V. Elektroschwache Präzisionsmessungen

Michael Kobel
SoSe 2011

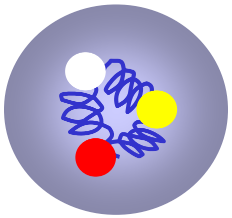
V.7.3. Anomales magnetisches Moment $(g-2)_\mu$

- Das gyromagnetische Verhältnis *g* verknüpft Spin und magnetisches Moment $\vec{\mu}_S = g\left(\frac{e}{2m}\right)\vec{S}$
- Dirac Theorie für punktförmige Spin-1/2 Teilchen: $g = 2$ aber ...
  - Proton
  - Hyperonen

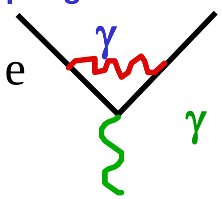
  } **g >> 2**

  - Elektron
  - Myon

  } **g almost equal to 2**



coupling to virtual fields



- Das *anomale* magnetische Moment des Myons ist

$$a_\mu = \frac{(g-2)_\mu}{2} \approx \frac{\alpha}{2\pi} \approx \frac{1}{800}$$

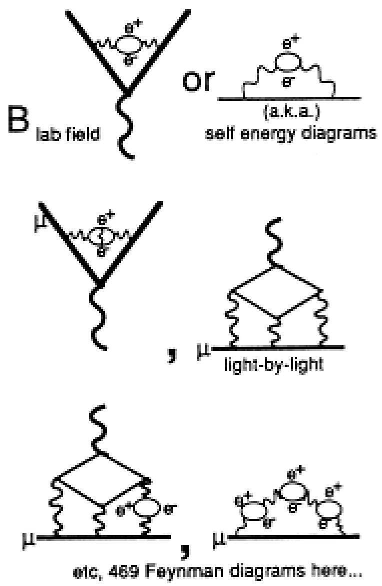
Muon anomalous magnetic moment

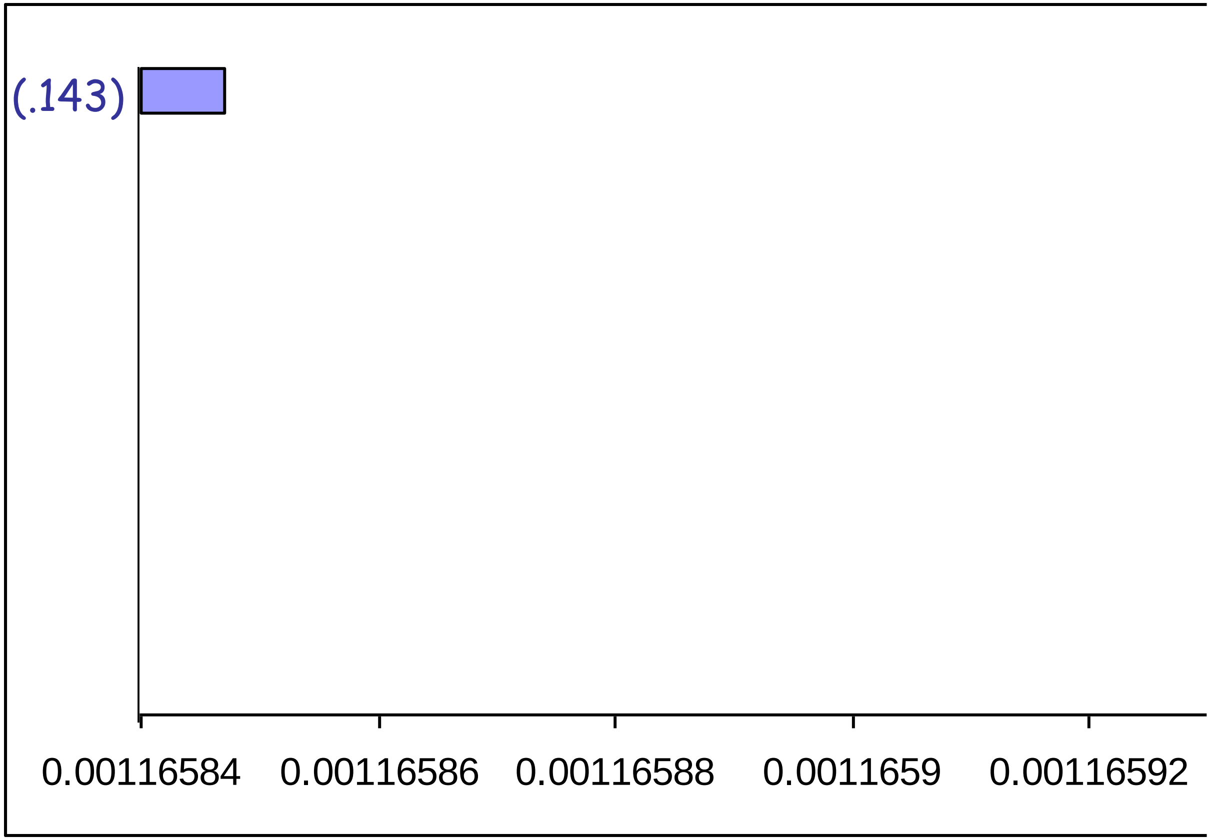
Coupling to X goes as m_μ^2/m_X^2
factor of 40,000 compared to e

$$a_\mu(SM) = a_\mu(QED) + a_\mu(weak) + a_\mu(had)$$

x 10^{-10}

$a_\mu(QED) = 11658471.935$





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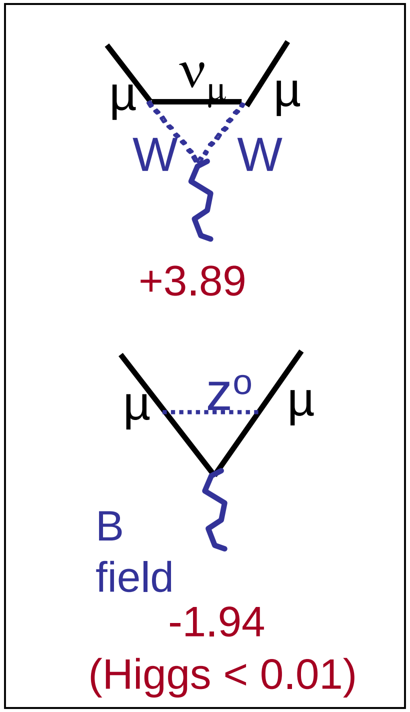
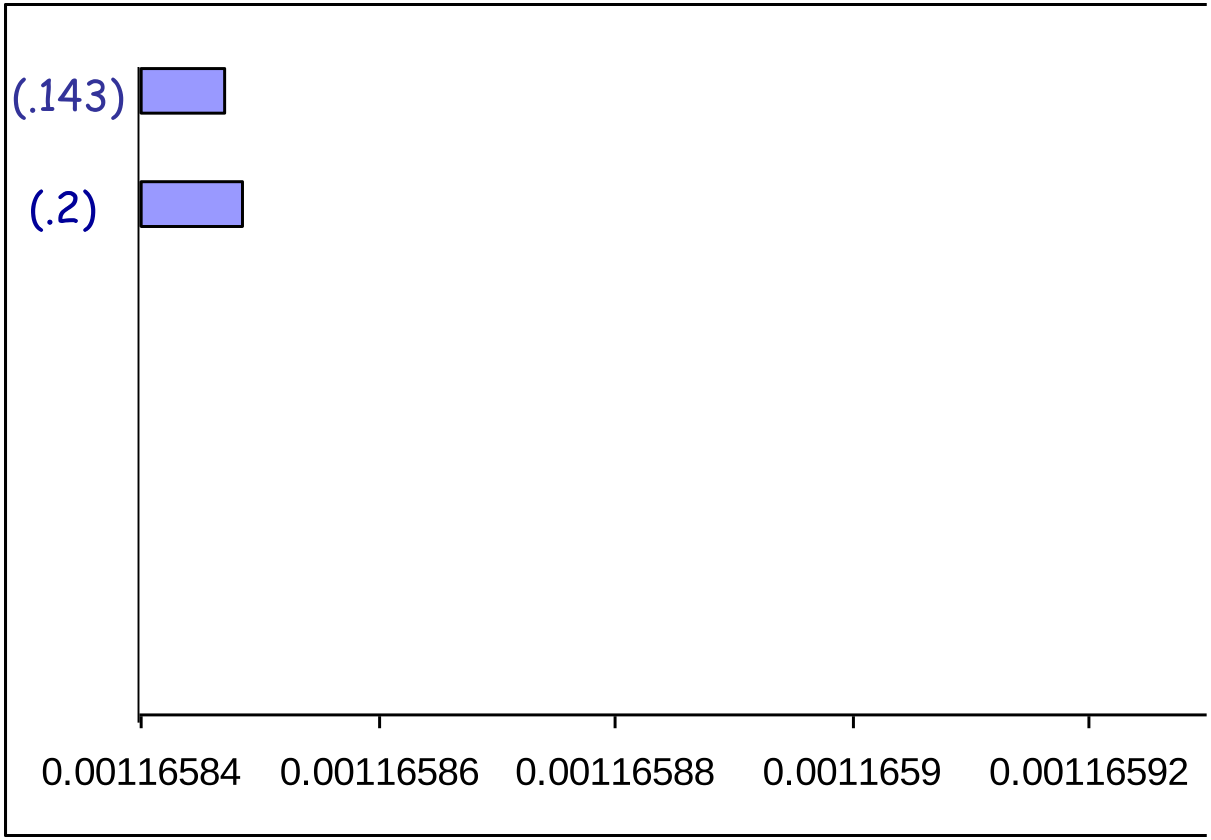
$\times 10^{-10}$

$a_\mu(QED) = 11658471.935$ (.143)

$+ a_\mu(weak) =$ 15.4__ (.2)





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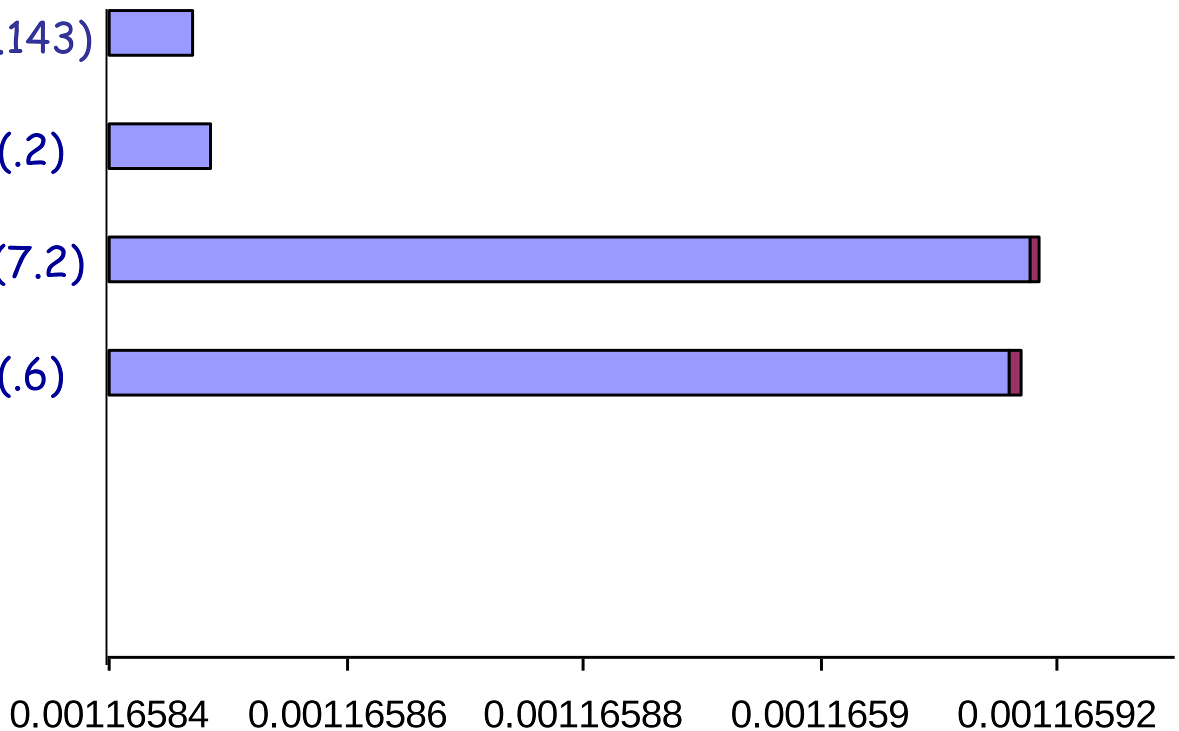
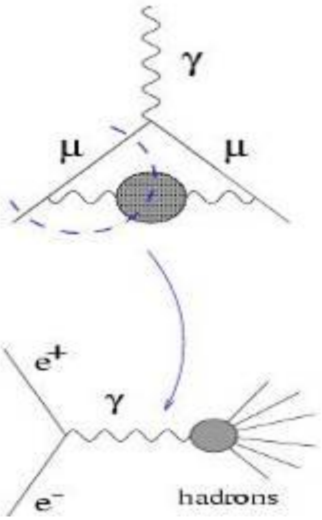
$+ a_\mu(had1^{st}o) =$ 696.3___ (7.2)

$+ a_\mu(had\ h.o.) =$ -10.0___ (.6)





Requires Data

Muon anomalous magnetic moment

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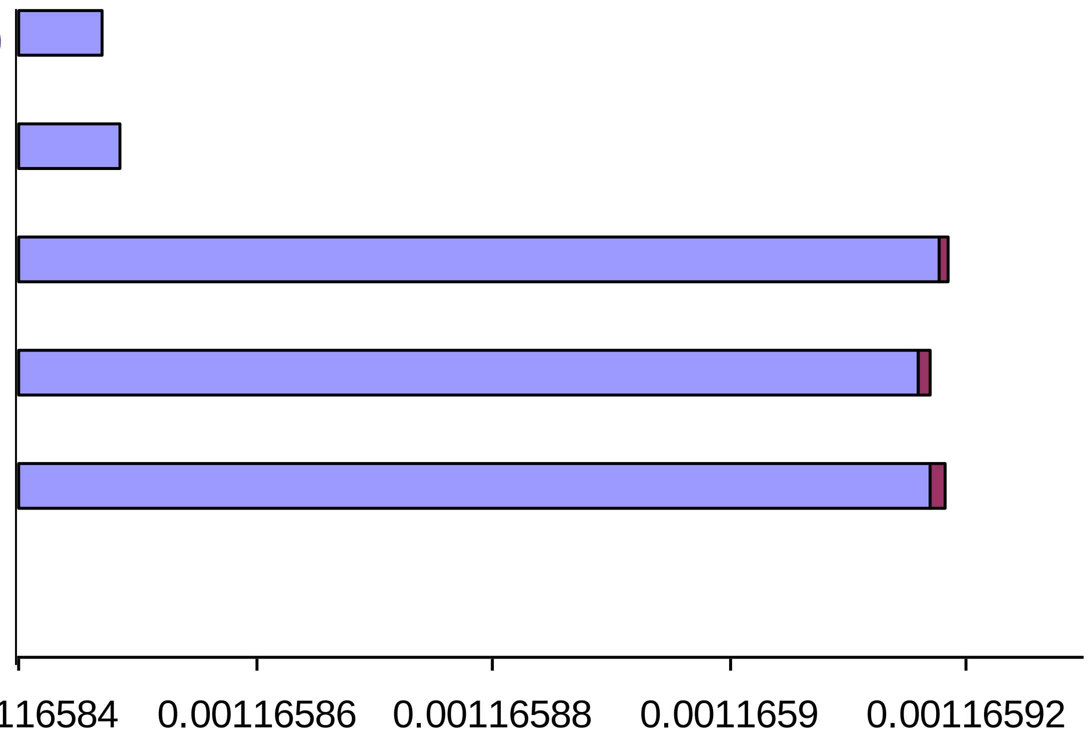
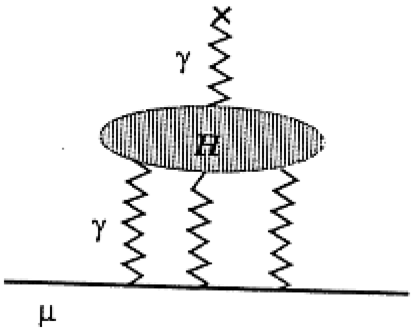
+ a_μ(had h.o.) = -10.0__ (.6)

+ a_μ(hadl-by-l) = + 13.6__ (2.5)





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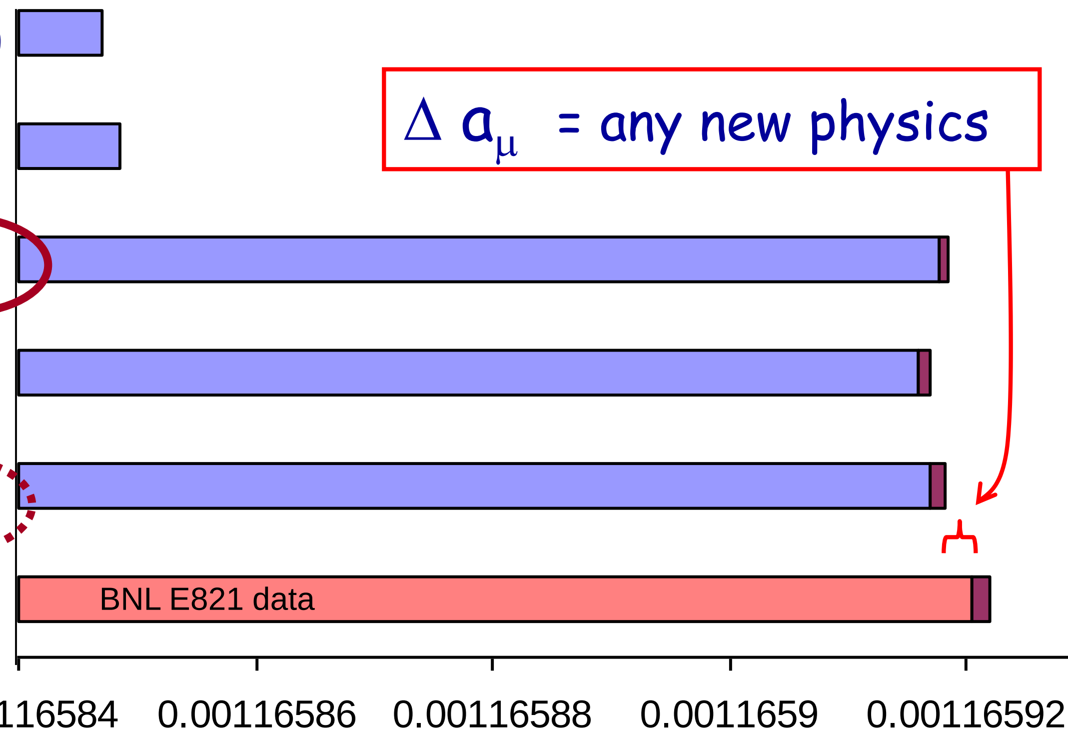
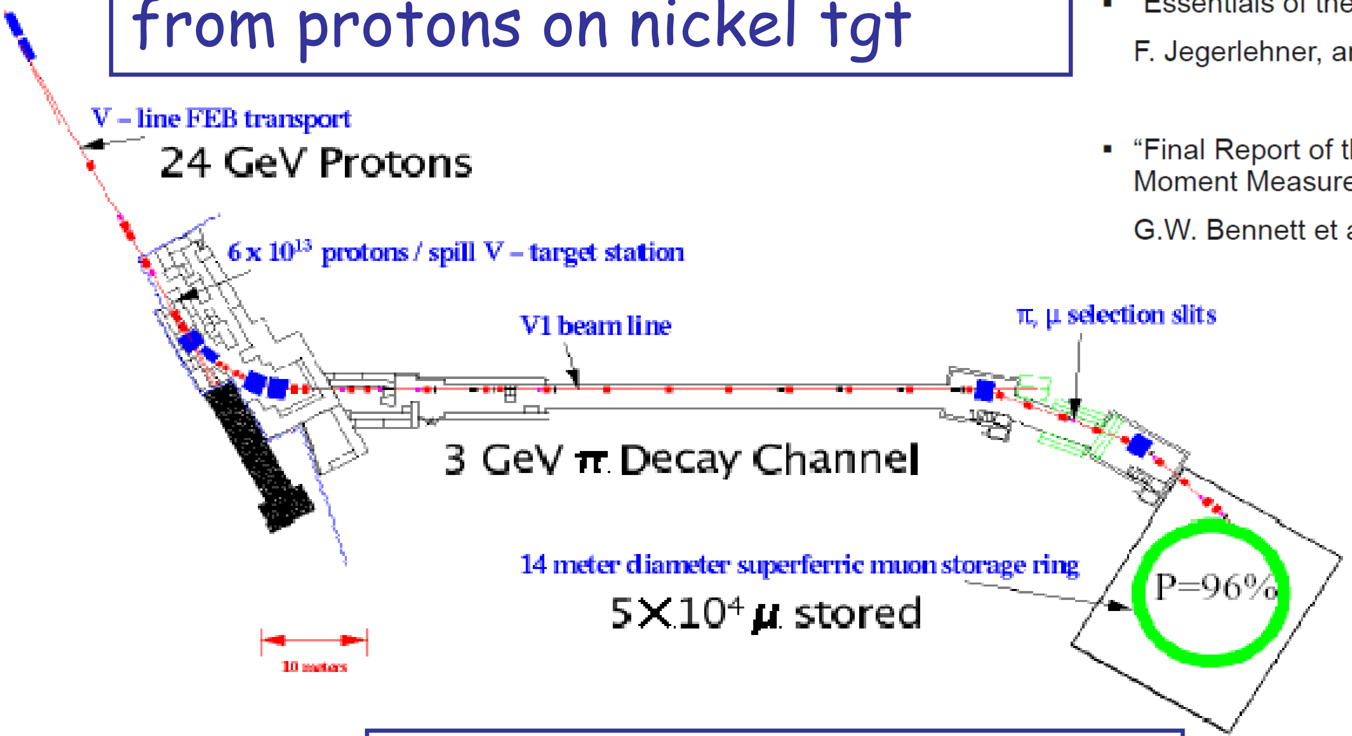


Priscilla Cushman
University of Minnesota

How to Measure a Magnetic Moment

- "Muon g-2: Review of Theory and Experiment" (**2007**)
  J. Miller, E. Rafael, B. Roberts, arXiv:hep-ph/0703049v2
- "Essentials of the Muon g-2" (**2007**)
  F. Jegerlehner, arXiv:hep-ph/0703125v3
- "Final Report of the Muon E821 Anomalous Magnetic Moment Measurement at BNL" (**2006**)
  G.W. Bennett et al., arXiv:hep-ex/0602035v1

Brookhaven provides the pions from protons on nickel tgt



Forward-going daughter muons are polarized

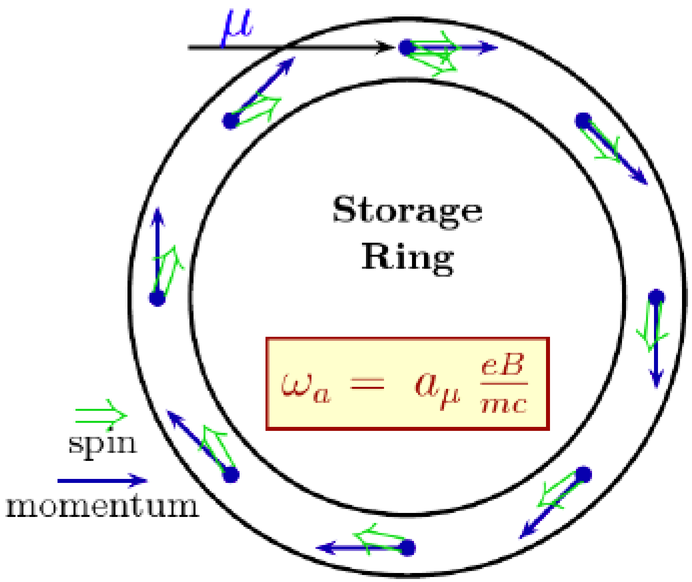
$$\overset{\leftarrow}{\mu^-} \longleftarrow \overset{0}{\pi^-} \longrightarrow \overset{\rightarrow}{\bar{\nu}_\mu}$$

How to Measure a Magnetic Moment

ω_c (T_c = 149 ns) $\omega_a = \omega_s - \omega_c$ (precesses ~12^0 per cycle)

$$\omega_s = \left[1 + \gamma \frac{(g-2)}{2}\right] \frac{eB}{m\gamma} \quad \text{and} \quad \omega_c = \frac{eB}{m\gamma}$$

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

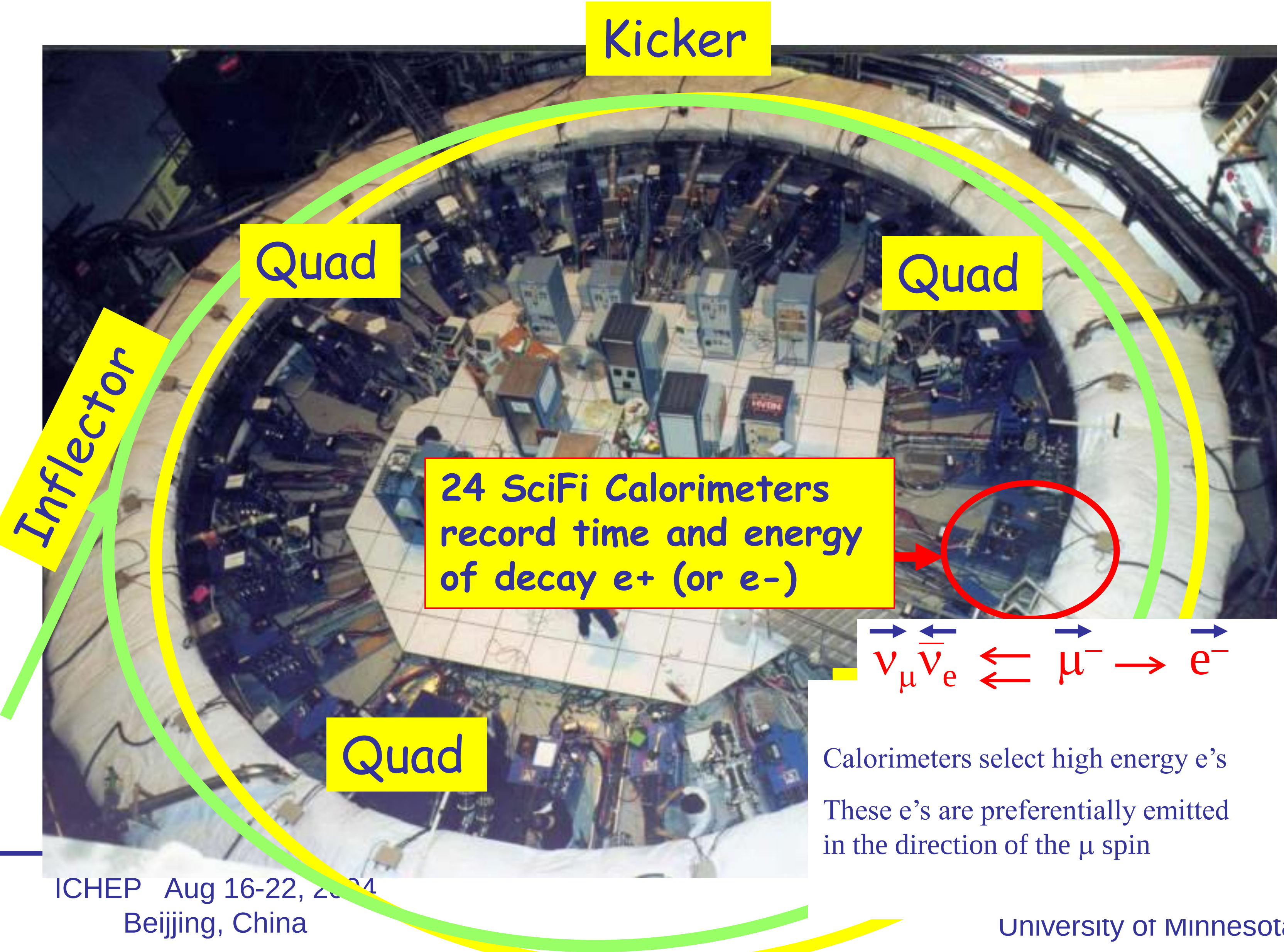


Quadrupole E field gives additional term in ω_a : $+ \frac{e}{m}\left(a_\mu - \frac{1}{\gamma^2 - 1}\right) \beta \times E$

Which vanishes at the "magic momentum" of **3.094 GeV/c**

WEAK-FOCUSSING MUON STORAGE RING

B = 1.45 T P_μ= 3.094 GeV/*c* R_{ring} = 7.112 m R_{stor} = 4.5 cm



$\vec{\nu}_\mu \overleftarrow{\bar{\nu}_e} \Leftarrow \vec{\mu}^- \rightarrow \vec{e}^-$

Calorimeters select high energy e's

These e's are preferentially emitted in the direction of the μ spin

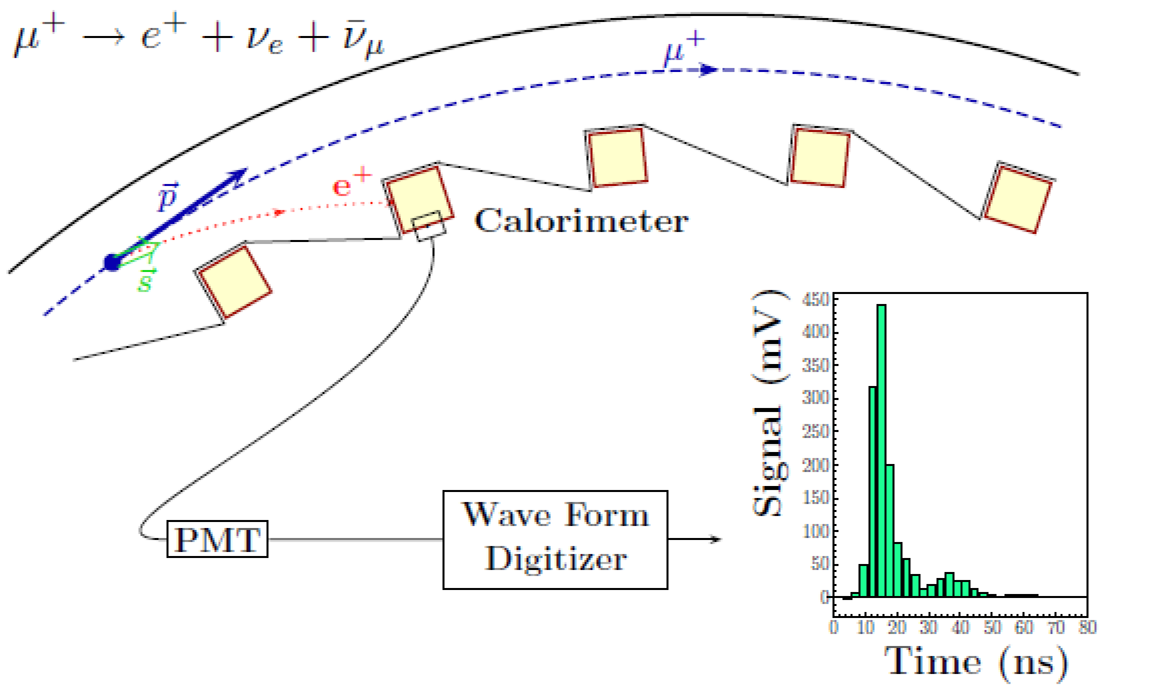
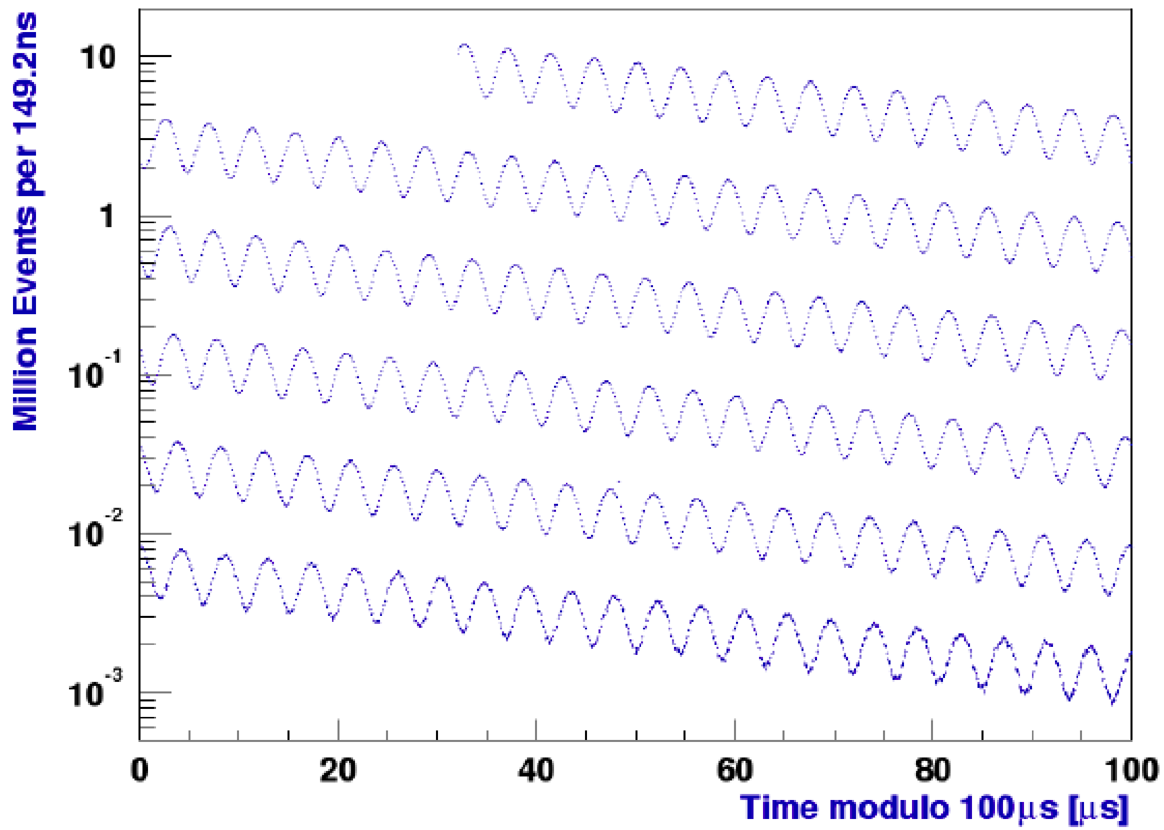


Fig. 4. Decay of μ^+ and detection of the emitted e^+ (PMT=Photomultiplier)

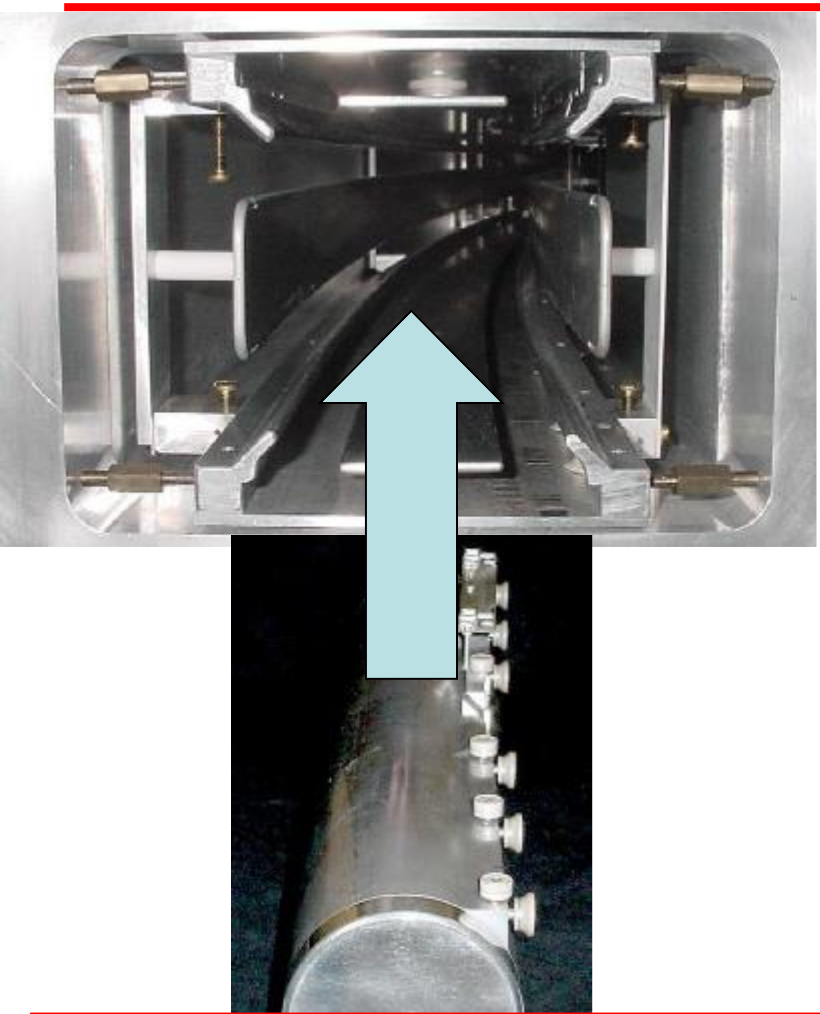
Laboratory observable

Electron number oscillation with time in the lab frame

$$N_d(t,E) = N_{d0}(E)e^{-t/\gamma\tau}[1 + A_d(E)\cos(\omega_a t + \phi_d(E))]$$



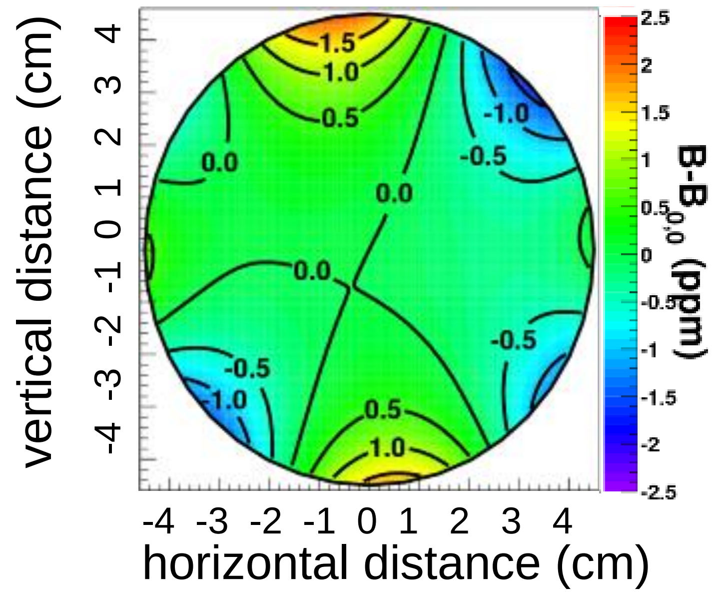
Measuring the Magnetic Field



17 calibrated NMR probes inside the trolley measure the field every cm

0.5 ppm contours are 750 nT over an average field of 1.45 Tesla.

muon sees the field averaged over azimuth



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Blind Analysis

Decay positrons

$$\omega_a = a_\mu \frac{e}{m} B$$

NMR

$$\mu_p \bullet B = \hbar \omega_p$$

$$a_\mu = \frac{R}{\lambda - R}$$

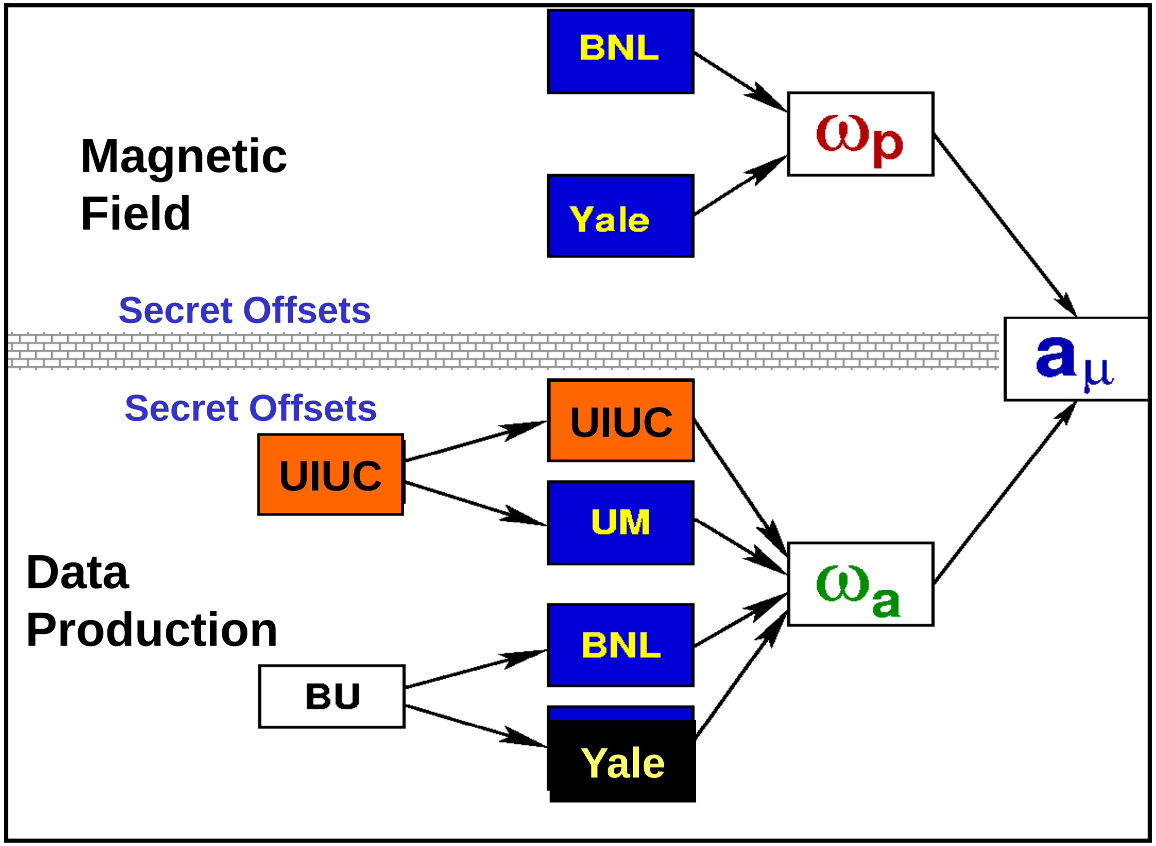
where $R = \omega_a / \omega_p$ is measured by E821

and $\lambda = \mu_\mu / \mu_p$ from muonium hyperfine structure

Offline Team (5 analyses)	Magnet Team (2 analyses)
ω_a	ω_p

- Both ω's and all analyses have computer-generated secret offsets.
- Study stability of R under all conditions
- Finish all studies and assign all uncertainties BEFORE revealing offset.

Finally, remove offsets to double-blind analysis



$$a_\mu = 116\,592\,08(6) \times 10^{-10} \qquad (0.5\ \text{ppm})$$

Final average PHYSICAL REVIEW D 73, 072003 (2006)

Theory prediction: needs precise value of α_{em}

[The electron g-2...

a_e^{SM} = $(1/2)(\alpha/\pi)$ - $0.328\,478\,444\,002\,90(60)\,(\alpha/\pi)^2$

Schwinger 1948 — Sommerfield; Petermann; Suura & Wichmann '57; Elend '66; MP '06

$A_2^{(4)}(m_e/m_\mu) = 5.197\,386\,70\,(28) \times 10^{-7}$

$A_2^{(4)}(m_e/m_\tau) = 1.837\,62\,(60) \times 10^{-9}$

$+\ 1.181\,234\,016\,827\,(19)\,(\alpha/\pi)^3$

Kinoshita, Barbieri, Laporta, Remiddi, … , Li, Samuel; Mohr & Taylor '05; MP '06

$A_2^{(6)}(m_e/m_\mu) = -7.373\,941\,64\,(29) \times 10^{-6}$

$A_2^{(6)}(m_e/m_\tau) = -6.5819\,(19) \times 10^{-8}$

$A_3^{(6)}(m_e/m_\mu, m_e/m_\tau) = 1.909\,45\,(62) \times 10^{-13}$

- ~~1.7283~~ $(35)\,(\alpha/\pi)^4$ New revised value: -1.9144 (35)

Kinoshita & Lindquist '81, … , Kinoshita & Nio '05; Aoyama, Hayakawa, Kinoshita & Nio, June '07

$+\ 0.0\,(3.8)\,(\alpha/\pi)^5$ In progress (12672 diagrams!)

Mohr & Taylor '05; Aoyama, Hayakawa, Kinoshita & Nio, in progress.

$+\ 1.671\,(19) \times 10^{-12}$ Hadronic

Mohr & Taylor '05; Davier & Hoecker '98, Krause '97, Knecht '03

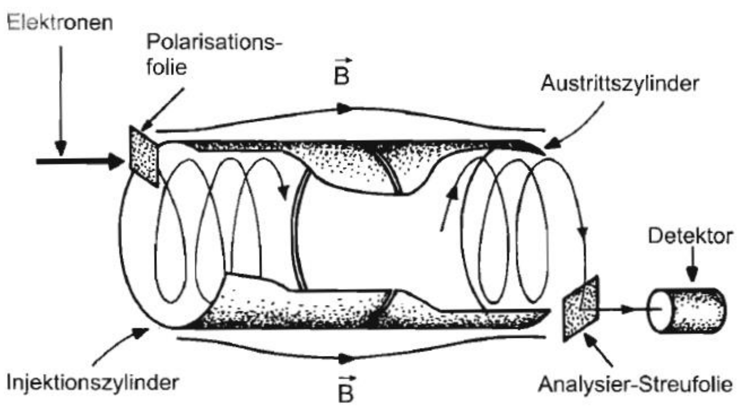
$+\ 0.0297\,(5) \times 10^{-12}$ Electroweak

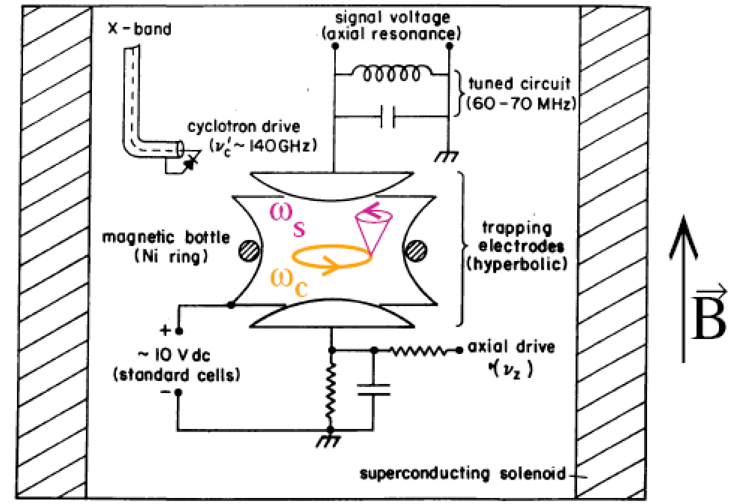
Mohr & Taylor '05; Czarnecki, Krause, Marciano '96

DEHMELT 1958: $\Delta g/g = 3 \times 10^{-5}$

DEHMELT, V. DYCK, SCHWINBERG 1987: $\Delta g/g = 4 \times 10^{-12}$

Messung von $(g\text{-}2)_e$





- Penning Trap
  - statische elekrische (10 V) und magnetische (5 T) Felder
  - halte **einzelnes** Elektron über **mehrere Monate** fest
- Messe das Verhältnis von
  - Spin Präzession: $\hbar\omega_s = g\mu_B B$
  - Zyklotron Umlauf: $\hbar\omega_c = 2\mu_B B$

$$\frac{\omega_s - \omega_c}{\omega_c} = \frac{g-2}{2}$$

result

- $(g-2)_e$ experiment:

  The new measurement of the electron g-2 is:

  $a_e^{exp} = 1159652180.85\ (76) \times 10^{-12}$ Odom et al, PRL97 (2006) 030801

  vs. old (factor of 6 improvement, 1.7σ difference):

  $a_e^{exp} = 1159652188.3\ (4.2) \times 10^{-12}$ Van Dyck et al, PRL59 (1987) 26

- Cf. theory mit α^{-1} =137,035 998 78(91) from Rb clock
  - $a_e^{theo} = 1159652183.3(7.7) \times 10^{-12}$

- Turn it around:
  - Assume validity of QED
  - Determine α from $(g-2)_e$ (and other)
  - Result 2017 : α^{-1} = 137,035 999 08(02)

Vergleich Experiment <-> Theorie für $(g-2)_\mu$

- Jegerlehner u.a.
  - ~3.0-3.4 σ Abweichung vom SM
  - Mögl. Quellen:
    - Zufall
    - Experiment
    - Theorie
    - SUSY??

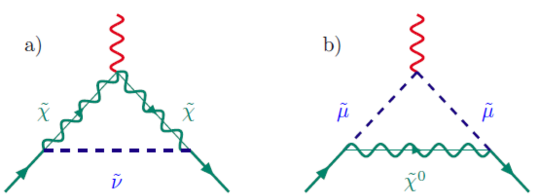


Fig. 16. Physics beyond the SM: leading SUSY contributions to $g-2$ in supersymmetric extension of the SM

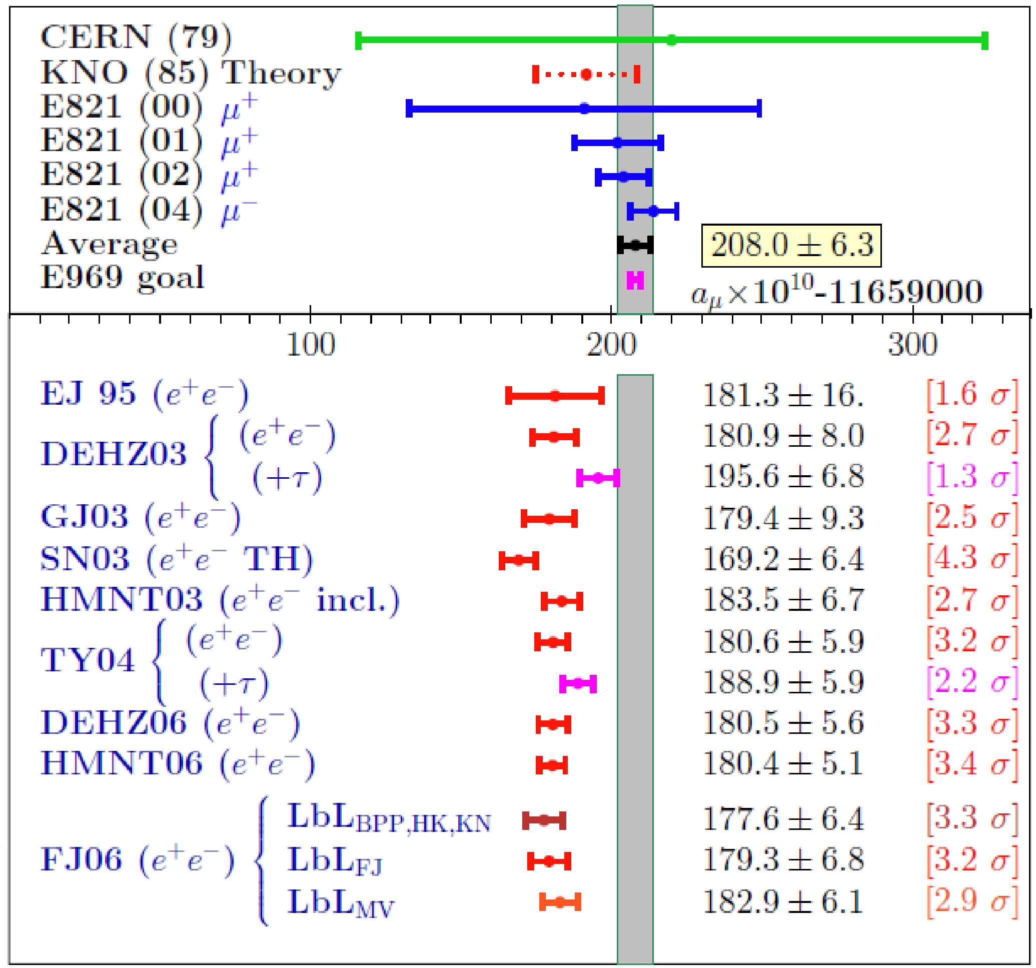
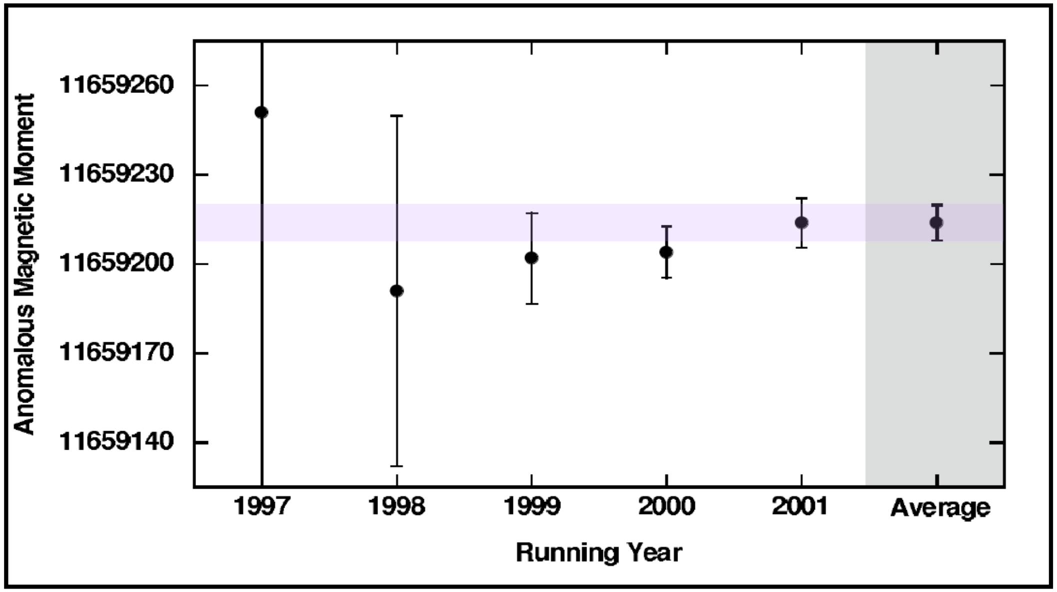


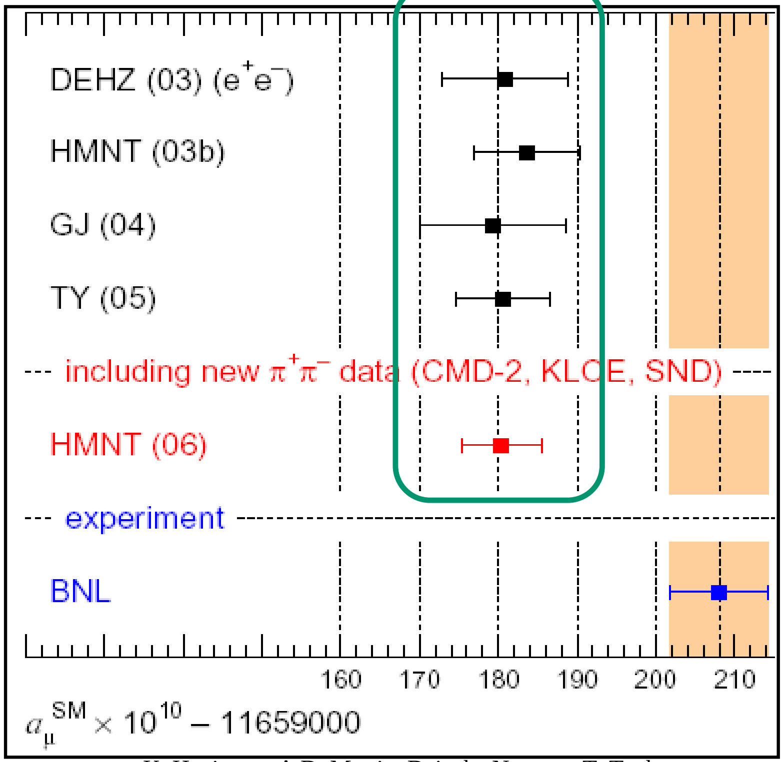
Fig. 14. Comparison between theory and experiment. Results differ by different L.O. hadronic vacuum polarizations and variants of the LbL contribution. Some

E821 Experimental Results



James P Miller, Eduardo de Rafael, B Lee Roberts
Rep.Prog.Phys. 70, 795 (2007).

Theory + Exp.



K. Hagiwara, A.D. Martin, Daisuke Nomura, T. Teubner

$$\alpha_\mu(\text{expt.}) = 11659208(6)\times 10^{-10}(0.5\,\text{ppm})$$

$$\alpha_\mu(\text{theor.}) = 11659178(6)\times 10^{-10}(0.5\,\text{ppm})$$

$$\Delta\alpha_\mu \equiv \alpha_\mu(\text{expt.}) - \alpha_\mu(\text{theor.}) = (30\pm 9)\times 10^{-10}\quad (3.4\sigma)$$

2013: transport of ring from BNL to FNAL

…for using more intense and more pure beam

First beam: 2017

Update between 2007 and 2020

$$\alpha_\mu(\text{expt.}) = 11659208(6)\times 10^{-10}(0.5\,\text{ppm})$$

$$\alpha_\mu(\text{theor.}) = 11659178(6)\times 10^{-10}(0.5\,\text{ppm})$$

$$\Delta\alpha_\mu \equiv \alpha_\mu(\text{expt.}) - \alpha_\mu(\text{theor.}) = (30\pm 9)\times 10^{-10}\ \ (3.4\sigma)$$

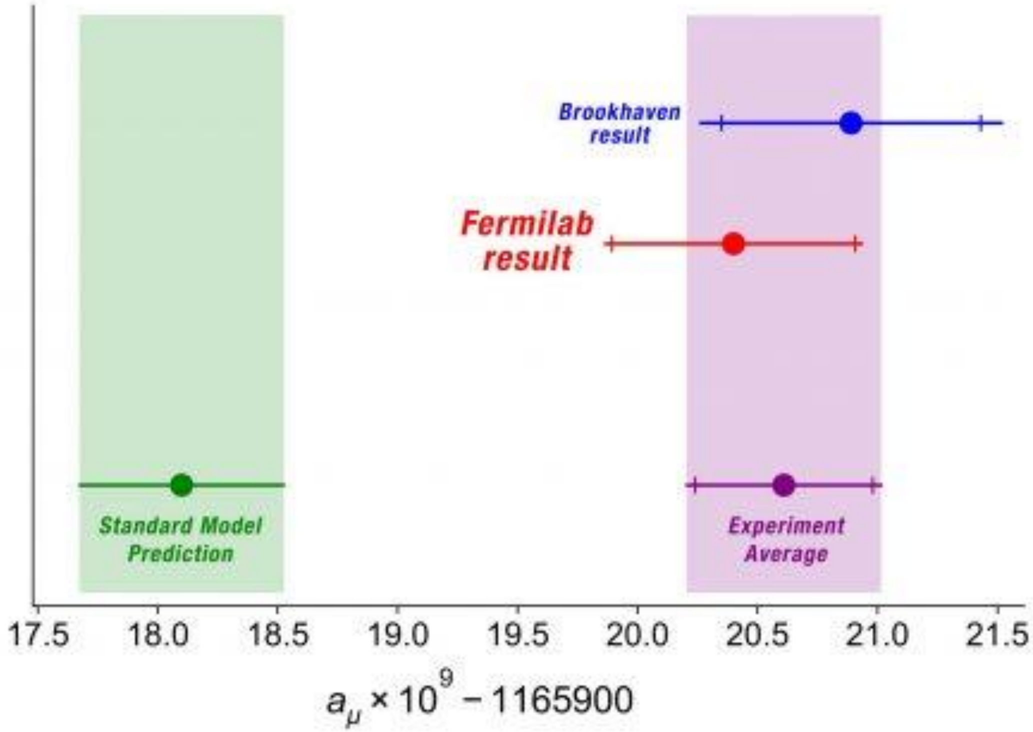
Progress 13 years later (2020) before new measurement
https://news.fnal.gov/2020/06/physicists-publish-worldwide-consensus-of-muon-magnetic-moment-calculation/

*a_μ (expt) = 116592**09**(6) x 10^{-10} (0.5 ppm)*
*a_μ (theo) = 116591**81(4)** x 10^{-10} (0.4 ppm)*

Δa_μ = (28 ± 8) x 10^{-10} (3.7 σ)

7.4.2021: results from FNAL
https://muon-g-2.fnal.gov/key-contribution-from-brookhaven.html

https://news.fnal.gov/2021/04/first-results-from-fermilabs-muon-g-2-experiment-strengthen-evidence-of-new-physics/



a_μ (expt) = 116592**06(4)** x 10^{-10} (0.5 ppm)
a_μ (theo) = 11659181(4) x 10^{-10} (0.4 ppm)

$\Delta a_\mu = (25 \pm 6) \times 10^{-10}$ (4.2 σ)