Search for Muon to Electron Conversion : The COMET experiment

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University of Minnesota, US

Outline

1: CLFV Physics
2: What is $\mu \to e$ Conversion ?
3: New $\mu \to e$ Conversion Experiment
4: COMET Experiment
5: COMET Staged Approach
6: COMET Phase-α
7: Other Physics with COMET
8: PRISM
9: Summary

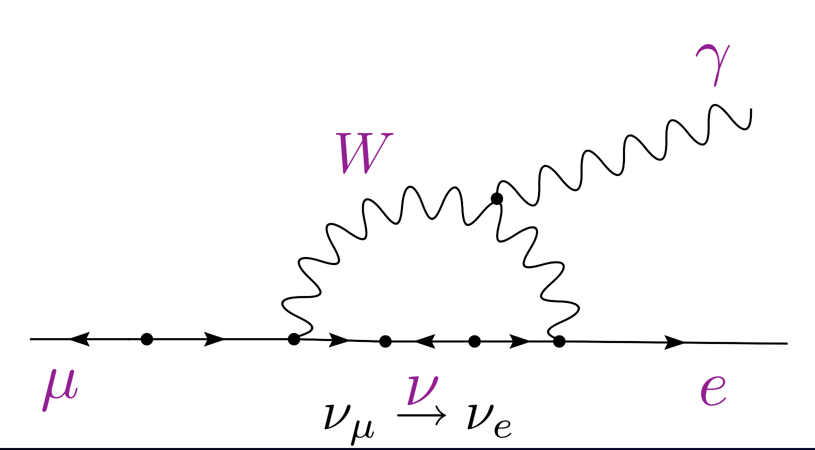
(1)

CLFV Physics

Thirty-six views of Mt. Fuji

Why CLFV ?

1 CLFV has a clear signature of BSM since the SM contribution is negligibly small.



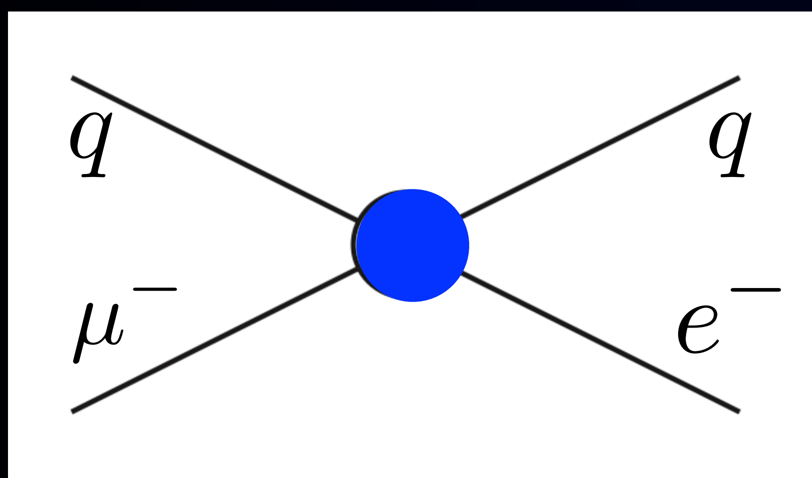
$$BR \sim 0(10^{-54})$$

2 CLFV has reached BSM physics scale of $\Lambda \sim O(10^4)$ TeV, and the upcoming searches will reach $\Lambda \sim O(10^5)$ TeV.

dimension 6 operators: Rate $\propto \dfrac{1}{\Lambda^4} \rightarrow \times\, 10{,}000$

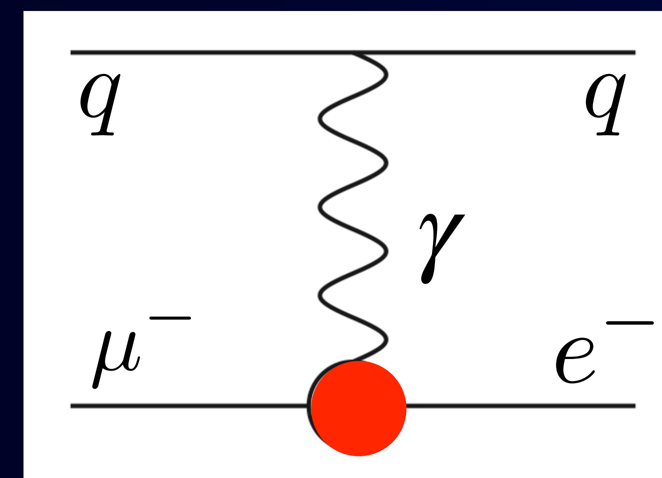
$\mu \to e$ Conversion in EFT

Contact Interaction



$\pm$

Photonic Interaction



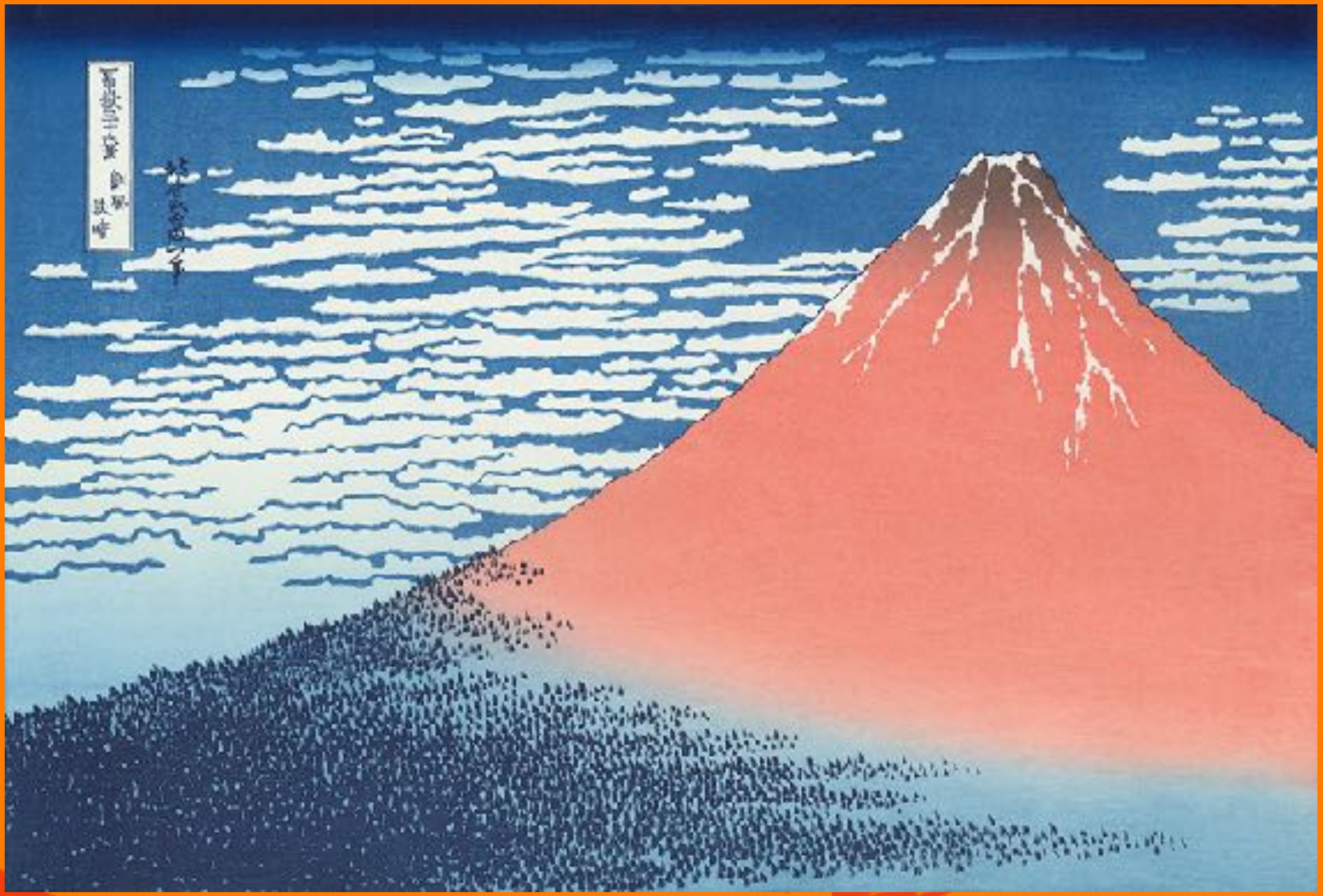
- scalar (L/R) (spin independent)
- vector (L/R) (spin independent)
- pseudoscalar (L/R) (spin dependent)
- axial vector (L/R) (spin dependent)
- tensor (L/R) (spin dependent)

For protons and neutrons

- dipole (L/R) (spin independent)
- two photons (L/R) $\mu e F F$

V. Cirigliano, S. Davidson, YK, Phys. Lett. B 771 (2017) 242
S. Davidson, YK, A. Saporta, Eur. Phys. J. C78 (2018) 109
S. Davidson, YK, Y. Uesaka, M. Yamanaka, Phys. Rev. D102, 11504 (2020)

What is $\mu \to e$ conversion ?



$\mu \rightarrow e$ Conversion in a muonic atom

$$\mu^- + (A,Z) \rightarrow e^- + (A,Z)$$

Event Signature :
a single mono-energetic electron

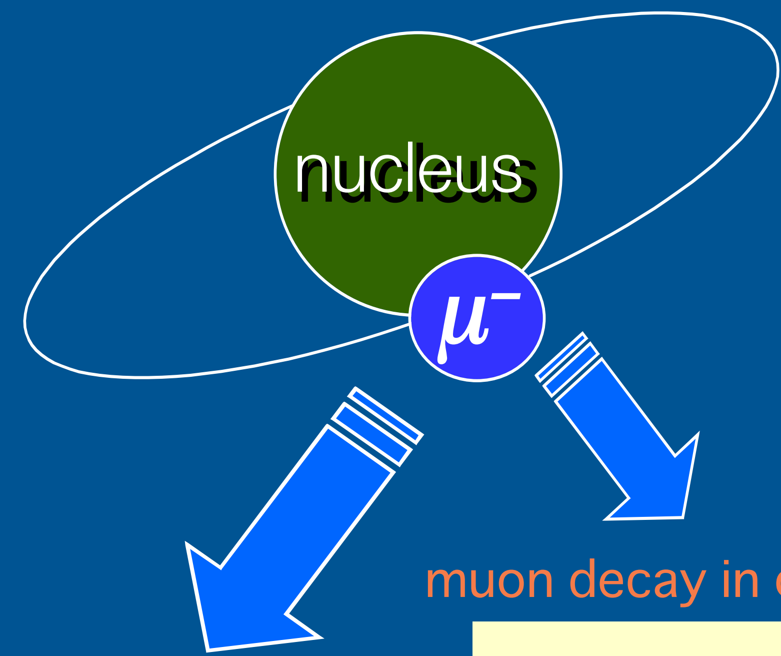
$$E_{\mu e} = \frac{(m_N + m_\mu - B_\mu)^2 - m_N^2 + m_e^2}{2(m_N + m_\mu - B_\mu)}$$

nucleus	z	$E_{\mu e}$ (MeV)
Al	13	104.97
Ti	22	104.3
Pb	82	94.9

Coherent process :

- enhancement by the number of nucleons, when the final states are the ground state. $\propto Z^5$

1s state in a muonic atom



muon decay in orbit

$$\mu^- \rightarrow e^- \nu \bar{\nu}$$

nuclear muon capture

$$\mu^- + (A,Z) \rightarrow \nu_\mu + (A,Z-1)$$

	Z	CR limit
sulphur	16	$<7 \times 10^{-11}$
titanium	22	$<4.3 \times 10^{-12}$
copper	39	$<1.6 \times 10^{-8}$
gold	79	$<7 \times 10^{-13}$
lead	82	$<4.6 \times 10^{-11}$

$$\mathrm{CR}(\mu^- \mathrm{N} \rightarrow e^- \mathrm{N}) \equiv \frac{\Gamma(\mu^- \mathrm{N} \rightarrow e^- \mathrm{N})}{\Gamma(\mu^- \mathrm{N} \rightarrow \mathrm{all})}$$

Backgrounds for $\mu \to e$ conversion

intrinsic physics backgrounds

- Bound muon decay in orbit (DIO)
  $(\mu^- N \to e^- \nu_\mu \bar{\nu}_e N)$
- Radiative muon nuclear capture (RMC)
  $(\mu^- N \to \nu_\mu N' \gamma; \gamma \to e^+ e^-)$
- Particles from muon nuclear capture

beam-related backgrounds

- Radiative pion nuclear capture (RPC)
  $(\pi^- N \to N' \gamma; \gamma \to e^+ e^-)$
- Beam electrons
- Muon decay in flights
- Neutron induced background
- Antiproton induced background

cosmic-ray and other backgrounds

- Cosmic-ray induced background
- False tracking

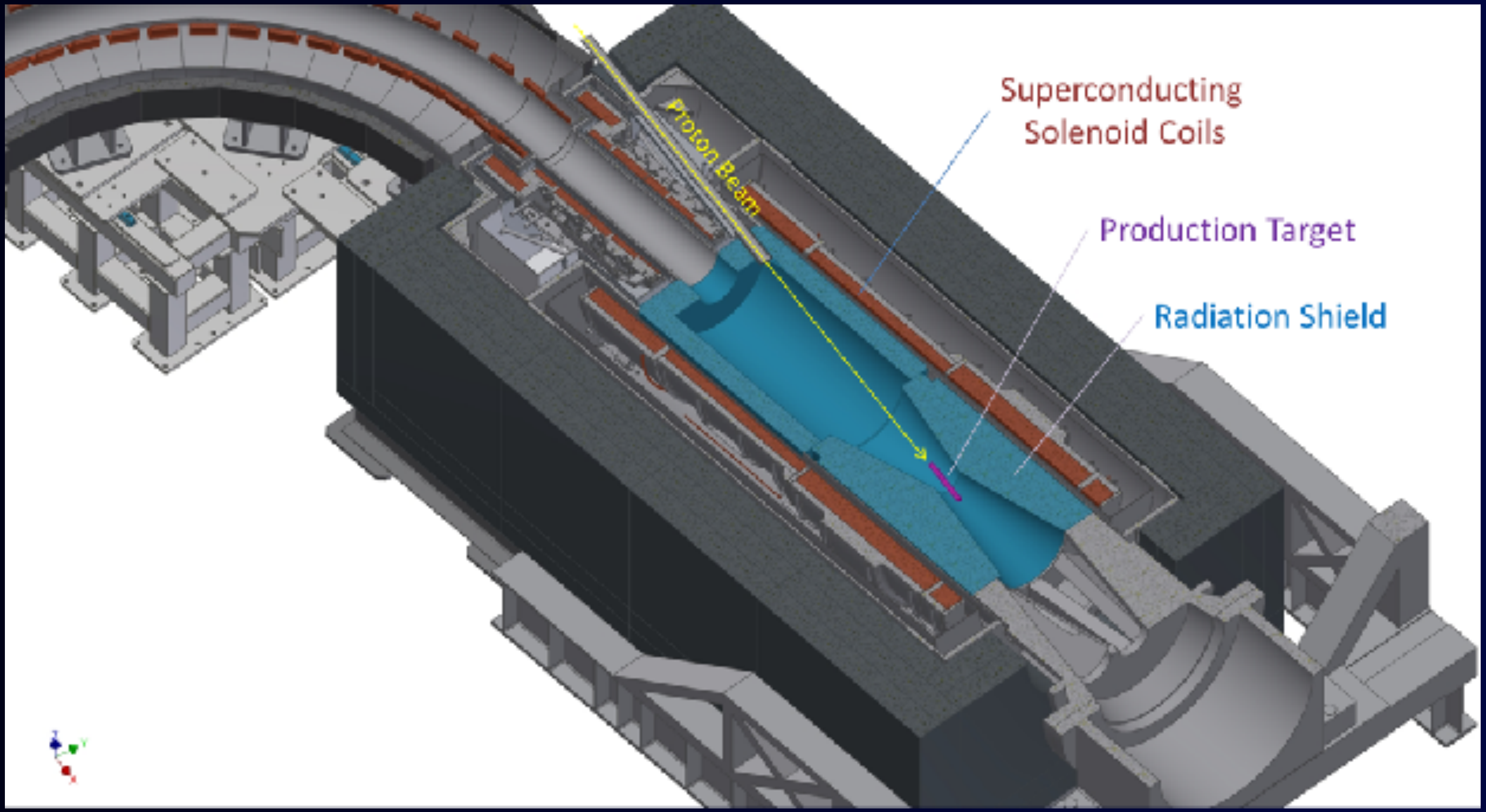
New $\mu \to e$ Conversion Experiments

$$B(\mu N \to eN) \le 10^{-16}$$

with a factor of 10,000 improvement

Improvements for Signal Sensitivity

Pion capture system: High field (5 T) superconducting solenoid magnets surround a proton target.

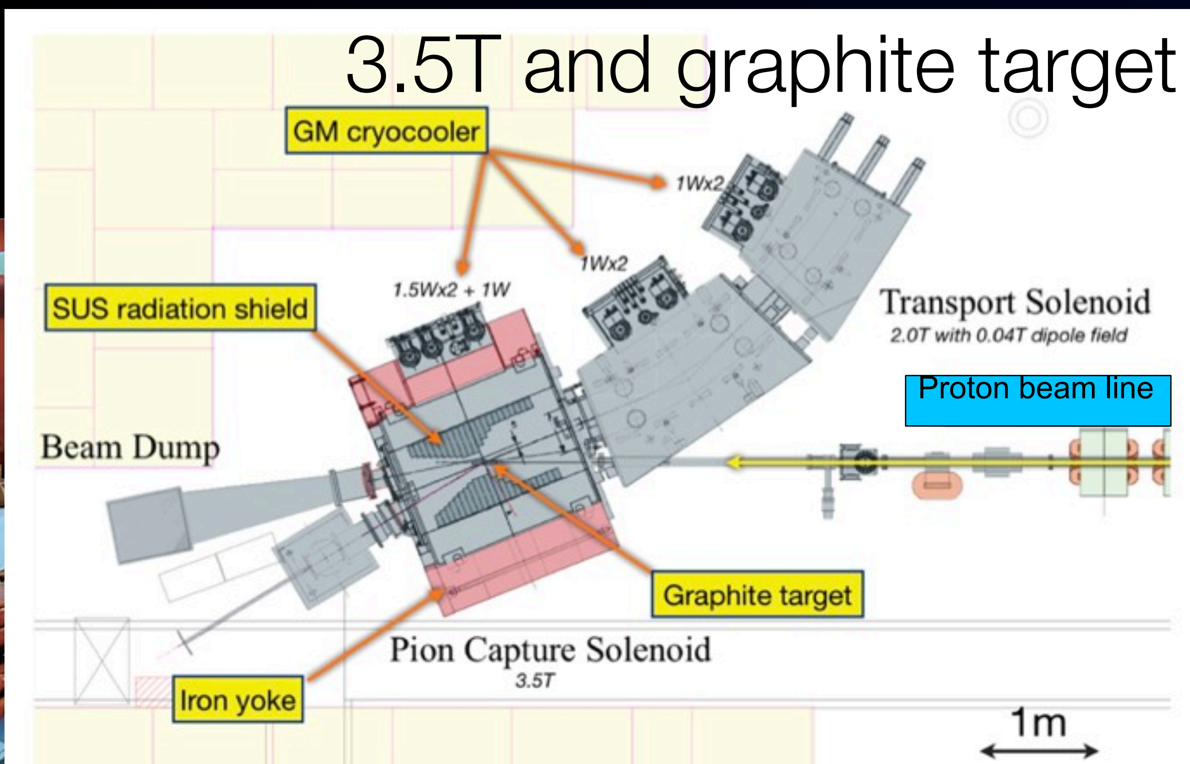


10^{11} μ/s for 50 kW proton beam power or 10^{18} muons in total

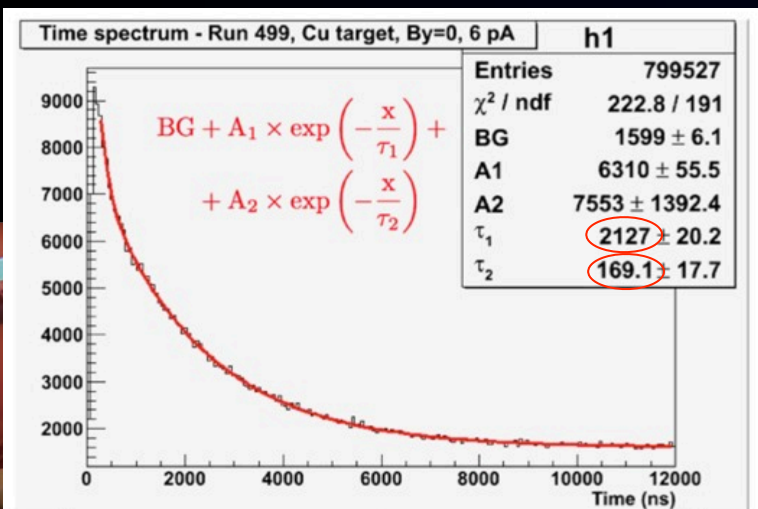
The previous experiment used 10^{14} muons.

MuSIC at RCNP, Osaka University (2011 -)

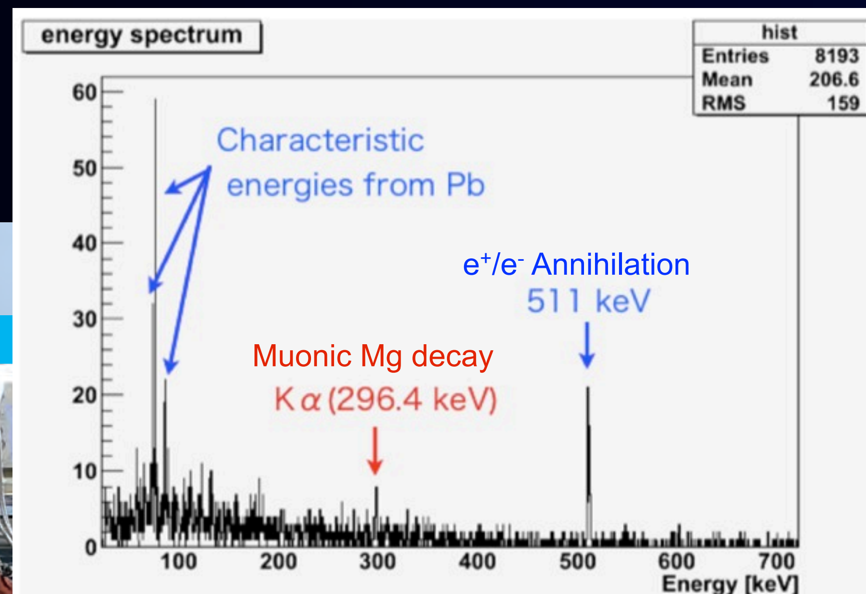
Muon Science Intense Channel (MuSIC) since 2011



MuSIC at RCNP, Osaka University (2011 -)



	Free muon*	Cu**	Plastic scint.**
τ (ns)	2197.03 ± 0.04	163.5 ± 1	2026.3 ± 1.5



MuSIC muon yields

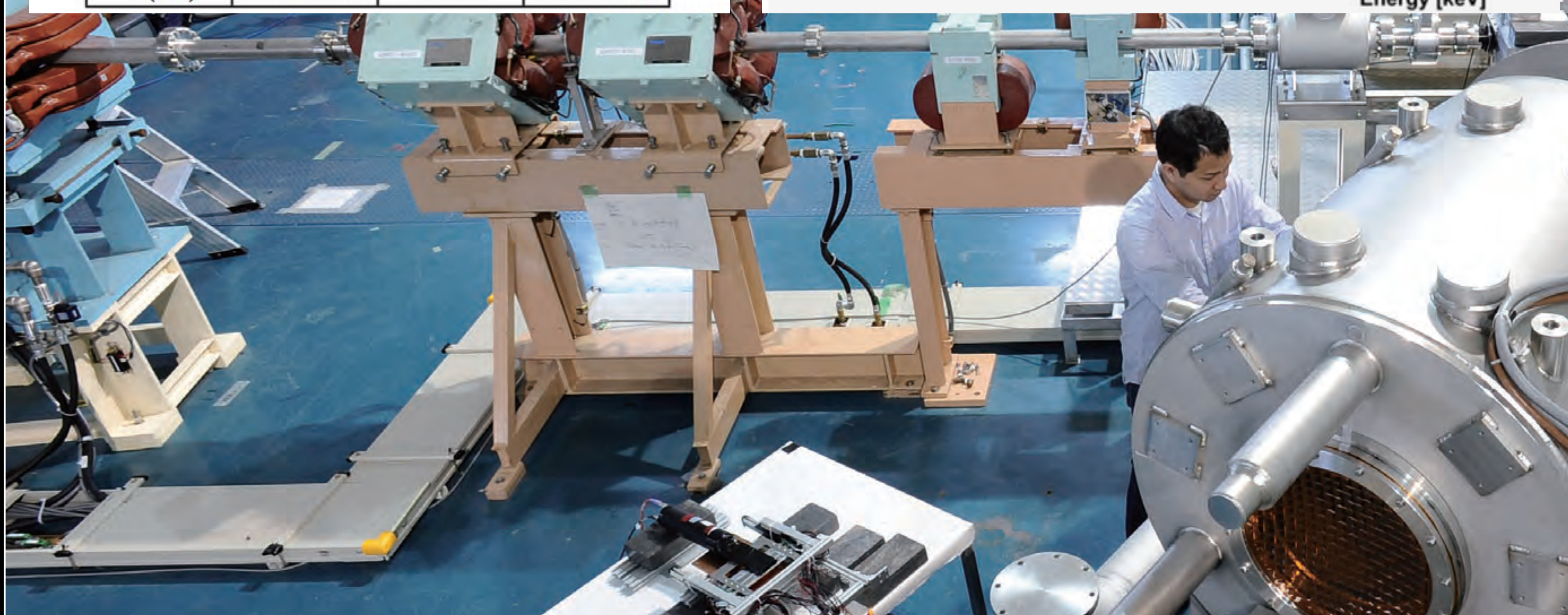
μ^+ : 3×10^8/s with 400W

μ^- : 1×10^8/s with 400W

PSI muon yields

μ^+ : $O(10^8)$/s with 1.4MW

μ^- : $O(10^8)$/s with 1.4MW



10^{11}/s with 50 kW, possible!

Improvements for Background Rejection

Beam-related backgrounds → Beam pulsing with separation of 1μsec — measured between beam pulses

proton extinction = #protons between pulses/#protons in a pulse $< 10^{-10}$

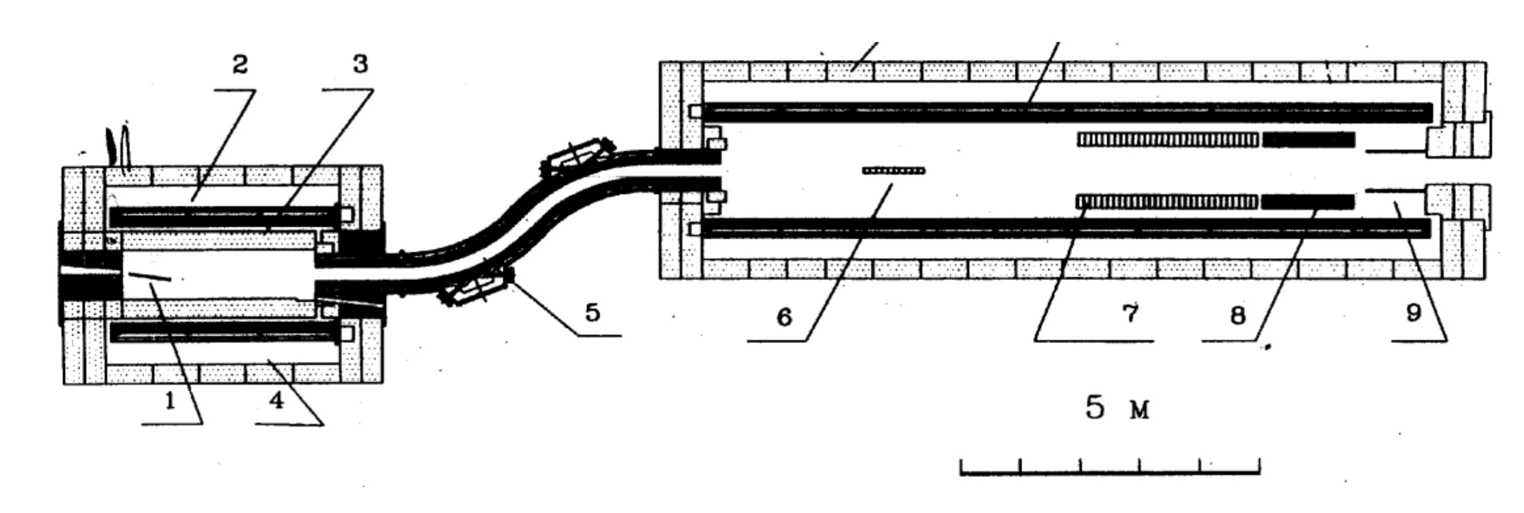
Muon DIF background → curved solenoids for momentum selection — eliminate energetic muons (>75 MeV/c)

Muon DIO background → low-mass trackers in vacuum & thin target — improve electron energy resolution

based on the MELC proposal at Moscow Meson Factory

From MELC to MECO

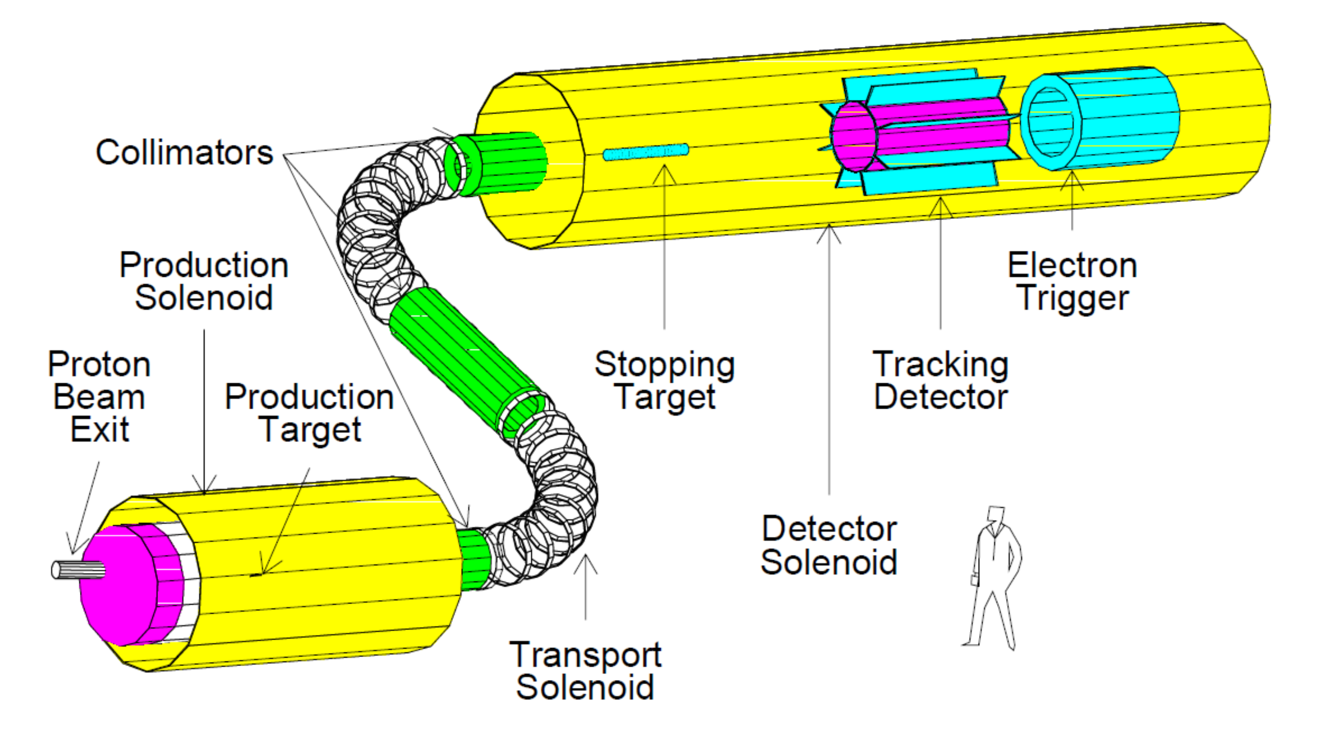
MELC



Proposal (1992)
at Moscow
Meson Factory

R. M. Dzhilkibaev and V. M. Lobashev, Sov. J. Nucl. Phys. 49, 384 (1989)

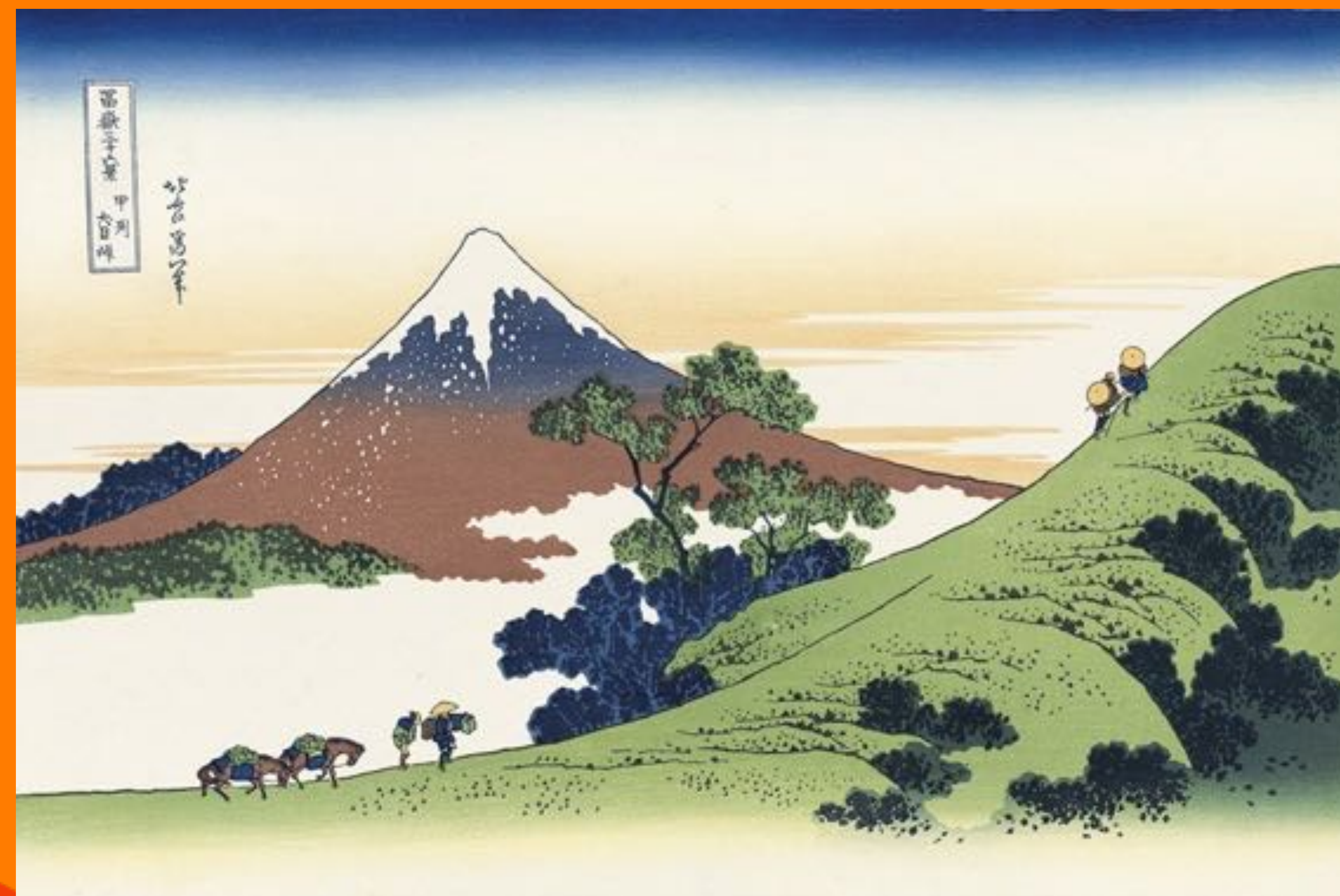
MECO



BNL E940 (1997)
one of the RSVP (rare symmetry violating processes with KOPIO)

terminated in 2005

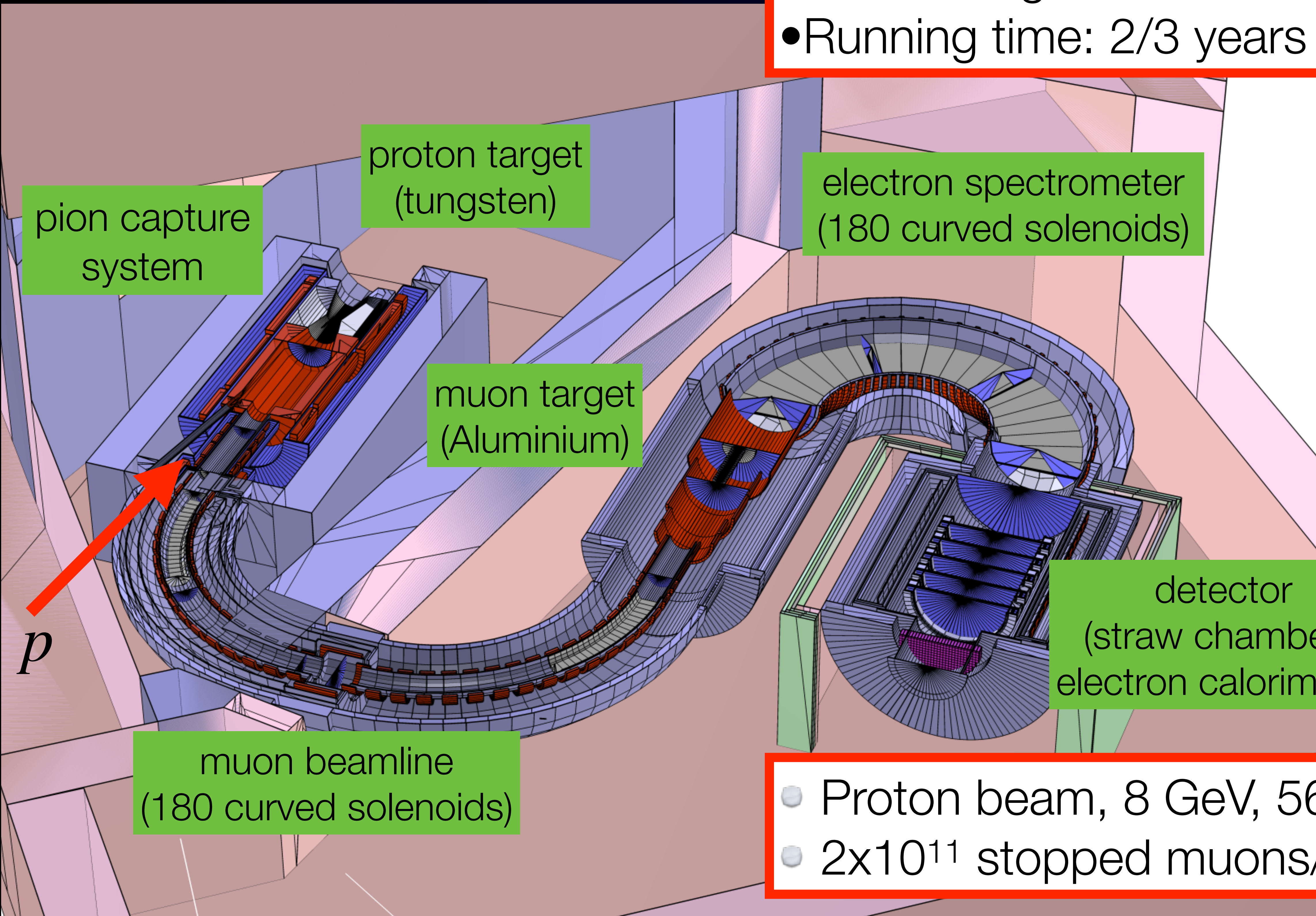
COMET at J-PARC



COMET = COherent Muon to Electron Transition

COMET

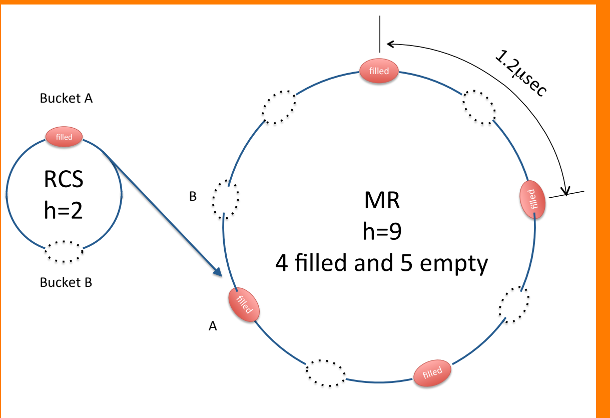
- Single event sensitivity : 1.4×10^{-17}
- 90% CL limit : $< 3.2 \times 10^{-17}$
- x10000 from SINDRUM-II
- Total background: 0.32 events
- Running time: 2/3 years (2×10^{7} sec)

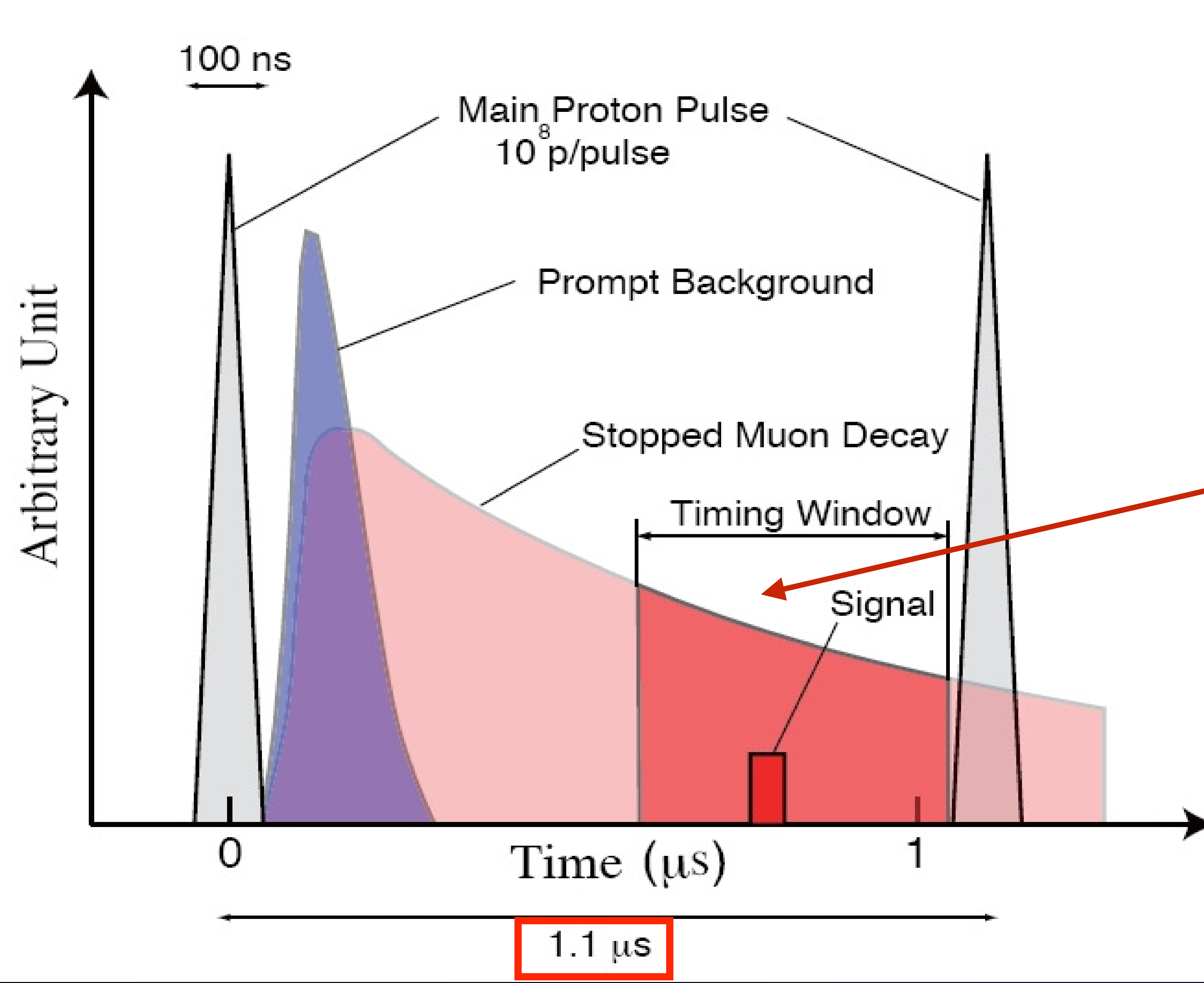


- Proton beam, 8 GeV, 56kW
- 2×10^{11} stopped muons/s

Japan Proton Accelerator Research Complex (J-PARC)

Pulsed Proton Beam Time Structure at J-PARC



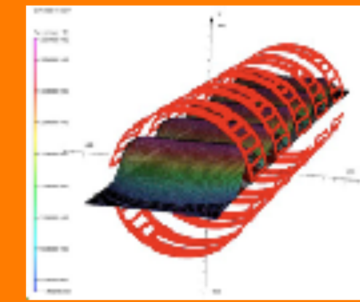


Aluminum muon target (muonic atom lifetime of 864 ns is good for 1.1μs repetition.)

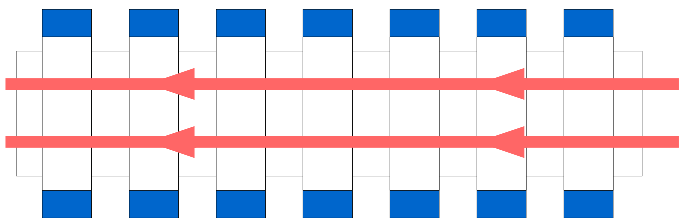
Delayed time window to avoid beam background (from 700 ns to 1.1μs)

Proton extinction factor (proton leakage between pulses) ~ 10^{-10}

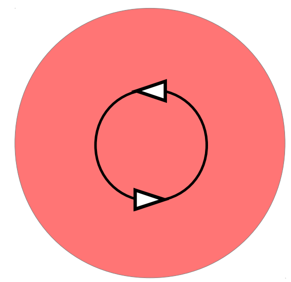
Bunched slow extraction with every other RF bunch filled by protons.



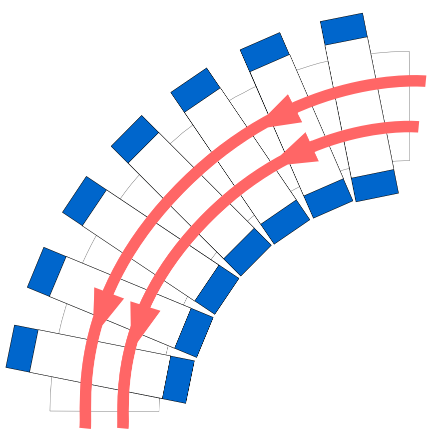
Curved Solenoids with Dipole field



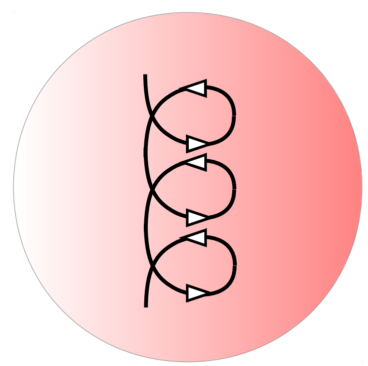
- Uniform B field
- Linear field lines



Helical motion about field lines



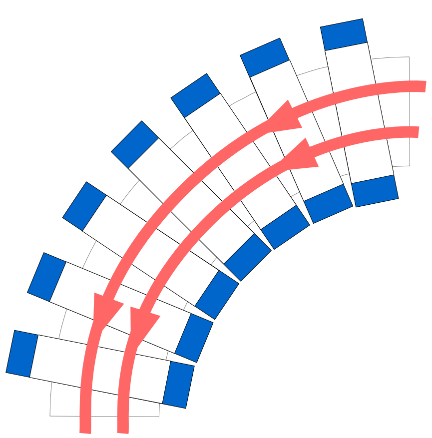
- Radial gradient in magnetic field
- Cylindrical field lines



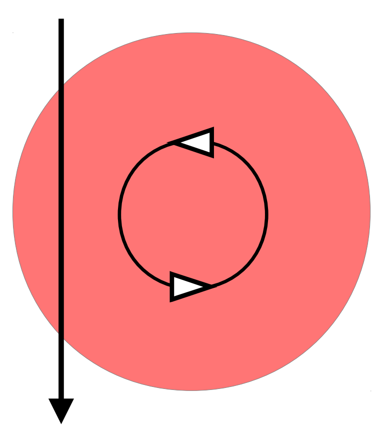
Helical motion about a drifting centre

$$D_{\mathrm{drift}} \propto \frac{p}{qB}\frac{s}{R}$$

$$\begin{aligned} D &= \frac{1}{qB}\left(\frac{s}{R}\right)\frac{p_L^2+\frac{1}{2}p_T^2}{p_L}, \\ &= \frac{1}{qB}\left(\frac{s}{R}\right)\frac{p}{2}\left(\cos\theta+\frac{1}{\cos\theta}\right) \end{aligned}$$



- Radial gradient in magnetic field
- Cylindrical field lines
- dipole field normal to the bending plane

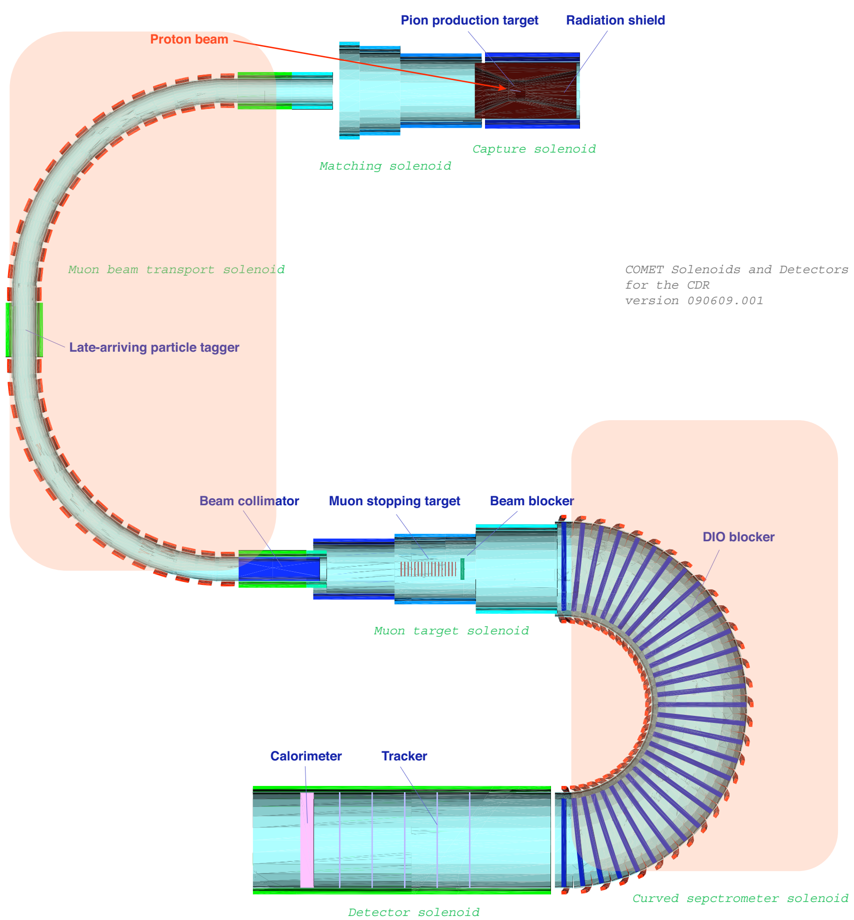


Helical motion of selected momentum p_0 staying in the bending plane

$$\mathrm{B_{dipole}} \propto \frac{p_0}{qR}$$

$$B_{\mathrm{comp}} = \frac{1}{qR}\frac{p_0}{2}\left(\cos\theta_0+\frac{1}{\cos\theta_0}\right)$$

COMET Features



muon beam line	2x 90° bend (same direction)
electron spectrometer	180° bend curved solenoids

Selection of low momentum muons

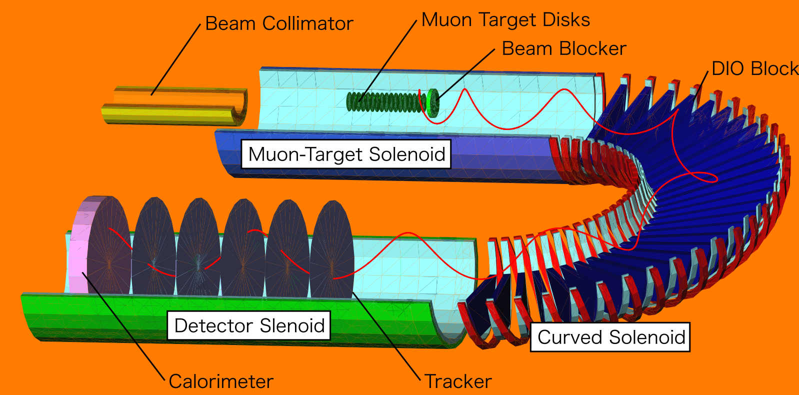
- eliminate high energy electrons from muon decays in flight

momentum selection capability is proportional to bending angle

Selection of 105 MeV signal electrons

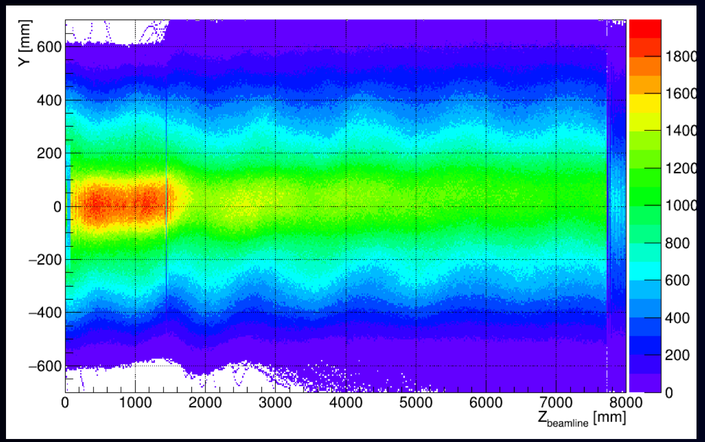
- eliminate neutrons and gamma-rays from muon target
- eliminate protons from muon target
- eliminate low energy DIO electrons from muon decays from muon target

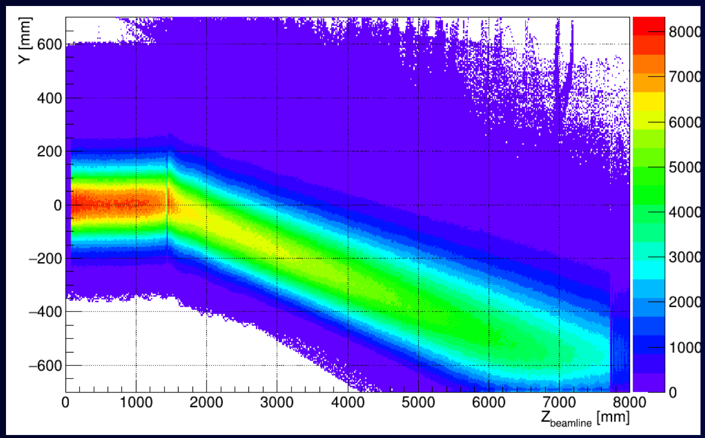
Electron Spectrometer in COMET Phase-II



105 MeV/c signal electrons	52 MeV/c DIO electrons

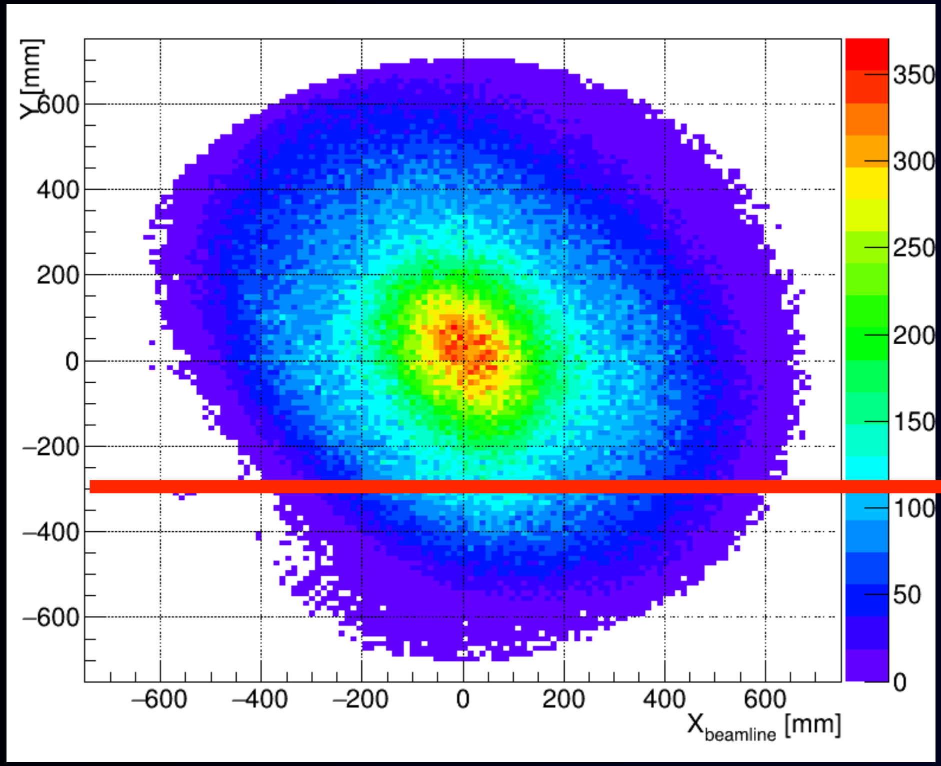
B_{dipole}=-0.22T





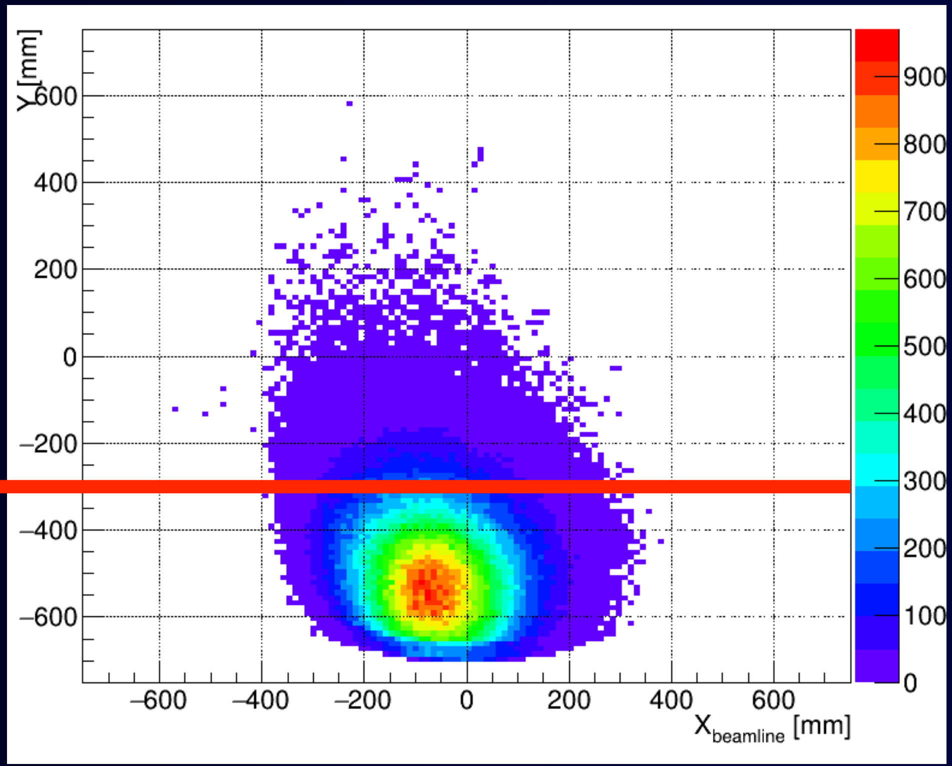
at the end of the electron spectrometer

vertical



horizontal

vertical



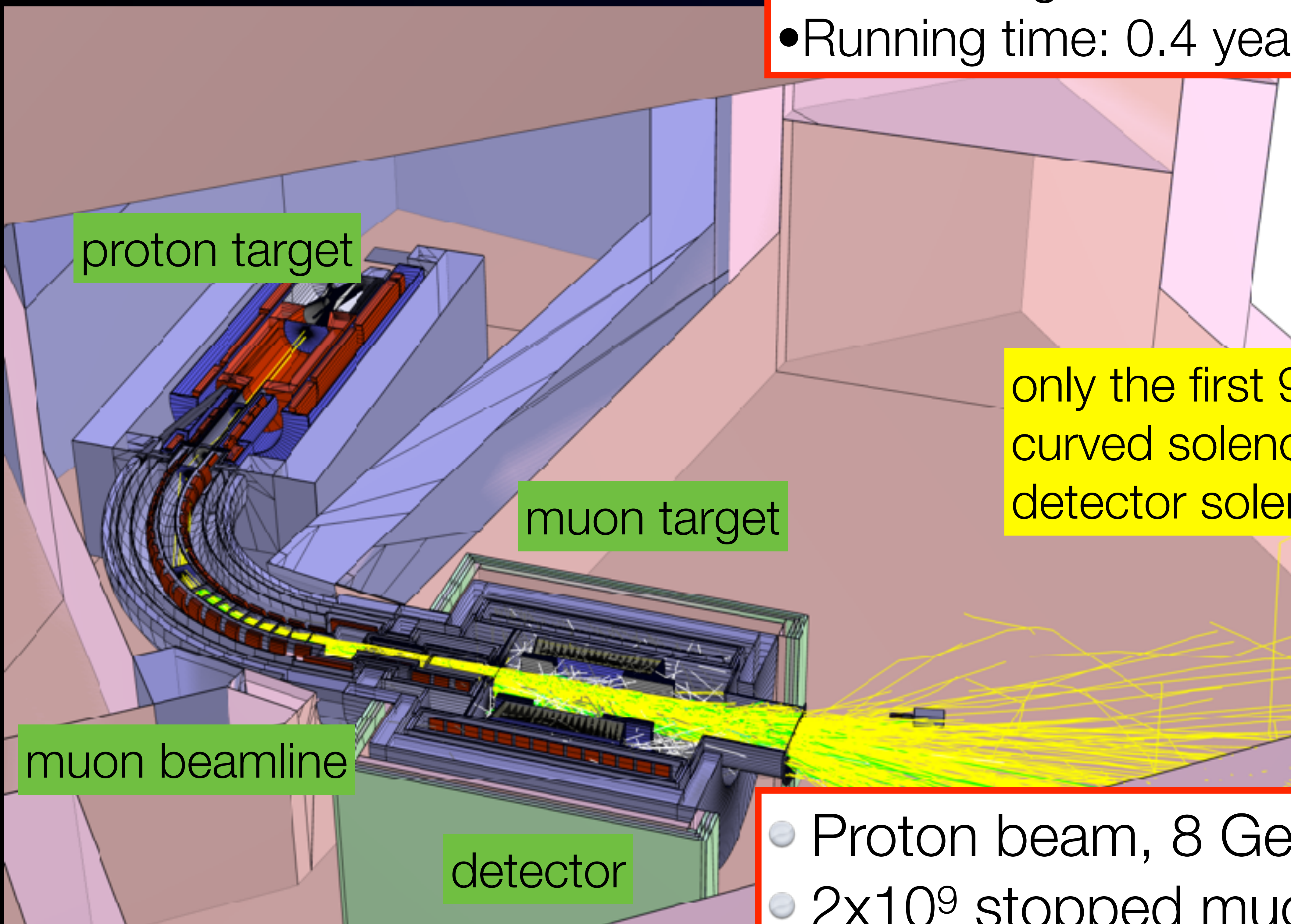
horizontal

removed

COMET
Staged Approach

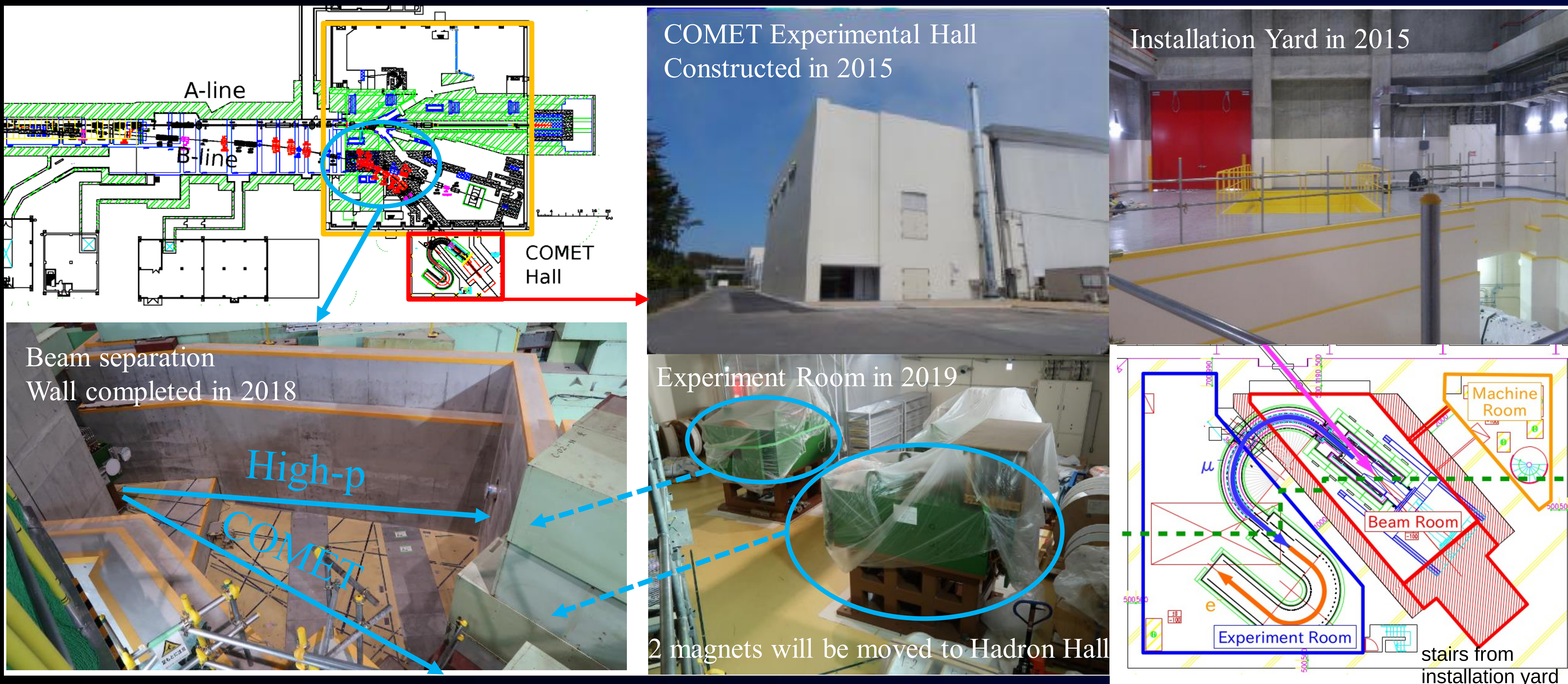
COMET Phase-I (2016 -)

- Single event sensitivity : 2×10^{-15}
- 90% CL limit : < 5×10^{-15}
- x100 from SINDRUM-II
- Total background: 0.32 events
- Running time: 0.4 years (1.2×10^{7}sec)



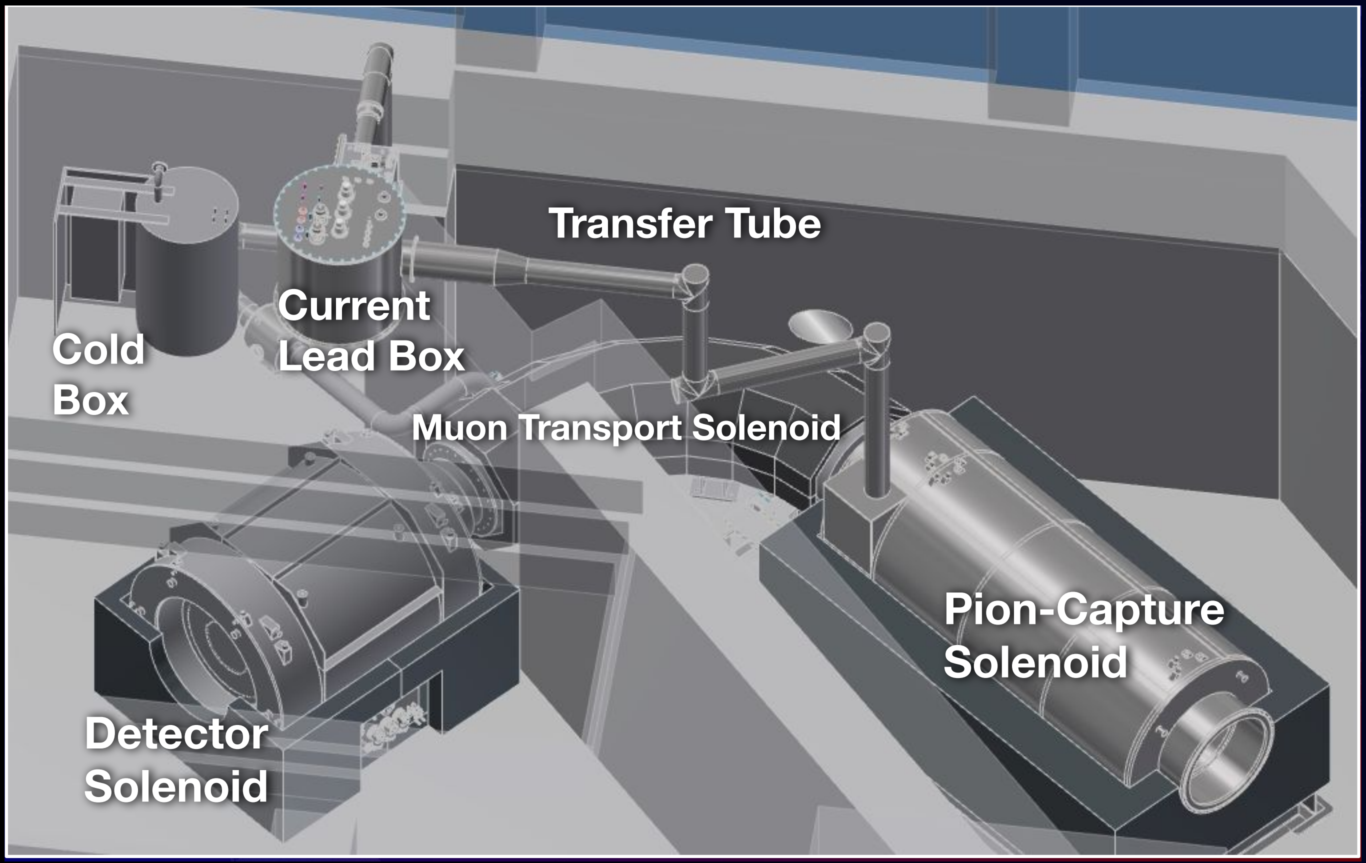
- Proton beam, 8 GeV, 3.2kW
- 2×10^{9} stopped muons/s

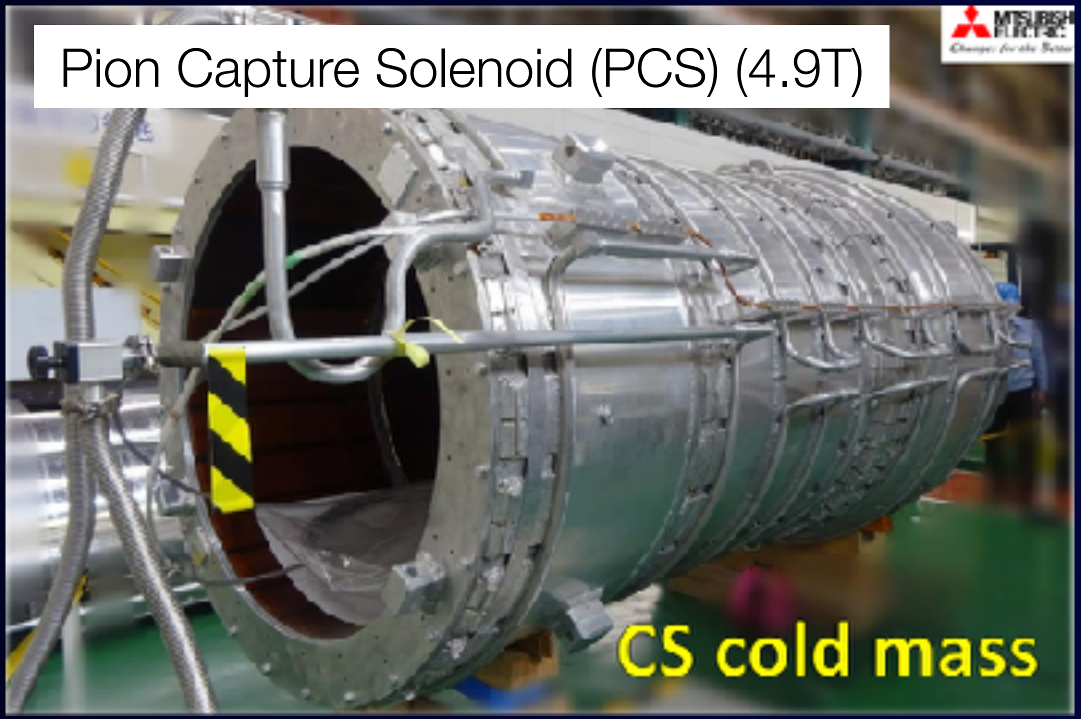
COMET Facility at J-PARC

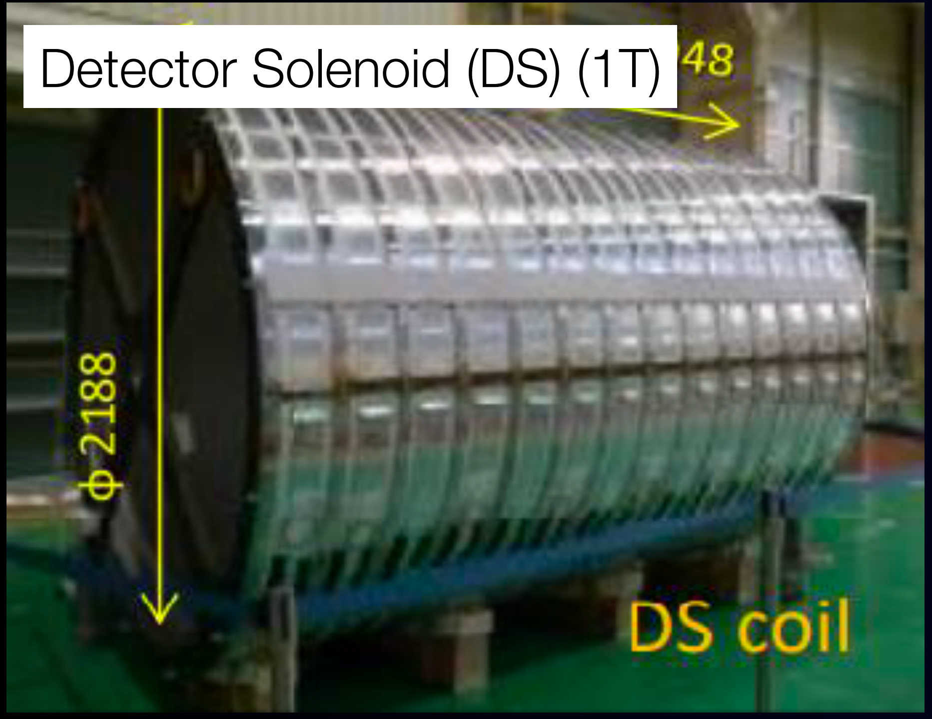


- COMET experimental hall building, completed in 2015
- Cryogenic system, completed in 2021
- New proton C line, completed in 2022

COMET Phase-I : Superconducting Solenoid Construction

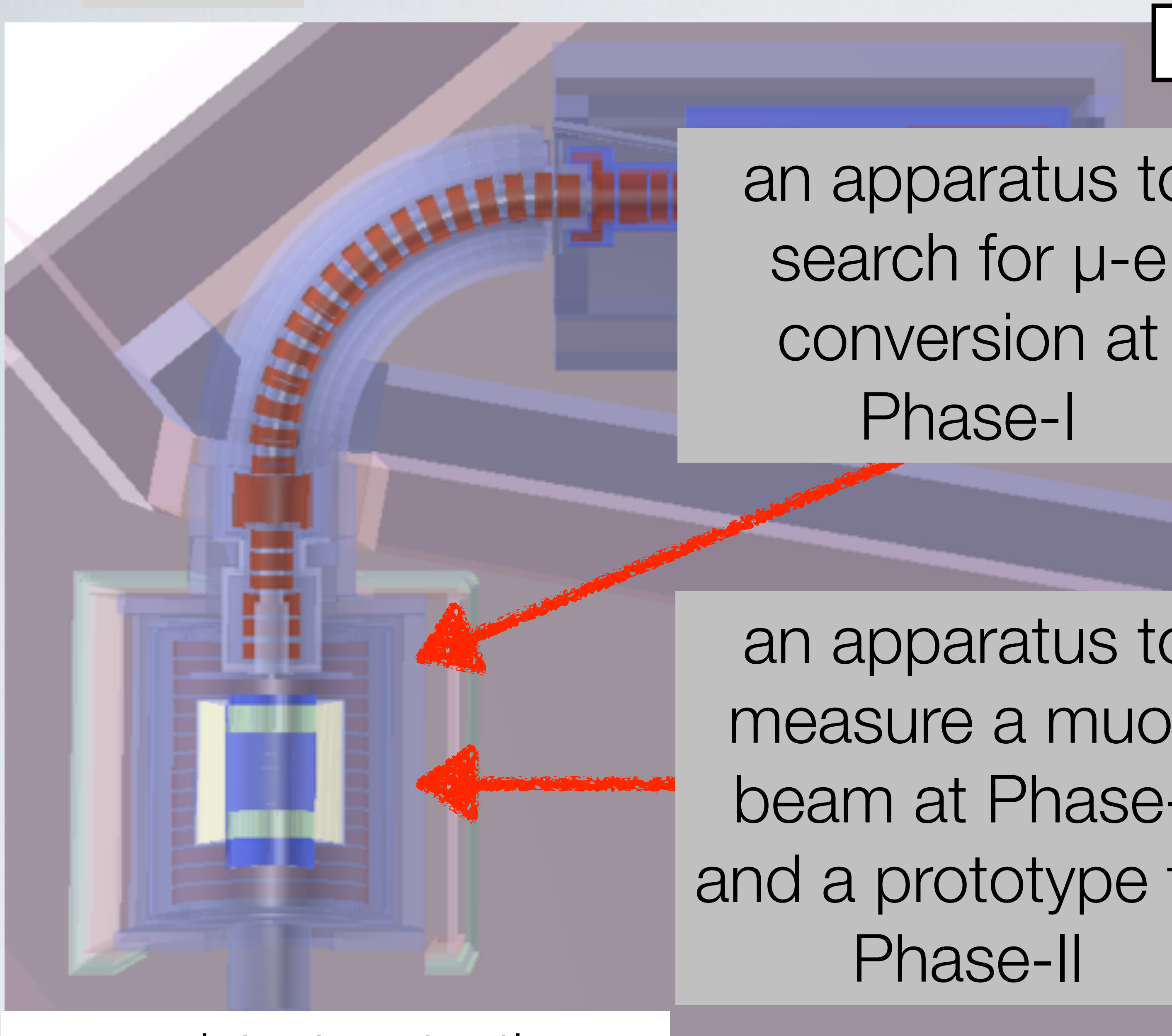






- PCS had ground fault problem. It has been fixed in 2023.
- MTS excitation complete in 2023.
- DS assembly will be complete in 2024.

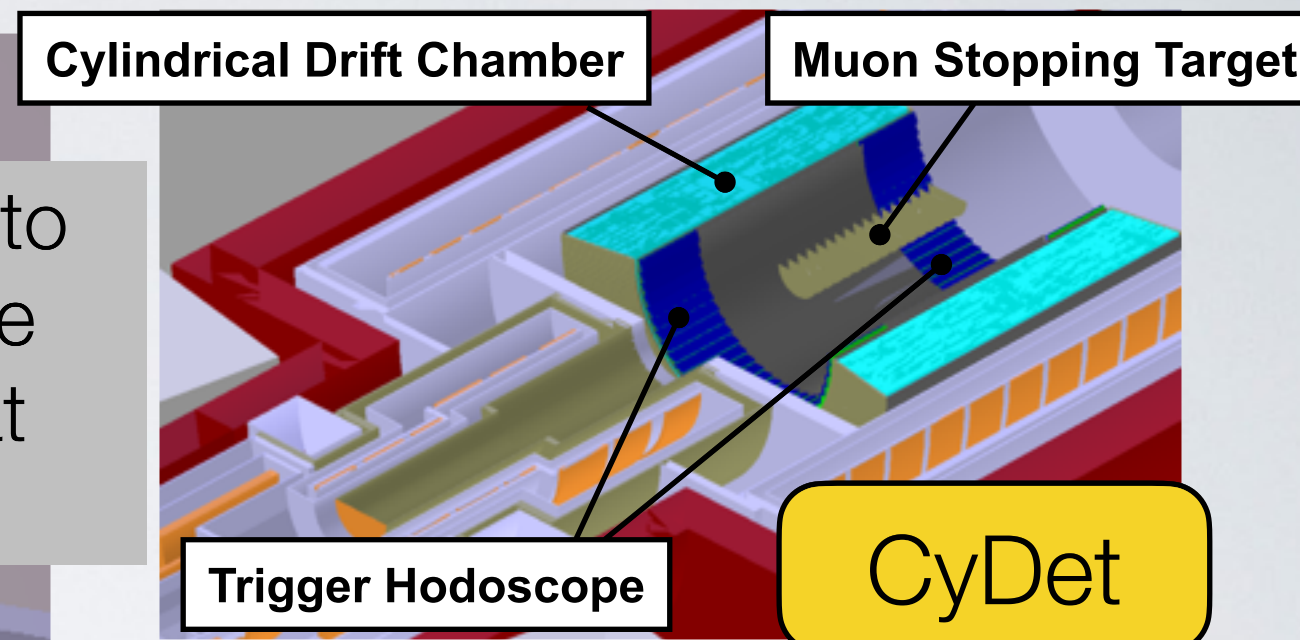
Two Detectors, CyDet and StrECAL , for COMET Phase-I

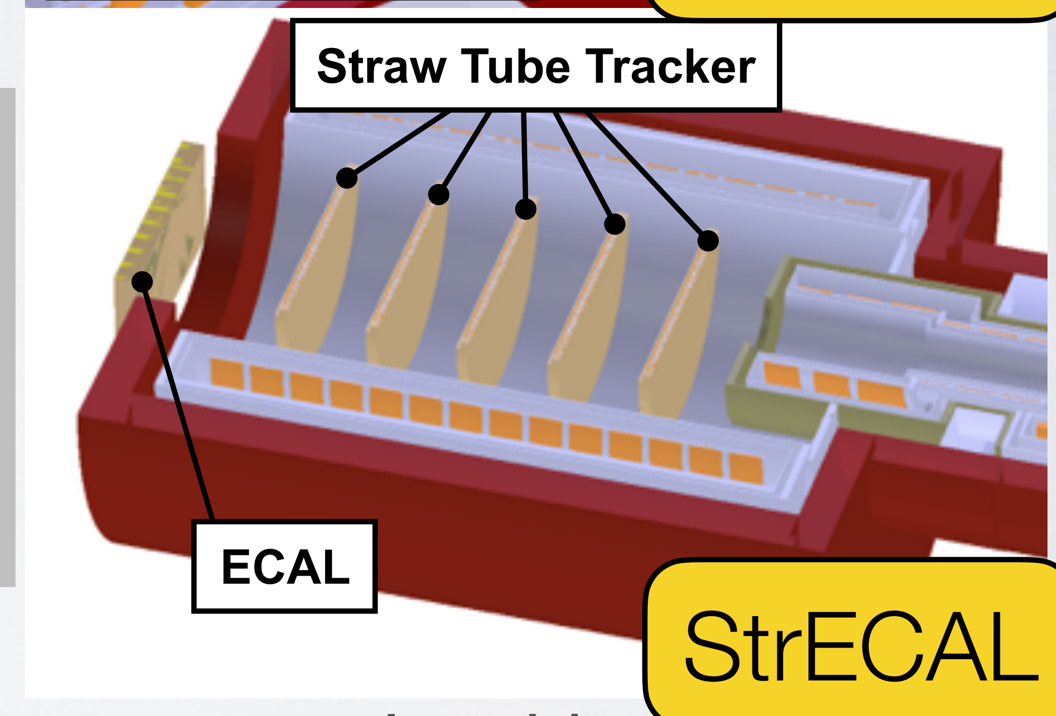


an apparatus to search for μ-e conversion at Phase-I

an apparatus to measure a muon beam at Phase-I and a prototype for Phase-II

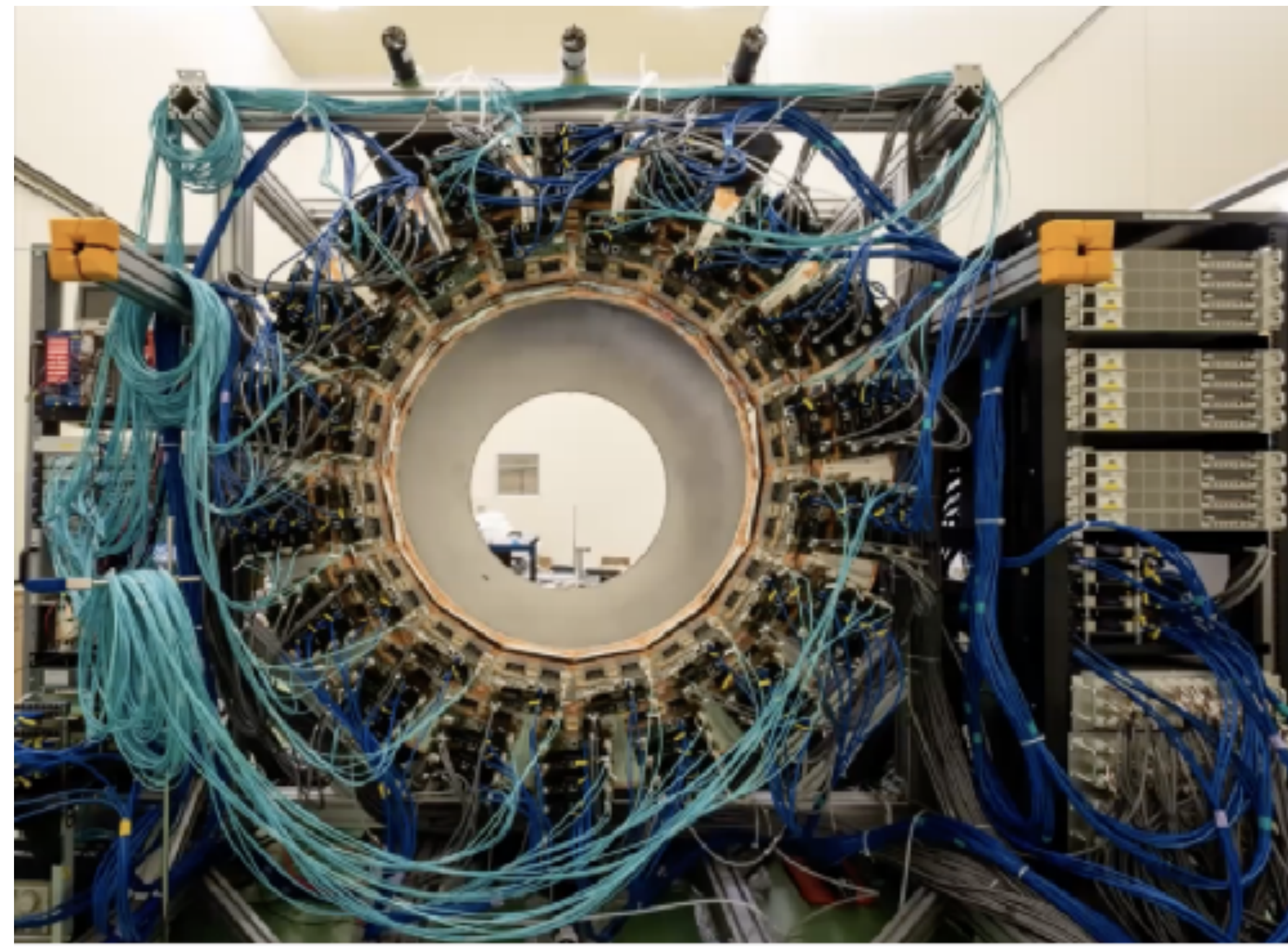
one detector at a time

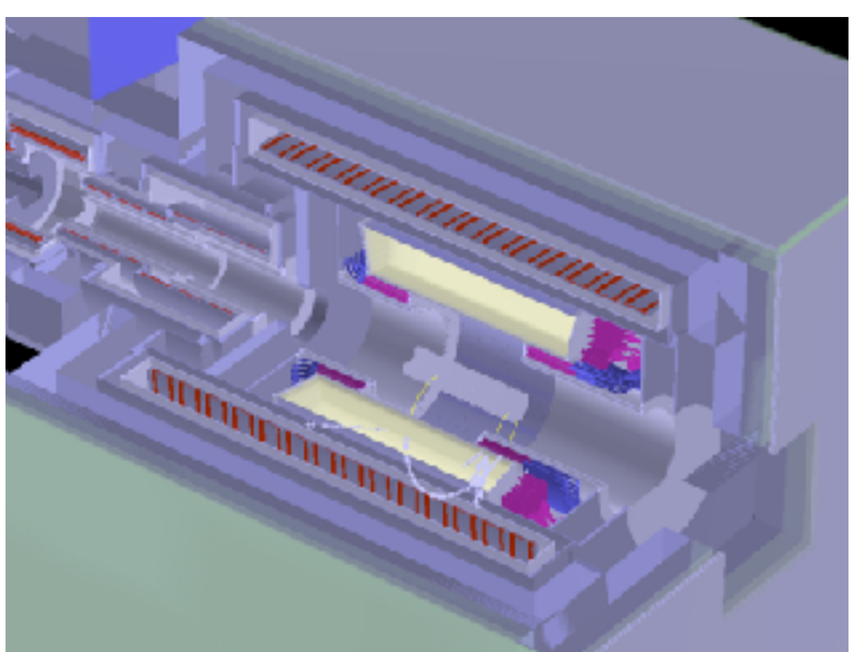




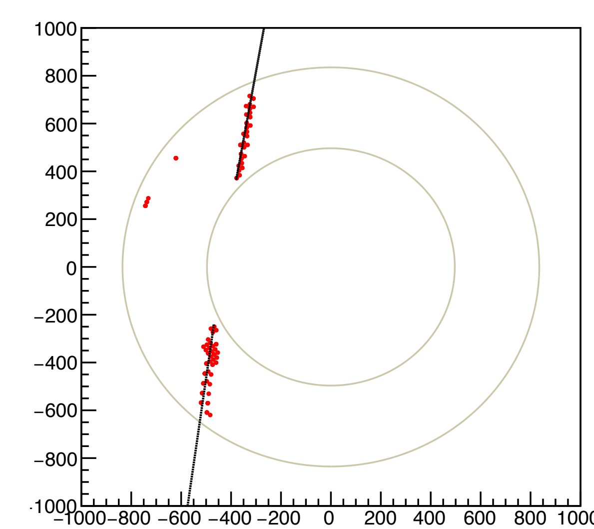
Cylindrical Drift Chamber (CDC)

- Cylindrical Drift Chamber (CDC)
  - large inner bore (R=50 cm): to avoid DIO electrons and beam flush.
  - Helium based gas: to minimize multiple scattering
  - all stereo layers: z information of tracks for few layers' hits
- Cylindrical Trigger Hodoscope (CTH)
  - two layers of plastic scintillators



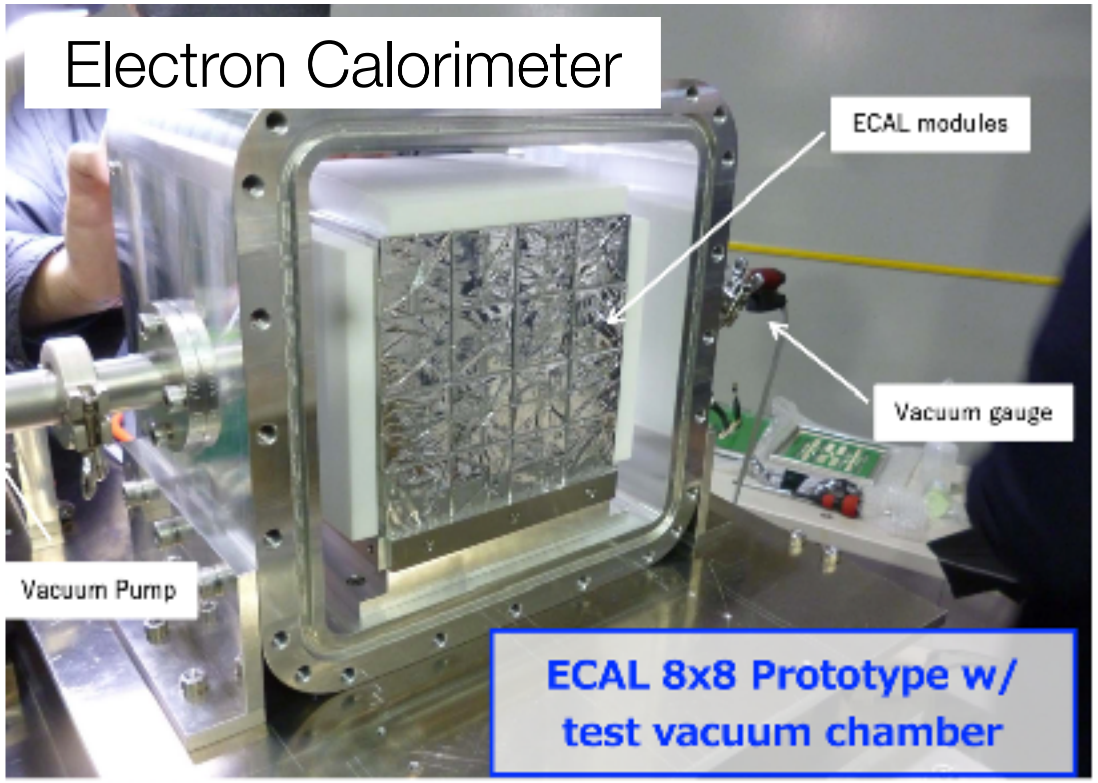


- CDC completed by Osaka Univesity and IHEP in 2019.
- Cosmic ray tests underway at KEK and J-PARC.



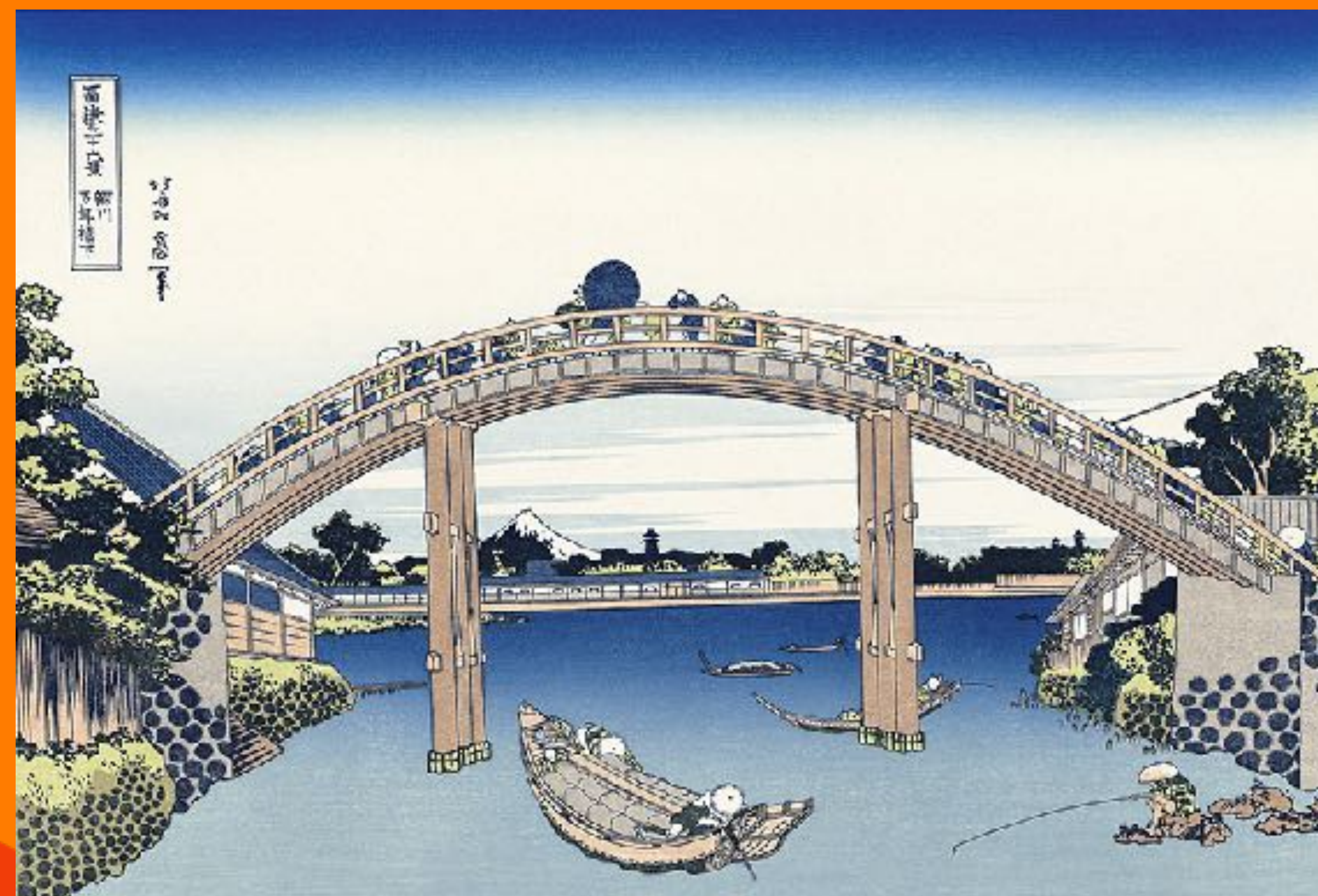
Straw Tracker and Electron Calorimeter

- Straws
  - adhesion welding
  - 20μm thick, 9,75mm dia. (Phase-I)
  - 12μm thick, 5mm dia. (Phase-II)
- One station has four planes (x,x',y,y')
- 150 μm position resolution
- DRS4 readout electronics (GHz)
- Assembly underway at J-PARC.



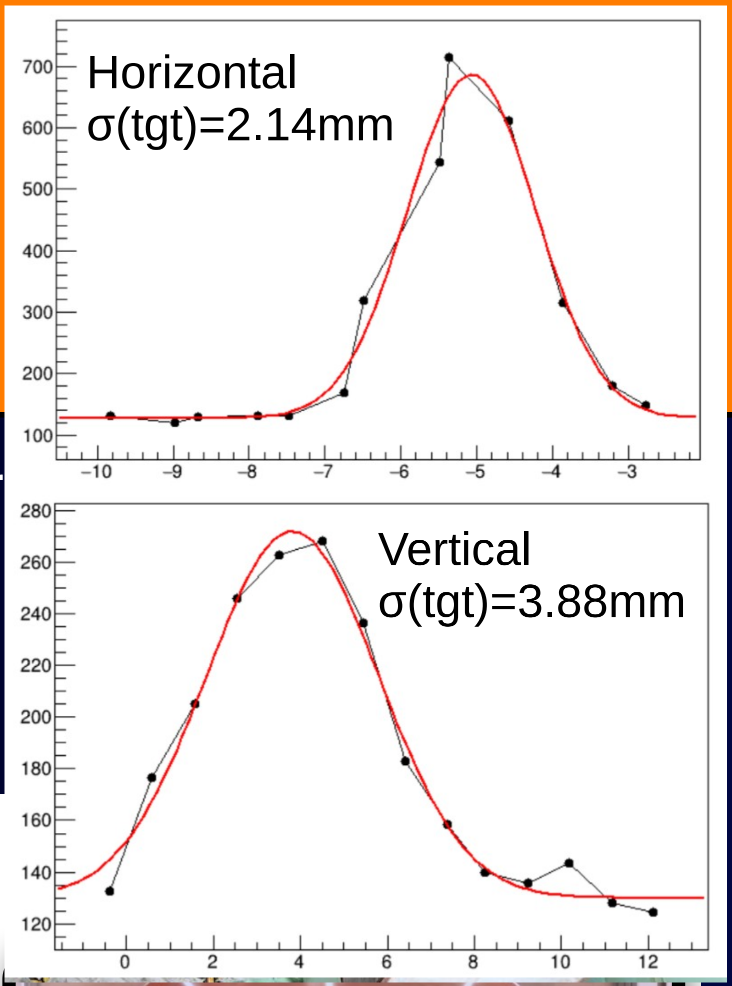
- LYSO crystals (500 for Phase-I)
- APD readout
- Energy resolution 4.4%@105 MeV
- Position resolution <10mm@105MeV
- Time resolution <1.0 nsec
- Assembly underway at Kyushu Univ.

COMET Phase-α



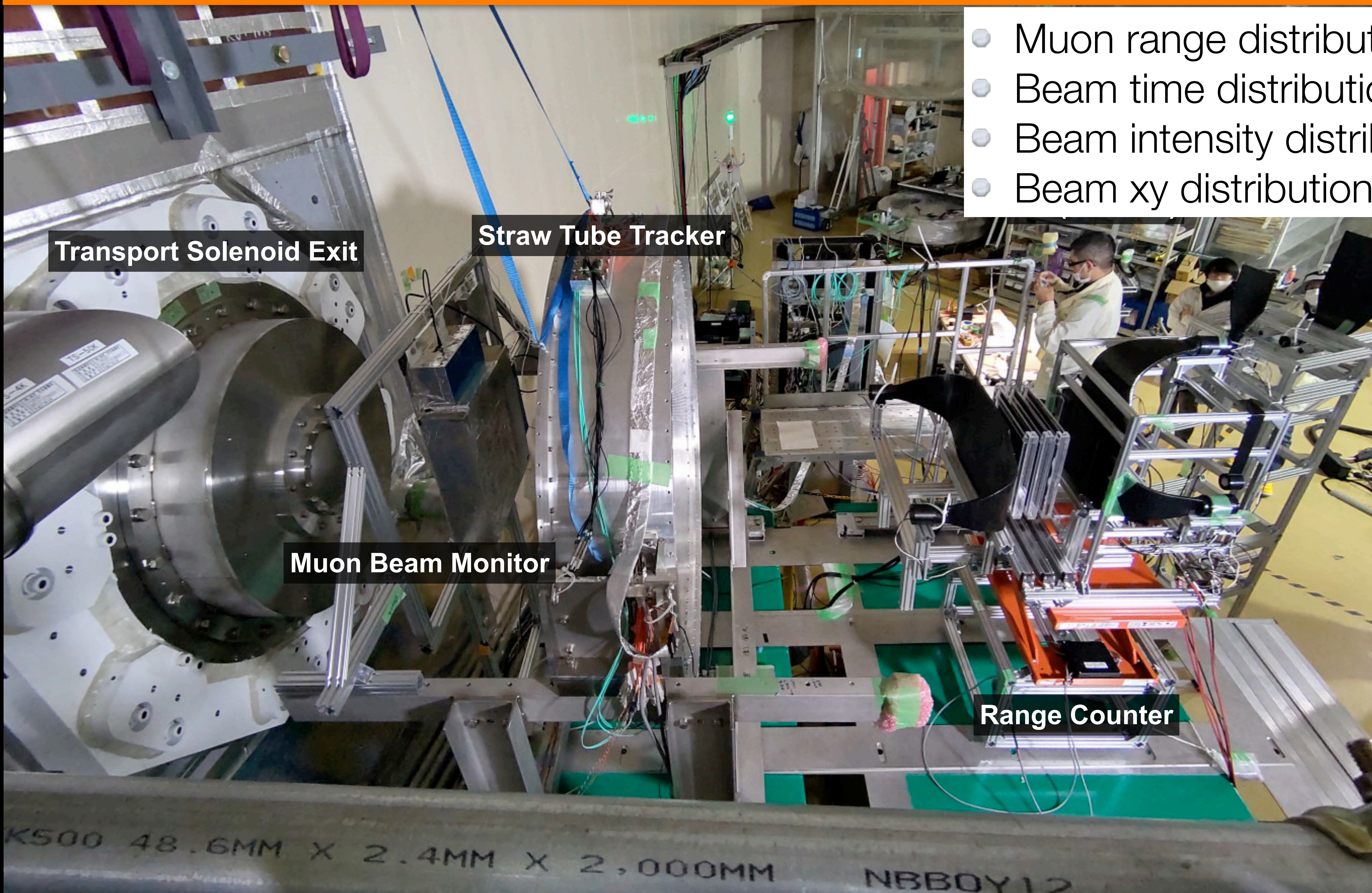
COMET Phase α (2023) Proton Beam Area

Proton beam commissioning: 0.26 kW beam power
Proton bunch time structure was the same as COMET Phase-I.



COMET Phase α (2023) Experimental Area

- Muon range distribution
- Beam time distribution
- Beam intensity distribution
- Beam xy distribution



COMET Phase α (2023)

Observation of the first muon beam on February 11th, 2023

Upcoming schedule:
The engineering run is expected to start in early 2026, followed by the physics run with lower beam intensity and then to the designed intensity.

$$B(\mu N \rightarrow eN) \leq 10^{-17}$$

with a factor of 100,000 improvement

preliminary

Refinement of COMET (Phase-II)+

	Phase-I	Phase-II
proton beam	8 GeV, 3.2 kW	8 GeV, 56 kW
proton target	graphite	tungsten
transport	90° bend	180° bend
muons stop	1.2×10^{9}/s	5×10^{10}/s
run time	150 days	200 days
detector	CyDet	StrECAL
90% CL	$< 7 \times 10^{-15}$	$< 4.6 \times 10^{-17}$
backgrounds	0.03 events	0.32 events

- Increase of the number of muons stopped in the muon target
- Increase of the signal acceptance by the collimator in the electron spectrometer
- Increase of running time

Other Physics Topics with COMET

$\mu^- \to e^+$ conversion in muonic atom

$$\mu^- + N(A,Z) \to e^+ + N(A,Z-2)$$

- Lepton number violation (LNV) and CLFV
- *not* exchange of light Majorana neutrino, $< m_{\mu e} > = \sum U_{\mu i} U_{ei} m_{\nu_i}$
- exchange of heavy new particles of TeV LNV Physics

signal signature

$$E_{\mu e^+} = m_\mu - B_\mu - E_{rec} - (M(A,Z-2) - M(A,Z))$$

conversion to ground state

Current limits

$$\mu^- + \mathrm{Ti} \to e^+ + \mathrm{Ca(gs)} \le 1.7 \times 10^{-12}$$

$$\mu^- + \mathrm{Ti} \to e^+ + \mathrm{Ca(ex)} \le 3.6 \times 10^{-11}$$

J. Kaulard et al. (SINDRUM-II), Phys. Lett. B422 (1998) 334.

backgrounds

- radiative muon nuclear capture (RMC)

$$\mu^- + N(A,Z) \to N(A,Z-1) + \nu + \gamma; \gamma \to e^+ e^-$$

$$E_{RMC} = m_\mu - B_\mu - E_{rec} - (M(A,Z-1) - M(A,Z))$$

$\mu^- \rightarrow e^+$ conversion in muonic atom

$$\mu^- + N(A,Z) \rightarrow e^+ + N(A,Z-2)$$

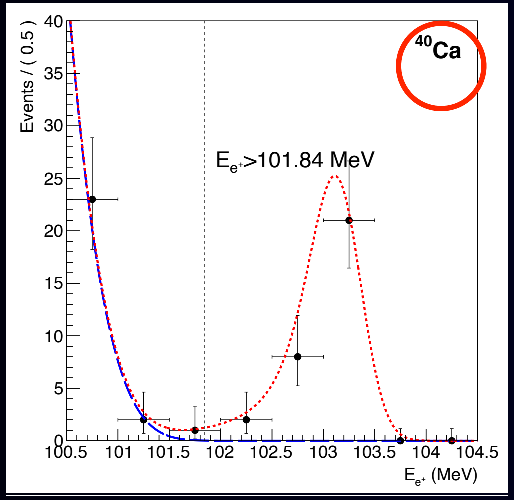
- COMET Phase-I; aluminum
- COMET Phase-II; dedicated ?

Requirements of Target $N(A,Z)$

$$E_{\mu^- e^+} > E_{RMC}^{end} \rightarrow$$

$$M(A,Z-1) > M(A,Z-2)$$

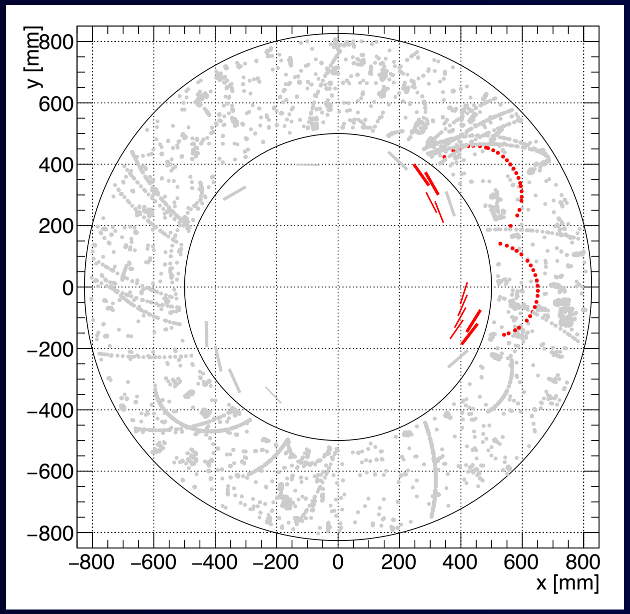
B. Yeo, YK, M. Lee and K. Zuber, Phys. Rev. D96 (2017) 075027



T.S. Wong, Ph.D. thesis (Osaka Univ.), 2020

$$\mu^- + N \rightarrow N' + \nu_\mu + \gamma$$

- COMET Phase-I plans to measure the Photon spectrum near the end-point (90-100 MeV) for aluminium
- CDC, as a pair spectrometer with photon conversion at the inner wall (CFRP) of the CDC.



D. Pietres, Ph.D. thesis (Osaka Univ.), 2023

Search for $\mu \to eX$

$\mu \to eX$

X is a light, invisible, neutral particle with LFV coupling to leptons.
: axion like particle (ALP)
: light flavour violating Z'

$$\mathscr{L}_{alp} = \sum_{i,j} \frac{\partial_\mu a}{2f_a} \bar{\ell}_i \gamma^\mu [C^V_{i,j} + C^A_{i,j}] \gamma^5 \ell_j$$

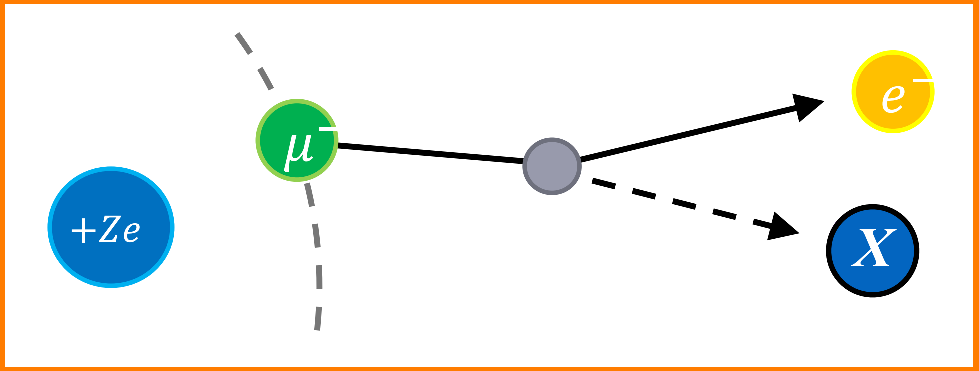
$$\Gamma(\ell_i \to \ell_j a) = \frac{1}{16\pi} \frac{m_{\ell_i}^2}{F_{ij}^2} \left(1 - \frac{m_a^2}{m_{\ell_i}^2}\right)^2$$

$$\propto 1/f_a^2$$

$$F_{ij} = \frac{2f_a}{\sqrt{|C^V_{ij}|^2 + |C^A_{ij}|^2}}$$

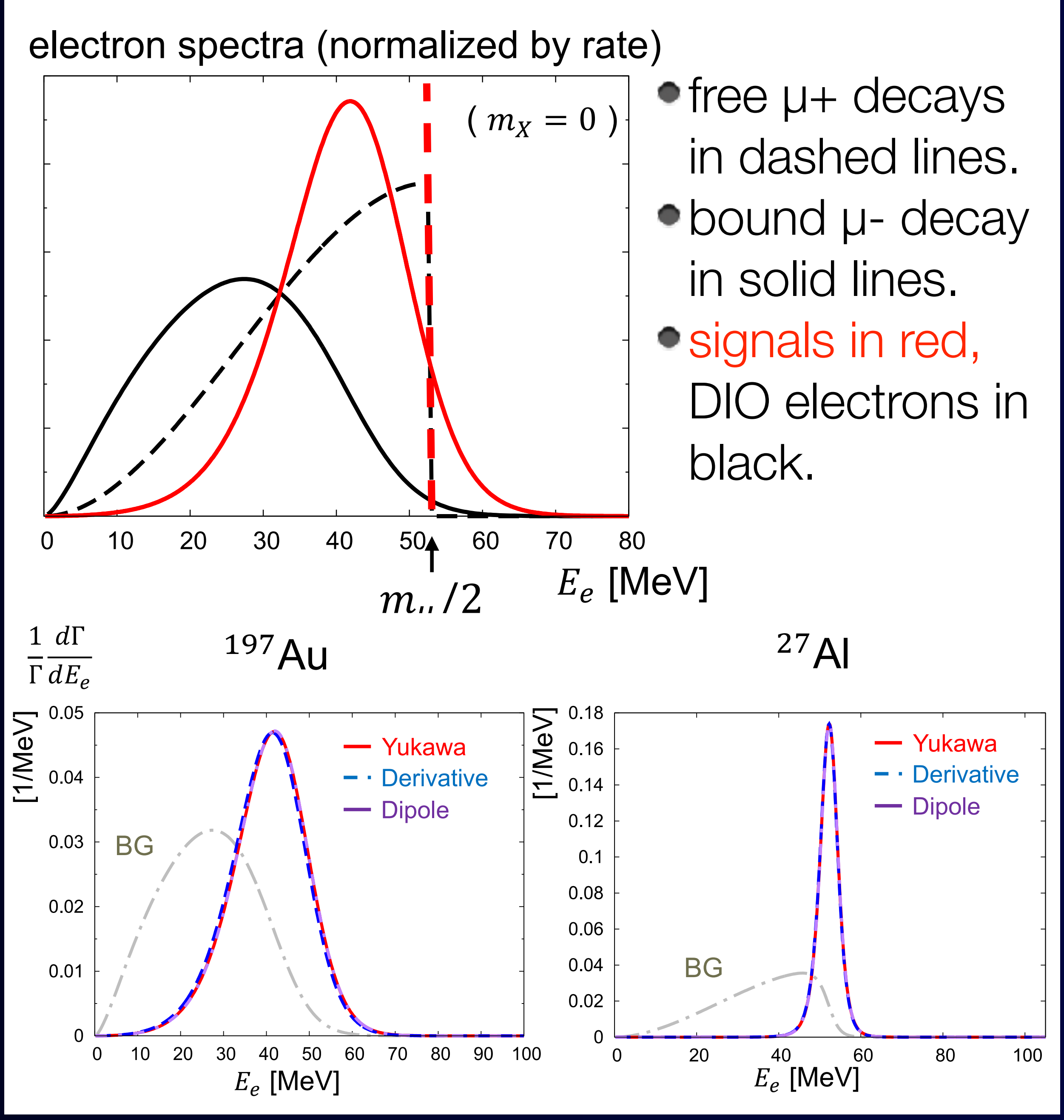
- Jodidio et al. (TRIUMF) 1986
  - polarised muons
  - $BR(\mu^+ \to e^+ a) < 2.6 \times 10^{-6}$
  - $F_{e\mu} > 5.5 \times 10^9$ GeV
- TWIST (TRIUMF) 2014
  - Michel parameters
  - $BR(\mu^+ \to e^+ a) < 5.8 \times 10^{-5}$
  - $F_{e\mu} > 1.2 \times 10^9$ GeV
- Crystal Box (LAMPF) 1988
  - NaI(Tl) crystals
  - $BR(\mu^+ \to e^+ a\gamma) < 1.1 \times 10^{-9}$
  - $F_{e\mu} > 9.8 \times 10^8$ GeV
- MEG-II fwd (PSI), planned
  - polarized muons
  - $BR(\mu^+ \to e^+ a) < 10^{-7}$
  - $F_{e\mu} > 10^9 - 10^{10}$ GeV
- Mu3e-online (PSI), planned
  - $25 < m_a < 90$ MeV
  - $BR(\mu^+ \to e^+ a) < 10^{-8}$
  - $F_{e\mu} > 10^{10}$ GeV

Bound $\mu^- \to e^- X$



- Advantage :
  - a signal peak of $m_X \sim 0$ is not on the DIO Michel edge.
    - $\mu^+ \to e^+ \gamma X$ for MEG II
  - Systematics with different target
- Disadvantage :
  - Not mono-energetic
  - background distribution
- Preliminary COMET study:
  - Phase-I, $B < O(10^{-5})$
  - Phase-II, $B < O(10^{-(8-9)})$
    - $f_a > 10^{10-11}$ GeV

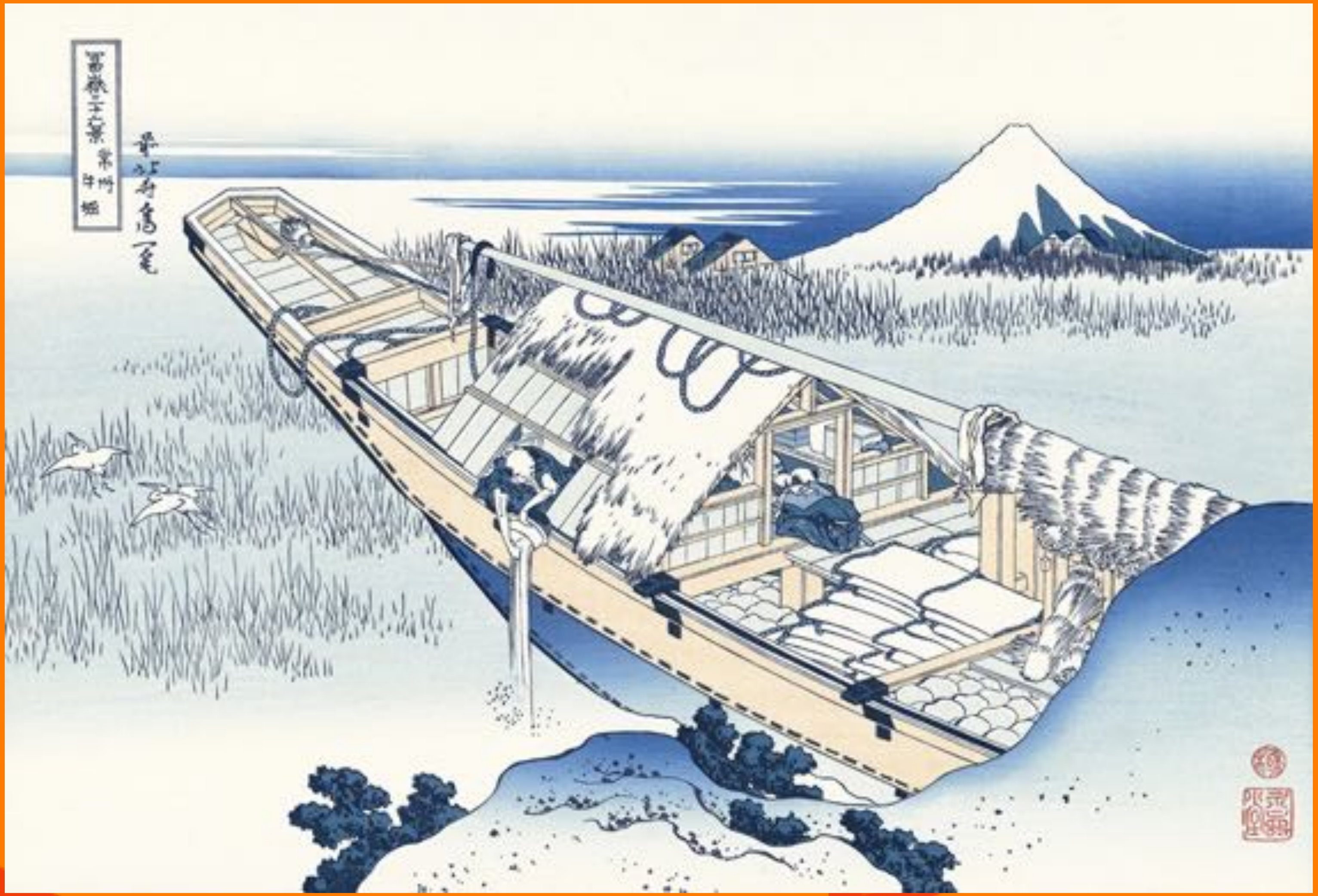
T. Xing, C. Wu, H. Miao, H.B. Li, W. Li, Y. Yuan, Y. Zhang, Chine. Physics C, 47 (2023) 013108



Y. Uesaka, Phys. Rev. D102, 095007 (2020)

- use the detector calibration data of π^+ and μ^+ (a la Jure Zupan, 2023)

Long future…



$$B(\mu N \to eN) \leq 10^{-18}$$

with a factor of 1000,000 improvement

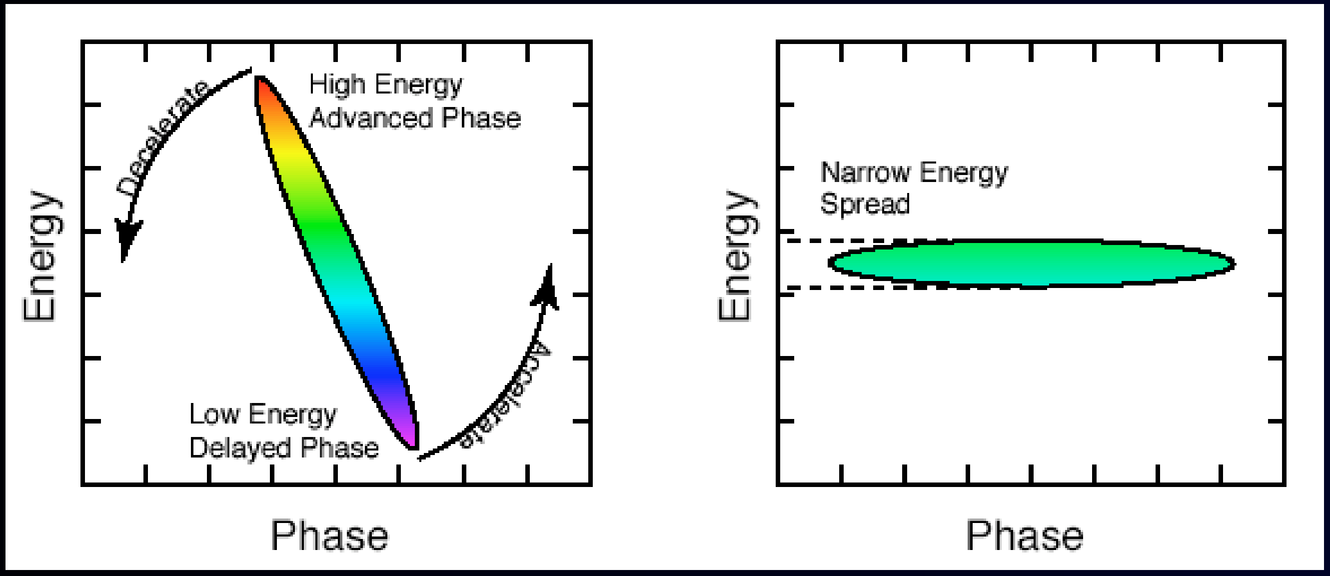
Future $\mu \rightarrow e$ conversion experiments

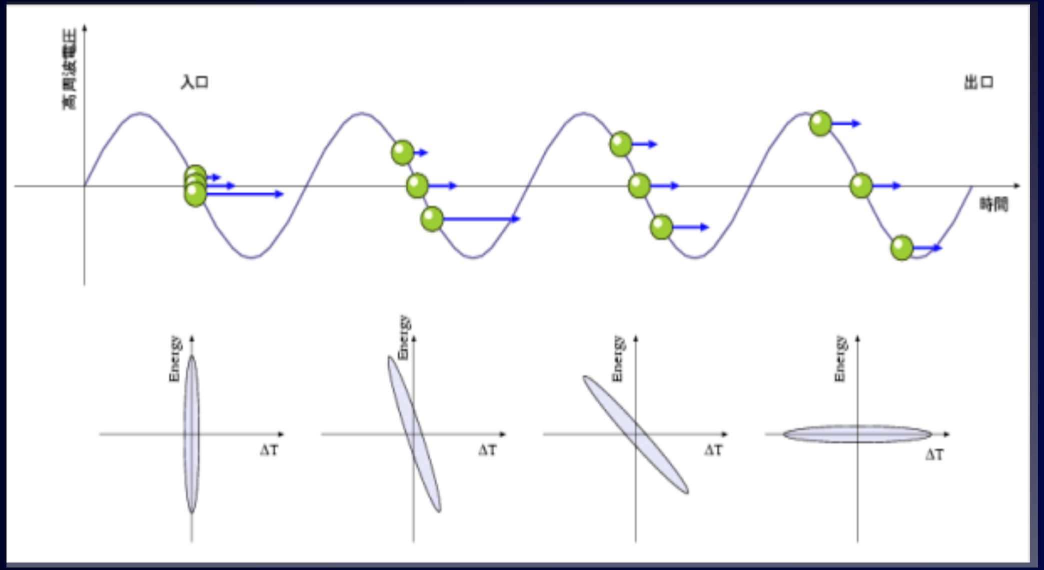
1 Better muon beam qualities

narrow beam energy spread (phase rotation)
small beam emittance (muon cooling)

synergy with muon collider R&D

Phase rotation (synchrotron oscillation)





Future $\mu \to e$ conversion experiments

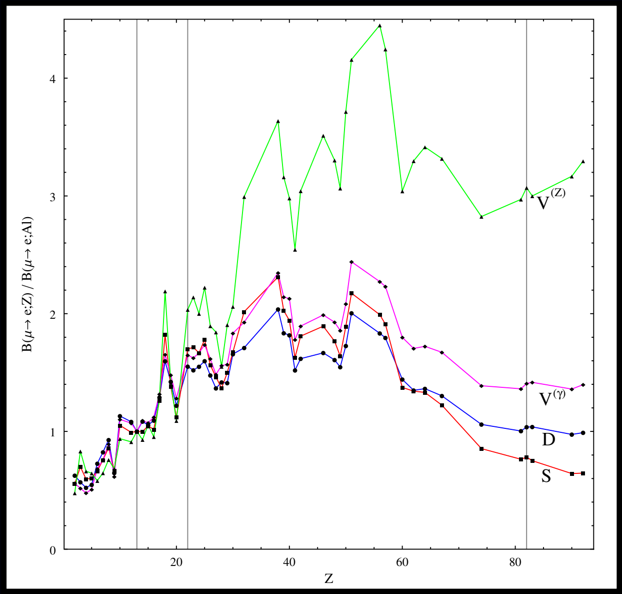
2 High Z muon target

→early starting time of measurements

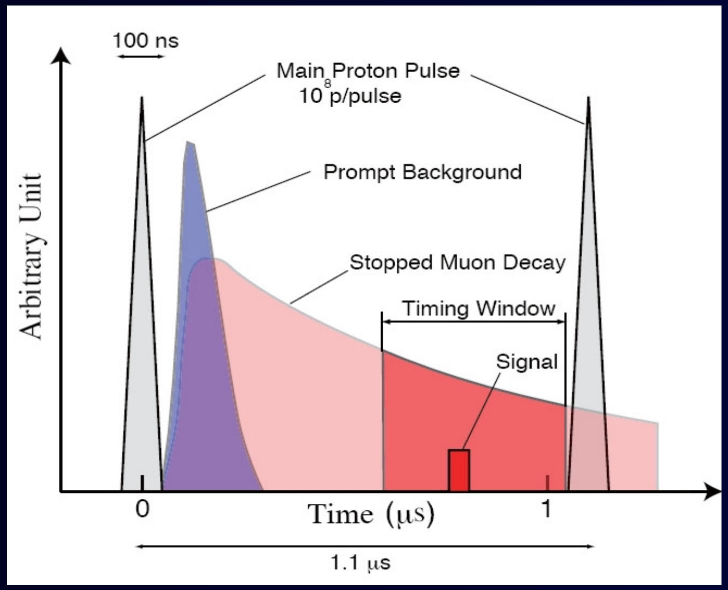
→no pions in a muon beam.

→a long muon beam line (100 m?)

Target Z dependence (one int. at a time)



measurements starts after 700 ns

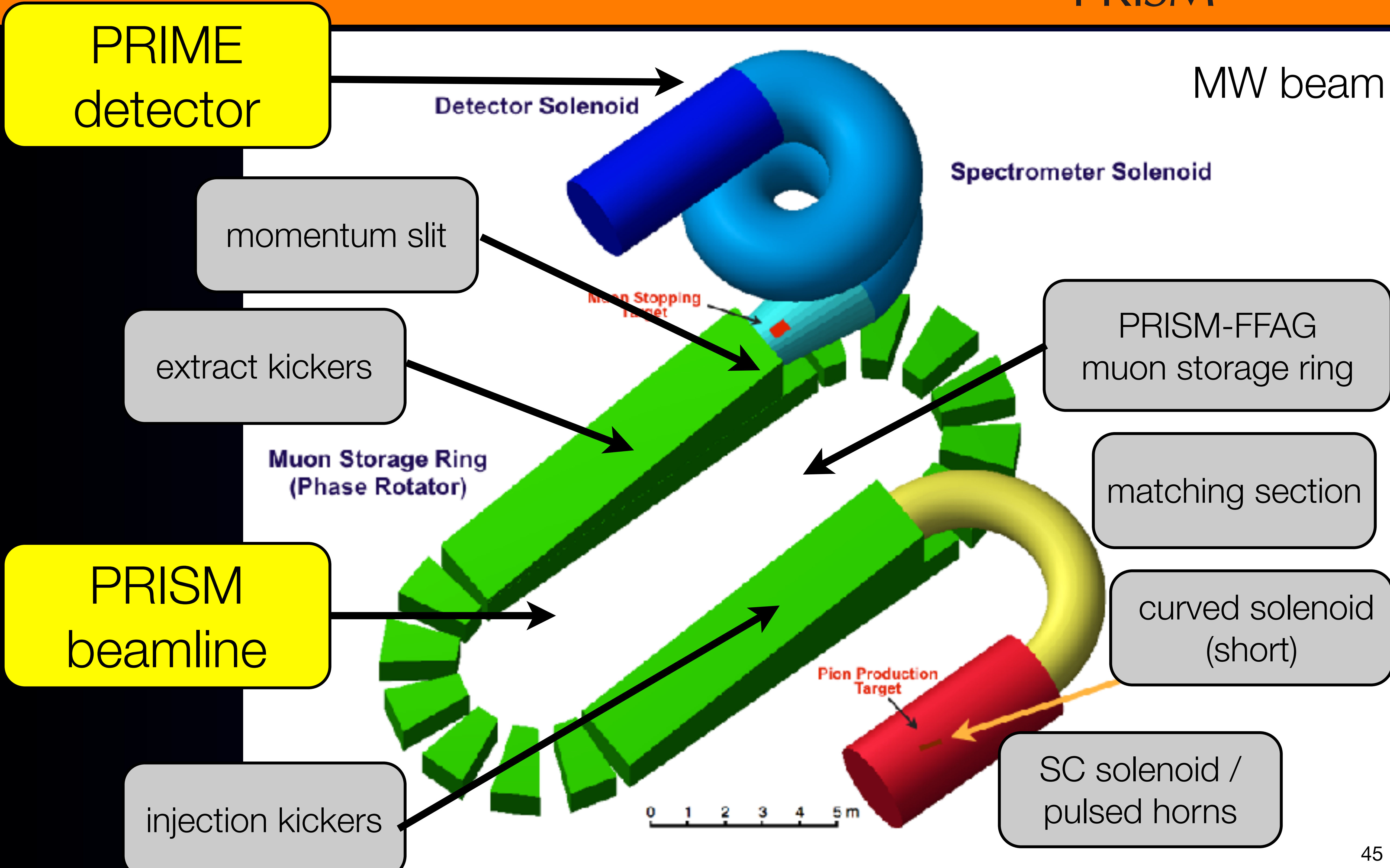


R. Kitano, M. Koike and Y. Okada, Phys.Rev. D66 (2002) 096002; D76 (2007) 059902

V. Cirigliano, R. Kitano, Y. Okada, and P. Tuzon, Phys. Rev. D80 (2009) 013002

PRISM=Phase Rotated Intense Slow Muon source

PRISM/PRIME (2003)



PRISM FFA R&D at Osaka University (2003 - 2007)

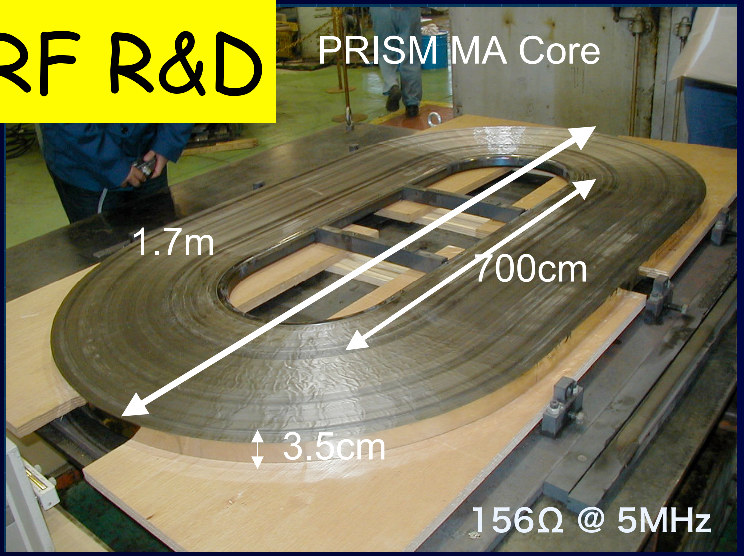
PRISM

COMET

Fixed Field Alternating Gradient Synchrotron (FFA)

- Accelerator ring suitable for acceptation low-energy muons
  - large beam acceptance
  - fast beam acceleration
  - synchrotron oscillation

RF R&D



FFA R&D at Osaka

- Scaling FFA with DFD triplet magnets

$$B(r) \propto \left(\frac{r}{r_0}\right)^5$$

PRISM FFA Phase Rotation at Osaka University (2003 - 2007)

T. Nakanishi, Ms.thesis (2008)

demonstration of phase rotation has been made.

Summary

Summary

- $\mu \rightarrow e$ conversion is one of the important muon CLFV processes.
- COMET Phase-I at J-PARC is aiming at CR < 7×10^{-15} (90% CL) a factor of 100 better than the current limit.
- COMET Phase-II aims at CR<7×10^{-18}, a factor of 10,000 (or 100,000) better, following Phase-I.
- $\mu \rightarrow e$ conversion experiments which utilize a muon storage ring (FFA) might be a future option.

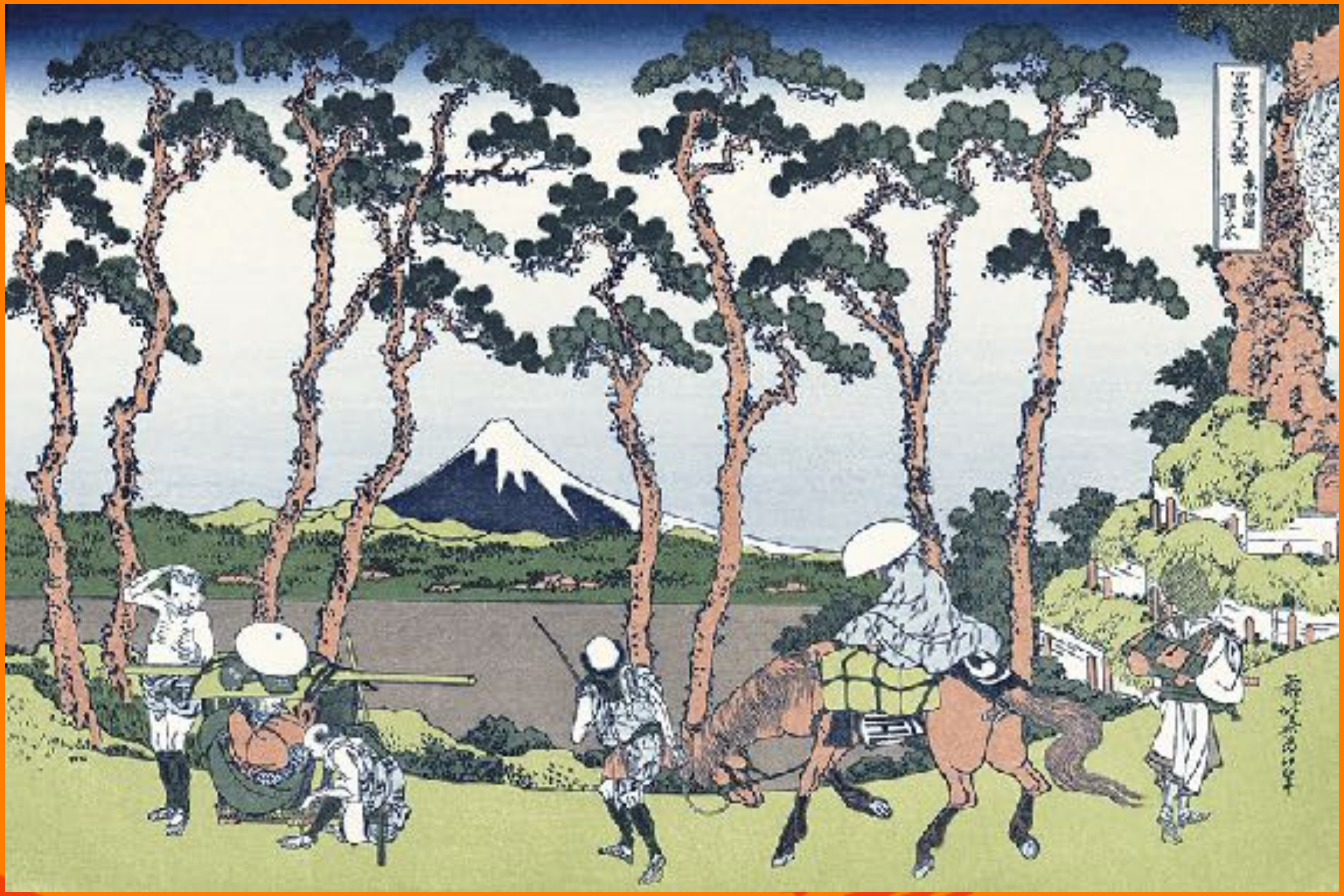
my dog, IKU

Thanks!

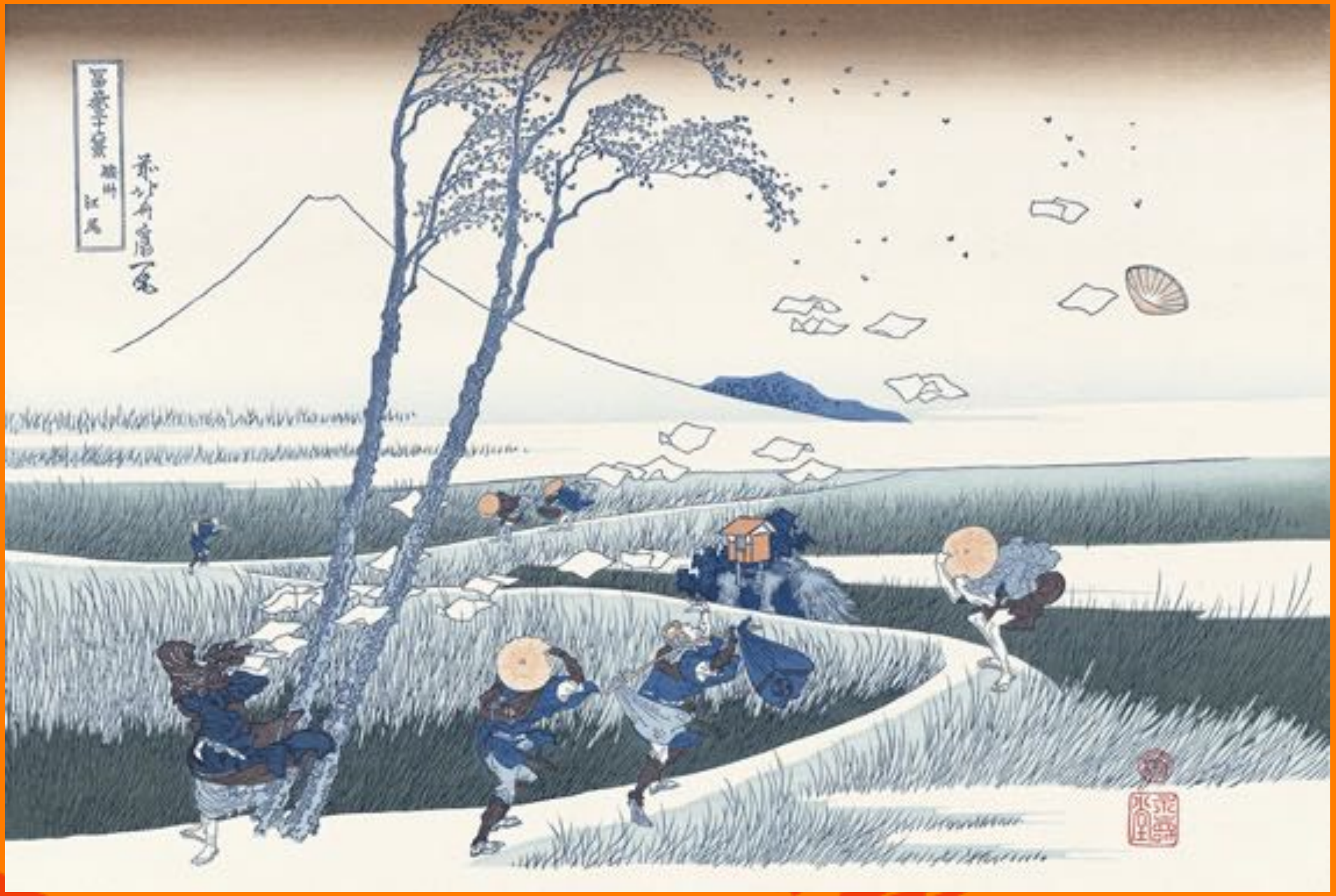
Thanks!

COMET character

Backup



Backup



COMET Phase-I Backgrounds

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

† This estimate is currently limited by computing resources.

from COMET Phase-I Technical Design Report