Axion dark matter search
and the
Storage ring proton EDM experiment
Yannis Semertzidis, CAPP/IBS and KAIST

Axion dark matter search

• Infrastructure completion well underway.
• Plan to answer whether axions are the dark matter…

Proton, deuteron sensitive EDM

• Storage ring p,d EDMs @ $<10^{-29}$e-cm level
• Probing NP $\sim10^3$-$10^4$ TeV
• Storage ring EDMs: Great physics opportunity
South Korea’s Nobel dream

The Asian nation spends more of its economic output on research than anywhere else in the world. But it will need more than cash to realize its ambitions.

BY MARK ZASTROW

Behind the doors of a drab brick building in Daejeon, South Korea, a major experiment is slowly taking shape. Much of the first-floor lab space is under construction, and one glass door, taped shut, leads directly to a pit in the ground. But at the end of the hall, in a pristine lab, sits a gleaming cylindrical apparatus of copper and gold. It’s a prototype of a device that might one day answer a major mystery about the Universe by detecting a particle called the axion — a possible component of dark matter.

If it succeeds, this apparatus has the potential to rewrite physics and win its designers a Nobel prize. “It will transform Korea, there’s no question about it,” says physicist Yannis Semertzidis, who leads the US$7.6-million-per-year Centre at South Korea’s premier technical university, KAIST. But there’s a catch: no one knows whether axions even exist. It’s the kind of high-risk, high-reward project...
Center for Axion and Precision Physics research. Established 15 October, 2013 at KAIST.
Center for Axion and Precision Physics Research: CAPP/IBS at KAIST, Korea

- Four groups, goal: ~60 people within 3-5 years
- 15 research fellows, ~20 graduate students
- 10 junior/senior staff members
- Engineers, Technicians
- Future: Dedicated IBS building at KAIST
Korea Undergraduate / Graduate / H.S. Science Program (KUSP)  
CAPP/IBS at KAIST, Summer 2016

We are happy to answer any of your questions about KUSP 2016. Please contact us!  
KUSP team: +82-42-350-8168, +82 -42-350-8166 / kusp@ibs.re.kr

multicultural environment, which will extremely enrich personal experience.

Though it will be held in Korea, KUSP is an international program and thereby the official language will be English.

1. Date
July 4 - August 5, 2016 (5 weeks)

2. Target students
-International and domestic undergraduate and graduate students in physics or related disciplines  
  (e.g. electric engineering, computer science, mathematics, etc.)
-Highly motivated high school students

3. Eligibility

http://kusp.ibs.re.kr/
KUSP, July, 2016
CAPP-Physics

- Establish Experimental Particle Physics group.

Involved in important physics questions:

- Strong CP problem
- Cosmic Frontier (Dark Matter axions)
- Storage ring proton EDM (most sensitive hadronic EDM experiment, flavor conserving CP-violation, BAU)
- Muon g-2; muon to electron conversion (flavor physics)
CAPP/IBS’s Physics goals address some of the most important issues.

https://www.quantamagazine.org
Axion mass target and technique

Microwave cavities

Open resonators

Monopole-Dipole Interactions, No dark matter assumed (ARIADNE)
## Axion exp. development plan

<table>
<thead>
<tr>
<th></th>
<th>2014</th>
<th>2015</th>
<th>2016</th>
<th>2017</th>
<th>2018</th>
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<tbody>
<tr>
<td><strong>Magnet</strong></td>
<td>Prototype, testing of cable characteristics.</td>
<td></td>
<td>25T, 10cm inner bore design</td>
<td>Work on 35T, 10cm inner bore construction</td>
<td>Magnet delivery of 35T, 10cm bore</td>
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<tr>
<td><strong>Lab space</strong></td>
<td>Temporary building: Lab design and preparation</td>
<td></td>
<td>Occupation</td>
<td></td>
<td></td>
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<tr>
<td><strong>Axion dark matter</strong></td>
<td>Proc. Equipment Study res. geom.</td>
<td>Development of high Q resonators</td>
<td></td>
<td>Production of high-Q resonators</td>
<td></td>
</tr>
<tr>
<td><strong>Electronics, amplifiers</strong></td>
<td>Establ. Collabor. w/ KRISS</td>
<td>Design for 1-10GHz Obtain JPAs, test. Develop higher freq. ampl.</td>
<td></td>
<td>Ampl. deliveries from KRISS</td>
<td></td>
</tr>
<tr>
<td><strong>Axion cavity Exp.</strong></td>
<td>Design of exp., procure a low field magnet</td>
<td></td>
<td>Experimental setup. First test run.</td>
<td></td>
<td>Swap magnets</td>
</tr>
</tbody>
</table>
-Creation Hall-

CAPP Research Bldg. at KAIST Munji Campus
Seven, low vibration pits, two with magnetic shielding
LVP assignment

ARIADENE and SC R&D

1. cooling the small toroidal cavity, Major R=50 cm
2. wet DF (Leiden)
3. wet $^3$He 8T/Loch (Janis)
4. dry DF (Bluefors)
5. dry DF (Bluefors)

~20 T wet SuNAM magnet
12 T wet Oxford magnet + new wet DF
25 T wet BNL magnet

Slide: ByeongRok Ko
### Expected axion mass range per magnet

<table>
<thead>
<tr>
<th>Location</th>
<th>Magnet</th>
<th>Fridge</th>
<th>Search range</th>
</tr>
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<tbody>
<tr>
<td>C105</td>
<td>dry 8T/110mm</td>
<td>dry DF</td>
<td>1-2 GHz</td>
</tr>
<tr>
<td>C105</td>
<td>dry 8T/155mm</td>
<td>dry DF</td>
<td>1-2 GHz</td>
</tr>
<tr>
<td>Pit3</td>
<td>wet 12T/180mm toroid</td>
<td>wet DF (need ~50 liters $^3$He)</td>
<td>0.5-1.3 GHz</td>
</tr>
<tr>
<td>Pit4</td>
<td>wet 9T/5inches</td>
<td>wet $^3$He</td>
<td>3-4 GHz</td>
</tr>
<tr>
<td>Pit5</td>
<td>wet 12T/320mm</td>
<td>wet DF (need ~50 liters $^3$He)</td>
<td>0.5-1.3 GHz</td>
</tr>
<tr>
<td>Pit6</td>
<td>wet 20T/65mm</td>
<td>dry DF</td>
<td>3-4 GHz</td>
</tr>
<tr>
<td>Pit7</td>
<td>wet 25T/100mm</td>
<td>dry DF</td>
<td>2-10 GHz</td>
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</tbody>
</table>

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**Diagram:**

- **Axion Coupling $g_{a\gamma}$ (GeV$^{-1}$)**
- **Axion Mass (µeV)**
- **Cavity Frequency (GHz)**
- **Non RF-cavity Techniques**
- **White Dwarf and Supernova Bounds**
- **Minimum Coupling**
- **Warm Dark Matter**
- **Too Much Dark Matter**
- **Axion Cold Dark Matter**
- **Axion Heavy and Admixtures**

**Slide:** ByeongRok Ko
### Present magnet acquisition plan

<table>
<thead>
<tr>
<th>Magnet source</th>
<th>Status</th>
<th>2016</th>
<th>2017</th>
<th>2018</th>
<th>2019</th>
<th>2020</th>
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<tr>
<td>BNL magnet</td>
<td>Outsourcing</td>
<td></td>
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<tr>
<td></td>
<td>(to be approved)</td>
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<td></td>
<td></td>
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<tr>
<td>Oxford magnet</td>
<td>NFEC (approved)</td>
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</tr>
<tr>
<td>SuNAM magnet</td>
<td>NFEC (to be approved)</td>
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<td></td>
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<tr>
<td>Small toroidal</td>
<td>Outsourcing</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>magnet</td>
<td>(plan)</td>
<td></td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

---two R&D magnets presently here:

1) wet magnet (9 T/5 inches) and $^3$He system
2) dry magnet (8 T/155 mm) and DF system

---one wet DF (Leiden) and one dry DF (Bluefors)
Status in HEP-NP

1. LHC discovered the Higgs

2. No sight of SUSY yet at LHC (~1TeV)

3. No EDM discovered so far (fine tuning ~1%)

4. What’s next?
Our Universe is very delicate: Change the SM parameters and could be uninhabitable.

“Natural”, since only we can “live” in a Universe with these “fine-tuned” parameters.

No new physics at the TeV! (new physics in another universes)
A balanced approach is best . . . !

Fig. 1: 95% of the universe are made of two mysterious substances, dark matter and dark energy that cannot be explained in the Standard Model. By their very names it is clear that these things are somehow hidden from our view. New particles could hide by being very massive or by having extremely feeble interactions. It is clear that we need to look in all possible directions. In our quest for new physics high energy and low energy/high precision experiments nicely complement each other and together hopefully answer our questions to Nature.
Storage Ring Muon $g-2$: Rigorous Test of the Standard Model
A circulating particle with charge $e$ and mass $m$:

- **Angular momentum**

  $$L = mvr$$

- **Magnetic dipole moment**

  $$\vec{\mu} = g \frac{e\hbar}{2m\hbar} \frac{\vec{L}}{\hbar} = g\mu_B \frac{\vec{L}}{\hbar}, \ g = 1$$

  $$\mu = IA = \frac{e}{2\pi r / v} \pi r^2 = \frac{erv}{2} \frac{L}{mvr} = \frac{e\hbar}{2m\hbar} \frac{L}{\hbar} = \mu_B \frac{L}{\hbar}$$

($\mu_B$ : Bohr magneton)
Dirac: For particles with intrinsic angular momentum (spin $S$)

$$\vec{\mu} = g \frac{e}{2m} \vec{S}, \ g = 2$$

In a magnetic field ($B$), there is a torque:

$$\vec{\tau} = \vec{\mu} \times \vec{B} \Rightarrow \frac{d\vec{S}}{dt} = \vec{\mu} \times \vec{B}$$
**g-factors:**

- Proton \((g_p=+5.586)\) and the neutron \((g_n=-3.826)\) are composite particles.
- The ratio \(g_p/g_n=-1.46\) close to the predicted \(-3/2\) was the first success of the constituent quark model.
- The \(g_e-2\) (of the electron) is non-zero mainly due to quantum field fluctuations involving QED. A “soup” of virtual particles coming in and out of existence…
- The anomalous magnetic moment of leptons can be estimated with high accuracy
Today we can estimate and measure with high accuracy many possible states.

\[ g = 2 + \frac{\alpha}{\pi} + c_2 \left( \frac{\alpha}{\pi} \right)^2 + \cdot \cdot \cdot \]

\[ a(\text{QED}) = \frac{1}{2} \frac{\alpha}{\pi} + C_2 \left( \frac{\alpha}{\pi} \right)^2 + C_3 \left( \frac{\alpha}{\pi} \right)^3 + C_4 \left( \frac{\alpha}{\pi} \right)^4 + C_5 \left( \frac{\alpha}{\pi} \right)^5 + \cdot \cdot \cdot \]
Electron Magnetic Dipole Moment


\[
\vec{\mu} = -g \left( \frac{e}{2m} \right) \vec{s}
\]

\[
\frac{d\vec{s}}{dt} = \vec{\mu} \times \vec{B}
\]

\[
g / 2 = 1.001159 \ 652 \ 180 \ 73 \ (28) \ [0.28 \ ppt]
\]

\[
\frac{g}{2} = 1 + C_2 \left( \frac{\alpha}{\pi} \right) + C_4 \left( \frac{\alpha}{\pi} \right)^2 + C_6 \left( \frac{\alpha}{\pi} \right)^3 + C_8 \left( \frac{\alpha}{\pi} \right)^4
\]

\[
+ C_{10} \left( \frac{\alpha}{\pi} \right)^5 + \ldots + a_{\mu\tau} + a_{\text{hadronic}} + a_{\text{weak}}, \quad (4)
\]

It’s a triumph of QED!

FIG. 1. Most accurate measurements of the electron \( g / 2 \) (a), and most accurate determinations of \( \alpha \) (b).

FIG. 2 (color). Cylindrical Penning trap cavity used to confine a single electron and inhibit spontaneous emission.
**g-factors: Muon case**

- The $g_\mu$-2 is more sensitive to a class of particles than the $g_e$-2 by $(m_\mu/m_e)^2 \sim 40,000$. Muon is sensitive to a …thicker “soup” of virtual particles.

- Muons are sensitive to W, Z, and New Physics, e.g. SUSY: neutralino
\( g - 2 \) for the muon, SM contributions

Largest contribution: \[ a_\mu = \frac{\alpha}{2\pi} \approx \frac{1}{800} \]

Other standard model contributions:
- QED
- hadronic
- weak
Muons (heavier than electrons) are more sensitive to weak interaction forces (standard model (SM))

Muons become (sometimes) $10^3$ times heavier!

Weak interactions
Spin Precession Rate at Rest

\[ \frac{d\vec{s}}{dt} = \vec{\mu} \times \vec{B} + \vec{d} \times \vec{E} \]

There is a large asymmetry in this equation: \( \mu \) is relatively large, \( d \) is compatible with zero.
The Principle of g-2

At rest: \[ \frac{d\vec{s}}{dt} = \vec{\mu} \times \vec{B} \]

Moving: Thomas precession!

\[ c = \frac{eB}{m} \]

\[ = \frac{g eB}{2m} + (1) \frac{eB}{m} \]

\[ a = s \]

\[ c = \left( \frac{g}{2} \right) \frac{eB}{m} \implies a = a \frac{eB}{m} \]

Independent of velocity!
Effect of Radial Electric Field

- Low energy particle
- ...just right
- High energy particle
Breakthrough concept: Freezing the horizontal spin precession due to E-field

\[ \vec{\omega}_a = -\frac{q}{m} \left\{ a\vec{B} - \left[ a - \left( \frac{mc}{p} \right)^2 \right] \frac{\vec{\beta} \times \vec{E}}{c} \right\} \]

Muon g-2 focusing is electric: The spin precession due to E-field is zero at “magic” momentum (3.1 GeV/c for muons, 0.7 GeV/c for protons, …)

\[ p = \frac{mc}{\sqrt{a}}, \text{ with } G = a = \frac{g}{2} \]

The “magic” momentum concept was used in the muon g-2 experiments at CERN, BNL, and …now at FNAL.
The electric focusing does not influence the $g\text{-}2$ precession rate.

Spin Precession in $g\text{-}2$ Ring (Top View)

$$\vec{\omega}_a = a \frac{e}{m} \vec{B}$$

Momentum vector

Spin vector
Detectors and vacuum chamber

- muon spin
- Sci-Fi Calorimeter module
- Measures Energy and time
Energy Spectrum of Detected Positrons depends on spin direction

![Graph showing energy spectrum and spin vectors](image-url)

- **Momentum vector**
- **Spin vector**

**Software Energy Threshold**
- Muon g-2: Precision physics in a Storage Ring
- Statistics limited... to improve sensitivity by a factor of 4 at Fermilab
Muon g-2: 4 Billion $e^+$ with $E>2$GeV

$$dN / dt = N_0 e^{\frac{-t}{\tau}} \left[ 1 + A \cos(\omega_a t + \phi_a) \right]$$

Sub-ppm accuracy, statistics limited
Comparison of Theory/Experiment

The result is 3.5 s.d. away from theory! What is it?

Figure 1: Standard model predictions of $a_\mu$ by several groups compared to the measurement from BNL.
The muon ring moved to Fermilab (22 June – 25 July 2013)
The muon ring arrived at Fermilab
The muon ring moved to Fermilab
The ring has been reassembled and fully powered to 1.45T! First data: 2017
Muon g-2 experiment: Best challenge to the Standard Model

- E821 at BNL: 1997-2004
- E969 at FNAL: first data in 2017

**LIFE OF A MUON:**
THE g-2 EXPERIMENT

- Protons from the AGS (Alternating Gradient Synchotron).
- Pions, 1/6 the weight of protons, are created.
- Pions decay to muons.
- Muons are fed into a uniform magnetic field and travel in a circle.
- Muons are tiny magnets spinning on the axis like tops.
- After each turn, a muon's spin axis changes by 12°, yet it keeps on traveling in the same direction.
- After several turns, the muons spontaneously decay to electrons and neutrinos in the direction of the muons' spin.

One of 24 detectors sees an electron, giving the muon spin direction; 'g' is this angle divided by the magnetic field strength the muon is traveling through the ring.
Systematic errors for the muon g-2 exp. at BNL and at FNAL (projections)

<table>
<thead>
<tr>
<th>Category</th>
<th>E821 [ppb]</th>
<th>E989 Improvement Plans</th>
<th>Goal [ppb]</th>
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<tbody>
<tr>
<td>Gain changes</td>
<td>120</td>
<td>Better laser calibration</td>
<td>20</td>
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<td></td>
<td>low-energy threshold</td>
<td></td>
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<tr>
<td>Pileup</td>
<td>80</td>
<td>Low-energy samples recorded</td>
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<td>calorimeter segmentation</td>
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<td>Lost muons</td>
<td>90</td>
<td>Better collimation in ring</td>
<td>20</td>
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<tr>
<td>CBO</td>
<td>70</td>
<td>Higher $n$ value (frequency)</td>
<td></td>
</tr>
<tr>
<td>$E$ and pitch</td>
<td>50</td>
<td>Better match of beamline to ring</td>
<td>&lt; 30</td>
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<tr>
<td></td>
<td></td>
<td>Improved tracker</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>Precise storage ring simulations</td>
<td>30</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>180</strong></td>
<td>Quadrature sum</td>
<td><strong>70</strong></td>
</tr>
</tbody>
</table>
Yet another idea with RF matching

- RF matching can be another solution for the scraping
- Stretching the beam with opposite phase, and bring it back with correct phase

Simulation: Dr. Soohyung Lee
Circuit simulation

ADS simulation

HV DC

Capacitor
Combine HV DC and RF

RF power amp.

RF for 20 us

RF source
1.3 MHz

ADS simulation results

Slide: Dr. YoungIm Kim
J-PARC Muon g-2 experiment

• Totally independent experiment
• Very different systematic errors
• Much more uniform B-field
• Accepting all muon decays
Fundamental particle EDM: study of CP-violation beyond the Standard Model
Proton EDM proposal: \( d = 10^{-29} \text{e}\cdot\text{cm} \)

- High sensitivity experiment:
- Blowing up the proton to become as large as the sun, the sensitivity to charge separation along N-S would be \( r < 0.1 \mu\text{m} \)!
Electric Dipole Moments: P and T-violating when $\vec{d} \parallel$ to spin

$$\vec{\mu} = g \left( \frac{q}{2m} \right) \vec{s},$$

$$\vec{d} = \eta \left( \frac{q}{2mc} \right) \vec{s}$$

$$\mathcal{H} = -\vec{\mu} \cdot \vec{B} - \vec{d} \cdot \vec{E}$$

T-violation: assuming CPT cons. $\Rightarrow$ CP-violation
Why is there so much matter after the Big Bang:

We see:

From the SM:

\[
\frac{n_B}{n} = (6.08 \pm 0.14) \times 10^{-10}
\]

\[
\frac{n_B}{n} = 10^{18}
\]
Andrei Sakharov 1967:

**CP-Violation** is one of three conditions to enable a universe containing initially equal amounts of matter and antimatter to evolve into a matter-dominated universe, which we see today....
CP-violation is established

• The observed SM CP-violation is not enough to explain the apparent Baryon Asymmetry of our Universe by $\sim 10$ orders of magnitude (only good for about ten to a hundred galaxies!).

• A new, much stronger CP-violation source is needed to explain the observed BAU.
Purcell and Ramsey:

“The question of the possible existence of an electric dipole moment of a nucleus or of an elementary particle...becomes a purely experimental matter”

Phys. Rev. 78 (1950)
Measuring an EDM of Neutral Particles

\[ H = -(dE + \mu B) \cdot I/I \]

\[ \omega_1 = \frac{2\mu B + 2dE}{\hbar} \]

\[ \omega_2 = \frac{2\mu B - 2dE}{\hbar} \]

\[ d = \frac{\hbar(\omega_1 - \omega_2)}{4E} \]

\[ \omega_d = 5 \text{ nrad/s} \]

d = 10^{-29} \text{ e cm}
E = 100 \text{ kV/cm}
A charged particle between Electric Field plates would be lost right away...
Proton storage ring EDM experiment is combination of beam + a trap
Stored beam: The radial E-field force is balanced by the centrifugal force.
The Electric Dipole Moment precesses in an Electric field

\[ \frac{d\vec{s}}{dt} = \vec{d} \times \vec{E} \]

Yannis Semertzidis
The proton EDM uses an ALL-ELECTRIC ring: spin is aligned with the momentum vector

\[ \vec{\omega}_a = 0 \]

\[ \frac{d\vec{s}}{dt} = \vec{d} \times \vec{E} \]

Momentum vector
Spin vector

\[ p = \frac{mc}{\sqrt{a}} = 0.7 \text{ GeV/c} \]

\[ p = \frac{mc}{\sqrt{a}} = 15\text{MeV/c} \]

for electrons!
Example: The proton EDM ring

Total circumference: 300 m
Bending radius: 40 m
E: 10 MV/m

Weak vertical focusing
Stronger horizontal focusing
The proton EDM ring (alternate gradient)

Straight sections are instrumented with quads, BPMs, polarimeters, injection points, etc., as needed.

Requirements:
Weak vertical focusing (B-field sensitivity)
Below transition (reduce IBS)
Currently: CSR, Heidelberg, 35 m circ., $10^{-13}$ Torr
Monitoring the proton spin direction as a function of time: Proton Polarimeter
pEDM polarimeter principle (placed in a straight section in the ring): probing the proton spin components as a function of storage time

Brantjes et al., NIMA 2012.

\[ \varepsilon_H = \frac{L - R}{L + R} \]

\[ \varepsilon_V = \frac{D - U}{D + U} \]

carries EDM signal increases slowly with time

carries in-plane (g-2) precession signal

Micro-Megas detector, GEMs, MRPC or Si.
Large polarimeter analyzing power \((A \geq 50\%)\) at \(P_{\text{magic}} = 700\text{MeV/c}\).

Fig. 4. Angle-averaged effective analyzing power. Curves show our fits. Points are the data included in the fits. Errors are statistical only.

Fig. 4. The angle averaged effective analyzing power as a function of the proton kinetic energy. The magic momentum of 0.7GeV/c corresponds to 232MeV.
Purifying signals and improving FOM

Signals overlap with background. The major BG is secondary protons.

Final triggers are formed from the coincidence of the three scintillation counters.
Storage Ring Proton EDM
Breakthrough:

Statistics!

Instead of using the secondary, low intensity beams, use the original proton beam!
Proton Statistical Error (230MeV):

\[ \sigma_d = \frac{2\hbar}{E_R PA \sqrt{N_c f \tau_p T_{tot}}} \]

\( \tau_p : 10^3 \text{s} \)  
Polarization Lifetime (Spin Coherence Time)

\( A : 0.6 \)  
Left/right asymmetry observed by the polarimeter

\( P : 0.8 \)  
Beam polarization

\( N_c : 10^{11} \text{p/cycle} \)  
Total number of stored particles per cycle

\( T_{tot} : 10^7 \text{s} \)  
Total running time per year

\( f : 1\% \)  
Useful event rate fraction (efficiency for EDM)

\( E_R : 7 \text{ MV/m} \)  
Average radial electric field strength

\[ \sigma_d = 1.0 \times 10^{-29} \text{ e-cm / year} \]
Technically driven pEDM timeline

- Two years systems development (R&D); CDR; ring design, TDR, installation

- CDR by fall of 2017

- Proposal to a lab: fall 2017
Let’s indulge on proton sensitivity

• Spin coherence time ($10^4$ seconds), stochastic cooling-thermal mixing, …

• Higher beam intensity, smaller IBS

• Reliable E-field 15 MV/m with negligible dark current

• >5% efficient polarimeter, run longer

• Potential gain $>10^2$ in statistical sensitivity: $\sim 10^{-30}$-$10^{-31}$ e-cm!
Sensitivity to Rule on Several New Models

If found it could explain Baryogenesis (p, d, n, $^3$He)

Electron EDM new physics reach: 1-3 TeV

Much higher physics reach than LHC; complementary

Generic Physics Reach of $d_p \sim 10^{-29}\text{e-cm}$

$$d_p \sim 0.01 \left( \frac{m_p}{\Lambda_{NP}} \right)^2 \tan \phi^{NP} e / 2m_p$$

$$\sim 10^{-22} \left( \frac{1\text{TeV}}{\Lambda_{NP}} \right)^2 \tan \phi^{NP} e \cdot \text{cm}$$

If $\phi^{NP}$ is of $O(1)$, $\Lambda_{NP} \sim 3000\text{TeV}$ Probed!
If $\Lambda_{NP} \sim O(1\text{TeV})$, $\phi_{NP} \sim 10^{-7}$ Probed!

**Unique Capabilities!**
Importance and Promise of Electric Dipole Moments

Frank Wilczek

January 22, 2014

The additional symmetry has another remarkable consequence. It predicts the existence of a new very light, very weakly interacting spin 0 particle, the axion. The possible existence of axions raises the stakes around these ideas, because it entails major cosmological consequences. Indeed, if axions exist at all, they must provide much of the astronomical “dark matter”, and quite plausibly most of it.

Better bounds on $\theta$, or especially an actual determination of its value, would allow us to sharpen these considerations considerably. Better measurements of fundamental electric dipole moments are the most promising path to such bounds, or measurement.
In 2014 we have received the P5 endorsement for the proton EDM experiment under all funding scenarios!

P5: Particle Physics Project Prioritization Panel setup by DOE and NSF. It took more than a year for the HEP community to come up with the report.
Storage ring EDM

- High precision experiments: Proton EDM experiment is a must do.

- Complementary approach to:
  - LHC in Europe
  - ILC in Japan
  - Very large hadron collider (SppC) in China
  - Neutrino Physics in the USA
Why should we be part of it

• High precision experiments can provide the next breakthrough in HEP/NP.

• Needed as input to indicate New-Physics level before next large accelerator project.

• Great for students, post docs, faculty. Well rounded physics education, opportunities for new ideas.
Recent important dates

• April 21, Thursday, srEDM collaboration meeting, KAIST, South Korea

• April 22, Friday morning, Pioneering workshop on EDMs, Daejeon, South Korea

• May 11, Wednesday, 12:00 – 18:00 Precision tracking for spin/beam dynamics, part of IPAC2016, Busan, South Korea
Next important dates

- September 6 & 7, we are presenting the proton EDM method at CERN:
Summary

• The axion dark matter effort is going very well, according to schedule (next talk: Dr. Woohyung Chung)

• Storage ring EDM effort is timely

• Ultimate sensitivity for $p < 10^{-29} - 10^{-30} \text{ e-cm}$

• SUSY-like physics reach: $10^3 - 10^4 \text{TeV}$, it can show the way ahead.

• It’s an immense Physics opportunity for Korea and the world.
Extra slides
**10x10 cm² test detector**

**Slide: Dr. SeongTae Park**

- Under assembling.
- Will be tested soon and go beam test with APV25.
New polarimeter lab is ready

Clean booth (class 10,000)

2x2 cm² GEM

$^{55}\text{Fe}$ test result with the first GEM detector at CAPP
Spin Coherence Time: need $\sim 10^3$ s

- Not all particles have same deviation from magic momentum, or same horizontal and vertical divergence (all second order effects)

- They cause a spread in the $g$-2 frequencies:

$$d\omega_a = a\mathcal{G}_x^2 + b\mathcal{G}_y^2 + c\left(\frac{dP}{P}\right)^2$$

- Present design parameters allow for $10^3$ s.
- Much longer SCT with thermal mixing (S.C.)?
Main Devices

COSY:
- ≈184m circumference
- (Un)polarized proton/deuteron beams
- Momentum range: 0.3-3.7 GeV/c
- Electron/stochastic cooling

Edda Polarimeter:
- Scintillator rings and bars
- Carbon target
- Polarimeter not ideal but best we have!
Measurement Principle

Beam Preparation:
- Inject vertically polarized deuteron beam
- Accelerate
- Cool (with e-cooler) and bunch
- Put spin into horizontal plane (with rf-solenoid on spin tune resonance)

Watch decay of up-down asymmetry (horizontal polarization)

$\tau_{SC} \approx 20 \text{ s}$
Sextupole Scans

obtain this picture by rastering the MXS-MXG plane, maximum SCT lies on zero chromaticity lines

SCT goal accomplished!
The proton EDM ring evaluation  Val Lebedev (Fermilab)

Beam intensity $10^{11}$ protons limited by IBS

<table>
<thead>
<tr>
<th></th>
<th>Soft focusing</th>
<th>Strong focusing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circumference, m</td>
<td>263</td>
<td>300</td>
</tr>
<tr>
<td>$Q_x/Q_y$</td>
<td>1.229/0.456</td>
<td>2.32/0.31</td>
</tr>
<tr>
<td>Particle per bunch</td>
<td>1.5$\cdot10^8$</td>
<td>7$\cdot10^8$</td>
</tr>
<tr>
<td>Coulomb tune shifts, $\Delta Q_x/\Delta Q_y$</td>
<td>0.0046/0.0066</td>
<td>0.0146/0.0265</td>
</tr>
<tr>
<td>Rms emittances, x/y, norm, $\mu$m</td>
<td>0.56/1.52</td>
<td>0.31/2.16</td>
</tr>
<tr>
<td>Rms momentum spread</td>
<td>1.1$\cdot10^{-4}$</td>
<td>2.9$\cdot10^{-4}$</td>
</tr>
<tr>
<td>IBS growth times, x/y/s, s</td>
<td>300/(-1400)/250</td>
<td>7500</td>
</tr>
<tr>
<td>RF voltage, kV</td>
<td>13</td>
<td>10.3</td>
</tr>
<tr>
<td>Synchrotron tune</td>
<td>0.02</td>
<td>0.006</td>
</tr>
</tbody>
</table>
### Systematic errors

**TABLE III. Main systematic errors of the experiment and their remediation.**

<table>
<thead>
<tr>
<th>Effect</th>
<th>Remediation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radial B-field</td>
<td>SQUID BPMs with 1 fT/$\sqrt{\text{Hz}}$ sensitivity eliminate it.</td>
</tr>
<tr>
<td>Geometric phase</td>
<td>Plate alignment to better than 100 $\mu$m, plus CW and CCW storage. Reducing B-field everywhere to below 10-100 nT. BPM to 100 $\mu$m to control the effect.</td>
</tr>
<tr>
<td>Non-Radial E-field</td>
<td>CW and CCW beams cancel the effect.</td>
</tr>
<tr>
<td>Vert. Quad misalignment</td>
<td>BPM measurement sensitive to vertical beam oscillation common to CW and CCW beams.</td>
</tr>
<tr>
<td>Polarimetry</td>
<td>Using positive and negative helicity protons in both the CW and CCW directions cancels the errors.</td>
</tr>
<tr>
<td>Image charges</td>
<td>Using vertical metallic plates except in the quad region. Quad plates’ aspect ratio reduces the effect.</td>
</tr>
<tr>
<td>RF cavity misalignment</td>
<td>Limiting longitudinal impedance to 10k$\Omega$ to control the effect of a vertical angular misalignment. CW and CCW beams cancel the effect of a vertically misplaced cavity.</td>
</tr>
</tbody>
</table>
Total current: zero. Any radial magnetic field in the ring sensed by the stored particles will cause their vertical splitting.
Distortion of the closed orbit due to $N^{th}$-harmonic of radial B-field

\[ y(\vartheta) = \sum_{N=0}^{\infty} \frac{\beta R_0 B_{rN}}{E_0 (Q_y^2 - N^2)} \cos (N\vartheta + \varphi_N) \]

- Clockwise beam
- The N=0 component is a first order effect!
- Counter-clockwise beam
- Time [s]
SQUID BPM to sense the vertical beam splitting at 1-10kHz

FIG. 3. A schematic of a possible SQUID BPM station. The system is shielded with a superconducting Nb tube, Al tube for RF-shield, and several mu-metal layers.
Total noise of (65) commercially available SQUID gradiometers at KRISS

From YongHo Lee’s group KRISS/South Korea
Under development by Selcuk Haciomeroglu at CAPP.
Need absolute field: <0.5nT
Need gradient field: <0.1nT/m
Shipped to Korea for integration

Achieved so far:
Absolute field: <0.5nT
Gradient field: <2.0nT/m
Almost there!
Major characteristics of a successful Electric Dipole Moment Experiment

• Statistical power:
  – High intensity beams
  – Long beam lifetime
  – Long Spin Coherence Time

• An indirect way to cancel B-field effect
• A way to cancel geometric phase effects
• Control detector systematic errors
• Manageable E-field strength, negligible dark current
Storage ring proton EDM method

• All-electric storage ring. Strong radial E-field to confine protons with “magic” momentum. The spin vector is aligned with momentum horizontally.

• High intensity, polarized proton beams are injected Clockwise and Counter-clockwise with positive and negative helicities. Great for systematics (e.g., geometrical phases).

• Great statistics: up to $\sim 10^{11}$ particles with primary proton beams and small phase-space parameters.
What has been accomplished?

- Polarimeter systematic errors (with beams at KVI, and stored beams at COSY).
- Precision beam/spin dynamics tracking.
- Stable lattice, IBS lifetime: $\sim10^4$s (Lebedev, FNAL)
- Spin coherence time $10^3\text{s}$; role of sextupoles understood (using stored beams at COSY).
- Feasibility of required electric field strength $>10\text{ MV/m}$, 3cm plate separation (JLab)
- Analytic estimation of electric fringe fields and precision beam/spin dynamics tracking. Stable!
- (Paper already published or in progress.)
## Physics strength comparison

<table>
<thead>
<tr>
<th>System</th>
<th>Current limit [e cm]</th>
<th>Future goal</th>
<th>Neutron equivalent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neutron</td>
<td>$&lt;1.6 \times 10^{-26}$</td>
<td>$\sim 10^{-28}$</td>
<td>$10^{-28}$</td>
</tr>
<tr>
<td>$^{199}$Hg atom</td>
<td>$&lt;10^{-29}$</td>
<td></td>
<td>$10^{-25-10^{-26}}$</td>
</tr>
<tr>
<td>$^{129}$Xe atom</td>
<td>$&lt;6 \times 10^{-27}$</td>
<td>$\sim 10^{-30-10^{-33}}$</td>
<td>$10^{-26-10^{-29}}$</td>
</tr>
<tr>
<td>Deuteron nucleus</td>
<td></td>
<td>$\sim 10^{-29}$</td>
<td>$3 \times 10^{-29}$- $5 \times 10^{-31}$</td>
</tr>
<tr>
<td>Proton nucleus</td>
<td>$&lt;7 \times 10^{-25}$</td>
<td>$\sim 10^{-29-10^{-30}}$</td>
<td>$10^{-29-10^{-30}}$</td>
</tr>
</tbody>
</table>
PAC/Snowmass strong endorsement

- BNL PAC on EDM proposal (2008): “enthusiastic endorsement of the physics...need to demonstrate feasibility of systems”

- Snowmass writeup: “…Ultimately the interpretability of possible EDMs in terms of underlying sources of CP violation may prove sharpest in simple systems such as neutron and proton,…”

- FNAL PAC EDM EOI (2012): “The Physics case for such a measurement is compelling since models with new physics at the TeV scale (e.g., low energy SUSY) that have new sources of CP-violation can give contributions of this order.... The PAC recommends that Fermilab and Brookhaven management work together, and with potential international partners, to find a way for critical R&D for this promising experiment to proceed.”
The challenge

• The electron EDM experiment needs an efficient polarimeter at 15MeV/c. FOM = $\sqrt{f A^2}$ > 0.01.

• Young scientist positions (YS) at IBS/Korea, Research Funds: 300M KRW/year for five years!

• Senior scientist positions (SS) at IBS/Korea, Research Funds: 500M KRW/year for three years!
Storage Ring EDM Collaboration

- Aristotle University of Thessaloniki, Thessaloniki/Greece
- Research Inst. for Nuclear Problems, Belarusian State University, Minsk/Belarus
- Brookhaven National Laboratory, Upton, NY/USA
- Budker Institute for Nuclear Physics, Novosibirsk/Russia
- Royal Holloway, University of London, Egham, Surrey, UK
- Cornell University, Ithaca, NY/USA
- Institut für Kernphysik and Jülich Centre for Hadron Physics Forschungszentrum Jülich, Jülich/Germany
- Institute of Nuclear Physics Demokritos, Athens/Greece
- University and INFN Ferrara, Ferrara/Italy
- Laboratori Nazionali di Frascati di l'INFN, Frascati/Italy
- Joint Institute for Nuclear Research, Dubna/Russia
- Indiana University, Indiana/USA
- Istanbul Technical University, Istanbul/Turkey
- University of Massachusetts, Amherst, Massachusetts/USA
- Michigan State University, East Lansing, Minnesota/USA
- Dipartimento do Fisica, Universita’ “Tor Vergata” and Sezione INFN, Rome/Italy
- University of Patras, Patras/Greece
- CEA, Saclay, Paris/France
- KEK, High Energy Accel. Res. Organization, Tsukuba, Ibaraki 305-0801, Japan
- University of Virginia, Virginia/USA

http://www.bnl.gov/edm

>20 Institutions
>80 Collaborators

Storage ring proton EDM proposal to DOE NP, Nov 2011
Why now?

• Exciting progress in electron EDM using molecules.

• Several neutron EDM experiments under development to improve their sensitivity level.

• Proton EDM has large STATISTICAL sensitivity; great way to handle SYSTEMATICS.
E-field plate module: Similar to the (26) FNAL Tevatron ES-separators
E-field plate module: Similar to the (26) FNAL Tevatron ES-separators
Why a large radius ring (sr pEDM)?

1. Electric field needed is moderate (≤10MV/m). New techniques with coated Aluminum is a cost savings opportunity.

2. Long horizontal Spin Coherence Time (SCT) w/out sextupoles. The EDM effect is acting for time ~SCT.
Field Emission from Niobium

Buffer chemical polish: less time consuming than diamond paste polishing

Field strength > 18 MV/m

Conventional High Voltage processing: solid data points
After Krypton Processing: open data points

Work of M. BastaniNejad
CP-violation phase from Higgs

EDMs will eventually be discovered: $d_e, d_n, d_p \ldots d_D$
Magnitudes of $\approx 10^{-28}$ expected for Baryogenesis
Atomic, Molecular, Neutron, Storage Ring (All important)

CP violation phase in: Hee, $H_{\gamma\gamma}$, $H_{tt}$, 2HD Model...
Uniquely explored by 2 loop edms! Barr-Zee effect
May be our only window to Hee, Huu and Hdd couplings
Guided by experiment: $H \rightarrow \gamma\gamma$  $(H \rightarrow \tau^+\tau^-, \mu^+\mu^-)$ etc.
Updates Anxiously Anticipated!

The Higgs may be central to our existence!
Electric Dipole Moments in Magnetic Storage Rings

\[ \frac{d\vec{s}}{dt} = \vec{d} \times (\vec{v} \times \vec{B}) \]

E.g. 1 T corresponds to 300 MV/m for relativistic particles

Yannis Semertzidis
### Storage Ring Electric Dipole Moments

<table>
<thead>
<tr>
<th>Fields</th>
<th>Example</th>
<th>EDM term</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dipole magnetic field ((B))</td>
<td>Muon g-2</td>
<td>Tilt of the spin precession plane. (Limited sensitivity due to spin precession)</td>
<td>Eventually limited by geometrical alignment. Requires CW and CCW injection to eliminate systematic errors</td>
</tr>
</tbody>
</table>
| Combination of electric and magnetic fields \((E, B)\) | Deuteron, \(^3\)He, proton, etc. | Mainly: \[
\frac{d\vec{s}}{dt} = \vec{d} \times (\vec{v} \times \vec{B})
\] | Most powerful. Small ring. Need to build combined B and E-field system. Reduce vertical E-field. |
| Radial Electric field \((E)\)               | Proton, etc.     | \[
\frac{d\vec{s}}{dt} = \vec{d} \times \vec{E}
\] | Large ring, CW & CCW storage. Simplest to achieve. Reduce radial B-field. |
Indirect Muon EDM limit from the g-2 Experiment

\[ \vec{\omega} = \frac{e}{m} \left\{ \alpha B + \frac{\eta}{2c} (\vec{v} \times \vec{B}) \right\} \]

\[ \vec{\omega} = \vec{\omega}_a + \vec{\omega}_{edm} \]

\[ \tan \theta = \frac{\omega_{edm}}{\omega_a} \]

Ron McNabb’s Thesis 2003:

\( < 2.7 \times 10^{-19} \text{e} \cdot \text{cm} \text{ 95\% C.L.} \)

Yannis Semertzidis
Two different labs could host the storage ring EDM experiments

- AGS/BNL, USA: proton “magic” (simpler) ring
- COSY/IKP, Jülich/Germany: deuteron or a combination ring
Anomalous magnetic moment factors

\[ \frac{1}{\gamma^2 - 1} - G = 0 \implies \gamma = \sqrt{\frac{1}{G} + 1} \]

\[ \rightarrow G > 0 \text{ for } \gamma > 1, \text{ if only electric fields are applied} \]

\[ \gamma = \sqrt{\frac{1}{G} + 1} \iff p = \frac{m}{\sqrt{G}} \]

\[ \frac{\mu_p}{\mu_N} = 2.792\,847\,356 \pm 23 \rightarrow G_p = 1.7928473565 \]
\[ \frac{\mu_d}{\mu_N} = 0.857\,438\,2308 \pm 72 \rightarrow G_d = -0.14298727202 \]
\[ \frac{\mu_{\text{He}-3}}{\mu_N} = -2.127\,497\,718 \pm 25 \rightarrow G_{3\text{He}} = -4.1839627399 \]

Nuclear magneton: \( \mu_N = \frac{e\hbar}{2m_p c} = 5.050\,783\,24 \pm 13 \cdot 10^{-27} \text{ J T}^{-1} \)

\[ \rightarrow \text{Magic momentum for protons: } p = 700.74 \text{ MeV/c} \]
\[ \rightarrow \text{Deuterons, He-3: } \]

\[ E_r = \frac{GBq\beta\gamma^2}{1 - G\beta^2\gamma^2} \approx GBq\beta\gamma^2 \]
Neutron EDM Limits

Beam experiments

Trap experiments

1.0 \times 10^{-26} \text{ e-cm}


Year

B. Morse
The nEDM@PSI collaboration

13 Institutions, 7 Countries, 50 individuals
The target sensitivity for nEDM is $10^{-26}$ ecm or better, for n2EDM $10^{-27}$ ecm or better.
Key Features of nEDM@SNS

- Sensitivity: $\sim 2 \times 10^{-28}$ e-cm, 100 times better than existing limit
- In-situ Production of UCN in superfluid helium (no UCN transport)
- Polarized $^3$He co-magnetometer
  - Also functions as neutron spin precession monitor via spin-dependent $n$-$^3$He capture cross section using wavelength-shifted scintillation light in the LHe
  - Ability to vary influence of external B-fields via “dressed spins”
    - Extra RF field allows synching of $n$ & $^3$He relative precession frequency
- Superconducting Magnetic Shield
- Two cells with opposite E-field
- Control of central-volume temperature
  - Can vary $^3$He diffusion (mfp) - big change in geometric phase effect on $^3$He

Arguably the most ambitious of all neutron EDM experiments
History/Status of nEDM@SNS

• **2011**: NSAC Neutron Subcommittee
• **2013**: Critical R&D successfully demonstrated
• **2014-2017**: Critical Component Demonstration (CCD) phase begun
  – Build working, full-scale, prototypes of technically-challenging subsystems (use these in the full experiment)
  – 4yr NSF proposal for 6.5M$ CCD funded
  – DOE commitment of ≈ 1.8M$/yr for CCD
• **2018-2020**: Large scale Integration and Conventional Component Procurement
• **2021**: Begin Commissioning and Data-taking
The TUM EDM experiment

- Initially a ‘conventional’ Ramsey experiment
- UCN trapped at room temperature, ultimately cryogenic trap
- Double chamber with co-magnetometer option
- $^{199}$Hg, Cs, $^{129}$Xe, $^3$He, SQUID magnetometers
- Portable and modular setup, including magnetically shielded room
- Ultimate goal: $10^{-28}$ ecm sensitivity, staged approach (syst. and stat.)

I. Altarev et al., Il Nuovo Cimento 35 C 122 (2012)
Most hardware built & tested

E.g.: passive magnetic shielding factor > 6 million @ 1 mHz (without ext. compensation coils!)

- The smallest gradients over an extended volume ever realized: < 50 pT / m stable gradient over EDM cell volume
- Residual field drift < 5 fT in typical Ramsey cycle time
- Hg and Cs magnetometry on < 20 fT level:
  - Cs sensor head assembly
  - Raw 199-Hg FPD signal
- Basically all magnetic field related systematics under control
Peter Fierlinger, TUM, magnetic shielding factor > 6M at 1mHz!

Physics Today, August 2015
No New-Physics breakthrough from anywhere...
Freezing Spin Motion with E- and B-Fields

Using a combination of vertical dipole B-fields and radial E-fields to freeze the spin. The required E-field is

\[ E_R = \frac{GB_v c \beta \gamma^2}{1 - G \beta^2 \gamma^2} \approx GB_v c \beta \gamma^2 \]

Protons: \( p_p = 0.701 \) GeV/c, \( E_R = 16.8 \) MV/m, \( B_v = 0 \) T \( \rightarrow R_B = 25 \) m
Various options for EDM@COSY, Juelich

EDM with E- and B-Fields for different Particles

„all-in-one“ storage ring

**Protons:** $p_p = 0.701 \text{ GeV/c}$
$E_R = 16.8 \text{ MV/m}, B_V = 0.16 \text{ T}$

**Deuterons:** $p_d = 1.0 \text{ GeV/c}$
$E_R = -4.0 \text{ MV/m}, B_V = 0.05 \text{ T}$

**Helium-3:** $p_{3\text{He}} = 1.285 \text{ GeV/c}$
$E_R = 17.0 \text{ MV/m}, B_V = -0.05 \text{ T}$

„all-in-one“ storage ring

**Protons:** $p_d = 0.527 \text{ GeV/c}$
$E_R = 16.8 \text{ MV/m}, B_V = 0.02 \text{ T}$

**Deuterons:** $p_d = 1.0 \text{ GeV/c}$

**Helium-3:** $p_{3\text{He}} = 0.946 \text{ GeV/c}$

Dedicated deuteron storage ring

**Deuterons:** $p_d = 1.0 \text{ GeV/c}$
$E_R = -12.0 \text{ MV/m}, B_V = 0.48 \text{ T}$
EDMs of hadronic systems are mainly sensitive to

- Theta-QCD (part of the SM)
- CP-violating sources beyond the SM

Alternative simple systems are needed to be able to differentiate the CP-violating source (e.g. neutron, proton, deuteron, ...).

pEDM at $10^{-29}$ e\cdot cm is > an order of magnitude more sens. than the best current nEDM plans
Hadronic contribution (had1)

Cannot be calculated from pQCD alone because it involves low energy scales.

However, by dispersion theory, this $a_\mu(\text{had1})$ can be related to

$$R = \frac{\sigma(e^+e^- \rightarrow \text{hadrons})}{\sigma(e^+e^- \rightarrow \mu^+\mu^-)}$$

measured in $e^+e^-$ collisions.

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