Muon Physics: An Introduction

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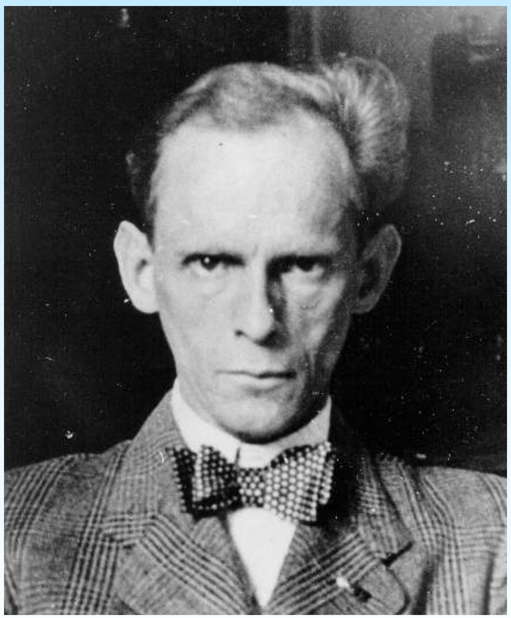
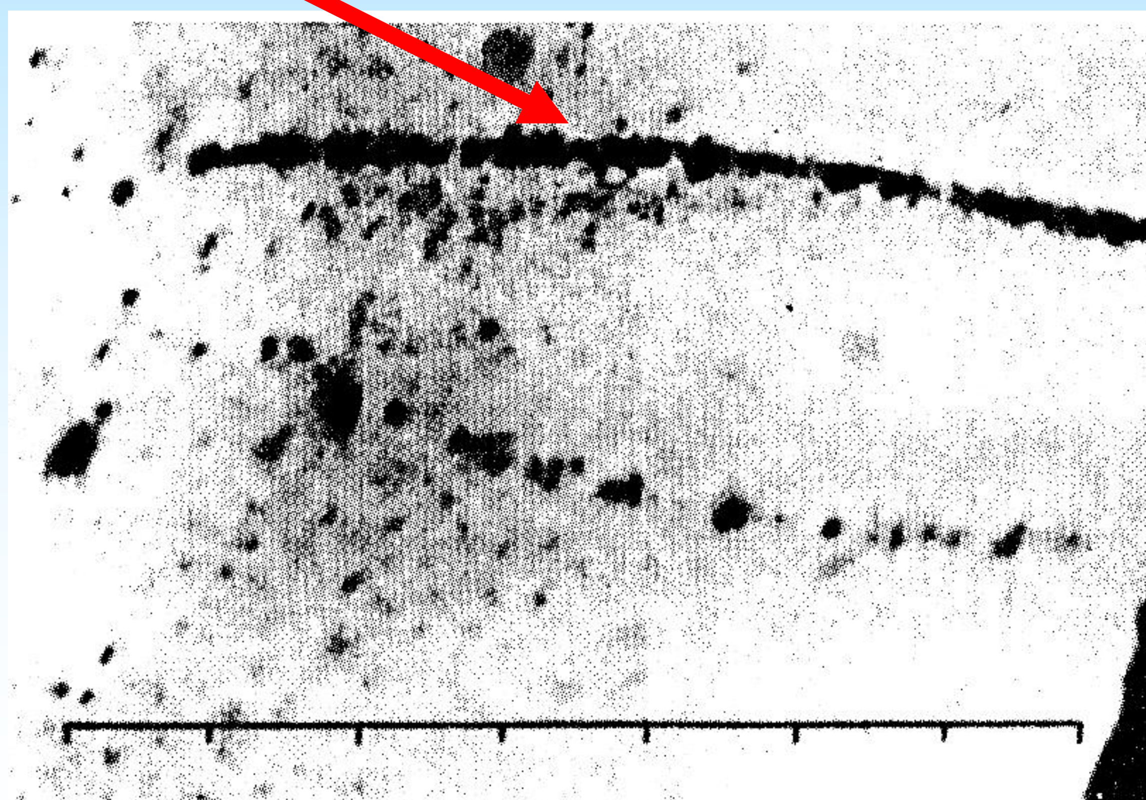
Muon first observed in cosmic rays in 1933

Paul Kunze,

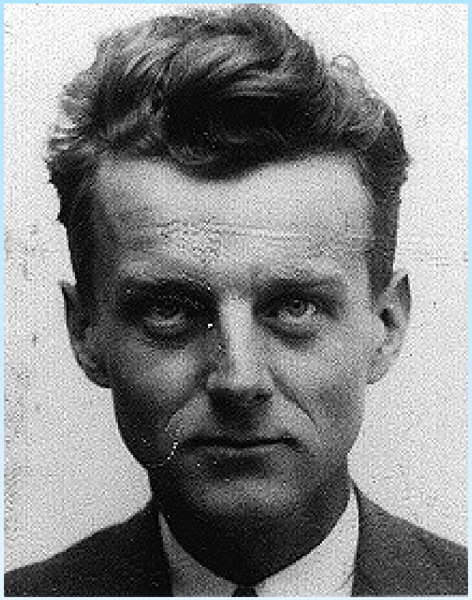
Z. Phys. 83, 1 (1933)



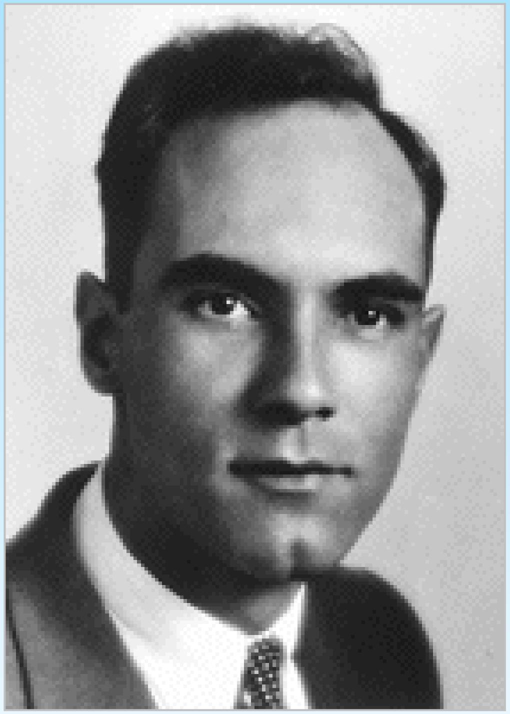
"a particle of uncertain nature"



Identified in 1936



Study of cosmic rays by Seth Neddermeyer and Carl Anderson



MAY 15, 1937 PHYSICAL REVIEW VOLUME 51

Note on the Nature of Cosmic-Ray Particles

SETH H. NEDDERMEYER AND CARL D. ANDERSON
California Institute of Technology, Pasadena, California

(Received March 30, 1937)

MEASUREMENTS[1] of the energy loss of particles occurring in the cosmic-ray showers have shown that this loss is proportional massive than protons but more penetrating than electrons obeying the Bethe-Heitler theory, we have taken about 6000 counter-tripped photo-

Confirmed by: Street & Stevenson, Nishina, Tekeuchi & Ichimiya

NOVEMBER 1, 1937 PHYSICAL REVIEW VOLUME 52

LETTERS TO THE EDITOR

Prompt publication of brief reports of important discoveries in physics may be secured by addressing them to this department. Closing dates for this department are, for the first issue of the month, the eighteenth of the preceding month, for the second issue, the third of the month. Because of the late closing dates for the section no proof can be shown to authors. The Board of Editors does not hold itself responsible for the opinions expressed by the correspondents.

Communications should not in general exceed 600 words in length.

New Evidence for the Existence of a Particle of Mass Intermediate Between the Proton and Electron

Anderson and Neddermyer[1] have shown that, for energies up to 300 and 400 Mev, the cosmic-ray shower particles

between those of the proton and electron. If this is true, it should be possible to distinguish clearly such a particle from an electron or proton by observing its track density and magnetic deflection near the end of its range, although it is to be expected that the fraction of the total range in

J. C. Street
E. C. Stevenson

Research Laboratory of Physics,
Harvard University,
Cambridge, Massachusetts,
October 6, 1937.

[1] Anderson and Neddermeyer, Phys. Rev. **50**, 263 (1936).
[2] Street and Stevenson, Phys. Rev. **51**, 1005 (1937).

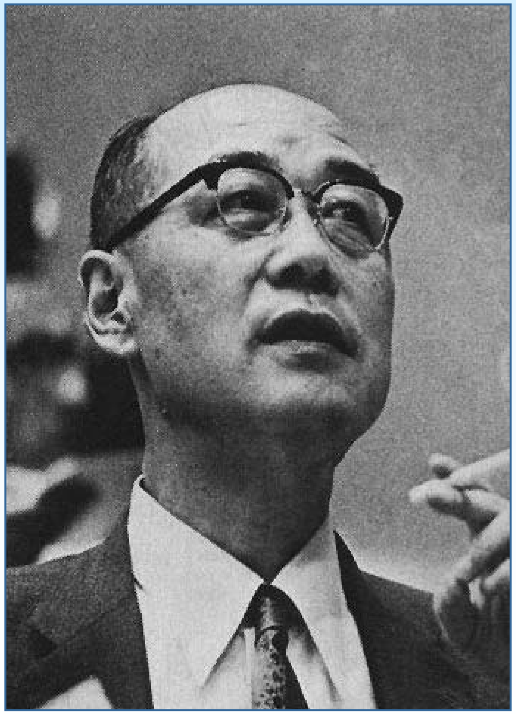
DECEMBER 1, 1937 PHYSICAL REVIEW VOLUME 52

On the Nature of Cosmic-Ray Particles

Y. Nishina, M. Takeuchi, and T. Ichimiya
Institute of Physical and Chemical Research, Tokyo

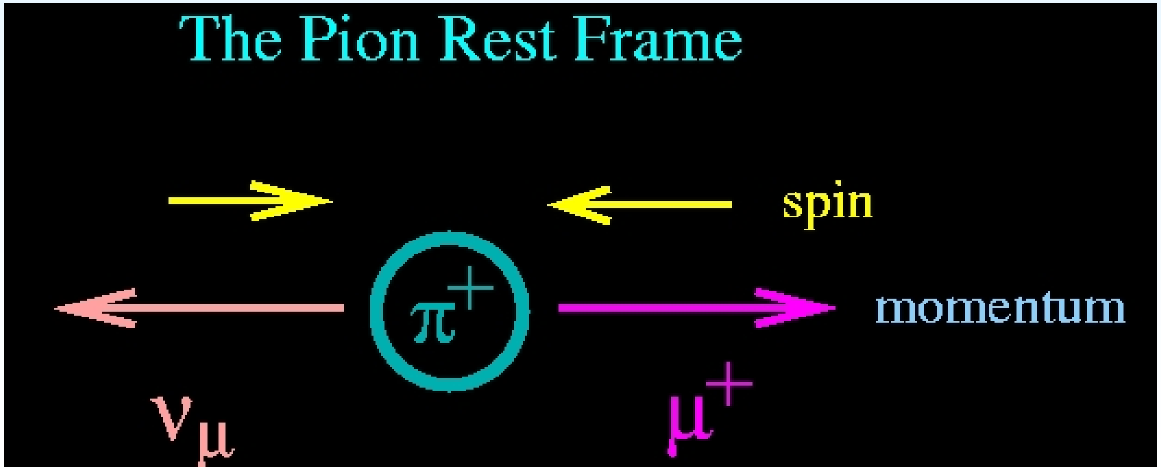
(Received August 28, 1937)

It took 10 years to conclude that the muon interacted too weakly with matter to be the "Yukawa" particle which was postulated to carry the nuclear force



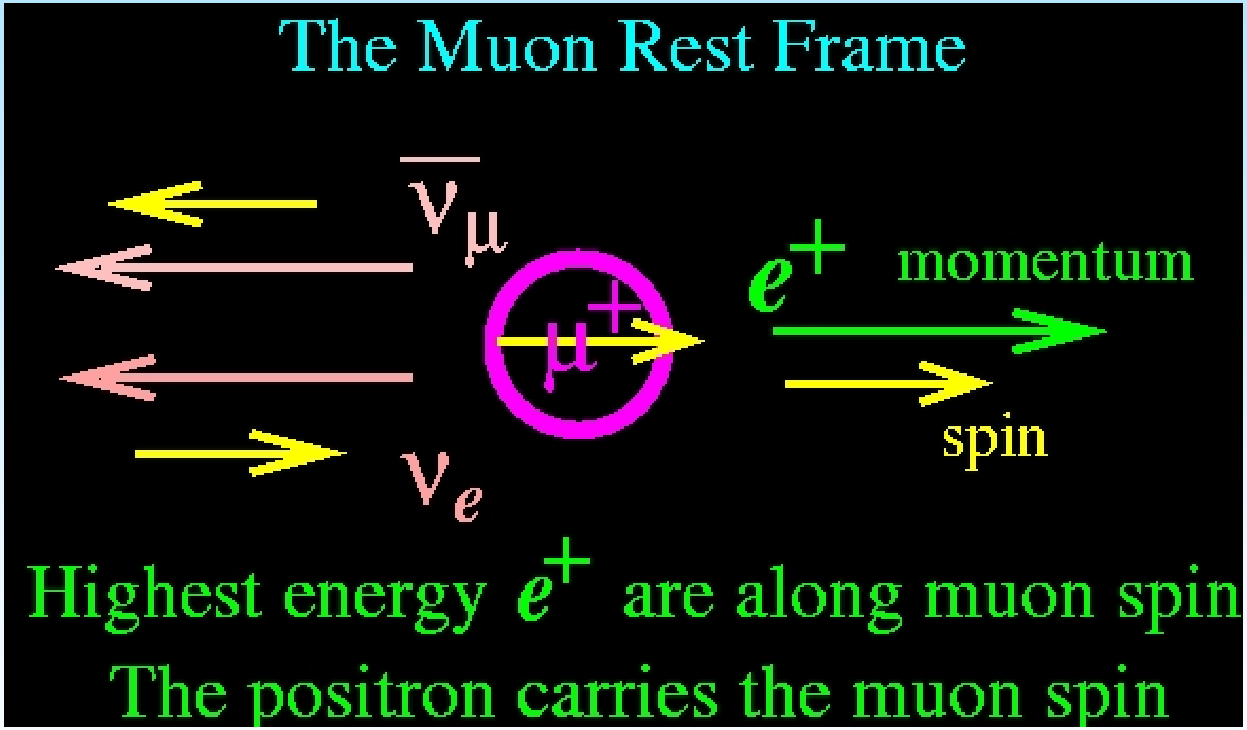
Properties of the Muon

- Lifetime ~2.2 μs, practically forever
- m_μ/m_e = 206.768 277(24)
- produced polarized
  - in-flight decay: both "forward" and "backward" muons are highly polarized



Death of the Muon

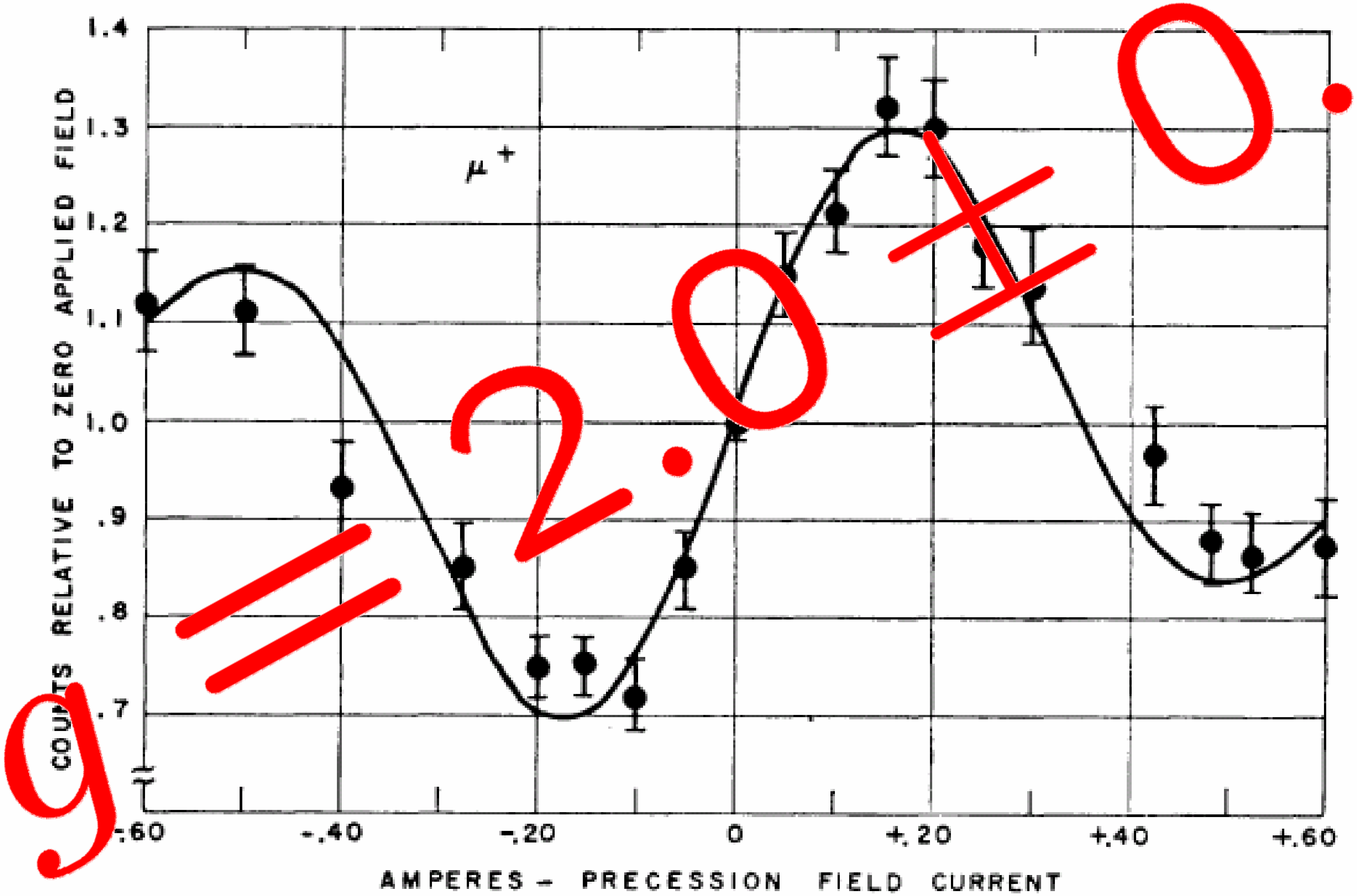
- Decay is self analyzing



- The highest energy $e^\pm$ from $\mu^\pm$ decay carry information in the spin direction.

First muon spin rotation experiment

VIII. Negative muons stopped in carbon sh... asymmetry (also leaked backwards) of $a\sim -1/20$, i.e. about 15% of that for μ^+



$g = 2.0 \pm 0.1$

electrons in (2) should serve as an analyzer for the muon polarization. They also point out that the longitudinal

close wound directly on the carbon to provide a uniform field of 79 gauss per ampere.

PHYSICAL REVIEW VOLUME 118, NUMBER 1 APRIL 1, 1960

Accurate Determination of the μ^+ Magnetic Moment*

R. L. GARWIN,† D. P. HUTCHINSON, S. PENMAN,‡ AND G. SHAPIRO§
Columbia University, New York, New York

(Received August 4, 1959)

Note added in proof.—Experiments which have recently been reported to us [J. Lathrop, et al. and A. Bearden et al., Phys. Rev. Letters (to be published)] indicate a mass value of $M_\mu = 206.76_{-0.02}^{+0.03} M_e$. This yields a value of $g_\mu = 2(1.00113_{-0.00012}^{+0.00016})$. Although the assigned errors are now slightly greater than above, it is to be noted that the new result represents a direct measurement, rather than a lower limit. The agreement

$$a = \frac{\alpha}{2\pi} = 0.001161$$

The muon behaves like a heavy electron!

The Muon Trio:

- Muon Magnetic Dipole Moment a_μ chiral changing

$$\bar{u}_\mu[ef_1(q^2)\gamma_\beta + \frac{ie}{2m_\mu}f_2(q^2)\sigma_{\beta\delta}q^\delta]u_\mu$$

$$\vec{\mu}_s = g_s\left(\frac{e\hbar}{2m}\right)\vec{s}$$

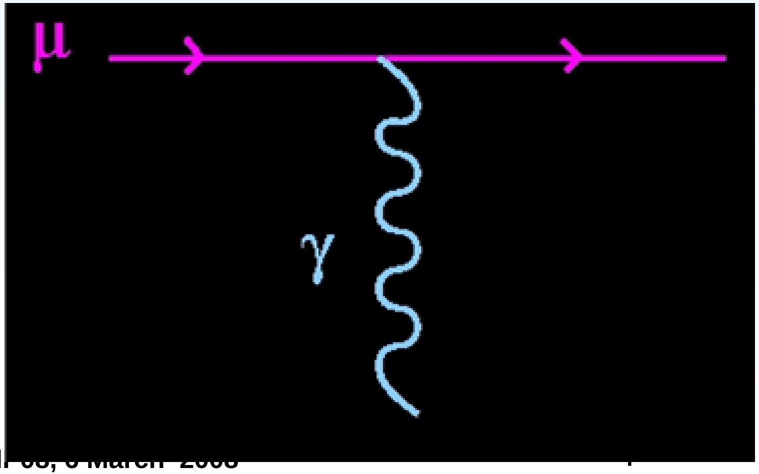
$$f_1(0) = 1 \qquad f_2(0) = a_\mu \qquad \mu = (1+a)\frac{e\hbar}{2m}$$

- Muon EDM

$$\bar{u}_\mu\left[\frac{ie}{2m_\mu}f_2(q^2) - f_3(q^2)\gamma_5\right]\sigma_{\beta\delta}q^\nu u_\mu$$

$$a = \frac{(g-2)}{2}$$

$$f_2(0) = a_\mu \qquad f_3(0) = d_\mu;\ \text{EDM}$$



The Muon Trio:

- Muon Magnetic Dipole Momoment a_μ chiral changing

$$\bar{u}_\mu [e f_1(q^2)\gamma_\beta + \frac{ie}{2m_\mu} f_2(q^2)\sigma_{\beta\delta}q^\delta] u_\mu$$

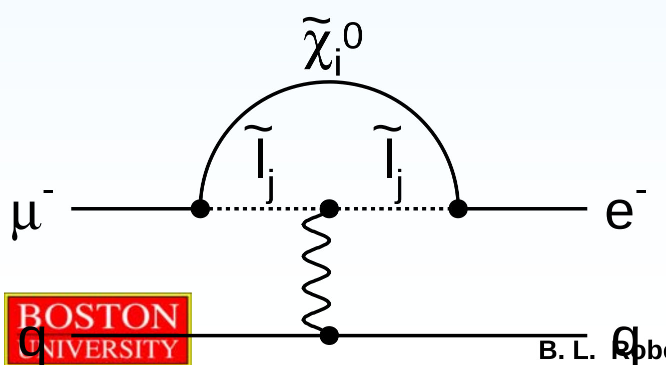
$$f_1(0) = 1 \qquad f_2(0) = a_\mu$$

- Muon EDM

$$\bar{u}_\mu \left[\frac{ie}{2m_\mu} f_2(q^2) - f_3(q^2)\gamma_5\right] \sigma_{\beta\delta} q^\nu u_\mu$$

$$f_2(0) = a_\mu \qquad f_3(0) = d_\mu;\ \text{EDM}$$

- Lepton Flavor Violation



$$\mu^- A \rightarrow e^- A$$

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

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

The First $\mu^- N \to e^- N$ Experiment Steinberger and Wolf

- After the discovery of the muon, it was realized it could decay into an electron and a photon or convert to an electron in the field of a nucleus.
- Without any flavor conservation, the expected branching fraction for $\mu^+ \to e^+ \gamma$ is about 10^{-5}.
- Steinberger and Wolf looked for $\mu^- N \to e^- N$ for the first time, publishing a null result in 1955, with a limit

$$R_{\mu e} < 2 \times 10^{-4}$$

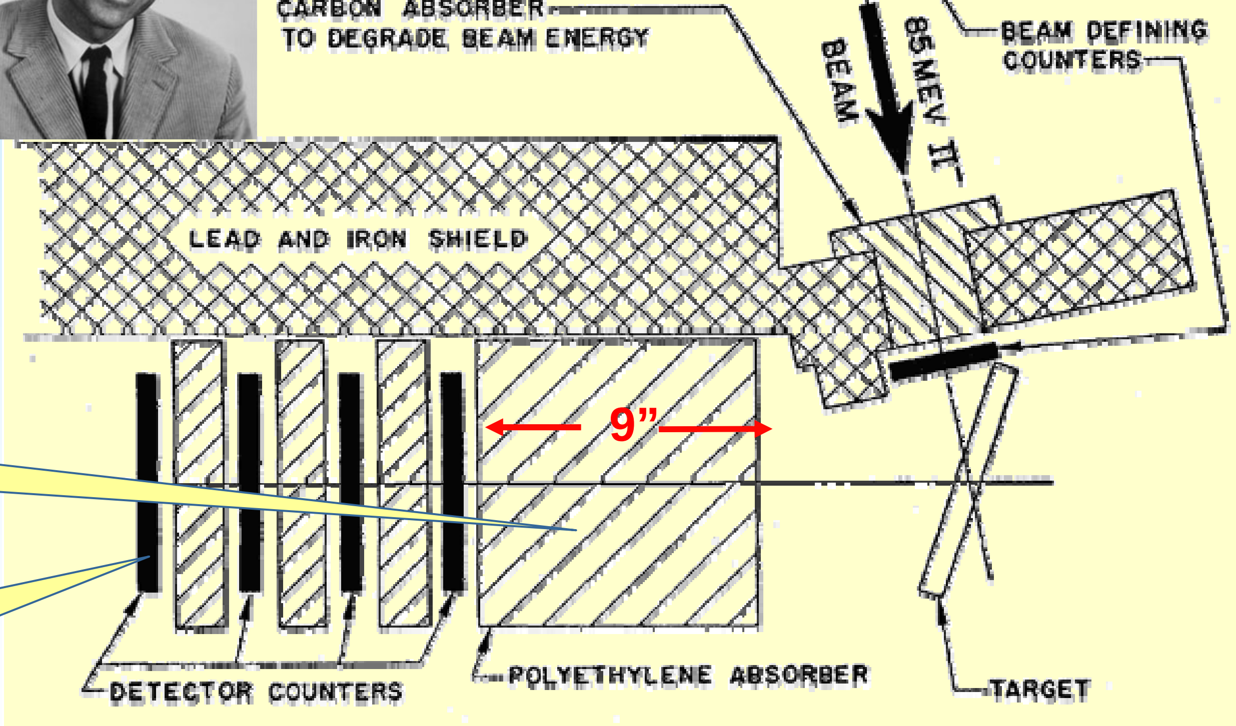
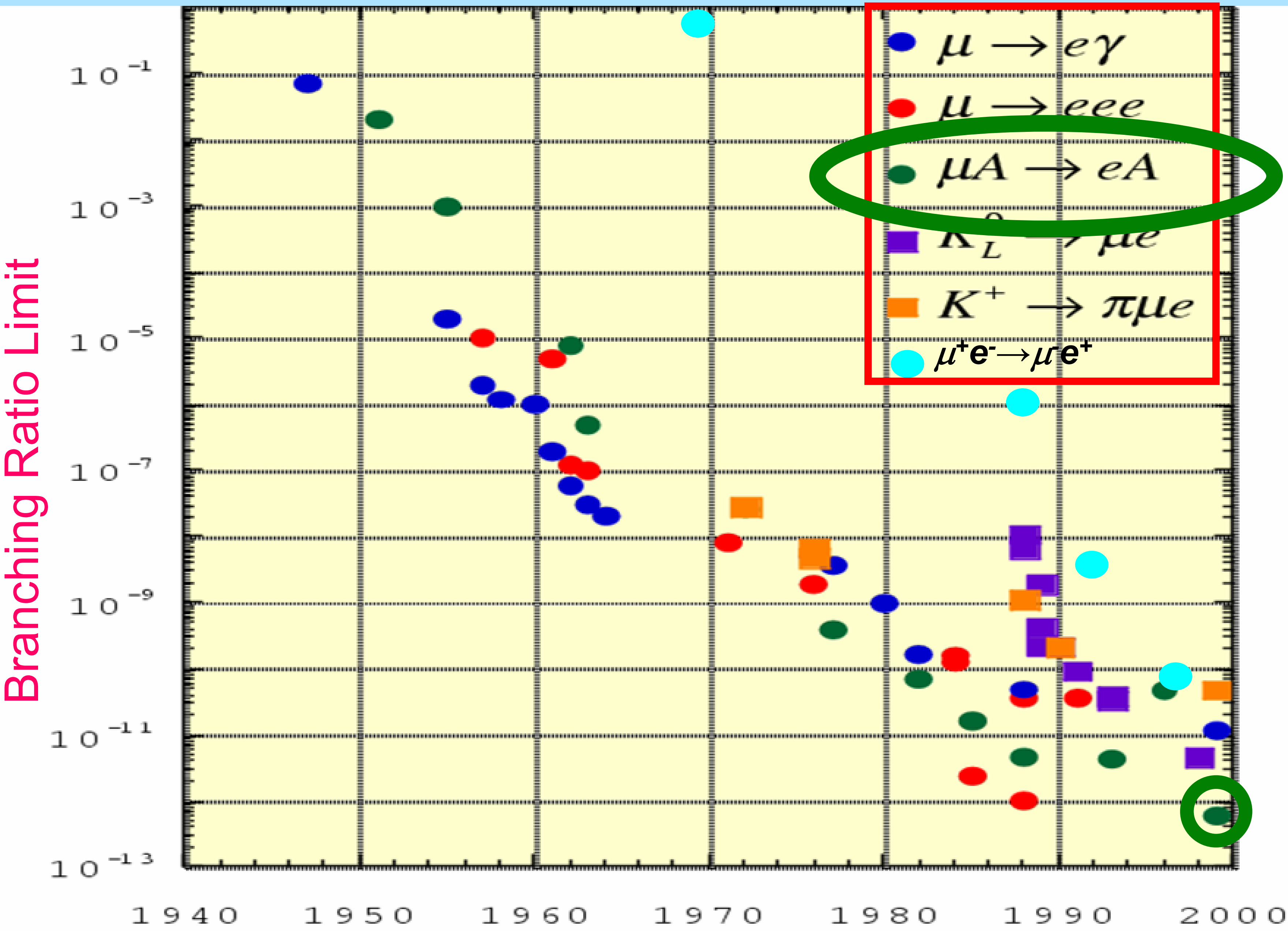


FIG. 1. Experimental arrangement.

Absorbs e^- from μ^- decay

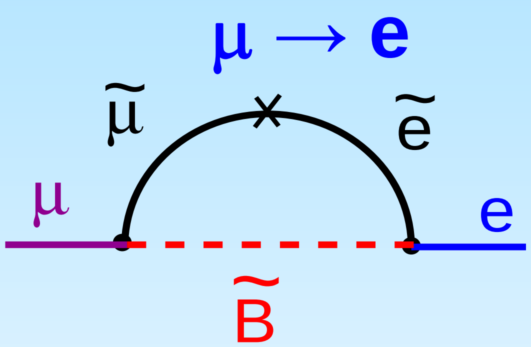
Conversion e^- reach this counter

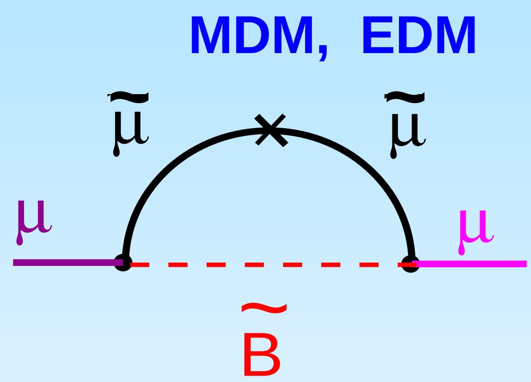
Past and Future of LFV Limits



SUSY connection between MDM, EDM and the lepton flavor violating transition moment $\mu \rightarrow e$

SUSY $\Rightarrow$ slepton mixing





$$\begin{pmatrix} m^2_{\tilde e\tilde e} & \Delta m^2_{\tilde e\tilde\mu} & \Delta m^2_{\tilde e\tilde\tau} \\ \Delta m^2_{\tilde\mu\tilde e} & m^2_{\tilde\mu\tilde\mu} & \Delta m^2_{\tilde\mu\tilde\tau} \\ \Delta m^2_{\tilde\tau\tilde e} & \Delta m^2_{\tilde\tau\tilde\mu} & m^2_{\tilde\tau\tilde\tau} \end{pmatrix}$$

What have we learned from the muon thus far:

- The strength of the weak interaction
  - i.e. the Fermi constant G_F (more properly G_μ)
- The V - A nature of the weak interaction
- Lepton flavor conservation in μ-decay
- VEV of the Higgs field: $\frac{G_F}{\sqrt{2}} = \frac{1}{2v^2}$
- Induced form-factors in nuclear μ-capture especially the induced pseudoscalar coupling
- Possible evidence of new physics in a_μ