Search for muon to electron conversion with COMET experiment at J-PARC

Sep. 27, 2025

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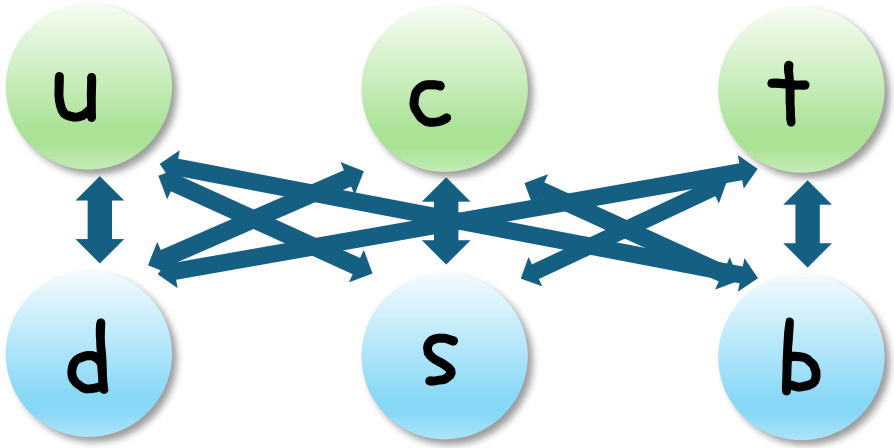
SSP2025

Introduction

Introduction

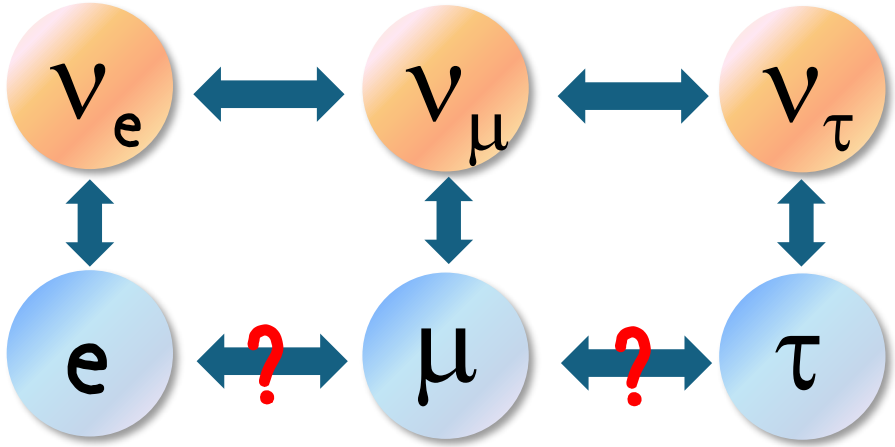
flavor mixing

quark



Established
(CKM)

lepton



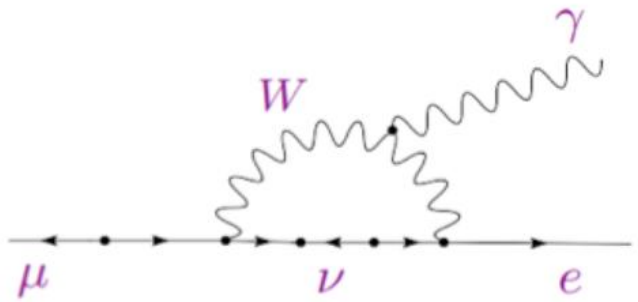
Experimentally verified
(neutrino oscillation)

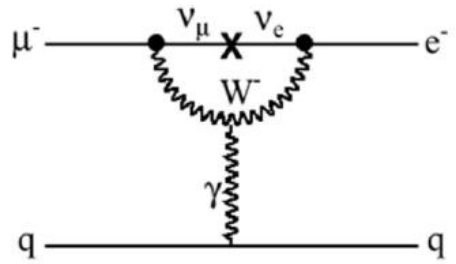
Never observed yet!

Charged lepton flavor violation (CLFV)

$\mu \to e\gamma$、$\mu^- N \to e^- N$、$\mu \to eee$ → Forbidden in the SM

SM + ν oscillation





$$\mathrm{BR}(\ell_1 \to \ell_2\gamma) = \frac{3\alpha}{32\pi}\left|\sum_{j=1}^{3} U_{\ell_1 j} U^*_{\ell_2 j} \frac{m^2_{\nu_j}}{M^2_W}\right|^2 \cong \mathcal{O}(10^{-55} - 10^{-54})$$

$$R_{\mu e} = \frac{\Gamma(\mu \to e)}{\Gamma(\mathrm{capture})} \cong \mathrm{O}(\alpha) \times \mathrm{BR}(\mu \to e\gamma) \lesssim 10^{-54}$$

Branching ratio(BR) ~O(10^{-54})　Impossible to observe…

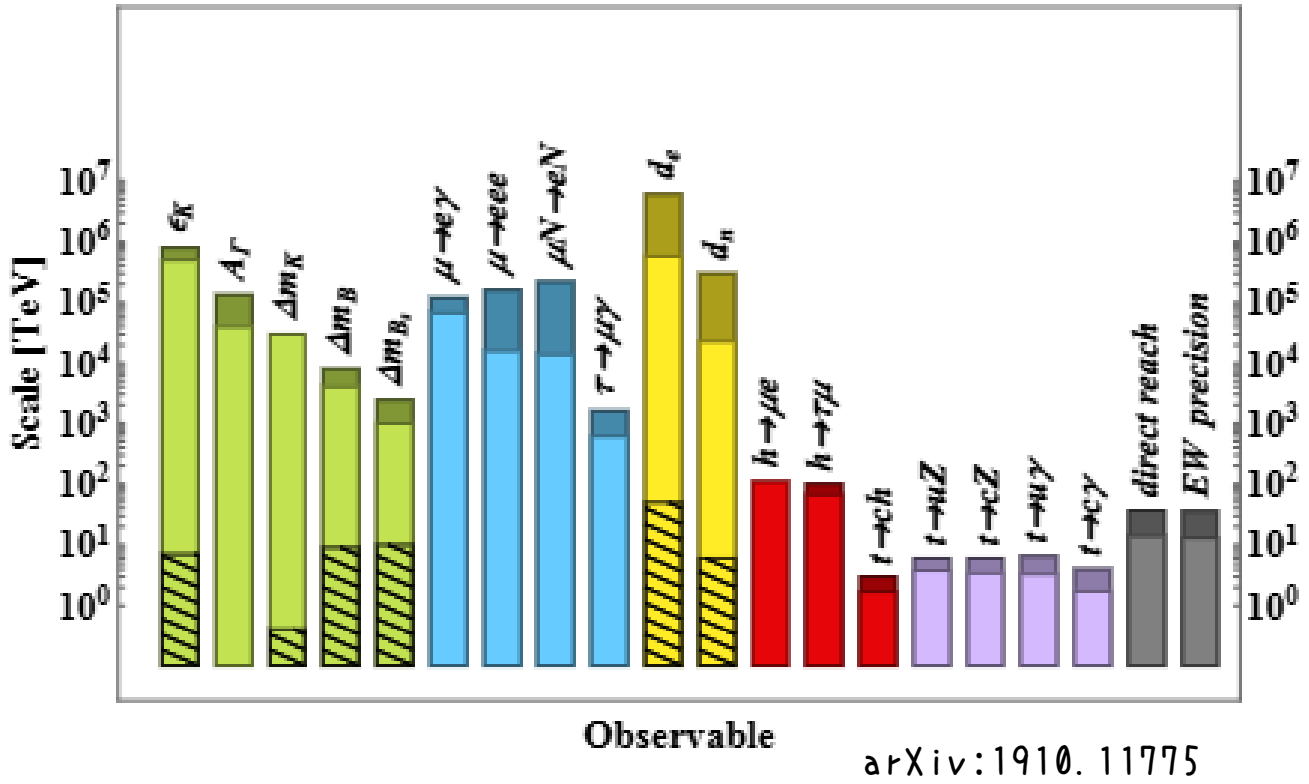
Discovery of CLFV -> Beyond Standard Model(BSM)

How much sensitive to BSM

Table 8
"DNA" of flavour physics effects for the most interesting observables in a selection of SUSY and non-SUSY models ★★★ signals large effects, ★★ visible but small effects and ★ implies that the given model does not predict sizable effects in that observable.

	AC	RVV2	AKM	δLL	FBMSSM	LHT	RS
$D^0-\bar{D}^0$	★★★	★	★	★	★	★★★	?
ϵ_K	★	★★★	★★★	★	★	★★	★★★
$S_{\psi\phi}$	★★★	★★★	★★★	★	★	★★★	★★★
$S_{\phi K_S}$	★★★	★★	★	★★★	★★★	★	?
$A_{CP}(B\to X_s\gamma)$	★	★	★	★★★	★★★	★	?
$A_{7,8}(B\to K^*\mu^+\mu^-)$	★	★	★	★★★	★★★	★★	?
$A_9(B\to K^*\mu^+\mu^-)$	★	★	★	★	★	★	?
$B\to K^{(*)}\nu\bar{\nu}$	★	★	★	★	★	★	★
$B_s\to\mu^+\mu^-$	★★★	★★★	★★★	★★★	★★★	★	★
$K^+\to\pi^+\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$K_L\to\pi^0\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$\mu\to e\gamma$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
$\tau\to\mu\gamma$	★★★	★★★	★	★★★	★★★	★★★	★★★
$\mu+N\to e+N$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
d_n	★★★	★★★	★★★	★★	★★★	★	★★★
d_e	★★★	★★★	★★	★	★★★	★	★★★
$(g-2)_\mu$	★★★	★★★	★★	★★★	★★★	★	?

W. Altmannshofer et al. Nucl. Phys. B 830(2010)17

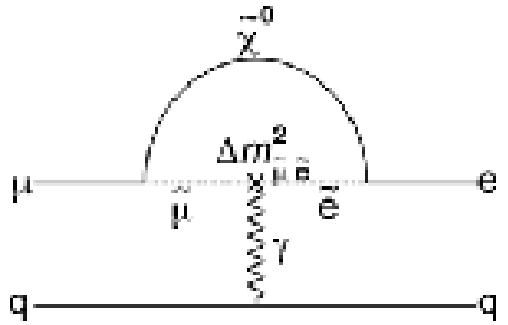


arXiv:1910.11775

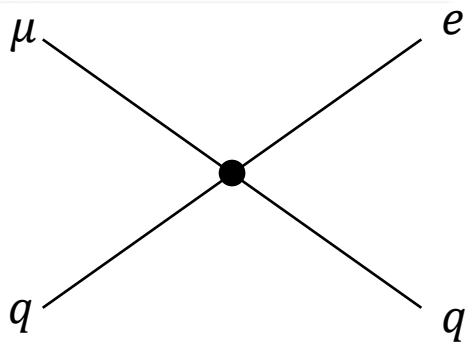
Muon LFV experiments are sensitive to many BSM models and very high NP scale.

μ→eγ、 μ⁻N→e⁻N

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



photonic

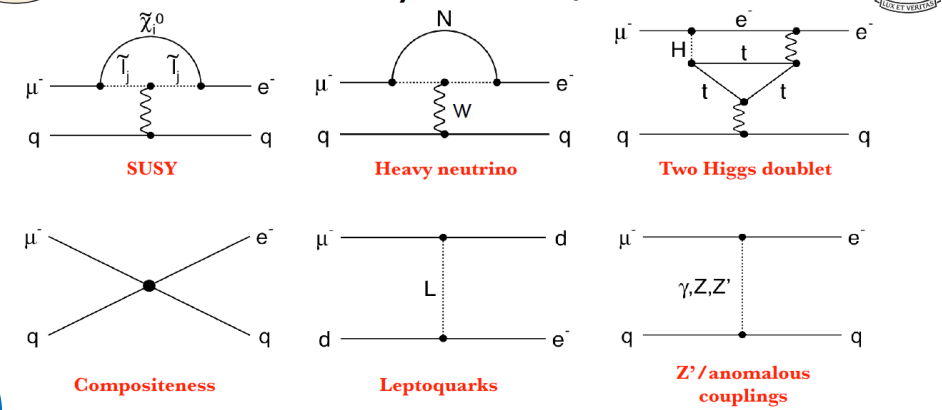


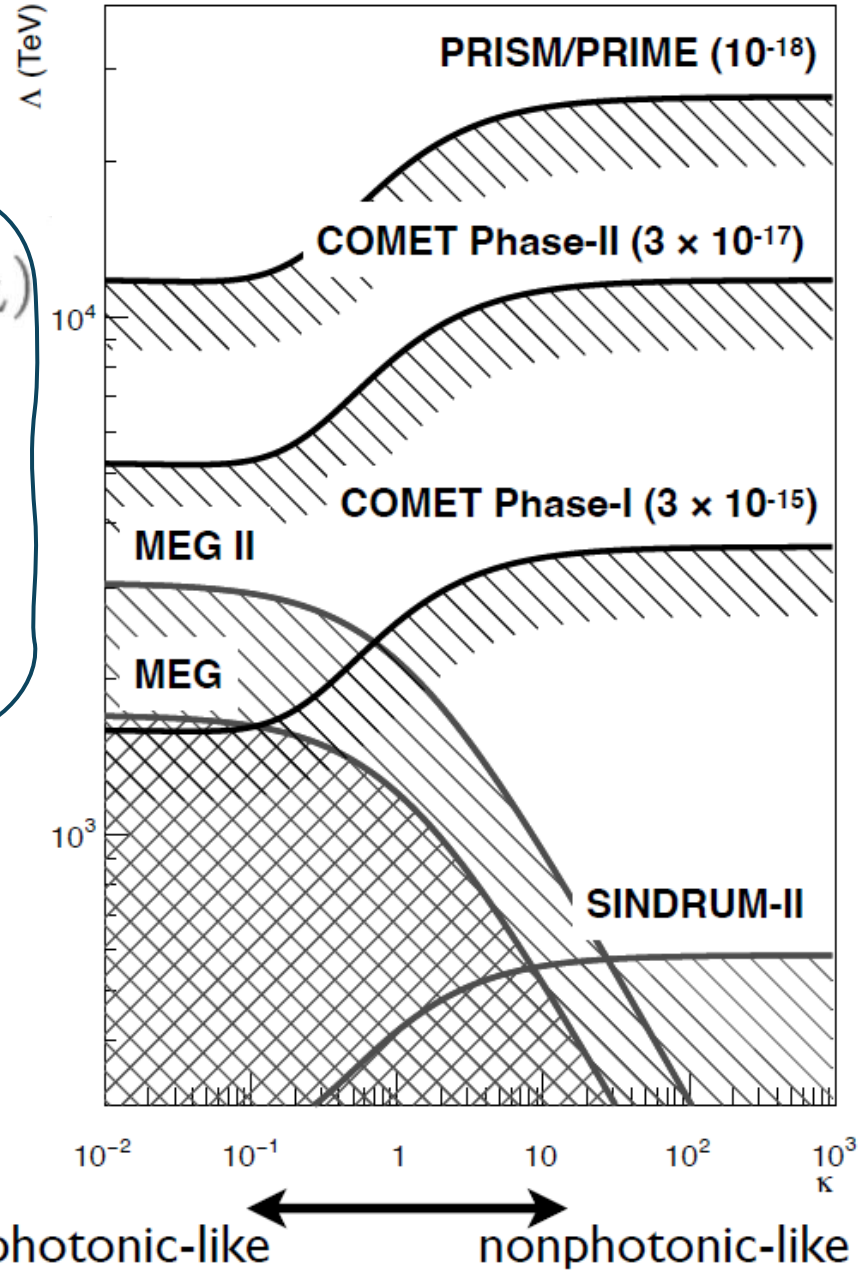
non-photonic

Examples of BSM
(μ⁻N→e⁻N)
SUSY-GUT
SUSY-SEASAW
Little Higgs
Leptquarks
etc…

BR~O(10⁻¹⁵)

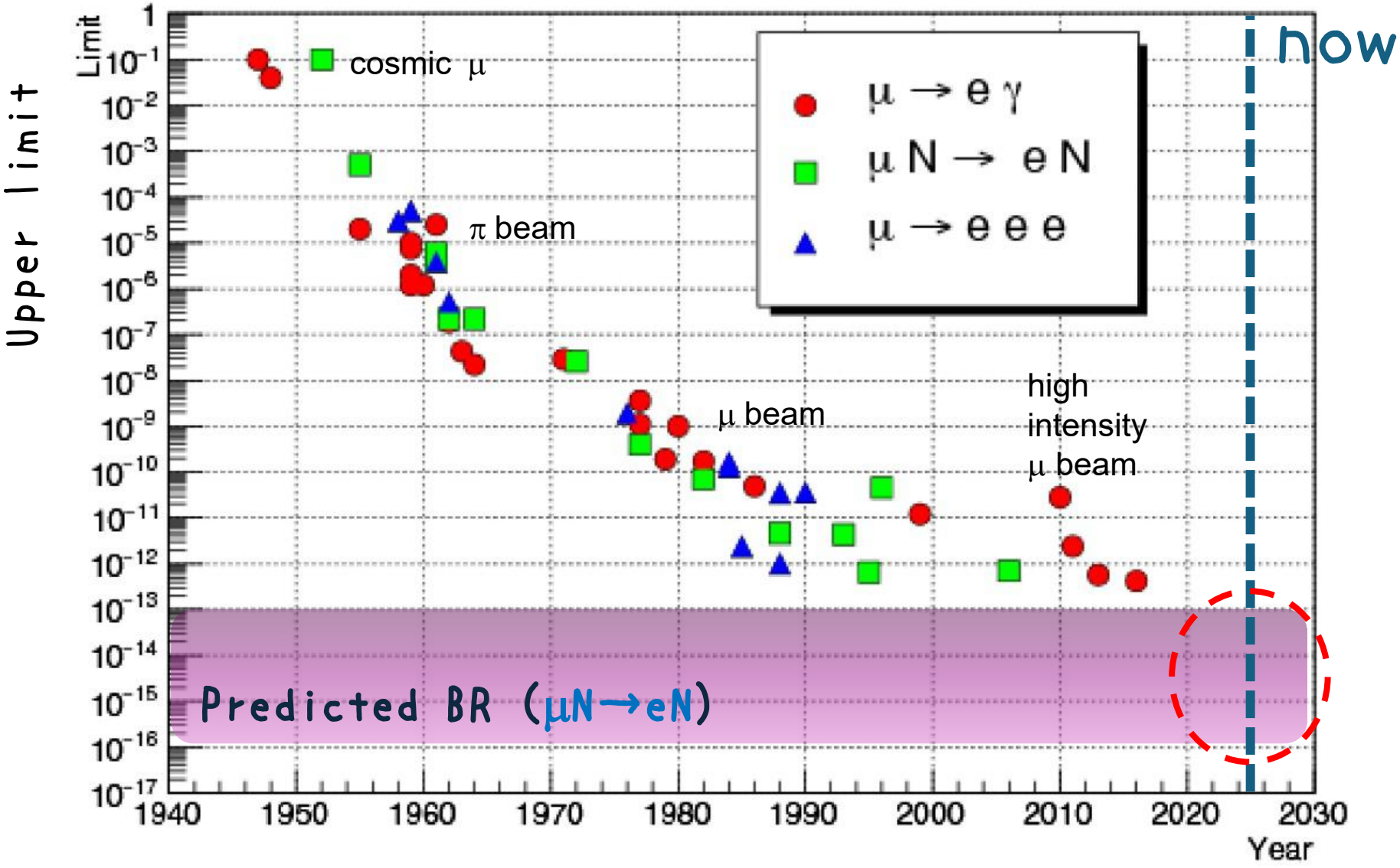
New Physics and μ→e





- Any signal observation would be an unambiguous sign of **New Physics**

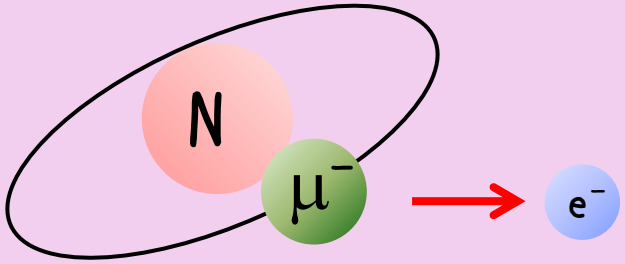
History of CLFV search



F. Renga, Rev. Phys. 4, 100029(2019) (partially added)

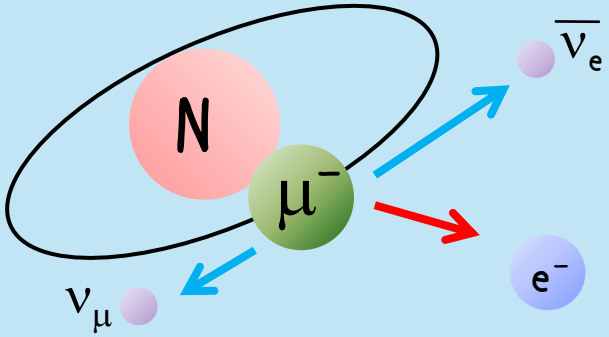
Measurement of μ-e conversion

Signal



- mono-energetic electron
  $E_e = m_\mu - B_\mu \sim 105$ MeV (N=Al)
- Coherent process

BGs

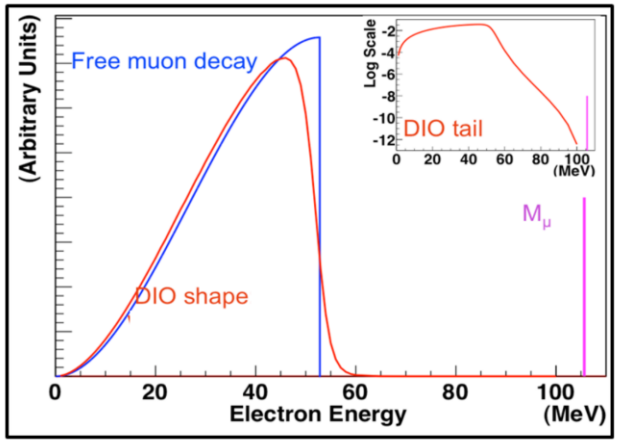


- Decay in Orbit (DIO)
- Radiative π/μ-capture
- Decay in Flight (DIF)
- Cosmic-rays

Current limit BR < 7×10^{-13} (90% C.L. by SINDRUM-II@PSI, N=Au)

Issues

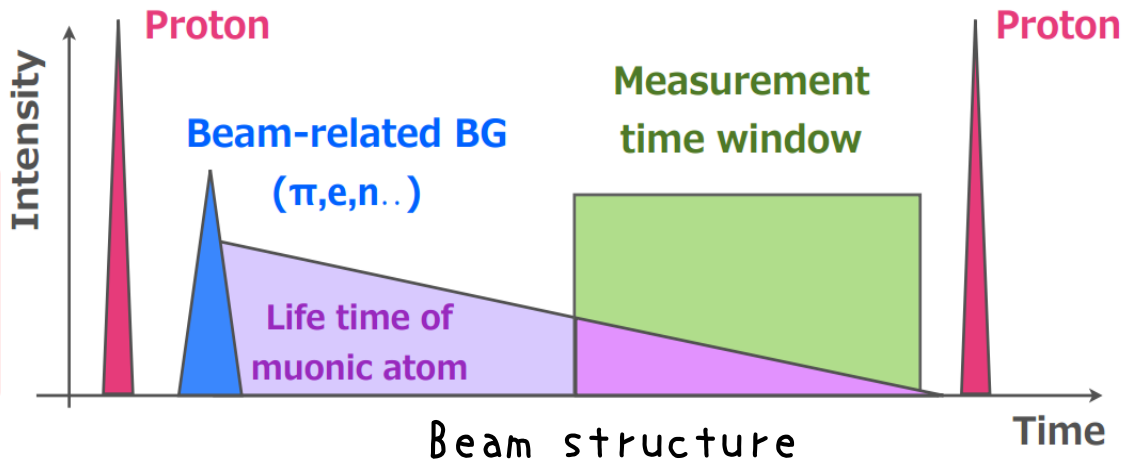
① high intensity (HI) μ beam
② BG reduction
③ high res. detector

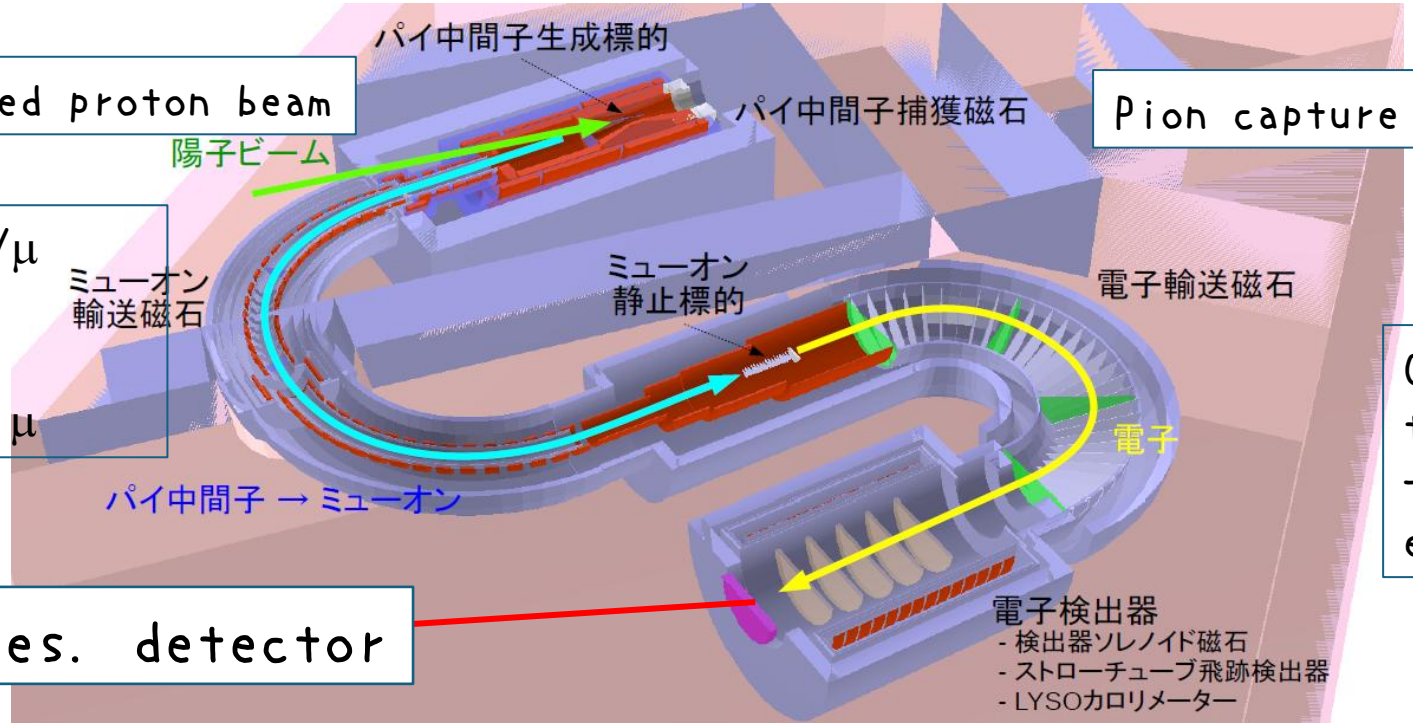


COMET Search for μ-e conversion@J-PARC

Solutions

① J-PARC high intensity beam
② Pulsed beam, Transport solenoid
③ New detector





HI pulsed proton beam

Pion capture solenoid

Curved π/μ solenoid -> low momentum μ

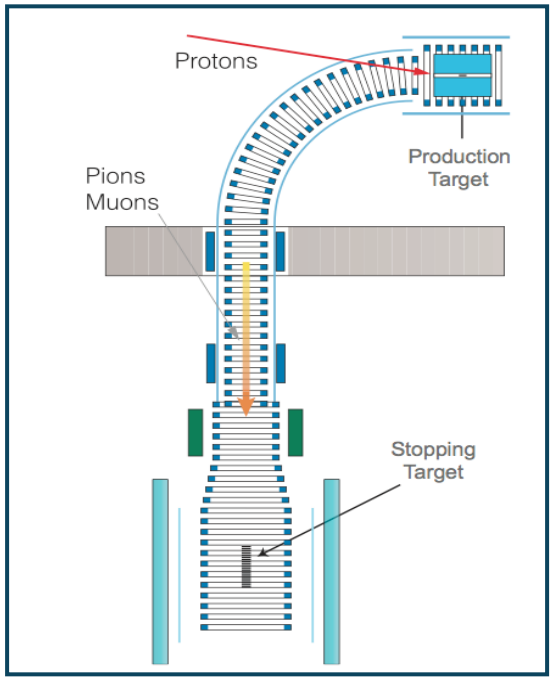
Curved electron transport solenoid -> high momentum electron

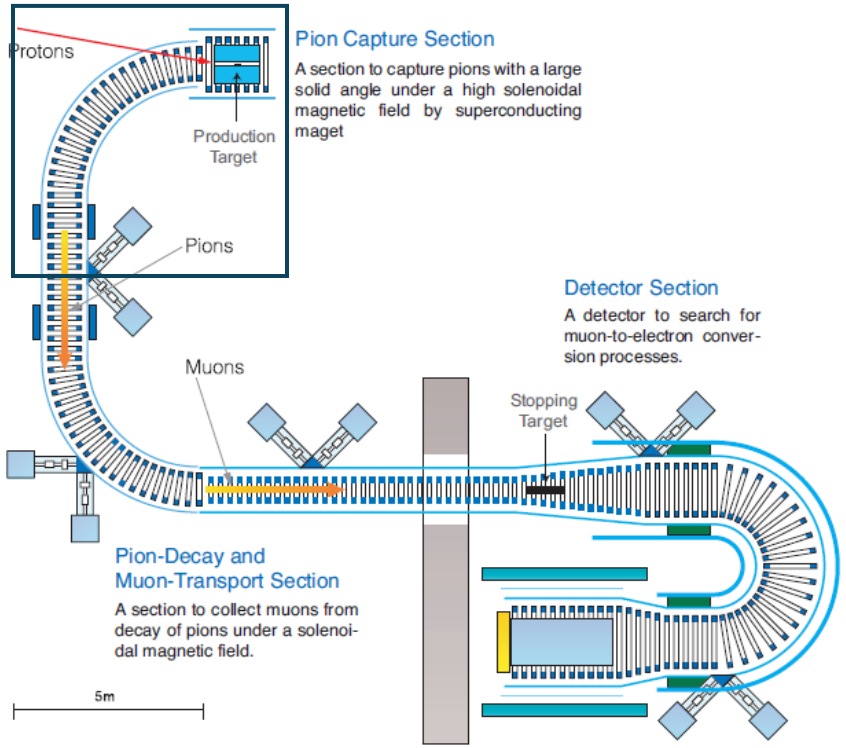
High res. detector

Goal sensitivity (SES) : 3×10^{-17} (x10000 better)

COMET experiment

Staging approach





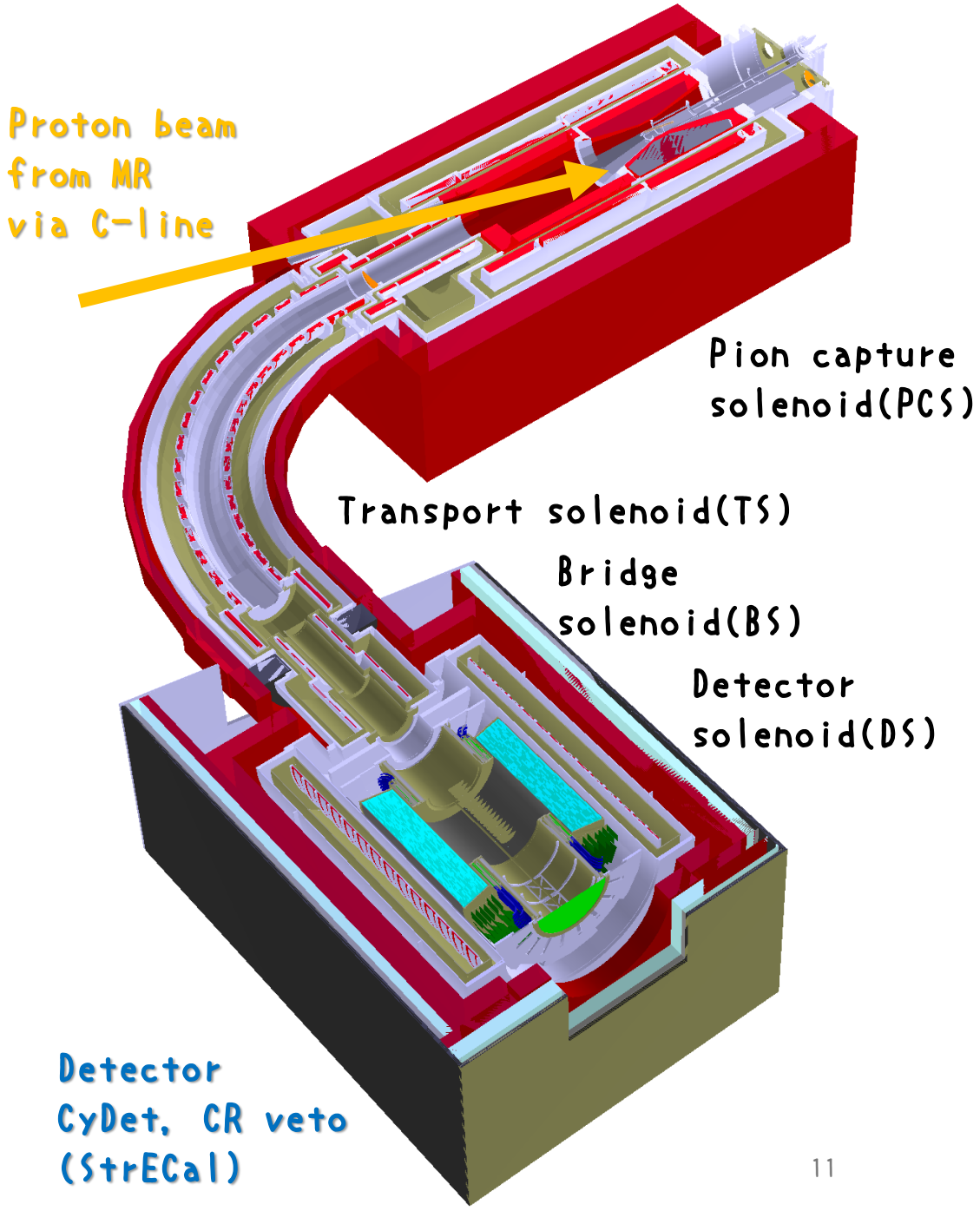
	Phase-I (2027)	Phase-II (2030's)
Single Event Sensitivity	$<10^{-14}$ (x100 improvements of current limit)	$<10^{-16}$ (x10000 improvements of current limit)
Beam power	3.2 kW	56 kW

+ Beam measurement w/ Phase-II detector

COMET Phase-I

- Physics run
  - Sensitivity $O(10^{-15})$
  - Detector : CyDet
- Beam measurement
  - Including R&D for Phase-II
  - Detector : StrECal

Preparations for Phase-I are progressing.



Current status of COMET Phase-I

COMET collaboration

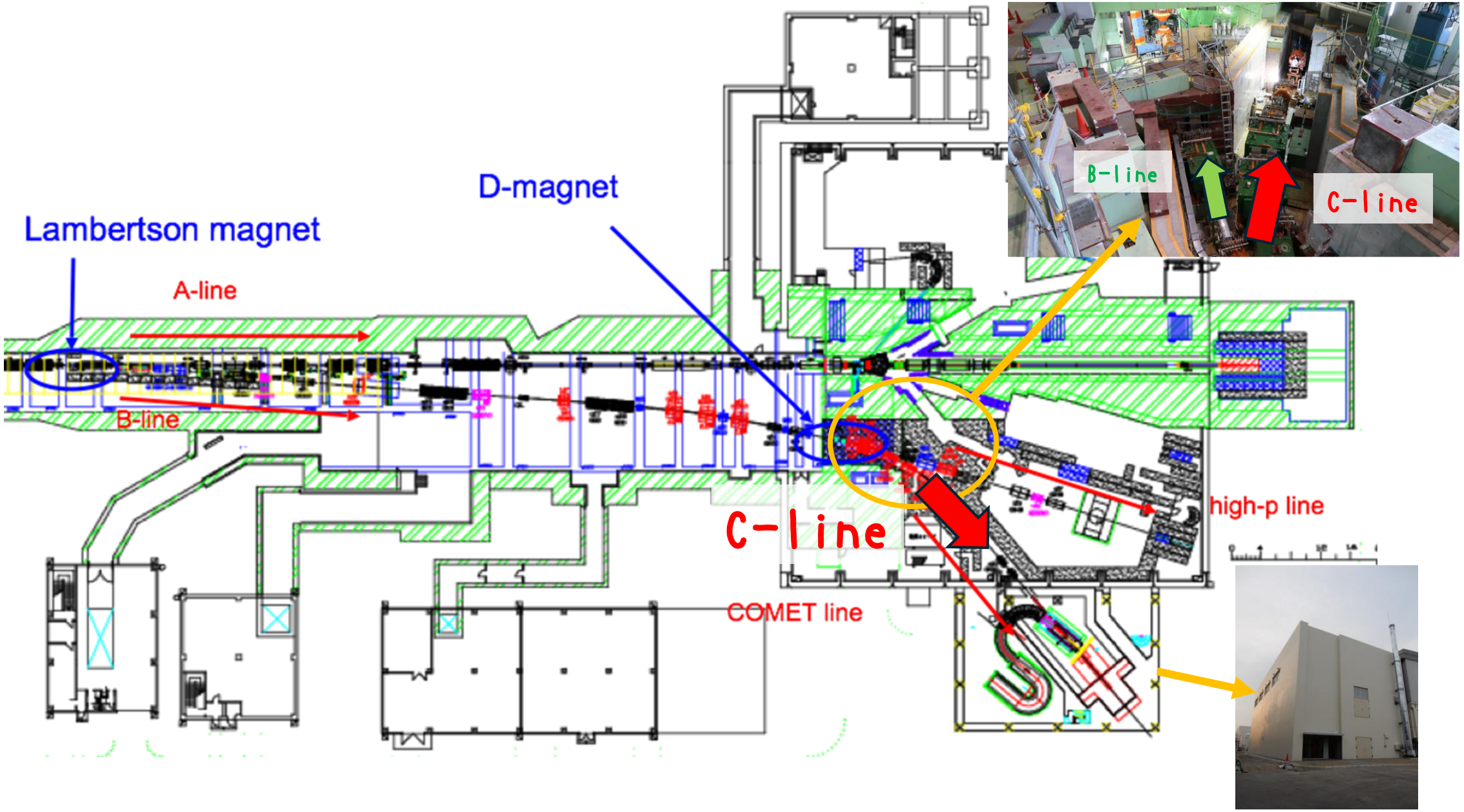
44th Collaboration meeting
at J-PARC (Nov. 2024)

46th Collaboration meeting
at LPCA (Jun. 2025)

>200 collaborators
17 countries


J-PARC
Hadron Experiment Facility
COMET
Material/Life-Science Facility (MLF)
(muon source, pulse neutron source)
Accelerator-driven
Transmutation exp facility
Neutrino Experiment Facility
(T2K, towards SK)
Linac
(330m, 400MeV)
3GeV Synchrotron (RCS)
(350m ring, 25Hz, 1MW)
30GeV Synchrotron (MR)
(1600m ring, 0.75MW)

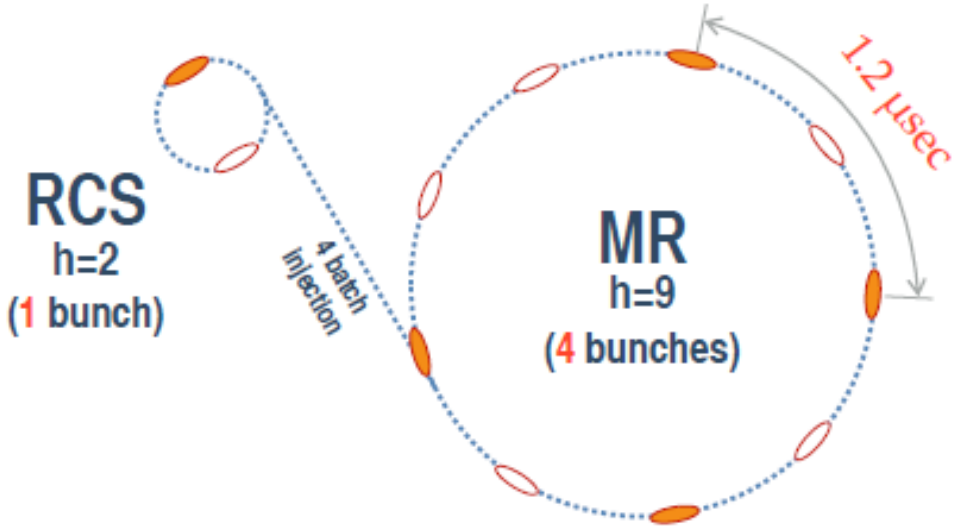
COMET beam line at J-PARC HD

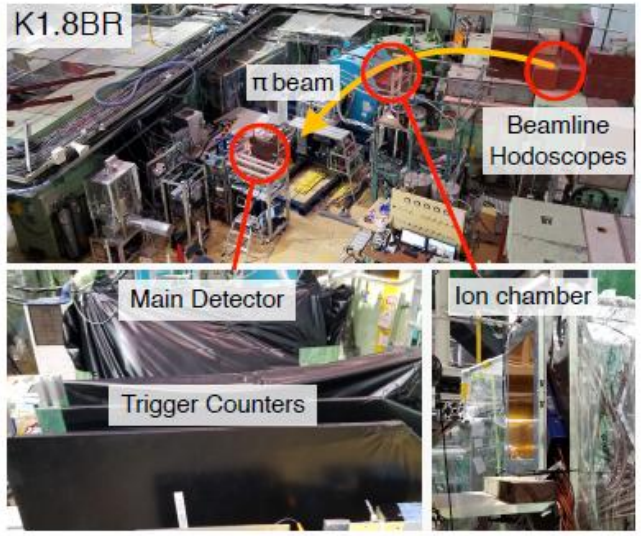


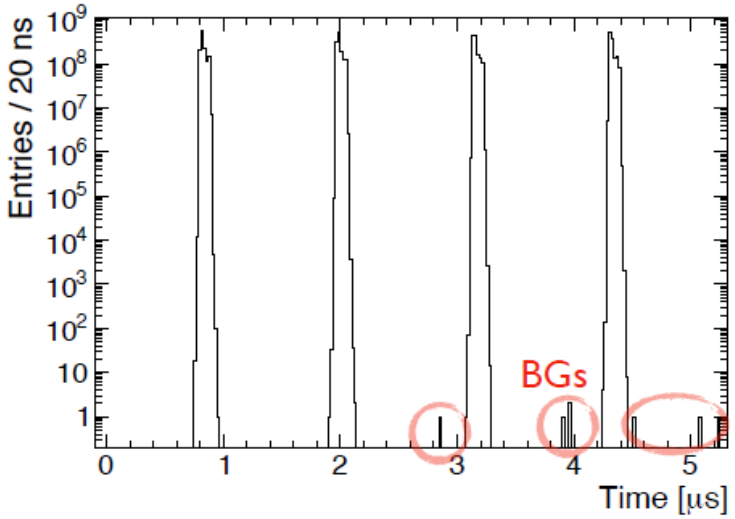
Proton beam

- J-PARC proton beam
  - Accelerated up to 8 GeV
    - To minimize antiproton
  - Bunched slow extraction
    - 4 out of 9 buckets
    - Extinction < 10^{-10}

    fraction of residual protons
- Measured extinction
  - @K1.8BR of HD(T78 in 2021)
  - < 1.0×10^{-10}





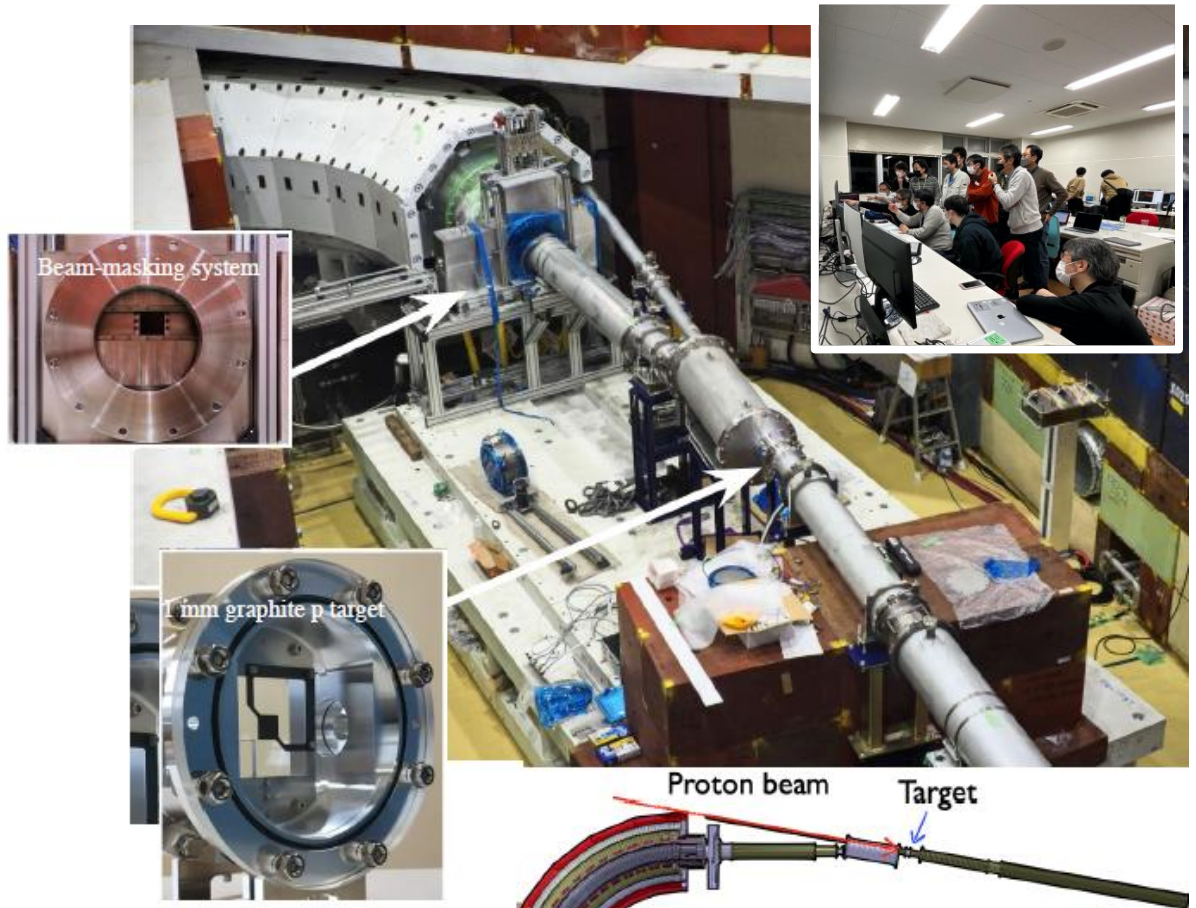


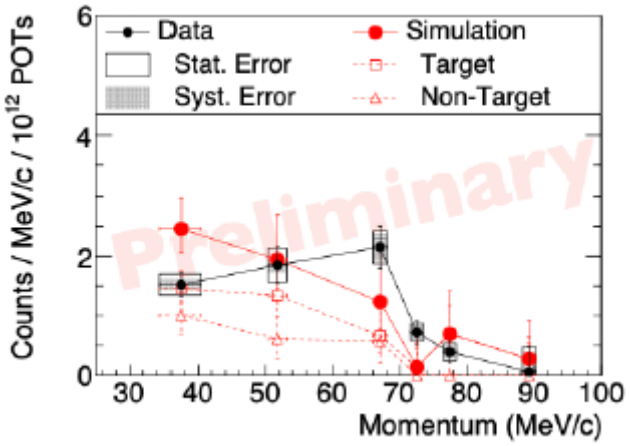
High purity beam enabled by J-PARC!

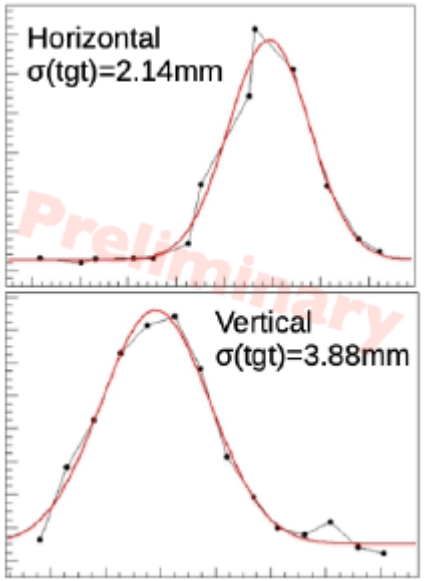
COMET Phase-α

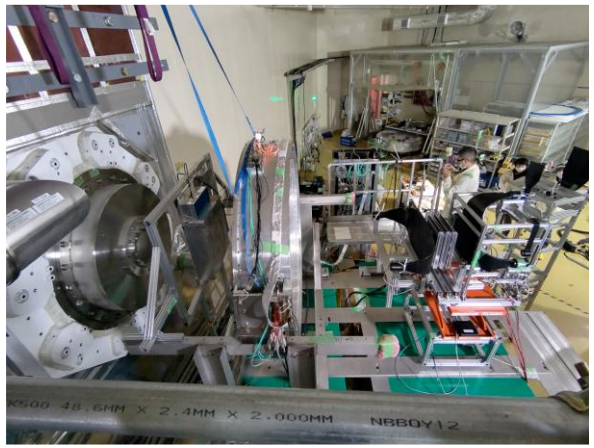
first proton beam in COMET hall

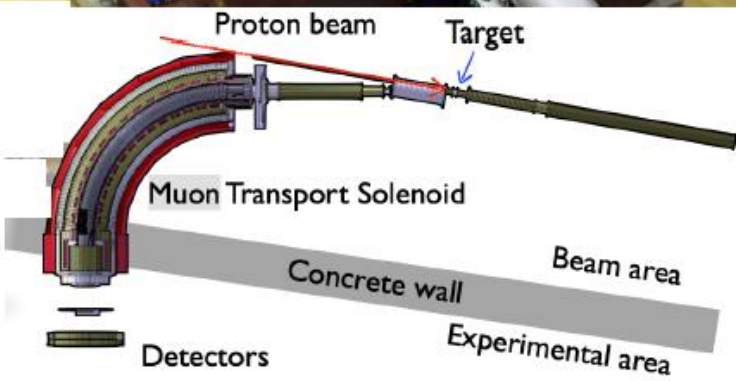
- The 1st commissioning of the COMET beam line (HD C-line) was already done in 2023.
- The muon beam was successfully transported to detector area.



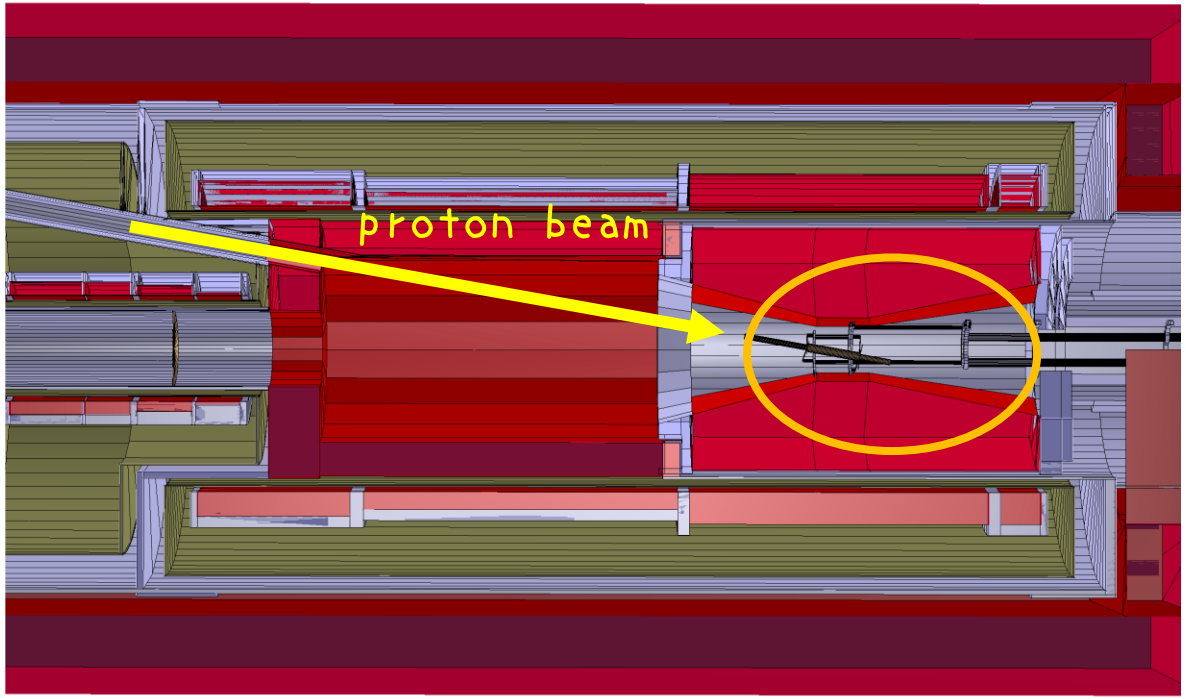


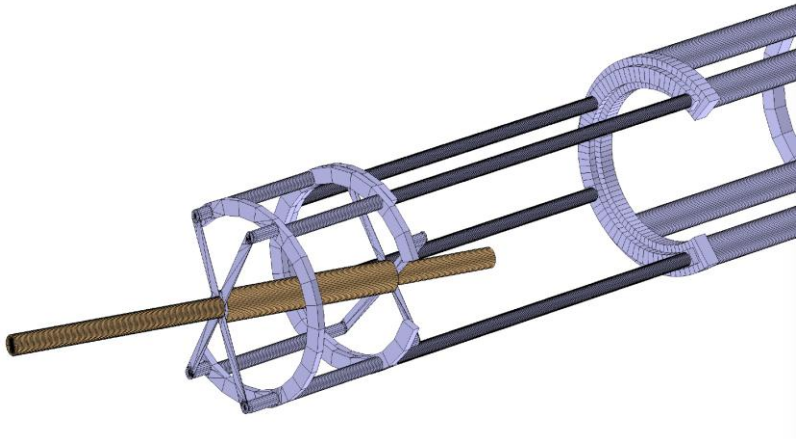


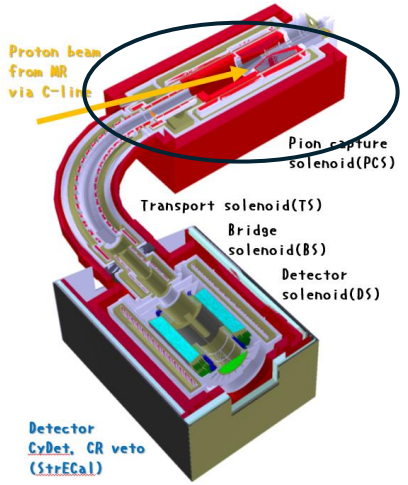


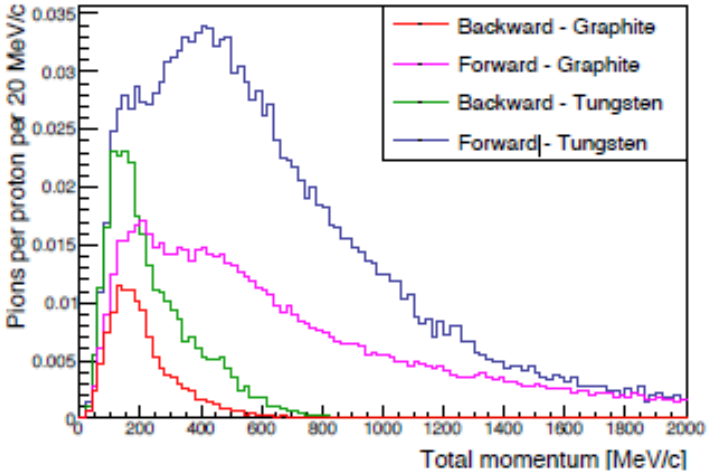


Proton target





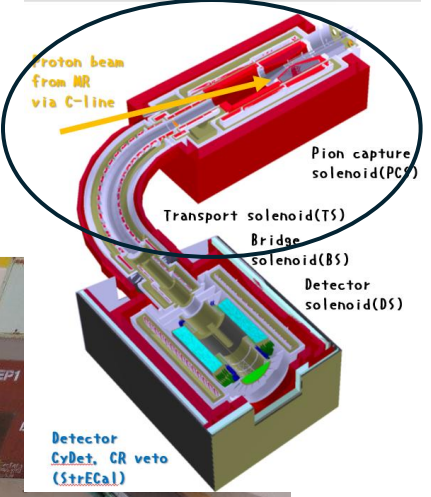




Target : Graphite (Tungsten for Phase-II)
in Pion Capture Solenoid(PCS) with 4-5 T B-field.

Design work was almost done.

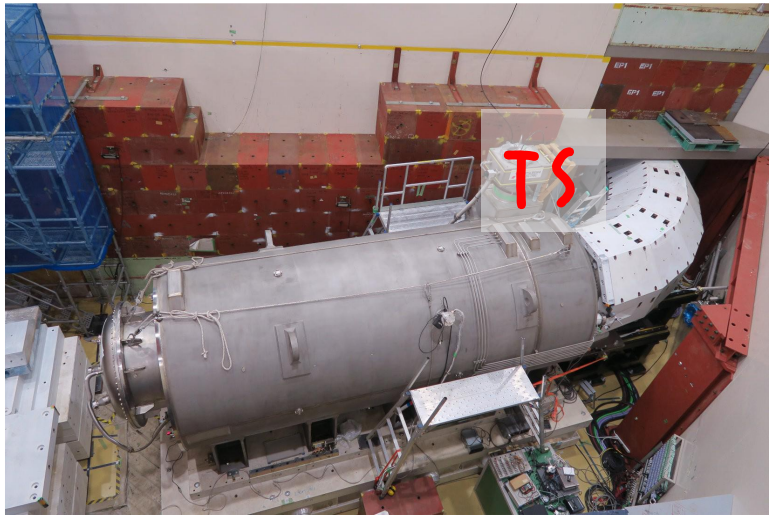
Pion Capture Solenoid (PCS)

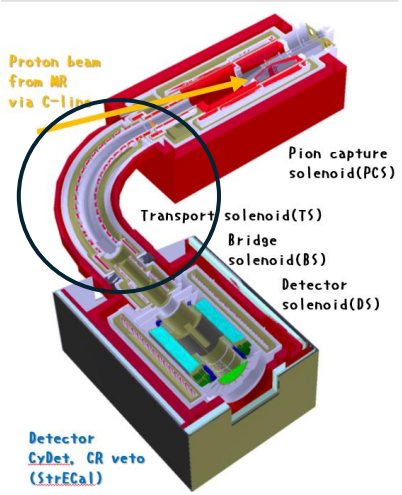


PCS was installed last November.

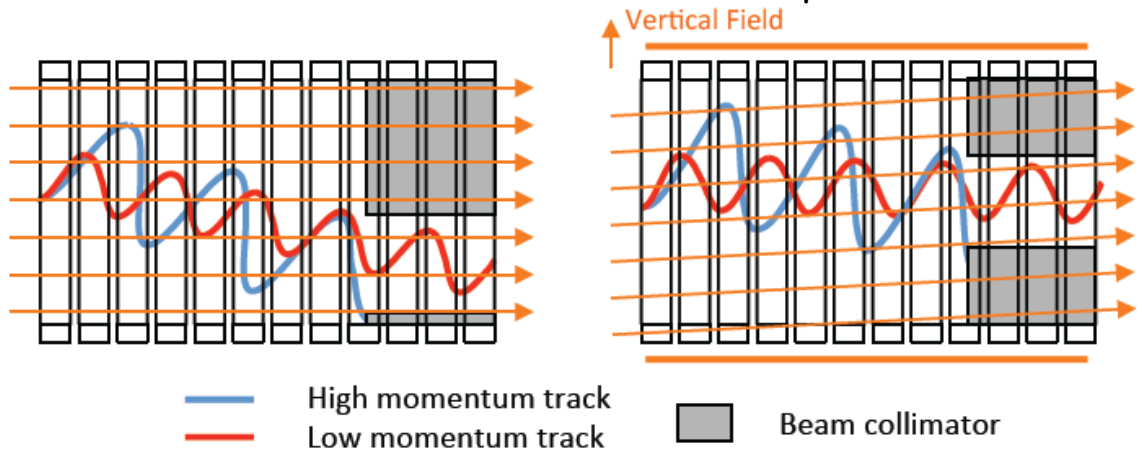
Muon Transport

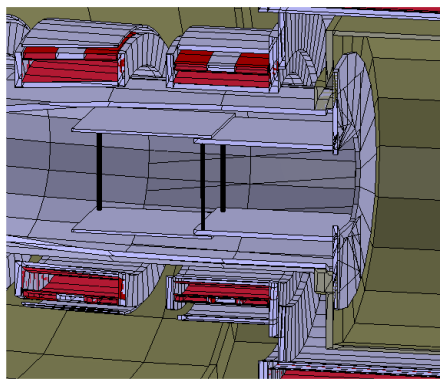
- 90 deg. curved transport solenoid (TS).
- Low-p particles are selected and high-p particles are rejected using the TS with additional dipole field.
- TS operation was successfully confirmed in Phase-α
- Beam collimator design was done.

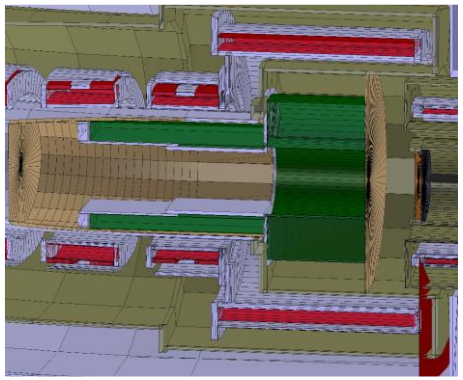




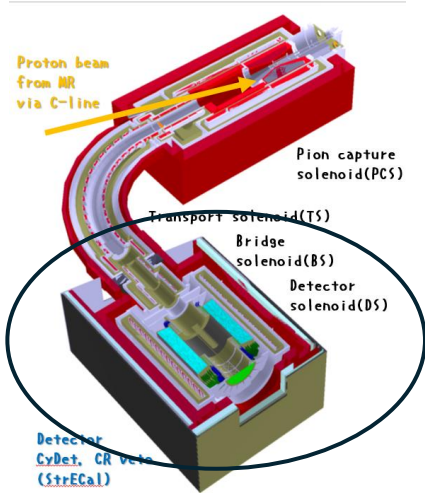
3 T + ~0.04 T dipole

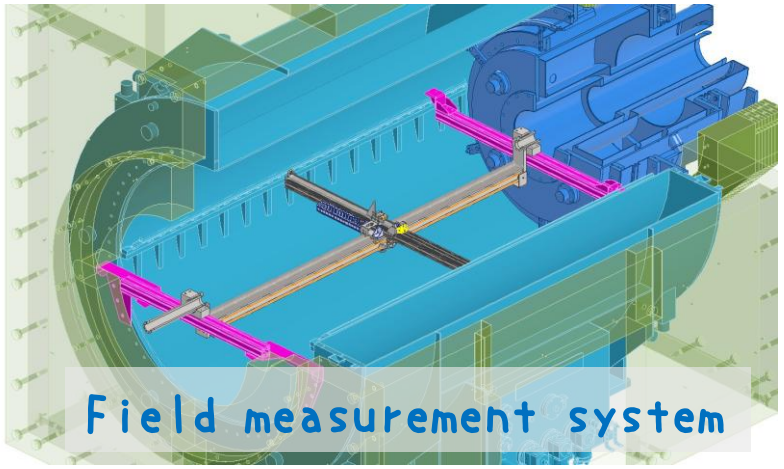






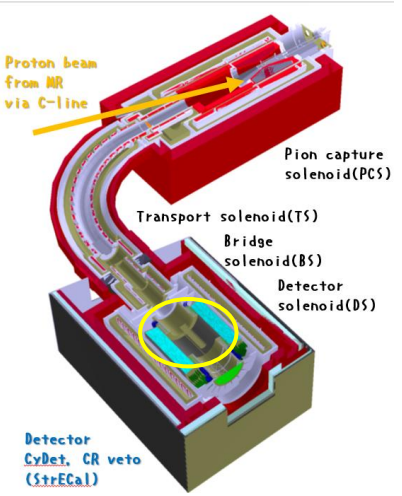
Detector Solenoid (DS)& Bridge Solenoid (BS)





- DS was delivered to KEK in 2024.
- BS was delivered to J-PARC in 2022.
- Installation in COMET hall is ongoing.
- Field measurement will follow.

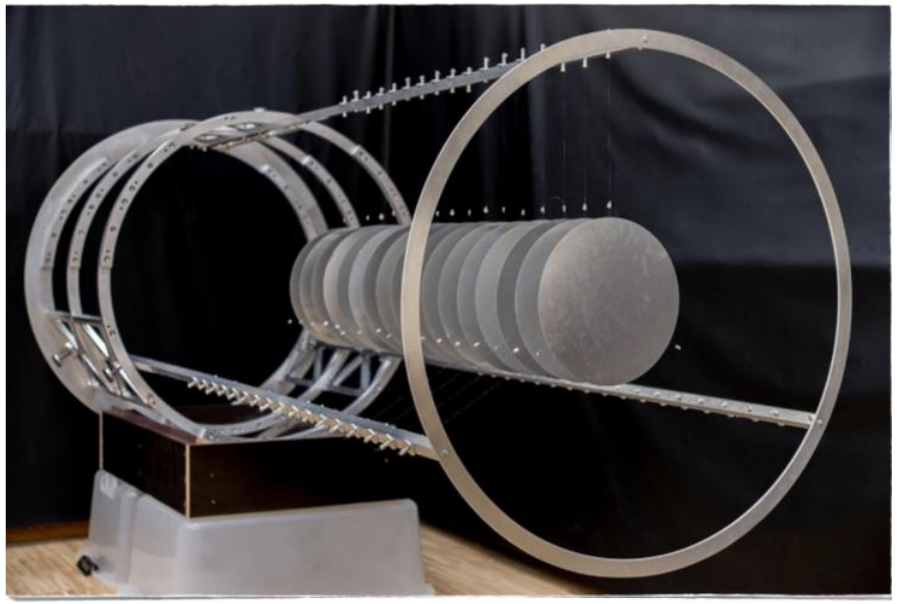
Muon stopping target



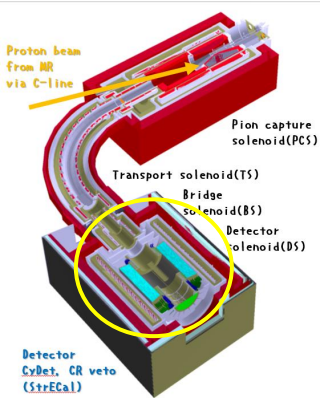
Al target

- 17 discs
- 10 cm radius, 200 μm thickness, 50 mm spacing.
- Prototype was constructed.

- 4.7×10^{-4} μ/proton for Phase-I
- Optimization is underway.



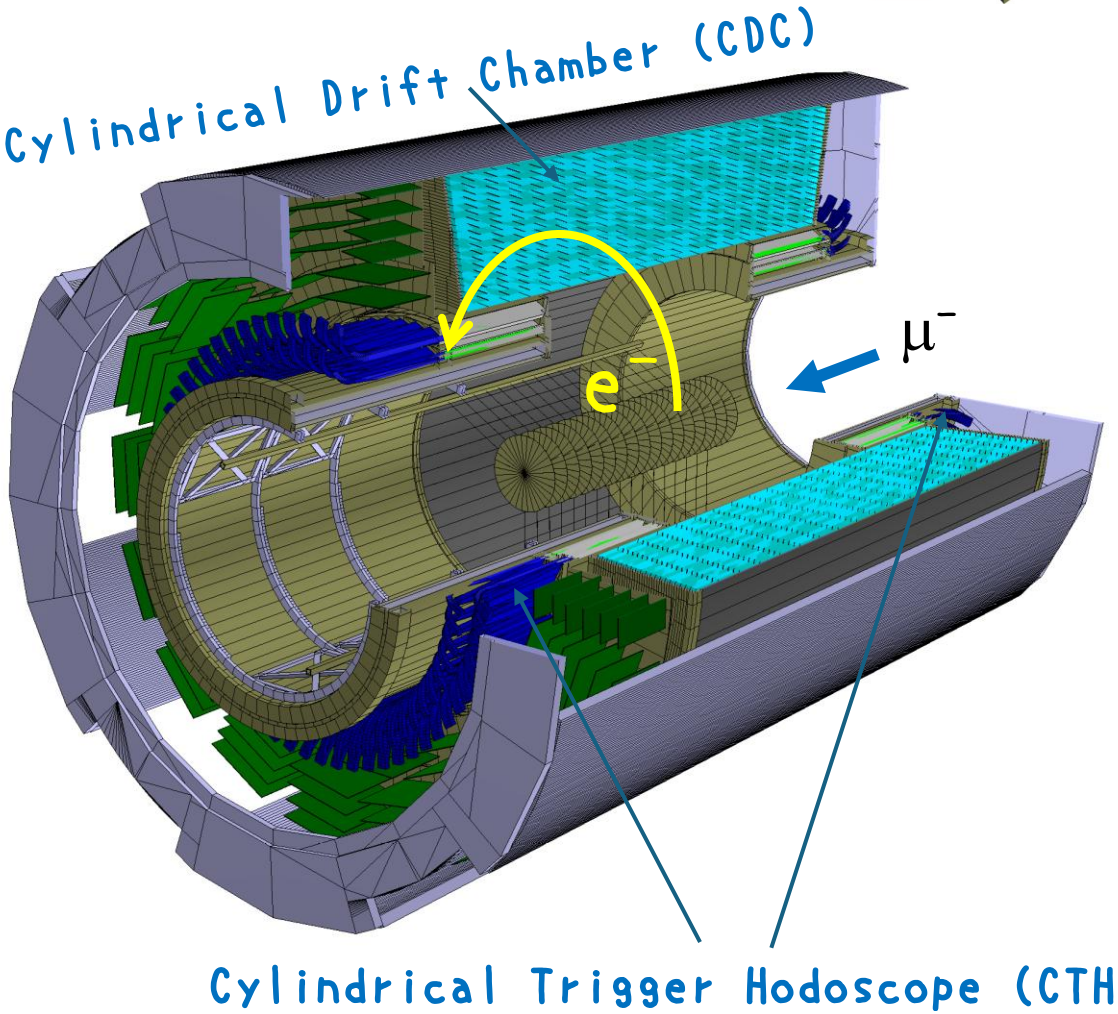
Physics Detector: CyDet (Cylindrical Detector System)



Detector surrounds muon stopping target.

- High hit rate
- High radiation level

- Cylindrical Drift Chamber (CDC)
  - Electron tracking -> momentum
- Cylindrical Trigger Hodoscope (CTH)
  - Triggering
  - Timing measurement

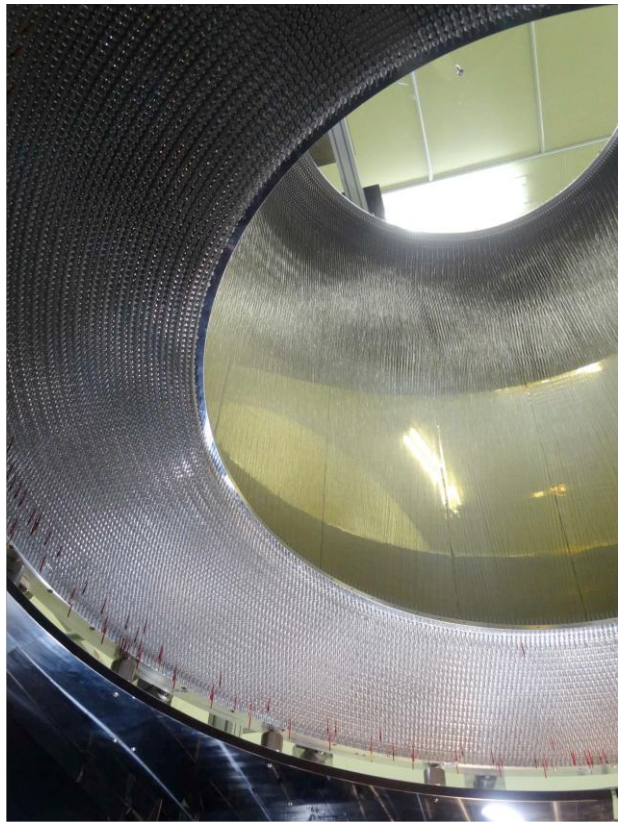


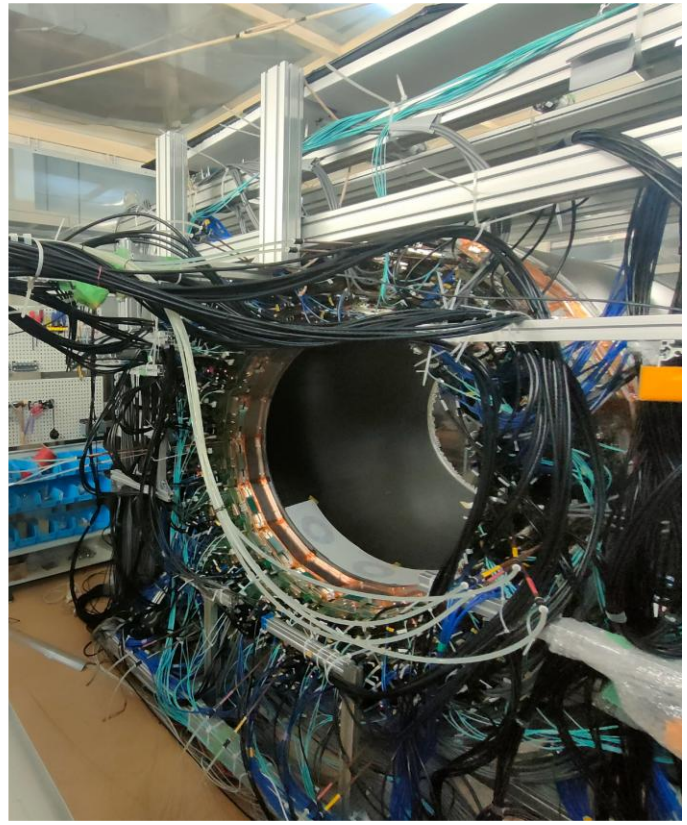
CDC

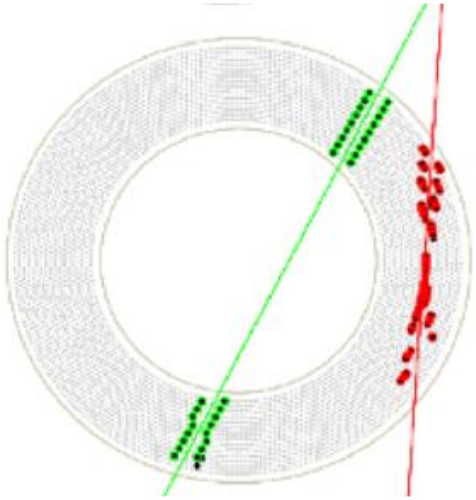
- Drift chamber
- He:iso-C_4H_{10}=90:10
- ~5000 sense wire
  - full stereo angle
- ~250 cells +20 layers
- Momentum res.
  - < 200keV/c

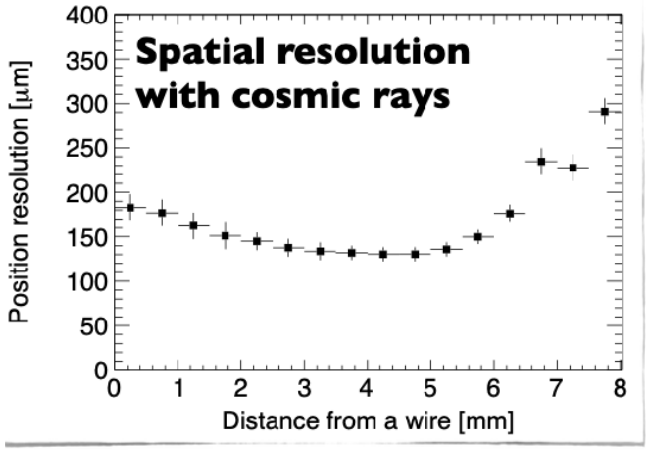
Basic performance test with cosmic rays has been done.

Full readout test, construction of gas system are ongoing.



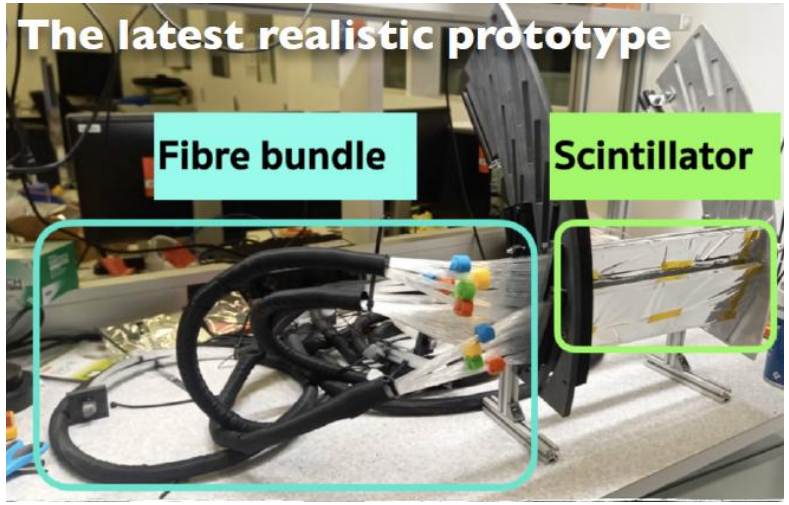


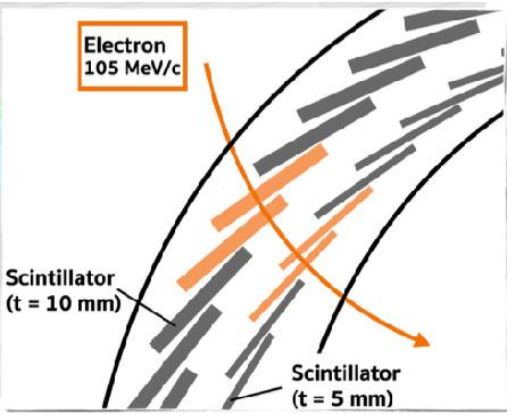


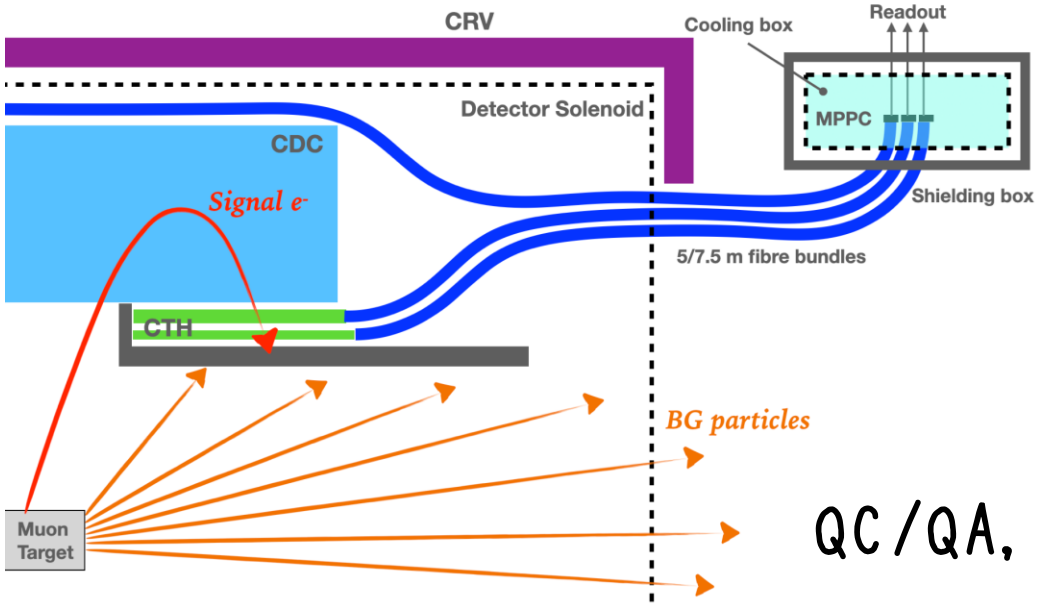


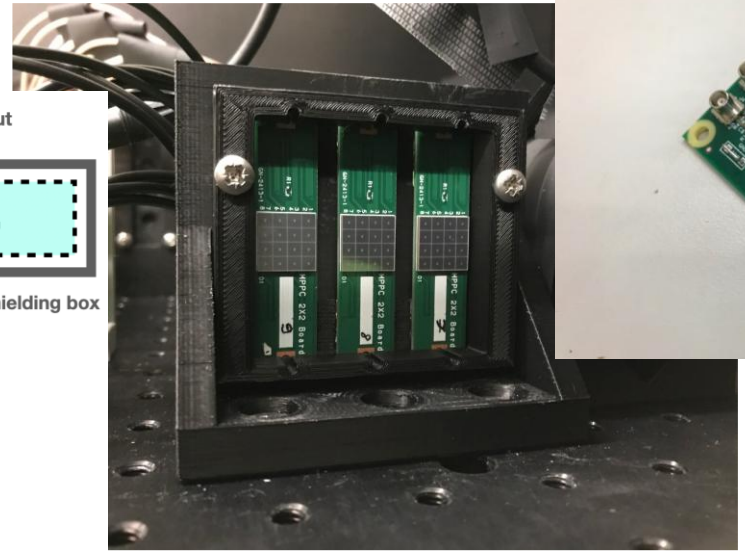
CTH

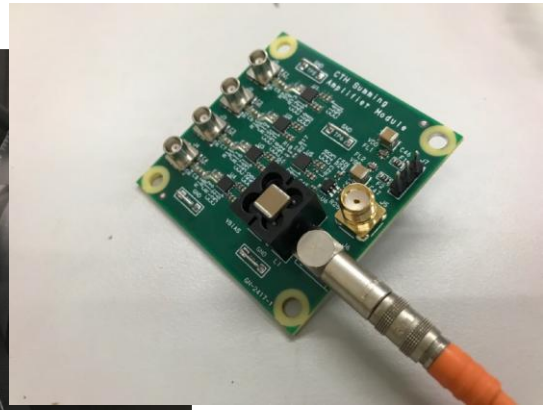
- Scintillator + fibre + MPPC
- 4-fold coincidences
  - Trigger rate < 100 kHz
- Timing res. < 1 ns
- MPPCs placed outside of DS to avoid radiation damage.







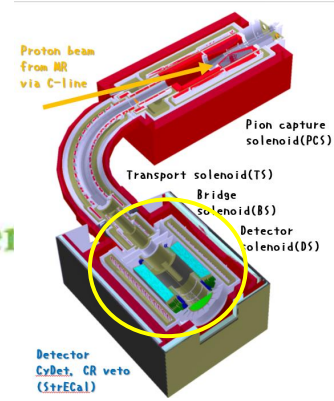




QC/QA, construction are ongoing.

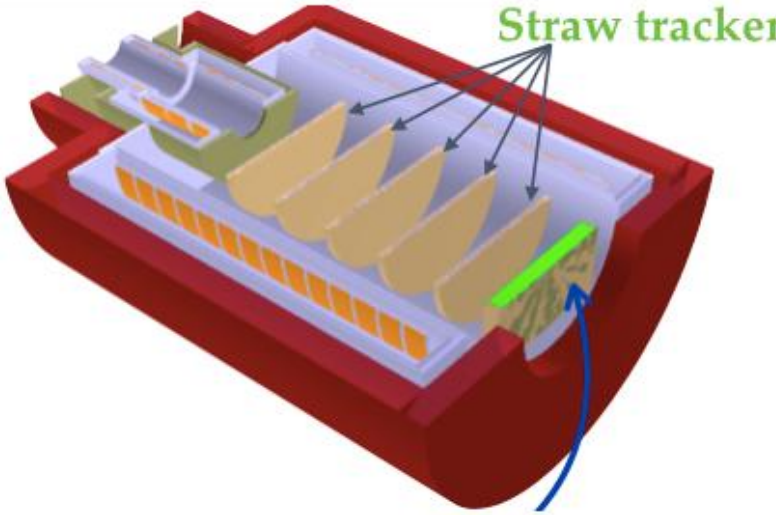
Beam Detector: StrECal

(Straw tube tracker + Electron Calorimeter)



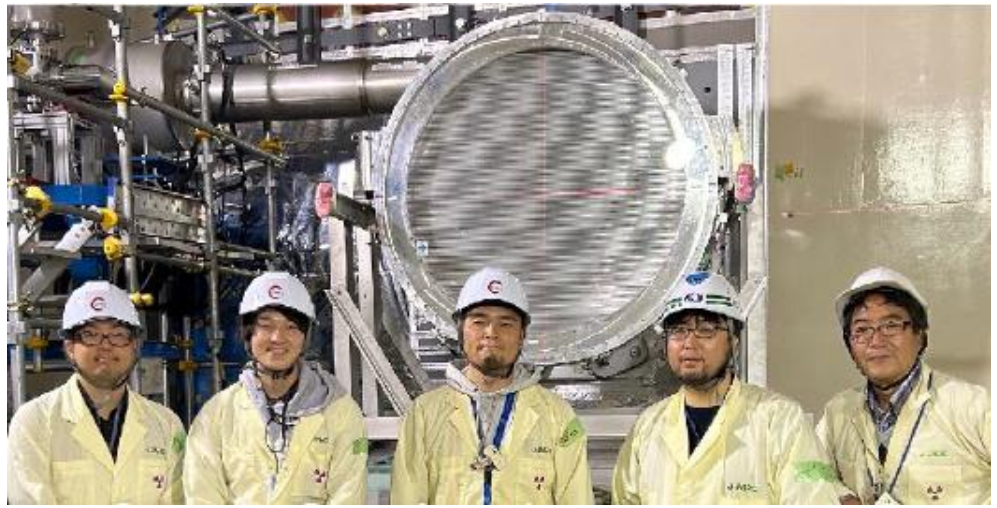
Straw tube tracker

- Very thin-wall tube gas detector **low-material budget**
- Measurement of electron momentum
- Resolution < 200 keV/c @ 105 MeV/c

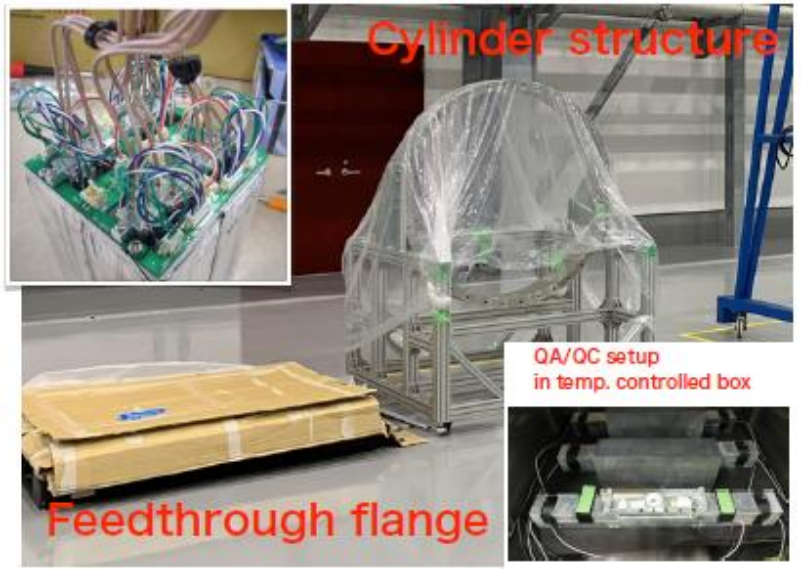


Ecal (Electron Calorimeter)

- LYSO + APD
- Measurement of energy, timing, position
- Trigger generation, PID

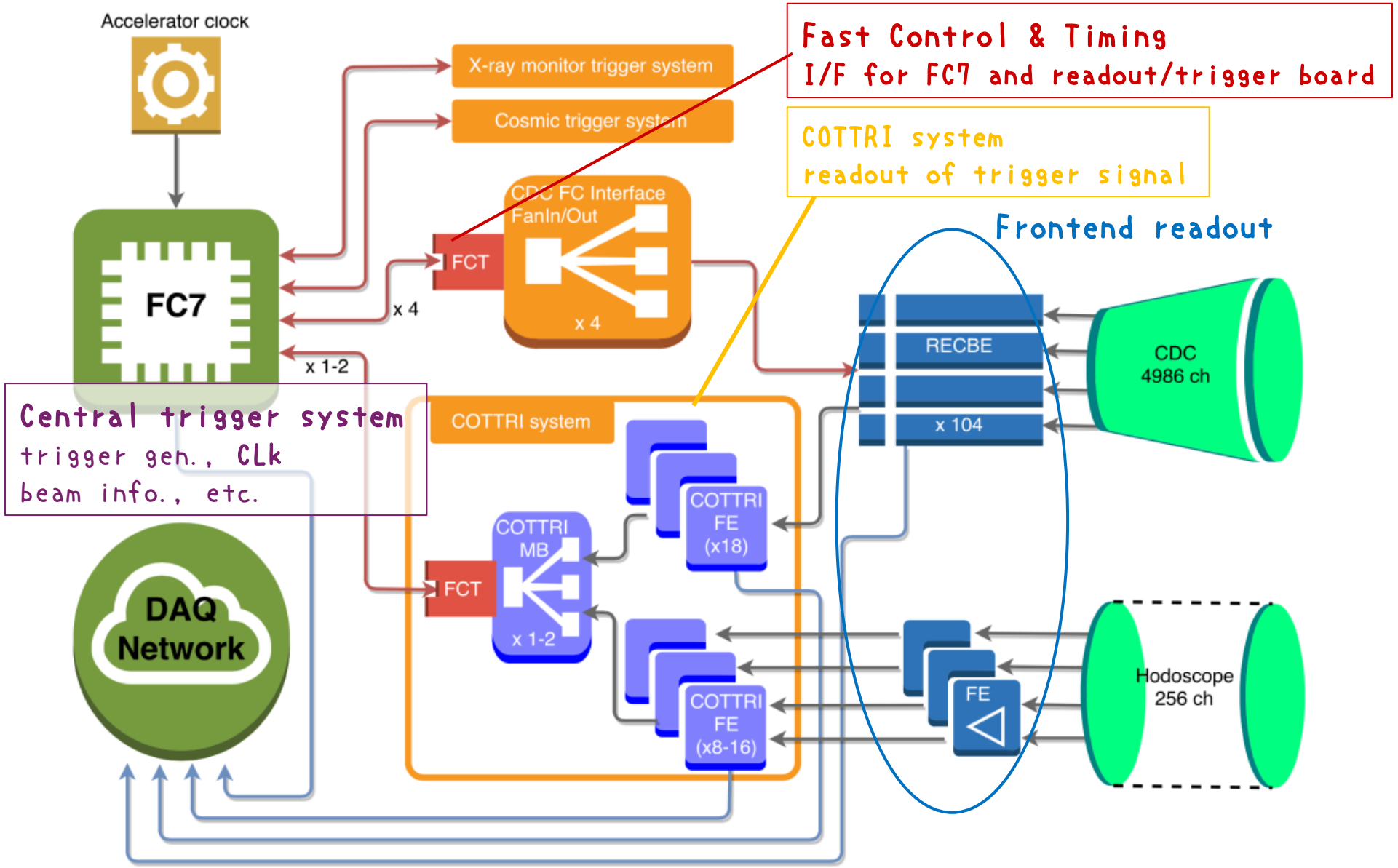


Straw tube tracker

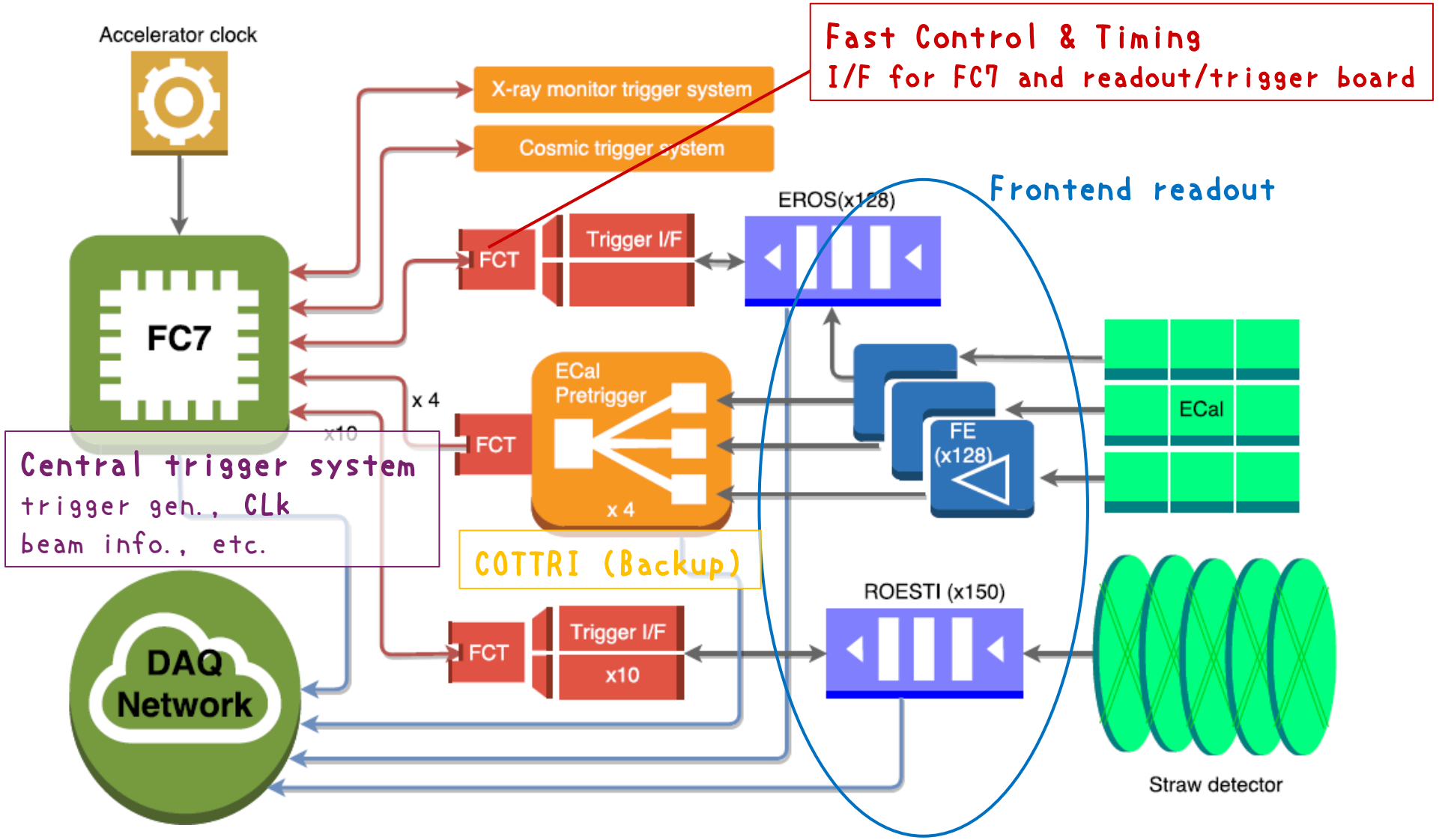


ECal

Trigger system (CyDet)

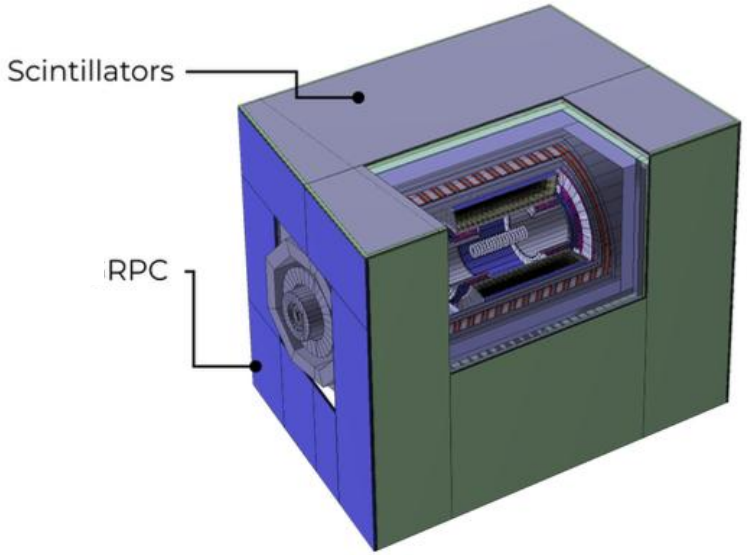


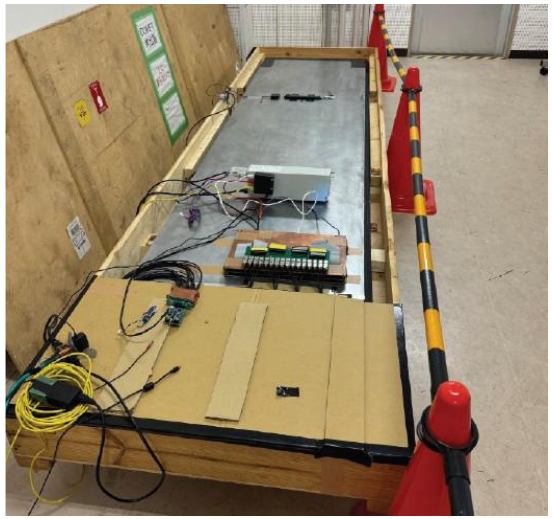
Trigger system (StrECal)

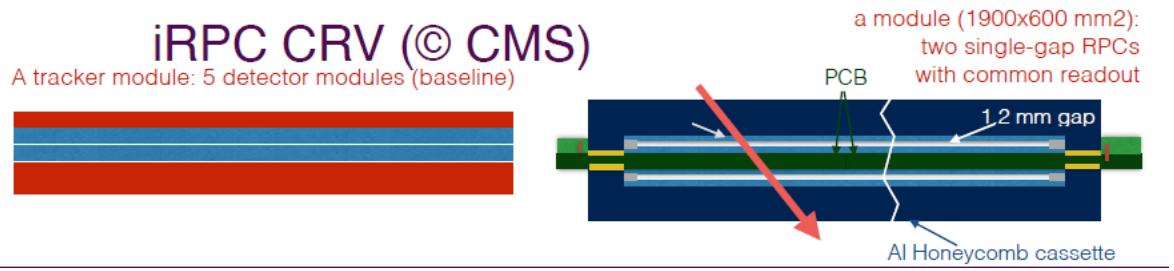


Cosmic Ray Veto (CRV) Detector

- Hybrid CRV
  - Scintillator
    - 4 layers
    - Readout by MPPCs through wavelength-shifting fibres.
  - RPC
    - Existing RPCs (CMS, ARGO)
    - Evaluation is ongoing.





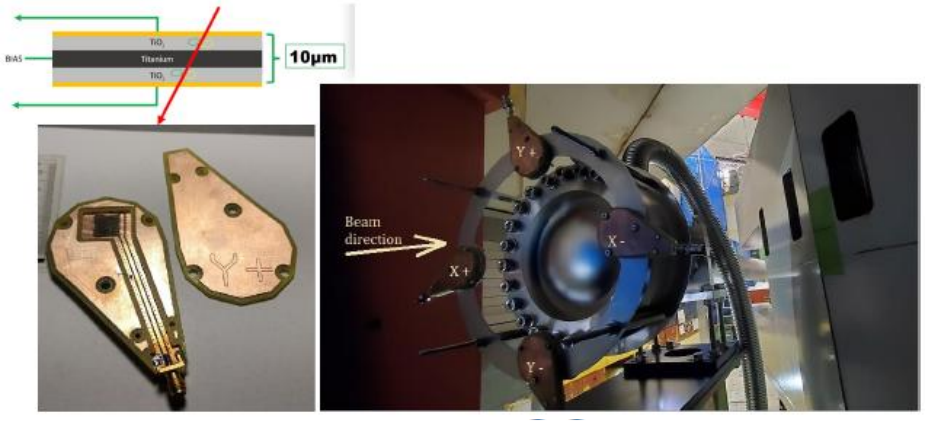


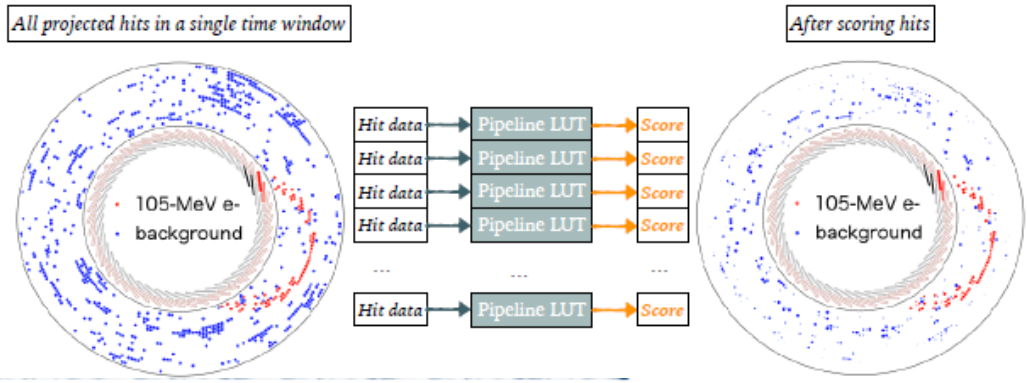
1st scintillator module was constructed and being commissioned.

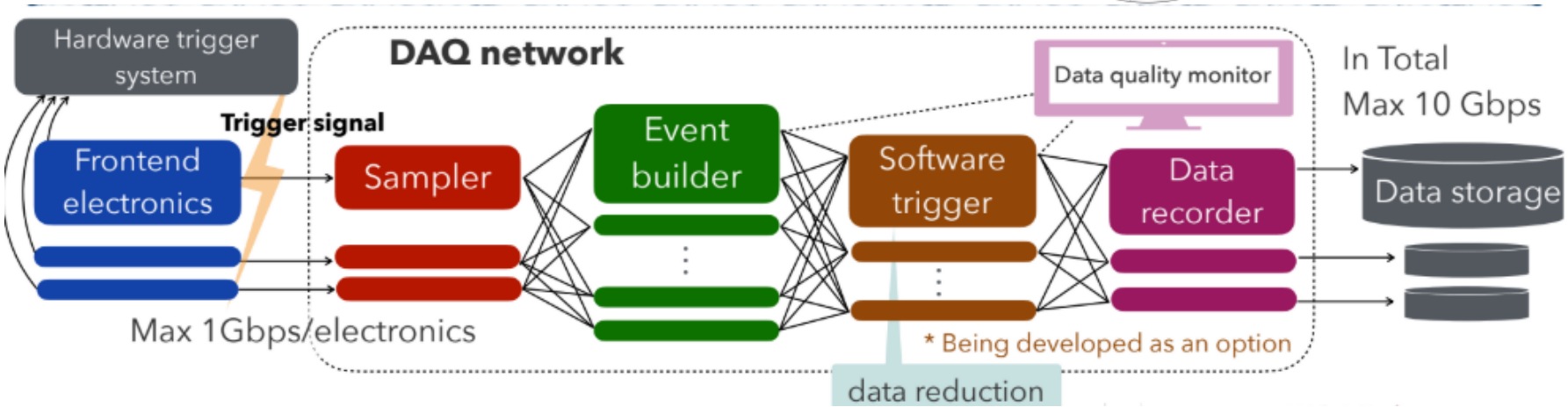
Various new technologies

- Proton beam monitor
  - TiO_2, diamond, SiC
- ML based online trigger system
- New DAQ system based on streaming scheme

and so on.







Phase-I sensitivity & BG estimation

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

N_μ	Number of muons @target	1.5×10^{16}
f_{cap}	Fraction of captured muons to total muons	0.61
f_{gnd}	Fraction of μ-e conv. to the ground state	0.9
$A_{\mu-e}$	Signal acceptance	0.041

Signal acceptance

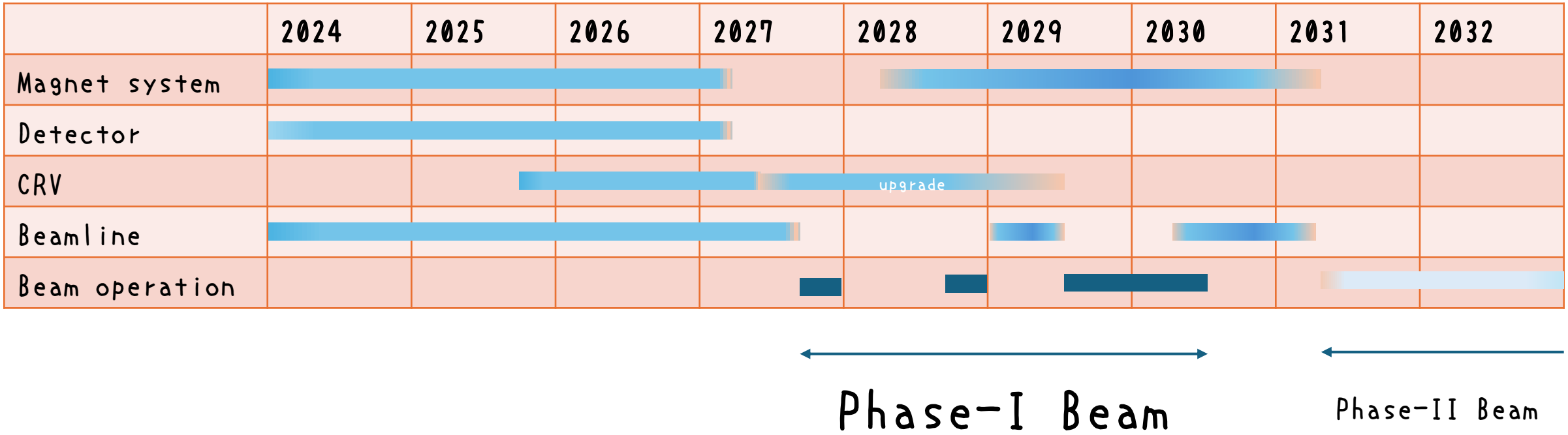
Event selection	Value	Comments
Online event selection efficiency	0.9	
DAQ efficiency	0.9	
Track finding efficiency	0.99	
Geometrical acceptance + Track quality cuts	0.18	
Momentum window ($\varepsilon_{\mathrm{mom}}$)	0.93	103.6 MeV/c < P_e <106.0 MeV/c
Timing window ($\varepsilon_{\mathrm{time}}$)	0.3	700 ns < t < 1170 ns
Total	0.041	

BG estimation

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

More improvements with more realistic simulation are ongoing.
Real data is important.

Schedule


2024
2025
2026
2027
2028
2029
2030
2031
2032
Magnet system
Detector
CRV
upgrade
Beamline
Beam operation
Phase-I Beam
Phase-II Beam

Summary

- Muon to electron conversion is one of the important CLFV processes.
- COMET experiment at J-PARC is a search experiment for μ-e conversion with a sensitivity of $O(10^{-17})$.
- In COMET Phase-I, "beam measurement" and "μ-e conversion search with an intermediate sensitivity" are planed.
- Phase-I preparations are ongoing to start the experiment in 2027.
  - Good extinction is achieved.
  - Muon transportation is established.
  - Full solenoids are prepared and being integrated.
  - Detectors are in preparations.
  - Realistic simulation studies are ongoing.