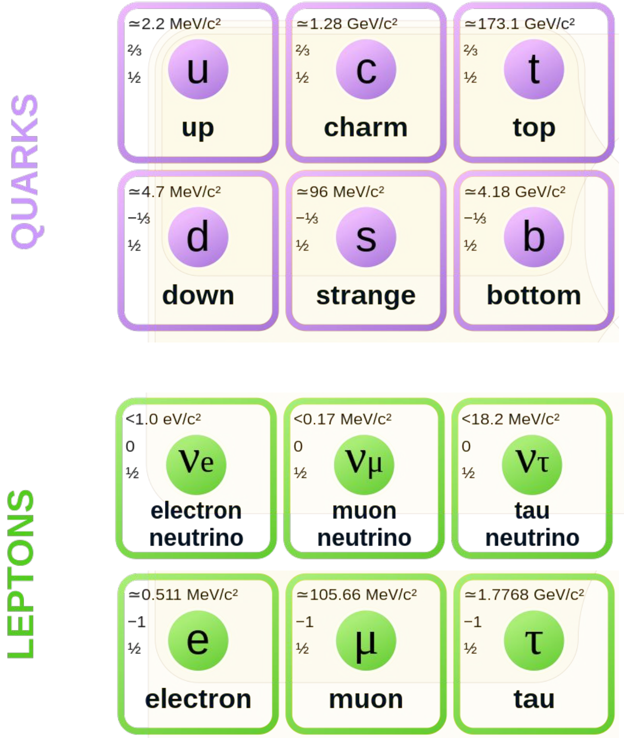
Search for cLFV with COMET experiment

Summary of my work as Ph.D student

Standard model and flavor violation



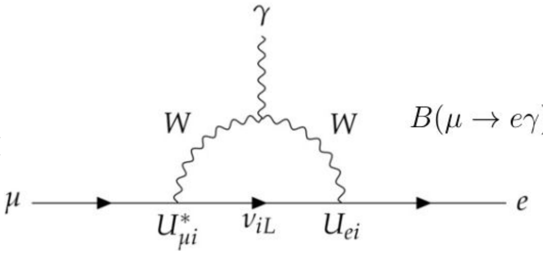
Quark mixing (CKM) -> established ✅

Neutrino oscillation -> established ✅

cLFV -> **not observed yet** ❌

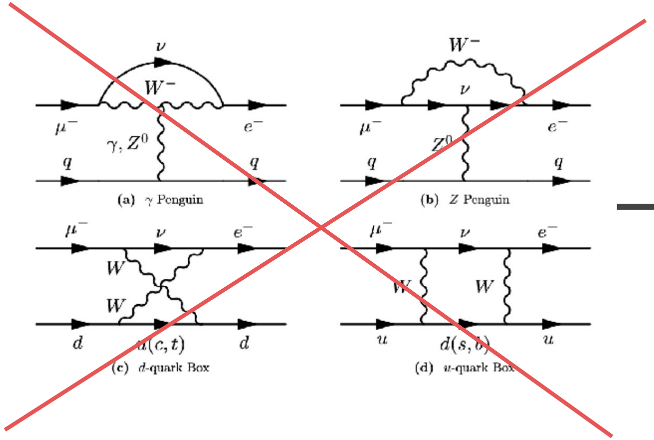
Charged lepton flavor violation (cLFV)

By including **neutrino oscillation** in the SM:



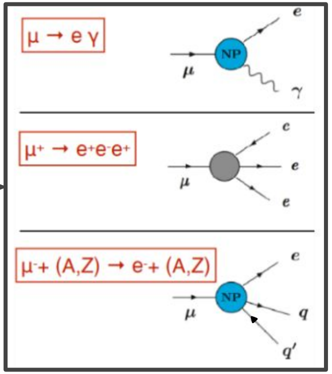
$$B(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_{j=1}^{3} U_{ej}U^*_{\mu j}\frac{m^2_{\nu j}}{M^2_W}\right|^2 \sim O(10^{-54})$$

→ theoretically possible, but **impossible to observe**…



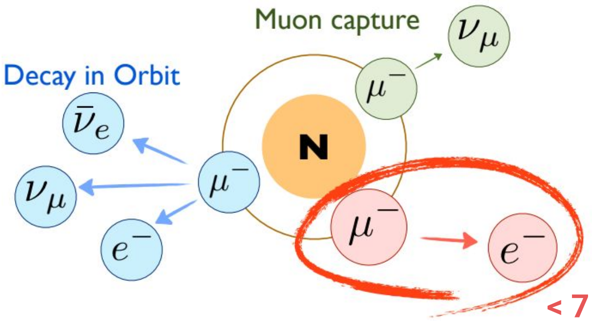
Any observation of cLFV cannot be explained only by neutrino oscillation.

It would be a **clear sign** of **BSM** physics!



Muon-to-electron conversion

Muonic atom decays:

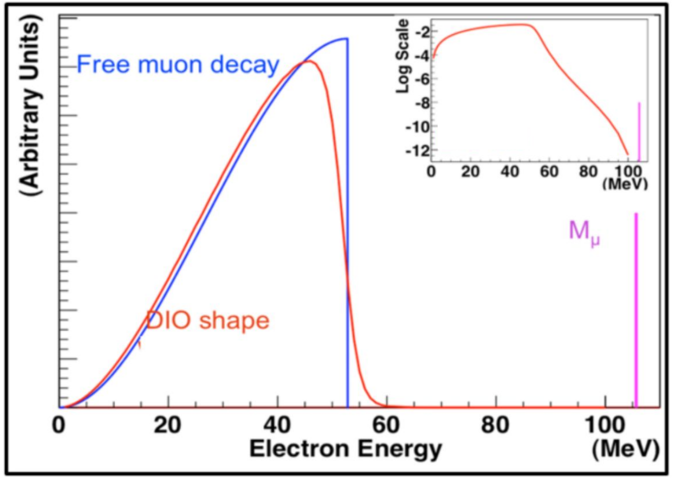


< 7 x 10^{-13}
(SINDRUM-II)

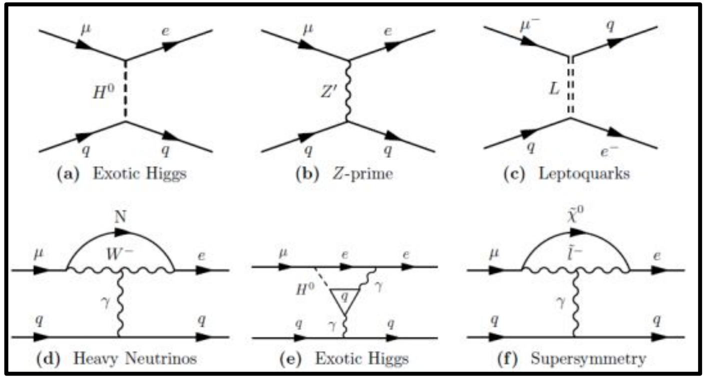
mono-energetic electron

$$E_{\mu e} = m_\mu - B_\mu - E_{recoil}.$$

(104.97 MeV for Al)



Examples of BSM models:



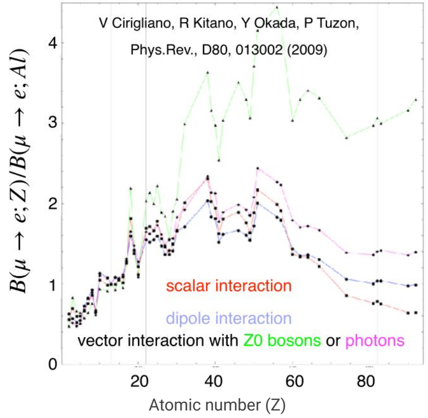
with different predicted conversion rate. Some of them are expected to be reachable by ongoing experiments: **~O(10^{-15}-10^{-17})**

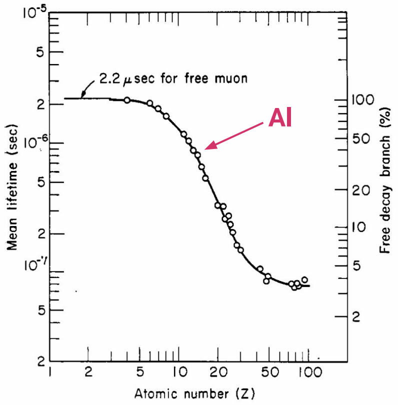
This could significantly help to **constrain theoretical models**.

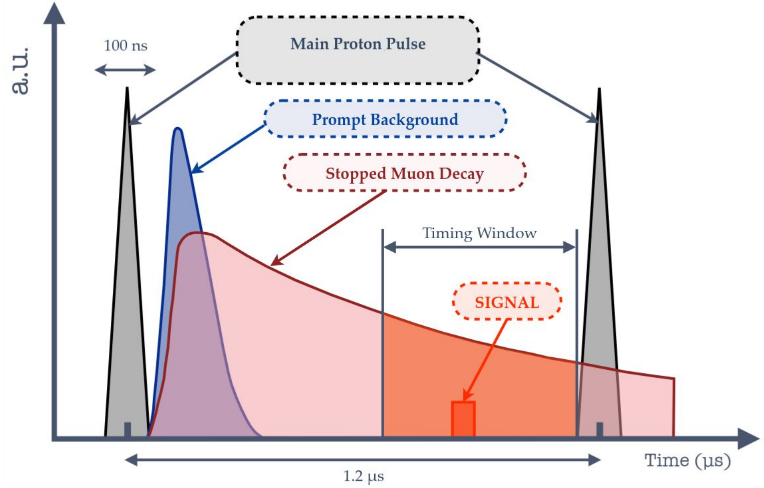
COMET measurement strategy

Muonic atom choice:
Aluminum

Material target	Atomic number (Z)	Muonium lifetime (ns)
Aluminum	13	864
Titanium	22	330
Lead	82	74

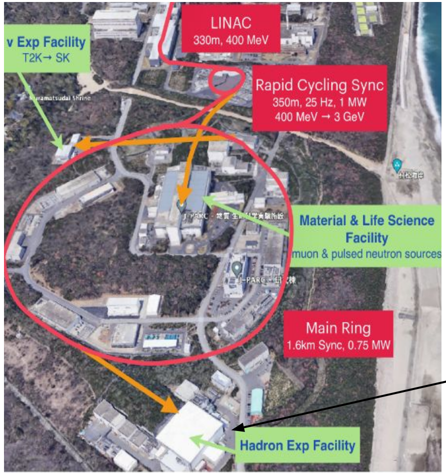


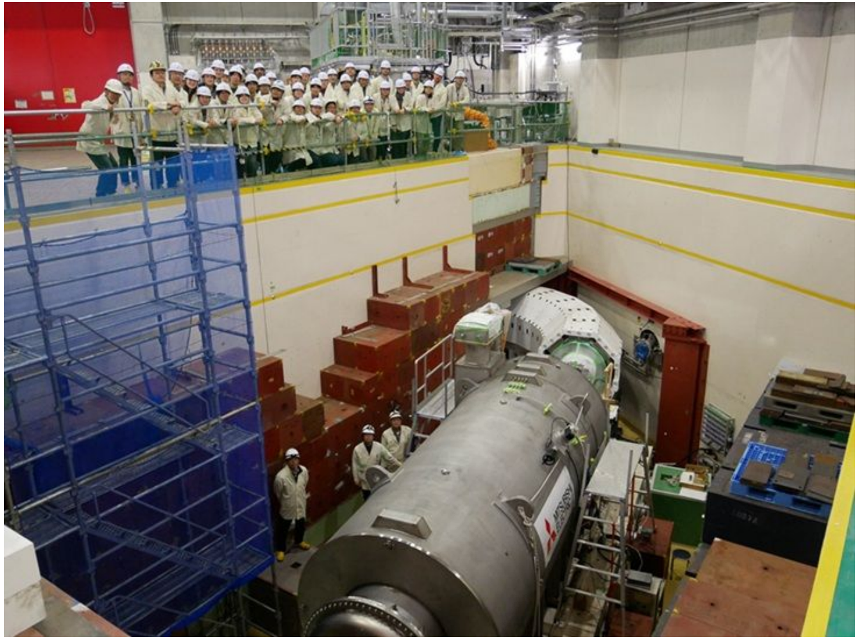


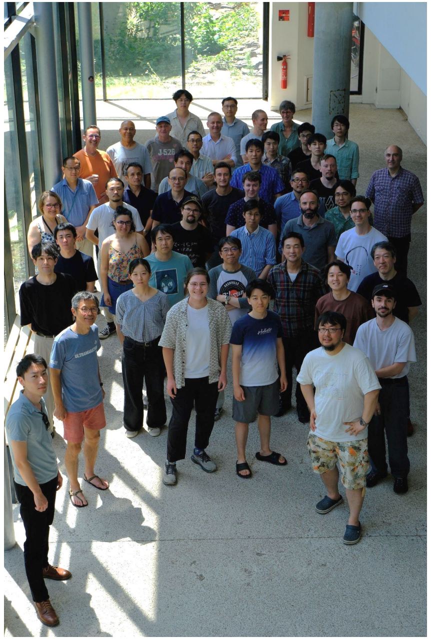


- Use a **pulsed** proton beam → narrow pulses (100 ns).
- Define a **delayed measurement** window (700 ns - 1117 ns) around the muonic atom lifetime.
- **Aluminum** muonic atom is a good compromise regarding its conversion rate and lifetime.

COMET experiment at J-PARC



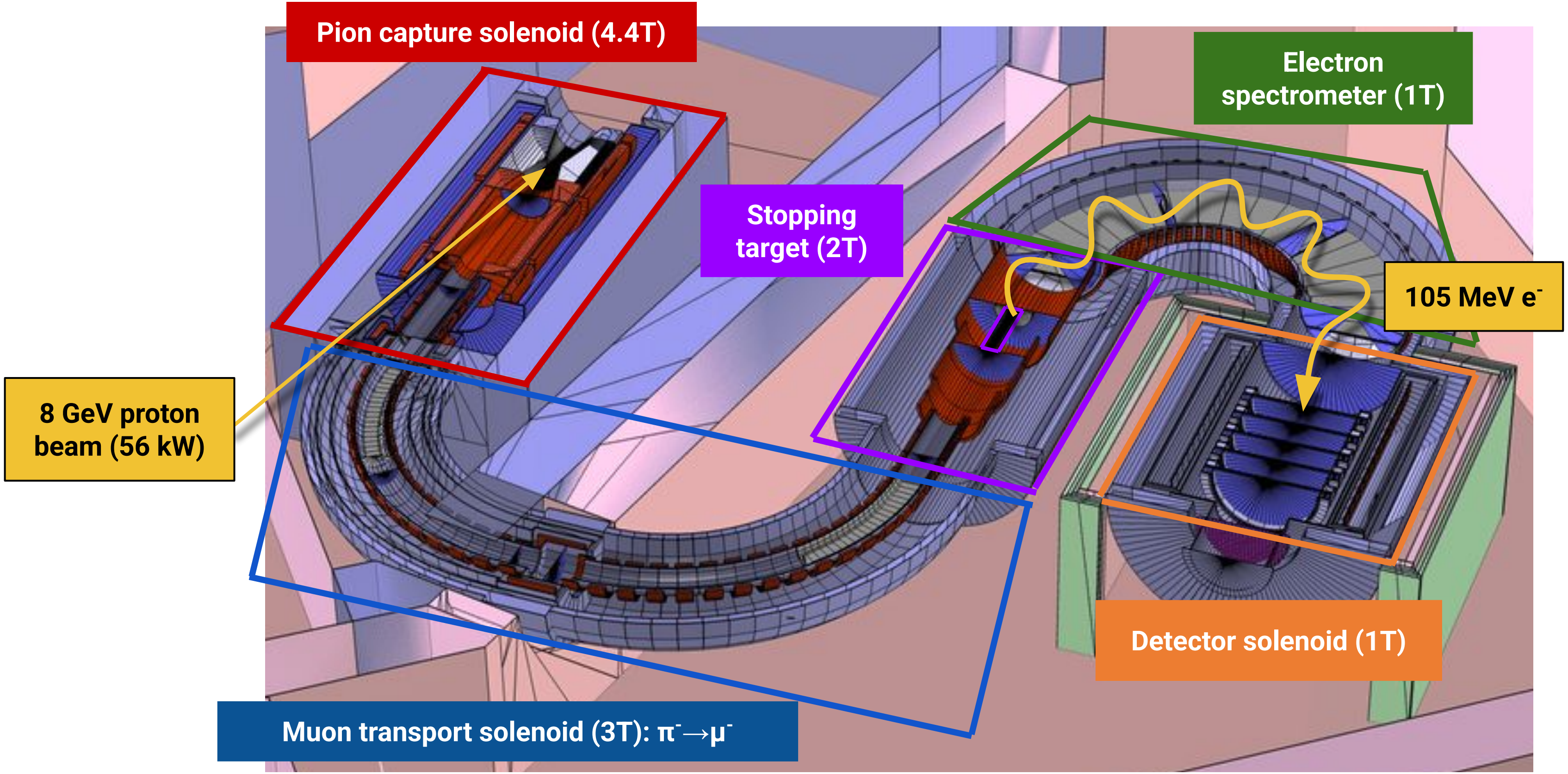




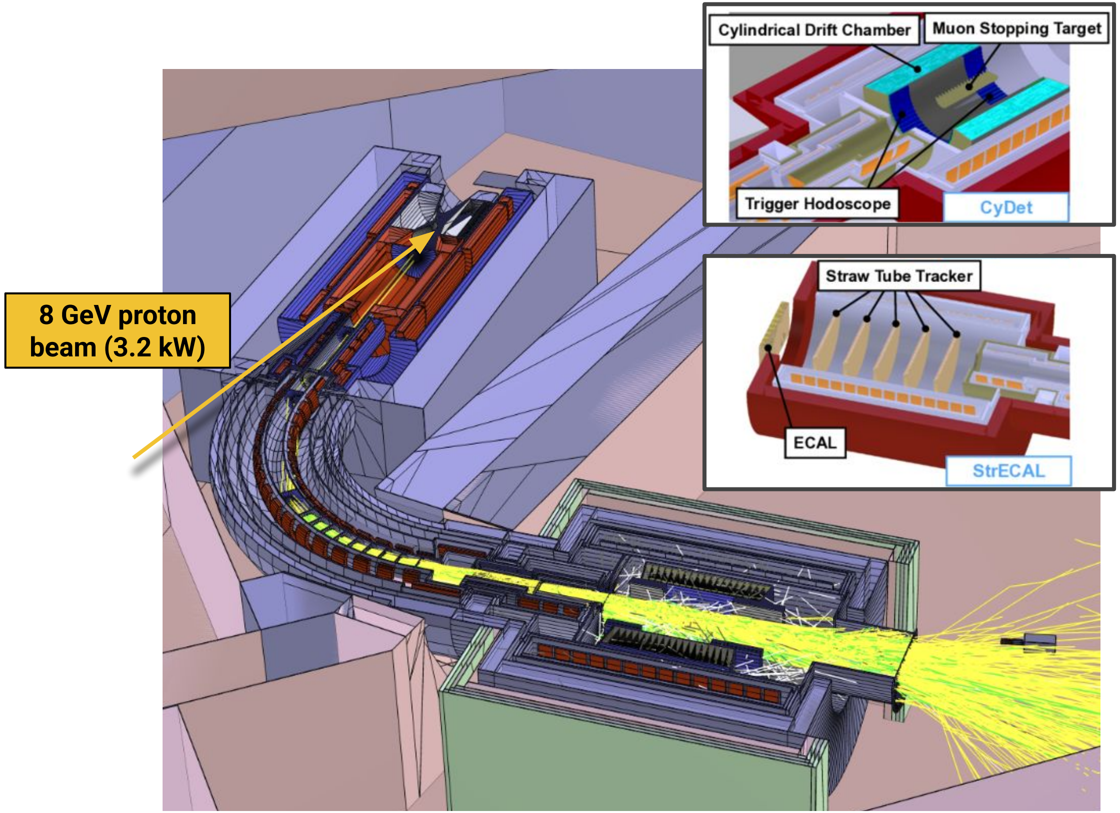
大強度陽子加速器施設
J-PARC
Japan Proton Accelerator Research Complex

> 200 collaborators from 17 countries

COMET design



COMET Phase-I



COMET Phase-I

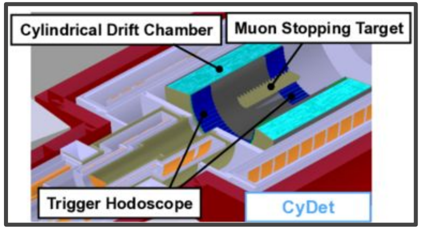
- Physics run:
  - Detector: **CyDet**
  - Target sensitivity O(10^{-15})
  - (x100 current limit)
- Beam measurement:
  - Detector: StrECAL
  - And R&D for Phase-II

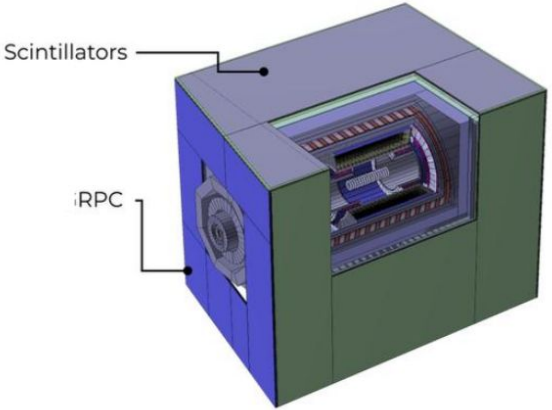
COMET Phase-II

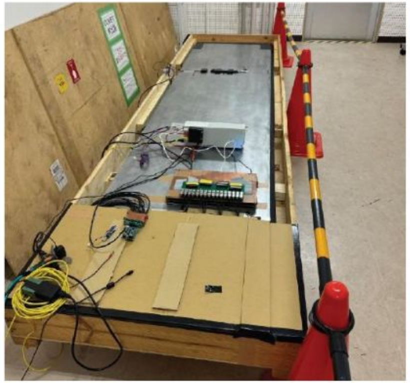
- Intensity increase to 56 kW
- Detector: StrECAL
- Full design (previous slide)
- Target sensitivity O(10^{-17})
- (x10,000 current limit)

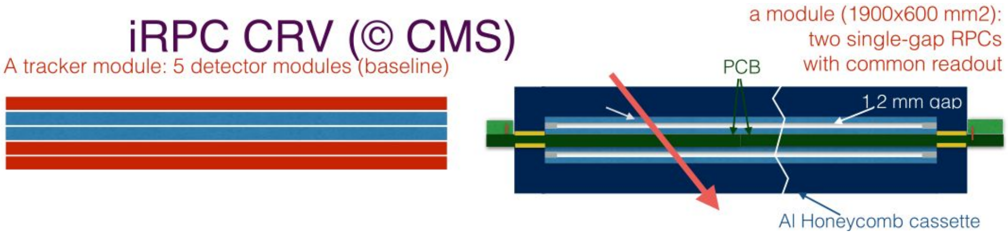
Cosmic Ray Veto (CRV)

- **Cosmic rays** is one of the most crucial background source.
  - Estimation using backward Monte-Carlo simulations.
- Hybrid design for CRV:
  - **Scintillators** (top)
    - 4 layers
    - readout by MPPCs through wavelength-shifting fibres
  - **Resistive plate chambers**
    - existing RPCs
      - CMS iRPC (front & back)
      - Argo RPC (sides)
    - 5 layer as baseline
- First scintillator module was constructed and currently being **commissioned** with cosmic rays.

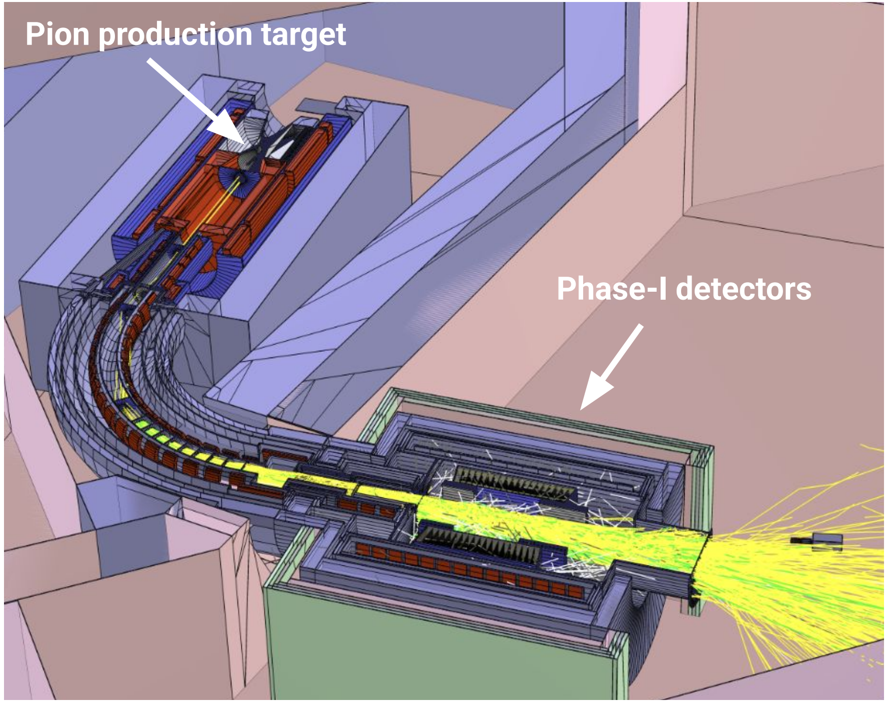








Study of radiation levels on detectors - Overview



Goal: Study **radiation levels** on detectors.

❖ Simulation framework: **ICEDUST**, based on GEANT4 and ROOT.

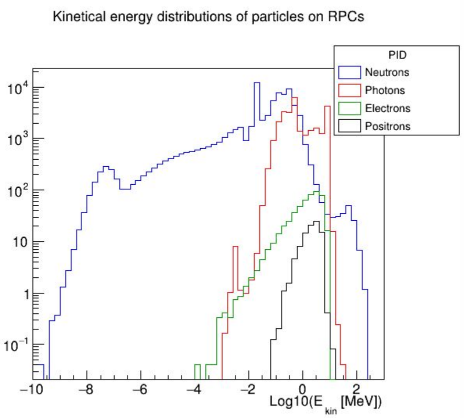
❖ The full chain is simulated:

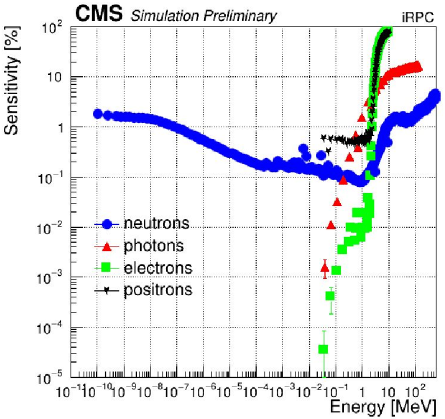
→ proton on target interaction,

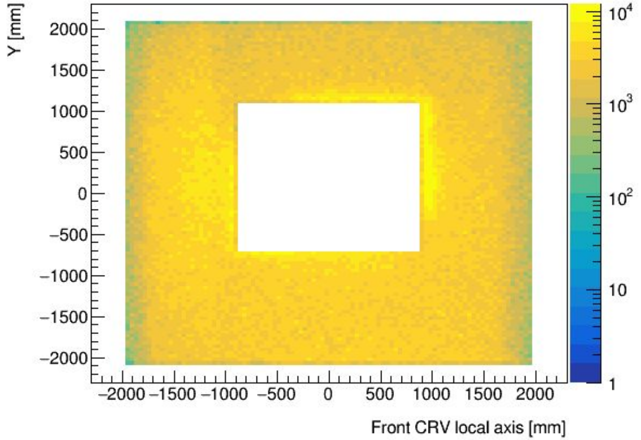
→ muon beam transport,

→ detectors simulation.

Study of radiation levels on detectors - Results (CRV)







Intense Muon Beam → **High** Expected Radiation **Rates** on Detectors.

Goal: Reduce radiation rates to ensure COMET’s sensitivity to new physics!

Some shielding designs

Multiple Shielding Hypotheses Considered:

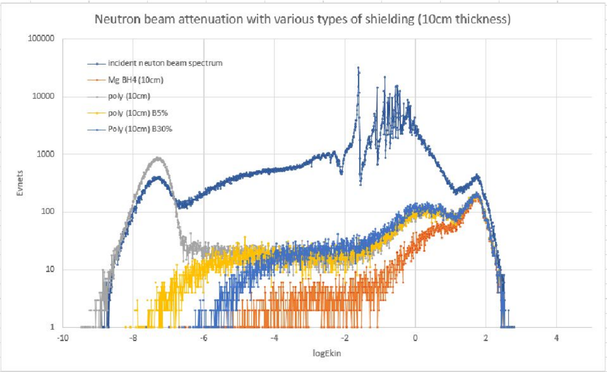
- Various shielding materials
- Different geometries
- Upstream and downstream regions

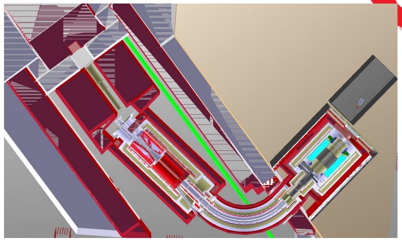
Results: Some options were not cost-effective. Others showed good results. **However, the reduction remains insufficient!**

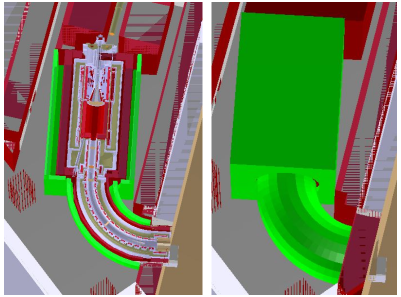
→ **Working group established to optimize the beamline.**

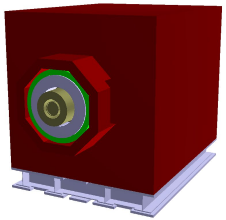
Working group : JC Angélique-JL Gabriel - LPC Caen T. Clouvel – C. Carlaganu - LPC Clermont

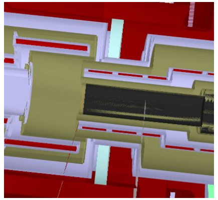
All spectra on the same figure for comparison.

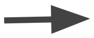






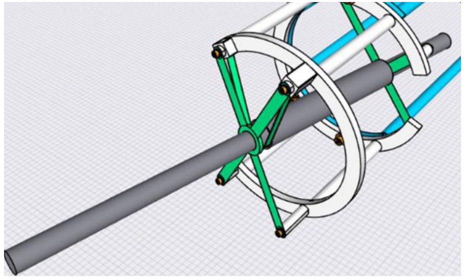


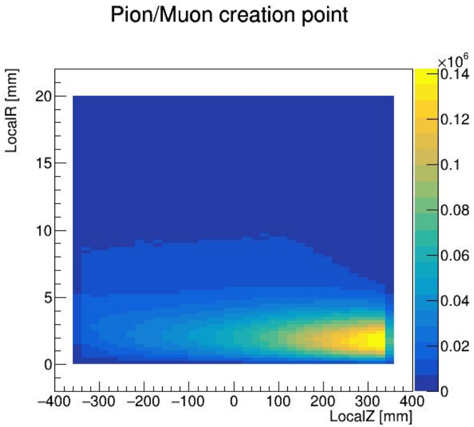


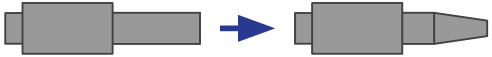


	Integrated photon flux on front CRV	Integrated neutron flux on front CRV
Effect of a 10cm HDPE/w 30% boron	- 31.2 % ± 0.8 %	- 28.6 % ± 0.5 %

Optimization of the proton target - Overview







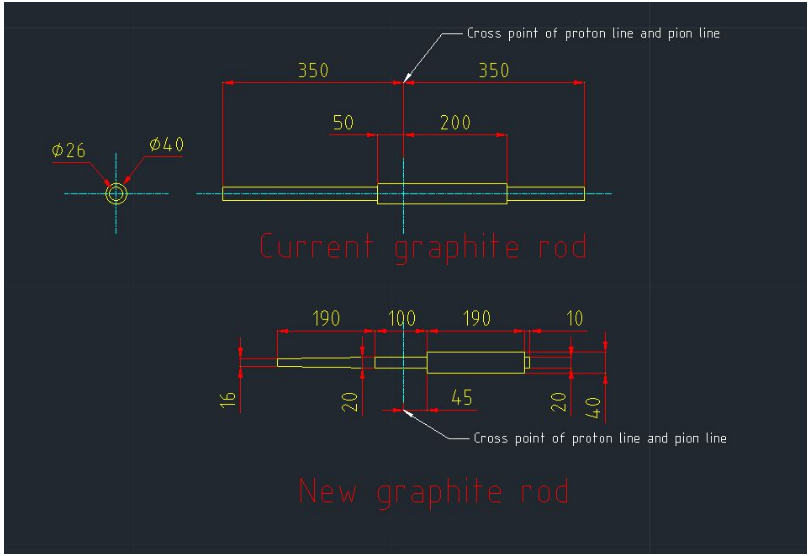
Default Target: 70 cm graphite target, composed of three cylinders (radii: 1.3 cm or 2 cm).

Objective: Comprehensive optimization of the proton target to reduce radiation rates on detectors.

Optimized Parameters:

- ❖ **Length:** Shortened to minimize radiation.
- ❖ **Position:** Centered at the optimal location for the PCS magnetic field.
- ❖ **Shape:** Added conical design to allow low-energy pions/muons to exit the target more easily.
- ❖ **(Material)**

Optimization of the proton target - Results



Detector	Integrated neutron flux	Integrated photon flux
Front CRV	$-(16.0 \pm 0.1)\%$	$-(16.6 \pm 0.3)\%$
Left CRV	$-(17.2 \pm 1.1)\%$	$-(16.3 \pm 1.1)\%$
Right CRV	$-(18.1 \pm 1.4)\%$	$-(15.4 \pm 0.9)\%$
Top scintillator CRV	$-(14.0 \pm 1.3)\%$	$-(20.5 \pm 1.0)\%$
Top trapezoid CRV	$-(13.0 \pm 1.3)\%$	$-(9.3 \pm 2.7)\%$
Back CRV	$-(11.6 \pm 0.8)\%$	$-(14.9 \pm 0.3)\%$
Inner US CTH	$-(9.5 \pm 1.0)\%$	$-(9.7 \pm 1.8)\%$
Outer US CTH	$-(9.1 \pm 1.3)\%$	$-(10.2 \pm 1.8)\%$
Inner DS CTH	$-(11.2 \pm 1.2)\%$	$-(10.2 \pm 1.2)\%$
Outer DS CTH	$-(11.2 \pm 1.6)\%$	$-(11.4 \pm 1.2)\%$
CDC gas volume	$-(9.1 \pm 0.4)\%$	$-(8.1 \pm 0.3)\%$

Table 5: Expected effect of new target design on neutron and photon flux on detectors.

Achieve **lower radiation levels** at each detector while maintaining a **stopped muon count comparable** to the default target (≤1–2% variation).

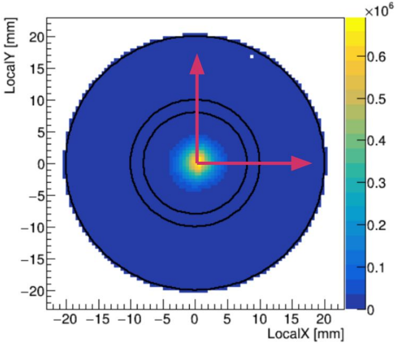
Optimization of the proton target - Validation

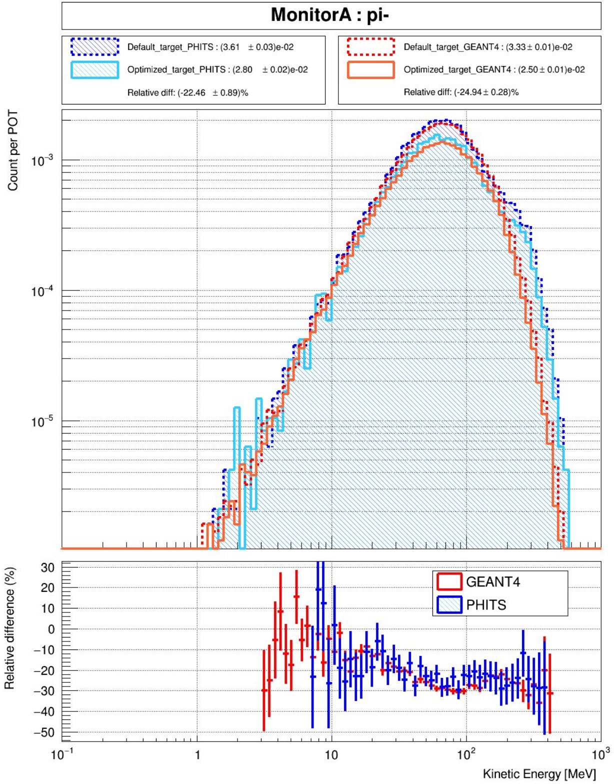
Validation Tests:

- ❖ Multiple physics models tested.
- ❖ Beam alignment uncertainties
- ❖ Cross-validation with PHITS simulation framework

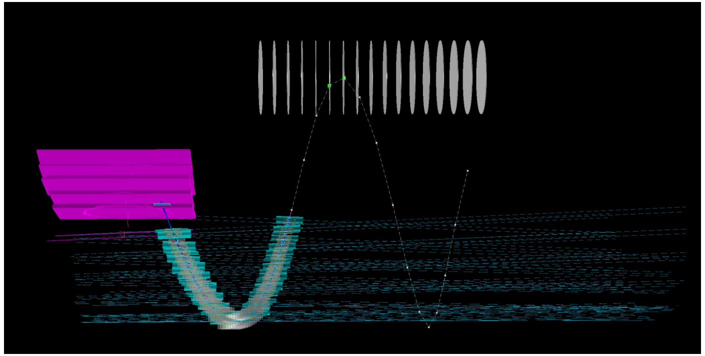
Outcome: Current validation tests **confirm the positive effect** of the proton target optimization.

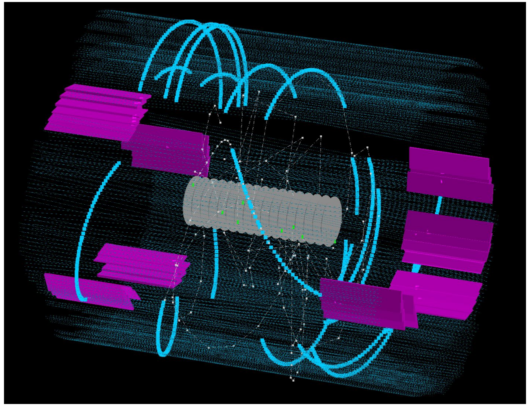
Physics lists
QGSP_BERT_HP
QGSP_BIC_HP
FTFP_BERT_HP





Tracking development for sensitivity update



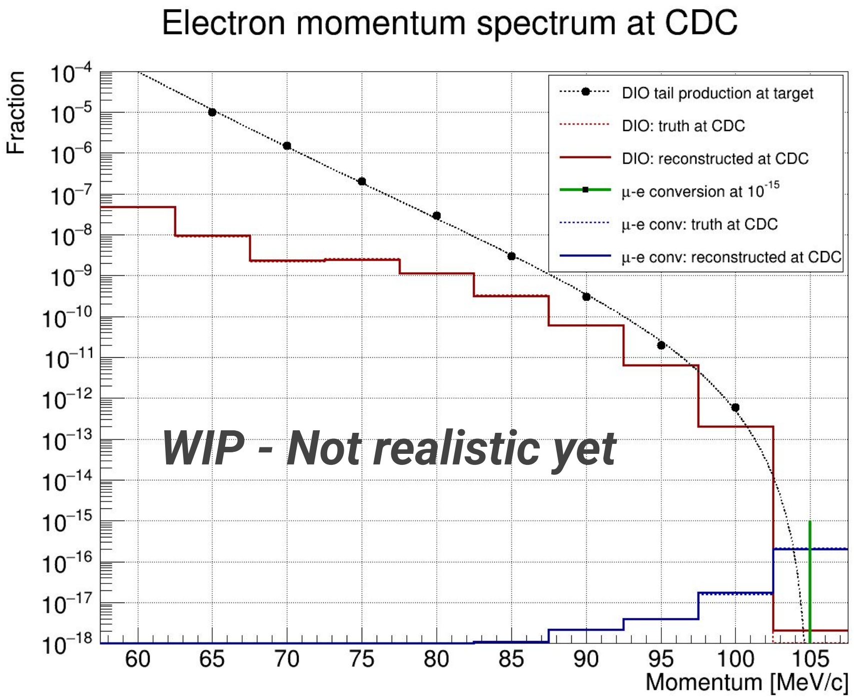


10 events of single DIO e- of 100 MeV/c

Summary of current tracking conditions:

- Simple standalone GENFIT tracking code was run on different monoenergetic DIO simulations. (From 65 to 105 MeV/c, by step of 1 MeV/c)
- **No noise** or secondaries considered for now.
- Position & momentum seeds are using MC true values with arbitrary seed uncertainties to maximise convergence rate.
- Using both **CTH & CDC hits**.
- Only fitting the **first loop** for multi loop trajectories.
- CDC response to be included soon.

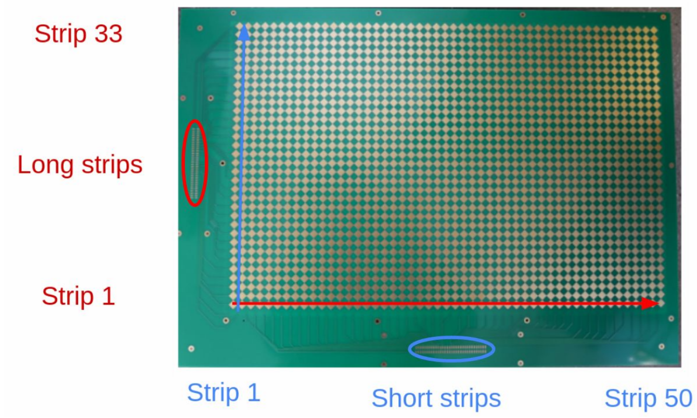
Tracking development for sensitivity update - preliminary results



This is only a tentative plot. Currently preparing the full script chain for the study, the values are probably still unrealistic for now.

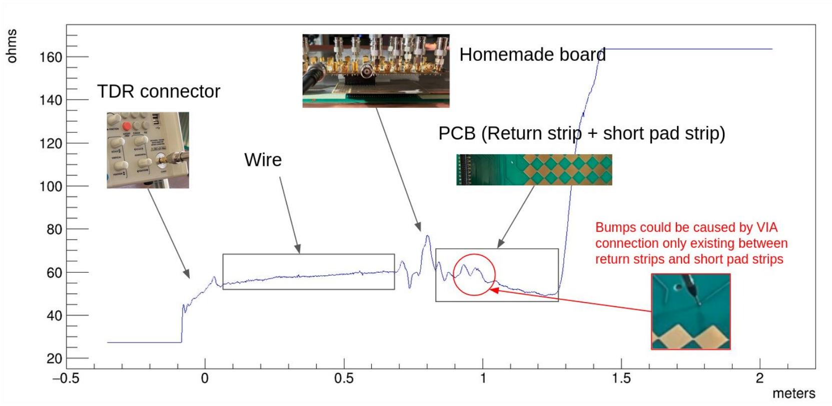
The goal is to study the expected electron spectrum that will be measured during the upcoming **commissiong run in 2028**.

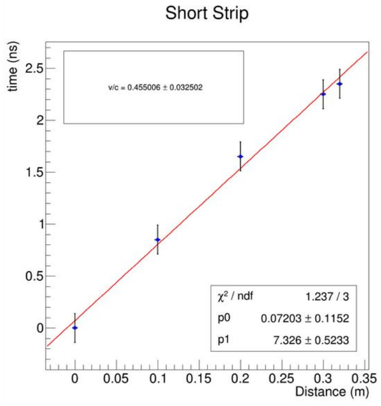
Characterisation of a PCB prototype at IP2I

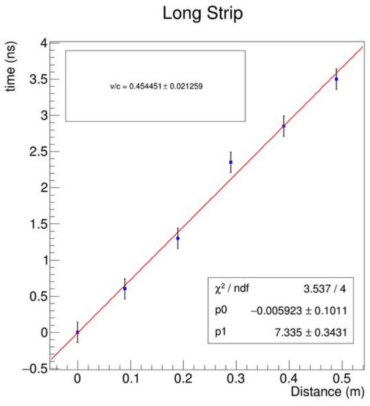


A PCB prototype dedicated to the readout of CRV-RPCs for COMET experiment was characterized with Gustave Garde.

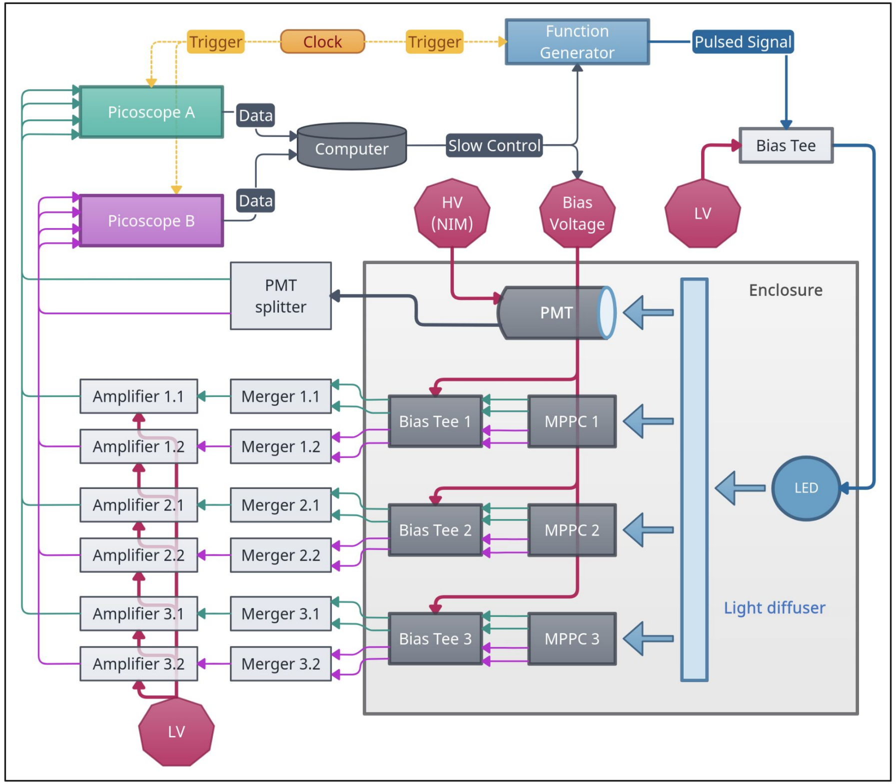
- Propagation speed: **v/c ~ 0.45.**
- Impedance match with CMS FEB: about **~ 10% losses** are expected.
- Problems to correct for the next prototype: **VIAs** to be removed and **Ground Plane** to be added on the return lines.





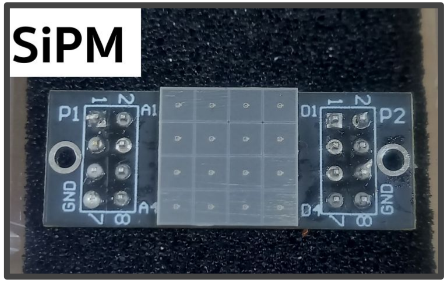


Quality-Control of SiPM used for CTH

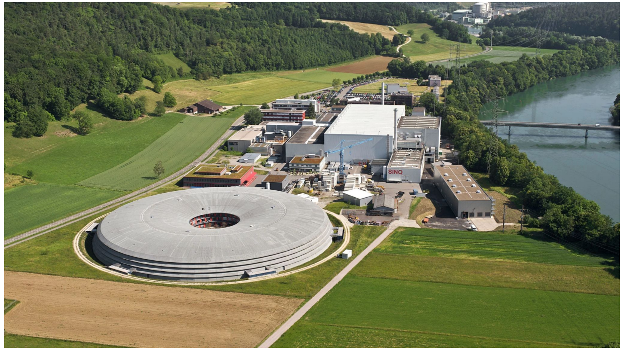


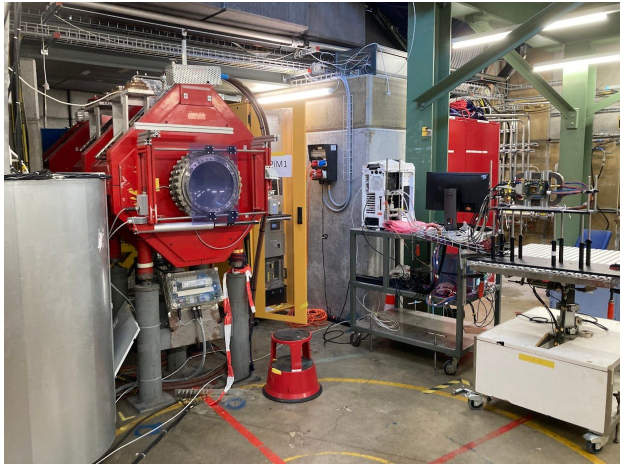
Two-Month Mission in Tokai, Japan:

- Participation in quality control measurements for **Silicon Photomultipliers (SiPMs)** used in the **CTH sub-detector**.
- Opportunity to visit the **experimental hall** in person and meet more members of the collaboration.



Beam test at Paul Scherrer Institute (PSI)





Beam Test Participation at PSI, Switzerland (November 1–8, 2023):

- Used a beam composed of **muons, pions, and electrons**.
- Measured **secondary particles** induced by a **tungsten target,** improving understanding of particle interactions.
- Assessed **detector efficiency and response** for:
  - **Range Counter (RC)** (Phase-α)
  - A section of the **Cylindrical Trigger Hodoscope (CTH)**.

Summary & schedule

- COMET Phase-I will search for **neutrinoless muon to electron conversion** with a target sensitivity which is a factor of 100 better than the current limit.

- The **Phase-I** is expected to start with low intensity (~10% power) **runs in january 2028** for **commissioning** the detector and the muon beam line before reaching the nominal beam intensity.

- In addition to the physics measurement, COMET Phase-I will fully **characterise the muon beam and the backgrounds** with prototypes of COMET Phase-II detectors.

- I should defend my Ph.D before december 2026.

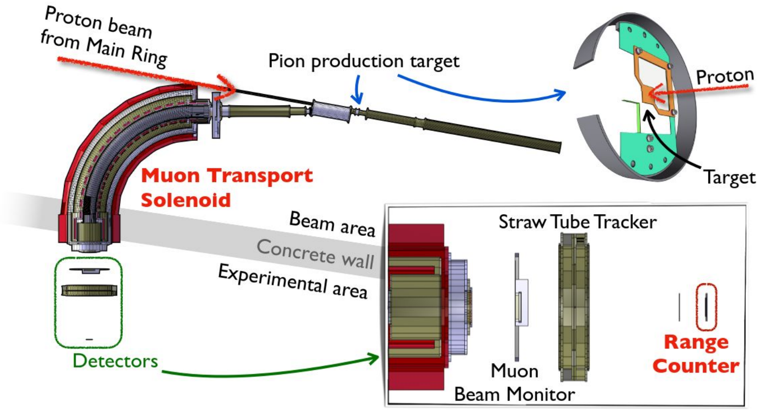
Backup slides

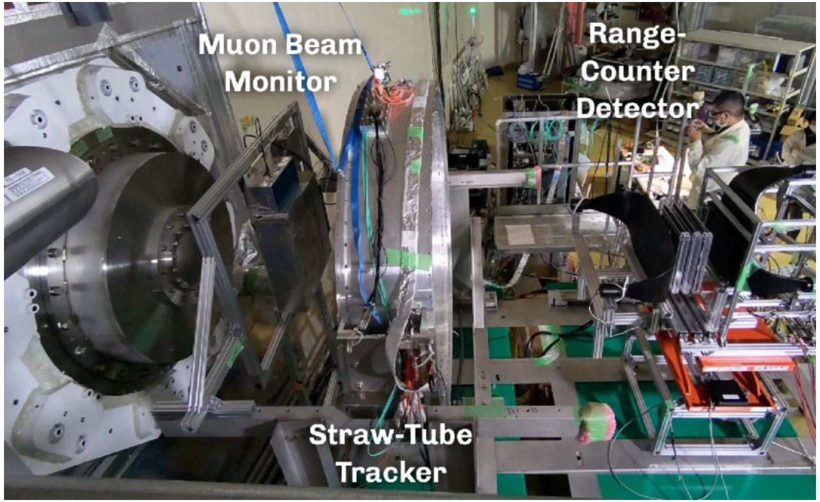
COMET Phase-α (2023)

The 1st commissioning of the COMET facility

- **Proton beam:**
  - ➢ Slowly-extracted pulsed 8 GeV proton beam at 260 W (~1/10 of Phase-I).
  - ➢ Thin graphite pion-production target (1mm).
  - ➢ Beam tuning and beam profile measurement were performed.

- **Muon beam:**
  - ➢ The muon beam was successfully transported to detector area.
  - ➢ **First muon momentum spectrum measurement for COMET!**

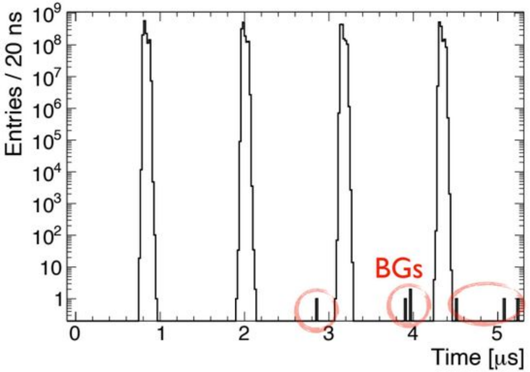




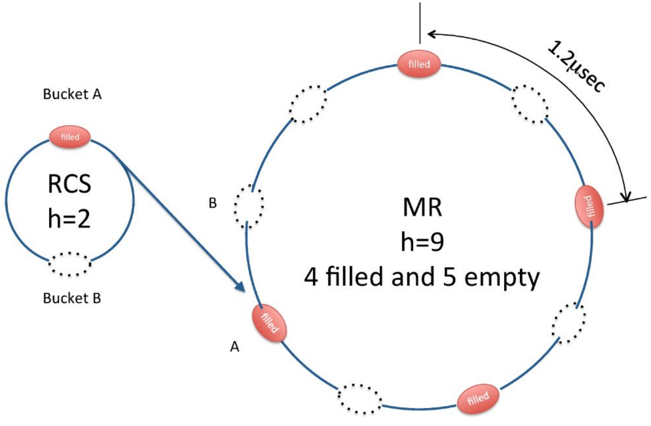
K. Oishi, et al., Nucl.Instrum.Meth.A 1082 (2026) 170904

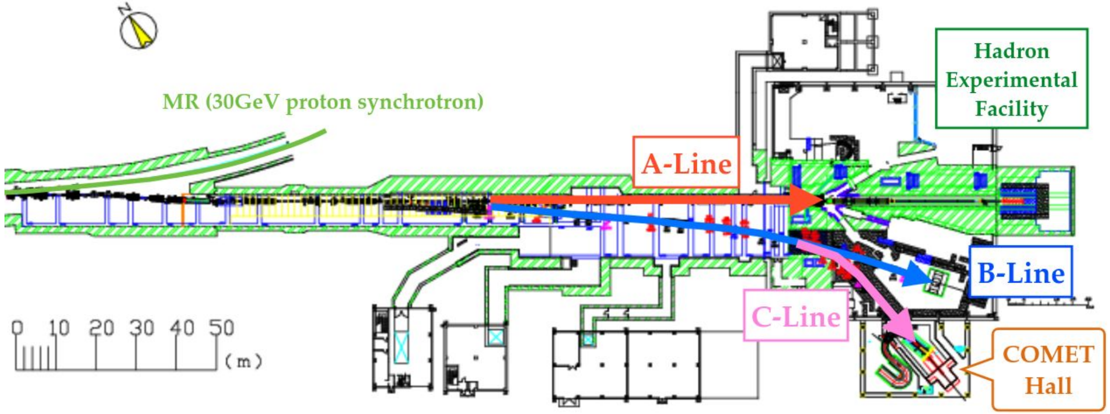
Proton beam line

- **J-PARC proton beam:**
  - **Slow extraction** of the bunches
    ↳4 out of 9 buckets
- **Beam "Extinction"** (fraction of residual protons between bunches):



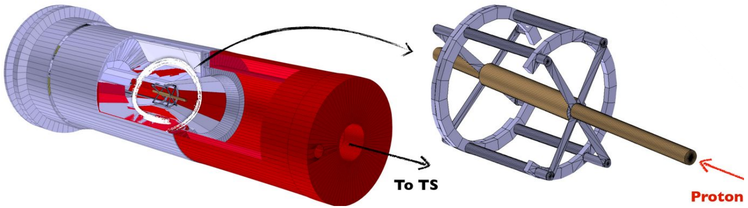
  - Measured **< 1.0x10⁻¹⁰** @K1.8BR of HD(T78 in 2021).

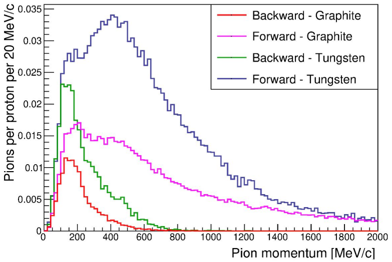




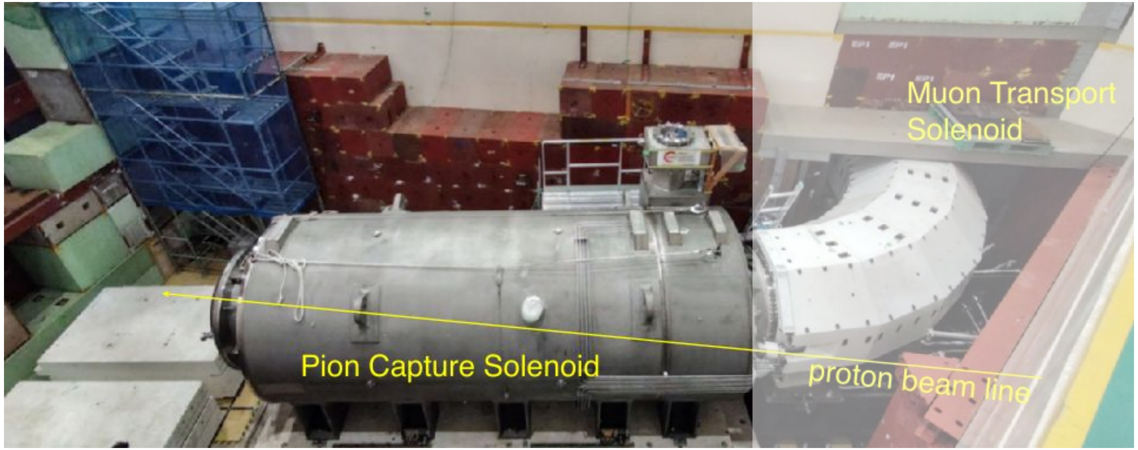
Proton target and Pion capture solenoid (PCS)

- **Proton target:**
  - **Graphite** target used for Phase-I.
  - Tungsten target used for Phase-II.



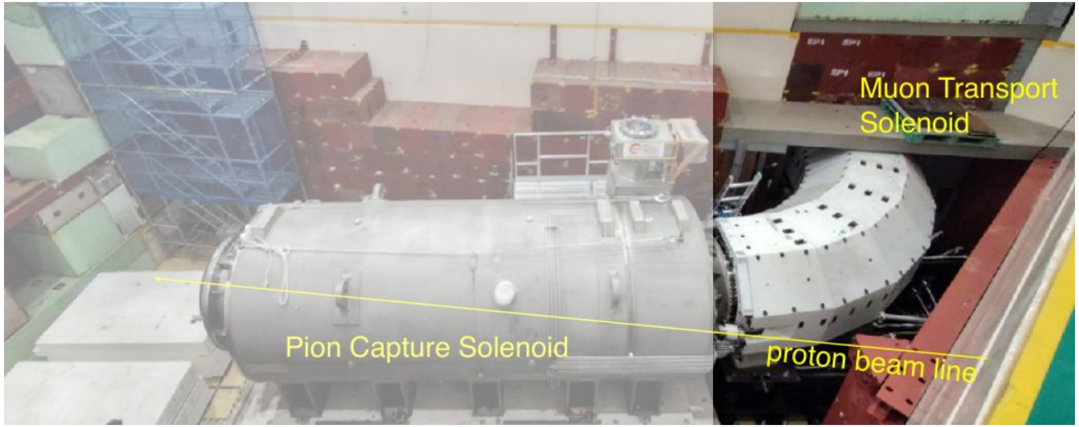


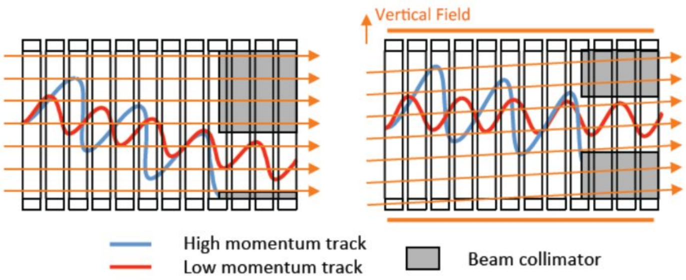
- **Pion capture solenoid:**
  - 4.4T magnetic field to extract pions in the **backward direction.**
  - Installed in November 2024.



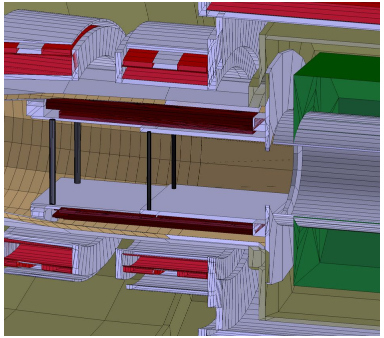
Muon transport solenoid (MTS) and beam collimator

- 90 deg. curved muon transport solenoid (3T).
- MTS operation was successfully confirmed in Phase-α
- Low momentum particles are selected and high momentum particles are rejected with an additional **dipole field** (~0.04T).
- Beam **collimator** designed for charge and momentum selection.





Trajectories in the transport solenoid



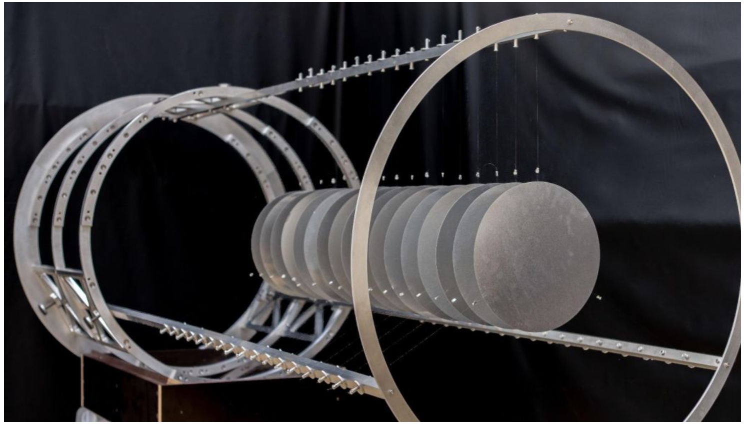
Bridge and detector solenoids

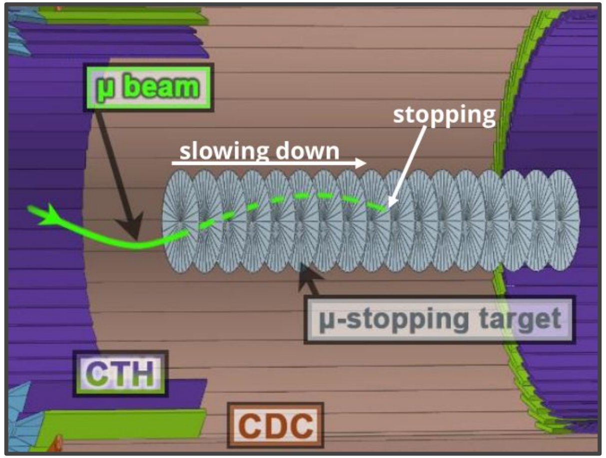
- BS magnet was **delivered** to J-PARC in 2022.
- DS magnet **tested successfully** in 2024 in Tsukuba. It arrived at the COMET hall few weeks ago. The initial check was carried out without any problem. **Important milestone!**
- Field measurement will follow.

Muon stopping target

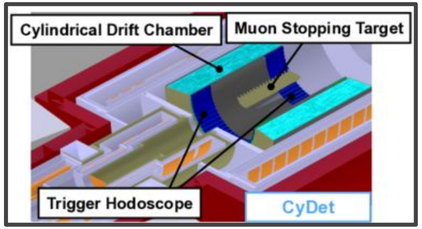
- **Aluminium target:**
  - 17 discs.
  - 10cm radius, 200μm thickness and 50mm spacing.
  - Stability & performance tests of Al. alloys concluded.

- **Germanium detector:**
  - To be place further downstream to measure muonic X-rays for **normalisation**.





Cylindrical Drift Chamber (CDC)



- ❖ Signal electron tracking → **momentum** measurement.
- ❖ Momentum resolution requirement:
  - ➢ below **200 keV/c** @ 105 MeV/c
- ❖ Helium based gas (**He: iso-C_4H_{10}= 90:10**) to minimise multiple scattering.
- ❖ ~5000 (gold plated) sense wires in 20 layers
  - ➢ **Stereo** wire → **3D position measurement**
- ❖ Basic performance test with cosmic rays done.
- ❖ Full readout test, construction of gas system are ongoing
- ❖ Studies of the track reconstruction with a high hit occupancy are also ongoing

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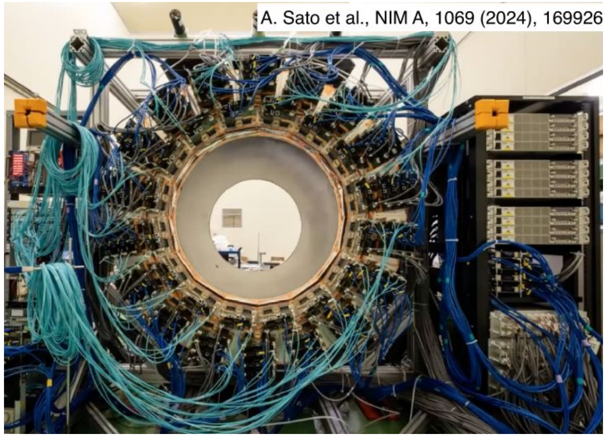
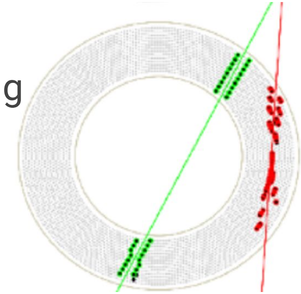
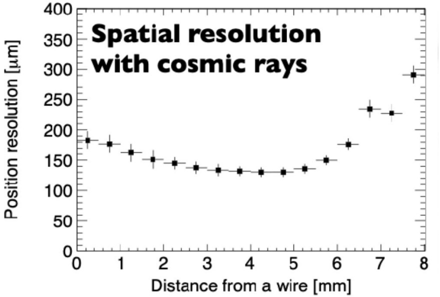
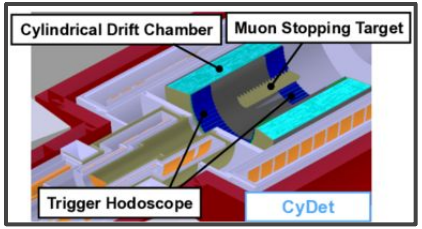


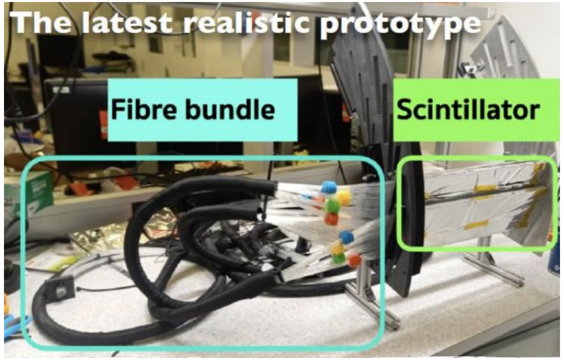


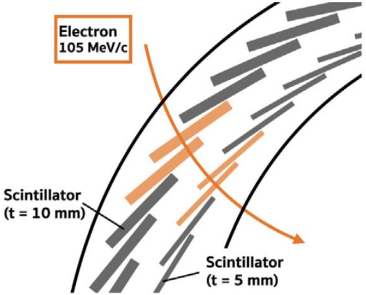


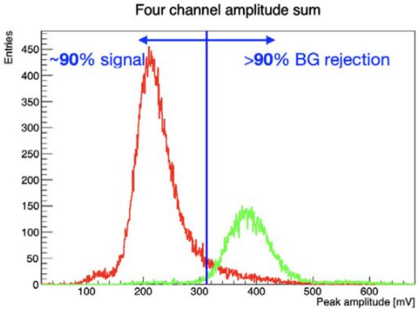
Cylindrical Trigger Hodoscope (CTH)



- For trigger and **timing** measurement, but also showed great performance in **e/μ separation**.
- Timing resolution requirement:
  - below **1 ns**.
- 2 wheels of 2×64 plastic scintillators + fibre + MPPCs
  - >40 p.e. for a detection efficiency > 99%
- **4-fold coincidences** for trigger
  - Trigger rate < 100 kHz.
- MPPCs are cooled to -36°C
  - radiation damage,
  - placed outside of DS.
- Front-end electronics is being **commissioned**.
- Mass production will start soon.







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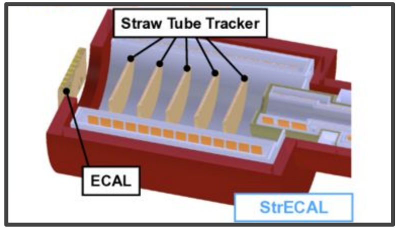
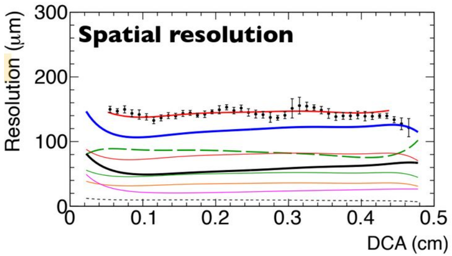
Straw Tube Tracker



- Signal electron tracking → **momentum** measurement.
- Momentum resolution requirement:
  - below **200 keV/c** @ 105 MeV/c
- Thin-wall straw tube gas detector
  - 9.75 mmΦ straw with 20 μm thickness
- Prototype showed great results:
  - spatial res. ~110 μm.
  - mom res < 200 keV/c is achievable.
  - operated in vacuum of < 0.1 Pa.
- The 1st station was **commissioned** in Phase-α.
  - Others are being **constructed**.



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Electromagnetic Calorimeter (ECAL)

- Measurement of **energy, position, timing**.
  - Provides trigger and PID for Phase-I beam measurement program, and for Phase-II physics measurement.
- Energy resolution requirements:
  - below **5% energy** resolution @ 105 MeV.
- LYSO crystal scintillators
  - High density (7.1 g/cm^3), high light yield (70% NaI), and fast time response (40 ns).
  - Dimension of 2×2×12 cm^3.
  - ~2000 crystals.
- Prototype 8x8 crystals performance (@ 105 MeV/c):
  - Energy res. 3.9%,
  - Position res. 0.77 cm,
  - Timing res. 0.5 ns.
- Detector construction is **ongoing**.