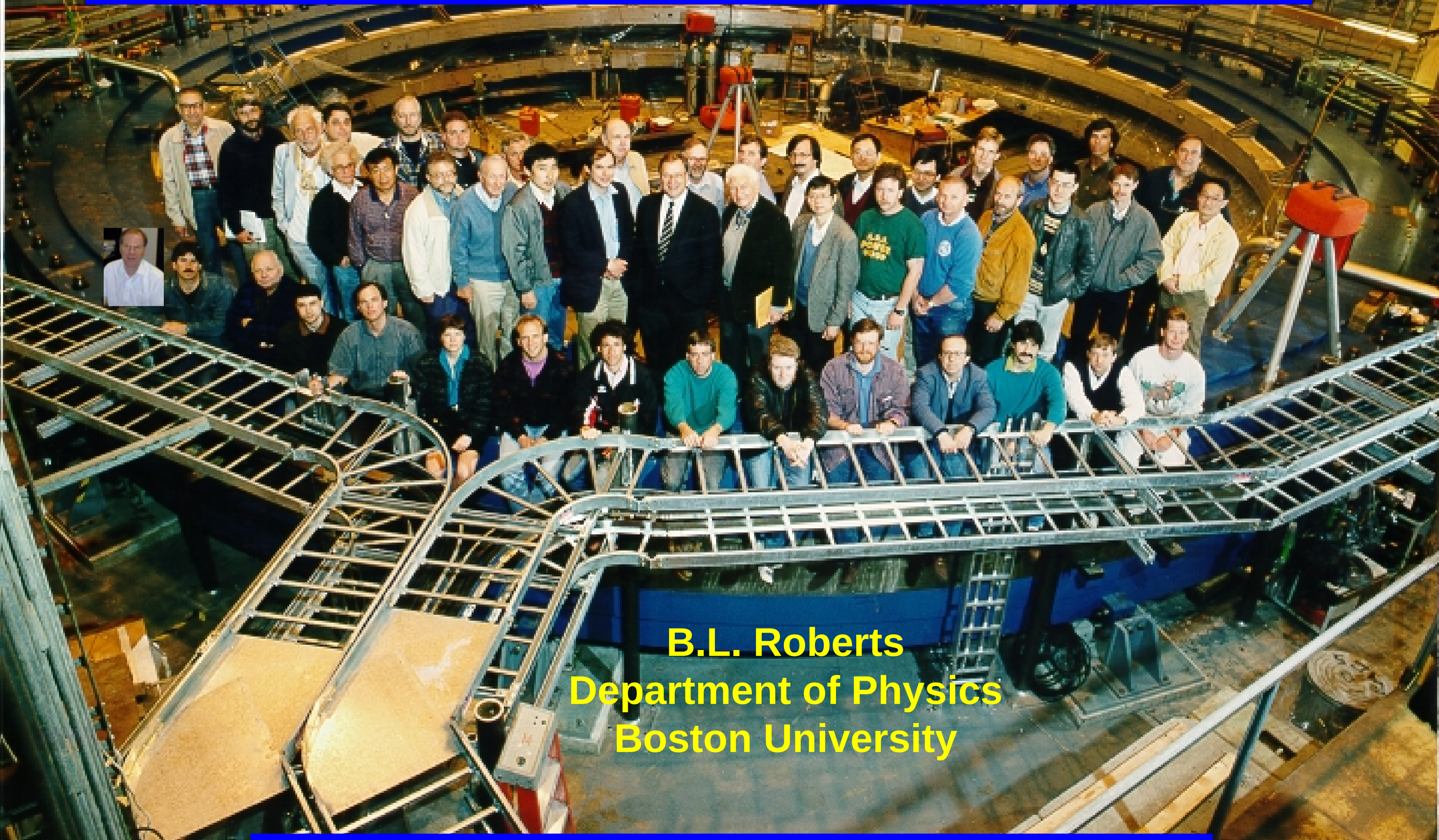
The Muon:
A Laboratory for Particle Physics



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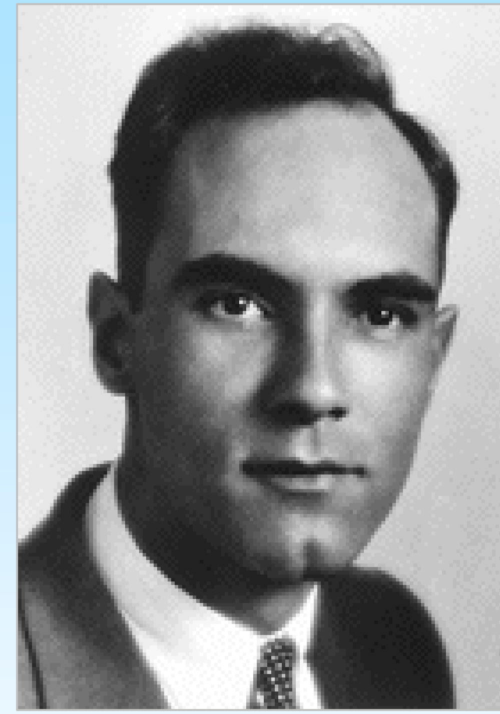
Outline

- Introduction to the muon
- Selected weak interaction parameters
- Magnetic and electric dipole moments
- Lepton Flavor Violation
- Summary and conclusions.

The Muon: Discovered in 1936

Discovered in 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 and Stevenson

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

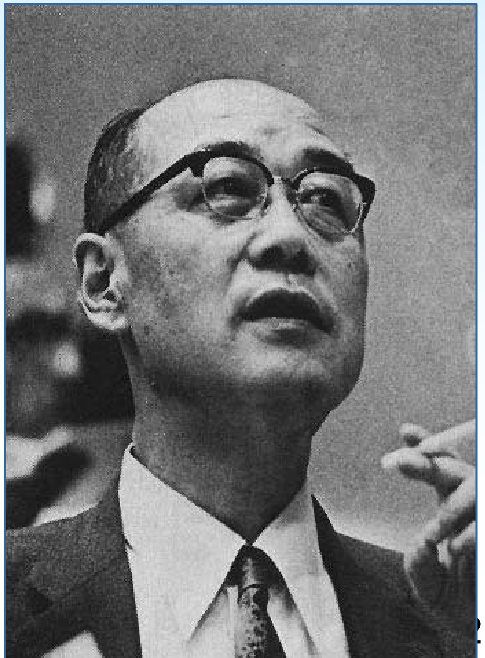
between those of the proton and electron. If this is true, it should be possible to distinguish clearly such a particle from an electron or proton by observing its track density

tracks of high energy particles.

J. C. STREET
E. C. STEVENSON

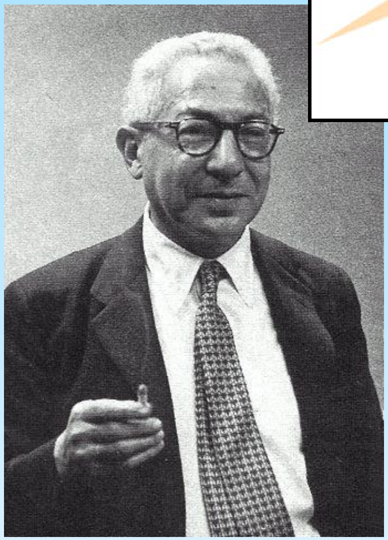
Research Laboratory of Physics,
Harvard University,
Cambridge, Massachusetts,
October 6, 1937.

[1] Anderson and Neddermeyer, Phys. Rev. **50**, 263 (1936).
[2] Street and Stevenson, Phys. Rev. **51**, 1005 (1937).
[3] Neddermeyer and Anderson, Phys. Rev. **51**, 885 (1937).



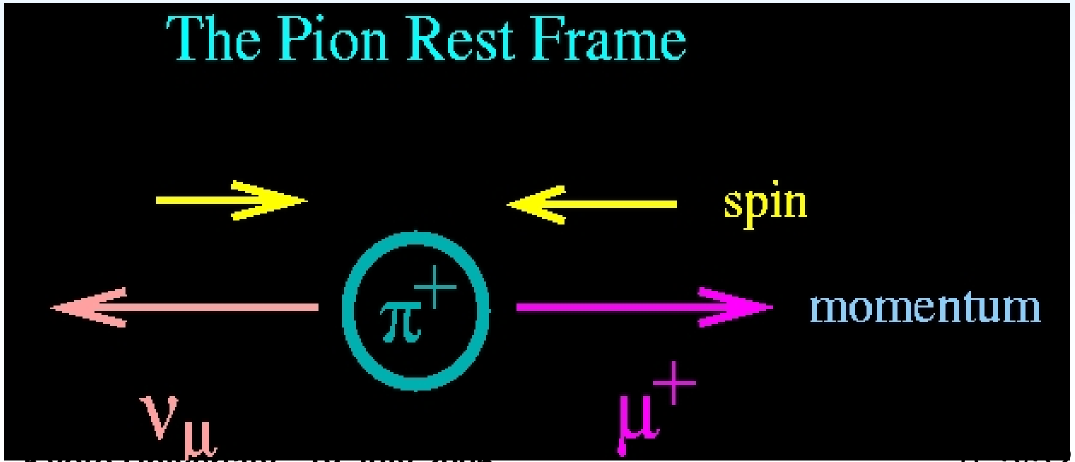
It interacted too weakly with matter to be the "Yukawa" particle which was postulated to carry the nuclear force

The discovery of the muon was a big surprise…



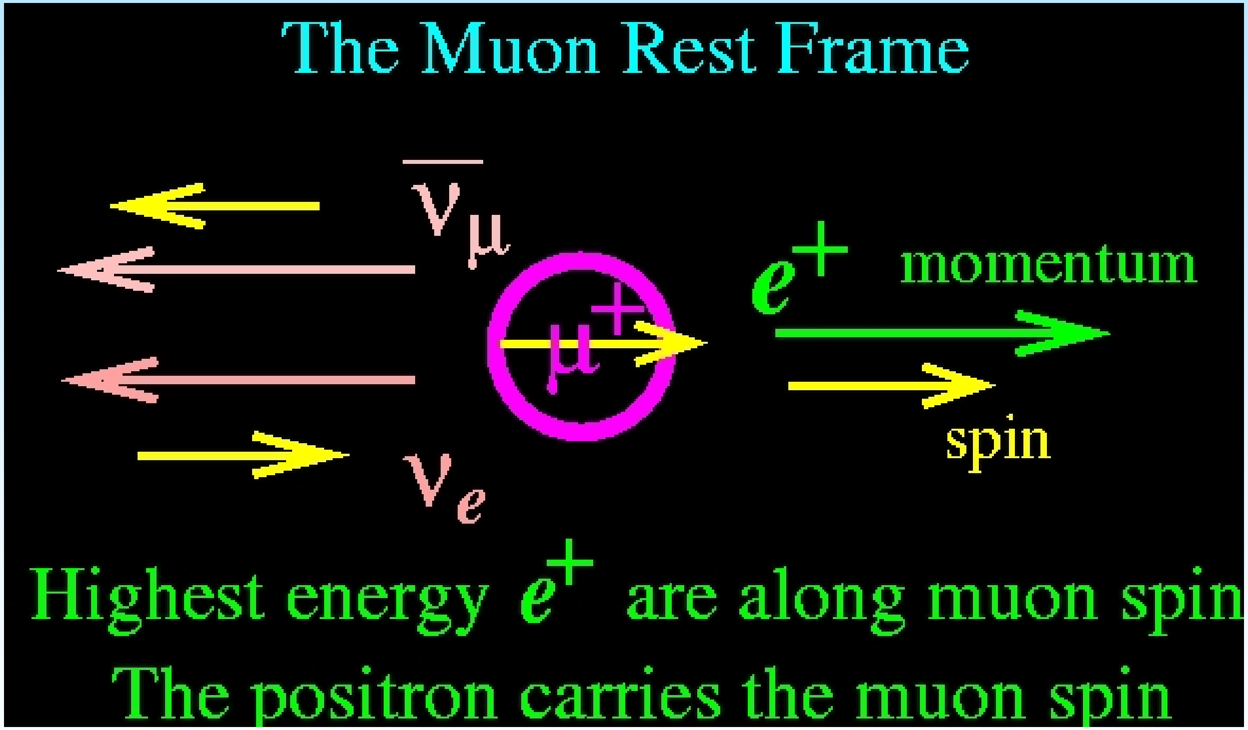
- Lifetime ~2.2 μs, practically forever
- 2^{nd} generation lepton
- m_μ/m_e = 206.768 277(24)
- produced polarized
  - in-flight decay: both "forward" and "backward" muons are highly polarized
- Paul Scherrer Institut

has 10^8 μ/s in a beam



Death of the Muon

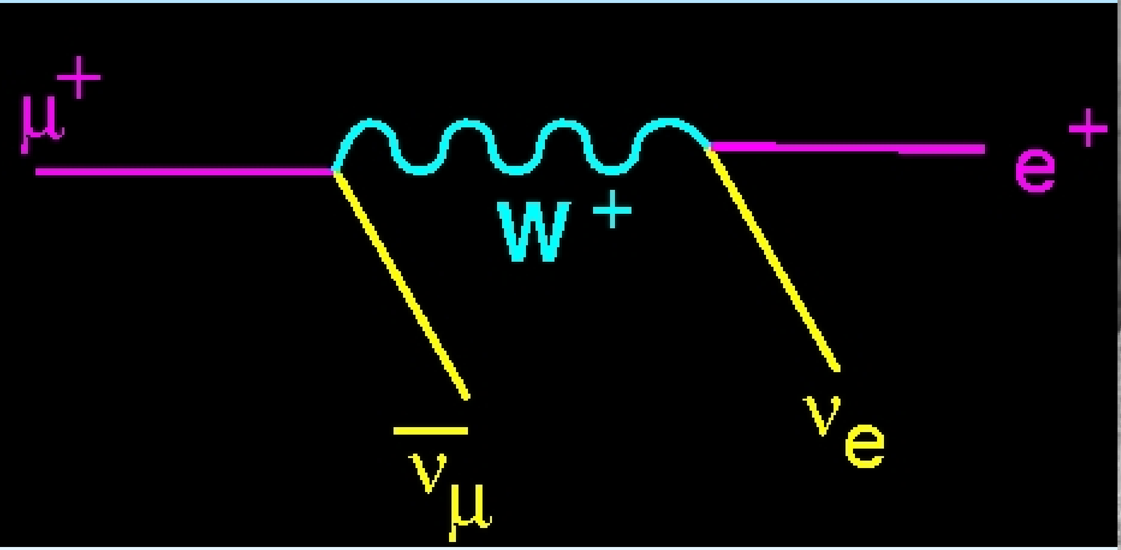
- Decay is self analyzing

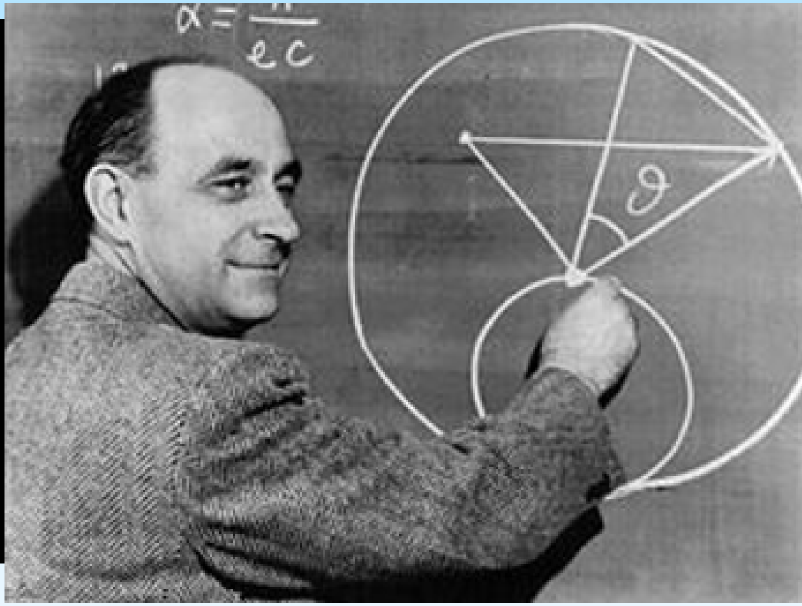


What have we learn from the μ's death?

- The strength of the weak interaction
  - i.e. the Fermi constant G_F (more properly G_μ)
- The fundamental nature of the weak interaction
  - i.e. is it scalar, vector, tensor, pseudo-scalar, pseudo-vector or pseudo-tensor?
- 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

A precise measurement of τ_{μ^+} leads to a precise determination of the Fermi constant G_F



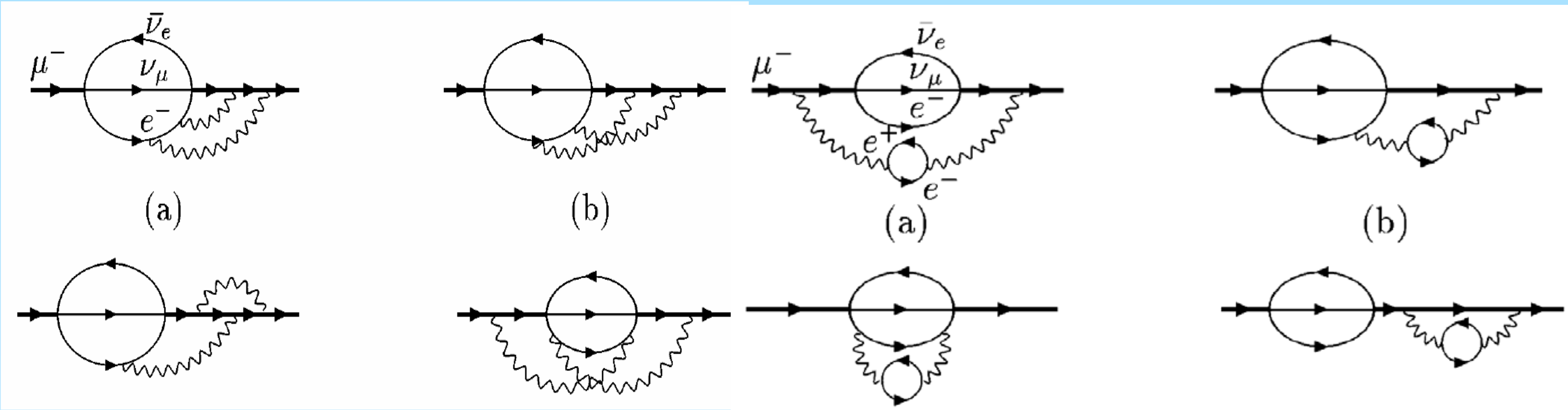


$$\frac{1}{\tau} = \frac{G_F^2 m_\mu^5}{192\pi^3}(1+\delta)$$

$$\frac{G_F}{\sqrt{2}} = \frac{g^2}{8M_W^2}(1+\Delta r)$$

from radiative corrections

δ



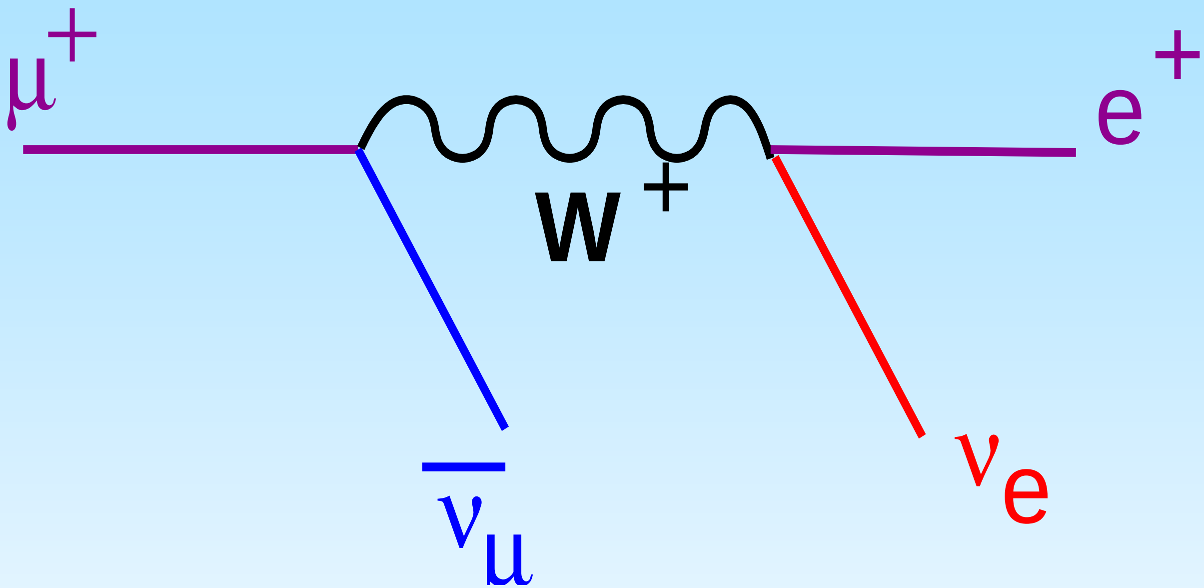
$$\tau_\mu^{-1} = \frac{G_F^2 m_\mu^5}{192\pi^3} F\left(\frac{m_e^2}{m_\mu^2}\right)\left(1 + \frac{3}{5}\frac{m_\mu^2}{M_W^2}\right) \times \left[1 + \left(\frac{25}{8} - \frac{\pi^2}{2}\right)\frac{\alpha(m_\mu)}{\pi} + C_2 \frac{\alpha^2(m_\mu)}{\pi^2}\right],$$

where $F(x) = 1 - 8x + 8x^3 - x^4 - 12x^2 \ln x$, $\quad \alpha(m_\mu)^{-1} = \alpha^{-1} - \frac{2}{3\pi}\ln\left(\frac{m_\mu}{m_e}\right) + \frac{1}{6\pi} \approx 136$

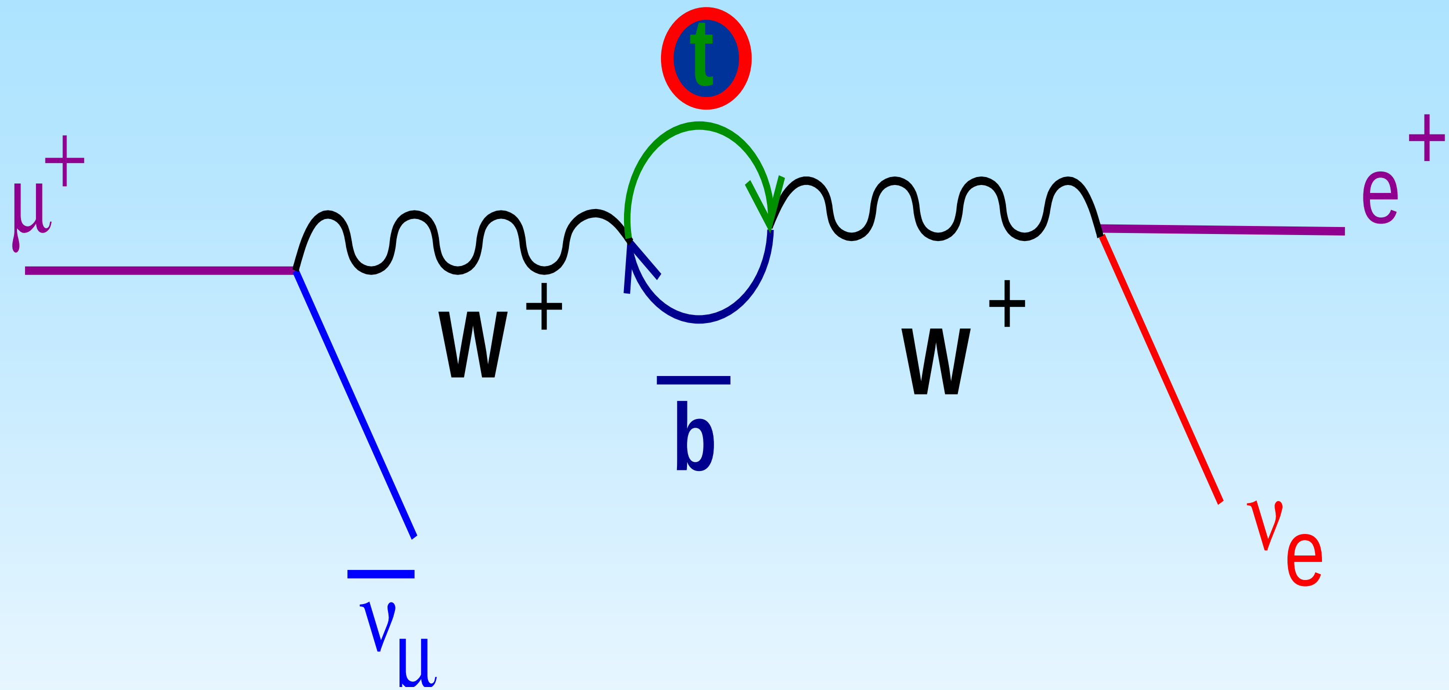
and $\qquad C_2 = \frac{156815}{5184} - \frac{518}{81}\pi^2 - \frac{895}{36}\zeta(3) + \frac{67}{720}\pi^4 + \frac{53}{6}\pi^2 \ln(2).$

The $\mathcal{O}(\alpha^2)$ corrections to μ decay have been completed in 1999[1]. The dominant theoretical uncertainty reduced from 16 to < 0.3 ppm.

τ_μ helped predict the mass of the top quark



τ_μ helped predict the mass of the top quark



Predictive power in weak sector of SM. Difference between the charged current $t\bar{b}$ and neutral current propagators $t\bar{t},\ b\bar{b}\cdots$ The radiative correction shown above depends on m_t^2. Comparisons of charged, vrs. neutral currents gives information on m_t.

The Electro-Weak Working Group Fits:

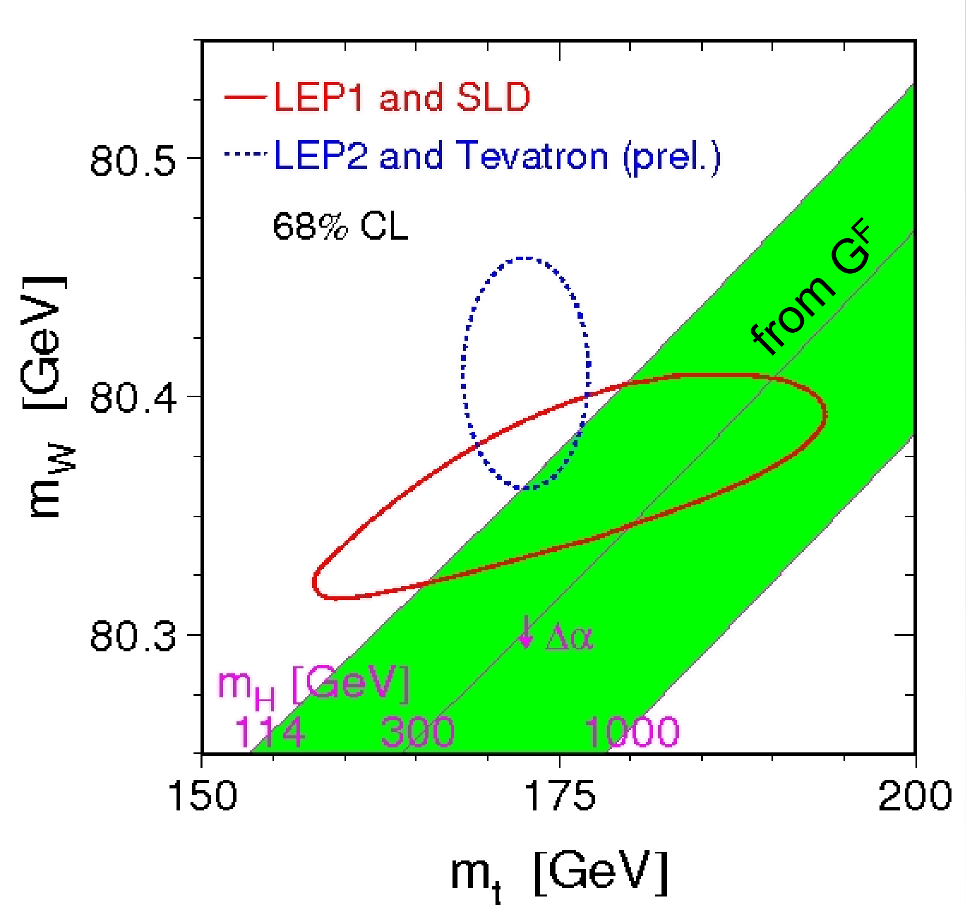
Predicted

$$m_t = 179^{+12}_{-9}\,\text{GeV}$$

Input: G_F (17 ppm),
α (4 ppb at q^2=0),
αM_Z (23 ppm),

Measured:

$$m_t = 172.7 \pm 2.9\,\text{GeV}$$



The μLan experiment at PSI will accumulate 10^{12} μ-decays and measure G_μ to ~1 ppm. If LHC provides a Higgs Mass, then the precision of the confrontation with the SM will greatly improve

The Weak Lagrangian (Leptonic Currents)

- Lepton current is (vector – axial vector) "(V – A)"

$$J_\sigma^{\text{lept}} \propto \bar{u}(1+\gamma_5)u$$

- It might have been: V$\pm$A or S$\pm$V$\pm$A or most general form:

Scalar $\pm$ Vector $\pm$ Weak-Magnitism
$\pm$ PseudoScalar $\pm$ Axial-Vector $\pm$ Tensor

There have been extensive studies at PSI by Gerber, Fetscher, et al. to look for other couplings in muon decay. Search continues with TWIST at TRIUMF.

At present, none have been found.

If the Strong Interaction is Present

- Then we have a more general current, which in principle can have 6 ***induced*** form factors in the current.

$$\mathcal{L} \propto J_{\lambda}^{\text{had}} J^{\lambda}_{\text{lept}} + HC$$

Leptonic and hadronic currents

- For nuclear μ^- capture (and also in β-decay) there are induced form-factors and the hadronic V-A current contains 6 terms.
  - in μ capture the induced pseudoscaler term becomes important

β - decay

$$< B|V_\lambda|A > =$$
$$(\ )\bar{u}(p')[g_V(q^2)\gamma_\lambda - g_{WM}(q^2)\sigma_{\lambda\nu}q_\nu - ig_S(q^2)q_\lambda]u(p)$$

vector, weak magnitism, scalar

2nd class

$$< B|A_\lambda|A > =$$
$$(\ )\bar{u}(p')[g_A(q^2)\gamma_\lambda\gamma_5 - ig_P(q^2)q_\lambda\gamma_5 - g_T(q^2)\gamma_5\sigma_{\lambda\nu}q_\nu]u(p)$$

axial vector, pseudoscalar, tensor

The Muon Trio:

- Muon Magnetic Dipole Momoment a_μ chiral changing

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

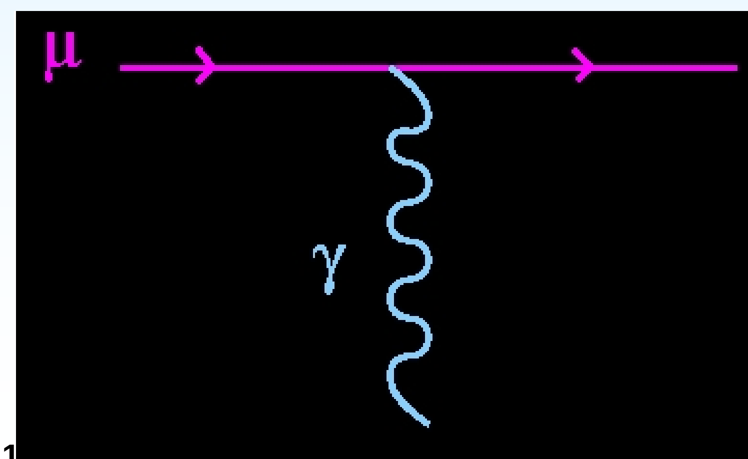
$$\vec{\mu}_s = g_s\left(\frac{e\hbar}{2m}\right)\vec{s} \qquad \mu = (1+a)\frac{e\hbar}{2m}$$

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

- Muon EDM

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

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



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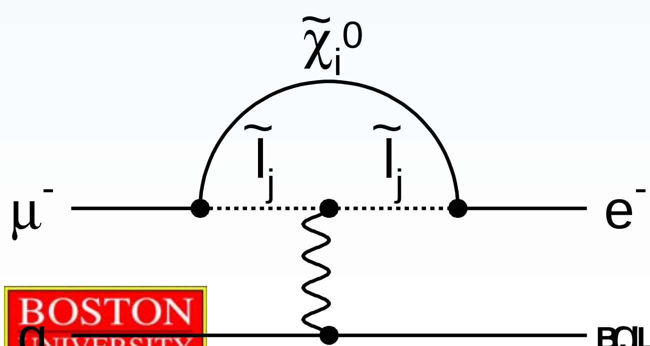
$$f_2(0) = a_\mu \qquad f_3(0) = d_\mu;\ \mathrm{EDM}$$

- Lepton Flavor Violation



$$\mu^- A \to e^- A$$

$$\mu^+ \to e^+\gamma$$

$$\mu^+ \to e^+e^-e^+$$

Magnetic Moments (Field started by Stern)

1924. № 10.

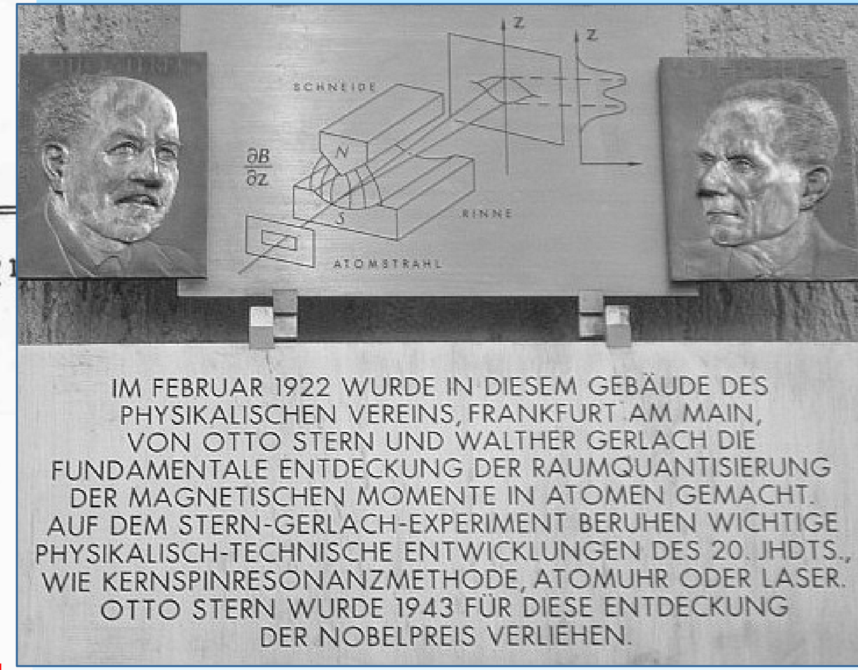
ANNALEN DER PHYSIK.

VIERTE FOLGE. BAND 74.

1. *Über die Richtungsquantelung im Magnetfeld*[1]; *von Walther Gerlach und Otto Stern.*

(Hierzu Tafel III.)

Nr. der Aufnahme	Entfernung des unabgelenkten Strahles von der Schneide	Mittlere Ablenkung des abgestoßenen Strahles	
		berechnet	beobachtet
15	0,32 mm	$0{,}10_1$ mm	$0{,}10_3$ mm
14	0,21 mm	$0{,}14_8$ mm	0,15 mm



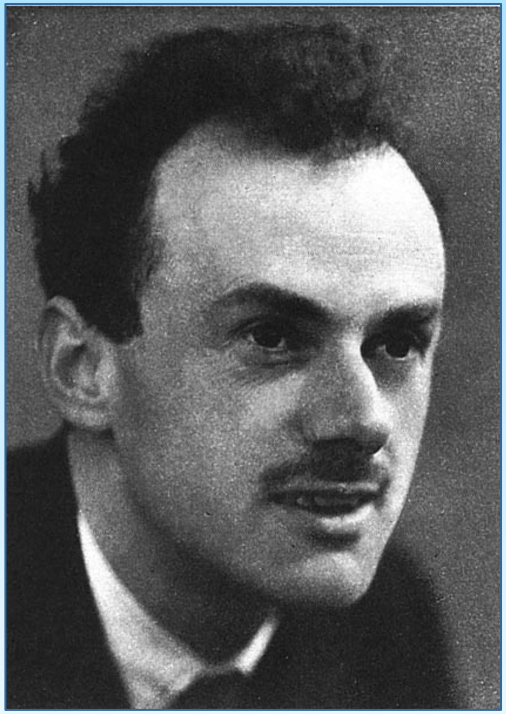
(in modern language)

(and in English)

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

$$\Rightarrow g = 2$$

Dirac Equation Predicts g=2



Non-relativistic reduction of the Dirac Equation for an electron in a weak magnetic field.

$$i\hbar\frac{\partial\psi}{\partial t} = [\frac{p^2}{2m} - \frac{e}{2m}(\vec{L}+2\vec{S})\cdot\vec{B}]\psi$$

PHYSICAL REVIEW VOLUME 74, NUMBER 3 AUGUST 1, 1948

The Magnetic Moment of the Electron†

P. KUSCH AND H. M. FOLEY
Department of Physics, Columbia University, New York, New York

(Received April 19, 1948)

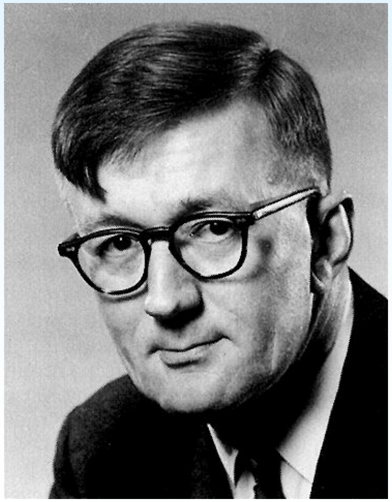
A comparison of the g_J values of Ga in the $^2P_{3/2}$ and $^2P_{\frac{1}{2}}$ states, In in the $^2P_{\frac{1}{2}}$ state, and Na in the $^2S_{\frac{1}{2}}$ state has been made by a measurement of the frequencies of lines in the *hfs* spectra in a constant magnetic field. The ratios of the g_J values depart from the values obtained on the basis of the assumption that the electron spin gyromagnetic ratio is 2 and that the orbital electron gyromagnetic ratio is 1. Except for small residual effects, the results can be described by the statement that The possibility that the observed effects may be explained by perturbations is precluded by the consistency of the result as obtained by various comparisons and also on the basis of theoretical considerations.

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

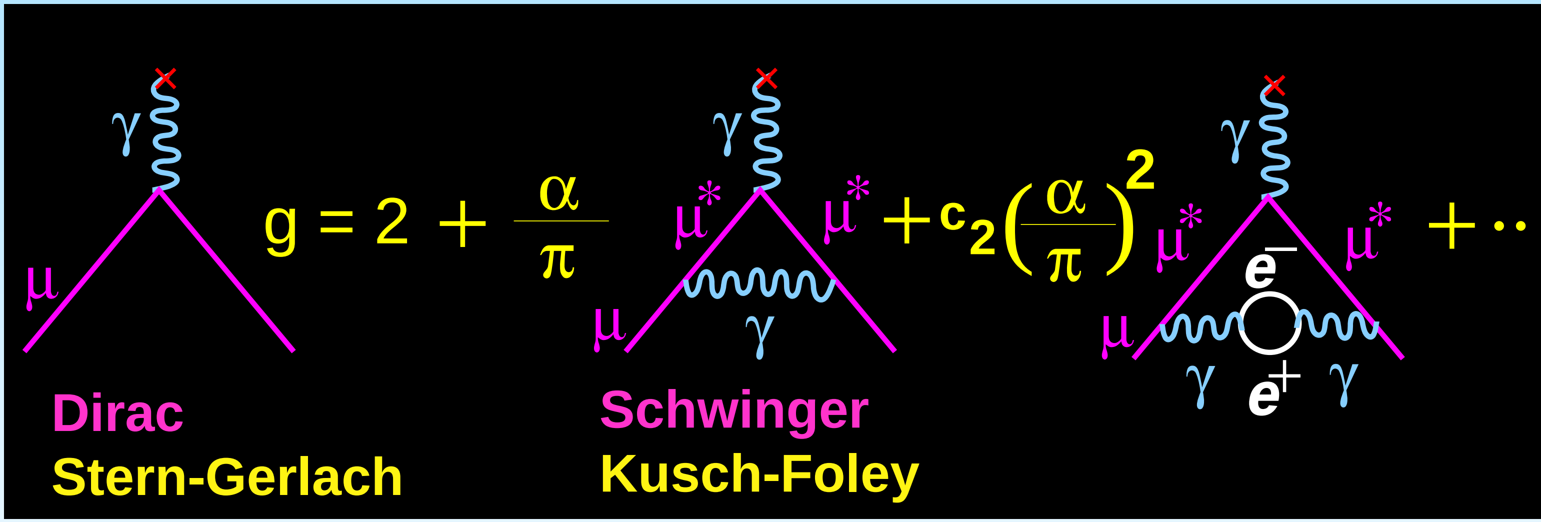
$$\mu = (1 + a)\frac{e\hbar}{2m}$$

Dirac + Pauli moment

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

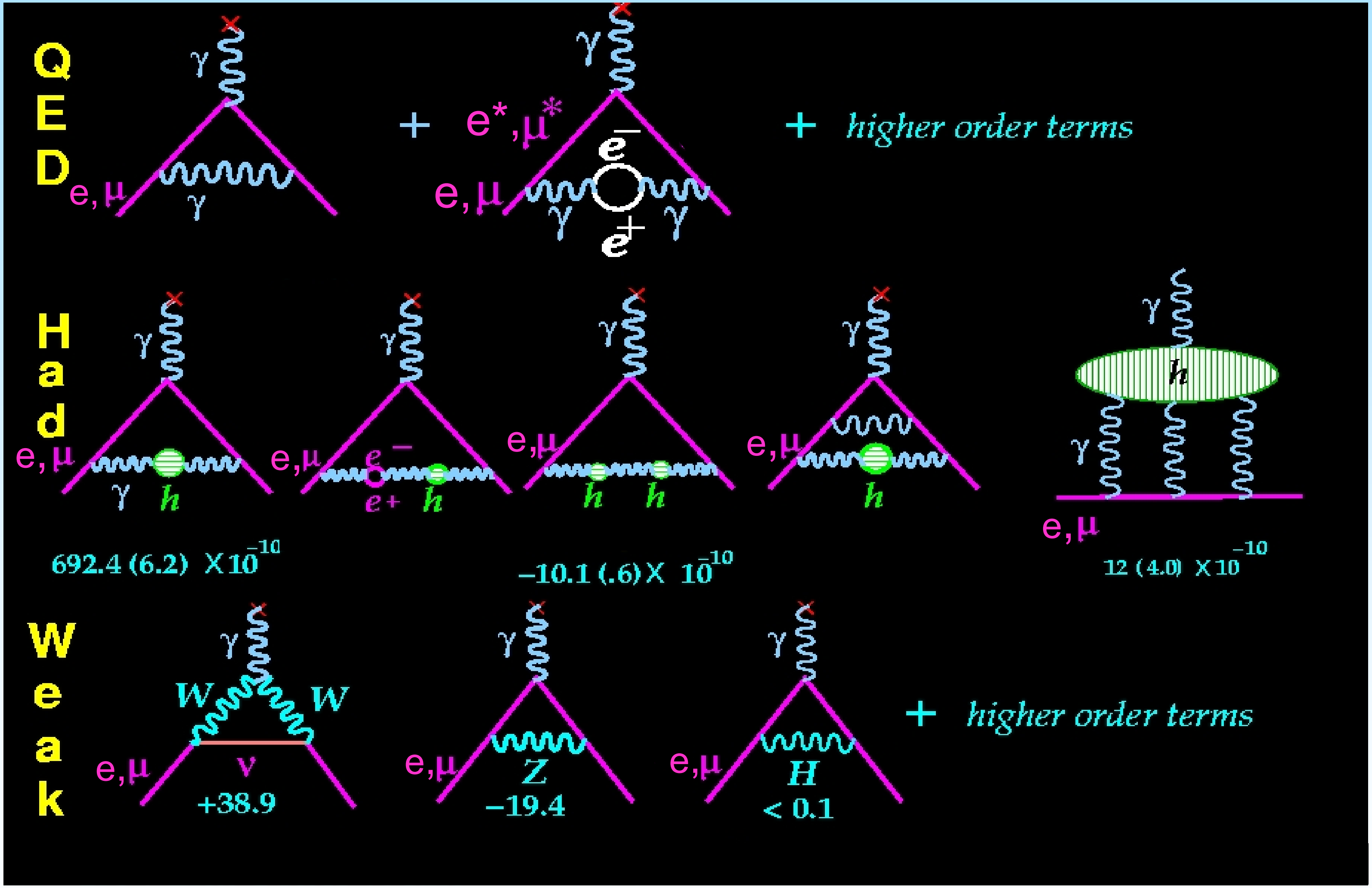


Radiative corrections change g



$$a(\mathrm{QED}) = \frac{1}{2}\frac{\alpha}{\pi} + C_4\left(\frac{\alpha}{\pi}\right)^2 + C_6\left(\frac{\alpha}{\pi}\right)^3 + C_8\left(\frac{\alpha}{\pi}\right)^4 + C_{10}\left(\frac{\alpha}{\pi}\right)^5 + \cdots$$

The SM Value for electron and muon anomalies



e vrs. μ : relative contribution of heavier things $\left(\frac{m_\mu}{m_e}\right)^2 \simeq 42,000$

a_μ is sensitive to a wide range of new physics

- substructure

$$\delta a_\mu(\Lambda_\mu) \simeq \frac{m_\mu^2}{\Lambda_\mu^2}$$

- SUSY (with large tanβ)

$$a_\mu(\mathrm{SUSY}) \simeq \frac{\alpha(M_Z)}{8\pi \sin^2\theta_W}\frac{m_\mu^2}{\tilde{m}^2}\tan\beta\left(1-\frac{4\alpha}{\pi}\ln\frac{\tilde{m}}{m_\mu}\right)$$

$$\simeq (\mathrm{sgn}\mu)\, 13\times 10^{-10} \tan\beta \left(\frac{100\ \mathrm{GeV}}{\tilde{m}}\right)^2$$

- many other things (extra dimensions, etc.)

We measure the difference frequency between the spin and momentum precession

$$\omega_a = \omega_S - \omega_C = \left(\frac{g-2}{2}\right)\frac{eB}{mc} \quad B \Rightarrow \langle B \rangle_{\mu-\text{dist}}$$

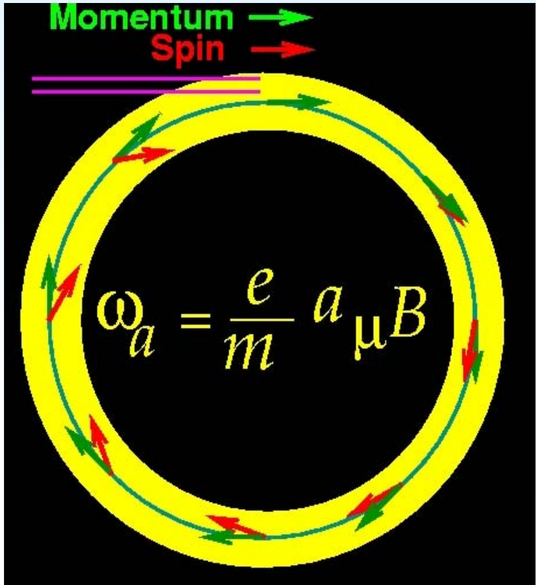
With an electric quadrupole field for vertical focusing

$$\vec{\omega}_a = -\frac{e}{m}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right]$$

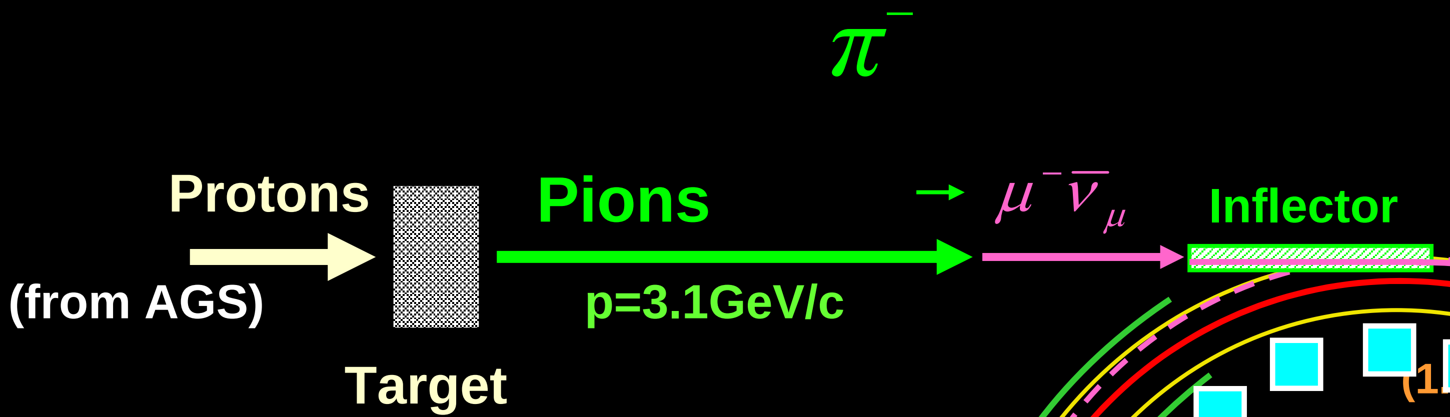
0

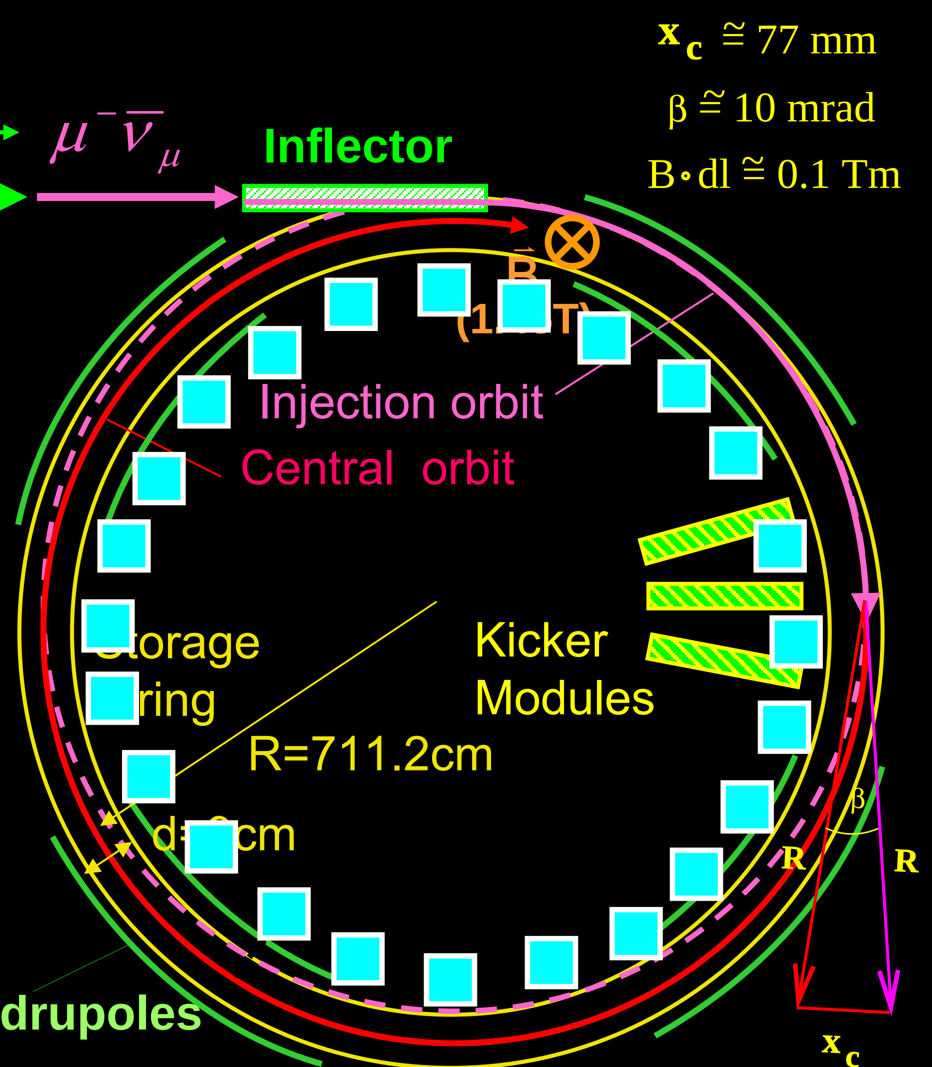
$$\gamma_{\text{magic}} = 29.3$$

$$p_{\text{magic}} = 3.09\ \text{GeV/c}$$



Experimental Technique

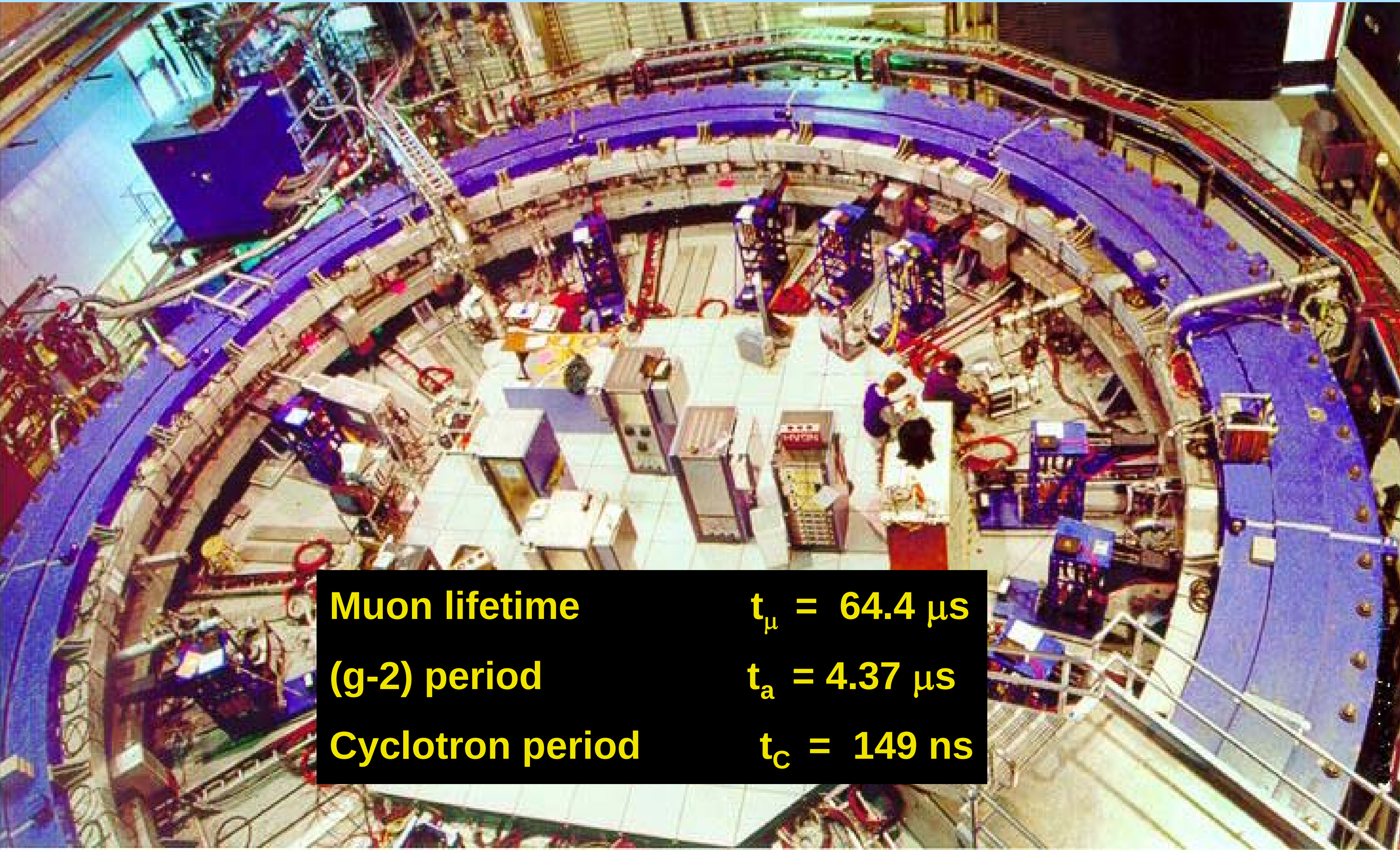




- Muon polarization
- Muon storage ring
- injection & kicking
- focus by Electric Quadrupoles
- 24 electron calorimeters

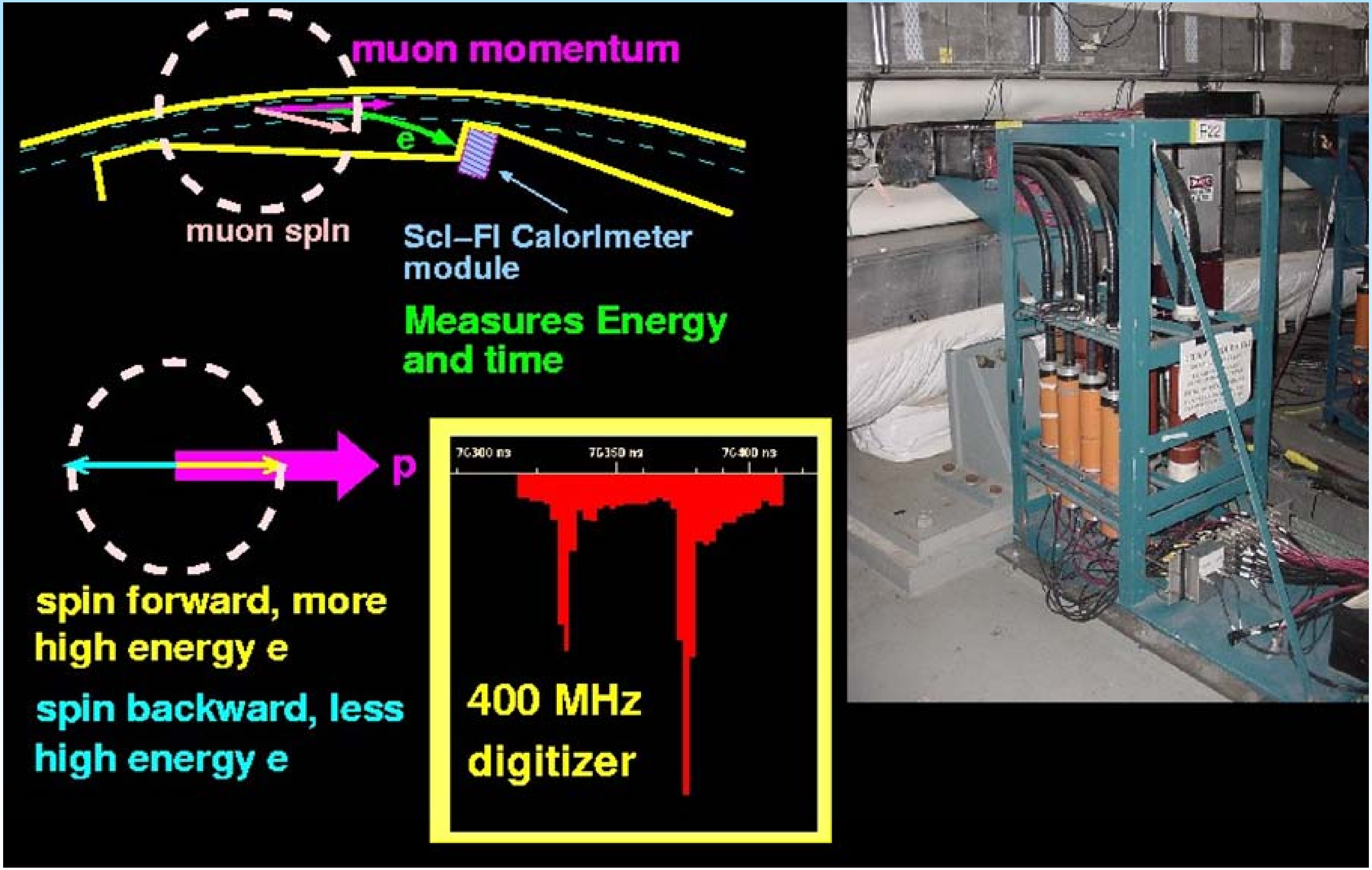
$$\vec{\omega}_a = -\frac{e}{m} a_\mu \vec{B}$$

muon (g-2) storage ring



Muon lifetime	t_{μ} = 64.4 μs
(g-2) period	t_a = 4.37 μs
Cyclotron period	t_C = 149 ns

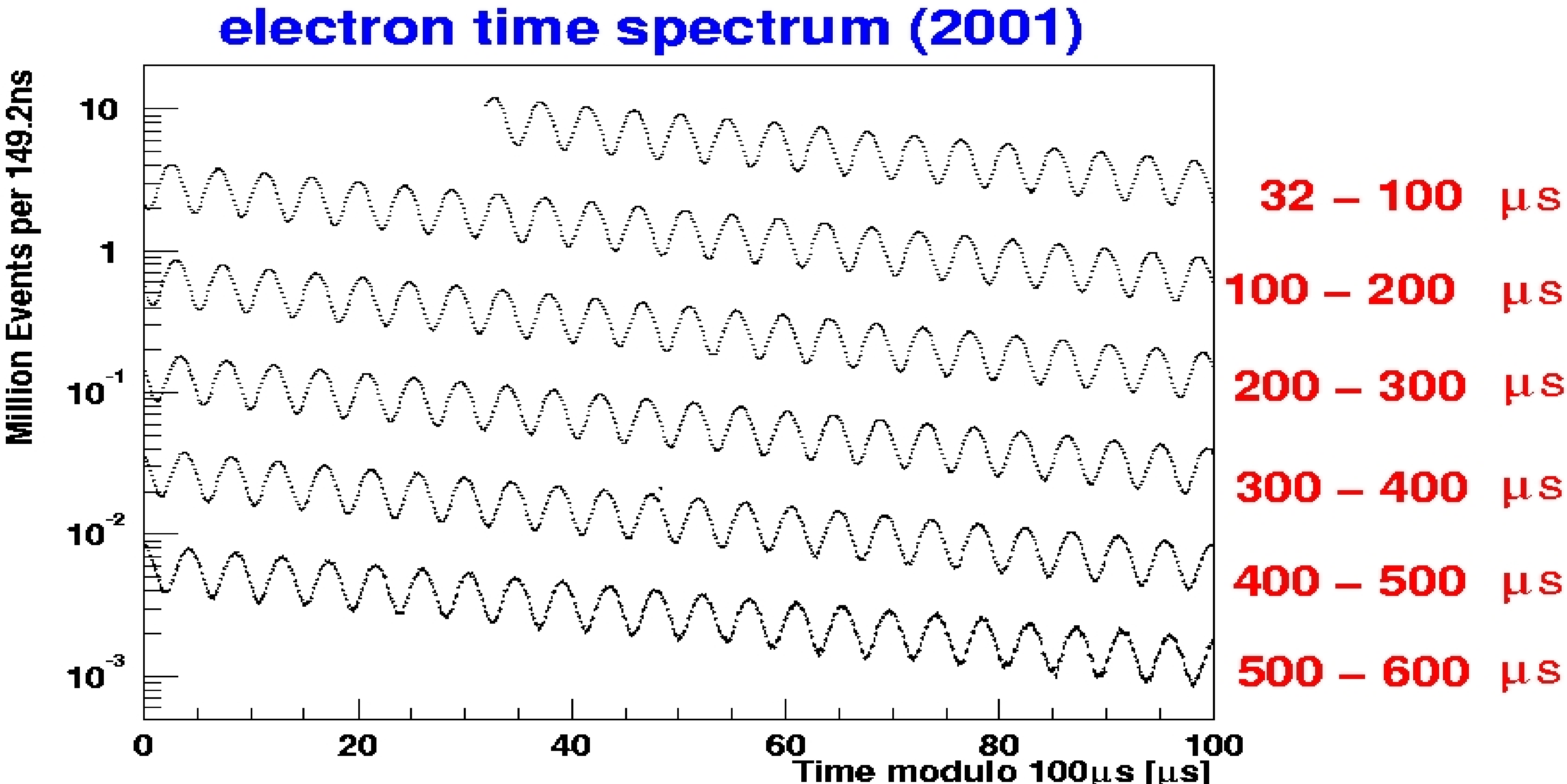
Detectors and vacuum chamber



We count high-energy electrons as a function of time.

$$4 \times 10^9 \quad e,\ E_{e^-} \geq 1.8\ \text{GeV}$$

$$f(t) \simeq N_0 e^{-\lambda t}[1 + A \cos \omega_a t + \phi)]$$



The ± 1 ppm uniformity in the average field is obtained with special shimming tools.

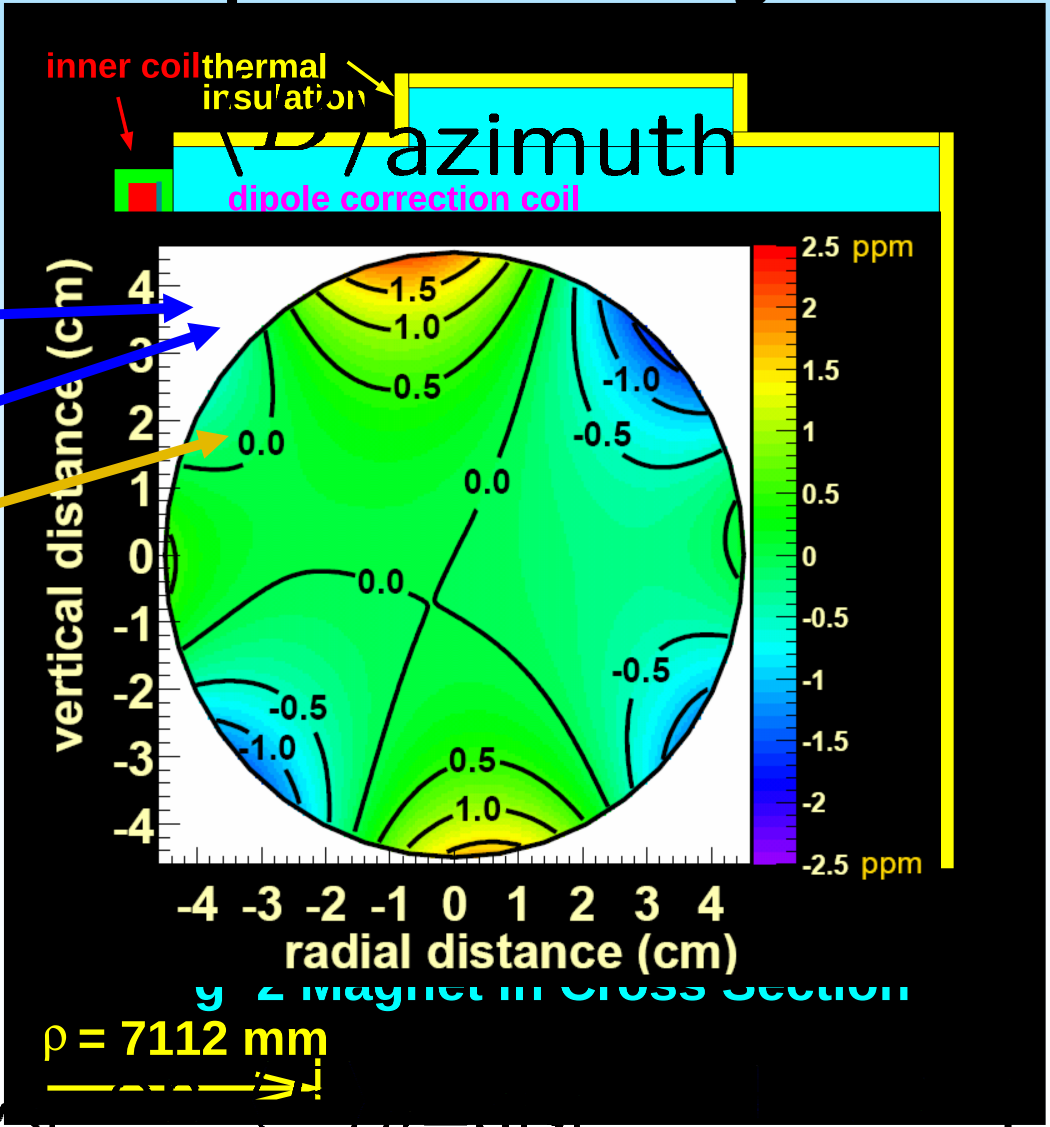
We can shim the

dipole,

quadrupole

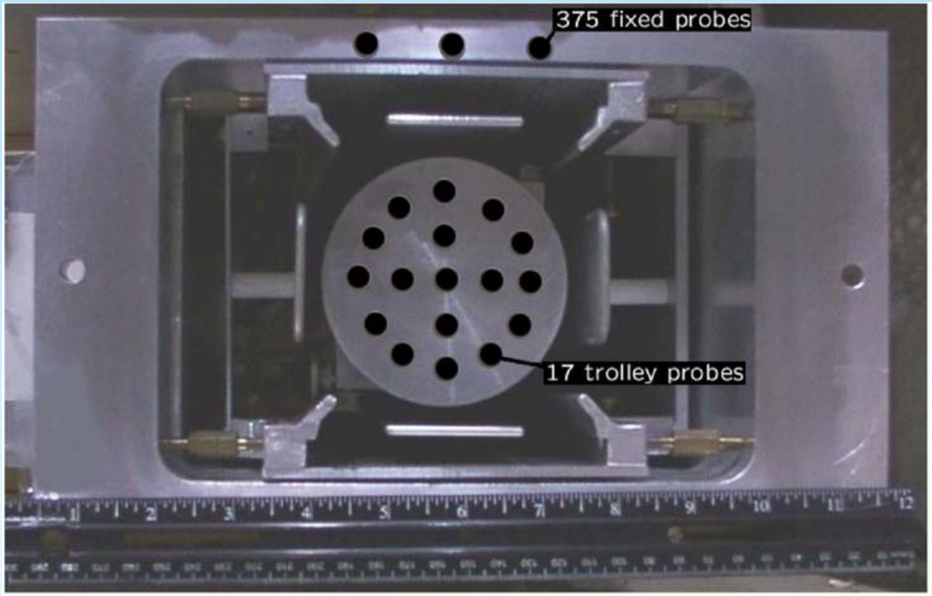
sextupole

independently

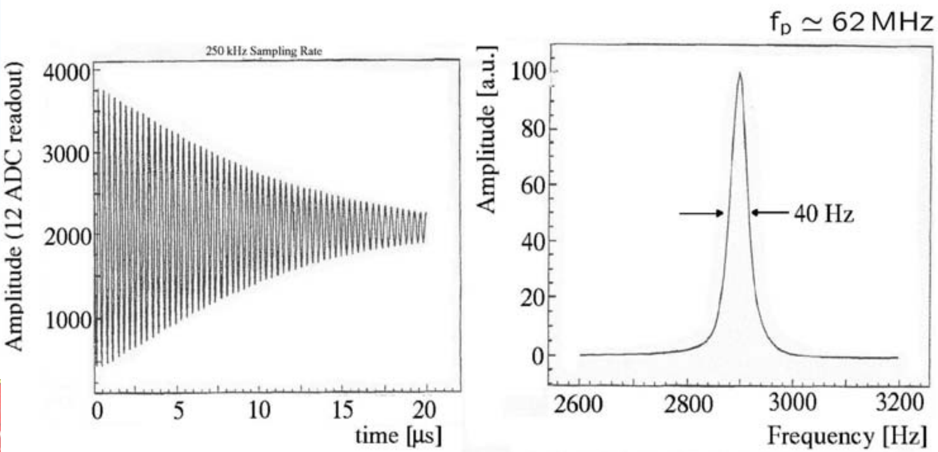


0.5 ppm contours

The magnetic field is measured and controlled using pulsed NMR and the free-induction decay.



Free induction decay signals:



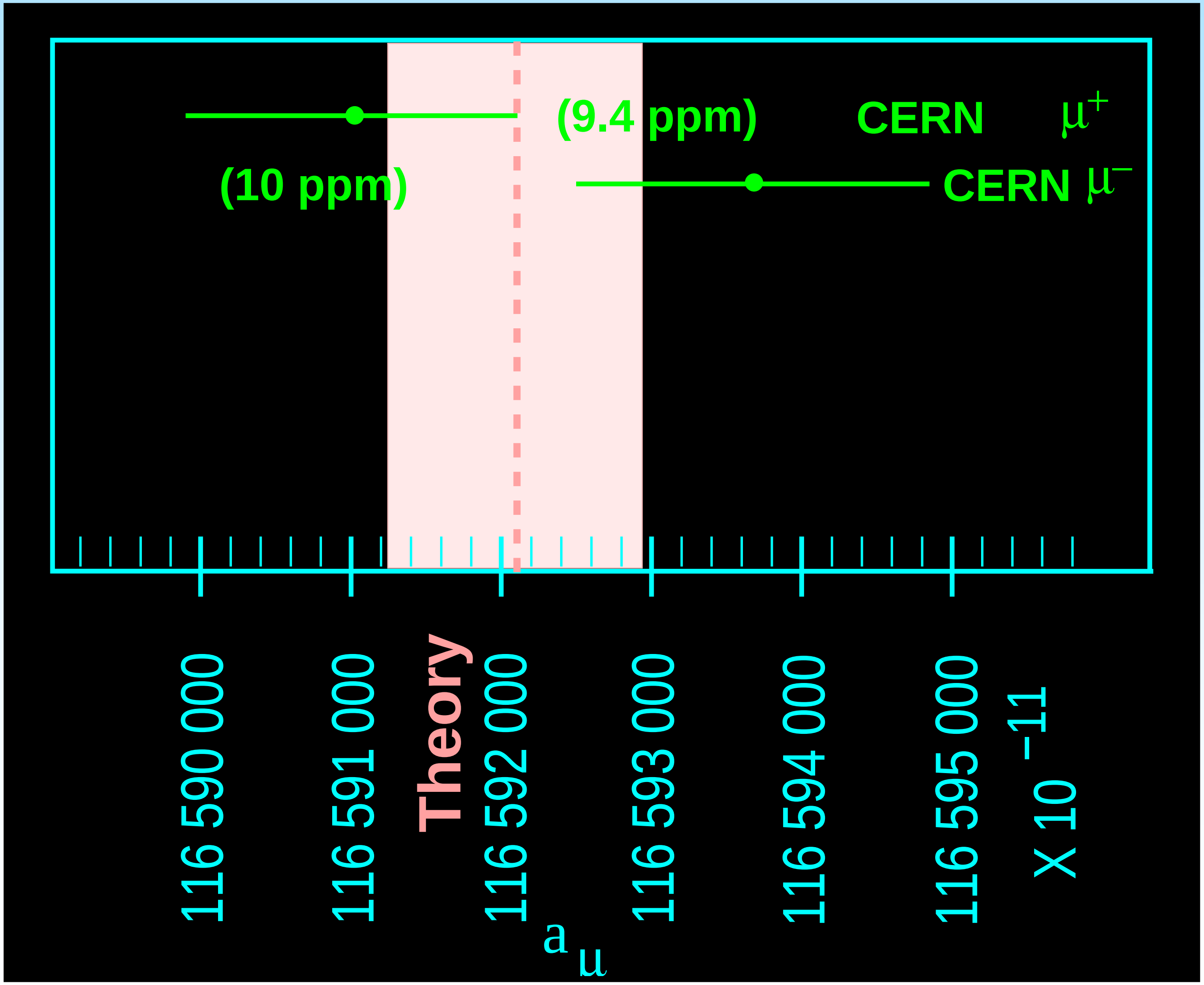
- Calibration to a spherical water sample that ties the field to the Larmor frequency of the free proton ω_p.
- So we measure ω_a and ω_p

$$a_\mu = \frac{\frac{\omega_a}{\omega_p}}{\frac{\mu_\mu}{\mu_p} - \frac{\omega_a}{\omega_p}}$$

When we started in 1983, theory and experiment were known to about 10 ppm.

Theory uncertainty was ~ 9 ppm

Experimental uncertainty was 7.3 ppm

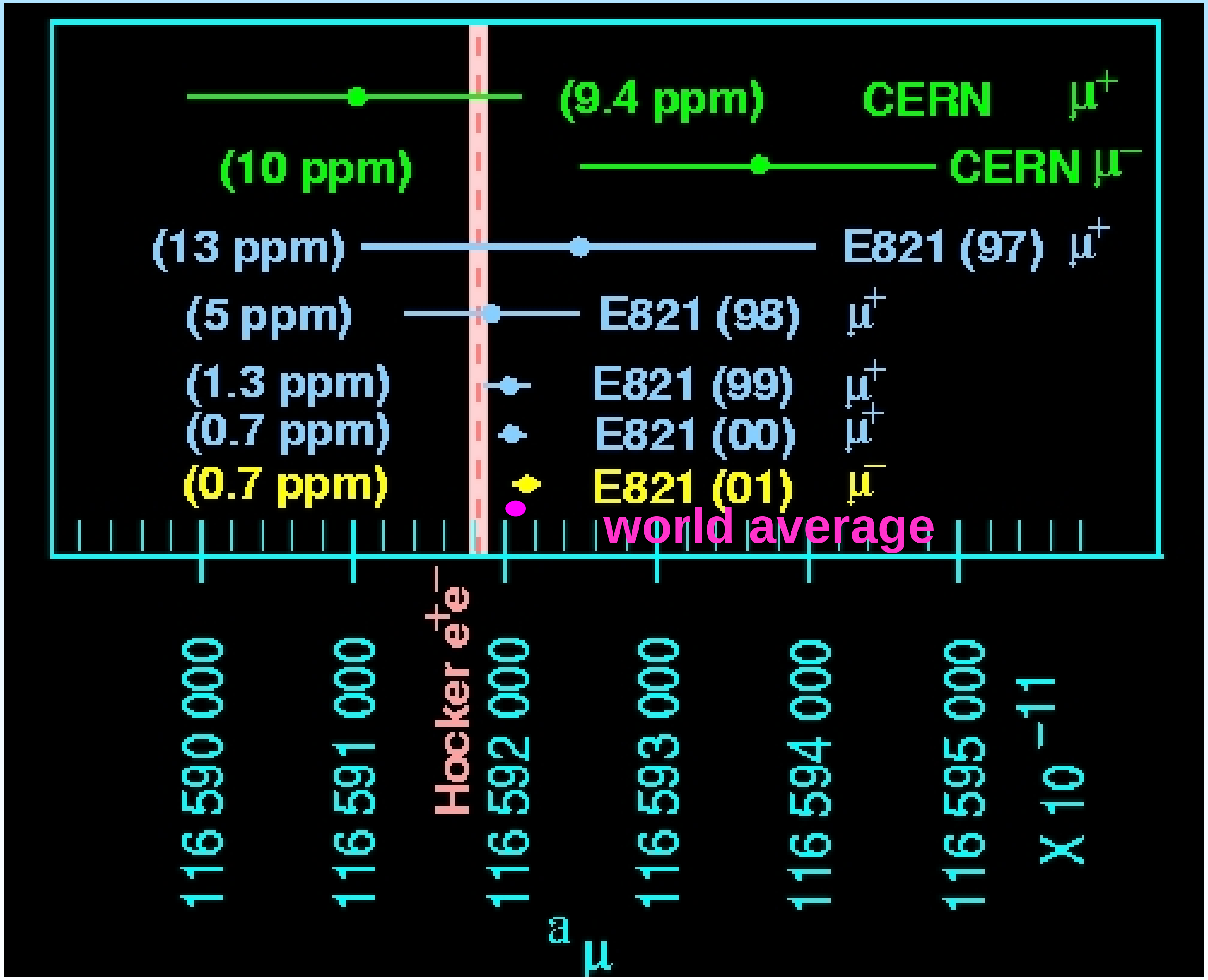


E821 achieved 0.5 ppm and the e^+e^- based theory is also at the 0.6 ppm level. Both can be improved.

All E821 results were obtained with a "blind" analysis.

$\sigma_{\text{stat}} = \pm 0.46$ ppm

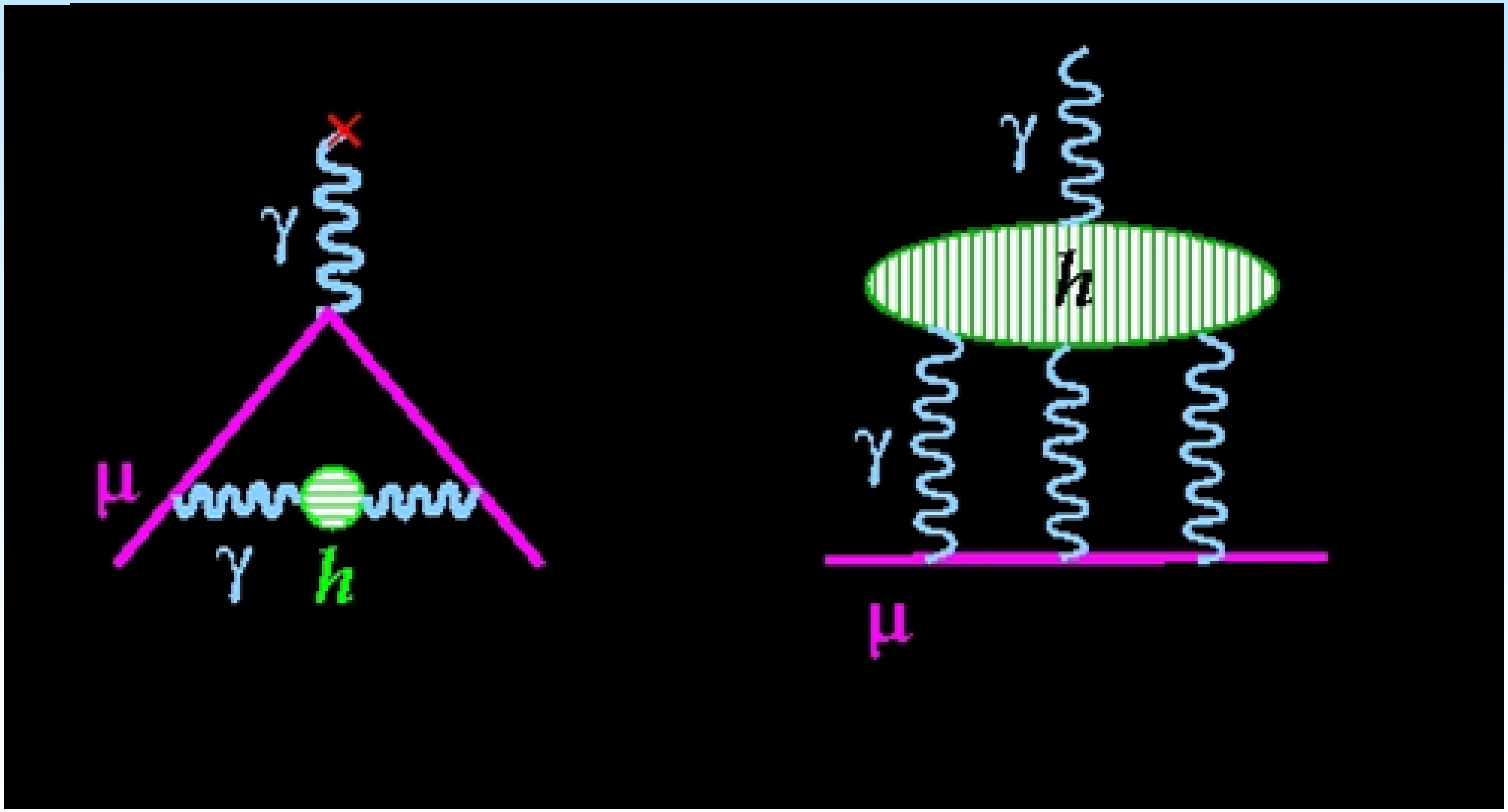
$\sigma_{\text{syst}} = \pm 0.28$ ppm



$$a_\mu = 11\,659\,208(6) \times 10^{-10} \text{ (0.54 ppm)}$$

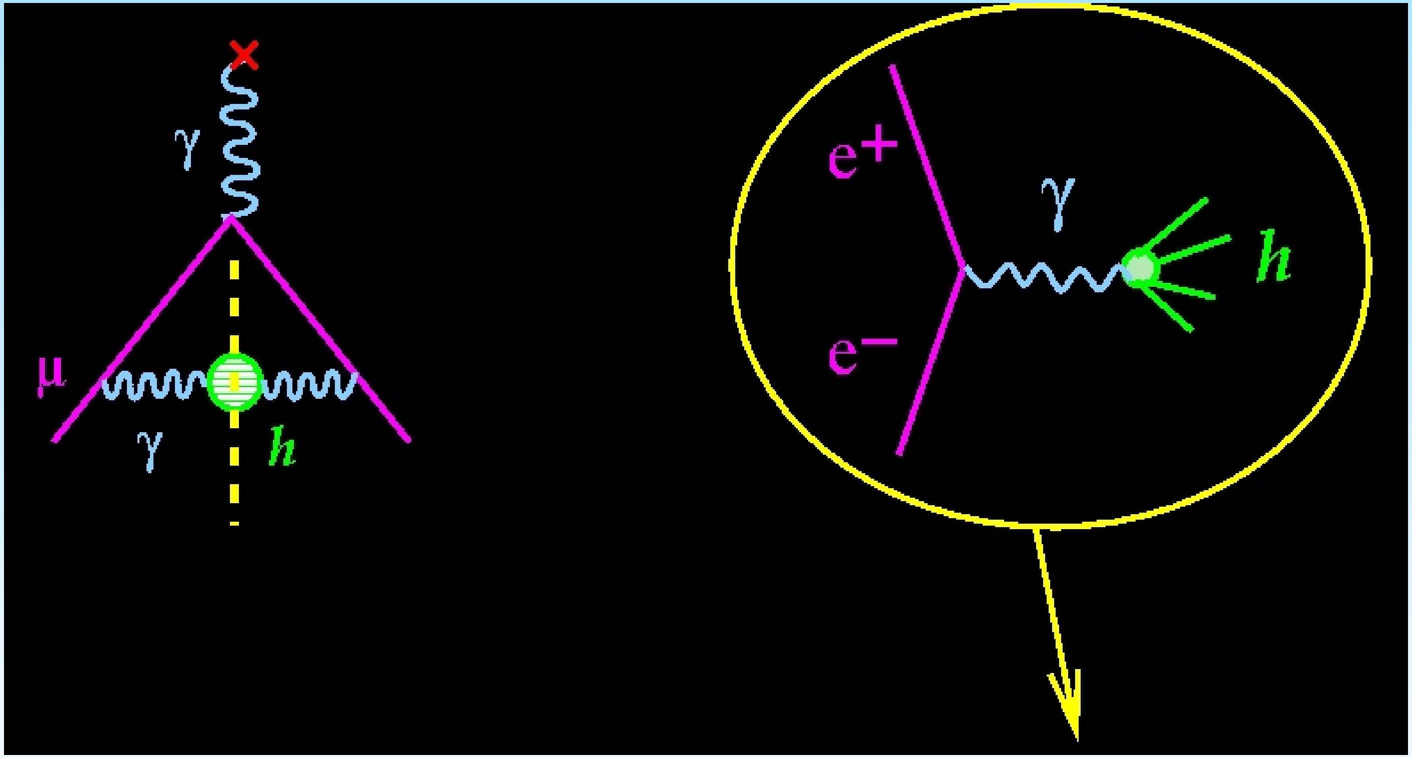
To compare with theory, there are two hadronic issues:

- Lowest order hadronic contribution
- Hadronic light-by-light



$$a_\mu = 11\,659\,208(6) \times 10^{-10} \ (0.54\,\mathrm{ppm})$$

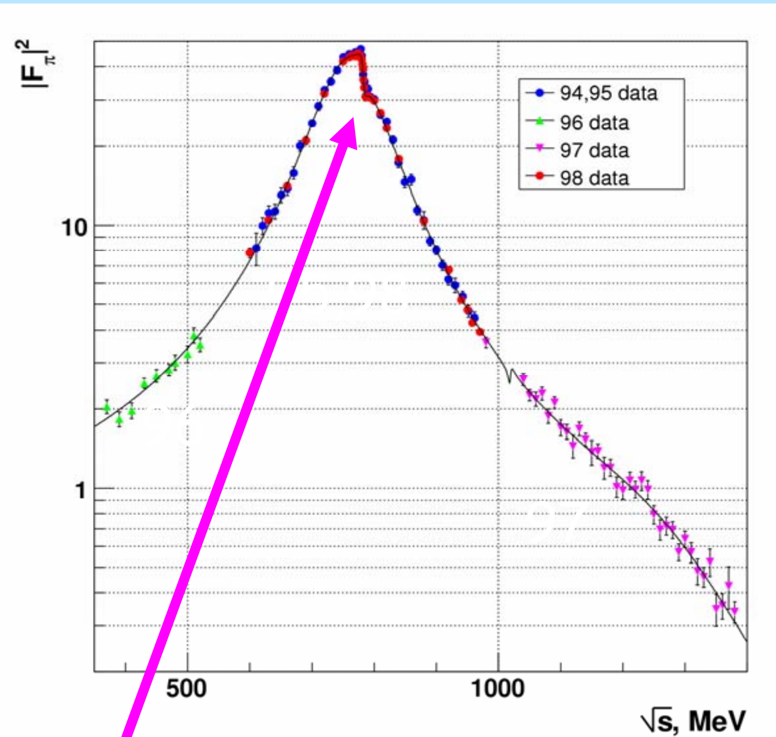
Lowest Order Hadronic from e^+e^- annihilation



$$a_\mu(\text{had}) = \left(\frac{\alpha m_\mu}{3\pi}\right)^2 \int_{4m_\pi^2}^{\infty} \frac{ds}{s^2} K(s) \left(\frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)}\right)$$

Two experiments at the Budker Insitute at Novosibirsk have measured R(s) to better than a percent.

CMD-2



ρ–ω meson interference

1994-1995
114k π+π-

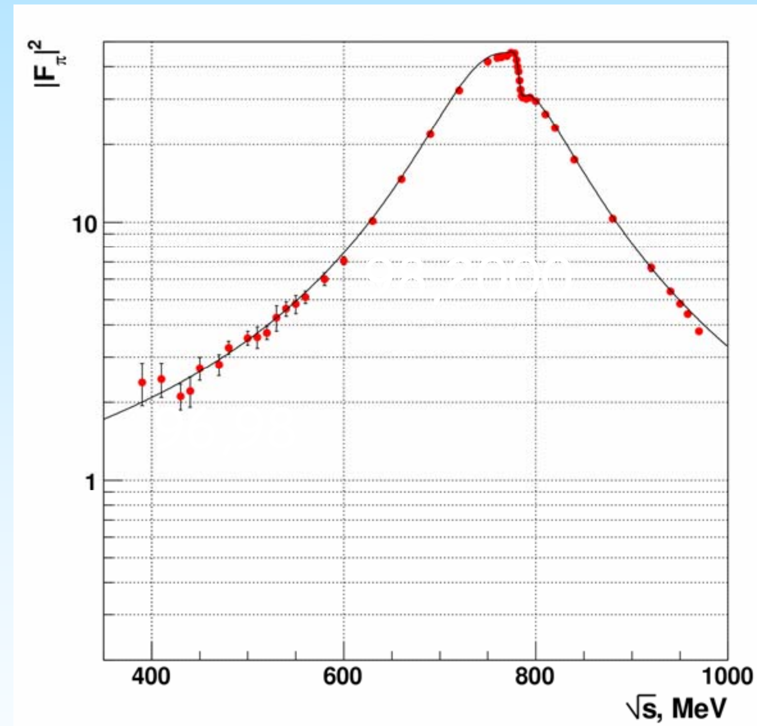
1996
4k π+π-

1997
33k π+π-

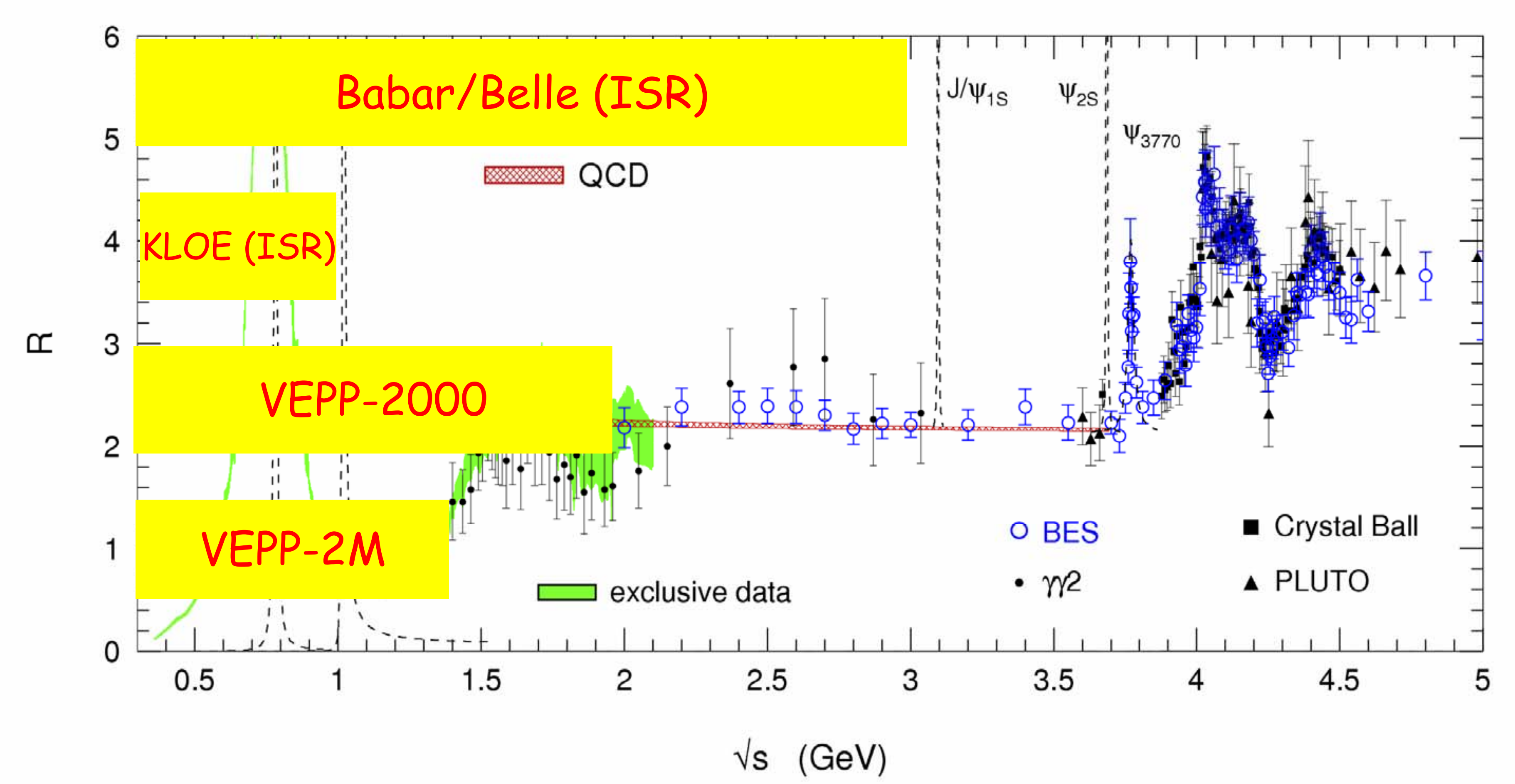
1998
~1M π+π-

2000
~2M π+π-

SND



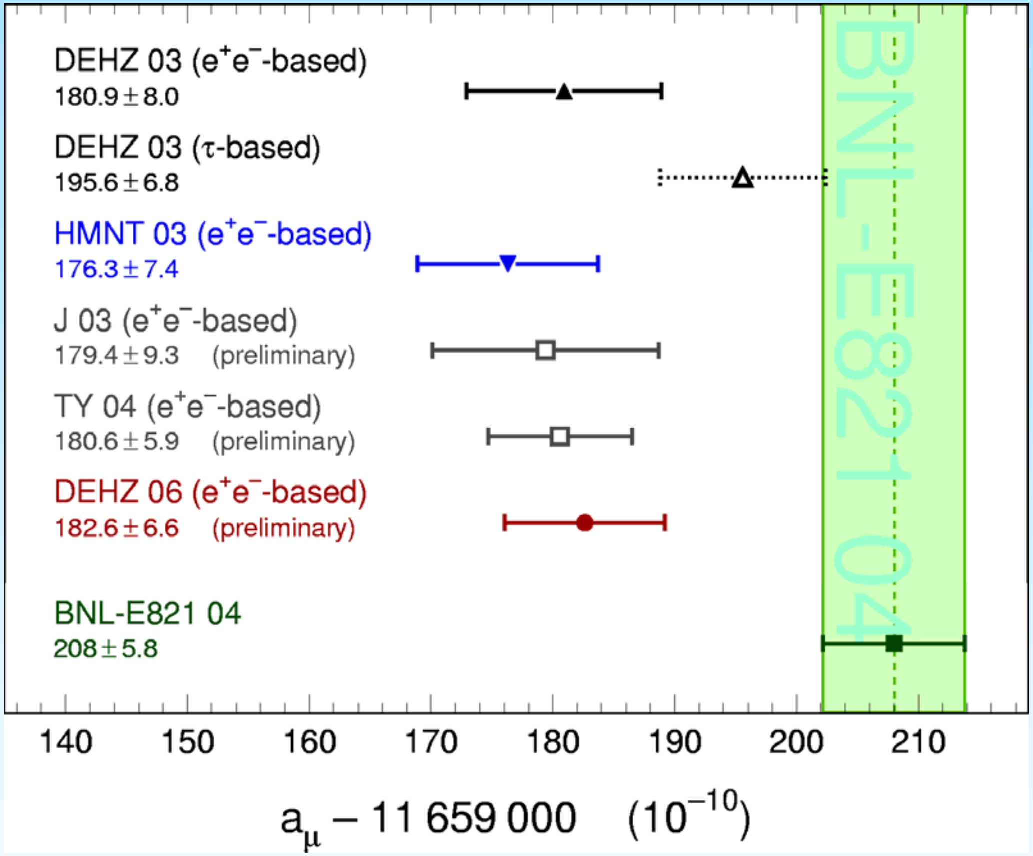
R(s) measurements at low s



At low s the cross-section is measured independently for each final state

from Davier/Höcker

Summary of muon (g-2) (from M. Davier at LM06)



$$a_\mu\,[\mathrm{exp}] - a_\mu\,[\mathrm{SM}] = (25.4 \pm 8.8) \times 10^{-10}$$

➡ 2.9 „standard deviations“

Electric and Magnetic Dipole Moments

Phys. Rev. 78 (1950)

On the Possibility of Electric Dipole Moments for Elementary Particles and Nuclei

E. M. PURCELL AND N. F. RAMSEY
Department of Physics, Harvard University, Cambridge, Massachusetts
April 27, 1950

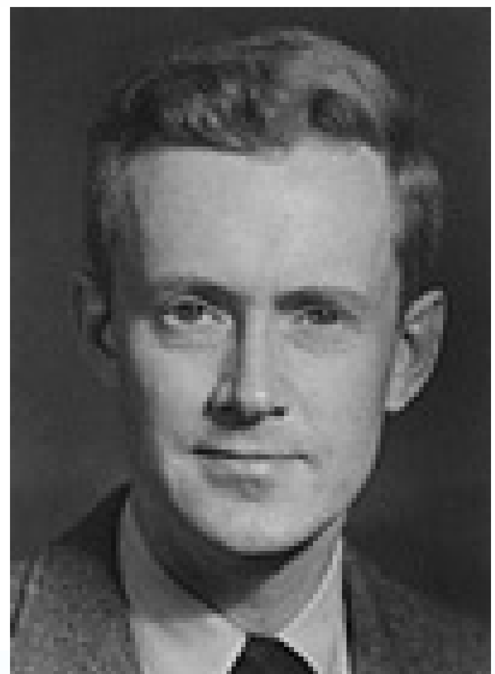
It is generally assumed on the basis of some suggestive theoretical symmetry arguments[1] that nuclei and elementary particles can have no electric dipole moments. It is the purpose of this note to point out that although these theoretical arguments are valid when applied to molecular and atomic moments whose electromagnetic origin is well understood, their extension to nuclei and elementary particles rests on assumptions not yet tested.

One form of the argument against the possibility of an electric dipole moment of a nucleon or similar particle is that the dipole's orientation must be completely specified by the orientation of the angular momentum which, however, is an axial vector specifying a direction of circulation, not a direction of displacement as would be required to obtain an electric dipole moment from electrical charges. On the other hand, if the nucleon should spend part of its time asymmetrically dissociated into opposite magnetic poles of the type that Dirac[2] has shown to be theoretically possible, a circulation of these magnetic poles could give rise to an electric dipole moment. To forestall a possible objection we may remark that this electric dipole would be a polar vector, being the product of the angular momentum (an axial vector) and the magnetic pole strength, which is a pseudoscalar in conformity with the usual convention that electric charge is a simple scalar.

The argument against electric dipoles, in another form, raises directly the question of parity. A nucleon with an electric dipole moment would show an asymmetry between left- and right-handed coordinate systems; in one system the dipole moment

The authors wish to thank Mr. Smith for suggesting an important correction to our original calculation on the neutron-electron interaction experiment.

[1] A typical argument is given by H. A. Bethe, *Elementary Nuclear Theory* (John Wiley and Sons, Inc., New York).
[2] P. A. M. Dirac, Phys. Rev. **74**, 817 (1948).
[3] Havens, Rabi, and Rainwater, Phys. Rev. **72**, 634 (1947).
[4] E. Fermi and L. Marshall, Phys. Rev. **72**, 1139 (1947).
[5] L. W. Alvarez and F. Bloch, Phys. Rev. **57**, 111 (1940).
[6] N. F. Ramsey, Phys. Rev. **76**, 996 (1949).



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Transformation Properties of Electric and Magnetic Dipole Moments

$$\mathcal{H} = -\vec{\mu} \cdot \vec{B} - \vec{d} \cdot \vec{E}$$

$\vec{\mu}$ $\vec{d}$ $\parallel$ to $\vec{\sigma}$

	$\vec{E}$	$\vec{B}$	$\vec{\mu}$ or $\vec{d}$
P	$-$	$+$	$+$
C	$-$	$-$	$-$
T	$+$	$-$	$-$

An EDM implies both *P* and *T* are violated. An EDM at a measureable level would imply non-standard model $\not{CP}$.

However, it should be emphasized that while such arguments are appealing from the point of view of symmetry, they are not necessarily valid.

Ultimately the validity of all such symmetry arguments must rest on experiment.

N.F. Ramsey,

Phys. Rev. 109, 225 (1958)

indicates the existence of a 27-day recurring period which has thus far been followed through four cycles. Presumably, this variation is associated with a solar phenomenon, characterized by this period, which introduces a modulating effect upon the primary cosmic-ray flux. A detailed discussion of these results will be published later.

* Assisted by the joint program of the Office of Naval Research and the U. S. Atomic Energy Commission, and by the U. S. National Committee for the IGY through the National Science Foundation. Field operations sponsored by the National Geographic Society.

[1] See review articles by H. Elliott, in *Progress in Cosmic-Ray Physics*, edited by J. G. Wilson (North-Holland Publishing Company, Amsterdam, 1952), Vol. 1, and by V. Sarabhai and N. W. Nerurkar, in *Annual Review of Nuclear Science* (Annual Reviews, Inc., Stanford, 1956), Vol. 6, p. 1.
[2] S. E. Forbush, J. Geophys. Research **59**, 525 (1954).
[3] H. V. Neher and E. A. Stern, Phys. Rev. **98**, 845 (1955).
[4] P. Meyer and J. A. Simpson, Phys. Rev. **99**, 151 (1955).
[5] J. R. Winckler and K. A. Anderson, Phys. Rev. **108**, 148 (1957).
[6] J. Winckler (private communication).
[7] M. A. Pomerantz, Phys. Rev. **77**, 830 (1950); and G. W. McClure, Phys. Rev. **86**, 536 (1952).
[8] M. A. Pomerantz, Phys. Rev. **102**, 870 (1956), and earlier references contained therein.

Time Reversal, Charge Conjugation, Magnetic Pole Conjugation, and Parity

N. F. Ramsey
Lyman Physics Laboratory, Harvard University, Cambridge, Massachusetts
(Received November 14, 1957)

UNTIL recently various theorems on the properties of elementary particles and of nuclei were based on parity arguments whose validity was questioned[1] only rarely. It is now known from the theoretical work of Lee and Yang[2] and from the experiments of Wu, Ambler, *et al.*[3] and of others[4,5] that the parity arguments are often not valid. Recently some of the properties previously derived from parity arguments have been rederived from other symmetry properties such as time-reversal invariance,[6,7] invariance under the combined operation (*TCP*) of time reversal, charge conjugation, and parity,[8–11] etc. Landau,[6] for example, has shown from a time-reversal argument that particles cannot possess electric dipole moments.

However, it should be emphasized that while such arguments are appealing from the point of view of symmetry, they are not necessarily valid. Ultimately the validity of all such symmetry arguments must rest upon experiment. For example, if magnetic monopoles exist and if elementary particles are differently coupled to north and to south poles, the conclusions drawn from the normal symmetry arguments would be modified. Dirac[12] has shown that it is theoretically possible that such magnetic poles should exist and that their possibility of existence might be related to the experimentally observed quantization of electric charge.

In a theory which includes the effects of magnetic poles, the *TCP* theorem would be replaced by a *TMCP* theorem where *T* represents simple time reversal, *M* magnetic pole conjugation, *C* electric charge conjugation, and *P* simple inversion of space coordinates. It is of course possible to express the theorem in various ways, such as

$$(TM)\quad(MC)\quad(PM)=T'\quad C'\quad P',$$

where T' indicates an extended time reversal whose definition includes magnetic pole conjugation as well, C' represents conjugation of both electric and magnetic charges, and P' represents a parity transformation which includes magnetic pole conjugation as well. This method of writing has the advantage that consistency with Maxwell's equations requires that a simple parity transformation be accompanied by either magnetic pole conjugation or electric charge conjugation (but not both) since otherwise a magnetic field would be a mixture of a vector and a pseudovector depending on its mixed origin from magnetic and electric poles. On the other hand, this requirement would equally well be satisfied if the theorem were written as (*TC*) (*MC*) (*PC*). A still different but equivalent procedure leading to a *TMCP* or equivalent *TC′P* theorem could be based on treating the magnetic charges in the fundamental equations as pseudoscalars with respect to both space and time reflections.

Since the experimental observations of parity nonconservation, it has been generally assumed,[6,7] pending further experiments,[7] that there should be invariance under the combination of *P* and *C* together in which case from the usual *TCP* theorem, invariance under *T* alone is inferred. On the other hand, with the possibility of magnetic poles, the above *TMCP* theorem would apply and invariance under *P* and *C* would imply invariance under *T* and *M* together and not each alone. If this were the case, the present proof[6] for the nonexistence of electric dipole moments for particles would no longer apply; an electric dipole moment could be proportional to the product of a magnetic pole and a spin angular momentum in which case each would change sign under *TM*, but their product and resulting electric field would not. A particle (such as all presently observed particles) whose magnetic monopole is zero could still possess an electric dipole moment by the above mechanism provided it were differently coupled to fields of north pole particles than to those of south poles. Such a coupling asymmetry, in addition to making possible the existence of an electric dipole moment, would also imply an added possible particle degeneracy since magnetic pole conjugation alone would provide a transformation to a particle of opposite magnetic pole coupling asymmetry and opposite electric dipole moment while the electric charge would be unaltered.

PHYSICAL REVIEW VOLUME 108, NUMBER 1 OCTOBER 1, 1957

Experimental Limit to the Electric Dipole Moment of the Neutron

J. H. SMITH,* E. M. PURCELL, AND N. F. RAMSEY
Oak Ridge National Laboratory, Oak Ridge, Tennessee, and Harvard University, Cambridge, Massachusetts
(Received May 17, 1957)

An experimental measurement of the electric dipole moment of the neutron by a neutron-beam magnetic resonance method is described. The result of the experiment is that the electric dipole moment of the neutron equals the charge of the electron multiplied by a distance $D=(-0.1\pm2.4)\times10^{-20}$ cm. Consequently, if an electric dipole moment of the neutron exists and is associated with the spin angular momentum, its magnitude almost certainly corresponds to a value of D less than 5×10^{-20} cm.

1. INTRODUCTION

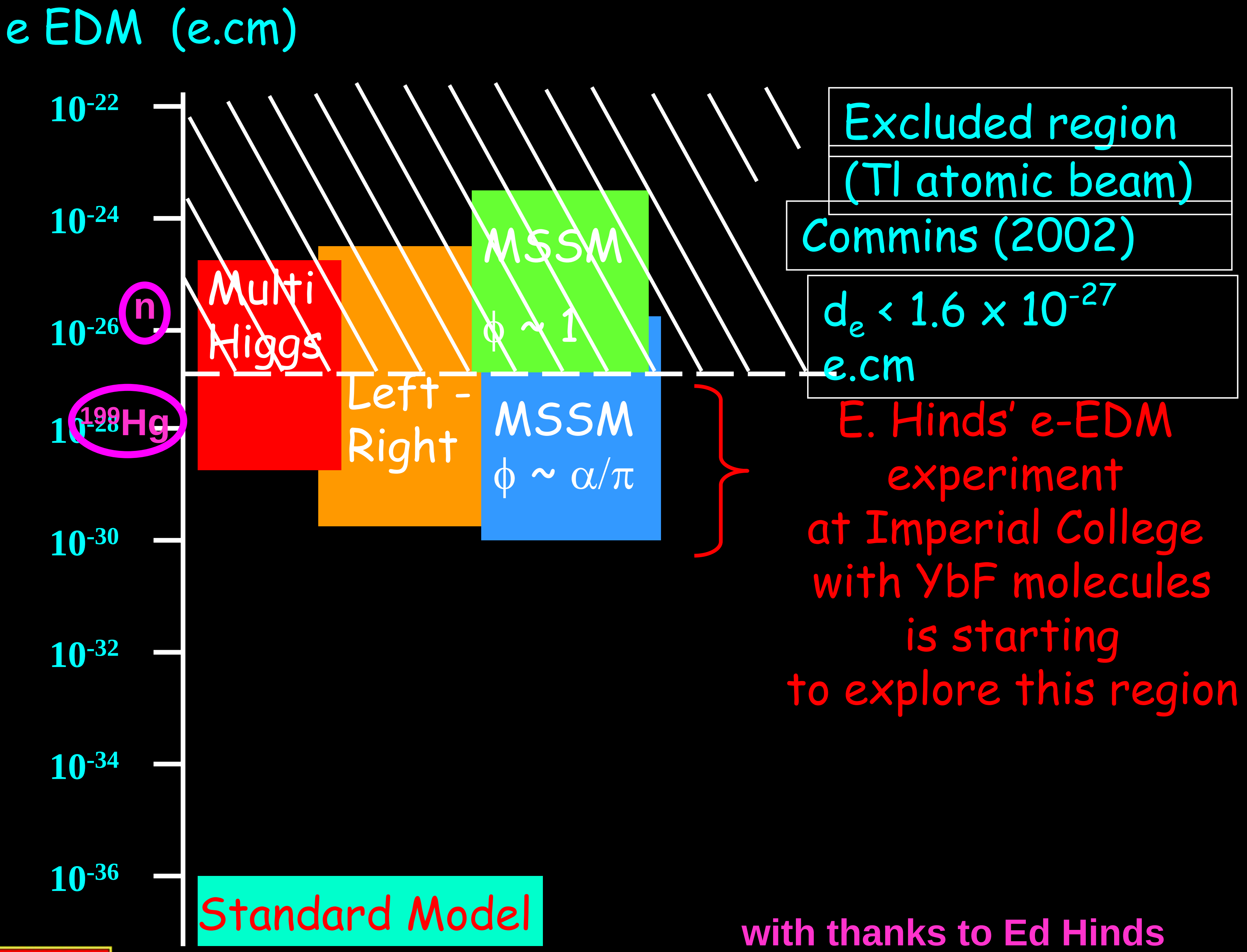
SEVERAL years ago Purcell and Ramsey[1] pointed out that the usual parity arguments for the nonexistence of electric dipole moments for nuclei and elementary particles, although appealing from the point of view of symmetry, were not necessarily valid. In particular they pointed out that the validity of the parity assumption must rest on experimental evidence and that the experimental evidence was not as conclusive as then generally supposed in the case of nuclei and elementary particles, even though there was abundant evidence for the assumption in the case of electromagnetic forces. Analysis of the experimental evidence against the existence of electric dipole moments

decay, the angular distributions of π-μ-e decays, and existence of electric dipole moments of particles. The effects of the first two of these have been observed by Wu, Ambler, Hayward, Hoppes, and Hudson,[7] and by Garwin, Lederman, and Weinrich.[8] Since electric moments are primarily determined by the strong forces, Lee and Yang[6] showed that the effect of mixed parity should produce an electric dipole moment even smaller than the upper limit set by the experiment described in the present paper. In their most recent theories, Lee and Yang[9] no longer anticipate the existence of an electric dipole moment for the neutron, and arguments involving time-reversal invariance[9,10] can be advanced against its existence. These arguments, however, like the original ones of parity, can be questioned.

Present EDM Limits

Particle	*Present EDM limit* (e-cm)	*SM value* (e-cm)
n	3×10^{-26} (90%CL)	10^{-32} to 10^{-31}
e^-	1.6×10^{-27} (90%CL)	$< 10^{-41}$
μ	$< 10^{-18}$ (CERN) $\sim 10^{-19}$ * (E821)	$< 10^{-38}$
^{199}Hg	2.1×10^{-28} (95%CL)	

*not yet final



with thanks to Ed Hinds

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Muon EDM: Naïve scaling would imply that

$$\left|\frac{d_\mu}{d_e}\right| \sim \frac{m_\mu}{m_e} \quad \Rightarrow \quad d_\mu < \mathcal{O}(10^{-25})\ e\ \mathrm{cm}$$

but in some models the dependence is greater.

VOLUME 85, NUMBER 24 PHYSICAL REVIEW LETTERS 11 DECEMBER 2000

Enhanced Electric Dipole Moment of the Muon in the Presence of Large Neutrino Mixing

K. S. Babu,[1] B. Dutta,[2] and R. N. Mohapatra[3]

[1]*Department of Physics, Oklahoma State University, Stillwater, Oklahoma 74078*
[2]*Center for Theoretical Physics, Department of Physics, Texas A & M University, College Station, Texas 77843*
[3]*Department of Physics, University of Maryland, College Park, Maryland 20742*

(Received 12 July 2000)

The electric dipole moment (edm) of the muon (d_μ^e) is evaluated in supersymmetric models with nonzero neutrino masses and large neutrino mixing arising from the seesaw mechanism. It is found that if the seesaw mechanism is embedded in the framework of a left-right symmetric gauge structure, the interactions responsible for the right-handed neutrino Majorana masses lead to an enhancement in d_μ^e to values as large as $5 \times 10^{-23} e$ cm, with a correlated value of $(g-2)_\mu \simeq 13 \times 10^{-10}$. This should provide a strong motivation for improving the edm of the muon to the level of $10^{-24} e$ cm as has recently been proposed.

$$\Delta_{\mathrm{now}} = (25.4 \pm 8.8) \times 10^{-10}$$

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Spin Frequencies: μ in B field with MDM & EDM

$$\omega_C = \frac{eB}{mc\gamma} \qquad \omega_S = \frac{geB}{2mc} + (1-\gamma)\frac{eB}{\gamma mc}$$

$$\omega_a = \omega_S - \omega_C = \left(\frac{g-2}{2}\right)\frac{eB}{mc}$$

$$\gamma_{\text{magic}} = 29.3$$

$$\omega_a \quad + \quad \frac{e}{m}\left[\frac{\eta}{2}\left(\frac{\vec{E}}{c} + \vec{\beta}\times\vec{B}\right)\right]$$

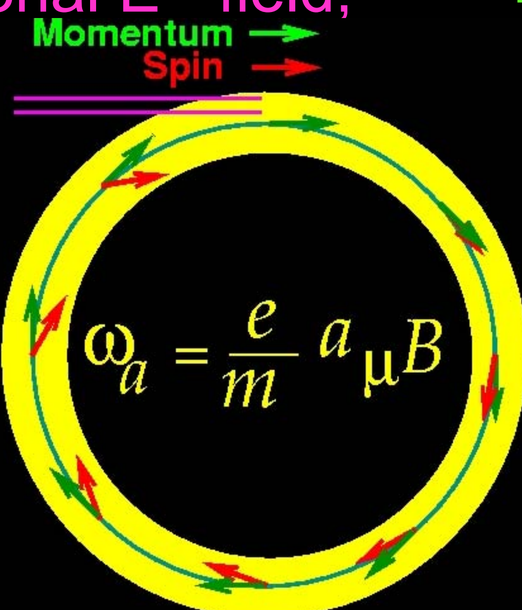
spin difference frequency = ω_s - ω_c

The motional E - field, β X B, is
than labo
fields (~G

η

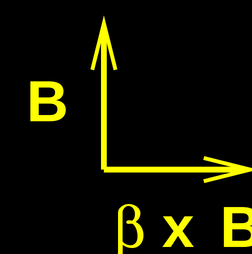
le)

10^{-14} e cm



The EDM
spin to p
of plane.

The highest energy decay e± are along the muon spin direction



Dedicated EDM Experiment

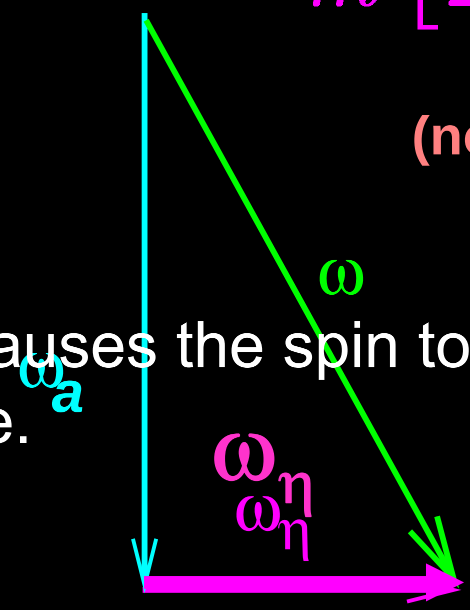
$$\vec{\omega} = -\frac{e}{m}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right] \rightarrow 0$$

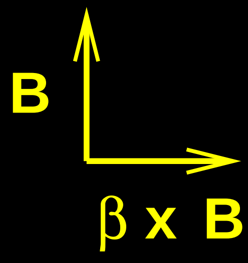
Use a radial E-field to turn off the ω_a precession

$$+ \frac{e}{m}\left[\frac{\eta}{2}\left(\frac{\vec{E}}{c} + \vec{\beta}\times\vec{B}\right)\right]$$

(not to scale)

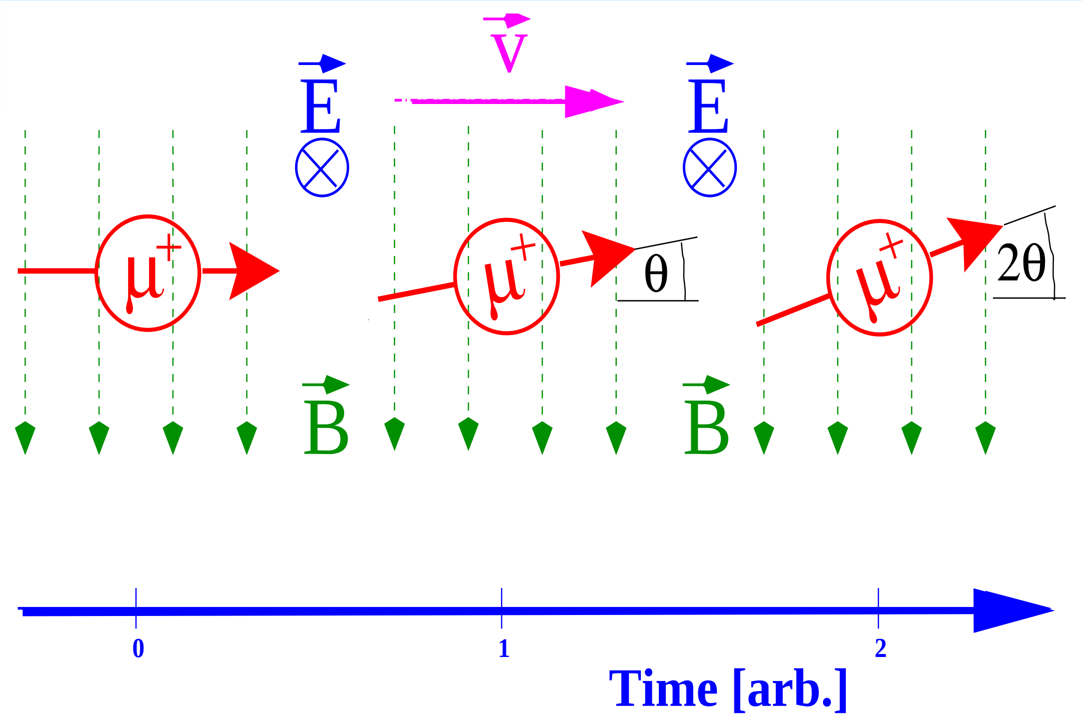
With ω_a = 0, the EDM causes the spin to steadily precess out of the plane.





"Frozen spin" technique

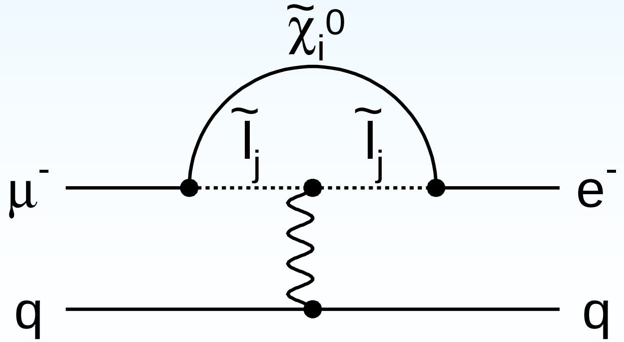
- Turn off the (g-2) precession with radial E
- Look for an up-down asymmetry building up with time



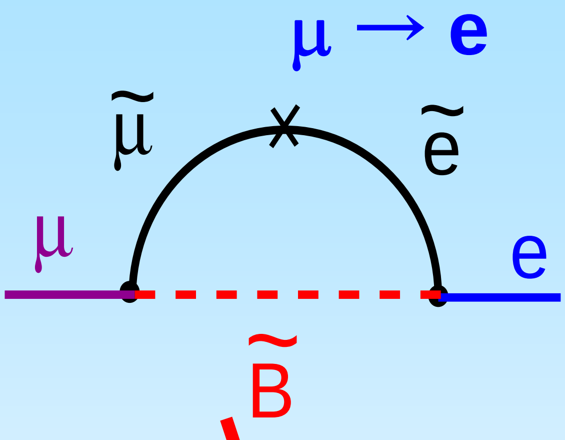
Lepton Flavor Violation (the transition moment)

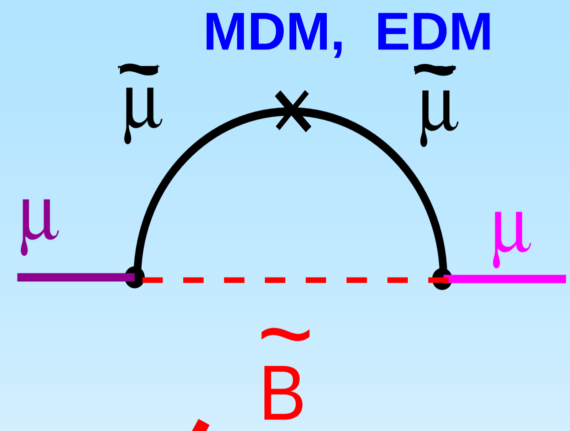
$$\mu^- A \to e^- A$$
$$\mu^+ \to e^+ \gamma$$
$$\mu^+ \to e^+ e^- e^+$$

- The standard-model gauge bosons do not permit leptons to mix, but new physics at the TeV scale such as SUSY does.



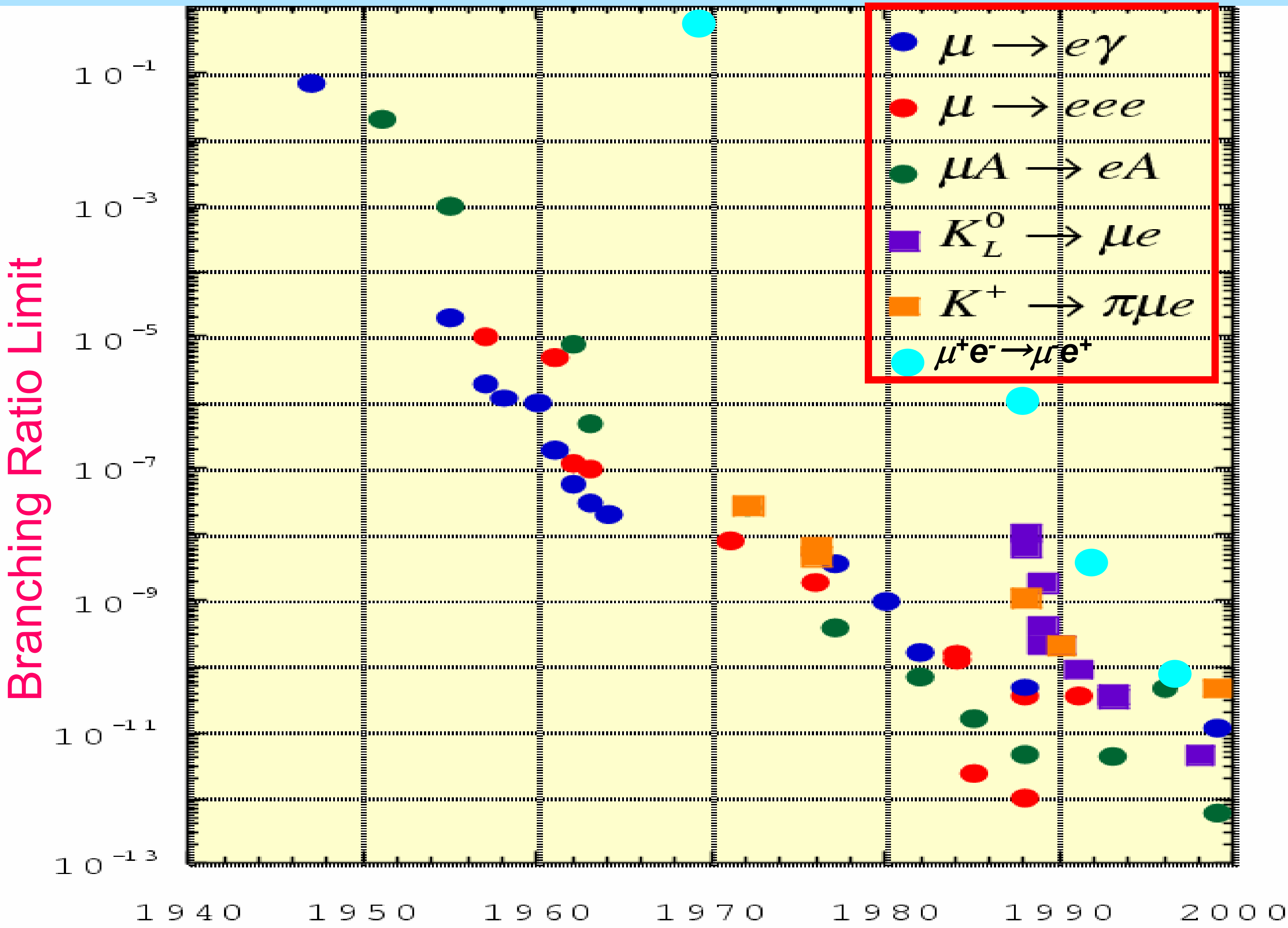
SUSY connection between a_μ , D_μ , $\mu \rightarrow e$





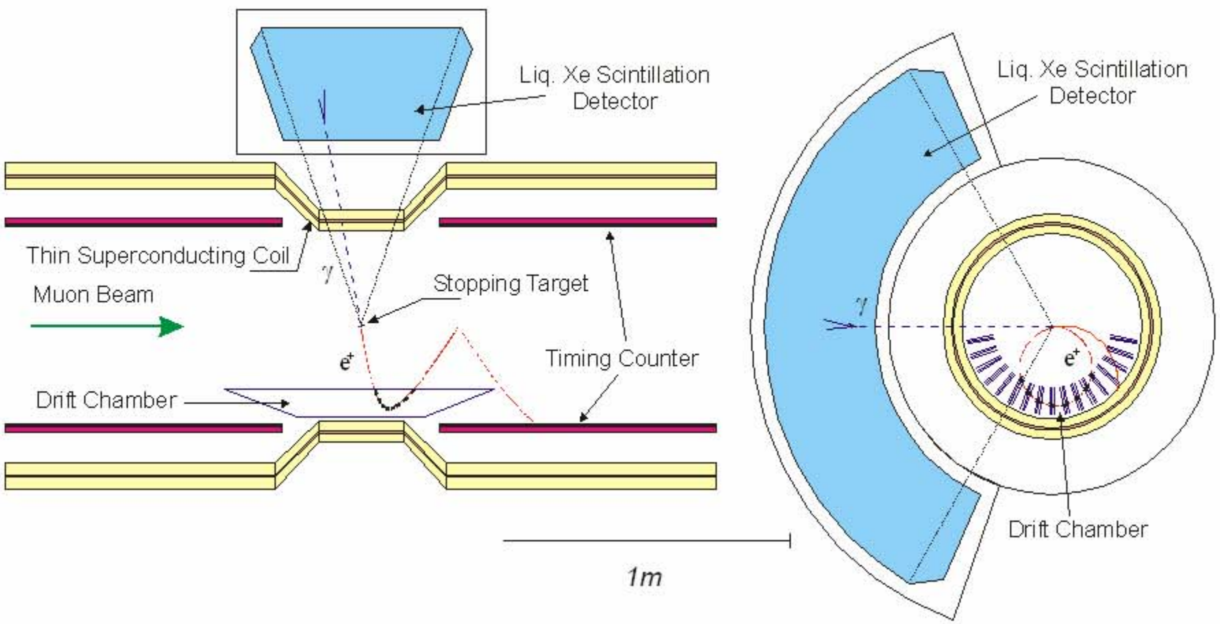
$$\begin{pmatrix} m^2_{\tilde{e}\tilde{e}} & \Delta m^2_{\tilde{e}\tilde{\mu}} & \Delta m^2_{\tilde{e}\tilde{\tau}} \\ \Delta m^2_{\tilde{\mu}\tilde{e}} & m^2_{\tilde{\mu}\tilde{\mu}} & \Delta m^2_{\tilde{\mu}\tilde{\tau}} \\ \Delta m^2_{\tilde{\tau}\tilde{e}} & \Delta m^2_{\tilde{\tau}\tilde{\mu}} &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

Past and Future of LFV Limits

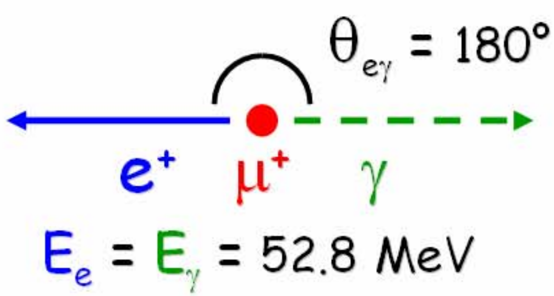


MEG Experiment (@PSI) $\mu^+ \rightarrow e^+ \gamma$

The Detector



- **Muon beam stopped** in a **150** μm target
- **Liquid Xenon calorimeter** for γ detection (using scintillation light)
- **(Thin wall) solenoid spectrometer & drift chambers** for e^+ momentum
- **Scintillation counters** for e^+ timing



Easy signal selection for μ+ decaying at rest

Discovery Potential: Single event sensitivity ~ 1 X 10^{-13}

Summary and Outlook

- The muon has provided us with much knowledge on how nature works.
- New experiments on the horizion continue this tradition.
- Muon (g-2), with a precision of 0.5 ppm, has a 2.9 σ discrepancy with the standard model.
  - Upgrade, E969 waits for funding decision in 10/06
- This new physics, if confirmed, would show up in an EDM and perhaps LFV as well.
- MEG is set to turn on and collect data in the next year.
- Muon-electron conversion holds the best experimental prospect for going much further on LFV.

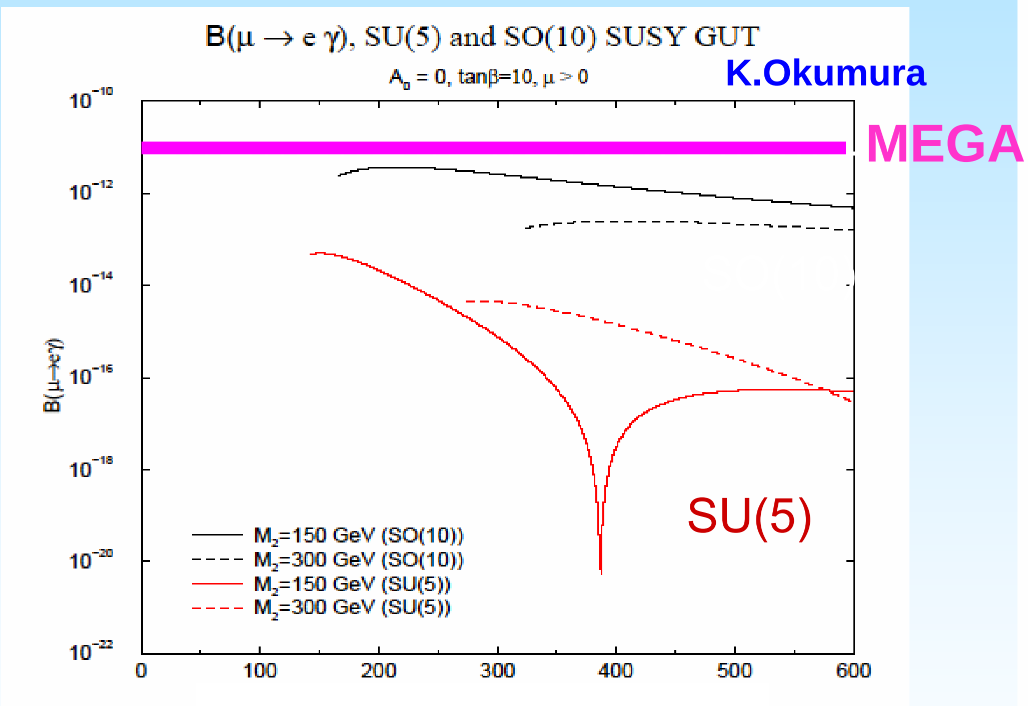
- **There is plenty of room for new surprises!**

μ → e γ branching ratio (typical example)

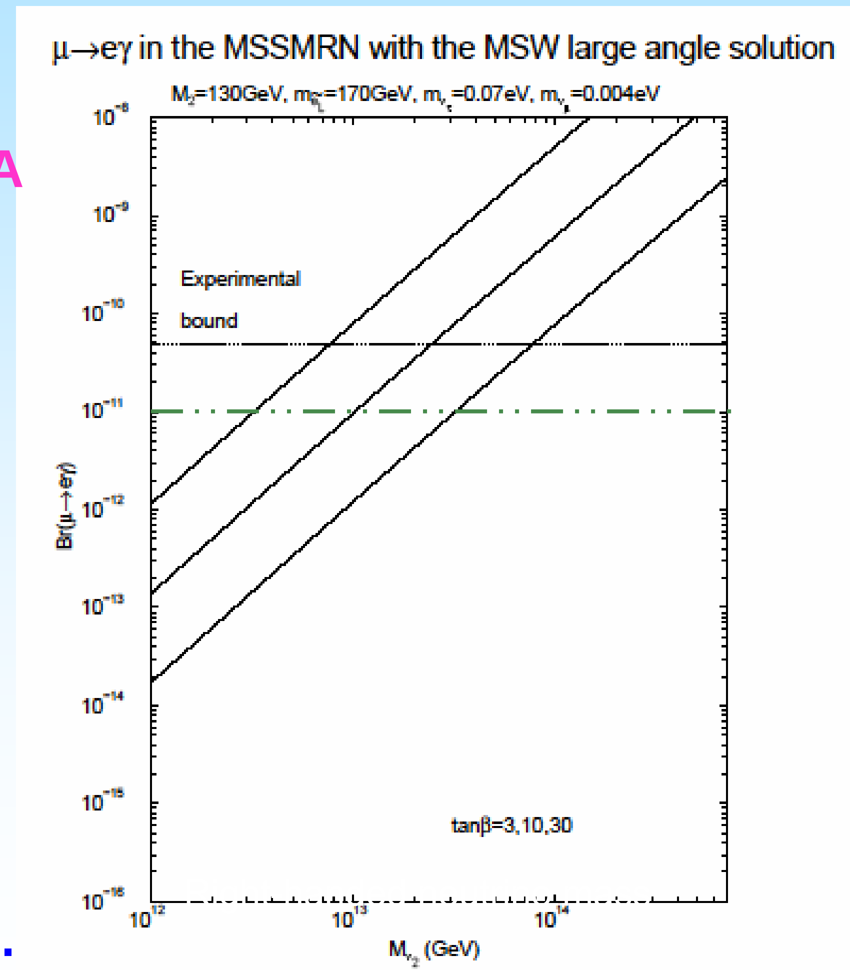
SUSY seesaw model

SU(5) and SO(10) SUSY GUT

J.Hisano and D.Nomura,2000



Right-handed selectron mass



The branching ratio can be large in particular for SO(10) SUSY GUT model.

thanks to Y. Okada

Comparison of three muon processes in various new physics models

SUSY GUT/Seesaw	$B(\mu \rightarrow e\gamma) \gg B(\mu \rightarrow 3e) \sim B(\mu A \rightarrow eA)$ Various asymmetries in polarized μ decays.
SUSY with large tan β	$\mu \rightarrow e$ conv. can be enhanced. Z-dependence in $\mu \rightarrow e$ conv. branching ratio.
Triplet Higgs for neutrino	$B(\mu \rightarrow 3e) >$ or $\sim B(\mu \rightarrow eg) \sim B(\mu A \rightarrow eA)$
RL model	$B(\mu \rightarrow 3e) \gg B(\mu \rightarrow eg) \sim B(\mu A \rightarrow eA)$ Asymmetry in $\mu \rightarrow 3e$
RPV SUSY	Various patterns of branching ratios and asymmetries

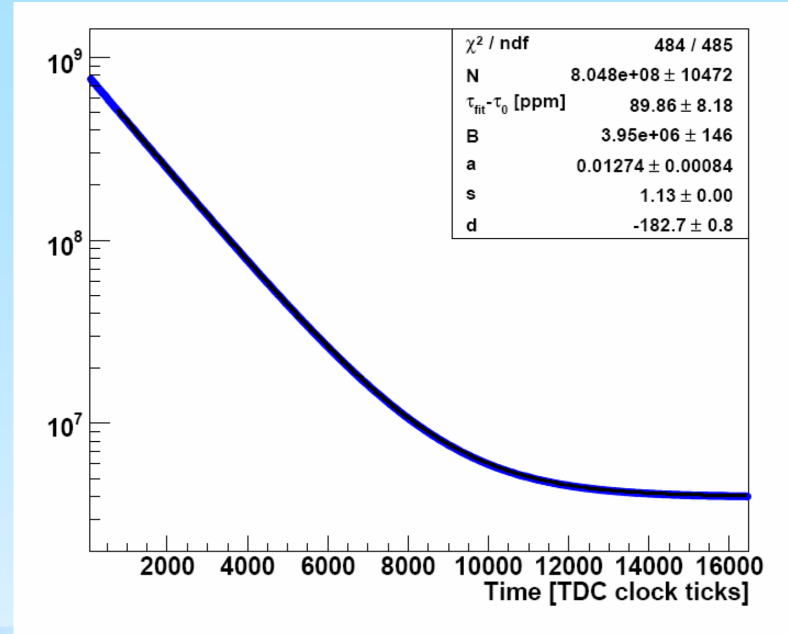
want to measure all three LFV processes to disentangle the models

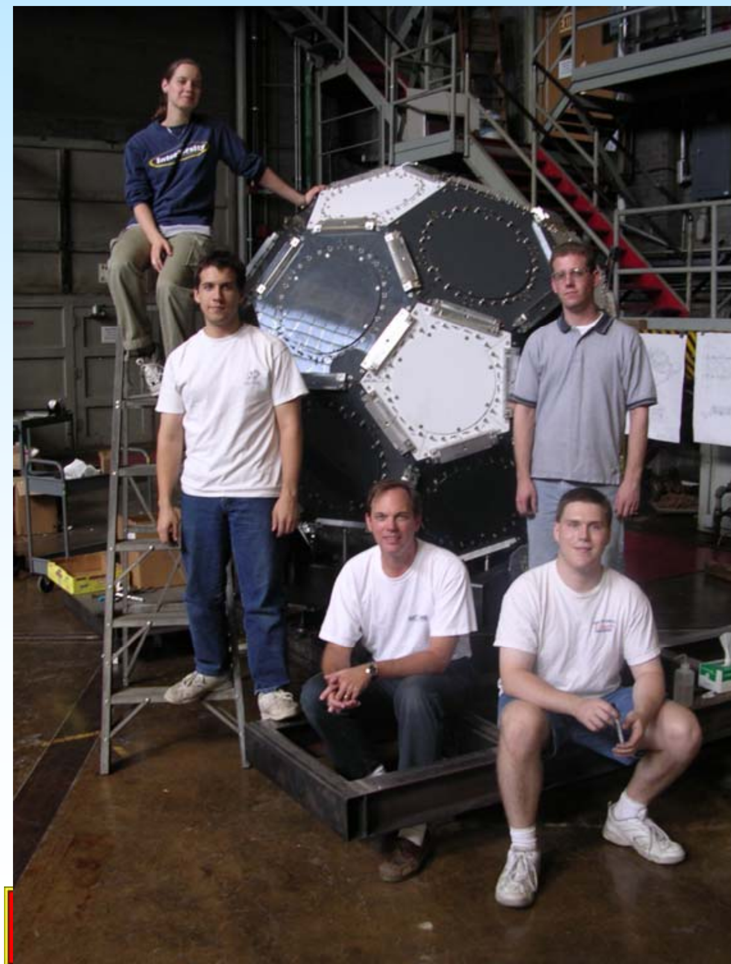
thanks to Y. Okada

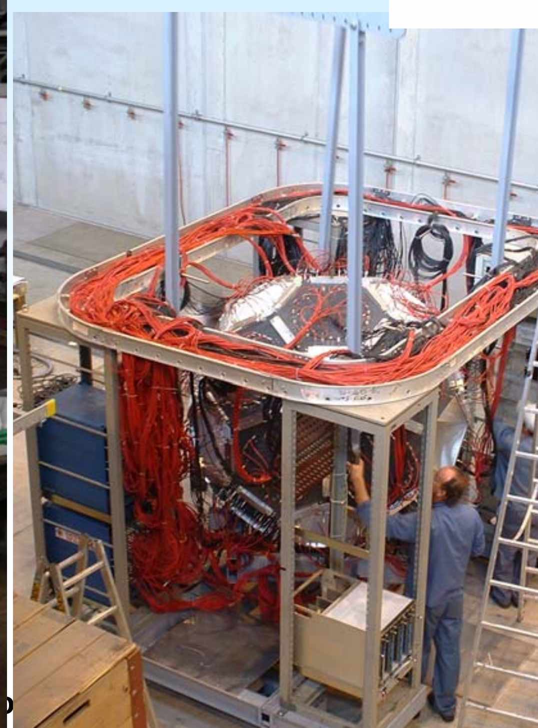
μLan @ PSI aims for a factor of 20 improvement

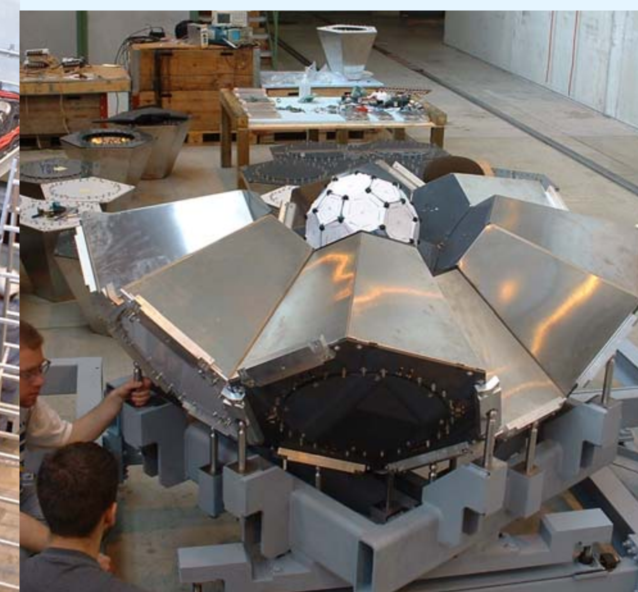
Fit to 2004 data set,

$\sigma_{stat} \approx 8.2$ ppm









Recent Developments:

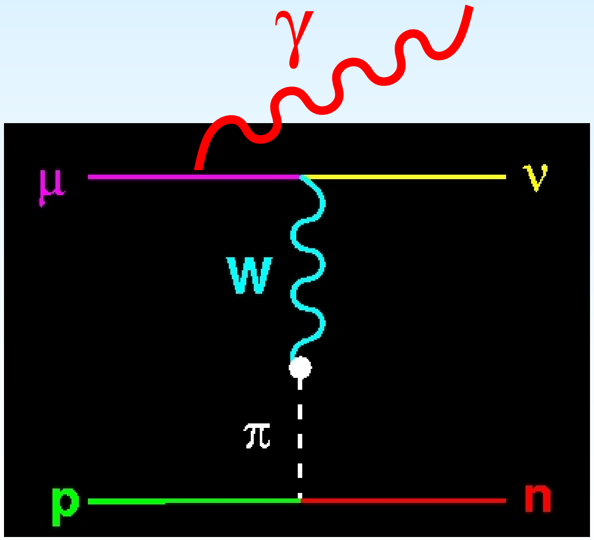
The induced pseudoscalar coupling in nuclear μ-capture

$$< B|A_\lambda|A >=$$
$$(\ )\bar{u}(p')g_A(q^2)\gamma_\lambda\gamma_5 + ig_P(q^2)q_\lambda\gamma_5 + g_T(q^2)\gamma_5\sigma_{\lambda\nu}q_\nu]u$$

further enhanced in radiative muon capture (RMC).

TRUIMF experiment saw a 3σ discrepancy with PCAC prediction.

A new ordinary muon capture (OMC) experiment at PSI, MuCap, hopes to resolve this 3 σ discrepancy.

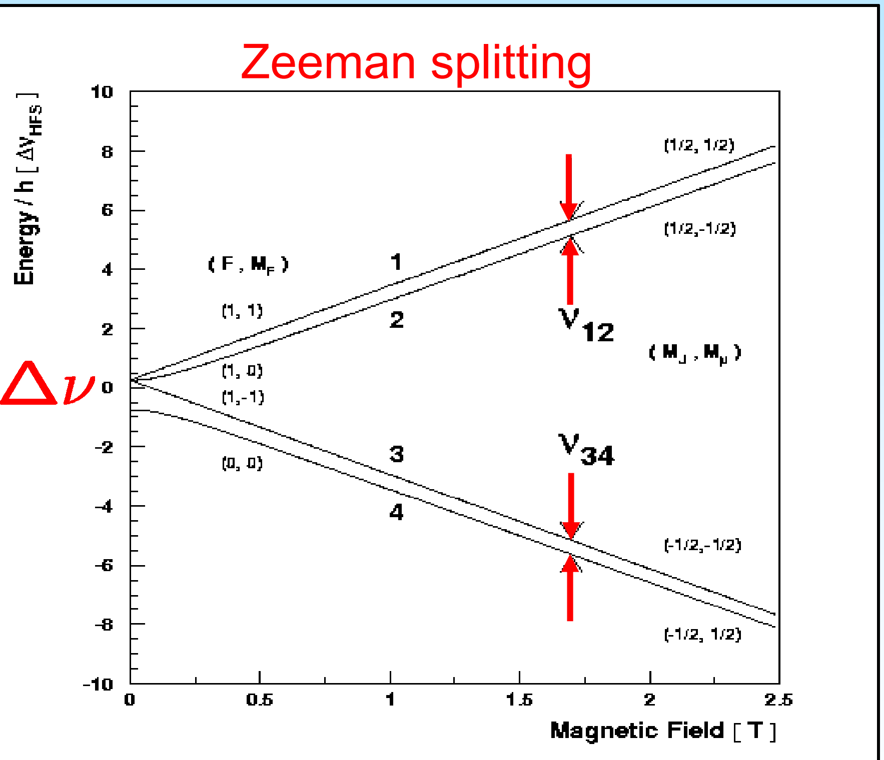


However, a new TRIUMF measurement of the atomic "ortho to para transition rate" seems to remove much of this problem.
Clark, et al., PRL 96, 073401 (2006)

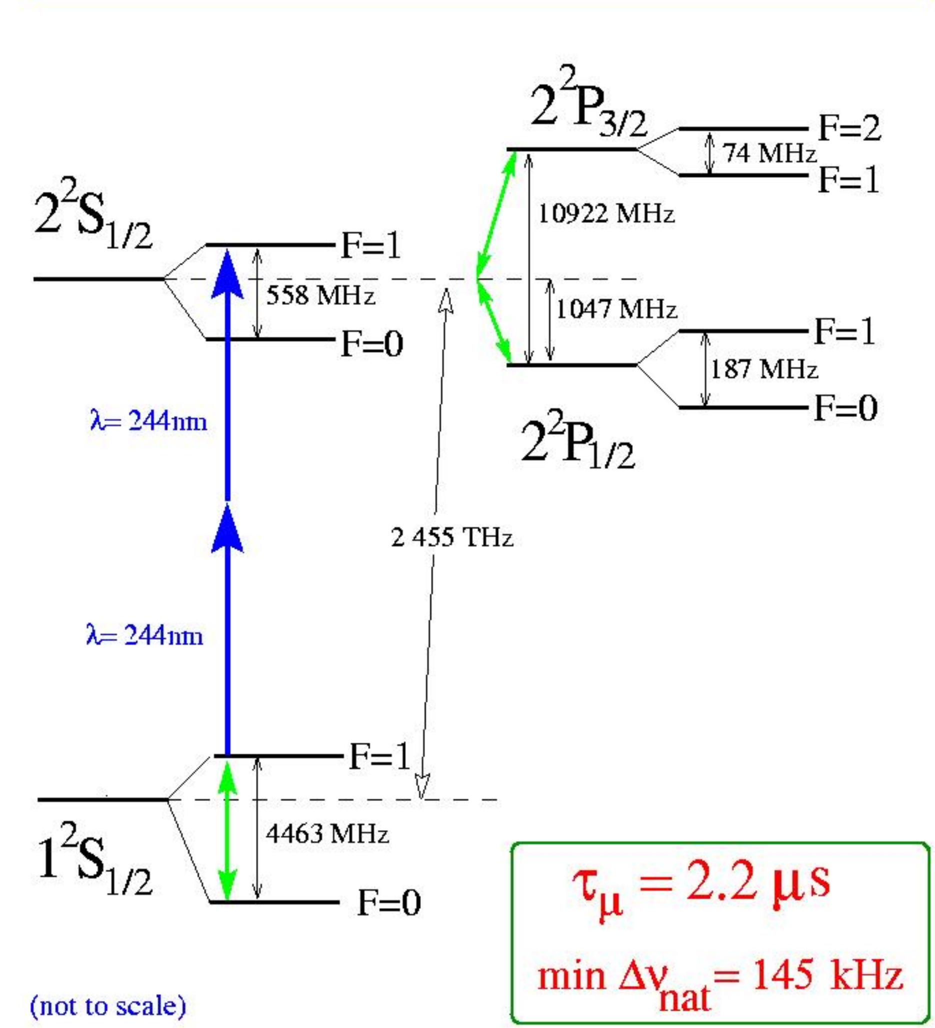
Muonium

$$\mu^+ e^-$$

Hydrogen (without the proton)



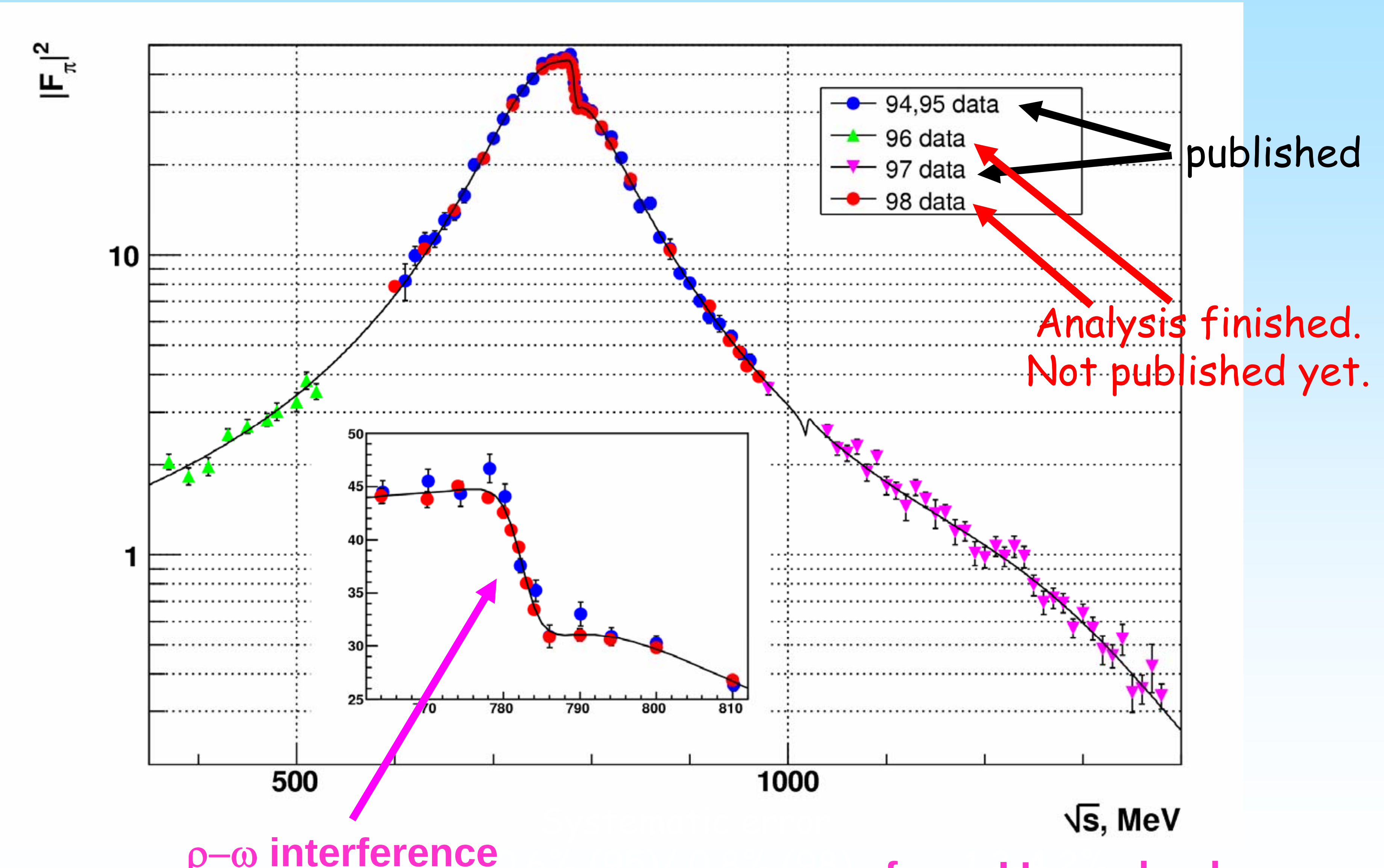
Muonium (M=μ^+e^-) Energy Levels n=1 and n=2



μ_μ/μ_p = 3.183 345 24(37) (120 ppb)

where μ_p comes from proton NMR in the same B field

Pion formfactor (CMD-2)



from: I Logashenko

Implications for a_μ

Davier,Marciano-2004:

$\Delta a_\mu = (23.9 \pm 7.2_{had,LO} \pm 3.5_{other} \pm 5.8_{exp}) \cdot 10^{-10}$

- $0.610 < \sqrt{s} < 0.960$ GeV

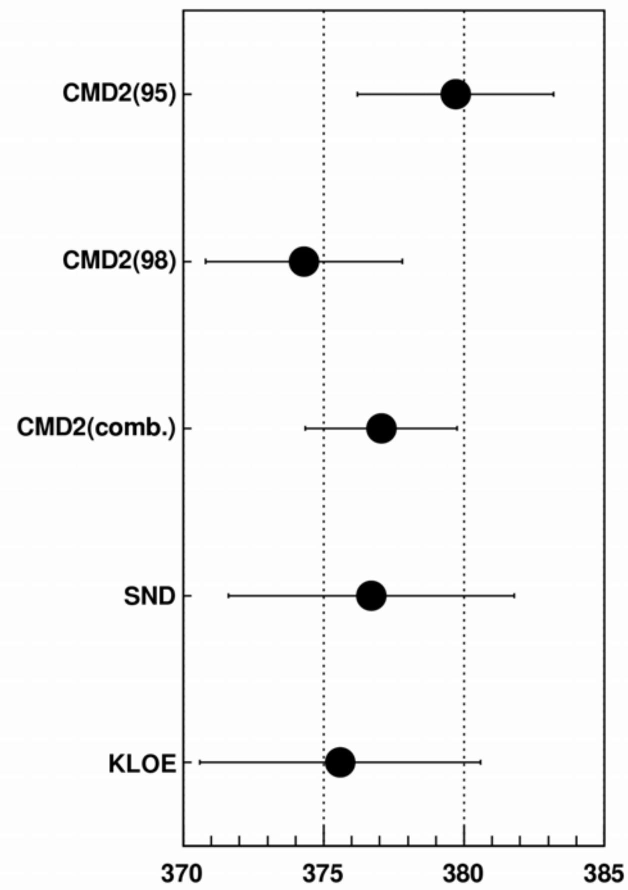
CMD-2 (95): $379.7 \pm 2.6 \pm 2.3$ (3.5)

CMD-2 (98): $374.3 \pm 1.8 \pm 3.0$ (3.5)

CMD-2 (comb): $377.05 \pm 2.2 \pm 1.5$ (2.7)

SND: $376.7 \pm 1.3 \pm 4.9$ (5.1)

KLOE: $375.6 \pm 0.8 \pm 4.9$ (5.0)

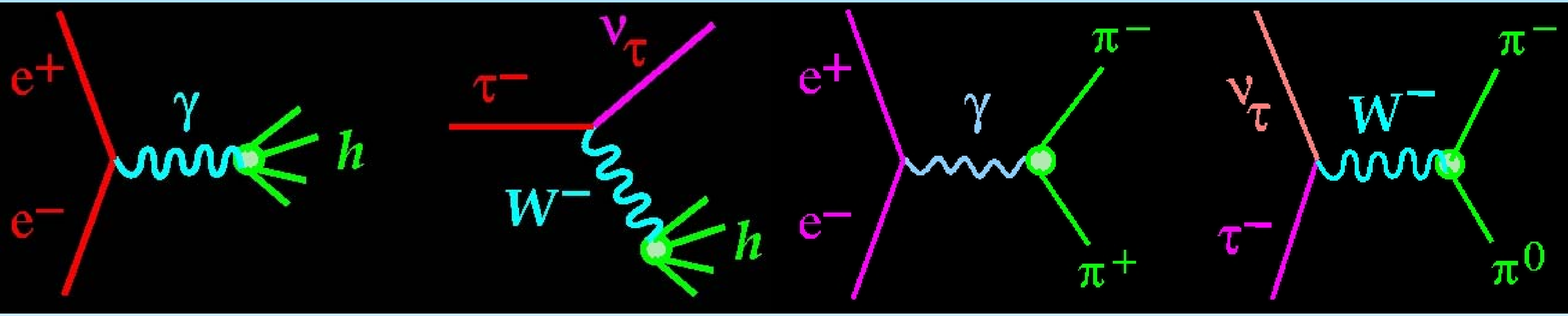


$a_\mu(had; 0.6 < \sqrt{s} < 1.0 \text{ GeV})$

S.Eidelman, private communication

from I. Logaseheko

a(had) from hadronic τ decay?

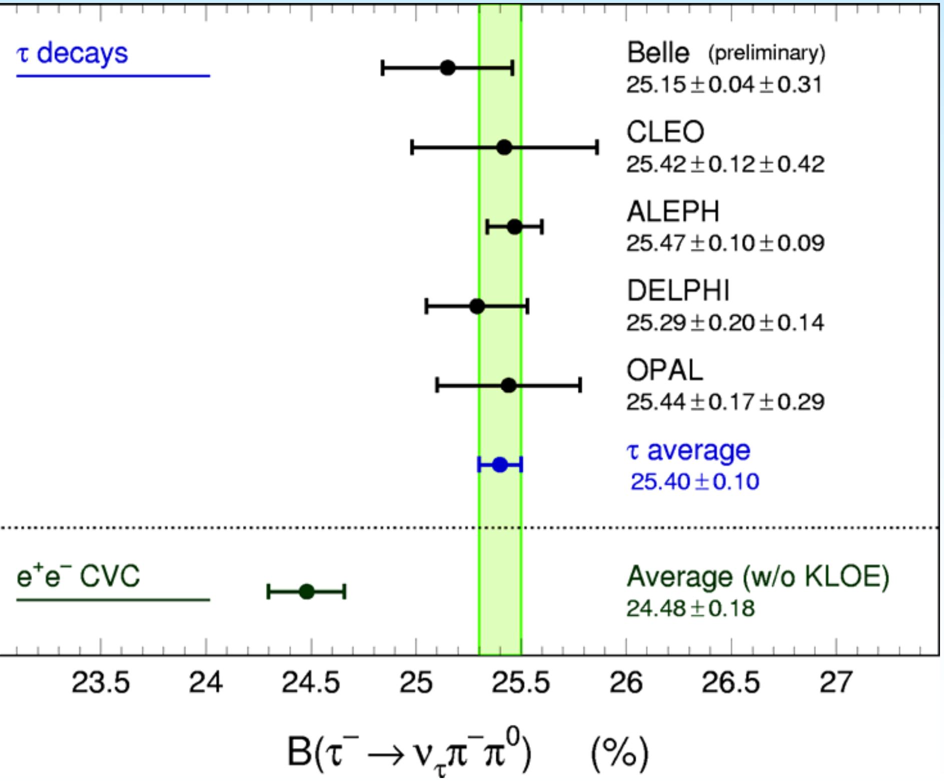


- Assume: CVC, no 2nd-class currents, isospin breaking corrections.
  - e^+e^- goes through neutral ρ
  - while τ-decay goes through charged ρ
- n.b. τ decay has no isoscalar piece, e^+e^- does
- Many inconsistencies in comparison of e^+e^- and τ decay:

Testing CVC with one number

Infer τ branching fractions (more robust than spectral functions) from e^+e^- data:

$$BR_{CVC}(\tau^- \to \pi^-\pi^0\nu_\tau) = \frac{6\pi|V_{ud}|^2 S_{EW}}{m_\pi^2} \int_0^{m_\tau} ds\,\mathrm{kin}(s)\,\nu^{SU(2)-\mathrm{corrected}}(s)$$



Difference: BR[τ] – BR[e^+e^- (CVC)]:

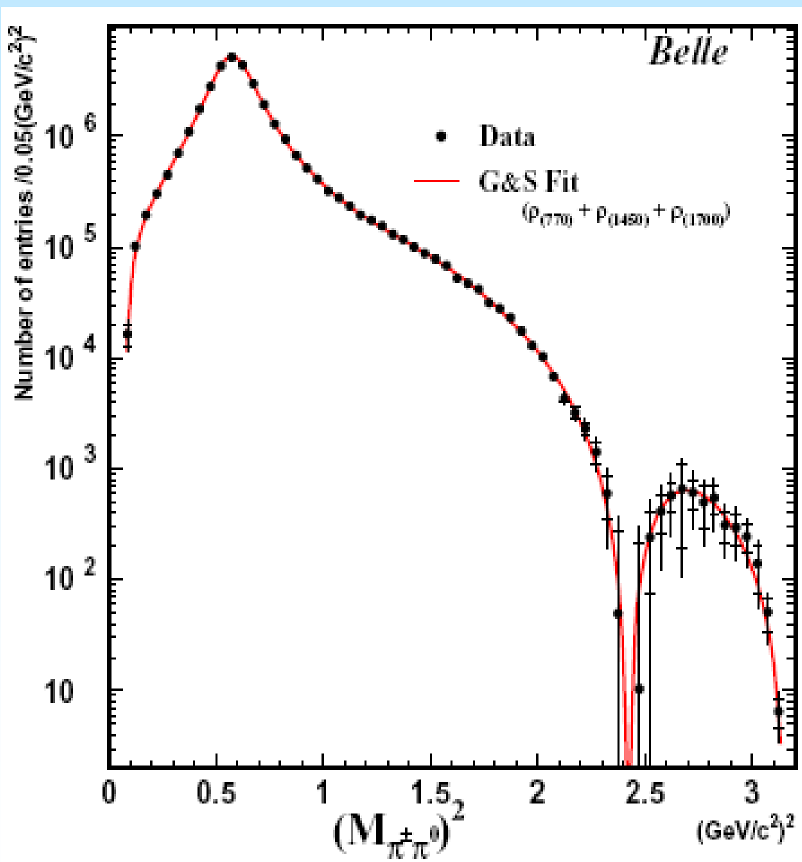
Mode	$\Delta(\tau - e^+e^-)$	\`Sigma'
$\tau^- \to \pi^-\pi^0\nu_\tau$	+ 0.92 ± 0.21	4.5
$\tau^- \to \pi^- 3\pi^0\nu_\tau$	- 0.08 ± 0.11	0.7
$\tau^- \to 2\pi^-\pi^+\pi^0\nu_\tau$	+ 0.91 ± 0.25	3.6

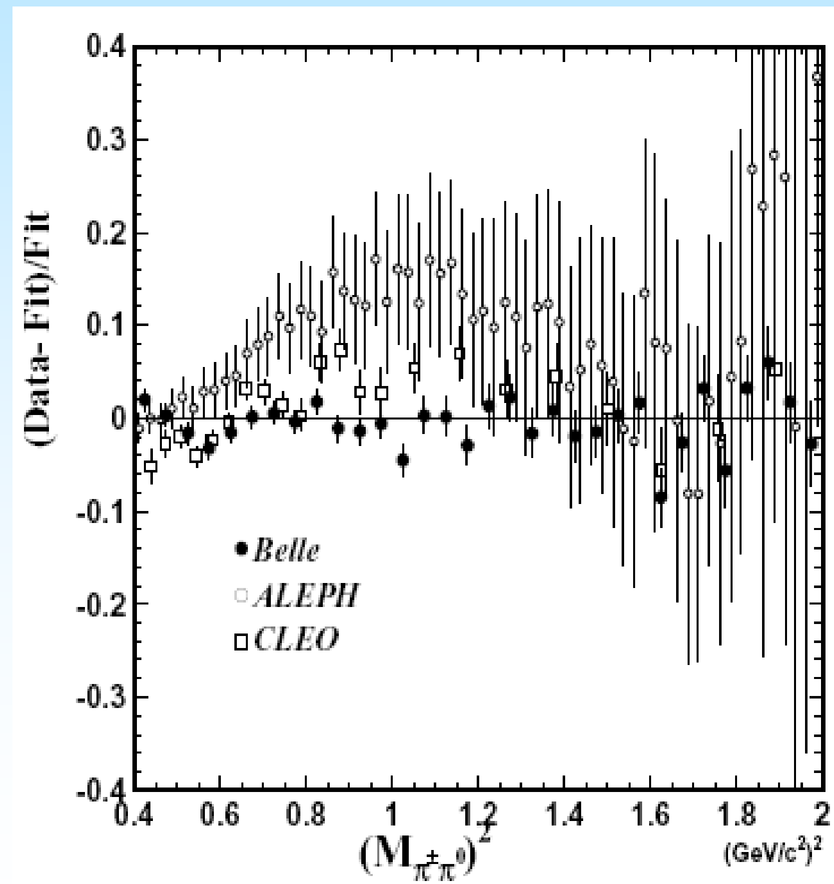
ee data on $\pi^-\pi^+\pi^0\pi^0$ not satisfactory

from Michel Davier

$\tau^- \to \pi^- \pi^0 \nu_\tau$: preliminary results from BELLE

- **preliminary results from BELLE on τ $\pi\pi$ spectral function presented at EPS 2005**
- **high statistics: see dip at 2.4 GeV^2 for first time in τ data**
- **discrepancies with ALEPH/CLEO at large mass and ee data at low mass**





The use of τ-decay is in question

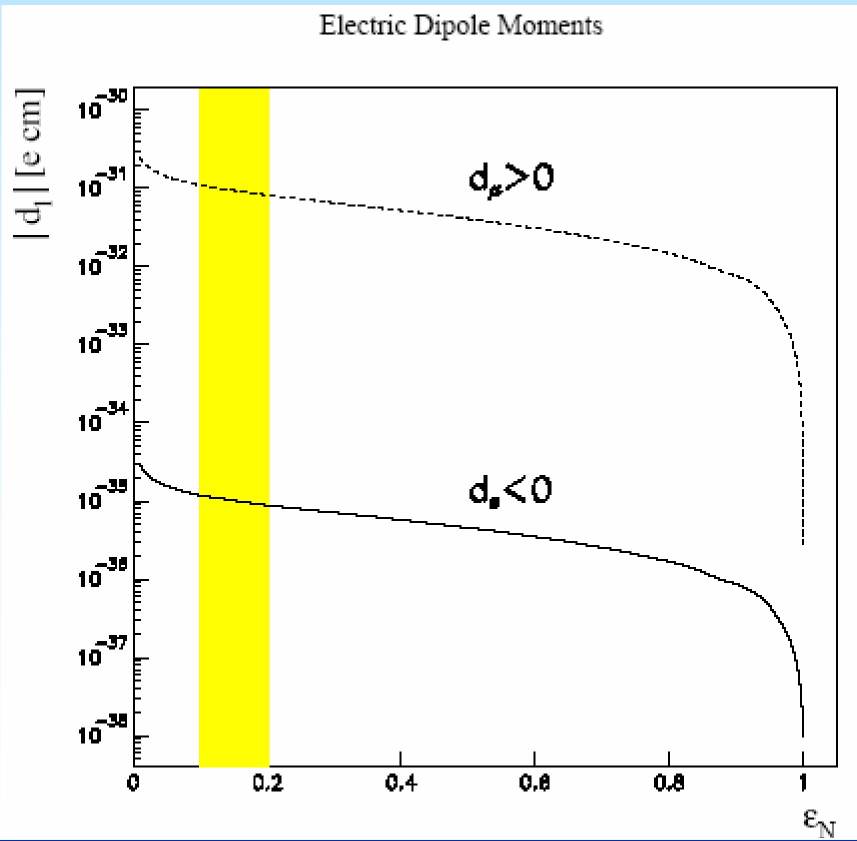
- Until the discrepancies between the individual τ data sets can be resolved, and CVC can be shown to hold independently it's clear that only the e^+e^- data can be used to determine a_μ(had)

➢ **The agreement between SND and CMD-2 invalidates the use of τ data until a better understanding of the discrepancies is achieved (an interesting question as such)**

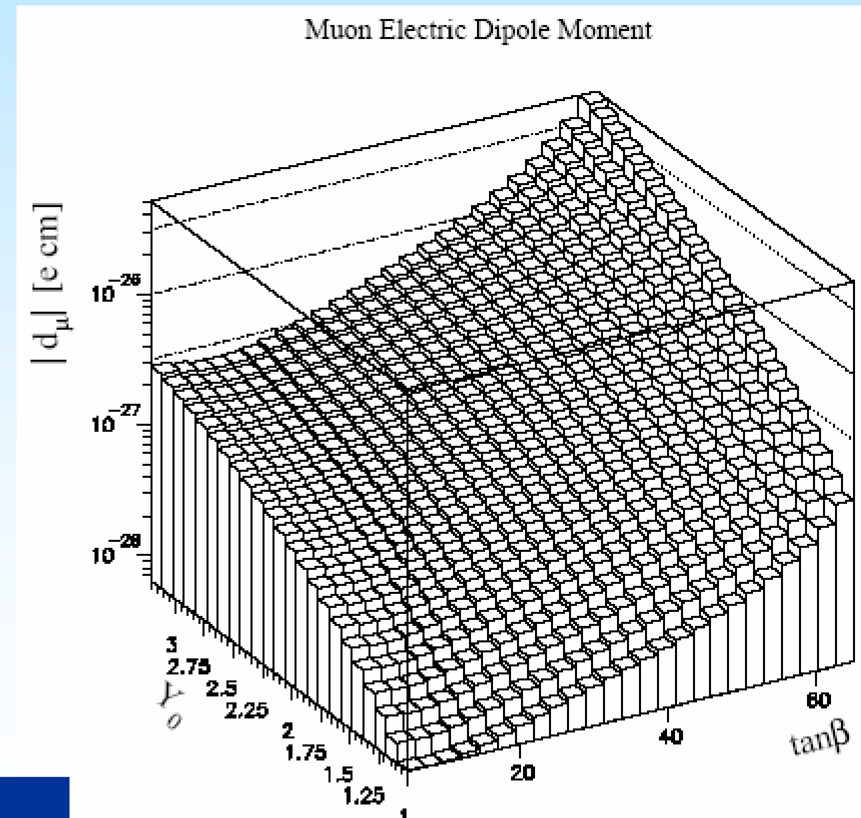
Michel Davier at Lepton Moments, June 2006

Model calculations of μ EDM

μ EDM may be enhanced above $m_\mu/m_e \times$ e EDM



Magnitude increases with magnitude of ν Yukawa couplings and tan β

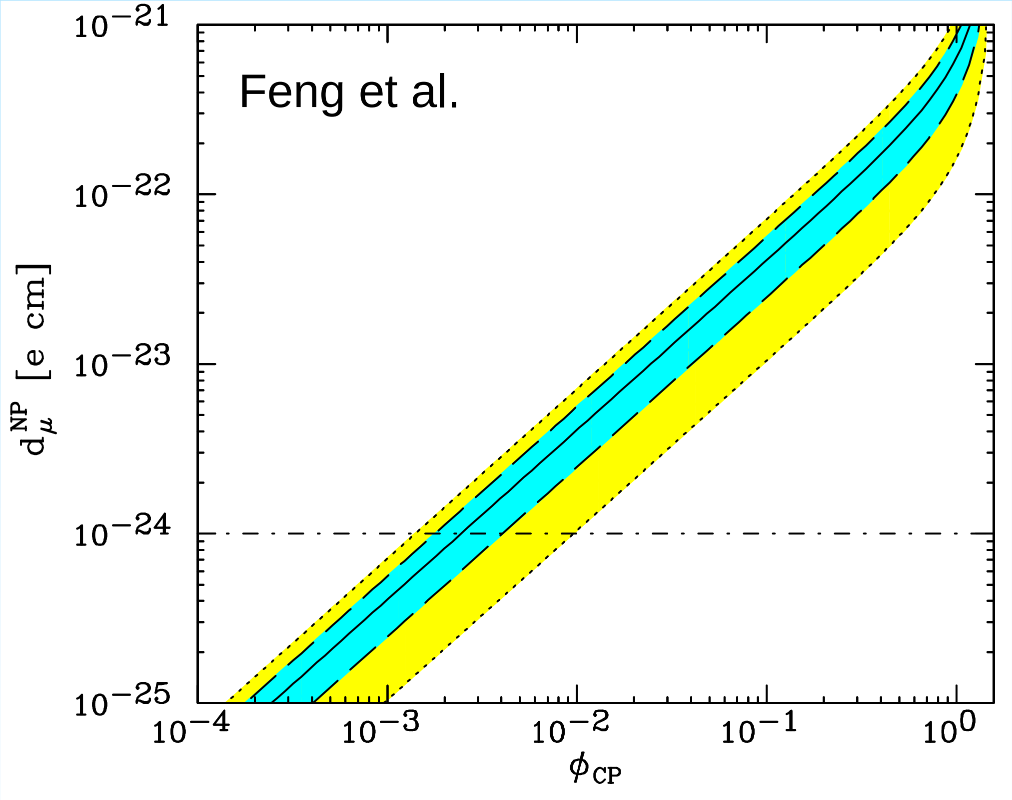


arXiv:hep-ph/0111324 v2 30 Nov 2001

μ EDM greatly enhanced when heavy neutrinos non-degenerate

from John Ellis

a_μ implications for the muon EDM



assuming that

$$a_\mu^{NP} = 3(1) \times 10^{-9}$$

$\pm\, 2\,\sigma$

$\pm\, 1\,\sigma$

$$d_\mu^{NP} \simeq 3 \times 10^{-22} \left(\frac{a_\mu^{NP}}{3 \times 10^{-9}} \right) \tan \phi_{CP} \quad \mathrm{e \cdot cm}$$

where ϕ_{CP} is a CP violating phase.

mu2e @ FNAL???

Cancelled

Future Experiments:

- ~~MECO Experiment @ BNL~~

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

  - ~~10^{-17} single event sensitivity~~

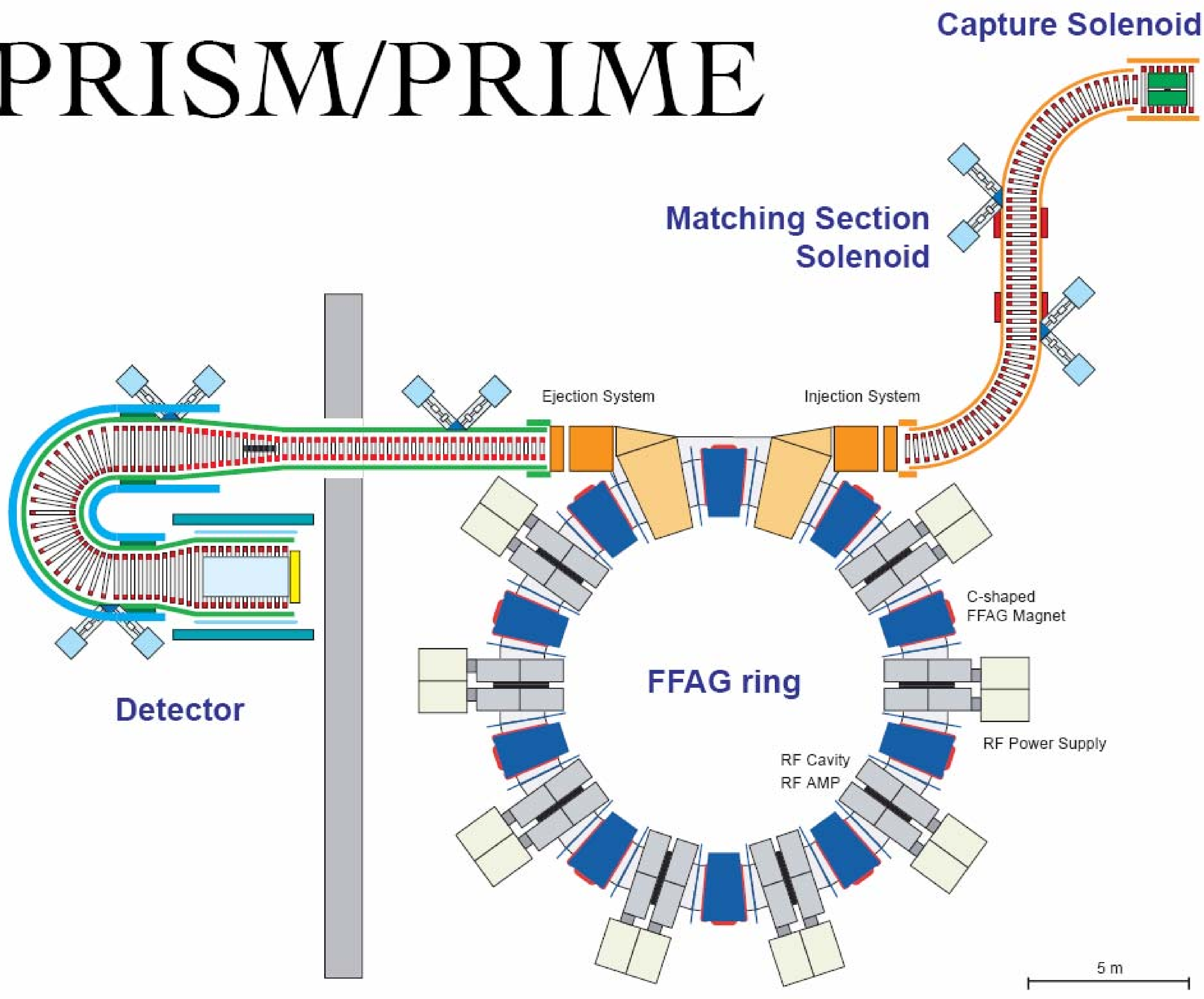
Cancelled

- MEG Experiment @PSI

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

  - Under Construction Data Begins in 2006

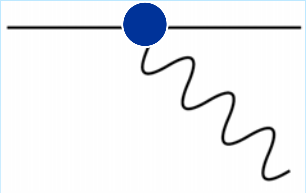
PRISM/PRIME



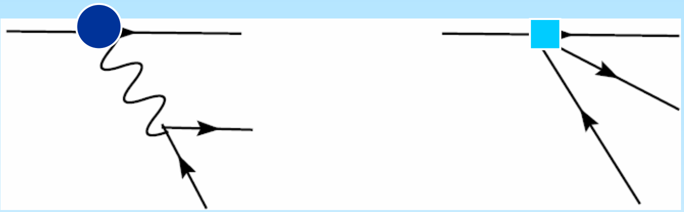
Capture Solenoid
Matching Section Solenoid
Ejection System
Injection System
C-shaped FFAG Magnet
FFAG ring
Detector
RF Power Supply
RF Cavity
RF AMP
5 m

Comparison of three processes

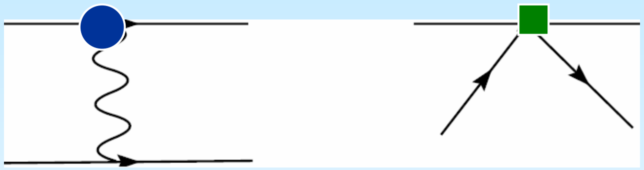
$$\mu^+ \to e^+\gamma$$



$$\mu^+ \to e^+e^+e^-$$



$$\mu^- A \to e^- A$$



If the photon penguin process dominates, there are simple relations among these branching ratios.

$$B(\mu^+ \to e^+e^+e^-) \sim 6\times 10^{-3} B(\mu \to e\gamma)$$

$$\frac{\sigma(\mu^- Ti \to e^- Ti)}{\sigma(\mu^- Ti \to capture)} \sim 4\times 10^{-3} B(\mu \to e\gamma)$$

This is true in many, but not all SUSY modes.

thanks to Y. Okada

LFV Experiments:

- ~~MECO Experiment @ BNL~~ **Cancelled**

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

  - 10^{-17} single event sensitivity

- MEG Experiment
  - Under Construction Data Begins in 2006

- PRISM-PRIME

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

  - LOI to J-PARC FFAG under construction
  - 10^{-18} – 10^{-19} single event sensitivity