# $\mu$-e conversion search at J-PARC


Satoshi MIHARA

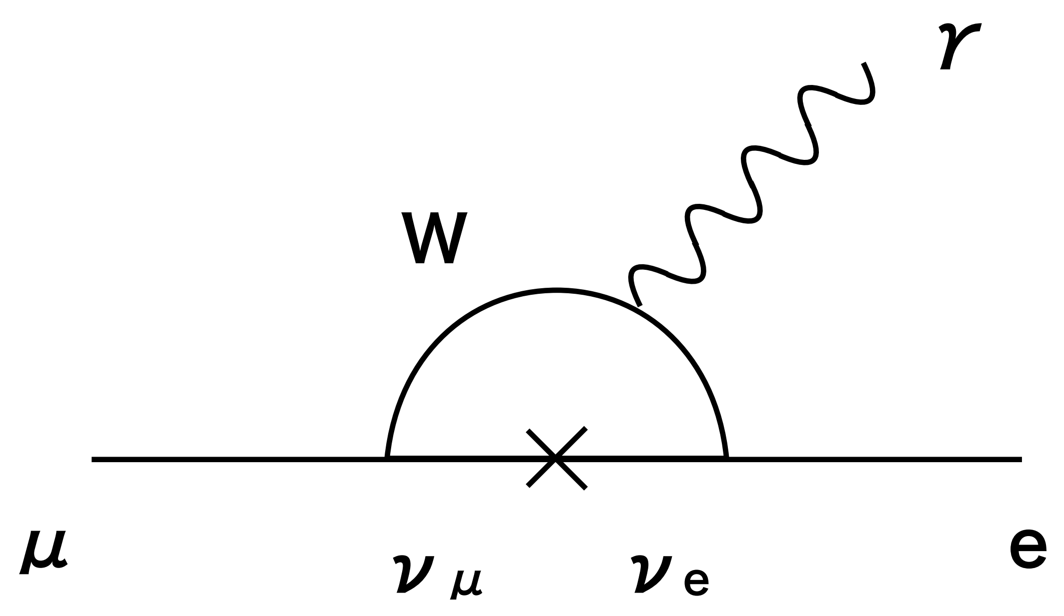
KEK/J-PARC/SOKENDAI

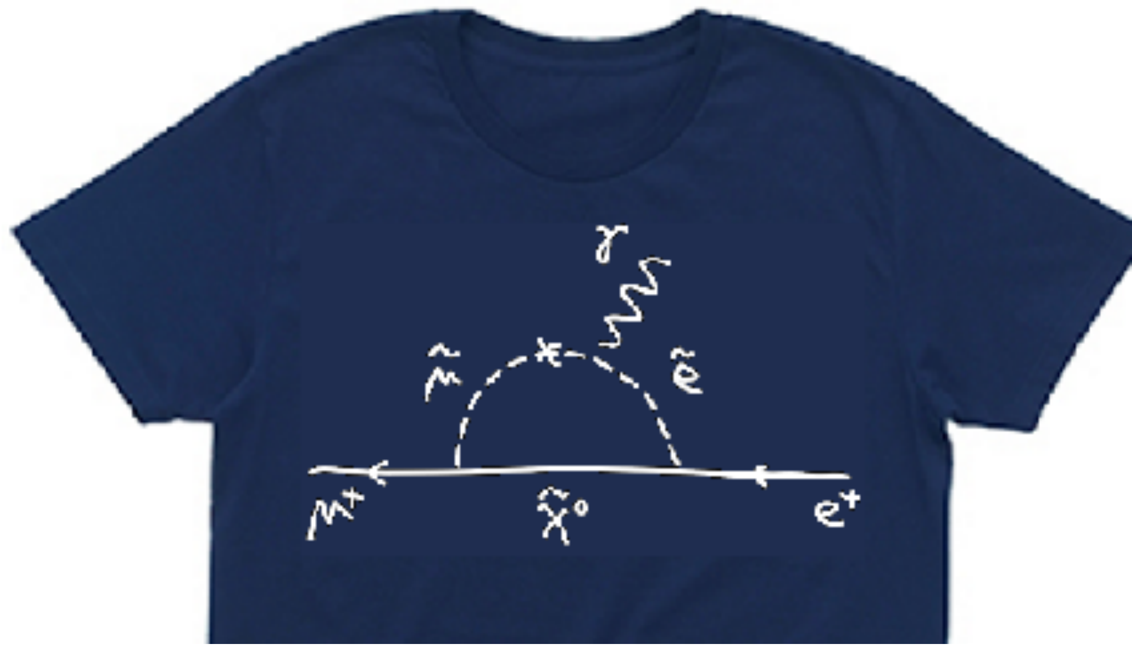
# Outline

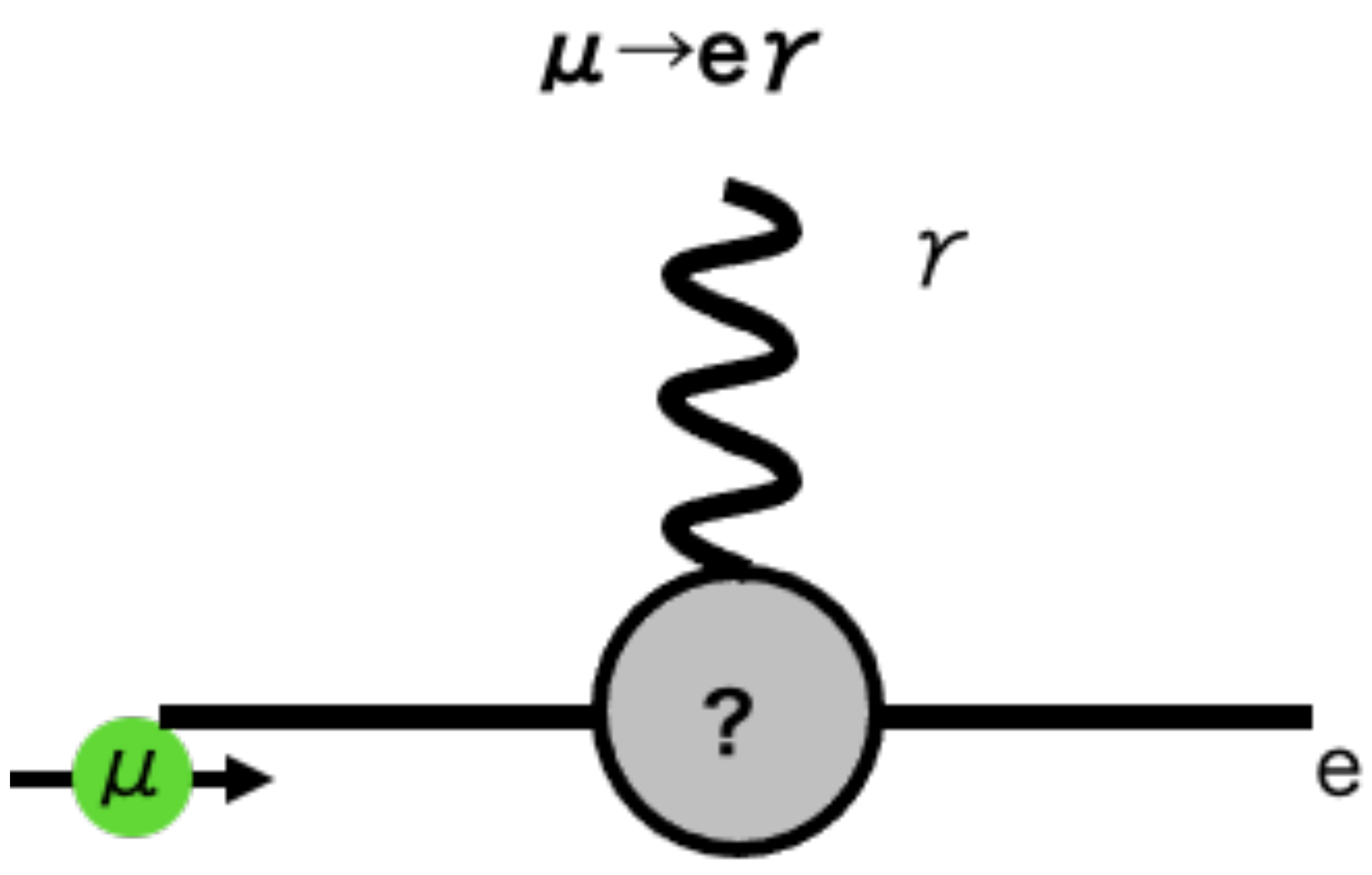
- Introduction
- cLFV physics with muon beam
- COMET: $\mu$-e conversion search at J-PARC
- Prospects and summary

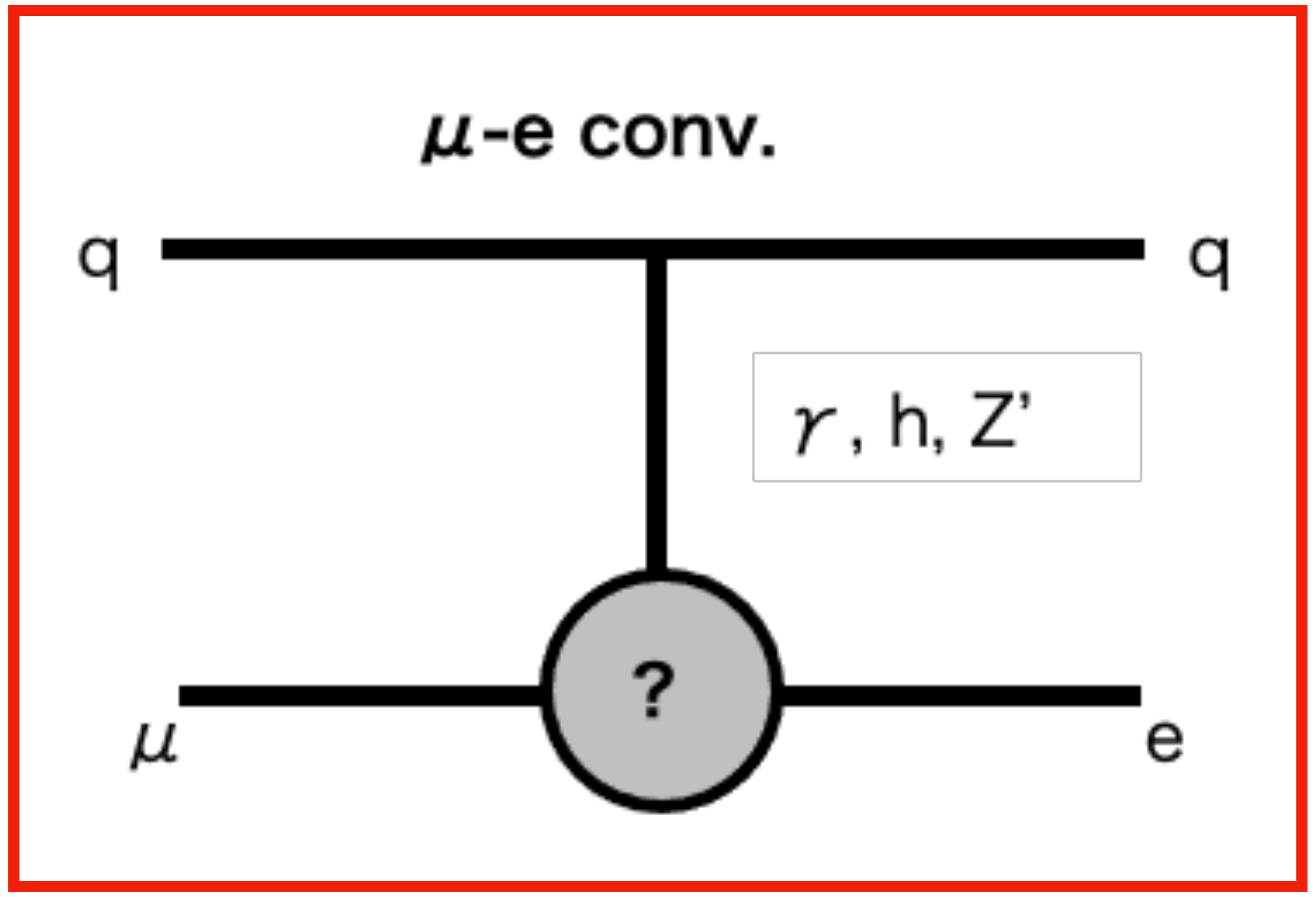
# Charged Lepton Flavor Violation

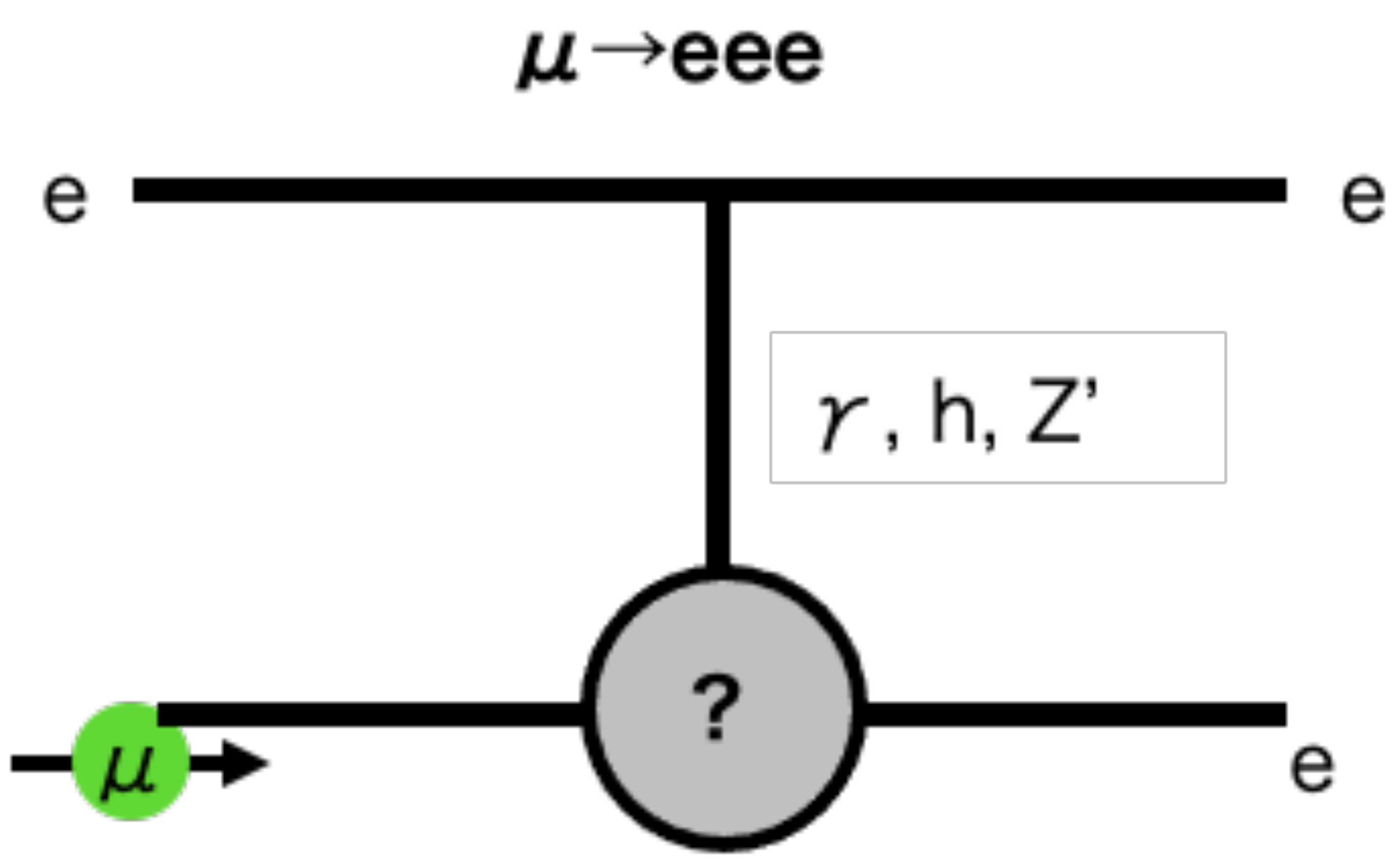
- cLFV rate in the Standard Model with non-zero neutrino mass is too small to be observed in experiments; O(BR) < $10^{-54}$
  - No SM Physics Background
  - Observation = clear evidence of NP
- Motivated by many kinds of new physics models BSM
- Origin of neutrino mass

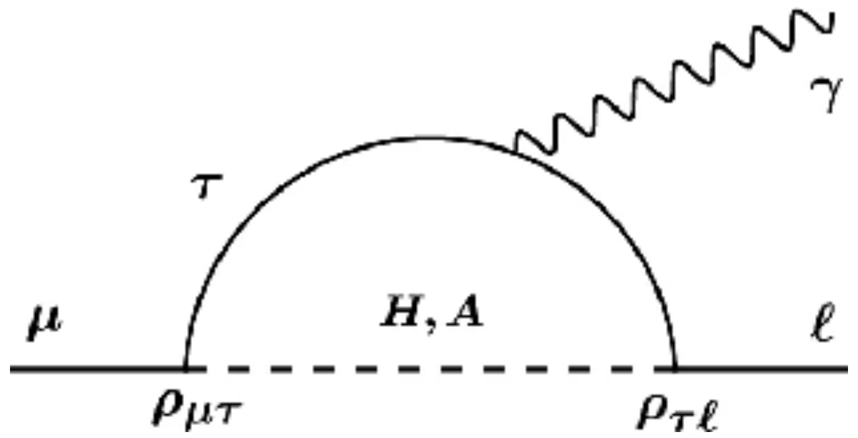


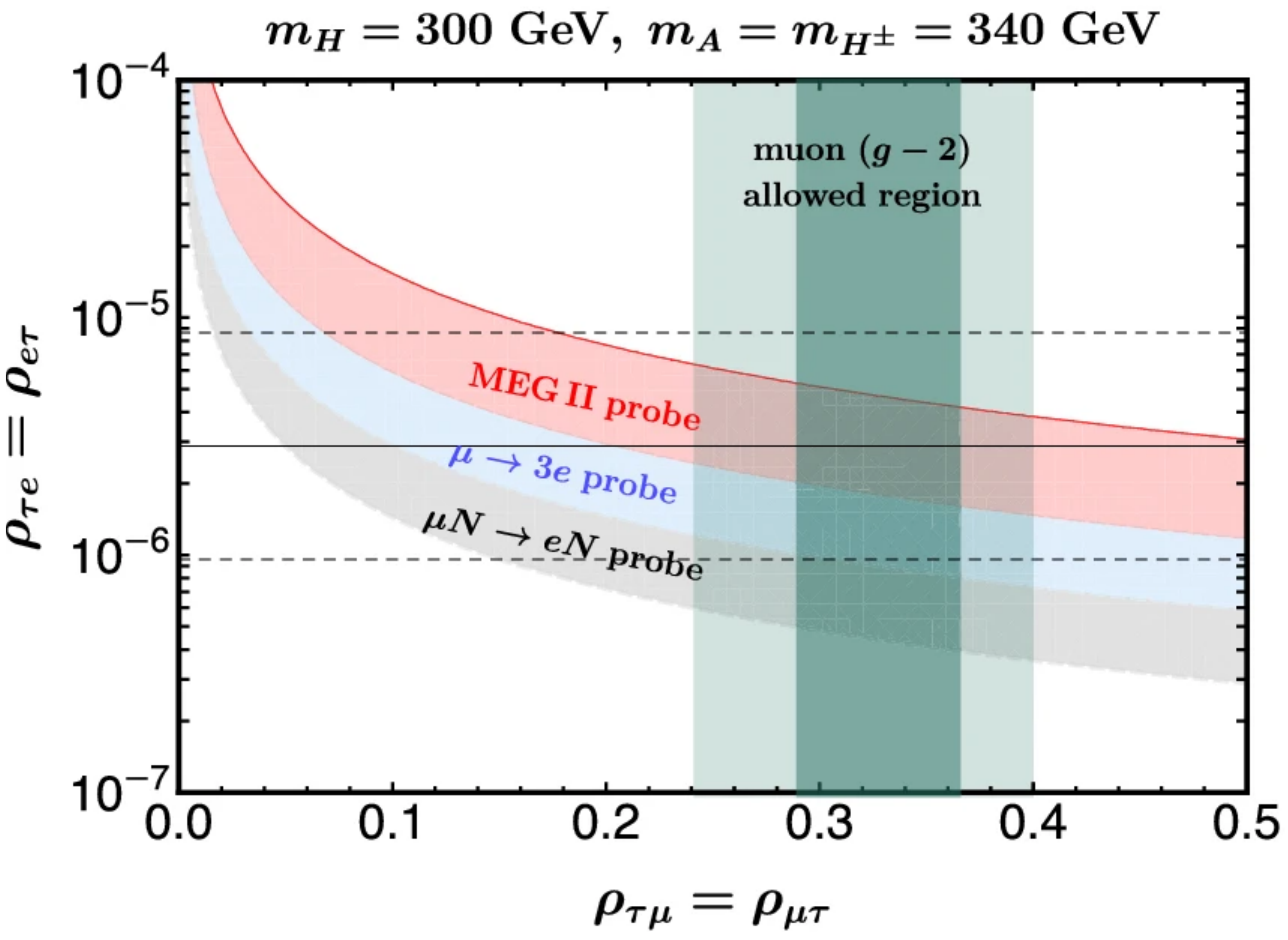



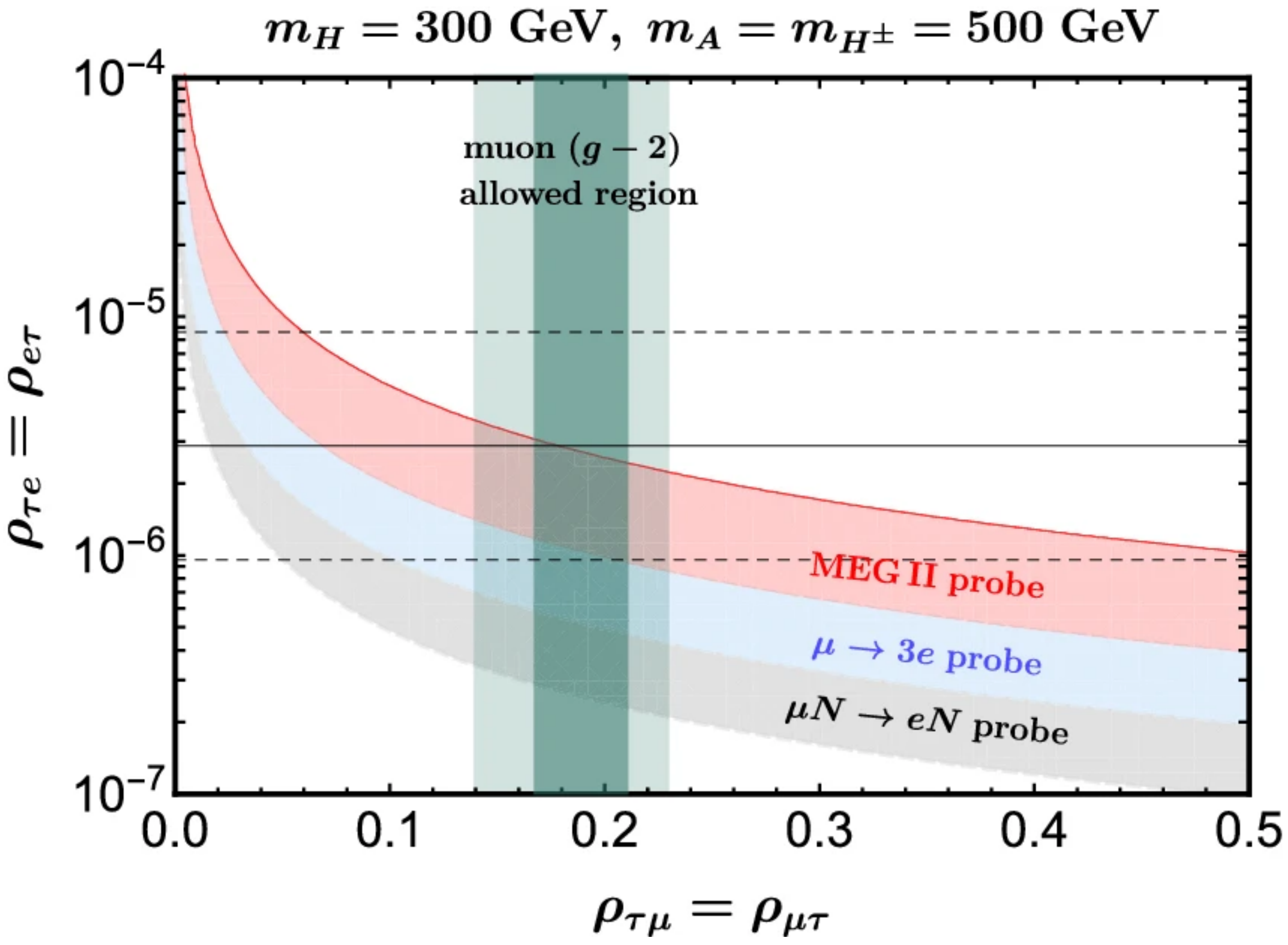


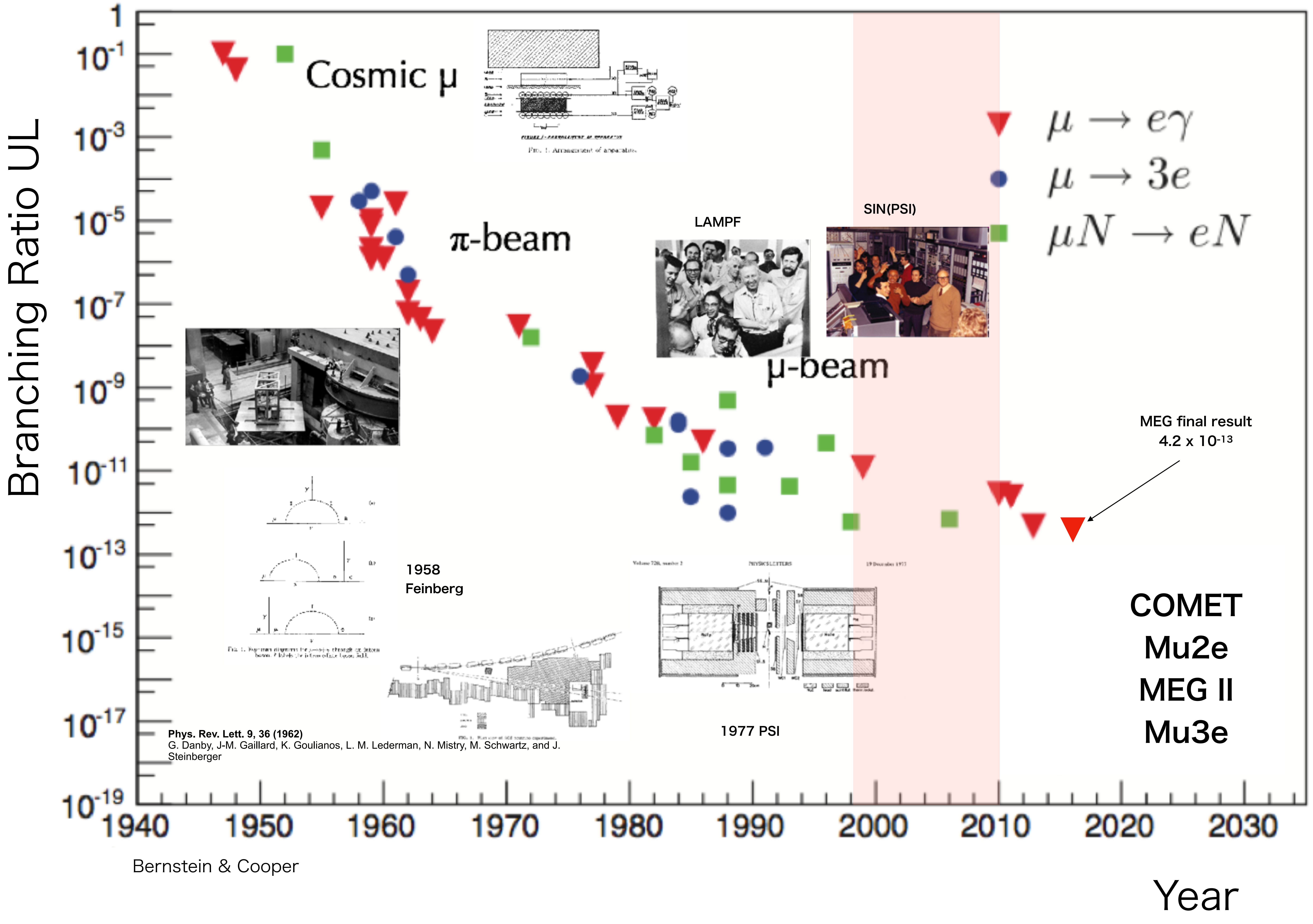





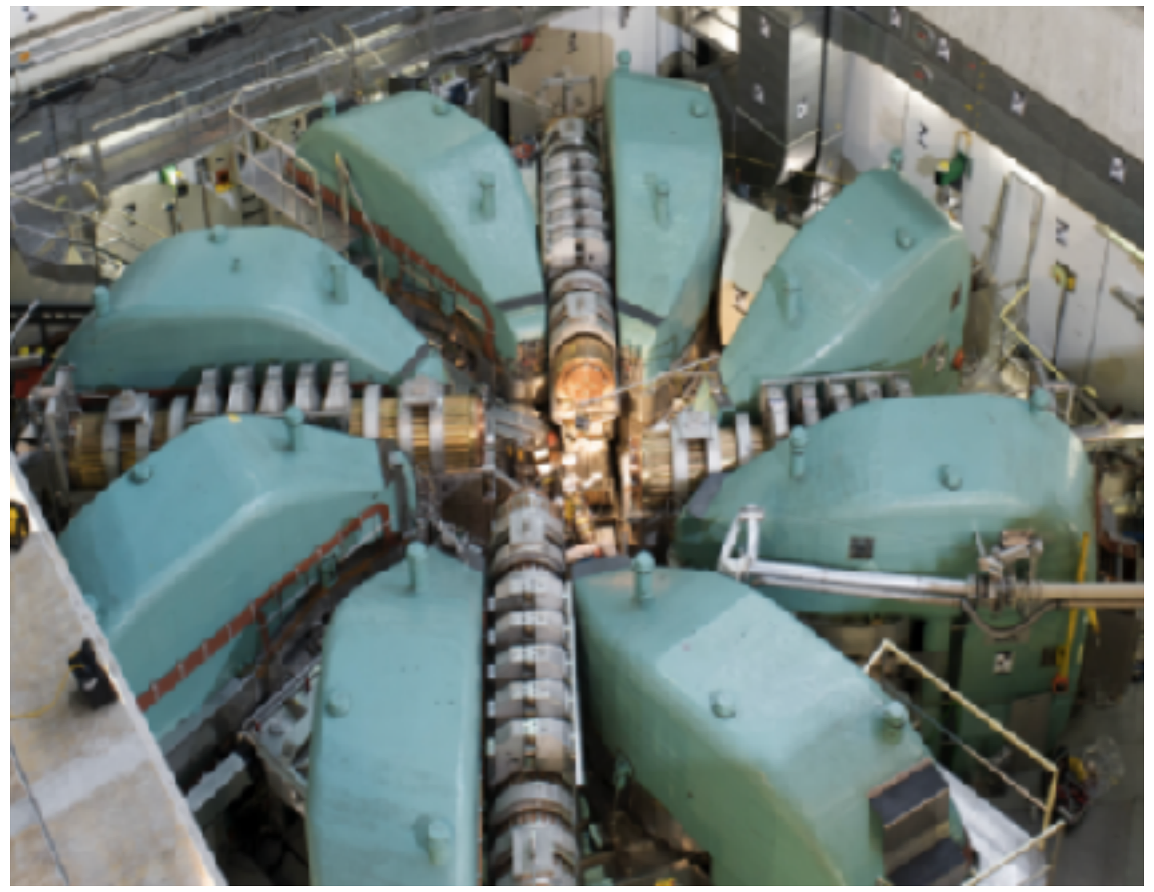

Hou, WS., Kumar, G. Charged lepton flavor violation in light of muon $g$–2
. *Eur. Phys. J. C* **81,** 1132 (2021). https://doi.org/10.1140/epjc/s10052-021-09939-3




Bernstein & Cooper

# Current Status of Charged Lepton Flavor Violation Search

- $\mu \to e\gamma$
  - MEG Br($\mu \to e\gamma$) < $4.2 \times 10^{-13}$
- $\mu \to eee$
  - SINDRUM BR($\mu \to eee$) < $1.0 \times 10^{-12}$
- $\mu$-e conversion
  - SINDRUM II R($\mu$-e: Au) < $7 \times 10^{-13}$



PSI Ring Cyclotron
590MeV, 1.4MW


FNAL
8GeV, 8kW

J-PARC
8GeV, 3.2-56kW

# Current Status of Charged Lepton Flavor Violation Search

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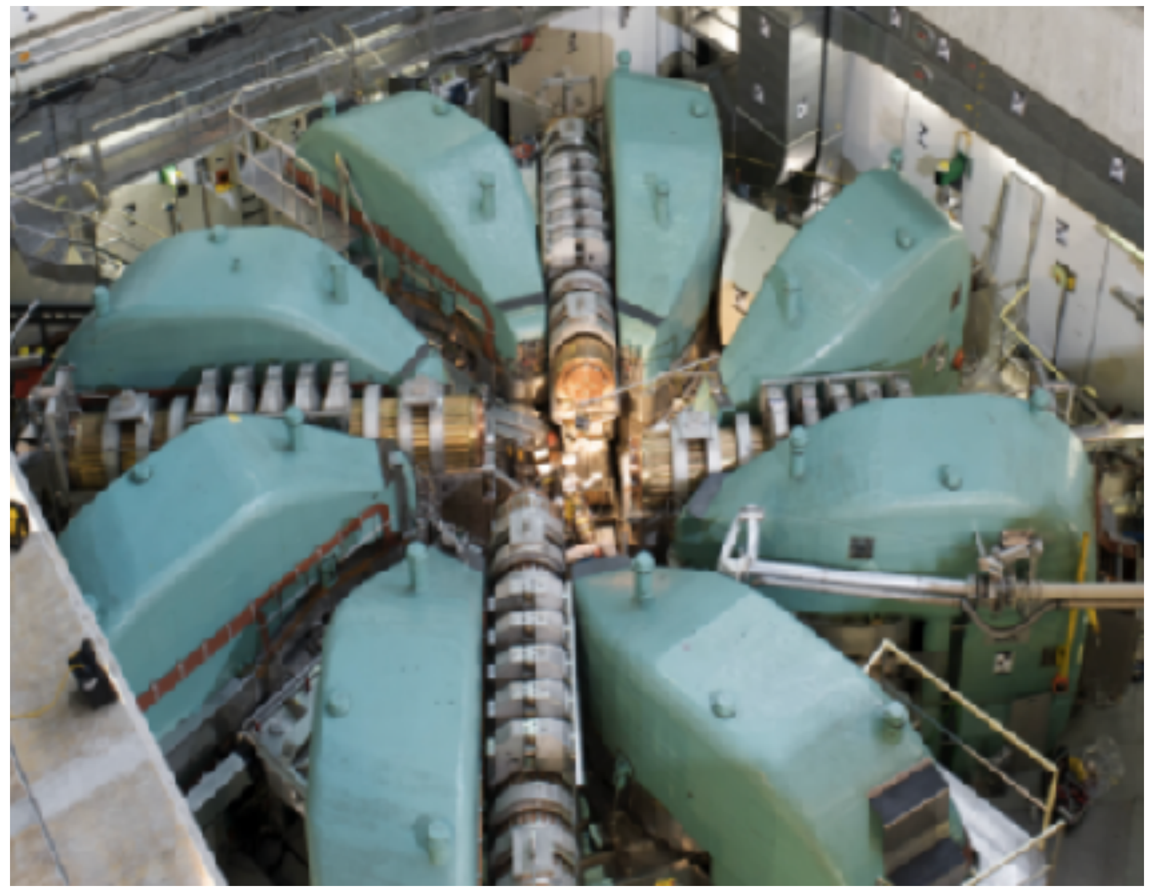
**→ MEG II**

- $\mu \to eee$
  - SINDRUM BR($\mu \to eee$) < 1.0x10$^{-12}$

**→ Mu3e**

- $\mu$-e conversion
  - SINDRUM II R($\mu$-e: Au) < 7x10$^{-13}$

**→ COMET/Mu2e**



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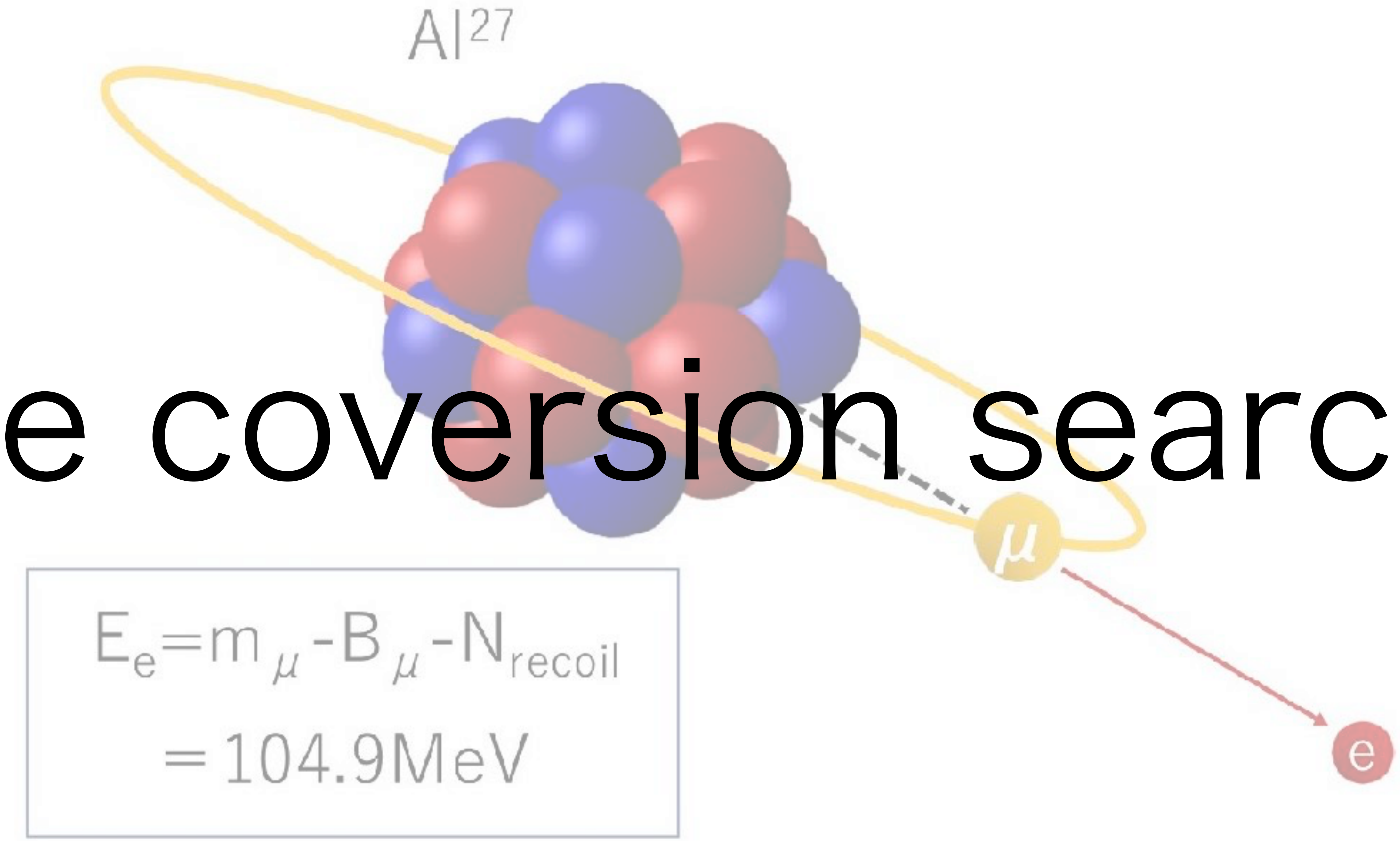
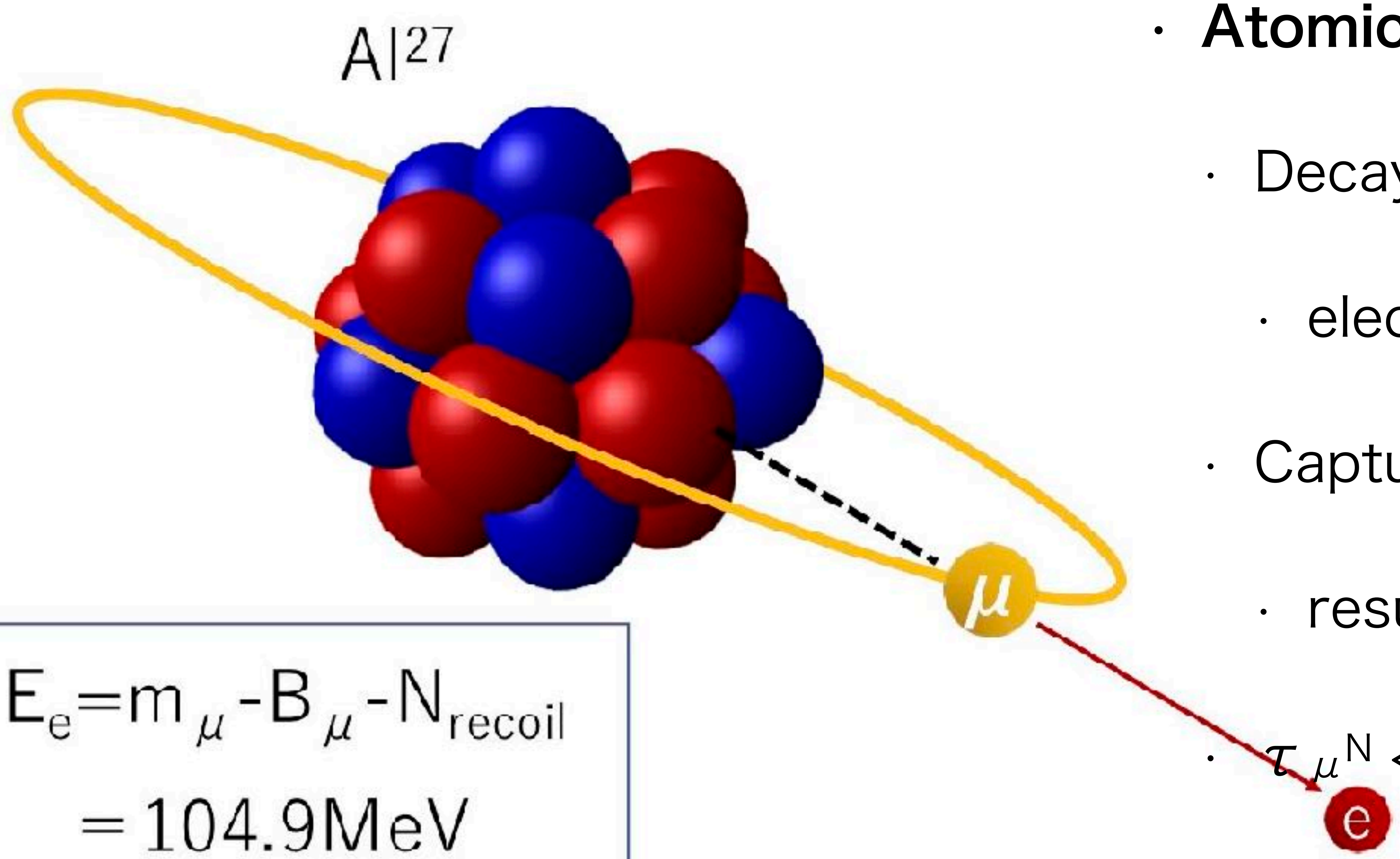



# $\mu$-e coversion search

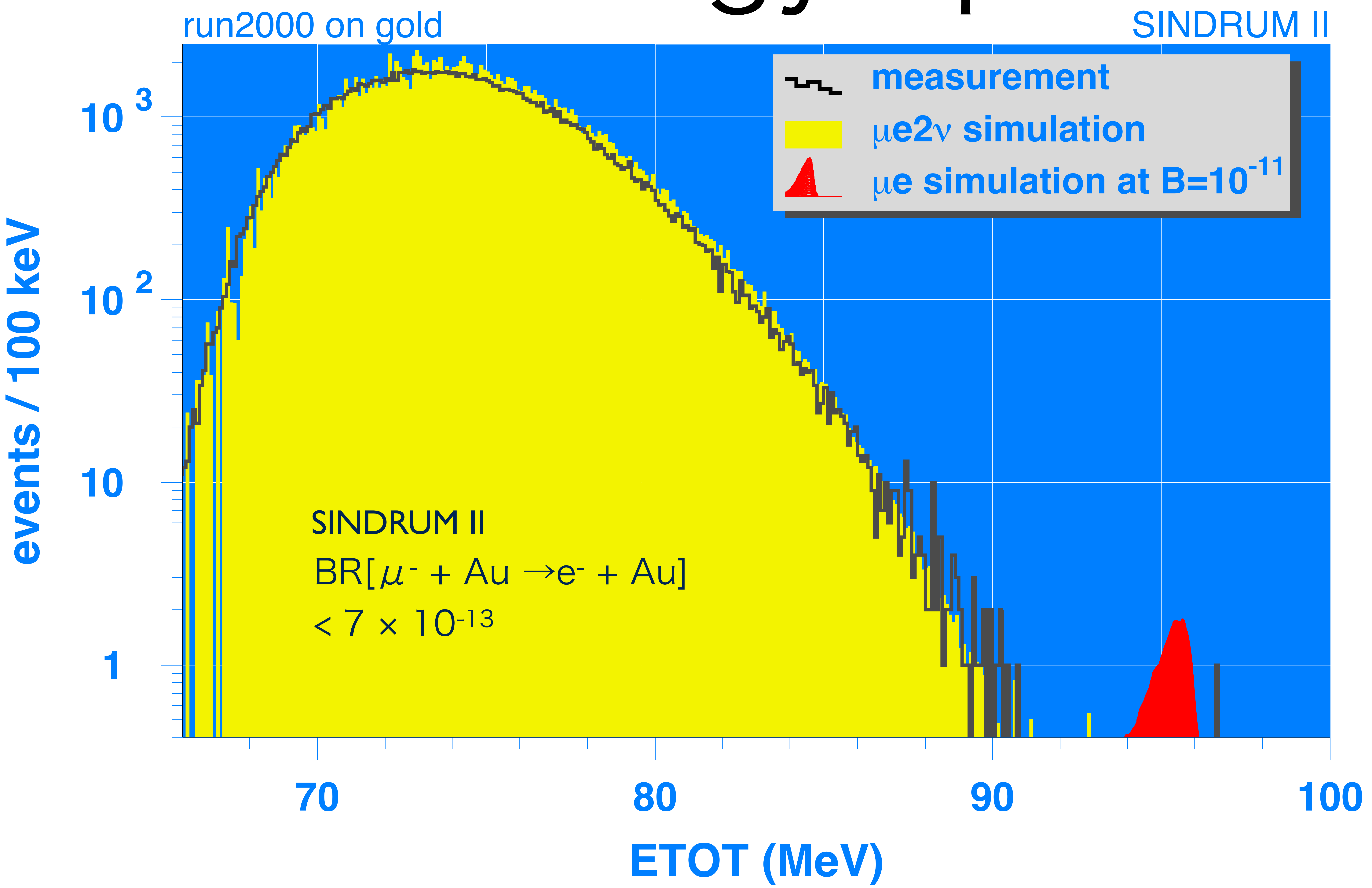
# $\mu$-e conversion




$$E_e = m_\mu - B_\mu - N_{recoil}$$
$$= 104.9\,\text{MeV}$$

- **Atomic capture of $\mu^-$**
  - Decay in orbit (DIO) $\boxed{\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu}$
    - electron gets recoil energy
  - Capture by nucleus $\boxed{\mu^- + (A,Z) \rightarrow \nu_\mu + (A,Z-1)}$
    - resultant nucleus is different
  - $\tau_\mu^N < \tau_\mu^{free}$ ($\tau_\mu^{Al}$ = 860 nsec)
  - **$\mu$-e conversion** $\boxed{\mu^- + (A,Z) \rightarrow e^- + (A,Z)}$
    - $E_{\mu e}(\text{Al}) \sim m_\mu - B_\mu - E_{rec} = 104.97\,\text{MeV}$
      - $B_\mu$: binding energy of the 1s muonic atom

# Electron Energy Spectrum



# Lessons from SINDRUM II

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- Use precisely pulsed muon beam instead of DC muon beam

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- Select the target nucleus

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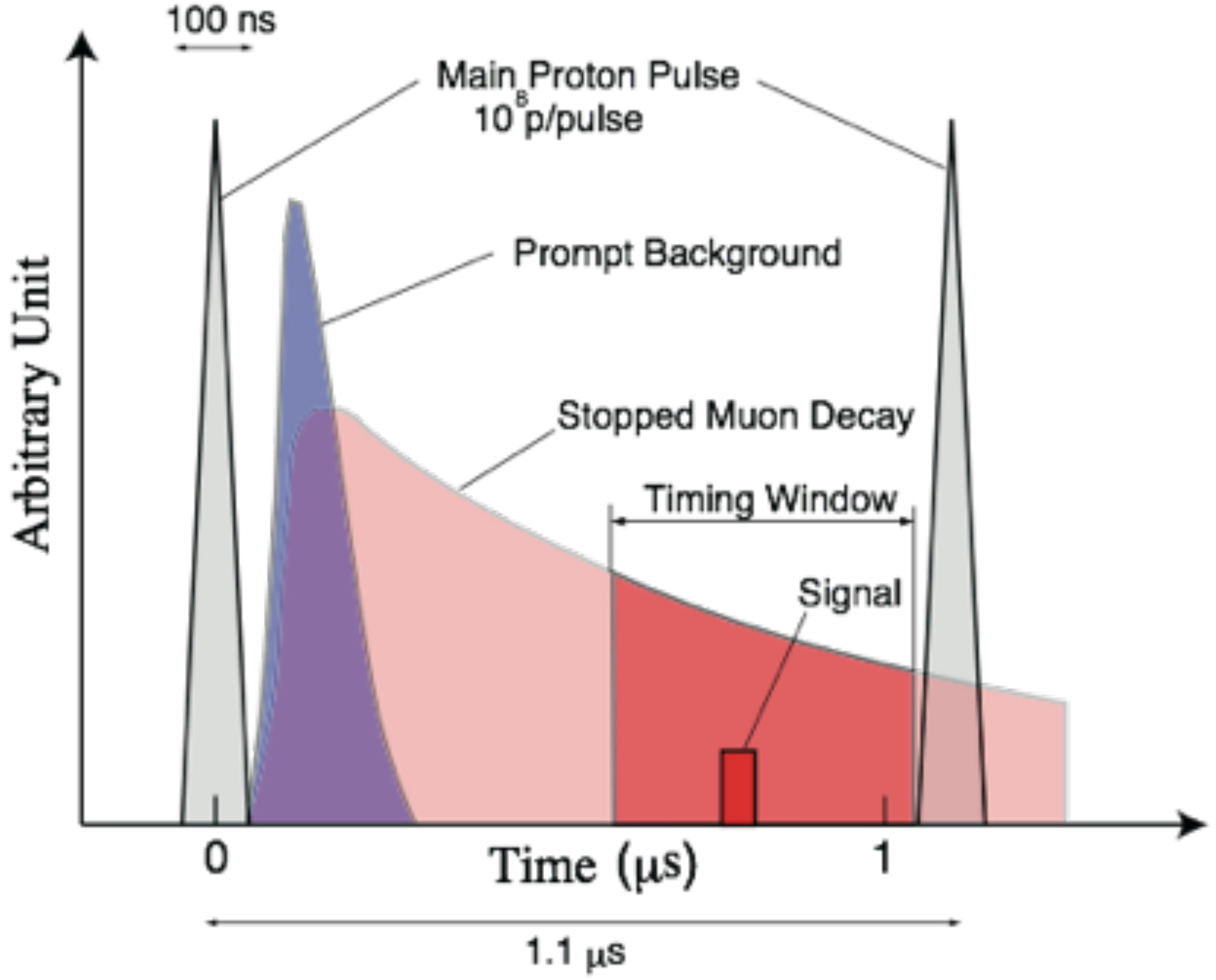
- Use precisely pulsed muon beam instead of DC muon beam
- Select the target nucleus
- Optimize the time structure of the pulsed muon beam

# $\mu$-e conversion signal and BG

- Signal
  - Electron from the muon stopping target with a characteristic energy with a delayed timing
- Background
  - Decay in Orbit Electron
  - Radiative muon capture
  - Cosmic-ray
  - Anti-protons
  - and others




Tiny leakage of protons in between consecutive pulses can cause a background through Beam Pion Capture process:

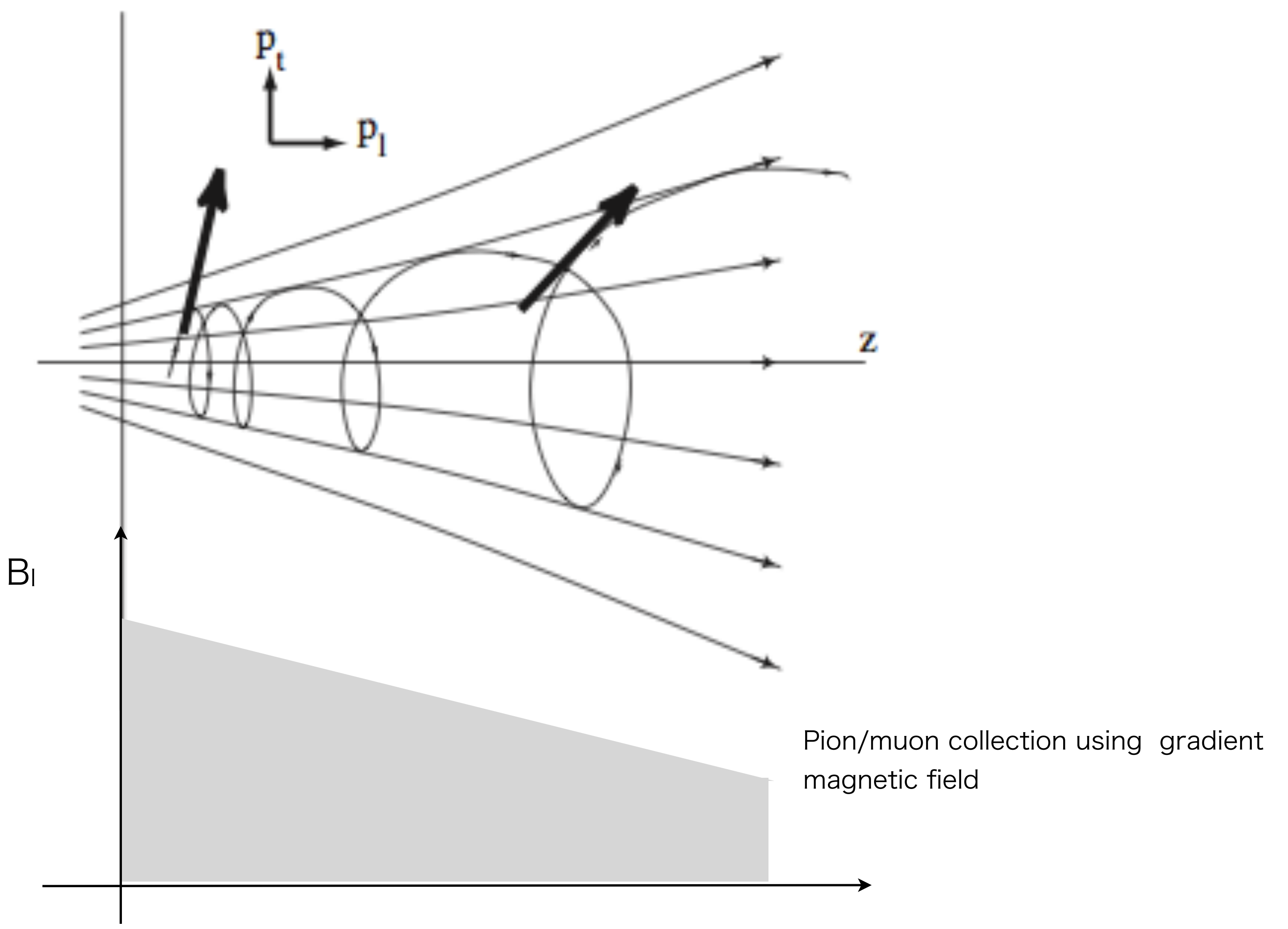
- $\pi^- + (A,Z) \rightarrow (A,Z-1)^* \rightarrow \gamma + (A,Z-1)$

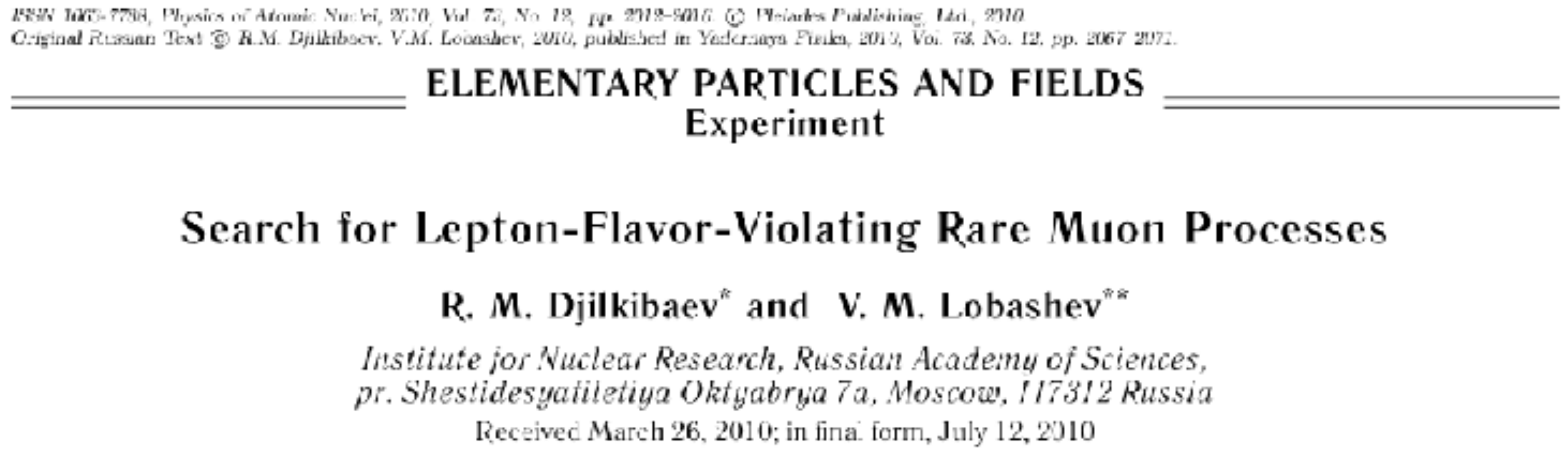
  $\gamma \rightarrow e^+ e^-$

$$R_{ext} = \frac{\text{Number of protons between pulses}}{\text{Number of protons in a pulse}} < 10^{-10}$$

# MELC Proposal

- Pion production in magnetic field
- Pion/muon collection using gradient magnetic field
- Beam transport & momentum selection with curved solenoid magnets



ISSN 1063-7788, Physics of Atomic Nuclei, 2010, Vol. 73, No. 12, pp. 2012–2016. © Pleiades Publishing, Ltd., 2010.
Original Russian Text © R.M. Djilkibaev, V.M. Lobashev, 2010, published in Yadernaya Fizika, 2010, Vol. 73, No. 12, pp. 2067–2071.


ELEMENTARY PARTICLES AND FIELDS
Experiment

**Search for Lepton-Flavor-Violating Rare Muon Processes**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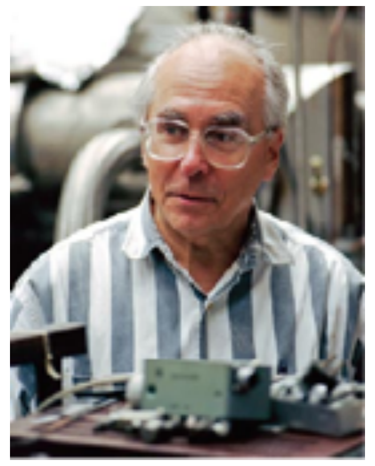
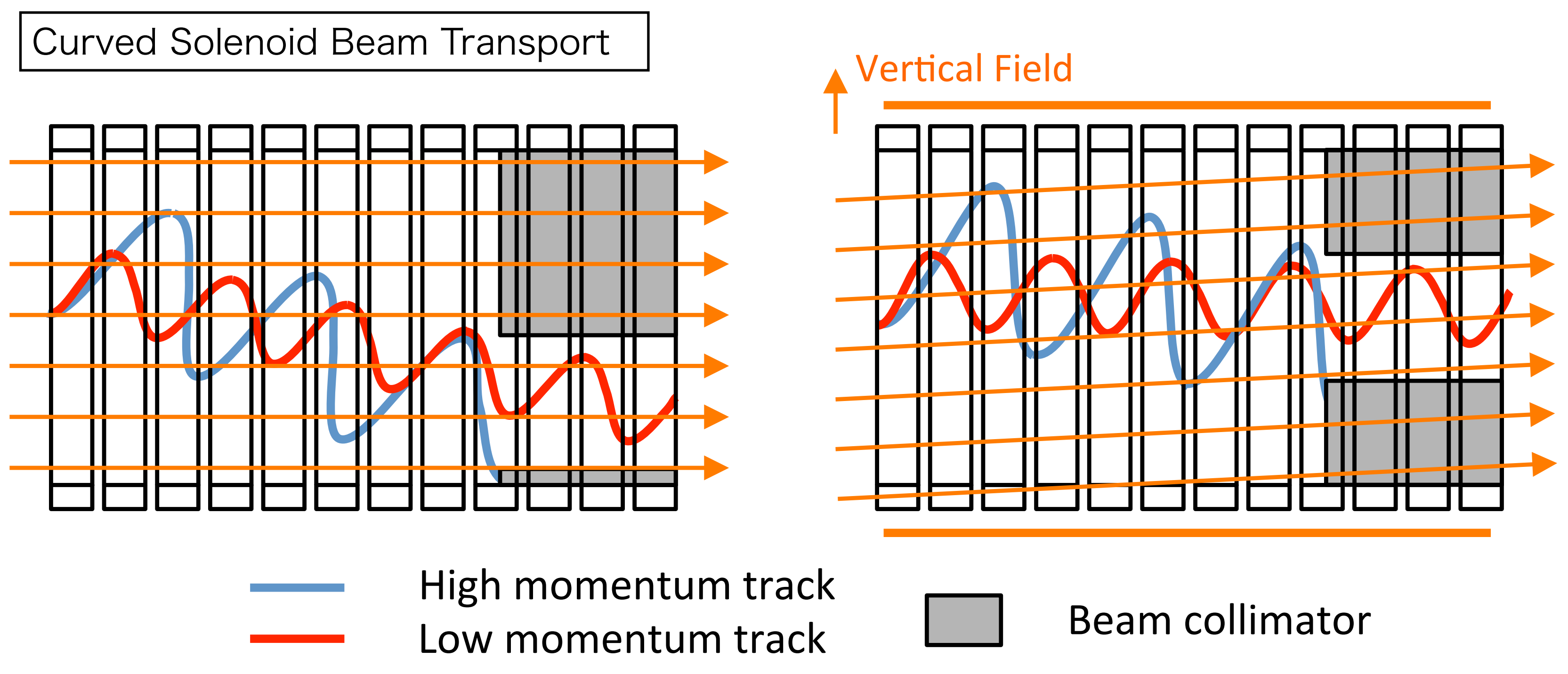
Received March 26, 2010; in final form, July 12, 2010

Vladimir Lobashev 1934-2011
CERN Courier Vol 51, No 8




- Momentum and charge separation
- Same scheme used in COMET Phase-II electron spectrometer

# COMET at J-PARC


J-PARC Facility
(KEK/JAEA)
LINAC
400 MeV
Neutrino beam to Kamioka
Material and Life Science Facility
Rapid Cycle Synchrotron
Energy : 3 GeV
Repetition : 25 Hz
Design Power : 1 MW
Nuclear and Particle
Physics Exp. Hall
Main Ring
Max Energy : 30 GeV
Design Power for FX : 0.75 MW
Expected Power for SX : > 0.1 MW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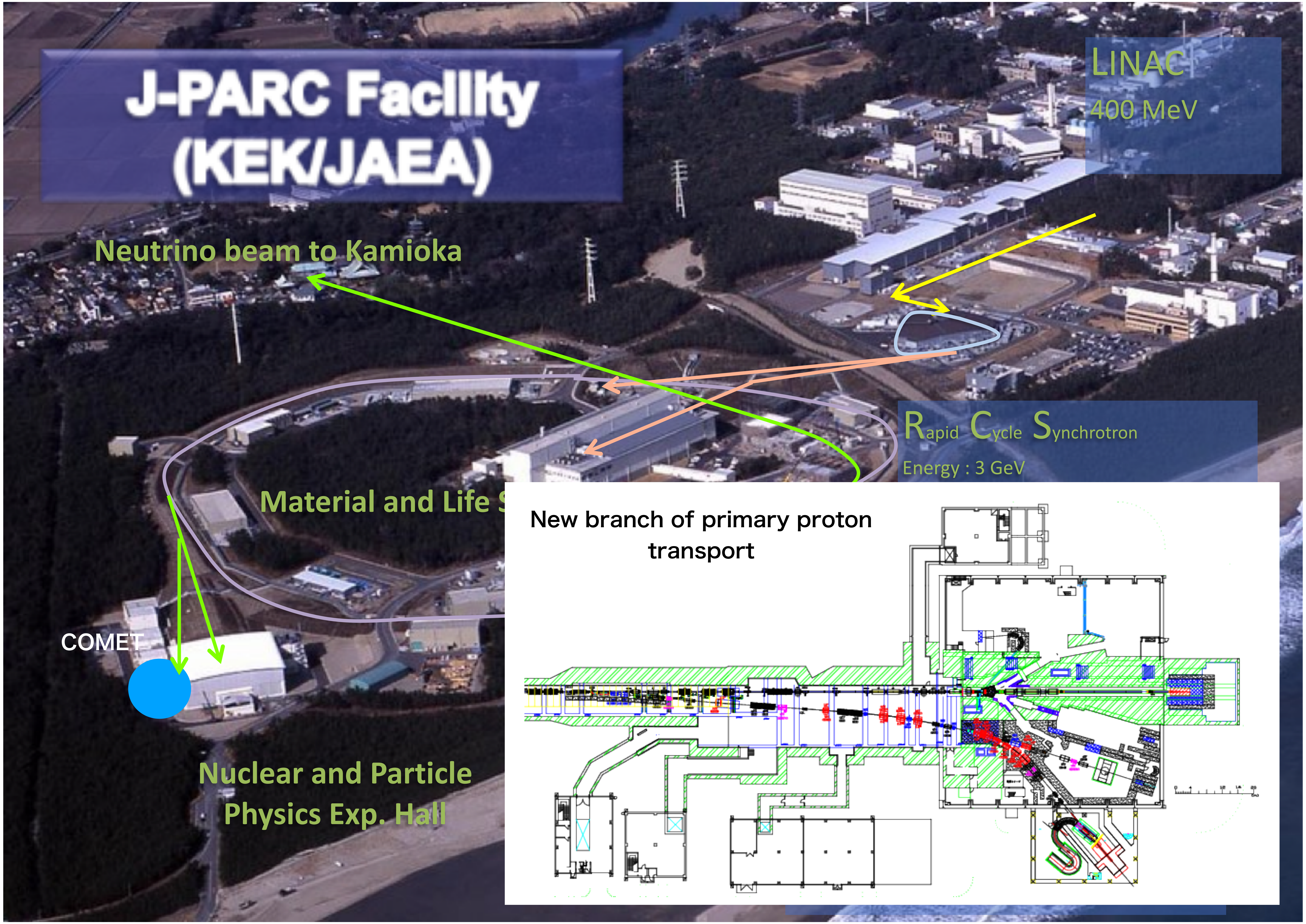
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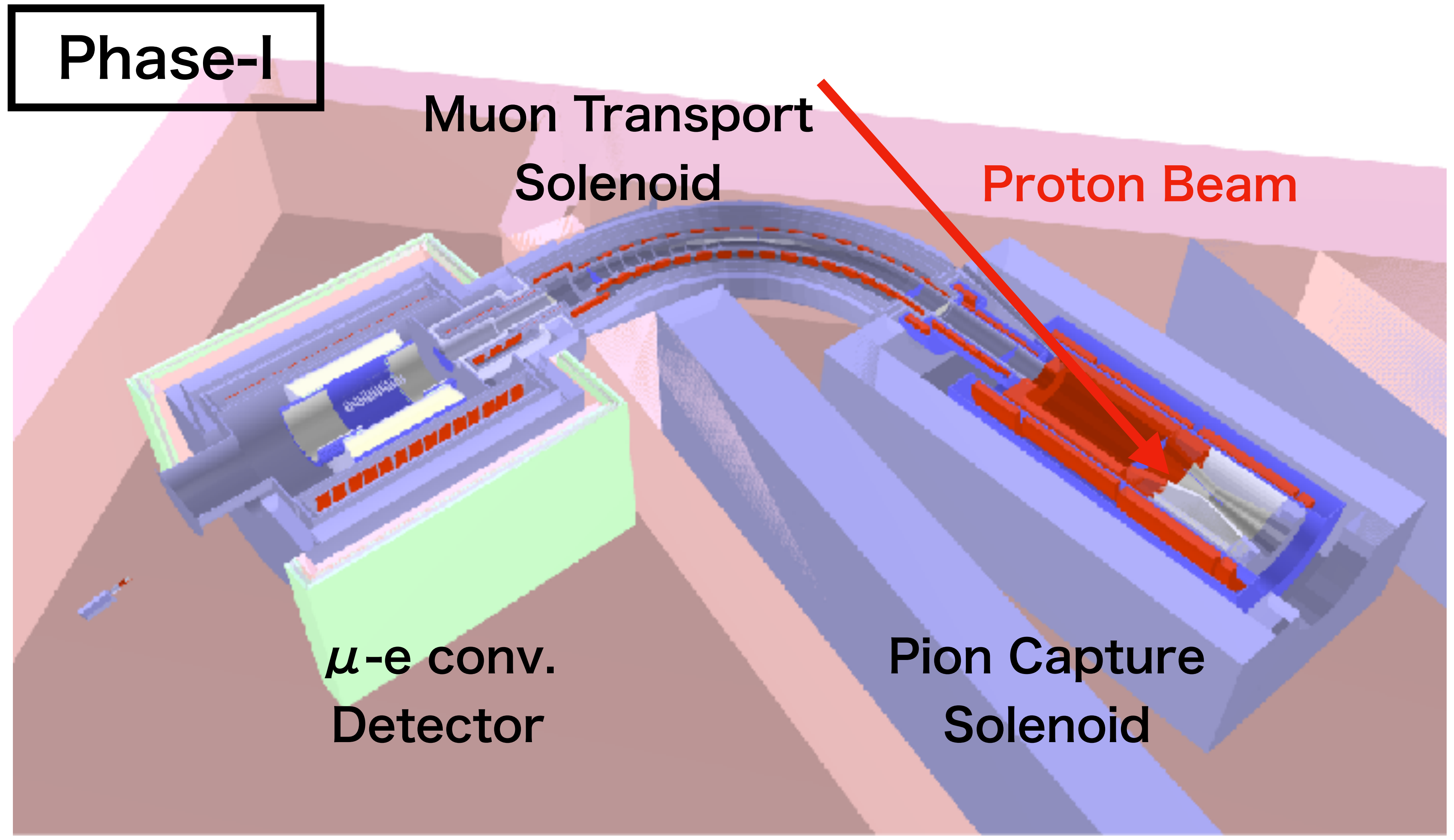
New branch of primary proton
transport

# COMET Phase I & II

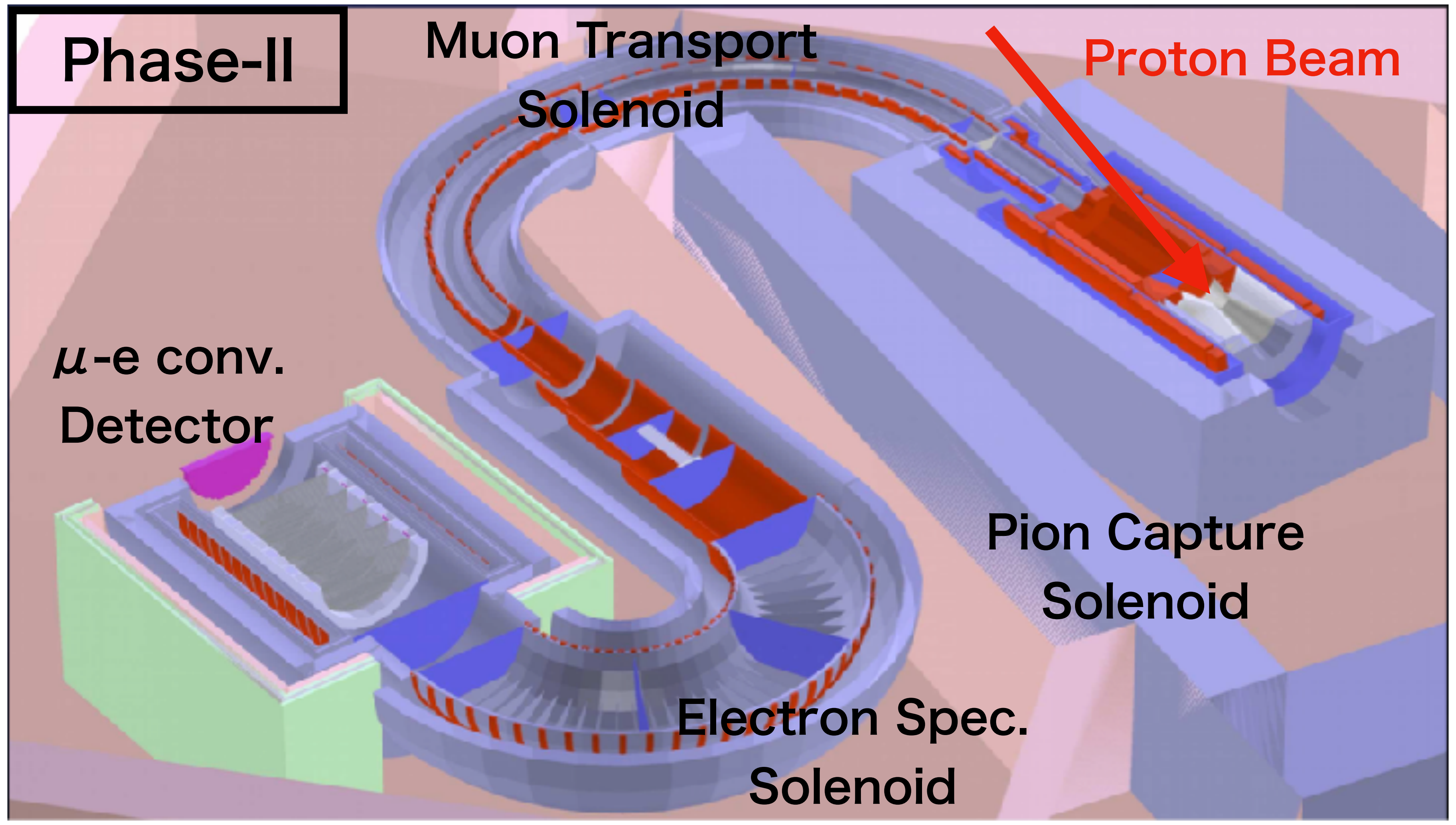
## Target Sensitivity <$10^{-14}$ with 3.2kW beam

- Proton beam line construction completed in JFY2021
- Graphite as a pion production target
- Pion Capture Solenoid construction is in the 3rd year of multi-year construction contract (FY2020-2022)
- Physics Detector
  - CDC and trigger hodoscope in a solenoid
  - Muon stopping target (Al) at the center of the solenoid
  - Beam engineering run in JFY2022 and physics in JFY2023-2024



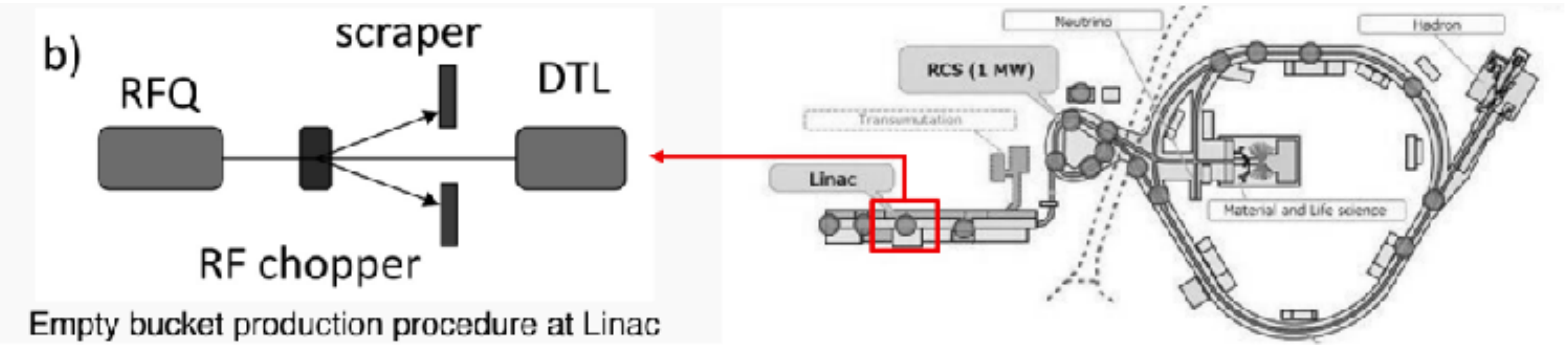

## Target Sensitivity <$10^{-16}$ with 56kW beam

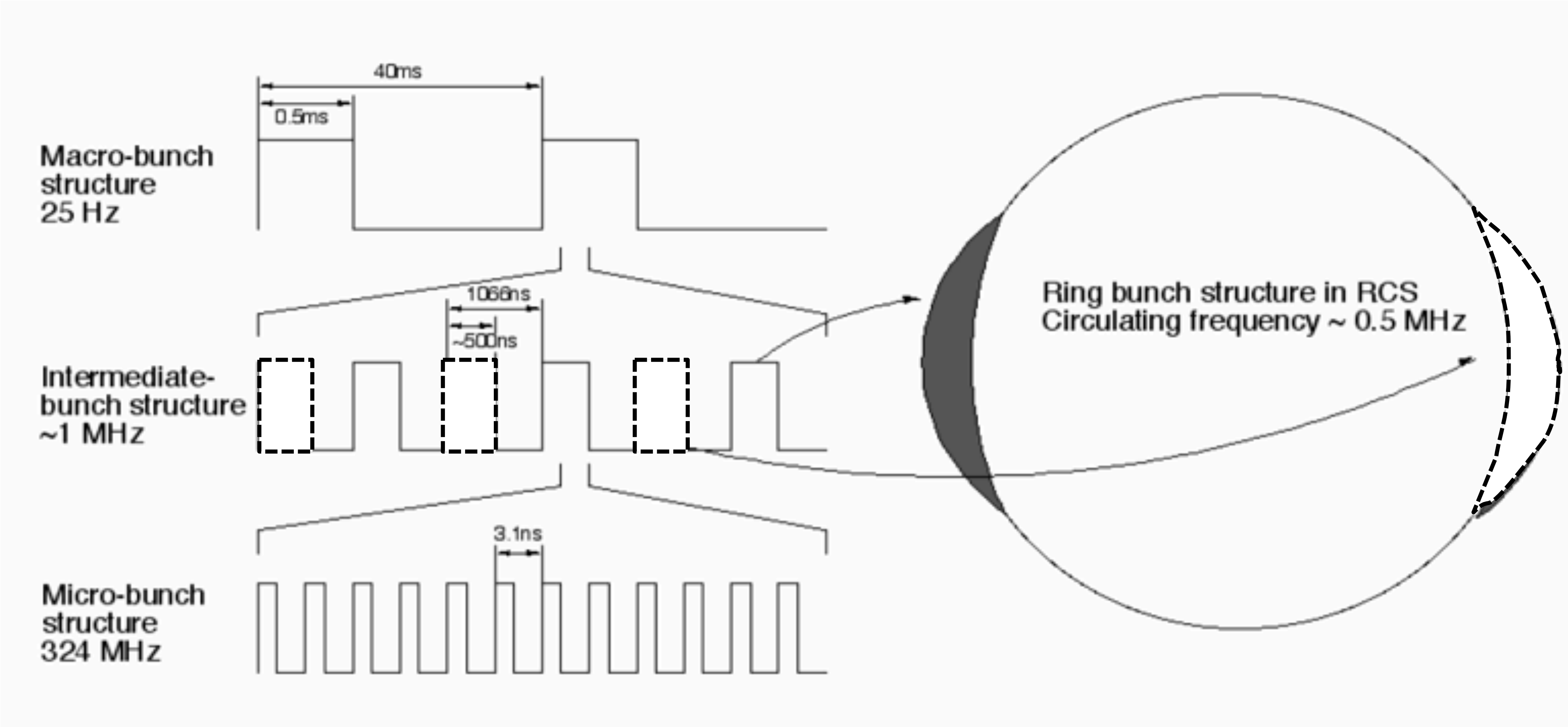
- Extension of muon transport solenoid to cope with higher proton beam power
- More efficient beam background suppression
- Much less pion contamination in longer transport
- Tungsten alloy as a pion production target
- Electron spectrometer solenoid to suppress the detector counting rate
- •Physics detector
  - Straw-tube tracker and LYSO calorimeter
  - Muon stopping target (Al + others) in a gradient magnetic field for the purpose of signal electron collection with a magnetic mirroring

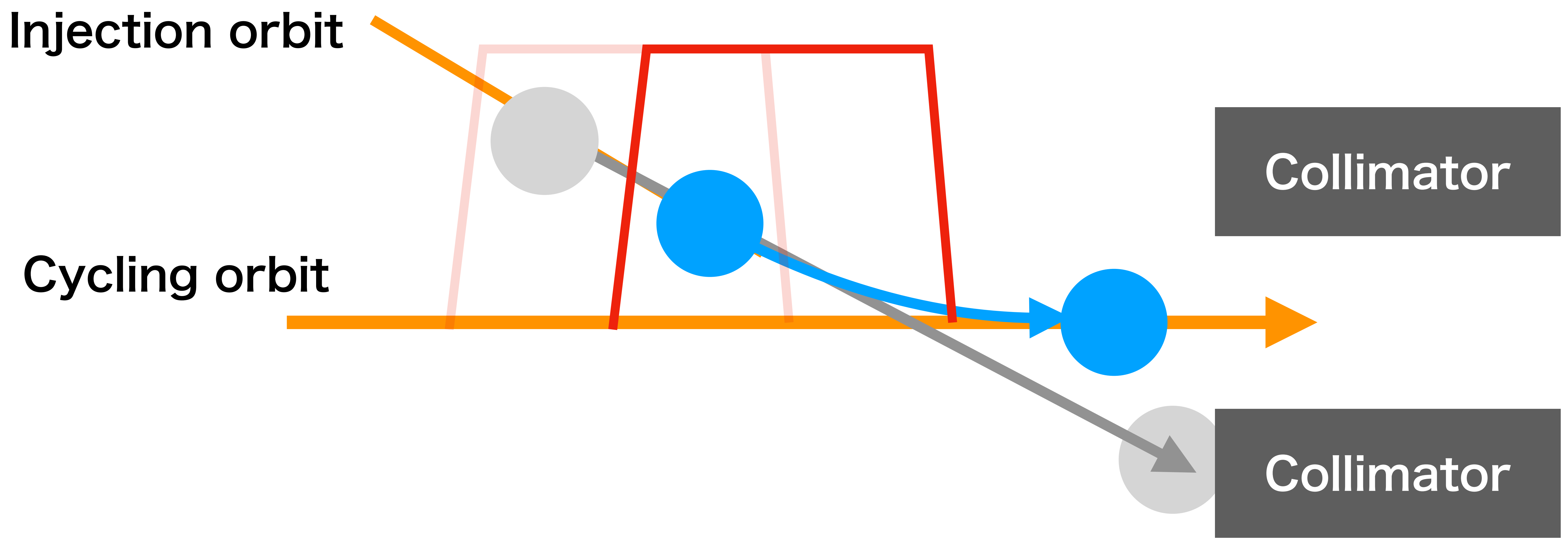


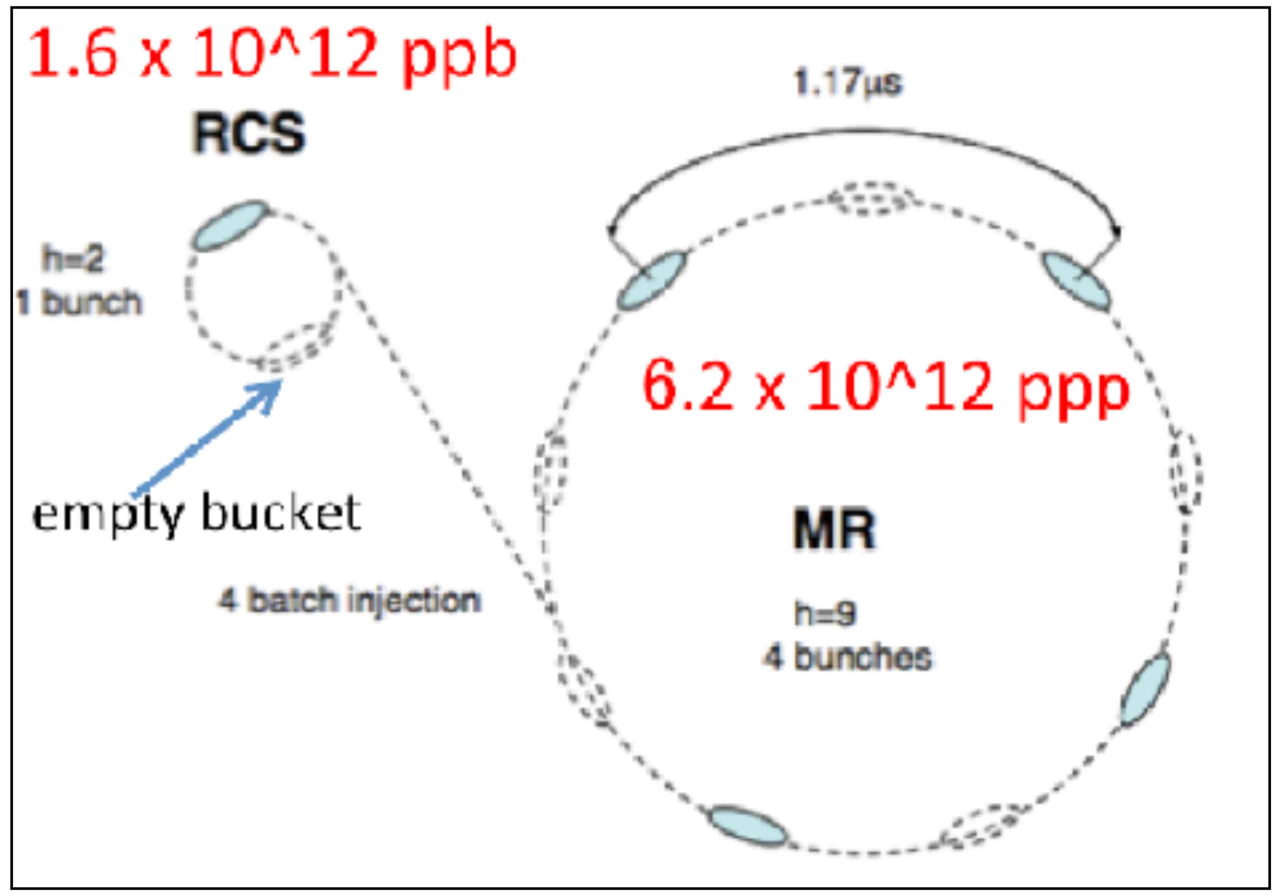
# Proton Beam for COMET

- LINAC → RCS (h=2) → MR (h=9)
- COMET requires MR operation at 8GeV (instead of 30GeV for HD hall experiments and T2K)
- **Empty buckets to prepare suitable pulse time structure for COMET**
  - **RF Chopper in LINAC**
- Proton beam extracted from MR without destroying the bunch structure to generate pulsed-muon beam with a suitable pulse timing
  - Dedicated injection method for COMET to kick remaining protons in empty buckets out (**Single Bunch Kicking**)
- Proton beam extinction factor measurement using secondary beam in 2021
  - $<1\times10^{-10}$ (90% C.L.) extinction factor has already been achieved, which is sufficient for Phase I



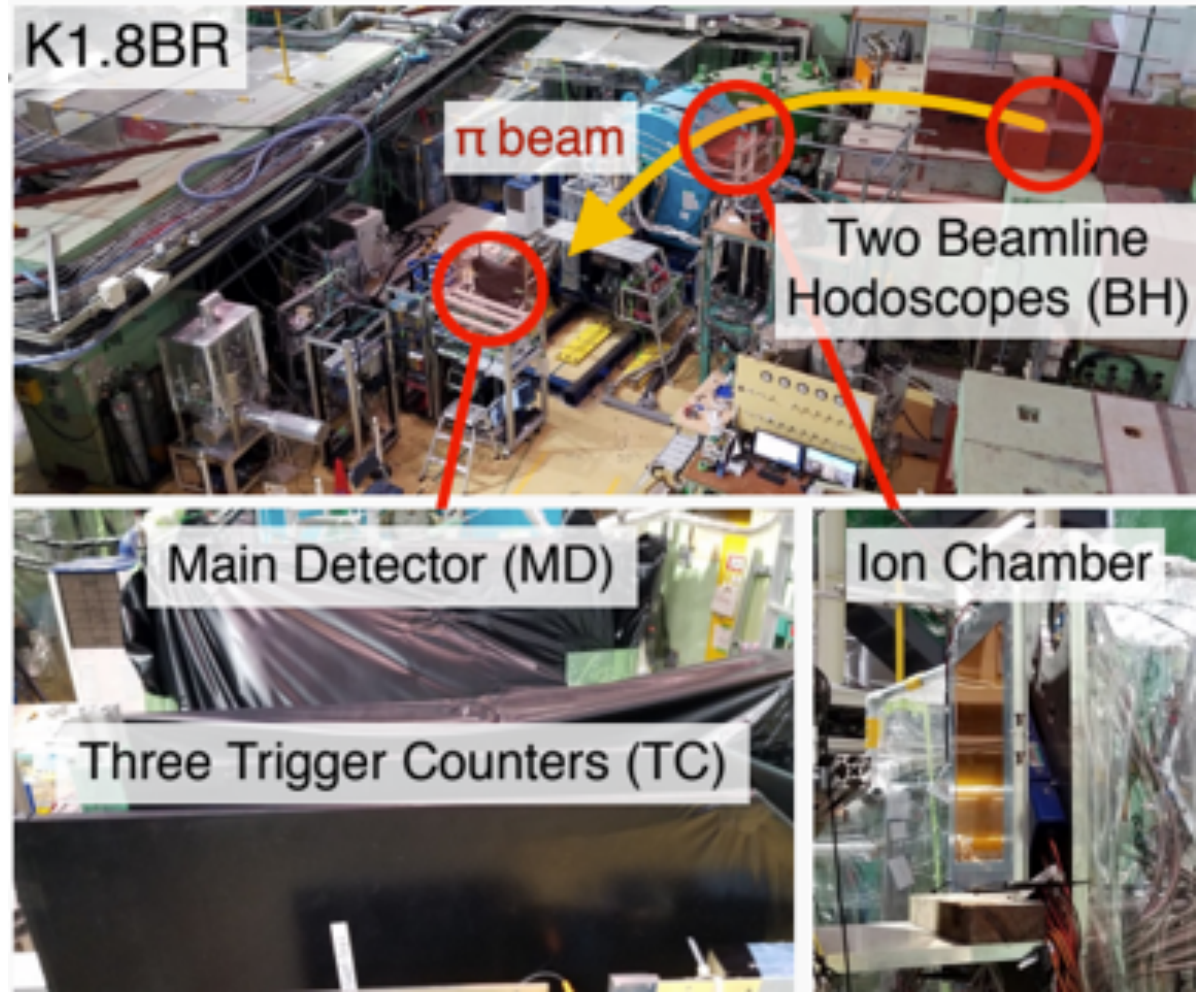



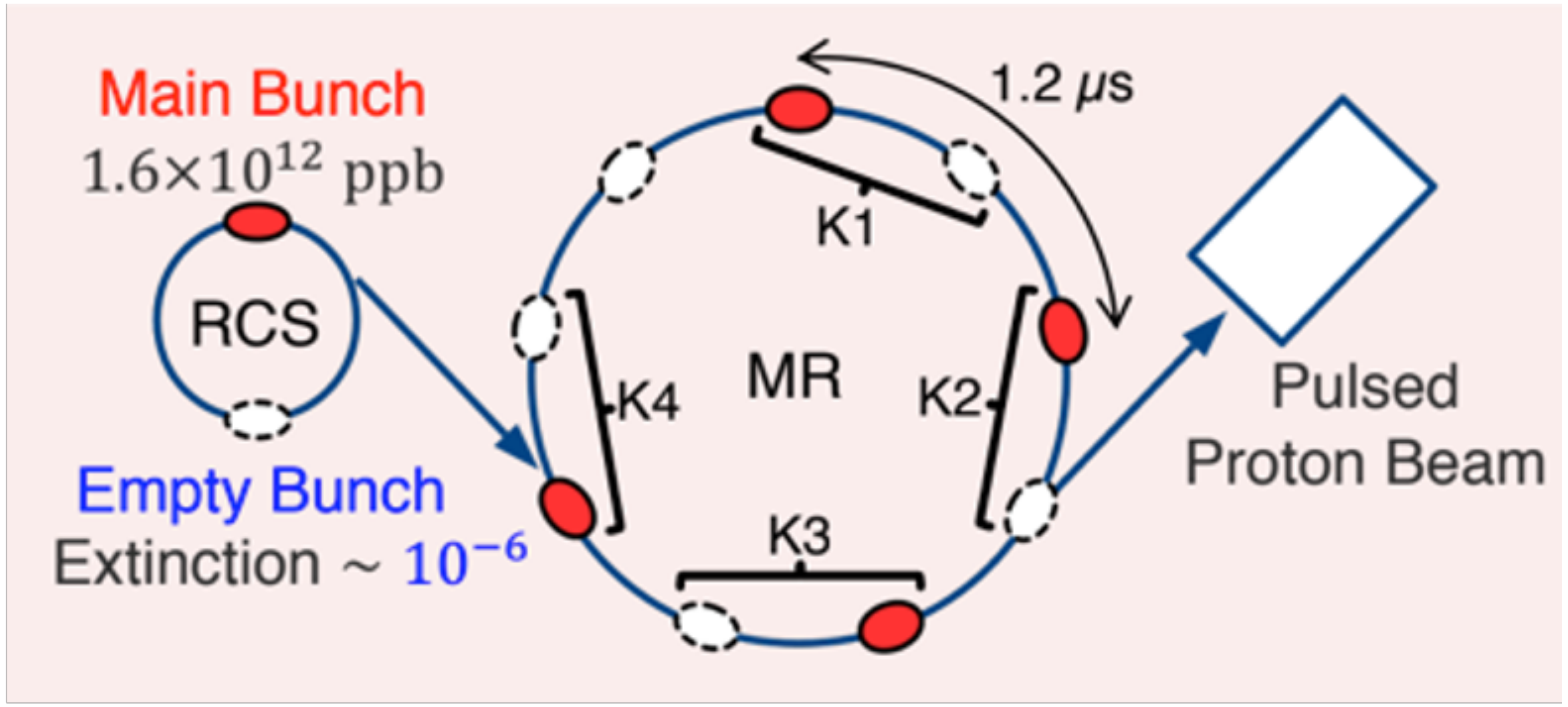



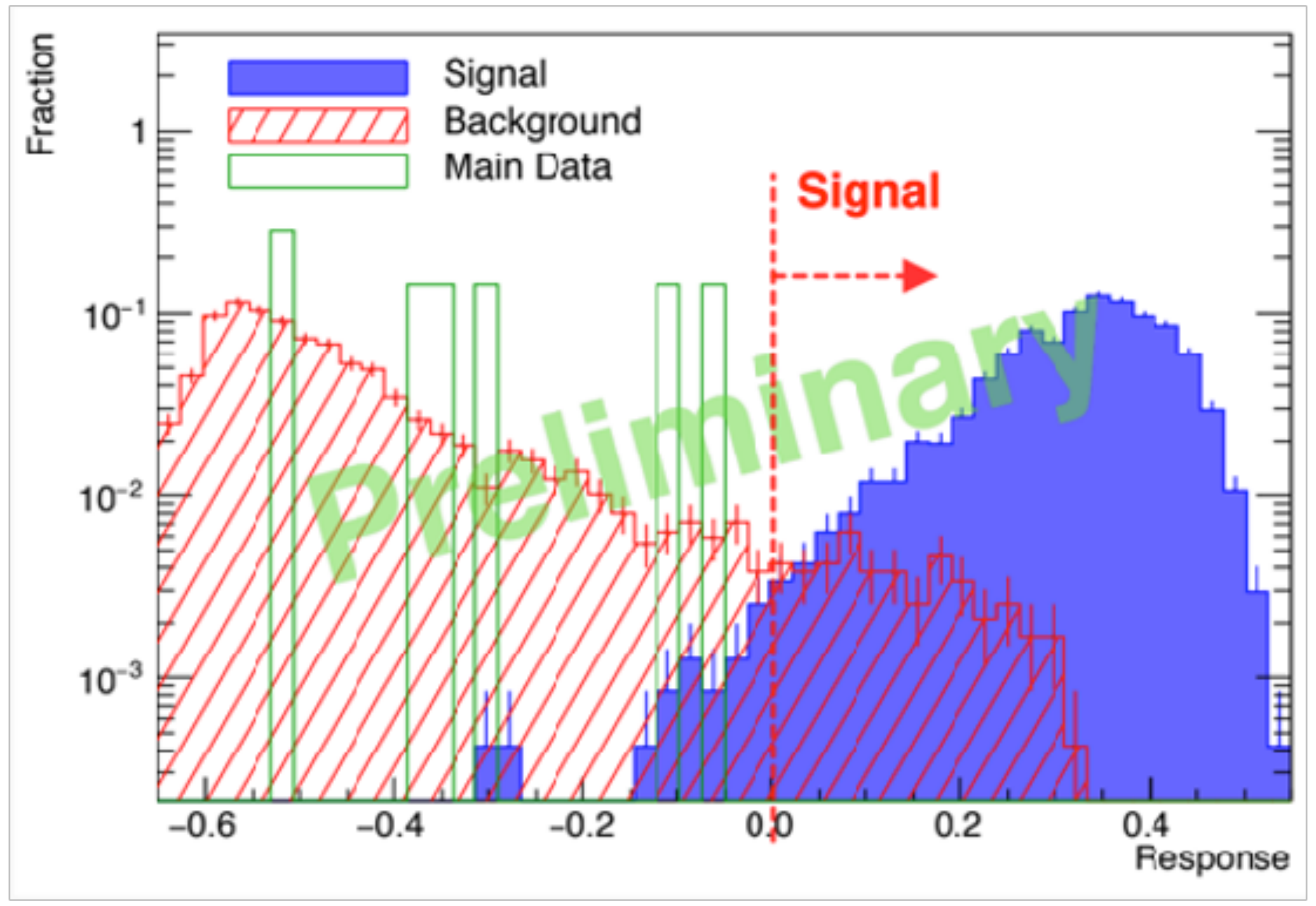



# J-PARC Beam Extinction Study

- Beam extinction measurement using secondary beam in 2018
- Residual protons observed in an empty bucket
- Improved in 2021 beam test by adjusting injection kicker timing
  - Detailed analysis in progress by Kyohei NOGUCHI (Ph.D thesis)
  - **< 1 x $10^{-10}$ at 90% C.L.**

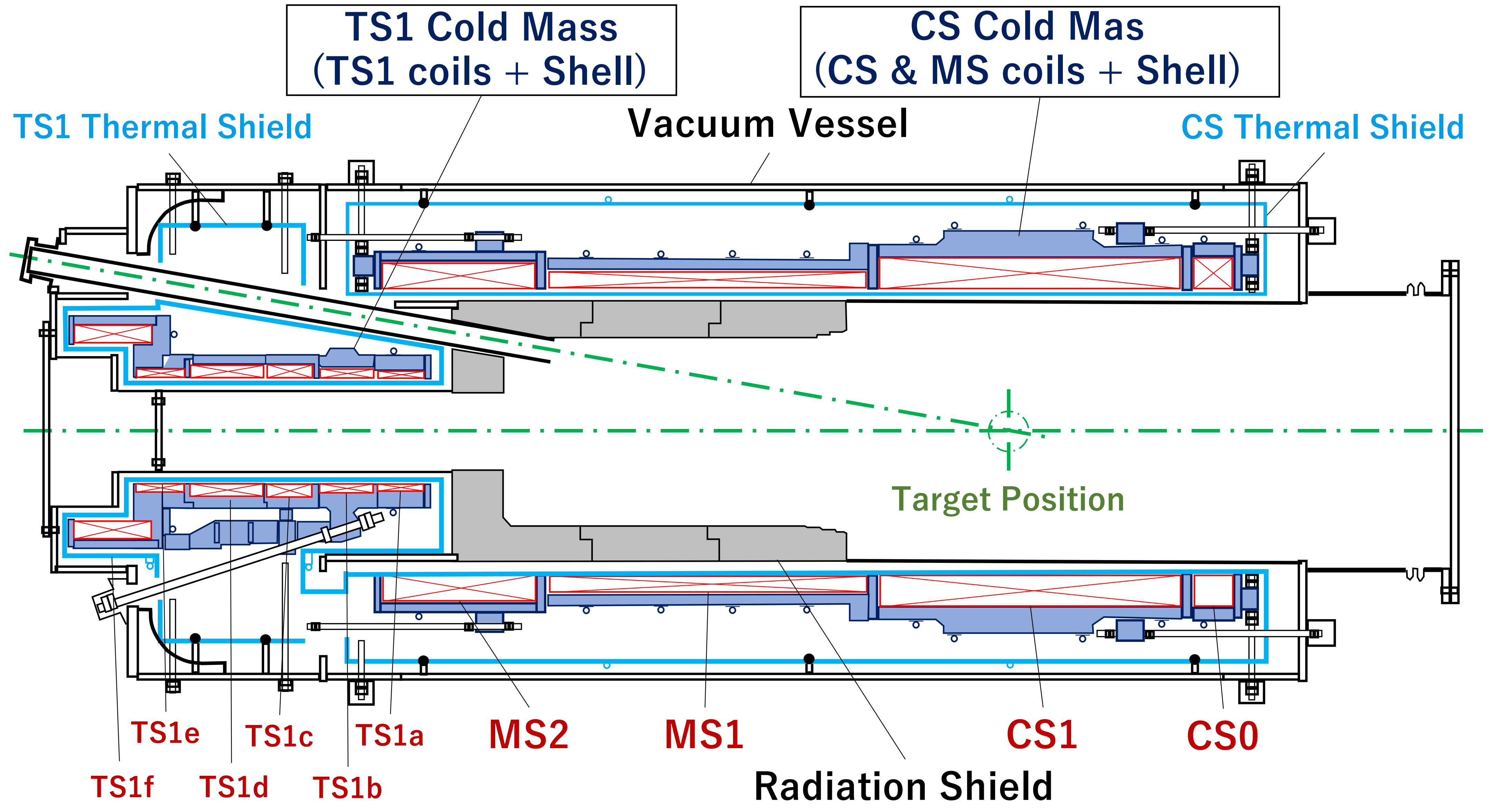


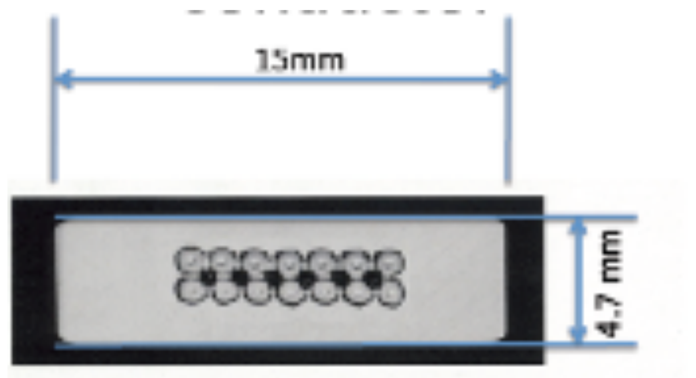



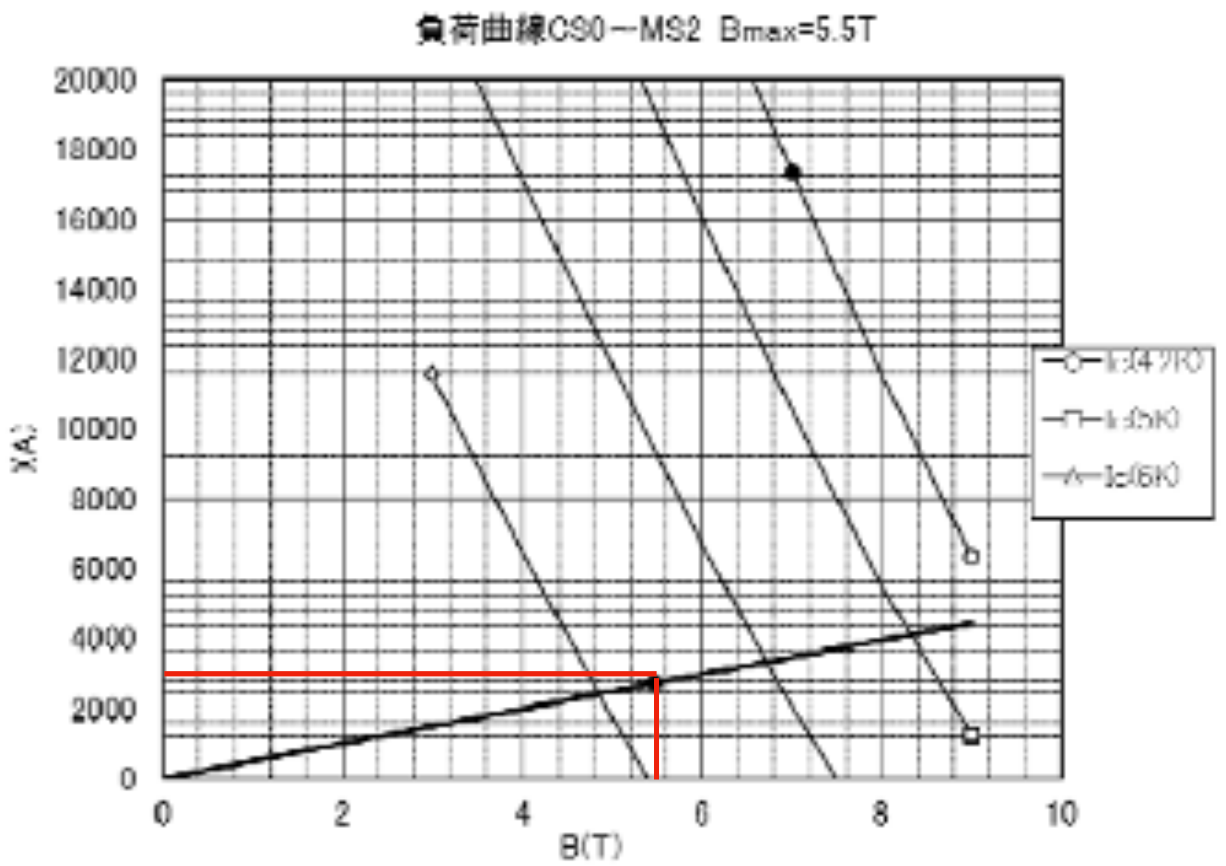
# Pion Capture Solenoid

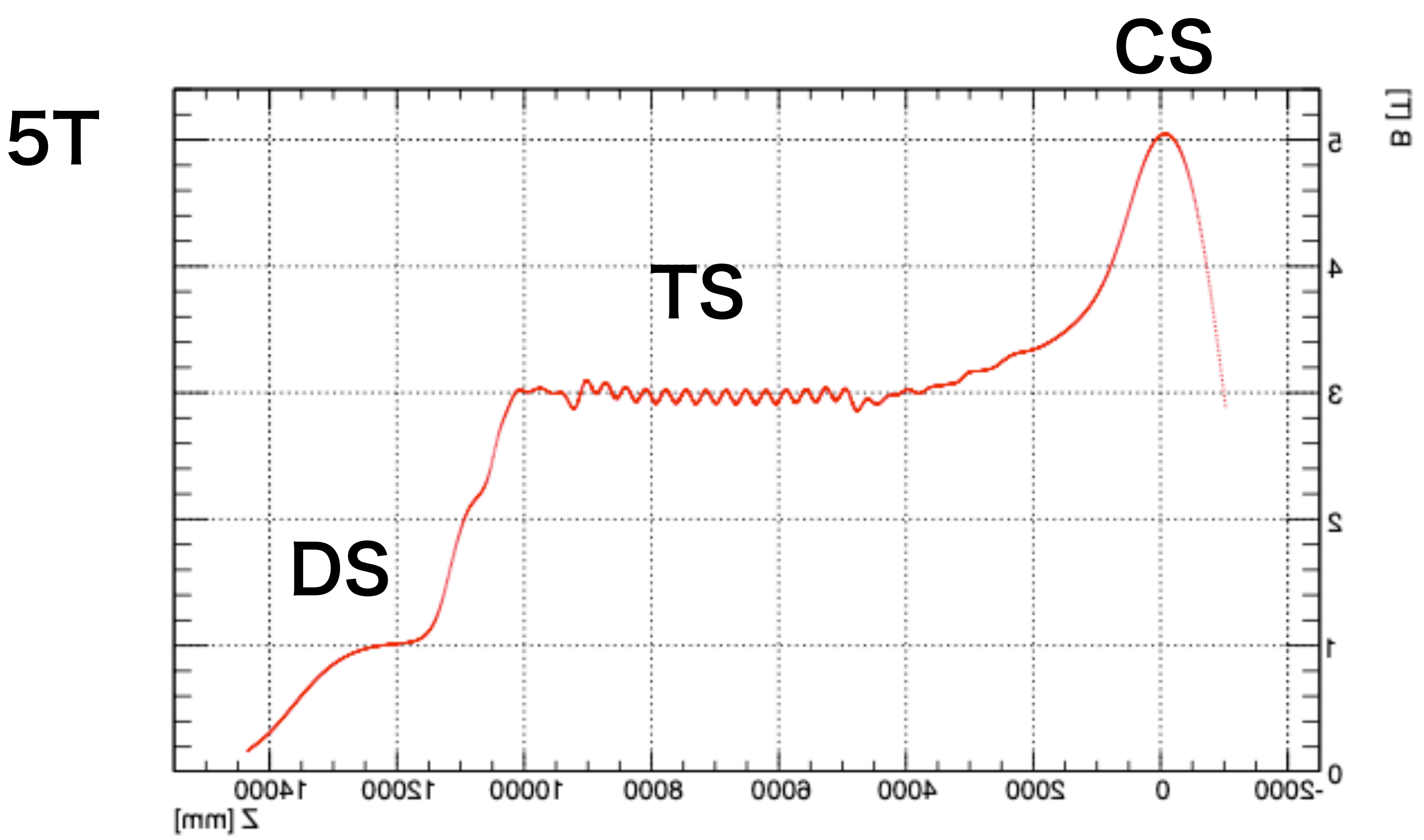
- Pion capture with 5T (max) magnetic field
- Pion production target at the center
  - Graphite in Phase I
  - Tangsten alloy in Phase II
- Tolerable against radiation from the target
  - Aluminum stabilized SC cables



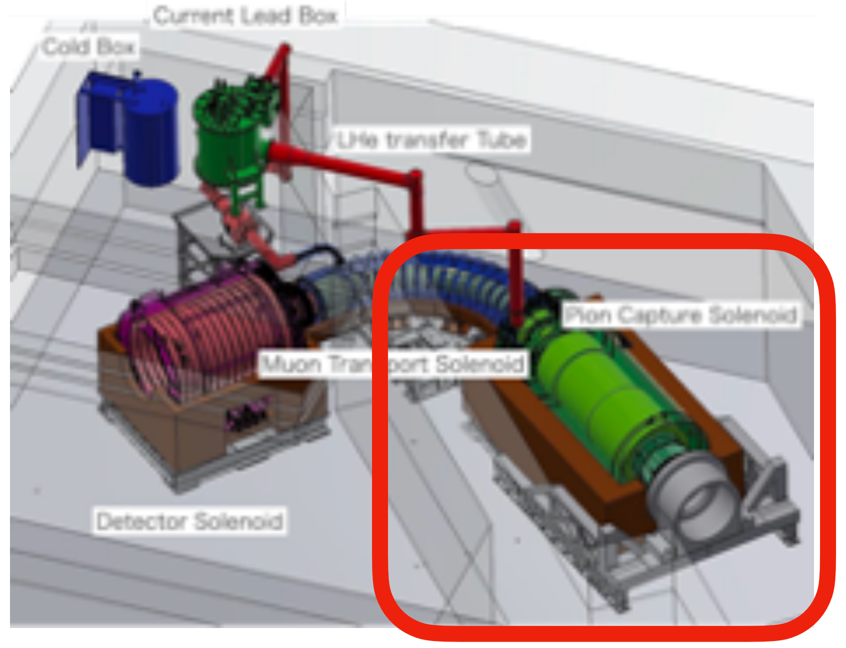



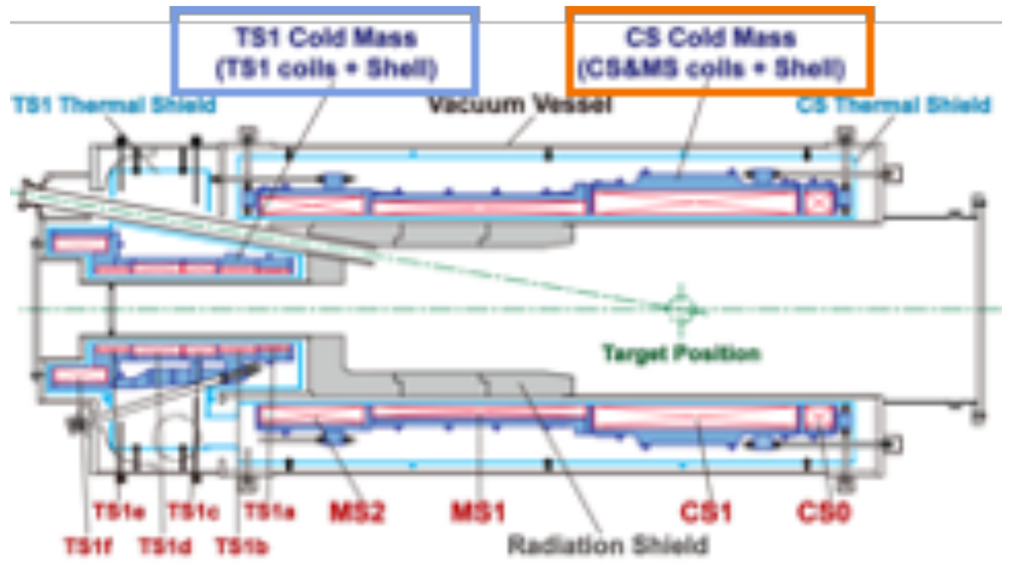

COMET design value
Size: 4.7x15mm
Offset yield point of Al@4K: >85MPa
RRR@0T: >500
Al/Cu/SC: 7.3/0.9/1
14 SC strands: 1.15mm dia.

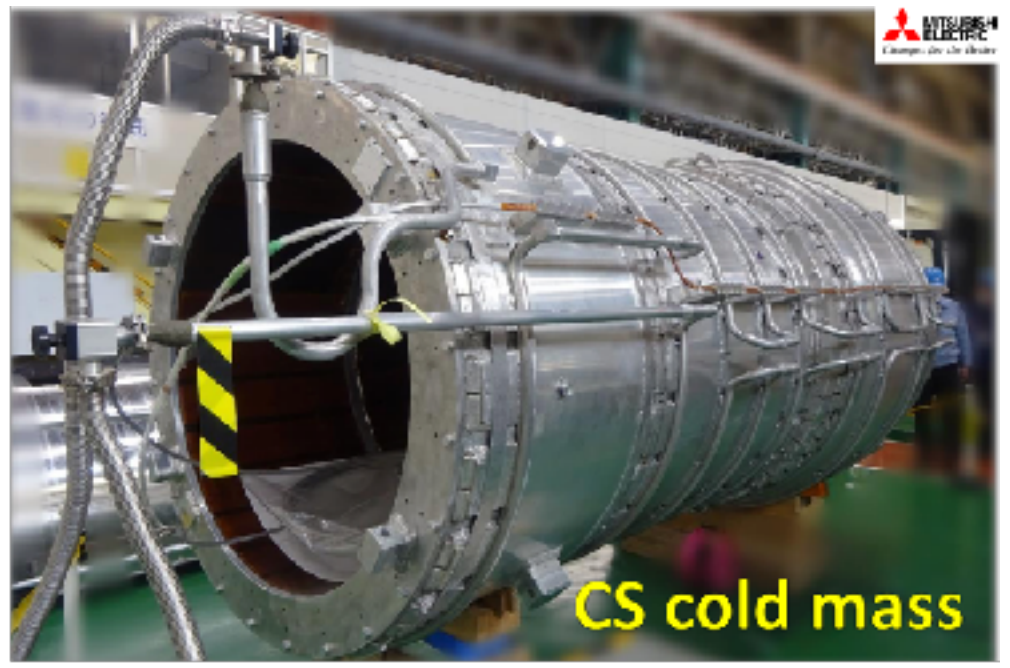


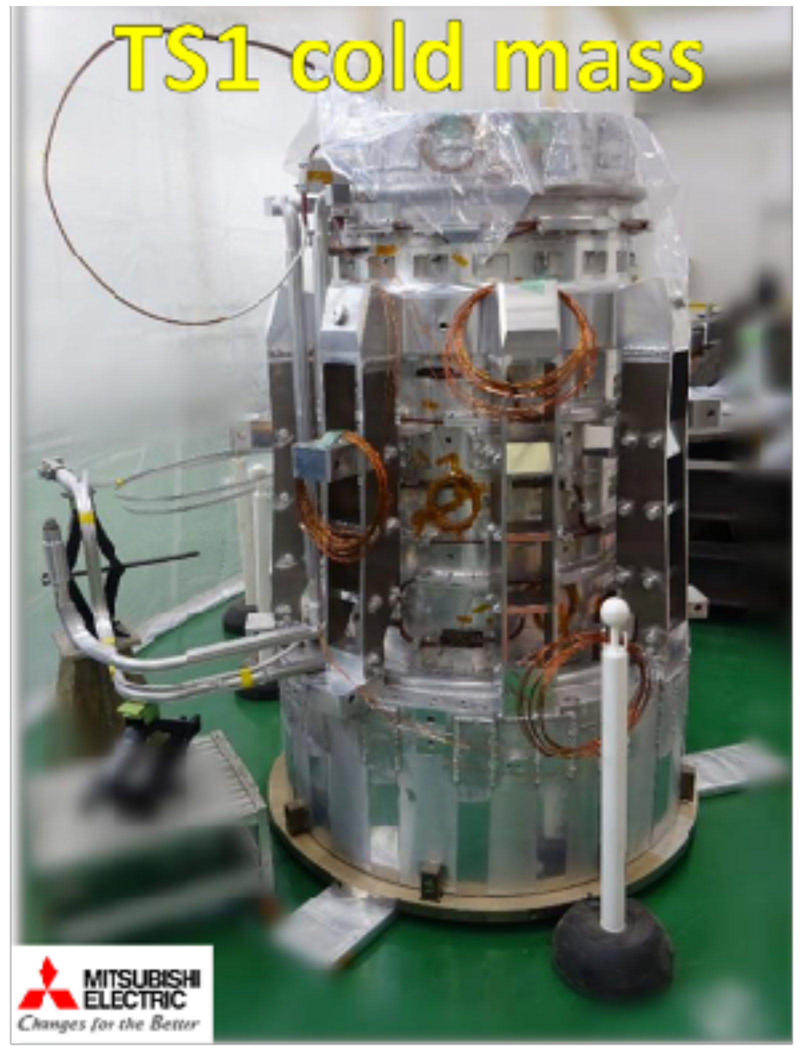



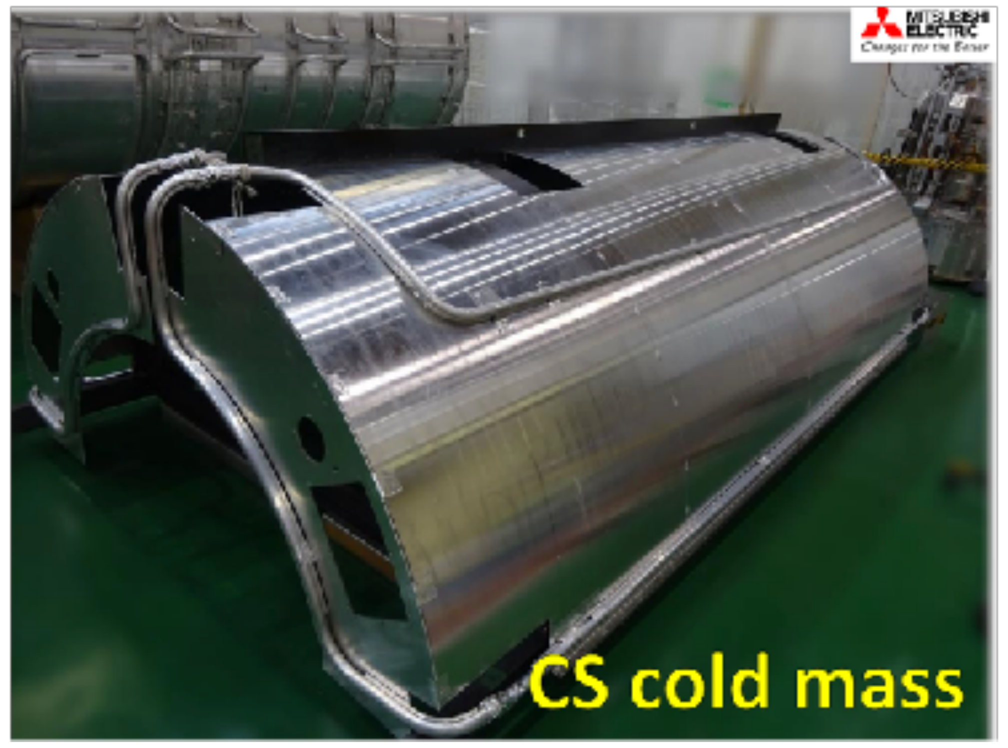
# Pion Capture Solenoid Construction





- ✓ Coil winding started in 2015 and completed in 2019
- ✓ Cold mass assembly in 2020
- ✓ Cryostat construction in 2021
- ✓ Return yoke construction in 2021
- Magnet assembly and delivery to J-PARC in 2022

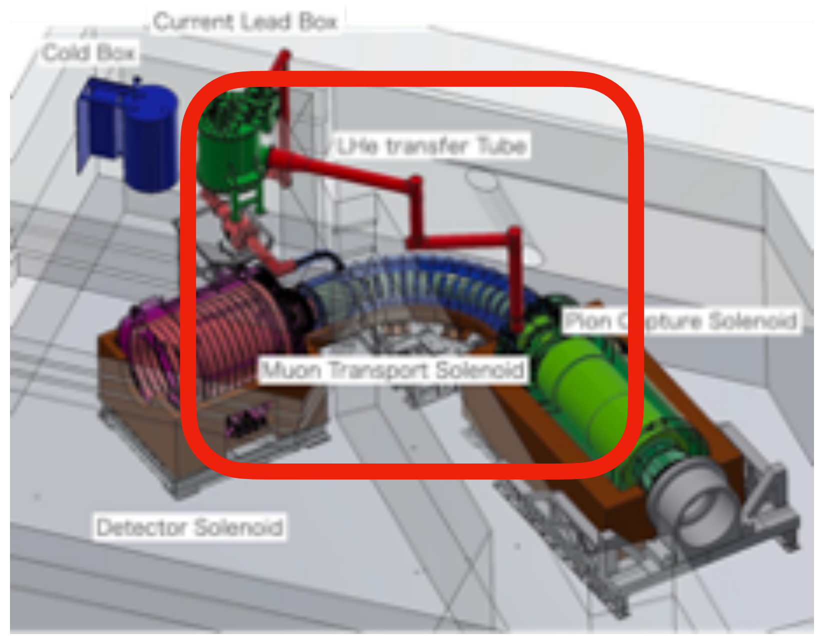
# MTS Installation and Operation

✓ Construction in 2013-2014

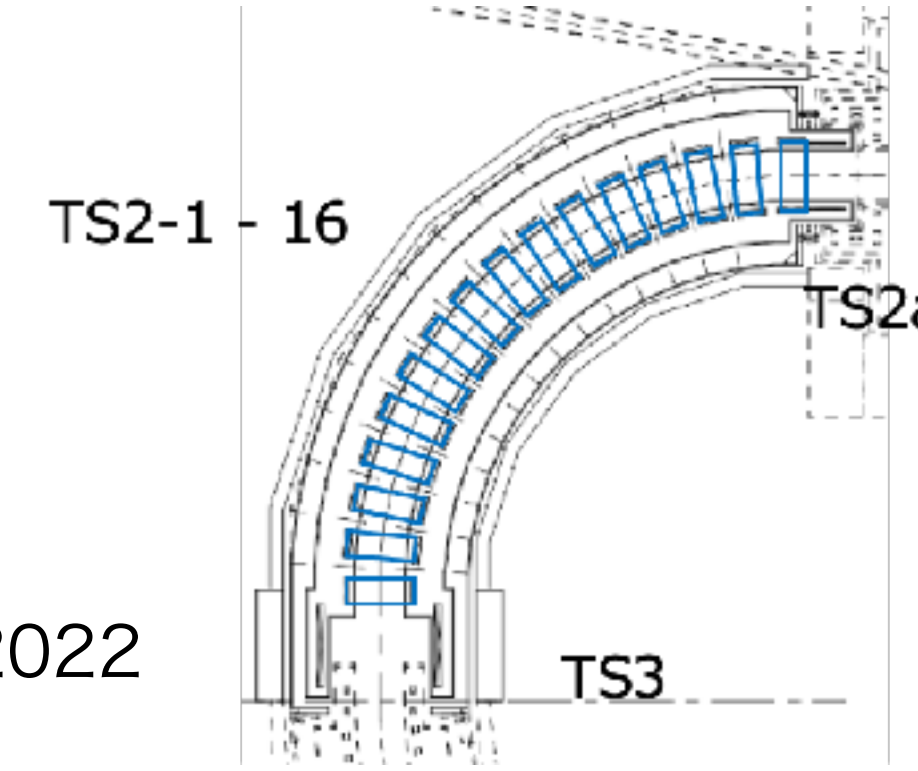
✓ Installation in 2015

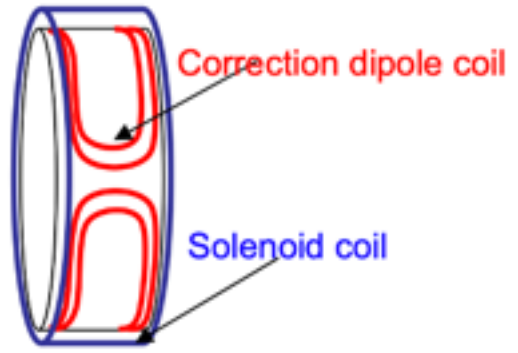
✓ Cooling and excitation test in 2022

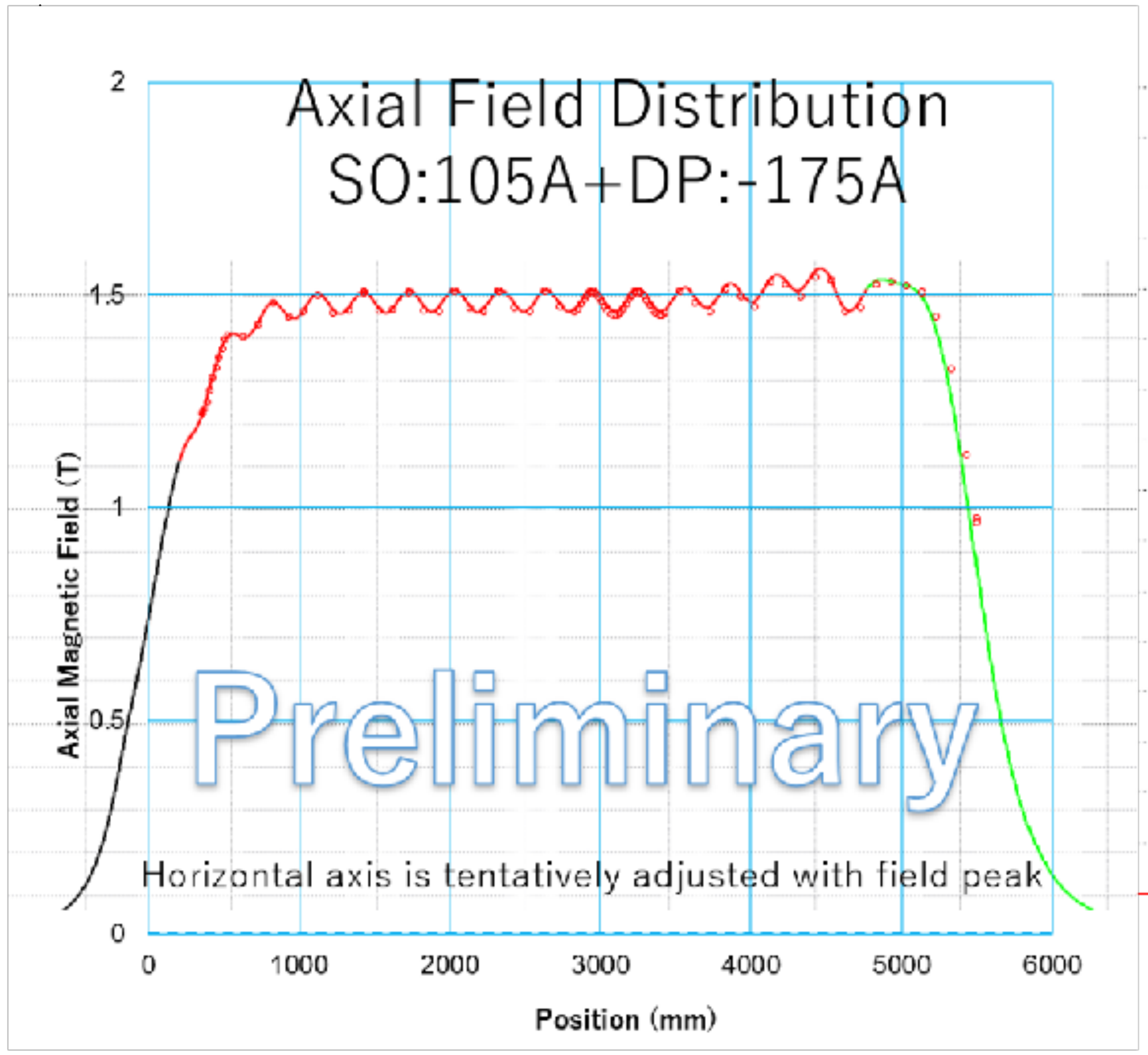
# Muon Transport Solenoid

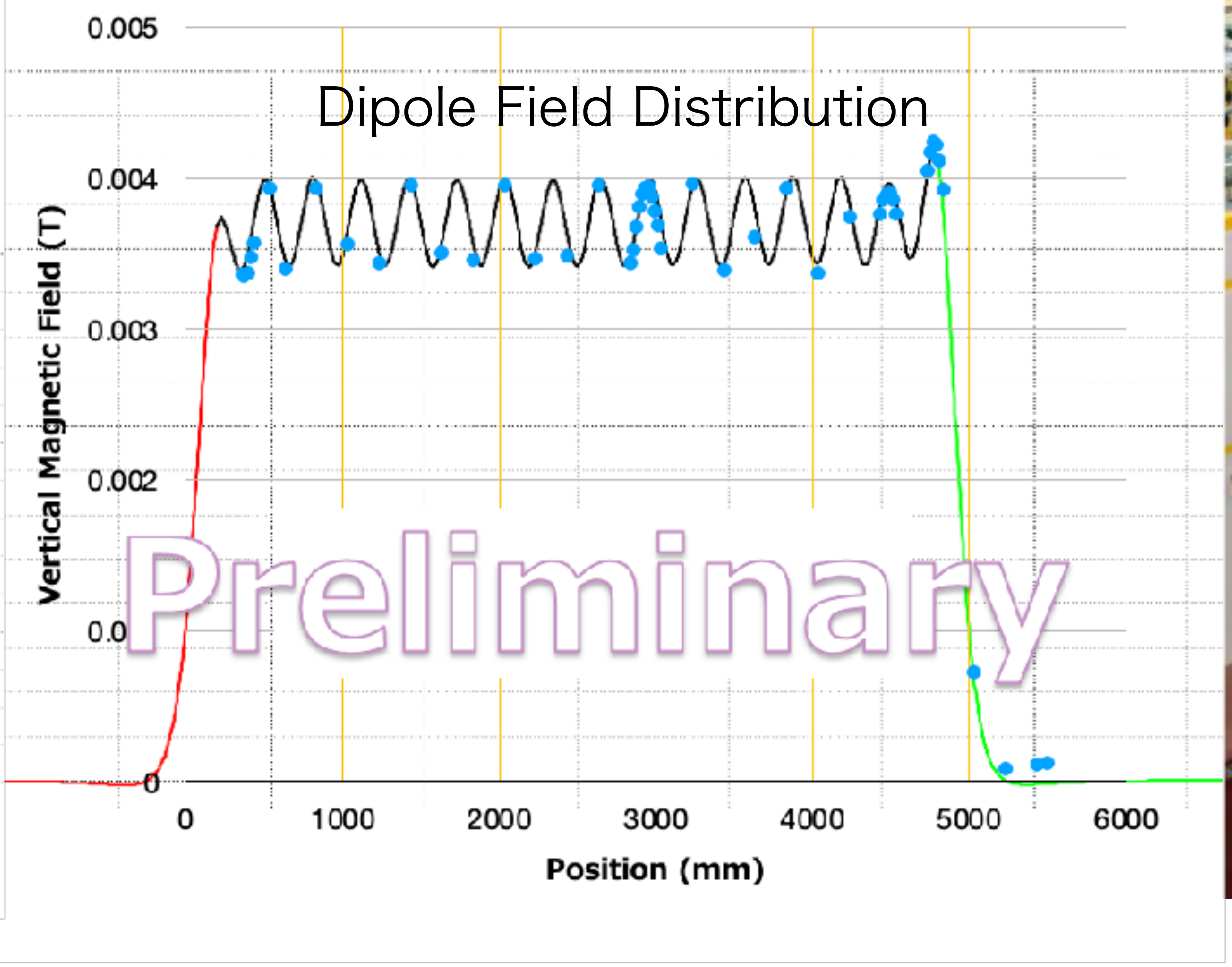


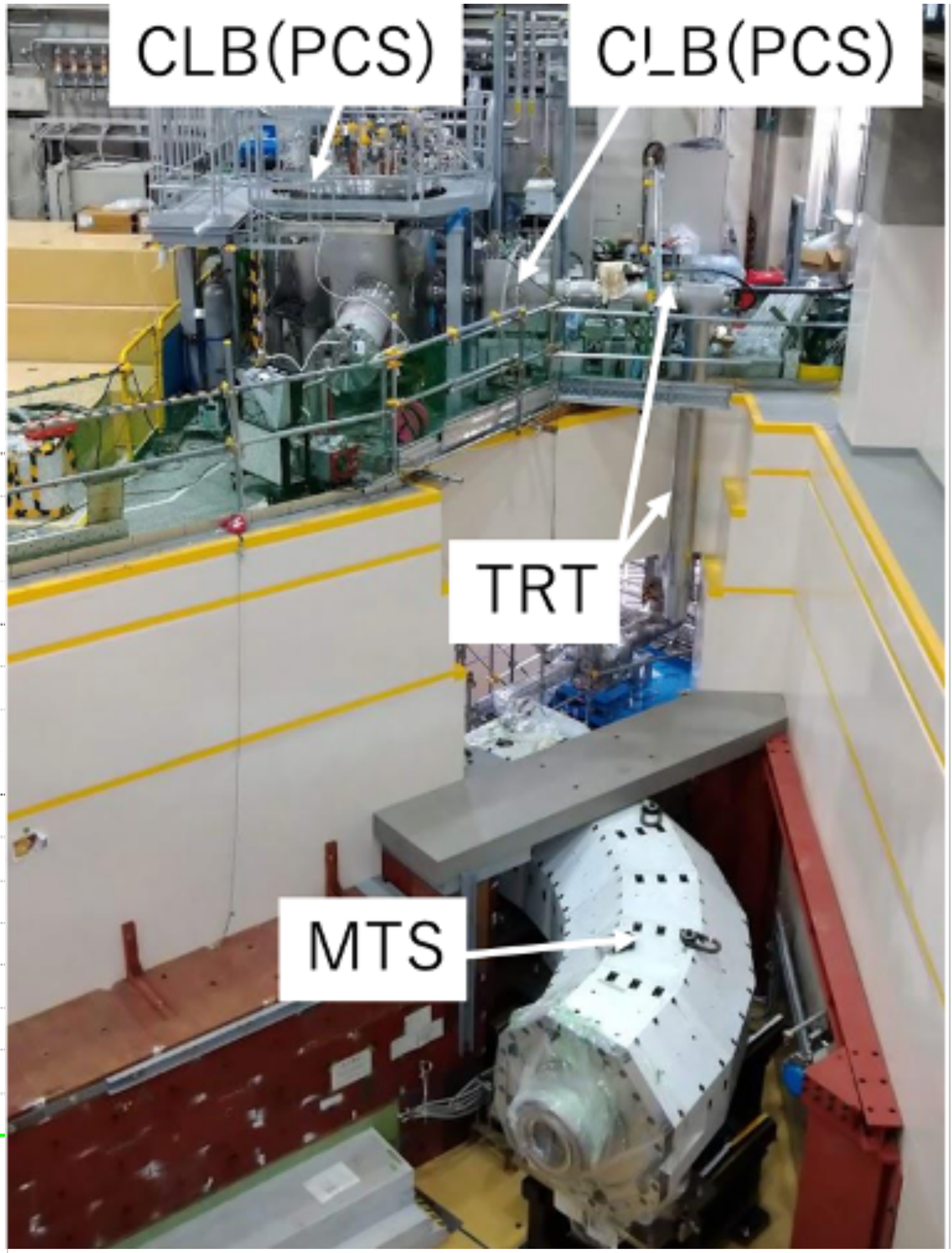

- 3T toroid field by Solenoid + correction dipole field
- Cu-stabilized SC wire
- Indirect cooling with 2-phase LHe pipe
- Cooling & Excitation test (up to 1.5T) successful in 2022



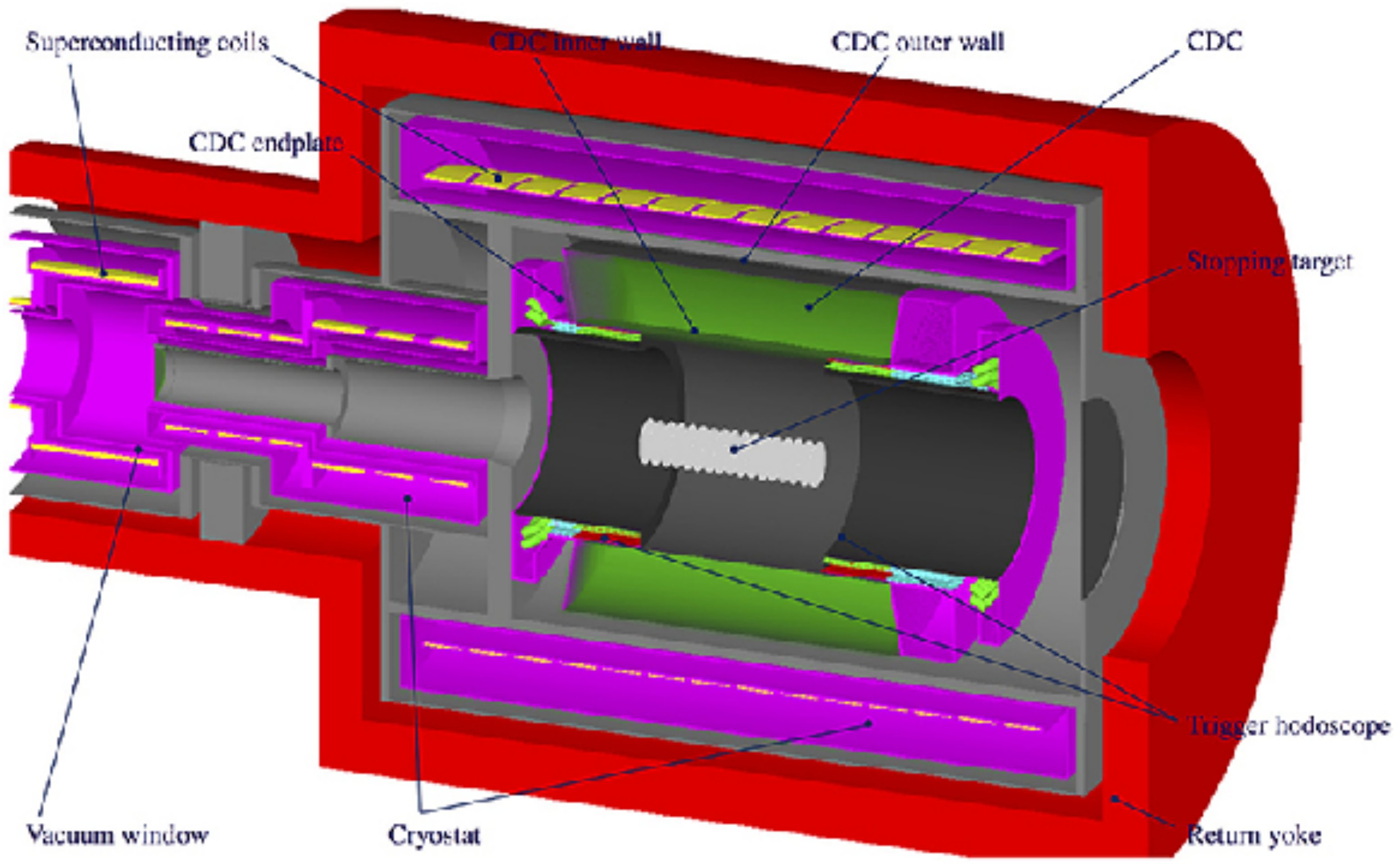



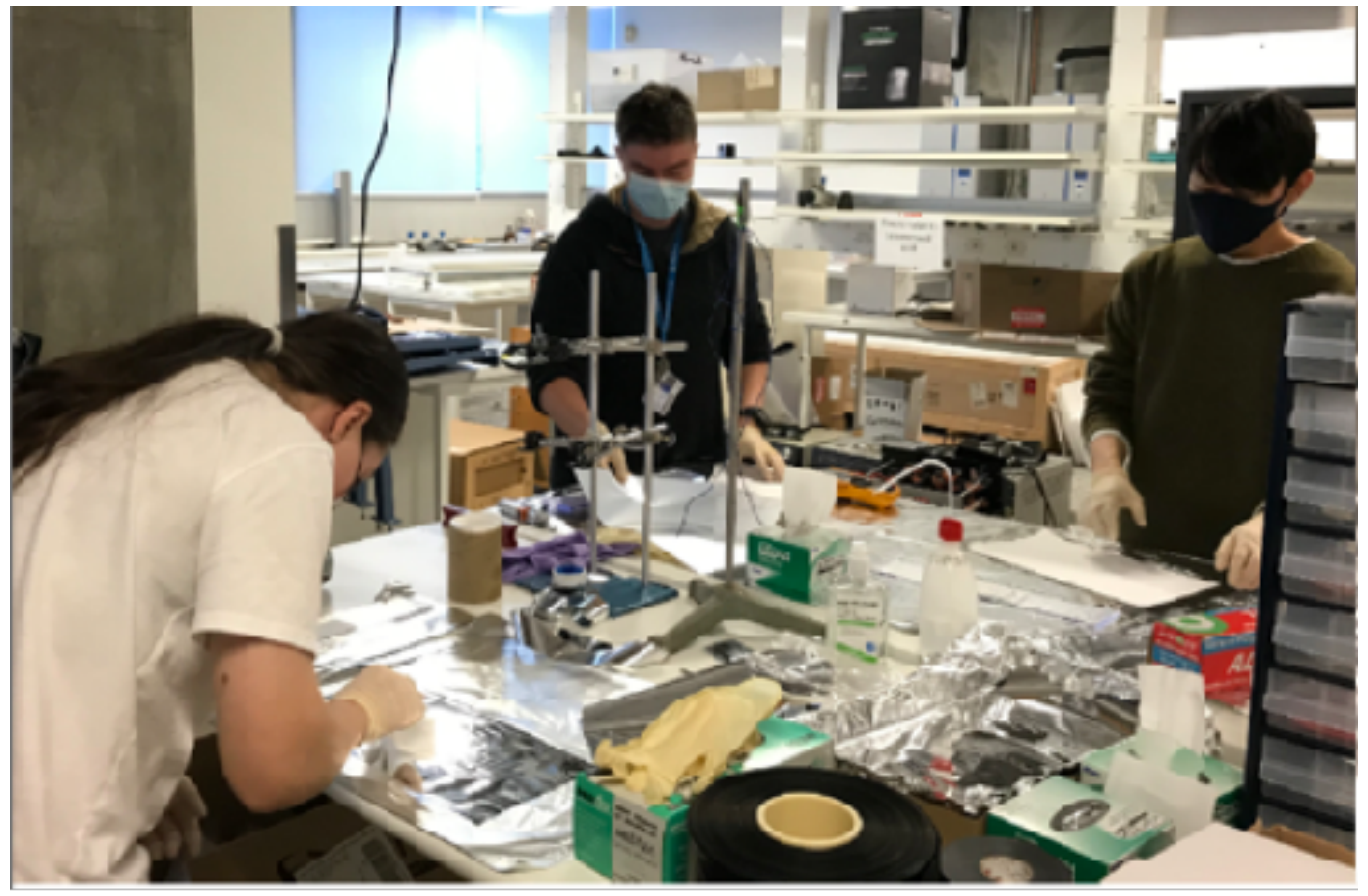



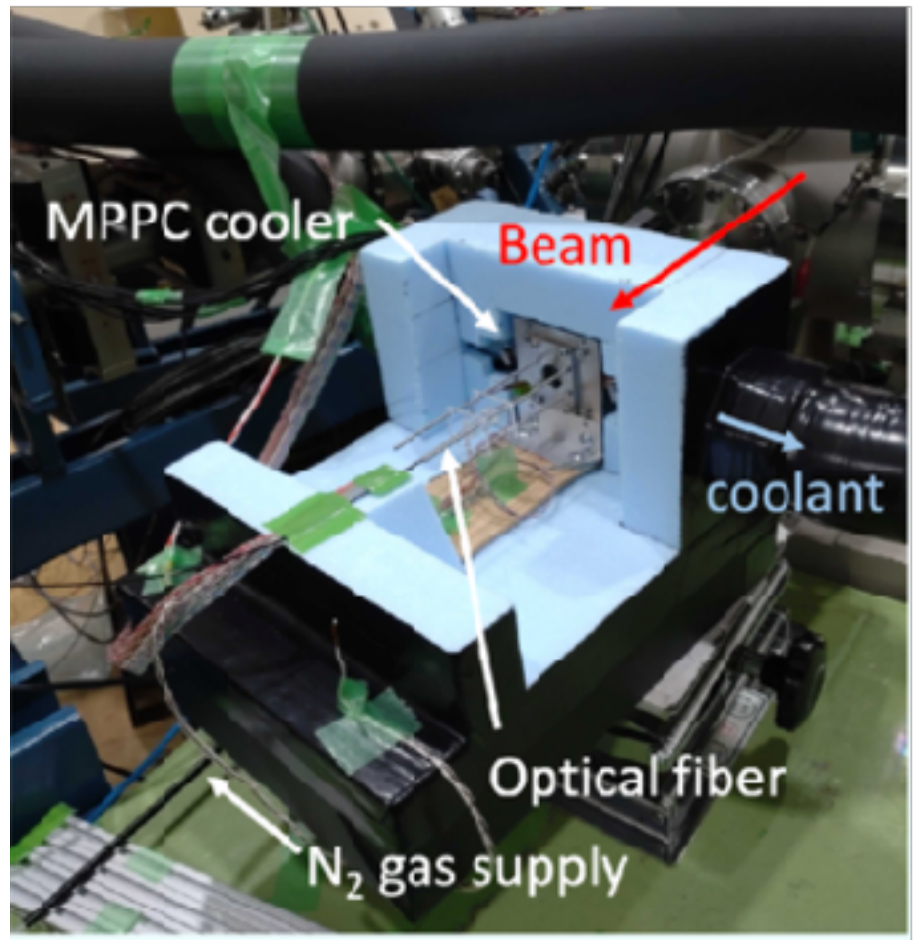



# COMET Phase-I Detector CyDet

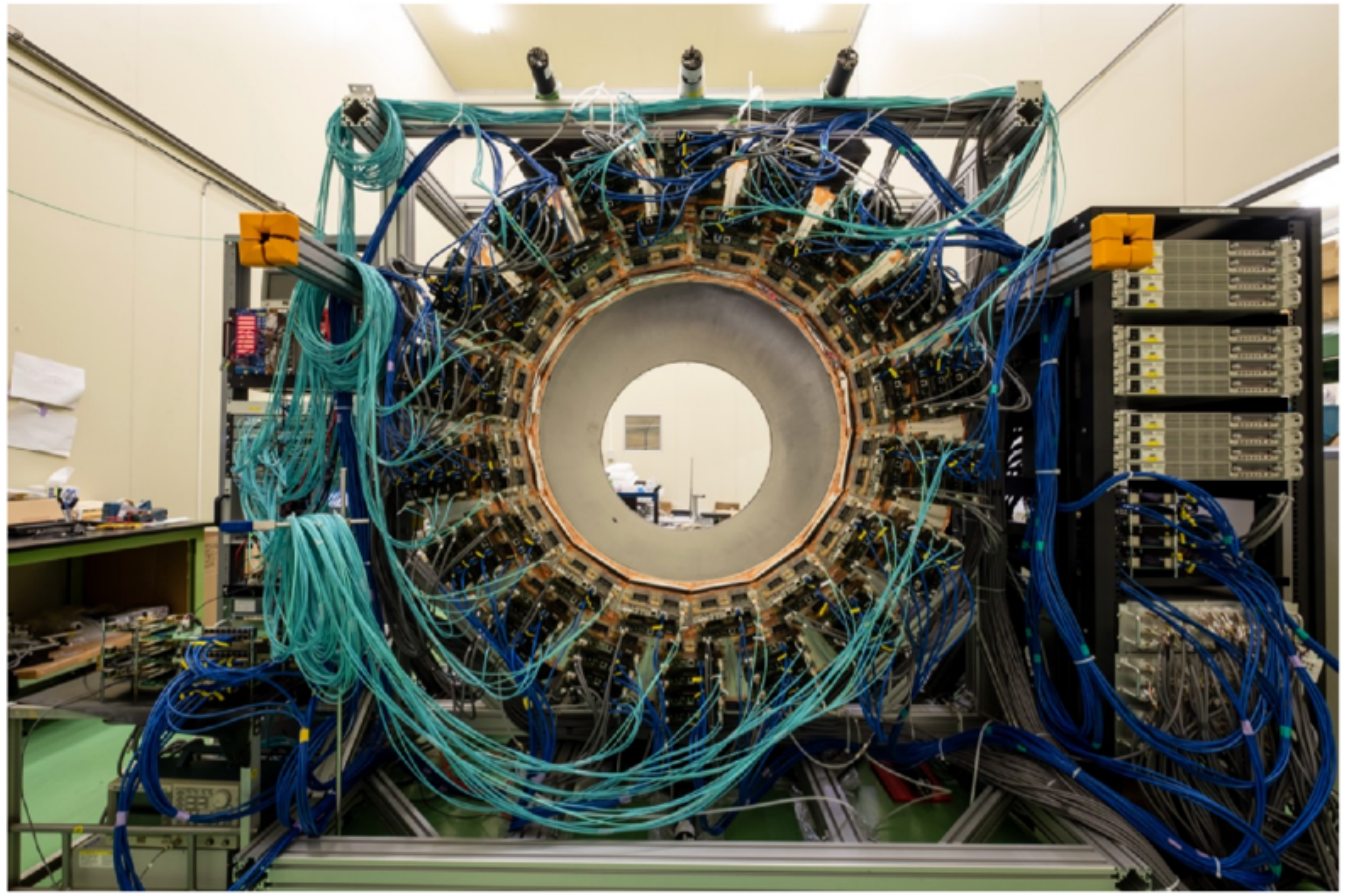


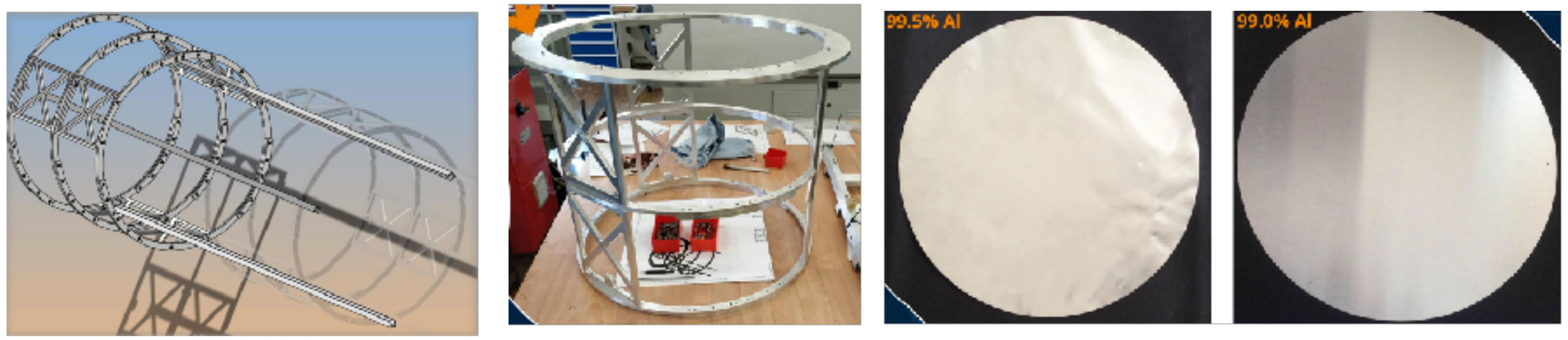

CTH construction in Monash Univ. and SiPM cooling optimization in Osaka






CDC has been operational in Tsukuba since 2016

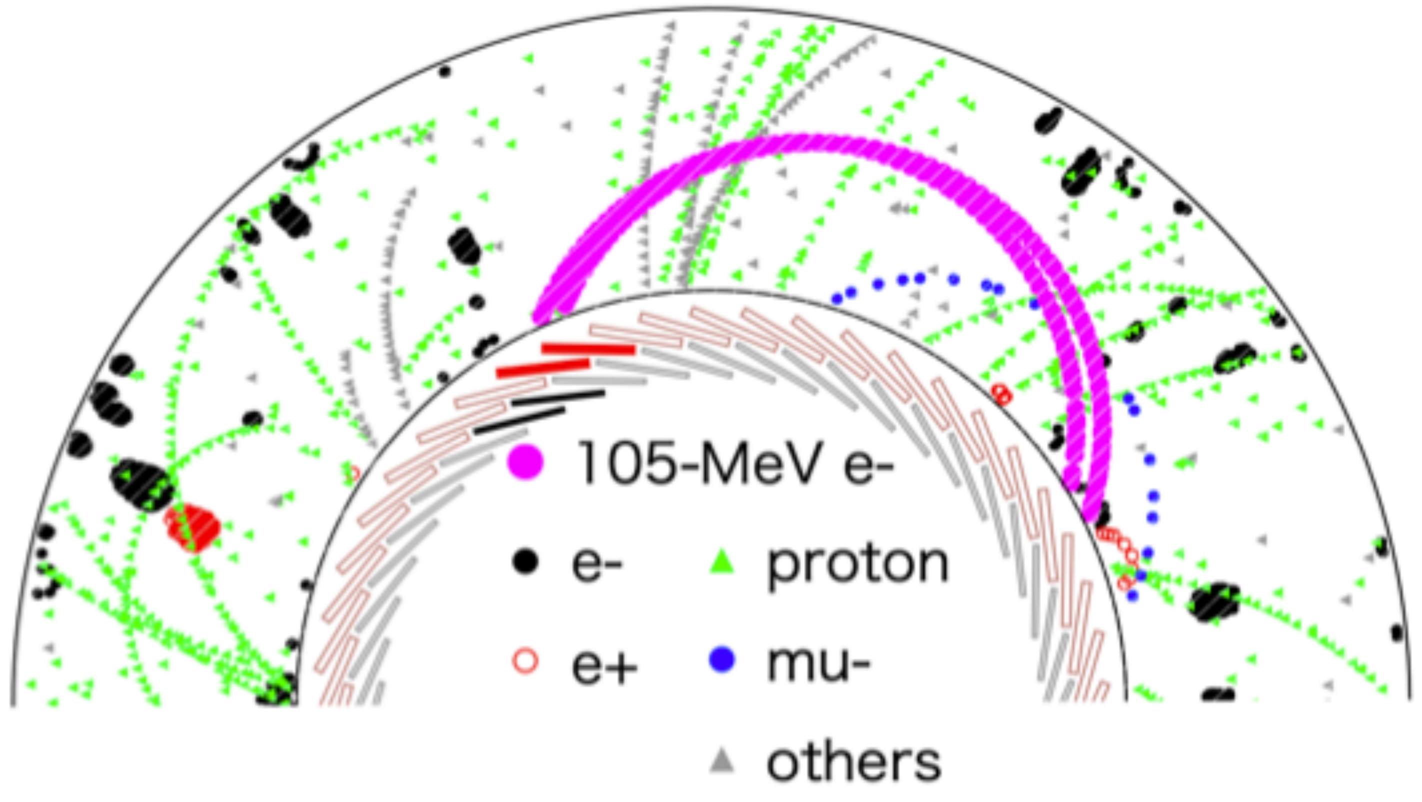


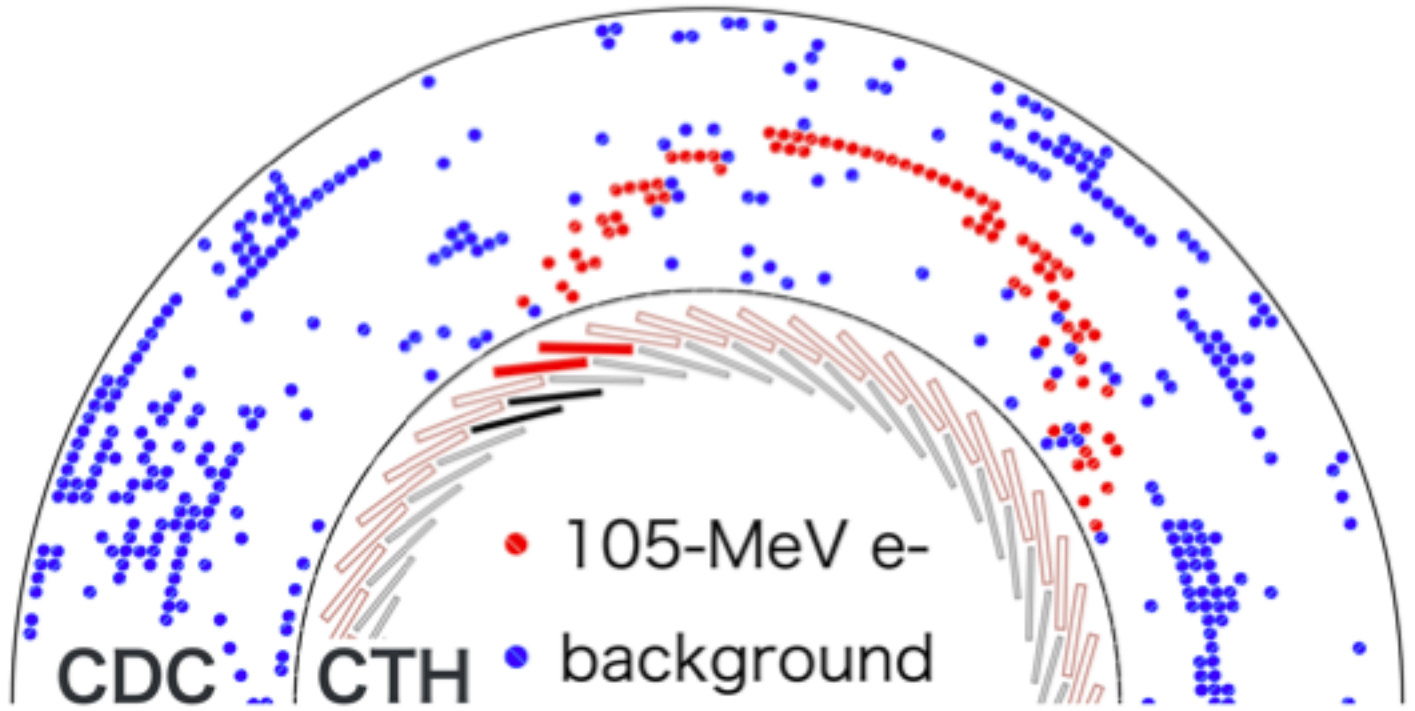


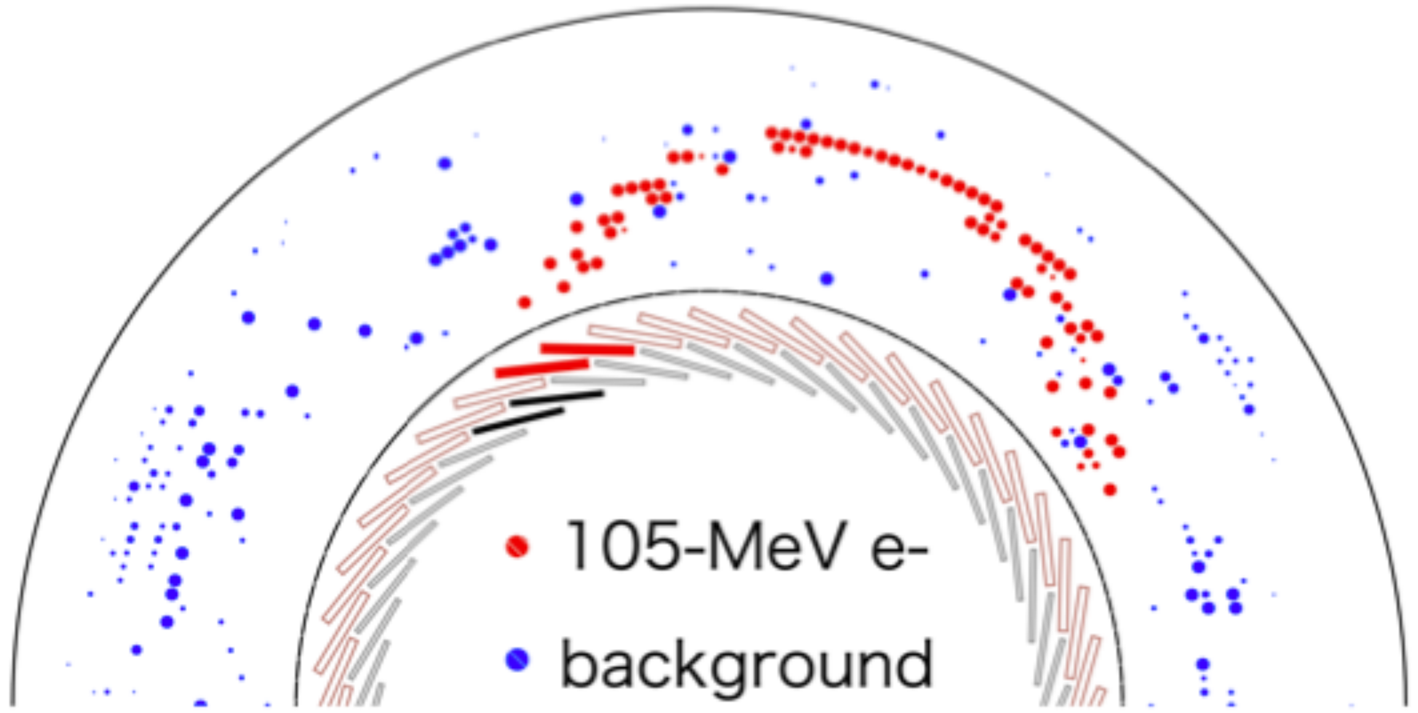

Target support construction in Dresden

# COMET Phase-I Trigger

- $10^9$ muon stops / second generate 2MHz hits on the Cylindrical Trigger Hodoscope (CTH)
  - 2 layers of scintillators
  - 2 layers of Cherenkov
- CTH 4-fold coincidence rate is estimated to be 91kHz. This is higher than the COMET DAQ system capability of 26kHz.
- Online trigger system (COMET trigger - COTTRI) developed to reduce the trigger rate down to 13kHz
  - CDC-hit information is classified using ML techniques



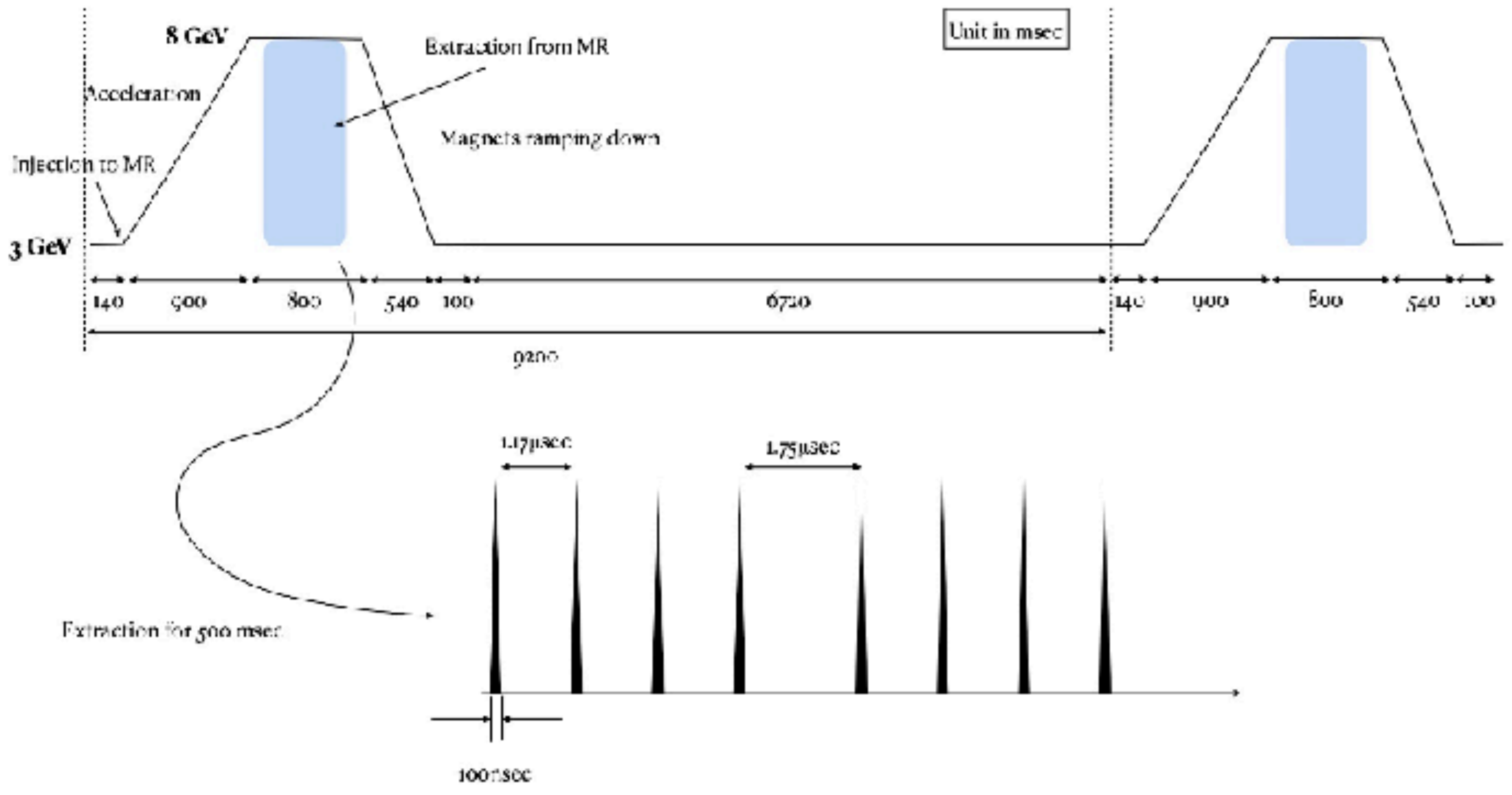



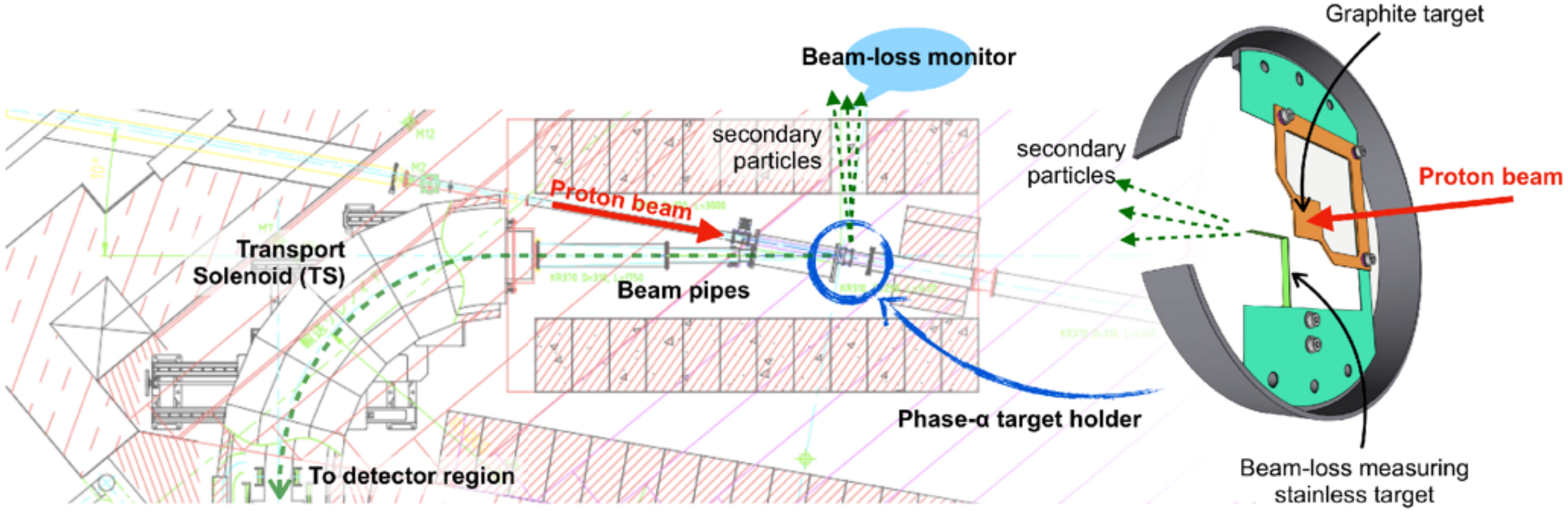



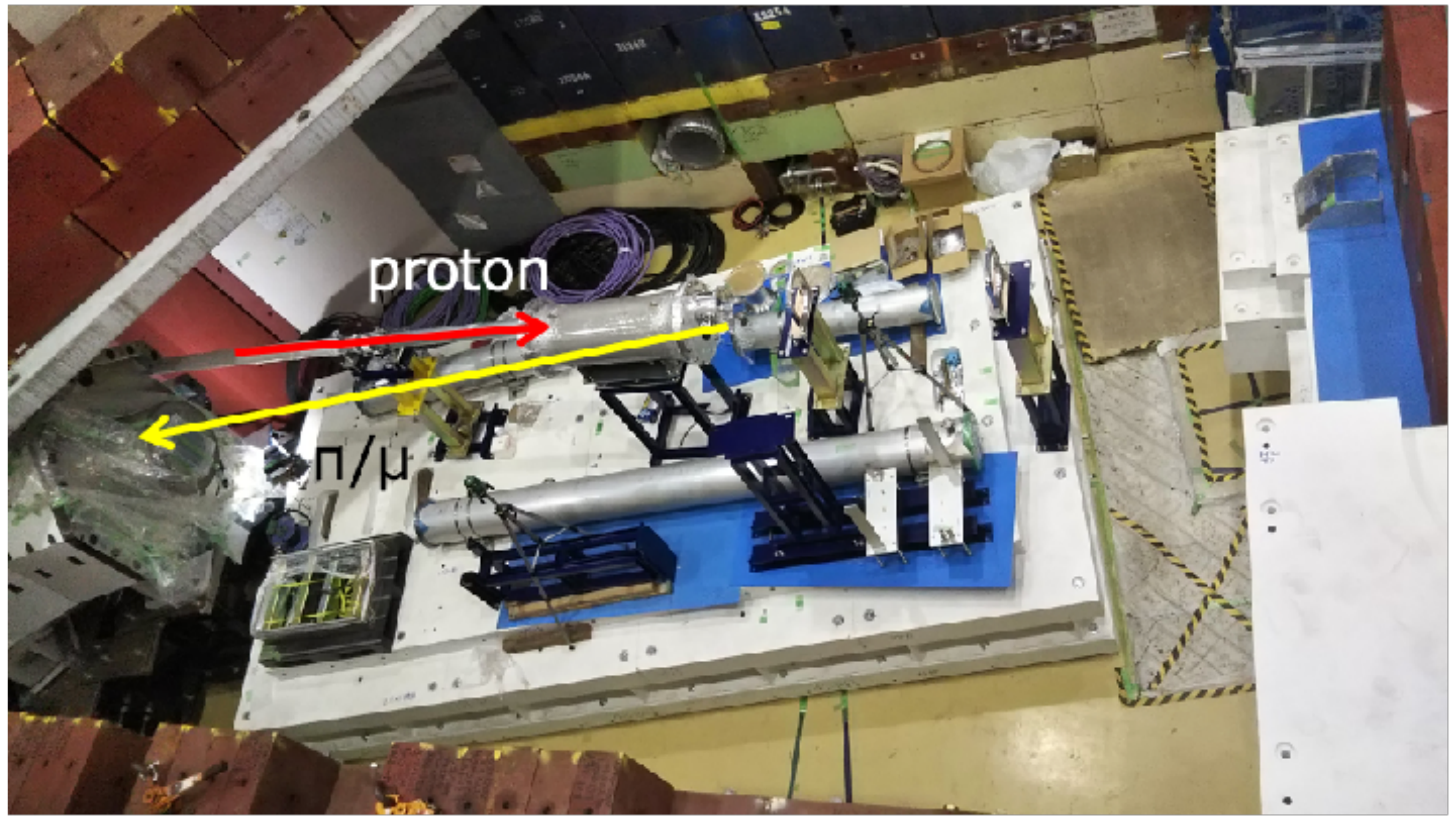

Yu Nakazawa arXiv:2010.16203v3

# COMET Engineering Run (Phase α)

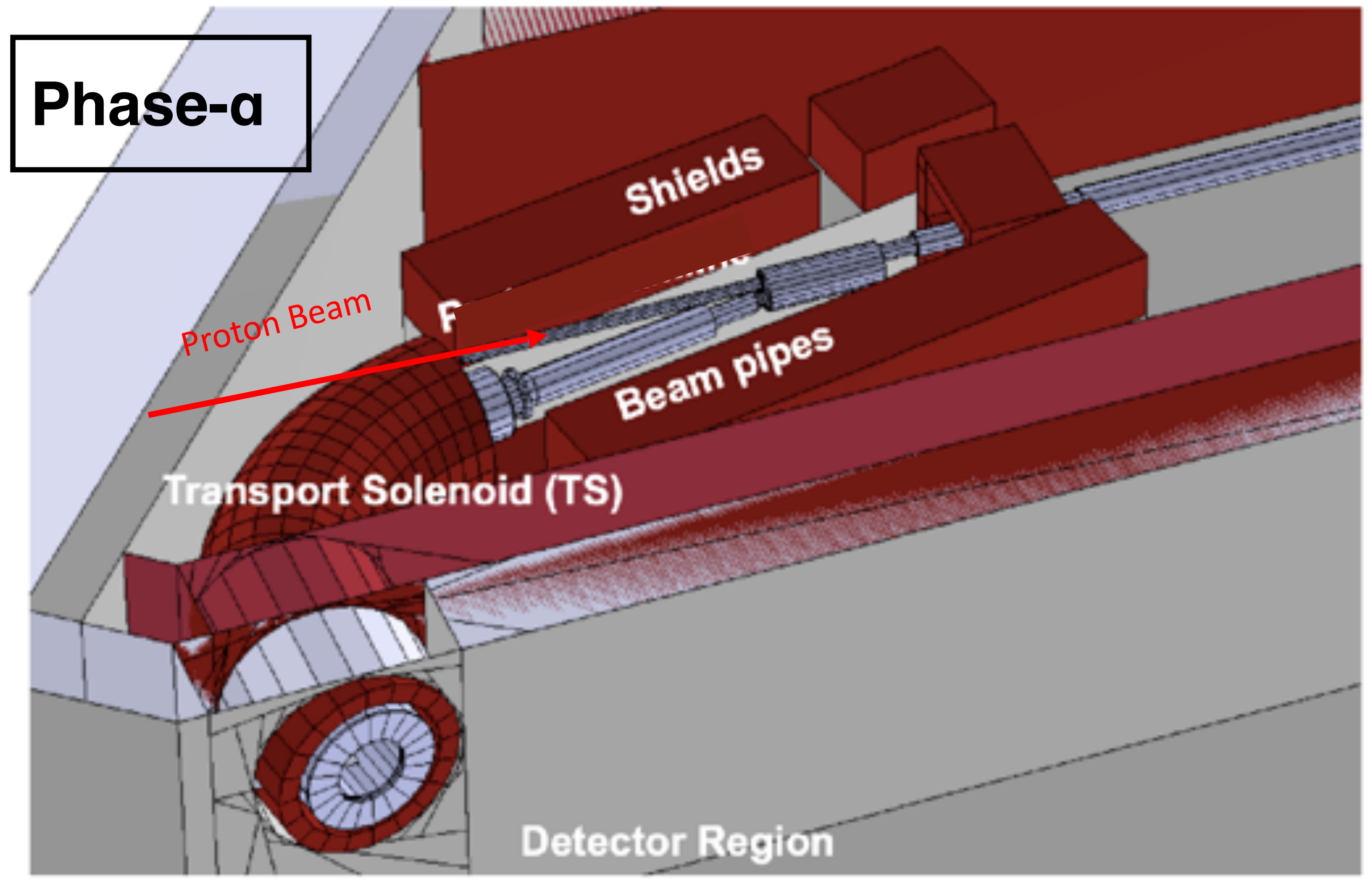
- Need a reliable estimate of the number of muons reaching the muon stopping target (and other particles – $\pi^{\pm}$, $e^{\pm}$)
- No data available of particle (backward) production in the p+A reaction at 8GeV
- Large ambiguity of anti-proton production cross section as it is close to the threshold
- Proton beam diagnostics w/o PCS
- Profile and beam extinction factor
- Once PCS installed, there is no sufficient space around the pion production target

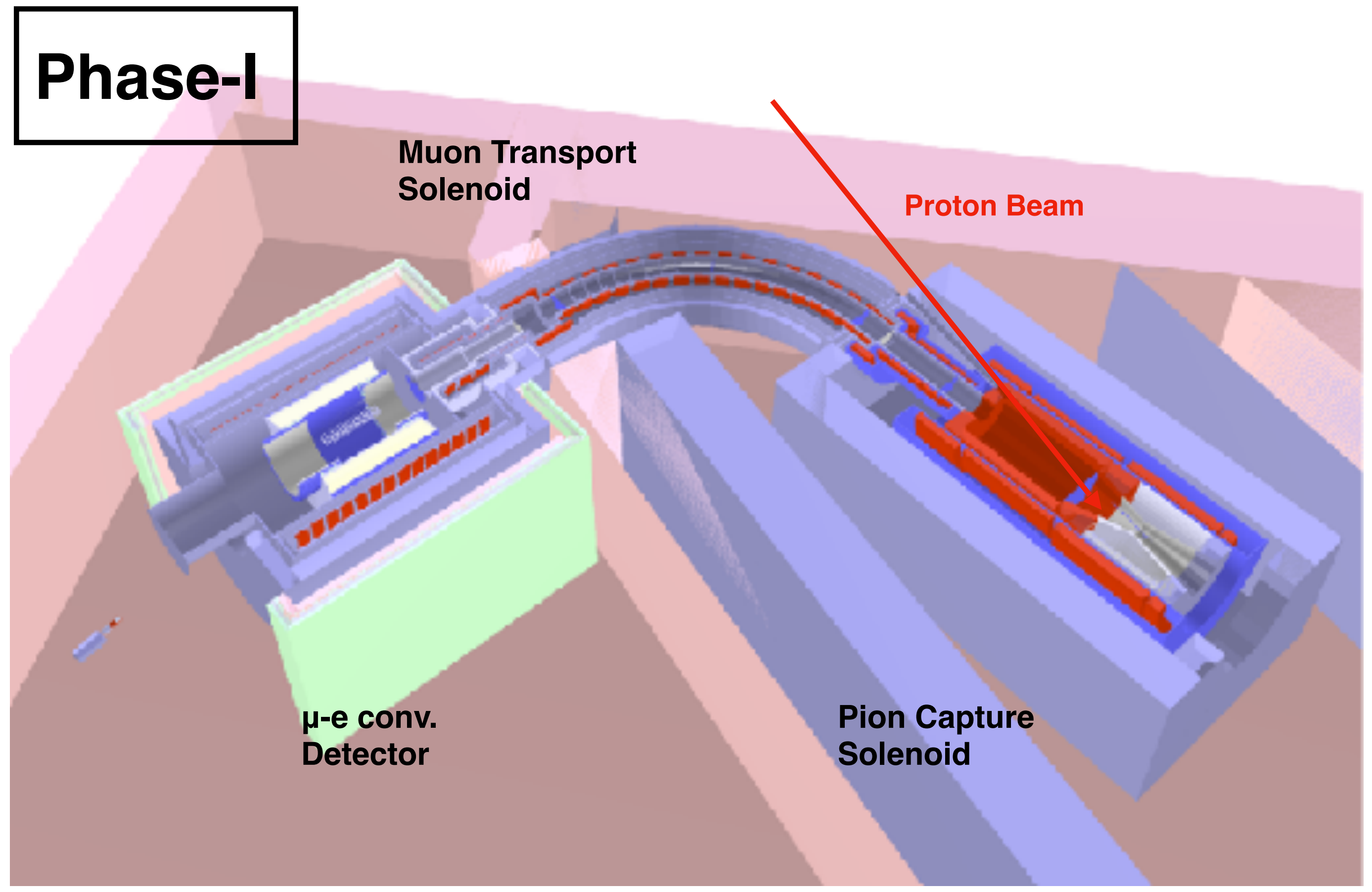


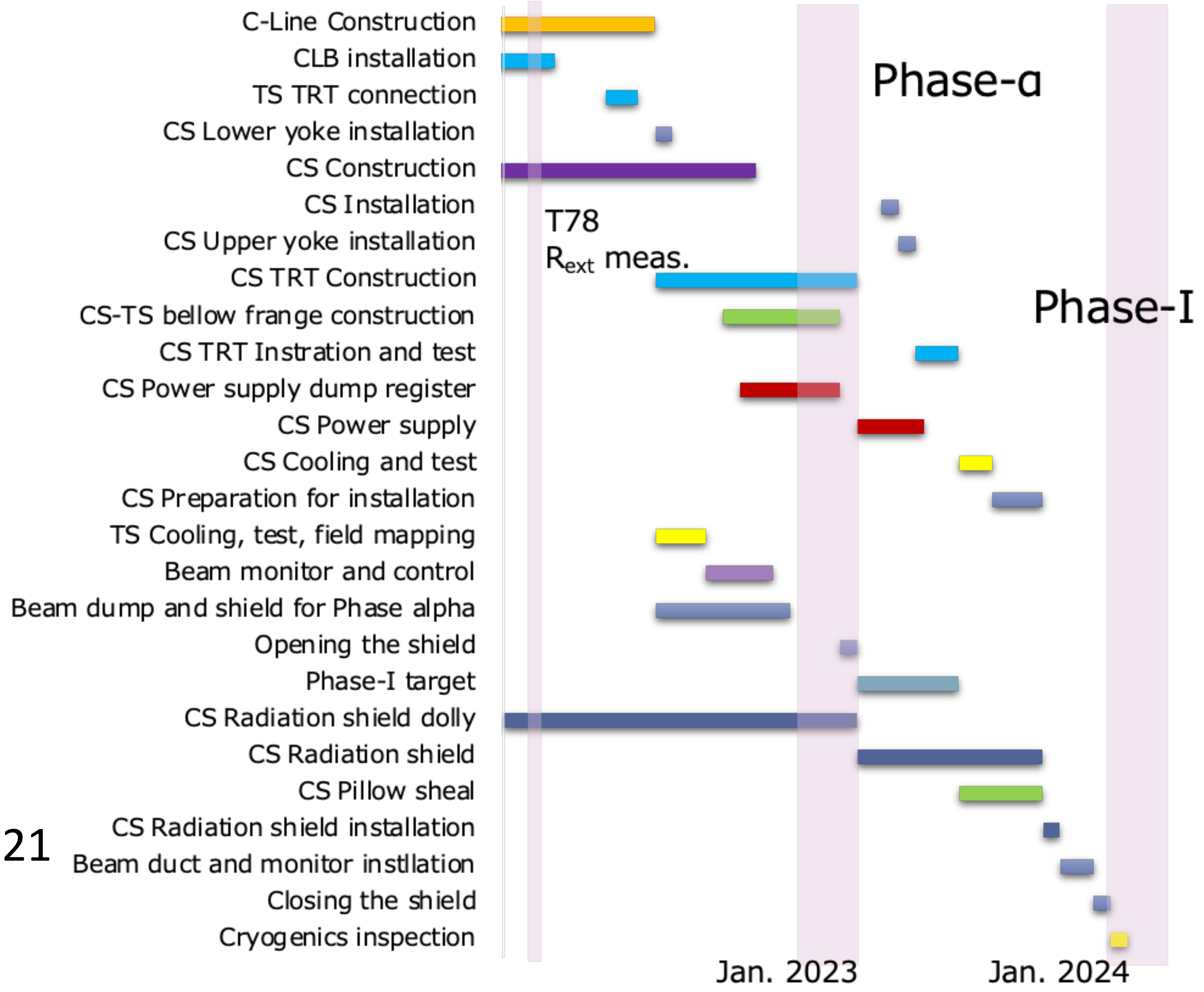



# Schedule of Phase α & Phase I



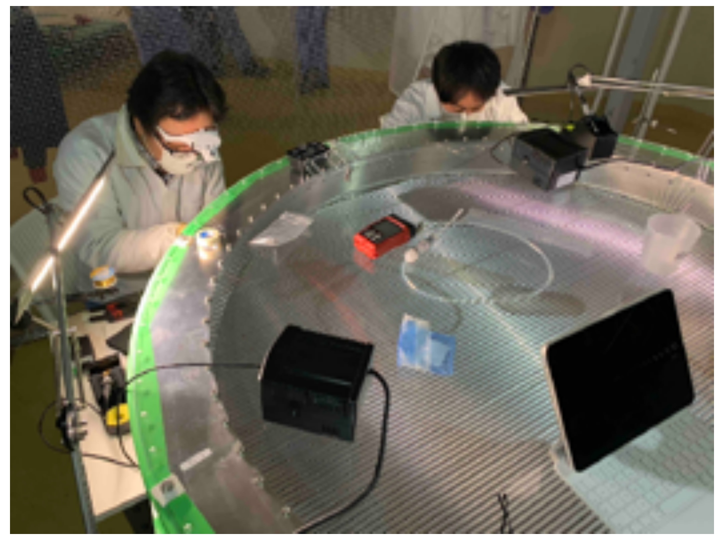
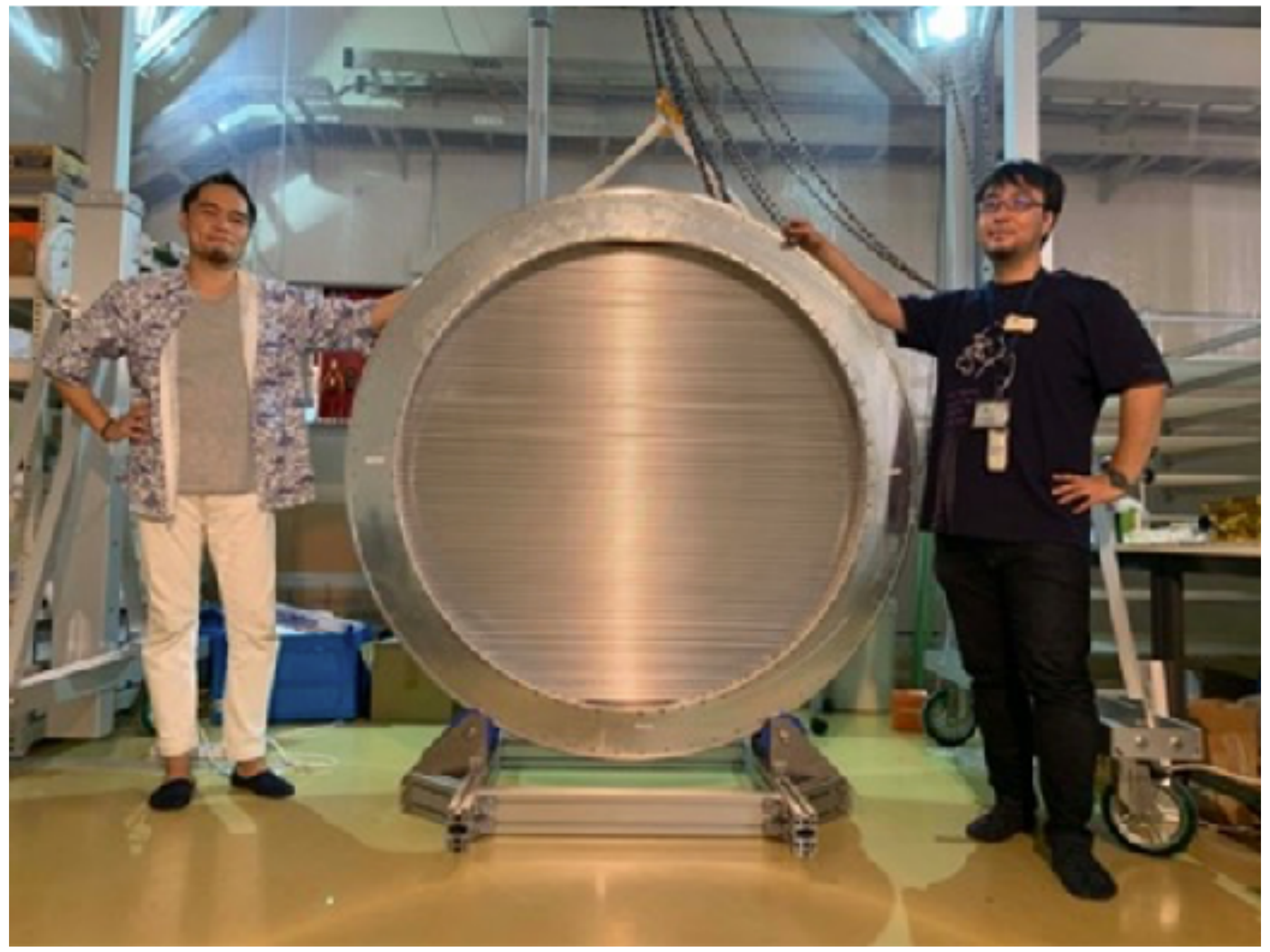



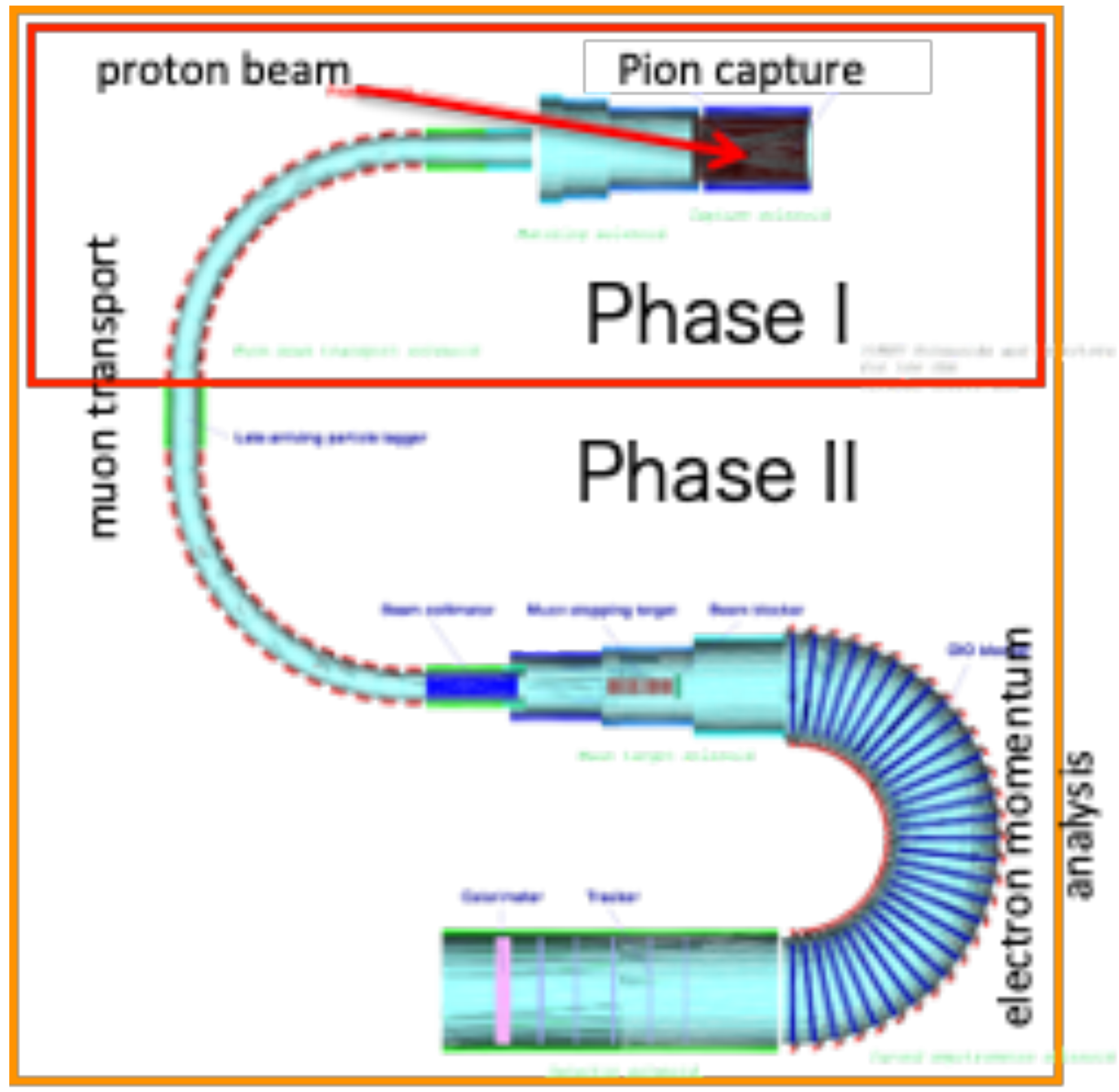



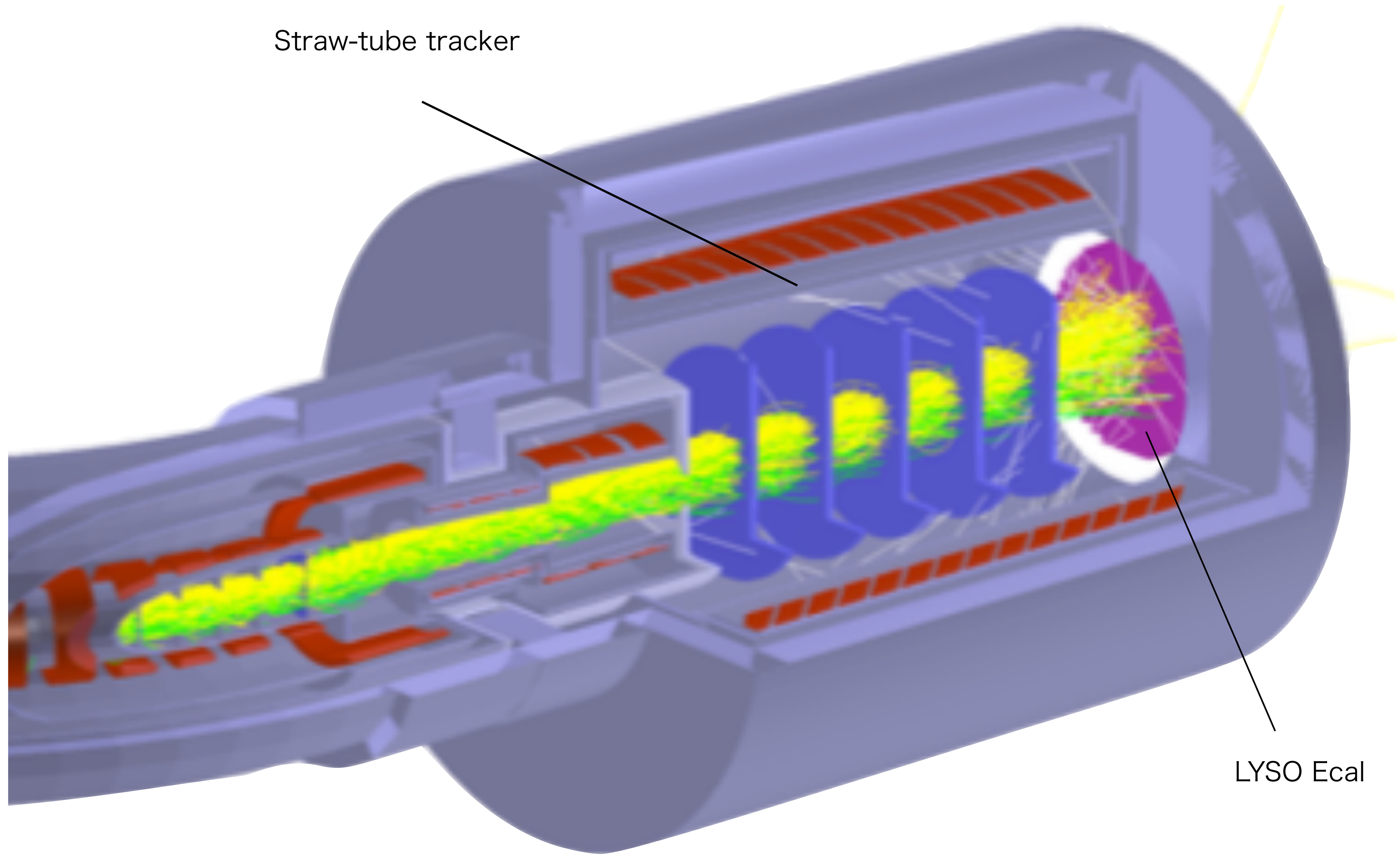

- ✓8GeV test and $R_{ext}$ measurement in May. 2021
- Phase-α Eng. Run in FY2022
- Phase-I Phys. Run in FY2023

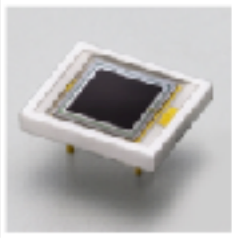
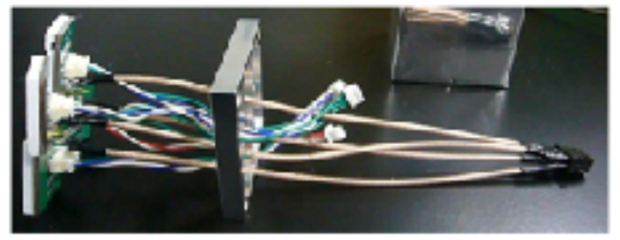
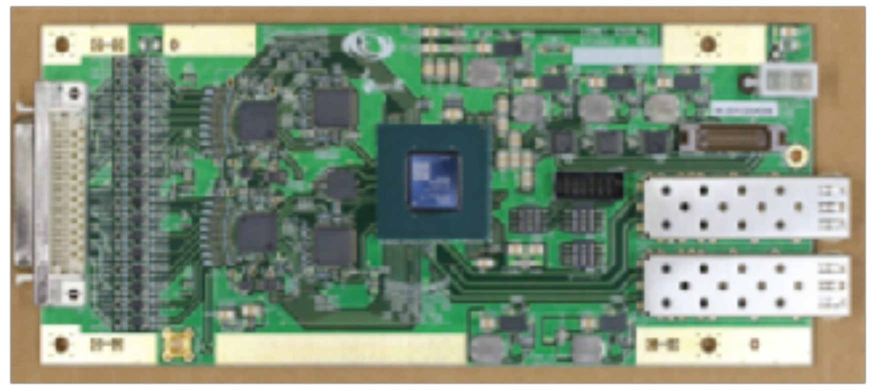
# Toward COMET Phase II

- For the purpose of beam measurement in COMET Phase I, COMET is developing another detector system composed of straw-tube tracker and LYSO calorimeter
    - StrEcal system
    - Prototype of Phase-II detector

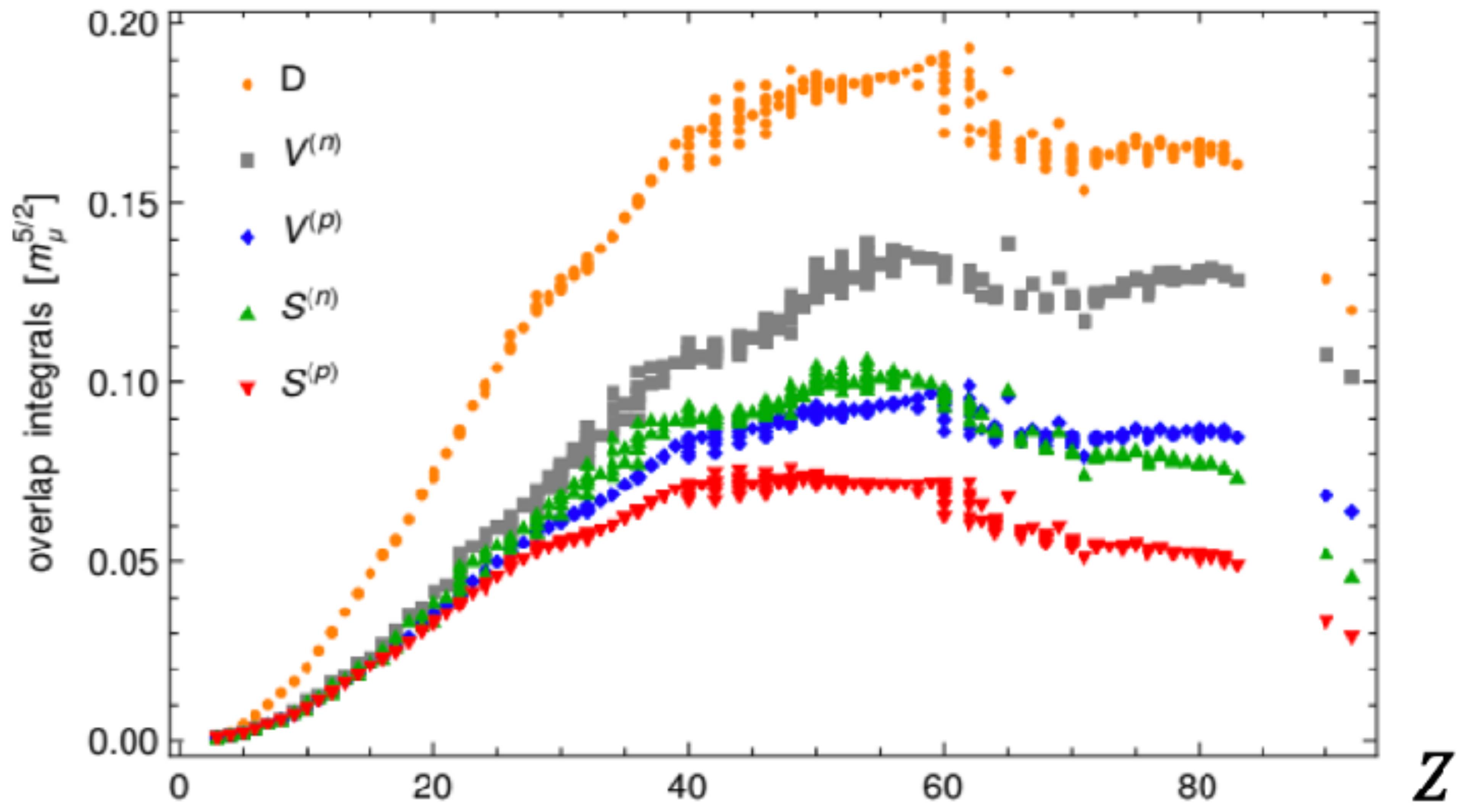




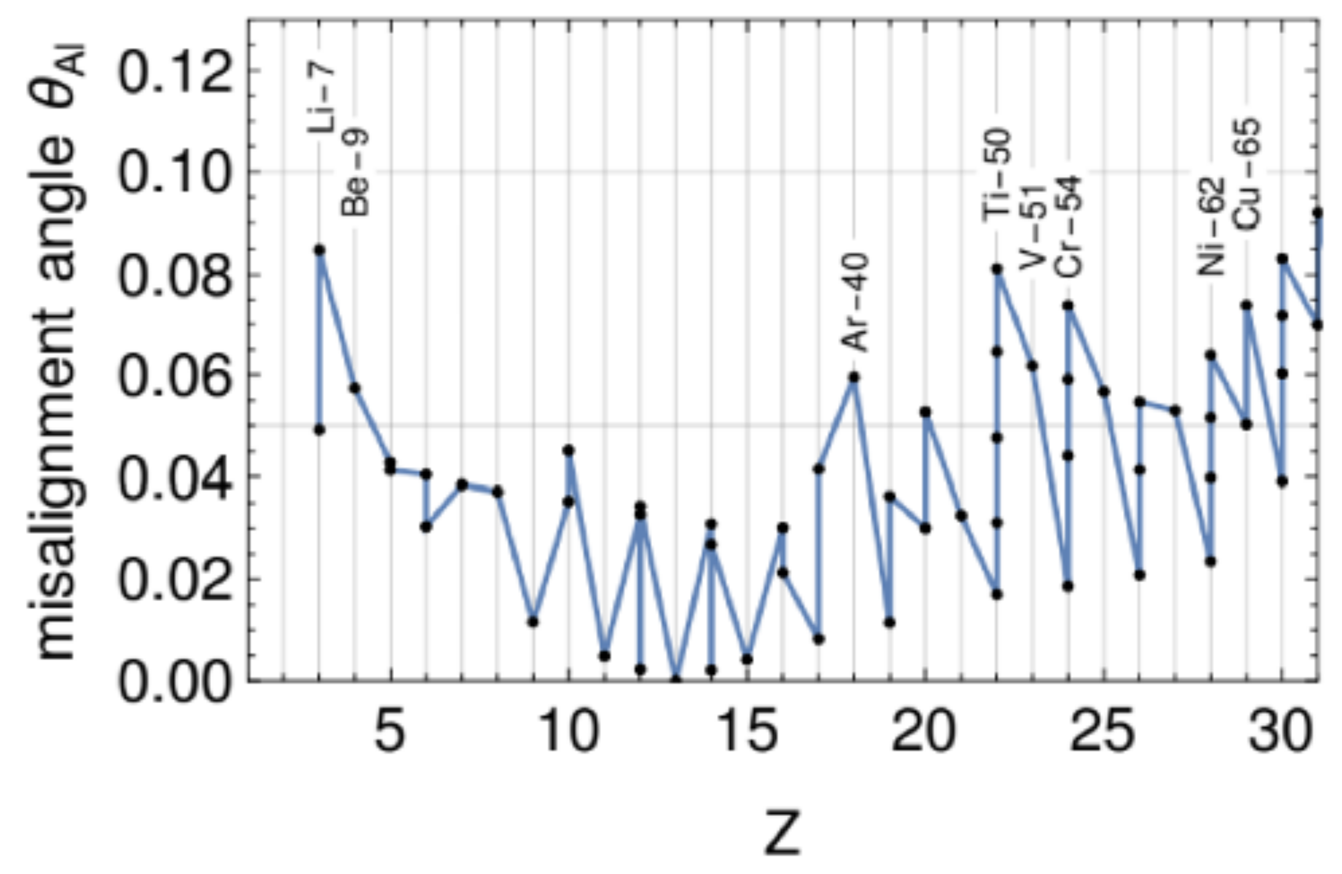




# Once the signal is found…

- Comparison of signal rates of $\mu \to e\gamma$, $\mu \to eee$, and $\mu$-e conversion will clarify the physics behind cLFV reactions
- Even discovery only in $\mu$-e conversion
  - Different target material contains different quark contents
  - May be possible to see the target dependence on the mu-e conversion rate
  - Discriminate the principal interaction of the mu-e conversion?
    - Vector type, Dipole type, or Scaler type?
- Target material
  - Li, C, Si, **Al**, Ar, Ti, Pb…



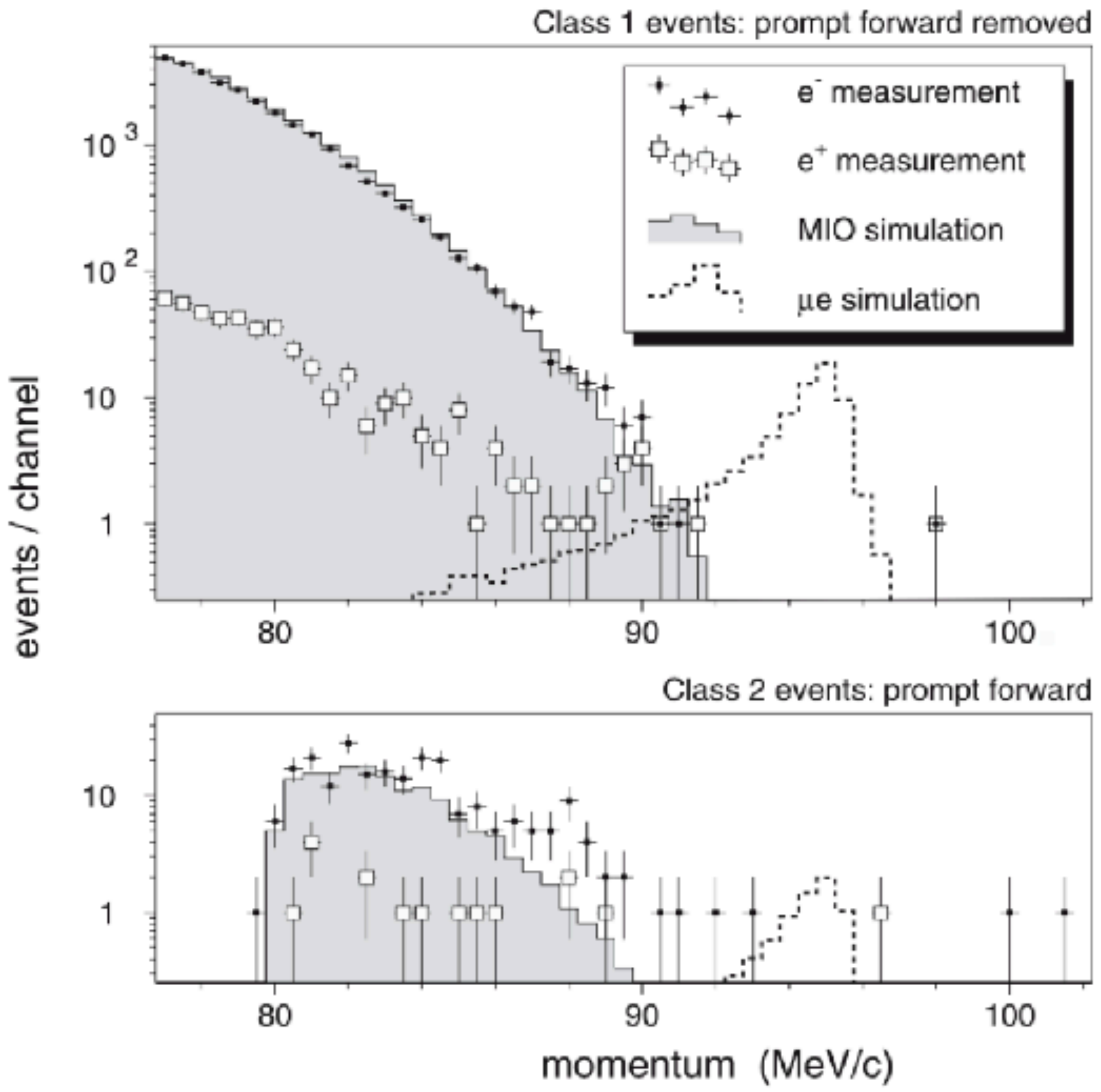

arXiv:2203.00702v1

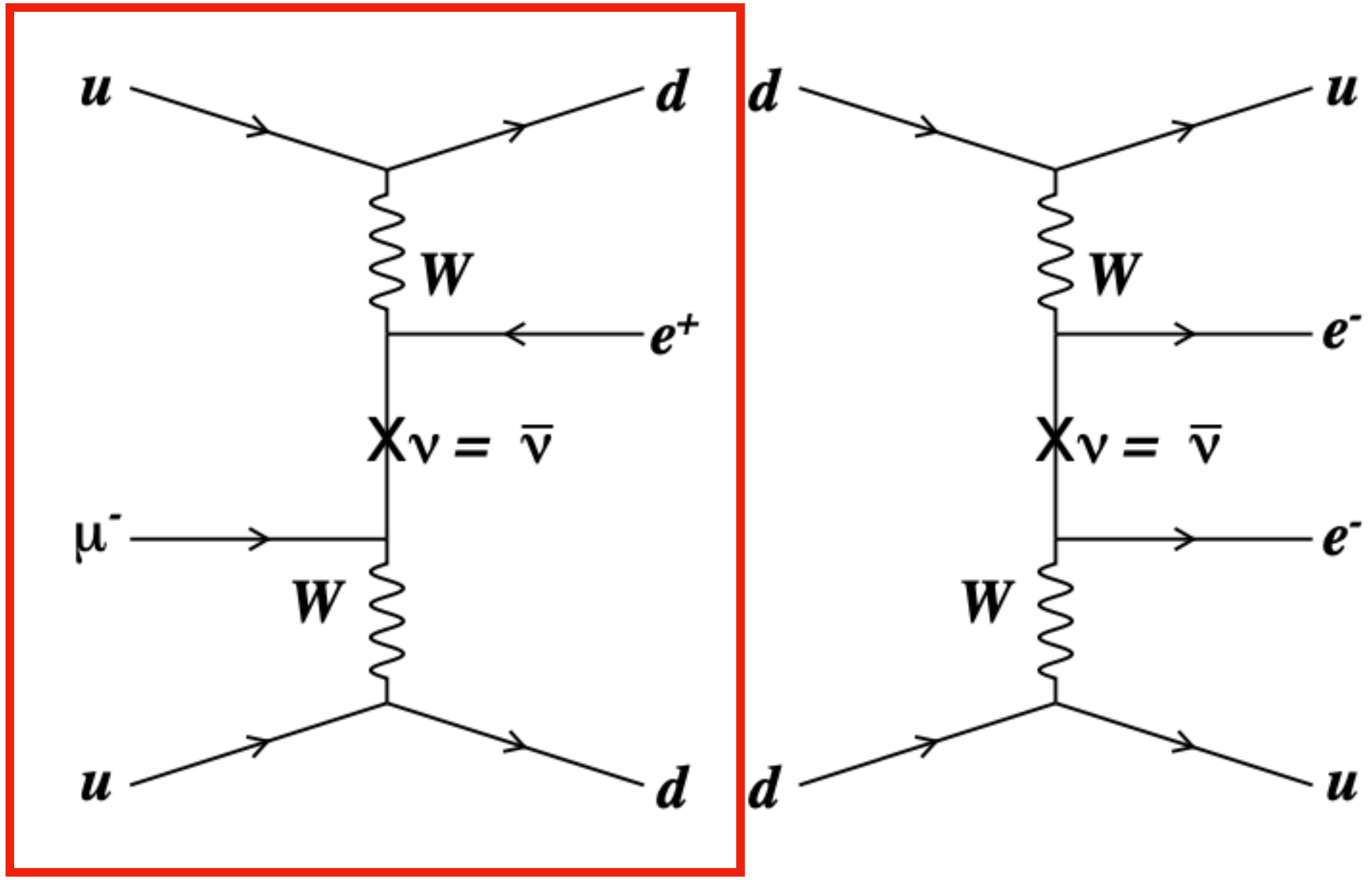



| | Al | Ti |
|---|---|---|
| lifetime | 864 ns | 330 ns |
| time window | 0.3 | 0.2 |
| signal | 1 | 1.5 |
| net | 0.3 | 0.3 |

# Another possible search

- $\mu^-$ - $e^+$ reaction
- Possible in COMET Phase I & mu2e





https:// doi.org/10.3390/universe8040227

# Summary and Prospects

- Strong motivation to search for cLFV
  - $\mu \to e\gamma$, $\mu \to eee$, $\mu$-e conversion
- COMET searches for mu-e conversion with sensitivities better than
  - $< 10^{-14}$ in Phase I
  - $< 10^{-16}$ in Phase II
- Beam extinction measurement was carried out in 2021. COMET achieved $< 10^{-10}$ (at 90% C.L, statistically limited) of $R_{ext.}$. Further detailed study will be carried out in Phase I
- COMET engineering run (Phase $\alpha$) in JFY 2022 & physics run (Phase I ) in JFY 2023-2024 to reach the target sensitivity $< 10^{-14}$
- COMET anticipates to achieve even better sensitivity $< 10^{-16}$ in Phase II by extending the solenoid magnets and employing dedicated detector system