A Search for Muon-to-Electron Conversion at J-PARC
— The COMET Experiment —

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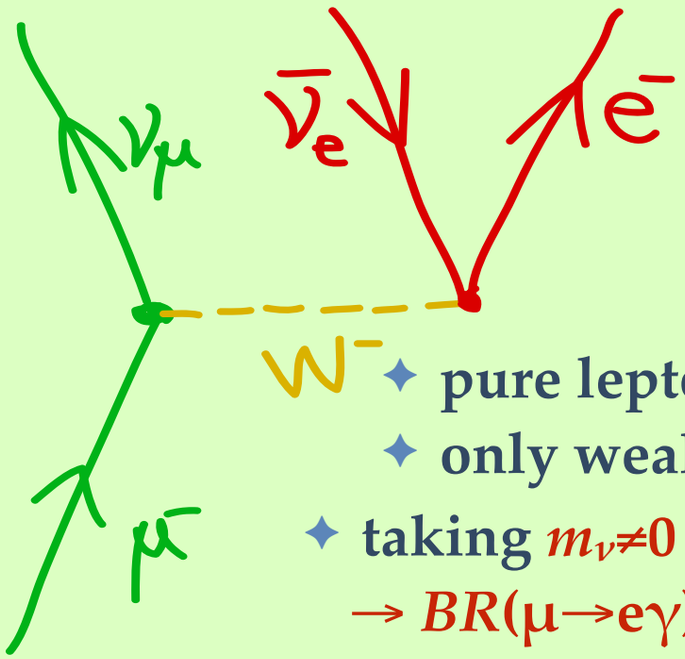
on behalf of the COMET collaboration

Contents

Search for Charged Lepton Flavour Violation in μ-processes

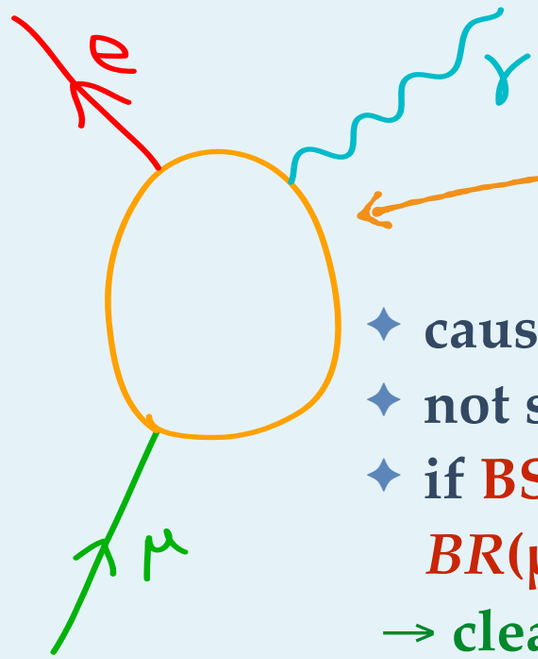
- **Muon is Best Probe to search for CLFV; *eg*. $\mu^+ \to e^+\gamma$, $\mu^- N \to e^- N$, $\mu^+ \to e^+e^+e^-$**

μ decay in SM



- pure leptonic
- only weak interaction
- taking $m_\nu \neq 0$ into account
  → $BR(\mu \to e\gamma) < O(10^{-54})$

μ LFV in BSM

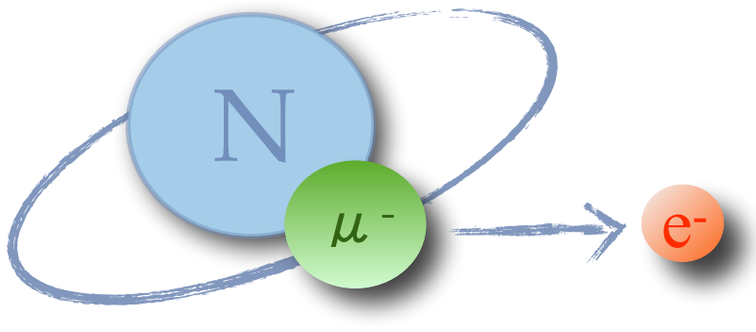


- causable via **new particle**
- not suppressed by tiny m_ν
- if **BSM** assumed…
  $BR(\mu \to e\gamma) = O(10^{-16}\text{-}10^{-13})$
  → clear evidence of BSM

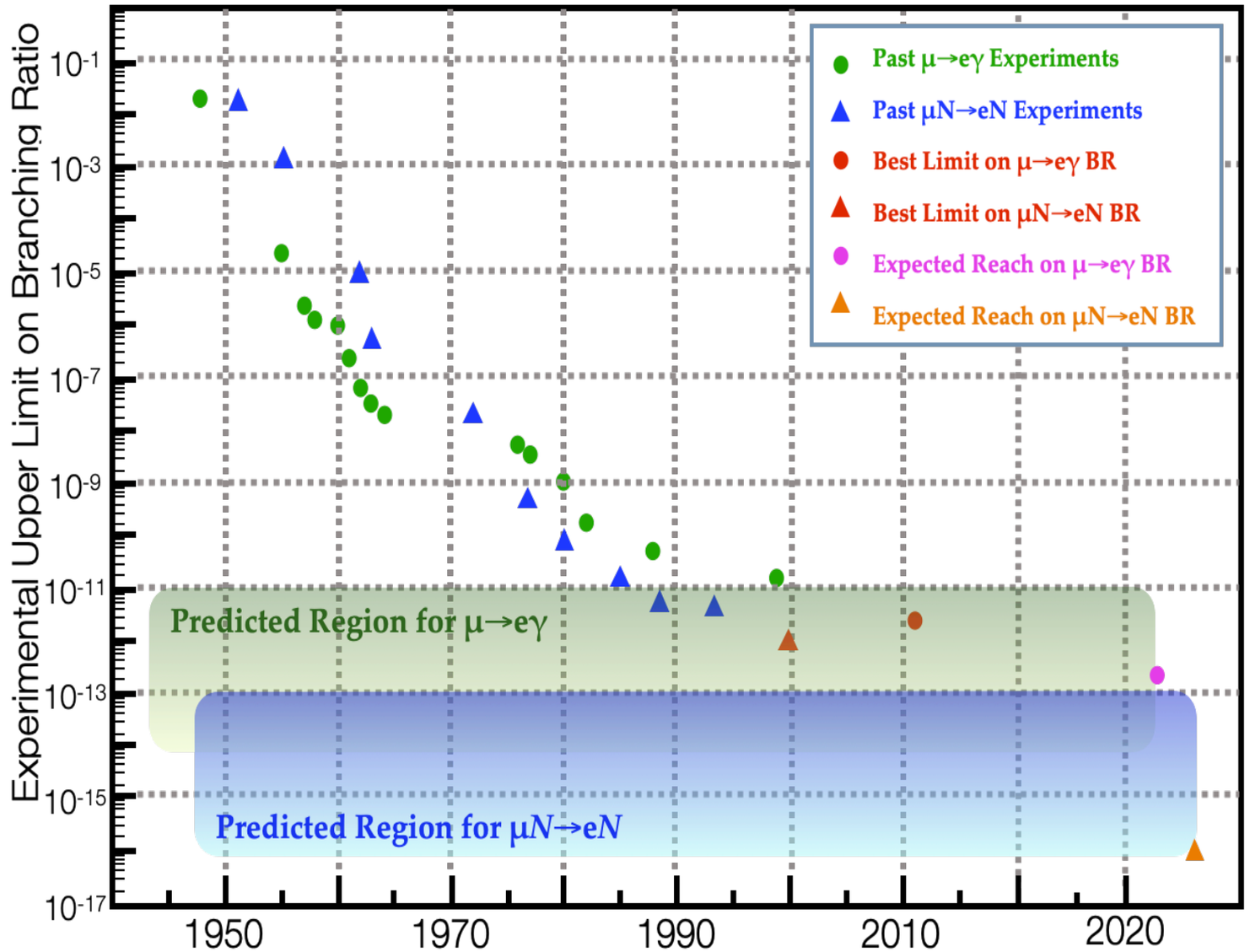
- **Try to Explore New Physics via "*Charged Lepton Flavour Violation*"**
- **Among "Quark", "Neutrino" = Known as Flavour violated**
- **"Charged Lepton Flavour Violation (cLFV)" = Never Observed so far**
  - Very sensitive to the TeV-scale new physics beyond Standard Model
    → **Complementary** and **Competitive** to the **Energy Frontier (*eg*. LHC)**

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

- **"Muon-to-Electron Conversion in Muonic Atom ($\mu^- N \rightarrow e^- N$)"**
  - **Charged LFV, So-called "μ-e Conversion"**
  - **One of the most prominent process of muon LFV**



- **"Signal"**
  - $E_e = m_\mu - B_\mu - E_{recoil}$ ~105 MeV (muonic Al)
- **"Background"**
  - **Beam-related**
  - **Normal muon decay in Orbit (DIO)**
  - **Cosmic-ray induced**



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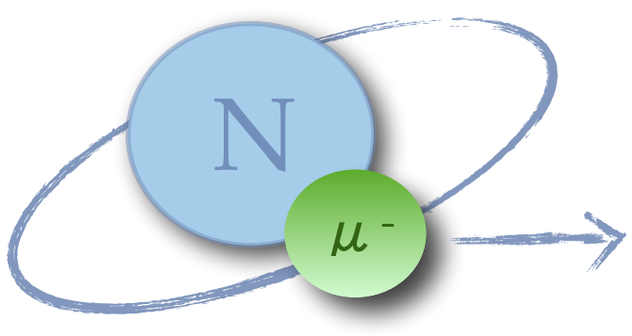

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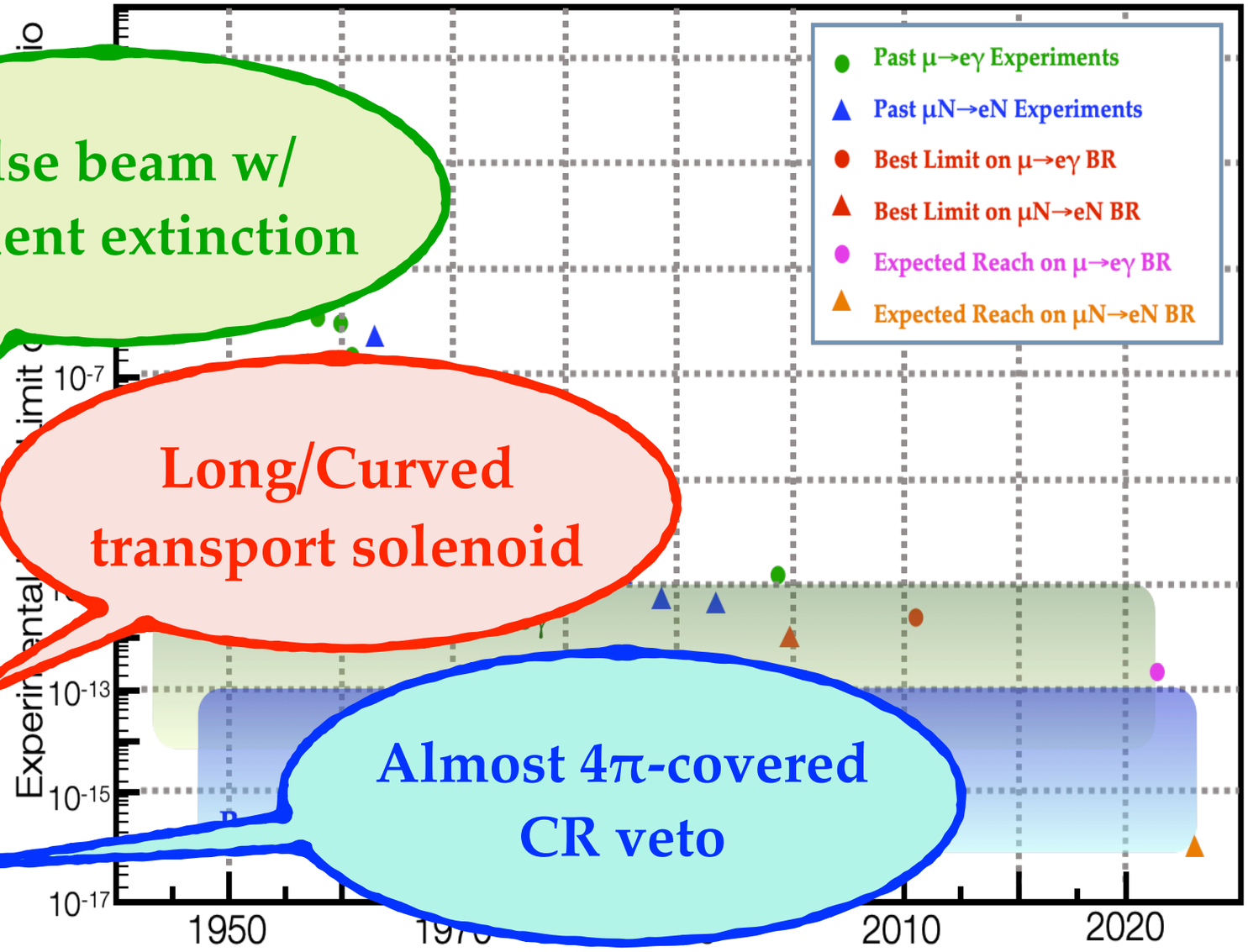
Pulse beam w/ excellent extinction

Long/Curved transport solenoid

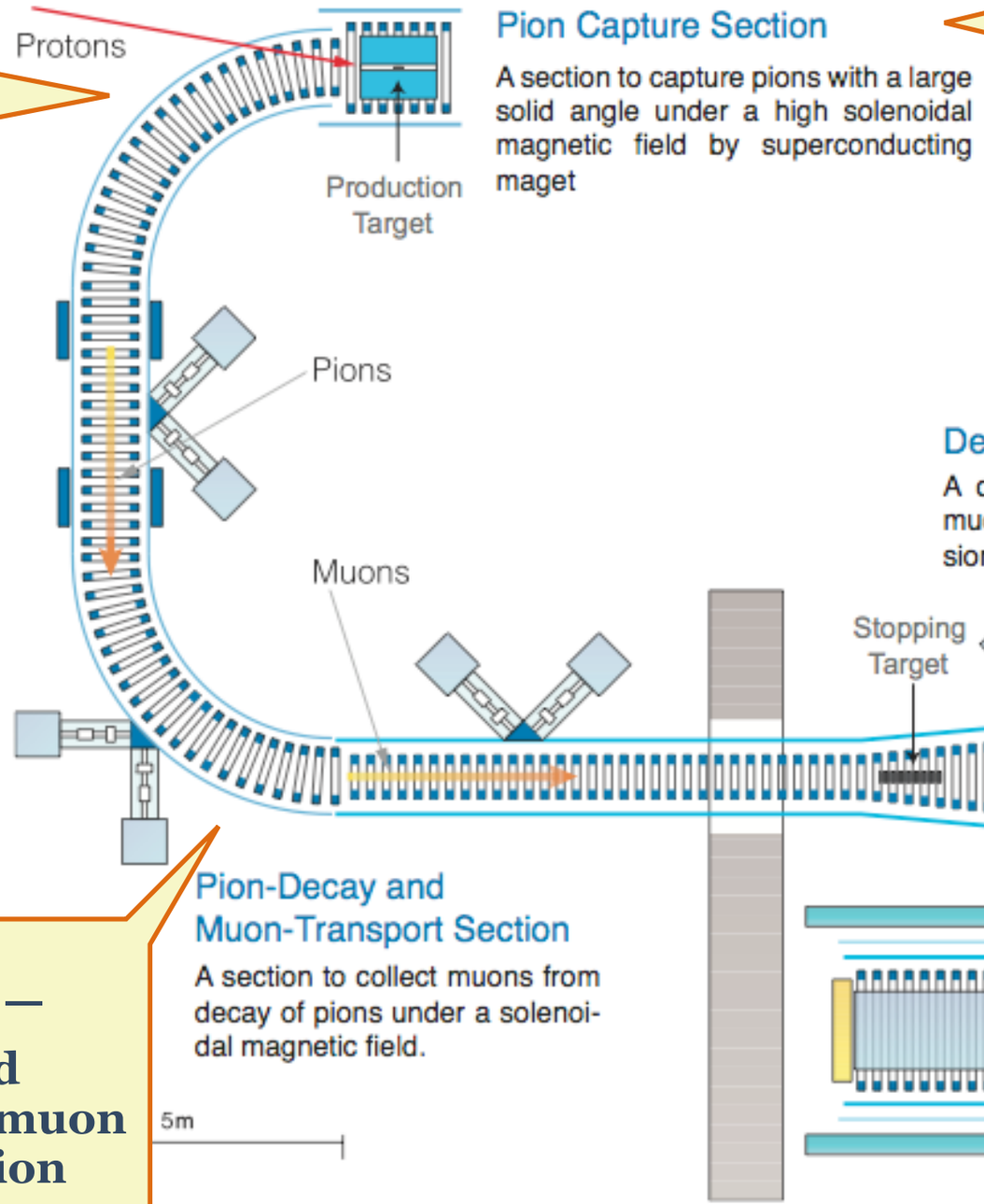
Almost 4π-covered CR veto



The COMET Experiment

- **Enabled by "Four Features" → Aim to achieve target sensitivity of $O(10^{-17})$**

— Feature(1) —
High Intensity Pulsed Proton Beam by J-PARC



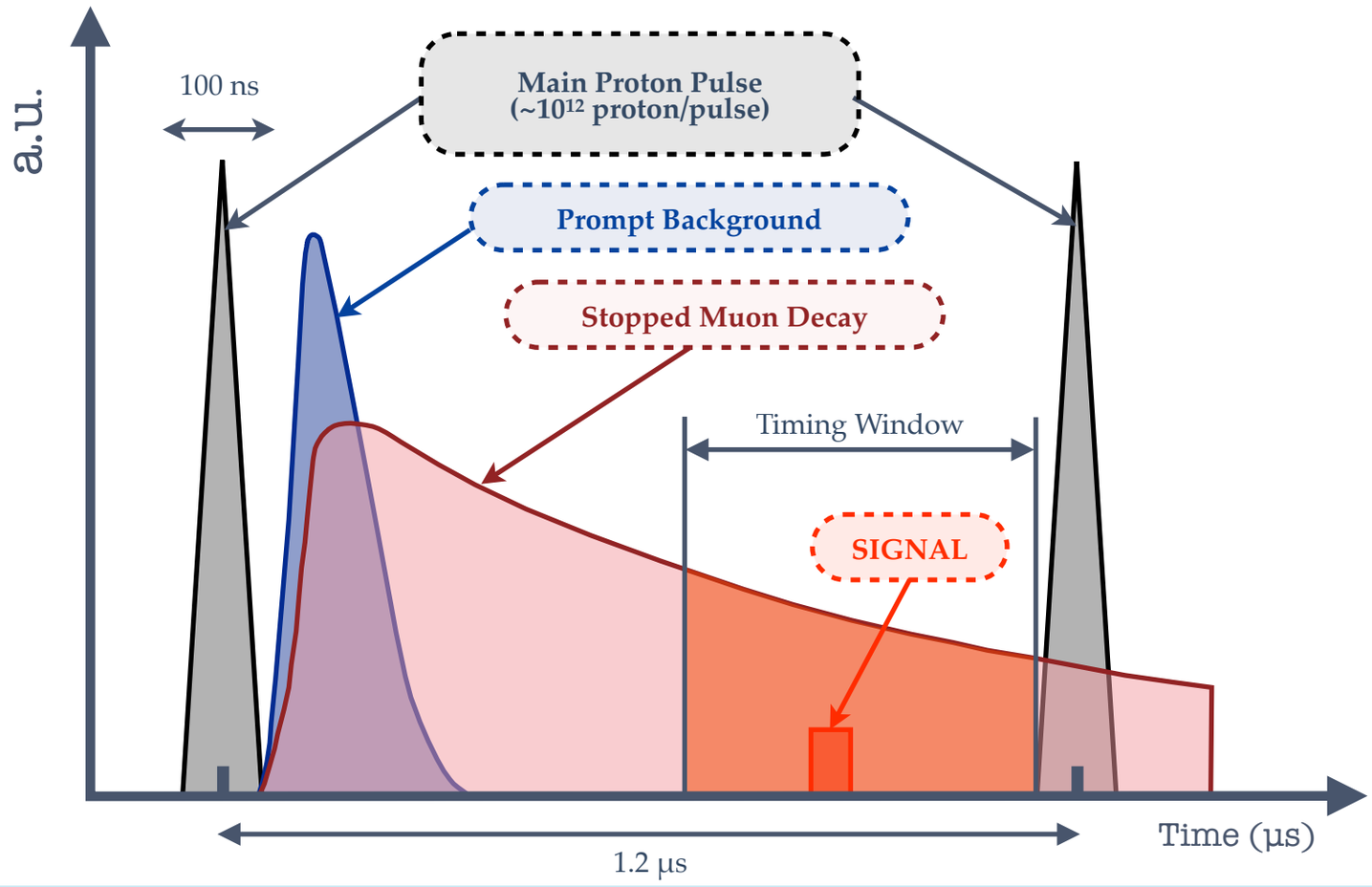
— Feature(2) —
High Efficiency 5T-Solenoidal Pion Capture System

— Feature(3) —
Long/Curved Solenoidal pion/muon transport section

— Feature(4) —
High resolution, vacuum compatible electron spectrometer can select momentum.

Beam-related Background to Search for μ-e Conv.

- **Dominant Background**
  - Beam-related prompt Background, mainly caused by pion decays
  - Muonic atom (of Al) has a lifetime of ~1μsec
  - Delayed DAQ-window right before the next proton bunch allows for BG-free Search
- **Extinction is ESSENTIAL !**

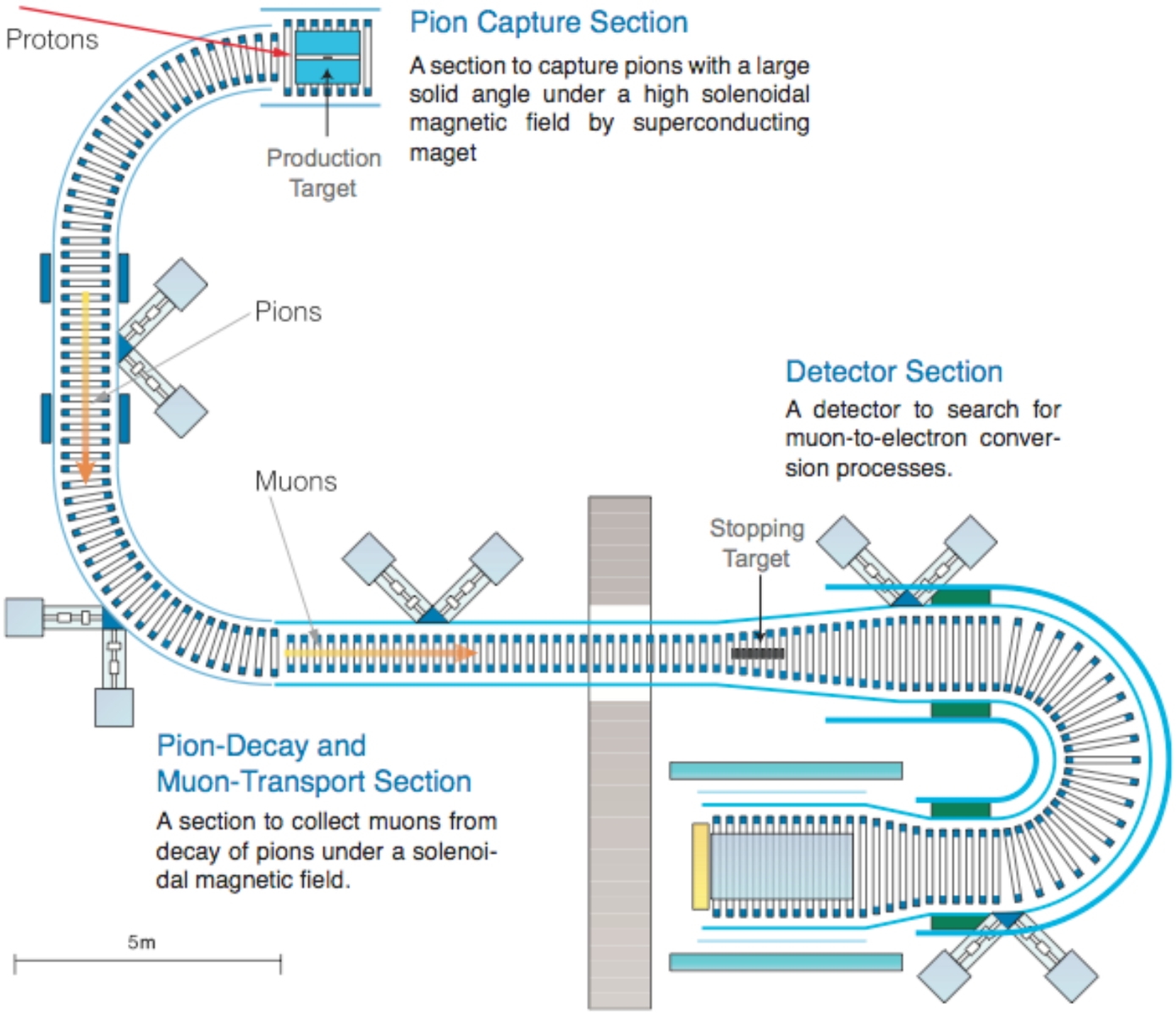


$$\text{Extinction} = \frac{\#\text{ of leaked protons in between bunches}}{\#\text{ of filled protons in main bunches}}$$

Extinction should be $<10^{-10}$ at least to achieve the COMET Goal

(Single Event Sensitivity : 10^{-17})

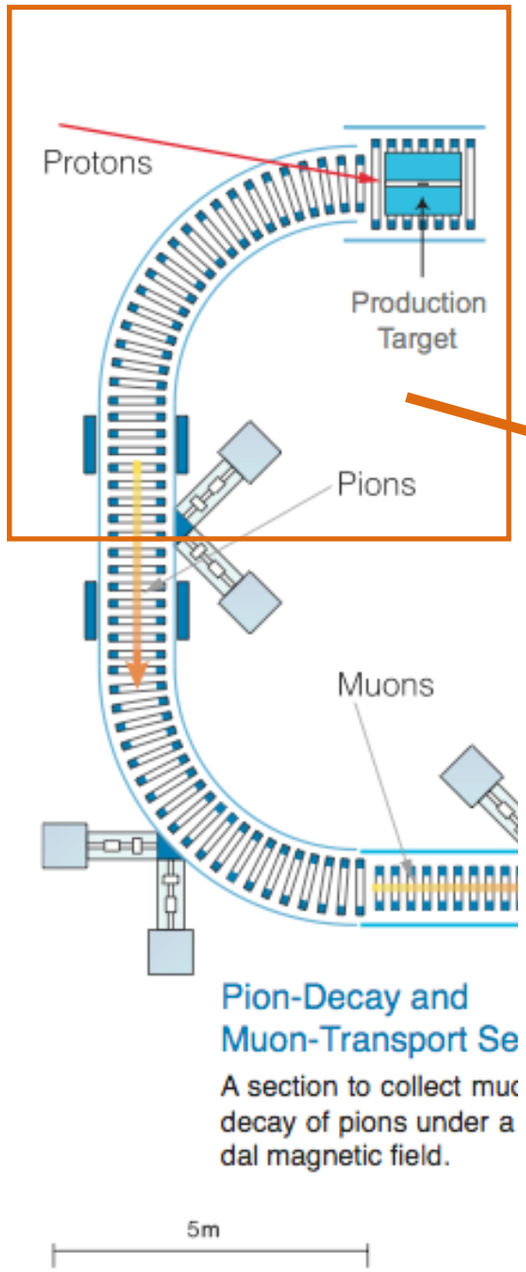
Two-Staged Approach

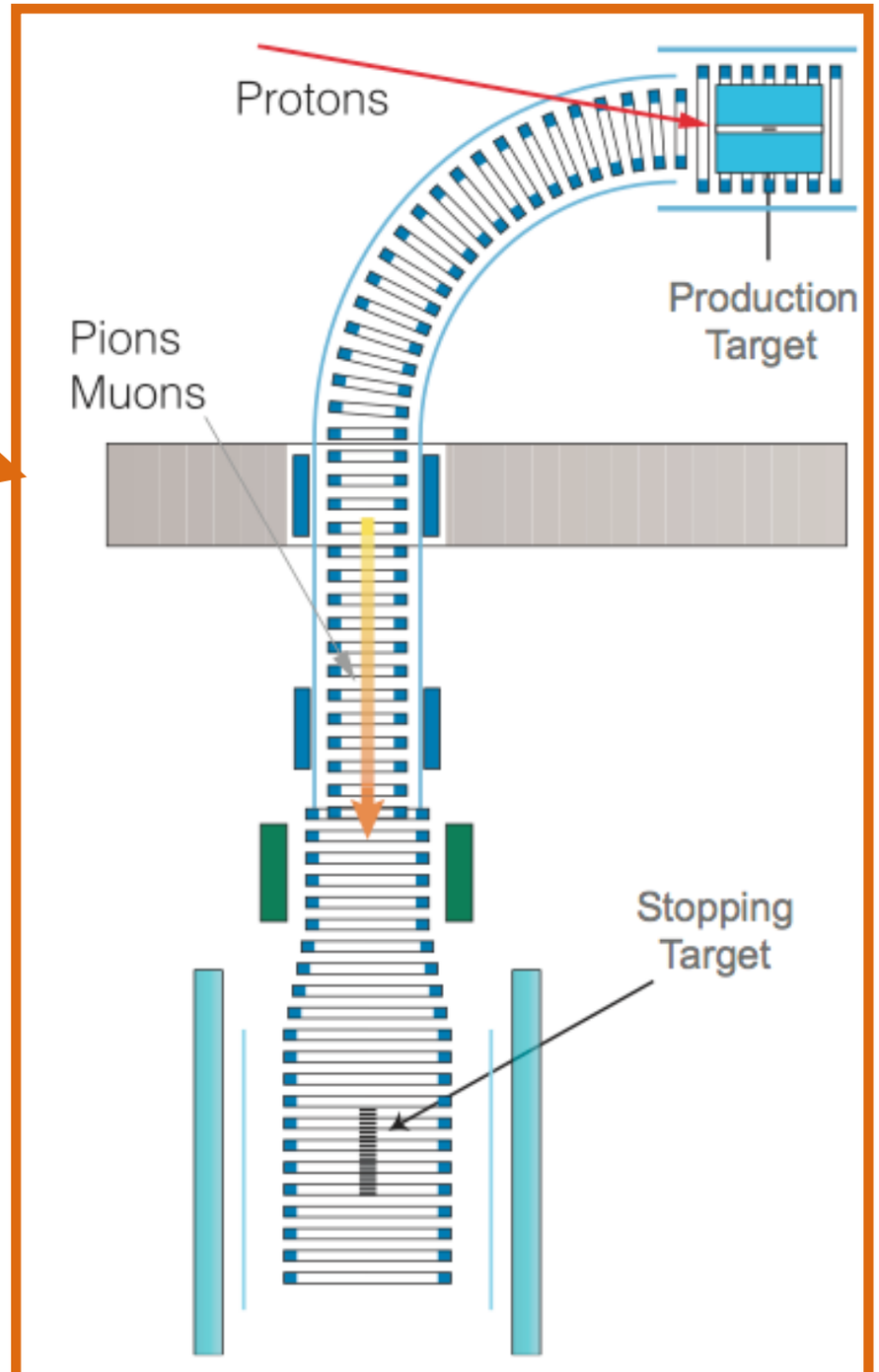


- **COMET Phase-I**
  - Construct up to first 90° bend and place detector.
  - Perform direct beam measurement
    - No backward σ_π data so far
    - No real BG data so far
  - Perform μ-e Search with an intermediate sensitivity ($O(10^{-15})$)

- **COMET Phase-II**
  - Complete all transport
  - Perform μ-e Search with a full sensitivity ($O(10^{-17})$)

Two-Staged Approach





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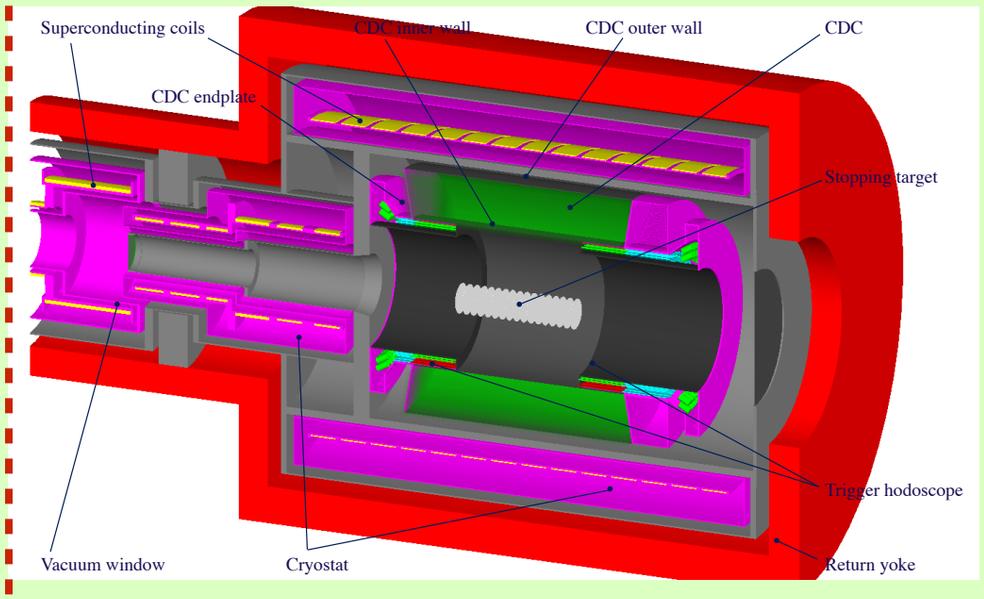
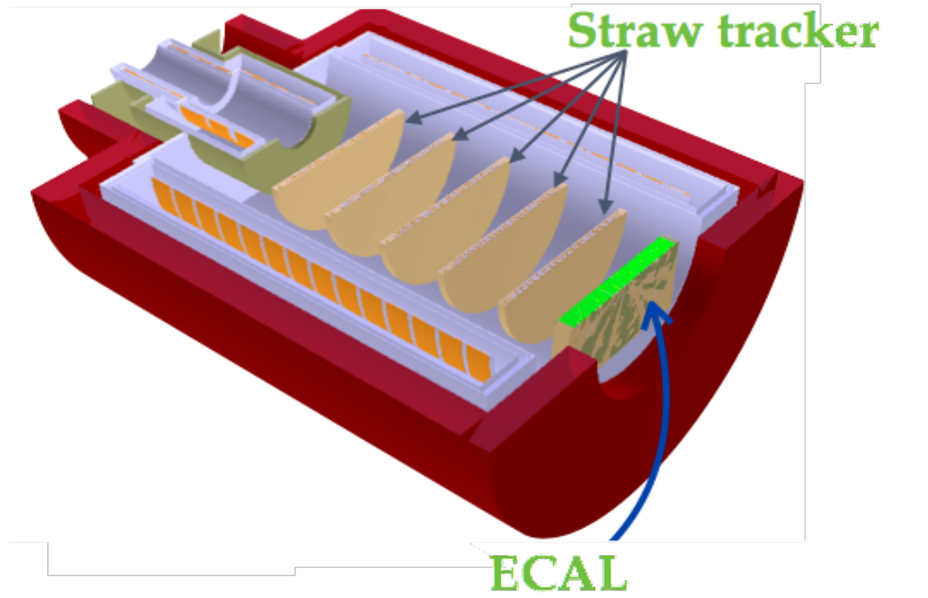
Detectors for COMET Phase-I

For μ-e Conversion Search



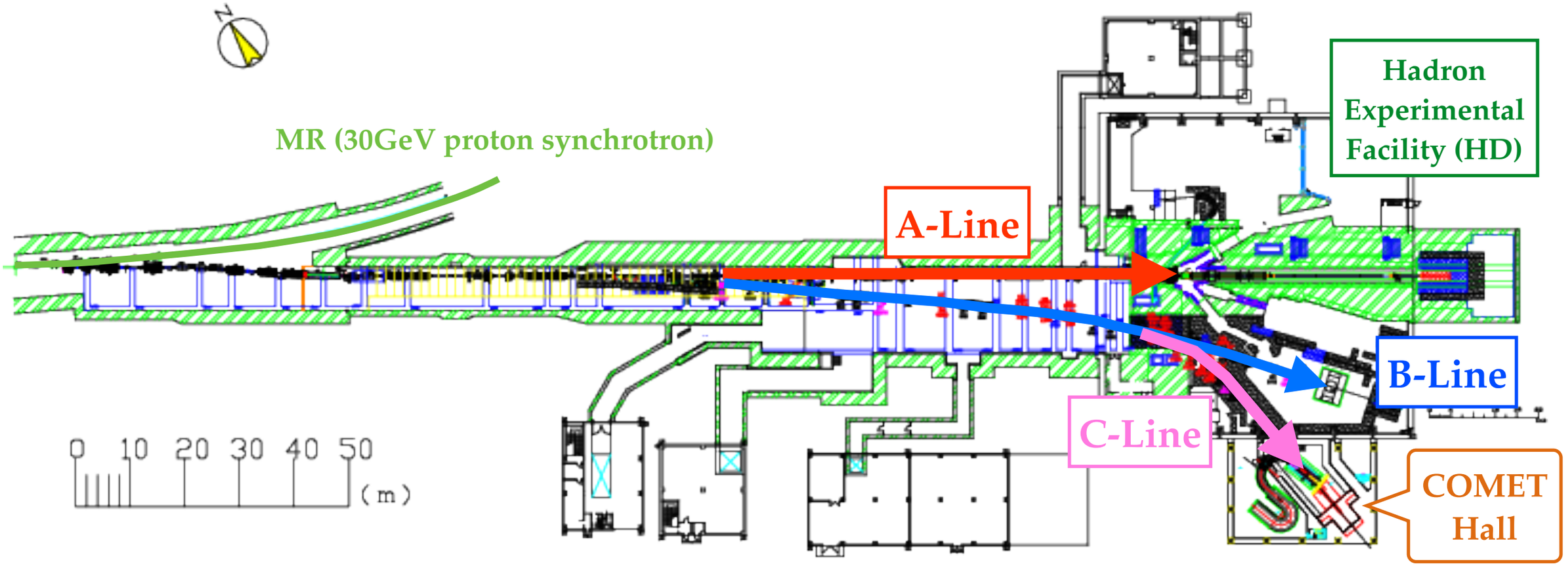
- "CyDet" = Cylindrical Detector System
- For Phase-I, centre part of beam is dominated by BG, *i.e.* Cylindrical Drift Chamber and Cylindrical Trigger Hodoscope is employed to search for μ-e conversion.
- He-iC_4H_{10} gas-mixture to reduce material budget, Hollow cylinder design to have a BG tolerance

For Beam Measurement



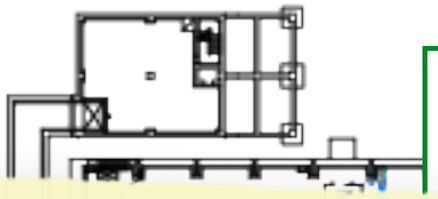
- "StrECAL" = Straw tracker and ECAL
- To measure all delivered beam including BG, vacuum-compatible tracker and calorimeter is employed
- Straw = Planer/Low-mass, LYSO crystal ECAL = High resolution / High density
- Same concept as Phase-II detector
  👉 Prototype of Phase-II Final Detector

Current Status (1) — Facility Construction —



- Dedicated proton beam line, Completed
  - Three proton beam lines in Hadron Experimental Facility. **A-Line** and **B-Line** are in operation. **C-Line**, dedicated for COMET, was just completed in spring 2022, and 1st commissioning w/ low intensity beam was conducted in spring 2023.
- Inside COMET hall, pion/muon transport system is under construction.
  - Transport solenoid is already completed. Other components, pion capture solenoid, detector solenoid *etc*., are under construction.

Current Status (1) — Facility Construction —



Hadron Experimental Facility (HEF)

Pion Capture Solenoid

Construction Completed !!
Final check is ongoing, Will be delivered to J-PARC next month.

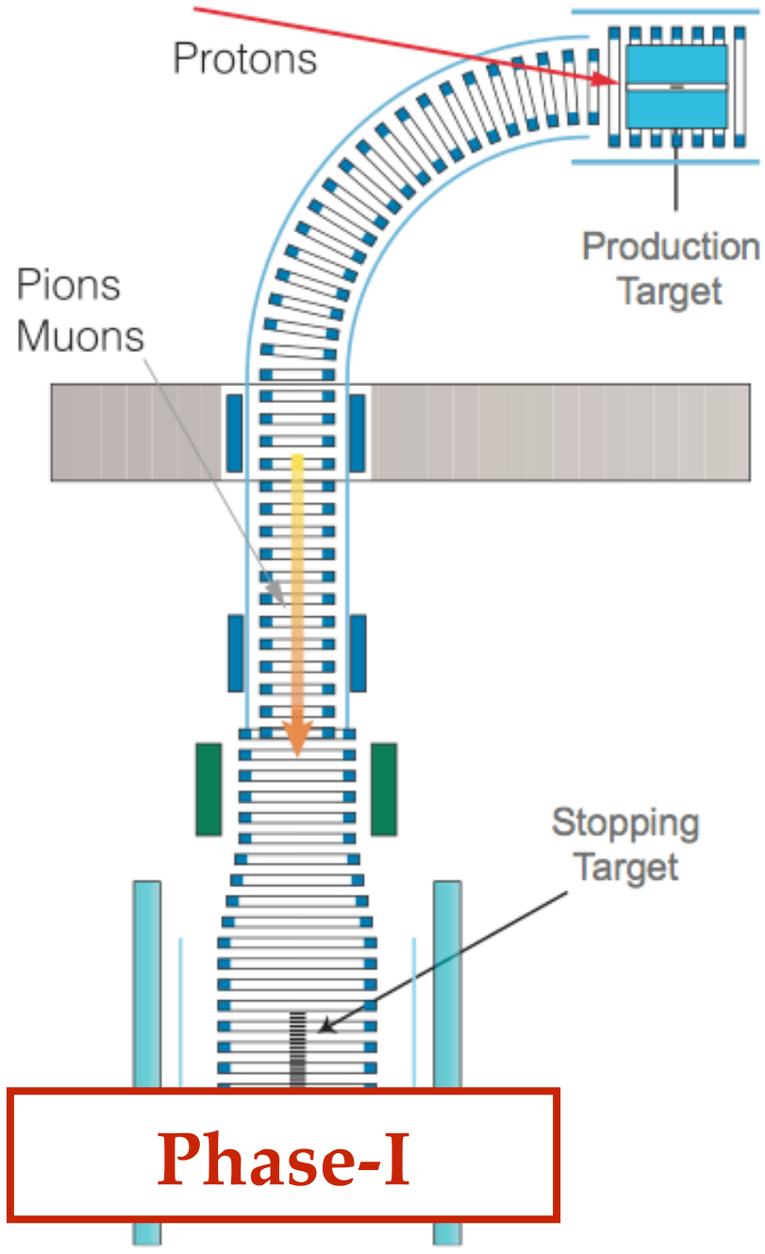
Detector Solenoid

Fabrication Completed !!
Cooling, Excitation tests completed,
Confirmed at 10, 95, 134 and 189 A,
Will be delivered to J-PARC next spring.

solenoid, detector solenoid *etc*., are under construction.

Current Status (2) — COMET Phase-α —

- Dedicated primary proton beam-line, "C-Line", completed in 2022
- **Low intensity proton (Phase-I x0.1) was delivered and commissioned in 2023**
  - w/ Muon Transport Solenoid but w/o Pion Capture Solenoid



- Backward π/μ yield measured
- Beam momenta was measured
  - Compared/Validated MC
- Real operation of Muon Transport Solenoid (Curved Solenoid)

The First Proton-beam Commissioning dedicated for COMET

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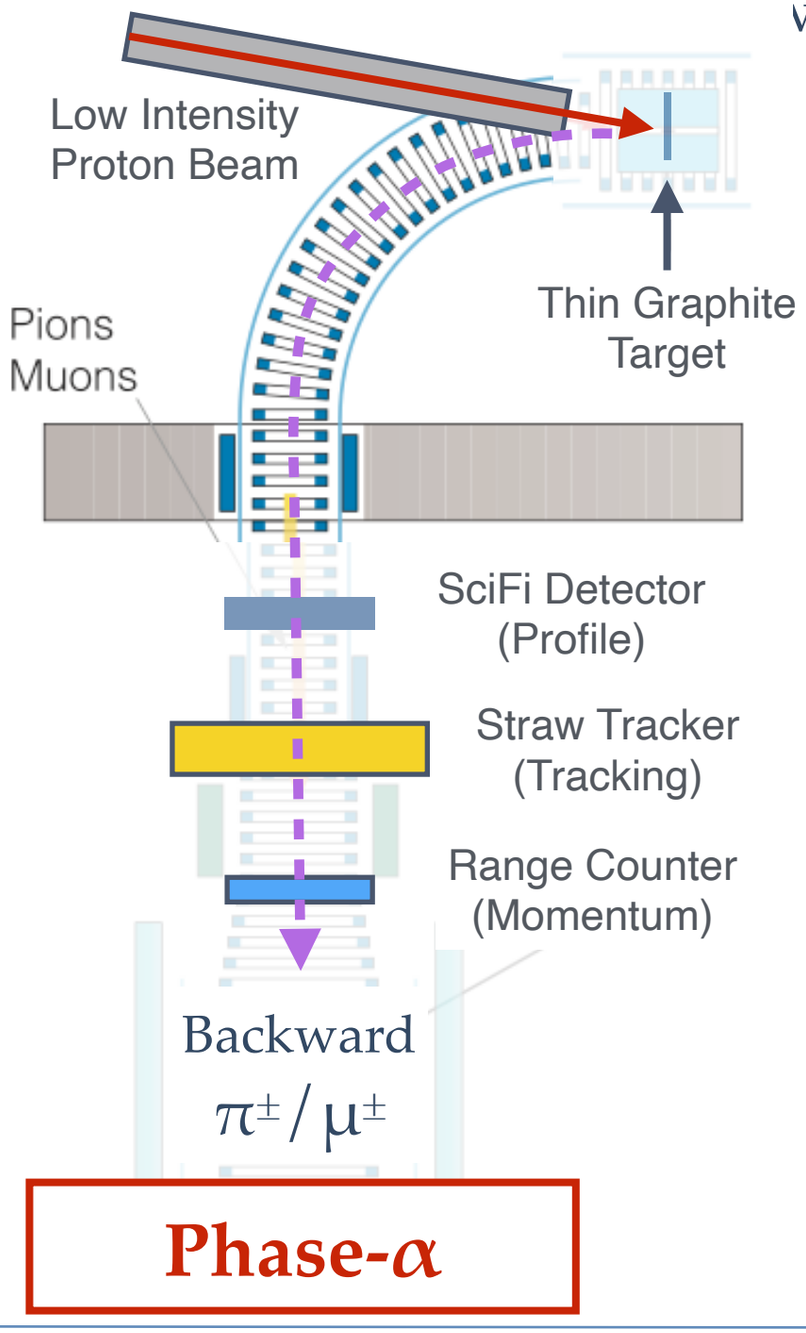

w/ Muon Transport Solenoid but w/o Pion Capture Solenoid

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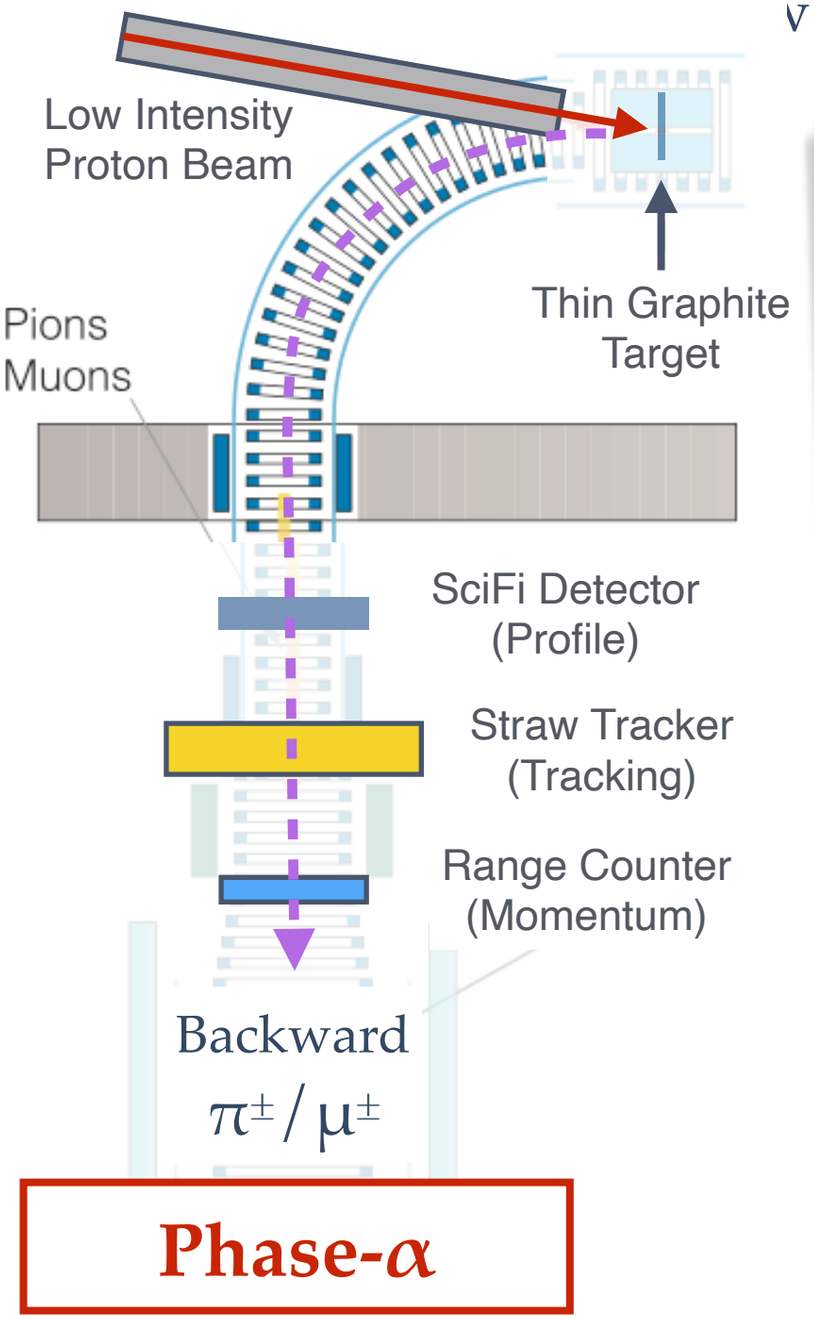
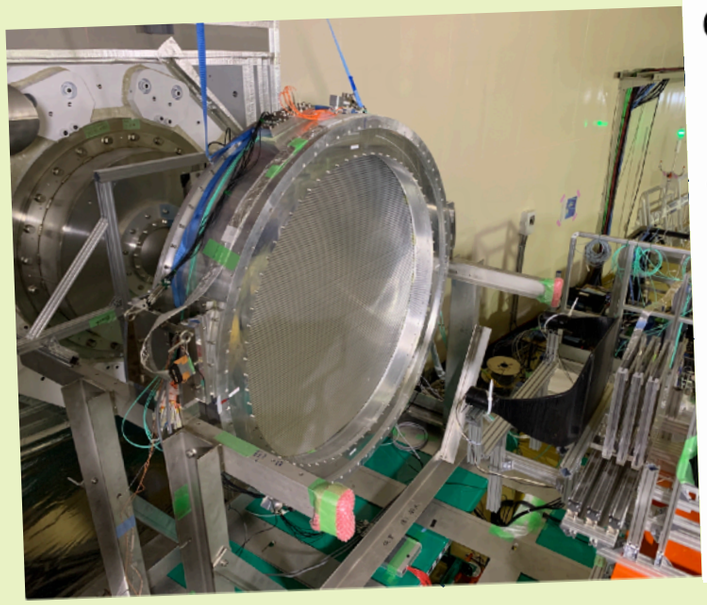
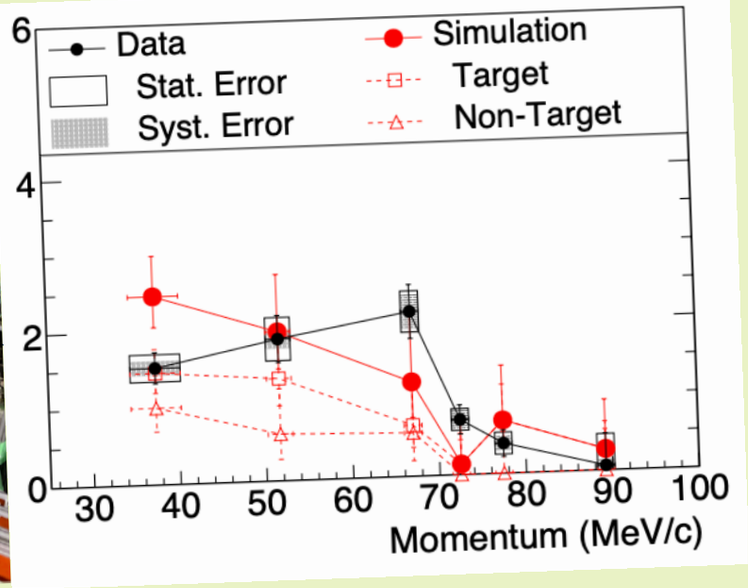


v/ Muon Transport Solenoid but w/o Pion Capture Solenoid

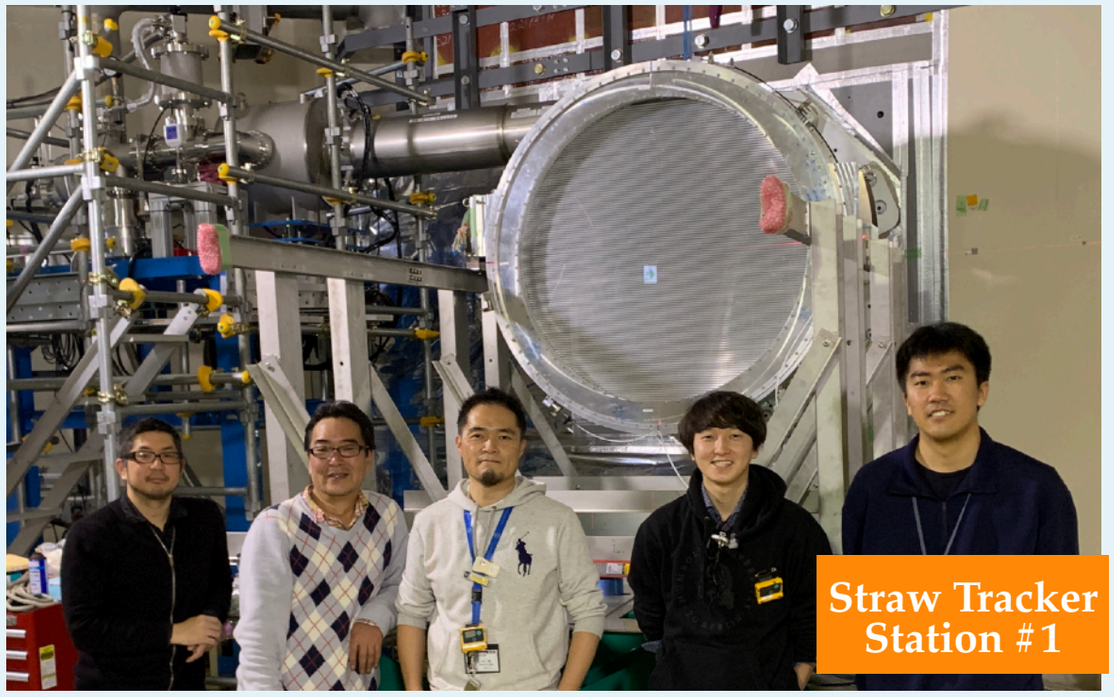




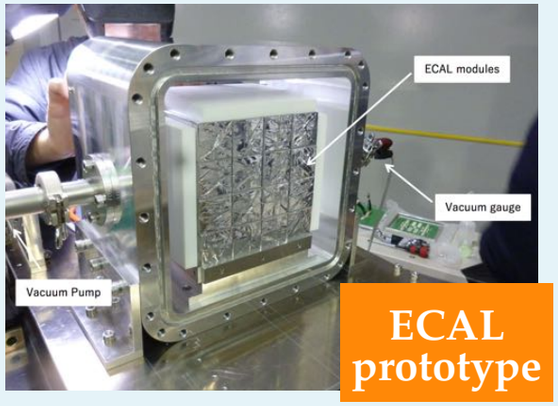
The First Proton-beam Commissioning dedicated for COMET

Current Status (3) — Detector Construction —

StrECAL (for beam measurement)

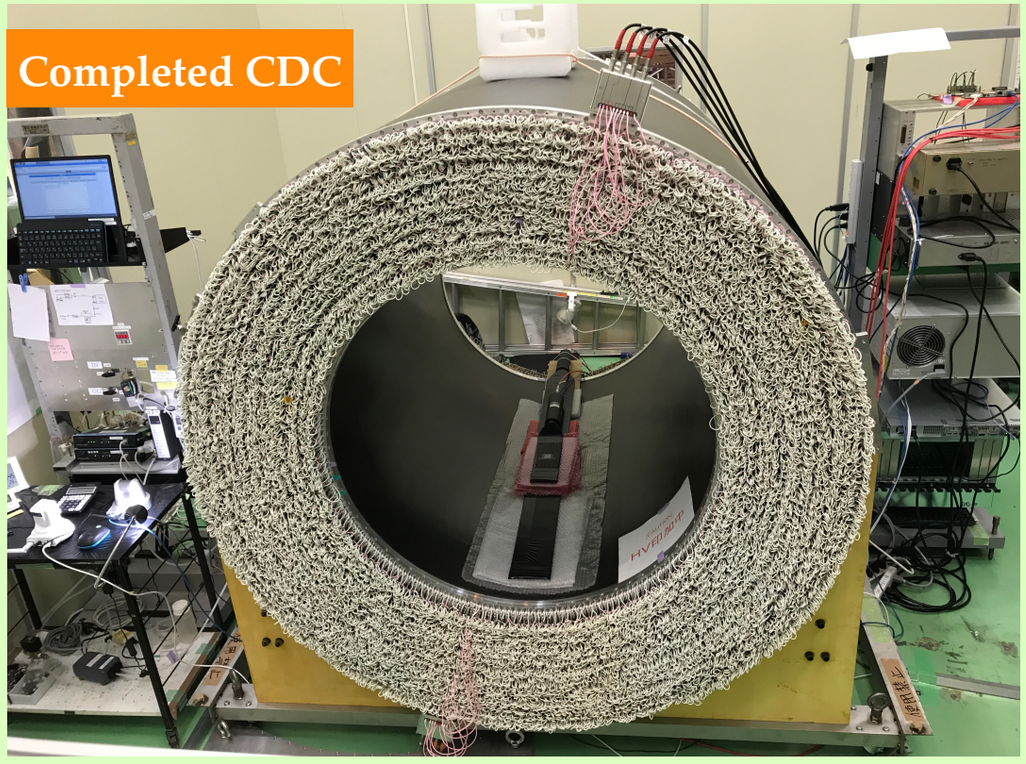


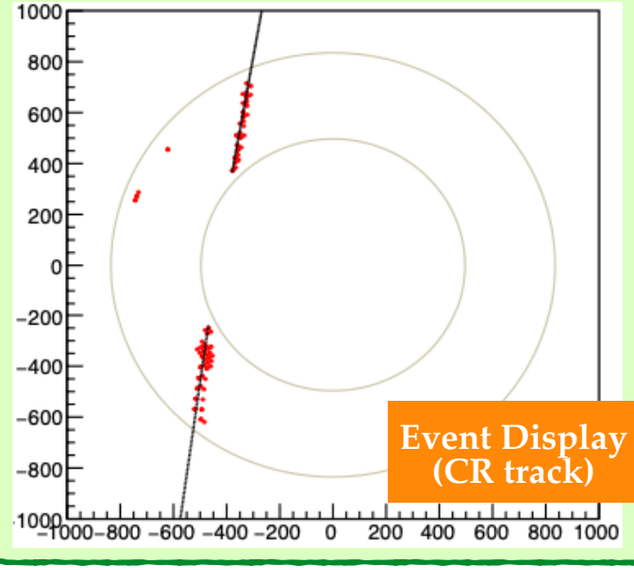
- Straw Stations, 5 Stations in total, are under construction.
- Will be completed in 2025.



- ECAL prototype successfully completed.
- Detector assembly is ongoing.

CyDet (for μ-e conv. search)





- CDC, completed and under commissioning with cosmic-ray.
- Trigger hodoscope is under construction.

Towards the Start of COMET Phase-I

- **Construction on all items are ongoing at a fast pace.**
  - **Facility;**
    - **The unfinished magnets, the Pion Capture Solenoid and the Detector Solenoid, are already completed. PCS will come soon, and DS will be delivered next spring.**
    - **Beamline commissioning will follow immediately.**
  - **Detector;**
    - **CyDet. CDC commissioning with all FE/Trig-chain will continue. Trigger hodoscope will be completed in JFY2024.**
    - **StrECAL. Straw tracker and ECAL, assembly is ongoing and expect to be completed in JFY2025.**
  - **Accelerator;**
    - **Proton Extinction and Bunched-Slow Extraction efficiency has been confirmed to be OK. *i.e.* Ready for COMET Phase-I**
- **All component for COMET Phase-I will be completed by the end of JFY2025, and the engineering run will start in 2026.**

— Conclusions —

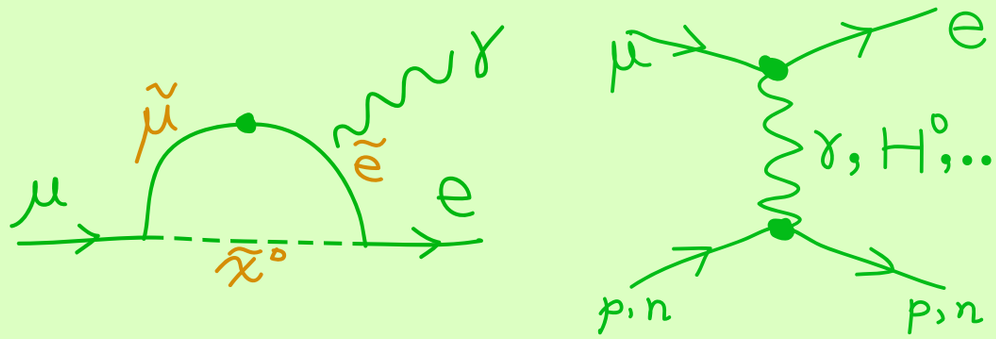
- **Charged Lepton Flavour Violation = Clear evidence of New Physics BSM**
  - **Muon is one of the best probe to explore New Physics**
  - **eg. $\mu^- N \rightarrow e^- N$, $\mu^+ \rightarrow e^+\gamma$, $\mu^+ \rightarrow e^+e^-e^+$, *et al.***
- **COMET is searching for $\mu^- N \rightarrow e^- N$ at J-PARC with $\mathcal{O}(10^{-17})$ sensitivity**
  - **Two-staged apploach**
    - **Phase-I: Construct 1/4 of transport solenoid and perform "Direct beam measurement" & "$\mu^- N \rightarrow e^- N$ Search w/ an intermediate sensitivity of $\mathcal{O}(10^{-15})$"**
    - **Phase-II: Construct remaining 3/4 of solenoid and carry out to search for $\mu^- N \rightarrow e^- N$ w/ a full sensitivity of $\mathcal{O}(10^{-17})$**
- **Towards the Start of Phase-I**
  - **Dedicated proton beam line, Completed**
  - **Curved Transport Solenoid, Completed**
  - **Pion Capture and Detector Solenoids will come soon**
  - **Detector Installation, Will be completed in JFY2025**
  - **Engineering Run will be performed in JFY2026, and then the Physics data-taking will follow.**

backups

"$\mu^- N \to e^- N$" *vs.* "$\mu^+ \to e^+ \gamma$"

- **Very similar, *twin* processes**
- **But, big differences from points-of-view of *Physics* and *Experiment***
- **Searching for both processes is important**

Differences in *Physics*



- sensitivity for *photonic* process and *non-photonic* process is different
- μ→eγ : photonic👍 non-photonic👎
- μ-e conv : photonic👍 non-photonic👍

→ **Very powerful tool to probe properties of new physics when the signal is discovered.**

Differences in *Experiment*

μ→eγ Search
Signal = Coincidence
⬇️
Dominant B.G. is
Accidental Overlap

Challenge = Detector

DC beam !
(PSI *et.al.*)

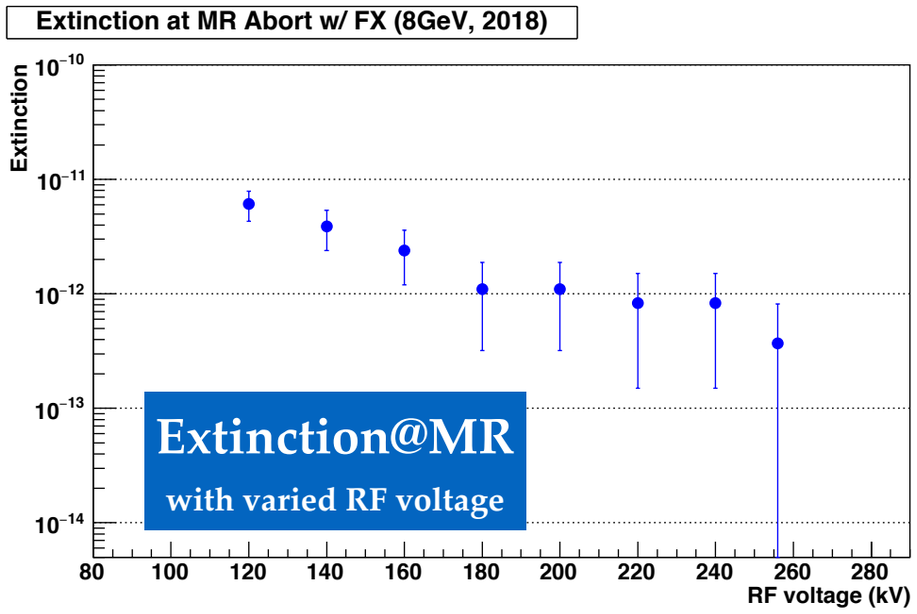
μ*N*→e*N* Search
Signal = Mono-E e⁻
⬇️
Dominant B.G. is
Beam related

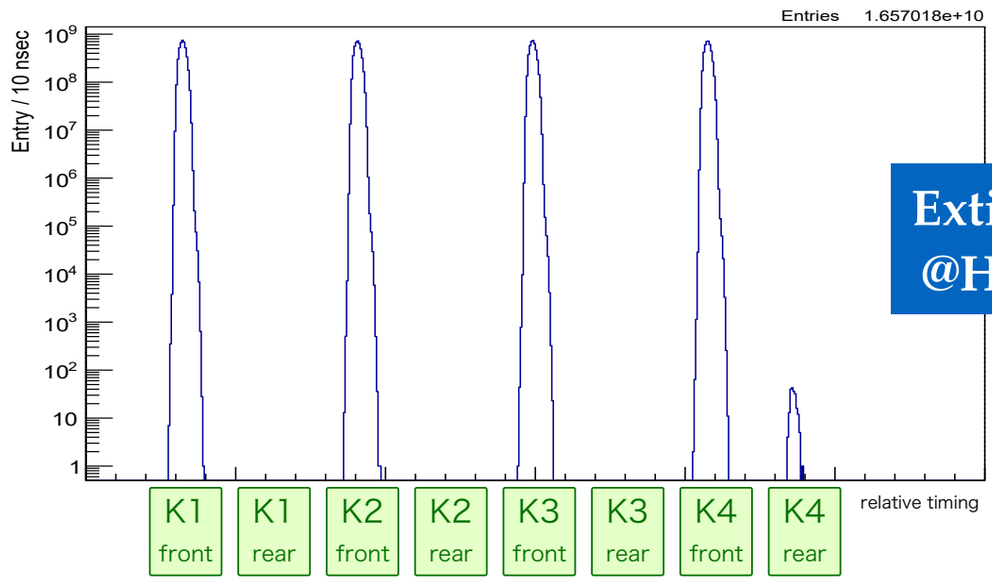
Challenge = Beam

Pulse beam !
(J-PARC *et.al.*)

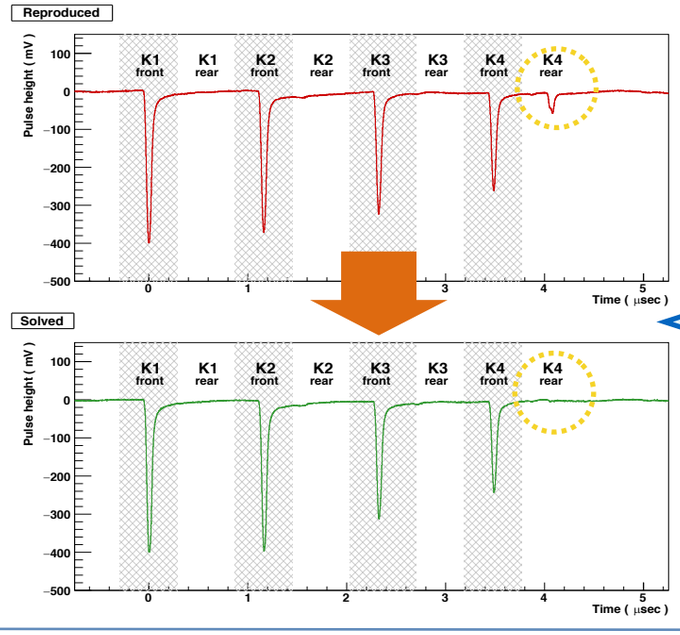
Accelerator Development for COMET

- **Dedicated 8-GeV Operation Tests have been carried out repeatedly so far.**
  - Operation chain; injection/acceleration/extraction, successfully established.
  - Good bunched slow-extraction efficiency of >97% , achieved



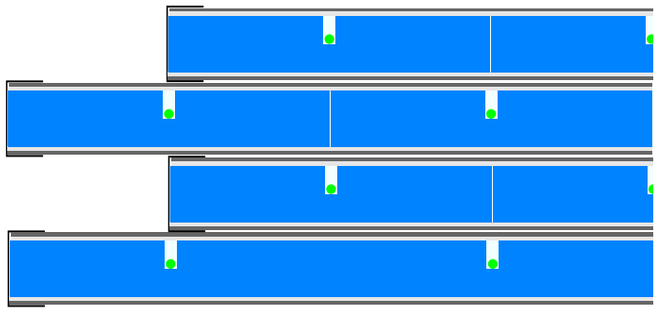


- **Extinction development** was also successfully conducted at Main Ring Proton Synchrotron and Secondary Beam Line in Hadron Experimental Facility.
- **Excellent extinction ($O(10^{-12})$-$O(10^{-11})$)** in MR, confirmed. Observed Small leaks in secondary beam was also successfully solved. **Proton-beam extinction is now ready for COMET !!**



Solution for this small leakage was found and already verified by beam.

Other detector systems



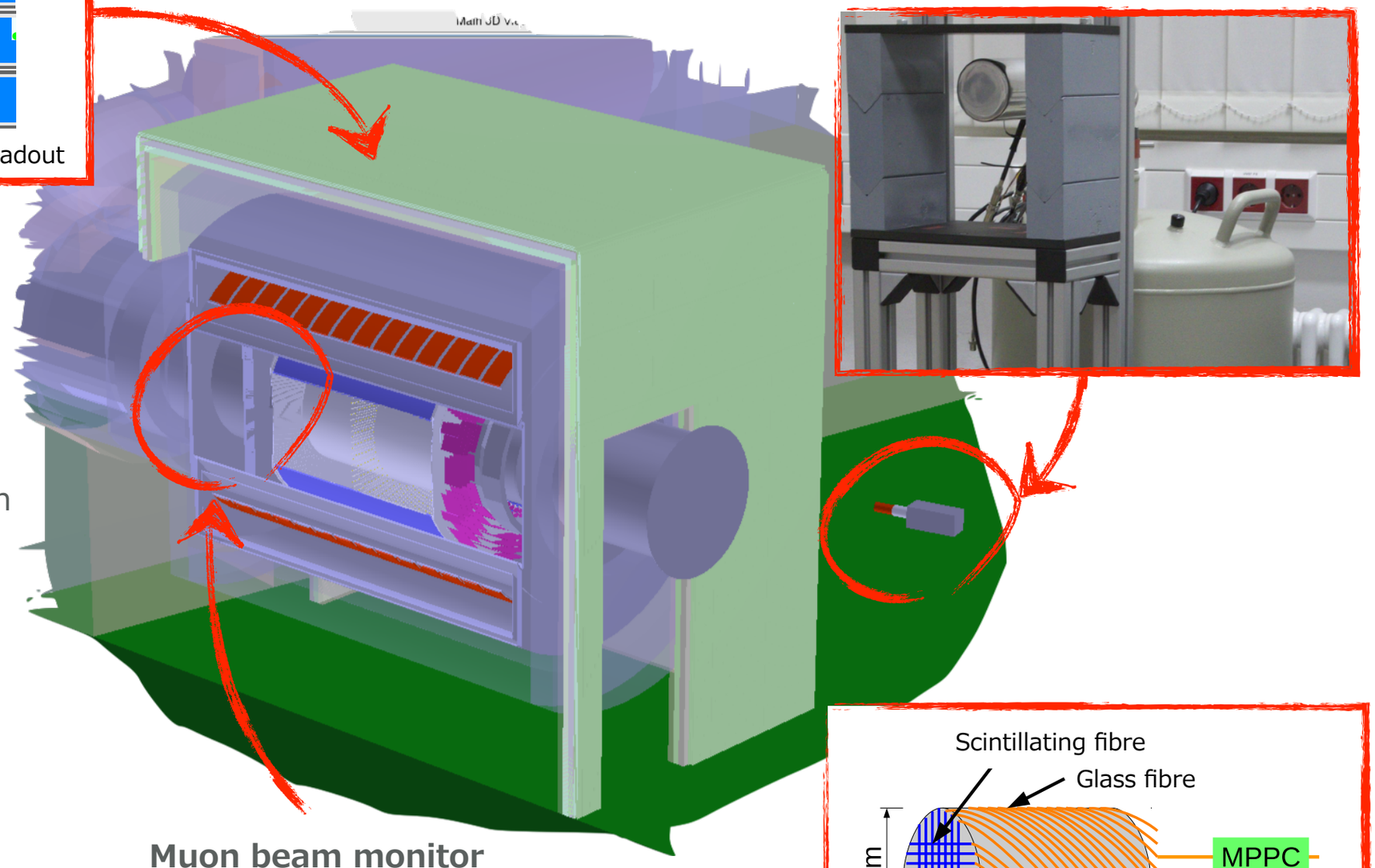
Plastic Scintillator+WLS fibre ×4 layers, SiPM readout

Cosmic-ray Veto (CRV)

- Inefficiency less than 0.4%
- Radiation tolerance @10^{11} n/cm^2

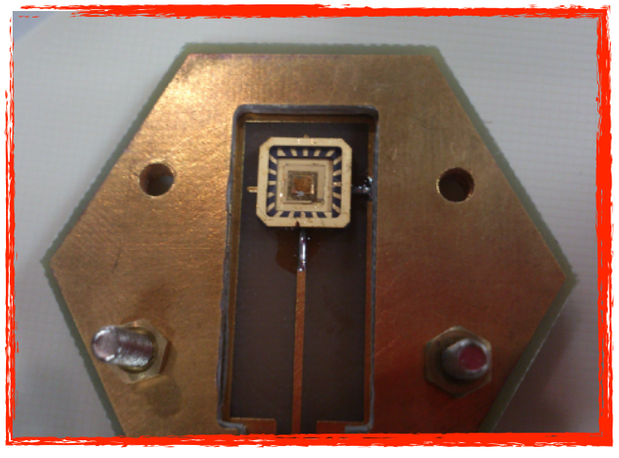
Germanium Detetor (GeDet)

- Measure the muonic X-ray to determine the precise normalisation factor
- A prototype detector has been developed



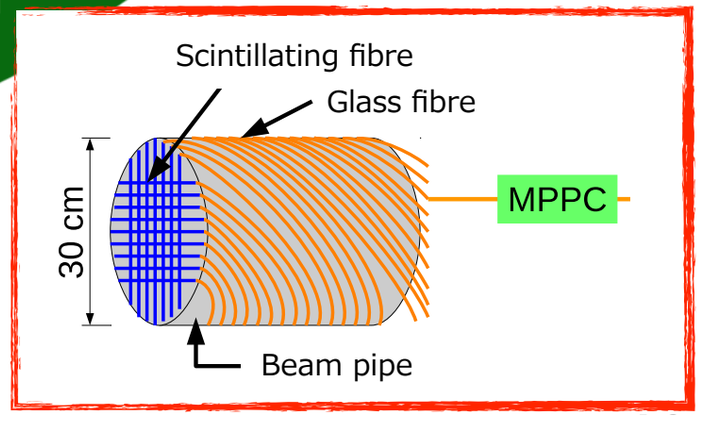
Extinction Monitor

- Diamond detector has shown excellent performance to distinguish the single leakage proton in-between high-intense proton bunches (*)
- TiO_2 detector also being considered alternatively (**)



Muon beam monitor

- Can provide the timing and beam profile at the end of the curved solenoid
- Still under the discussions/R&D



(*) DOI: 10.18429/JACoW-IPAC2019-FRXXPLS2

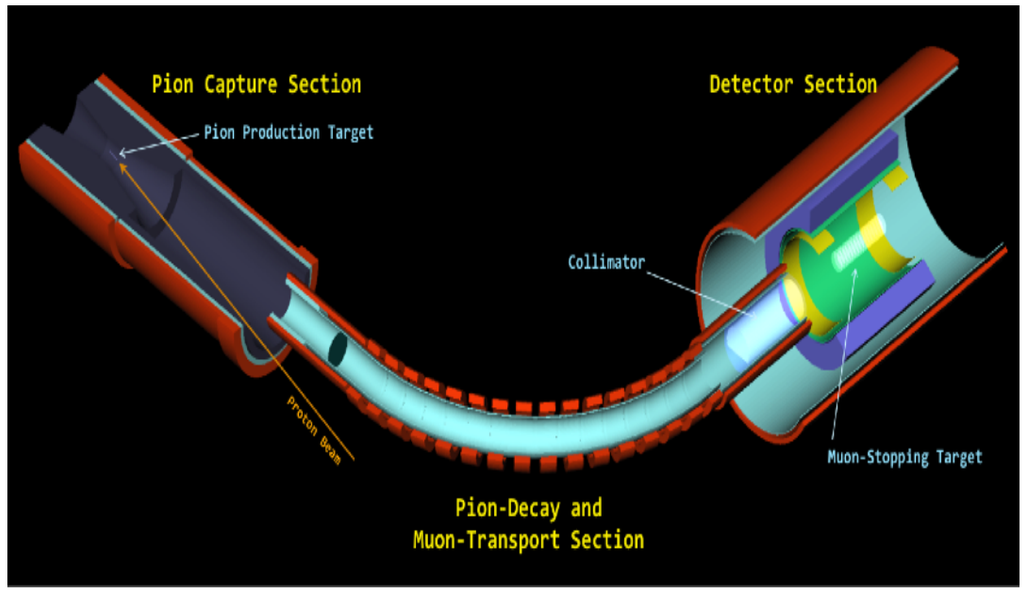
(**) DOI: 10.1109/SENSORS56945.2023.10324967

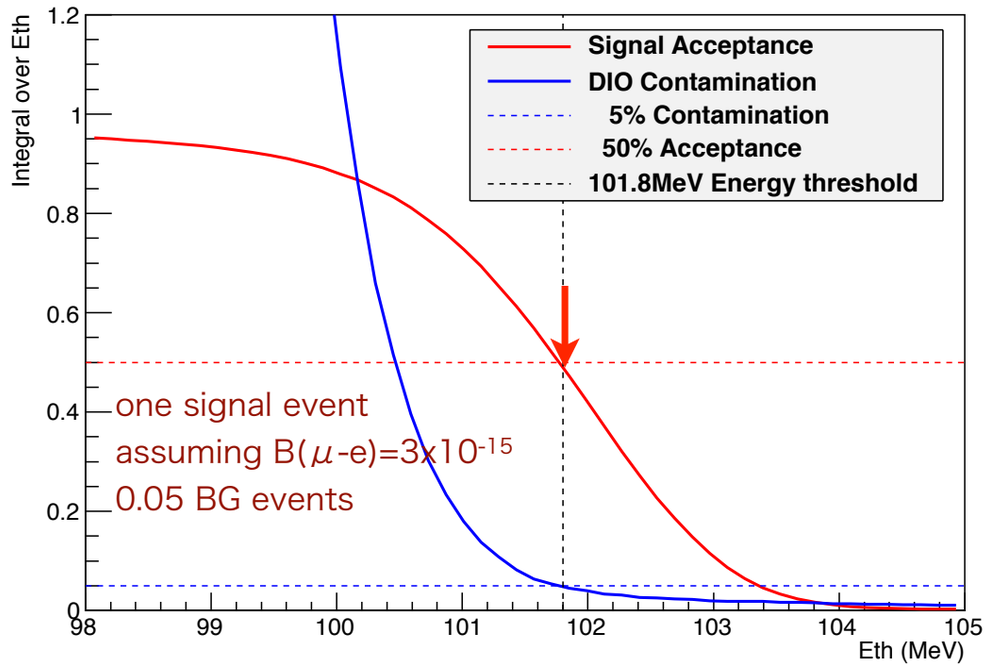
Sensitivity Estimation for Phase-I

- 8GeV, 3.2kW proton beam is assumed
  - 2.5×10^{12} protons/sec
  - 10^{-10} of extinction is supposed
- 150 days (1.2×10^{7} sec) running time
- Expected single event sensitivity

$$\mathcal{B}(\mu^- + \mathrm{Al} \to \mathrm{e}^- + \mathrm{Al}) = \frac{1}{N_\mu^{stop} \cdot f_{cap} \cdot \mathcal{A}_{\mu-e}}$$

- $\mathcal{B}(\mu\text{+Al}\to\text{e+Al}) = 3.1\times10^{-15}$
- Upper limit at 90% C.L.
  - $\mathcal{B}(\mu\text{+Al}\to\text{e+Al}) < 7.0\times10^{-15}$
  - ***cf.*** present limit $< 7\times10^{-13}$ (SINDRUM-II)





Expected backgrounds for Phase-I

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

† This estimate is currently limited by computing resources.

Summary of COMET Phase-I & Phase-II

	COMET-Phase-I	COMET-Phase-II
experiment starts (*)	**in ~2026**	Ready in 3 years after Phase-I completion
beam power	**3.2kW (8GeV, 400nA)**	**56kW (8GeV, 7μA)**
running time	**150 days**	**2.0 x 10^7 (sec)**
# of protons	3.0 x 10^(19)	8.5 x 10^(20)
# of muon stops	1.5 x 10^(16)	2.0 x 10^(18)
muon rate	5.8 x 10^9	1.0 x 10^(11)
# of muon stops / proton	0.00052	0.00052
# of BG	0.02	0.3
S.E.S.	**3.1 x 10^(-15)**	**2.6 x 10^(-17)**
U.L. (90%CL.)	7.0 x 10^(-15)	6.0 x 10^(-17)

*** including the engineering run**