Measuring the Leading Order Hadronic contribution to the muon g-2 in the space-like region

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in collaboration with
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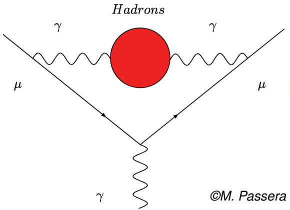
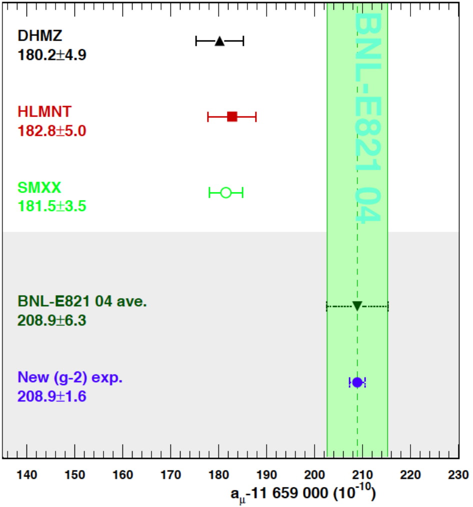
Outline

- ⋆ Standard time-like $a_\mu^{\rm HLO}$ evaluation
- ⋆ From the time-like to the space-like formula
- ⋆ Original proposal:
  extracting $\Delta\alpha_{\rm had}(t)$ from Bhabha
- ⋆ A new perspective:
  using $\mu e \to \mu e$ scattering in fixed target experiment
- ⋆ Working hypothesis, preliminary considerations on systematics and feasibility study
- ⋆ Conclusions



- Based on
  - ⋆ C.M.C.C. *et al.*
    "A new approach to evaluate the leading hadronic corrections to the muon g-2"
    Phys. Lett. B **746** (2015) 325
  - ⋆ G. Abbiendi *et al.*
    "Measuring the leading hadronic contribution to the muon g-2 via $\mu\, e$ scattering"
    `arXiv:1609.08987 [hep-ex]`, submitted to EPJC

Current a_μ status



T. Blum *et. al.*, "The Muon *g*-2 Theory Value: Present and Future"
arXiv:1311.2198 [hep-ph]

DHMZ, **HLMNT** two recent theory parameterizations
SMXX expected value & error with future improvements on $\sigma_{\rm had}$ data
BNL-E821 current experimental value from BNL
New (g-2) exp. expected error from future Fermilab and J-PARC experiments (assuming E821 central value)

Current a_μ status

Today: $a_\mu^{\rm exp} = (11659208.9 \pm 5.4_{\rm stat} \pm 3.3_{\rm sys}) \times 10^{-10}$ [0.5 ppm] BNL E821

- after QED, $a_\mu^{\rm HLO}$ is the largest contribution, bringing the largest theoretical error (together with HLxL) *driven by experimental errors*. In units 10^{-10}:

Knecht's talk at FCCP2015

QED	$+11658471.9$	[T. Aoyama et al. (2015)]
HVP-LO	$+692.3(4.2)$	[M. Davier et al. (2011)]
	$+694.9(4.3)$	[K. Hagiwara et al. (2011)]
HVP-NLO	$-9.84(7)$	[K. Hagiwara et al. (2011)]
HVP-NNLO	$+1.24(1)$	[A. Kurz et al. (2014)]
HLxL	$+10.5(2.6)$	[J. Prades et al. (2009)]
	$+11.5(4.0)$	[F. Jegerlehner, A. Nyffeler (2009)]
EW 1 loop	$+19.48(1)$	[(1972)]
EW 2 loops	$-4.12(10)$	[C. Gnendiger et al. (2013)]

tiny HLxL NLO: 0.3(2)
[G. Colangelo et al. (2014)]

$a_\mu^{\rm exp} - a_\mu^{\rm SM} = (27.4 \pm 8.0) \cdot 10^{-10}$ $[3.4\sigma]$ for $a_\mu^{\rm HLxL} = (10.5 \pm 2.6) \cdot 10^{-10}$, $a_\mu^{\rm HVP\text{-}LO} = 692.3 \pm 4.2 \cdot 10^{-10}$

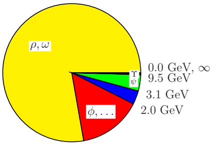
$a_\mu^{\rm exp} - a_\mu^{\rm SM} = (23.7 \pm 8.6) \cdot 10^{-10}$ $[2.8\sigma]$ for $a_\mu^{\rm HLxL} = (11.6 \pm 4.0) \cdot 10^{-10}$, $a_\mu^{\rm HVP\text{-}LO} = 694.9 \pm 4.3 \cdot 10^{-10}$

- Next Fermilab and J-PARC experiments aim to shrink the experimental error from the current 0.5 ppm down to $\lesssim 0.14$ ppm
- Theory is not ready yet for such precision, needs to catch up!

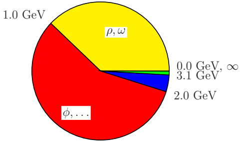
$$a_\mu^{\rm HLO} = \frac{\alpha}{\pi^2}\int_0^\infty \frac{ds}{s} K(s)\, {\rm Im}\,\Pi_{\rm had}(s+i\epsilon) \qquad K(s) = \int_0^1 dx \frac{x^2(1-x)}{x^2+(1-x)\frac{s}{m_\mu^2}}$$

$$a_\mu^{\rm HLO} = \frac{\alpha^2}{3\pi^2}\int_{4m_\pi^2}^\infty \frac{ds}{s} K(s) R_{\rm had}^{\gamma}(s)$$ (with dispersion relations and optical theorem)

F. Jegerlehner, A. Nyffeler, Phys. Rept. 477 (2009) 1



contributions

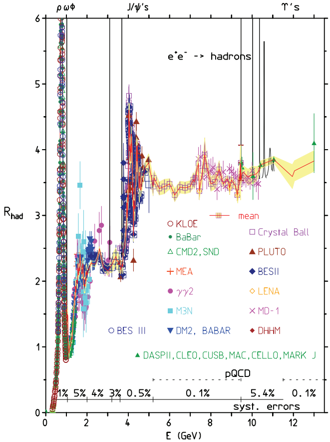


errors

$a_\mu^{\rm HLO} = 6870\ (42)_{\rm tot} \times 10^{-11}$ F. Jegerlehner, arXiv:1511.04473 (includes BESIII 2π)

$= 6928\ (33)_{\rm tot} \times 10^{-11}$ Davier et al, Tau2016, Beijing, Sep 2016, Preliminary

$= 6949\ (37)_{\rm exp}\ (21)_{\rm rad} \times 10^{-11}$ Hagiwara et al, JPG 38 (2011) 085003



M. Passera, PSI2016, October 2016

Alternative approach: space-like evaluation

By performing first the $\int ds$ and using again dispersion relations, we get

$$a_\mu^{\rm HLO} = \frac{\alpha}{\pi}\int_0^1 dx(x-1)\bar{\Pi}_{\rm had}(t(x)) = \frac{\alpha}{\pi}\int_0^1 dx(1-x)\Delta\alpha_{\rm had}(t(x))$$

$$a_\mu^{\rm HLO} = \frac{\alpha}{\pi}\int_{-\infty}^0 \frac{dt}{\beta t}\left(\frac{1-\beta}{1+\beta}\right)^2 \bar{\Pi}_{\rm had}(t) = -\frac{\alpha}{\pi}\int_{-\infty}^0 \frac{dt}{\beta t}\left(\frac{1-\beta}{1+\beta}\right)^2 \Delta\alpha_{\rm had}(t)$$

where

$$t(x) = -\frac{x^2 m_\mu^2}{1-x} \qquad \beta = \sqrt{1-4m_\mu^2/t} \qquad t = \begin{cases} 0^- & \text{for } x \to 0^+ \\ -\infty & \text{for } x \to 1^- \end{cases}$$

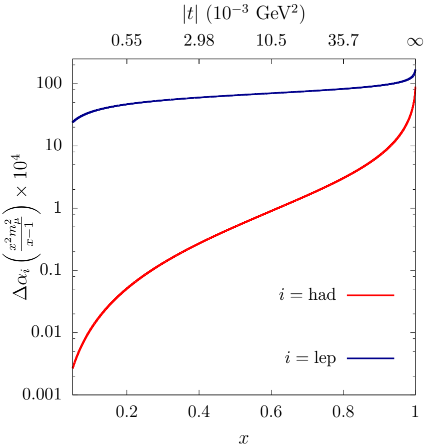
$\Delta\alpha_{\rm had}(t)$ is the hadronic contribution to the running of $\alpha_{\rm QED}(q^2) = \frac{\alpha}{1-\Delta\alpha(q^2)}$

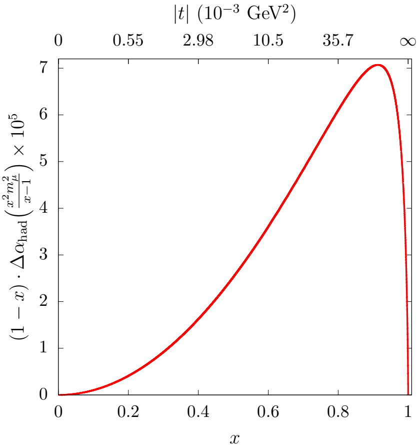
- ⋆ $\Delta\alpha_{\rm had}(t)$ in the integrand is evaluated in the space-like region (negative transfer momenta) where it is a smooth function
- ⋆ we propose to *measure* the running of $\alpha_{\rm QED}(t<0)$ to evalutate $a_\mu^{\rm HLO}$

see also G.V. Fedotovich, CMD-2 Collaboration, Nucl. Phys. Proc. Suppl. 181-182 (2008) 146

similar approach also used for lattice calculations of $a_\mu^{\rm HLO}$

General considerations





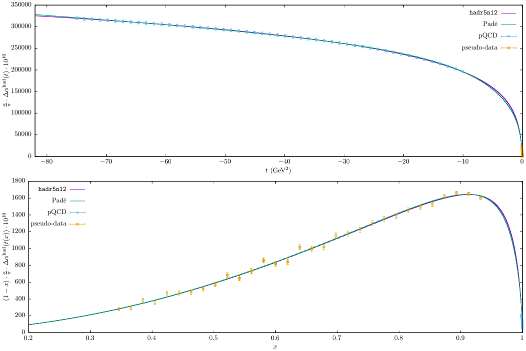
- $\Delta\alpha_{\text{had}}(t(x))$ (red) as a function of x
- $\Delta\alpha_{\text{lep}}(t(x))$ (blue) as a function of x

- integrand function $(1-x)\Delta\alpha_{\text{had}}(t(x))$

$$x_{\text{peak}} \simeq 0.914$$
$$t_{\text{peak}} \simeq -0.108\ \text{GeV}^2$$

- To get $\Delta\alpha_{\rm had}(t)$, the goal is to measure the (absolute) running of $\alpha_{\rm QED}(t)$ from the distribution of the t variable in
  - $\rightarrow$ Bhabha events at e^+e^- (low-energy) colliders **original proposal**
  - $\rightarrow$ or μe scattering events in a fixed target experiment **new proposal**

$$\alpha(t) = \frac{\alpha}{1 - \Delta\alpha_{\rm other}(t) - \Delta\alpha_{\rm had}(t)} \qquad \Delta\alpha_{\rm had}(t) = 1 - \Delta\alpha_{\rm other}(t) - \frac{\alpha}{\alpha(t)}$$



Strategy:

- measure $\Delta\alpha_{\rm had}(t)$ within the experimental kinematical range
- get large $|t|$ values from elsewhere
- fit $\Delta\alpha_{\rm had}(t)$
- get the integrand function and the value of $a_\mu^{\rm HLO}$

Roughly, to be competitive with the current evaluations, $\Delta\alpha_{\rm had}(t)$ needs to be know at some % level

Original proposal: Bhabha scattering

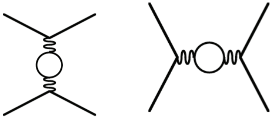
C.M.C.C., M. Passera, L. Trentadue, G .Venanzoni, Phys. Lett. B **746** (2015) 325

- Generally, being $\Delta\alpha_{\rm had}(t) = \mathcal{O}(10^{-3})$ in the peak region and

$$\frac{1}{2}\frac{\delta\sigma}{\sigma} \simeq \frac{\delta\alpha}{\alpha} \simeq \delta\Delta\alpha_{\rm had}$$

the cross section must be known with an accuracy at a few 10^{-4} level

- (Large angle) Bhabha at high-luminosity low-energy colliders can access the region around $t_{\rm peak}$ $\rightarrow$ $\Delta\alpha_{\rm had}(t)$ can be extracted from data



A few warning remarks:

⋆ s and t channel intrinsically mix
$\rightarrow$ a non-trivial numerical procedure has to be devised to extract $\Delta\alpha_{\rm had}(t)$

⋆ $\Delta\alpha_{\rm had}(s > 0)$ enters s channel diagrams and can limit the theoretical accuracy

⋆ need to normalize to a process "not dependent" on $\Delta\alpha_{\rm had}$, known with high accuracy:
  - small angle Bhabha $\mapsto$ difficult with current detectors' design
  - $e^+e^- \rightarrow \gamma\gamma$ $\mapsto$ difficult to control with needed accuracy

New perspective: $\mu e \to \mu e$ scattering in fixed target experiment

G. Abbiendi *et al.* **arXiv:1609.08987 [hep-ex]**, submitted to EPJC

Presented by G. Venanzoni at the *Physics Beyond Colliders Kickoff Meeting*, September 2016, CERN

$\mapsto$ A 150 GeV high-intensity ($\sim 1.3\times 10^7$ μ's/s) muon beam is available at CERN NA

$\mapsto$ Muon scattering on a low-Z target ($\mu e \to \mu e$) looks an ideal process

- it is a pure t–channel process $\to$

$$\frac{d\sigma}{dt} = \frac{d\sigma_0}{dt}\left|\frac{\alpha(t)}{\alpha}\right|^2$$

- Assuming a 150 GeV incident μ beam we have

$s \simeq 0.164\ \mathrm{GeV}^2$ $\quad -0.143 \lesssim t < 0\ \mathrm{GeV}^2$ $\quad 0 < x \lesssim 0.93$ **it spans the peak!**

Benefits:

- the highly boosted kinematics allows to access a wide angular range in the CM
- the same detector can be exploited for signal and normalization
- the same process is used for signal and normalization:
  the region $x \lesssim 0.3$, where $\Delta\alpha_{\rm had}(t) < 10^{-5}$, can be used for normalization

- We are investigating a setup where e and μ scattering angles are measured with high precision to measure t

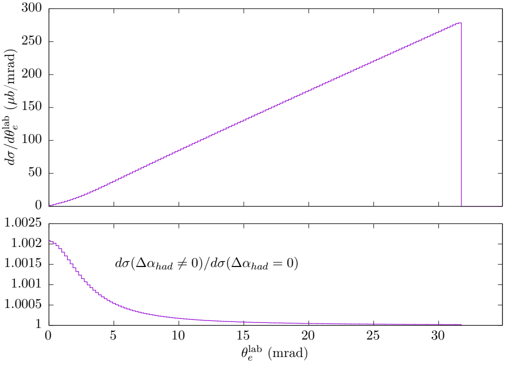
Kinematics and LO cross-section

- the $2 \to 2$ kinematics in the lab. frame reads

$$t = 2m_e^2 - 2m_e E_e, \qquad s = m_\mu^2 + m_e^2 + 2m_e E_\mu^i \qquad r \equiv \frac{\sqrt{(E_\mu^i)^2 - m_\mu^2}}{E_\mu^i + m_e}$$

$$E_e = m_e \frac{1 + r^2 c_e^2}{1 - r^2 c_e^2}, \qquad \theta_e = \arccos\left(\frac{1}{r}\sqrt{\frac{E_e - m_e}{E_e + m_e}}\right) \qquad c_e \equiv \cos\theta_e$$

- $0 < \theta_e < 31.85$ mrad $\longleftrightarrow$ $139.8 > E_e > 1$ GeV $\longleftrightarrow$ $-0.143 < t < -0.001$ GeV^2

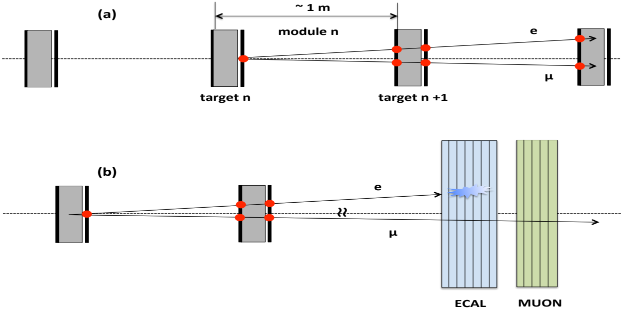


$\rightarrow$ differential cross-section at LO (including vacuum polarization) as a function of θ_e

$\rightarrow$ effect due to $\Delta\alpha_{\rm had}(t)$

$\rightarrow$ for instance the region $\theta_e > 20 \div 25$ mrad can be used as normalization

Working hypothesis for target and detector

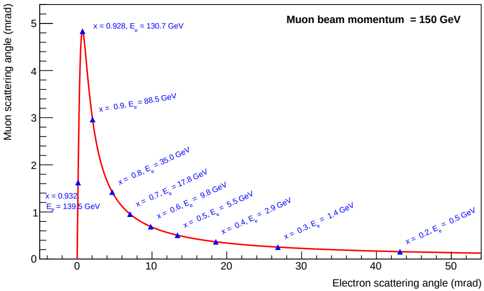


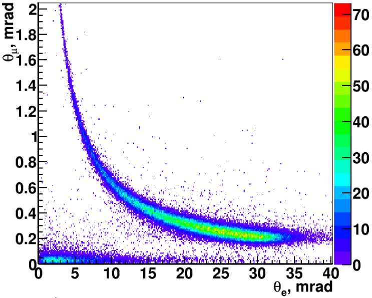
- Distributed target and tracking system

Twenty Be (or C) 3cm-layers coupled to two Si 0.3mm-planes, spaced by $\sim$1m air gaps

- ⋆ Low-Z material minimizes multiple scattering and background, still providing enough luminosity with the available rate of $\sim 1.3 \times 10^7$ muons/s
- ⋆ downstream ECAL for e and muon system for μ to discriminate μ/e at small angles
- ⋆ preliminary studies with GEANT4 show a 0.02 mrad angular resolution

Systematics considerations





⇑

events due to e^+e^- pairs

- μ and e scattering angles are correlated
- ⋆ the constraint is useful to select elastic events, reject background and reduce systematics on t determination
- ⋆ below (2-3) mrad μ and e angles overlap, to be resolved by μ/e identification
- ⋆ multiple scattering breaks the correlation:
  simulation and data will help to optimize the detector and reduce systematics

Statistics & theory side

- ↦ From preliminary studies, it is expected that after two years of data taking a *statistical* error of $\sim$0.3% on $a_\mu^{\rm HLO}$ is within reach

  to be compared with $\sim$0.6%, the *total* error on current evaluations

- ↦ Besides experimental systematics, high-precision MC tools must be developed to reduce theoretical systematics down to a few 10^{-5} level both for process simulation and normalization
  - ⋆ experience on Bhabha at flavour-factories is really helpful
    ↪ QED radiative corrections (RC) under control at the 10^{-4} level
  - ⋆ lower $\sqrt{s}$ and less-radiating muon (w.r.t. electron) reduce the impact of RC (and their uncertainty)
  - ⋆ in the ratio signal/normalization some common RC are expected to cancel (at least to some extent)
    ↪ more stable upon inclusion of higher-order RC
  - ⋆ inclusion of exact 2-loop RC would improve the accuracy and may be necessary
    ↪ warning: existing calculations for Bhabha not straightforwardly applicable because of different μ and e mass scales
  - ⋆ work is in progress

Conclusions

- ⋆ A new strategy to evaluate the leading-order hadronic contribution to the muon anomaly has been proposed and is being investigated in detail
- ⋆ It is independent and complementary (completely different systematics) to the standard method
- ⋆ It requires high-precision *direct* measurement of the running of $\alpha_{\rm QED}(q^2)$ in the space-like, *i.e.* negative momentum transfer, region.

  Two scenarios with different systematics:

  $\rightarrow$ from Bhabha scattering at low energy colliders

  $\hookrightarrow$ difficult to control the systematic uncertainties in current configurations (it would need dedicated detectors at present flavour factories)

  $\rightarrow$ from $\mu e \to \mu e$ scattering in a fixed low-Z target experiment, exploiting the 150 GeV high-intensity muon beam available at CERN North Area

  $\hookrightarrow$ very promising to reach the per mill goal!
- ⋆ To reach or, better, improve the current accuracy on $a_\mu^{\rm HLO}$, both experimental and theoretical systematics must be under control below the 10^{-4} level

  $\hookrightarrow$ very challenging!
- ⋆ Work is in progress to study, optimize and find the best detector/target layout and to develop high-precision Monte Carlo tools for data analysis