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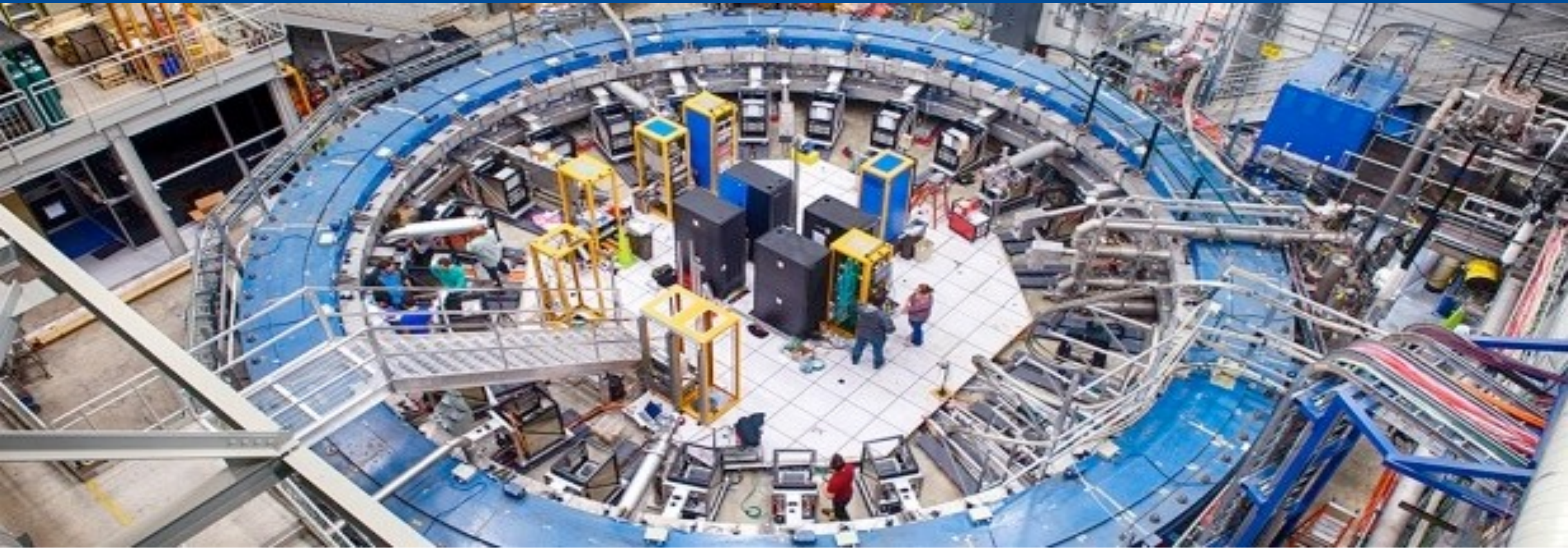
Istituto Nazionale di Fisica Nucleare



History of the Muon g-2 experiment and the Muon Precision Physics Program

Graziano Venanzoni

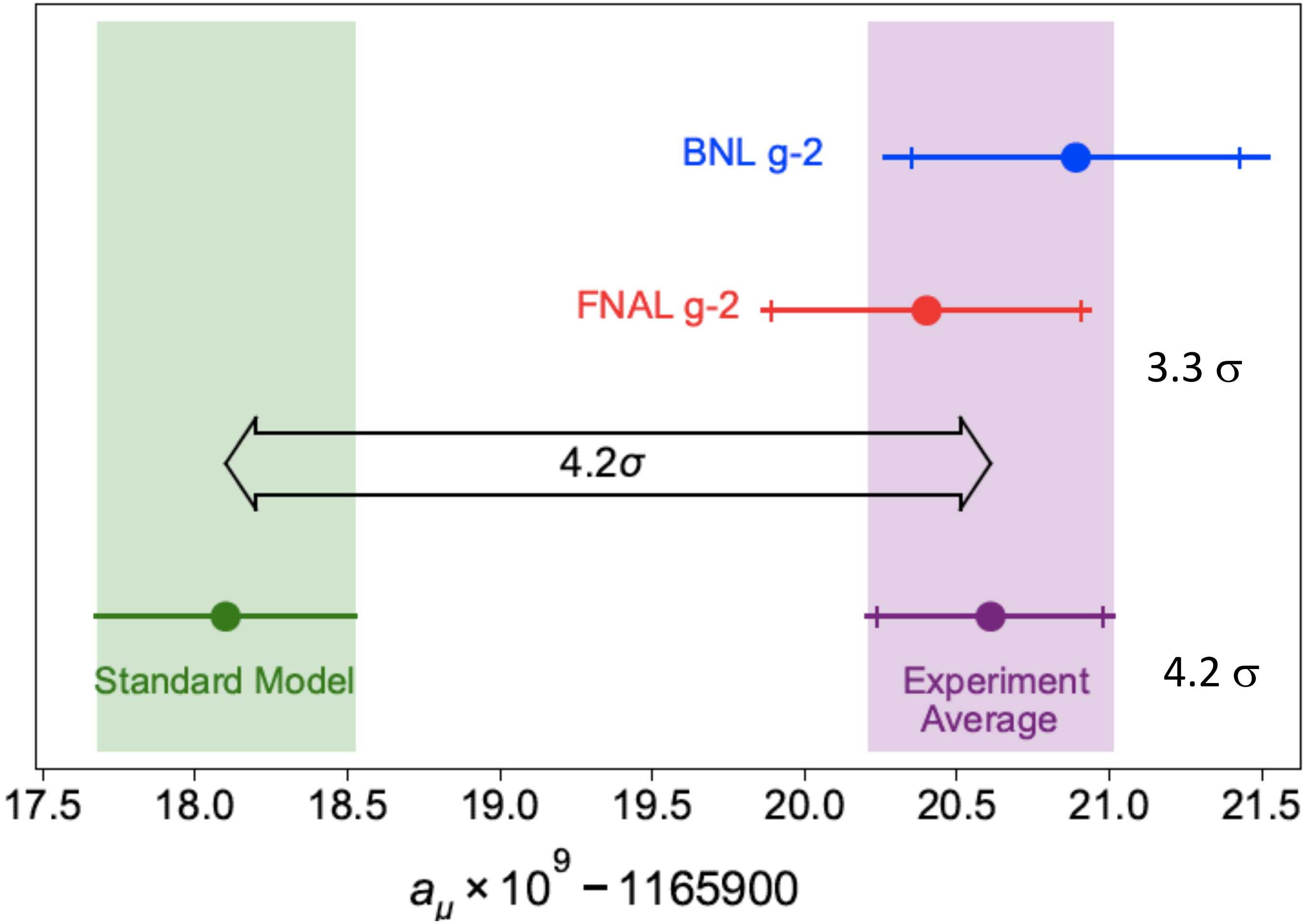
University of Liverpool and Sezione INFN Pisa

LEVERHULME TRUST

Workshop on Muon Precision Physics

7-9 November 2022
The Spine
Europe/London timezone

April 7th 2021: First results from the Muon g-2 experiment at Fermilab



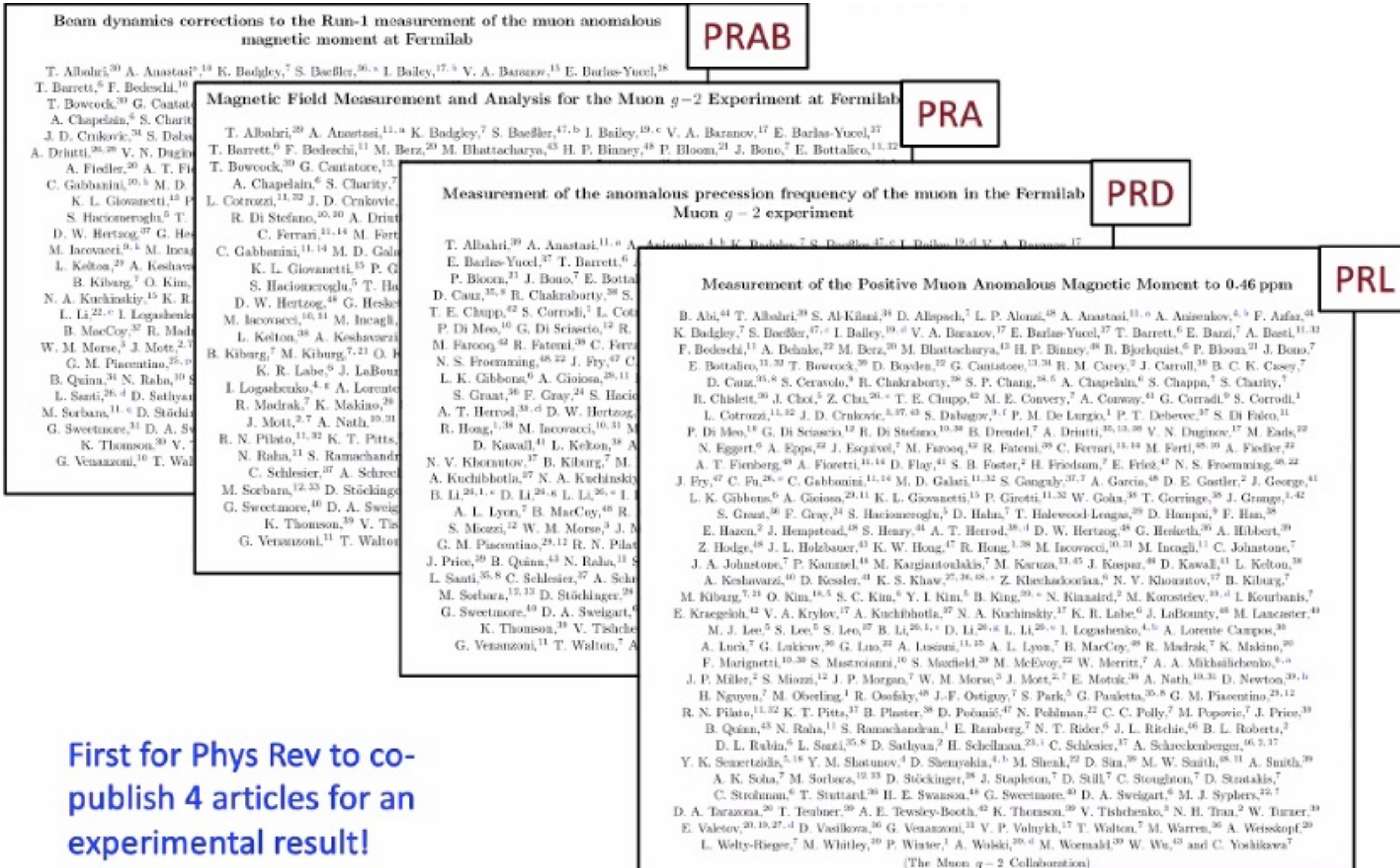
3.7 σ

3.3 σ

4.2 σ

$$a_\mu(\text{FNAL}) = 116\,592\,040(54) \times 10^{-11} \quad (0.46\,\text{ppm})$$

4 Phys Rev journals on April 2021(>1000 citations)



First for Phys Rev to co-publish 4 articles for an experimental result!

Muon g-2 Coll, Phys. Rev. Lett. 126 (2021) 14, 141801

New York Times: 8th April 2021


"All the News That's Fit to Print"

The New York Times

Late Edition

VOL. CLXX .... No. 59,022 — NEW YORK, THURSDAY, APRIL 8, 2021 — $3.00

Biden Tax Plan Aims to Curtail Use of Havens

Loophole Has Enriched Global Corporations

Contagious Variant Is Fueling Surge in Infections Across the U.S.

PAIR OF SETBACKS FOR ASTRAZENECA OVER ITS VACCINE

BLOOD CLOT CONCERNS

U.K. Curbs Use by Adults Under 30 as the E.U. Outlines Risks

ISIS and African Militants Join In a Marriage of Convenience

New York to Provide $2.1 Billion For Undocumented Immigrants

A Particle's Tiny Wobble Could Upend the Known Laws of Physics

Adventurers Fleeing Pandemic Strain the West's Rescue Teams

- News reported in all newspapers, socials (>3000 media outlets covered the story)
- Huge public engagement (3 billions views in the 24h following the release)


A Particle's Tiny Wobble Could Upend the Known Laws of Physics

By DENNIS OVERBYE

Evidence is mounting that a tiny subatomic particle seems to be disobeying the known laws of physics, scientists announced on Wednesday, a finding that would open a vast and tantalizing hole in our understanding of the universe.

The result, physicists say, suggests that there are forms of matter and energy vital to the nature and evolution of the cosmos that are not yet known to science.

"This is our Mars rover landing moment," said Chris Polly, a physicist at the Fermi National Accelerator Laboratory, or Fermilab, in Batavia, Ill., who has been working toward this finding for most of his career.

The particle under scrutiny is the muon, which is akin to an electron but far heavier, and is an integral element of the cosmos. Dr. Polly and his colleagues — an international team of 200 physicists from seven countries — found that muons did not behave as predicted when shot through an intense magnetic field at Fermilab.

The aberrant behavior poses a firm challenge to the bedrock theory of physics known as the Standard Model, a suite of equations that enumerates the fundamental particles in the universe (17, at last count) and how they interact.

"This is strong evidence that the muon is sensitive to something that is not in our best theory," said Renee Fatemi, a physicist at the University of Kentucky.

The results, the first from an experiment called Muon g-2, agreed with similar experiments at the Brookhaven National Laboratory in 2001 that have teased physicists ever since.

At a virtual seminar and news conference on Wednesday, Dr. Polly pointed to a graph displaying white space where the Fermilab findings deviated from the theoretical prediction. "We can say with fairly high confidence, there

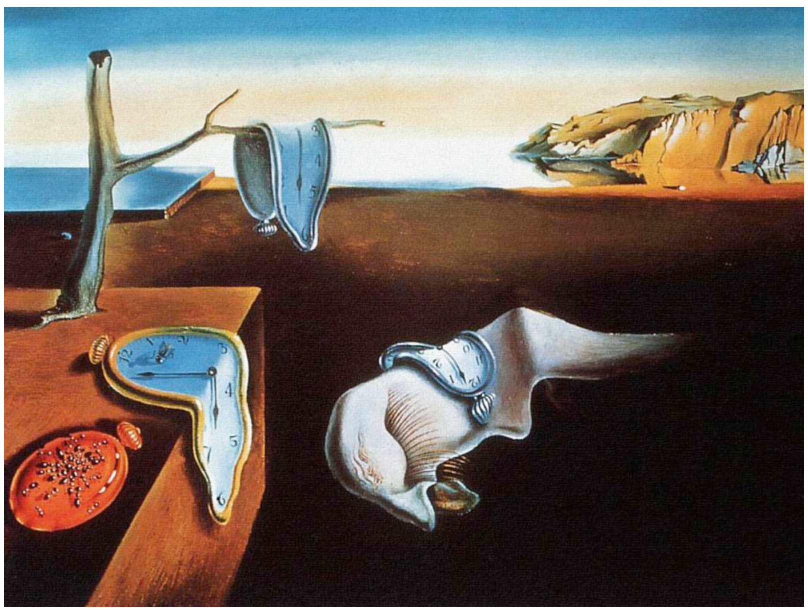
Continued on Page A19

REIDAR HAHN/FERMILAB, VIA ASSOCIATED PRESS

A ring at the Fermi National Accelerator Laboratory in Illinois is used to study the wobble of muons.

April 7 2021

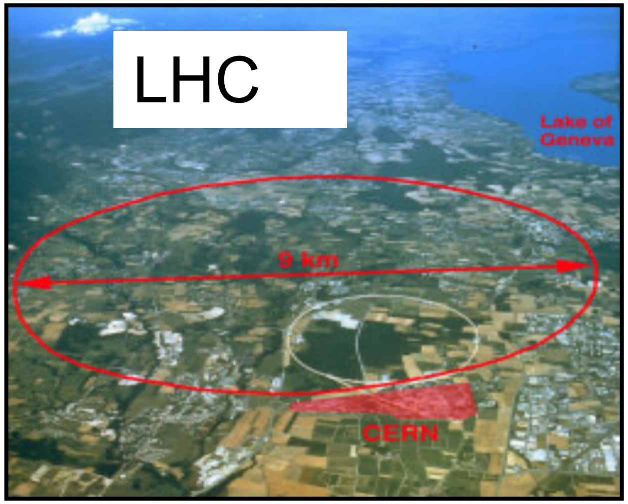
"DOES THE MUON G-2 EXPERIMENT OPEN A **NEW ERA** FOR **PHYSICS**?"



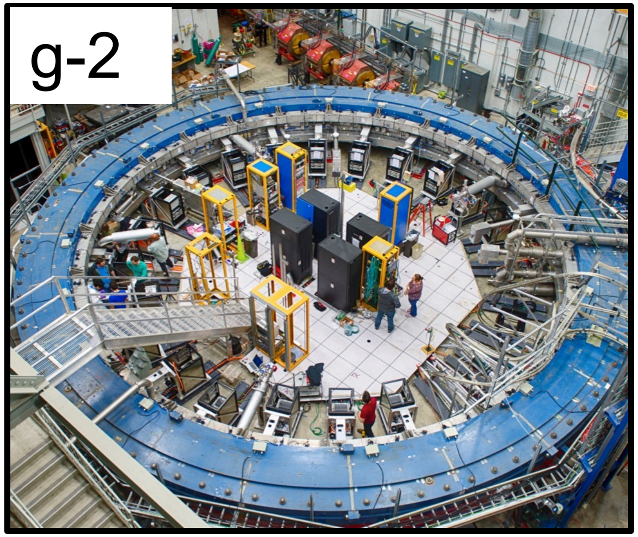
"What **monsters** might be lurking there?" (Chris Polly, April 7 2021)

Two ways to look for New Physics

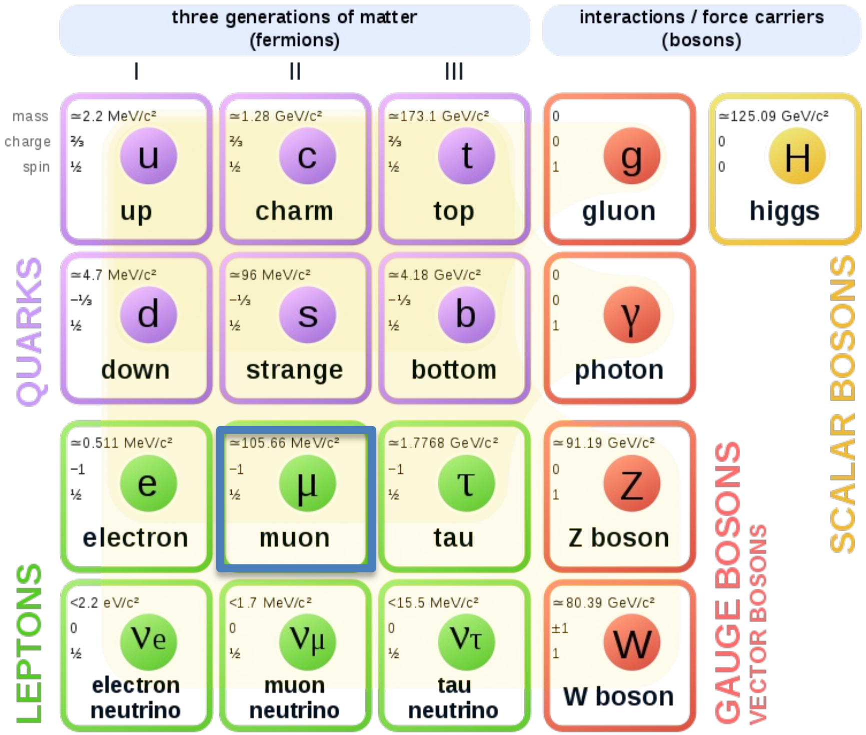
- **High Energy:** increasingly high-energy machines (LHC, ILC / Fcc) are designed and new high-mass "particles" are searched (direct observation). Large detectors and collaborations



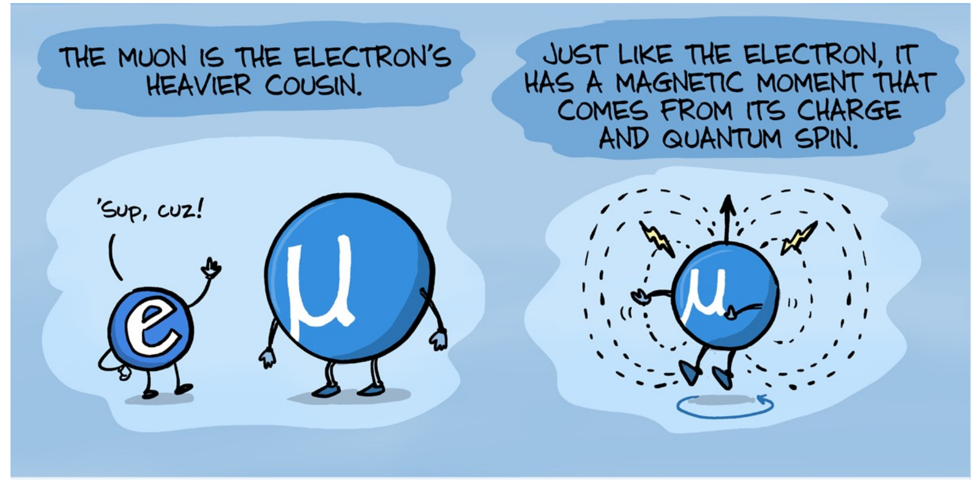
- **High Intensity:** through precision measurements, new low-energy physics effects are sought (deviations from theory). Small scale detectors and collaborations, very high statistics



The Muon (μ)



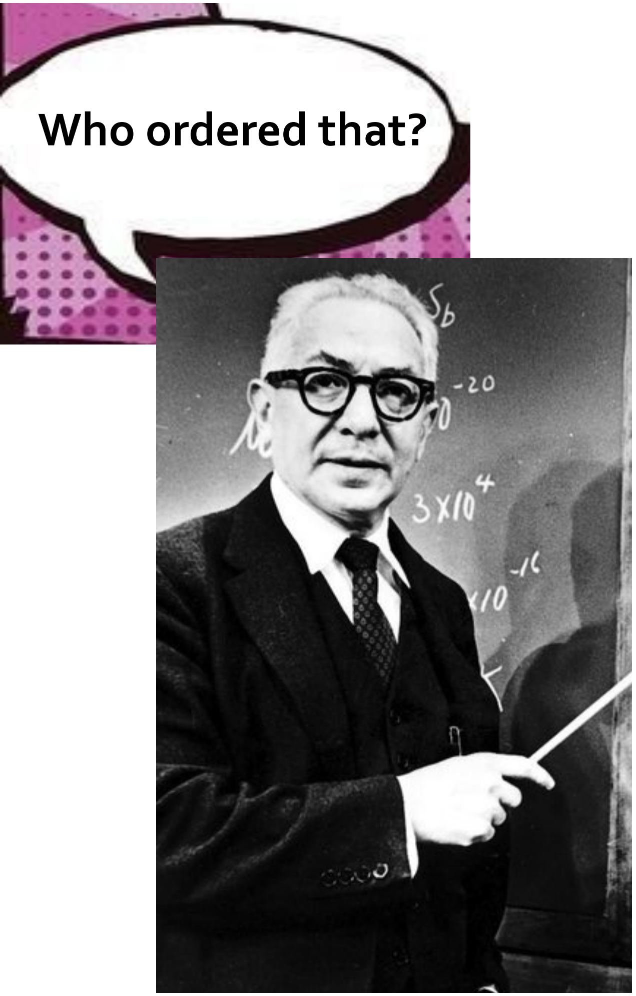
The Standard Model of elementary particles describes all known particles and their interactions via electromagnetic, weak and strong forces. The particles which constitute the matter are grouped in 3 families and nobody knows why



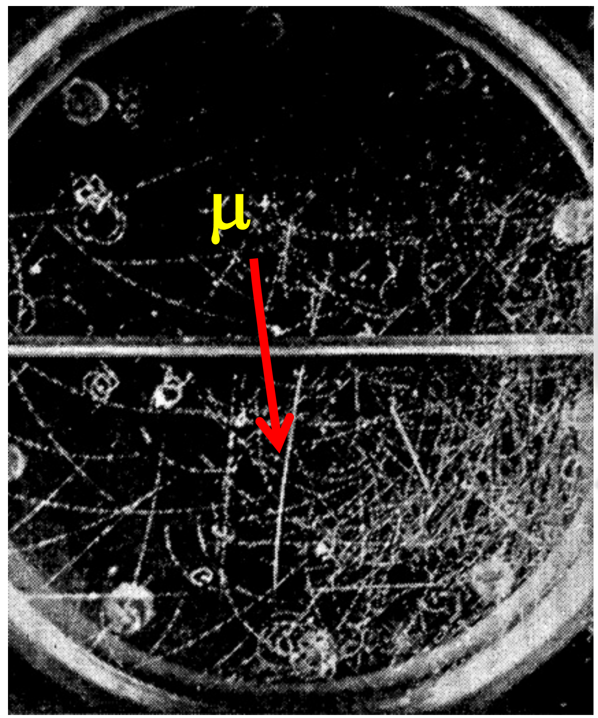
The muon is an elementary particle similar to the electron, with the same electric charge, but with a mass about 200 times larger. As the electron It has an intrinc angular and magnetic moment

$m_\mu \sim 200\, m_e$, Lifetime ~2.2 μs, $S_\mu = 1/2$

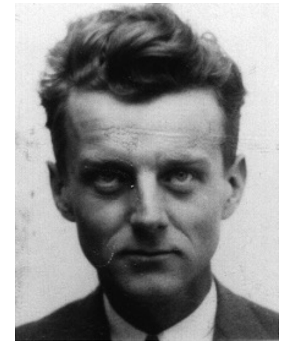
Discovered in 1936 (in cosmic rays)



Isaac Rabi Nobel Prize 1944

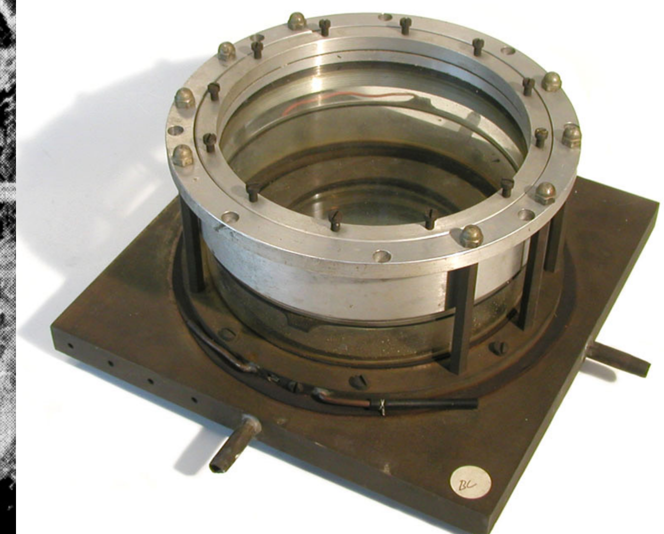


Muon trace in a cloud chamber (Anderson and Neddermeyer 1936)



Seeth Neddermeyer

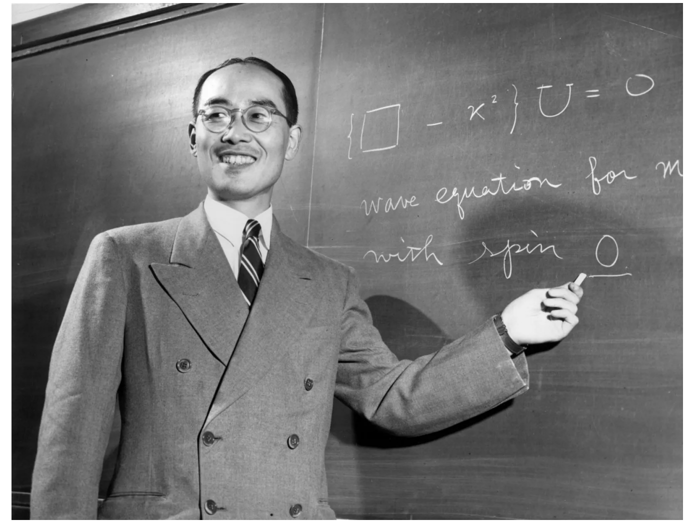
Carl Anderson



cloud chamber (1935)

"A Ten-years joke"

- After the discovery the muon (called at that time mesotron) was confused with the particle responsible for the nuclear force (Yukawa particle)
- This confusion was clarified by an epic experiment done by Conversi Pancini Piccioni in Rome in 1944-1945 under the bombs
- They had to move the equipment in a School (close to the Vatican) because the Laboratory was not safe



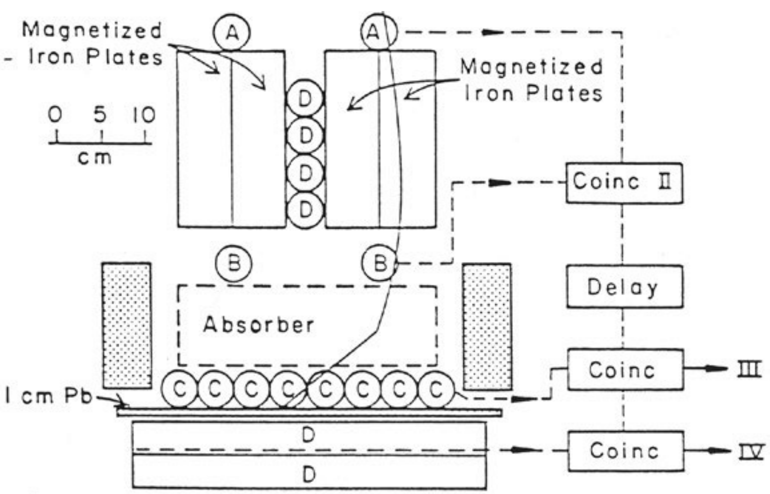
Hideki Yukawa

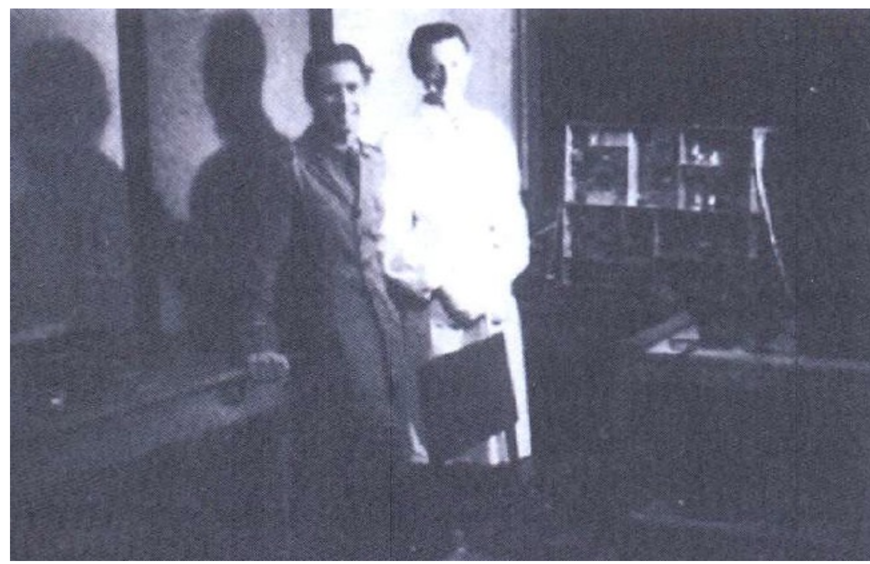
On the Disintegration of Negative Mesons

M. Conversi, E. Pancini, and O. Piccioni*

Centro di Fisica Nucleare del C. N. R. Istituto di Fisica dell'Università di Roma, Italia

December 21, 1946



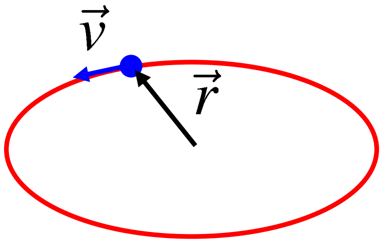


Marcello Conversi and Oreste Piccioni in the basement of the Virgilio high school

The Muon g-2

- A charge particle in a plane orbit has **angular momentum** $\vec{L}$ and **magnetic moment** $\vec{\mu}$

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



- The ratio $\frac{\vec{\mu}}{\left(\frac{q}{2m}\right)\vec{L}}$ is called gyromagnetic ratio g. Classically **g=1**

- For an elementary particle of Spin = 1/2 (e,μ) Dirac equation predicts **g = 2**

$$\vec{\mu} = \frac{e}{2m}\vec{\sigma} \equiv g\frac{e}{2m}\vec{S}; \quad \vec{S} = \frac{\vec{\sigma}}{2}; \quad g = 2$$

- The magnetic anomaly is defined as **a = (g-2)/2. g=2 → a=0** according to Dirac

1948: Measurement of g of the electron

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

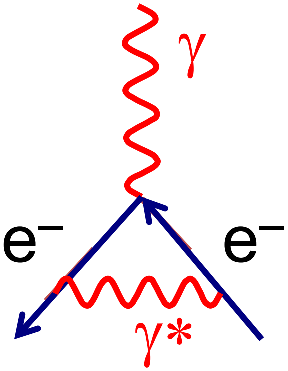
(Received April 19, 1948)

A comparison of the g_J values of Ga in the $^2P_{3/2}$ and $^2P_{1/2}$ states, In in the $^2P_{1/2}$ state, and Na in the $^2S_{1/2}$ 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 $g_S = 2(1.00119 \pm 0.00005)$. 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.

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

a= 0 according to Dirac

1948: Triumph of Quantum Field Theory (QED)



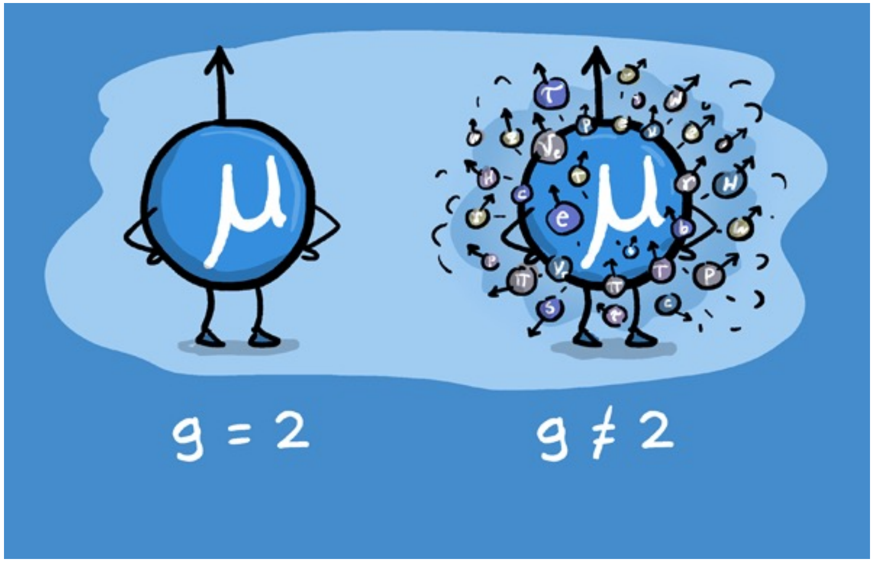
$$a = \frac{(g-2)}{2} = \frac{\alpha}{2\pi} = 0.001161$$

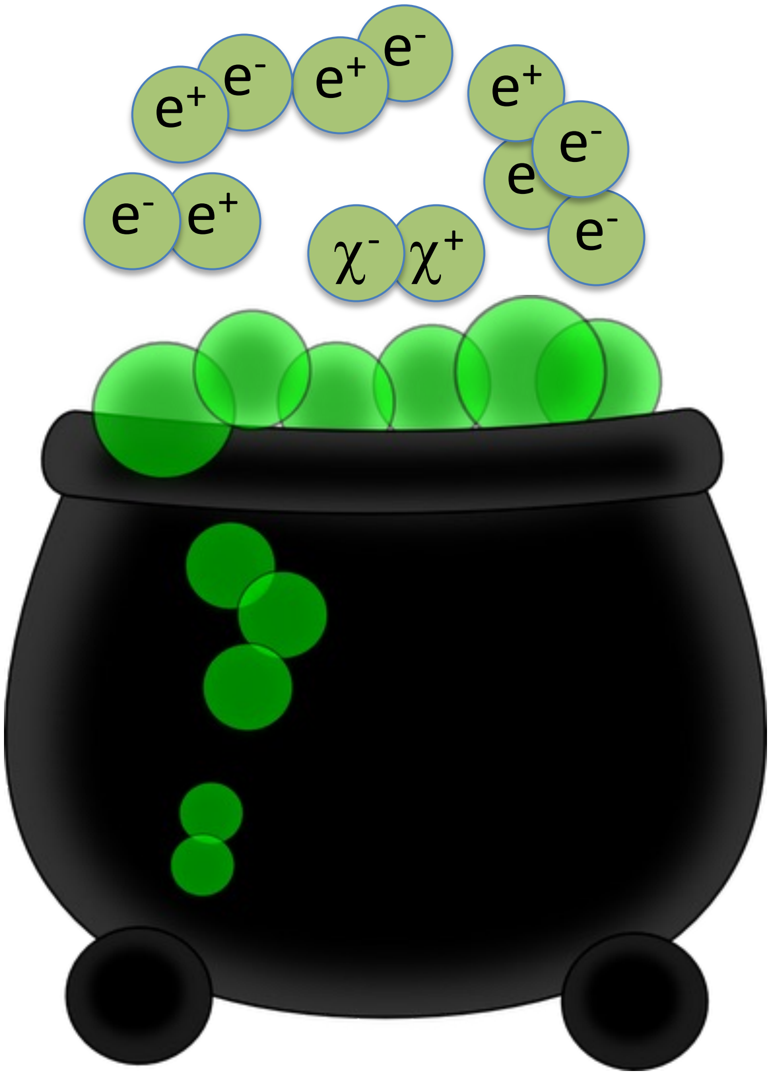
a>0; g>2

At the end it's all the Quantum Vacuum

- The vacuum is filled with pairs of particles and antiparticles that exist for a very short time and are therefore called **virtual**.

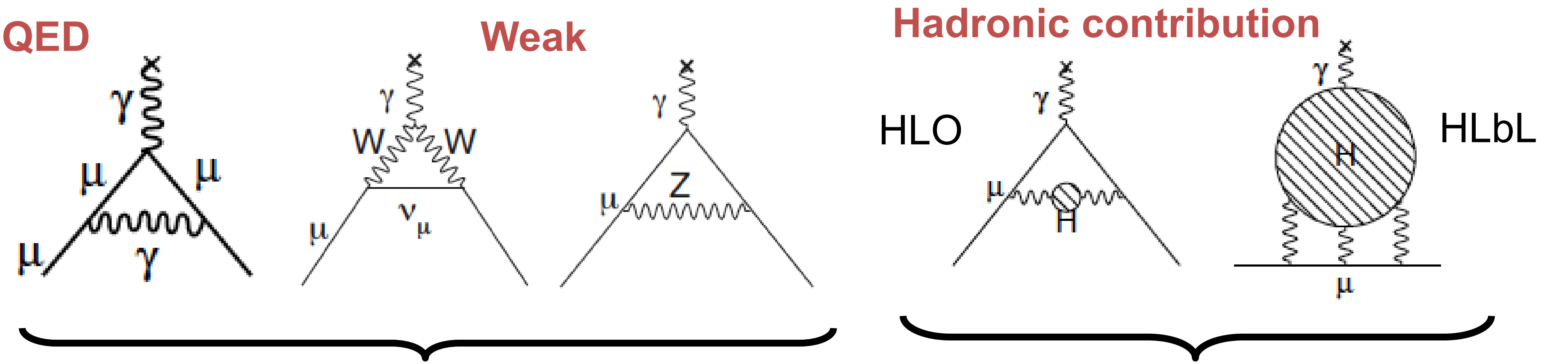
- They produce tangible effects on the physical phenomena we observe → $g \neq 2$





$a_\mu = (g-2)/2$ can be computed very precisely!

Muon g-2



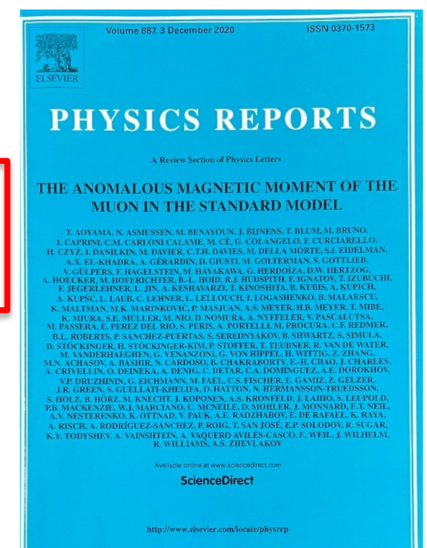
Precisely known

Large uncertainty
(significant work going on)

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

$$a_\mu(\mathrm{SM}) = 116\,591\,810(43) \times 10^{-11} \quad (0.37\,\mathrm{ppm})$$

Theory Initiative (WP20): T. Aoyama et al. Phys. Rept. 887 (2020)


Volume 887, 3 December 2020 ISSN 0370-1573

ELSEVIER

PHYSICS REPORTS

A Review Section of Physics Letters

THE ANOMALOUS MAGNETIC MOMENT OF THE MUON IN THE STANDARD MODEL

T. AOYAMA, N. ASMUSSEN, M. BENAYOUN, J. BIJNENS, T. BLUM, M. BRUNO, I. CAPRINI, C.M. CARLONI CALAME, M. CÈ, G. COLANGELO, F. CURCIARELLO, H. CZYŻ, I. DANILKIN, M. DAVIER, C.T.H. DAVIES, M. DELLA MORTE, S.I. EIDELMAN, A.X. EL-KHADRA, A. GÉRARDIN, D. GIUSTI, M. GOLTERMAN, S. GOTTLIEB, V. GÜLPERS, F. HAGELSTEIN, M. HAYAKAWA, G. HERDOÍZA, D.W. HERTZOG, A. HOECKER, M. HOFERICHTER, B.-L. HOID, R.J. HUDSPITH, F. IGNATOV, T. IZUBUCHI, F. JEGERLEHNER, L. JIN, A. KESHAVARZI, T. KINOSHITA, B. KUBIS, A. KUPICH, A. KUPŚĆ, L. LAUB, C. LEHNER, L. LELLOUCH, I. LOGASHENKO, B. MALAESCU, K. MALTMAN, M.K. MARINKOVIĆ, P. MASJUAN, A.S. MEYER, H.B. MEYER, T. MIBE, K. MIURA, S.E. MÜLLER, M. NIO, D. NOMURA, A. NYFFELER, V. PASCALUTSA, M. PASSERA, E. PEREZ DEL RIO, S. PERIS, A. PORTELLI, M. PROCURA, C.F. REDMER, B.L. ROBERTS, P. SÁNCHEZ-PUERTAS, S. SEREDNYAKOV, B. SHWARTZ, S. SIMULA, D. STÖCKINGER, H. STÖCKINGER-KIM, P. STOFFER, T. TEUBNER, R. VAN DE WATER, M. VANDERHAEGHEN, G. VENANZONI, G. VON HIPPEL, H. WITTIG, Z. ZHANG, M.N. ACHASOV, A. BASHIR, N. CARDOSO, B. CHAKRABORTY, E.-H. CHAO, J. CHARLES, A. CRIVELLIN, O. DEINEKA, A. DENIG, C. DETAR, C.A. DOMINGUEZ, A.E. DOROKHOV, V.P. DRUZHININ, G. EICHMANN, M. FAEL, C.S. FISCHER, E. GÁMIZ, Z. GELZER, J.R. GREEN, S. GUELLATI-KHELIFA, D. HATTON, N. HERMANSSON-TRUEDSSON, S. HOLZ, B. HÖRZ, M. KNECHT, J. KOPONEN, A.S. KRONFELD, J. LAIHO, S. LEUPOLD, P.B. MACKENZIE, W.J. MARCIANO, C. MCNEILE, D. MOHLER, J. MONNARD, E.T. NEIL, A.V. NESTERENKO, K. OTTNAD, V. PAUK, A.E. RADZHABOV, E. DE RAFAEL, K. RAYA, A. RISCH, A. RODRÍGUEZ-SÁNCHEZ, P. ROIG, T. SAN JOSÉ, E.P. SOLODOV, R. SUGAR, K.Y. TODYSHEV, A. VAINSHTEIN, A. VAQUERO AVILÉS-CASCO, E. WEIL, J. WILHELM, R. WILLIAMS, A.S. ZHEVLAKOV

Available online at www.sciencedirect.com

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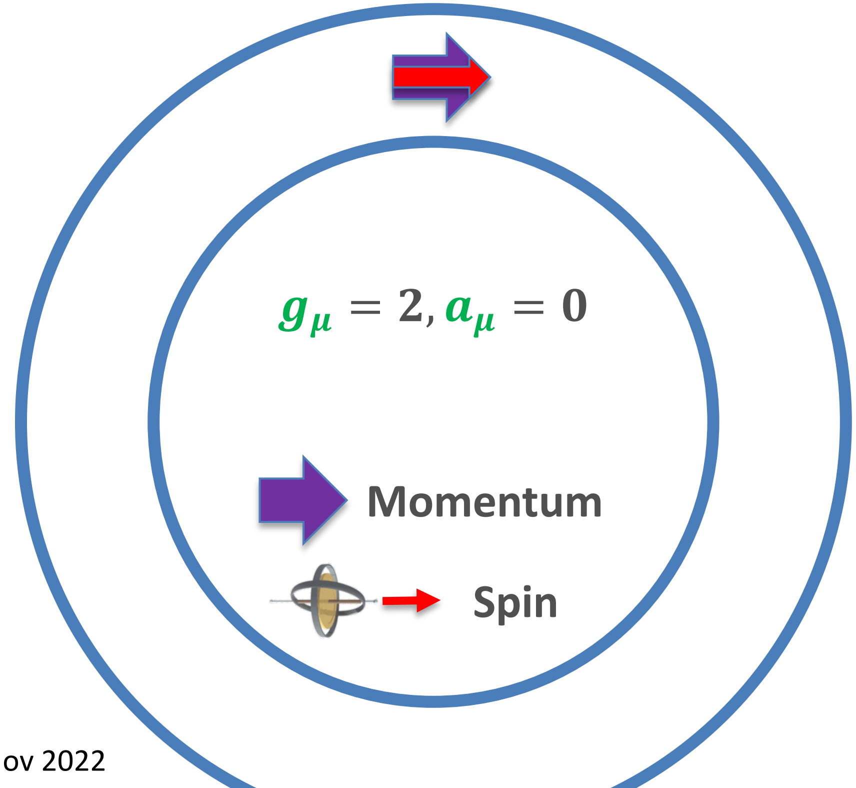
a_μ can be measured very precisely …

- The frequency with which the spin moves ahead of the momentum in a magnetic field B (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

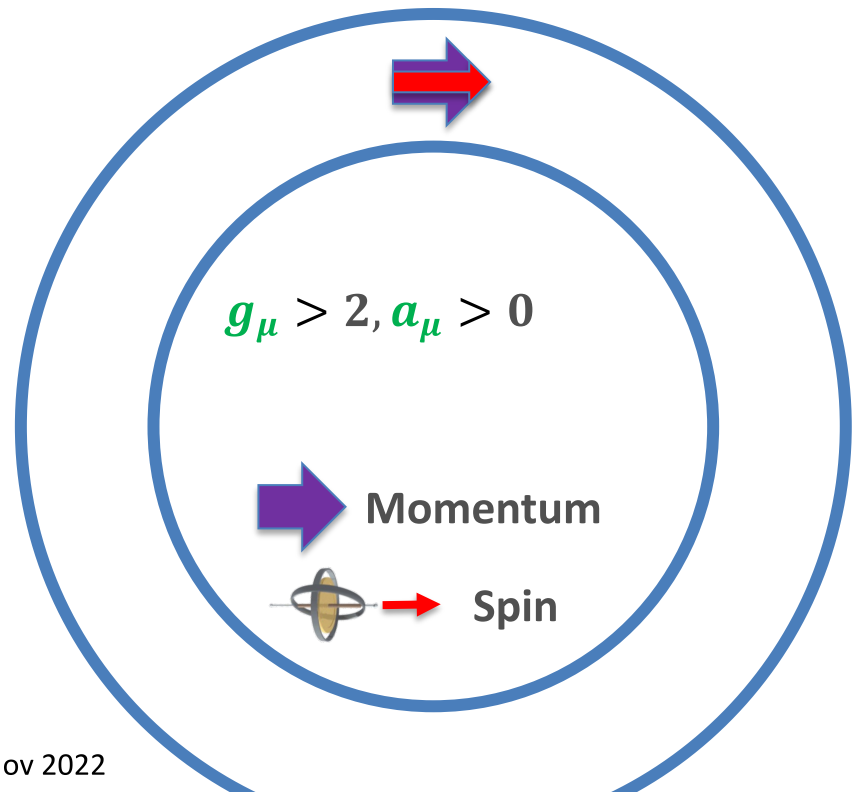


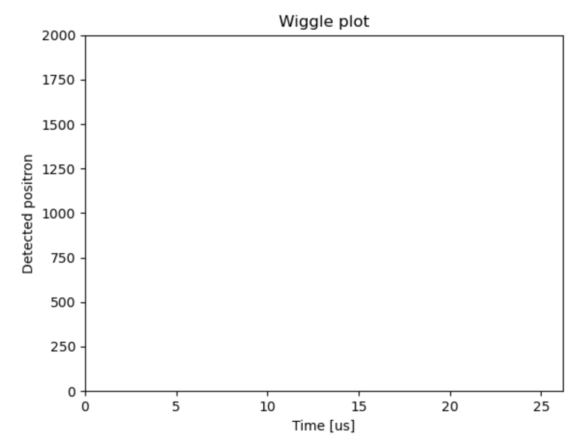
a_μ can be measured very precisely …

- The frequency with which the spin moves ahead of the momentum in a magnetic field B (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





By measuring directly a_μ x800 more sensitive than an experiment which measures g

Current experiments δa_μ < 1ppm

History of muon g-2 experiments (1960-2000)

- The storage ring method was developed at CERN and improved at BNL through a series of experiments with increasing precision which allowed to test the SM at the level of strong (CERN) and EW (BNL) effects

$\pm$	Measurement	σ_{a_μ}/a_μ	Sensitivity	Reference
μ^+	$g = 2.00 \pm 0.10$		$g = 2$	Garwin *et al*[30], Nevis (1957)
μ^+	$0.001\,13^{+0.00016}_{-0.00012}$	12.4%	$\frac{\alpha}{\pi}$	Garwin *et al*[33], Nevis (1959)
μ^+	0.001 145(22)	1.9%	$\frac{\alpha}{\pi}$	Charpak *et al*[34] CERN 1 (SC) (1961)
μ^+	0.001 162(5)	0.43%	$(\frac{\alpha}{\pi})^2$	Charpak *et al*[35] CERN 1 (SC) (1962)
$\mu^\pm$	0.001 166 16(31)	265 ppm	$(\frac{\alpha}{\pi})^3$	Bailey *et al*[36] CERN 2 (PS) (1968)
μ^+	0.001 060(67)	5.8%	$\frac{\alpha}{\pi}$	Henry*et al*[46] solenoid (1969)
$\mu^\pm$	0.001 165 895(27)	23 ppm	$(\frac{\alpha}{\pi})^3$ + Hadronic	Bailey *et al*[37] CERN 3 (PS) (1975)
$\mu^\pm$	0.001 165 911(11)	7.3 ppm	$(\frac{\alpha}{\pi})^3$ + Hadronic	Bailey *et al*[38] CERN 3 (PS) (1979)
μ^+	0.001 165 919 1(59)	5 ppm	$(\frac{\alpha}{\pi})^3$ + Hadronic	Brown *et al*[48] BNL (2000)
μ^+	0.001 165 920 2(16)	1.3 ppm	$(\frac{\alpha}{\pi})^4$ + Weak	Brown *et al*[49] BNL (2001)
μ^+	0.001 165 920 3(8)	0.7 ppm	$(\frac{\alpha}{\pi})^4$ + Weak + ?	Bennett *et al*[50] BNL (2002)
μ^-	0.001 165 921 4(8)(3)	0.7 ppm	$(\frac{\alpha}{\pi})^4$ + Weak + ?	Bennett *et al*[51] BNL (2004)
$\mu^\pm$	0.001 165 920 80(63)	0.54 ppm	$(\frac{\alpha}{\pi})^4$ + Weak + ?	Bennett *et al*[51, 26] BNL WA (2004)

J. Miller, E. De Rafael, L. Roberts, Rept. Prog. Phys. 70 (2007) 795

Let's go through the history of the muon g-2 experiments

The Muons

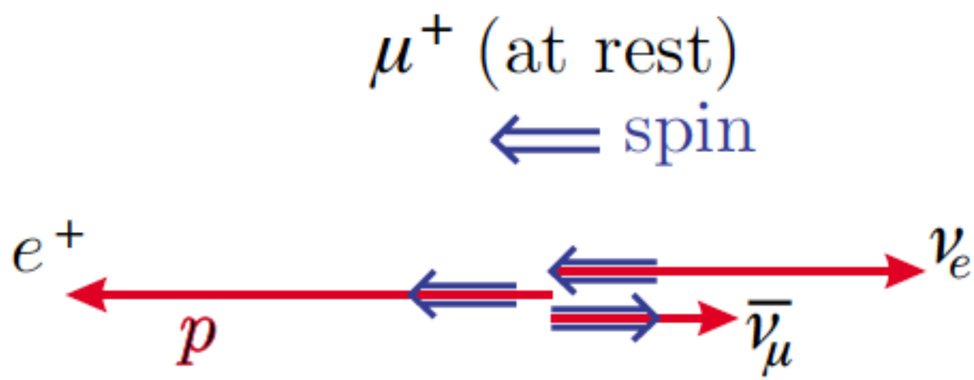
– produced polarized in "forward" direction

$$\pi^- \longrightarrow \mu^- \; \bar{\nu}_\mu$$

– decay with information on where their spin was at the time of decay

$$\mu^- \longrightarrow e^- \; \bar{\nu}_e \; \nu_\mu$$

S-p correlation fundamental to all muon anomaly experiments



High energy positrons have momentum along the muon spin. The opposite is true for electrons from μ^-.

Detect high energy electrons. The time dependence of the signal tracks muon precession.

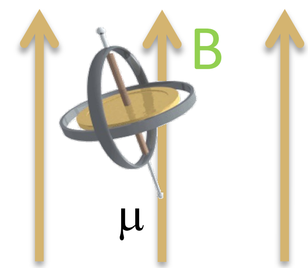
highest energy $e^\pm$ carry μ spin information

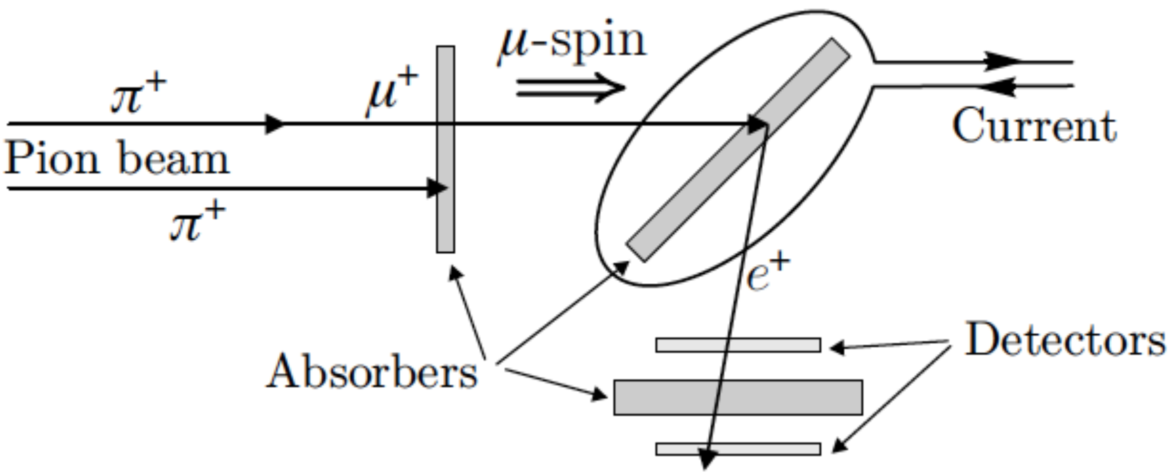
Lee and Yang (1956)

Photo from the Nobel Foundation archive.
Chen Ning Yang
Prize share: 1/2

Photo from the Nobel Foundation archive.
Tsung-Dao (T.D.) Lee
Prize share: 1/2

The parity violation in the production and decay of the muon offers a way to measure the muon magnetic moment

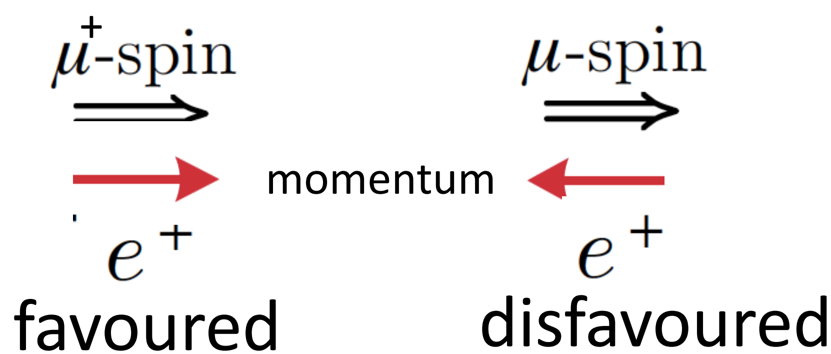




$$\omega_s = g\frac{eB}{2mc}$$

+

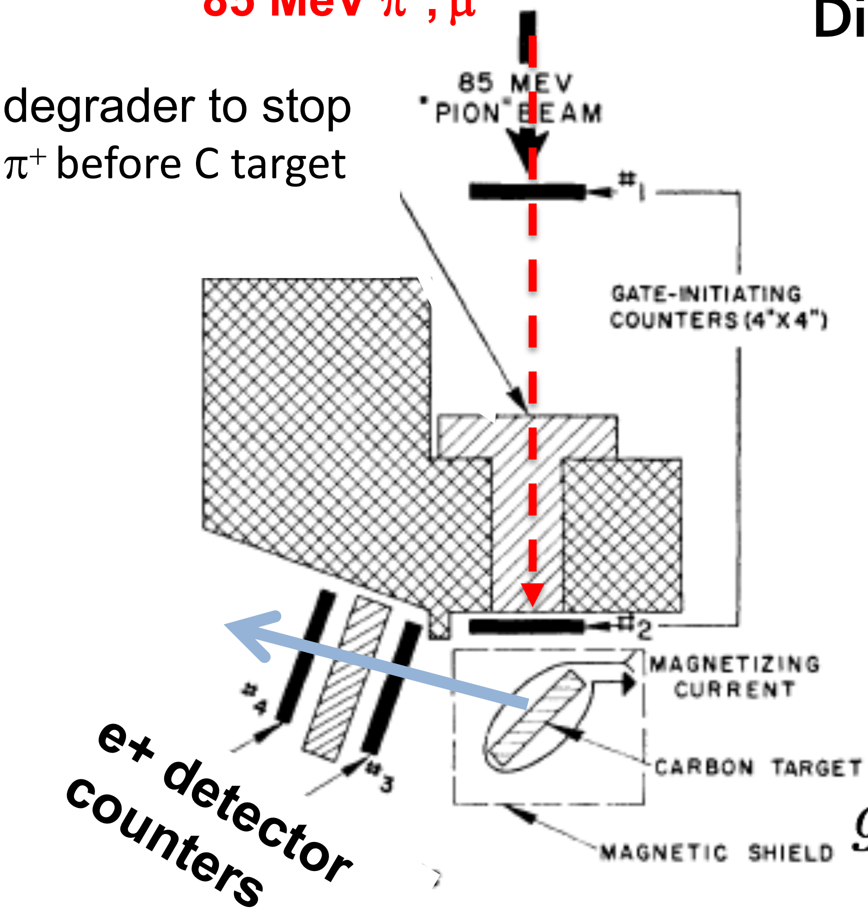
The rate of high energy decay electrons is time modulated by the precession of the magnetic moment with a frequency which depends on g



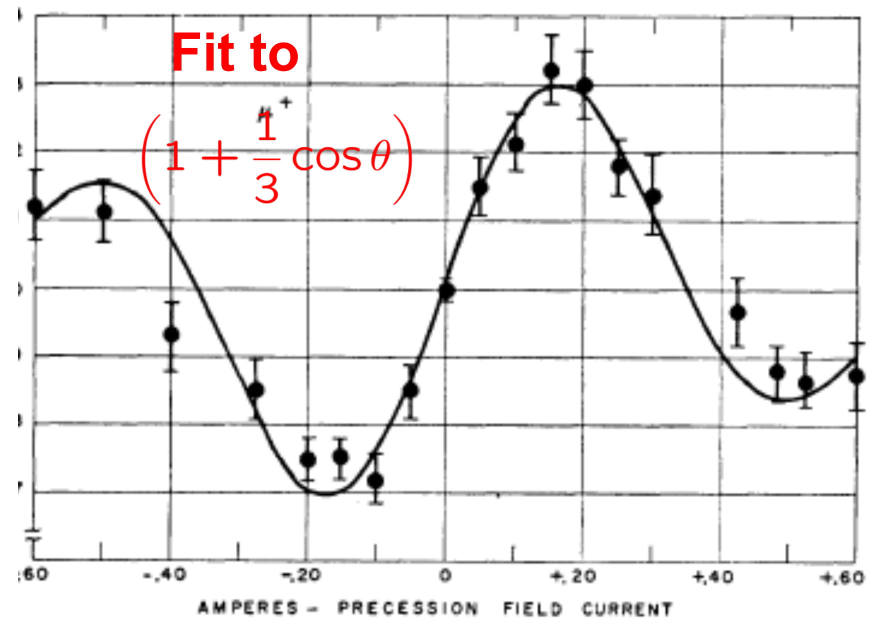
History: the first measurement of g_μ

- 1957: Garwin, Lederman, Weinrich at Nevis (Just after Yang and Lee parity violation paper - confirmation)

85 MeV π^+, μ^+



Direct measurement of *g* -- asym vs field



$$g_\mu = 2.00 \pm 0.10$$

5% uncertainty

muons behave like electrons

Cassels, et al. (Liverpool) 1957
Stopped $\vec{\mu}^+$ from π^+ decay

- Counted e^+ decays vs. time in a 100.9 G B field.

$$g_\mu = 2.004 \pm 0.014$$

0.7% uncertainty

stopped μ then decay → e^+

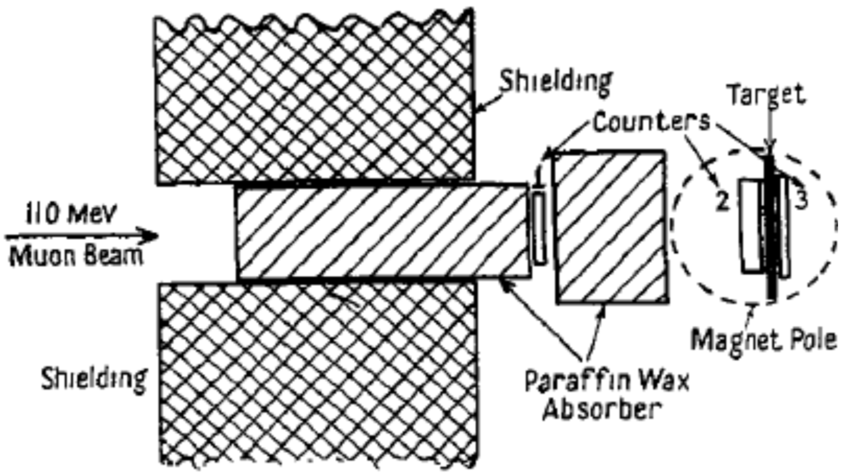
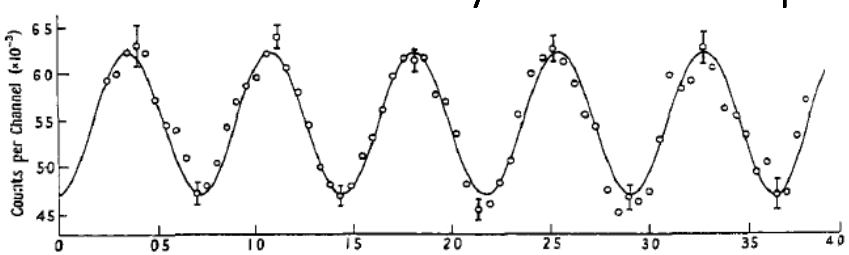


Figure 1 Layout of experimental apparatus

156 inch Cyclotron in Liverpool



exponential from τ_μ divided out

"The value of g itself should be sought in a comparison of the **precession** and **cyclotron** frequencies of muons in a magnetic field. The two frequencies are expected to differ only by the **radiative correction**" → Birth **of Storage Ring** method!

W. E. Bell and E. P. Hincks, Phys. Rev. 84, 1243 (1951)

The CERN muon g-2 experiments (1960-1979)

Muon g-2

F. Farley, E. Picasso The Muon (g−2) Experiments at CERN
Ann. Rev. Nucl. Part. Sci. 29 (1979) 243-282

The history of the muon $(g-2)$ experiments

B. Lee Roberts* SciPost Phys. Proc. 1, 032 (2019)

Review

The 47 years of muon $g-2$

F.J.M. Farley[a,*], Y.K. Semertzidis[b]

[a] *Yale University, New Haven, CT 06520, USA*
[b] *Brookhaven National Laboratory, Upton, NY 11973, USA*

Received 30 October 2003

Fig. 10. The first experimental magnet in which muons were stored at CERN for up to 30 turns. Left to right: Georges Charpak, Francis Farley, Bruno Nicolai, Hans Sens, Antonio Zichichi, Carl York and Richard Garwin.

They measure a_μ since the measure the spin relative to the momentum

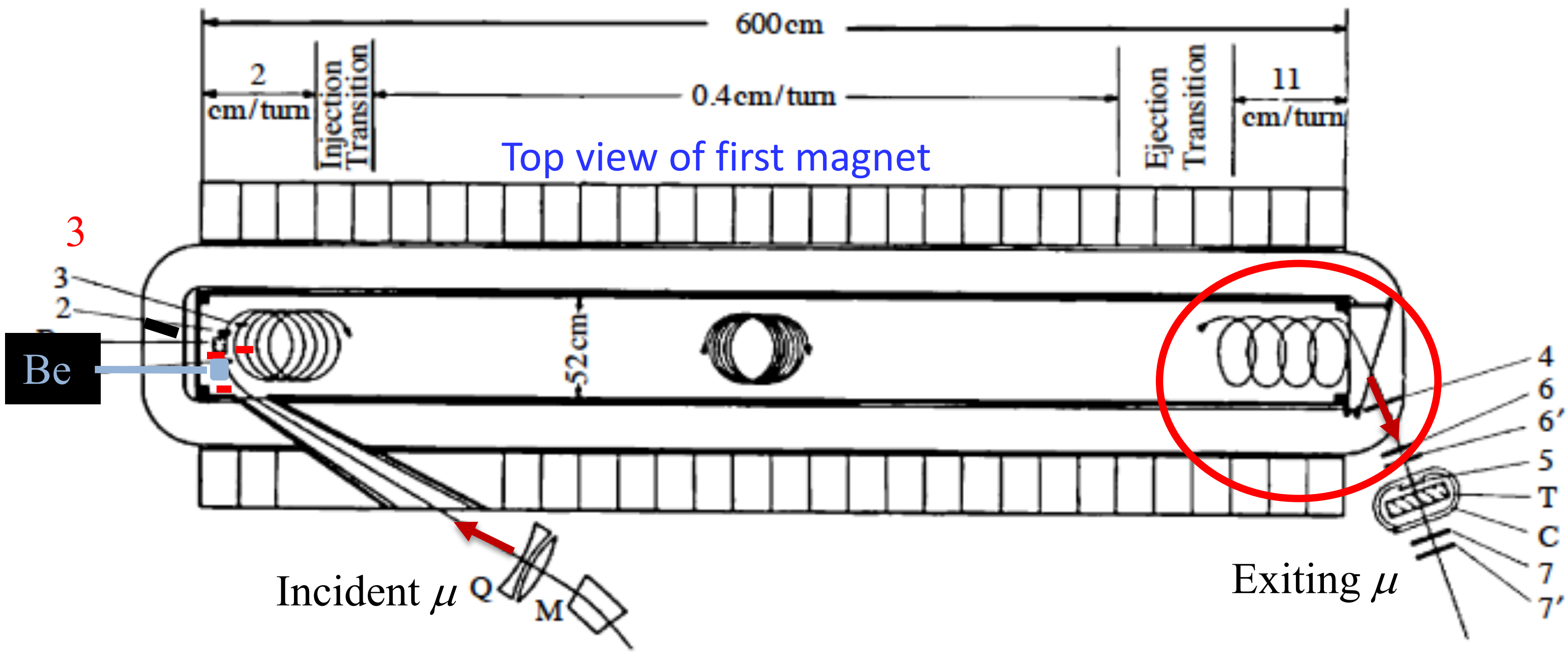
$$\vec{\omega}_a = \omega_S - \omega_C = = -\frac{Qe}{m} a_\mu \vec{B}$$

$a_\mu = (g_\mu - 2)/2 \sim g_\mu/1000$

CERN I, 1958-1962

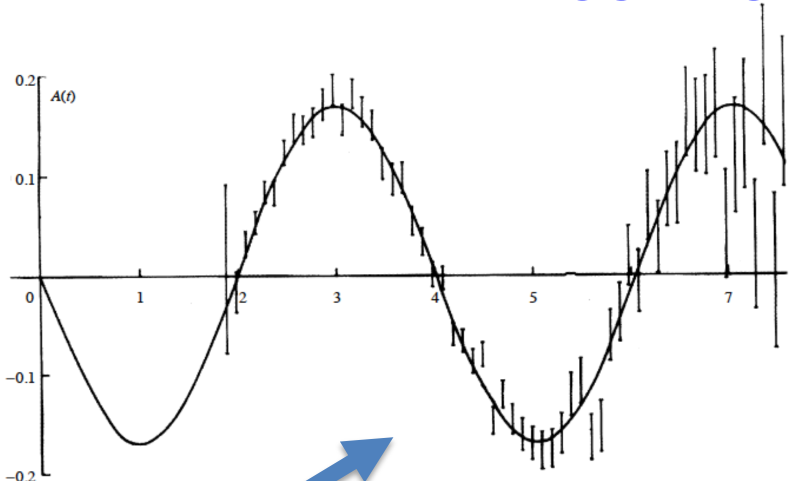
With 100 MeV/c muc

Muon g-2



- Inject polarized muon into a long magnet (B ≈ 1.5 T) with a small gradient – particles drift in circular orbits to the other end: 7.5 μs = 1600 turns
- Extract muons with a large gradient into a polarization monitor where they stopped
- Time in the magnetic field was measured by counters
- Measure the time dependent forward-backward decay asymmetry

CERN I, 1958-1962



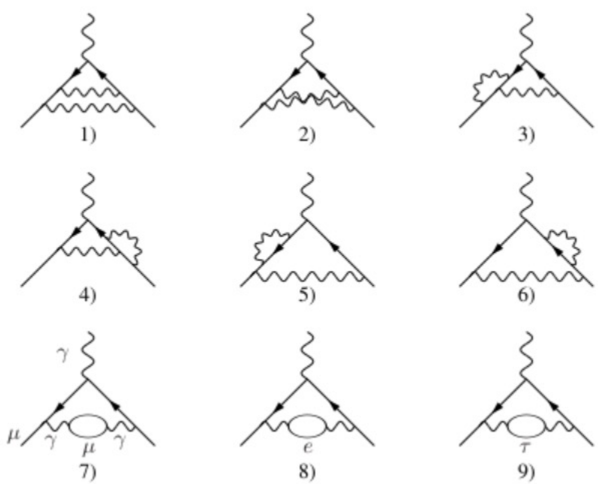
= $A(t) = A_0 \sin(\omega_a t + \varphi)$

$\omega_a = a_\mu (e/mc)\, \overline{B}$

$\simeq 10^3\ \mu^+$ recorded

a_μ(expt) = 0.001162(5) **(4300 ppm)**

a_μ(theory) = 0.001165



QED, second order

$$a_\mu \approx 0.5\left(\frac{\alpha}{\pi}\right) + 0.766\left(\frac{\alpha}{\pi}\right)^2$$

https://link.springer.com/book/10.1007/978-3-319-63577-4

CERN II, 1962-1968:
The First Storage Ring (proton beam)

- Go to p_μ = 1.27 GeV/c, γ_μ = 12; $\gamma\tau$ = 27 μs;
- Used a weak-focusing magnetic storage ring; B_z = 1.71 T
- **p + N → π → μ which are stored**

π production target inside

10.5 GeV/c Proton beam

Background flash in the counters was horrendous!

polarization 26%

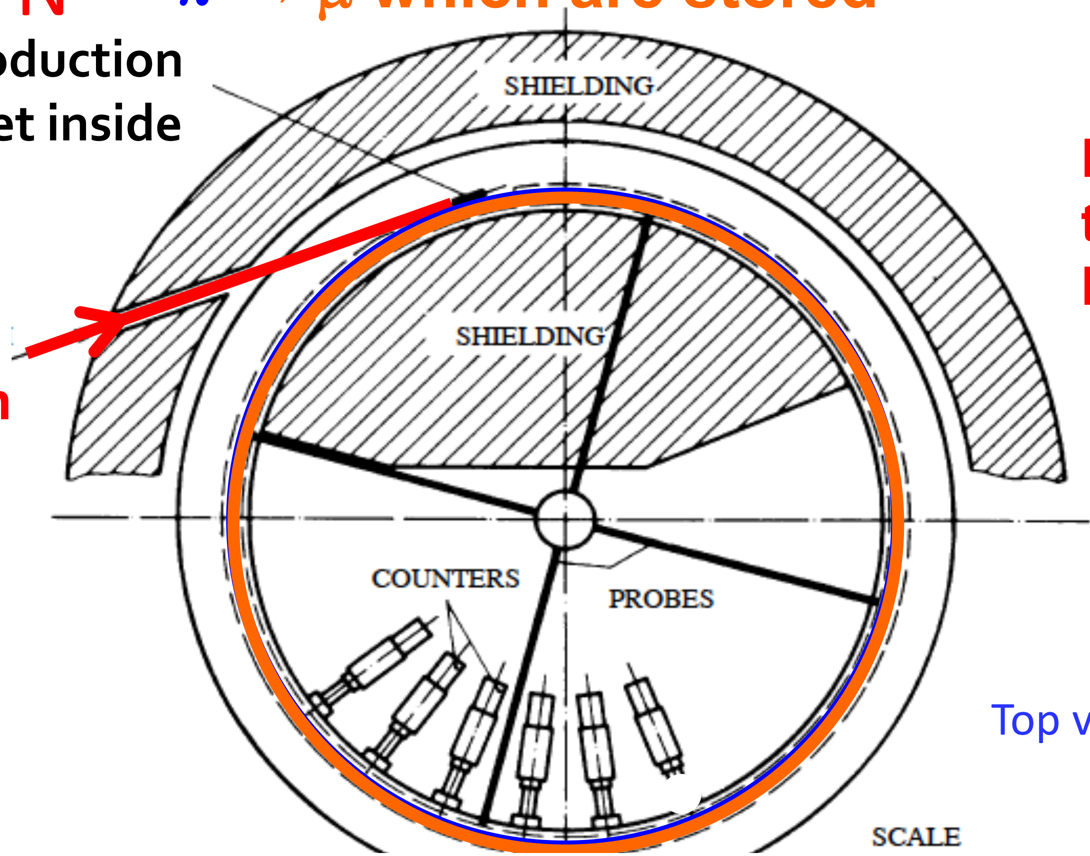


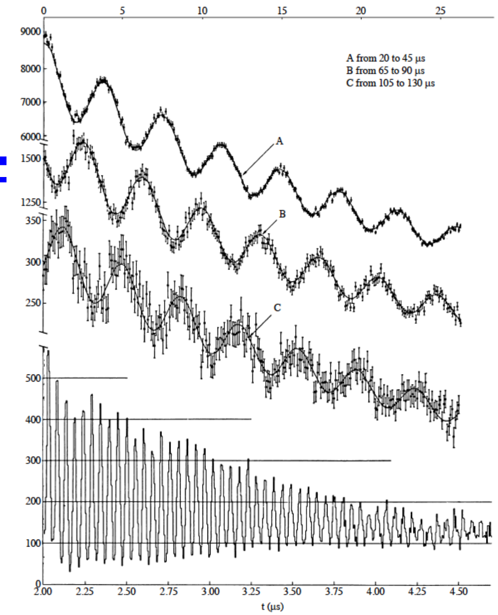
Fig. 17. The first muon storage ring: diameter 5 m, muon momentum 1.3 GeV/c, time dilation factor 12. The injected pulse of 10.5 GeV protons produces pions at the target, which decay in flight to give muons.

Top view of the second magnet

CERN II, 1962-1968

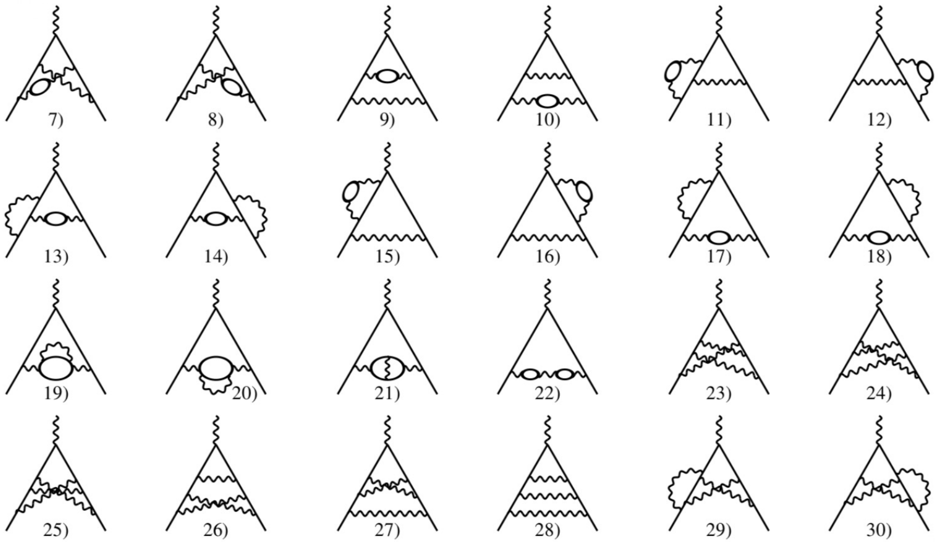
$$f(t) \simeq N_0 e^{-\lambda t}[1 + A\cos(\omega_a t + \phi)]$$

$$\frac{\delta\omega_a}{\omega_a} = \frac{\sqrt{2}}{\omega_a A \gamma \tau \sqrt{N}}$$



$a_\mu(\text{expt}) = 0.00116616(31)$ **(266 ppm)**

$a_\mu(\text{theory}) = 0.001165877(3)$



QED, third order

$$a_\mu \approx 0.5\left(\frac{\alpha}{\pi}\right) + 0.766\left(\frac{\alpha}{\pi}\right)^2 + 24.050\left(\frac{\alpha}{\pi}\right)^3$$

https://link.springer.com/book/10.1007/978-3-319-63577-4

The concept of magic momentum

- How to keep the muons vertically confined?
  - 2nd CERN used radial variation in *B* field (big systematic)

→ Use electrostatic quadrupoles - but adds complications

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

$$(p_\mu = 3.09 \text{ GeV}/c)$$

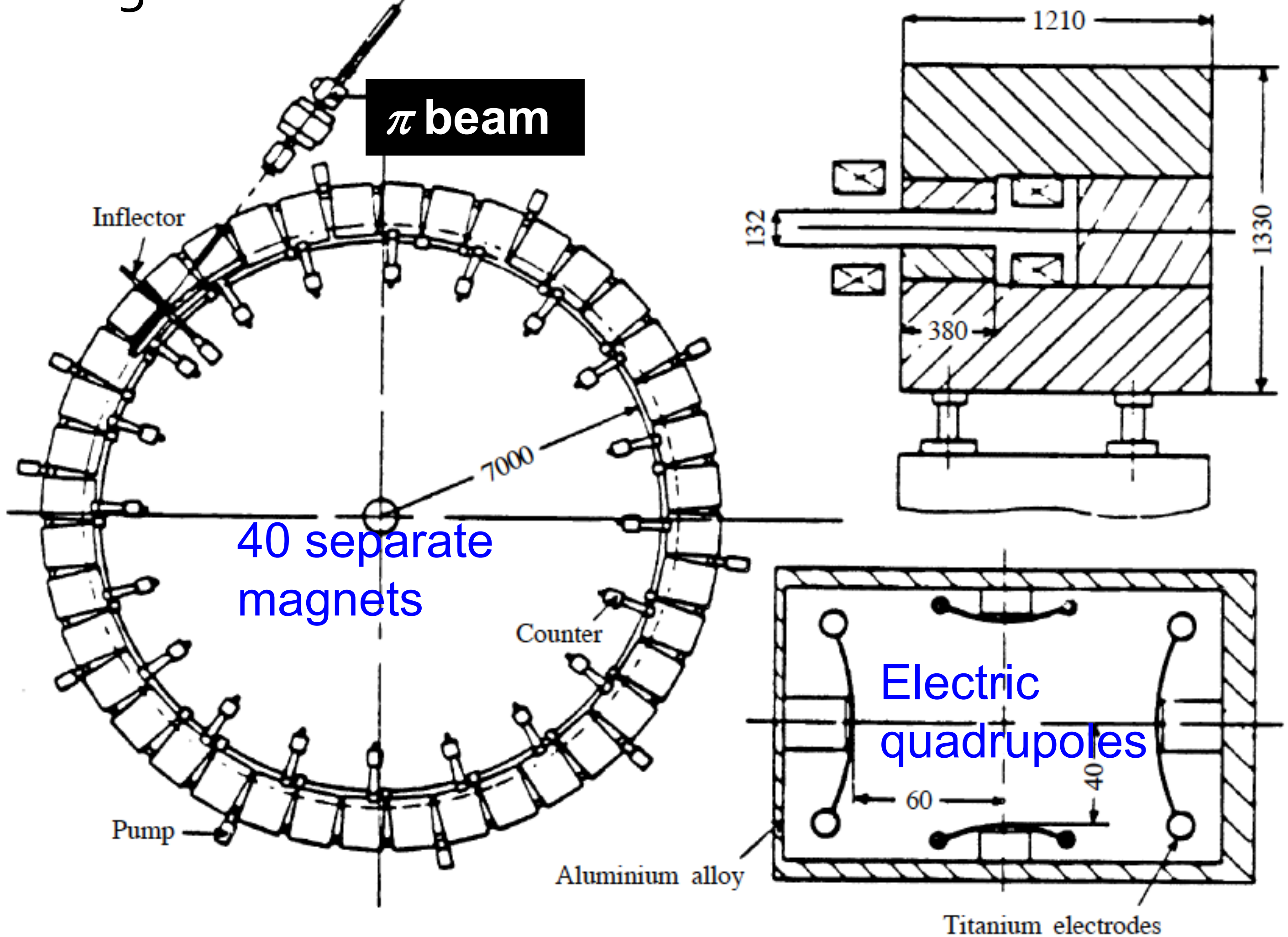
If we choose $\gamma = 29.3$ then coefficient vanishes! The MAGIC momentum!

So we can worry less about the electric field (but still will need corrections)

Had a_μ been, say 100x smaller, would need *p* ~ 30 GeV/c

CERN III, 1969-1976

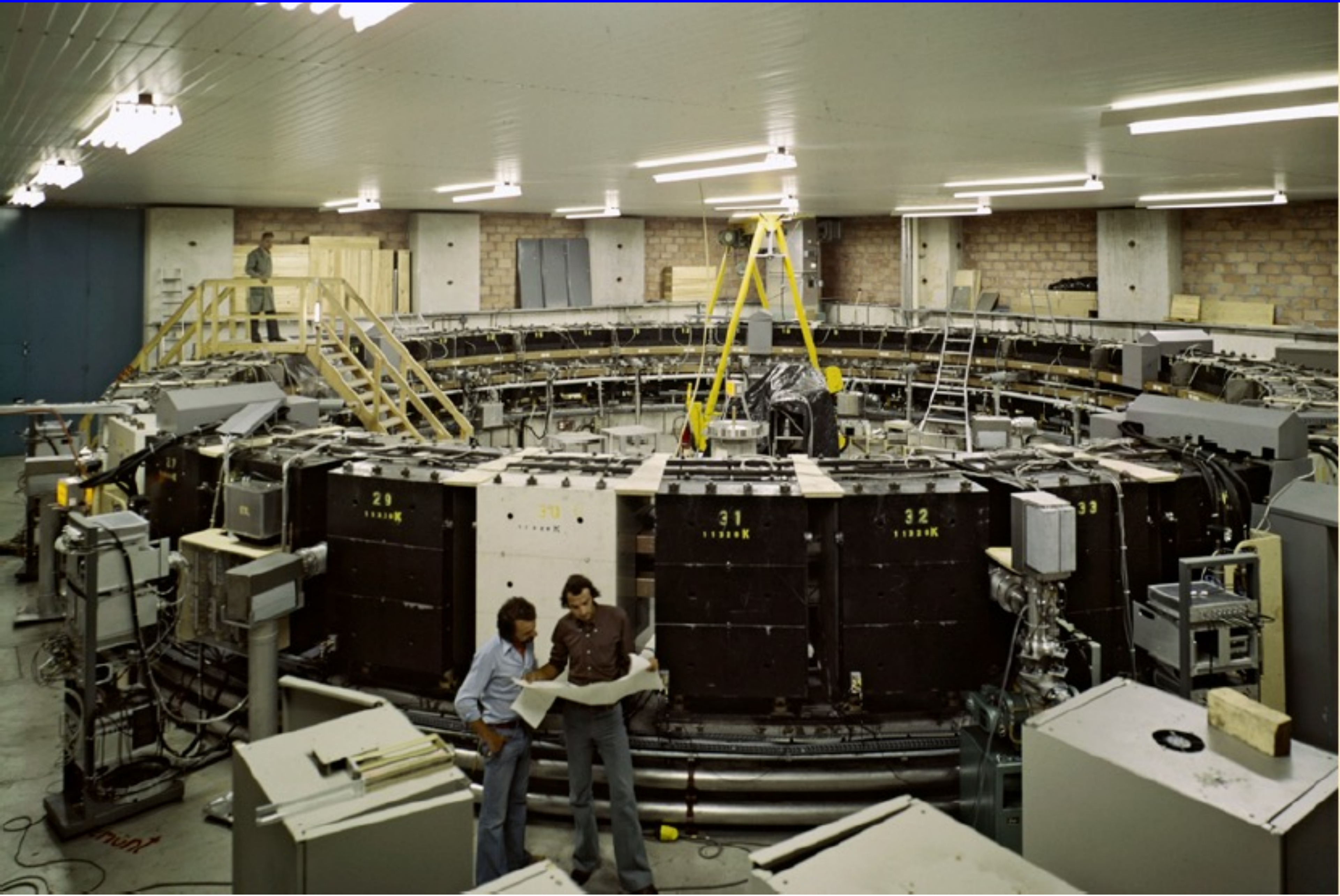
- Inject pions at 3.2 GeV Muon lifetime dilates to 64 μs
- Use $\pi \rightarrow \mu$ decay to kick muons onto stable orbits
- Magic momentum and Electric field for vertical focusing



Still have pion flash at injection!

Not as bad as for CERN2

3rd Muon g-2 experiment at Cern



CERN III, 1969-1976

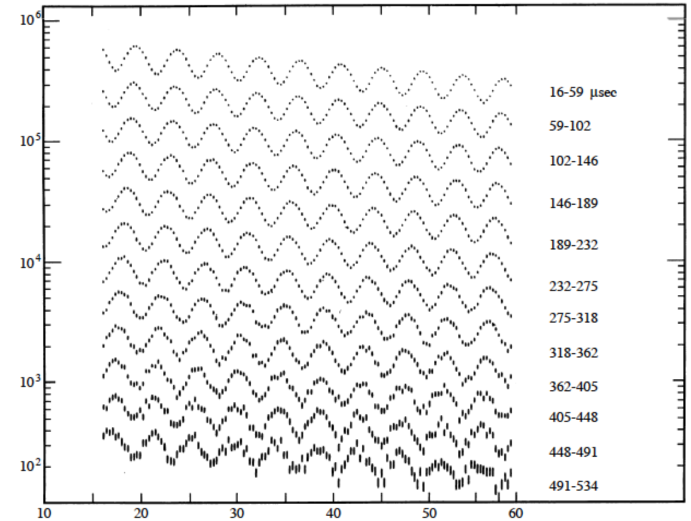
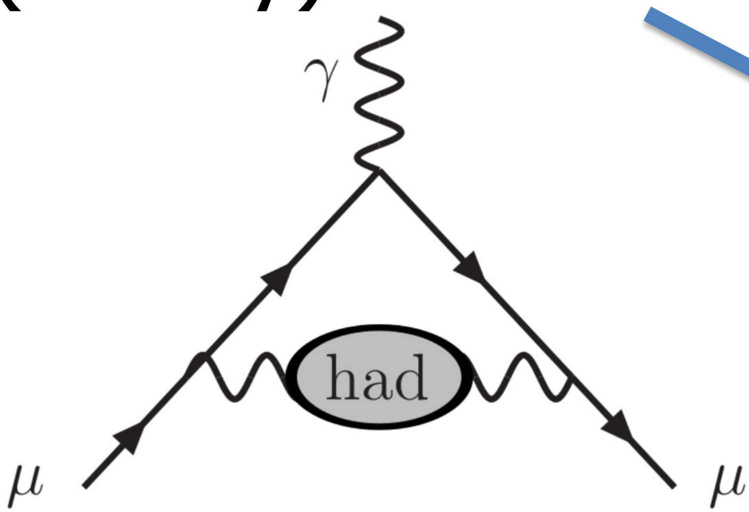


Fig. 25. The second muon storage ring: decay electron counts versus time (in microseconds) after injection. The range of time for each line is shown on the right (in microseconds).

a_μ(expt) = 0.00116592**4(9)** **(7.3 ppm)**

a_μ(theory) = 0.001165921**(13)**



HVP (hadronic vacuum polarization)

a_μ^{HAD} ~ 700^{-10} (~60 ppm)

https://link.springer.com/book/10.1007/978-3-319-63577-4

Setting the stage for Brookhaven E821

μ g–2 Muon g-2

In 1984 QED was calculated to fourth order

Hadronic uncertainties were greatly reduced

Time for new experiment at Brookhaven AGS at sub ppm

Improvements:

Much higher intensity

3 superconducting coils

Circular aperture

Inject muons into ring with inflector and kicker

In-situ B measurements with NMR probes

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)

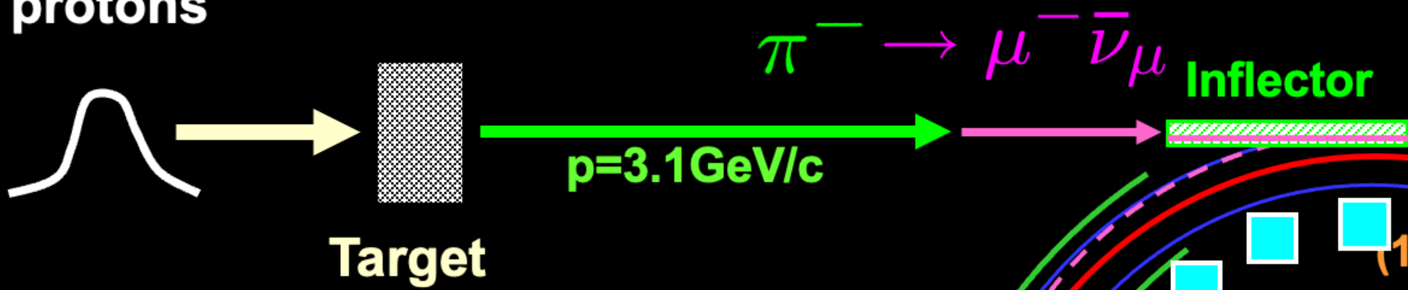
E821 Experimental Technique

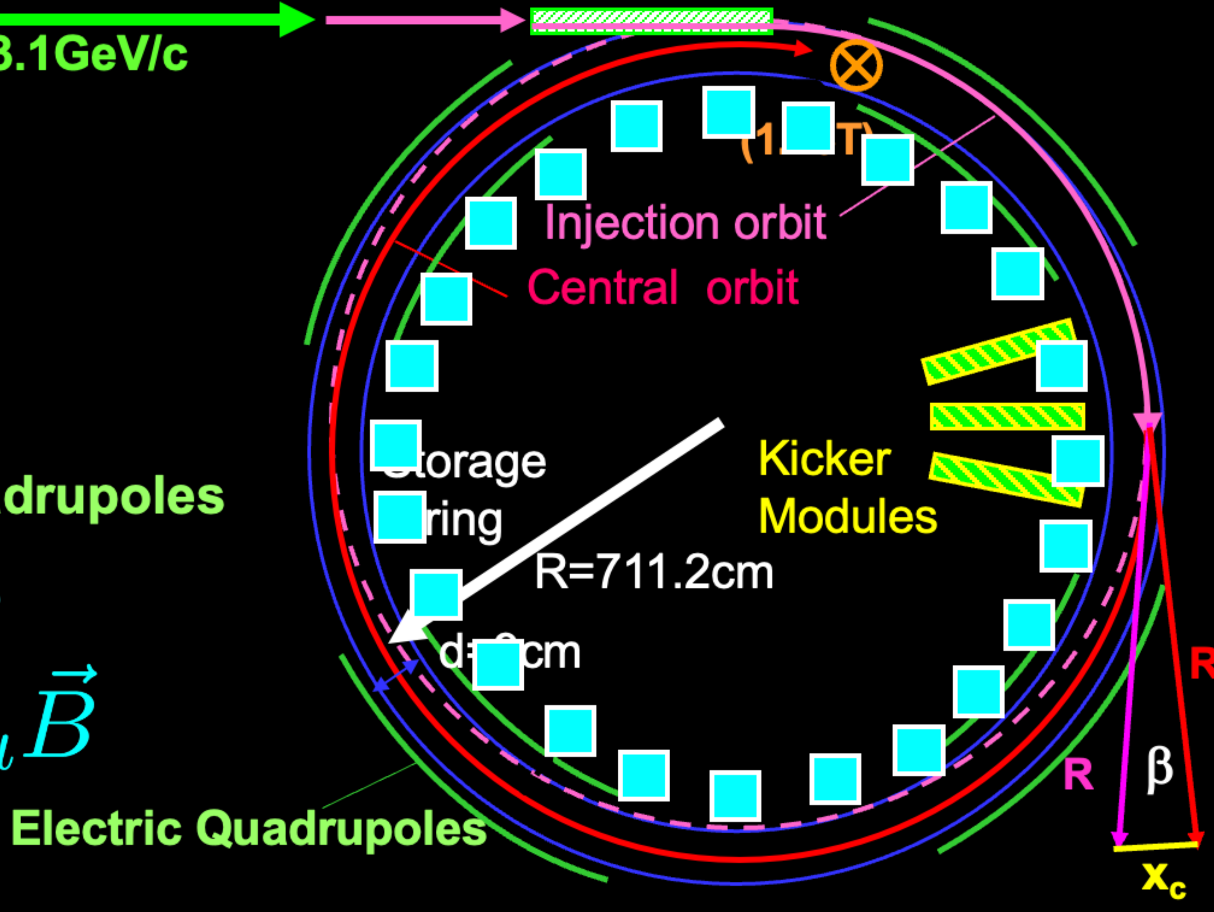
25ns bunch of $\geqslant$ 1 X 10^{12} protons

$x_c \approx 77$ mm

$\beta \approx 10$ mrad

$B \cdot dl \approx 0.1$ Tm

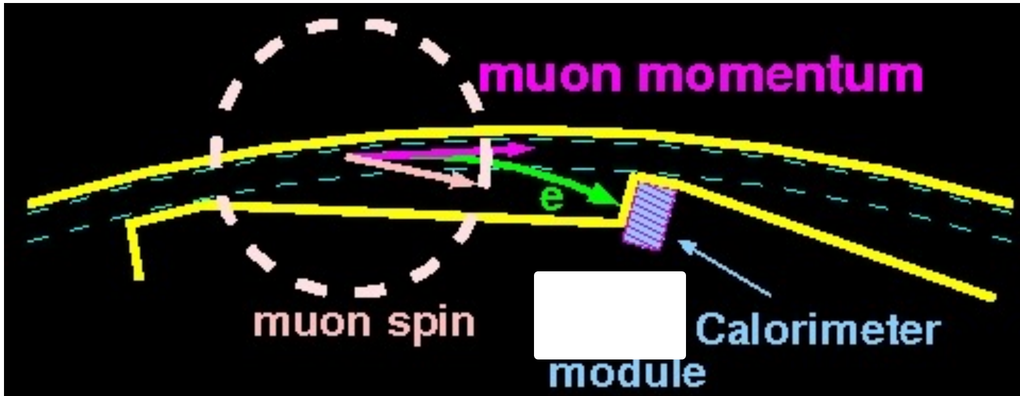




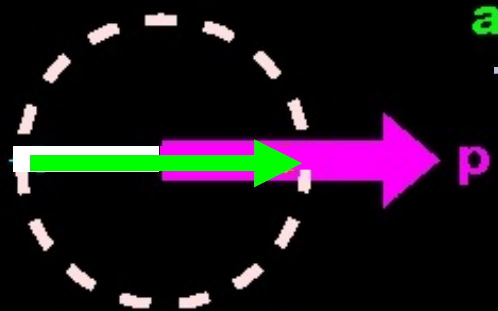
- Muon polarization
- Muon storage ring
- injection & kicking
- focus with Electric Quadrupoles
- 24 electron calorimeters

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

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

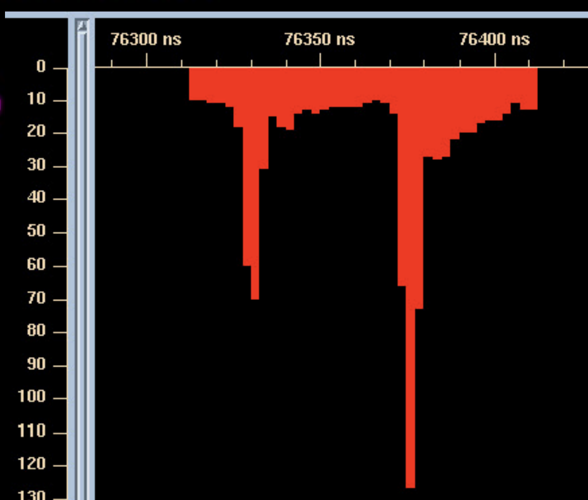


Measures Energy and time



spin forward, more high energy e

spin backward, less high energy e

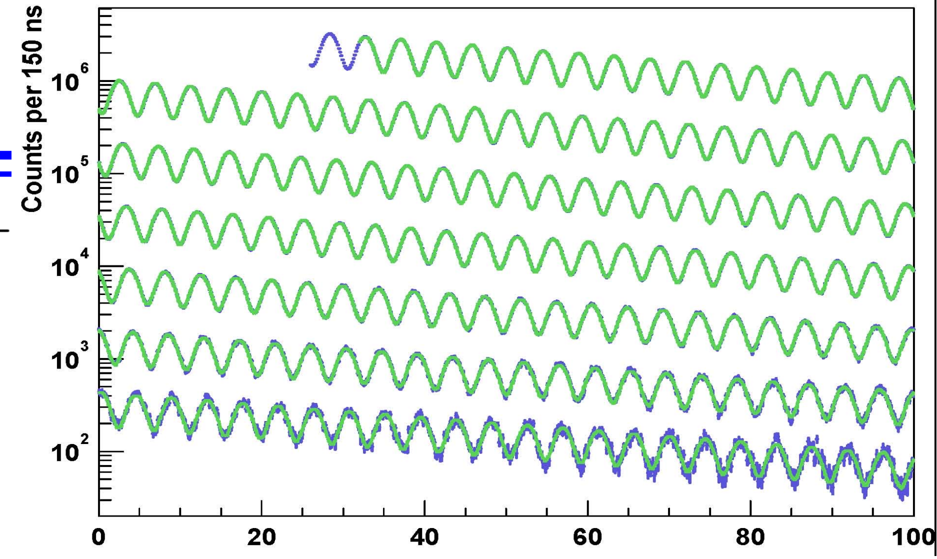


Waveform digitizer gives t, E

Picture of a Lead-Scifi Calorimeter from E821

E821, 1984-2001

$3.6 \times 10^9\ e^-$



(2006)

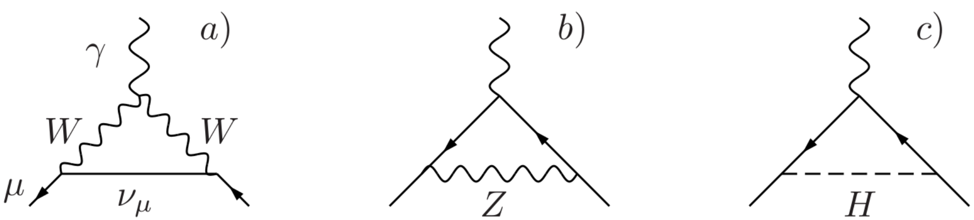
a_μ(expt) = 0.00116592089(63) **(0.54 ppm)**

a_μ(theory) = 0.00116591820(73)

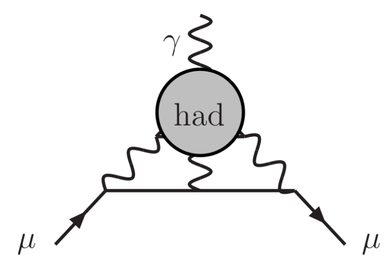
(HMNT 03)

EW

Hadronic light-by-light



$a_\mu^{EW} \sim 15.3^{-10}$ (~1.3 ppm)

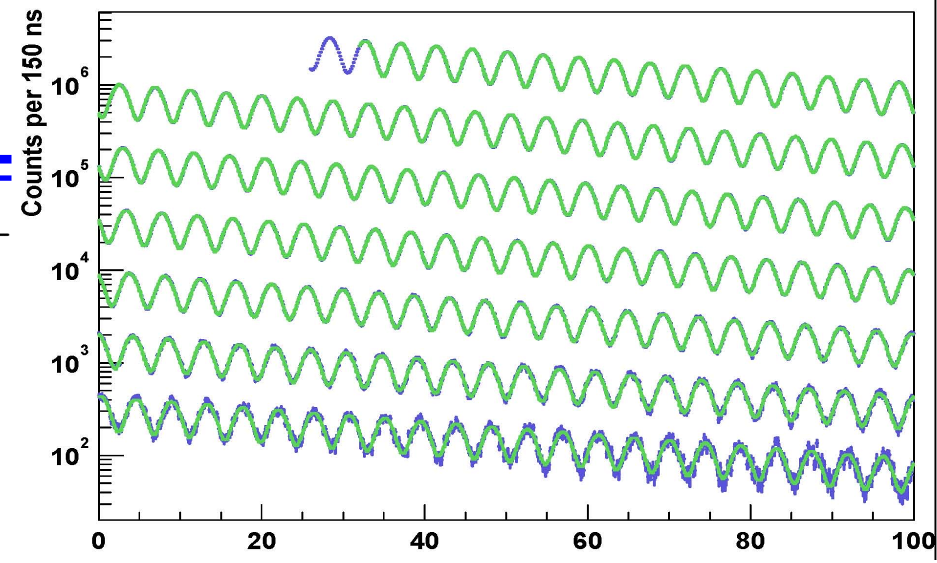


$a_\mu^{HLbL} \sim 9.2^{-10}$ (~0.8 ppm)

https://link.springer.com/book/10.1007/978-3-319-63577-4

E821, 1984-2001

$3.6 \times 10^9\ e^-$

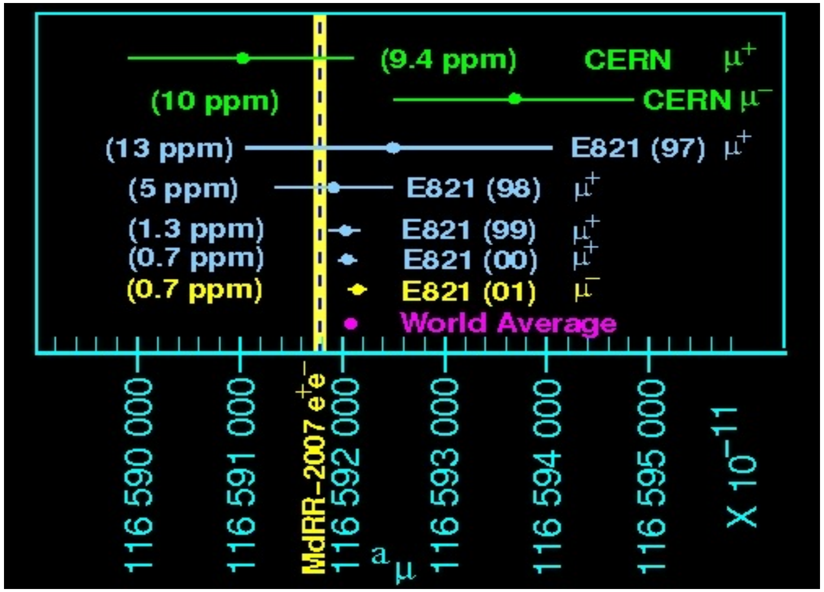


$$a_\mu(\text{expt})^{(2006)} = 0.0011659208\mathbf{9(63)} \quad \mathbf{(0.54\ ppm)}$$

$$a_\mu(\text{theory})_{(\text{HMNT } 03)} = 0.0011659182\mathbf{0(73)}$$

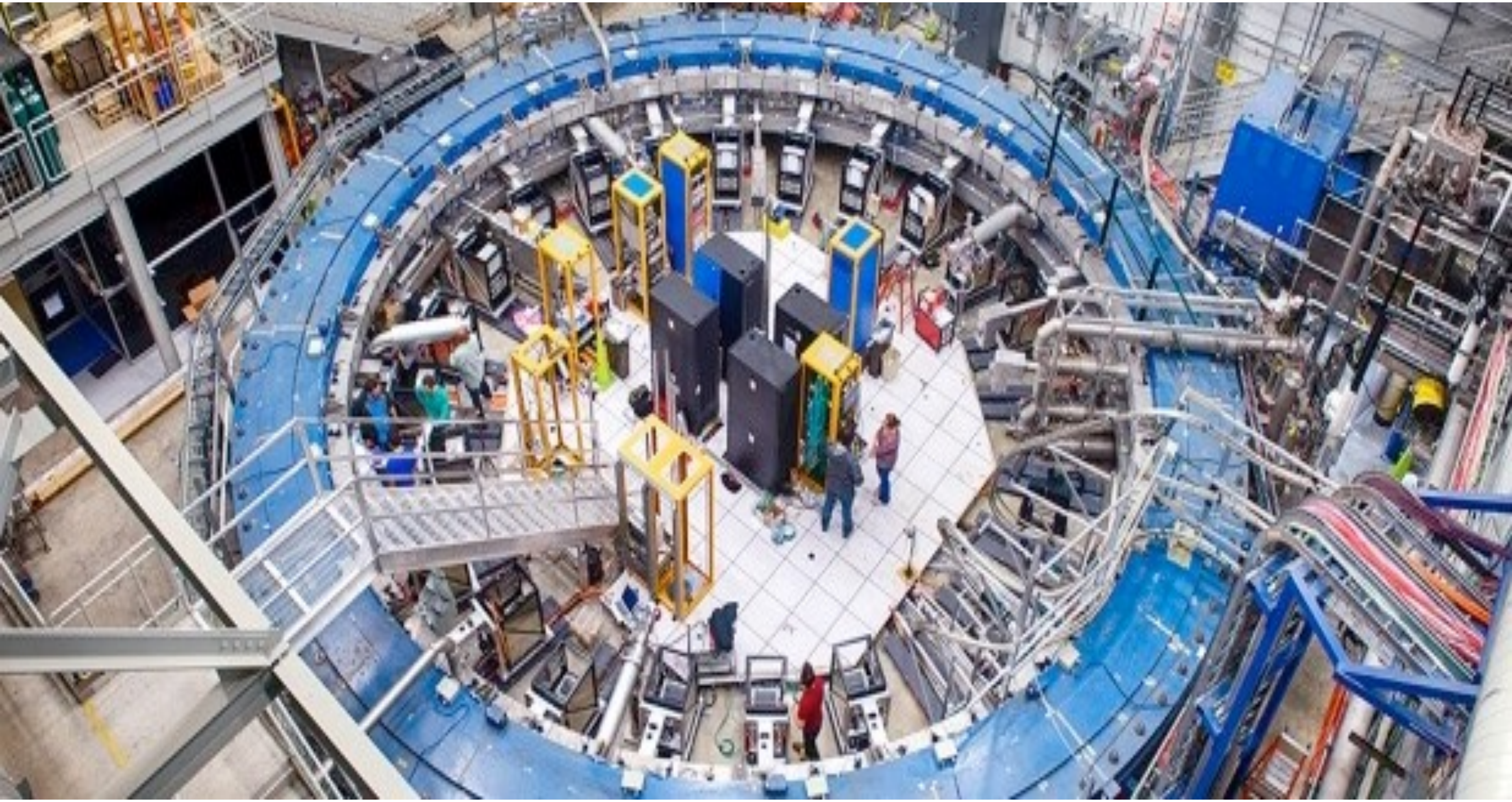
$$a_\mu^{BNL} - a_\mu^{SM} =$$
$$= (279 \pm 76)\times 10^{-11}\ (3.7\sigma)$$

~3 "standard deviations" with SM
→ Hint of new physics?



Muon g-2 Storage Ring at Femilab (2009 - present)

Muon g-2



4 key elements for E989 at FNAL

- Consolidated method (same ring of the BNL experiment)
- More muons (x20)
- Improved beam and detector → Reduced systematics
- New crew → new ideas

- **E821 at Brookhaven**

$$\left.\begin{aligned}\sigma_{stat} &= \pm 0.46 \text{ ppm} \\ \sigma_{syst} &= \pm 0.28 \text{ ppm}\end{aligned}\right\} \sigma = \pm 0.54 \text{ ppm}$$

↳ $0.2\omega_a \oplus 0.17\omega_p$

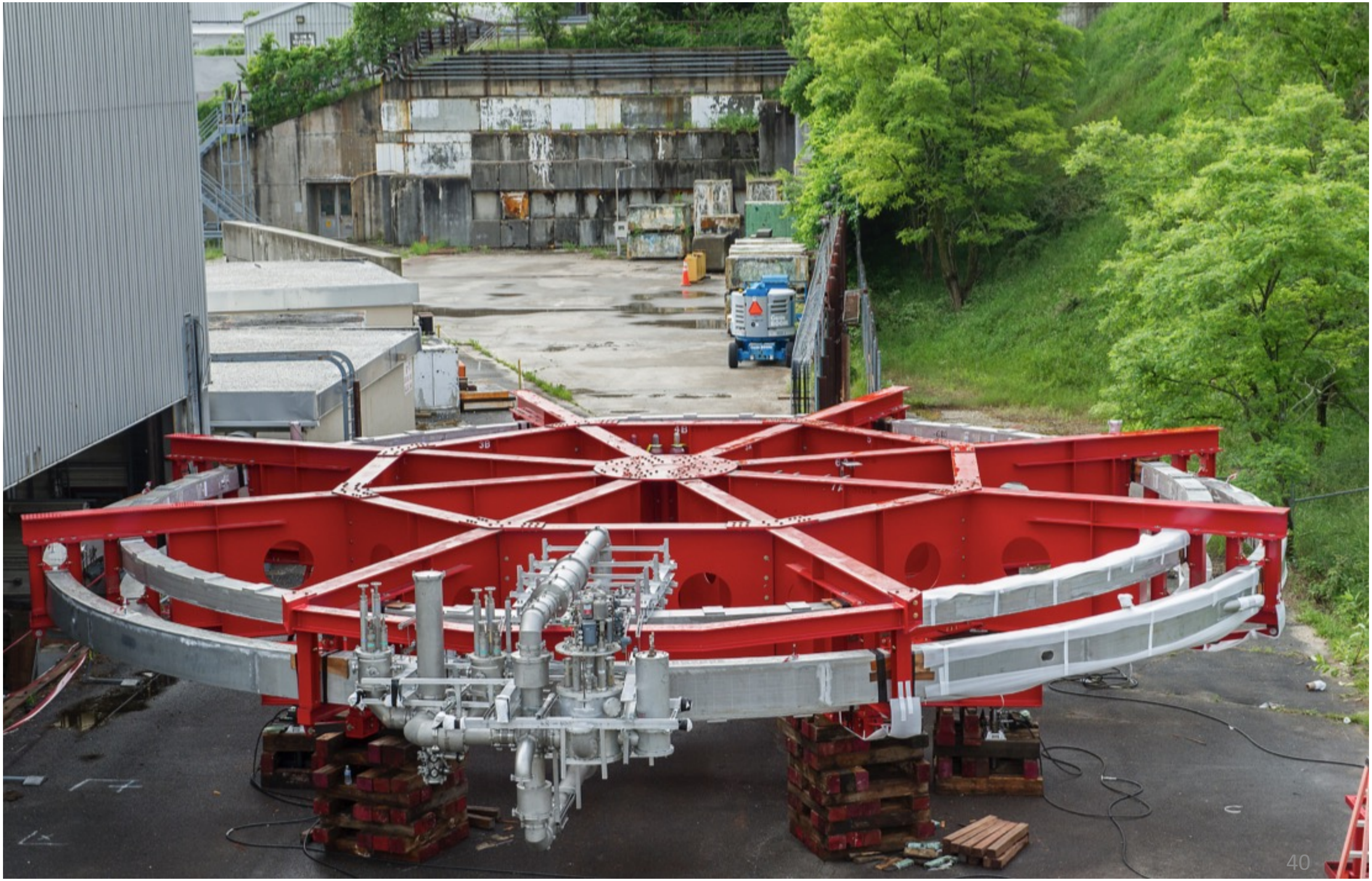
- **E989 at Fermilab**

$$\left.\begin{aligned}\sigma_{stat} &= \pm 0.1 \text{ ppm} \\ \sigma_{syst} &= \pm 0.1 \text{ ppm}\end{aligned}\right\} \sigma = \pm 0.14 \text{ ppm}$$

$0.07\omega_a \oplus 0.07\omega_p$

June 2013: The ring leaves from BNL

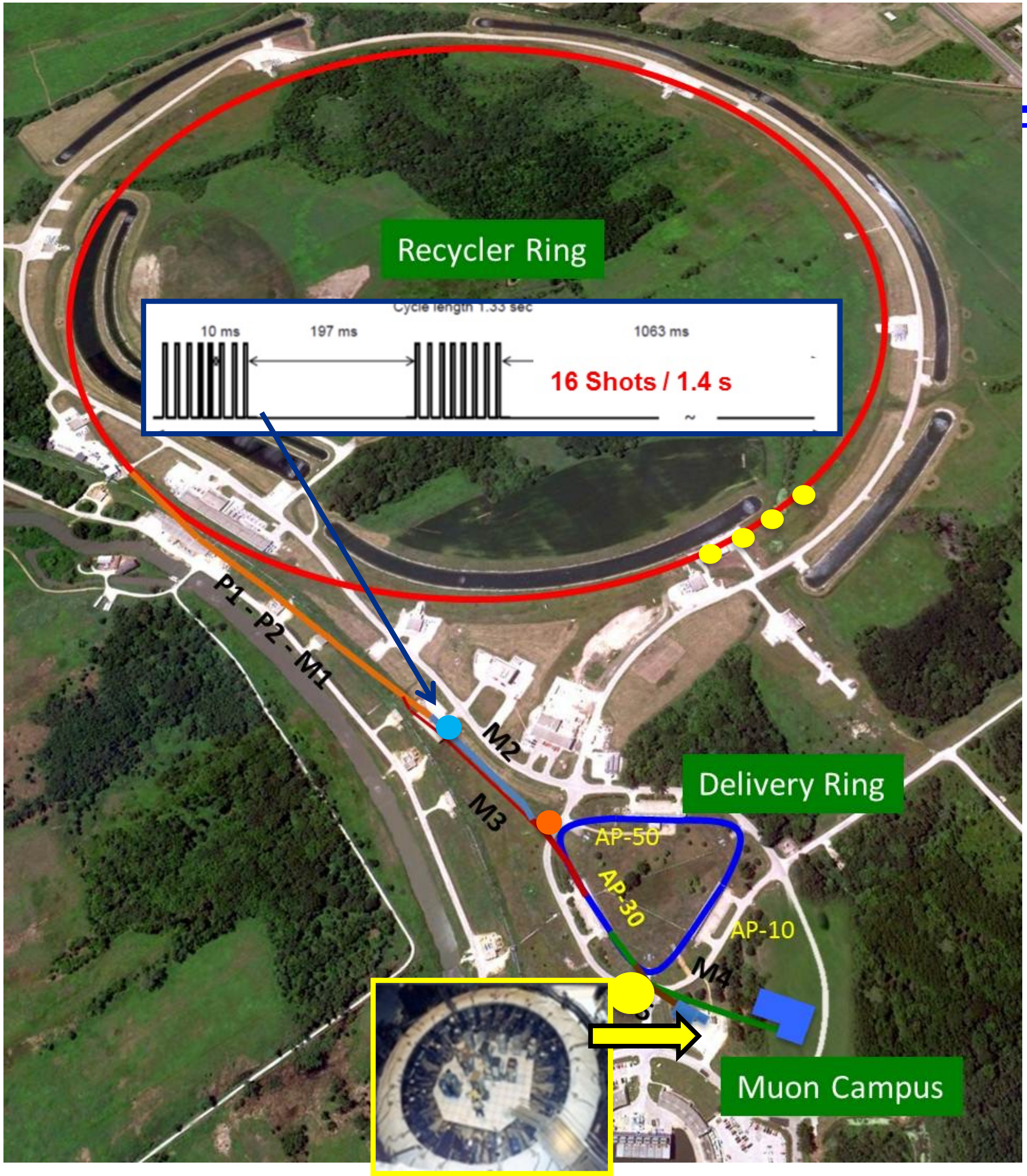
Muon g-2



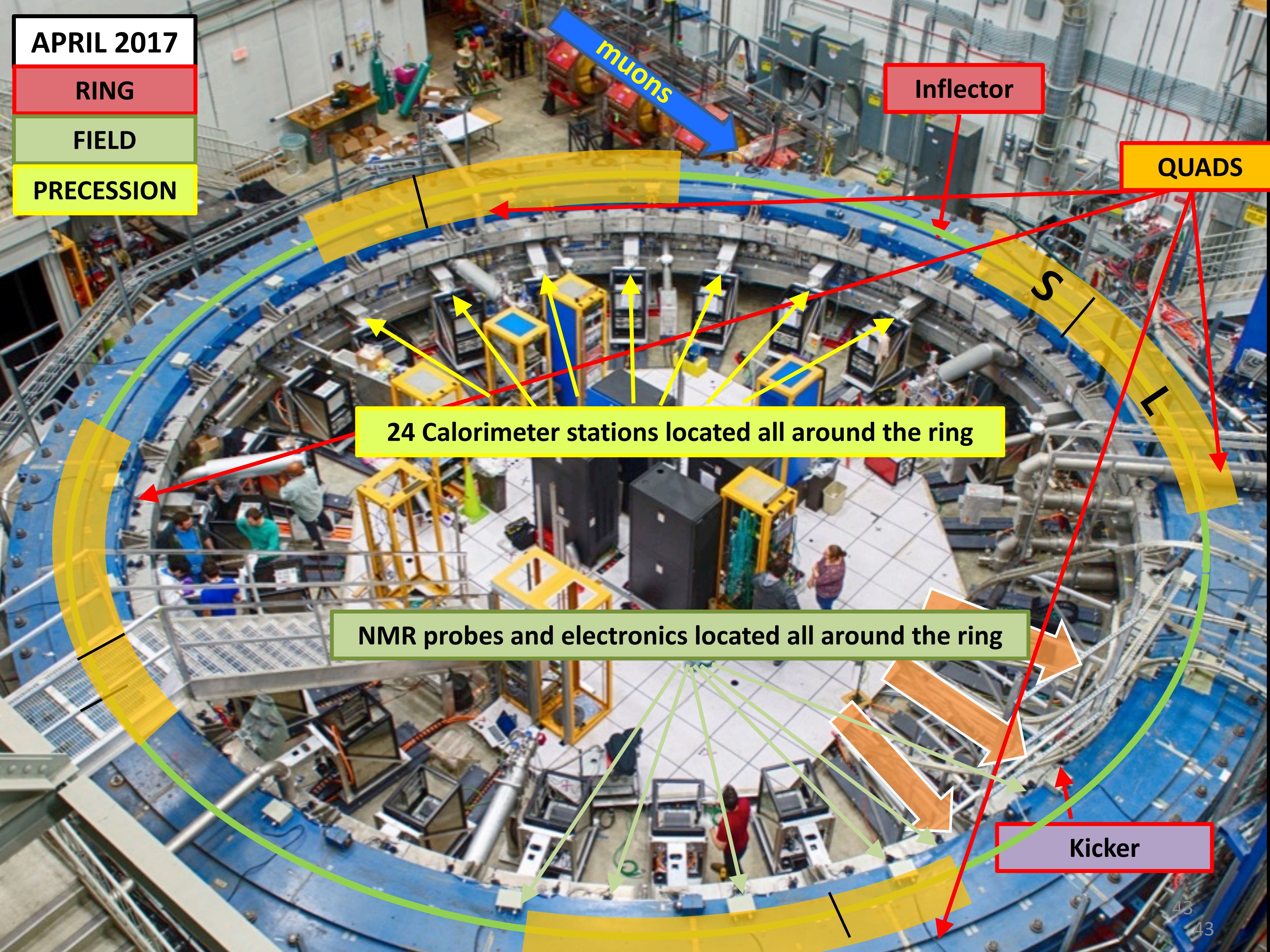
The magnet reassembled and powered in Fermilab

Muon g-2

Creating the Muon Beam for g-2

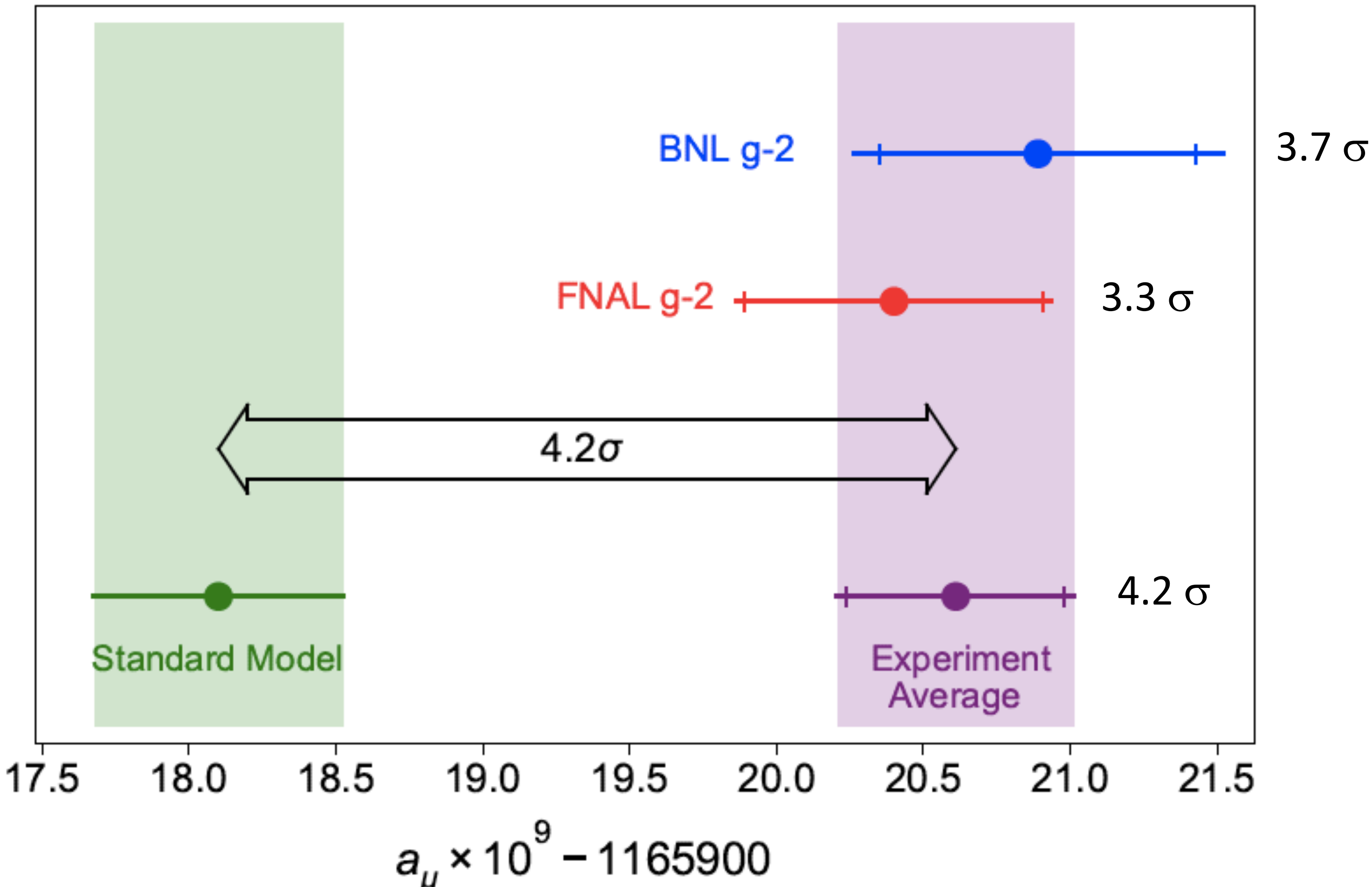


- 8 GeV p batch into Recycler
- Split into 4 bunches
- Extract 1 by 1 to strike target
- Long FODO channel to collect $\pi \rightarrow \mu\nu$
- $p/\pi/\mu$ beam enters DR; protons kicked out; π decay away
- μ enter storage ring


APRIL 2017
RING
FIELD
PRECESSION
muons
Inflector
QUADS
S
L
24 Calorimeter stations located all around the ring
NMR probes and electronics located all around the ring
Kicker

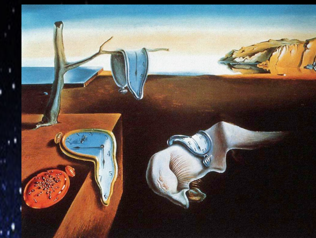
Result

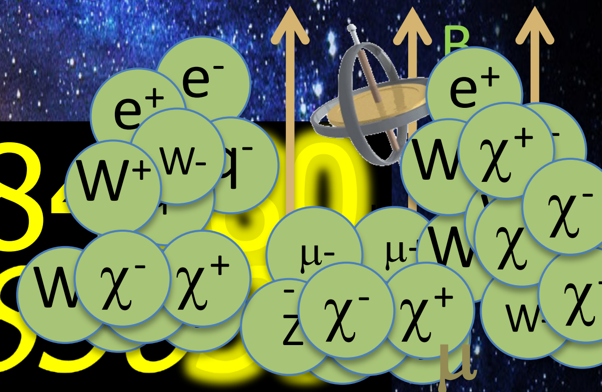
$$a_\mu(\text{Exp}) = 116\,592\,061(41) \times 10^{-11} \quad (0.35\,\text{ppm})$$



$$a_\mu(\text{Exp}) - a_\mu(\text{SM}) = (251 \pm 59) \times 10^{-11}$$

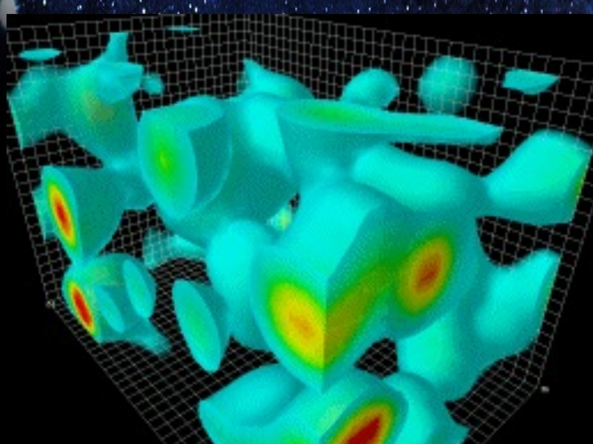
Are we seeing something new ?

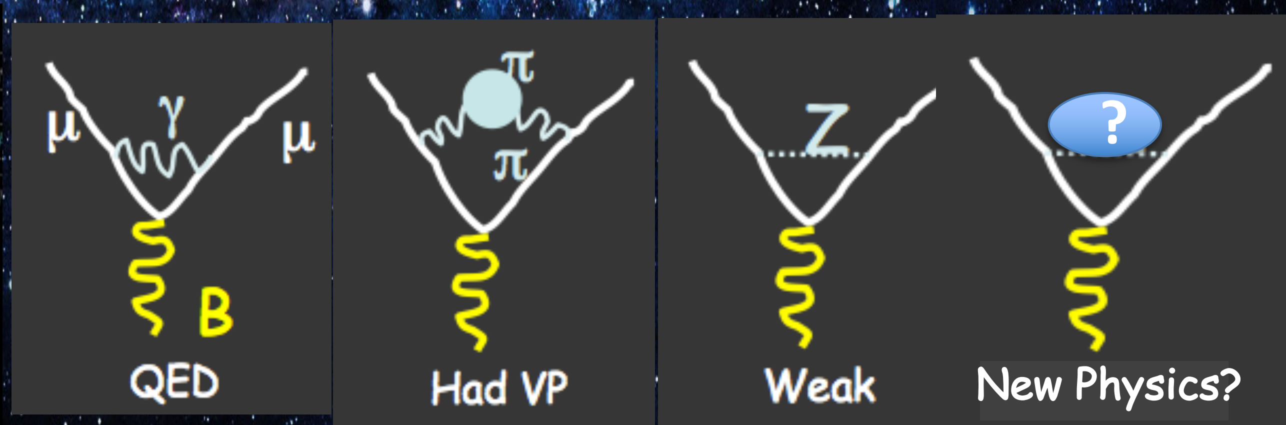




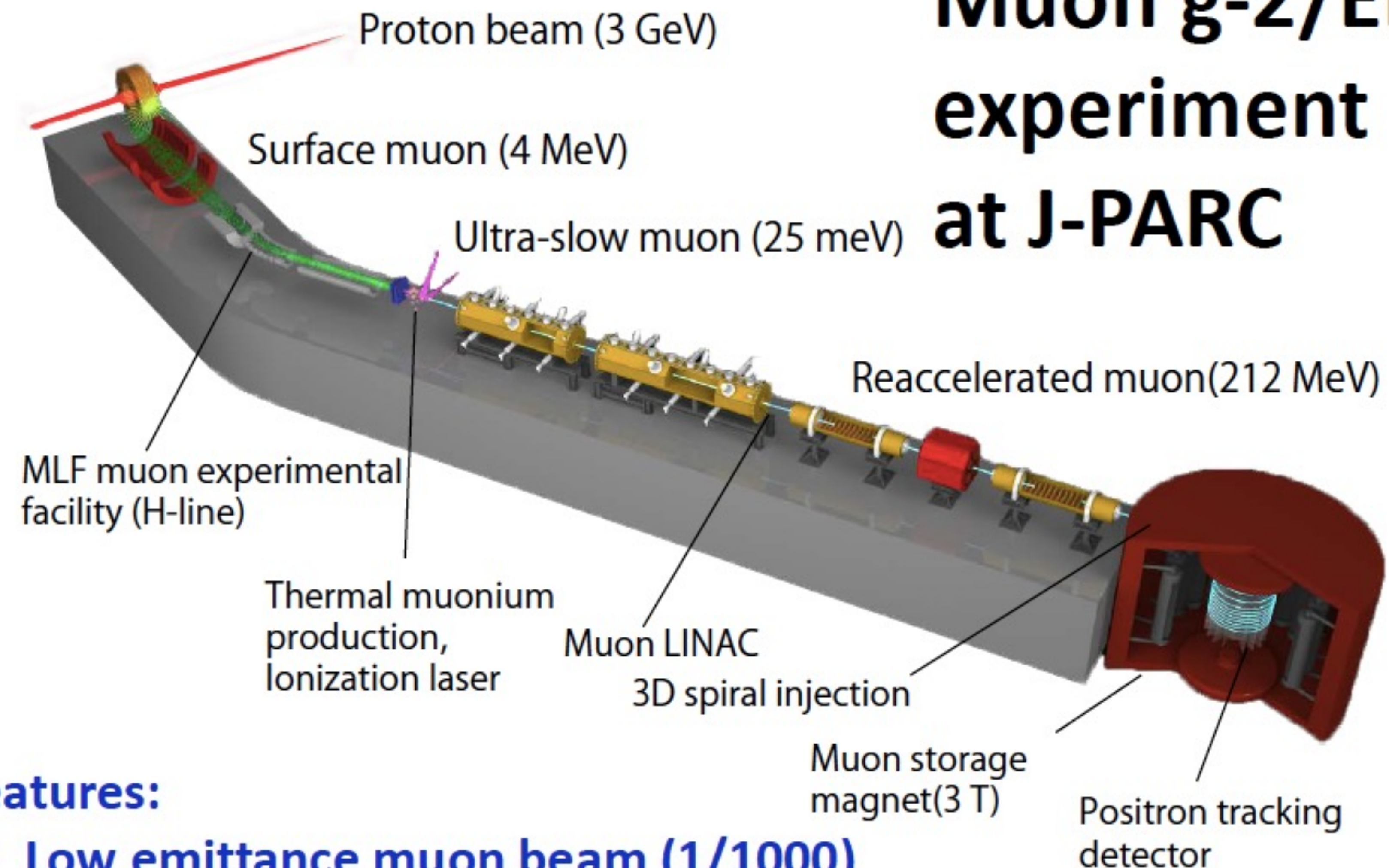
g(expt) 2.00233184

g(theory) *2.0023318*





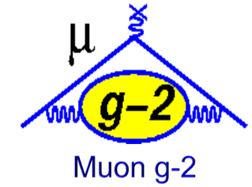
Muon g-2/EDM experiment at J-PARC



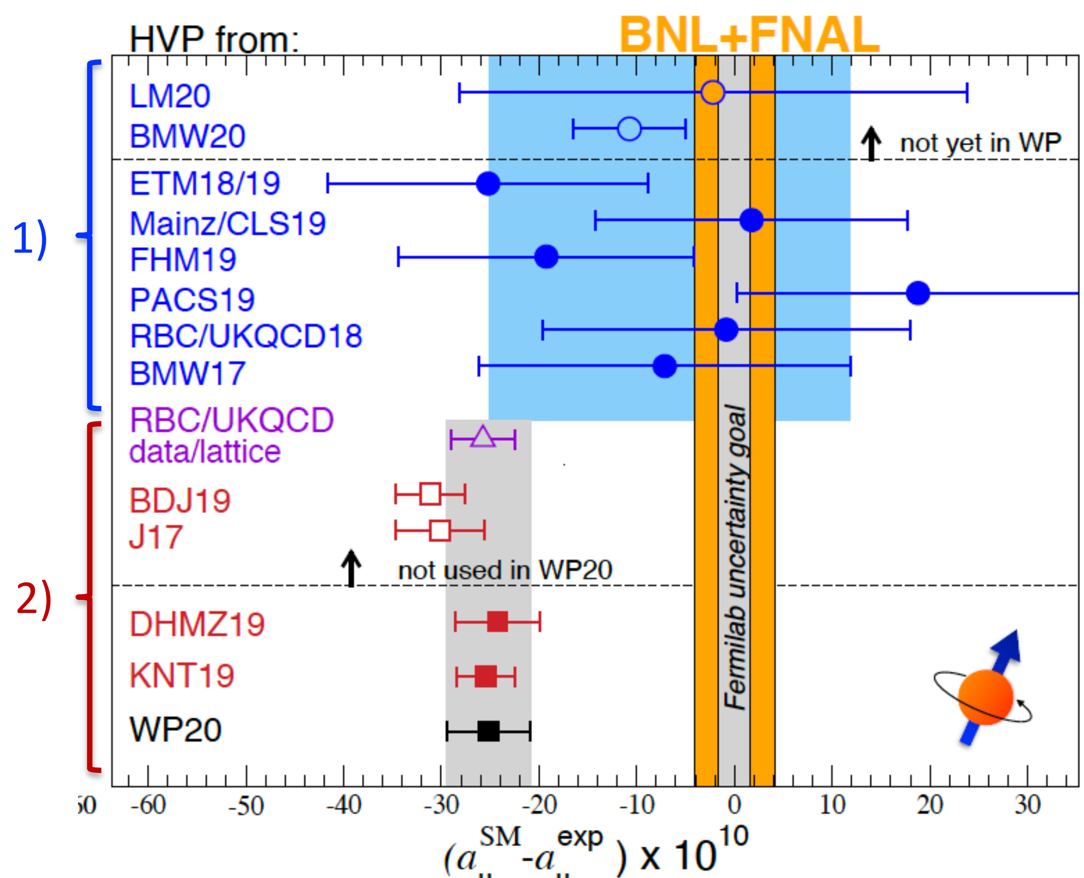
Features:

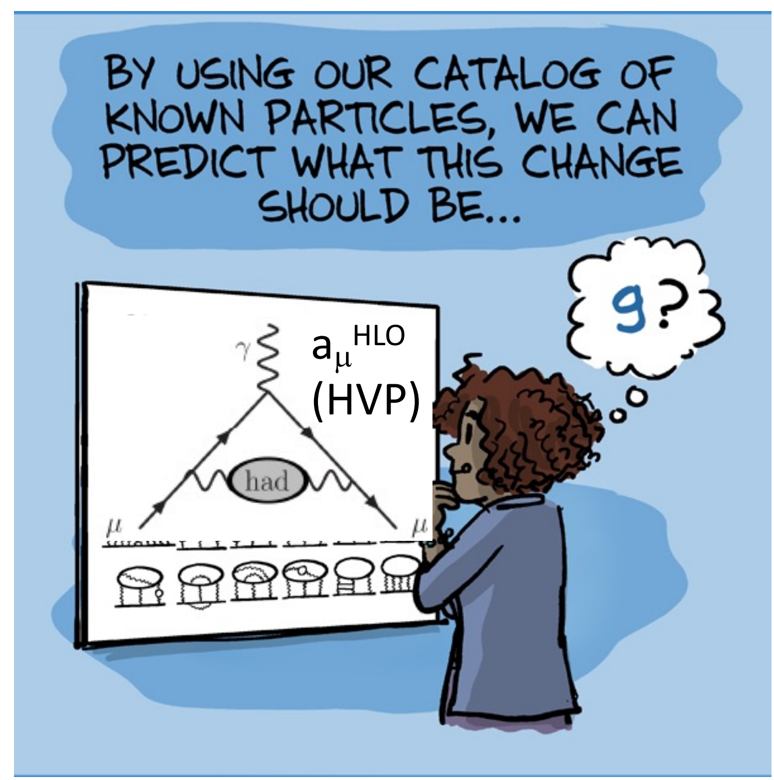
- **Low emittance muon beam (1/1000)**
- **No strong focusing (1/1000) & good injection eff. (x10)**
- **Compact storage ring (1/20)**
- **Tracking detector with large acceptance**
- **Completely different from BNL/FNAL method**

Is the SM calculation "correct"?

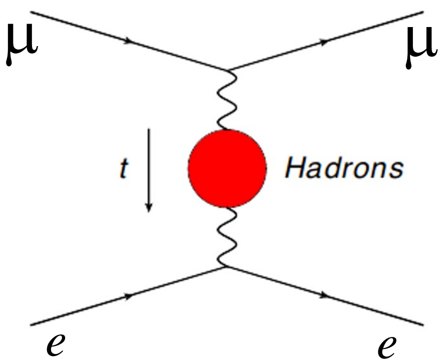


- The contribution from the strong interaction (Hadronic Vacuum Polarization, **HVP**) is challenging
- Tension between two different methods: 1) "lattice calculation"; 2) "dispersive approach"
- Ongoing work to clarify the tension

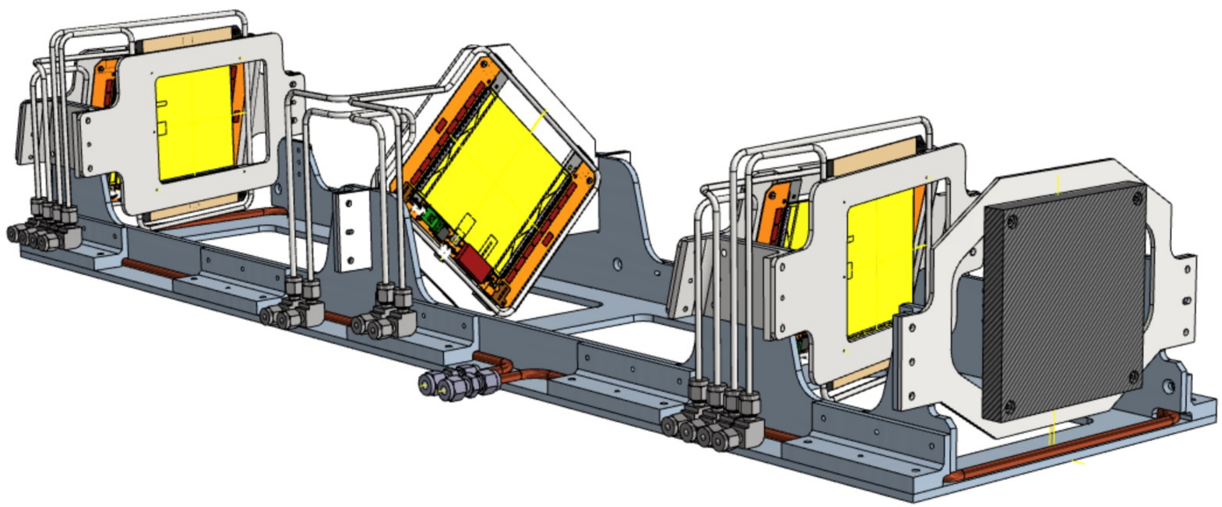




A "novel" way for HVP…MUonE experiment at CERN



μe → μe



Alternative (competitive) measurement of HVP for a_μ

-*C. M. Carloni Calame et al PLB 746 (2015) 325*

-*G. Abbiendi et al Eur.Phys.J.C* 77 (2017) 3, 139

-LoI https://cds.cern.ch/record/2677471/files/SPSC-I-252.pdf

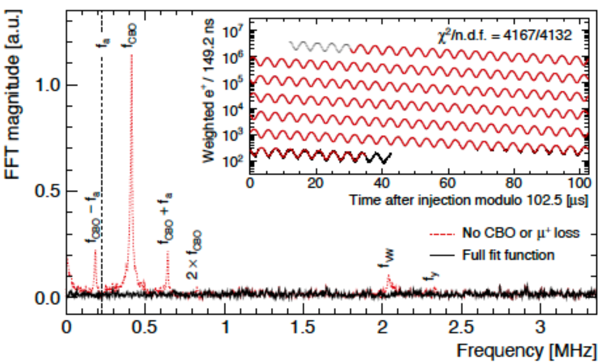
UK & Italian (INFN) contribution on g-2: **Experiment**

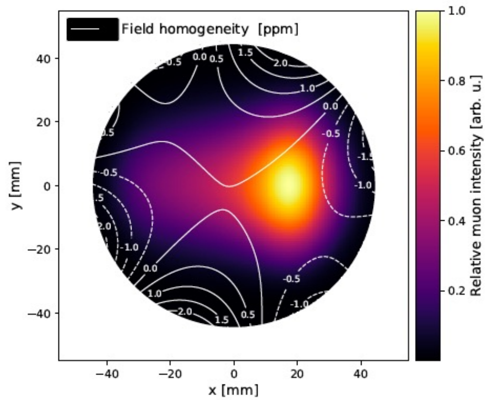
Muon g-2

- Straw tracking detector (UK) and laser calibration system (INFN)
- Management roles (Mark Lancaster and G.V. co-spokes); Ops managers, Run coordinators; Detector responsibility; Analysis conveners
- Analysis roles: Precession frequency ("Omega_a" Europa team); magnetic field; Beam dynamics; Search for Electric Dipole Moments
- DAQ, Offline/data reconstruction
- Data taking

Tracking detector modules installed in the storage ring vacuum chamber

Laser calibration system



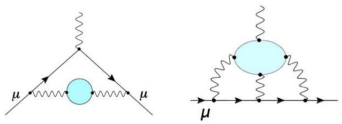


UK & Italian (INFN) contribution on g-2: **Theory**

Muon g-2

- A > 20 years **common** activity on the evaluation of the Muon g-2 (>1000 citations)
- Evaluation of HVP and Radiative corrections in e+ e- data
- Participation to Working groups

Muon g-2 Theory Initiative



RADIO MONTECARLOW

STRONG 2020

ELSEVIER

Physics Reports
Volume 887, 3 December 2020, Pages 1-166

The anomalous magnetic moment of the muon in the Standard Model

T. Aoyama [1, 2, 3], N. Asmussen [4], M. Benayoun [5], J. Bijnens [6], T. Blum [7, 8], M. Bruno [9], I. Caprini [10], C.M. Carloni Calame [11], M. Cè [9, 12, 13], G. Colangelo [14], F. Curciarello [15, 16], H. Czyż [17], I. Danilkin [12], M. Davier [18], C.T.H. Davies [19], M. Della Morte [20], S.I. Eidelman [21, 22], A.X. El-Khadra [23, 24] … A.S. Zhevlakov [78]

Show more

Review | Published: 23 February 2010

Quest for precision in hadronic cross sections at low energy: Monte Carlo tools vs. experimental data

Working Group on Radiative Corrections and Monte Carlo Generators for Low Energies, S. Actis, A. Arbuzov, G. Balossini, P. Beltrame, C. Bignamini, R. Bonciani, C. M. Carloni Calame, V. Cherepanov, M. Czakon, H. Czyż, A. Denig, S. Eidelman, G. V. Fedotovich, A. Ferroglia, J. Gluza, A. Grzelińska, M. Gunia, A. Hafner, F. Ignatov, S. Jadach, F. Jegerlehner, A. Kalinowski, W. Kluge, … C. Z. Yuan

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The European Physical Journal C **66**, 585–686 (2010) | Cite this article

Springer Link

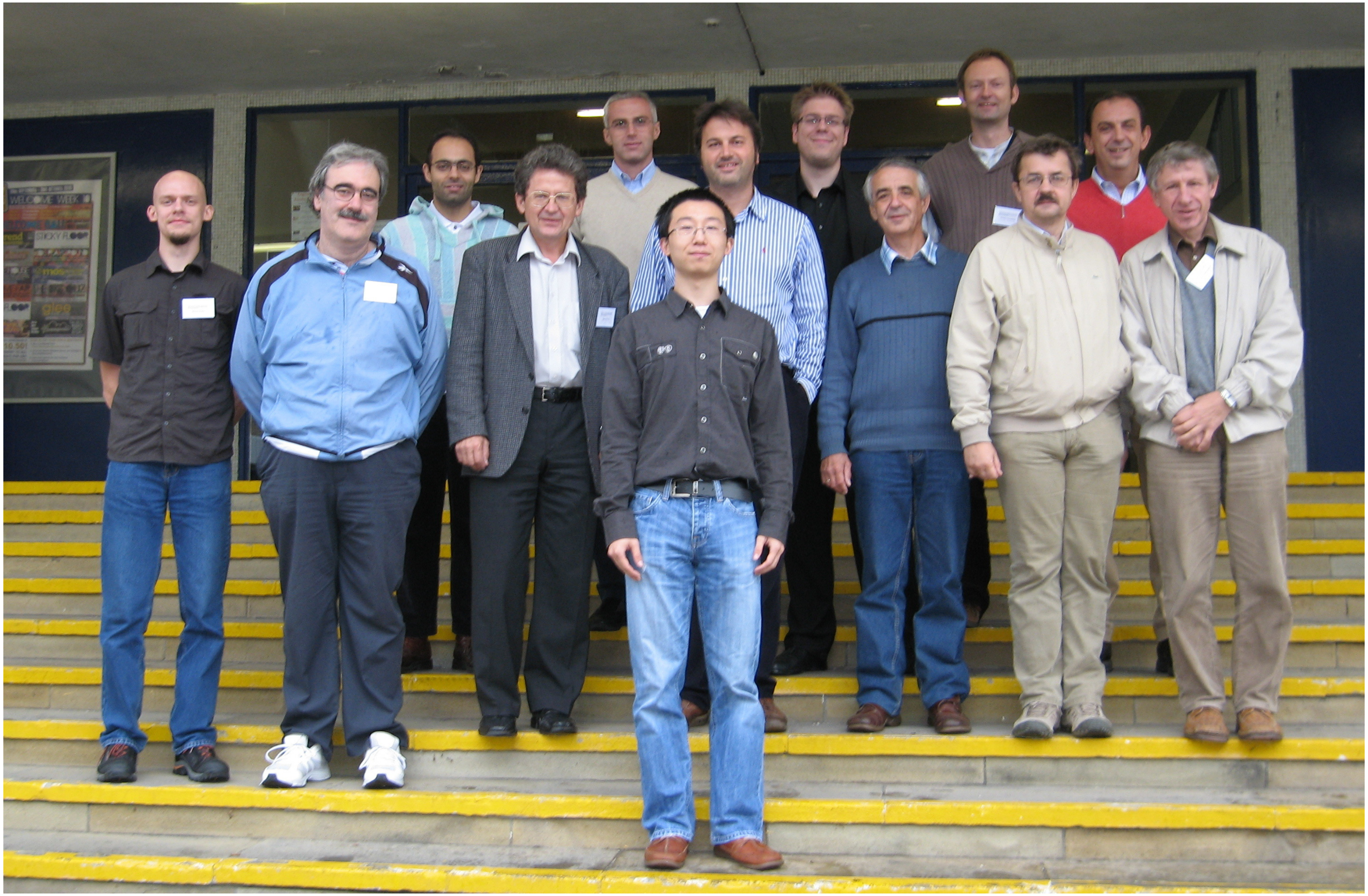
Regular Article - Experimental Physics | Open Access | Published: 28 March 2018

Combination of KLOE $\sigma(e^+e^- \to \pi^+\pi^-\gamma(\gamma))$ measurements and determination of $a_\mu^{\pi^+\pi^-}$ in the energy range $0.10 < s < 0.95$ GeV^2

The KLOE-2 collaboration, A. Anastasi, D. Babusci, M. Berlowski, C. Bloise, F. Bossi, P. Branchini, A. Budano, L. Caldeira Balkeståhl, B. Cao, F. Ceradini, P. Ciambrone, F. Curciarello, E. Czerwinski, G. D'Agostini, E. Danè, V. De Leo, E. De Lucia, A. De Santis, P. De Simone, A. Di Cicco, A. Di Domenico, D. Domenici, A. D'Uffizi, … T. Teubner + Show authors

Journal of High Energy Physics **2018**, Article number: 173 (2018) | Cite this article

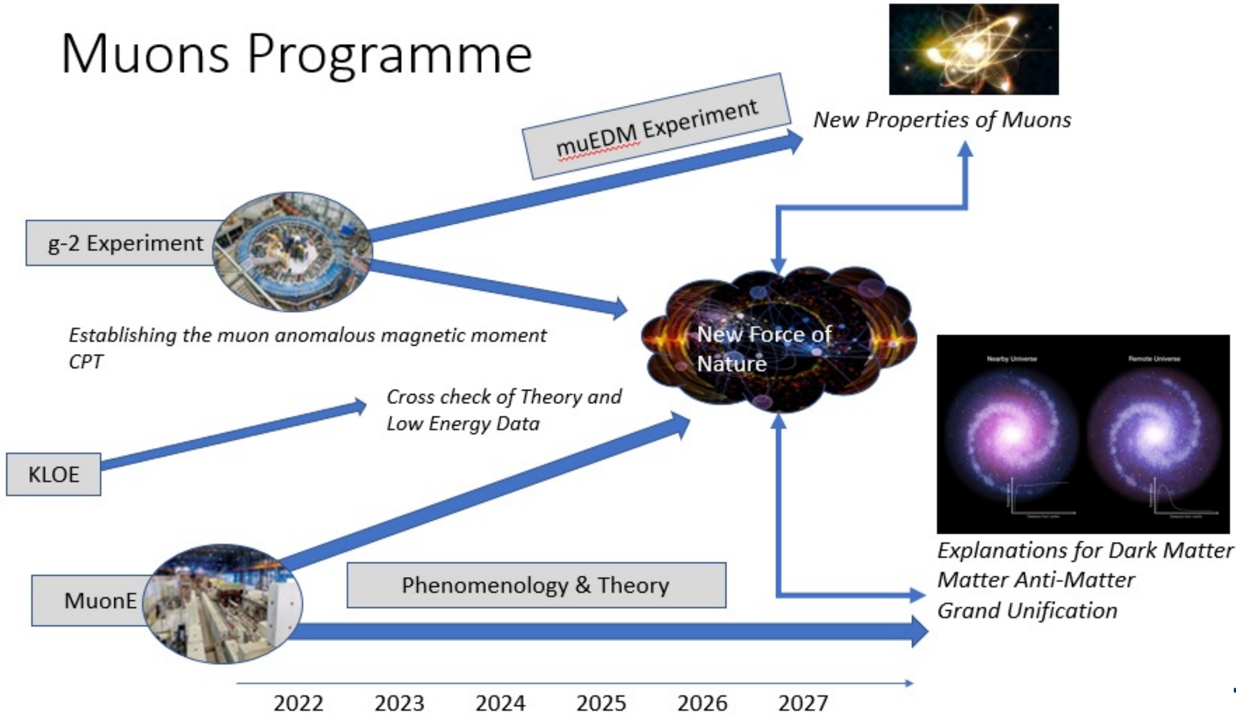
Meeting in Liverpool in 2010



8th Radio MonteCarLow WG meeting, http://agenda.infn.it/conferenceDisplay.py?confId=2770

The "Muon Precision Physics Program"

Muon g-2



LEVERHULME TRUST

- 5 years grant funded by the **Leverhulme Trust**
- Rich Experimental and Theory program (dipole moments, Flavour violation decay)
- Built on the experience and synergy of UK and INFN groups
- Advance on technological aspects
- Mentoring and training of students and early-career researchers
- An unique opportunity to advance this exciting field!

UNIVERSITY OF LIVERPOOL

INFN Istituto Nazionale di Fisica Nucleare

Today (7th November)

Muon g-2

	History of the Muon g-2 experiment and the Muon Precision Physics Program *The Spine*	*Graziano Venanzoni* 14:30 - 15:00
15:00	**Muon Precision physics: the technological prospects** *The Spine*	*Gianluigi Casse* 15:00 - 15:30
	Coffee Break *The Spine*	15:30 - 15:50
16:00	**Muon Program at Fermilab** *The Spine*	*Brendan Casey* 15:50 - 16:20
	Anomalies with muons at LHCB *The Spine*	*Niels Tuning* 16:20 - 16:50
17:00	**The Precision frontier of particle physics** *The Spine*	*Antonio Masiero* 16:50 - 17:20

Tuesday 8th November: HVP

Muon g-2

09:00	**Status of the MUonE experiment** *The Spine*	*Umberto Marconi*	09:00 - 09:20
	MUonE Theory *The Spine*	*Carlo Michel Carloni Calame*	09:20 - 09:40
	Extraction of Dalpha *The Spine*	*Giovanni Abbiendi*	09:40 - 10:00
10:00	**Software for MUonE** *The Spine*	*Marcin Kucharczyk*	10:00 - 10:20
	Coffee Break *The Spine*		10:20 - 10:40
	Results on October Test Beam & Activity on MUonE at IC *The Spine*	*Geoff Hall et al.*	10:40 - 11:05
11:00	**Activity on MUonE in Pisa** *The Spine*	*Anna Driutti*	11:05 - 11:25
	Activity on MUonE in Perugia *The Spine*	*Matteo Magherini*	11:25 - 11:45
12:00	**Activity on MUonE in Liverpool and discussion on common activity and plans on MUonE** *The Spine*	*Themis Bowcock*	11:45 - 12:25

HVP MUonE

	HVP from Lattice *The Spine*	*Christoph Lehner*	13:30 - 13:55
14:00	**HVP dispersive approach** *The Spine*	*Alex Keshavarzi*	13:55 - 14:20
	Status of e+e- data from energy scan *The Spine*	*Fedor Ignatov*	14:20 - 14:40
	Status of e+e- data from ISR *The Spine*	*Riccardo Alberti*	14:40 - 15:00
15:00	**Strong2020 activity** *The Spine*	*Alberto Lusiani*	15:00 - 15:15
	Coffee Break *The Spine*		15:15 - 15:35
	KLOE data and prospects with 1.7 fb-1 *The Spine*	*Stefan Mueller*	15:35 - 15:55
16:00	**Status of Phokhara, what is missing for NNLO?** *The Spine*	*Henryk Czyz*	15:55 - 16:15
	Activity on HVP e+e- in Uppsala/Warsaw *The Spine*	*Andrzej Kupsc*	16:15 - 16:35
	Activity on HVP e+e- in Liverpool *The Spine*	*Thomas Teubner*	16:35 - 16:55
17:00	**Status of Strong2020 Workstop in June 2023 at UZH** *The Spine*	*Adrian Signer*	16:55 - 17:10
	Discussion on common activity and plans on HVP e+e- *The Spine*	*Graziano Venanzoni*	17:10 - 17:30

HVP "lattice" vs "dispersive" approach

Wednesday 9th November: dipole moments, LFV

Muon g-2

09:00	**Status of the Muon g-2 experiment with respect to Run2/3/4/5/6 analyses** *The Spine*	*Kevin Labe* 09:00 - 09:25
	Possible BSM explanation for the muon g-2 *The Spine*	*Peter Athron* 09:25 - 09:50
10:00	**Activity on g-2 in Italy** *The Spine*	*Lorenzo Cotrozzi* 09:50 - 10:10
	Activity on g-2 in UK *The Spine*	*Saskia Charity* 10:10 - 10:30
	Discussion on common activity and plans on g-2 *The Spine*	*Joe Price* 10:30 - 11:00
11:00	**Coffee Break** *The Spine*	11:00 - 11:20
	EDMs in BSM theory *The Spine*	*Maxim Pospelov* 11:20 - 11:45
12:00	**Status of experimental searches on EDM** *The Spine*	*Yannis Semertzidis* 11:45 - 12:10
	EDM activity at PSI *The Spine*	*Dr Philipp Schmidt-Wellenburg* 12:10 - 12:35

Muon Dipole Moments

Muon Lepton Flavour Violation decay

14:00	**muEDM studies at Fermilab** *The Spine*	*Aakaash Narayanan* 14:00 - 14:20
	Low energy muons delivery studies at Fermilab *The Spine*	*Steven Boi* 14:20 - 14:40
	EDM activity in Liverpool and possible plans *The Spine*	*Joe Price* 14:40 - 15:00
15:00	**Coffee Break** *The Spine*	15:00 - 15:20
	LFV theory talk *The Spine*	*Paride Paradisi* 15:20 - 15:45
16:00	**Review of LFV searches & UK activites** *The Spine*	*Becky Chislett* 15:45 - 16:10
	Conclusion of the workshop *The Spine*	16:10 - 16:30

Conclusion

- A +60years rich history of the muon g-2 experiments which allowed to test the SM at <0.5 ppm precision.
- An intriguing discrepancy is present. Possibly a sign of new Physics?
- New (and current) experimental (and theory) initiatives on muon physics ongoing
- The "Muon Precision Physics Program" funded by Leverhulme Trust will play a central role and will act as an icebreaker to free a path for further experimental and theoretical progress.
- An important part of this project will be the mentoring and training of students and early-career researchers

LEVERHULME TRUST

UNIVERSITY OF LIVERPOOL

- Ben Alston
- Ian Bamber
- Rachel Bearon
- Themis Bowcock
- Saskia Charity
- Julie Clarke
- Karl Coleman
- Rick Cosstick
- Laura Harkness-Brennan
- Louise Hobson
- Anthony Hollander
- Joe Price
- Thomas Teubner
- Wiebe Van Der Hoeck
- Joost Vossebeld
- Carsten Welsch

INFN
Istituto Nazionale di Fisica Nucleare

For continuous support and funding over all these years and the Italian colleagues for >20 years of common activities and friendship


ONE THING IS FOR SURE: THE HUNT IS ON, AND NEW DISCOVERIES ARE ON THE HORIZON.
Muon g-2 @ Fermilab
Muon g-2 @ J-Park
Theory Initiative
MUonE @ CERN
Stay tuned!

END

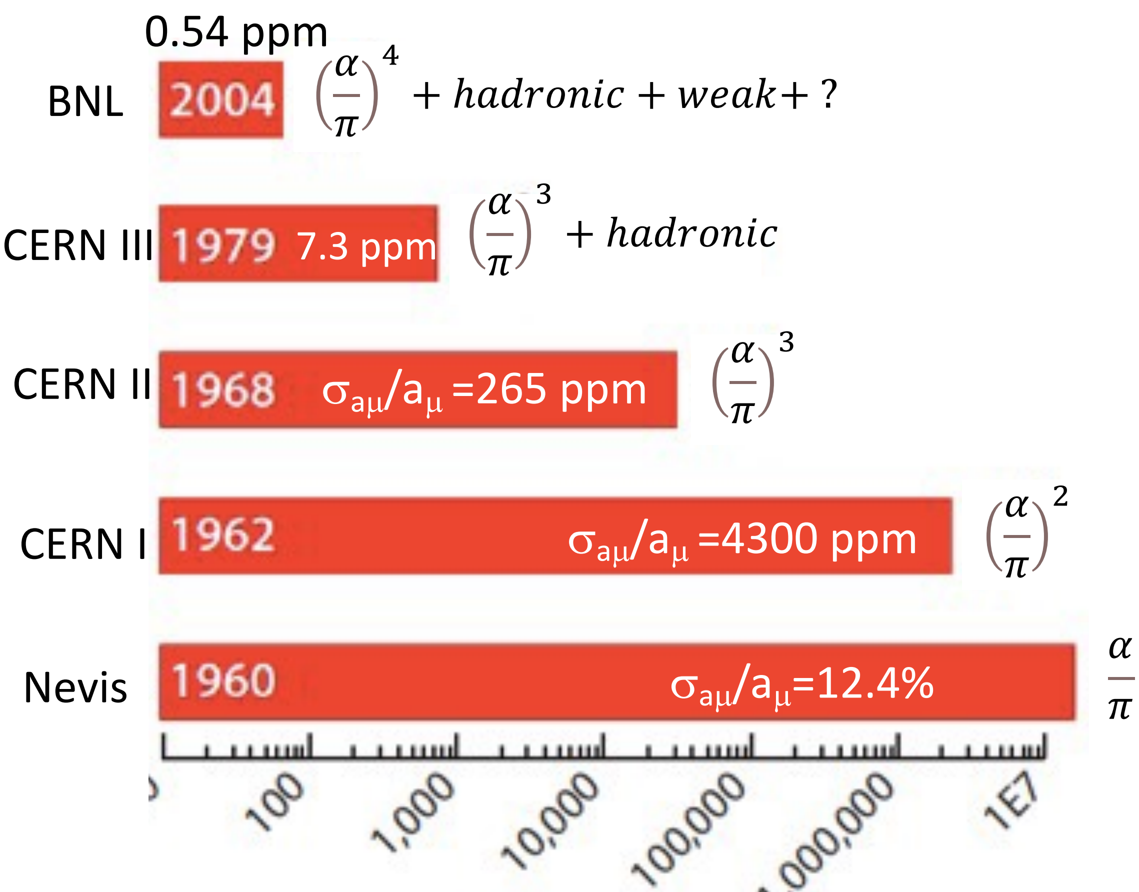
t [μs]

History of muon g-2 experiments (1960-2000)

Muon g-2

0.54×10^{-6}

$a_\mu^{BNL} = 116\,592\,089\,(63)\times 10^{-11}$ (2001)



Uncertainty on $a_\mu \times 10^{-11}$

contribution to a_μ $(\times 10^{-11})$:

116 584 712…	*6937 (44)*	*153.6(1)*
(0.9999…)	(5.9×10^{-5})	(1.3×10^{-6})

QED	QCD	EW
4 Loops >900 diagrams	HLbL	
	HVP	
3 Loops >100 diagrams		
2 Loops 9 diagrams		
1 Loop 1 diagram		

Comparisons of g-2 experiments

Muon g-2

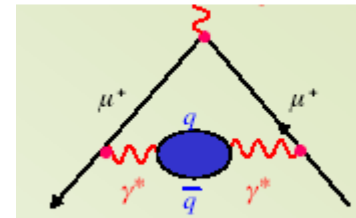
Prog. Theor. Exp. Phys. **2019**, 053C02 (2019)

<table>
<tr><th></th><th>BNL-E821</th><th>Fermilab-E989</th><th>JPARC-E34</th></tr>
<tr><td>Muon momentum</td><td colspan="2">3.09 GeV/c</td><td>300 MeV/c</td></tr>
<tr><td>Lorentz γ</td><td colspan="2">29.3</td><td>3</td></tr>
<tr><td>Polarization</td><td colspan="2">100%</td><td>50%</td></tr>
<tr><td>Storage field</td><td colspan="2">$B = 1.45$ T</td><td>$B = 3.0$ T</td></tr>
<tr><td>Focusing field</td><td colspan="2">Electric quadrupole</td><td>Very weak magnetic</td></tr>
<tr><td>Cyclotron period</td><td colspan="2">149 ns</td><td>7.4 ns</td></tr>
<tr><td>Spin precession period</td><td colspan="2">4.37 μs</td><td>2.11 μs</td></tr>
<tr><td>Number of detected e^+</td><td>5.0×10^9</td><td>1.6×10^{11}</td><td>5.7×10^{11}</td></tr>
<tr><td>Number of detected e^-</td><td>3.6×10^9</td><td>–</td><td>–</td></tr>
<tr><td>a_μ precision (stat.)</td><td>460 ppb</td><td>100 ppb</td><td>450 ppb</td></tr>
<tr><td>(syst.)</td><td>280 ppb</td><td>100 ppb</td><td><70 ppb</td></tr>
<tr><td>EDM precision (stat.)</td><td>$0.2 \times 10^{-19}\ e \cdot \mathrm{cm}$</td><td>–</td><td>$1.5 \times 10^{-21}\ e \cdot \mathrm{cm}$</td></tr>
<tr><td>(syst.)</td><td>$0.9 \times 10^{-19}\ e \cdot \mathrm{cm}$</td><td>–</td><td>$0.36 \times 10^{-21}\ e \cdot \mathrm{cm}$</td></tr>
<tr><td></td><td>Completed</td><td>Running</td><td>In preparation</td></tr>
</table>

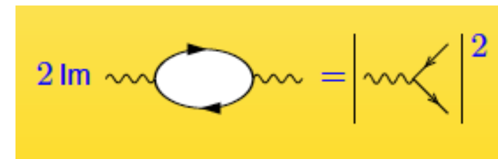
a_μ^{HLO} calculation, traditional way: time-like data

Muon g-2

[C. Bouchiat, L. Michel,'61; N. Cabibbo, R. Gatto 61; L. Durand '62-'63; M. Gourdin, E. De Rafael, ' 69; S. Eidelman F. Jegerlehner 95, Davier et al '97, Hagiwara et al 2003,…]



$$a_\mu^{HLO} = \frac{1}{4\pi^3}\int_{4m_\pi^2}^{\infty} \sigma_{e^+e^- \to hadr}(s) K(s)\, ds$$



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

Traditional way: based on precise experimental (time-like) data:

$a_\mu^{HLO} = (693.1 \pm 4.0) 10^{-10}$ (TI)

- Main contribution in the low energy region (highly fluctuating!)
- Current precision at 0.6%