THE COMET EXPERIMENT

to Search for μ-e Conversion at J-PARC

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On behalf of the COMET Collaboration

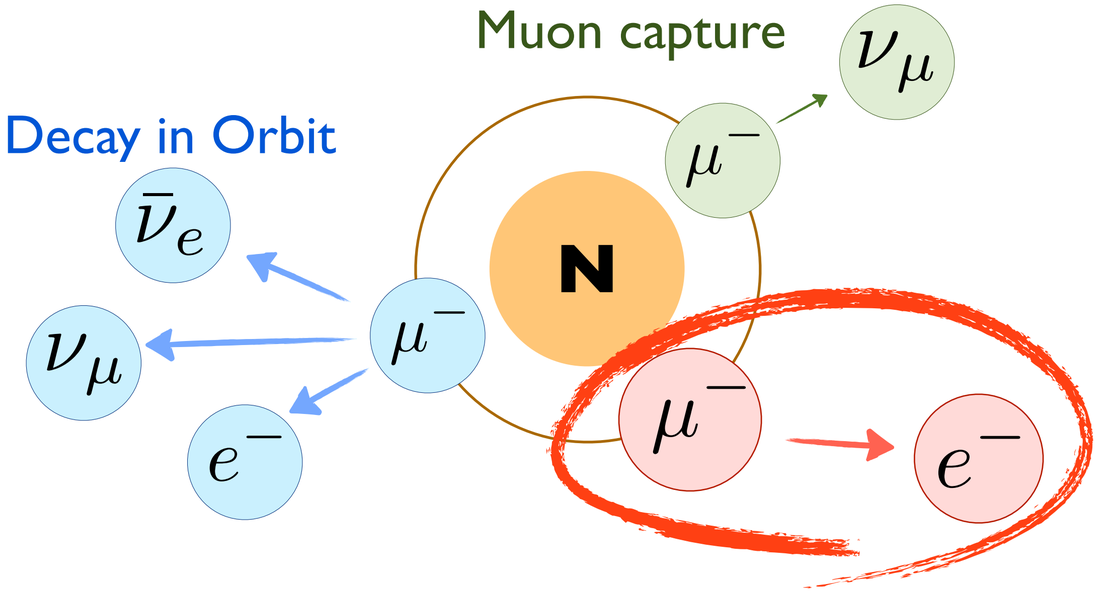
A brief status report:

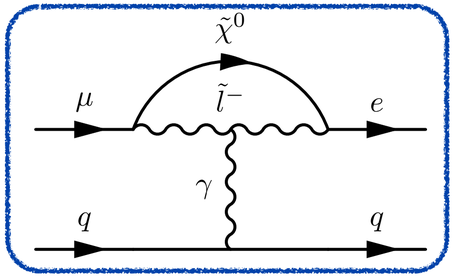
1. Introduction
2. Facility
3. Detectors
4. Closing

Muon4Future 2025
Istituto Veneto di Scienze, Lettere ed Arti, Venice, Italy
28th May 2025

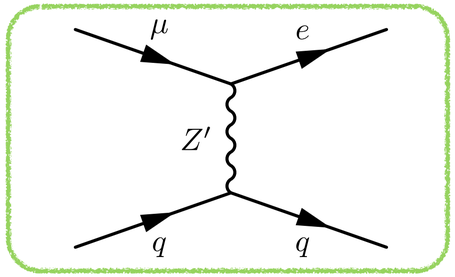
Introduction

Muon-to-Electron Conversion





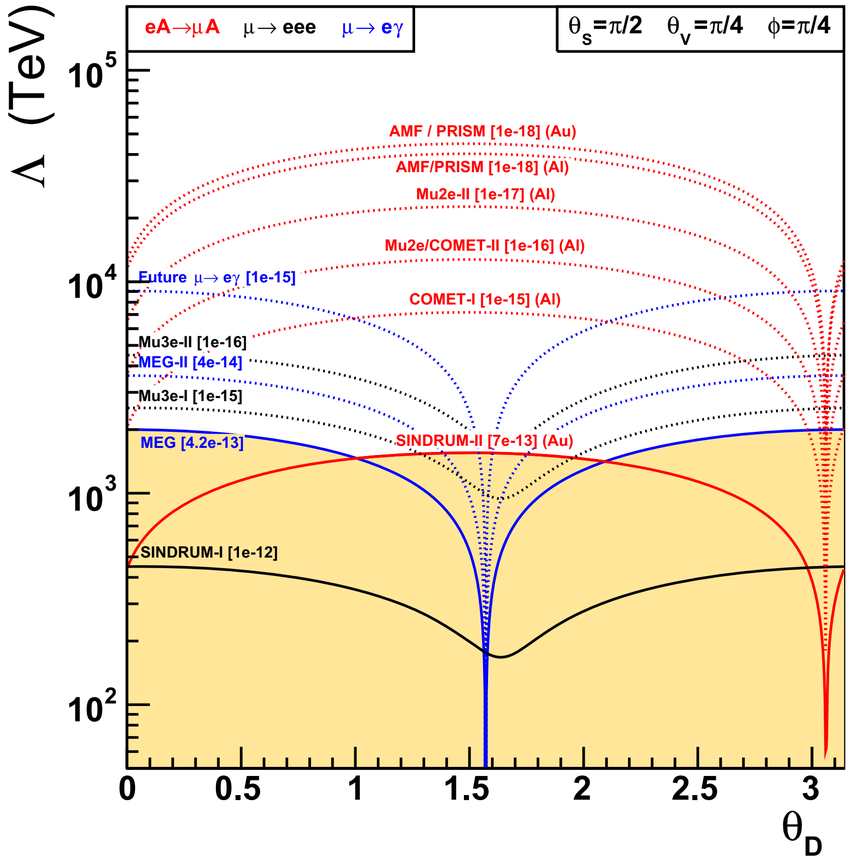
Photonic process



Four-fermion process

A charged lepton flavour-violating process

- Muon decays to single electron with no neutrino.
  - ⋆ Strongly suppressed in the SM including the neutrino oscillation.
  - ⋆ Branching ratio: BR(μN→eN) ~ BR(μ→eγ) < 10^{-54}
- Reach up to **~10^{-15}** in several Beyond SMs.
  - ⋆ Z', leptoquarks, heavy right-handed neutrinos, SUSY-GUT, etc
- Model discrimination with μ→eγ and μ→eee



Davidson, S., Eur. Phys. J. C 82, 836 (2022).

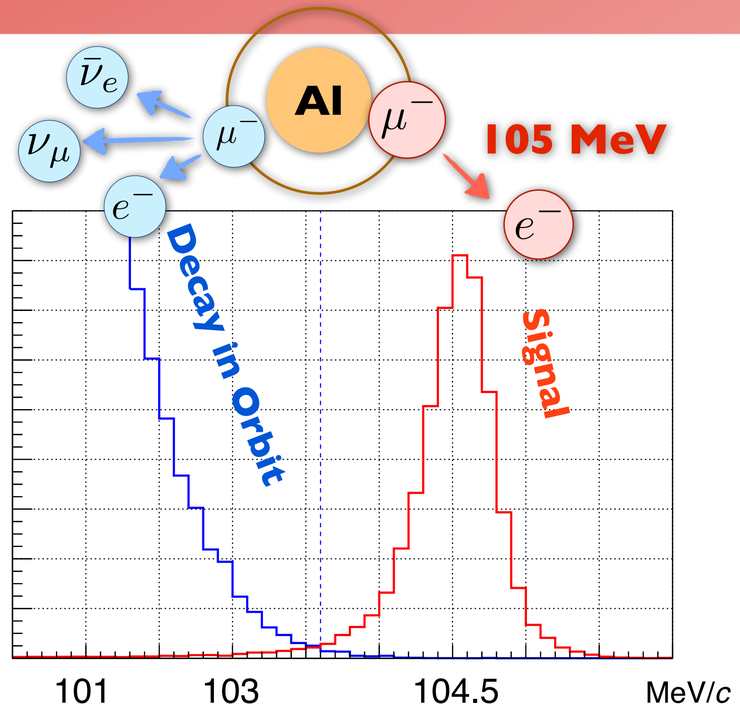
Experimental Principle

Signal & intrinsic BGs

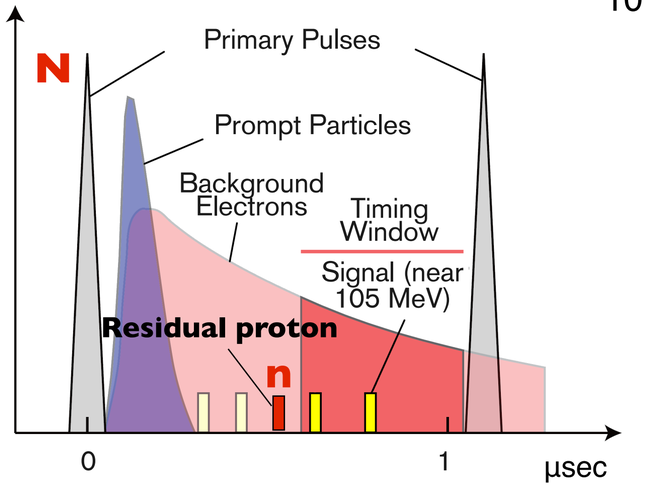
- Signal: $\mu^- + N \rightarrow e^- + N$
  - ⋆ Monochromatic energy of **105 MeV** (Al)
- Intrinsic physics backgrounds: **decay-in-orbit (DIO)**
  - ⋆ Contaminate the signal region w/ a finite resolution.
  - ⋆ **Momentum resolution < 200 keV/c** is required.

Intense bunched muon beam

- World-class intensity proton beam @ J-PARC.
  - ⋆ To gain high statistics of muons.
  - ⋆ **An effective transport line from π to μ** is essential.
  - ⋆ Backgrounds arise from the proton and its secondaries.
    - ❖ Antiproton, radiative pion capture, muon decay in flight, etc...
- Bunched beam structure
  - ⋆ **Delayed timing window** for masking the beam BGs.
  - ⋆ The fraction of residual protons between the bunches (**extinction** = n/N in the right fig.) < 10^{-10}



Electron momentum spectrum
w/ BR(μN→eN) = 10^{-15}



Bunched Beam Structure

COMET Experiment

Searching for μ-e conversion at J-PARC

- The final goal: **O(10^{-17})** sensitivity.
  - ⋆ 10, 000× improvement over the current limit.
- Dedicated facility and muon transport line being constructed.
- Two-staged plan: Phase-I and Phase-II

Phase-I

- ✓ **Sensitivity O(10^{-15})**
- ✓ **Physic measurement**
  - **by cylindrical detectors 'CyDet'**
- ✓ **Beam & BG measurement**
  - **by a tracker & calorimeter 'StrECAL'**

Phase-II

- ✓ **Sensitivity O(10^{-17})**
- ✓ **Physic measurement**
  - **by StrECAL**

Reused

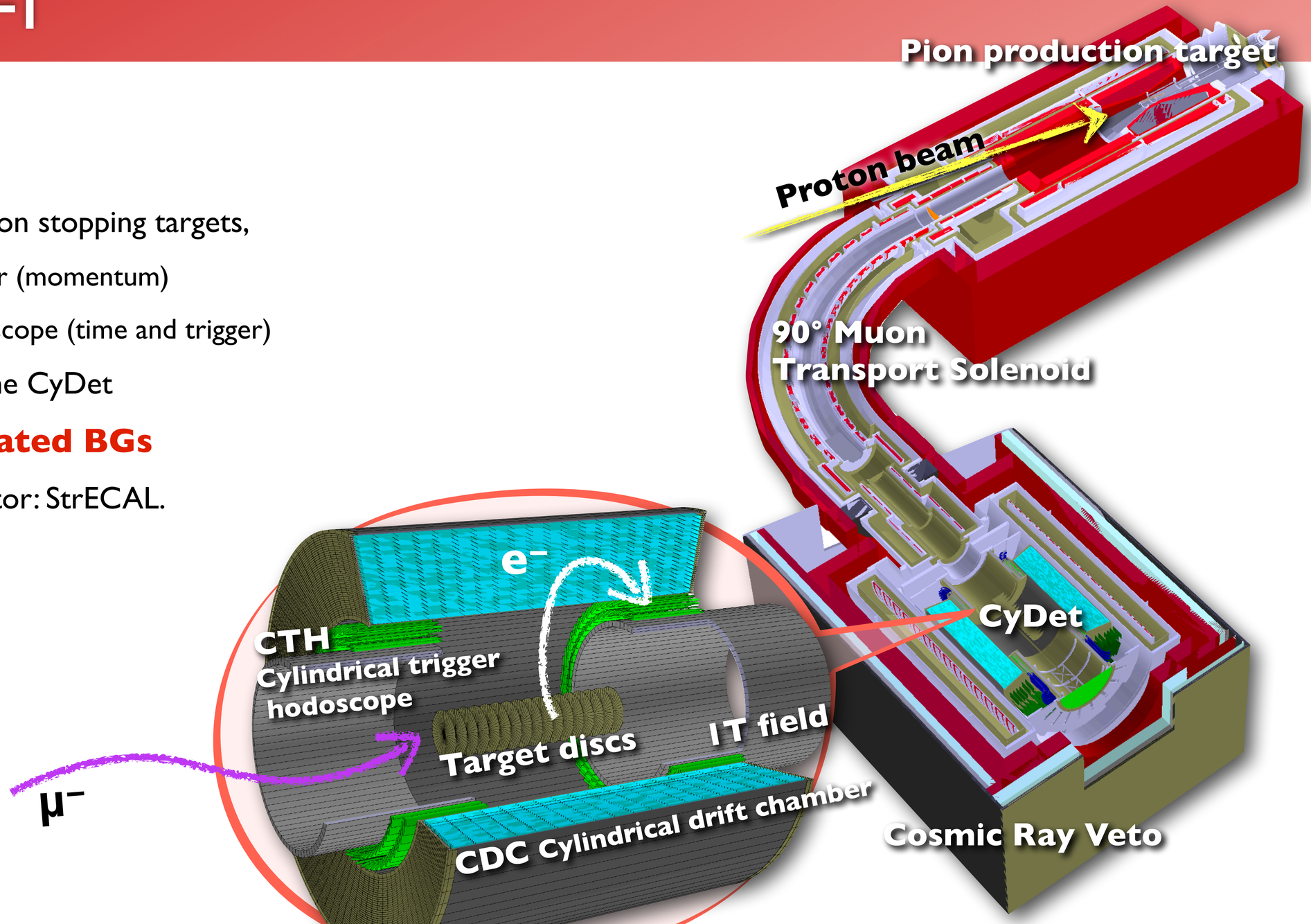
Phase-I

Sensitivity O(10^{-15})

- π→μ in the transport solenoid.
- **CyDet** combining with the muon stopping targets,
  - ⋆ **CDC**: Cylindrical Drift Chamber (momentum)
  - ⋆ **CTH**: Cylindrical Trigger Hodoscope (time and trigger)
- Cosmic Ray Veto surrounding the CyDet

Beam profile & beam-related BGs

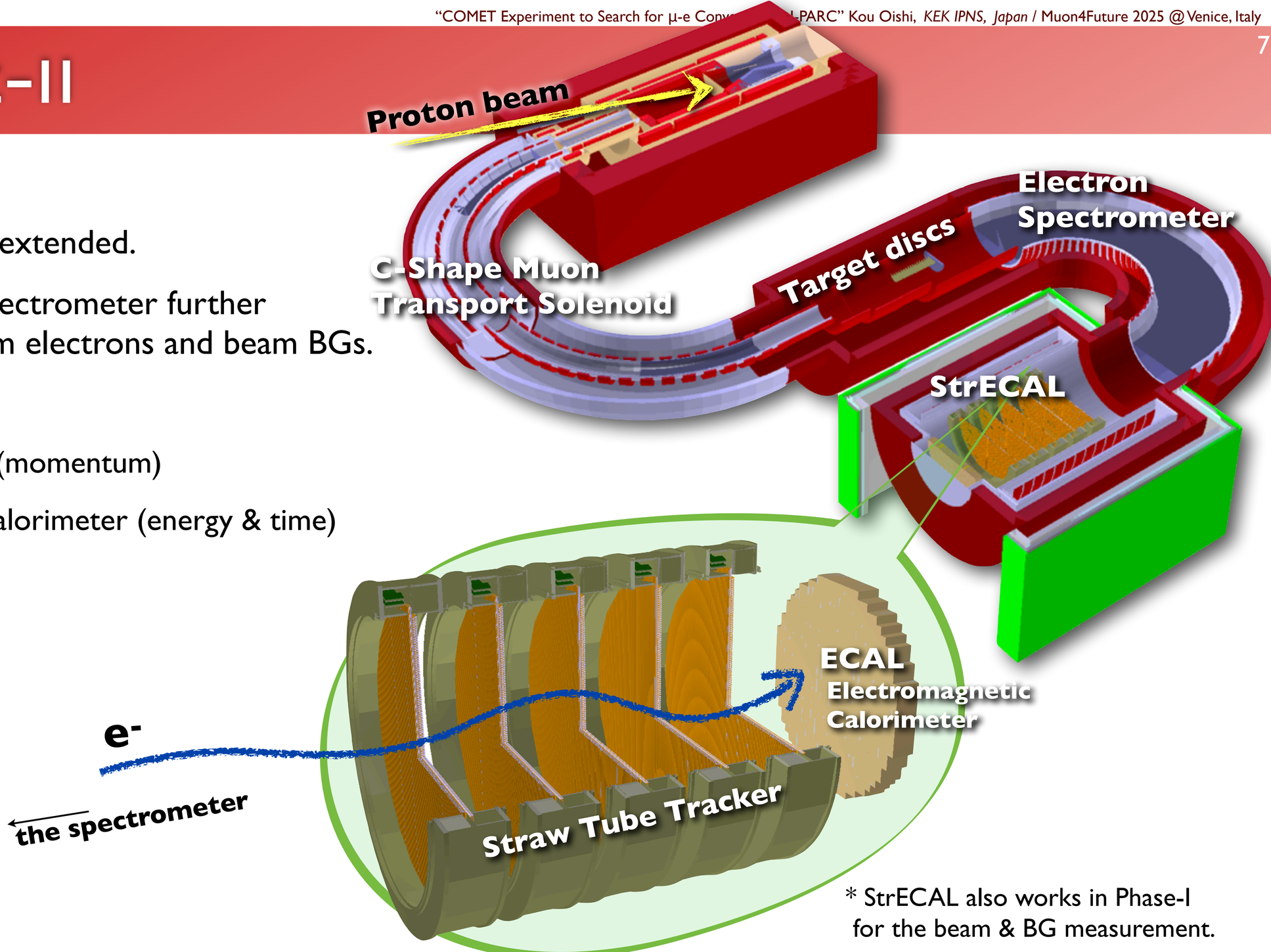
- Measured by the Phase-II detector: StrECAL.



PHASE-II

Sensitivity O(10^{-17})

- The transport line will be extended.
- The additional electron spectrometer further suppresses low momentum electrons and beam BGs.
- **StrECAL** combining
  - ⋆ **Straw Tube Tracker** (momentum)
  - ⋆ **ECAL**: Electromagnetic calorimeter (energy & time)
    - ❖ Provides trigger signals.



* StrECAL also works in Phase-I for the beam & BG measurement.

COMET Collaboration

November 2024 @ J-PARC

Our Collaborators

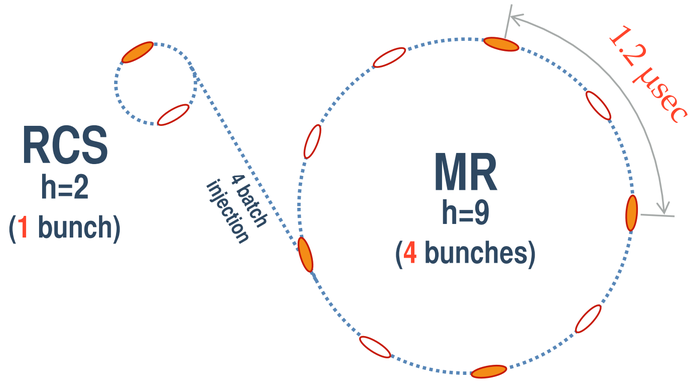
with the delivered solenoid magnet

Facility

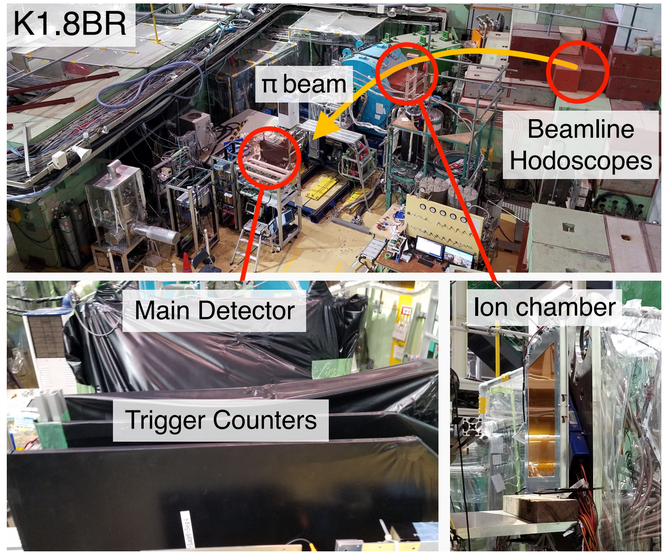
Proton Beam

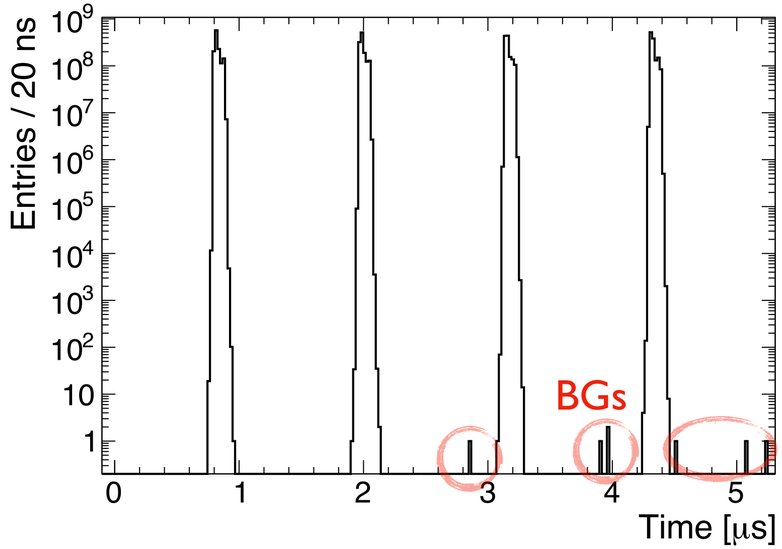
J-PARC Proton Beam for COMET

- Accelerated up to 8 GeV
  - ★ (1) To minimise antiprotons.
  - ★ (2) '**Extinction**' < 10^{-10}
    - ❖ The fraction of residual protons
- 3.2 (56) kW for Phase-I (Phase-II)
- Bunched slow extraction
  for the timing-window measurement
  - ★ 4 out of 9 buckets will be filled.



Bunched beam operation for COMET





No inter-bunch contaminations in T78 exp.

The measured extinction is < 1.0×10^{-10}

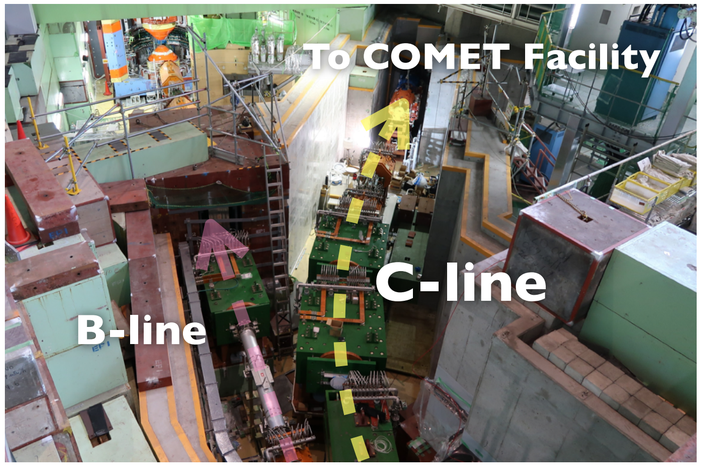
- @ K1.8BR of the Hadron Facility (T78 exp. in 2021)

K. Noguchi, et al., Proc. of Sci., 402 (2022)

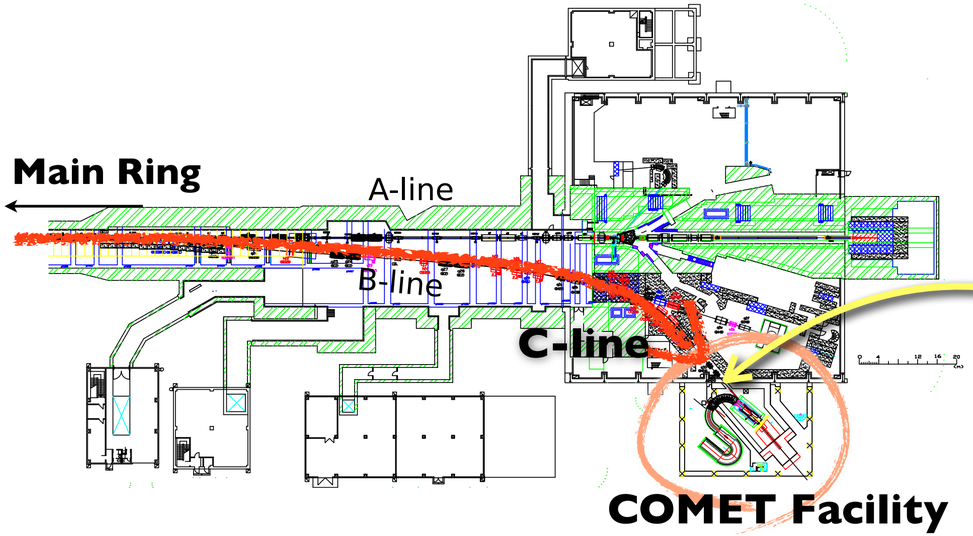
COMET Proton Beam Line

COMET Beam Line (C-Line)

- Dedicated beam line for COMET
- Proton beam monitors are being developed.
  - ⋆ Diamond, TiO_2, and SiC: High radiation tolerance
- **Commissioning of the 8 GeV slow extraction succeeded.**
  - ⋆ COMET Phase-α (later)



The C-Line branching point



Beam line for COMET (red line)

P. Chetry, et al., IEEE Sensors Journal, 23 (1) (2023), 724-732

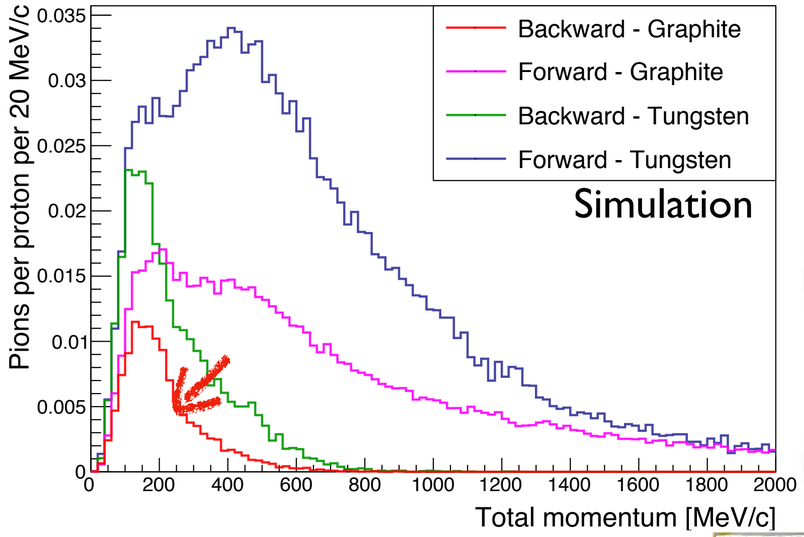
Pion Production Section

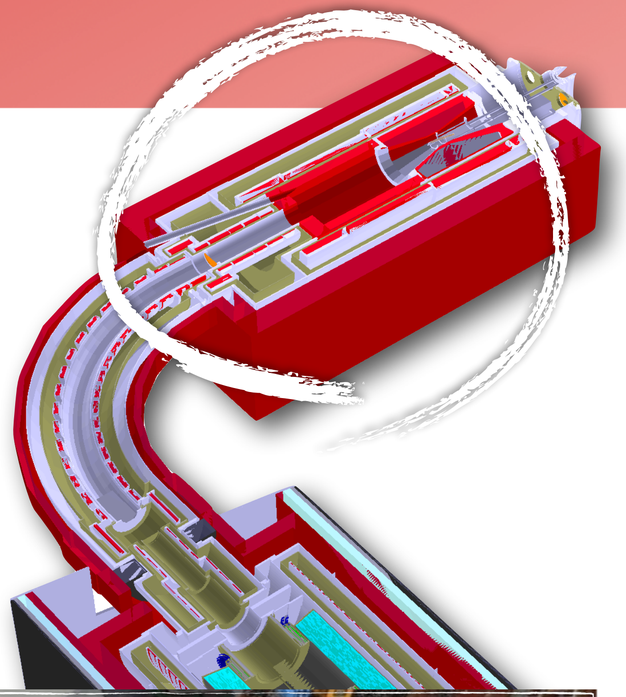
Proton Target

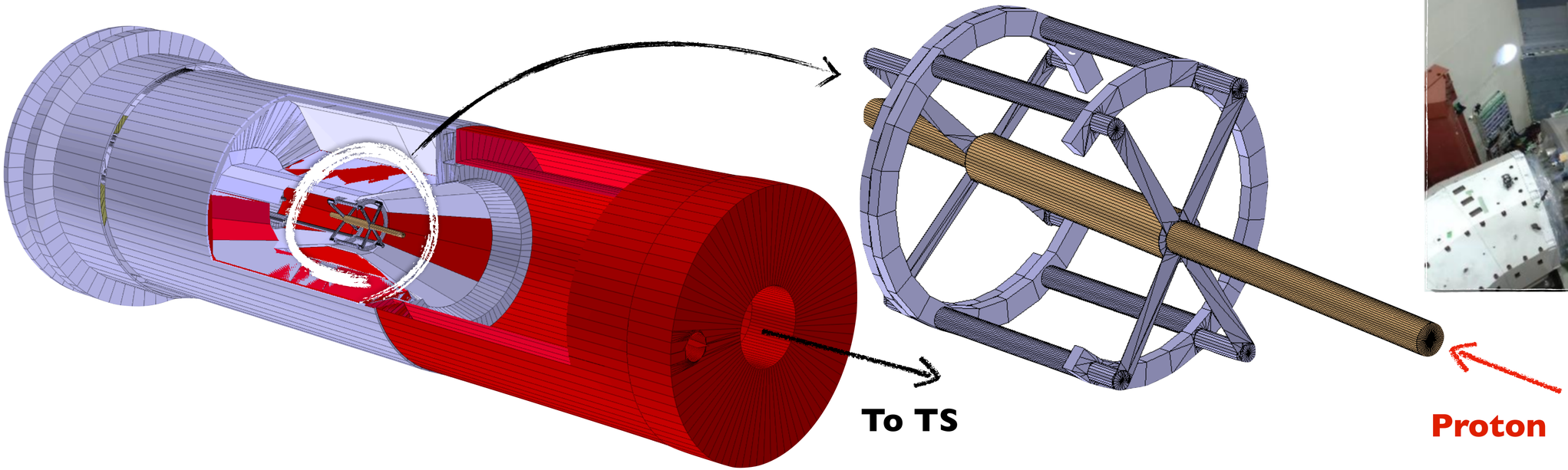
- Graphite (Tungsten) for Phase-I (II).

Pion capture solenoid

- 4.4 T superconducting magnet
- Pions extracted in the backward direction.
  - ⋆ Better exclusive collection of low-momentum pions
- Delivered and installed in 2024!



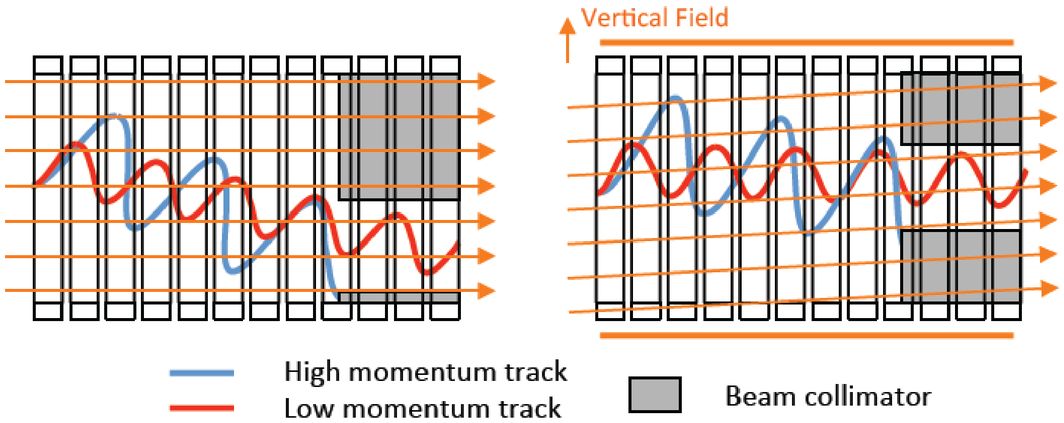




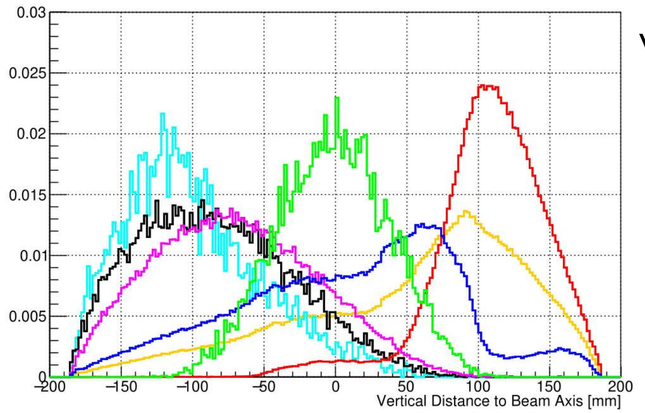
Muon Transport Solenoid

Characteristic 90°-bent solenoid

- The helical trajectories centre drifts vertically.
  - ★ Additional dipole magnetic field for compensation
  - ★ Charge and momentum selection with optimum collimators.
- The magnet and beam collimator are designed to select the target low-momentum μ^-.
  - ★ μ^- of 30–50 MeV/c tend to stop in the aluminium target.

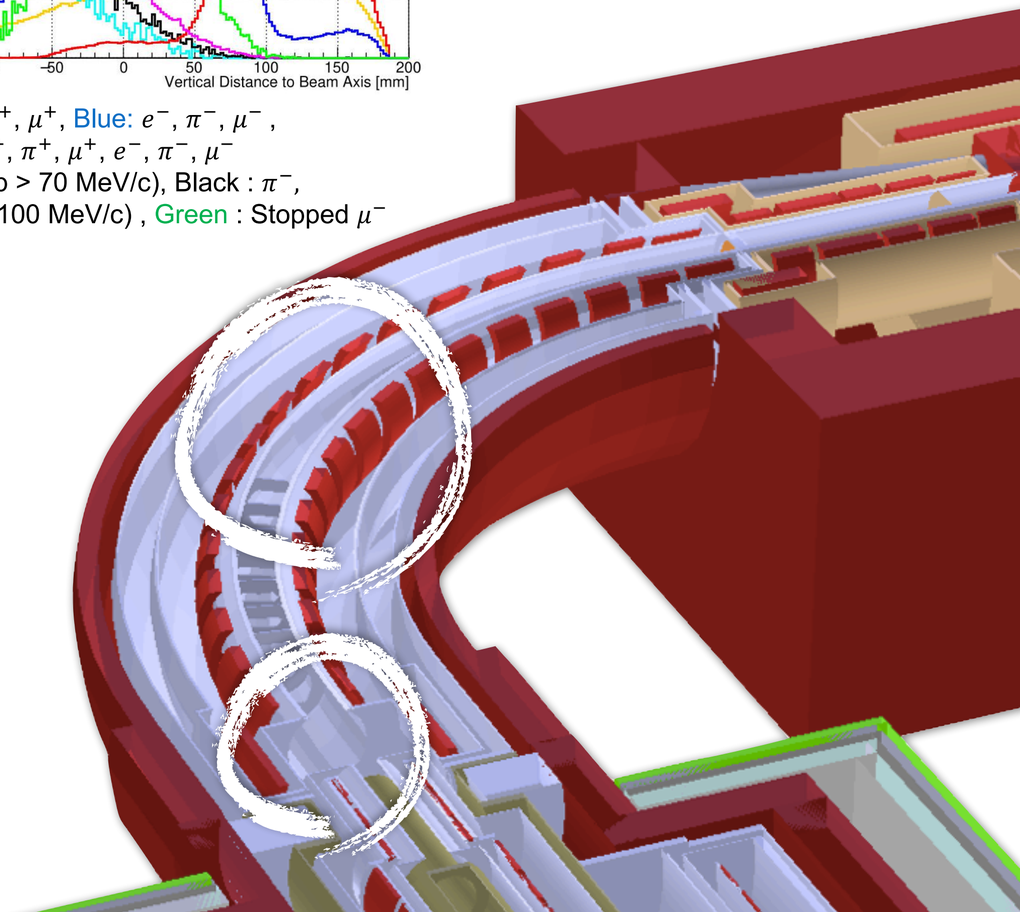


Trajectories in the transport solenoid



Vertical positions of different particle types before the collimator

Red : p, e^+, π^+, μ^+, Blue: e^-, π^-, μ^- ,
Orange : p, e^+, π^+, μ^+, e^-, π^-, μ^-
Magenta: μ^-(p > 70 MeV/c), Black : π^-,
Cyan: e^- (p> 100 MeV/c) , Green : Stopped μ^-



N. Sumi, et al., IEEE Trans. Appl. Supercond. 33 (5) (2023), 1–5
Y. Arimoto, et al., IEEE Trans. Appl. Supercond. 34 (5) (2024), 1–5

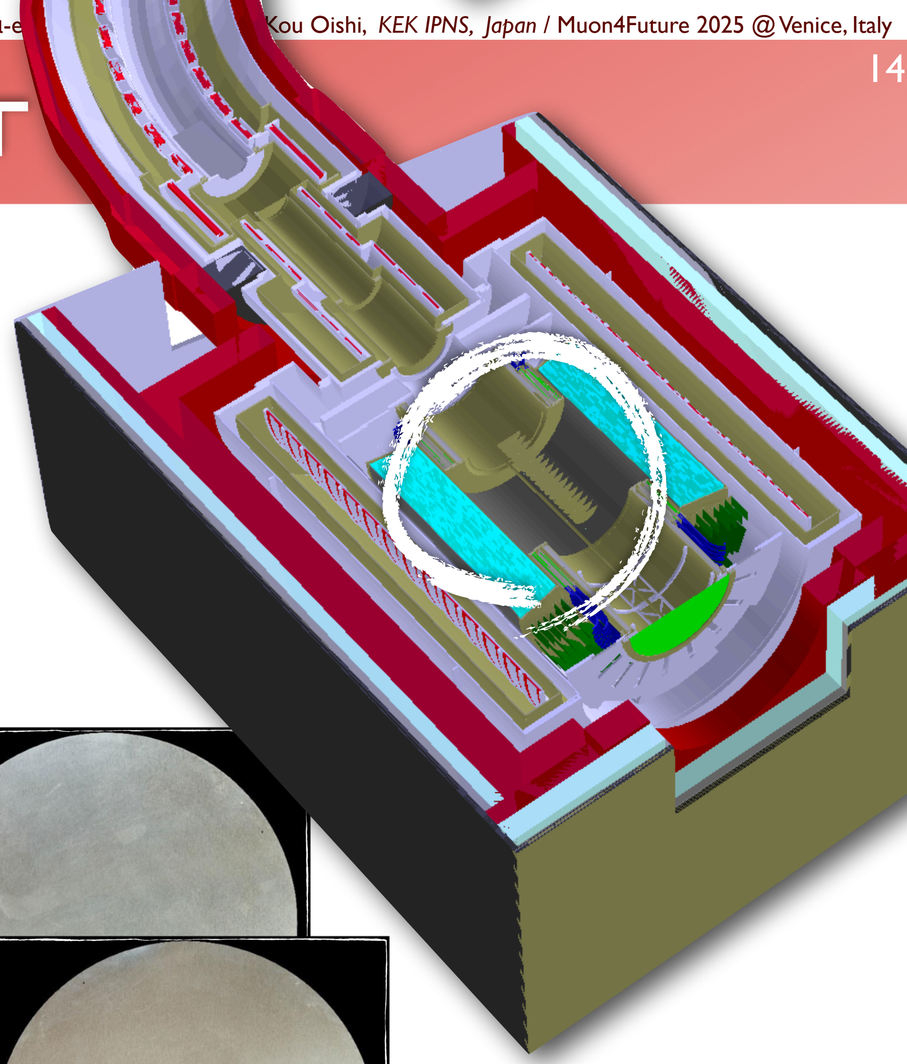
Muon Stopping Target

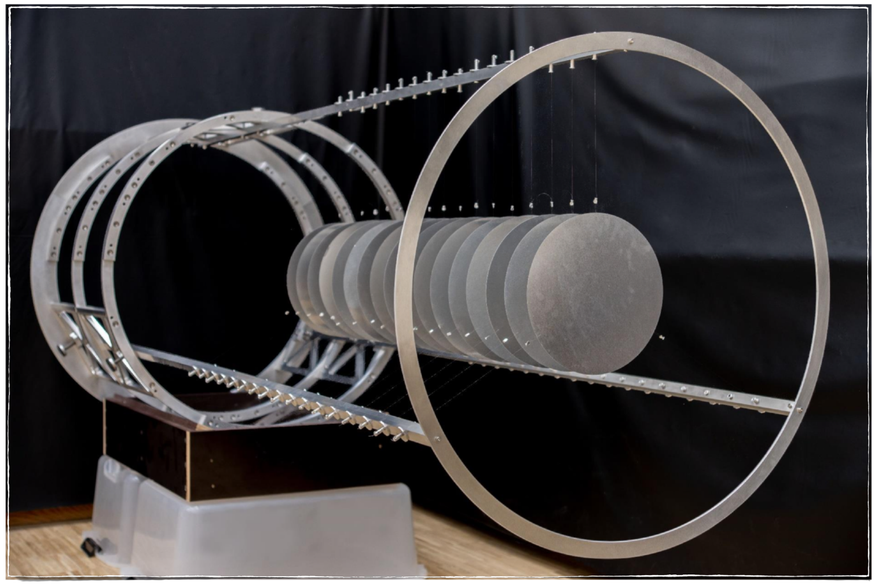
Aluminium Target

- 17 aluminium discs
  - ⋆ 10 cm radius, 200 μm thickness, and 50 mm spacing.
  - ⋆ Stability and performance tests of various aluminium alloys are ongoing.
- 4.7×10^{-4} stopping muons / proton for Phase-I

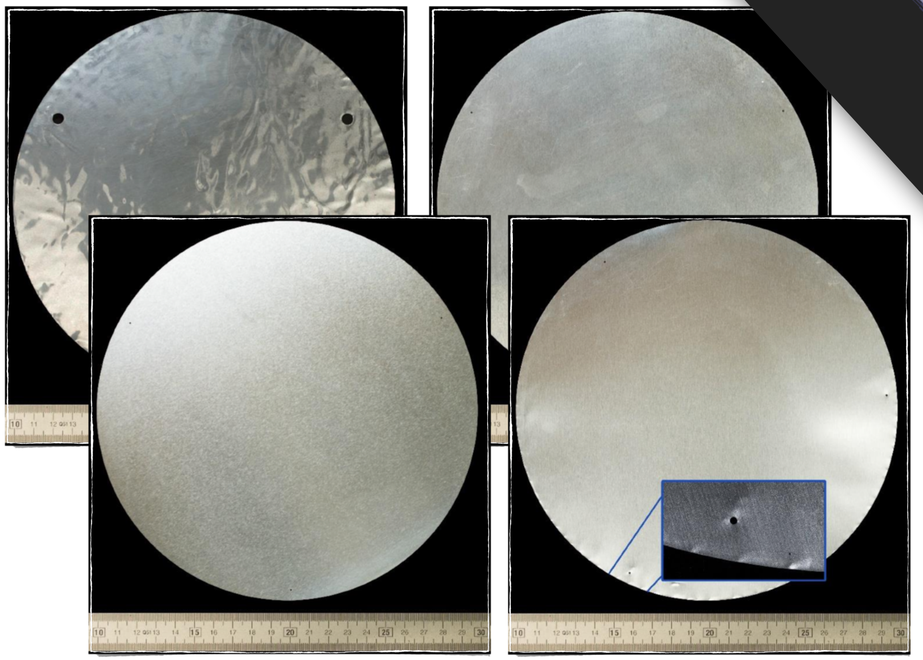
Germanium Detector

- To be placed to measure muonic X-rays for normalisation.





Prototype of the target and support

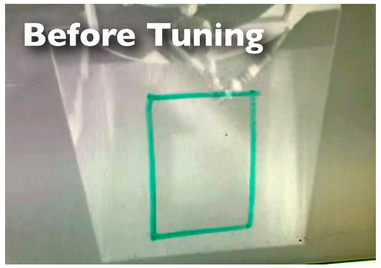


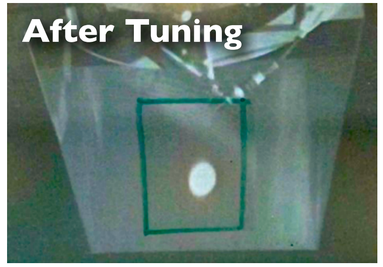
Test production with different aluminium alloys

PHASE-α

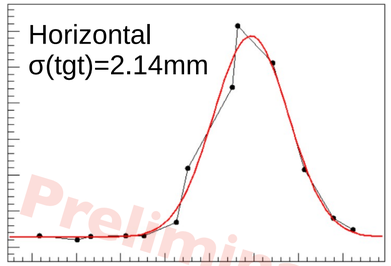
The 1st Commissioning of the COMET facility in 2023

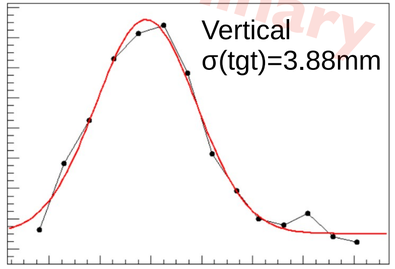
- Proton Beam
  - ⋆ Slow-extracted pulsed 8 GeV proton beam at 260 W (~1/10 of Phase-I)
  - ⋆ Beam tuning and profile measurement were well performed.
- The muon beam was successfully transported by the TS.
  - ⋆ Muon momentum spectrum was measured for the first time!



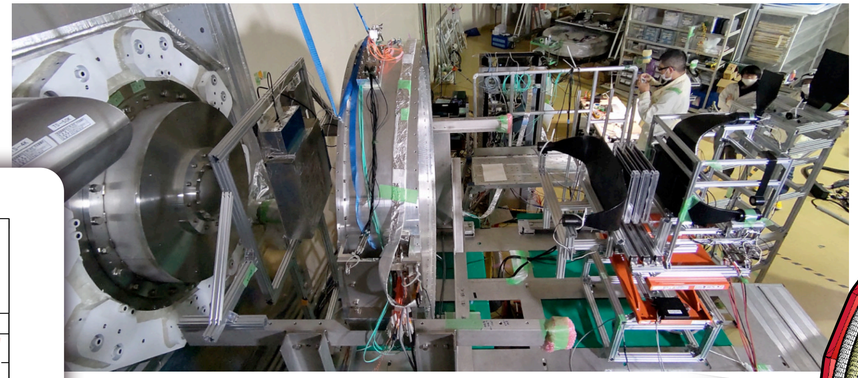


Phosphor plate response before and after beam tuning

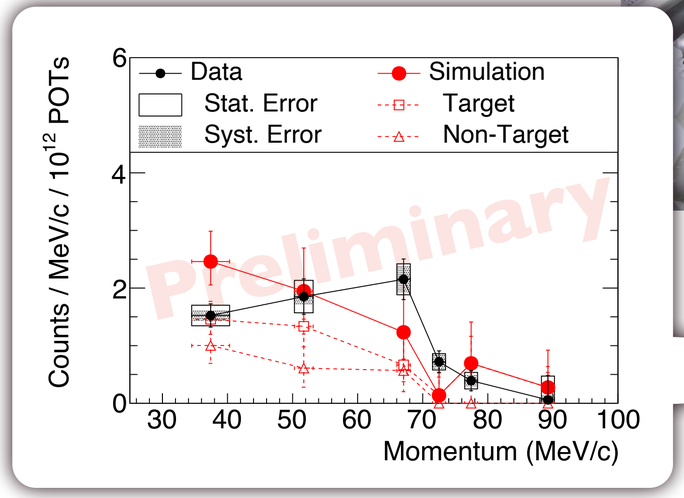


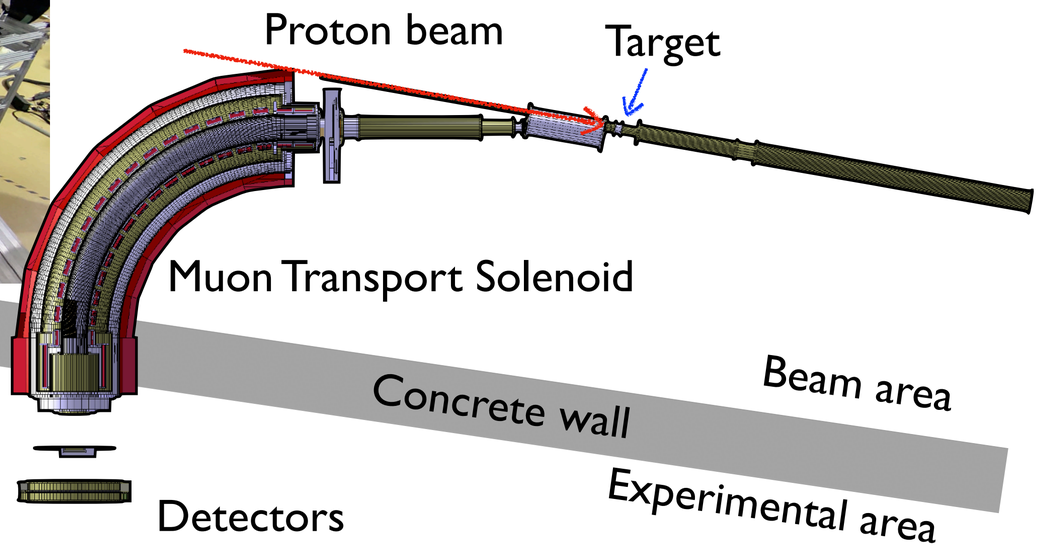


Measured beam size



Phase-α Detectors



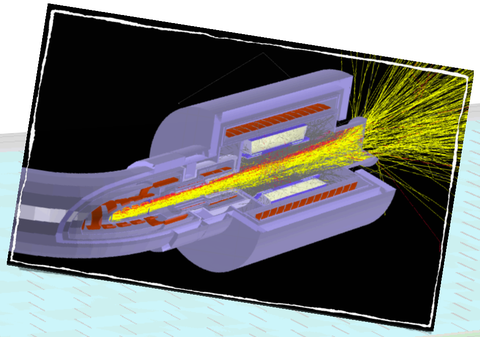


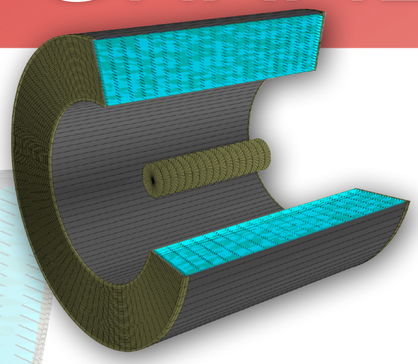
Detectors

Cylindrical Drift Chamber

Requirements

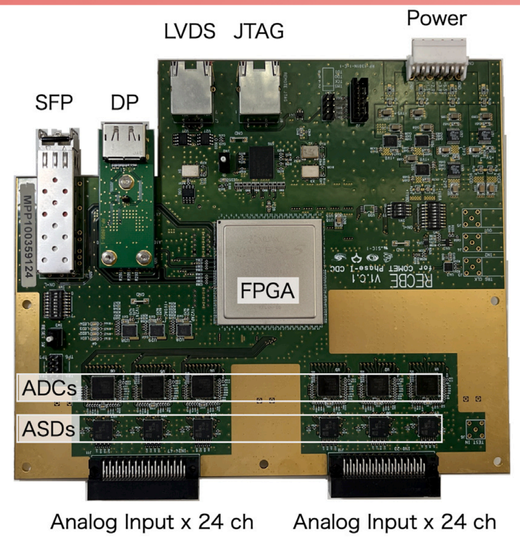
- Measure signal electrons' momentum avoiding beam particles.
- Spatial resolution < 200 μm

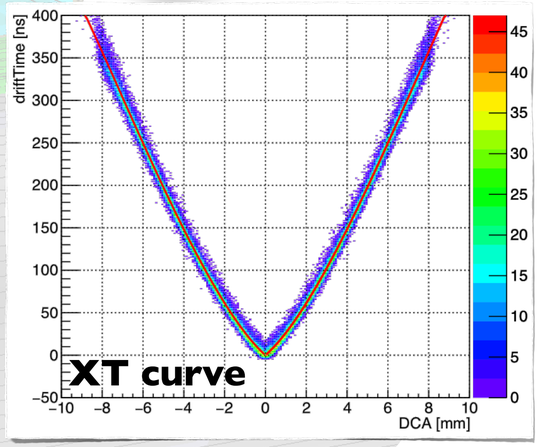




Design

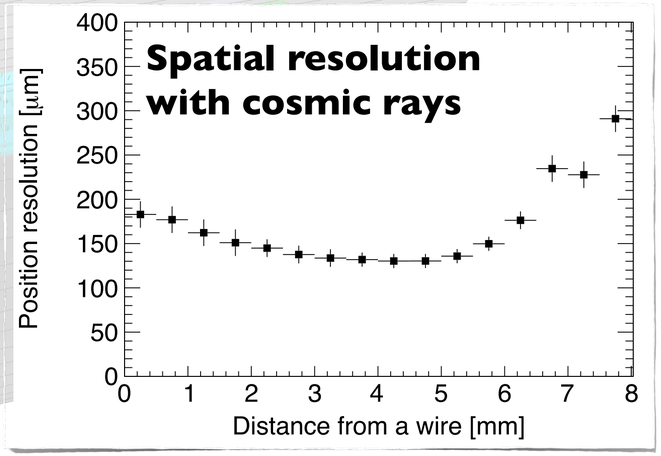
- ~5000 (Au plated W) sense wires in 20 layers
  - ⋆ Stereo wire configuration for **3-dimensional position measurement**
- Chamber radius: 496 mm to 840 mm
  - ⋆ Suppress hits by DIO electrons < 60 MeV/c
- Gas: **He : iso-C_4H_{10} = 90:10**

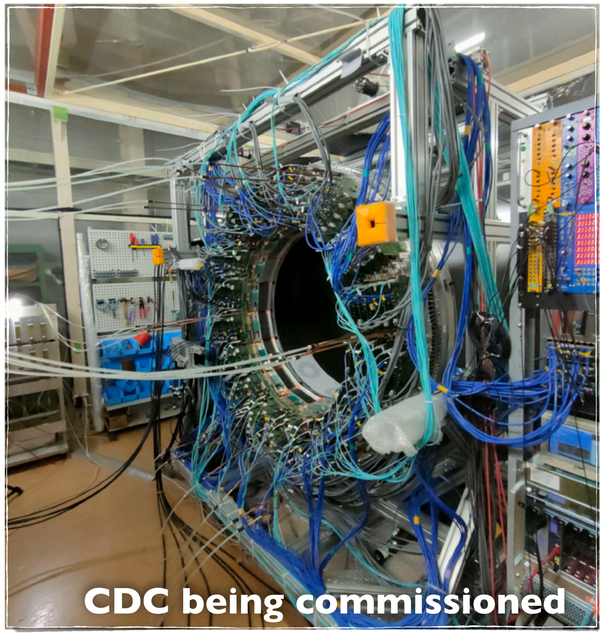




CDC Construction completed in 2016

- Commissioning ongoing
  - ⋆ Performance evaluation with cosmic rays
  - ⋆ Chain test of the front- and back-ends electronics including the trigger system.





A. Sato, et al., Nucl. Instrum. Methods Phys. Res. A, 1069 (2024), 169926

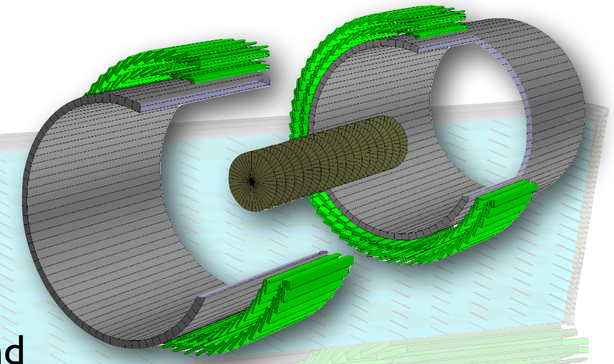
Cylindrical Trigger Hodoscope

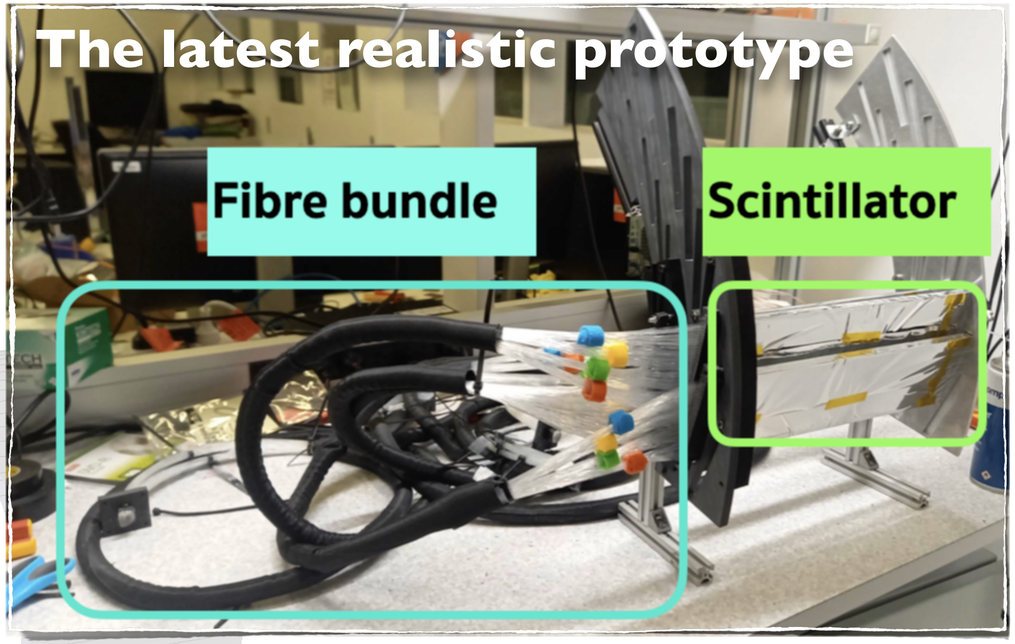
Requirements

- (Primary) trigger decision
- T_0 measurement for tracking

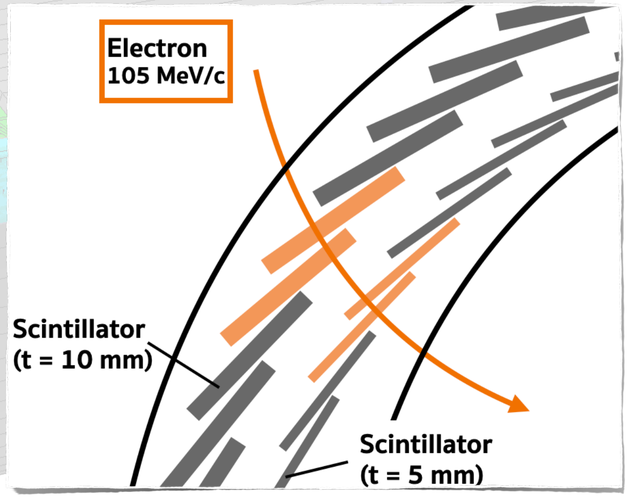
Design

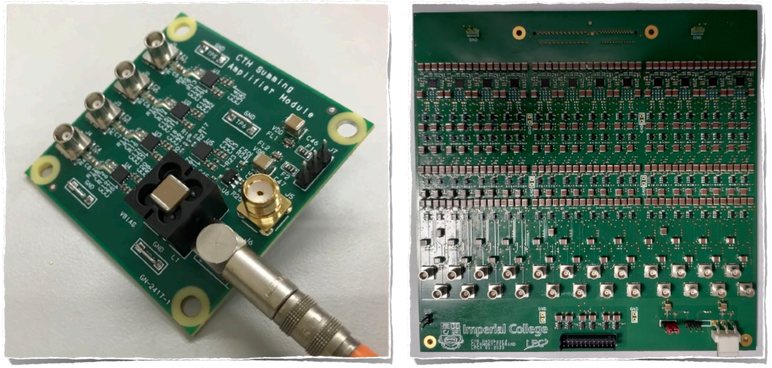
- 2×64 plastic scintillators installed at each end
  - ⋆ Thickness: (inner) 5 mm (outer) 10 mm
  - ⋆ Readout by MPPCs through a plastic fibre bundle.
  - ⋆ > 40 p.e. for a detection efficiency > 99%
- MPPCs operated < −36°C
  - ⋆ Against radiation damage.
- For reasonable trigger rate,
  - ⋆ 4-fold coincidence
  - ⋆ Inner lead shield to block gamma rays from inside.
- Front-end electronics being produced
- Mass production will start.





Lateral view





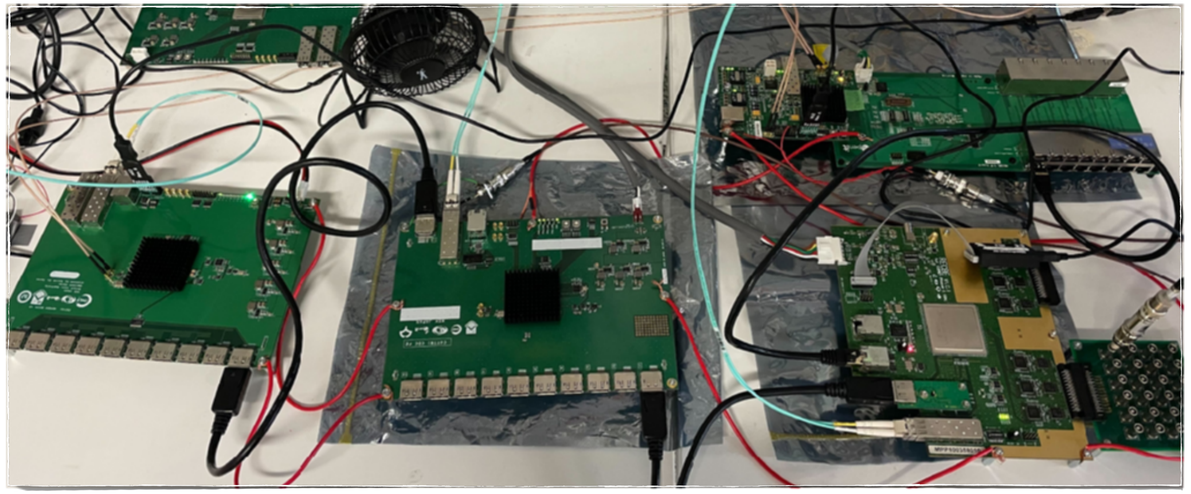
Frontend electronics

Y. Fujii, et al., Nucl. Instrum. Methods Phys. Res. A, 1067 (2024), 169665

Trigger System

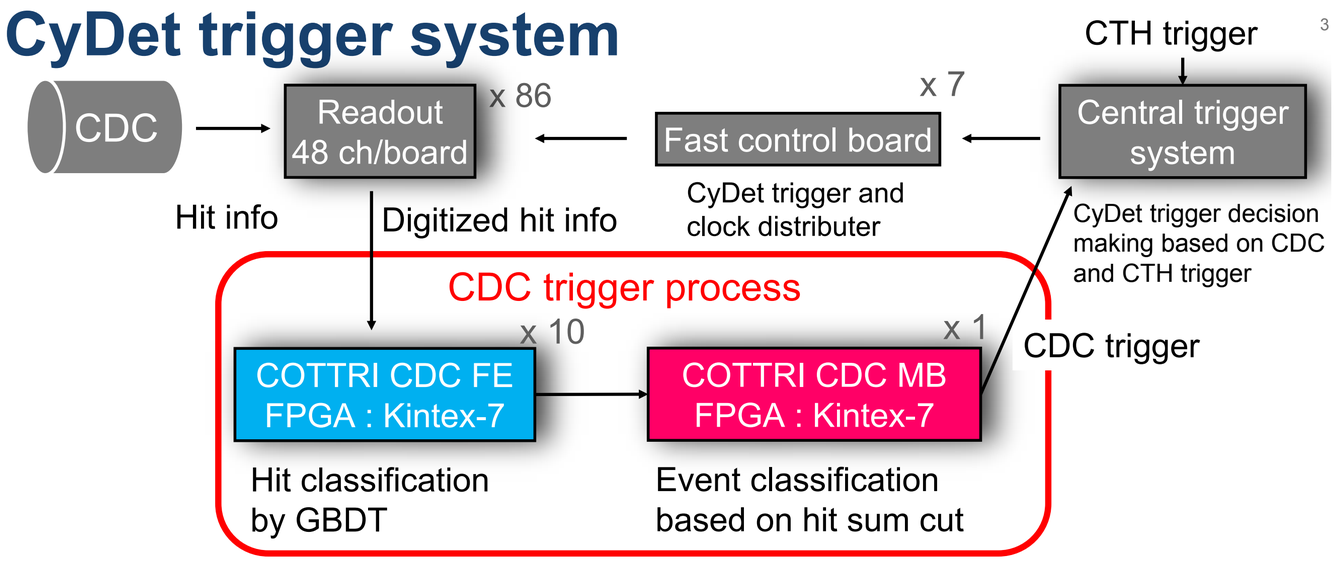
Trigger electronics

- FC7: the central trigger-administrating electronics
  - ⋆ **FC7**: general use FPGA board supporting gigabit data transfer (developed by CMS@CERN).
  - ⋆ Both the CyDet and StrECAL system share it.
- COTTRI: Frontend digitiser & trigger boards for CyDet
  - ⋆ Online waveform processing with flash ADC chips.



Trigger scheme

- CyDet trigger is being developed to achieve a trigger rate < ~20 kcps.
- Machine learning-based trigger logic on FPGA
  - ⋆ Boosted decision tree for hit classification
  - ⋆ Neural network for online tracking
- Software trigger is getting attractive.

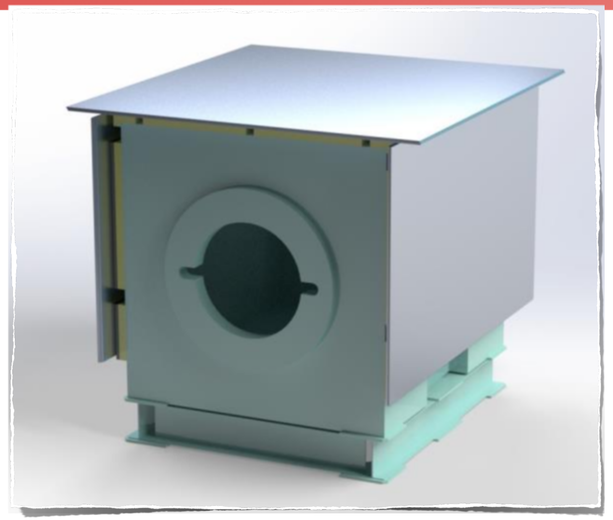


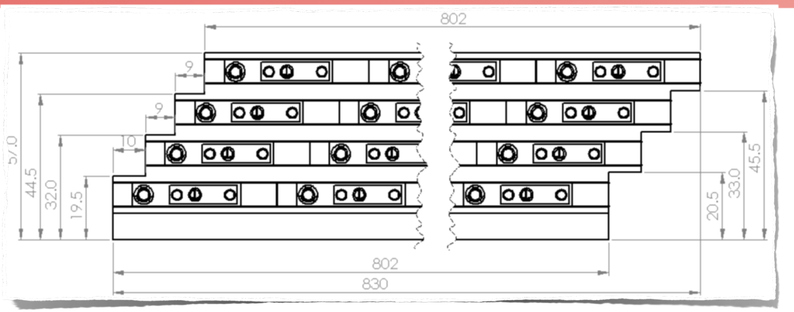
M. Miyataki, et al., IEEE NSS&MIC&RTSD (2024)

Cosmic Ray Veto

Requirements

- Detection efficiency > 99.99%
  - ⋆ CR is one of the most crucial BG sources.

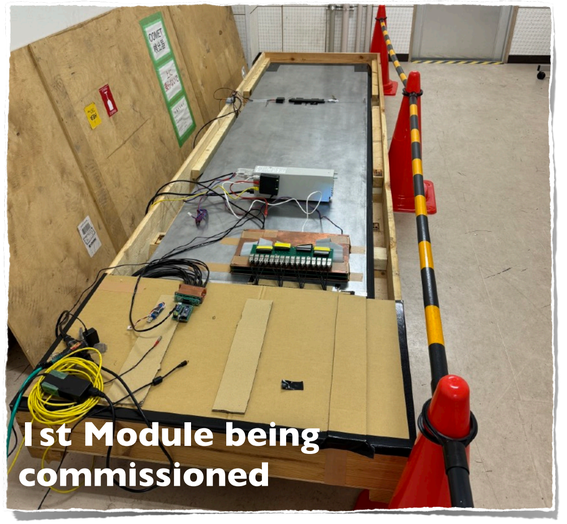




Top and side CRV module

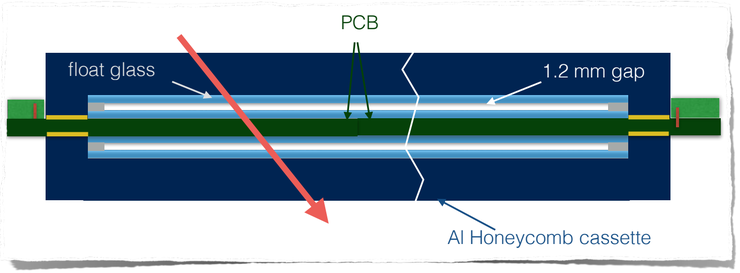
Design

- Top&side: **plastic scintillating stripes**
  - ⋆ 4 layers on each side
  - ⋆ readout by MPPCs through wavelength-shifting fibres
- Front&back: **Resistive Plate Chamber strips**
  - ⋆ A module with 2D-aligned RPC strips
  - ⋆ 5 to 7 layers on each side



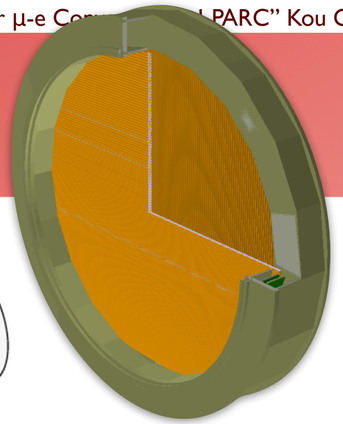
1st module of the lateral CRV modules

- Being commissioned with cosmic rays to evaluate the detection efficiency



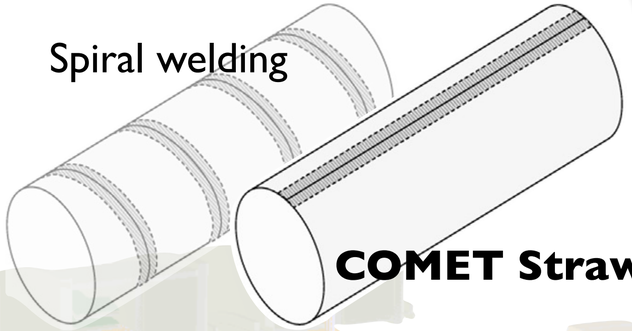
RPC module

Straw Tube Tracker



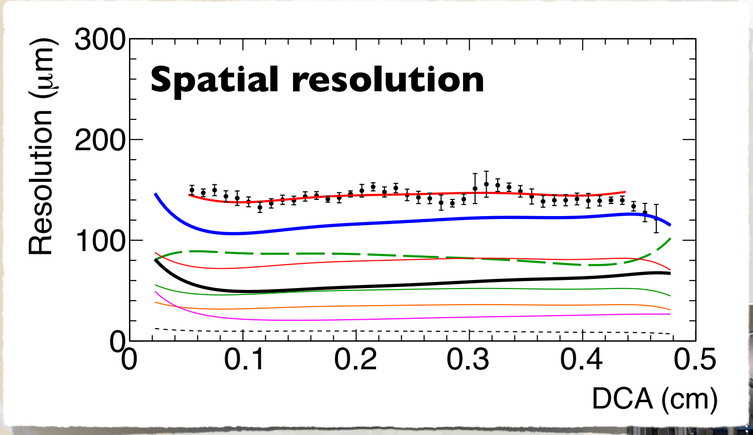
Requirements

- Momentum resolution < 200 keV/c
  - ⋆ Operation in a vacuum of < 100 Pa



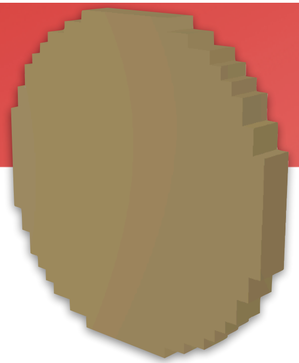
Thin-wall straw tube

- 9.75 mmΦ straw with 20 μm thickness
  - ⋆ Ultrasonic welding for less material budget.
  - ⋆ 5 mmΦ with 12 μm in Phase-II
- **Ar:C_2H_6 = 50:50**
- A prototype test showed a **spatial resolution of ~ 110 μm**.
  - ⋆ Momentum resolution < 200 keV is achievable.
  - ⋆ Succeeded operation in vacuum of < 0.1 Pa.
- The 1st station was commissioned in Phase-α.
  - ⋆ The 2nd and 3rd stations are being constructed.



H. Nishiguchi, et al., Nucl. Instrum. Methods Phys. Res. A, 958 (2020) 162800

ECAL



Requirements

- Particle identification for the beam measurement.
- Energy resolution < 5%
  to suppress trigger rate of DIO electrons.

LYSO Crystal Scintillators

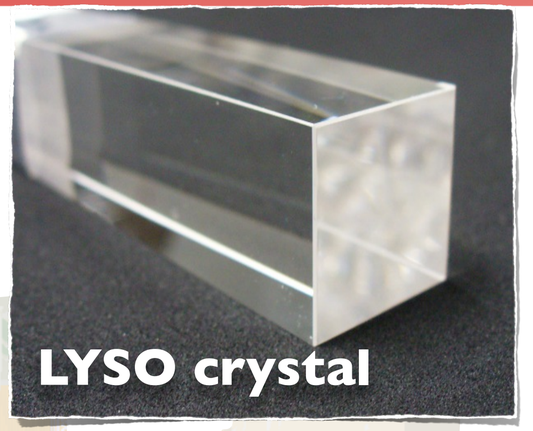
- High density (7.1 g/cm^3), high light yield (70% NaI), and fast time response (40 nsec)
- Dimension of 2×2×12 cm^3.
- Readout by 10×10 mm^2 APD + FE electronics
- ~2000 crystals (~ 1 mΦ sensitive area.)

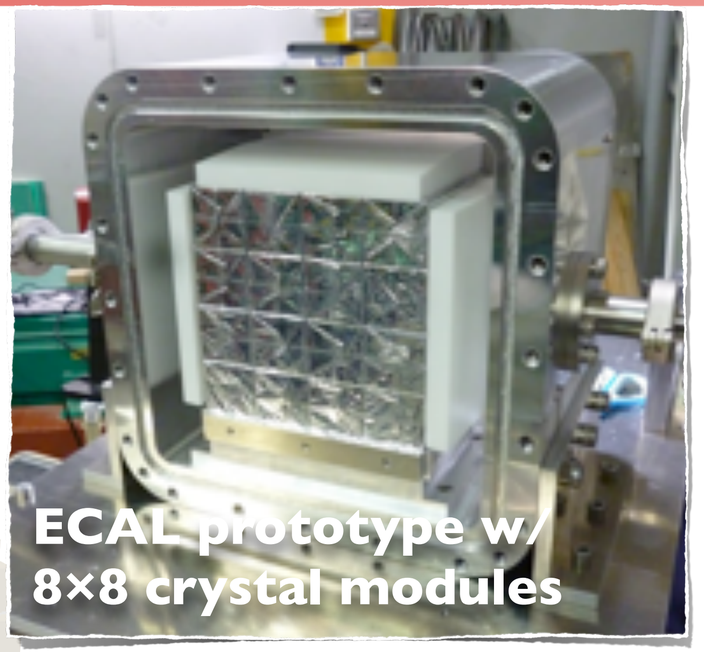
Prototype w/ 8×8 crystals

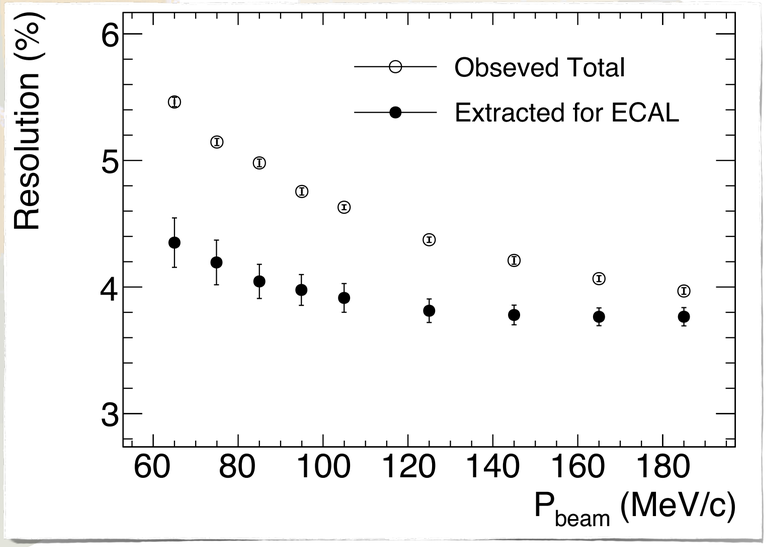
- Good performance at 105 MeV/c
  - ⋆ **Energy resolution of 3.9%**
  - ⋆ **Position resolution of 7.7 mm**
  - ⋆ **Timing resolution of 0.5 nsec**

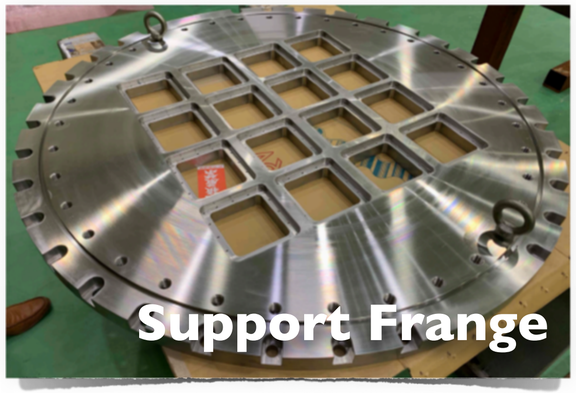
Detector construction beginning

- Quality control of the crystal modules construction









CLOSING

Phase-I Sensitivity

Single Event Sensitivity (SES)

✦ Estimated **3×10^{-15}** for 150 days operation.

$$B(\mu^- + \mathrm{Al} \to e^- + \mathrm{Al}) = \frac{1}{N_\mu \cdot f_{\mathrm{cap}} \cdot f_{\mathrm{gnd}} \cdot A_{\mu\text{-}e}} = 3 \times 10^{-15} \quad (\text{as SES})$$

★ **N_μ = 1.5×10^{16}** : the number of muons stopped in the target

★ **f_{cap} = 0.61** : the fraction of captured muons to total muons on target

★ **f_{gnd} = 0.9** : the fraction of μ-e conversion to the ground state in the final state

★ **$A_{\mu\text{-}e}$ = 0.041** : the net acceptance for the μ-e conversion signal (see below)

Physics Backgrounds

✦ "Prompt beam" and "delayed beam" components will be directly evaluated.

Event selection	Value
Online event selection efficiency	0.9
DAQ efficiency	0.9
Track finding efficiency	0.99
Geometrical acceptance + Track quality cuts	0.18
Momentum window ($\varepsilon_{\mathrm{mom}}$)	0.93
Timing window ($\varepsilon_{\mathrm{time}}$)	0.3
Total	0.041

The COMET Collaboration, et al., Prog. Theor. Exp. Phys. 2020 (3) (2020), 033C01.

Physics background sources

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
	Anti-proton induced backgrounds	0.0012
Others	Cosmic rays†	< 0.01
Total		0.032

† This estimate is currently limited by computing resources.

Summary & Schedule

COMET experiment will search for μ-e conversion at J-PARC.

- Aims at single event sensitivity: 3×10^{-15} (Phase-I) and $O(10^{-17})$ (Phase-II).
- Perform a direct measurement of the beam profile and backgrounds in Phase-I.
- The facility & beam line construction is getting completed.
- The detector construction is also progressing.
  - ⋆ CyDet, StrECAL, and Cosmic Ray Veto
- We will start with low-intensity (~10% power) commissioning & data taking runs.