From Dirac equation to the precision measurement of the anomalous magnetic moment of the muon

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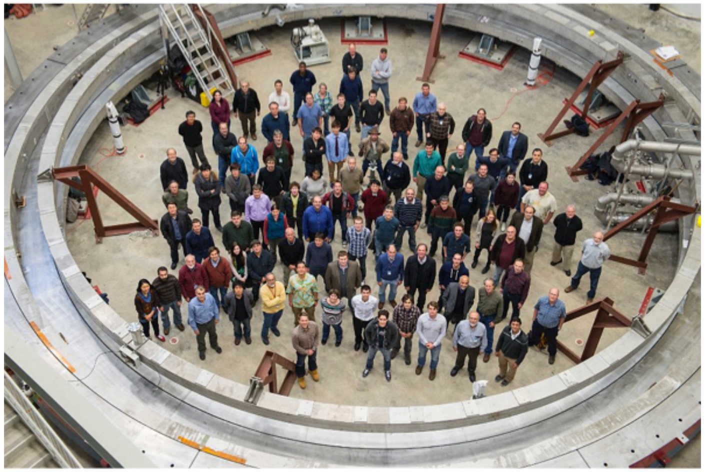
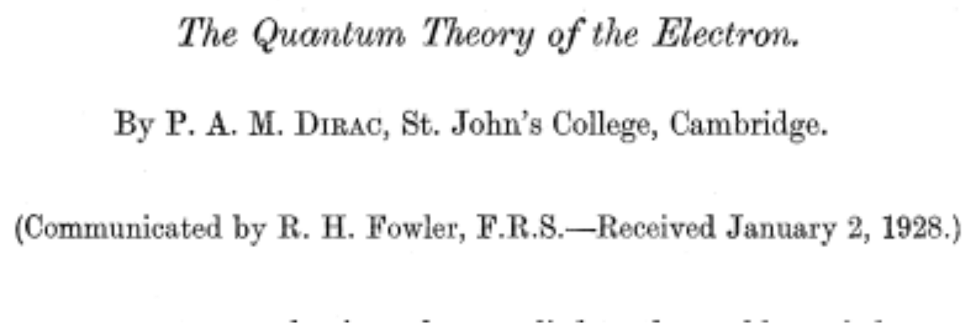


Seminar at Novosibirsk State University
February 2 2016

"One cannot escape the feeling that these mathematical formulae have an independent existence and an intelligence of their own, that they are wiser than we are, wiser even than their discoverers, that we get more out of them than we originally put in to them."

Heinrich Hertz
1857 – 1894

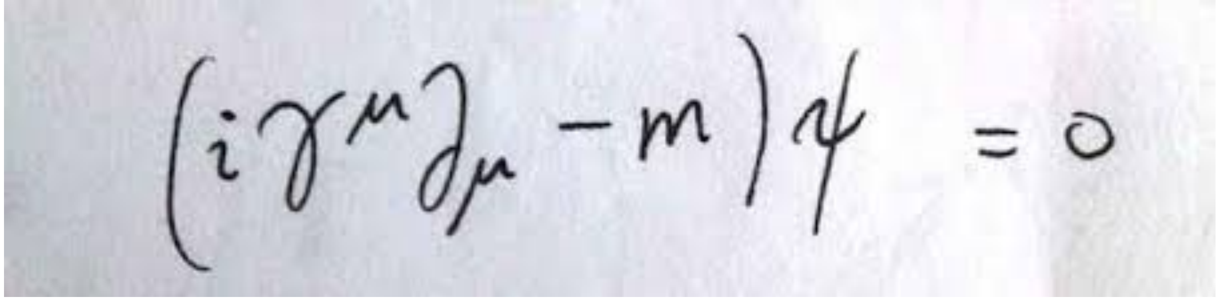
Dirac Equation (1928)



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.)



$$(i\gamma^{\mu}\partial_{\mu} - m)\psi = 0$$

4-components equation (4 equations)

- **It describes the electron behaviour including Relativistic Theory and Quantum Mechanics**
- **It predicts the spin of the electron and the associated magnetic moment**
- **It predicts the existence of antimatter (anti-electron or positron)**
- **A new concept of the matter based on the properties of the electro magnetic quantum field (Quantum Field Theory, Quantum Electrodynamics)**

Unification of (Special) Relativistic Theory (SR) and Quantum Mechanics (QM)

- The quantum mechanics developed by Heisenberg and Schrödinger were based on old mechanics of Newton (v<<c).
- Fundamental dichotomies: light (SR) vs matter (QM); continuous (SR) vs disctrete (QM) which traces back to:
  - Ancient Greeks (Plenum vs Vacuum);
  - Newton (rigid bodies through empty space);
  - Maxwell (light as wave filling all space);
  - Thomson (matter built of electrons in the empty space);
  - Planck and Einstein (light compose of particles)
  - Bohr and Schrödinger (matter behaves as waves)

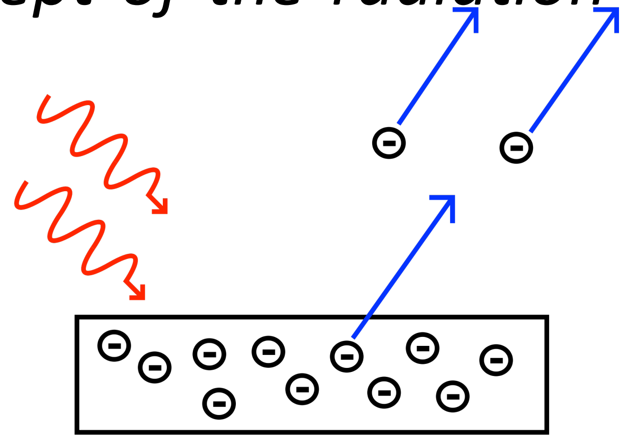
  → Light is a bit like particles and electrons are a bit like waves

However 2 main differences

1. If the light is to be made of particles they should carry an arrow that keeps record of the light's polarization

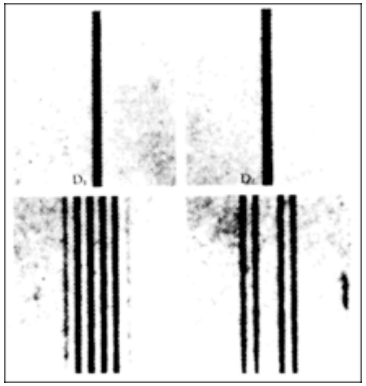
2. Photons are evanescent. Light can be radiated or absorbed, i.e. photons can be created or destroyed. Different from Matter which is done of stable buildings blocks (electrons)

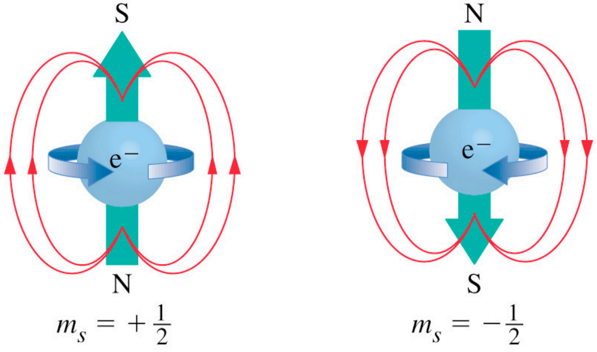
- *The Dirac equation forced physicists to trascend all these dichotomies → unified concept of the radiation and matter (QED)*



First prediction of Dirac equation: the spin

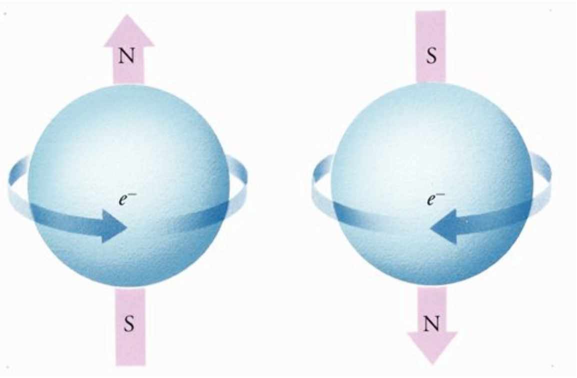
- **Difficulties with Bohr atomic theory**:
  - Number of electrons which could occupy each orbit (2) – Pauli exclusion principle
  - Spectral lines of atoms in Magnetic field
- **1925:** Two Dutch graduate students, **Samuel Goudsmit** e **George Uhlenbeck** devised a possible explanation of magnetic response problems: electrons behaves as tiny magnets with B generated by their rotation about their axis (Spin!). This would also explain why 2 electrons for each orbit (↑↓)
- They postulate also for the giromagnetic ratio g=2 (Magnetic moment/spin) whereas classical mechanics for a rotating object predicts g=1





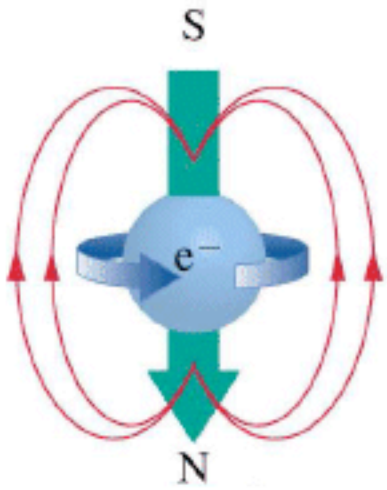
Dirac prediction: the spin of electron and the anti-electron

- Two equations with E>0 describes the spin of electron with S=±1/2 and g=2
- Two equations with E<0 describes an anti-electron
- The anti-electron was discovered in 1932 in cosmic rays



S=+1/2 S=-1/2

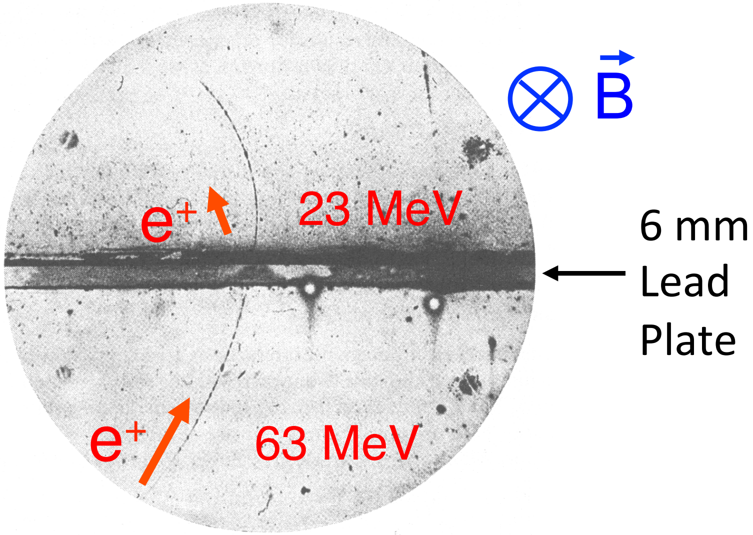
Momento magnetico



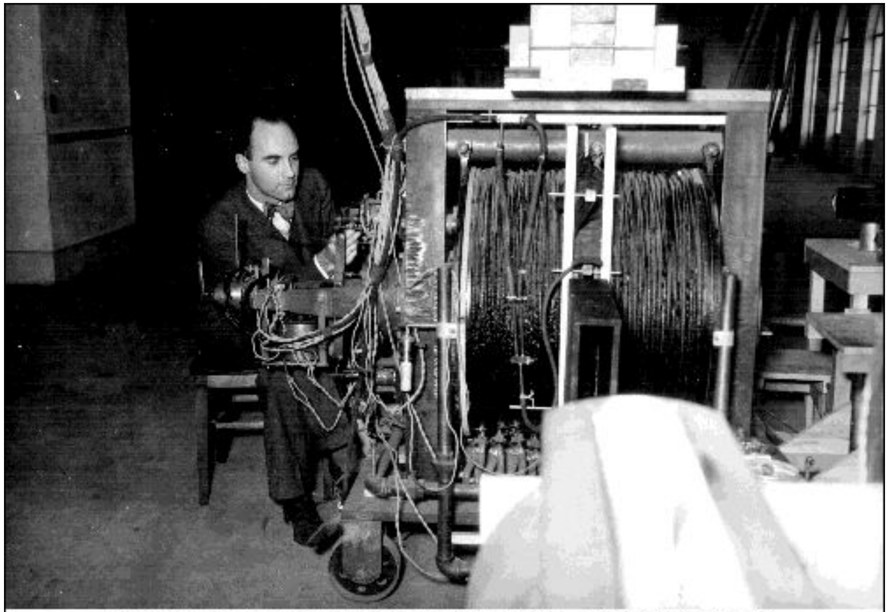
$$\mu_b = \frac{e\hbar}{2m_e}$$

1932: Discovery of the positron (anti-electron)

★Cosmic ray track in cloud chamber:



C.D.Anderson, Phys Rev 43 (1933) 491



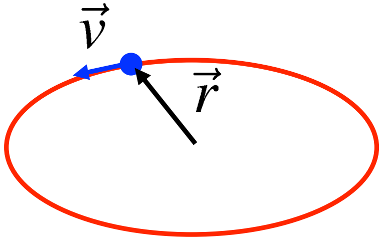
- e^+ enters at bottom, slows down in the lead plate – know direction
- Curvature in B-field shows that it is a positive particle
- Can't be a proton as would have stopped in the lead

- Since then many anti-particles discoveried. The physics reason goes beyond the Dirac Equation and postulates that for each particle an anti-particle should exist with the same mass but opposite charge (and other quantum numbers)

The giromagnetic ratio g

- A charge particle in a plane orbit has angular momentum L and magnetic moment μ

$$\mu = \frac{q}{2m}\vec{L}$$



- The ratio μ/(q/2m)L is called giromagnetic ratio g. Classically **g=1**

- For the electron Dirac equation predicts for a magnetic moment due to spin 2 x the classic one, **g=2,** in agreement with the conjecture of Goudsmit e Uhlenbeck

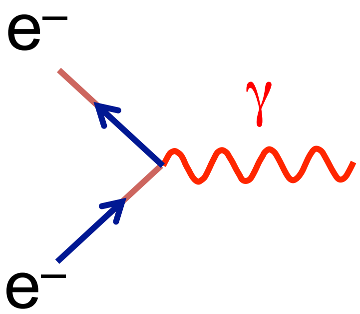
$$\vec{\mu} = \frac{q}{m}\vec{S} \quad = \quad \vec{\mu} = g\frac{q}{2m}\vec{S}$$

- Triumph of Dirac equation

The Deepest meanings: Quantum Field Theory

- Photons and electrons (and other particles) are (discrete) excitation of the fields which fill all the space (continuous)
- The Vacuum is not really “empty”. Infact Quantum uncertainty combined with QFT implies that pairs of (virtual) particle and antiparticles can be crated and destroyed → Quantum fluctuations of dynamical vacuum has real effects (on mass and charge of real particles)
- Quantum field Theory (QFT, or QED) was born
- At the point (mid of 30’s) Dirac (like Einstein) took a separate path. His contribution to the development of QED was marginal.
- He Died in 1984 at 82.

The development of the Quantum Electrodynamics (QED)



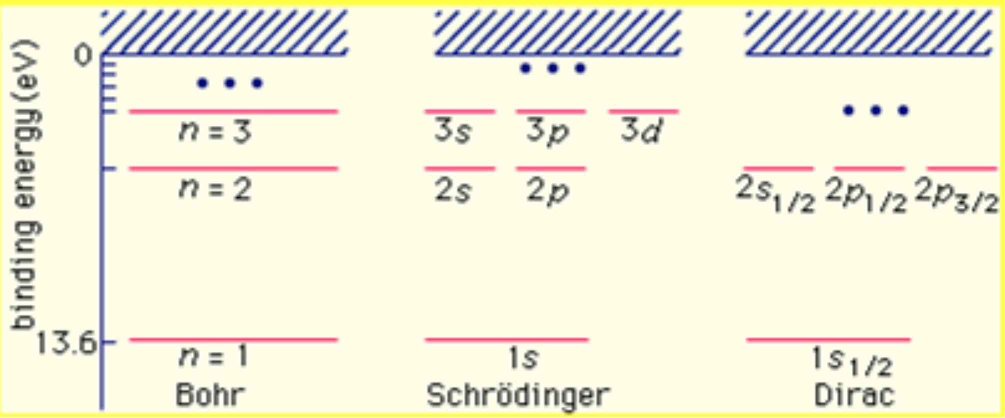
- In ~1930 the QED was born and described well the processes of interaction between electrons and photons
- But in 1947, the conference of Shelter Island, were found two surprising effects: the discovery of the "Lamb shift" and the anomalous magnetic moment of the electron
- The conference of Shelter Island was a turning point in the development of QED. They participated in the physical that would have a decisive role in the solution of these anomalies: Hans Bethe, Richard Feynman, Julian Schwinger and others

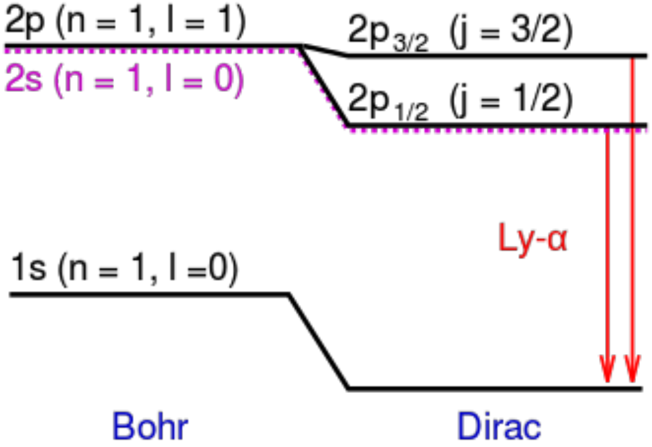
Shelter Island (1947)

FIG. 1. Participants at the Shelter Island conference (left to right): I. I. Rabi, L. Pauling, J. Van Vleck, W. E. Lamb, G. Breit, D. MacInnes, K. K. Darrow, G. E. Uhlenbeck, J. Schwinger, E. Teller, B. Rossi, A. Nordsieck, J. von Neumann, J. A. Wheeler, H. A. Bethe, R. Serber, R. E. Marshak, A. Pais, J. R. Oppenheimer, D. Bohm, R. P. Feynman, V. F. Weisskopf, H. Feshbach (not in the picture, H. A. Kramers). Courtesy of the Archives of the National Academy of Sciences.

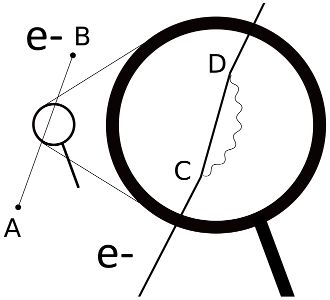
1947: Lamb Shift

- Shift of the $2S_{1/2}$ state wrt $2P_{1/2}$ in H (+1050 MHz) as measured by Willis Lamb (1913–2008)



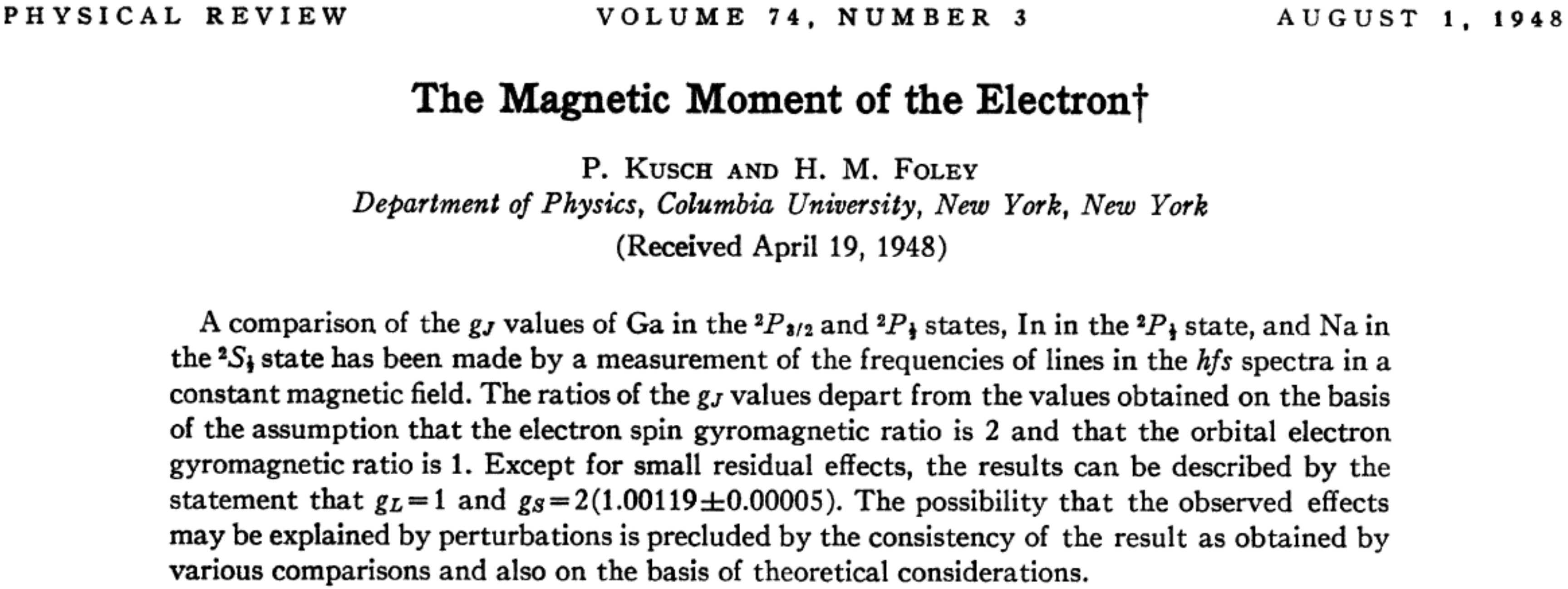


- The shift was due to the interaction of the electron with virtual particles of the vacuum (electron mass corrections)
- However, these adjustments were not easy to calculate



1947: Measurement of the (anomalous) magnetic moment of the electron

- Kush and Foley studying the response of the atoms of gallium to an external magnetic field found a value for the electron gyromagnetic factor **g** of ~ 0.1% larger than predicted by Dirac theory



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)

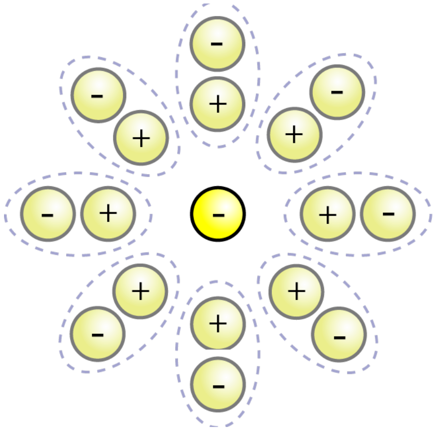
A comparison of the g_J values of Ga in the $^2P_{3/2}$ and $^2P_{\frac{1}{2}}$ states, In in the $^2P_{\frac{1}{2}}$ state, and Na in the $^2S_{\frac{1}{2}}$ state has been made by a measurement of the frequencies of lines in the *hfs* spectra in a constant magnetic field. The ratios of the g_J values 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 $g_L=1$ and $g_S=2(1.00119\pm0.00005)$. 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.

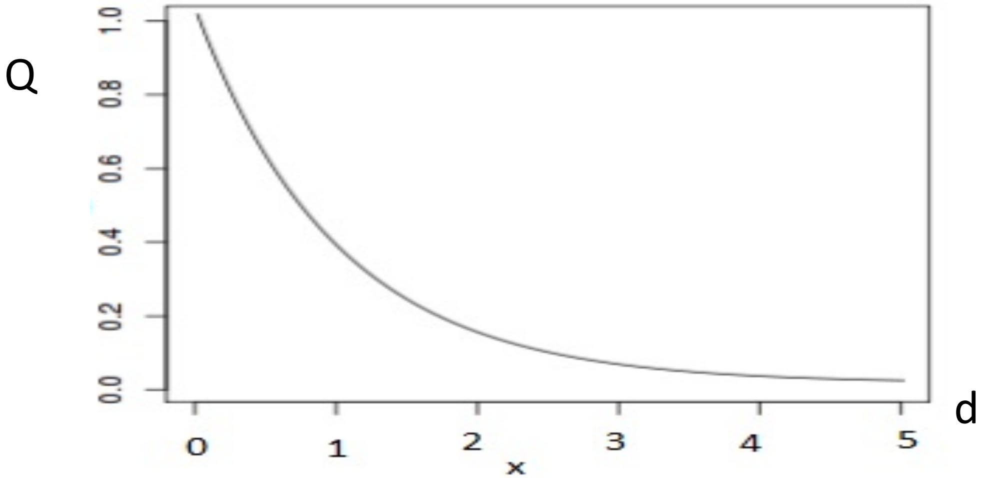
$$\boxed{g = 2(1.00119 \pm 0.00005); a = \frac{(g-2)}{2} = 0.00119 \pm 0.00005}$$

a= 0 according to Dirac

Effects of polarization of the quantum vacuum

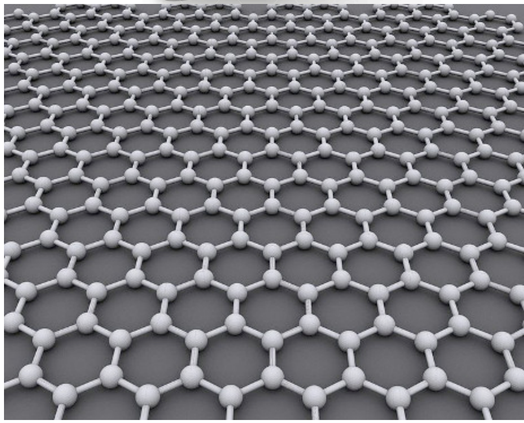
- The presence of a charge causes a polarization of virtual pairs of vacuum





- At great distances these virtual particles will screen the ”bare" charge and so we observe a reduction of the charge.
- As we enter the cloud of virtual particles, this screening effect decreases and the observed charge increases (strenghtening of the coupling)

The problems with infinites (Renormalization)



- The distance with which we see the charge, corresponds to the resolution of the instrument.
- The higher is the resolution the closer we approach the bare electron charge
- The theoretical value of the charge with infinite resolution is infinite!

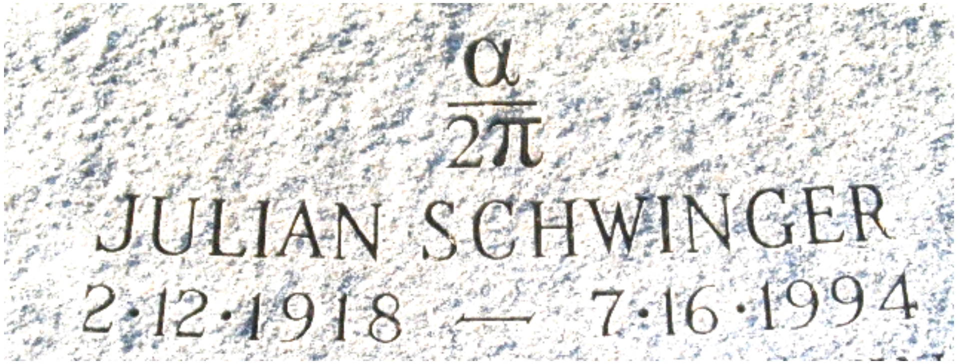
  But no microscope has infinite resolution, then the "true" value of the charge is never achieved (like the horizon)
- What you want to calculate is the value of the charge to the resolution of our experiment.

  This procedure is what is meant by the term "renormalization"

QED Triumph

- Applying the procedure of renormalization (in non-relativistic approximation), Bethe explained the Lamb shift.
- In the same years the relativistic formulation was developed by Feynman, Schwinger and Tomonaga. Schwinger computed the corrections due to self energy to the electron gyromagnetic factor, finding a value in good agreement with the experimental measurement of Kush and Foley

$$a = \frac{(g-2)}{2} = \frac{\alpha}{2\pi} = 0.001161$$



Nobel prizes

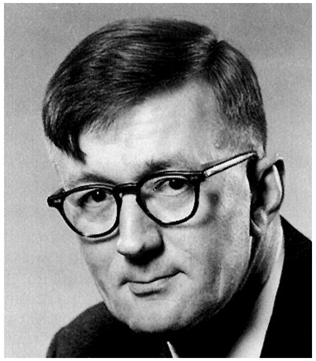
- The crisis and the triumph of QED in the postwar years was one of the more exciting chapters of modern physics that had several players who were all awarded the Nobel Prize.
  And definitely a place: the conference
  of Shelter Island (1947)

Willis E. Lamb
Premio Nobel 1955

Julian Schwinger
Premio Nobel 1965

Richard P. Feynman
Premio Nobel 1965

Sin-Itiro Tomonaga
Premio Nobel 1965



Polykarp Kusch
Premio Nobel 1955

The anomalous magnetic moment of electron and muon (a=(g-2)/2)

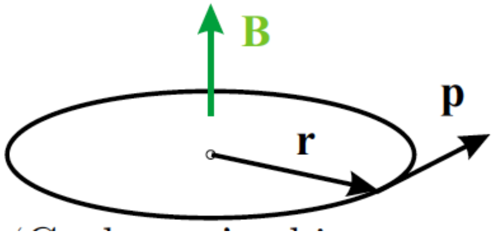
- Since 1947, over the next 60 years, the measurement of the anomalous magnetic moment of the electron and muon (its big brother, with a mass 210 times larger than m_e) improved in accuracy by a factor of 10^8
- Also the theoretical prediction have been refined reaching a similar accuracy
- The muon is much more sensitive to new physics contribution of the electron, despite is being measured 1000 worse.

  How is the anomalous magnetic moment of the muon (and electron) measured and what are these contributions of new physics?

How to measure the muon anomaly?

- A charged particle with spin put in a magnetic field (uniform) rotates in a circular orbit with angular frequency (called cyclotron):

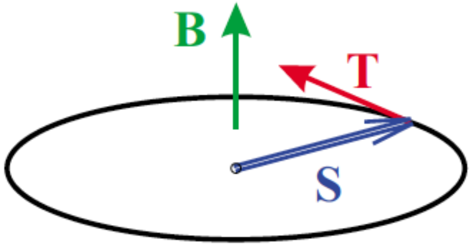
$$\omega_c = \frac{qB}{m}$$



Ciclotron orbit, ω_c

- The presence of the magnetic field acts on the spin by rotating it around the field direction (precession frequency of the spin)

$$\omega_s = g\frac{qB}{2m}$$



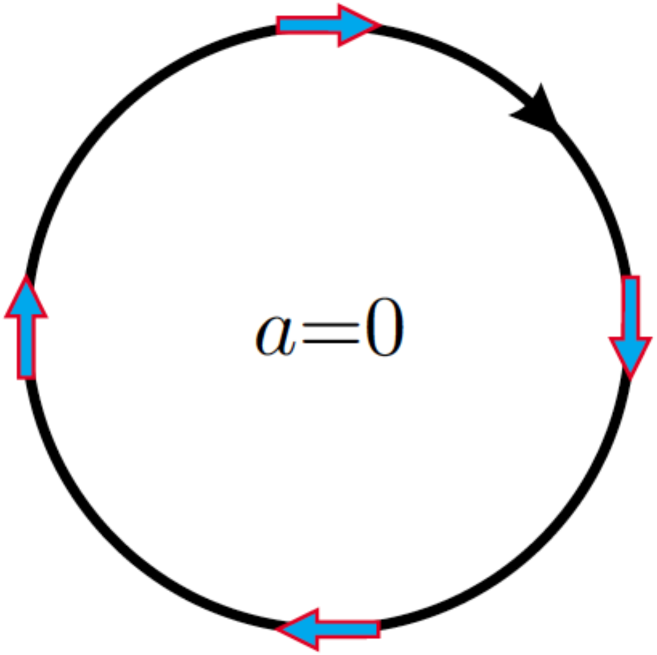
Spin precession, ω_s

How to measure the muon anomaly?

- The frequency with which the spin moves ahead of the momentum (anomalous precession frequency ω_a) is:

$$\omega_a = \omega_s - \omega_c = a\frac{eB}{m}$$

- If g=2 (a=0) spin remains locked to momentum

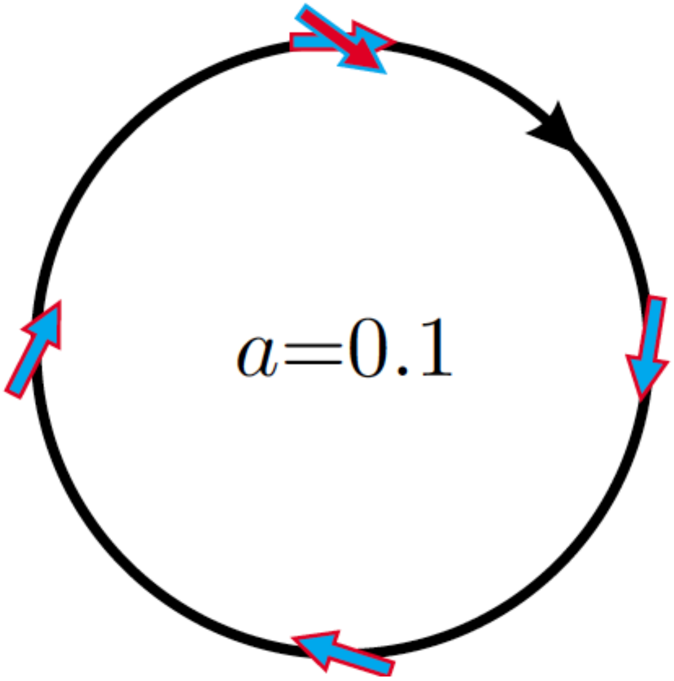


How to measure the muon anomaly?

- The frequency with which the spin moves ahead of the momentum (anomalous precession frequency ω_a) is:

$$\omega_a = \omega_s - \omega_c = a\frac{eB}{m}$$

- If g>2 (a>0) spin advances respect to the momentum



How to measure the muon anomaly?

- The frequency with which the spin moves ahead of the momentum (anomalous precession frequency ω_a) is:

$$\omega_a = \omega_s - \omega_c = a\frac{eB}{m}$$

- If g>2 (a>0) spin go ahead to the momentum

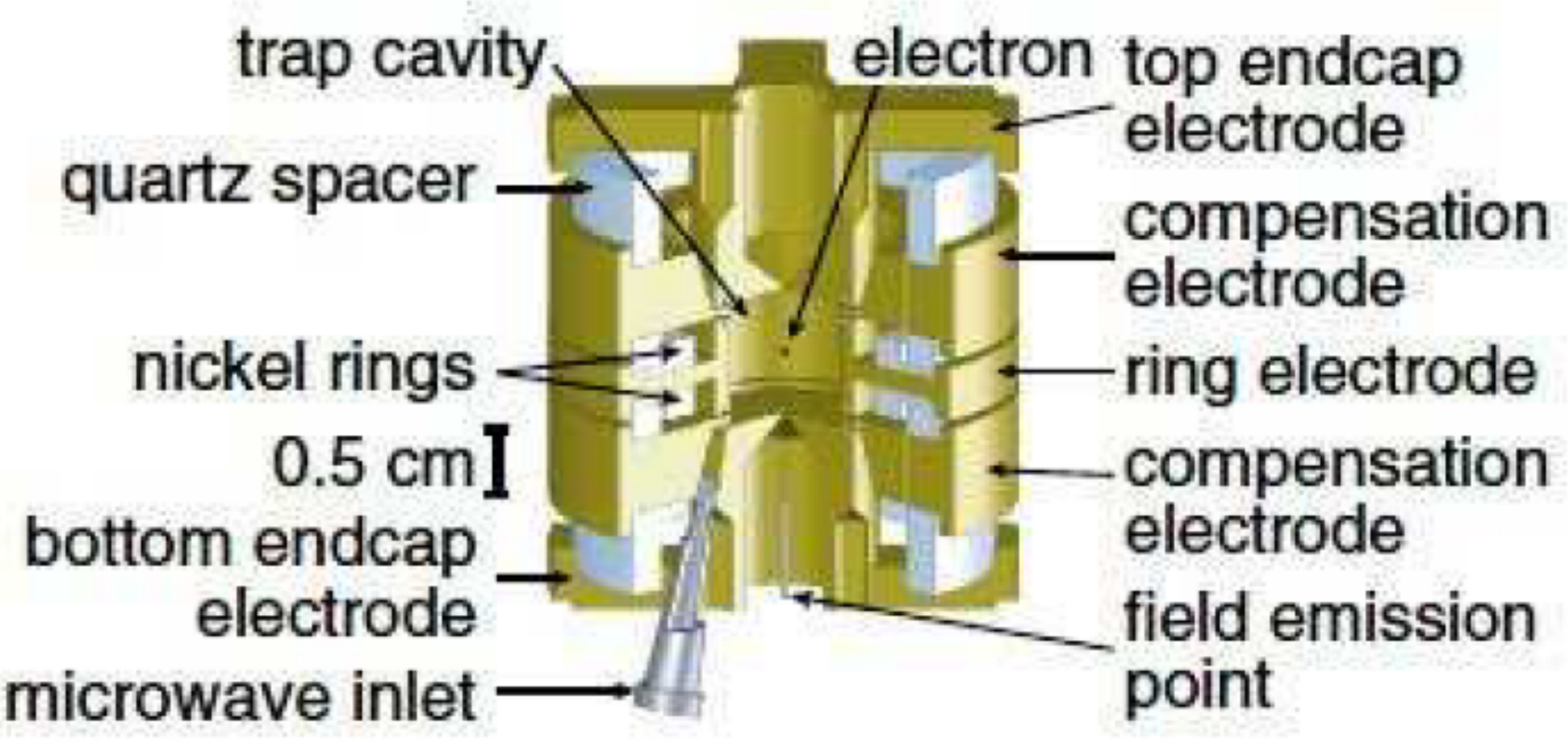
- One measures the anomalous precession frequency ω_a and the magnetic field B obtaining ***a***:

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

Measurement of a_e

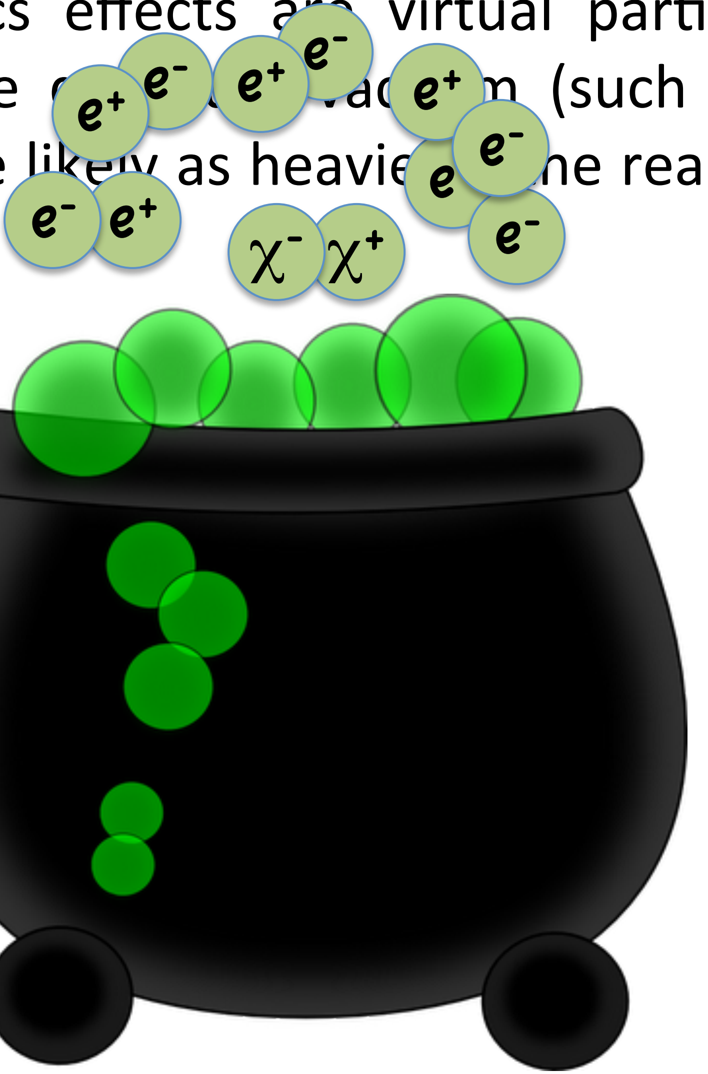
- The e- is confined in a region using magnetic and electric field [Penning trap]. It has been obtained by Gabrielse et al. (2008):

$$a_e(\mathrm{exp}) = 1\,159\,652\,180.73\,(0.28) \times 10^{-12} \quad [0.24\ ppb]$$



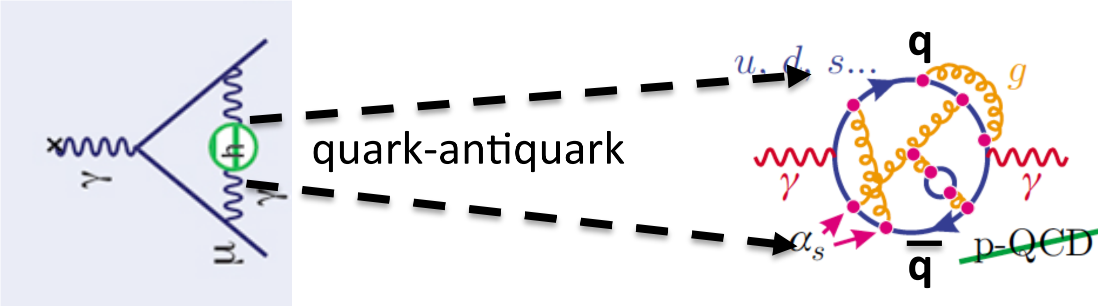
Why muon is more sensitive to New Physics effects?

- The muon has a mass 200 times heavier then electron. It ‘s much more sensitive to effects of new physics than electron. These new physics effects are virtual particles created by fluctuations of the quantum vacuum (such as the electron pair) and are more likely as heavier the real particle (~mass squared)



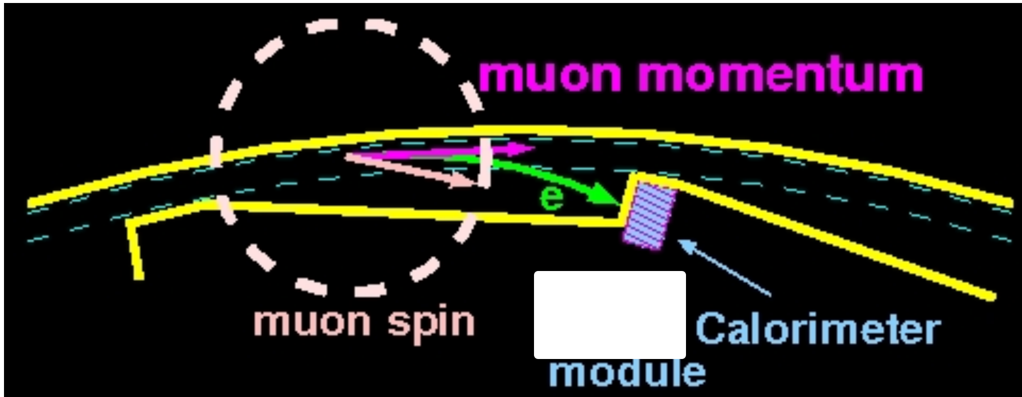
Measurement of the muon anomaly a_{μ}

- The measurement of the anomalous magnetic moment of the muon requires a much larger equipment that for the electron. The muons are trapped in a ring of a ~ 14 m in diameter with magnetic field B = 14 kGauss. The measurement of the spin of the muon is calculated looking at the direction dell'e- emitted in muon decay $\mu^{\pm} \rightarrow e^{\pm}\bar{\nu}\nu$ (produced by pions in forward directions)
- Epic experiment at CERN in '70 have shown that to the anomaly of the muon also contribute also virtual quark pairs and strong effects, produced in the quantum vacuum fluctuations

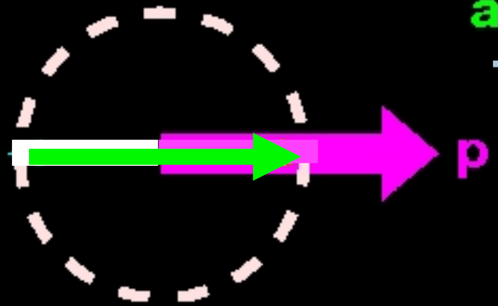


Not easy to compute!!
Need experimental
e+ e- data (like at
VEPP2M/VEPP2000 !)

$e^{\pm}$ from $\mu^{\pm} \rightarrow e^{\pm}\nu\bar{\nu}$ are detected

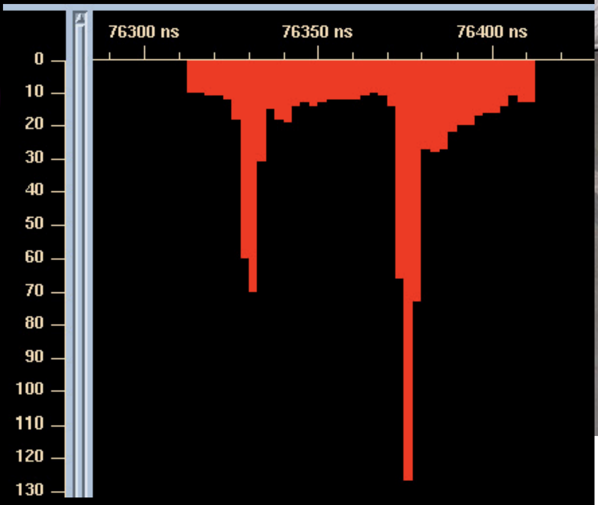


Measures Energy and time

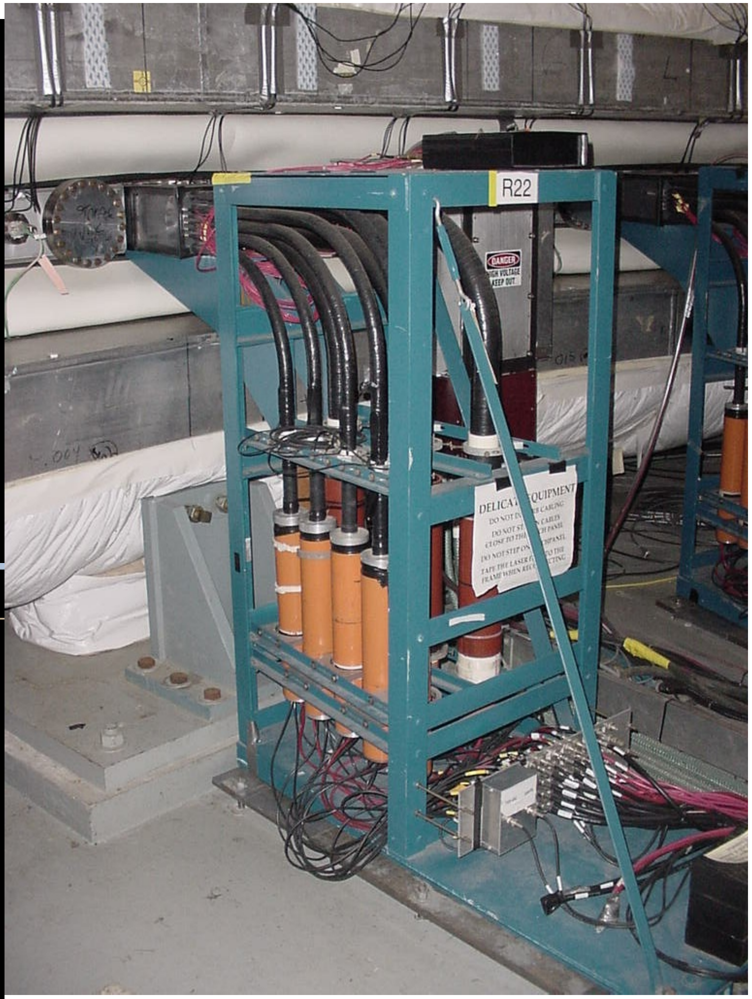


spin forward, more high energy e

spin backward, less high energy e

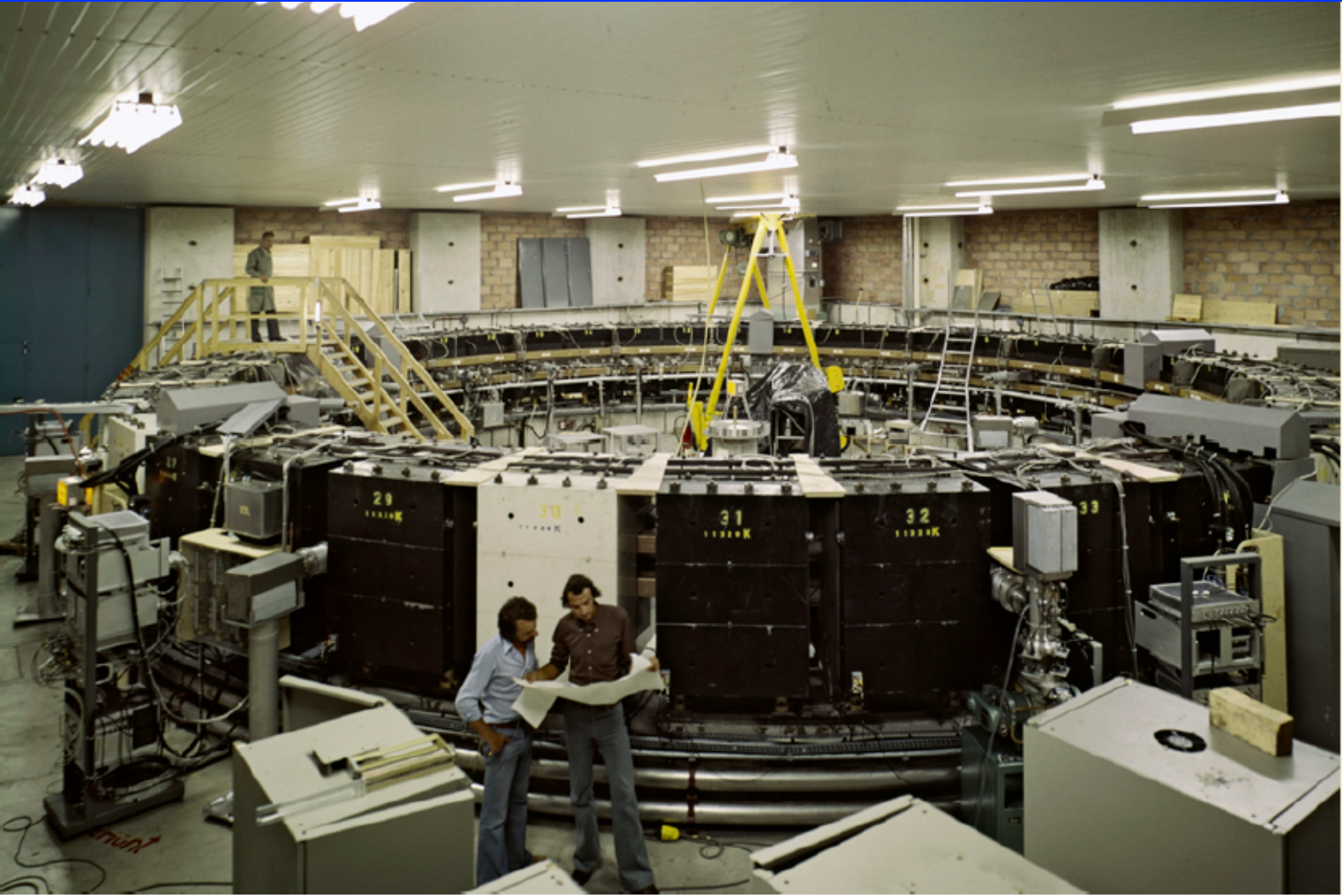


Waveform digitizer gives t, E

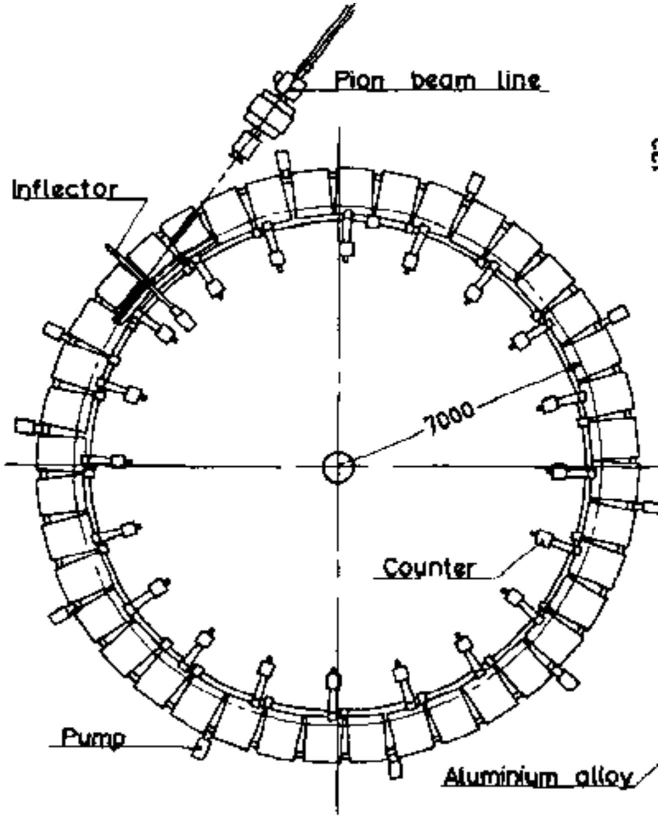


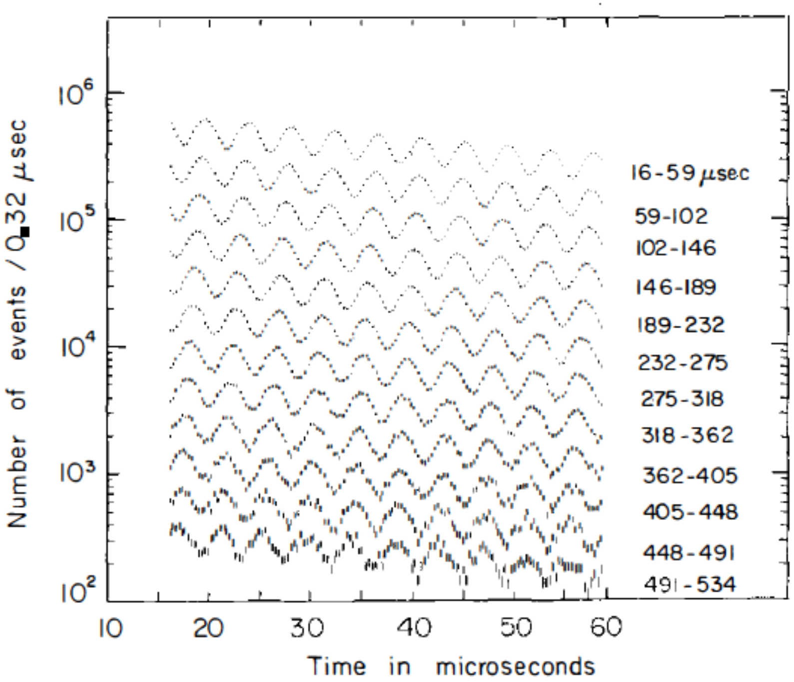
Picture of a Lead-Scifi Calorimeter from E821

Muon G-2 experiment at Cern (1979)



The Cern experiment: a triumph of QED

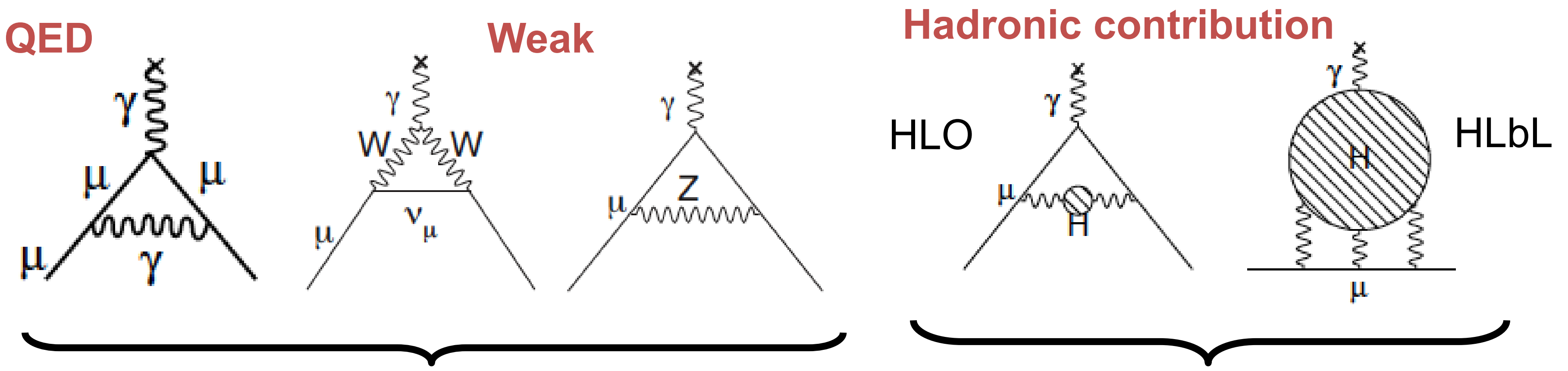




$$a_\mu^{EXP} = 1\,165\,924\,(8.5) \times 10^{-9}\ (7\text{ ppm}).$$

QED terms	Muon	Numerical values ($\times 10^9$)	
2nd order: A	0.5	Total QED:	1 165 852 (1.9)
4th order: B	0.765 782 23	Strong interactions:	66.7 (8.1)
6th order: C	24.452 (26)	Weak interactions:	2.1 (0.2)
8th order: D	135 (63)	Total theory:	1 165 921 (8.3)
10th order: E	420 (30)		

Standard Model contribution to (g-2)



Precisely known

Large uncertainty
(significant work going on)

$$a_\mu^{SM} = a_\mu^{QED} + a_\mu^{Had} + a_\mu^{Weak}$$

$a_\mu^{QED} \sim \alpha/2\pi \sim O(10^{-3})$ $a_\mu^{Weak} \sim O(10^{-9})$ $a_\mu^{HAD} \sim O(10^{-8})$

$\delta a_\mu^{QED} \sim 1.4\text{x}10^{-12}$ $a_\mu^{Weak} \sim 2\text{x}10^{-11}$ $\delta a_\mu^{HAD} \sim 5\text{x}10^{-10}$

In the '70 at CERN a_μ was measured with an uncertainty of $8\text{x}10^{-9}$ (7ppm), of the same order of δa_μ^{SM} (sensitive to hadronic contribution)

Today:

a_μ^{SM}: the QED contribution

$$a_\mu^{QED} = (1/2)(\alpha/\pi)$$ Schwinger 1948

$$+\ 0.765857408\ (27)\ (\alpha/\pi)^2$$

Sommerfield; Petermann; Suura & Wichmann '57; Elend '66; MP '04

$$+\ 24.05050959\ (42)\ (\alpha/\pi)^3$$

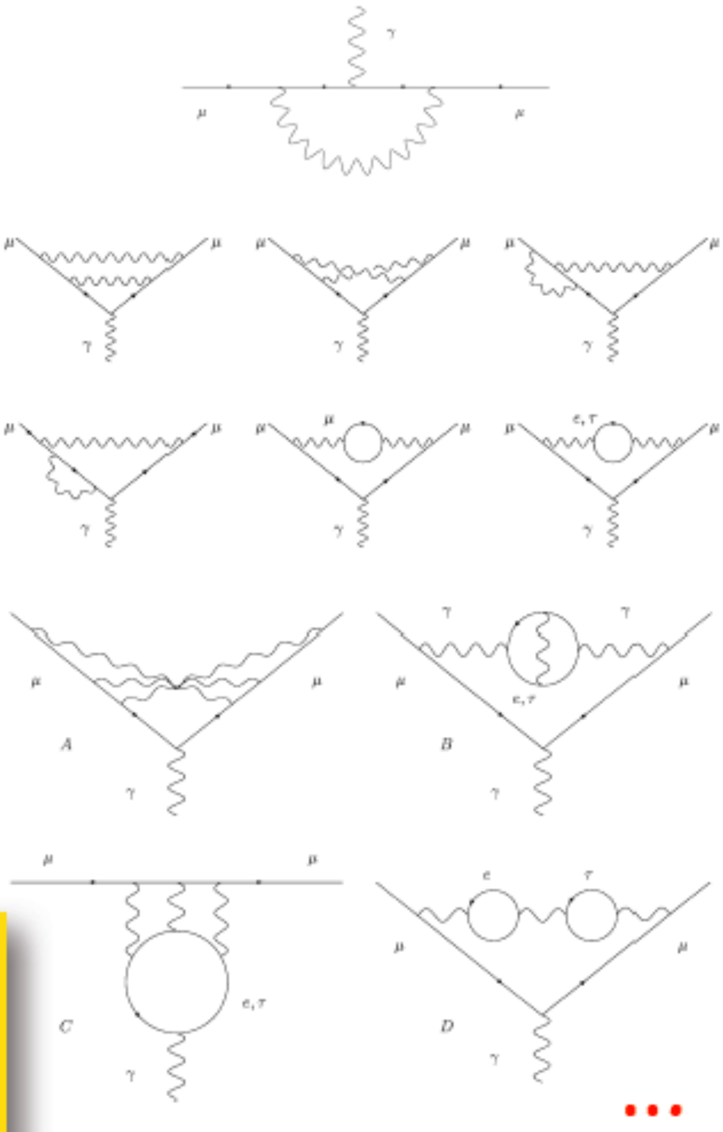
Remiddi, Laporta, Barbieri ... ; Czarnecki, Skrzypek; MP '04;
Friot, Greynat & de Rafael '05, Mohr,Taylor & Newell '08

$$+\ 130.805\ (8)\ (\alpha/\pi)^4$$

Kinoshita & Lindquist '81, ... , Kinoshita & Nio '04, '05;
Aoyama, Hayakawa, Kinoshita & Nio, June & Dec 2007

$$+\ 663\ (20)\ (\alpha/\pi)^5$$ In progress...

Kinoshita et al. '90, Yelkhovsky, Milstein, Starshenko, Laporta,
Karshenboim,..., Kataev, Kinoshita & Nio '06, Kinoshita et al. 2011



Adding up, we get:

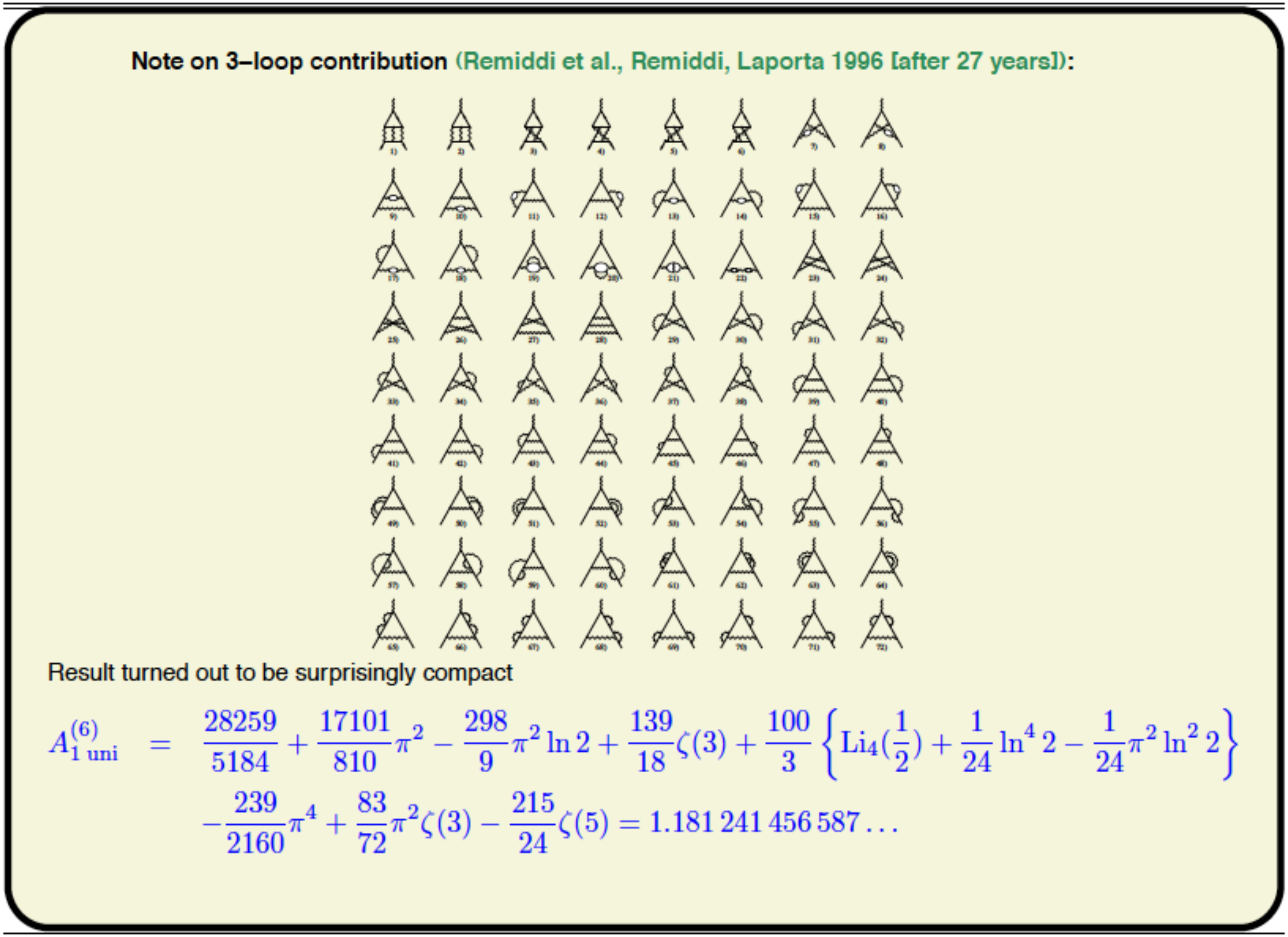
$a_\mu^{QED} = 116584718.08\ (14)(04) \times 10^{-11}$

from coeffs, mainly from 5-loop unc ↲ ↳ from δα('08)

with $\alpha = 1/137.035999084(51)$ [0.37 ppb]

$\delta a_\mu^{QED} = 0.001\text{ppm}$

Impressive calculation…hundreds of diagrams



Note on 3–loop contribution (Remiddi et al., Remiddi, Laporta 1996 [after 27 years]):

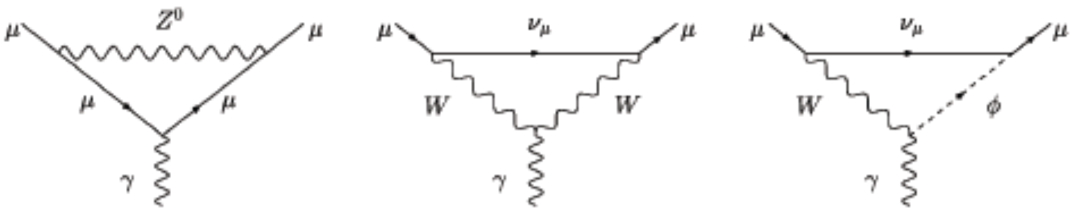
Result turned out to be surprisingly compact

$$A_{1\ \mathrm{uni}}^{(6)} = \frac{28259}{5184} + \frac{17101}{810}\pi^2 - \frac{298}{9}\pi^2\ln 2 + \frac{139}{18}\zeta(3) + \frac{100}{3}\left\{\mathrm{Li}_4\left(\frac{1}{2}\right) + \frac{1}{24}\ln^4 2 - \frac{1}{24}\pi^2\ln^2 2\right\} - \frac{239}{2160}\pi^4 + \frac{83}{72}\pi^2\zeta(3) - \frac{215}{24}\zeta(5) = 1.181\,241\,456\,587\ldots$$

F. Jegerlehner WydziiałFizyki, Uniwersytet Warszawski – December 15, 2008 –

a_μ^{SM}: the Electroweak contribution

- **One-loop term:**



$$a_\mu^{\rm EW}(\text{1-loop}) = \frac{5G_\mu m_\mu^2}{24\sqrt{2}\pi^2}\left[1+\frac{1}{5}\left(1-4\sin^2\theta_W\right)^2 + O\left(\frac{m_\mu^2}{M^2_{Z,W,H}}\right)\right] \approx 195\times10^{-11}$$

1972: Jackiv, Weinberg; Bars, Yoshimura; Altarelli, Cabibbo, Maiani; Bardeen, Gastmans, Lautrup; Fujikawa, Lee, Sanda;

Studenikin et al. '80s

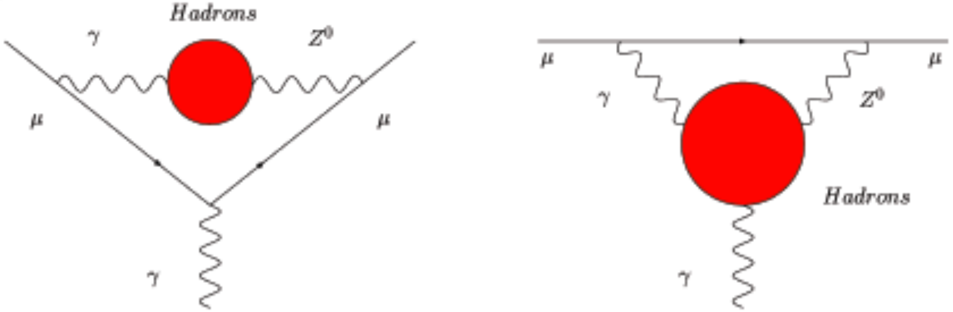
- **One-loop plus higher-order terms:**

a_μ^{EW} = 154 (2) (1) × 10^{-11}

Kukhto et al. '92; Czarnecki, Krause, Marciano '95; Knecht, Peris, Perrottet, de Rafael '02; Czarnecki, Marciano, Vainshtein '02; Degrassi, Giudice '98; Heinemeyer, Stockinger, Weiglein '04; Gribouk, Czarnecki '05; Vainshtein '03.

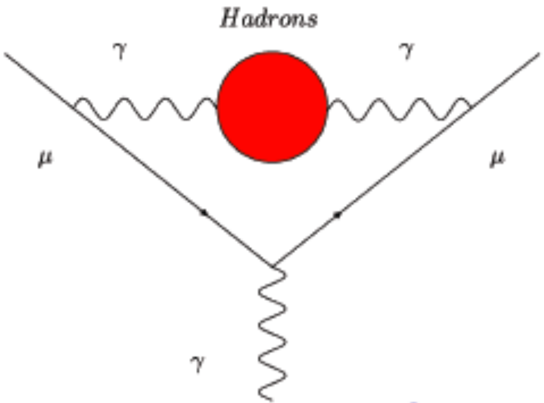
Higgs mass variation, M_{top} error, 3-loop nonleading logs

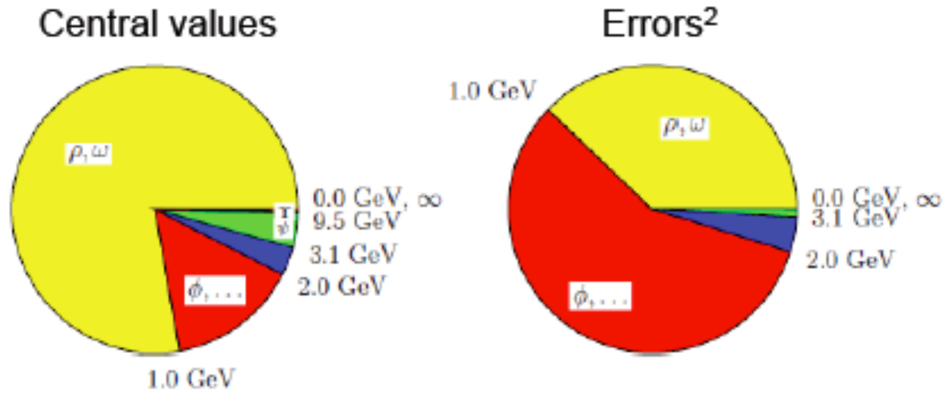
Hadronic loop uncertainties:



$\delta a_\mu^{\rm Weak}$ =0.02 ppm

a_μ^{SM}: the hadronic leading-order (HLO) contribution





F. Jegerlehner and A. Nyffeler, Phys. Rept. 477 (2009) 1

$$K(s) = \int_0^1 dx \frac{x^2(1-x)}{x^2+(1-x)s/m_\mu^2}$$

$$a_\mu^{\rm HLO} = \frac{1}{4\pi^3}\int_{4m_\pi^2}^{\infty} ds\, K(s)\, \sigma^{(0)}(s) = \frac{\alpha^2}{3\pi^2}\int_{4m_\pi^2}^{\infty} \frac{ds}{s} K(s)\, R(s)$$

$a_\mu^{HLO} = 6903\ (53)_{tot} \times 10^{-11}$ F. Jegerlehner, A. Nyffeler, Phys. Rept. 477 (2009) 1

$= 6923\ (42)_{tot} \times 10^{-11}$ Davier et al, arXiv:1010.4180 (incl. BaBar & KLOE10 2π)

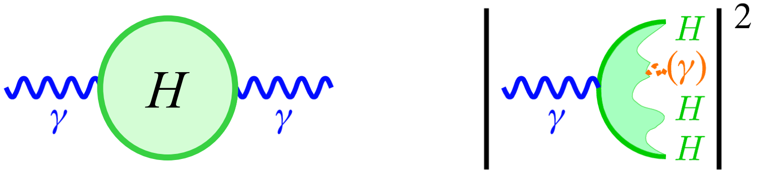
$= 6949\ (37)_{exp}\ (21)_{rad} \times 10^{-11}$ Hagiwara et al. (HLMNT11), arXiv:1105.3149

$\delta a_\mu^{HLO} = 0.4$ ppm

Radiative Corrections are crucial! S.Actis et al, Eur. Phys. J. C66 (2010) 585

a_μ^{HLO}:

L.O. Hadronic contribution to a_μ can be estimated by means of a dispersion integral:



$$a_\mu^{had} = \left(\frac{\alpha \ m\mu}{3\pi}\right)^2 \int_{4m_\pi^2}^{\infty} ds \frac{R(s)\,\hat{K}(s)}{\bigcirc\!\!\!\!\; s^2}$$

1 / s^2 makes low energy contributions especially important:

$$\boxed{e^+e^- \to \pi^+\pi^-}$$

in the range < 1 GeV contributes to 70% !

$$R(s) = \frac{\sigma_{tot}(e^+e^- \to \gamma^* \to q\,\bar{q} \to hadrons)}{\sigma_{tot}(e^+e^- \to \gamma^* \to \mu^+\mu^-)}$$

- K(s) = analytic kernel-function
- above sufficiently high energy value, typically 2…5 GeV, use *pQCD*

Input:

a) hadronic electron-positron cross section data (G.dR 69, E.J.95, A.D.H.’97,….)

b) hadronic τ- decays, which can be used with the help of the CVC-theorem and an isospin rotation (plus isospin breaking corrections)

(A., D., H. ’97)

Cross section data:

Two approaches:

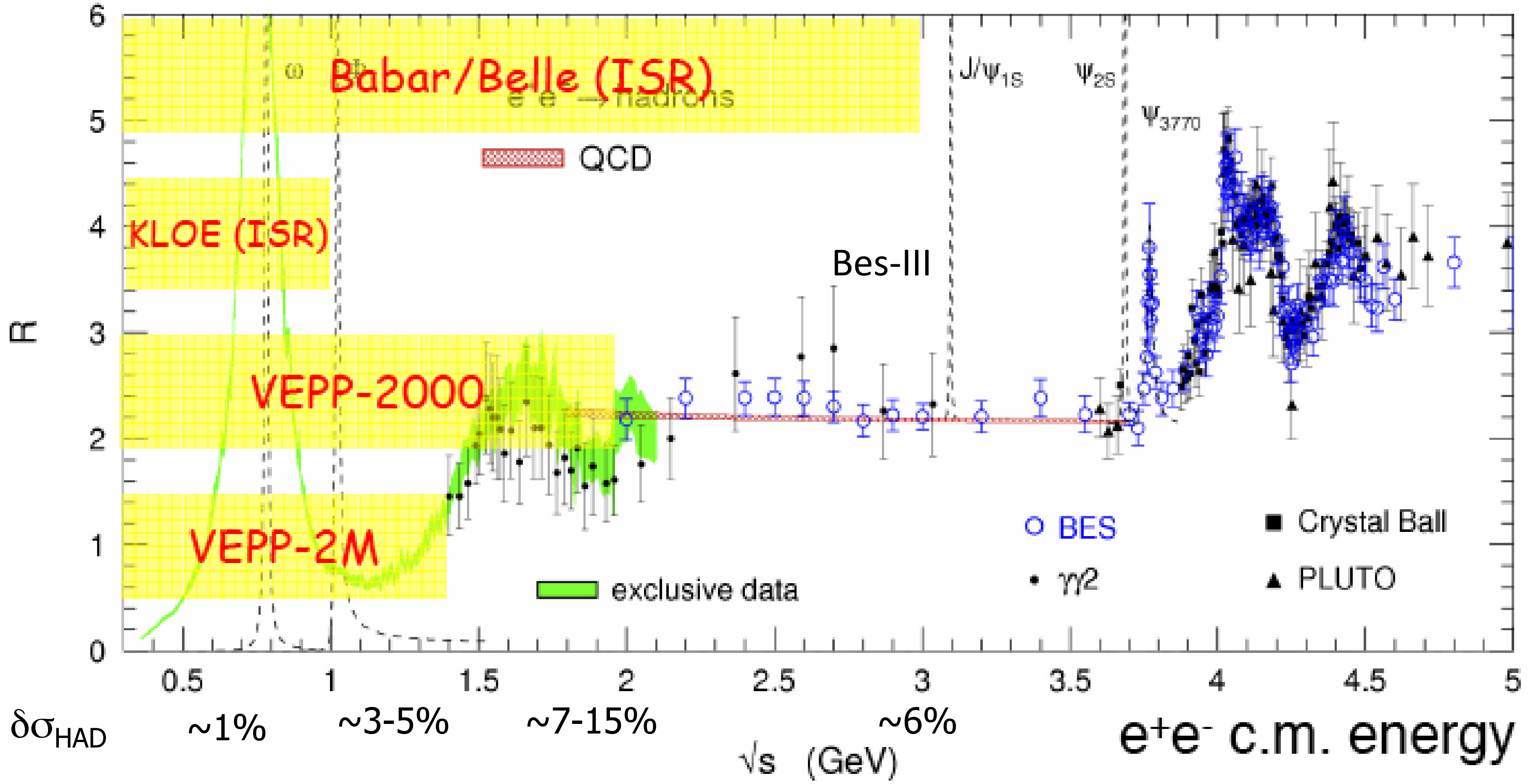
Energy scan (CMD2/3, SND, BES,CLEO):

- energy of colliding beams is changed to the desired value
- “direct” measurement of cross sections
- needs dedicated accelerator/physics program
- needs to measure luminosity and beam energy for every data point

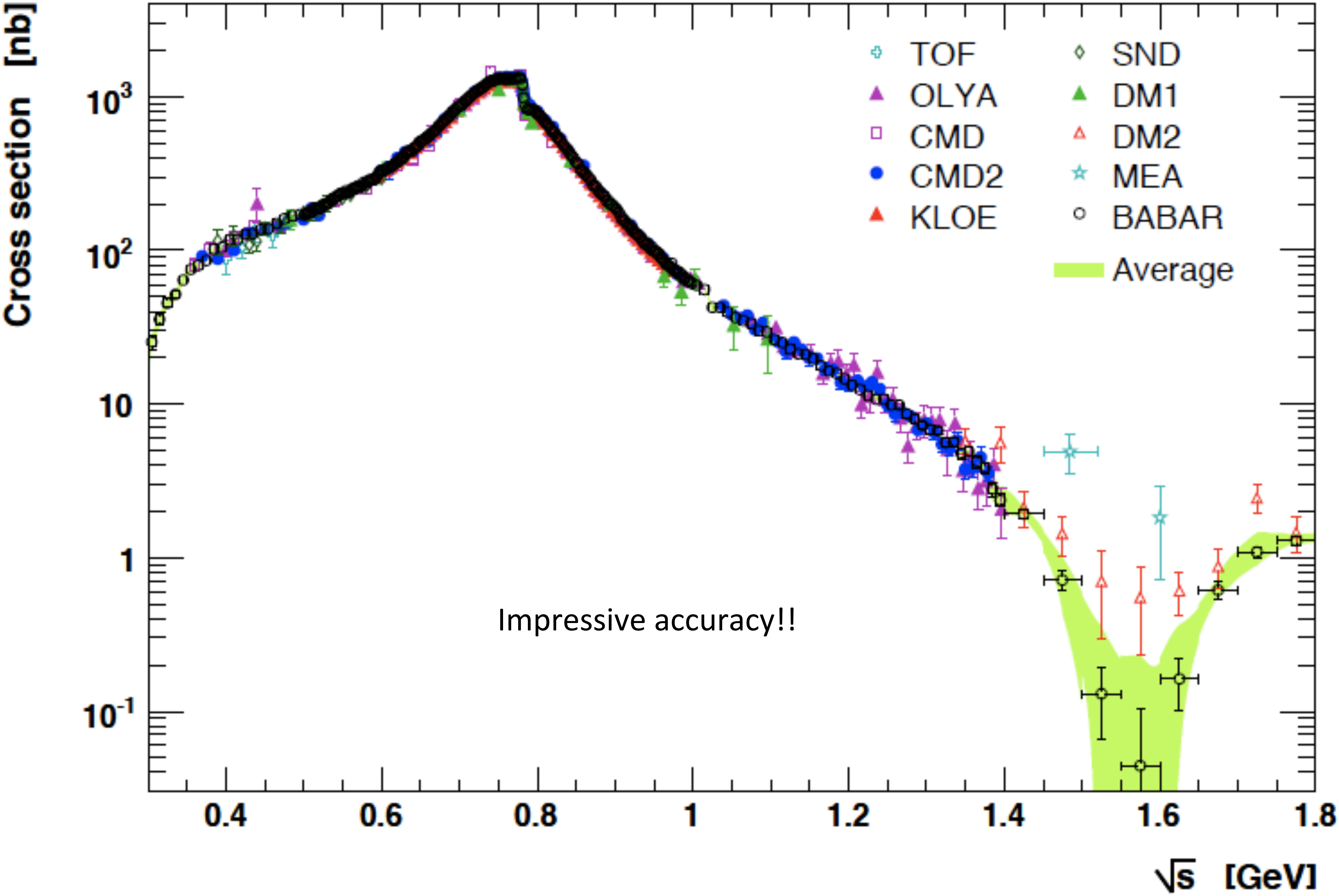
Radiative return (KLOE, BABAR, BELLE, BESIII):

- runs at fixed-energy machines (meson factories)
- use initial state radiation process to access lower energies or resonances
- data come as by-product of standard physics program
- requires precise theoretical calculation of the radiator function
- luminosity and beam energy enter only once for all energy points
- needs larger integrated luminosity

e^+e^- data: current and future/activities



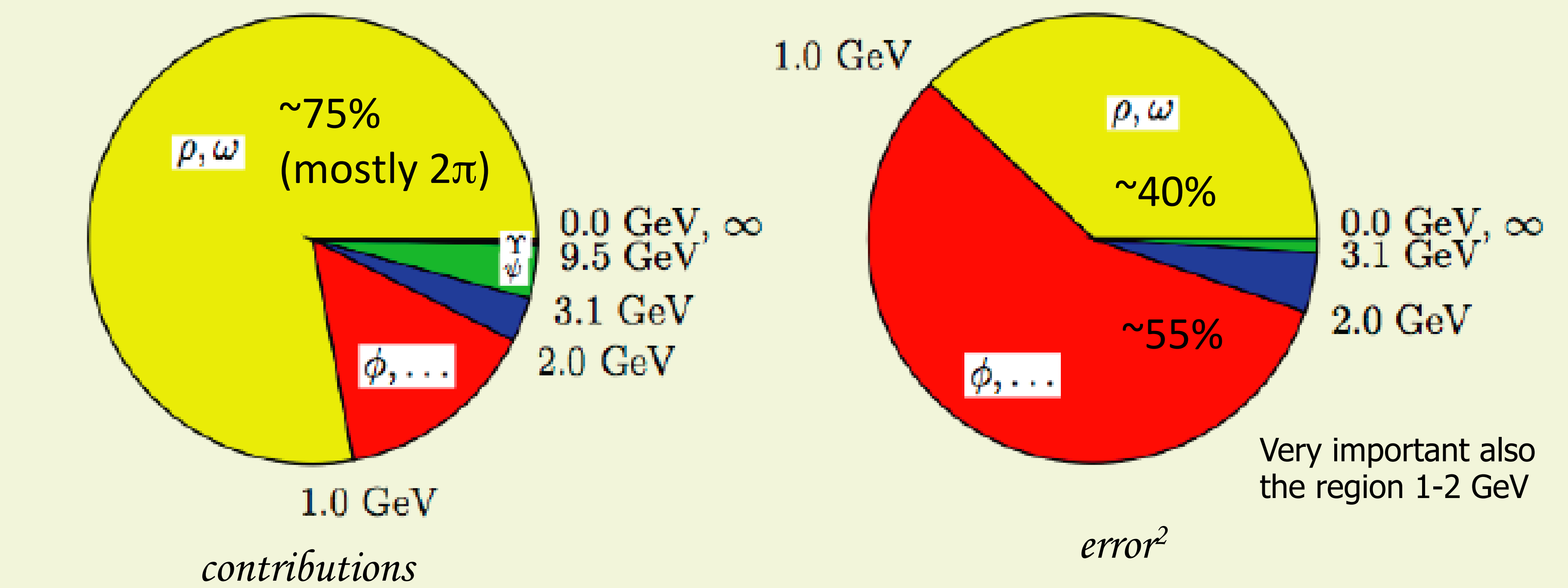
Measured cross section for $e^+e^- \rightarrow \pi^+ \pi^-$



Impressive accuracy!!

Dispersion Integral:

Contribution of different energy regions to the dispersion integral and the error to a_μ^{had}



Very important also the region 1-2 GeV

contributions

error²

Impressive accuracy reached (mainly) thanks to Novosibirsk precise measurement in e+e- collision !!!!!

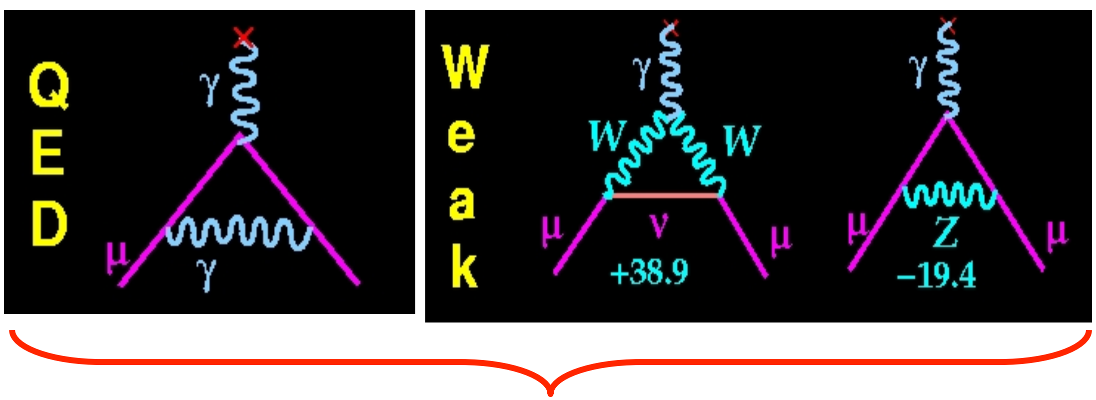
$a_\mu^{HLO} = (690.9\pm\mathbf{4.4})10^{-10}$
[Eidelman, TAU08]

δa_μ^{HLO} ~0.7%

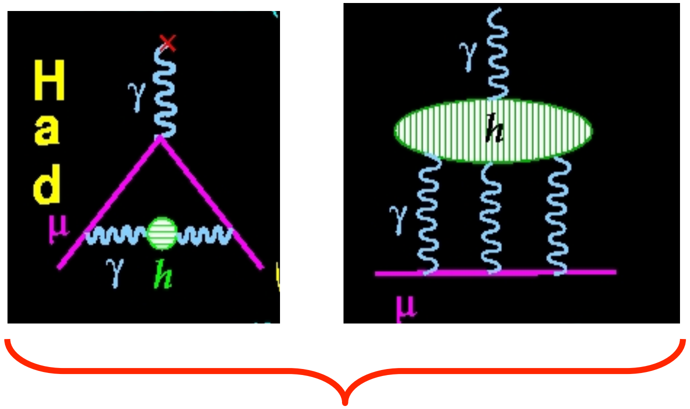
$\delta a_\mu^{exp} \rightarrow 1.5\ 10^{-10} = 0.2\%$ on a_μ^{HLO}

New g-2 exp.

The SM Value for a_μ



well known



significant work ongoing

Contribution	Result ($\times 10^{-11}$) units
QED (leptons)	$116\ 584\ 718.09 \pm 0.14 \pm 0.04_{\alpha}$
HVP(lo)	$6\ 923 \pm 42$
HVP(ho)	-97.9 ± 0.9
HLxL	105 ± 26
EW	$154 \pm 2_{Higgs} \pm 1_{had}$
Total SM	$116\ 591\ 802 \pm 42 \pm 26 \pm 2 (49_{tot})$

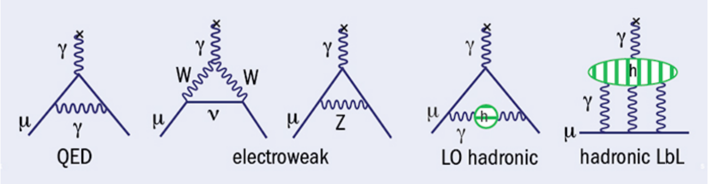
$$\sigma_{\text{exp}} = \pm 63$$

1984-2001: Measurement of a_μ at BNL

The measurement of the g-2 of the muon has been repeated with x15 better accuracy at Brookhaven National Laboratory (USA)

The result (which reached a precision of 0.54 parts per million) was surprising and showed:

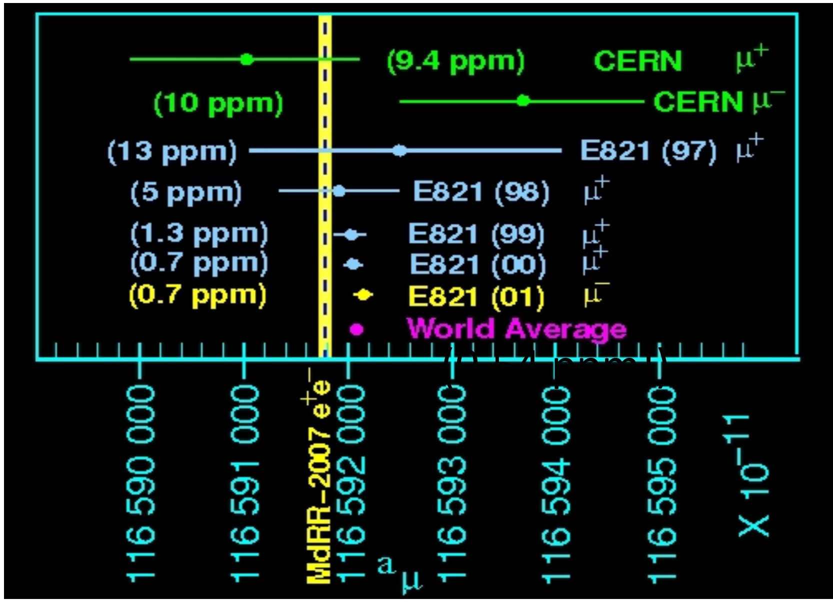
1) that to the magnetic anomaly contributed not only e, quarks, but also the messengers of the EW interaction and even the Higgs



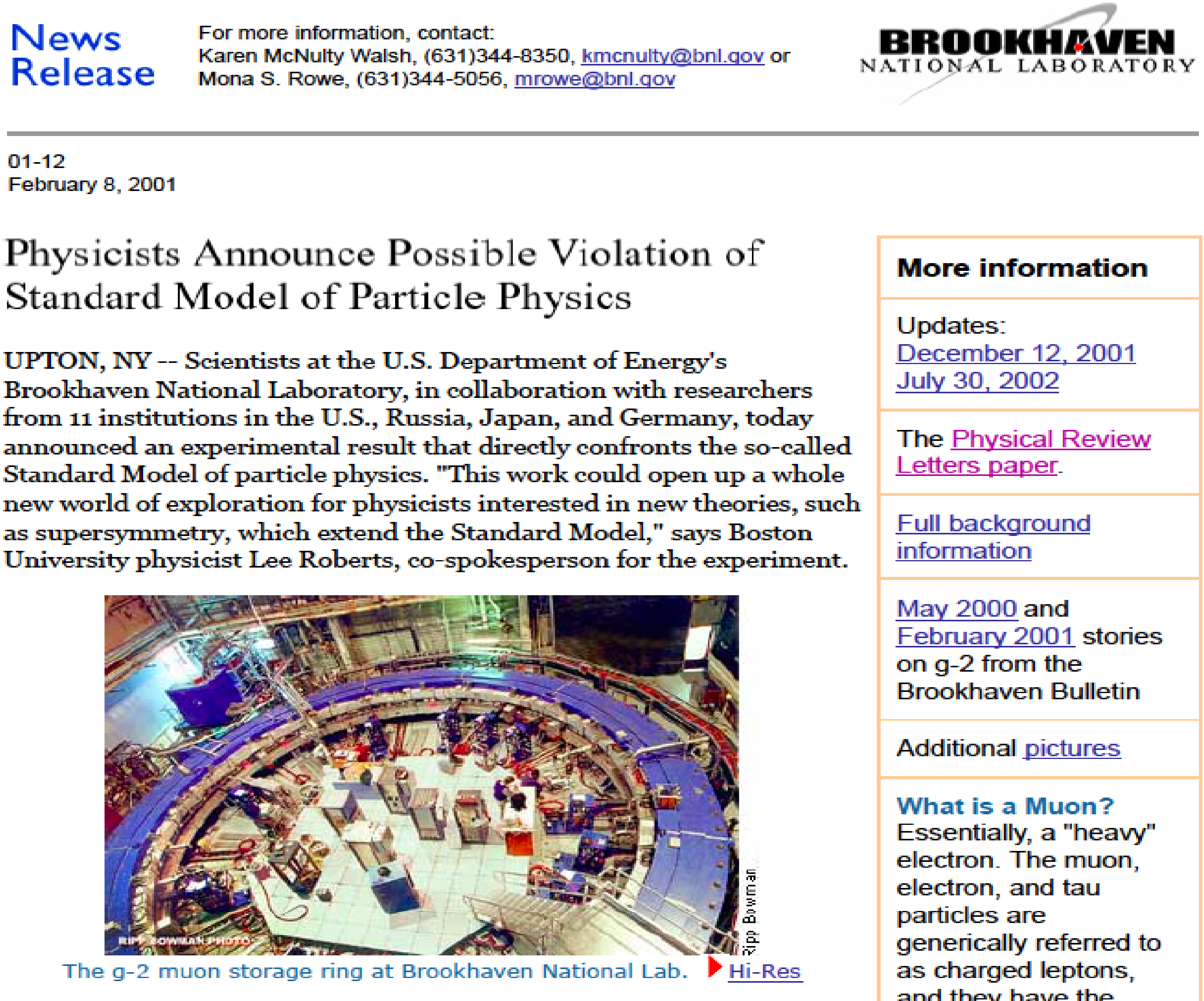
2) a "discrepancy" with the theoretical prediction of the Standard Model of 3 standard deviations (the probability of this happening due to a statistical fluctuation is 0.3%)

$$\boxed{a_\mu^{E821} - a_\mu^{SM} = (287 \pm 80) \times 10^{-11}\ (3.6\,\sigma)}$$

This discrepancy, although not conclusive, could be explained by the contribution to the anomaly of the muon of particles still unknown, such as **supersymmetric** particles (which are now looking at LHC) or new photons (particles of spin equal to 1) with a mass nonzero (which may explain **the dark matter** of the Universe)



A possible crack in the Standard Model?



News Release

For more information, contact:
Karen McNulty Walsh, (631)344-8350, kmcnulty@bnl.gov or
Mona S. Rowe, (631)344-5056, mrowe@bnl.gov

BROOKHAVEN
NATIONAL LABORATORY

01-12
February 8, 2001

Physicists Announce Possible Violation of Standard Model of Particle Physics

UPTON, NY -- Scientists at the U.S. Department of Energy's Brookhaven National Laboratory, in collaboration with researchers from 11 institutions in the U.S., Russia, Japan, and Germany, today announced an experimental result that directly confronts the so-called Standard Model of particle physics. "This work could open up a whole new world of exploration for physicists interested in new theories, such as supersymmetry, which extend the Standard Model," says Boston University physicist Lee Roberts, co-spokesperson for the experiment.

The g-2 muon storage ring at Brookhaven National Lab. ▶ Hi-Res

More information

Updates:
December 12, 2001
July 30, 2002

The Physical Review Letters paper.

Full background information

May 2000 and February 2001 stories on g-2 from the Brookhaven Bulletin

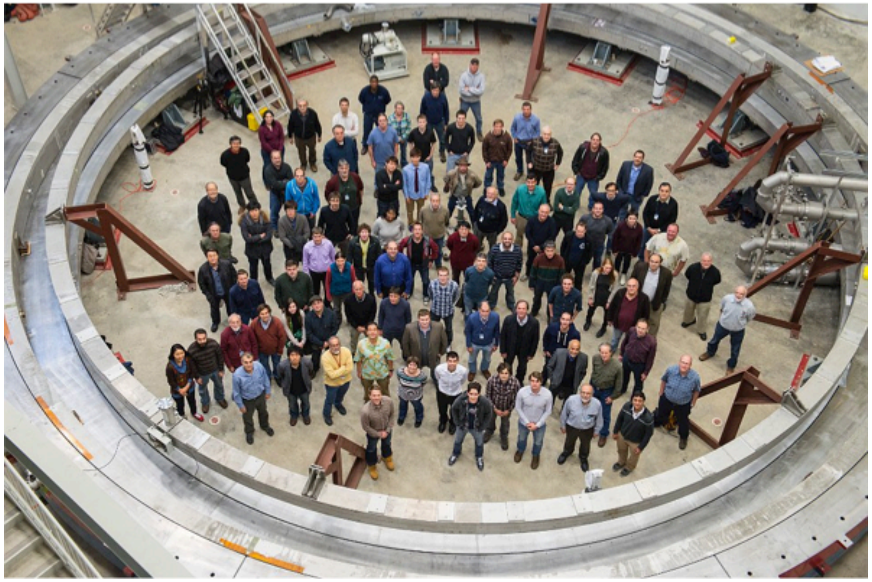
Additional pictures

What is a Muon?
Essentially, a "heavy" electron. The muon, electron, and tau particles are generically referred to as charged leptons, and they have the

A possible crack in the Standard Model

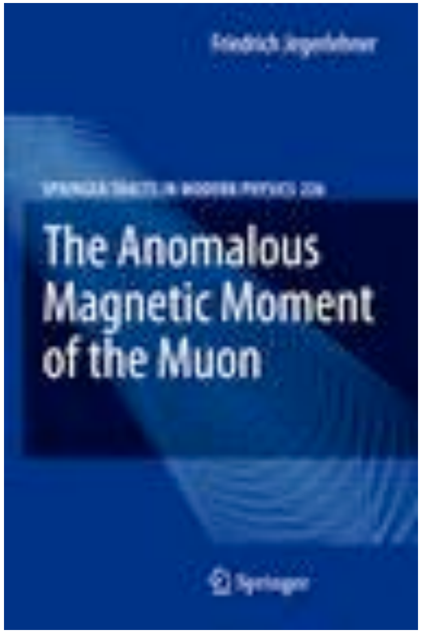
In order to understand if it is a crack in the Standard Model or a statistical fluctuation or any instrumental effect, is being built at Fermilab in Chicago (USA), a new experiment will measure the anomaly of the muon with a precision of 140 parts per billion.

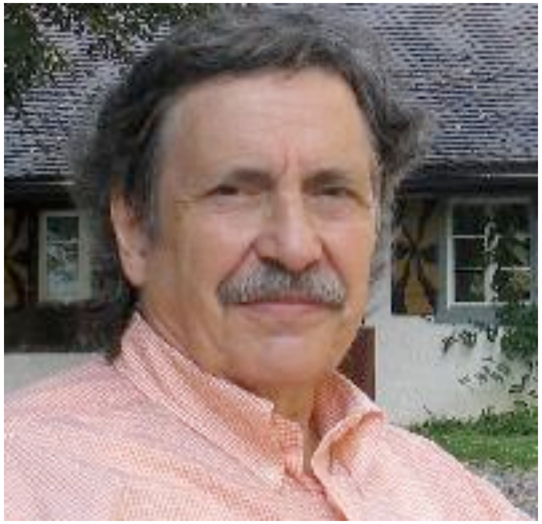
Also thanks to the result of this experiment, in which participates also Russia (Dubna and Novosibirsk) and Italy, in a few years we will know if the Standard Model should be abandoned in favor of a more complete theory



The anomalous magnetic moment of the muon

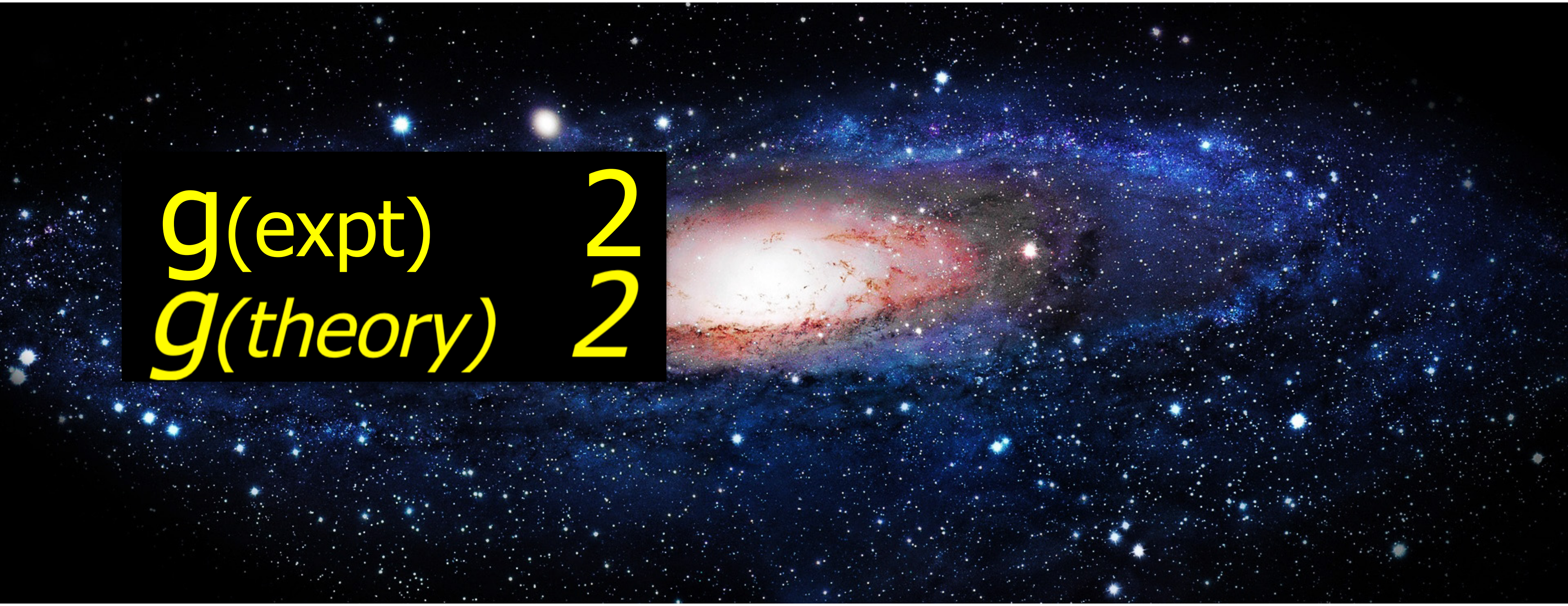
“The closer you look the more there is to see”





Fred Jegerlehner

Now let’s retrace the gyromagnetic factor of the muon digit by digit

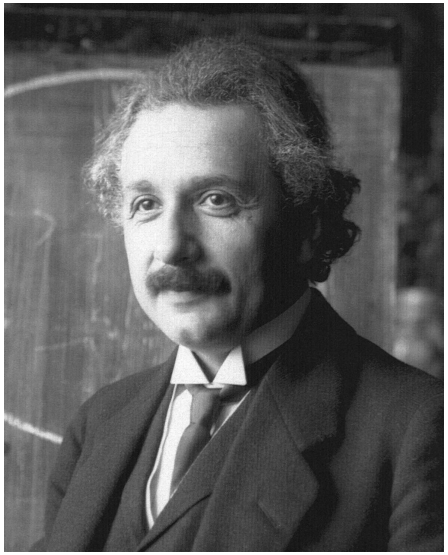


g(expt) 2

g(theory) 2

$$\left(\frac{1}{2m}(\vec{P}+e\vec{A})^2+\frac{e}{2m}\vec{\sigma}\cdot\vec{B}-eA^0\right)\psi_A=(E-m)\psi_A$$

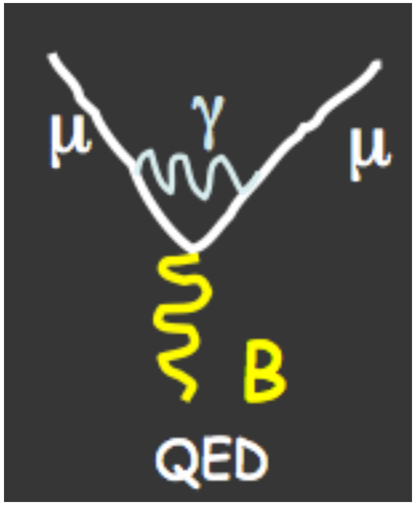
Quantum mechanics meets relativity -> anti-matter



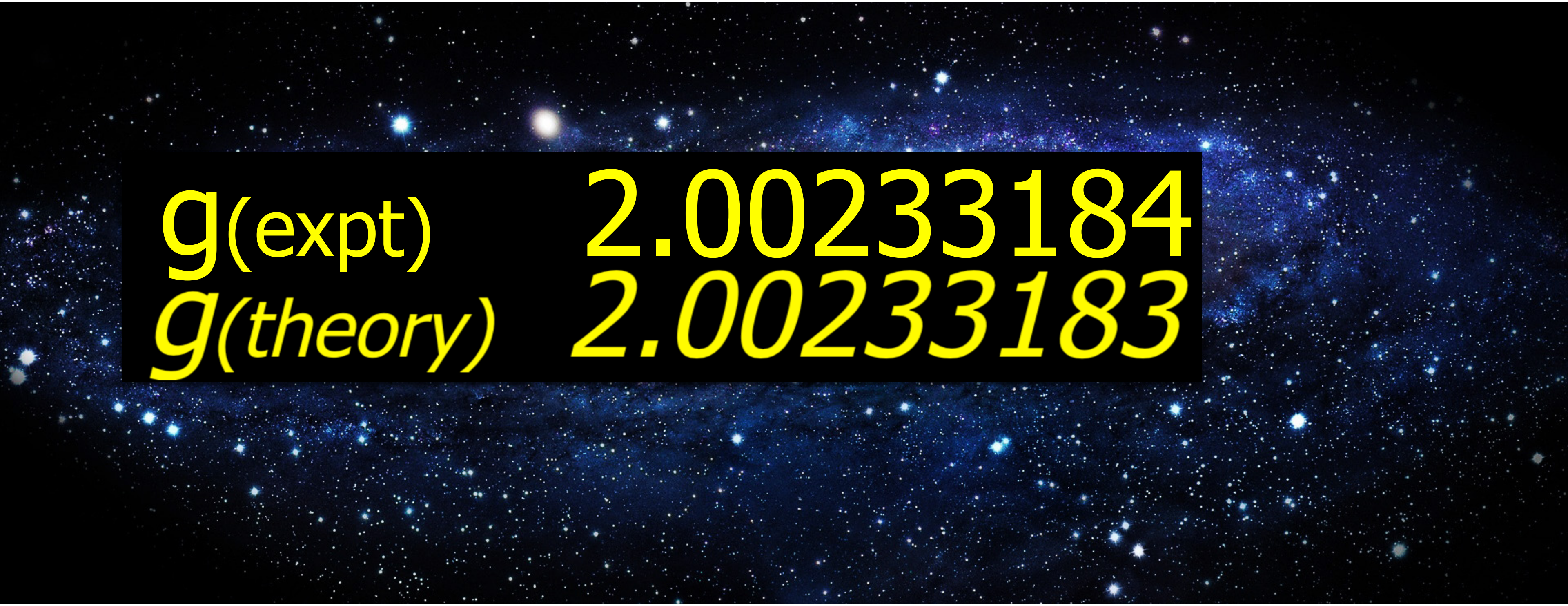
g(expt)	2.00
g(theory)	*2.00*

g(expt) 2.002331

g(theory) 2.002331

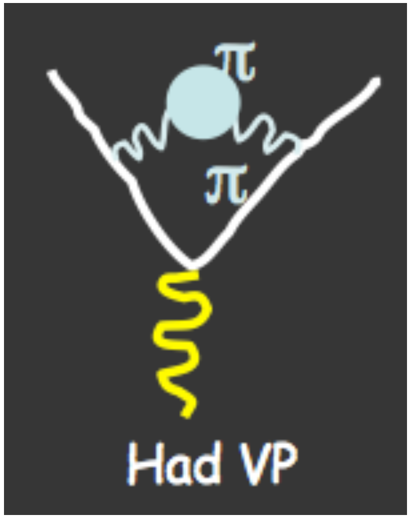


Quantum
Electrodynamics ->
Electricity &
Magnetism

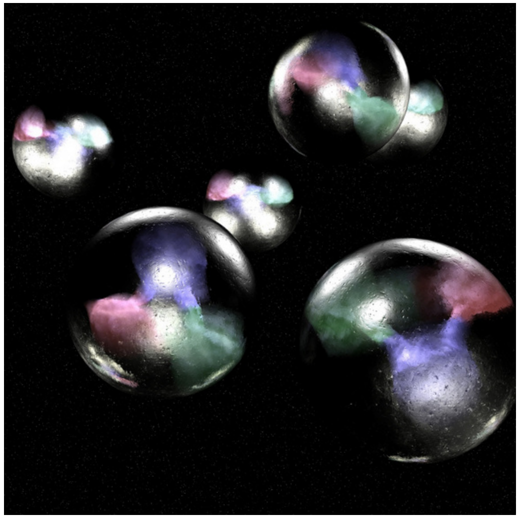


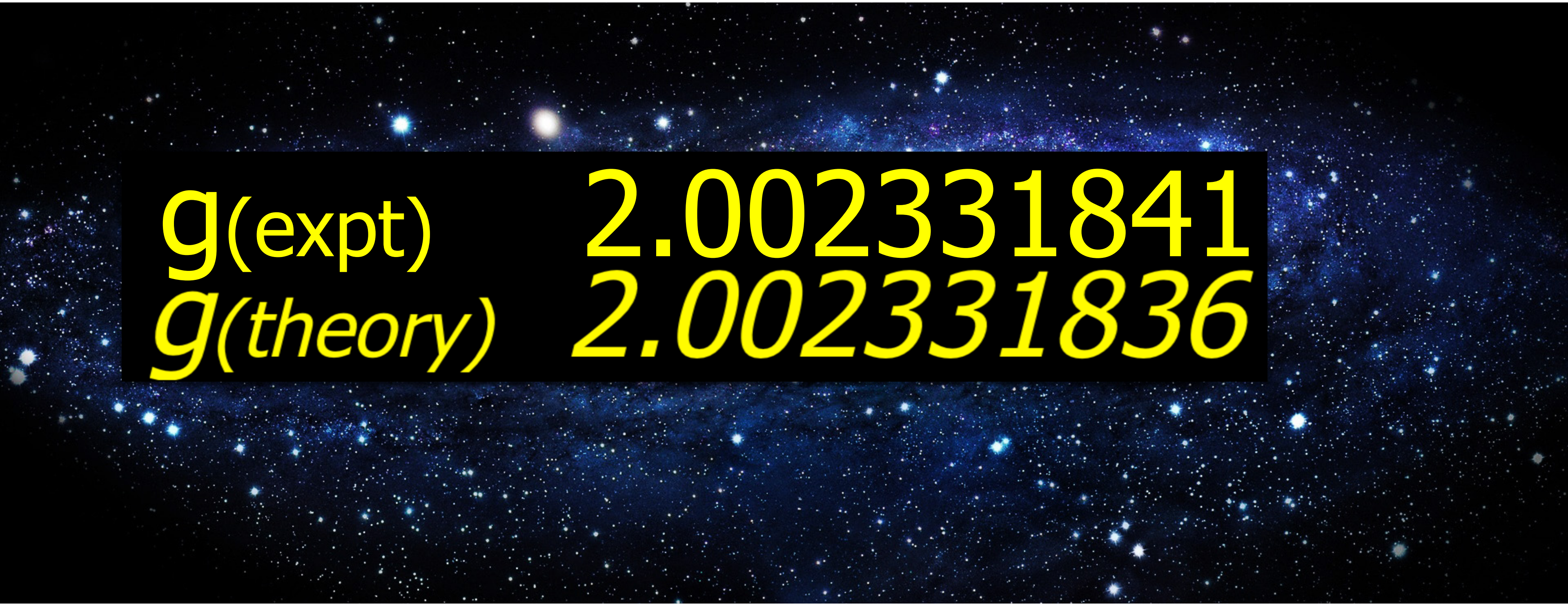
g(expt) 2.00233184

g(theory) 2.00233183

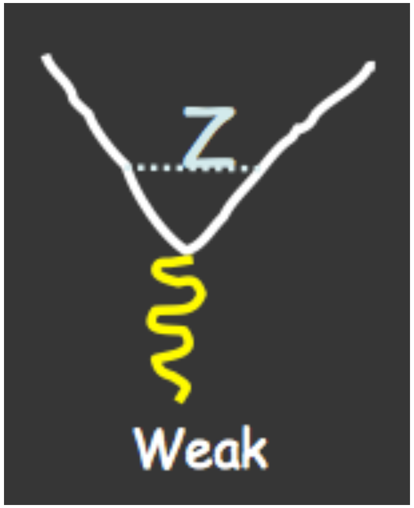


Quantum Chromodynamics -> Strong force that binds nuclei

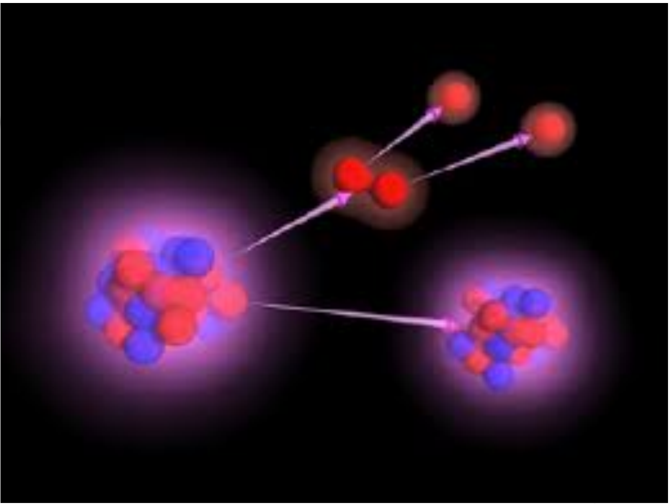




g(expt)	2.002331841
g(theory)	*2.002331836*

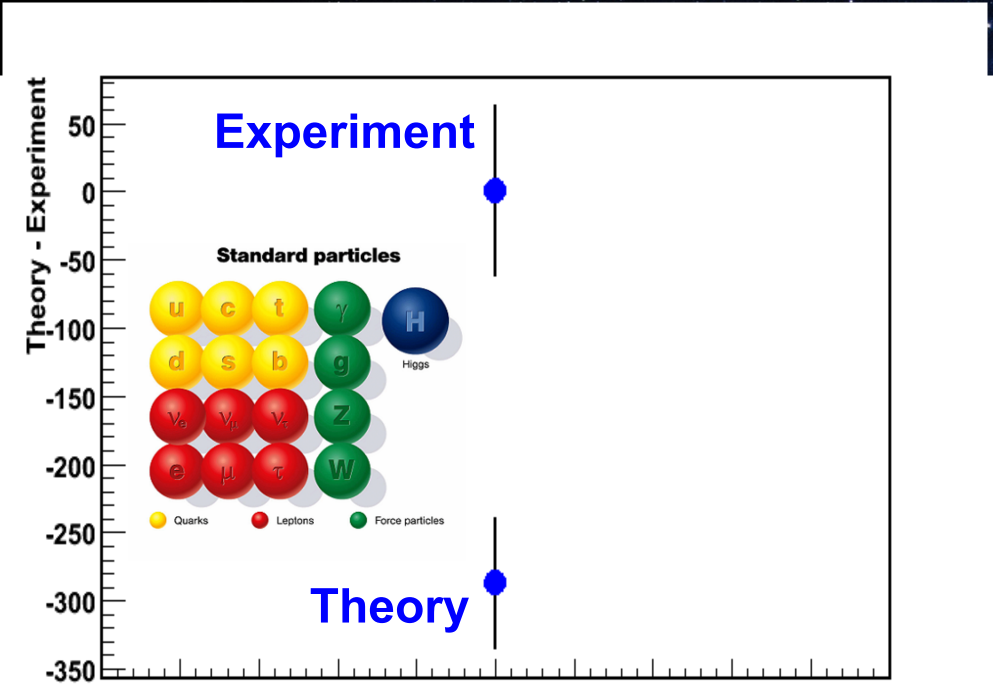


Electroweak Theory->
Weak force that
makes nuclei (and
muons) unstable



g(expt) 2.00233184178

g(theory) *2.00233183630*

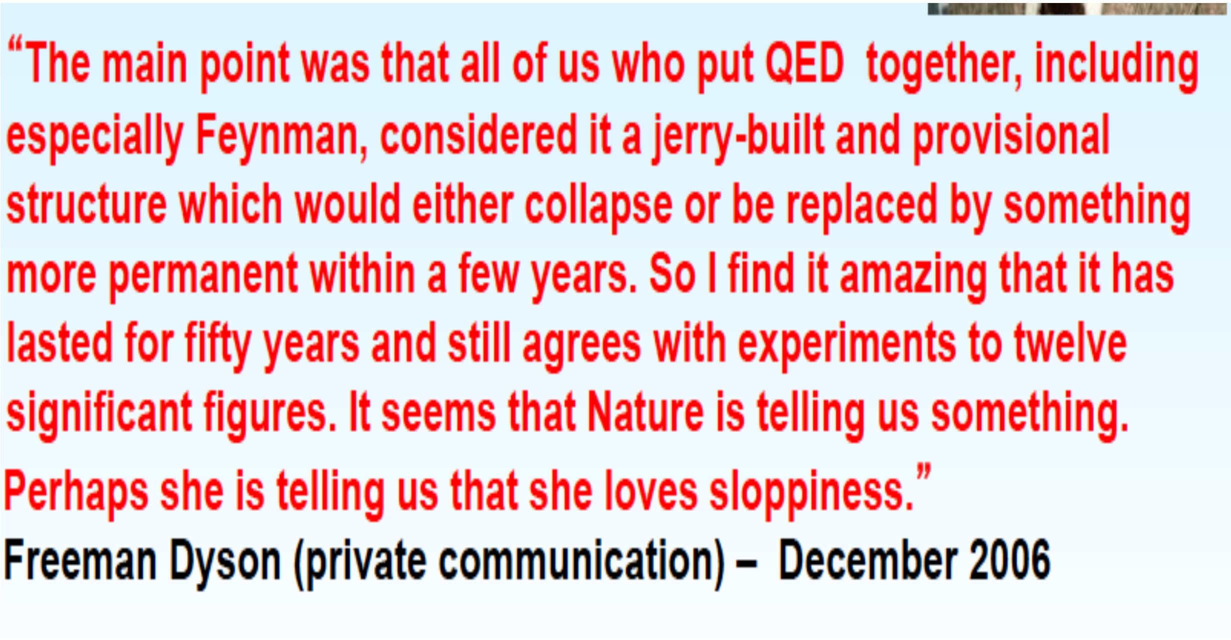



Dark Matter

If it will or not new physics we'll tell you in a few years !!

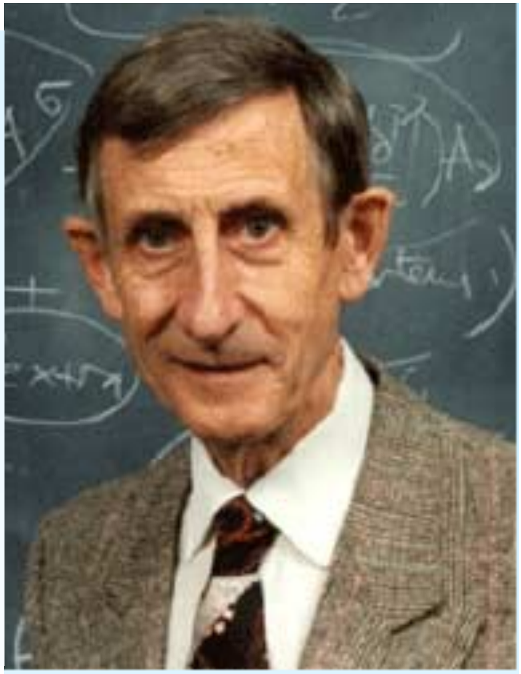
A final observation

QED has been verified by experiments of the anomalous magnetic moment of 12 significant digits!



"The main point was that all of us who put QED together, including especially Feynman, considered it a jerry-built and provisional structure which would either collapse or be replaced by something more permanent within a few years. So I find it amazing that it has lasted for fifty years and still agrees with experiments to twelve significant figures. It seems that Nature is telling us something. Perhaps she is telling us that she loves sloppiness."

Freeman Dyson (private communication) – December 2006



Thanks!!!!

Grazie!