Summary of Muon Working Group

Report on \((g - 2)\), EDM and \(m_{\nu_\mu}\)

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Summary Conclusions of the Working Group

We believe that exciting opportunities exist for muon physics at JKJ, and that there is substantial discovery potential in the program of muon physics which we propose.
The Program of Muon Physics:

- $(g - 2)$ experiment to 0.05 ppm.
- Muon EDM to $10^{-24}$ $e$ cm.
- Limit for $m_{\nu\mu}$ from 170 keV to $\leq 8$ keV.
- $\mu^- \rightarrow e^-$ to branching level of $10^{-18}$ using the PRISM facility.
Machine Requirements

These experiments (except for $m_{\nu\mu}$) need 90th harmonic operation of the 50 GeV synchrotron, with single bunch fast extraction, as proposed for the PRISM facility.
Magnetic Moments, $g$-Factors, etc.

\[ \vec{\mu}_s = g_s \left( \frac{e}{2m} \right) \vec{s}, \quad \mu = (1 + a) \frac{e\hbar}{2m}, \quad a = \frac{g - 2}{2} \]

$\vec{\mu}$ - magnetic moment; $g$ - gyromagnetic ratio

$\vec{s}$ is the spin.

- Dirac Equation Predicts $g \equiv 2$
- In nature radiative corrections make $g \neq 2$.

\[ g = 2 + \frac{\alpha}{\pi} \quad \text{Kusch and Foley, Schwinger, 1947} \]
Theory for Muon \((g - 2)\)

\[\begin{align*}
\mu & \rightarrow \gamma & + & \gamma \\
116.584 & 795.7(2) & (6.2) & \times 10^{-10} \\
\mu & \rightarrow \gamma & \mu & \rightarrow \gamma \\
692.4 & (6.2) & \times 10^{10} & \quad -10.1 & (6) & \times 10^{10} \\
\mu & \rightarrow \gamma & \mu & \rightarrow \gamma & \mu & \rightarrow \gamma \\
W & \rightarrow W & W & W \\
+38.9 & & & -19.4 \\
\mu & \rightarrow \gamma & \mu & \rightarrow \gamma & \mu & \rightarrow \gamma \\
H & \rightarrow \gamma & H & \rightarrow \gamma & H & \rightarrow \gamma \\
< 0.1 & & & & & \quad 8.5 & (4.0) & \times 10^{-10} \\
\end{align*}\]

1st + 2nd Order Weak = \(-15.1 (4) \times 10^{10}\)
$a_\mu(\text{Had})$ from Dispersion Theory

Use of $\tau$-decays $\Rightarrow$ Isospin, CVC, no $2^{nd}$-class currents, only isovector current.

$$a_\mu(\text{had}; 1) = \left(\frac{\alpha m_\mu}{3\pi}\right)^2 \int_{4m_\pi^2}^\infty \frac{ds}{s^2} K(s)R(s)$$

where $$R(s) = \frac{\sigma(e^+e^- \rightarrow \text{hadrons})}{\sigma(e^+e^- \rightarrow \mu^+\mu^-)}$$
New Physics Contribution?

- substructure?  
  \[ \Delta a_\mu = \frac{m_\mu^2}{\Lambda^2} \]
  \[ \Lambda \geq 5 \text{ Gev} \]

- anomalous gauge boson coupling?  
  Triple Gauge Vertex  
  \[ g_w = 2 \ ? \]
  W boson substructure?
Supersymmetry

\[ a_\mu \text{ is sensitive to SUSY with large } \tan \beta \]

\[ \text{toy model with equal } \tilde{m} \text{ and large } \tan \beta: \]

\[ a_\mu (\text{SUSY}) \sim 150 \times 10^{-11} \tan \beta \left( \frac{100 \text{ GeV}}{\tilde{m}} \right)^2 \]

\[ \sim 1.31 \text{ ppm } \tan \beta \left( \frac{100 \text{ GeV}}{\tilde{m}} \right)^2 \]
The Experimental Technique

Protons from AGS → Target

Pions $\pi^+ \rightarrow \mu^+ \nu_\mu$

$\mathbf{x_c} \approx 77 \text{ mm}$

$\beta \approx 10 \text{ mrad}$

$B \cdot dl \approx 0.1 \text{ Tm}$

Ideal Orbit

Injection Orbit

Storage Ring

Inflector
Spin Precession

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

\[ + \quad \frac{e}{m} \left[ \frac{\eta}{2} \left( \frac{\vec{E}}{c} + \vec{\beta} \times \vec{B} \right) \right] \]

\[ d_\mu = \frac{\eta}{2} \left( \frac{e\hbar}{2mc} \right) \simeq \eta \times 4.7 \times 10^{-14} \quad e \text{ cm} \]

and

\[ a_\mu = \left( \frac{g - 2}{2} \right) \]
The EDM causes the spin to precess out of the plane!
The Storage Ring Magnet
The Average Field $\langle B \rangle_{\phi}$ is:

In 1999 Quadrupole $\simeq 2.0$ ppm of $B_0$, in 2000 $\simeq 0.2$ ppm of $B_0$. Perfect for NuMass!
Measurements of $a_\mu$

- CERN $\mu^+$
  - (9.4 ppm)
  - E821 (97)
- CERN $\mu^-$
  - (0.7 ppm)
  - E821 (00)
- Theory (DH98)
  - (13 ppm)
  - (5 ppm)
  - (1.3 ppm)
  - (0.7 ppm)

Values:
- 116 590 000
- 116 591 000
- 116 592 000
- 116 593 000
- 116 594 000
- 116 595 000
- $10^{-11}$
Measurements of $a_\mu$

Brookhaven Muon g-2 Data

BNL'98

BNL'99

BNL'00

World Average

DEHZ ee

Standard Model Prediction

DH'98

$\alpha \times 10^{10} - 11659000$

160

180

200

220

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Measurements of $\alpha_\mu$

Brookhaven Muon g-2 Data

BNL'98
BNL'99
BNL'00
World Average

Standard Model Prediction

$\alpha_\mu \times 10^{10} - 11659000$

BNL'98
DEHZ $\tau$
DEHZ ee
DH'98

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What if SUSY were true and we knew the Masses?

- Then the SUSY contribution to $(g - 2)$ would become part of the “new standard model”.
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- Then the SUSY contribution to $(g - 2)$ would become part of the “new standard model”.
- The measurement of $(g - 2)$ would provide one of the cleanest measurements of $\tan \beta$. 
If the difference with theory means non-SM physics:

- There should be an electric dipole moment (⇒ a new $CP$-violation) produced by this same non-standard model physics. If it’s SUSY, the EDM comes from the $Im$ part of the amplitude producing $(g - 2)$ discrepancy.

- Model predictions vary between $10^{-20}$ and $10^{-24}$ $e$ cm.

- $B$-factory results show the need to go to flavor conserving process where SM $CP$-violation is very small to see new physics. ⇒ $EDM$
## EDM Limits

<table>
<thead>
<tr>
<th>Particle</th>
<th>Present EDM Limit (e-cm)</th>
<th>Standard Model Value (e-cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>n</td>
<td>$6.3 \times 10^{-26}$</td>
<td>$10^{-31}$</td>
</tr>
<tr>
<td>$e^-$</td>
<td>$\sim 1 \times 10^{-27}$</td>
<td>$10^{-38}$</td>
</tr>
<tr>
<td>$\mu$</td>
<td>$&lt; 10^{-18}$ (CERN)</td>
<td>$\sim 10^{-35}$ Estimated</td>
</tr>
<tr>
<td></td>
<td>$\sim 10^{-19}$ (E821)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\sim 10^{-24}$ New</td>
<td>Dedicated Experiment</td>
</tr>
</tbody>
</table>
If we could turn off $\omega_a$

e.g. with a radial $\vec{E}$ field, the spin would rise monotonically with time.
The Muon Neutrino Mass Experiment

Use storage ring as a spectrometer, inject pions, and measure the forward muons.

Using several “tricks”, one should be able to reduce the direct limit from 170 keV, to $\leq 8$ keV. With emulsions as have been pioneered here in Japan, maybe to 1 keV.
Summary

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- The direct limit on the muon neutrino mass can be improved by a factor of 20 to 100.
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- A sensitive search for a muon EDM \(\geq 10^{-24} \, e\) cm with a substantial chance for success for finding one is possible.
- The direct limit on the muon neutrino mass can be improved by a factor of 20 to 100.
- The large harmonic \(h = 90\), and single bunch fast extraction are very important to reach these new goals.
Conclusions

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Come join us to do it!
Experimental Technique for $m_{\nu_\mu}$
The Endpoint Region after Cuts

Distance difference between $\pi$ and highest energy $\mu$

![Graph showing data distribution with counts and distance differences]
Time Spectrum, $E > 2.0\text{GeV}$

$\sigma_{\text{stat}} \approx 0.7 \text{ ppm}$

$$f(t) = N_0 e^{-\lambda t} [1 + A \cos(\omega_\alpha t + \phi)]$$

4 Billion Positrons with $E > 2$ GeV