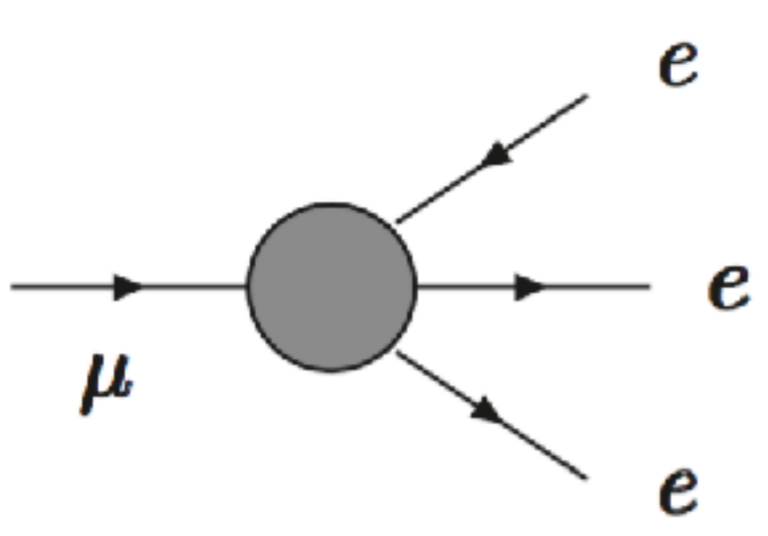
INTENSITY frontier GDR-InF

Experimental Searches for cLFV

C Cârloganu, LPC/IN2P3/CNRS

cLFV in muon channels (SM with $m_\nu > 0$, BR(mu-> egamma) ~10-54)

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



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

vertex;
coincidence

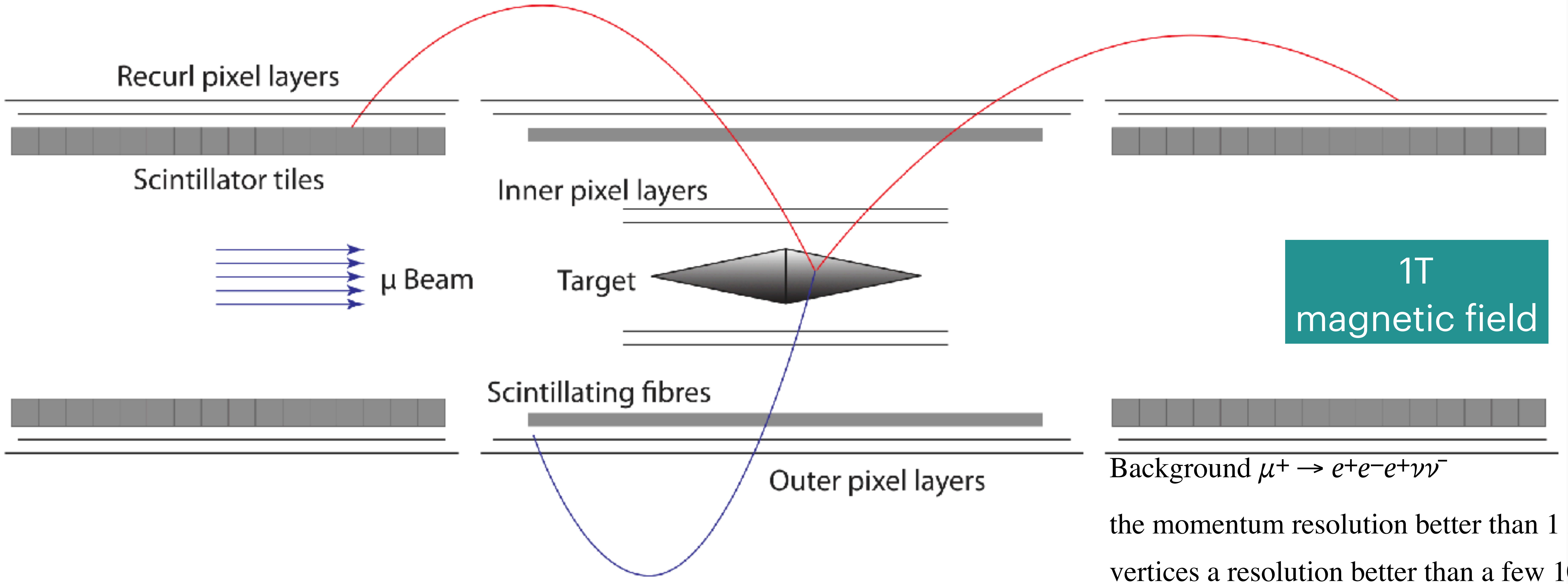
BR(μ → eee) 90% C.L.		
PSI/SINDRUM	**1988**	**1.0×10^{-12}**
JINR	1991	3.6×10^{-11}
PSI/PSI/Mu3e		10^{-15}, 10^{-16}

Technical Design Report for the Phase I Mu3e Experiment, September 2020 Nucl.Instrum.Meth.A 1014, 165679, 2021

Compact Muon Beam Line in PiE5 area

↓

High Intensity Muon Beam (HIMB)



1T magnetic field

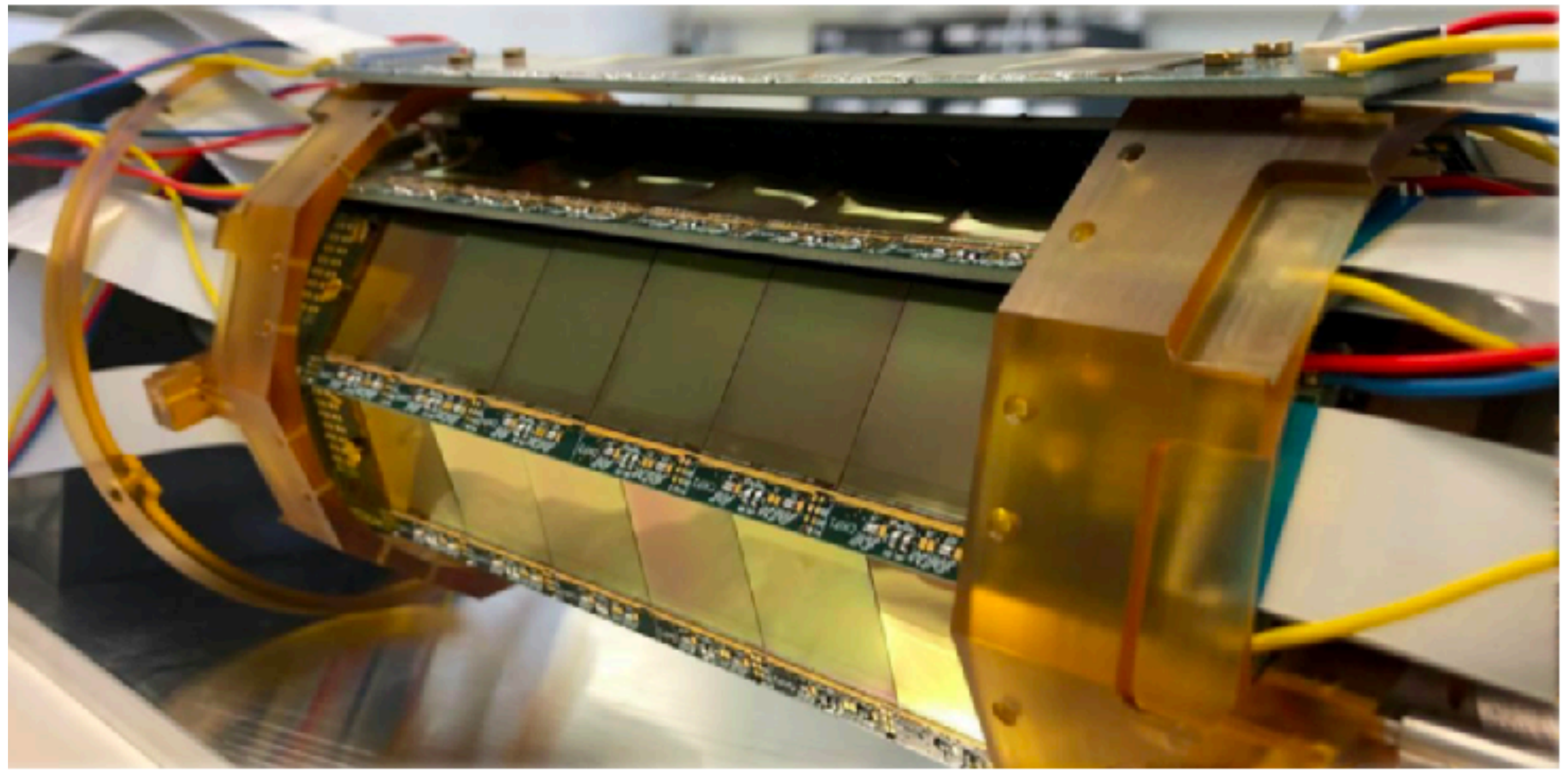
Background $\mu^+ \to e^+e^-e^+\nu\bar{\nu}$

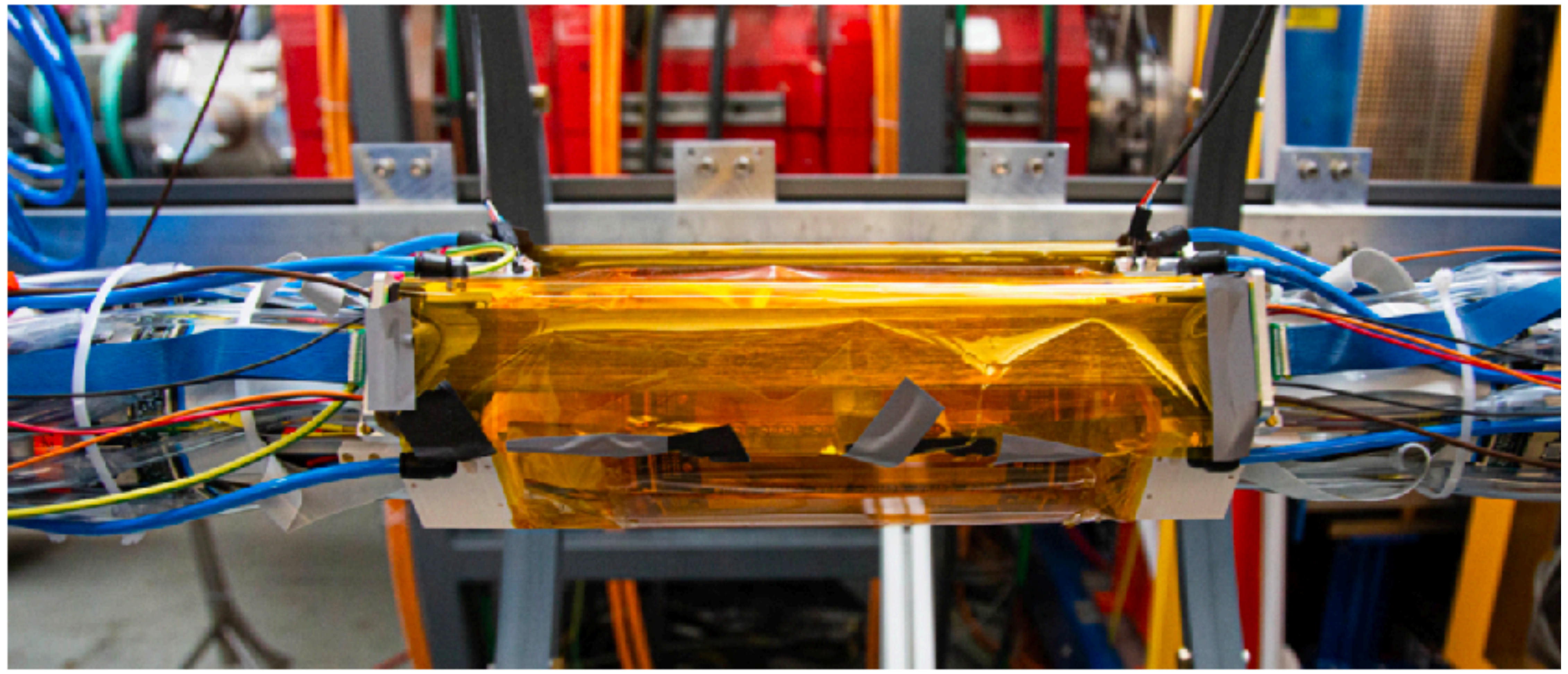
the momentum resolution better than 1 MeV/c,

vertices a resolution better than a few 100 μm

decay time : nanosecond level or better.

Demonstrator vertex detector mounted on the experimental cage with cables attached and scintillating fibre ribbon in its front The pixel detector is surrounded by Kapton foil as part of the simplified helium distribution.





2021 : Mu3e Integration Run at PSI. (integration of services and demonstrator detectors and operation in helium atmosphere within the Mu3e magnet with the muon beam turned on).

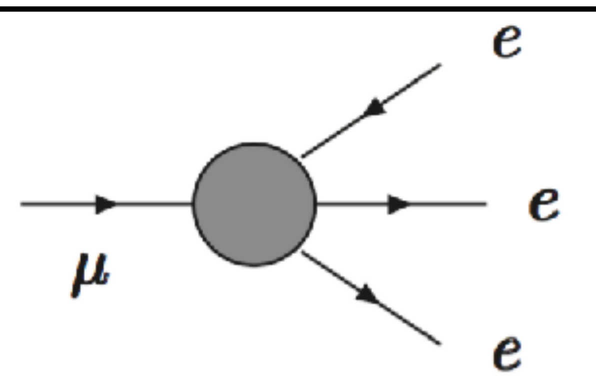
2022 : cosmic muon run : achieved synchronisation.

2023 : commissioning of the inner detector

2024 : Final integration of all sub- detectors, commissioning of the full detector, and physics data taking

cLFV in muon channels

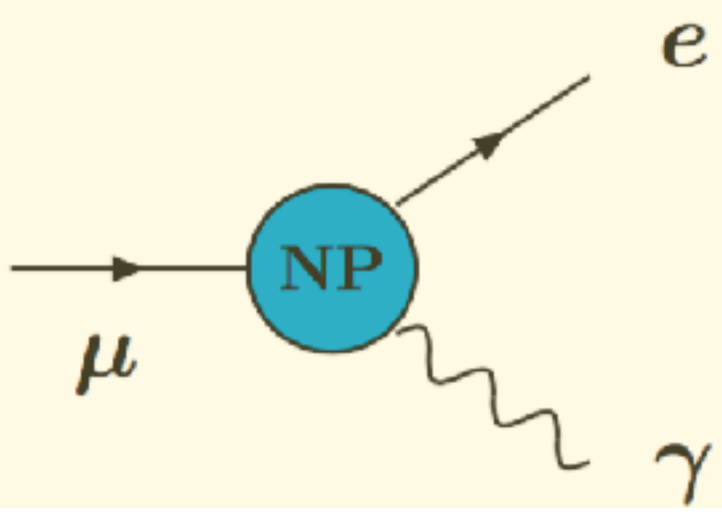
$\mu^+ \to e^+e^-e^+$



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

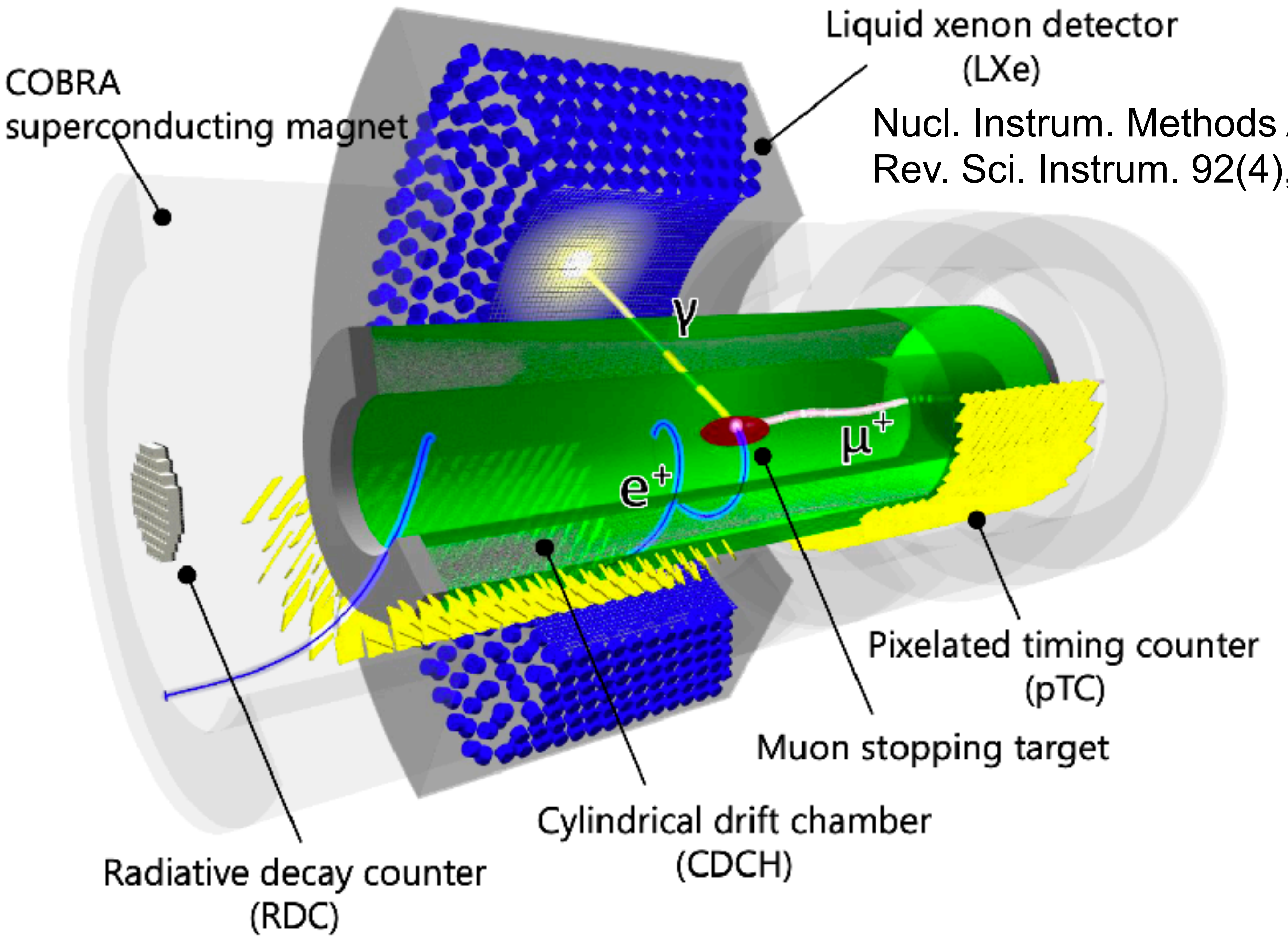
BR(μ → eee) 90% C.L.		
PSI/SINDRUM	**1988**	**1.0×10^{-12}**
PSI/PSI/Mu3e		10^{-15}, 10^{-16}

$\mu \to e\,\gamma$



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		6×10^{-14}

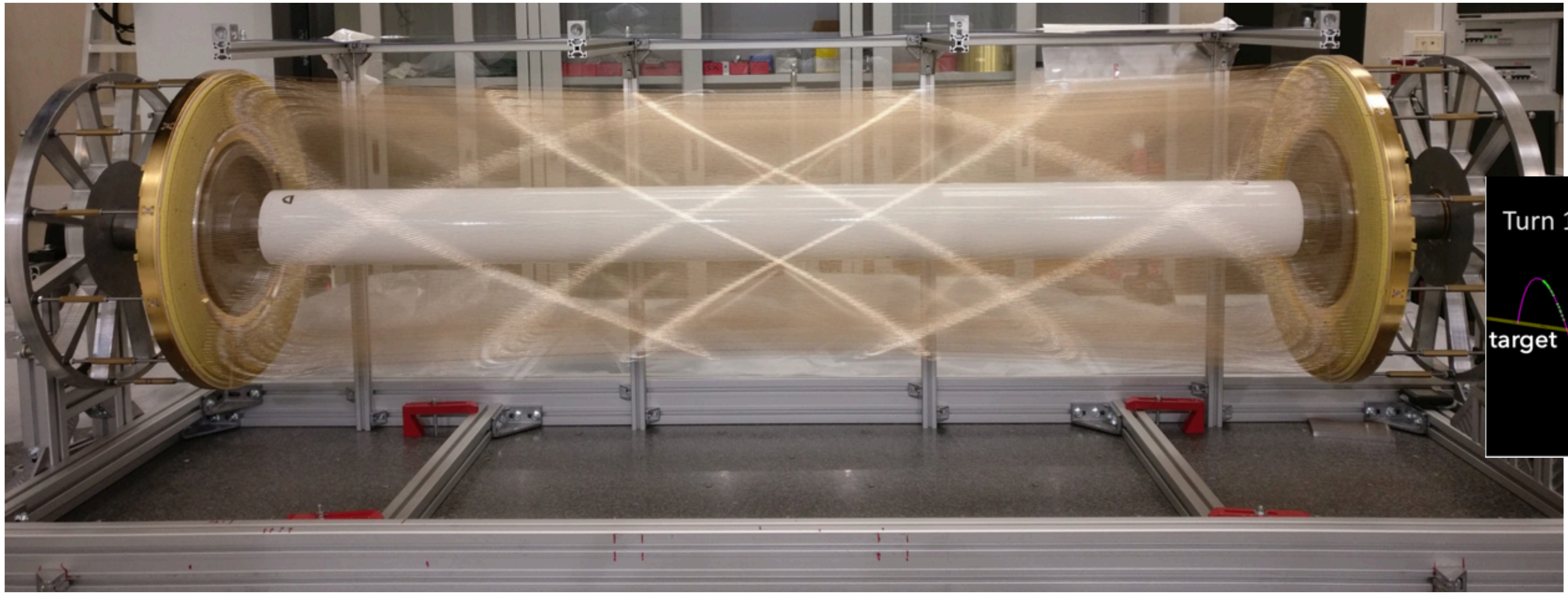


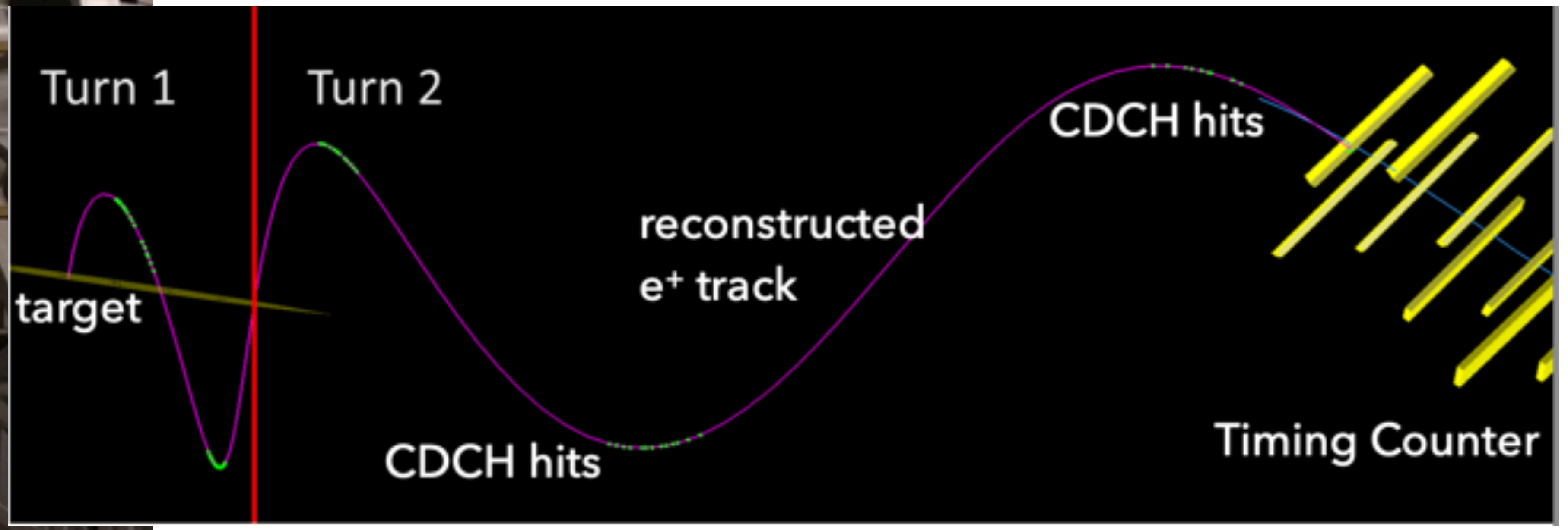
Nucl. Instrum. Methods A 944, 162511 (2019);
Rev. Sci. Instrum. 92(4), 043707 (2021)

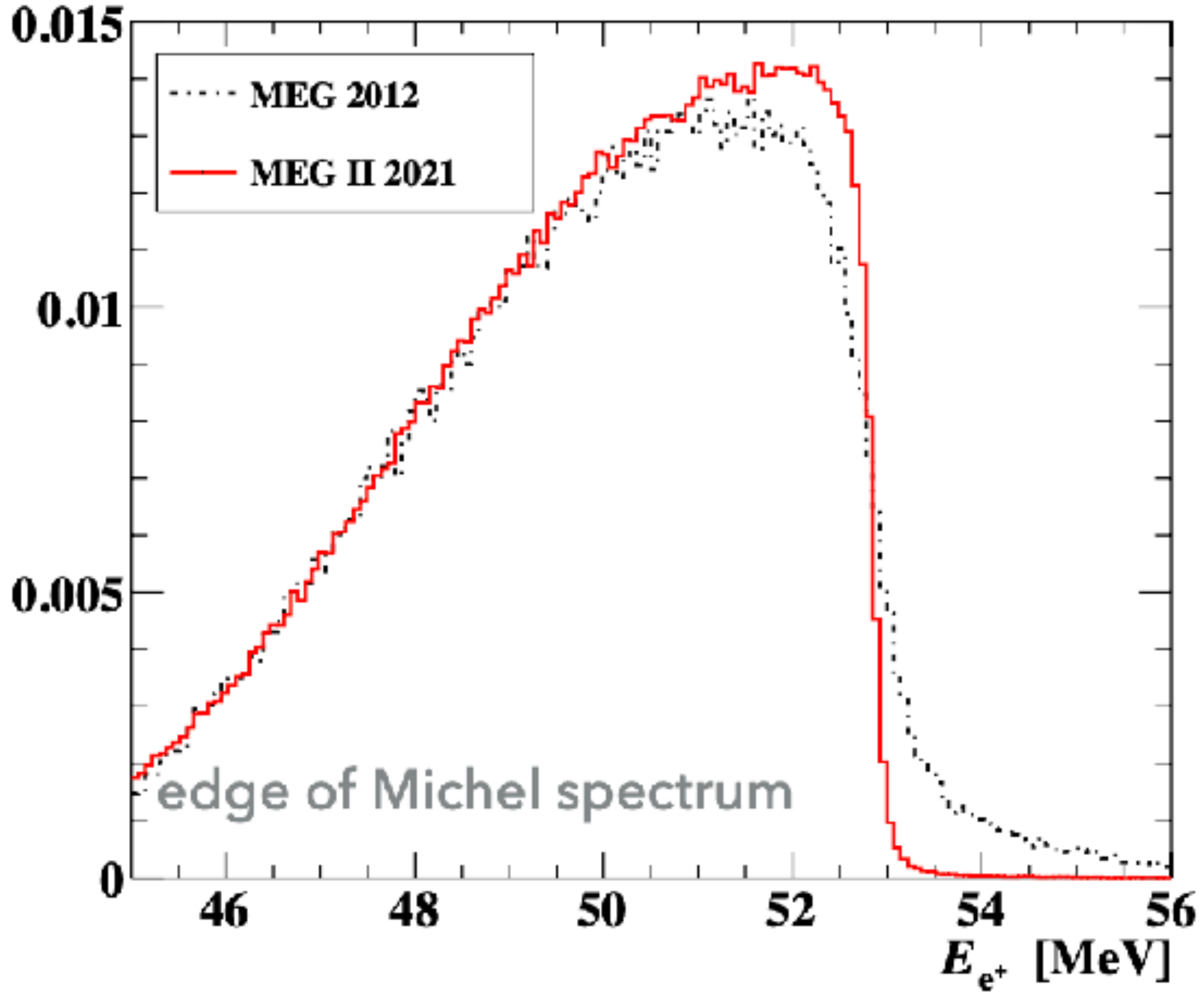
Table 6 Resolutions (Gaussian σ) and efficiencies measured at R_μ = $4 \times 10^7\ s^{-1}$, compared with the predictions from [3, 57].

Resolutions	Foreseen	Achieved	**MEG**
E_{e^+} (keV)	100	89	320
ϕ_{e^+} [a)], θ_{e^+} (mrad)	3.7/6.7	4.1/7.2	9.4
y_{e^+}, z_{e^+} (mm)	0.7/1.6	0.74/2.0	2.4 / 1.7
E_γ(%) (w<2 cm)/(w>2 cm)	1.7/1.7	2.0/1.8	
$u_\gamma, v_\gamma, w_\gamma$ (mm)	2.4/2.4/5.0	2.5/2.5/5.0	5 / 5 / 6
$t_{e^+\gamma}$ (ps)	70	78	122
Efficiency (%)			
ε_γ	69	62	63
ε_{e^+}	65	67	30
ε_{TRG}	≈99	80	99

MEG2 : Cylindrical drift chamber







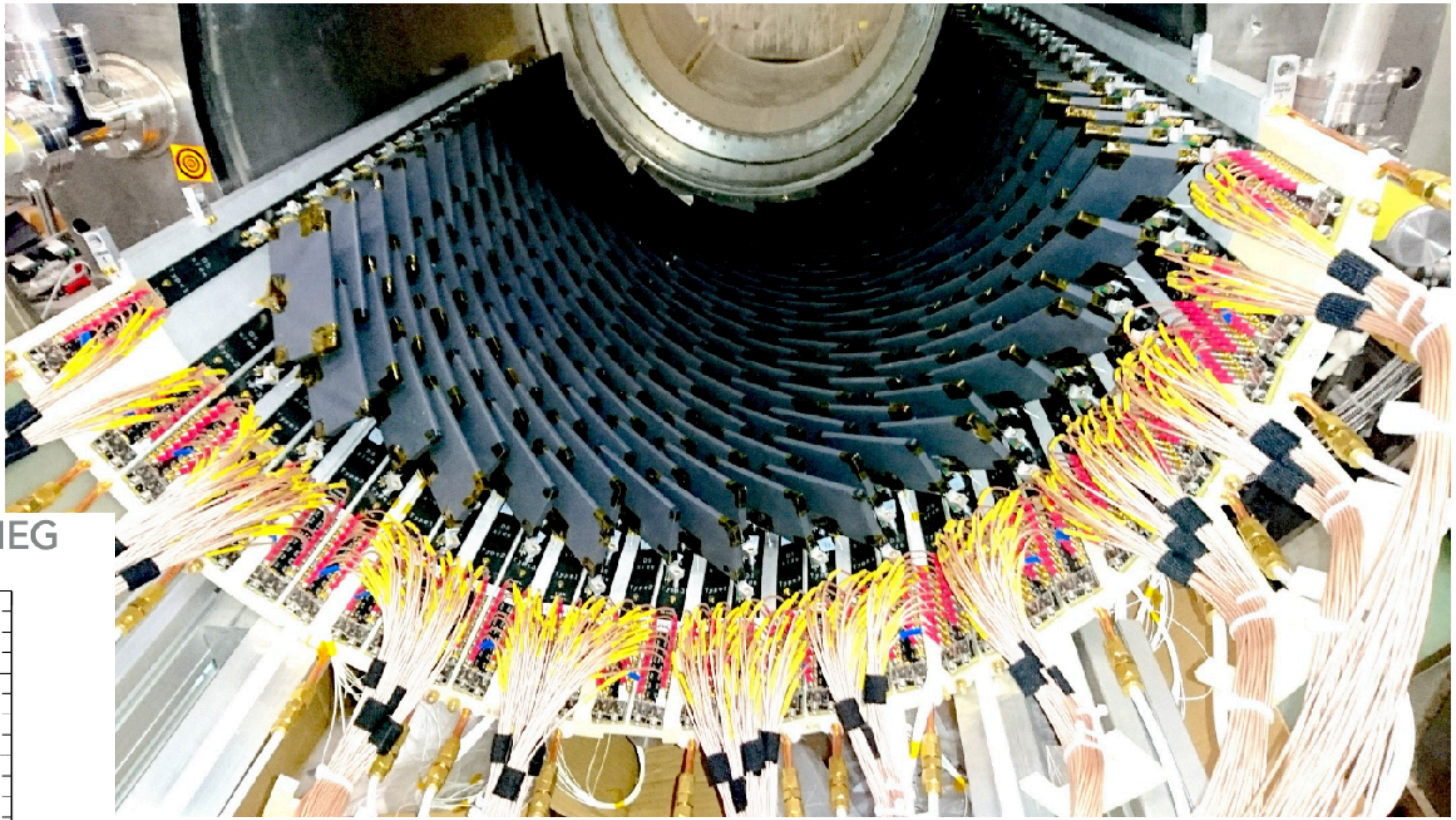
Low material: $1.58 \times 10^{-3} X_0$/e^+-turn (cf. $2.0 \times 10^{-3} X_0$ for MEG)

- He-Isobutane (90:10) with oxygen 0.5% + isopropyl alcohol 1.5%
- Radius of 17 - 29cm, 1.93m long
- 9 layers of drift cells
- 1,728 Au-plated W anode wires (20μm)
- innermost cells at 5 × > 1MHz for $10^7 \mu$ /sec, max occupancy ~25%
- ~110μm position resolution

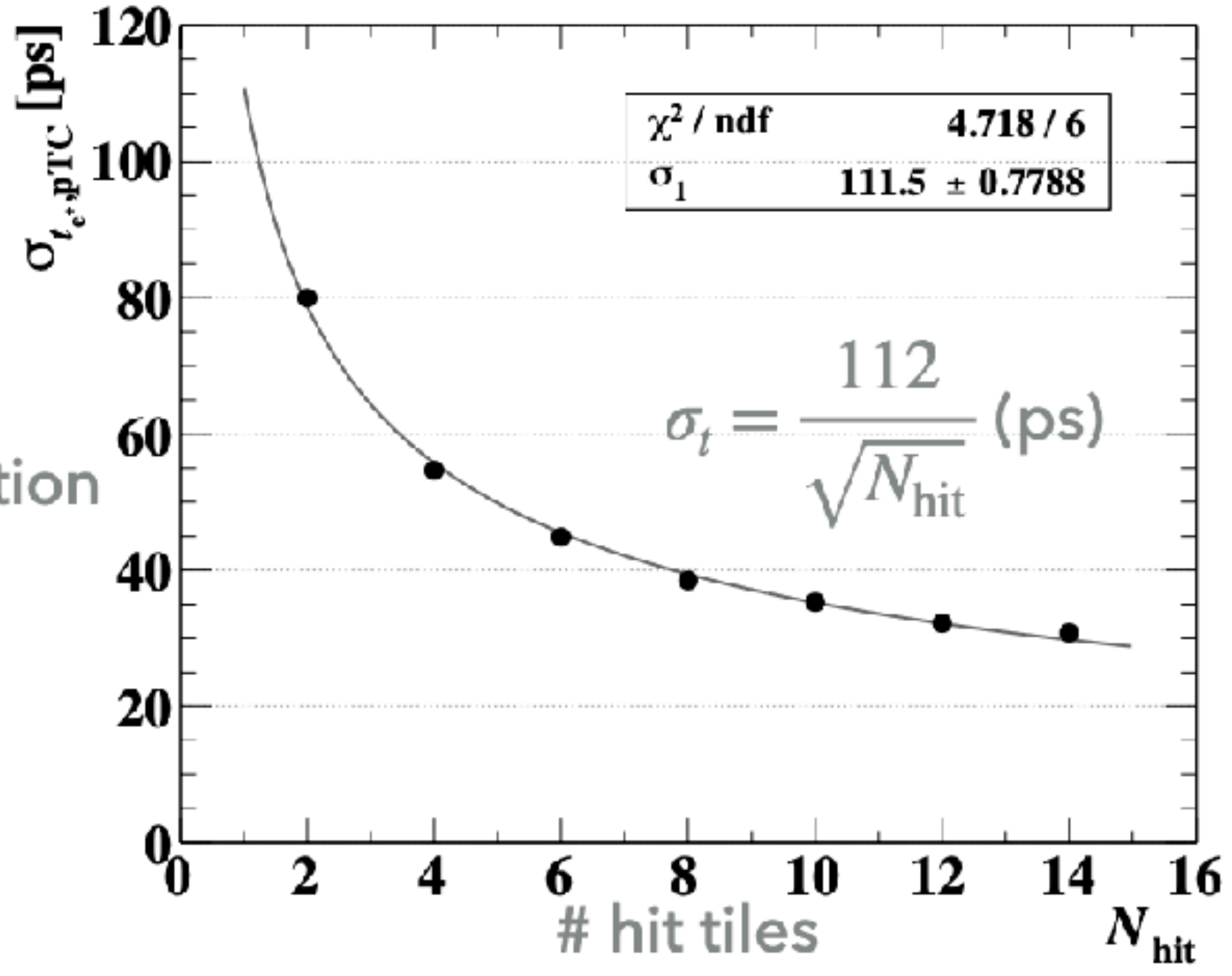
$\sigma_{E_e^+}$ ~90 keV (cf. MEG 320 keV)

MEG2: PIXELATED TIMING COUNTER (PTC)

256 tile scintillators on each side
~100ps resolution / tile
e+ hits 9 tiles on average → ~**37ps**



cf. ~65ps MEG



timing resolution (psec)

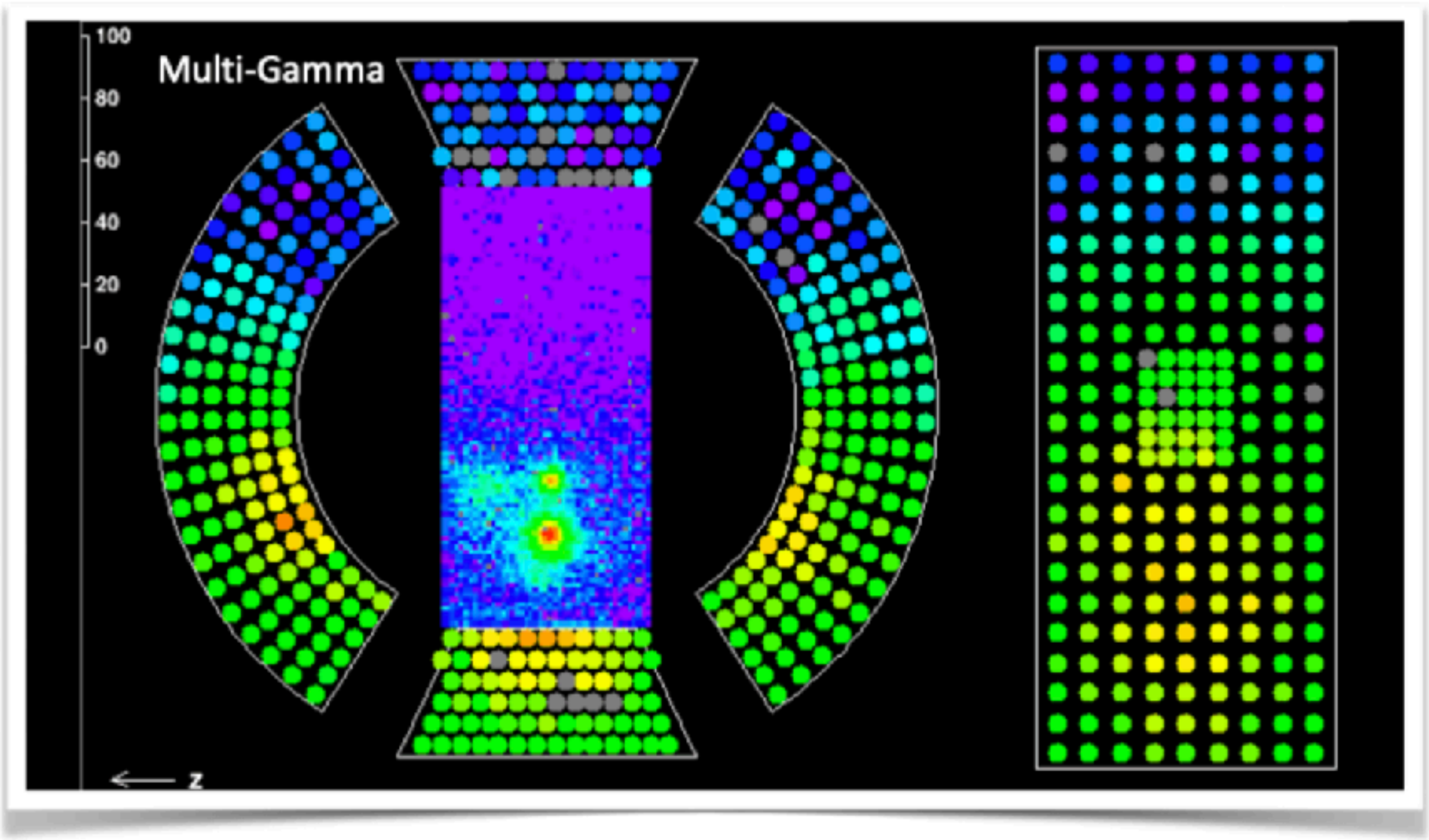
$$\sigma_t = \frac{112}{\sqrt{N_{\mathrm{hit}}}}\ \text{(ps)}$$

hit tiles

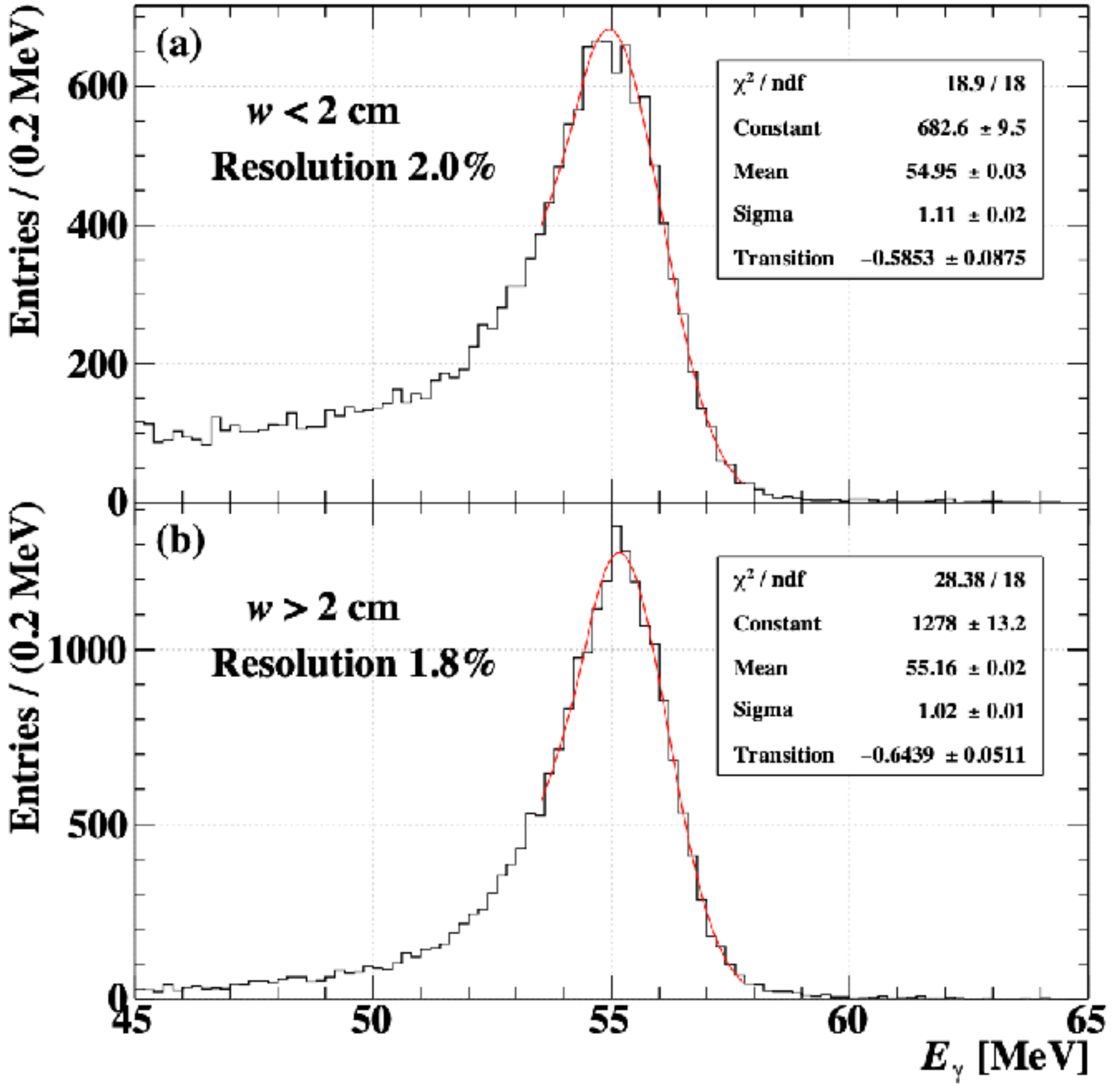
MEG2: LIQUID XENON PHOTON DETECTOR (LXE)

- 4,092 MPPCs (15x15mm²) on front face   cf. MEG uses 2″ PMTs

  Better uniformity enables more precise reconstruction of position & energy
- 668 2″ PMTs on other faces



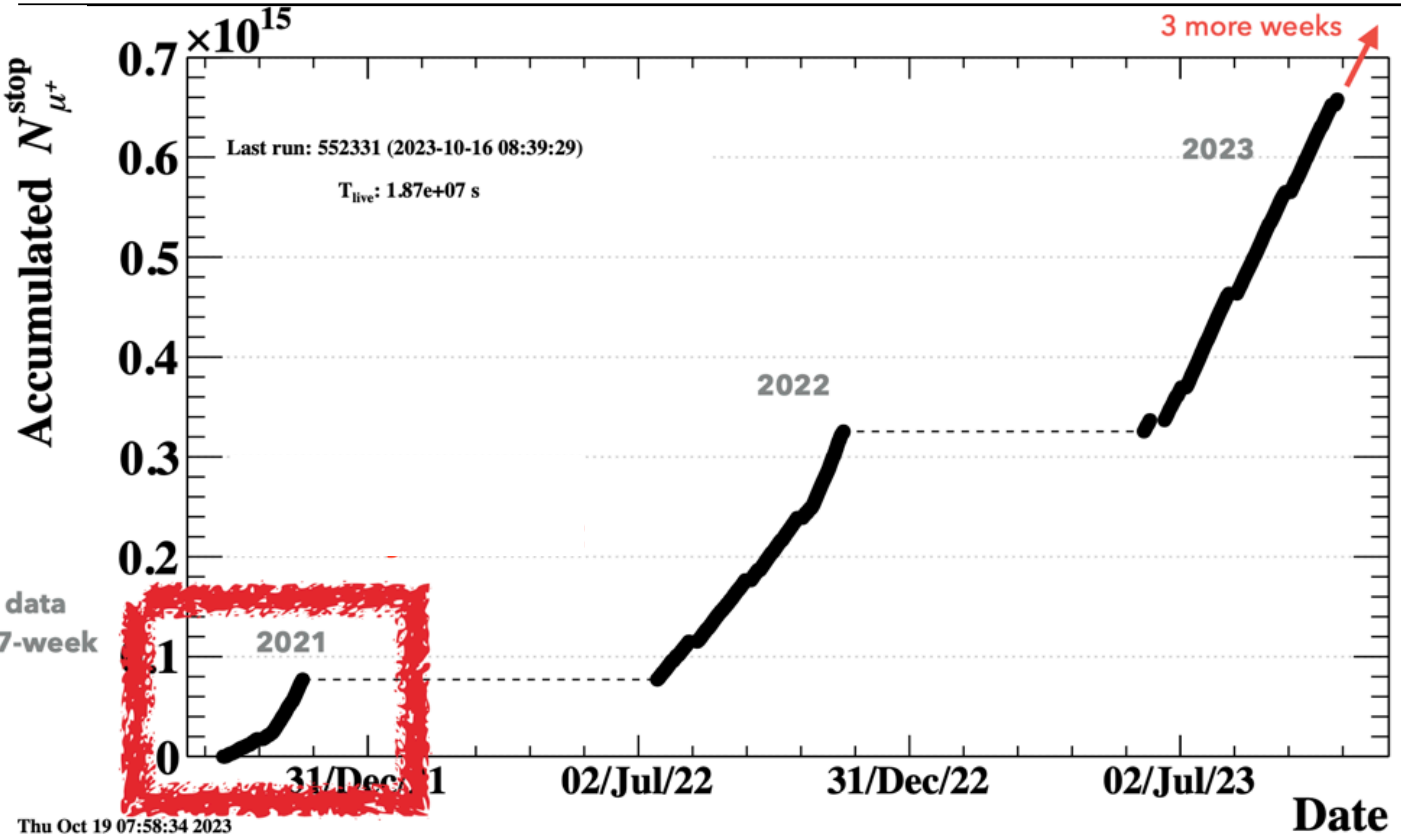
Multiple photons are separated by position & timing and simultaneously measured



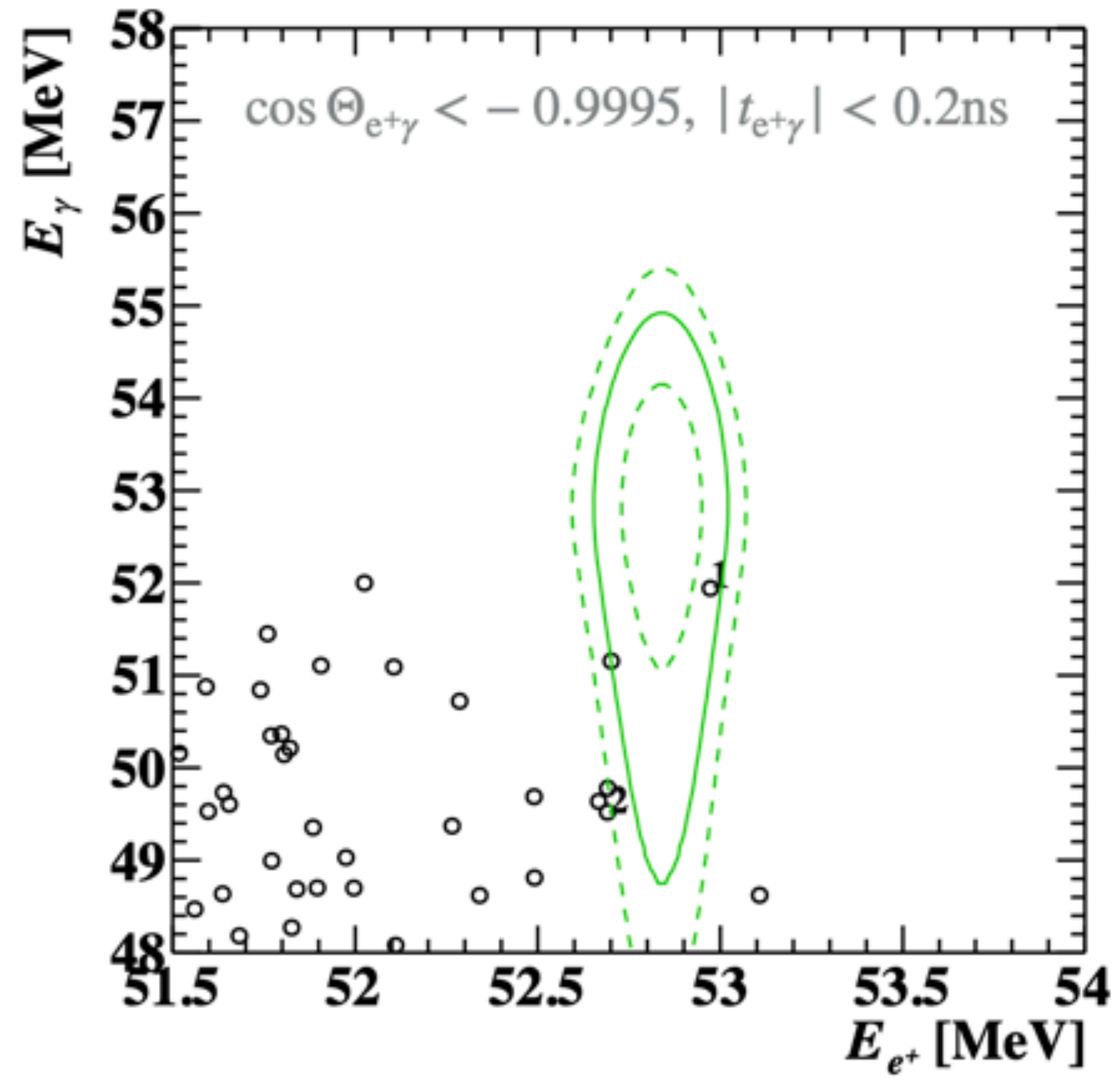
55 MeV monochromatic gamma ray from

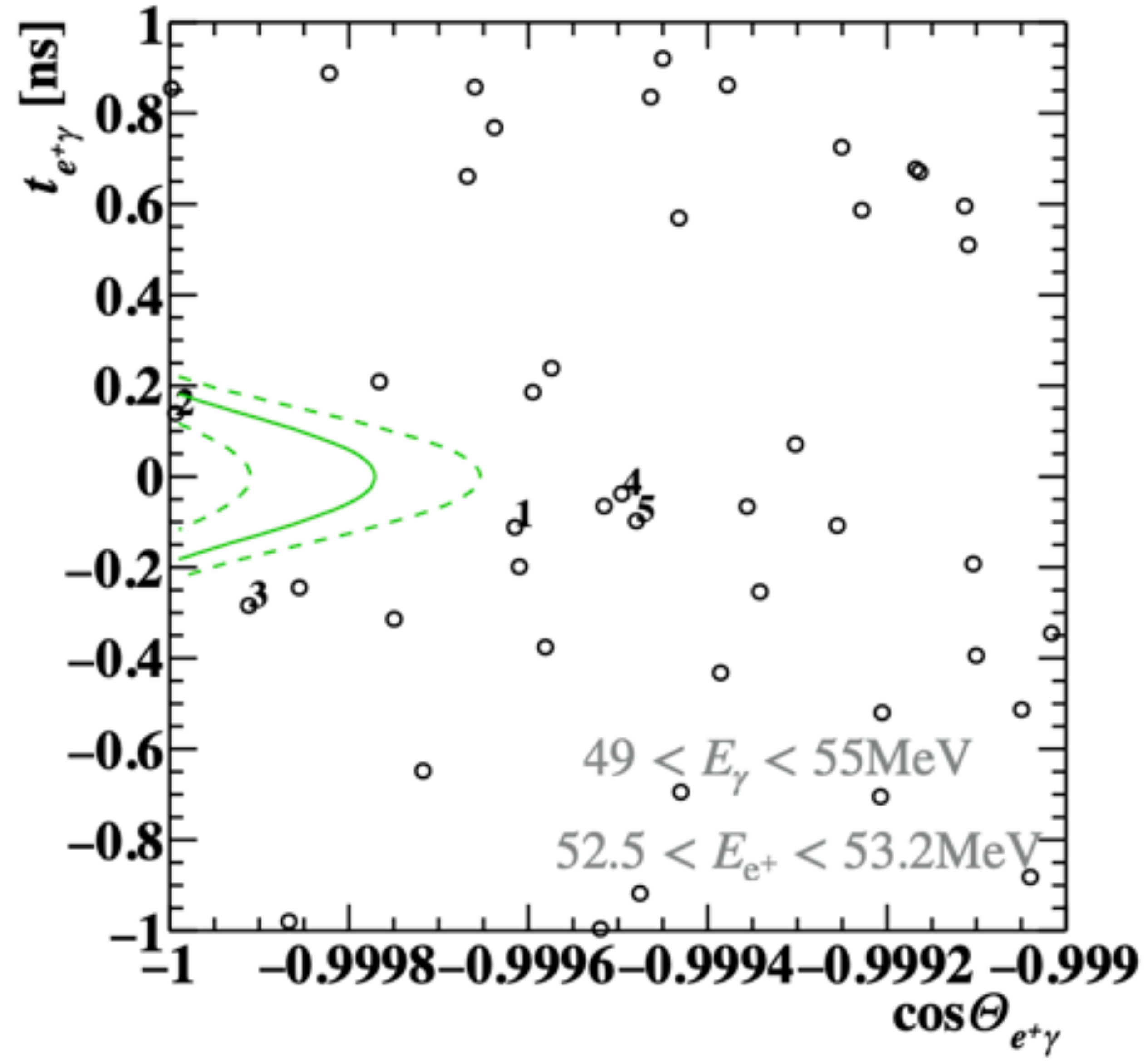
$\pi^- p \rightarrow \pi^0 n \rightarrow \gamma\gamma n$

MEG2: Data



The first physics data obtained in the 7-week Run in 2021





UNBLINDED 2021 DATA

THE FIRST RESULT OF MEG II ON SEARCH FOR $\mu^+ \to e^+\gamma$

SUMMARY AND PROSPECTS

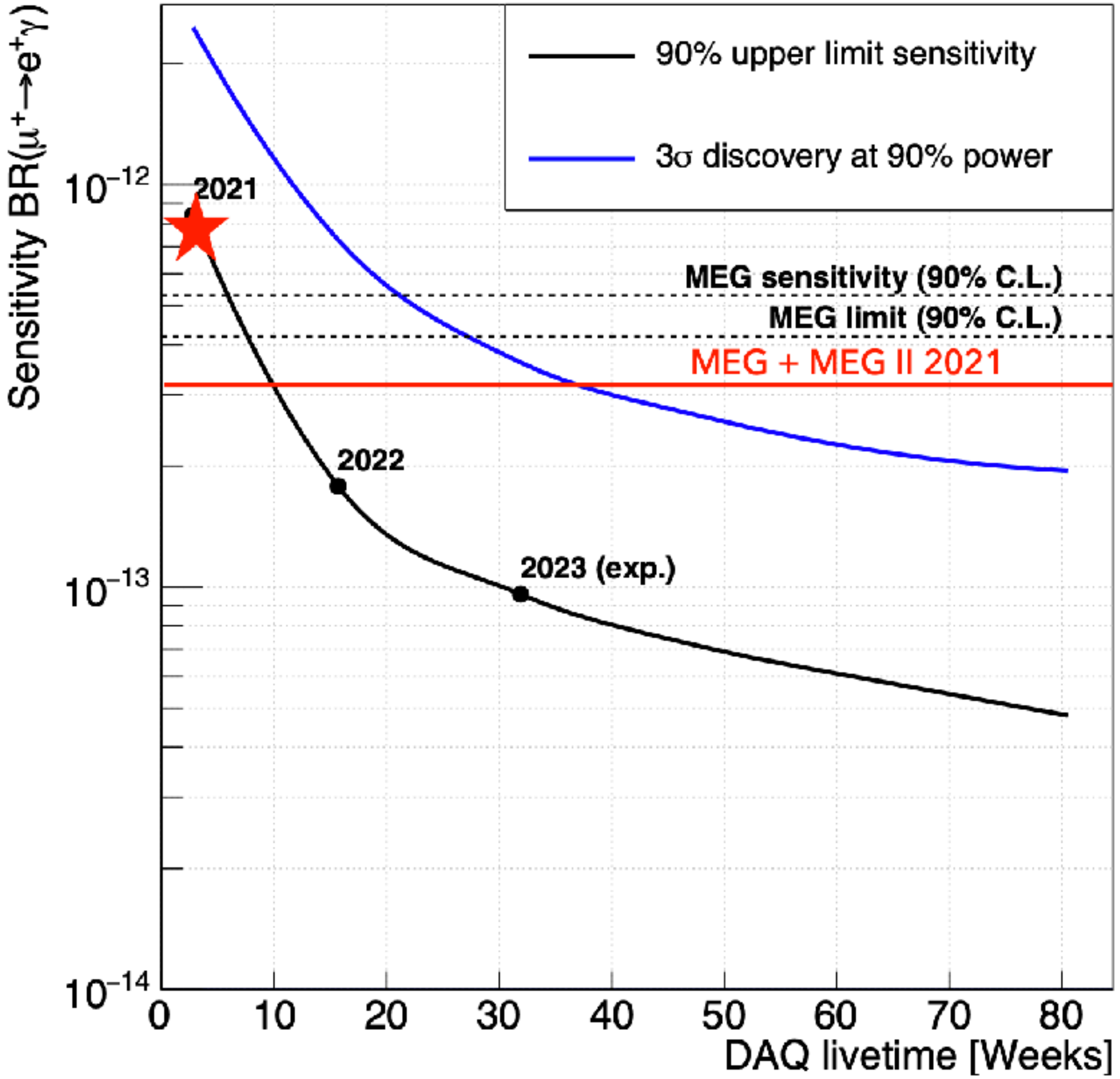
- The first 7-week data in 2021 achieved a Sensitivity ~60% of MEG 2009-2013.

$$\mathscr{B}_{90} = 7.5 \times 10^{-13}$$

- A combination MEG + MEG II provides the most stringent limit on the branching ratio of $\mu^+ \to e^+\gamma$

$$\mathscr{B}_{90} = 3.1 \times 10^{-13}$$

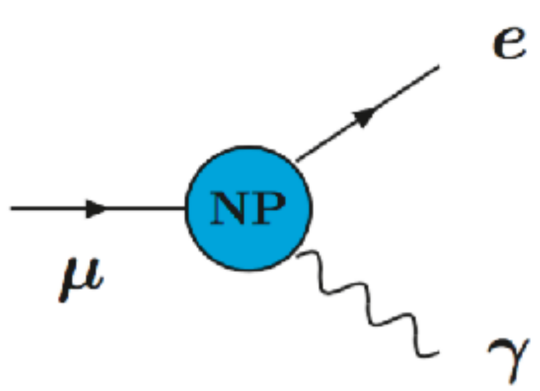
- Expected to finalize the 2022 data analysis in ~a half year.



arXiv:2310.12614, Submitted to EPJ C

cLFV in muon channels

$\mu \to e\gamma$



Coincident
back-to-back e^+ - γ
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BR($\mu \to e\gamma$) 90% C.L.		
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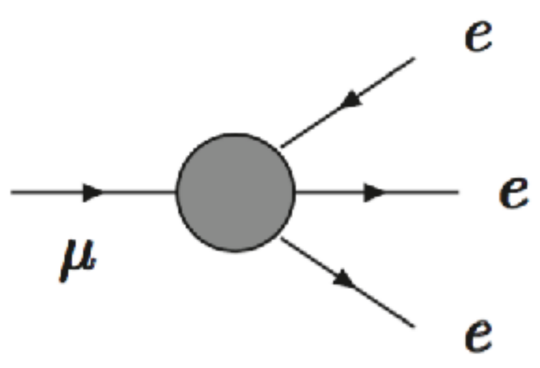
$\mu^+ \to e^+e^-e^+$



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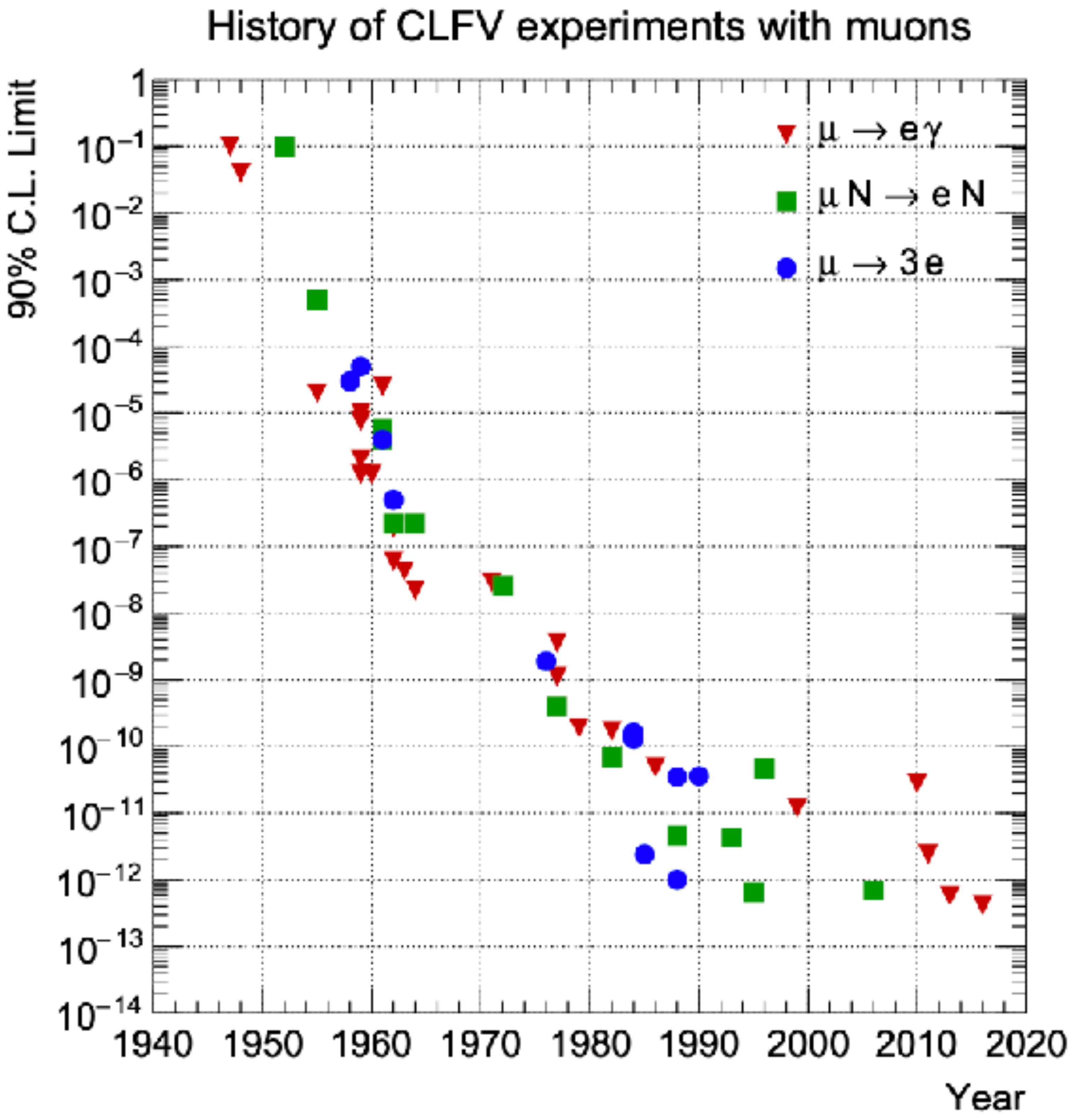
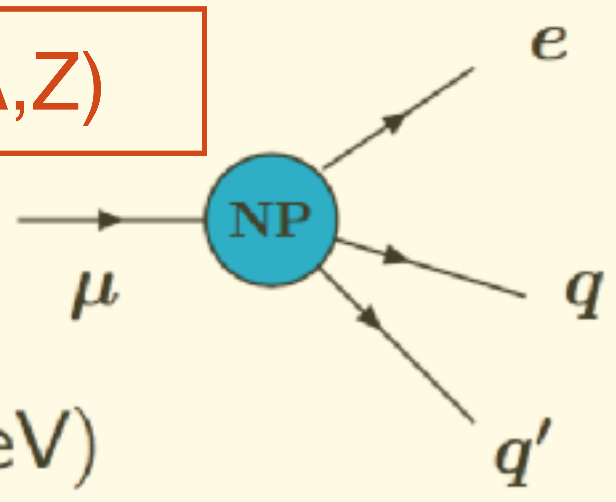


$\mu^- + (A,Z) \to e^- + (A,Z)$



eV)

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

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

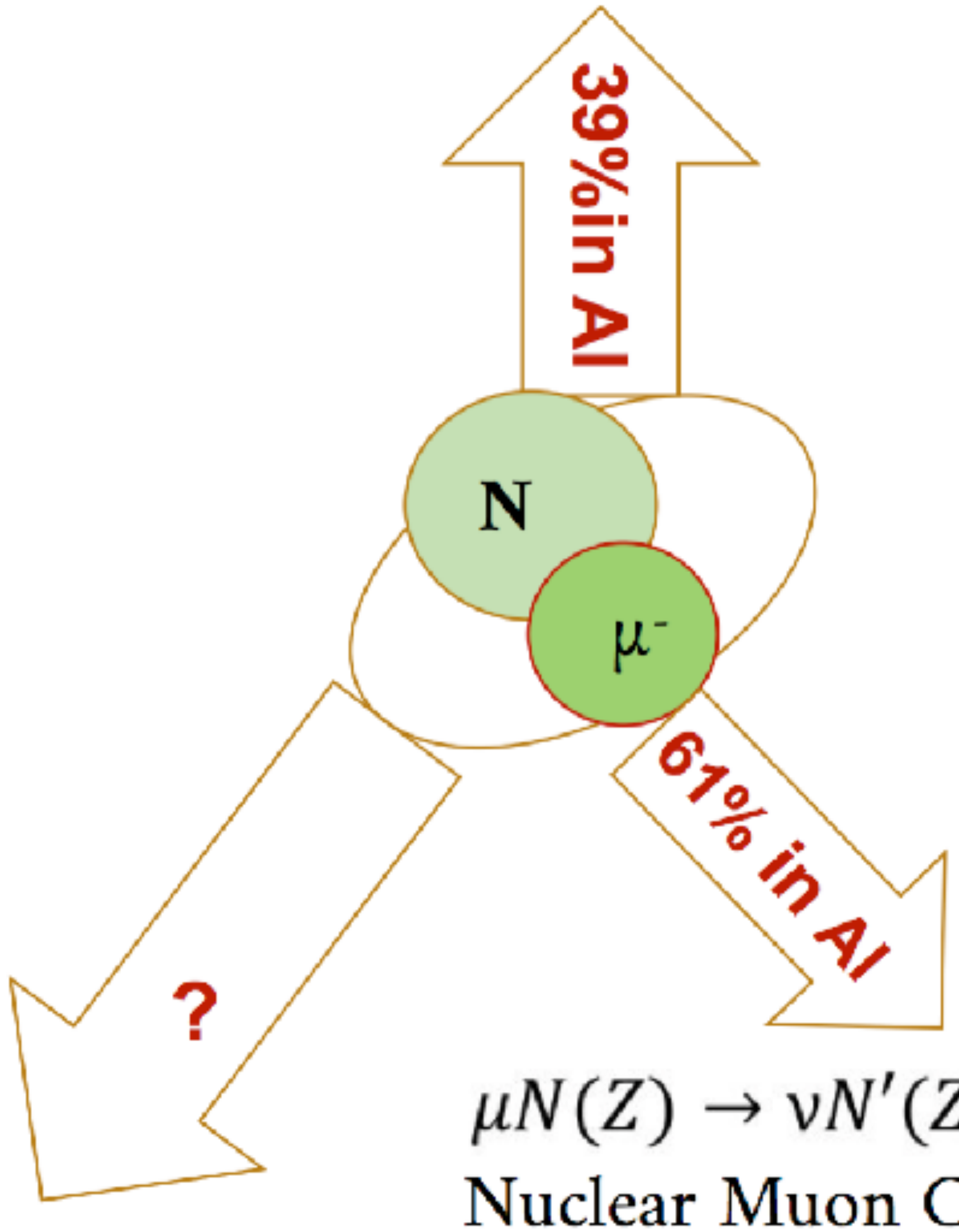
Muonic atoms

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

+

muonic X-Rays

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



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

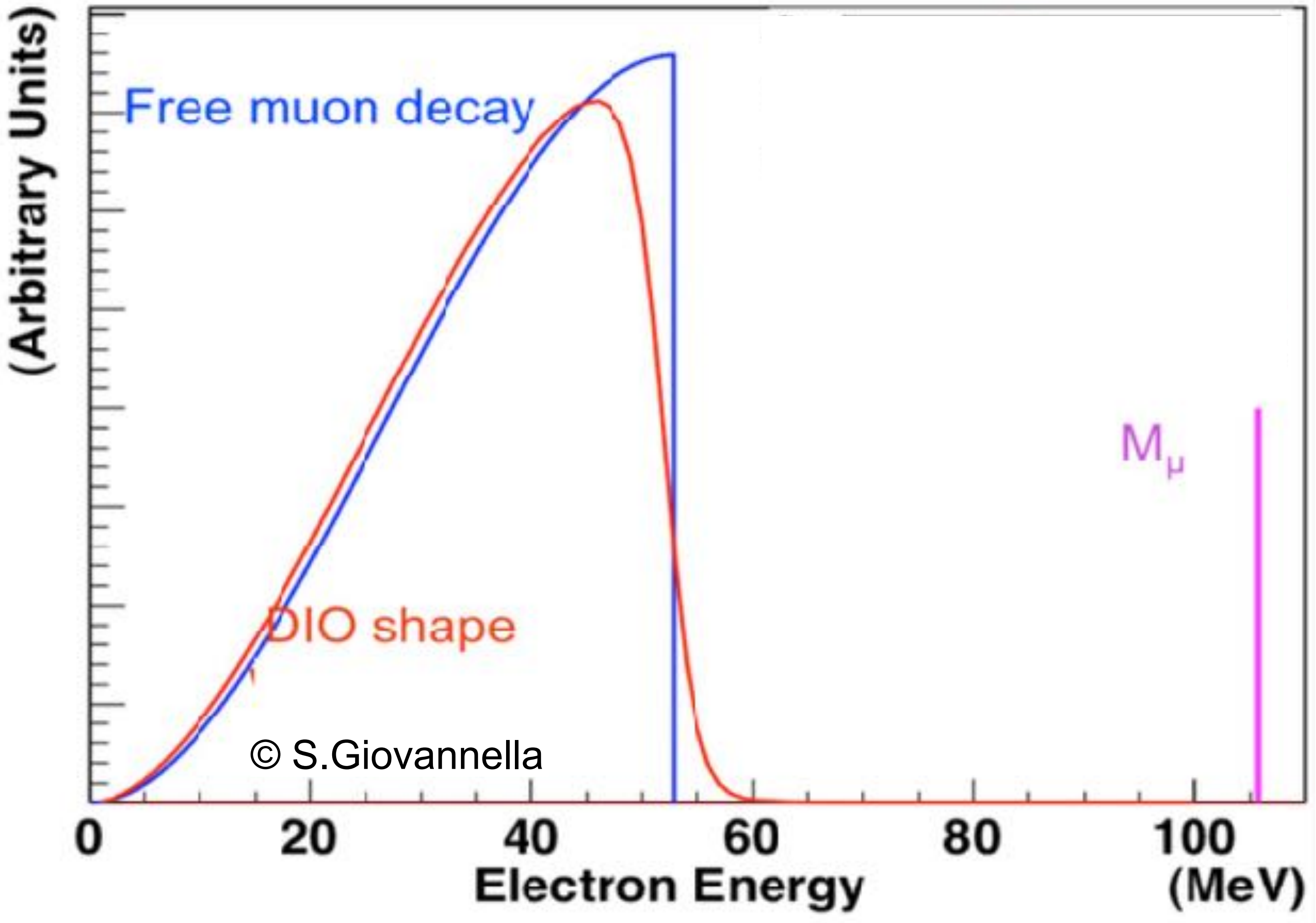
Nuclear Muon Capture

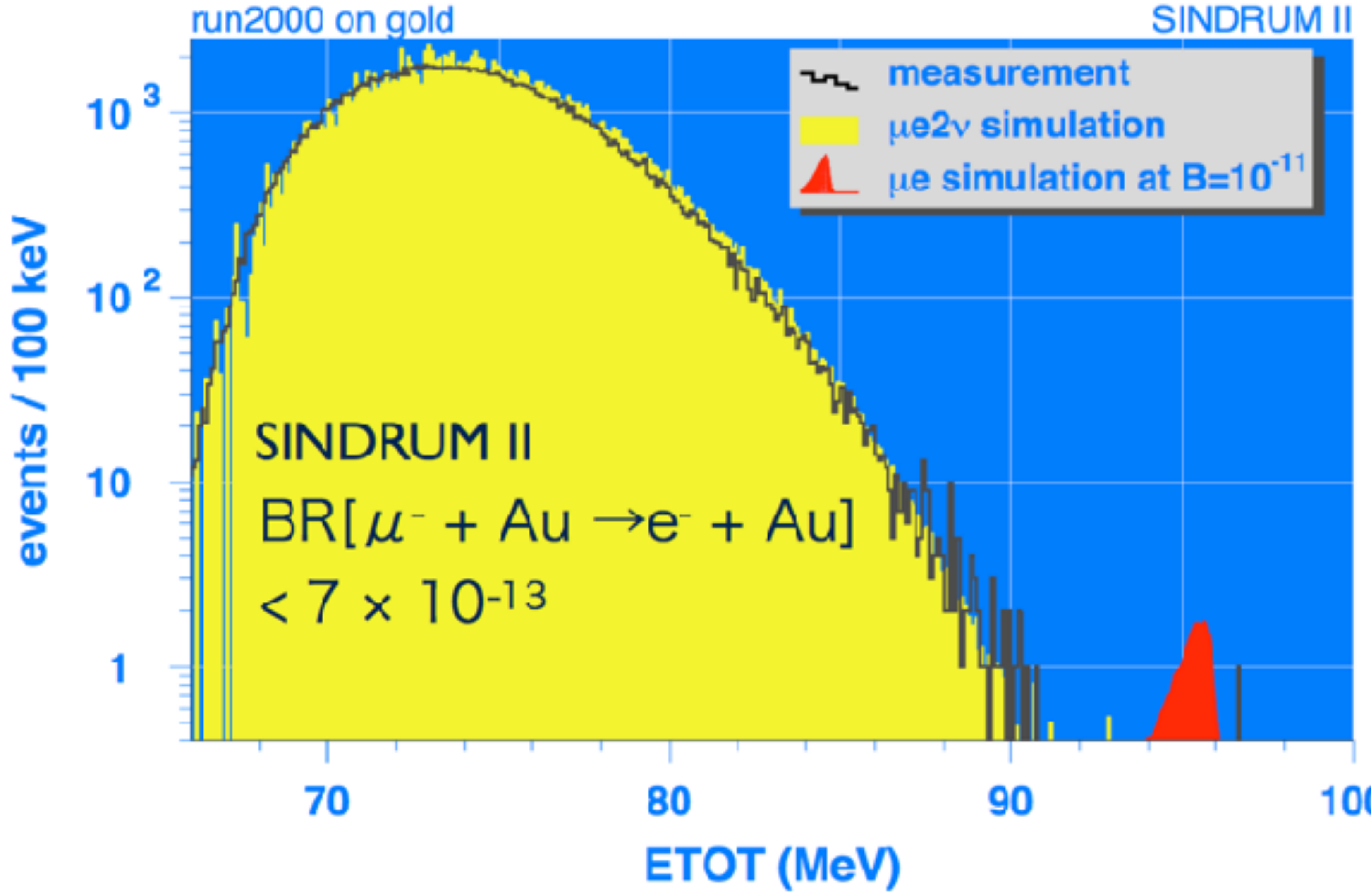
⇩

low energy neutrons, protons,γ's

⇩

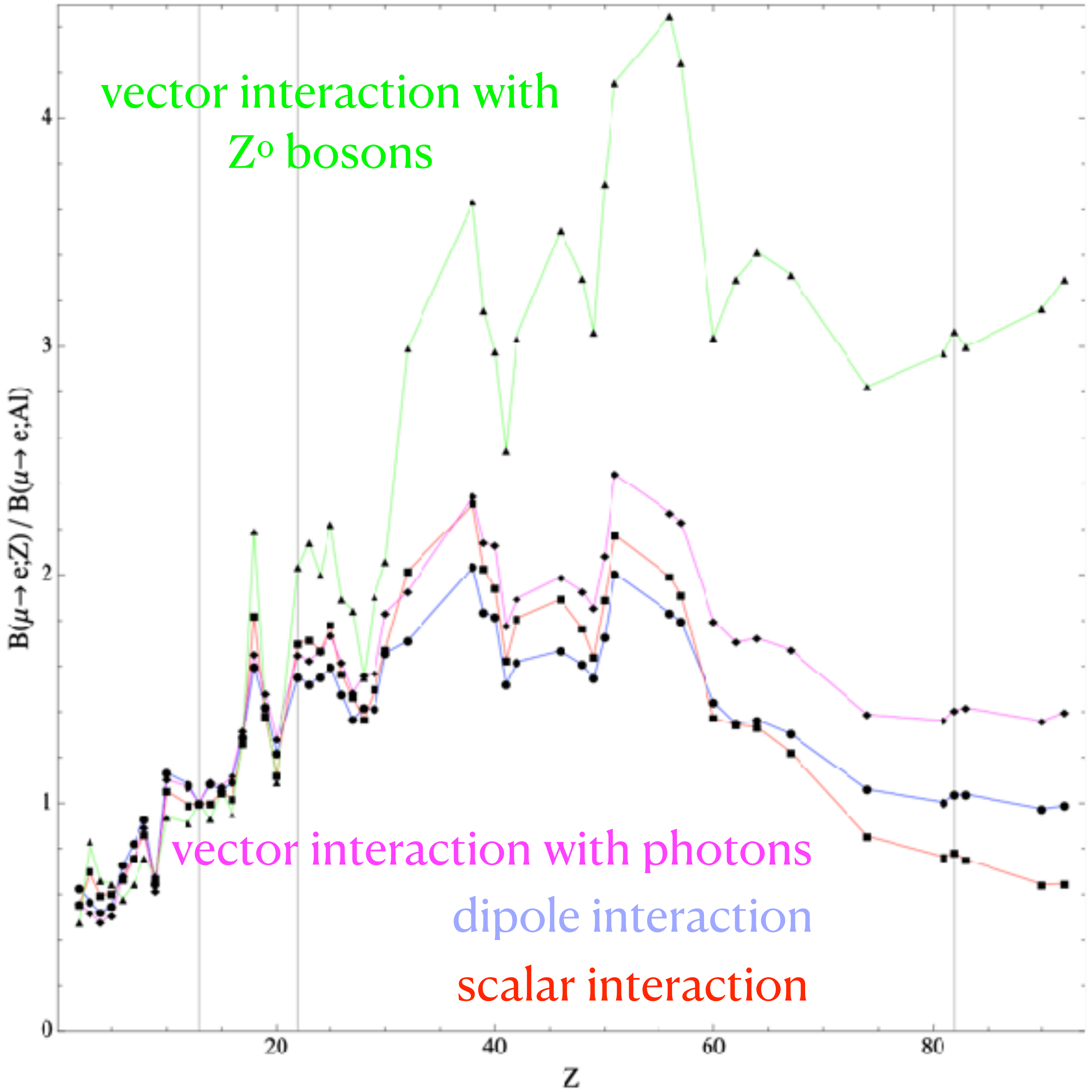
noise in the detector





Required momentum resolution : better than 200 keV/c

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

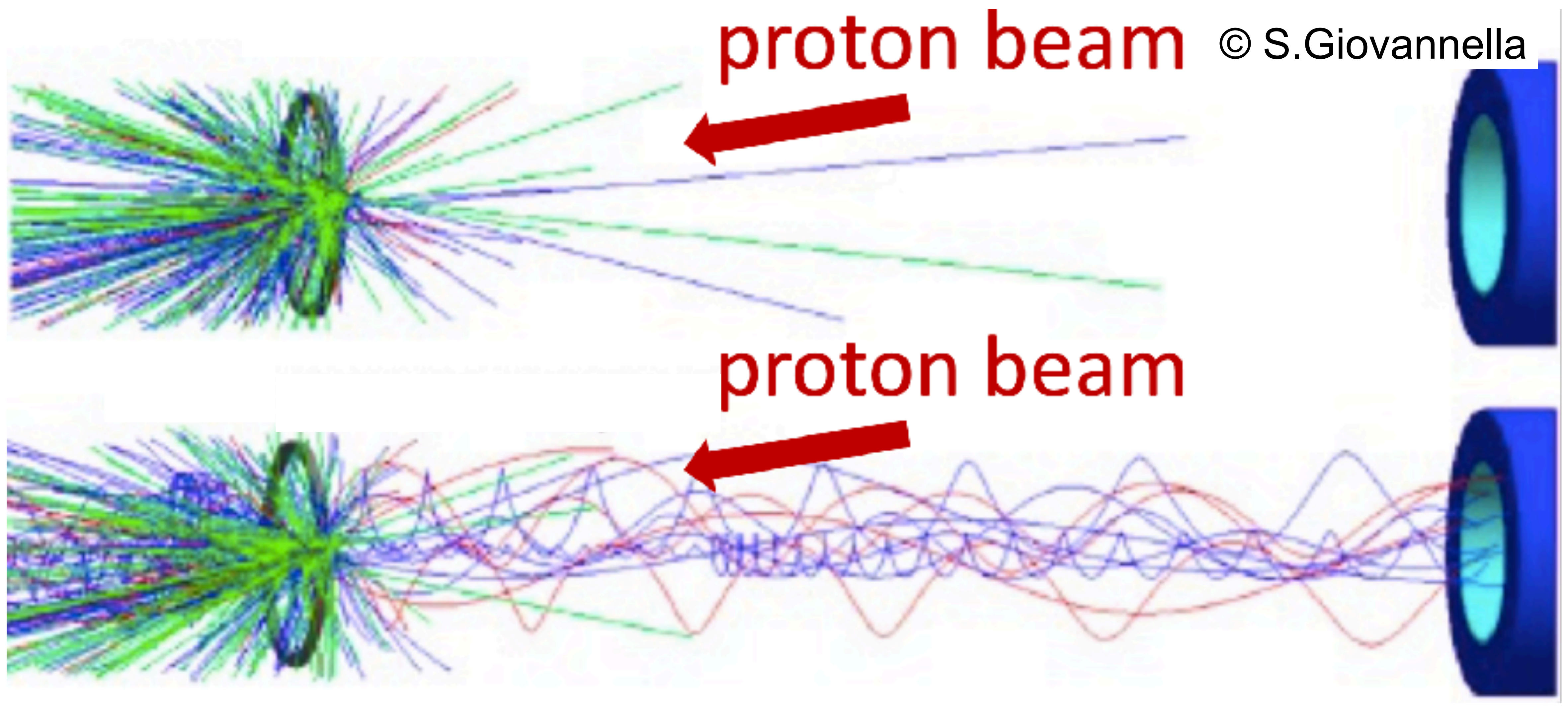


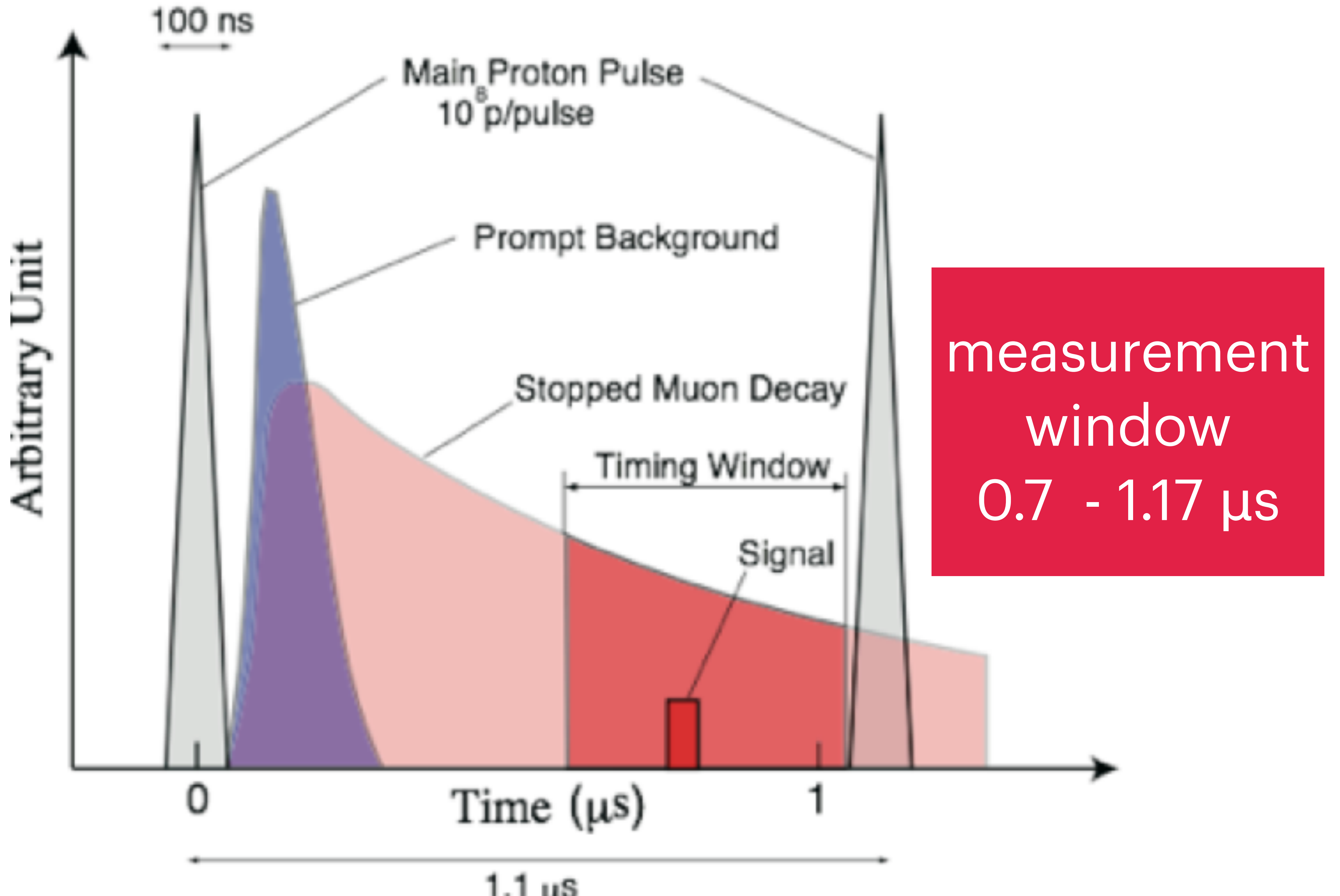
μ − e conversion in muonic atoms :: experimental concept

© 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

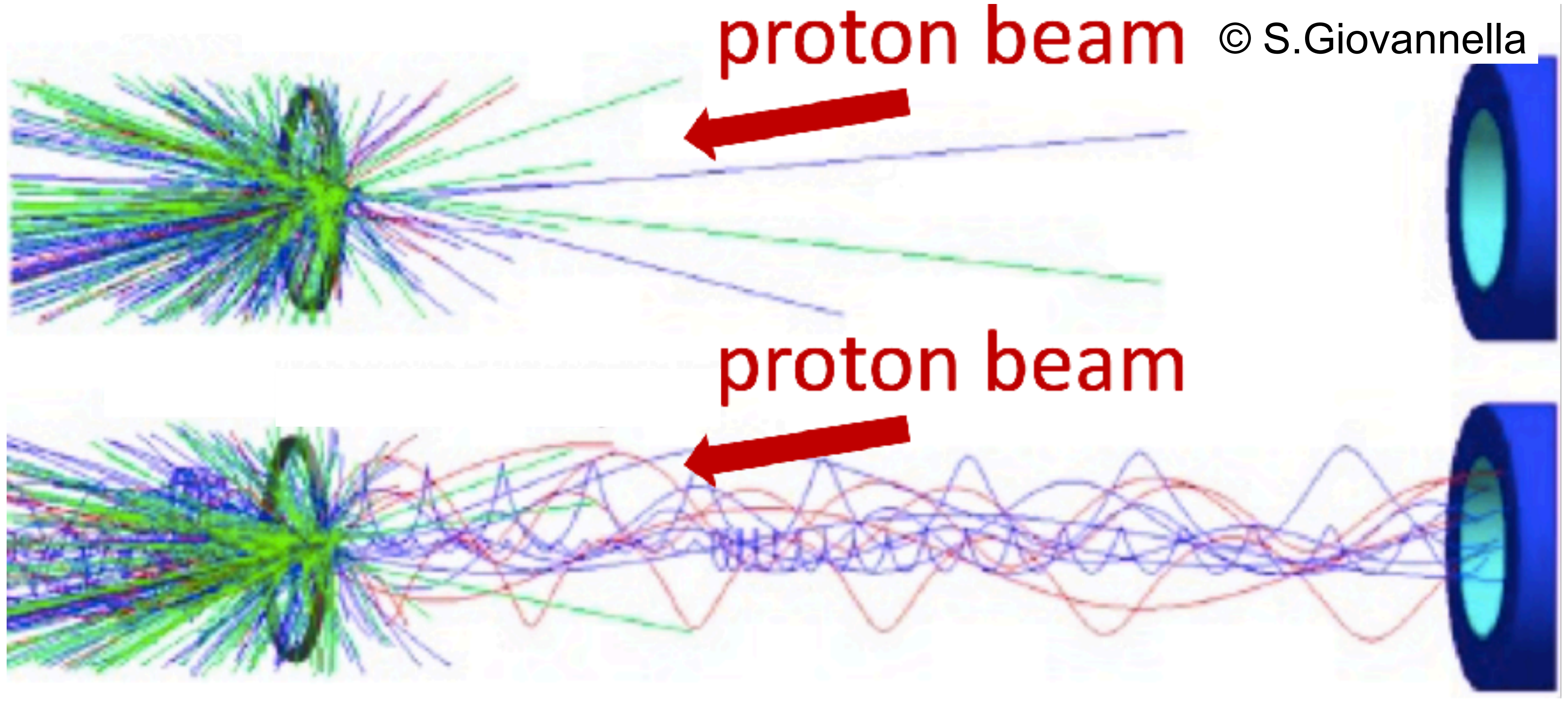
$O(10^{10})$ out-of-time protons suppression

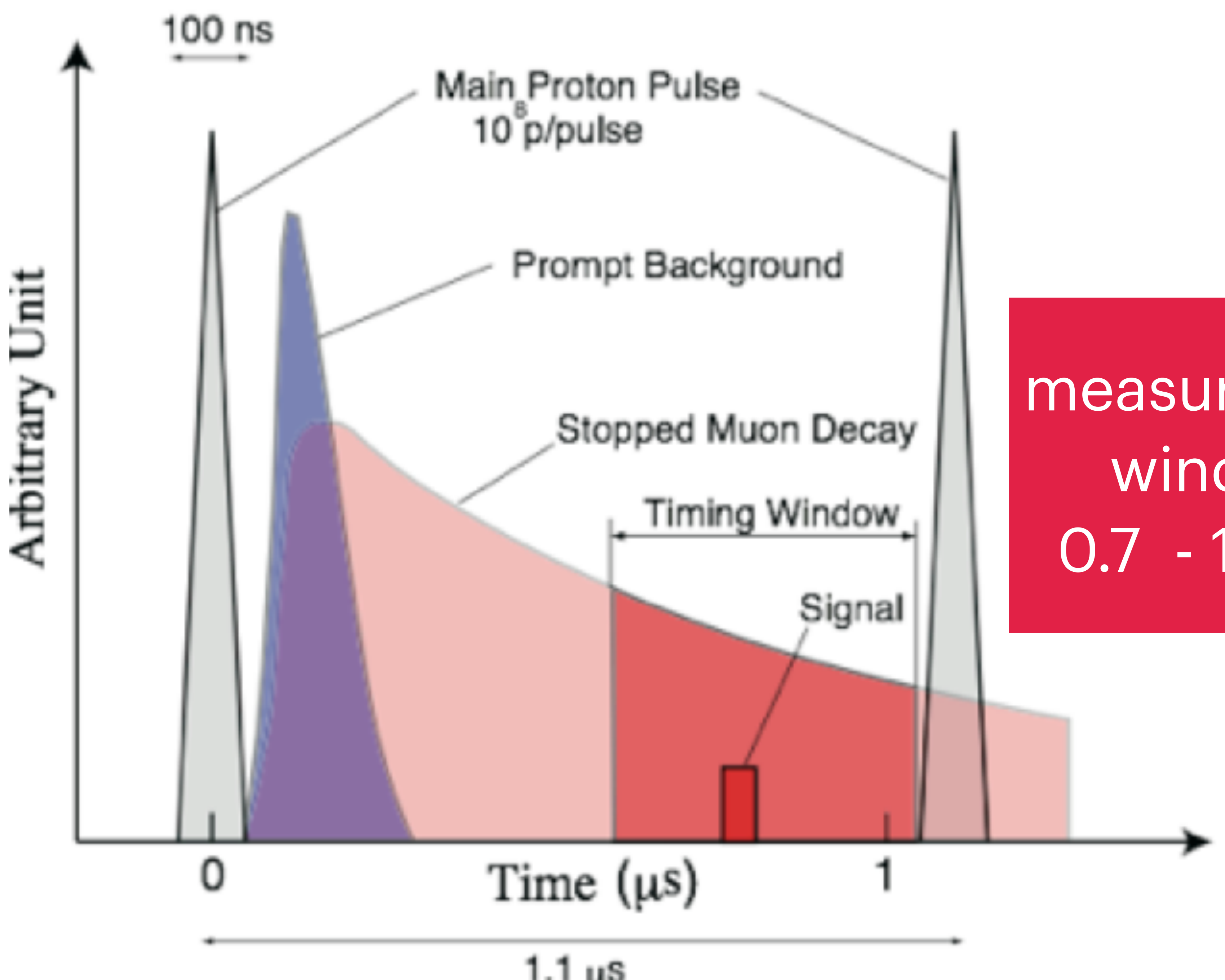
Material target	Atomic number (Z)	Muonium lifetime (ns)
Aluminum	13	864
Titanium	22	330
Lead	82	74

© 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





measurement window
0.7 - 1.17 μs

Delayed DAQ gate to suppress prompt backgrounds

Narrow proton pulses

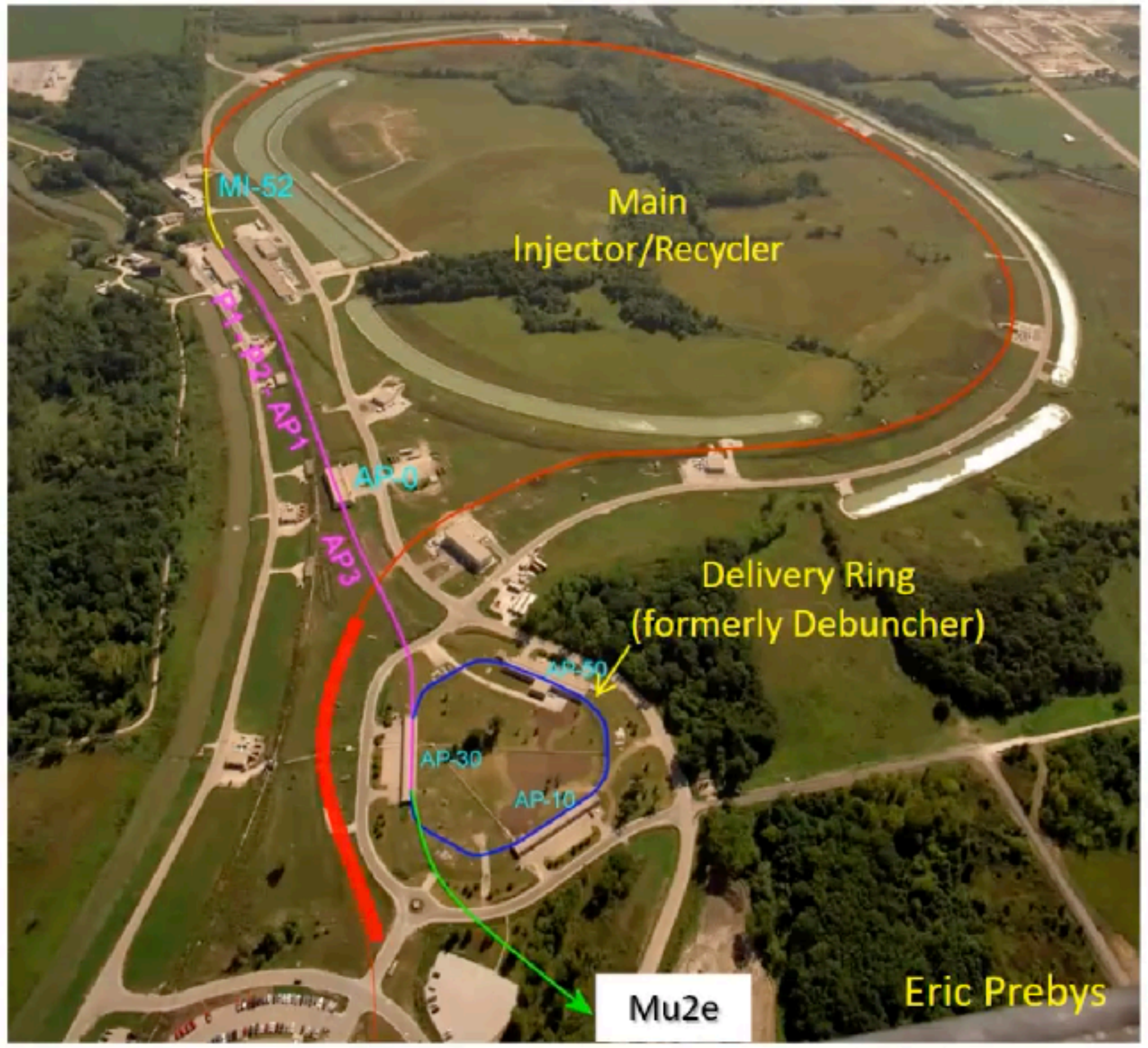
O(10^{10}) out-of-time protons suppression

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

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

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

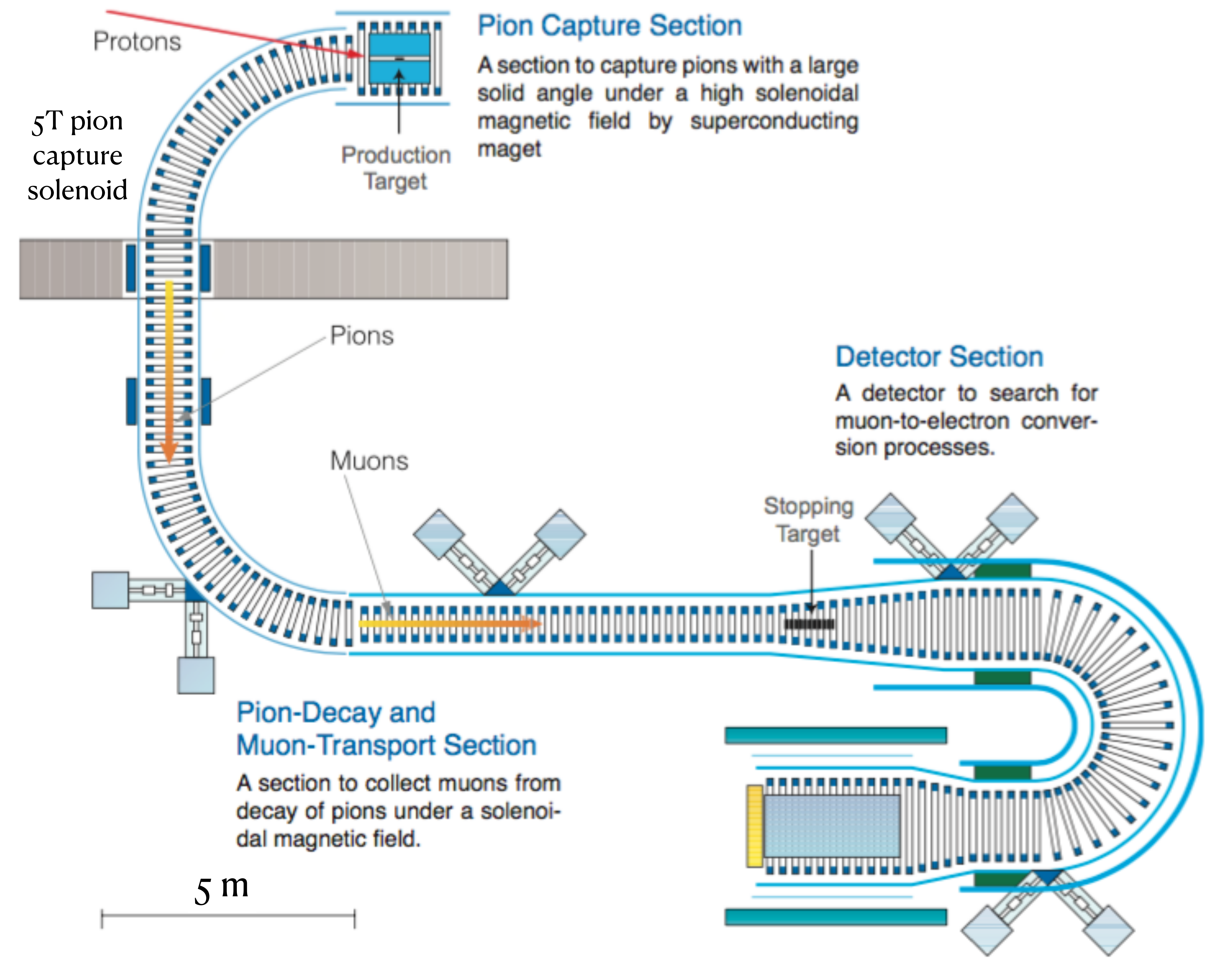
This requires:
- **10^{18} stopped muons**
- high background suppression (**$N_{bckg} \ll 0.5$**)

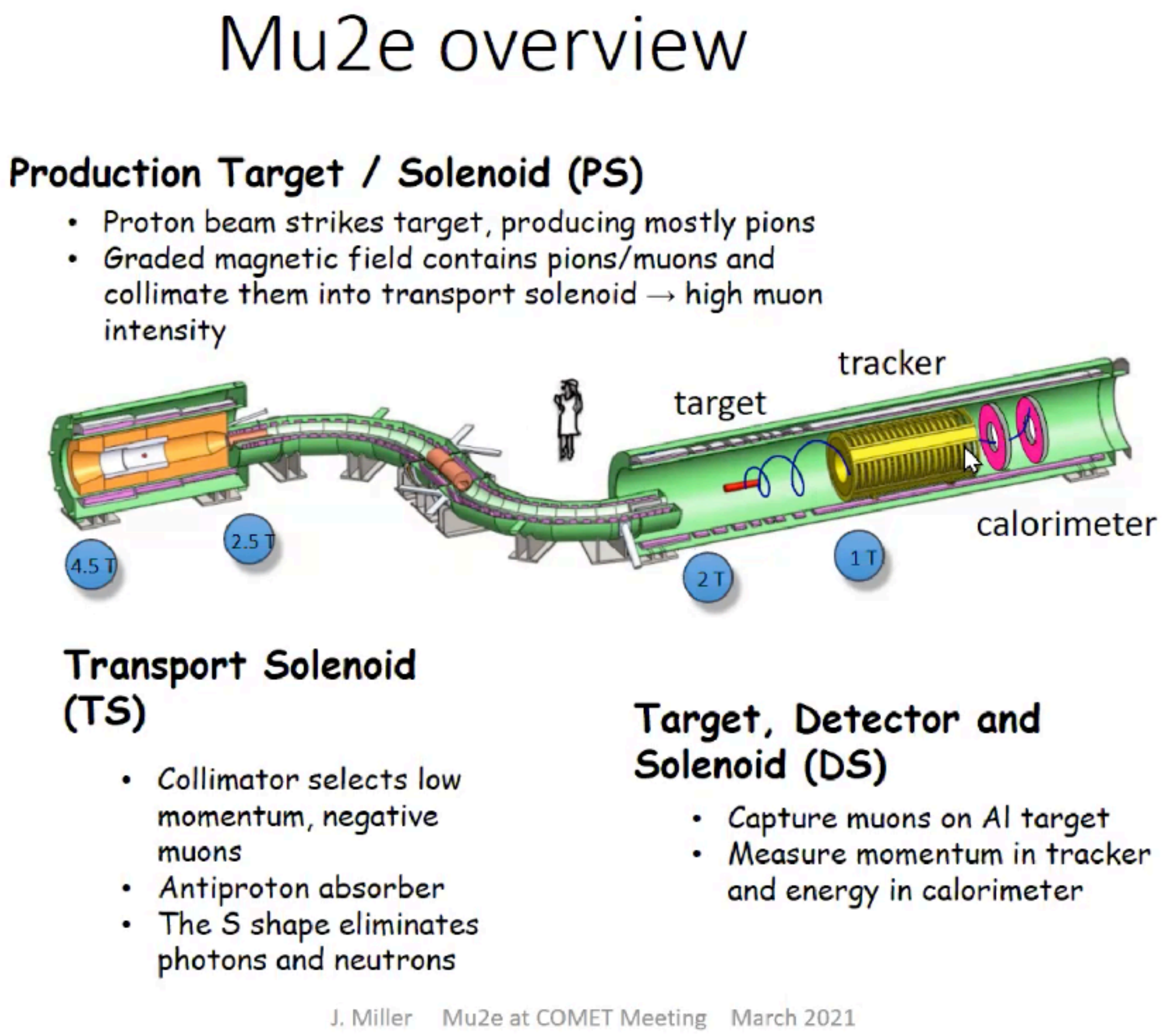


Booster Synchrotron

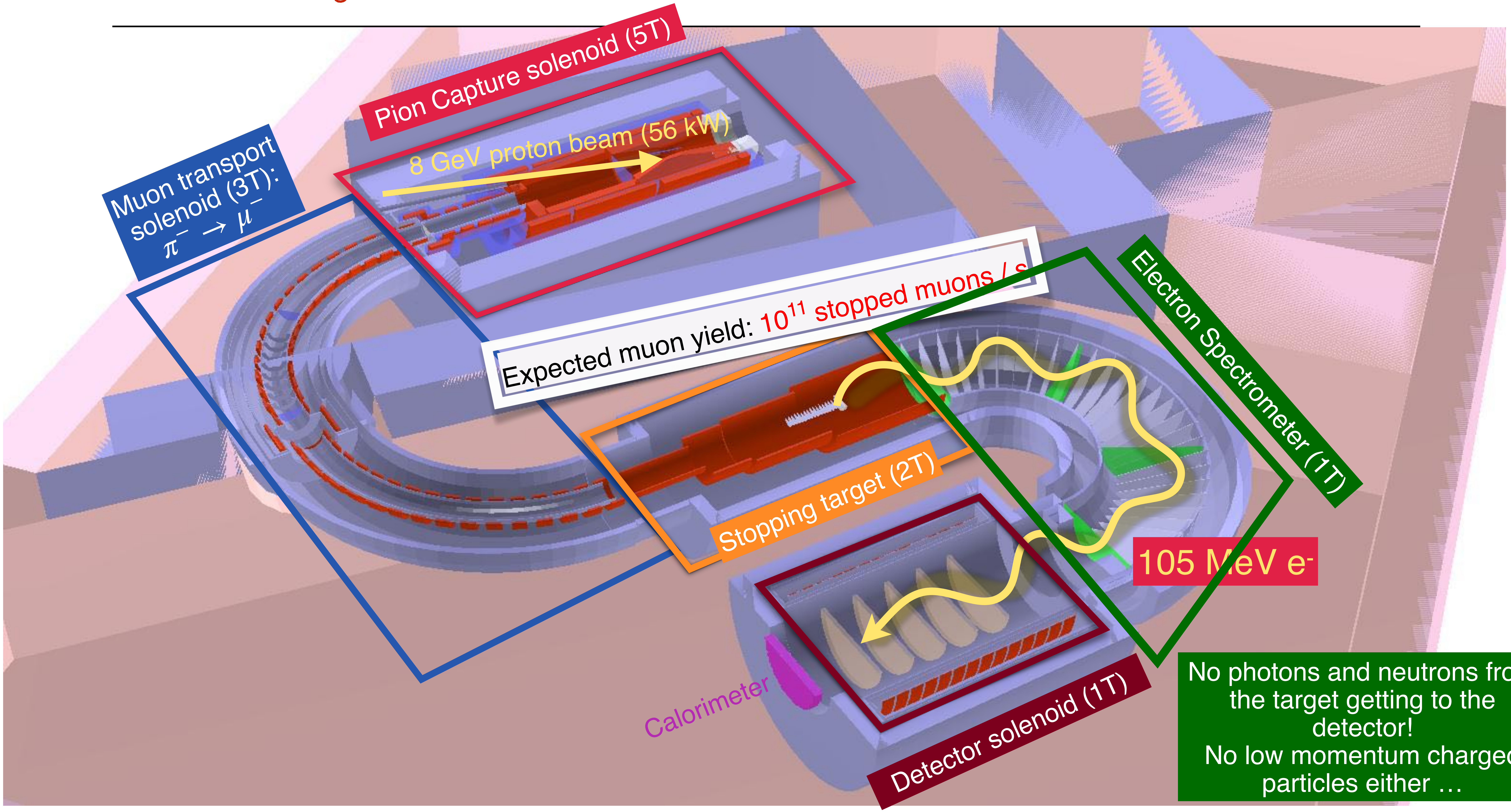
8 GeV proton beam (56 kW)
Tungsten proton target
1.2 10^{11} stopped muons/s

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



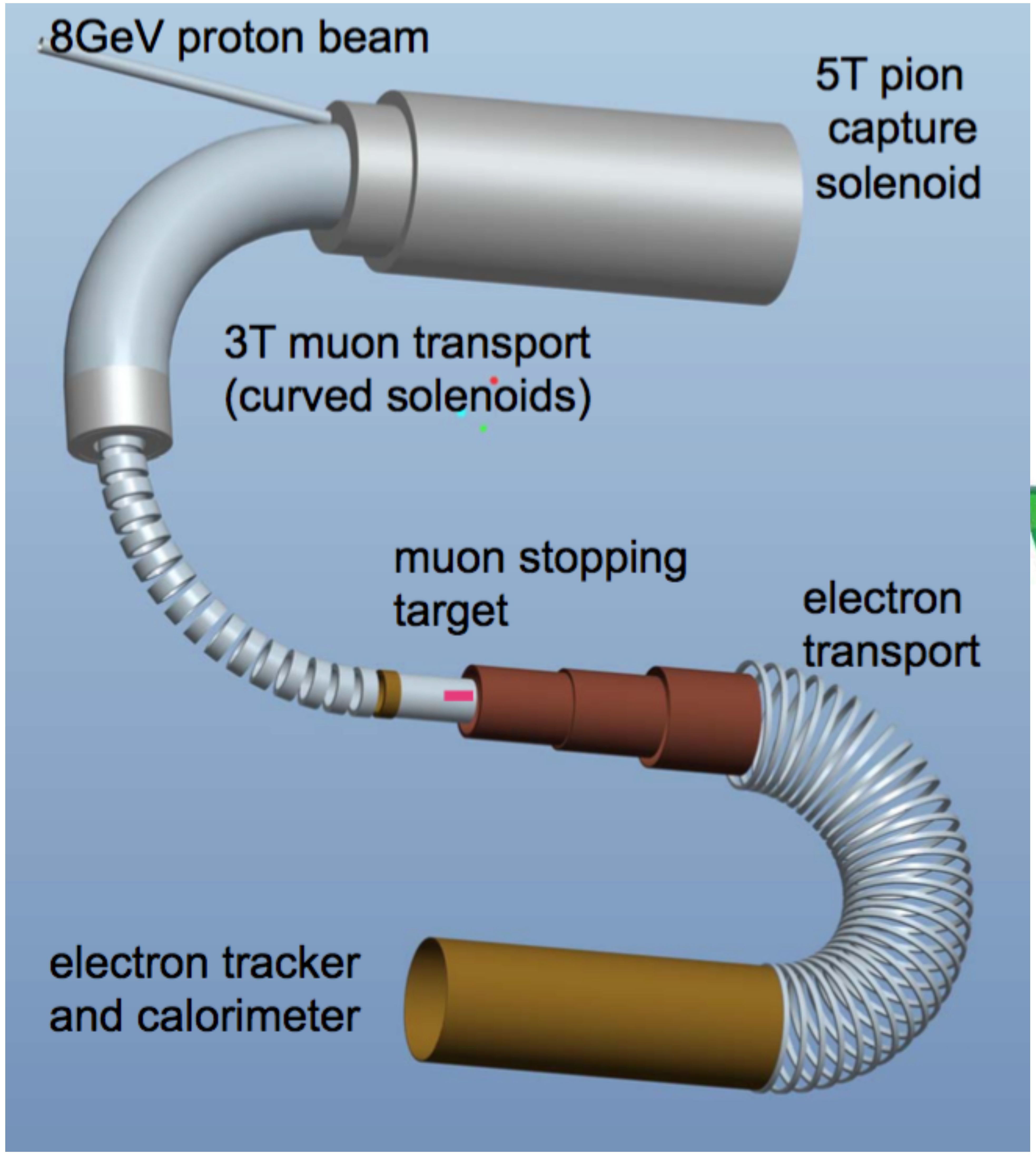


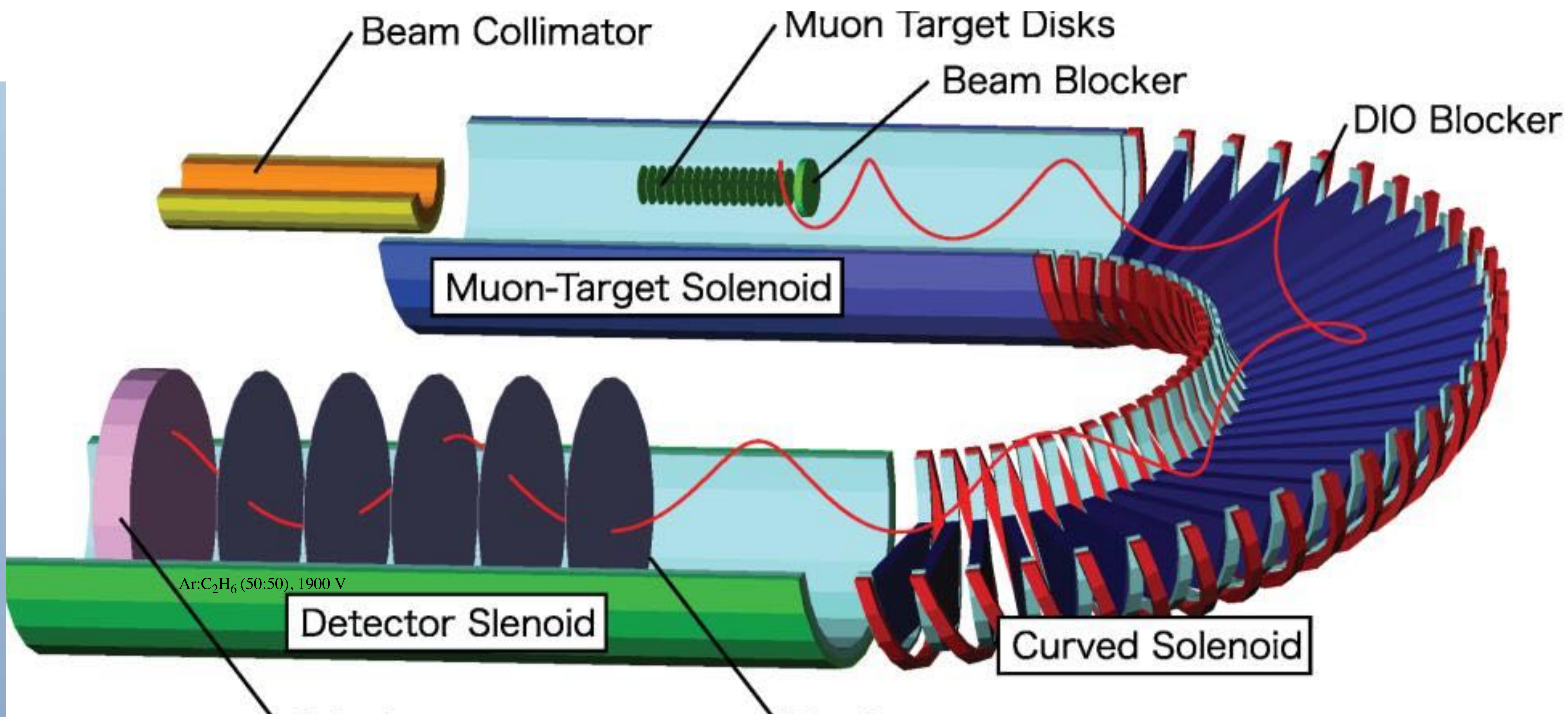
COMET design



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

COMET design :: detection section





Electromagnetic calorimeter

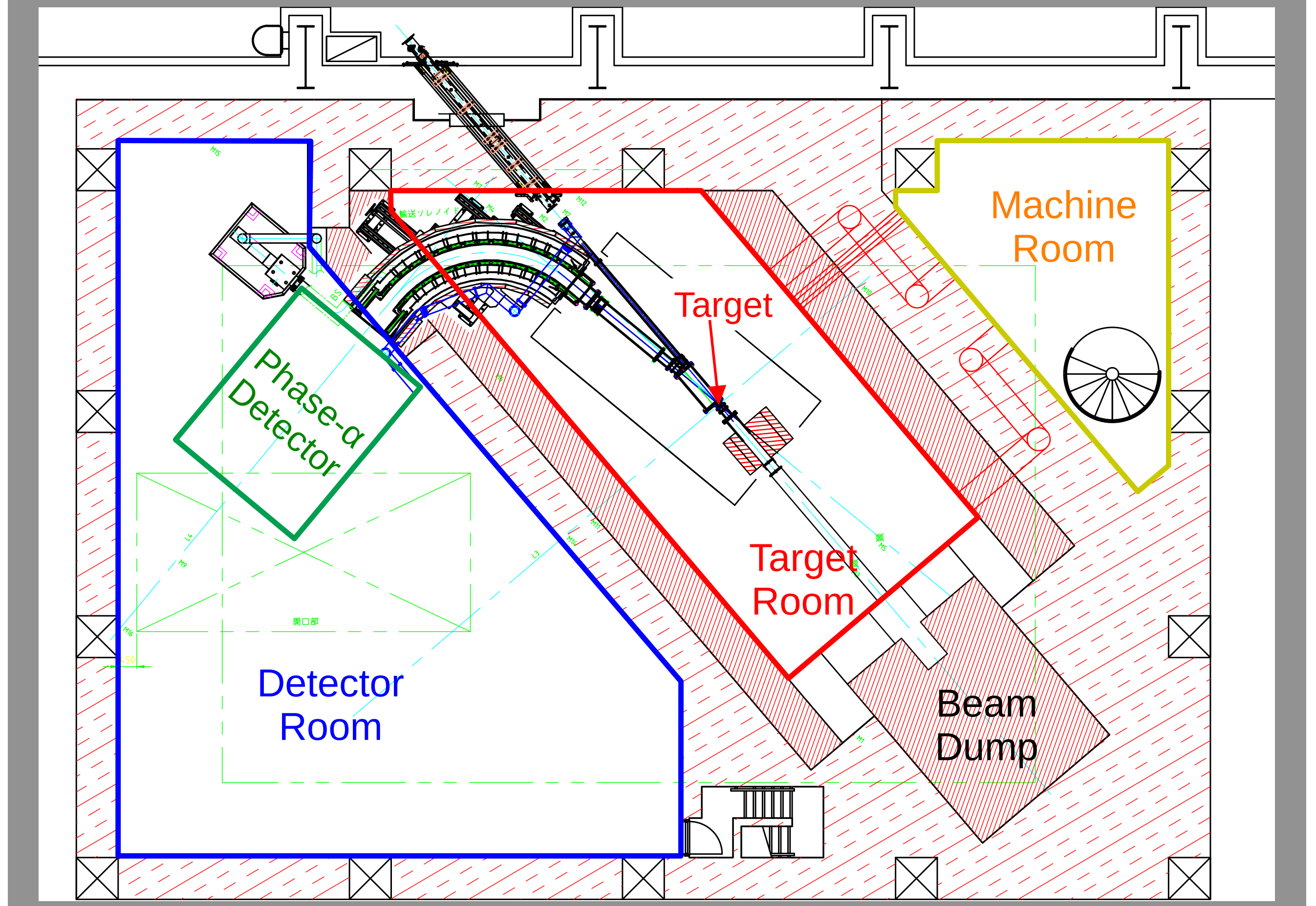
- trigger & timing: response time faster than 100 ns
- electron energy : ΔE/E < 5% (@105 MeV)
- cluster position: σ_x<1 cm
- 50 cm of radius
- made of 1920 LYSO crystals 2×2×12 cm³ (10.5 X_0)
- read out by APDs (operates @ 1 T)

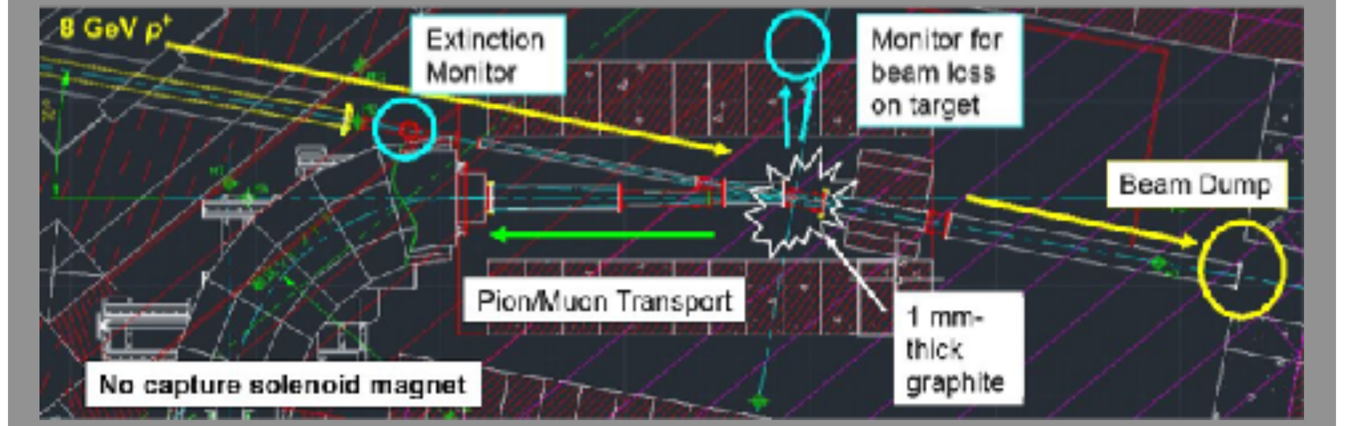
Straw tubes tracker

- 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(,5) -stage experiment

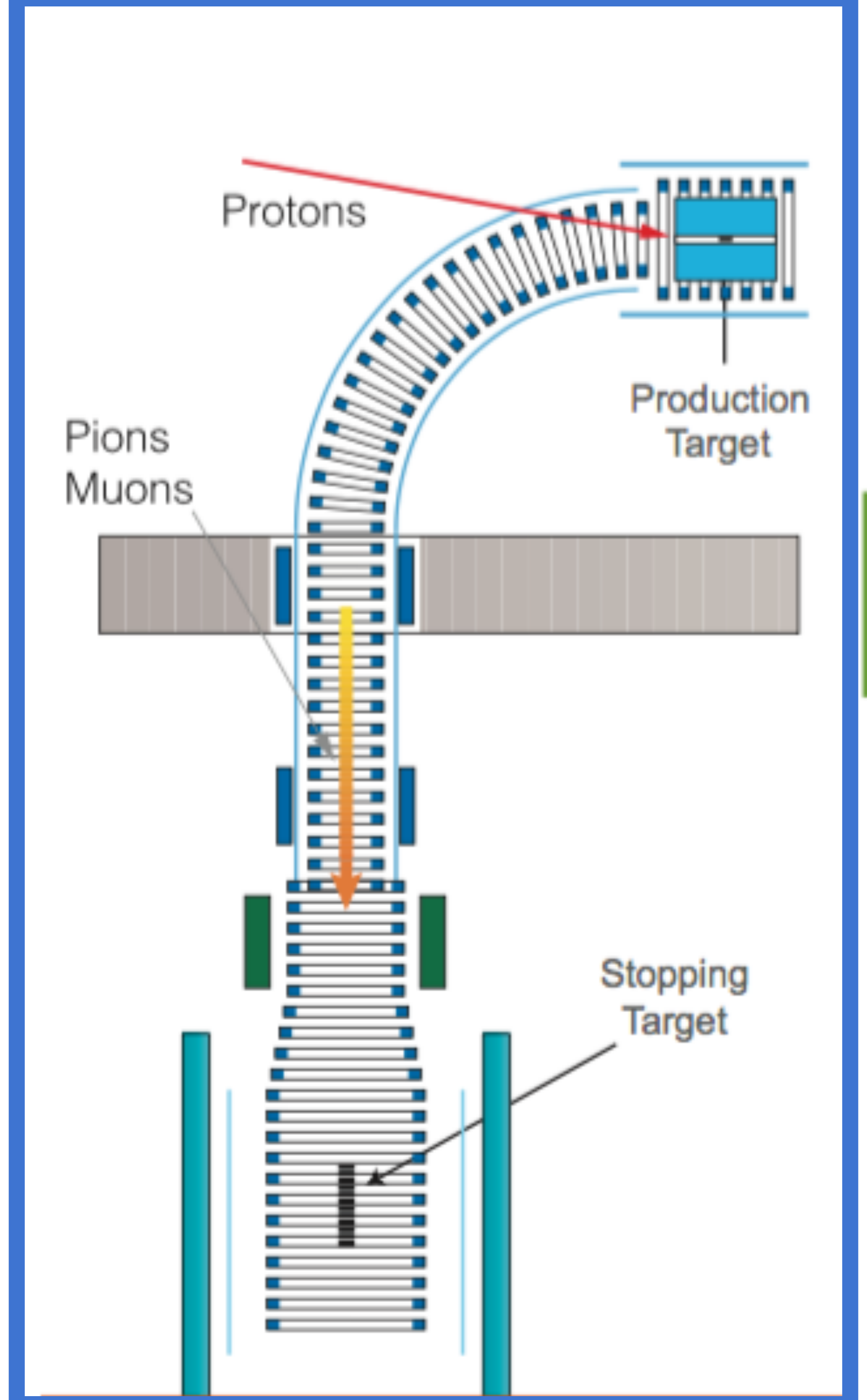
Phase α 2022





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

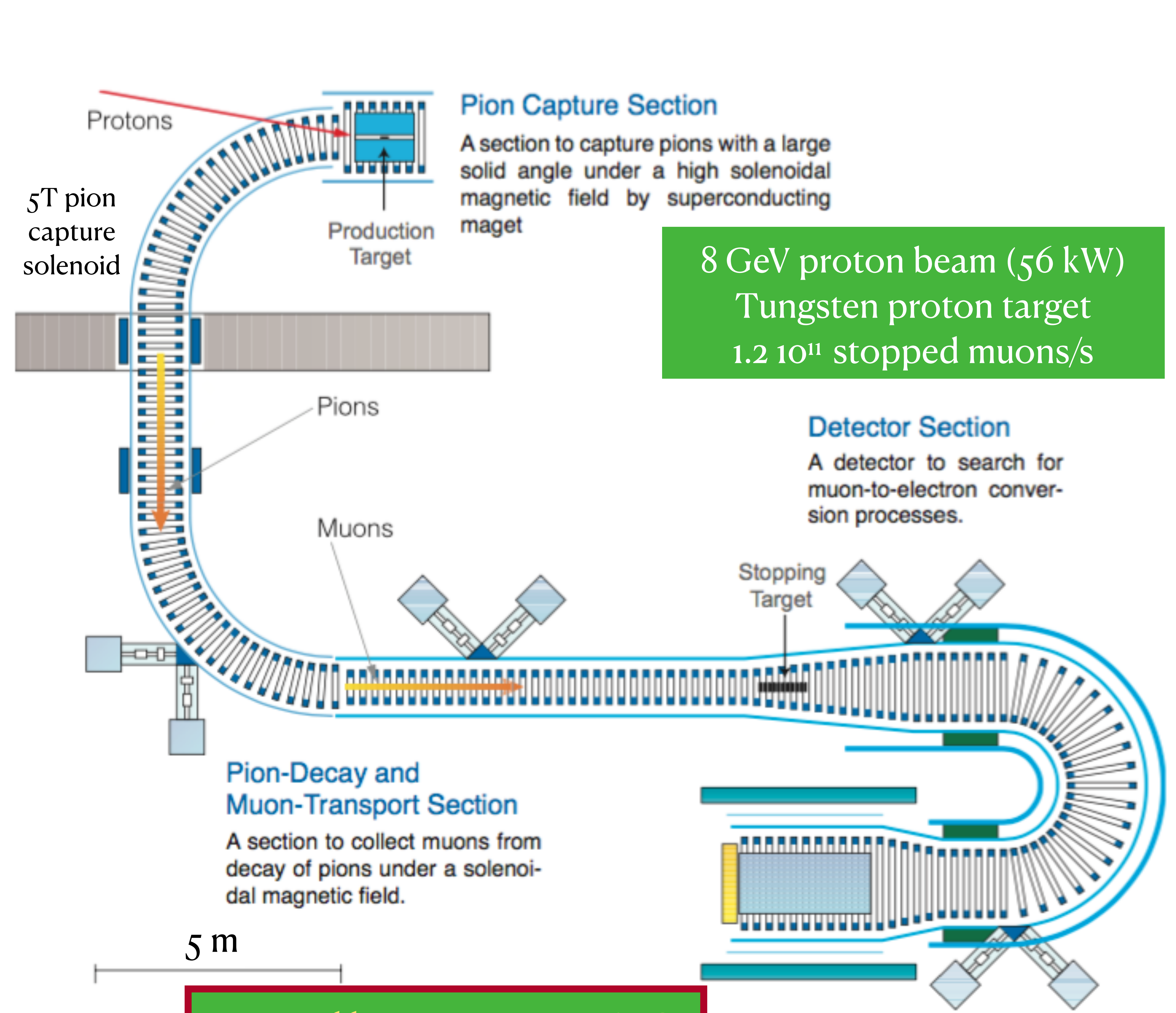
Phase I



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)

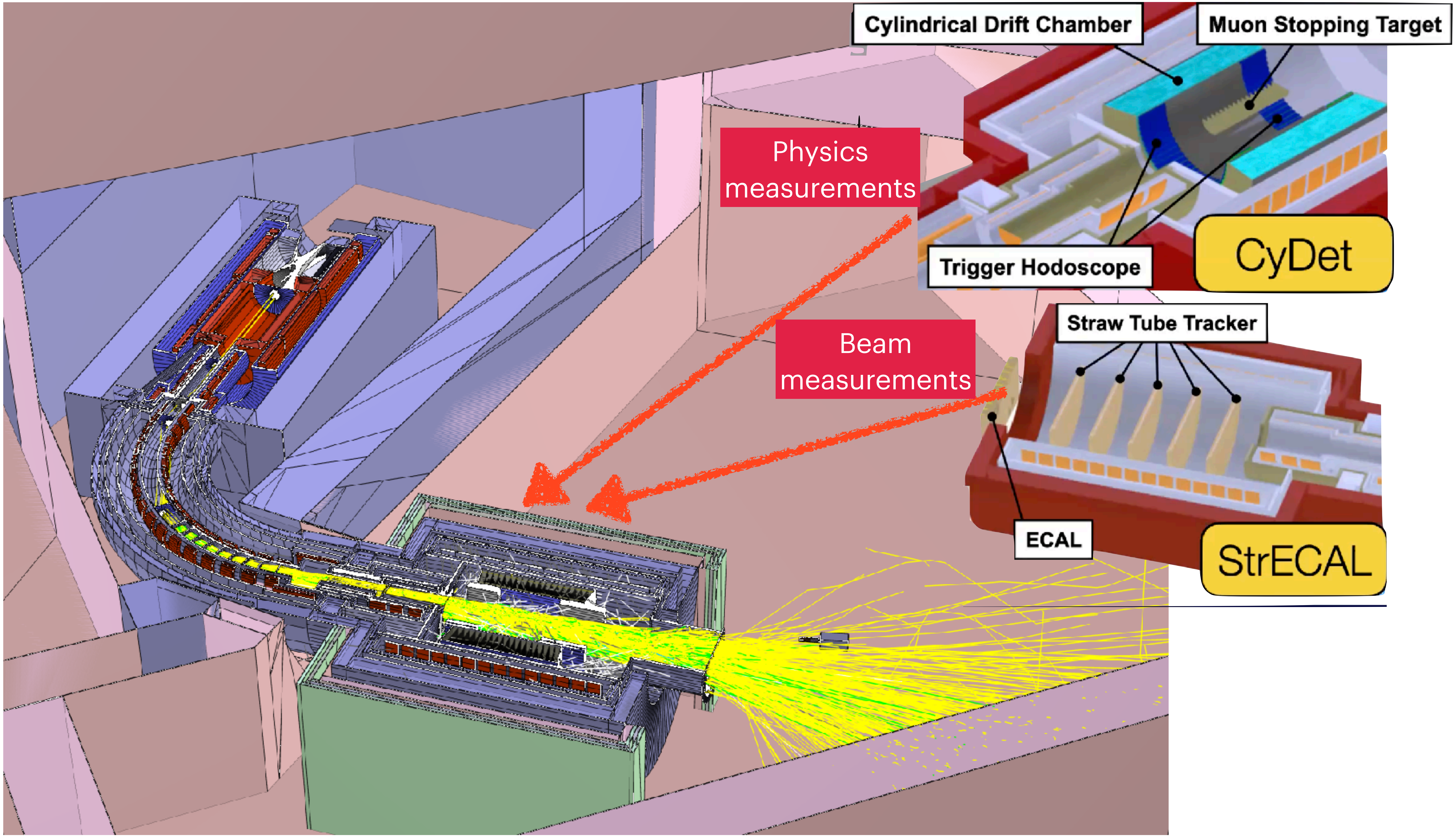
Phase II



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

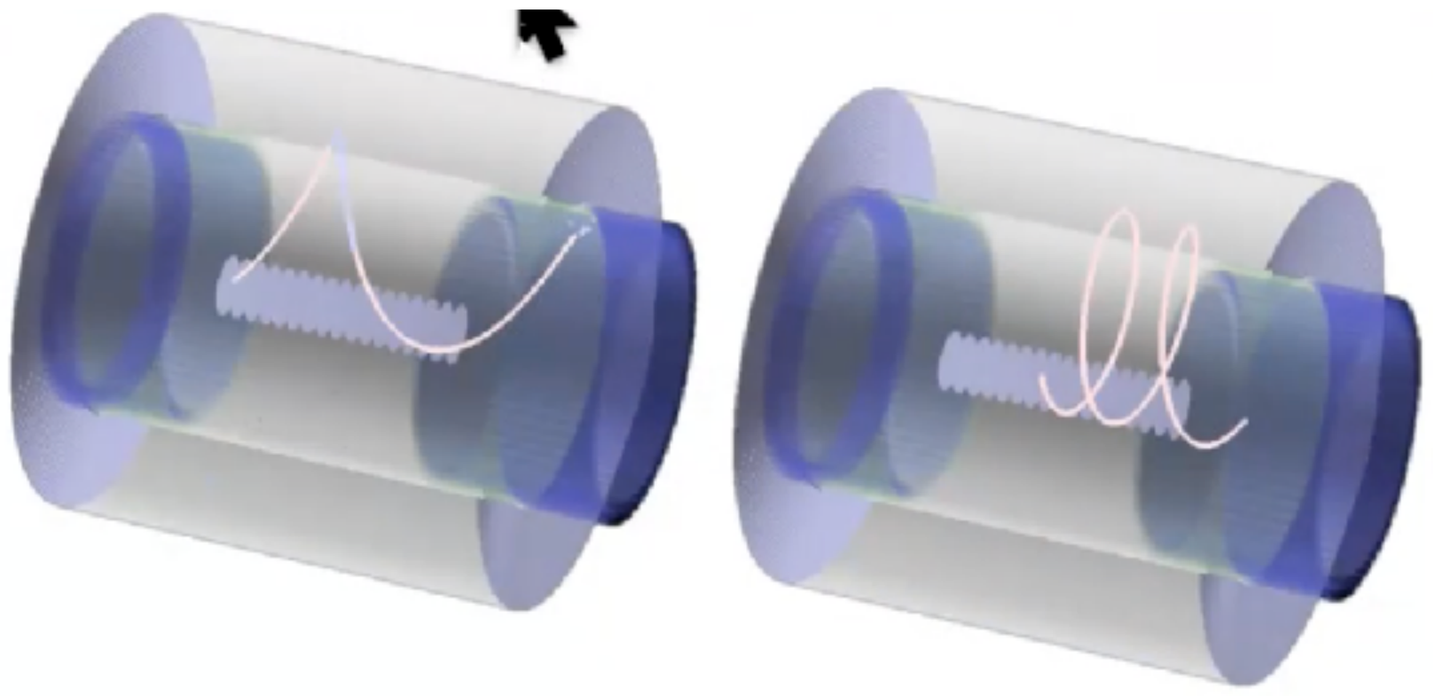
Expected limit : 7 10^{-17} @ 90% CL
Total background: 0.32 events
Running time: 1 yr (2 10^7 s)

COMET Phase I



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

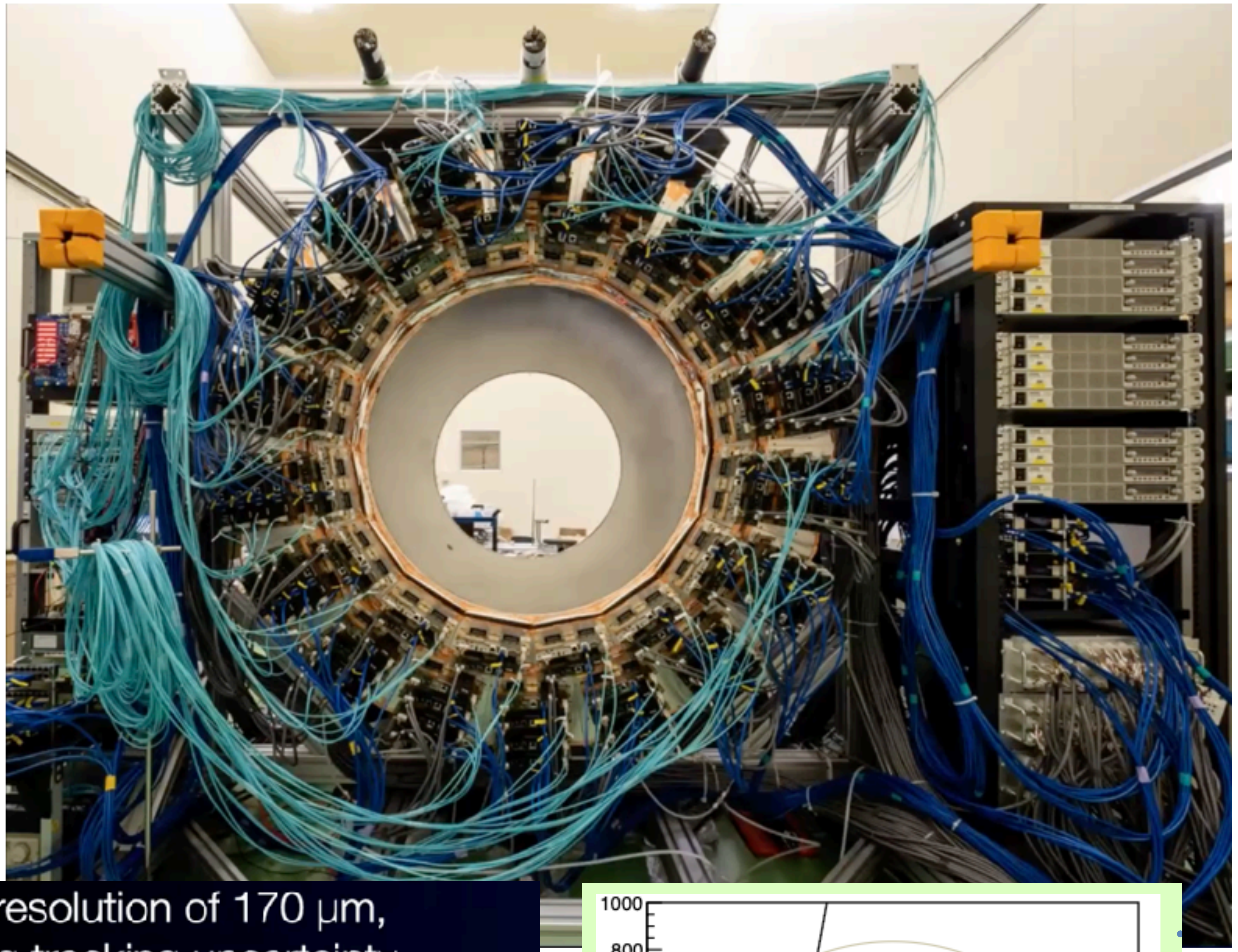


- CDC fully read out since 2019
- Currently at KEK being commissioned with cosmic rays

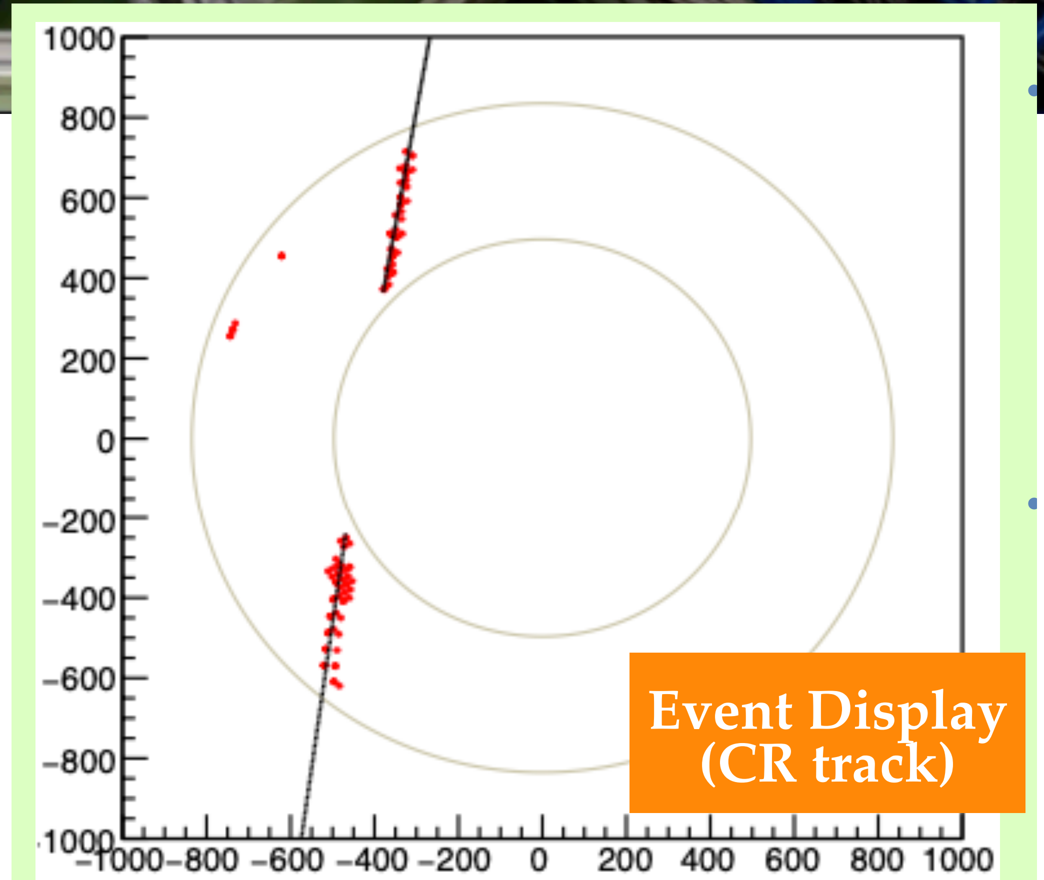
- signal tracks (~100 MeV/c) contained inside the CDC for better signal resolution
- triggered events : 60% single turn tracks & 40% multiple turn tracks

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

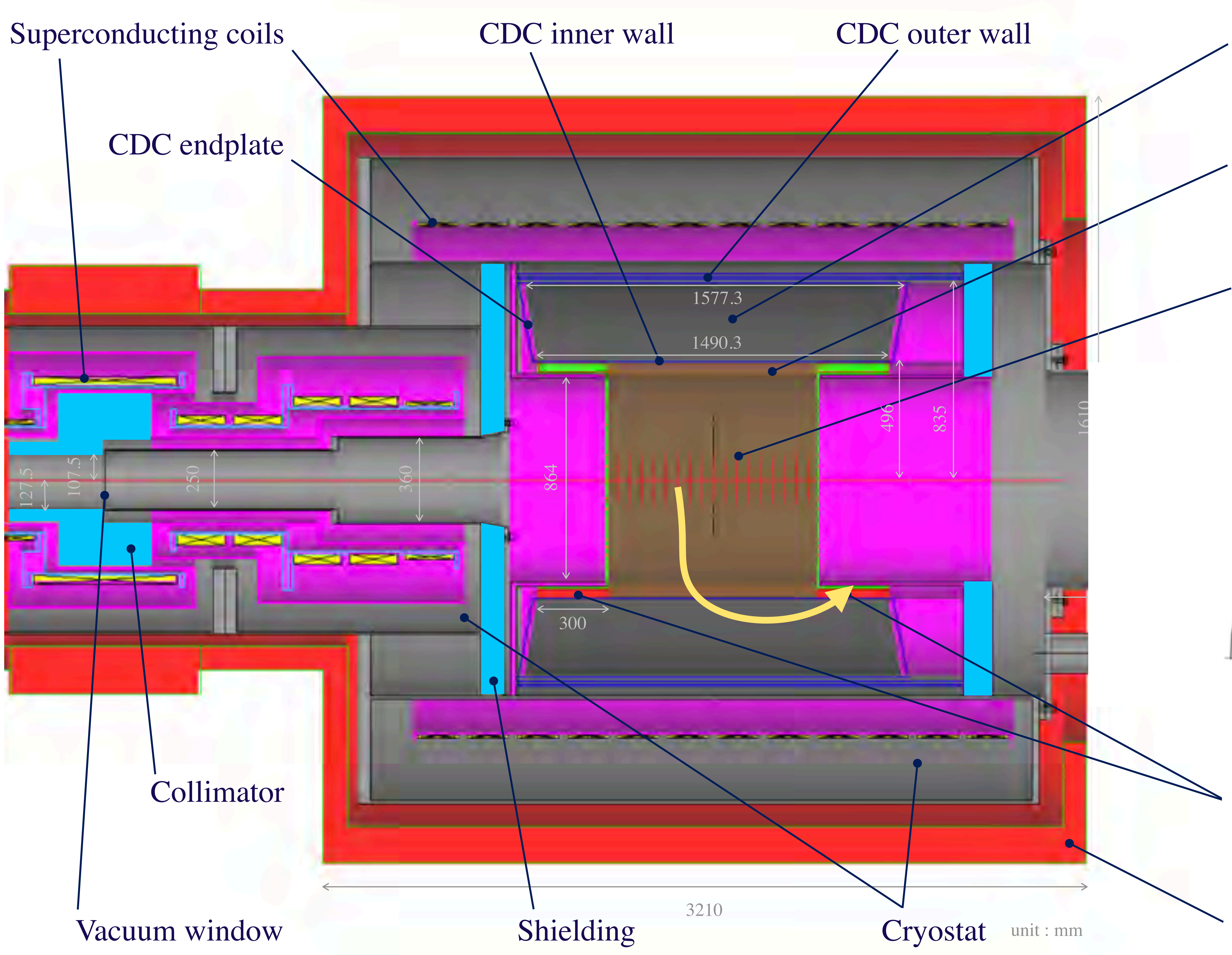
Test of a small prototype of the COMET cylindrical drift chamber
Nucl. Inst. Meth A 1015 (2021) 165756.

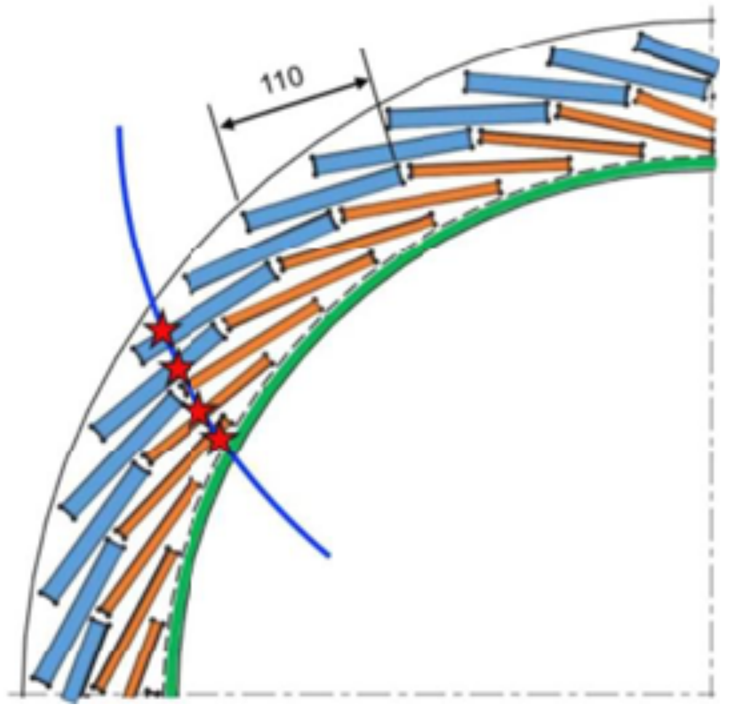


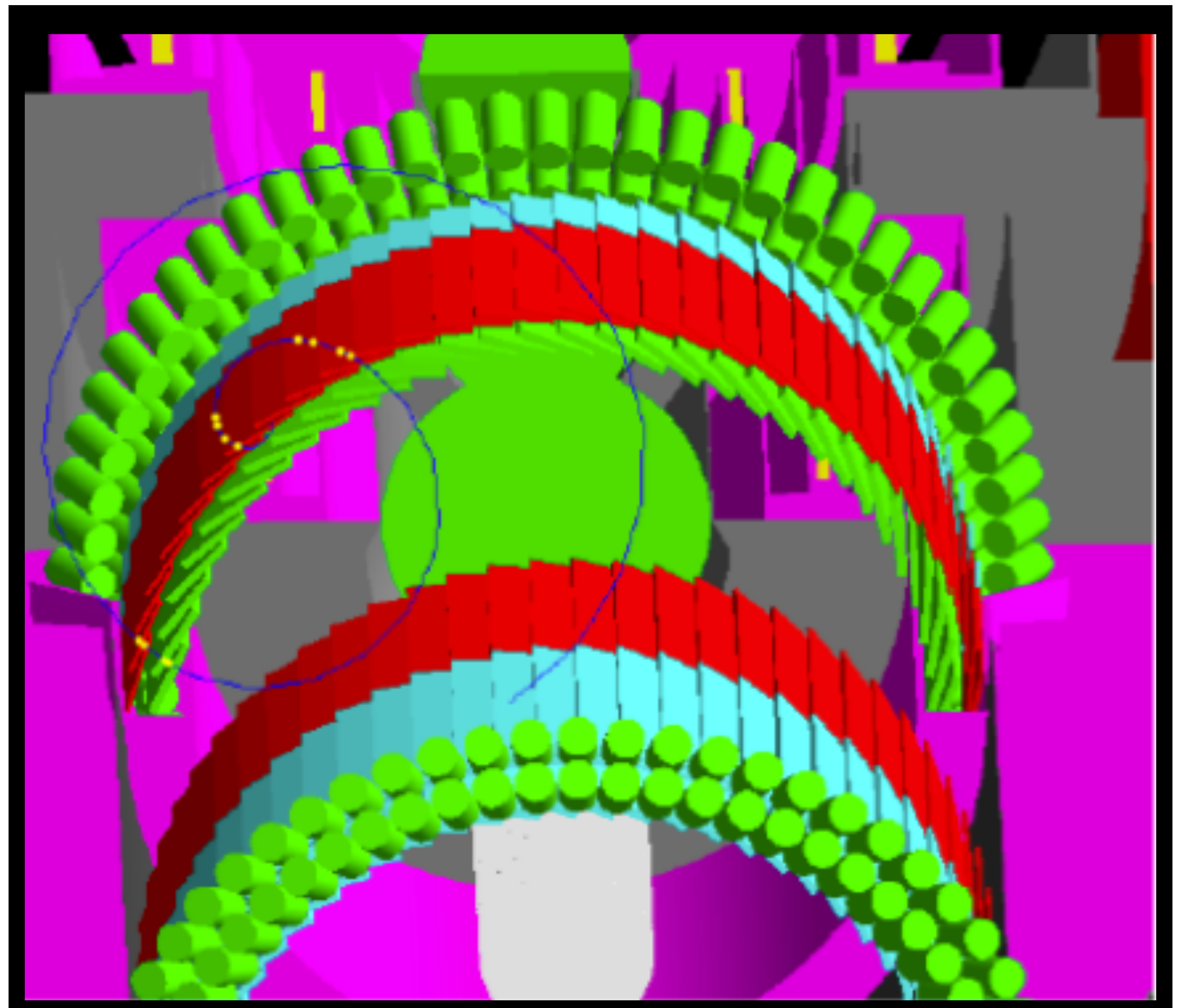
- Spatial resolution of 170 μm, including tracking uncertainty, achieved.
- Hit efficiency of 98% achieved
- Significant noise reduction achieved
- Detail study of detector response
  - space-charge effects
  - crosstalks
- Water cooling testing of the CDC readout underway



COMET Phase-I :: Electron Detectors (CyDet)





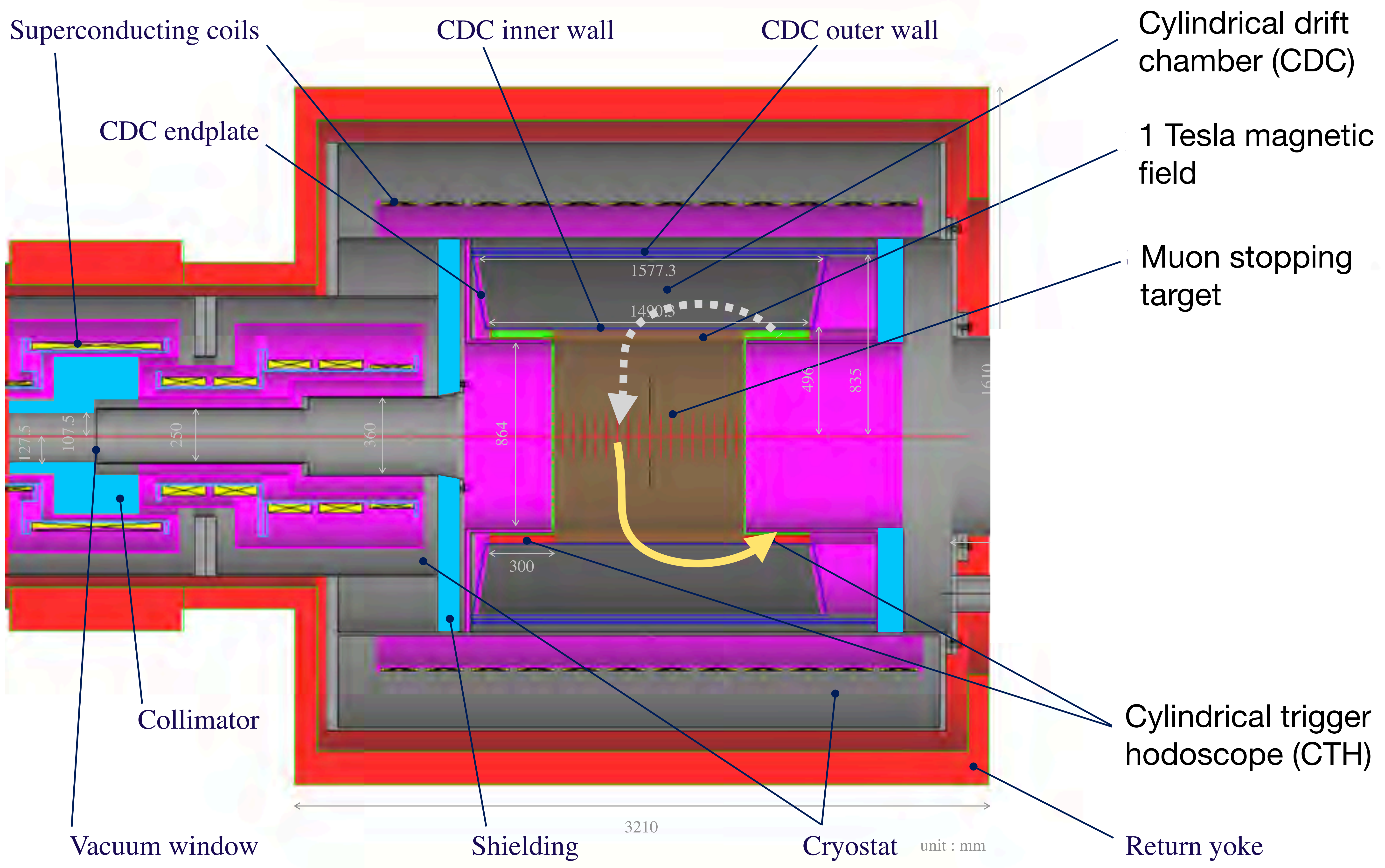


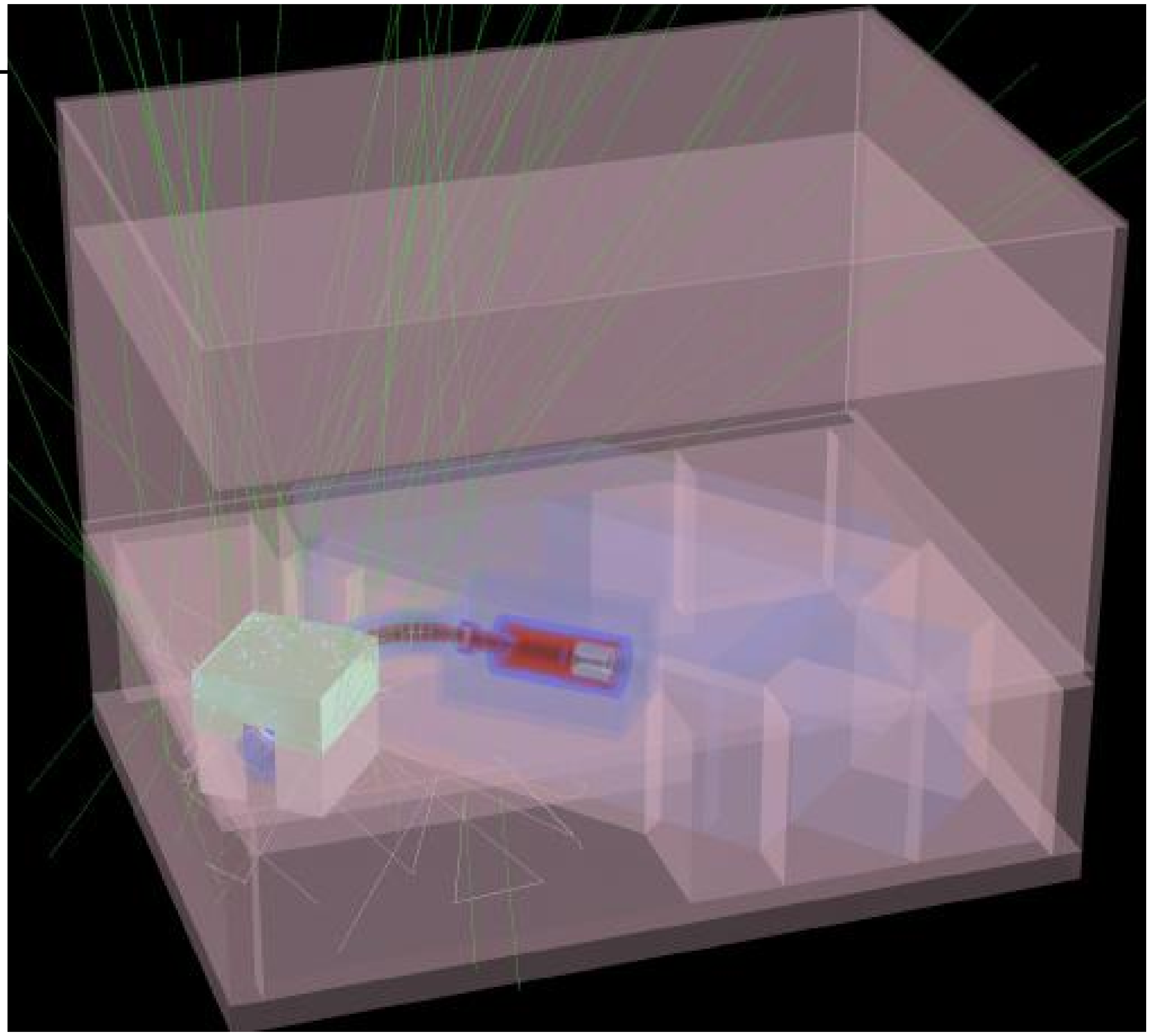
2-rings of ultra fast scintillators (64 segments, 33/36 x 1 x 1 cm3) read by optical fibres and SiPMs

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

Four-hold coincidence provides trigger and PID

COMET Phase-I :: Atmospheric background

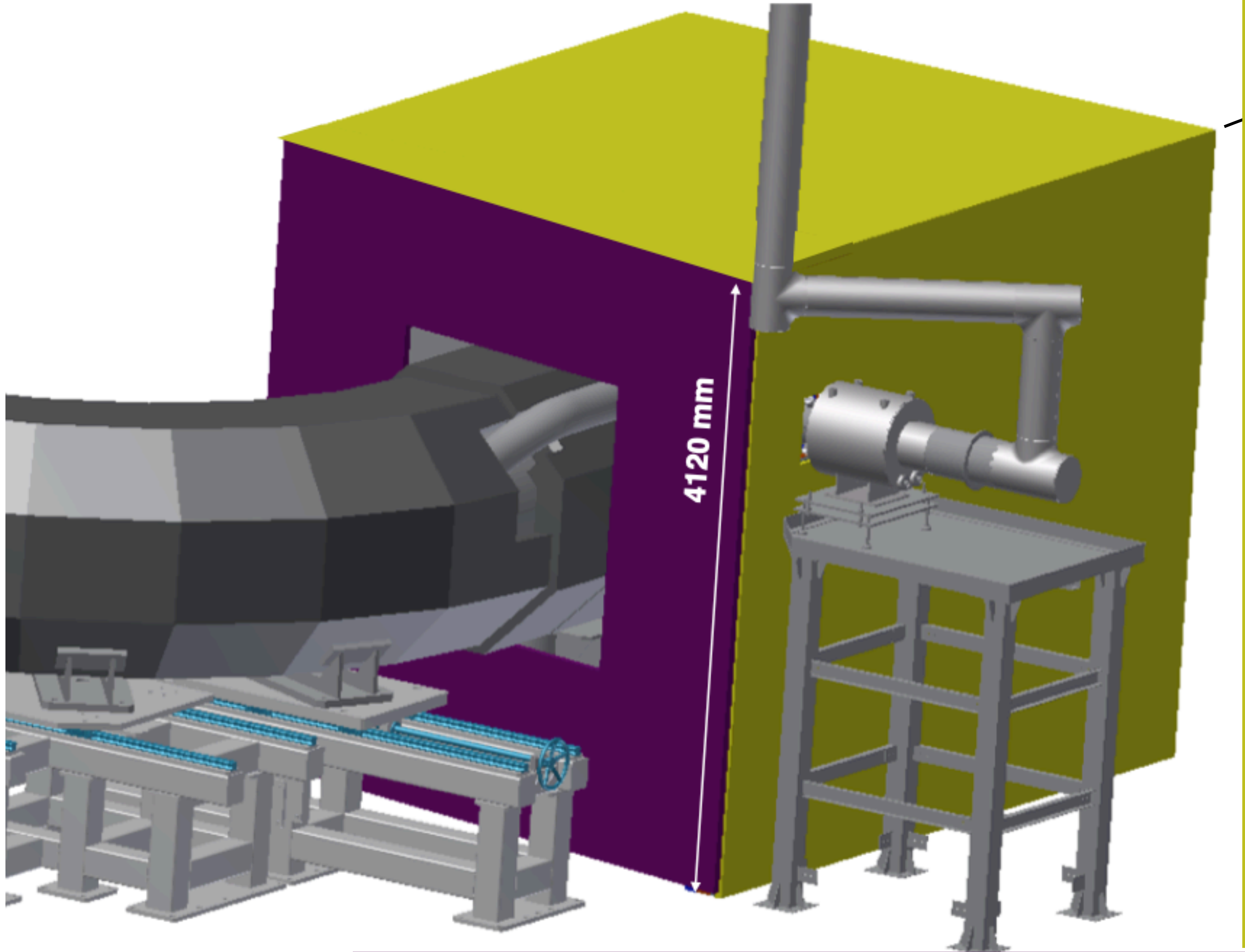




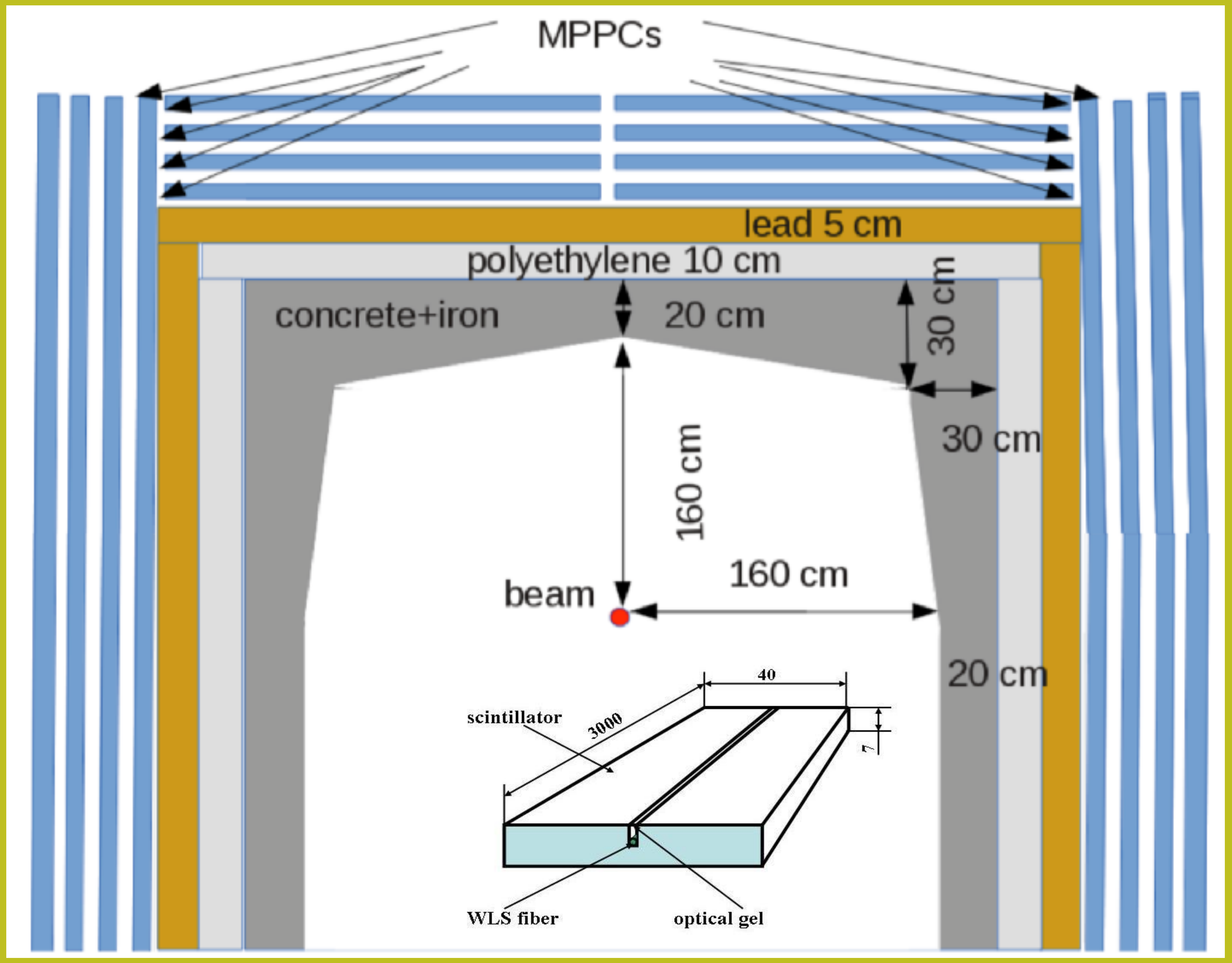
Atmospheric muons = main background

Cover as hermetically as possible the detectors (C with very high efficiency veto counters (CRV)

requirement : < 0.01 evts for COMET Phase 1
(The short data acquisition foreseen helps!)



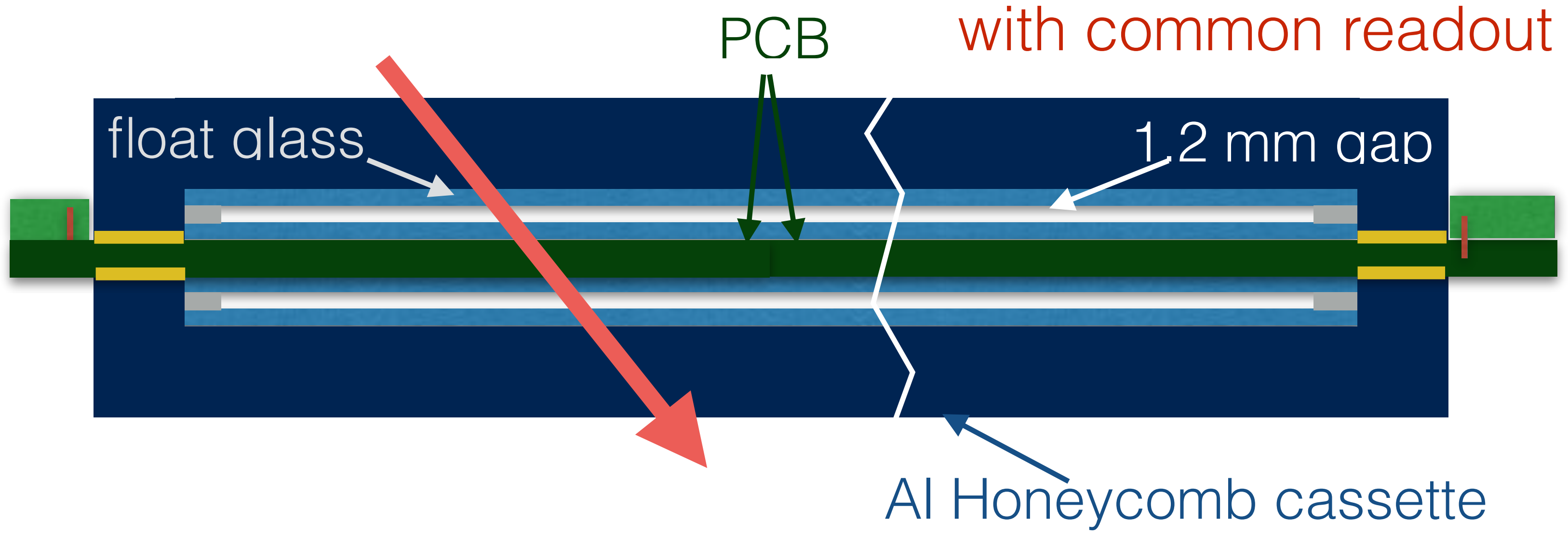
Scintillators CRV



GRPC CRV

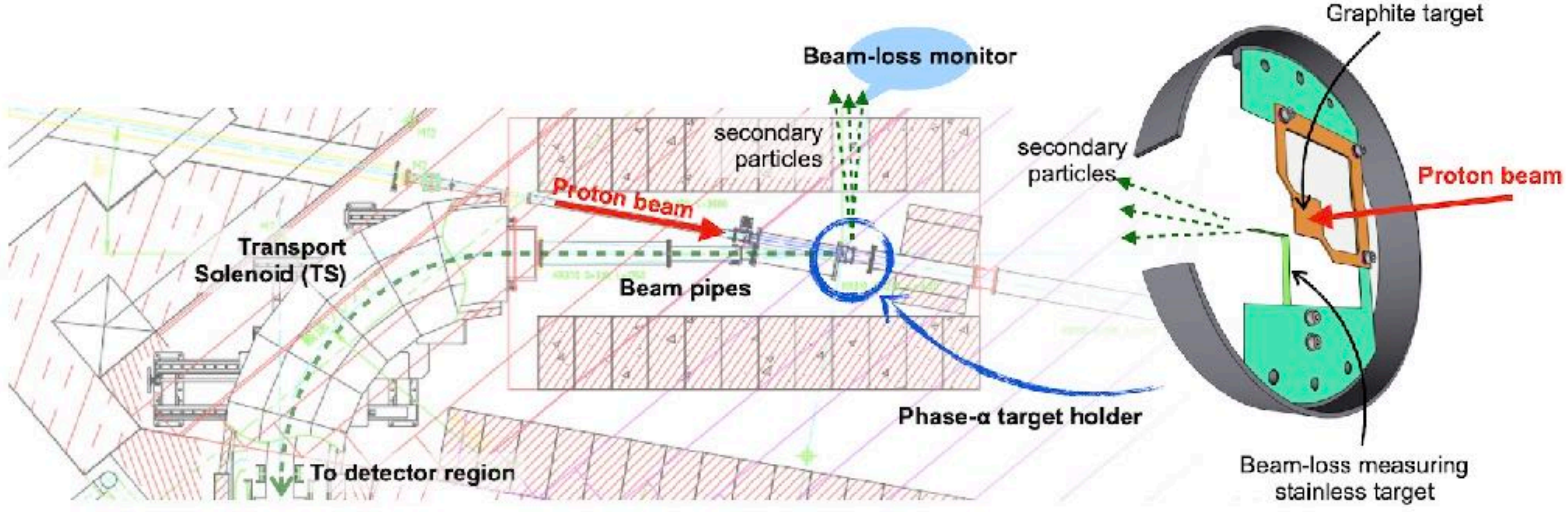
A tracker module: 7 detector modules (baseline)

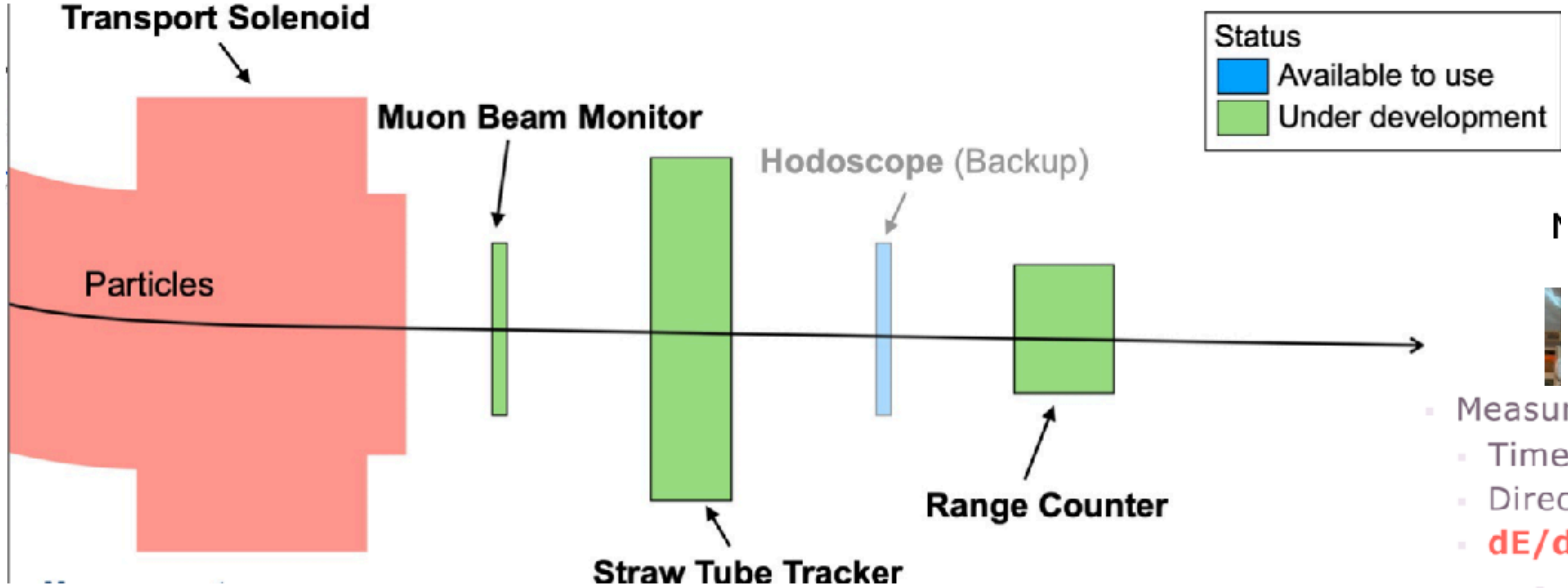
a module (1900x600 mm2): two single-gap GRPCs with common readout



COMET Phase α :: Engineering run w/o Pion Capture Solenoid

- **Commissioning of the proton beamline and muon beam transport**
- **Beam time in**
  - **10th − 14th February (commissioning)**
  - **3rd − 4th & 9th – 15th March**
  - **February 2024**

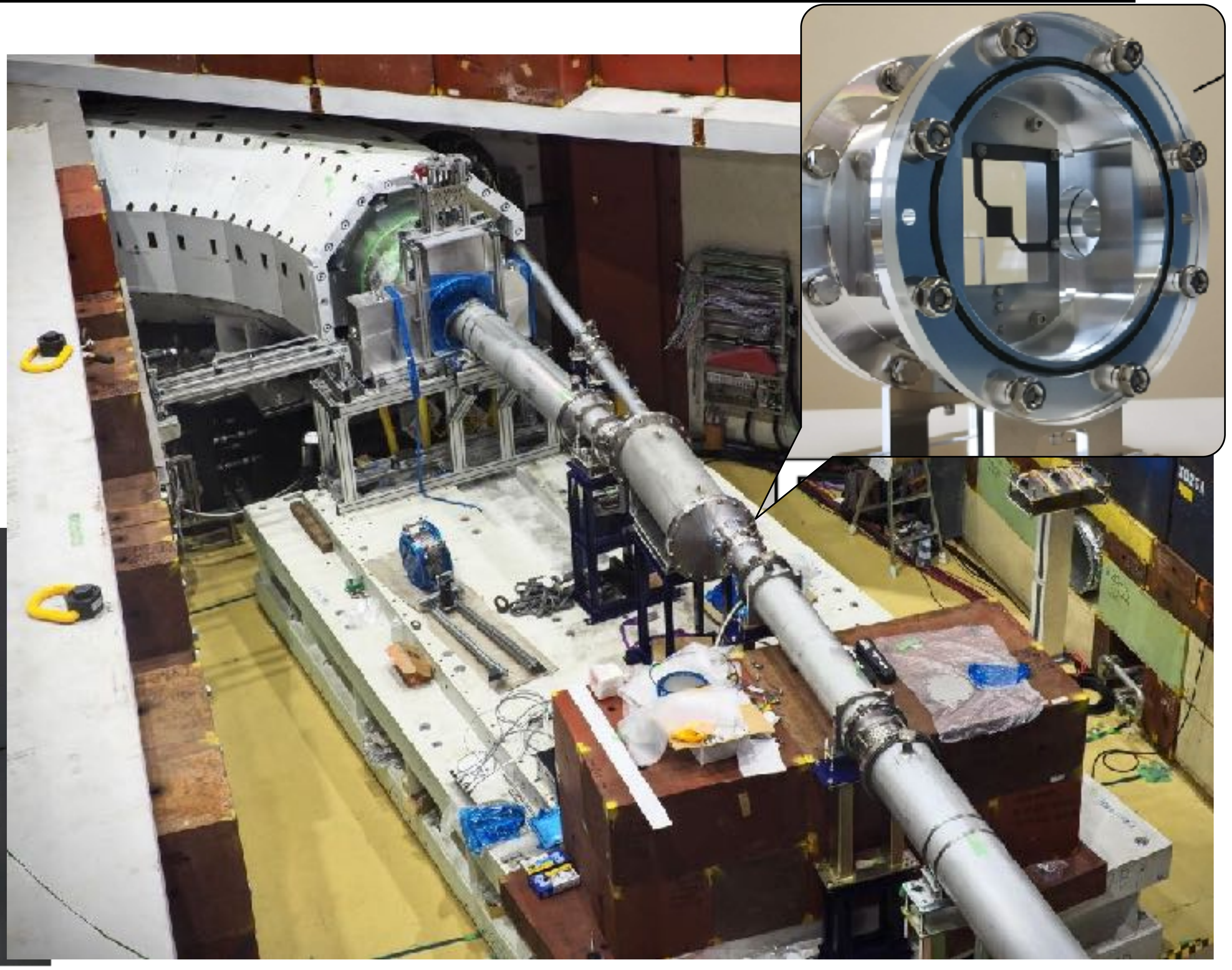




- Measurements
  - Time and position by the **Muon Beam Monitor** and **Straw Tube Tracker**
  - Direction by the **Straw-tube Tracker**.
  - **dE/dx, TOF, and decay time measured by the Range Counter**
    - **For momentum and PID reconstruction**

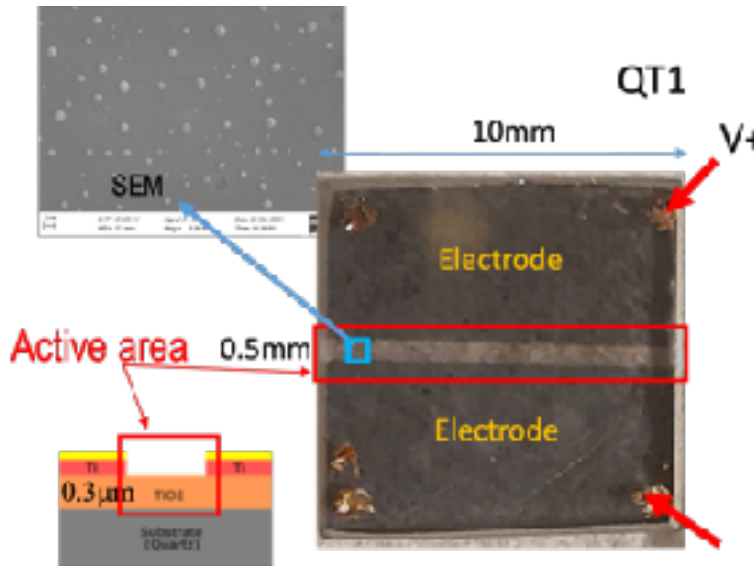
COMET Phase α :: Engineering run w/o Pion Capture Solenoid

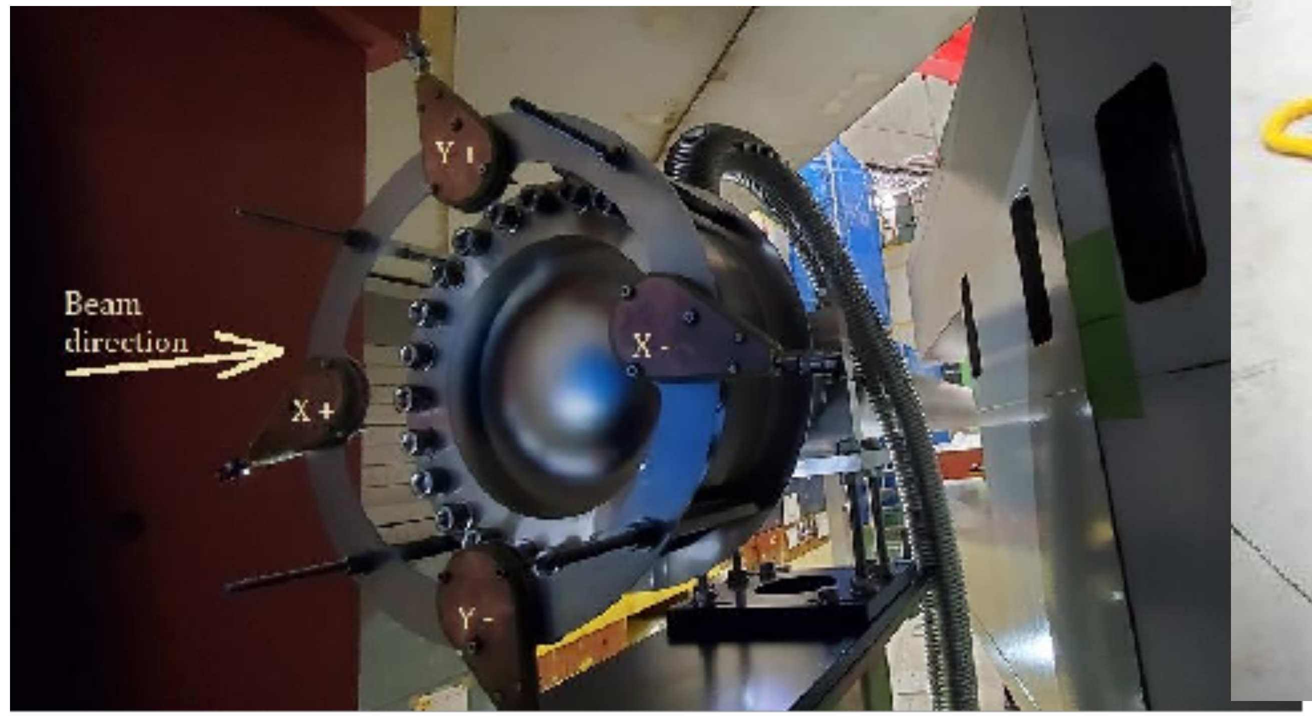
- A thin Pion Production Target contained in the beam vacuum chamber.
- Same muon Transport Solenoid as in Phase-I & II.
- Beam-masking system with two moving collimator slits in front of the Transport Solenoid.

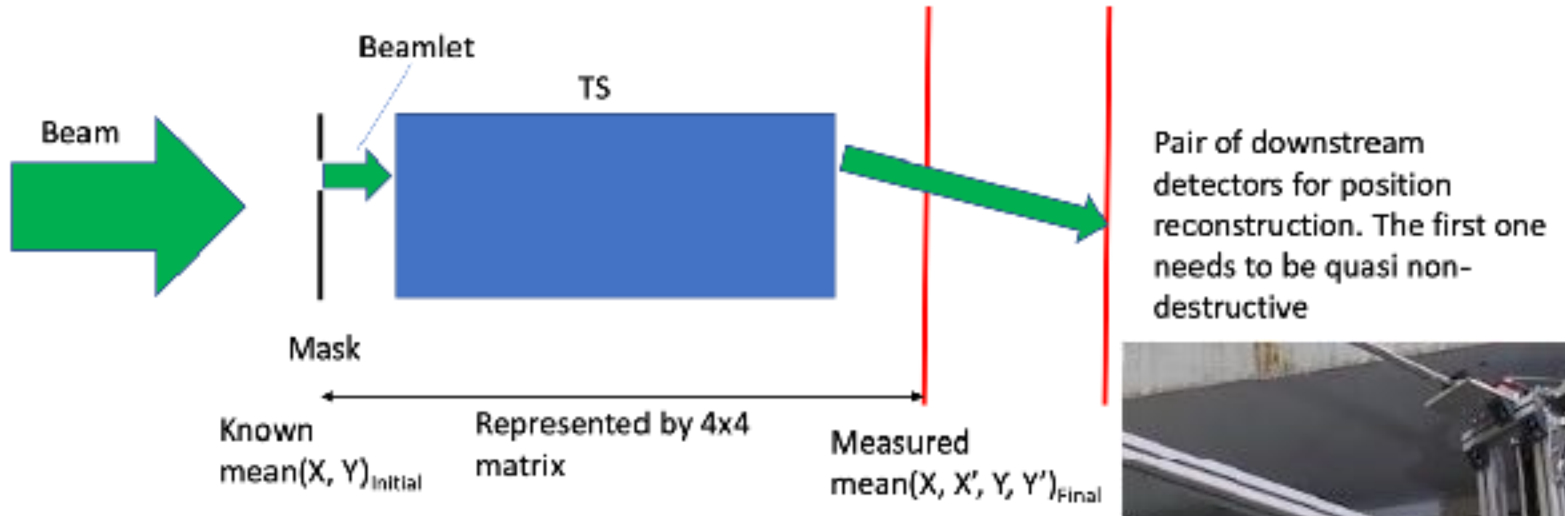


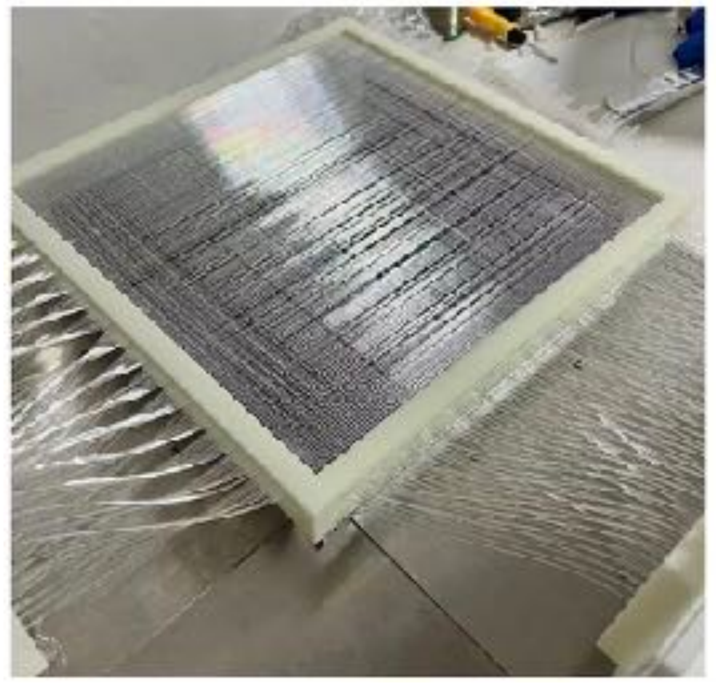
Proton Beam Monitor

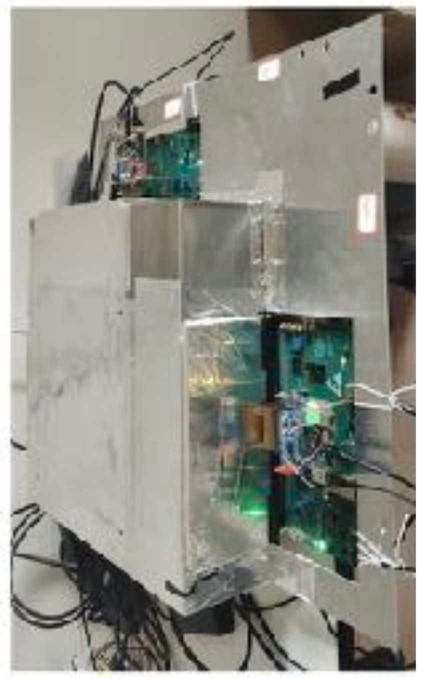
- Polycrystalline TiO_2 developed in India. Very thin (0.3 μm) and much cheaper (handmade) than diamonds.
- Eight modules were attached around the vacuum windows at the entrance and end of the COMET beam room.





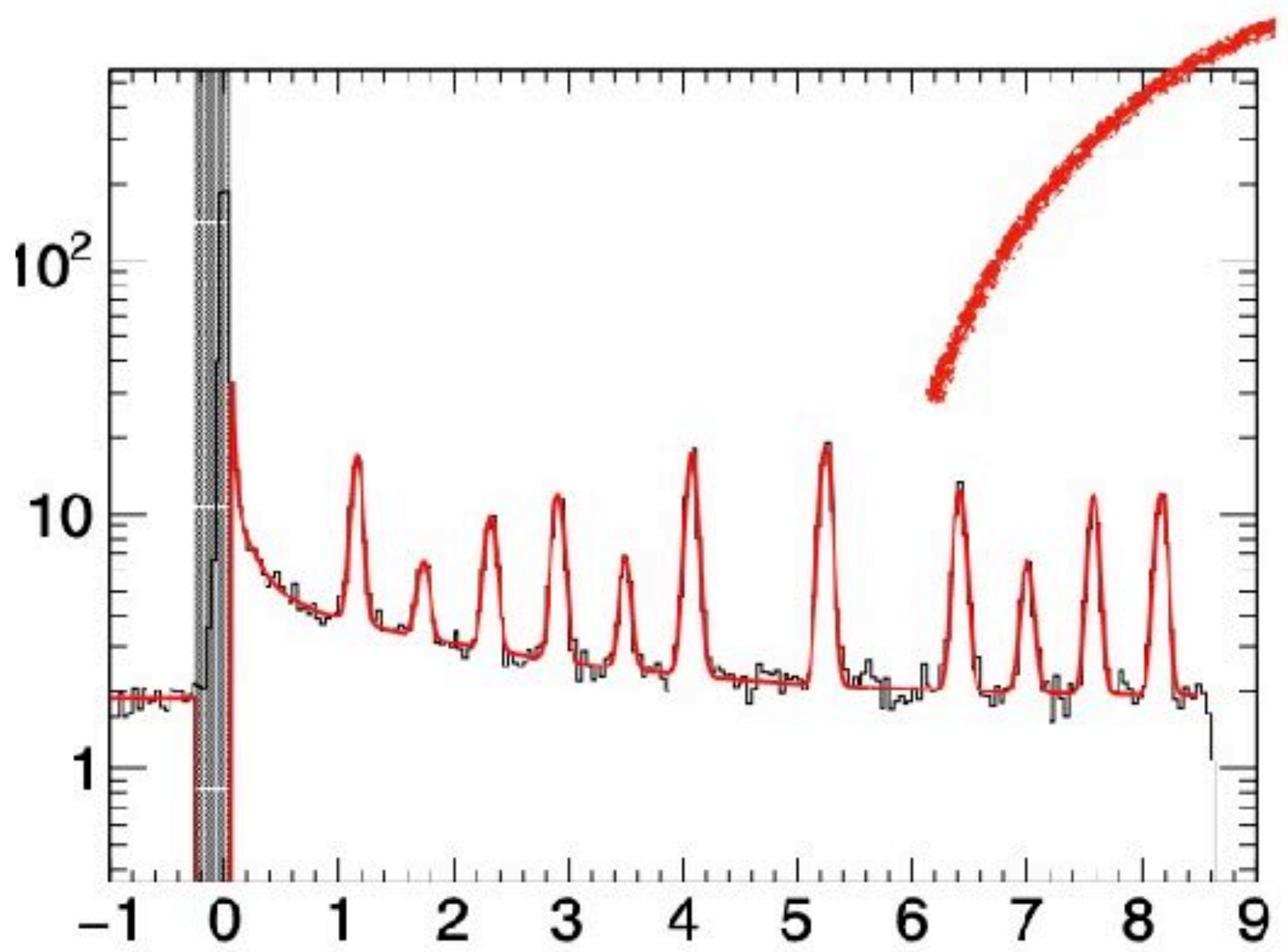


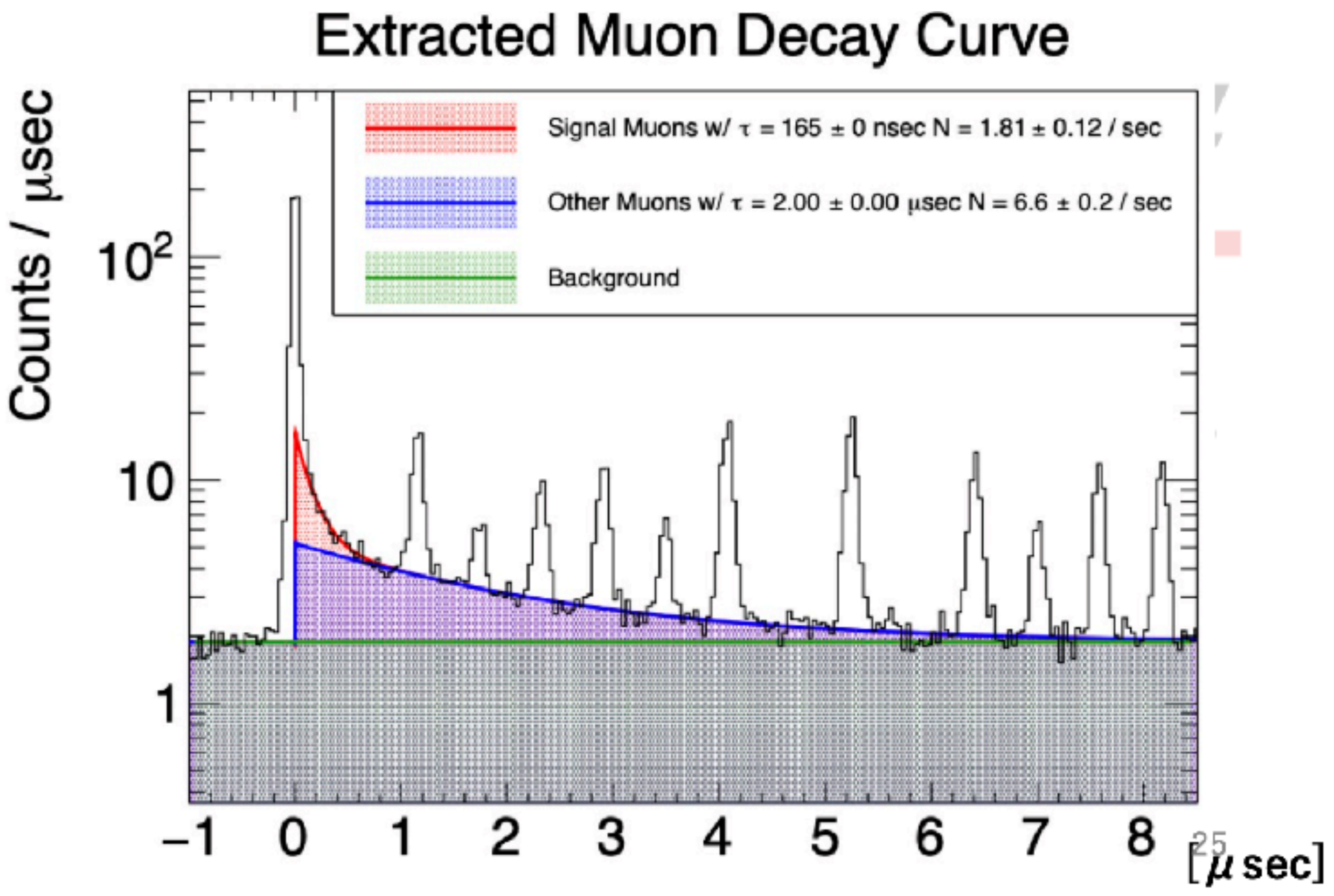


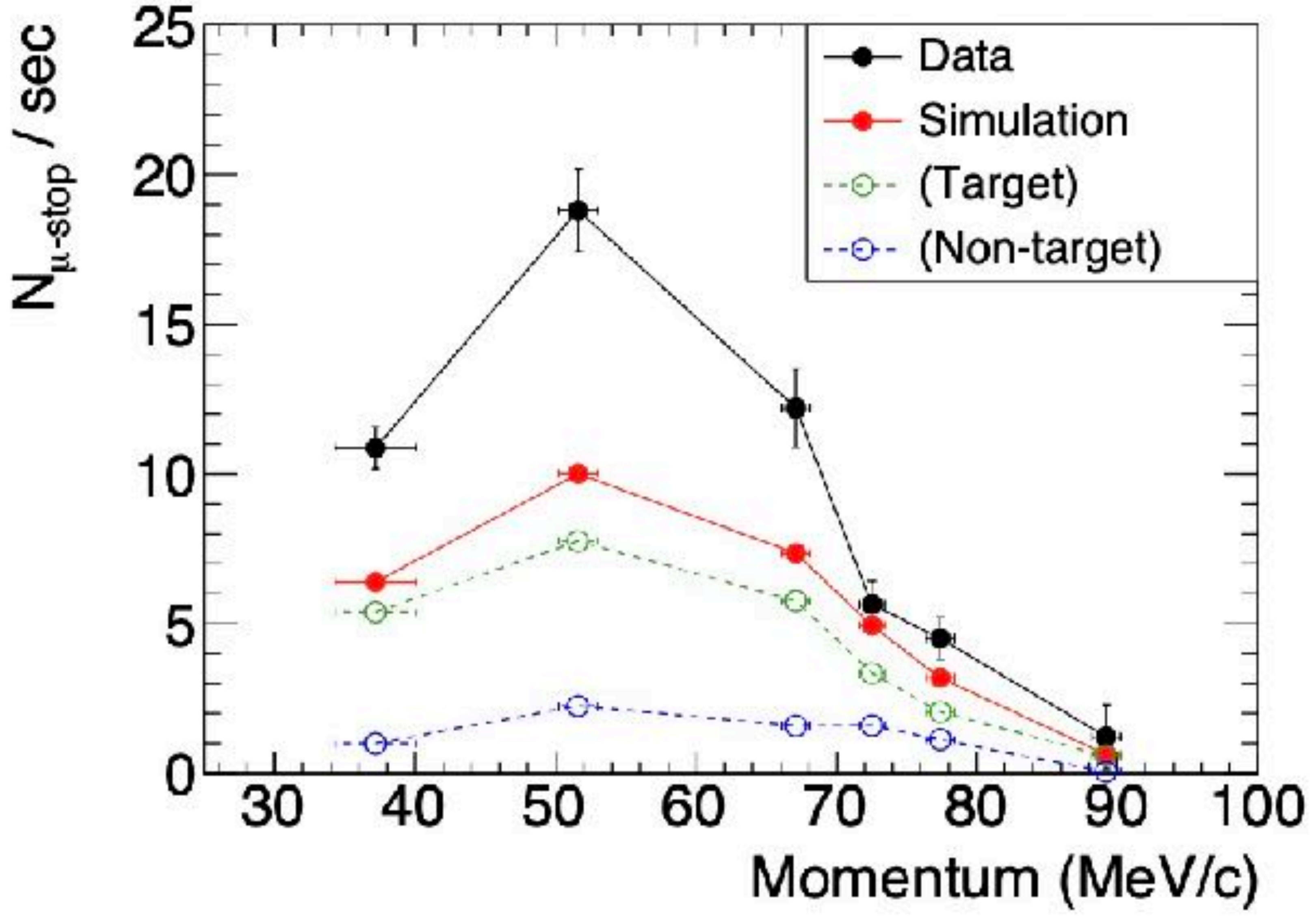


Muon beam monitor

- Chinese hodoscope with 1 mm^2 plastic scintillating fibres, read by SiPMs.
- 30×30 cm^2 area holds 2D-aligned 128+128 fibres.
- ~3 nsec time resolution.



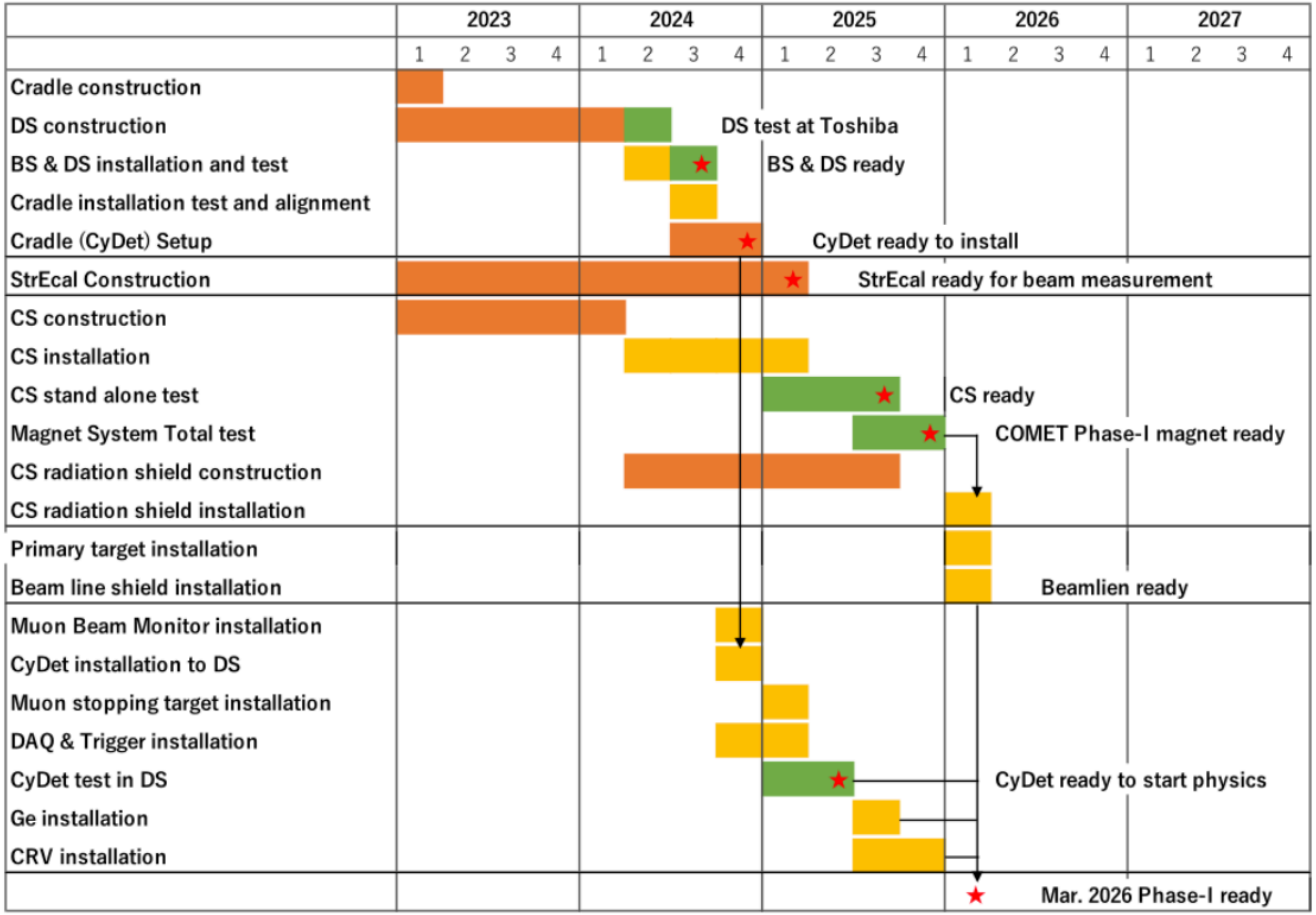




- Statistical errors only
- Overall difference (data/sim.) ranges 1.5-1.7
- The simulation data is the most conservative one, predicting lowest muon yield.
  - This is the 1st data of backward pion production taken at 8GeV
  - Factor of ~2 difference among different models
- Systematic error estimation in progress

Testbeam 1-8 Novembre 2023
@ PSI

test of the Range Counter and CTH measurement of the secondaries produced in a W target


2023
2024
2025
2026
2027
1 2 3 4
Cradle construction
DS construction
BS & DS installation and test
Cradle installation test and alignment
Cradle (CyDet) Setup
StrEcal Construction
CS construction
CS installation
CS stand alone test
Magnet System Total test
CS radiation shield construction
CS radiation shield installation
Primary target installation
Beam line shield installation
Muon Beam Monitor installation
CyDet installation to DS
Muon stopping target installation
DAQ & Trigger installation
CyDet test in DS
Ge installation
CRV installation
DS test at Toshiba
BS & DS ready
CyDet ready to install
StrEcal ready for beam measurement
CS ready
COMET Phase-I magnet ready
Beamlien ready
CyDet ready to start physics
Mar. 2026 Phase-I ready