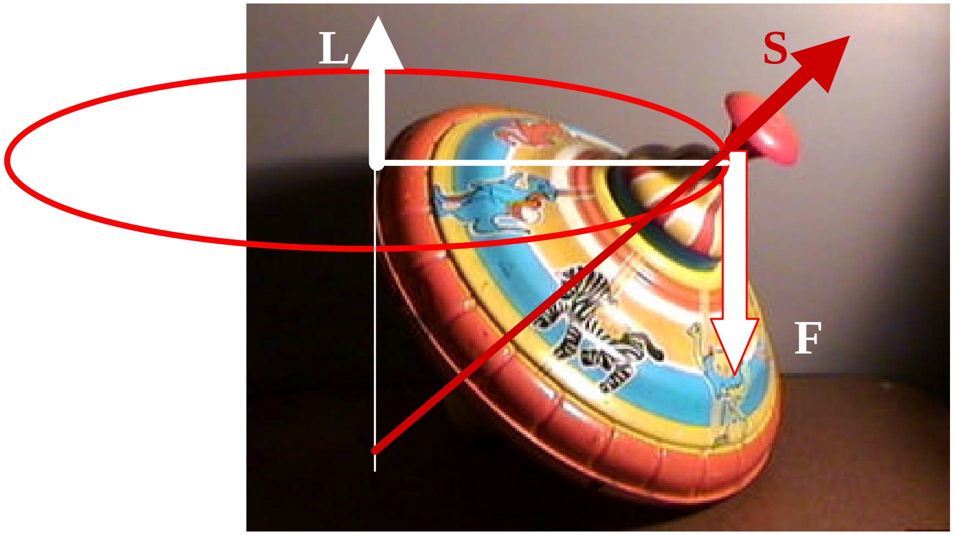
Brookhaven Muon g-2 Experiment
A Virtual Accelerator to Probe the Standard Model



I = ??

Professor Priscilla Cushman
University of Minnesota

SLAC Summer School Topical Conference   Aug 22-24, 2001

Goals of E821

- **20-fold improvement in Muon Anomalous Magnetic Moment**
  - *Test of Electroweak Renormalizability*
  - *Search for "new physics"*
- **Improved limit on Muon Electric Dipole Moment**
  - $d_m < 5 \times 10^{-21}$ *e-cm*
- **Dilated Muon Lifetime in accelerated frame of reference**
- **Tests of CPT**
  - *Compare* $t(m^+)$ *vs* $t(m^-)$
  - *Compare* $a(m^+)$ *vs* $a(m^-)$

The g-2 Collaboration

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Why Study Magnetic Moments Anyway?

$$m = g \frac{e\hbar}{2mc} \frac{s}{2}$$

Where g is the gyromagnetic ratio which relates the angular momentum to the intrinsic spin

g=2   for charged, point-like, spin 1/2 particles.

Hadrons

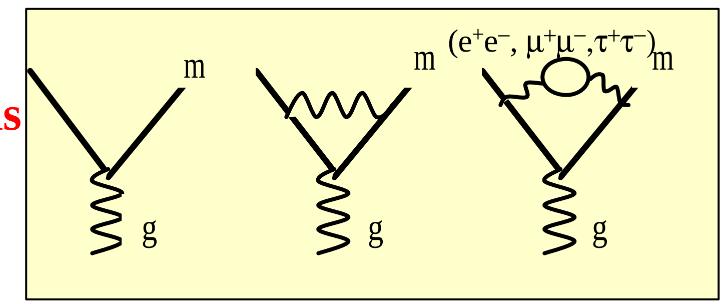
Large deviations => quark substructure

g(neutron) = -3.82 ≠ 0

g(proton) = +5.58 ≠ 2

Leptons

Small deviations => coupling to virtual fields



Deviations from g=2 are characterized by the Anomaly: $a_m = \frac{g-2}{2}$ (a_m ~ .001 for a muon)

THEORY (Standard Model) says:

$$a_m = a_m(QED) \quad + \; a_m(weak) \quad + \; a_m(hadron)$$

$\sim 10^{-3}$ | $\sim 10^{-9}$ | 67×10^{-9}

a_m =.001165847056(29) + .00000000151(04) + .0000006739(67) ⇨ **0.57 ppm**

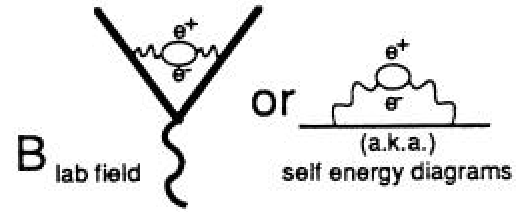
Compare to Experiment:

a_m (CERN combined)	.001165923*	(8*)	⇨	7.3 ppm
a_{m+} (BNL'97)	.001165925*	(15*)	⇨	13 ppm
a_{m+} (BNL'98)	.001165919*	(6*)	⇨	5 ppm
a_{m+} (BNL'99)	.0011659202	(16)	⇨	1.3 ppm
a_{m+}(BNL'00) (by Dec '01)	.00116592**	(8)	⇨	0.7 ppm

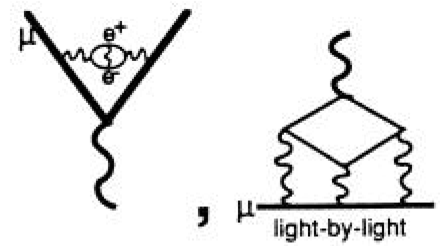
QED Contributions to the Muon Anomaly

Structure of QED is identical for e and μ, but with different values due to asymmetry in the vacuum polarization terms, i.e. Muons are heavier!

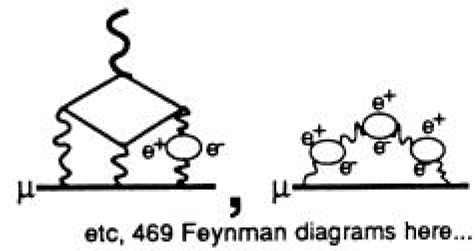
$$\left(\frac{a}{p}\right)$$



$$\left(\frac{a}{p}\right)^{2}$$



$$\left(\frac{a}{p}\right)^{3}$$



$$\left(\frac{a}{p}\right)^{4}$$

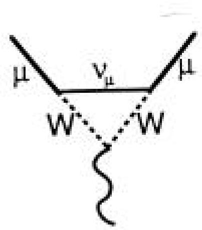
Over 700 Feynman diagrams, whew!

Weak Contribution

(corrections go as

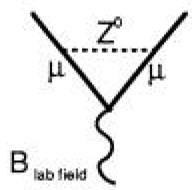
m_L^2/m_W^2**)**

1st Order Diagrams (Higgs contribution is negligible)



$$a_\mu^W = \frac{10}{3}\frac{G_F m_\mu^2}{8\sqrt{2}\pi^2} + \vartheta\left(\frac{m_\mu}{m_W}\right)^4$$

(+3.3 ppm)



$$a_\mu^Z = -\left(\frac{5}{3} - \frac{(3-4\cos^2\theta_W)^2}{3}\right)\frac{G_F m_\mu^2}{8\sqrt{2}\pi^2} + \vartheta\left(\frac{m_\mu}{m_W}\right)^4$$

(-1.6 ppm)

2-loop Diagrams (Reduces electroweak by 22.6 %)

(both boson and fermion loops)

Total EW = + 1.30 ± 0.03 ppm

Electron Anomalous Magnetic Moment

Theory

$$a_e = a_e(QED) + a_e(Weak) + a_e(hadron)$$

$$\sim 10^{-3} \quad + 0.030 \times 10^{-12} \quad + 1.642\ (27) \times 10^{-12}$$

Coefficients known to better than 1 ppb in a_e

$$a_e(QED) = 0.5\left(\frac{a}{p}\right) - 0.328478965\ldots\left(\frac{a}{p}\right)^2 + 1.181241456\ldots\left(\frac{a}{p}\right)^3 - 1.5098\ (384)\left(\frac{a}{p}\right)^4$$

But what is α?

$1/\alpha = 137.03\ldots..$

[24 ppb quantum Hall effect]
[56 ppb ac Josephson effect]
[58 ppb muonium hyperfine structure]
[37 ppb de Broglie λ of neutron beam]

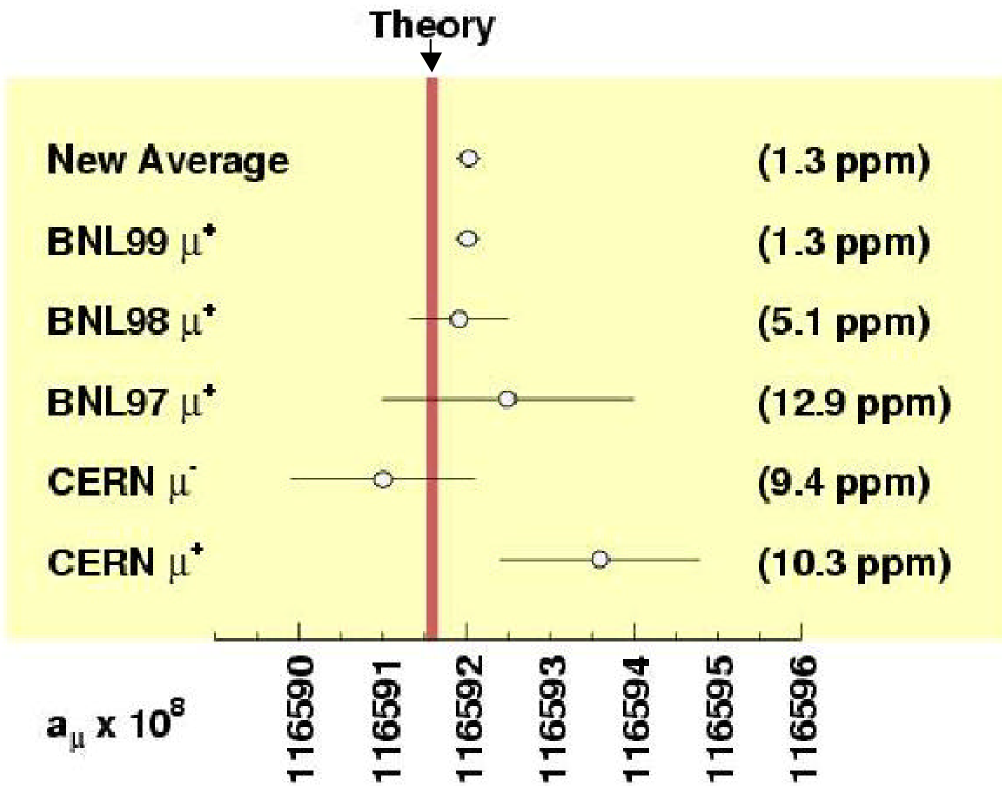
Experiment (Dehmelt, Van Dyck, etc. at Univ. of Washington)

$a(e^-) = 1\ 159\ 652\ 188.4\ (4.3) \times 10^{-12}$ (3.7 ppb)

$a(e^+) = 1\ 159\ 652\ 187.9\ (4.3) \times 10^{-12}$ (3.7 ppb)

Turn it around: Best value for fine structure constant comes from the Electron Anomaly

Experimental Results vs Theory



$$a_\mu^{theory} = 116\,591\,596(67)\times10^{-11} \quad (0.57 \text{ ppm})\ ^\dagger$$
$$a_\mu^{expt} = 116\,592\,03(15)\times10^{-10} \quad (1.3 \text{ ppm})\ ^\ddagger$$

$$a_\mu^{expt} - a_\mu^{theory} = 42(16)\times10^{-10}$$

A Sampler of "New Physics"

Compositeness	g-2 reach for Standard Model answer
★ muon (m_μ^2/Λ^2)	$\Lambda > 5$ TeV
★ W^+, W^-	$\Lambda > 400$ GeV
μ form factors ($1-k^2/\Lambda^2$)	(W^+) $\Lambda > 450$ GeV
	(Z^0) $\Lambda > 64$ GeV
	(γ) $\Lambda > 180$ GeV
excited bosons	$m_W^*, m_Z^* > 70$-140 GeV
★ W magnetic moment	$(g_W-2)/2 < 0.02$

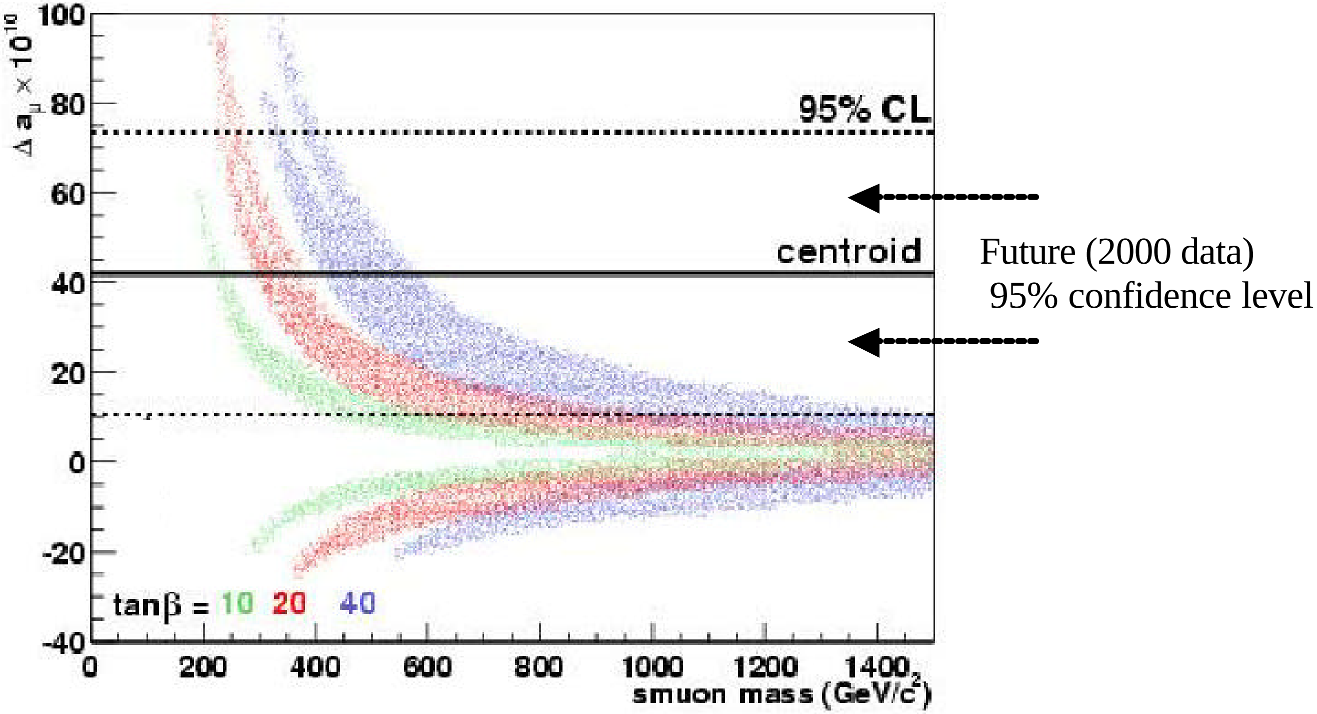
Extensions to Standard Model

Light Higgs	$m_H > 300$ MeV
Super-heavy Higgs	$m_H > 500$ GeV
Z-prime (E6, LR)	$m_{Z`} > 30$-130 GeV
W_R^+, W_R^-	$m_{W`} > 250$ GeV
leptoquarks	$m_{\Phi L} > 186$ GeV
large extra dimensions	$M_s > 1.5$ TeV
Supersymmetry	$m_{LS} > 130$ GeV
★ Sugra (large tan β)	$a_m \sim (1.3\ \text{ppm}) \tan\beta (100\ \text{GeV}/m)^2$

Allowed Regions of SUSY (direct searches) in a_m space

(courtesy of Toru Goto)

What if $\Delta a_\mu = a^{SUSY}$?



At 95% CL, the left-handed scalar muon mass must by smaller than 600, 900 and 1500 GeV/c^2 for $\tan\beta$ 10, 20 and 40, respectively.

Hadronic Contributions

Data required

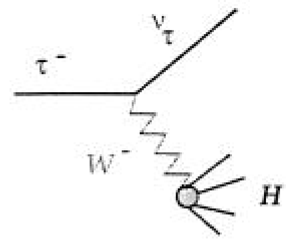
1st order thru

R(s)

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

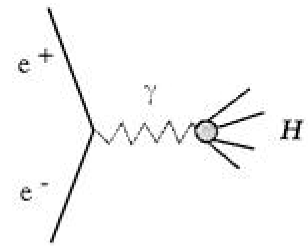
(*69.24 $\pm$ 0.53 ppm,* Davier + Hocker '98)

t **-decays**
(CLEO, ALEPH)



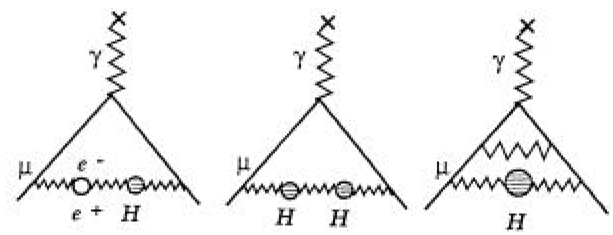
Thru CVC and isospin

$$R(s) = \frac{\sigma(e^+e^- \Rightarrow hadrons)}{\sigma(e^+e^- \Rightarrow \mu^+\mu^-)}$$



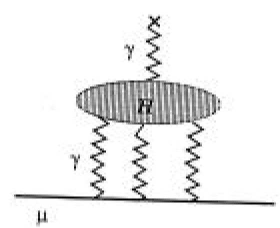
higher order

(*-1.00 $\pm$ 0.05 ppm,* Alemany, Davier, Hocker '98)



Light-by-light (model dependent)

(*-0.85 $\pm$ 0.21 ppm,* Average of Hayakawa, Kinoshita '98
and Bijnens, Pallante, Prades '96)



Comparison of First Order Hadronic Evaluations

$$< a_\mu >_{\text{exp}} = (116\ 592\ 023 \pm 151) \times 10^{-11}$$

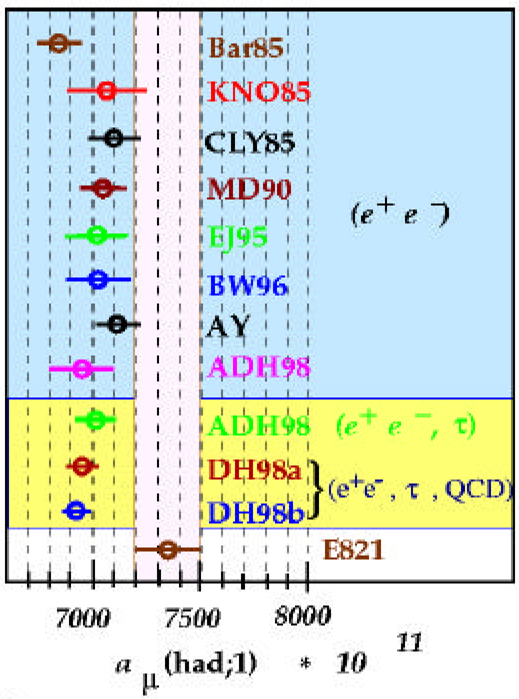
$$a_\mu\,(\text{QED}) = 116\ 584\ 705.7\,(2.9) \times 10^{-11}$$

$$a_\mu\,(\text{Weak}) = 152\,(4) \times 10^{-11}$$

$$a_\mu\,(\text{Higher order hadronic}) = -185 \pm 26 \times 10^{-11}$$

Subtracting these from $< a_\mu >_{\text{exp}}$ gives

$$a_\mu\,(\text{Had};1) + a_\mu\,(\text{New?}) = 7350\,(153) \times 10^{-11}$$



B. Lee Roberts: had1_comp.ps

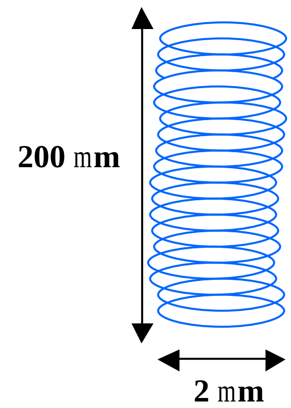
How to Measure a Magnetic Moment

Store your particle in a magnetic bottle (uniform B and quadrupole E) and watch it precess

ELECTRONS

Penning Trap (N_e = 1)
E = meV (T=4.2 °K)

$$w_s = \frac{g\,eB}{2\,mc}$$

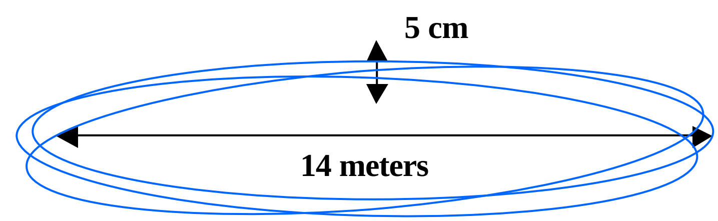


MUONS *oops!, they decay! So dilate them...*

Storage Ring (N_m = 1600 - 17000)
E = 3 GeV

$$w_s = 1 + g\,\frac{(g-2)}{2}\,\frac{eB}{mcg} \quad \text{and} \quad w_c = \frac{eB}{mcg}$$

$$w_a = w_s - w_c = \frac{(g-2)}{2}\,\frac{eB}{mc}$$

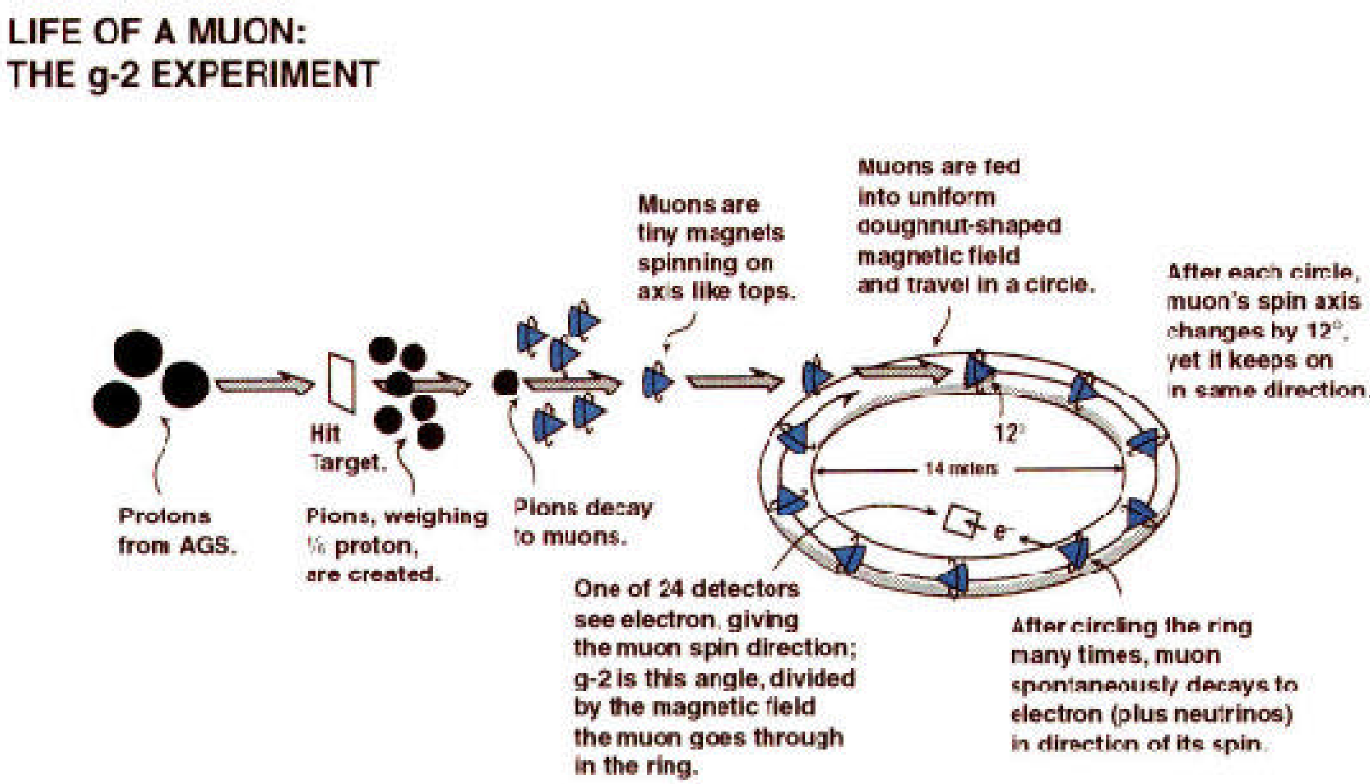


Quadrupole E field gives additional term in w_a : $+ \frac{e}{mc}\left(a_m - \frac{1}{g^2 - 1}\right) b \times E$

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

The BNL g-2 Experiment

from a muon's point of view



The g-2 Muon Storage Ring is a Technological Wonder!
Some Fun Factoids

- The World's Largest Diameter Superconducting Coil
- Powered by a 5 Volt, 5200 Amp Power Supply
  Regulated to < 0.3 ppm
- Held by straps: Shrinks by $\Delta r = 30$ cm when cooled,
  Expands by $\Delta r = 3$ mm when powered
- 680 Tonne, 14 m diameter C-shaped Magnet
  Yoke machined to $\Delta r = 130 \mu m$ over 7 m
  Pole tips (vacuum cast .004% carbon steel) machined flat to 0.8 μm
- Field at B = 1.45 Tesla
  Uniform to 1 ppm with current feedback
  Measured to 0.3 ppm using NMR (375 fixed probes & 17 trolley probes)
- Quench resistor is a 40 mΩ iron grid resistor weighing 100 lbs.
  to dissipate 6.1 M joules in 30 seconds. ($\Delta T = 700^{o}C$)

Blind Analysis

Decay positrons

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

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 (4 + analyses): ω_a

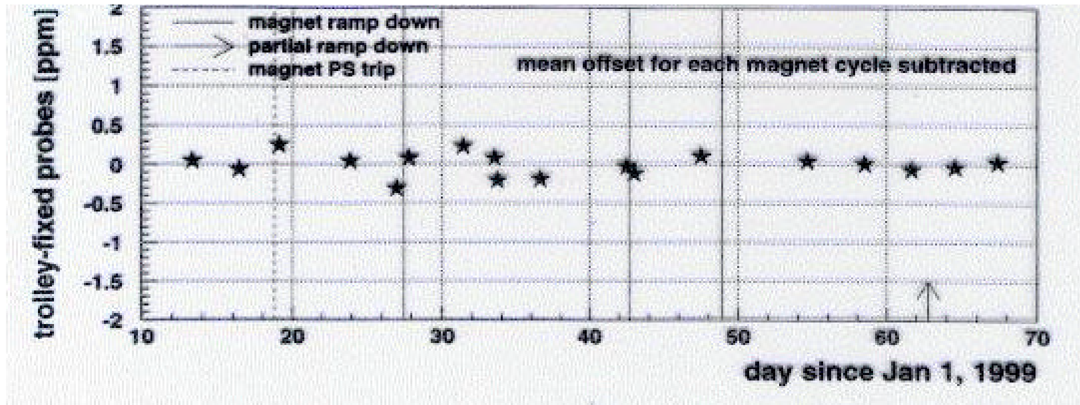
Magnet Team (2 analyses): ω_p

- 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.

Beam Tube Trolley

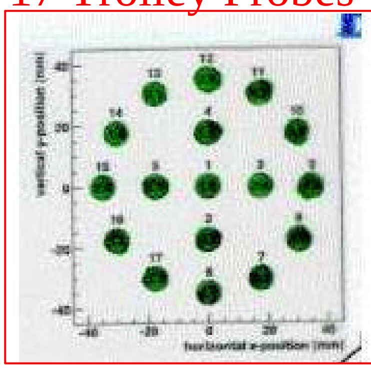
Maps the Magnetic Field once every couple days (NMR probes)

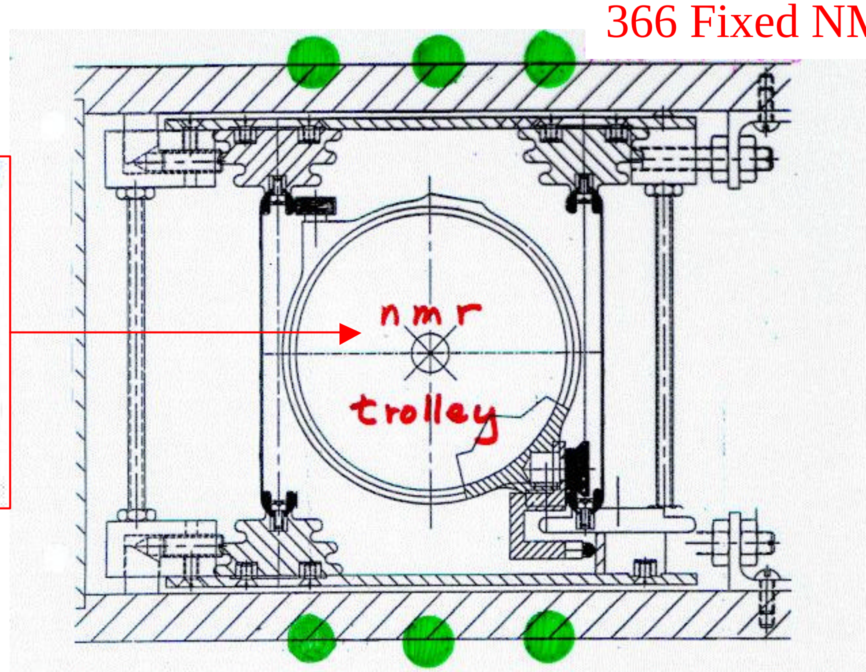
[Trolley - Fixed Probes] in ppm (σ = 0.15 ppm)



366 Fixed NMR Probes

17 Trolley Probes

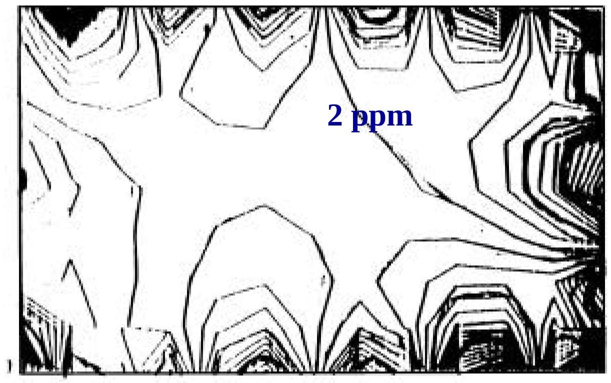


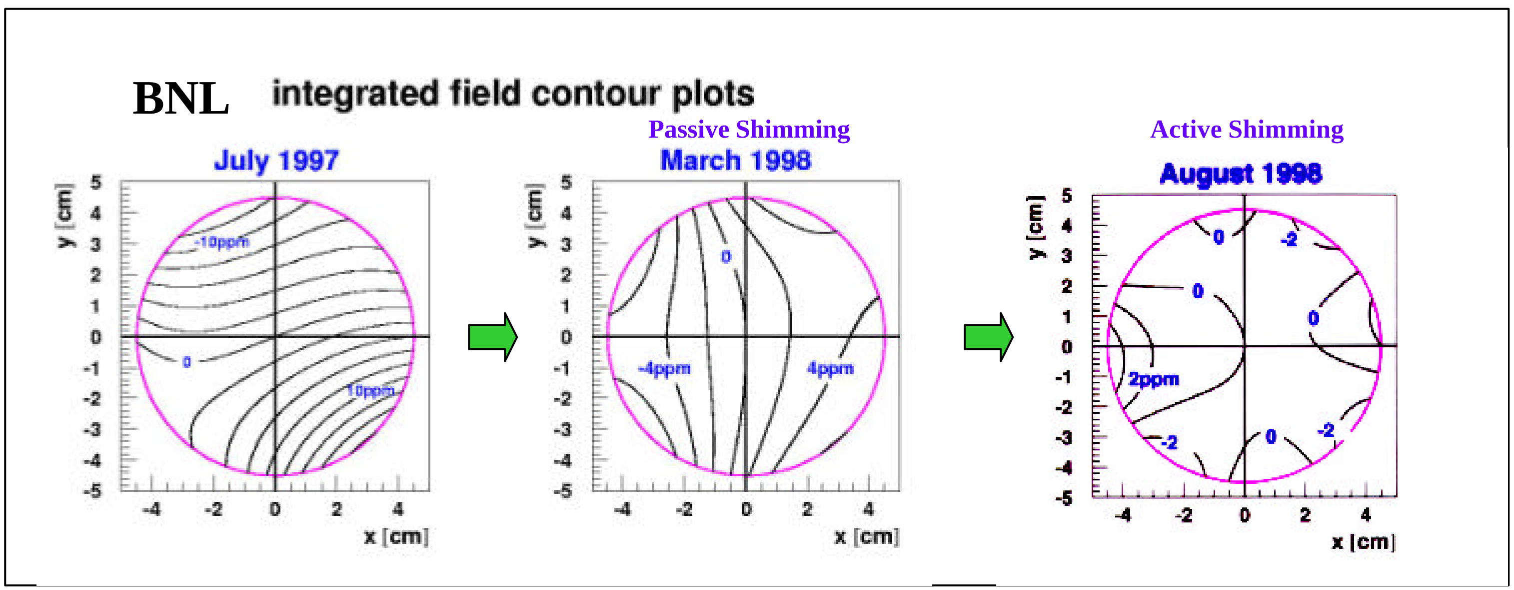


Magnetic field integrated over azimuth. 2 ppm contours (3 μT)

Goal: 1 ppm homogeneity, measured to 0.1 ppm

CERN field contour





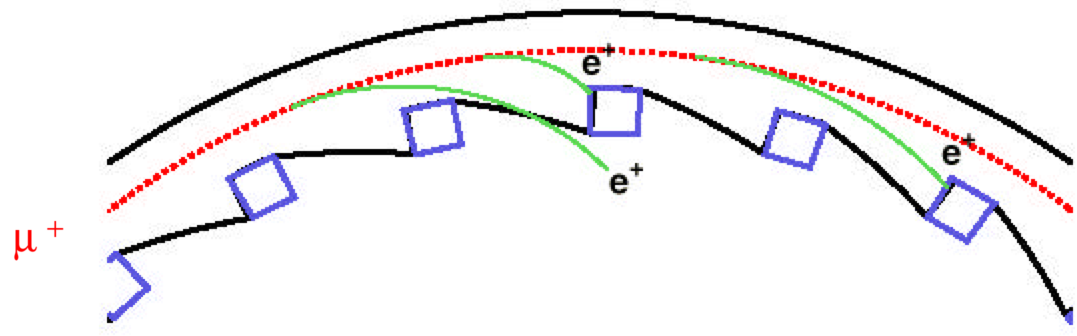
NMR Proton Frequency

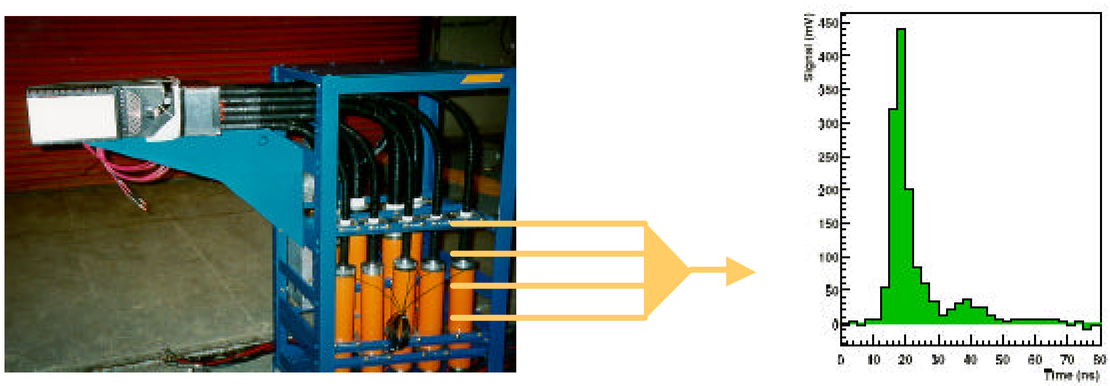
w_p / 2p = 61,791,256 ± 25 Hz

B_0	Calibrated Spherical H_2O Probe	0.05 ppm
$B(r, t_0)$	Trolley NMR calibration and B_0	0.22
$B(r, t)$	Interpolation with fixed probes	0.15
$B(r, t)$	Inflector fringe field (gone in 2000)	0.20
<B> => ω_p	Average over muon distribution	0.12
Others	(Trolley voltage; kicker eddy currents; higher multipoles)	0.15

Total Systematic Uncertainty on ω_p 0.4 ppm

w_a *Analysis: Finding the Positron Arrival Time*

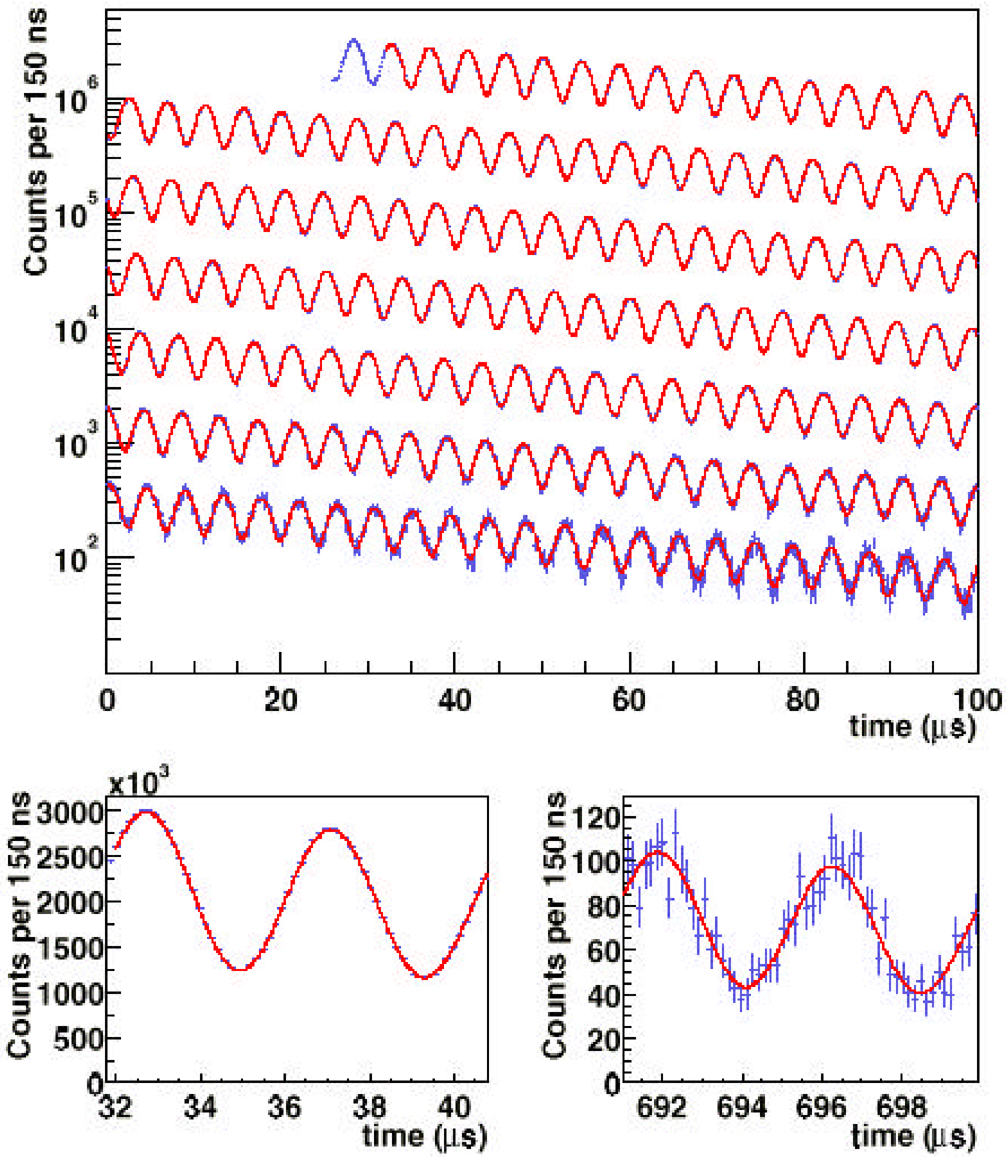




Complete waveform from calorimeter is digitized with 2.5 ns sampling

- **Find pulses from 24 detectors around ring**
- **Parameterize pulse shape for each detector and run condition**
- **Energy and time cuts to remove background, understand pileup**
- **Fill Histogram: Number of decay e's vs fitted pulse time**

ω_a Analysis = Fitting the wiggle



<u>The Challenge</u>

1999: 0.9×10^9 e^+ ($E > 2$ GeV)

Obtain an acceptable χ^2 /dof with 10^9 events in one histogram of 4000 bins!

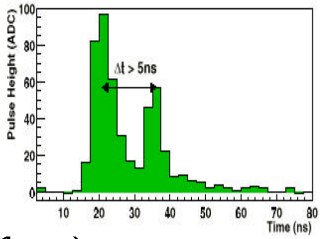
$N_o\, e^{-t/\tau}\, (1 + A \cos(\omega_\alpha t + \varphi))$

is no longer good enough.

Main Disturbances

- Pileup of real pulses <5 ns apart

  1% at earliest times: model and subtract



- Muon Losses

  bump beam high and scrape edges (first 11 μs)
  triple coincidences of scintillator paddles measure what's left

- Rate dependent calorimeter response

  changes the effective energy threshold
  in situ laser calibration system

- Coherent Betatron Oscillations

  image of the inflector exit moves around the ring as a beat frequency of w_c and w_b
  fiber harp and traceback chamber measure stored muon profile vs time

- Bunched beam

  randomize time spectrum in bins of cyclotron period

Strategy: Put additional terms in fitting function or

Find an insensitive method and
Establish the magnitude of all unaccounted uncertainties

Multi-parameter fits

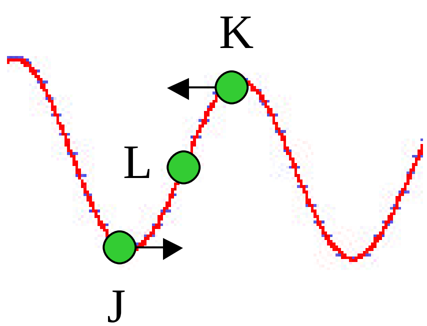
Modify 5-par fit: $N(t) = N_0\, e^{-t/\tau} (1 - A(E) \cos(\omega_a t + \varphi(E)))$ as follows

$n(t) = [\, N(t) + PU(t) + B(t)] \times [\, 1 + CBO(t)] \times [\, 1 + MuLoss(t)]$

10^{-2} 10^{-5} 10^{-4} 10^{-2}

Ratio Method

Split data into histograms J,K, L and form ratio

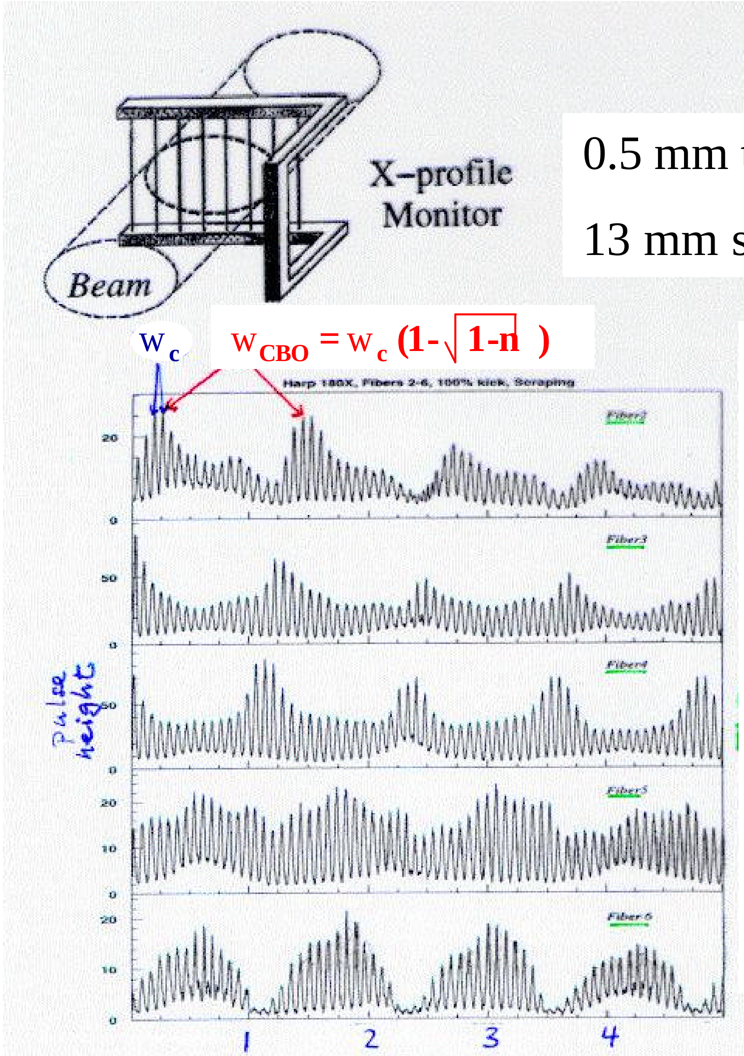


$$\frac{J\,(+\,1/2 \text{ wiggle}) + K\,(-\,1/2 \text{ wiggle}) - 2L\,(+\,0)}{J\,(+\,1/2 \text{ wiggle}) + K\,(-\,1/2 \text{ wiggle}) + 2L\,(+\,0)}$$

$= \;\; A(E) \cos(\omega_a t + \varphi(E)) \times [1 + PU(t)]$

where the frequency is isolated from the "exponentially" falling background distribution

Fiber Harp measures beam dynamics (destructively)



Time (μs)

0.5 mm thick fibers

13 mm spacing

FIBER

1

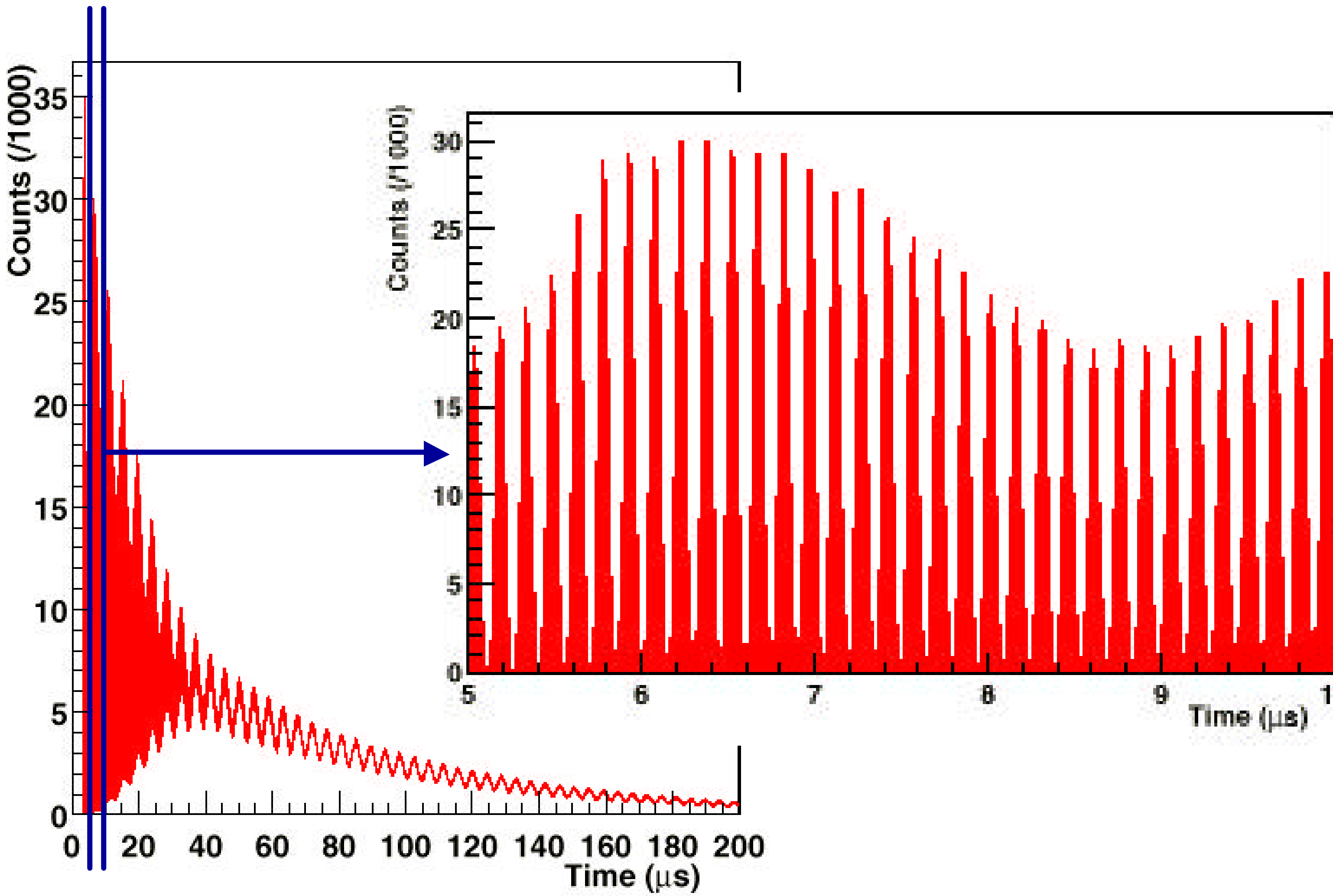
2

3

4

5

“Fast Rotation” - Cyclotron Frequency of muon bunches

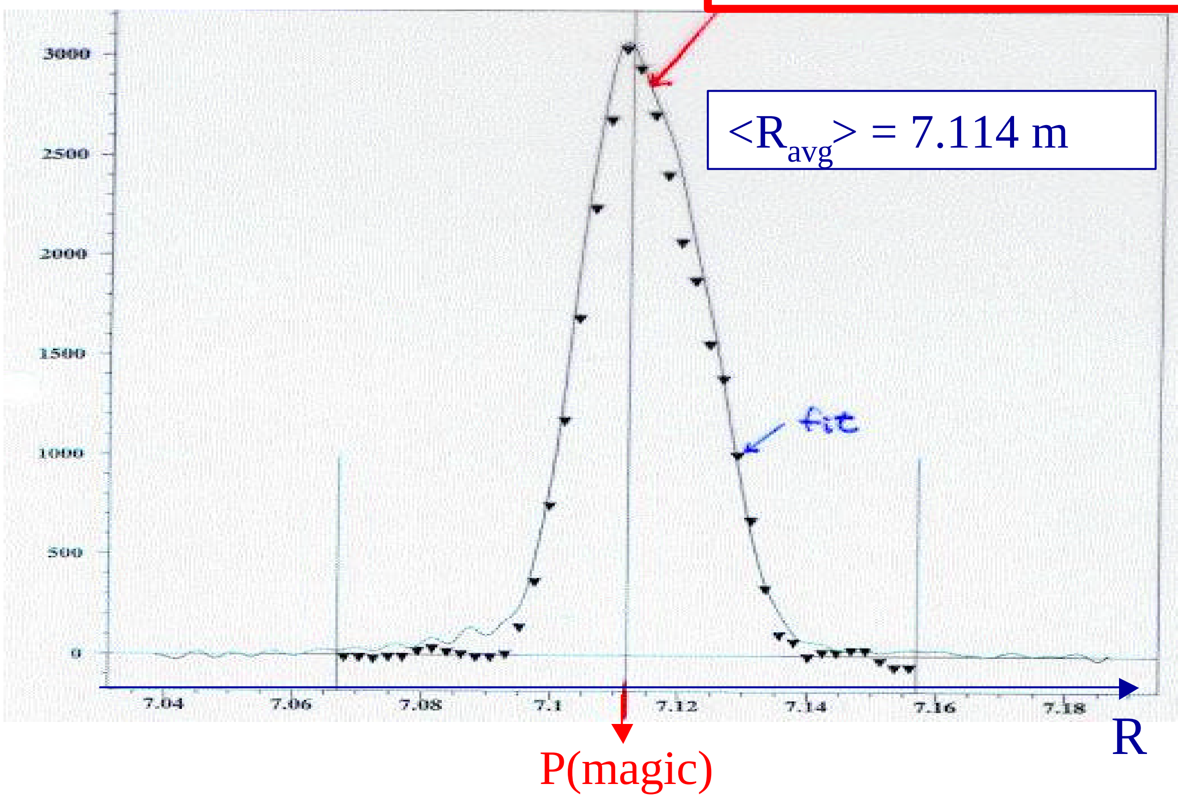


For ω_a analysis, randomize across a bin width of 149.185 ns

Rate of muon debunching => Muon radial distribution

E-Field Correction	**0.52 ppm**
Pitch Correction	**0.29 ppm**
	0.81 + 0.08 ppm

Fourier Transform of
cyclotron frequency at early times



$$\frac{\Delta P}{P_o} = (1\text{-}n)\frac{\Delta R}{R_o}$$

Systematic Uncertainties

Total $\delta\omega_a$ systematics = 0.25 ppm

Pileup	0.13 ppm
AGS background mis-tunes	0.10 ppm
Muon Losses	0.10 ppm
Timing Shifts	0.10 ppm
E-Field and Pitch correction	0.08 ppm
Binning and Fitting procedure	0.07 ppm
Coherent Betatron	0.05 ppm
Bin randomization (debunching)	0.04 ppm
Gain Instability	0.02 ppm

Total $\delta\omega_p$ systematics = 0.40 ppm

Total statistical = 1.25 ppm

Total Uncertainty = 1.3 ppm

4 Independent Analyses and 2 Production Streams

Production stream	Analysis	χ^2/dof	$R \pm \delta$ statistics (ppm)
ADAMO	13-parameter fit Fit pileup, mu loss, CBO. Fix φ_p	1.012 ± 0.023	143.25 ± 1.24
ADAMO	10-parameter fit Subtract pileup I. Fit mu loss, CBO	1.005 ± 0.023	143.08 ± 1.24
ADAMO	Ratio Method Subtract pileup I.Study mu loss, CBO	(1.004 ± 0.025	143.03 ± 1.28)
ROOT	Ratio Method Subtract pileup I.Study mu loss, CBO	0.986 ± 0.025	143.37 ± 1.28
ROOT	8-parameter fit Subtract pileup II. Fit CBO. Fix mu loss from counters	1.016 ± 0.005	143.30 ± 1.23

143.17 ± 1.24 ± 0.5

Conclusions

- Most precise a_μ in a single experiment
  - ⟹ 1.3 ppm on the anomaly (2.6 ppb on g)
  - ⟹ World Average is now at 1.3 ppm
- Experimental value differs from SM by 2.6 σ
  - ⟹ provide new limits on speculative theories
  - ⟹ encourages better determination of a_μ(hadronic)
- Data for 0.7 ppm is being analyzed now
- Data-taking for μ^- is completed
  - ⟹ CPT limit
  - ⟹ Combined μ^+ μ^- statistics will reach 0.4 ppm
- Further experiments planned for the g-2 storage ring
  - ⟹ direct mass limit on ν_μ
  - ⟹ electric dipole moment of muon