Testing the Standard Model: The Muon (g−2) Experiment

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- What is $(g-2)_\mu$?
- What is its Standard Model prediction?
- How do we measure it?
- What are a few of its implications for physics beyond the Standard Model?

The Muon g−2 Collaboration

Author list for last paper: 68 individuals, 11 institutions, 4 countries

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Fairfield University	Fairfield, Connecticut, USA
Universität Heidelberg	Heidelberg, Germany
University of Illinois	Urbana, Illinois, USA
KEK	Tsukaba, Japan
University of Minnesota	Minneapolis, Minnesota, USA
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Yale University	New Haven, Connecticut, USA

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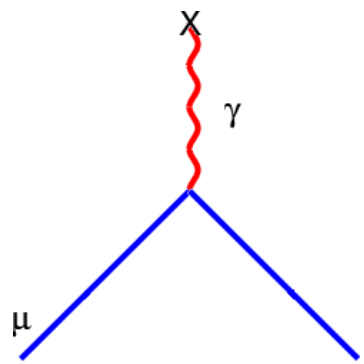
$g-2$: The Basics

g is the magnitude of the magnetic moment of a particle in units of the Bohr magneton:

$$\vec{\mu} = g\,\mu_B\,\vec{S}$$

For a spin Dirac point particle, to leading order, g=2:



However, from experiment:

$g \simeq$ 5.586 for proton (not a point particle!)

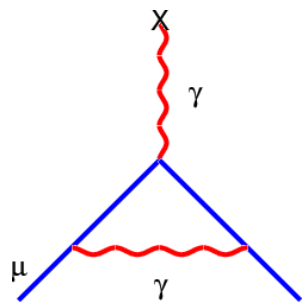
$g \simeq$ 2.002 for electron and muon (beyond leading order!)

g can be both measured and calculated very precisely: comparing the two provides a test of the Standard Model.

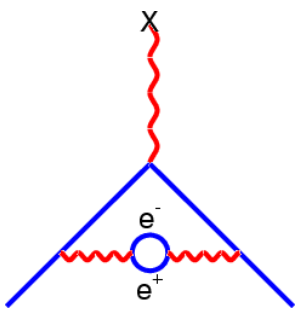
Perturbations: g≠2

The value of g is modified by quantum field fluctuations, resulting in the anomalous magnetic moment:

$$a_\mu = \frac{g-2}{2} = \frac{\alpha}{2\pi} + \ldots \approx \frac{1}{800}$$



First Order QED Vertex Correction



Higher Order Loop Correction

$$a_\mu^{\text{Theory}} = a_\mu^{\text{QED}} + a_\mu^{\text{Had}} + a_\mu^{\text{Weak}} + a_\mu^{\text{New Physics}}$$

a_μ^{SM}	116 591 596	±	67		± 0.6
a_μ^{QED}	116 584 706	±	3	10^6	± 0.025
a_μ^{had}	6739	±	67	57.8	± 0.6
a_μ^{weak}	151	±	4	1.30	± 0.03
	$\times 10^{-11}$			ppm	

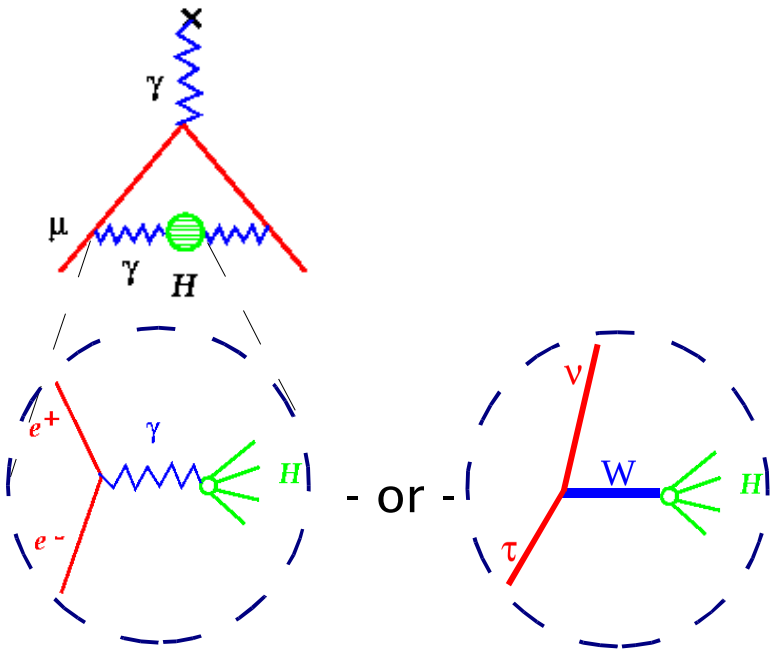
Loop corrections are proportional to m^2, so the muon is 4×10^4 times more sensitive than the electron.

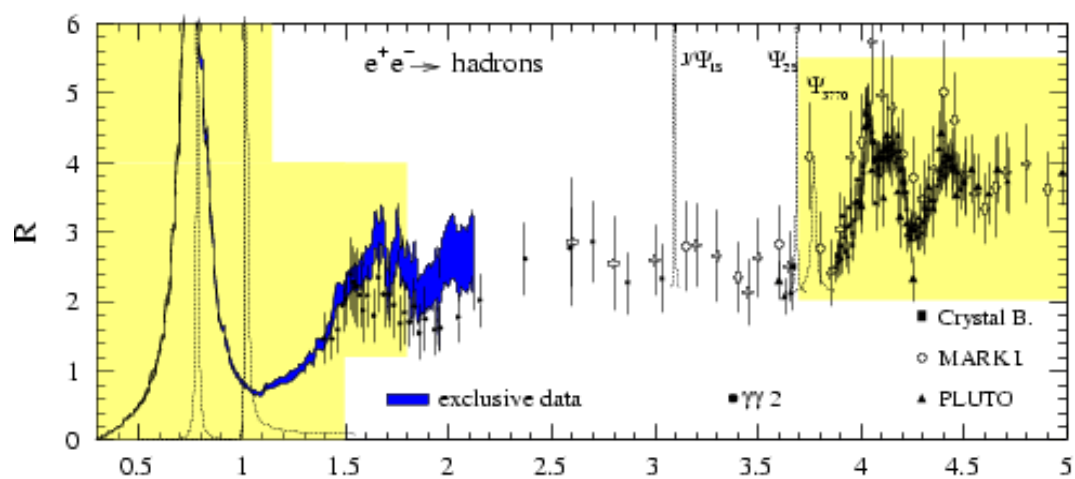
Hadronic Contribution

Can't calculate from first principles, but can relate to real hadron production in e^+e^- collisions and τ decay:

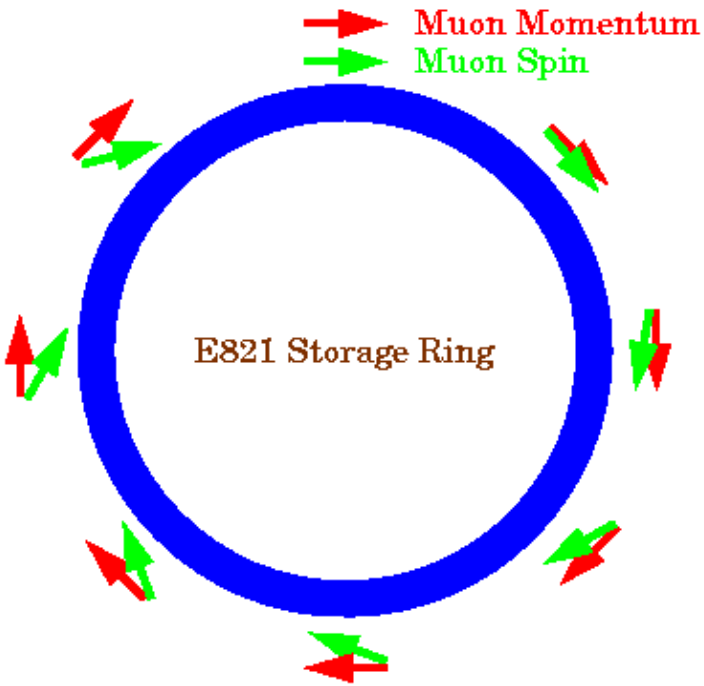
$$a_\mu^{had,1} \propto \int_{4m_\pi^2}^{\infty} ds \frac{K(s)}{s} R(s)$$

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





Muon Spin Precession in $\vec{B}$, $\vec{E}$ Field



Basic idea of experiment: Store a polarized beam of muons in a magnetic field and watch their spins rotate.

Equation describing spin motion:

$$\vec{\omega}_a = \vec{\omega}_s - \vec{\omega}_c = \frac{e}{m_\mu c}\left[a_\mu \vec{B} - \boxed{\left(a_\mu - \frac{1}{\gamma^2 - 1} \right)} \vec{\beta} \times \vec{E} \right]$$

$\rightarrow 0$ for $\gamma = 29.3$

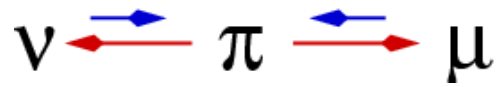
At the "magic" $\gamma = 29.3$, ω_a is independent of electric field.

- 3.09 GeV muons
- Uniform vertical magnetic field
- Electric quadrupole field for confinement

Can determine a_μ by measuring ω_a and B_z: $a_\mu = \left(\frac{\omega_a}{B_z}\right)\left(\frac{m_\mu c}{e}\right)$

Parity Violation: Polarizer and Polarimeter

Parity violation in pion decay ($\pi^+ \rightarrow \nu_\mu + \mu^+$) creates longitudinally polarized muons:

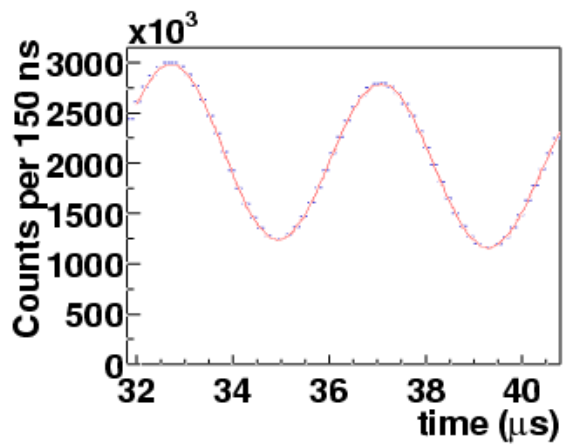


Parity violation in muon decay ($\mu^+ \rightarrow \bar{\nu}_\mu + \nu_e + e^+$) allows the muon spin direction to be measured: in the CM frame, positrons are emitted preferentially parallel to the muon spin direction.

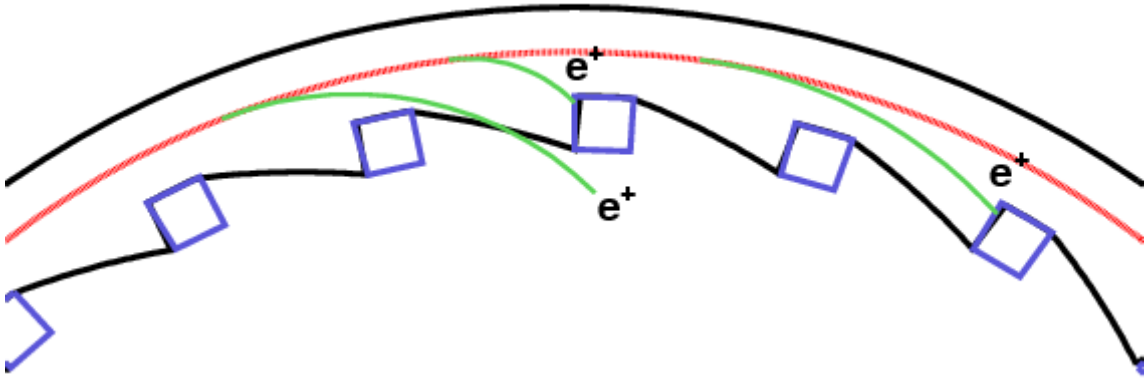
$$E_{lab} \approx \gamma E_{CM}(1+\cos\vartheta_{CM})$$

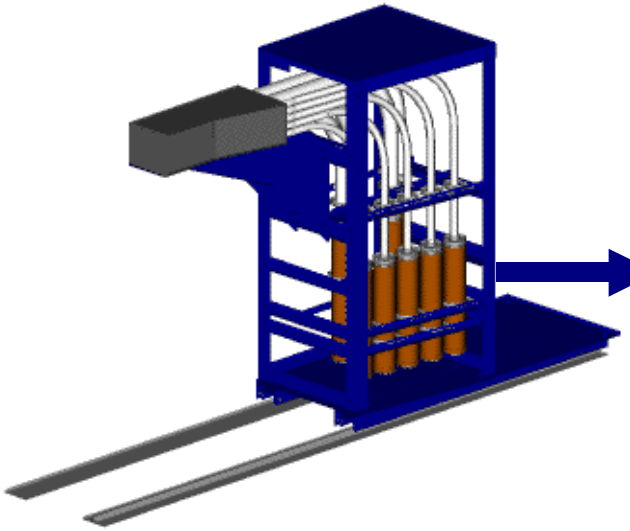
$\Rightarrow$ In the lab frame, forward-going positrons are boosted to higher energies.

$\Rightarrow$ Rate of high-energy decay positrons is modulated at ω_a:

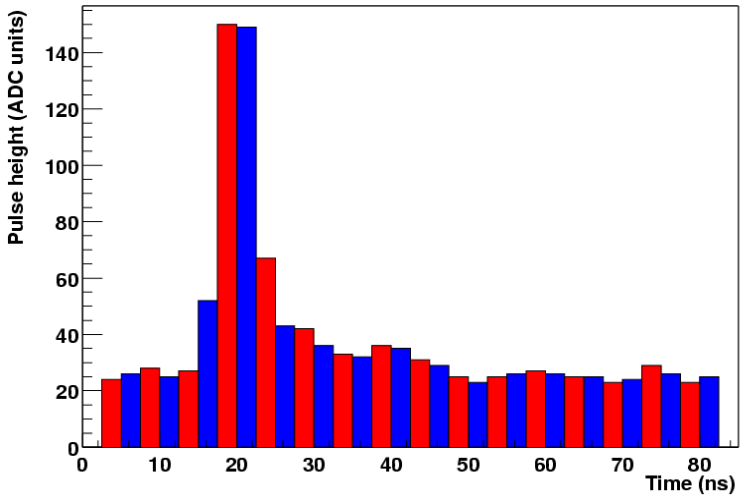


Detectors: from muons to bytes

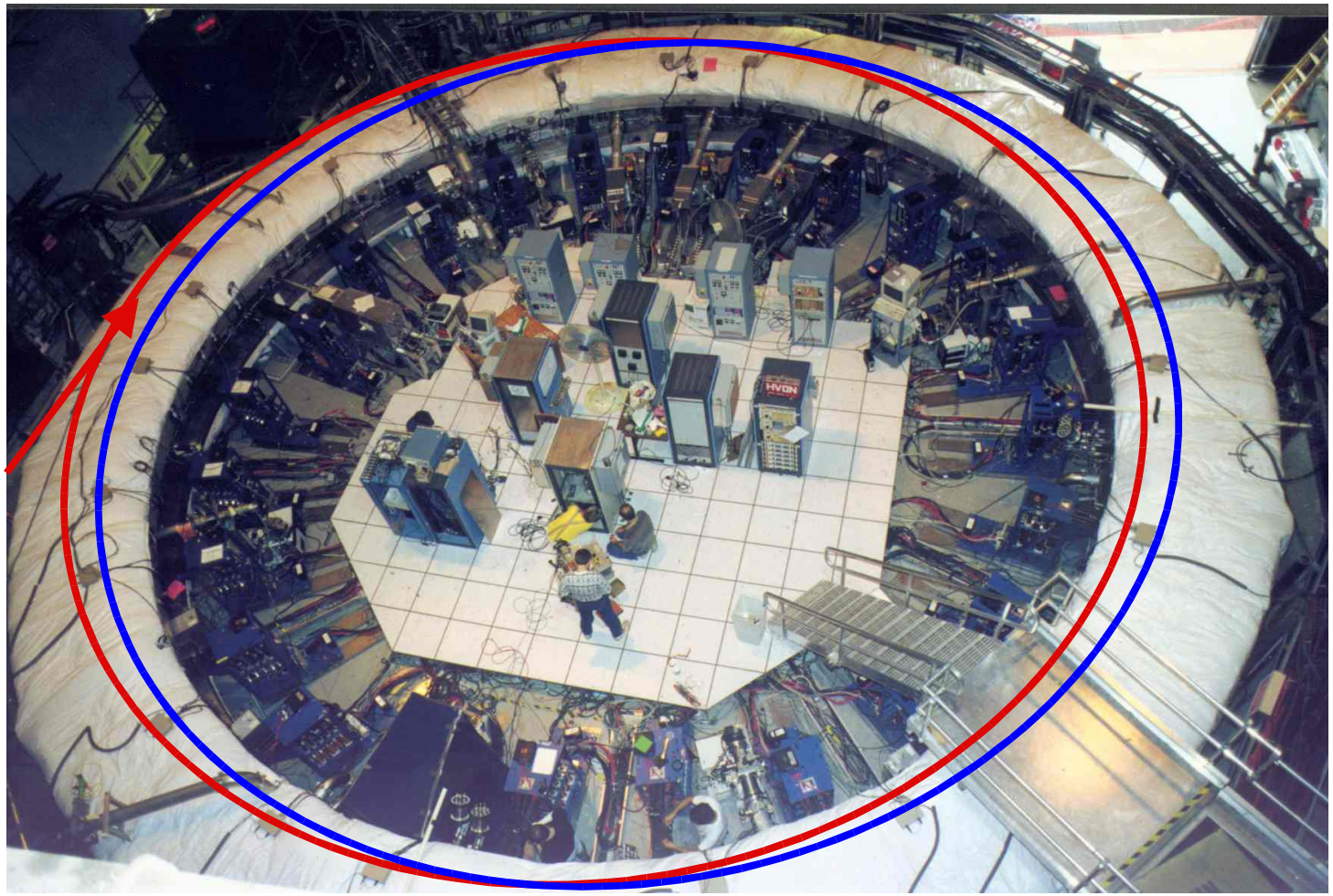




Waveform digitizer (WFD)



Storage Ring and Muon Kicker



R=7.112 m
B=1.45 T

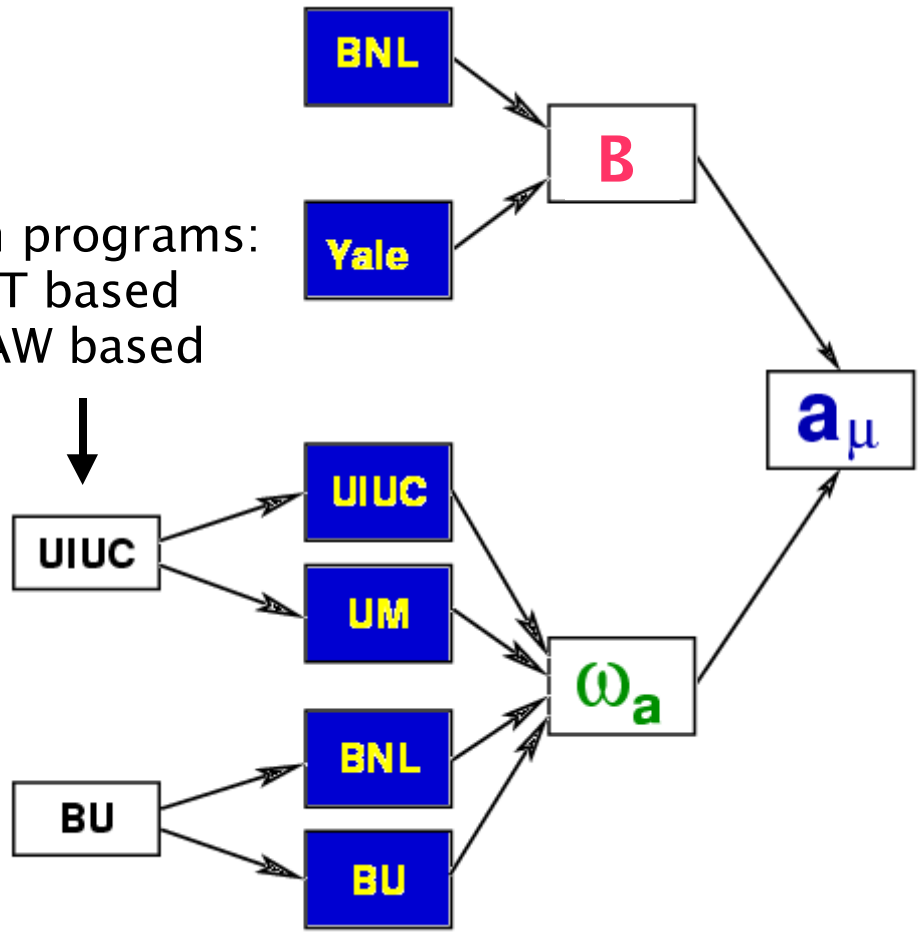
$P_\mu = 3.094$ GeV/c $\quad \gamma\tau = 64.4\ \mu s$

$\tau_{cyc} = 149$ ns $\quad \tau_a = 4.37\ \mu s$

"Blind" Analysis

Two event reconstruction programs:

- C++/ROOT based
- Fortran/PAW based

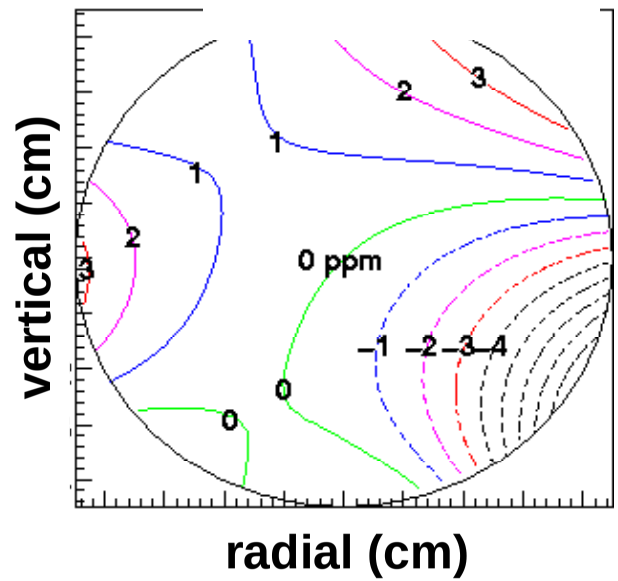


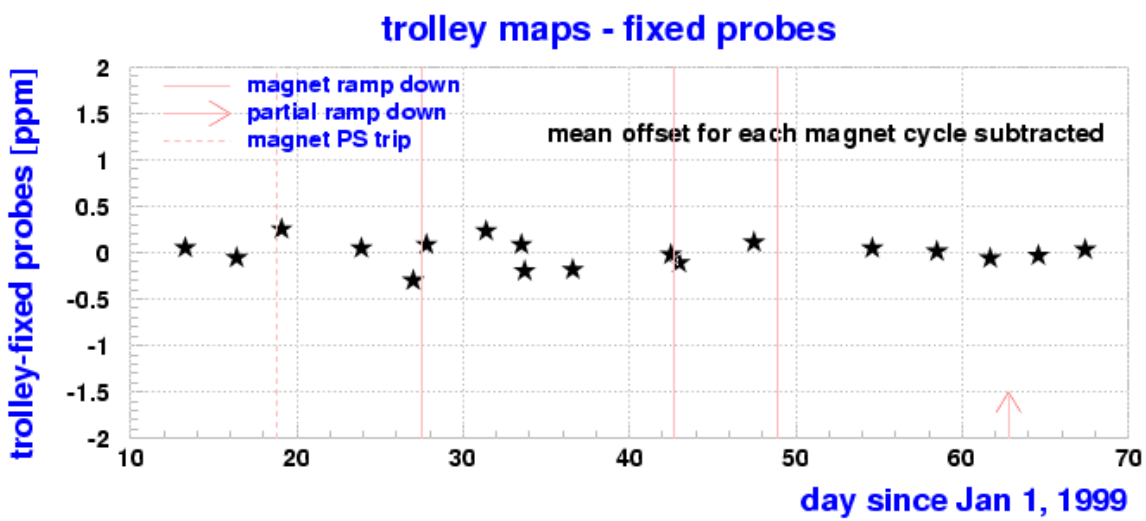
B and ω_a are analyzed separately and independently... both groups present their results with secret offsets that are only revealed once the results are final.

Local offsets within the groups are removed once all analyses are self-consistent.

$\omega_p = \mu_p B$: *Measuring the magnetic field*

- Field changes are monitored using 375 NMR probes fixed above and below the vacuum chamber.
- 17 probe NMR trolley operates in vacuum to map out field in storage region (2-3 times per week).
- Absolute calibration to spherical reference probe before and after data taking periods.





Fixed probes track the field between trolley runs with an uncertainty below 0.15 ppm

ω_p: Result and Systematics

TABLE I. Systematic errors for the $\widetilde{\omega}_p$ analysis

Source of errors	Size [ppm]
Absolute calibration of standard probe	0.05
Calibration of trolley probes	0.20
Trolley measurements of B_0	0.10
Interpolation with fixed probes	0.15
Inflector fringe field	0.20
Uncertainty from muon distribution	0.12
Others †	0.15
Total systematic error on $\widetilde{\omega}_p$	0.4

† higher multipoles, trolley temperature and its power supply voltage response, and eddy currents from the kicker.

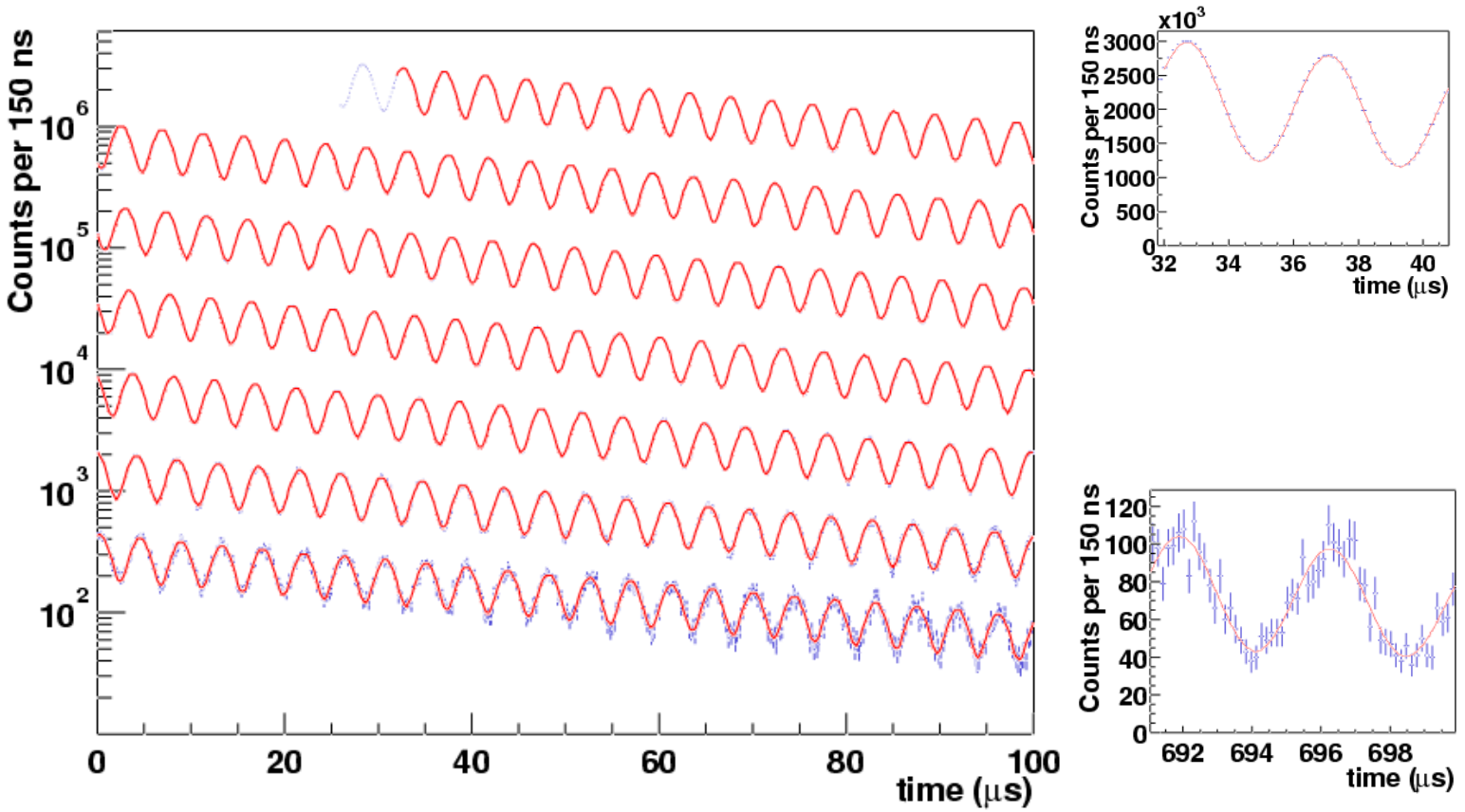
$$\omega_p / 2\pi = 61{,}791{,}256 \pm 25\, Hz$$

The g−2 Time Spectrum

The 1999 data set:
9×10^8 e^+ with E>2 GeV

Ideal functional form:

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



ω_a: Correcting the Fitting Function

5 parameter fitting function: $$N(t) = N_0 e^{-\frac{t}{\gamma\tau}}[1 + A\cos(\omega_a t + \phi)]$$

<u>Corrections to Data</u>

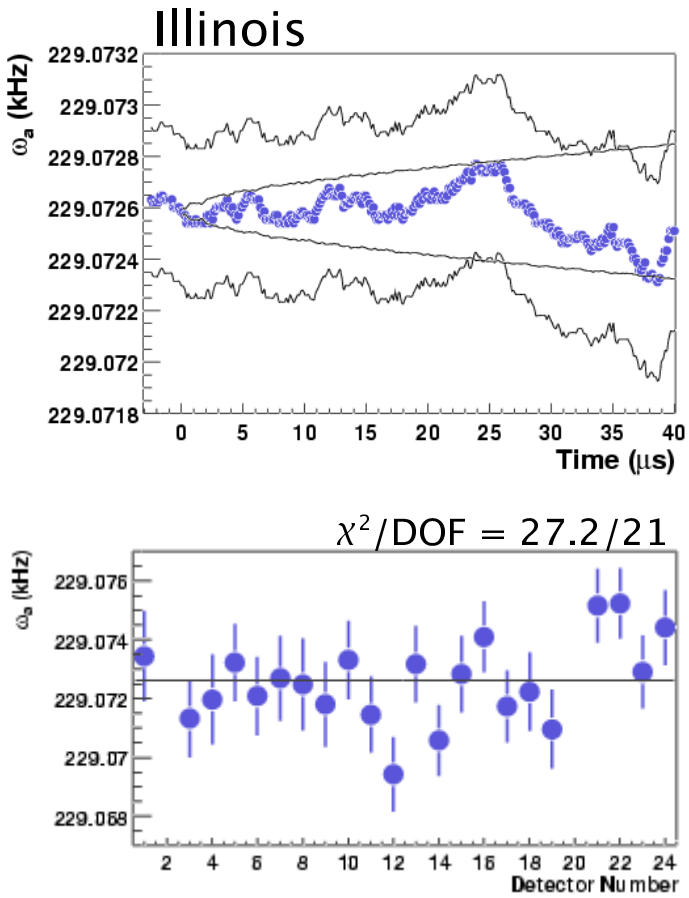
- Overlapping pulses
- Beam debunching
- Gain changes

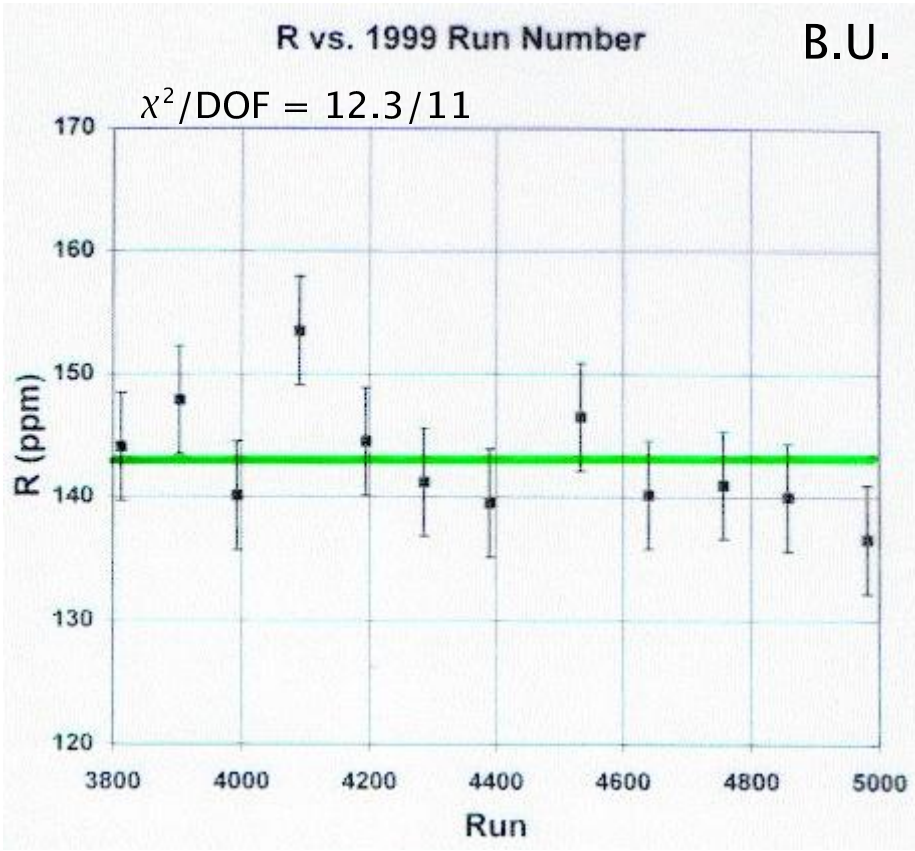
<u>Modifications to Fit Function</u>

- Overlapping pulses
- Coherent Betatron Oscillation
- Muon Losses

(These affect χ^2 much more than ω_a)

ω_a: Consistency Checks





ω_a: Systematic Uncertainties

TABLE II. Systematic errors for the ω_a analysis.

Source of errors	Size [ppm]
Pileup	0.13
AGS background	0.10
Lost muons	0.10
Timing shifts	0.10
E field and vertical betatron oscillation	0.08
Binning and fitting procedure	0.07
Coherent betatron oscillation	0.05
Beam debunching/randomization	0.04
Gain changes	0.02
Total systematic error on ω_a	0.3

$$\omega_a/2\pi = 229{,}072.8 \pm 0.3\,Hz$$

Determining a_μ

a_μ is finally determined by taking a ratio of two frequencies:

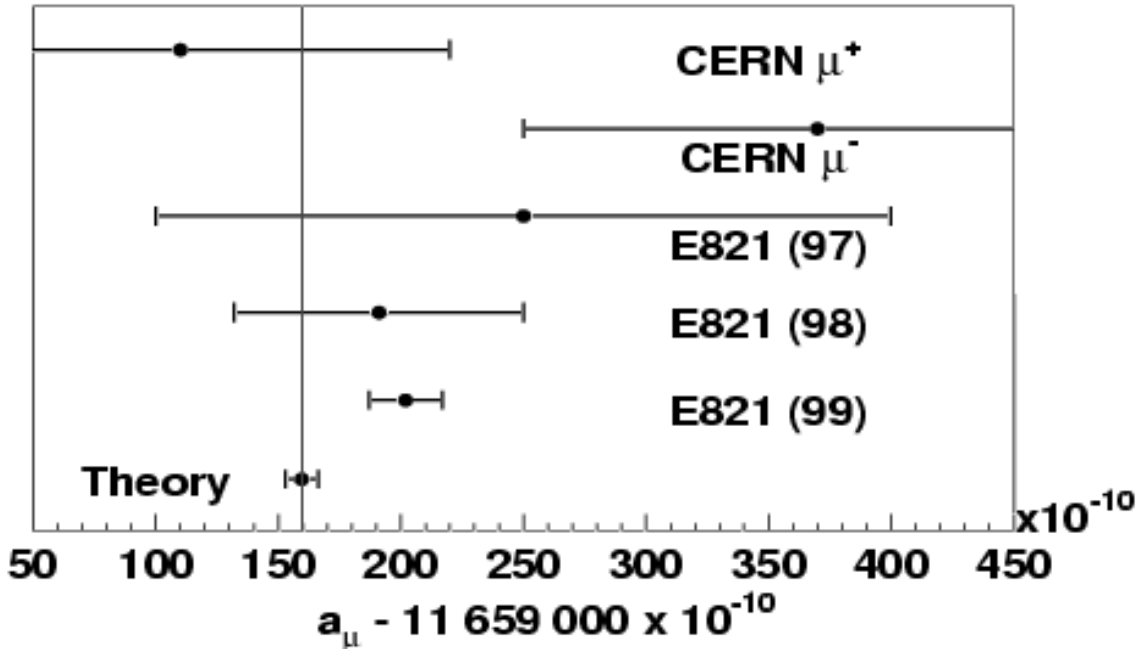
$$a_\mu = \frac{R}{\lambda - R}$$

Where, $R = \frac{\omega_a}{\omega_p}$ Measured by E821

$\lambda = \frac{\mu_\mu}{\mu_p}$ From muonium hyperfine structure

$= 3.183\ 345\ 39(10)$ D.E. Groom, et. al., Review of Particle Physics, *Eur. Phys. J.* **C15**, p. 1, (2000)

a_μ: Result



a_μ (99) =11 659 202 (14)(6) X 10^{-10} (1.3 ppm)

a_μ (SM) =11 659 159.6 (6.7) X 10^{-10} (0.57 ppm)

a_μ (World Ave) - a_μ (SM) = 43(16) X 10^{-10}

New Physics?

Lots of theoretical interest:

- Supersymmetry
- Muon substructure
- Leptoquarks
- Anomalous W couplings
- ... and many more

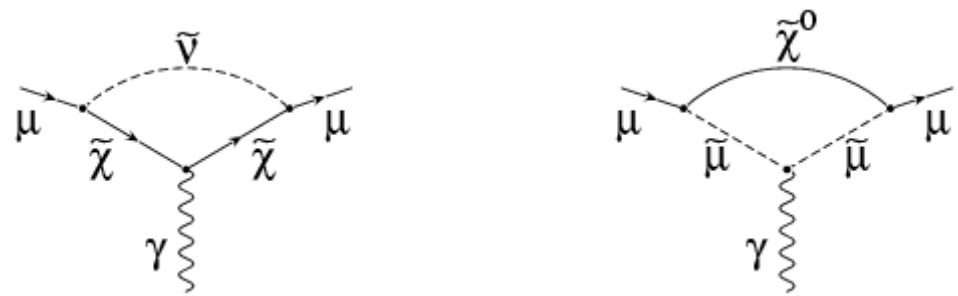
At least 47 recent hep-ph preprints!

Three talks at this Symposium: tomorrow's "SUSY and Cosmology" session:

- Howard Baer, "Impact of muon anomalous magnetic moments on SUSY models"
- Wai-Yee Keung, "Two-loop physics in EDM and (g-2)"
- Lian-Tao Wang, "Analysis and implications of the recent measurement of muon (g-2)"

SUSY?

For a_μ, dominant contributions from smuon-neutralino and sneutrino-chargino loops:

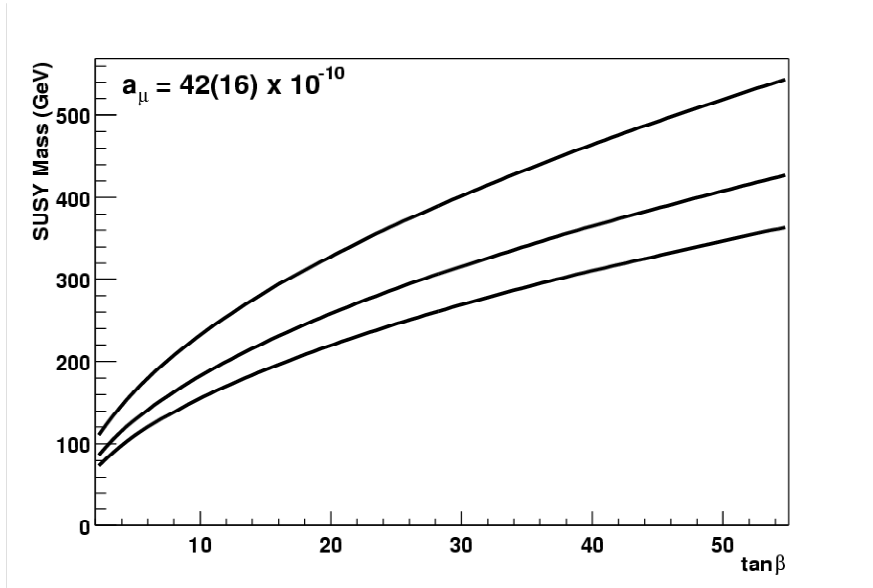


In a model with degenerate sparticle masses:

$$|a_\mu| \simeq 130 \times 10^{-11} \left(\frac{100\ GeV}{\tilde{m}} \right)^2 \tan\beta$$

$$\tilde{m} \simeq (55\ GeV) \sqrt{\tan\beta}$$

(assuming that our discrepancy is due entirely to SUSY...)



(Czarnecki and Marciano, hep-ph/0102122)

Conclusions

- Very precise determination of muon (g-2): $\delta a_\mu = 1.3$ ppm
- New measurement differs from the Standard Model prediction by 2.6 σ.
- Statistics? "Mistake"? New physics? All are possibilities.
- Uncertainty in SM value will be reduced by new e^+e^- and τ data.
- Data from 2000 run currently being analyzed: 4 times as many positrons.
- 2001 run just finished: negative muons.