Muon Magnetic Moment

Final Report of the Muon E821
Anomalous Magnetic Moment Measurement at BNL

February 20, 2006

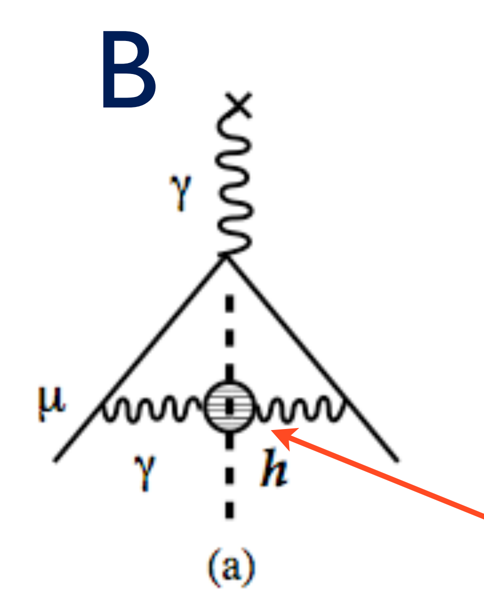
The muon magnetic moment is related to its intrinsic spin by the gyromagnetic ratio g_μ:

$$\vec{\mu}_\mu = g_\mu \left(\frac{q}{2m}\right) \vec{S}, \tag{1}$$

where $g_\mu = 2$ is expected for a structureless, spin-$\frac{1}{2}$ particle of mass m and charge $q = \pm e$. Radiative corrections (RC), which couple the muon spin to virtual fields, introduce an anomalous magnetic moment defined by

$$a_\mu = \frac{1}{2}(g_\mu - 2). \tag{2}$$

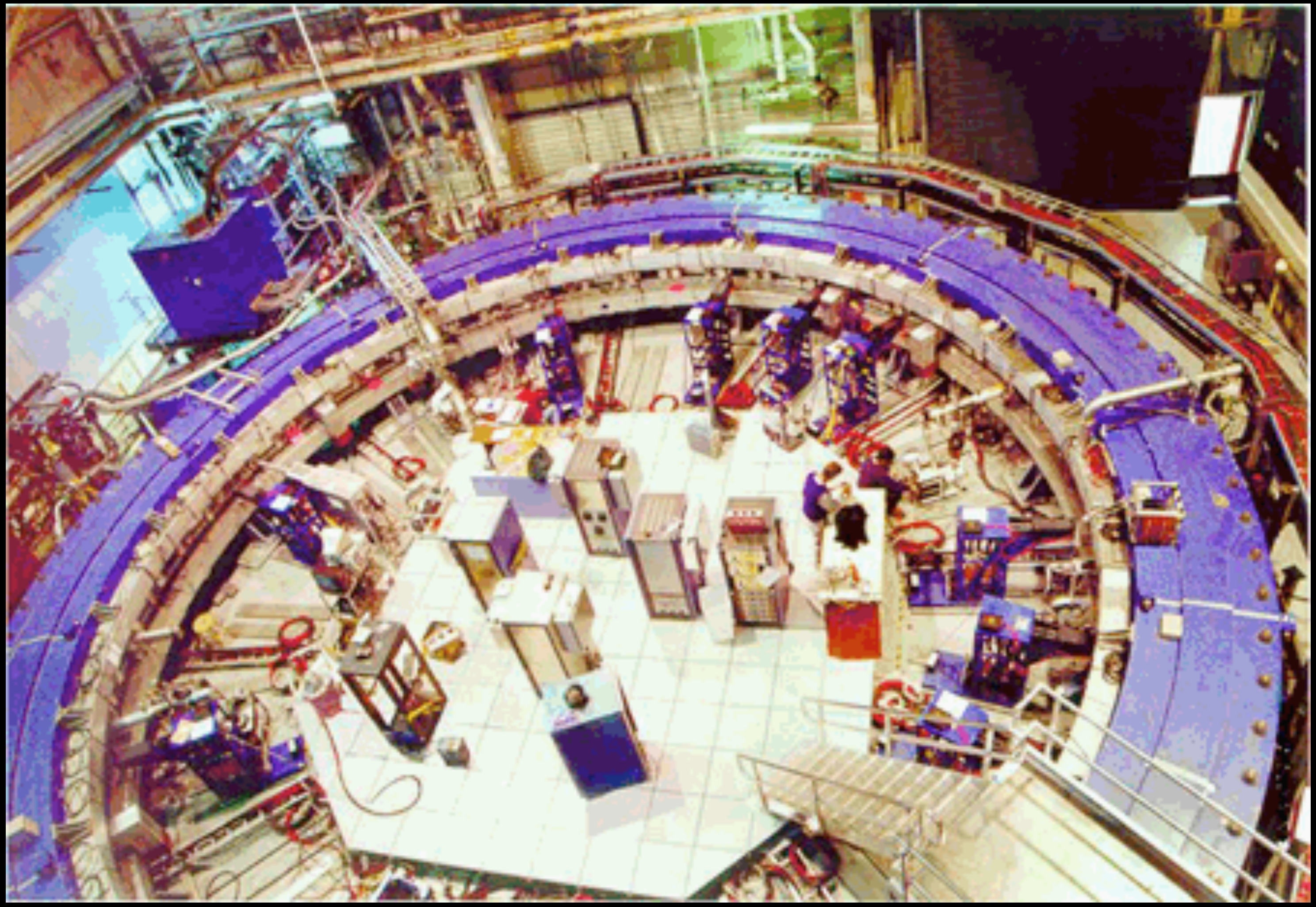
The leading RC is the lowest-order (LO) quantum electrodynamic process involving the exchange of a virtual photon, the "Schwinger term," [1] giving $a_\mu(\mathrm{QED;LO}) = \alpha/2\pi \approx 1.16 \times 10^{-3}$. The complete standard model value of a_μ, currently evaluated to a precision of approximately 0.6 ppm (parts per million), includes this first-order term along with higher-order QED processes, electroweak loops, hadronic vacuum polarization, and other higher-order hadronic loops. The measurement of a_μ, carried out to a similar precision, is the subject of this paper. The difference between experimental and theoretical values for a_μ is a valuable test of the completeness of the standard model. At sub-ppm precision, such a test explores physics well above the 100 GeV scale for many standard model extensions.



? new stuff ?

Hadron Vacuum Polarization

g-2 at Brookhaven



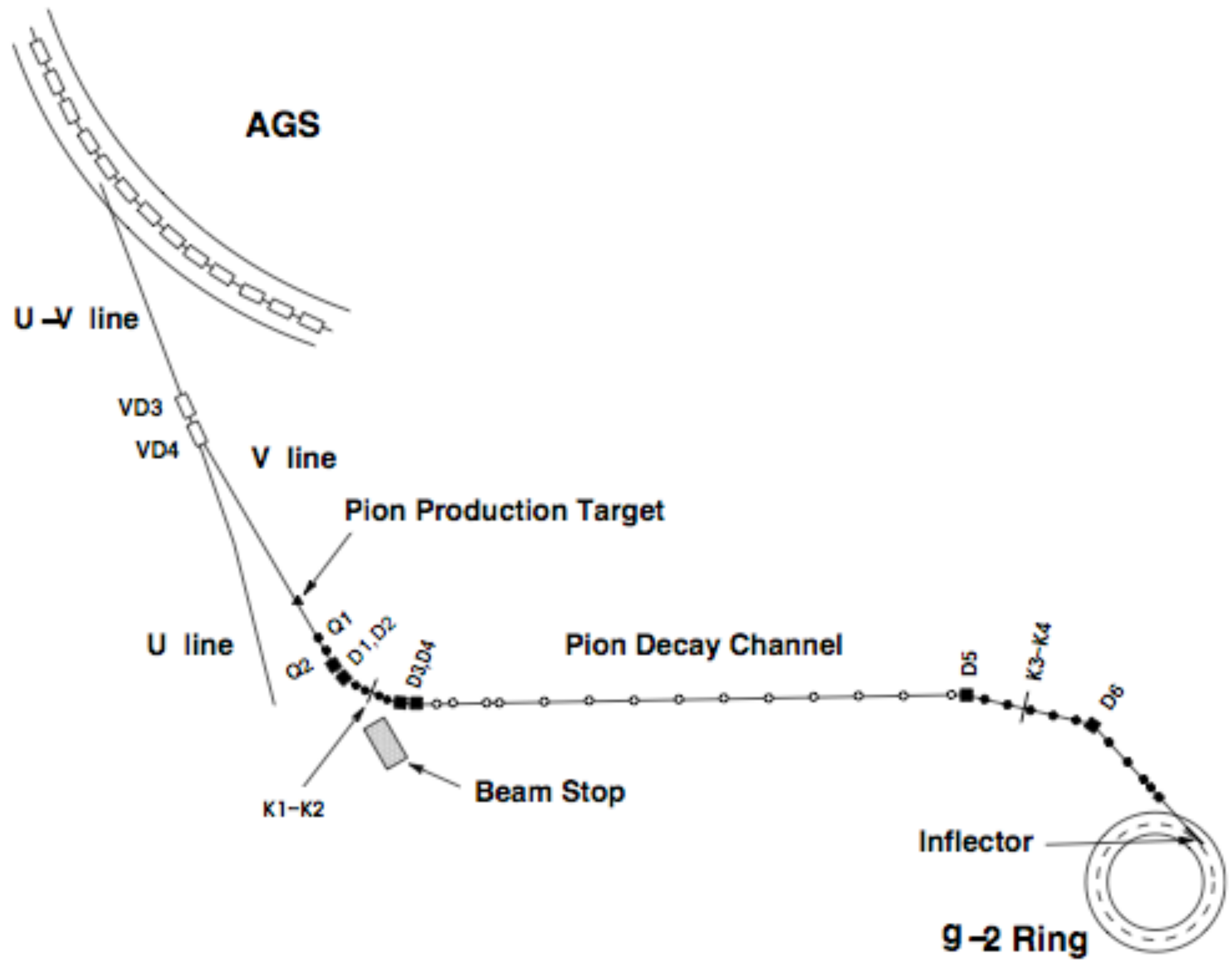


FIG. 3: Plan view of the pion/muon beamline. The pion decay channel is 80 m and the ring diameter is 14.1 m.

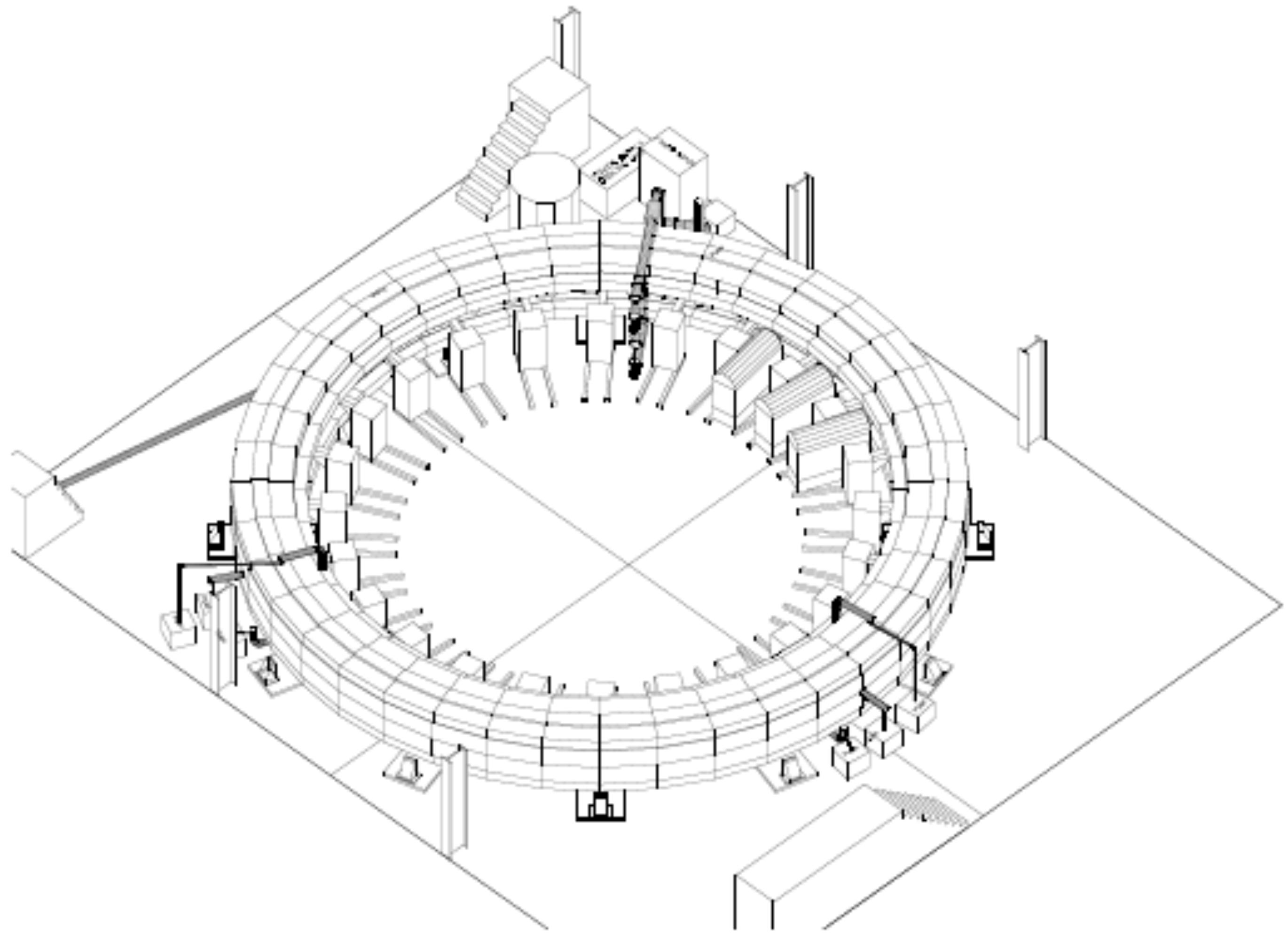
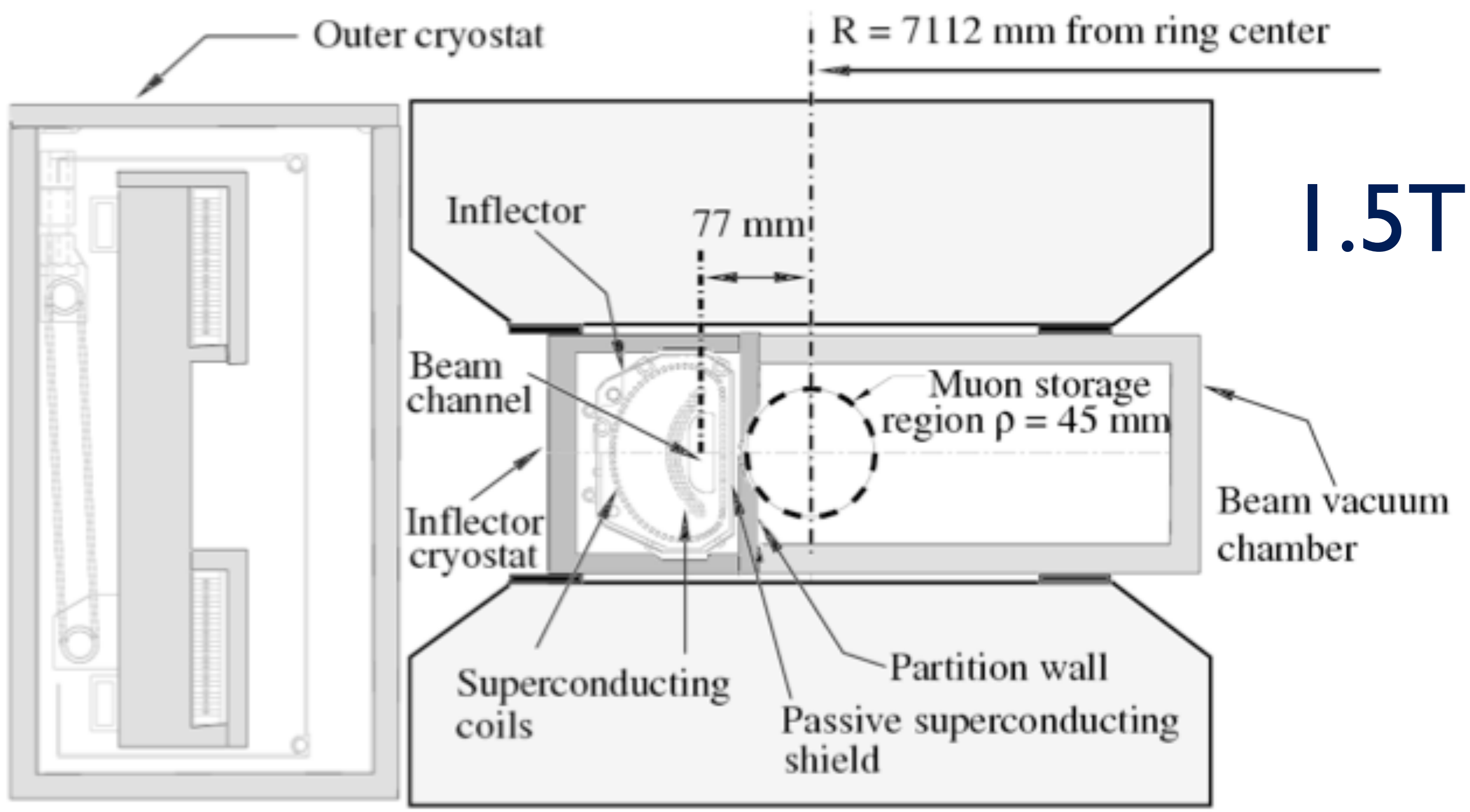


FIG. 6: A 3D engineering rendition of the E821 muon storage ring. Muons enter the back of the storage ring through a field-free channel at approximately 10 o'clock in the figure. The three kicker modulators at approximately 2 o'clock provide the short current pulse, which gives the muon bunch a transverse 10 mrad kick. The regularly spaced boxes on rails represent the electron detector systems.



1.5T

FIG. 4: The inflector/storage ring geometry. The downstream end of the inflector is shown, with the beam channel to the left of the storage region (larger radius). The ring center is to the right. Note the limited space between the pole pieces, which has to contain the inflector and its cryostat along with the beam vacuum chamber. The current in the inflector flows into the page in the "C" shaped arrangement of conductors just to the left of the beam channel, and out of the page in the conductors that form a backward "D". The superconductor crosses over the beam channel to connect the two coils.

anomalous precession frequency

The cyclotron ω_c and spin precession ω_s frequencies for a muon moving in the horizontal plane of a magnetic storage ring are given by:

$$\vec{\omega}_c = -\frac{q\vec{B}}{m\gamma}, \qquad \vec{\omega}_s = -\frac{gq\vec{B}}{2m} - (1-\gamma)\frac{q\vec{B}}{\gamma m}. \tag{3}$$

Thomas

The anomalous precession frequency ω_a is determined from the difference

$$\vec{\omega}_a = \vec{\omega}_s - \vec{\omega}_c = -\left(\frac{g-2}{2}\right)\frac{q\vec{B}}{m} = -a_\mu \frac{q\vec{B}}{m}. \tag{4}$$

note relativistic γ factor

vertical focusing electric quadrupoles gives a B field in the muon rest frame

$$\vec{\omega}_a = -\frac{q}{m}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta} \times \vec{E}}{c}\right].$$

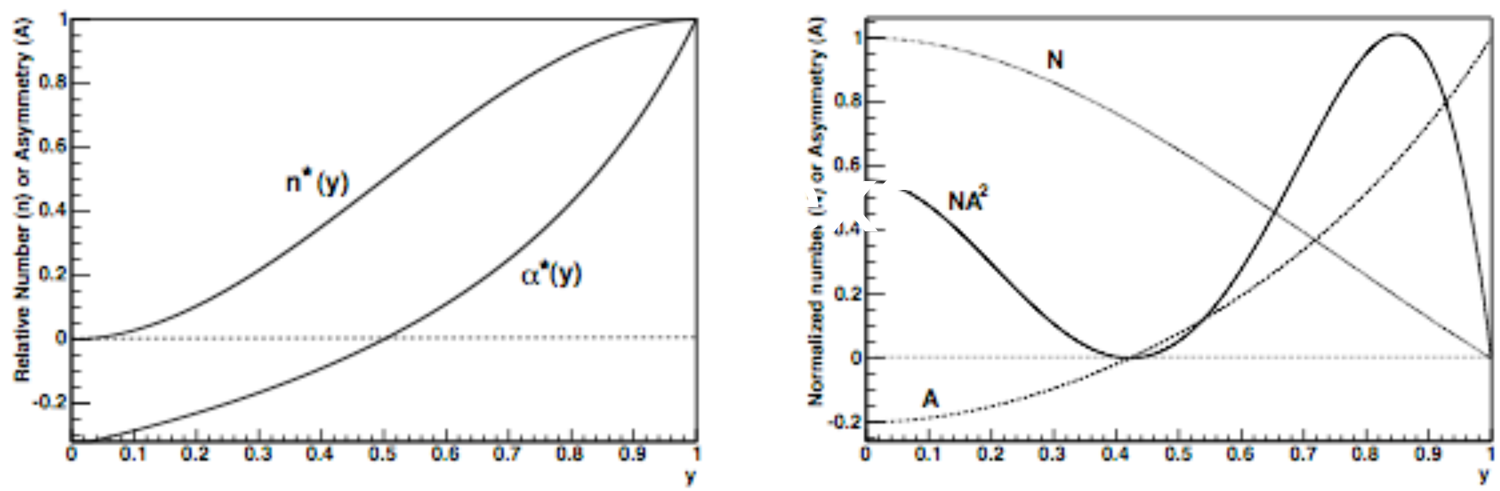
Choose "magic momentum" Υ=29.3 cancels a_μ to leading order, $\alpha/(2\pi)$

measure ω_a, B

$\mu^- \rightarrow \nu_\mu + e^- + \nu_e$

Parity-violating weak decay of muon gives correlation between muon spin and electron direction

e opp muon spin



(a) Center-of-mass frame

(b) Lab frame

FIG. 1: Relative number and asymmetry distributions versus electron fractional energy y in the muon rest frame (left panel) and in the laboratory frame (right panel). The differential figure-of-merit product NA^2 in the laboratory frame illustrates the importance of the higher-energy electrons in reducing the measurement statistical uncertainty.

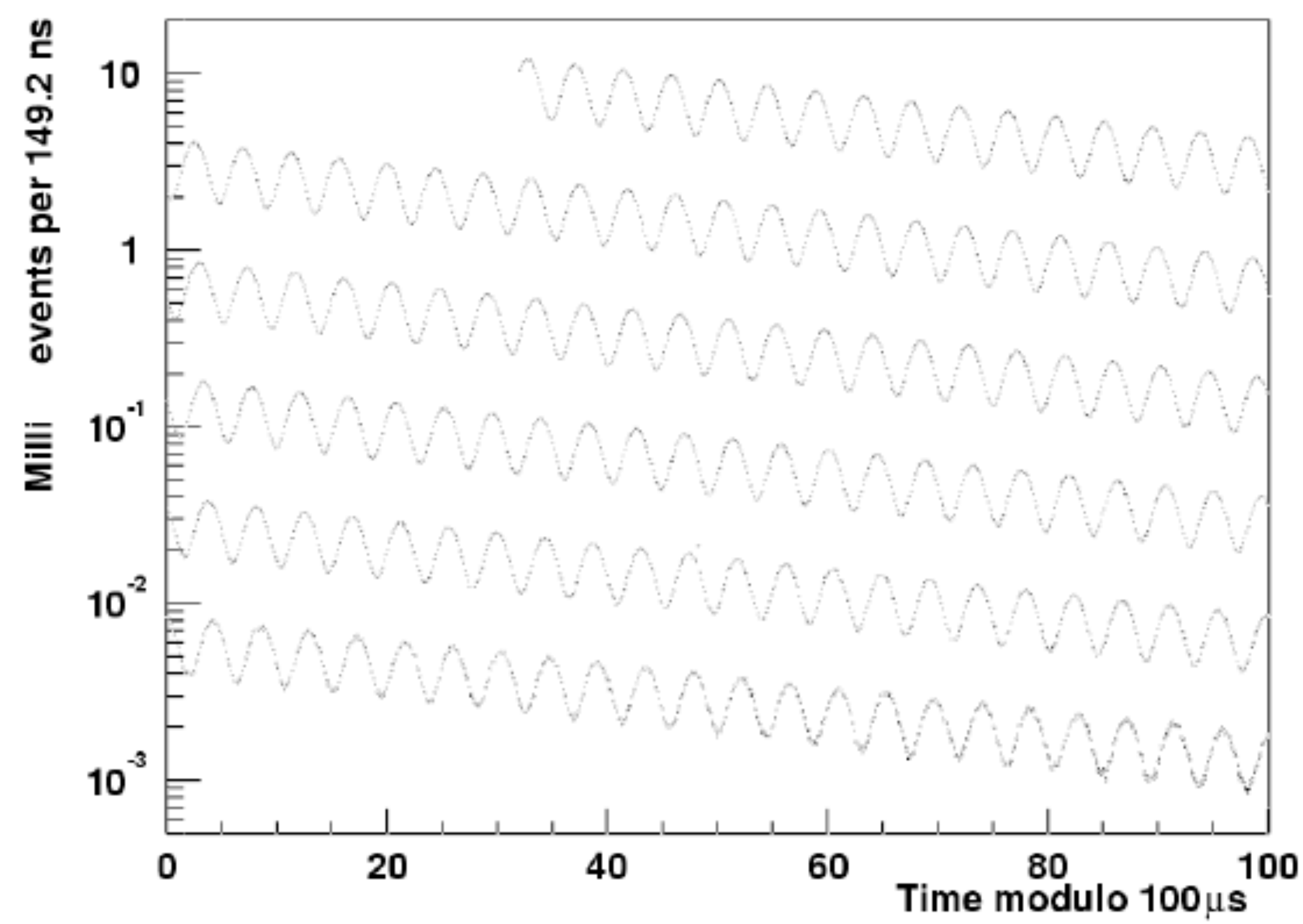


FIG. 2: Distribution of electron counts versus time for the 3.6 billion muon decays in the R01 μ^- data-taking period. The data is wrapped around modulo 100 μs.

B field measurement

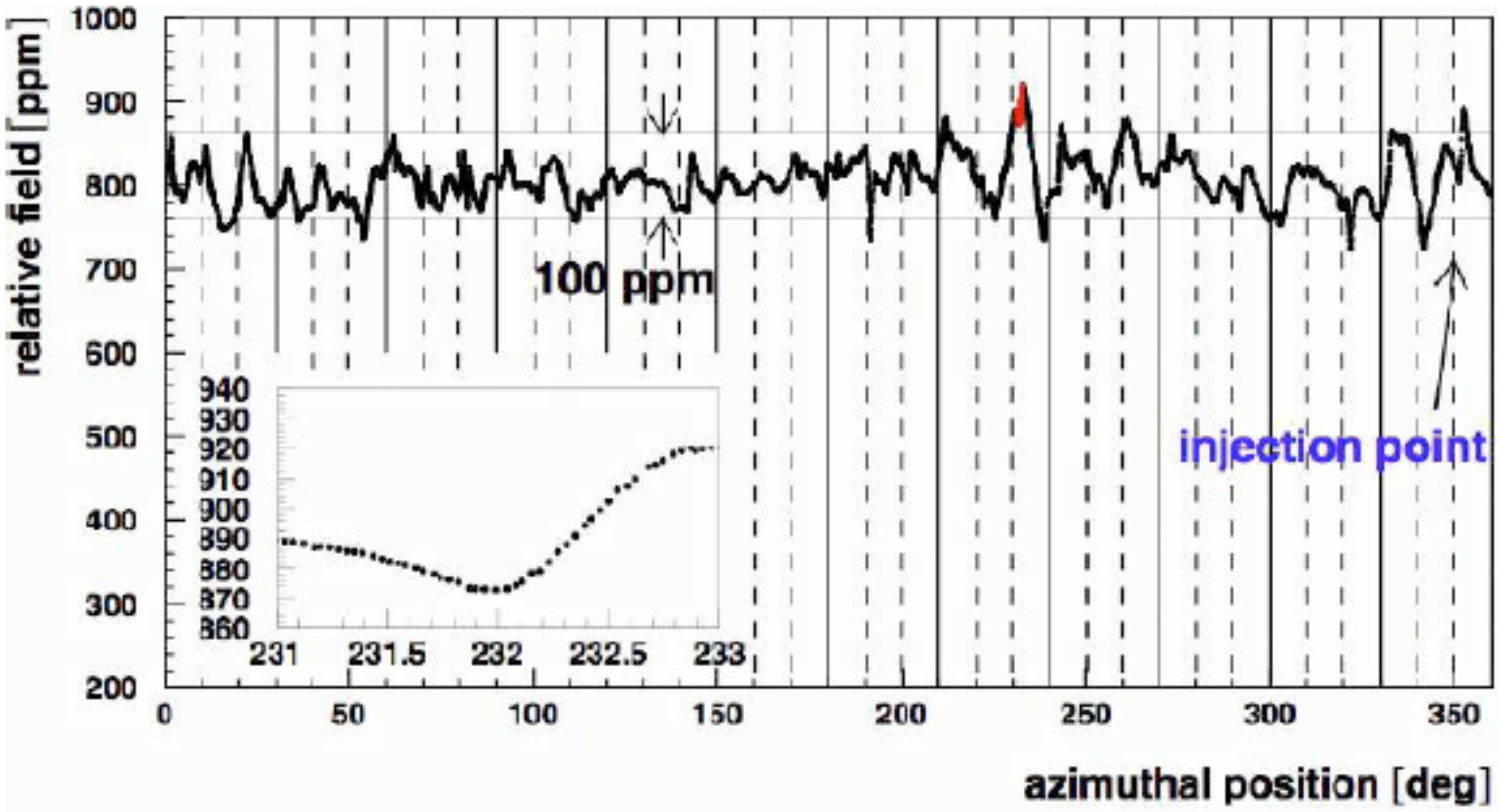


FIG. 26: The NMR frequency measured with the center trolley probe relative to a 61.74 MHz reference versus the azimuthal position in the storage ring for one of the measurements with the field trolley during the R01 period. The continuous vertical lines mark the boundaries of the 12 yoke pieces of the storage ring. The dashed vertical lines indicate the boundaries of the pole pieces. The inset focuses in on the measurements over an interval of two degrees. The point-to-point scatter in the measurements is seen to be small.

To determine a_μ, we divide ω_a by $\widetilde{\omega}_p$, where $\widetilde{\omega}_p$ is the measure of the average magnetic field seen by the muons. The magnetic field, measured using NMR, is proportional to the free proton precession frequency, ω_p. The muon anomaly is given by:

$$a_\mu = \frac{\omega_a}{\omega_L - \omega_a} = \frac{\omega_a/\widetilde{\omega}_p}{\omega_L/\widetilde{\omega}_p - \omega_a/\widetilde{\omega}_p} = \frac{\mathcal{R}}{\lambda - \mathcal{R}}, \quad (11)$$

where ω_L is the Larmor precession frequency of the muon. The ratio $\mathcal{R} = \omega_a/\widetilde{\omega}_p$ is measured in our experiment and the muon-to-proton magnetic moment ratio

g_p=5.585 694 713 (046)
m_mu = 106 MeV

$$\lambda = \omega_L/\omega_p = 3.18334539(10) \quad (12)$$

is determined from muonium hyperfine level structure measurements [12, 13].

Friday Feature™, M. Gold physics 492, Spring 2017

The standard model theoretical summary is given in Table XVI. Two results are presented, representing the two slightly different e^+e^--based evaluations of the leading-order hadronic vacuum polarization contribution. The theoretical expectation should be compared to our experimental result (Eq. 58):

$$a_\mu(\text{Expt}) = 11\,659\,208.0(6.3) \times 10^{-10} \quad (0.54\,\text{ppm}).$$

The difference

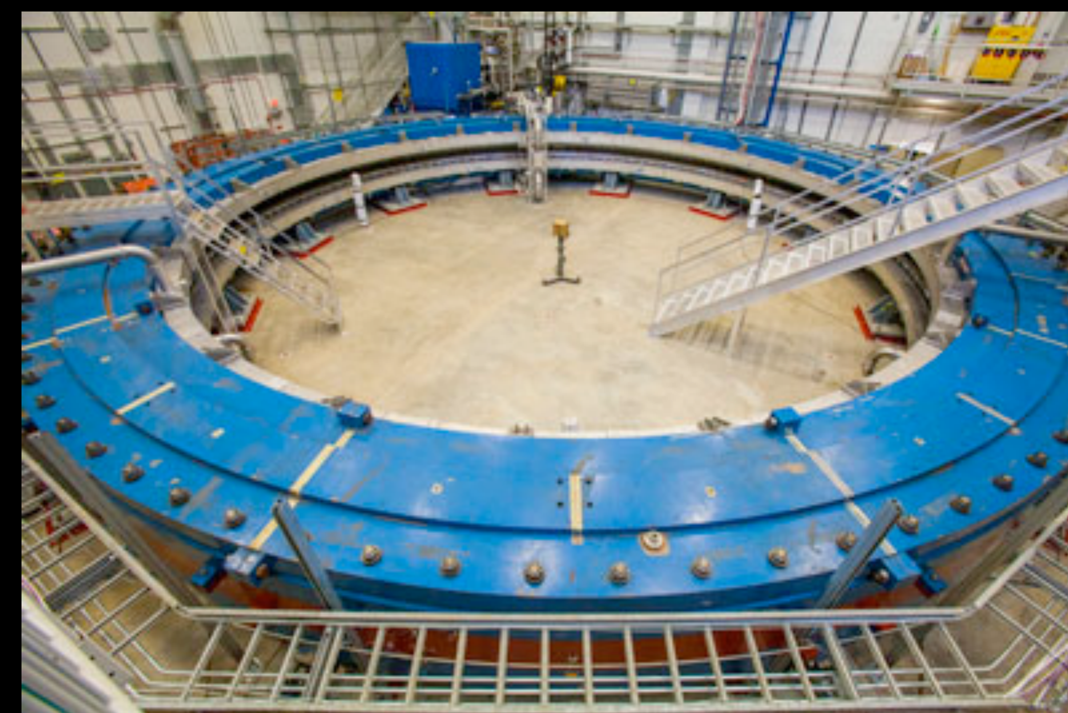
$$\Delta a_\mu(\text{Expt} - \text{SM}) = (22.4 \pm 10 \text{ to } 26.1 \pm 9.4) \times 10^{-10}, \tag{64}$$

has a significance of 2.2 to 2.7 standard deviations. Use of the τ-data gives a smaller discrepancy.

To show the sensitivity of the measured muon $(g-2)$ value to the electroweak gauge bosons, the electroweak contribution given in Eq. 61 is subtracted from the standard model values in Table XVI. The resulting difference with theory is

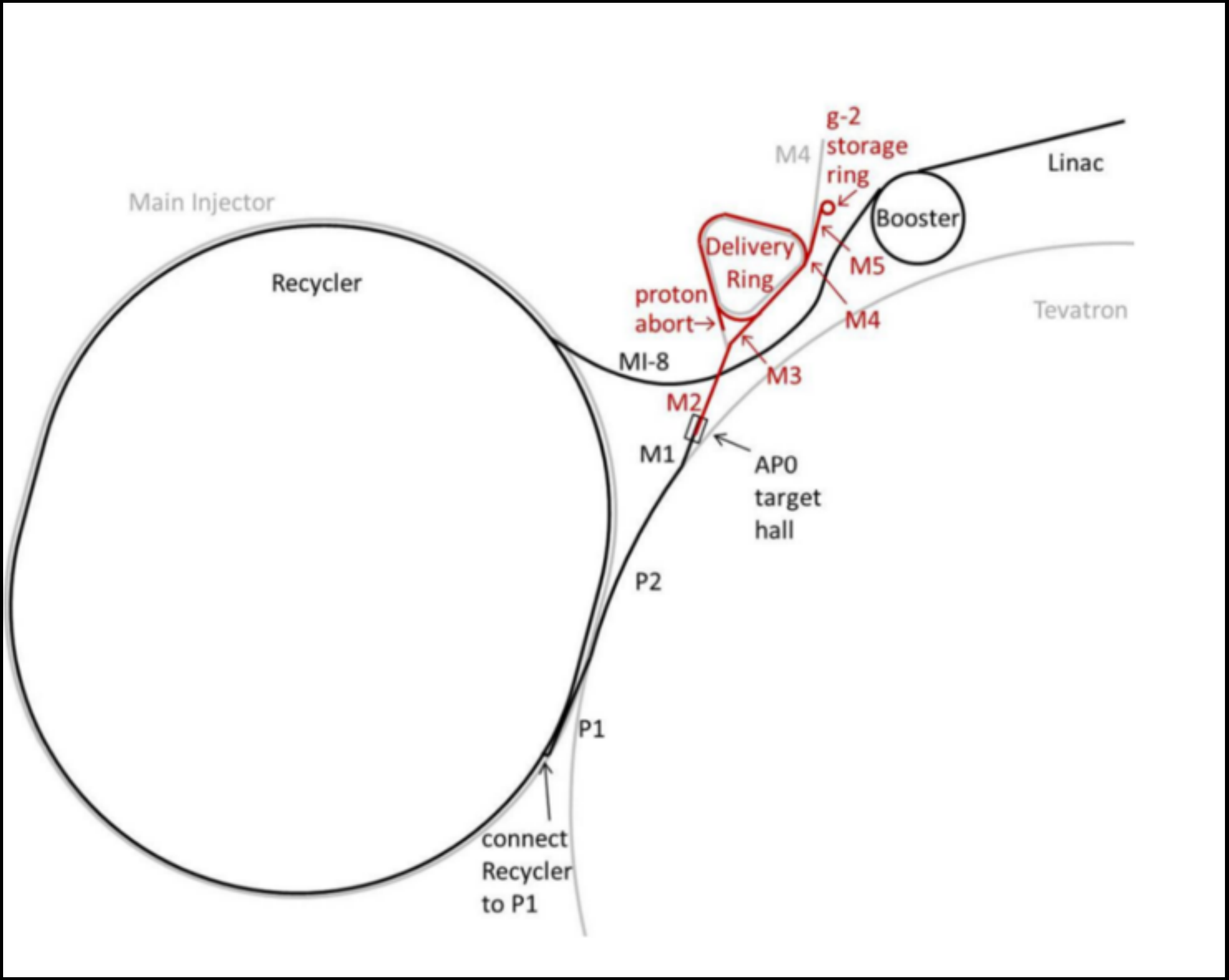
$$\Delta a_\mu = (38 \text{ to } 41 \pm 10) \times 10^{-10}, \tag{65}$$

In the summer of 2013, the Muon g-2 team successfully transported a 50-foot-wide electromagnet from Long Island to the Chicago suburbs in one piece. The move took 35 days and traversed 3,200 miles over land and sea.



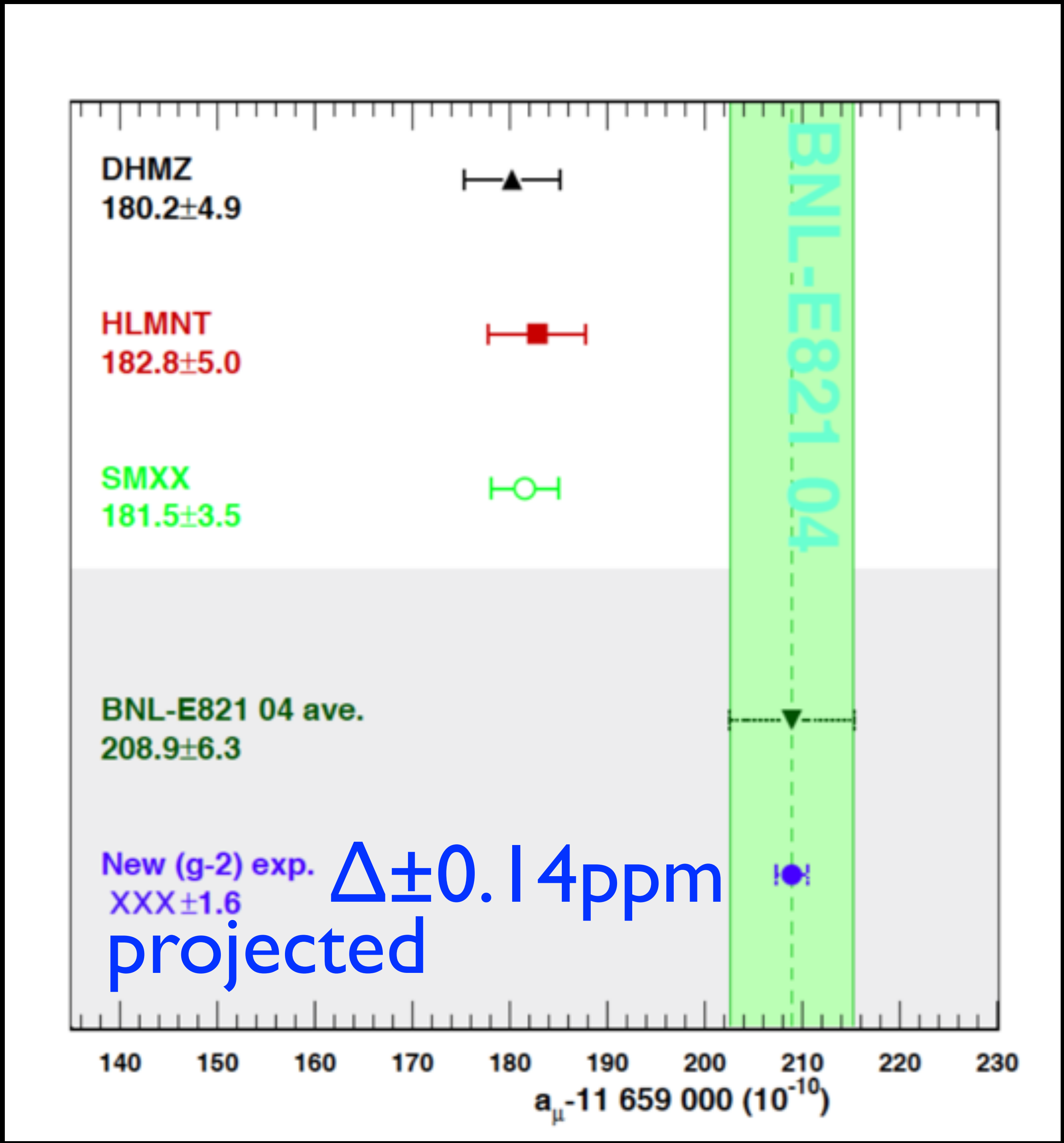
GOAL: precision of 0.14 ppm, factor of 3.8 better…

g-2 at Fermilab



The Muon g-2 experiment at Fermilab

https://arxiv.org/pdf/1701.02807.pdf



status of theory

	Value ($\times 10^{-11}$) units
QED	116 584 718.95 ± 0.08
HVP	6 850.6 ± 43
HLbL	105 ± 26
EW	153.6 ± 1.0
Total SM	116 591 828 ± 49

±0.49 ppm

QED (10th order or 5 loops)

Hadron Vacuum Polarization ← e^+e^- data

Hadron light-by-light

EWK W,Z

exp. challenge 1

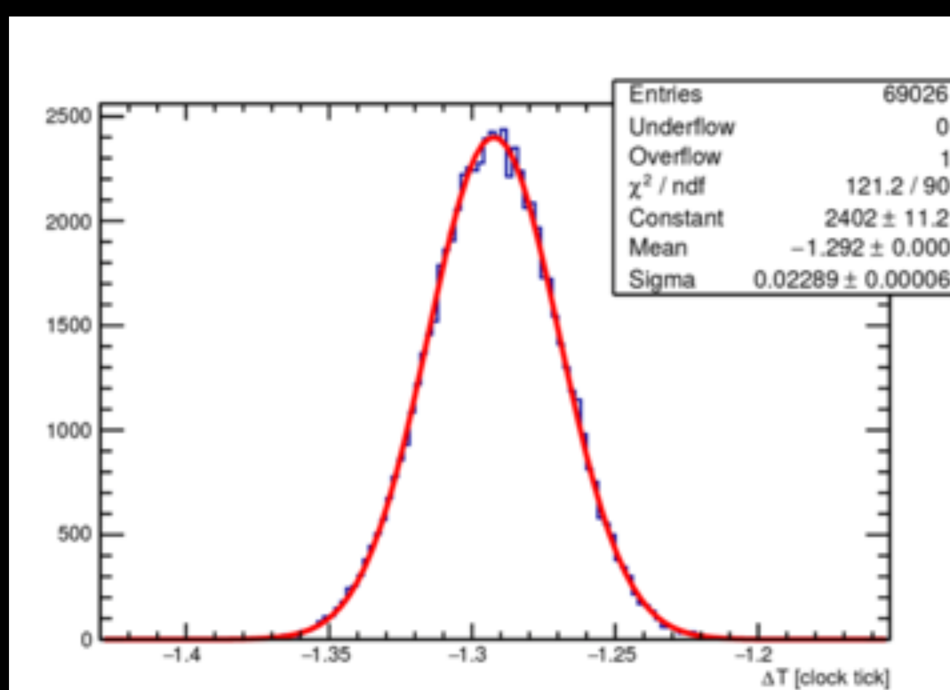
statistics

Category	E821 [ppb]	E989 Improvement Plans	Goal [ppb]
Intra-fill gain change	120	Better laser calibration	
		Low-energy threshold	20
Pileup	80	Low-energy samples recorded	
		Calorimeter segmentation	40
Lost muons	90	Better collimation in ring	20
CBO	70	Change CBO frequency	< 30
E and pitch	50	Improved tracker	
		Precise storage ring simulations	30
Total	180	Quadrature sum	70

$$a_\mu(\text{Expt}) = 11\,659\,208.0(6.3) \times 10^{-10} \quad (0.54\,\text{ppm}).$$

exp. challenge 2 $\Delta\omega_a$ calorimeter design goals

1. Positron hit time measurement with an accuracy of 100 psec for a positron energy > 100 MeV;
2. The measured deposited energy must have a resolution better than 5% at 2 GeV;
3. Allow 100% pile-up separation above 5 nsec, and 66 % below 5 nsec;
4. Gain stability monitored at subpermill level over the course of 700 μs fill where rate varies by 10^4.



laser measured
hit time resolution
25ps @ 3GeV

exp. challenge 3

B field from $\Delta\omega_p$

$$\hbar\omega_p = 2\mu_p|\vec{B}|.$$

1. Producing as uniform magnetic field as possible by shimming the magnet;
2. Stabilizing B in time at the sub-ppm level by feedback, with mechanical and thermal stability;
3. Monitoring B to the 20 ppb level around the storage ring during data collection;
4. Periodically mapping the field throughout the storage region and correlating the field map to the monitoring information without turning off the magnet between data collection and field mapping. It is essential that the magnet not be powered off unless absolutely necessary;