



Status of the COMET Experiment at J-PARC

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on behalf of the COMET Collaboration



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NATAL | BRAZIL

COMET ... **CO**herent **M**uon to **E**lectron **T**ransition

Experiment searching for **charged Lepton Flavor Violation**
utilizing intense muon beam

- ▶ Muon-to-Electron Conversion
- ▶ COMET Experiment
- ▶ Current Status
- ▶ Summary



Muon-to-Electron Conversion

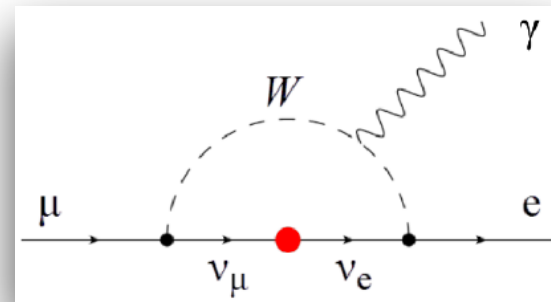
Muon-to-Electron Conversion

► Charged Lepton Flavor Violation (cLFV)

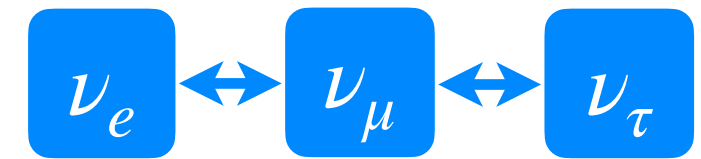
$\mu \rightarrow e\gamma$ $\mu \rightarrow eee$ $\mu^- N \rightarrow e^- N$ not observed yet

► Essentially forbidden in the SM

$$BR(\mu \rightarrow e\gamma) \propto \left(\frac{\Delta m_{\nu_{ij}}^2}{M_W^2} \right)^2 < O(10^{-54})$$



Neutrino oscillation



cLFV

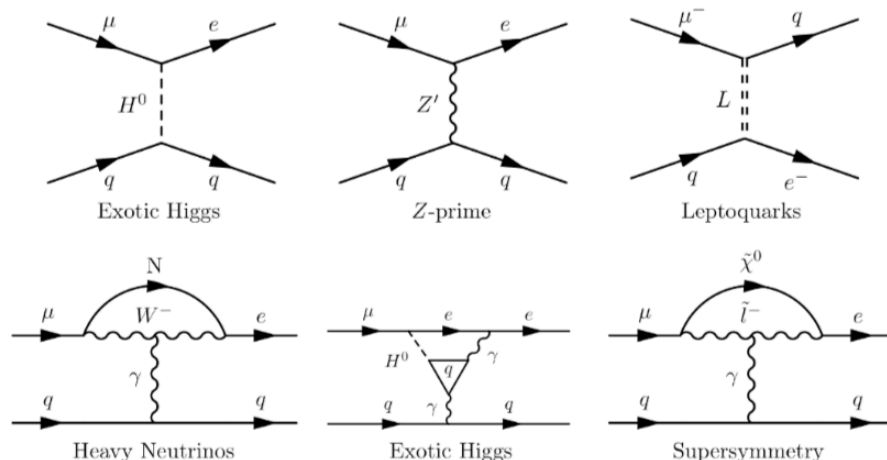
Experimental observation = Clear evidence of the New Physics

► Theoretical models beyond SM → Sizable branching ratio of cLFV

$$BR(\mu \rightarrow e\gamma) = O(10^{-16} \sim 10^{-18})$$

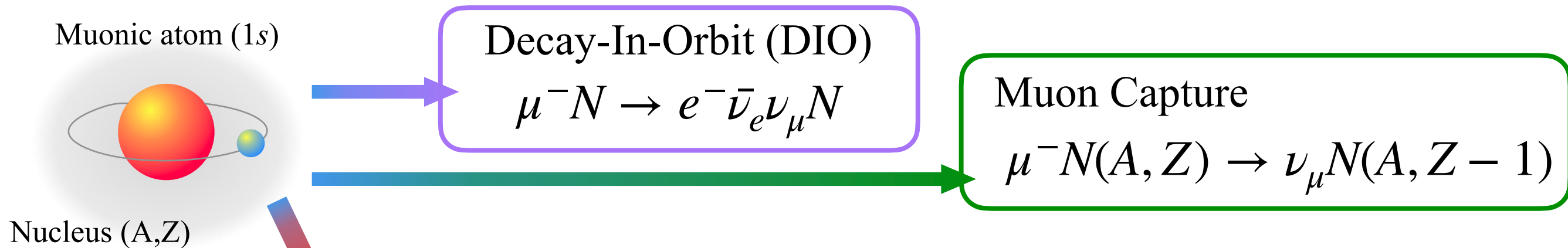
Current upper limits

$\mu^- N \rightarrow e^- N$	$BR(\mu^- Au \rightarrow e^- Au) < 7 \times 10^{-13}$
$\mu^+ \rightarrow e^+ \gamma$	$BR(\mu^+ \rightarrow e^+ \gamma) < 1.5 \times 10^{-13}$



**Heading towards a potential discovery
with several orders-of-magnitude sensitivity improvement**

Muon-to-Electron Conversion



$\mu - e$ conversion

$$\mu^- N \rightarrow e^- N$$

- ▶ Mono-energetic single electron

$$E_e = m_\mu - B_\mu - E_{recoil}$$

(~105 MeV/c for Al nucleus)

Backgrounds

- ▶ Intrinsic background ... DIO

- ▶ Beam induced background at the prompt timing

ex. Radiative Pion Capture:

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

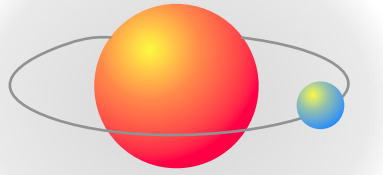
can be avoided by **selecting delayed** e^-

- ▶ Cosmic ray background

The whole system is surrounded
by **veto counters**

Muon-to-Electron Conversion

Muonic atom (1s)



Nucleus (A,Z)

Decay-In-Orbit (DIO)

$$\mu^- N \rightarrow e^- \bar{\nu}_e \nu_\mu N$$

Muon Capture

$$\mu^- N(A, Z) \rightarrow \nu_\mu N(A, Z - 1)$$

$\mu - e$ conversion

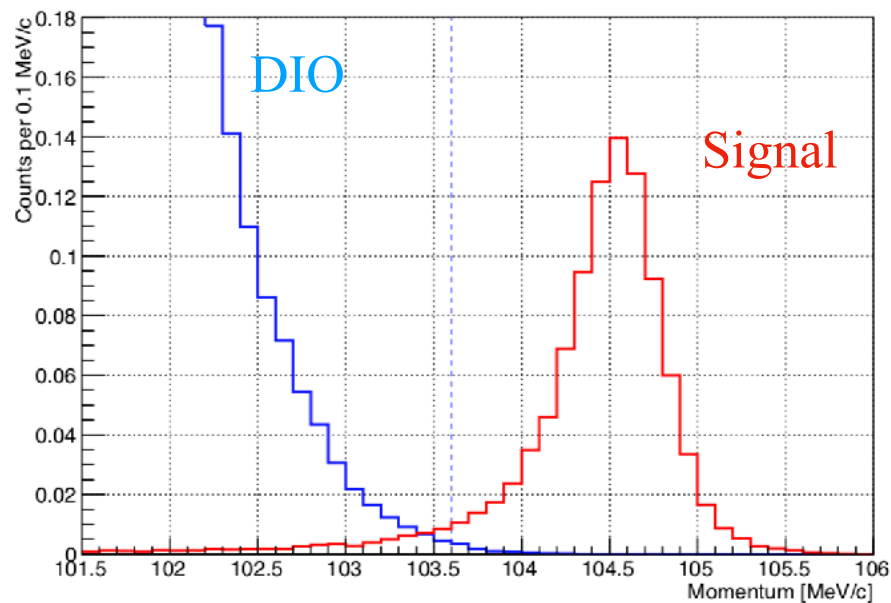
$$\mu^- N \rightarrow e^- N$$

► Mono-energetic signal electron

$$E_e = m_\mu - B_\mu - E_{recoil}$$

(~105 MeV/c for Al nucleus)

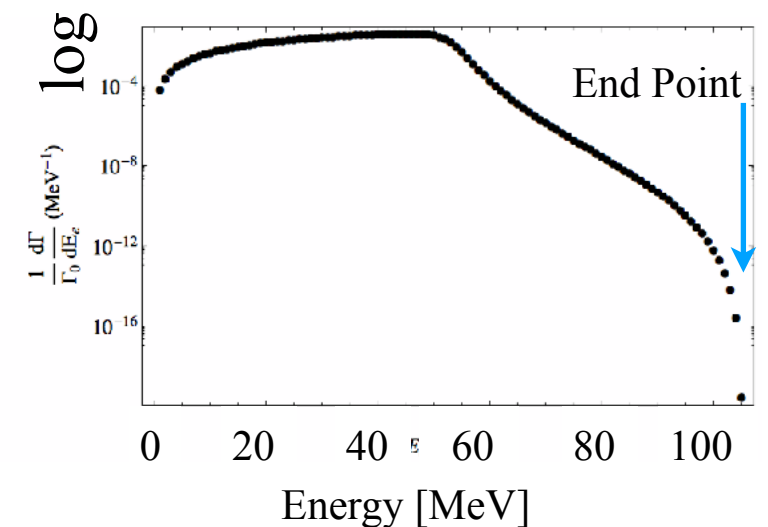
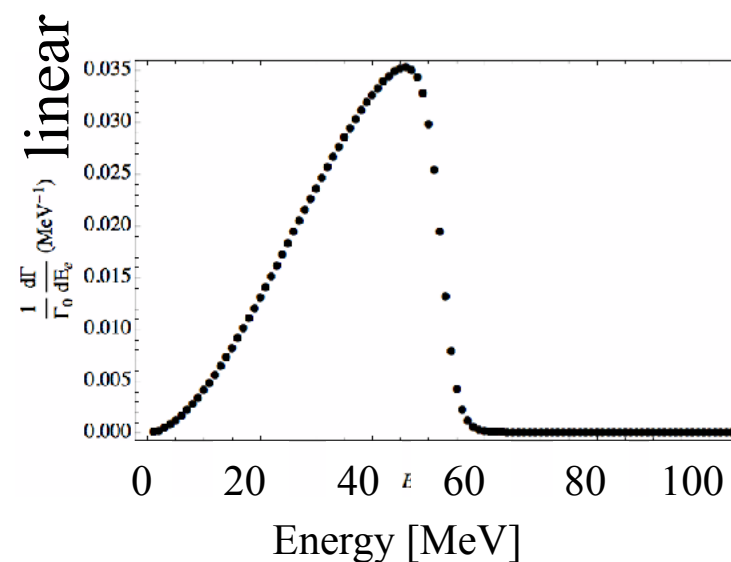
Signal and DIO (BR=3 × 10⁻¹⁵)



Backgrounds

► Intrinsic background ... DIO

- Rejected by the detector geometrical acceptance
- Nucleus recoil ... higher tail extended
- Precise momentum measurement

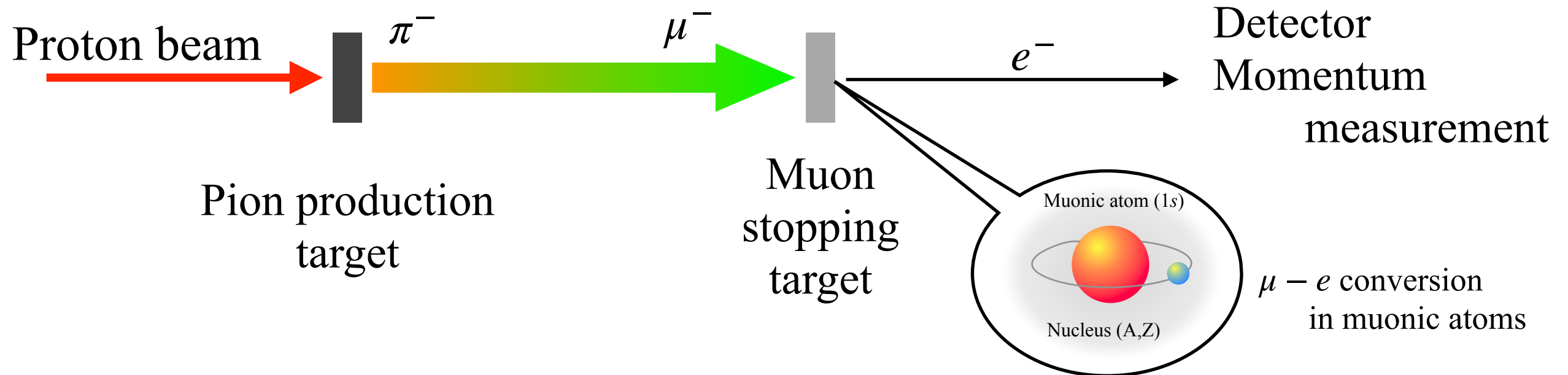




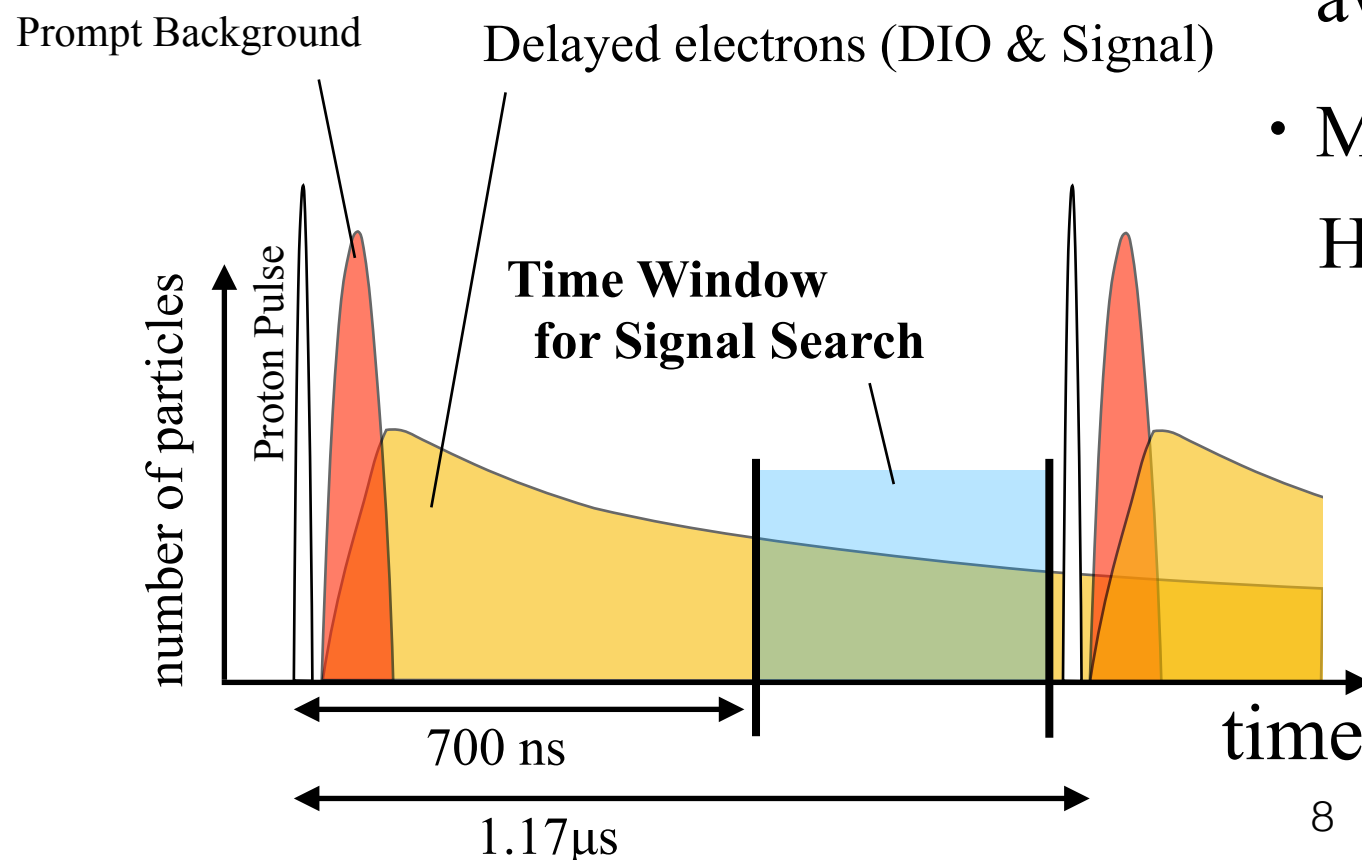
COMET Experiment

COMET Experiment

► Principle of the Experiment



► Utilizing a Pulsed Beam



- Delayed time window
 - avoid prompt beam-related backgrounds
 - Material of stopping target
- Heavier nucleus ...
Large overlap with muon wave function
 but short life time of muon

- **Aluminum** stopping target

$$\tau_{\mu} \text{ in Al} \sim \mathbf{0.9 \mu\text{sec}}$$

COMET Experiment

► The COMET experiment will be conducted at **J-PARC** (Tokai, Japan).

Staging approach (Phase-I, Phase-II)

► Proton beam

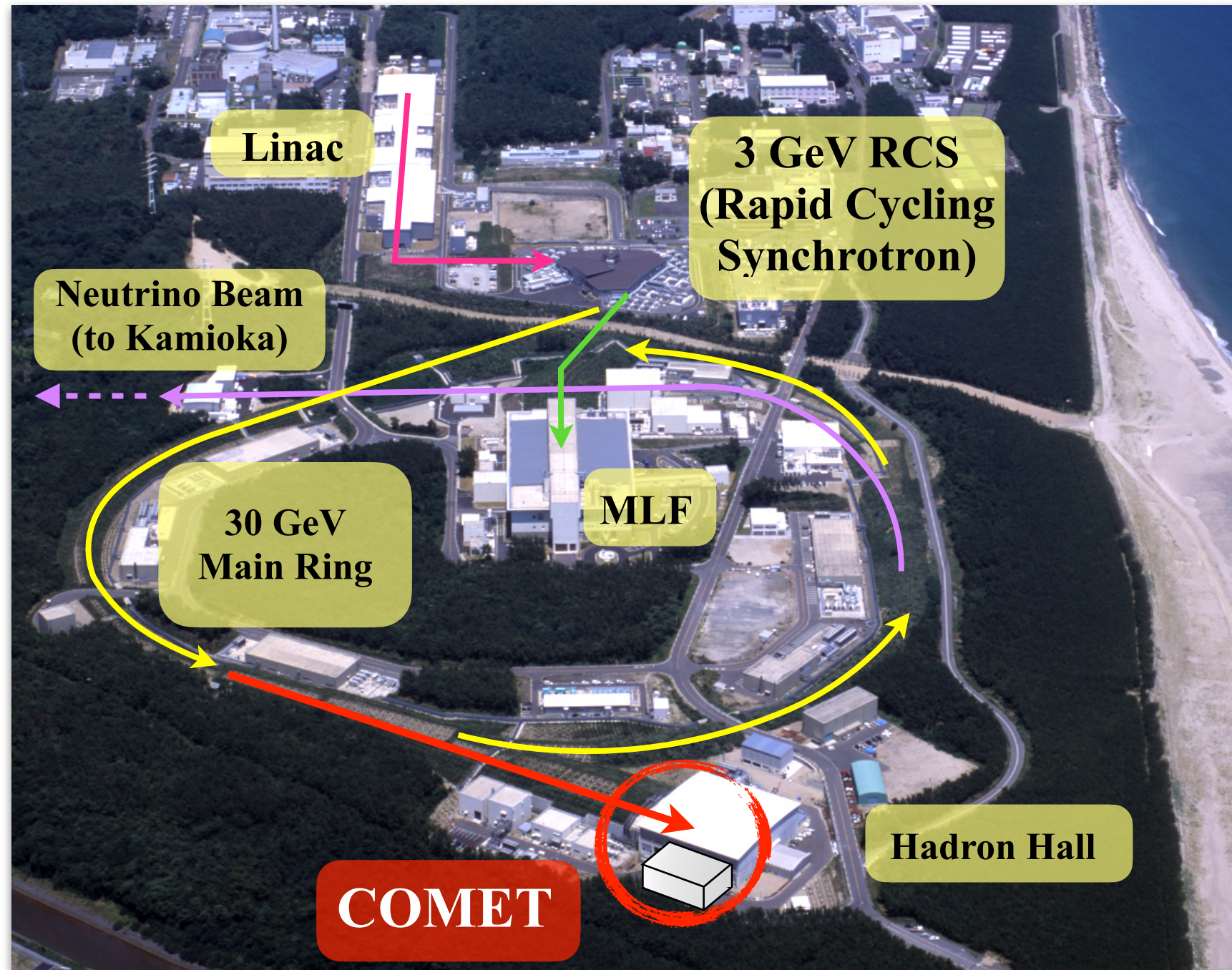
- **8 GeV**
- Pulsed structure
1.17 μsec repetition

- **3.2 kW** for Phase-I
56 kW for Phase-II

► Good extinction factor

- Ratio of off-timing protons

$$= \frac{\text{protons between bunches}}{\text{protons filled in bunches}}$$
- $O(10^{-10})$ required
- measured : **1.02×10^{-10}**



COMET Experiment (Phase-II)

Proton beam
from MR

Pion Capture Section

Collect the low momentum, backward pions
with a high magnetic field

Pion Production
Target

Transport Section

Pion $\rightarrow$ Muon Decay Volume
Momentum and charge selection
with curved solenoid and dipole field,
and beam collimator

▶ Search for $\mu - e$ conversion
with single event sensitivity
of 2×10^{-17}
 $\times 10000$ better than the current upper limit

Muon Stopping
Target

Electrons

Electron Spectrometer

Select momentum
($\sim 105 \text{ MeV/c}$)
& charge

Eliminate off-momentum
backgrounds

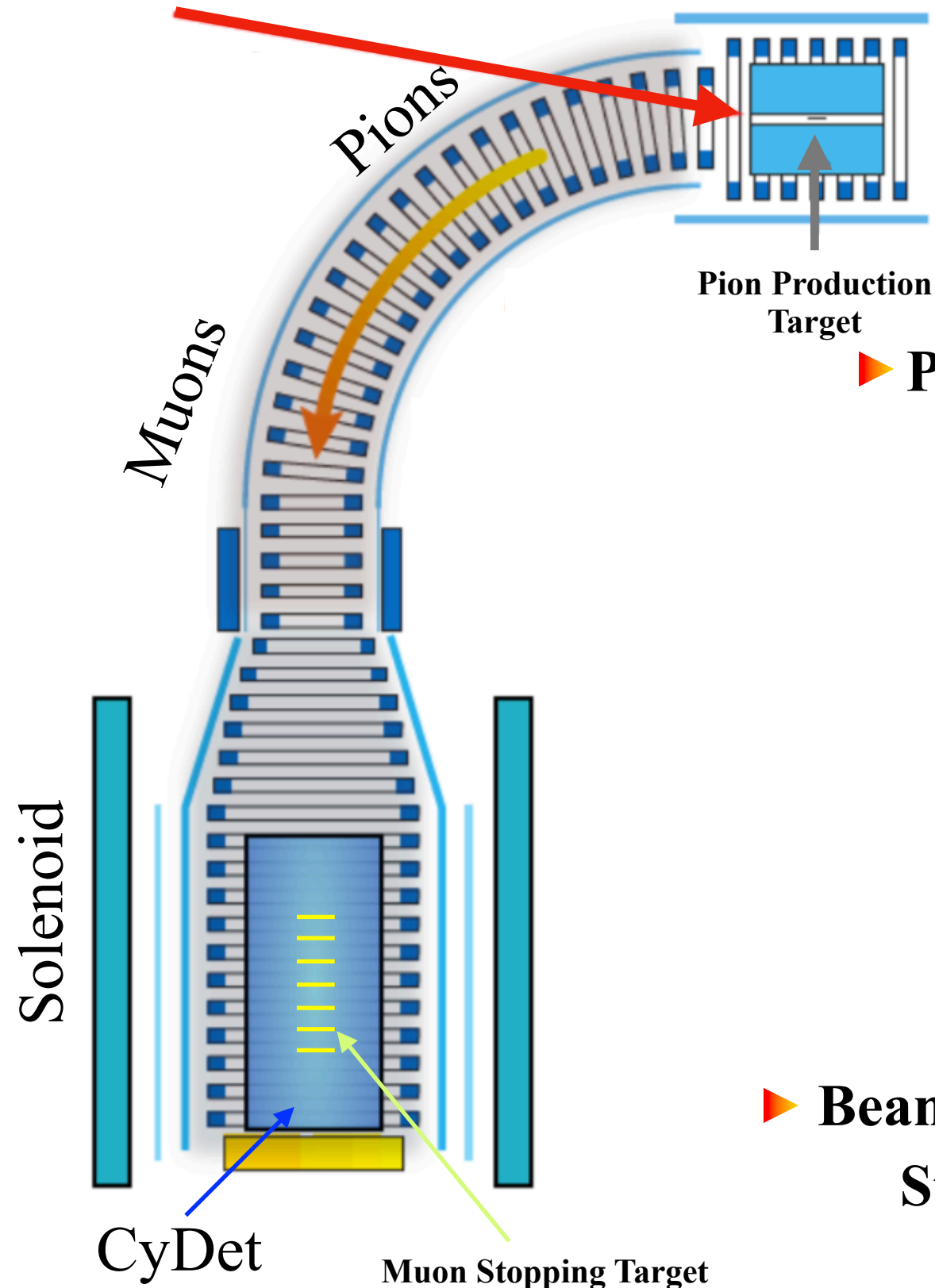
Detectors

Straw tube tracker
& ECAL

Precise measurement of
momentum & energy

COMET Experiment (Phase-I)

Proton beam from MR



Aims of Phase-I

- ▶ Search for $\mu - e$ conversion with single event sensitivity of 3×10^{-15}
- ▶ Beam measurement to investigate beam quality and background

▶ Physics detector

- Cylindrical Detector system (**CyDet**)
 - Cylindrical Drift Chamber (**CDC**)
 - Cylindrical Trigger Hodoscopes (**CTH**)
 - Surrounding the muon stopping target (17 Aluminum disks)
- Cosmic Ray Veto (**CRV**)
- Germanium Detector for normalization

▶ Beam detector

StrECAL

- Straw Tube Tracker
- Electron Calorimeter

with X-ray

Single Event Sensitivity

► Single Event Sensitivity (S.E.S) =
$$\frac{1}{N_{\mu} \times f_{cap} \times f_{gnd} \times A_{\mu e}}$$

N_{μ} = number of muons stopping on the target

f_{cap} = fraction of muon capture

f_{gnd} = fraction of nucleus which is not excited by $\mu - e$ conv.

$A_{\mu e}$ = Total Acceptance for e^- from $\mu - e$ conv.

	Phase-I	Phase-II
Beam power	3.2 kW	56 kW
Protons on target	3×10^{19}	3×10^{21}
Stopped muons on target	1.5×10^{16}	1.5×10^{18}
Running time	~ 5 months	~ 1 year
S.E.S	3×10^{-15}	2×10^{-17}

c.f. SIMDRUM-II: $\text{BR}(\mu^- Au \rightarrow e^- Au) < 7 \times 10^{-13}$



Current Status

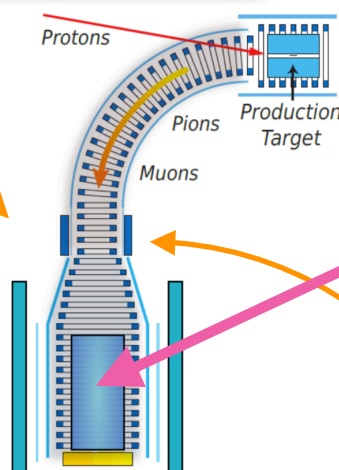
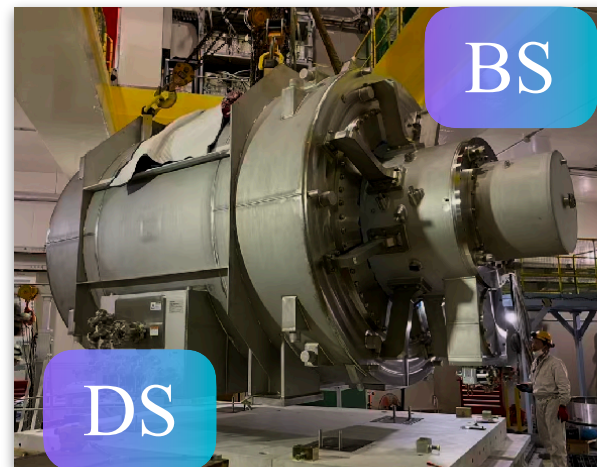
Towards Phase-I

Beamline

► Superconducting Solenoid Magnets

Capture Solenoid (CS), Transport Solenoid (TS), Bridge Solenoid (BS), Detector Solenoid (DS)

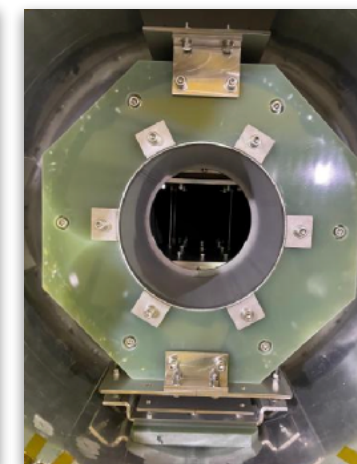
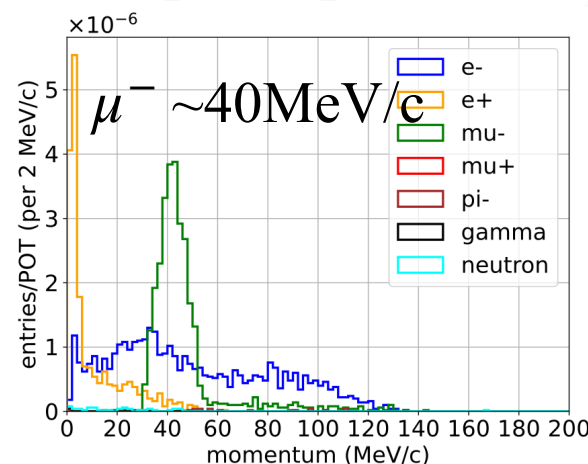
- Installation of all magnets was finished in 2025 Nov.



- **Field measurement of DS** will take place.
- Precise field map for track reconstruction

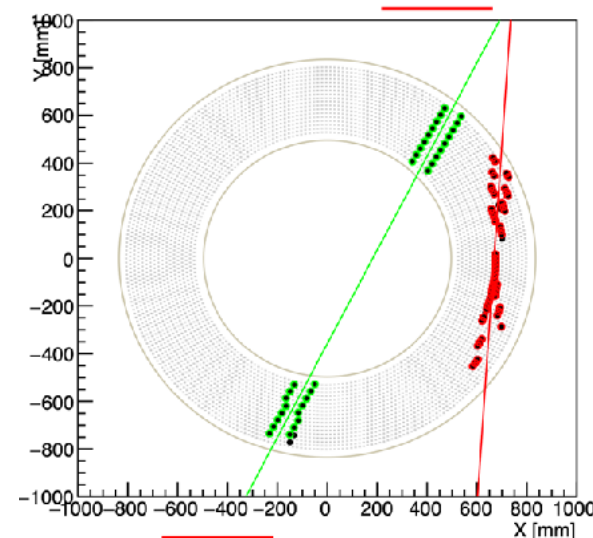
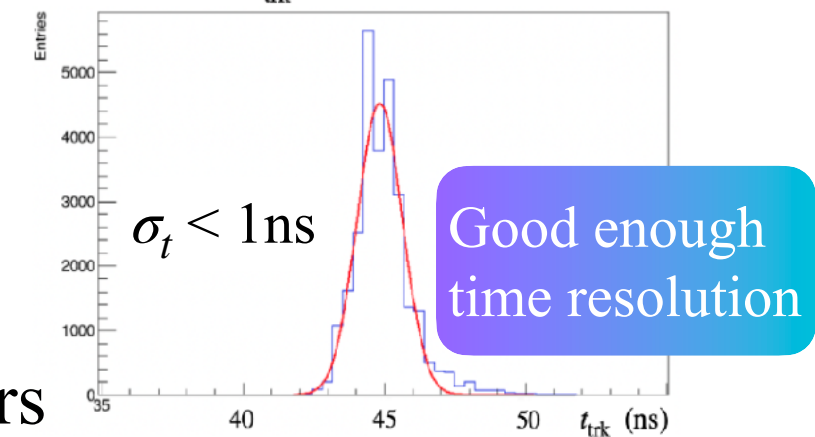
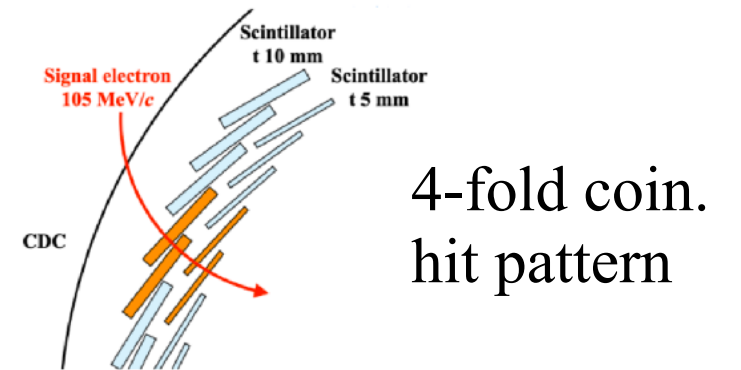
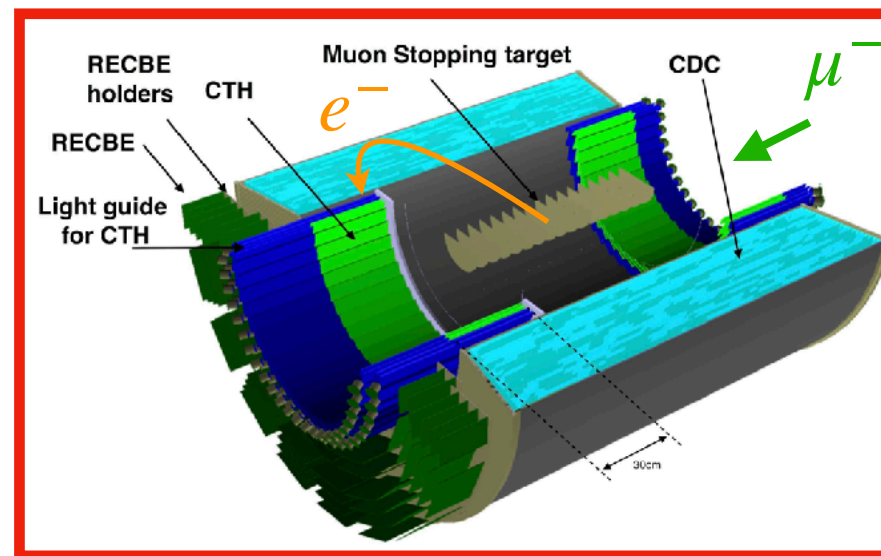
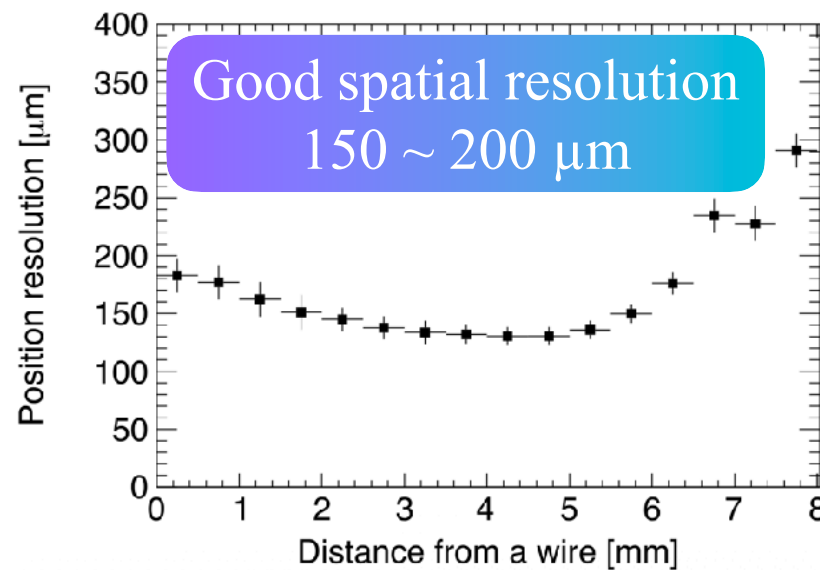
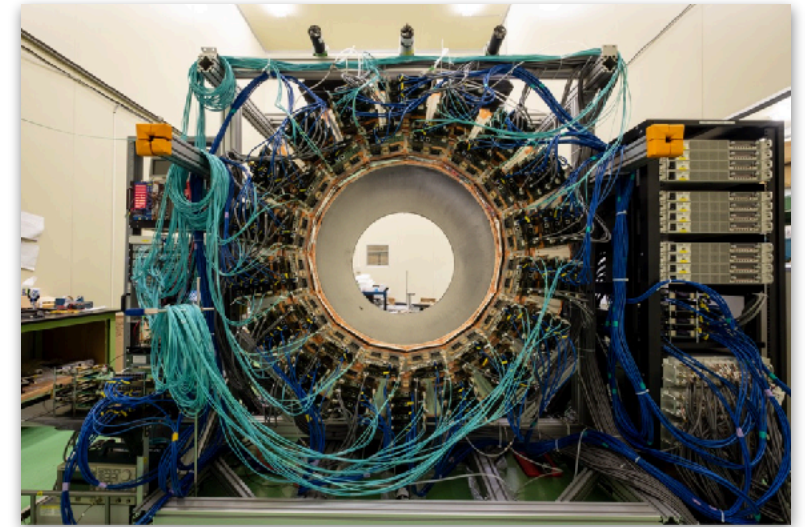
► Beam Collimator

- Muon beam optimized by the dedicated simulation
- Beam collimator designed, fabricated and installed.



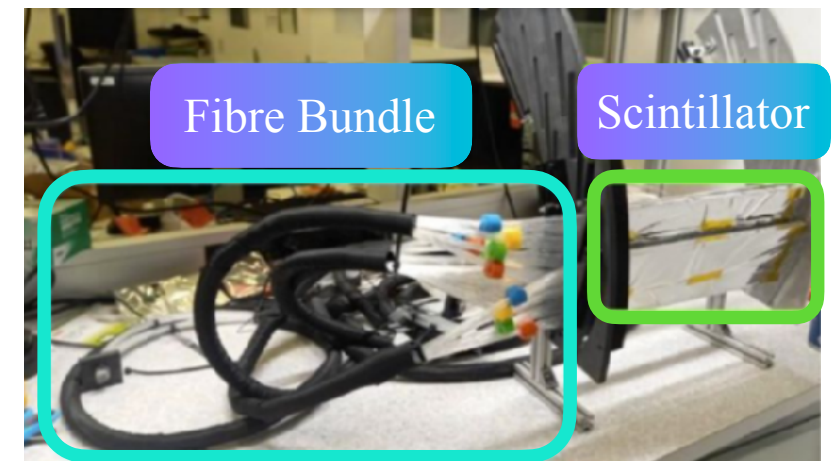
► CDC

- Magnet field : 1T • Gas: He:i-C₄H₁₀ (90:10)
- 20 layers, 4986 sense wires, alternating stereo angle ($\pm 64 \sim 75$ mrad)
- Momentum resolution = 200 keV/c



► CTH

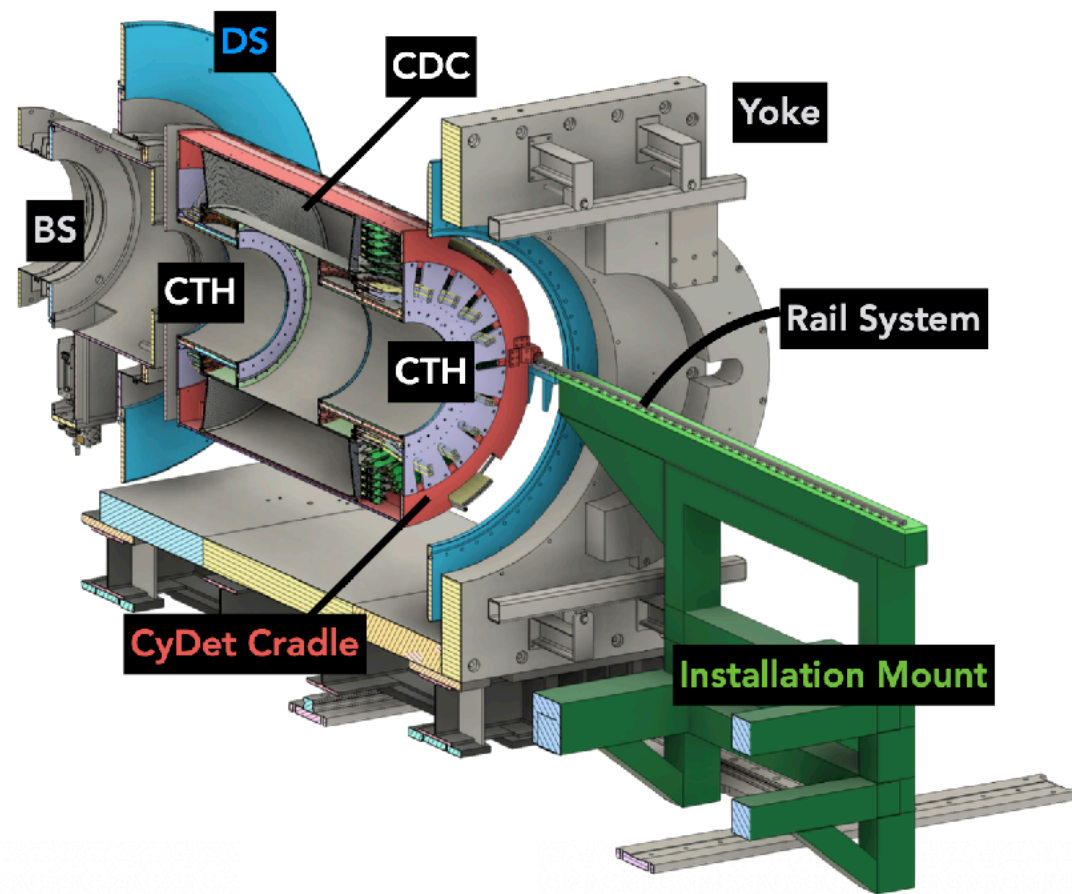
- 2 wheels of 2×64 plastic scintillators at Upstream/Downstream
- Trigger : 4-fold coincidence
- Commissioned with prototype



Event display of cosmic-ray test

Phase-I Detector System CyDet

- ▶ Preparation towards CDC+CTH integration and installation ongoing
 - CDC and CTH will be integrated in a stainless-steel support frame.
 - now testing the integration scheme



Support Frame



CTH Frame

► Straw Tube Tracker

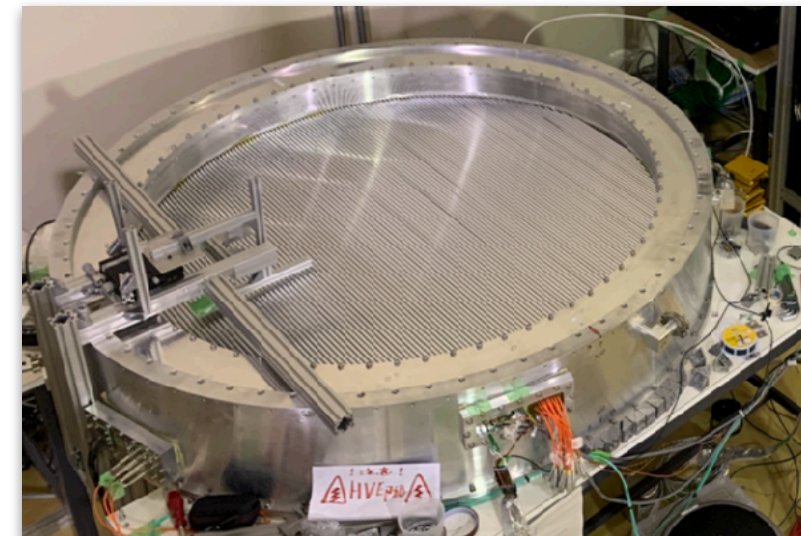
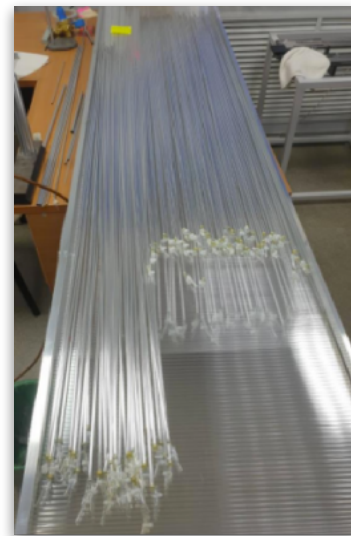
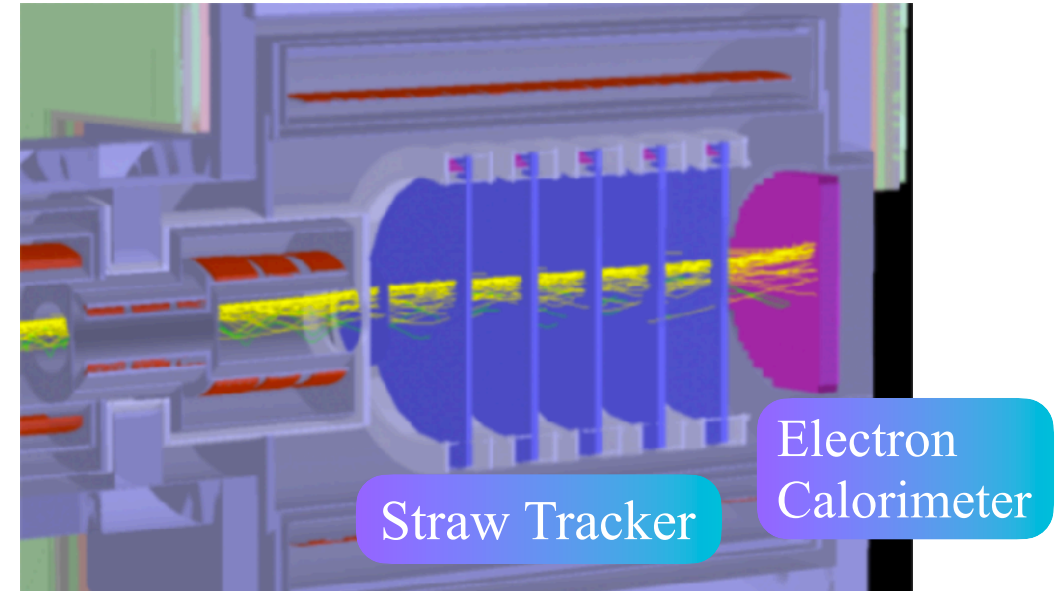
- 4 planes $\times$ 5 stations
(3 constructed, 2 under construction)

- Low mass straw tube

Phase-I : 20 μ m thick, 9.75 mm diameter

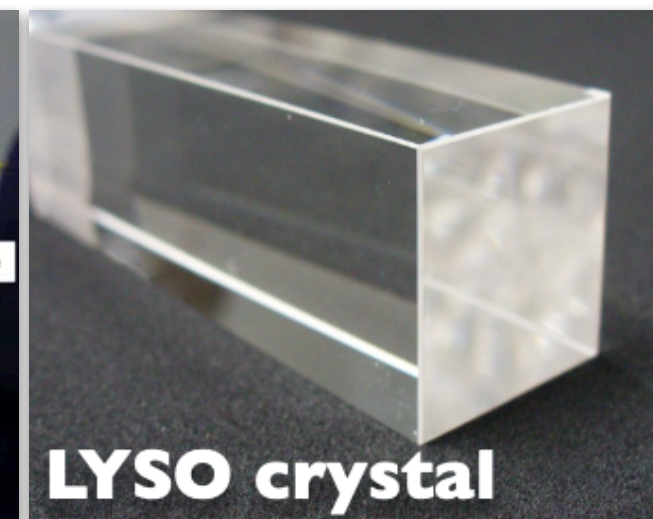
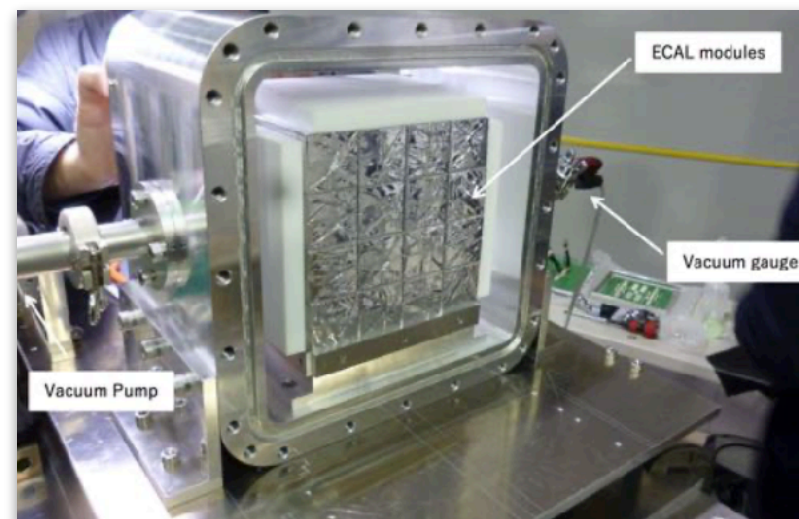
Phase-II : 12 μ m thick, 5 mm diameter

- Operation in vacuum
- Ar:C₂H₆ (50:50)
- Spatial resolution : 110 μ m



► Electron Calorimeter

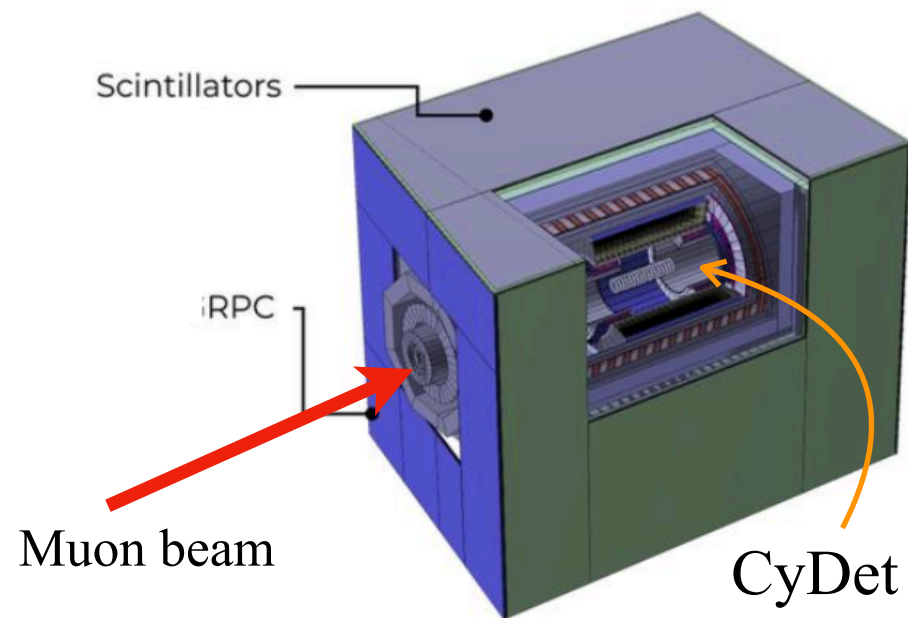
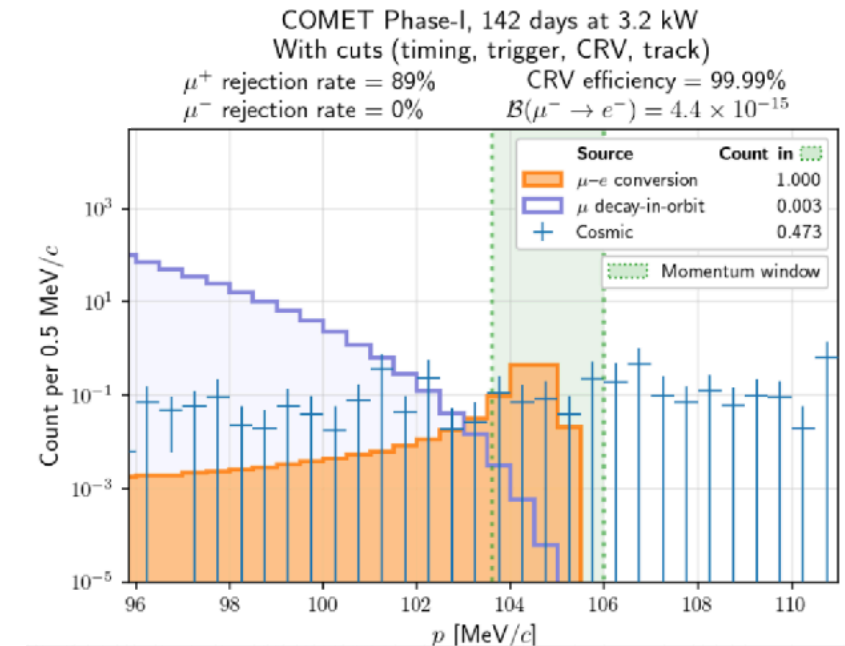
- 1920 LYSO crystals (2 $\times$ 2 $\times$ 12 cm)
- Energy resolution : 4.4 %
- Spatial resolution : 5.8 mm



Cosmic Ray Veto (CRV)

- ▶ Suppress cosmic rays by a factor of 10^{-4}
- ▶ Full coverage except the beam holes, using different technologies

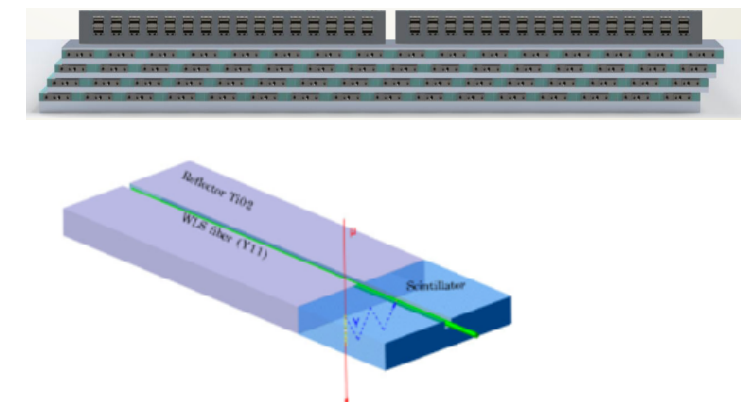
- Top CRV : Plastic scintillators
- Side CRV : ARGO-RPC modules (recycled RPC) / Plastic Scintillators
- Upstream/Downstream CRV : iRPC modules (RPC with CMS technology)



- ▶ Scintillator CRV
Preparation in J-PARC ongoing



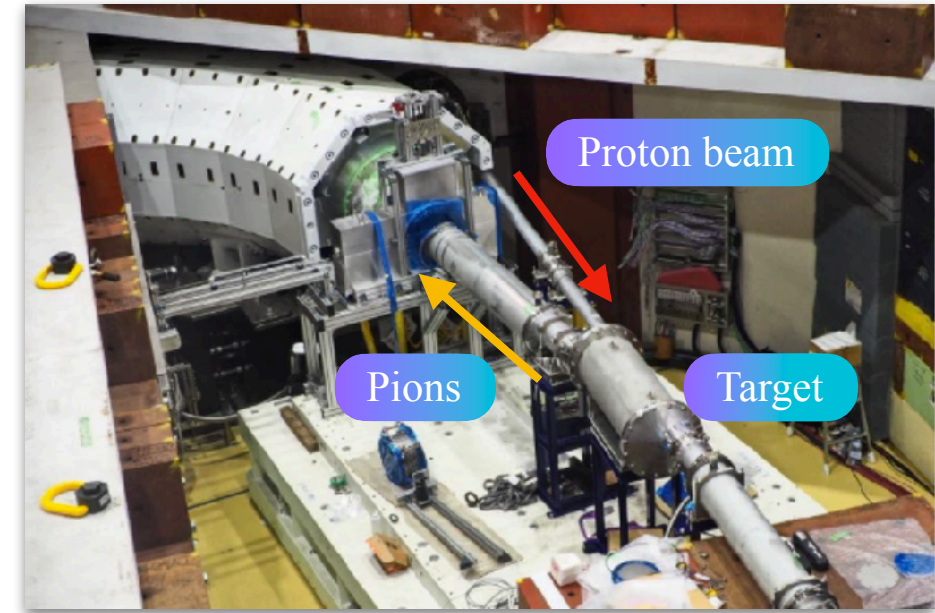
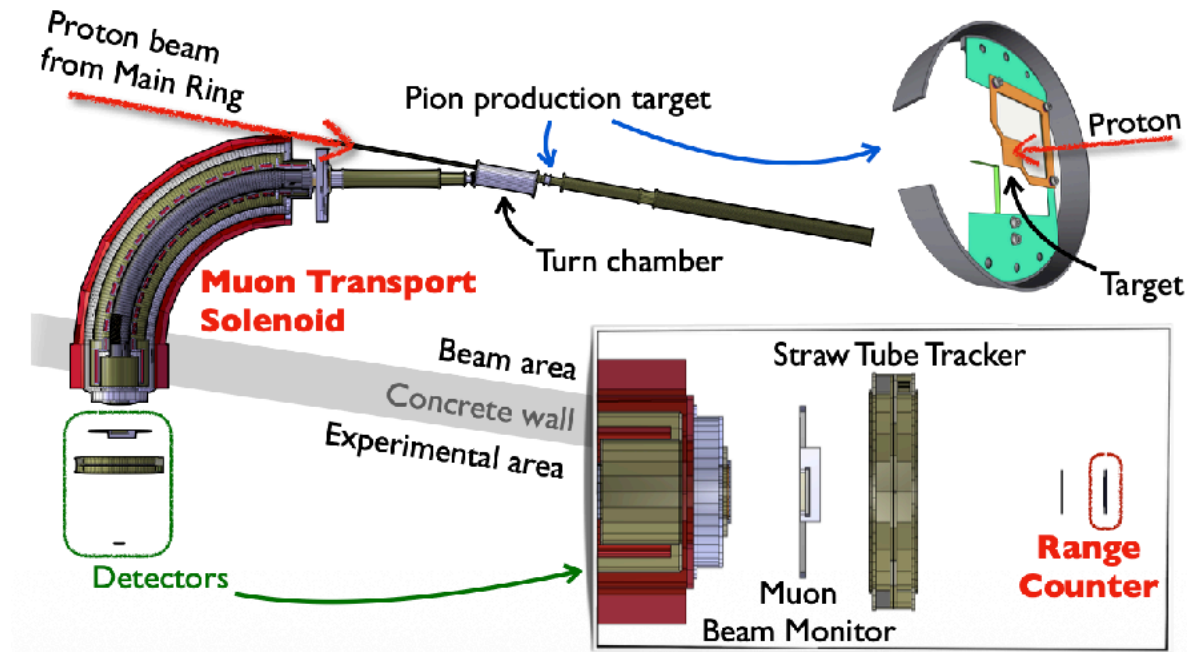
Scintillator CRV test



- ▶ ARGO-RPC
Irradiation test @ CERN performed

- ▶ iRPC
borrowed from CMS
Discussion on integration ongoing

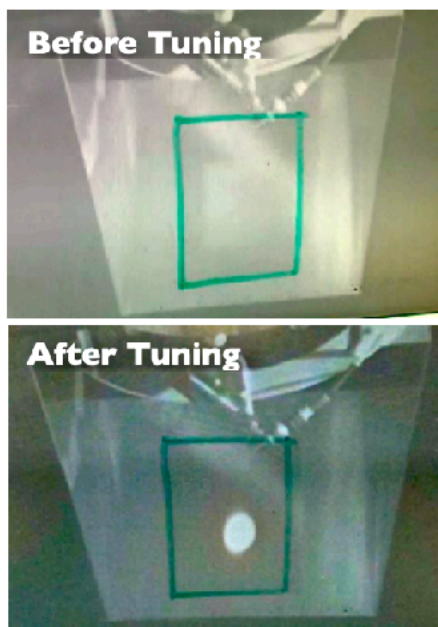
- **The first beam commissioning in 2023**
for COMET proton beamline and Transport Solenoid
w/o Capture Solenoid



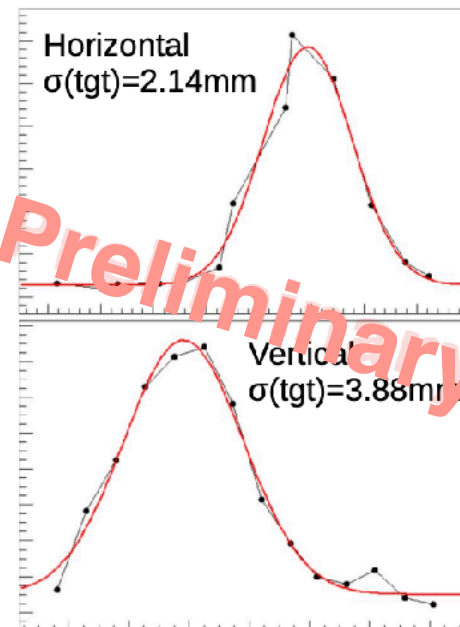
► **Proton Beam**

- 8 GeV, 260 W
- Same filling pattern and extraction mode as Phase-I
- Thin graphite pion production target

Beam spot
on a phosphor
plate



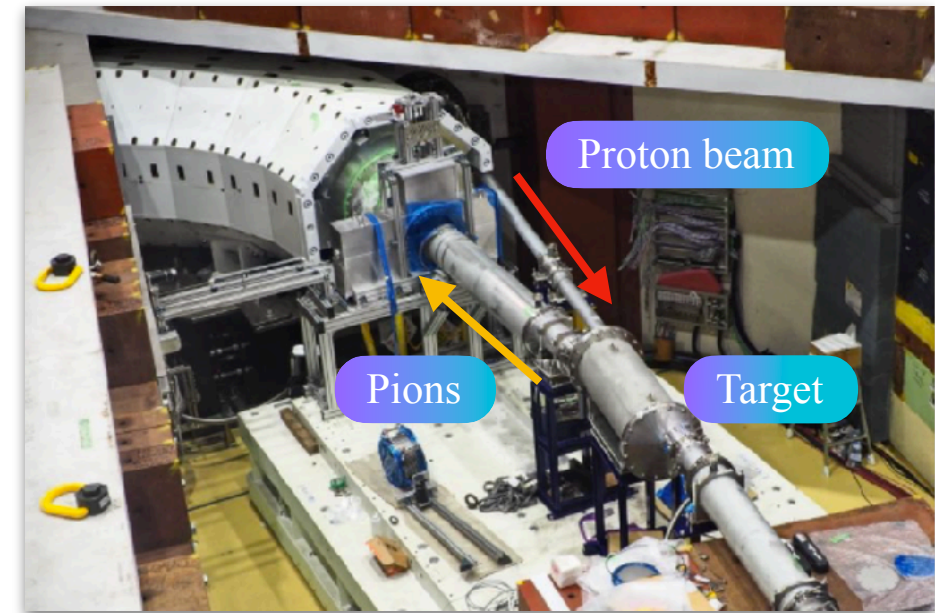
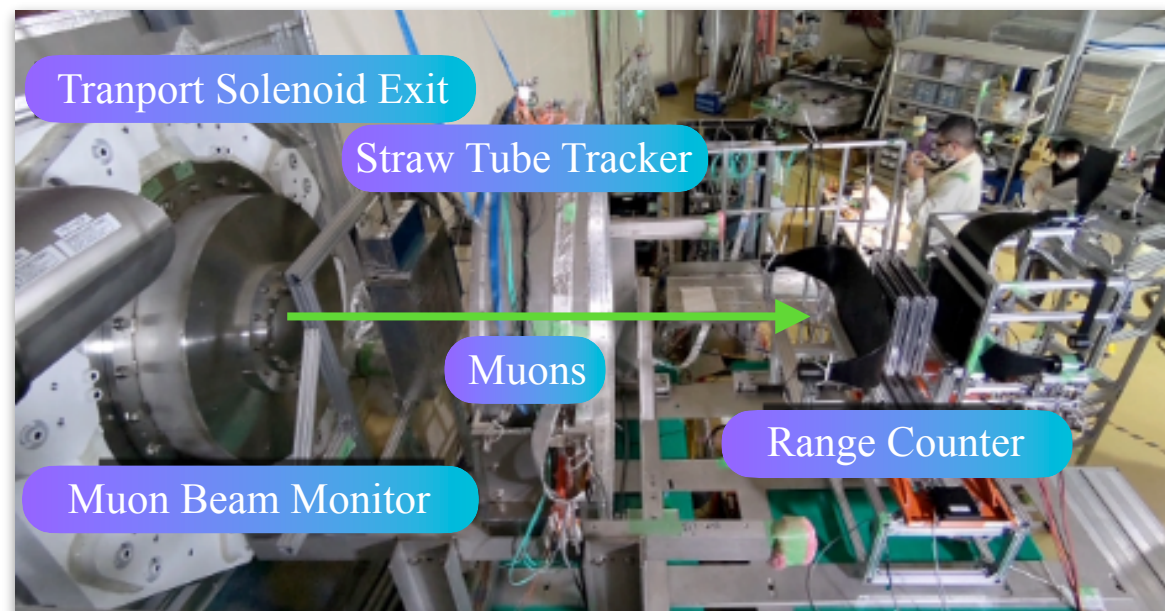
Phosphor plate response
before and after beam tuning



Measured beam dimensions

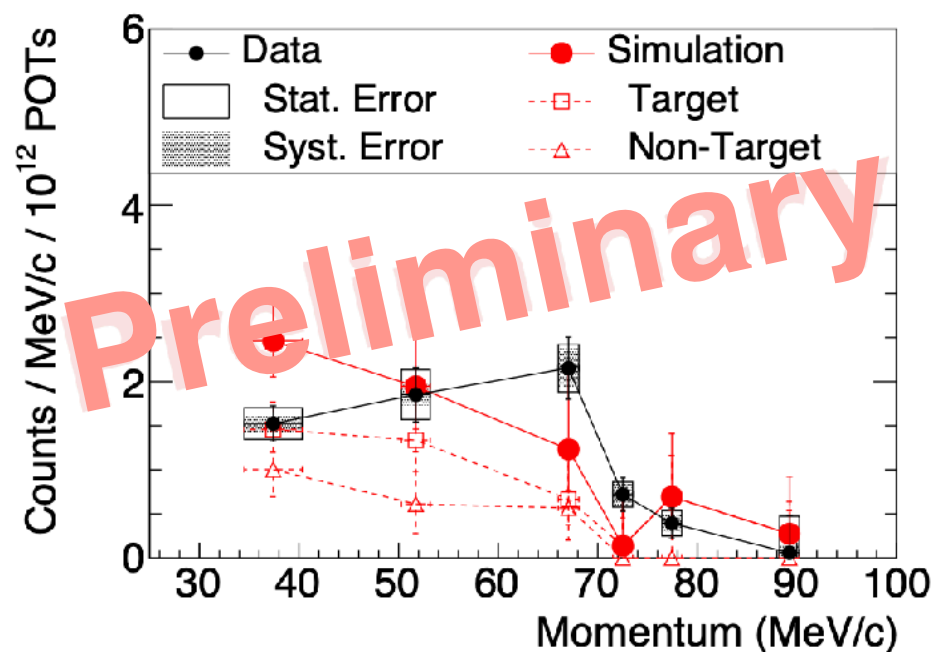
- Proton Beam was tuned and the profile was measured.

- **The first beam commissioning in 2023**
for COMET proton beamline and Transport Solenoid
w/o Capture Solenoid



- **Muon beam was successfully transported by TS.**

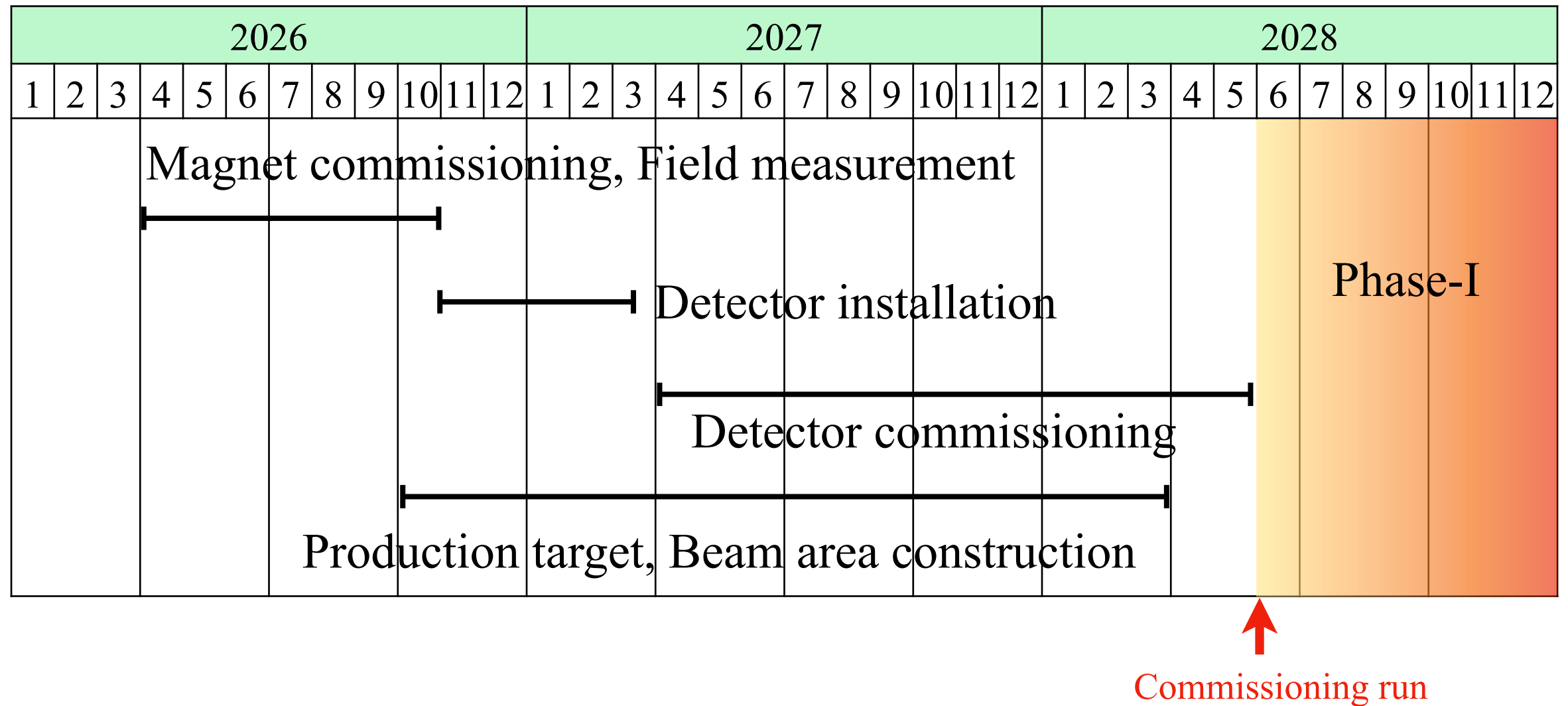
- Muon momentum ...
measured by Range Counter



- The data analysis and internal review
were completed.

The final results will be published soon.

Schedule



- We will start COMET Phase-I commissioning in 2028.
 - Low intensity beam (10% power) at the beginning
 - Beam & detector commissioning
 - Measurement of Michel edge, DIO Michel peak, DIO high-momentum tail

Summary

- ▶ COMET Experiment is searching for $\mu - e$ conversion at J-PARC.
Sensitivity : 3×10^{-15} for Phase-I , 2×10^{-17} for Phase-II
- ▶ All magnets were installed.
- ▶ Preparations for each component are steadily progressing towards Phase-I.
- ▶ The first beam commissioning (Phase- α) was carried out successfully.
- ▶ Phase-I experiment will start in 2028 with low intensity.



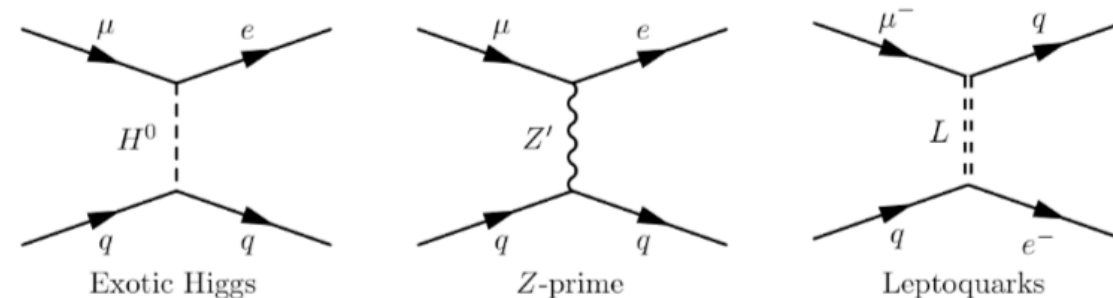
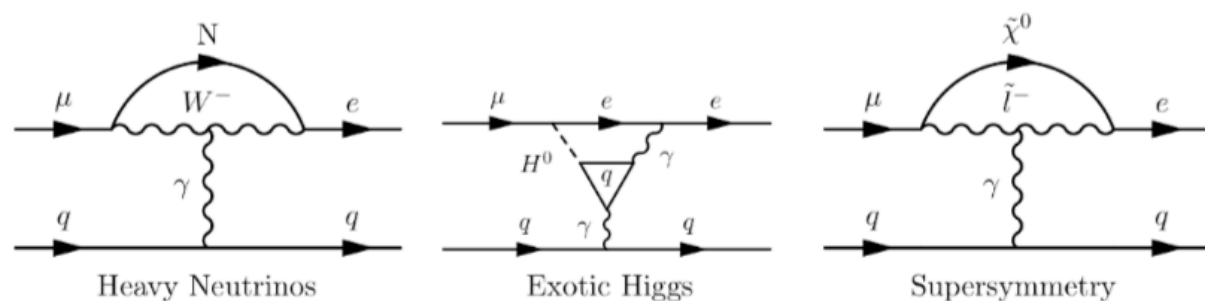
Back up

► Effective Lagrangian

$$\mathcal{L} = \frac{1}{1 + \kappa} \frac{m_\mu}{\Lambda^2} \bar{\mu}_R \sigma^{\mu\nu} e_L F_{\mu\nu} + \frac{\kappa}{1 + \kappa} \frac{1}{\Lambda^2} (\bar{\mu}_L \gamma^\mu e_L) (\bar{q}_L \gamma_\mu q_L)$$

Photonic

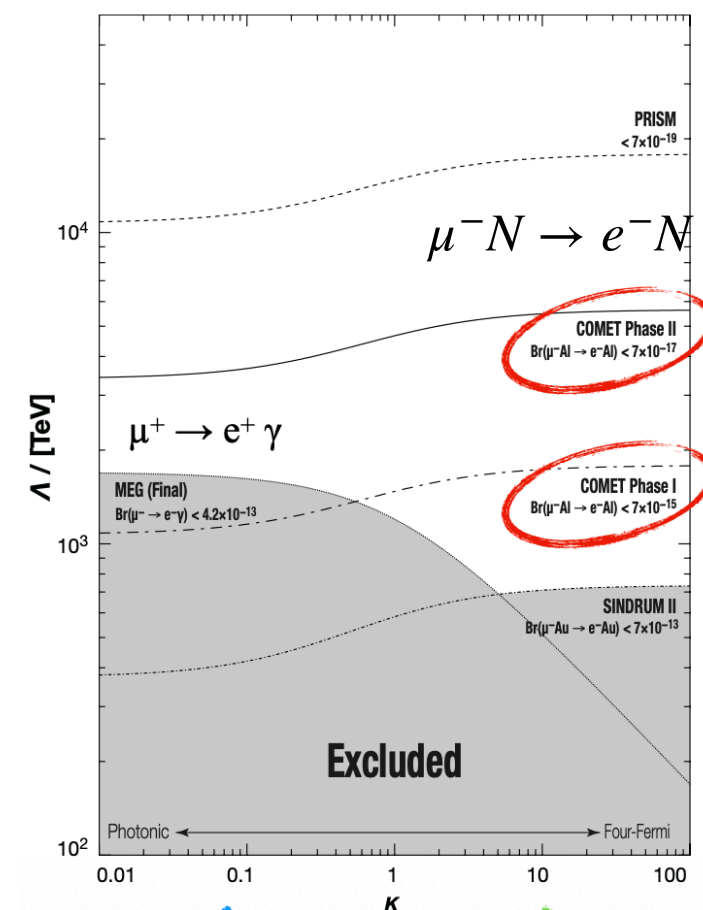
Non-Photonic



μ -e conversion in the nuclear field

= Sensitive to both Photonic
and Non-Photonic processes

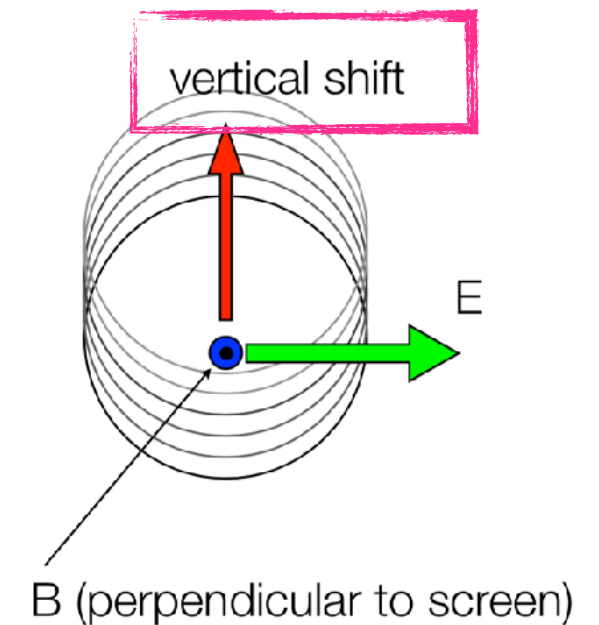
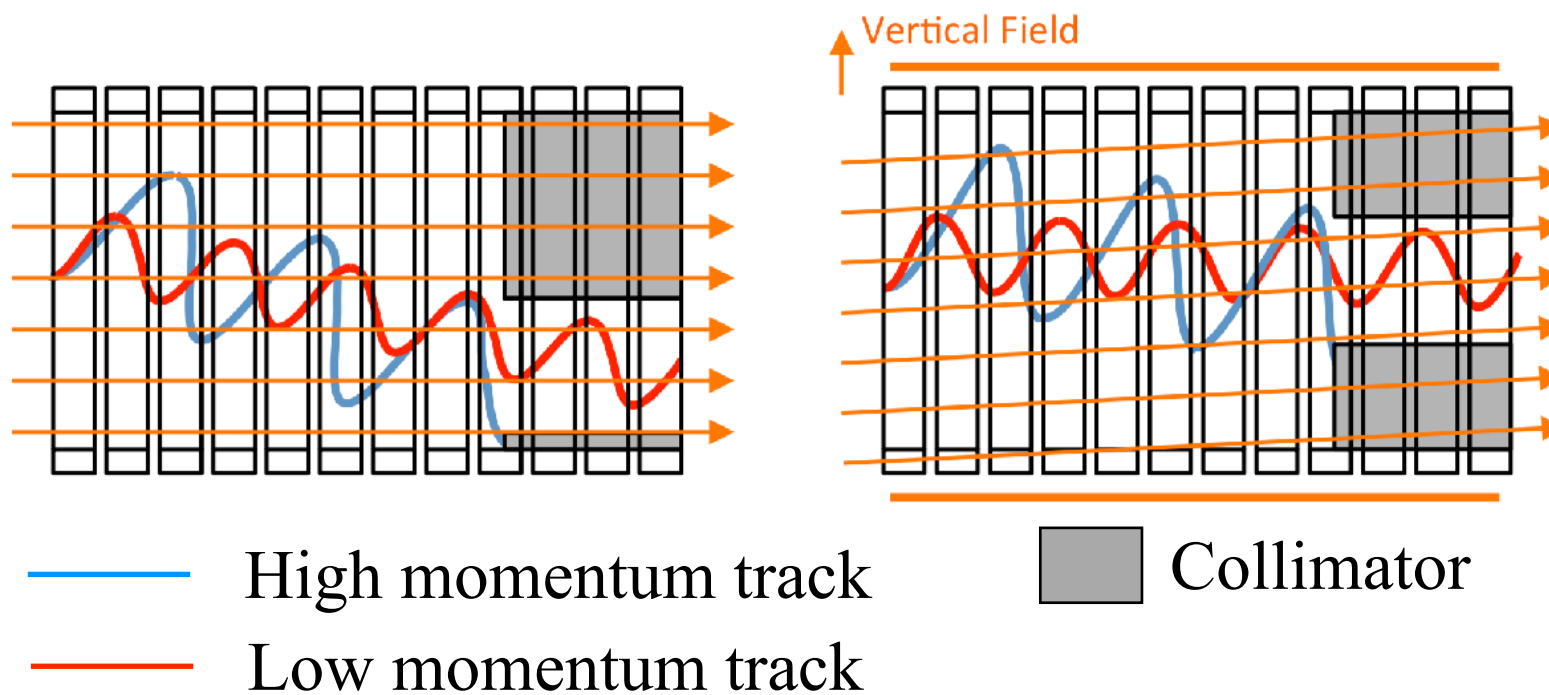
complementary to $\mu \rightarrow e\gamma$



Transport Solenoid

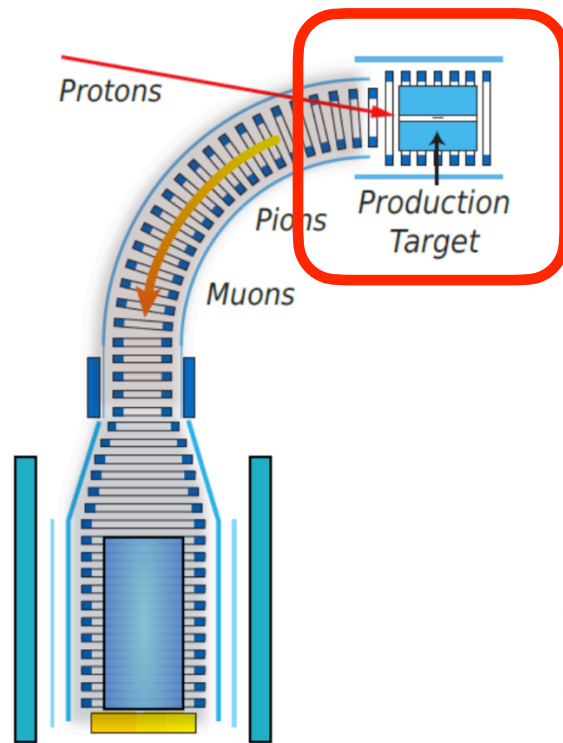
► Momentum & Charge selection in a Curved Solenoid

$$D = \frac{p}{qB} \theta_{bend} \frac{1}{2} \left(\cos \theta + \frac{1}{\cos \theta} \right)$$

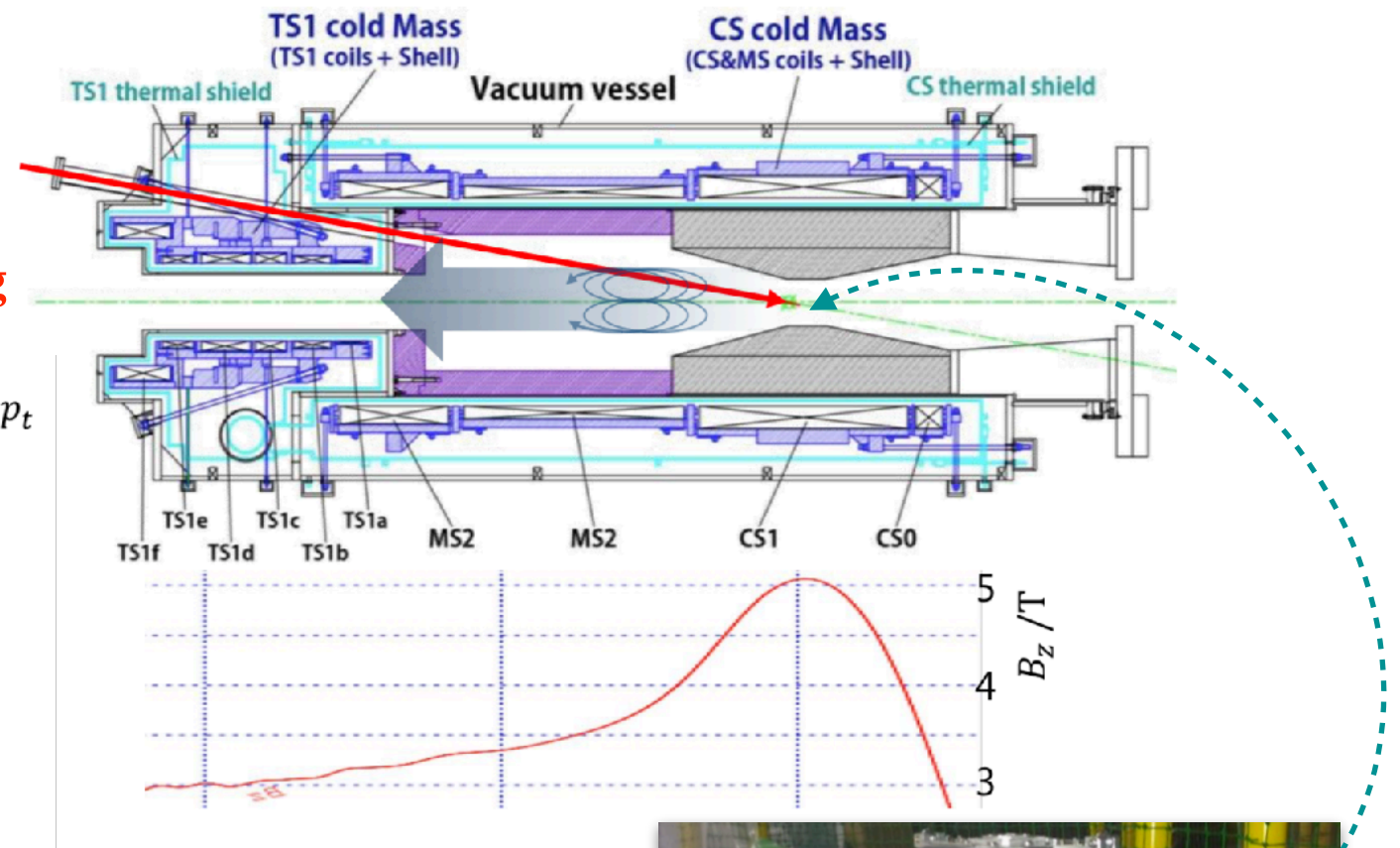
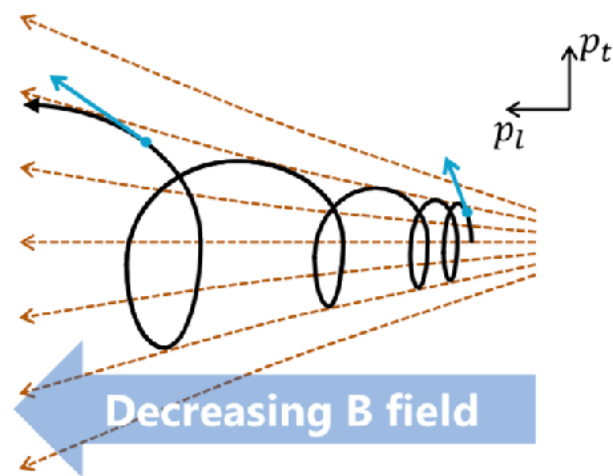


momentum selection
by applying correction field

Production Target & Pion Capture Solenoid

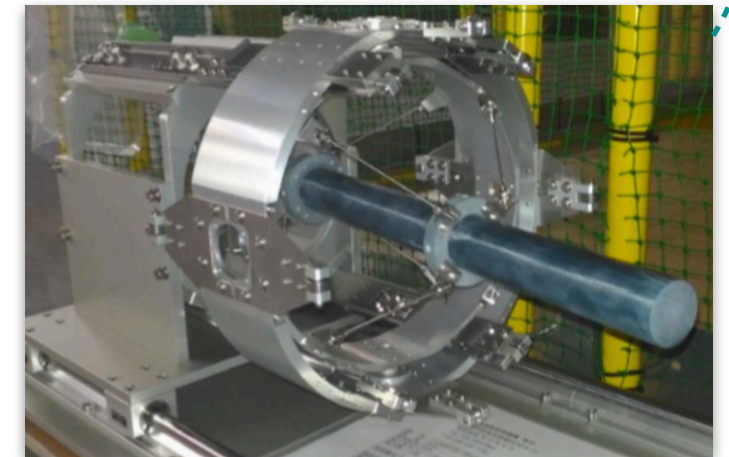


**Proton beam
from
J-PARC Main Ring**



► Target rod

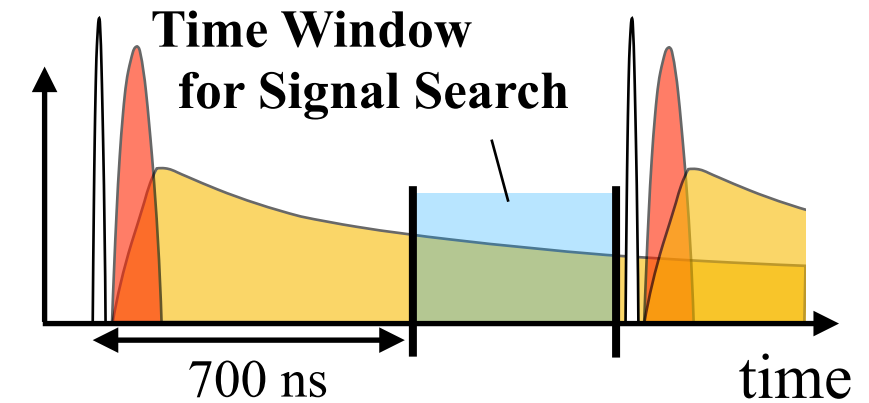
- Graphite, optimized shape with dedicated simulation study



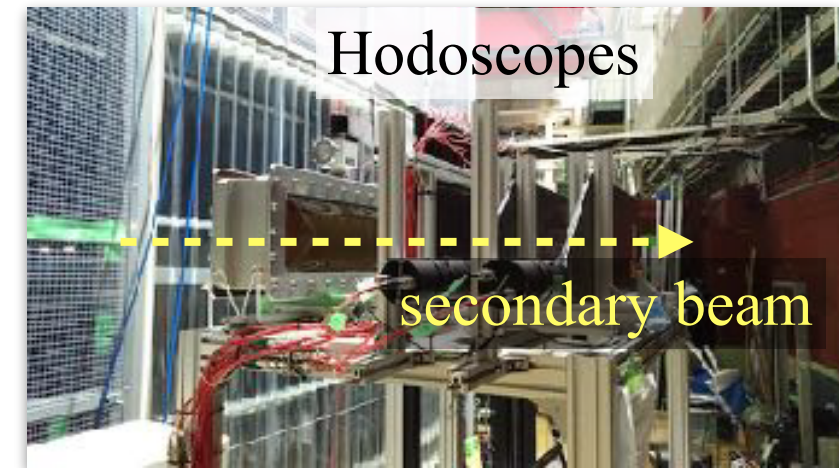
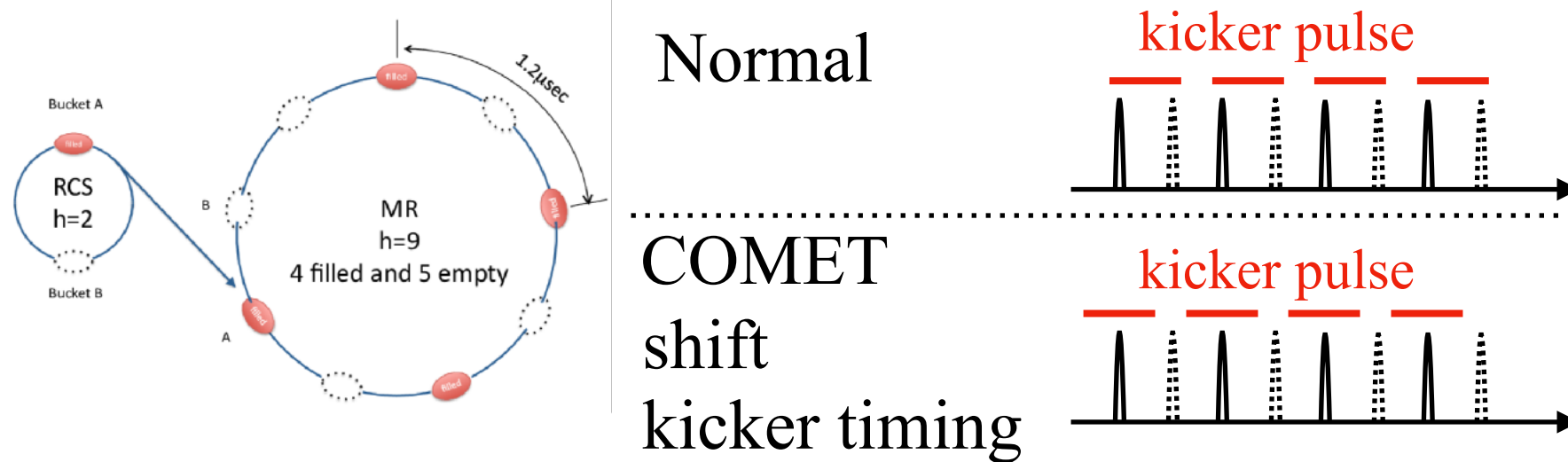
Prototype of the production target

Proton Extinction

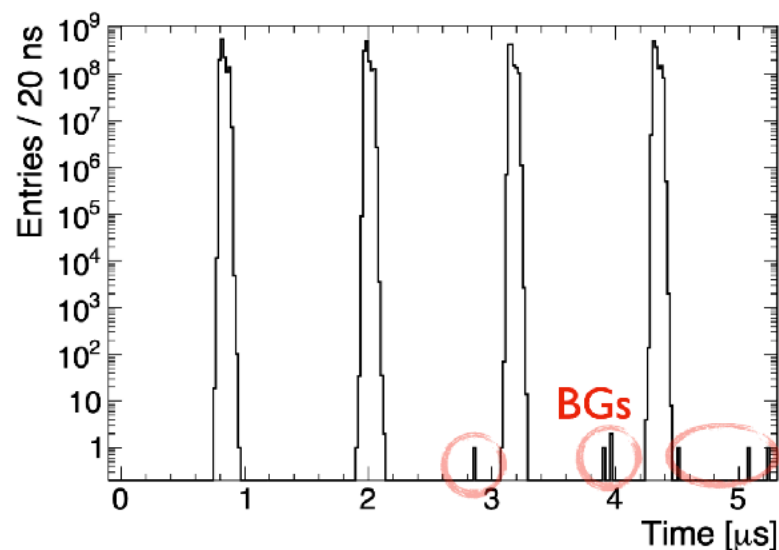
- ▶ Protons between bunches
 $\Rightarrow$ background in the time window for signal
 Extinction factor $< 10^{-10}$ required



- ▶ Accelerator operation mode for COMET

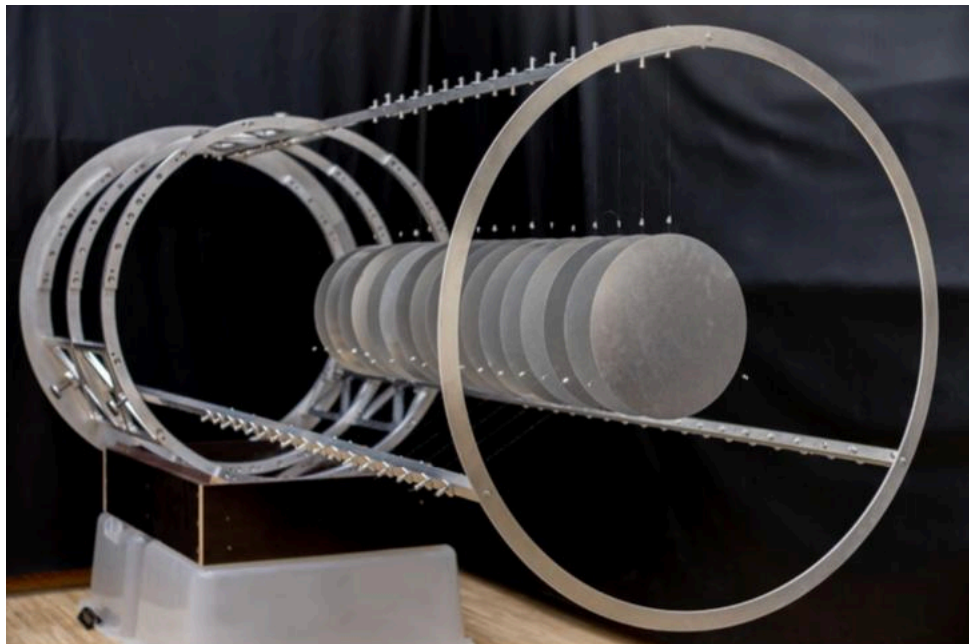


- ▶ Measurement @ Hadron Hall MR 8 GeV proton beam, Slow extraction utilizing secondary particles from the primary target in Hadron Hall



Extinction factor
 $< 1.02 \times 10^{-10}$ (90% C.L.)

Muon Stopping Target, Germanium Detector



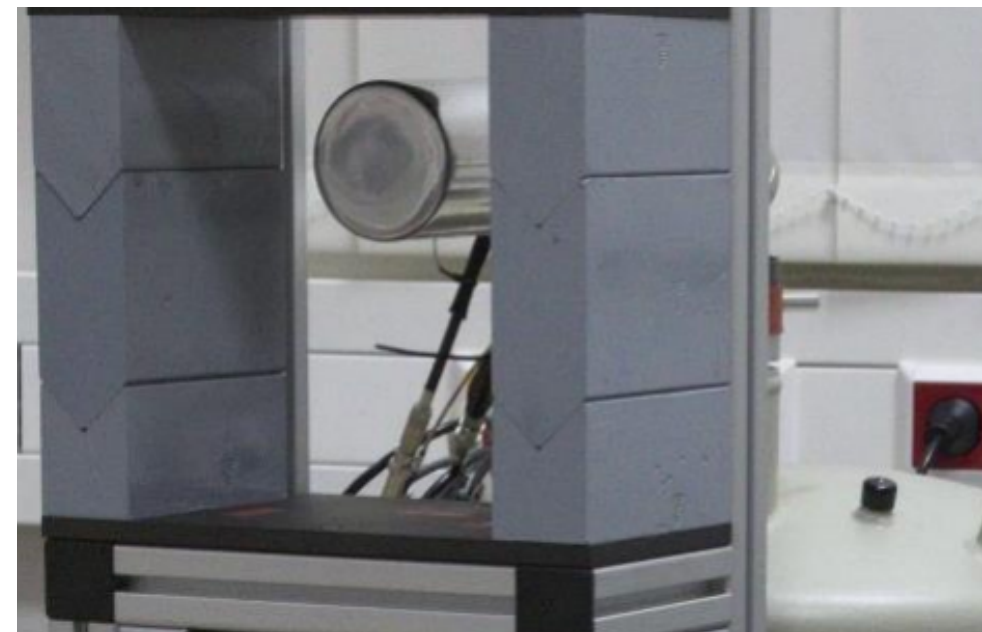
Muon Stopping Target

- 17 Al disks
- 100mm radius
- 200 μm radius

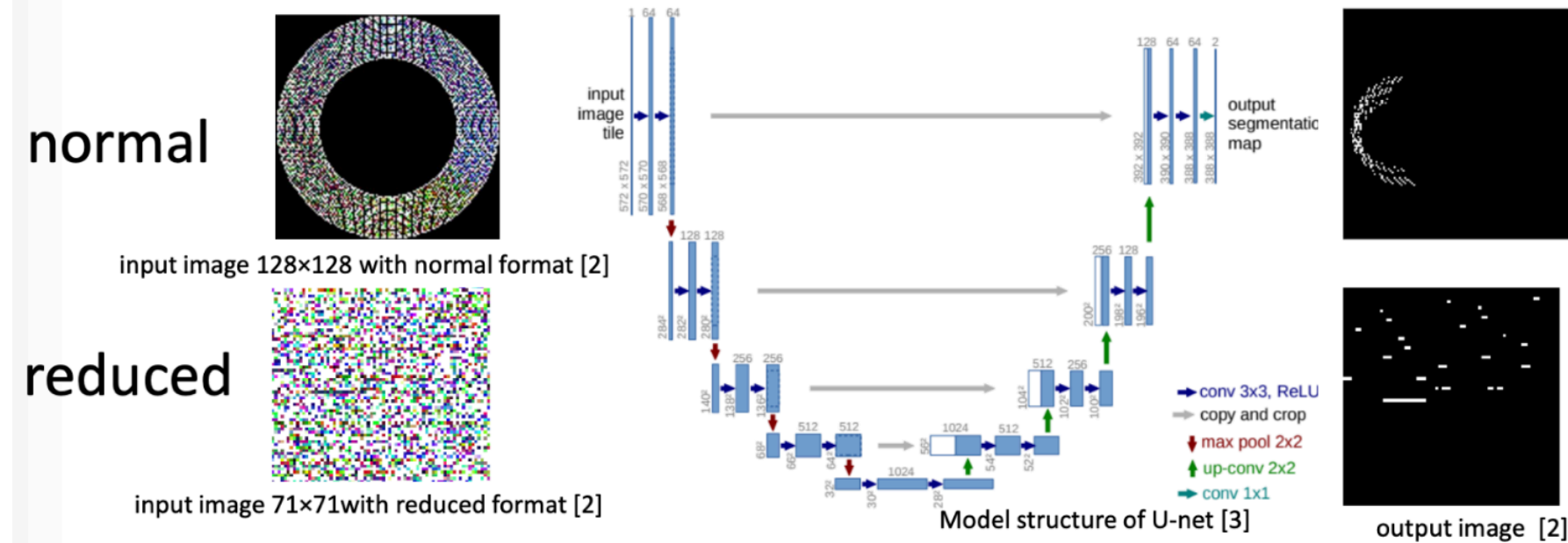
further optimization ongoing

Germanium Detector

- placed a few meter away
from the stopping target
- Normalization of the number of
stopped muons with X-ray from
the muonic atoms



U-net deep-learning reconstruction scheme



Cellular Automaton

Various methods were developed.

