Overview of muon EDM searches:
the past, the present and the future

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Kick-off workshop for the search of a muon EDM using the frozen spin technique at PSI

17-19 Feb 2020, PSI
Content

• Motivation and history of muon EDM searches
• Overview of muon EDM experiments
• Summary

Theory: A. Crivellin (today, 9:10 am)
PSI muEDM: P. Schmidt-Wellenburg (today, 9:50 am)
FNAL g-2/EDM: J. Price (tomorrow, 9 am)
J-PARC g-2/EDM: T. Mibe (tomorrow, 9:40 am)
Motivation of muon EDM searches

- One of the least tested areas of the Standard Model
  - Current limit 23 orders of magnitude above SM prediction (CKM matrix)

- Model-independent search
  - Ambiguity in muon g-2 measurement
  - Generic new physics based on g-2 discrepancy
  - New source of CP-violation

- Model-dependent search
  - Lepton universality, SUSY, LFV models’ EFT, etc
History of muon EDM searches

SM: M. Pospelov and A. Ritz, PRD 89, 056006 (2014)
History of muon EDM searches

SM ~ $O(10^{-42})$
Muon EDM from BSM Physics

SM \sim O(10^{-42})

Past
On-going
Proposed

Bennett et al PRD2009
J-PARC / FNAL
Lepton flavor violating models EFT analysis
Crivellin et al arXiv:1907.11494v1
MSSM
LR SUSY see-saw
Babu et al PRL2009
Babu et al PRD2000
Hiller et al PRD2010
linear
quadratic
cubic
Muon EDM vs other EDM searches

SM ~ $O(10^{-42})$

Searches in all systems are complementary and when combined will establish the source of new CP-violation.
# Summary of muon EDM searches

<table>
<thead>
<tr>
<th>Year</th>
<th>Location</th>
<th>Publication</th>
<th>Limit [e cm] (95% C.L.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1958</td>
<td>Columbia University</td>
<td>PRL 1, 144 (1958)</td>
<td>$2.9 \times 10^{-15}$</td>
</tr>
<tr>
<td>1960</td>
<td>Columbia University</td>
<td>PR 118, 1086 (1960)</td>
<td>$3.3 \times 10^{-16}$</td>
</tr>
<tr>
<td>1960</td>
<td>CERN</td>
<td>Il Nuovo Cimento XVII 3 (1960)</td>
<td>$1.5 \times 10^{-16}$</td>
</tr>
<tr>
<td>1961</td>
<td>CERN</td>
<td>Il Nuovo Cimento XXII 5 (1961)</td>
<td>$2.8 \times 10^{-17}$</td>
</tr>
<tr>
<td>1978</td>
<td>CERN</td>
<td>J. Phys. G 4, 345 (1978)</td>
<td>$1.05 \times 10^{-18}$</td>
</tr>
<tr>
<td>2003</td>
<td>J-PARC</td>
<td>2003 (LOI) [J-PARC L22]</td>
<td>$O(10^{-24})$</td>
</tr>
<tr>
<td>2009</td>
<td>BNL</td>
<td>PRD 80, 052008 (2009)</td>
<td>$1.8 \times 10^{-19}$</td>
</tr>
<tr>
<td>2027?</td>
<td>PSI</td>
<td>PRD 98, 113002 (2018)</td>
<td>$5 \times 10^{-23}$</td>
</tr>
</tbody>
</table>

4 orders of magnitude in 50 years
Important notes about muon EDM searches

Many experiments have been performed or proposed for the measurement of the EDM of charged particles. These generally run into a difficulty which does not exist for neutral particles. The problem caused by the charge is simply that to measure an EDM one must apply an electric field at the particle in order to generate an interaction energy for the parameter being observed. A charged particle cannot exist unaccelerated in an electric field.

Il Nuovo Cimento XI 6 (1959)

dipole moments to of the order $e \times 10^{-13}$ cm. The existence of longitudinally polarized beams of mu mesons and the availability of muon decay as a polarization analyzer suggest a convenient method by means of which one may search for a muon electric dipole moment.

We note that a transverse electric field will exert a torque proportional to $\vec{\sigma} \times \vec{E}$ which will cause the spin vector $\vec{\sigma}$ to precess away from the longitudinal direction.

In the present experiment the electric field was that created in the rest system of the muon moving in a magnetic field $\vec{B}$, and equal to $(1/c) \times \vec{\sigma} \times \vec{B}$. As shown in Fig. 1, the particles are first

PRL 1, 144 (1958)
Overview of muon EDM searches

• Pre-storage ring:
  Columbia (1958-1959), CERN I (1960-1961)

• Storage ring (parasitic with g-2):

• Lattice storage ring (frozen spin):

• Compact storage ring (frozen spin):
  PSI (2006), PSI (2026-2027)

Closely related to the developments in muon g-2 measurements
Motivation back then: origin of muon rest mass, structure in muon (vs electron)
Pre-storage ring (Columbia 1958)

The presence of an electric dipole moment $\frac{e\hbar}{mc}$ would cause a rotation of the spin vector out of the horizontal plane by an amount

$$\theta = 2\gamma\beta \theta_0,$$

where $\theta_0$ is the total angle through which the trajectory is deflected by the magnetic fields and $\gamma = \frac{1}{\sqrt{1 - \beta^2}}$.

#1, #2, #3, #4 - counters

carbon absorber

carbon target

precessing coil

Muon Polarimeter
Pre-storage ring (Columbia 1958)

The presence of an electric dipole moment $fe \mu c$ would cause a rotation of the spin vector out of the horizontal plane by an amount

$$\theta = 2 \theta_0 \gamma,$$

where $\theta_0$ is the total angle through which the trajectory is deflected by the magnetic fields and $\gamma = 1/(1 - \beta^2)^{1/2}$

**Measurements**

$\theta = +0.64 \pm 0.024$ radians (105° run),

$\theta = +0.017 \pm 0.028$ radians (153° run).

$$f = \frac{\theta_s}{2 \beta \gamma \theta_0}$$

Combining the two runs, the value of the electric dipole moment of the muon is found to be (in units of $e\mu c$)

$f = 0.006 \pm 0.005$.

This corresponds to a unit charge multiplied by a distance of $(1.1 \pm 0.9) \times 10^{-15}$cm. The result is consistent with a vanishing dipole moment expected on the basis of time-reversal invariance.
Pre-storage ring (Columbia 1959)  A follow up with improved apparatus

\[ f = \frac{\theta_s}{2\beta\gamma\theta_0} \]

Surrounded by Helmholtz coils
Pre-storage ring (Columbia 1959)  A follow up with improved apparatus

**Table I. Summary of data.**

<table>
<thead>
<tr>
<th>Position</th>
<th>$a_1$</th>
<th>$aP_1$</th>
<th>$\sigma_1$</th>
<th>$aP_1$</th>
<th>$\theta=aP_1/\sigma_1$ radians</th>
<th>$f$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A$ (88° run)</td>
<td>1.45±0.03</td>
<td>0.18±0.01</td>
<td>1.004±0.003</td>
<td>0.002±0.0015</td>
<td>0.011±0.008</td>
<td>0.002±0.002</td>
</tr>
<tr>
<td>$B$ (259° run)</td>
<td>1.55±0.04</td>
<td>0.22±0.01</td>
<td>0.995±0.005</td>
<td>−0.0025±0.0025</td>
<td>−0.011±0.011</td>
<td>−0.007±0.0008</td>
</tr>
</tbody>
</table>

Surrounded by Helmholtz coils

Because of the complete up-down symmetry of the production process, it is unlikely that the muons have an initial component of polarization out of the horizontal plane. The use of the total bending angle is therefore justified\(^{17}\) and combining the results of positions $A$ and $B$, one obtains

$$f = -0.0004\pm 0.0007.$$  

This corresponds to an $\text{EDM} \leq 6\times 10^{-18}$ cm. We note that $(f)$ is approximately an upper limit for the probability amplitude for both parity and time reversal mixing.
Pre-storage ring (CERN 1960-1961)

85 MeV/c for 28 turns

A Method for Trapping Muons in Magnetic Fields, and Its Application to a Redetermination of the EDM of the Muon.

G. Charpak (*), L. M. Lederman (**), J. C. Sens and A. Zichichi

CERN - Geneva

(ricavuto il 4 Aprile 1960)

Summary. — A method for trapping muons in magnetic fields is described together with its application to higher accuracy determination of the electric dipole moment of the muon. The value found is:

$$\text{EDM} < e(5 \pm 5) \times 10^{-17} \text{cm}$$

consistent with time reversal invariance.

85 MeV/c for 1200 turns

A New Limit to the Electric Dipole Moment of the Muon.

G. Charpak (*), P. J. M. Farley, R. L. Garwin (**), T. Muller (**), J. C. Sens and A. Zichichi

CERN - Geneva

(ricavuto il 18 Settembre 1961)

Summary. — By storing polarized positive muons in a magnetic field for as many as 1200 revolutions, a new upper limit to the electric dipole moment has been determined. The value is

$$\text{EDM} < (3 \pm 6) \times 10^{-8} \frac{e\hbar}{mc}$$

or

$$\text{EDM} < e \cdot (0.6 \pm 1.1) \times 10^{-17} \text{cm}$$

consistent with time-reversal invariance.

Slowly moving towards a storage ring for higher sensitivity
Pre-storage ring (CERN 1960)

EDM signal \( \Theta_s = 2f \beta \gamma \Theta_0 \)

Orbit angle \( \Theta_0 = \frac{eB}{mc\gamma} t \)

\( \Theta_0 < 2\pi \)  
Columbia

\( \Theta_0 = 2n\pi, n \leq 28 \)  
CERN

Compare many turns vs 1 turn

Fig. 4. – Counter layout for the measurement of the electric dipole moment.

\[ a = \frac{N_{up} - N_{down}}{N_{up} + N_{down}} \]
Pre-storage ring (CERN 1960)

Table I. - Results obtained for particles which have made, in the mean 11.5, 16.5 and 19.5 turns (Group I, II and III respectively). $a_{\text{early}}$ refers to the asymmetry for muons, which have made, in the mean, one turn (ranging from $\frac{1}{2}$ to $\frac{3}{2}$ turns).

<table>
<thead>
<tr>
<th>Group</th>
<th>Late turns</th>
<th>$a_{\text{early}}$ (%)</th>
<th>$a_{\text{late}}$ (%)</th>
<th>$a_{\text{int}}$ $a_{\text{early}}$ (%)</th>
<th>$\langle \Theta_{\text{spin}} \rangle$ (rad.)</th>
<th>$\langle \Theta_{\text{orbit}} \rangle$ (rad.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>6$\frac{1}{2}$ - 18$\frac{1}{2}$</td>
<td>8.01 ± 0.84</td>
<td>6.98 ± 0.40</td>
<td>1.04 ± 0.94</td>
<td>0.062 ± 0.047</td>
<td>66.0</td>
</tr>
<tr>
<td>II</td>
<td>11$\frac{1}{2}$ - 26$\frac{1}{2}$</td>
<td>7.28 ± 1.81</td>
<td>7.04 ± 0.87</td>
<td>0.24 ± 2.00</td>
<td>0.014 ± 0.100</td>
<td>97.0</td>
</tr>
<tr>
<td>III</td>
<td>15$\frac{1}{2}$ - 26$\frac{1}{2}$</td>
<td>7.41 ± 1.24</td>
<td>7.19 ± 0.94</td>
<td>0.22 ± 1.55</td>
<td>0.013 ± 0.080</td>
<td>116</td>
</tr>
</tbody>
</table>

Combining the 3 values of $\Theta_{\text{spin}}$/$\Theta_{\text{orbit}}$ which are listed in Table I, one finds:

$$f = (2.7 \pm 2.8) \cdot 10^{-4}.$$  

This corresponds to an upper limit for the EDM of $e\cdot(5.0 \pm 5.0) \cdot 10^{-17}$ cm, and is consistent with time reversal invariance.
Pre-storage ring (CERN 1961)

Upgraded polarimeter
Flip vertical component of the spin into forward or backward

\[ A_n = \frac{(c_{n+} - c_{n-})}{(c_{n+} + c_{n-})} = \frac{2\beta I \cdot A \sin \omega t}{(a^2 + 4f^2\beta^2)^{1/2}} \]

Fig. 2. – The polarization analyser (seen from above): A) muon neutral shield; C) 6 mm lucite sheet; D) mirror; E) 8 cm thick CH₂I₂ target; F) lucite container; G) flipping coil; H) 1 cm Arneo iron shielding box; I) 2 cm Arneo iron shielding box.

Curve Amperes per 1 µs, time channel

best fit for g-2 signal

Asymmetry per group of 4 channels

EDM of muon = e \cdot (0.6 \pm 1.1) \cdot 10^{-17} \text{ cm}
Spin dynamics in a magnetic dipole storage ring

\[ \vec{\omega}_s - \vec{\omega}_c = -\frac{e}{m}\left\{ a\vec{B} + \left( \frac{1}{\gamma^2 - 1} - a \right) \frac{\vec{\beta} \times \vec{E}}{c} + \frac{\eta}{2} \left( \frac{\vec{E}}{c} + \vec{\beta} \times \vec{B} \right) \right\} \]
Spin dynamics in a magnetic dipole storage ring

\[ \vec{\omega}_s - \vec{\omega}_c = - \frac{e}{m} \left\{ a \vec{B} + \left( \frac{1}{\gamma^2 - 1} - a \right) \vec{\beta} \times \vec{E} \right\} + \frac{\eta}{2} \left( \frac{\vec{E}}{c} + \vec{\beta} \times \vec{B} \right) \]

\( \vec{\omega}_a : \text{AMM} \)

\( \vec{\omega}_\eta : \text{EDM} \)
Spin dynamics in a magnetic dipole storage ring

\[ \vec{\omega}_s - \vec{\omega}_c = -\frac{e}{m} \left\{ a \vec{B} + \left( \frac{1}{\gamma^2 - 1} \right) \vec{\beta} \times \vec{E} + \frac{\eta}{2c} \left( \frac{\vec{E}}{c} + \vec{\beta} \times \vec{B} \right) \right\} \]

- \( \vec{\omega}_a \): AMM
- \( \vec{\omega}_\eta \): EDM

BNL, FNAL: use \( \gamma = 29.3 \)
J-PARC: no E-field focusing

precession plane
Spin dynamics in a magnetic dipole storage ring

\[ \vec{\omega}_s - \vec{\omega}_c = -\frac{e}{m} \left\{ a \vec{B} + \left( \frac{1}{\gamma^2 - 1} - a \right) \vec{\beta} \times \vec{E} \right\} + \frac{\eta}{2} \left( \frac{\vec{E}}{c} + \vec{\beta} \times \vec{B} \right) \]

**ωₐ**: AMM

**ωₜotal**: AMM + EDM

δ ~ mrad for 
\[ d_\mu \sim 10^{-19} \text{ e cm} \]

\[ \delta = \tan^{-1} \left( \frac{\eta \beta}{2a_\mu} \right) \]

EDM signal 90° out of phase with g-2 signal
- g-2 max/min: s aligned/anti-aligned with p
- EDM max/min: s 90°/270° from p
New limits on the electric dipole moment
of positive and negative muons

J Bailey†, K Boretzky, F Combley, H Drummond, F J M Farley†, J H Field†, W Flegel†, P M Hattersley*, F Krienen†, F Lange†, E Picasso†
and W von Rüden†

(CERN Muon Storage Ring Collaboration)

† Daresbury Laboratory, Warrington, UK
‡ Physikalisches Institut, Universität Bern, Bern, Switzerland
§ Department of Physics, University of Sheffield, Sheffield, UK
¶ Institut für Physik der Universität Mainz, Mainz, Germany

* Royal Military College of Science, Shrivenham, Wiltshire, UK
* European Organization for Nuclear Research, CERN, Geneva, Switzerland
* Department of Physics, University of Birmingham, Birmingham, UK

Received 9 August 1977

Abstract. New measurements of the electric dipole moment of muons of both charges have been made in the Muon Storage Ring at CERN. The values found are

$D_+ = (8.6 \pm 4.9) \times 10^{-14}$ emu

$D_- = (0.8 \pm 4.3) \times 10^{-14}$ emu

(Errors are at one standard deviation.) We conclude, at 95\% confidence level, that $|D_-| < 9.05 \times 10^{-14}$ emu.
New limits on the electric dipole moment of positive and negative muons

J Bailey et al.

Storage ring (parasitic with g-2, CERN 1975-76)

Abstract: New measurements of the electric dipole moment of muons of both charges have been made in the Muon Storage Ring at CERN. The values found are

\[D_+ = (8.6 \pm 4.0) \times 10^{-10} \text{ cm}^2\]

\[D_- = (0.8 \pm 4.0) \times 10^{-10} \text{ cm}^2\]

(errors are of one standard deviation). We conclude, at 95\% confidence level, that \(D_- < 1.05 \times 10^{-10} \text{ cm}^2\).

B=1.47 T, Aperture=8 cm (V) x 12 cm (H), R=7 m, p=3.094 GeV/c, Quad coverage=72\%, 24 kV

Fig. 1. Plan view of the muon storage ring and a cross section through one of the forty magnets. For most of the data taking 22 electron detectors were used. These were distributed around the ring at intervals which were as nearly uniform as possible.
Oscillating vertical component of the spin causes up-down phase difference on electron detectors

\[
N_{\text{up}} = \frac{1}{2} Ne^{-t/\tau}(1 - A_\mu \cos(\omega t + \psi) + A_e \sin(\omega t + \psi))
\]

\[
N_{\text{down}} = \frac{1}{2} Ne^{-t/\tau}(1 - A_\mu \cos(\omega t + \psi) - A_e \sin(\omega t + \psi)).
\]

\[
A_e = (0.164 \pm 0.019)\delta \quad \text{Simulation}
\]
Oscillating vertical component of the spin causes up-down phase difference on electron detectors

\[ N_{up} = \frac{1}{2} Ne^{-i\gamma}(1 - A_{\mu} \cos(\omega t + \psi) + A_e \sin(\omega t + \psi)) \]

\[ N_{down} = \frac{1}{2} Ne^{-i\gamma}(1 - A_{\mu} \cos(\omega t + \psi) - A_e \sin(\omega t + \psi)) \]

\[ A_e = (0.164 \pm 0.019)\delta \]

Table 1. Summary of runs.

<table>
<thead>
<tr>
<th>Run</th>
<th>Sign</th>
<th>No of steps (million)</th>
<th>( \Delta \psi = \phi_{up} - \phi_{down} ) (mrad)</th>
<th>Dipole moment (e cm ( \times 10^{-19} ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1975 A</td>
<td>( \mu^+ )</td>
<td>1.1</td>
<td>-14.9 (17.1)</td>
<td>7.7 (8.8)</td>
</tr>
<tr>
<td>B</td>
<td>( \mu^- )</td>
<td>1.9</td>
<td>-26 (13.2)</td>
<td>-1.3 (6.8)</td>
</tr>
<tr>
<td>1976 A</td>
<td>( \mu^+ )</td>
<td>2.1</td>
<td>-27.0 (11.5)</td>
<td>14.9 (6.3)</td>
</tr>
<tr>
<td>B</td>
<td>( \mu^- )</td>
<td>0.8</td>
<td>+16 (18.8)</td>
<td>0.9 (10.3)</td>
</tr>
<tr>
<td>C</td>
<td>( \mu^- )</td>
<td>1.5</td>
<td>+19 (13.6)</td>
<td>1.0 (7.4)</td>
</tr>
<tr>
<td>D</td>
<td>( \mu^+ )</td>
<td>2.2</td>
<td>-6.3 (11.8)</td>
<td>3.3 (6.1)</td>
</tr>
<tr>
<td>E</td>
<td>( \mu^- )</td>
<td>1.8</td>
<td>+5.5 (13.4)</td>
<td>2.8 (6.9)</td>
</tr>
<tr>
<td>Weighted averages</td>
<td>( \mu^+ )</td>
<td>5.4</td>
<td>-16.5 (7.4)</td>
<td>8.6 (4.0)</td>
</tr>
<tr>
<td></td>
<td>( \mu^- )</td>
<td>6.0</td>
<td>+16 (7.2)</td>
<td>0.8 (3.8)</td>
</tr>
<tr>
<td>((\mu^+ + \mu^-)) overall</td>
<td></td>
<td>11.4</td>
<td>-7.2 (5.2)</td>
<td>3.7 (2.7)</td>
</tr>
</tbody>
</table>

\[ D_{\mu^+} = (8.6 \pm 4.5) \times 10^{-19} \text{ e cm} \]

\[ D_{\mu^-} = (0.8 \pm 4.3) \times 10^{-19} \text{ e cm} \]

Assuming the CPT theorem they can be combined to give for the muon

\[ D_{\mu} = (3.7 \pm 3.4) \times 10^{-19} \text{ e cm} \]

\[ (\delta \sim \text{mrad for } \Delta m \sim 10^{19} \text{ e cm}) \]
Improved limit on the muon electric dipole moment

Three independent searches for an electric dipole moment (EDM) of the positive and negative muons have been performed, using spin precession data from the muon $g-2$ storage ring at Brookhaven National Laboratory. Details on the experimental apparatus and the three analyses are presented. Since the individual results on the positive and negative muons, as well as the combined result, $d_\mu = (0.0 \pm 0.9) \times 10^{-19}$, are all consistent with zero, we set a new muon EDM limit, $|d_\mu| < 1.8 \times 10^{-19}$ (95% C.L.). This represents a factor of 5 improvement over the previous best limit on the muon EDM.
Storage ring (parasitic with g-2, BNL 1999-2001)

Improved limit on the muon electric dipole moment

Three independent searches for an electric dipole moment (EDM) of the positive and negative muons have been performed, using spin precession data from the muon g-2 storage ring at Brookhaven National Laboratory. Details on the experimental apparatus and the three analyses are presented. Since the individual results on the positive and negative muons, as well as the combined result, \( d_\mu = (0.0 \pm 0.9) \times 10^{-19} \text{\mu cm} \), are all consistent with zero, we set a new muon EDM limit, \( |d_\mu| < 1.8 \times 10^{-19} \text{\mu cm} \) (95% C.L.). This represents a factor of 5 improvement over the previous best limit on the muon EDM.

Tracker-based measurement [vertical angle oscillation]

PSD+Calorimeter-based measurements [vertical position oscillation, up-down phase difference]
Storage ring (parasitic with g-2, BNL 1999-2001)

- g-2 analysis prefers high-energy positrons (> 1.7 GeV)
- EDM analysis prefers mid-energy positrons

Figure of merit = $NA^2$
Vertical Angle Oscillation

\[ N(t) = e^{-t/\tau_e}(N_0 + W \cos(\omega t + \Phi)) \]

1. Fit for g-2 phase

2. Fix g-2 phase and fit for \( A_{\text{EDM}} \)

EDM signal 90 out of phase with g-2 signal

\[ \delta = \tan^{-1}\left( \frac{\eta \beta}{2a_\mu} \right) \]

\[ \delta \sim \text{mrad} \] for \( d_\mu \sim 10^{-19} \text{ e cm} \)
Vertical Position Oscillation

Vertical hit distribution seen by calorimeters

Positron count versus (g-2) phase

Mean vertical position versus (g-2) phase

90 deg out of phase

**Vertical Phase Gradient**

![Diagram of Muon Decay Directions](image)

- **Outward decays (270°)**
- **Inward decays (90°)**

**g-2 Wiggle**

*Example: inward-going positrons*

**φ(y), Fitted Phase vs. Vertical Position**

*Midplane symmetry*

---

Vertical Phase Gradient

Outward decays (270°)

Inward decays (90°)

Midplane asymmetry
Storage ring (parasitic with g-2, BNL 1999-2001)

<table>
<thead>
<tr>
<th>Analysis</th>
<th>Mean value</th>
<th>Stat. error</th>
<th>Syst. error</th>
<th>Total error</th>
<th>95% C.L.</th>
</tr>
</thead>
<tbody>
<tr>
<td>CERN (1978)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$(\mu^+)$</td>
<td>8.6</td>
<td>4.0</td>
<td>2.0</td>
<td>4.5</td>
<td></td>
</tr>
<tr>
<td>$(\mu^-)$</td>
<td>0.8</td>
<td>3.8</td>
<td>2.0</td>
<td>4.3</td>
<td></td>
</tr>
<tr>
<td>Combined $\mu^+\mu^-$</td>
<td>-3.7</td>
<td>2.8</td>
<td>2.0</td>
<td>3.4</td>
<td>10.5</td>
</tr>
<tr>
<td>E821</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Traceback $(\mu^+)$</td>
<td>0.0</td>
<td>1.6</td>
<td>0.1</td>
<td>1.6</td>
<td></td>
</tr>
<tr>
<td>FSD $(\mu^+)$</td>
<td>-0.1</td>
<td>0.7</td>
<td>1.2</td>
<td>1.4</td>
<td></td>
</tr>
<tr>
<td>Average $\mu^+$</td>
<td>-0.1</td>
<td>0.6</td>
<td>0.8</td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>PSD $(\mu^-)$</td>
<td>-0.1</td>
<td>0.3</td>
<td>0.7</td>
<td>0.7</td>
<td></td>
</tr>
<tr>
<td>Combined $\mu^+\mu^-$</td>
<td>0.0</td>
<td>0.2</td>
<td>0.9</td>
<td>0.9</td>
<td>1.8</td>
</tr>
</tbody>
</table>

\[ d_\mu = (0.0 \pm 0.9) \times 10^{-19} \text{ e cm.} \]

This corresponds to the limit

\[ |d_\mu| \leq 1.8 \times 10^{-19} \text{ e cm (95% C.L.),} \]
3 ways to search for a muon EDM

1. Vertical Angle Oscillation (Tracker)
2. Vertical Position Oscillation (Calorimeter)
3. Vertical Phase Gradient (Calorimeter)
Storage ring (parasitic with g-2, J-PARC 2024-2026)

Search for a muon EDM
Vertical Angle Oscillation (Tracker)
Spin dynamics in a magnetic dipole storage ring

\[
\vec{\omega}_s - \vec{\omega}_c = -\frac{e}{m} \left\{ a \vec{B} + \left( \frac{1}{\gamma^2 - 1} - \alpha \right) \frac{\vec{\beta} \times \vec{E}}{c} + \frac{\eta}{2} \left( \frac{\vec{E}}{c} + \frac{\vec{\beta} \times \vec{B}}{c} \right) \right\}
\]

\( \omega_a : \text{AMM} \)

\( \omega_\eta : \text{EDM} \)

4 Conclusions

Some popular “non-standard” models of CP violation predict that the muon EDM is not very much bigger than about a few \( \times 100 d_s \). A substantially larger \( d_\mu \) is possible in specific versions of left-right symmetric models and leptoquark models. However, if \( d_\mu \) is of order \( 10^{-19} - 10^{-20} \text{ e cm} \), one would expect even larger electric and weak dipole form factors of the \( \tau \) which should eventually be measurable at LEP. Nevertheless, future experimental determinations of \( d_\mu \) will be of interest. It seems also worthwhile to search for experimental methods which would substantially increase the sensitivity to this form factor.

Frozen-spin technique for EDM search

\[ \vec{\omega}_s - \vec{\omega}_c = -\frac{e}{m} \left\{ a \vec{B} + \left( \frac{1}{\gamma^2 - 1} - a \right) \frac{\beta \times \vec{E}}{c} \right\} \]

_apply_ \( E \sim aBc\beta\gamma^2 \)

\[ \omega_a : \text{AMM} \]

\[ \omega_\eta : \text{EDM} \]

Silenko et al.: J-PARC Letter of Intent: Search for the Permanent Muon Electric Dipole Moment at the $10^{-24}$ e cm Level.

\[ p = 0.5 \text{ GeV/c} \]
\[ B_z = 0.25 \text{ T} \]
\[ E_r = 2 \text{ MV/m} \]
\[ R = 7 \text{ m} \]
\[ \langle R \rangle = 11 \text{ m} \]
\[ B+E = 2.6 \text{ m} \]
\[ \text{Intervals} = 1.7 \text{ m} \]
Lattice storage ring (frozen spin, J-PARC 2003)

Y. Semertzidis
EDM Workshop, BNL (2001)

Total count versus time
[pure exponential, no g-2 oscillation]

Up-down asymmetry versus time
[Slowly builds up]
Compact storage ring (frozen spin, PSI 2006)

Muon EDM beam schematics

- Target E
- μE1 beam line
- Trigger
- Inflector
- ~20 turns injection
- Design orbit (r = 42 cm)
- B (1 T)
- E (6.4 kV/cm)


A. Adelmann, K. Kirch, Search for the muon electric dipole moment using a compact storage ring arXiv:hep-ex/0606034

A. Adelmann, K. Kirch, C.J.G. Onderwater, T. Schietinger, A. Streun to be published

Klaus Kirch Measuring the muon EDM at PSI Valencia, Jul. 2008
Compact storage ring (frozen spin, PSI 2018)

Proposal for a dedicated compact $\mu$-EDM at PSI

- Weak focusing magnet
- Polarized $\mu$ beam
- Trigger from beam telescope for start of inflector ramp (resonance $\frac{1}{2}$ integer injection*)
  - **One** muon at a time $\sim 200$ kHz rate
  - Tracking detector for positrons (resolution $\sim 0.25 \times 0.25$ mm$^2$)
- Optional calorimeter

Detector prototype:
Combination of scintillating tiles (timing) and thin MAPS (track, momentum)
Projected sensitivity

Apply **frozen spin technique**

- PSI $\mu$E1: $2 \times 10^8 \mu^+/s$ \quad $\gamma = 1.57$
- Polarization from pion decay: $P = 0.9$
- Mean asymmetry of muon decay: $\alpha = 0.3$
- Compact conventional magnet:
  \[
  B = 1.5 \ T \Rightarrow R = 0.28 \text{m}, \quad E = 10 \text{MV/m}
  \]
  
  \[
  \sigma(d_\mu) < 5 \times 10^{-23} \text{ecm}
  \]

- Detection rate: $200 \text{ kHz}$
- Run time: $2 \times 10^7 \text{ s}$
  \[
  \Rightarrow N = 4 \times 10^{12} \text{ positrons per year.}
  \]
# Summary of muon EDM efforts

Adapted from Chupp et al., Rev. Mod. Phys., Vol. 91, No. 1, 015001-45

| Experiment  | $|p|$ (GeV/c) | $\gamma$ | $|B|$ (T) | $|E|$ (kV/cm) | $|E'|/\gamma$ (MV/cm) | $R$ (m) | Goal (e cm) |
|-------------|--------------|----------|----------|--------------|-----------------------|--------|-------------|
| J-PARC l-EDM | 0.5          | 5.0      | 0.25     | 22           | 0.76                  | 7.0    | $10^{-24}$  |
| PSI (2006) | 0.125        | 1.57     | 1.0      | 6.4          | 2.3                   | 0.42   | $7 \times 10^{-23}$ |
| Fermilab E989 | 3.094       | 29.3     | 1.45     | 0            | 4.3                   | 7.112  | $10^{-21}$  |
| J-PARC E34 | 0.3          | 3.0      | 3.0      | 0            | 8.5                   | 0.333  | $10^{-21}$  |
| PSI (2018) | 0.125        | 1.57     | 1.5      | 10           | 3.45                  | 0.28   | $5 \times 10^{-23}$ |

for g-2 cancellation
experienced E-field in rest frame
Summary

- Muon EDM is one of the least tested area of SM and is sensitive to a rich variety of BSM physics
- Six measurements in the past 60 years and it’s current limit is $1.8 \times 10^{-19}$ e cm
- Experiments at FNAL and J-PARC aim to reach $O(10^{-21})$ e cm
- Frozen-spin technique is the most sensitive approach so far and its realization will open up muon EDM as a probe to new physics
- Frozen-spin technique at PSI could reach
  - PSI-A/B: $O(10^{-21})$ e cm within a year of data
  - PSI-C: $5 \times 10^{-23}$ e cm within a year of data
THANK YOU!