Search for Charged Lepton Flavor Violation with Muons

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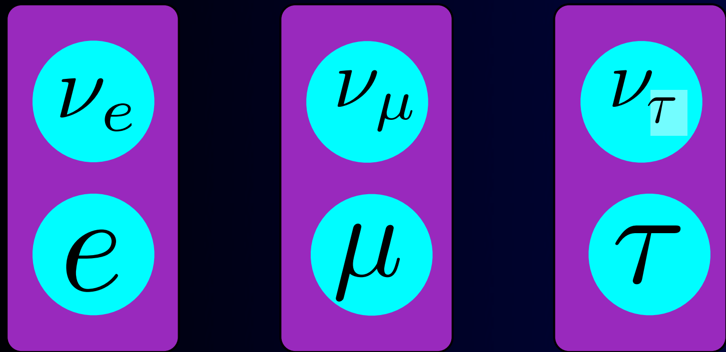
Réunions plénières du GDR neutrino au LLR
April 29th, 2010
Paris, France

Why Charged Leptons in Neutrino Physics ?

SU(2) weak doublets formed by neutrinos and charged leptons.



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Non-Standard Interaction (NSI) contributes to the both if the weak SU(2) symmetry holds.

Outline

- Why Charged Lepton Flavor Violation (cLFV) ?
- cLFV Experiments
  - $\mu \to e\gamma$
  - μ-e conversion
- Proposed Searches for μ-e conversion at Sensitivity $<10^{-16}$
  - COMET at J-PARC
- μ-e conversion at Sensitivity of $<10^{-18}$
- R&D at Osaka University
  - MUSIC project
- Summary

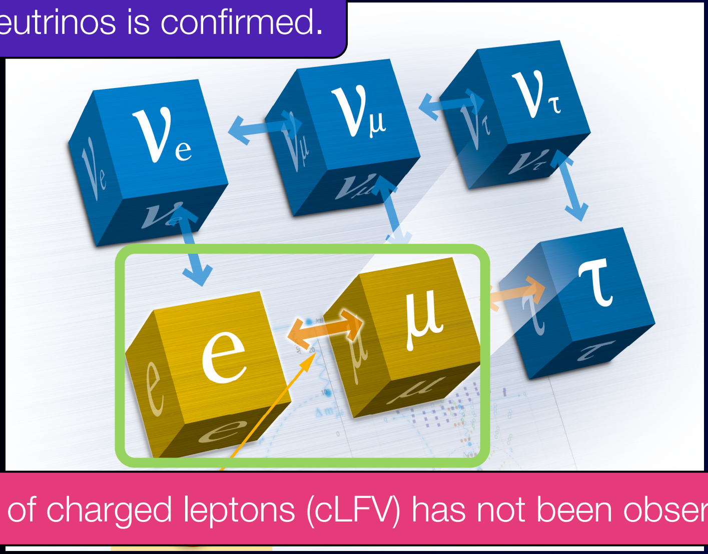
cover pages with block prints of “the fifty-three stations of the Tokaido” (from Tokyo to Osaka) by Hiroshige Utagawa (1797-1858)

Why
Charged Lepton
Flavor Violation ?

Shinagawa

What is Lepton Flavor Violation of Charged Leptons (cLFV) ?

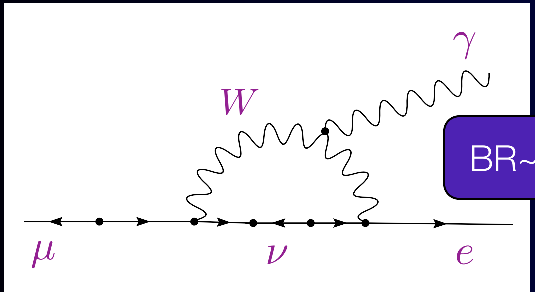
LFV of neutrinos is confirmed.



LFV of charged leptons (cLFV) has not been observed.

cLFV in the SM with massive neutrinos

$$B(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_l (V_{MNS})^*_{\mu l}(V_{MNS})_{el}\frac{m^2_{\nu_l}}{M^2_W}\right|^2$$



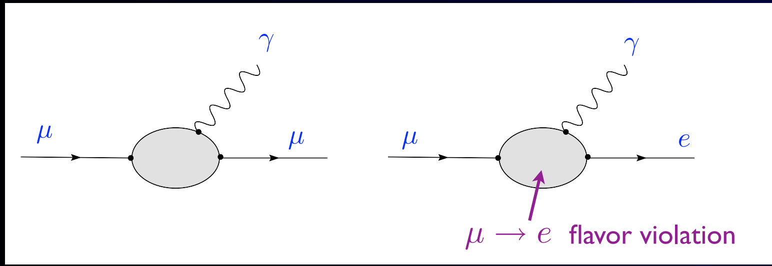
BR~O(10^{-54})

1 Observation of cLFV would indicate a clear signal of physics beyond the SM with massive neutrinos.

Relation of cLFV and muon anomalous g-2

$$\delta a_\mu = a_\mu^{\mathrm{exp}} - a_\mu^{\mathrm{SM}} = (27.6 \pm 8.1) \times 10^{-10} \quad 3.4\sigma$$

$$\delta a_\mu^{\mathrm{EW}} = (15.4 \pm 0.2) \times 10^{-10}$$



2 New physics contributing to muon g-2 would also contributes to cLFV.

General Consideration on cLFV
- Effective Lagrangian

$$\mathcal{L}_{\rm LFV} = y\frac{em_\mu}{\Lambda^2}\bar{\mu}_R\sigma^{\mu\nu}e_L F_{\mu\nu} + \text{h.c.} + \cdots$$

$$\text{BR}(\mu\to e\gamma) = y^2\frac{3(4\pi)^3\alpha}{G_F^2\Lambda^4}$$

Λ :new physics scale

- For tree diagrams,

$$\text{BR}(\mu\to e\gamma) = 1\times10^{-11}\times\left(\frac{400\text{TeV}}{\Lambda}\right)^4\left(\frac{y}{1}\right)^2$$

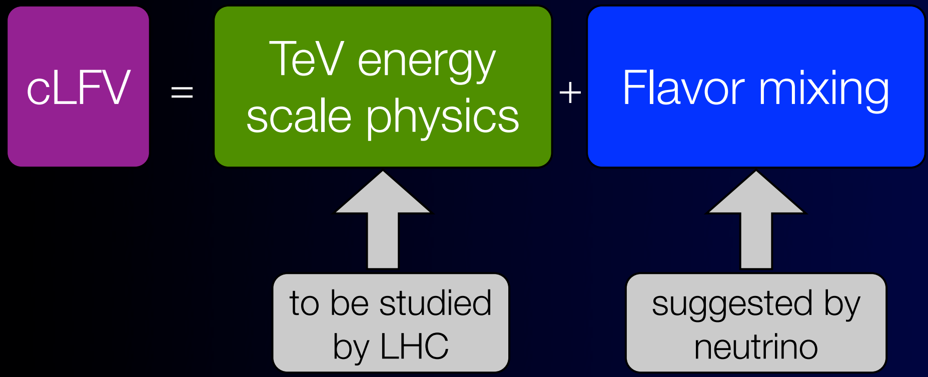
> sensitive to high energy scale

- For loop diagrams,

$$\text{BR}(\mu\to e\gamma) = 1\times10^{-11}\times\left(\frac{2\text{TeV}}{\Lambda}\right)^4\left(\frac{\theta_{\mu e}}{10^{-2}}\right)^2 \qquad y = \frac{g^2}{16\pi^2}\theta_{\mu e}$$

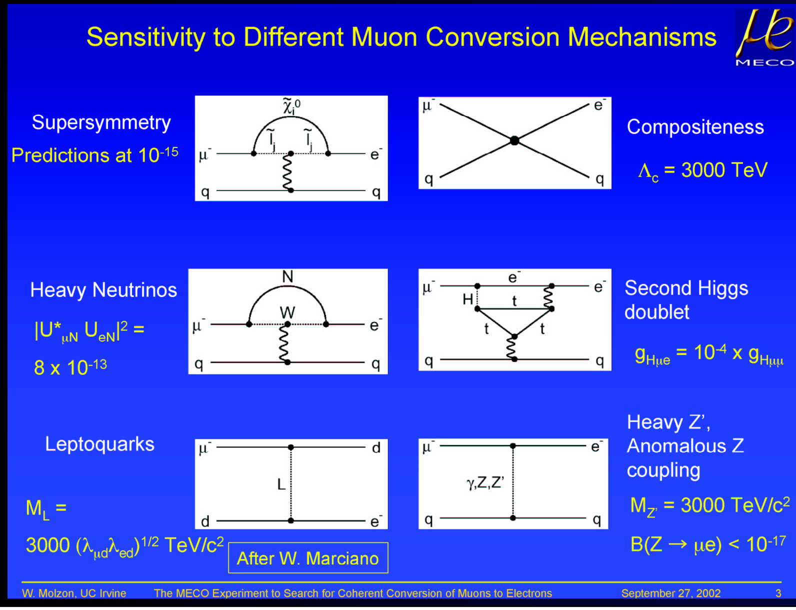
> sensitive to TeV energy scale with reasonable mixing

Relation to High Energy Frontier



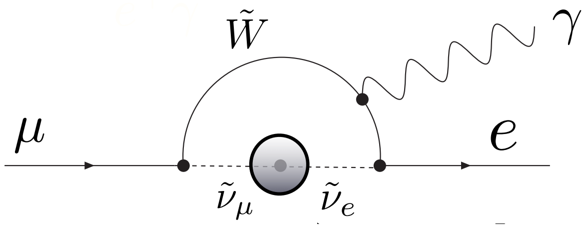
3 The physics of cLFV is complementary to that of LHC and neutrino physics.

Various Models Predict Charged Lepton Mixing.



LFV in SUSY Models

an example diagram

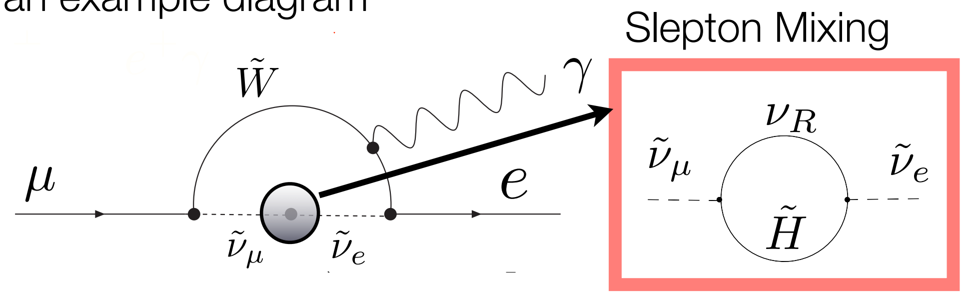


Since neutrinos are mixed & LFC is violated, sleptons can mix.

$$\mathrm{BR}(\mu \to e\gamma) \simeq 1 \times 10^{-11} \left(\frac{150\ \mathrm{GeV}}{m_{\mathrm{SUSY}}}\right)^4 \left(\frac{\tan\beta}{20}\right)^2 \left(\frac{\Delta_{21}}{3 \times 10^{-4}}\right)^2$$

LFV in SUSY Models

an example diagram



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slepton mass matrix

$$m^2_{\tilde{l}} = \begin{pmatrix} m^2_{11} & m^2_{12} & m^2_{13} \\ m^2_{21} & m^2_{22} & m^2_{23} \\ m^2_{31} & m^2_{32} & m^2_{33} \end{pmatrix}$$

Minimal SUSY Scenario

$\Delta m^2_{ij} = 0$ @ Planck energy scale

New physics at high energy scale would introduce off-diagonal mass matrix elements, resulting in slepton mixing.

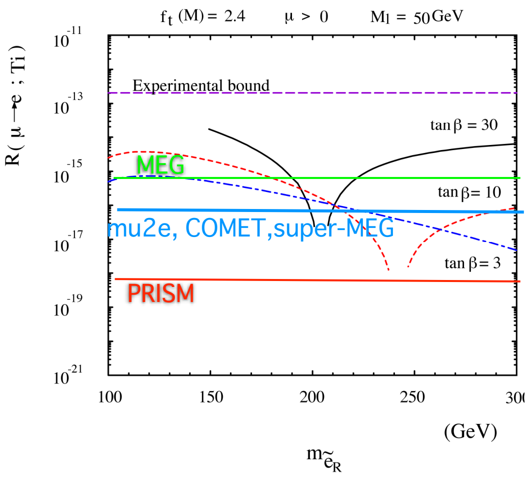
neutrino seesaw mechanism (~10^{15}GeV)

grand unification (GUT) (~10^{16}GeV)

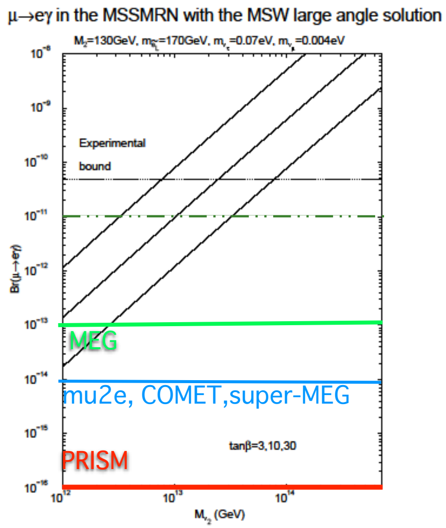
$\Delta m^2_{ij} \neq 0$ @ Weak energy scale (100 GeV)

4 cLFV have potential to study physics at very high energy scale like 10^{16} GeV.

SUSY Predictions for cLFV

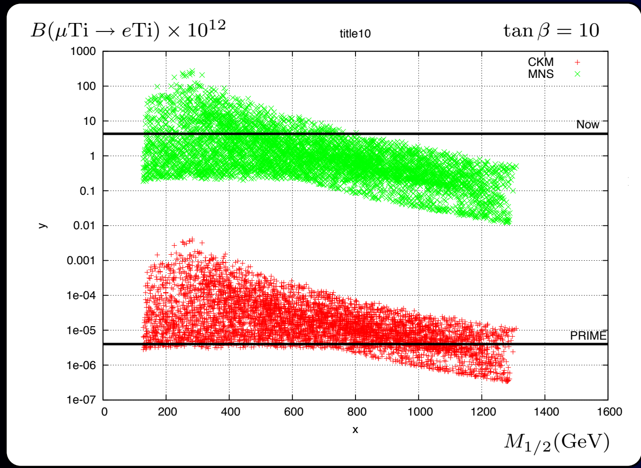


SU(5) SUSY GUT



SUSY Seesaw Model

SUSY Prediction for muon to electron conversion



Calibbi, Faccia, Masiero, Vempati, hep-ph/0605139

BR~10^{-12}

BR~10^{-18}

5

Theoretical predictions are just below the present experimental bound.

cLFV Physics Motivation Summary

1. Observation of cLFV would indicate a clear signal of physics beyond the SM with massive neutrinos.
2. New physics contributing to muon g-2 would also contributes to cLFV.
3. The physics of cLFV is complementary to that of LHC and neutrino physics.
4. cLFV have potential to study physics at very high energy scale like 10^{16} GeV.
5. Theoretical predictions are just below the present experimental bound.

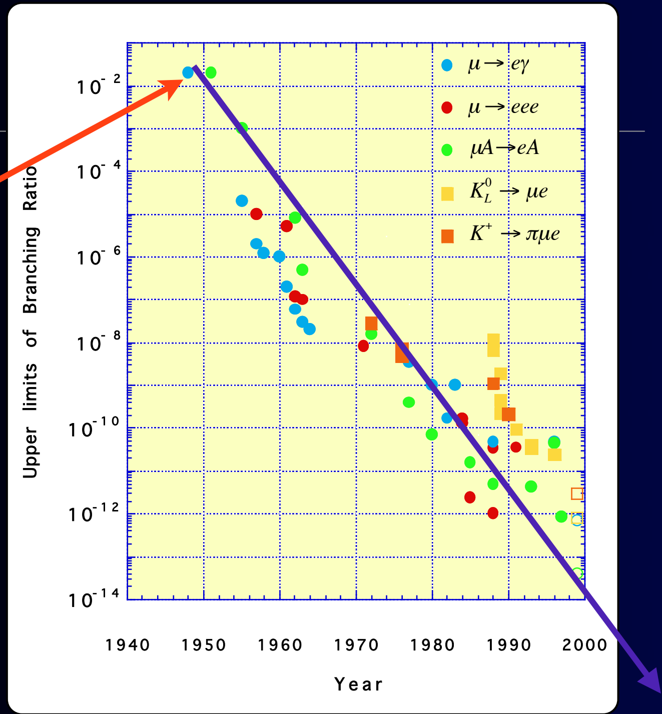
cLFV Experiments

at Kawasaki

cLFV History

First cLFV search

Pontecorvo in 1947



Charged Lepton Flavor Violation with Muons

ΔL=1

Process	current	future
$\bullet \mu^+ \to e^+\gamma$	$<10^{-11}$	$<10^{-14}$
$\bullet \mu^+ \to e^+e^+e^-$	$<10^{-12}$	$<10^{-14}$
$\bullet \mu^- + N(A,Z) \to e^- + N(A,Z)$	$<10^{-12}$	$<10^{-18}$
$\bullet \mu^- + N(A,Z) \to e^+ + N(A,Z-2)$		

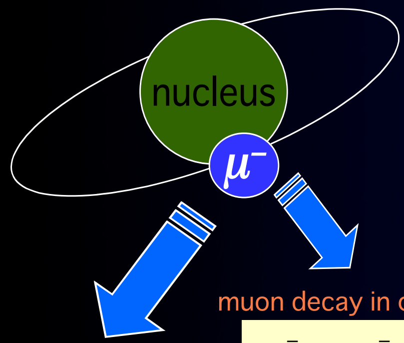
ΔL=2

Process	current	future
$\bullet \mu^+e^- \to \mu^-e^+$	$<10^{-3}G_F$	$<10^{-4}G_F$
$\bullet \mu^- + N(A,Z) \to \mu^+ + N(A,Z-2)$		
$\bullet \nu_\mu + N(A,Z) \to \mu^+ + N(A,Z-1)$		
$\bullet \nu_\mu + N(A,Z) \to \mu^+\mu^+\mu^- + N(A,Z-1)$		

μ→e conversion
in
a muonic atom

What is a Muon to Electron Conversion ?

1s state in a muonic atom



muon decay in orbit

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

nuclear muon capture

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

Neutrino-less muon nuclear capture (=μ-e conversion)

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

lepton flavors changes by one unit.

$$B(\mu^- N \to e^- N) = \frac{\Gamma(\mu^- N \to e^- N)}{\Gamma(\mu^- N \to \nu N')}$$

μ-e Conversion
Signal and Backgrounds

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

- Signal
  - single mono-energetic electron

$$m_\mu - B_\mu \sim 105MeV$$

- The transition to the ground state is a coherent process, and enhanced by a number of nucleus.

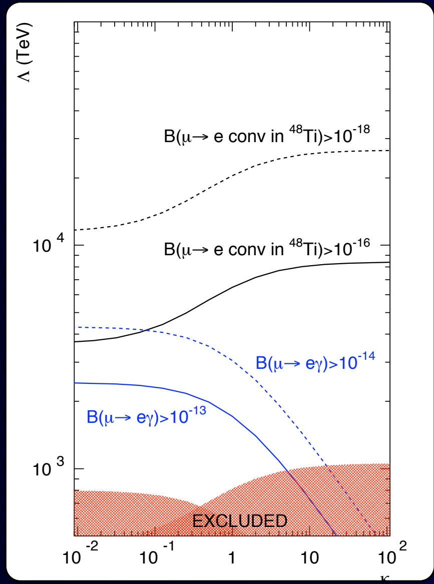
$$\propto Z^5$$

- Backgrounds
  - Intrinsic physics background
    - muon decay in orbit (DIO)
  - beam-related background
    - radiative pion capture
    - muon decay in flight (DIF)
  - cosmic-ray background
  - tracking failure
  - etc....

Physics Sensitivity Comparison between μ→eγ and μ-e Conversion

Photonic (dipole) and non-photonic contributions

	photonic (dipole)	non-photonic
μ→eγ	yes (on-shell)	no
μ-e conversion	yes (off-shell)	yes



more sensitive to new physics

Experimental Comparison between $\mu \to e\gamma$ and μ-e Conversion

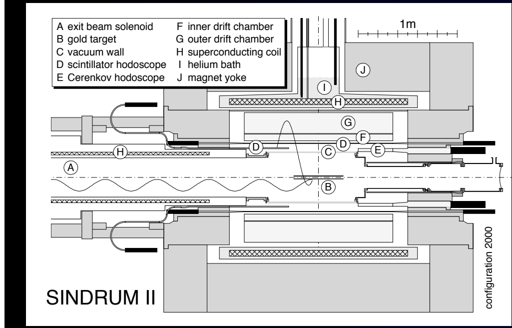
	background	challenge	beam intensity
• $\mu \to e\gamma$	accidentals	detector resolution	limited
• μ-e conversion	beam	beam background	no limitation

- $\mu \to e\gamma$: Accidental background is given by $(\text{rate})^2$. The detector resolutions have to be improved, but they (in particular, photon) would be hard to go beyond MEG from present technology. The ultimate sensitivity would be about 10^{-14} (with about 10^8/sec) unless the detector resolution is radically improved.
- μ-e conversion : Improvement of a muon beam can be possible, both in purity (no pions) and in intensity (thanks to muon collider R&D). A higher beam intensity can be taken because of no accidentals.

μ-e conversion might be a next step.

Previous Measurements

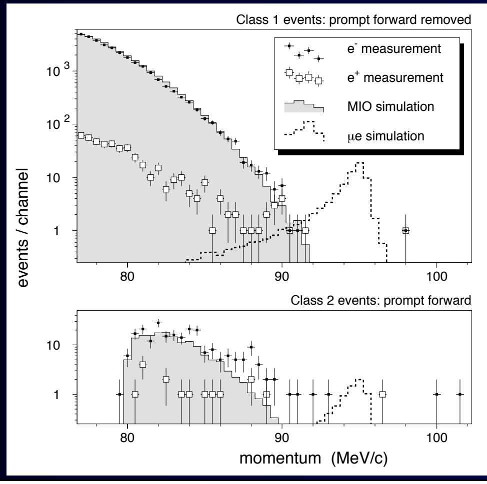
SINDRUM-II (PSI)



PSI muon beam intensity ~ $10^{7\text{-}8}$/sec beam from the PSI cyclotron. To eliminate beam related background from a beam, a beam veto counter was placed. But, it could not work at a high rate.

Published Results (2004)

$$B(\mu^- + Au \rightarrow e^- + Au) < 7 \times 10^{-13}$$



Experimental Design for Muon to Electron Conversion

at Tenryu river, Shizuoka

Improvements for Signal Sensitivity

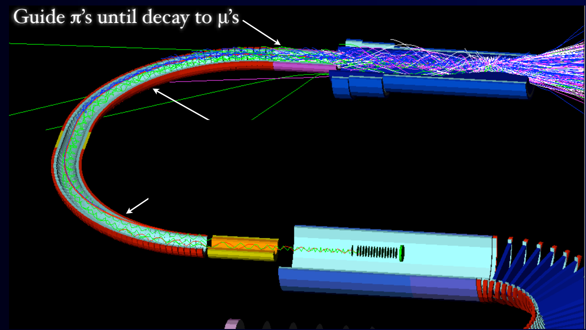
To achieve a single sensitivity of 10^{-16}, we need

10^{11} muons/sec (with 10^{7} sec running)

whereas the current highest intensity is 10^{8}/sec at PSI.

Pion Capture and Muon Transport by Superconducting Solenoid System

(10^{11} muons for 50 kW beam power)



a few % of acceptance

Improvements for Background Rejection

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

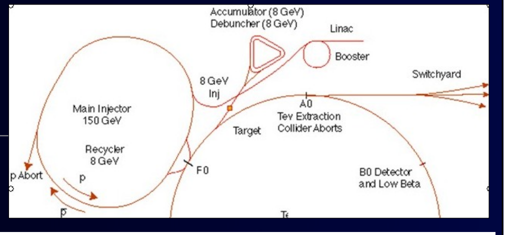
proton extinction = #protons between pulses/#protons in a pulse < 10^{-9}

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

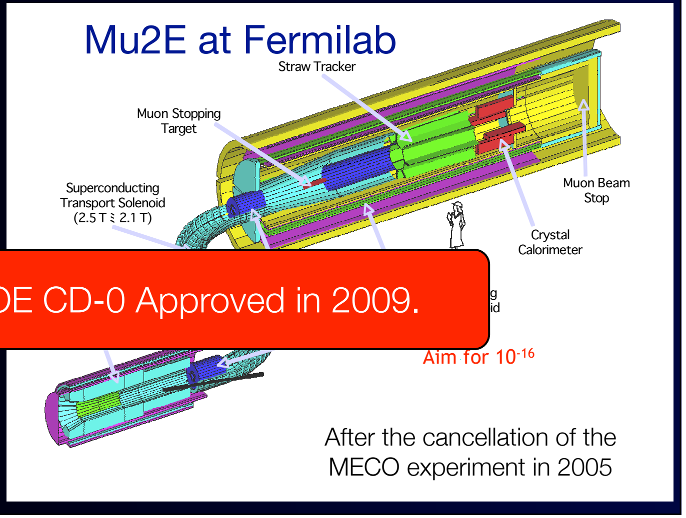
Muon DIF background → curved solenoids for momentum selection — eliminate energetic muons (>75 MeV/c)

base on the MELC proposal at Moscow Meson Factory

Mu2E
at Fermilab



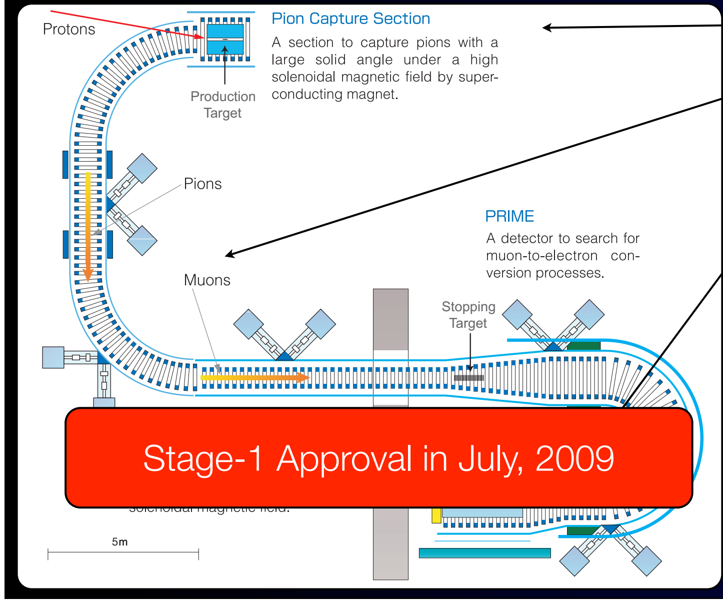
- After Tevatron shutdown, use the antiproton accumulator ring and debuncher ring for beam pulsing.
- Proton beam power is 20 and >200 k pre and post Project-X, respectively.



DOE CD-0 Approved in 2009.

COMET (COherent Muon to Electron Transition) in Japan

$B(\mu^- + Al \to e^- + Al) < 10^{-16}$



Proton Beam

The Muon Source
- Proton Target
- Pion Capture
- Muon Transport

The Detector
- Muon Stopping Target
- Electron Transport
- Electron Detection

Stage-1 Approval in July, 2009

proposed to J-PARC

COMET Collaboration List

49 people from 14 institutes (April 2010)

Department of physics and astronomy, University of British Columbia, Vancouver, Canada
D. Bryman
TRIUMF, Canada
T. Numao, I. Sekachev

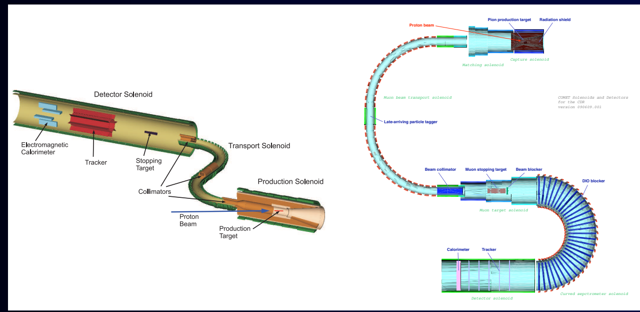
JINR, Dubna, Russia
V. Kalinnikov, A. Moiseenko, D. Mzhavia, J. Pontecorvo, B. Sabirov, Z. Tsamaiaidze, and P. Evtukhouvich
BINP, Novosibirsk, Russia
D. Grigorev

Department of Physics, Brookhaven National Laboratory, USA
R. Palmer, Y. Cui
Department of Physics, University of Houston, USA
E. Hungerford, K. Lau

Imperial College London, UK
A. Kurup, J. Pasternak, Y. Uchida, P. Dauncey, U. Egede, P. Dornan
University College London, UK
M. Wing, M. Lancaster, R. D'Arcy
University of Glasgow
P. Soler

Institute for Chemical Research, Kyoto University, Kyoto, Japan
Y. Iwashita,
Department of Physics, Osaka University, Japan
M. Aoki, T. Hiasa, Md.I. Hossain, T. Itahashi, Y. Kuno, H. Nakai, H. Sakamoto, A. Sato
Department of Physics, Saitama University, Japan
M. Koike, J. Sato, M. Yamanaka
Department of Physics, Tohoku University, Japan
Y. Takubo,
High Energy Accelerator Research Organization (KEK), Japan
Y. Arimoto, Y. Igarashi, S. Ishimoto, S. Mihara, H. Nishiguchi, T. Ogitsu, M. Tomizawa, A. Yamamoto, M. Yoshida and K. Yoshimura

Design Difference Between Mu2e and COMET



	Mu2e	COMET
Muon Beam-line	S-shape	C-shape
Electron Spectrometer	Straight solenoid	Curved solenoid

Charged Particle Trajectory in Curved Solenoids

- A center of helical trajectory of charged particles in a curved solenoidal field is drifted by

$$D = \frac{p}{qB}\theta_{bend}\frac{1}{2}\left(\cos\theta + \frac{1}{\cos\theta}\right)$$

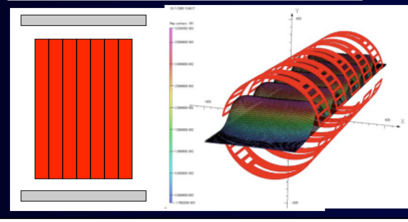
D : drift distance
B : Solenoid field
θ_{bend} *: Bending angle of the solenoid channel*
p : Momentum of the particle
q : Charge of the particle
θ *: atan(*P_T/P_L*)*

  - This can be used for charge and momentum selection.

- This drift can be compensated by an auxiliary field parallel to the drift direction given by

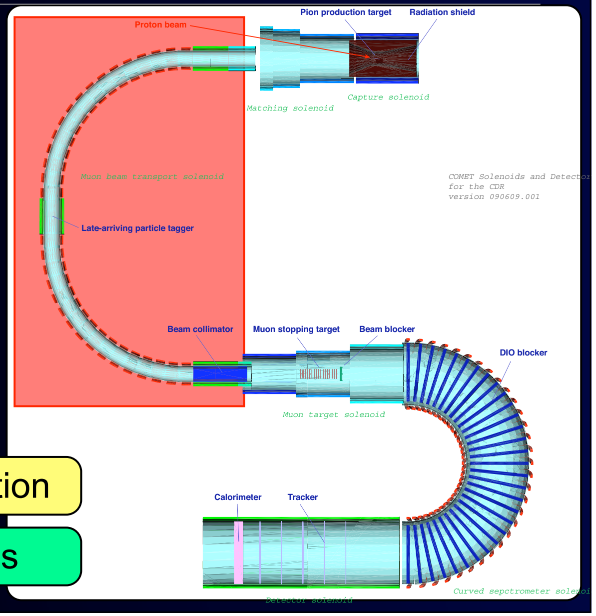
$$B_{comp} = \frac{p}{qr}\frac{1}{2}\left(\cos\theta + \frac{1}{\cos\theta}\right)$$

p : Momentum of the particle
q : Charge of the particle
r : Major radius of the solenoid
θ *: atan(*P_T/P_L*)*



Muon Transport System for COMET

- The muon transport system consists of curved solenoids.
  - bore radius : 175 mm
  - magnetic field : 2 T
  - bending angle : 180 degrees
  - radius of curvature : 3 m
- Dispersion is proportional to a bending angle.
- muon collimator after 180 degree bending.
- Elimination of muon momentum > 70 MeV/c

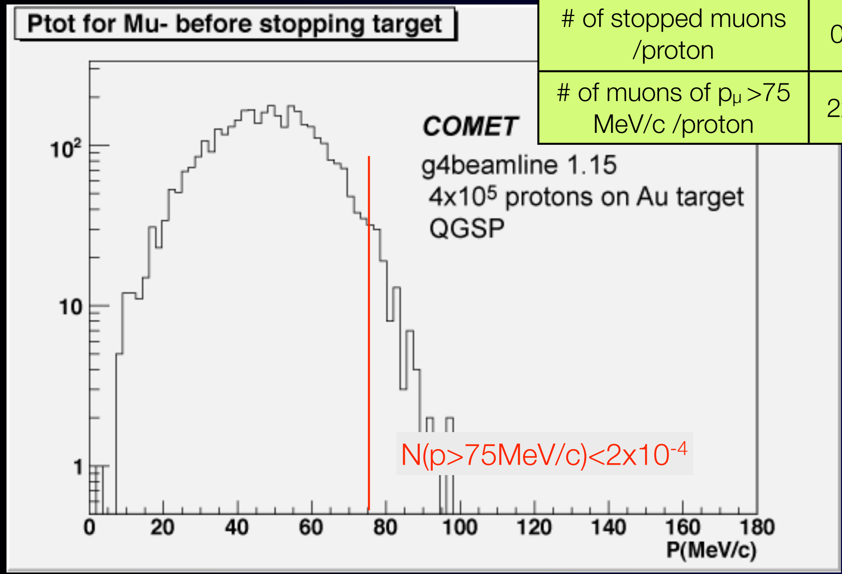


good momentum selection

no high-energy muons

Muon Momentum Spectrum at the End of the Transport Beam Line

# of muons /proton	0.009
# of stopped muons /proton	0.003
# of muons of p_{μ} >75 MeV/c /proton	2×10^{-4}



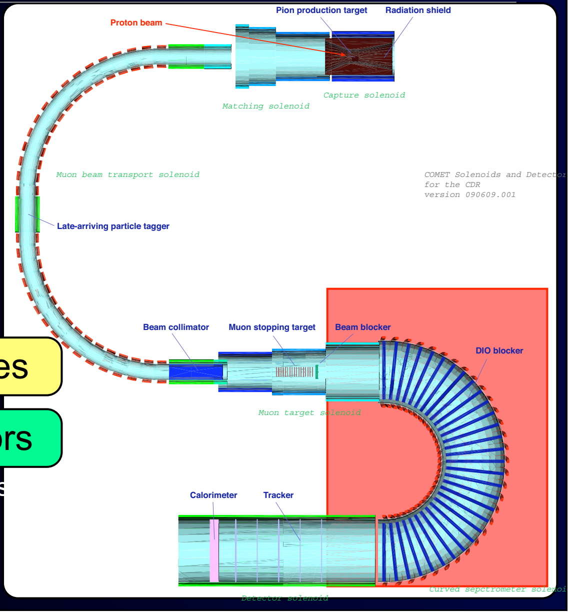
Electron Transport System for COMET

- The electron transport
  - bore : 700 mm
  - magnetic field : 1T
  - bending angle : 180 degrees
- Electron momentum ~ 104 MeV/c
- Elimination of negatively-charged particles less than 80 MeV/c
- Elimination of positively-charged particles (like protons from muon capture)

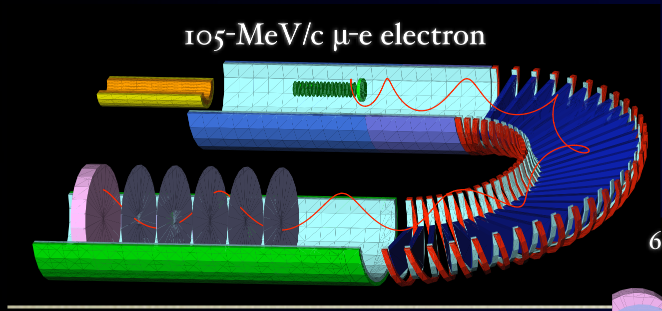
reduction of detector rates

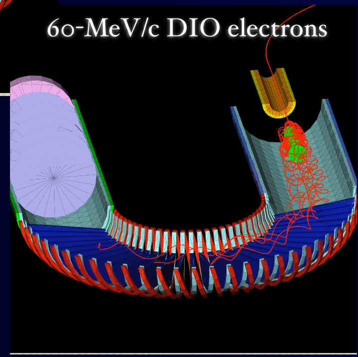
no protons in the detectors

- a straight solenoid where detectors are placed follows the curved spectrometer.

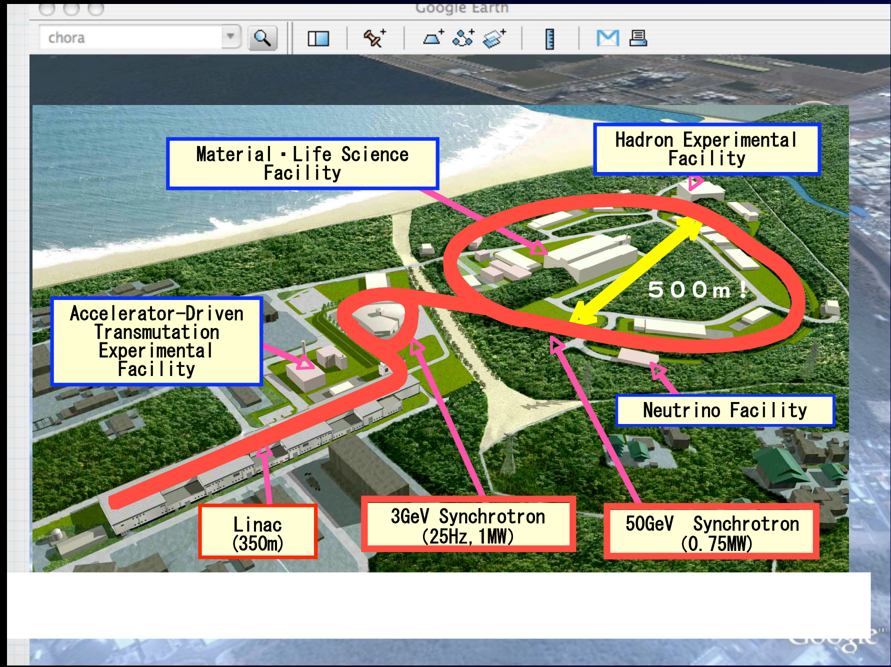


Event Displays for Curved Solenoid Spectrometer



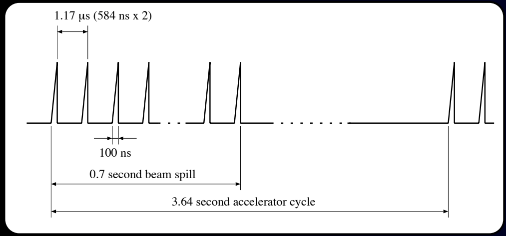


J-PARC at Tokai, Japan

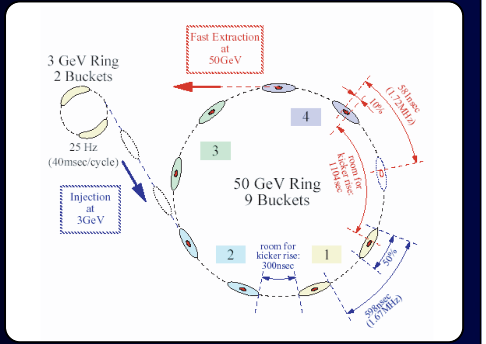


Proton Beam at J-PARC (1)

- A pulsed proton beam is needed to reject beam-related prompt background.
- Time structure required for proton beams.
  - Pulse separation is ~ 1µsec or more (muon lifetime).
  - Narrow pulse width (<100 nsec)



- Pulsed beam from slow extraction.
  - fill every other rf buckets with protons and make slow extraction
  - spill length (flat top) ~ 0.7



Signal Sensitivity (preliminary) - 2×10^7 sec

- Single event sensitivity

$$B(\mu^- + Al \rightarrow e^- + Al) \sim \frac{1}{N_\mu \cdot f_{cap} \cdot A_e},$$

  - N_μ is a number of stopping muons in the muon stopping target. It is 2×10^{18} muons.
  - f_{cap} is a fraction of muon capture, which is 0.6 for aluminum.
  - A_e is the detector acceptance, which is 0.04.

total protons	8.5×10^{20}
muon transport efficiency	0.008
muon stopping efficiency	0.3
# of stopped muons	2.0×10^{18}

$$B(\mu^- + Al \rightarrow e^- + Al) = 2.6 \times 10^{-17}$$

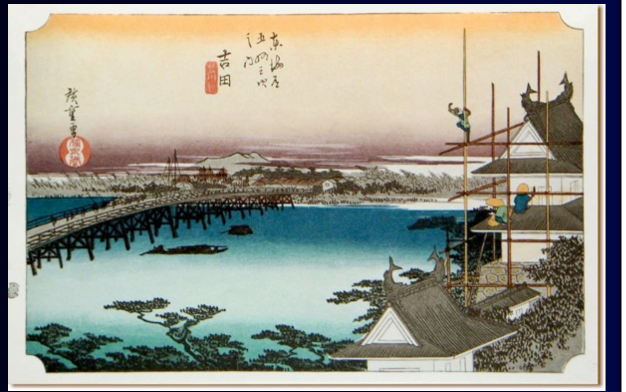
$$B(\mu^- + Al \rightarrow e^- + Al) < 6 \times 10^{-17} \quad (90\% C.L.)$$

BG with asterisk needs beam extinction.

Background Rejection Summary (preliminary)

	Backgrounds	Events	Comments
(1)	Muon decay in orbit	0.05	230 keV resolution
	Radiative muon capture	<0.001	
	Muon capture with neutron emission	<0.001	
	Muon capture with charged particle emission	<0.001	
(2)	Radiative pion capture*	0.12	prompt
	Radiative pion capture	0.002	late arriving pions
	Muon decay in flight*	<0.02	
	Pion decay in flight*	<0.001	
	Beam electrons*	0.08	
	Neutron induced*	0.024	for high energy neutrons
	Antiproton induced	0.007	for 8 GeV protons
(3)	Cosmic-ray induced	0.10	10^{-4} veto & $2x10^{7}$sec run
	Pattern recognition errors	<0.001	
	Total	0.4	

10^{-18} Sensitivity
with PRISM/PRIME

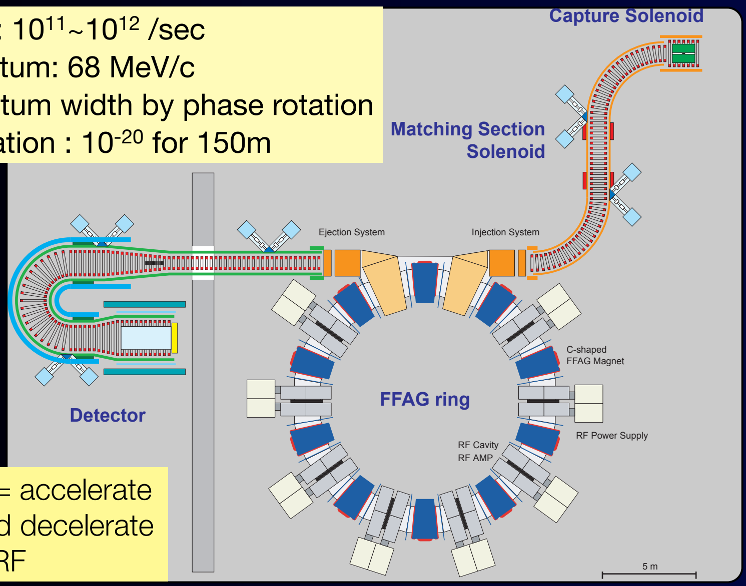


at Yoshida (Toyohashi), Aichi

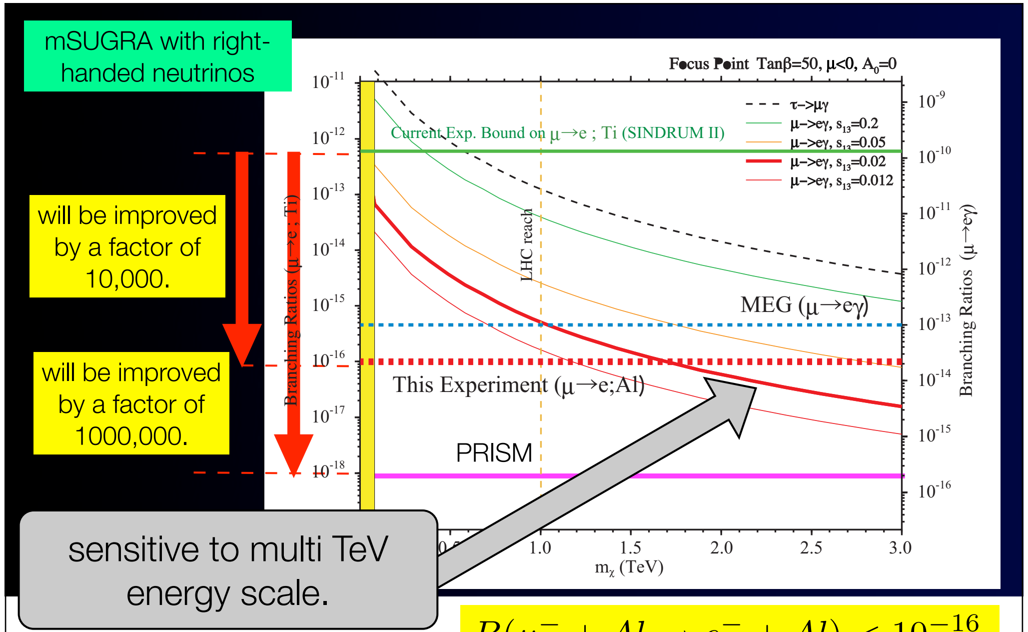
PRISM Muon Beam
PRIME Detector

PRISM=Phase Rotated Intense Slow Muon source

muon intensity: 10^{11}~10^{12} /sec
central momentum: 68 MeV/c
narrow momentum width by phase rotation
pion contamination : 10^{-20} for 150m



Phase rotation = accelerate slow muons and decelerate fast muons by RF



Sensitivity Goals

$$B(\mu^- + Al \rightarrow e^- + Al) < 10^{-16}$$

$$B(\mu^- + Ti \rightarrow e^- + Ti) < 10^{-18}$$

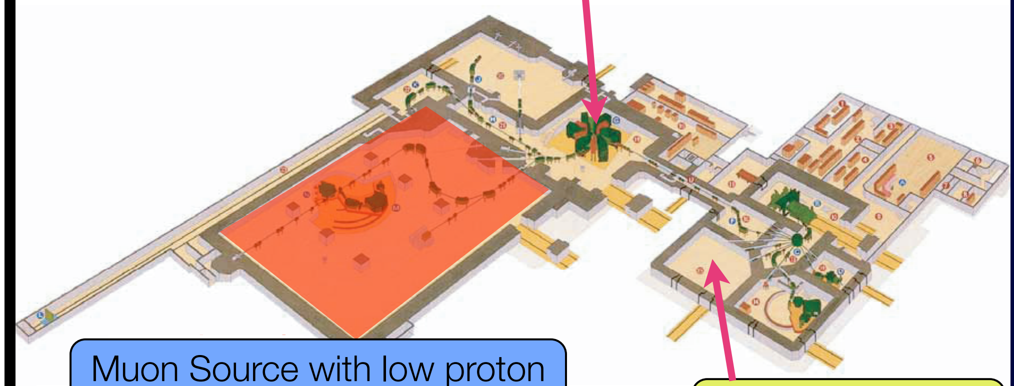
R&D on the PRISM-FFAG Muon Storage Ring at Osaka University

R&D at
Osaka University
Japan

at Okazaki, Aichi

Research Center for Nuclear Physics (RCNP), Osaka University

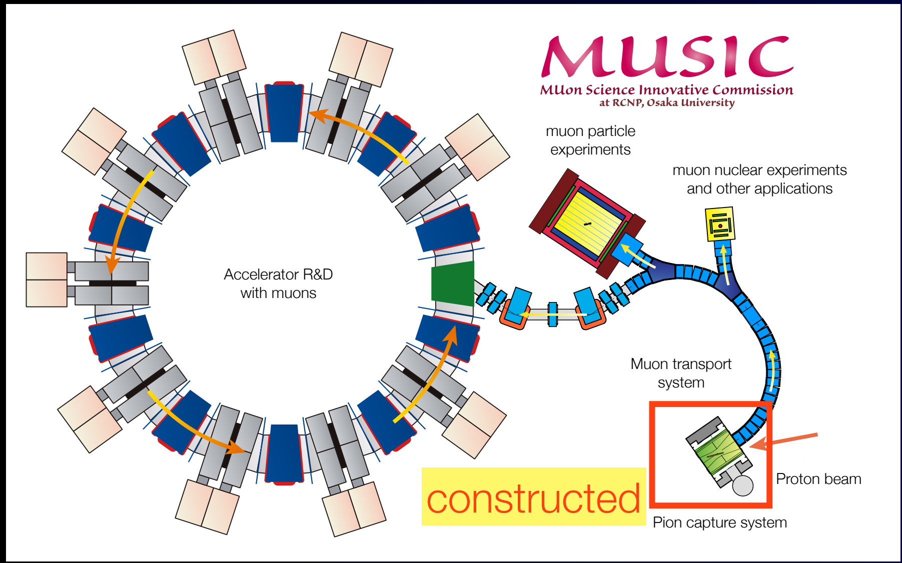
Research Center for Nuclear Physics (RCNP), Osaka University has a cyclotron of 400 MeV with 1 microA. The energy is above pion threshold.

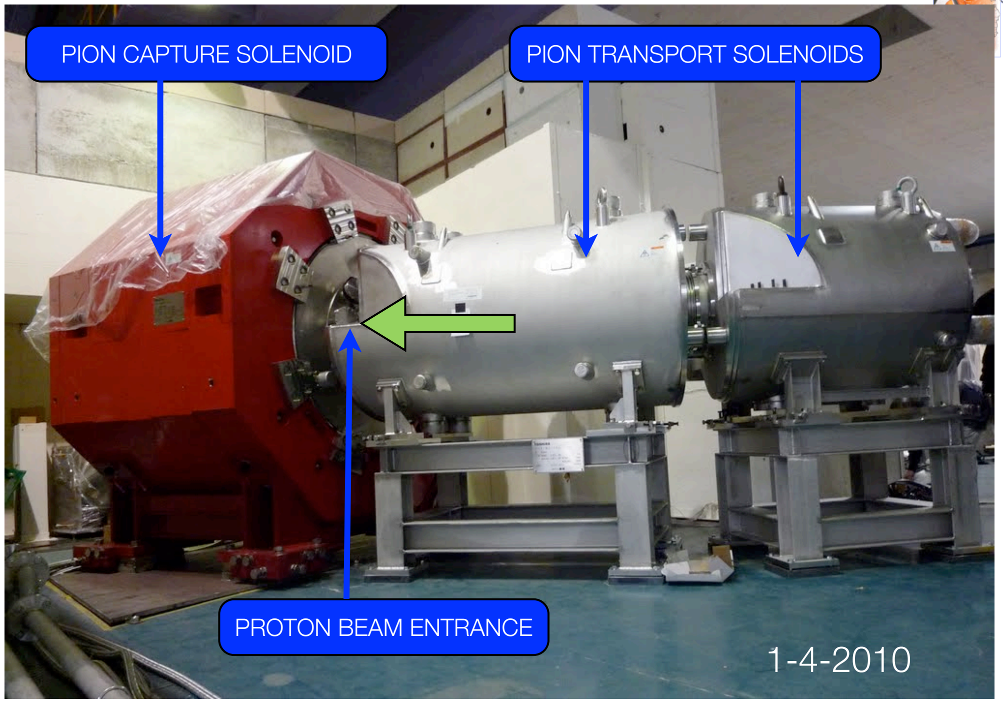


Muon Source with low proton power at Osaka U.?

PRISM-FFAG R&D

muon yield estimation
50 kW : 10^{11} muons/sec (for COMET)
0.4 kW : 10^{9} muons/sec (for MUSIC)




PION CAPTURE SOLENOID
PION TRANSPORT SOLENOIDS
PROTON BEAM ENTRANCE
1-4-2010

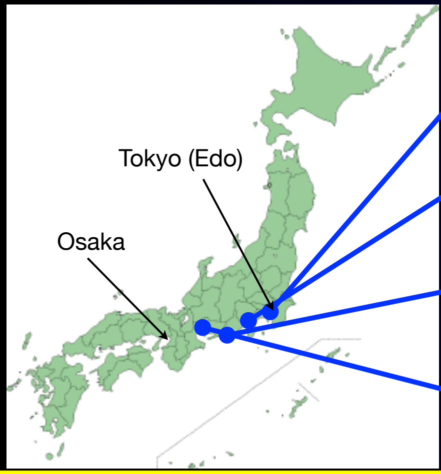
Summary

- Physics motivation of cLFV processes would be significant and robust in 10-15 years from now.
- Among various muon cLFV processes, μ-e conversion might be the next step.
- The COMET experiment at J-PARC is aiming at a search for μ-e conversion for 2.6 x 10^{-17} single event sensitivity. The COMET has received stage-1 approval at the J-PARC PAC, aiming its start in around 2015.
- Further prospect aiming at better than 10^{-18} sensitivity, PRISM/PRIME has been considered.
- As R&D the MUSIC project for an intense muon source at Osaka University is undertaken.

The COMET Conceptual Design Report is available at http://comet.phys.sci.osaka-u.ac.jp/internal/publications/comet-cdr-v1.0.pdf/view

New Collaborators to the COMET is highly welcomed.

The fifty-three stations of the Tokaido (from Tokyo to Osaka) block prints by Hiroshige Utagawa (1797-1858)



A journey has not been complete...