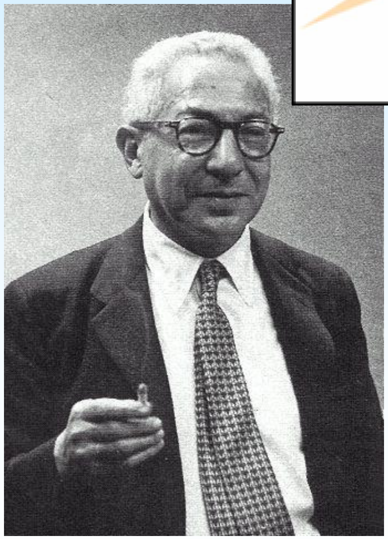
Precision Measurements with the Muon:

Lifetime and Dipole Moments



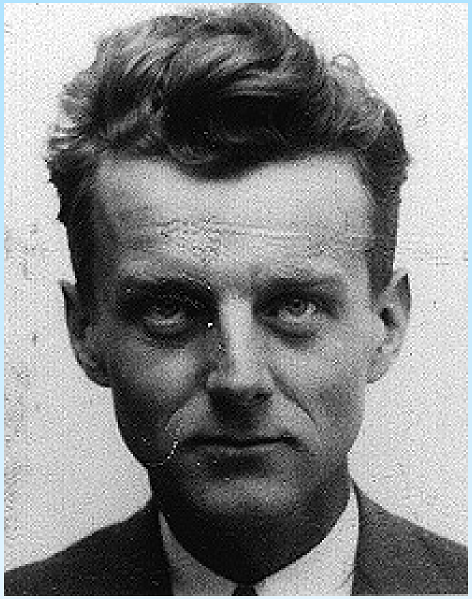
B.L. Roberts
Department of Physics
Boston University

roberts @bu.edu http://physics.bu.edu/roberts.html

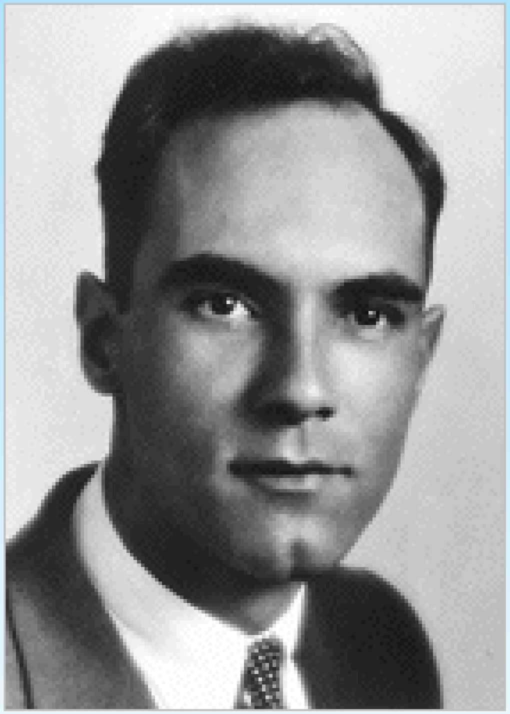
Outline

- Introduction to the muon
- Selected weak interaction parameters
- Magnetic and electric dipole moments
- 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 & 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 Neddermeyer[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

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).

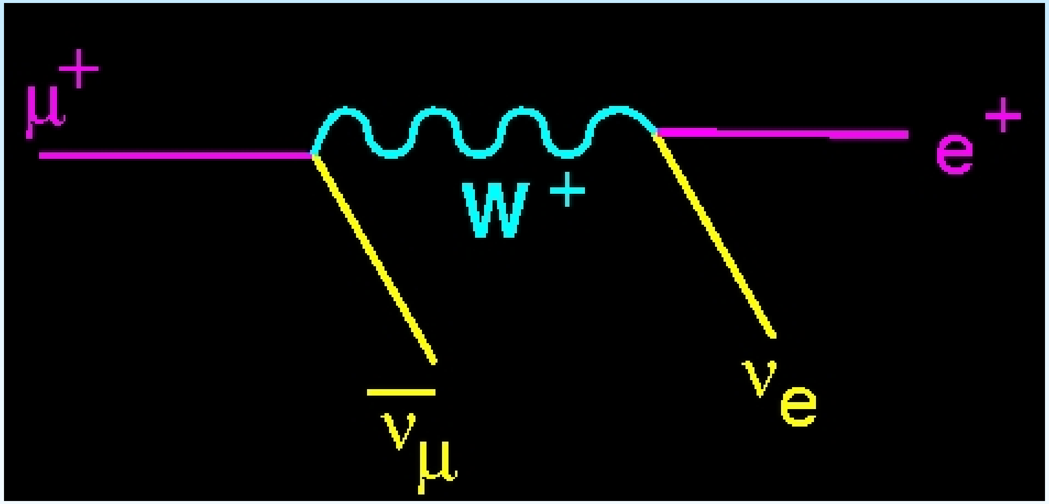
DECEMBER 1, 1937 PHYSICAL REVIEW VOLUME 52

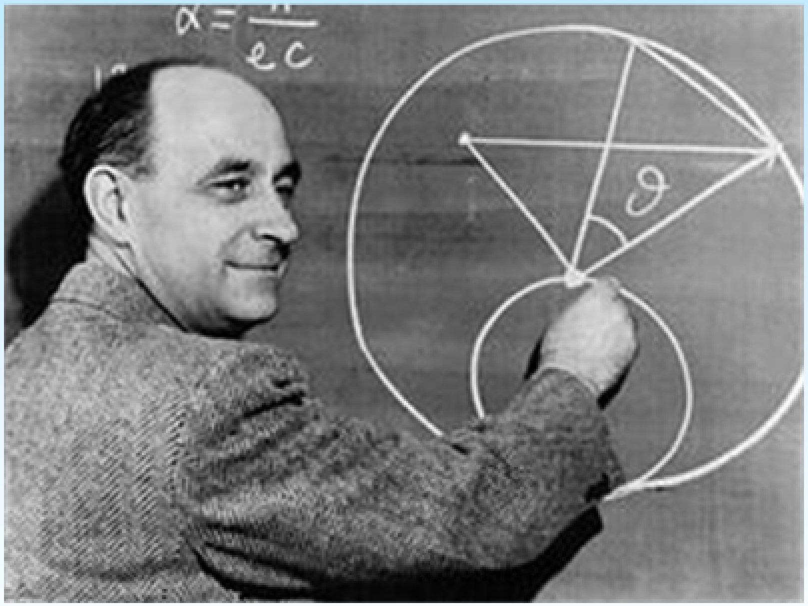
On the Nature of Cosmic-Ray Particles

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

(Received August 28, 1937)

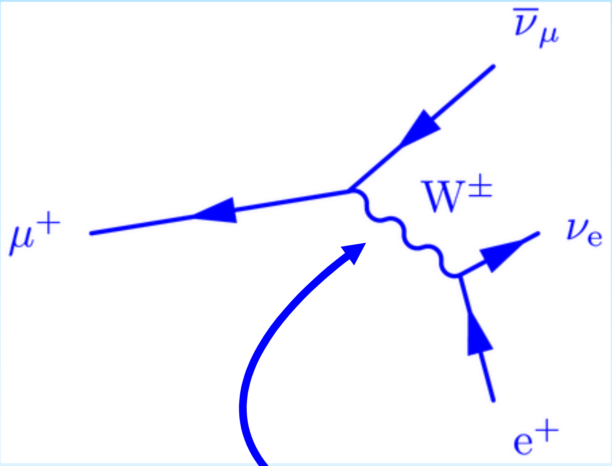
The Muon Lifetime





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

Muon decay gives us unique access to the electroweak scale



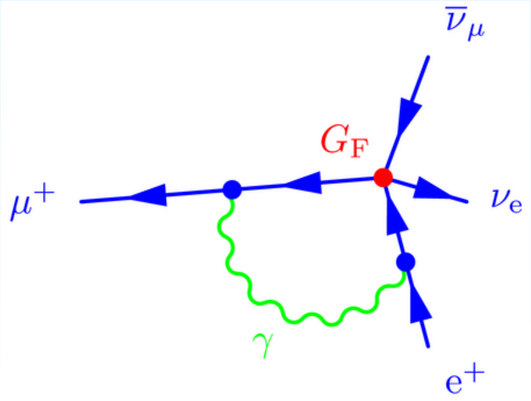
The muon decays only via the weak interaction

The V-A theory factorizes into a pure weak contribution,

plus

radiative corrections (including hadronic).

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



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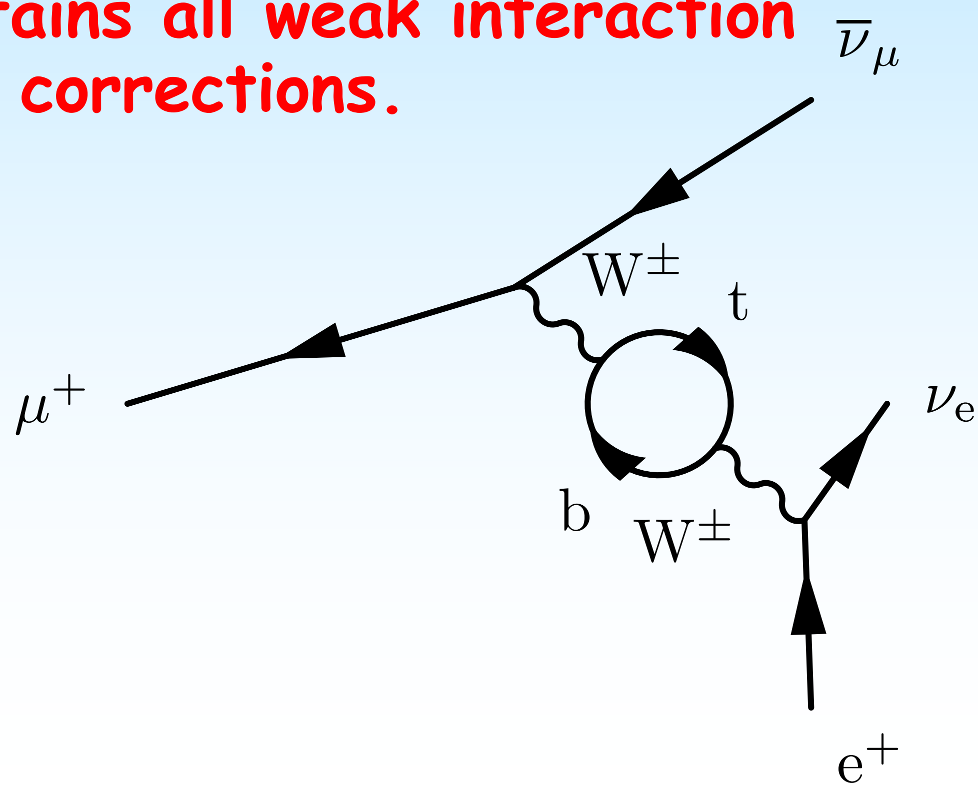
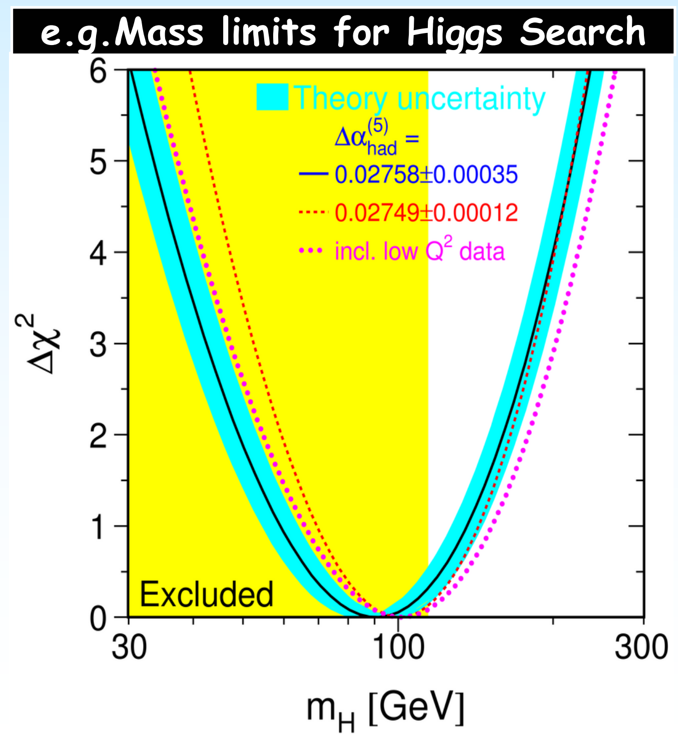
The Fermi constant is an implicit input to all precision electroweak studies

$$\frac{G_{\mathrm{F}}}{\sqrt{2}} = \frac{g^2}{8M_{\mathrm{W}}^2}\left(1 + \Delta r(m_{\mathrm{t}}, m_{\mathrm{H}}, \ldots)\right)$$

Contains all weak interaction loop corrections.





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τ_μ helped predict the mass of the top quark, today, part of the Electroweak working group fits

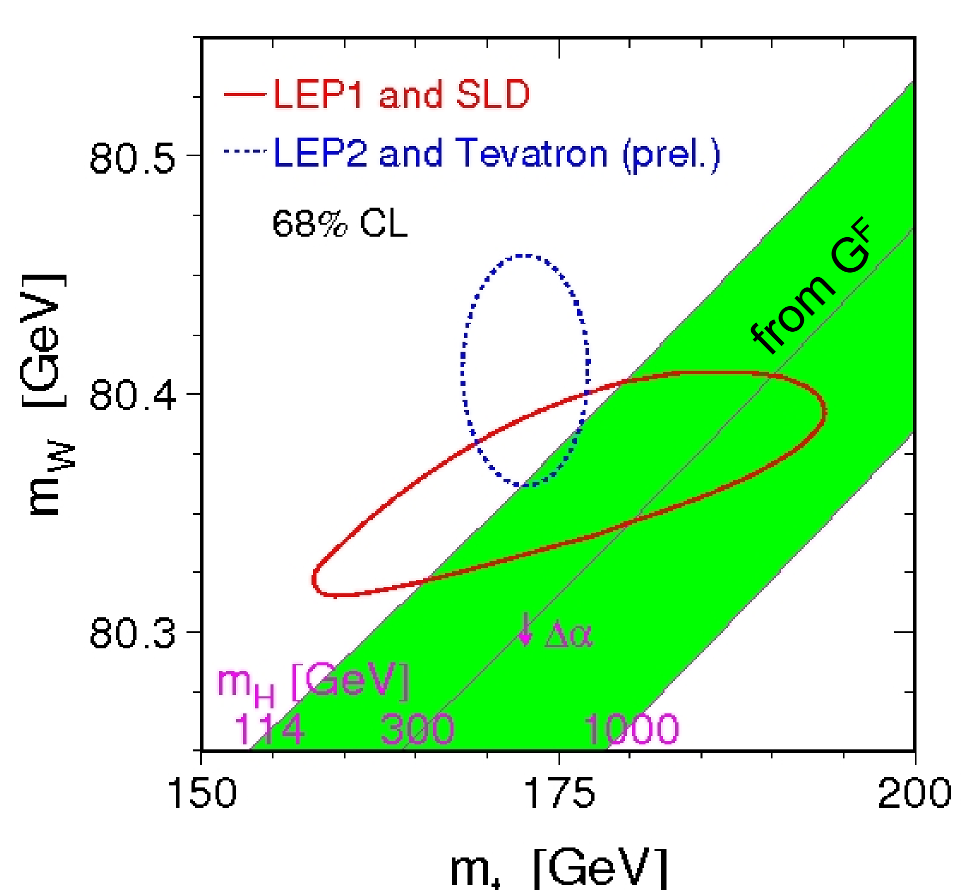
Predicted

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

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

Measured:

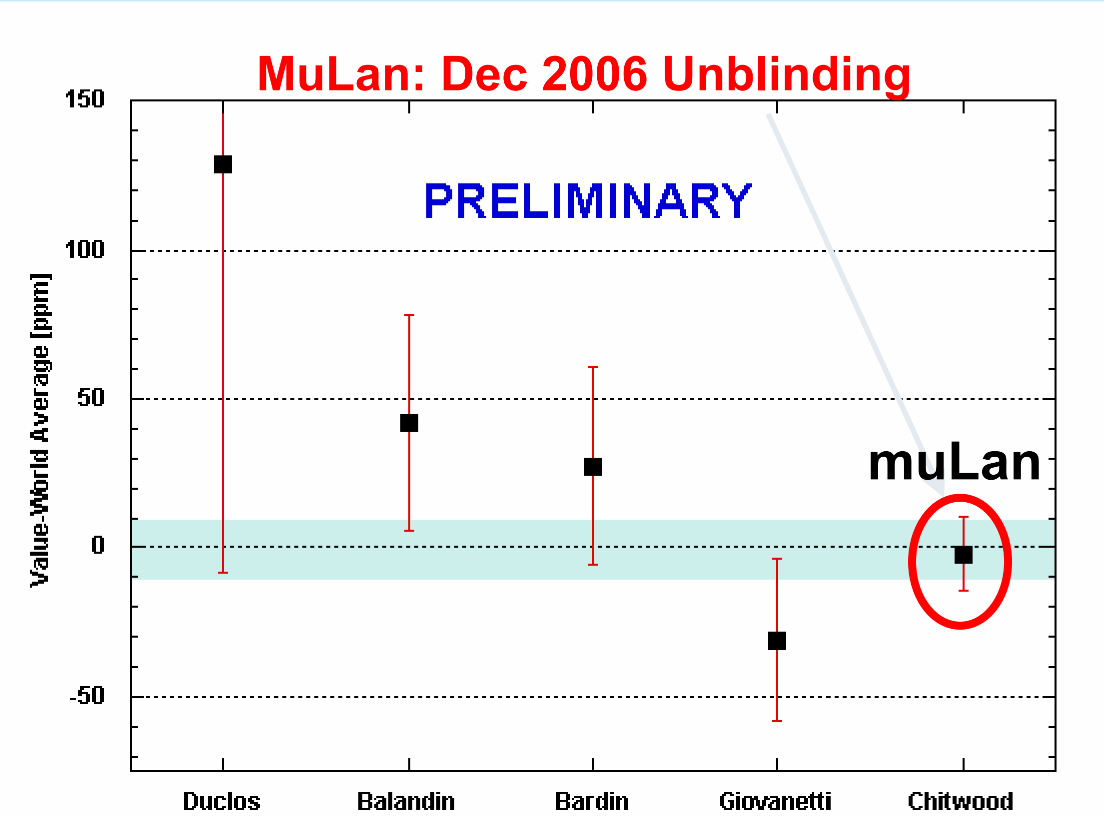
$$m_t = 172.7 \pm 2.9\,\mathrm{GeV}$$

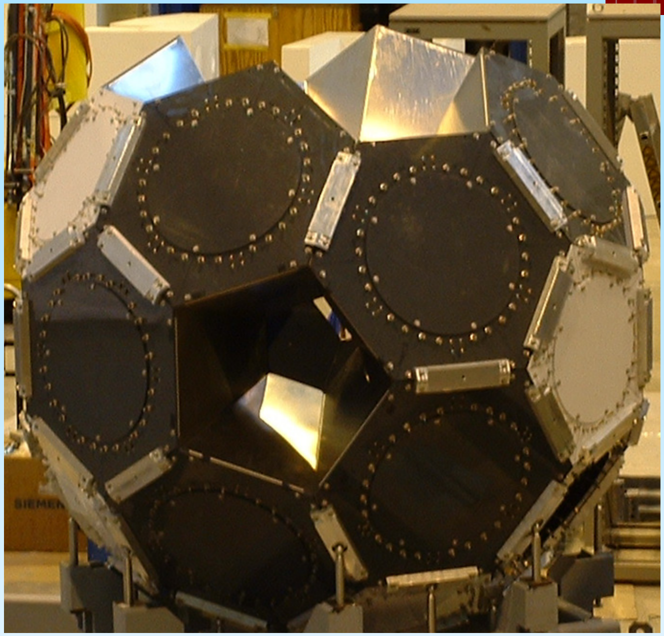


The μLan experiment at PSI will accumulate >10^{12} μ-decays → G_μ to ~1 ppm. If LHC provides a Higgs Mass, then the precision of the confrontation with the SM will greatly improve

MuLan has a new ~13 ppm τ_μ measurement

Will be officially announced soon





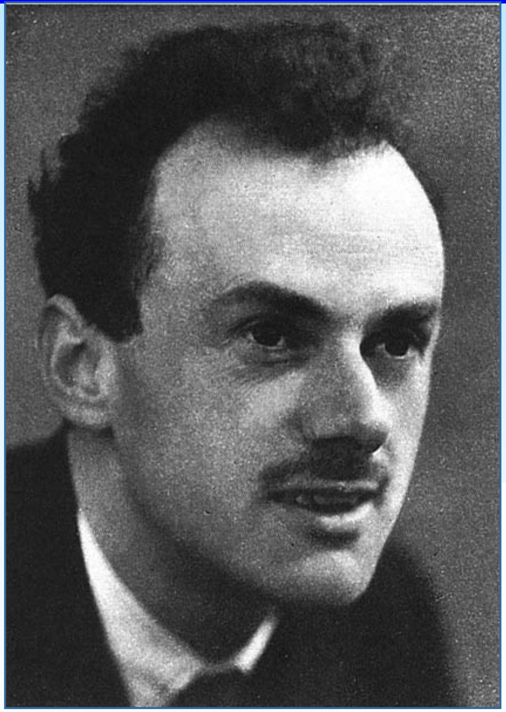
NEW

~1 ppm result to follow from 2006, and also from the 2007 run

What have we learn from the μ's death? (Much of it here at PSI)

- 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, etc. ?
- 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
  - ***new muCap result!***
- Future Lifetime measurement?
  - The radiative corrections can support another order of magnitude on τ_μ, (beyond muLan) but that would go way beyond the precision of the other electroweak parameters.

Magnetic and Electric Dipole Moments



The Quantum Theory of the Electron.

By P. A. M. DIRAC, St. John's College, Cambridge.

(Communicated by R. H. Fowler, F.R.S.—Received January 2, 1928.)

§ 4. *The Hamiltonian for an Arbitrary Field.*

To obtain the Hamiltonian for an electron in an electromagnetic field with scalar potential A_0 and vector potential $\mathbf{A}$, we adopt the usual procedure of substituting $p_0 + e/c \,.\, A_0$ for p_0 and $\mathbf{p} + e/c \,.\, \mathbf{A}$ for $\mathbf{p}$ in the Hamiltonian for no field. From equation (9) we thus obtain

$$\left[p_0 + \frac{e}{c} A_0 + \rho_1 \left(\boldsymbol{\sigma}, \mathbf{p} + \frac{e}{c}\mathbf{A} \right) + \rho_3 mc \right] \psi = 0. \qquad (14)$$

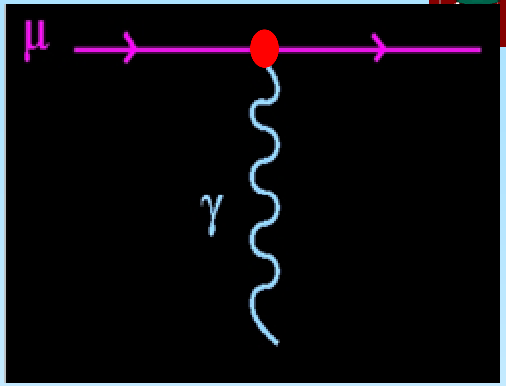
This differs from (1) by the two extra terms

$$\boxed{\frac{eh}{c}(\boldsymbol{\sigma}, \mathbf{H}) + \frac{ieh}{c}\rho_1(\boldsymbol{\sigma}, \mathbf{E})}$$

in F. These two terms, when divided by the factor $2m$, can be regarded as the additional potential energy of the electron due to its new degree of freedom. The electron will therefore behave as though it has a magnetic moment $eh/2mc \,.\, \boldsymbol{\sigma}$ and an electric moment $ieh/2mc \,.\, \rho_1 \boldsymbol{\sigma}$. This magnetic moment is just that assumed in the spinning electron model. The electric moment, being a pure imaginary, we should not expect to appear in the model. It is doubtful whether

Electric and Magnetic Dipole Moments:

$$\Gamma_\mu = eF_1\ \bar{\psi}_R \gamma_\mu \psi_R \quad + \quad \frac{ie}{2m} F_2\ \ \bar{\psi}_R \sigma_{\mu\nu} q^\nu \psi_L$$



- 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

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

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

An aside: General Dipole Operator

$$\mathcal{L}_{mdm} = a_\mu \frac{e}{4m_\mu} \bar{\mu} \sigma^{\alpha\beta} F_{\alpha\beta} \qquad \mathcal{L}_{edm} = -\frac{i}{2} d_\mu \bar{\mu} \sigma^{\alpha\beta} \gamma_5 \mu F_{\alpha\beta}$$

Marciano has introduced the dipole operator

$$\mathcal{L}_{dm} = \frac{1}{2}\left[D \bar{\mu} \sigma^{\alpha\beta} \frac{1+\gamma_5}{2} + D^* \bar{\mu} \sigma^{\alpha\beta} \frac{1-\gamma_5}{2} \right] \mu F_{\alpha\beta}$$

with

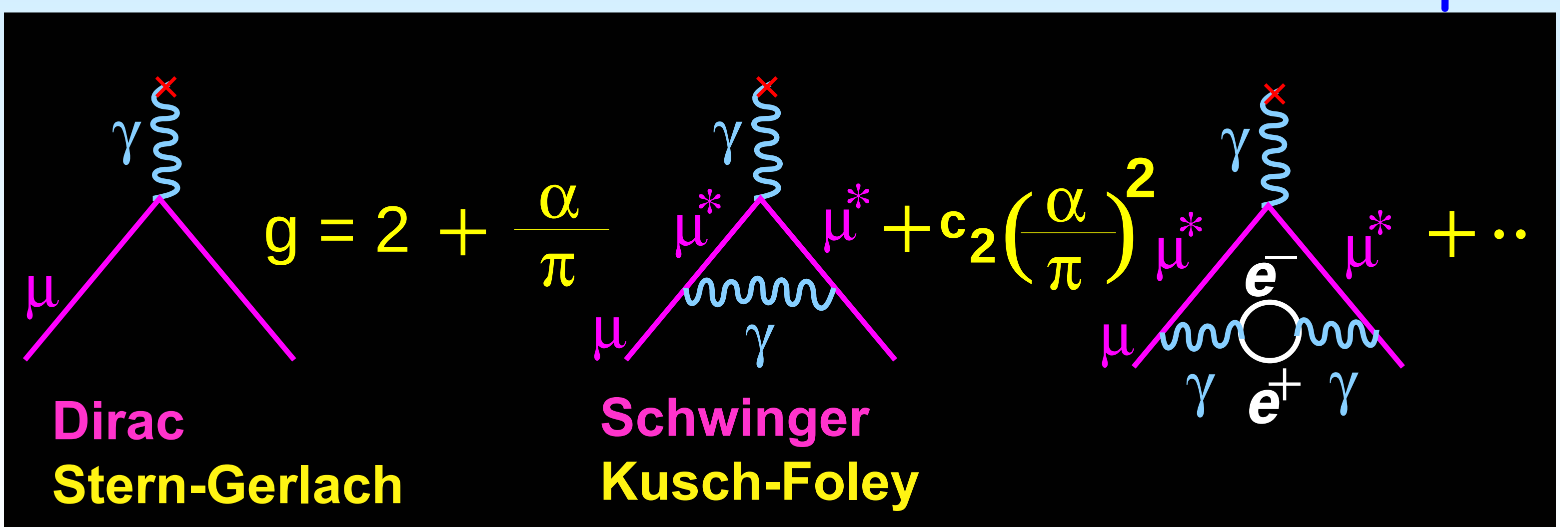
$$Re\ D = a_\mu \frac{e}{2m_\mu} \text{ and } Im\ D = d_\mu$$

Muon
Magnetic Dipole Moment

It's convenient to write the magnetic moment as a sum of two pieces:

$$\mu = (1 + a)\frac{e\hbar}{2m}$$ Dirac + Pauli moment $$a = \frac{g-2}{2}$$

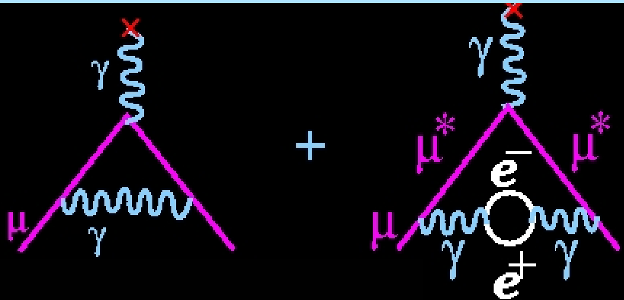
Radiative corrections contribute to a for leptons



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

The SM Value for the muon anomaly (10^{-10})

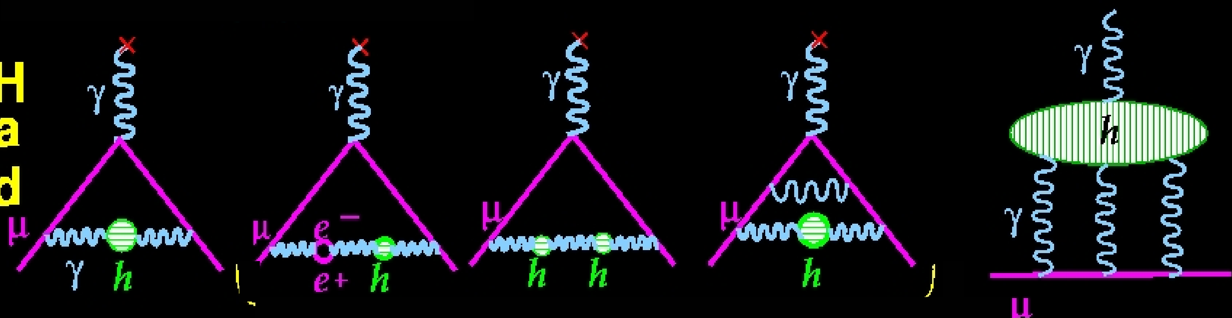
QED



$$+\cdots+C_5\left(\frac{\alpha}{\pi}\right)^5$$

11 658 471.809 (.017)

Had

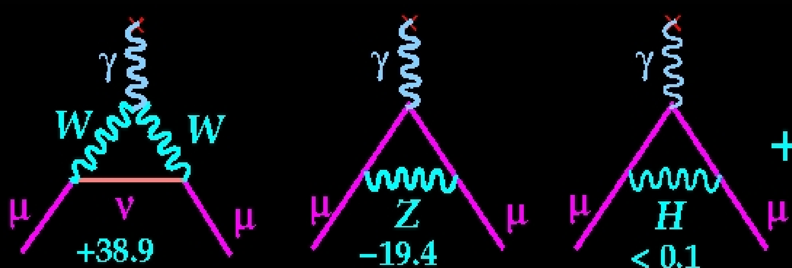


690.1 (4.7)*

−9.79 (.09)*

11.0 (4.0)†

Weak



$$+ + \cdots$$

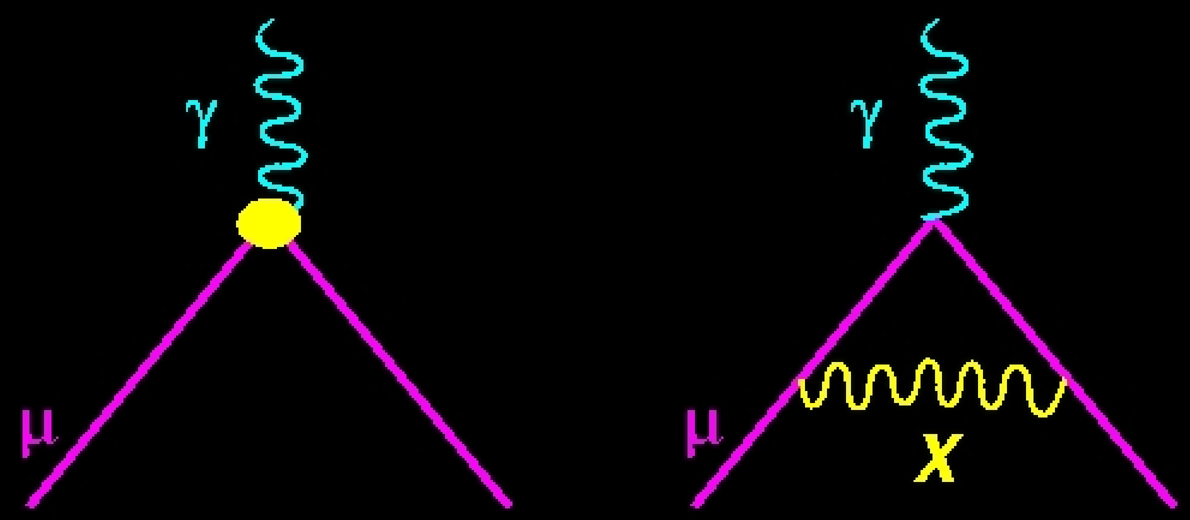
15.4 (.2)

---

11 659 178.5 (6.1)†

*Hagiwara, et al., hep-ph/0611102, Davier et al., hep-ph/0701163. †see hep-ph/0703049

Since a_μ represents a sum over **<u>all</u>** physics, it is sensitive to a wide range of potential new physics

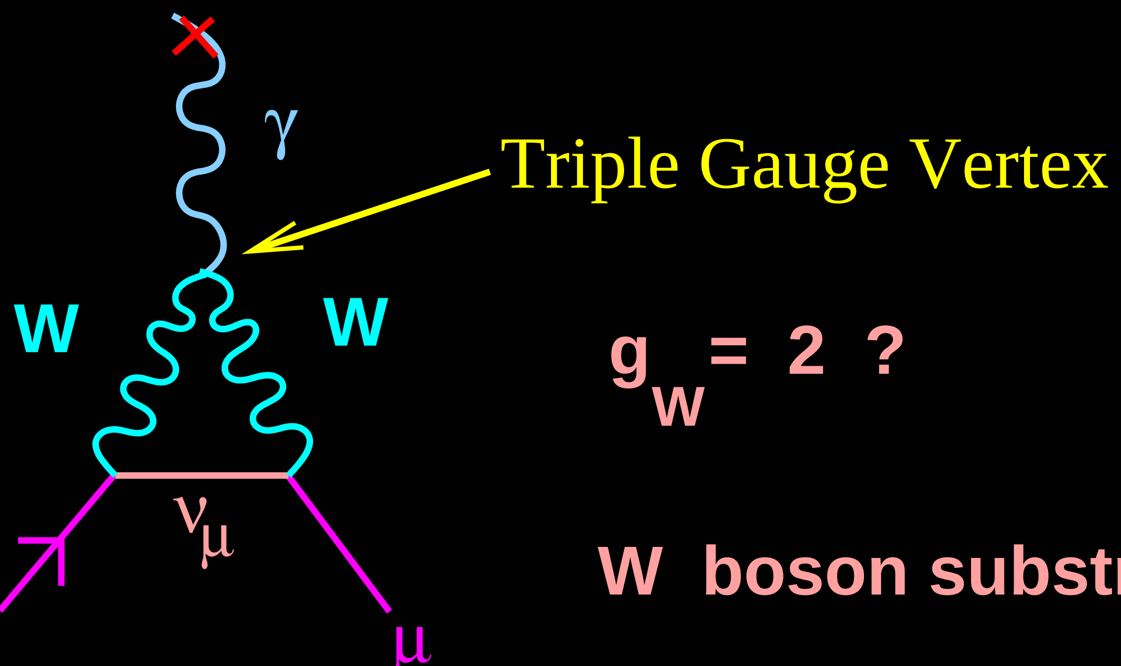


Since a_μ represents a sum over **all** physics, it is sensitive to a wide range of potential new physics

- muon substructure

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

- anomalous $W\gamma\gamma$ couplings



$g_W = 2$?

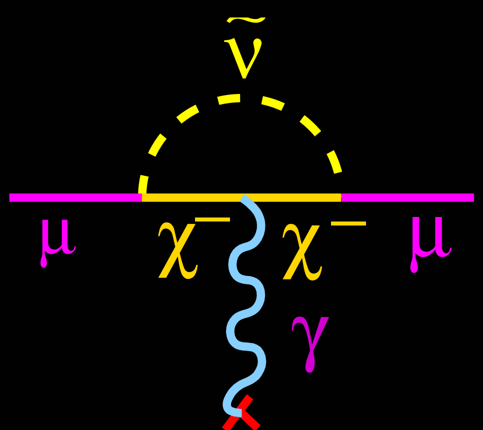
W boson substructure?

Since a_μ *represents a sum over* **all** *physics, it is sensitive to a wide range of potential new physics*

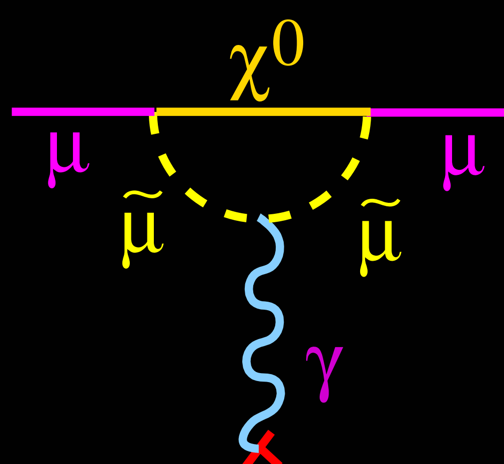
- muon substructure

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

- anomalous $W\gamma\gamma$ couplings
- SUSY (with large tanβ)



+



- many other things (extra dimensions, etc.)

Since a_μ represents a sum over **all** physics, it is sensitive to a wide range of potential new physics

- muon substructure

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

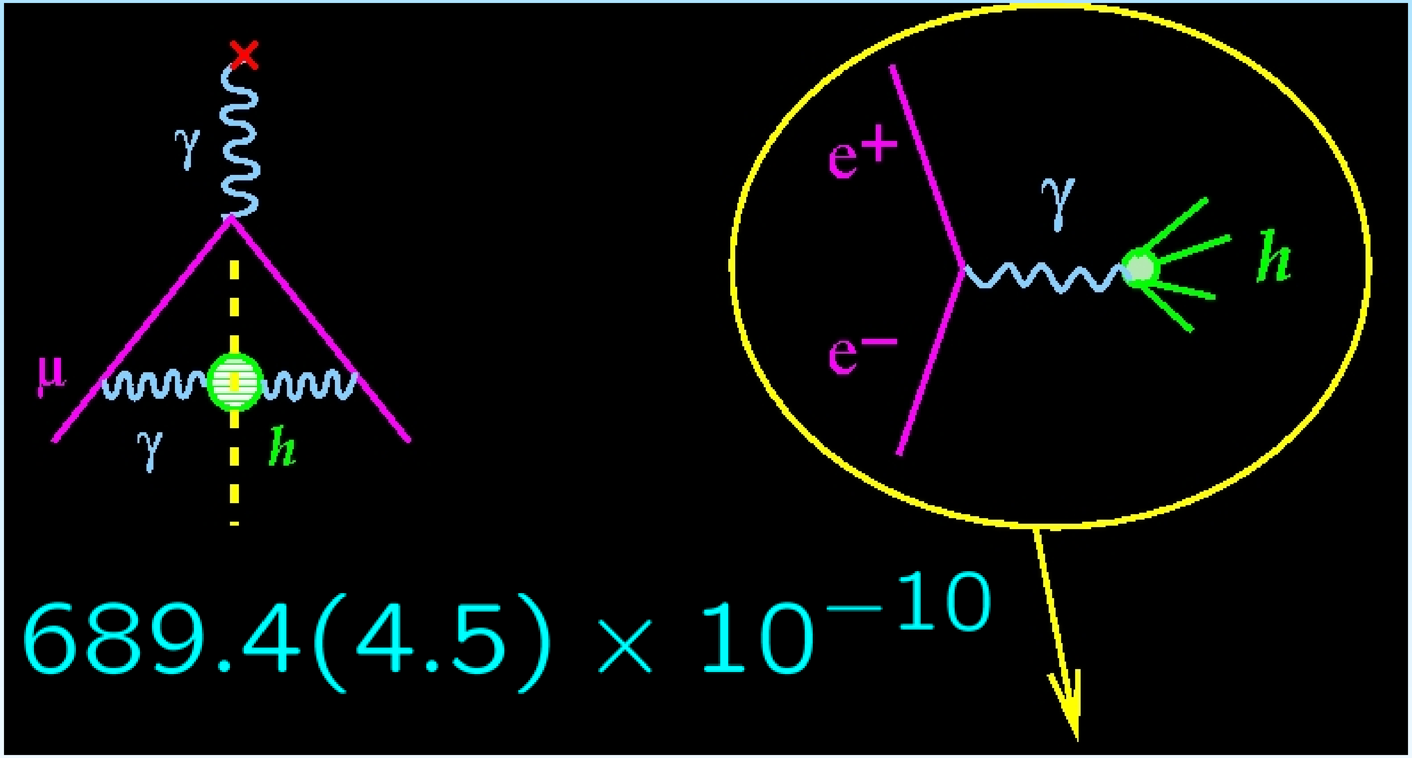
- anomalous $W\gamma\gamma$ couplings
- SUSY (with large tan*β*)

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

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

- many other things (extra dimensions, etc.)

Lowest Order Hadronic from e^+e^- annihilation



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

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

We measure the difference frequency between the spin and momentum precession

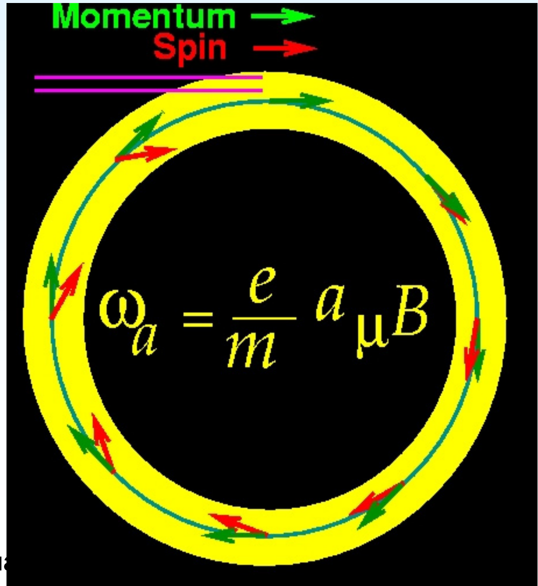
$$\omega_a = \omega_S - \omega_C = \left(\frac{g-2}{2}\right)\frac{eB}{mc} \qquad B \Rightarrow \langle B \rangle_{\mu-\text{dist}}$$

With an electric quadrupole field for vertical focusing

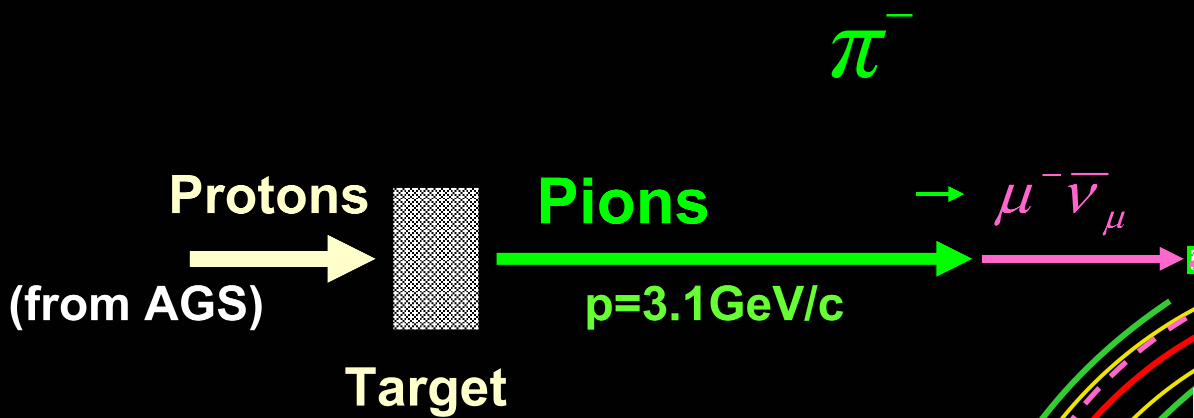
$$\vec{\omega}_a = -\frac{e}{m}\left[a_\mu \vec{B} - \cancelto{0}{\left(a_\mu - \frac{1}{\gamma^2-1}\right)\frac{\vec{\beta}\times\vec{E}}{c}}\right]$$

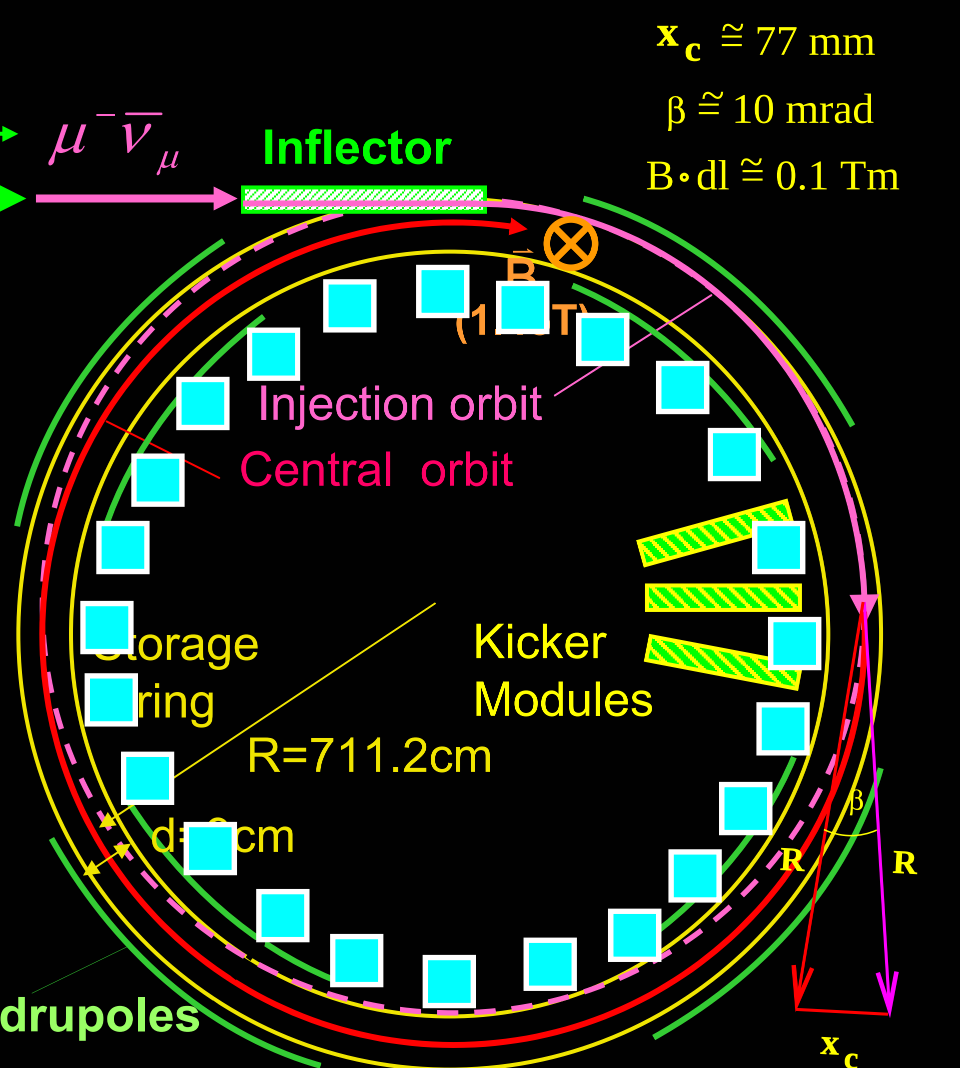
$$\gamma_{\text{magic}} = 29.3$$

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



Experimental Technique



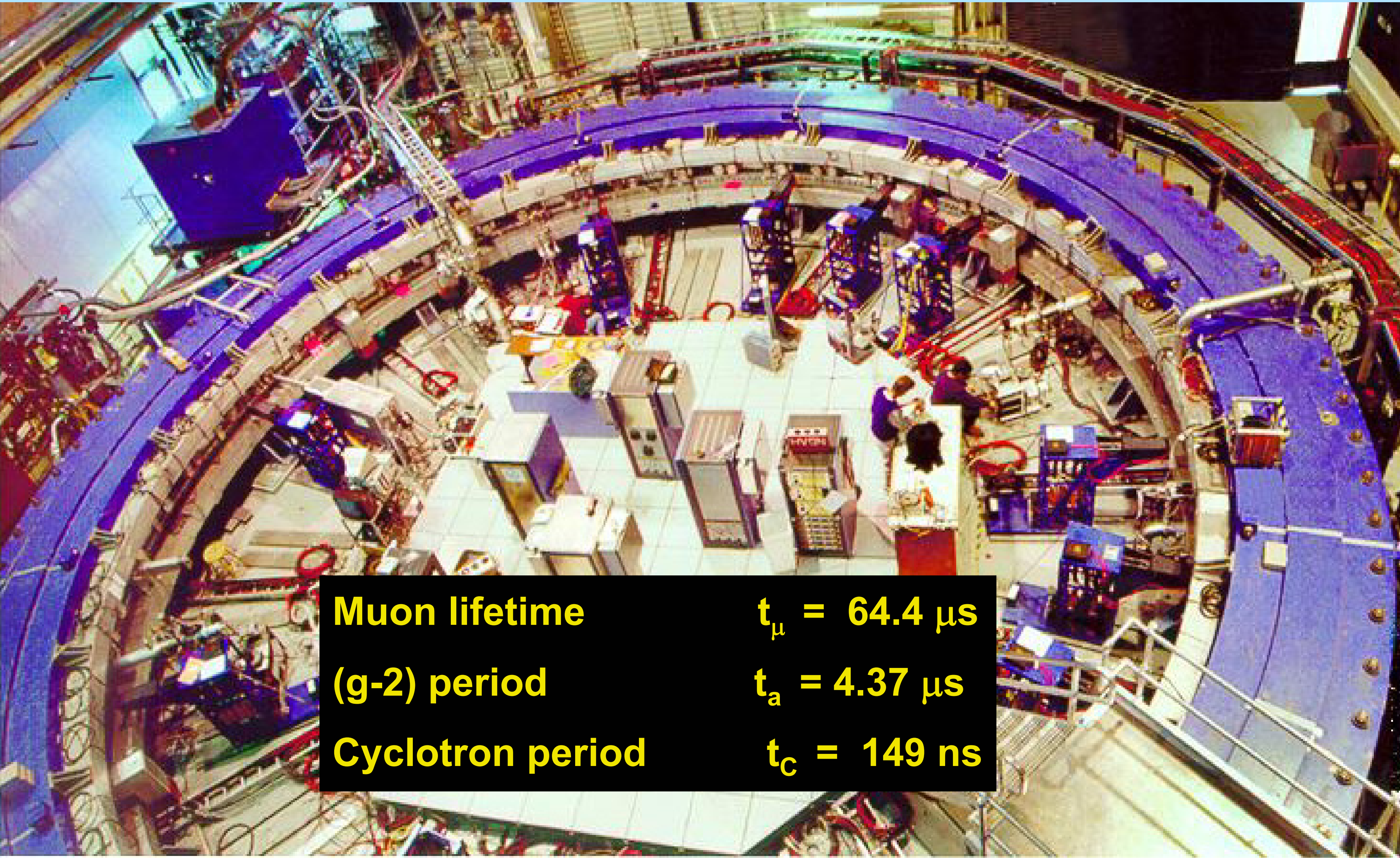


- Muon polarization
- Muon storage ring
- injection & kicking
- focus by Electric Quadrupoles
- 24 electron calorimeters

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

(thanks to Q. Peng)

muon (g-2) storage ring



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

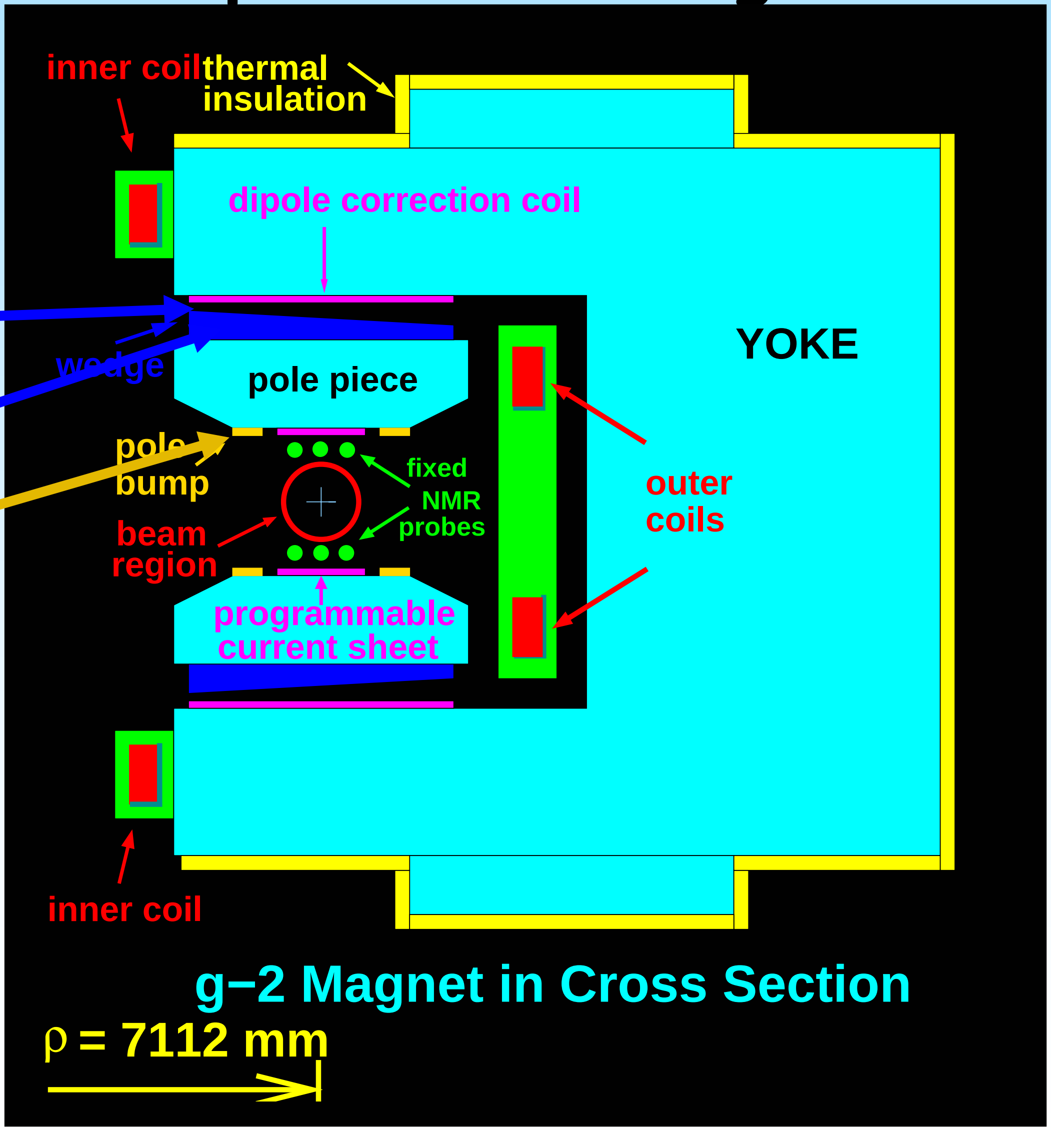
We can shim the

dipole,

quadrupole

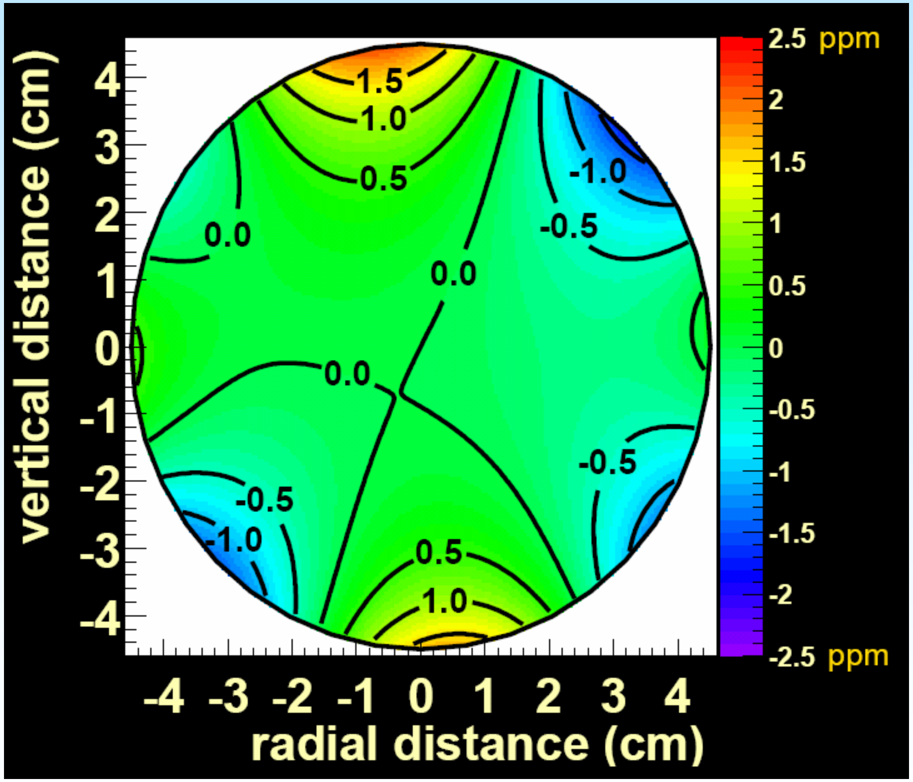
sextupole

independently



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

$$\langle B \rangle_{\text{azimuth}}$$



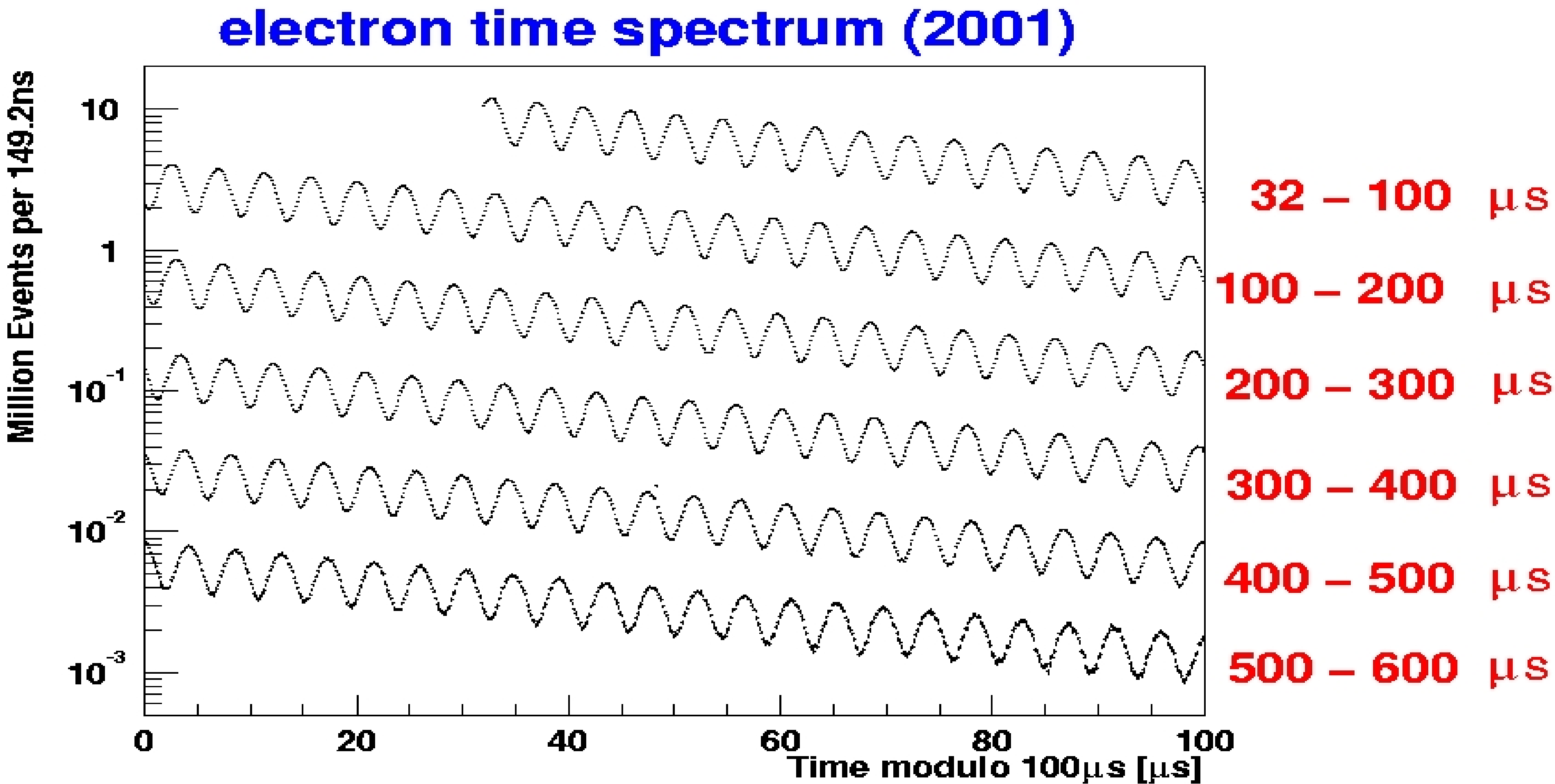
0.5 ppm contours

$$\sigma_{\text{syst}} \text{ on } \langle B \rangle_{\mu-\text{dist}} = \pm 0.03 \text{ ppm}$$

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

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

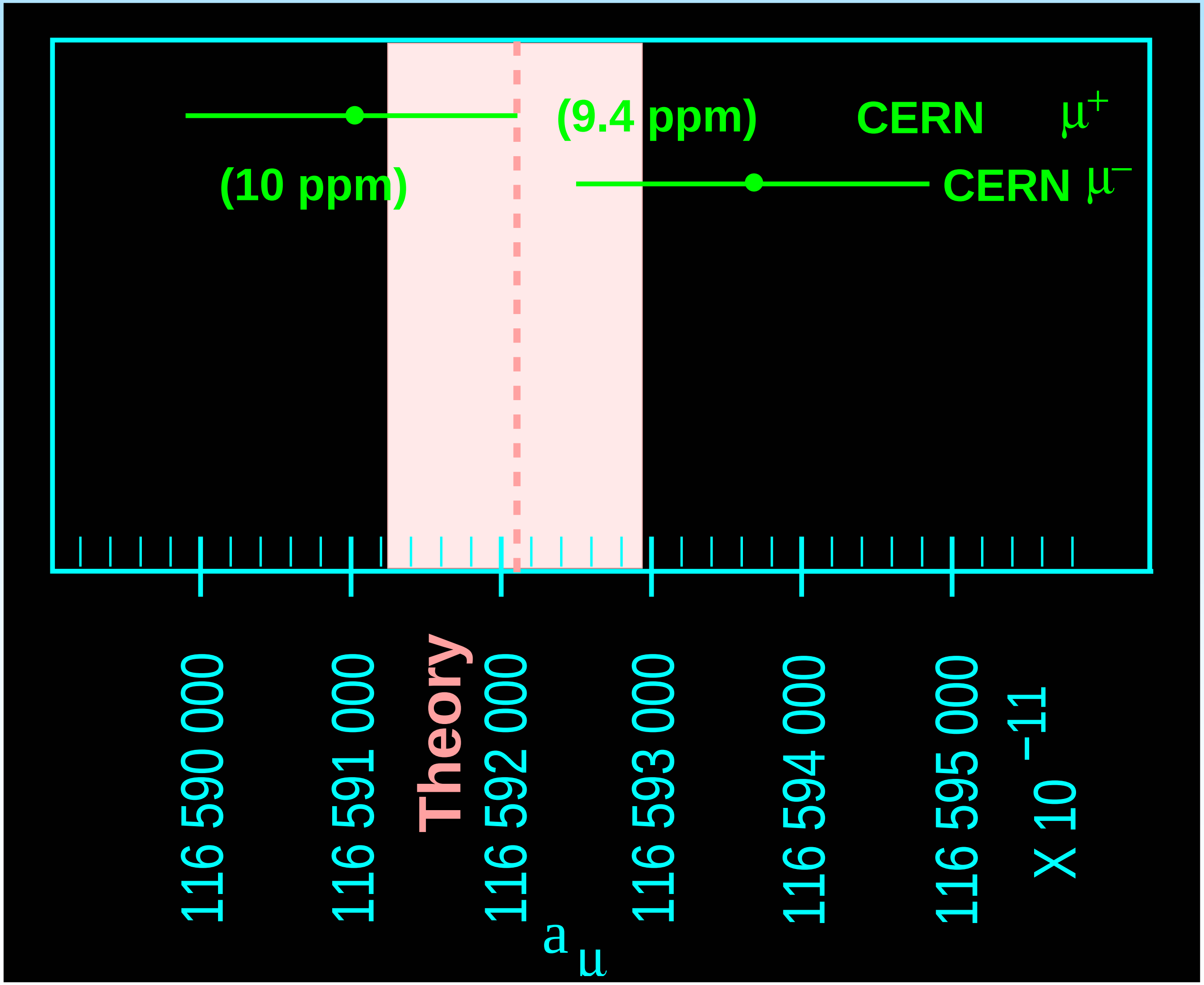
$$f(t) \simeq N_0 e^{-\lambda t}[1 + A\cos\omega_a t + \phi)]$$



In 1983, just before we started our experiment, theory and experiment were known to about 10 ppm.

Theory uncertainty was ~ 9 ppm

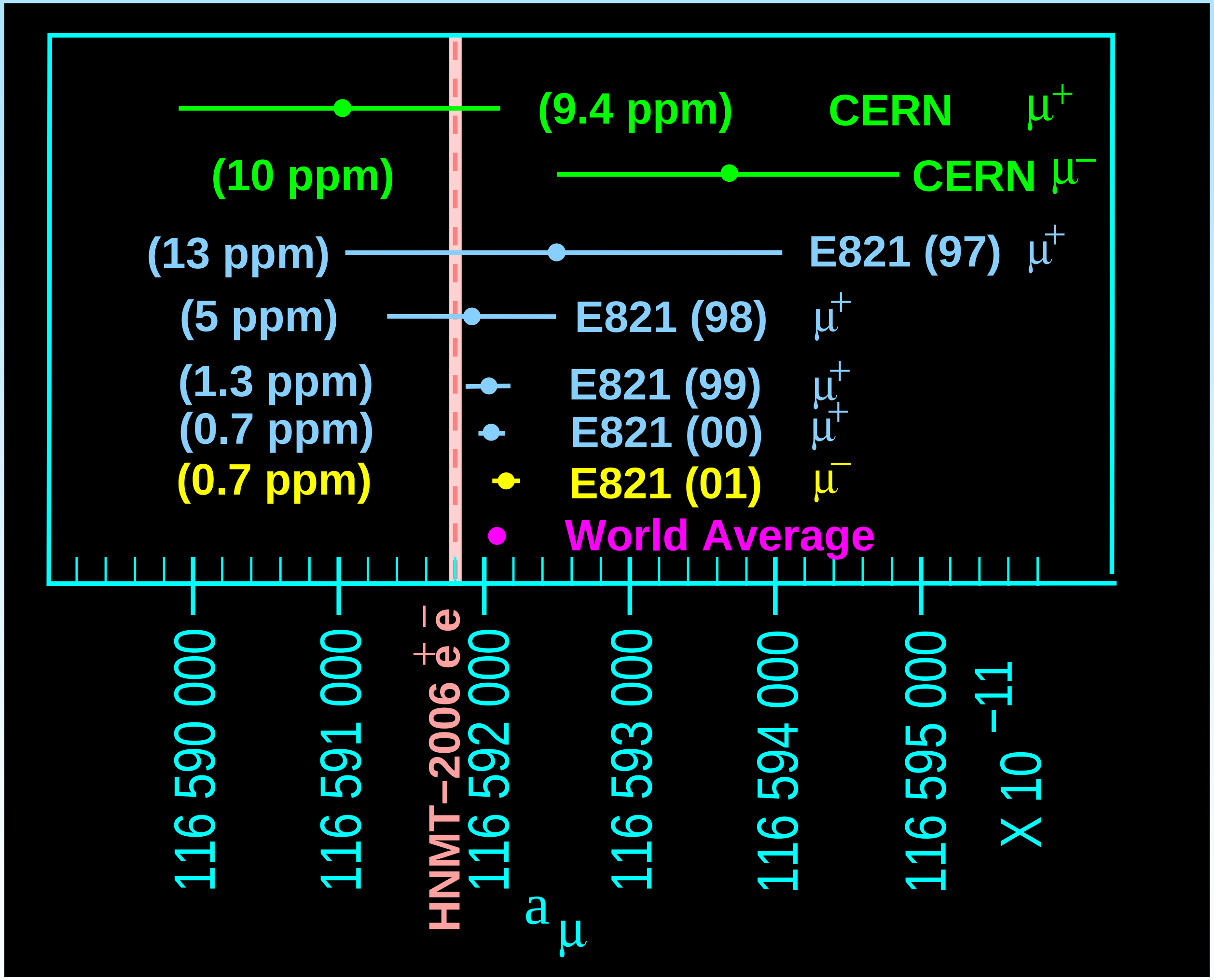
Experimental uncertainty was 7.3 ppm



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

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

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



HMNT = Hagiwara, et. al., hep-ph0611102

$$a_\mu = 11\,659\,208.0(6.3) \times 10^{-10} \; (0.54 \text{ ppm})$$

Difference with the standard model is 3.4 σ

$$a_\mu(sm07) = 11\,659\,178.5(6.1)\times 10^{-10}\ (0.44\ \mathrm{ppm})^\dagger$$

$$a_\mu(E821) = 11\,659\,208.0(6.3)\times 10^{-10}\ (0.54\ \mathrm{ppm})$$

$$\Delta_{sm} = a_{exp} - a_{sm} = 29.5(8.8) \times 10^{-10}$$

†see J. Miller, E. de Rafael and L. Roberts, hep-ph/0703049

If the electroweak contribution is left out of the standard-model value, we get a 5.1 σ difference.

$$a_\mu^{EW} = 15.4(.1)(.2) \times 10^{-10}$$

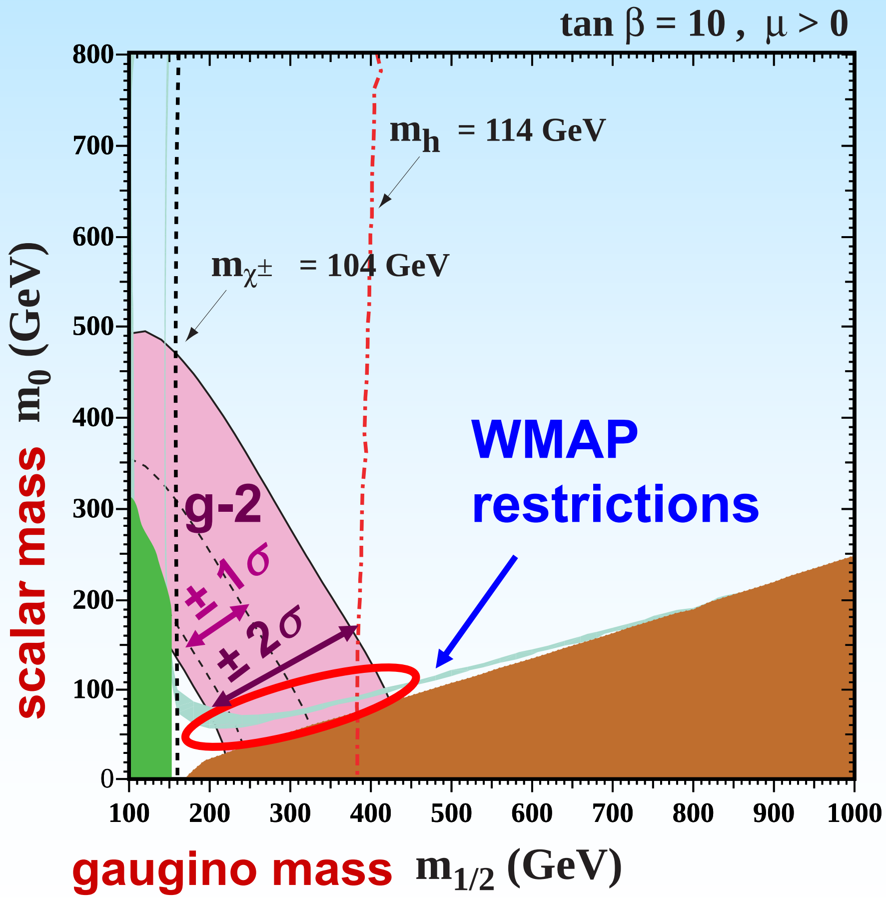
$$\Delta = a_{exp} - (a_{sm} - a_{EW}) = 44.9(8.8) \times 10^{-10}$$

- Even if you believe that there is no discrepancy between E821 and the standard model, without the EW contribution there is a significant difference.

Now if you will permit me a flight of fancy...

It's amusing to note that if we assume that SUSY is the source of the (g-2) difference, it forms a consistent picture with other constraints on the SUSY LSP (lightest supersymmetric partner) being the dark matter candidate.

using $\Delta = 29.5 \pm 8.8$



Historically muon (g-2) has played an important role in restricting models of new physics.

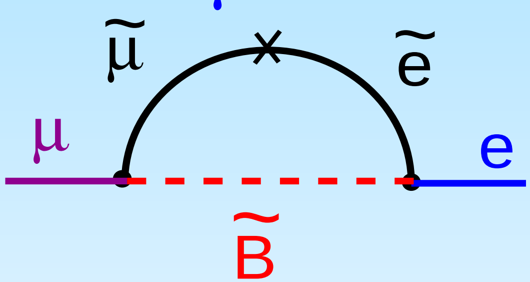
CMSSM calculation Following Ellis, Olive, Santoso, Spanos, Phys. Rev. **D 71,** 095007 (2005)

(provided by K. Olive 3/07)

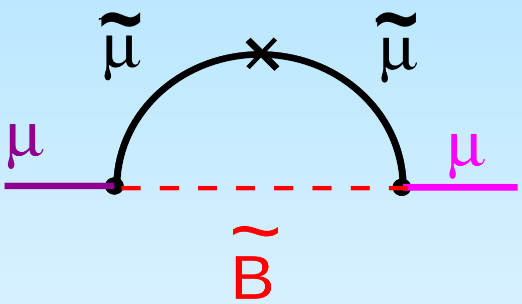
To continue this flight of fancy for a moment

If SUSY exists, the sleptons will mix, and there is a connection between a_μ , D_μ , $\mu \rightarrow e$

$\mu \rightarrow$ e



MDM, EDM



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

Electric Dipole Moments

E.M. Purcell and N.F. Ramsey, 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

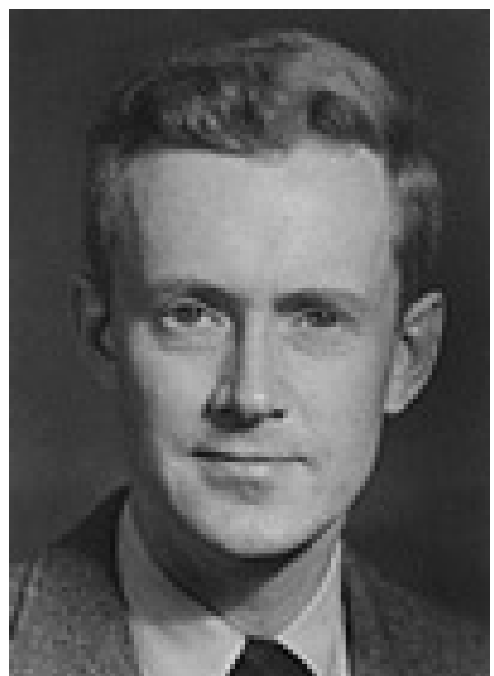
It is generally assumed on the basis of some suggestive theoretical symmetry arguments[1] that nuclei and elementary particles can have no electric dipole moments. It is the purpose of this note to point out that although these theoretical arguments are valid when applied to molecular and atomic moments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

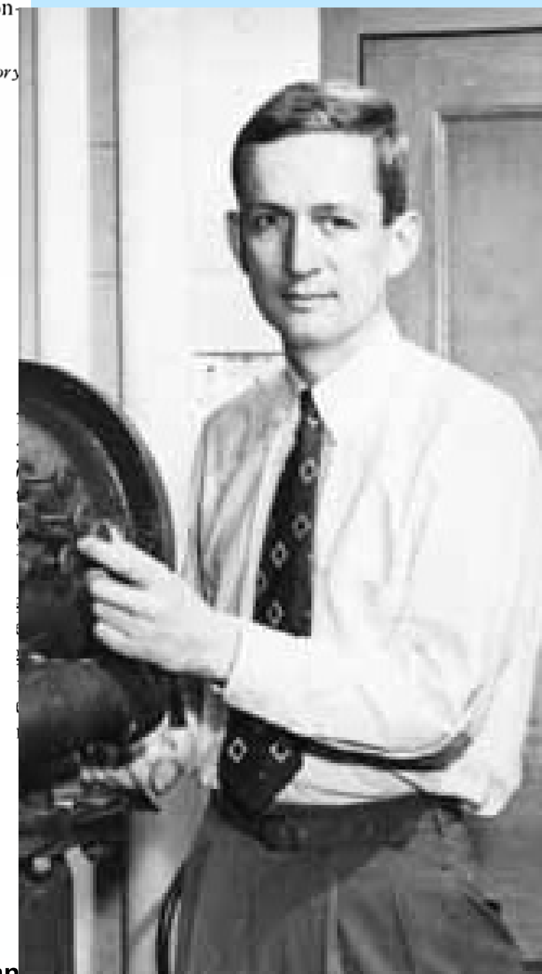
One form of the argument against the possibility of an electric dipole moment of a nucleon or similar particle is that the dipole's orientation must be completely specified by the orientation of the angular momentum which, however, is an axial vector specifying a direction of circulation, not a direction 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

The argument against electric dipole moments, in another form, raises directly the question of parity.

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).





Transformation Properties of Electric and Magnetic Dipole Moments

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

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

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

An EDM implies both *P* and *T* are violated. Assuming CPT symmetry, an EDM at a measureable level would imply non-standard model ~~*CP*~~.

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)

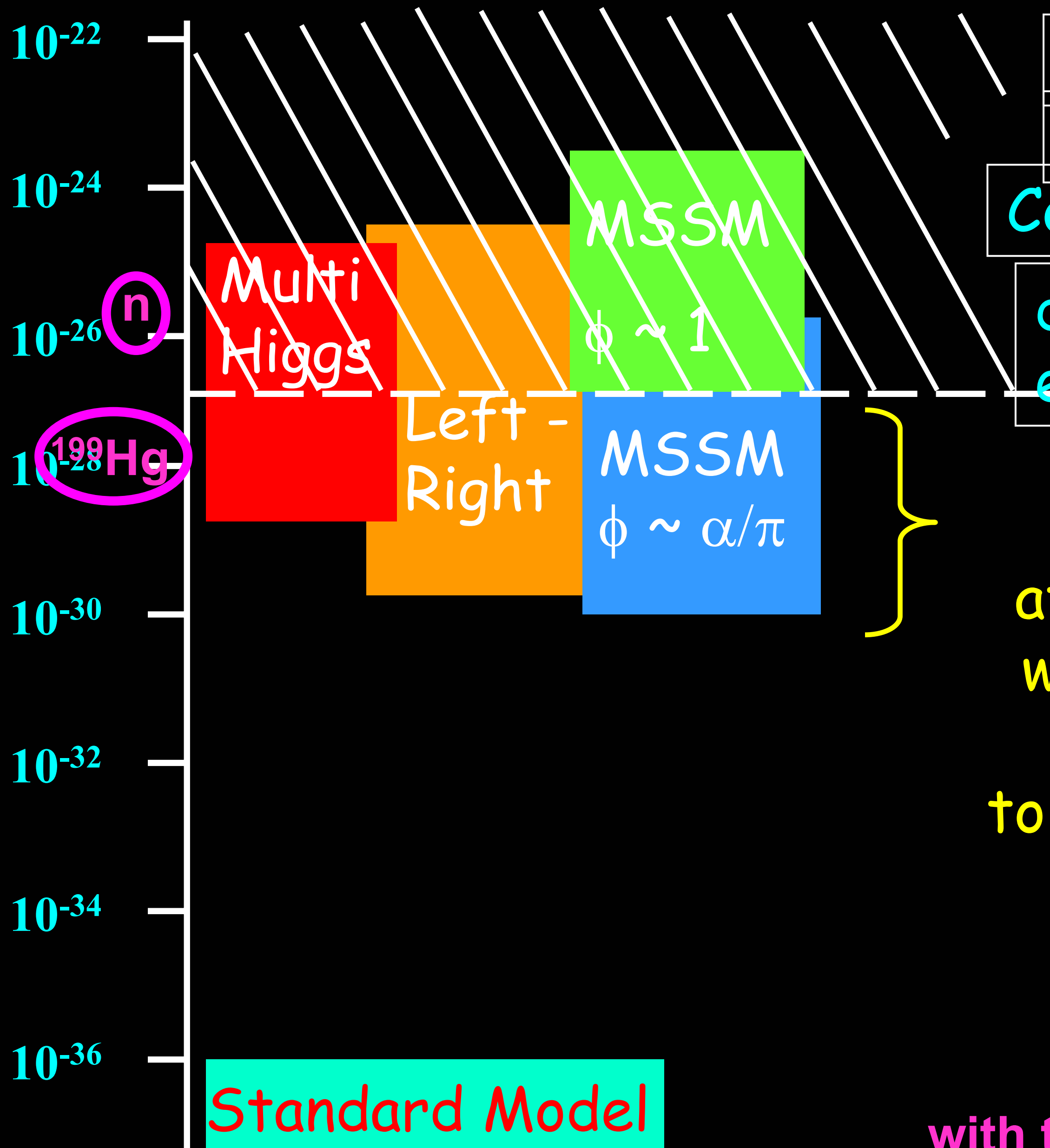
An experimental measurement of the electric dipole moment of the neutron by a neutron-beam magnetic resonance method is described. The result of the experiment is that the electric dipole moment of the neutron equals the charge of the electron multiplied by a distance $D=(-0.1\pm2.4)\times10^{-20}$ cm. 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

e EDM (e.cm)



Excluded region
(Tl atomic beam)
Commins (2002)
$d_e < 1.6 \times 10^{-27}$ e.cm

E. Hinds' e-EDM experiment
at Imperial College
with YbF molecules
is starting
to explore this region

with thanks to Ed Hinds

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.

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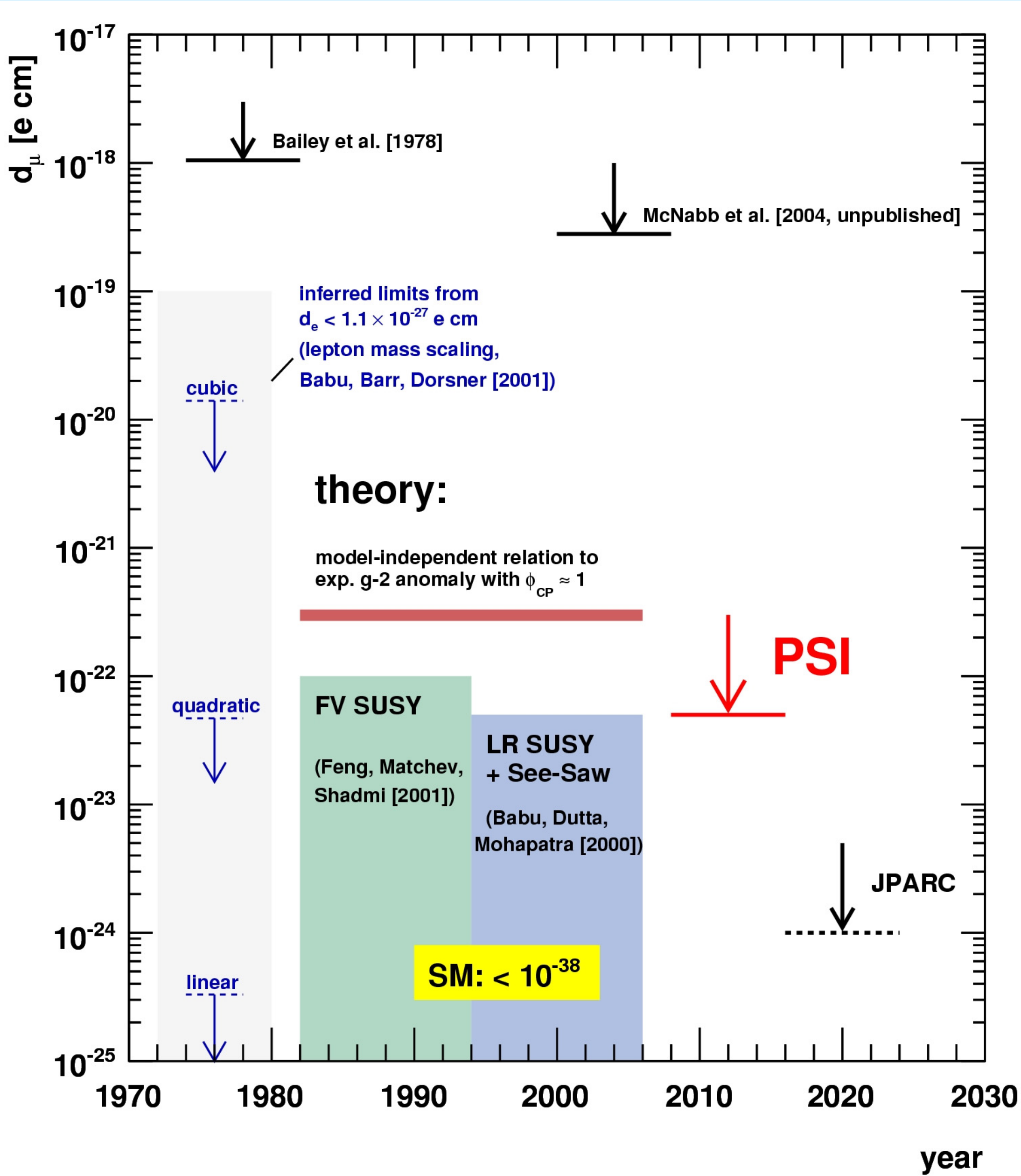
Enhanced Electric Dipole Moment of the Muon in the Presence of Large Neutrino Mixing

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)

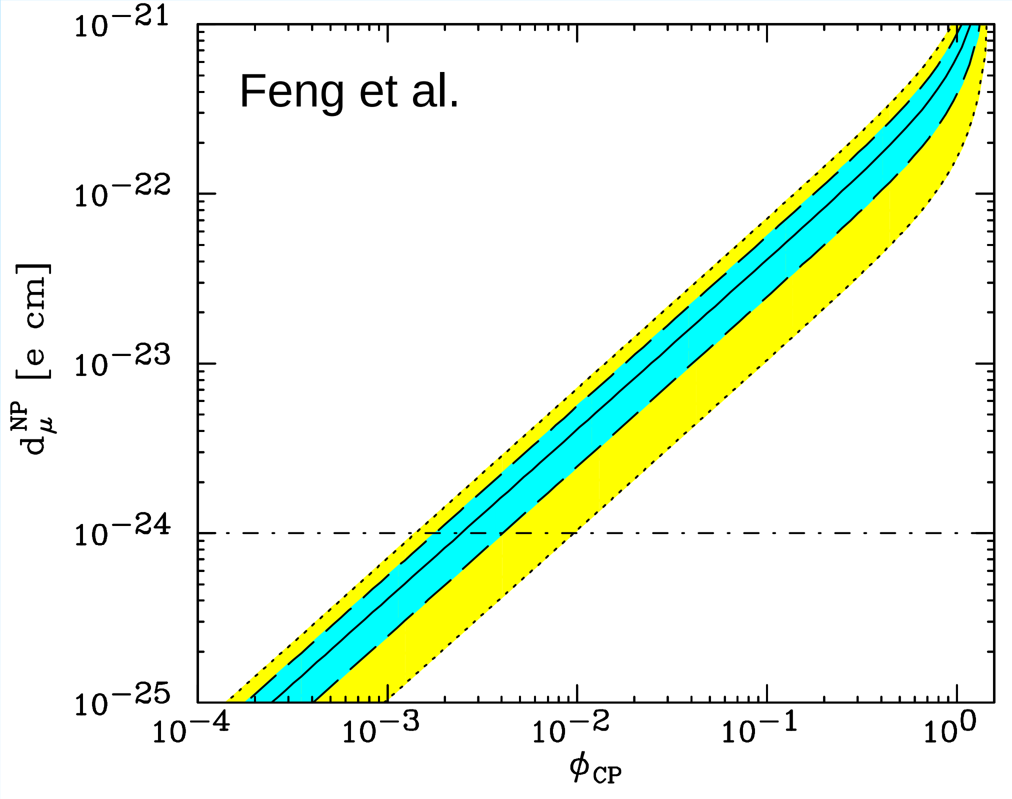
The electric dipole moment (edm) of the muon (d_μ^e) is evaluated in supersymmetric models with nonzero neutrino masses and large neutrino mixing arising from the seesaw mechanism. It is found that if the seesaw mechanism is embedded in the framework of a left-right symmetric gauge structure, the interactions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

$$\Delta_{\mathrm{now}} = (27.6 \pm 8.1) \times 10^{-10}$$

Muon EDM Limits: CERN3 and E821 @ BNL

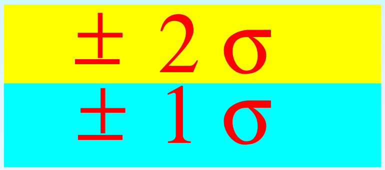


a_μ implications for the muon EDM



assuming that

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



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

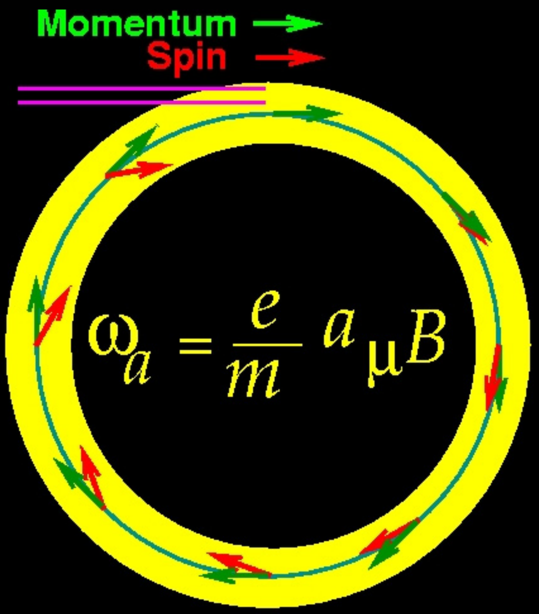
where ϕ_{CP} is a CP violating phase.

Spin Frequencies: μ in B field with MDM & EDM

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

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

spin difference frequency = $\omega_s - \omega_c$



Spin Frequencies: μ in B field with MDM & EDM

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

$$\gamma_{\mathrm{magic}} = 29.3 \qquad \omega_a$$

spin difference frequency = ω_s - ω_c

Spin Frequencies: μ in B field with MDM & EDM

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

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

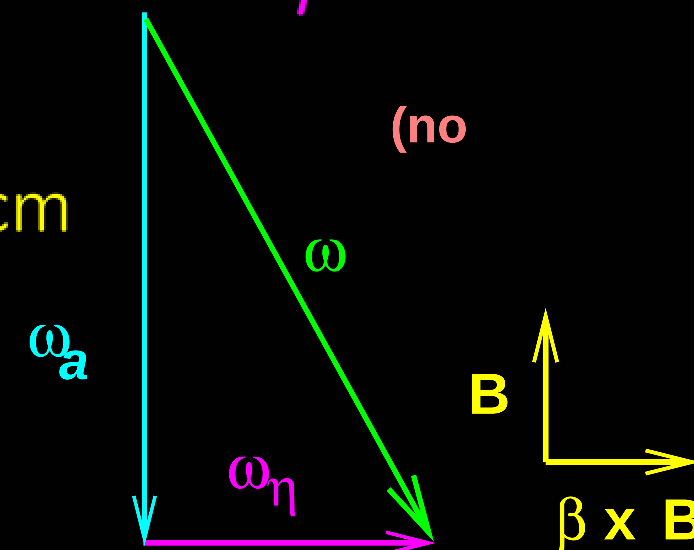
$$+ \quad \frac{e}{m}\left[\frac{\eta}{2}\left(\frac{\vec{E}}{c} + \vec{\beta} \times \vec{B}\right)\right]$$

$$\omega_\eta$$

The motional E - field, β X B, is **<u>much</u>** stronger than laboratory electric fields (~GV/m).

$$d_\mu = \frac{\eta}{2}\left(\frac{e\hbar}{2mc}\right) \simeq \eta \times 4.7 \times 10^{-14} \quad e \text{ cm}$$

$$a_\mu = \left(\frac{g-2}{2}\right)$$



Dedicated EDM Experiment

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

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

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

With $\omega_a = 0$, the EDM causes the spin to steadily precess out of the plane.

ω_η

since $\omega^2 = \omega_a^{\,2} + \omega_\eta^{\,2}$, the Δ_{SM} could be an EDM

what value EDM would this correspond to?

$$|d_\mu| = 1.8(.5) \times 10^{-19}\ e\mathrm{cm}$$

obviously this would be exciting.

See: Feng, et al., Nucl. Phys. **B 613** (2001) 366

The present limits are:

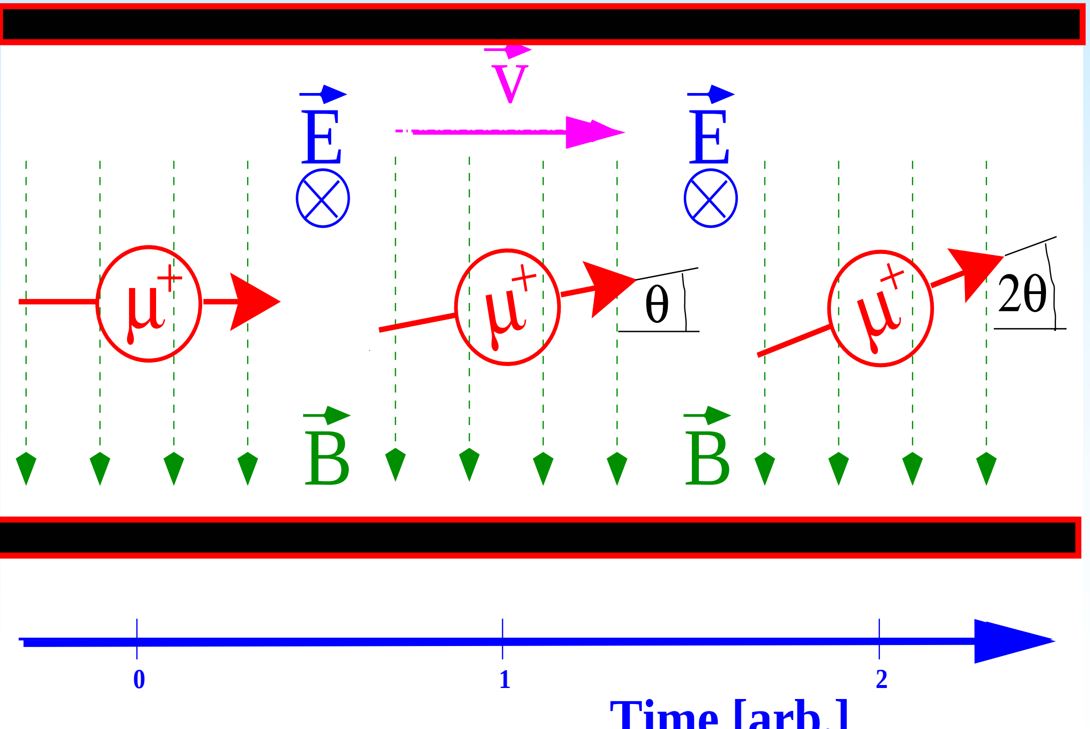
$$< 10^{-18}\ \mathrm{(CERN)}$$
$$\sim 10^{-19} *\ \mathrm{(E821)}$$

SM value $< 10^{-38}$

*preliminary

"Frozen spin" technique to measure EDM

- Turn off the (g-2) precession with radial $\boldsymbol{E}$
- Up-Down detectors measure EDM asymmetry
- Look for an up-down asymmetry building up with time
- Side detectors measure (g-2) precession
  - To prove the spin is frozen



$$a = \frac{\text{up} - \text{down}}{\text{up} + \text{down}}$$

See the Poster: Search for a μ-EDM

A. Adelmann[1], K. Kirch[1], C.J.G. Onderwater[2], T. Schietinger[1], A. Streun[1]

Search for the muon electric dipole moment using a compact storage ring

hep-ex/0606034

A. Adelmann and K. Kirch*
Paul Scherrer Institut (PSI), CH-5232 Villigen PSI, Switzerland

(Dated: June 15, 2006)

The recently proposed *'New Method of Measuring Electric Dipole Moments in Storage Rings'* [1, 2, 3] could be used in an experiment using the existing muon beam μE1 at PSI. A high muon polarization and a rather low momentum of $p_\mu \sim 125$ MeV/c allow for an almost table-top storage ring and increase the intrinsic sensitivity and, thus, partially compensate for limitations due to lower event statistics. A measurement of the muon electric dipole moment with a sensitivity of better than $d_\mu \sim 5 \times 10^{-23}$ e·cm within one year of data taking appears feasible.

B = 1 T

p_μ = 125 MeV/c

$\beta_\mu = 0.77, \quad \gamma_\mu = 1.57$

P ≈ 0.9

E = 0.64 MV/m

R = 0.35 m

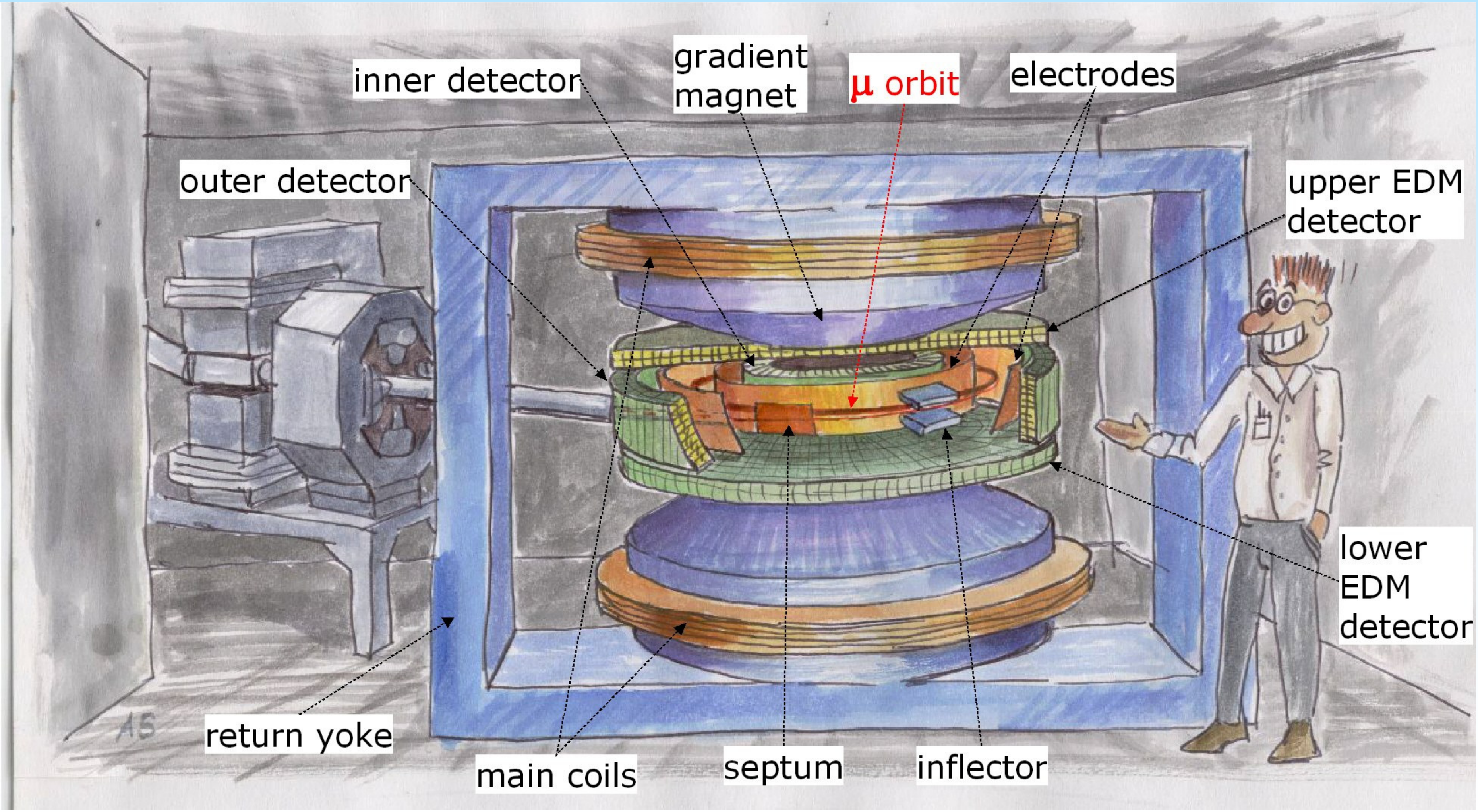
$$\sigma_{d_\mu} \simeq \frac{1.1 \times 10^{-16}}{\sqrt{N}}$$

In 1 year of running @ PSI

$$\sigma_{d_\mu} \simeq 5 \times 10^{-23} \mathrm{e} \cdot \mathrm{cm}$$

The storage ring is modest in size

Injection studies look promising.



Summary and Outlook

- A dedicated m-EDM experiment could be developed here at PSI that could reach interesting sensitivity.
- *This would provide a unique opportunity for PSI to contribute to the worldwide effort in precision physics.*
- The muon has provided us with much knowledge on how nature works, and there is plenty of room for future surprises.
- Muon (g-2), with a precision of 0.5 ppm, has a 3.4 σ discrepancy with the standard model using e^+e^- data for the hadronic contribution.
- This new physics would show up in an EDM and perhaps LFV as well.

THE END

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