COMET Experiment

& potential collaborative work with NA61/SHINE

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on behalf of the COMET Collaboration
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NA61/SHINE workshop @Okayama Univ.

Imperial College London

Science & Technology Facilities Council | UK Research and Innovation

Outline

- μ-e conversion
- COMET Experiment
  - Introduction
  - Phase-α
  - Phase-I
  - Phase-II
  - Pion production in COMET

Charged Lepton Flavour Violation (CLFV)

In the Standard Model,

$$\mathscr{B}(\mu \to e\gamma) = 0$$

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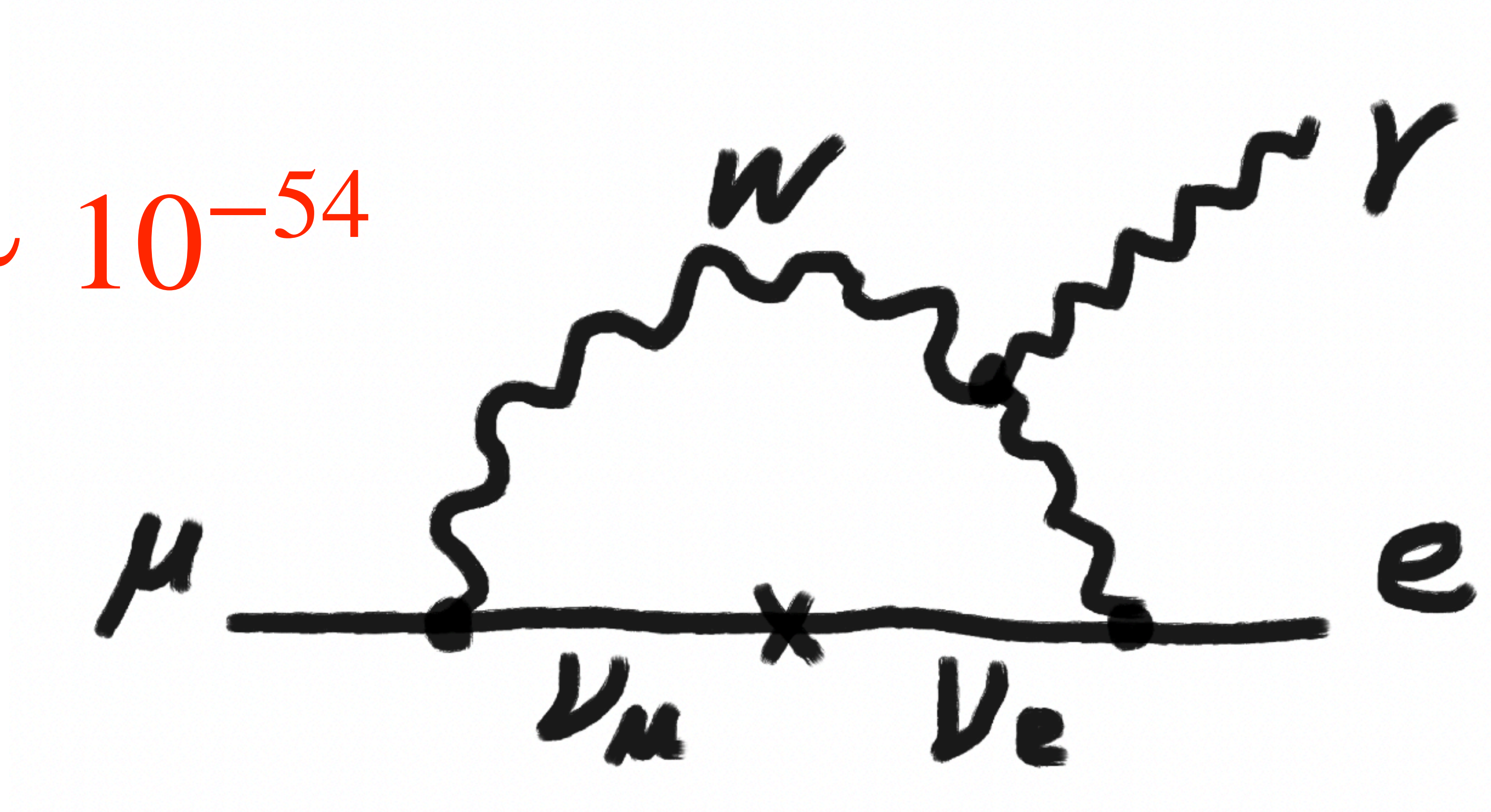
We know neutrinos oscillate, then

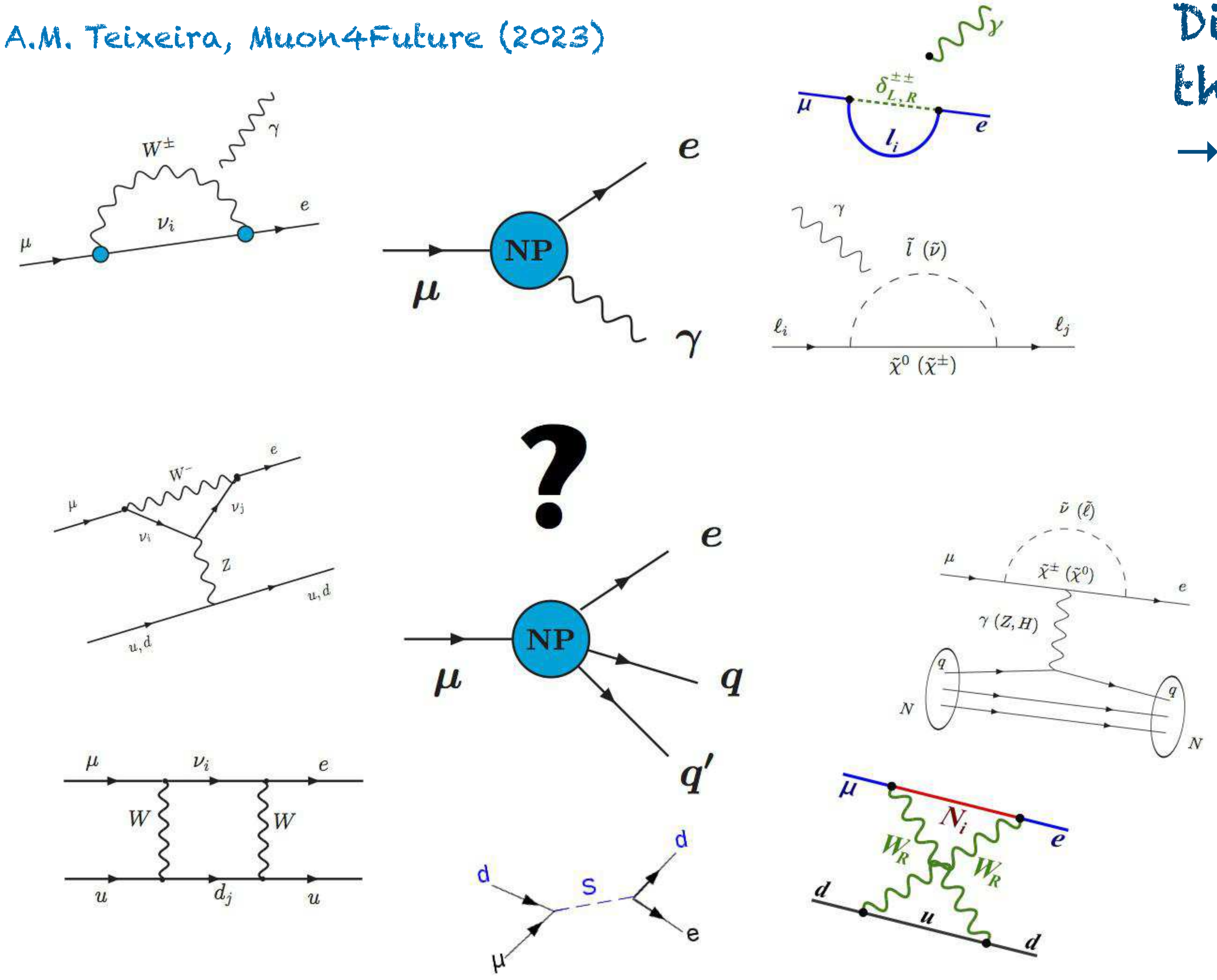
$$\mathscr{B}(\mu \to e\gamma) = \frac{3\alpha}{32\pi} \sum_i \left| U_{\mu i} U_{ei} \frac{\Delta m_i^2}{M_W^2} \right|^2 \sim 10^{-54}$$



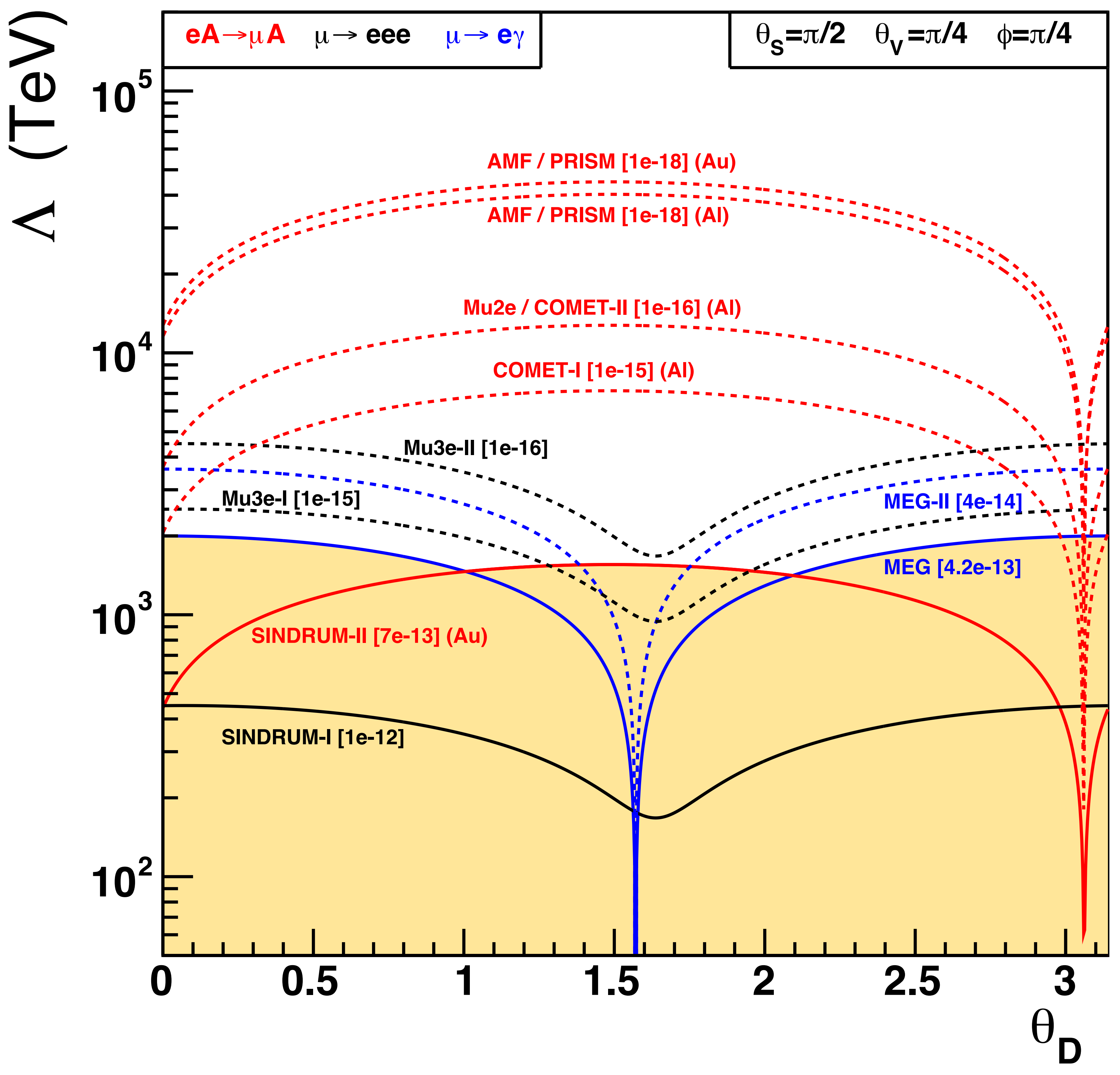
Charged Lepton Flavour Violation (CLFV)

And more possibilities in new physics...

A.M. Teixeira, Muon4Future (2023)

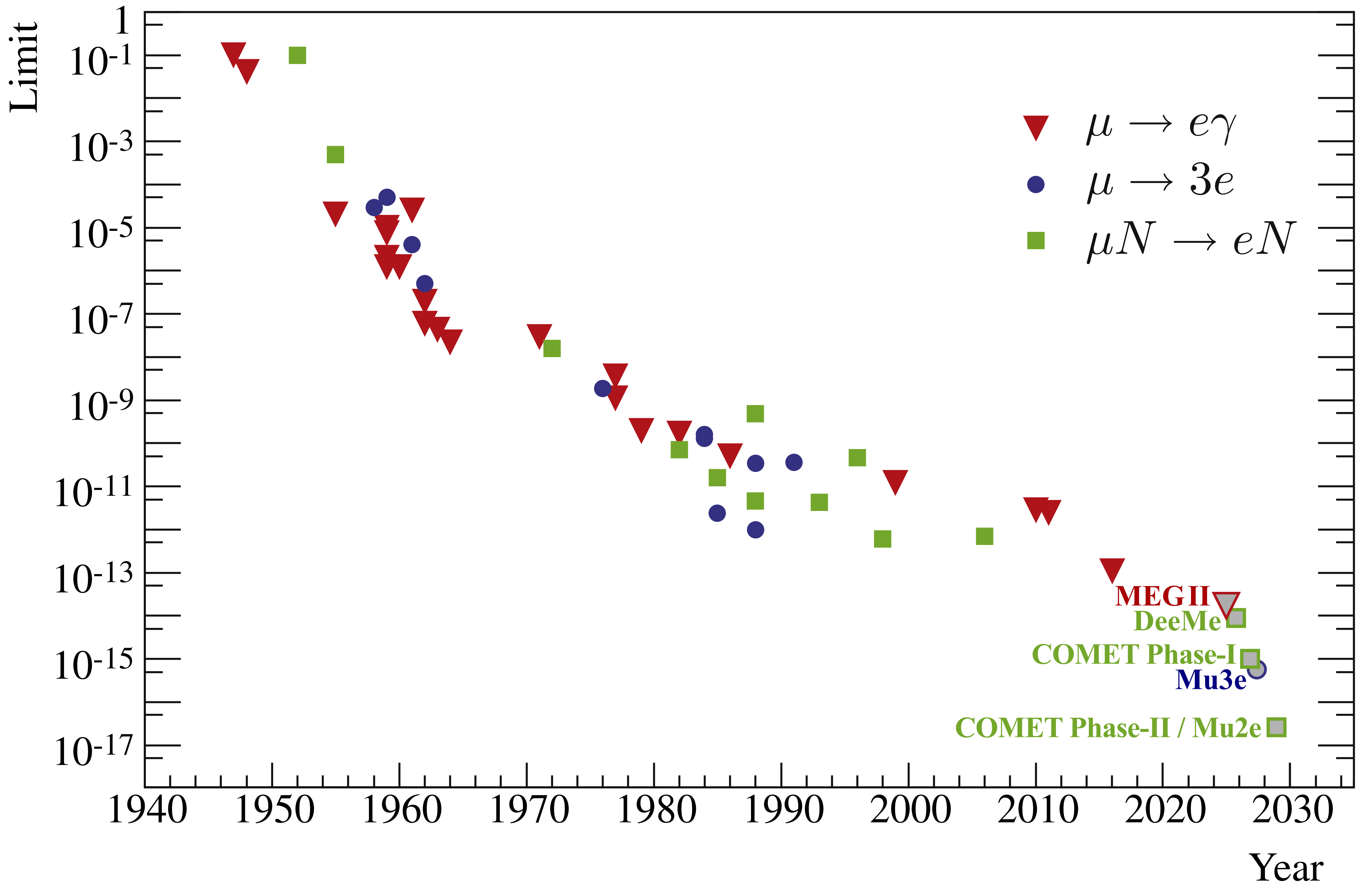


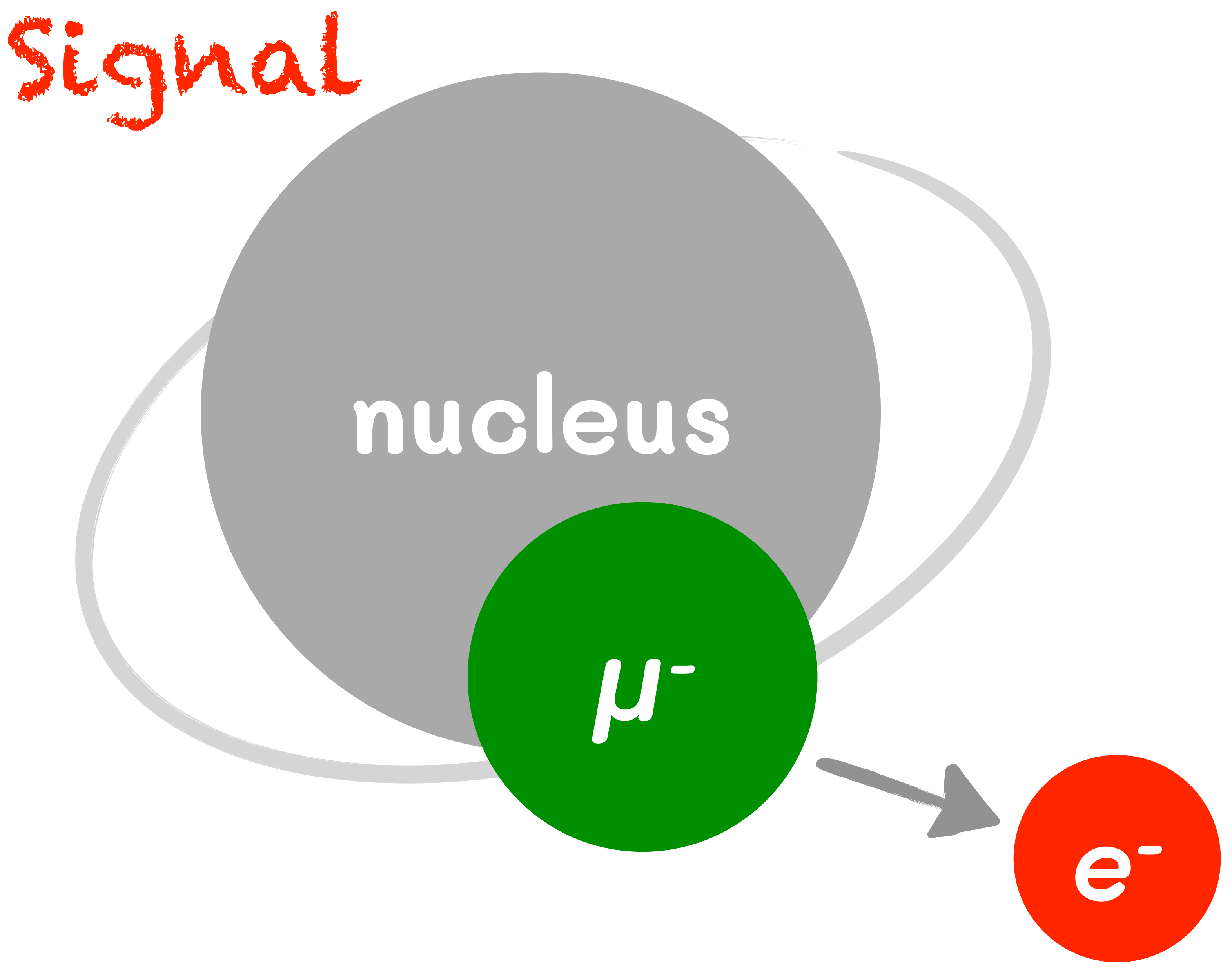
Different CLFV processes are sensitive to the different interactions
→ complementary to pin down NP models



μ-e conversion : Signal

The History





$$E_e = M_\mu - B_{\mu,\mathrm{Al}} - E_{\mathrm{recoil,Al}} \sim 105\ \mathrm{MeV}$$

$$\tau_{\mu,\mathrm{Al}} = 864\ \mathrm{ns}$$

Mono-energetic electron

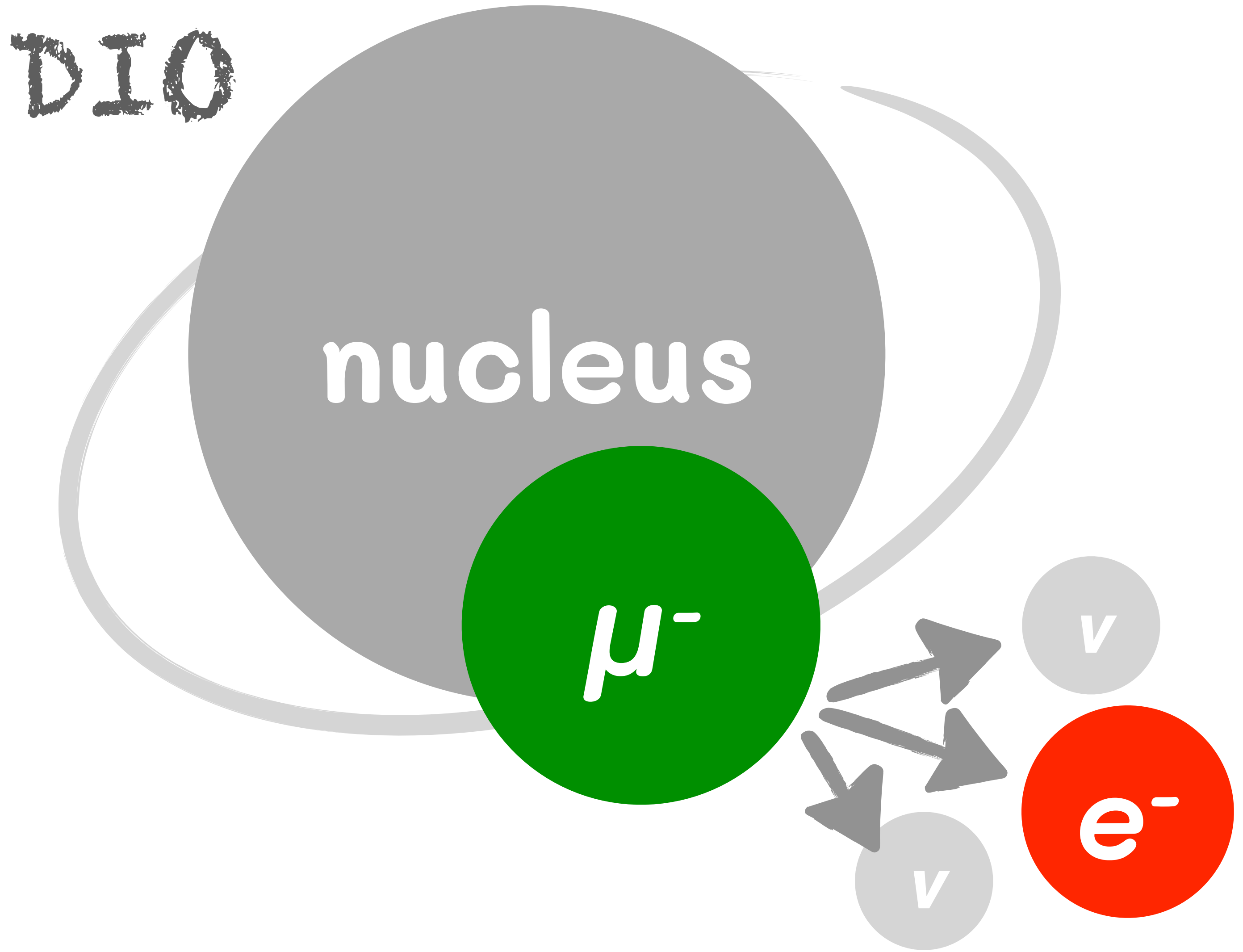
Current upper limit: 7.0×10^{-13} @90% C.L. by SINDRUM II with Au target (2007)

Clear sign of the New Physics if discovered

μ-e conversion : Backgrounds

Intrinsic

Muon Decay-in-obit (DIO)



Beam-induced

Prompt

(Mostly) pion-induced particles

Delayed

Decay products of muons

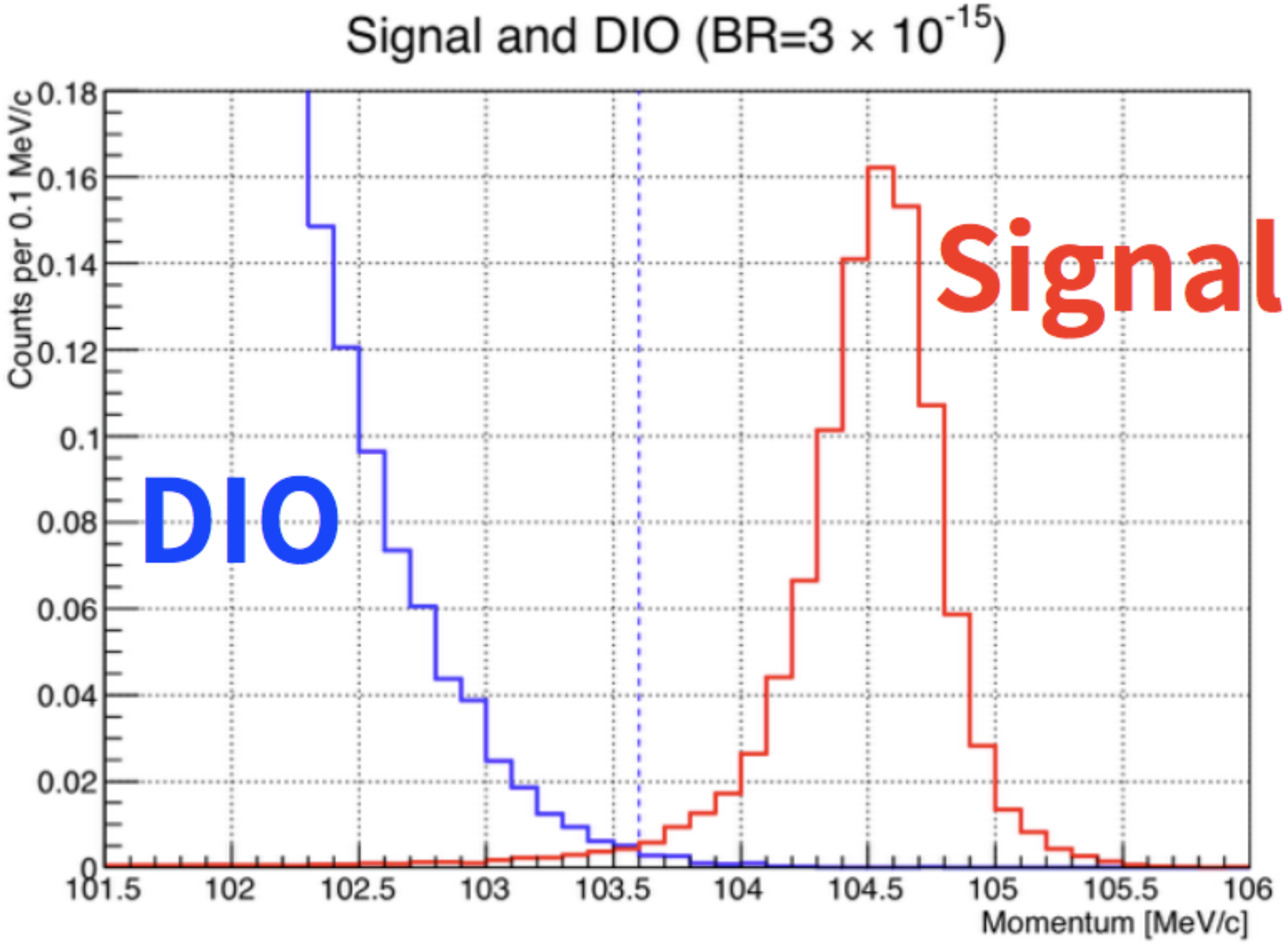
Magnetically trapped particles

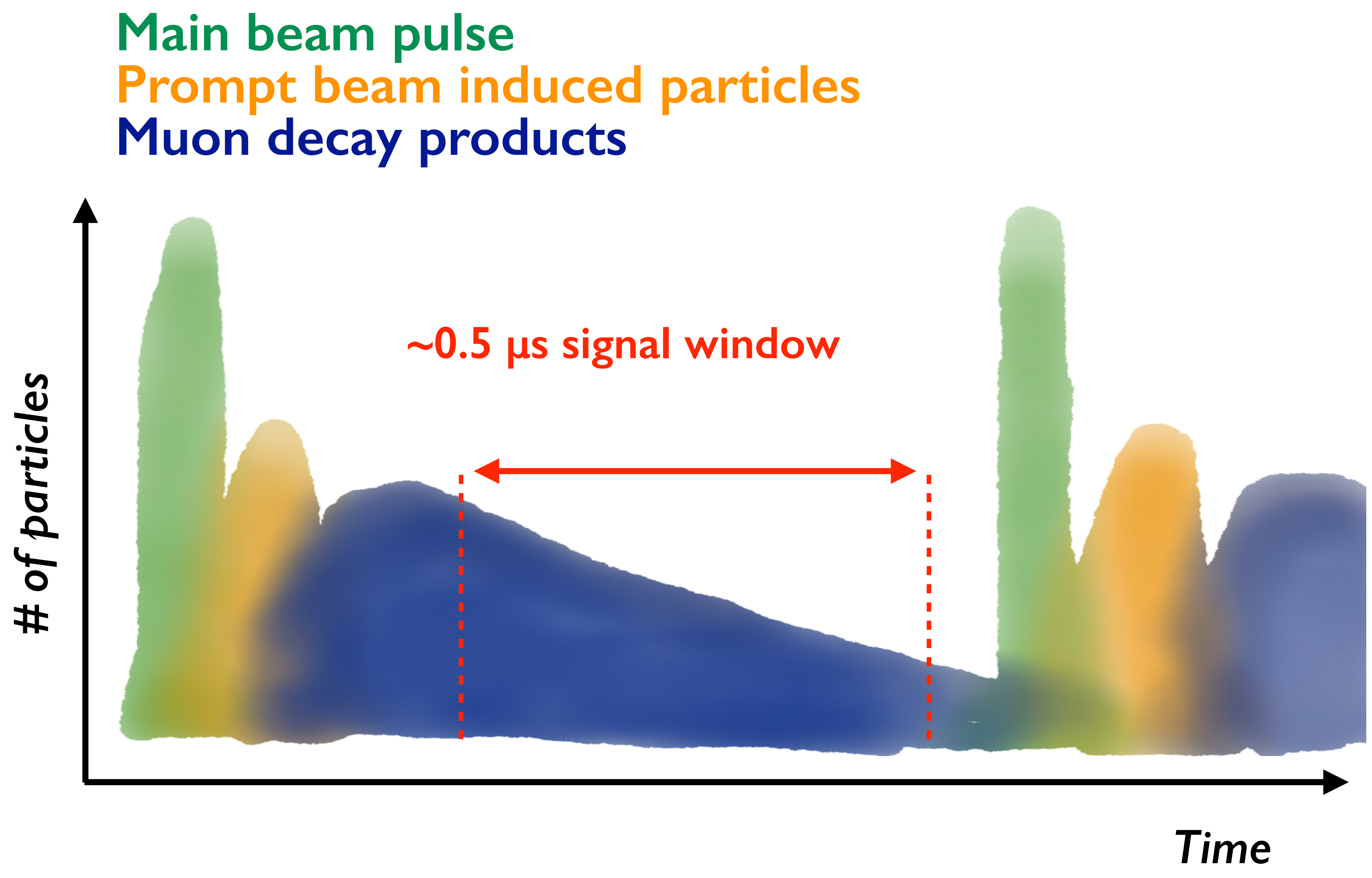
Antiprotons

Cosmic-ray induced

Rarely, it could induce ~100 MeV/c charged particles inside the detector

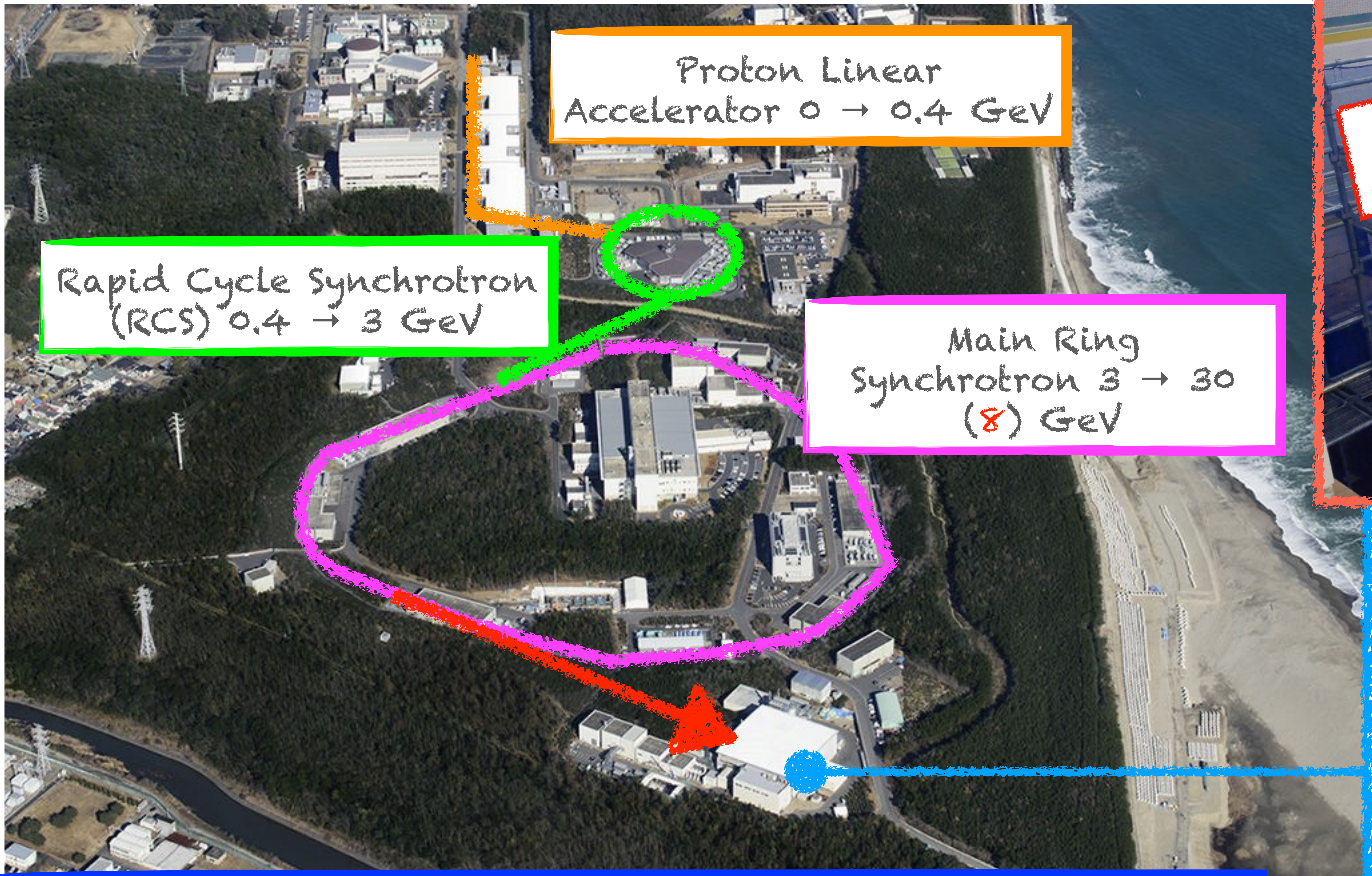
Measurement Concept in modern μ-e searches



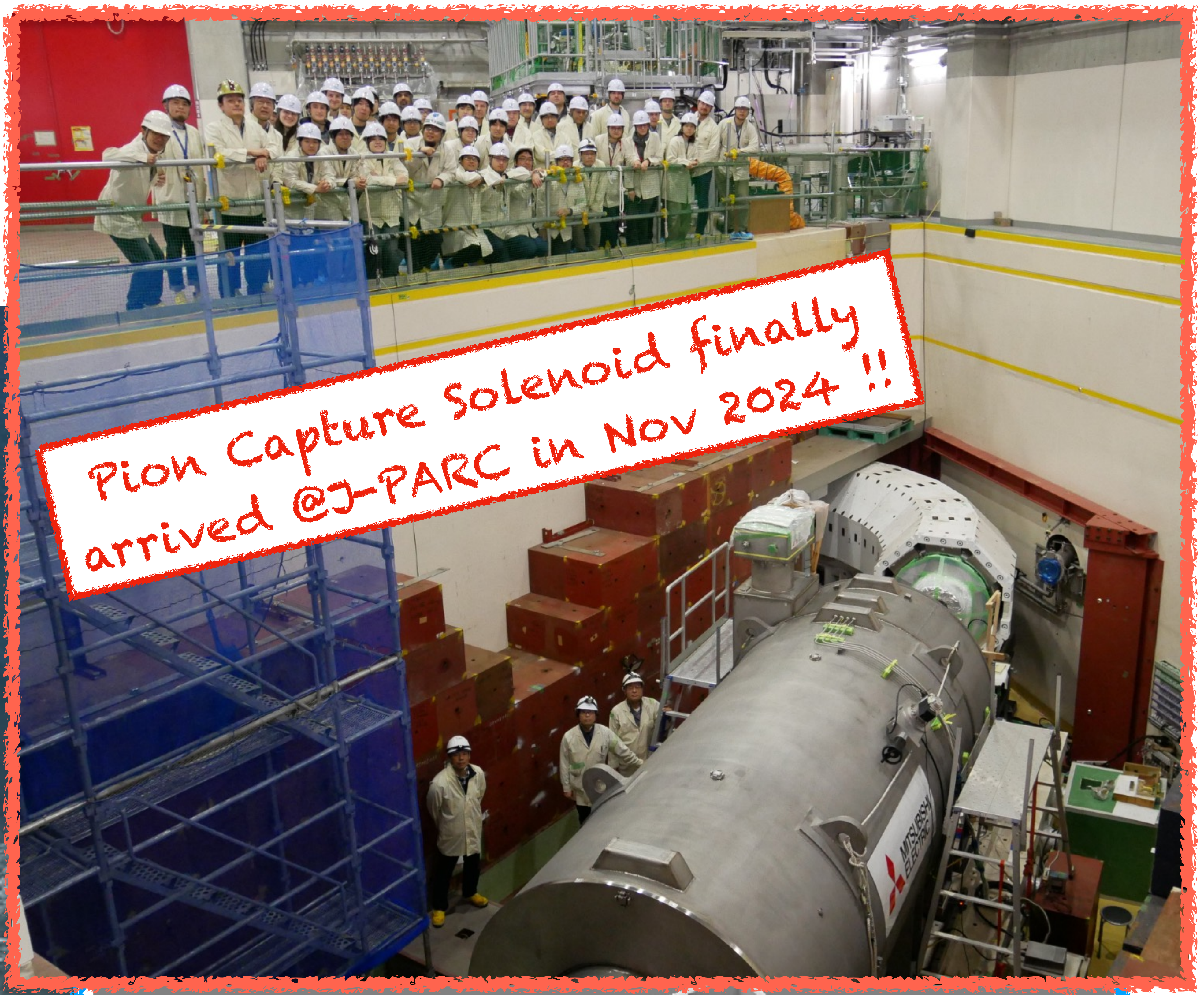


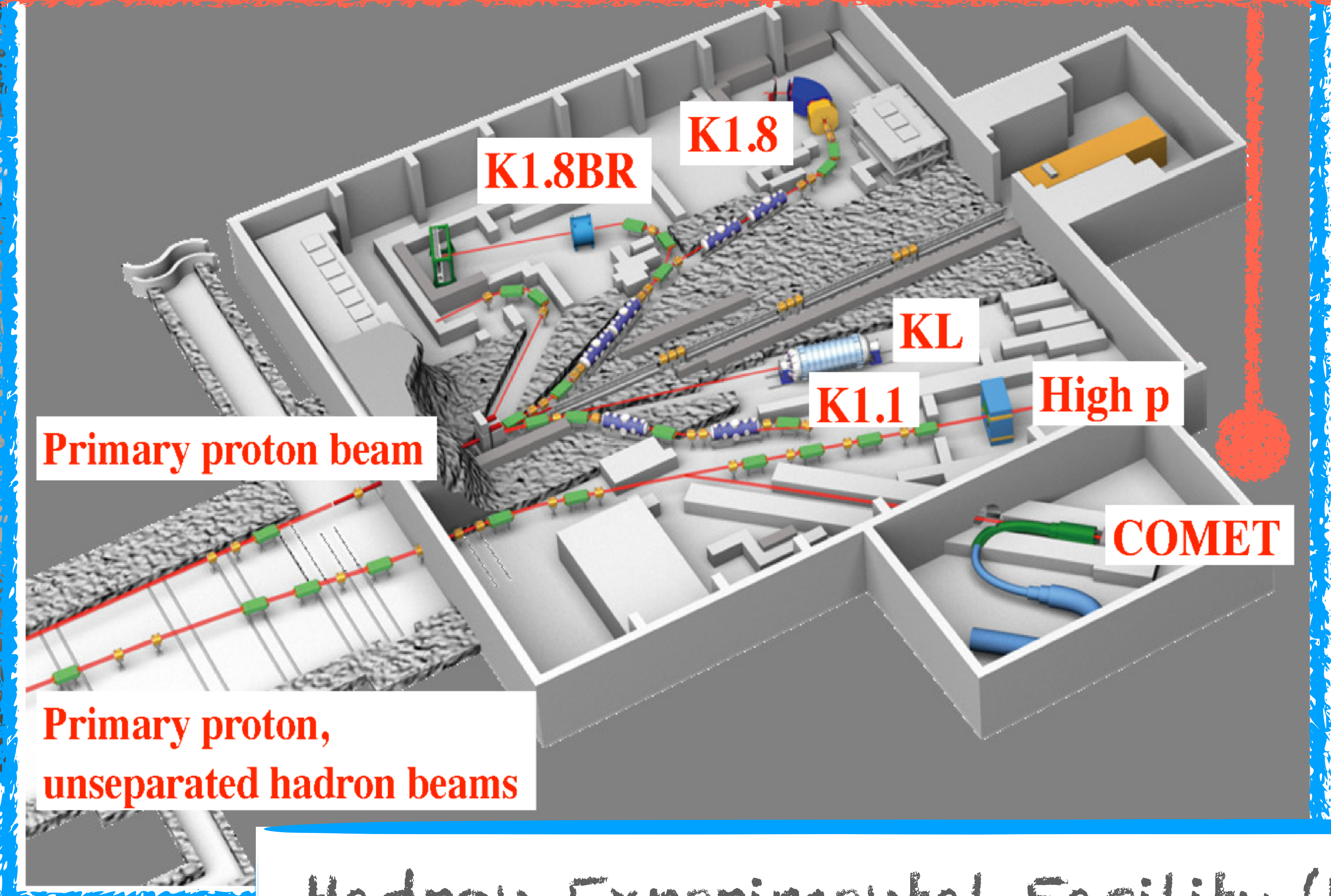
Good momentum measurement × Delayed time window w/ pulsed beam

COMET Experiment



J-PARC (Japan Proton Accelerator Research Complex) @ Tokai village, JAPAN

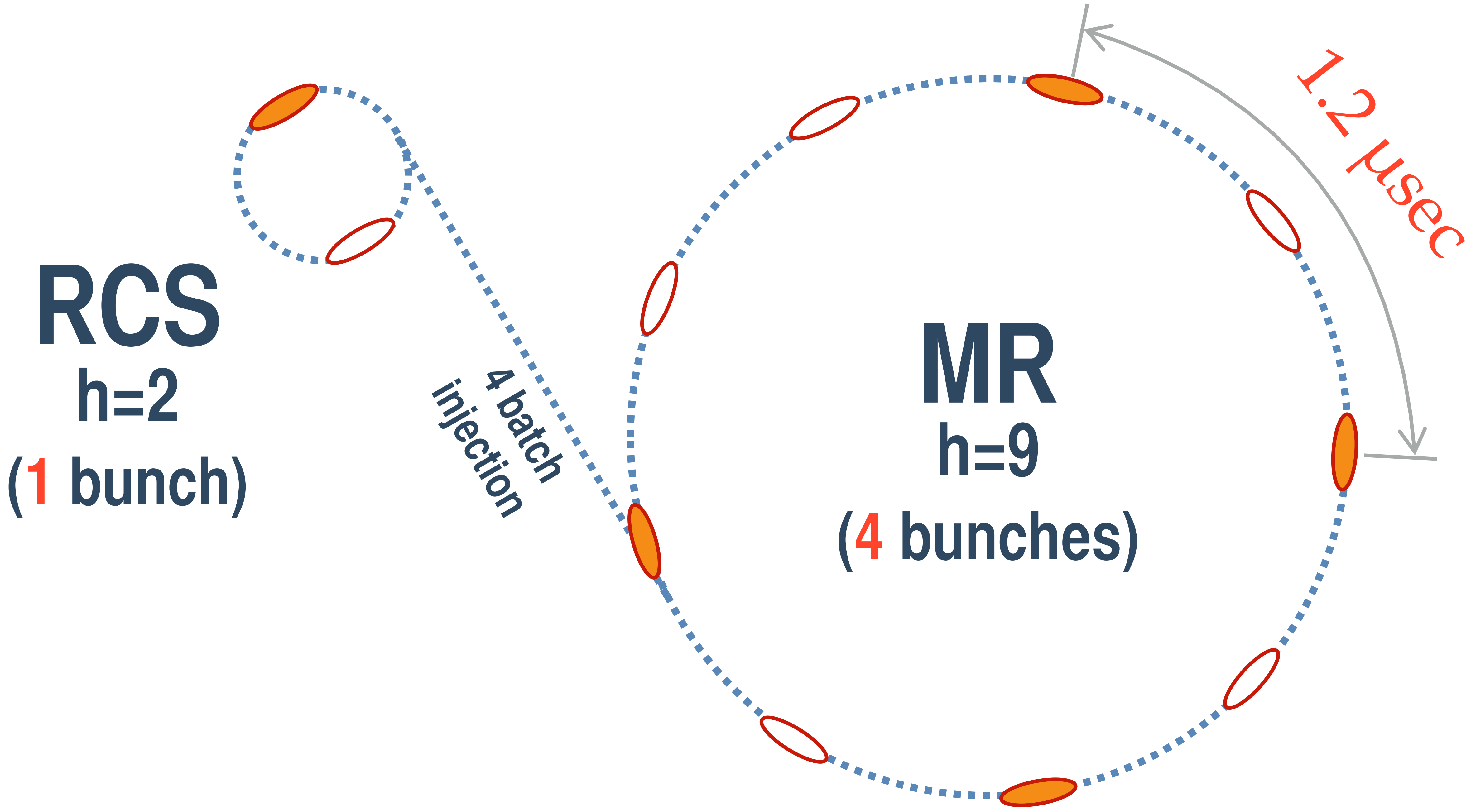


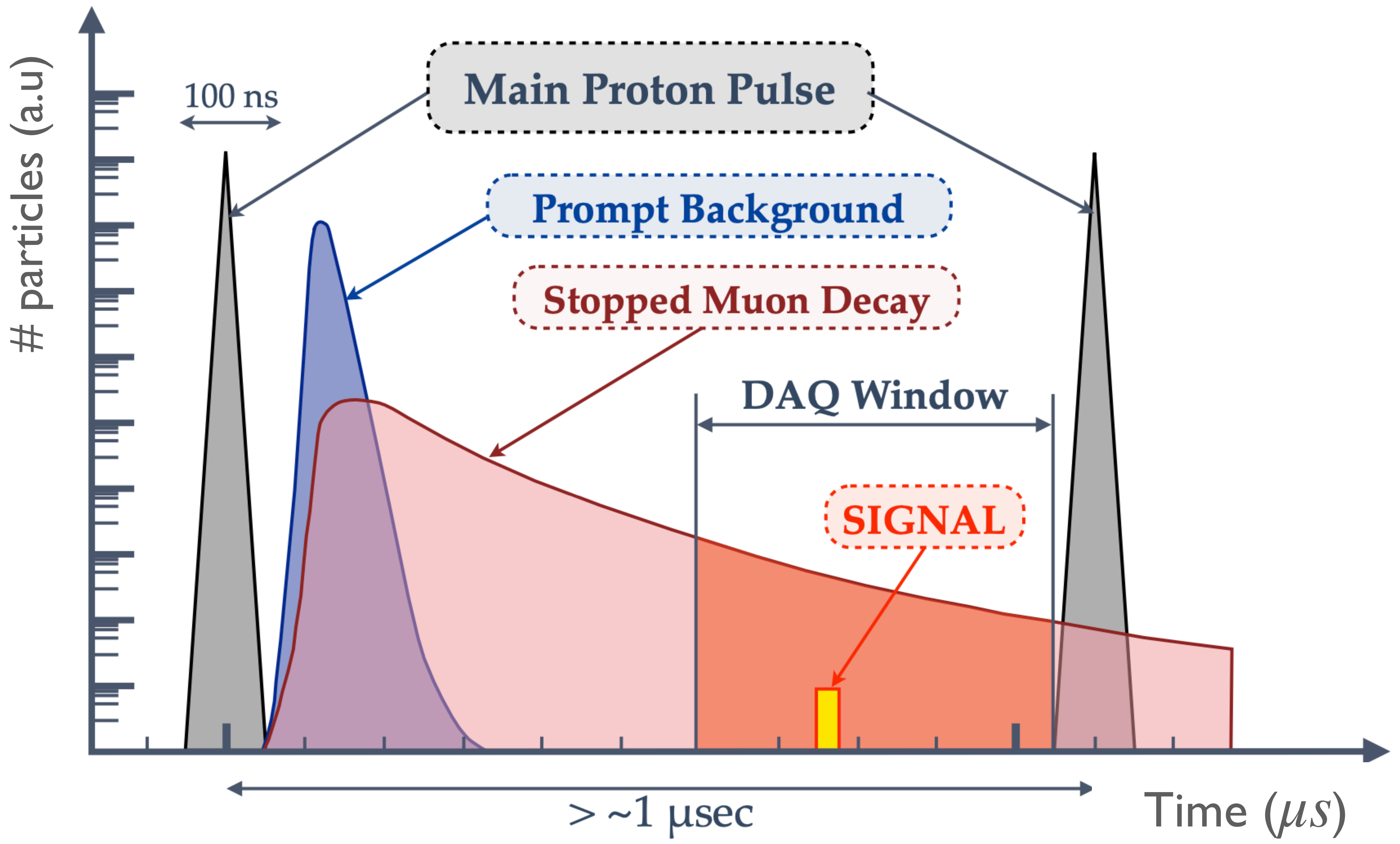


Hadron Experimental Facility (HEF)

Proton beam

- A 8 GeV proton beam is extracted from the J-PARC Main Ring
  - Normally 30 GeV
  - Keep bunch structure unlike other hadron/nuclear experiments
- "8GeV" is explicitly chosen to suppress antiprotons (details will be discussed later)
- A highly pulsed beam is essential to avoid any beam induced prompt particles pop into the delayed time window
  - This is realised by filling 1/2 of proton beam buckets at RCS

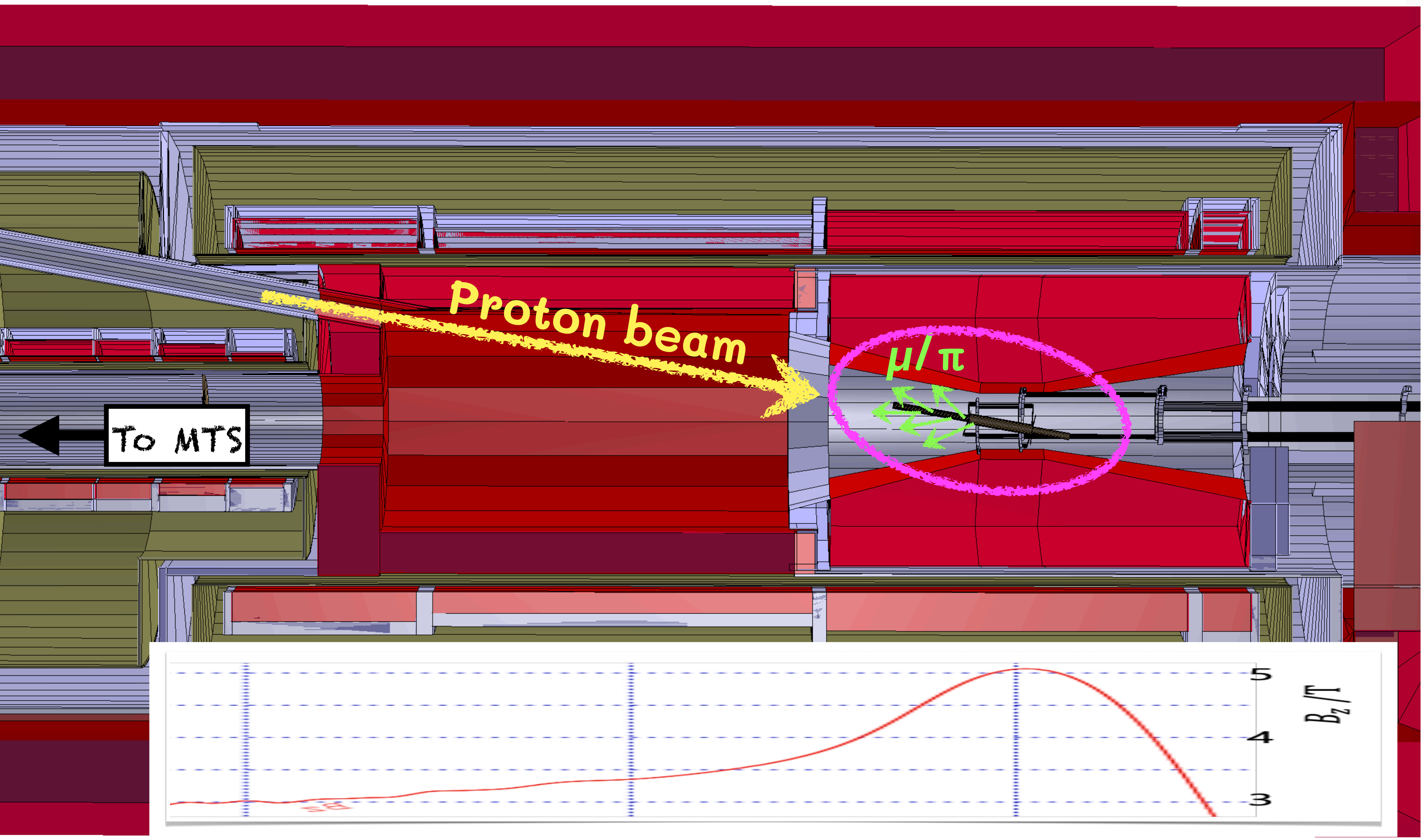


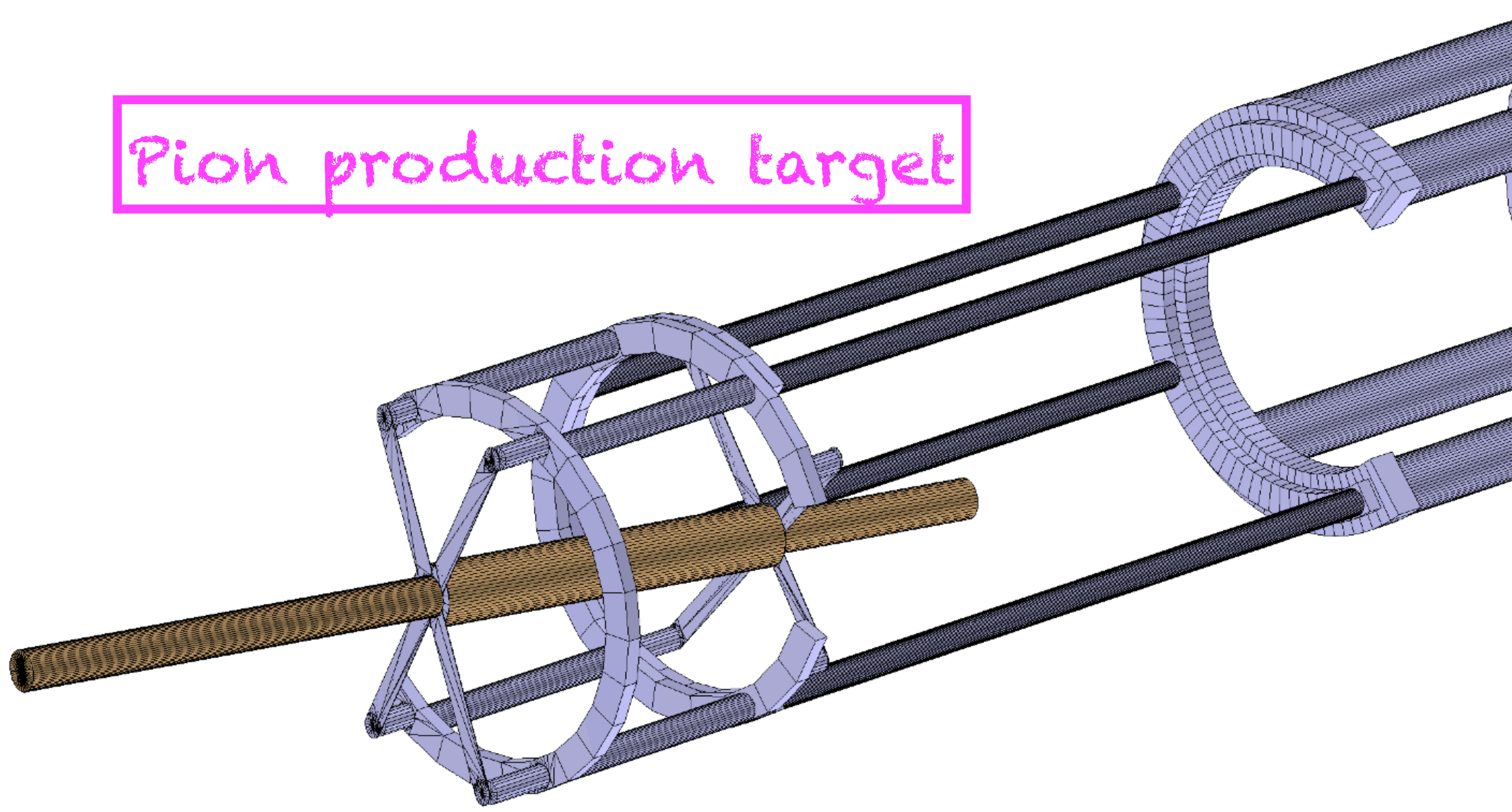


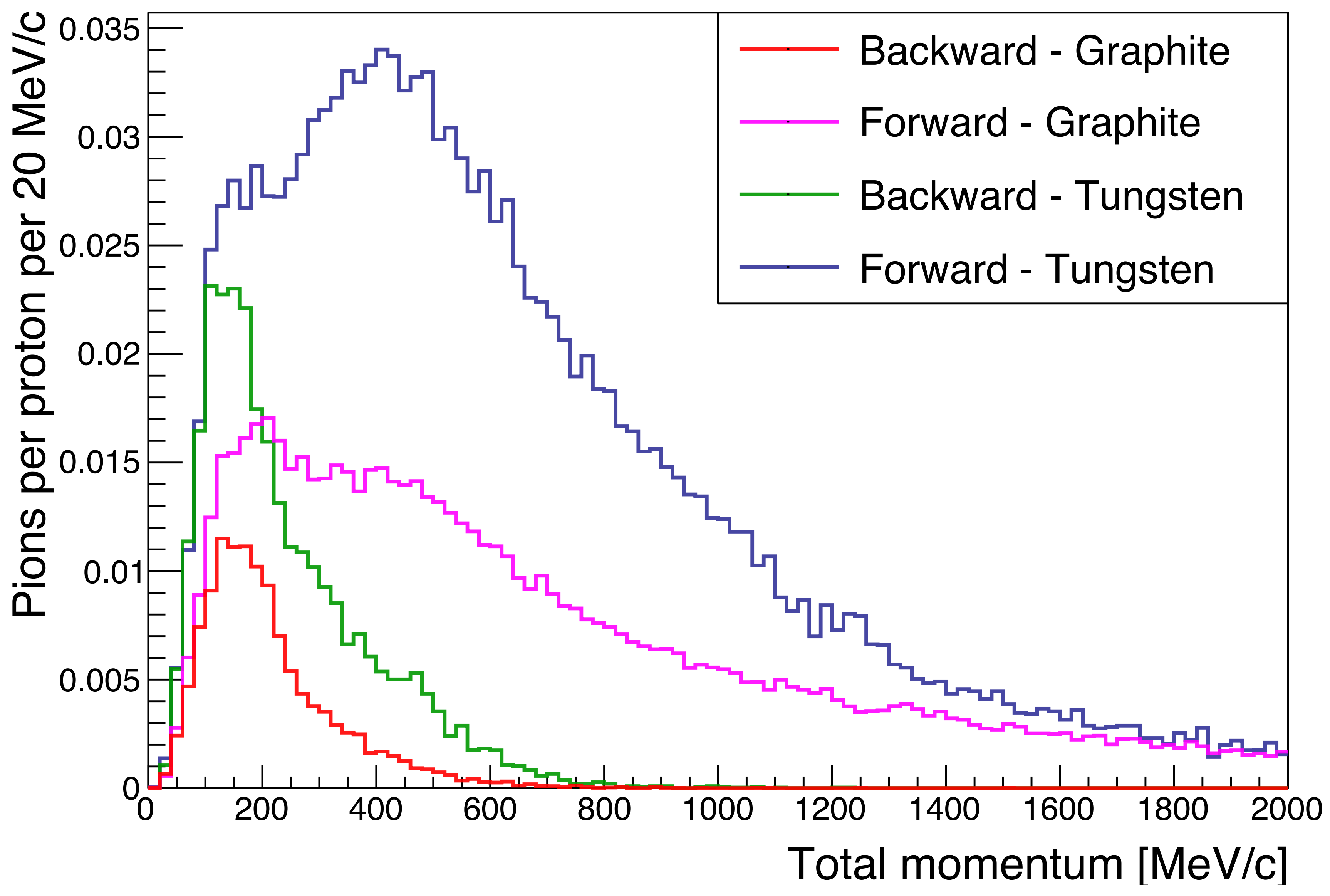
Muon beam

- What we need:
  - low momentum (<60 MeV/c) muons to stop them easily
  - Less of other particles to suppress backgrounds, especially, high momentum ones
- Muon beam is created by "full-stopping" protons at the target
  - Unlike other muon experiments; PSI, J-PARC MLF using a disk type target
- Backward muons/pions to be collected for selecting them w/ relatively low-momentum
- Transporting them by using a "curved" solenoid with a correction dipole field

Pion Capture Solenoid



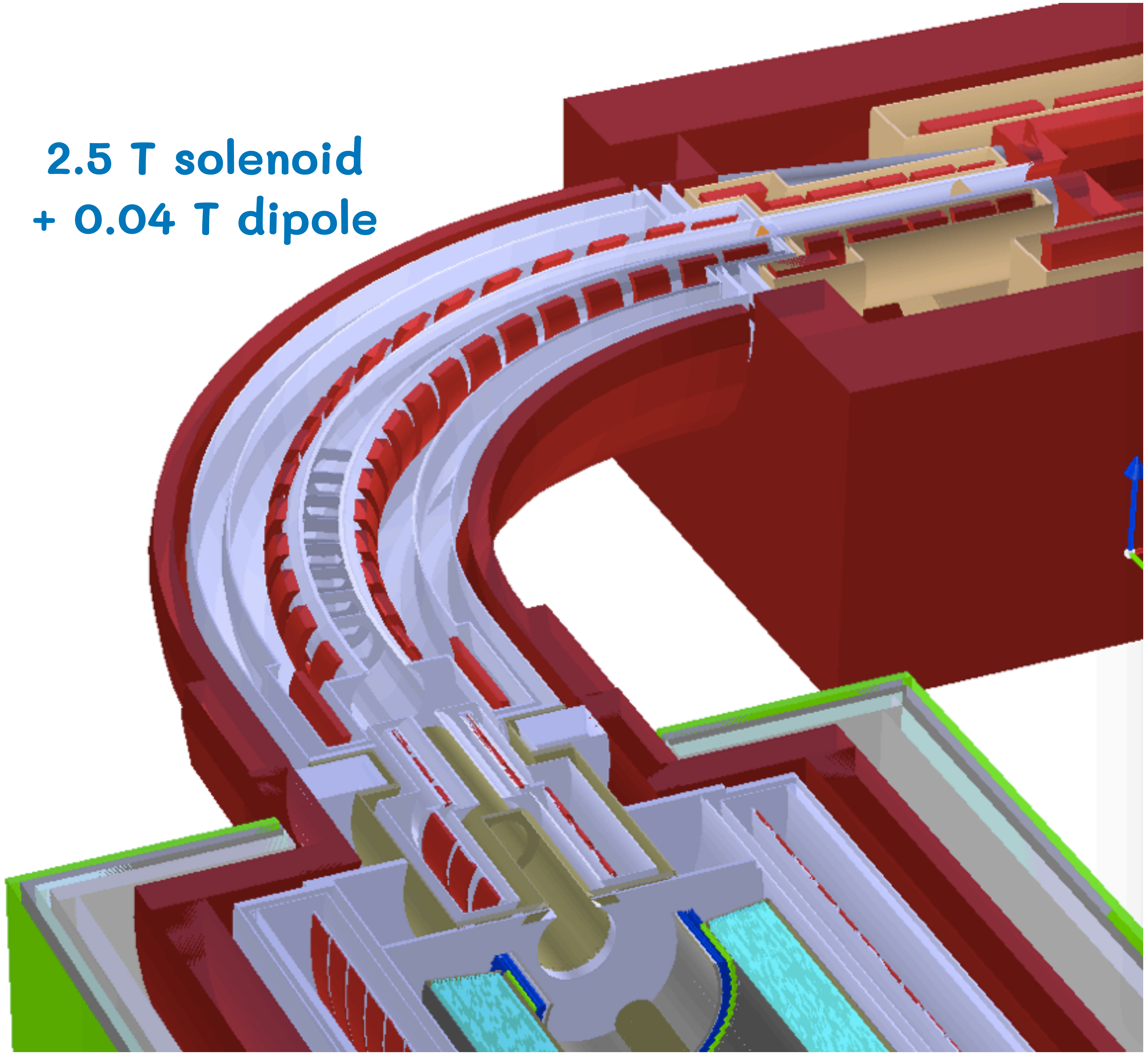


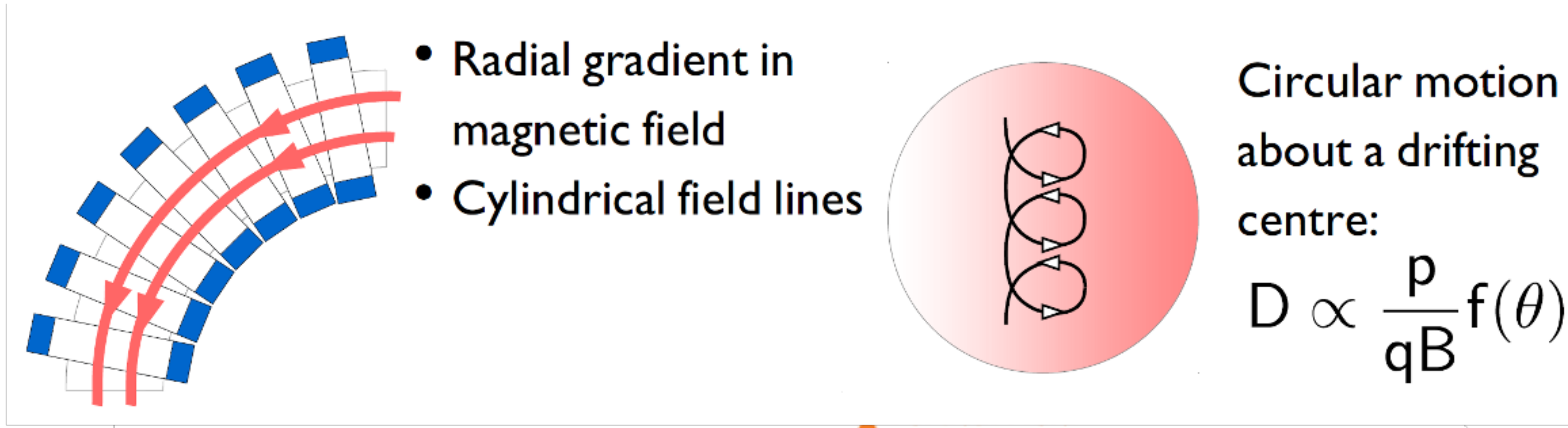


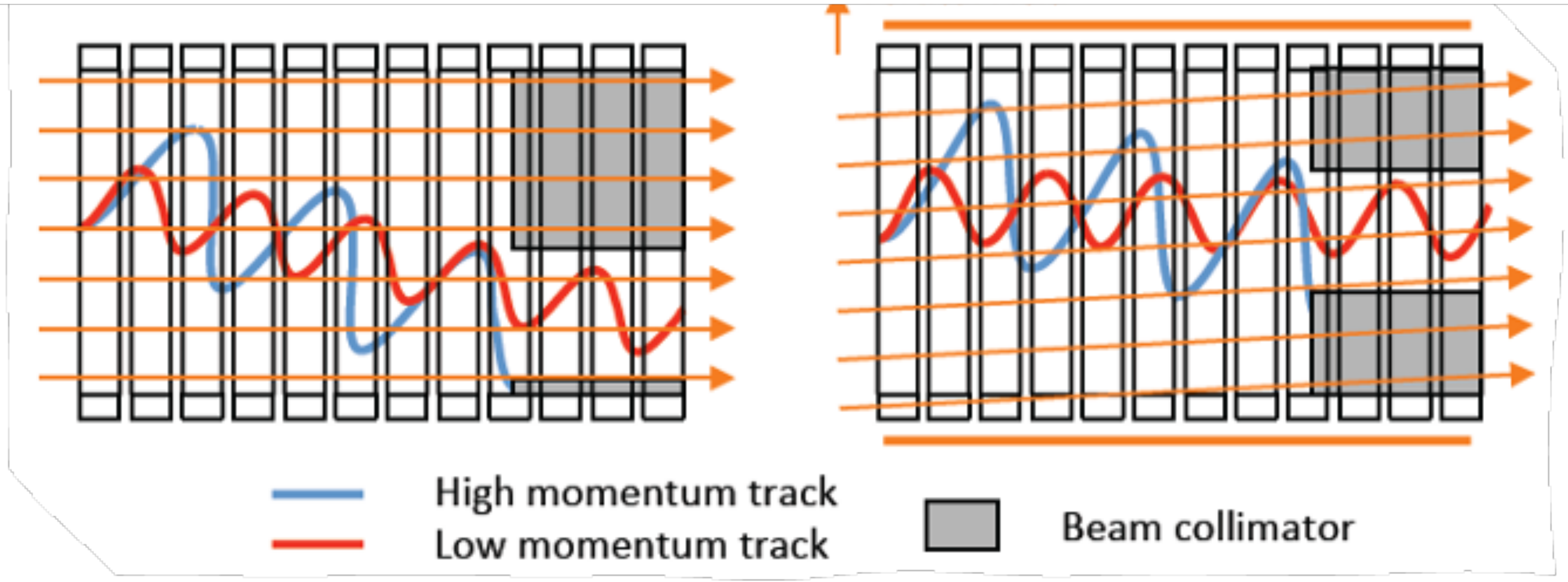
- Collect "backward-going" pions/muons which tend to have lower momentum than forward ones

Muon Transport Solenoid

2.5 T solenoid
+ 0.04 T dipole

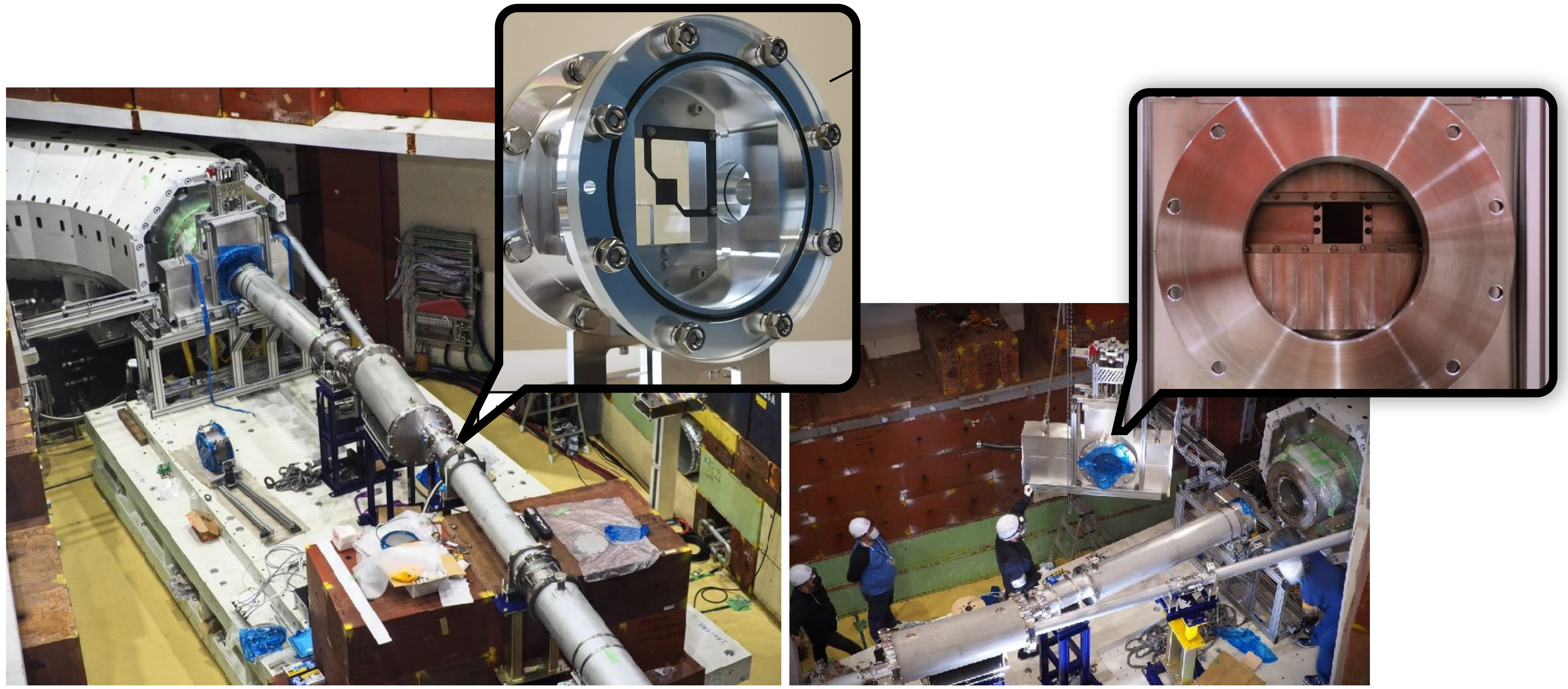




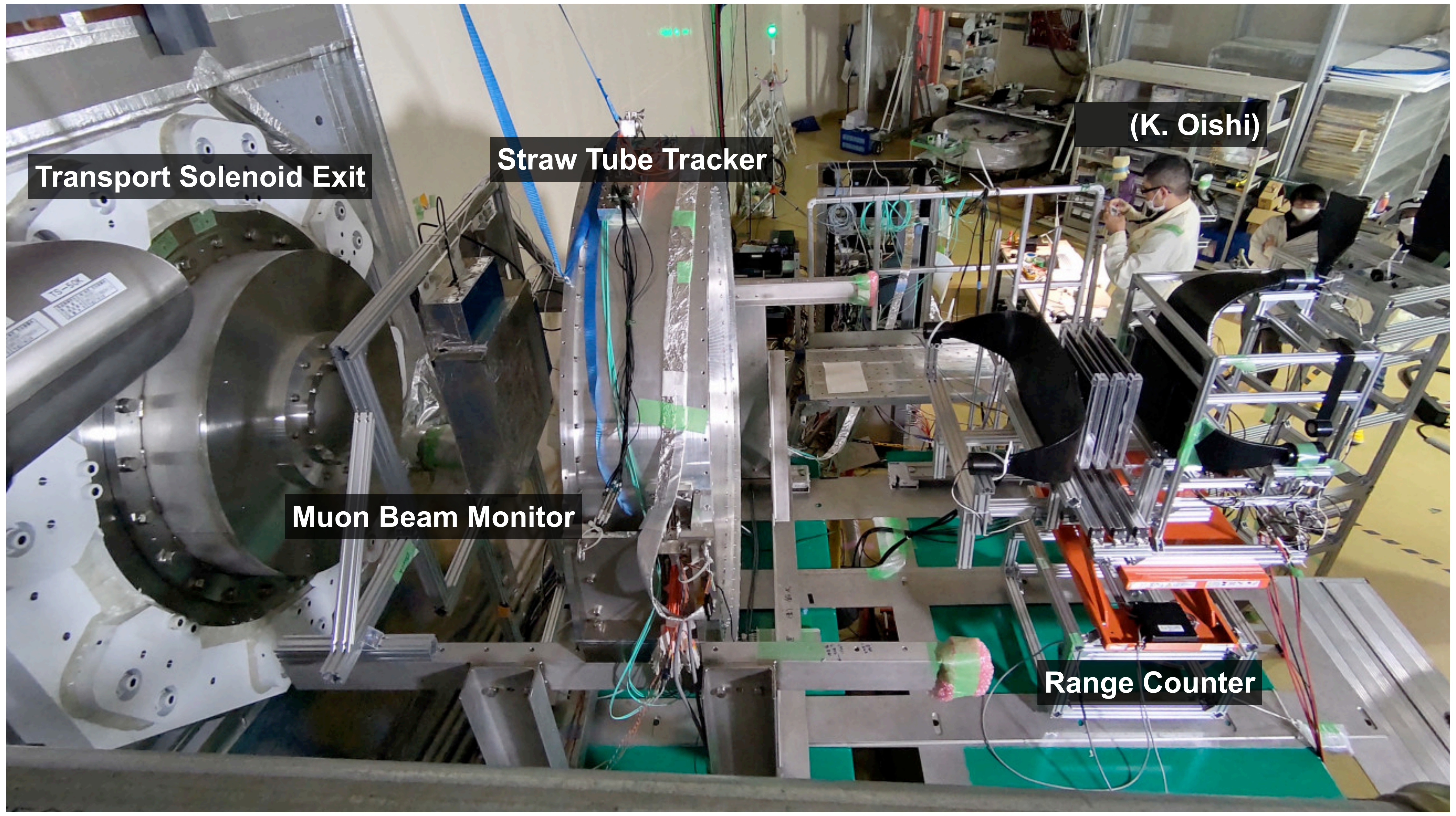


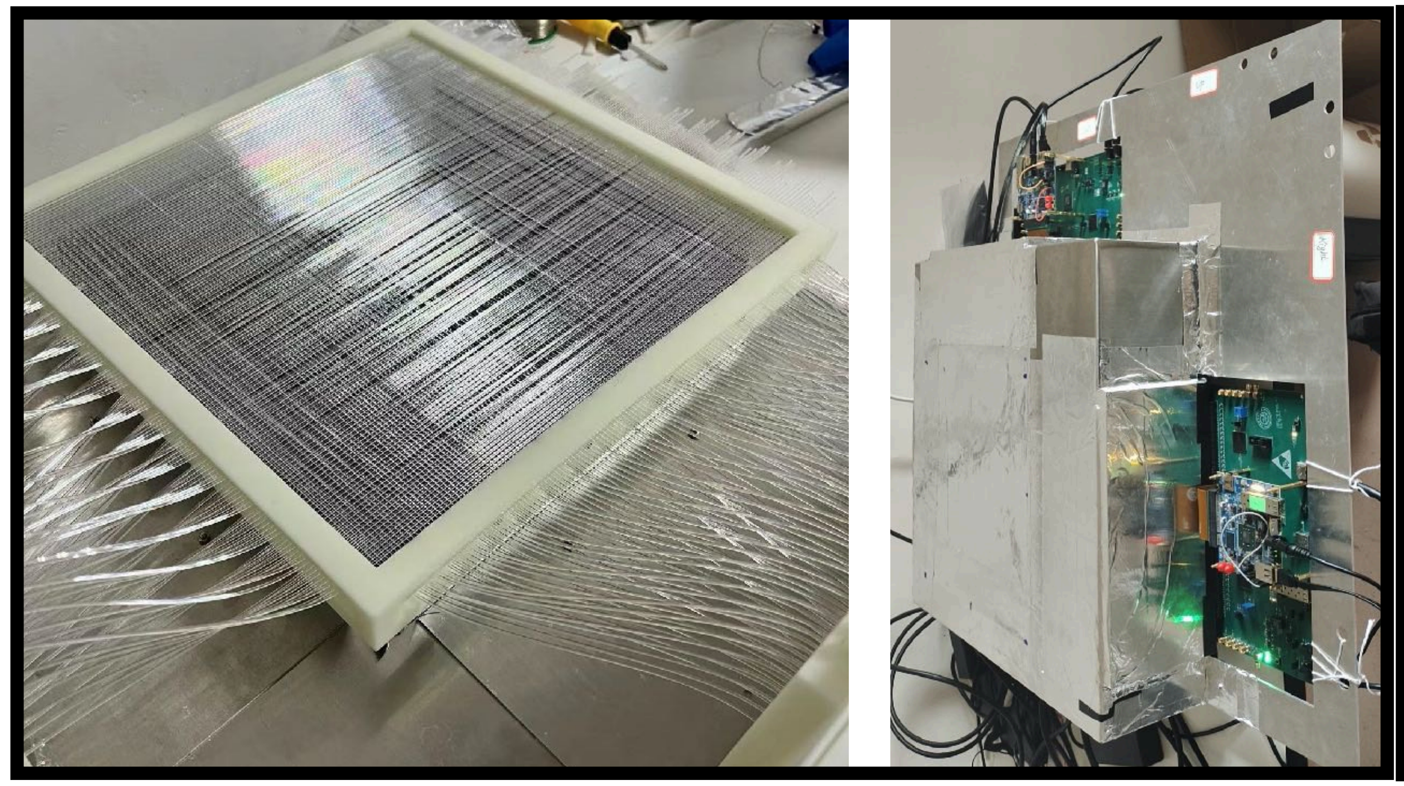
The curved solenoid + correction dipole fields effectively filter high momentum and/or positive particles

Phase-α: First muons @ COMET Hall

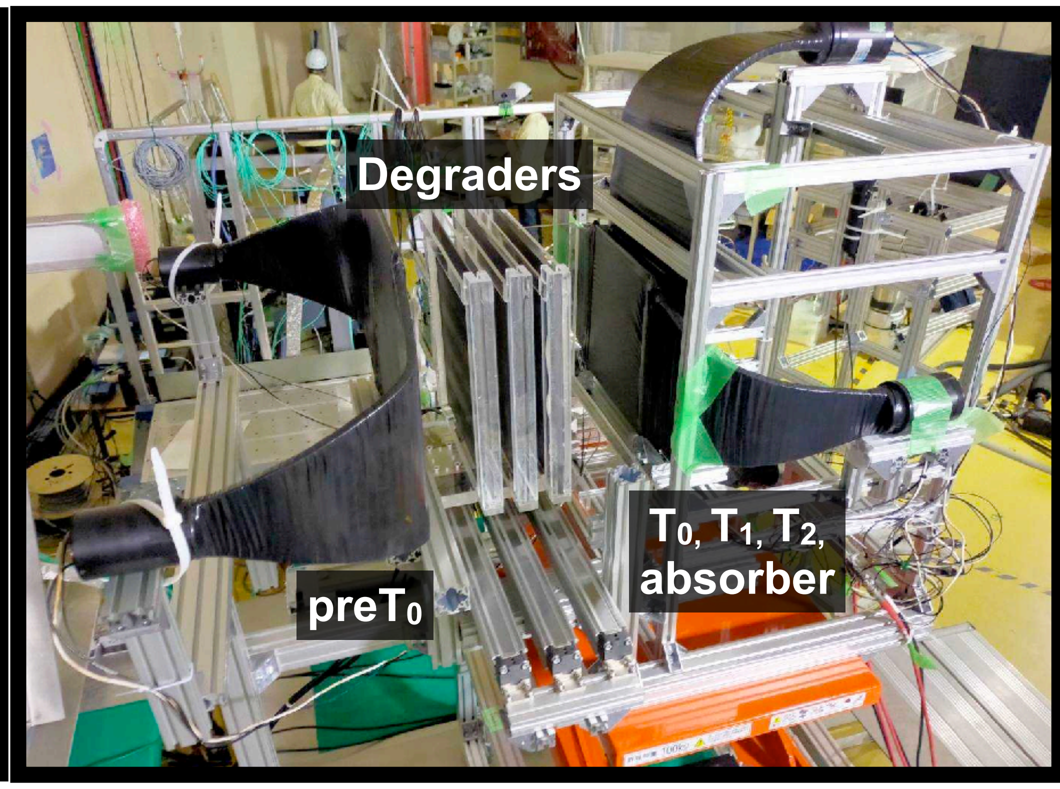


- Before the PCS arrival, proton beam delivery and muon transportation had been tested as "COMET Phase-α" in 2023-2024
- Both were done in success despite the significant beam-time cut



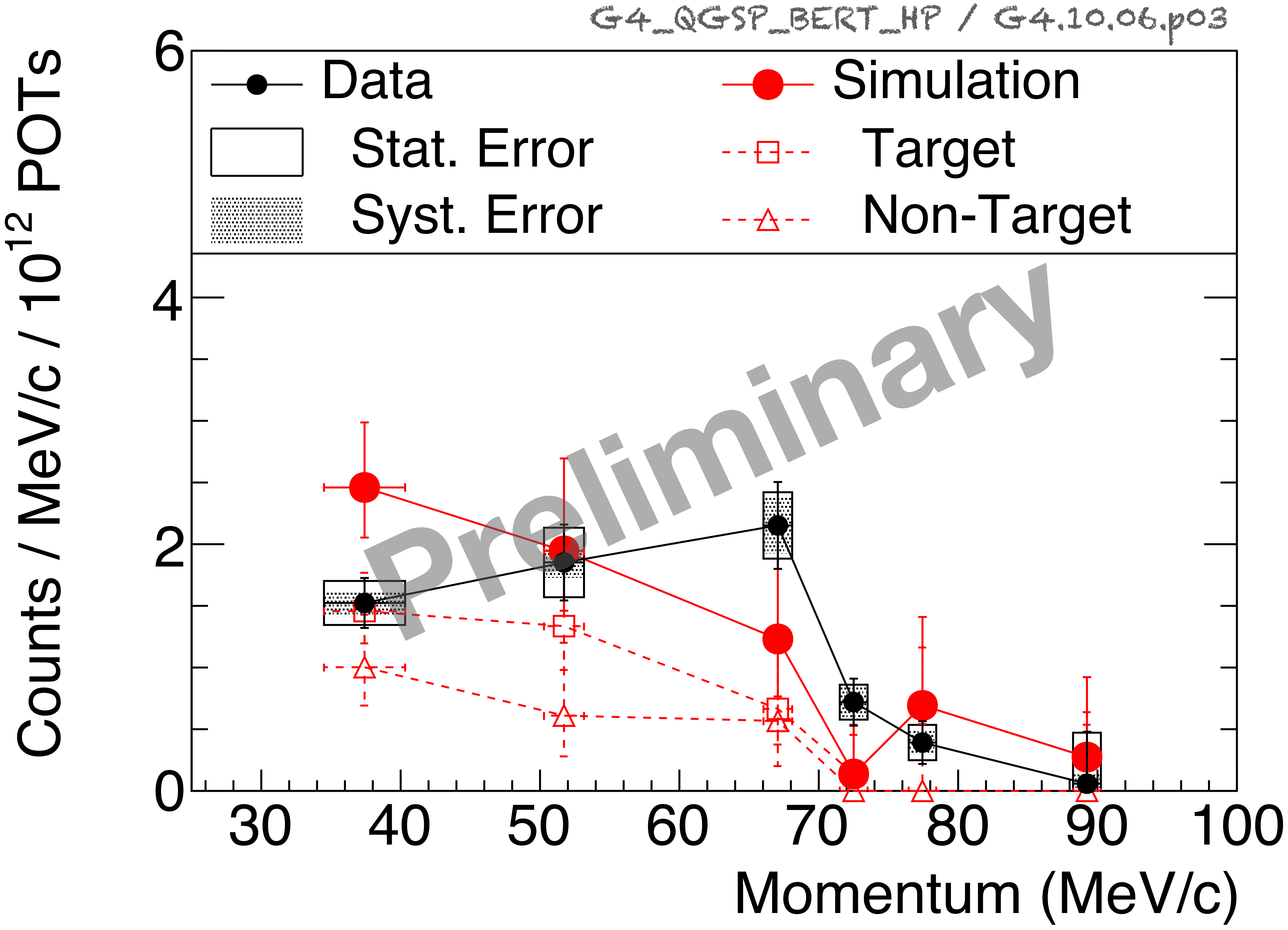


Muon position/timing detector



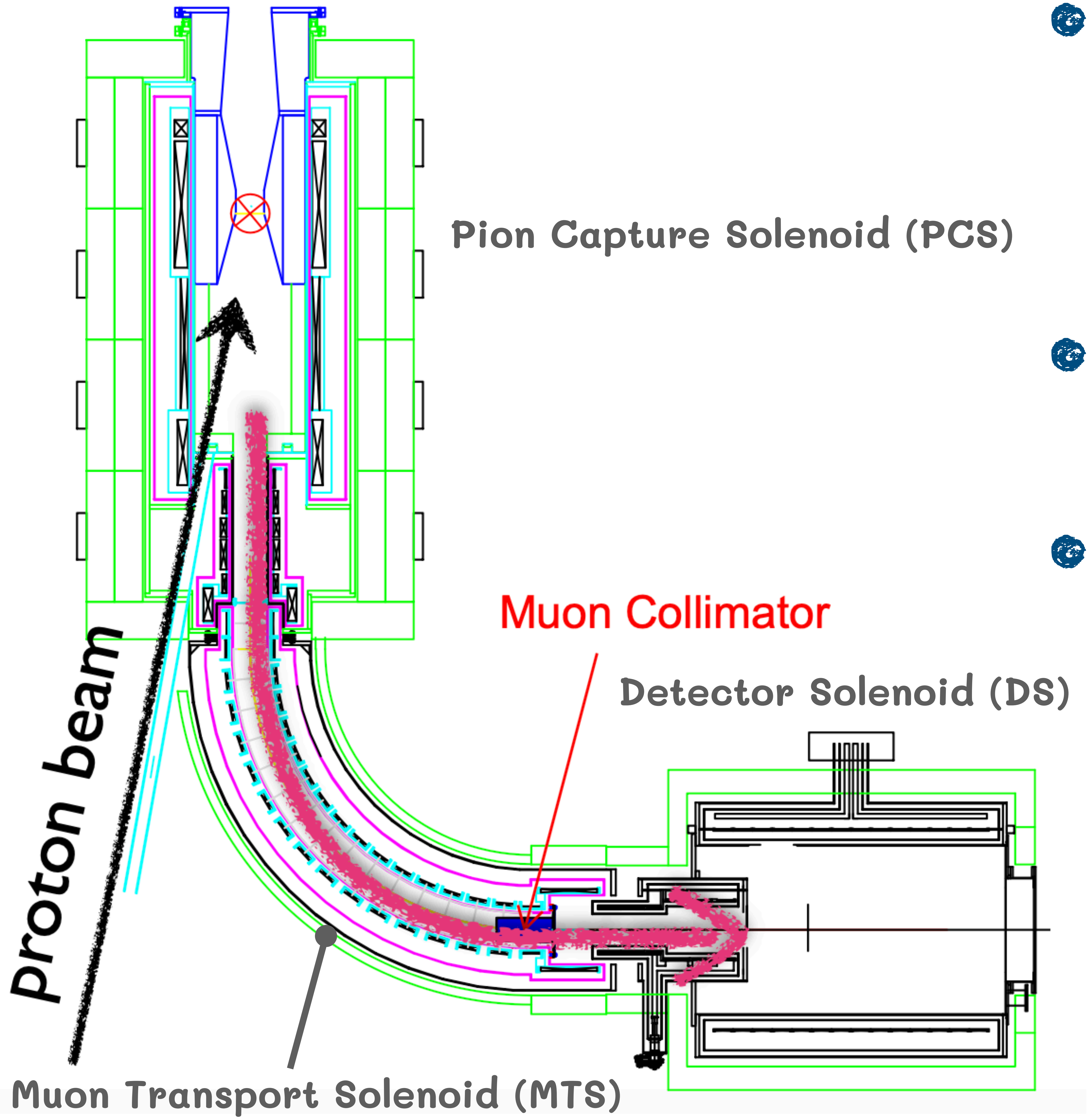
Range counter

Phase-α: (Preliminary) result



- Muon events were selected by using the timing of Range counters for different degrader thickness (=momentum)
- Global trends agree between data/MC
- Further checks are ongoing to publish the official result

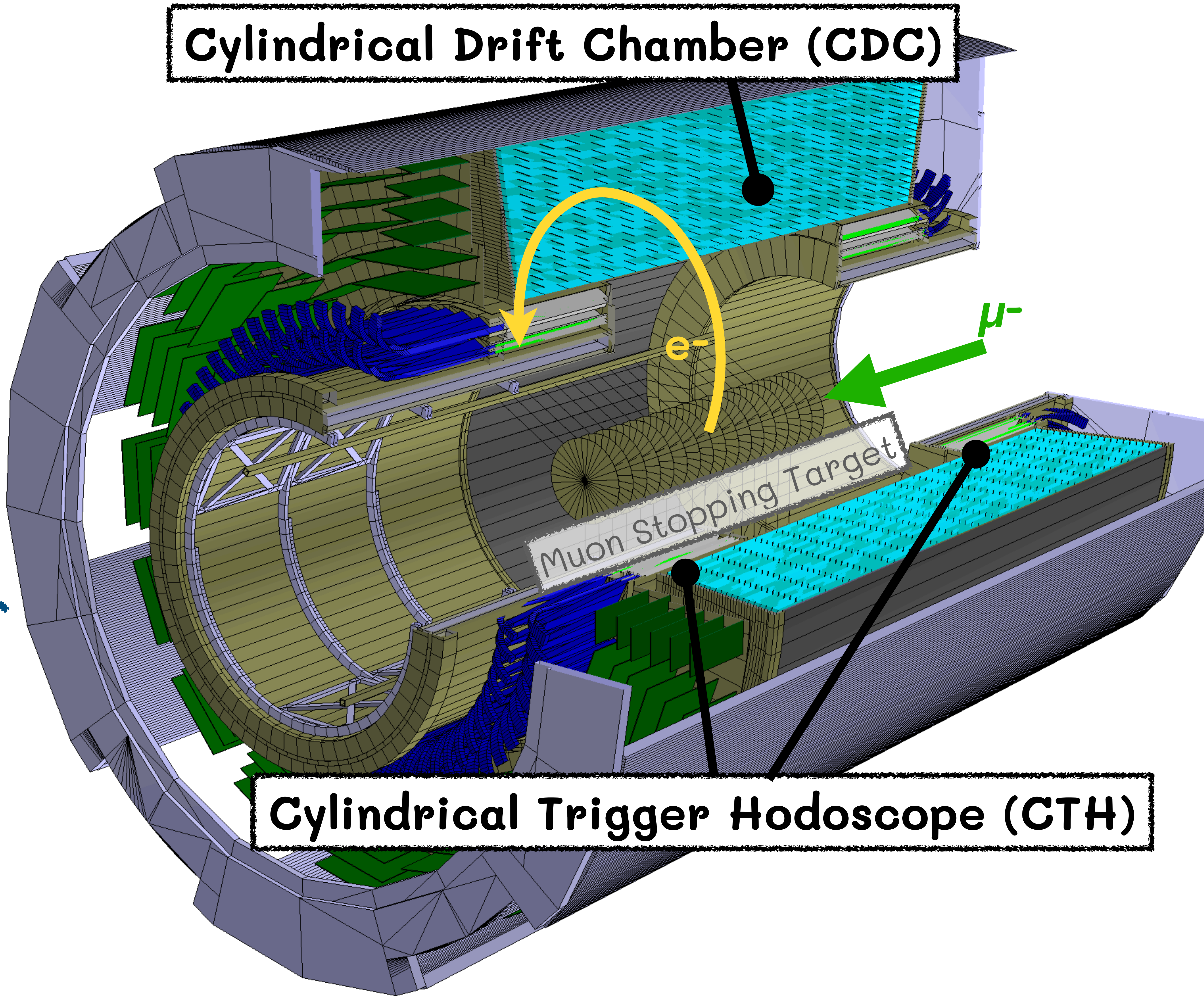
COMET Phase-I



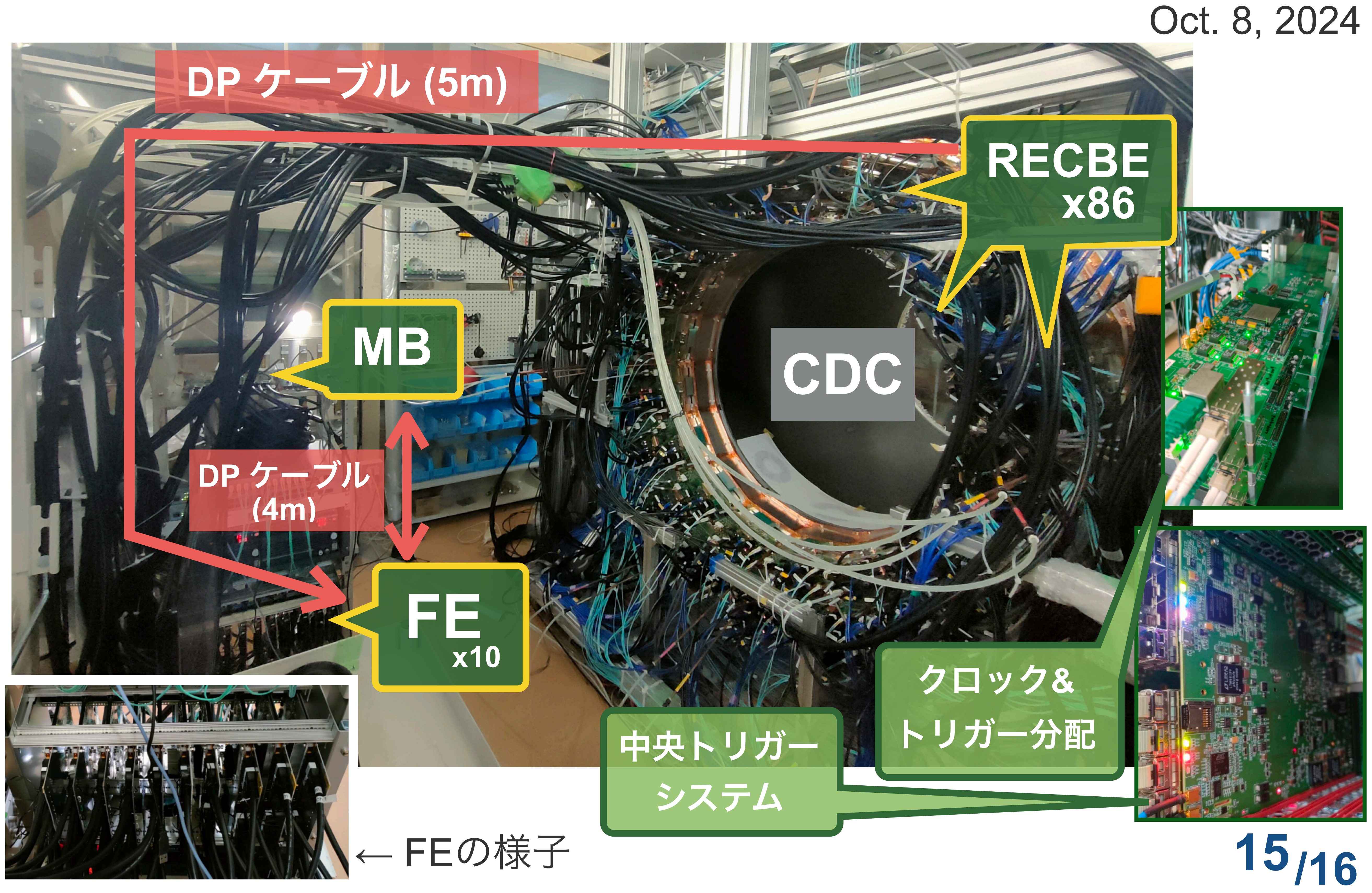
- To demonstrate the basic concept, while conducting the physics measurement quickly compared to the full-set of COMET (Phase-II)
- Proton beam ×1/10, a graphite target instead of tungsten
- A first 90° curved solenoid + detector solenoid at the end
    - Physics measurement w/ cylindrical detectors
    - Direct muon beam and background measurements w/ planar detectors

Physics Measurement in Phase-I

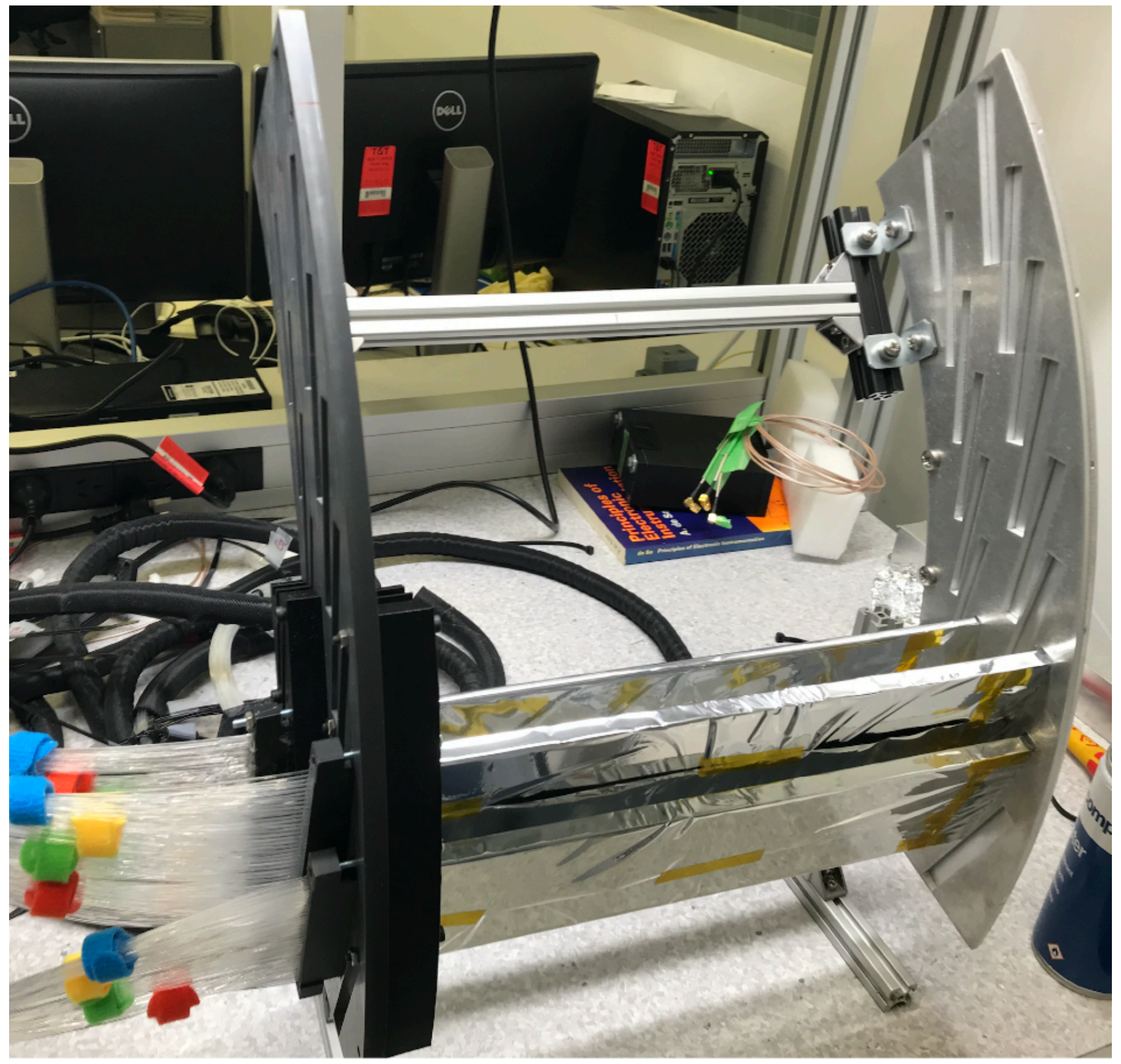
- Target single event sensitivity: 3×10^{-15} with 150 days-long DAQ time
- Cylindrical detectors to avoid beam concentration around the centre
- Good momentum resolution with a helium-based wire drift chamber
  - 200 keV/c @105 MeV/c in σ
- Hit rate is so high that a fast timing measurement and clever triggering are important keys



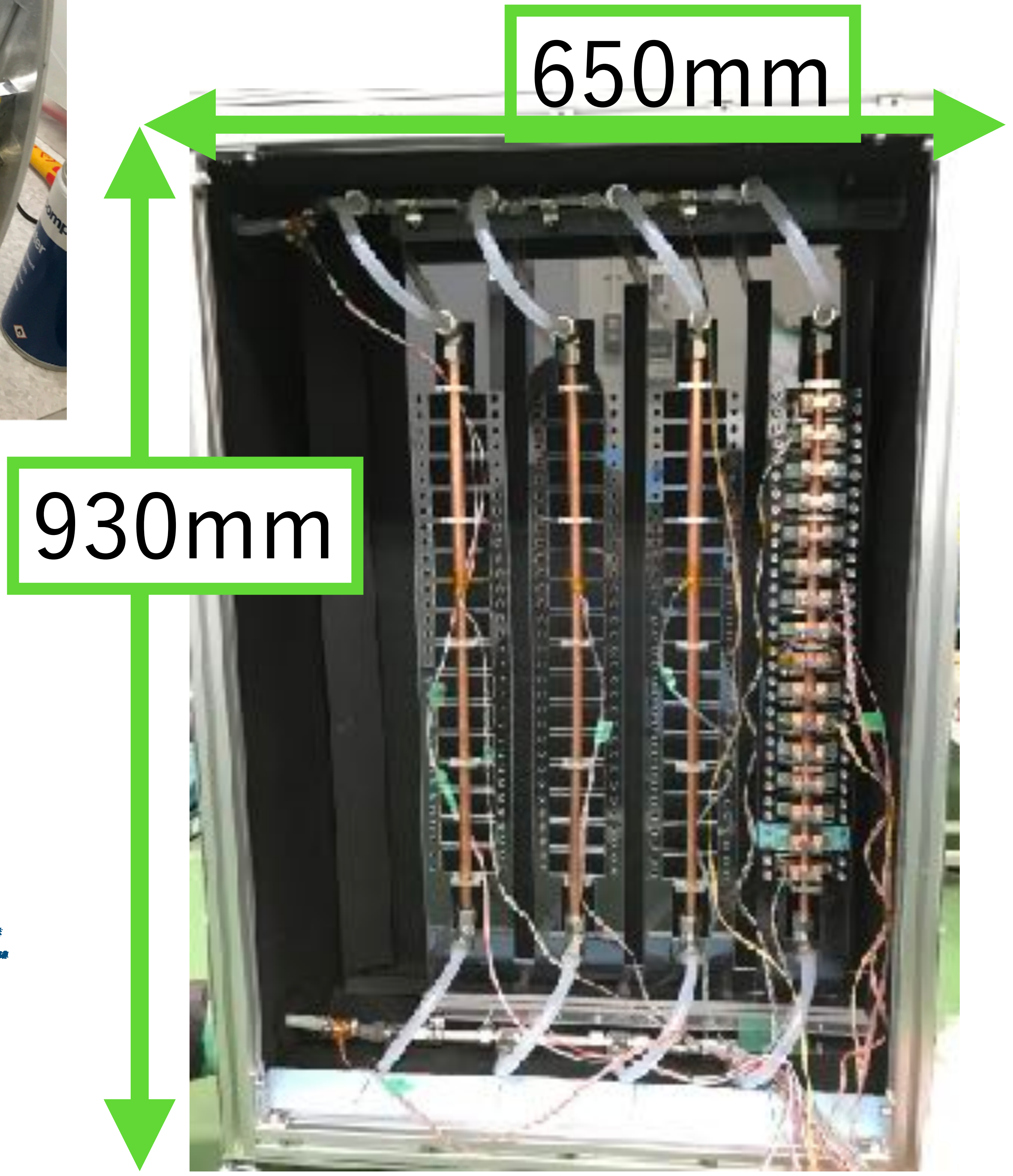
Physics Measurement in Phase-I



All CDC electronics have been installed!

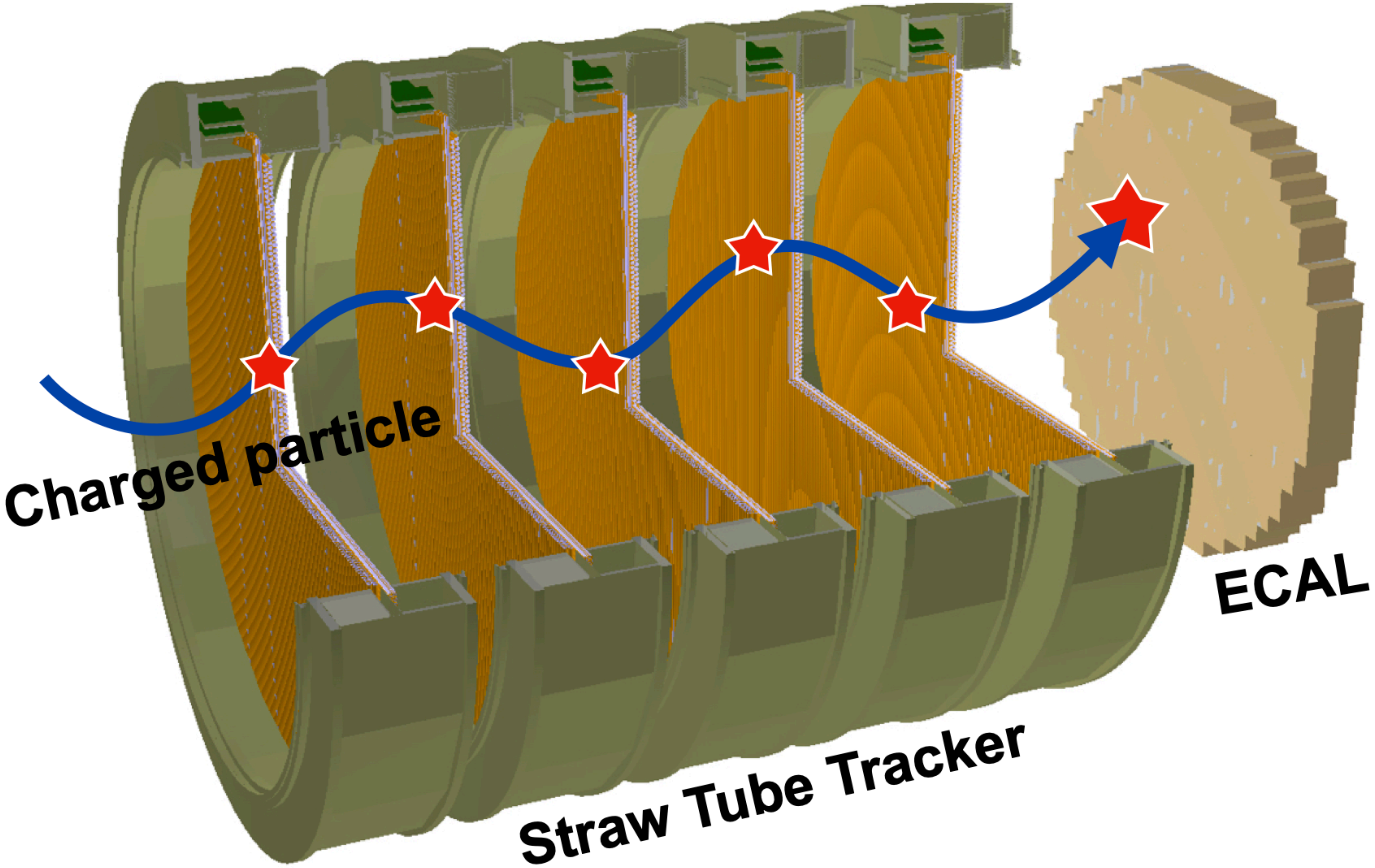


CTH prototype was tested and requirements were met



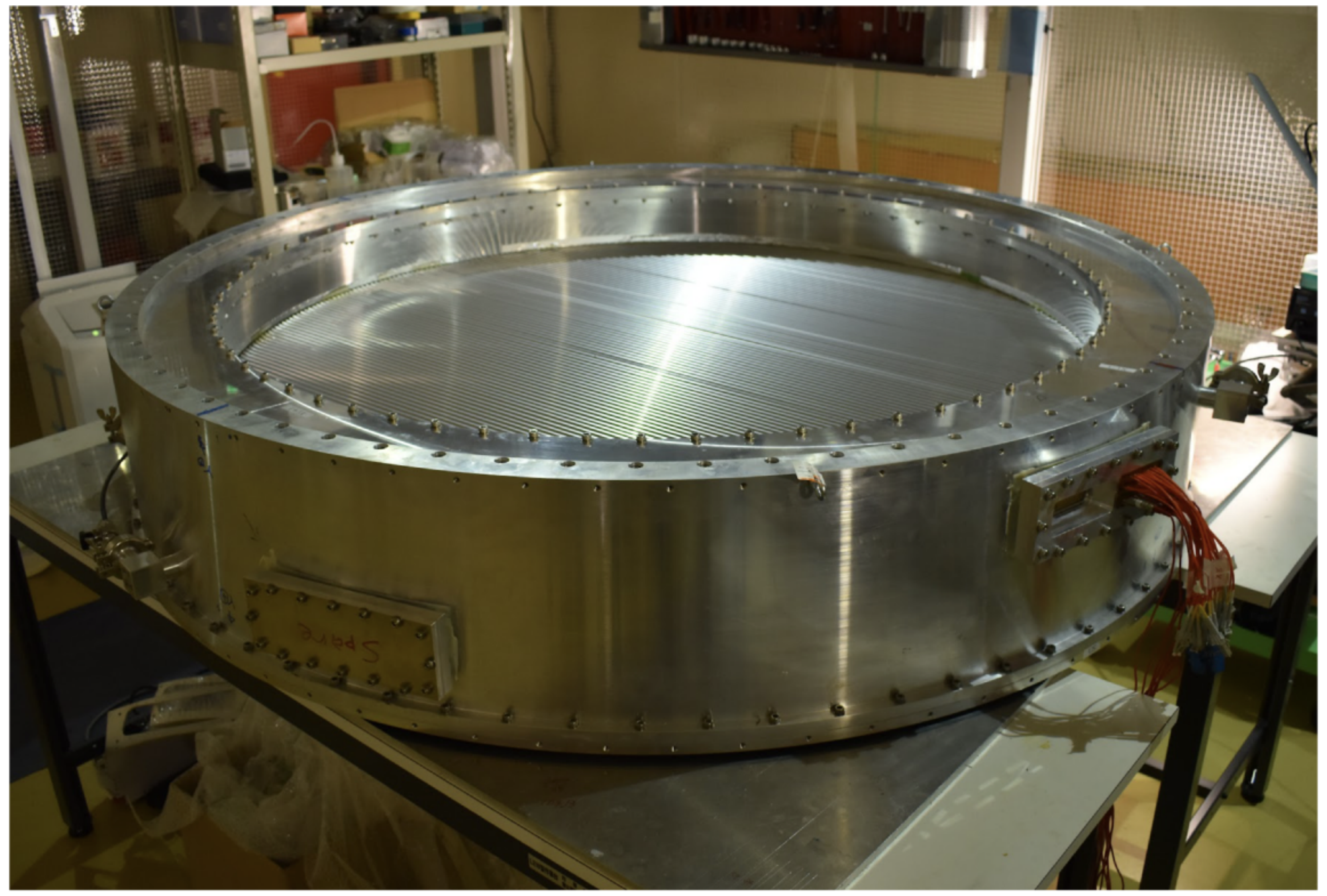
MPPC cooling system was built and tested in the last month

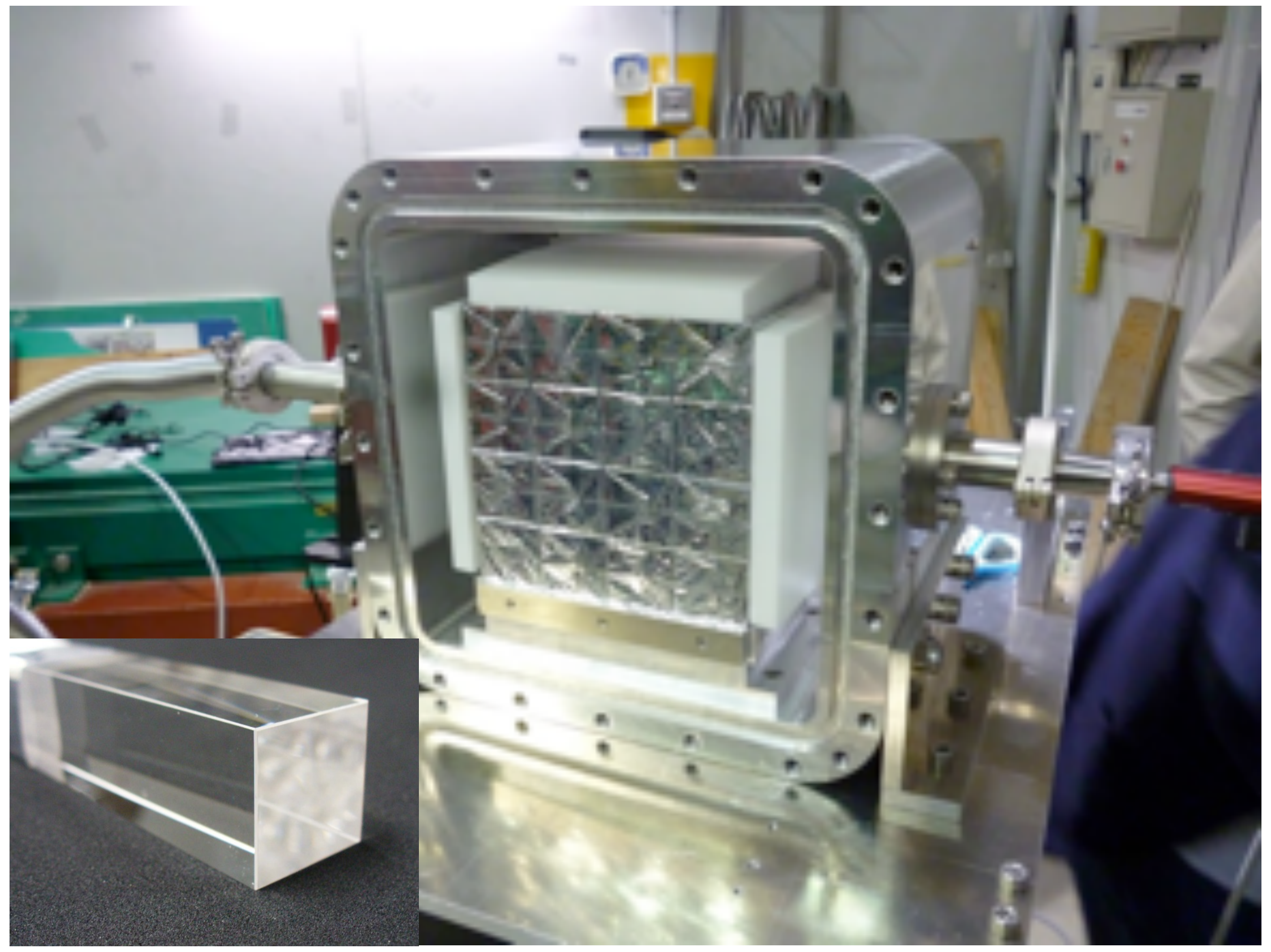
Beam Measurement in Phase-I

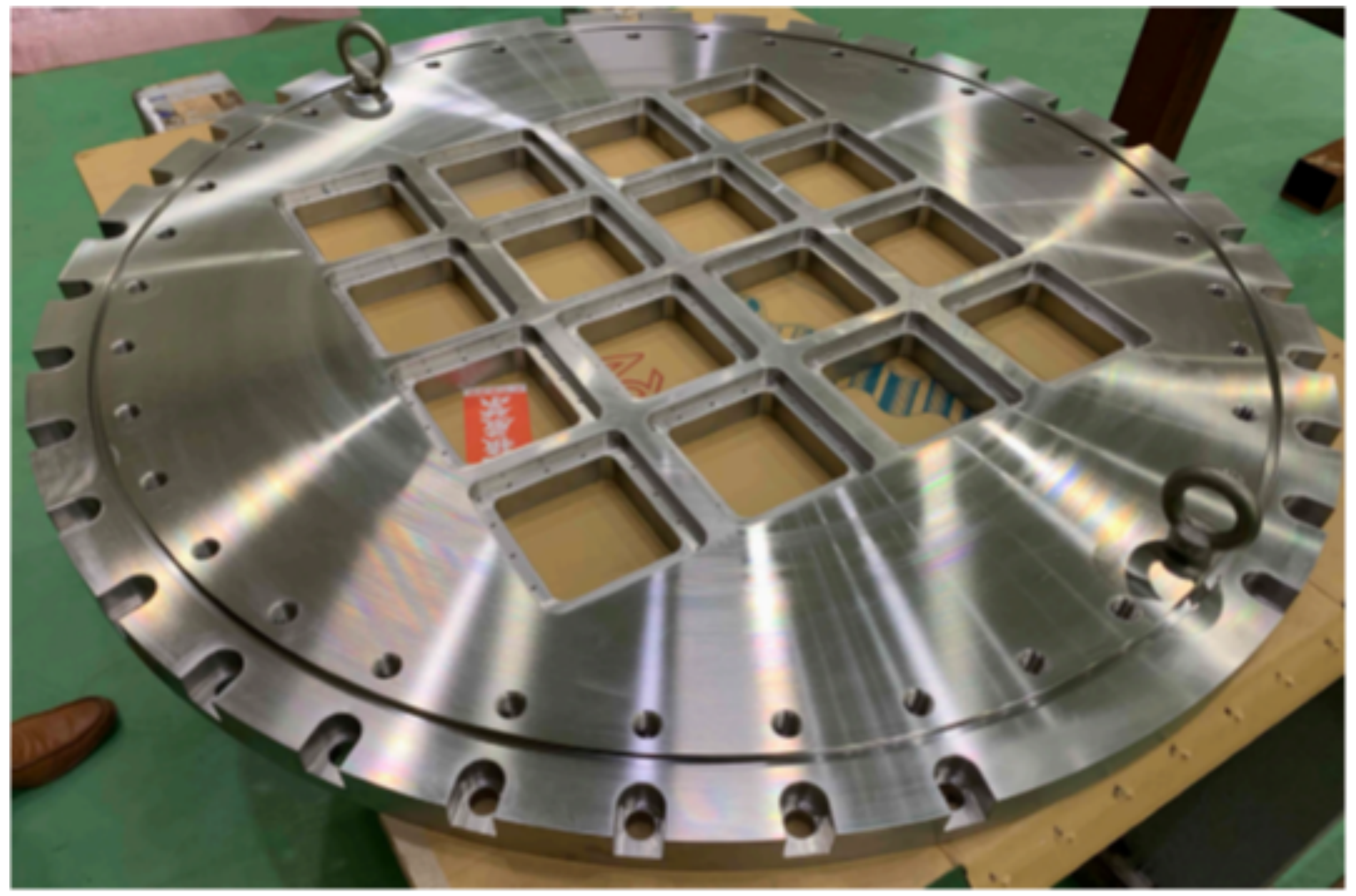


- Everything put in vacuum to minimise the multiple scattering
- Straw-tube trackers with an extremely thin wall
- LYSO crystals to bring a fast timing response with an excellent energy resolution
- More importantly, they are "prototypes" of Phase-II detectors

Beam Measurement in Phase-I



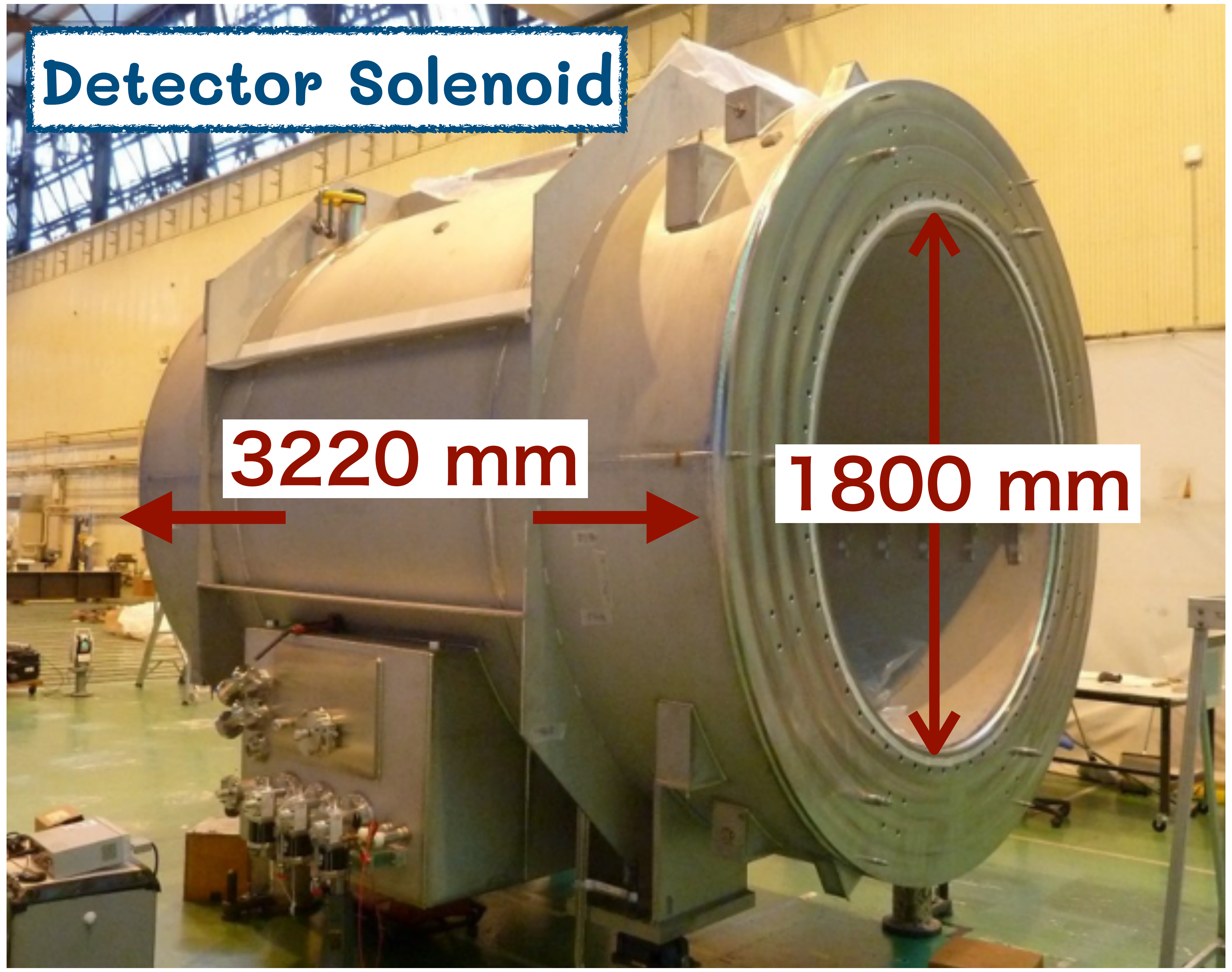




- The 1st station of straw-tube tracker was built
  - 2nd and 3rd are being assembled
- The ECAL prototype was tested and performance was verified
- ECAL construction is ongoing

Phase-I magnets status

COMET Superconducting Magnet System as of Dec.2024

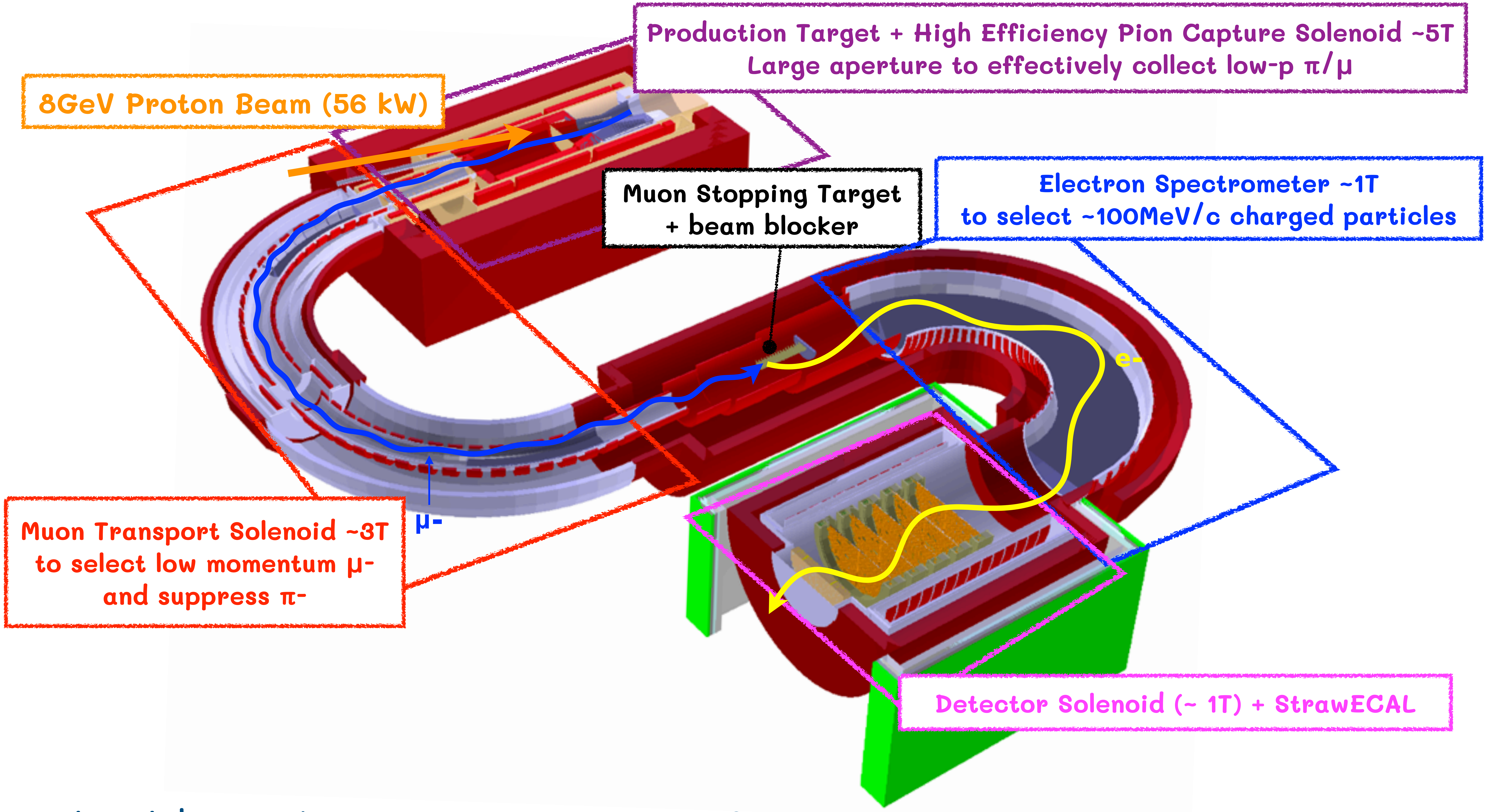


- All magnets have been manufactured and delivered in J-PARC/KEK
- PCS was connected to the MTS in 2024

COMET Phase-II

- Aiming to start in few years after the completion of Phase-I
- Beam power ×10 (3.2 kW → 56 kW)
- Production section
  - Graphite → Tungsten (high-Z to increase pion production)
    - Radiation cooling → Water (or equivalent) + contact cooling
- Full muon transportation
  - Additional 90° bending to complete C-shaped solenoid
  - Much less pion decay products at the muon stopping target
- Curved electron spectrometer
  - Highly suppress DIO and low momentum secondaries
- Roughly ×100 sensitivity improvement in total

COMET Phase-II

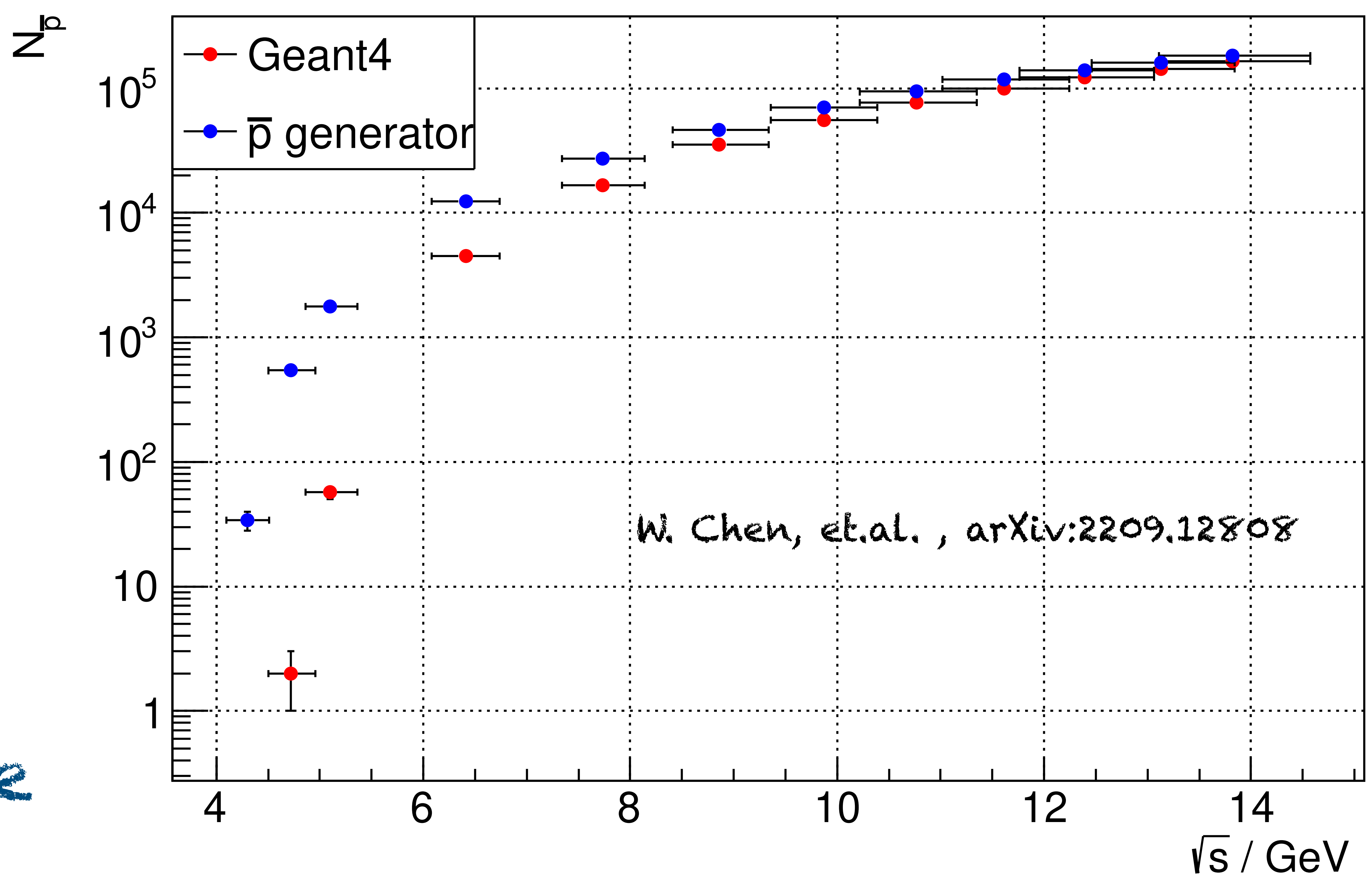


Possible issues in Phase-II

- Radiation level will be much higher in Phase-II
    - Once we start the full-intensity run, PCS area will not be accessible for a long-term
    - The target design and choice of material should be decided with an EXTRA CARE!
- COMET standard MC production (based mostly on Geant4) will be very inefficient
    - More efforts to be put in MC generator R&Ds
- Rare backgrounds are almost impossible to be reproduced by the G4-based full-simulation and unreliable at 10^{-17} level of sensitivity
    - Cosmic-ray: can be vetoed, but coming from everywhere
    - Antiprotons: produced by the proton beam, slow and long-lived

Simulation problems

- Antiproton production:
    - Near the kinematical threshold, there is huge uncertainty in the production cross-section of anti-protons
    - Nor sufficient experimental data to be compared with...
    - Some studies indicate large uncertainty in the production rate between G4 and other models
- Pion/muon productions:
    - Large discrepancies in μ/π yields observed in different MC models



μ/π yields at the 3 m backward from the proton target
From COMET Phase-I TDR

Models	Simulator	$N(\pi^- + \mu^-)/p$ at 3 m
CEM	MARS	0.061 ± 0.001
CEM/LAQGSM	MARS	0.138 ± 0.001
LAQGSM	MARS	0.144 ± 0.001
LAQGSM	GEANT	0.1322 ± 0.0007
QGSP_BERT	GEANT	0.0511 ± 0.0002
QGSP_BIC	GEANT	0.1278 ± 0.0005
FTFP_BERT	GEANT	0.0440 ± 0.0002

* Those are from VERY OLD Geant4!!

So what?

- We always state that Phase-I results can be used to improve the Phase-II design to further improve the sensitivity
  - This is not 100% true, because the proton target will be different in Phase-II!
  - It may be too late if we wait for full Phase-I result to optimise the Phase-II design
  - It is more ideal/efficient if target design can be optimised independently based on experimental data
- However, no data is available for now
  - It is always best to measure if possible

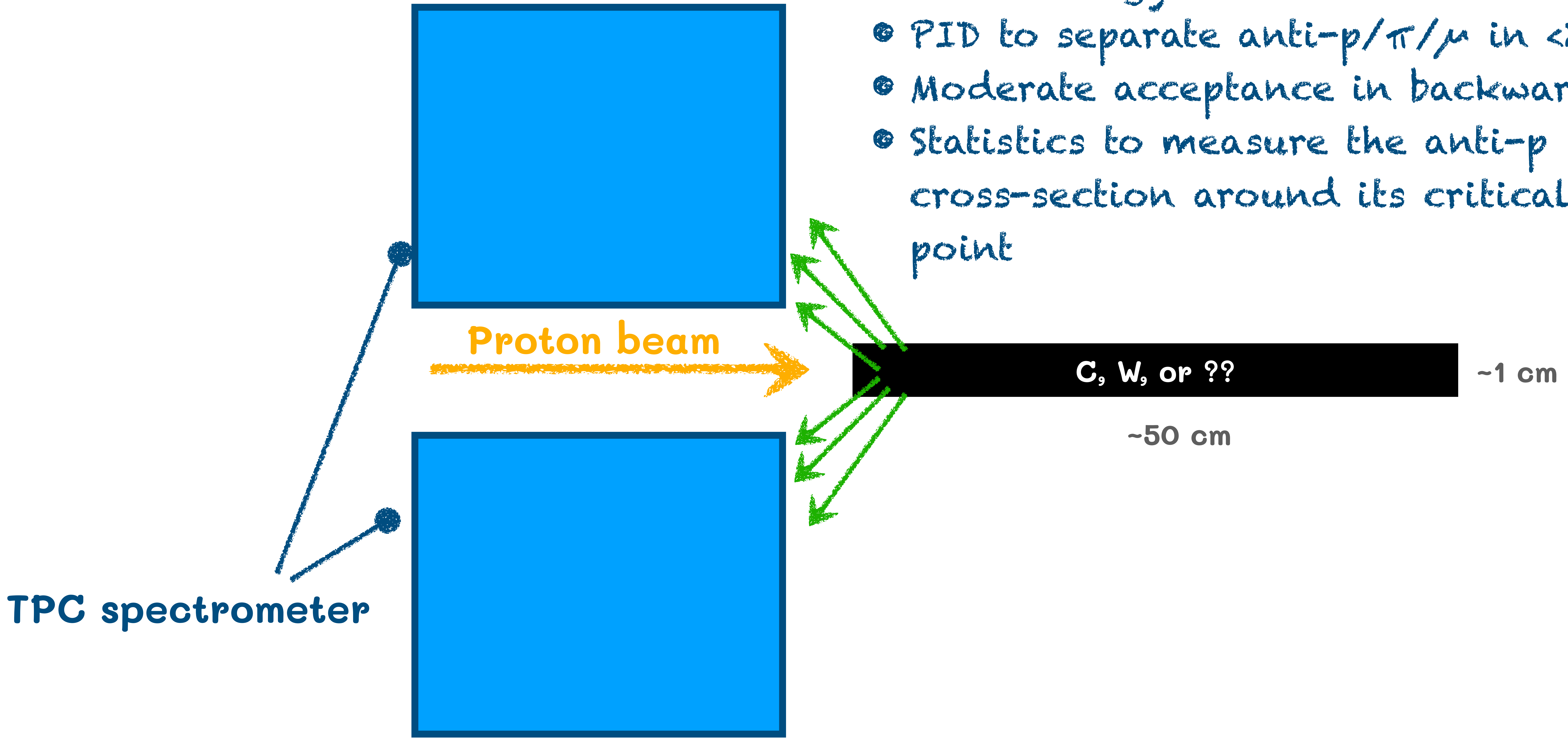
Possible collaborative works (1)

- There should be great opportunities for us in NA61 low-energy mode to collaborate with
- Actual measurements:
  - Case 1: Sweep the energy around 8 GeV to measure antiproton production rate as a function of the angle, especially for the backward direction
  - Case 2: Measure the pions/muons production rate with different target materials to investigate alternative options
- Above two can probably done with a single configuration
- We may be able to co-exist with other projects as COMET only focuses on backward-going particles

Very rough idea

Requirements:

- Beam energy around 8 GeV
- PID to separate anti-p/π/μ in <200 MeV/c
- Moderate acceptance in backward region
- Statistics to measure the anti-p production cross-section around its critical energy point



Possible collaborative works (2)

- Technical collaborations:
  - Software development, detector R&Ds as well as exchanging researchers...
- More clever suggestions are very welcomed!

Summary

- COMET searches for the μ-e conversion with 100/10,000 times better sensitivities in its Phase-I/Phase-II than the current limit (7.0×10^{-13})
- Phase-α well performed to confirm the muon transportation working as designed
- Intensive Phase-I preparations are ongoing to start our physics measurement in few years
- Phase-II will follow with further 100 better sensitivity (or even better...)
    - Better understanding on the hadronic model around Ep=8 GeV is essential
- There are huge benefits to work together with the NA61/SHINE collaboration
    - Antiproton production is yet to known around Ep = 8 GeV
    - Better understanding on the pion/muon productions is also valuable
    - Software R&Ds, e.g. MC generator
- Let's keep in touch

Back up

Far Future

- PRISM / PRIME
  - There already is a plan to go further down to 10^{-20} single event sensitivity
- Muon collider
  - PRISM / PRIME muon storage ring could be a source of the muon collider (why not?)