Leading hadronic contribution to muon g-2 from lattice QCD and the MUonE experiment

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in collab. w. N. Cardoso (IST, Lisbon)

and exp. and th. effort
Muon g-2 Status

Thanks to Everyone for your E↵ort!

• All here to improve SM Prediction and Measurement of $a_\mu$
• Wouldn’t be here except for rare combination of circumstances:
  (1) We can measure $a_\mu$ really well
  (2) You can predict $a_\mu$ really well
  (3) The comparison can change future direction of physics

• 3.5⇥10 vs 15⇥10.

• Great challenge for physics! Thanks for your e↵orts!

$\alpha_\mu$ from the experiment: FNAL E989

- $\alpha_\mu^{exp} = 11659208.0(6.3) \times 10^{-10}(0.54\text{ppm})$ [BNL, 2006-2008]

- New experiments (J-PARC, FNAL) expected to perform 4x more precise measurement (E 989@FNAL by Jun 2020)

- Successful commissioning run in 2017!

D. Kawall (@Mainz, Muon g-2 Theory Initiative): Data set comparable to BNL statistics [June 2018]
https://indico.him.uni-mainz.de/event/11/contributions
\[ a_\mu^{exp} = 11659208.0(6.3) \times 10^{-10}(0.54\text{ppm}) [\text{BNL, 2006-2008}] \]

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https://indico.him.uni-mainz.de/event/11/contributions
From the experiment: J-PARC E34

3 GeV proton beam
(1MW, double pulses, 25Hz)

Surface muon beam (4 MeV)
$\varepsilon \sim 1000 \pi \text{ mm } \cdot \text{ mrad}$

Ultra slow $\mu^+$ production by Resonant Laser Ionization of Muonium ($\sim 10^6 \mu^+/s$)

Re-acceleration LINAC
($\sim 200 \text{ MeV}$)
$\varepsilon \sim 1 \pi \text{ mm } \cdot \text{ mrad}$

Target precision
$\Delta(g-2) = 0.1 \text{ ppm}$
$\Delta\text{EDM} = 10^{-21} \text{ e } \cdot \text{ cm}$

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

T. Yamazaki (@KEK 2018 g-2 WS): muon RF acceleration for the first time 5 months ago!
Muon g-2 Status

<table>
<thead>
<tr>
<th></th>
<th>2011</th>
<th>2017</th>
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<tr>
<td>QED</td>
<td>11658471.81 (0.02)</td>
<td>11658471.90 (0.01) [arXiv:1712.06060]</td>
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<tr>
<td>EW</td>
<td>15.40 (0.20)</td>
<td>15.36 (0.10) [Phys. Rev. D 88 (2013) 053005]</td>
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<tr>
<td>LO HLbL</td>
<td>10.50 (2.60)</td>
<td>9.80 (2.60) [EPJ Web Conf. 118 (2016) 01016]</td>
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<td>0.30 (0.20) [Phys. Lett. B 735 (2014) 90]</td>
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<th>KNT18</th>
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<tr>
<td>LO HVP</td>
<td>694.91 (4.27)</td>
<td>693.27 (2.46) [Phys. Rev. D 97 (2018)]</td>
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<tr>
<td>NLO HVP</td>
<td>-9.84 (0.07)</td>
<td>-9.82 (0.04) [Phys. Rev. D 97 (2018)]</td>
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<td>NNLO HVP</td>
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<td>Theory total</td>
<td>11659182.80 (4.94)</td>
<td>11659182.05 (3.56) [Phys. Rev. D 97 (2018)]</td>
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<tr>
<td>Experiment</td>
<td>11659209.10 (6.33) world avg</td>
<td></td>
</tr>
<tr>
<td>Exp - Theory</td>
<td>26.1 (8.0)</td>
<td>27.1 (7.3) [Phys. Rev. D 97 (2018)]</td>
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<td>(\Delta a_\mu)</td>
<td>3.3(\sigma)</td>
<td>3.7(\sigma) [Phys. Rev. D 97 (2018)]</td>
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</table>

A. Keshavarzi@Mainz, Muon g-2 Theory Initiative WS. 18-22
MUonE project

- A high precision measurement of $a_\mu^\text{had, LO}$ with a 150 GeV $\mu$ beam on $e^-$ target at CERN

- In space-like (Euclidean) momenta region

- Obtain $a_\mu^\text{had, LO}$ by utilising the running of $\alpha_\text{QED}$ in a space-like process

$$a_\mu^\text{had, LO} = \frac{\alpha}{\pi} \int_0^1 dx (1-x) \Delta \alpha_\text{had}[Q^2(x)]$$

[Lautrup, de Rafael '69]
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- Proposal to measure precisely the $Q^2$ - dependent fine-structure constant:

$$\alpha(Q^2) = \frac{\alpha(O)}{1 - \Delta \alpha(Q^2)}$$  

- Physics Beyond Colliders@CERN
MUonE: space-like evaluation of $a_\mu^{\text{had}, \text{LO}}$

- The running contributions can be split into the hadronic and the leptonic part:

$$\Delta \alpha(Q^2) = \Delta \alpha_{had}(Q^2) + \Delta \alpha_{lep}(Q^2)$$

- MUonE will measure total $\Delta \alpha(Q^2)$ in low-$Q^2$ region

- Subtracting the purely leptonic part gives leading order HVP:

$$\Delta \alpha(Q^2) - \Delta \alpha_{lep}(Q^2) \equiv \Delta \alpha_{had}(Q^2)$$

$$a_\mu^{\text{had}, \text{LO}} = \frac{\alpha}{\pi} \int_0^1 dx (1 - x) \Delta \alpha_{had}[Q^2(x)]$$

known up to three loops [Steinhauser ‘98]
for some $Q^2$ four loops [Baikov et al. ‘13, Sturm ‘13]
MUonE: space-like evaluation of $a_{\mu}^{\text{had}, \text{LO}}$

- combination of many exp. data sets
- smooth integrand
- single experiment enough - but high accuracy needed (one-loop effect)
MUonE experimental setup

- A high precision measurement of $a_{\mu}^{\text{HVP, LO}}$ with a 150 GeV $\mu$ beam on $e^-$ target at CERN

- $\approx 60$ modules (distributed target) each $\sim 0.5$ m length

- Modular apparatus: each module has $\approx 1$ cm Beryllium target and 3/4 state-of-the-art Silicon strips detectors

- Signal angular region: $\theta_e \leq 45$ mrad $\theta_\mu \leq 5$ mrad

- Expected intrinsic angular resolution: 0.02 mrad

- Main challenge: multiple scattering (tests in progress)
MUonE: Theory Update

- A high precision measurement of $a_\mu^{\text{HVP, LO}}$
  with a 150 GeV $\mu$ beam on $e^-$ target at CERN

- ≈60 modules (distributed target) each ~ 0.5m length

- Modular apparatus: each module has ≈1 cm

  Beryllium target and 3/4 state-of-the-art Silicon strips detectors

- Signal angular region: $\theta_e \leq 45$ mrad $\theta_\mu \leq 5$ mrad

- Expected intrinsic angular resolution: 0.02 mrad

- Main challenge: multiple scattering (tests in progress)
To extract $\Delta \alpha_{\text{had}}(t)$ from this measurement, the ratio of the SM cross sections in the signal and normalisation regions must be known at $\lesssim 10\text{ppm}$!

- **Theory in low-$Q^2$** ([dominating HVP integral]):
  
  
  \[
  \int_{s_{0}}^{s_{1}} ds K(s) = \frac{1}{4} \frac{\pi^3}{m^2} \mu \int_{x_0}^{x_1} x^2 (1 - x) dx K(t(x)) 
  \]

  

  [NNLO had. contributions Fael, Passera]

  [Fixed-order NNLO+ Resumation Broggio, Signer, Ulrich]

  [MC@NNLO Carloni, Montagna, Nicrosini, Piccinini, Czyz ...]

  [...]

- **Theory in intermediate-$Q^2$**: Lattice QCD or analytic continuation of the R-ratios

- **Theory in high-$Q^2$**: PT

  [Chetyrkin et al. '96]

  [Harlander&Steinhauser '02]
Lattice determinations of HVP

Progress in lattice determinations of HVP [K. Miura, Wed. 9am]

Complementary approach: interplay between exp. and lattice determinations of HVP

@Granada: C. Lehner: a connection of lattice HVP to the R-ratio data [C.LEHNER, FRI 14.00]

In this talk: demonstrate what can lattice do for and vice versa

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\[ \Delta \alpha(Q^2) - \Delta \alpha_{lep}(Q^2) \equiv \Delta \alpha_{had}(Q^2) \quad \Rightarrow \quad a^\text{had,LO}_\mu = \frac{\alpha}{\pi} \int_0^1 dx (1 - x) \Delta \alpha_{had}[Q^2(x)] \]

\[ Q^2 = \frac{x^2 m^2_\mu}{1 - x} \]
MUonE: space-like evaluation of $a_{\mu}^{\text{had, LO}}$

→ Subtracting the purely leptonic part gives leading order HVP:

$$\Delta \alpha(Q^2) - \Delta \alpha_{\text{lep}}(Q^2) \equiv \Delta \alpha_{\text{had}}(Q^2)$$

$$a_{\mu}^{\text{had, LO}} = \frac{\alpha}{\pi} \int_0^1 \text{d}x (1 - x) \Delta \alpha_{\text{had}}[Q^2(x)]$$

$Lautrup, de Rafael '69$

$[T. Blum '03]$
MUonE: space-like evaluation of $a_{\mu}^{\text{had, LO}}$

Subtracting the purely leptonic part gives leading order HVP:

$$\Delta \alpha(Q^2) - \Delta \alpha_{\text{lep}}(Q^2) \equiv \Delta \alpha_{\text{had}}(Q^2)$$

$$a_{\mu}^{\text{had, LO}} = \frac{\alpha}{\pi} \int_0^1 dx (1 - x) \Delta \alpha_{\text{had}}[Q^2(x)]$$

$$Q^2 = \frac{x^2 m_{\mu}^2}{1 - x}$$

$$a_{\mu}^{\text{had, LO}} = \left(\frac{\alpha}{\pi}\right)^2 \int_0^\infty dQ^2 \sqrt{\frac{1}{Q^2(4m_{\mu}^2 + Q^2)}} \left(\sqrt{\frac{4m_{\mu}^2 + Q^2 - \sqrt{Q^2}}{4m_{\mu}^2 + Q^2 + \sqrt{Q^2}}}\right)^2 \hat{\Pi}(Q^2)$$

$$a_{\mu}^{\text{had, LO}} = \left(\frac{\alpha}{\pi}\right)^2 \int_0^\infty dQ^2 f(Q^2) \hat{\Pi}(Q^2)$$

[Lautrup, de Rafael '69]

[T. Blum '03]
MUonE: space-like evaluation of $a_\mu^{\text{had, LO}}$

⇒ Subtracting the purely leptonic part gives leading order HVP:

$$\Delta \alpha(Q^2) - \Delta \alpha_{\text{lep}}(Q^2) \equiv \Delta \alpha_{\text{had}}(Q^2)$$

$$a_\mu^{\text{had, LO}} = \frac{\alpha}{\pi} \int_0^1 dx (1-x) \Delta \alpha_{\text{had}}[Q^2(x)]$$

$$Q^2 = \frac{x^2 m_\mu^2}{1-x}$$

$$a_\mu^{\text{had, LO}}(Q^2) = \left(\frac{\alpha}{\pi}\right)^2 \int_0^\infty dQ^2 \frac{1}{\sqrt{Q^2(4m_\mu^2 + Q^2)}} \left(\frac{\sqrt{4m_\mu^2 + Q^2} - \sqrt{Q^2}}{\sqrt{4m_\mu^2 + Q^2 + \sqrt{Q^2}}}ight)^2 \hat{\Pi}(Q^2)$$

⇒ $f(Q^2)$ diverges as $Q^2 \to 0$

⇒ Dominant contribution to the integral: $Q^2 \approx m_\mu^2$
MUonE: space-like evaluation of $a_{\mu}^{{\text{had, LO}}}$

- **Lattice:** also Euclidean mom.

- **Smooth integrand**

  $$a_{\mu}^{{\text{had, LO}}} = \left( \frac{\alpha_s}{\pi} \right)^2 \int_0^{\infty} dQ^2 f(Q^2) \hat{\Pi}(Q^2)$$

- **$\hat{\Pi}(Q^2) = 4\pi^2 (\Pi(Q^2) - \Pi(0))$** accessible directly

- **Low-$Q^2$ not covered** (momenta quantization & limitation in lattice sizes)

- **Deterioration of signal/noise as $Q^2 \rightarrow 0$**
Hybrid method: separate integration ranges to control the systematics

\[ a_{\mu}^{\text{had}, \text{LO}} = \left( \frac{\alpha}{\pi} \right)^2 \int_0^{Q_{\text{max}}} dQ^2 f(Q^2) \hat{\Pi}(Q^2) \]

Motivated by the observation that the systematics error grows with \( Q_{\text{cut}}^2 \)

- Physically motivated \( \tau \)-model for \( I=1 \) HVP: 80% of HVP from \( Q^2 < 0.1 \text{GeV}^2 \), 90% from \( Q^2 < 0.2 \text{GeV}^2 \)
- Applied for determining strange quark HVP [RBC/UKQCD, JHEP 1604 (2016)]
- Compared with TMR method for light/strange/charm HVP [CLS/Mainz, JHEP 1710 (2017)]
Hybrid method: MUonE experiment + lattice

\[ a_{\mu}^{had,LO} = \frac{\alpha}{\pi} \int_0^{0.93...} dx (1 - x) \Delta \alpha_{had}[Q^2(x)] + \left( \frac{\alpha}{\pi} \right)^2 \int_{0.14}^{Q_{\text{max}}^2} dQ^2 f(Q^2) \times \hat{\Pi}(Q^2) + \left( \frac{\alpha}{\pi} \right)^2 \int_{Q_{\text{max}}^2}^{\infty} dQ^2 f(Q^2) \times \hat{\Pi}_{\text{pert.}}(Q^2) \]

- \( I_0 \)  
  - lattice QCD
  - R-ratios

[I\_0][I\_1][I\_2]

[Chetyrkin et al. '96]  
[Harlander&Steinhauser '02]
Hybrid method: MUonE experiment + lattice

\[ a_{\mu}^{had,LO} = \frac{\alpha}{\pi} \int_0^{0.93} dx (1 - x) \Delta \alpha_{had}[Q^2(x)] + \left( \frac{\alpha}{\pi} \right)^2 \int_{0.14}^{Q^2_{\text{max}}} dQ^2 f(Q^2) \times \hat{\Pi}(Q^2) + \left( \frac{\alpha}{\pi} \right)^2 \int_{Q^2_{\text{max}}}^{\infty} dQ^2 f(Q^2) \times \hat{\Pi}_{\text{pert}}(Q^2) \]

- \( I_0 \)
- \( I_1 \) contribution to the HVP from the lattice: control of systematics easily attainable
- \( I_2 \) lattice QCD
- R-ratios
HVP: Intermediate-\(Q^2\) range integration

\[
a^\text{had,LO}_\mu = \frac{\alpha}{\pi} \int_0^{0.93} dx (1 - x) \Delta \alpha_{\text{had}}[Q^2(x)] + \left( \frac{\alpha}{\pi} \right)^2 \int_{0.14}^{Q_{\text{max}}} dQ^2 f(Q^2) \times \hat{\Sigma}(Q^2) + \left( \frac{\alpha}{\pi} \right)^2 \int_{Q_{\text{max}}}^{\infty} dQ^2 f(Q^2) \times \hat{\Sigma}_{\text{pert.}}(Q^2)
\]

\[
I_0
\]

\[
I_1
\]

\[
I_2
\]

- \(I_1\) on CLS ensembles with \(N_f=2\) O(a) improved Wilson fermions (A5,E5,F6,G8,N6,O7)
- \(m_n\approx180\text{-}440\text{MeV}\), continuum extrapolation (0.05-0.09\text{fm}), chiral extrapolation to \(m_n,\text{phys}\)
- Partially quenched: s, c \(\kappa_s,\kappa_c\) taken from [CLS/Mainz, JHEP 1710 (2017)]
- Neglecting isospin breaking effects \(m_u\neq m_d\) and \(\alpha_{\text{em}}\neq 0\) and disconnected contribution
- \(m_nL \geq 4\), long-distance effects effects in \(I_1\) not yet explored explicitly
- VP function from the off-diagonal component of the conserved-conserved current correlator: \(\Pi(Q^2) = \frac{\Pi_{\mu\nu}(Q)}{p_{\mu}p_{\nu}}\)
HVP: Intermediate-$Q^2$ range integration

$m_π = 311$ MeV
$L^3\times T = 48^3 \times 96$
$a = 0.066$ fm
$N_{\text{cfg}} = 50$
$N_{\text{meas}} = 480$

- Statistical precision in $I_1$ (still) determined by $\Pi(0)$
  $$\Pi(Q^2) = 4\pi^2(\Pi(Q^2) - \Pi(0))$$

- Expansion of the quark propagator around zero spatial momentum

- Strange & Charm contributions:
  $$\Pi(0) = -\frac{\partial \Pi_{\mu\nu}(Q)}{\partial Q_\mu \partial Q_\nu}|_{Q^2=0}$$
  [de Divitiis, Petronzio, Tantalo; Phys.Lett. B718 (2012)]

  $$\Pi(0) = -\frac{1}{2} - \frac{1}{2} - \frac{1}{4}$$

- Light contribution: $Q^2 \rightarrow 0$ extrapolation
\[ \Pi(Q^2) = 4 \pi^2 (\Pi(Q^2) - \Pi(0)) \]

- Statistical precision in $I_1$ (still determined by $\Pi(0)$

- Expansion of the quark propagator around zero spatial momentum

- Strange & Charm contributions: $\Pi(0) = -\frac{\partial \Pi_{\mu \nu}(Q)}{\partial Q_\mu, \partial Q_\nu} |_{Q^2=0}$ [de Divitiis, Petronzio, Tantalo; Phys.Lett. B718 (2012)]

- Light contribution: $Q^2 \rightarrow 0$ extrapolation

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HVP: Intermediate-$Q^2$ range integration

- Padé/conformal polynomial fits $[0.14, Q^2_{\text{cut}}]$ GeV$^2$
- Numerical integration $[Q^2_{\text{cut}}, 4.0]$ GeV$^2$, $Q^2_{\text{cut}} = 0.5-1.0$ GeV$^2$

Unlike for LO HVP at the full $Q^2$-range —> important to get $\Pi(Q^2)$ at high-$Q^2$ correctly

- Padé approximants guaranteed to converge to the actual $\Pi(Q^2)$ [Aubin, Blum,Golterman,Peris Phys.Rev. D86 (2012)]
- Higher order Pade’s needed, if fitting momenta $Q^2 > 0.5$ GeV$^2$
HVP: Intermediate-\(Q^2\) range integration

→ Continuum + chiral extrapolation: \(\alpha_1 + \alpha_2 m_\pi^2 + \alpha_3 m_\pi^2 \ln(m_\pi^2) + \alpha_4 a\) (light/strange)

→ Preliminary result \(I_1^{u,s,c} = 79.5(3.5) \times 10^{-10}\); 4% uncertainty in \(I_2\) corresponds to \(\approx 0.5\%\) in the full HVP

→ Further work: more statistics at near physical \(m_\pi\), O(a) improved vector current [T.Harris, H. Meyer Phys.Rev. D92 (2015)]

→ Additional caveats: cutoff effects, isospin breaking corrections, finite volume effects, disconnected contribution
Hybrid strategy for the HVP: $\mu^{\text{One}} + \text{Lattice} + \text{P.T.}$

- Low momentum region
  - Experiment (NLO, NNLO, radiative corrections ... )

- $\hat{f}(Q^2)$
- $Q^2_{\text{cut}}$, $Q^2_{\text{exp,max}}$, $Q^2_{\text{max}}$

- Lattice: models + num. integration

- Continuum limit: $a \to 0$
- Finite volume corrections
- Chiral extrapolation
- Isospin breaking corrections ($m_u \neq m_d$ and $\alpha_{\text{em}} \neq 0$)
Hybrid strategy for the HVP: \( \mu \text{One} \) + Lattice: models + num. integration + P.T.

- Continuum limit: \( a \rightarrow 0 \)
- Finite volume corrections
- Chiral extrapolation
- Isospin breaking corrections (\( m_u \neq m_d \) and \( q_{em} \neq 0 \))

\[ \hat{F}(Q^2) \]

\[ Q^2_{\text{cut}} \]

\[ Q^2_{\text{exp,max}} \]

\[ Q^2_{\text{max}} \]

Low momentum region

- Experiment (NLO, NNLO, radiative corrections ... )
Summary & Outlook

- **μOne** experiment: space-like mu-e scattering [setup and status]
- In the 2-3 years, 0.3% statistical uncertainty in HVP expected
- Measuring the running of $\alpha_{\text{QED}}$ in the $Q^2 \in [0.001,0.14]$ GeV$^2$ which dominates the HVP

- Hybrid method [Golterman et. al. '14] (Exp.+Lat.+P.T.): $I = I_0 + I_1 + I_2$
- $I_1$ from the lattice, CLS ensembles with Nf=2 O(a) improved Wilson fermions
- Outlook: cross-checks with different lattice discretizations, TMR, use $m_{n,\text{phys}}$, revisit strategy for $a_{\mu}$ light

- Useful input from the lattice community: for $\hat{\Pi}(Q^2)$ at fixed momentum transfer (a→0; V→∞ limit)
- Muon g-2 Theory Initiative (~Fermilab '16, [KEK/UConn. '17], Mainz '17) white paper in preparation
- In the mean time: have a look @ [H.Meyer, H. Wittig PPNP Review, arXiv:1807.XXXXX -> NEW!! Lattice & Muon g-2]
- MUonE: L.O.I. to SPSC®CERN due for submission next year - welcome to join us!
Thank you!
Acknowledgements

• This work was supported by TCHPC (Research IT, Trinity College Dublin).

• Most calculations were performed on the Lonsdale and Kelvin clusters maintained by the Trinity Centre for High Performance Computing. This cluster was funded through grants from Science Foundation Ireland.

• Part of the simulations reported in this talk were performed on a dedicated PC cluster at CERN. We are grateful to the CERN IT Department for technical support.

• We acknowledge Santander Supercomputacion support group at the University of Cantabria for providing access to Altamira Supercomputer at the Institute of Physics of Cantabria (IFCA-CSIC), member of the Spanish Supercomputing Network, for performing simulations/analyses.

• This work was supported by a grant from the Swiss National Supercomputing Centre (CSCS) under project ID s642.
The projected Accuracy of the MUonE experiment

- Attempt to estimate the total uncertainty after MUonE has collected the data
- Pseudo data generated by using the MC simulations of the relevant cross sections
- Error only statistical
- Is combined fit of experimental and lattice data going to give even better precision?
# Measured CLS Nf=2 gauge ensembles

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<th>Nf=2</th>
<th>$\beta$</th>
<th>L/a</th>
<th>$a[\text{fm}]$</th>
<th>$m_\pi[\text{MeV}]$</th>
<th>N$_{\text{cfg}}$</th>
<th>N$_{\text{meas}}$</th>
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<td>A5</td>
<td>5.2</td>
<td>32</td>
<td>0.0755(11)</td>
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<tr>
<td>E5</td>
<td>5.3</td>
<td>32</td>
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<td>437</td>
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<td>702</td>
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<tr>
<td>F6</td>
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<td>480</td>
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<td>G8</td>
<td>5.3</td>
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<td>185</td>
<td>25</td>
<td>100</td>
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<tr>
<td>N6</td>
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<td>48</td>
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<td>270</td>
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<tr>
<td>O7</td>
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<td>64</td>
<td>0.0486(6)</td>
<td>268</td>
<td>40</td>
<td>640</td>
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</table>
Long distance contributions

\[ G(x_0) \bar{K}(x_0)/m_\mu \]

- For different quark flavors

- [H. Meyer @ Mainz, Muon g-2 Theory Initiative] CLS/Mainz Nf=2+1
**MUonE Timeline**

from G. Venanzoni’s talk at Physics Beyond Colliders WG meeting, June 13-14 2018

- **2018-2019**
  - Detector optimization studies: simulation; Test Run at CERN (2018); Mainz/Desy with few GeV e- (2019); Fermilab with 60 GeV μ (TBC)
  - Theoretical studies
  - Set up a collaboration
  - Letter of Intent to the SPSC

- **2020-2021**
  - Detector construction and installation

**2021–2024**

- Data taking: staged detector for a first (pilot) run +2 years with full detector

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LHC schedule

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C.M. Carloni Calame (INFN, Pavia)