Mesurement of the Negative Muon Anomalous Magnetic Moment to 0.7 ppm

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New physics search

Energy Frontier (High energy experiment)
- LHC, ILC → observe new heavy particle by direct production

Luminosity Frontier (Precise experiment)
- Muon physics
- B physics
- K physics
- EDM search

Complementary

The muon (g-2) measurement is one of the most sensitive test of the SM.
Magnetic Moment
Magnetic moment is a strength of coupling between a magnetic field and a charged particle with a spin.

\[ \vec{\mu} = g \frac{e}{2m} \vec{s} \]

In the case of \( \mu \) and \( e(\text{spin1/2, Dirac e.q.}) \), we find

\[ \vec{\mu} = g \frac{e}{2m} \vec{s} = g \frac{e}{2m} \frac{\vec{\sigma}}{2} \]

\[
\begin{align*}
\text{Force from B} & \quad \vec{r} = \vec{\mu} \times \vec{B} \\
\text{Potential energy} & \quad U = -\vec{\mu} \cdot \vec{B}
\end{align*}
\]

\[
\Rightarrow g = 2
\]
Anomalous magnetic moment

Gap between experiment result and "2"

\[ g^{\text{exp}} = 2.0023318 \]

Higher order correction

Internal structure

Anomalous magnetic moment

\[ a = \frac{g - 2}{2} \]

\[ a^{\text{QED}} = C_1 \left( \frac{\alpha}{\pi} \right) + C_2 \left( \frac{\alpha}{\pi} \right)^2 + C_2 \left( \frac{\alpha}{\pi} \right)^2 + \cdots \]

\[ \alpha = 1/137 \]
Magnetic moment and New physics

In the SM, there are corrections from QCD and EW as well as QED.

A measurement of \( a_\mu \) provide one of the most sensitive test of the SM.

\( \rightarrow \) can be a breakthrough in reaching to beyond the SM.

(Because the mass is so much heavier than electron’s there is larger contribution.)
The $a_\mu$ is particularly sensitive to SUSY (smuon-neutrino and sneutrino-chargino loops).

- Large $\tan \beta$
- Degenerate spectrum of superparticles with mass $\tilde{m}$

\[ a_\mu (\text{SUSY}) \approx 140 \times 10^{-11} \left( \frac{100 \text{ GeV}}{\tilde{m}} \right)^2 \tan \beta \]
Located on Long Island, New York, Brookhaven

RHIC (Relativistic Heavy Ion Collider). 2000-

- First heavy ion accelerator
- Only spin-polarized proton collider
- PHENIX experiment etc.

AGS booster (Alternating Gradient Synchrotron)

- Radius: 7.1m
- B: 1.45 T
Experiment overview

**Point ①**: Polarized muon

**Point ②**: a measurement using a difference on rates of μ and the spin rotation

**Point ③**: Measurement magnetic field

**Point ④**: Get information about μ spin from decay e⁺
Point 1: Polarized muon

Beam injection:
- 0.37 Hz, 12 bunch
- $5 \times 10^{12}$ proton / bunch
- Bunch interval: 33 ms

24 GeV proton

Proton extraction

Proton transport

$\pi$ production

Decay channel

$\mu$ spectrometer

Target: Ni

$\pi$ spectrometer

Storage ring

$\pi$ rest frame

Spin = 0

Helicity: left-handed

$\nu \leftarrow \pi^+ \rightarrow \mu^+$

Polarized

$\mu$ spin is initially lined up in the direction of the momentum.
Point② : Measurement principle

To measure $a_{\mu}$

- spin precession frequency ($\omega_s$)
- cyclotron frequency ($\omega_c$)
- angular frequency difference ($\omega_a = \omega_s - \omega_c$)

Larmor

$$\vec{\omega}_s = \gamma \left( \frac{g-2}{2} \right) \frac{eB}{m\gamma} = a_\mu \frac{eB}{m}$$

Thomas

$$\vec{\omega}_c = \frac{eB}{m\gamma}$$

Considering the interaction with $E$ to confine $\mu$,

$$\vec{\omega}_a = \frac{e}{m} \left[ a_\mu \vec{B} - \left( a_\mu - \frac{1}{\gamma^2 - 1} \right) \vec{\beta} \times \vec{E} \right]$$
Point②: Measurement principle

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

It is easier if the second term is disappeared.

\[ a_\mu - \frac{1}{\gamma^2 - 1} = 0 \quad a_\mu \approx 0.001166 \quad \gamma = 29.3 \]

\[ \gamma = \frac{E}{m} \quad p_\mu = 3.094[GeV / c] \]

Magic momentum!

Accurate determination \( a_\mu \)
\= Accurate measurement of \( B \) and \( \omega_a \)
Additional idea to get higher precision
⇒ use Larmor frequency of proton

\[ \omega_a = a_\mu \frac{eB}{m_\mu} \quad \omega_s = \frac{g_\mu}{2} \frac{eB}{m_\mu} \quad \text{(Larmor precession)} \]

\[ a_\mu = \frac{\omega_a}{\omega_s - \omega_a} = \frac{\omega_a / \omega_p}{\omega_s / \omega_p - \omega_a / \omega_p} = \frac{R}{\lambda - R} \]

\[ \lambda \equiv \frac{\omega_s}{\omega_p} = \frac{\mu_\mu}{\mu_p} = 3.18334539(10) \]

\[ R \equiv \frac{\omega_a}{\omega_p} \quad \text{These two are measured to obtain } a_\mu^{14} \]
Point 3: Magnetic field measurement

NMR (Nuclear Magnetic Resonance)

- A proton sets up a magnetic field $B$ and the energy level is split into two.

\[
\omega_p = 61791400(11) \text{Hz}
\]

- This technique is used for MRI
There is a correlation between $\mu$ spin direction and $e$ emission direction due to the P violation.

$$N = N_0 e^{(-t/\gamma\tau)} \left\{ 1 - A \cos(\omega_a + \phi) \right\}$$

$\gamma\tau = 64.4\mu s$

$[\mu$ polarization($\sim 95\%)$] $\times$ [asymmetry in $\mu$ - $e$ decay]

e direction highly correlated to the muon spin direction

Fitting to the time distribution of the detected electrons in a given energy bin.

$$\frac{\omega_a}{2\pi} = 229073.59(15)(5) Hz$$
Point ④ : Detector

Maximizes the acceptance of the high energy electron
24 detector stations (15 degree intervals)
- Calorimeter $\rightarrow$ Electron energy
  - consists of scintillating fibers embedded in lead
  - depth: $13X_0$
- 5 scintillator paddles $\rightarrow$ Electron time
Result
Final result: $a_{\mu^-} = \frac{R}{\lambda - R} = 11659214(8)(3) \times 10^{-10} (0.7 \text{ ppm})$

$R_{\mu^-} = \frac{\omega_a}{\omega_p} = 0.0037072083(26)$

Previous result
$R_{\mu^+} = 0.0037072048(25)$

New average
$a_{\mu} = 11659203(6) \times 10^{-10} (0.5 \text{ ppm})$

2.7σ deviation!!!

$a_{\mu} (SM) = 11659181(8) \times 10^{-10} (0.7 \text{ ppm})$
Current situation

SM prediction has been improved.

\[ a_{\mu}^{SM} = 116591834(2)(41)(26) \times 10^{-11} \]

\[ \Delta a_{\mu} = a_{\mu}^{exp} - a_{\mu}^{SM} = 255(63)(49) \times 10^{-11} \]

3.2σ deviation!!!

New experiment is needed to improve the experimental result.
### Proposed experiment

<table>
<thead>
<tr>
<th></th>
<th>BNL-E821</th>
<th>Fermilab</th>
<th>J-PARC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Muon momentum</td>
<td>3.09 GeV/c</td>
<td>0.3 GeV/c</td>
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</tr>
<tr>
<td>gamma</td>
<td>29.3</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Storage field</td>
<td>B=1.45 T</td>
<td>3.0 T</td>
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<tr>
<td>Focusing field</td>
<td>Electric quad</td>
<td>None</td>
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</tr>
<tr>
<td># of detected μ+ decays</td>
<td>5.0E9</td>
<td>1.8E11</td>
<td>1.5E12</td>
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<tr>
<td># of detected μ- decays</td>
<td>3.6E9</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Precision (stat)</td>
<td>0.46 ppm</td>
<td>0.1 ppm</td>
<td>0.1 ppm</td>
</tr>
</tbody>
</table>
High Intensity Muon Beam for
Space-time Symmetry and
Origin of Matter/Universe

3 GeV Proton Beam
(333 uA)

Silicon Tracker

66 cm diameter
Ultra-Precision Magnet (3T)

Ultra cold μ+ source
Muon LINAC (300 MeV/c)

cLFV
Search for electron with Specific Energy and Timing

g-2/EDM
Measure spin precession vector
Parallel to B-field: g-2
Orthogonal to B-field: EDM
Measure the muon spin precession

Off magic momentum with ultra-cold muon beam at 300 MeV/c

Stored in ultra-precision B-field without E-field so that the $\beta \times E$ drops, $\omega_a$ and $\omega_d$ that are orthogonal become $\omega_a$ and $\omega_d$ that are independent, so $E$ can be eliminated, which is challenging

Many technical challenges are undergoing
Summary

The anomalous magnetic moment of the muon has played an important role in the search for BSM.

This is the final analysis of the anomalous magnetic moment from E821.

$$a_\mu = 11659203(6) \times 10^{-10} \, (0.5 \, ppm)$$

2.7σ deviation (current: 3.2σ)

To improve the result some new experiments are proposed.