Status of the new BNL (g-2)$_\mu$ Experiment.

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Abstract
An experiment to measure the anomalous magnetic moment of the muon is currently running at BNL. The 1997 run using pion injection resulted in a 13 ppm measurement. In spring 1998, a muon kicker was installed, and the 1998 and 1999 data represent a measurement at the one ppm level. Runs in 2000 and 2001 will reduce this to .35 ppm, representing a 20% measurement of the vector boson contribution to a_μ and constraining physics beyond the Standard Model.

1. Introduction

The anomalous magnetic moment of the muon provides a laboratory for testing the Standard Model (SM) to a precision comparable to that achievable in the next generation of high energy colliders. Deviations of the anomaly $a_\mu = \frac{(g-2)_\mu}{2}$ from the g=2 predicted for a purely pointlike Dirac particle are the result of interactions with virtual particles which couple to the electromagnetic field. In the search for physics beyond the SM, the muon moment is a better choice than that of the electron because the relative contributions to a_μ of heavier particles or new contact interactions scale as $(m_\mu/m_e)^2 \sim 4 \times 10^4$. Whereas the electron magnetic moment is a precise test of pure QED, the muon magnetic moment is sensitive to virtual hadrons and the weak vector bosons.

The last CERN experiment reached a precision of 7.3 ppm, which was sufficient to measure the modification of the photon propagator associated with virtual hadrons. Since that time, improved theoretical calculations (up to $(\frac{\alpha}{\pi})^5$ in QED [1], two-loop weak [2], higher-order hadronic [4],and hadronic light-by-light scattering [5]) and experiment (improved measurements of the hadronic cross section from e^+e^- and the electron anomaly a_e which yields the best measure of α) provide the SM prediction against which a new precision measurement can be compared:

$$\begin{aligned} a_\mu^{SM} = \quad & a_\mu^{QED} = 116584706(2) \times 10^{-11} \text{ [1]} \\ & + a_\mu^{WEAK} = \qquad 151(4) \times 10^{-11} \text{ [3]} \\ & + a_\mu^{HAD} = \qquad 6771(77) \times 10^{-11} \text{ [6]} \end{aligned}$$

The goal of the new BNL experiment is to measure a_μ to 0.35 ppm, thus testing electroweak renormalization by observing the expected contribution from weak bosons. It also provides a sensitive test for contributions beyond the standard model, especially for μ and W compositeness or anomalous couplings. If the standard model is confirmed, the high tan β region of many supersymmetric models will be severely constrained.

2. Hadronic Corrections

The uncertainty in a_μ^{HAD} currently limits the precision of our knowledge of a_μ^{SM}. The hadronic vacuum polarization contribution cannot be calculated from first principles, but can be related to the measured hadron production cross section R in e$^+$e$^-$ collisions, via a dispersion relation. The value and uncertainty quoted above also includes hadronic τ-decay data from ALEPH via the CVC hypothesis. Additional e$^+$e$^-$ collider data in the 1-3 GeV region from the BES spectrometer [7] and CMD-2 [8] has already reduced this uncertainty by almost a factor of 2. Since, however, there are still some unresolved issues on how to combine the e^+e^- and τ-decay data sets [9], we leave the above published number as it stands. Even further statistics will be compiled by these experiments and by DAΦNE. Eventually, the limiting factor will be the theoretical uncertainty ($\sim 0.13ppm$) in the hadronic light-by-light scattering term, which is not accessible to experimental parameterization.

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3. Experimental Method

Polarized muons are stored in a 14 m diameter storage ring with a uniform vertical dipole magnetic field $\vec{B}$ and an electric quadrupole field $\vec{E}$ to provide weak vertical focussing. The spin therefore precesses relative to the momentum vector with the frequency

$$\vec{\omega}_a = \frac{-e}{mc}\left[a_\mu \vec{B}\left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\vec{\beta} \times \vec{E}\right] \quad (1)$$

The dependence of ω_a on $\vec{E}$ is eliminated to first order by storing muons at γ=29.3, corresponding to a muon momentum of p = 3.094 GeV/c. a_μ is then extracted from the ratio of the measured anomalous precession to the free proton precession frequency ω_p in the same magnetic field (measured by the NMR probes).

$$a_\mu = \frac{\omega_a/\omega_p}{\mu_\mu/\mu_p - \omega_a/\omega_p} \quad (2)$$

where μ_μ/μ_p is calculated from the muonium hyperfine structure interval [10].

The muons are provided by the BNL AGS, which can deliver up to 60 $\times 10^{12}$ 24 GeV/c protons onto a nickel target every cycle ($\sim$ 2.5 s) in 6-12 fast-extracted bunches. The g-2 experiment has run under different conditions during its three dedicated runs. Pions produced at 3.1 GeV/c are transported to the ring along a 116 m beamline. A momentum slit and a bending magnet near the downstream end select either pions half a percent above the storage momentum (pion injection) or forward decay muons at the storage momentum (muon injection). Pion injection was the method used in the last CERN experiment and in the first BNL run in 1997. By 1998, a new muon kicker was commissioned, capable of producing a 0.01 rad momentum kick to the muons over their first couple turns. Current sheets carrying up to 4200 A for 300 ns produced a 16 mT vertical magnetic field superposed on the storage ring field. Muon injection improved the muon capture efficiency and removed much of the *flash* (charged and neutral particle background which is created when the pions which are NOT stored, interact with the ring and detectors). The detectors (blanked off at injection) can thus be gated on earlier in the fill. Altogether, muon injection results in more than an order of magnitude more statistics than pion injection.

4. Positron Detection

The decay positrons from $\mu^+ \rightarrow e^+\nu_e\bar{\nu}_\mu$ are detected by 24 lead-scintillating fiber calorimeters [11] read out by 400 MHz waveform digitizers (WFD's). Both time and energy information is extracted from their pulse samples. Due to parity violation in this weak decay, the high energy positrons preferentially point in the direction of the muon spin, so positrons with energy above 1.8 GeV will exhibit a muon decay spectrum modulated by ω_a with an asymmetry A.
$N(t) = N_o e^{-t/\tau_\mu}[1 - Acos(\omega_a t + \phi)]$

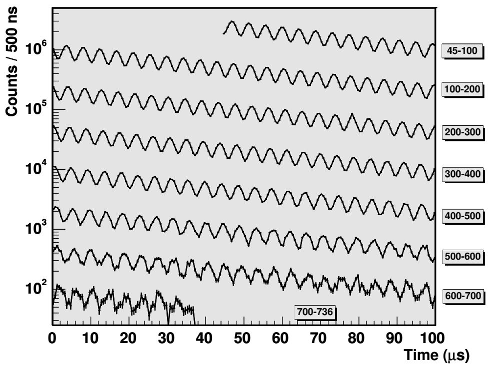

Figure 1. Time distribution (up to 736 μs) of 356 million positrons with E>1.8 GeV ($\sim$ 15% of our 1999 data sample).

5. Magnetic Field

The continuous superferric C-shaped storage ring magnet is excited by superconducting coils to produce a uniform field of 1.45 T in the storage region. The beam is injected into the magnet through a superconducting inflector magnet which locally cancels the magnetic field. The fringe field of the inflector magnet is shielded by a superconducting shield. The dipole field is monitored by 375 fixed NMR probes. Several times a week, a trolley with 17 NMR probes circles the ring in vacuum, mapping the B-field every centimetre in the storage region. The trolley probes are calibrated in place against a standard probe.

6. Muon Distribution

The B field value which is used to extract the g-2 value in equation 2, represents the average B field seen by all contributing muons. Therefore, the field measured by the NMR probes must be weighted by the actual muon distribution in the ring. The muon momentum distribution can be determined from the revolution frequency and the debunching of the muons after injection due to their differential rotation, which also gives an indirect measure of their radial profile. Two new detectors were comissioned after the 1997 pion

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injection run in order to measure the muon distribution directly. The traceback chamber is a set of 4 straw tube drift chambers located just in front of one of the calorimeters, from which one can reconstruct the path of the decay e^+ and trace it back to its birth point. The fiber harp is a skein of vertical and horizontal scintillating fibers which measures the radial and vertical beam profile inside the storage region. Although this measurement cannot be done during data-taking, since it interferes with the stored muons, it has yielded useful information about the betatron frequency and tune of the ring.

In 1997, 11 million e^+ were analysed for a published result [12] of a_μ=1165925(15)$\times 10^{-9}$. A preliminary result of a_μ=1165919.1(5.9)$\times 10^{-9}$ for 73 million e^+ collected in 1998 is in agreement with the previous result, despite the very different systematics involved in a higher statistics run using muon injection instead of pion injection. Another 2.8 billion decay positrons were accumulated in the 1999 run, currently under analysis. The CERN and BNL results and the world average are shown in figure 2. The statistical accuracy for 1999 and our eventual goal are shown using the central value of the combined CERN and E821 result. The band indicates the currently allowed region of the Standard Model prediction.

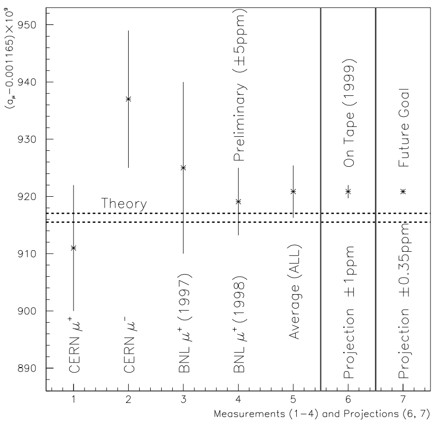

Figure 2. Overview of the g-2 results from the CERN and BNL measurements.

7. Systematic Errors and Future Plans

In 1997, the total systematic uncertainty of 2.9 ppm was mainly due to 1 ppm in $\vec{B}$ due to nonuniformities, trolley positioning, and temperature fluctuations; 0.9 ppm in $\langle B \rangle$ due to uncertainty in the muon distribution; 2.2 ppm from ω_a fitting errors due to *flash* and WFD time-dependent efficiency.

The WFD problem was fixed in hardware and the *flash* is much reduced for muon injection, so this last source of error was eliminated in the 1998 run. Further shimming has improved the uniformity of $\vec{B}$ and the ring has been thermally insulated, bringing the uncertainty in the field to 0.5 ppm for 1998 and possibly 0.4 ppm for 1999. A major contributer to that error is the inflector fringe field, which is large enough to interfere with the NMR probe measurement, due to a crack in its superconducting shield. A new inflector will be commissioned before the next run, removing this source of uncertainty. Other improvements slated to occur before the 2000 run are better trolley positioning, improved thermal insulation, and the deployment of plunging probes to do realtime cross-correlation. It is anticipated that the traceback chamber and fiber harp data will eventually reduce the uncertainty in the convolution of the muon distribution with the magnetic field map to 0.1 ppm.

High intensity running using muon injection is necessary to approach the final 0.35 ppm goal. Improvements in the AGS intensity and kicker performance may lead to approximately 50% increased muon storage. Thus, the systematics issues which become important in the determination of ω_a are pileup (two decay e^+ occurring within the detector time resolution and causing a systematic mismeasurement of energy), and details such as muon loss, betatron coherent interference, and binning effects. We plan to run in the future with twelve fills per AGS cycle, which will reduce the instantaneous rate, and hence pileup. We have improved our laser calibration system to control gain shifts to 0.2% and time shifts to 20 ps over a measurement period of 800 μs.

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