Muon (g-2) to 0.20 ppm

P969

B. Lee Roberts
Representing the new g-2 collaboration:
Boston, BNL, BINP, Cornell, Illinois, James Madison, Kentucky,
KVI-Groningen, LBL&UC-Berkeley, Minnesota, Yale

roberts@bu.edu http://physics.bu.edu/roberts.html
This is a new collaboration built on
the foundation of E821

• Core of our expertise from E821 remains

• New institutes have joined and we are actively recruiting additional collaborators

• Our precision storage ring remains the centerpiece of the experiment
Standard Model Value for $(g-2)$
from virtual radiative processes

**QED**
\[ 11.658 \pm 0.047 (0.29) \times 10^{-10} \]

**Had**
\[ 692.4 (6.2) \times 10^{-10} \]
\[ -10.1 (0.6) \times 10^{-10} \]
\[ + \text{ higher order terms} \]

**Weak**
\[ +38.9 \]
\[ -19.4 \]
\[ < 0.1 \]

1st + 2nd Order Weak = \[ 15.1 (0.4) \times 10^{-10} \]
Ongoing worldwide effort to improve knowledge of …

- Lowest order hadronic contribution
- Hadronic light-by-light

\[ 692.4 \pm 6.2 \times 10^{-10} \]

\[ 12 \pm 4.0 \times 10^{-10} \]
1\textsuperscript{st}-order hadronic from $e^+e^-$ annihilation and $\tau$ decay.

\[
a_{\mu}(\text{had}) = \left(\frac{\alpha m_\mu}{3\pi}\right)^2 \int_4^{\infty} \frac{ds}{s^2} K(s) \left(\frac{\sigma(e^+e^- \rightarrow \text{hadrons})}{\sigma(e^+e^- \rightarrow \mu^+\mu^-)}\right)
\]
Update: August 2004 (ICHEP)

- Precise $e^+e^-$ and $\tau$ data are incompatible ... especially at energies above the $\rho$

- New KLOE data using radiative return support the CMD2 $e^+e^-$ data

- Isospin correction issues for the $\tau$ data remain unresolved
2\pi \text{ contribution to } a_{\mu \text{ hadr}}

- KLOE has evaluated the Dispersions Integral in the Energy Range $0.35 < s_\pi^2 < 0.95$ GeV$^2$

\[ a_{\mu \pi\pi} = (388.7 \pm 0.8_{\text{stat}} \pm 3.5_{\text{syst}} \pm 3.5_{\text{theo}}) \times 10^{-10} \]

- Comparison with CMD-2 in the Energy Range $0.37 < s_\pi^2 < 0.93$ GeV$^2$

  KLOE: $375.6 \pm 0.8_{\text{stat}} \pm 4.9_{\text{syst}}$\times 10^{-10}$
  CMD2: $378.6 \pm 2.7_{\text{stat}} \pm 2.3_{\text{syst}}$\times 10^{-10}$

- At large values of $s_\pi^2 (> m_\rho^2)$ KLOE is consistent with CMD and therefore they confirm the deviation from $\tau$-data!

Courtesy of G. Venanzone
The problem of the $\pi^+\pi^-$ contribution:

- **Experimental situation:**
  - new, precise KLOE results in approximate agreement with latest CMD-2 data
  - $\tau$ data without $m(\rho)$ and $\Gamma(\rho)$ corr. in strong disagreement with both data sets
  - ALEPH, CLEO and OPAL $\tau$ spectral functions in good agreement within errors

- **Concerning the line shape discrepancy:**
  - SU(2) corrections: basic contributions identified and stable since long; overall correction applied to $\tau$ is $(-2.2 \pm 0.5)$%, dominated by uncontroversial short distance piece; additional long-distance corrections found to be small
  - $\rho$ lineshape corrections improves, but cannot correct difference above 0.7 GeV$^2$

---

The fair agreement between KLOE and CMD-2 devalidates the use of $\tau$ data until a better understanding of the discrepancies is achieved.
$a_{\mu}$ is sensitive to a wide range of new physics

- muon substructure

\[ \delta a_{\mu}(\Lambda_{\mu}) \sim \frac{m_{\mu}^2}{\Lambda_{\mu}^2} \]
$a_\mu$ is sensitive to a wide range of new physics

- anomalous $W\gamma\gamma$ couplings

$g_W = 2$ ?

W boson substructure?
$a_\mu$ is sensitive to a wide range of new physics

- SUSY (with large tan$\beta$)

\[
a_\mu (\text{SUSY}) \approx \frac{\alpha(M_Z)}{8\pi \sin^2 \theta_W} \frac{m_\mu^2}{\tilde{m}^2} \tan \beta \left( 1 - \frac{4\alpha}{\pi} \ln \frac{\tilde{m}}{m_\mu} \right)
\]

\[
\approx (\text{sgn}_\mu) \ 13 \times 10^{-10} \ \tan \beta \ \left( \frac{100 \ \text{GeV}}{\tilde{m}} \right)^2
\]
$a_\mu$ is sensitive to a wide range of new physics

- many other things (extra dimensions, etc.)
Where we came from:

~1983

\[ a_\mu \times 10^{-11} = \begin{array}{c} 116,590,000 \\ 116,591,000 \\ 116,592,000 \\ 116,593,000 \\ 116,594,000 \\ 116,595,000 \end{array} \]

CERN \( \mu^+ \) and CERN \( \mu^- \)
Today with $e^+e^-$ based theory:

All E821 results were obtained with a “blind” analysis.

$$a_\mu = \frac{\omega_a}{\frac{e}{mc}B}$$
Discrepancy with $e^+e^-$ based theory

\[ \Delta_{e^+e^-} = (25 \pm 9) \times 10^{-10} \ (2.7\sigma) \]

- What might this mean?
- New physics or a fluctuation?
  - Consider a SUSY example
In CMSSM, $a_\mu$ can be combined with $b \rightarrow s\gamma$, cosmological relic density $\Omega h^2$, and LEP Higgs searches to constrain $\chi$ mass.
The CMSSM plot with error on $\Delta a_\mu$ of $4.6 \times 10^{-10}$ (assuming better theory and a new BNL g-2 experiment)

$\Delta a_\mu = 24(4.6) \times 10^{-10}$ (discrepancy at 6 $\sigma$)

Current Discrepancy
Discrepancy with $e^+e^-$ based theory

$$\Delta_{e^+e^-} = (25 \pm 9) \times 10^{-10} \quad (2.7\sigma)$$

- What might this mean?
- New physics or a fluctuation?
  - Consider a SUSY example

- Either way, the muon (g-2) provides a wonderful test of the standard model
With a discrepancy like this…

• You’ve got to keep working
  – Either you confirm the discrepancy or
  – You show it’s not there…

• But you can’t ignore it!
  – The stakes are just too high.

• That’s why we’re here today.
The experimental concept remains the same:

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

\[
\gamma = 29.3
\]

\[
P_\mu = 3.09 \text{ GeV/c}
\]
And so does the ring
Strategy of the improved experiment

• More muons – E821 was statistics limited
  $\sigma_{\text{stat}} = 0.46$ ppm, $\sigma_{\text{syst}} = 0.3$ ppm
  - Backward-decay, higher-transmission beamline
  - New, open-end inflector
  - Upgrade detectors, electronics, DAQ

• Improve knowledge of magnetic field $B$
  - Improve calibration, field monitoring and measurement

• Reduce systematic errors on $\omega_a$
  - Improve the electronics and detectors
  - New parallel “integration” method of analysis
E821: Forward decay beam

Pion Production Target

U line
Q2 - Q1
D1, D2
D3, D4
K1-K2
Beam Stop

Pions @ 3.115 GeV/c

Decay muons @ 3.094 GeV/c

Pedestal vs. Time

Near side
Far side

Pedestal vs. Time
P969: Backward decay beam

Pions @ 5.32 GeV/c

Decay muons @ 3.094 GeV/c

No hadron-induced prompt flash

Expect for both sides

Approximately the same muon flux is realized
Muon capture and transmission in decay section will double by doubling quads

E821 lattice

Lattice doubled
Improved transmission into the ring

Inflector aperture

Storage ring aperture

E821 Closed End

P969 Proposed Open End
Systematic Error Evolution

<table>
<thead>
<tr>
<th>Systematic uncertainty (ppm)</th>
<th>1998</th>
<th>1999</th>
<th>2000</th>
<th>2001</th>
<th>E969 Goal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnetic field – ( \omega_p )</td>
<td>0.5</td>
<td>0.4</td>
<td>0.24</td>
<td>0.17</td>
<td>0.1</td>
</tr>
<tr>
<td>Anomalous precession – ( \omega_a )</td>
<td>0.8</td>
<td>0.3</td>
<td>0.3</td>
<td>0.21</td>
<td>0.1</td>
</tr>
</tbody>
</table>

- **Field improvements** will involve better trolley calibrations, better tracking of the field with time, temperature stability of room, improvements in the hardware.

- **Precession improvements** will involve new scraping scheme, lower thresholds, more complete digitization periods, better energy calibration.
\[ \langle B \rangle_\phi \text{ for 2001} \]

0.5 ppm contours

Free induction decay signals:

\[ f_0 \approx 62 \text{ MHz} \]

\[ \sigma_{syst} \text{ on } \langle B \rangle_\mu - \text{distribution} = \pm 0.03 \text{ ppm} \]
E821: Precession Measurement

- Muon momentum
- Muon spin
- Sci-Fi Calorimeter module
- Measures Energy and time

Spin forward, more high energy e
Spin backward, less high energy e

400 MHz digitizer
E969: Precession Measurement

### T Method

- $\chi^2 / \text{ndf} = 2280 / 1999$
- Norm $= 1246 \pm 2.5$
- Tau $= 6.404e+04 \pm 99$
- Asym $= 0.3947 \pm 0.0018$
- Omega $= 1.438e+06 \pm 85$
- Phi $= -40.4 \pm 0.0$

### Q Method

- $\chi^2 / \text{ndf} = 2334 / 1999$
- Norm $= 2340 \pm 2.6$
- Tau $= 6.431e+04 \pm 55$
- Asym $= 0.2016 \pm 0.0010$
- Omega $= 1.438e+06 \pm 93$
- Phi $= -40.4 \pm 0.0$
Fast, dense and segmented W-SciFi calorimeters

- 20-fold segmentation
- 0.7 cm $X_0$
- 14%/Sqrt(E)
Schedule

• FY 2005
  – R&D as funding permits
• FY 2006-2007
  – Construction
• FY 2008
  – Fall, pulse on demand, debugging
  – Spring, 3 week engineering run
• FY 2009
  – 2100 hours data collection
    (26 weeks @ 80 hr/wk)
Conclusions:
With a 2.7 $\sigma$ discrepancy …

- We can and **must** press ahead to the systematic limit of the technique
- The considerable investment to date at BNL can be further extended by modest upgrades
- We expect: $0.54 \text{ ppm} \rightarrow 0.2 \text{ ppm (projected)}$
  - In parallel, the theory effort continues and will improve to perhaps 0.3 ppm
- Muon (g-2) continues to address the most fundamental questions in our field
### Systematic errors on $\omega_a$ (ppm)

<table>
<thead>
<tr>
<th>Source</th>
<th>1999</th>
<th>2000</th>
<th>2001</th>
<th>E969</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pile-up</td>
<td>0.13</td>
<td>0.13</td>
<td>0.08</td>
<td>0.07</td>
</tr>
<tr>
<td>AGS Background</td>
<td>0.10</td>
<td>0.10</td>
<td>*</td>
<td></td>
</tr>
<tr>
<td>Lost Muons</td>
<td>0.10</td>
<td>0.10</td>
<td>0.09</td>
<td>0.04</td>
</tr>
<tr>
<td>Timing Shifts</td>
<td>0.10</td>
<td>0.02</td>
<td>0.02</td>
<td></td>
</tr>
<tr>
<td>E-Field, Pitch</td>
<td>0.08</td>
<td>0.03</td>
<td>*</td>
<td>0.05</td>
</tr>
<tr>
<td>Fitting/Binning</td>
<td>0.07</td>
<td>0.06</td>
<td>*</td>
<td></td>
</tr>
<tr>
<td>CBO</td>
<td>0.05</td>
<td>0.21</td>
<td>0.07</td>
<td>0.04</td>
</tr>
<tr>
<td>Beam Debunching</td>
<td>0.04</td>
<td>0.04</td>
<td>*</td>
<td></td>
</tr>
<tr>
<td>Gain Change</td>
<td>0.02</td>
<td>0.13</td>
<td>0.13</td>
<td>0.03</td>
</tr>
<tr>
<td><strong>total</strong></td>
<td>0.3</td>
<td>0.31</td>
<td>0.21</td>
<td>0.11</td>
</tr>
</tbody>
</table>

$\Sigma^* = 0.11$
Goal for $\omega_p$ systematic errors

<table>
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<tr>
<th>Source of Uncertainty</th>
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<tr>
<td>Absolute Calibration</td>
<td>0.05</td>
<td>0.05</td>
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</tr>
<tr>
<td>Calibration of Trolley</td>
<td>0.3</td>
<td>0.20</td>
<td>0.15</td>
<td>0.09</td>
<td>0.06</td>
</tr>
<tr>
<td>Trolley Measurements of B0</td>
<td>0.1</td>
<td>0.10</td>
<td>0.10</td>
<td>0.05</td>
<td>0.02</td>
</tr>
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<td>Interpolation with the fixed probes</td>
<td>0.3</td>
<td>0.15</td>
<td>0.10</td>
<td>0.07</td>
<td>0.06</td>
</tr>
<tr>
<td>Inflector fringe field</td>
<td>0.2</td>
<td>0.20</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Uncertainty from muon distribution</td>
<td>0.1</td>
<td>0.12</td>
<td>0.03</td>
<td>0.03</td>
<td>0.02</td>
</tr>
<tr>
<td>Other*</td>
<td></td>
<td>0.15</td>
<td>0.10</td>
<td>0.10</td>
<td>0.05</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>0.5</td>
<td>0.4</td>
<td>0.24</td>
<td>0.17</td>
<td>0.11</td>
</tr>
</tbody>
</table>

*higher multipoles, trolley voltage and temperature response, kicker eddy currents, and time-varying stray fields.
a(had) from hadronic $\tau$ decay?

- Must assume CVC, no second-class currents, make the appropriate isospin breaking corrections. $\tau$ decay has no isoscalar piece, while $e^+e^-$ does

Let’s look at the $\tau$ branching ratio and $F_{\pi}$ from the two data sets:
Tests of CVC (A. Höcker – ICHEP04)

\[
\text{BR}_{\text{CVC}}(\tau^- \rightarrow \pi^- \pi^0 \nu_\tau) = \frac{6\pi |V_{ud}|^2 S_{\text{EW}}}{m_\tau^2} \int_0^{m_\tau^2} ds \, \text{kin}(s) \cdot U^{\text{SU(2)}\text{corrected}}(s)
\]

Difference: \(\text{BR}[\tau] - \text{BR}[e^+e^-\text{CVC}]\):

<table>
<thead>
<tr>
<th>Mode (\tau^- \rightarrow \pi^- \pi^0 \nu_\tau)</th>
<th>(\Delta(\tau - e^+e^-))</th>
<th>„Sigma“</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\tau^- \rightarrow \pi^- \pi^0 \nu_\tau)</td>
<td>+0.94 ± 0.32</td>
<td>2.9</td>
</tr>
<tr>
<td>(\tau^- \rightarrow \pi^- 3\pi^0 \nu_\tau)</td>
<td>-0.08 ± 0.11</td>
<td>0.7</td>
</tr>
<tr>
<td>(\tau^- \rightarrow 2\pi^- \pi^+ \pi^0 \nu_\tau)</td>
<td>+0.91 ± 0.25</td>
<td>3.6</td>
</tr>
</tbody>
</table>

leaving out CMD-2:

\(B_{\pi^0} = (23.69 \pm 0.68)\%\)

\(\Rightarrow (7.4 \pm 2.9)\%\) relative discrepancy!
Comparison with $e^+e^-$ theory (from ICHEP04)

(from F. Teubert’s summary talk.)

<table>
<thead>
<tr>
<th>Muon</th>
<th>2001 Data</th>
<th>2000 Data</th>
<th>2002 Data</th>
<th>2003 Data</th>
<th>2004 Data</th>
</tr>
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<tbody>
<tr>
<td>BNL01 $\mu^-$</td>
<td>0.7 ppm</td>
<td>0.7 ppm</td>
<td>0.7 ppm</td>
<td>0.7 ppm</td>
<td>0.7 ppm</td>
</tr>
<tr>
<td>BNL00 $\mu^+$</td>
<td>0.7 ppm</td>
<td>0.7 ppm</td>
<td>0.7 ppm</td>
<td>0.7 ppm</td>
<td>0.7 ppm</td>
</tr>
<tr>
<td>BNL99 $\mu^+$</td>
<td>1.3 ppm</td>
<td>1.3 ppm</td>
<td>1.3 ppm</td>
<td>1.3 ppm</td>
<td>1.3 ppm</td>
</tr>
<tr>
<td>BNL98 $\mu^+$</td>
<td>5.1 ppm</td>
<td>5.1 ppm</td>
<td>5.1 ppm</td>
<td>5.1 ppm</td>
<td>5.1 ppm</td>
</tr>
<tr>
<td>BNL97 $\mu^+$</td>
<td>12.9 ppm</td>
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<tr>
<td>CERN $\mu^-$</td>
<td>9.4 ppm</td>
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\[ (a_{\mu}^+ - 116590000) \times 10^{-10} = 203 \pm (6 \text{ stat. } \oplus 5 \text{ syst.}) \]

\[ (a_{\mu}^- - 116590000) \times 10^{-10} = 214 \pm (6 \text{ stat. } \oplus 5 \text{ syst.}) \]

New $\mu^-$ data collected in 2001, confirms previous measurements using $\mu^+$

2.7σ from prediction

(was 1.9σ before inclusion of 2001 data)
**Outlook**

The biggest discrepancy is on the interpretation of the ratio of NC and CC as measured by NuTeV as a determination of $\sin^2\theta_{\text{eff}}$. However, this interpretation depends on theoretical uncertainties that must be reevaluated, before the $3\sigma$ discrepancy is taken at face value.

The biggest challenge to the SM is the deviation in the measurement of the anomalous magnetic moment of muons:

\[
(a_\mu - 11659000) \times 10^{-10} = 208 \pm 6
\]

\[
(a_\mu - 11659000) \times 10^{-10} = 183 \pm 7
\]

which is $2.7\sigma$ away from theory. The theoretical prediction is now much more robust, even though the discrepancy with tau data is not really understood.

The medium-term future is bright in our field. The EW precision measurements tells us that something has to happen at energy scales of $O(1 \text{ TeV})$... which happen to be the energy scale of LHC and $e^+ e^-$ linear colliders.
# Field Uncertainties - History

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*higher multipoles, trolley voltage and temperature response, kicker eddy currents, and time-varying stray fields.*
Field Shimming

![Graph showing relative field in ppm vs azimuthal position in degrees. Peaks and valley points are marked with arrows and numbers.](image)