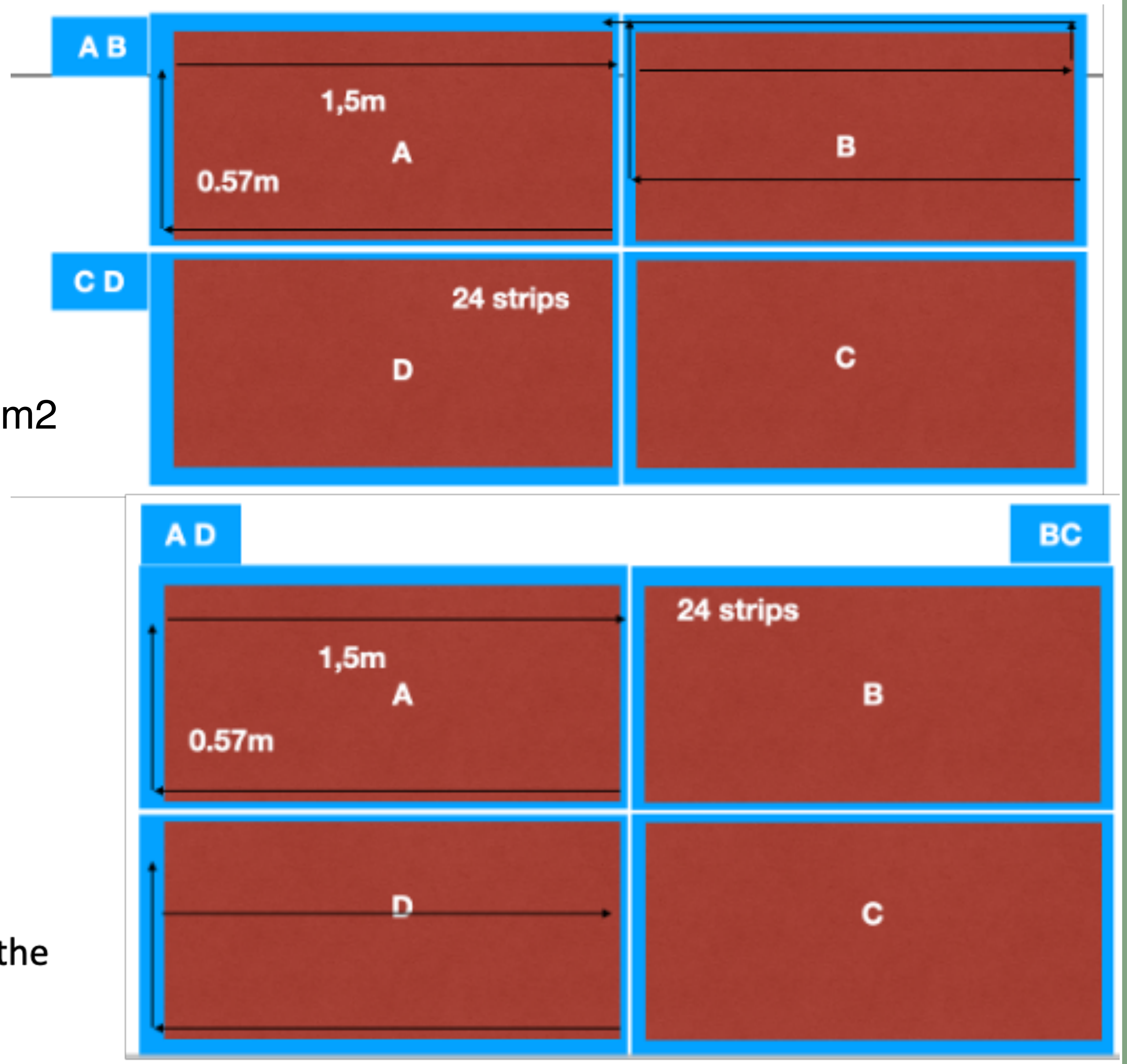




- 1 module = twin RPC bakelite, 1,24 x 1,5m2
- 2 modules sharing the same mechanical structure in honeycomb
- 8 modules /layer; 5 layers
- 1 ns timing resolution

Readout:

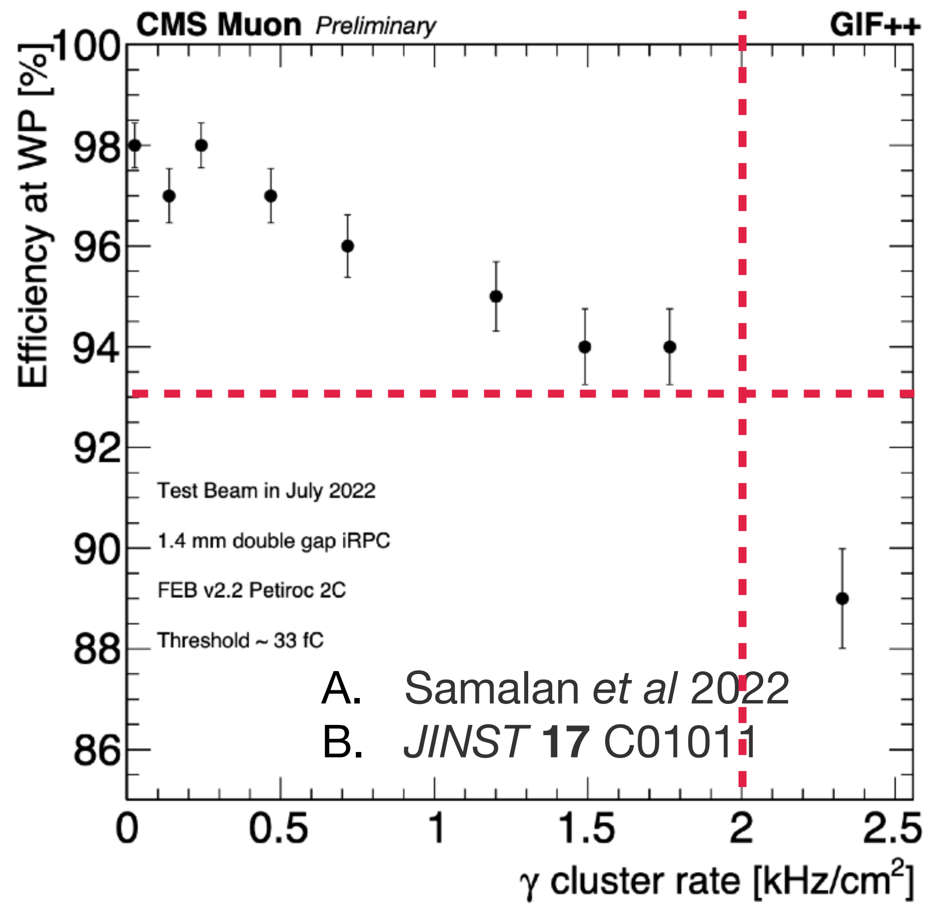
- two 0.57 x 1.5 m PCBs connected by flexes + a deported FEB
- 2.6 cm pitch with both side readout
- 1 FEB/module, physically situated on the sides.



French Contributions :: Radiation on Upstream CRV

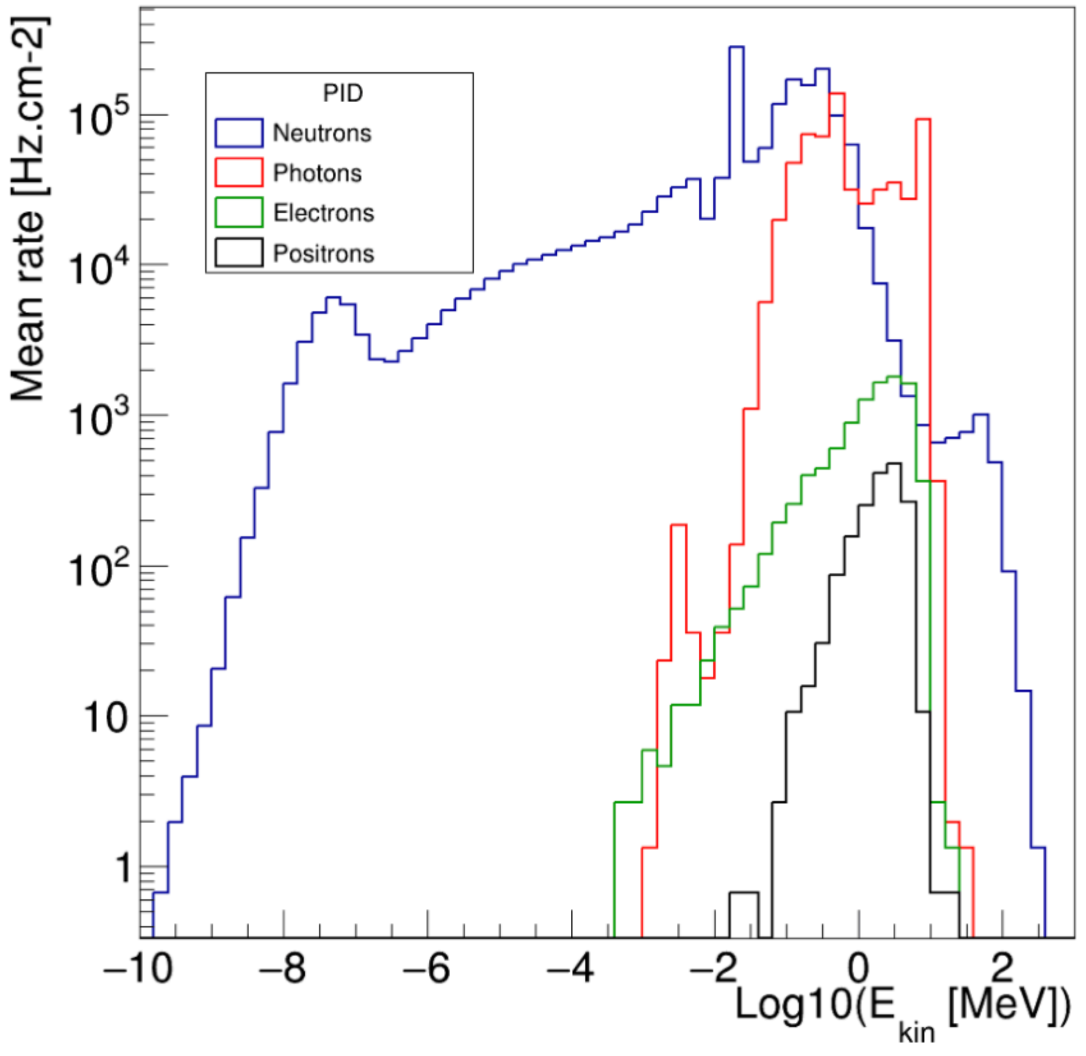
Fluence over full operation → integrity of the detectors

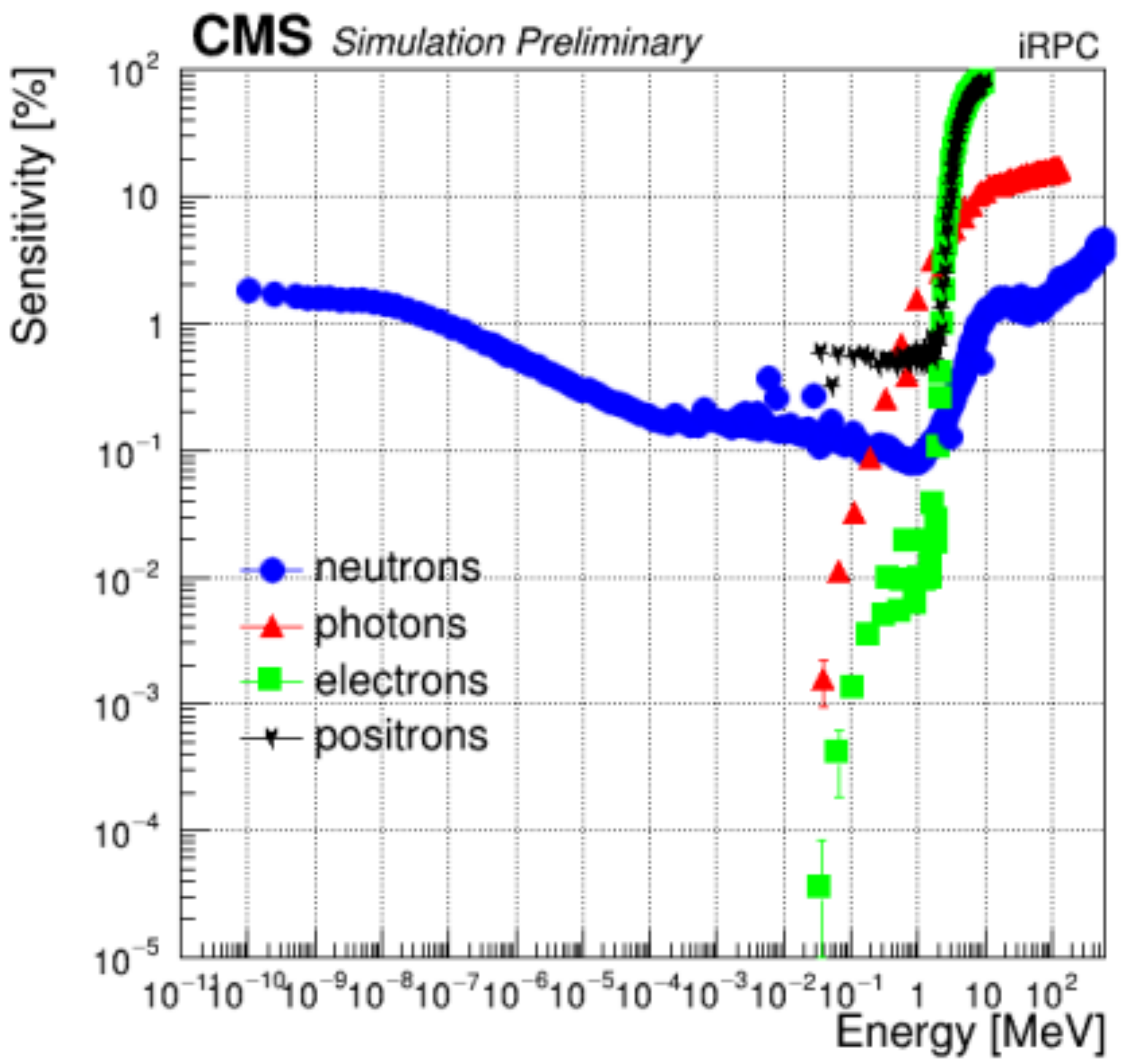
Instantaneous flux during operation → Rate of hits
→ significant loss of efficiency above 1.5 kHz/cm²
→ fake vetoes → dead time for COMET

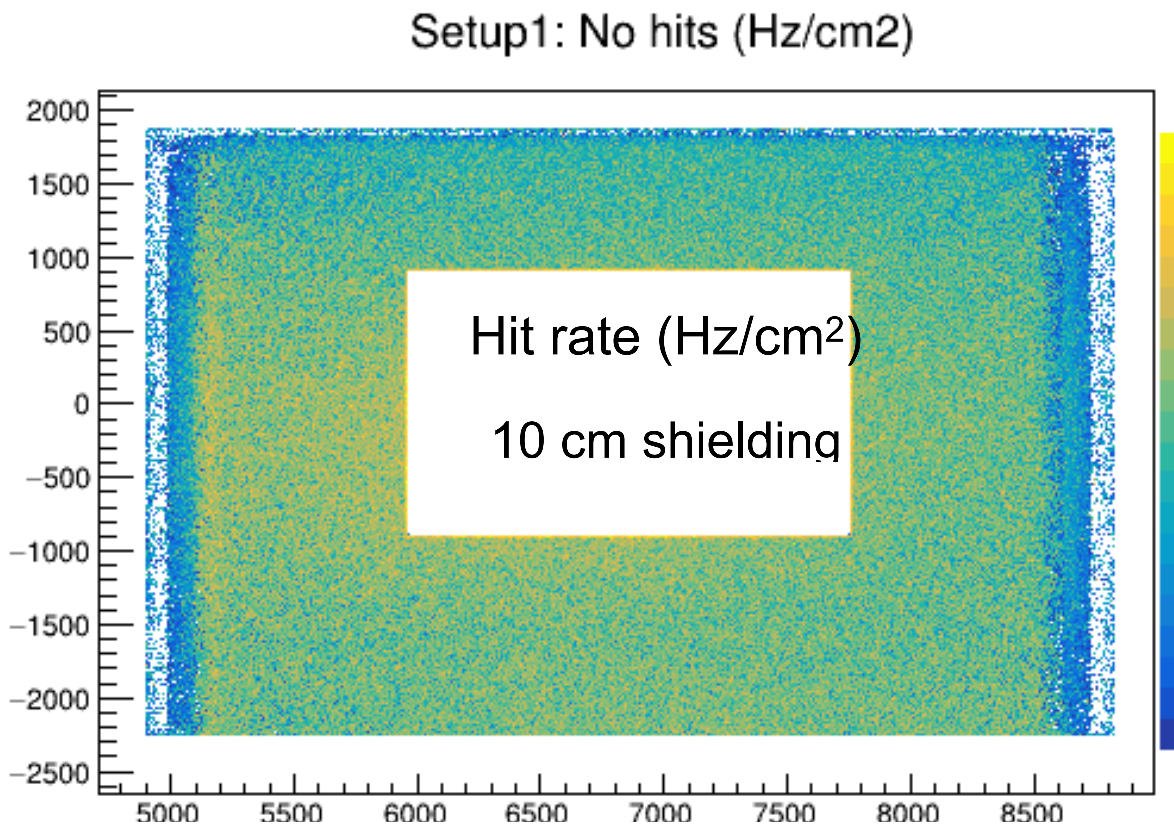


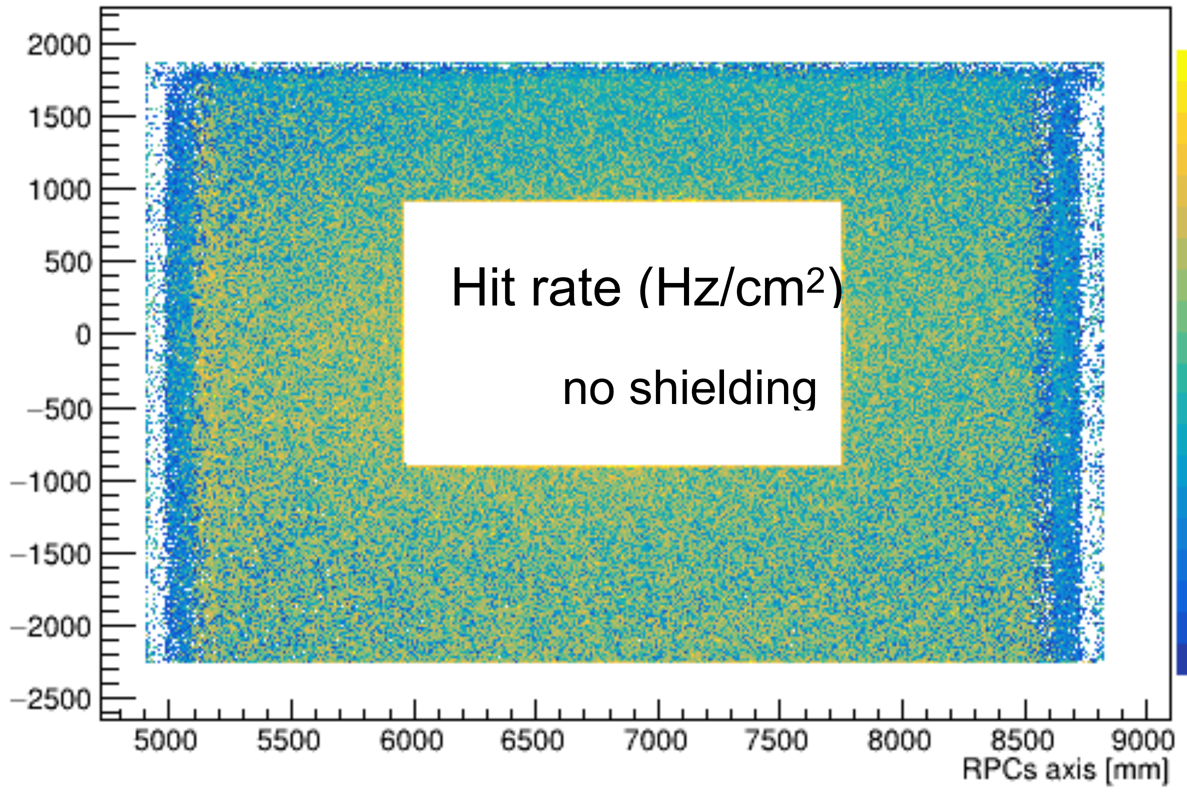
3 chambers in coincidence out of 5

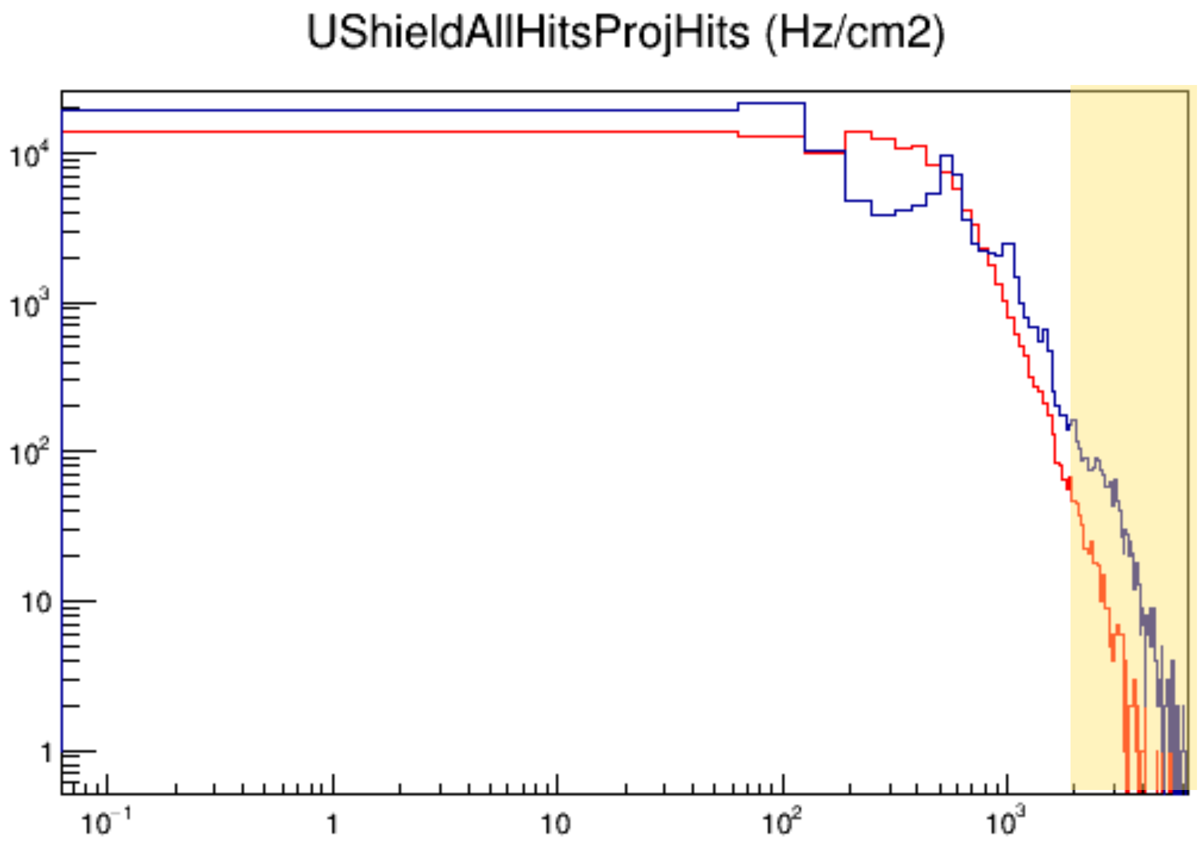
eff chamber	93	95	98
ineff CRV	$3.1\ 10^{-3}$	$1.2\ 10^{-3}$	10^{-4}



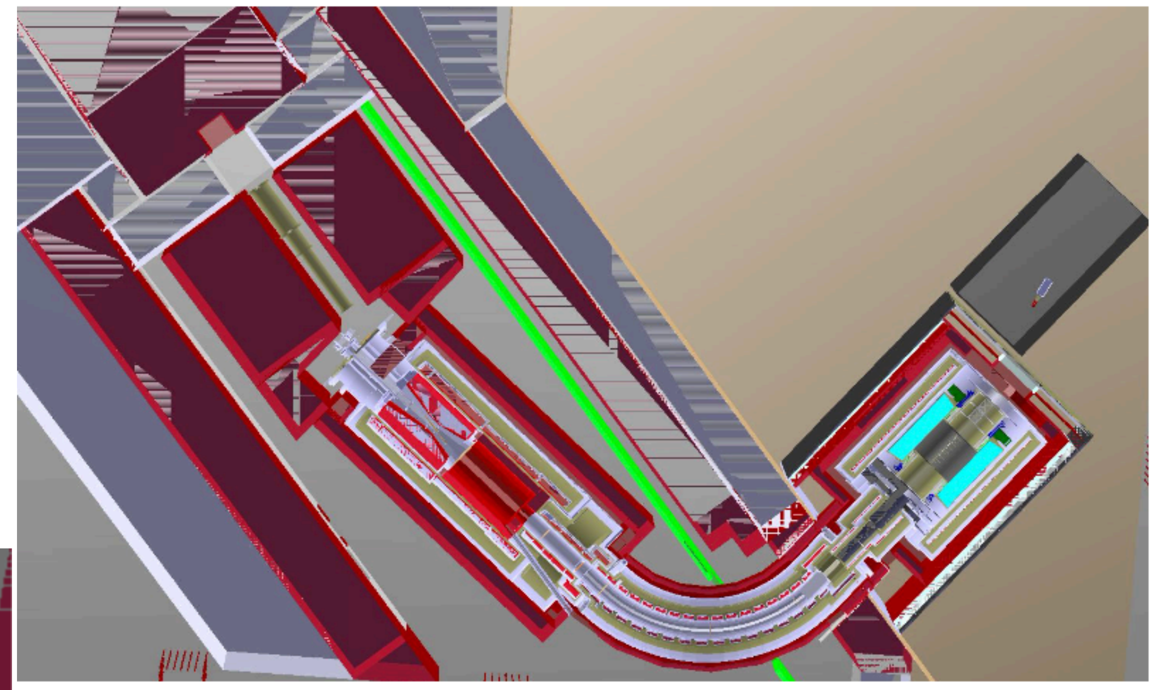


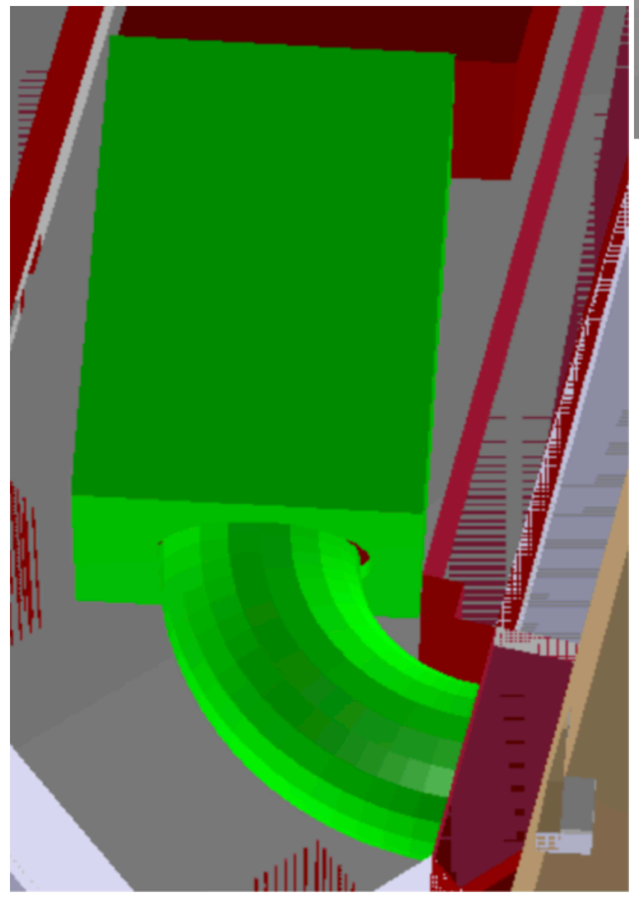






Testing shielding no 1: 3.5 cm
$Mg(BH_4)_2$ after the BS

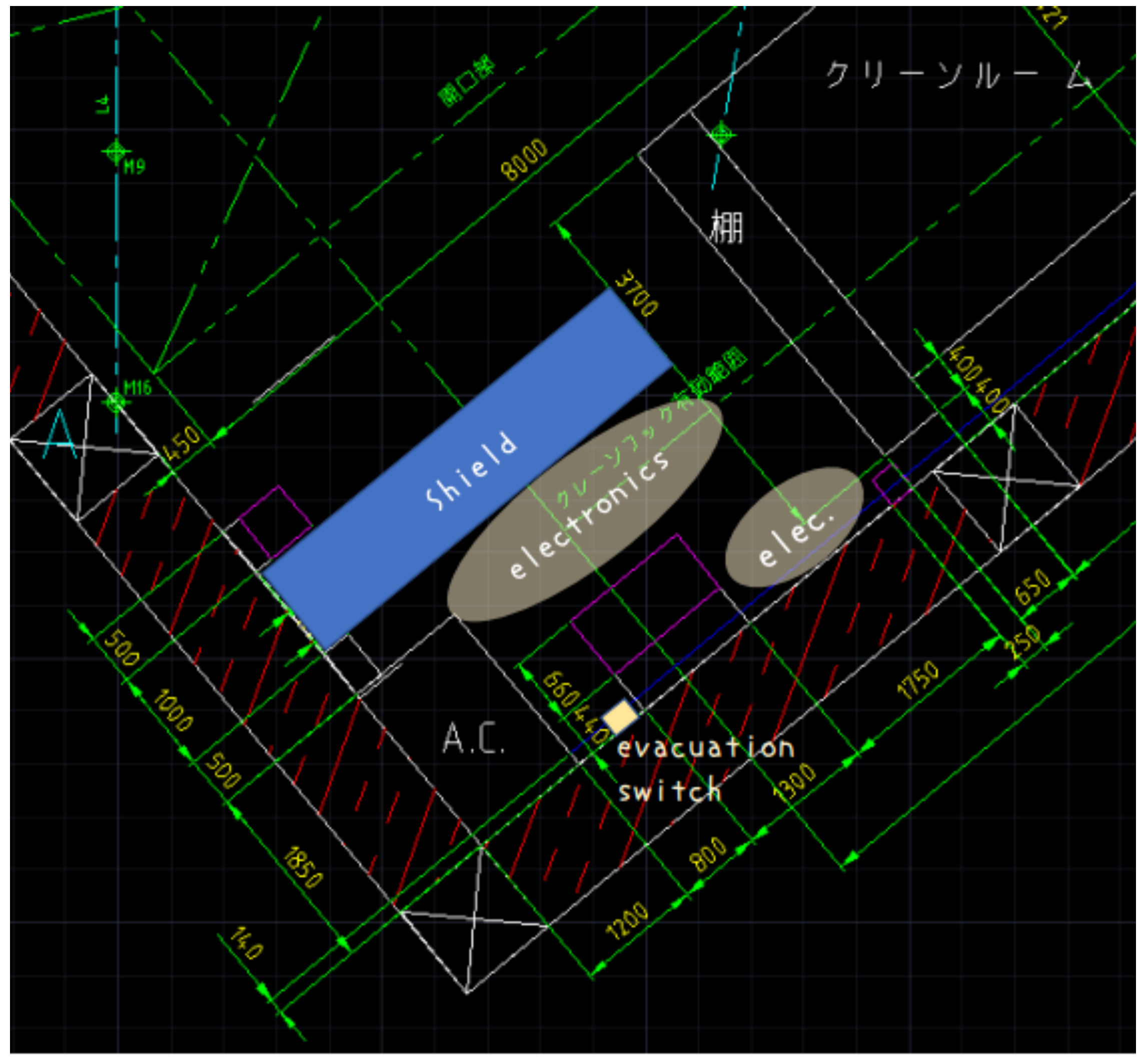


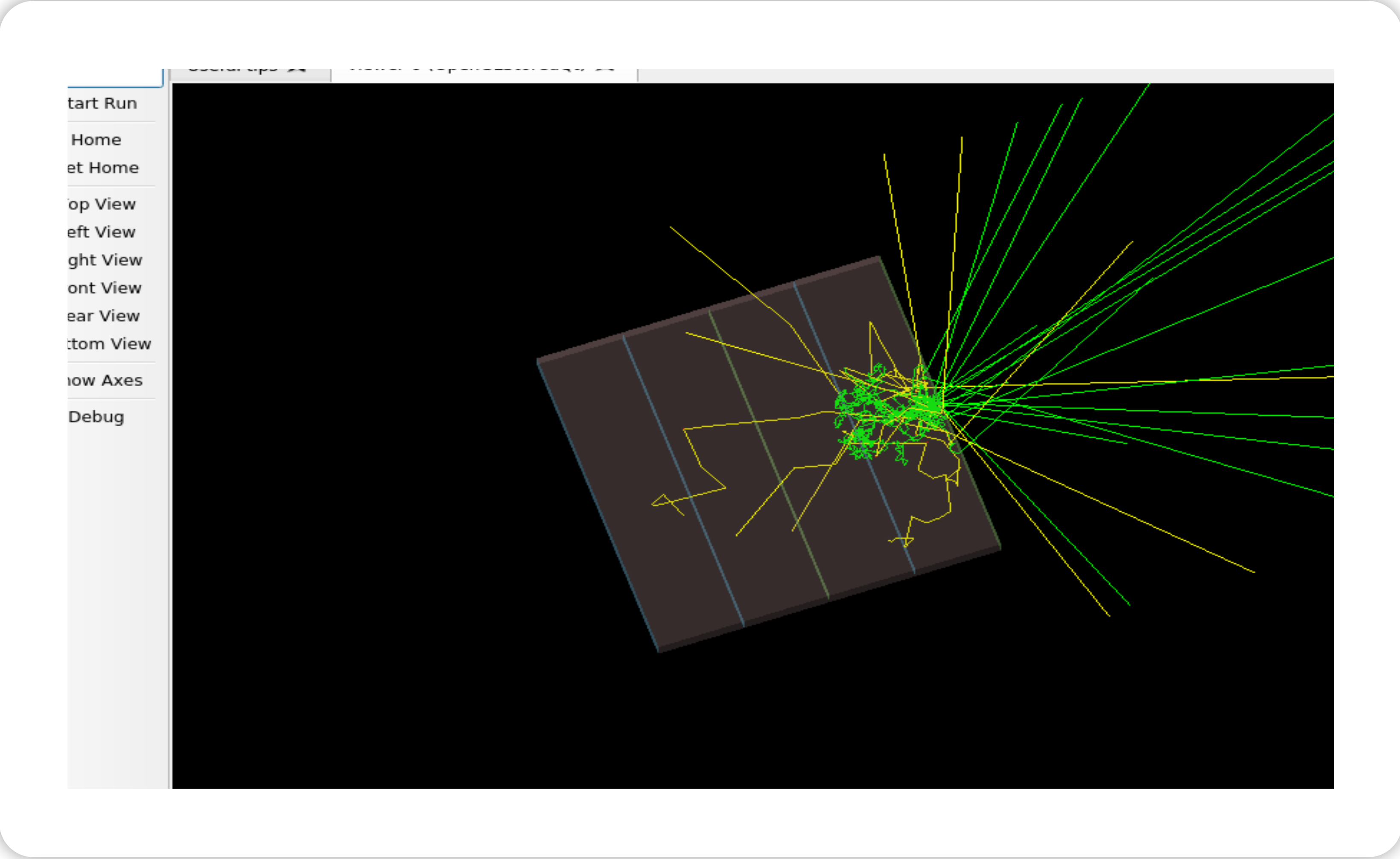


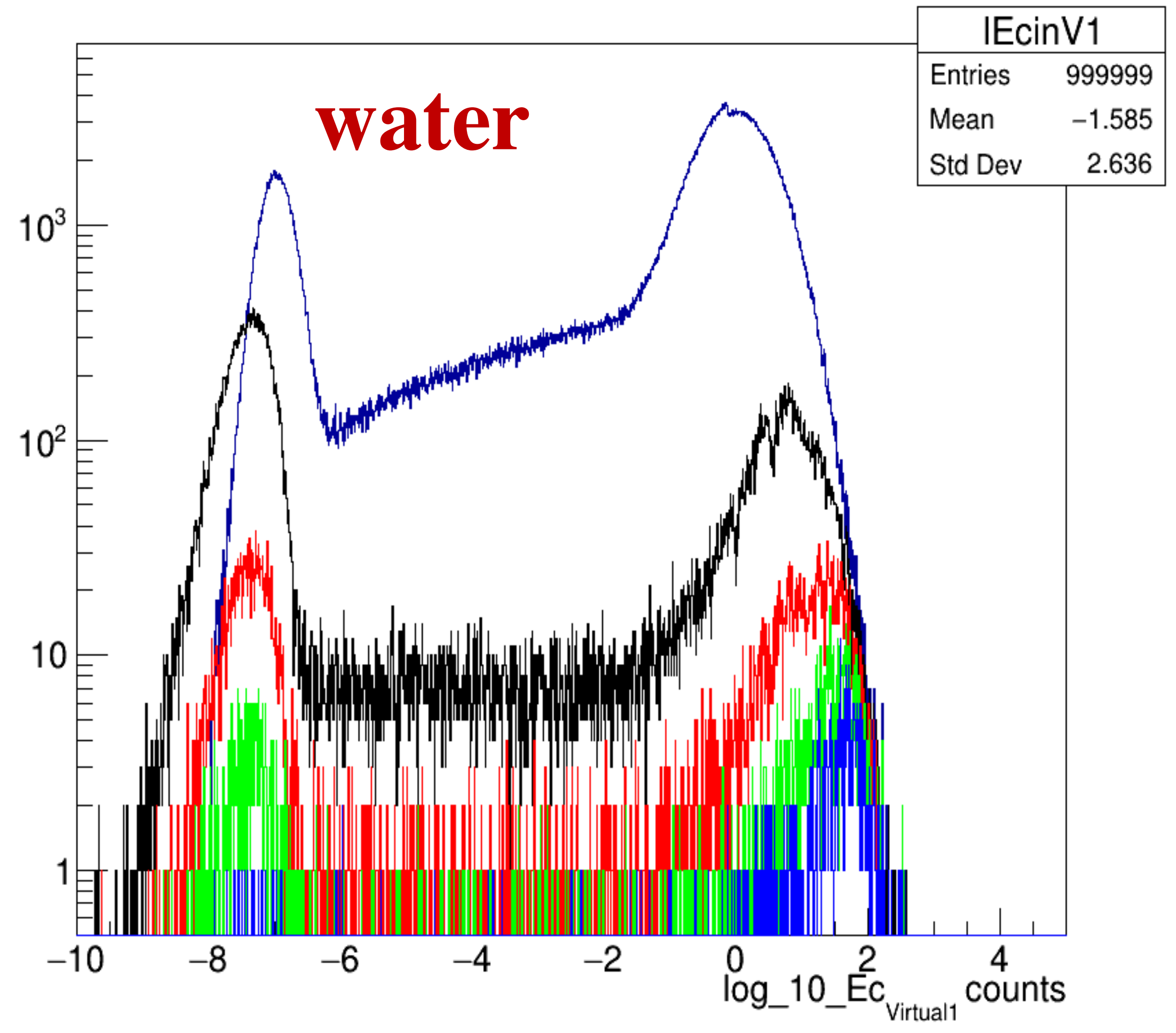
French Contributions :: Radiation Studies Working group

JC Angélique (LPC Caen)
JL Gabriel (LPC Caen)
K Ueno (Osaka U)
Y. Fukao (KEK) *et al*

Simulations with PHITs, ICEDUST, FLUKA , MCNPX, MARS





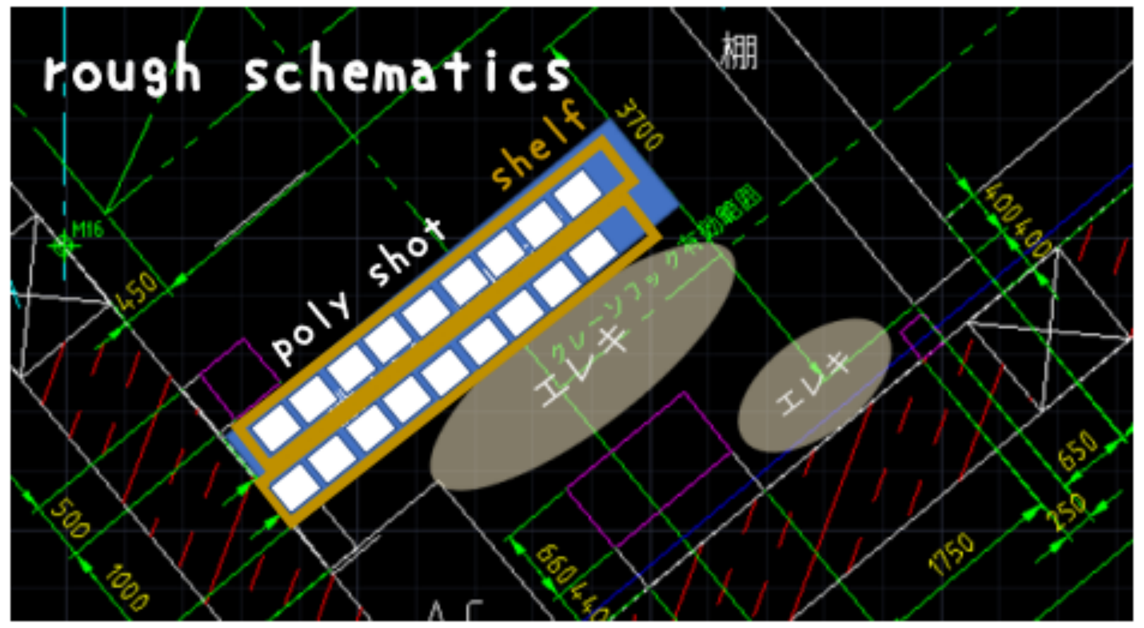


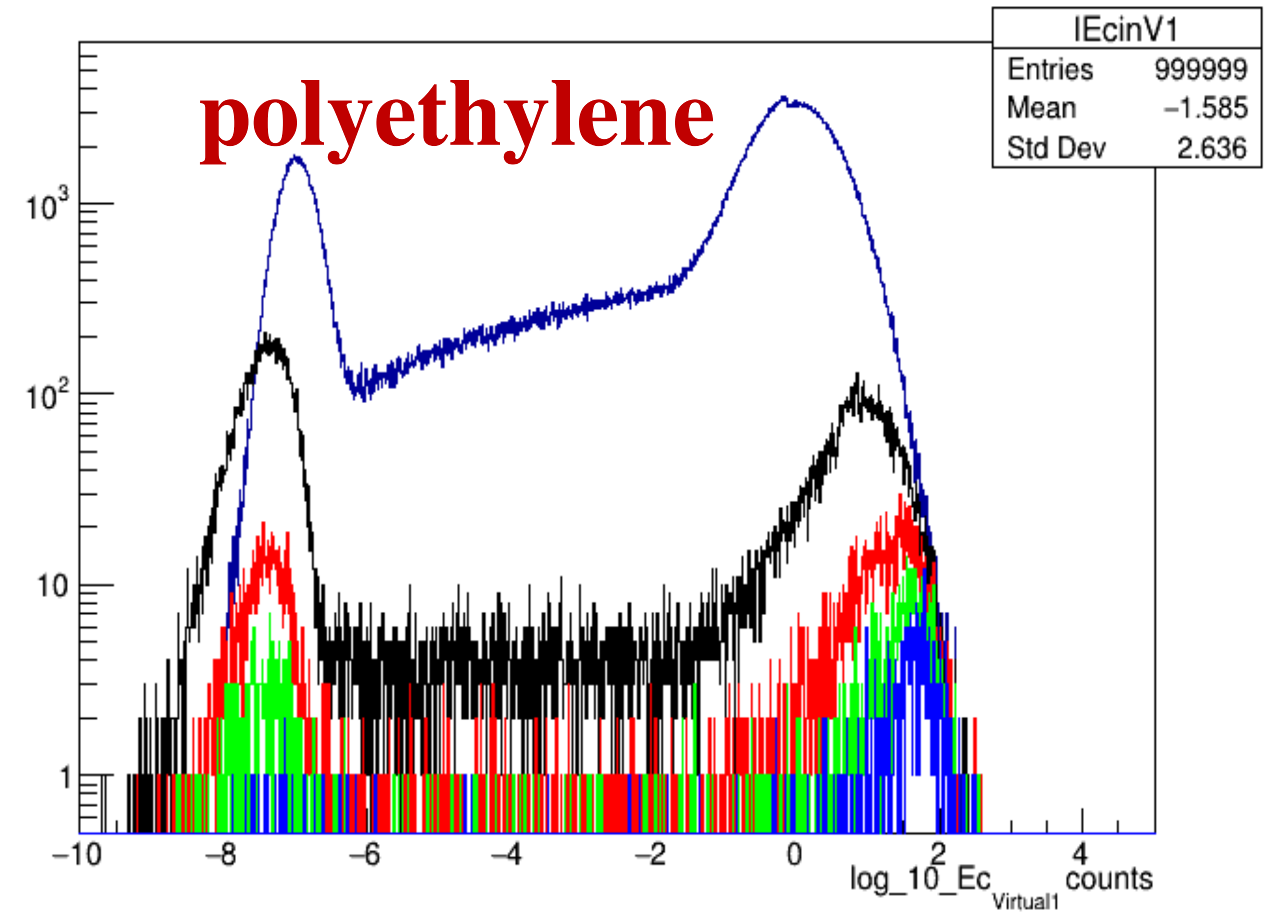
Rough design of shield

Shelf + shield material

from KOTO

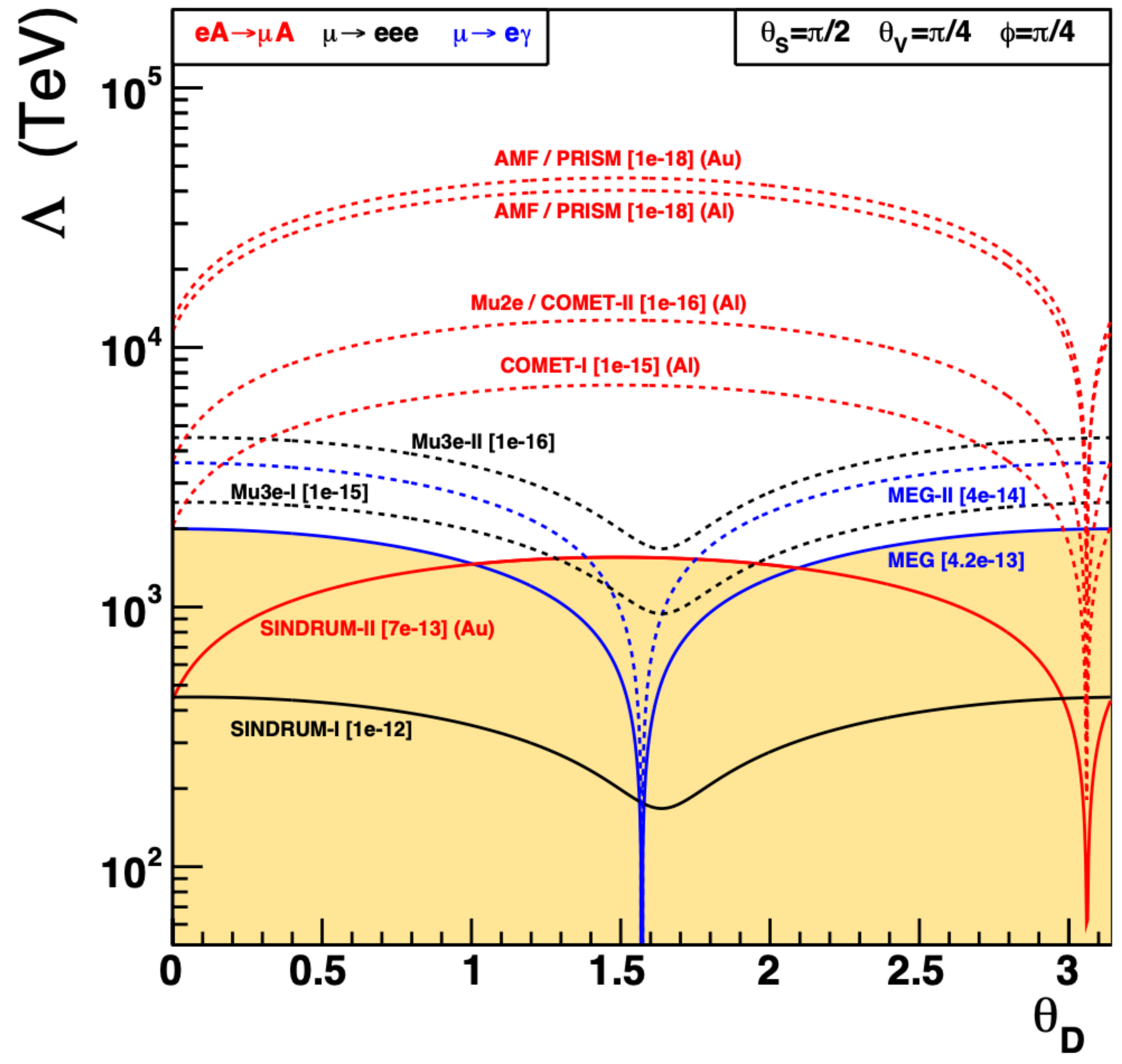
Poly shot(?)
(granulated polyethylene

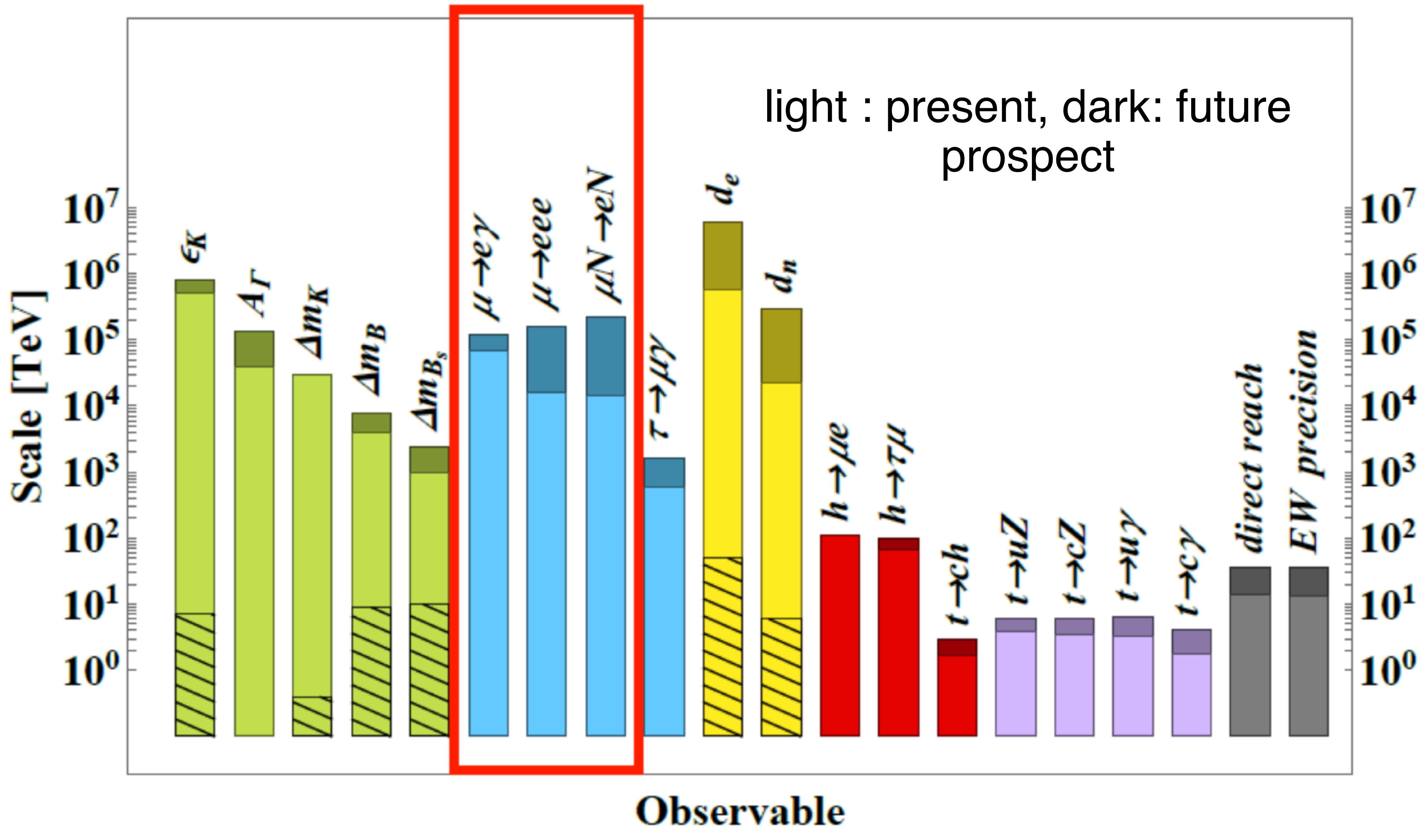




Conclusion

- COMET is a fixed target experiment → the financial cost for the signatories is limited to the subsystems they contribute to the experiment
- High discovery potential, provided that it will have the foreseen luminosity in a timely manner
- COMET Phase I is expected to start data taking by end 2026
- COMET intends to improve by a factor 10^4 the present limit $R_{\mu e} < 7\ 10^{-13}$ in two running phases





European Particle Physics Strategy Update (2019)