Measurement of the leading hadronic contribution to the muon g-2 via space-like data

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Work done in collaboration:

Presented to the “Physics Beyond Collider” CERN Study Group [http://pbc.web.cern.ch/]

Reference papers:

**A new approach to evaluate the leading hadronic corrections to the muon $g-2$**

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**Measuring the leading hadronic contribution to the muon $g-2$ via $\mu e$ scattering**

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Outline

✧ Muon anomalous magnetic moment $a_\mu = (g_\mu - 2)/2$
  ❖ introduction and status
✧ New approach to determine the leading hadronic contribution $a_\mu^{\text{HLO}}$ from the space-like region
✧ Proposal for a measurement of $a_\mu^{\text{HLO}}$ with $\mu e \rightarrow \mu e$ at CERN
✧ Detector considerations
✧ On-going work and plans
✧ Conclusions
Muon anomalous magnetic moment

Dirac equation - the magnetic dipole moment of a spin ½ particle (l = e, μ) is:

\[ \vec{M}_l = g_l \frac{e}{2m_l} \vec{\mathcal{S}} \]

gyromagnetic ratio \( g_l = 2 \)

QED – loop corrections give rise to the anomaly:

\[ a_l \equiv \frac{g_l - 2}{2} \]

This observable can be both precisely measured experimentally and predicted in the Standard Model, providing powerful tests of the SM.

\[ a_{\mu}^{SM} = a_{\mu}^{QED} + a_{\mu}^{EWK} + a_{\mu}^{Had} \]

\[ = (11659180.2 \pm 4.9) \times 10^{-10} \]

0.4 ppm


QED corrections known up to 5 loops, rel. precision \( \sim 7 \times 10^{-10} \)

Leading order term (Schwinger) \( = \alpha/2\pi \sim 0.00116 \)

EWK corrections

\( \sim 10^{-9} \)

rel. uncertainty less than 1%

Hadronic LO contribution

\( a_{\mu}^{HLO} = (692.3 \pm 4.2) \times 10^{-10} \)

rel. uncertainty 0.6%

Dominant Theoretical uncertainty

Measurement of $a_\mu$


$$a_\mu^{E821} = 11659208.9(6.3) \times 10^{-10}$$

Precise measurement: 0.54 ppm
Dominated by statistics

$$a_\mu^{E821} - a_\mu^{SM} \sim (28 \pm 8) \times 10^{-10}$$

Intriguing discrepancy with Standard Model: about 3.5 $\sigma$

*Sensitive to new physics (Supersymmetry, dark photons)*

New experiments in preparation at Fermilab and J-PARC are targeting a *reduction of the experimental error by a factor of 4*

Theoretical precision should be improved as well
$a_{\mu}^{HLO}$: standard approach

Dispersion relations, optical theorem:

$$a_{\mu}^{HLO} = \left(\frac{\alpha m_{\mu}}{3\pi}\right)^2 \int ds \frac{\hat{K}(s)R_{\text{had}}(s)}{s^2}$$

$R_{\text{had}}(s) = \sigma(e^+e^-\rightarrow\text{hadrons})/\sigma(e^+e^-\rightarrow\mu^+\mu^-)$

K smooth function

*Traditionally the integral is calculated by using the experimental measurements up to an energy cutoff, beyond which perturbative QCD can be applied.*

Main contribution: low-energy region ($1/s^2$ enhancement), highly fluctuating due to hadron resonances and thresholds effects

$$a_{\mu}^{HLO} = (692.3 \pm 4.2) \times 10^{-10}$$

Rel. uncertainty 0.6%

Alternative evaluations by lattice QCD not yet competitive, though expected to improve
**$a_{\mu}^{\text{HLO}}$: alternative approach (space-like data)**


-Initially proposed for use with Bhabha scattering data from flavour factories-

\[
a_{\mu}^{\text{HLO}} = \frac{\alpha}{\pi} \int_0^1 dx (1-x) \Delta \alpha_{\text{had}} [t(x)]
\]

\[
t(x) = -\frac{x^2 m_\mu^2}{1-x}, \quad 0 \leq -t < \infty
\]

\[
0 \leq x < 1
\]

$\Delta \alpha_{\text{had}}$ is the hadronic contribution to the running of $\alpha$ in the space-like region ($t<0$)

\[
\alpha(t) = \frac{\alpha}{1 - \Delta \alpha(t)}
\]

$\Delta \alpha = \Delta \alpha_{\text{lep}} + \Delta \alpha_{\text{had}}$

Integrand function smooth: no resonances
Low-energy enhancement: peak of the integrand at $x=0.914 \rightarrow t=-0.108\text{GeV}^2 \rightarrow \Delta \alpha_{\text{had}} \sim 0.8 \times 10^{-3}$
Measurement of $\Delta\alpha_{\text{had}}(t)$ spacelike at LEP

OPAL measurement: Bhabha scattering at small angle, with $1.8 < -t < 6.1$ GeV$^2$

about $10^7$ events
precision at the per mille level

$$
\frac{d\sigma}{dt} = \frac{d\sigma^{(0)}}{dt} \left[ \frac{\alpha(t)}{\alpha_0} \right]^2 (1 + \varepsilon)(1 + \delta_\gamma) + \delta_Z
$$

Born term for t-channel single $\gamma$ exchange
Effective coupling factorized

Other measurements in the space-like region by L3, VENUS
Experimental Proposal

Elastic scattering $\mu e \rightarrow \mu e$ with a $\mu$ beam of $E=150$ GeV on atomic electrons of a fixed target with low $Z$ (Be or C)

- From the measured differential cross section determine $\Delta \alpha_{\text{had}}(t)$ and then $\alpha_{\mu}^{\text{HLO}}$ by the space-like approach


\[
\frac{d\sigma}{dt} \approx \frac{d\sigma_0}{dt} \left| \frac{\alpha(t)}{\alpha(0)} \right|^2 \approx \frac{d\sigma_0}{dt} \left| \frac{1}{1 - \Delta \alpha(t)} \right|^2
\]

Leading mechanism. Higher-order corrections to be considered as well...
Elastic scattering $\mu e \rightarrow \mu e$ with a $\mu$ beam of $E=150$ GeV on atomic electrons of a fixed target with low $Z$

- Only t-channel at LO: running coupling $\alpha^2(t)$ factorized in the cross section
  - Instead Bhabha scattering at flavour factories involves both s- and t-channel diagrams

- Simple kinematics determined from the initial muon energy and either one energy or angle of the scattered particles, e.g. $t \equiv -2m_eE_e$
  - Or incoming muon energy determined from both $\theta_e$ and $\theta_\mu$

- For beam $E=150$ GeV the phase space extends up to: $x<0.932$, $-t<0.143$ GeV$^2$ corresponding to 87% of the $a_\mu^{\text{HLO}}$ integral.
  - The remaining 13% can be calculated by time-like data plus pQCD and/or Lattice QCD

- Boosted kinematics: $\theta_e<32$ mrad (for $E_e>1$ GeV), $\theta_\mu<5$ mrad
  - the whole acceptance can be covered with one 10x10cm$^2$ silicon sensor at 1m distance from the target, reducing many systematic errors
The scattering angles $\theta_e$ and $\theta_\mu$ are correlated: important constraint to select elastic events, rejecting radiative or inelastic processes.

- Ambiguity for scattering angles of 2-3 mrad to be solved by pID

Similar technique already used in the past by the NA7 experiment (pion form factor from $\pi e$ elastic scattering:

CERN muon beam M2

From SPS

Spill duration: 4.8 s within the SPS cycle of 16.8 s

High average intensity $> 10^7 \mu/s$


Table 3
Parameters and performance of the 160GeV/c muon beam

<table>
<thead>
<tr>
<th>Beam parameters</th>
<th>Measured</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam momentum $(p_\mu)/(p_\pi)$</td>
<td>$(160 \text{ GeV/c})/(172 \text{ GeV/c})$</td>
</tr>
<tr>
<td>Proton flux on T6 per SPS cycle</td>
<td>$1.2 \times 10^{13}$</td>
</tr>
<tr>
<td>Focussed muon flux per SPS cycle</td>
<td>$2 \times 10^{8}$</td>
</tr>
<tr>
<td>Beam polarisation</td>
<td>$(\sim 80 \pm 4)%$</td>
</tr>
<tr>
<td>Spot size at COMPASS target $(\sigma_x \times \sigma_y)$</td>
<td>$8 \times 8 \text{ mm}^2$</td>
</tr>
<tr>
<td>Divergence at COMPASS target $(\sigma_x \times \sigma_y)$</td>
<td>$0.4 \times 0.8 \text{ mrad}$</td>
</tr>
<tr>
<td>Muon halo within 15 cm from beam axis</td>
<td>16%</td>
</tr>
<tr>
<td>Halo in experiment $(3.2 \times 2.5 \text{ m}^2)$ at $(</td>
<td>x, y</td>
</tr>
</tbody>
</table>
Choice of the target and setup

Two contrasting needs:
- Large statistics of events at the peak to reach the necessary sensitivity (hence enough target material)
- Minimal distortions of the outgoing e/µ trajectories within the target material and small rate of radiative events (low Z)

The solution is a modular apparatus, a sequence of N identical modules:

- Considering a 150 GeV µ beam with \( I = 1.3 \times 10^7 \mu/s \)
  (available at CERN, M2/NorthArea)
- 20 Be layers, 3cm thick.
- In 2 years of data-taking (running time \( 2 \times 10^7 \text{s/y} \)) an integrated luminosity of \( 1.5 \times 10^7 \text{nb}^{-1} \) can be reached
- From a simplified simulation of the experiment we estimate a 0.3% statistical sensitivity on \( a_\mu^{\text{HLO}} \)
  (current precision 0.6%)
Detection technique

Sequence of 20 modules, each one:
- Target + 3 pairs of orthogonal Si strip planes (size: 1m x 0.1m x 0.1m)
  measuring angles with high resolution \( \sim 0.02 \) mrad

In addition Particle ID to solve the e/\( \mu \) ambiguity at angles \( \sim 2-3 \) mrad:
- Downstream calorimeter + muon detector

Whole acceptance contained in the detector, within single Si sensors \( \sim 10 \times 10 \text{cm}^2 \)

Incoming muon direction determined from the previous module; incoming momentum to be measured with a dedicated subdetector (as in COMPASS or NA62)
The role of Multiple Scattering

Main systematic effect for low energy electrons

*It breaks* the $\mu$-e angular correlation, moving events out of the kinematic constraint. It also causes **acoplanarity**, while two-body events are planar.

**Highland formula (PDG):**

$$\sigma = \frac{13.6}{\beta pc} z \sqrt{d/X_0} \left[ 1 + 0.038 \ln \left( \frac{d}{X_0} \right) \right]$$

Non-Gaussian tails $\sim 3\%$

**Vertices** of the $\mu + e \rightarrow \mu + e$ collisions will be uniformly distributed inside the target along the direction of the beam axis.

The observable angles (electron and muon angles) depend therefore on the particles’ path length inside the material and on their energies.

*We need a MSC model* to relate the observed angles to the scattering ones.

GEANT4, 1 GeV electrons, 3cm Be target

Gaussian core $\sigma = 3.6$ mrad
Test Beam

- At CERN SPS in the H8 Beam Line (27 Sep-3 Oct 2017)
- Existing setup (used by CMS and UA9): 5 pairs of Si strips planes (measuring orthogonal coords), 2 before and 3 after the target
  - Planes 2,3,4,5 to be housed on top of the table, to increase the angular acceptance from ~2mrad to ~20mrad
- $\mu$ beam at max intensity $E \sim 150-160$ GeV or electron beam with $E > \sim 12$ GeV
- Max rate: 10 kHz

Purposes:
- With e beam: test Multiple Scattering modeling of GEANT by comparing different thickness of C target (0.2 / 2 cm) or different materials (Be, Al)
- With $\mu$ beam: identify/reconstruct elastic $\mu e$ scattering events

Existing high resolution telescope as used by UA9:
M. Pesaresi et al., JINST 6 (2011) P04006
Theory developments

A fully exclusive MC generator describing the $\mu e$ scattering with all the relevant radiative corrections is a mandatory tool. This will be obtained in steps:

1. NLO QED corrections are already available in literature
2. Resummation of LL corrections to all orders, matched with NLO corrections.
   - Similar approach as in the BabaYaga MC for Bhabha scattering
   - But additional non-trivial issue: mass effects in this case are important.
3. NNLO QED corrections and matching with resummation of LL corrections at higher orders
   - some new due to different mass scales ($m_\mu$ and $m_e$).

Impact of LL corrections to $\mu e$ expected to be smaller than in Bhabha, as:

$$L_\mu = \log \left( \frac{s}{m_\mu^2} \right) \approx 2.7 \quad L_e = \log \left( \frac{s}{m_e^2} \right) \approx 13 \quad s = 0.165 \text{ GeV}^2$$

Forthcoming Theory workshops: Padova, 4-5 September 2017
Mainz, 19-23 February 2018
Plans

• **2017 - 2019**
  - Detector optimization studies
  - Test beams (first on 27 Sep-3 Oct 2017 at CERN)
  - First prototype of a detector module
  - Theoretical developments
  - Physics Beyond Colliders CERN Study Group (final report by end 2018)
  - Forming a collaboration
  - Letter of Intent to the SPSC

• **2020**
  - Detector construction and installation
    (maybe a staged version of the detector)

• **2021 – 2024**
  - Start the data taking after LS2 to measure $a_\mu^{HLO}$
    (not necessarily to the ultimate precision)
Conclusions

• Proposal of a new experiment to measure the leading hadronic contribution to the muon g-2, aiming at results in the same period of the new g-2 measurements from Fermilab and J-PARC.
  – New approach, space-like, from $\mu e$ scattering, competitive and independent from the standard time-like approach

• On-going studies of systematic errors from multiple scattering effects
  – In collaboration with GEANT4 developers
  – Test beam at CERN

• On-going theoretical developments: two-loop calculations and accurate MC generator describing multi-photon emission

• Plans for next year:
  – proto-experiment at CERN M2 - will require only one detector module
  – starting a Collaboration

contact us if you are interested!
BACKUP
Statistical sensitivity

\[ L = 1.5 \times 10^7 \text{ nb}^{-1} \]

\[ \sigma_{LO} = 245 \text{ \mu b} \]

\[ E_{e}^f > 1 \text{ GeV} \]

Distribution of $\mu e$ elastic scattering events as a function of $x$ and $t$, for an integrated luminosity equivalent to two years of data-taking: \( \sim 4 \times 10^{12} \text{ events} \)
Optimal Muon Beam Momentum

Fraction of the $a^\text{HLO}_\mu$ integral as a function of the muon beam momentum: $p_\mu = 150 \text{ GeV} \rightarrow 87\%$ of the integral ($0 < x < 0.93$)

E$_\mu \sim 120 \text{ GeV}$
$0 < x < x_{\text{peak}}$

Beyond the kinematic limit the integral can be determined using pQCD & time-like data, and/or lattice QCD results.
Resolution models

LO differential cross section
observable angular distribution
observable angular distribution, $E_e > 1$ GeV
observable angular distribution, $E_e > 2$ GeV

low energy electron scattered away from the original direction

$E_e > 1$ GeV
**Detector design/optimization**

- **Modeling MSC effects**
  - Geant4 is the tool: likely to be tuned on data.

- **Target material and geometry**
  - Best low Z material and geometry.
  - Active target to determine vertex positions.

- **Electromagnetic calorimeter needed to:**
  - Perform the PID: muon/electron discrimination.
    -- PID capabilities also reconstructing the electromagnetic shower in the tracking system.
  - Measure $E_e$ to get rid of events with $E_e < 1$ GeV
  - Triggering: (muon in) AND (ECAL $E > E_{th}$)
    -- There is an alternative trigger condition: (muon in) AND (2 prongs into a given module)
Systematics

- Acceptance
- Tracking
- Trigger
- PID
- Effects of $E_e$ energy cut
- Uncertainty in the location of interaction vertices: Segmented/active target to resolve the vertex position
- Uncertainty in the muon beam momentum: Scattering kinematic to determine the beam momentum
- Effects of Multiple Scattering:
  It requires dedicated measurements (test beam) and simulation improvements (Geant model)
- Definition of the signal (needs a dedicated MC generator for $\mu e$ describing multi-photon emission)
- Theoretical uncertainties on the $\mu e$ cross section (see next)

All the systematic effects must be known to ensure an error on the cross section $< 10$ppm
A MEASUREMENT OF THE SPACE-LIKE PION ELECTROMAGNETIC FORM FACTOR


“The pion form factor has been measured in the space-like q^2 region 0.014 to 0.26 (GeV/c)^2 by scattering 300 GeV pions from the electrons of a liquid hydrogen target”

“The q^2 variable for the final sample was determined from the angles alone, up to the kinematic ambiguity which was resolved using the shower detectors. In this procedure the only rejection criterion involving the momenta was a cut against electrons of less than 1 GeV/c”
NA7 experiment

Elastic scattering in the $(\theta_R, \theta_L)$ plane

"The scatter distribution of the measured polar angles of the right and left-going particles $(\theta_R, \theta_L)$. Our estimate of $q^2$ was made from the point on the theoretical kinematic curve nearest to these angle coordinates".

"A fraction of the hadronic background was rejected by requiring coplanarity of the incident and scattered tracks".

EPS-HEP, 5-12 July 2017, Venice, Italy
Experiment proposed to CERN

• Idea presented to the “Physics Beyond Collider Study Group” [http://pbc.web.cern.ch/]
• C. Matteuzzi and G. Venanzoni experiment representatives.
• Physics Beyond Collider Study Group will select experiments aiming to:
  – Enrich and diversify the CERN scientific program
  – Exploit the unique opportunities offered by CERN’s accelerator complex and scientific infrastructure
  – Complement the laboratory’s collider programme (LHC, HL-LHC and possible future colliders).
  – The scientific findings will be collected in a report to be delivered by the end of 2018. This document will also serve as input to the next update of the European Strategy for Particle Physics.
LHC roadmap, according to MTP 2016-2020*

*outline LHC schedule out to 2035 presented by Frederick Bordry to the SPC and FC June 2015