Search for Charged Lepton Flavor Violation with Muons

Yoshitaka Kuno
Department of Physics
Osaka University

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Osaka

Outline

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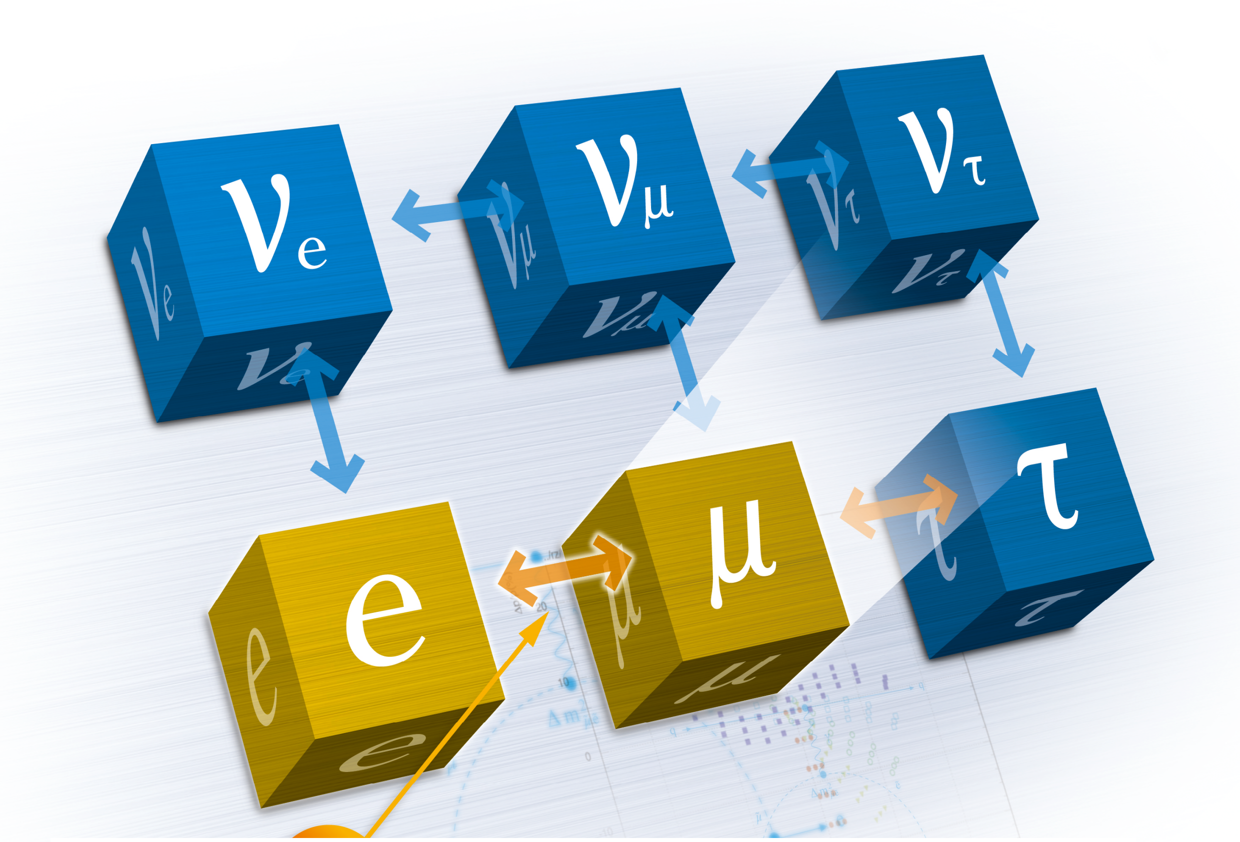
- Why Charged Lepton Flavor Violation (CLFV)?
- CLFV and Neutrinos
- CLFV Processes with Muons
  - $\mu \to e\gamma$
  - μ-e conversion
- COMET (J-PARC E21)
- Other muon CLFV Processes
- Summary



charged lepton flavor violation

Why Charged Lepton Flavor Violation (CLFV)?

Quarks, Neutrinos, and then Charged Leptons

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Quarks

Quark mixing observed

Quarks, Neutrinos, and then Charged Leptons

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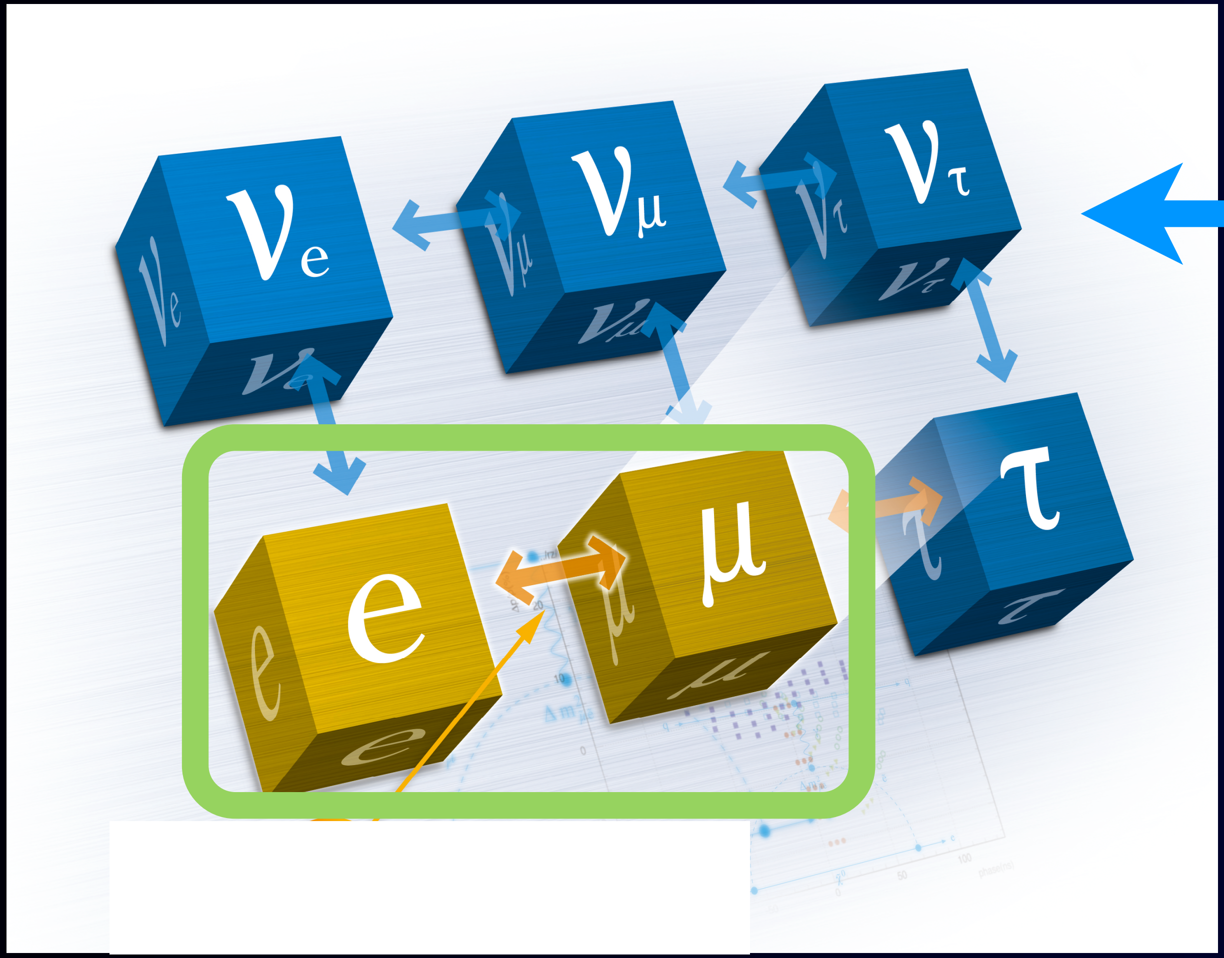
Quark mixing observed

Leptons



Neutrino mixing observed

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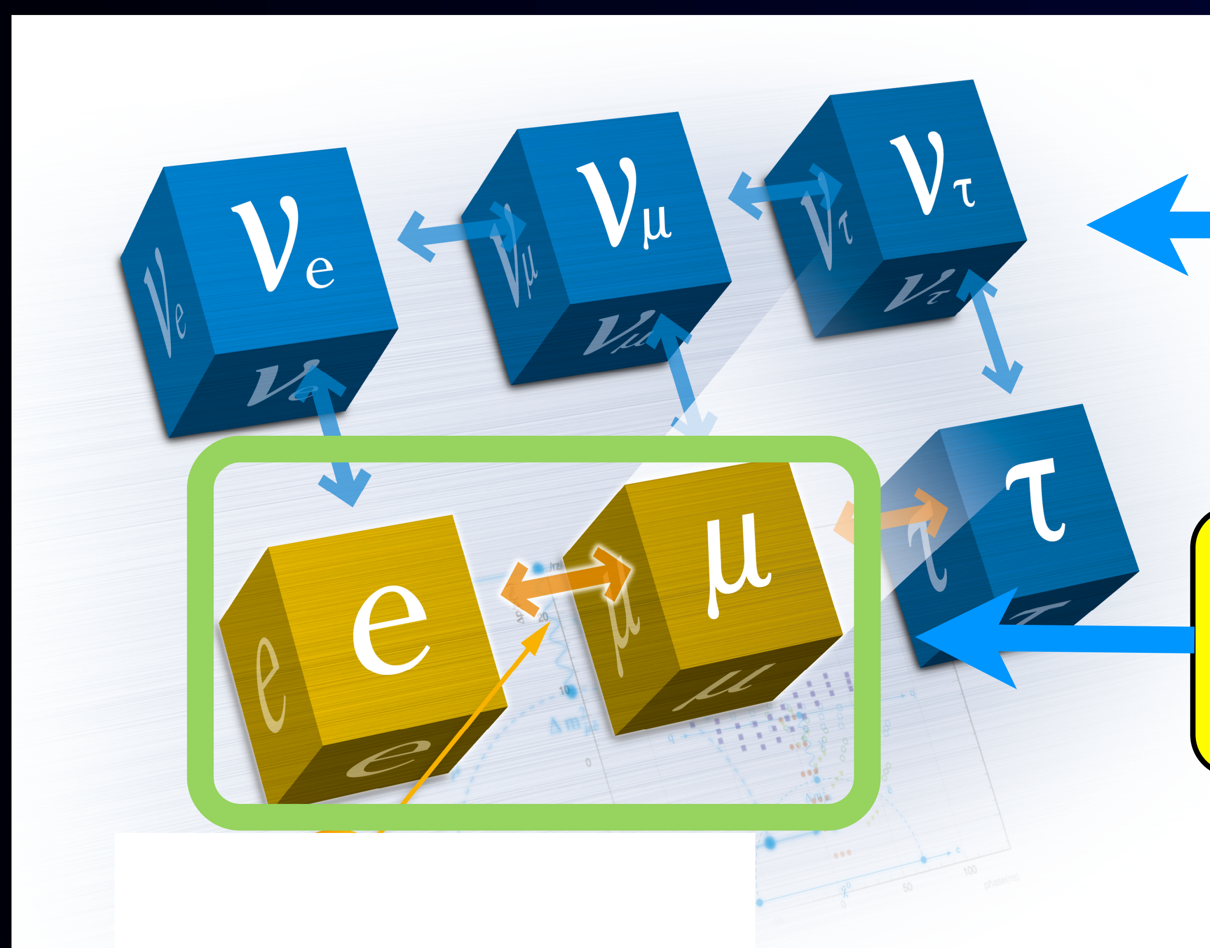

Neutrino mixing observed

Charged lepton mixing not observed.

Quarks, Neutrinos, and then Charged Leptons

Quarks

Quark mixing observed

Leptons

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Charged lepton mixing not observed.

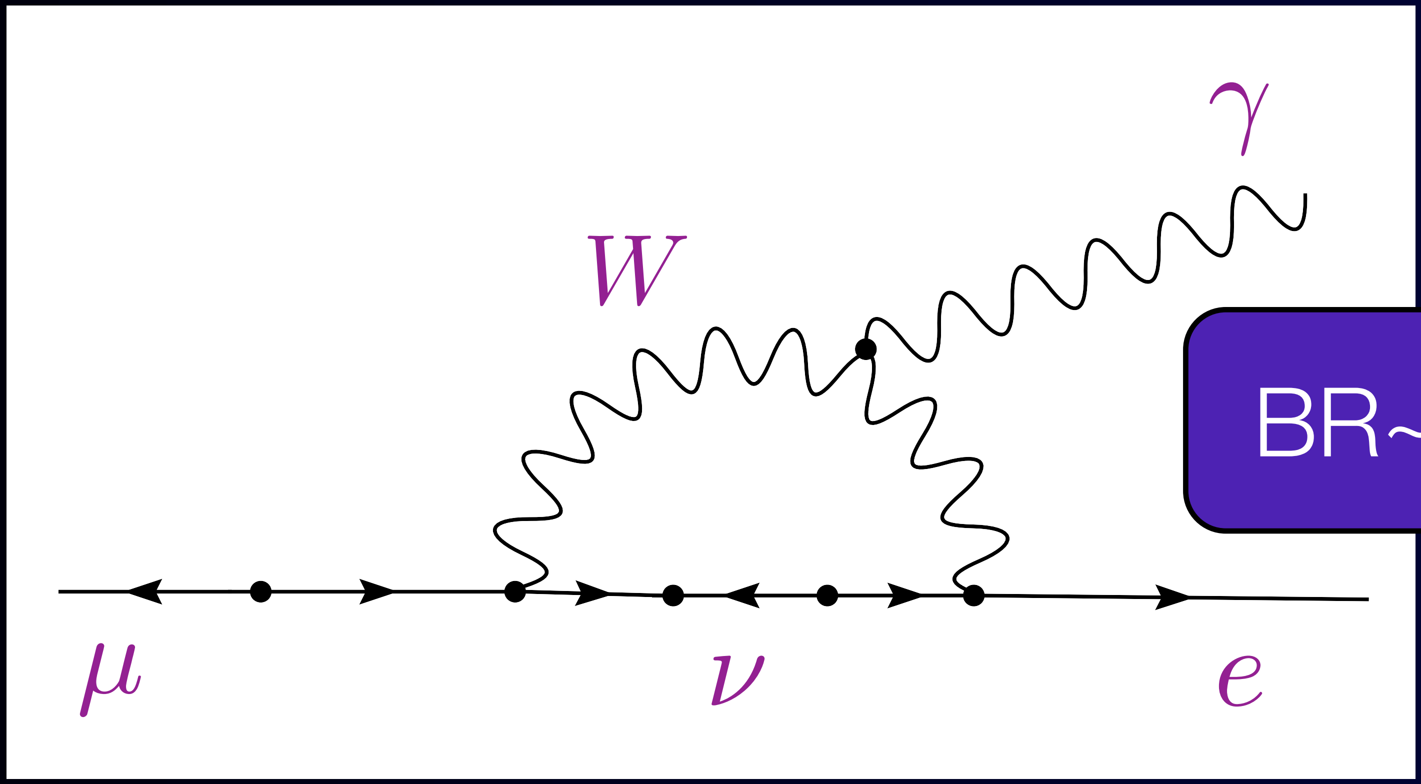
Charged Lepton Flavor Violation (CLFV)

Nobel Prize-wining class research

CLFV in the SM with massive neutrinos

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})

CLFV in the SM with massive neutrinos

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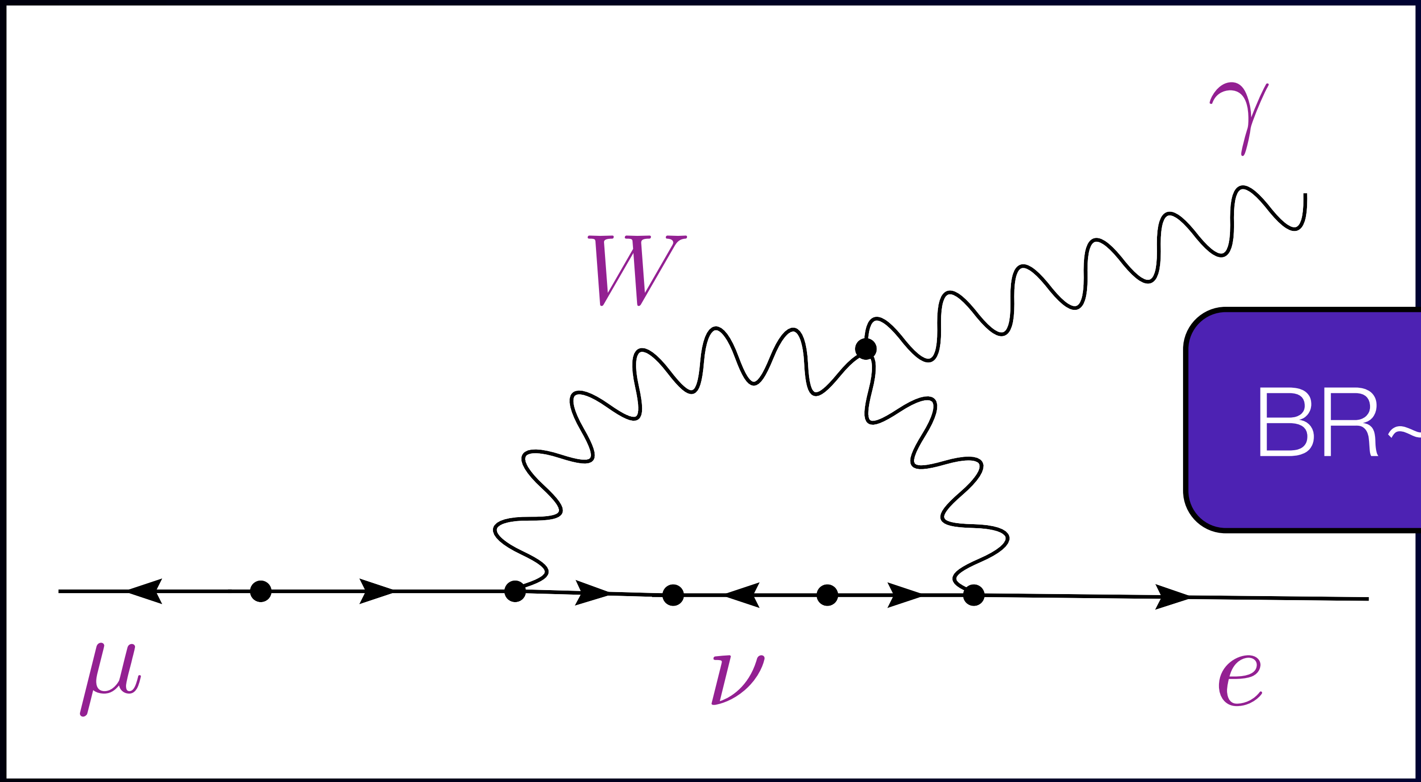

BR~O(10^{-54})

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

Rating of DNA of New Physics (a la Prof. Dr. A. Buras)

W. Altmannshofer, A.J. Buras, S. Gori, P. Paradisi, D.M. Straub, . **Nucl.Phys.B830:17-94 ,2010**.

	AC	RVV2	AKM	δLL	FBMSSM	LHT	RS
$D^0 - \bar{D}^0$	★★★	★	★	★	★	★★★	?
ϵ_K	★	★★★	★★★	★	★	★★	★★★
$S_{\psi\phi}$	★★★	★★★	★★★	★	★	★★★	★★★
$S_{\phi K_S}$	★★★	★★	★	★★★	★★★	★	?
$A_{\rm CP}\,(B \to X_s\gamma)$	★	★	★	★★★	★★★	★	?
$A_{7,8}(B \to K^*\mu^+\mu^-)$	★	★	★	★★★	★★★	★★	?
$A_9(B \to K^*\mu^+\mu^-)$	★	★	★	★	★	★	?
$B \to K^{(*)}\nu\bar{\nu}$	★	★	★	★	★	★	★
$B_s \to \mu^+\mu^-$	★★★	★★★	★★★	★★★	★★★	★	★
$K^+ \to \pi^+\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$K_L \to \pi^0\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$\mu \to e\gamma$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
$\tau \to \mu\gamma$	★★★	★★★	★	★★★	★★★	★★★	★★★
$\mu + N \to e + N$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
d_n	★★★	★★★	★★★	★★	★★★	★	★★★
d_e	★★★	★★★	★★	★	★★★	★	★★★
$(g-2)_\mu$	★★★	★★★	★★	★★★	★★★	★	?

Table 8: "DNA" of flavour physics effects for the most interesting observables in a selection of SUSY and non-SUSY models ★★★ signals large effects, ★★ visible but small effects and ★ implies that the given model does not predict sizable effects in that observable.

Different theoretical models

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$B_s\to\mu^+\mu^-$	★★★	★★★	★★★	★★★	★★★	★	★
$K^+\to\pi^+\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$K_L\to\pi^0\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$\mu\to e\gamma$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
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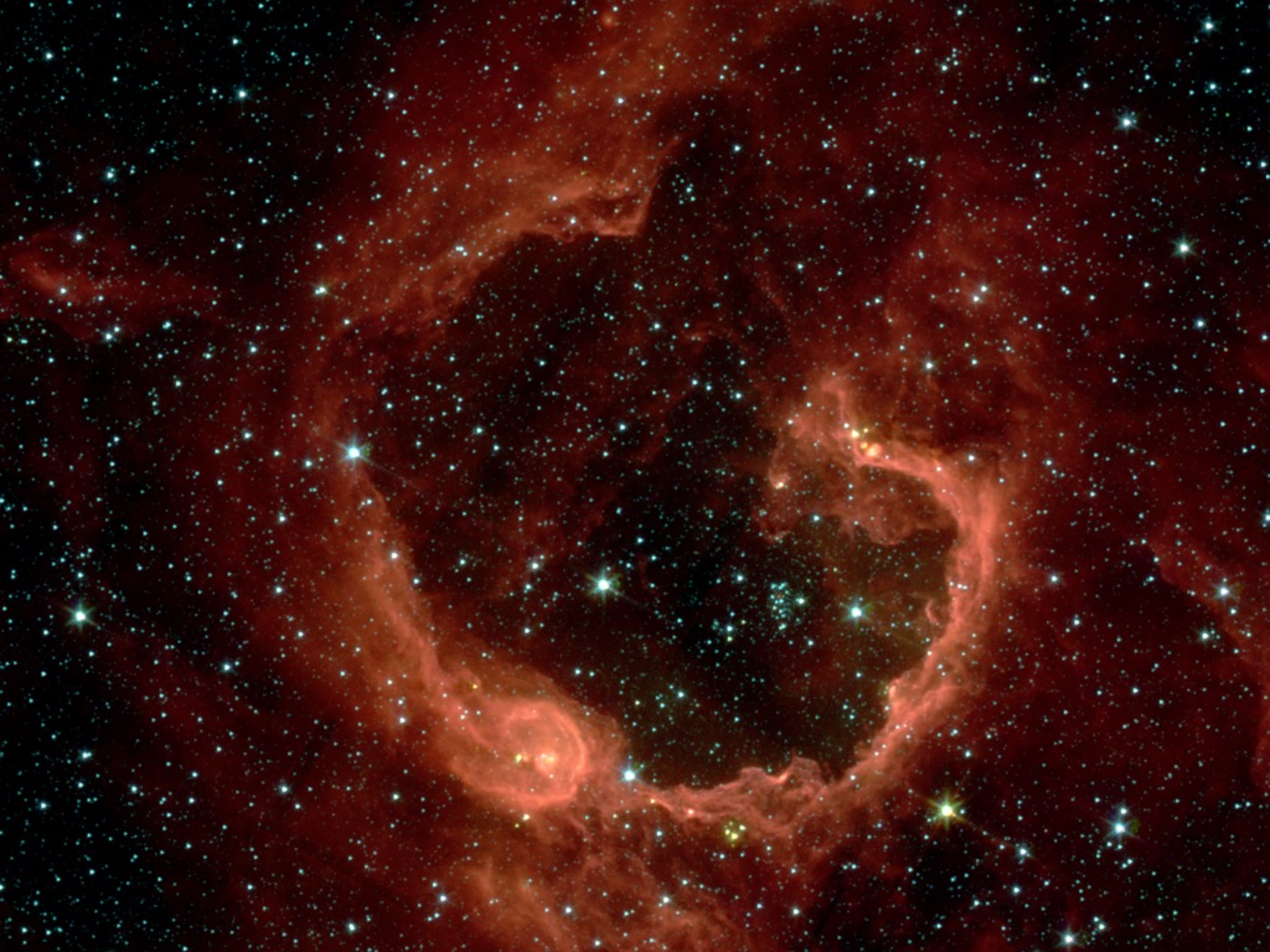
Different theoretical models

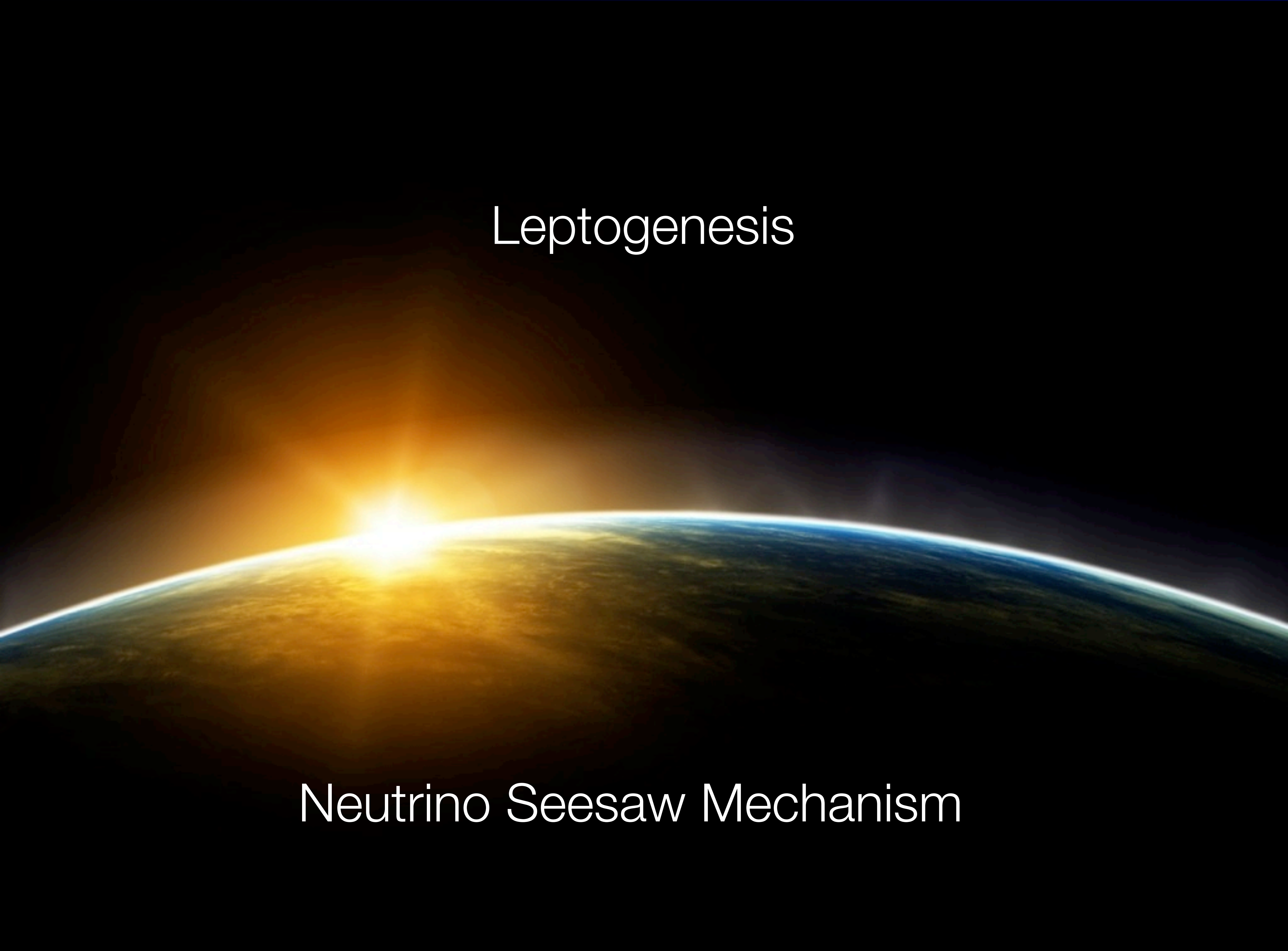
CLFV with muons get all three stars.

CLFV and Neutrinos

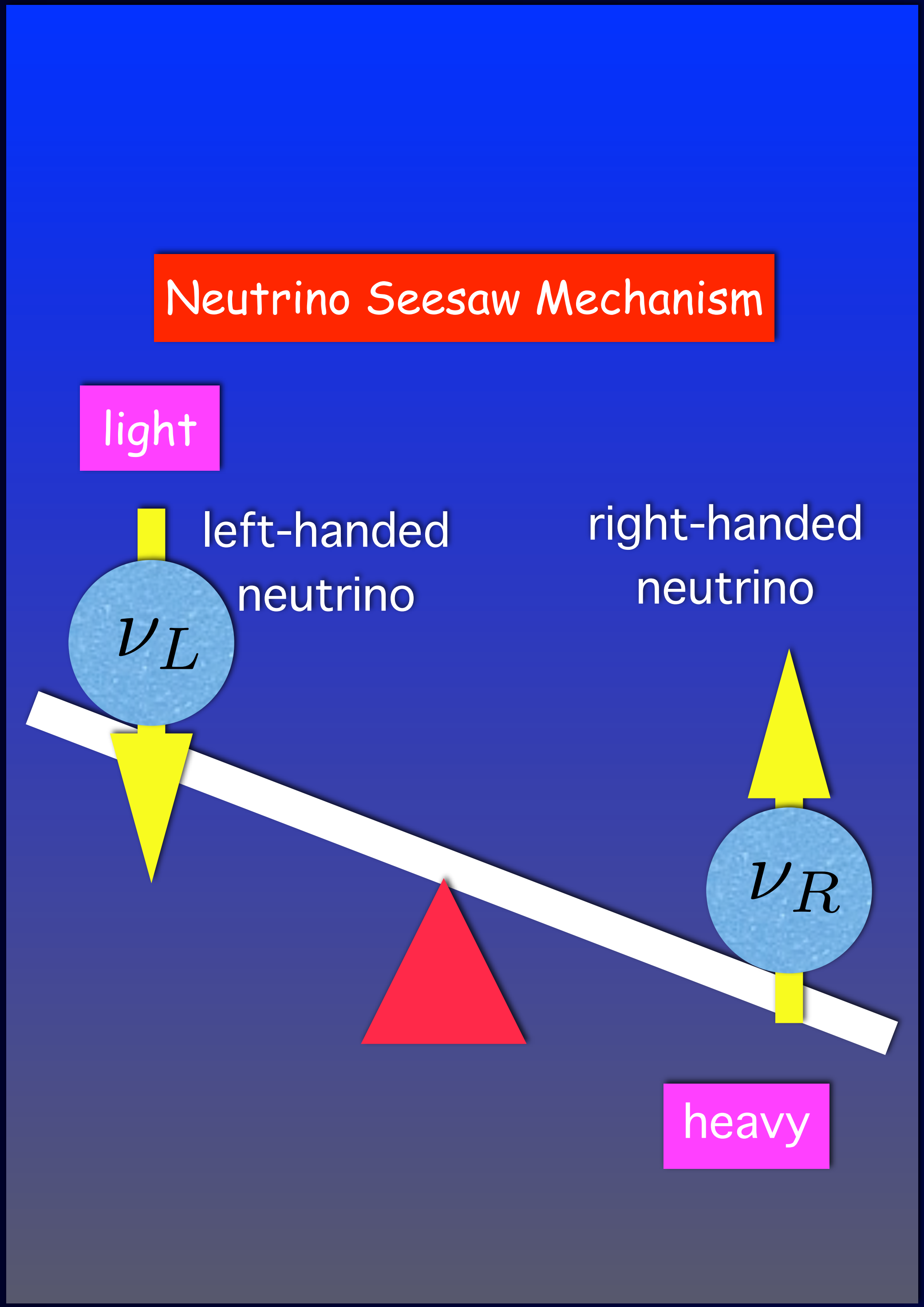



Why do we exist in the Universe?

Leptogenesis


Leptogenesis
Neutrino Seesaw Mechanism

How to Validate Neutrino Seesaw Mechanism?

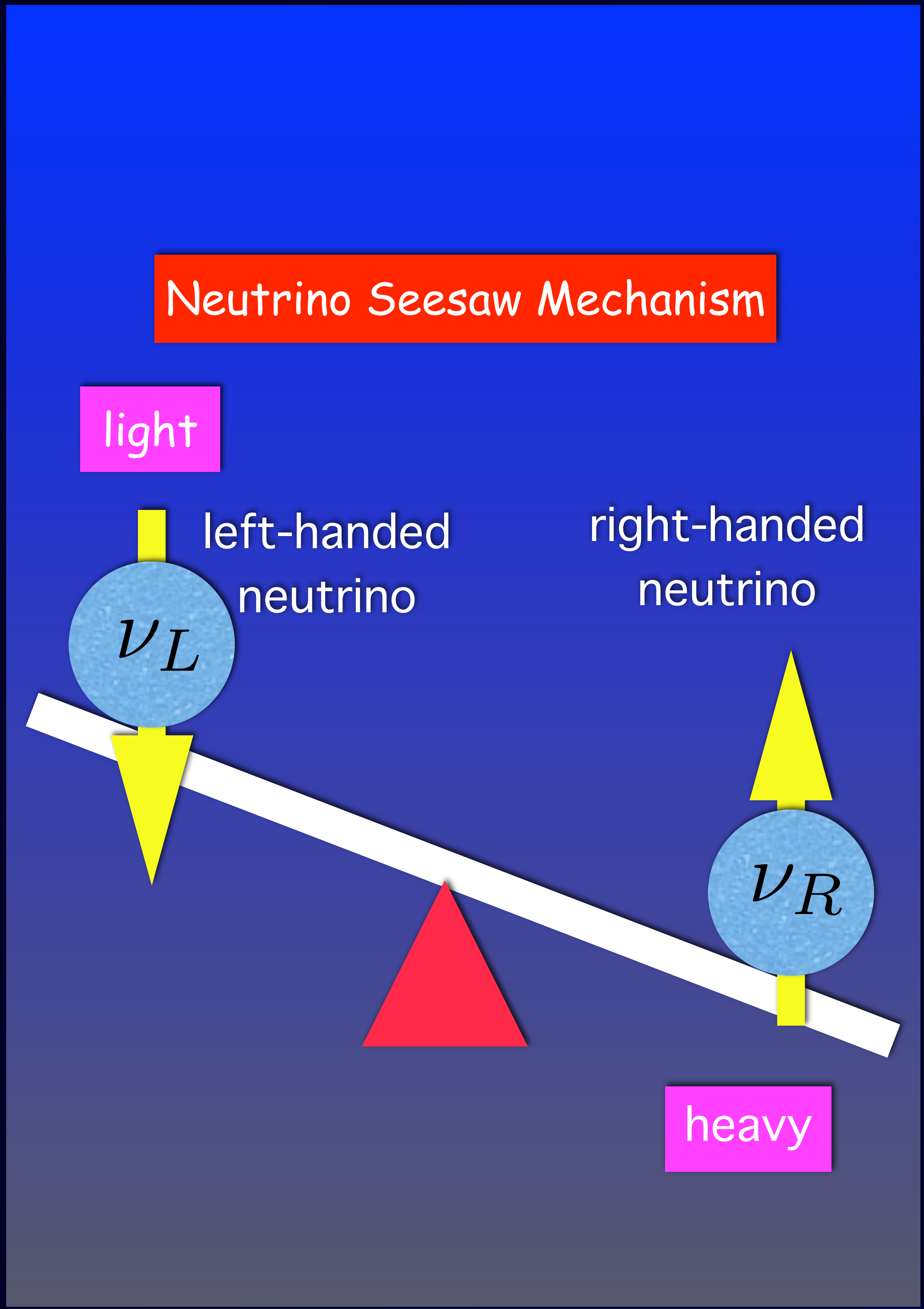


How to Validate Neutrino Seesaw Mechanism?

1 **Majorana Nature of Neutrinos**

Neutrinoless Double Beta Decays

Neutrinoless double beta decays address whether neutrinos are Majorana-type or not?



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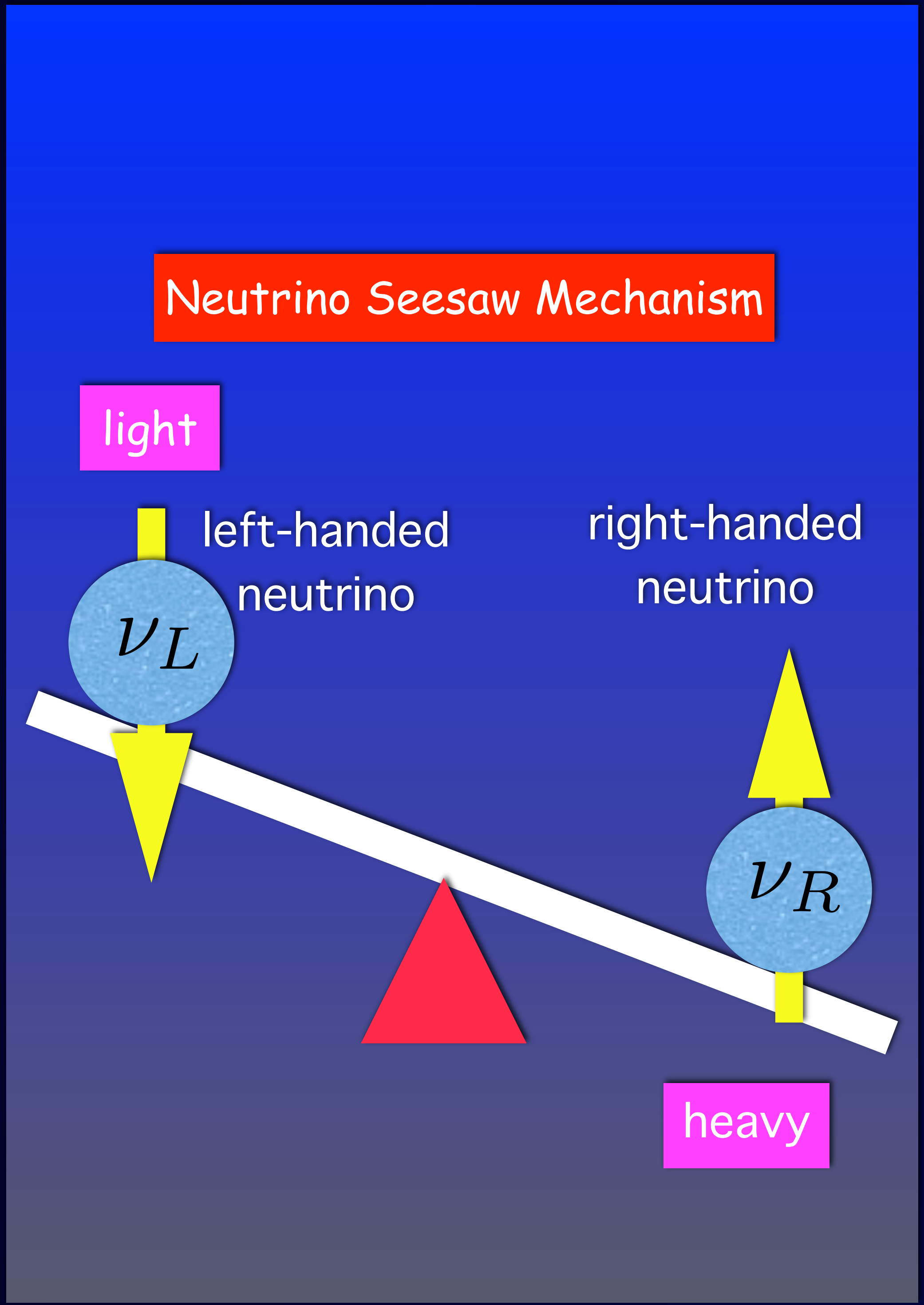
2 Heavy Partner of Neutrinos

CLFV

Search for CLFV is sensitive to the energy scale of heavy right-handed neutrinos in the neutrino seesaw models.



Scales of Electroweak Symmetry Breaking and Neutrino Mass Generation

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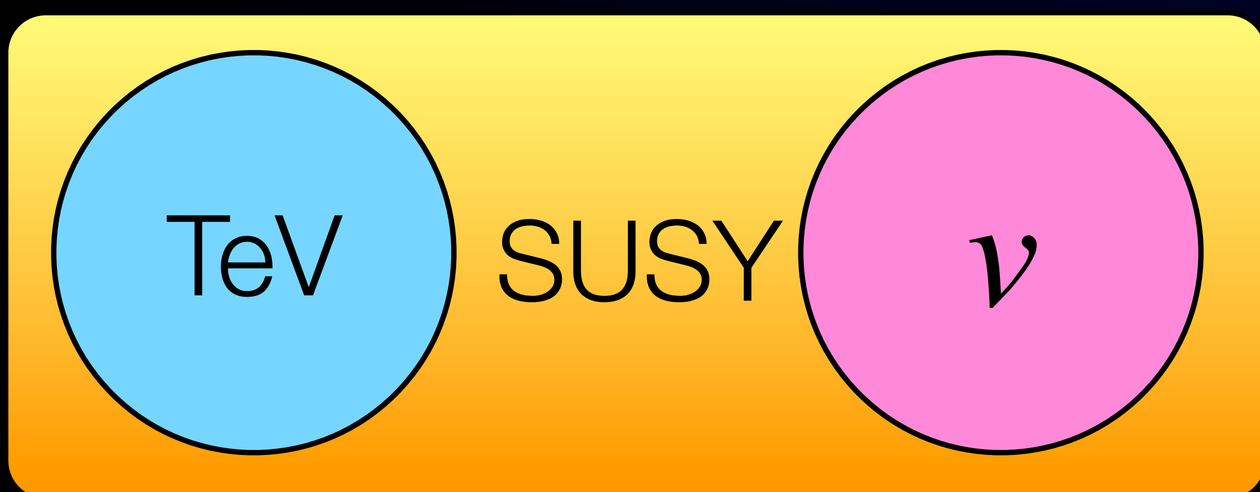
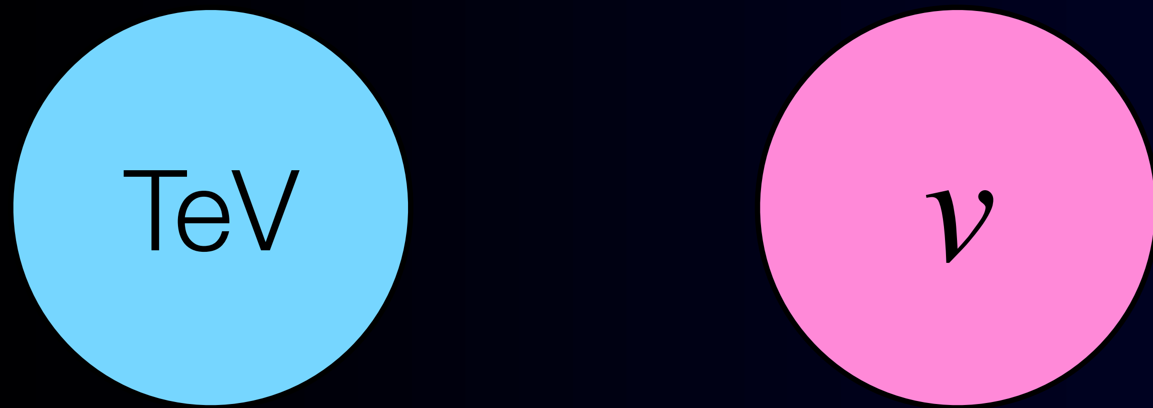


In supersymmetric models, even if the two scales are well separated, large CLFV is expected.

Scales of Electroweak Symmetry Breaking and Neutrino Mass Generation



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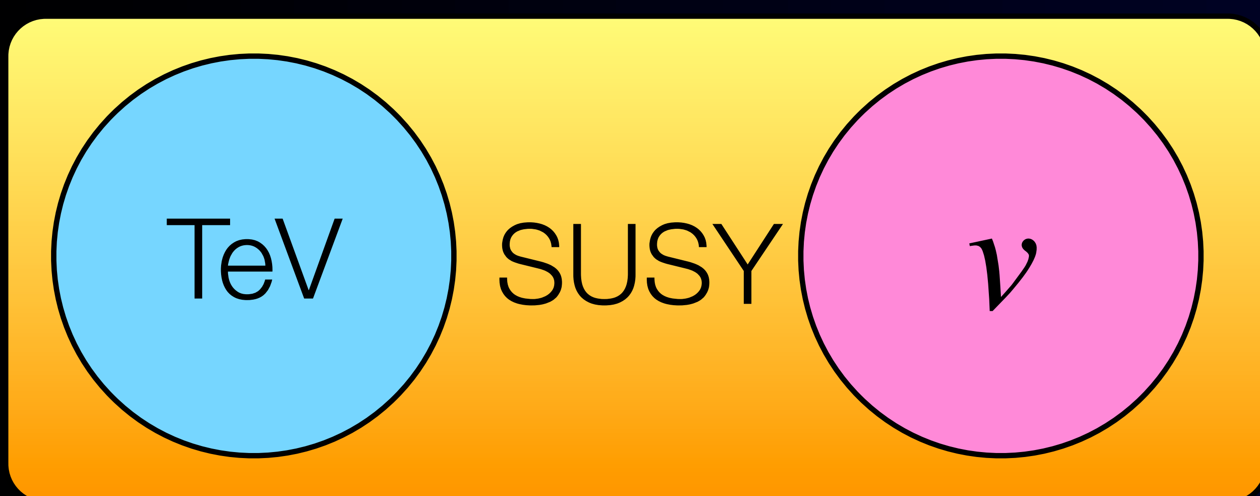

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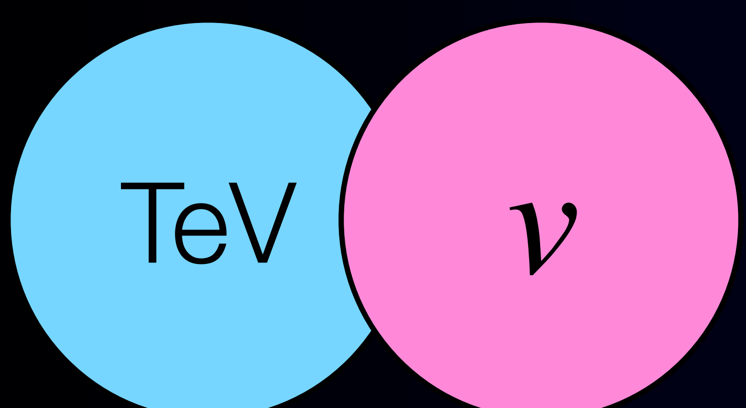

Even without supersymmetric models, the two scales are close, large CLFV is expected.

CLFV with SUSY and Neutrino Seesaw

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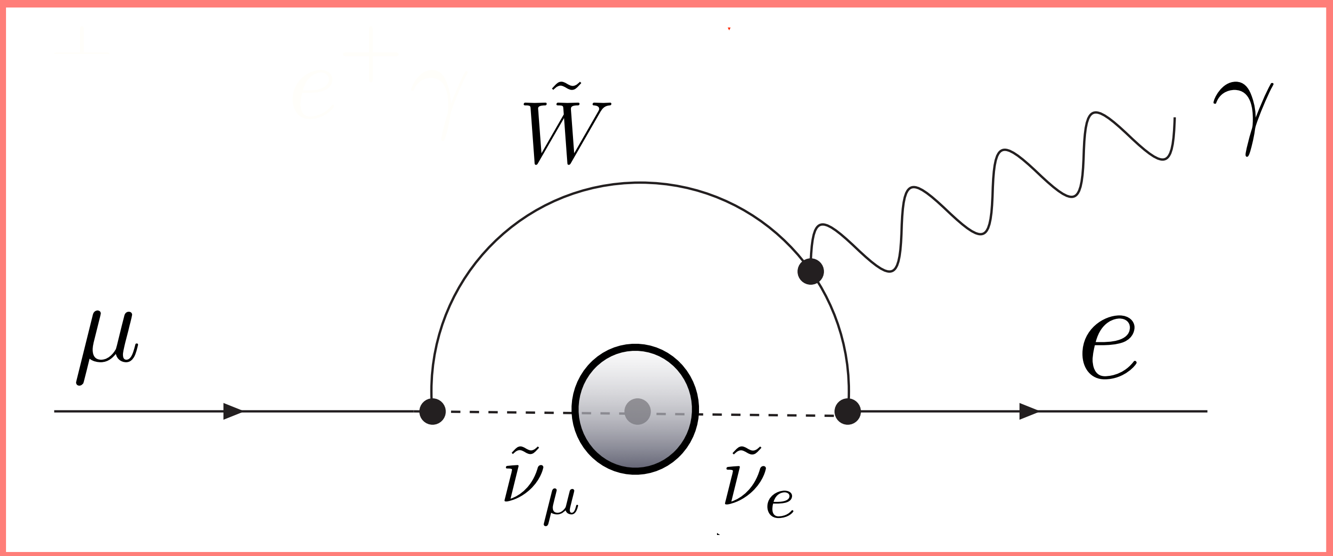
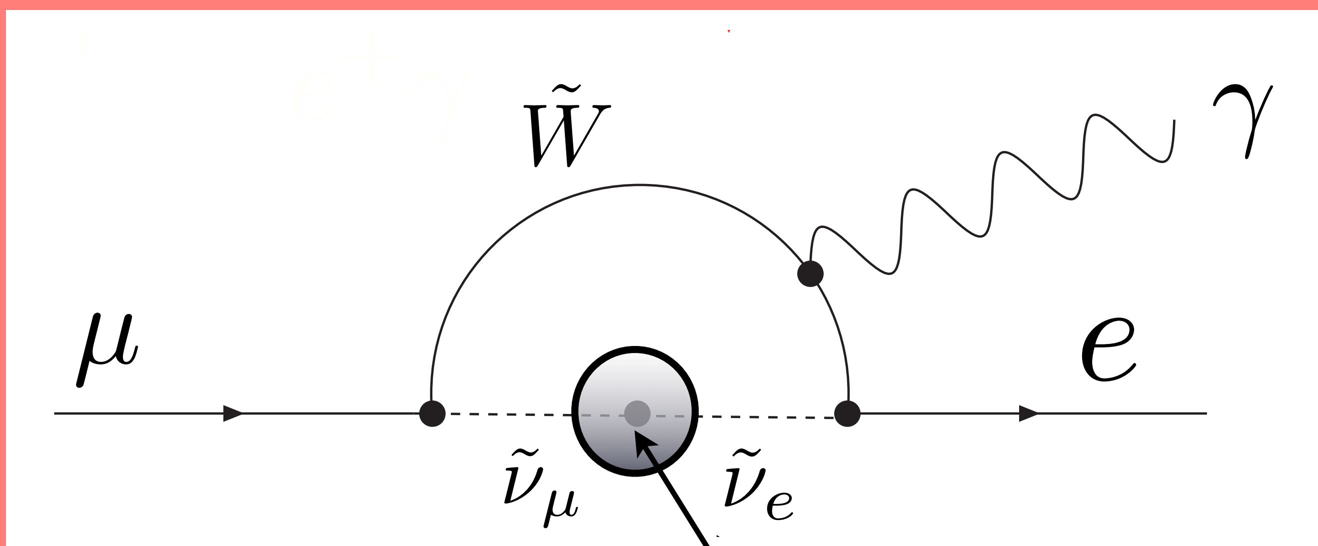
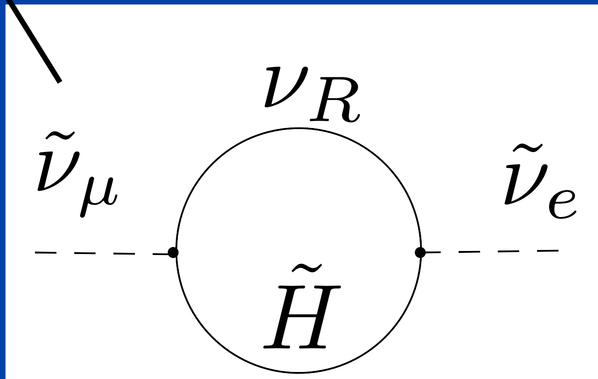


CLFV with SUSY and Neutrino Seesaw



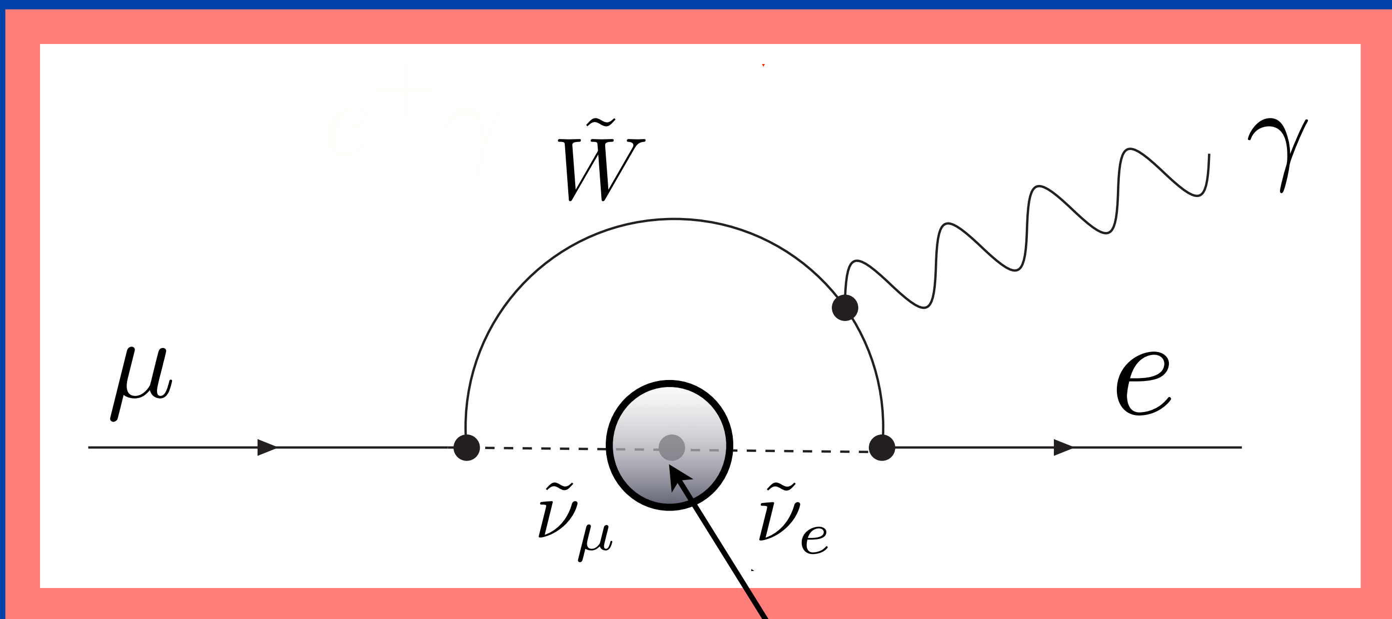
slepton mixing
(from RGE)



$$(m_L^2)_{21} \sim \frac{3m_0^2 + A_0^2)}{8\pi^2} h_\tau^2 U_{31} U_{32} \ln\left(\frac{M_{GUT}}{M_R}\right)$$

large θ_{13} → large CLFV

CLFV with SUSY and Neutrino Seesaw



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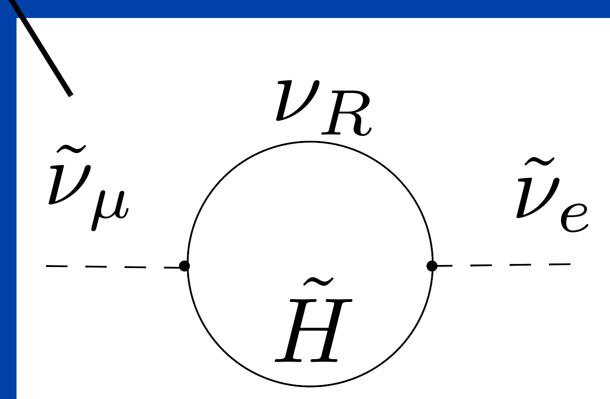

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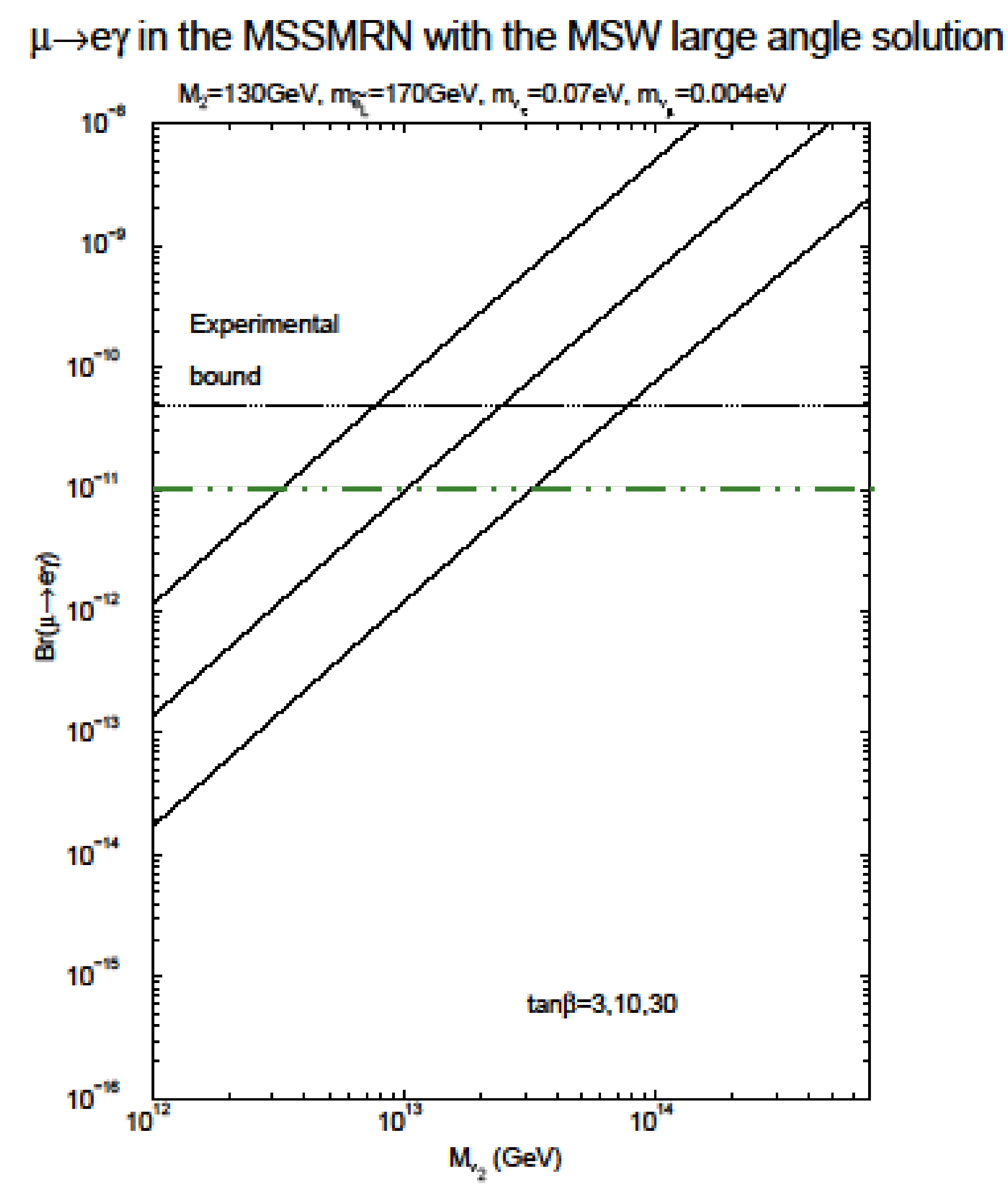
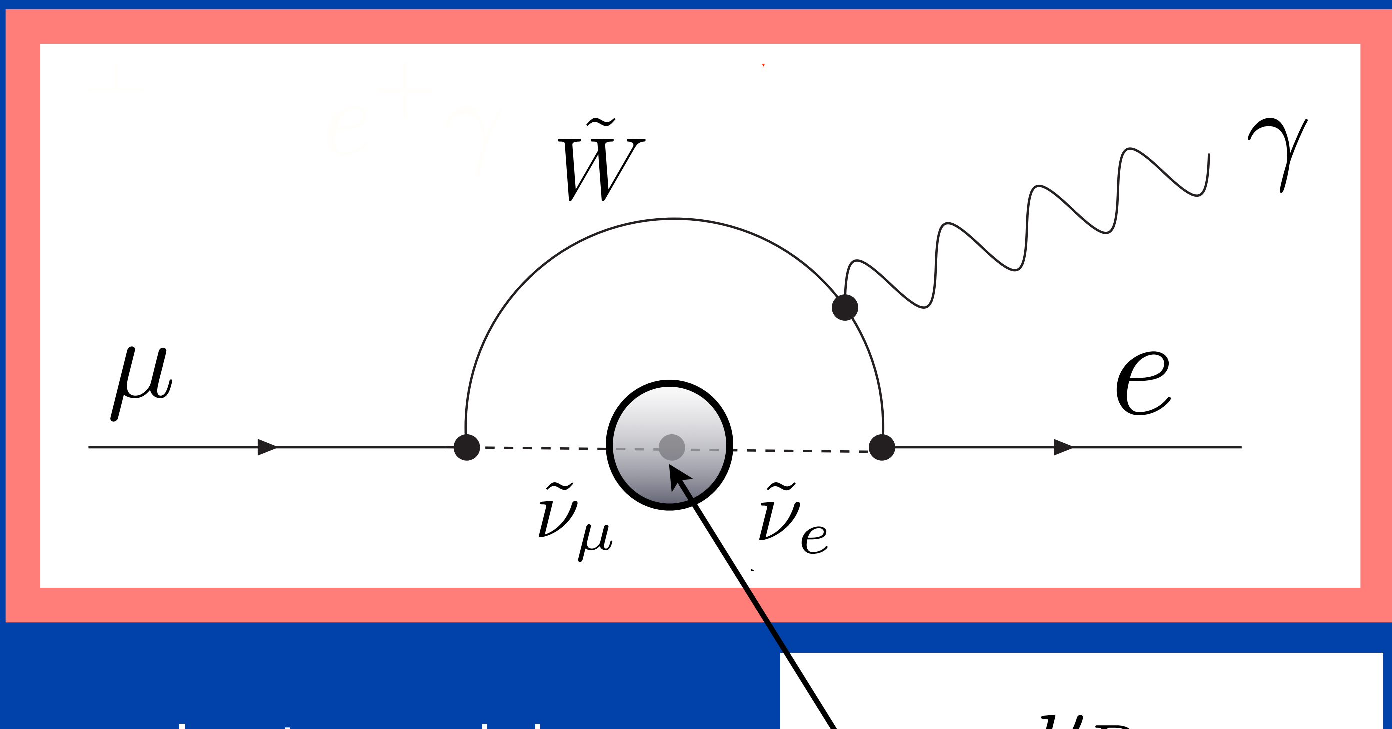


M$_R$ (right-handed neutrino mass)

CLFV with SUSY and Neutrino Seesaw



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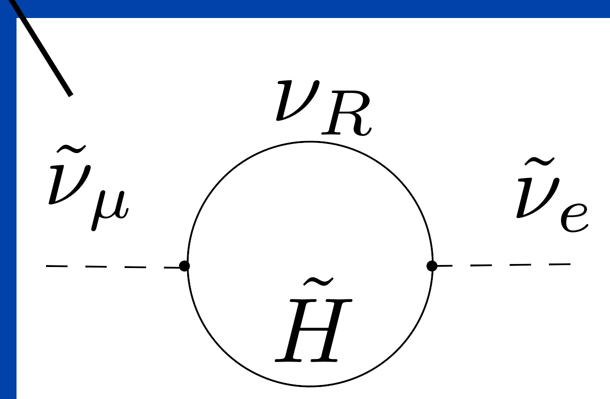

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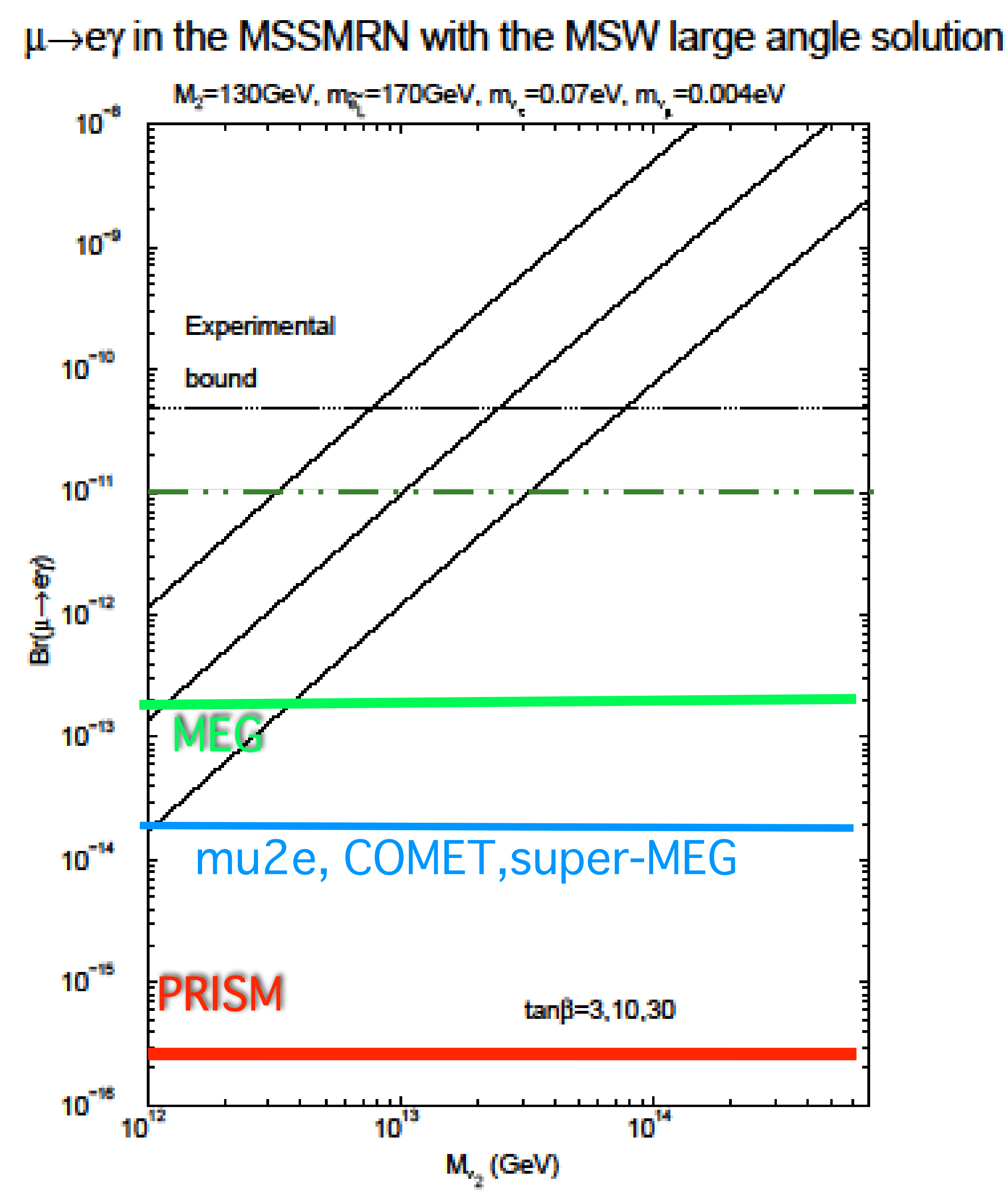
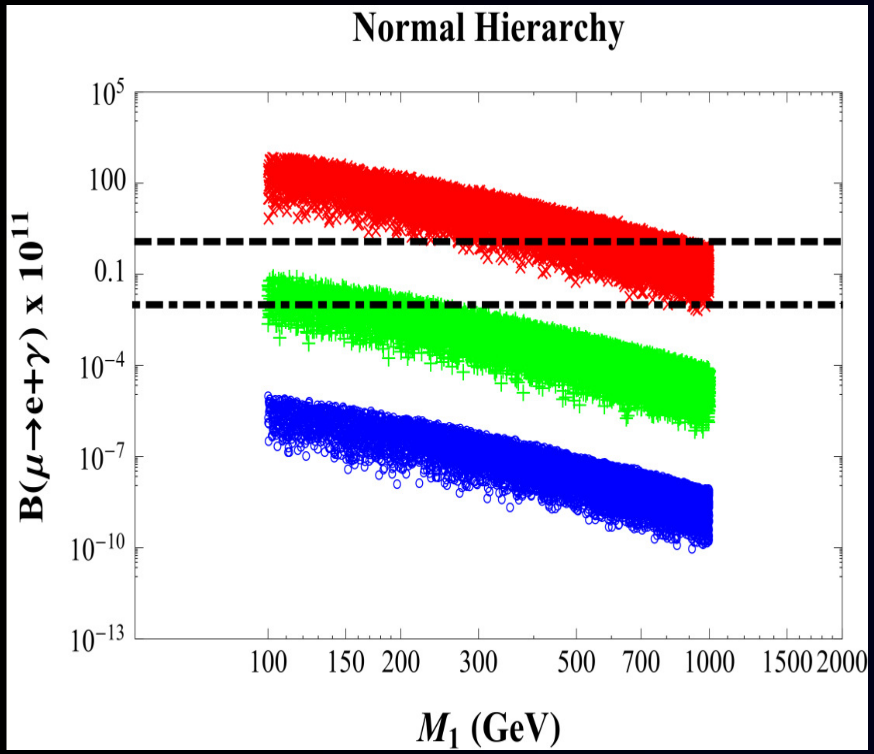
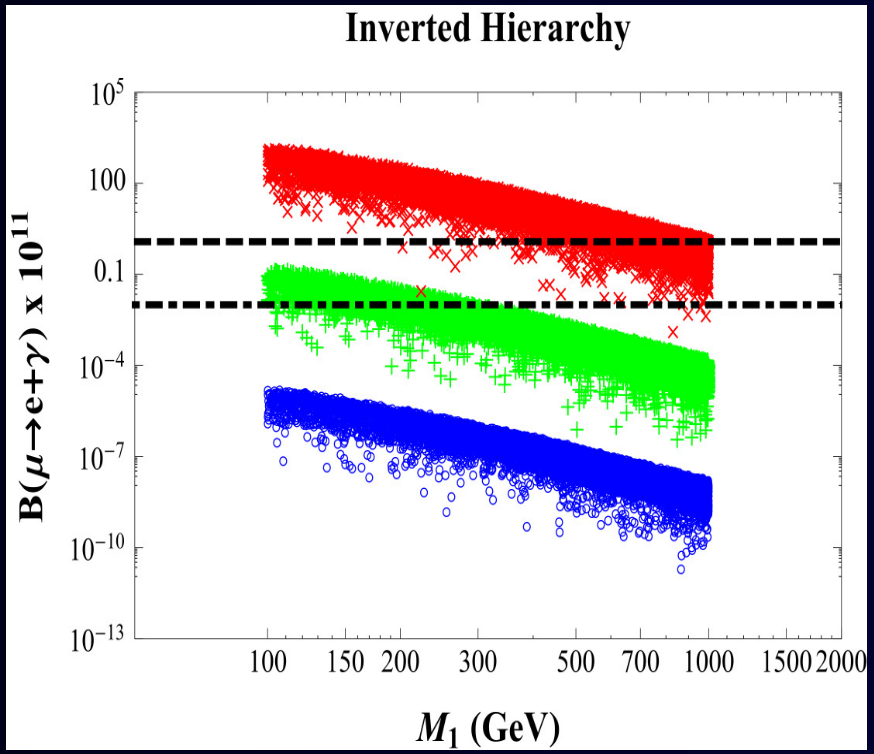


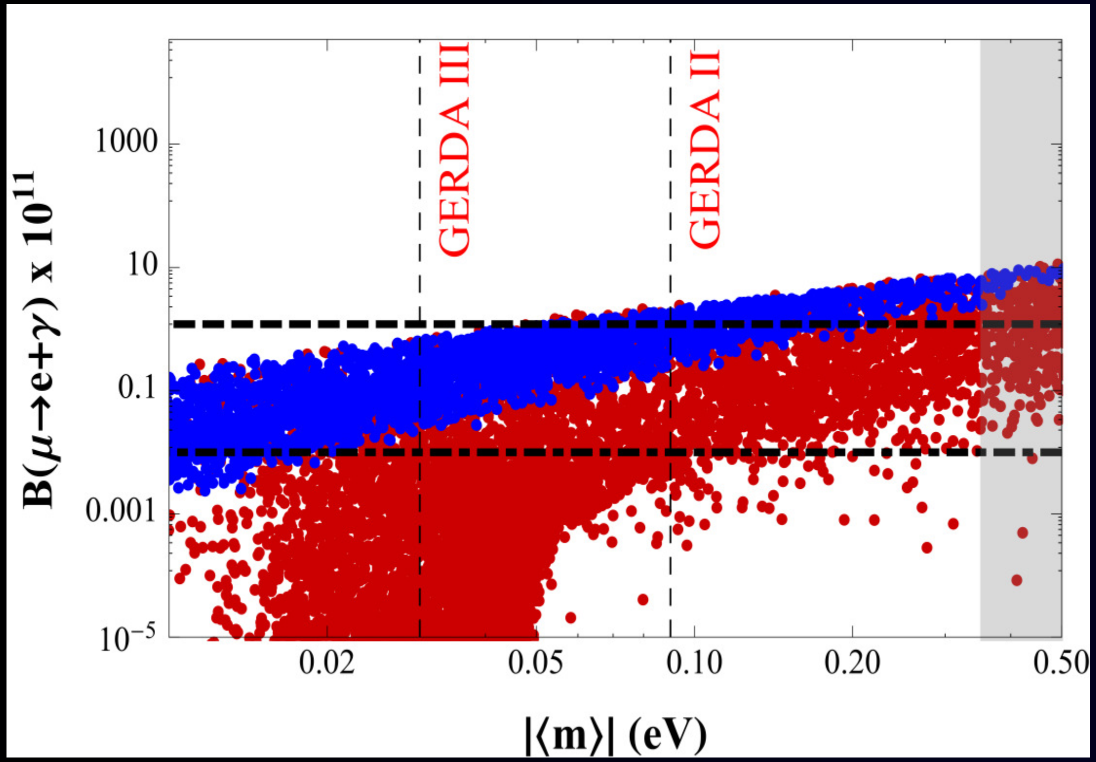
M_R (right-handed neutrino mass)

A. Ibara, E. Molinaro, S.T. Petcov, Phys. Rev. D84 (2011) 013005

CLFV with TeV Seesaw (Type-I)







TeV seesaw type-I models predict sizable branching ratio of CLFV with right-handed neutrino mass of O(TeV).

CLFV Process with Muons

Charged Lepton Flavor Violation with Muons

current future

ΔL=1

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

ΔL=2

- $\mu^+ e^- \to \mu^- e^+$
- $\mu^- + N(A,Z) \to \mu^+ + N(A,Z-2)$
- $\nu_\mu + N(A,Z) \to \mu^+ + N(A,Z-1)$
- $\nu_\mu + N(A,Z) \to \mu^+ \mu^+ \mu^- + N(A,Z-1)$

Charged Lepton Flavor Violation with Muons

ΔL=1

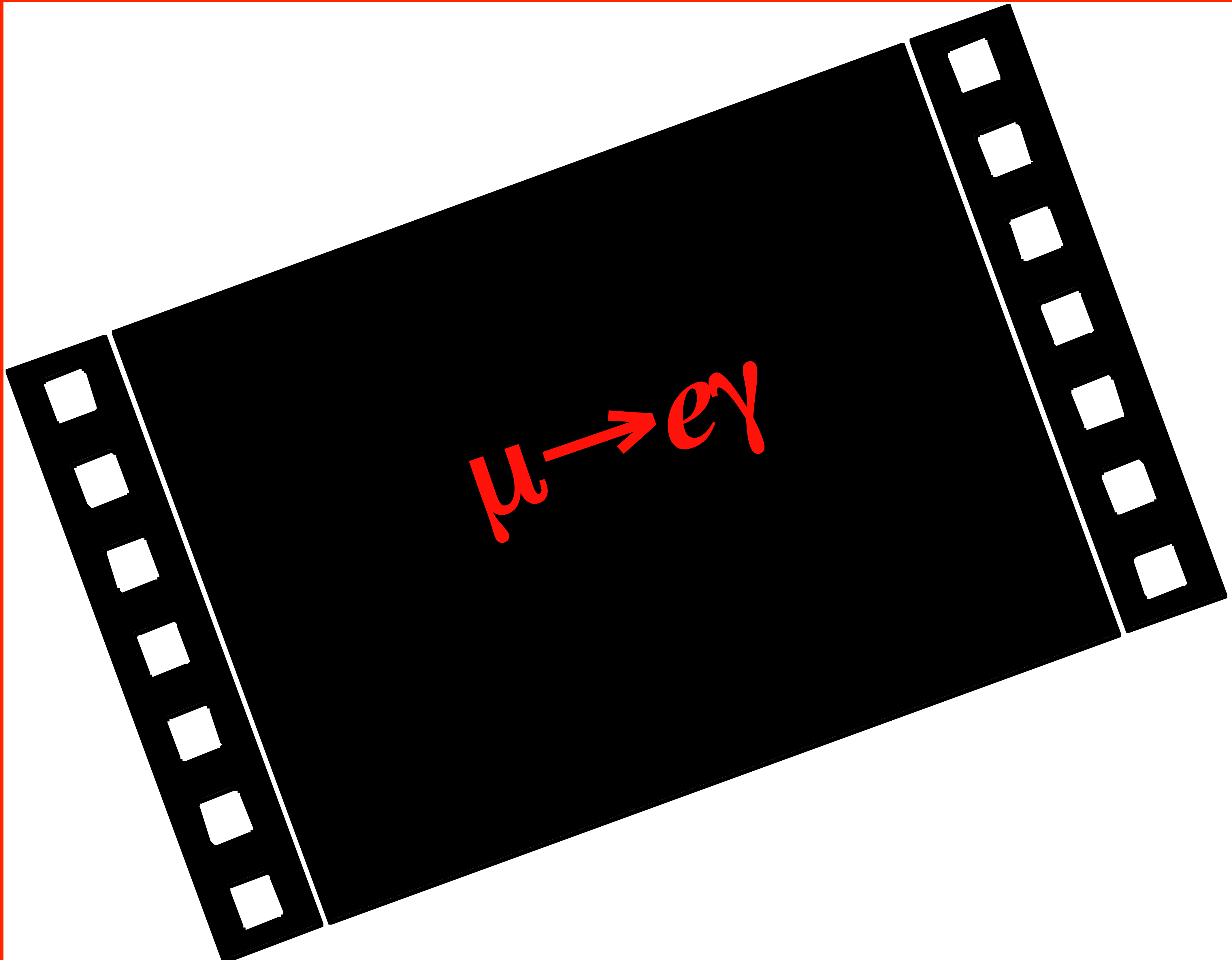
	current	future
$\mu^+ \to e^+\gamma$	$<10^{-11}$	$<10^{-14}$
$\mu^+ \to e^+e^+e^-$	$<10^{-12}$	$<10^{-14}$
$\mu^- + N(A,Z) \to e^- + N(A,Z)$	$<10^{-12}$	$<10^{-18}$

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

ΔL=2

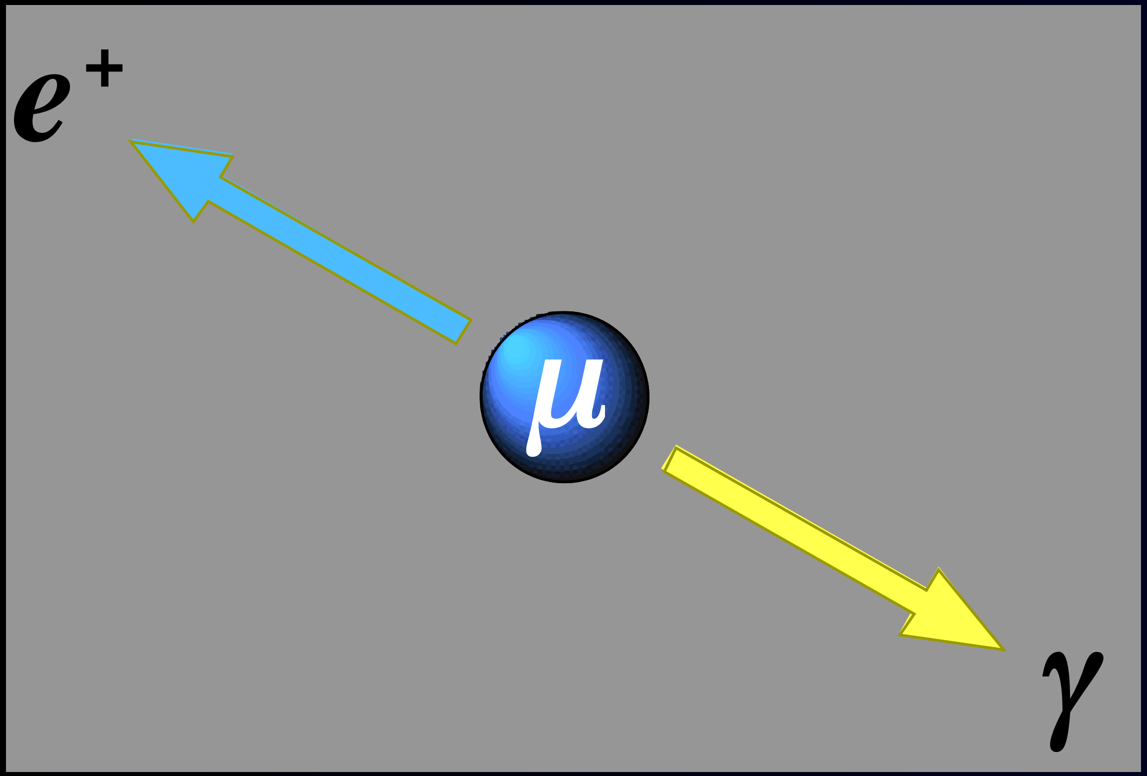
	current	future
$\mu^+e^- \to \mu^-e^+$	$<10^{-3}G_F$	$<10^{-4}G_F$

- $\mu^- + N(A,Z) \to \mu^+ + N(A,Z-2)$
- $\nu_\mu + N(A,Z) \to \mu^+ + N(A,Z-1)$
- $\nu_\mu + N(A,Z) \to \mu^+\mu^+\mu^- + N(A,Z-1)$


$\mu \to e\gamma$

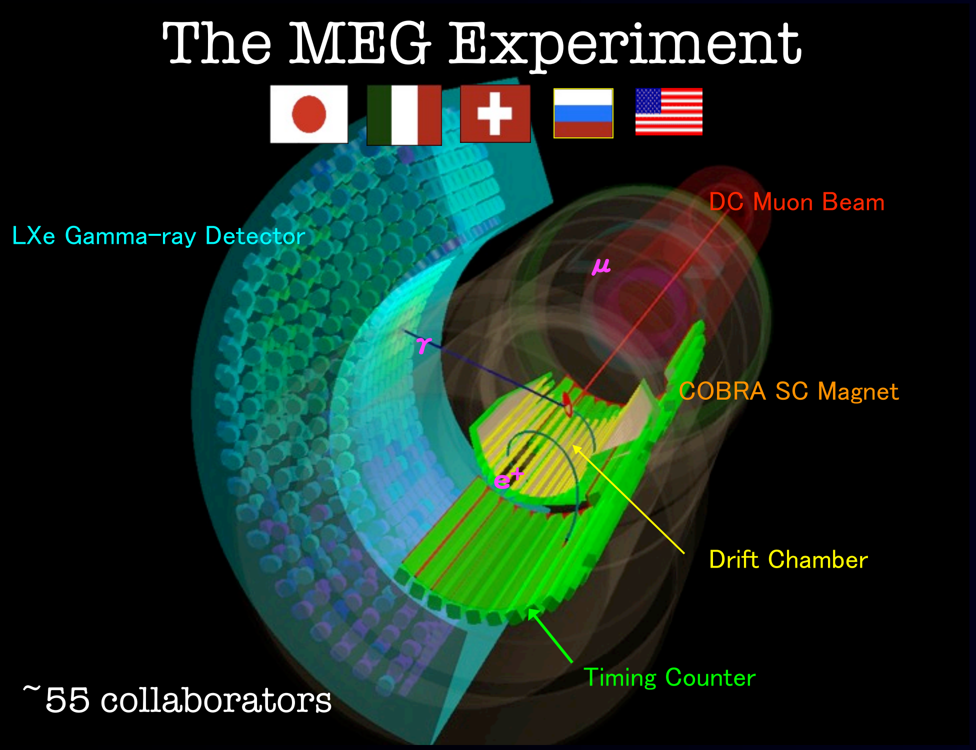
What is $\mu \to e\gamma$?

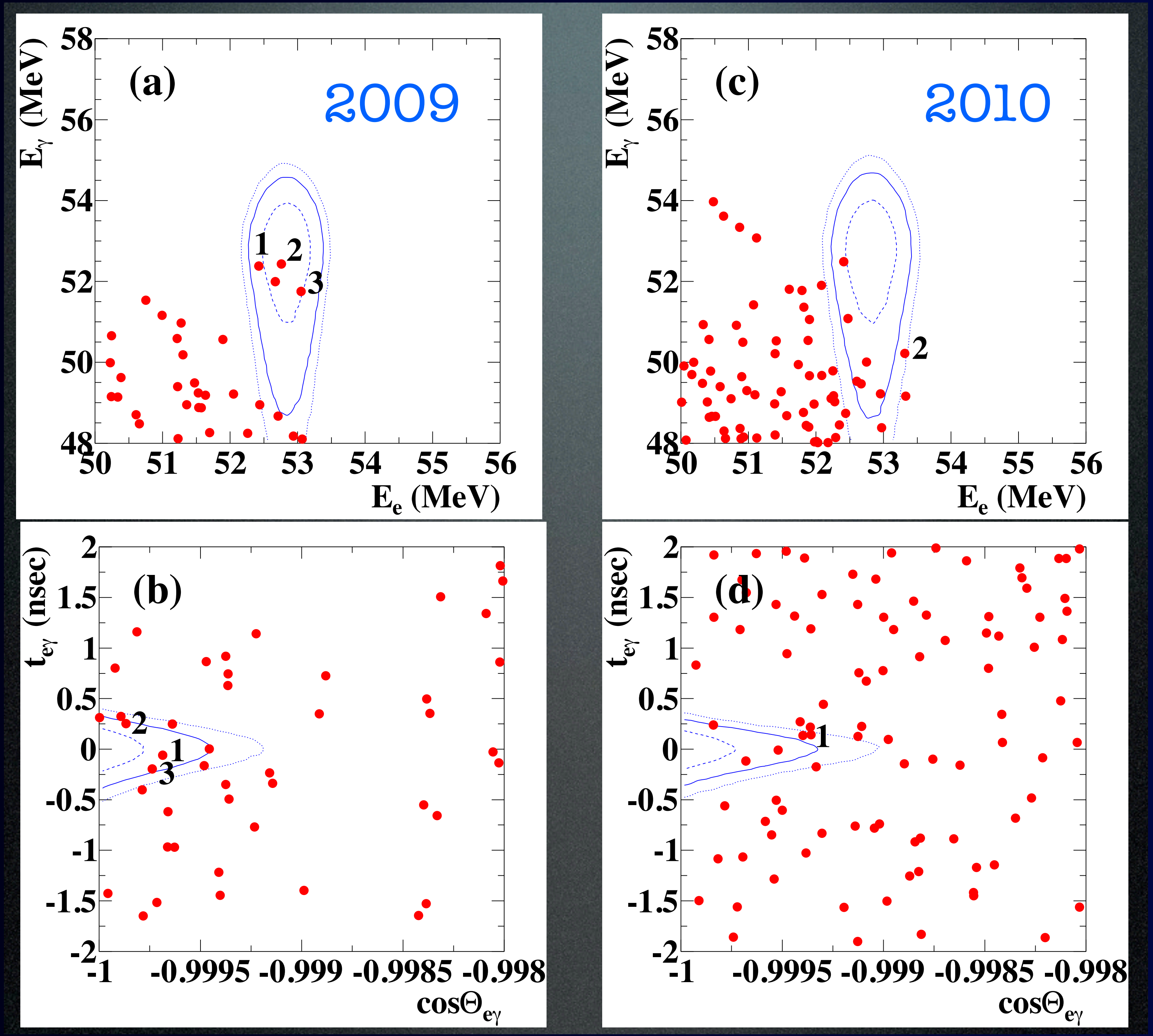
- Event Signature
  - $E_e = m_\mu/2$, $E_\gamma = m_\mu/2$ (=52.8 MeV)
  - angle $\theta_{\mu e}$=180 degrees (back-to-back)
  - time coincidence



- Backgrounds
  - prompt physics backgrounds
    - radiative muon decay $\mu \to e\nu\nu\gamma$ when two neutrinos carry very small energies.
  - accidental backgrounds
    - positron in $\mu \to e\nu\nu$
    - photon in $\mu \to e\nu\nu\gamma$ or photon from e^+e^- annihilation in flight.

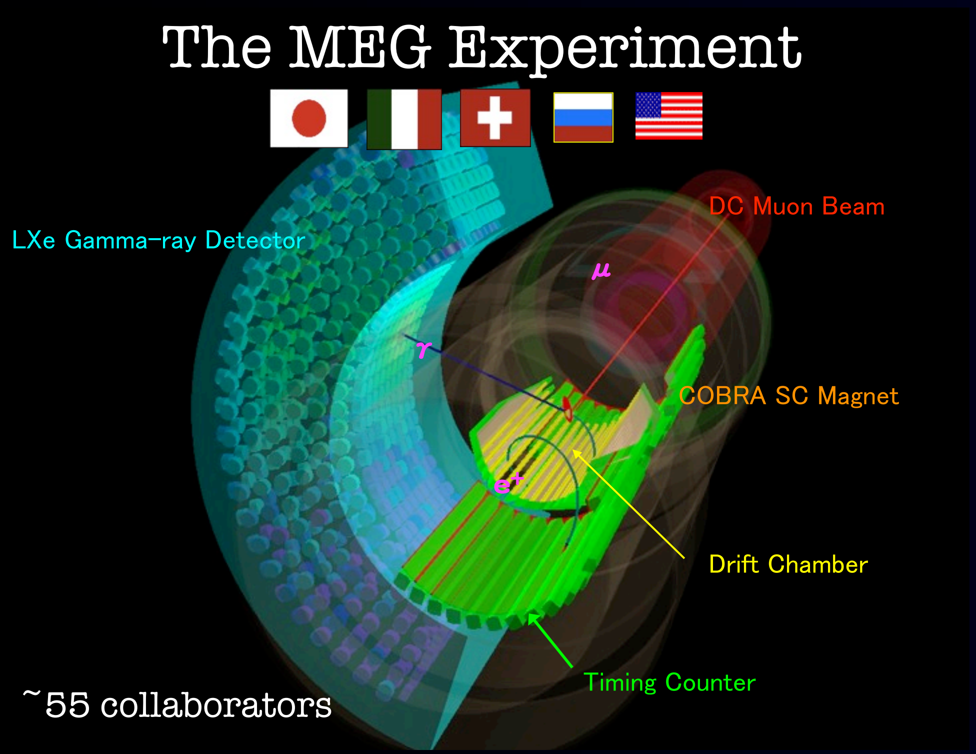
MEG at PSI and 2009/2010 Data

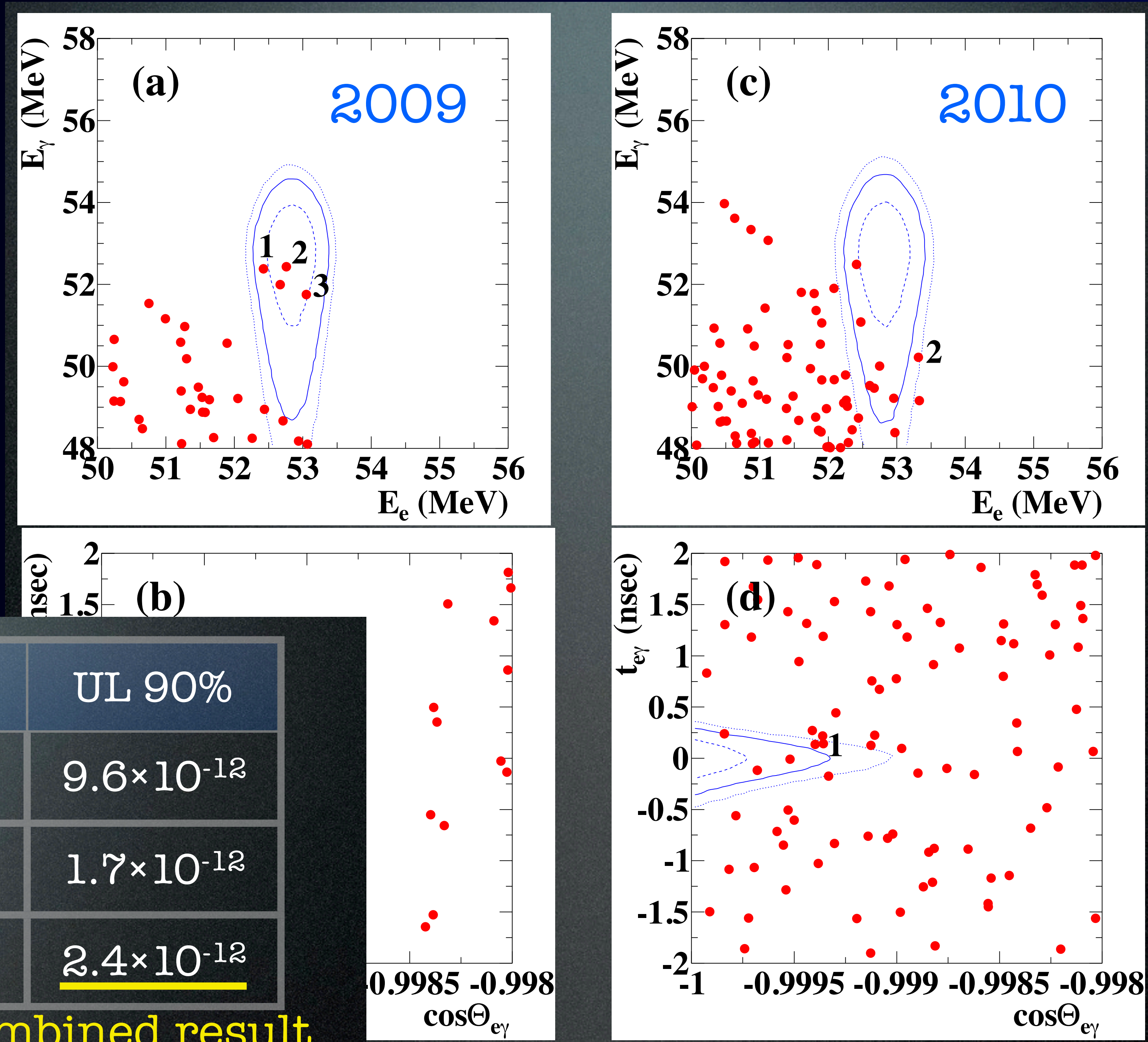




MEG at PSI and 2009/2010 Data

Goal is 10^{-13}





	BR(fit)	LL 90%	UL 90%
2009	3.2×10^{-12}	1.7×10^{-13}	9.6×10^{-12}
2010	-9.9×10^{-13}	--	1.7×10^{-12}
2009+2010	-1.5×10^{-13}	--	2.4×10^{-12}

combined result

(2009+2010expected UL = 1.6×10^{-12})

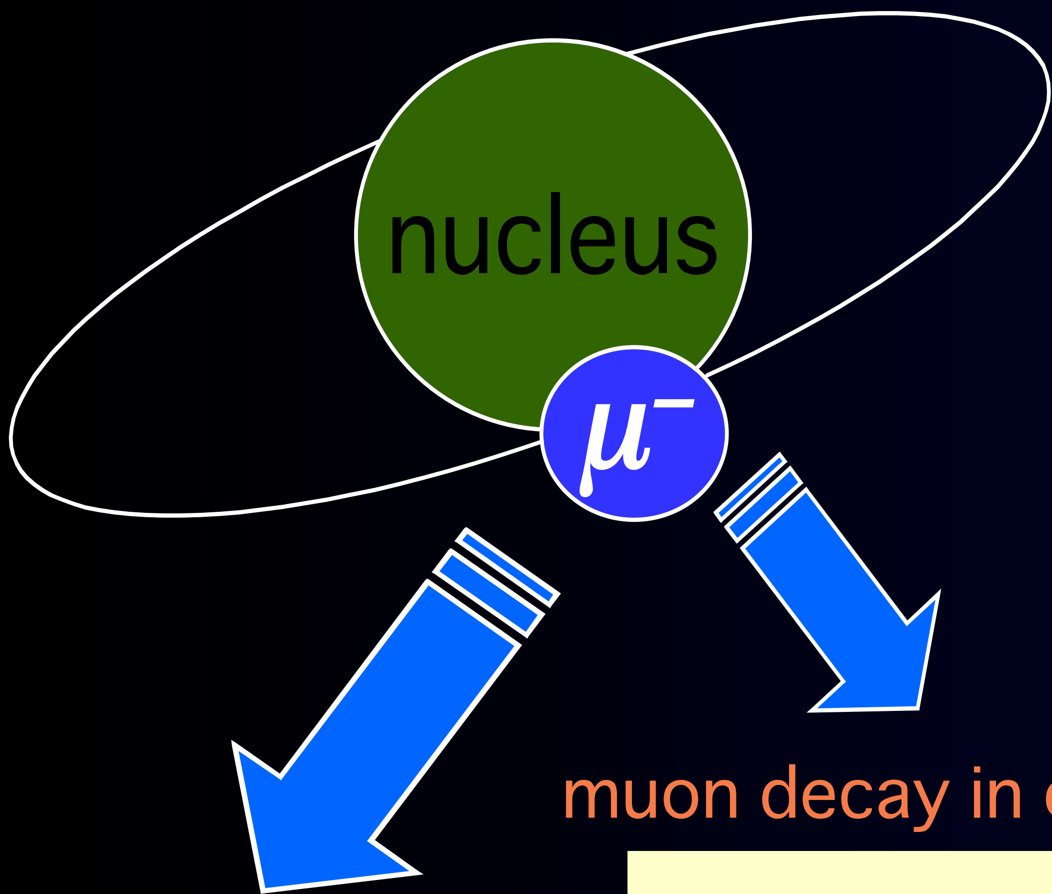
$\mu \rightarrow e$ conversion

in

a muonic atom

What is Muon to Electron Conversion?

1s state in a muonic atom



muon decay in orbit

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

nuclear muon capture

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

Neutrino-less muon nuclear capture

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

Event Signature :

a single mono-energetic electron of 100 MeV

Backgrounds:

(1) physics backgrounds (from muons, such as decay in orbit)

(2) beam-related backgrounds (radiative pion cap., muon decay in flight...)

(3) cosmic rays, false tracking

Why μ-e conversion, not μ→eγ?

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Physics

if photonic contribution dominates,

$$\frac{B(\mu N \to eN)}{B(\mu \to e\gamma)} = \frac{G_F^2 m_\mu^4}{96\pi^3\alpha} \times 3 \times 10^{12} B(A,Z) \sim \frac{B(A,Z)}{428}$$

- for aluminum, about 1/390
- for titanium, about 1/230

$B(\mu \to e\gamma) \sim 2.4\times10^{-12}$ ⇨ $B(\mu N \to eN) \sim 6.2 \times10^{-15}$

Many muons needed

But, <100 events at COMET

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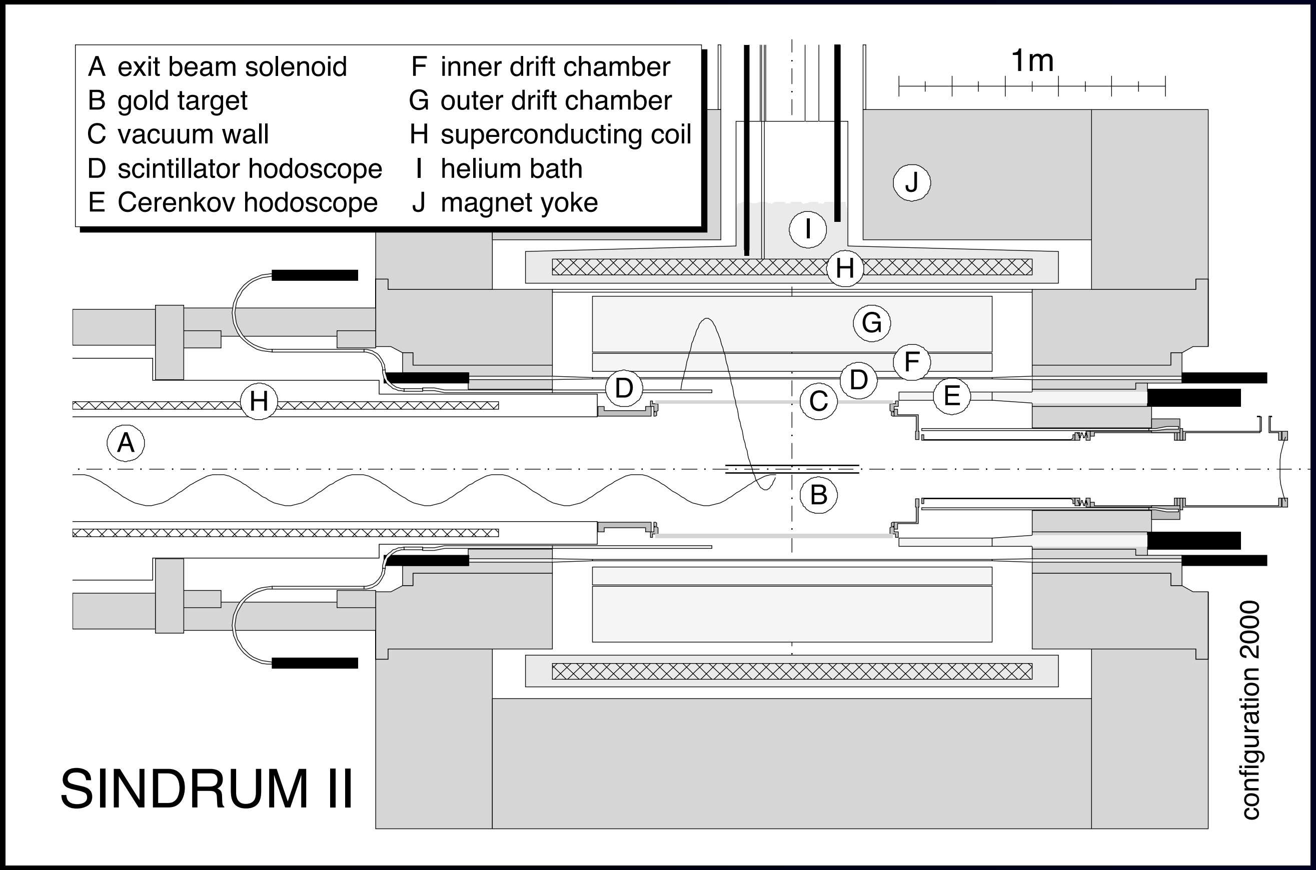
The next step would be μ-e conversion.

Previous Measurements

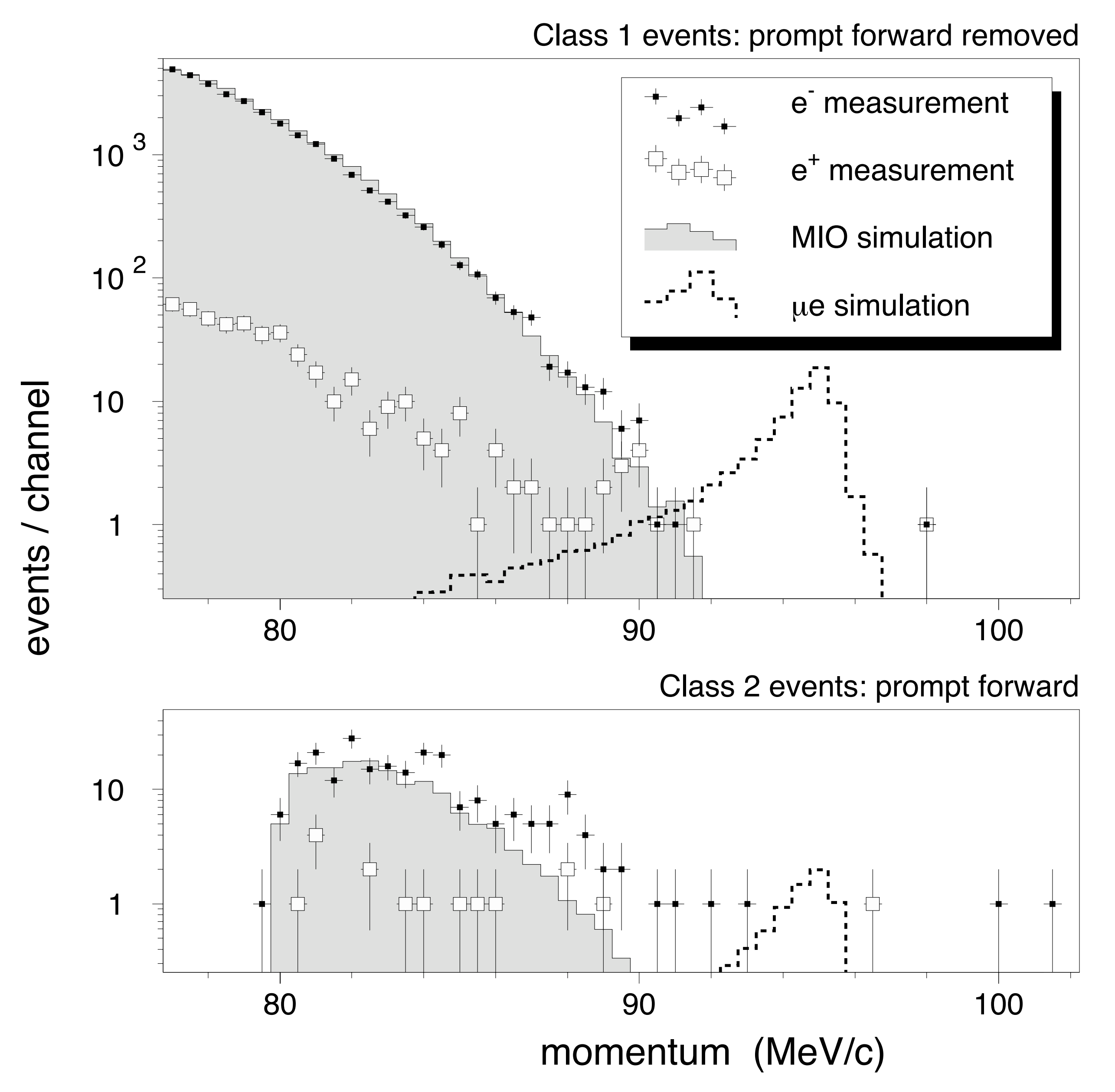
SINDRUM-II (PSI)



PSI muon beam intensity ~ 10^{7-8}/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)

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



Improvements for Signal Sensitivity

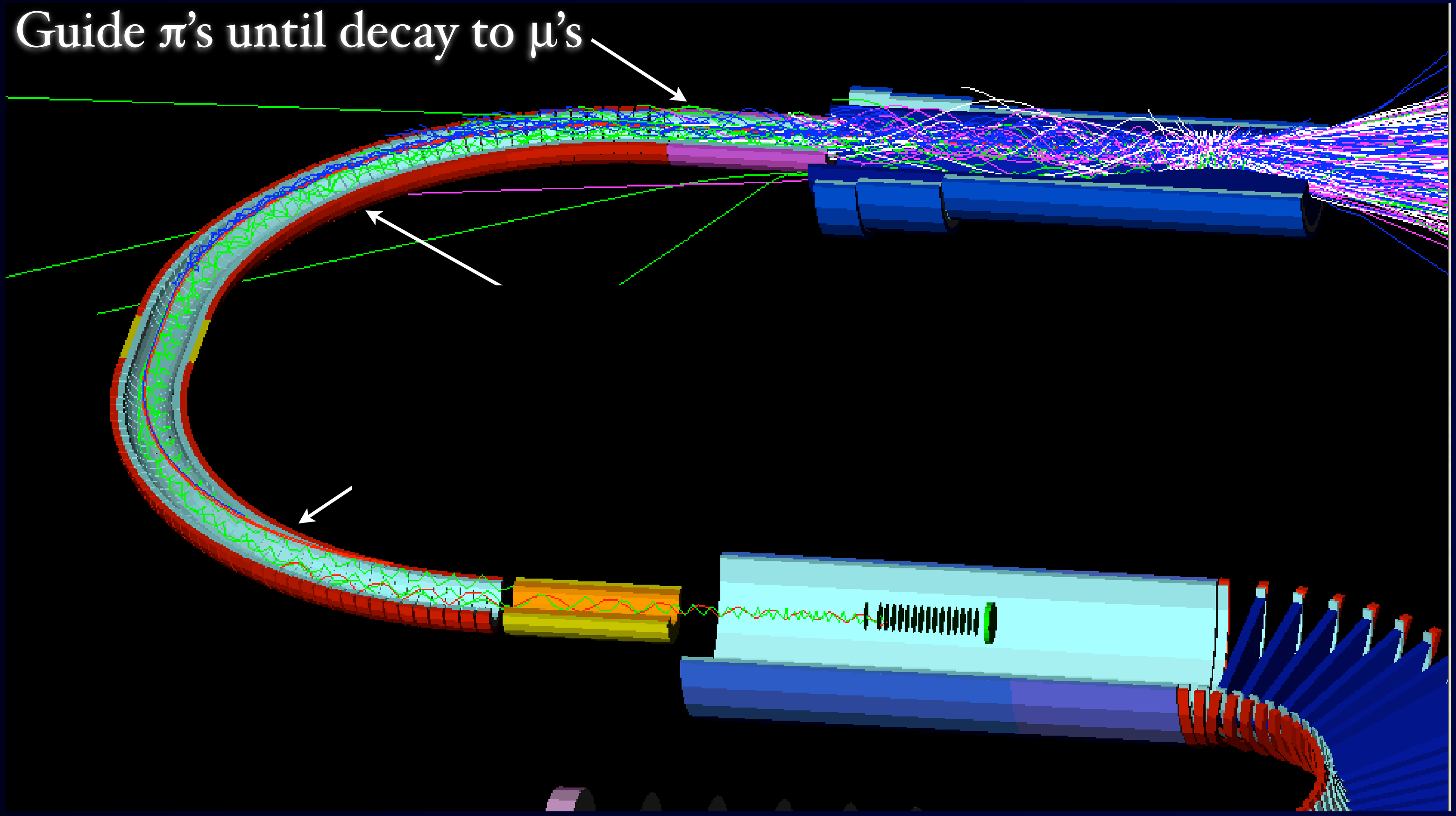
To achieve a single sensitivity of 10^{-17}, we need

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)



Improvements for Background Rejection

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

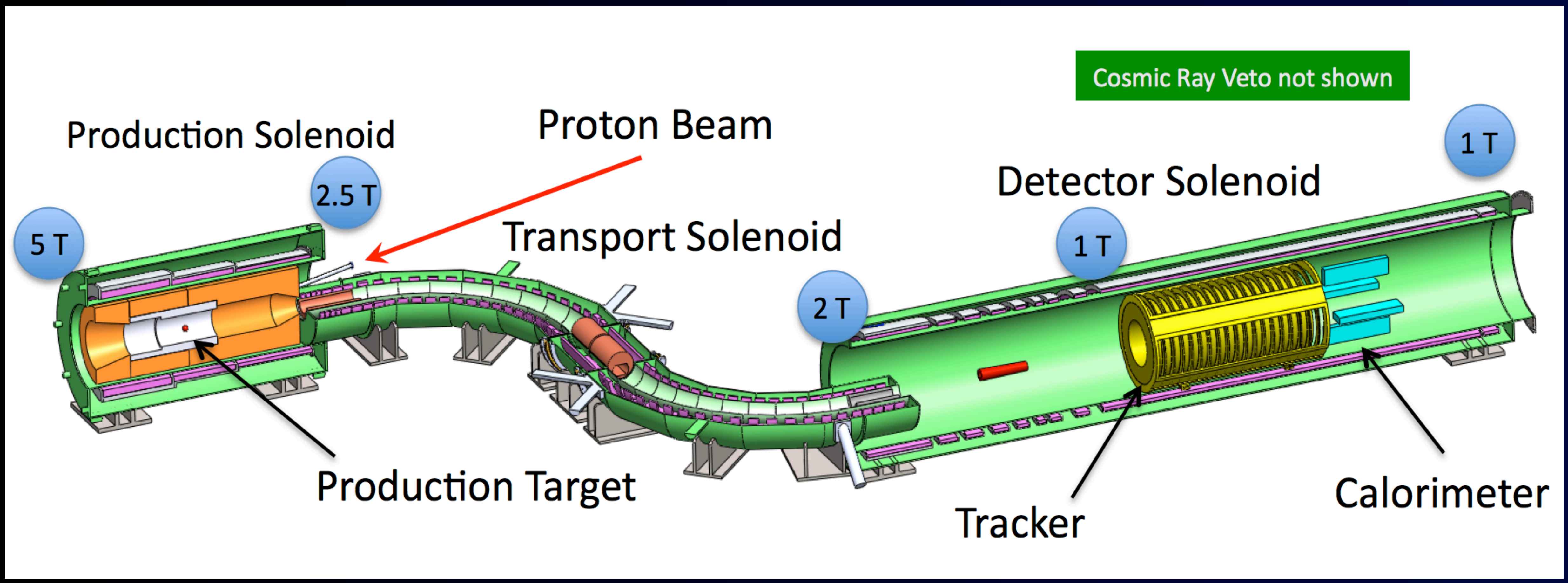
proton extinction = #protons between pulses/#protons in a pulse $< 10^{-9}$

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

μ-e conversion : Mu2e at Fermilab

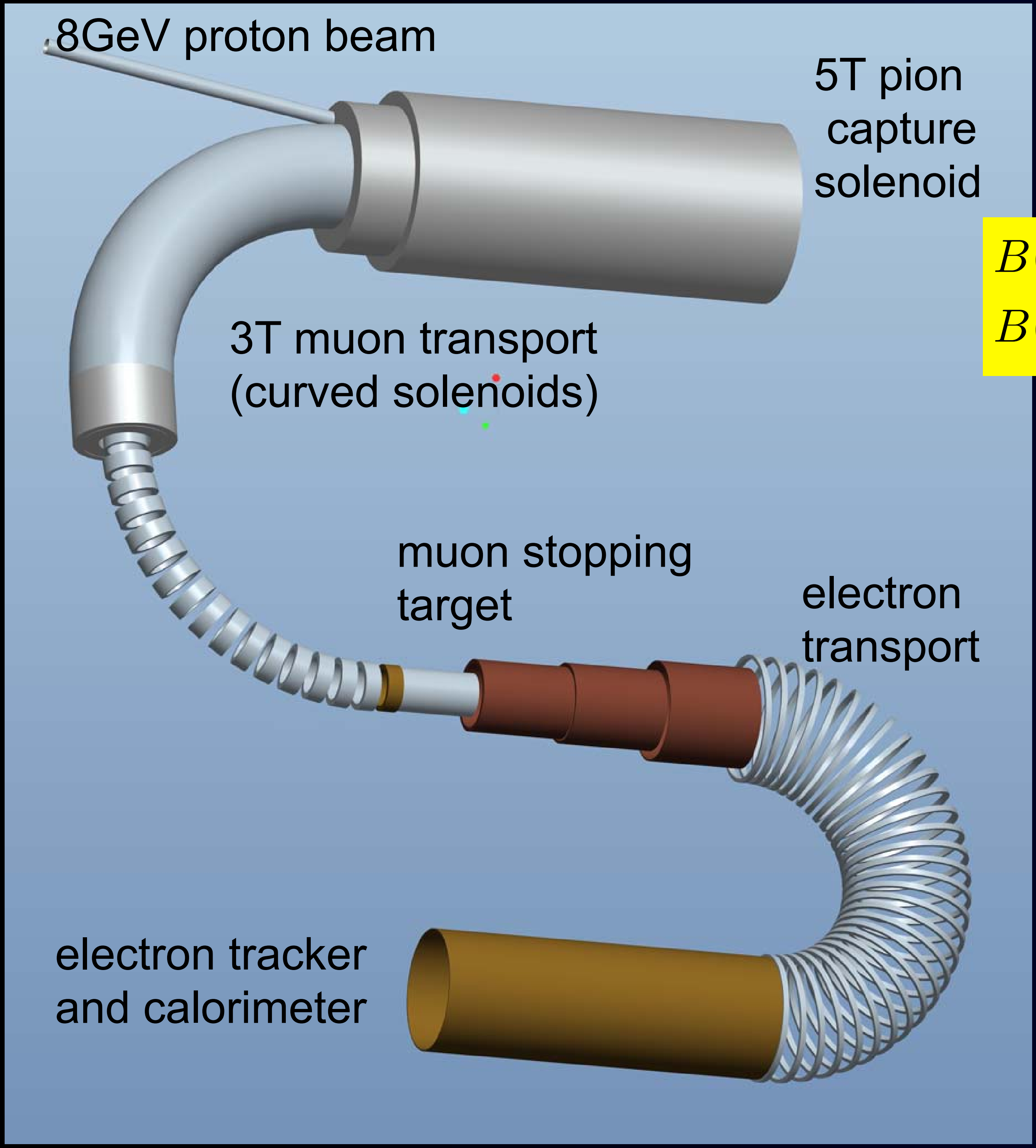


$$B(\mu^- + Al \to e^- + Al) = 2.6 \times 10^{-17}$$
$$B(\mu^- + Al \to e^- + Al) < 6 \times 10^{-17} \quad (90\% C.L.)$$

- Reincarnation of MECO at BNL.
- Antiproton buncher and accumulator rings are used to produce a pulsed proton beam.
- Approved in 2009, and CD0 in 2009.

COMET@J-PARC

μ-e conversion : COMET (E21) at J-PARC



Experimental Goal of COMET

$$B(\mu^- + Al \rightarrow e^- + Al) = 2.6 \times 10^{-17}$$
$$B(\mu^- + Al \rightarrow e^- + Al) < 6 \times 10^{-17} \quad (90\% C.L.)$$

- 10^{11} muon stops/sec for 56 kW proton beam power.
- C-shape muon beam line and C-shape electron transport followed by electron detection system.
- Stage-1 approved in 2009.

COMET Collaboration List

84 people from 20 institutes (August 2011)

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, S. Cook

University of Glasgow
P. Soler

JINR, Dubna, Russia
V. Kalinnikov, A. Moiseenko, G. Macharashvili, J. Pontecorvo, B. Sabirov, Z. Tsamaiaidze, and P. Evtukhouvich

BINP, Novosibirsk, Russia
D. Grigorev, A. Bondar, G. Fedotovich, A Ryzhenenkov, D. Shemyakin

ITEP, Russia
M. Danilov, A. Drutskoy, V. Rusinov, E.Tarkovsky

Department of physics and astronomy, University of British Columbia, Vancouver, Canada
D. Bryman

TRIUMF, Canada
T. Numao, I. Sekachev

Department of Physics, Brookhaven National Laboratory, USA
R. Palmer, Y. Cui

Department of Physics, University of Houston, USA
E. Hungerford, K. Lau

MPI-Munich
T. Ota

Tbilisi State University
M. Nioradze, Ni. Tsverava, Y. Tevxadze

Institute for Nuclear Science and Technology
Vo Van Thuan, T.P.H. Hoang

University of Science, HoChi Minh
Chau Vau Tao

University of Malaya
Wan Ahmad Tajuddin

University Technology Malaysia
Md. Imam Hossain

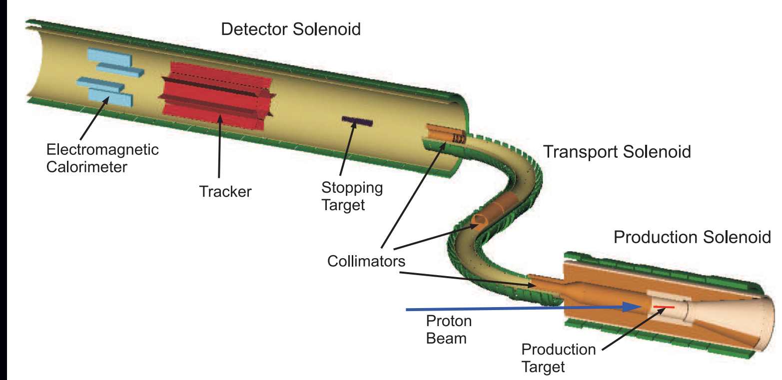
Kyoto University, Kyoto, Japan
Y. Iwashita, Y, Mori, Y. Kuriyama, J.B Lagrange

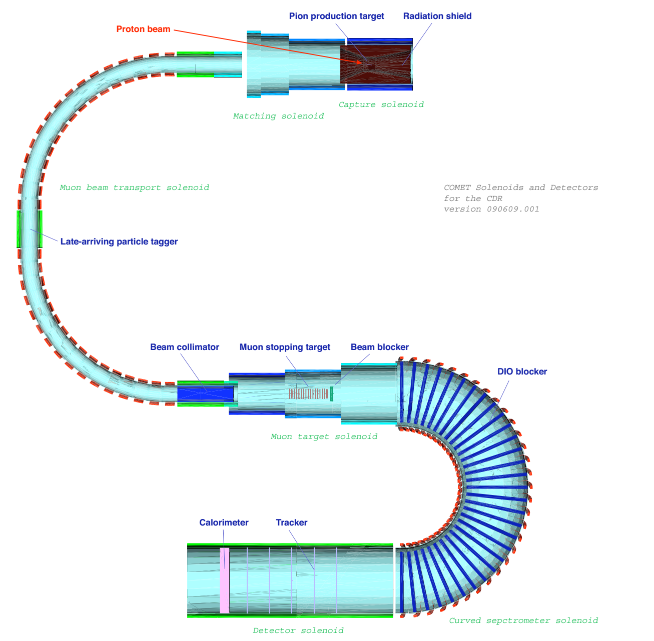
Department of Physics, Osaka University, Japan
M. Aoki, T. Hiasa, T. Hayashi, S. Hikida, Y. Hino, T. Itahashi, S. Ito, Y. Kuno, H. Nakai, T. H. Nam, H. Sakamoto, A. Sato, N.M.Truong

Department of Physics, Saitama University, Japan
M. Koike, and J. Sato

High Energy Accelerator Research Organization (KEK), Japan
Y. Arimoto, K. Hasegawa, Y. Igarashi, M. Ikeno, S. Ishimoto, Y. Makida, S. Mihara, H. Nishiguchi, T. Nakamoto, T. Ogitsu, C. Ohmori, Y. Takubo, M. Tanaka, M. Tomizawa, T. Uchida, A. Yamamoto, M. Yamanaka, M. Yoshida, M. Yoshii, K. Yoshimura

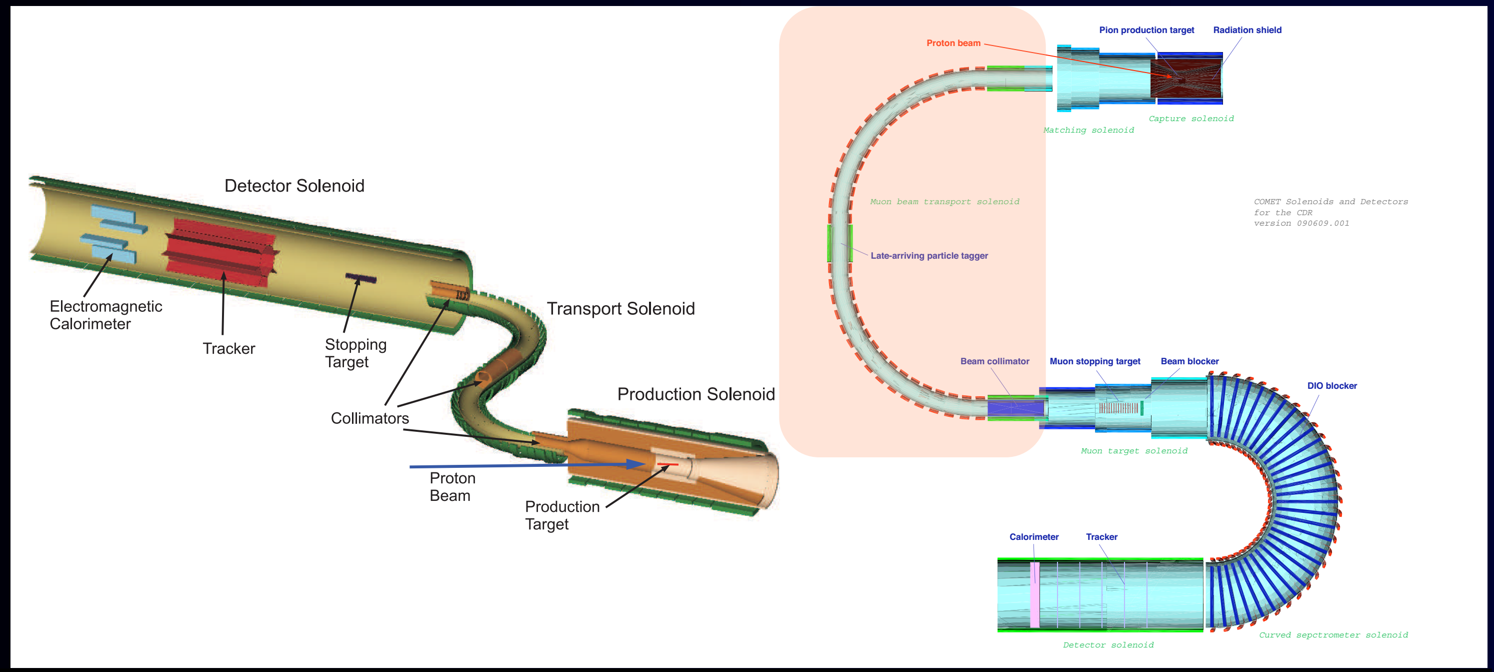
Comparison : COMET vs. Mu2e





	Mu2e@FNAL	COMET@J-PARC
muon beamline	S-shape	C-shape
electron spectrometer	Straight solenoid	Curved solenoid

Comparison : COMET vs. Mu2e



	Mu2e@FNAL	COMET@J-PARC
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Selection of low momentum muons

eliminate background from muon decay in flight

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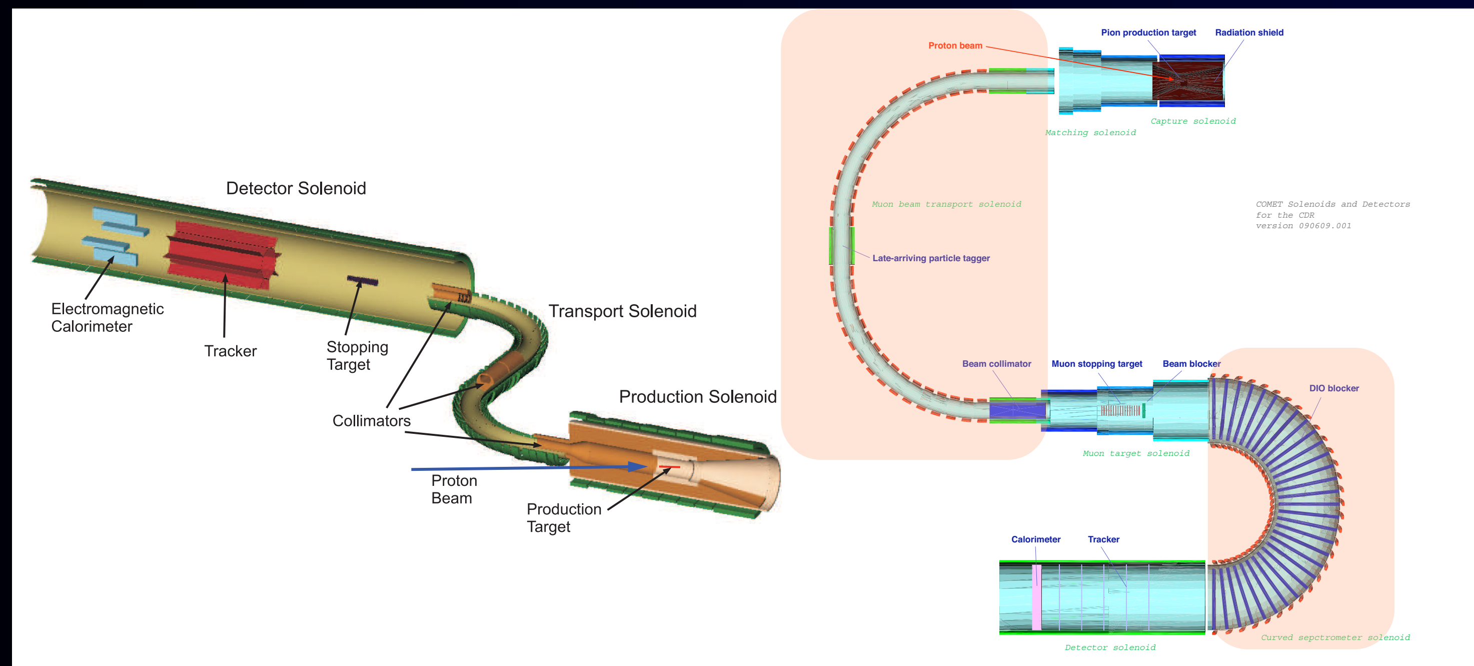


	Mu2e@FNAL	COMET@J-PARC
muon beamline	S-shape	C-shape
electron spectrometer	Straight solenoid	Curved solenoid

Selection of low momentum muons

eliminate background from muon decay in flight

Selection of 100 MeV electrons

eliminate protons from nuclear muon capture.

eliminate low energy events to make the detector quiet.

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

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

- Single event sensitivity

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

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

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

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

Background Rates

Radiative Pion Capture	0.05
Beam Electrons	< 0.1‡
Muon Decay in Flight	< 0.0002
Pion Decay in Flight	< 0.0001
Neutron Induced	0.024
Delayed-Pion Radiative Capture	0.002
Anti-proton Induced	0.007
Muon Decay in Orbit	0.15
Radiative Muon Capture	< 0.001
μ^- Capt. w/ n Emission	< 0.001
μ^- Capt. w/ Charged Part. Emission	< 0.001
Cosmic Ray Muons	0.002
Electrons from Cosmic Ray Muons	0.002
Total	0.34

‡ Monte Carlo statistics limited.

beam-related prompt backgrounds

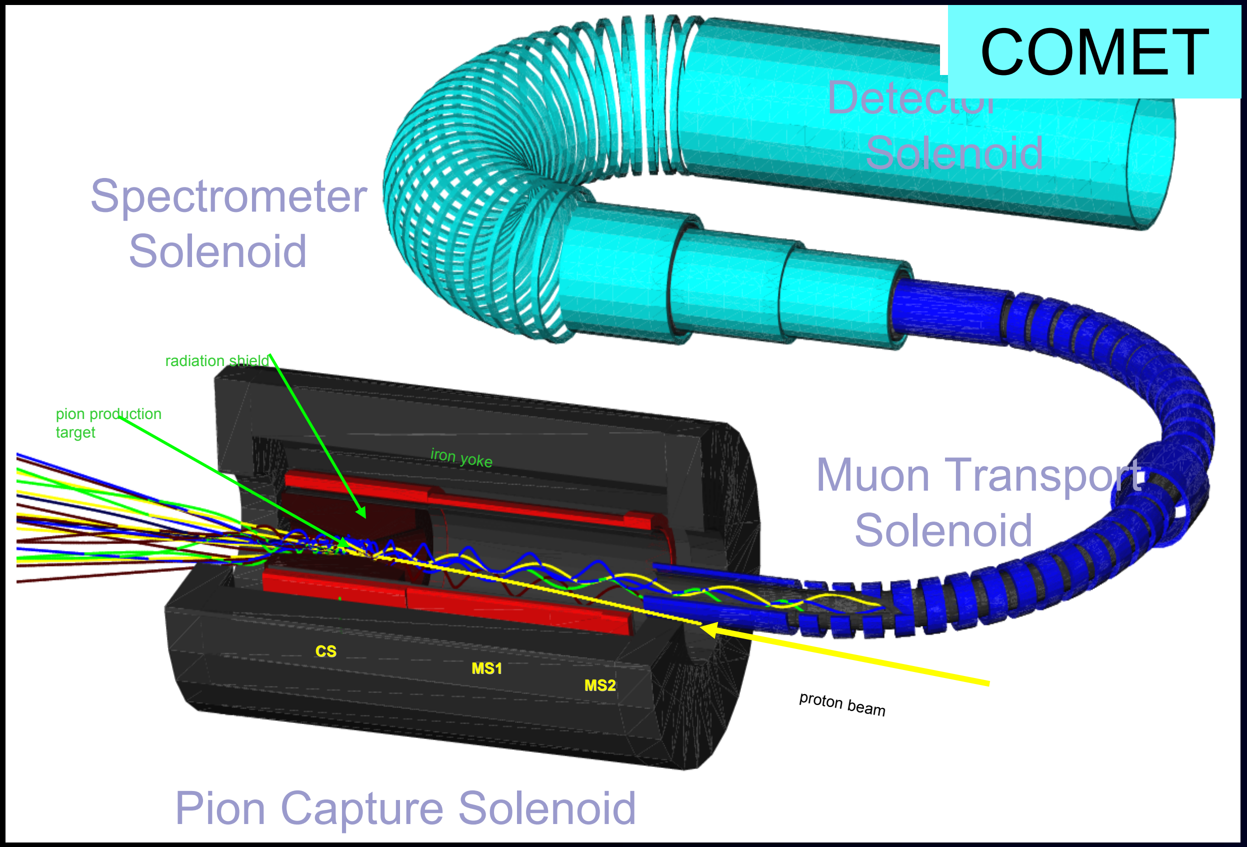
beam-related delayed backgrounds

intrinsic physics backgrounds

cosmic-ray and other backgrounds

Expected background events are about 0.34.

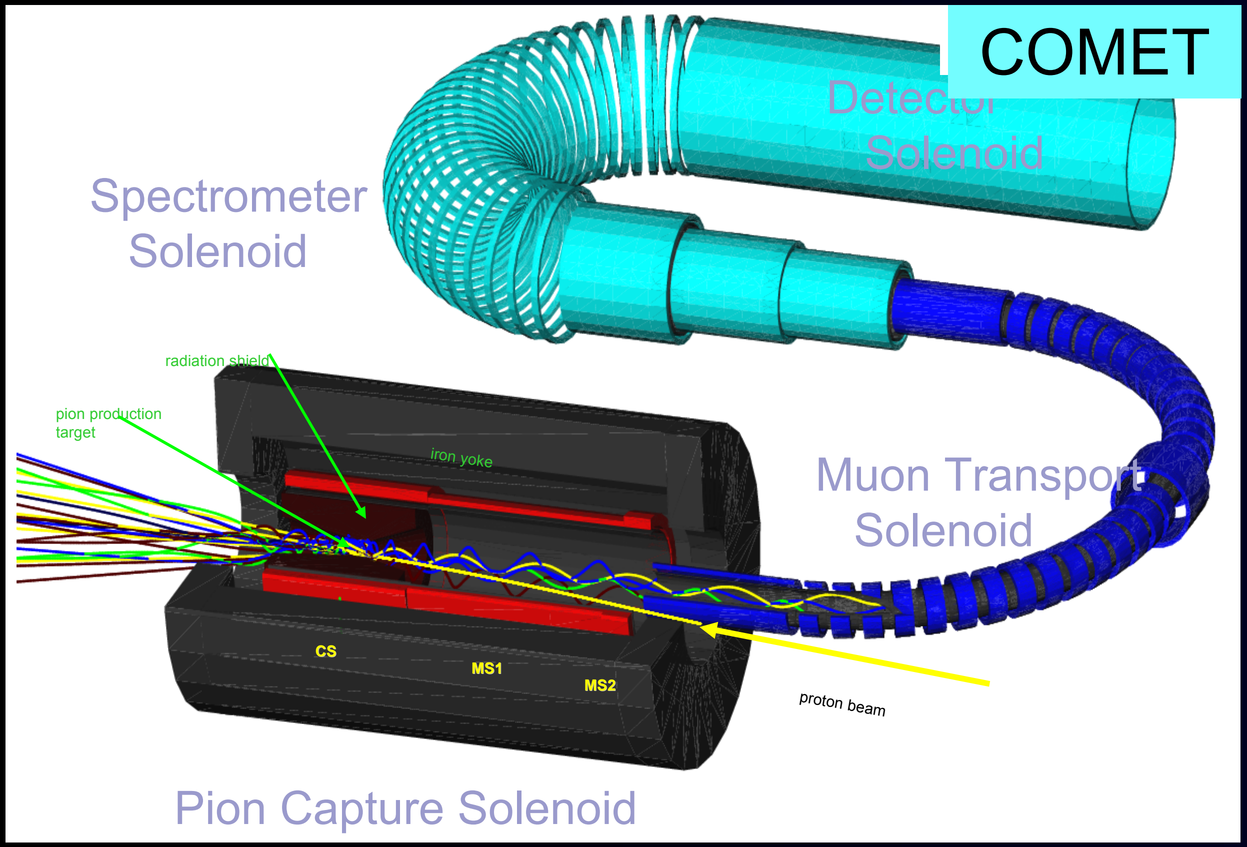
R&D Milestones for COMET



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

single event sensitivity: 2.6×10^{-17}

R&D Milestones for COMET



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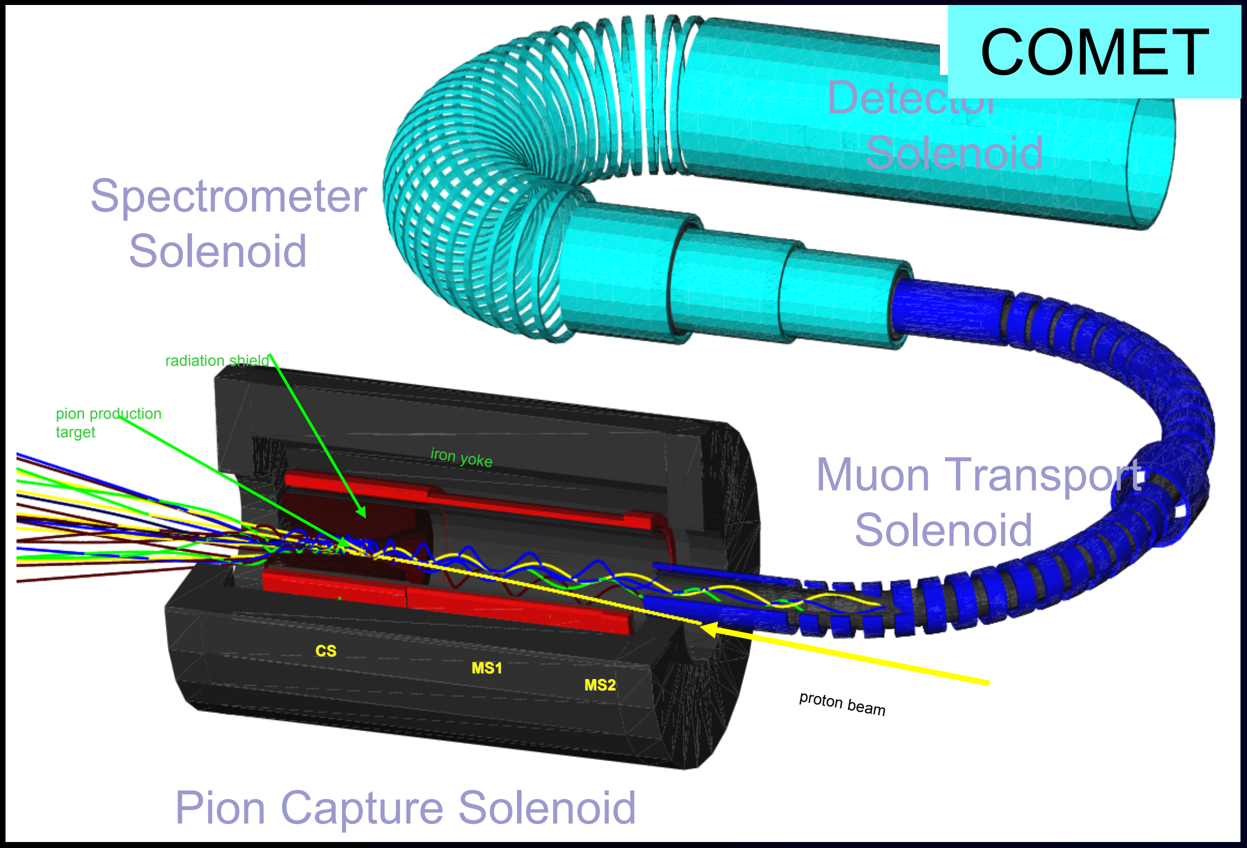
single event sensitivity: 2.6×10^{-17}

1 **Reduction of Backgrounds**

Beam pulsing

measurement is done between beam pulses to reduce beam related backgrounds. And proton beam extinction of $<10^{-9}$ is required.

R&D Milestones for COMET



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single event sensitivity: 2.6×10^{-17}

1 Reduction of Backgrounds

Beam pulsing

measurement is done between beam pulses to reduce beam related backgrounds. And proton beam extinction of $<10^{-9}$ is required.

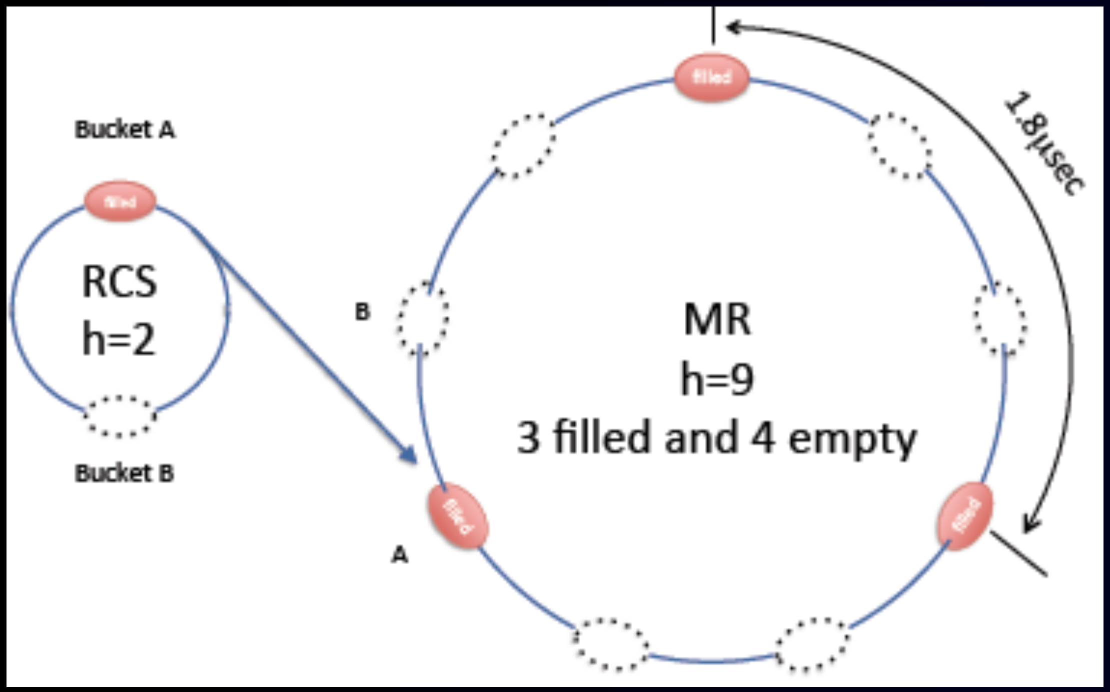
2 Increase of Muon Intensity

Pion capture system $\times 10^3$

high field superconducting solenoid magnets surrounding a pion production target

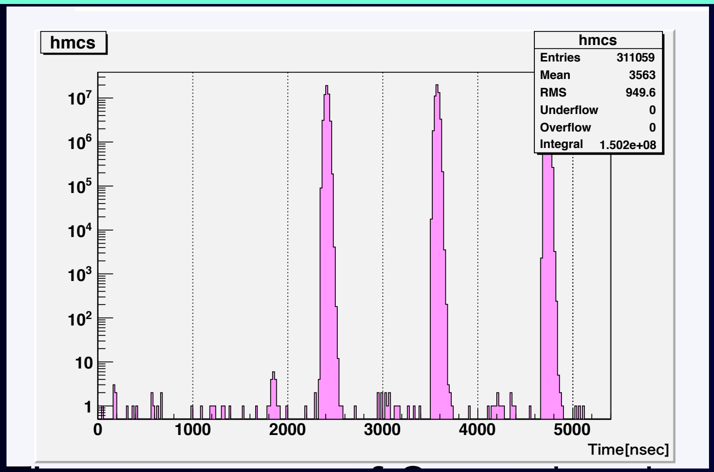
1 Proton Beam Extinction Studies

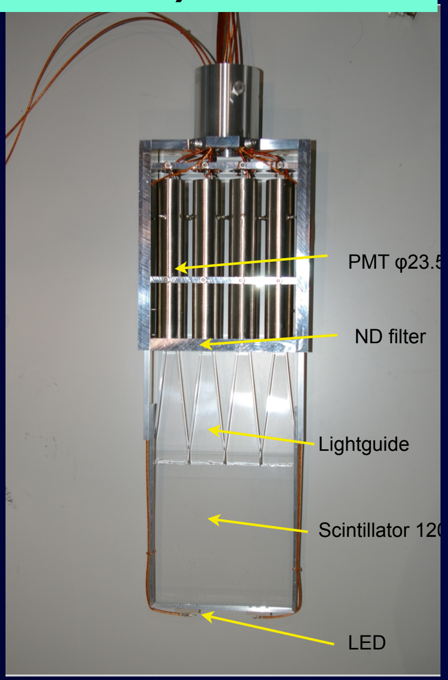
1 Proton Beam Extinction Studies



Measured at abort beamline (2010)

Measured at secondary beamline (2010)

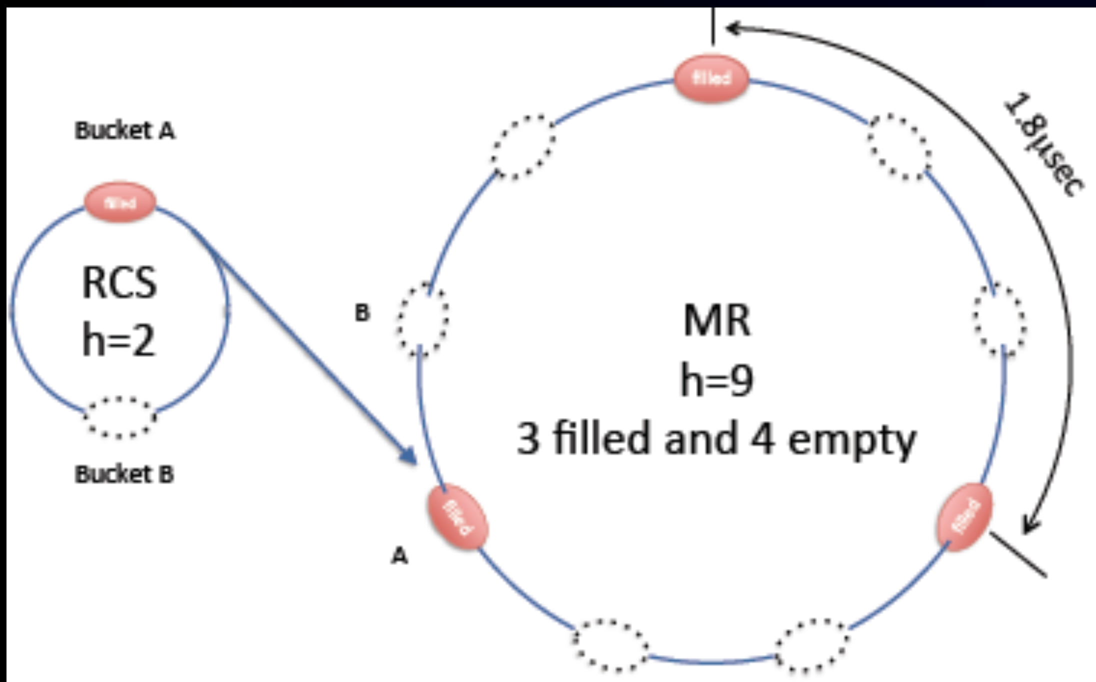




J-PARC MR proton extinction

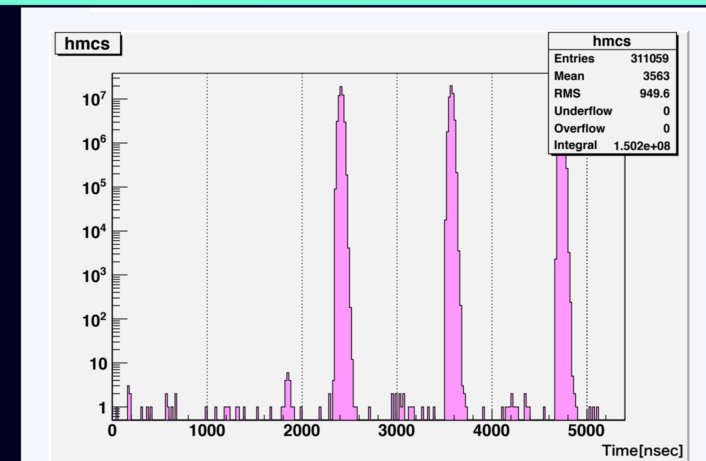
~ $O(10^{-7})$

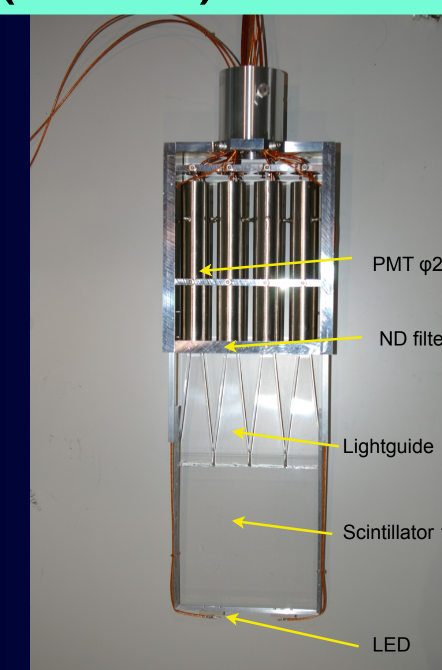
1 Proton Beam Extinction Studies



Measured at abort beamline (2010)

Measured at secondary beamline (2010)





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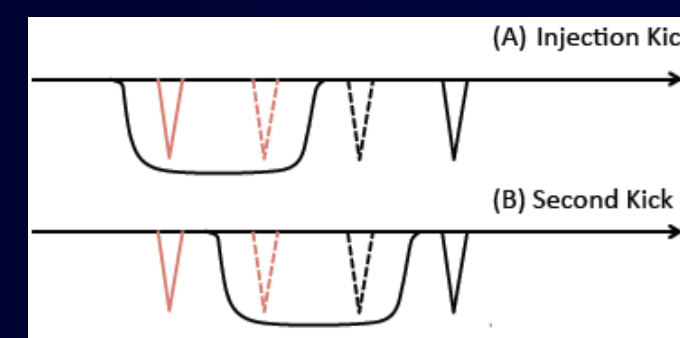
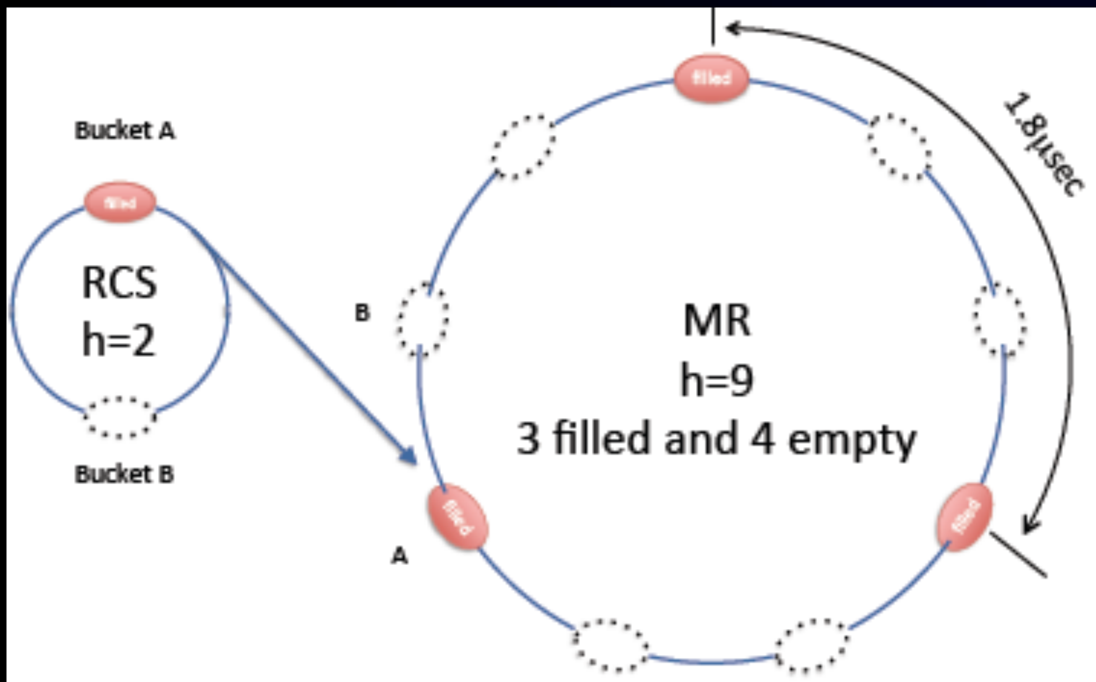


Double Injection Kicking

Tested at the abort (2010)

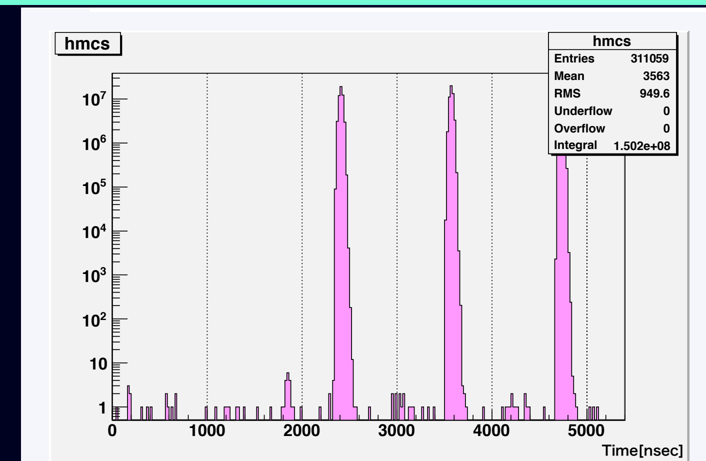
x additional O(10^{-6})

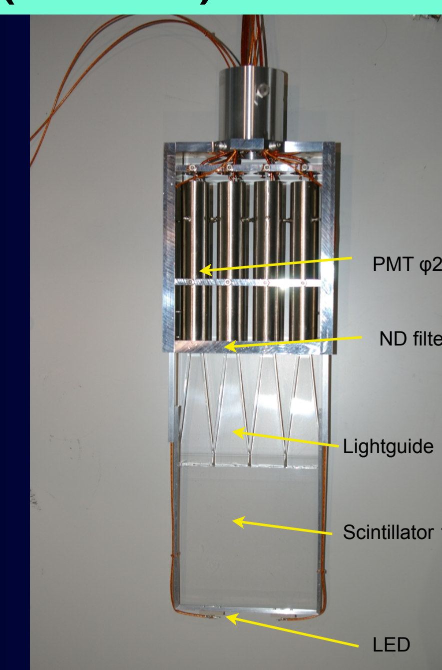
1 Proton Beam Extinction Studies



Measured at abort beamline (2010)

Measured at secondary beamline (2010)





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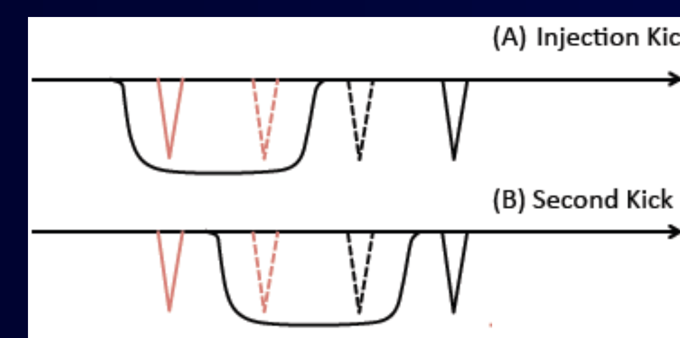


Double Injection Kicking

Tested at the abort (2010)

x additional O(10^{-6})

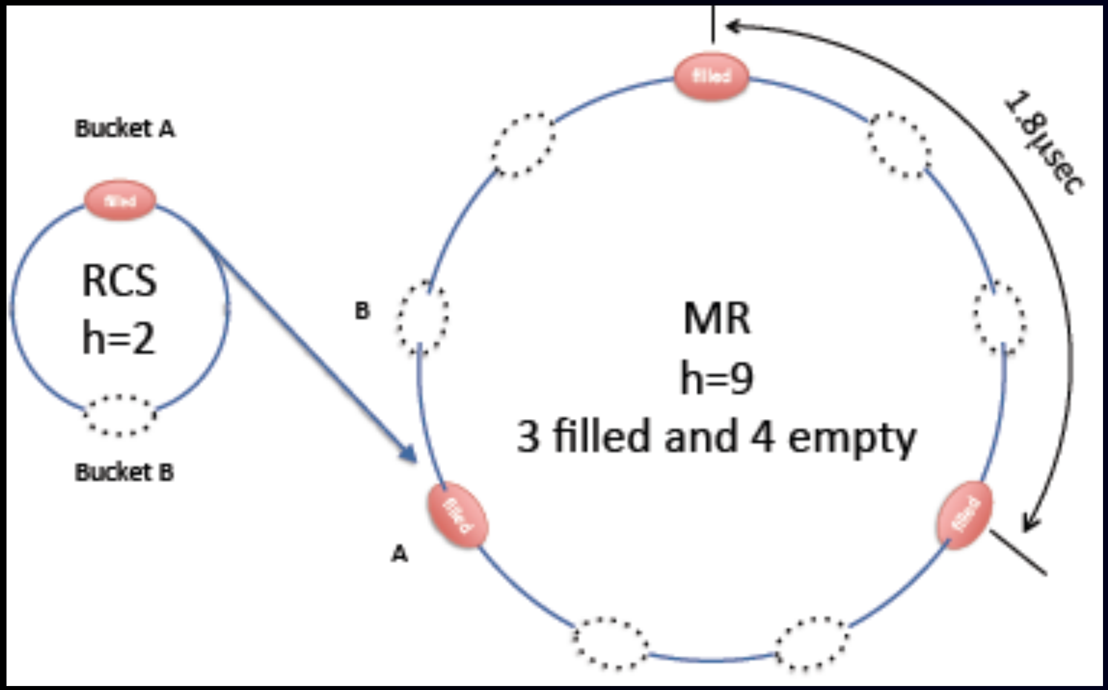
External Extinction Device

AC dipole magnet R&D

x additional O(10^{-3})

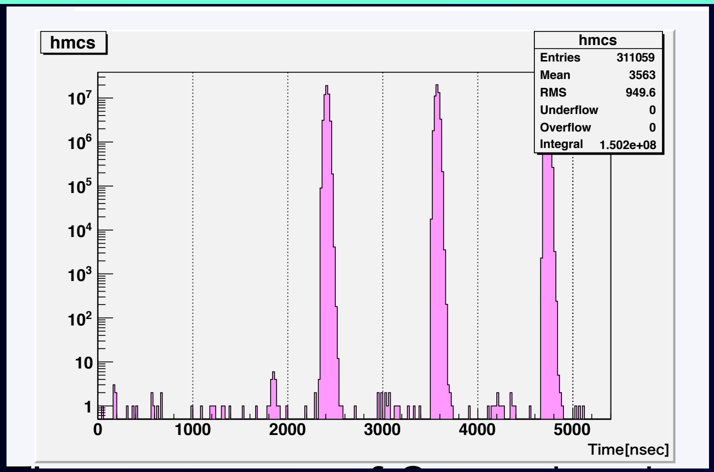
Proton Beam Extinction Studies

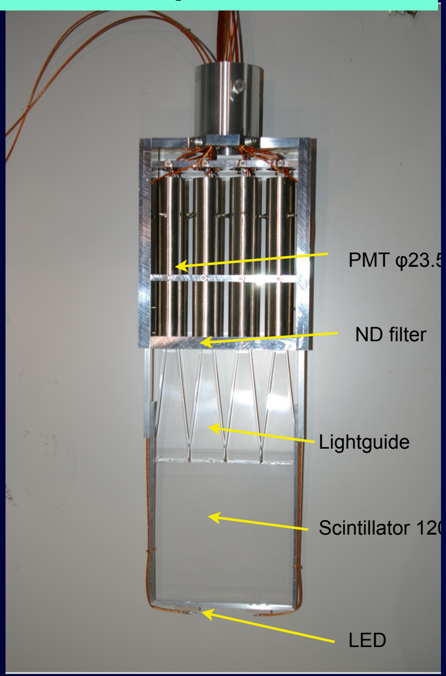
1



Measured at abort beamline (2010)

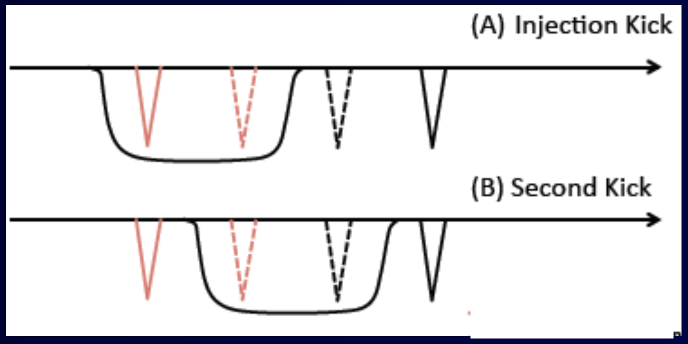
Measured at secondary beamline (2010)





J-PARC MR proton extinction

~ $O(10^{-7})$



Double Injection Kicking

Tested at the abort (2010)

x additional $O(10^{-6})$

External Extinction Device

AC dipole magnet R&D

x additional $O(10^{-3})$

COMET is confident to achieve proton extinction of $<O(10^{-9})$.

2

Pion Capture System@MuSIC

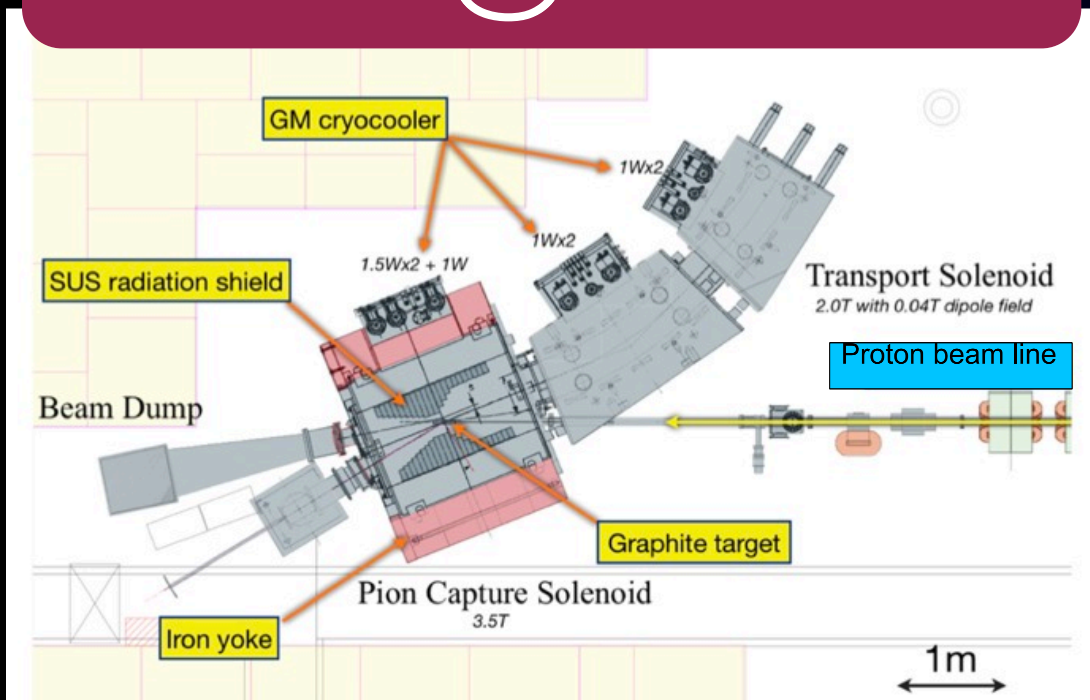
2

Pion Capture System@MuSIC

Demonstration of Pion Capture System

RCNP cyclotron
400 MeV, 1μA

MuSIC@Osaka-U



2 Pion Capture System@MuSIC

Demonstration of Pion Capture System

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400 MeV, 1μA

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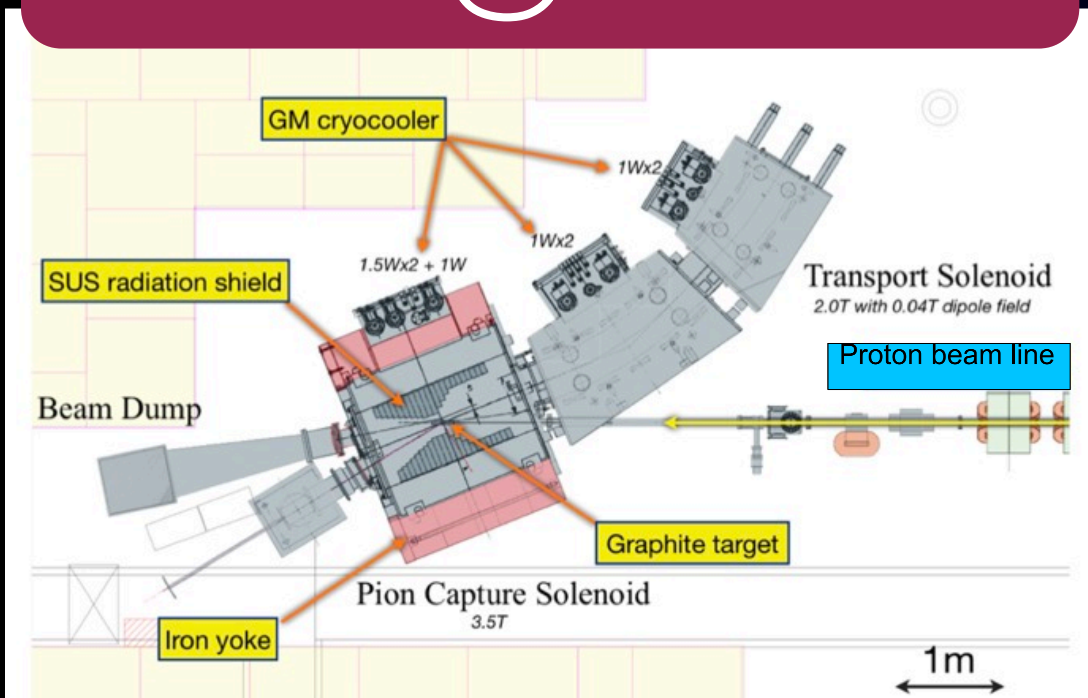
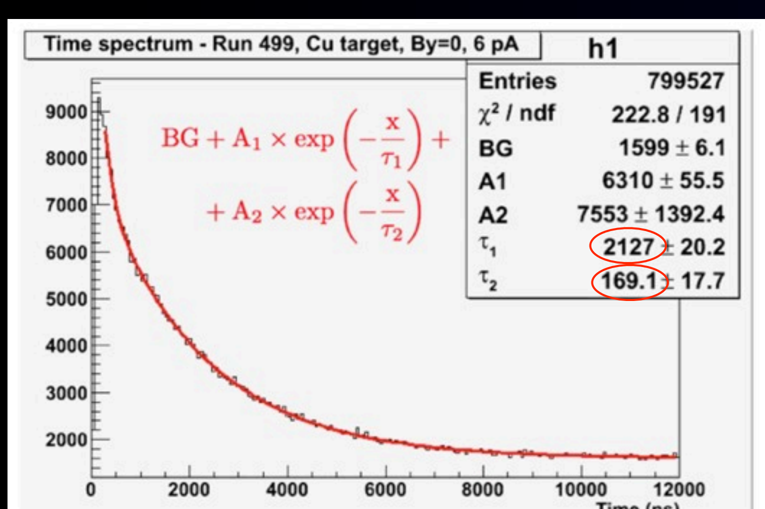
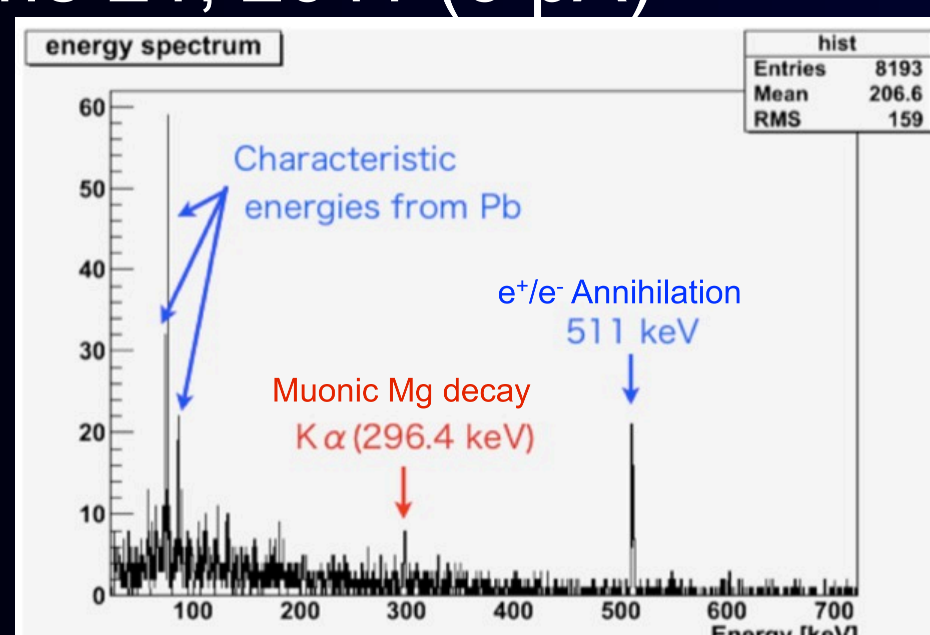


preliminary

Measurements on June 21, 2011 (6 pA)



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



MuSIC muon yields

μ^+ : 3x10^8/s for 400W

μ^- : 1x10^8/s for 400W

cf. 10^8/s for 1MW @PSI

Req. of x10^3 achieved...

Long-term Future Prospect: from COMET to PRISM

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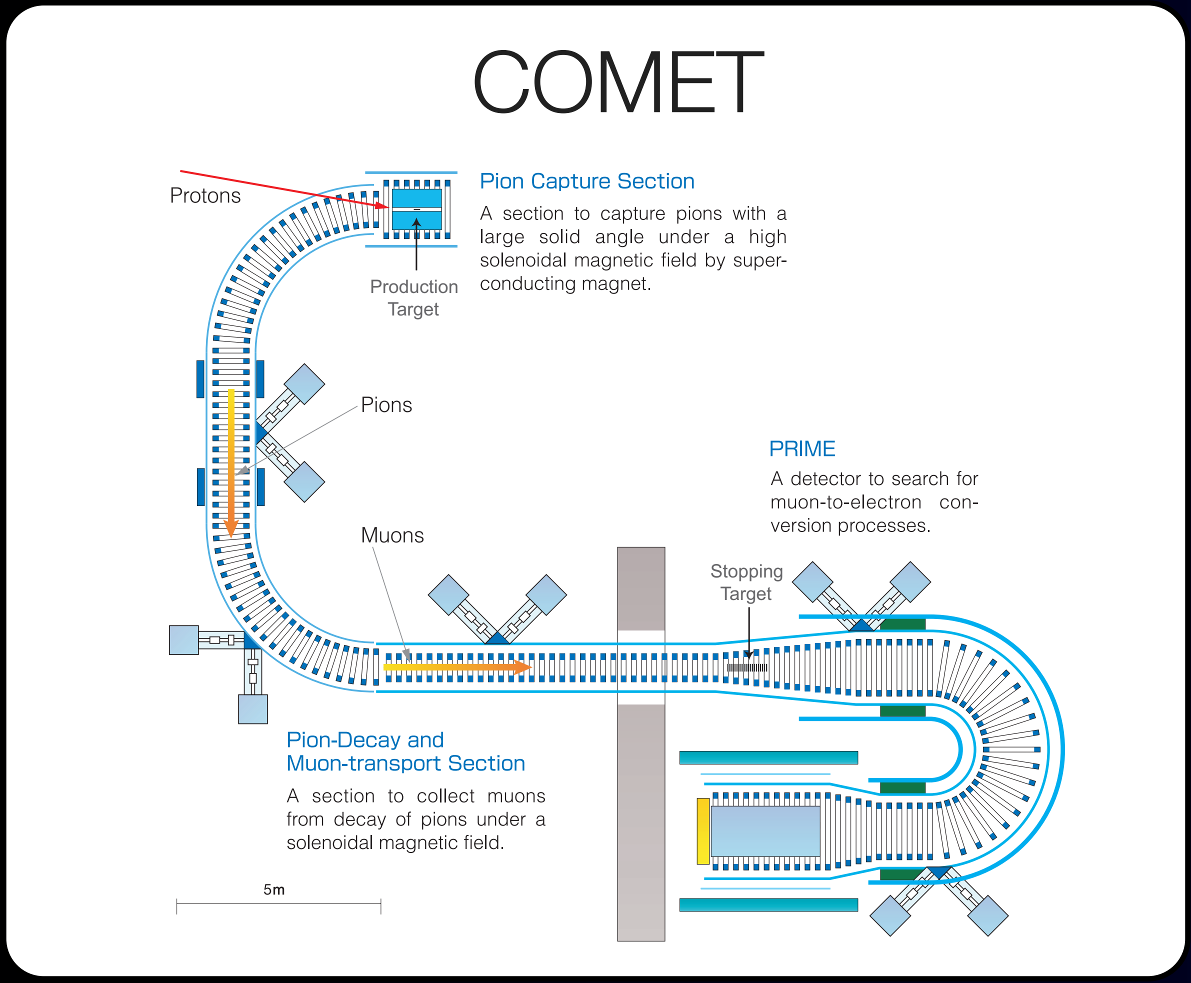
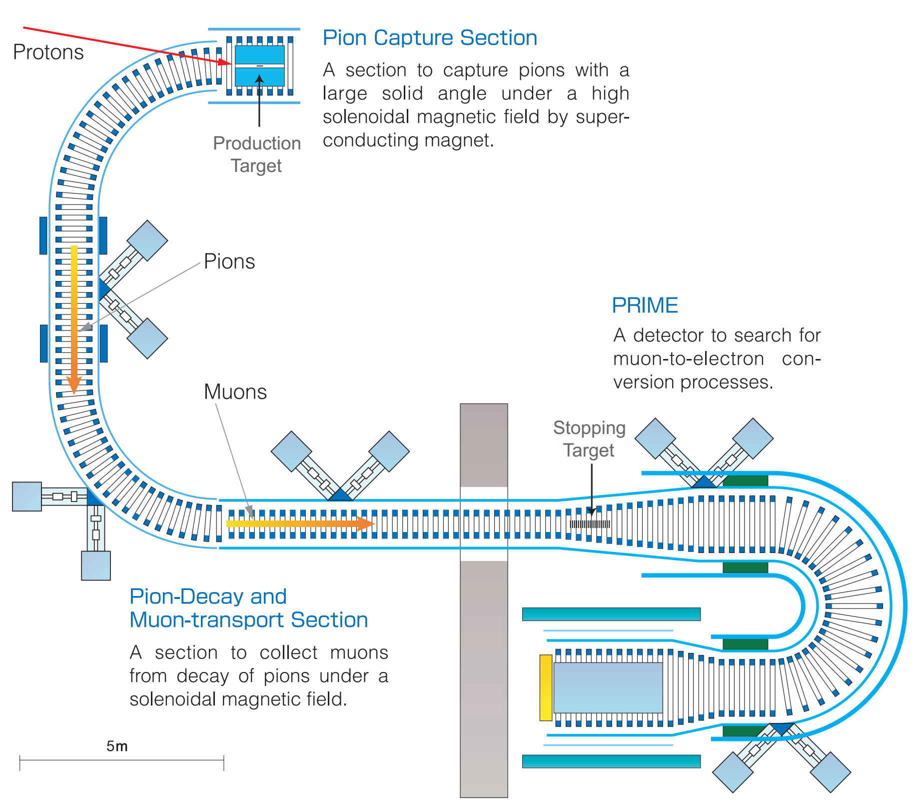


$$B(\mu^- + Al \to e^- + Al) < 10^{-16}$$

- without a muon storage ring.
- with a slowly-extracted pulsed proton beam.
- doable at the J-PARC NP Hall.
- regarded as the first phase / MECO type
- Early realization

Long-term Future Prospect: from COMET to PRISM

COMET



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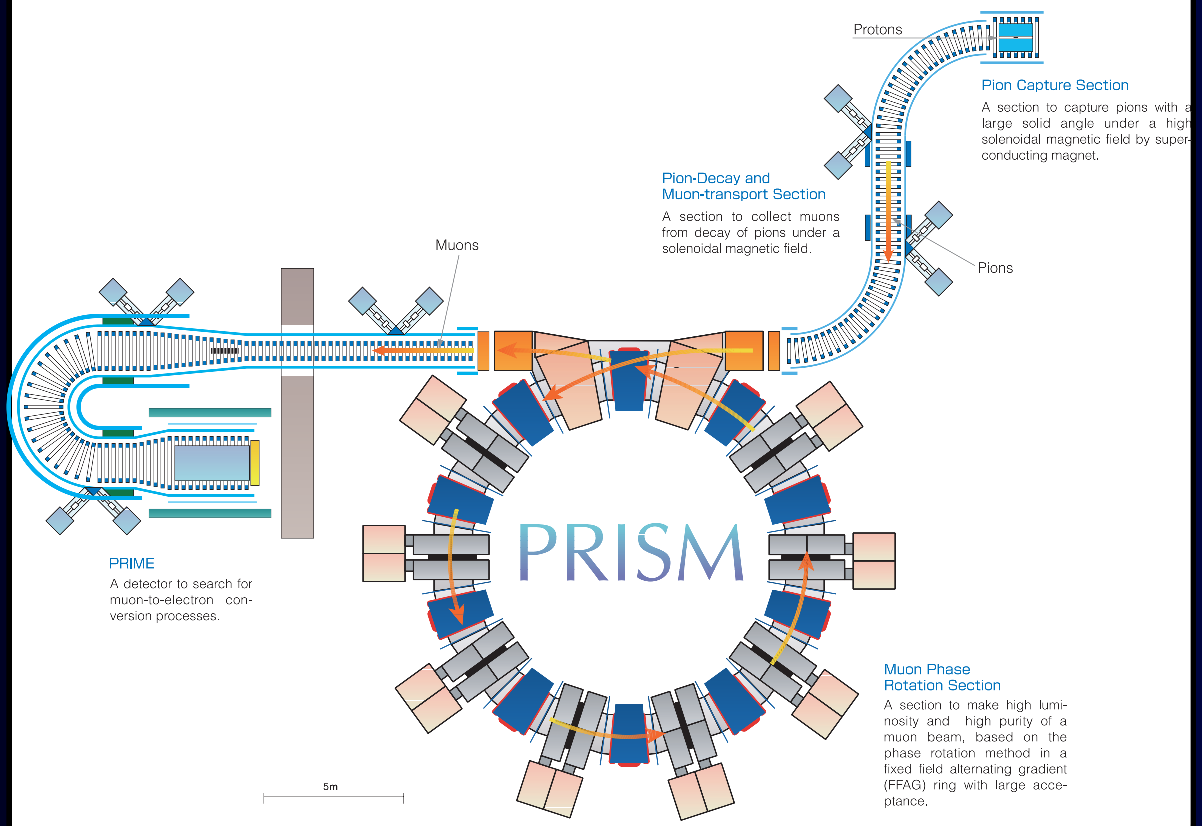
PRISM



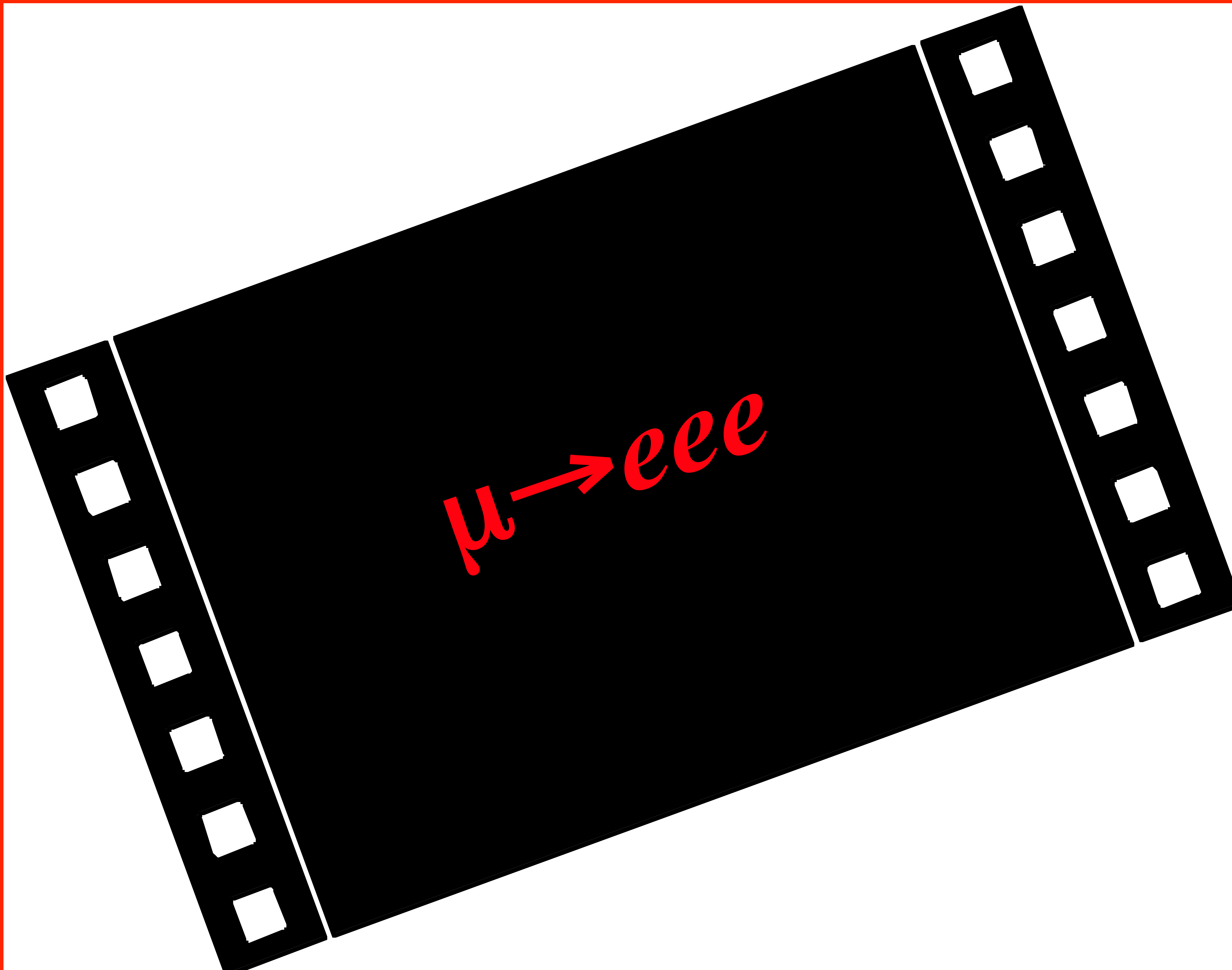
$$B(\mu^- + Ti \rightarrow e^- + Ti) < 10^{-18}$$

- with a muon storage ring.
- with a fast-extracted pulsed proton beam.
- need a new beamline and experimental hall.
- regarded as the second phase.
- Ultimate search

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

demonstration of phase rotation has been done.

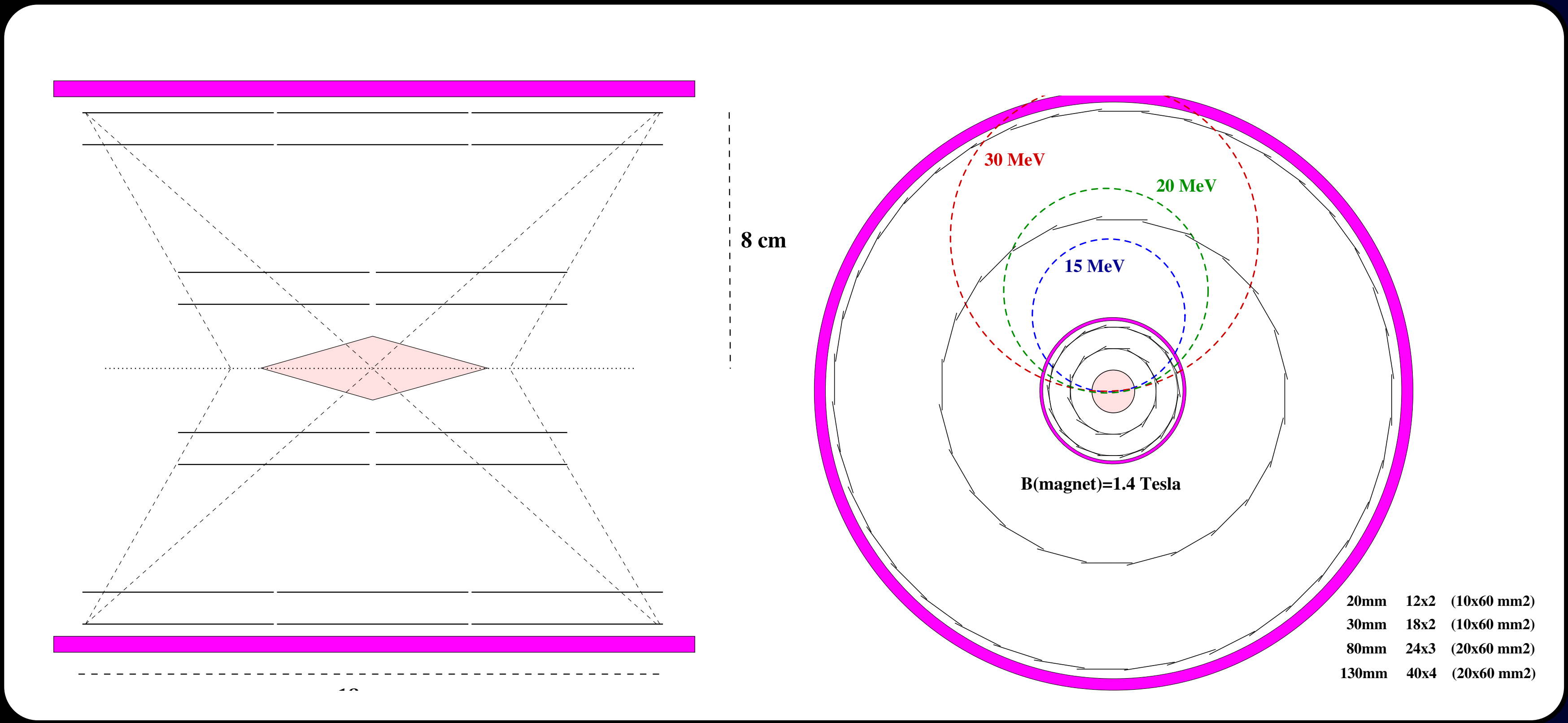
Other CLFV Processes

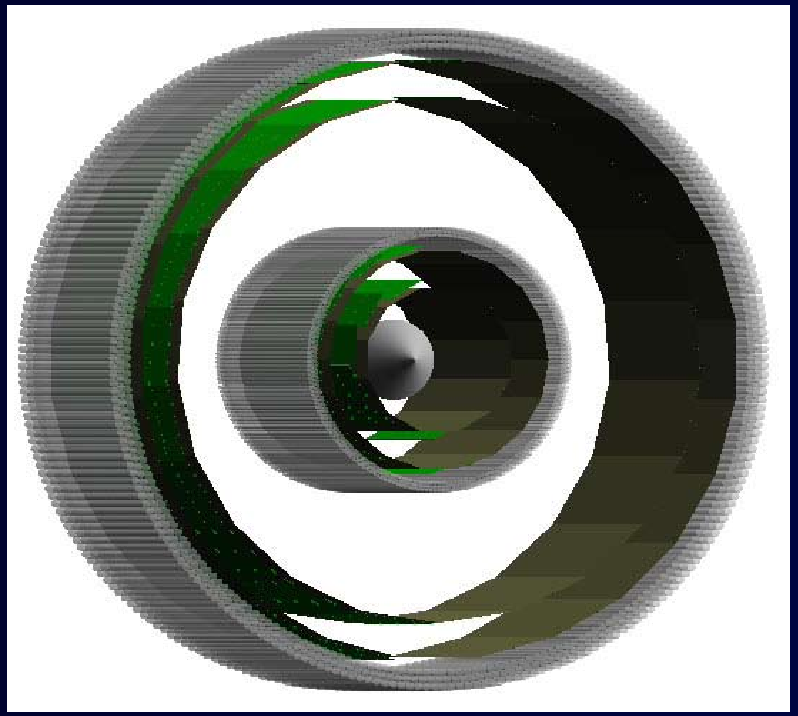

μ→eee

Proposed Search for μ→eee (Br<10^{-16}) at PSI

New Proposal from Univ. Heidelberg

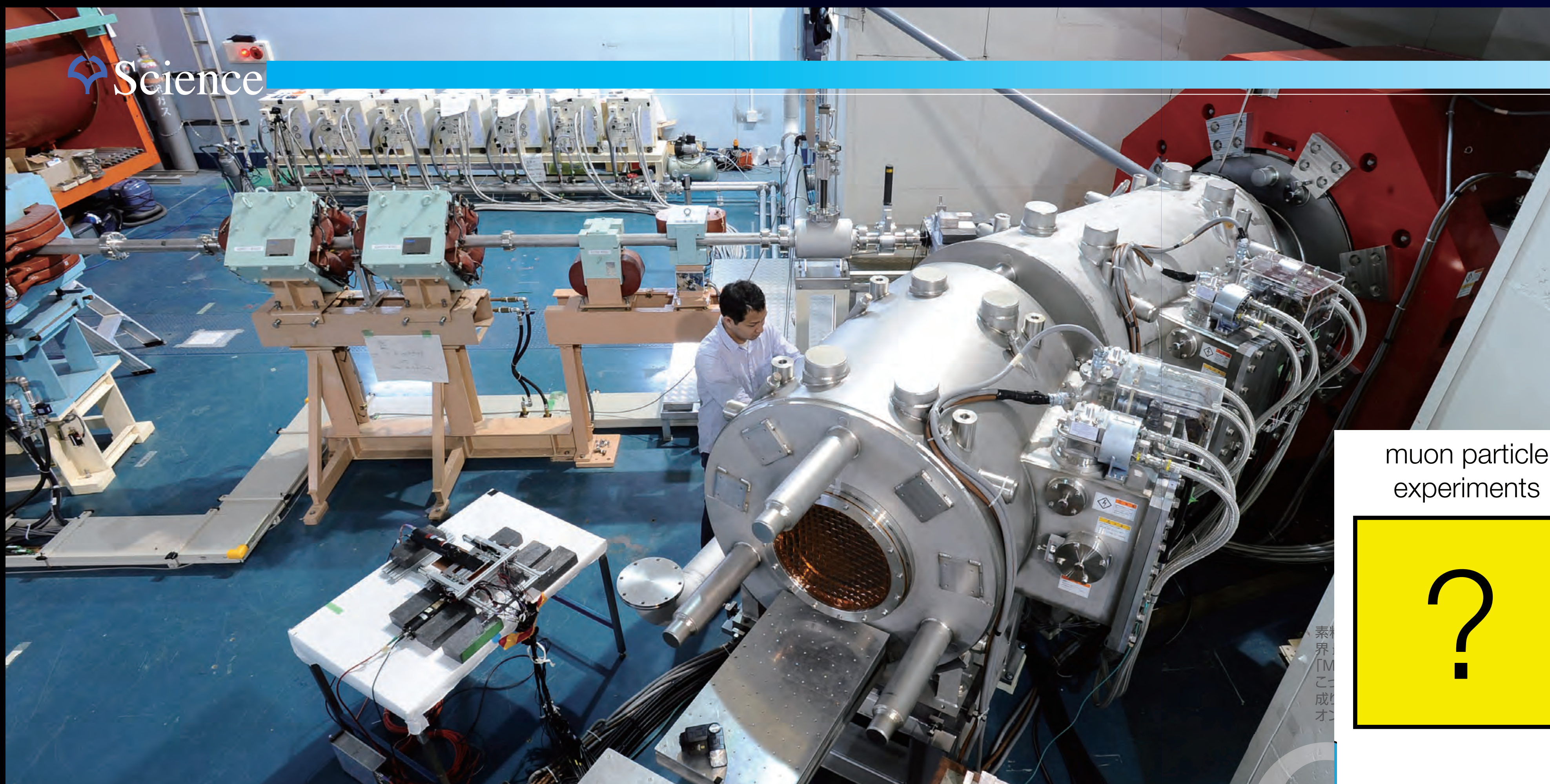
(presented by N, Berger at NuFACT11)

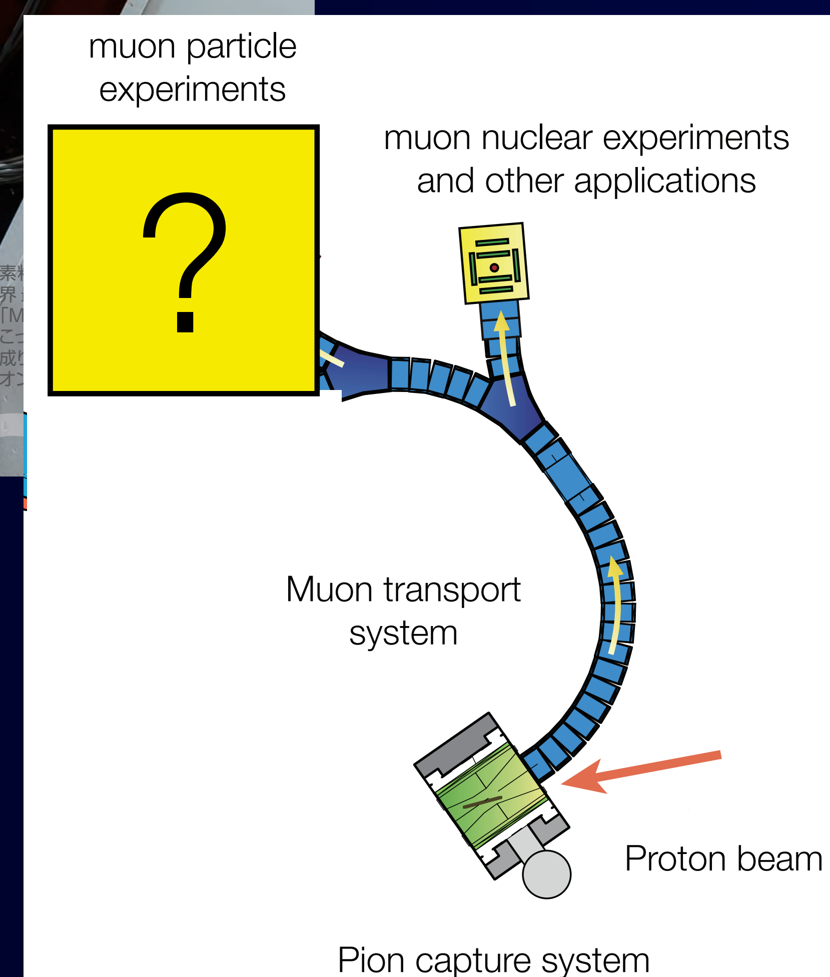




- High resolution silicon pad detectors for tracking and SciFi for timing
- Double-cone shaped target
- Small size detector
- Vertex can be determined by extrapolation of tracks

Search for $\mu \rightarrow eee$ ($Br<10^{-16}$) at MuSIC, Osaka

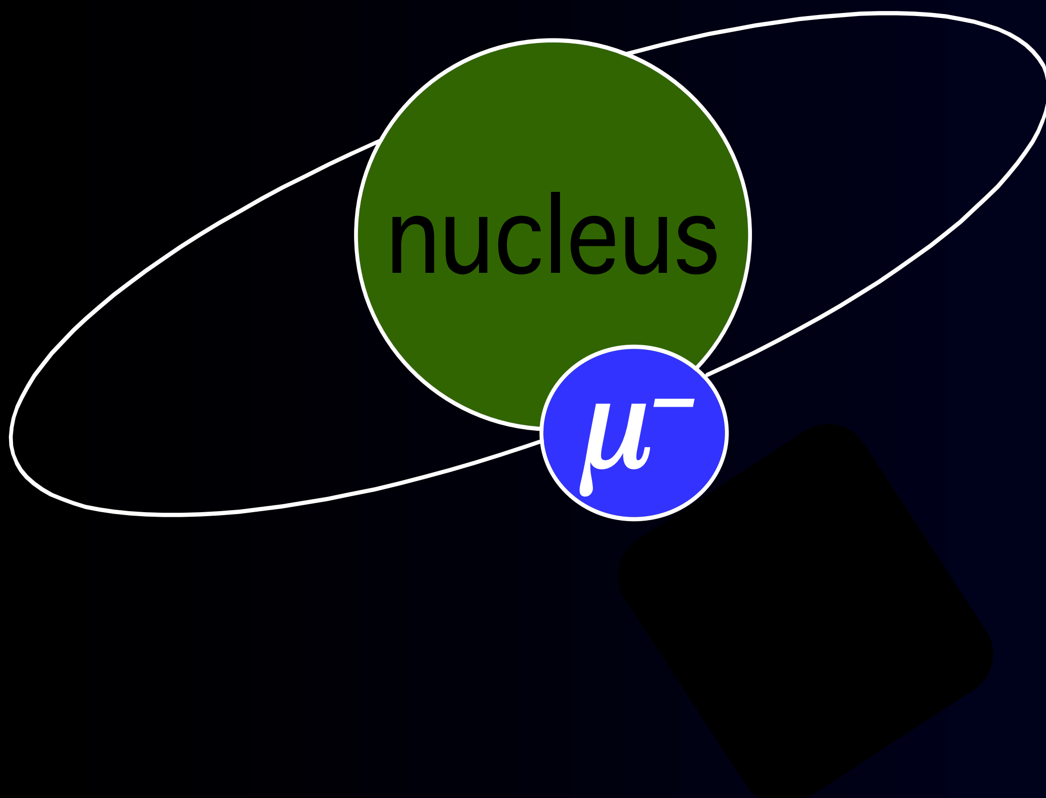




- extended target
- vertex measurements
- reduction of local det. rates
- budget request being processed.

Search for $\mu^- + e^- \rightarrow e^- + e^-$ in a muonic atom

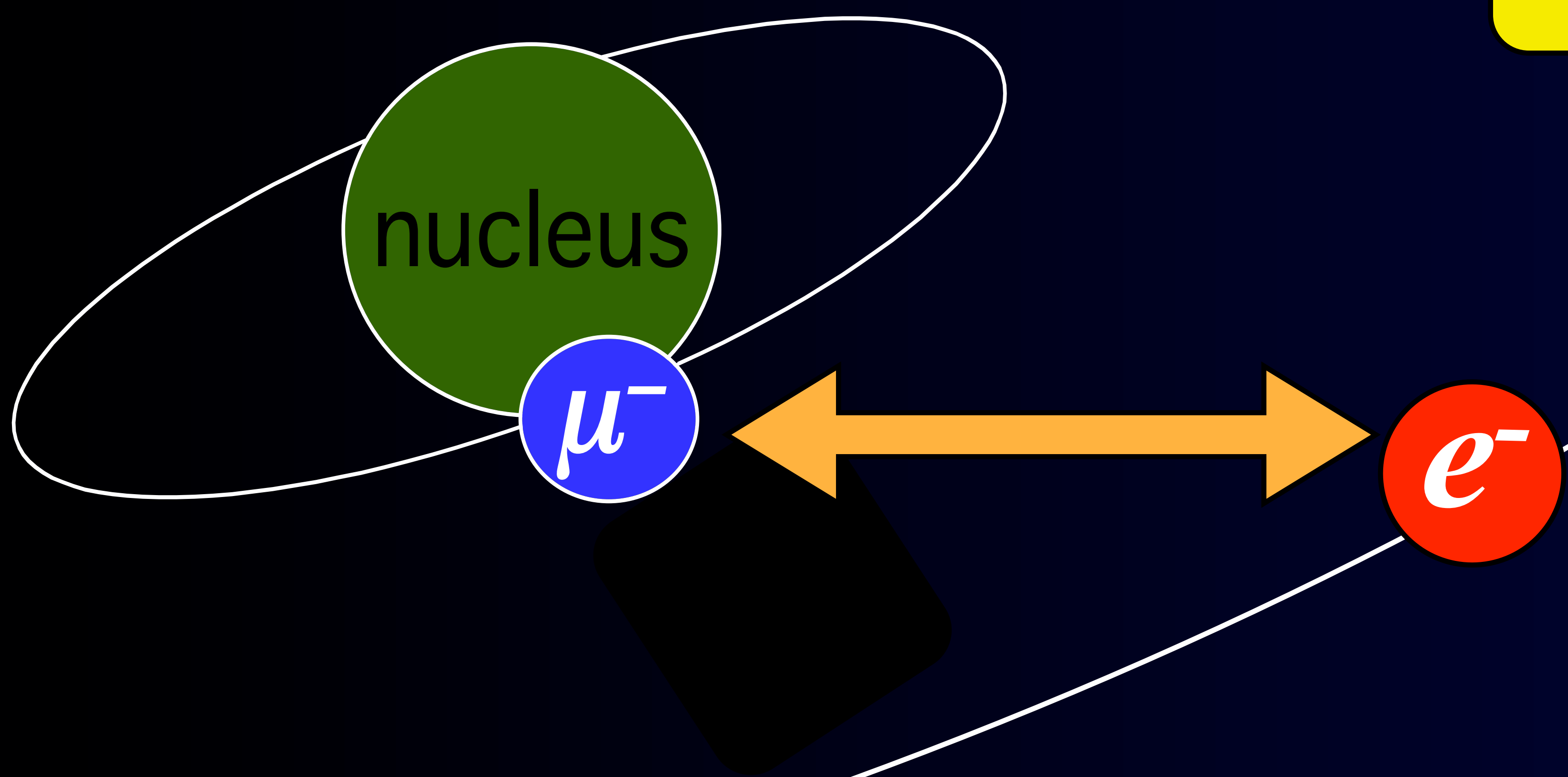
1s state in a muonic atom



Search for $\mu^- + e^- \rightarrow e^- + e^-$ in a muonic atom

1s state in a muonic atom

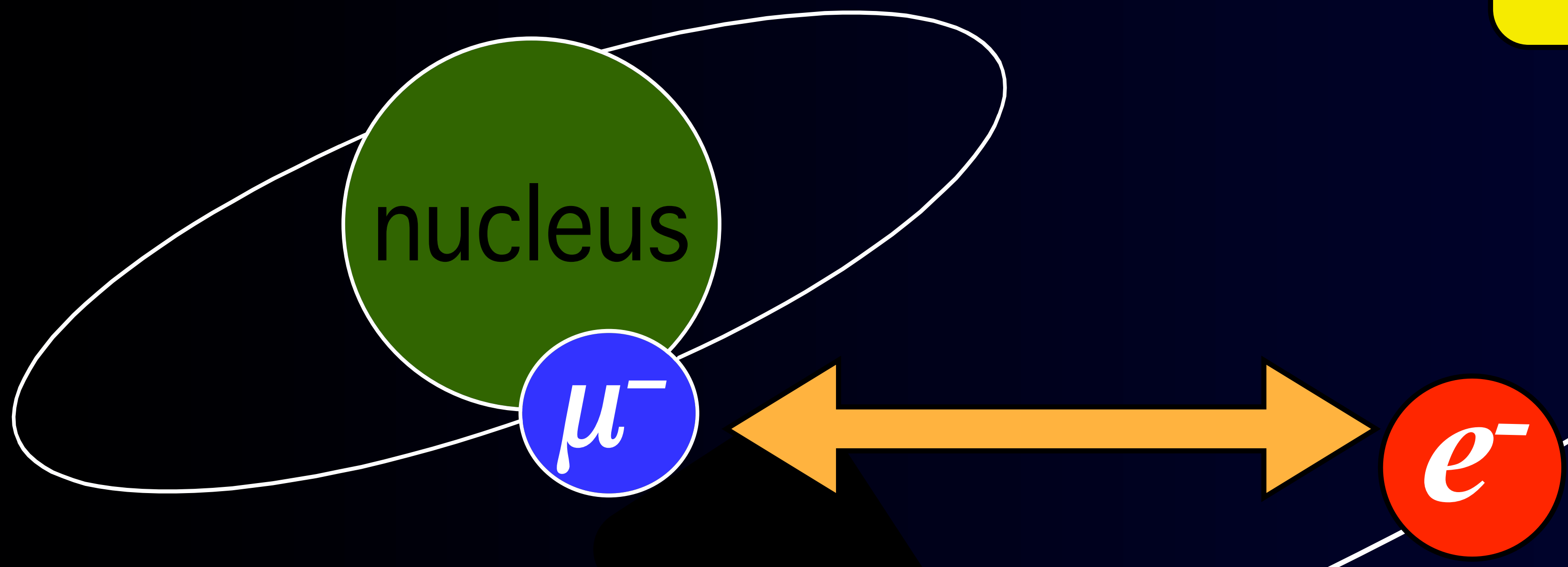
$$\mu^- + e^- \rightarrow e^- + e^-$$



Search for $\mu^- + e^- \rightarrow e^- + e^-$ in a muonic atom

1s state in a muonic atom

$$\mu^- + e^- \rightarrow e^- + e^-$$



The overwrap between μ^- and e^- is proportional to Z^3.

The rate is 10^{-17} to 10^{-18}.

ex. Z=82 (Pb), the overwrap increases by a factor of 5×10^5.over the muonium.

M. Koike, M. Yamanaka, Y. Kuno and J. Sato, Phys. Rev. Lett. 105 (2010) 121601

Summary

Summary

- CLFV would give the best opportunity to search for new physics beyond the SM.
- CLFV has strong relations to neutrino physics, and in particular to DBD.
- Various muon CLFV processes should be pursued to uncover physics behind.
- COMET@J-PARC and Mu2e@FNAL are aiming at S.E. sensitivity of $3\text{x}10^{-17}$.
- R&D on PRISM/PRIME for S.E. sensitivity of $3\text{x}10^{-19}$, is on-going.
- MuSIC project at Osaka University produces 10^{8} muons/s with 400 W proton beam, and $\mu \to eee$ can be considered.
- Discovery potential for CLFV is strong!