The Sum Rule of Physics:

Muon g-2

Gerry Bunce

Brookhaven National Lab

World of Physics

Stony Brook

16 April 2004

The study of physics leads to many practical applications, but basic research also (and this is its goal) gives a better understanding of the world. This understanding can be unintuitive and inaccessible, but the very ideas that are unintuitive are the beauty of the field and are its most important contribution to society. These ideas are completely new. Examples are relativity and equivalence of mass and energy, the uncertainty principle, quantum mechanics, antiparticles and annihilation and spontaneous creation out of energy, forces being the same (or not) if seen in a mirror, that electricity and magnetism are part of the same force, that forces are transmitted by the exchange of special particles. These are all part of the g-2 story, along with a few other non-intuitive ways of thinking that aren't as well "known" as those above--that of the weak force, which leads to our universe having a majority of matter and not an equal amount of anti-matter (which leads to our existence), is linked with the electric/magnetic force; and that a particle can be a "point" and still spin and generate a magnetic field. Spin leads to the exclusion principle and that electrons stack up in "orbits" in atoms--chemistry and the world that we are familiar with.

Forces ----> Fields

Strong: nuclear force ---holds nucleus together ---10^{-13} cm

Quarks, Gluons

Electric/Magnetic: atomic force ---chemistry ---infinite range

Electrically charged particles, Light

Weak: quark families ---radioactive decay ---<<10^{-13} cm

Quarks ---> quarks, electrons, muons, neutrinos, W, Z

Gravity: space-time ---astronomy ---infinite range

Mass, gravity waves

Forces are carried by Fields.

How does the moon know that the earth is there?

How do you know when you are about to get a shock from your car door?

How does a refrigerator magnet know it is approaching the refrigerator?

Does it matter whether there is a vacuum in between?

The muon g-2 experiment probes these fields with great precision.

Our theory of these forces (the Standard Model of Particle Physics) predicts g-2 with great precision.

We can test our understanding of the forces in our world with great sensitivity.

1. What is a muon?
2. What is g-2?
3. Why do we do this?
4. How do we do this?
5. What do we see?
6. Is this a big deal?
7. What is the future?

Particle	mass	radius	lifetime at rest
proton	$16{,}742 \times 10^{-28}$ gm	10^{-13} cm	stable
pion	2490×10^{-28} gm	10^{-13} cm	26 nano-seconds
muon	1885×10^{-28} gm	$<10^{-17}$ cm	2 μsec
electron	9×10^{-28} gm	$<10^{-20}$ cm	stable

(1 gram of hydrogen = 6×10^{23} atoms or protons)

(an atom is 100,000 x larger)

(light travels 1' in 1 nsec)

pion ↓ muon ↓ electron

---

① the pion and proton are "large" (!) and made of quarks, bound by strong force.

② the muon and electron are very small!, and interact with electric/magnetic and weak forces

③ muon is 200x heavier than electron, otherwise the "same"?

What is a muon?

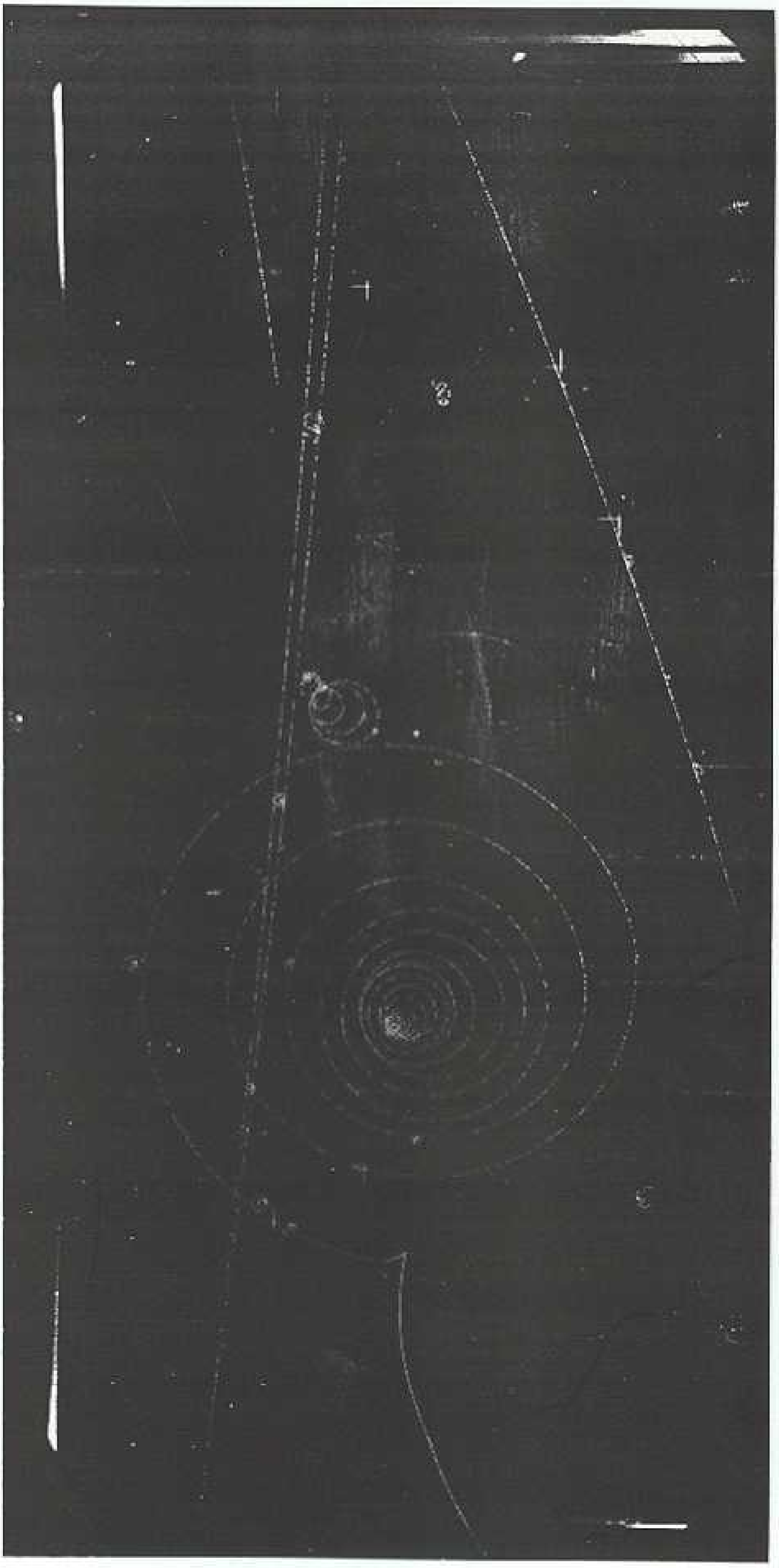
- heavy electron
  - first seen in cosmic rays 1940s
    - Powell - Nobel 1950

How do we make them in the lab?

1) accelerate protons in AGS

2) slam the protons into a target of protons and neutrons (Ni)
   - protons and neutrons are collections of 3 quarks
   - **the energy creates new particles called "pions"**
     - collections of (quark + anti-quark)

3) wait until the pions spontaneously decay → **muons.**



What is g-2? A loop of electric current generates a magnetic field.

A spinning charged object also creates a magnetic field.

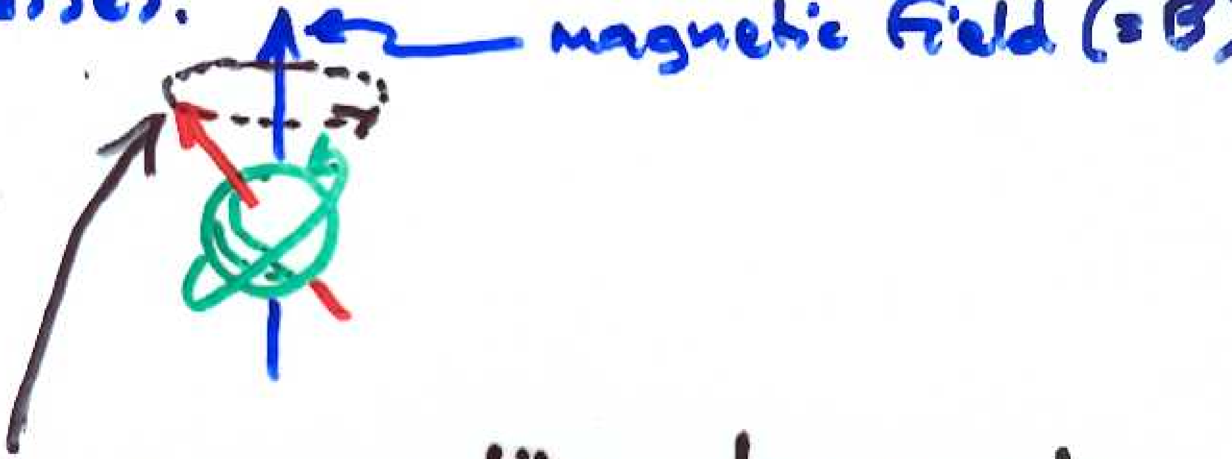
The spinning object also has angular momentum from the rotating mass.

The ratio of the magnetic field created by the revolving charge and the angular momentum from the revolving mass is g.

(= gyromagnetic ratio)

What is g-2 (cont.)

If we put the spinning particle into a magnetic field, the particle's spin (or magnetic field) precesses.



spin precesses like a top gyrates

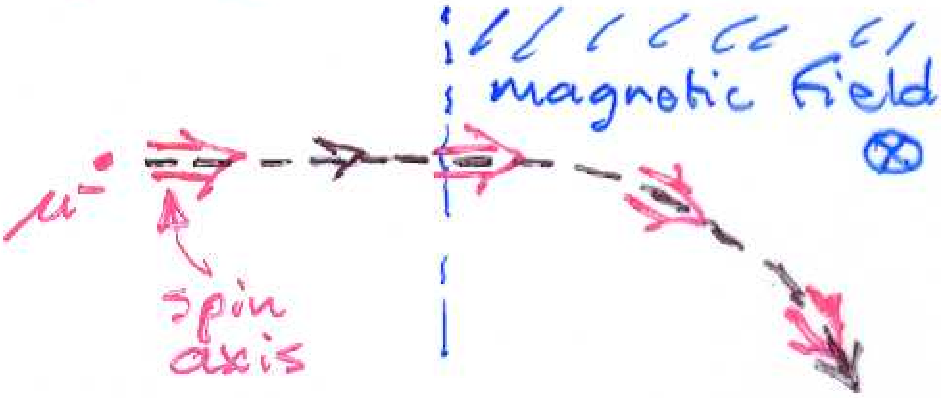
The rate of precession = g B.

But, what about g-2?

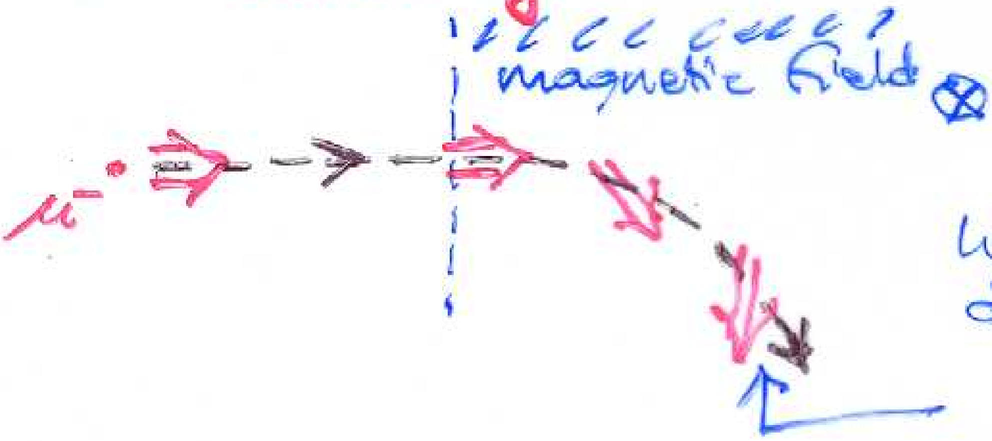
What is g-2?

g = ratio of the magnetic field created by a revolving charge and the angular momentum from the revolving mass

When $g = 2$, a charged particle (μ^-) going thru a magnet: its spin follows its direction:

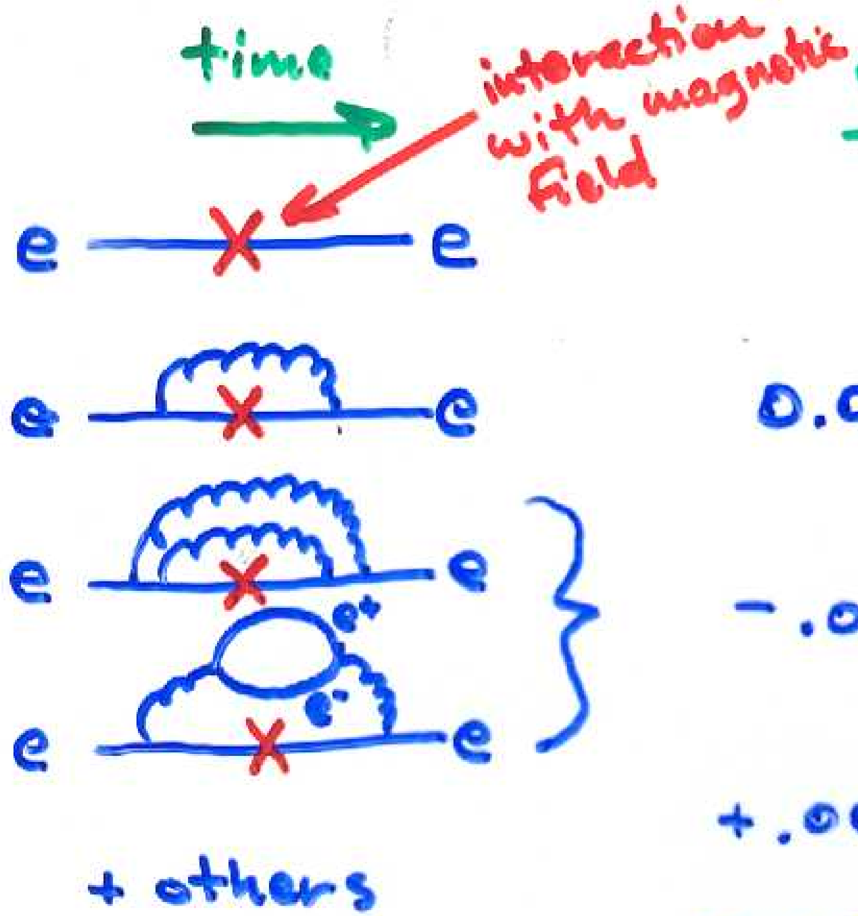


But when $g-2 \cong .002$:



We measure this difference: g-2

The electron g-2 is sensitive to the electro-magnetic force:



$g-2/2$
0
0.001 161 409 79
−.000 001 772 31
+.000 000 014 74
−.000 000 000 04

Theory $\left.\frac{g-2}{2}\right|_{\text{electron}}$ = .001 159 652 140 ± 28

Experiment = .001 159 652 188 ± 4

Difference = $48 \pm 28 \times 10^{-12}$

The electron g-2 agreement is a cornerstone of QED.

History Leading to Muon (g−2) Experiment at BNL

(A measurement of the magnetism associated with the muon)

Discovery	Year	Year of Nobel Prize
Electron by J.J. Thompson	1899	1906
Theory of electron spin		
W. Pauli	late 1920's	1945
P.A.M. Dirac	late 1920's	1933
Discovery of muon		
Powell	1947	1950
Quantum theory of electricity		
Feynman, Schwinger, Tommaga	late 1940's	1965
Shift of electron energy underpins		
Feynman theory--Lamb	1947	1955
First electron of g−2 experiment-- electron obeys Feynman theory		
Crane et al.	1953	
First muon (g−2) experiment-- the muon is like an electron, but 200 times heavier	1961	

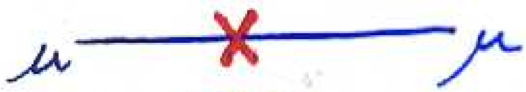
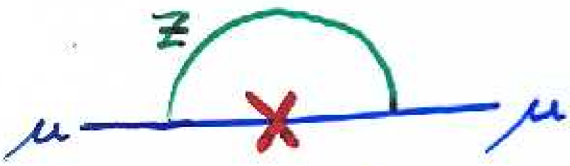
History Leading to Muon (g−2) Experiment at BNL

Discovery	Year	Year of Nobel Prize
Electron and muons are in different families of particles Lederman, Schwartz, Steinberger	1962	1988
Unified theory of electricity and radioactive decays Weinberg, Glashow, Salam	1970's	1979
Discovery of c−quark−− quarks have families Ting, Richter	1975	1976
3rd Muon g−2 experiment at CERN	1979	
Electron g−2 to 1 part/billion Dehmelt	1981	1989
Discovery of W and Z particles which carry the weak force Rubbia and Van de Meer	1983	1984
New AGS experiment to measure the contribution of W,Z to muon magnetism	1988−1995	

For the **muon**, heavier particles can also be created and annihilated which contribute to g-2 at a level

$$\left(\frac{m_{muon}}{m_{electron}}\right)^2 \approx 200^2 = 40000 \times \text{ larger}$$

than for the electron.

time →	g-2/2
	0
 + all electric/magnetic	+0.001 165 847 06 ± 2
 + all strong interaction	+0.000 000 068 82 ± 154
	+0.000 000 003 89
 + more weak	−0.000 000 001 94
	−0.000 000 000 44 ± 4
Theory $\frac{g-2}{2}$ muon =	0.001 165 917 39 ± 154
Experiment =	0.001 165 923 0 ± 84

difference = 6 ± 9 × 10⁻⁹

Why do we do this?

- the muon as it travels thru a magnet sees the
  - ✓ – electro-magnetic force
  - ✓ – strong force
  - ✓ – weak force
  - X – gravity
  - ? – a new force?

- these forces affect the muon's spin and change

$$g-2 = 0 \quad \text{to} \quad g-2 \approx .002$$

- our theory for these forces can predict g-2 exquisitely well

Theory: $\left.\frac{g-2}{2}\right|_{\text{electron}} = .001\ 159\ 652\ 140 \pm 28$

Experiment: $= .001\ 159\ 652\ 188 \pm 4$

Our experiment explores: are we missing any forces?

How do we do this?

---Need many muons spinning in same direction

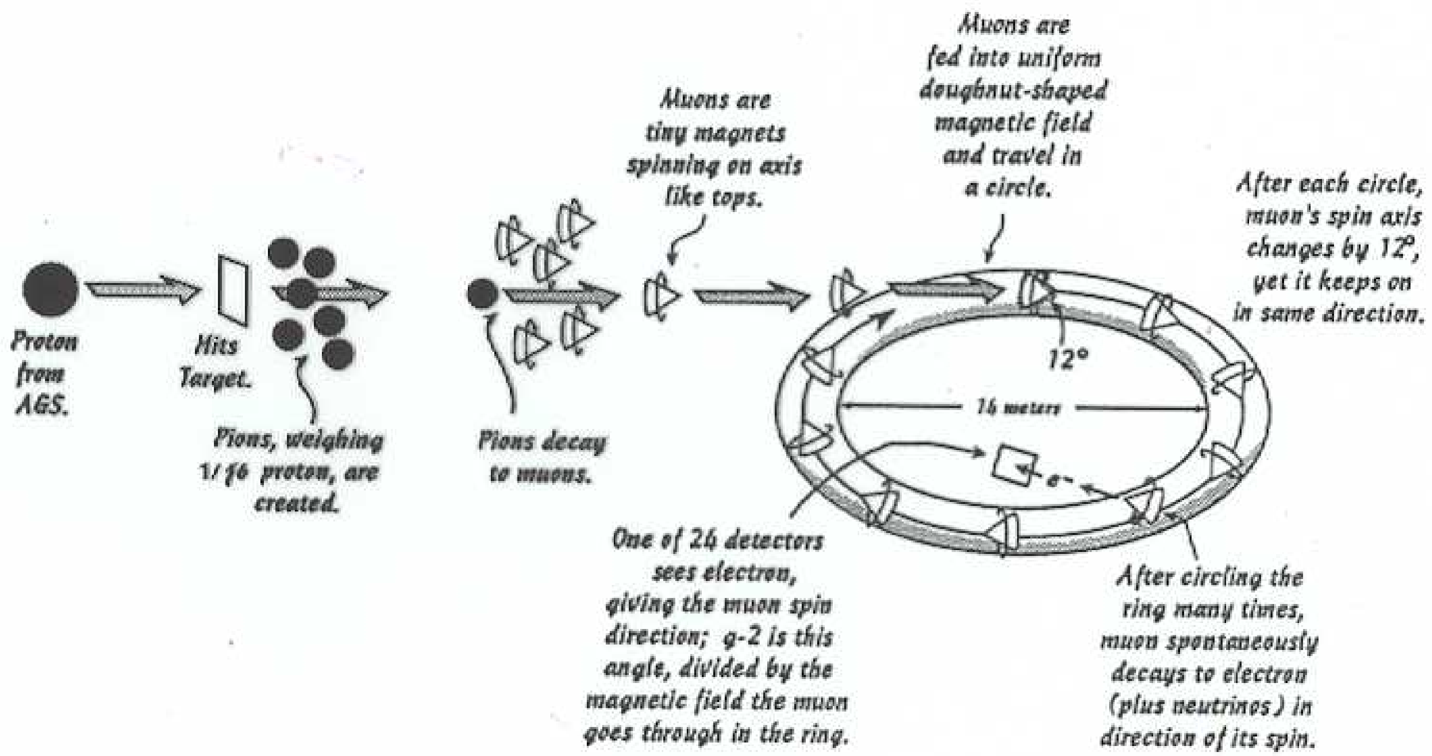
---Send muons into a uniform magnetic field

---Measure magnetic field (B) very precisely

---Measure advance of the spin of the muons (ω)

Then $(g-2)/2 = \omega / B$

Life of a Muon : The g-2 Experiment



Construction started in 1989.

Beam in 1995.

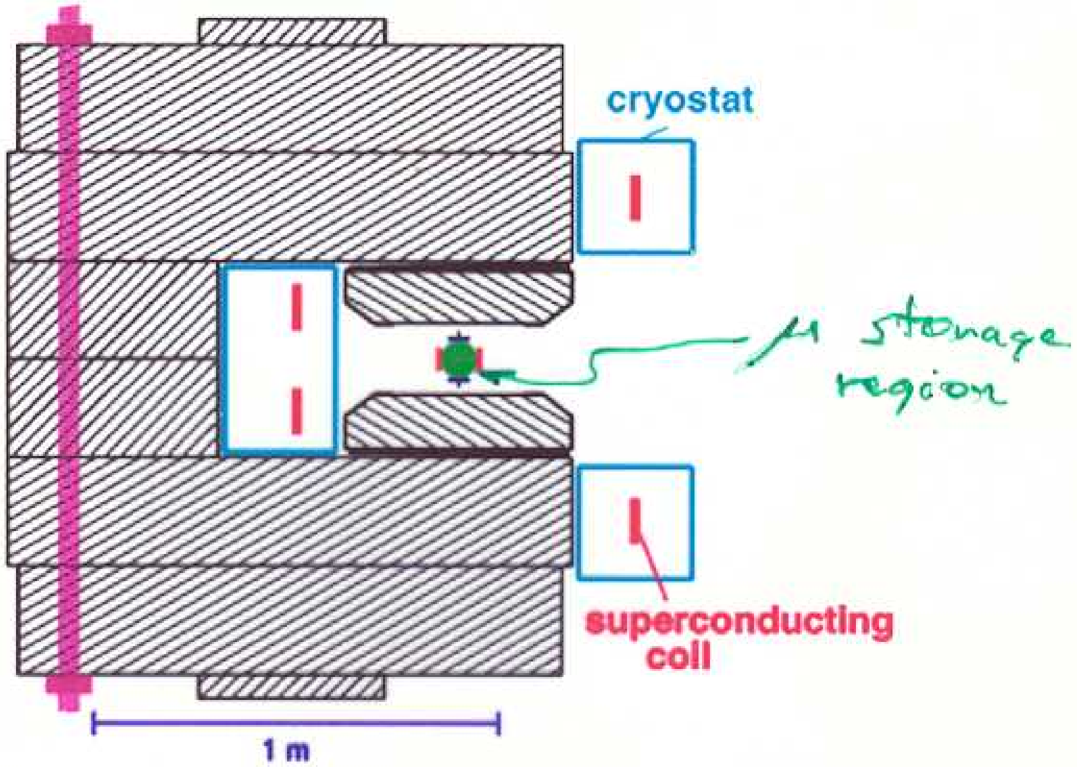
SEUBERT 1a 9/91 IR

- world's largest superconducting magnet
- g-2 magnet gap = 18 cm
- circumference ≈ 44 m
- field uniform to ± 1 ppm

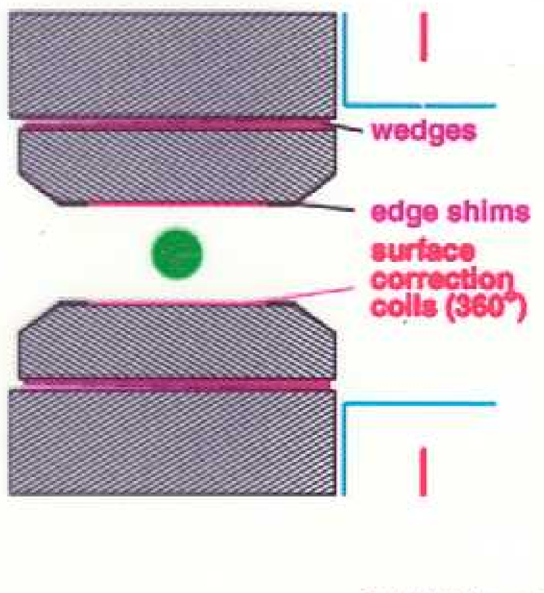
diam. (human hair) ≈ 50 μm

$$\frac{d(\text{hair})}{d(\text{gap})} = \frac{50 \times 10^{-6}}{2 \times 10^{-1}} \approx 250 \text{ ppm}$$

The E821 Ring Magnet

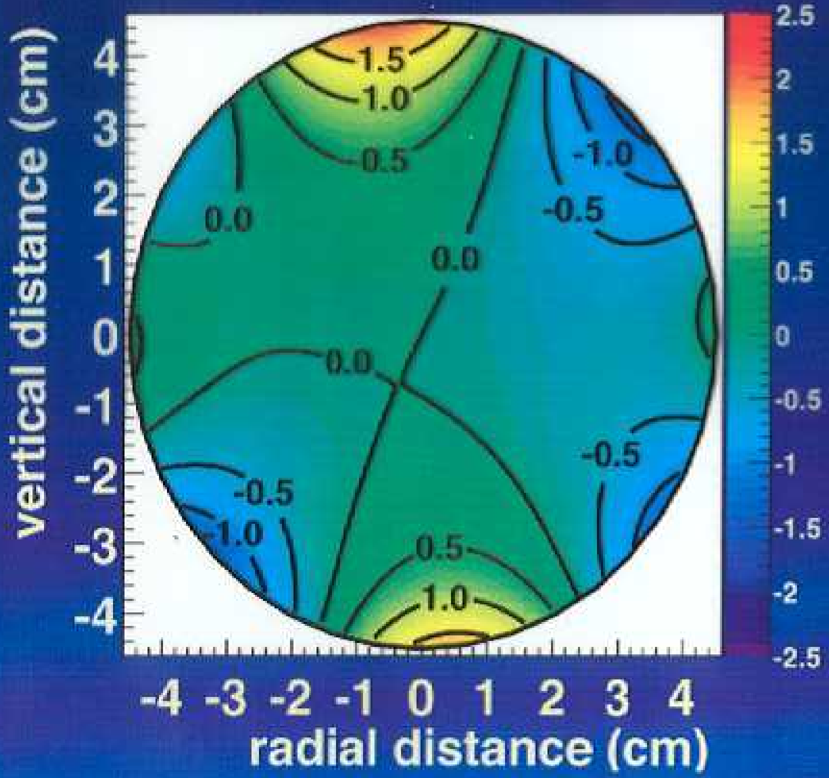


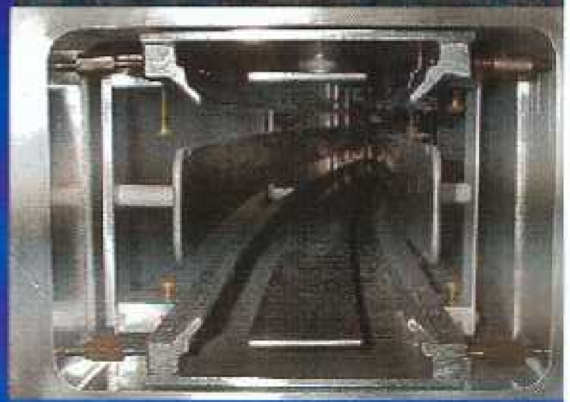
shimming tools:



Magnetic Field: Uniformity

Measured in terms of the proton NMR frequency (ω_p) inside the vacuum chamber every couple of days using 17 calibrated probes in a "trolley"





Absolute calibration from spherical water probe

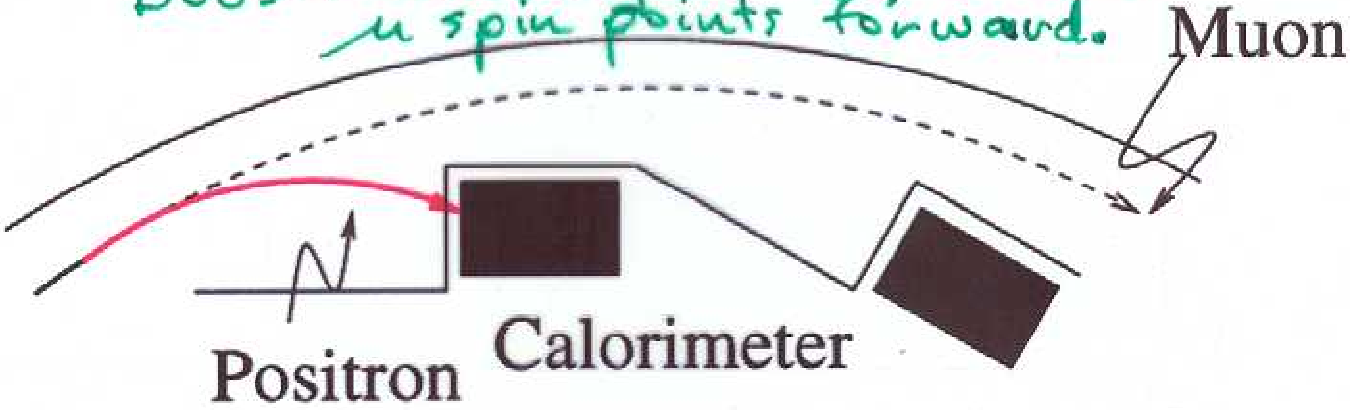
Polarimeter

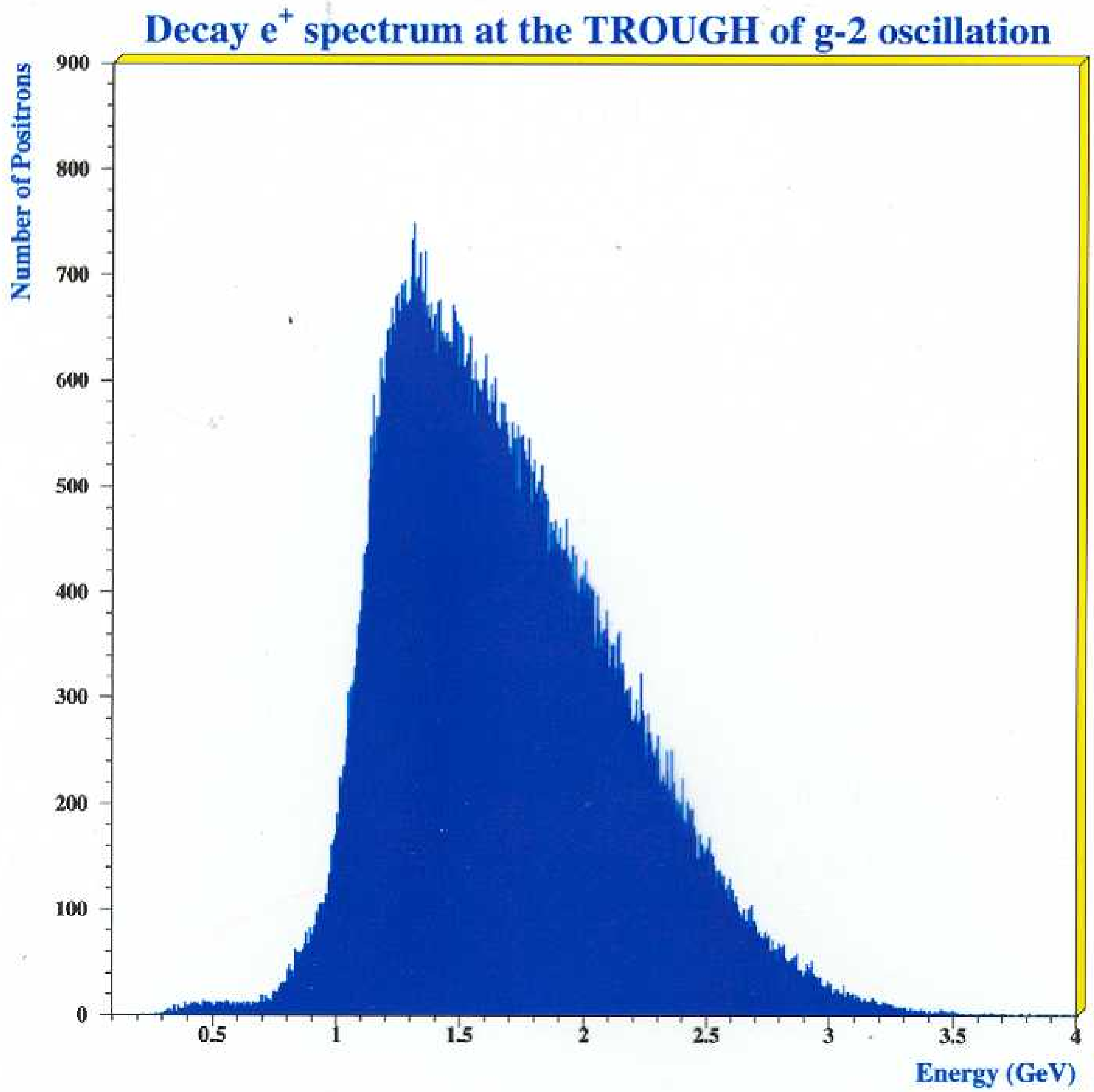
high energy positrons from muon decay

$$\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$$

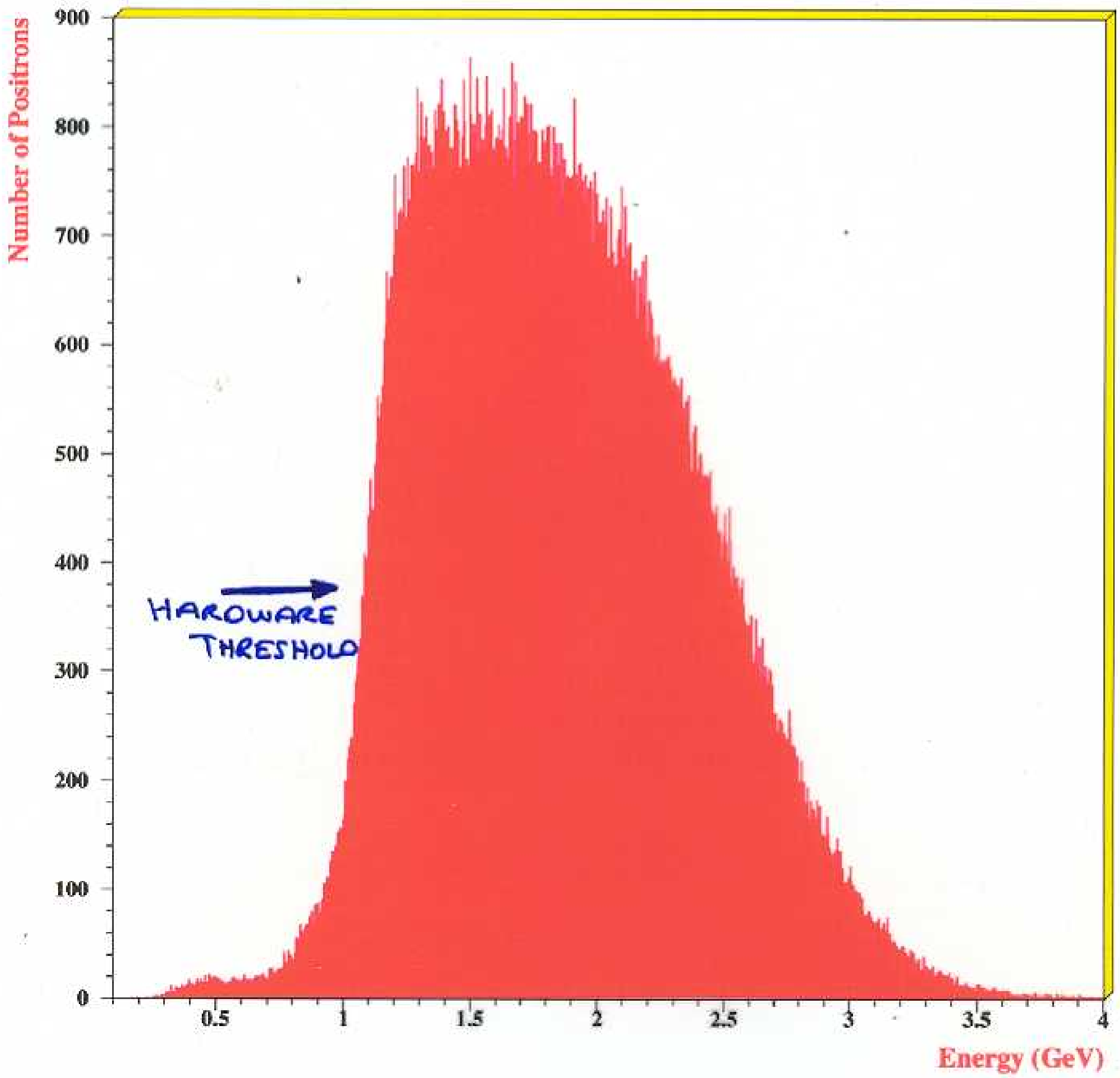
Parity violation: more e^+ in direction of muon spin.

Boost: more high energy e^+ when μ spin points forward.




Decay e+ spectrum at the TROUGH of g-2 oscillation
Number of Positrons
900
800
700
600
500
400
300
200
100
0
0.5
1
1.5
2
2.5
3
3.5
4
Energy (GeV)

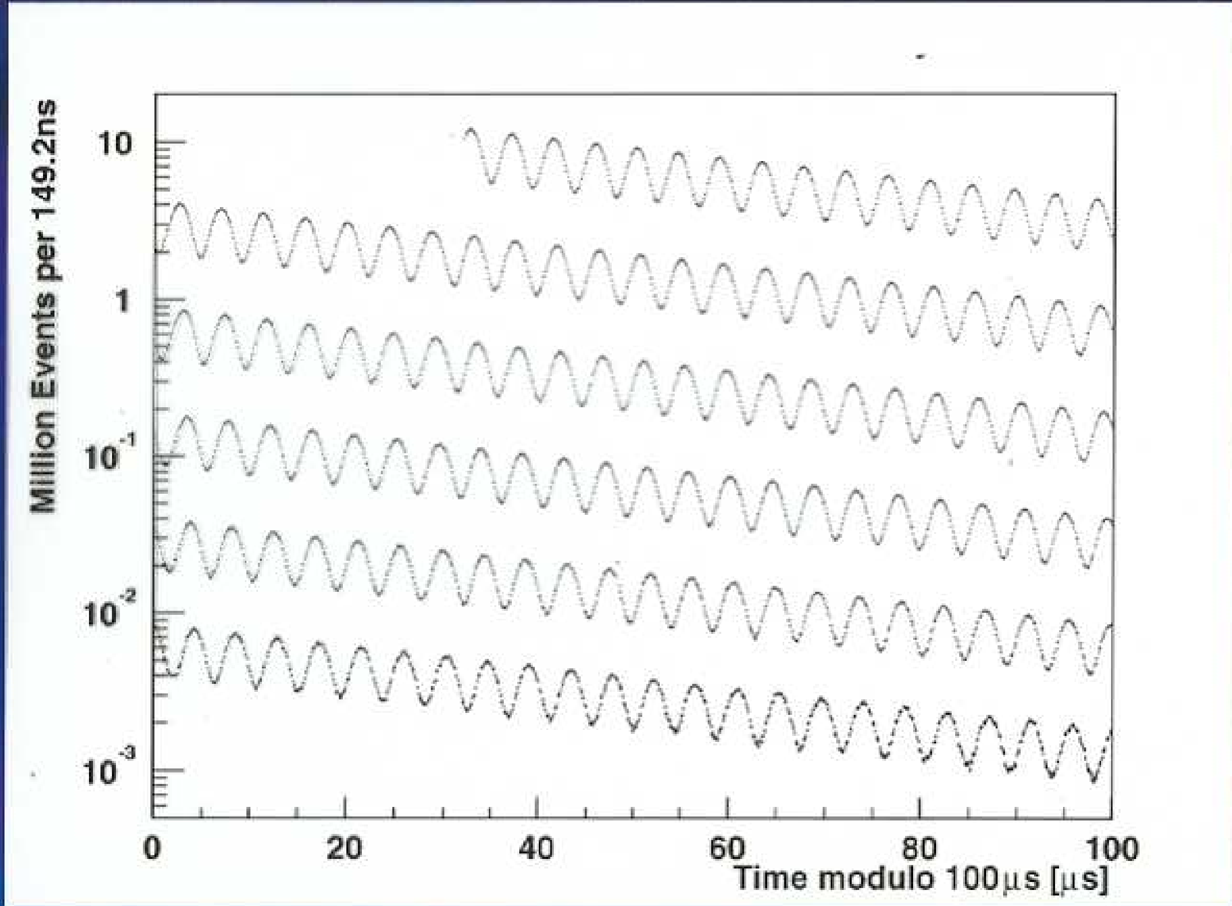
Decay e^+ spectrum at the PEAK of g-2 oscillation



$$\mu^+ \rightarrow e^+ \nu \bar{\nu}$$

The 2001 ω_a data

4×10^9 events with $t > 32\mu s$, $E > 1.8$ GeV



$$N(t) = N e^{-t/\gamma\tau} \left[1 + A cos\left(\omega_a t + \phi\right)\right]$$

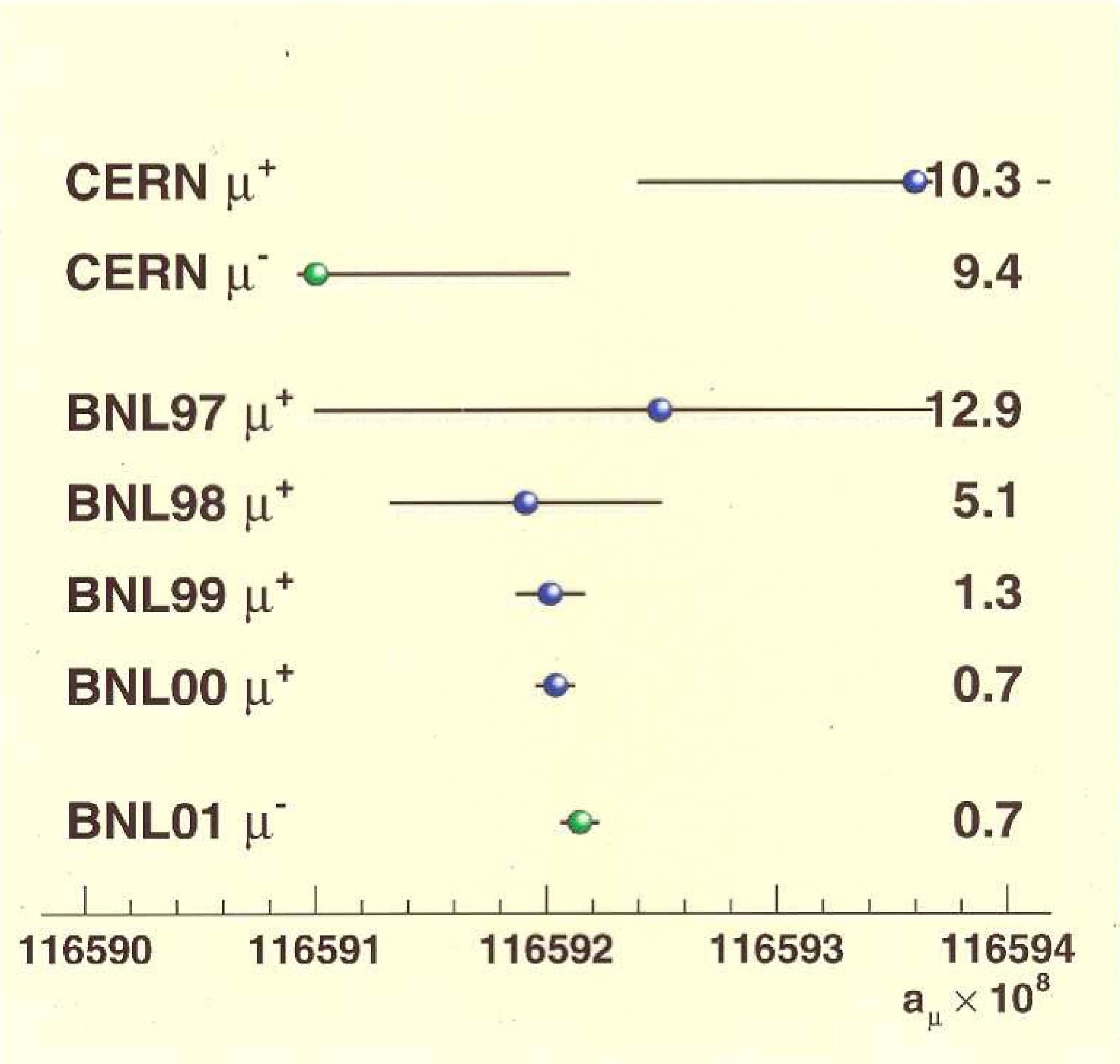
Comparing μ^+ and μ^- to Test CPT

Compare $R = \frac{\omega_a}{\omega_p}$

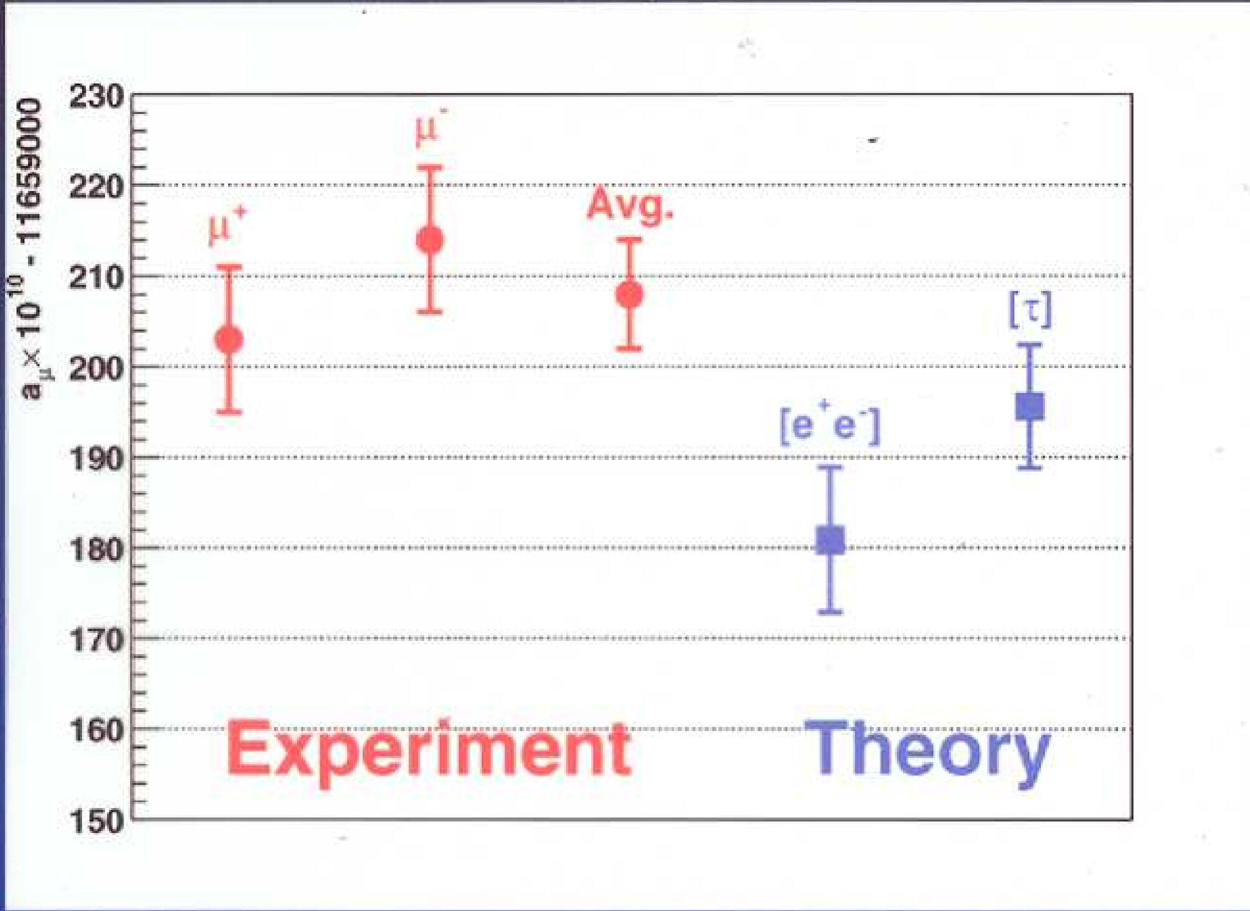
$R_{\mu^+} = 0.0037072048(25)$ $\quad$ $R_{\mu^-} = 0.0037072083(26)$

$$\epsilon = \frac{R_{\mu^+} - R_{\mu^-}}{\frac{1}{2}\left(R_{\mu^+} + R_{\mu^-}\right)} = (-9.4 \pm 9.7) \times 10^{-7}$$

$$a_\mu = 11\,659\,208(6) \times 10^{-10} \text{ [0.5 ppm]}$$


CERN μ+
10.3
CERN μ-
9.4
BNL97 μ+
12.9
BNL98 μ+
5.1
BNL99 μ+
1.3
BNL00 μ+
0.7
BNL01 μ-
0.7
116590
116591
116592
116593
116594
aμ × 10^8

Comparison to theory



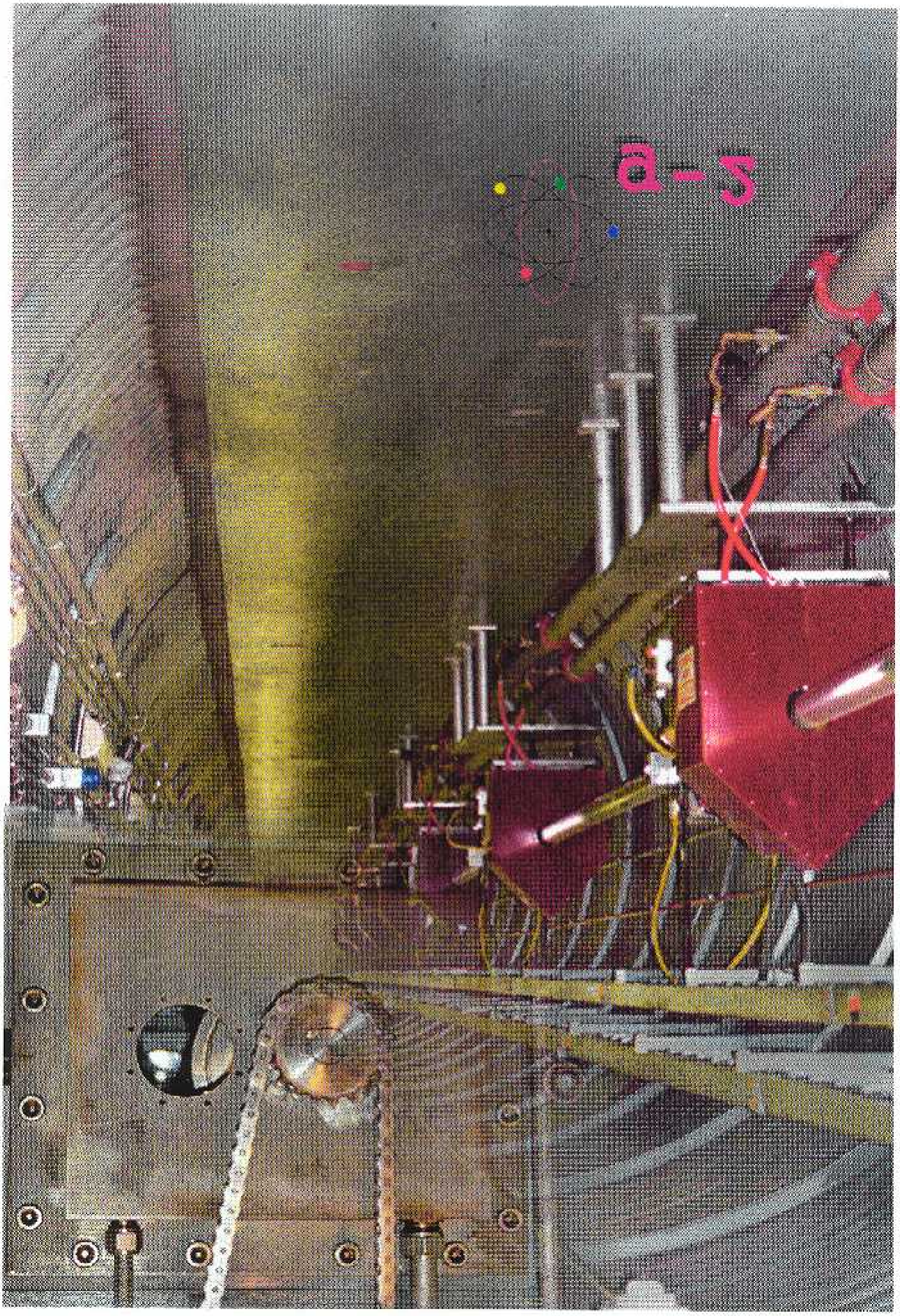
$$
\begin{aligned}
a_\mu^{exp} &= 11\,659\,208(6) \times 10^{-10} & \\
a_\mu^{th;ee} &= 11\,659\,181(8) \times 10^{-10} & \Delta a = 2.7\sigma \\
a_\mu^{th;\tau} &= 11\,659\,196(7) \times 10^{-10} & \Delta a = 1.4\sigma
\end{aligned}
$$

Collaboration

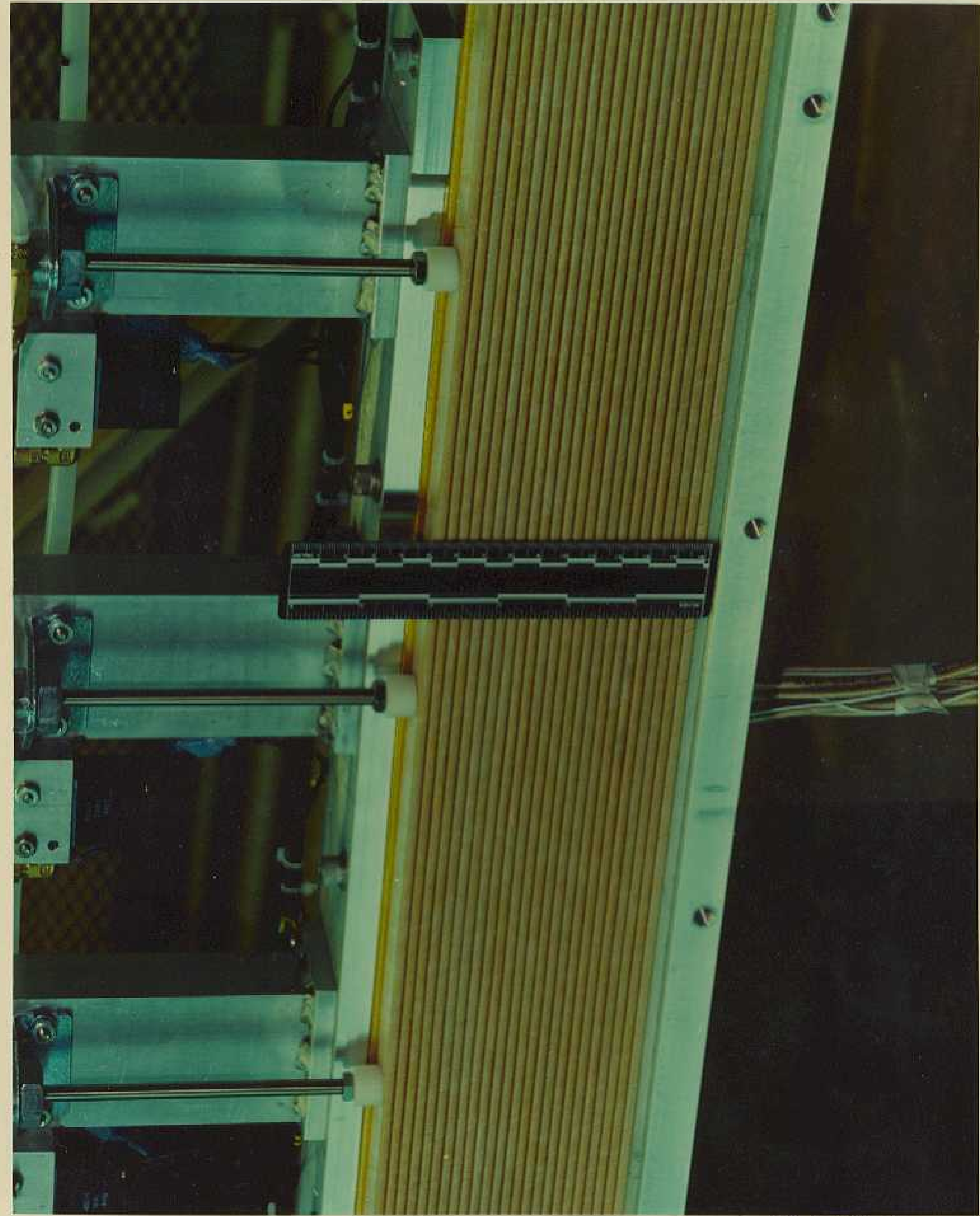
Most recent paper: 70 authors, 11 institutions, 5 countries

Boston University	Boston, Massachusetts, USA
Brookhaven National Laboratory	Upton, New York, USA
Budker Institute of Nuclear Physics	Novosibirsk, Russia
Cornell University	Ithaca, New York, USA
Universität Heidelberg	Heidelberg, Germany
University of Illinois	Urbana, Illinois, USA
KEK	Tsukaba, Japan
Kernfysisch Versneller Instituut	Groningen, The Netherlands
University of Minnesota	Minneapolis, Minnesota, USA
Tokyo Institute of Technology	Tokyo, Japan
Yale University	New Haven, Connecticut, USA

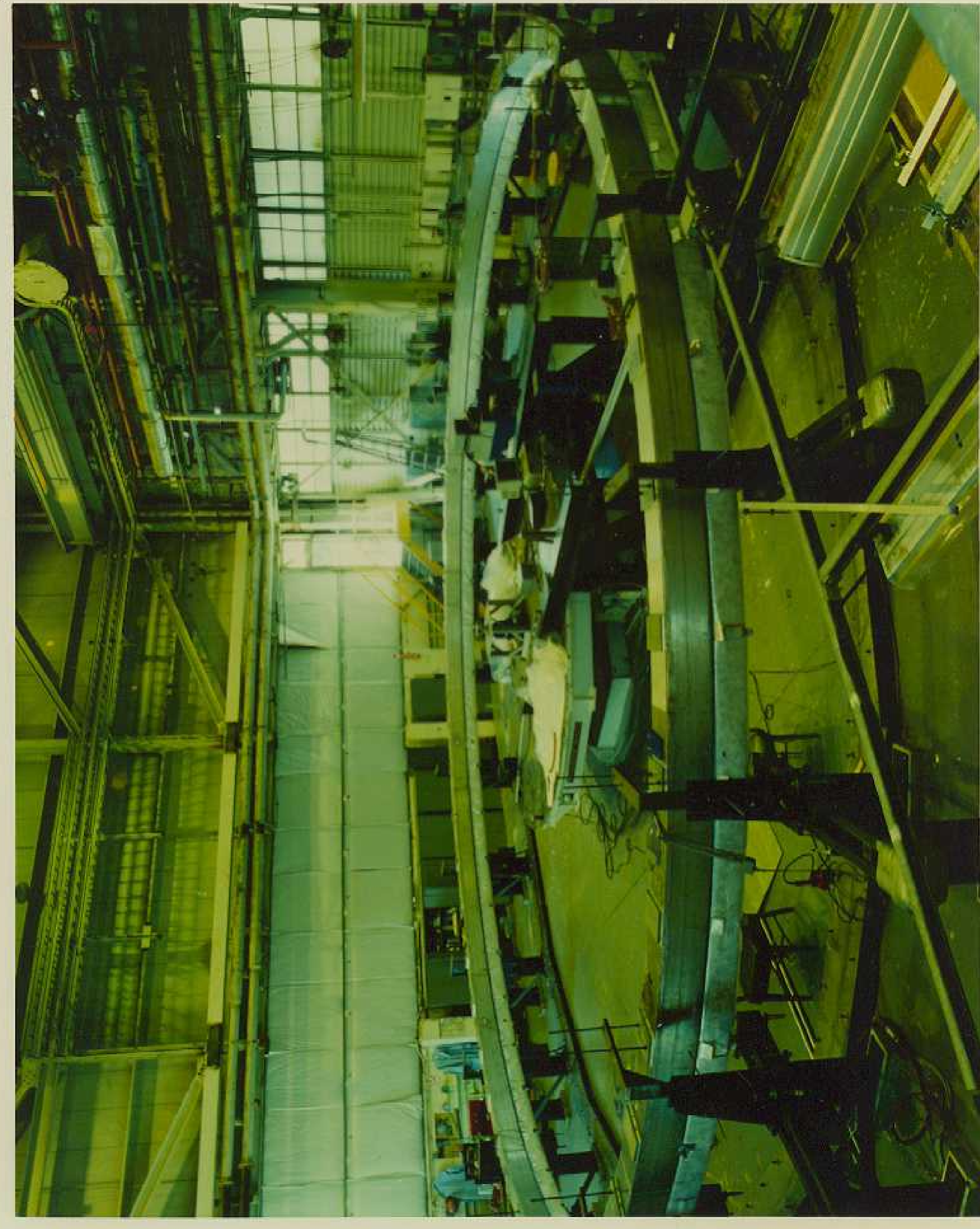
Funding: Department of Energy, National Science Foundation, National Computational Science Alliance, German Bundesminister für Bildung und Forschung, Russian Ministry of Science, and U.S.-Japan Agreement in High-Energy Physics.



CNS - 209-91



CN9 · 542-92



Conclusions and Outlook

- New measurement of $a_\mu^- = 11\,659\,214\,(8)(3) \times 10^{-10}$ (0.7 ppm)
  - Results for a_{μ^-} and a_{μ^+} are statistically compatible
    - Average anomaly $a_\mu = (11659208 \pm 6) \times 10^{-10}$ (0.5ppm)
      - $a_\mu^{EXP} - a_\mu^{SM}$ either 1.4σ (τ) or 2.7σ (e^+e^-)
        - There is (a lot) more e^+e^- data coming
          - There are attempts to get a_μ^{had} from lattice QCD.
            - Experiment still statistics limited ....