Most of contents are from CLFV 2023 presentations
and WG4 parallel session

Muon CLFV Experiments

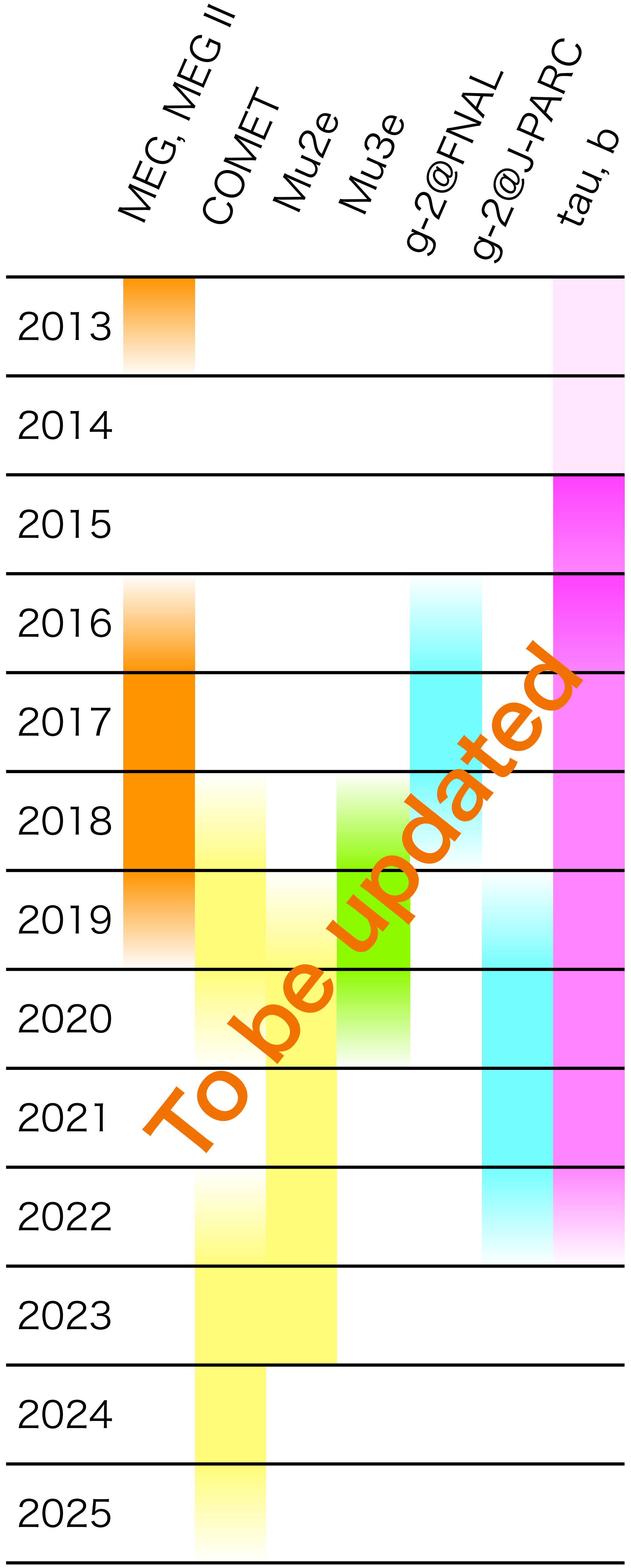
Satoshi MIHARA, KEK/J-PARC/SOKENDAI

NuFact 2023, Seoul National University, 2023/8/23

Outline

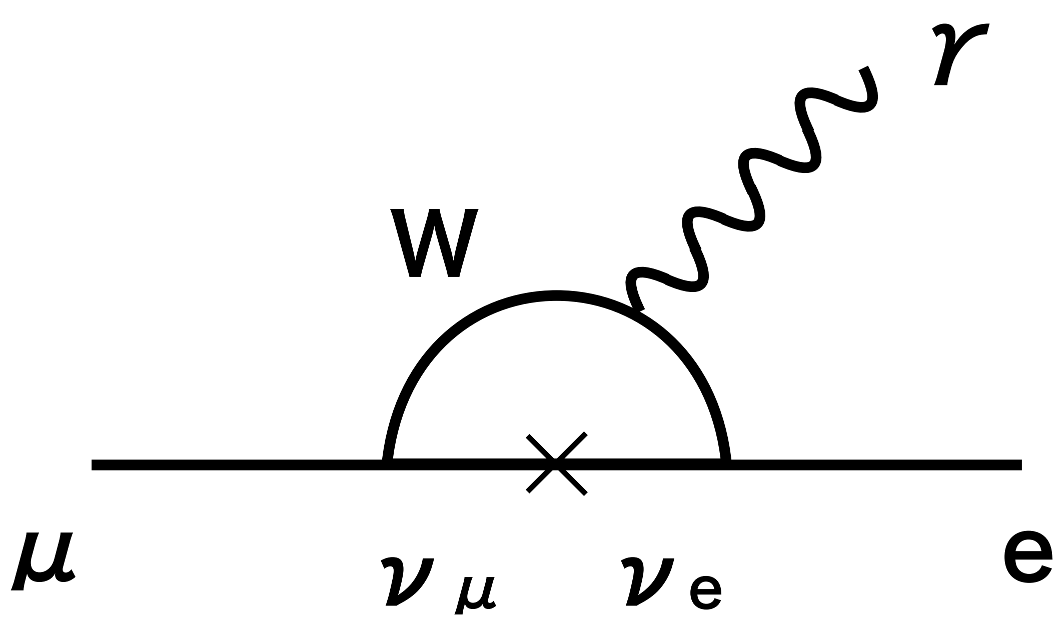
Muon CLFV experiments

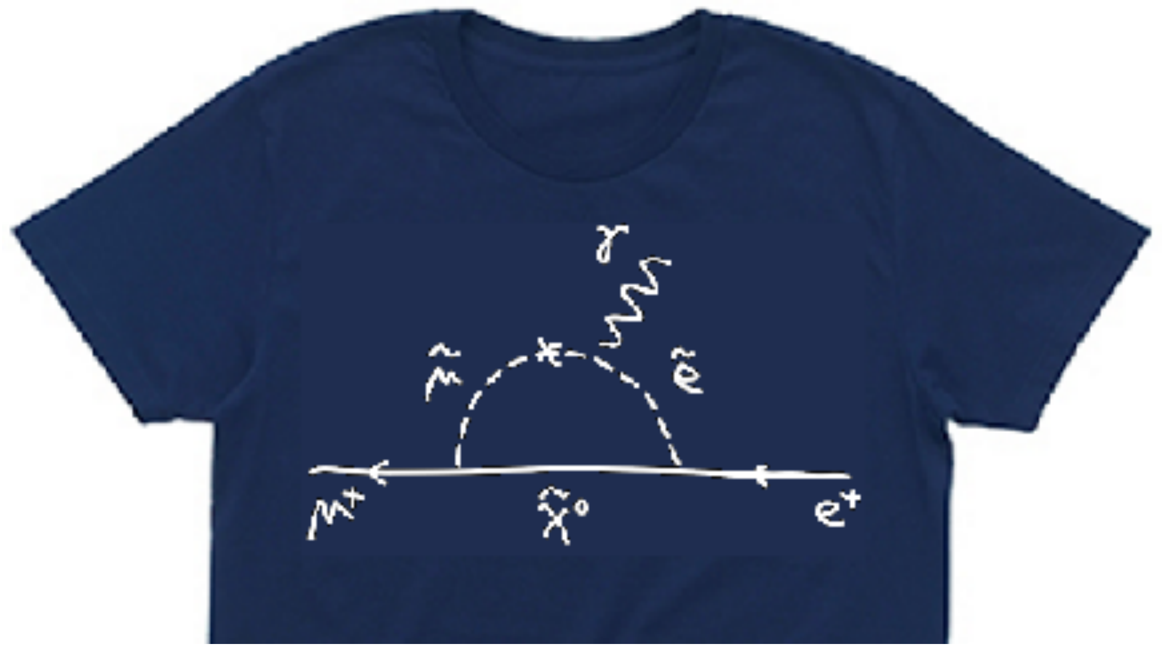
- Introduction
- Muon facilities
- Muon CLFV experiments
  - MEG II, Mu3e, COMET, Mu2e, DeeMe, MACE
- Summary



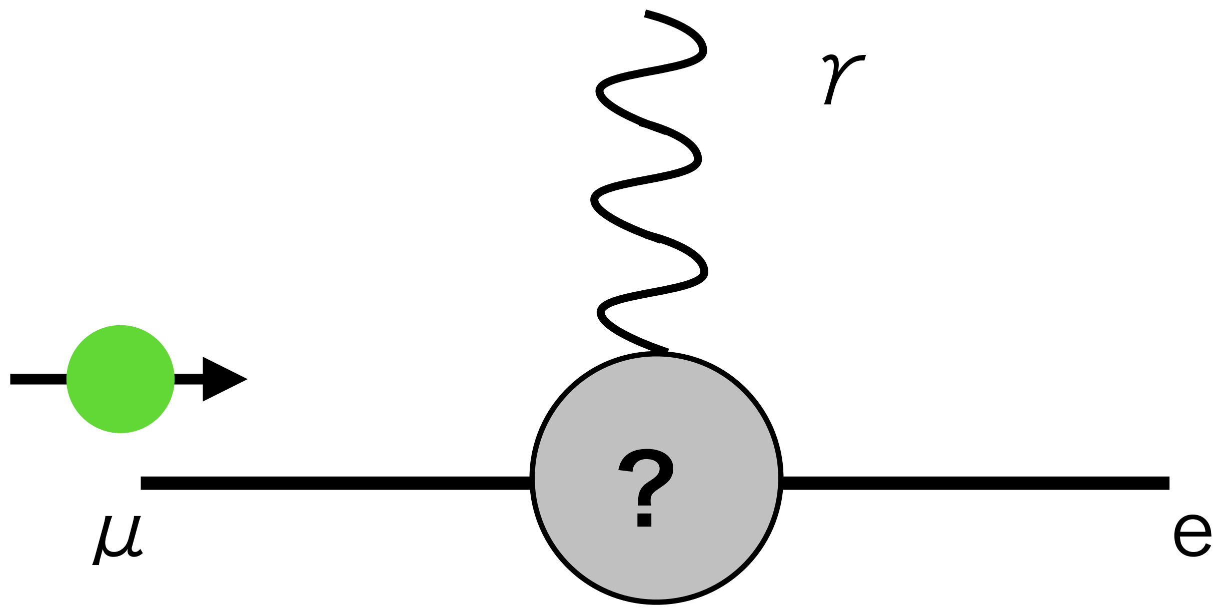
Introduction
Muon CLFV experiments

- 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

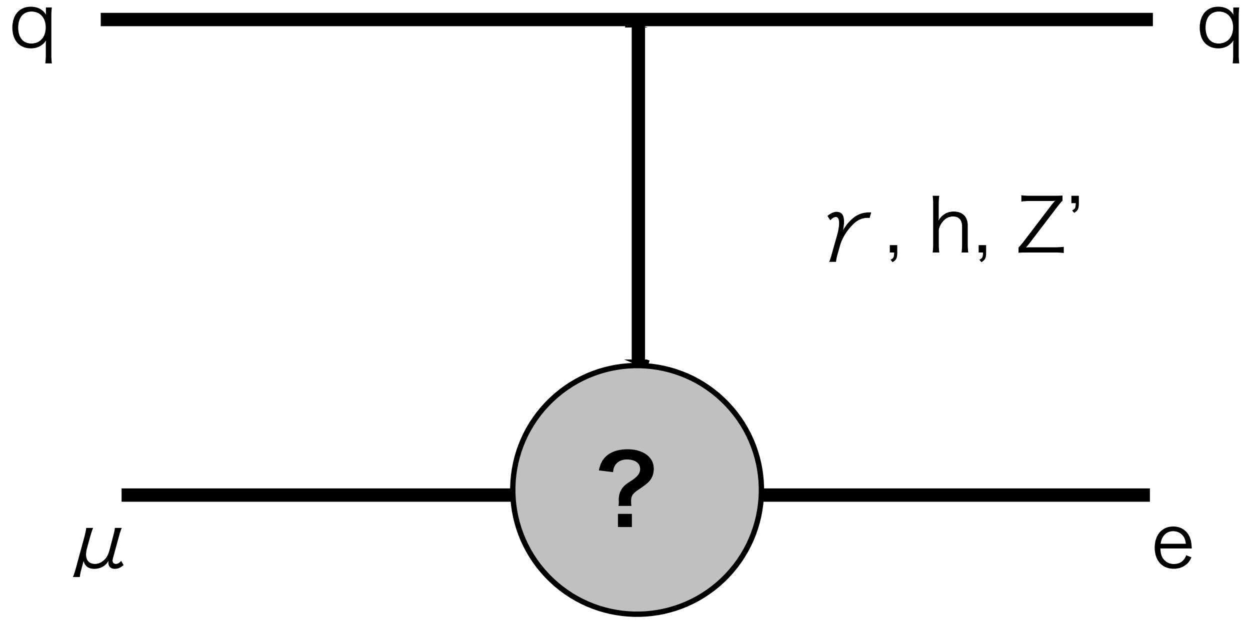




$\mu \rightarrow e\gamma$



μ-e conv.



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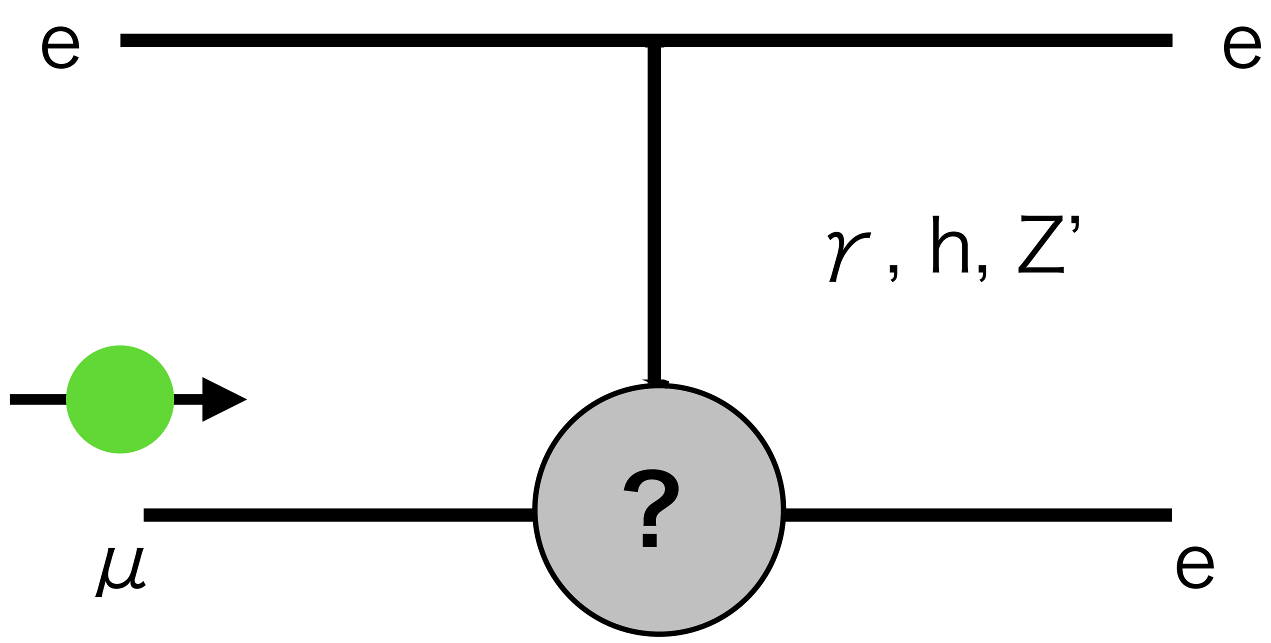

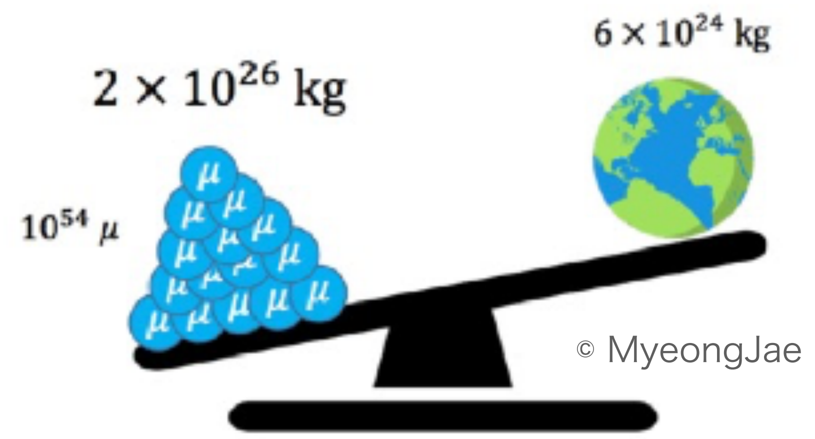

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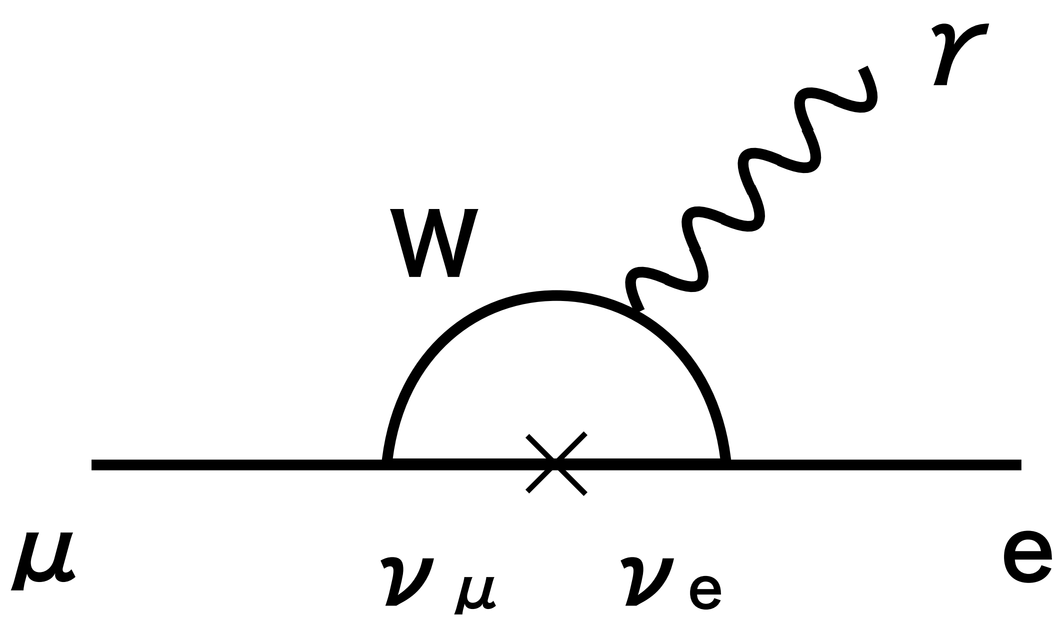
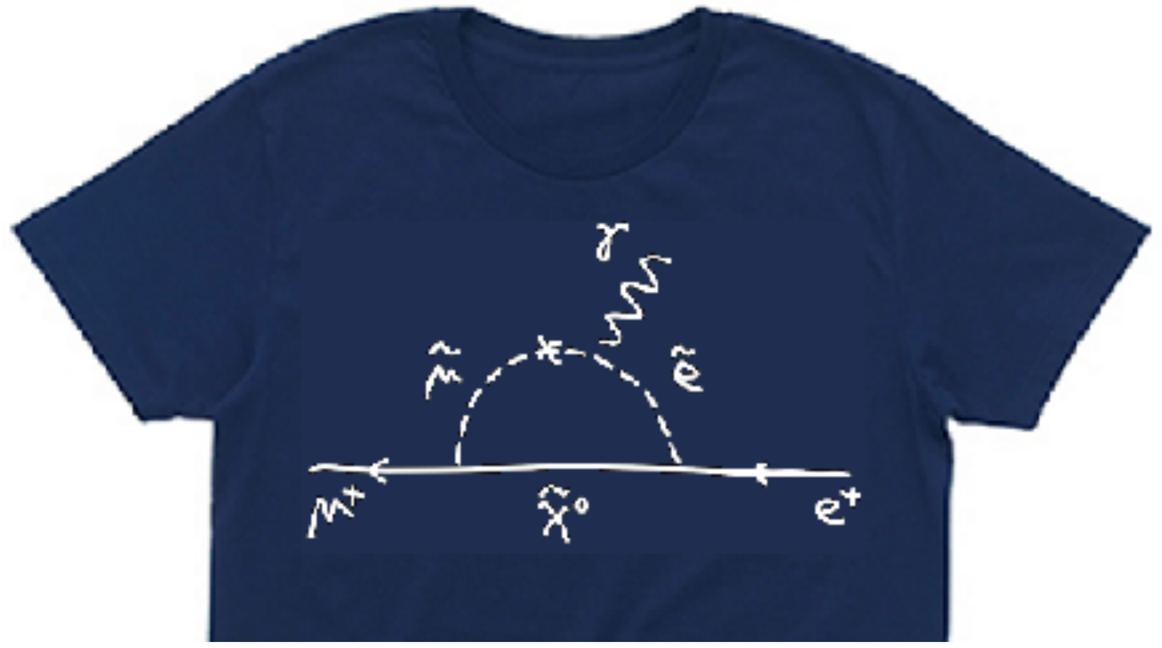
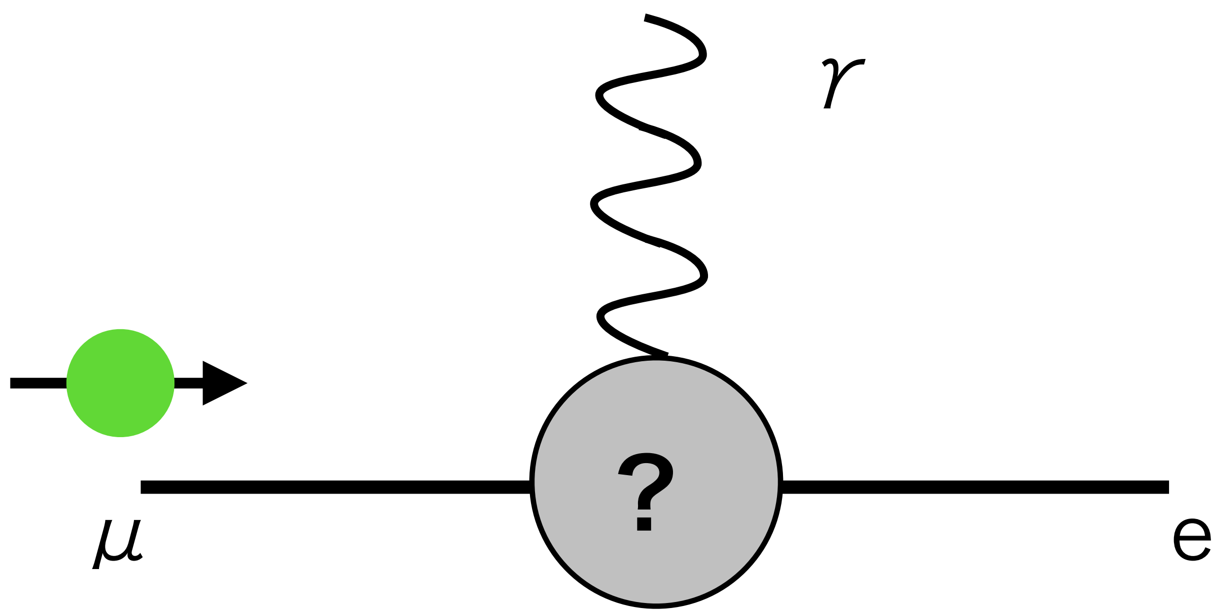




$\mu \to e\gamma$



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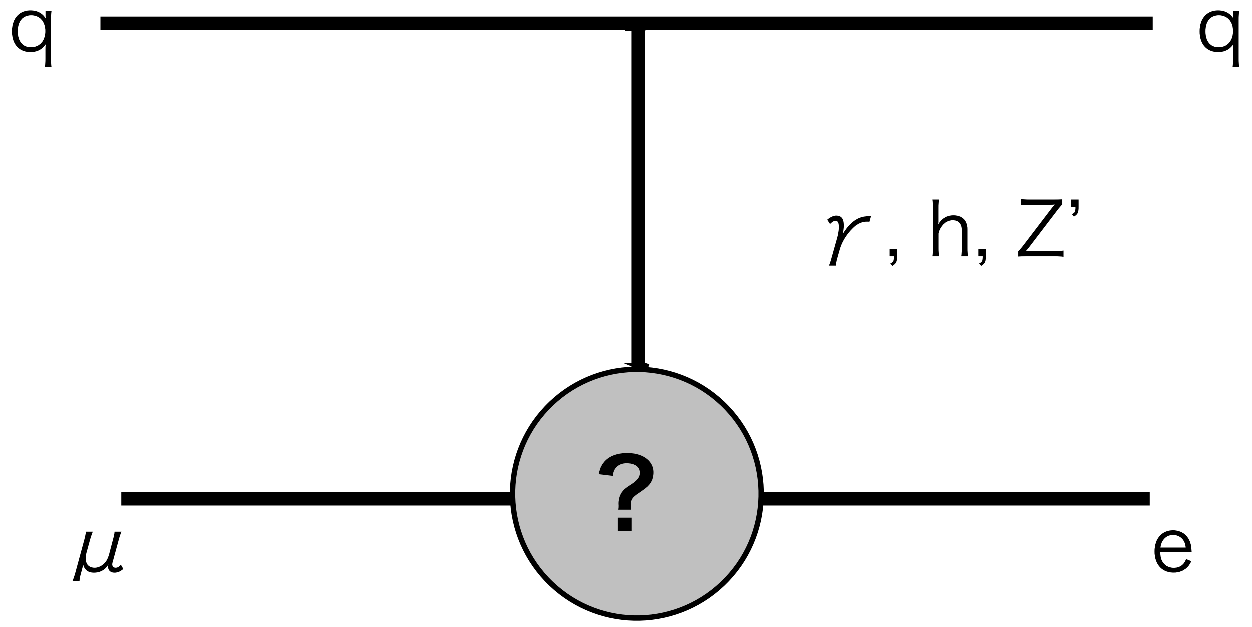

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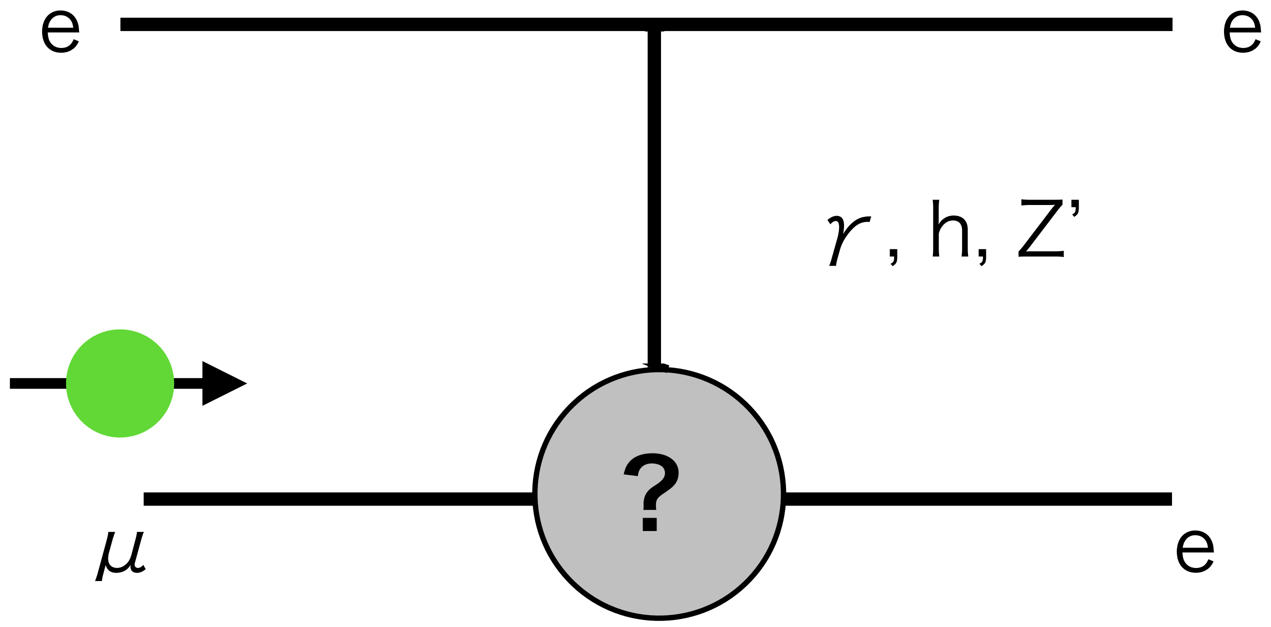

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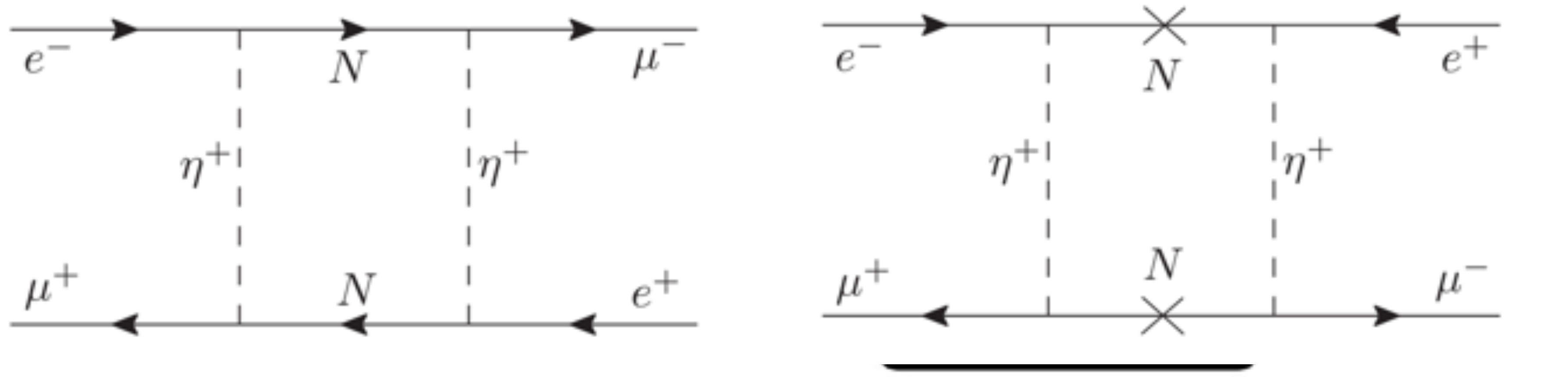

$Mu - \overline{Mu}$ transition

DOI: 10.1103/PhysRevD.105.015026, T. Fukuyama, Y. Miura, Y. Uesaka

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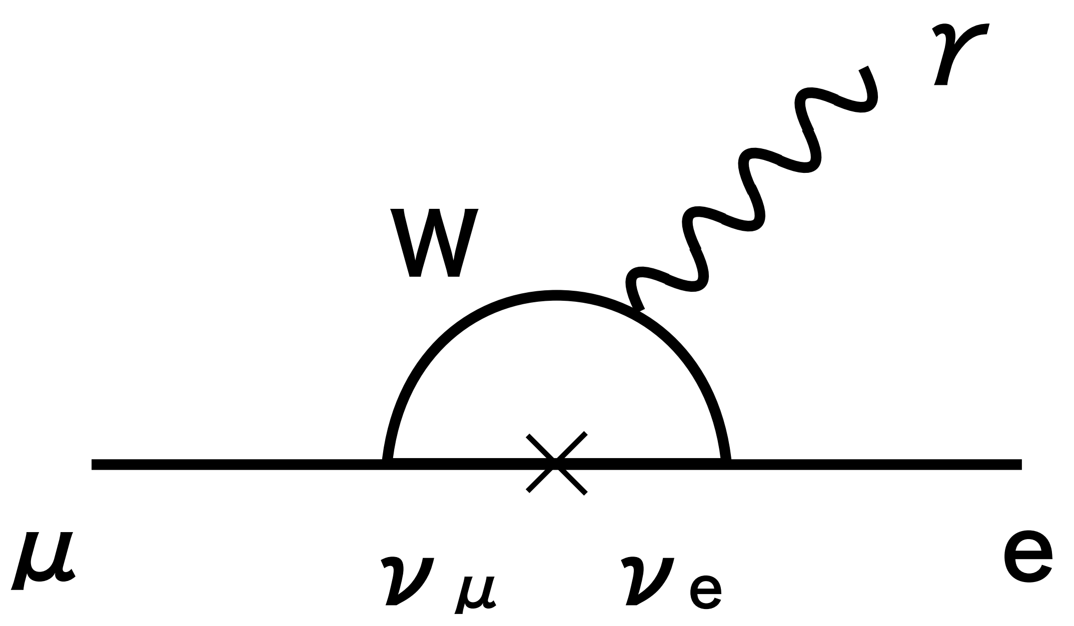

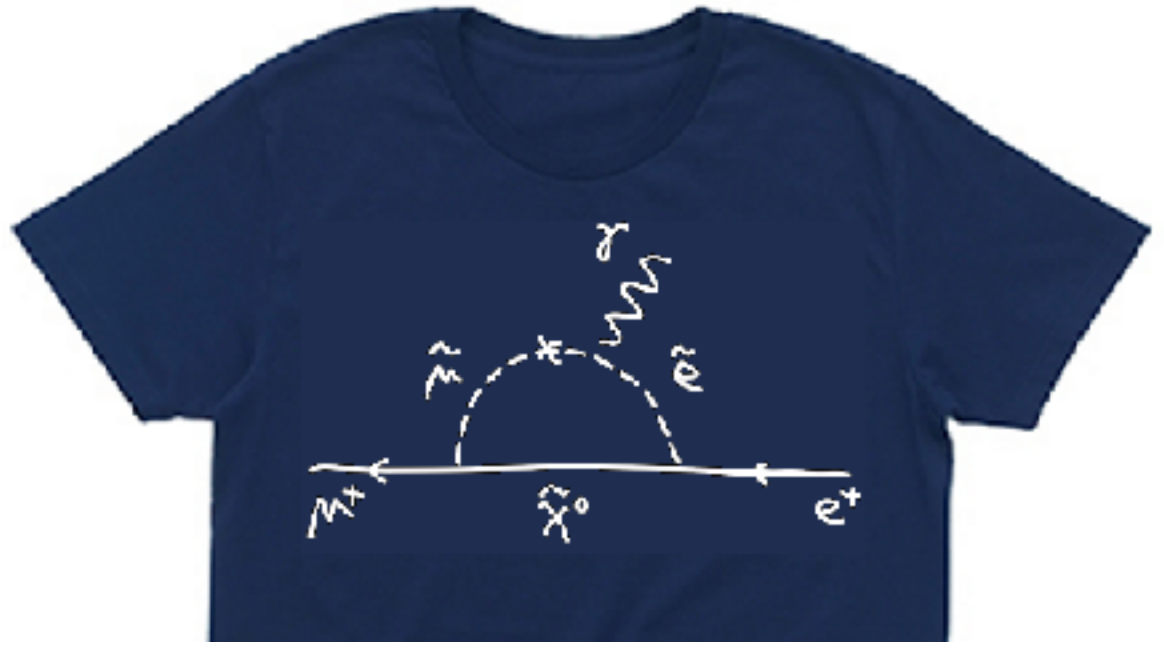

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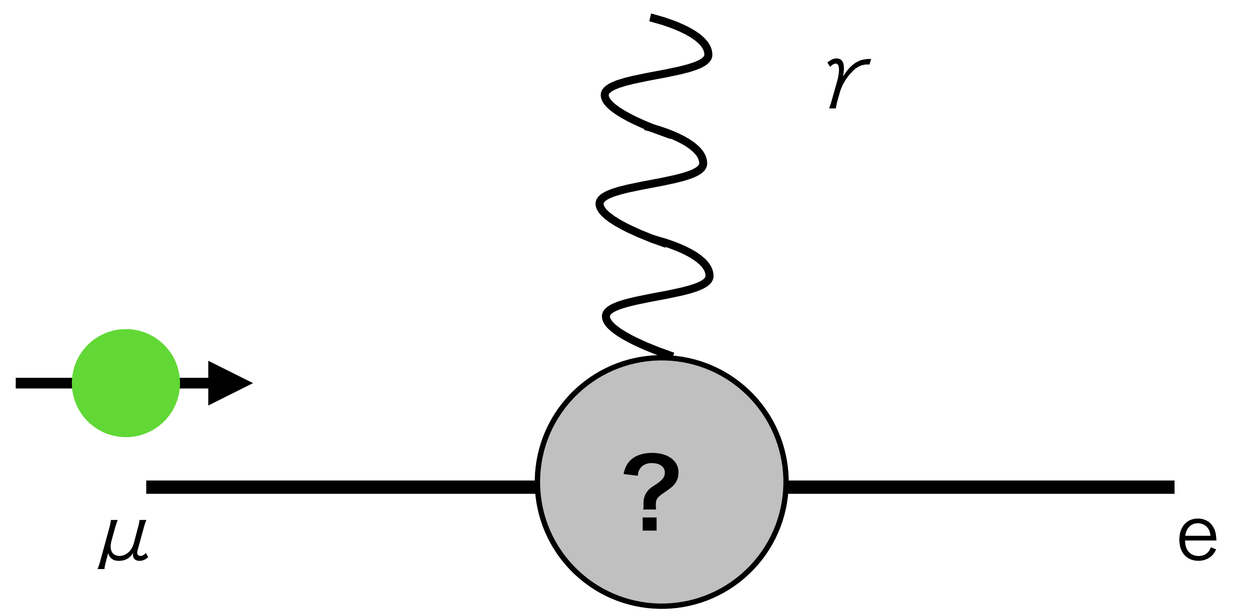

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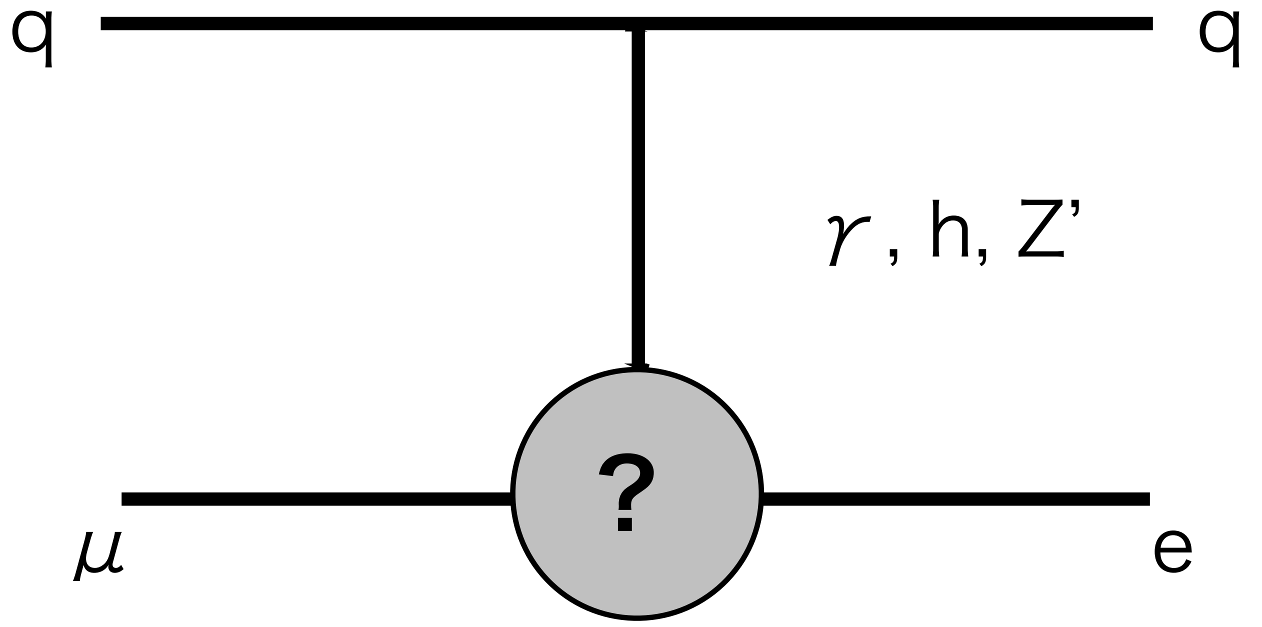

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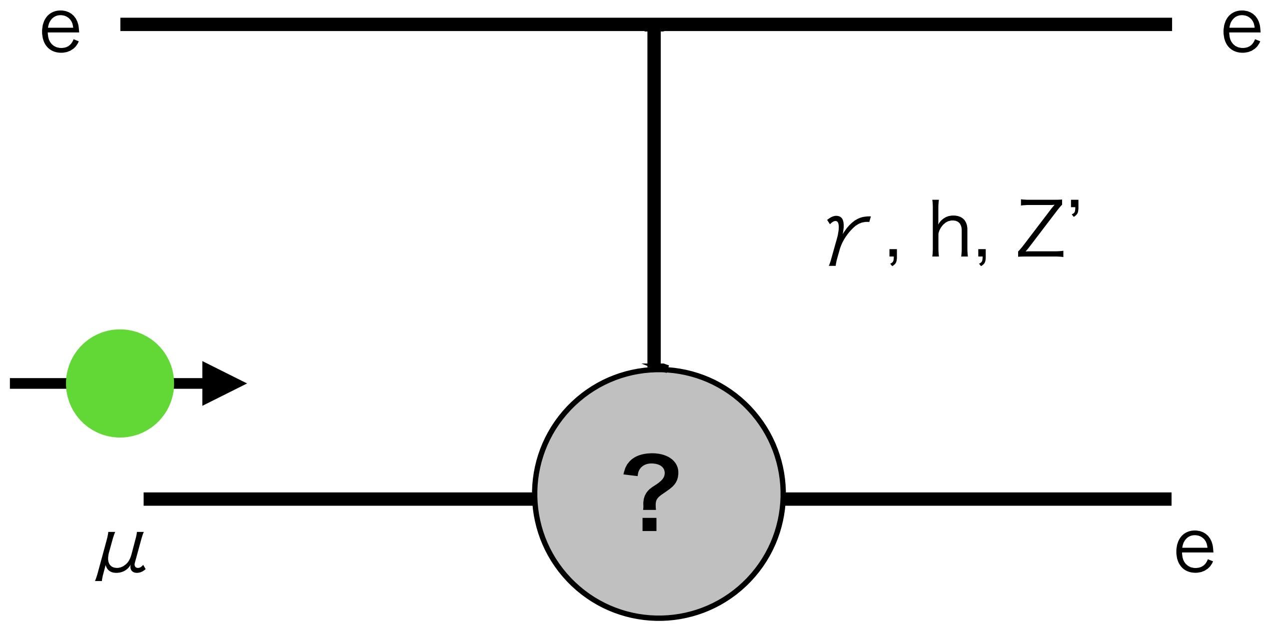
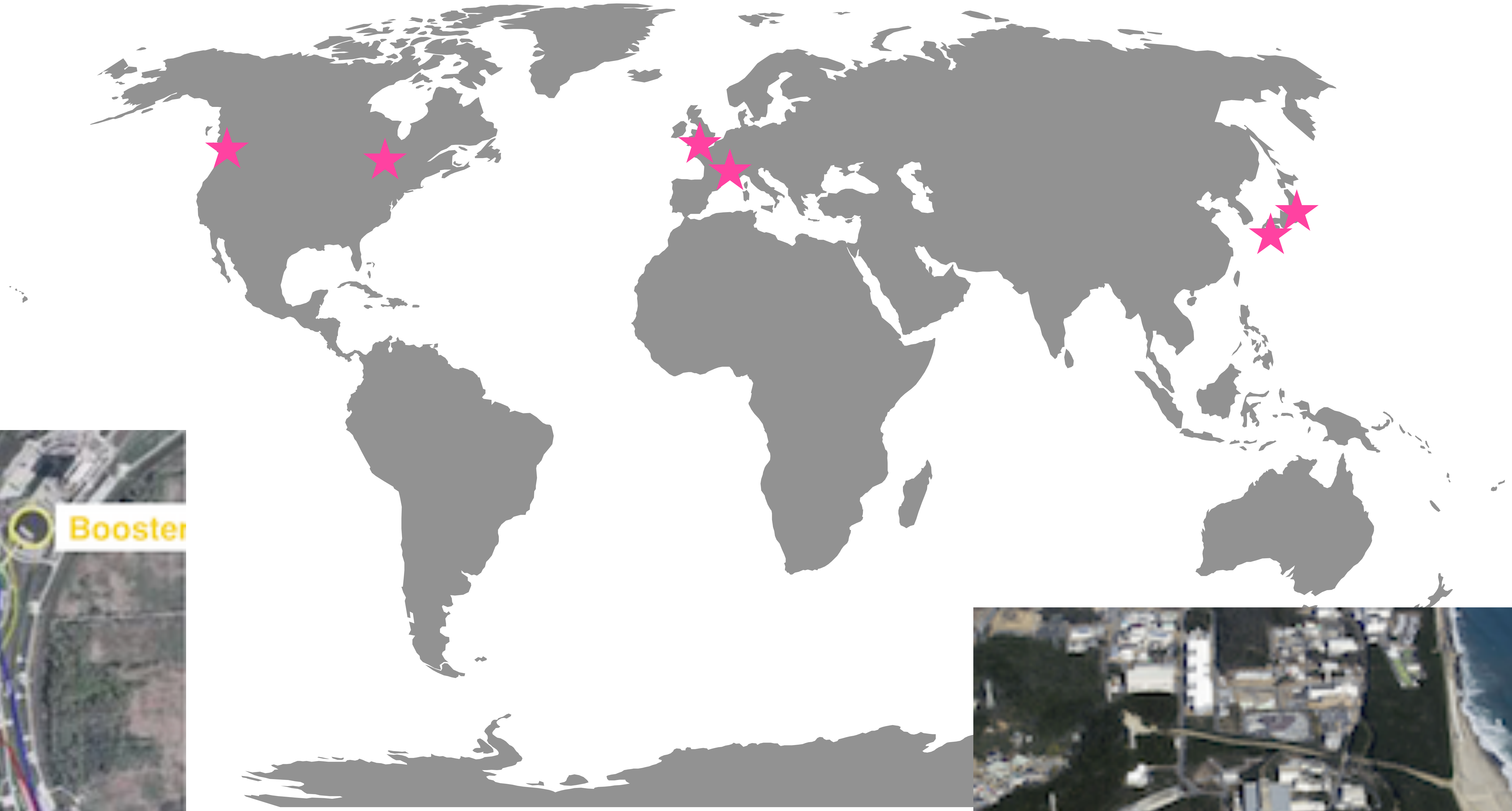


Muon facilities

Muon facility in the world

- J-PARC, RCNP (Japan)
- PSI (Switzerland)
- RAL (UK)
- FNAL (US)
- TRIUMF (Canada)

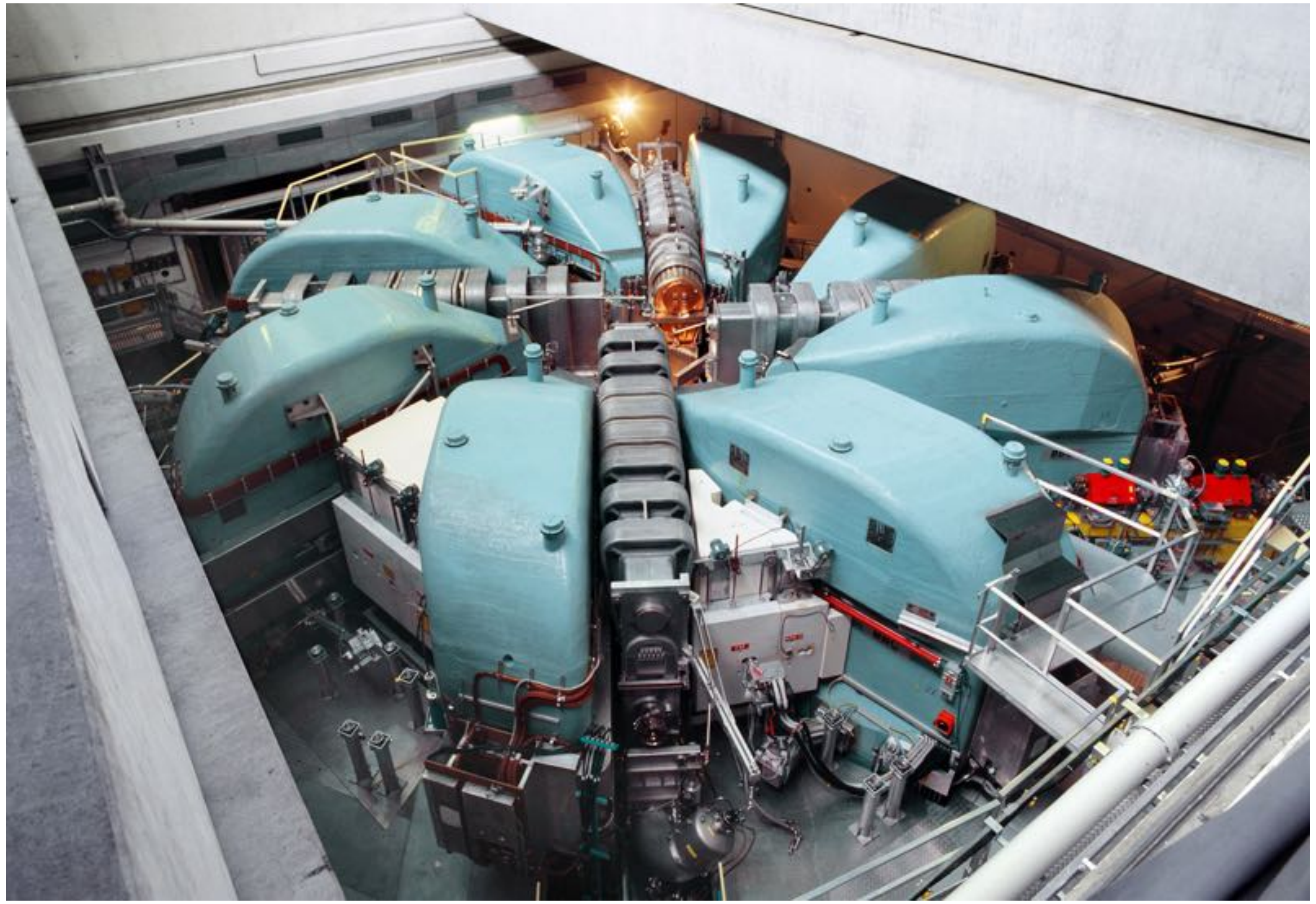


Muon CLFV experiments

- $\mu \to e\gamma$ MEG II at PSI
- μ-e conversion COMET at J-PARC & Mu2e at FNAL
- $\mu \to eee$ Mu3e at PSI

MEG II at PSI

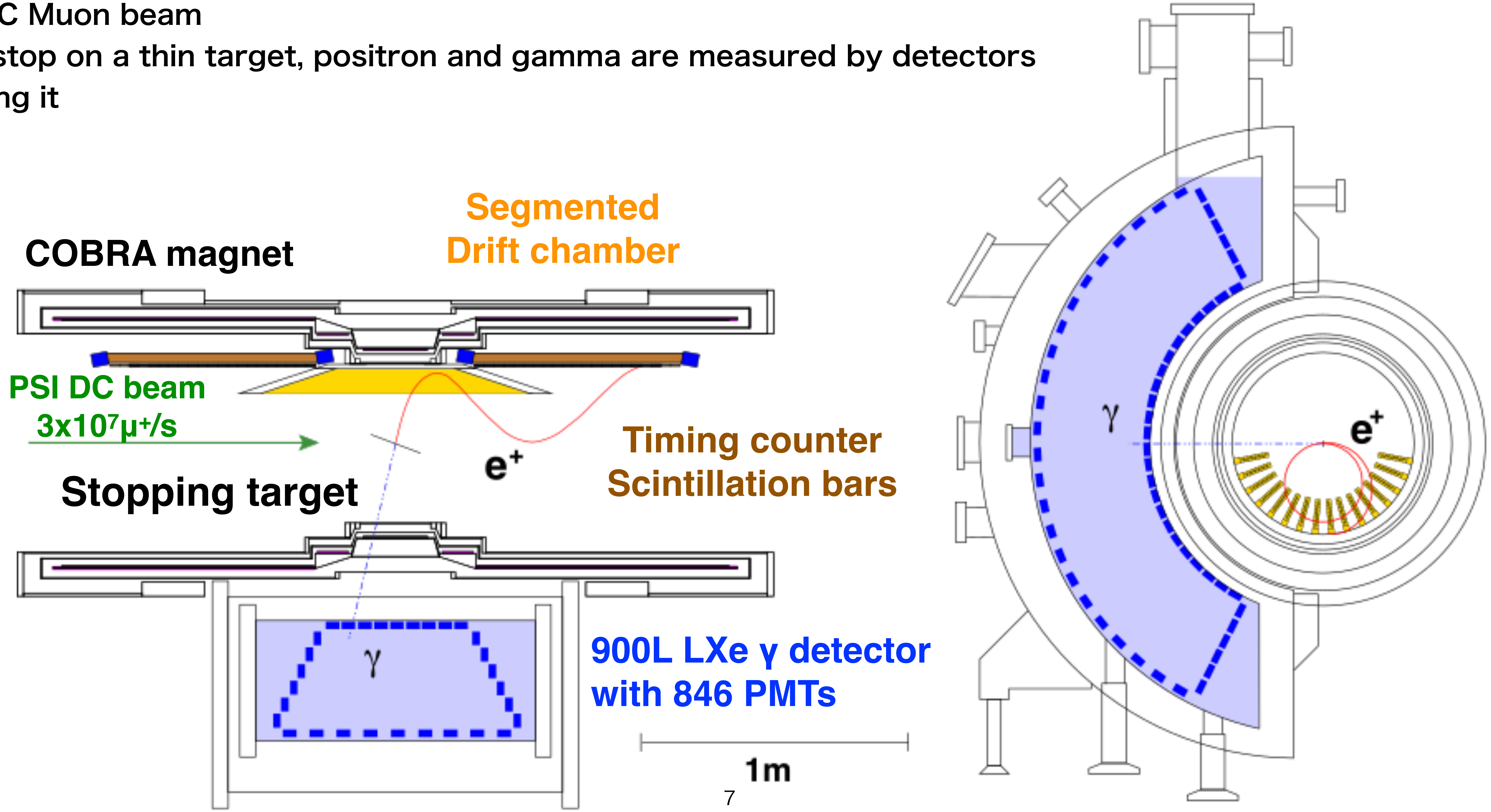
- $\mu \to e \gamma$ search



Alessandro Baldini, WG4 on 22/Aug

MEG: $\mu \rightarrow e \gamma$ search at PSI

- Surface DC Muon beam
- Muon (+) stop on a thin target, positron and gamma are measured by detectors surrounding it

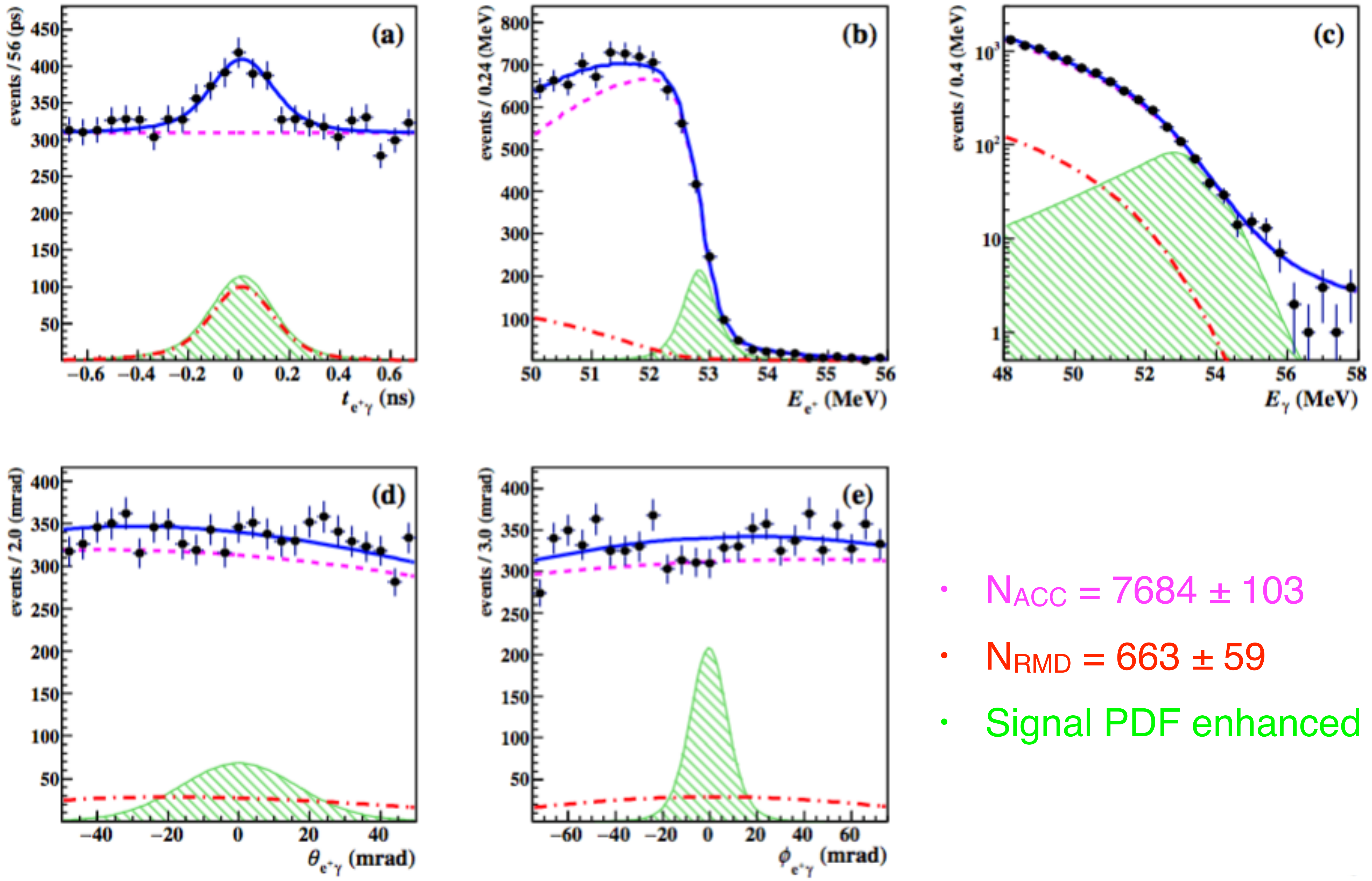


MEG Results

- Full dataset : 7.5×10^{14} μ^+ stopped on the target
- Blind analysis in (E_γ, $t_{e\gamma}$) plane
- Five observables E_γ,E_e,$t_{e\gamma}$,$\theta_{e\gamma}$,$\phi_{e\gamma}$
- Maximum likelihood analysis

- All PDFs well consistent with data

- The fit result was consistent with no signal

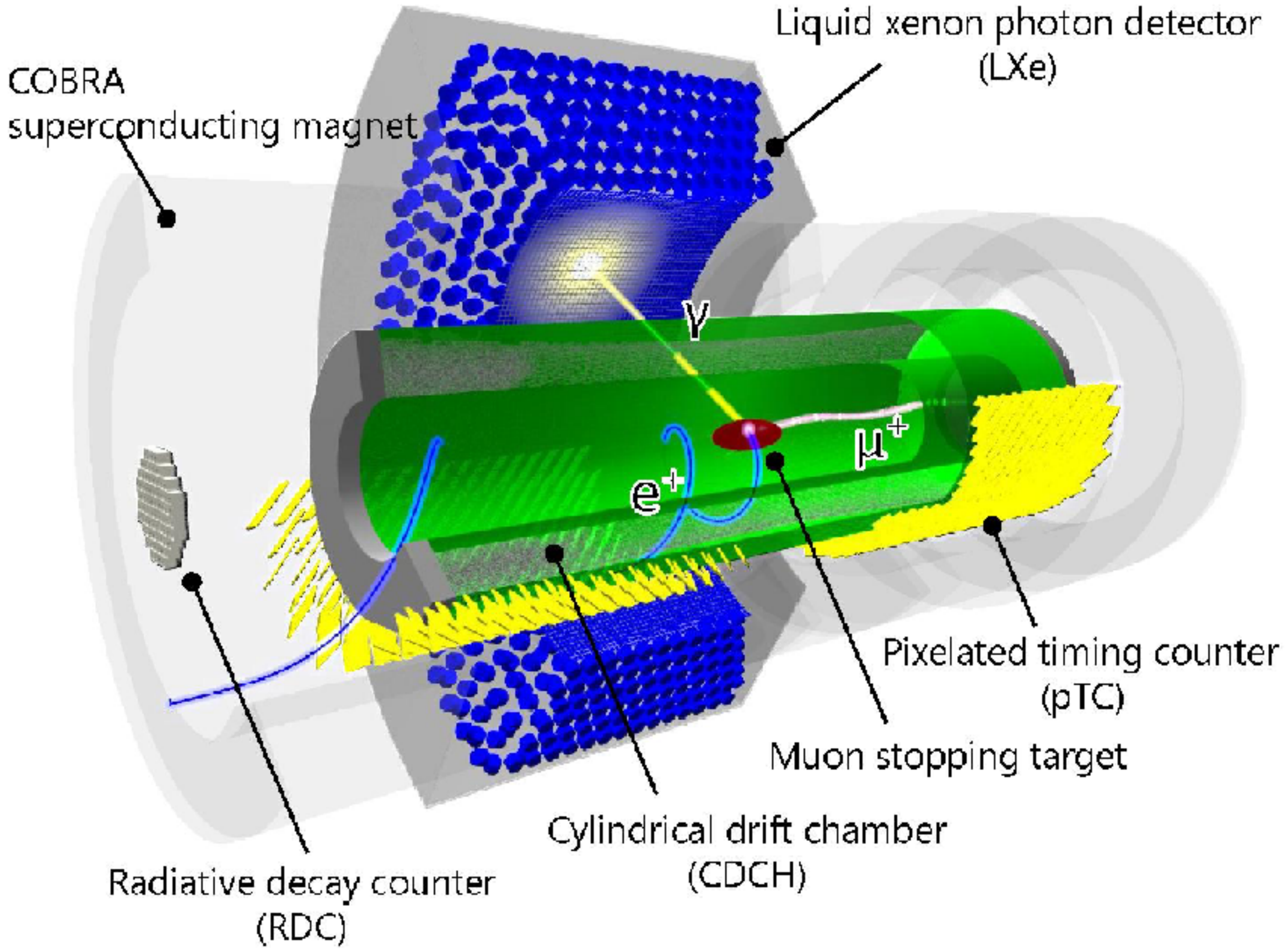


- $N_{ACC} = 7684 \pm 103$
- $N_{RMD} = 663 \pm 59$
- Signal PDF enhanced

- **$Br(\mu^+\to e^+\gamma) < 4.2\times10^{-13}$ @ 90% C.L.**

MEG II: Upgrade of MEG

- MEG achieved 4.2×10^{-13} @ 90% C.L.
  - Background was dominated by Accidental event overlaps
- MEG II aims at twice better resolutions than MEG in all components
- Double the muon beam rate
  - 7×10^{7} muon stops/s
- New detector to tag the radiative muon decay event
- New calibration method

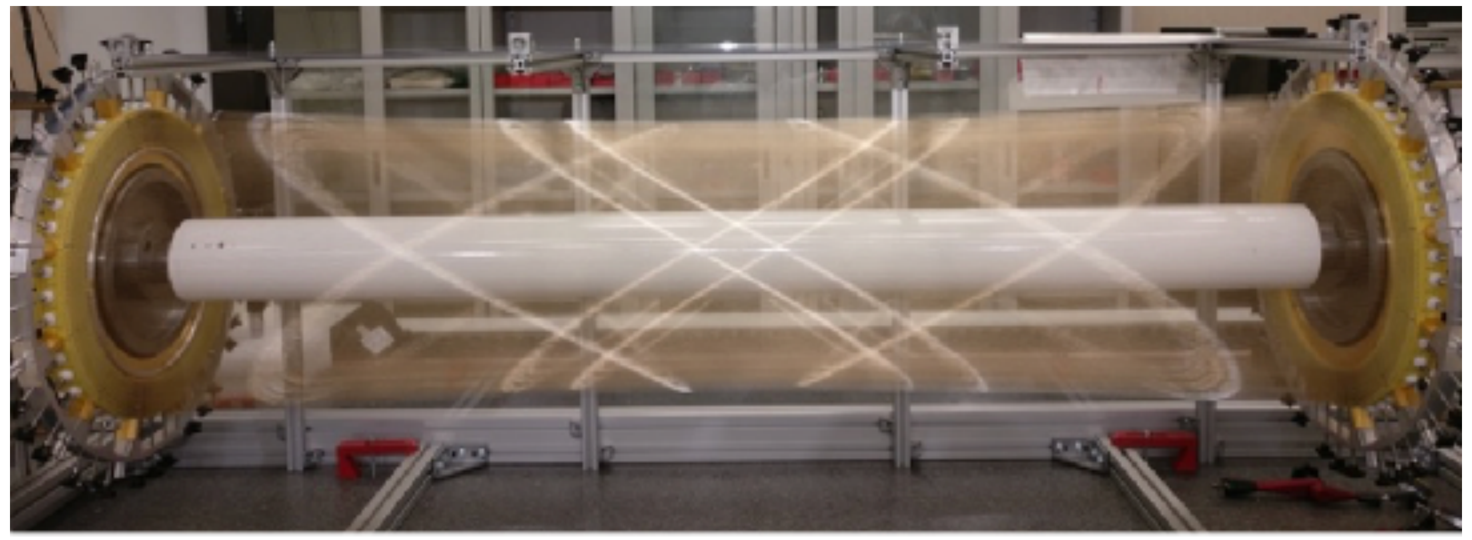


Target Sensitivity : 6×10^{-14} in 3 years running

MEG II Status

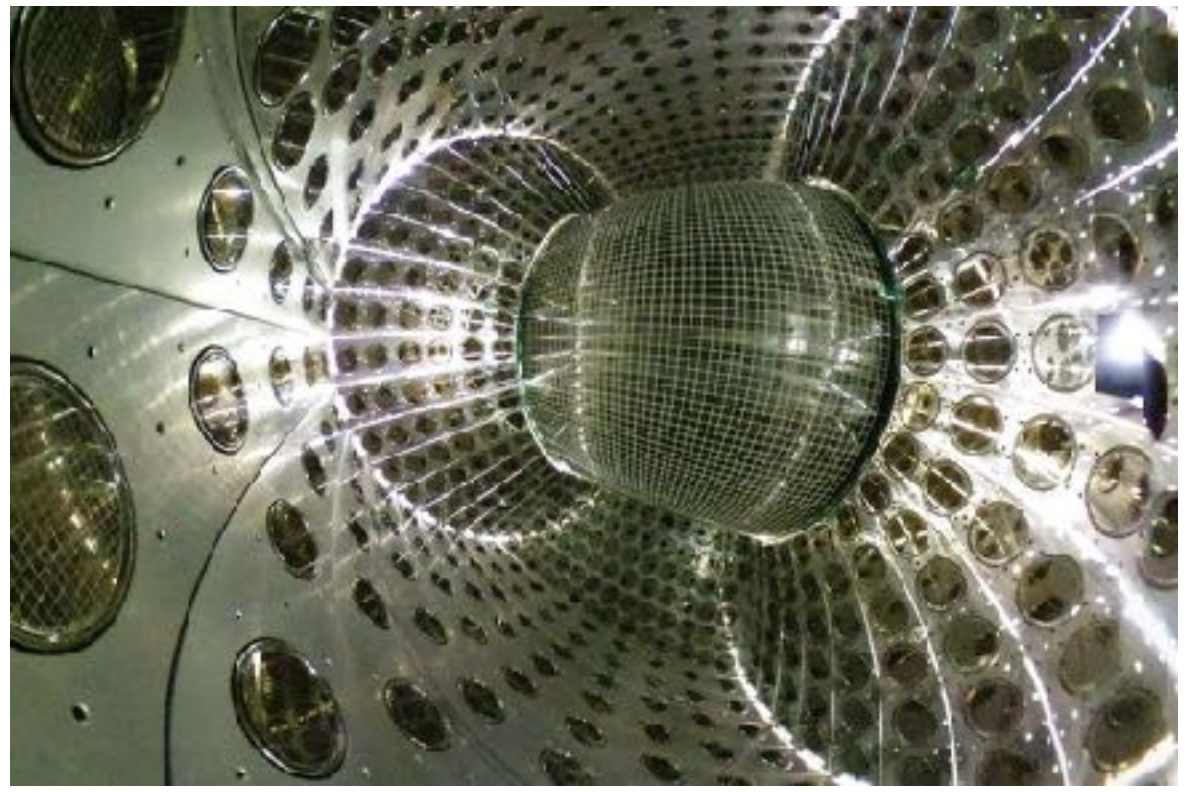
Detectors

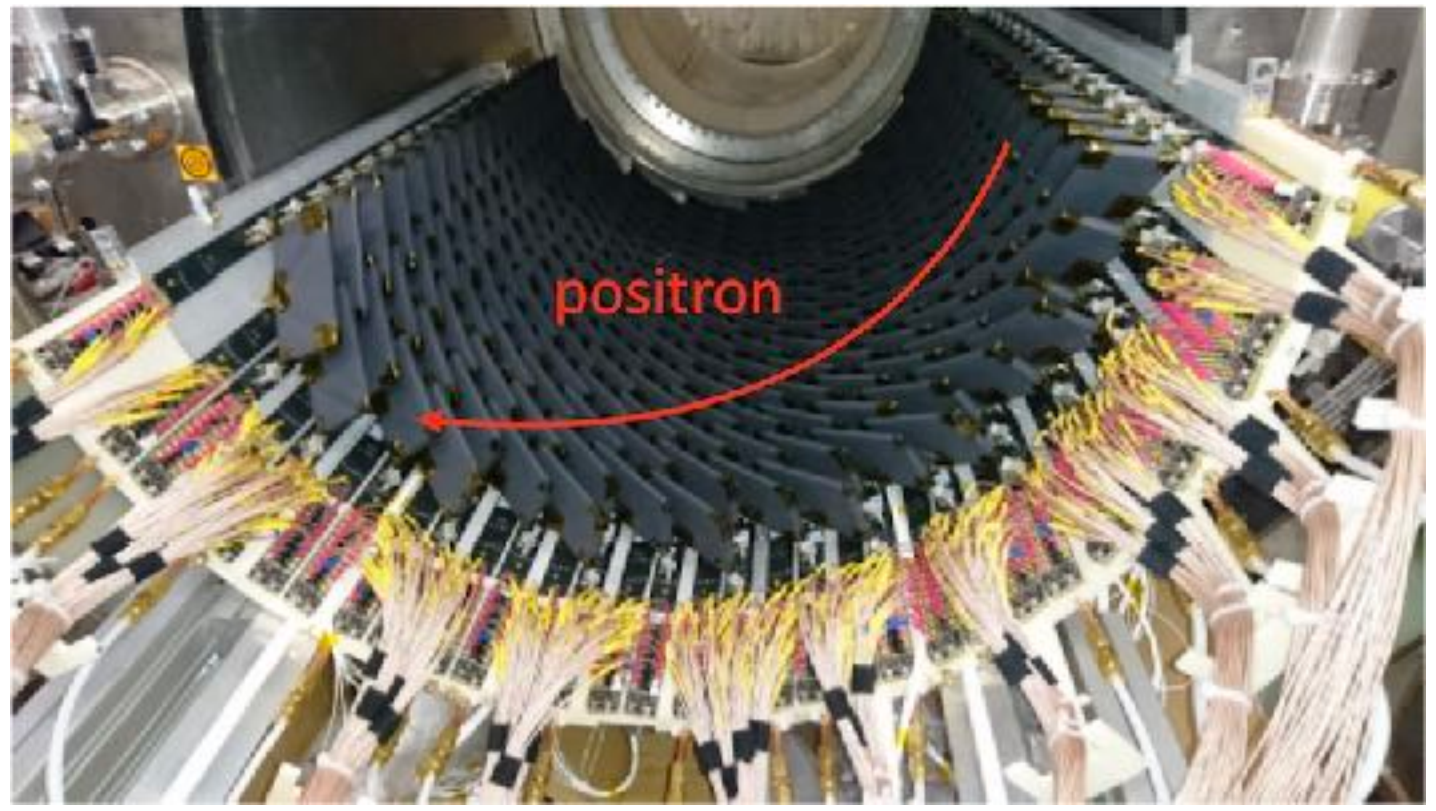
- Physics DAQ started in 2021
- Significant statistics collected in 2022 and even more in 2023.
- All newly installed detectors are working fine!
  - TDAQ as well!



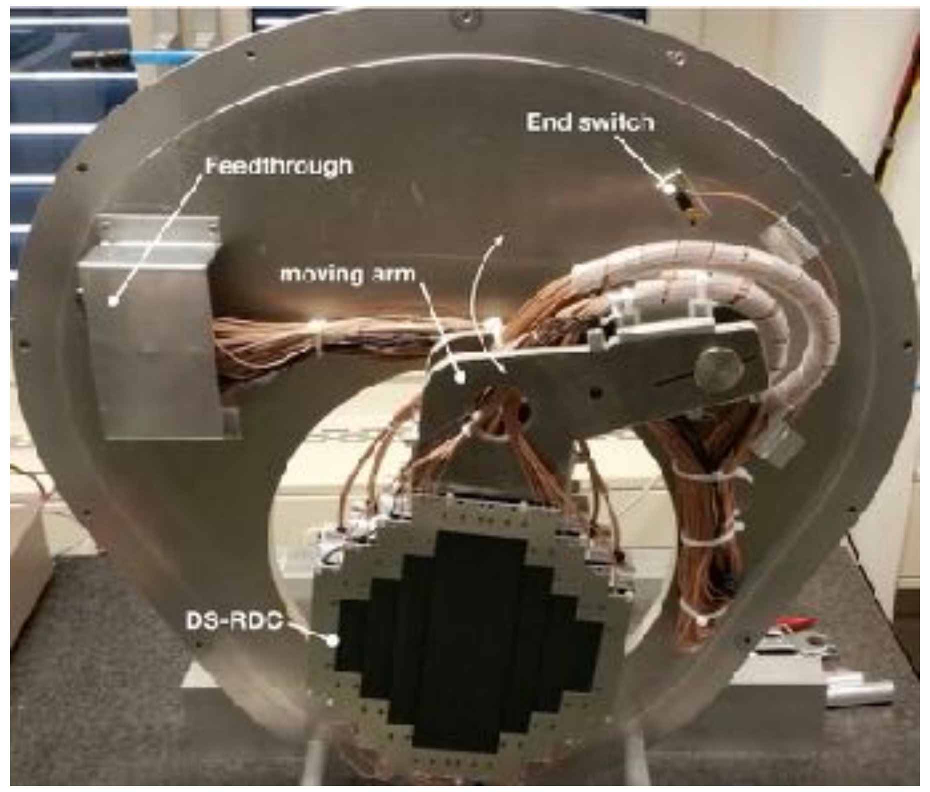
Single Volume Low mass Stereo-wire DC

LXe detector with MPPC on the front face





Pixelated timing counter



Radiative Decay Counter

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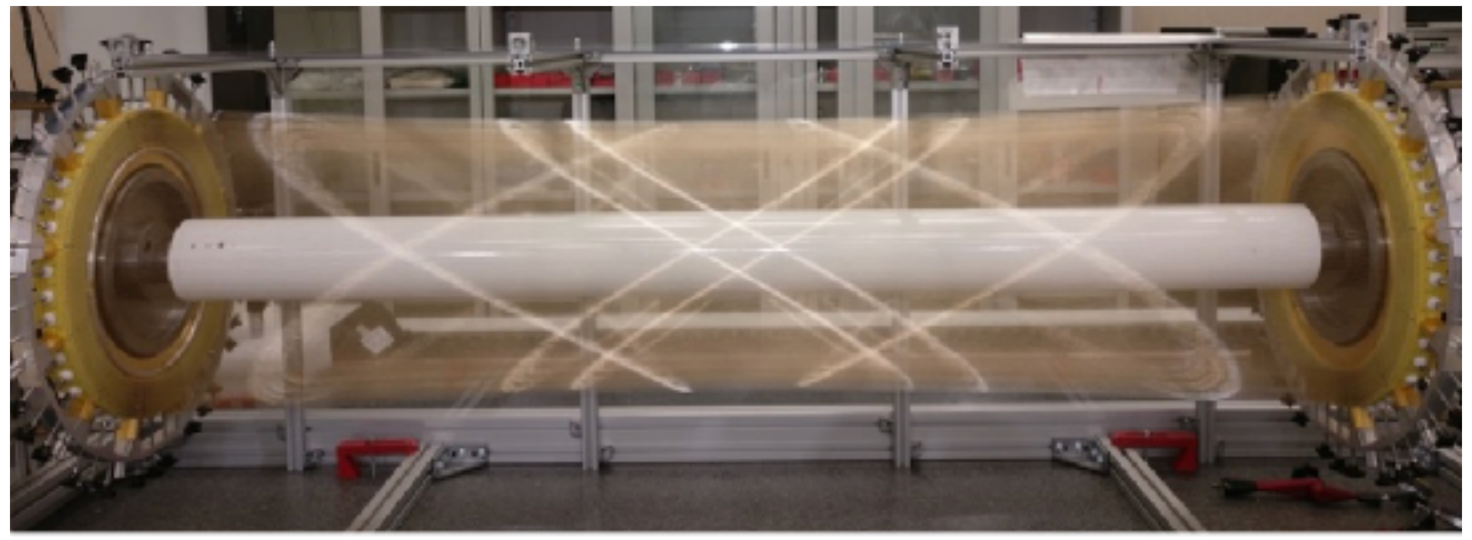

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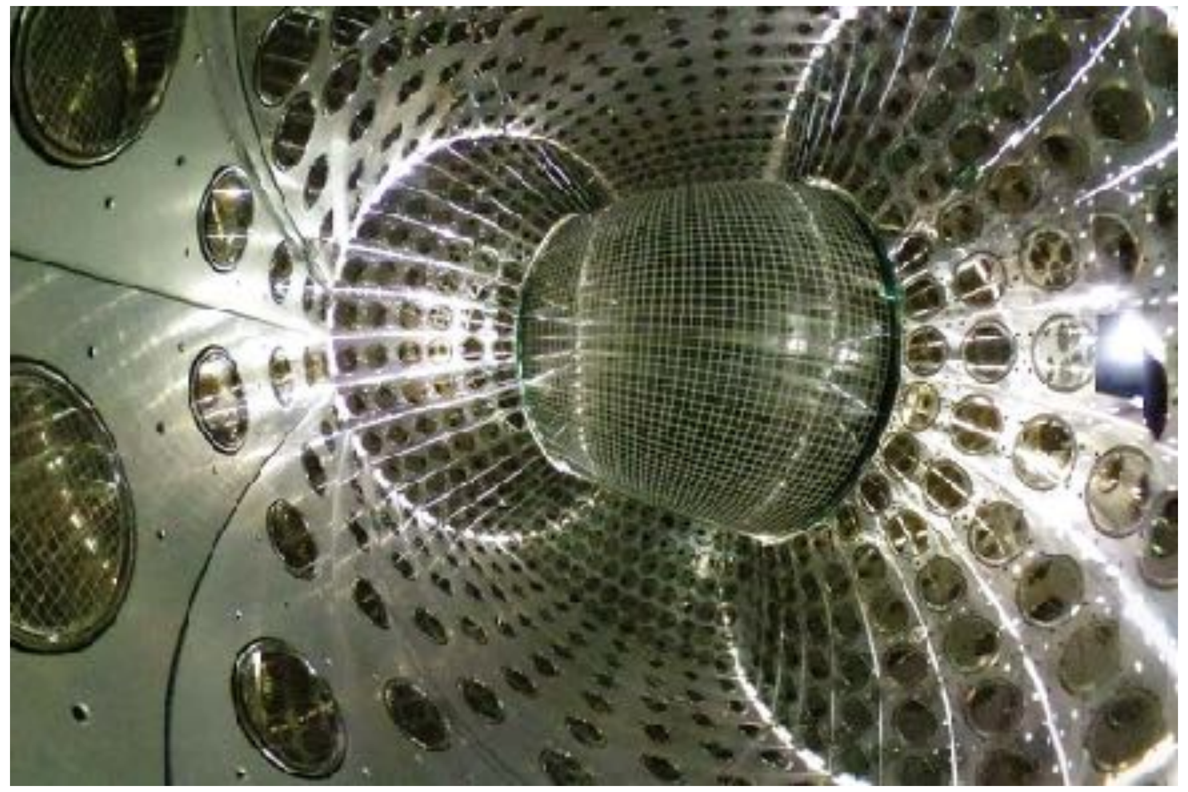

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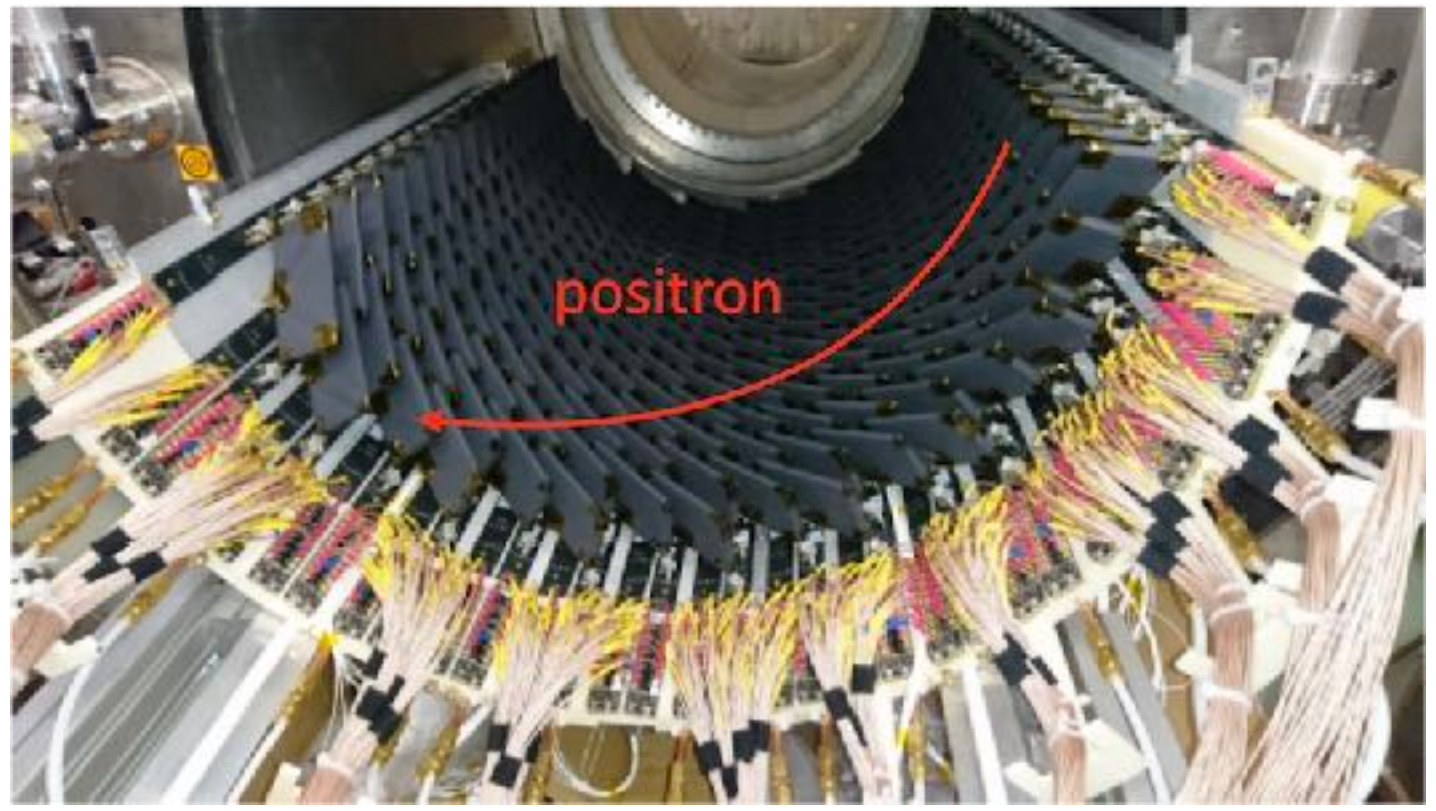

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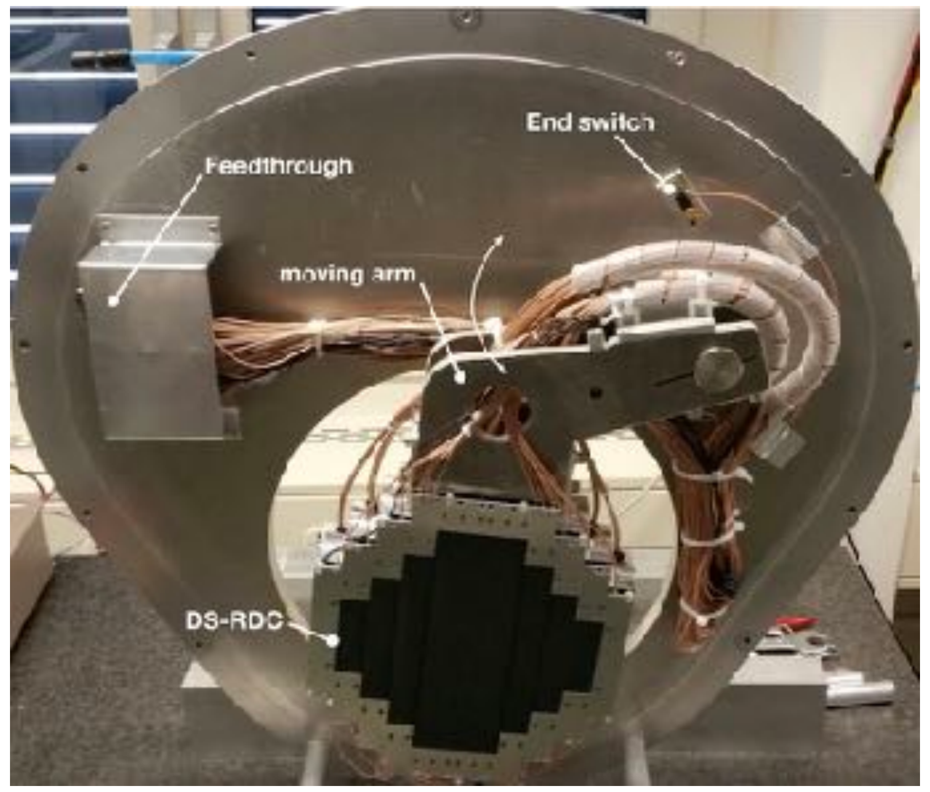

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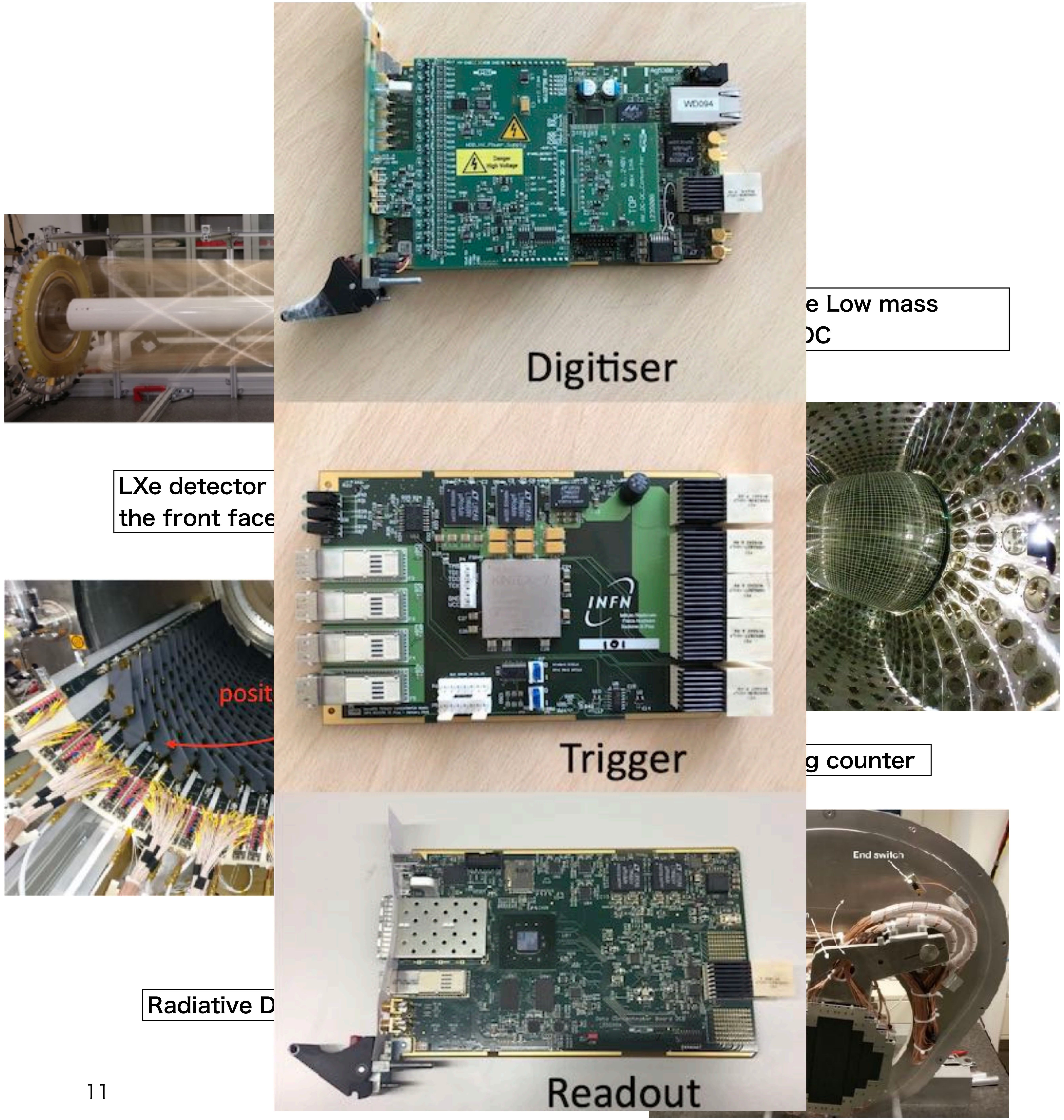


MEG II Detector Performance

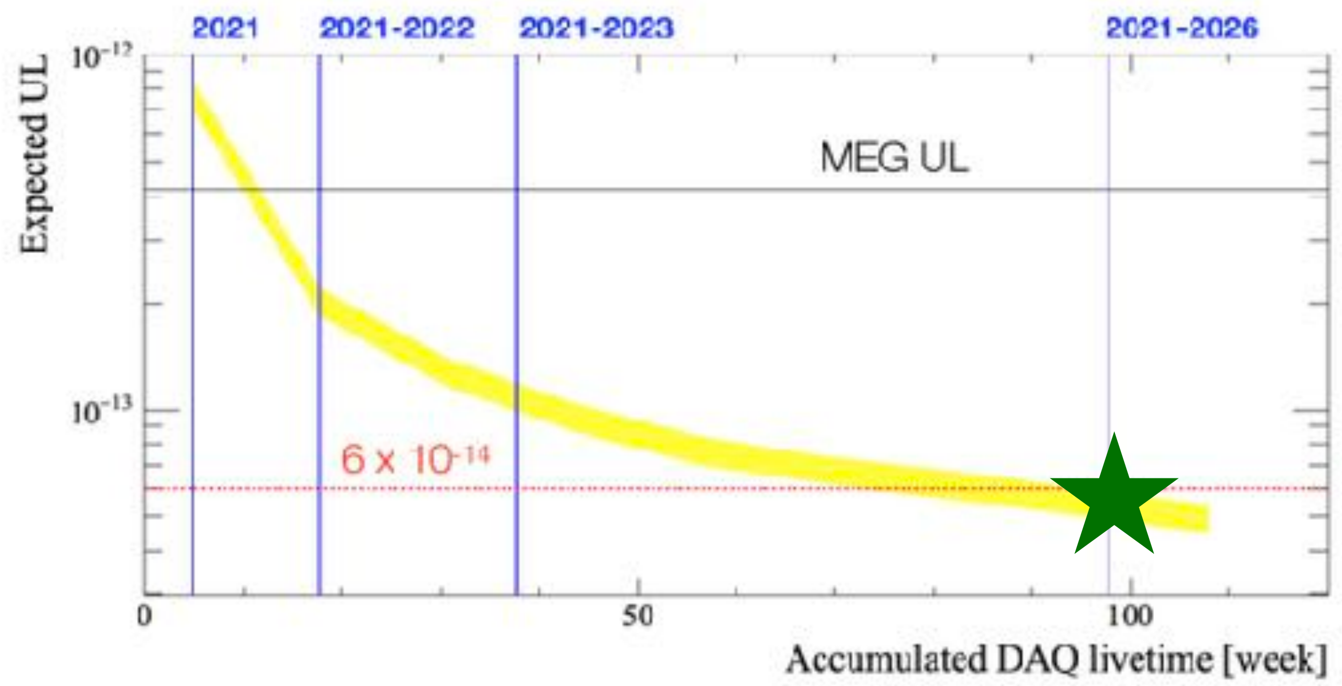
Variables	MEG	MEG II Design	MEG II Currently Achieved
ΔE_e[keV]	380	130	90
$\Delta\theta_e$, $\Delta\phi_e$[mrad]	9, 9	7.0, 5.5	8, 7
$Efficiency_e$[%]	40	70	65
ΔE_γ[%][deep/shallow]	1.7 / 2.4	1.0 / 1.1	1.7 / 2.0
$\Delta Position_\gamma$[mm]	5	2.4	2.5
$Efficiency_\gamma$[%]	60	70	60
$\Delta t_{e\gamma}$[psec]	120	85	80

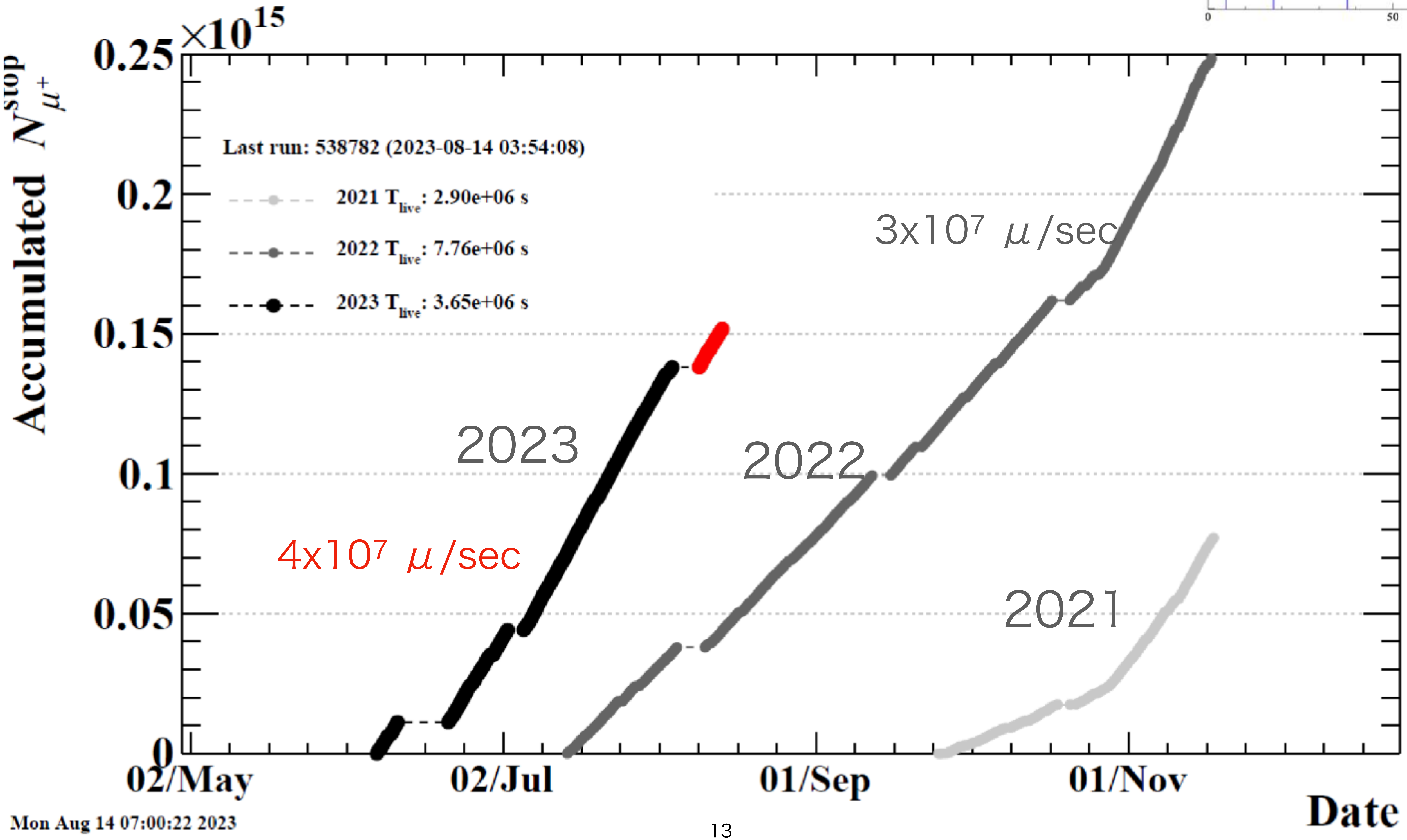
Positron

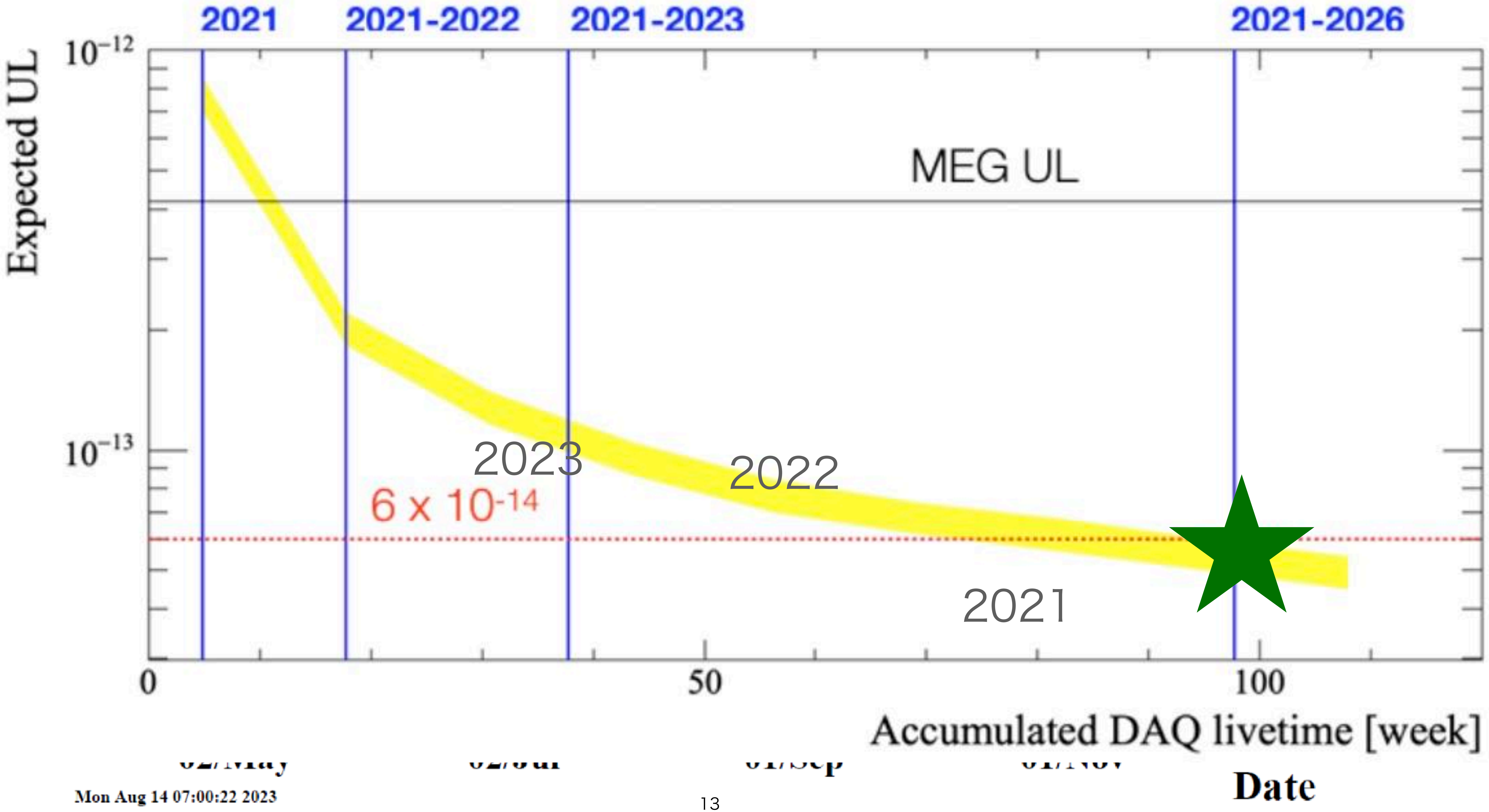
Photons

Comb

MEG II Prospects

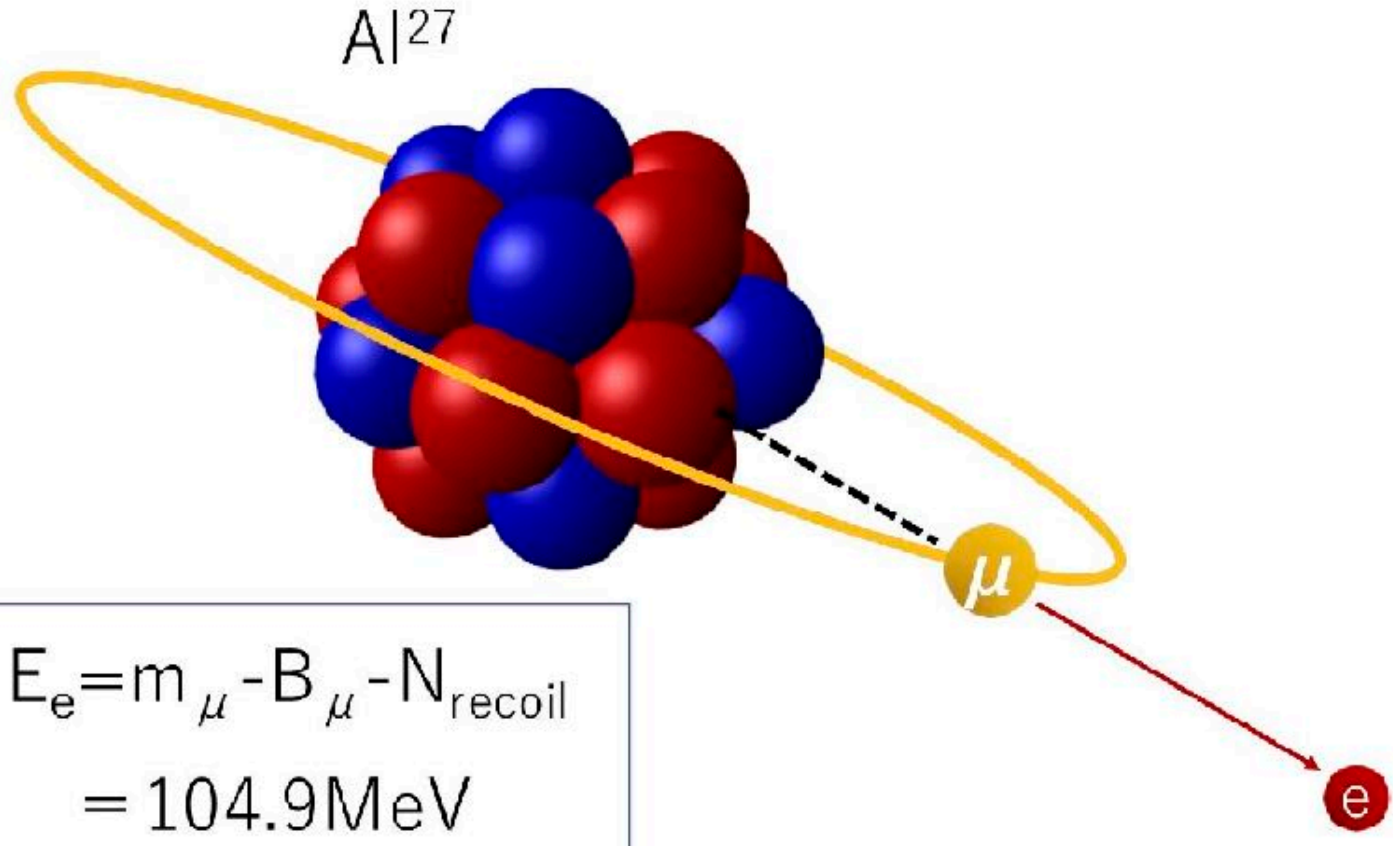





2021
2021-2022
2021-2023
2021-2026
10^{-12}
10^{-13}
Expected UL
MEG UL
2023
2022
2021
6×10^{-14}
0
50
100
Accumulated DAQ livetime [week]
Date
Mon Aug 14 07:00:22 2023

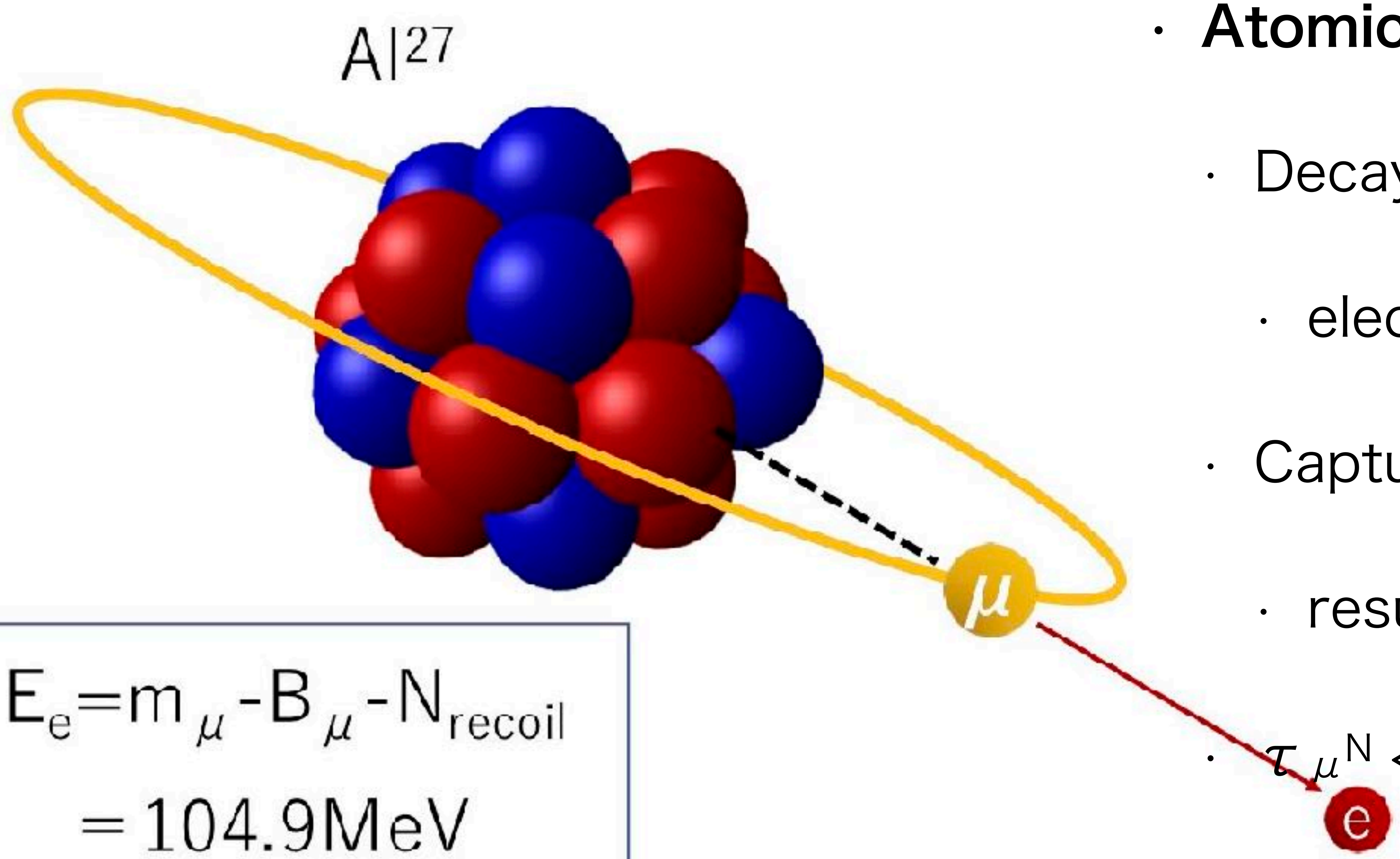
COMET & Mu2e

- μ-e conversion search



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

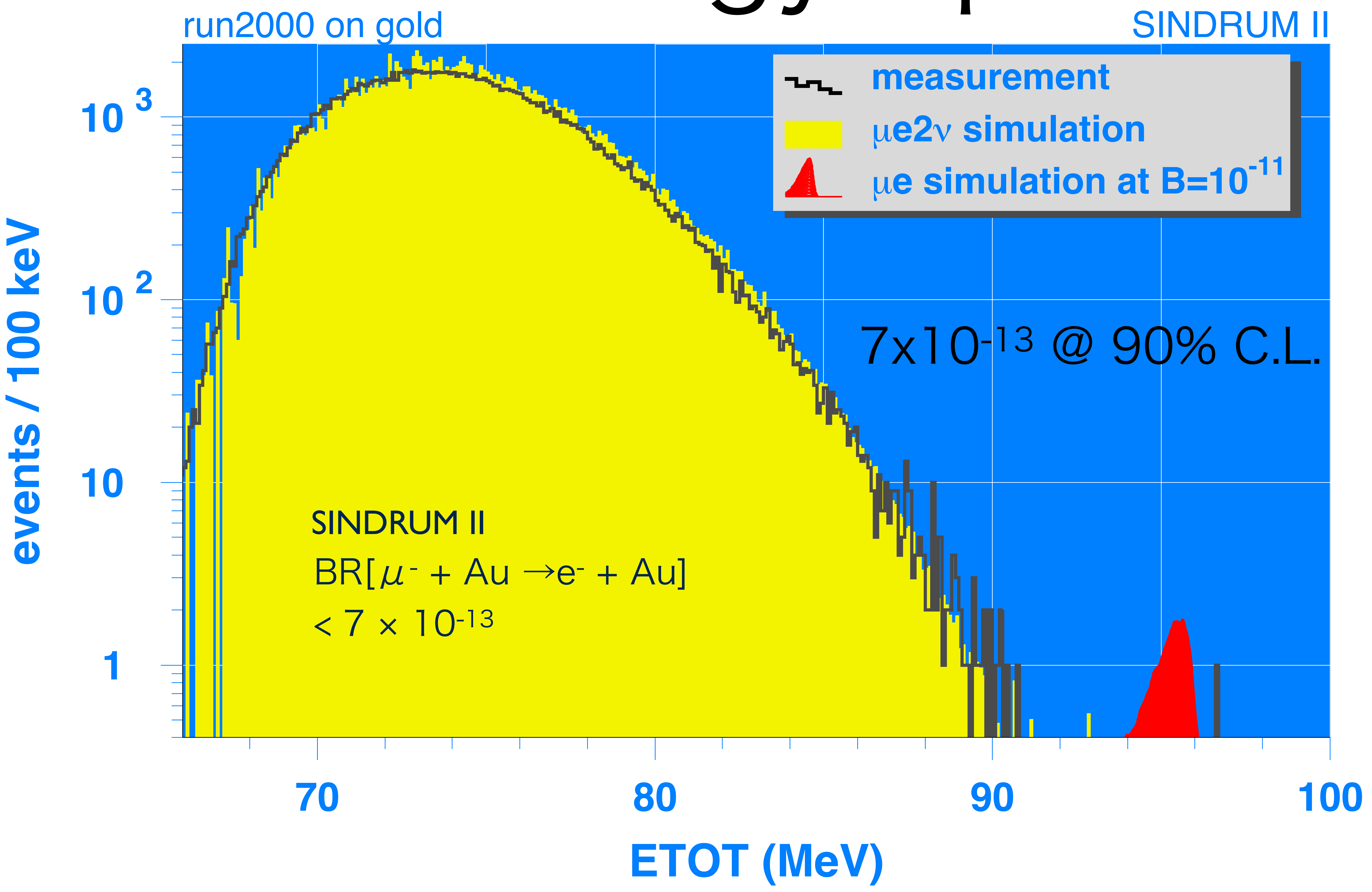
μ-e conversion



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

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

Electron Energy Spectrum



COMET

Chen Wu, WG4 on 25/Aug

MyeongJae Lee, WG4 on 22/Aug

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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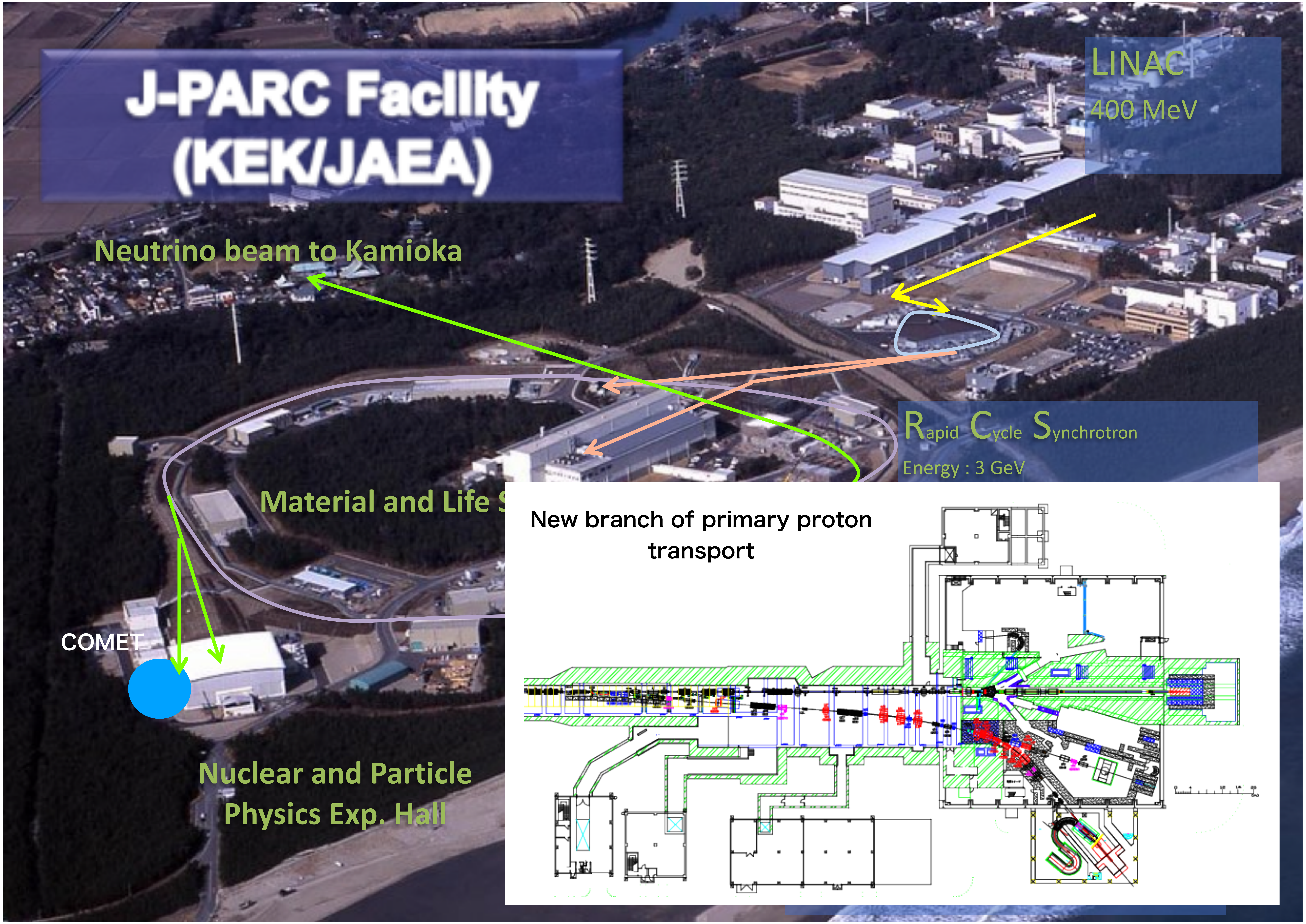
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400 MeV
Neutrino beam to Kamioka
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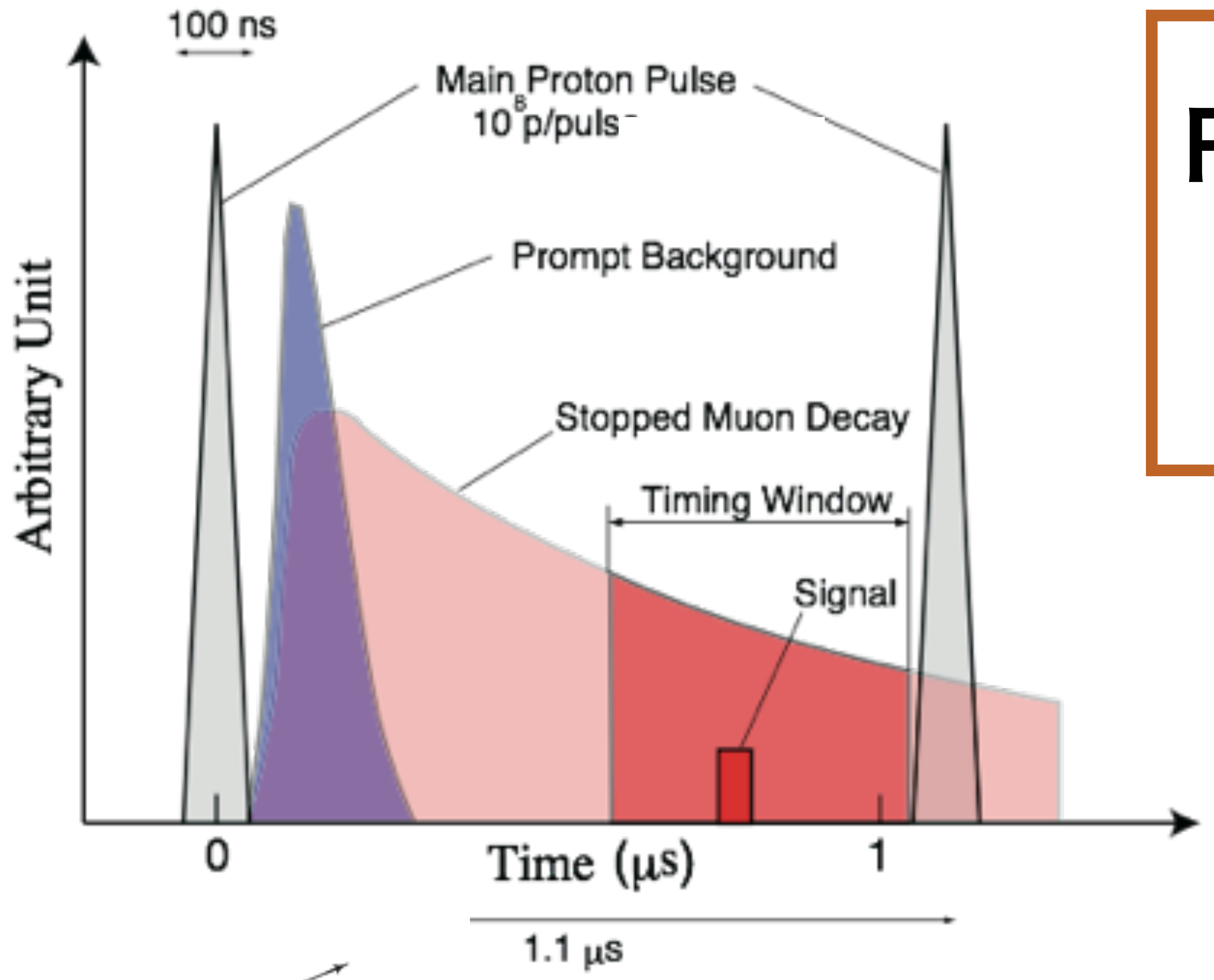
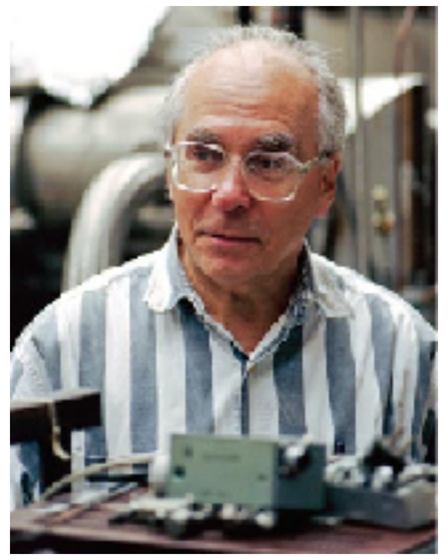
Material and Life S
New branch of primary proton transport
COMET
Nuclear and Particle
Physics Exp. Hall

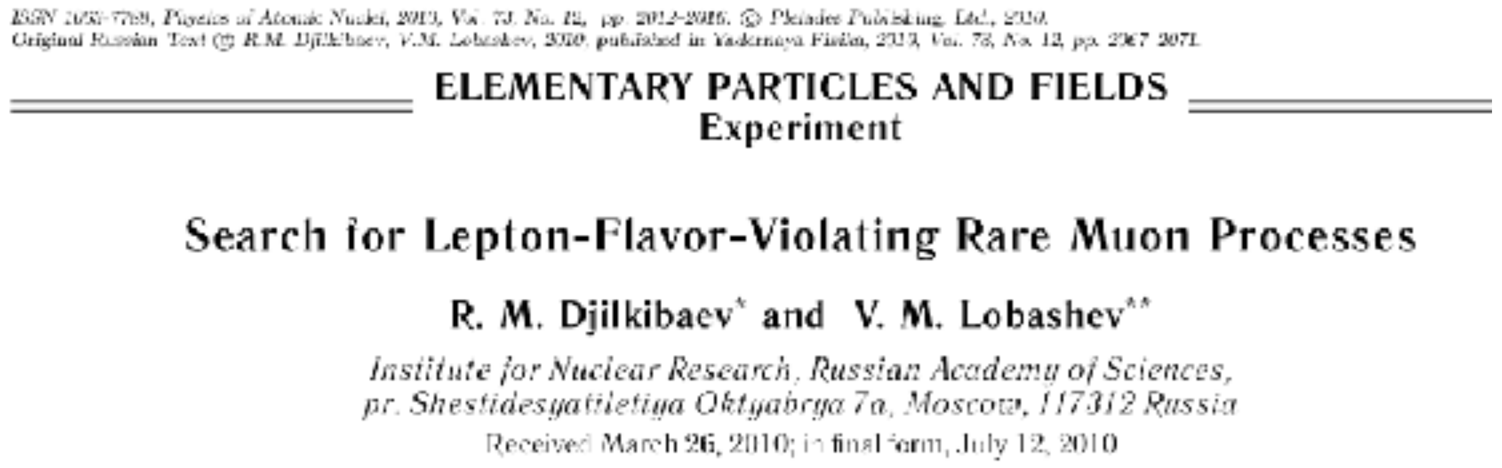
COMET Experiment

- Precisely pulsed proton beam from J-PARC MR
- Graphite (Phase-I) or Metal (Phase-II) target for pion production
- MELK Proposal (V. M. Lobashev)
    - Pion/Muon **collection using a strong and gradient magnetic field, Pion Capture Solenoid (PCS)**
    - Pion/Muon transport with **a curved solenoid**
- Stack of thin target disks to stop muons



$$R_{ext} = \frac{N_p \text{ btw pulses}}{N_p \text{ in a pulse}} < 10^{-10}$$



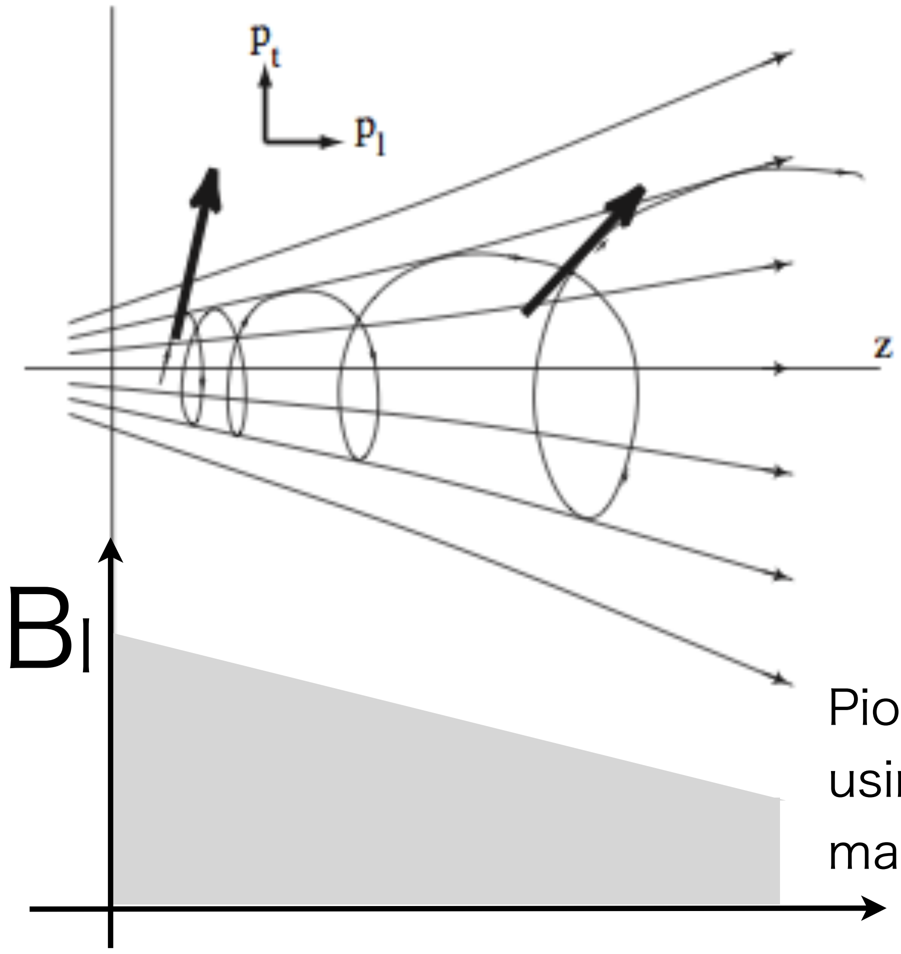

ELEMENTARY PARTICLES AND FIELDS
Experiment

Search for Lepton-Flavor-Violating Rare Muon Processes

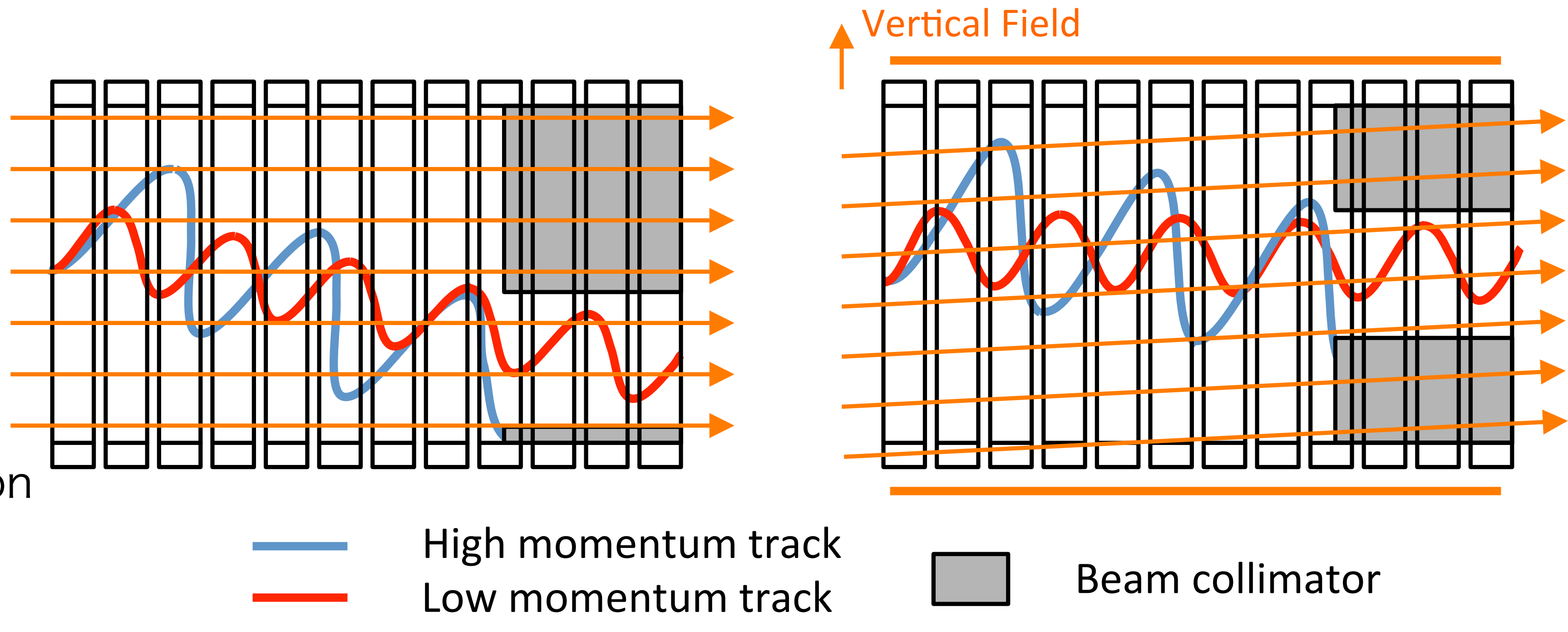
R. M. Djilkibaev and V. M. Lobashev

Institute for Nuclear Research, Russian Academy of Sciences, pr. Shestidesyatiletiya Oktyabrya 7a, Moscow, 117312 Russia

Received March 26, 2010; in final form, July 12, 2010



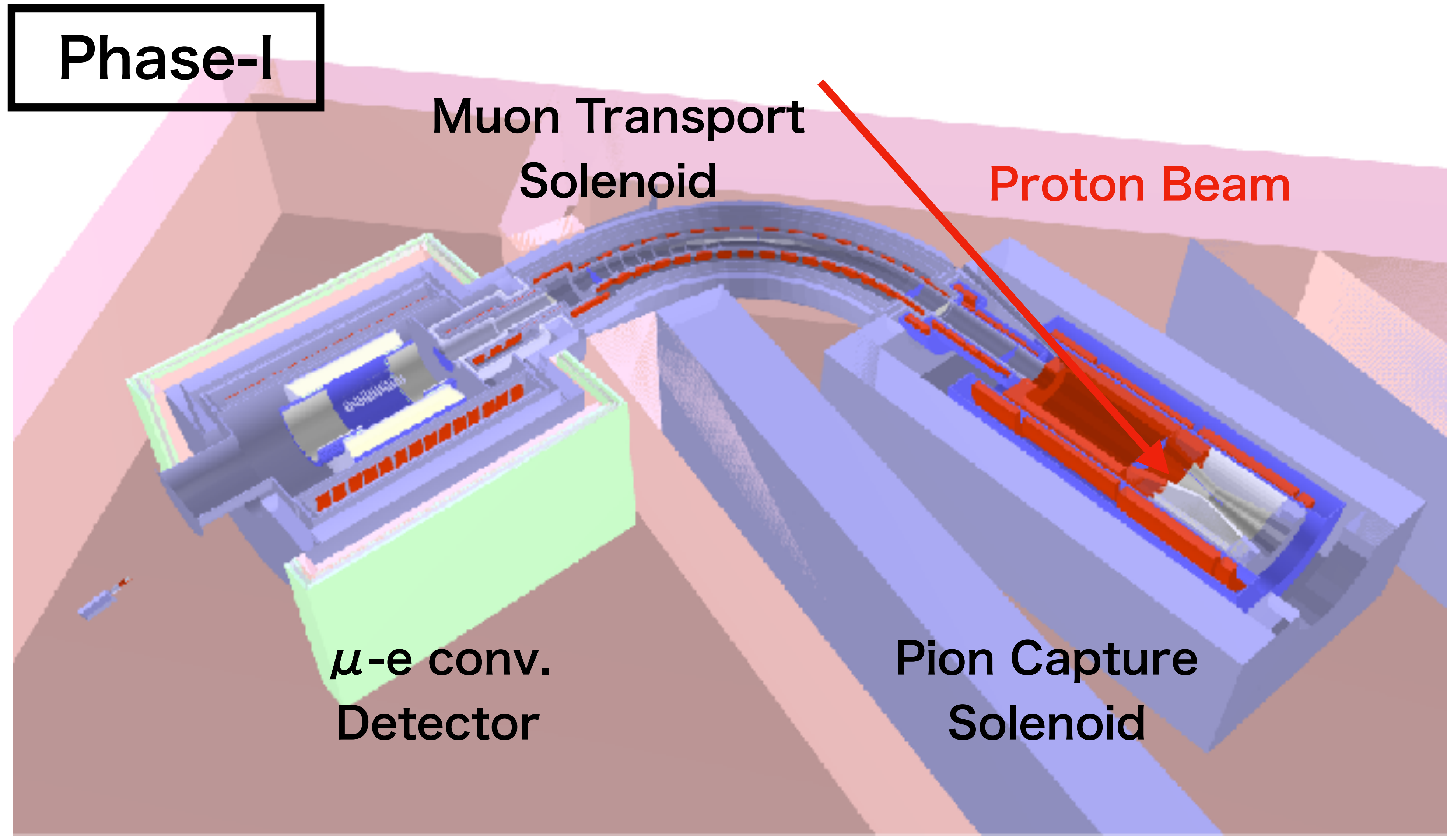
Pion/muon collection using gradient magnetic field



COMET Staging Approach

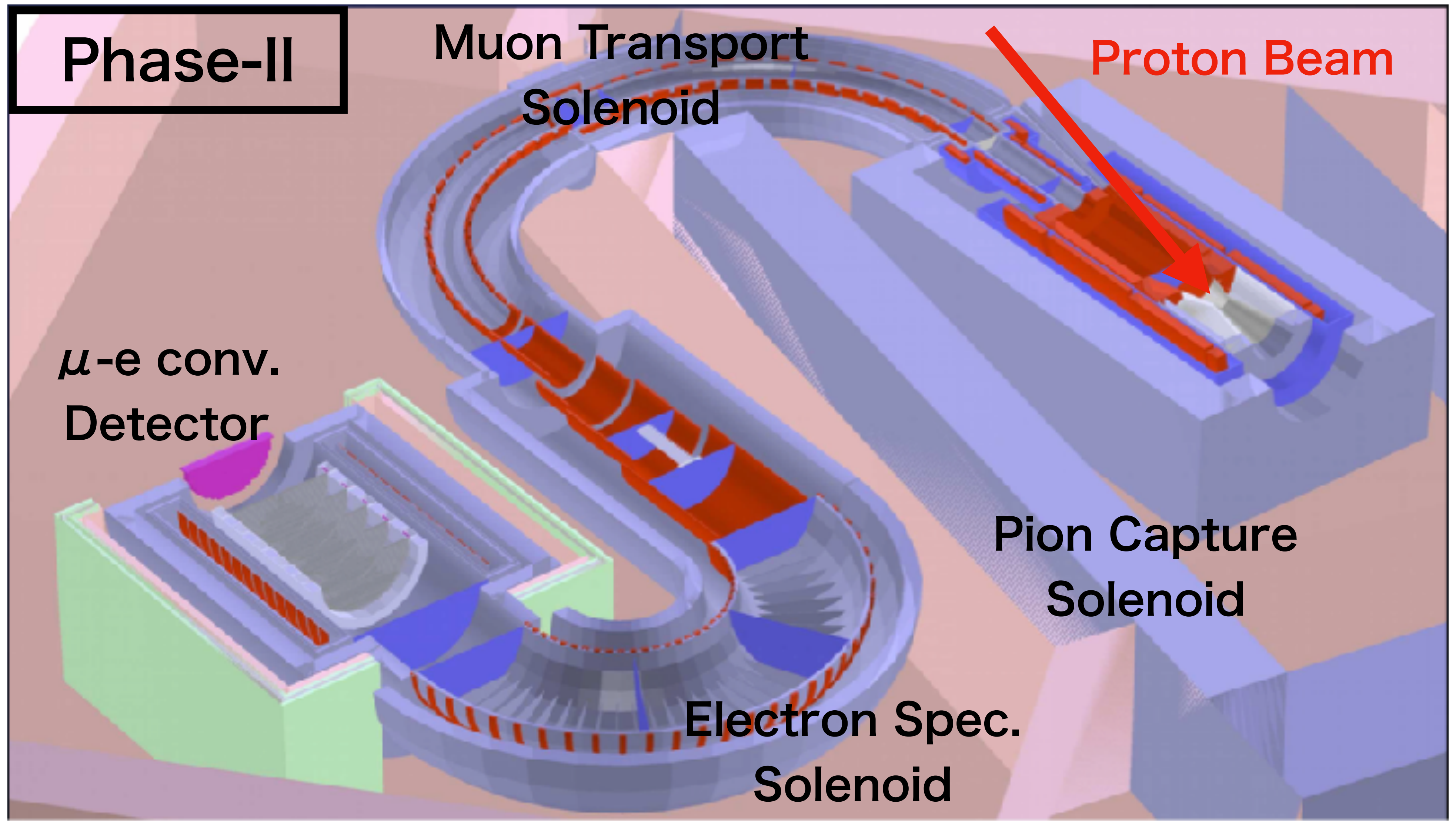
Target Sensitivity <10^{-14} with 3.2kW beam

- 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 (FY2020-2024)
- 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 JFY2025-



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



Phase-α

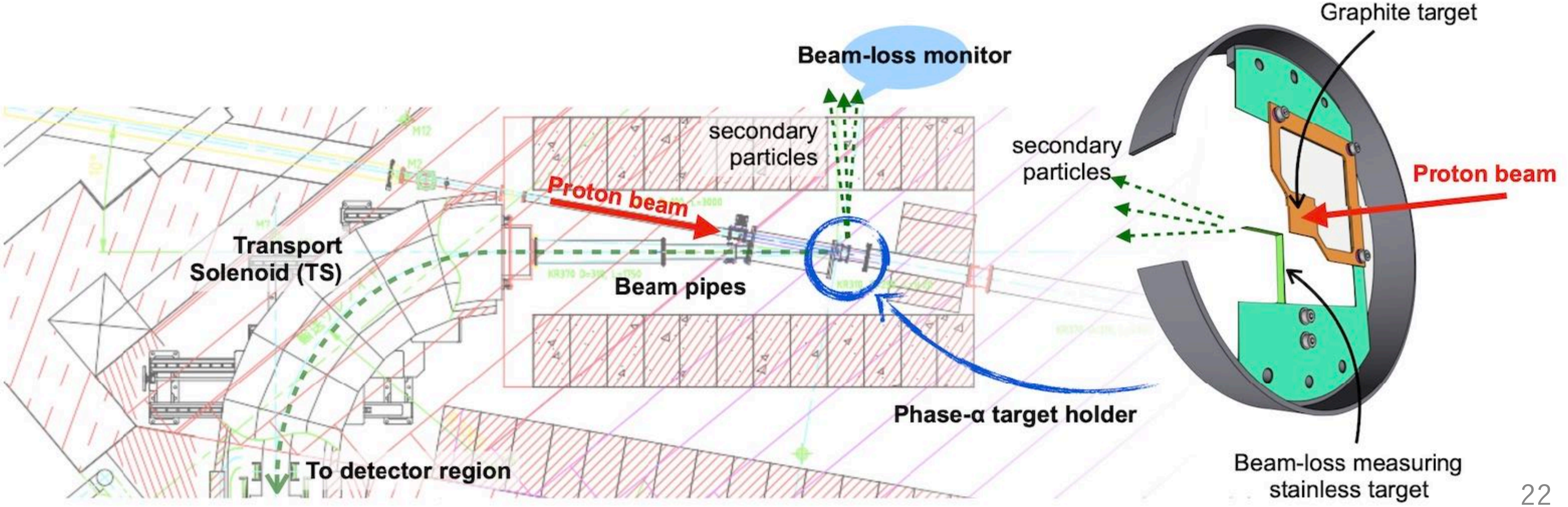
- **Commissioning of**
  - **the COMET proton beam line and**
  - **the COMET muon beam transport.**

- **Beam time in**
  - **10th − 14th February (commissioning)**
  - **3rd − 4th & 9th – 15th March**

Phase-α Setup

Beamline without the Pion Capture Solenoid & Field

- ✦ A thin Pion Production Target contained in the beam vacuum chamber.
- ✦ Muon Transport Solenoid to be used in Phase-I & II, too.
- ✦ Beam-masking system with two moving collimator slits in front of the Transport Solenoid



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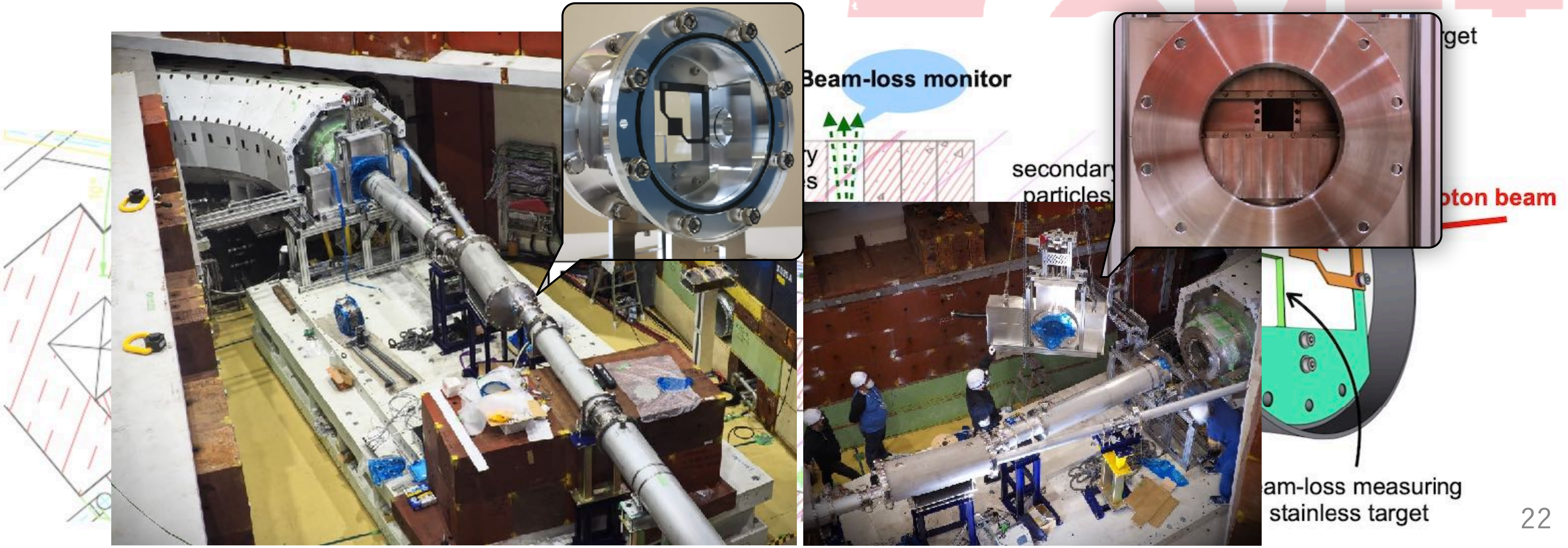
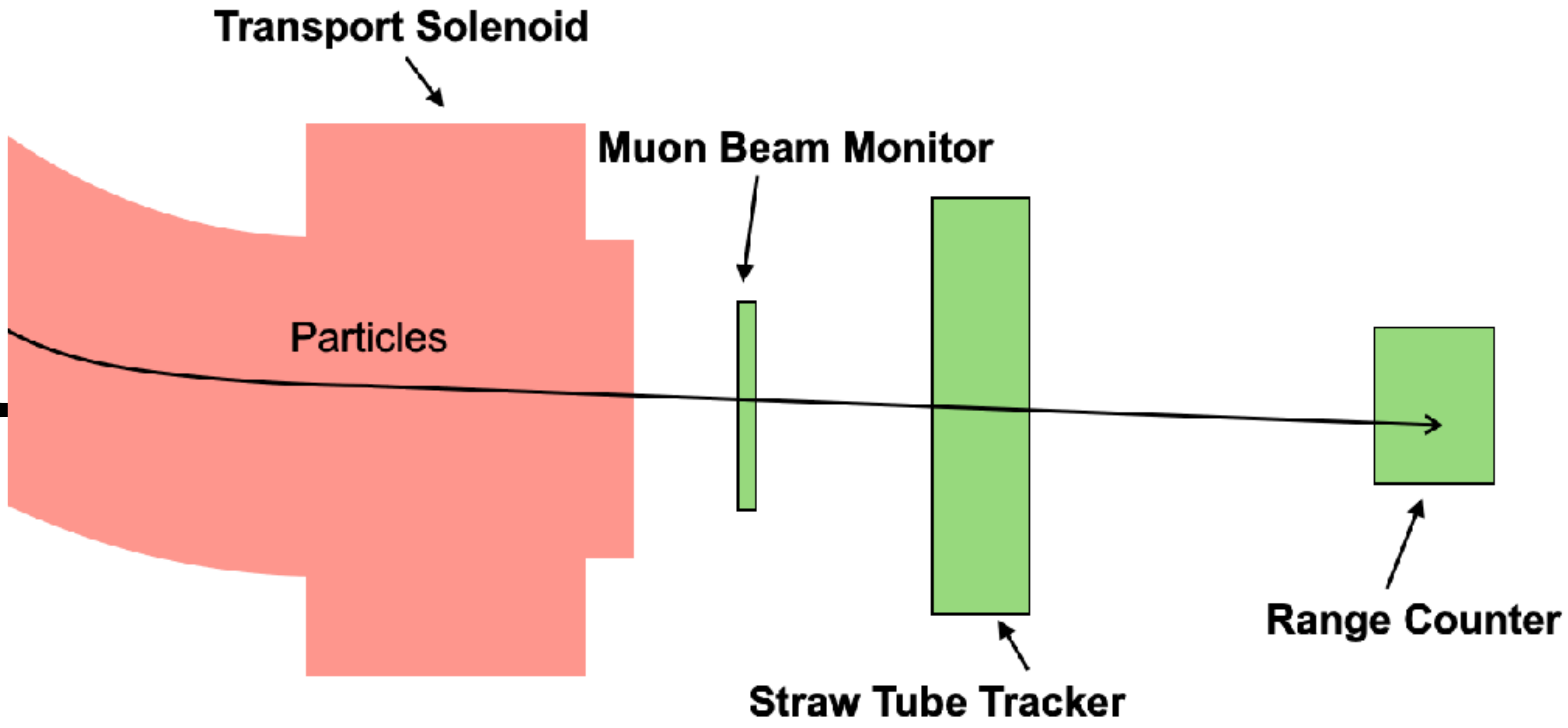


Detectors

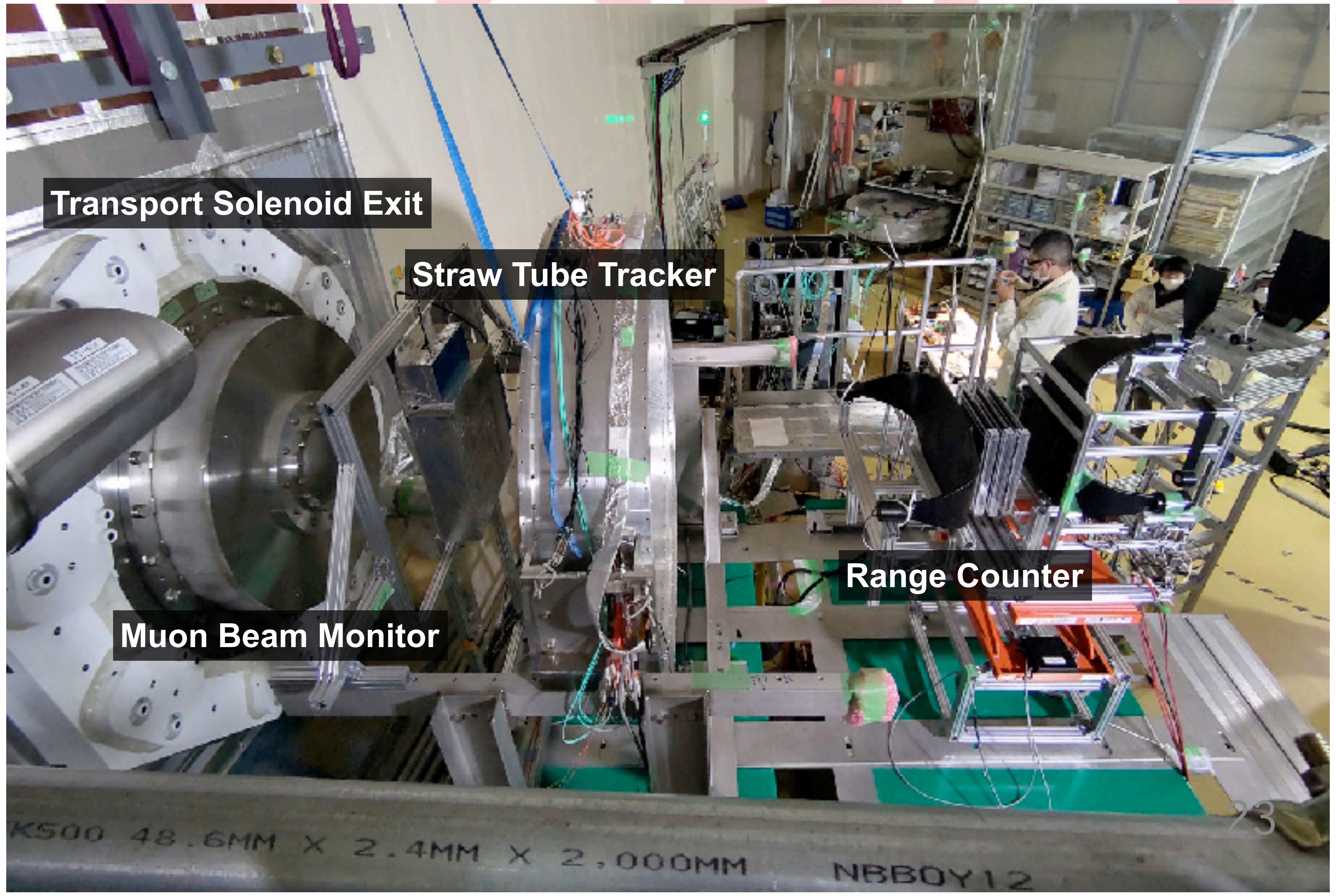


Detectors

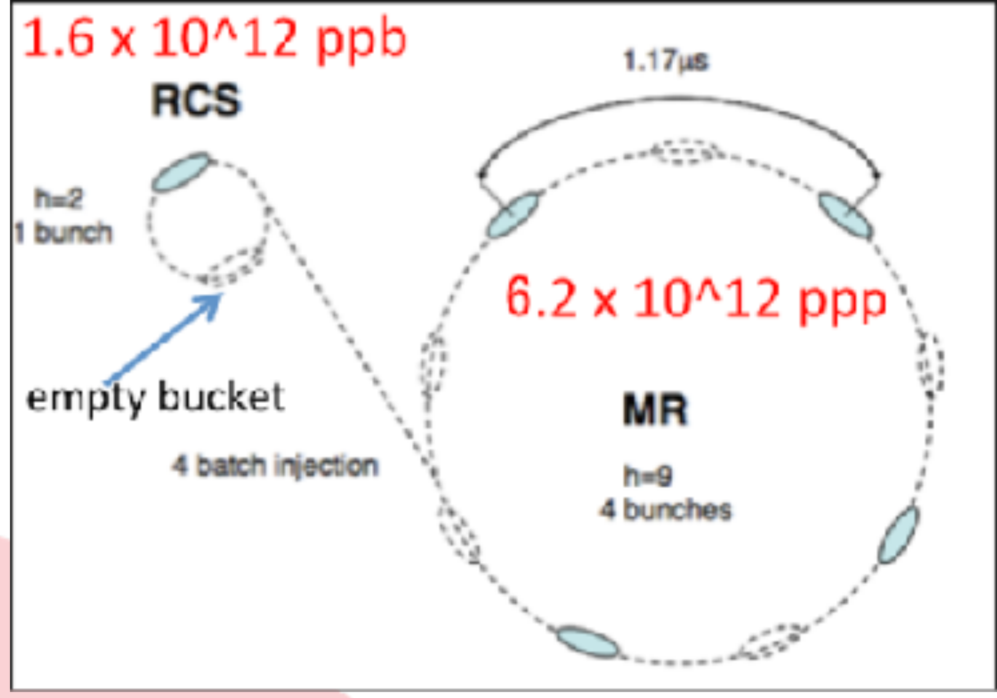
- ✦ Position measurement by the Muon Beam Monitor and Straw Tube Tracker
- ✦ Direction by the Straw Tube Tracker.
- ✦ Decay time measured by the Range Counter.
  - ★ For momentum reconstruction and muon identification
  - ★ Also generates trigger signals

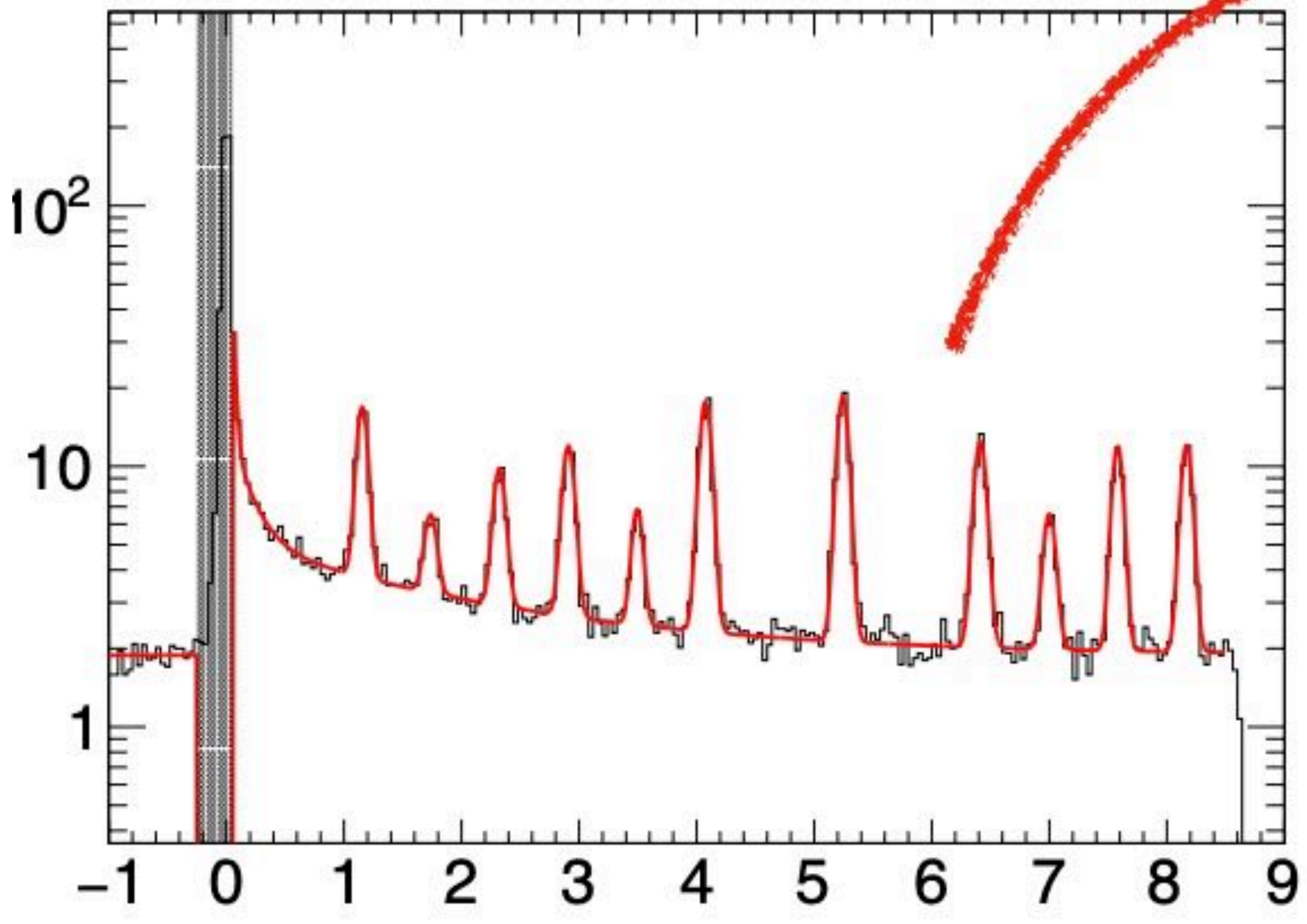
DAQ

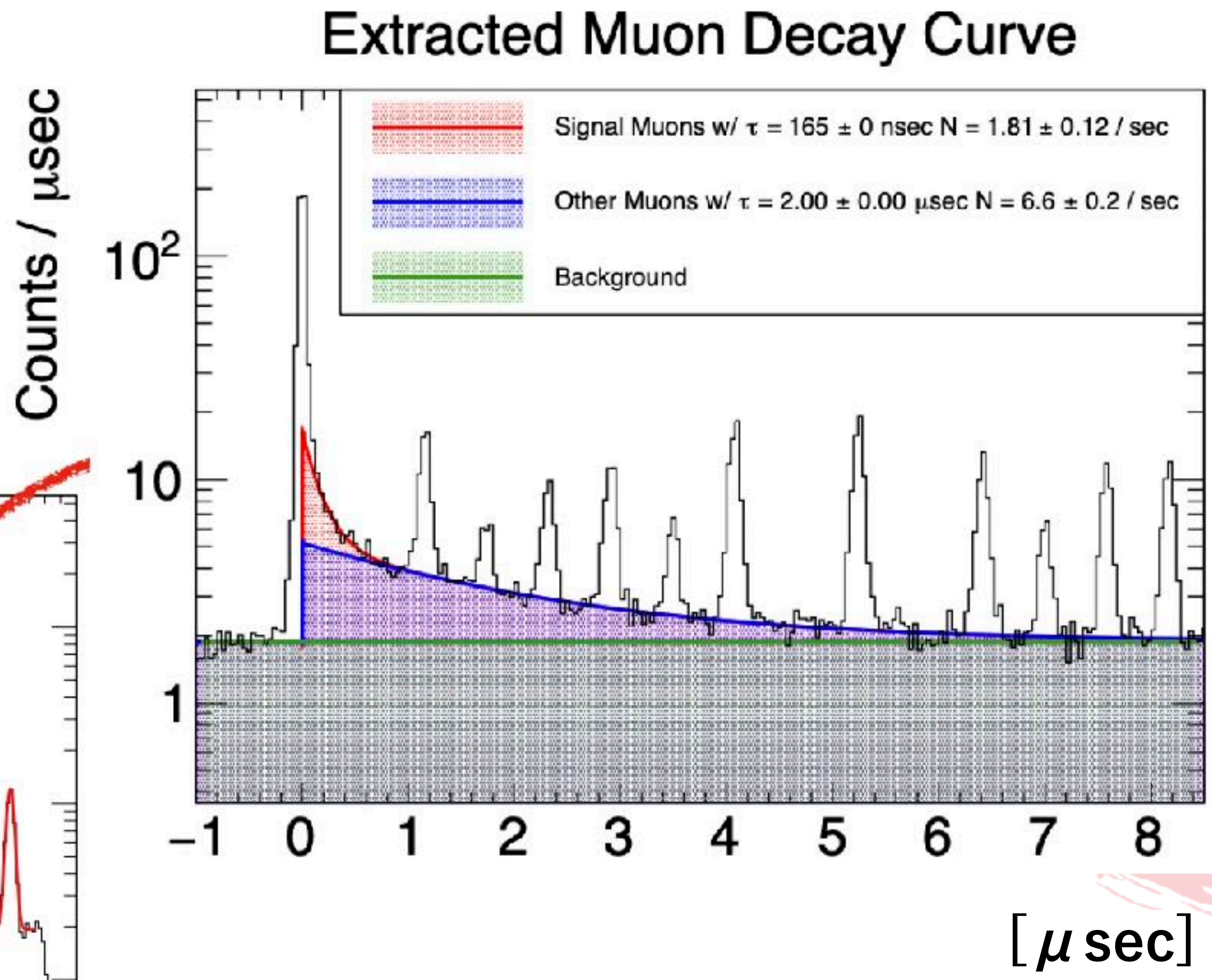
- ✦ Based on the MIDAS DAQ framework, officially adopted by COMET.



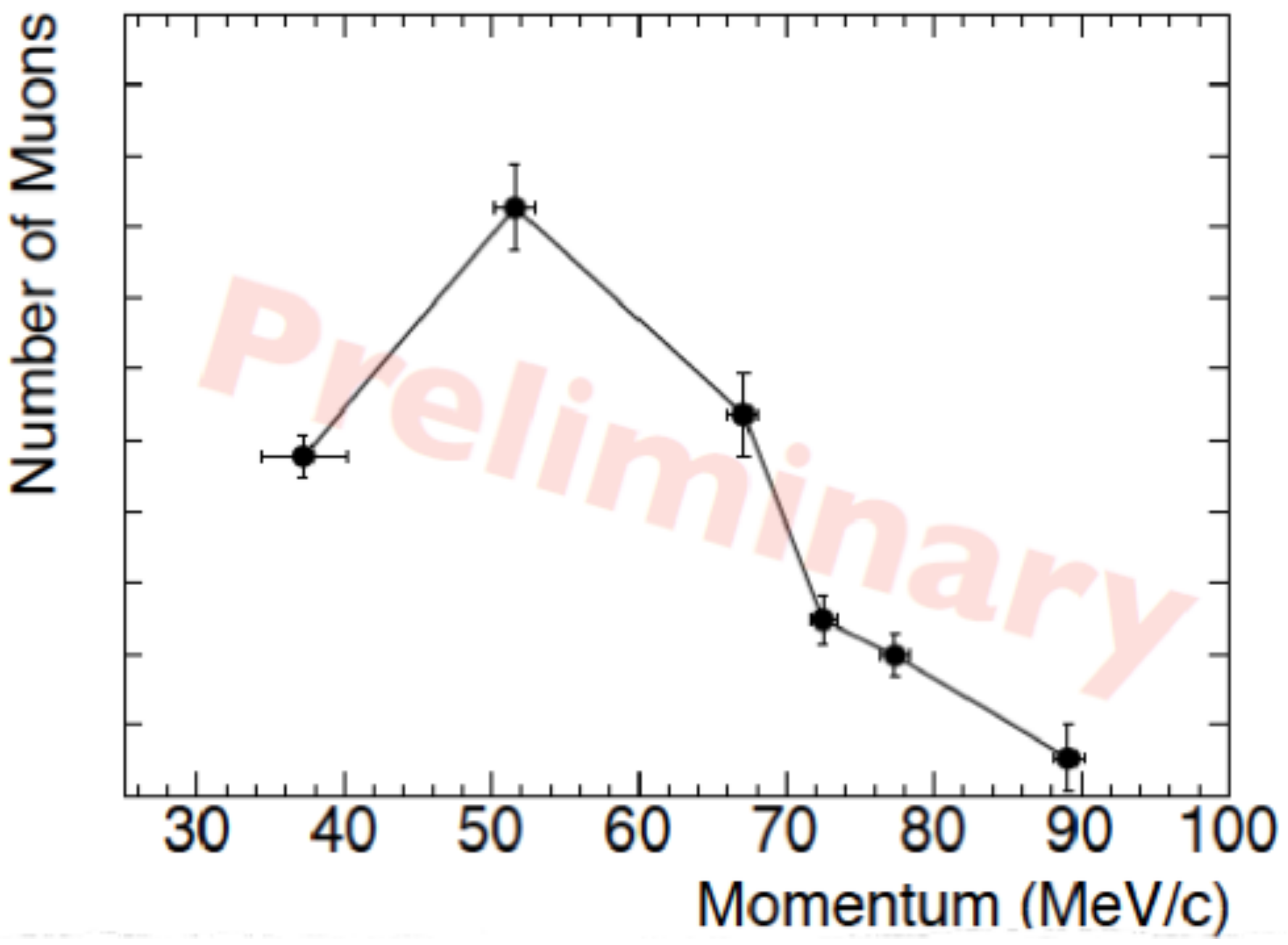
Muon Decay Curve Fitting





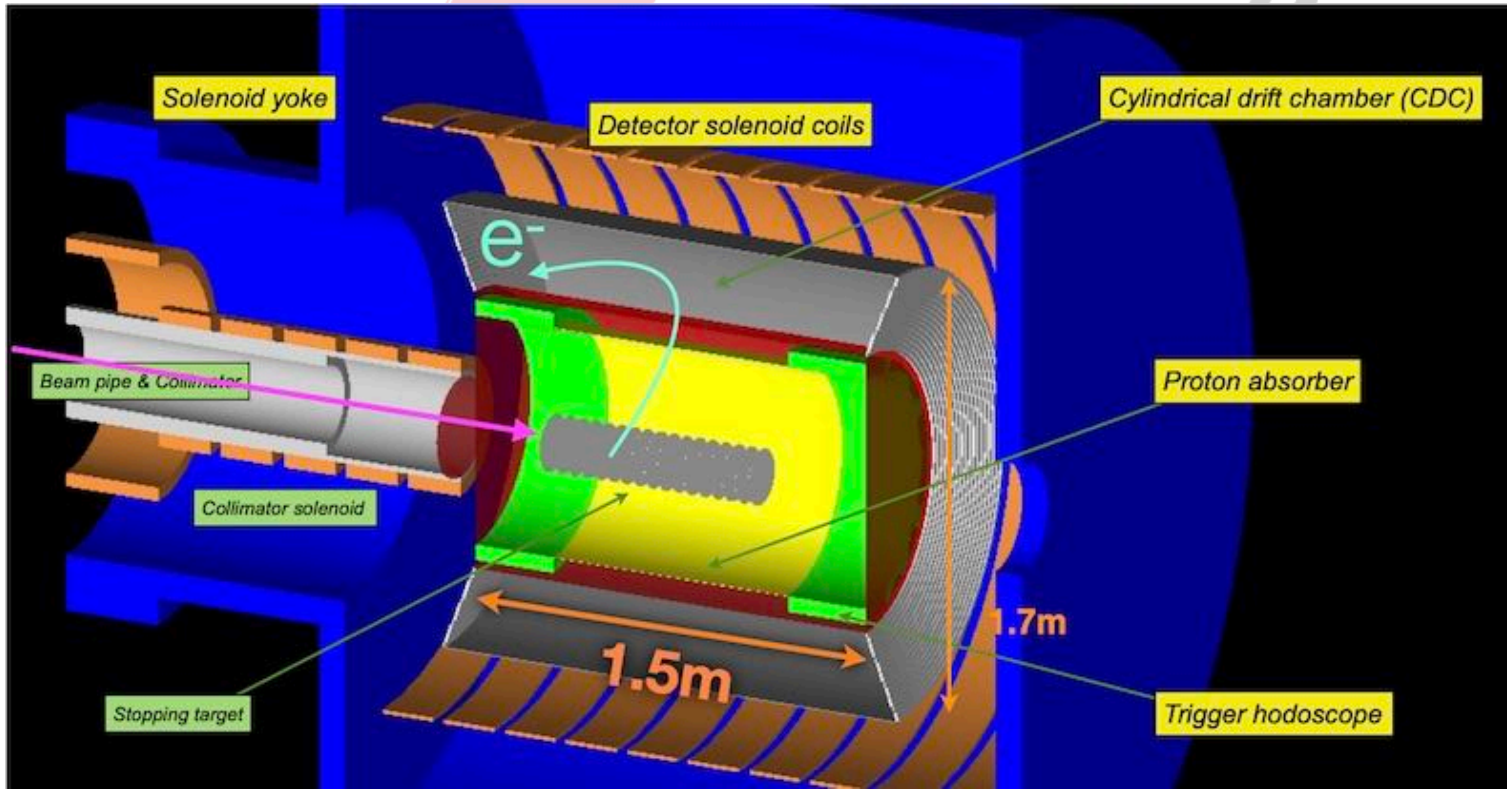


… and muon momentum spectrum

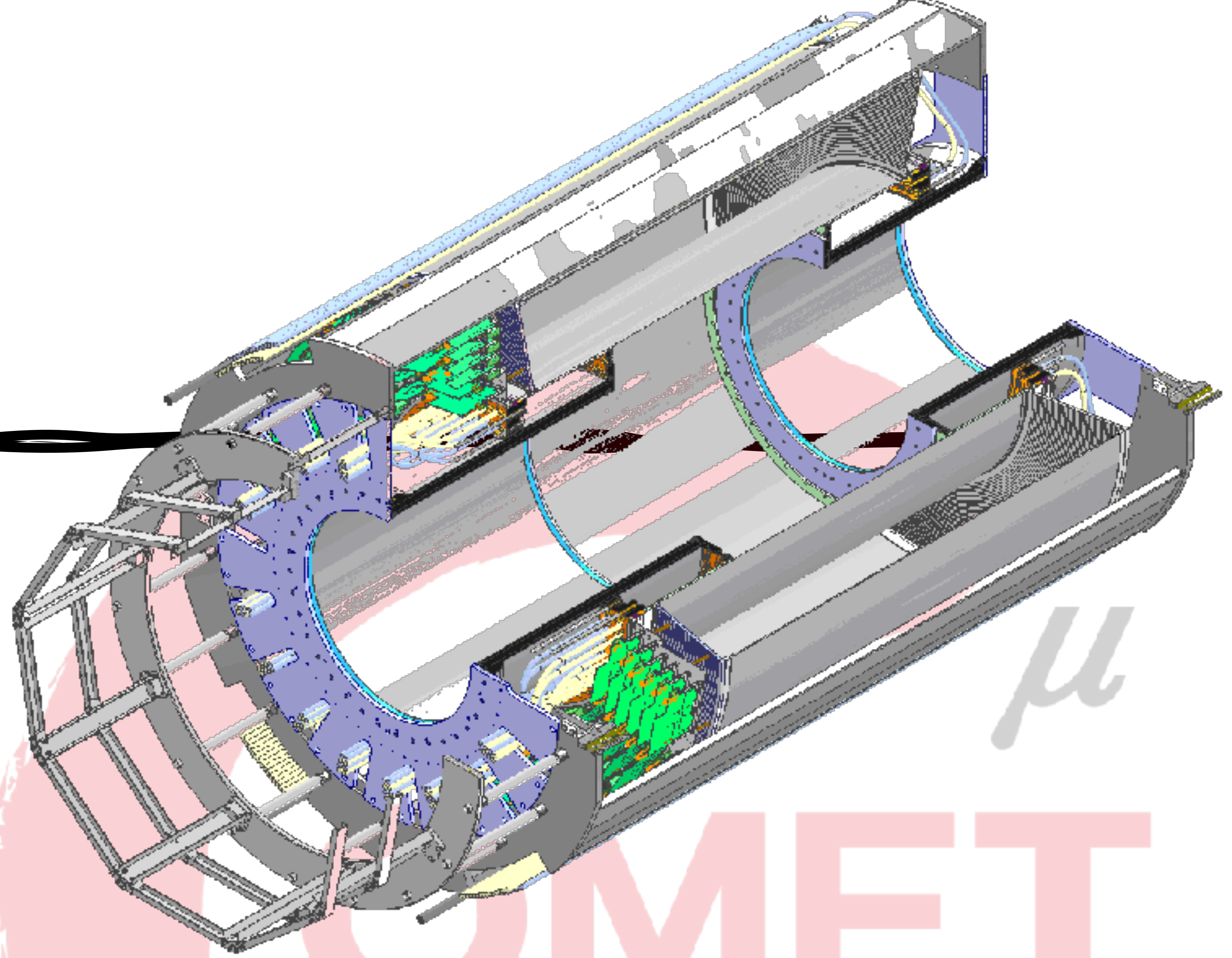


COMET Physics Detector

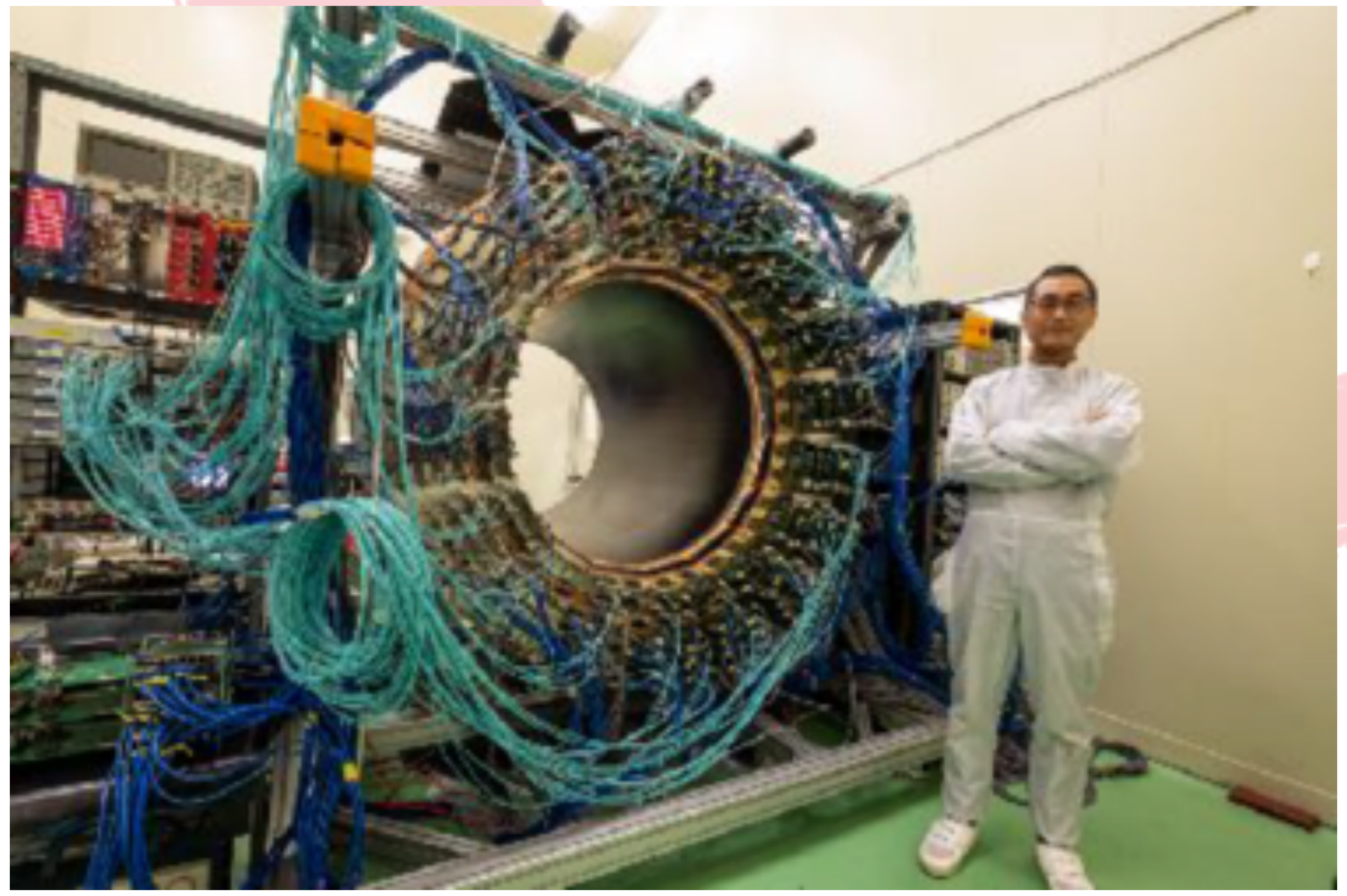
- COMET Phase-I Physics detector
  - CDC
  - CTH
  - Muon beam monitor
  - Muon stopping target
  - X-ray detector
  - CRV

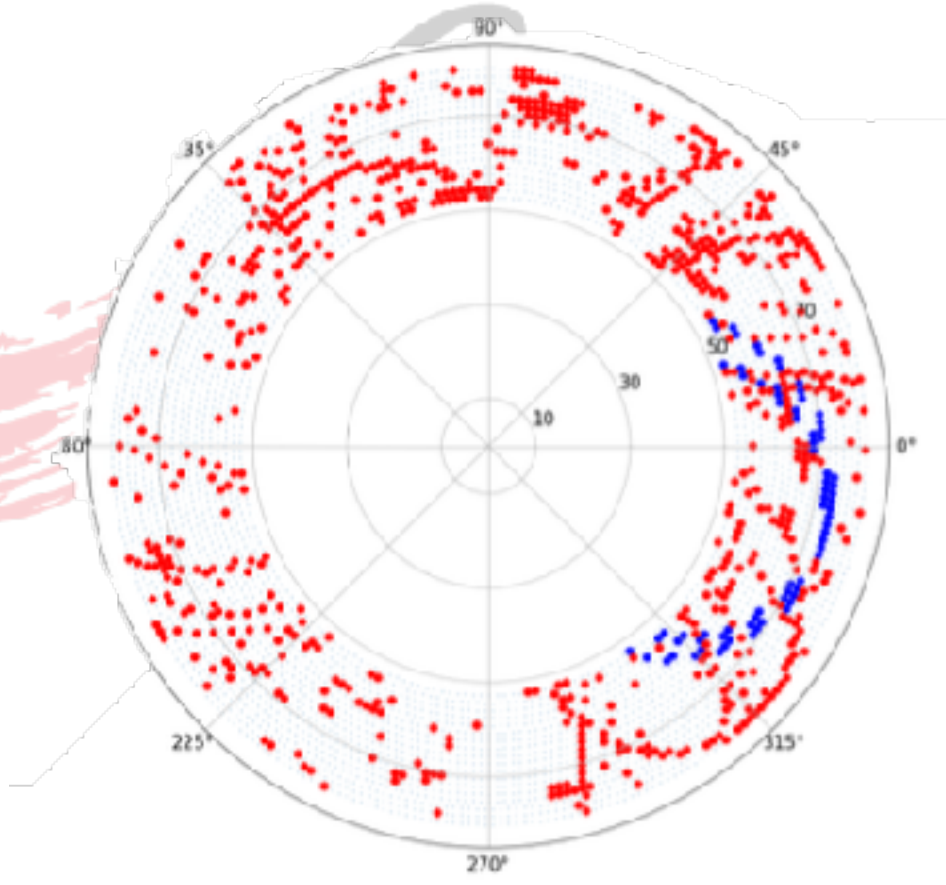


COMET CDC



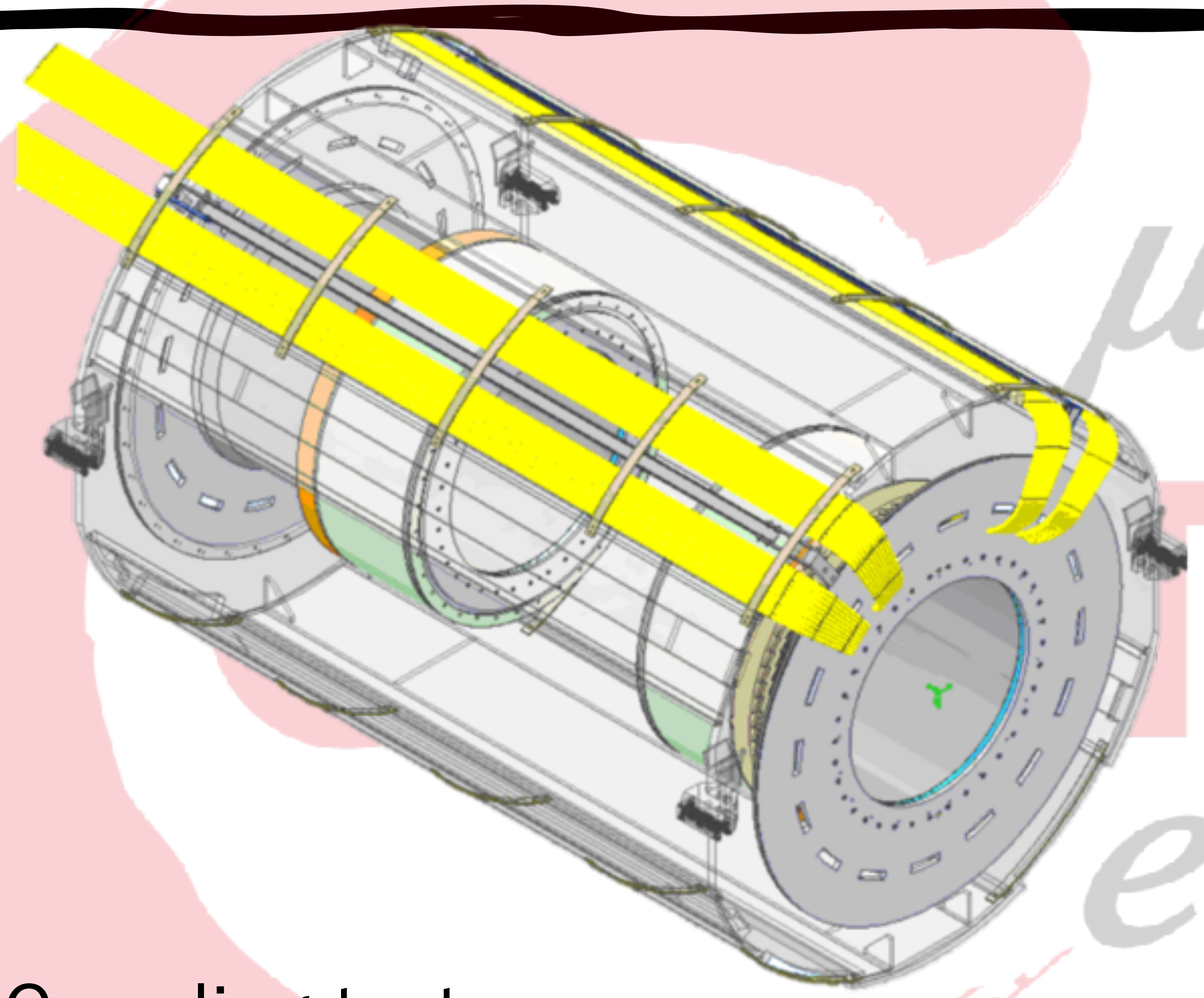
- Cylindrical Drift Chamber (CDC)
  - Main Detector of Phase-I Physics
  - 20 layers structure
  - -5,000 sense wires (Au coated W)
  - -15,000 field wires (Al)
  - All stereo layers - He base gas
  - (He : iC4H10 = 90 : 10)
- Readout by RECBE & FCT, Track trigger by COTTRI
- Construction completed in 2016, followed by CR test in KEK
- Moved to J-PARC in Sep. 2022. Conditioning in progress in J-PARC



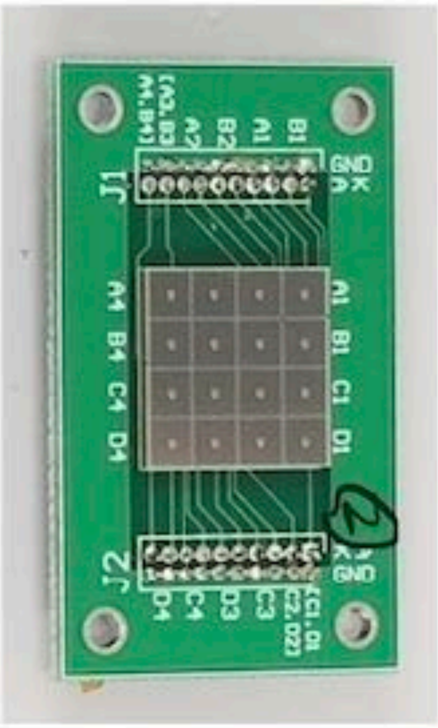


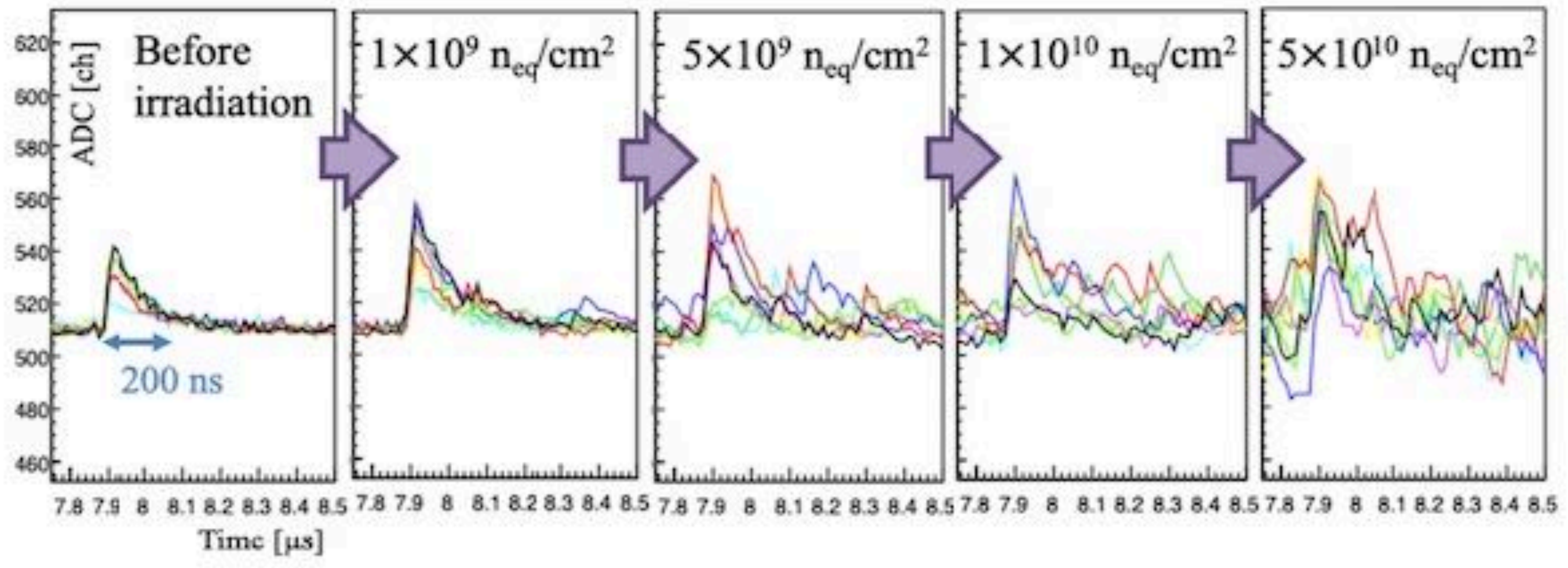
CTH – Cylindrical Trigger Hodoscope

- Two layers of plastic scintillators with MPPC readout through optical fibers
  - 5-8 m fibers to avoid radiation damage on MPPCs
  - MPPC cooling to suppress noise
- Components' delivery in progress
  - **Start assembly at J-PARC in JFY2023**
- Beam test in Australia to finalize the design



MPPC cooling test



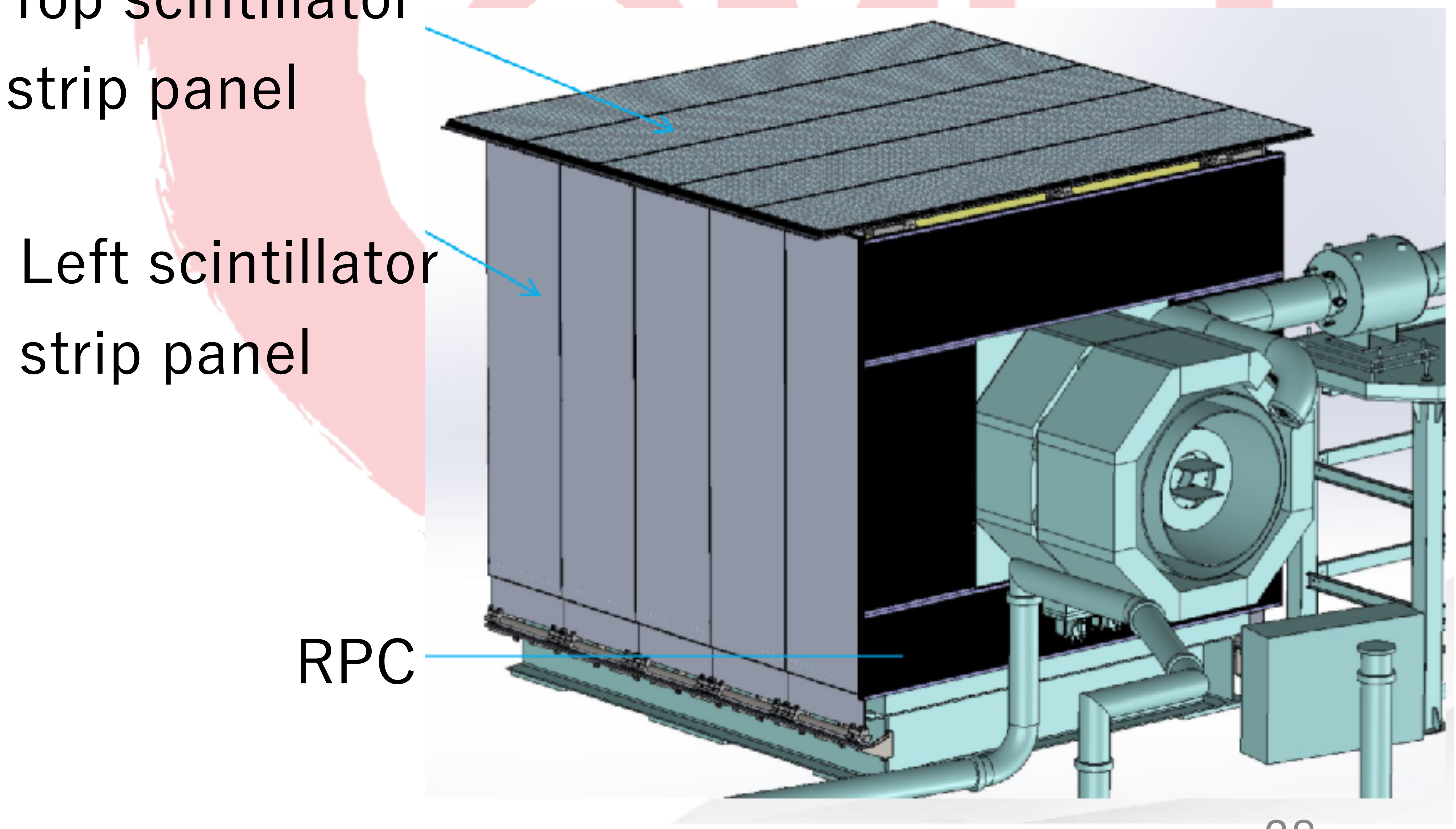


Signal for one channel (-36 °C, ~5.7 p.e.)

Cosmic Ray Veto (CRV) detector

- Scintillator strips covering the major parts of the walls
- RPC in the front area where neutron background is significant
- 1st module on the way to J-PARC, arriving in autumn

@JINR



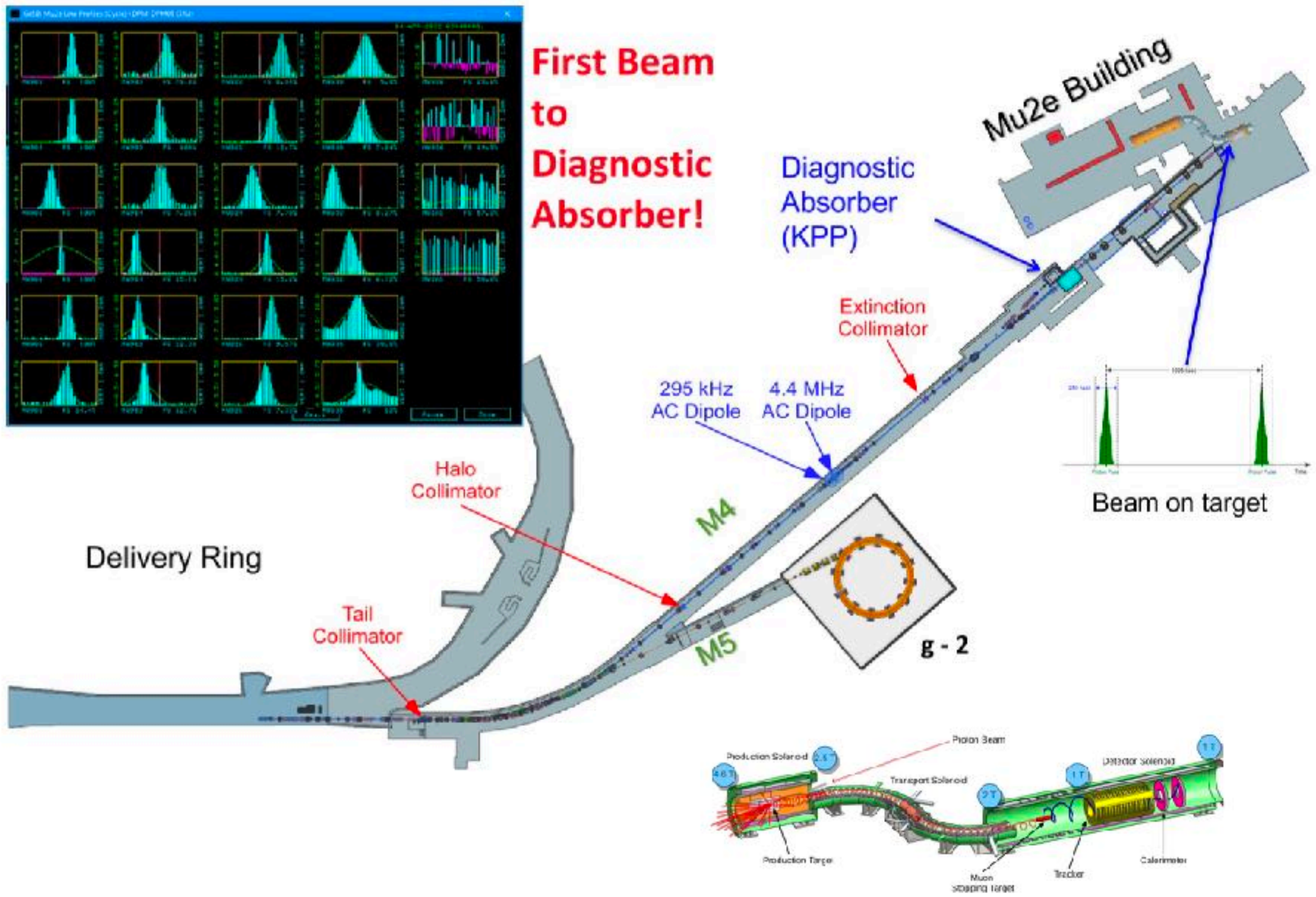
COMET time line

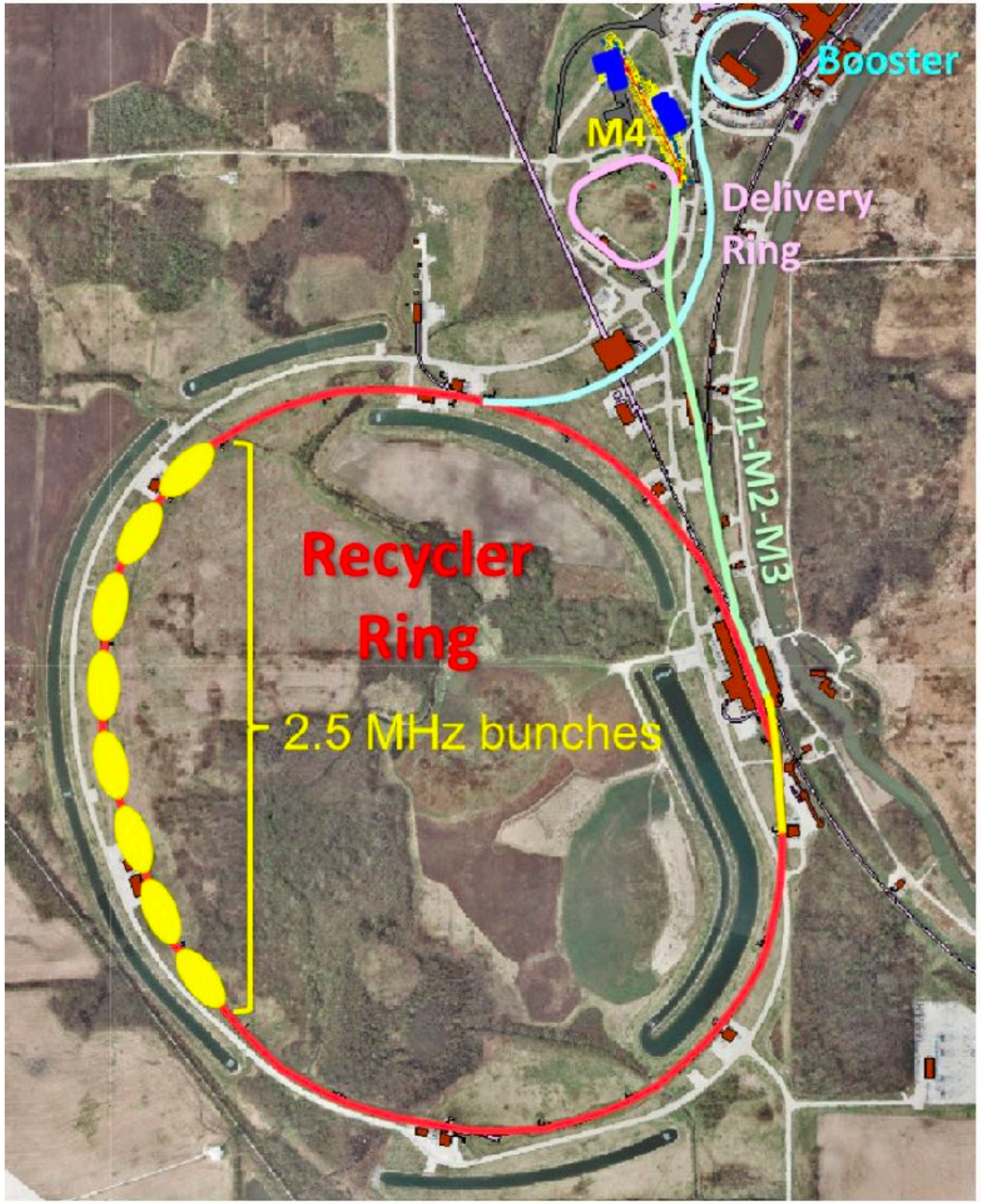
- Detector solenoid magnet delivery in autumn 2024 followed by detector installation
  - Physics detector to be ready at the end of 2024
- Capture solenoid magnet delivery in spring 2024 followed by installation and conditioning.
  - To be ready at the end of 2025
- Target and shield installation in early 2026.
- **Physics in spring 2026!**

Mu2e

Steven Boi, WG4 on 22/Aug

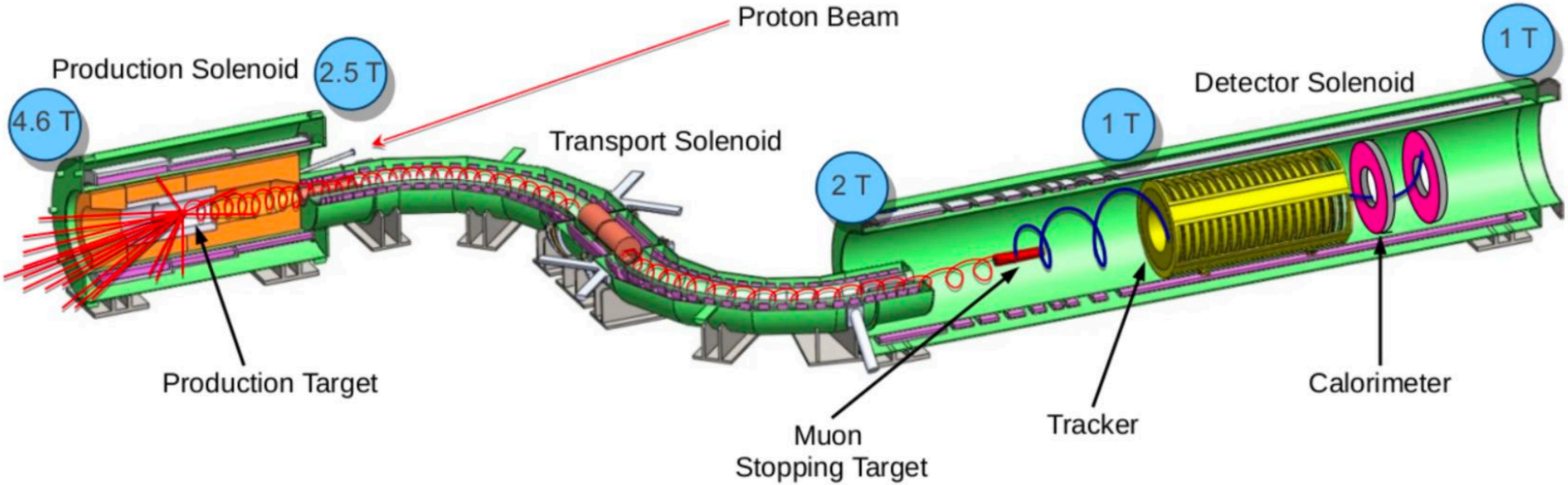
Mu2e at FNAL


First Beam
to
Diagnostic
Absorber!
Mu2e Building
Diagnostic
Absorber
(KPP)
Extinction
Collimator
295 kHz
AC Dipole
4.4 MHz
AC Dipole
Beam on target
Halo
Collimator
M4
Delivery Ring
Tail
Collimator
M5
g - 2


Booster
M4
Delivery
Ring
M1-M2-M3
Recycler
Ring
2.5 MHz bunches

Mu2e at FNAL

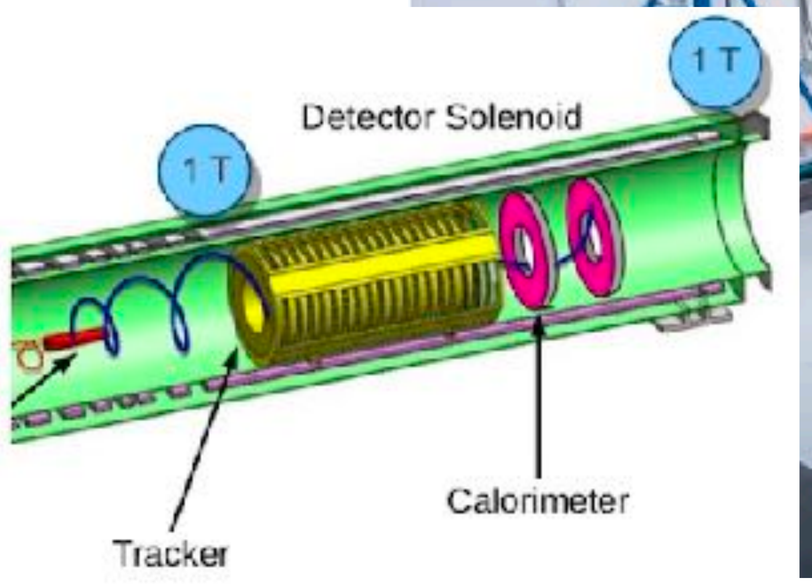
Booster
M4
Delivery
Ring

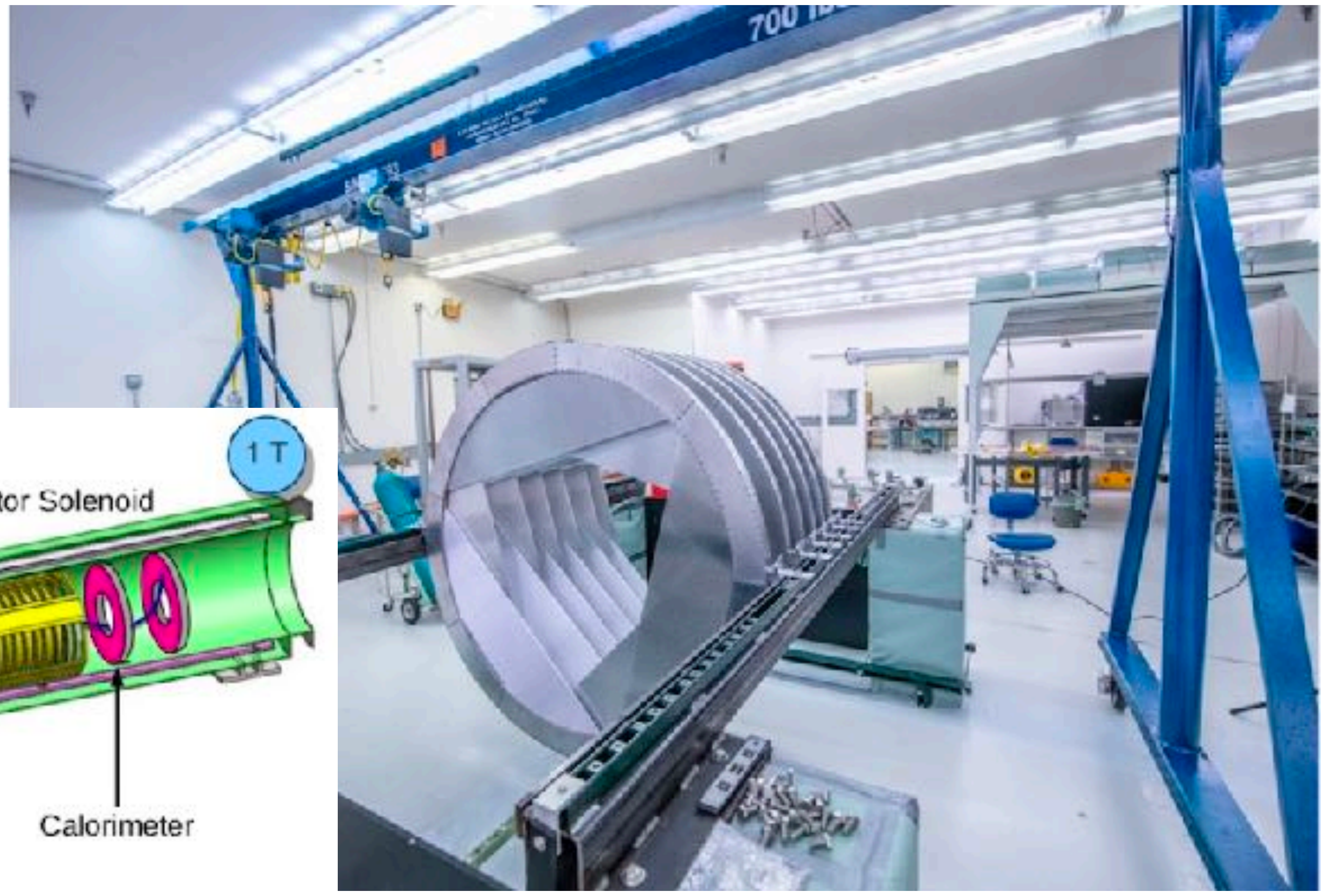


Proton Beam
Production Solenoid
2.5 T
4.6 T
Transport Solenoid
2 T
1 T
Detector Solenoid
1 T
Production Target
Muon
Stopping Target
Tracker
Calorimeter

Mu2e solenoids and detectors

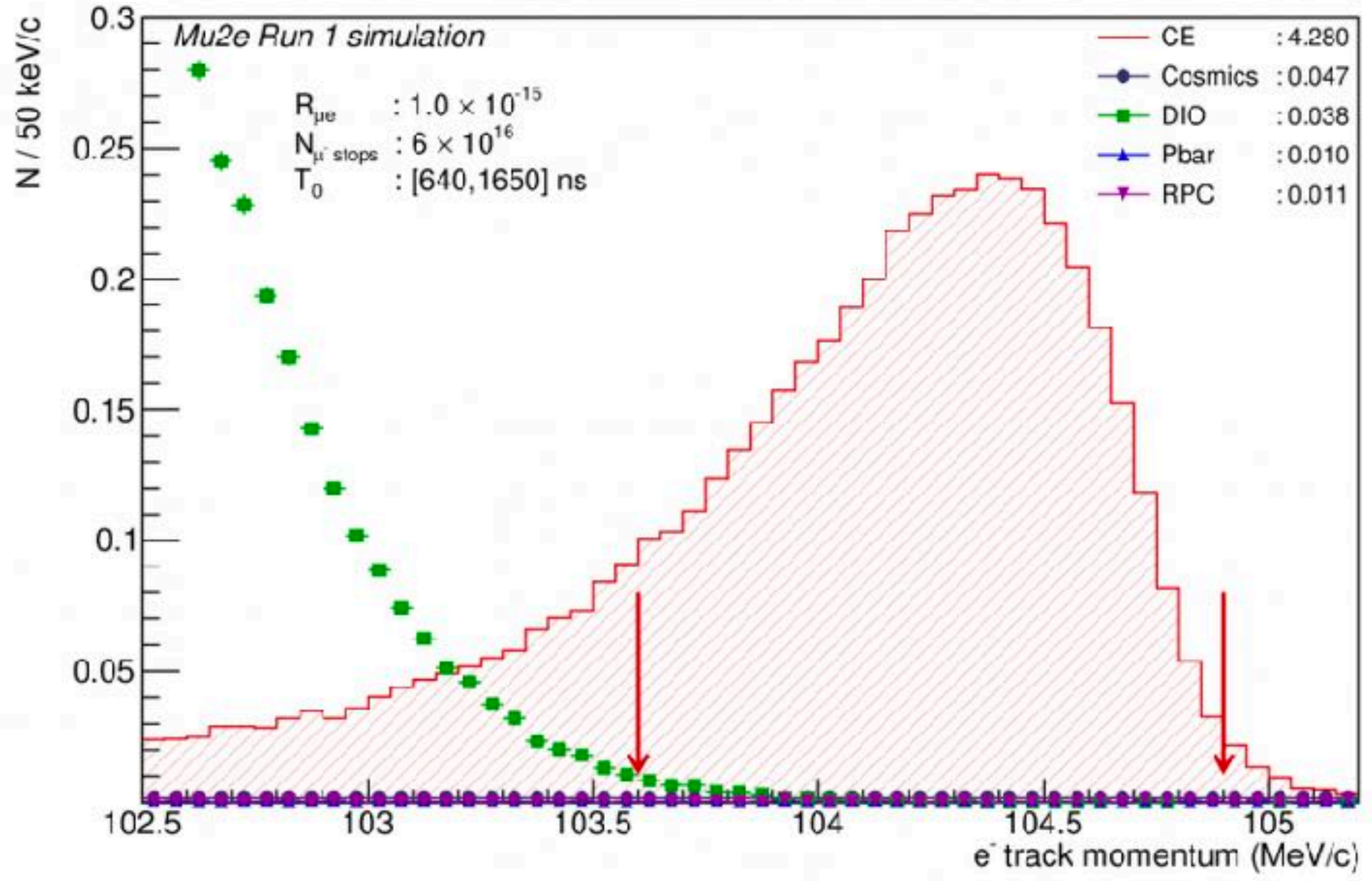
- Production, Transport, and Detector solenoids
    - All coils fabricated. TS almost complete
- Calorimeter
    - First disk completed, second disk underway
- Tracker
    - 26 / 36 planes are built
- CRV
    -

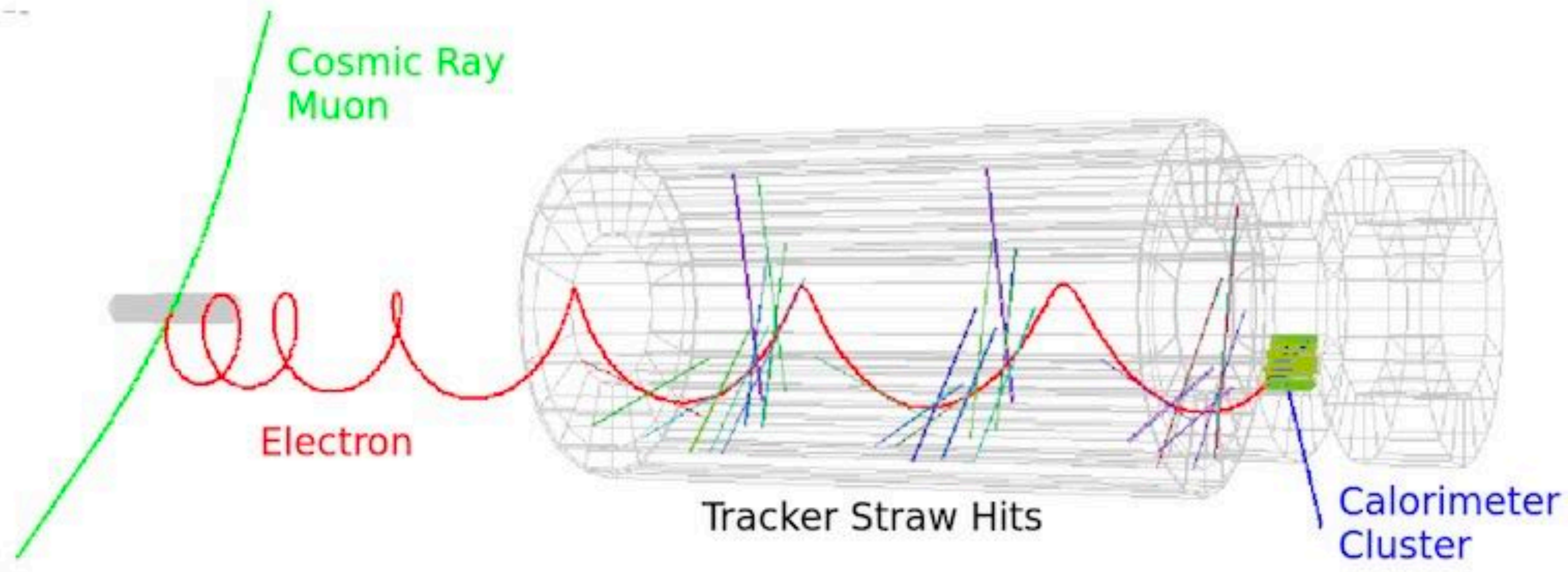




Mu2e time line

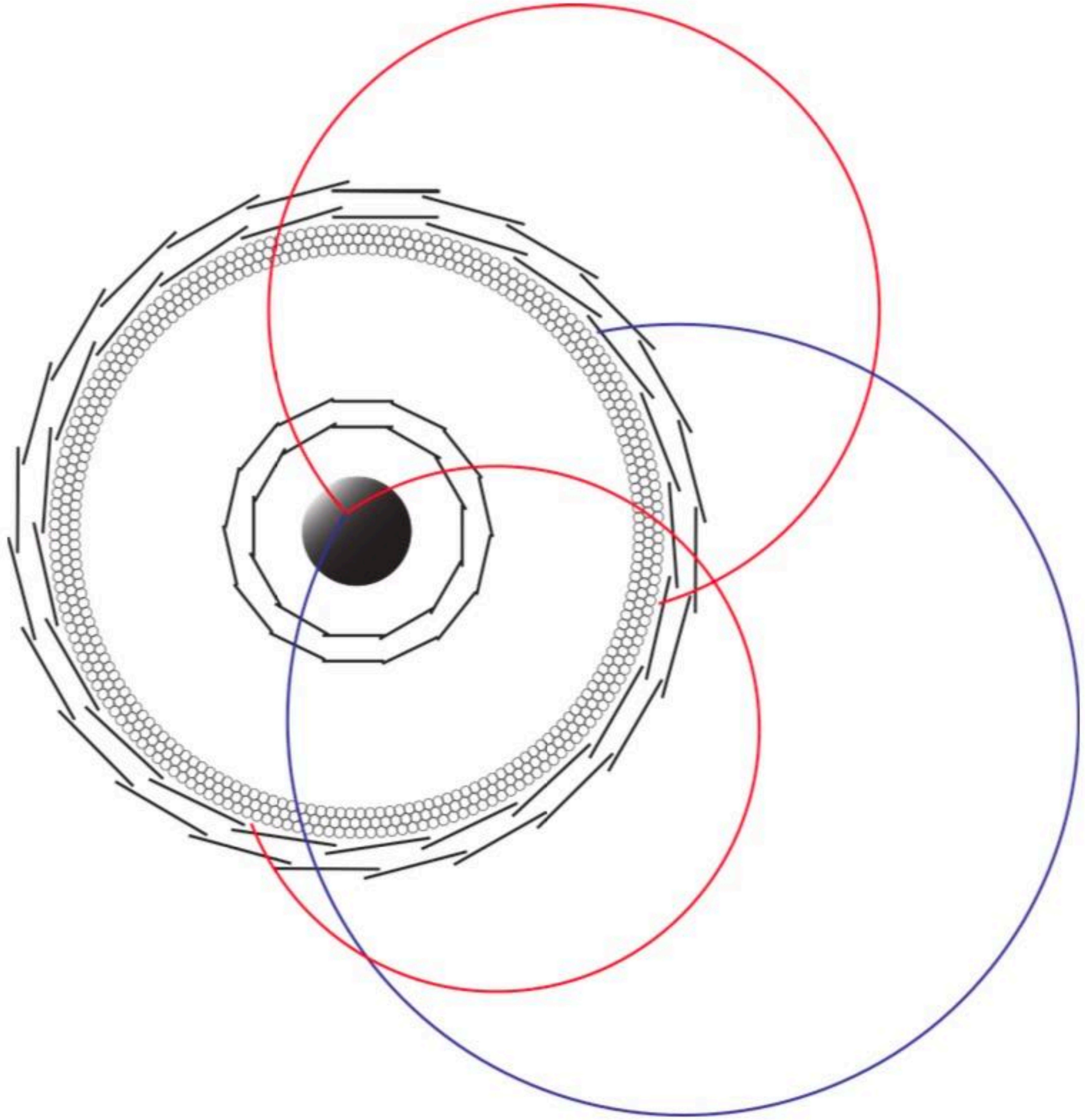
- Detector and beam commissioning through to 2026
  - Take Run 1 data until LBNF/PIP-II shutdown
  - x1000 improvement over SINDRUM-II
- Resume data collection in 2029 after long shutdown
  - x10000 improvement over SINDRUM-II





Mu3e at PSI

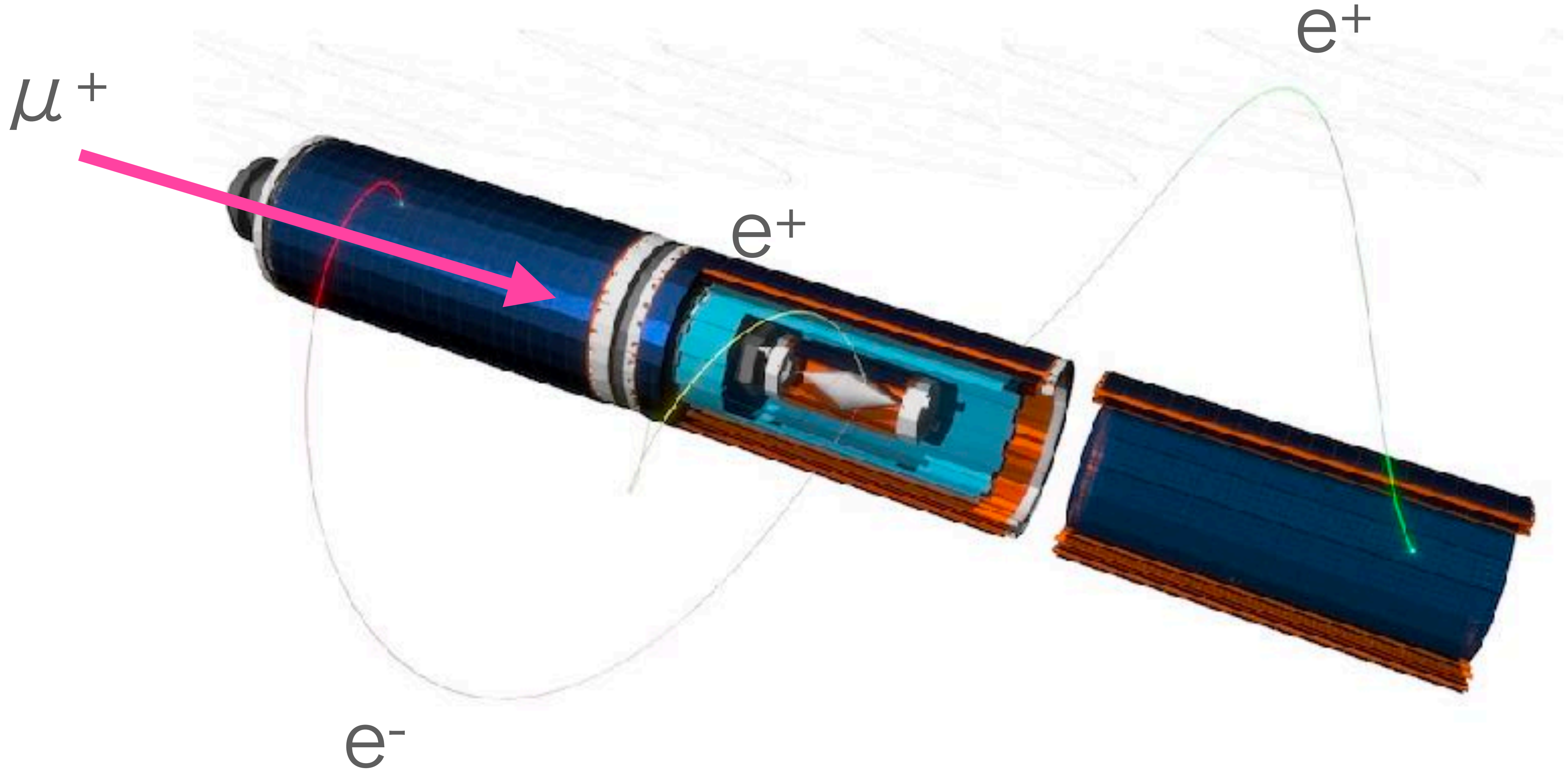
- $\mu \to eee$ search

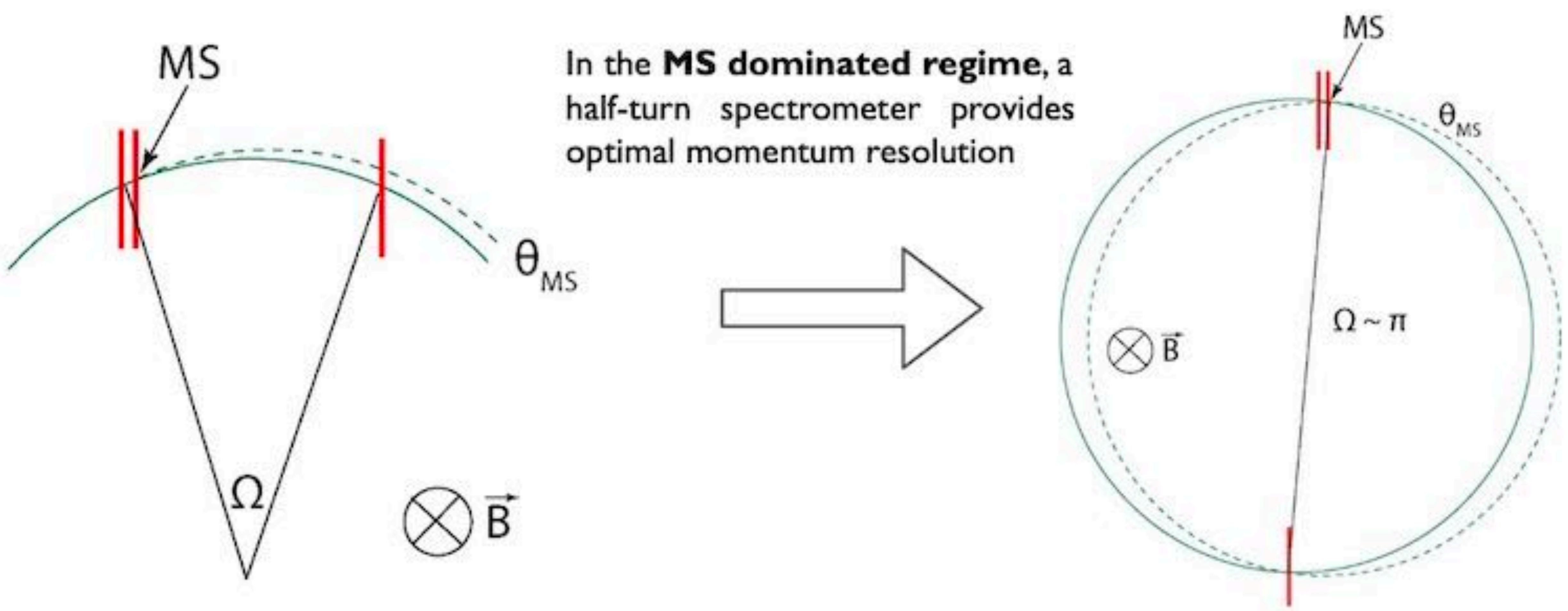


Martin Müller, WG4 on 22/Aug

Mu3e: $\mu\rightarrow$eee search at PSI

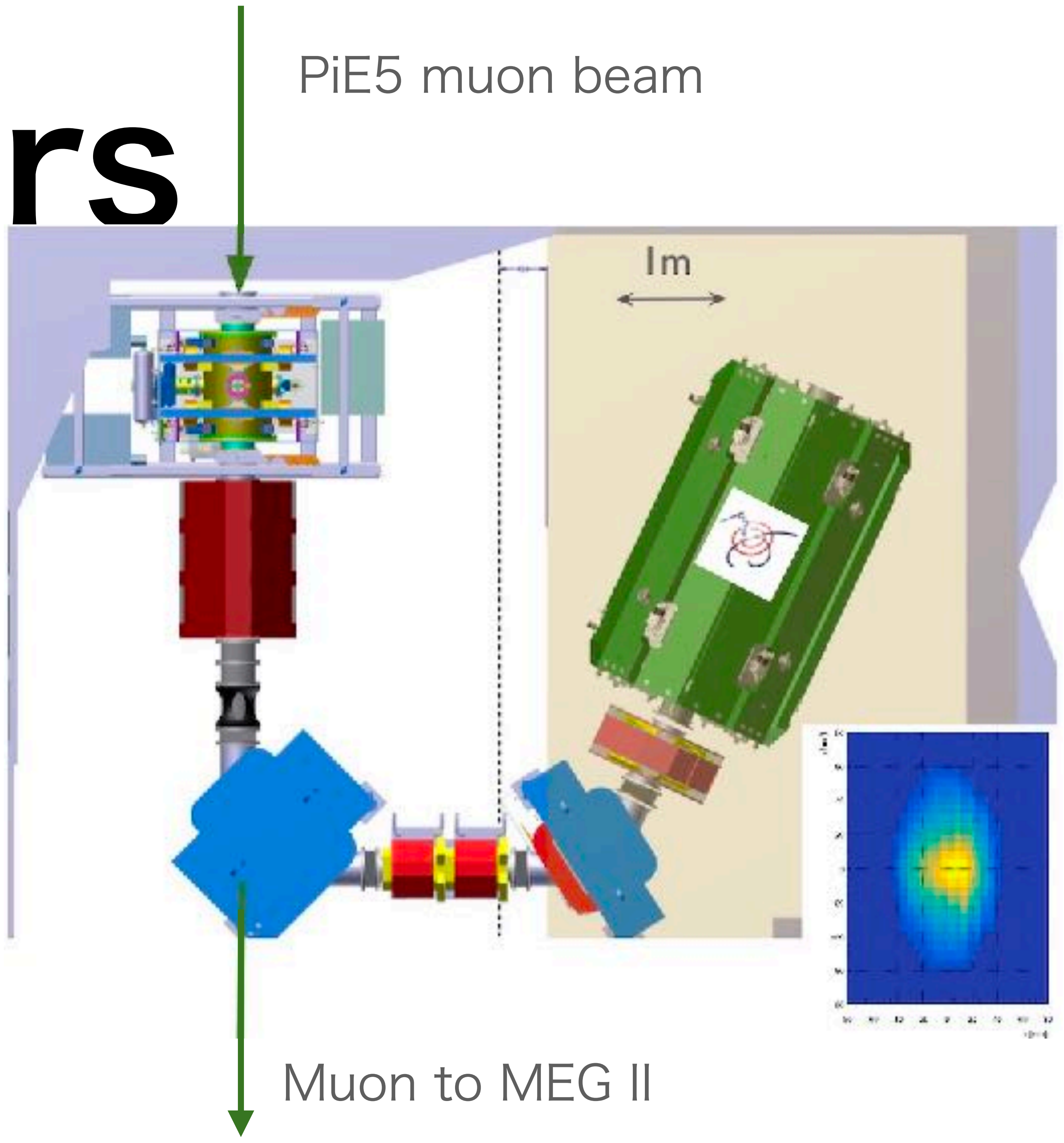
- $\mu^+ \rightarrow e^+e^+e^-$
  - Common vertex
  - Time coincident
  - $\Sigma E = m_\mu$
  - $\Sigma \mathbf{p} = 0$
- Backgrounds
  - Internal conversion
  - Accidental overlap

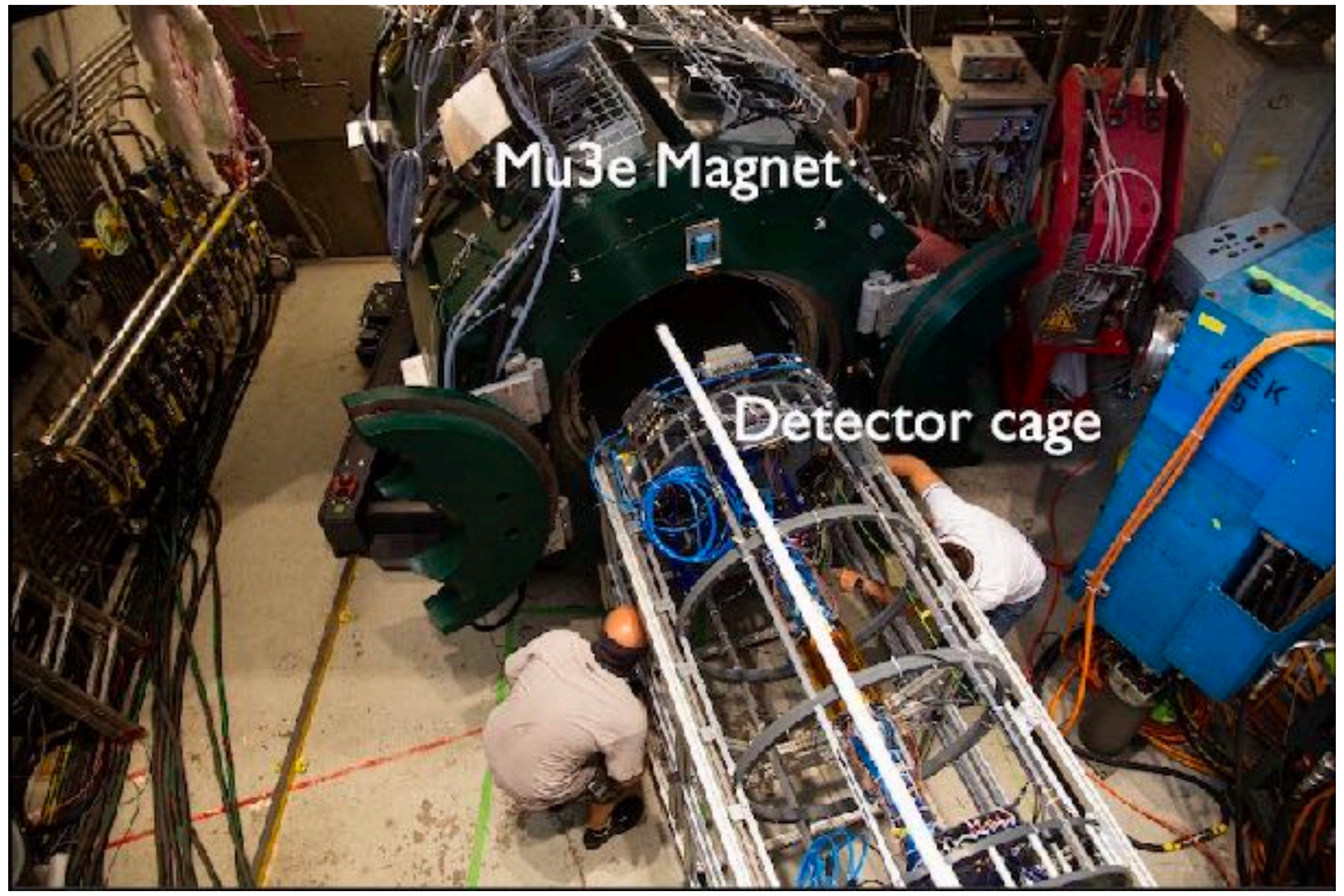


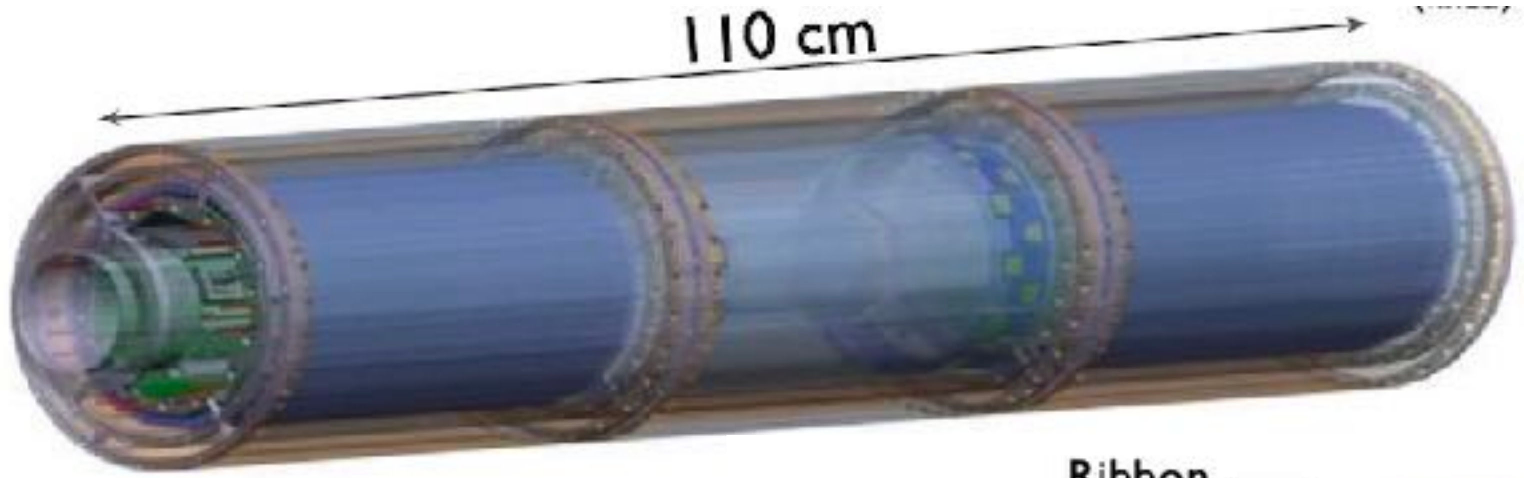


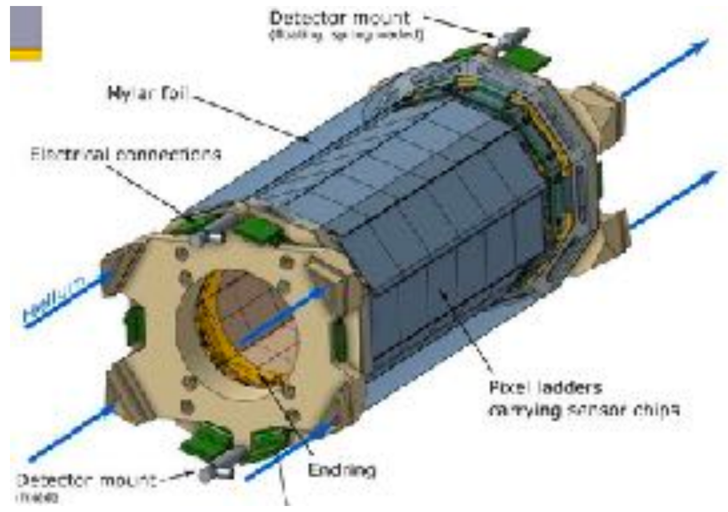
Mu3e beam line and detectors

- PiE5 beam line shared with MEG II
- Detector solenoid installed in PiE5
- High-voltage Monolithic Active Pixel Sensors (HV-MAPS), MuPix
- Timing detectors, fiber ribbons & tiles
- Sophisticated DAQ

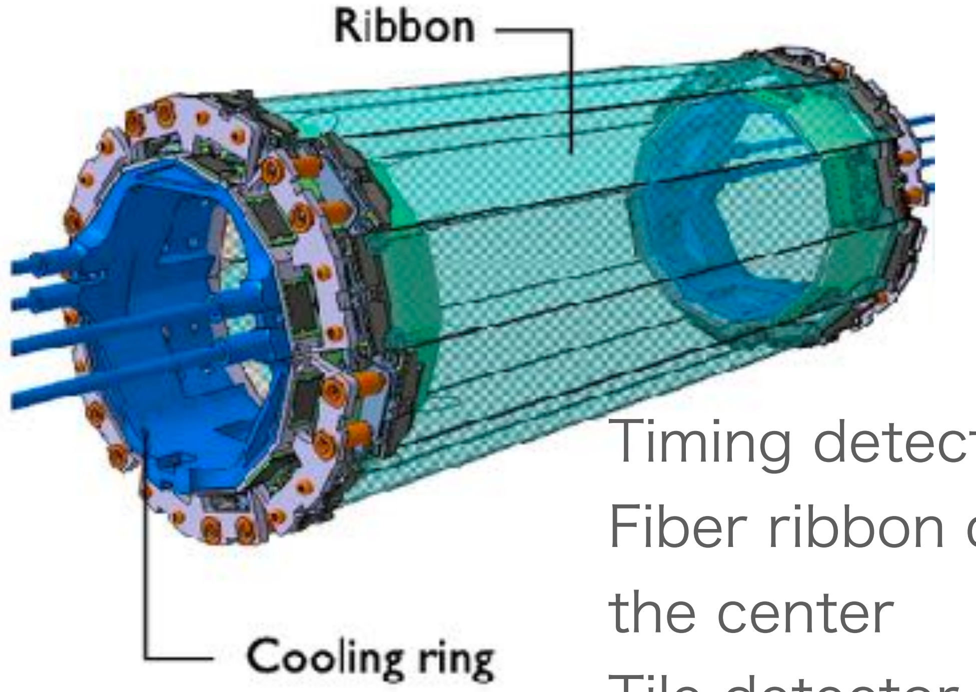








Vertex detector



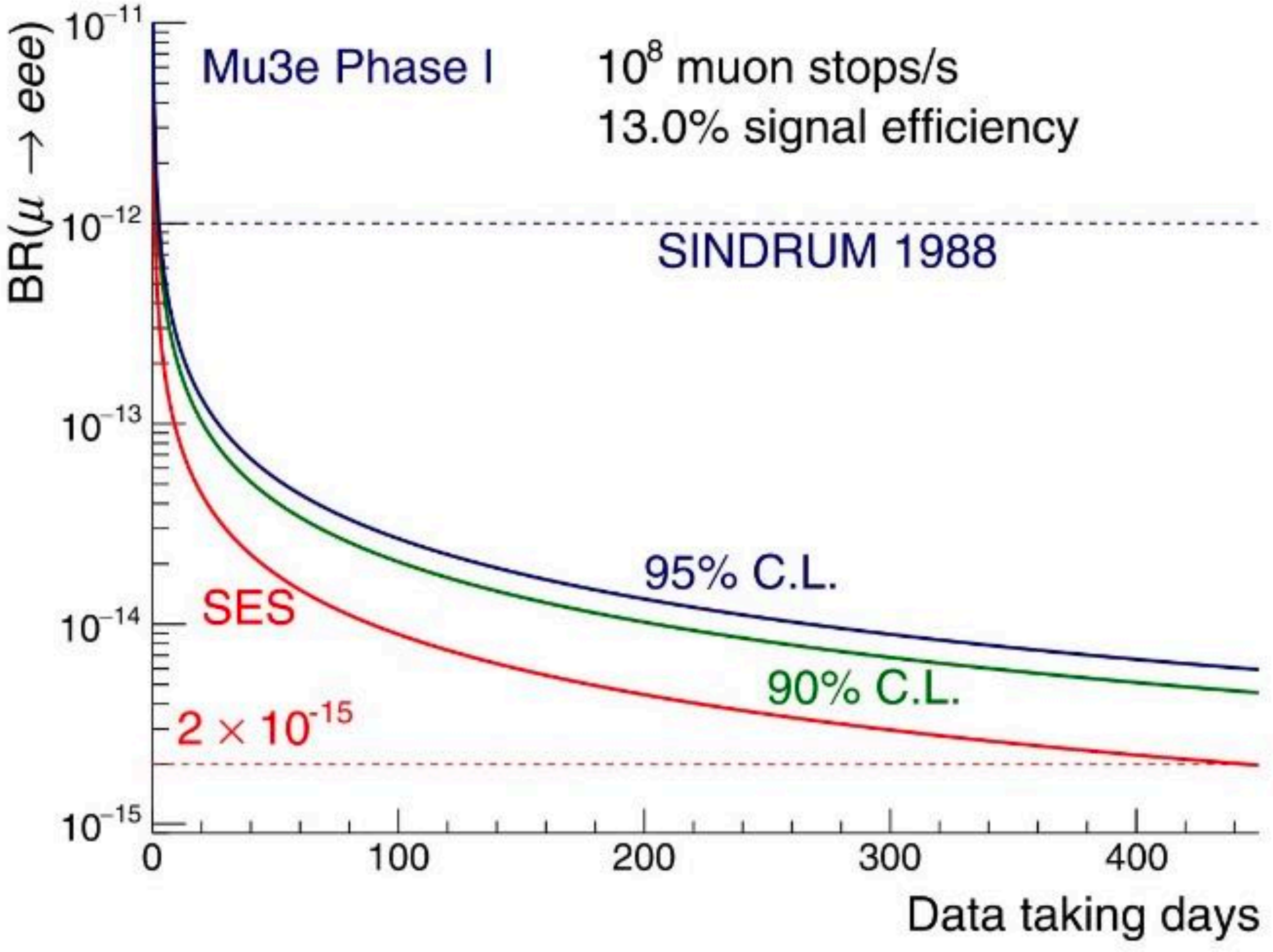
Timing detector
Fiber ribbon detector around the center
Tile detector in recurl stations

MuPix chip ladder

Tile detector

Mu3e time line

- Run at the πE5 CMBL
- Reach 2 x 10^{-15} S.E.S in 400 days
- First detector installation in 2023
- Infrastructure installation in next 1.5 years
- Commissioning in 2024-2025
- First physics data taking in 2025-2026
- … and Phase II



Summary
Muon CLFV experiments

- MEG II running, COMET started engineering run !
- Mu3e and Mu2e are starting in a few years
- Any single event, as long as confirmed, it's a clear evidence of new physics.
- Further interesting ideas!
  - $\mu^- + e^- \rightarrow e^- + e^-$
  - $MU - \overline{MU}$ oscillation

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