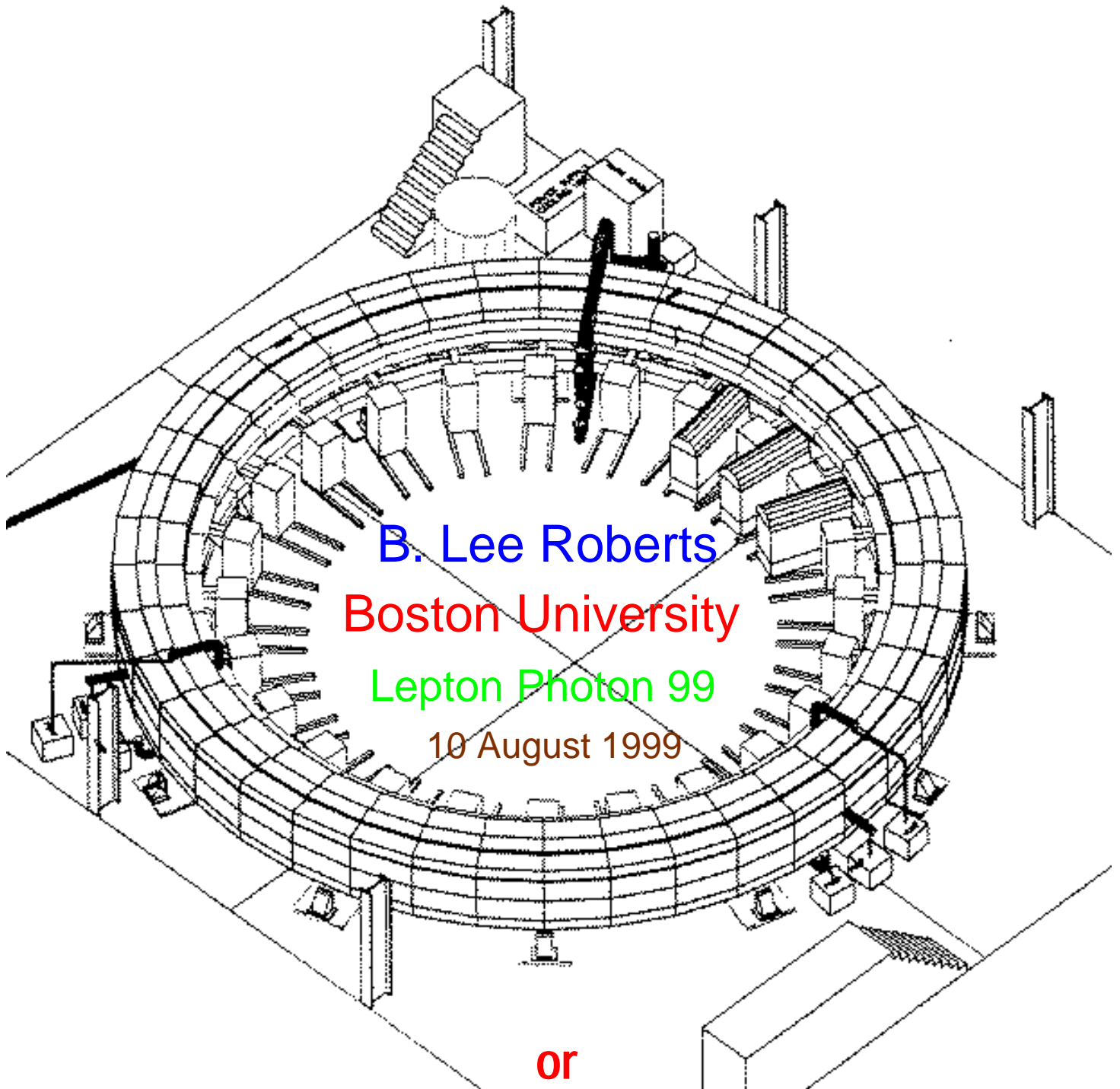


Recent Results from the Muon (g-2) Experiment



78 Years of Lepton-Photon Physics

Lepton-Photon Physics began in 1921

Otto Stern, Z. Phys. 7, 249 (1921)

Ein Weg zur experimentellen
Prüfung der Richtungsquantelung im Magnetfeld.

Von Otto Stern in Frankfurt a. Main.

Mit zwei Abbildungen. — (Eingegangen am 20. August 1921.)

Otto Stern and W. Gerlach

Annalen der Physik, 74, 673 (1924)

ANNALEN DER PHYSIK.

VIERTE FOLGE. BAND 74.

**1. Über die Richtungsquantelung im Magnetfeld¹⁾;
von Walther Gerlach und Otto Stern.**

(Hierzu Tafel III.)

Inhaltsübersicht: § 1. Theorie des Versuchs. — § 2. Apparatur. — § 3. Justierung der Apparatur. — § 4. Entwicklung des Atomstrahl-
ablenkerschlags. — § 5. Ausführung des Versuchs. — § 6. Versuchsergebnisse und Folgerungen daraus. — § 7. Ausmessung des inhomogenen Magnetfeldes. — § 8. Bestimmung des Bohrschen Magneton. — § 9. Ergebnis.

Abstoßung ist. Die Ausmessung und Berechnung von den
Aufnahmen Nr. 14 und Nr. 15 führte zu den Werten der
folgenden Tabelle:

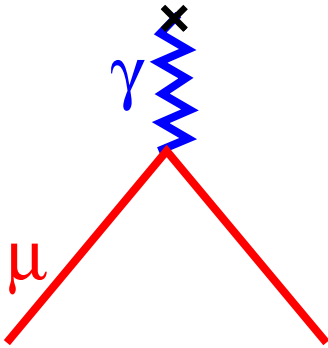
| Nr. der Aufnahme | Entfernung des unabgelenkten Strahles von der Schwärze | Mittlere Ablenkung des abgestoßenen Strahles | |
|---------------------|---|---|----------------------|
| | | berechnet | beobachtet |
| 13 | 0,33 mm | 0,10 ₁ mm | 0,10 ₂ mm |
| 14 | 0,21 mm | 0,14 ₂ mm | 0,15 mm |

Die Genauigkeit der Messungen schätzen wir auf 10 Proz.
Innerhalb dieser Fehlergrenzen zeigen also die Versuche, daß
das Silberatom im Normalzustand ein Bohrsches Magneton hat.

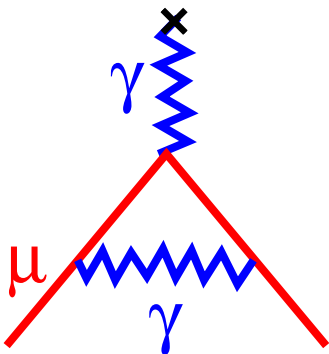
Magnetic Moments, g factors, etc.

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

If $\mu_e = 1$ Bohr Magneton, $g_s = 2$.



$$g = 2$$



**Kusch and Foley,
Schwinger, 1947**

$$+ \frac{\alpha}{\pi}$$

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

where

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

THEORETICAL VALUE FOR $(g - 2)$

Electron:

$$a_\mu(\text{Standard Model}) = a_\mu(\text{QED}) \quad \text{to } 4\text{ppb}$$

Muon:

Relative Contribution of heavier things : $\sim \left(\frac{m_\mu}{m_e}\right)^2$

$$a_\mu(\text{SM}) = a_\mu(\text{QED}) + a_\mu(\text{hadronic}) + a_\mu(\text{weak})$$

$$a_\mu(\text{New Physics}) = a_\mu(\text{Measured}) - a_\mu(\text{SM})$$

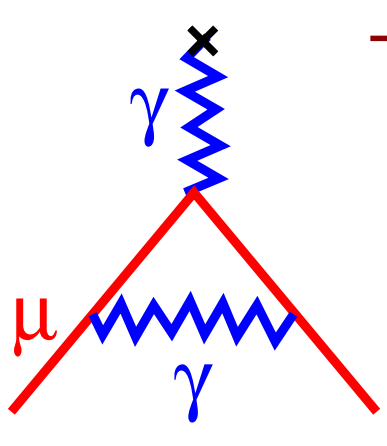
QED Contribution

$$a_\mu(\text{QED}) = C_1 \left(\frac{\alpha}{\pi}\right) + C_2 \left(\frac{\alpha}{\pi}\right)^2 + C_3 \left(\frac{\alpha}{\pi}\right)^3 + C_4 \left(\frac{\alpha}{\pi}\right)^4 + C_5 \left(\frac{\alpha}{\pi}\right)^5$$

Taking the value of α from the electron $(g - 2)$, T. Kinoshita, Rep. Prog. Phys. 59, 1459 (1996), yields the total QED value

$$a_\mu(\text{QED}) = 116\,584\,705.7(1.8)(0.5) \times 10^{-11} (\pm 16\text{ppb})$$

+ Higher Order Terms

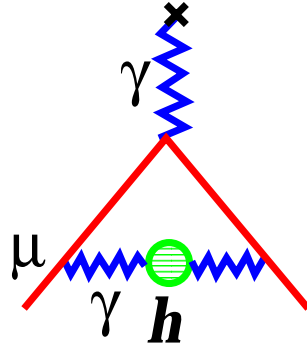


The diagram shows a muon line (red) forming a loop. A photon (blue wavy line) is emitted from the top vertex of the loop, marked with an 'x'. Another photon (blue wavy line) is emitted from the bottom vertex of the loop. The muon line is labeled with μ and the photon lines with γ .

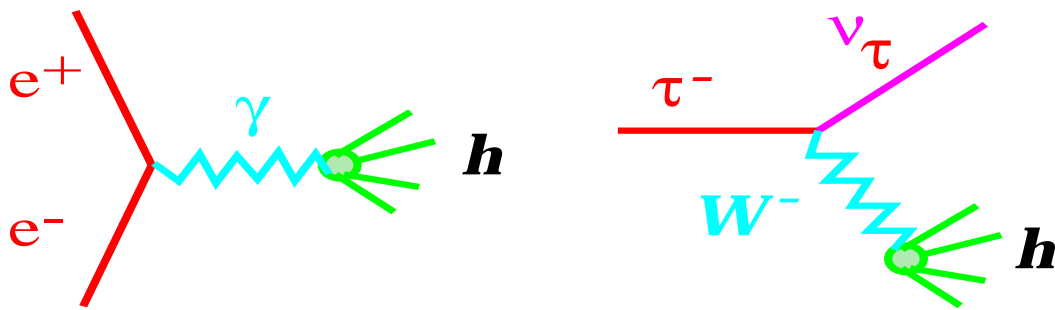
$$= \frac{\alpha}{2\pi}$$

in $\frac{\alpha}{\pi}$

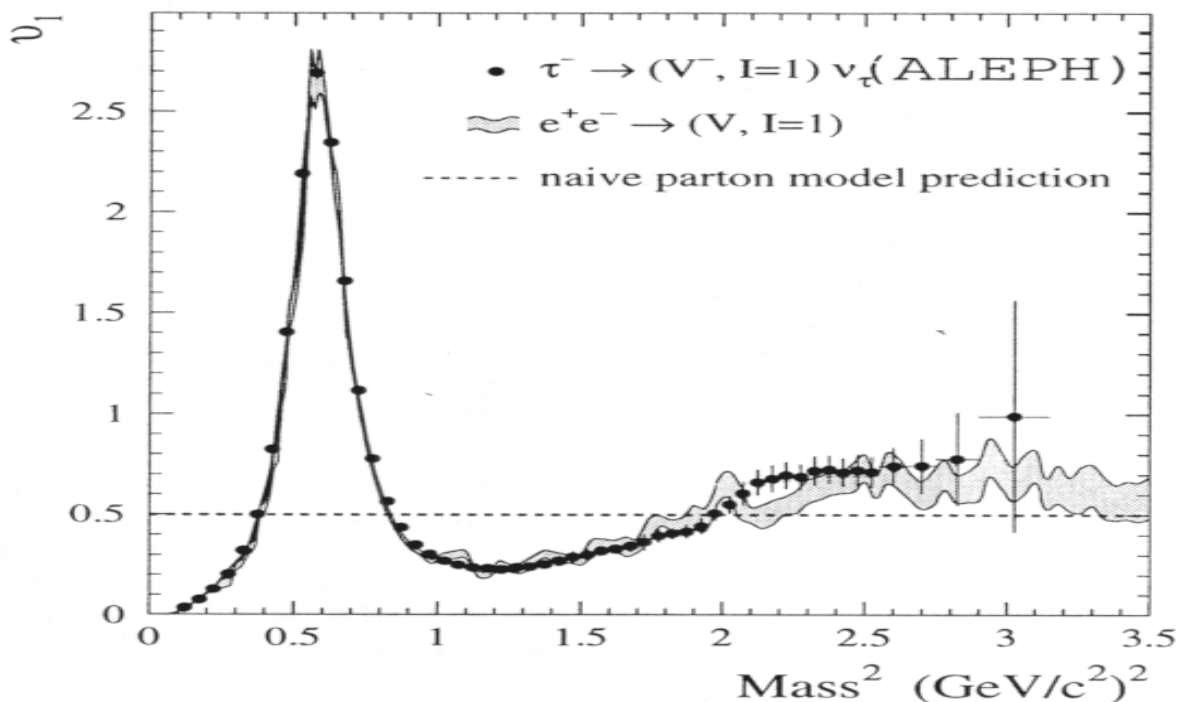
First Order Hadronic Contribution



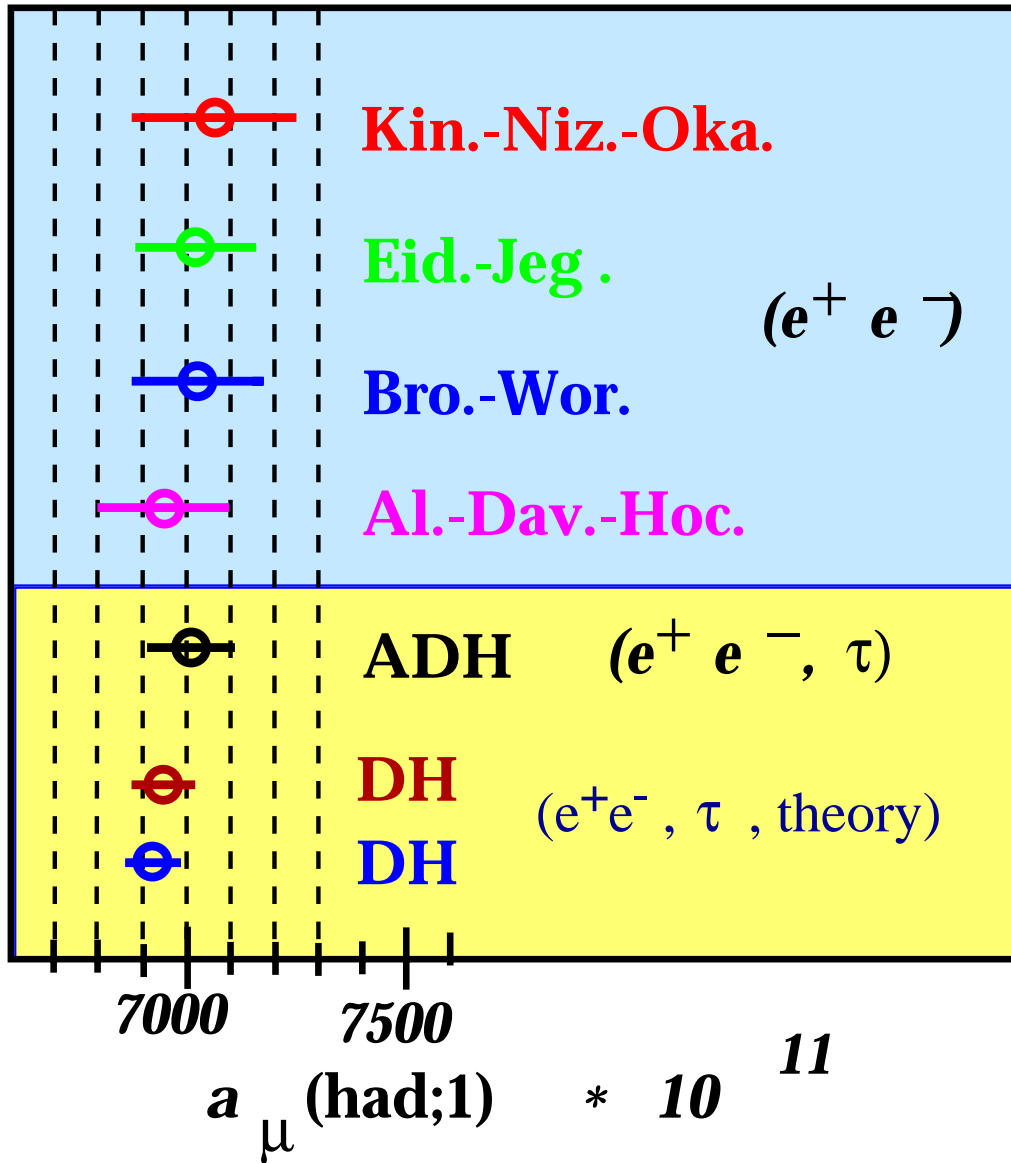
Determined experimentally from $e^+e^- \rightarrow \text{Hadrons}$ or using hadronic τ decays (assuming CVC, isospin conservation and the absence of 2^{nd} class currents)



$$a_\mu(\text{had}; 1) = \left(\frac{\alpha m_\mu}{3\pi}\right)^2 \int_{4m_\pi^2}^{\infty} \frac{ds}{s^2} K(s) R(s)$$



Values of 1st Order Hadronic Contribution



$$a_{\mu}(\text{had}; 1) = 7011(94) \times 10^{-11} \quad (60.13 \pm 0.81) \text{ ppm}$$

R. Alemany, M. Davier, A. Höcker, Eur.Phys.J. 2C (1998)123.

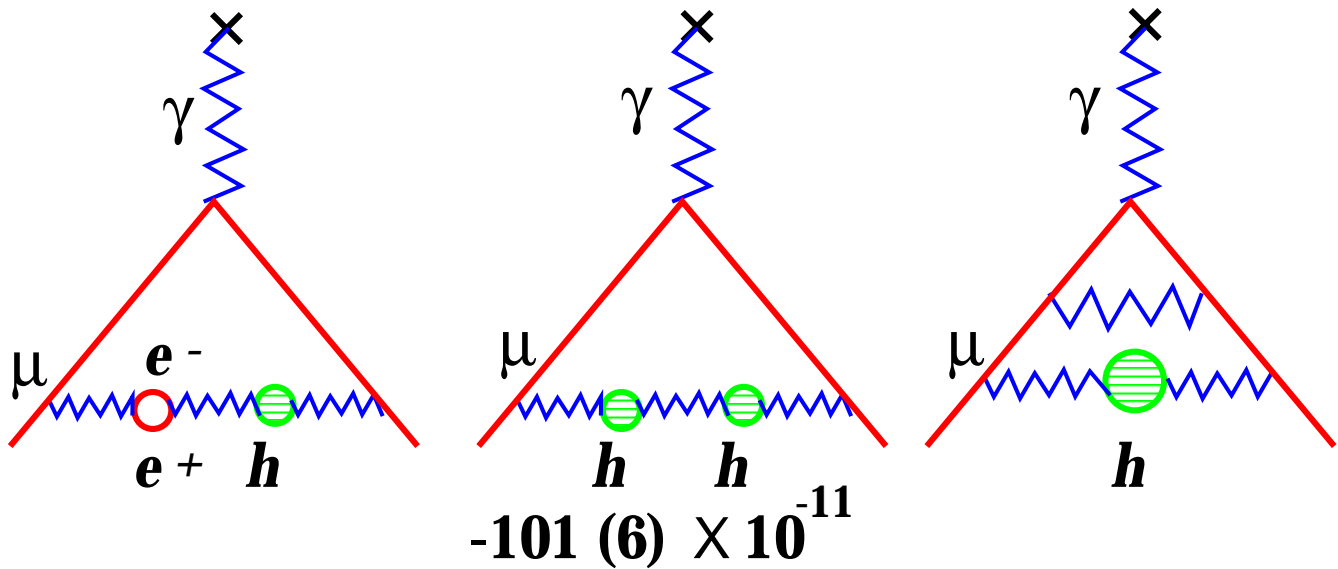
$$a_{\mu}(\text{had}; 1) = 6951(75) \times 10^{-11} \quad (59.62 \pm 0.64) \text{ ppm}$$

M. Davier and A. Höcker, Phys. Lett. 419 (1998) 419.

$$a_{\mu}(\text{had}; 1) = 6924(62) \times 10^{-11} \quad (59.39 \pm 0.53) \text{ ppm}$$

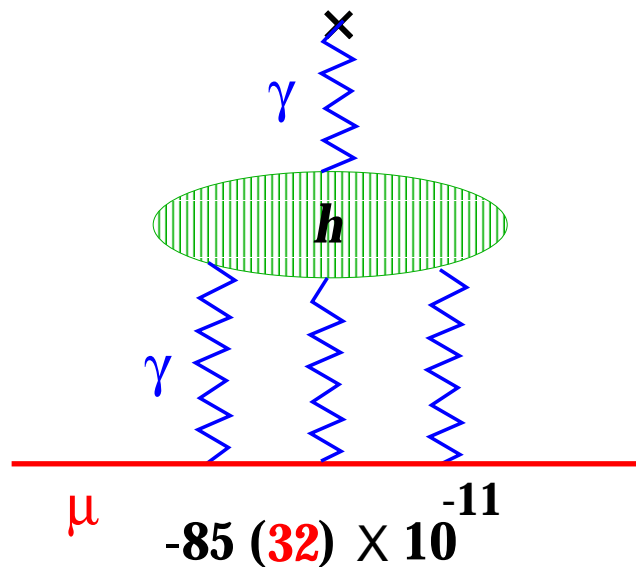
M. Davier and A. Höcker, Phys. Lett. 435 (1998) 427.

Higher Order Hadronic Contribution



Bernd Krause, Phys. Lett. B 390 (1997) 392

Hadronic Light-on-Light Contribution



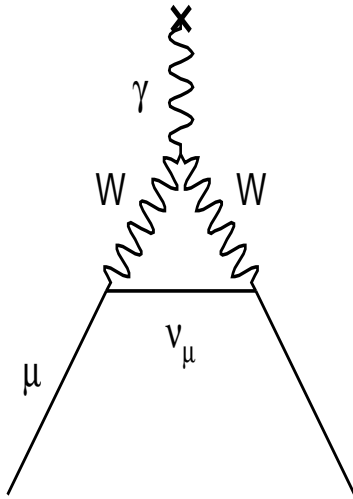
M. Hayakawa and T. Kinoshita, Phys. Rev. D57 (1998) 465
 and J. Bijnens, E. Pallante and J. Prades, Nucl. Phys. B474
 (1996) 379.

The Total Hadronic Contribution

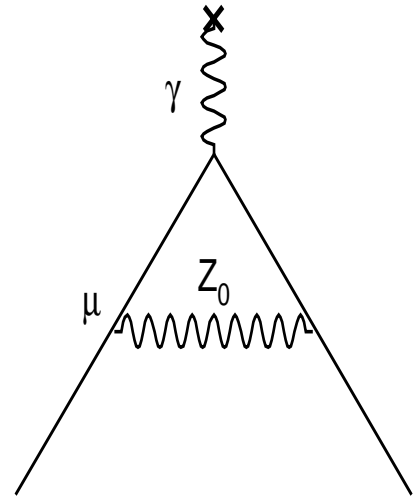
$$a_\mu(\text{had}; 1 + 2 + \text{lol}) = 6738 \text{ (70)} \times 10^{-11} \quad (57.79 \pm 0.60)$$

Weak Contribution

1st order

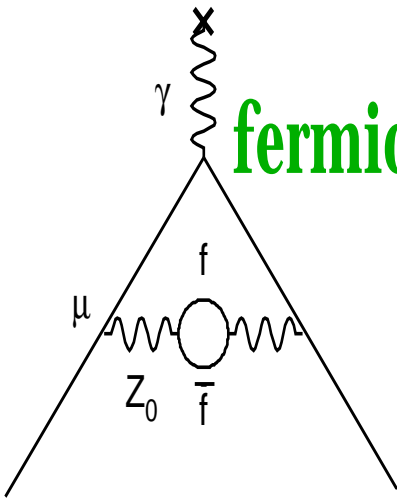


+389

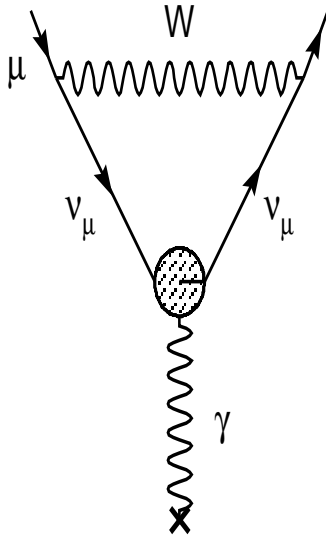


-194

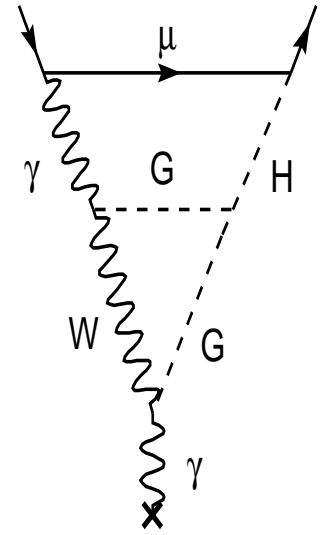
2nd order



fermionic



bosonic



+ many other 2nd order diagrams

$$a_{\mu}(\text{weak}; 1) = 195 \times 10^{-11} \quad (1.7) \text{ ppm}$$

$$a_{\mu}(\text{weak}; 1 + 2) = 151(4) \times 10^{-11} \quad (1.30 \pm 0.03) \text{ ppm}$$

A. Czarnecki, B. Krause and W.J. Marciano, Phys. Rev. D52 (1995) R2619 and Phys. Rev. Lett. 76 (1996) 3267

Summary

Theoretical and Experimental Information

$$a_\mu(\text{QED}) = 1\,165\,847\,05.7(2) \times 10^{-11} \quad (\pm 17 \text{ ppb})$$

$$a_\mu(\text{had}) = 6738(70) \times 10^{-11} \quad (57.79 \pm 0.60) \text{ ppm}$$

$$a_\mu(\text{weak}) = 151(4) \times 10^{-11} \quad (1.30 \pm 0.03) \text{ ppm}$$

The Total Standard Model Value of a_μ is

$$a_\mu(\text{SM}) = (116\,591\,594.7 \pm 70) \times 10^{-11} \quad (\pm 0.60 \text{ ppm})$$

The experimental value is

$$a_\mu(\text{exp}) = (116\,592\,350 \pm 730) \times 10^{-11} \quad (\pm 6.3 \text{ ppm})$$

or

$$a_\mu(\text{exp}) - a_\mu(\text{theory}) = (755 \pm 733) \times 10^{-11}$$

E821 goal: $\pm 40 \times 10^{-11}$ or $\pm 0.35 \text{ ppm}$

$(g - 2)$ is Sensitive to New Physics

If $\sigma_{a_\mu} = 0.35$ ppm then:

MUON SUBSTRUCTURE

$$\Delta a_\mu \sim \frac{m_\mu^2}{\Lambda^2} \quad \Lambda \geq 5 \text{ TeV} \quad \text{LHC domain}$$

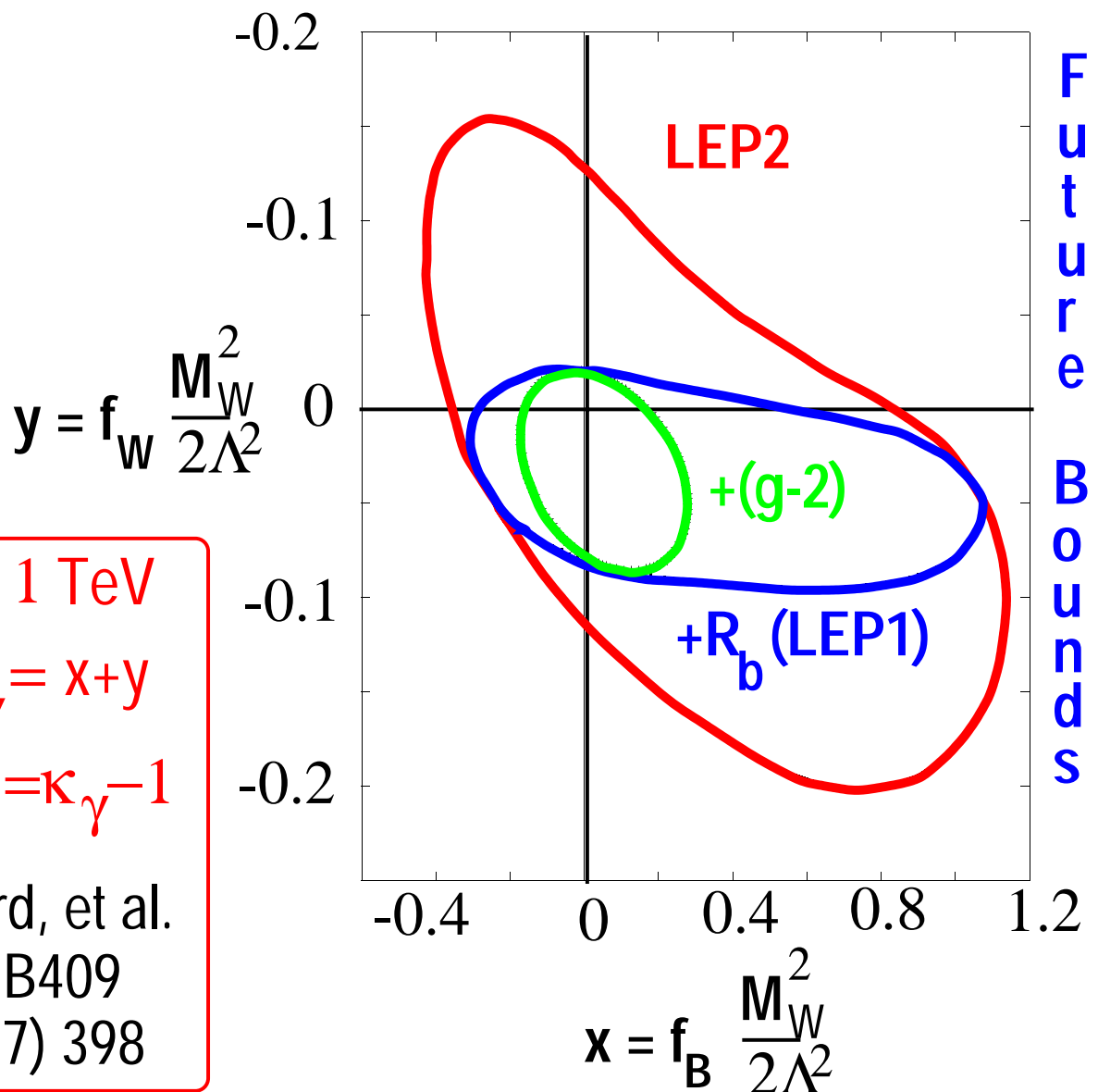
W COMPOSITENESS/ANOMALOUS COUPLINGS

$$\Lambda \geq 400 \text{ GeV}$$

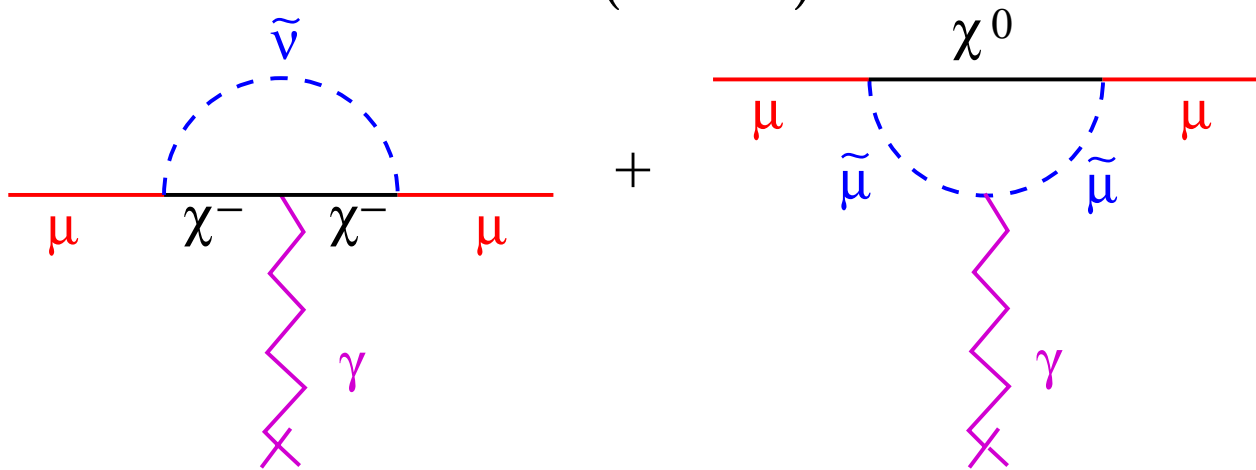
$$\text{LEP II} \sim 100 - 200 \text{ GeV}$$

$$\mu_W = \frac{e}{2m_W} (1 + \kappa + \lambda)$$

$$a_\mu(\kappa, \lambda) \simeq \frac{G_F m_\mu^2}{4\sqrt{2}\pi^2} \left[(\kappa - 1) \ln \frac{\Lambda^2}{m_W^2} - \frac{1}{3}\lambda \right]$$



SUPER SYMMETRY (SUSY)



a_μ is sensitive to any SUSY model with large $\tan \beta$

If $\tan \beta \gg 1$ the $\chi^- \tilde{\nu}$ diagram dominates.
For large $\tan \beta$:

$$\begin{aligned}
 a_\mu (\text{SUSY}) &\simeq \frac{\alpha}{8\pi \sin^2 \theta_W} \frac{m_\mu^2}{\tilde{m}^2} \tan \beta \\
 &\simeq 140 \times 10^{-11} \left(\frac{100 \text{ GeV}}{\tilde{m}} \right)^2 \tan \beta \\
 &\quad (1.23 \text{ ppm})
 \end{aligned}$$

If $\tilde{m} = 750 \text{ GeV}$ and $\tan \beta = 40$ then:

$$a_\mu (\text{SUSY}) = 100 \times 10^{-11}$$

- BNL Goal is $\pm 40 \times 10^{-11}$ ($\pm 0.35 \text{ ppm}$)
- $(g - 2)_\mu$ already improves LEP2 bounds.

- If $\tilde{\nu}$ is light, chargino production is suppressed.
- If the chargino is only slightly heavier than the $\tilde{\nu}$, the decay products are hard to detect.

Current E821 Collaboration

R.M. Carey, W. Earle, E. Efsthadiadis, M. Hare, E.S. Hazen, F. Krienen, J.P. Miller, J. Paley, O. Rind, B.L. Roberts, L.R. Sulak, A. Trofimov, - **Boston University**

H.N. Brown, G. Bunce, G.T. Danby, M. Grosse-Perdekamp, R. Larsen, Y.Y. Lee, W. Meng, J.-L. Mi, W.M. Morse, C. Özben, C. Pai, R. Prigl, R. Sanders, Y.K. Semertzidis, D. Warburton - **Brookhaven National Laboratory**

Y. Orlov - **Cornell University**

D. Winn - **Fairfield University**

A. Grossmann, K. Jungmann, I. Rheinhardt, G. zu Putlitz - **University of Heidelberg**

P.T. Debevec, W. Deninger, F. Gray, D.W. Hertzog, C.J.G. Onderwater, C. Polly, S. Sedyk, M. Sossong, D. Urner - **University of Illinois**

U. Haeberlen - **Max Planck Institute für Med. Forschung, Heidelberg**

P. Cushman, L. Duong, S. Giron, J. Kindem, I. Kronkvist, R. McNabb, D. Miller, C. Timmermans, D. Zimmerman - **University of Minnesota**

V.P. Druzhinin, G.V. Fedotovitch, B.I. Khazin, I. Logashenko, N.M. Ryskulov, S. Serednyakov, Yu.M. Shatunov, E. Solodov - **Budker Institute of Nuclear Physics, Novosibirsk**

A. Yamamoto - **KEK**

M. Iwasaki, M. Kawamura - **Tokyo Institute of Technology**

H. Deng, S.K. Dhawan, F.J.M. Farley, V.W. Hughes, D. Kawall, J. Pretz, S.I. Redin, A. Steinmetz - **Yale University**

The Technique

- Use the AGS to make a 3.1 GeV π beam.
- 115 m beamline choose π or μ at a momentum slit and bring the π or μ beam through an iron-free Superconducting Inflector.
- Store $\vec{\mu}$ in Ring by a kick, μ spin motion:

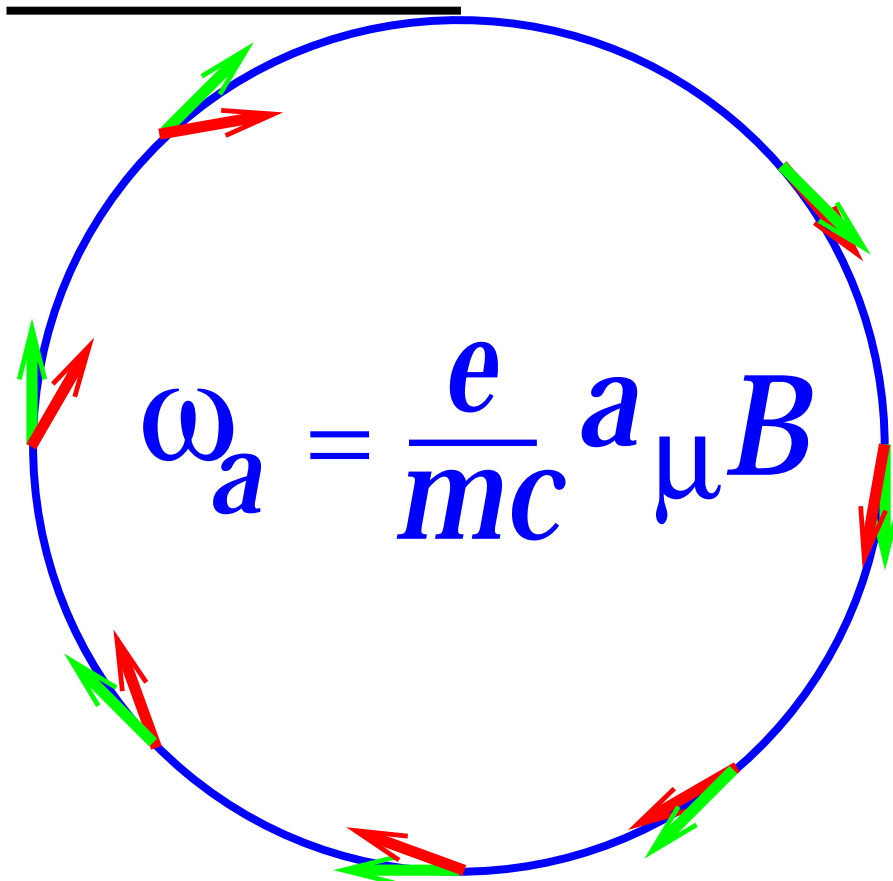
$$\vec{\omega}_a = \frac{d\Theta_R}{dt} = \frac{e}{mc} \left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1} \right) \vec{\beta} \times \vec{E} \right]$$

for magic γ $\left(a_\mu - \frac{1}{\gamma^2 - 1} \right) = 0$

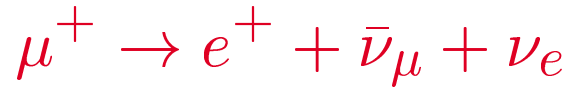
$\gamma = 29.3$ and $p_\mu = 3.094$ GeV/c.

Momentum \rightarrow

Spin \rightarrow



- Count High Energy Electrons, $E_e \geq 1.5$ GeV, from



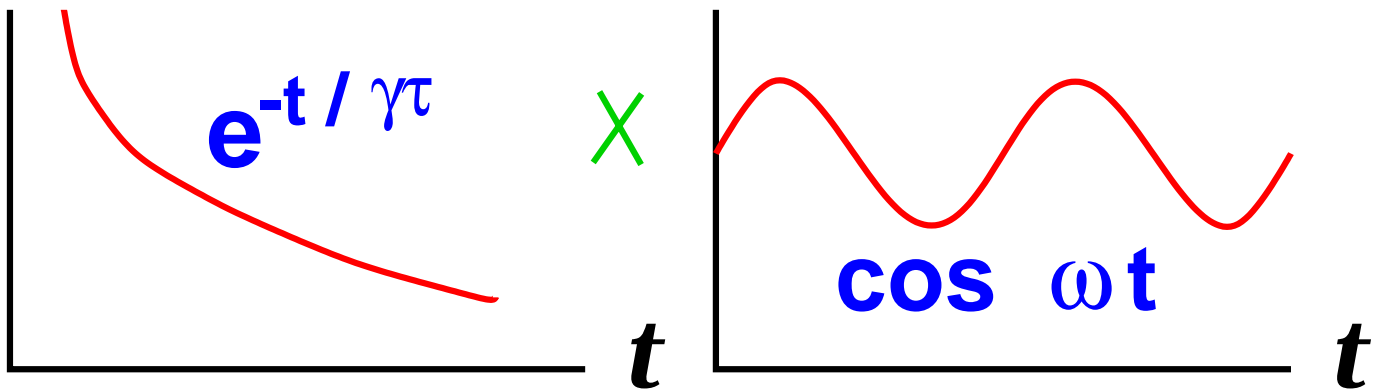
as a Function of Time.

- Fit Time Spectrum to

$$N(t) = N_0 e^{-t/\gamma\tau} [1 - A \cos(\omega_a t + \phi)]$$

to determine the $(g - 2)$ frequency

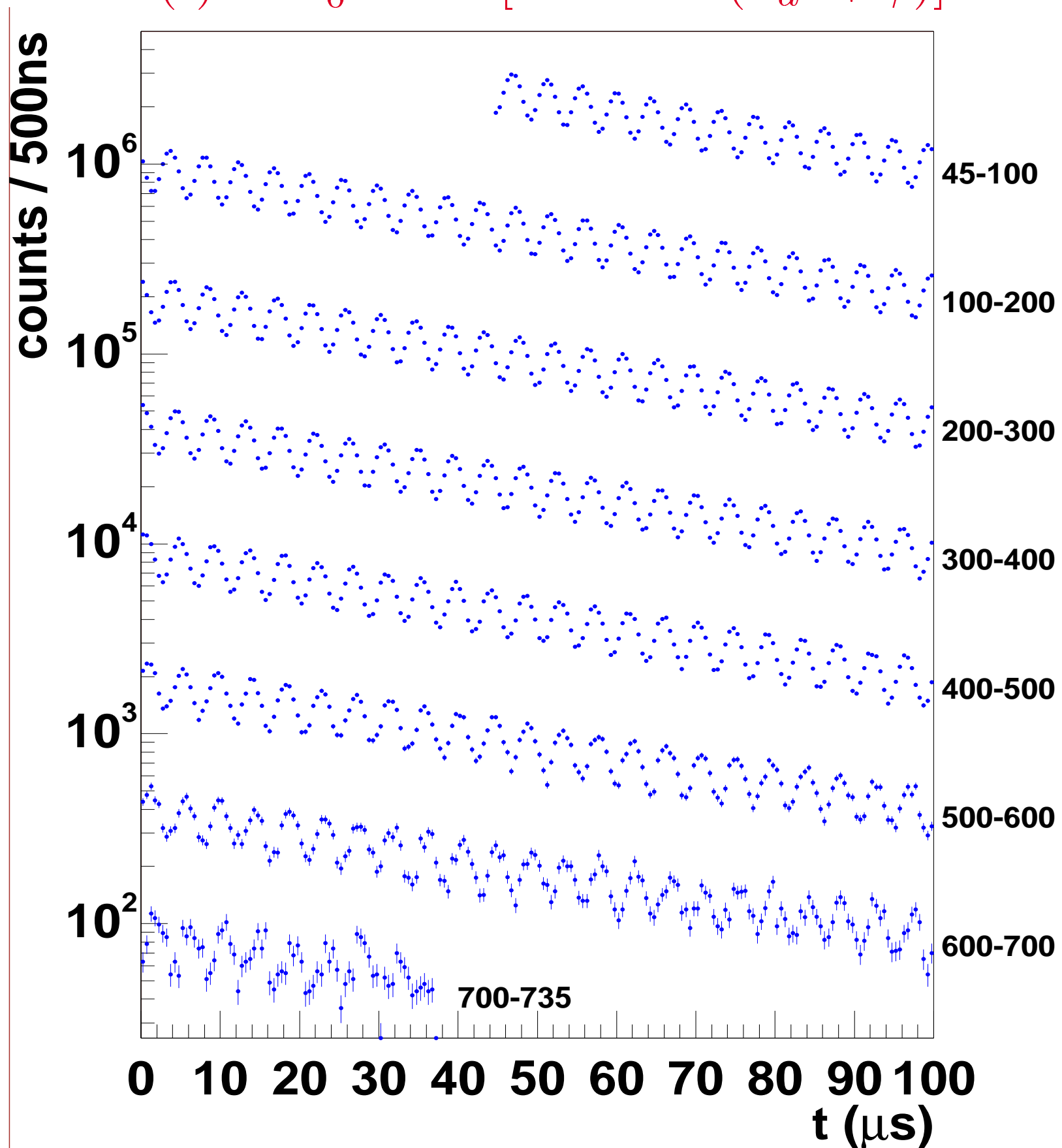
$$\delta\varepsilon = \frac{\delta\omega_a}{\omega_a} = \frac{\sqrt{2}}{2\pi f_a \tau_\mu N^{\frac{1}{2}} A}$$



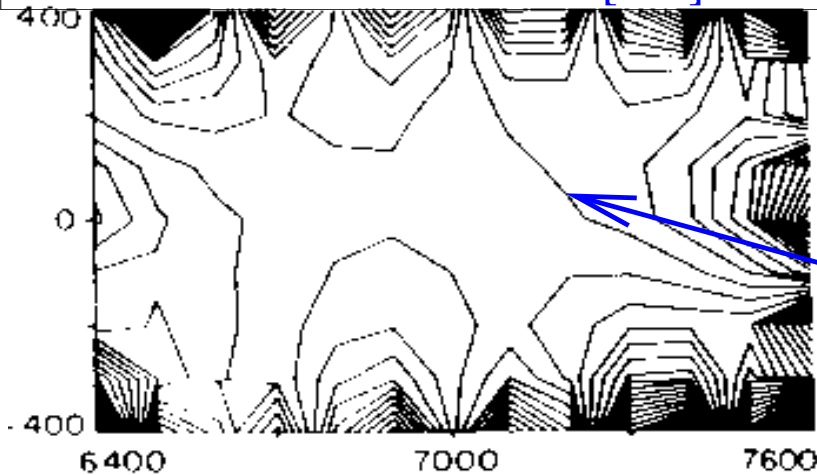
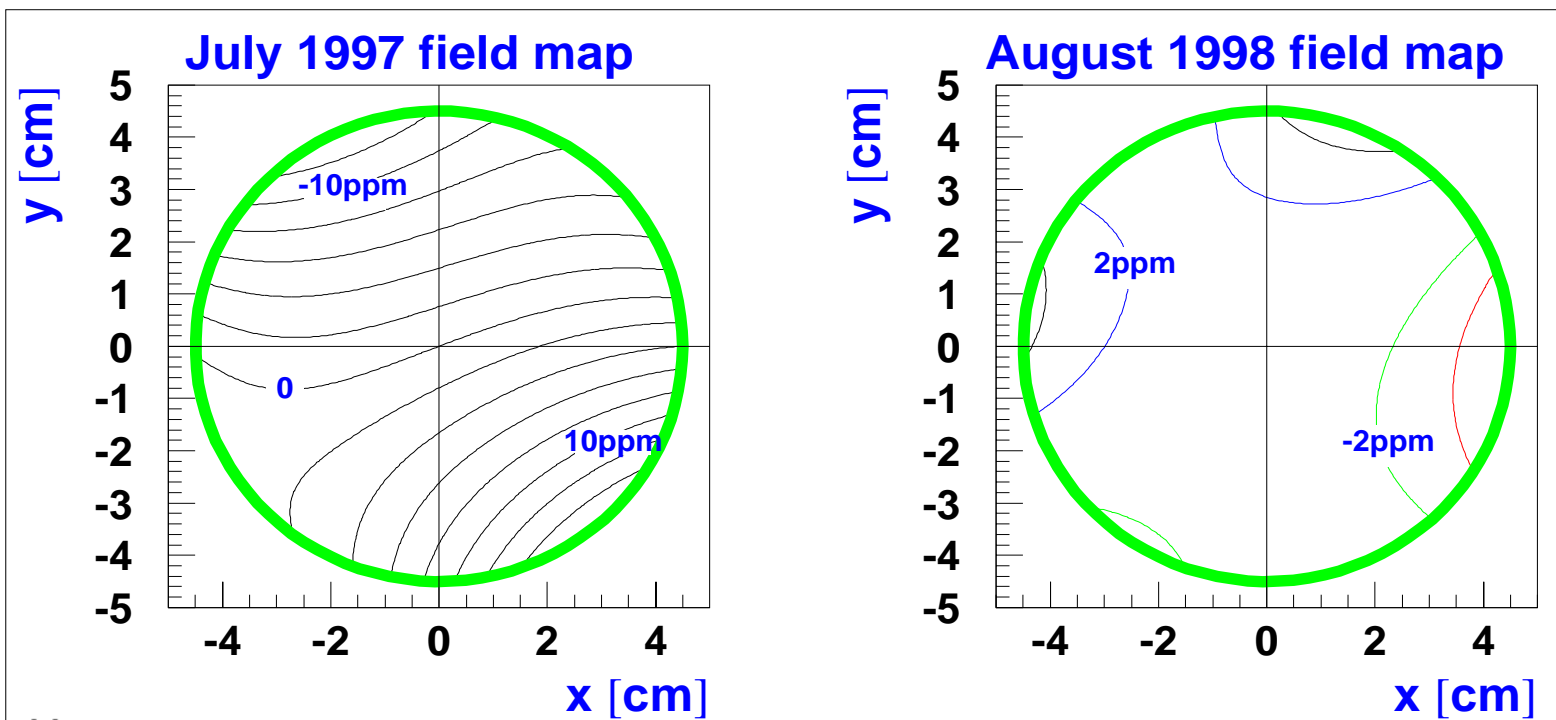
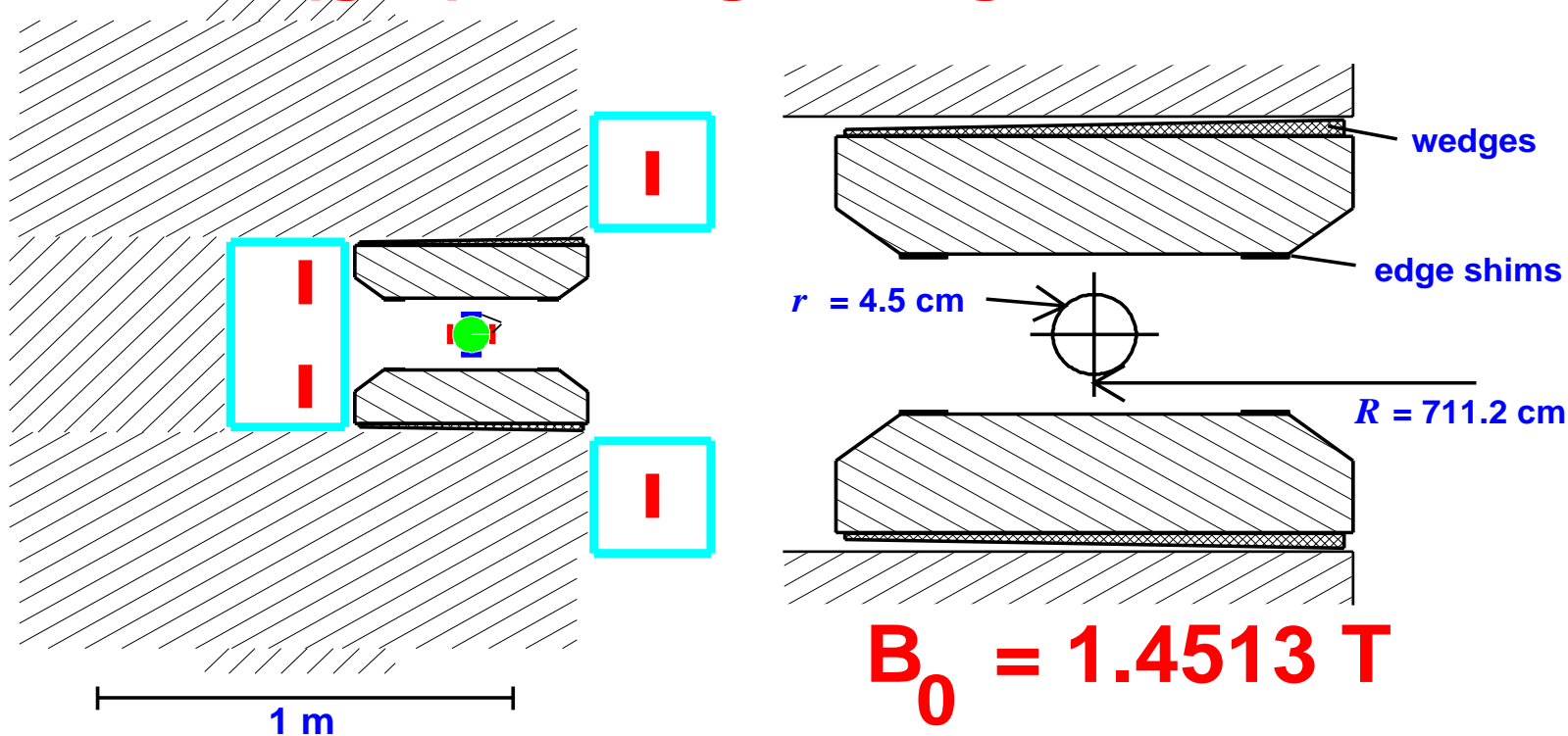
A Sample of the 1999 Data:

$E > 1.8 \text{ GeV}$, $357 \times 10^6 \text{ e}$

$$N(t) = N_0 e^{-t/\gamma\tau} [1 - A \cos(\omega_{at} + \phi)]$$



Muon (g-2) Storage Ring and B Field



CERN B Field

2 ppm contours

Inflector Chamber Height

711.2 cm^R

Inflector

7
~~78~~ mm

Pole

Need 0.1 Tm
~ 10 mrad^c kick

0.155

0.213

0.088

0.080

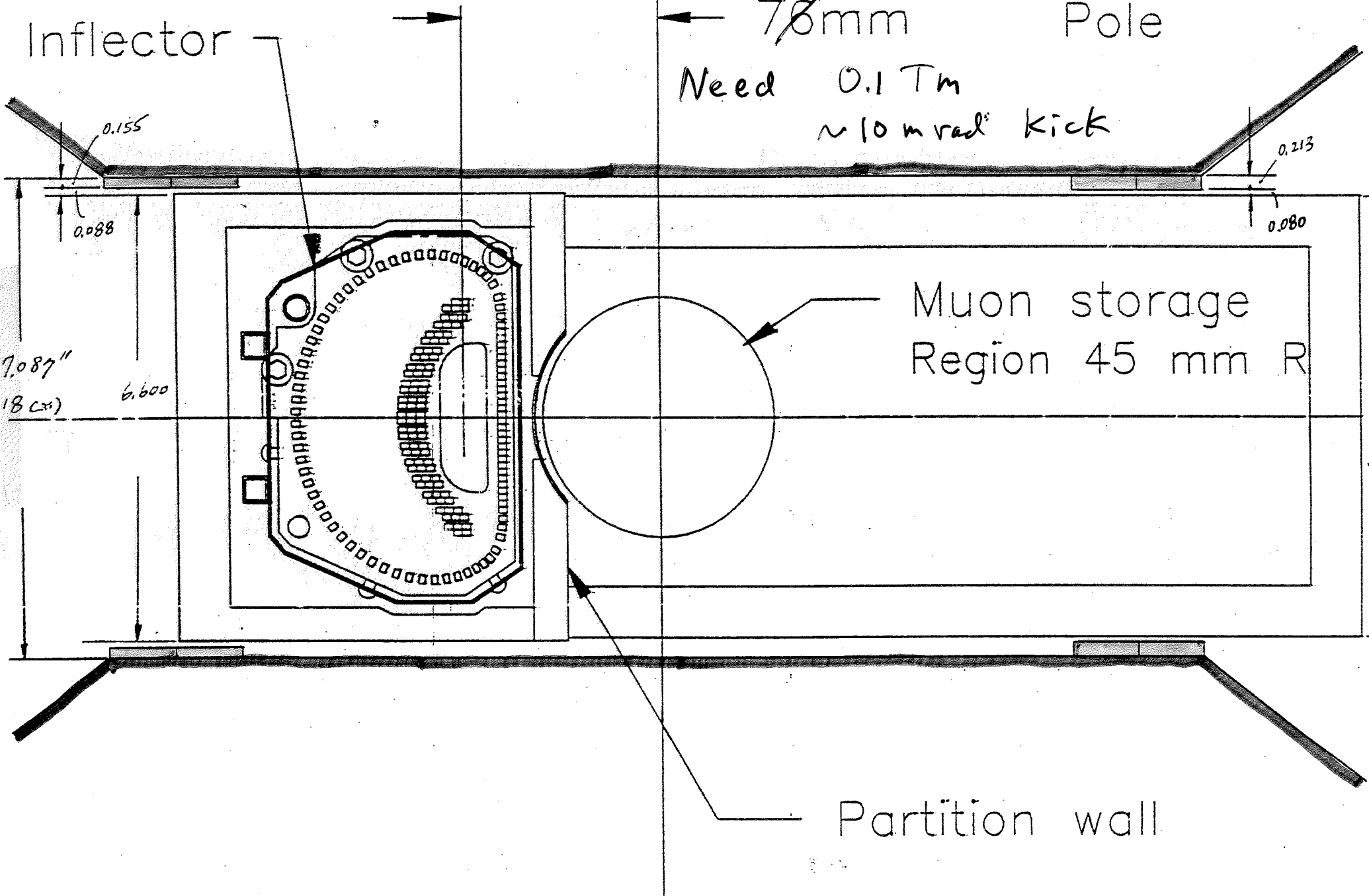
7.087"
(18 cm)

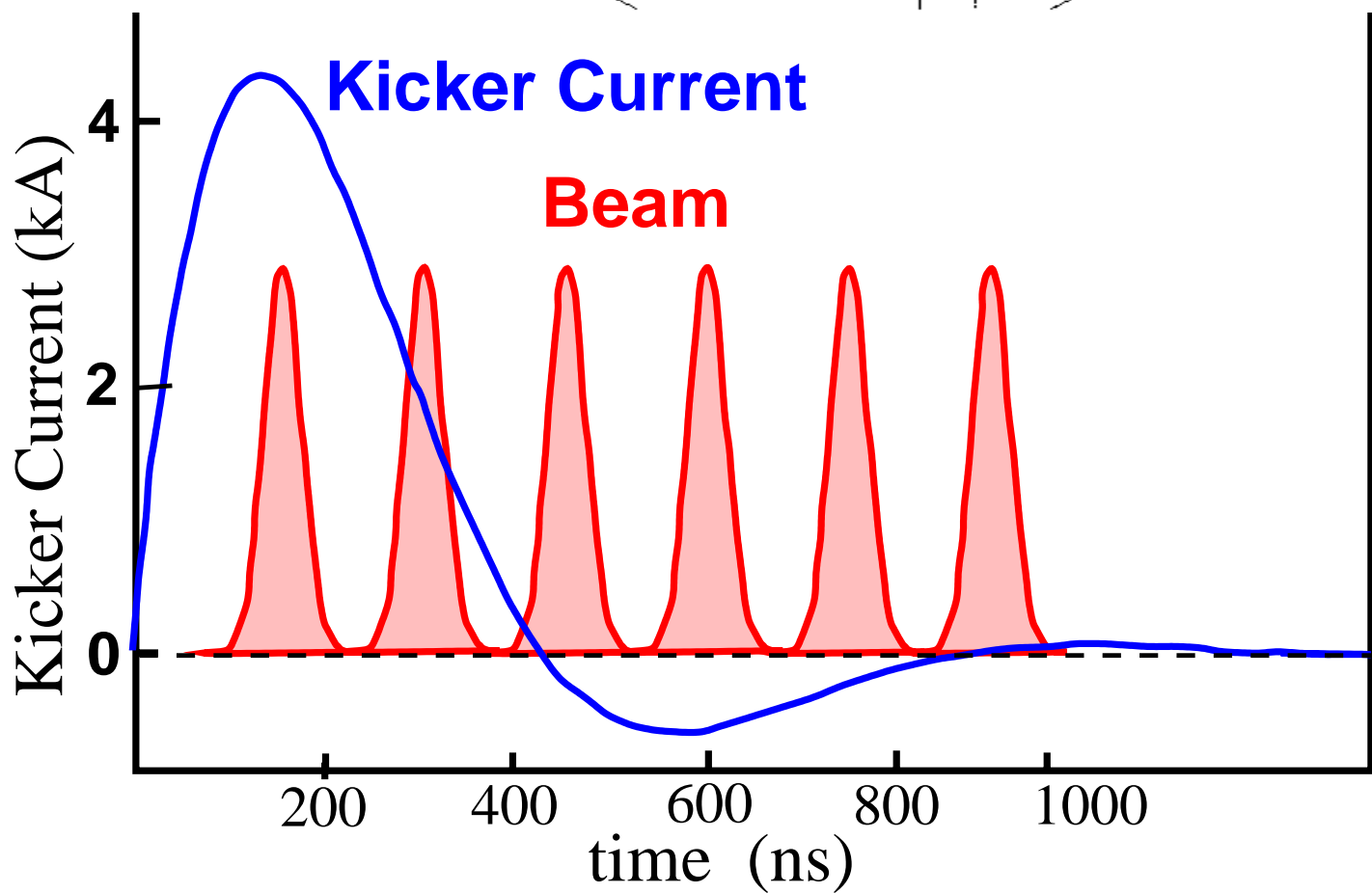
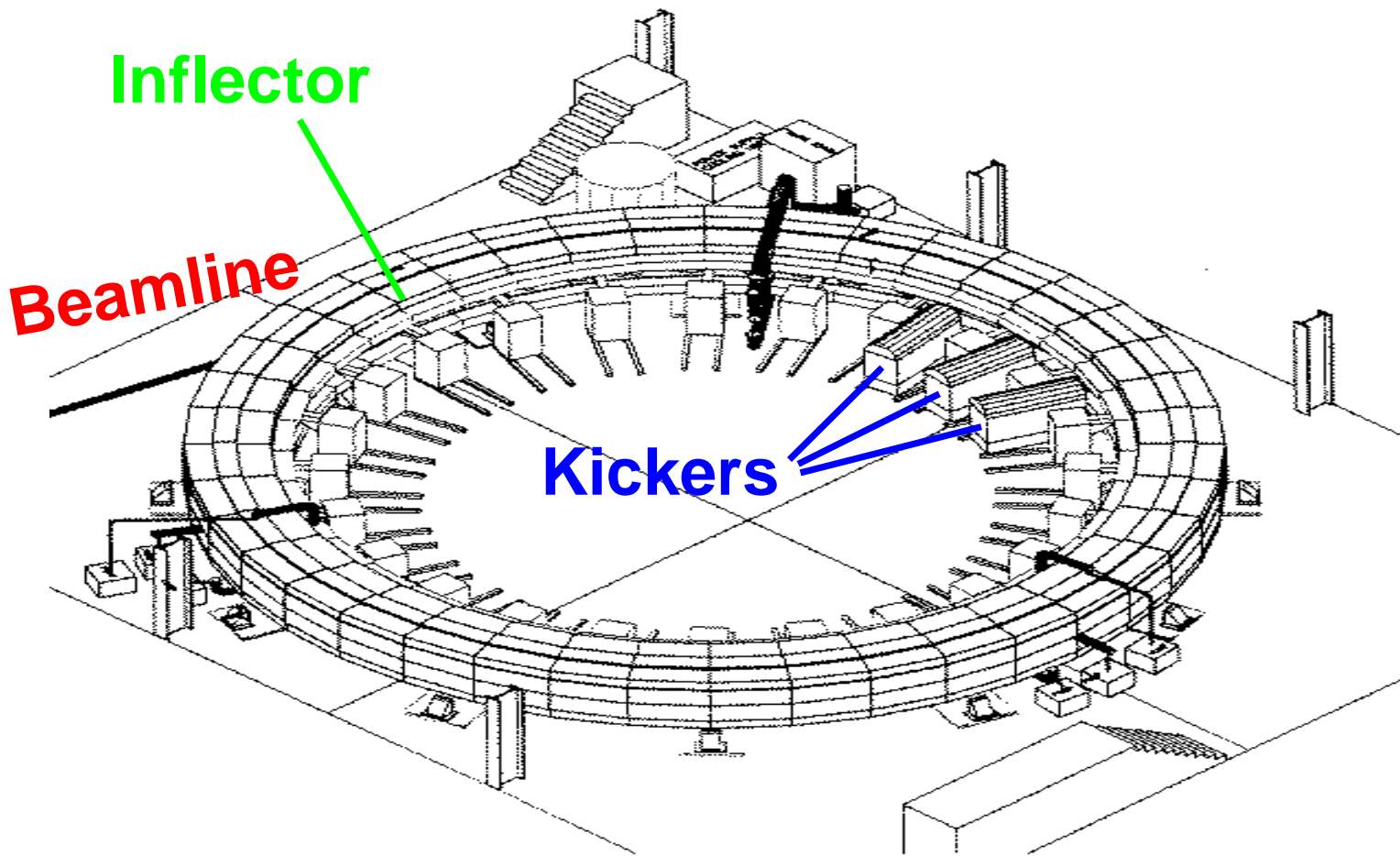
6.600

6.500

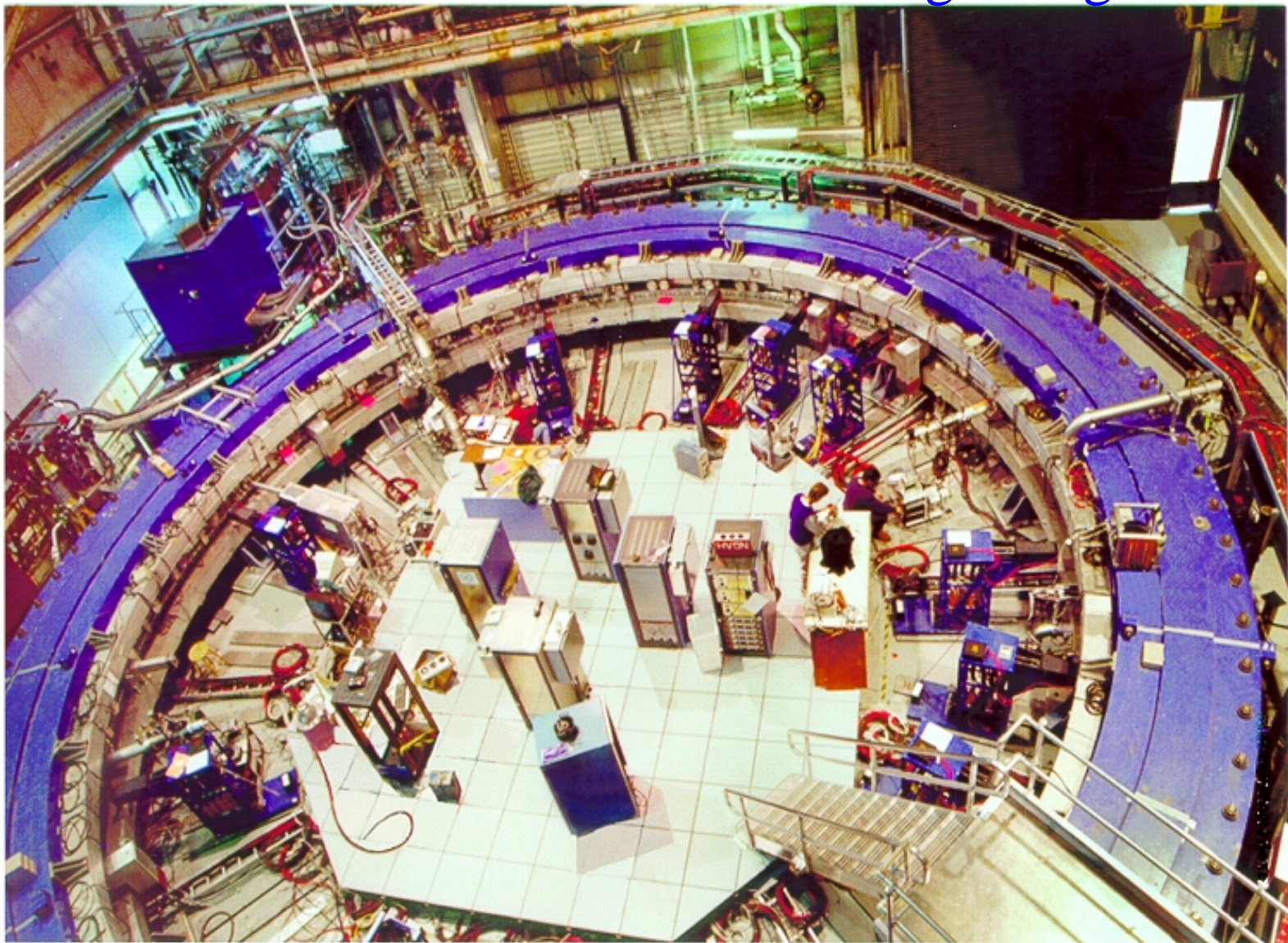
Muon storage
Region 45 mm R

Partition wall

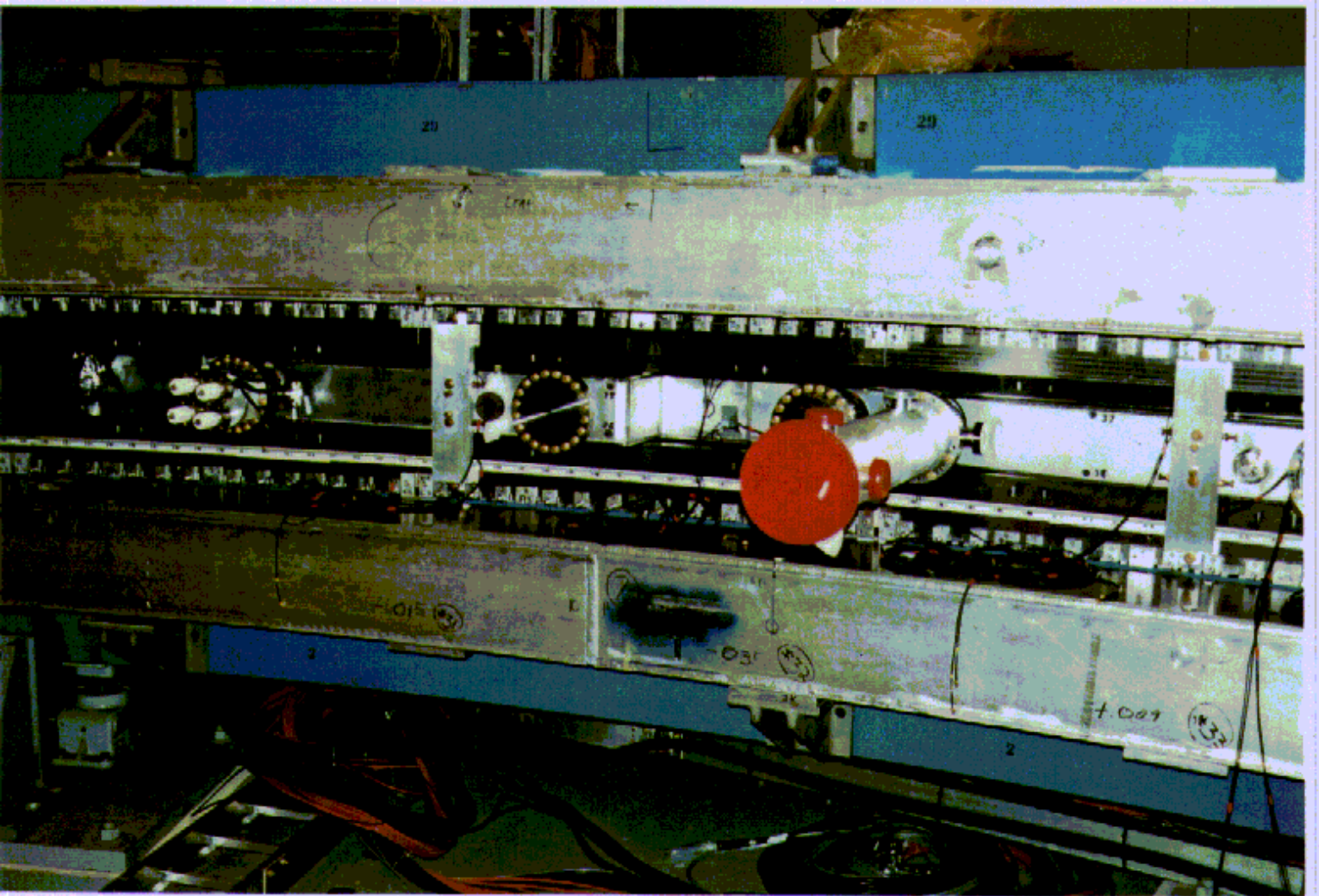




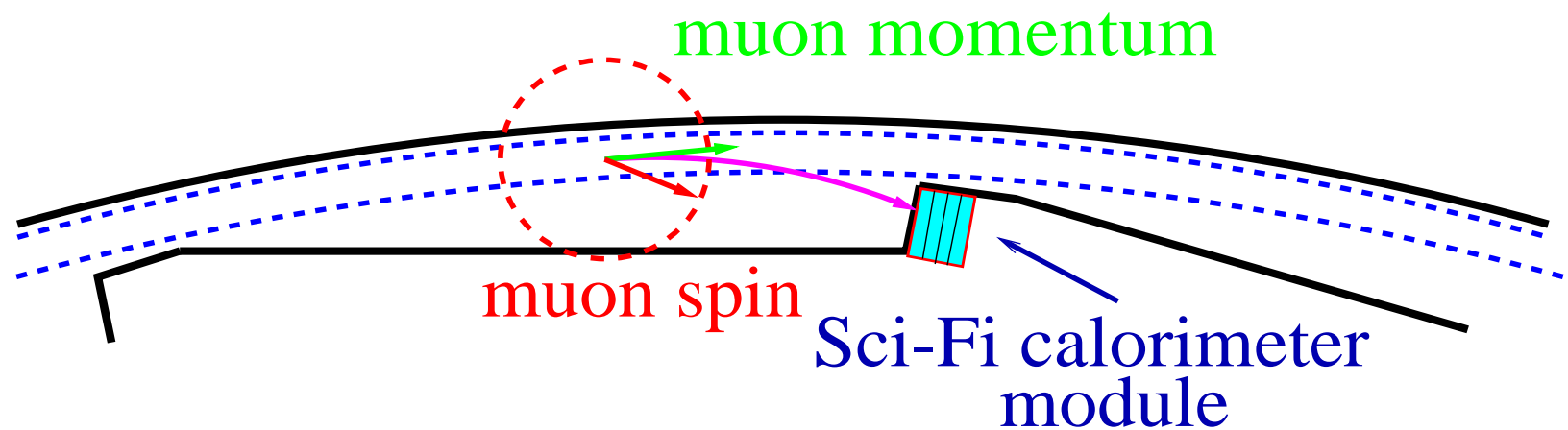
Brookhaven E821 Muon Storage Ring



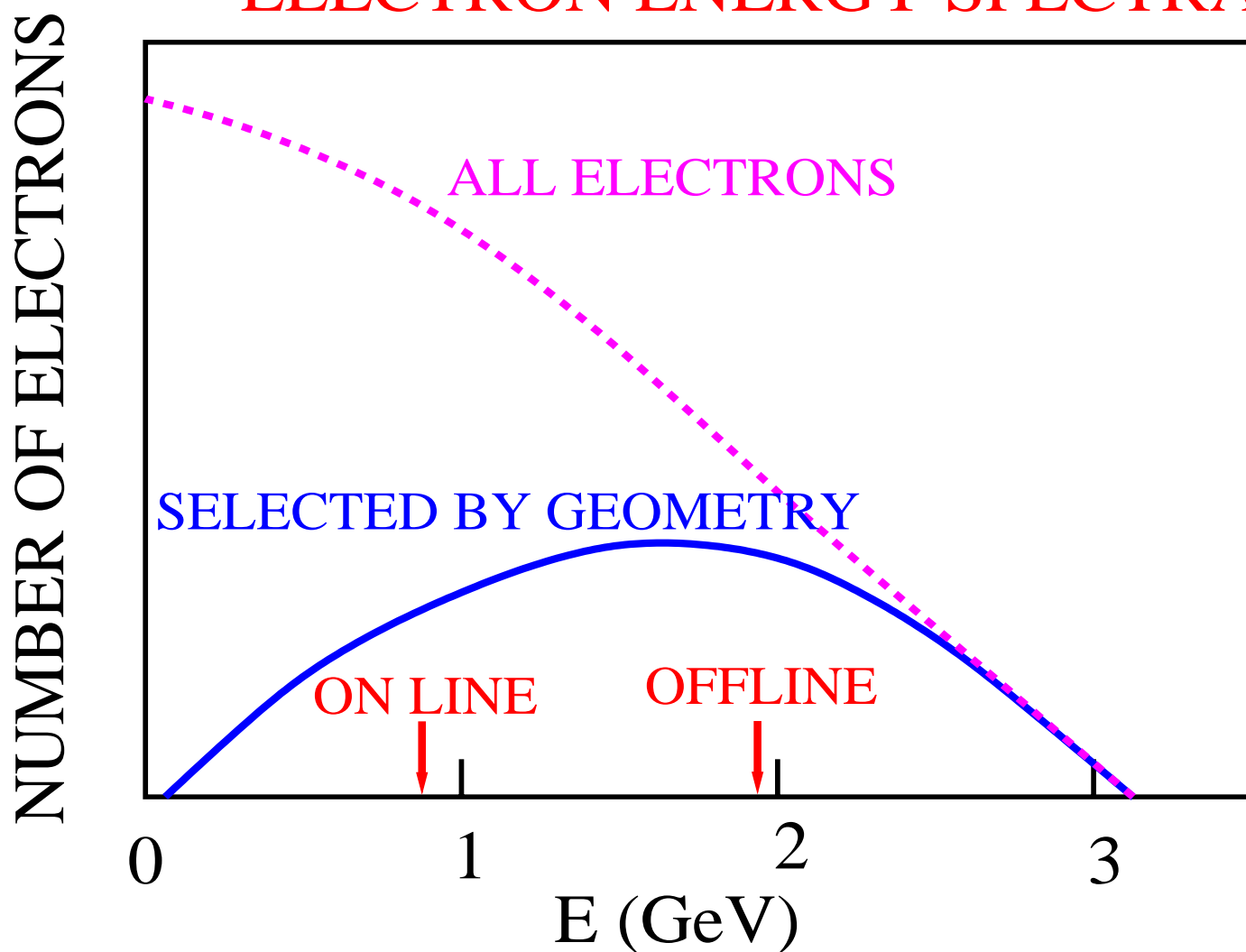
| <u>Parameter</u> | <u>Value</u> | <u>Comments</u> |
|-------------------|--|--|
| $(g-2)$ Frequency | $f_a \sim 0.23 \times 10^6 / \text{s}$ | $\omega_a = 2\pi f_a$ $\tau_a = 4.37 \mu\text{s}$ |
| Muon Lifetime | $\gamma\tau = 64.4 \mu\text{s}$ | |
| Muon kinematics | $p_\mu = 3.094 \text{ GeV}/c$ $\gamma_\mu = 29.3$ | |
| Cyclotron Period | $\tau_{cyc} = 149 \text{ ns}$ | |
| Central Radius | $\rho = 7112 \text{ mm}$ | (280'') |
| Magnetic Field | $B = 1.451 \text{ T}$ | |
| Storage Aperture | 9.0 cm circle | |
| In one lifetime: | 432 revolutions around ring 14.7 $(g-2)$ periods | |



Shape of the ring vacuum chamber is designed to optimize the decay electron detection.



ELECTRON ENERGY SPECTRA



High energy electrons carry largest Asymmetry

Data Analysis (Done blind):

$$\omega_a = \frac{e}{mc} a \mu B$$

$$\langle \omega_p \rangle, \langle \mathbf{B} \rangle \text{ (weighted)} \langle B \rangle = \int_V M(\mathbf{r}) \mathbf{B}(\mathbf{r}) d^3\mathbf{r}$$

Track \mathbf{B} with 366 fixed NMR Probes, ω_p

Map field periodically with trolley.

Calibrate trolley probes with plunging probe.

Calibrate plunging probe to spherical H_2O probe.

Weight ω_p (\mathbf{B}) with the muon distribution.

Determine $\langle \omega_p \rangle$ and thus $\langle \mathbf{B} \rangle$.

ω_a

Fit decay electron (positron) spectrum for ω_a

Remove offsets and divide to determine

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

400 MHz WFD (custom)

ata/raw/r0002479.dat

Control Data Options

Hel

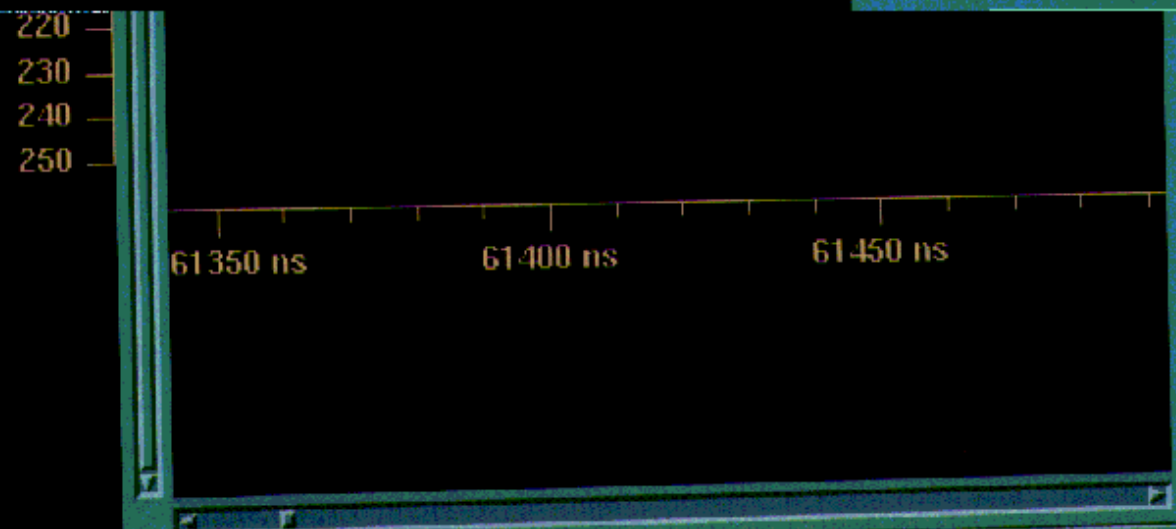


Detector

| | | |
|--|-----------------------------|-----------------------------|
| <input type="checkbox"/> 1 | <input type="checkbox"/> 2 | <input type="checkbox"/> 3 |
| <input type="checkbox"/> 4 | <input type="checkbox"/> 5 | <input type="checkbox"/> 6 |
| <input type="checkbox"/> 7 | <input type="checkbox"/> 8 | <input type="checkbox"/> 9 |
| <input type="checkbox"/> 10 | <input type="checkbox"/> 11 | <input type="checkbox"/> 12 |
| <input type="checkbox"/> 13 | <input type="checkbox"/> 14 | <input type="checkbox"/> 15 |
| <input checked="" type="checkbox"/> 16 | <input type="checkbox"/> 17 | <input type="checkbox"/> 18 |
| <input type="checkbox"/> 19 | <input type="checkbox"/> 20 | <input type="checkbox"/> 21 |
| <input type="checkbox"/> 22 | <input type="checkbox"/> 23 | <input type="checkbox"/> 24 |

Run: 2479
Event: 3
Spill: 1 (6)
Type: **EVENT**
Length: 143916

14904
C: 3229
a.total:
a.used:



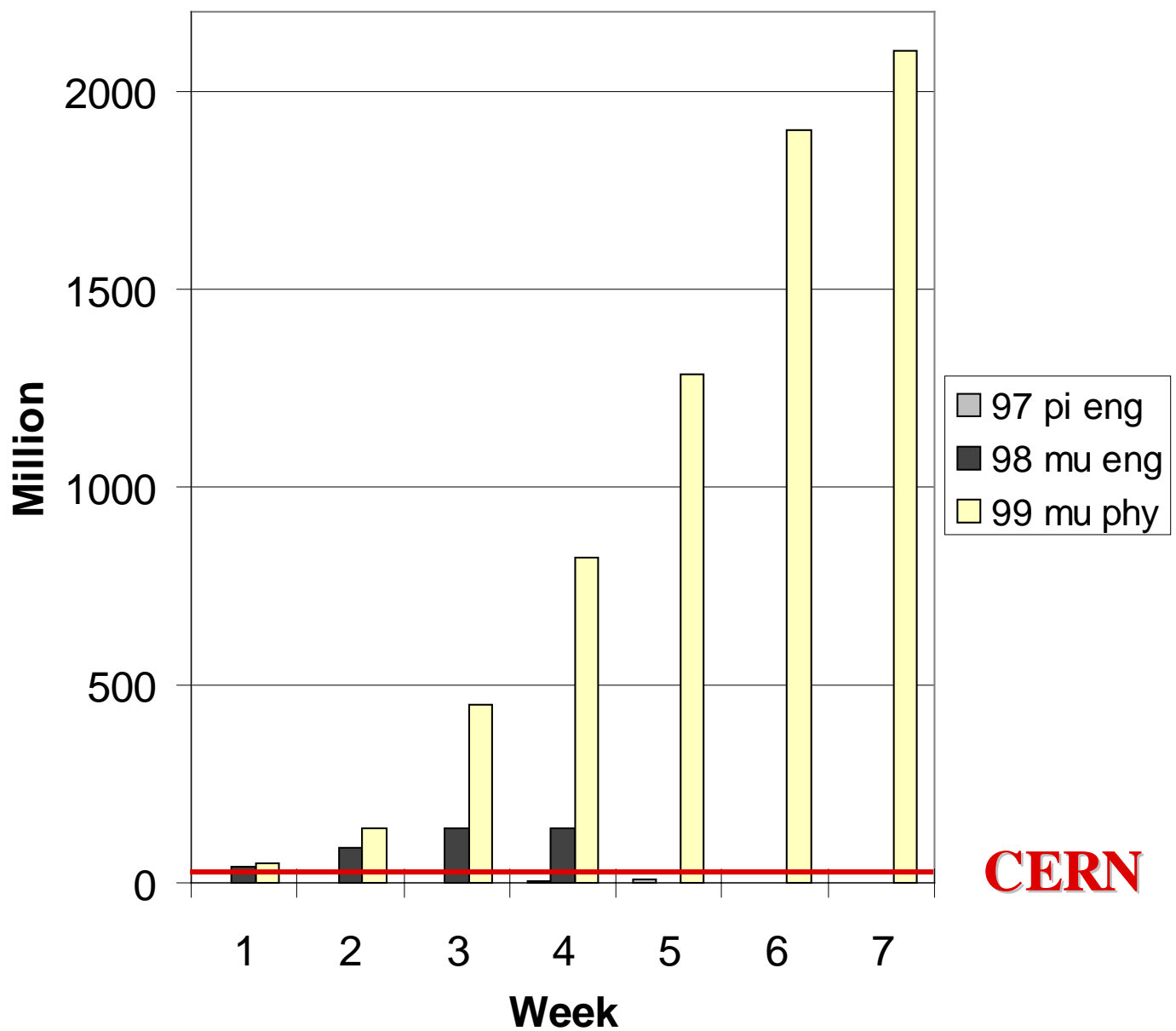
WFD:
MTD:
Mem:
Mem:

Options

Next Event Skp... Next Spill Find Pulse Zoom In Zoom Out

Data Volume

- Number of measured positrons with Energy $> 1.8\text{GeV}$.



CERN

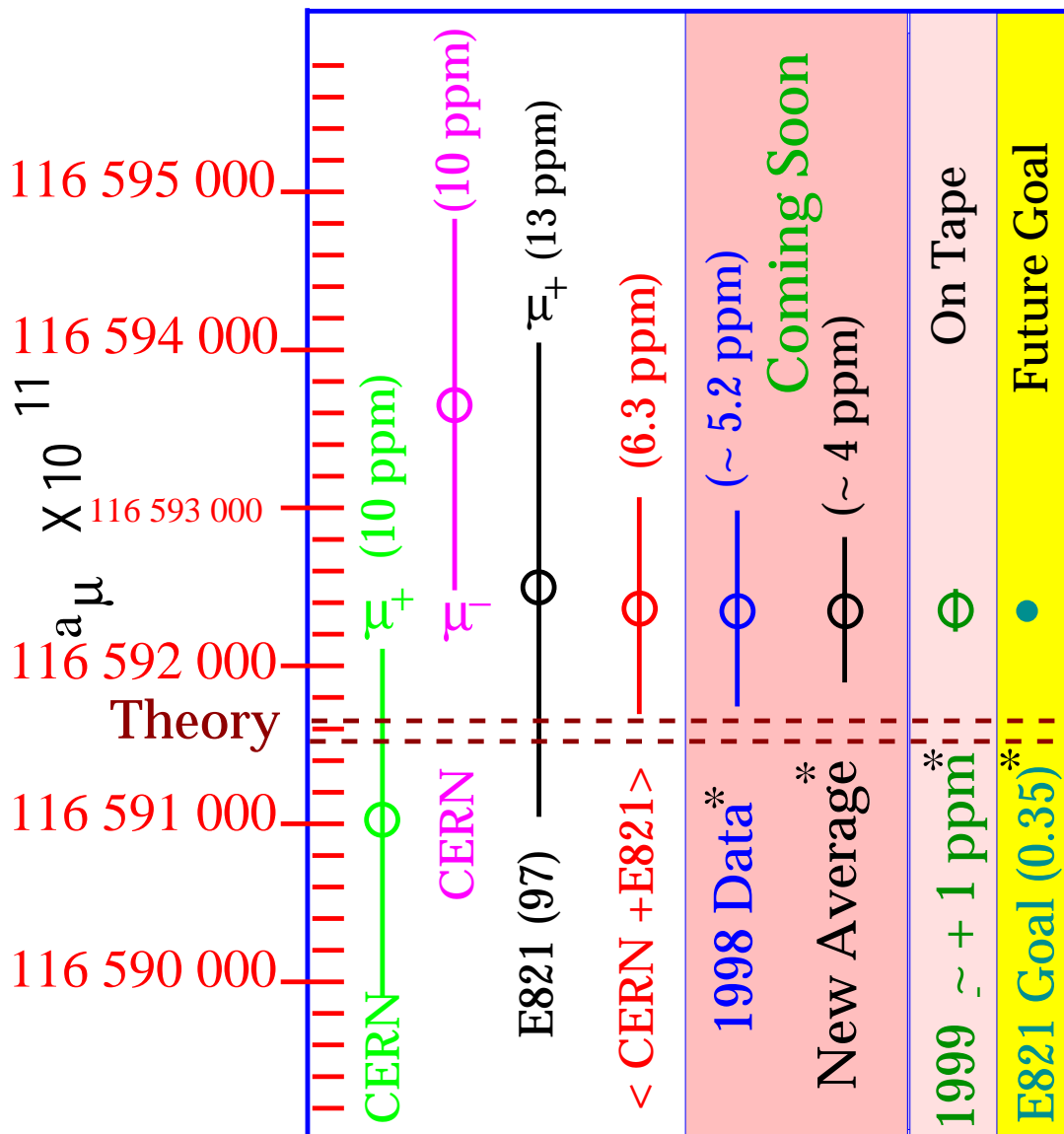
Results and Projections

(1997 Data) $R = \frac{\omega_a}{\omega_p} = 3.707\,220\,(47)\,(11)$

$a_\mu = \frac{R}{\lambda - R}$ $\lambda = \frac{\mu_\mu}{\mu_p} = 3.183\,345\,47\,(47)$

$a_\mu(E821) = (116\,592\,501 \pm 1516) \times 10^{-11}$ (± 13 ppm)

(BNL & CERN) $= (116\,592\,344 \pm 730) \times 10^{-11}$ (± 6.3 ppm)



*projected errors with current value

Systematic Errors

1997 Data:

Systematic error = ± 2.9 ppm (13 ppm total error)

The largest components, 2.0 and 1.5 ppm, 2.5 ppm of total, are gone!

The two dominant remaining systematic errors on ω_p (**B**) and $\langle \omega_p \rangle_\mu$ ($\langle \mathbf{B} \rangle_\mu$) were 1.0 and 0.9 ppm.

ω_p **B-Field** Related Errors from 1997, and projected errors for 1998 and 2000

| | 1997 (ppm) | 1998 Est (ppm) | 2000 Est (ppm) |
|--------------------------------|---------------|-------------------|-------------------|
| ω_p | 1 | 0.5 | 0.1 - 0.25 |
| $\langle \omega_p \rangle_\mu$ | 0.9 | 0.2-0.3 | 0.1 |

Conclusions:

- **The ($g-2$) Experiment has entered the production / running phase.**
- **A 5 ppm result will come soon.**
- **A 1 ppm result should come next year.**
- **The systematic errors are continuing to decrease faster than then statistical errors.**