Imperial College London

Charged Lepton Flavour Violation

—an introduction—

17 September 2014

TAU2014, Aachen

Yoshi Uchida

Historical Background

Lepton Flavour in the Standard Model

Lepton Flavour Violation and Neutrinos

Model Dependences

The Present Day

1947

10 years after discovery of the muon

having been distinguished from Yukawa's meson (Conversi *et al*)

Nuclear Capture of Mesons and the Meson Decay

B. Pontecorvo
National Research Council, Chalk River Laboratory, Chalk River, Ontario, Canada
June 21, 1947

...Returning to the actual decay of the meson, an experiment suggests itself which might answer the following question: Is the electron emitted by the meson with a mean life of about 2.2 microseconds accompanied by a photon of about 50 Mev? This experiment is being attempted at the present time, since it is felt that the available analysis[10] of the soft component in equilibrium with its primary meson component is probably insufficient to decide definitely whether the meson decays into either an electron plus neutral particle(s) or electron plus photon.

- Weak interaction universality from atomic e and μ-capture
  - discussion of whether muon decay involves "β-decay"s:

$$\mu \to e + \nu \quad \text{(with a single type of neutrino)}$$

1947

Studies of fundamental properties of muon decay

using $O(1000)$ cosmic events

decay into how many particles, and which ones

Search for Gamma-Radiation in the 2.2-Microsecond Meson Decay Process

E. P. HINCKS AND B. PONTECORVO
National Research Council, Chalk River Laboratory, Chalk River, Ontario, Canada
December 9, 1947

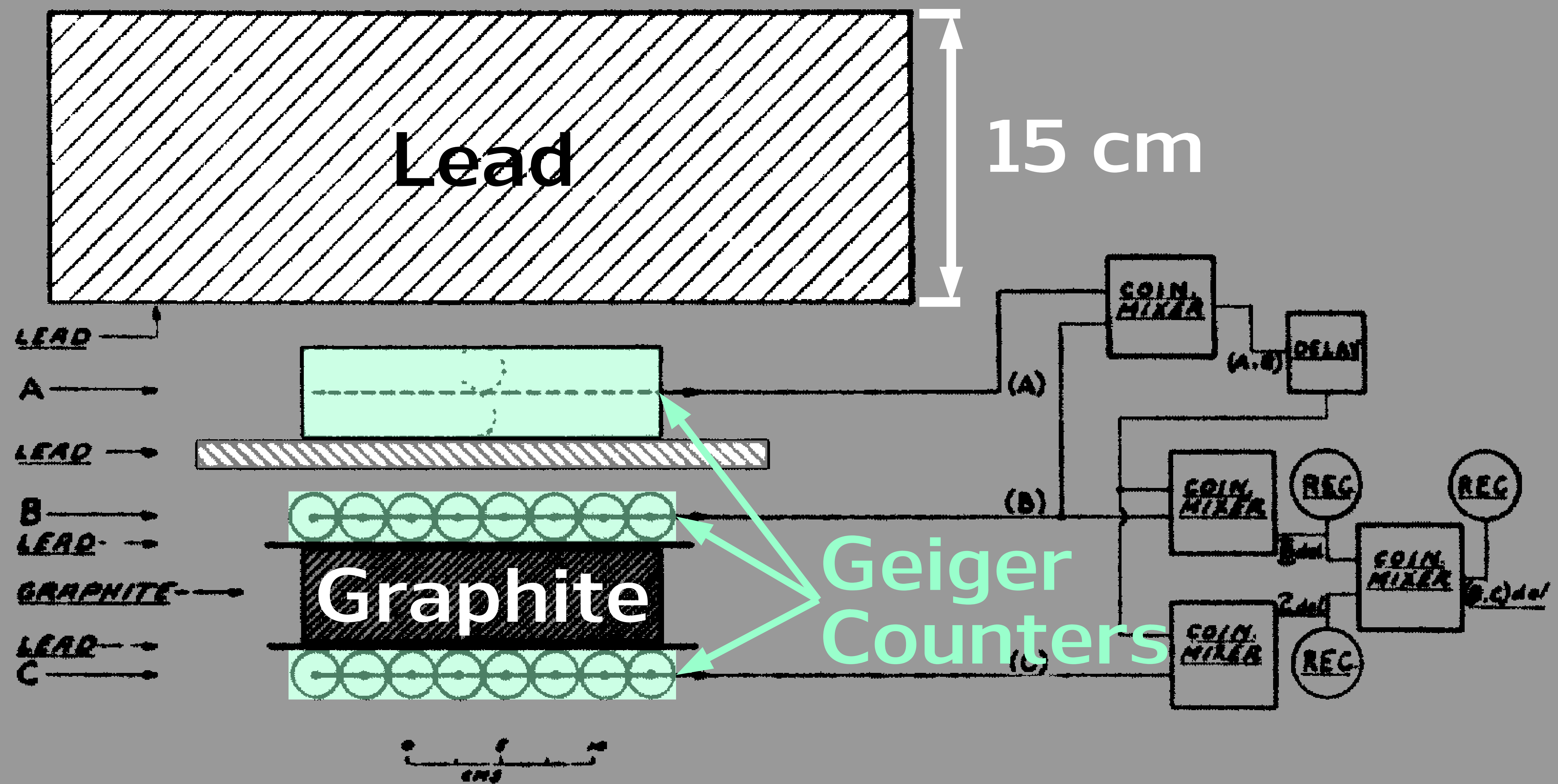
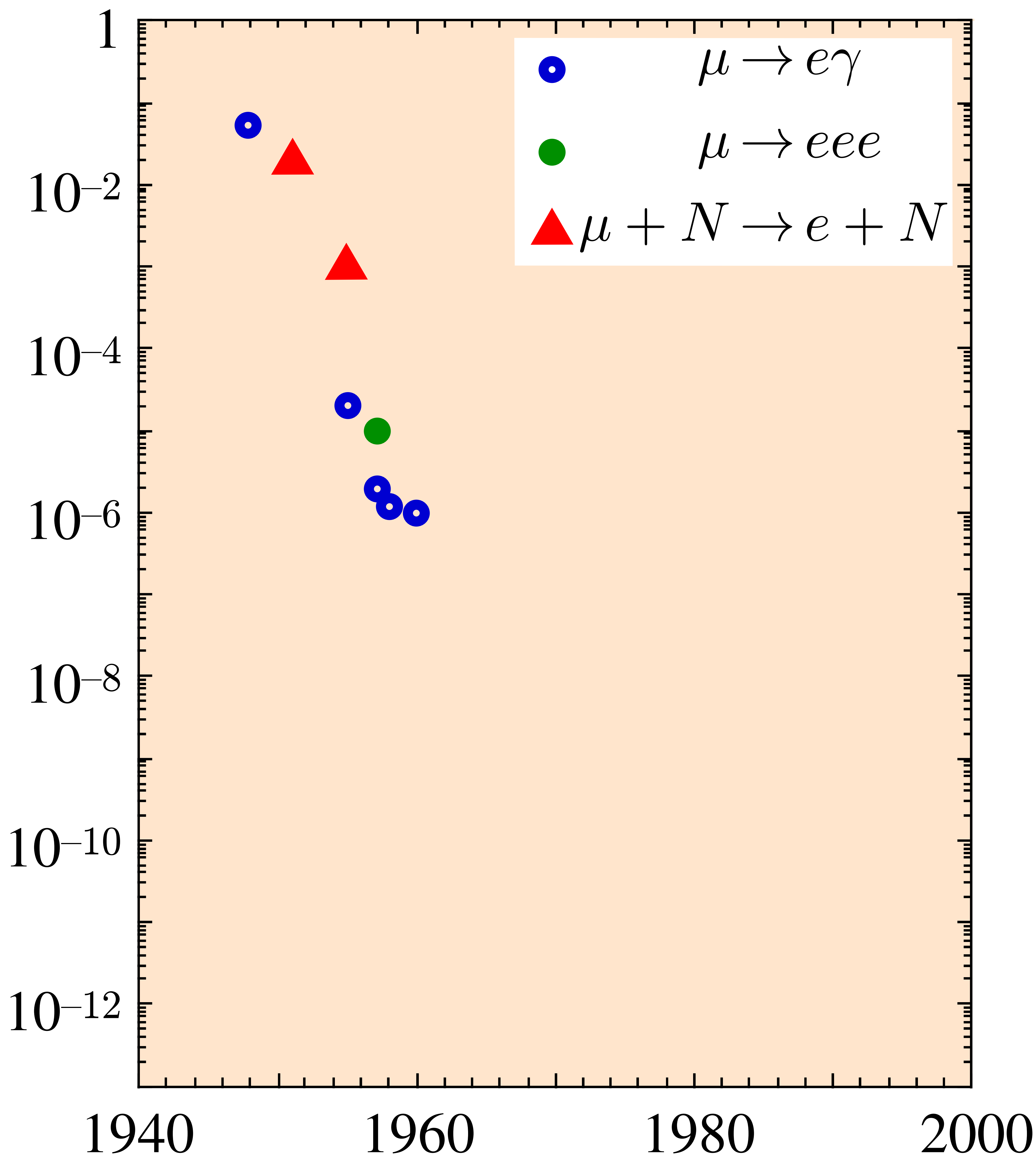


FIGURE 1 - ARRANGEMENT OF APPARATUS

Demonstrated $\mu \to e + \gamma$ is not a major component of μ-decay

Historical Progress on Muon Flavour Violation



90% C.L. upper limits on branching ratios

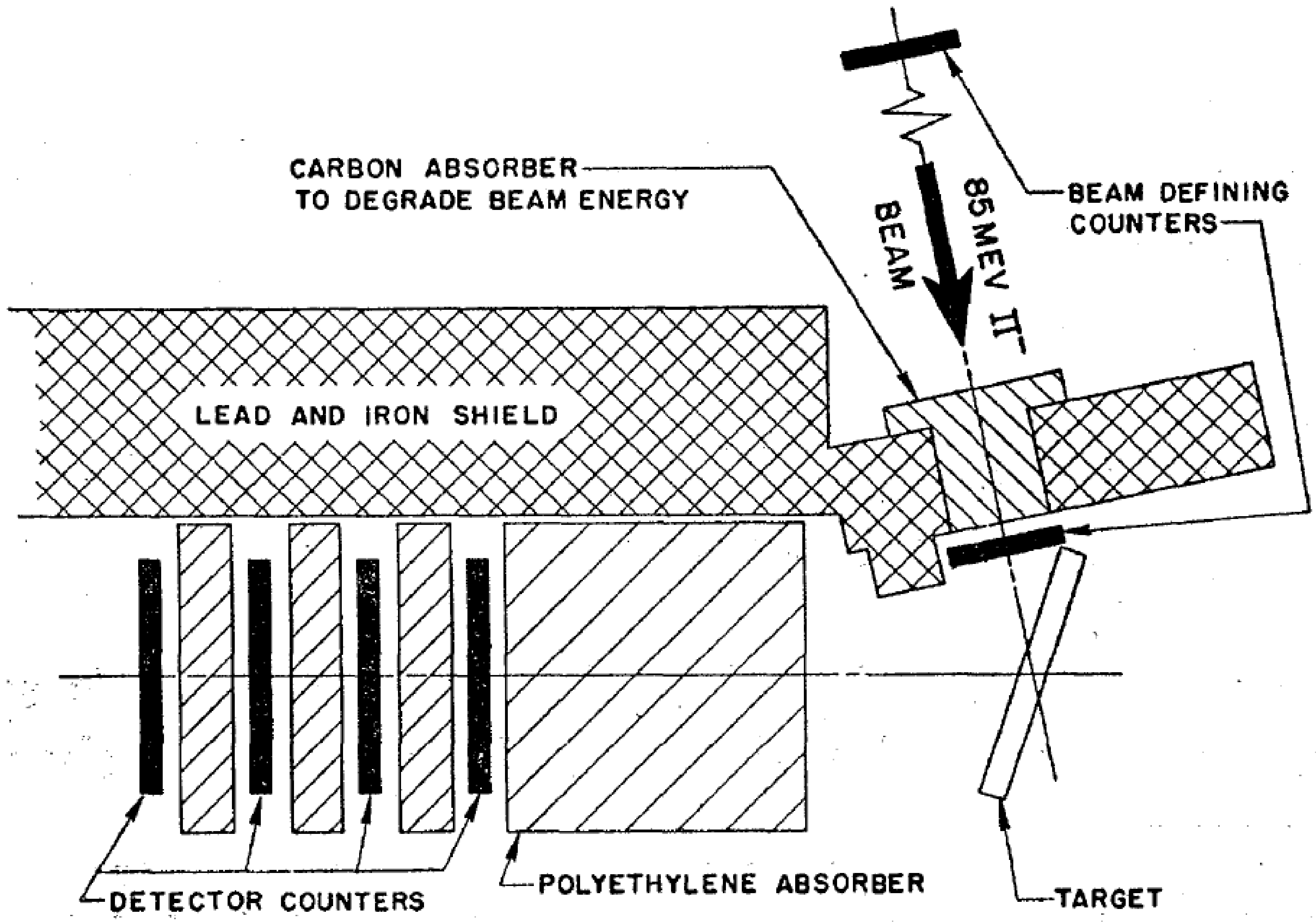
Yoshi.Uchida@imperial.ac.uk

1955

Electrons from Muon Capture*

J. STEINBERGER AND HARRY B. WOLFE
Columbia University, New York, New York
(Received August 31, 1955)

We have searched for the process $\mu^- + p \rightarrow p + e^-$ or $\mu^- + n \rightarrow n + e^-$ for μ mesons stopped in a Cu target. Scintillation counters were employed to detect the electrons from the process. No counts attributable to the electrons were obtained and we place an upper limit of $\sim 5 \times 10^{-4}$ for the relative rate of this process to that for the usual nuclear capture reaction.



1959

ELECTROMAGNETIC TRANSITIONS BETWEEN μ MESON AND ELECTRON*

S. Weinberg†
Columbia University, New York, New York

G. Feinberg‡
Brookhaven National Laboratory, Upton, New York

(Received June 15, 1959)

The existence of the ordinary μ decay, $\mu \to e + \nu + \bar{\nu}$, seems to prove that the muon and electron do not differ in any quantum numbers.[1] It follows that weak electromagnetic transitions between muons and electrons could occur, if there is a mechanism to produce them. For example, one such mechanism would exist if the μ decay was not caused by a direct $\bar{\mu} e \bar{\nu} \nu$ Fermi interaction but instead involved a virtual charged boson. This particular possibility seems ruled out, since the predicted[2] rate for $\mu \to e + \gamma$ would be considerably greater than the upper limit set by recent experiments.[3,4] The purpose of this note is to discuss phenomenologically (without attachment to any specific mechanism) other kinds of electromagnetic transitions between muon and electron that may be possible even if $\mu \to e + \gamma$ is somehow suppressed.

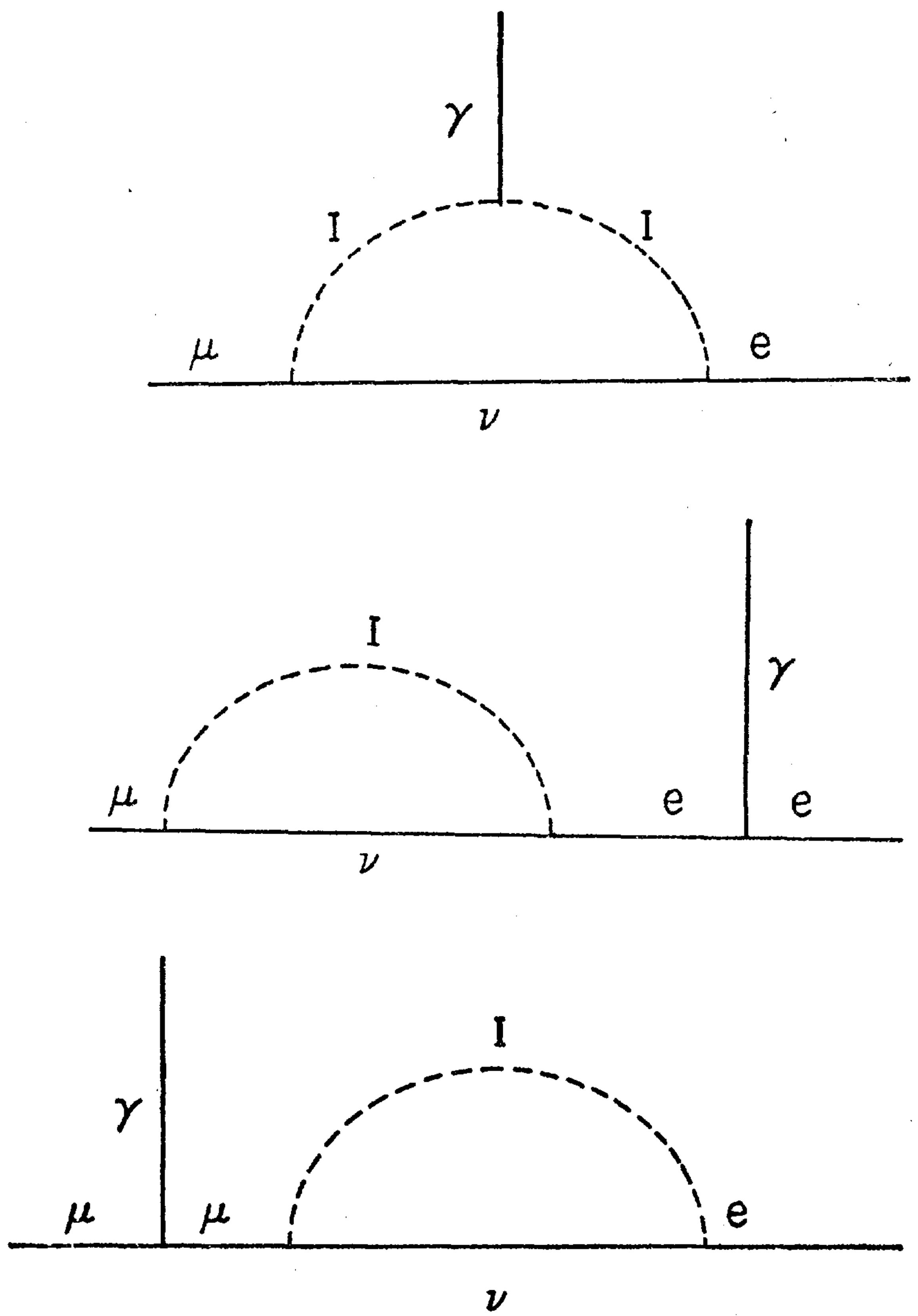
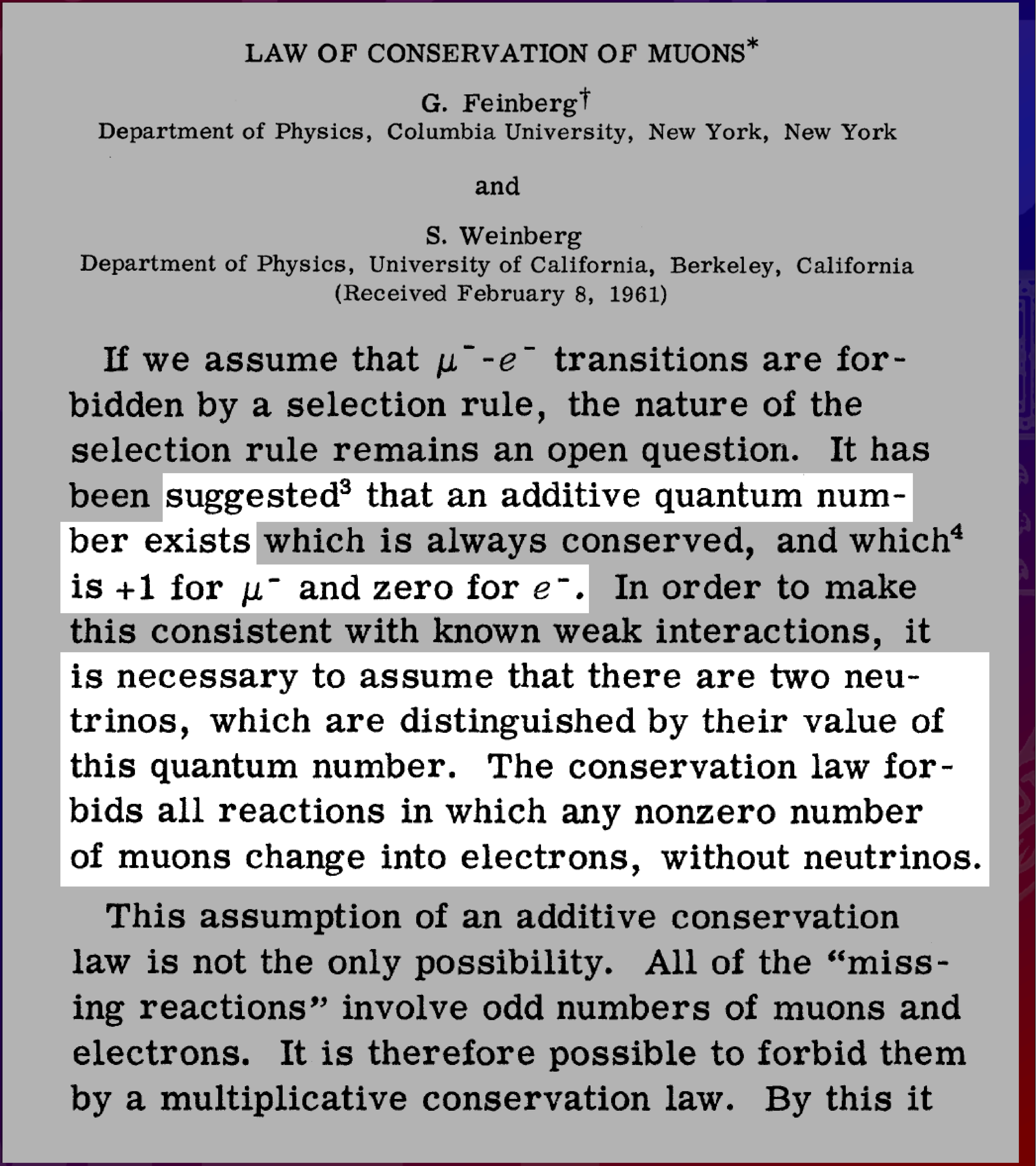


FIG. 1. Feynman diagrams for $\mu \to e + \gamma$ through an intermediate boson. I labels the intermediate boson field.

Feinberg, 1958

1961


LAW OF CONSERVATION OF MUONS*

G. Feinberg†
Department of Physics, Columbia University, New York, New York

and

S. Weinberg
Department of Physics, University of California, Berkeley, California
(Received February 8, 1961)

If we assume that $\mu^- - e^-$ transitions are forbidden by a selection rule, the nature of the selection rule remains an open question. It has been suggested[3] that an additive quantum number exists which is always conserved, and which[4] is +1 for μ^- and zero for e^-. In order to make this consistent with known weak interactions, it is necessary to assume that there are two neutrinos, which are distinguished by their value of this quantum number. The conservation law forbids all reactions in which any nonzero number of muons change into electrons, without neutrinos.

This assumption of an additive conservation law is not the only possibility. All of the "missing reactions" involve odd numbers of muons and electrons. It is therefore possible to forbid them by a multiplicative conservation law. By this it

also Salam, Nishijima, Schwinger and others

Lepton Flavour Conservation to $O(10^{-6})$

- Experimental evidence **accumulated in 1950s**
- **No evidence for** muon decays to an electron and a photon
  - severe constraint on models of the weak interaction
- **New conservation laws**
- Helped force lepton flavour conservation to be written into SM
  - two ($\rightarrow$ three) generations of massless neutrinos

Historical Background

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1955

Conservation of **electric charge:**

a consequence of **gauge invariance** and a massless gauge boson

Gauge invariance cannot explain "heavy particle" number (baryon number, lepton number etc) conservation

Conservation of Heavy Particles and Generalized Gauge Transformations

T. D. LEE, *Columbia University, New York, New York*

AND

C. N. YANG, *Institute for Advanced Study, Princeton, New Jersey*

(Received March 2, 1955)

The possibility of a heavy-particle gauge transformation is discussed.

If we take the conservation of heavy particles to mean invariance under the transformation

$$\psi_N \rightarrow e^{i\alpha}\psi_N, \quad \psi_P \rightarrow e^{i\alpha}\psi_P, \tag{1}$$

Such a gauge transformation is formally completely identical with the electromagnetic gauge transformation. Invariance under such a transformation therefore necessitates the existence of a neutral vector massless field coupled to all heavy particles. A nucleon would have a "heavy-particle charge" of $+\eta$ in such a field and an antinucleon would have a "heavy-particle charge" of $-\eta$. The force between two massive bodies therefore would contain a contribution from the Coulomb-like repulsion between such "heavy-particle charges." The total force including the gravitational attraction is:

$$\text{Force} = -G(M_1M_2/R^2) + \eta^2(A_1A_2/R^2). \tag{2}$$

Here M_1, M_2, A_1, and A_2 are the inertia masses and mass numbers of the two bodies.

Lepton Flavour Conservation in the Standard Model

- In the Standard Model:
  - Lepton flavour is conserved absolutely
    - not by “principle”, but through its structure
- Deviations from the SM can introduce Lepton Flavour Violation

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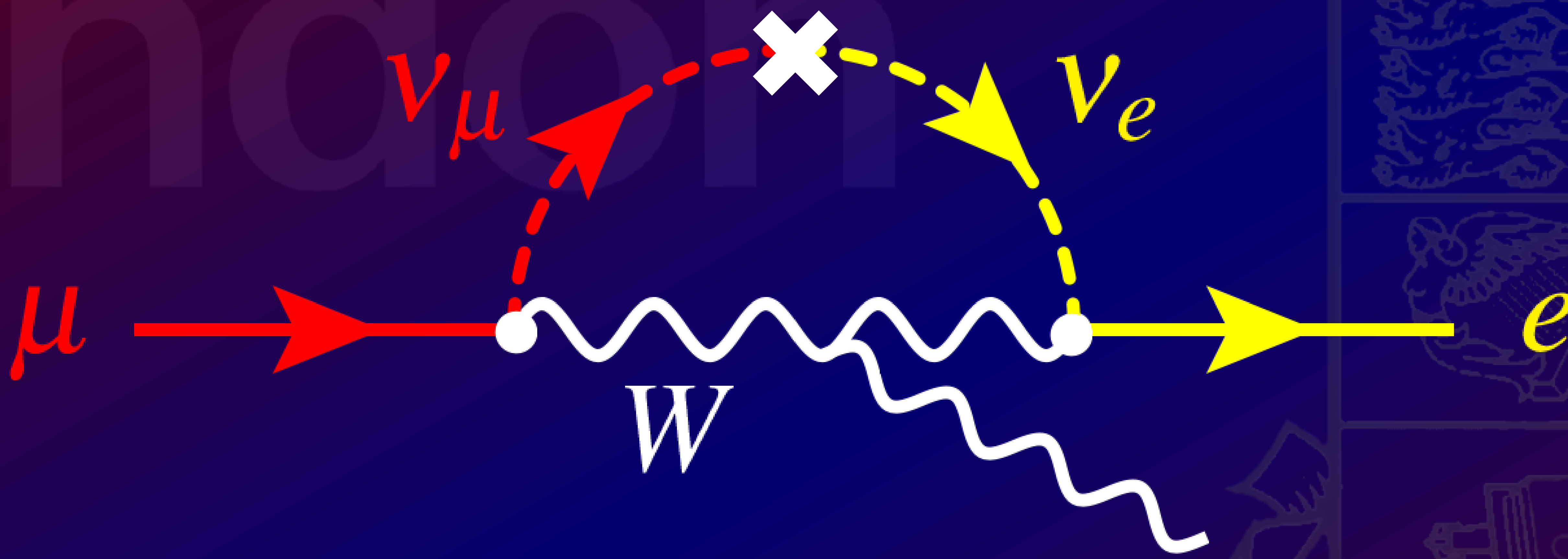
Charged Lepton Flavour Violation

- Beyond-the-Standard Model Physics can cause CLFV
  - e.g. massive neutrinos

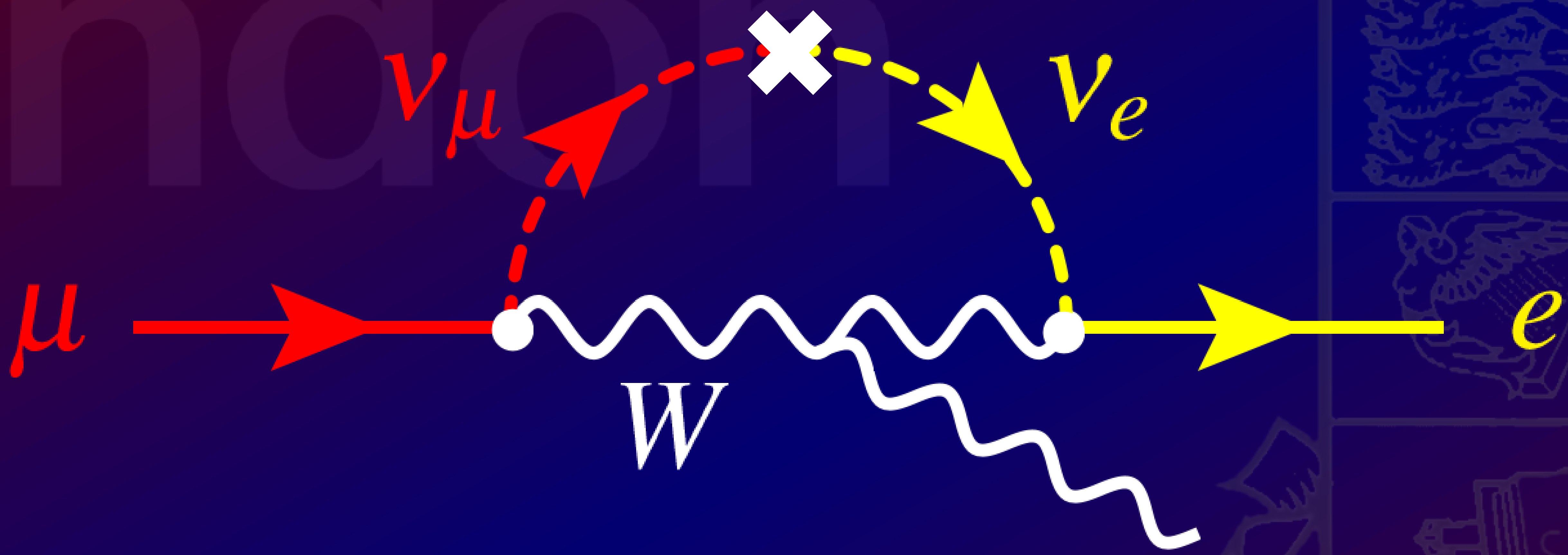


  - but this is ***GIM-suppressed:***

$$B(\mu \to e + \gamma) = \frac{3\alpha}{32\pi} \left| \sum_\ell V^*_{\mu\ell} V_{e\ell} \frac{\Delta m^2_{\nu_\ell}}{m^2_W} \right|^2$$

Charged Lepton Flavour Violation

- Beyond-the-Standard Model Physics can cause CLFV
  - e.g. **introduction of non-zero neutrino mass**



- but this is ***GIM-suppressed:***

$$B(\mu \to e + \gamma) \sim 10^{-54} \times \frac{\sin^2 2\theta_{13}}{0.15}$$

Charged Lepton Flavour Violation

- Beyond-the-Standard Model Physics can cause CLFV
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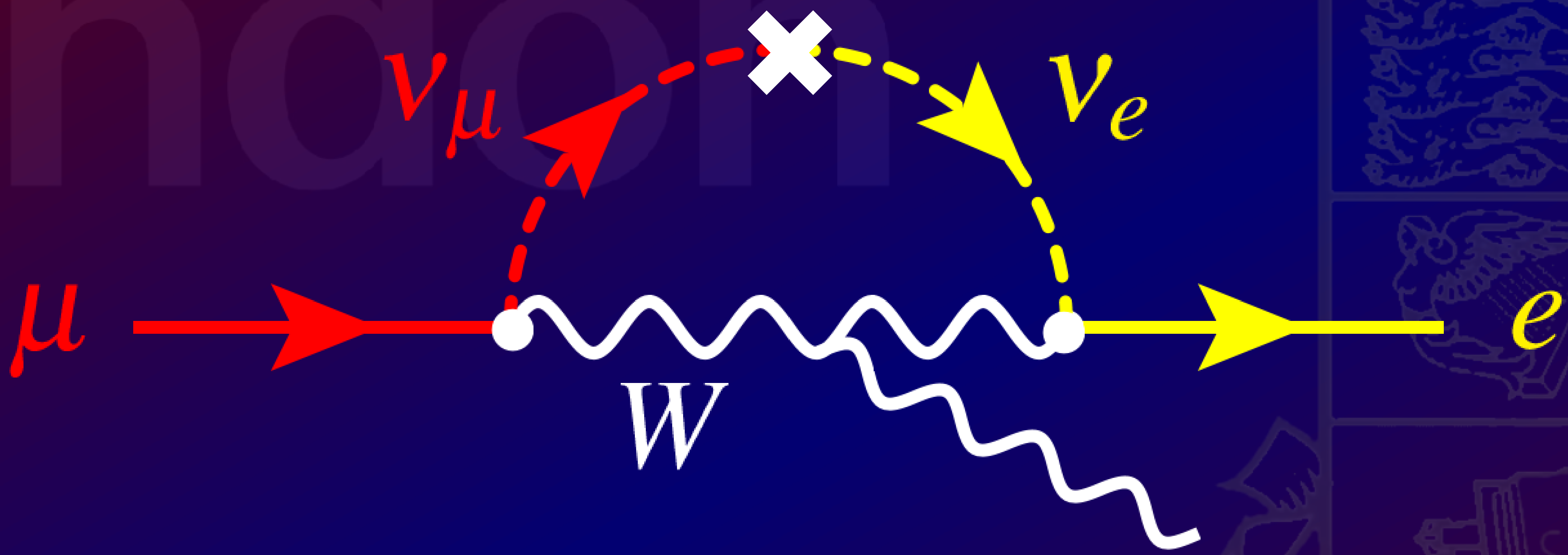


- but this is ***GIM-suppressed:***

$$B(\mu \to e + \gamma) \sim 10^{-54} \quad \left(\sim \frac{m_\mu}{30 m_\oplus}\right)$$

- if CLFV seen, ***unambiguous signal*** **for new physics (going beyond Dirac $m_\nu > 0$)**
  - no theoretical background uncertainties

Charged Lepton Flavour Violation

- Forbidden entirely in SM
- **BSM** Physics can give rise to CLFV
  - e.g. massive neutrinos
    - but CLFV GIM-suppressed to less than $O(10^{-50})$
    - background-free for further new physics
    - Majorana or Dirac? Lepton *Number* Violation?
  - **more generally, CLFV rates can be much larger**
  - **highly-sensitive probes to BSM physics**

See talks today

Type-I Seesaw Mechanism

D.N. Dinh, A. Ibarra, E. Molinaro, S.T. Petcov, J. High Energy Phys. 1208 (2012) 125

See talks today

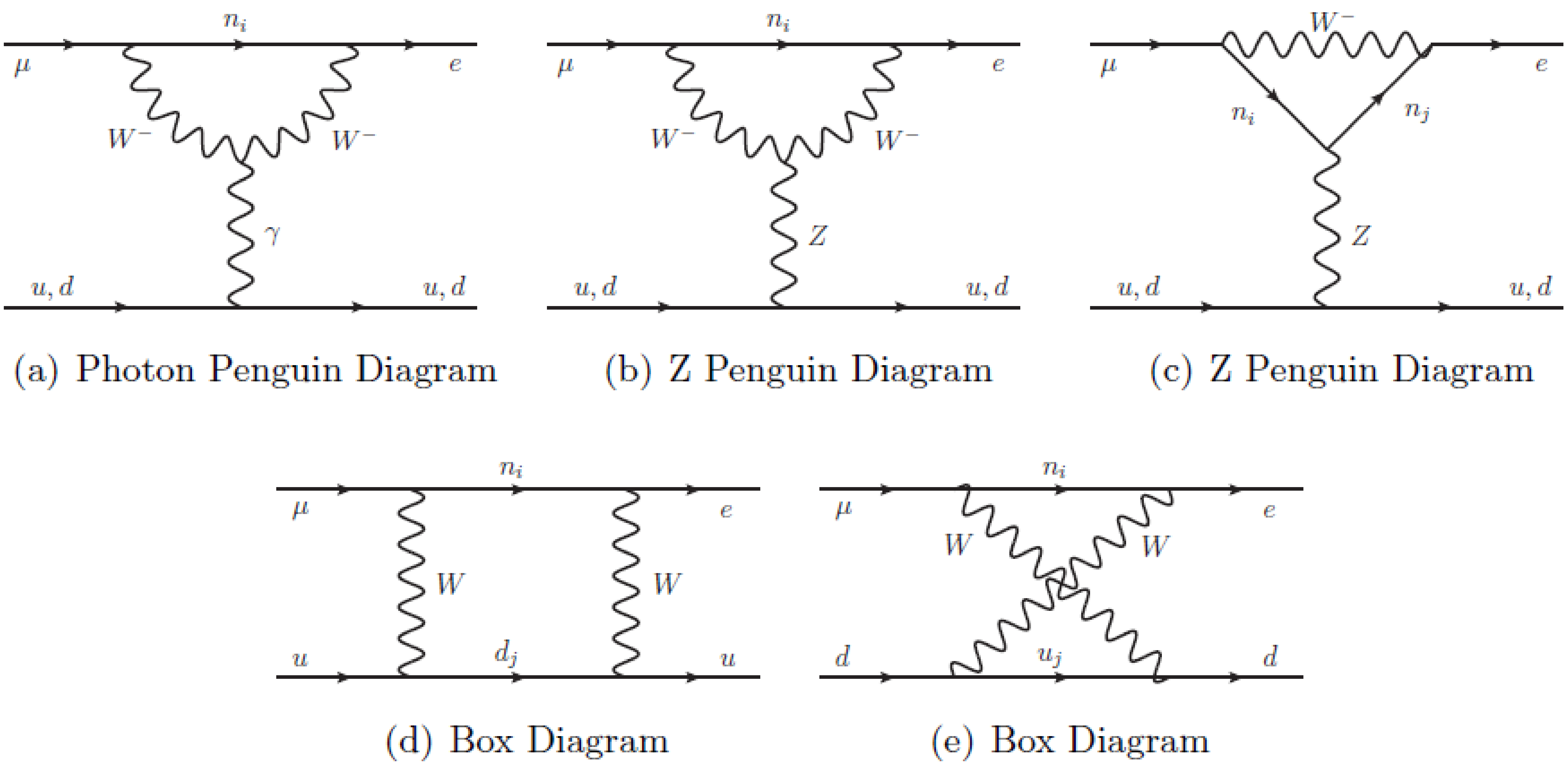
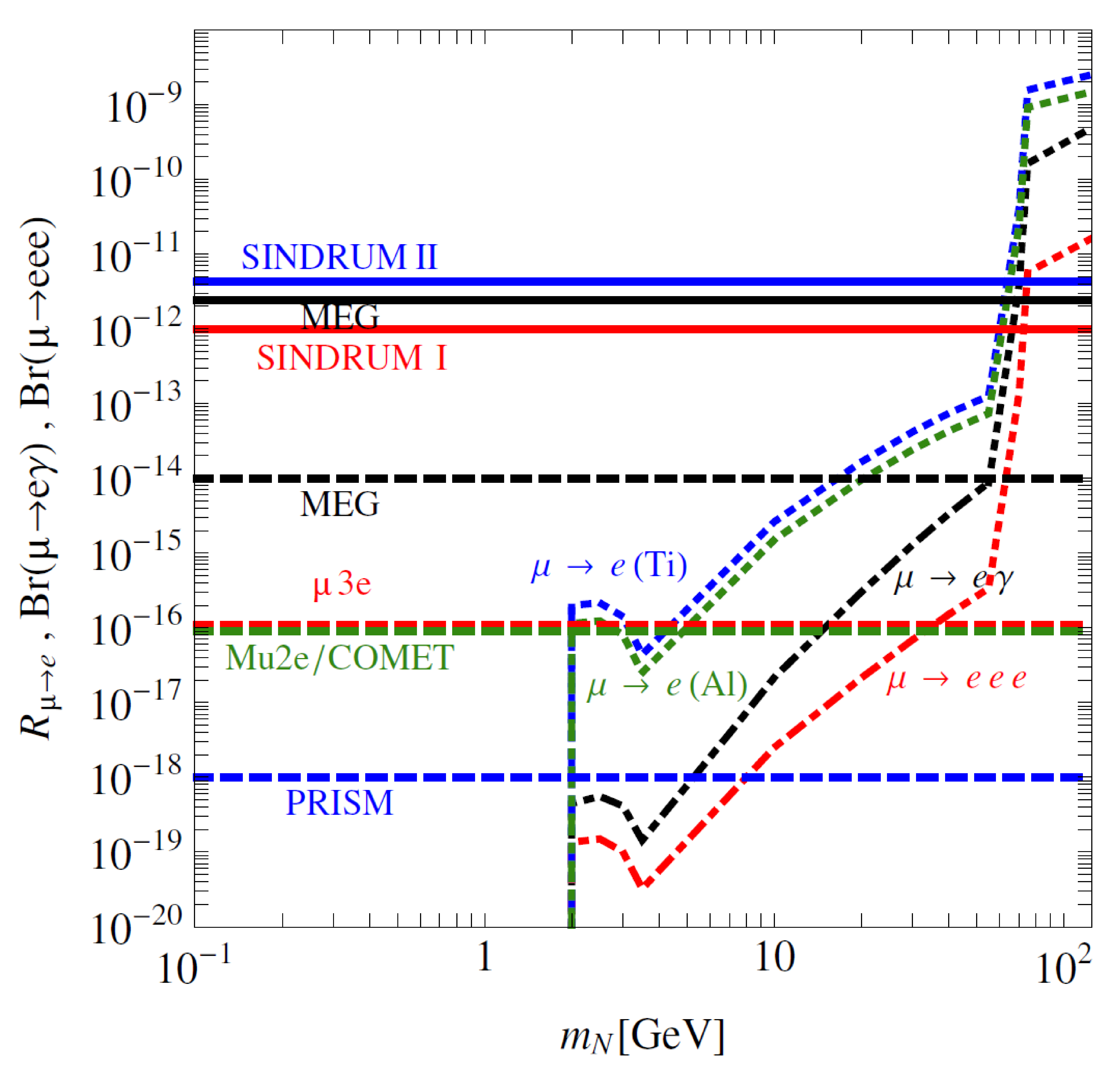


Figure 1. The five classes of diagrams contributing to μ to e conversion in the type-I seesaw model.

Type-I Seesaw Mechanism

D.N. Dinh, A. Ibarra, E. Molinaro, S.T. Petcov, J. High Energy Phys. 1208 (2012) 125



Concrete predictions of ratios between processes, and of absolute rates for given heavy neutrino mass m_N

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Further Beyond the Standard Model

- Many models can give rise to CLFV:
  - Seesaw mechanism
  - Supersymmetric Grand Unified Theories
  - Multiple Higgs doublets
  - Left-right symmetric models
  - Extra dimensions
  - Little Higgs
  - Extra generations of quarks and leptons

See talks today

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Key CLFV Muon Decay Processes

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

MEG at PSI

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

Mu3E at PSI

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

muon-to-electron conversion: **Mu2E** at Fermilab

COMET at J-PARC

See talks today

Muon-to-Electron Conversion

- Search for the process

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

muonic atom — mono-energetic electron ($E_e \leq$ 105 MeV)

- Time available after formation of muonic atom: up to about **1 microsecond (Z-dependent)**

- $E_e = m_\mu - E_{\text{bind}} - E_{\text{recoil}}$

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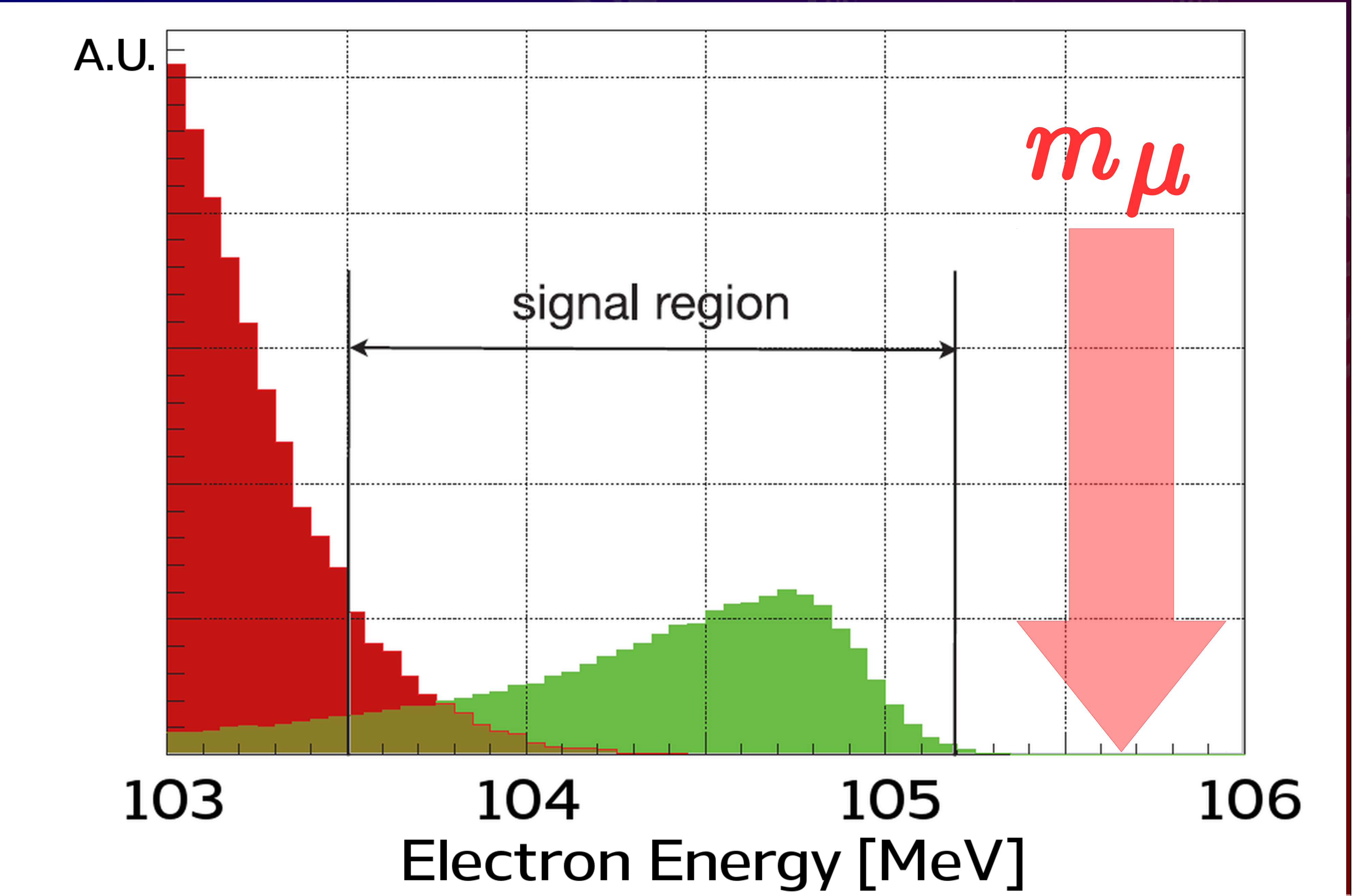
- $E_e = m_\mu - E_{\text{bind}} - E_{\text{recoil}}$
- **observed signal is smeared because** of detector effects



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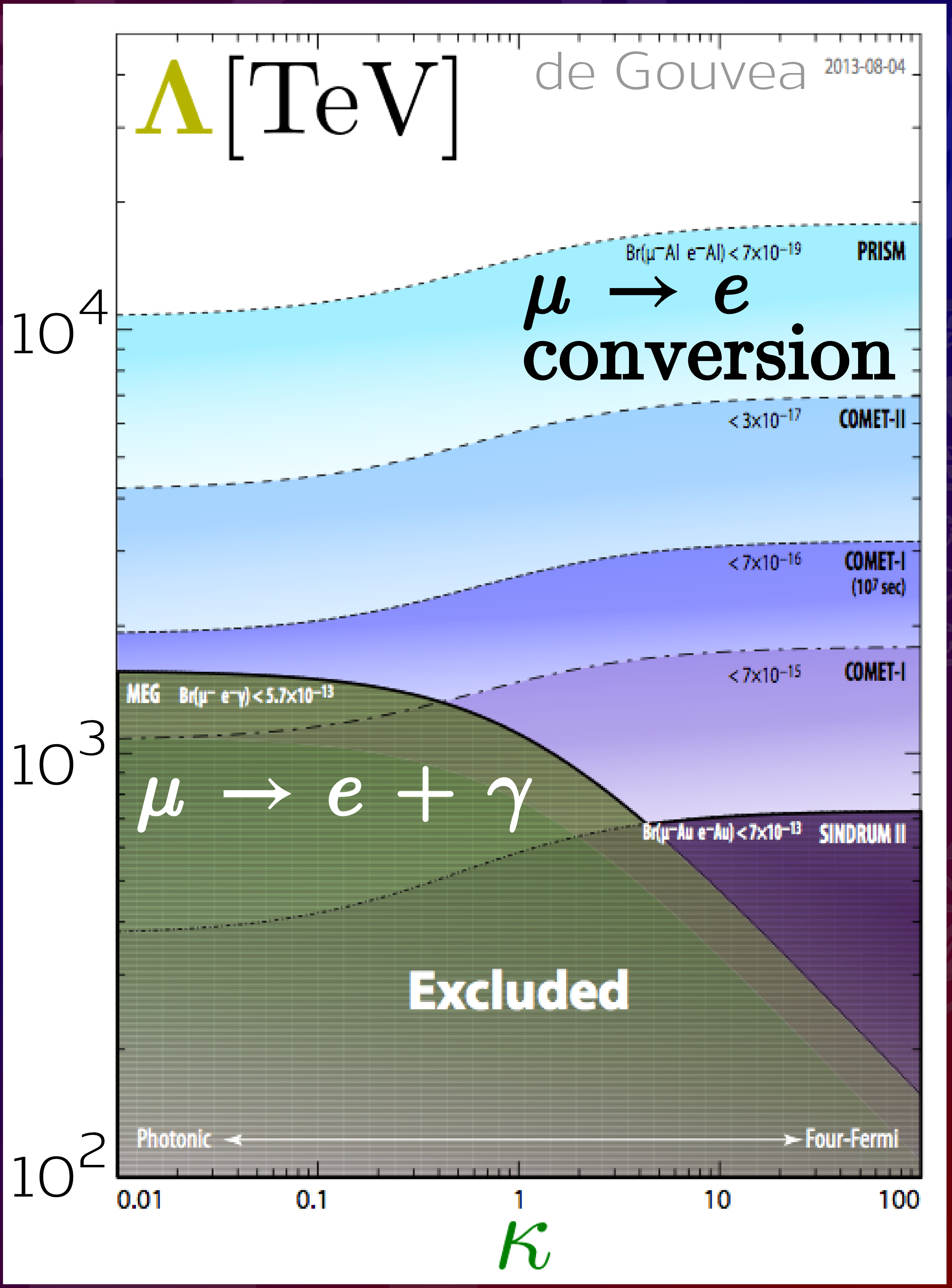
Complementarity Between CLFV Channels

- e.g., **Muon-to-electron conversion** and $\mu \to e + \gamma$
- Sensitive to different BSM physics

$$\mathcal{L} = \frac{1}{1+\kappa}\frac{m_\mu}{\Lambda^2}\bar{\mu}_R\sigma^{\mu\nu}e_L F_{\mu\nu} + \frac{\kappa}{1+\kappa}\frac{1}{\Lambda^2}(\bar{\mu}_L\gamma^\mu e_L)(\bar{q}_L\gamma^\mu q_L)$$

- $\Lambda^4 \propto 1/\mathrm{Br}$



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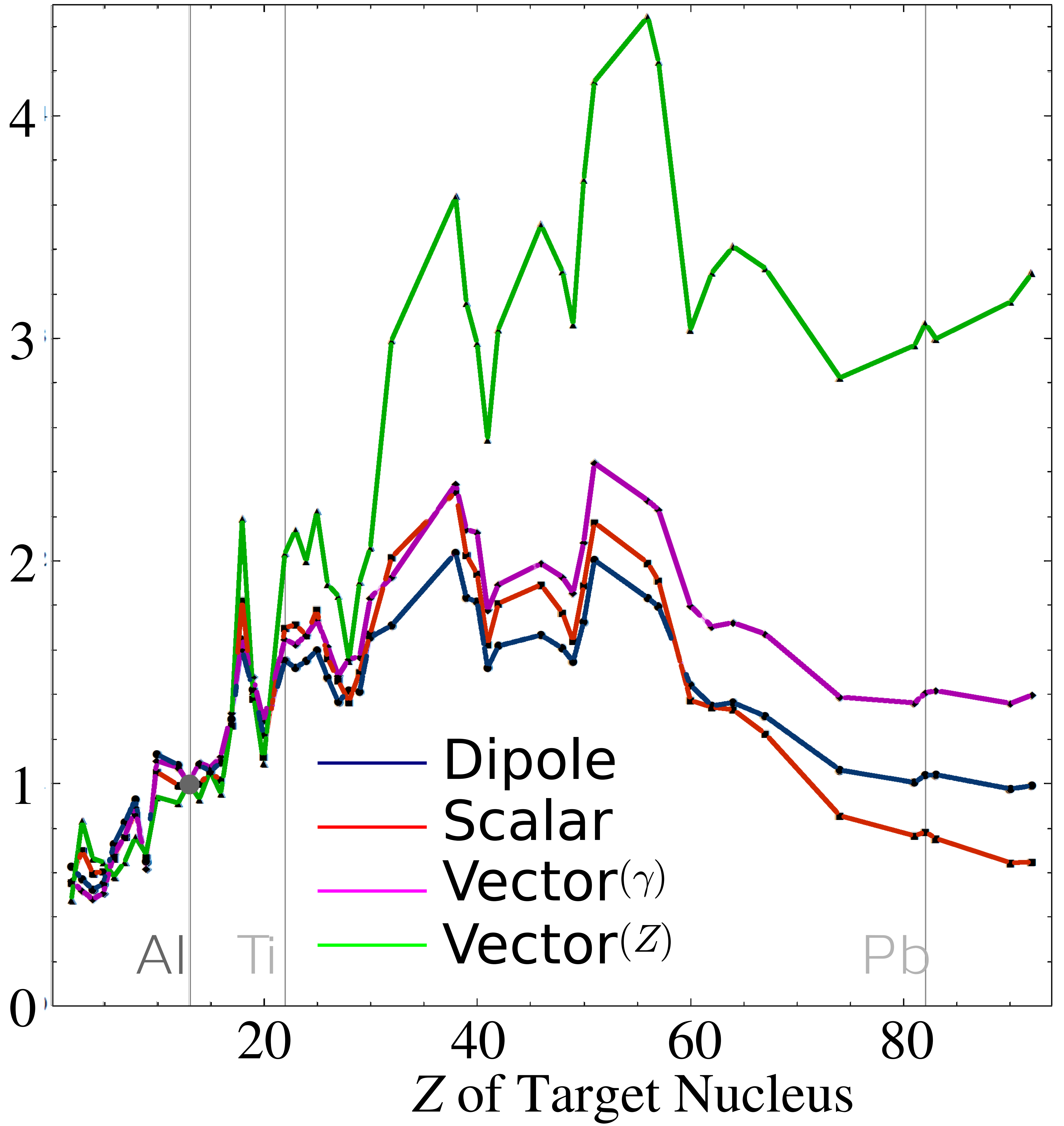
Relative dependences of the muon-to-electron conversion branching ratio on the target nucleus

for different models of New Physics interactions

Cirigliano, Kitano, Okada, and Tuzon, arXiv:0904.0957



Historical Background

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The Present Day

2006

from data taken in 2000 at PSI

A search for $\mu - e$ conversion in muonic gold

The SINDRUM II Collaboration

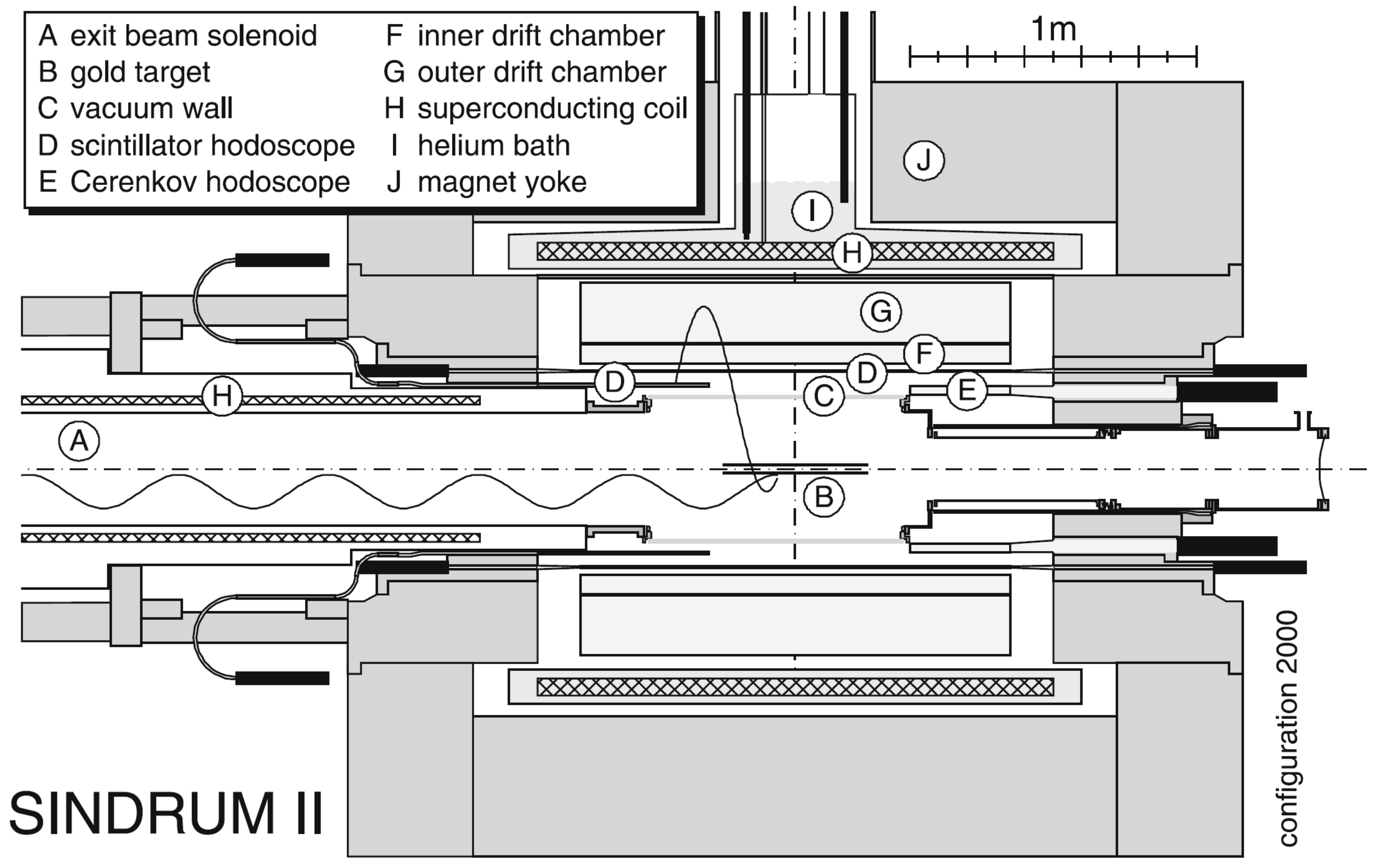
W. Bertl[1], R. Engfer[2], E.A. Hermes[2], G. Kurz[2], T. Kozlowski[3], J. Kuth[4], G. Otter[4], F. Rosenbaum[1], N.M. Ryskulov[1], A. van der Schaaf[2], P. Wintz[4], I. Zychor[3]

[1] Paul Scherrer Institut, Villigen, Switzerland
[2] Physik-Institut der Universität Zürich, Zurich, Switzerland
[3] IPJ Swierk, Swierk, Poland
[4] RWTH Aachen, Aachen, Germany

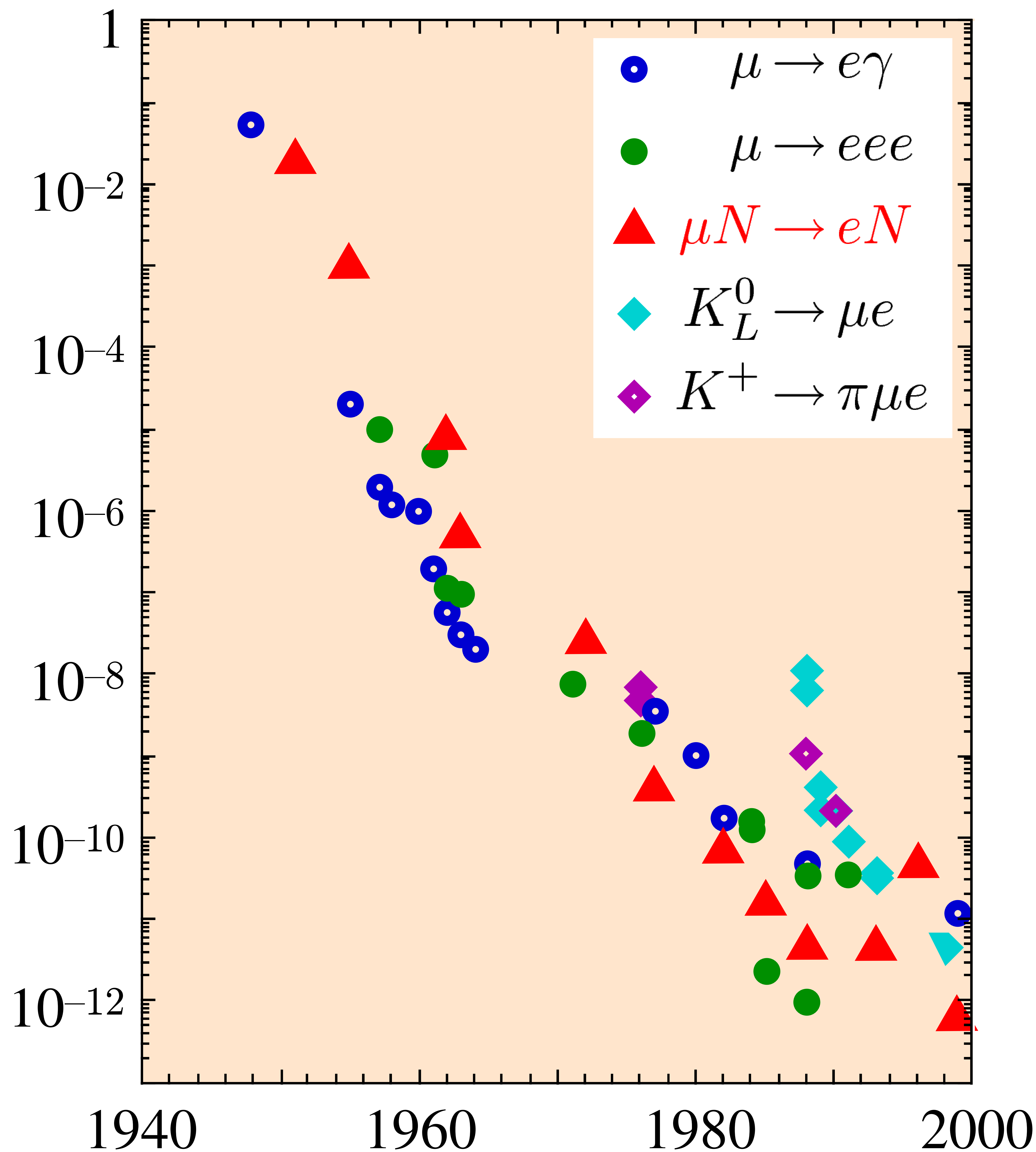
Abstract. We report on a search for $\mu - e$ conversion in muonic gold performed with the SINDRUM II spectrometer at PSI. The measurement resulted in $\Gamma(\mu^- \mathrm{Au} \rightarrow e^- \mathrm{Au}_{g.s.})/\Gamma_{capture}(\mu^- \mathrm{Au}) < 7 \times 10^{-13}$ (90%C.L.).

Current world best limit on μ-to-e conversion: $< 7\times10^{-13}$ (on Gold)

SINDRUM had a rich programme of CLFV measurements



Historical Progress on Muon Flavour Violation



90% C.L.
upper limits on
branching ratios

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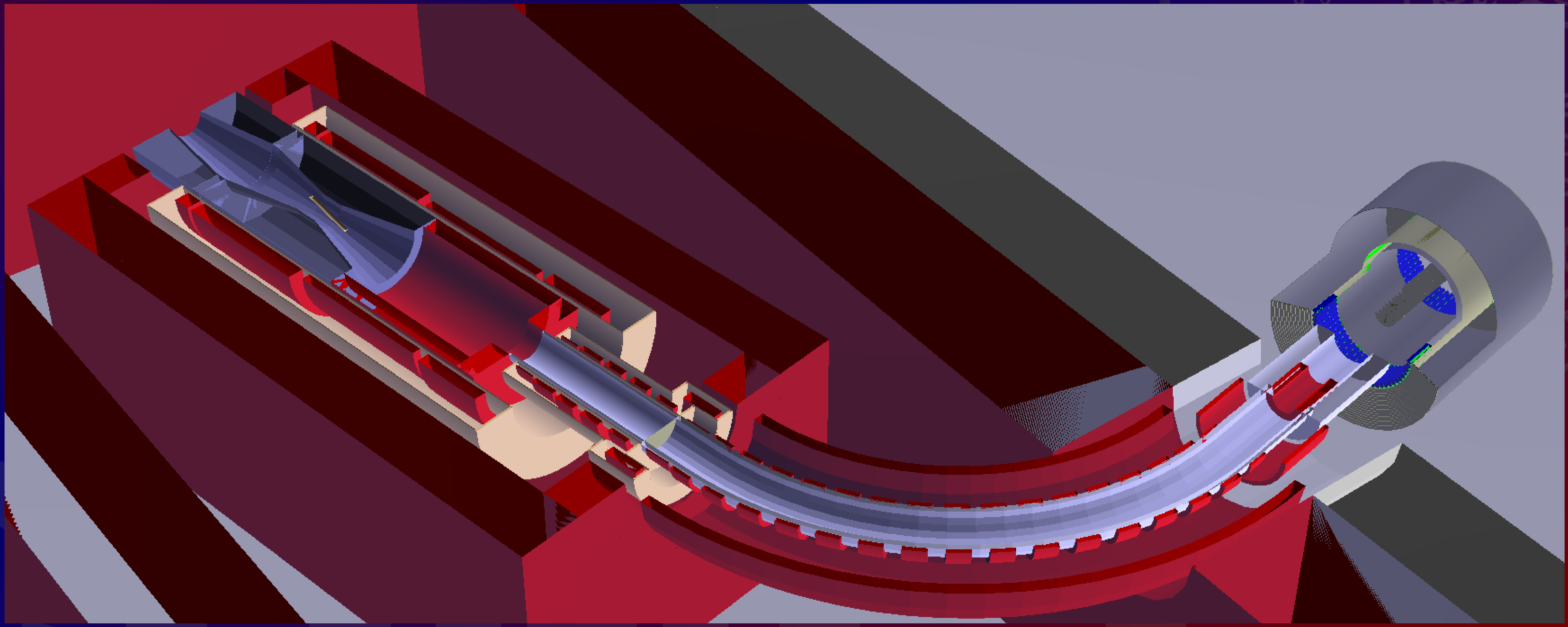
COMET Phase-I at J-PARC

- **Muon-to-electron conversion** at 100 times the sensitivity of current world limit, to start taking data in 2016
- First phase of full COMET programme
- Running at about **5% of the intensity of Phase-II**
- Also allows us to **study the beam line and backgrounds in-situ** to prepare for Phase-II



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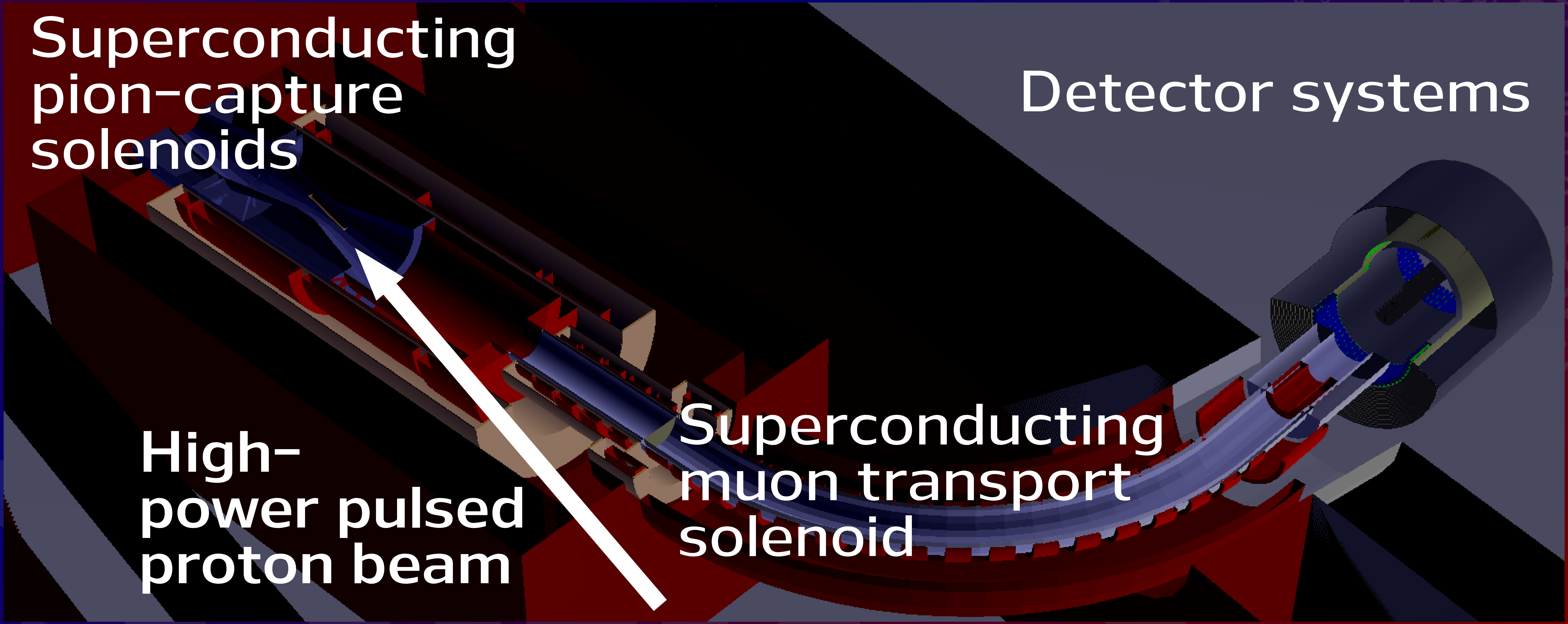

Experimental Limits on Lepton Flavour Violation

See talks today

Reaction	Present limit
$\mu^+ \rightarrow e^+\gamma$	$< 5.7 \times 10^{-13}$
$\mu^+ \rightarrow e^+e^+e^-$	$< 1.0 \times 10^{-12}$
$\mu^- Ti \rightarrow e^- Ti$	$< 6.1 \times 10^{-13}$
$\mu^- Au \rightarrow e^- Au$	$< 7 \times 10^{-13}$
$\mu^+ e^- \rightarrow \mu^- e^+$	$< 8.3 \times 10^{-11}$
$\tau \rightarrow e\gamma$	$< 3.3 \times 10^{-8}$
$\tau \rightarrow \mu\gamma$	$< 4.4 \times 10^{-8}$
$\tau \rightarrow \mu\mu\mu$	$< 2.1 \times 10^{-8}$
$\tau \rightarrow eee$	$< 2.7 \times 10^{-8}$
$\pi^0 \rightarrow \mu e$	$< 3.8 \times 10^{-10}$
$K_L^0 \rightarrow \mu e$	$< 4.7 \times 10^{-12}$
$K^+ \rightarrow \pi^+\mu^+e^-$	$< 1.3 \times 10^{-11}$
$K_L^0 \rightarrow \pi^0\mu^+e^-$	$< 7.6 \times 10^{-11}$
$Z^0 \rightarrow \mu e$	$< 1.7 \times 10^{-6}$
$Z^0 \rightarrow \tau e$	$< 9.8 \times 10^{-6}$
$Z^0 \rightarrow \tau\mu$	$< 1.2 \times 10^{-5}$

90% C.L.
upper limits on
branching ratios

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Summary

- **Charged lepton flavour violation is an extremely clean and sensitive probe** for physics beyond the Standard Model
  - No theoretical backgrounds to discovery
- **Experimentally and theoretically rich:**
  - **Numerous experimental channels**
  - **Significant model dependences**
  - A "discovery" would be followed by a thorough programme of precision study (à la neutrinos)
    - is muon $g-2$ a hint?
- **Significant advances now and in the near future....**

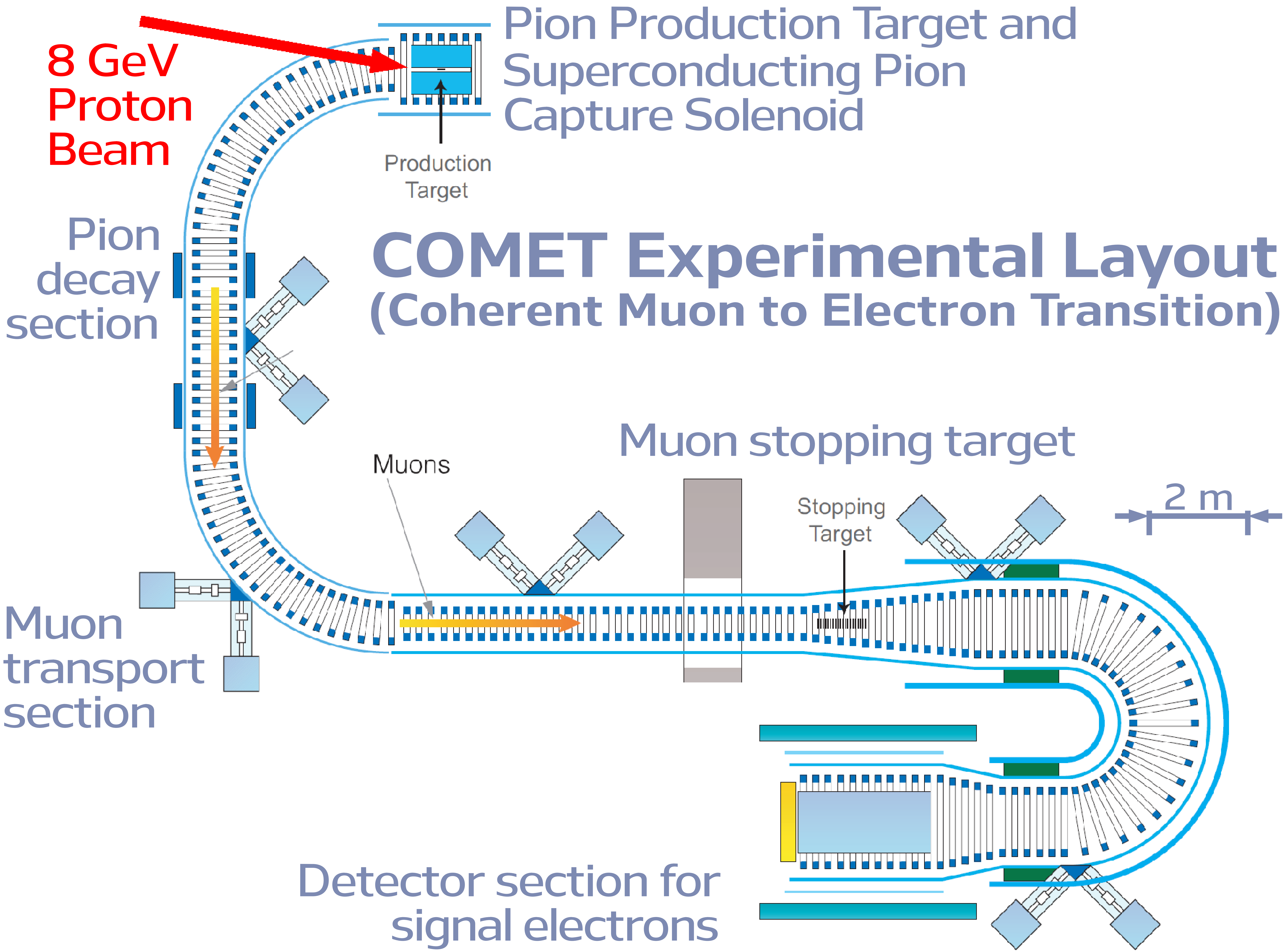
LFV Intro: Overview *RWTH Aachen University*	*Yoshi UCHIDA*	09:00 - 09:25
LVF Theory *RWTH Aachen University*	*Mrs. Emilie PASSEMAR*	09:25 - 09:45
Lepton Flavour Violating Tau Decays at Belle (BELLE) *RWTH Aachen University*	*Kiyoshi HAYASAKA*	09:45 - 10:05
LFV from LHCb: tau->3mu, tau->p2mu (LHCB) *RWTH Aachen University*	*Marcin CHRZASZCZ*	10:05 - 10:30
Coffee *RWTH Aachen University*		10:30 - 11:00
LFV Higgs *RWTH Aachen University*	*Mr. Patrice VERDIER*	11:00 - 11:20
LFV: Majorana neutrinos in B and D decays *RWTH Aachen University*	*Dr. Frank DEPPISCH et al.*	11:20 - 11:40
Recent results on searches for heavy Majorana neutrinos *RWTH Aachen University*	*Jon HARRISON*	11:40 - 12:00
CLFV in muon decays (MEG) *RWTH Aachen University*	*Emanuele RIPICCINI*	12:00 - 12:20
Mu2e Experiment *RWTH Aachen University*	*Dr. David BROWN*	12:20 - 12:40
The mu3e Experiment at PSI *RWTH Aachen University*	*Sandro BRAVAR*	12:40 - 13:00

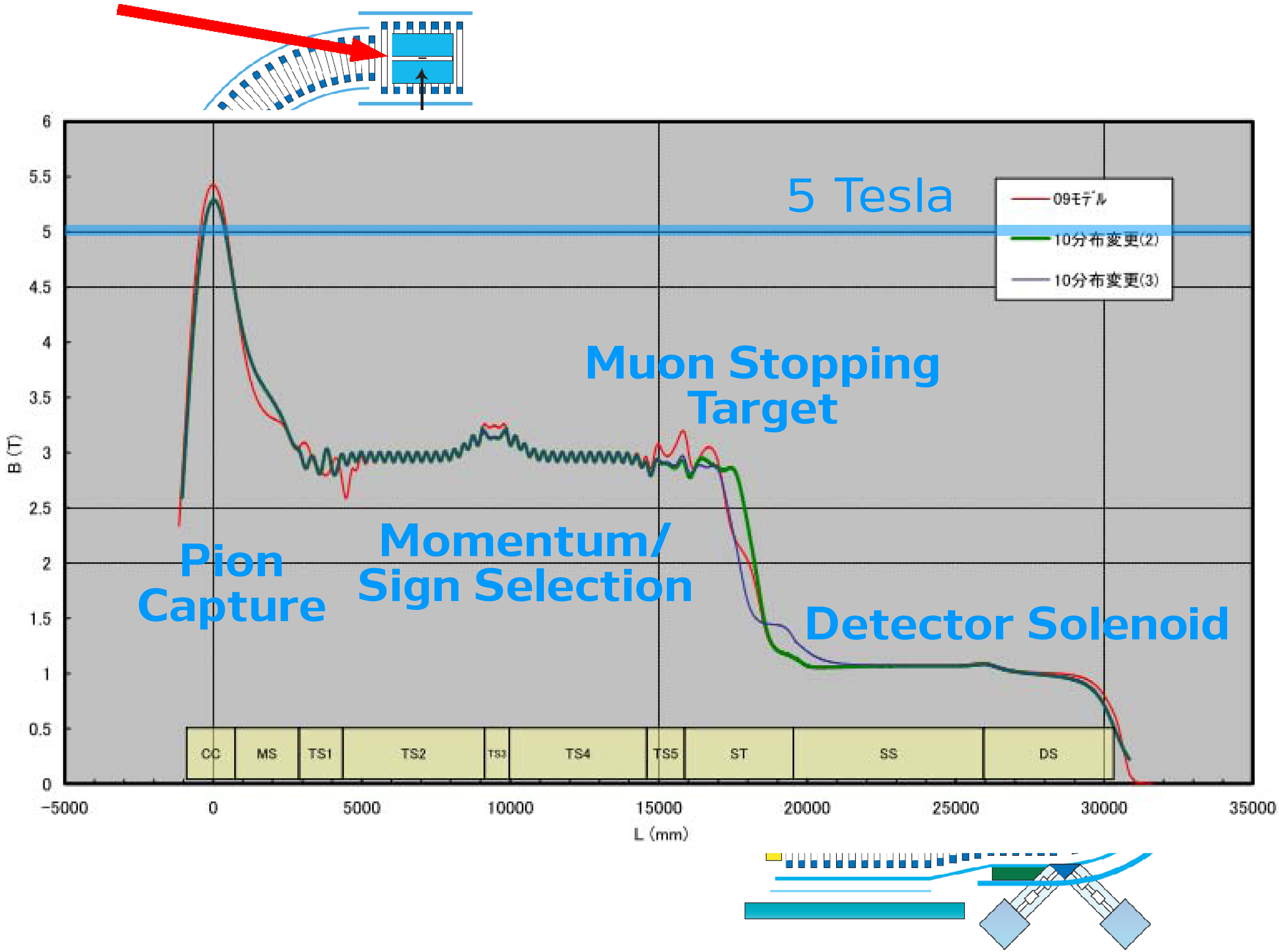

Comet
California
CPFC

Sources include

- "Introductory Muon Science", K. Nagamine
- "Rare Muon Decays and Lepton-Family Number Conservation", C. M. Hoffman
- "The Infancy and Youth of Neutrino Physics": B. Pontecorvo

and references therein


8 GeV
Proton
Beam
Pion Production Target and
Superconducting Pion
Capture Solenoid
Production
Target
COMET Experimental Layout
(Coherent Muon to Electron Transition)
Pion
decay
section
Muon stopping target
Muons
Stopping
Target
2 m
Muon
transport
section
Detector section for
signal electrons



5 Tesla
09モデル
10分布変更(2)
10分布変更(3)
Muon Stopping Target
Pion Capture
Momentum/ Sign Selection
Detector Solenoid
CC
MS
TS1
TS2
TS3
TS4
TS5
ST
SS
DS
B (T)
L (mm)