Optimization of the COMET Muon Beamline
— for the COMET experiment—

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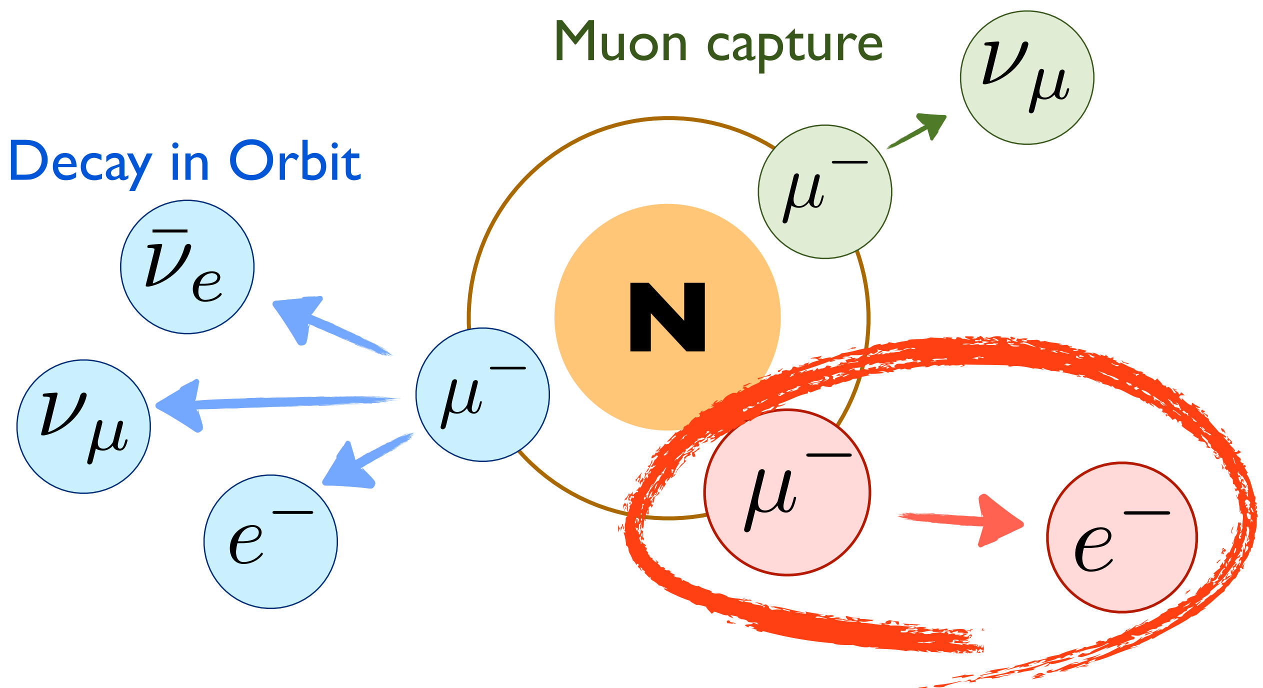
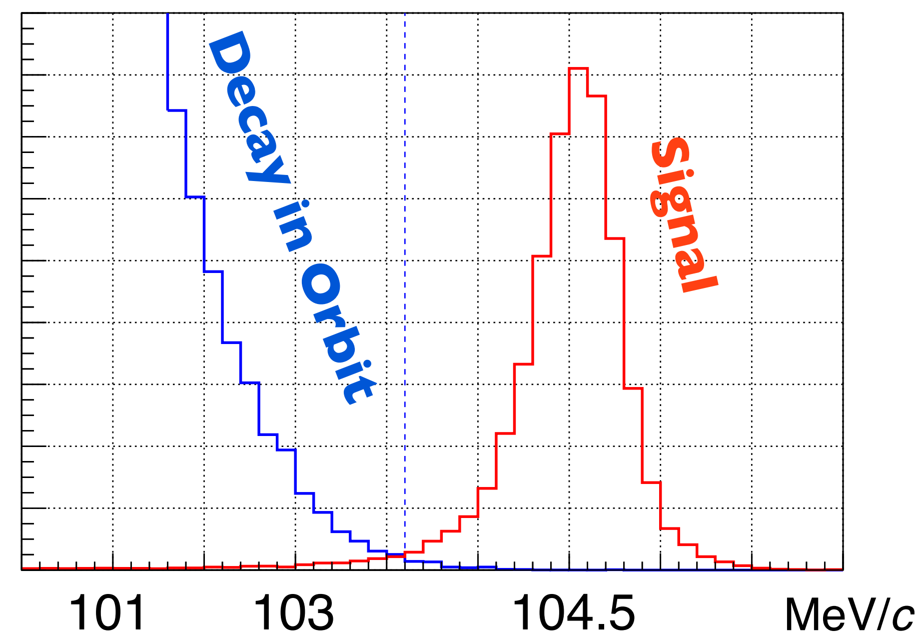
the LS2N laboratory, the University of Nantes, Nantes, France / 15th May 2025

Muon-to-Electron Conversion





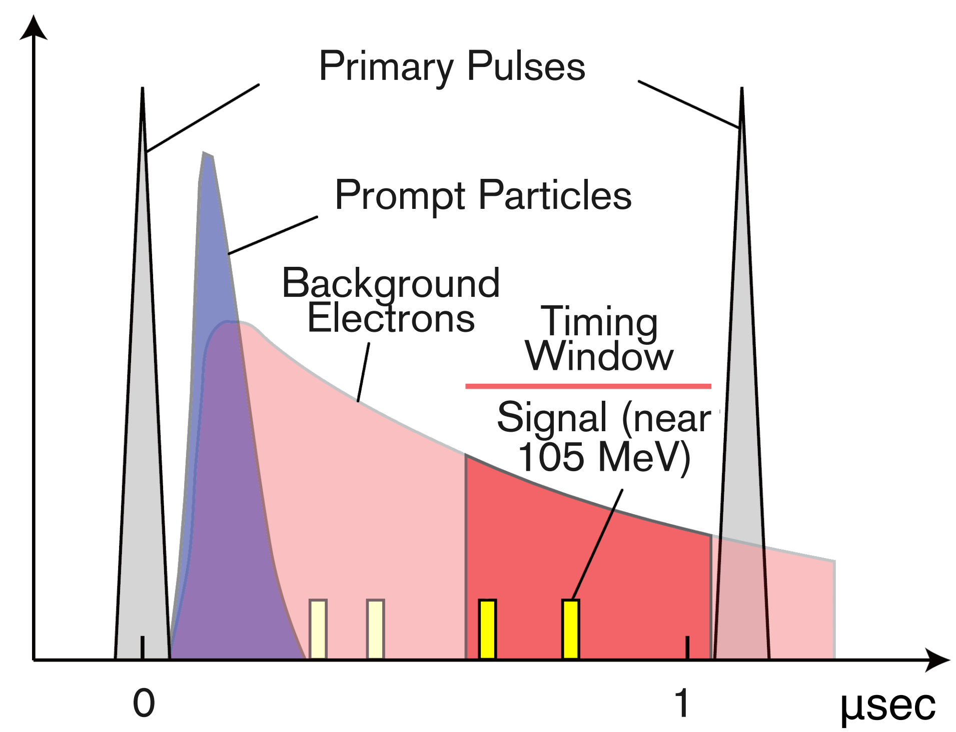
Electron momentum spectrum
w/ BR(μN→eN) = 10^{-15}

Neutrinoless muon decay

- Signal: μ^- + N → **e^-** + N
  - Monochromatic energy of **105 MeV** (Al)
- Branching ratio: BR(μN→eN) < 10^{-54} in the SM.
- Reach **~10^{-15}** in several Beyond-SM scenarios.

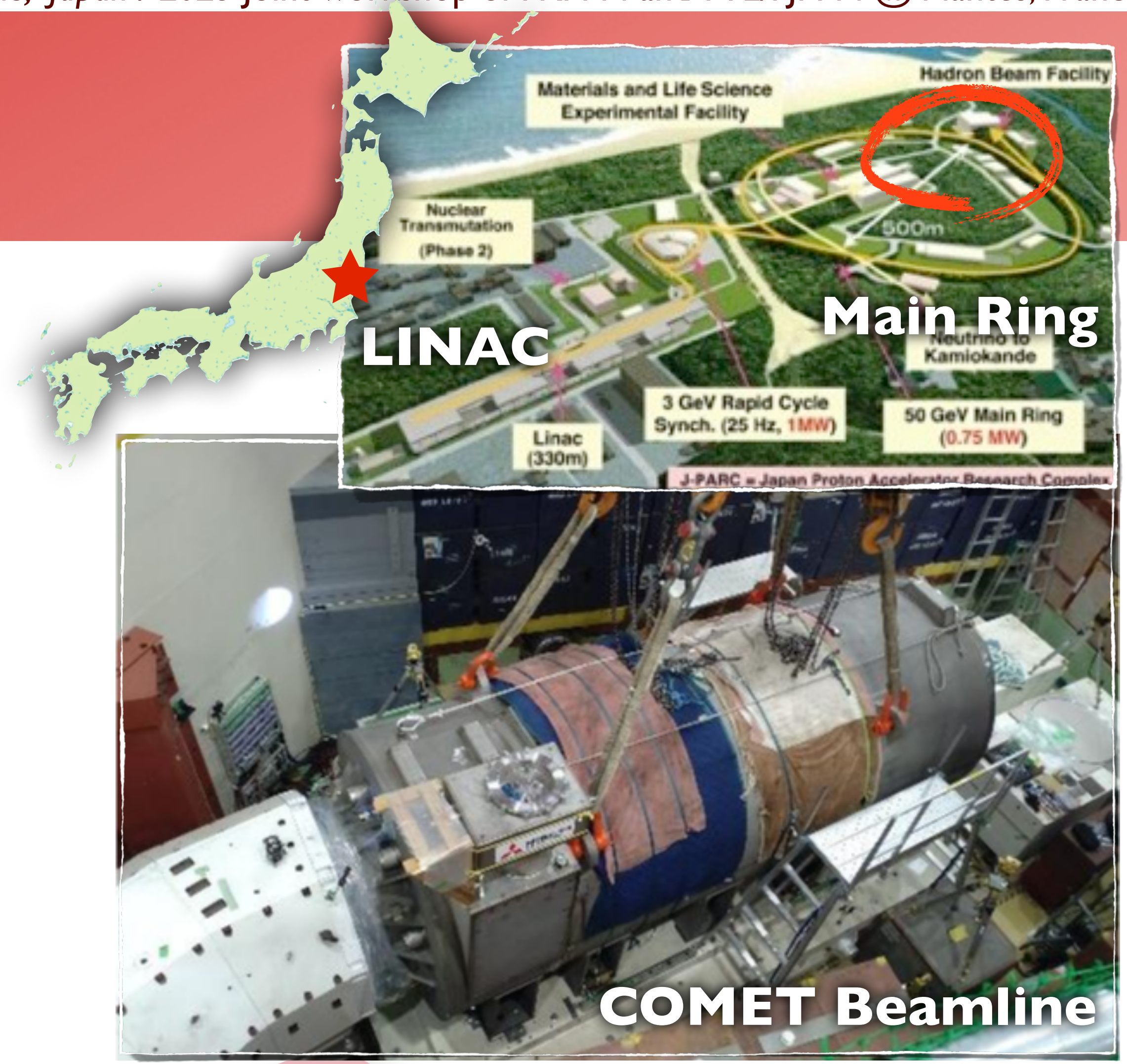
High intense muon beam & beam-induced BG

- High-intensity 8 GeV proton beam @ J-PARC, Japan.
  - **An effective transport line from π to μ** is required.
  - Backgrounds arise from the proton and its secondaries.
- Bunched beam structure
  - Delayed timing window for masking the BG.



Bunched Beam Structure & Delayed Timing Window

COMET



Searching for μ-e conversion at J-PARC

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

Building the muon transport line.

- The quality of the muon beam is a leading component of the sensitivity.

Phase-I

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

Phase-II

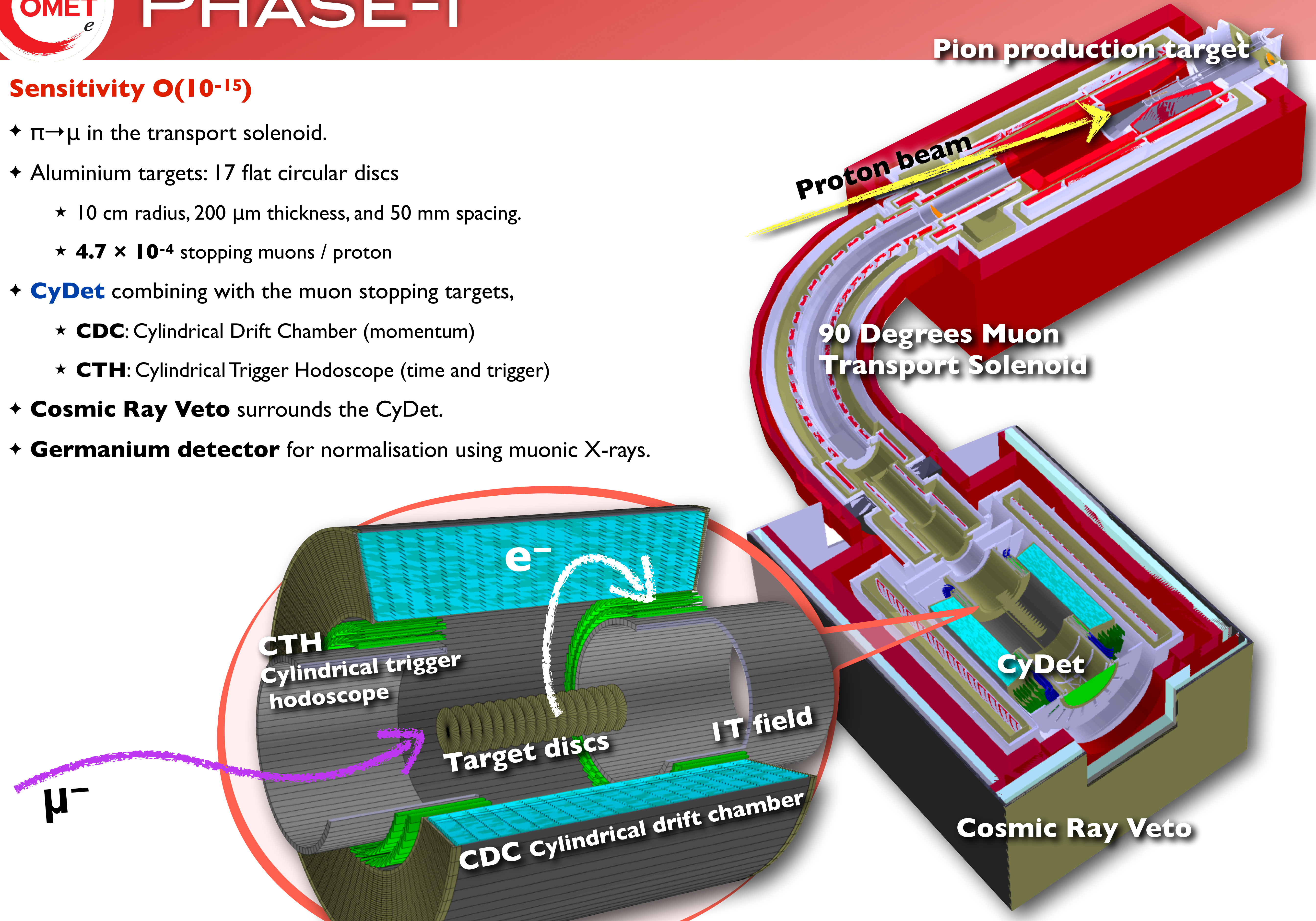
- ✓ **Sensitivity O(10^{-17})**
- ✓ **Physics measurement by StrECAL**

Collaboration

PHASE-I

Sensitivity O(10^{-15})

- $\pi \rightarrow \mu$ in the transport solenoid.
- Aluminium targets: 17 flat circular discs
  - 10 cm radius, 200 µm thickness, and 50 mm spacing.
  - **4.7×10^{-4}** stopping muons / proton
- **CyDet** combining with the muon stopping targets,
  - **CDC**: Cylindrical Drift Chamber (momentum)
  - **CTH**: Cylindrical Trigger Hodoscope (time and trigger)
- **Cosmic Ray Veto** surrounds the CyDet.
- **Germanium detector** for normalisation using muonic X-rays.



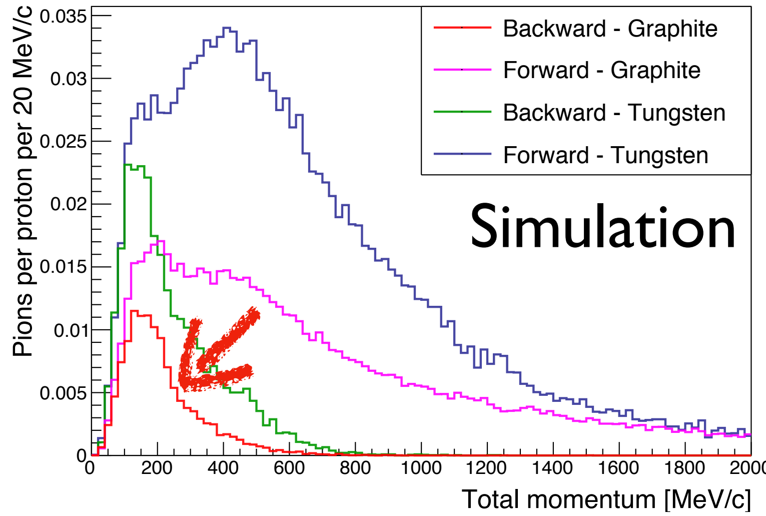
Pion Production Target

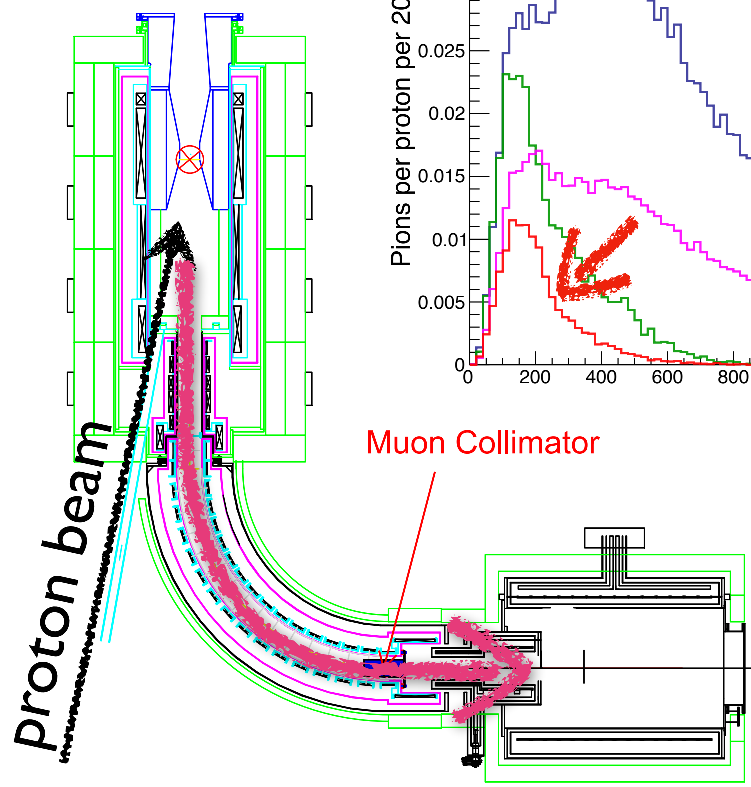
Proton Target

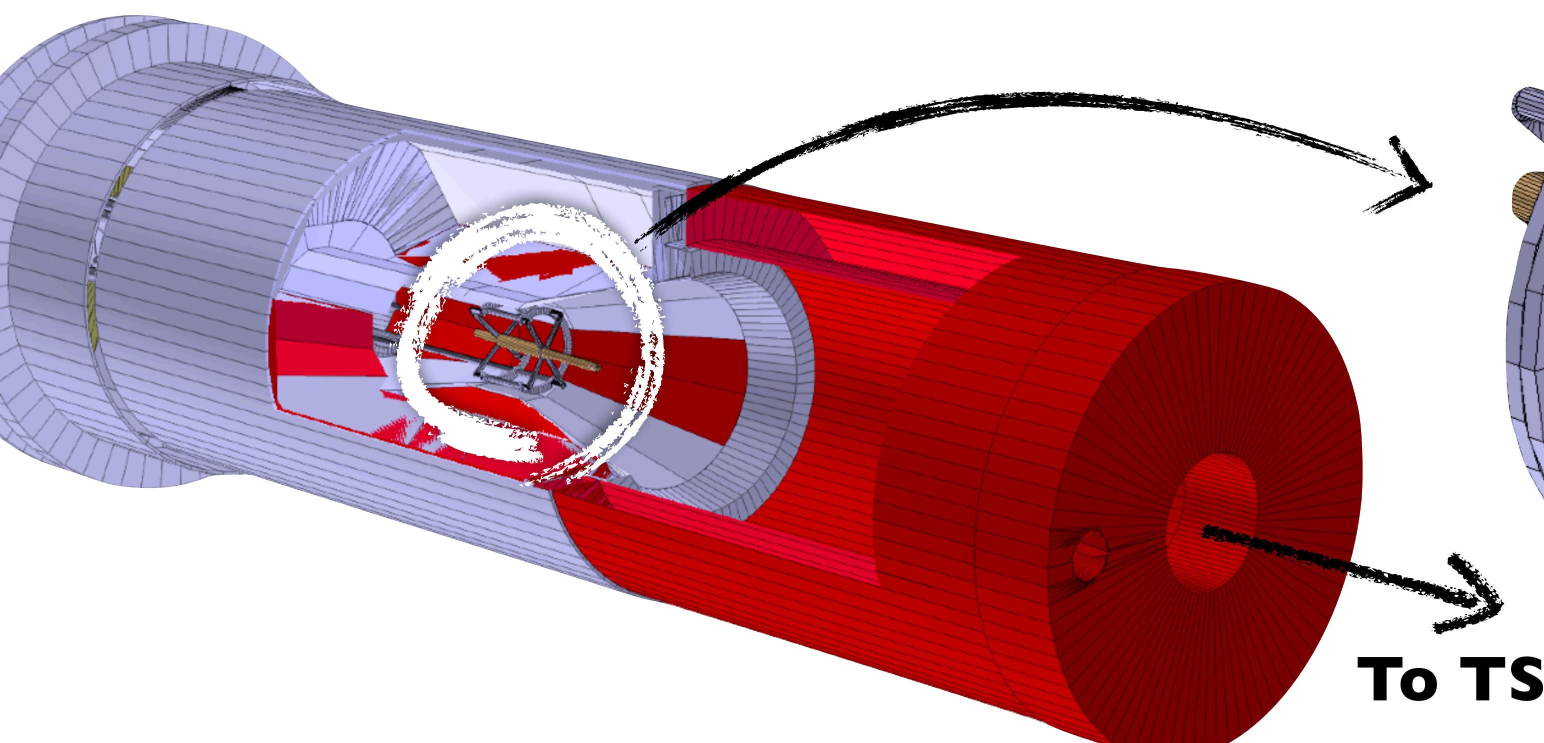
- A graphite rod

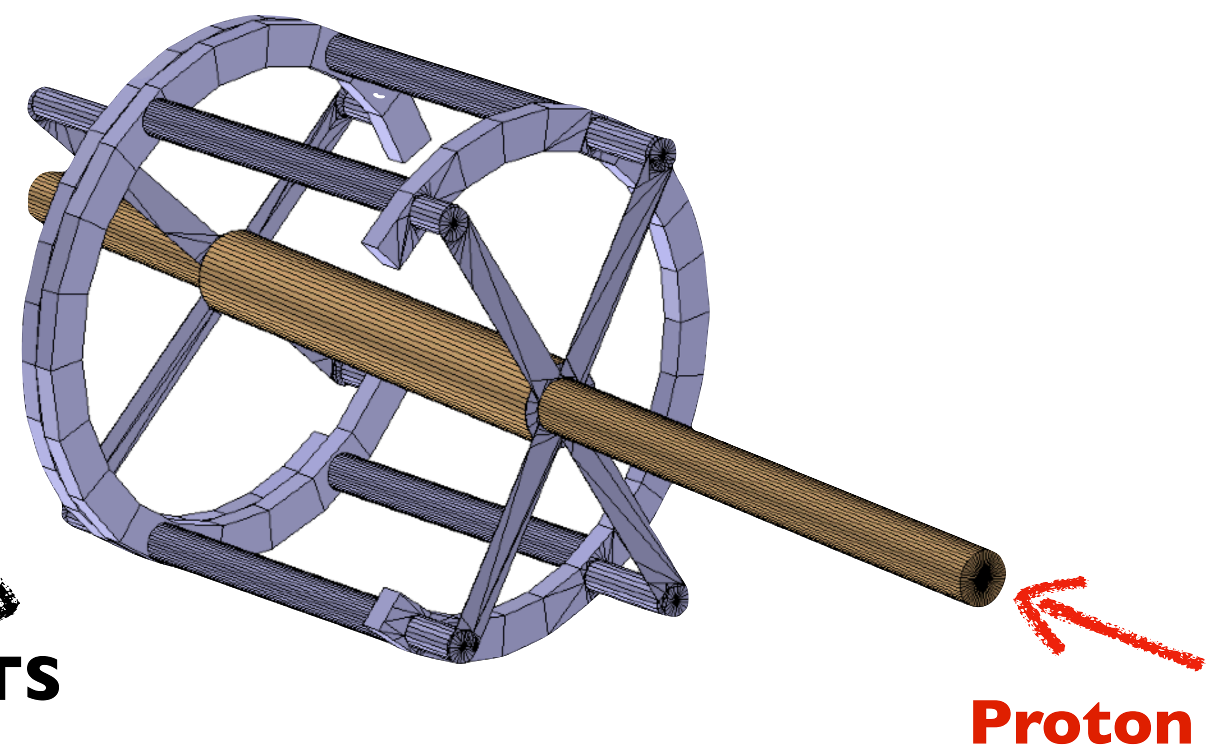
Pion Capture Solenoid

- 4.4 T superconducting magnet
- Pions and muons extracted to backward
  - Better collection of low-momentum pions.





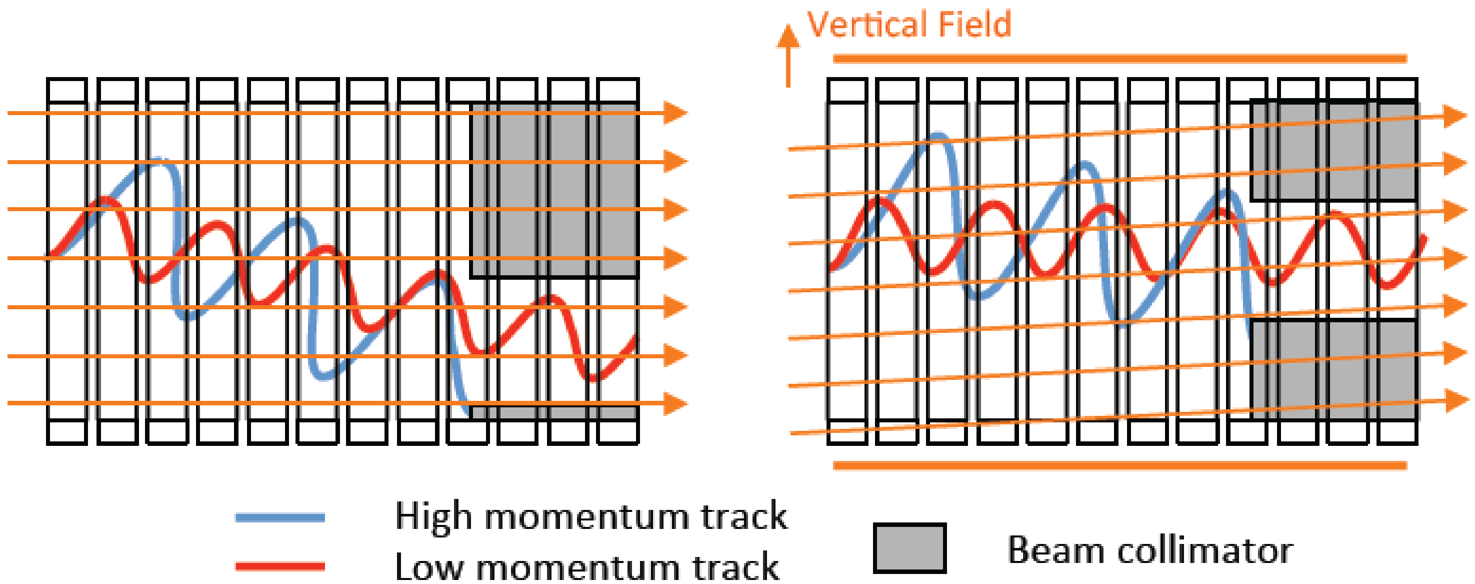




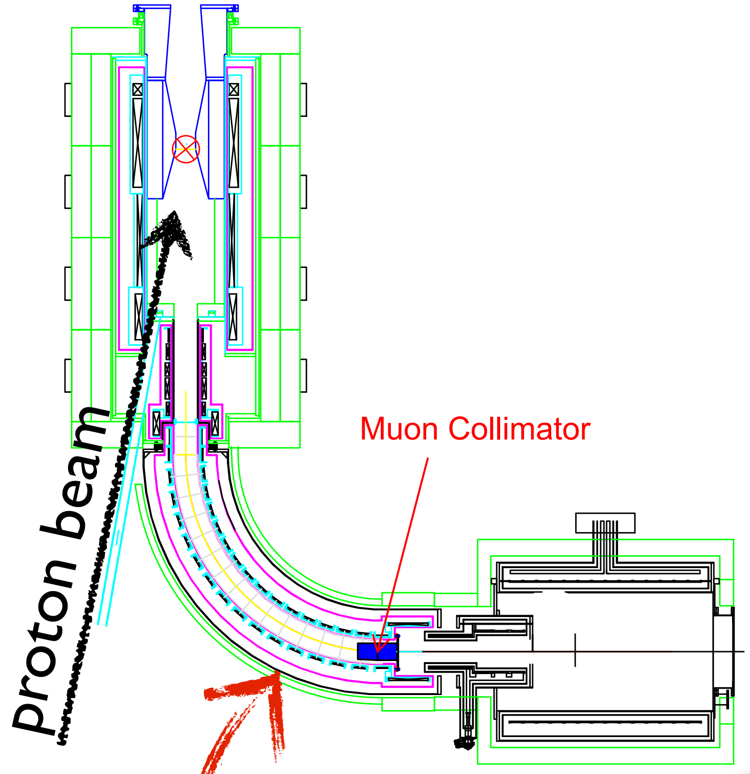
Muon Transport Solenoid

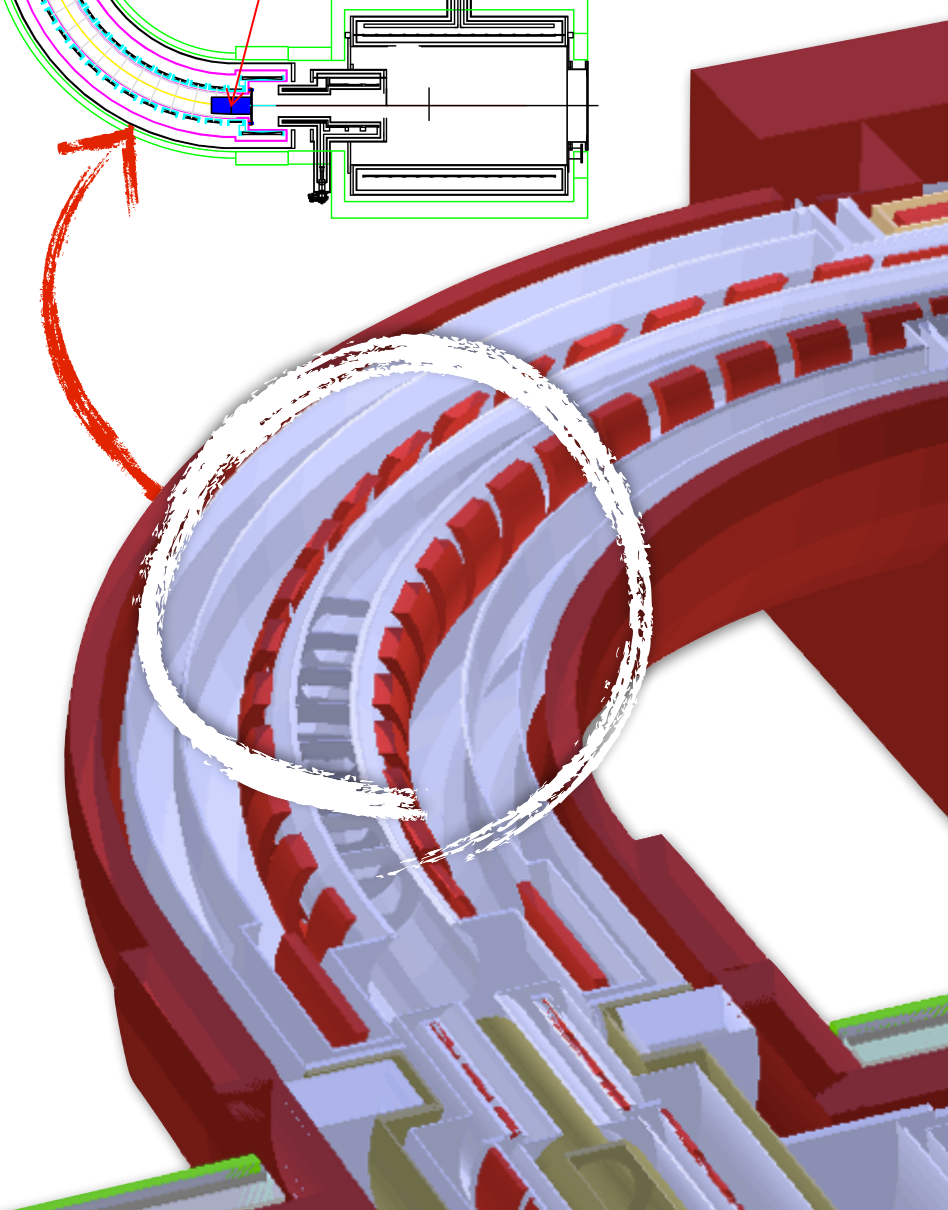
(90°-bent) Muon Transport Solenoid

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

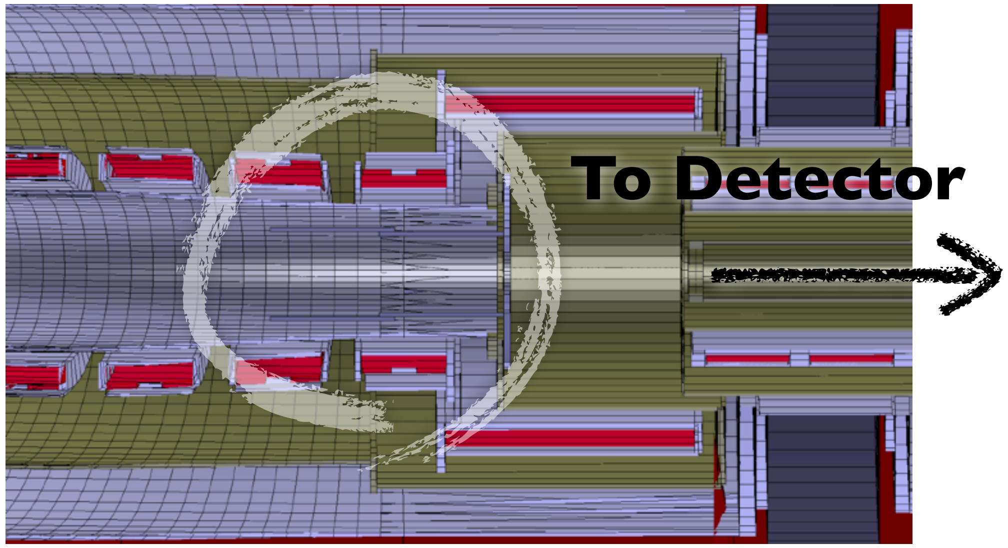


Trajectories in the transport solenoid





Beam Collimator

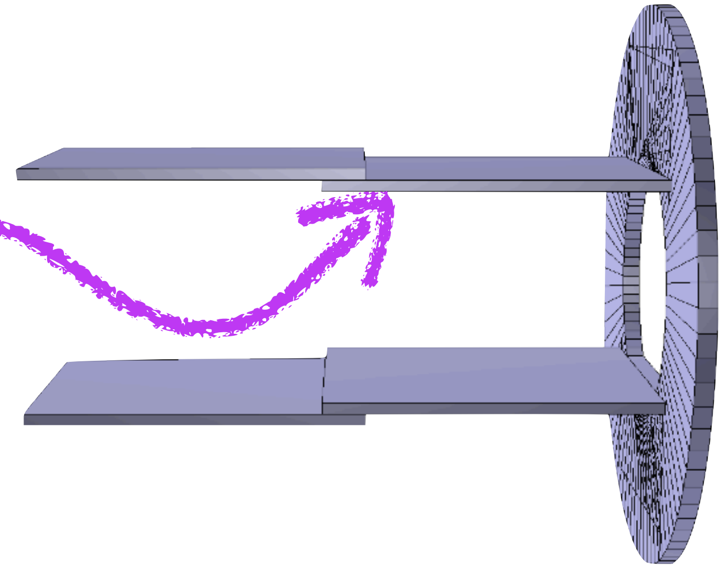


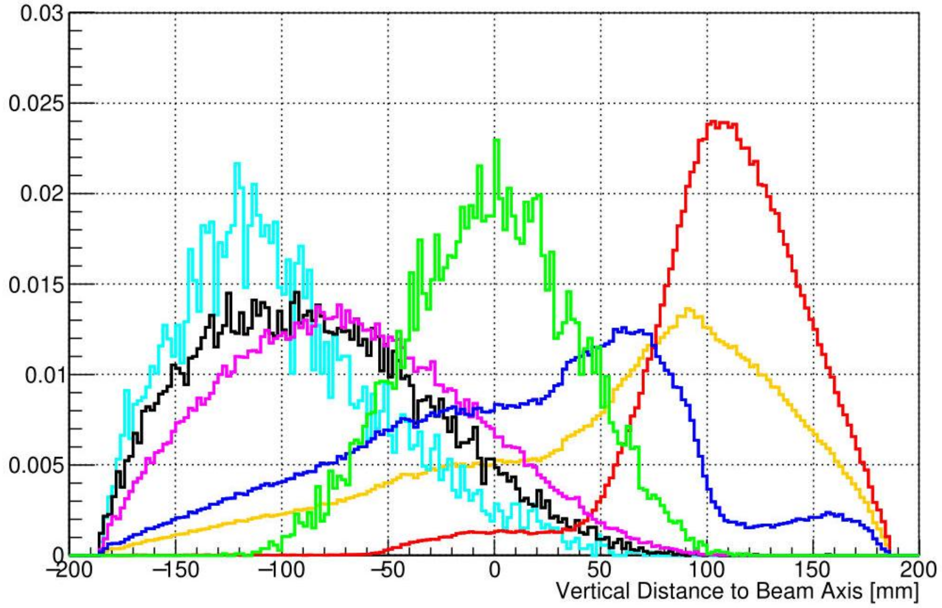
Beam collimator

- Non-target particles drift to the upper or bottom sides.
  - Positively charged particles → upper
  - High-momentum negative particles → bottom
- Stopped by the plates and ring-shaped collimators

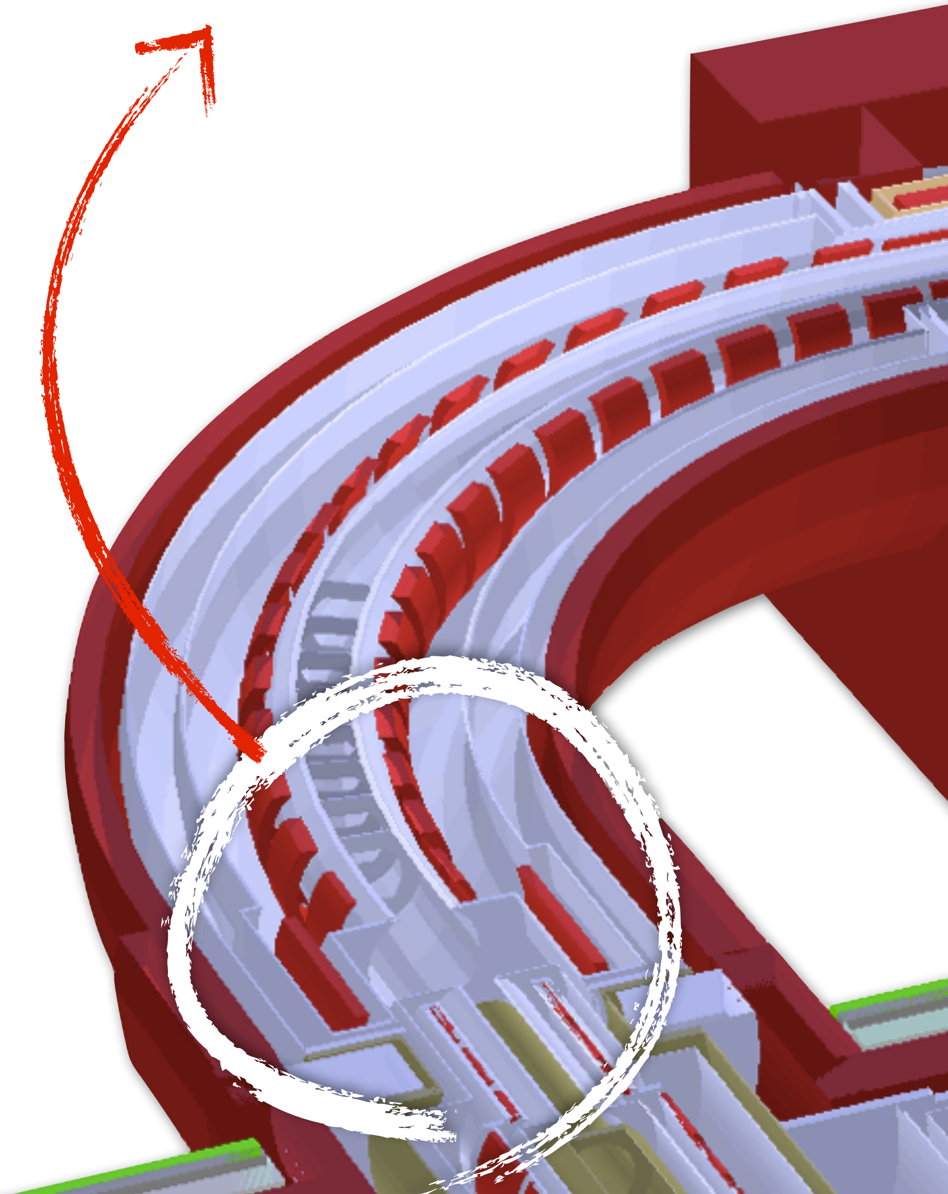
Still, a lot of scattered secondaries present.

- They give noise hits in the downstream detectors.
- BG suppression is a current issue — *One of our objectives*
  - BG hits make a high BG trigger rate ~ O(100k) cps.





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



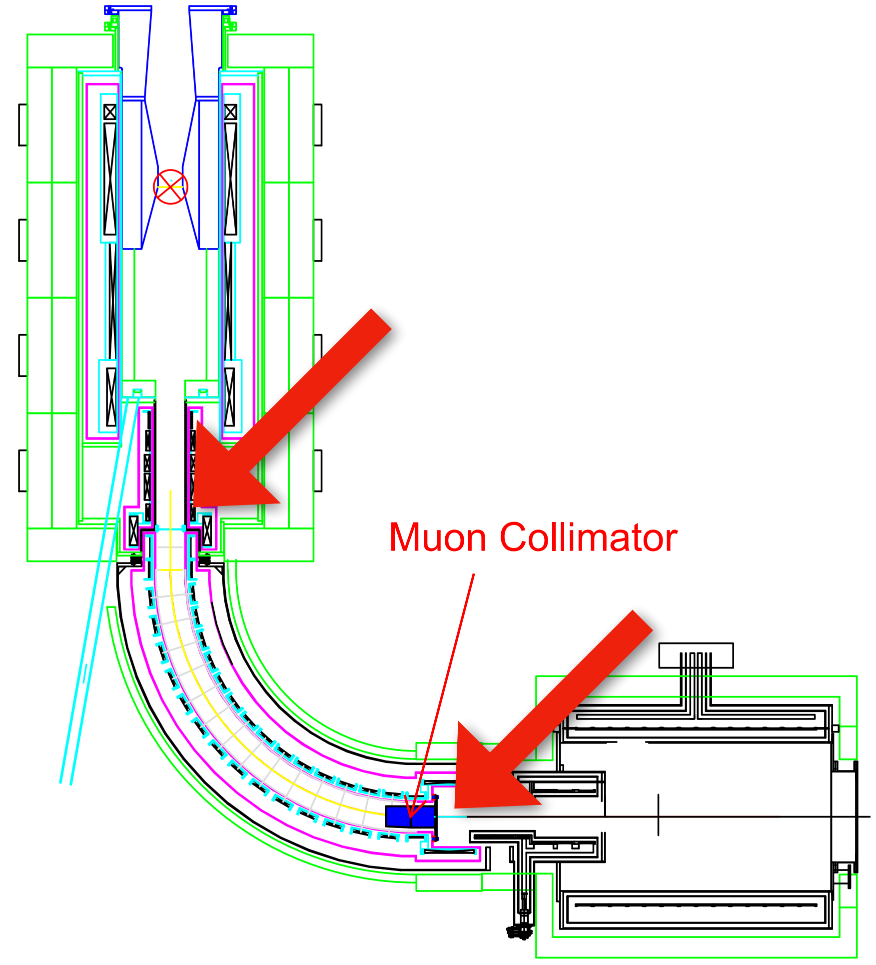
VACUUM WINDOWS

Necessary for safety but need to be thin

- We need to transport muons as slow as possible.
- Opposite requirements: toughness and thinness.

3D-printed vacuum windows

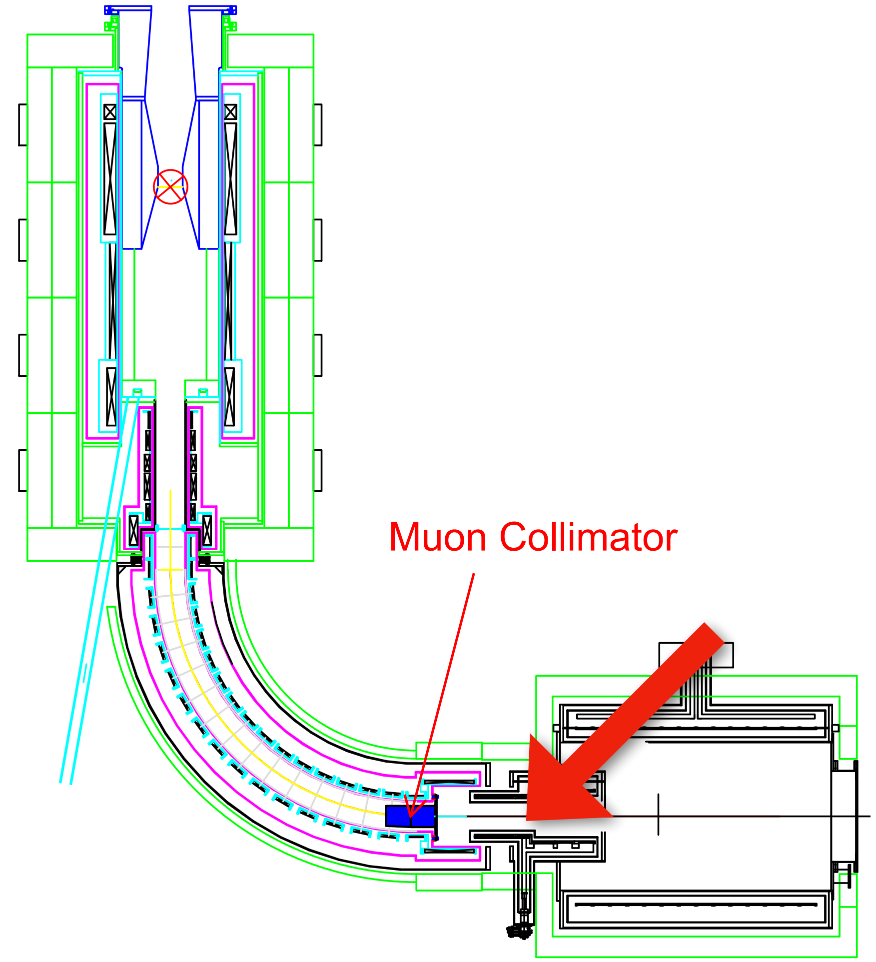
- Ti-based (*Ti-6Al-4V*) — Well prototyped
  - Enough pressure tolerance ~ 4 MPa
- **Al-based** ***(Al-Si10Mg)*** — *One of our objectives*
  - For less material amount
  - Prototyping R&D being performed.



Muon Beam Monitor

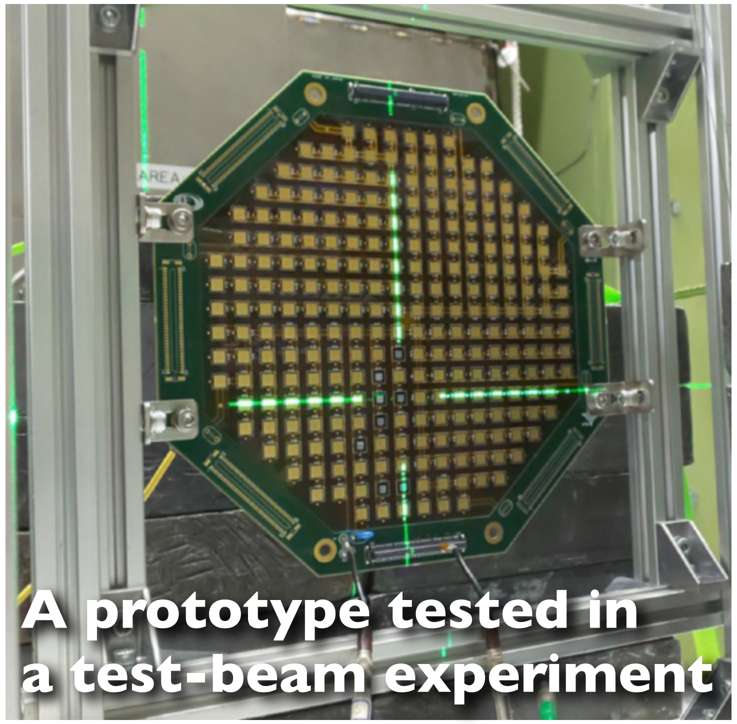
Monitor of the secondary beam intensity and profile

- Beam intensity fluctuation prevents stable detector and trigger operation.
  - Upward deviation leads to detector insensitivity.
  - Sources of systematic uncertainties.
  - Needs to be monitored.

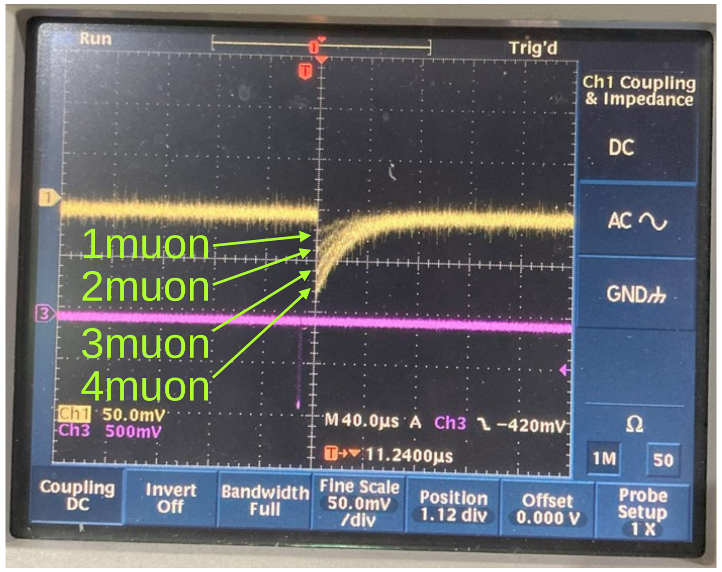


SiC sensors are being developed.

- Good radiation tolerance.
- A prototype tested with a muon beam at J-PARC.
  - Sufficient sensitivity and linearity.
- A dedicated ASIC readout chip is also being developed.
  - Variable amplifier gain for robustness.



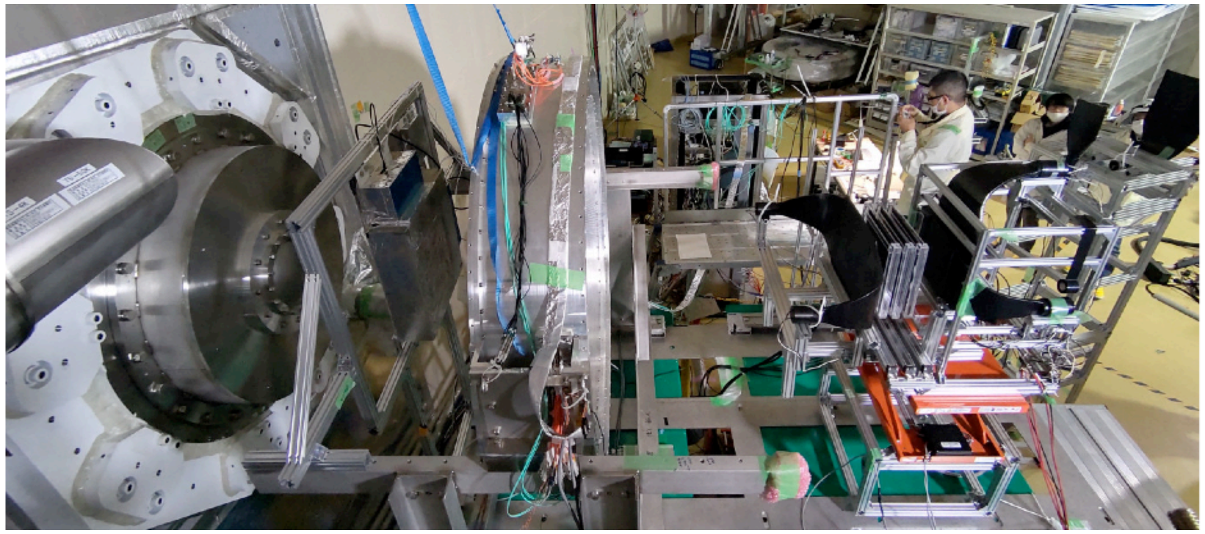
A prototype tested in a test-beam experiment



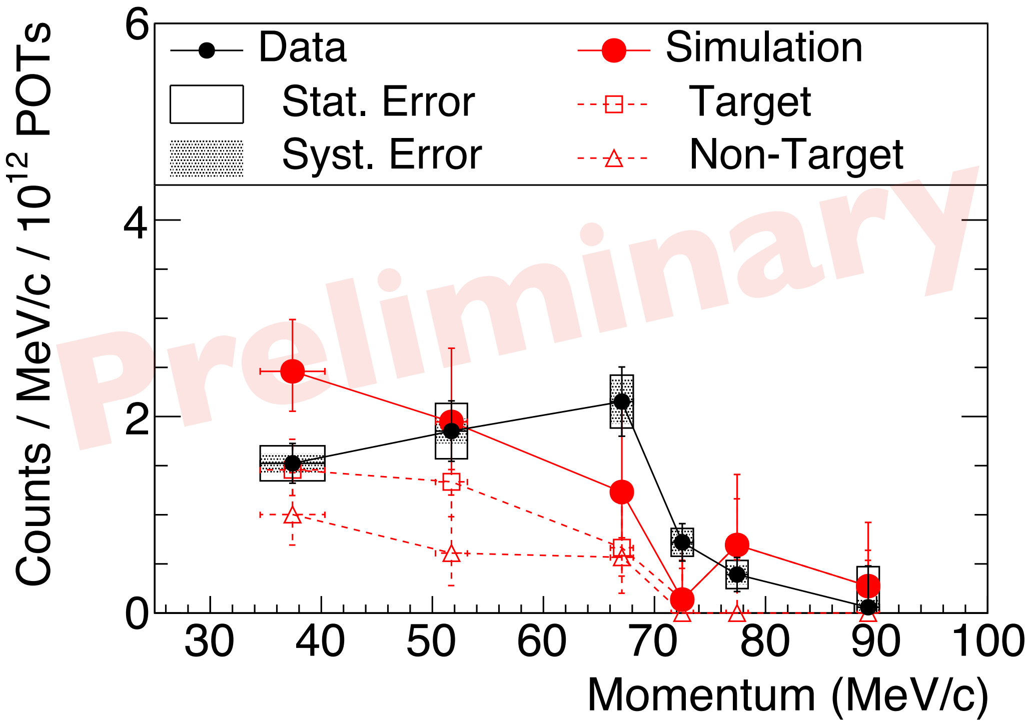
PHASE-α

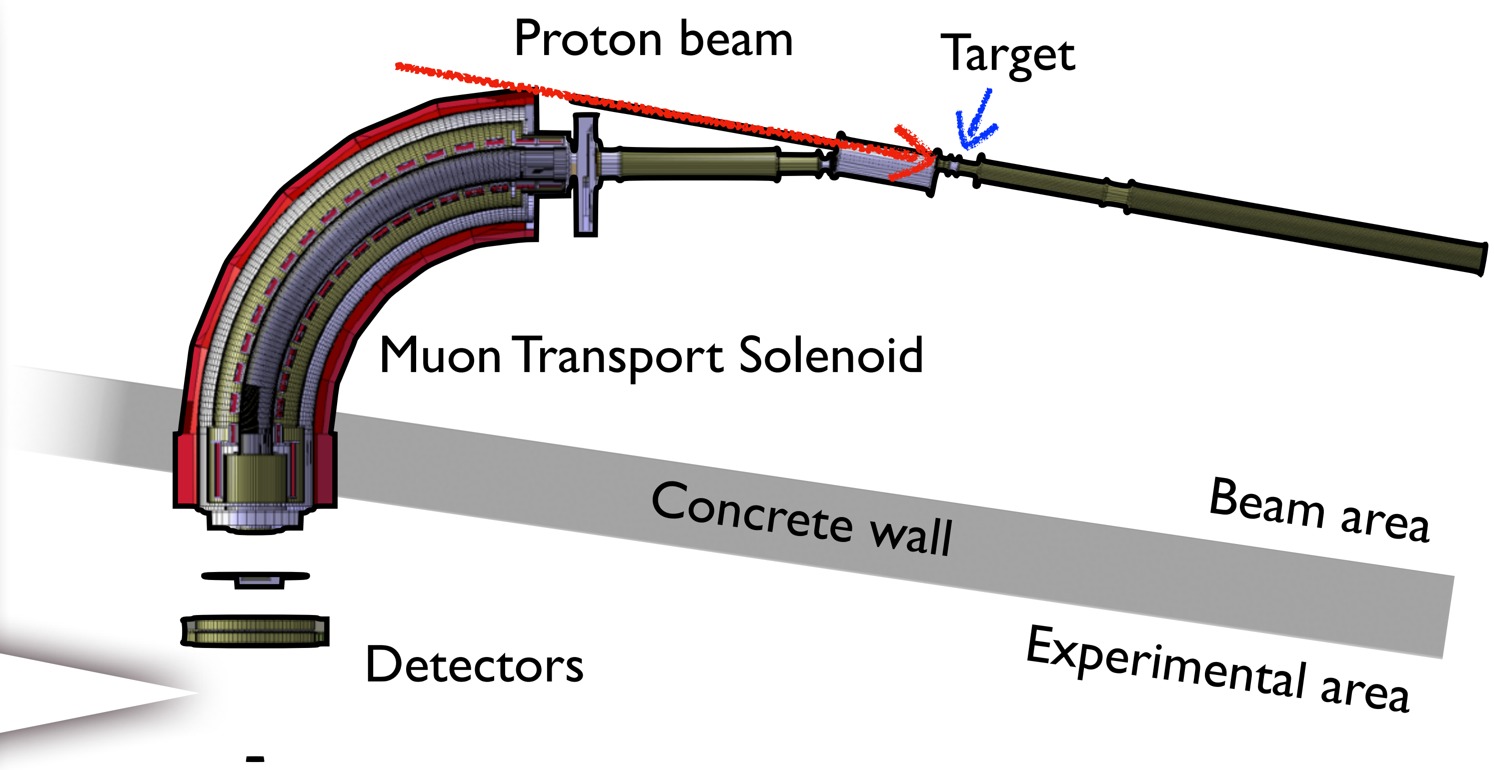
The 1st Commissioning of the COMET facility in 2023

- ✦ The muon beam was successfully transported by the Muon Transport Solenoid.
  - ★ Muon momentum spectrum was measured for the first time!
- ★ However, we also observed a fluctuation in the beam intensity bunch by bunch.
  - ★ Led us to think more seriously about BG hit rates in the detectors.



Phase-α Detectors

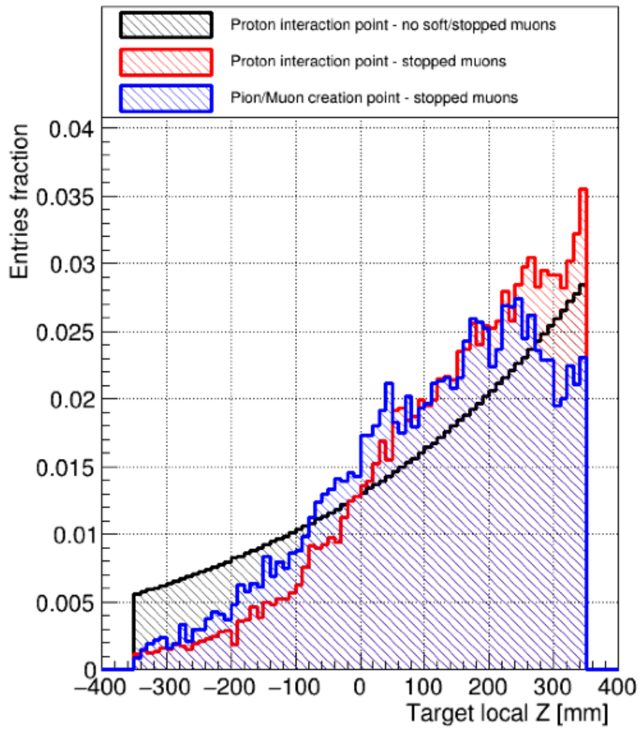




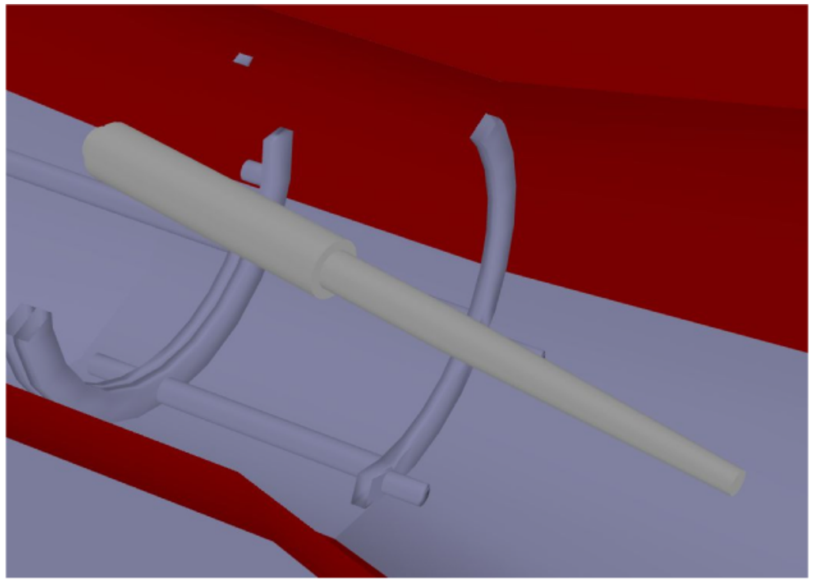
Objectives of Our Project

(I) Optimisation of the proton target and collimators

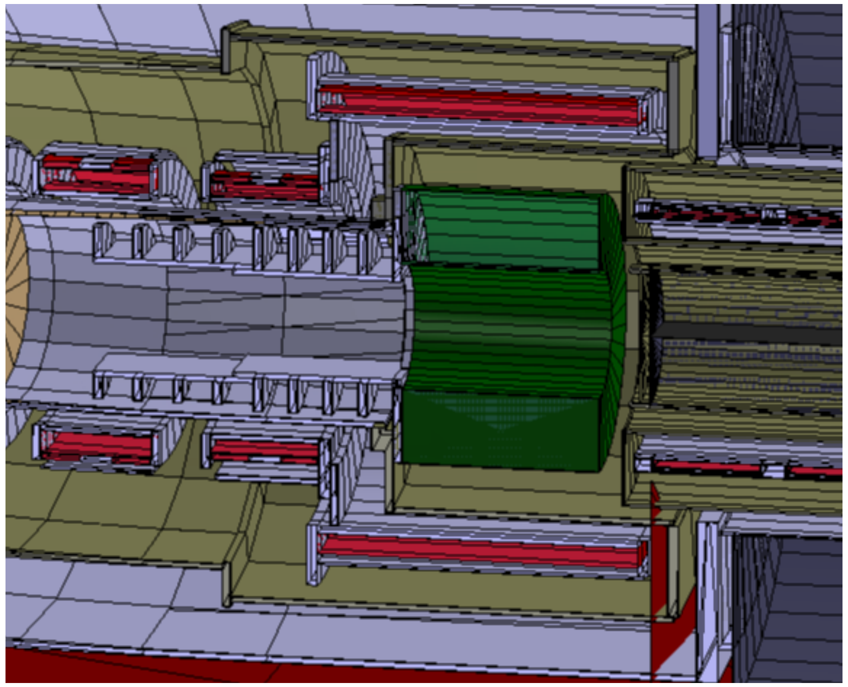
- The beamline components had been optimised to maximise the acceptance of low-momentum μ^-.
- Still, the BG hit rate in the detectors is our current serious issue.
  - A better muon acceptance brings a severer hit rate — a trade-off matter.
- We are finalising the design compromising these two opposite factors.
  - Dimensions and alignment of the ***pion production target*** and ***beam collimators***.
  - A shorter target gives a better BG particles suppression than the loss of the target muon; how much can we compromise?
  - More materials on the collimator plates are essential, but their mechanical and radiation hardness should be considered.
- The PhD student members in France and Japan are collaboratively working on this.
  - They have been making various nice outlooks for better BG-hit suppression.



(Blue) The π/μ generation point along the target



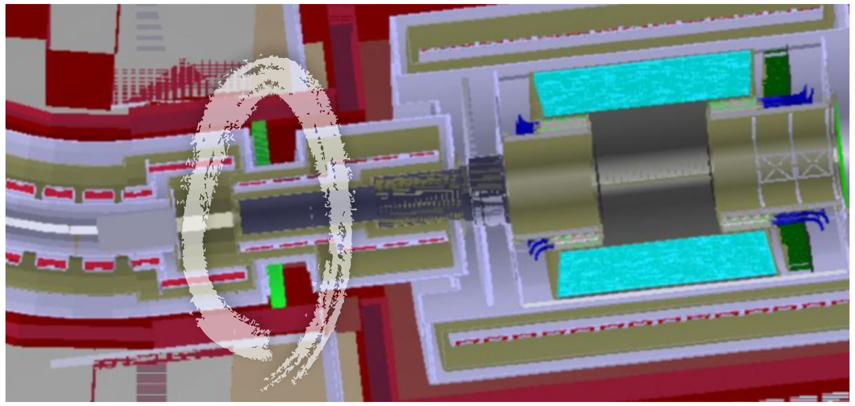
Potential different shape of the target



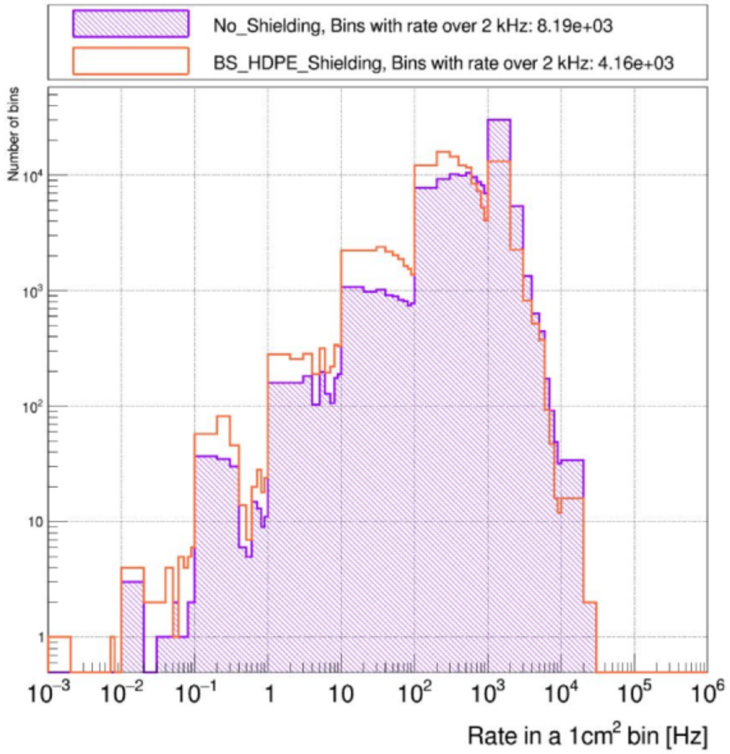
Additional materials around the collimator

Objectives of Our Project

(2) Design of feasible neutron shielding



- ✦ The neutrons also emerge from the proton beam injection and heavily damage the detectors' sensors and electronics.
- ✦ The collimator is also a neutron source:
  - ★ Another reason why the collimator design is further optimised.
- ✦ Our simulation studies are seeking a better shielding design.
  - ★ It simultaneously needs to be feasible in the cost point of view.
  - ★ For instance, boron-doped polyethylene blocks are effective.
    - ❖ ~25% reduction in neutron flux at the Cosmic Ray Veto being sensitive to neutrons.
- ✦ Together with Objective (1), these designs necessary to be completed soon.
  - ★ An impactful project for the COMET experiment.



(3) Development of further thinner vacuum windows

- ✦ A lighter and thinner vacuum window is genuinely better for the muon acceptance.
  - ★ Our Japanese member, S. Makimura, is developing a stable window fabrication with aluminium.
- ✦ Along with it, the other members will also validate it by simulation.
  - ★ The Muon Beam Monitor and its material effects are also involved in simulation validation.

Conclusion

The COMET experiment operates a high-intensity muon beam.

- To search for μ-e conversion with a sensitivity that improves the current limit by a factor of 100 in Phase-I.
- A dedicated beamline and its devices have been developed by the collaborators and our members.

Our project aims at further improvements of the new dedicated muon beamline.

- Various simulation studies are carrying on.
  - Balancing the experimental performance between signal acceptance and background suppression.
  - The CCIN2P3🇫🇷 and KEKCC🇯🇵 computing clusters are significantly appreciated.

A French-Japanese working group has been established.

- Co-supervised French (T. Clouvel) and Japanese (M. Miyataki) PhD students are leading the group and studies.
- Tight communication through weekly online meetings.
- Frequent face-to-face visits to work closely together.
  - T. Clouvel stayed in J-PARC 🇯🇵 for a month, and K. Oishi will stay in Clermont-Ferrand 🇫🇷 for a week. More will be happening!
- Collaboration meetings in J-PARC 🇯🇵 in March and in Clermont-Ferrand 🇫🇷 in June.

The Members (PhD students)

- Cristina Carloganu, **Thomas Clouvel** @ LPCA, France 🇫🇷
- Jean-Claude Angelique @ LPC Caen, France 🇫🇷
- Kou Oishi, Yoshinori Fukao, Shunsuke Makimura @ KEK, Japan 🇯🇵
- **Masaki Miyataki** @ University of Osaka, Japan 🇯🇵
- **Kenya Okabe** @ SOKENDAI, Japan 🇯🇵