THE COMET EXPERIMENT

to Search for μ-e Conversion at J-PARC

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On behalf of the COMET collaboration

J-PARC Symposium 2024
Mito City Civic Center, Ibaraki, Japan
16th October 2024

A brief status report:

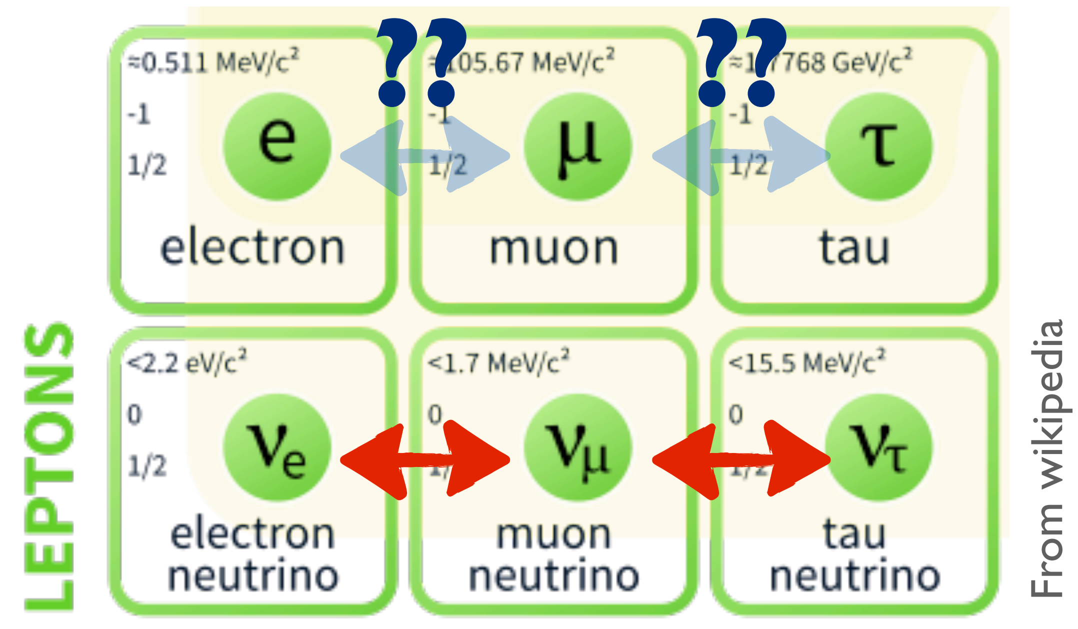
1. Introduction
2. Facility
3. Detectors
4. Sensitivity

Introduction

Lepton Flavour Violation

Neutral LFV

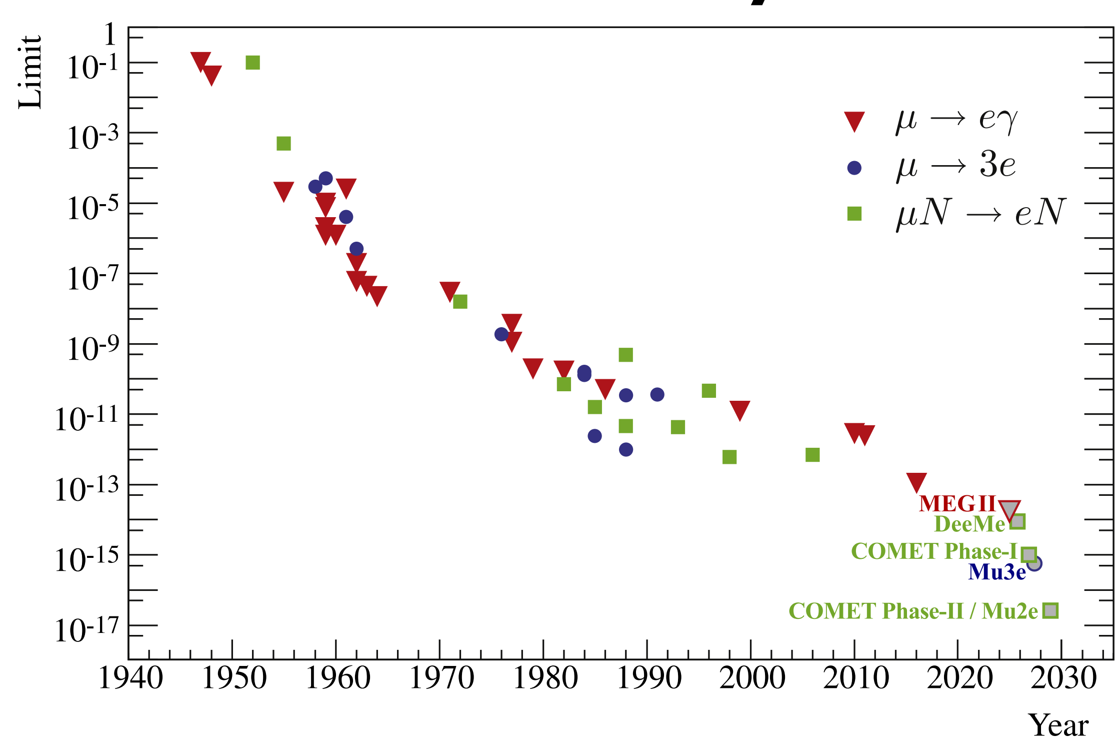
- Neutrino oscillation.
- The Standard Model (SM) was extended.



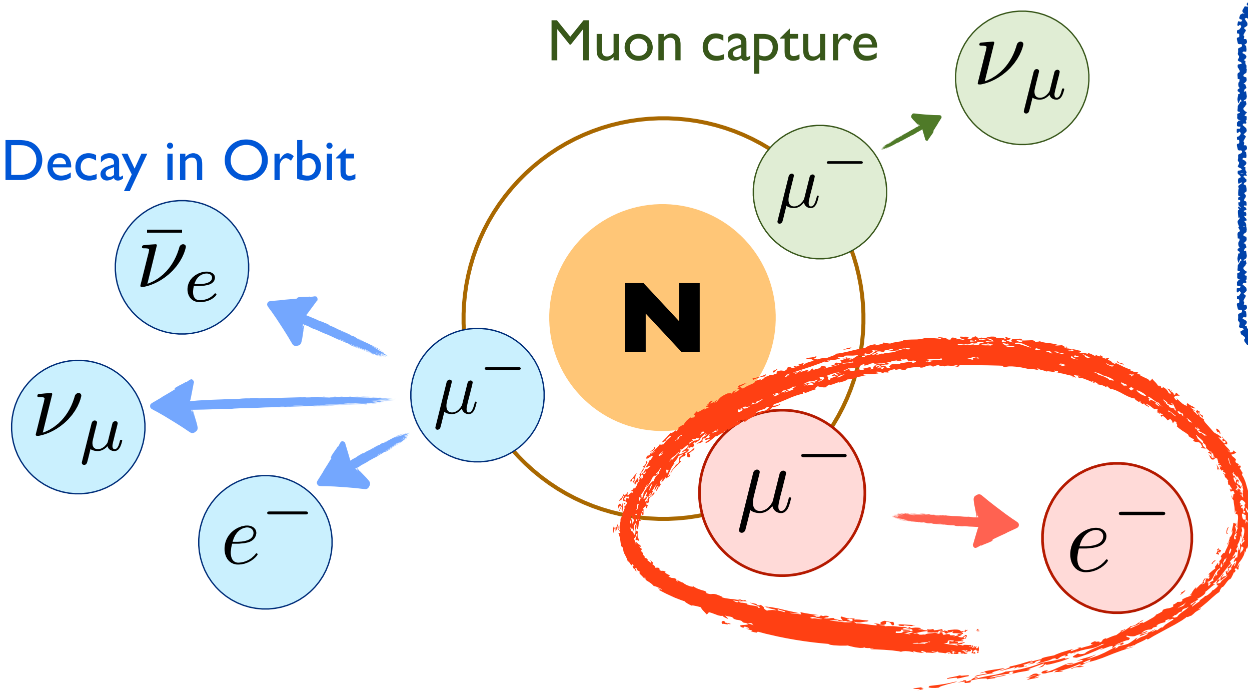
Charged LFV

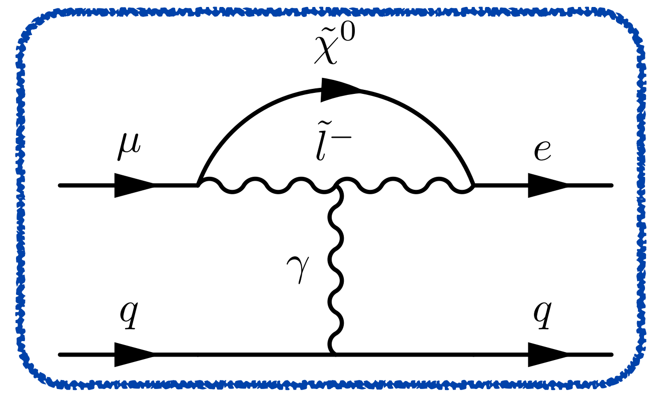
- Many experiments but no discovery
  - ⋆ μ → eγ (MEG II)
  - ⋆ μ → 3e (Mu3e)
  - ⋆ **μN → eN (DeeMe, Mu2e, COMET)**
  - ⋆ τ's rare decays and many in the past…
- A clear signal of new physics

The History

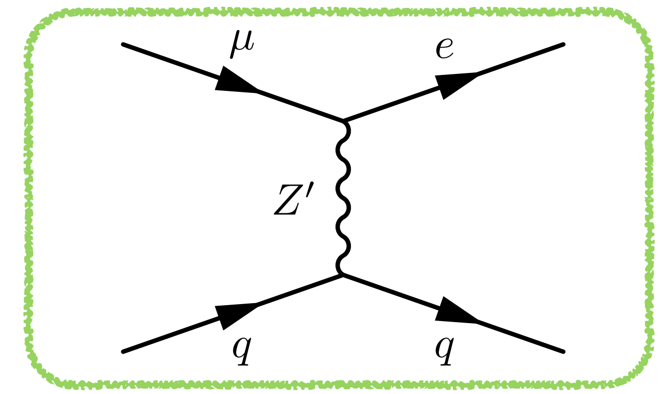


Muon-to-Electron Conversion





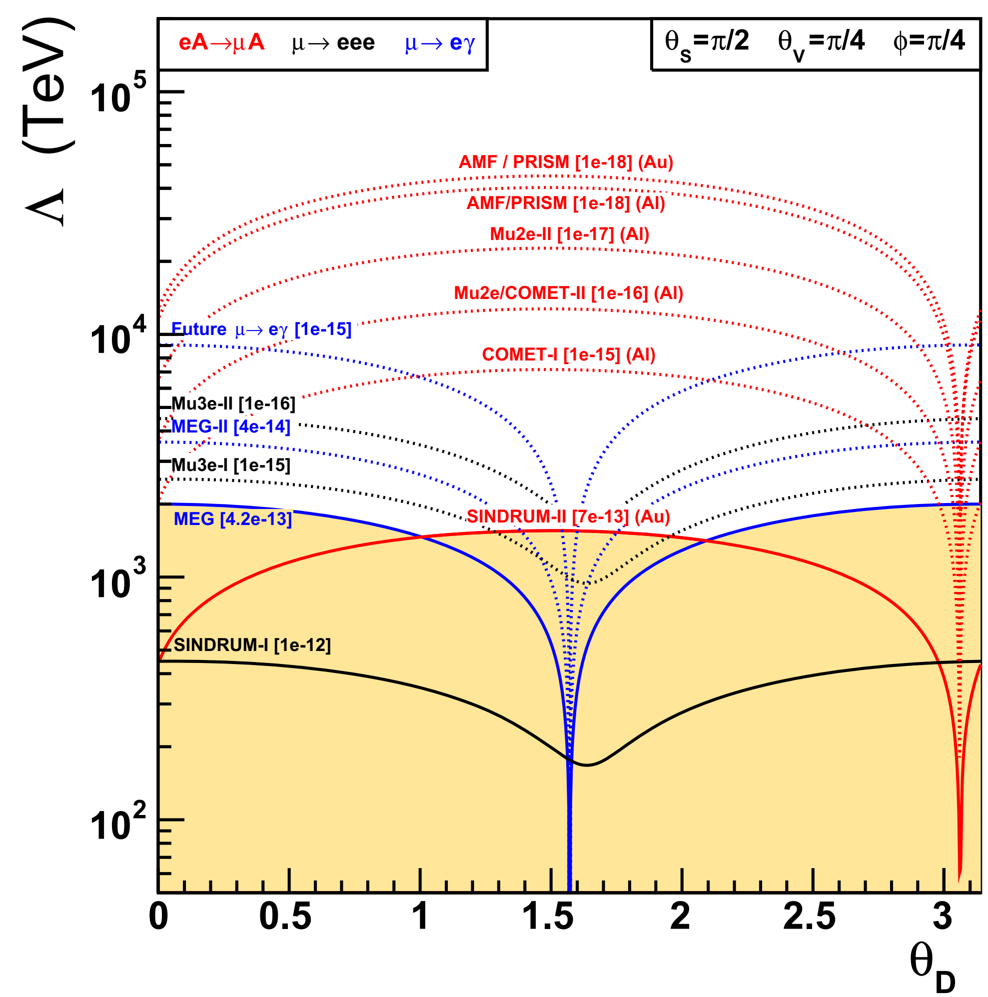
Photonic process



Four-fermion process

A charged LFV process

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

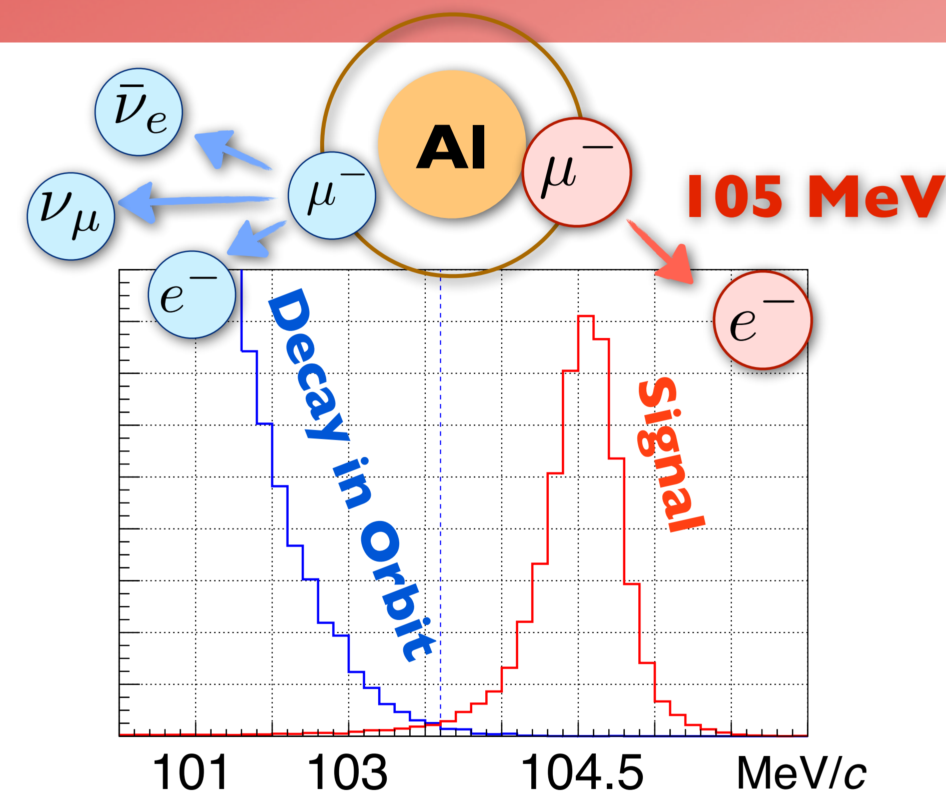


Davidson, S., Eur. Phys. J. C 82, 836 (2022).

Experimental Principle

Signal & intrinsic BGs

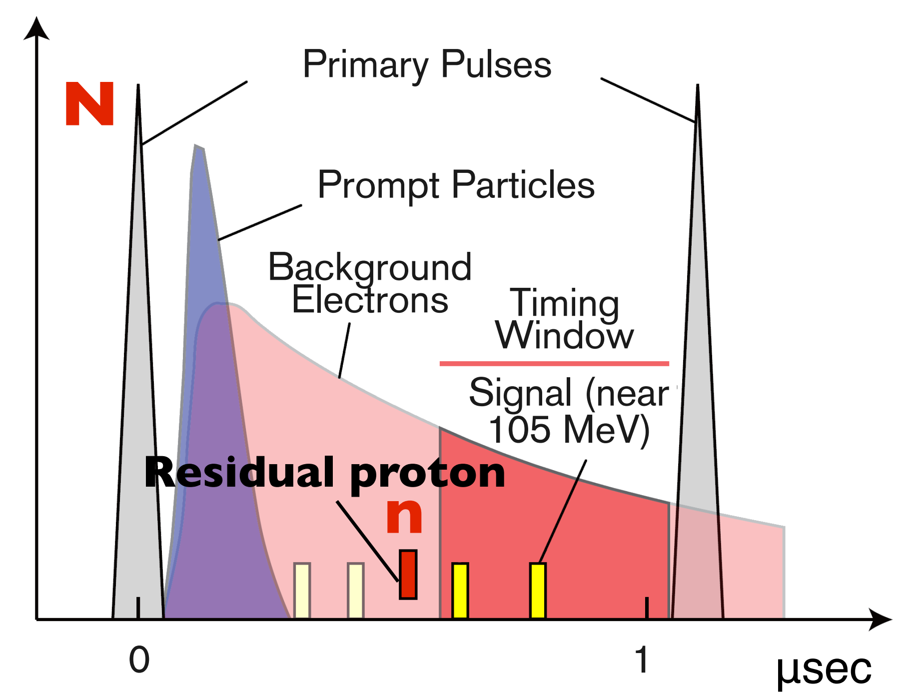
- Signal: $\mu^- + N \rightarrow e^- + N$
  - ★ Monochromatic energy of **105 MeV** (Al)
- Dominant intrinsic backgrounds: **decay-in-orbit (DIO)**
  - ★ Contaminate the signal region w/ a finite resolution.
  - ★ **Momentum resolution < 200 keV/c** is required.



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

High intense muon beam & beam BGs

- World-class intensity proton beam @ J-PARC.
  - ★ Gain high statistics of muons.
  - ★ **An effective transport line from π to μ** is required.
  - ★ 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}



Bunched Beam Structure & Delayed Timing Window

COMET Collaboration

International Collaboration

- ✦ 18 countries
- ✦ 50 institutes
- ✦ **>200 collaborators**

COMET Experiment

Searching for μ-e conversion at J-PARC

- The final goal: **O(10^{-17})** sensitivity.
  - 10, 000 times improved from the current limit.
- Building the facility and muon transport line.
- Two-staged plan
  - Phase-I and Phase-II

Phase-I

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

Phase-II

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

Reused

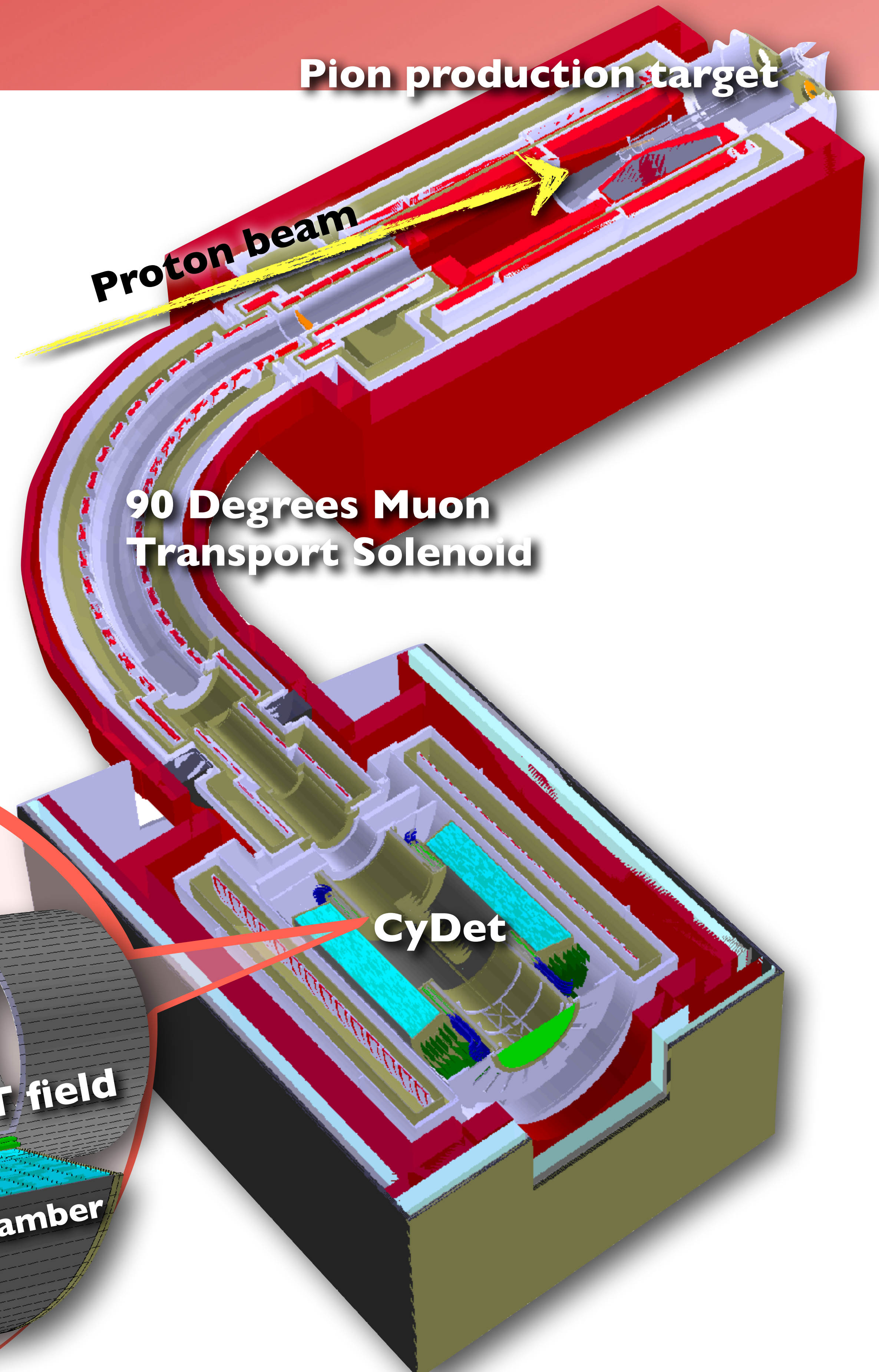
Phase-I

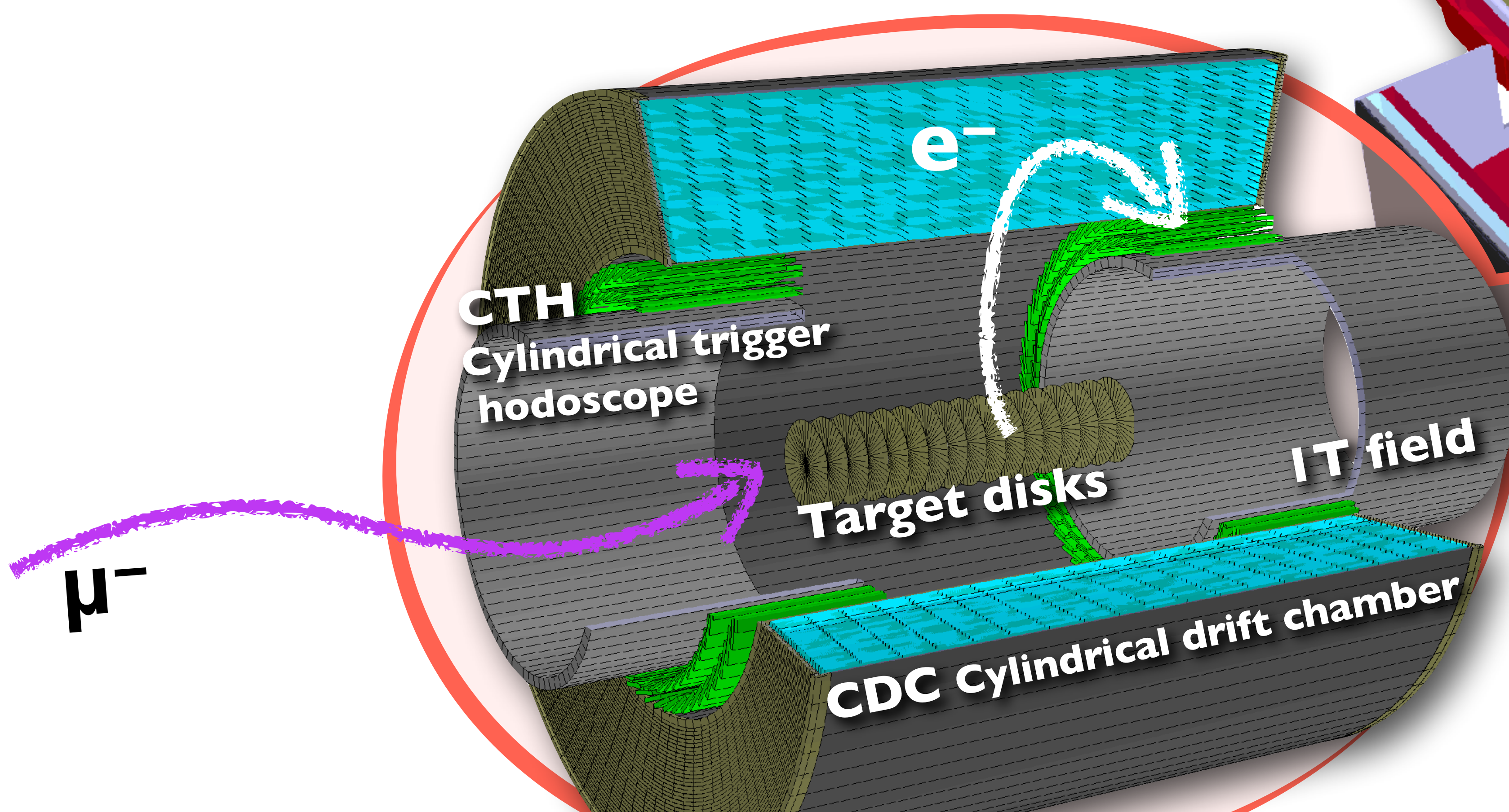
Sensitivity O(10^{-15})

- ✦ 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)

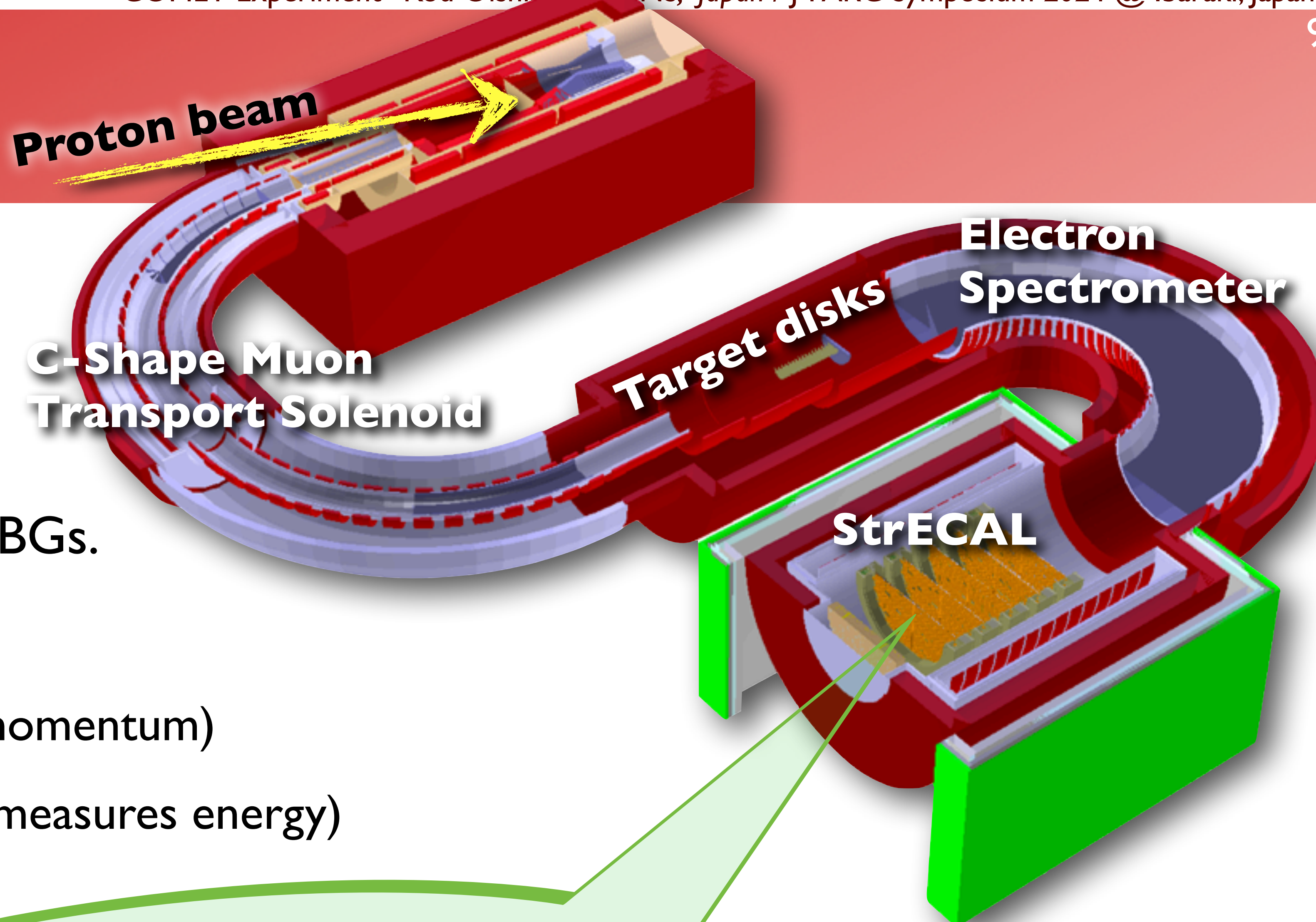
Beam profile & beam-related BGs

- ✦ Measured by the Phase-II detector: StrECAL.



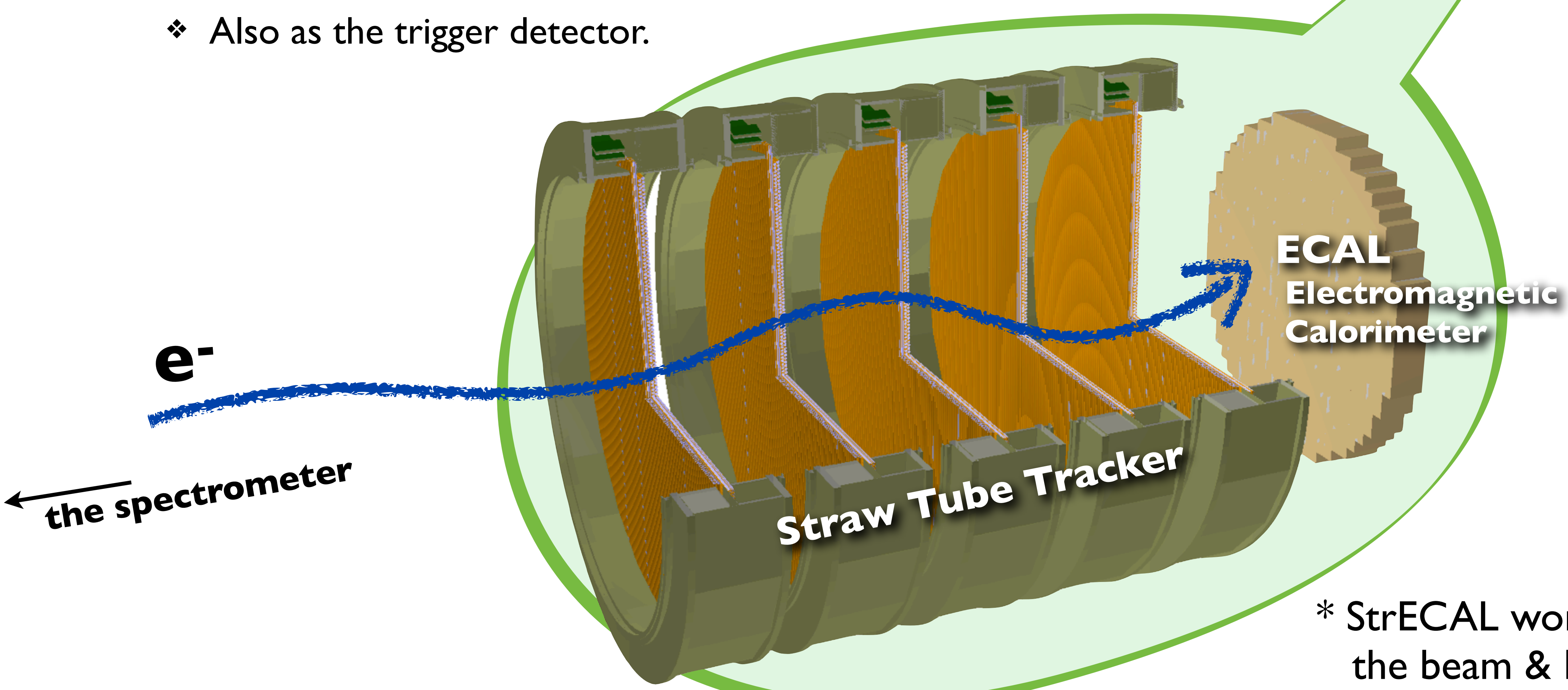


Phase-II



Sensitivity O(10^{-17})

- Additional transport solenoid.
- Electron spectrometer suppresses low momentum electrons and beam BGs.
- **StrECAL** combining
  - **Straw Tube Tracker** (measures momentum)
  - **ECAL**: Electromagnetic calorimeter (measures energy)
    - Also as the trigger detector.



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

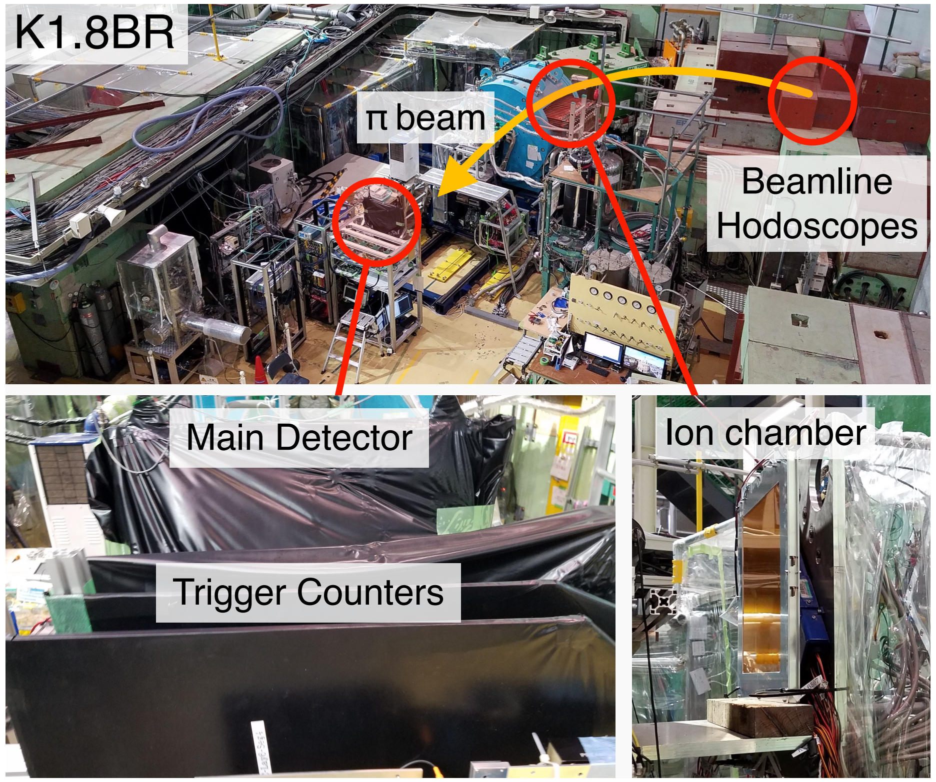
COMET

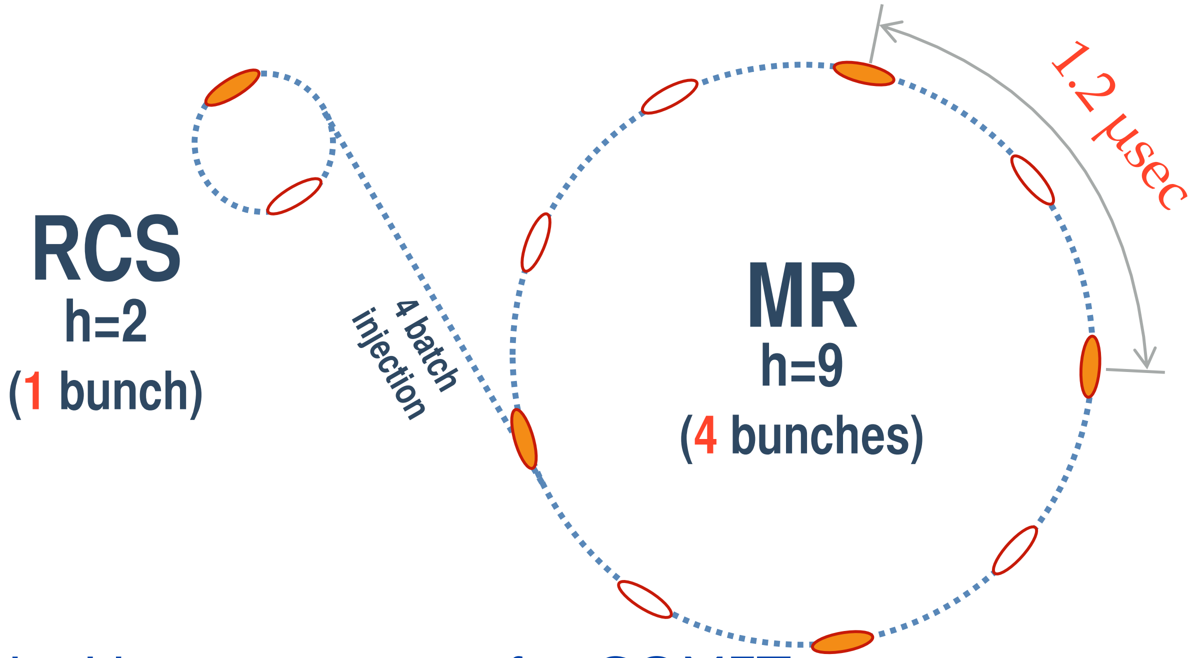
FACILITY

PROTON BEAM

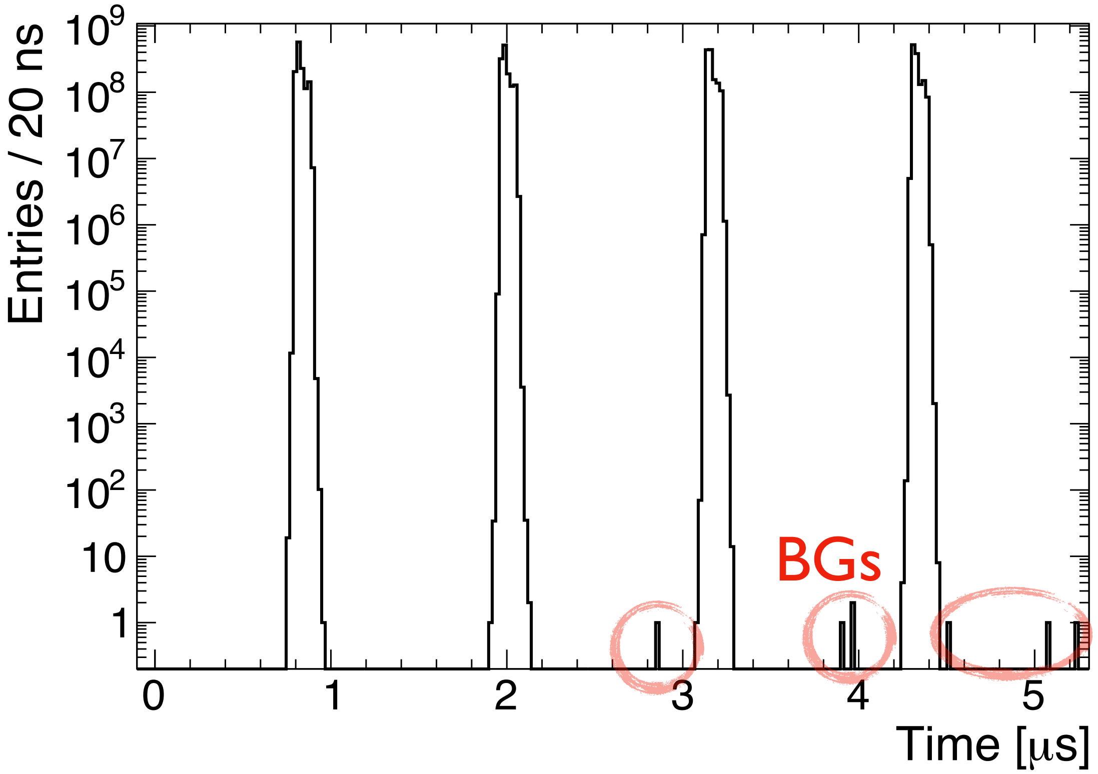
J-PARC Proton Beam for COMET

- 3.2 (56) kW for Phase-I (Phase-II)
- Bunched slow extraction for the timing-window measurement
- Accelerated up to 8 GeV
  - (1) To minimise antiprotons
  - (2) ‘**Extinction**’ < 10^{-10}
- **The measured extinction is < 1.0×10^{-10}**
  - @ K1.8BR of the Hadron Facility (T78 exp. in 2021)





Bunched beam operation for COMET

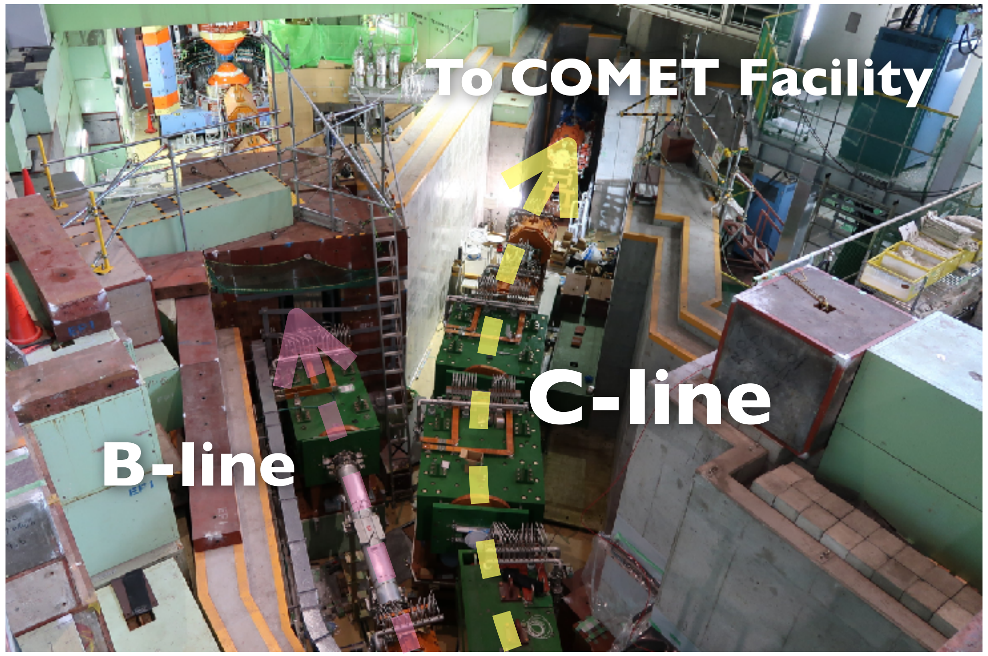


No inter-bunch contaminations in T78 exp.

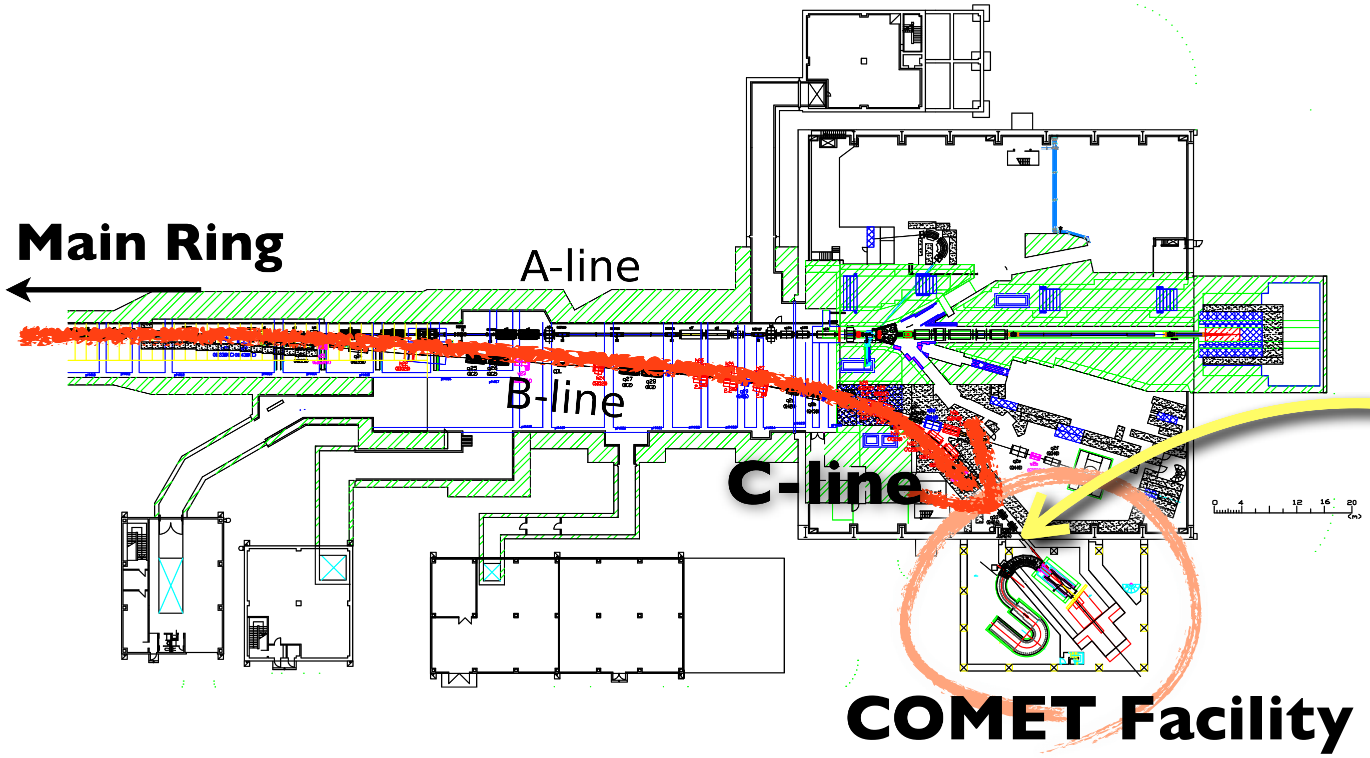
COMET Proton Beam Line

COMET Beam Line (C-Line)

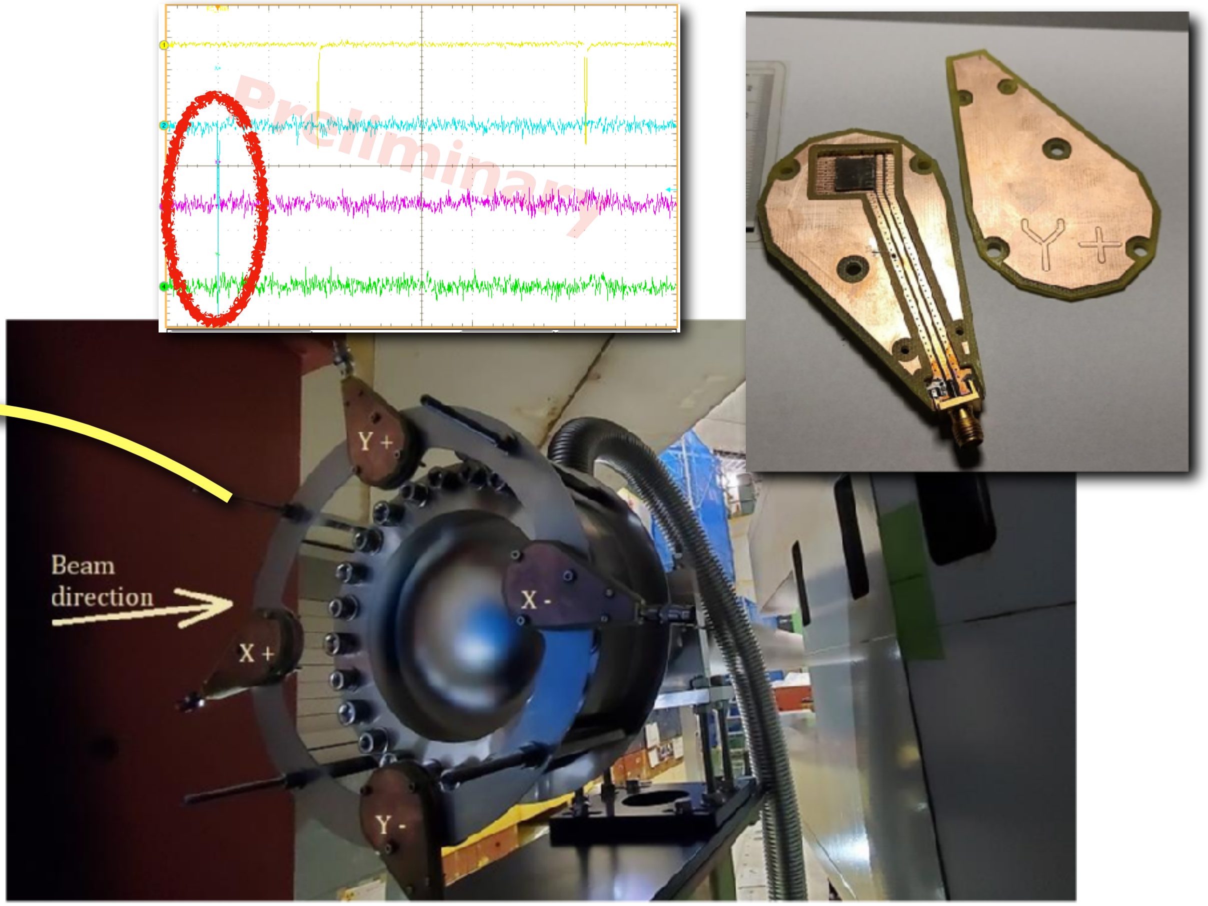
- Dedicated beam line for COMET
- Proton beam monitors are being developed.
  - Diamond, TiO_2, and SiC: High radiation tolerance
- **8 GeV SX commissioning succeeded.**
  - COMET Phase-α (later)



The C-Line branching point



Beam line for COMET (red line)



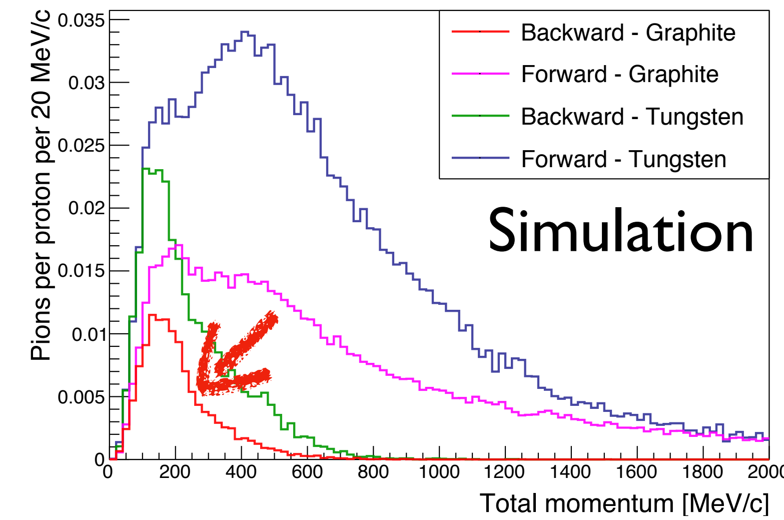
Proton to Stopped Muon (1)

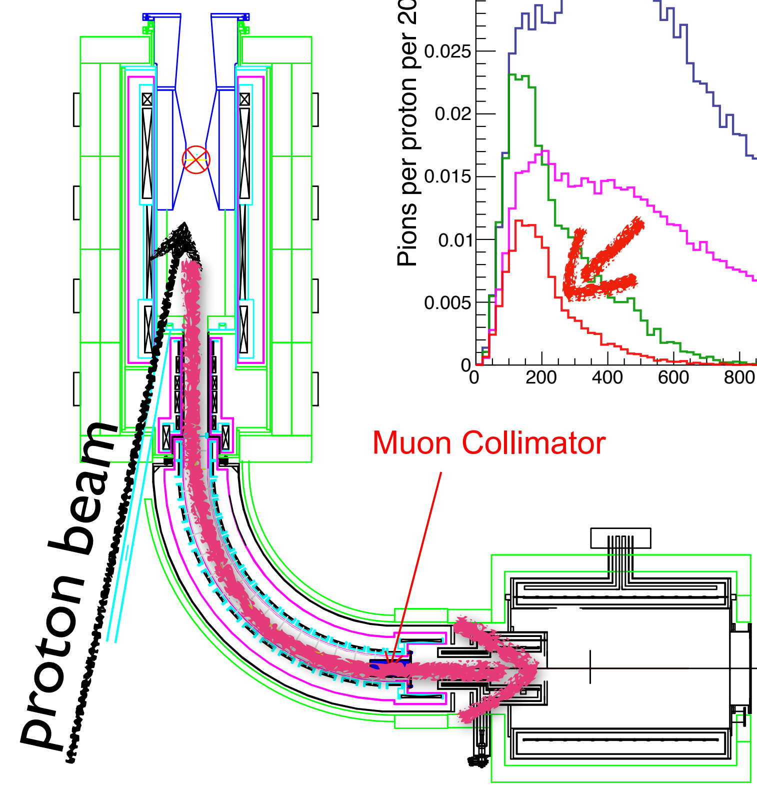
Proton Target

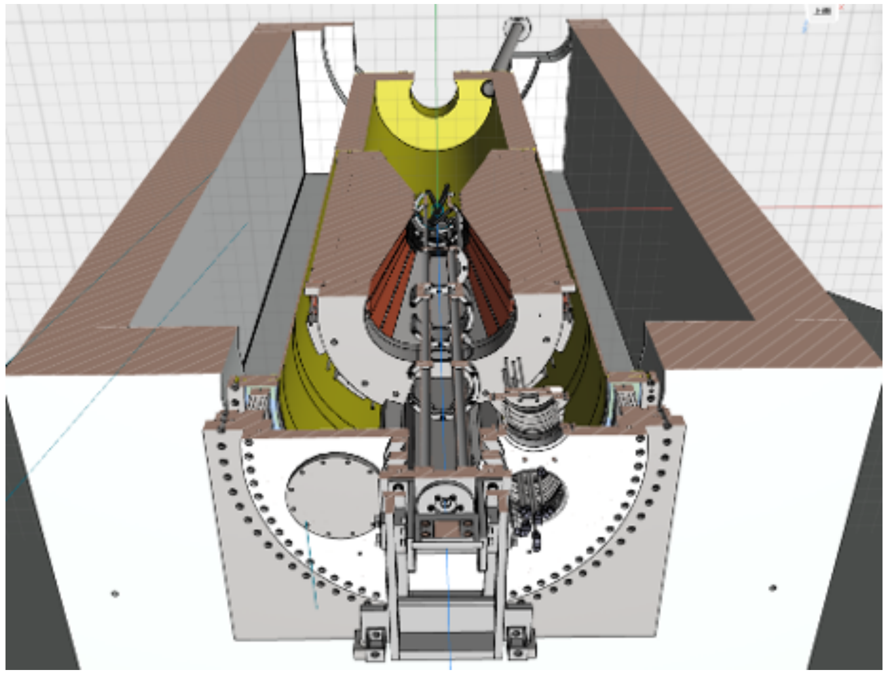
- ✦ Graphite (Tungsten) for Phase-I (II).

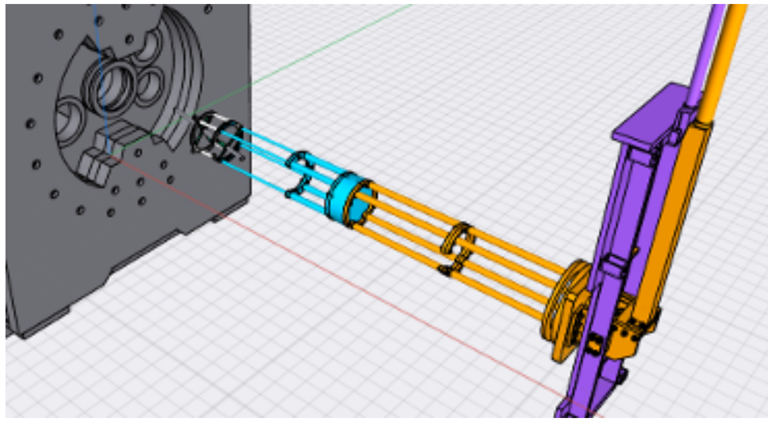
Pion capture solenoid

- ✦ 5 T superconducting magnet
- ✦ Pions are extracted to backward.
  - ★ Better collection of low-momentum pions





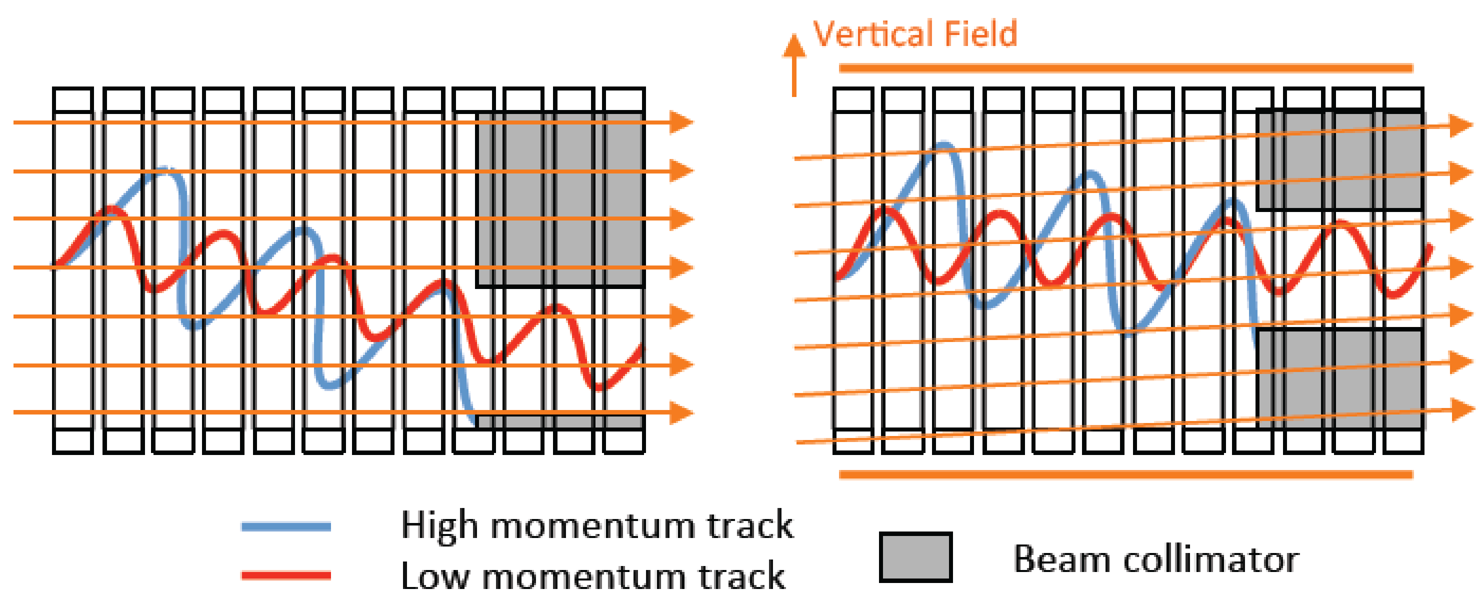




Proton to Stopped Muon (2)

(90°-bent) Muon Transport Solenoid

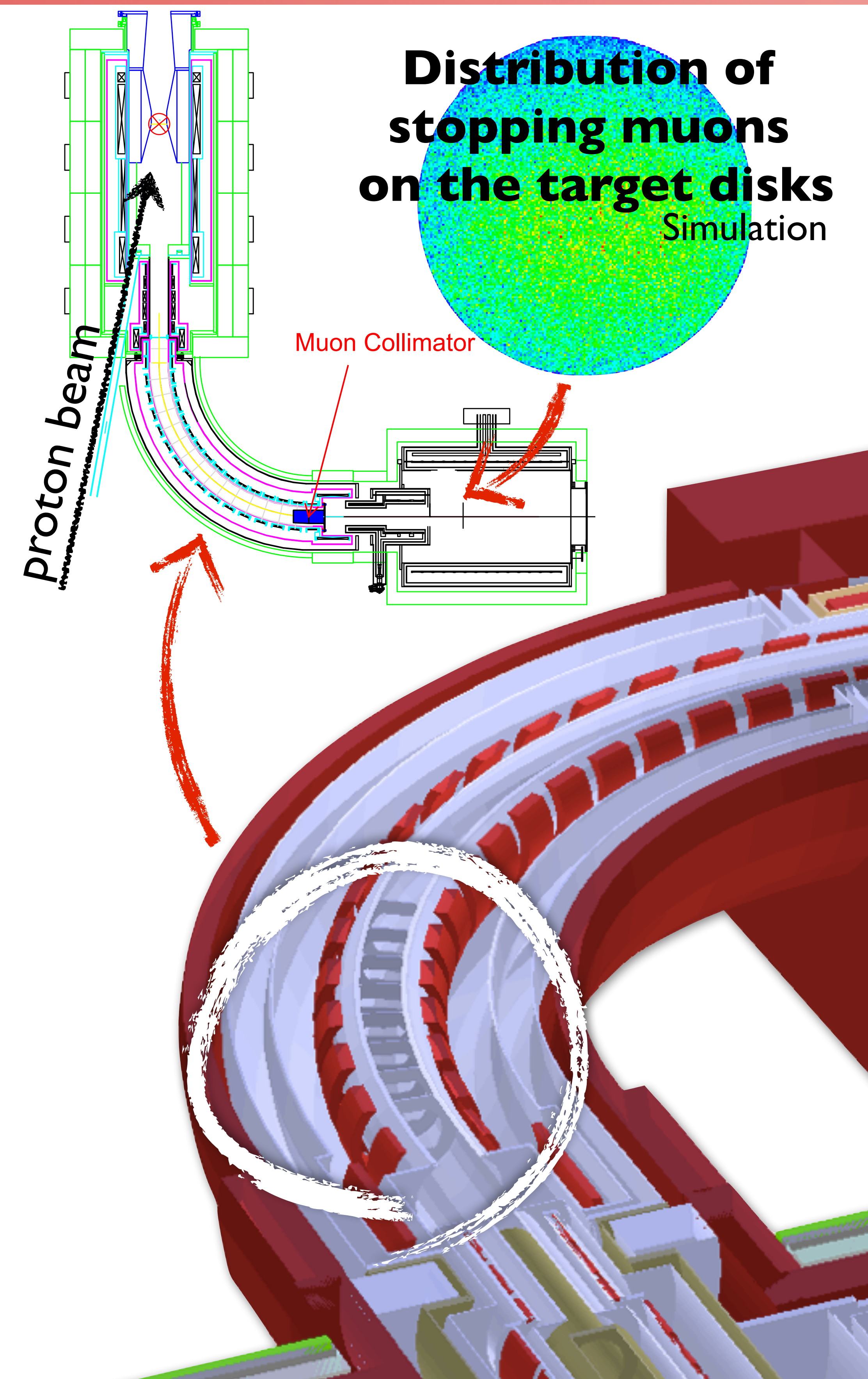
- The most crucial beamline component, installed in 2015.
- The helical trajectories centre drifts vertically.
  - Additional dipole magnetic field for compensation
  - Charge and momentum selection with optimum collimators



Trajectories in the transport solenoid

Al Muon Stopping Target

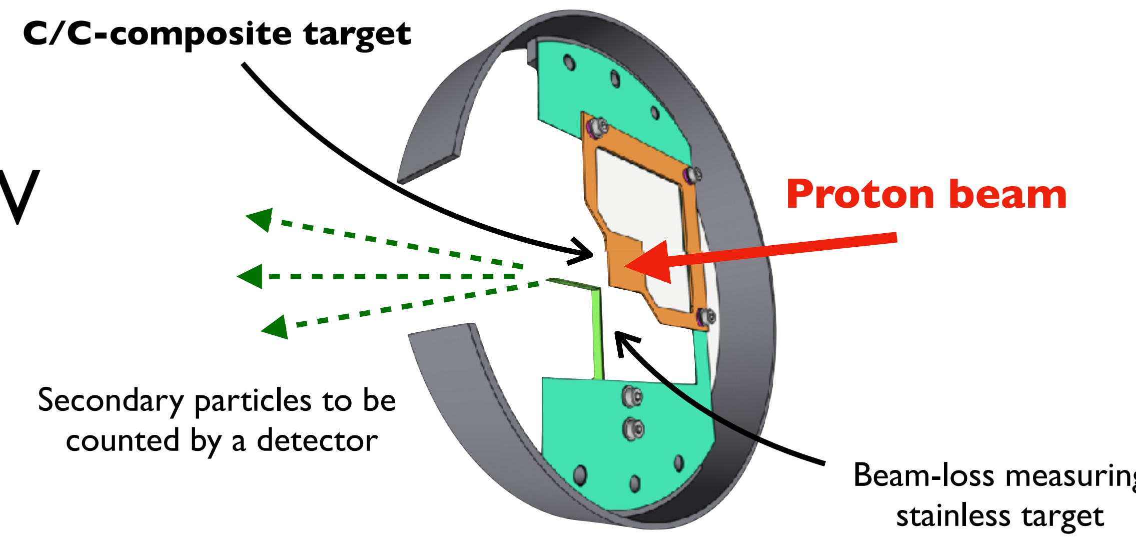
- 17 Flat circular disks
  - 10 cm radius, 200 μm thickness, and 50 mm spacing.
- 4.7×10^{-4} stopping muons / proton for Phase-I

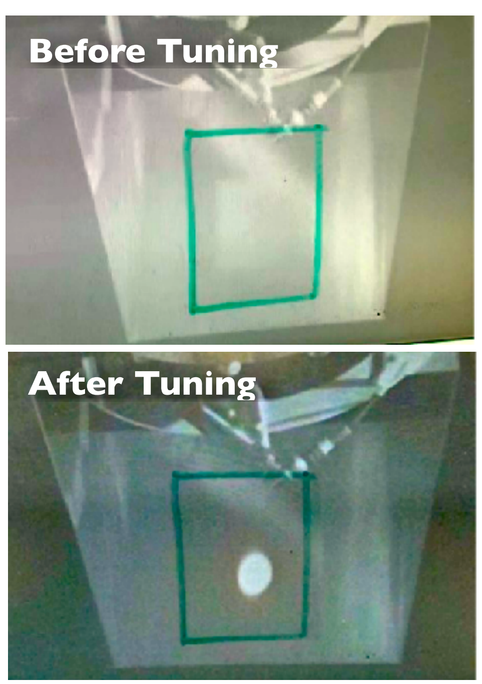


PHASE-α (1)

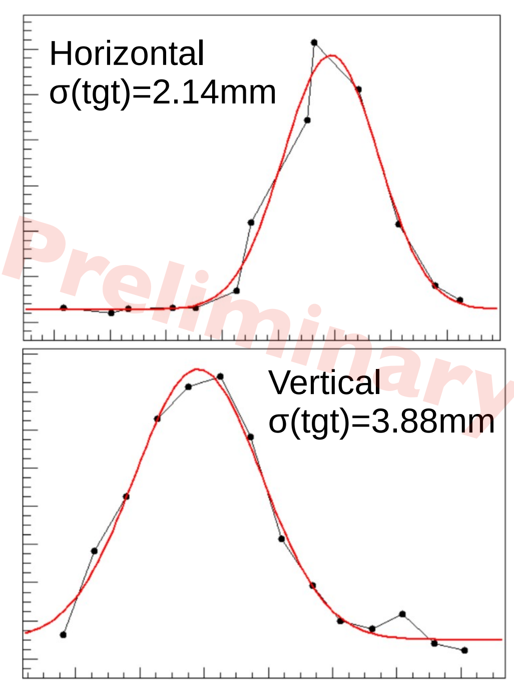
The 1st Commissioning of the COMET facility

- ✦ Proton Beam
  - ★ SX pulsed 8 GeV proton beam at 260 W
  - ★ Beam tuning was well performed.
  - ★ Proton beam profile was measured.

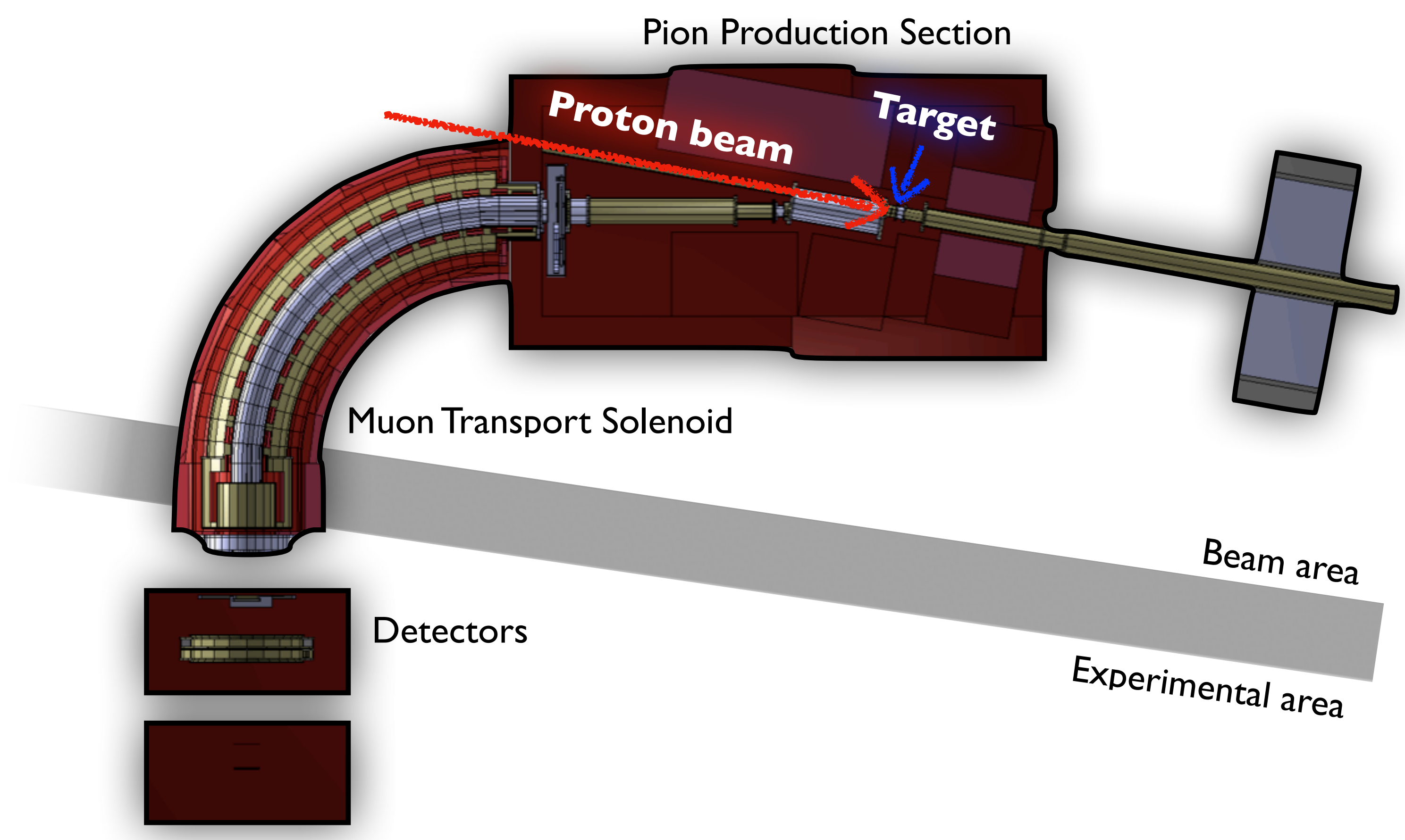




Phosphor plate response before and after beam tuning



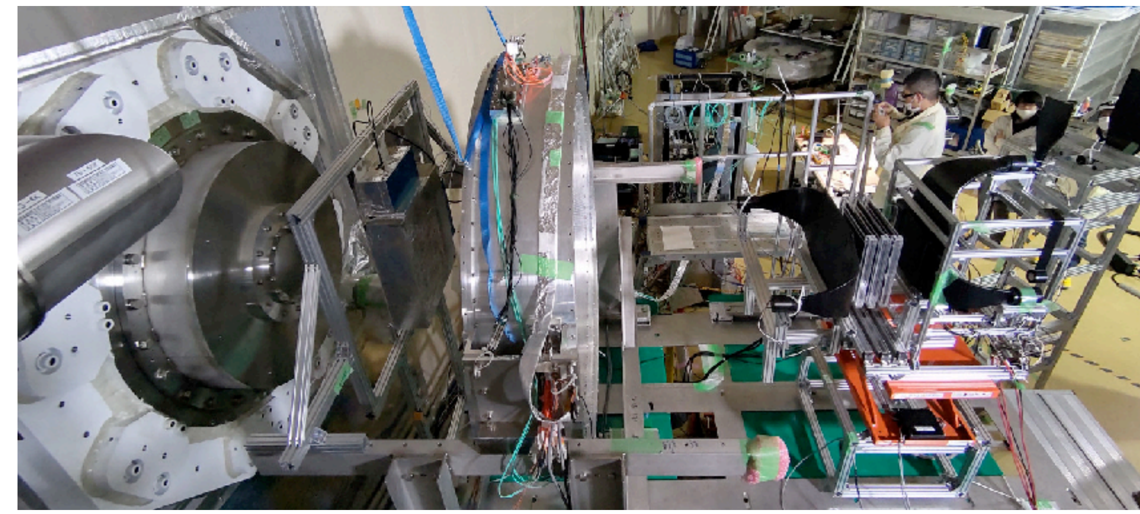
Measured beam dimensions



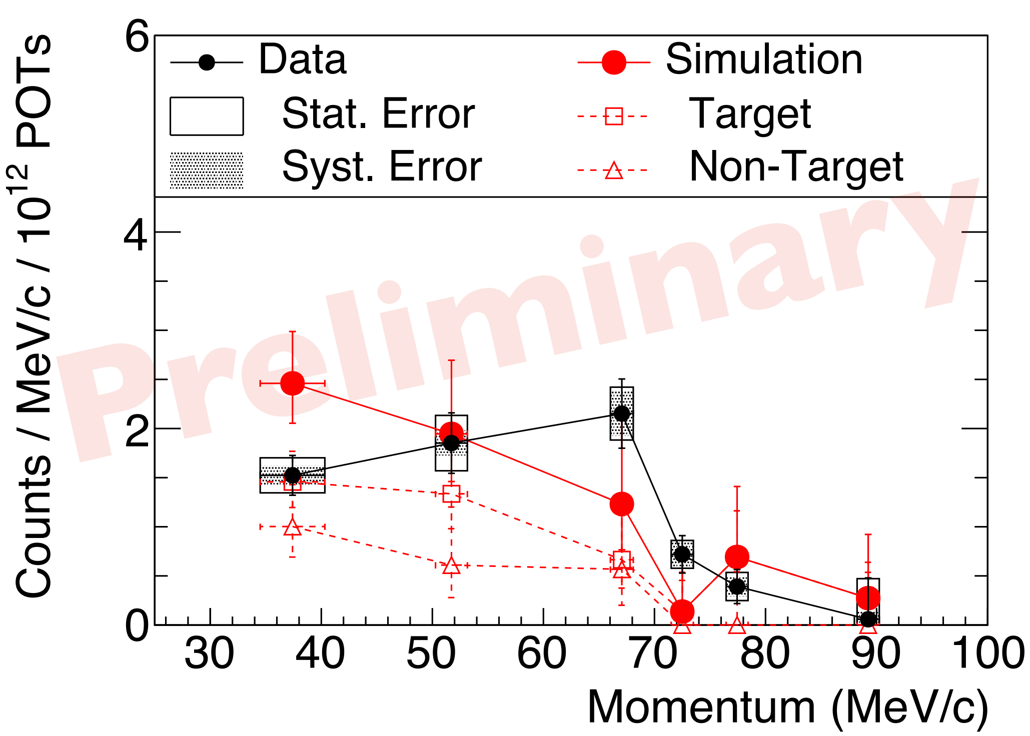
Phase-α (2)

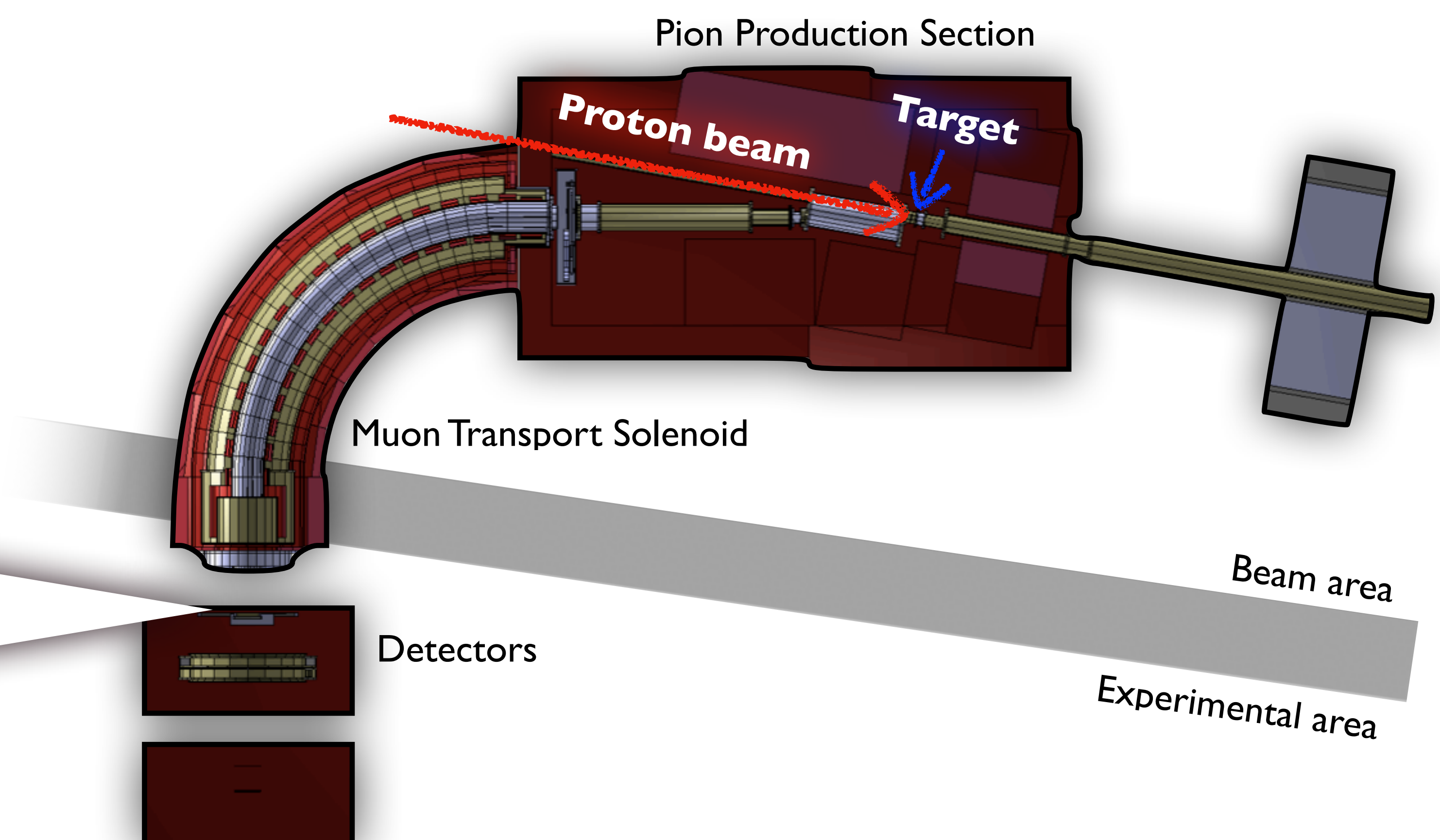
The 1st Commissioning of the COMET facility

- ✦ The muon beam was successfully transported by the Muon Transport Solenoid.
  - ★ The observed momentum spectrum is consistent with simulation.



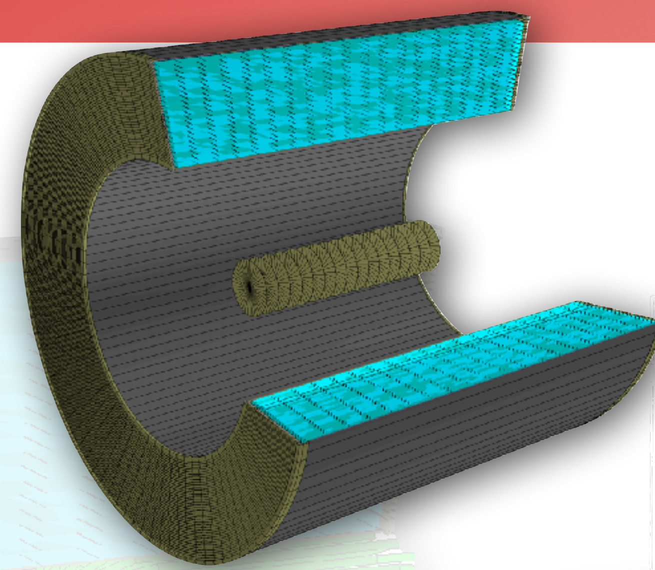
Phase-α Detectors

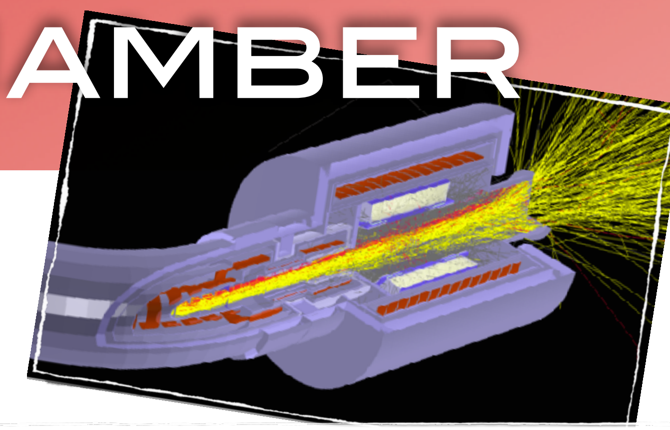




DETECTORS

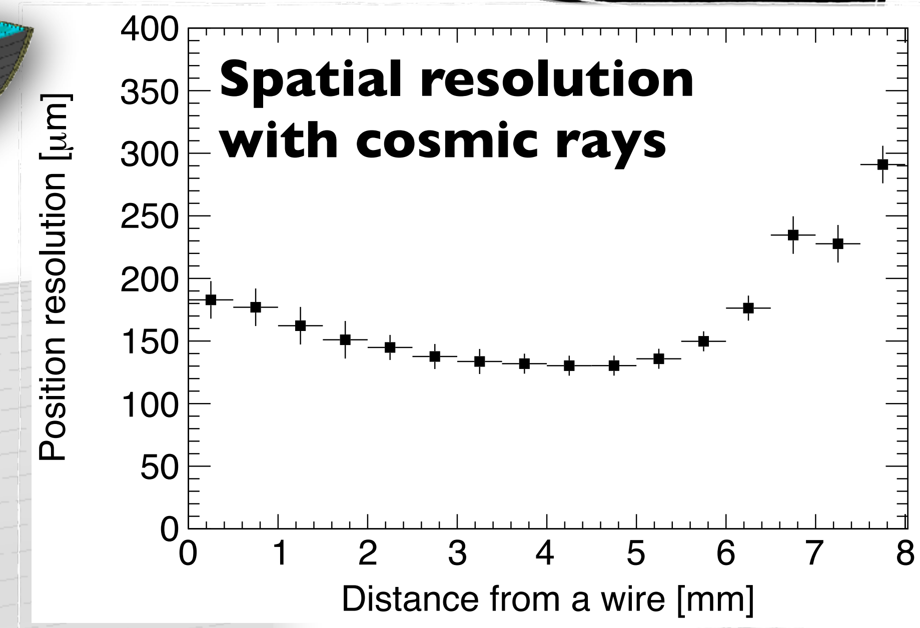
Cylindrical Drift Chamber





Requirements

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

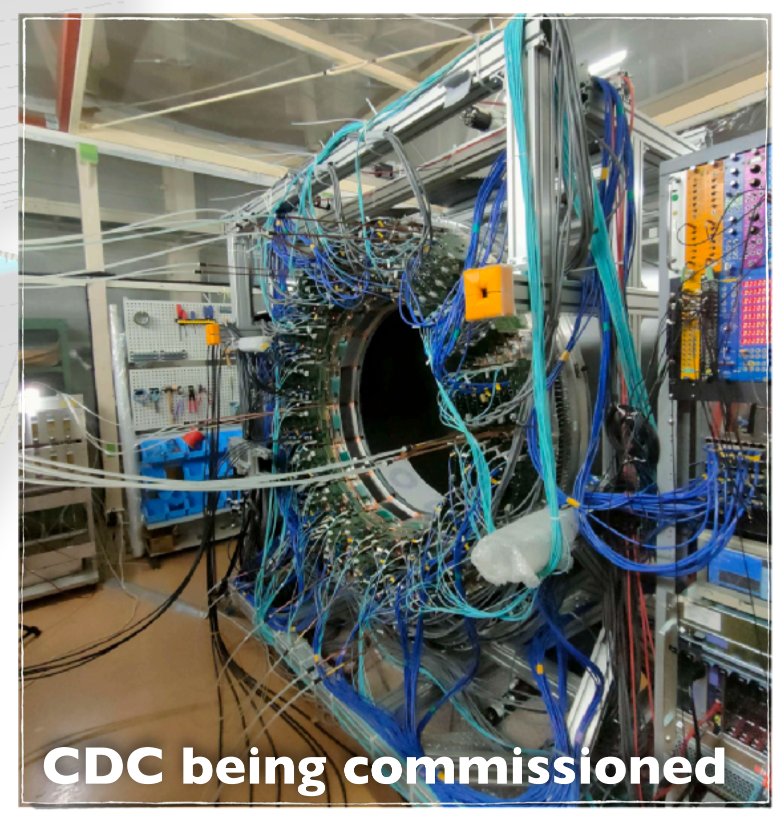


Design

- ~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

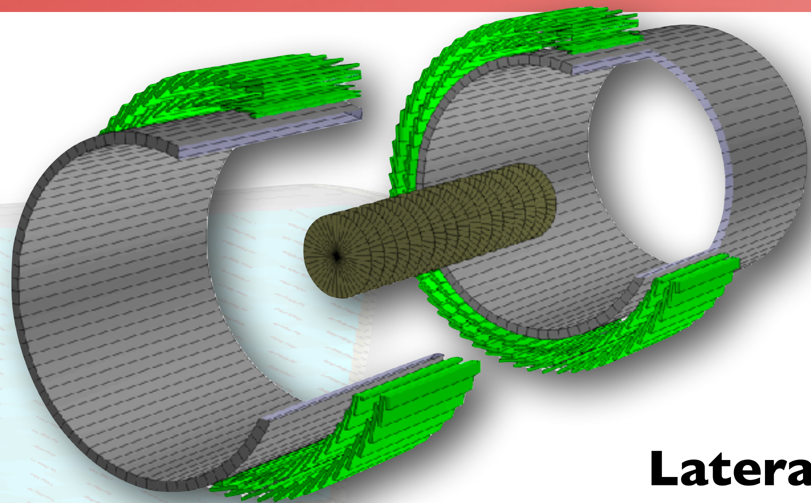
- Commissioning ongoing
  - Performance evaluation with cosmic rays
  - Chain test of the front- and back-ends



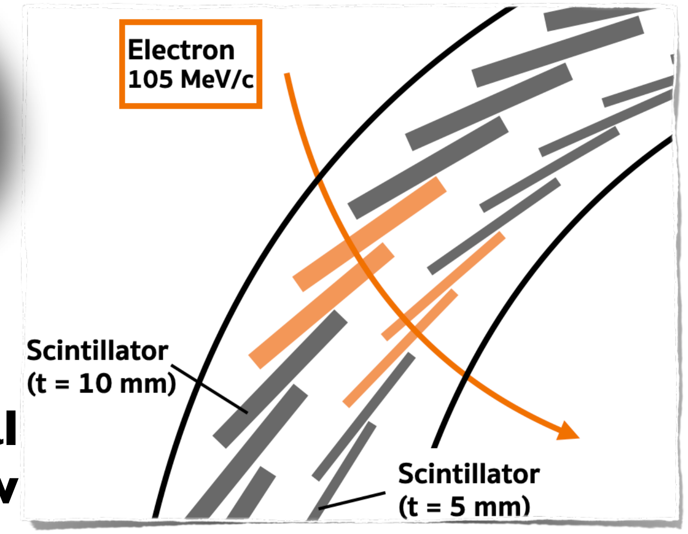
Cylindrical Trigger Hodoscope

Requirements

- (Primary) trigger decision
- T_0 measurement for tracking

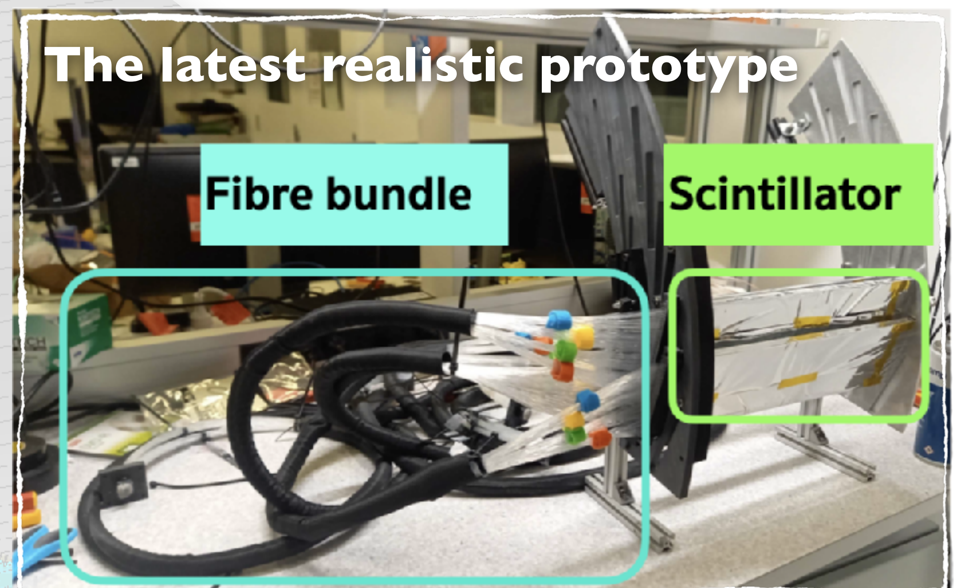


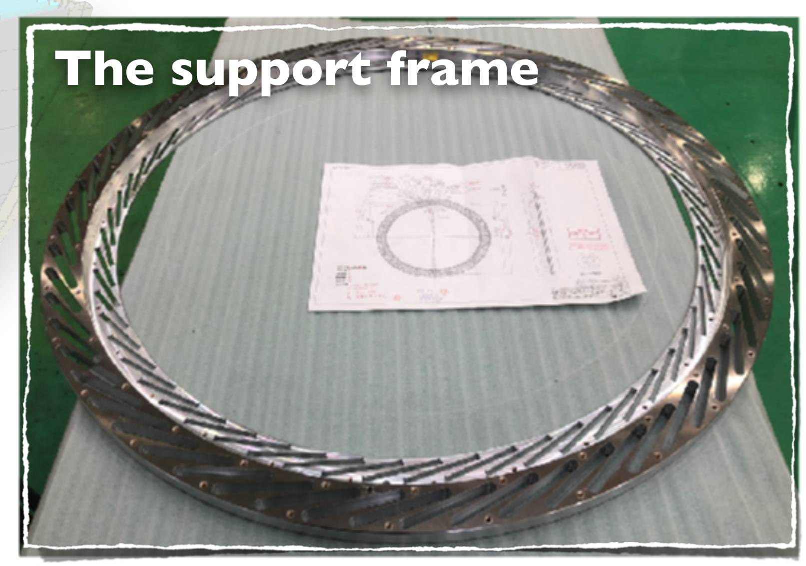
Lateral View



Design

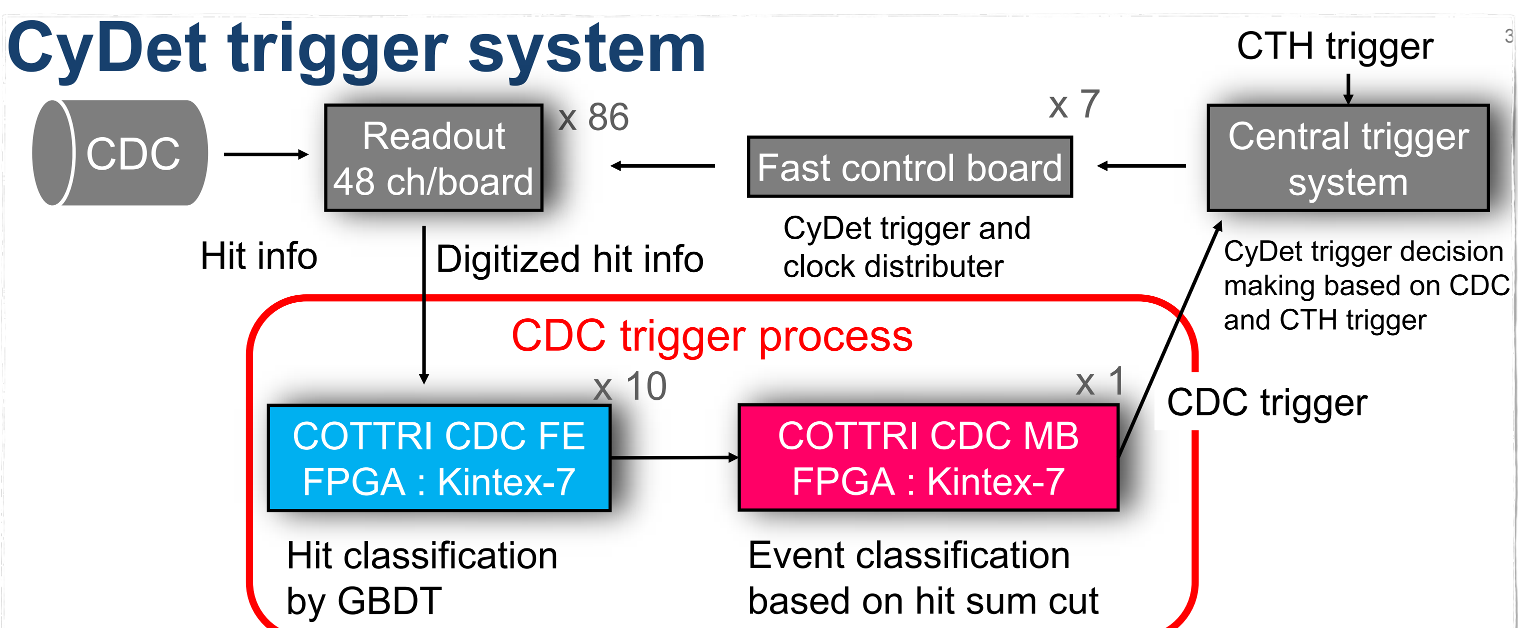
- 2×64 plastic scintillators installed at each end
  - Thickness: (inner) 5 mm (outer) 10 mm
  - Readout by MPPCs through a plastic fibre bundle.
  - > 40 p.e. for a detection efficiency > 99%
- MPPCs operated < −36 °C
- For reasonable trigger rate,
  - 4-fold coincidence
  - Inner lead shield to block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

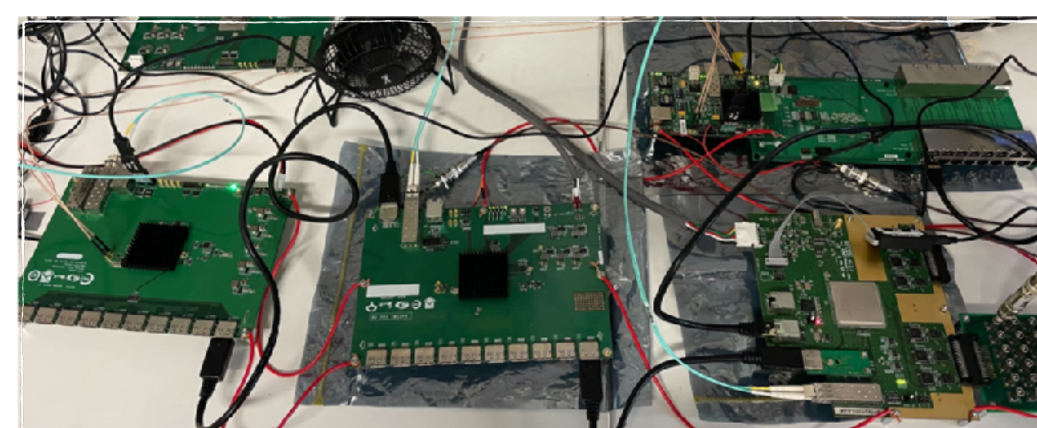




Trigger

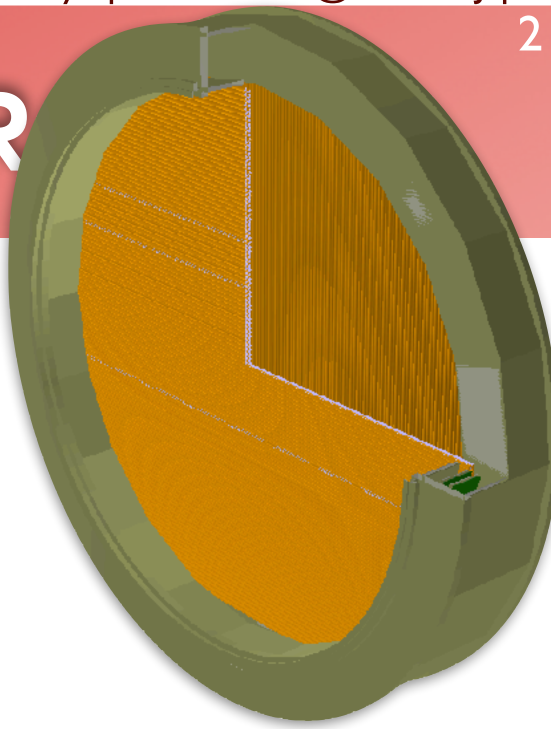
- A central board (FC7) administers trigger and readout.
  - Both the CyDet and StrECAL system can share it.
  - **FC7**: general use FPGA board supporting gigabit data transfer (developed by CMS@CERN).
- CyDet trigger is being developed to achieve a trigger rate < 13 kHz.
- Machine learning-based trigger logic on FPGA
  - Boosted decision tree for hit classification
  - Neural network for online tracking





CyDet Trigger Electronics

Straw Tube Tracker



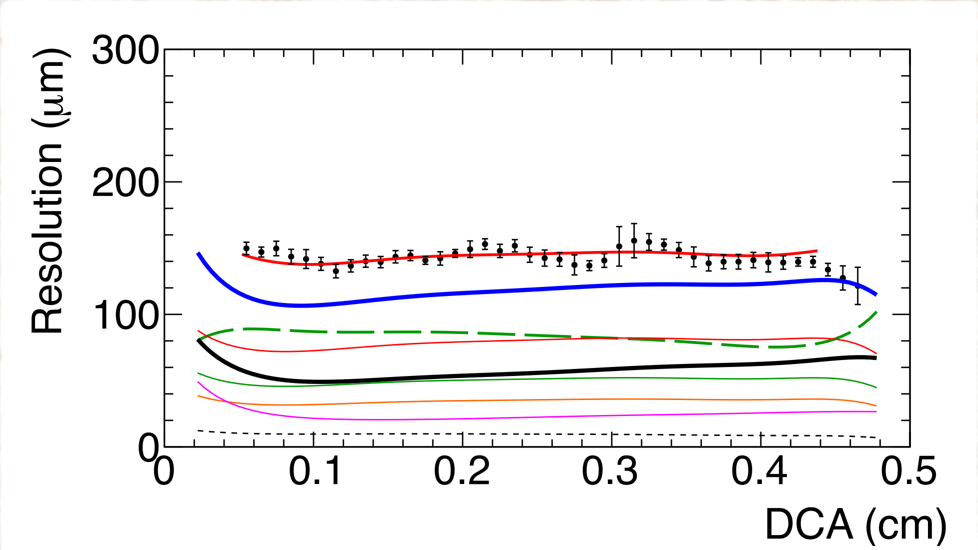
Straw station

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
  - ★ 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.



ECAL

Requirements

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

LYSO Crystal Scintillators

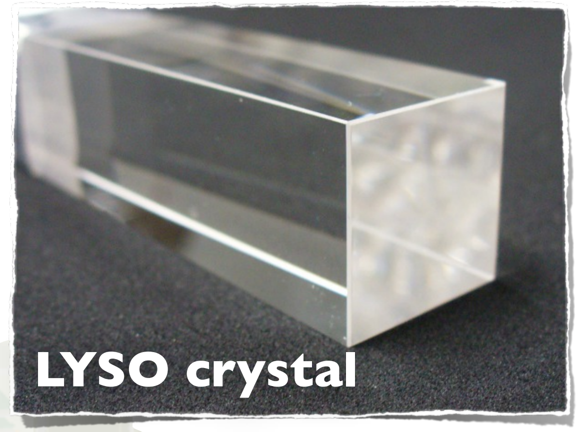
- ✦ High density (7.1 g/cm^3), high light yield (70% NaI), and fast time response (40 nsec)
- ✦ Dimension of 2×2×12 cm^3.
- ✦ Readout by 10×10 mm^2 APD + FE electronics
- ✦ ~2000 crystals (~ 1 mΦ sensitive area.)

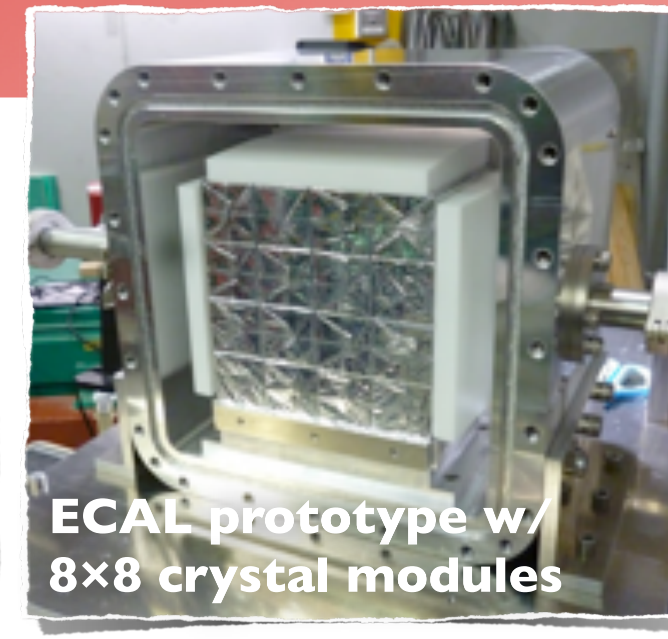
Prototype w/ 8×8 crystals

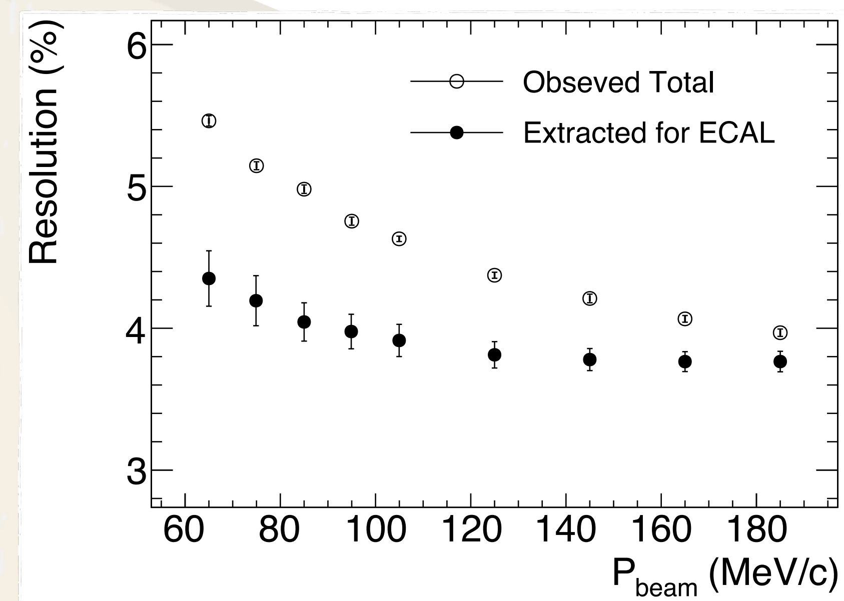
- ✦ Good performance at 105 MeV/c
  - ★ **Energy resolution of 3.9%**
  - ★ **Position resolution of 7.7 mm**
  - ★ **Timing resolution of 0.5 nsec**

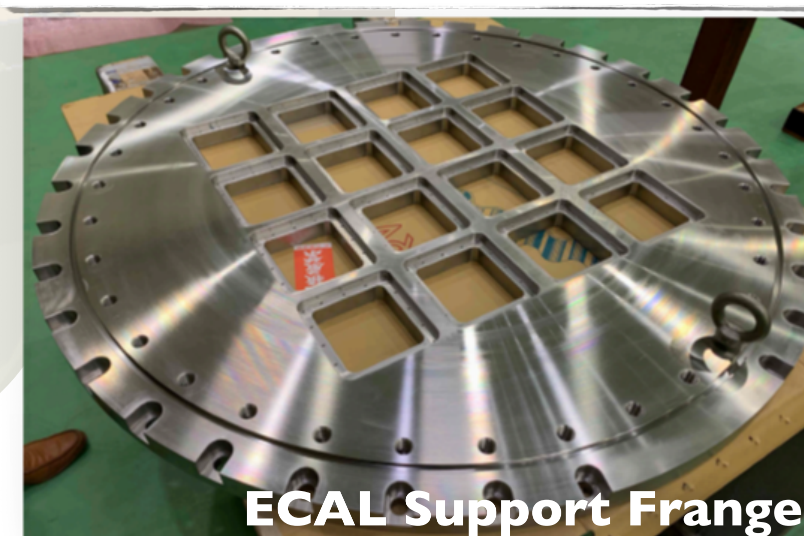
Detector construction beginning

- ✦ Quality control of the crystal modules construction

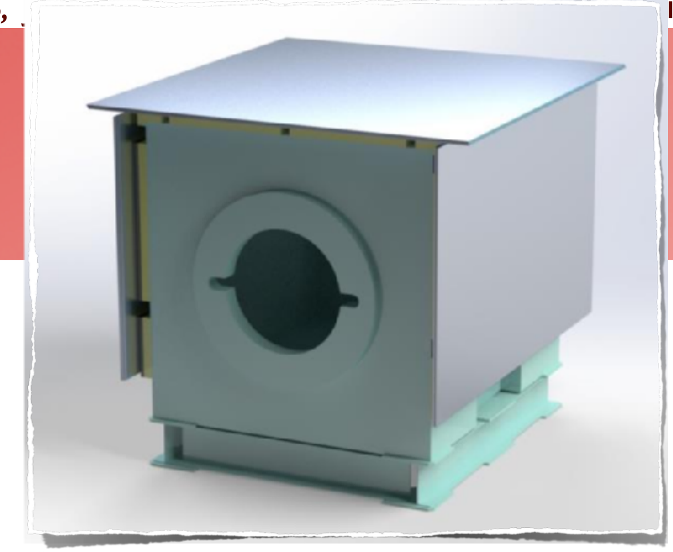


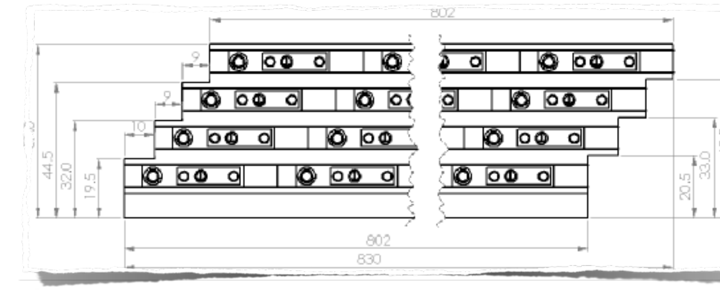




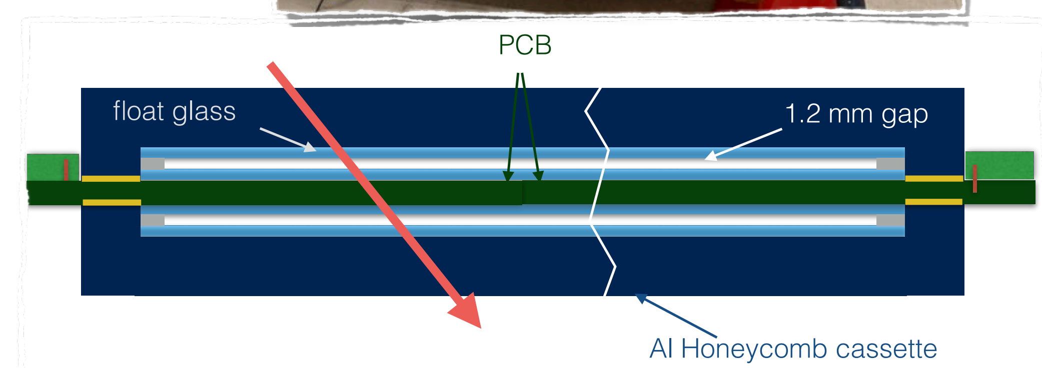


Cosmic Ray Veto





Top and side CRV module



GRPC module

Requirements

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

Design

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

1st module of the side CRV

- Being commissioned with cosmic rays to evaluate the detection efficiency

SENSITIVITY

Phase-I Sensitivity

Single Event Sensitivity (SES)

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

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

- **$N_\mu = 1.5 \times 10^{16}$** : 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)

Event selection	Value	Comments
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	103.6 MeV/c < P_e <106.0 MeV/c
Timing window ($\varepsilon_{\mathrm{time}}$)	0.3	700 ns < t < 1170 ns
Total	0.041	

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.

- P-147 **Manabu Moritsu**
  - "A study to suppress a sneaking cosmic muon background in the COMET experiment"
- P-154 **Alex Miles**
  - "Quality Control of Multi-Pixel Photon Counters Using the MPPC Integrated Light Evaluation System for the COMET Experiment"
- P-160 **Kenya Okabe**
  - "Performance evaluation of SiC muon beam monitor for COMET experiment"
- P-162 **Masaaki Higashide**
  - "Construction and basic performance evaluation of the straw tube tracker for the COMET experiment"
- P-167 **Ryo Nagai**
  - "Status of the COMET Cylindrical Drift Chamber at J-PARC"
- P-168 **Ryoka Sasaki**
  - "Performance test towards the construction of Cylindrical Trigger Hodoscope in COMET Phase-I"
- P-171 **Takahiro Mizuno**
  - "Development of MPPC cooling system for COMET trigger counter"
- P-274 **Chihiro Yamada**
  - "CyDet Trigger System for COMET Phase-I"
- P-283 **Hiroyuki Shidara**
  - "3D-Printed Aluminum Alloy Beam Window for COMET Project in Phase-I"
- P-286 **Yusuke Uchiyama**
  - "Radiation Shielding System for the COMET Pion Capture Solenoid"