NuFact 20|21

The 22nd International Workshop on neutrinos from accelerators

SEPT
6-11, 2021
Cagliari, Italy

Search for Muon to Electron Conversion at J-PARC - COMET Experiment

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8.09.2021

On behalf of COMET collaboration

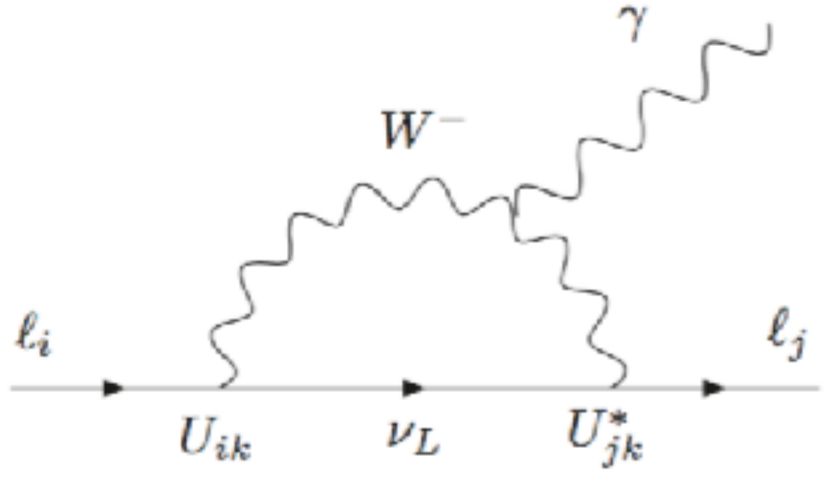
Fermion mixings in the SM

Quark sector:

- Flavour violated by charged current interactions $V_{ij}^{CKM} W^{\pm} \bar{q}_i q_j$
- Observed in oscillation/decay processes $K^0 - \bar{K}^0$, $b \to s\gamma$, $D^+ \to \pi^+ \mu^+ \mu^-$ $(c\bar{d} \to u\bar{d})$

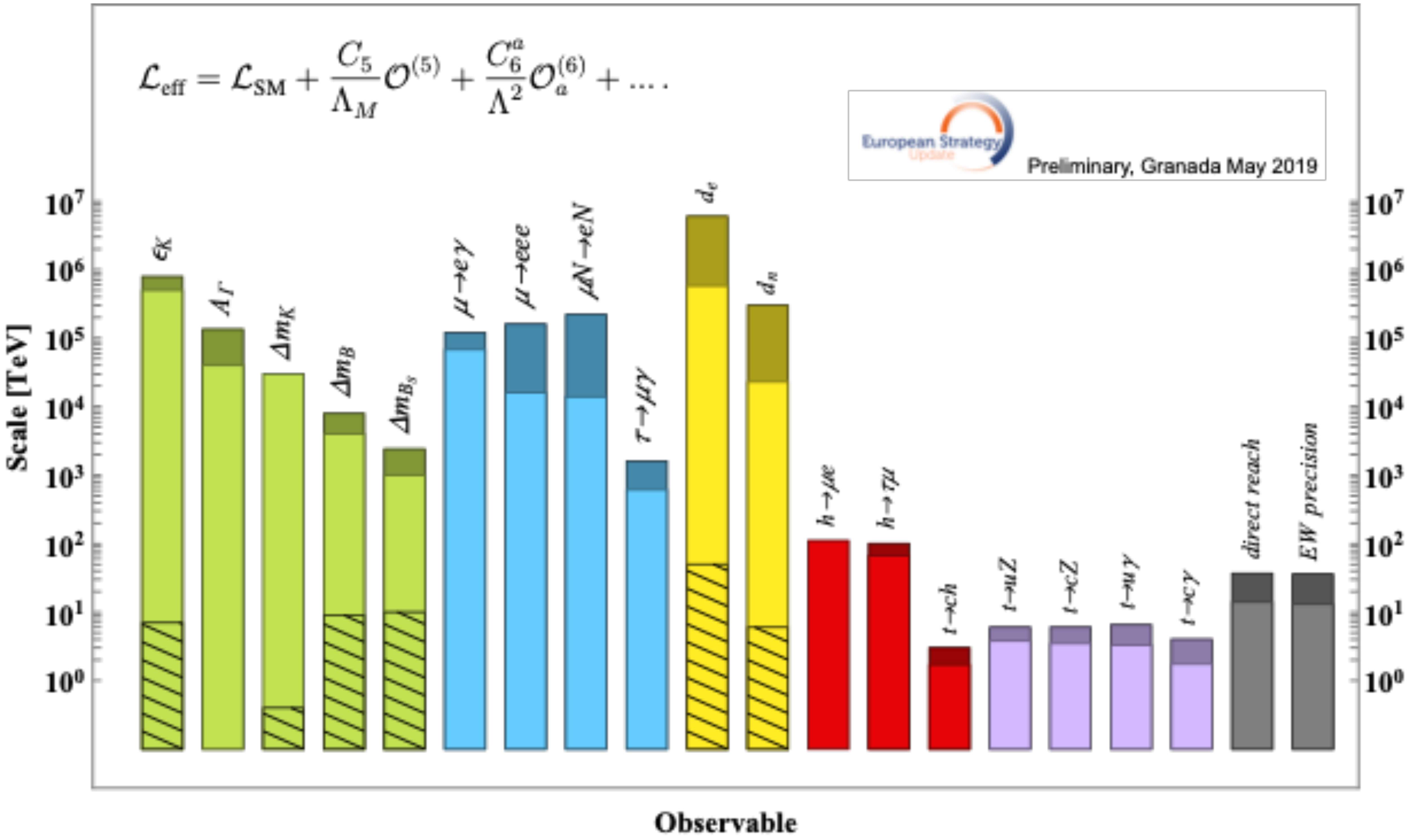
Lepton sector:

- Massive, oscillating neutrinos → flavour violation $U_{PMNS} W^{\pm} \bar{l} \nu$



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

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



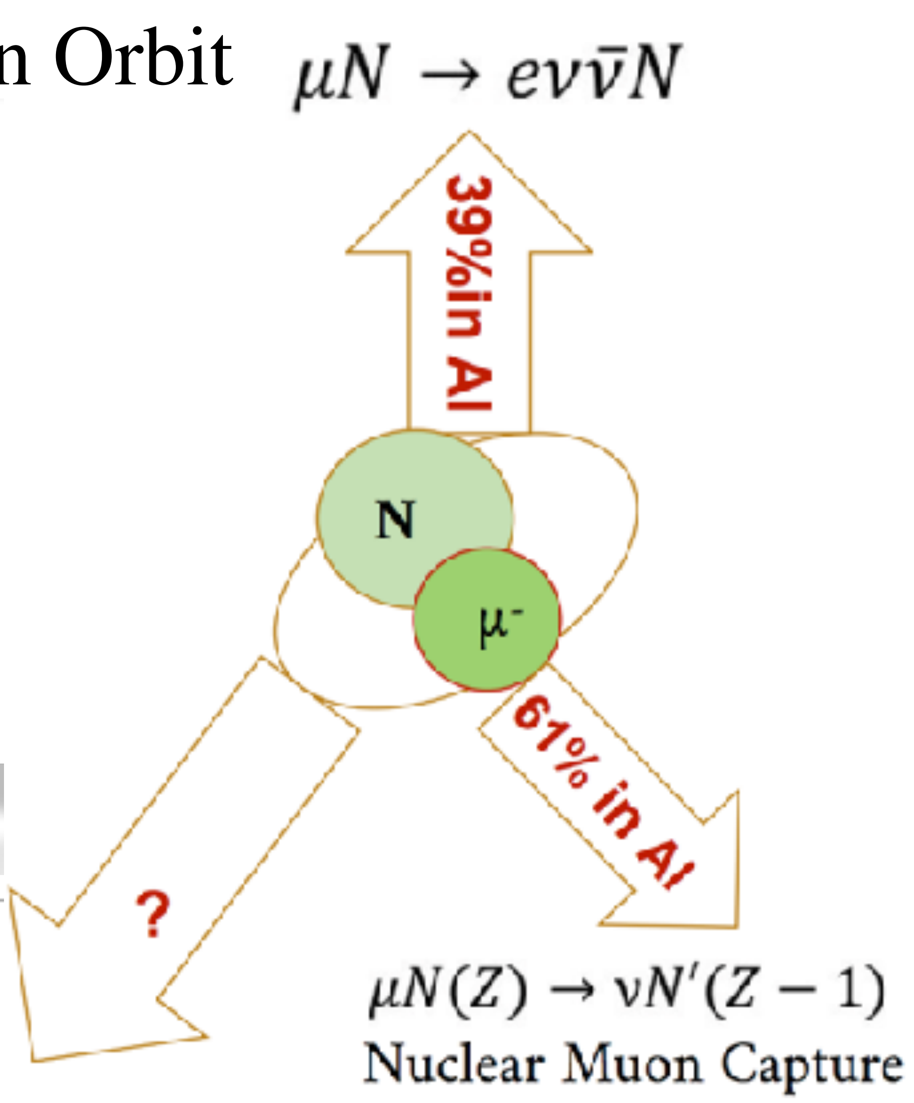
cLFV :: $\mu - e$ conversion in muonic atoms

Muonic atoms

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

+

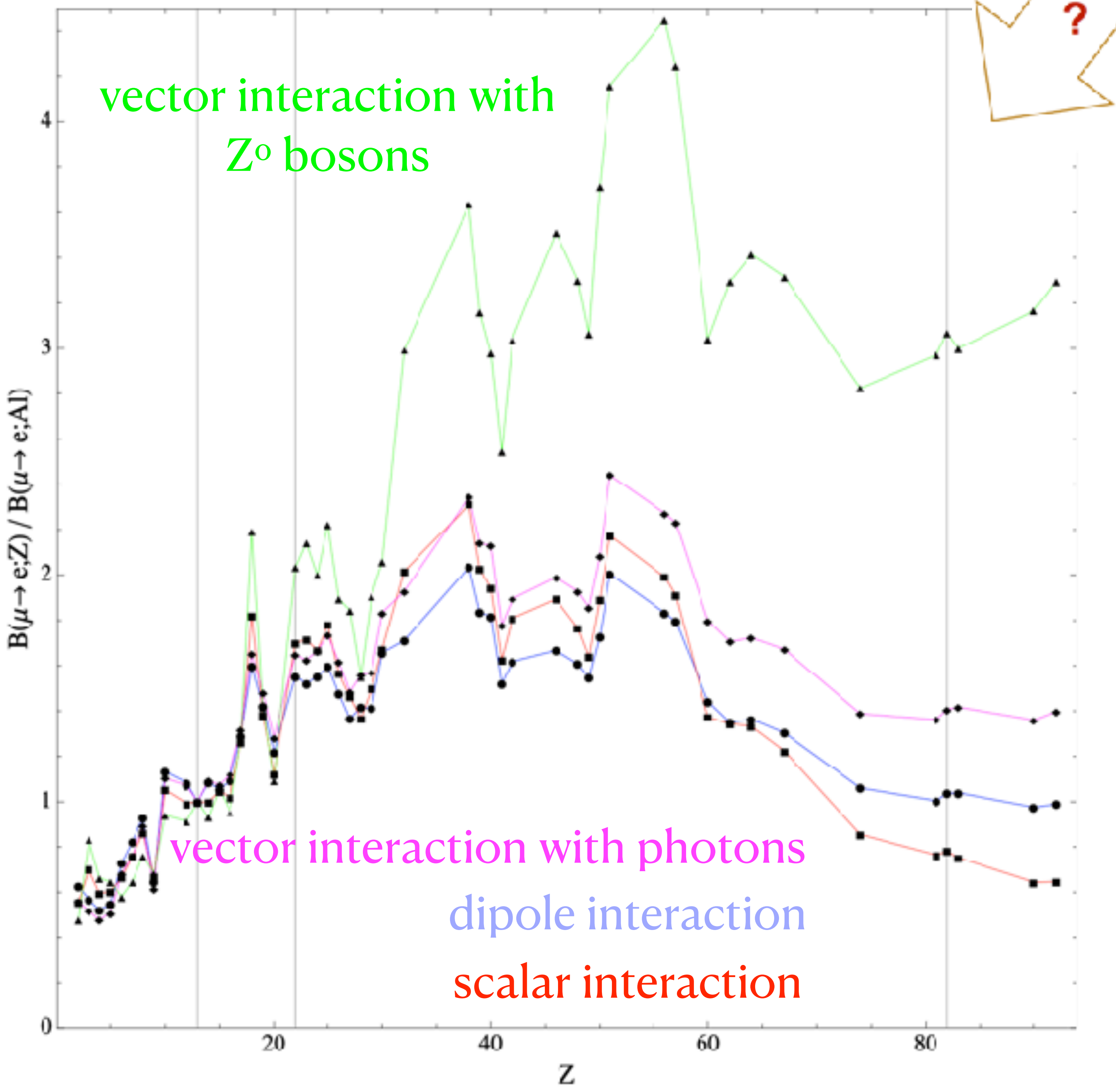
muonic X-Rays



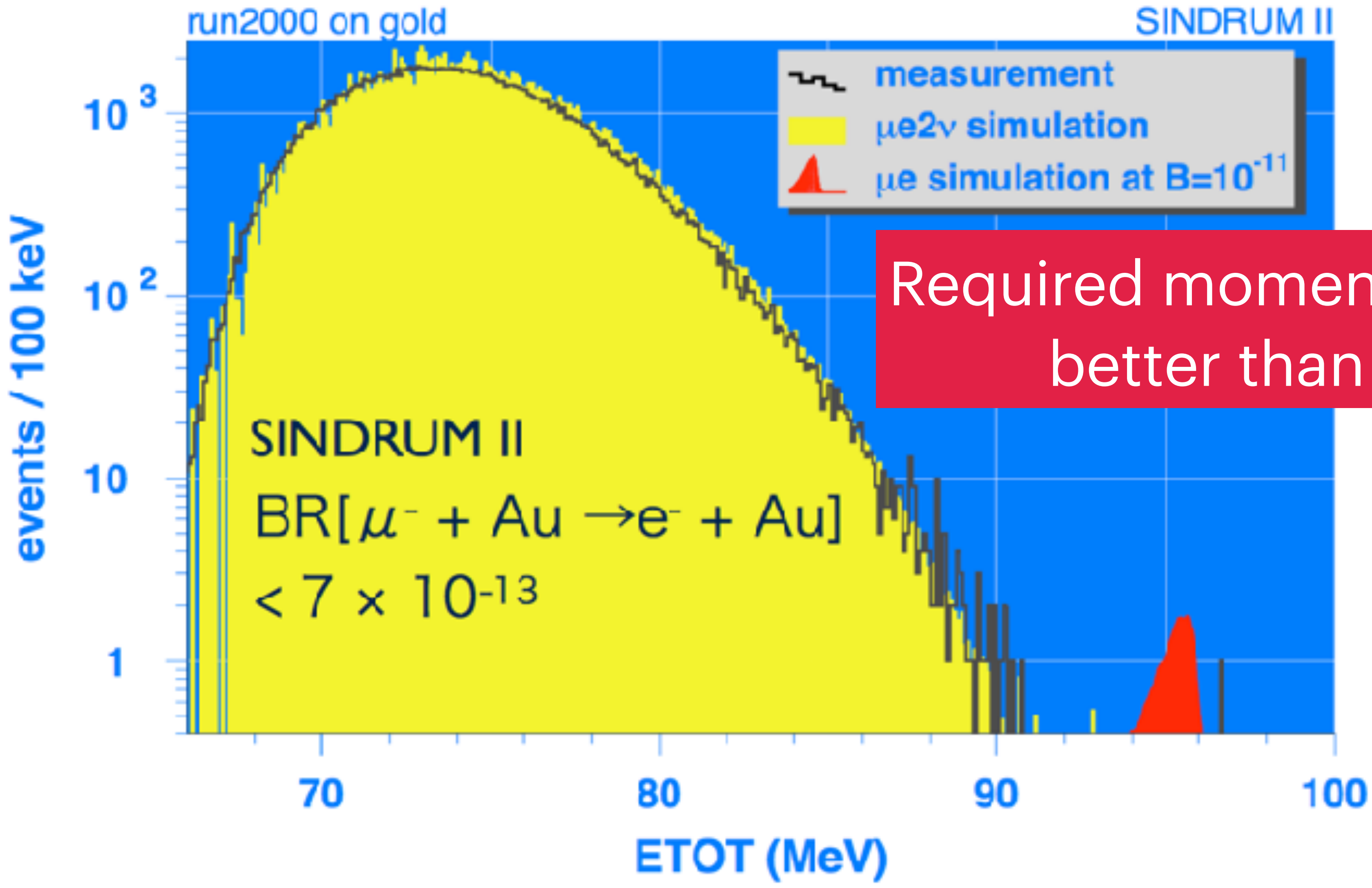
Decay In Orbit $\mu N \to e\nu\bar{\nu}N$

$\mu N(Z) \to \nu N'(Z-1)$
Nuclear Muon Capture

Signal:
coherent process ~Z^5 (maximal for $30 \le Z \le 60$)
a single mono-energetic electron of ~105 MeV at well defined time determined by the lifetime of the muonic atom (864 ns for Al)



V Cirigliano, R Kitano, Y Okada, P Tuzon,
Phys.Rev., D80, 013002 (2009)



Required momentum resolution : better than 200 keV/c

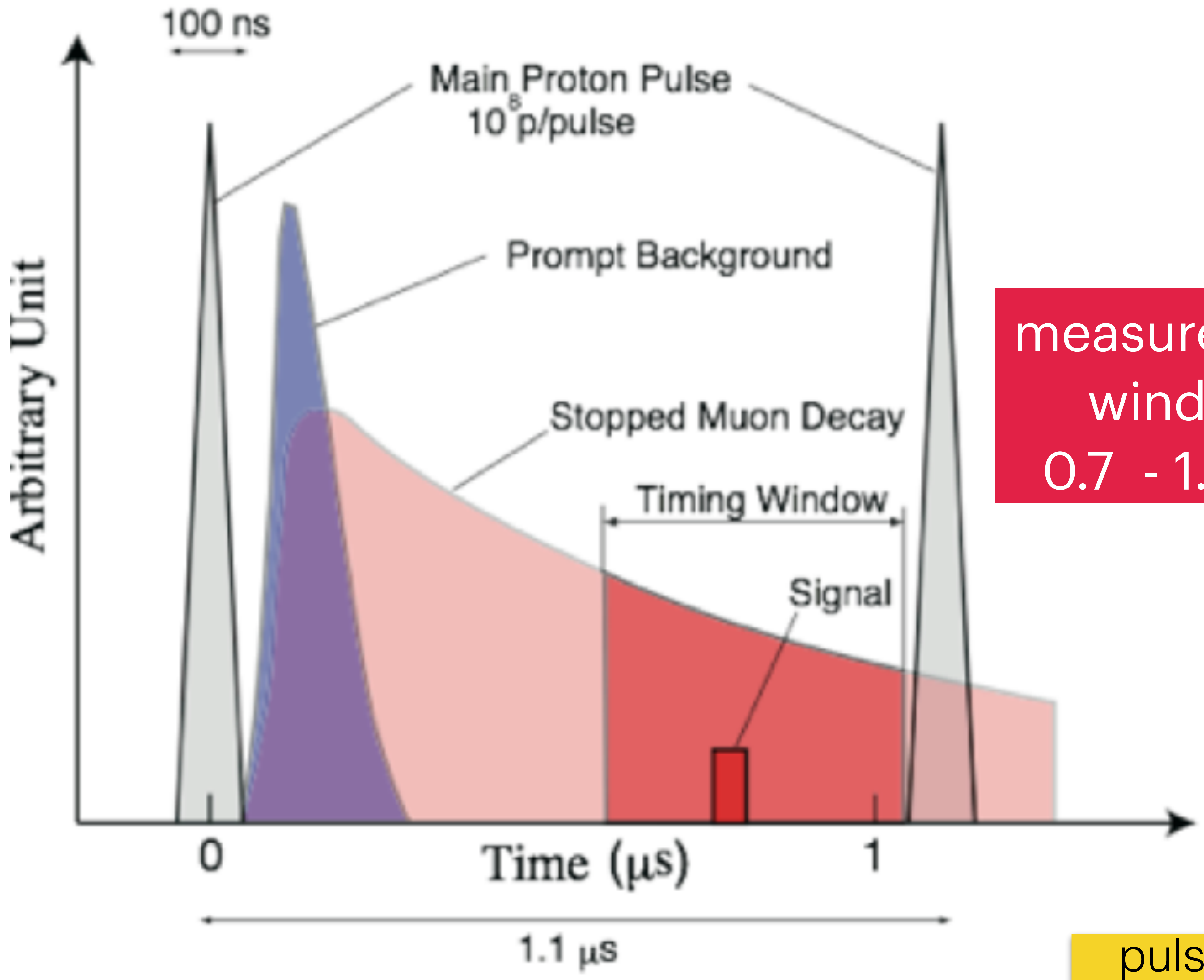
Present limits

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

μ − e conversion in muonic atoms :: COMET strategy

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

$$BR(\mu^- + Al \to e^- + Al) \sim \frac{N(e^-\ candidates) - N(background)}{N(stopping\ muons) \times capture\ probability}$$



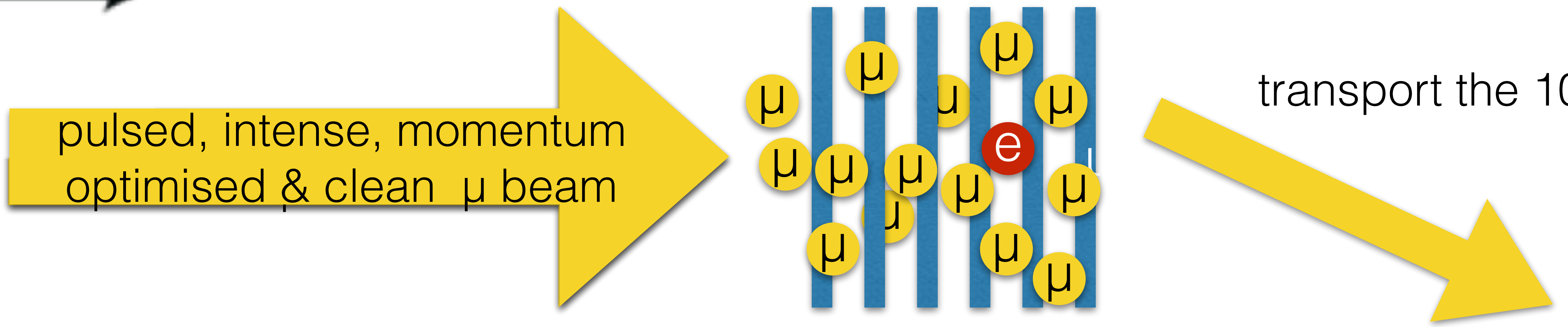
measurement window
0.7 - 1.17 μs

Improve by at least a factor 10000 the present limits :

- increase the muon capture rate
- decrease the (beam induced) backgrounds

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

Al target = good tradeoff between CR and muonic atom lifetime



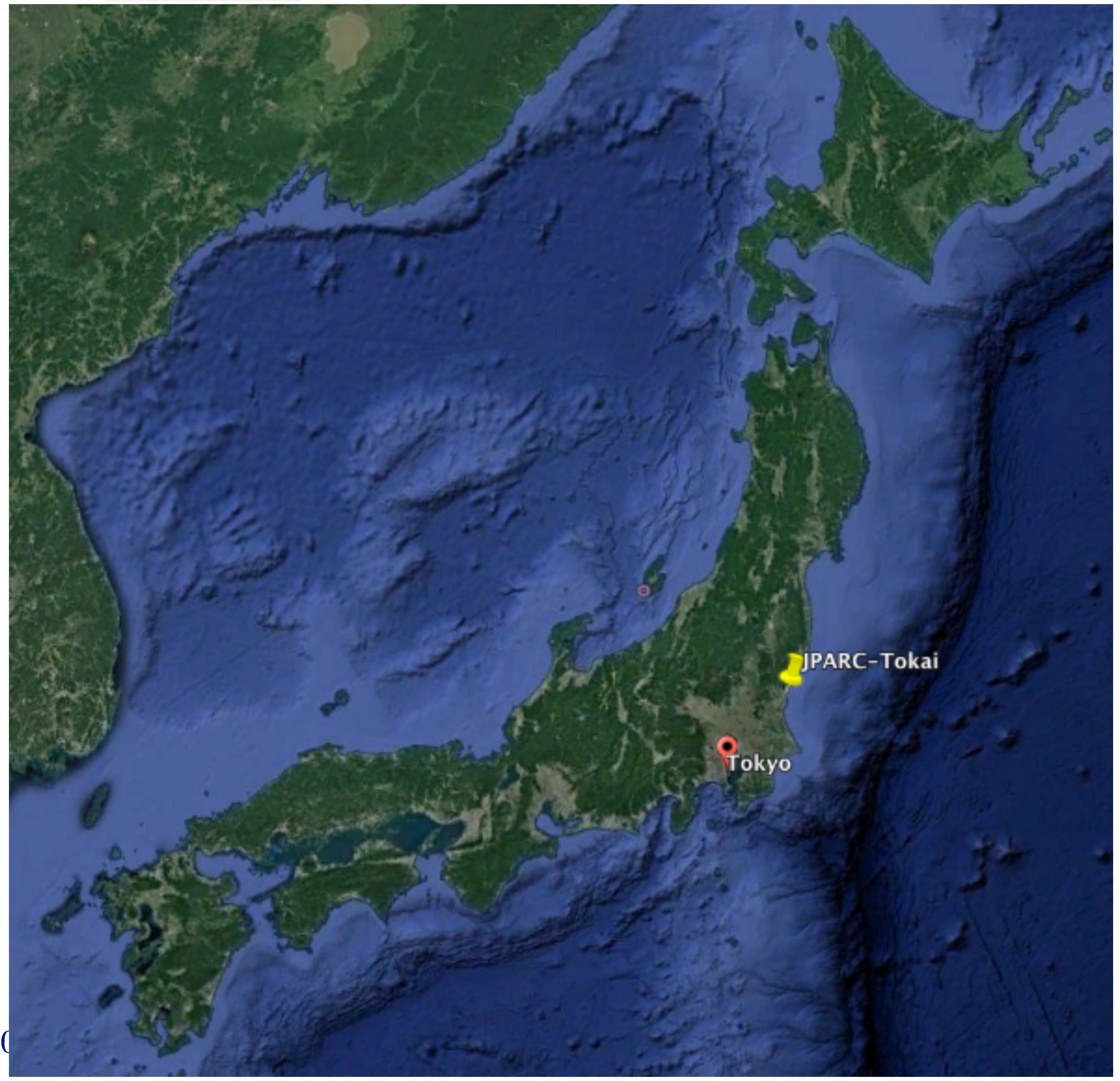
pulsed, intense, momentum optimised & clean μ beam

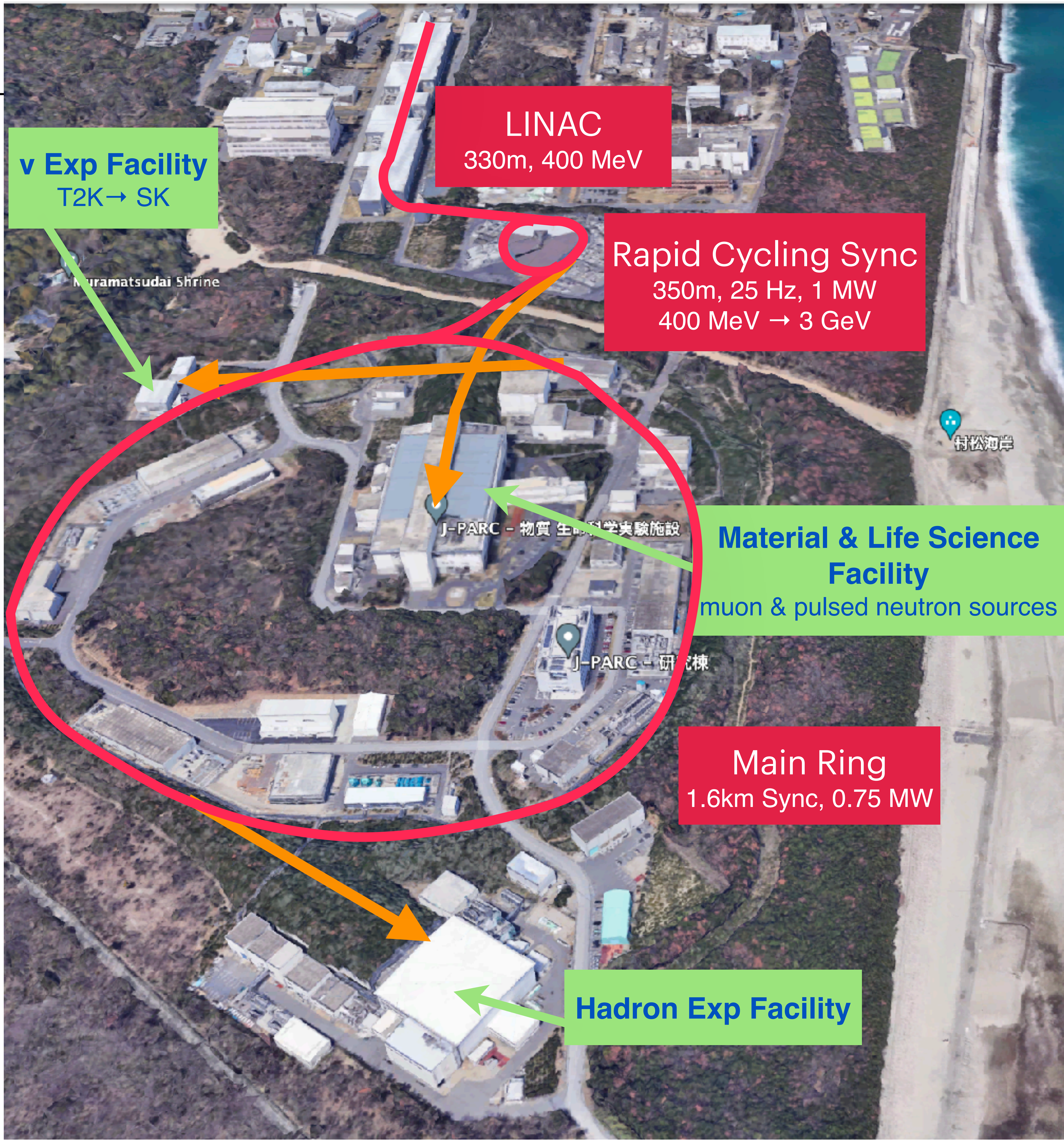
transport the 105 MeV e- !

Very precise measurement of the electron momentum

COMET @ JParc Facility (KEK /JAEA)

43 institutes,18 countries





LINAC
330m, 400 MeV

ν Exp Facility
T2K→ SK

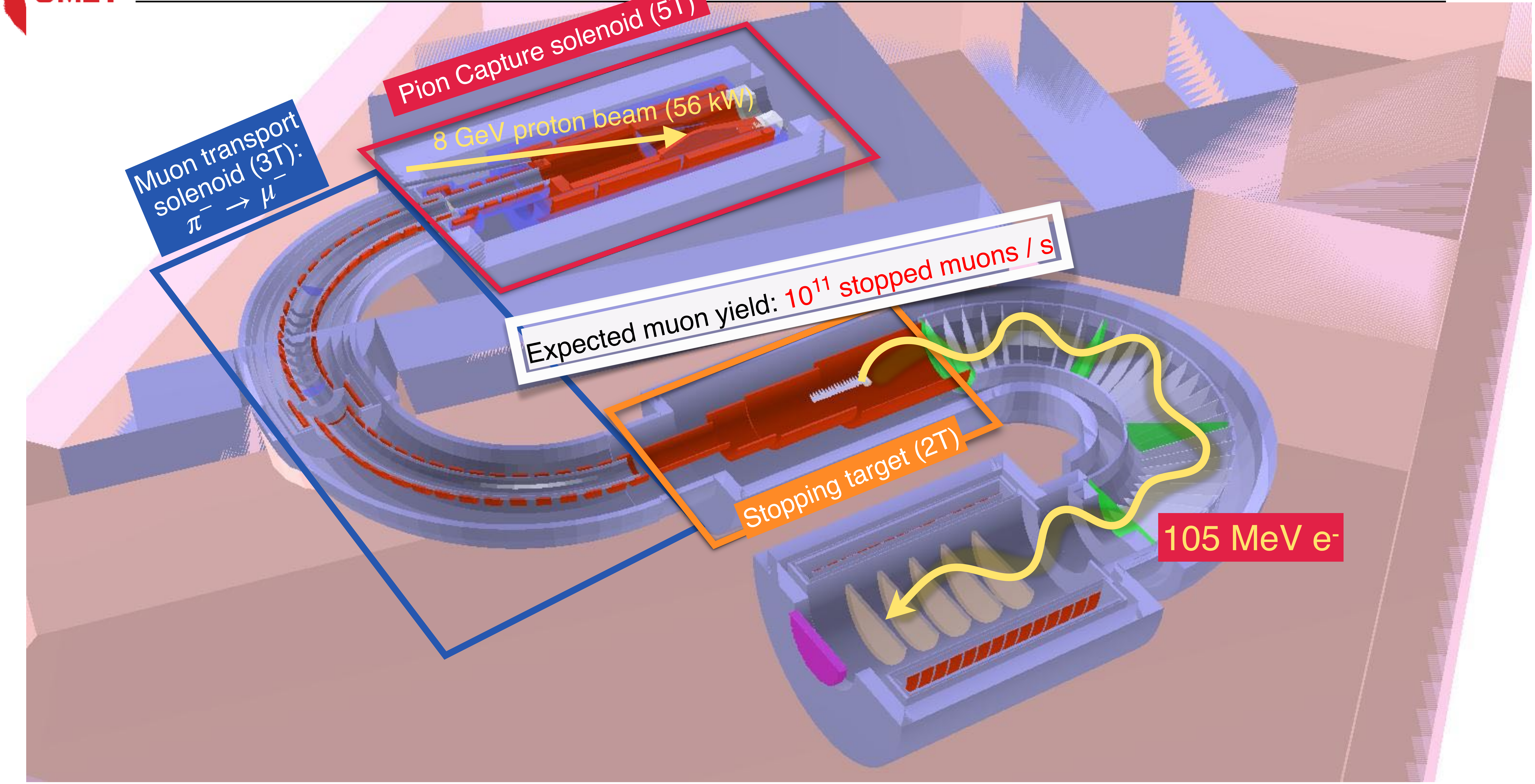
Rapid Cycling Sync
350m, 25 Hz, 1 MW
400 MeV → 3 GeV

Material & Life Science Facility
muon & pulsed neutron sources

Main Ring
1.6km Sync, 0.75 MW

Hadron Exp Facility

COMET design



Pion Capture solenoid (5T)

8 GeV proton beam (56 kW)

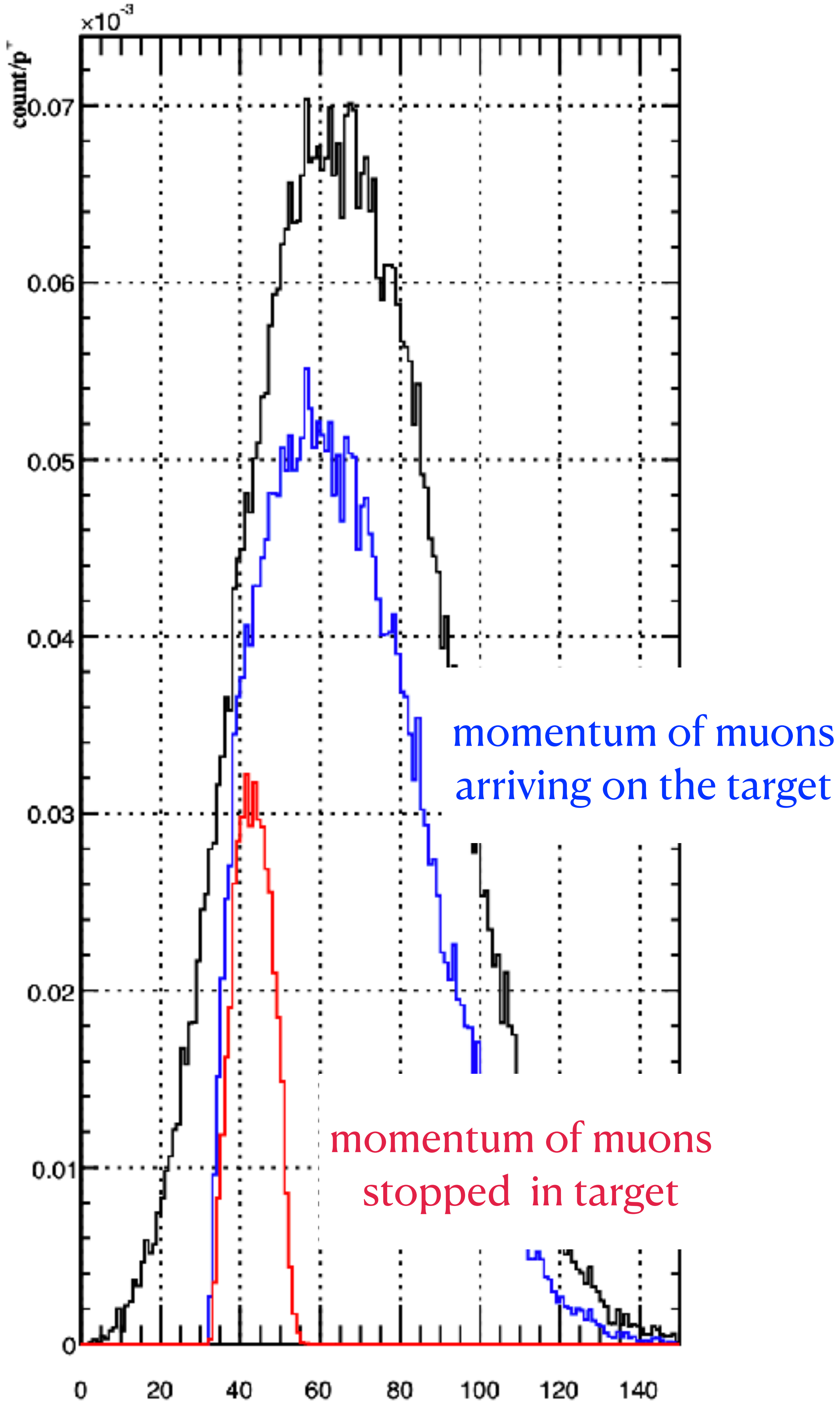
Muon transport solenoid (3T): $\pi^- \rightarrow \mu^-$

Expected muon yield: 10^{11} stopped muons / s

Stopping target (2T)

105 MeV e⁻

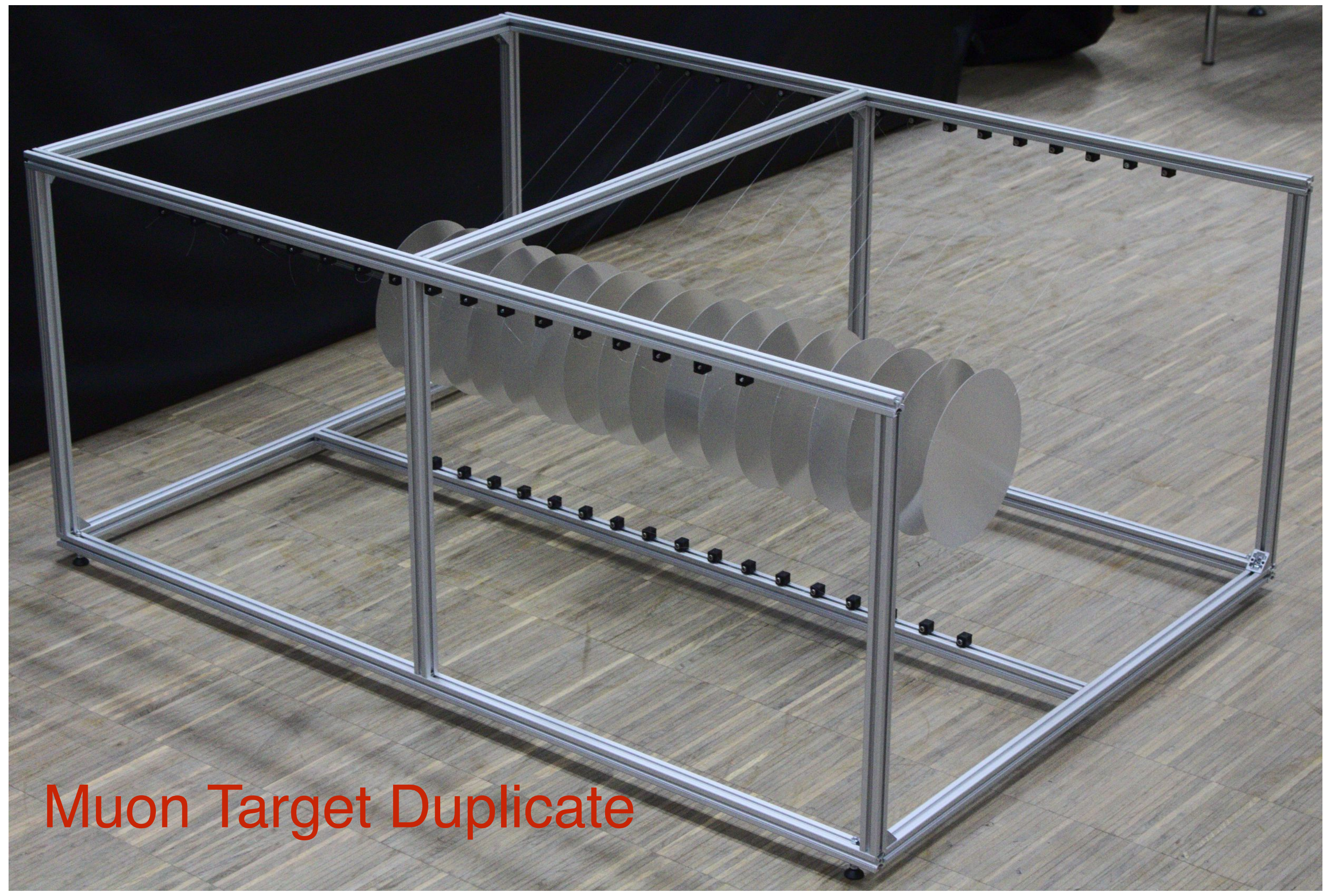
COMET Phase-I :: Muon Stopping Target



momentum of muons arriving on the target

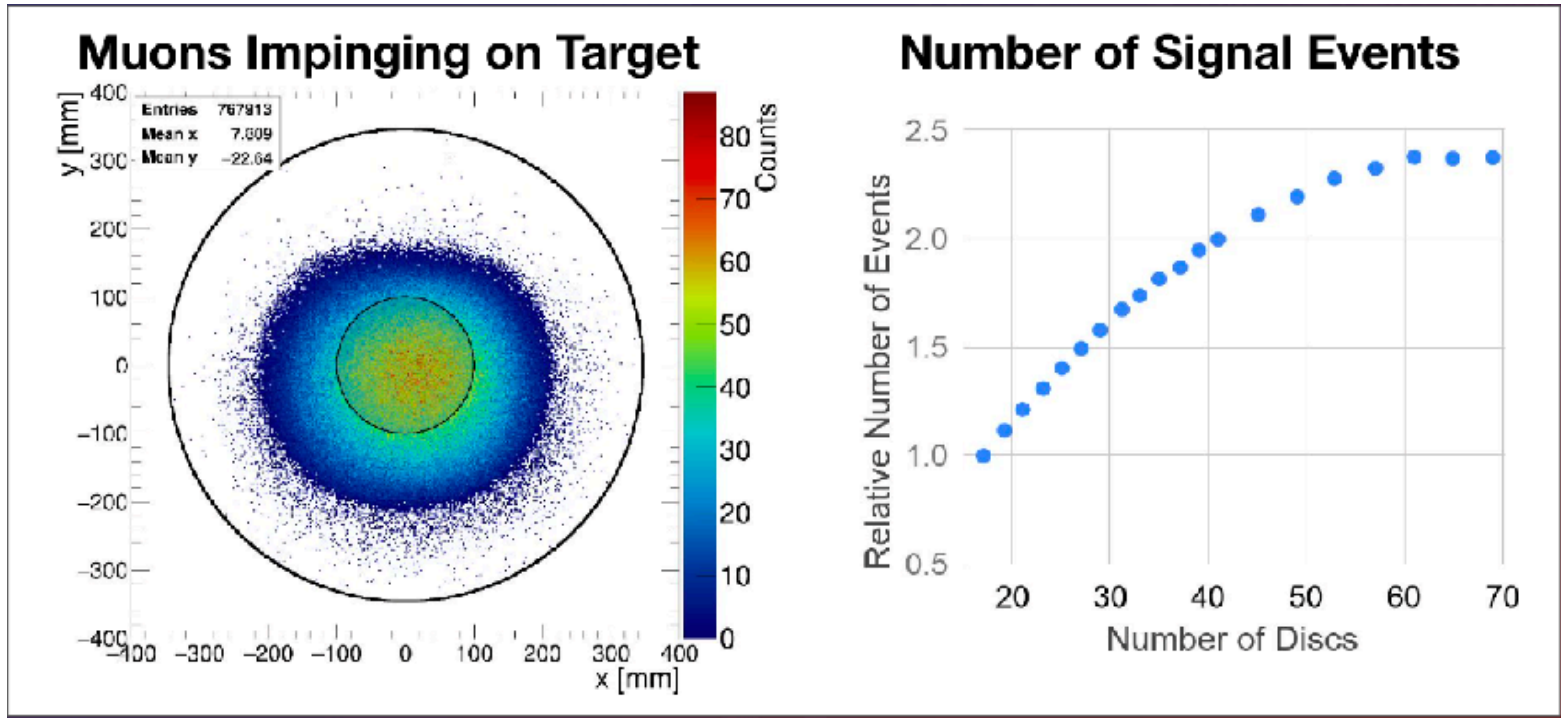
momentum of muons stopped in target

Baseline configuration: 17 Al disks (100 mm radius, 200 µm thick)



Muon Target Duplicate

Muon-stopping rate is currently being optimised against degradation of electron energy spectrum



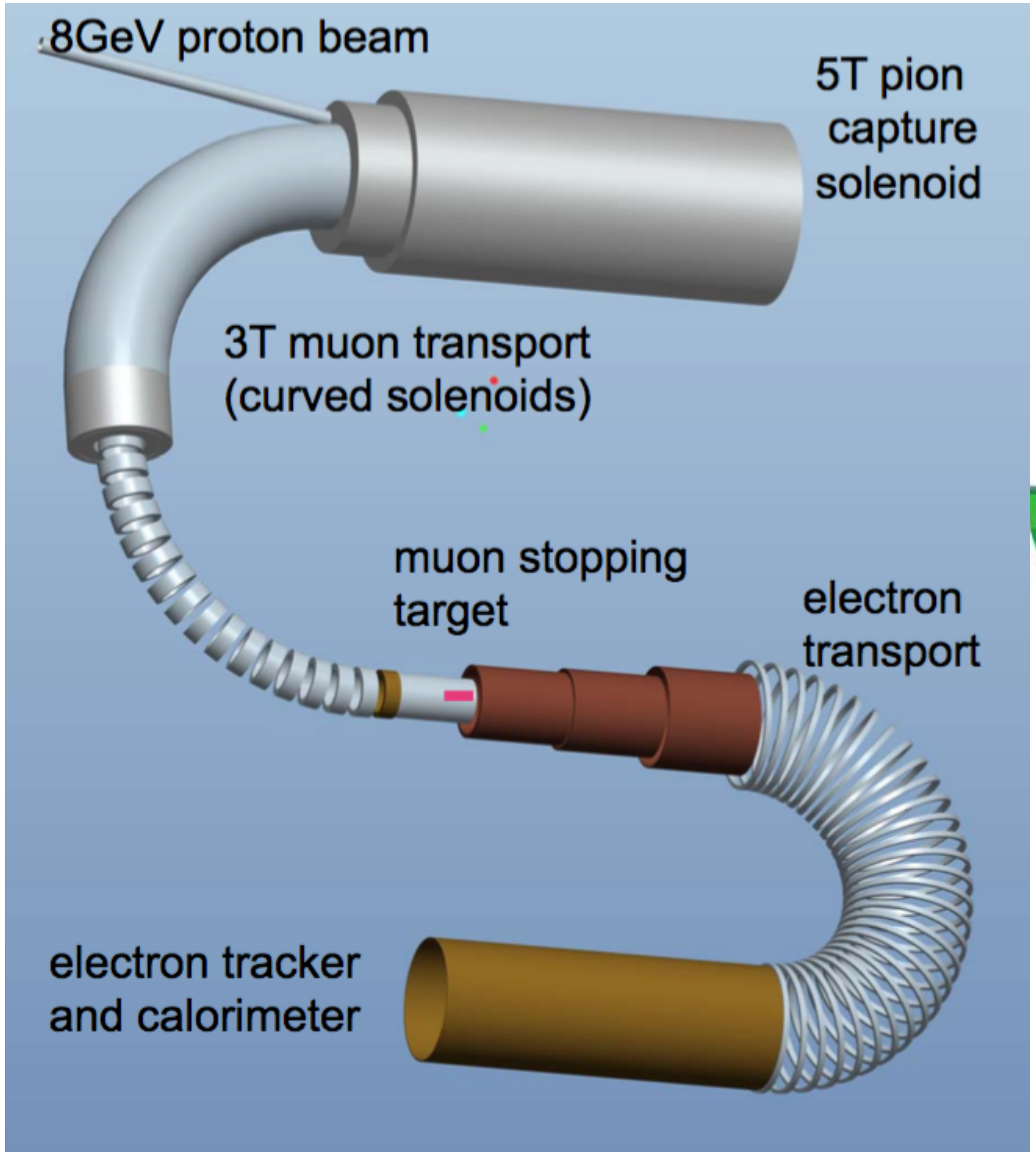
Muons Impinging on Target

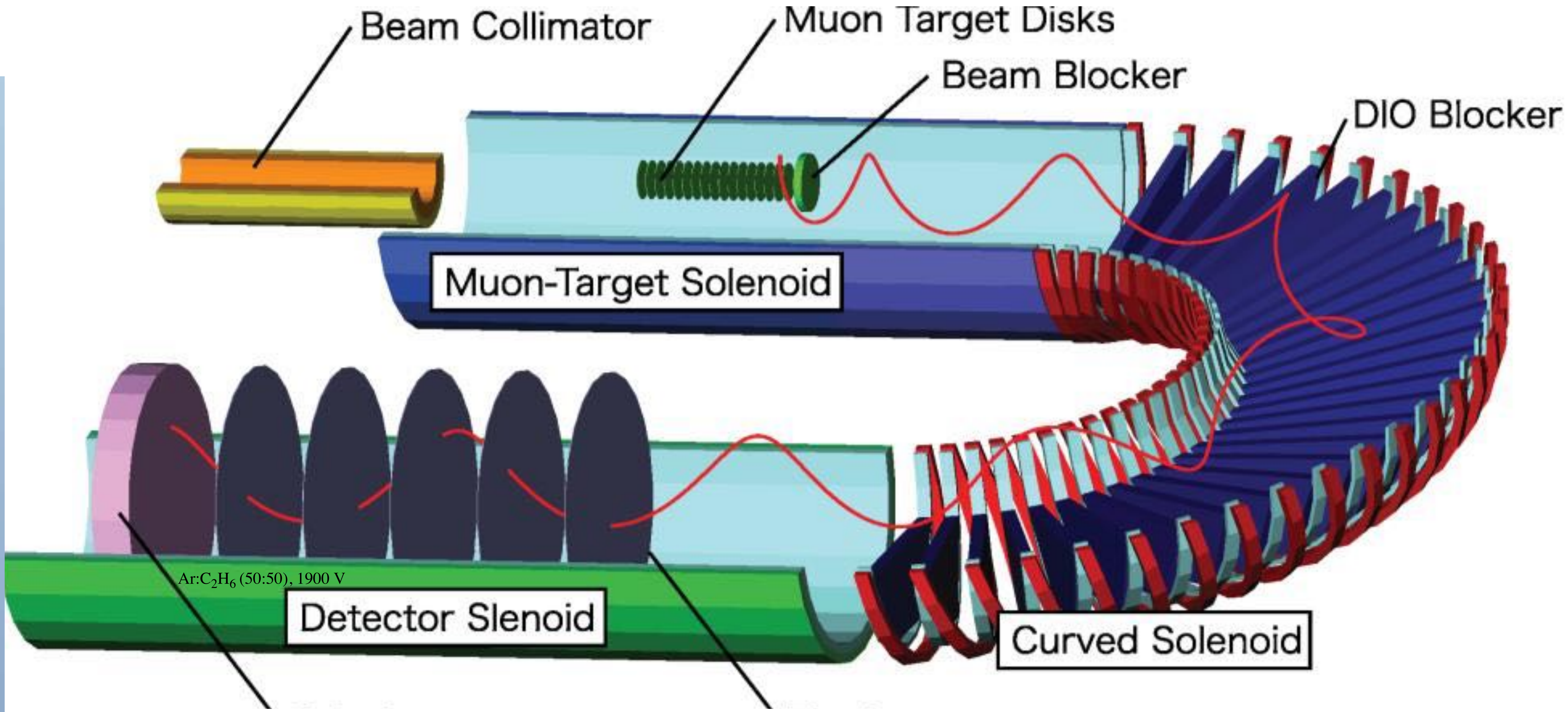
Number of Signal Events

COMET design

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

COMET design :: detection section





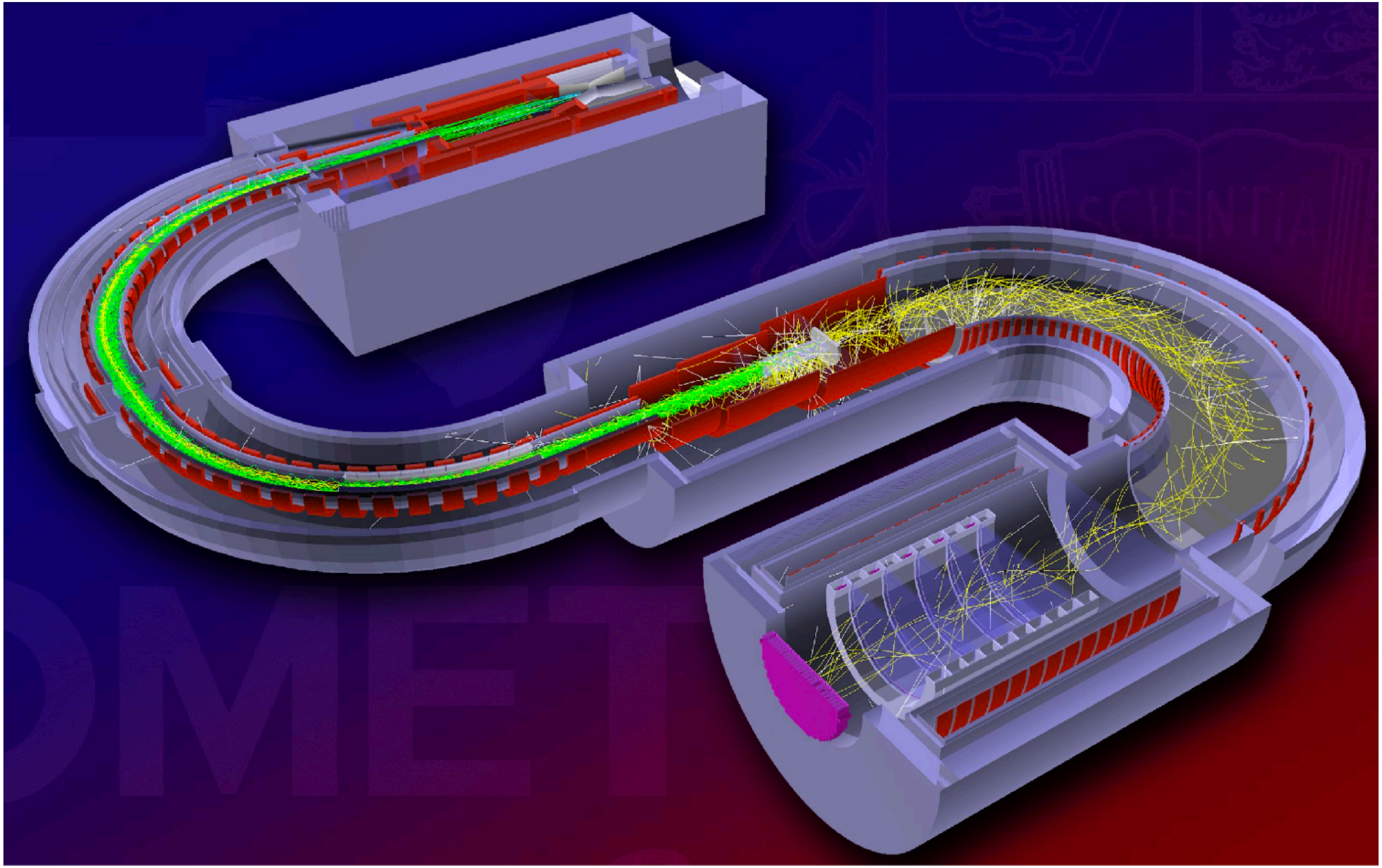
Electromagnetic calorimeter

- trigger & timing: response time faster than 100 ns
- electron energy : ΔE/E < 5% (@105 MeV)
- cluster position: σ_x<1 cm
- 50 cm of radius
- made of 1920 LYSO crystals 2×2×12 cm^3 (10.5 X_0)
- read out by APDs (operates @ 1 T)

Straw tubes tracker

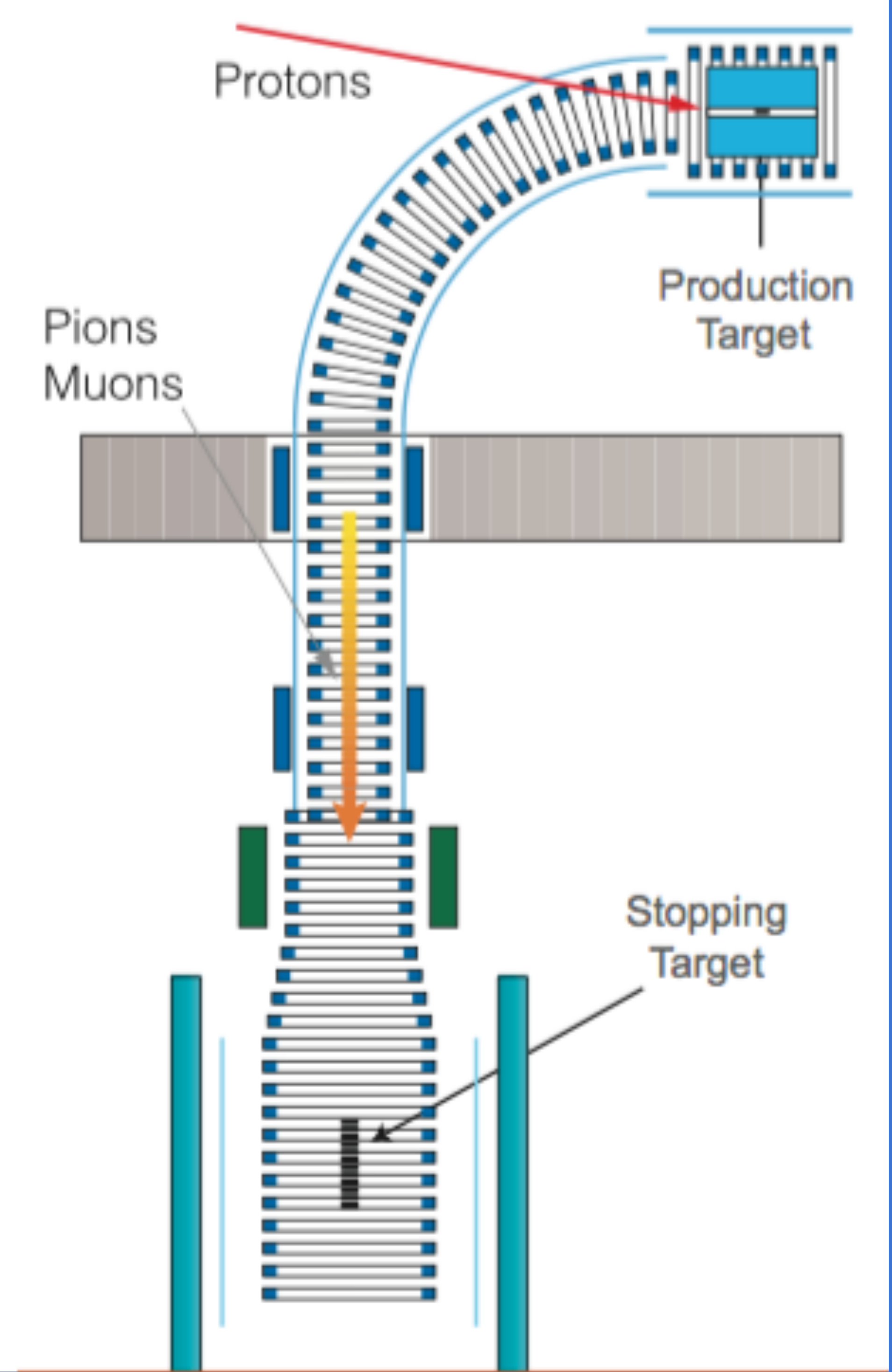
- operates in vacuum @ 1T
- Δp = 150~200 keV/c (@105 MeV/c)
- 12 µm thick, 5 mm diameter for Phase-II
- at least five stations

A simulated COMET event



COMET , a 2-stage experiment

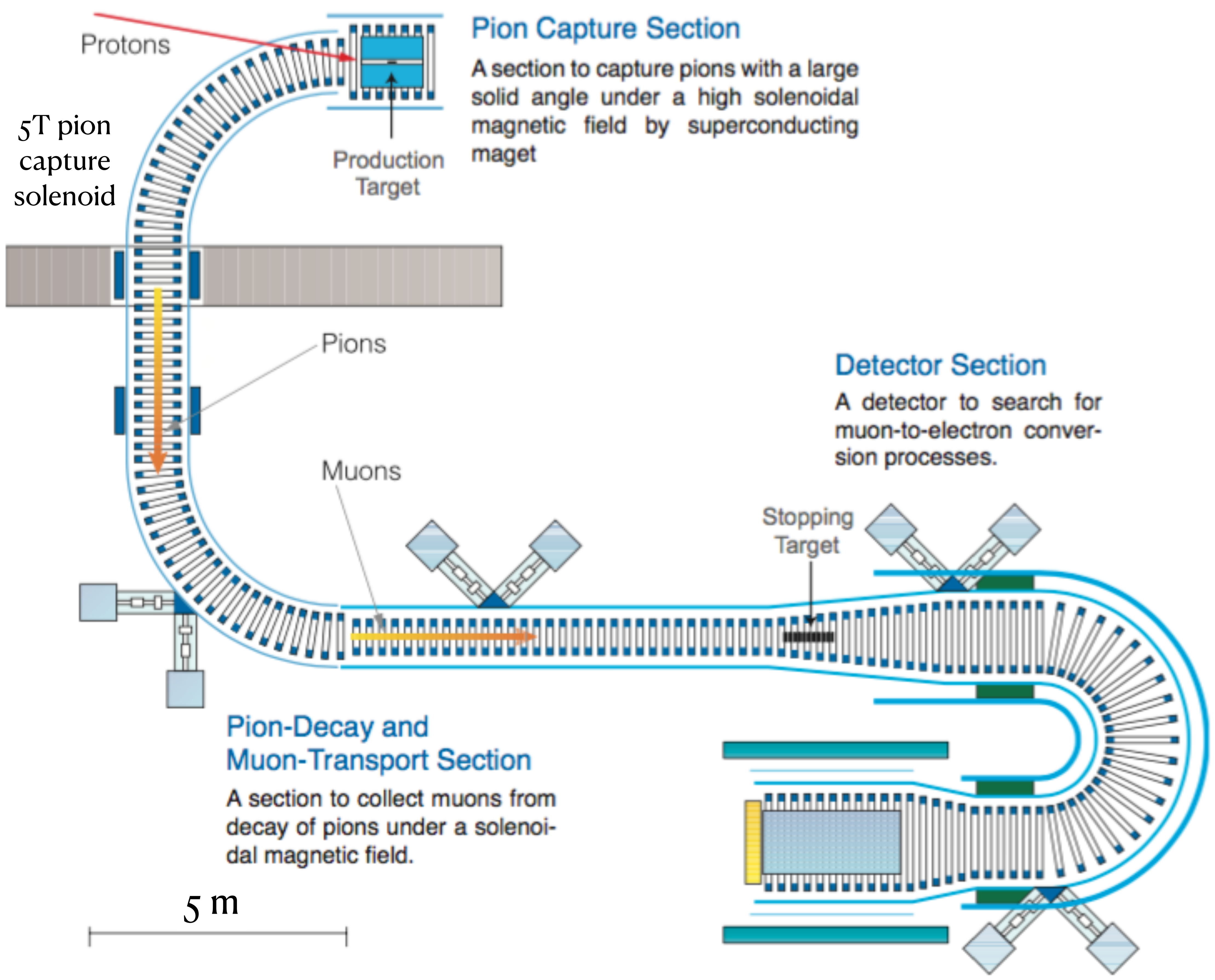
Phase I



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



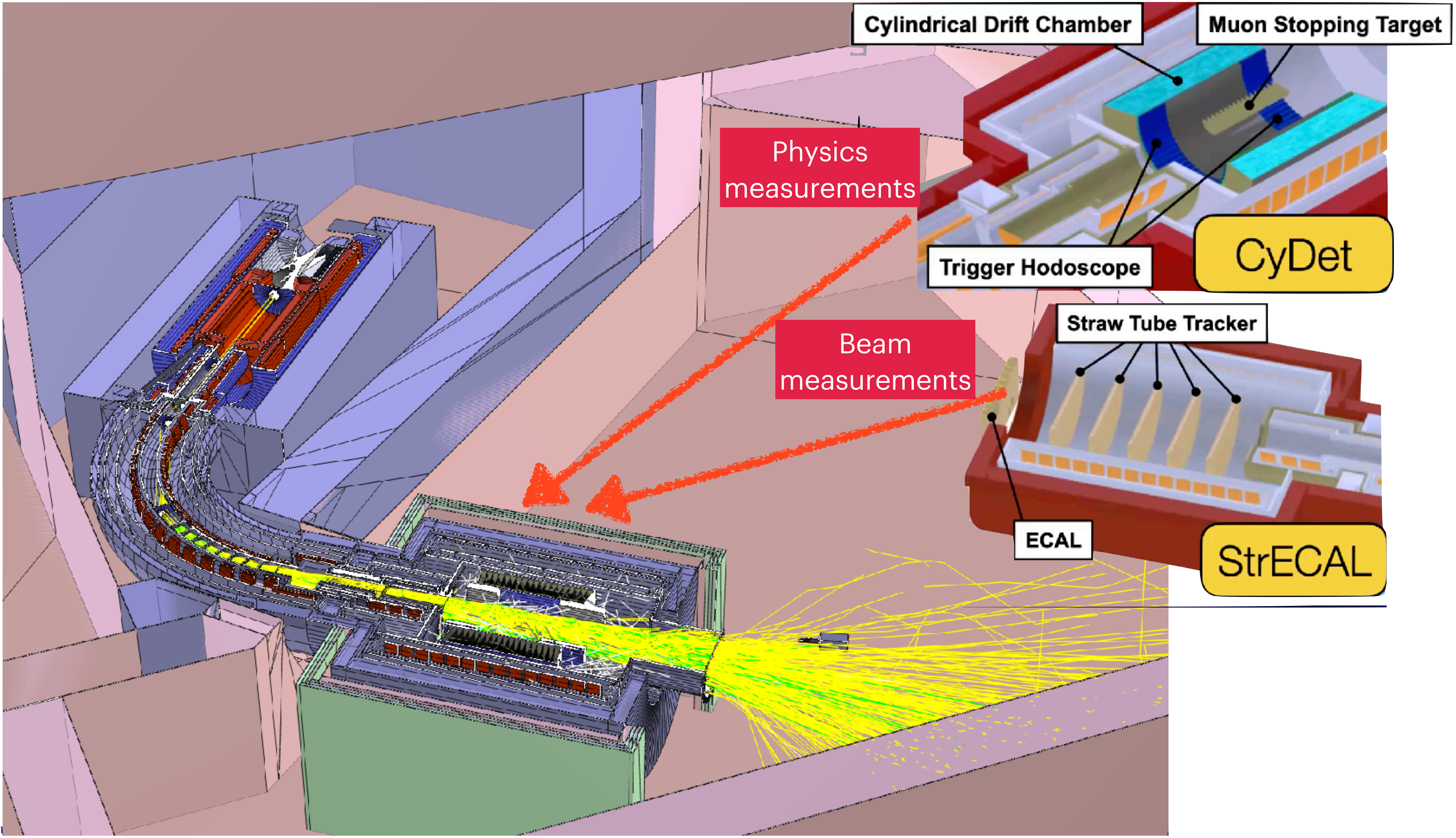
Pion Capture Section
A section to capture pions with a large solid angle under a high solenoidal magnetic field by superconducting maget

Detector Section
A detector to search for muon-to-electron conversion processes.

Pion-Decay and Muon-Transport Section
A section to collect muons from decay of pions under a solenoidal magnetic field.

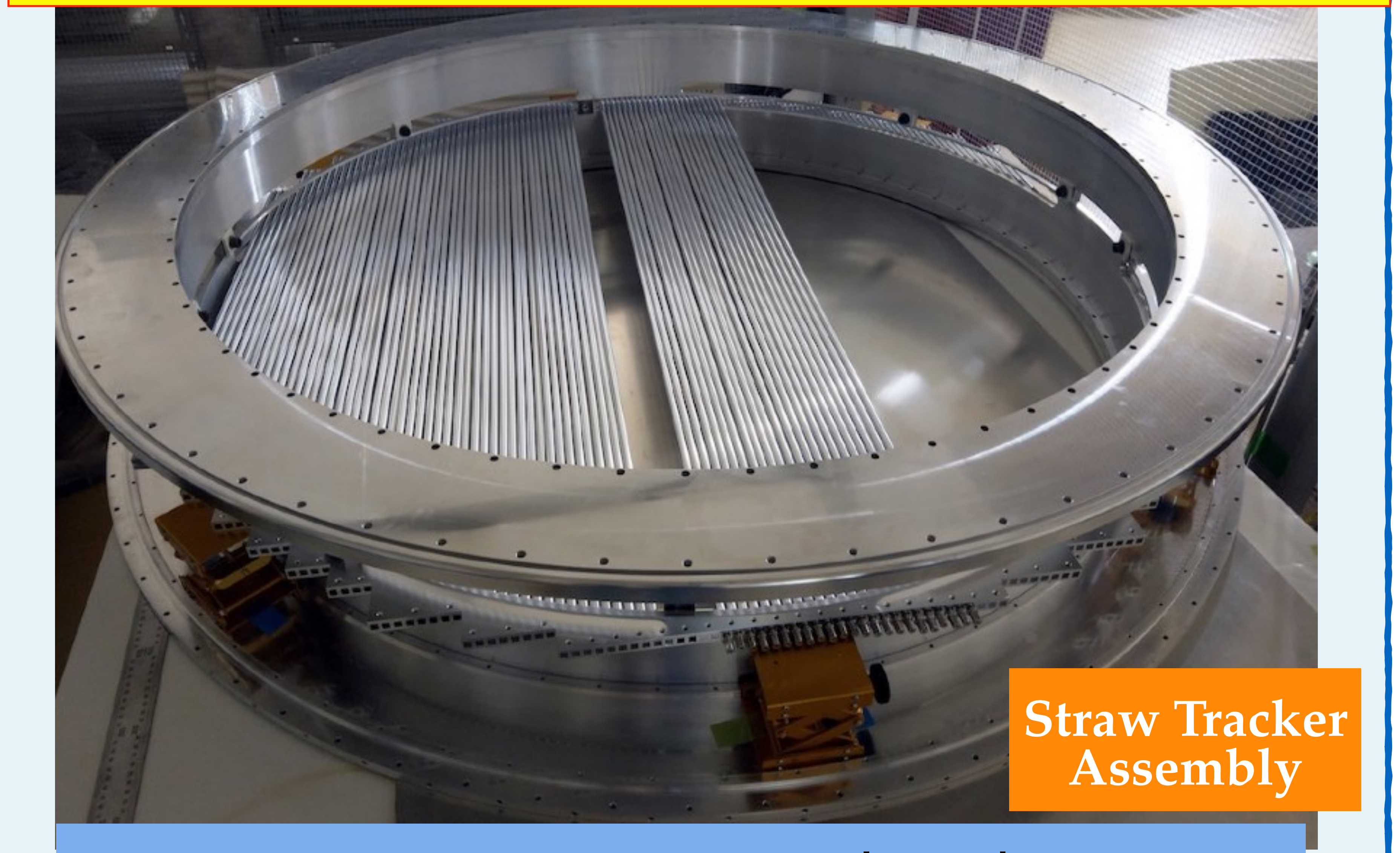
8 GeV proton beam (56 kW)
Tungsten proton target
1.2 10^{11} stopped muons/s

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


Cylindrical Drift Chamber
Muon Stopping Target
Physics measurements
Trigger Hodoscope
CyDet
Beam measurements
Straw Tube Tracker
ECAL
StrECAL

COMET Status :: StrawECAL

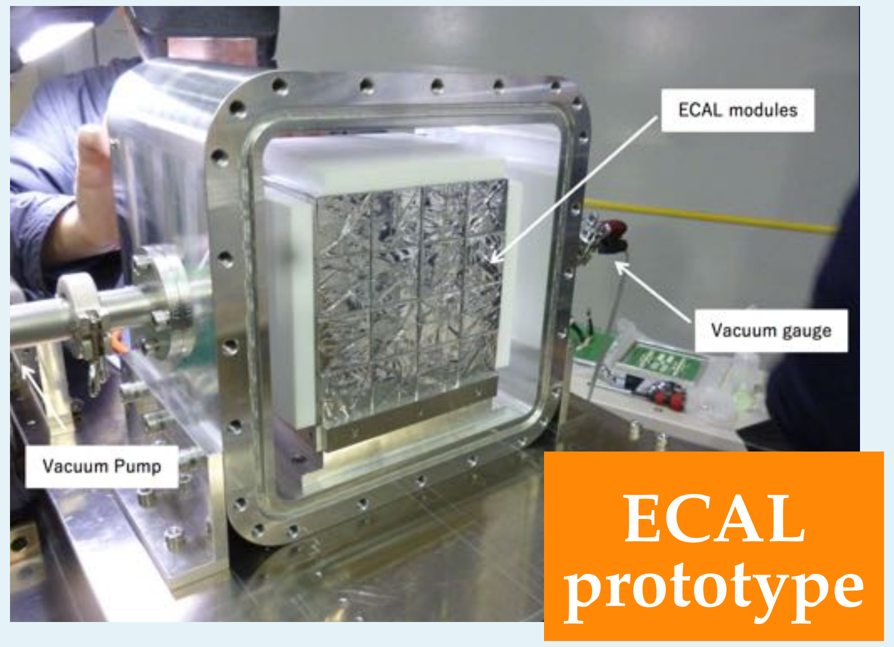
StrECAL :
Straw tracker+ECAL (for beam measurement)



Straw Tracker Assembly

First station completed !

- Five stations in total.

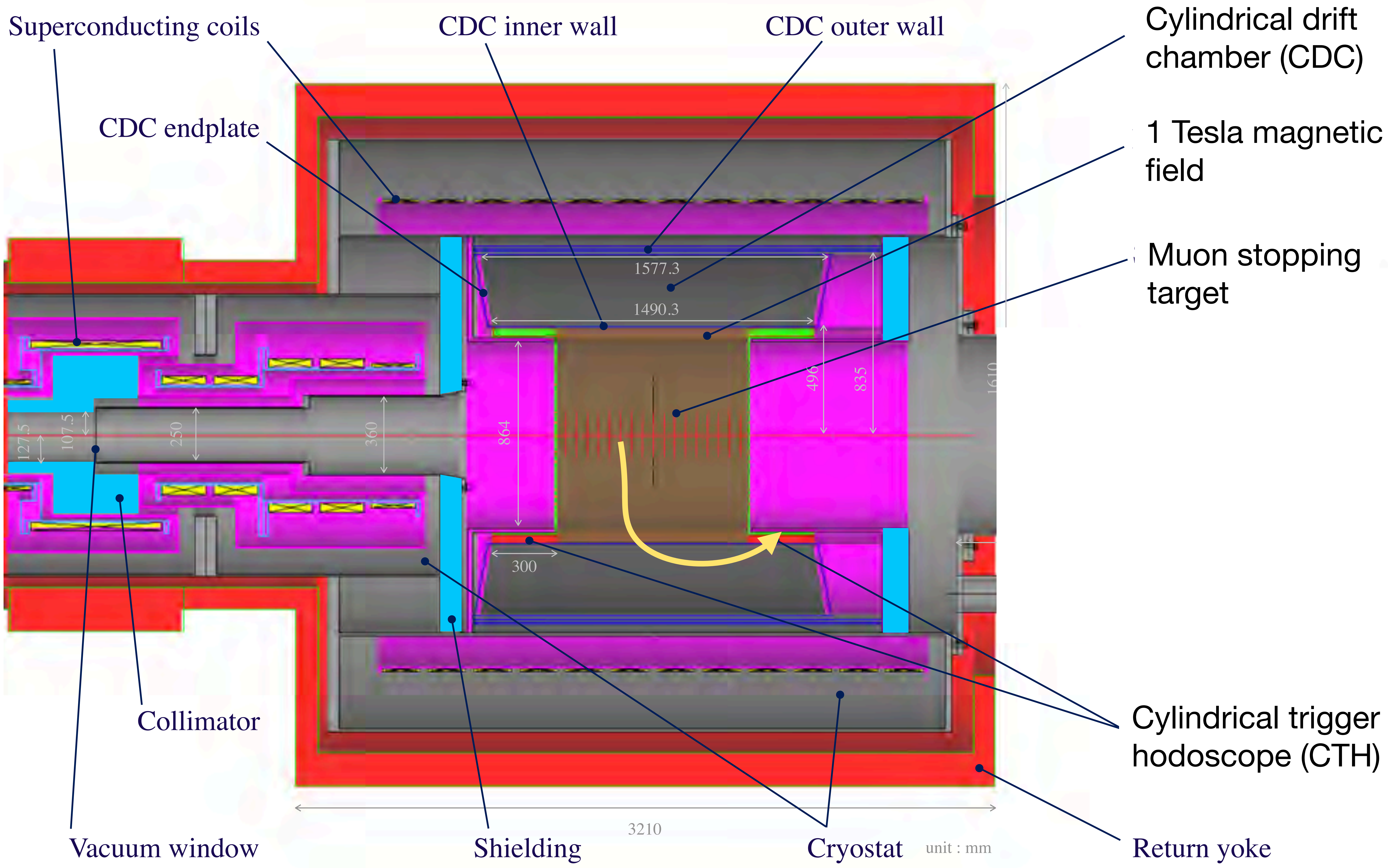


ECAL prototype

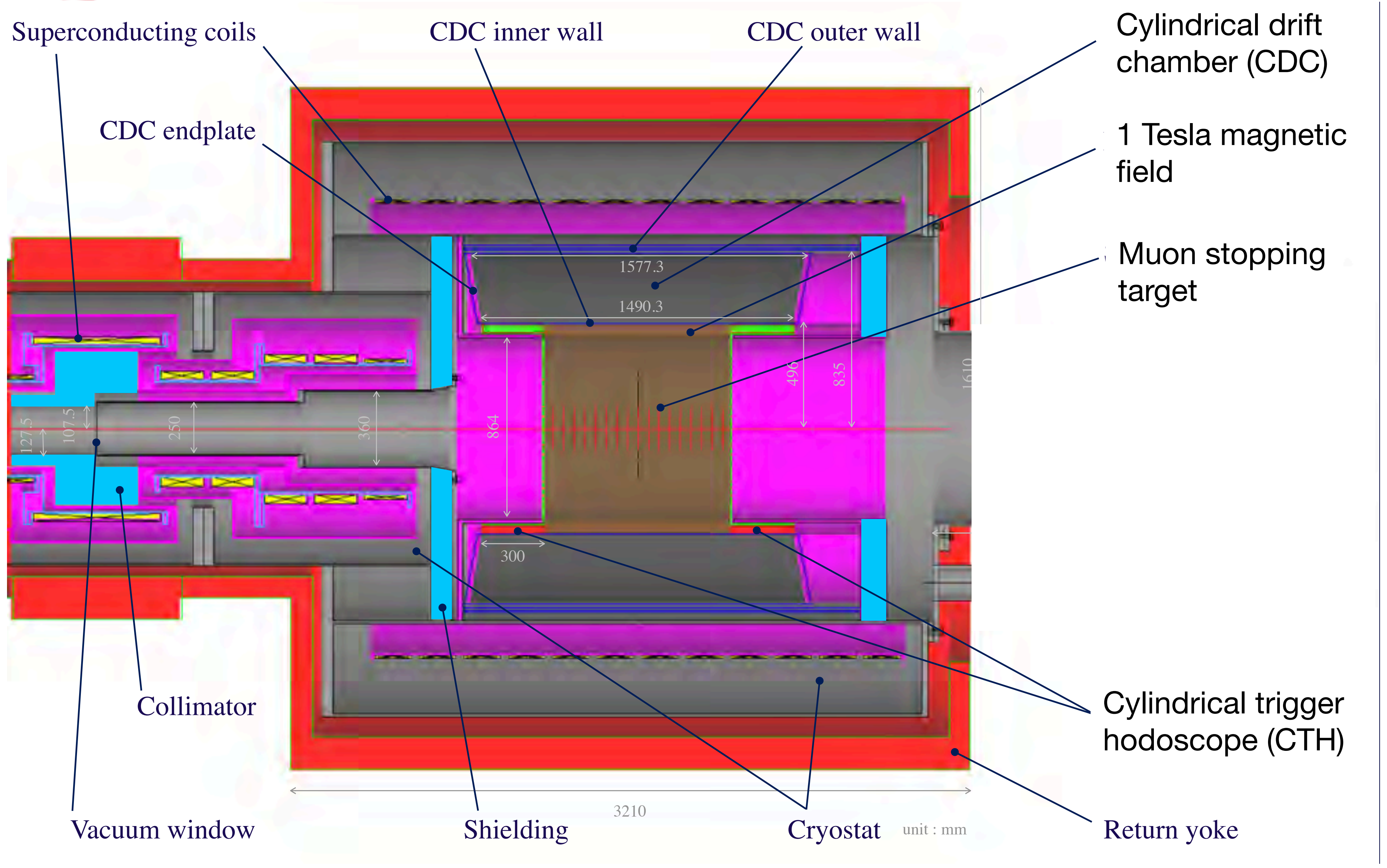
- ECAL prototype successfully completed.
- Detector assembly will start soon.

Please refer to
Hajime Nishiguchi's talk

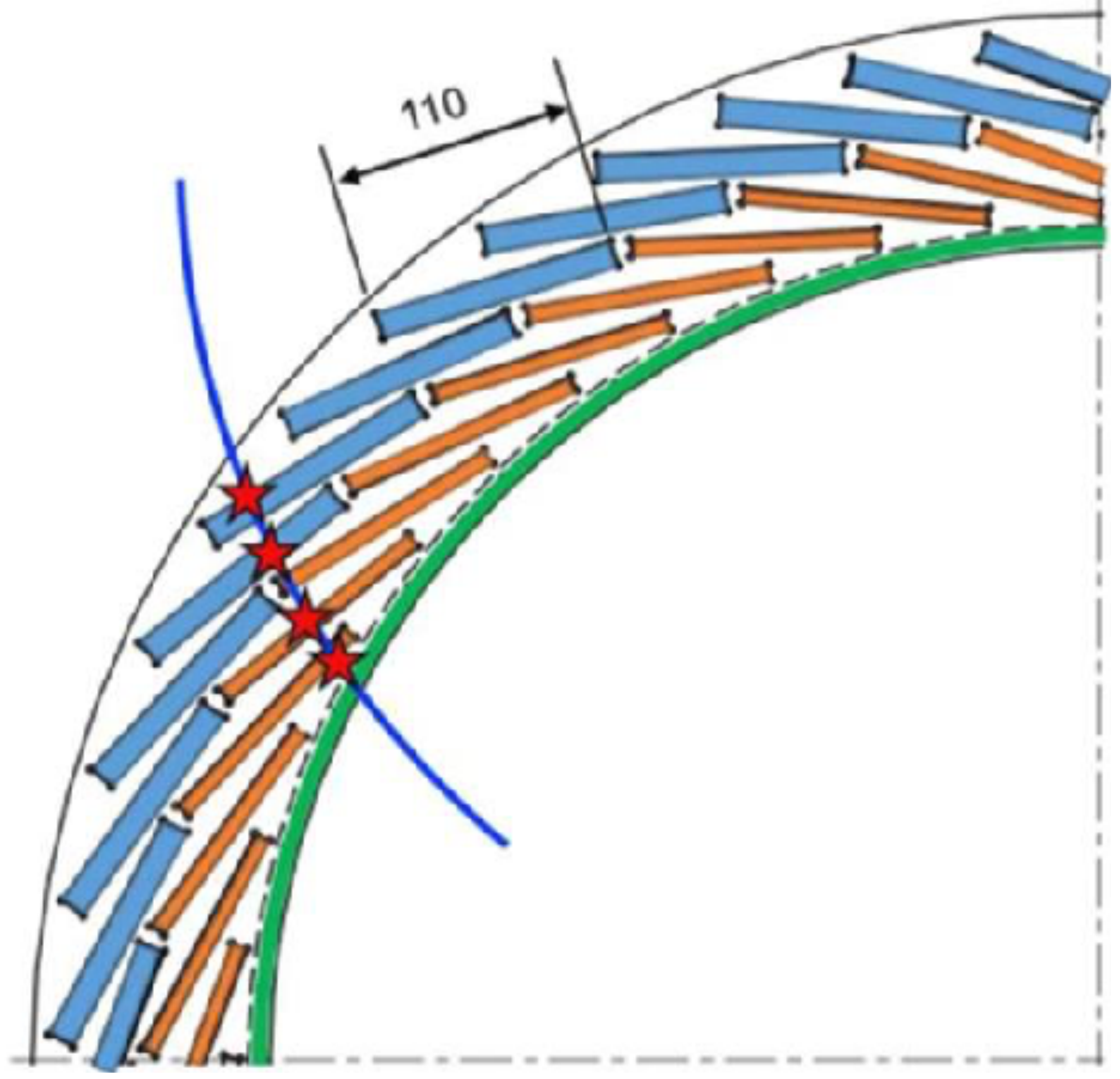
COMET Phase-I :: Electron Detectors (CyDet)

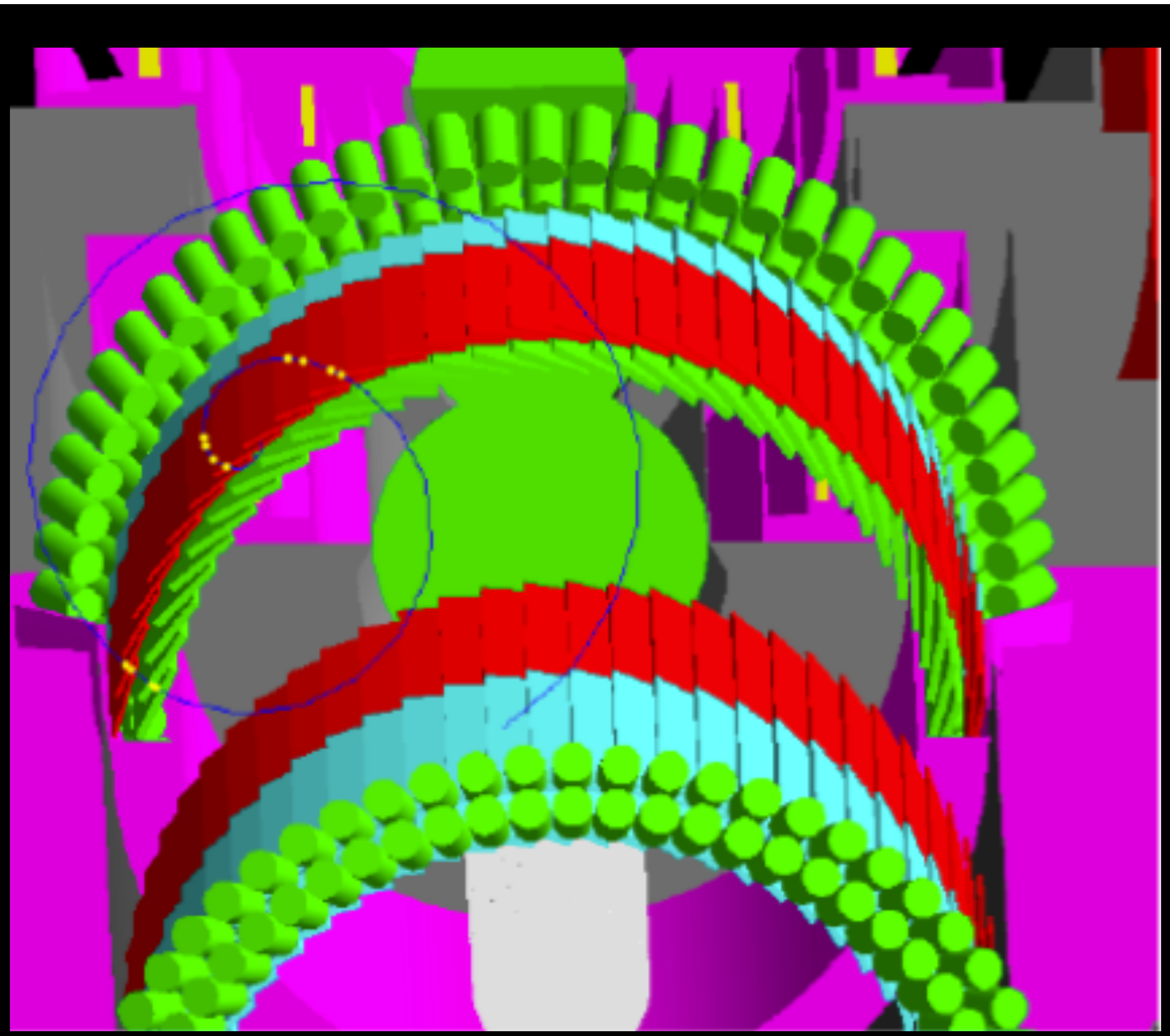


COMET Phase-I :: Electron Detectors :: CTH



Four-hold coincidence provides trigger and PID

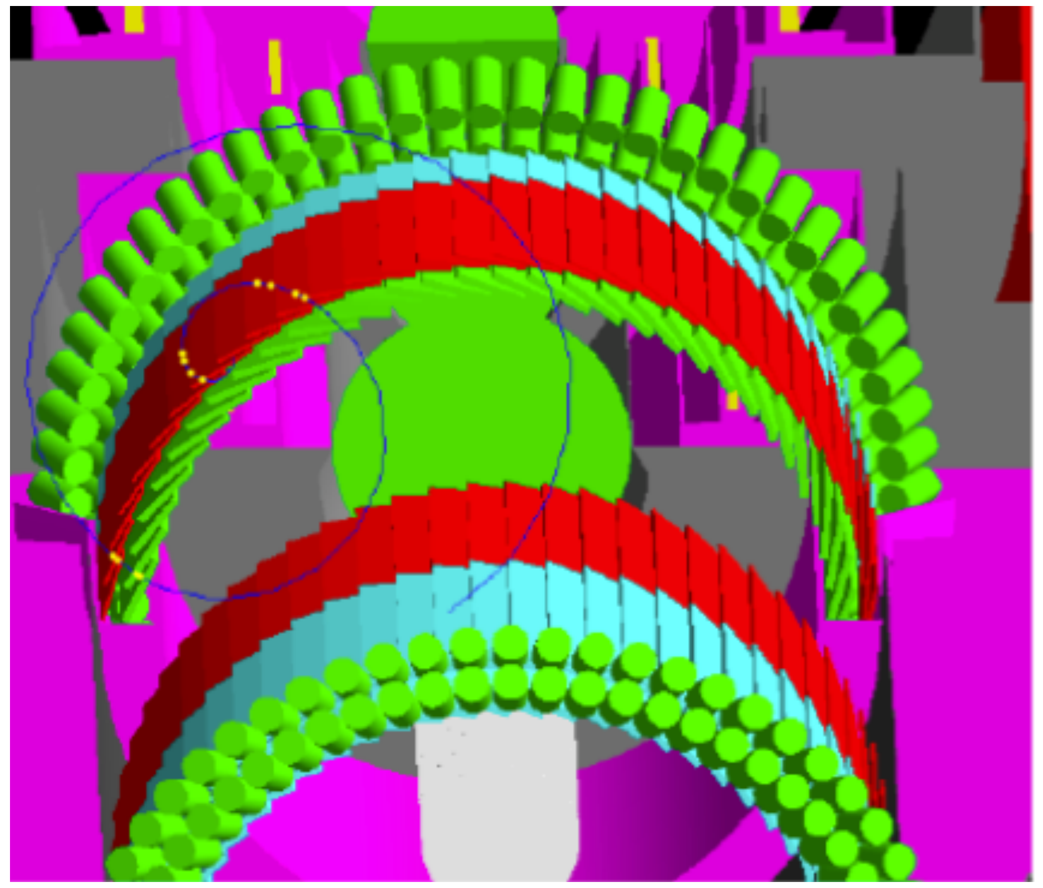




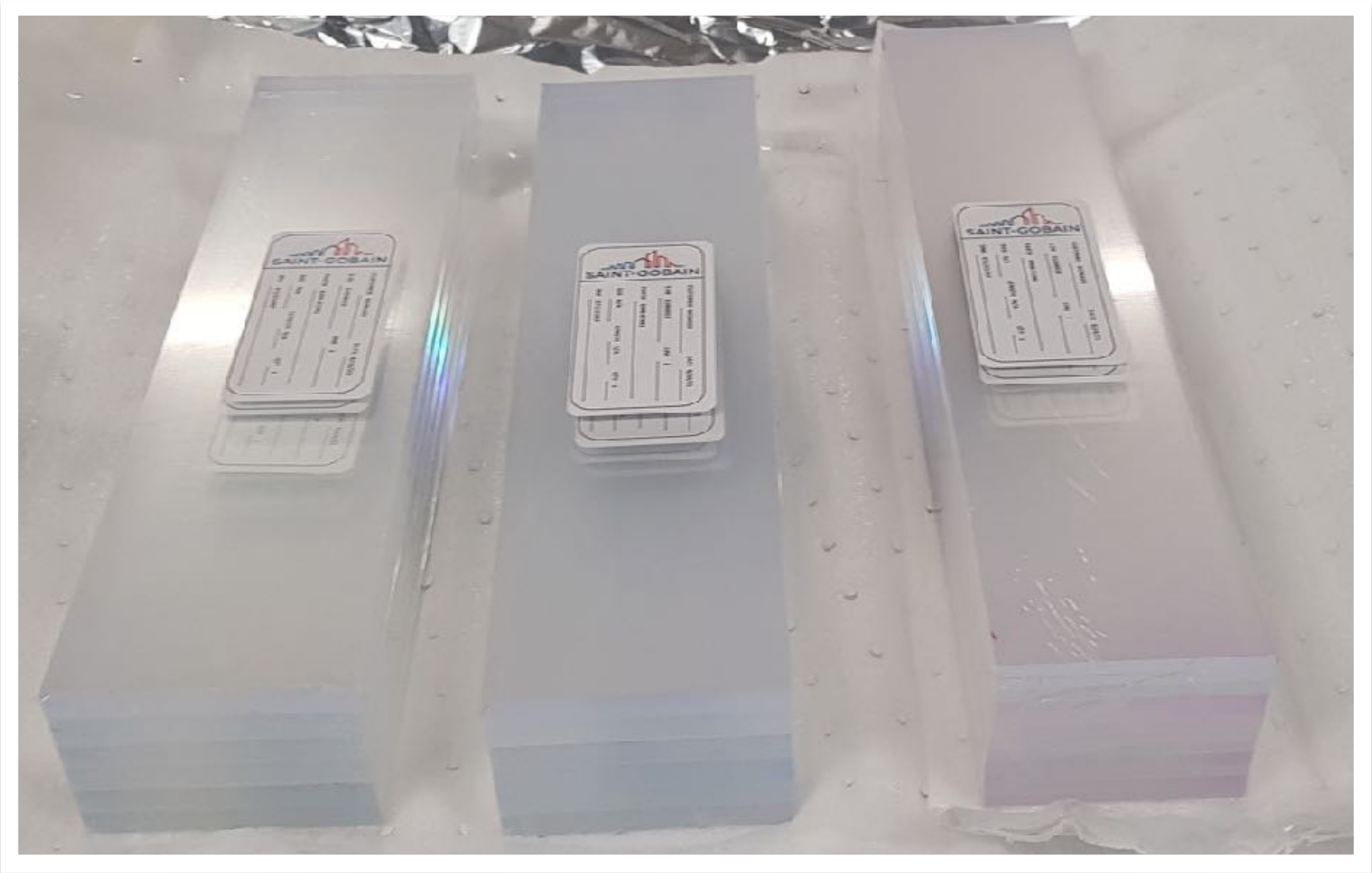
2-rings of ultra fast scintillators (64 segments, 33/36 x 1 x 1 cm3)
read by optical fibres and SiPMs

2-rings of Cherenkov counters (acrylic plastic, 300x90x10 mm3) to be added in a second step

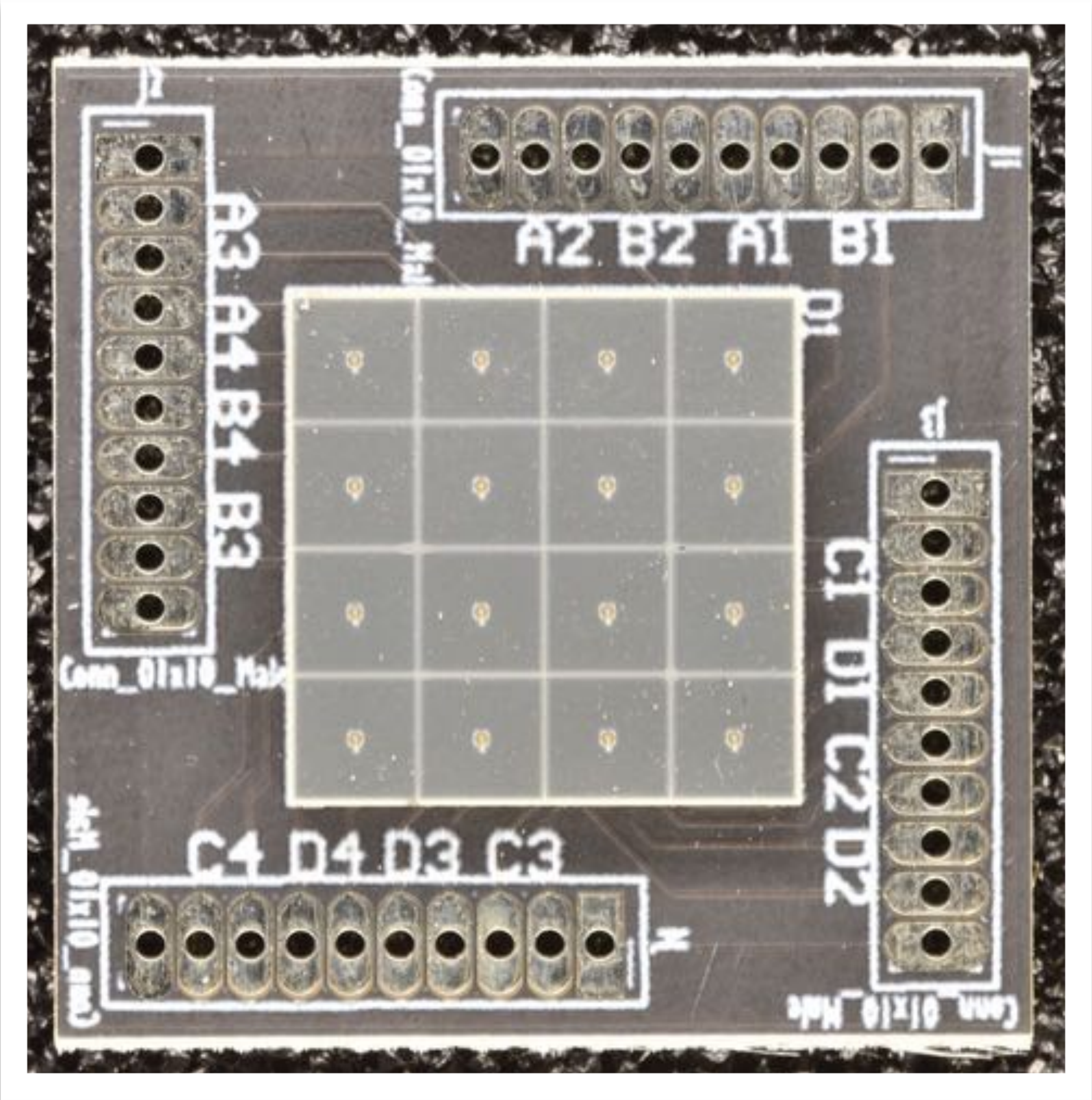
COMET Status :: CTH



plastic counters (BC-408 from Saint-Gobain).

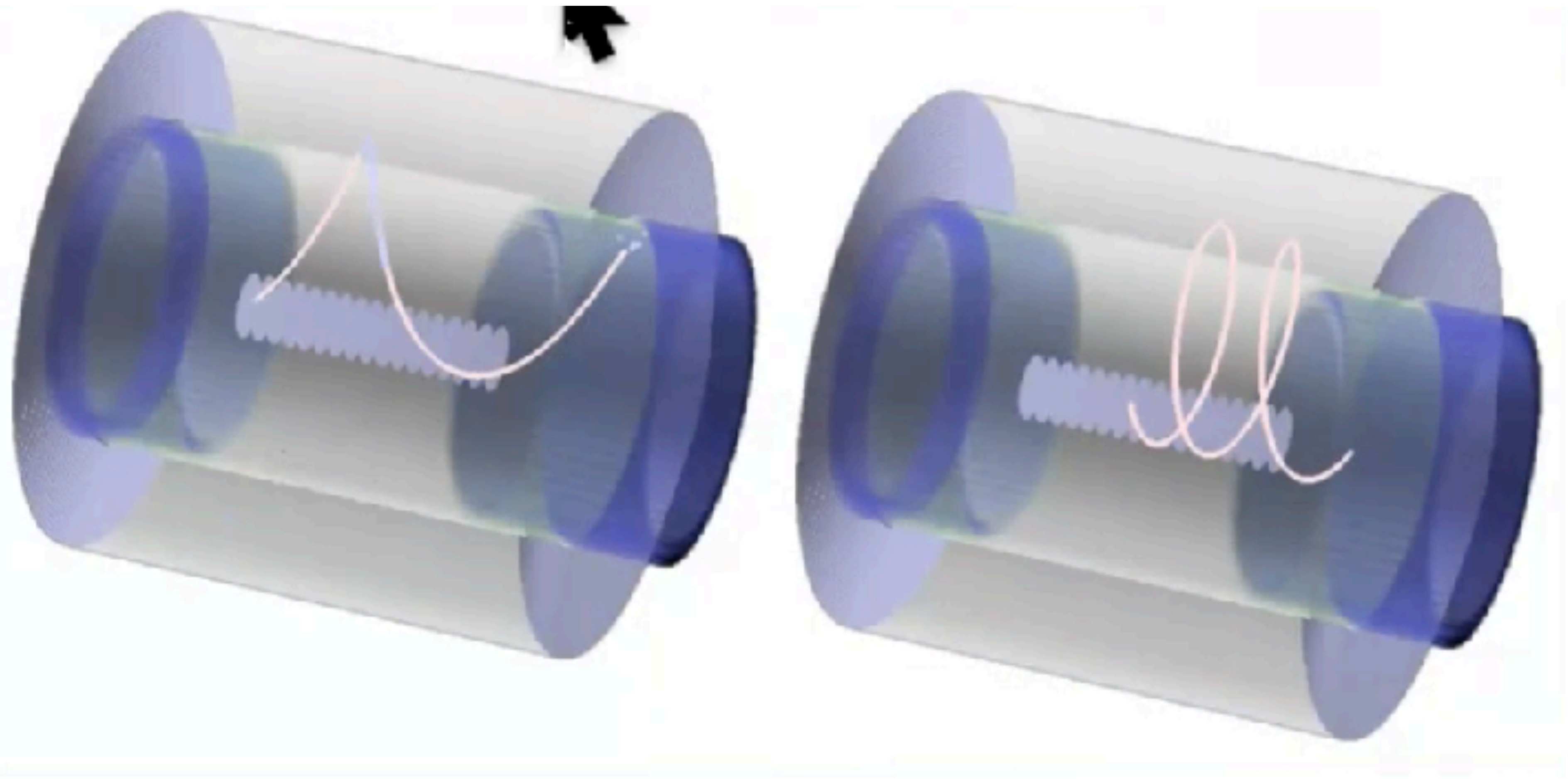


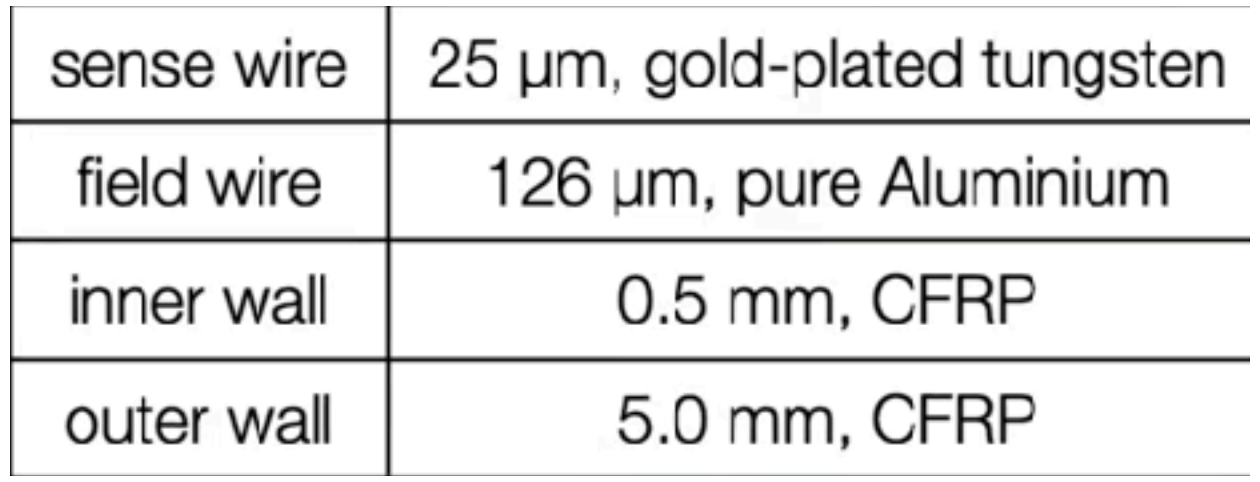
MPPC assembled on PCB



COMET Phase-I :: Cylindrical Drift Chamber

- 20 concentric sense layers
- mechanical design based on Belle II CDC
- all stereo layers ± 70 mrad (alternate)
- Helium based gas (He:iC4H10=90:10) to minimise multiple scattering
- large inner bore (~500 mm) to avoid beam flash and DIO





sense wire	25 μm, gold-plated tungsten
field wire	126 μm, pure Aluminium
inner wall	0.5 mm, CFRP
outer wall	5.0 mm, CFRP

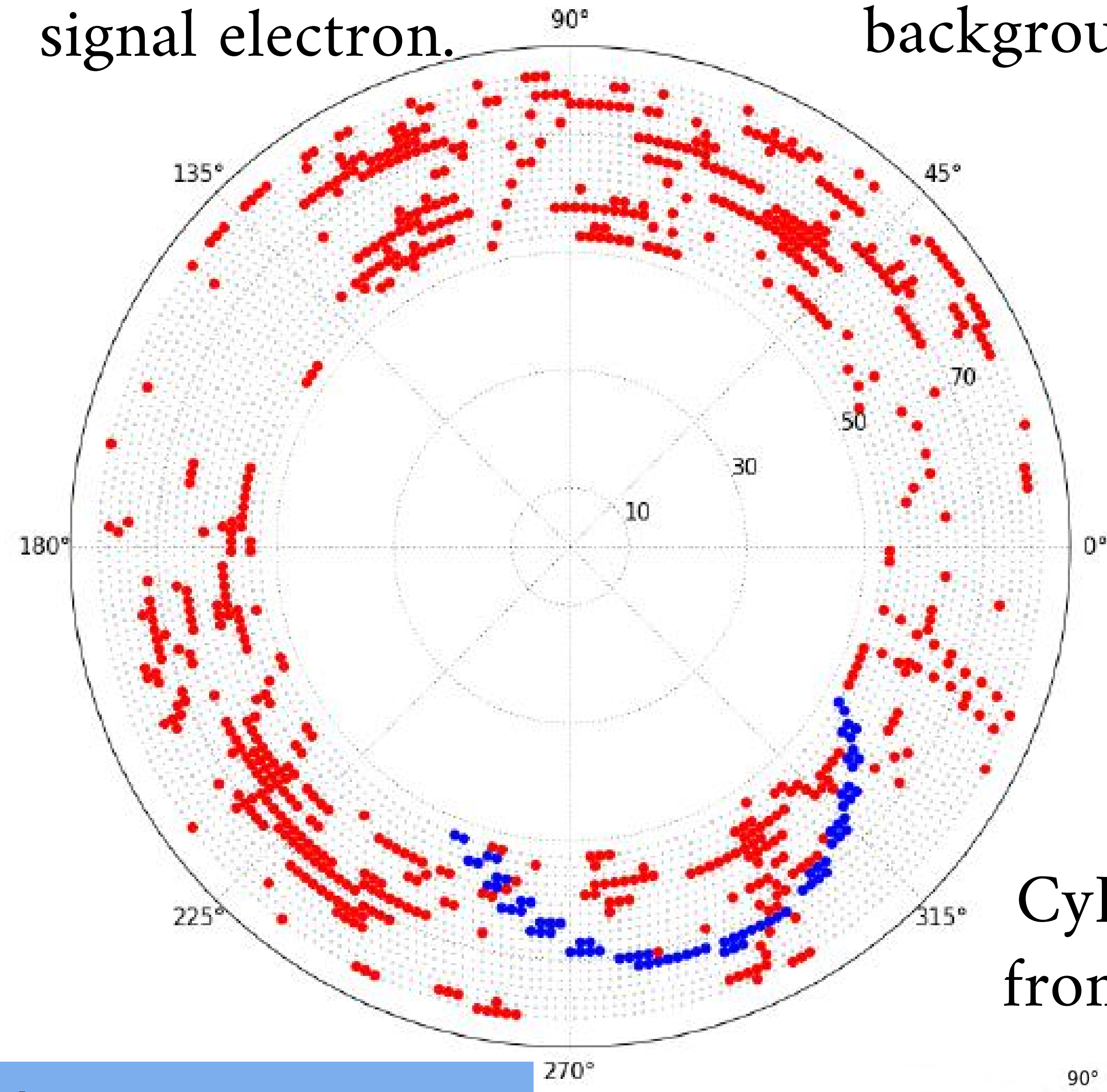
- signal tracks (~100 MeV/c) contained inside the CDC for better signal resolution
- triggered events : 60% single turn tracks & 40% multiple turn tracks

Momentum resolution: better than 200 keV/c @ 105 MeV/c

COMET Phase-I :: CDC :: Track Finder

Blue hits correspond to the signal electron.

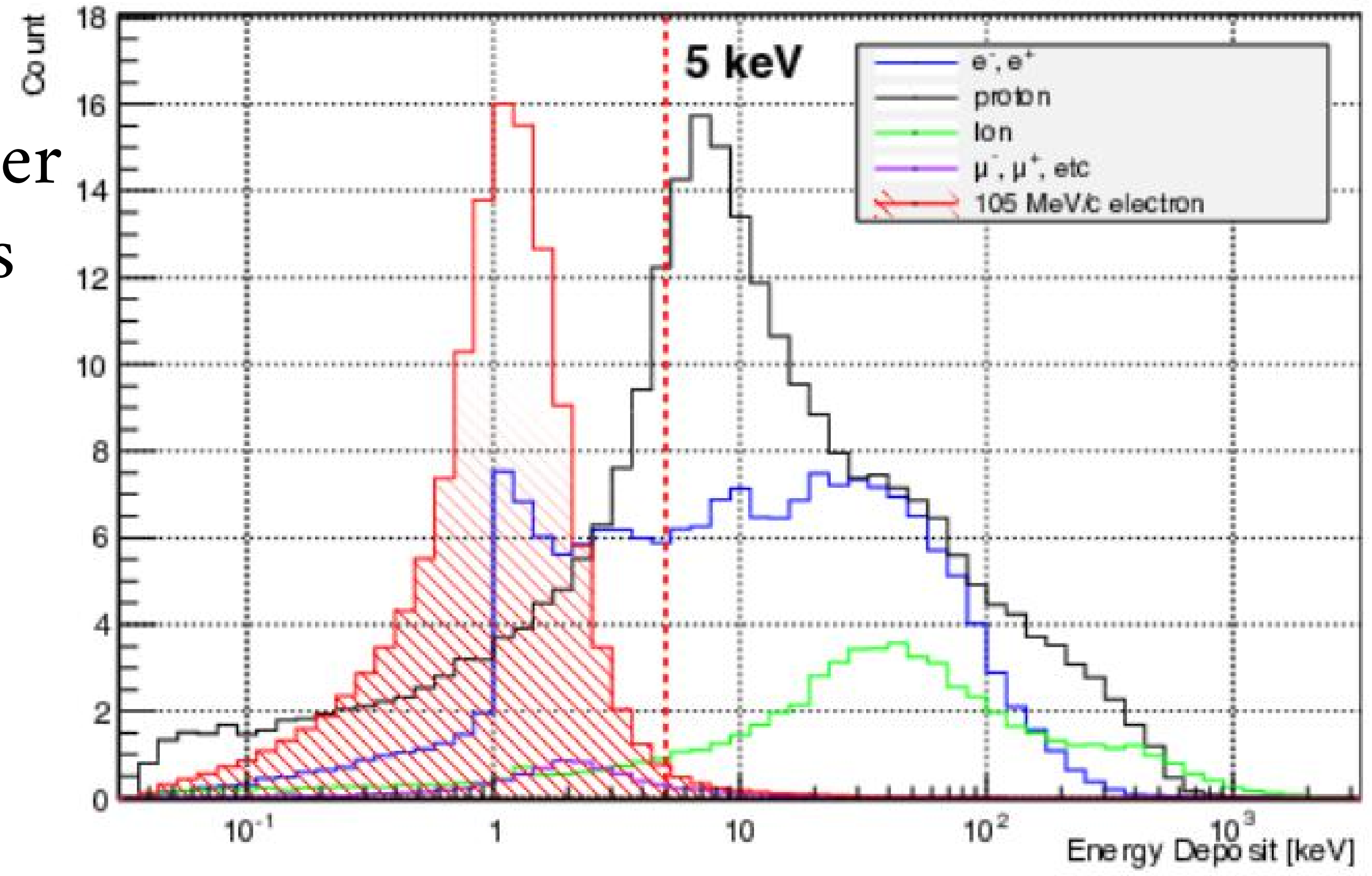
Red points are hits caused from background processes



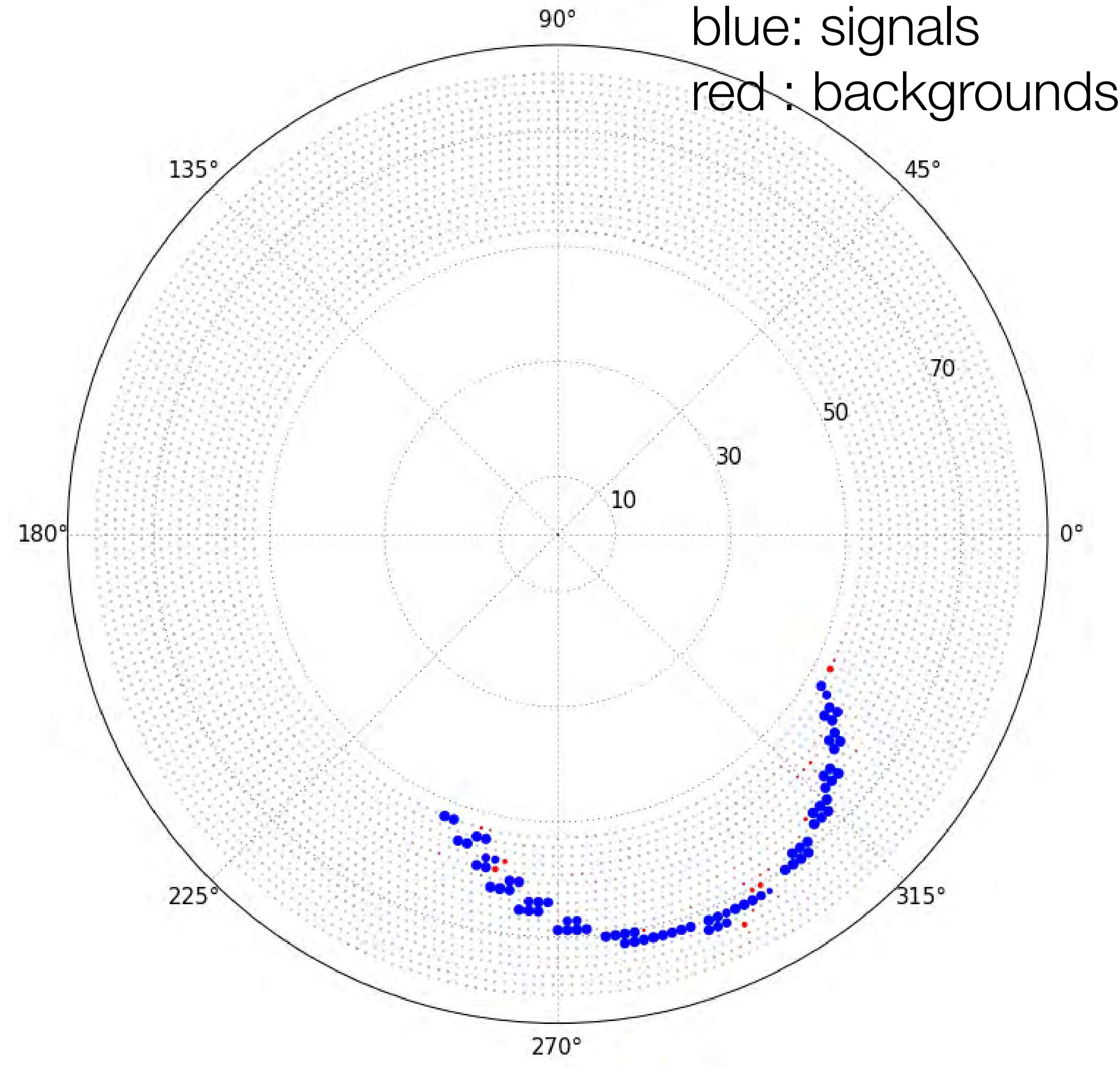
CyDet event. This is a projected view from the central plane of the detector

Most background hits are rejected based on timing, charge.

Total energy deposits per cell for signal electrons and noise hits



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



blue: signals
red : backgrounds

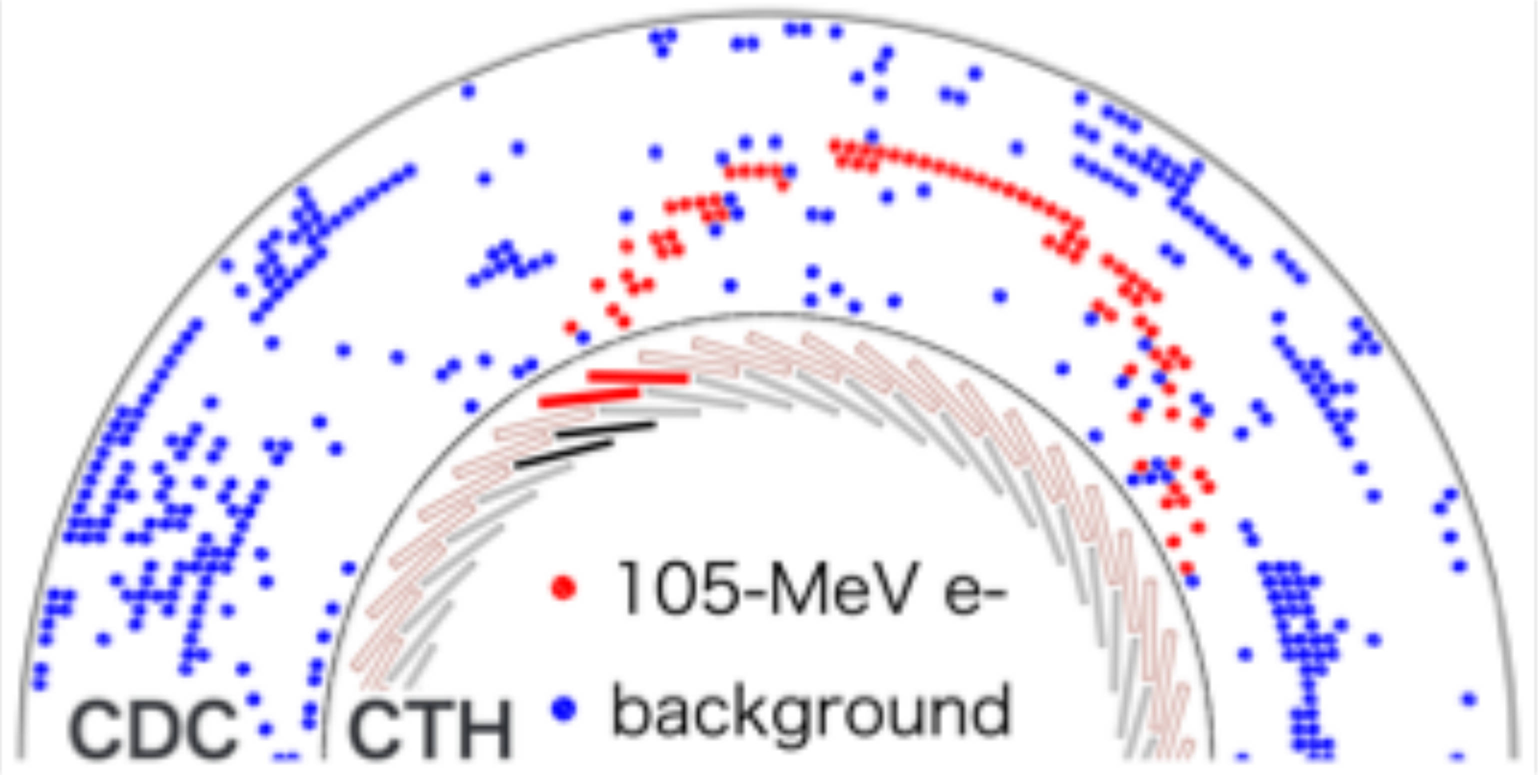
95% background rejection for 99% hit efficiency

Hit selection using Gradient Boosting Decision Trees (GBDT)

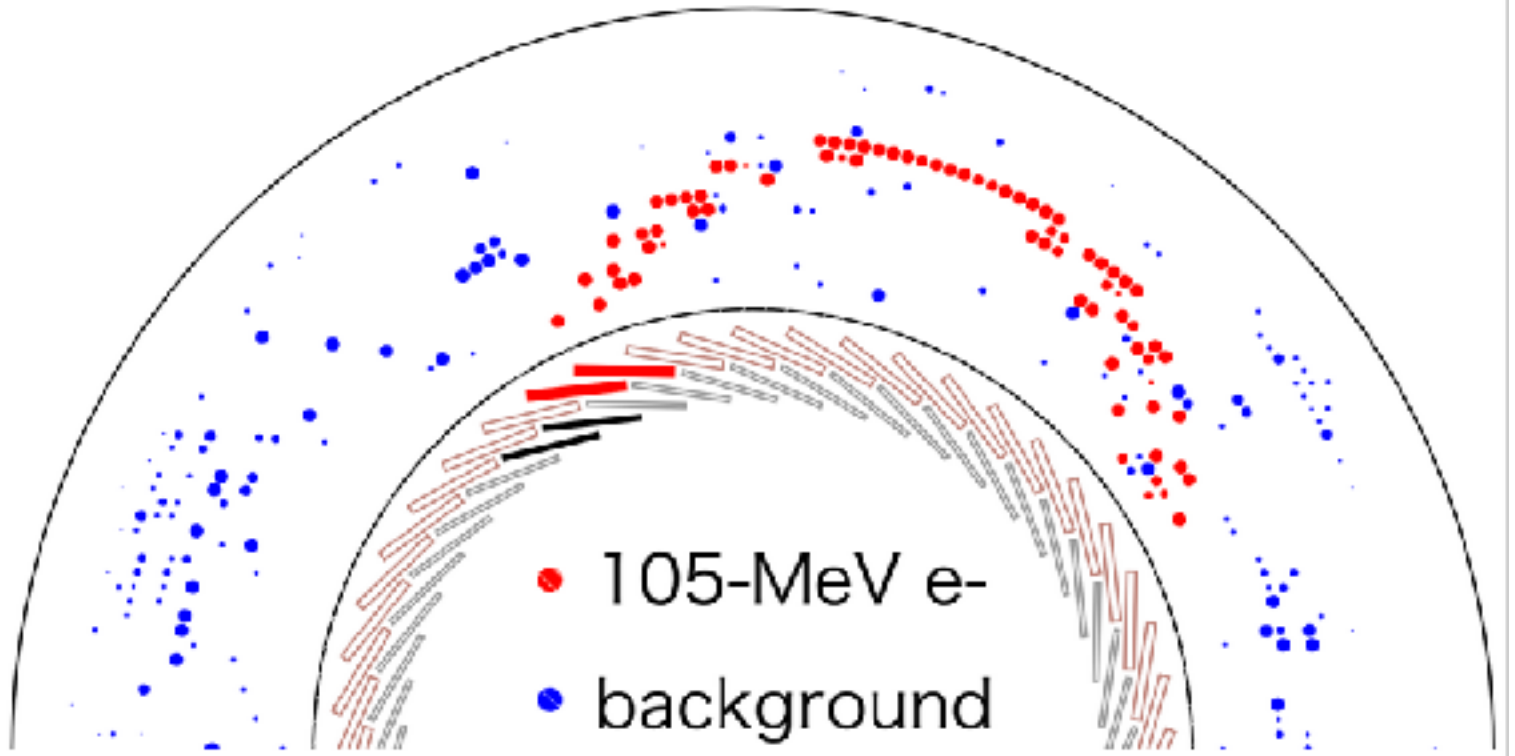
Classify hits using their local neighbours, charge and layer information

Lookup table stored in a FPGA on the trigger board COTTRI.

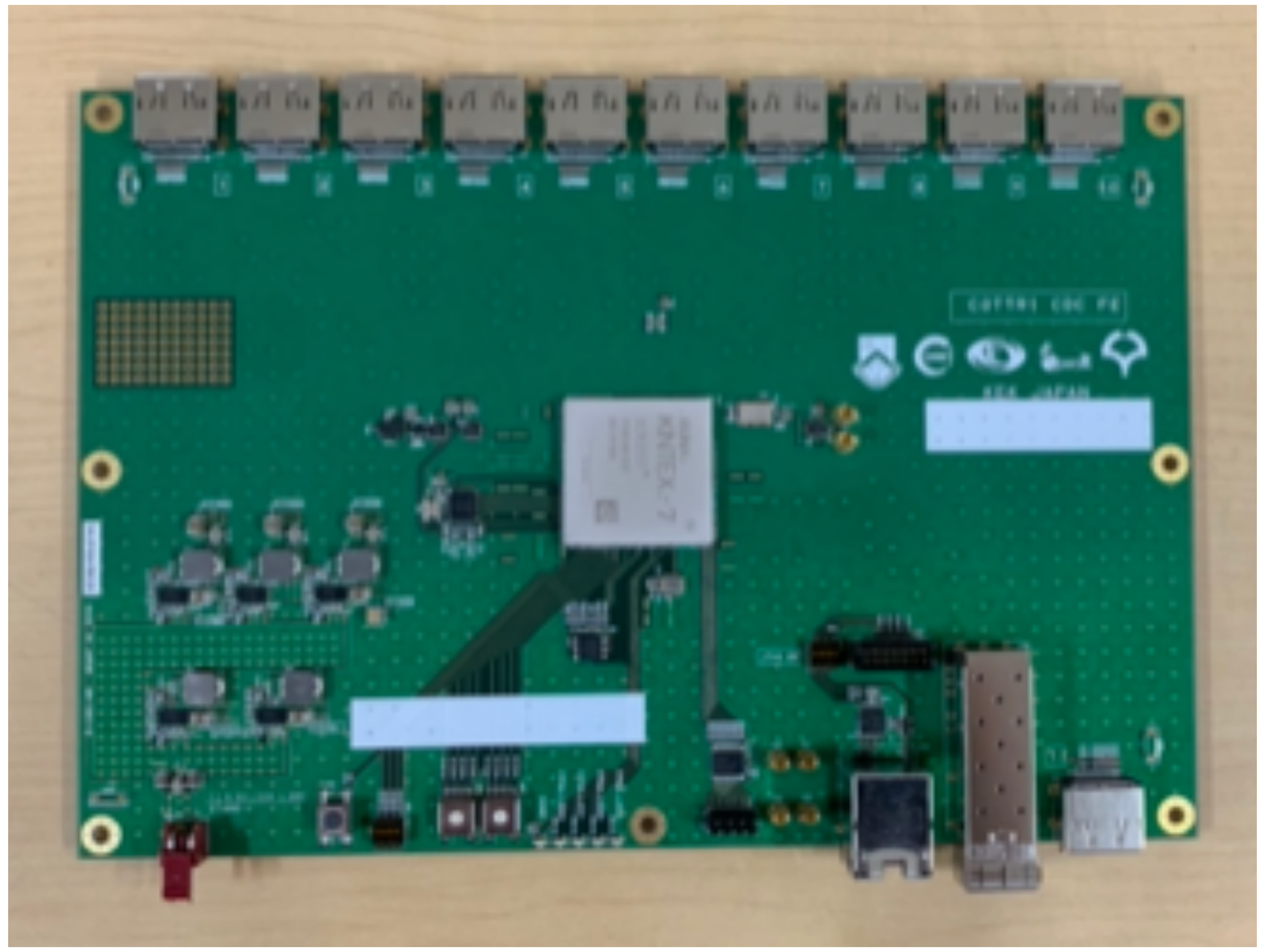
Trigger rate is reduced from 91 kHz to 13 kHz for 96% efficiency and 3.2μs latency



before GBDT



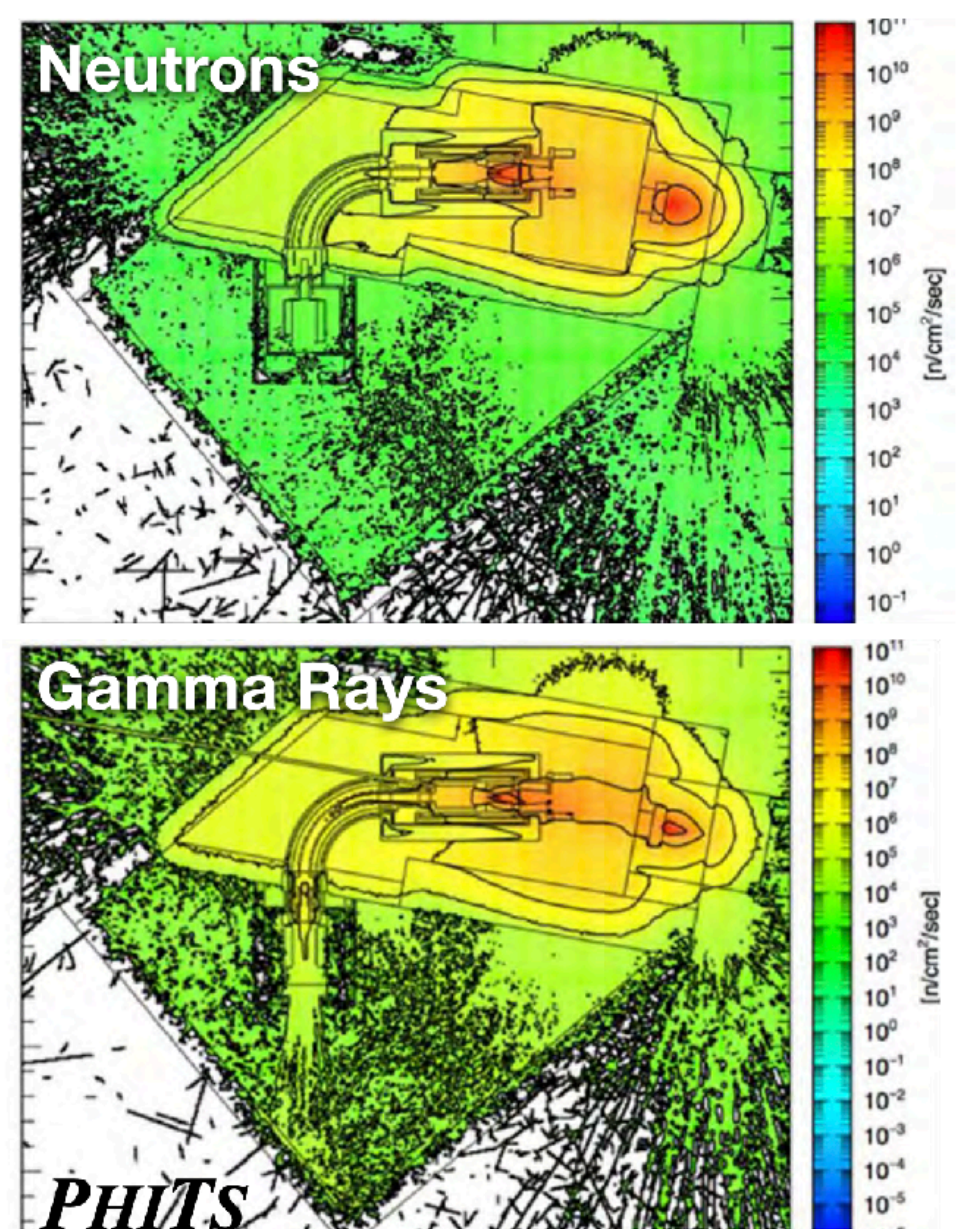
after GBDT



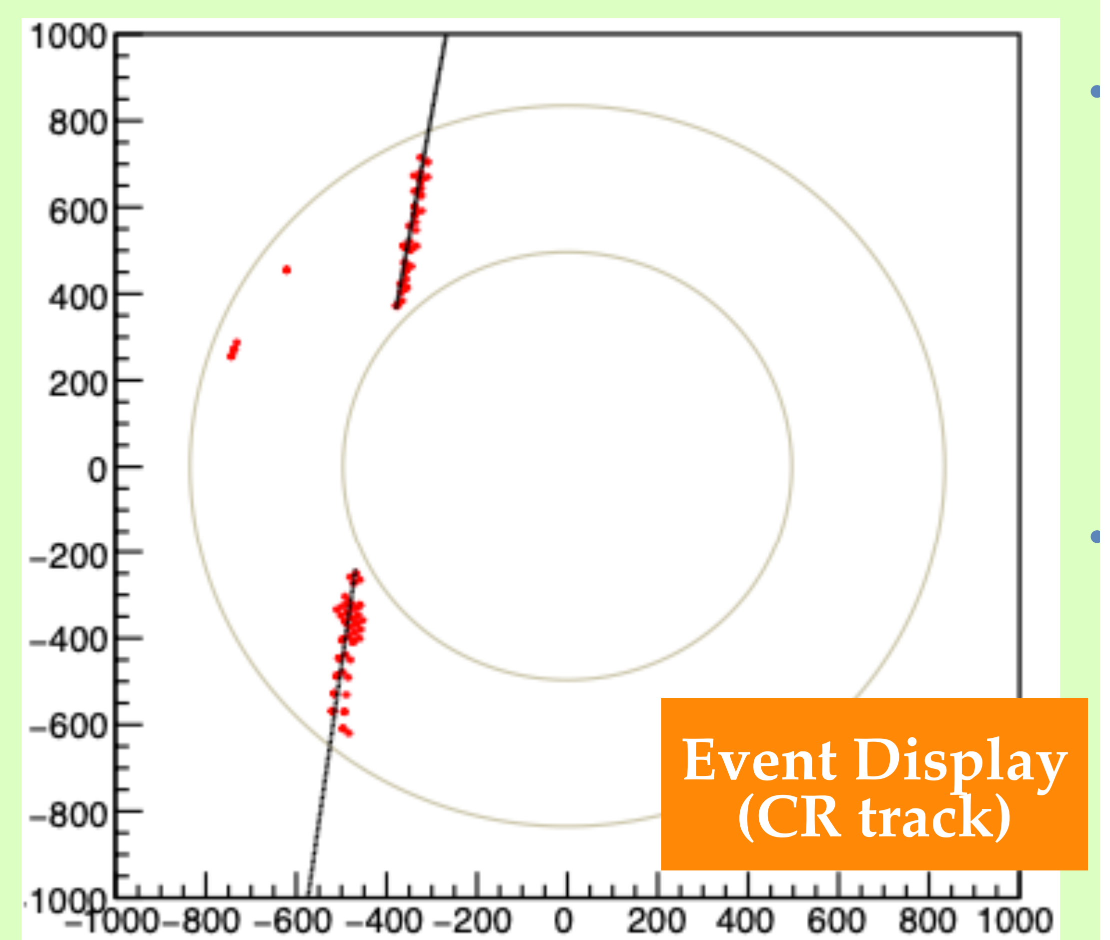
COTRI Trigger Board

- Y. Nakazawa, PhD thesis, Osaka University 2020
- Y. Nakazawa et al. IEEE NS, 2021

- 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
- Radiation issues
  - Electronics components
    - Regulators, optical transceiver etc.
  - FPGA
    - SEU, MBE etc.
- Irradiation tests carried out



COMET Status :: CDC

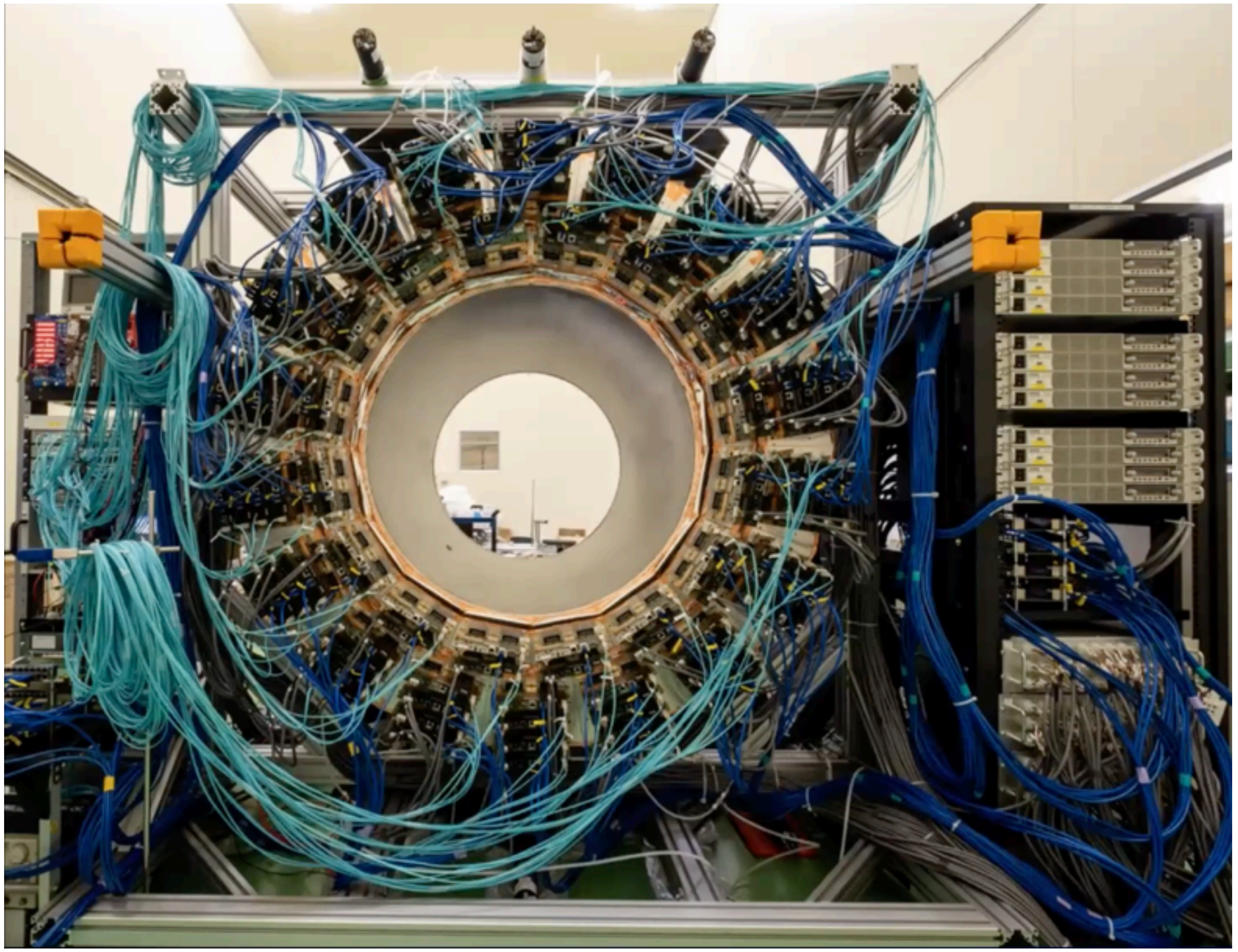


Event Display
(CR track)

- CDC completed in 2016
- fully read out since 2019

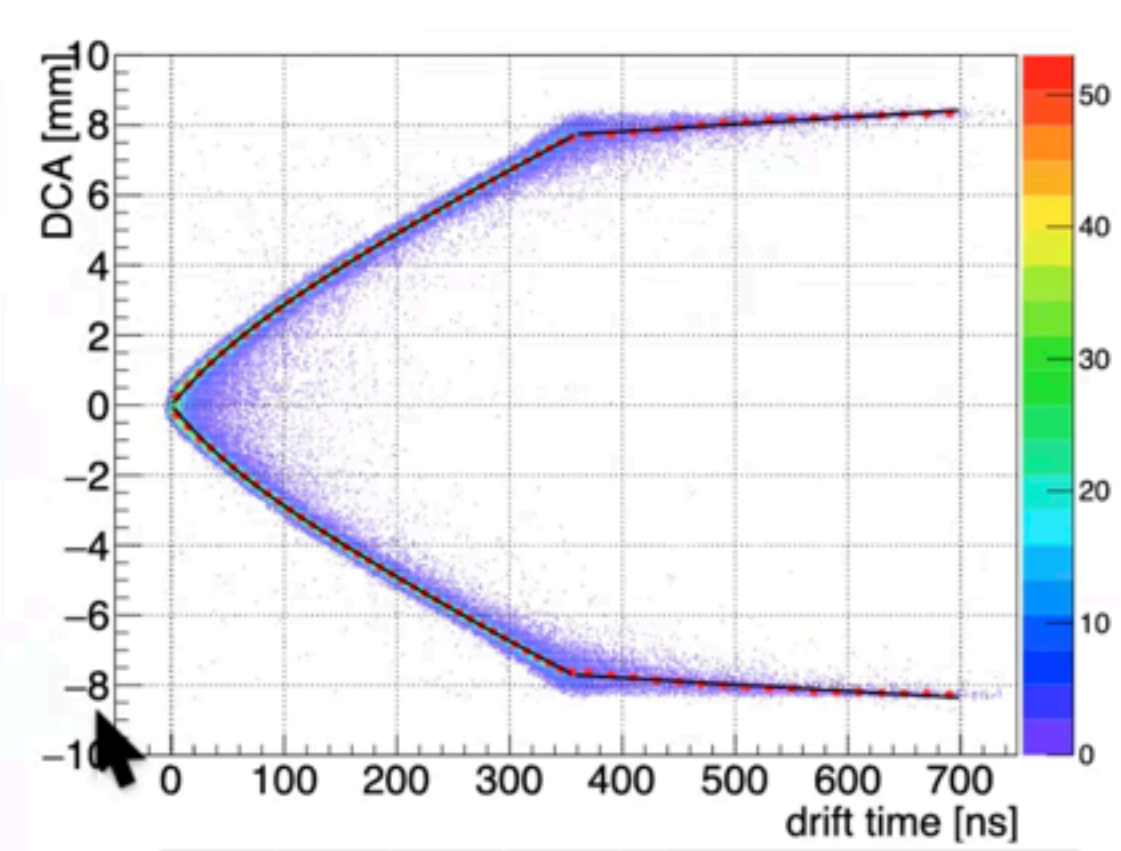
Currently at KEK being commissioned with cosmic rays

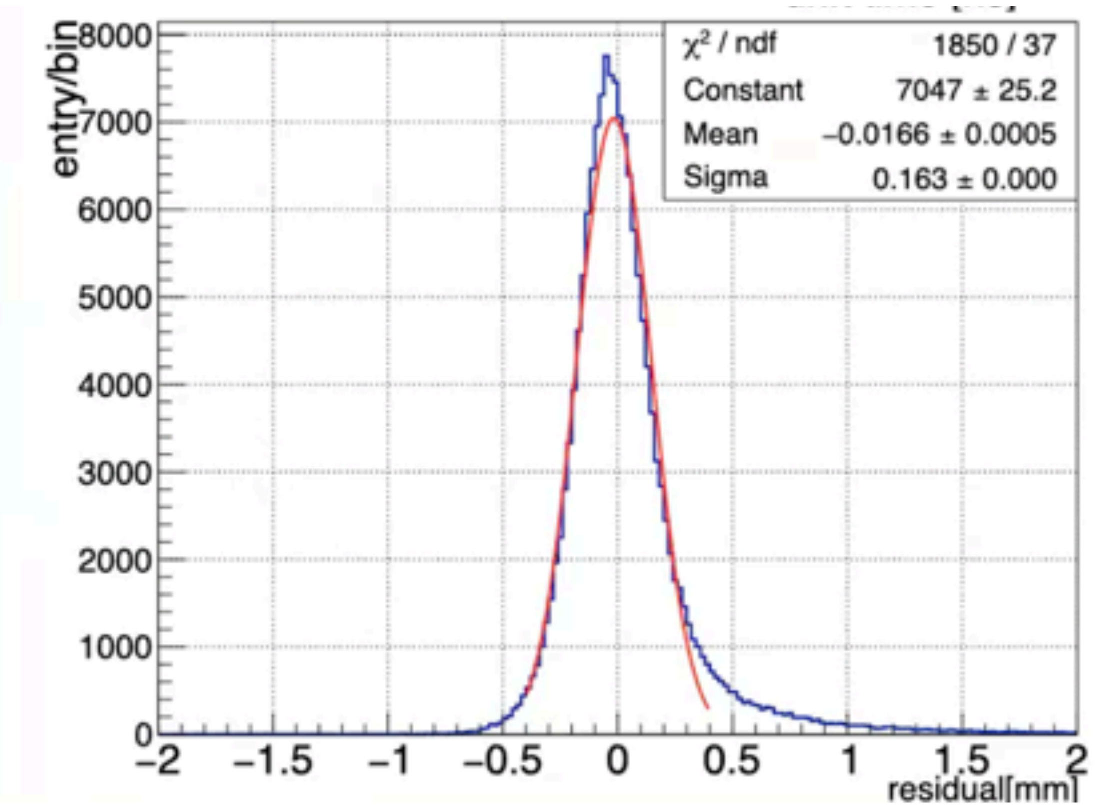
- Spatial resolution of 170 μm, including tracking uncertainty, achieved.
- Hit efficiency of 98% achieved
- Significant noise reduction achieved
- Detail study of detector response
  - space-charge effects
  - crosstalks
- Water cooling testing of the CDC readout underway



Test of a small prototype of the COMET cylindrical drift chamber
Nucl. Inst. Meth A 1015 (2021) 165756.

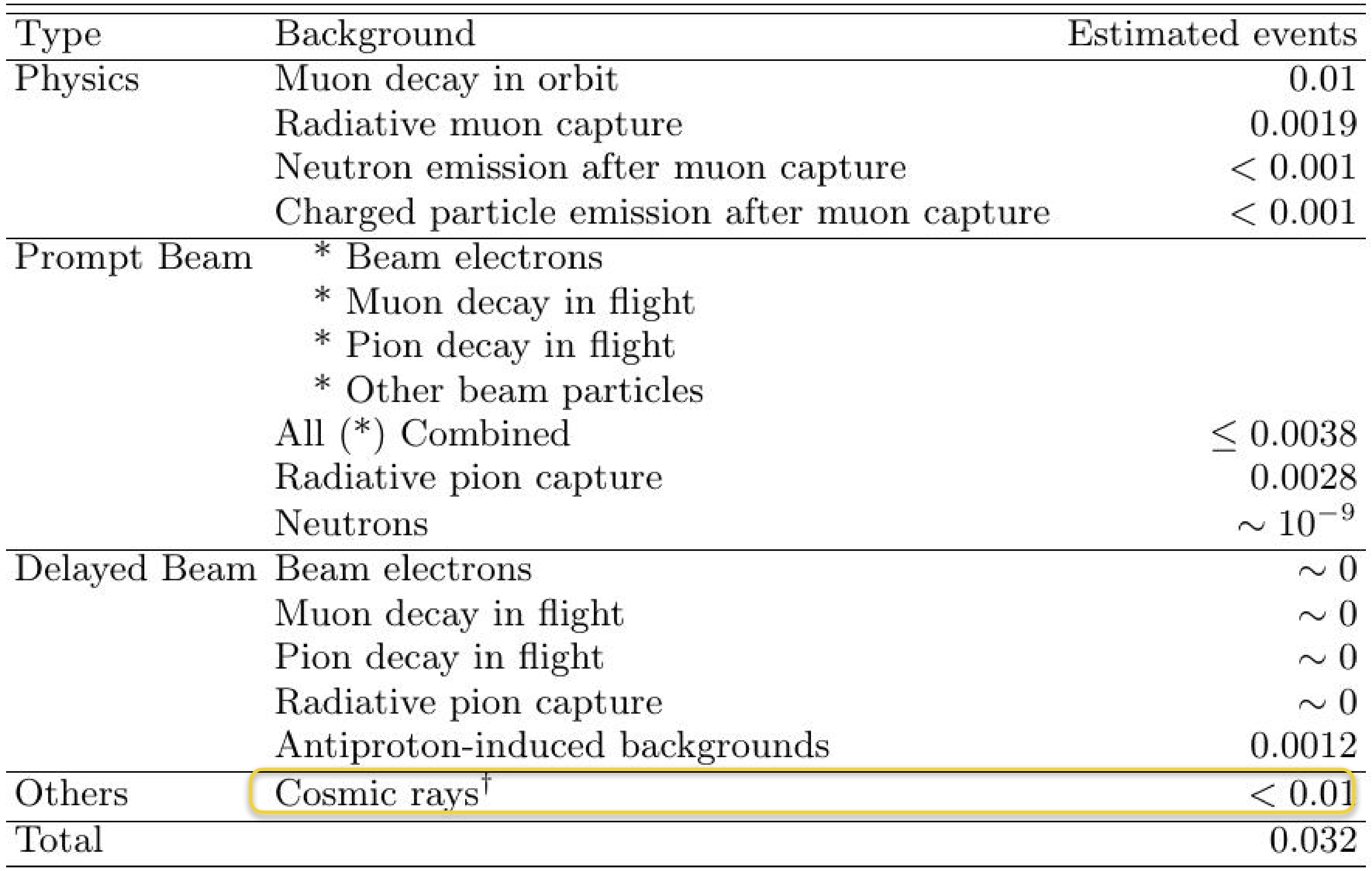
HV=1850 V
He /i-C4H10 90/10
100 cc/min





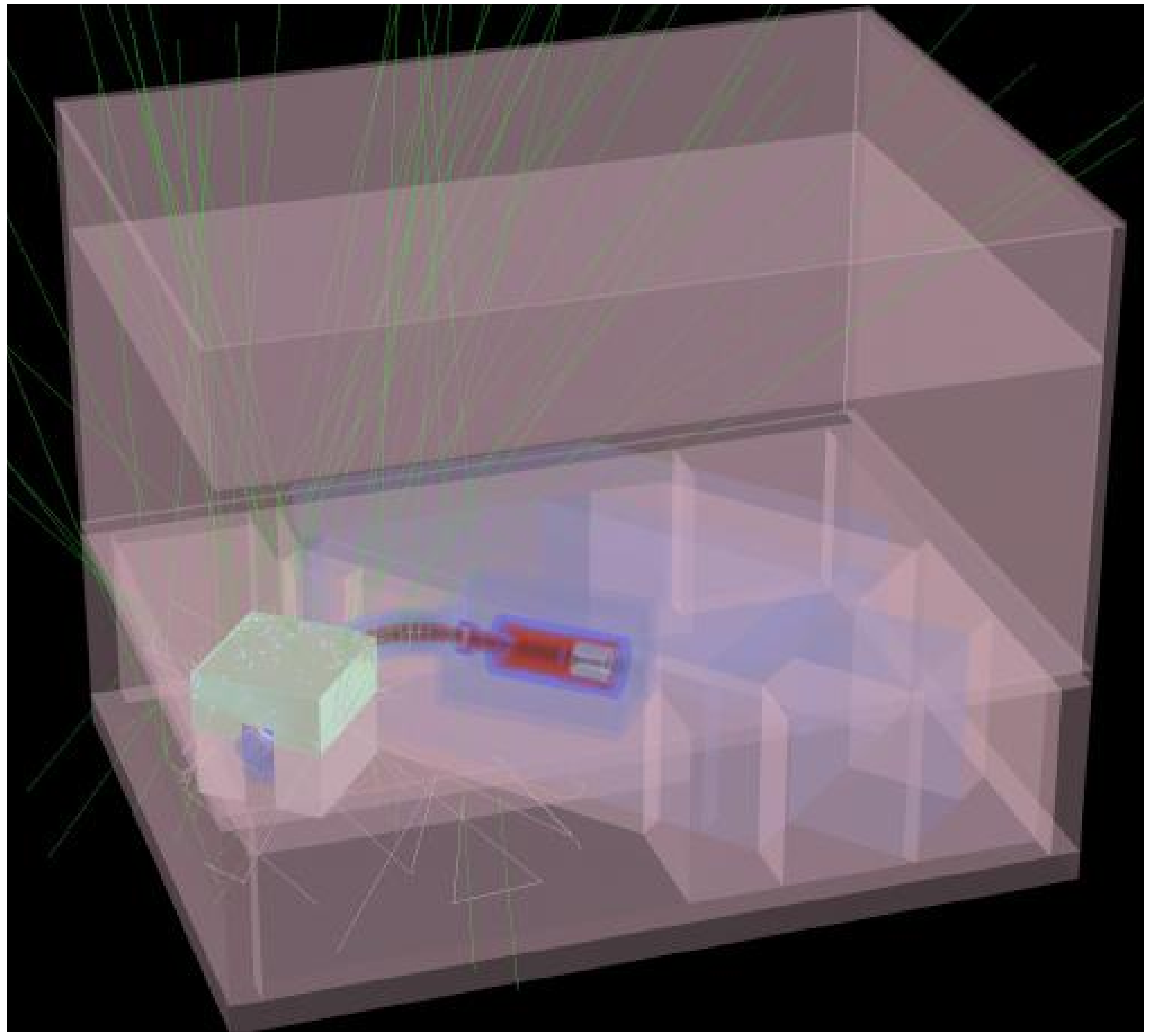
COMET Phase I :: Backrounds

$$BR(\mu^- + Al \to e^- + Al) = 3.1\times10^{-15}$$



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}

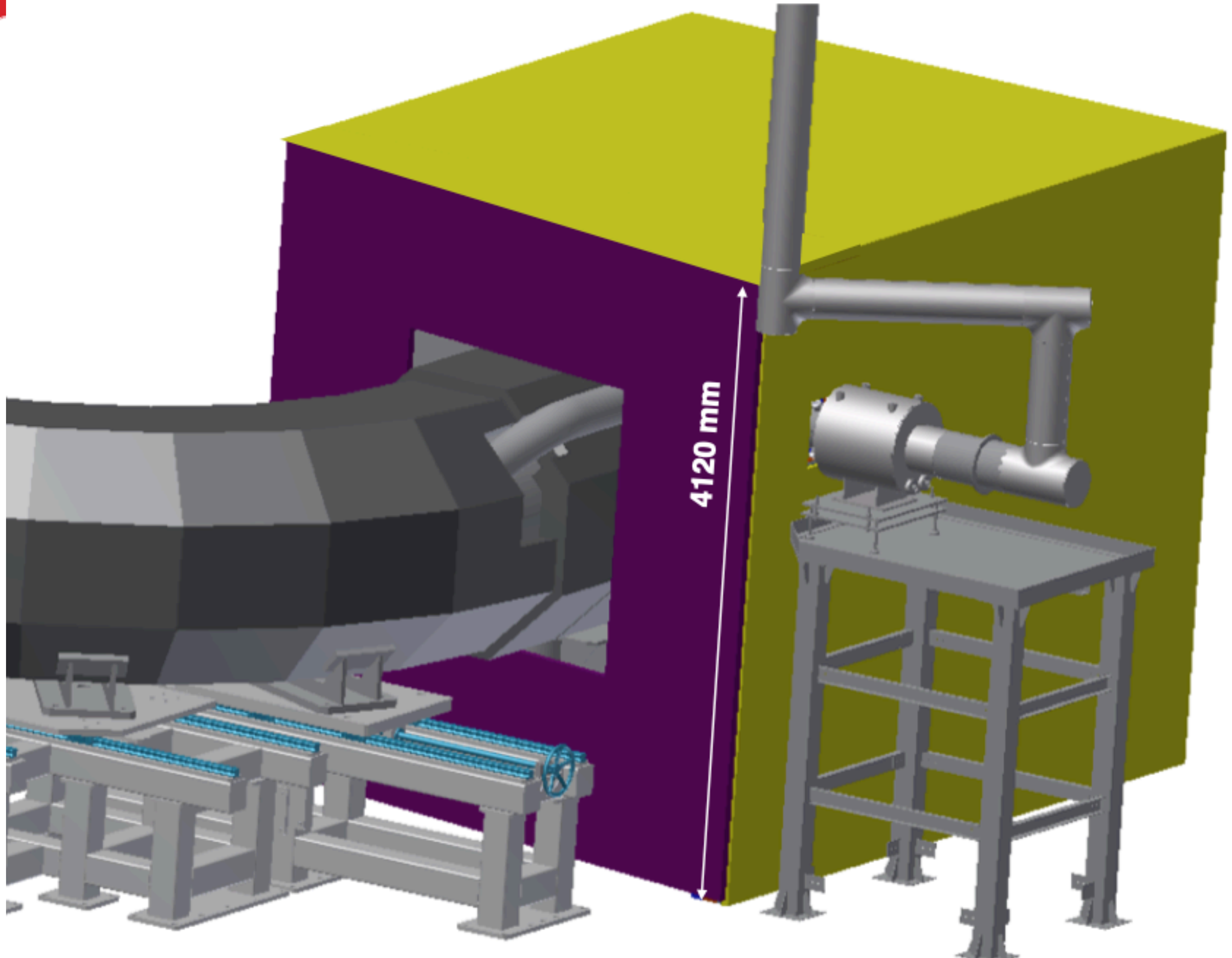


Atmospheric muons may interact with de detector and induce signal-like electrons

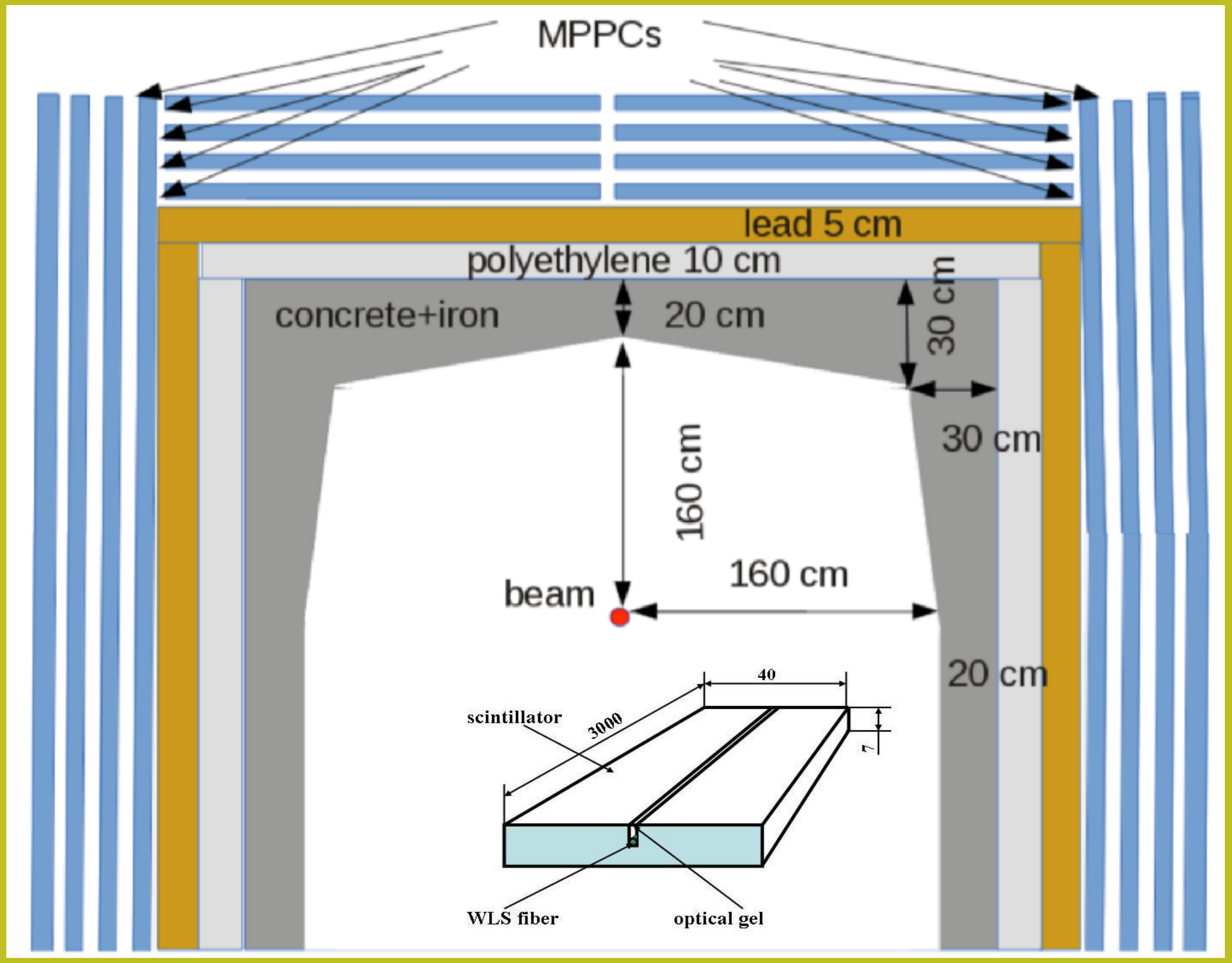
Need to cover as hermetically as possible the detectors (CDC) with very high efficiency veto counters (CRV)

The short data acquisition foreseen for Phase I helps !

COMET Phase I :: a hybrid CRV



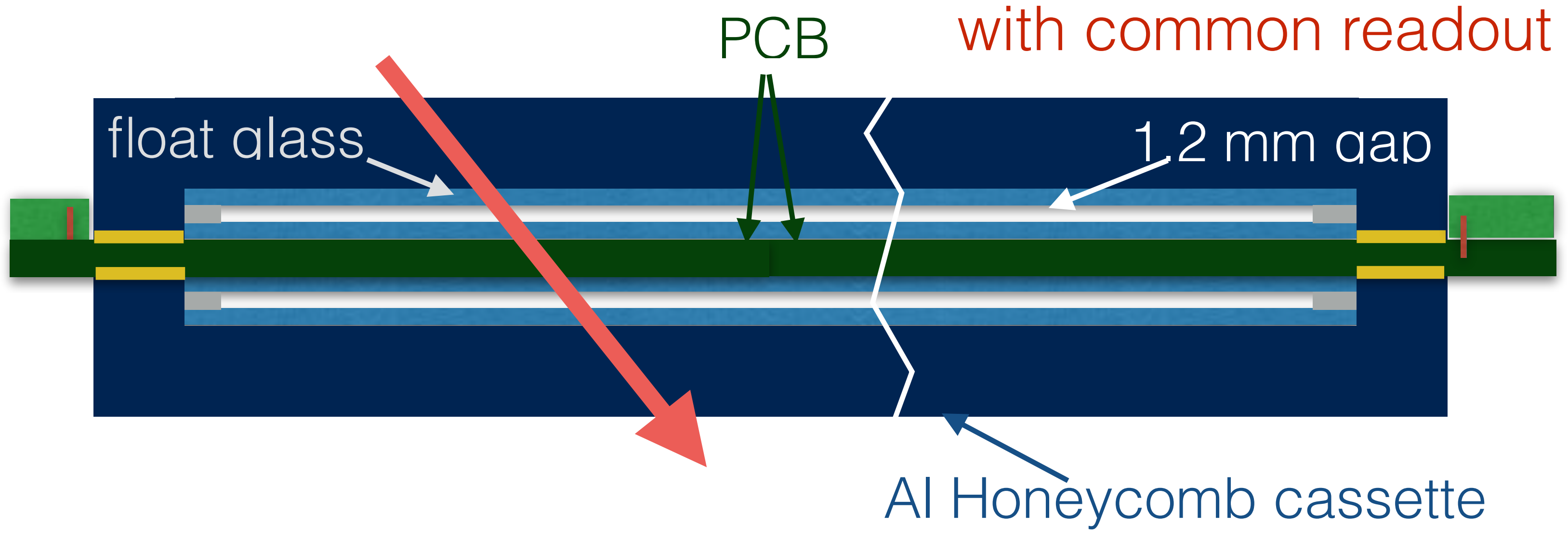
Scintillators CRV



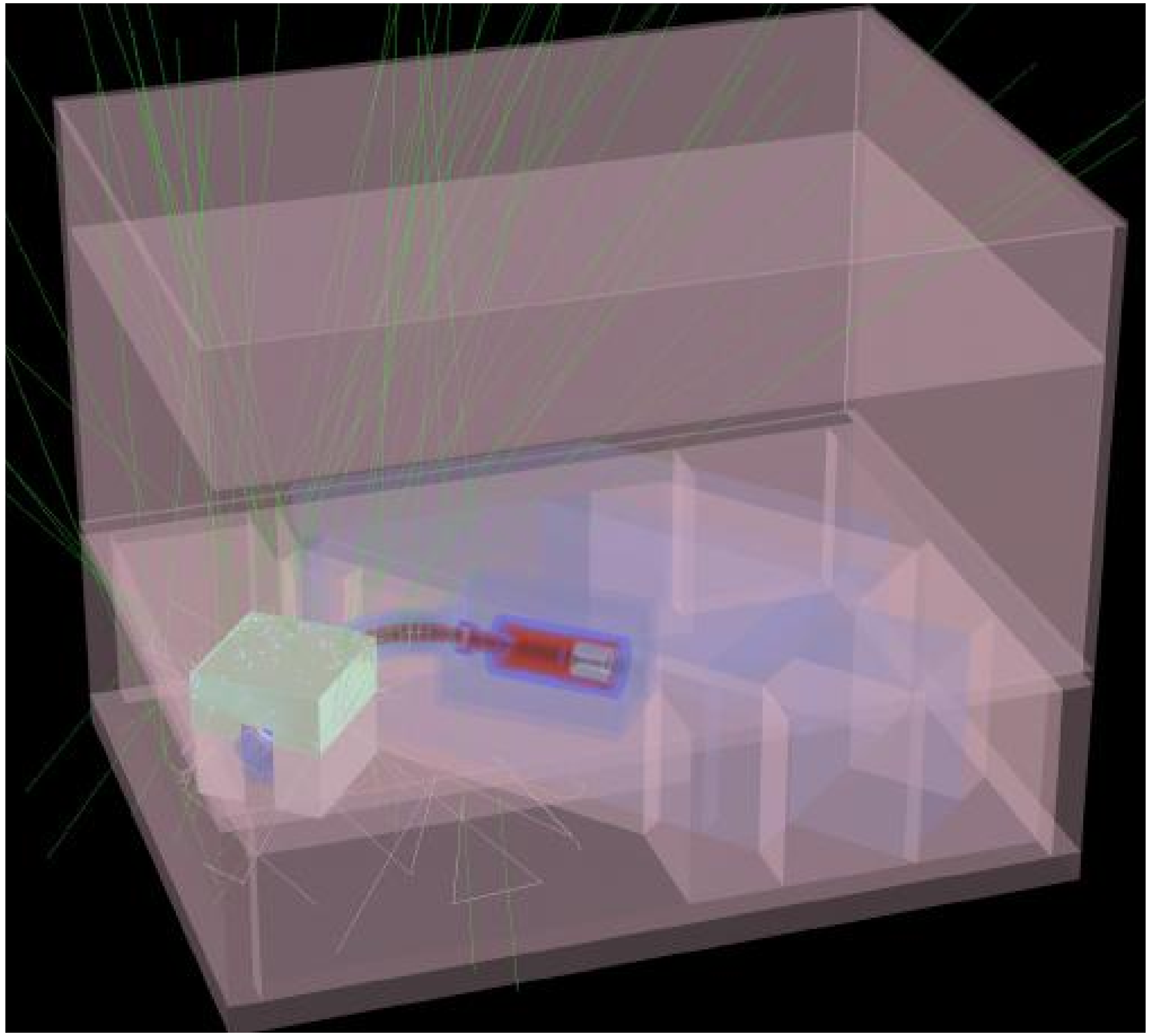
GRPC CRV

A tracker module: 7 detector modules (baseline)

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



A Backward MC to Estimate the Atmospheric Background



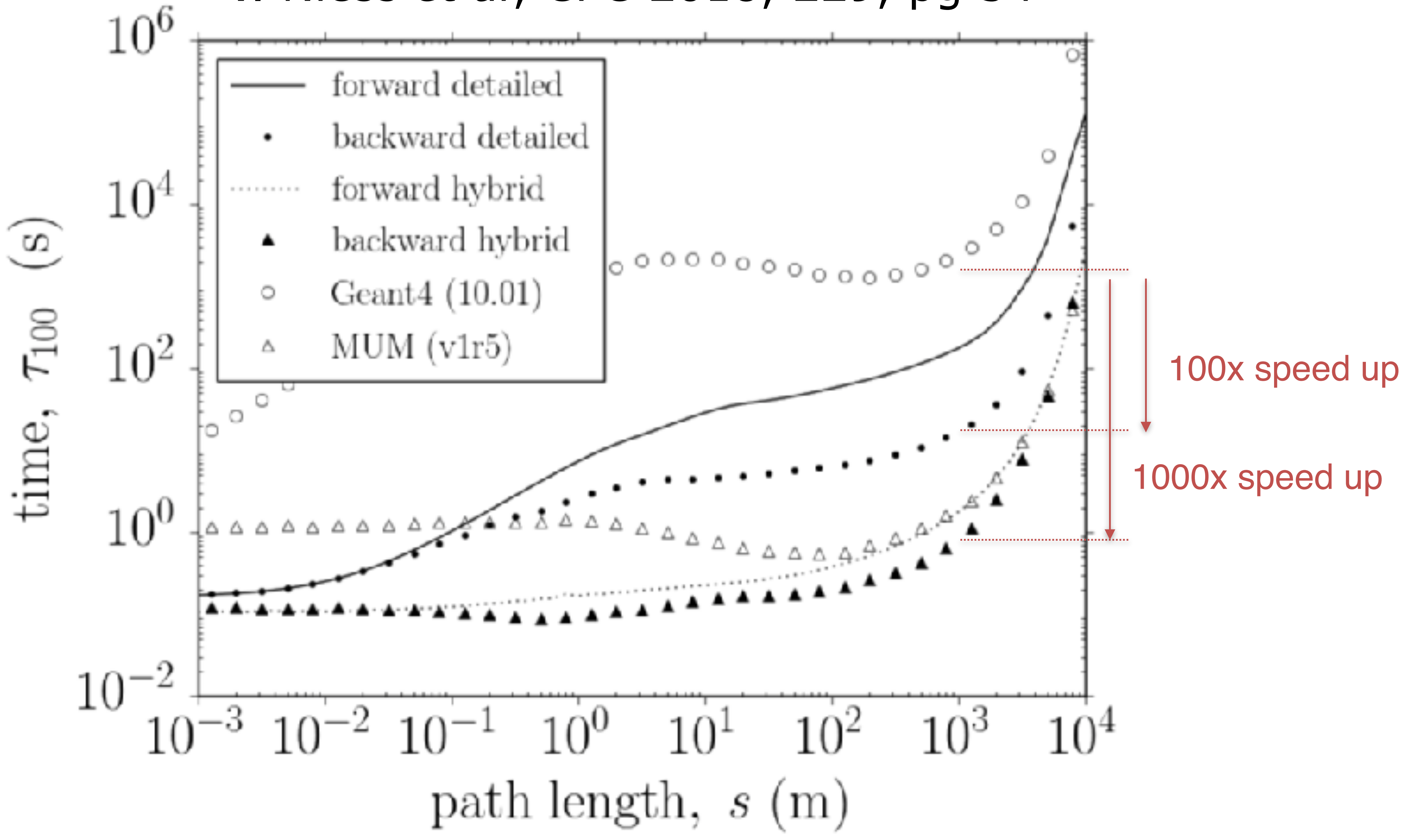
Non analog simulation using Importance Sampling and Backward Monte Carlo

- Run a standard SimG4 simulation with primary muons generated close to (and illuminating) the CDC
- Select candidate events using COMET signal selection criteria
- Backward propagate the selected primary muons up in the atmosphere

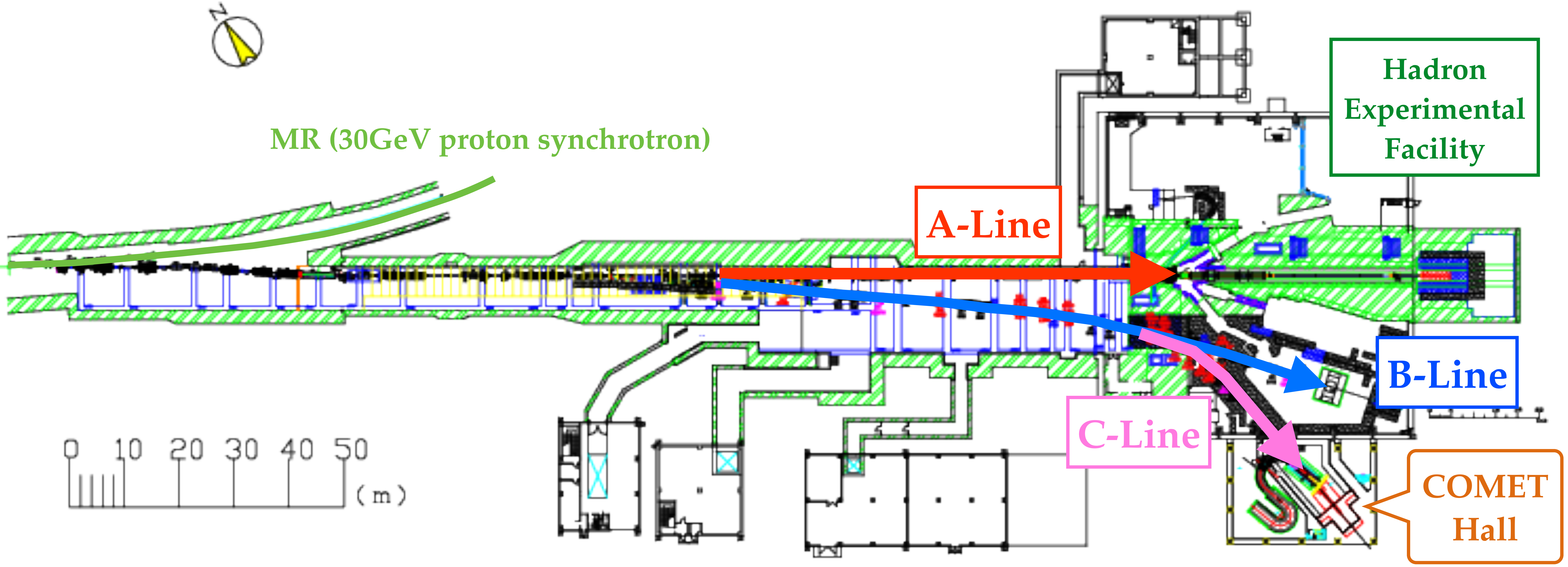
The corresponding MC rate (in Hz) is given by the ratio of the flux to the bias generation PDF

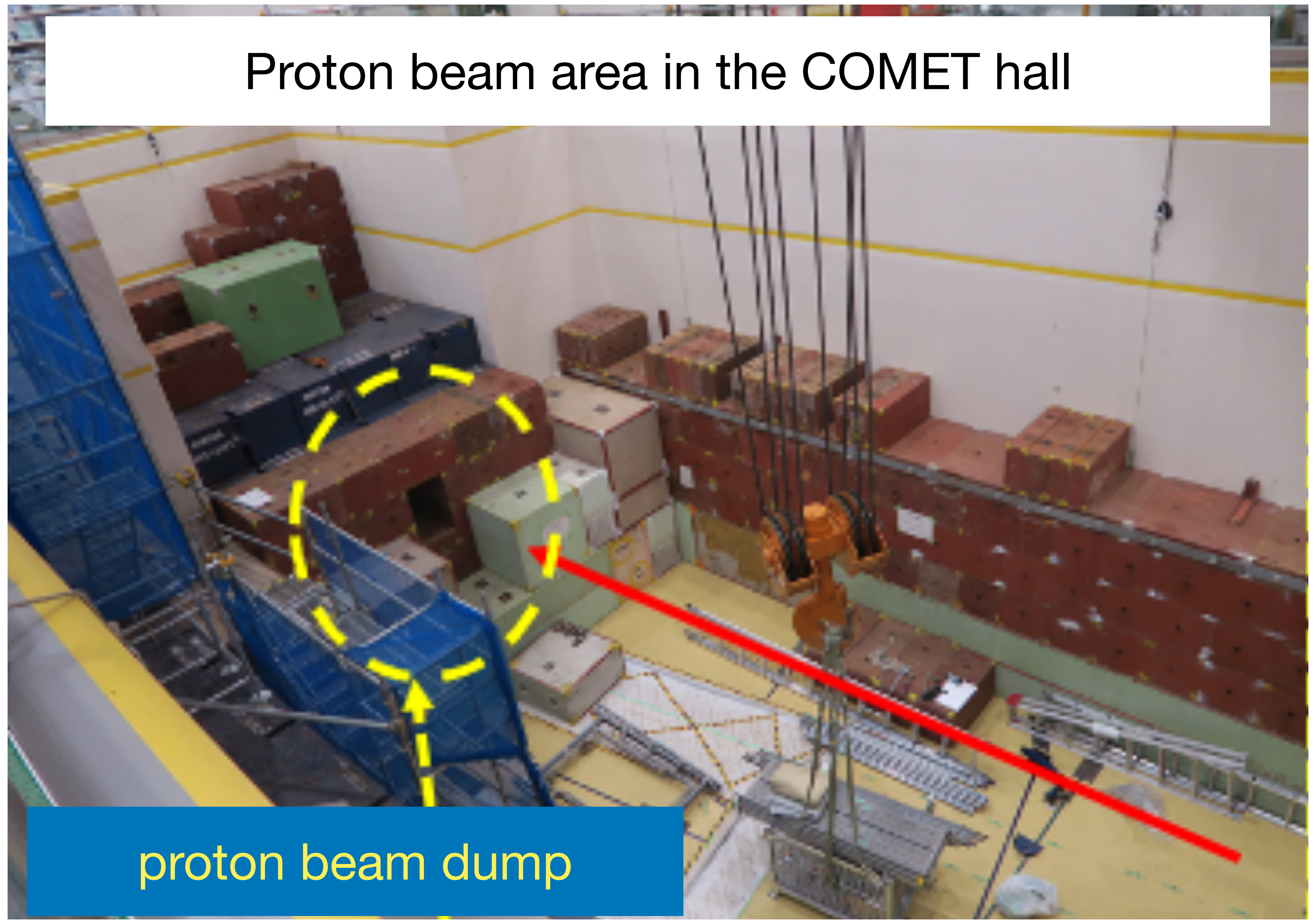
CPU time needed to simulate the transmitted flux with 1% accuracy

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



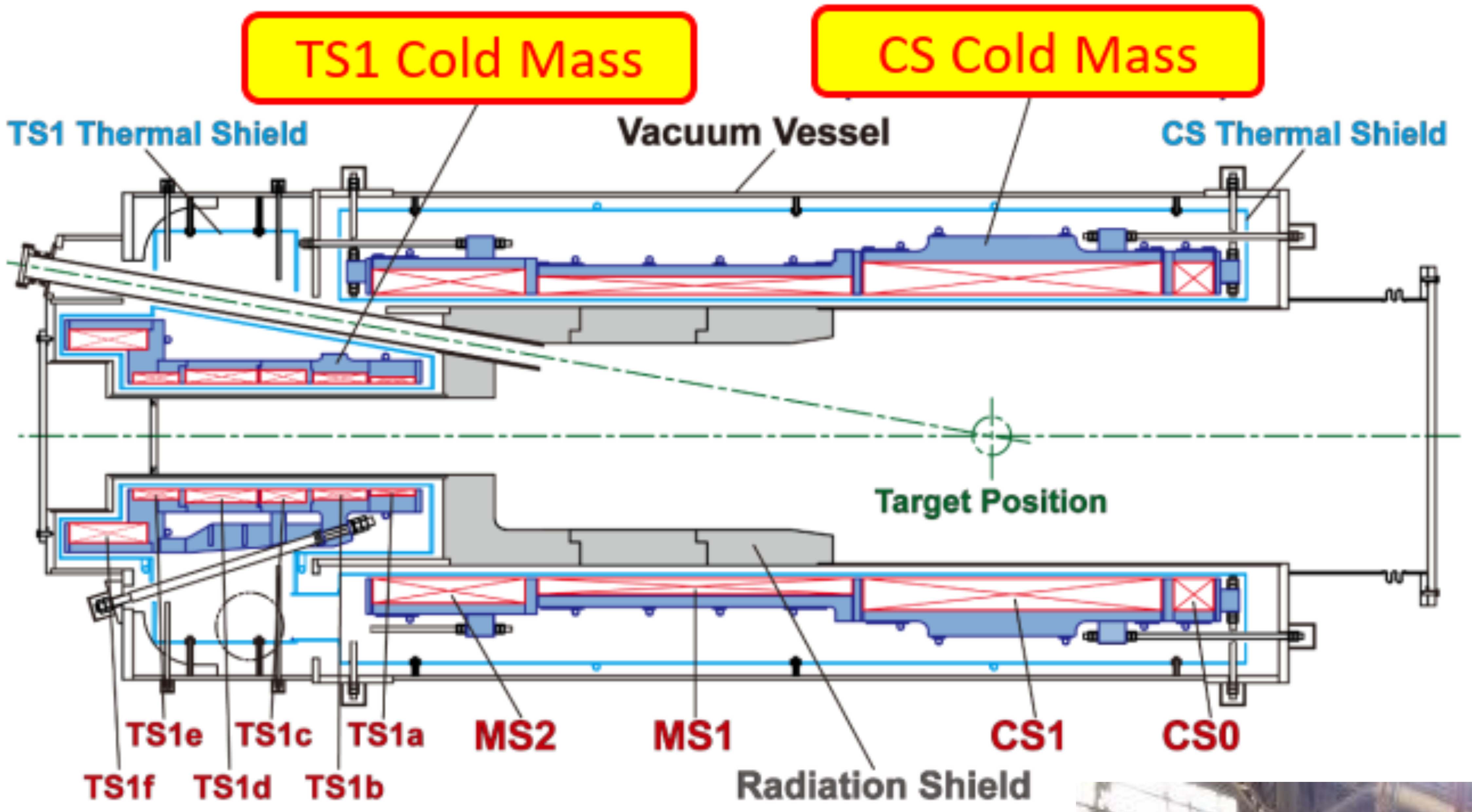
COMET Status :: Facility Construction



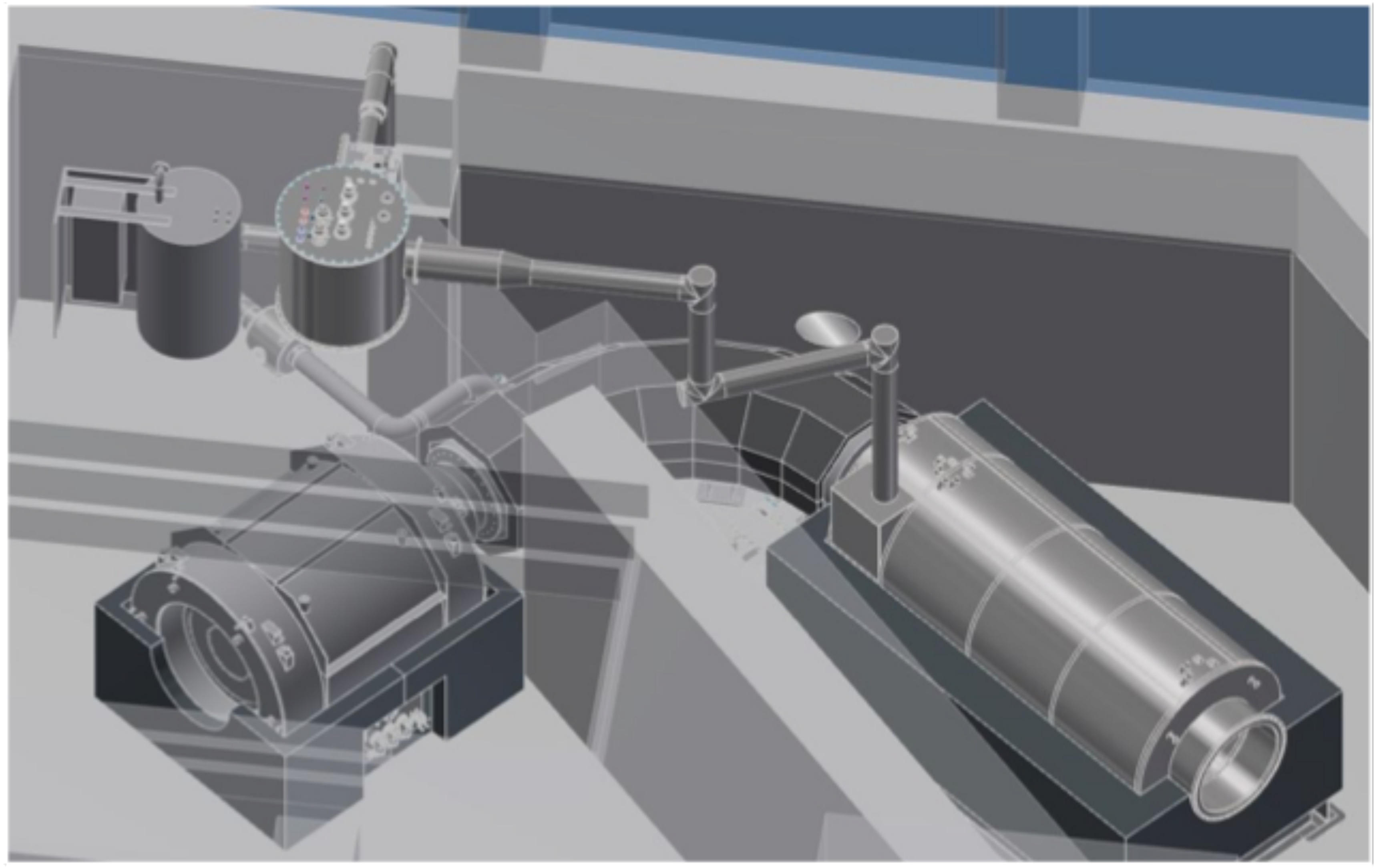


- The upstream of the proton C line has been completed in 2021.
- The proton beam area in COMET hall to be completed in 2022.

COMET Status :: Capture solenoids Construction



- The pion capture solenoids (CS and TS cold mass) will be delivered in summer 2023. The cryostats are under construction.
- The pion capture system to be completed by summer 2022.



CS cold-mass

TS1 cold-mass

COMET Phase1:: Proton Beam Extinction

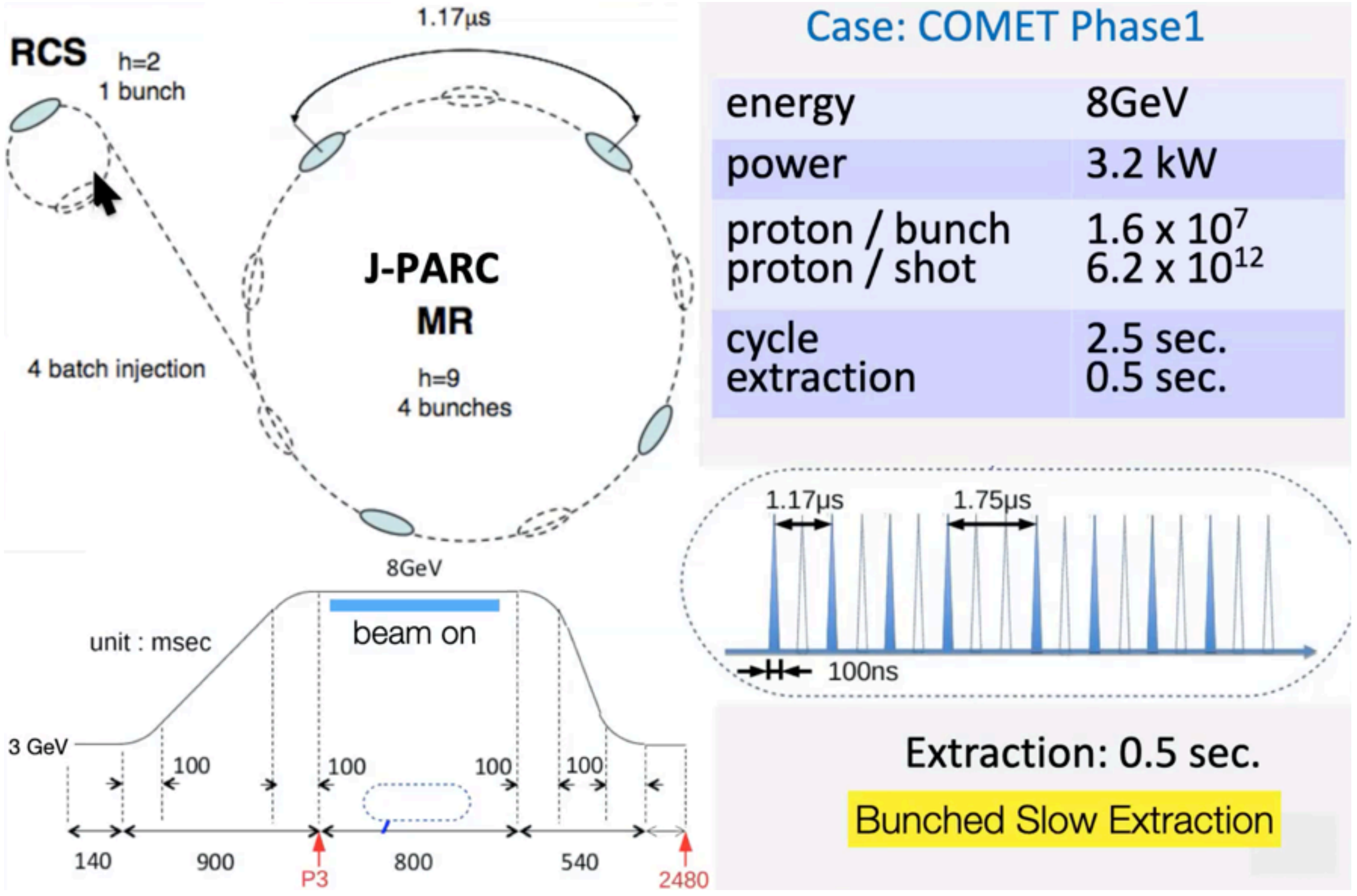
Pulsed beam to reduce the electron and pion beam background

Tiny leakage of protons in between consecutive pulses can cause a background through Beam Pion Capture process:

$$\pi^- + (A,Z) \rightarrow (A,Z-1)^* \rightarrow \gamma + (A,Z-1)$$
$$\gamma \rightarrow e^+ e^-$$

Requirement:

extinction less than 10^{-10} to reach design sensitivity $O(10^{-17})$

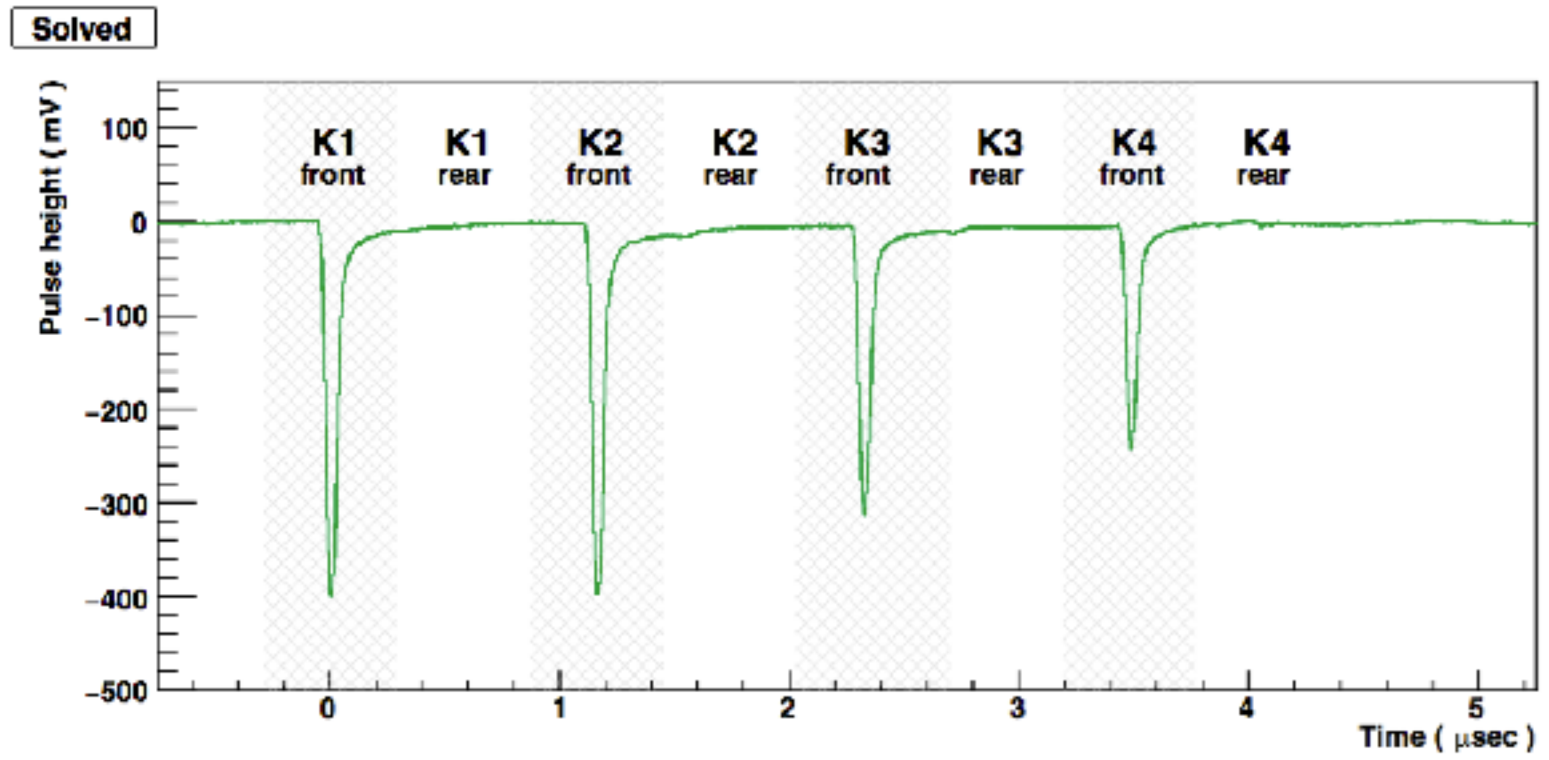


Case: COMET Phase1

energy	8GeV
power	3.2 kW
proton / bunch proton / shot	1.6×10^7 6.2×10^{12}
cycle extraction	2.5 sec. 0.5 sec.

Extraction: 0.5 sec.

Bunched Slow Extraction

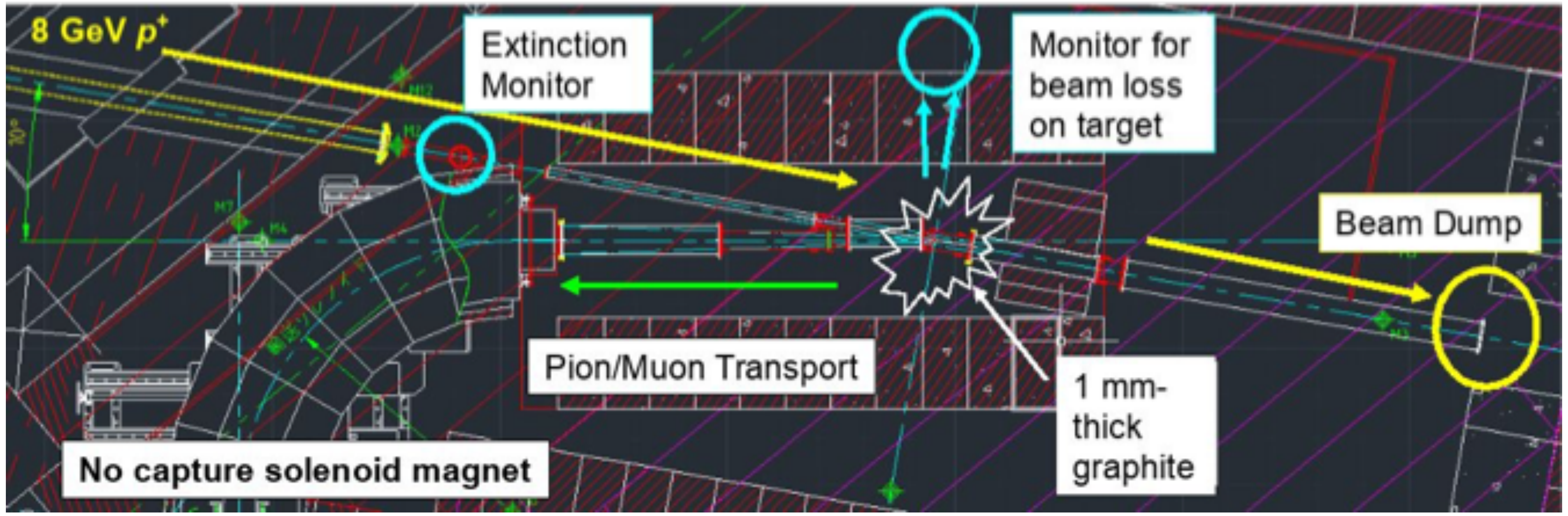


Tested in February 2019 and May 2021, see K. Noguchi's talk

COMET Phase α

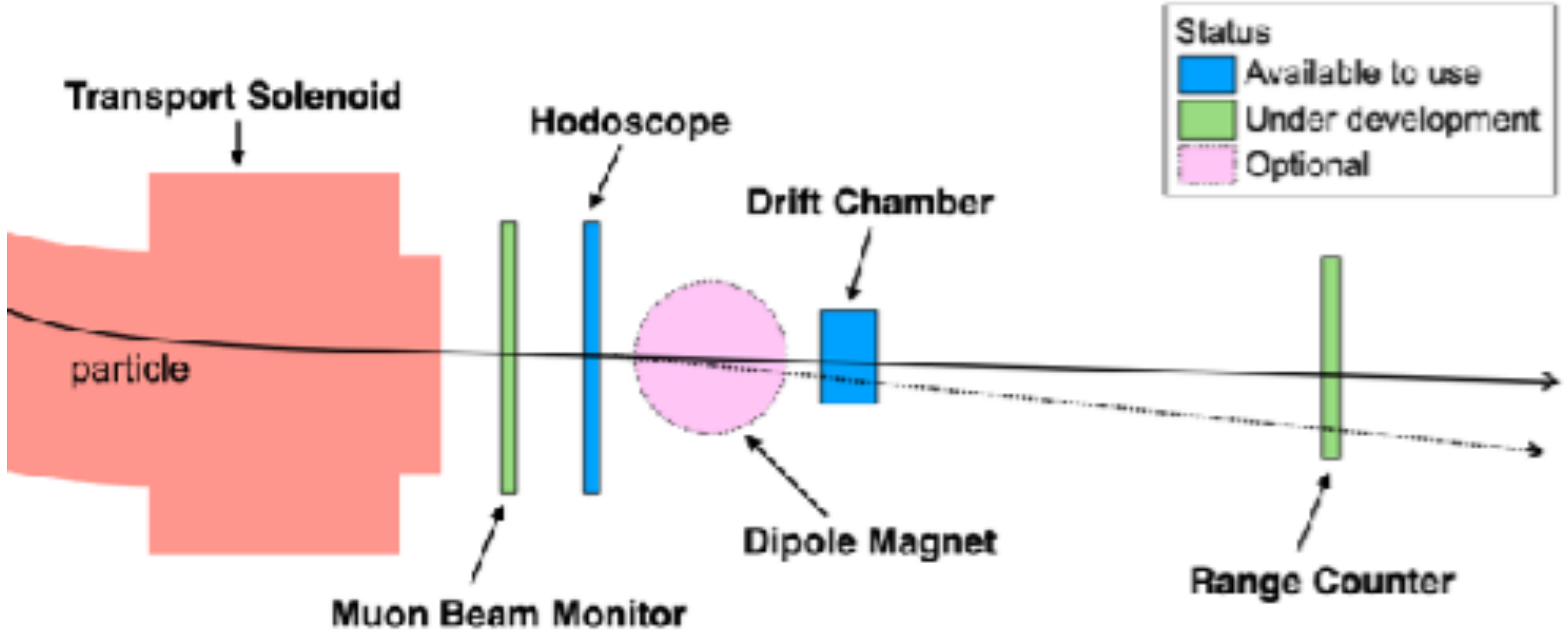
- Takes advantage of the early delivery (2022) of the 8 GeV proton beam to COMET
- Low intensity run (260 W) without Pion Capture Solenoid
- Thin graphite pion-production target
- Proton beam diagnostic detectors
- Secondary particle detectors

To be performed end of 2022



Goals

- proton beam commissioning @ COMET
- proton beam diagnostic @COMET
- measurements of pion and muon yields in the secondary beamline



COMET Phase I Timeline

- Facility:
  - Proton beam for the COMET experimental hall expected be completed in 2022.
  - The first commissioning of proton and muon beams (COMET Phase α) planned by end of 2022.
  - Completion of pion capture system foreseen in 2023.

- Detectors:
  - CyDet has been tested with cosmics at KEK and will be moved to J-PARC in 2022.
  - StrCAL will be ready by summer 2023.
  - CTH and CRV expected to be completed by end 2022 and 2023, respectively.

- Start of the COMET Phase-I engineering run foreseen for end 2023 followed immediately by physics data taking.

- COMET Phase-II expected to follow shortly COMET Phase-I.

Conclusion

- COMET at J-PARC will search for neutrinoless muon to electron conversion with an expected SES of 2.6×10^{-17} (4 orders of magnitude below the current limit) after 1 year of data taking using a 56 kW, 8 GeV proton beam.
- The experiment will proceed in two phases, with Phase-I (currently in preparation) expected to reach a S.E.S of 3×10^{-15} within 150 days of data taking using a less intense 8 GeV proton beam (3.2 kW).
- COMET Phase-preparation (proton beam, experimental area and detectors construction) proceeds rapidly and on schedule despite the pandemics
- COMET physics data expected in 2024.