Muon $g - 2$

Physics 403
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Slides adapted from Jörg Pretz
RWTH Aachen/ FZ Jülich

Outline

- Introduction & Motivation
- Method
- Experiment & Analysis
- Results
- Summary & Outlook

Introduction & Motivation

Magnetic Moment and *g*-Factor

$$g = \frac{\dfrac{\text{magnetic moment}}{(e\hbar/2mc)}}{\dfrac{\text{angular momentum}}{\text{n}}}$$

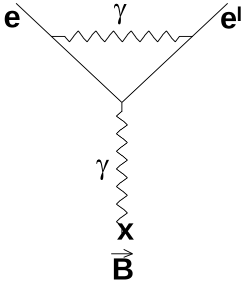
= 2 for Dirac particle

Magnetic Moment and *g*-Factor

$$g = \frac{\frac{\text{magnetic moment}}{(e\hbar/2mc)}}{\frac{\text{angular momentum}}{\hbar}}$$

= 2 for Dirac particle

higher order corrections:



lead to an

anomalous magnetic moment $a = \frac{g-2}{2} \approx \frac{\alpha}{2\pi} \approx 10^{-3}$

Electron

$$a_e(exp) \quad = \quad 1\,159\,652\,180.73\,(0.28) \cdot 10^{-12} \qquad (0.2\text{ppb})$$

D. Hanneke, S. Fogwell Hoogerheide, and G. Gabrielse, Phys. Rev. A 83, 052122 (2011)

$$a_e(th) \quad = \quad 1\,159\,652\,181.13\,(0.86) \cdot 10^{-12} \qquad (0.7\text{ppb})$$

Aoyama et al., arXiv:1201.2461 [hep-ph]

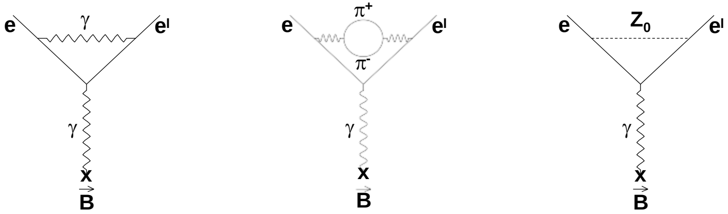
$$a_e(exp) - a_e(th) = -0.4(1.3) \cdot 10^{-12}$$

Electron

Contributions to a_e:

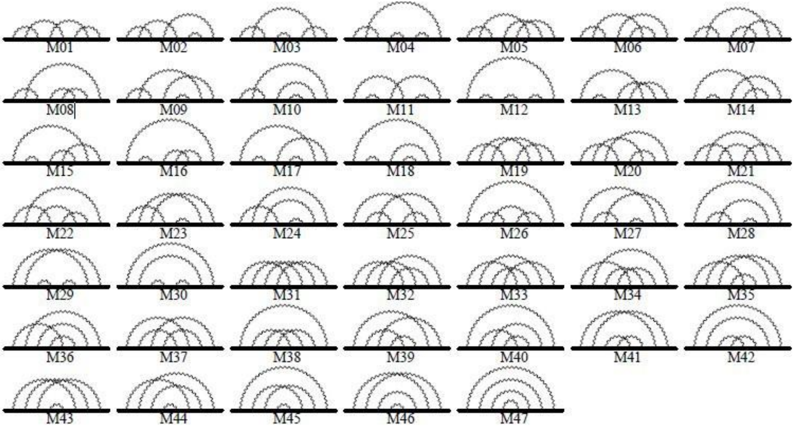
$$a_e = a_e^{em} + a_e^{had} + a_e^{weak}$$
$$= ((\approx 1) + 1.4\text{ ppb} + 0.04\text{ ppb})\, a_e$$

electro-mag. | hadronic | weak



$\Rightarrow$ a_e tests **QED** but it is not sensitive to **hadronic** and **weak** contributions!

Some 4 loop Corrections



T. Aoyama, M. Hayakawa, T. Kinoshita and M. Nio, Phys. Rev. D **85** (2012) 033007 [arXiv:1110.2826 [hep-ph]].

includes 5 loop corrections as well

Muon

$a_\mu(th) = 1\,165\,918.28(49)\cdot 10^{-9}(0.42\text{ppm})$

K. Hagiwara et al., J. Phys. G G **38** (2011) 085003 [arXiv:1105.3149 [hep-ph]].

Contributions to a_μ:

$$\begin{array}{cccccccc} a_\mu & = & a_\mu^{em} & + & a_\mu^{had} & + & a_\mu^{weak} & \\ & = & ((\approx 1\ ) & + & 60\text{ ppm} & + & 1.5\text{ ppm}\ )\ a_\mu & \\ & & \pm 1.3\text{ ppb} & & \pm 0.4\text{ ppm} & & \pm 0.02\text{ ppm} & \end{array}$$

Error of experiment:

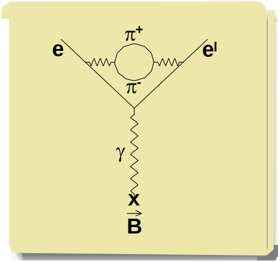
$$\frac{\sigma_{a_\mu}}{a_\mu} = 0.5\text{ppm (stat. and syst.)}$$

a_μ is sensitive to **hadronic** and **weak** contributions, because

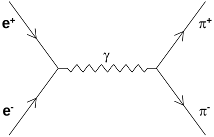
$$a_\mu^{had,weak,BSM} \approx (m_\mu/m_e)^2\ a_e^{had,weak,BSM}$$

(BSM: beyond Standard Model)

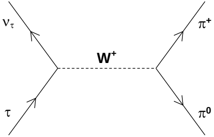
hadronic contribution: a_μ^{had}

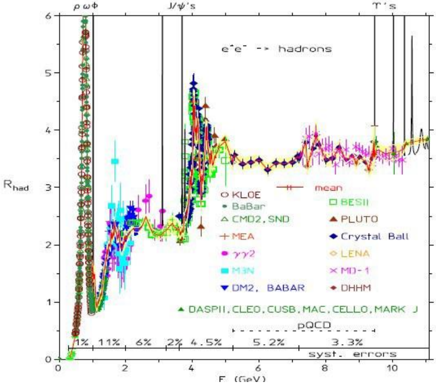


is related to



and





$$R_{had} = \frac{\sigma^{e^+e^- \to \text{hadrons}}}{\sigma^{e^+e^- \to \mu^+\mu^-}}$$

Error on a_μ^{had} limited by experimental data

Contributions beyond Standard Model

- Muon substructure: $a_\mu^{substr} \approx \left(\frac{m_\mu}{\Lambda}\right)^2$
  sensitivity $\Lambda \approx 5$ TeV (similar to LHC)
- SUSY models:
  $$a_\mu^{SUSY} \approx 140 \cdot 10^{-11} \left(\frac{100\text{GeV}}{M_{SUSY}}\right)^2 \tan\beta$$
  $$\approx 2 \cdot 10^{-9} (1.7 \text{ ppm})$$
  for $M_{SUSY} = 500$GeV and $\tan\beta = m_t/m_b$

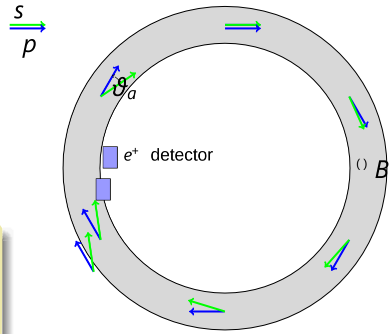
Method

Method

Observe μ spin precession in storage ring:

$$\omega_a = \frac{d\vartheta}{dt} = \frac{e}{m_\mu c} a_\mu B$$

ω_a from e^+ time spectrum
$\mu^+ \rightarrow e^+ \nu_e \overline{\nu}_\mu$:
due to parity violation:
correlation between
nb. of e^+ and spin of μ^+



$B \approx 1.5\text{T} \Rightarrow$ ring radius $R \approx 7\text{m}$ and

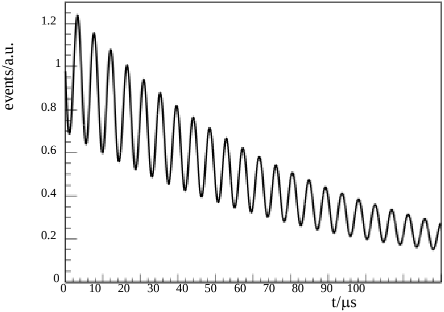
$$T_c = 150ns$$
$$T_a = \frac{2\pi}{\omega_a} = 4.4\mu s$$
$$\tau = 64\mu s$$

Method

decay spectrum:

$$dR(y,t) \propto e^{-t/\tau}\, n(y)\,(1 + A(y)\sin(\vartheta_a))$$

$$y = \frac{E^e}{E^\mu},\ \vartheta_a = \omega_a t$$



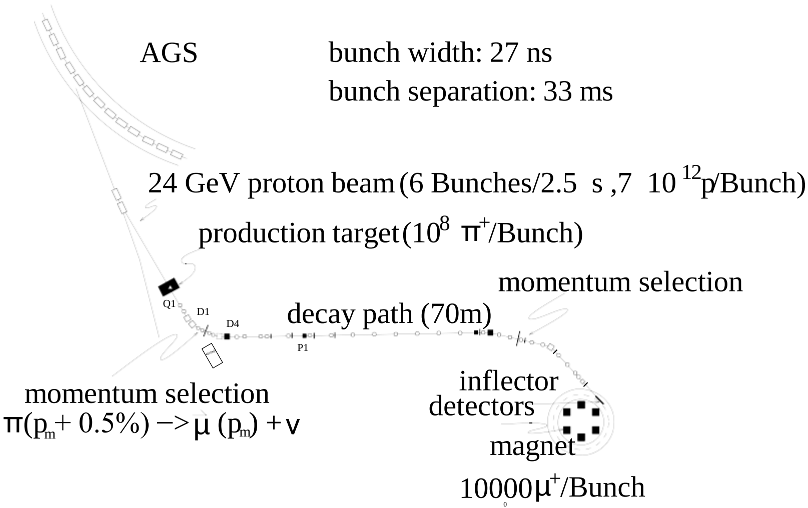
Experiment

Experiment

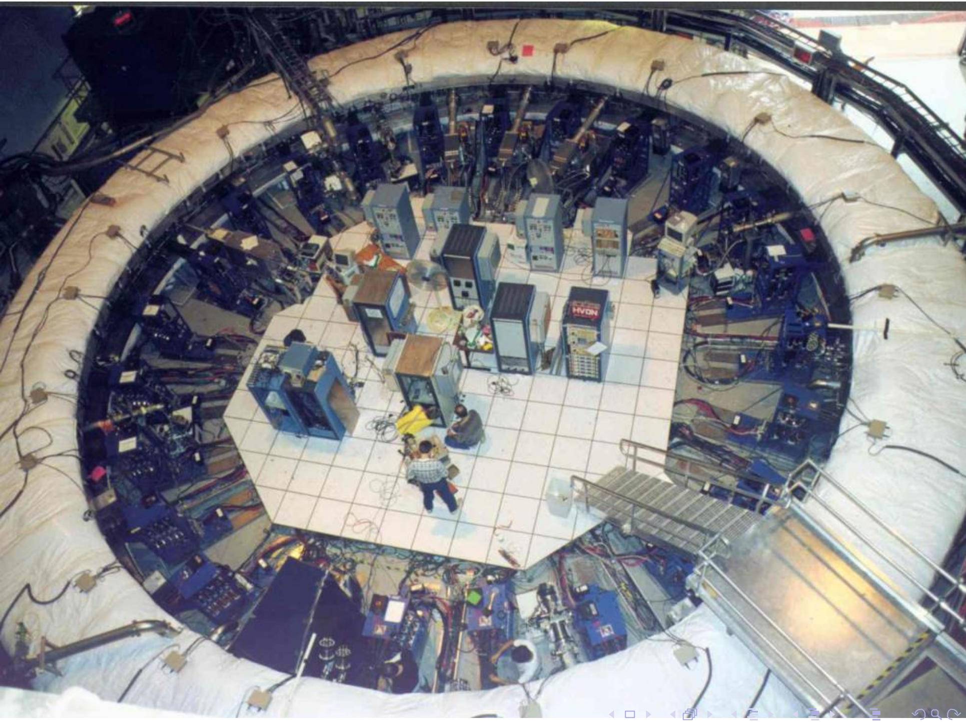
Components:

- Beamline (get polarized muons)
- Magnet (measurement of B)
- Detectors (measurement of ω_a)

Beamline

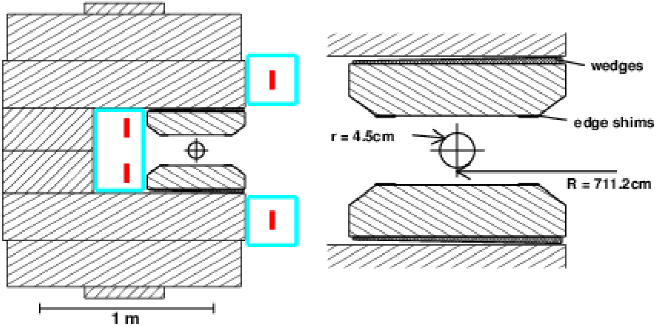


1 muon per 10^9 protons!


HVDN

Magnet

- Superferric Magnet (B=1.45 T)
- 4 Nb/Ti coils, I=5200 A
- Radius 7.112 m



Shimming:

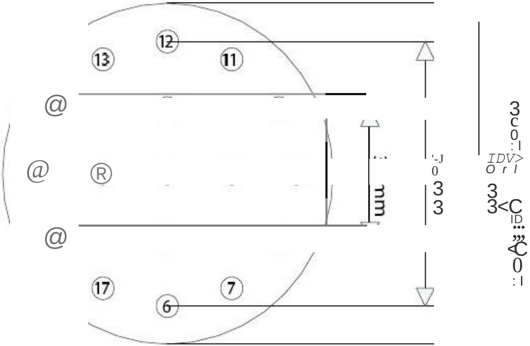
- edge shims
- wedges
- iron strips
- surface coils

B field measurement

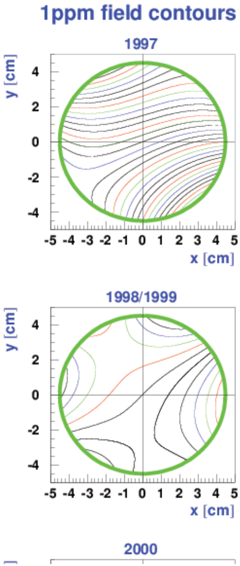
$$\omega_p = \frac{1}{2} g_p \frac{eB}{m_p c}$$

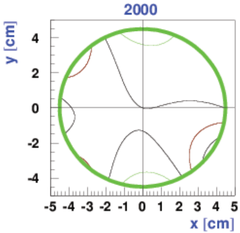
- field measurement by NMR
- difficulty is **not** to measure B at one point to < 1 ppm but over a large volume/ time scale
- ≈ 300 fixed NMR probes on top and bottom of the vacuum chamber, read out continuously
- Trolley with 17 NMR probes, which measures the field in the storage region every 2-3 days
- Standard probe for calibration
- note that NMR measures B
- difference between $B_\perp$ and B measured to be < 0.01ppm

Trolley



B-field in transverse direction



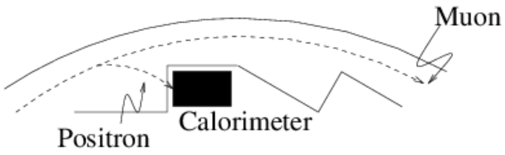


Systematic Error B

Source of error	Size[ppm]
Absolute calibration of standard probe	0.05
Calibration of trolley probes	0.09
Trolley measurements of B_0	0.05
Interpolation with fixed probes	0.07
Uncertainty from muon distribution	0.03
others	0.1
higher multipoles, trolley temperature	
eddy currents from kicker	
Total	0.17

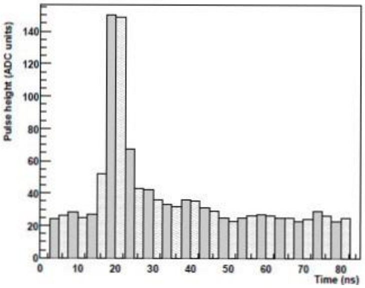
e^+ -Detectors

- 24 detectors inside the ring



- Lead/Scintillating Fibers
- energy resolution $\sigma \approx 10\%/\sqrt{E(\text{GeV})}$
- 15 radiation lengths
- PMT analog signals are digitized every 2.5 ns
- rate changes from 1 MHz to a few Hz from t=0 to t=10τ
- time stability on average 60 ps/10τ = 0.1 ppm
- laser system to check time and gain stability

e+ pulse



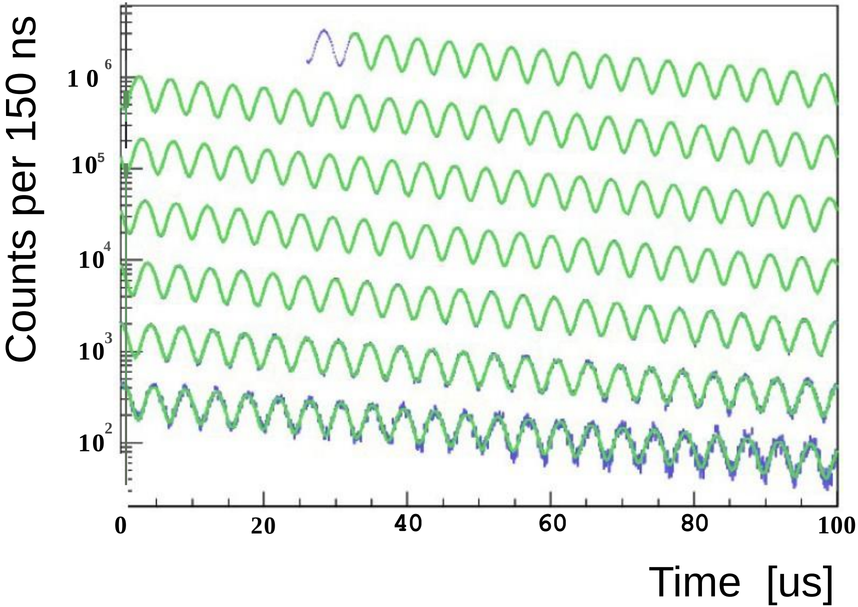
Pulse height (ADC units)
140
120
100
80
60
40
20
0
0
10
20
30
40
50
60
70
80
Time (ns)

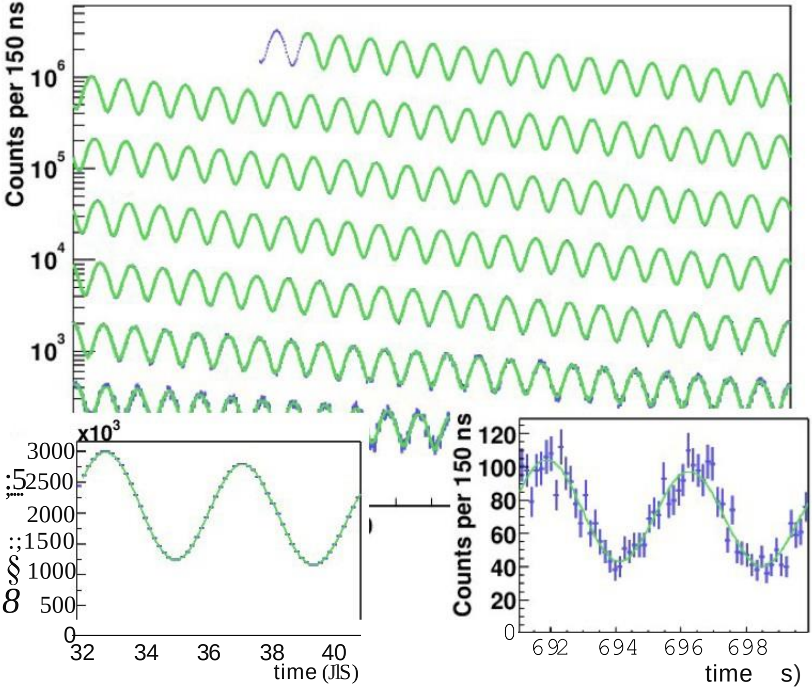
Determination of ω_a

Fit time spectrum with $4 \times 10^9 e^+$ with $E > 2$ GeV for ω_a:

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

- correct for/ include in fitting
  - pile-up (by looking at double pulses)
  - μ losses, (looking for coincidences in several detectors)
  - gain changes of PMT (looking at laser pulses)
  - betatron oscillation (N_0, A, φ modulated by $1 + A_b e^{-t^2/\tau_b^2} \cos(\omega_b t + \Phi_b)$)
- ≈ 15 parameters depending on fitting method only Φ correlates strongly with ω_a
- χ^2 of 0.98-1.02 reached as expected for ≈ 4000 degrees of freedom


Counts per 150 ns
10^6
10^5
10^4
10^3
10^2
0
20
40
60
80
100
Time [us]


Counts per 150 ns
10^6
10^5
10^4
10^3
x10^3
3000
2500
2000
1500
1000
500
0
32
34
36
38
40
time
Counts per 150 ns
120
100
80
60
40
20
0
692
694
696
698
time

Systematic Error ω_a

Source of error	Size[ppm]
Pileup	0.08
Lost Muons	0.09
horiz. betatron oscillations	0.07
Gain changes	0.12
others	0.11
AGS background, timing shifts	
E field and vertical betatron oscillations	
Beam debunching/ randomization, binning & fitting procedure	
Total	0.21

Final Result

Putting everything together

$$a_\mu = \frac{\frac{\omega_a}{\omega_p}}{\frac{\omega_\mu}{\omega_p} - \frac{\omega_a}{\omega_p}}$$

$\frac{\omega_a}{\omega_p}$ (this experiment)

$$\frac{\omega_\mu}{\omega_p} = \frac{\mu_\mu}{\mu_p} = 3.18334539(10) \quad \text{(muonium)}$$

$$a_\mu(exp) = 11\,659\,208.0(5.4)(3.3) \times 10^{-10} \qquad (0.54\text{ppm})$$

combination of 1997-2001 results

3 σ away from SM-expectiation!

CERN ⇔ BNL

CERN(1958-1662)	4300 ppm	muon is heavy electron
CERN(1962-1968)	270 ppm	$a_\mu \neq a_e$
CERN(1969-1976)	7 ppm	sensitive to hadronic contribution
BNL(1996-2001)	0.54 ppm	sensitive to weak contribution and BSM (?)
FNAL	goal: 0.14 ppm	

Summary & Outlook

- Comparison of theoretical and measured anomalous magnetic of muon allows stringent test of Standard Model
- Situation since $\approx$ 10 years: 3 σ difference between theory and experiment
- New efforts at Fermilab and in Japan with factor 4 smaller error
- BNL Experiment set also limit on muon EDM:
  $d_\mu = (-0.1 \pm 0.9) \times 10^{-19} e\cdot\text{cm}$
  $|d_\mu| < 1.9 \times 10^{-19} e\cdot\text{cm}$ (95% CL)

Time Magazine, Feb. 2001

W I N N E R S & L O S I R S

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Bags biggest landslide in Israeli history. Transformed from a hawk to a phoenix

ANTHONY HOPKINS
Hannibal star proves what many already know: beastly behavior gets results in Hollywood

THE MUON
Throws 30-year-old theory of the universe into doubt. Not bad for a subatomic particle

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Police claim Miami mayor hit wife with a tea canister. Good thing he isn't seeking re-election

HELMUT KOHL
Former German Chancellor fined for taking illegal campaign donations. What, no furniture?

60 MINUTES
Ratings slipping after 23 straight years in Top 10. Lucky CBS has another *Survivor*

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TIME, FEBRUARY 19, 2001