Lattice QCD and MUonE experiment

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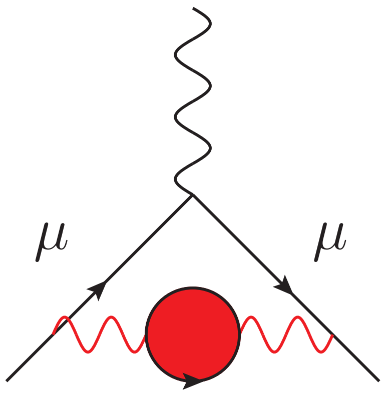
Trinity College Dublin

in collab. w. N. Cardoso (IST, Lisbon) **and** μONe

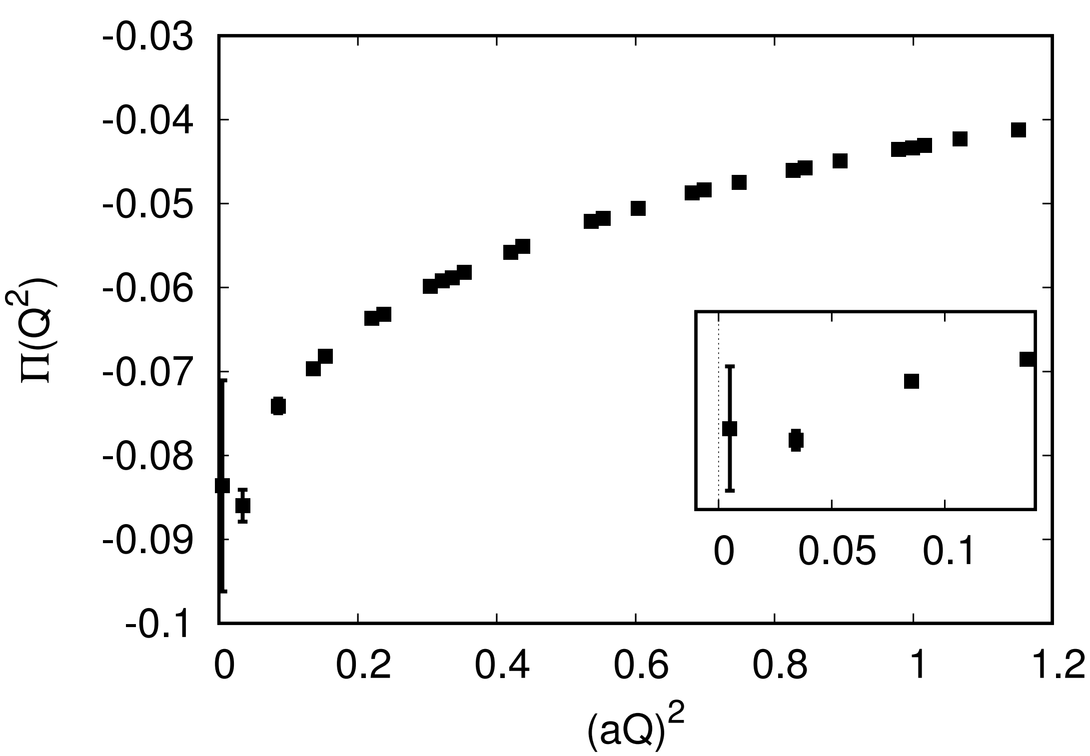
Third Plenary Workshop of the Muon g-2 Theory Initiative
Hadronic contributions to $(g\text{-}2)_\mu$, INT, Seattle, USA
September 9 - 13, 2019

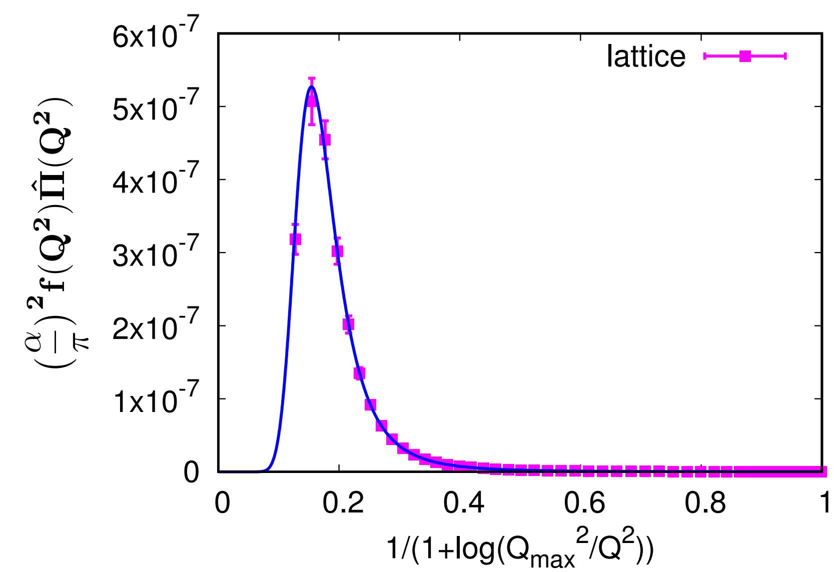
The leading hadronic contribution - HVP

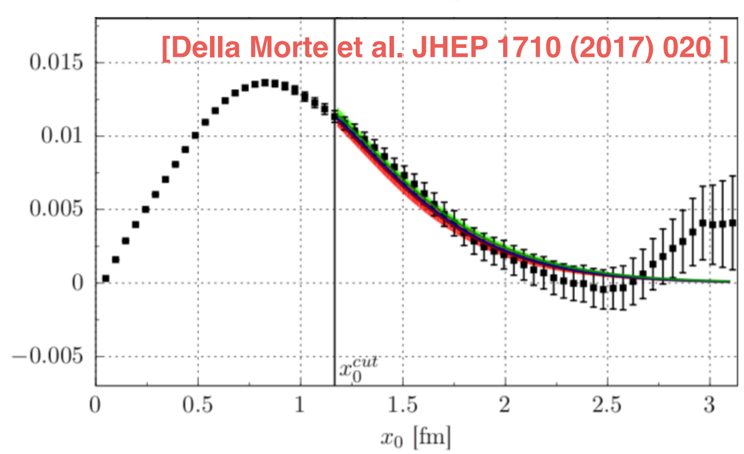


$$a_\mu^{HVP} = \left(\frac{\alpha}{\pi}\right)^2 \int_0^\infty dQ^2 f(Q^2) \times \hat{\Pi}(Q^2)$$

$$f(Q^2) = m_\mu^2 Q^2 Z^3(Q^2) \frac{1 - Q^2 Z(Q^2)}{1 + m_\mu^2 Q^2 Z^2(Q^2)} \qquad Z(Q^2) = \frac{\sqrt{Q^4 + 4m_\mu^2 Q^2} - Q^2}{2m_\mu^2 Q^2}$$



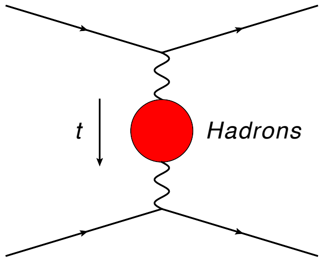




Summary of ways to enhance StN ratio:
[Talk by A. El-Khadra, Mon. 14.00]

MUonE project

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



➡ In space-like momenta region

➡ Obtain $a_\mu^{\text{had, LO}}$ by utilising the running of α_{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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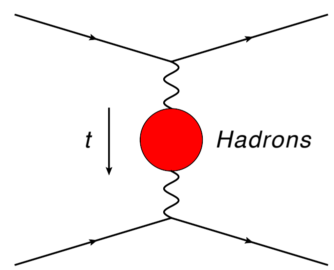

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[Lautrup, de Rafael '69]

➡ Proposal to measure precisely the Q^2 - dependent fine-structure constant:

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

[Phys.Lett. B746 (2015) 325-329 by Carloni, Passera,Trentadue, Venanzoni] @e+e- detector

[Eur.Phys.J. C77 (2017) no.3, 139 by Abbiendi et al.] Physics Beyond Colliders@CERN

[See talk by C. Carloni Calame, Tue. 16.00]

MUonE project

[LOI submitted to SPSC@CERN in June 2019]
https://cds.cern.ch/record/2677471

Collaboration:

48 experiment + 20 theory and growing ...!

1st MUonE Collaboration Meeting at CERN

25-26 March 2019
CERN
Europe/Zurich timezone

Search...

- Overview
- Timetable
- Contribution List
- Registration
- Participant List
- Videoconference Rooms

This is the first Collaboration meeting of the MUonE experiment at CERN. MUonE plans to measure the running of alpha(t) space-like by means of the elastic scattering μe→ μe. The required high-intensity muon beam is available at the M2 beam line of the CERN SPS. Such a measurement will provide direct sensitivity to the leading hadronic contribution to the muon anomaly, allowing, together with the measurements of the muon g-2 at Fermilab and J-PARC, a stringent test of the Standard Model.

The meeting will start in the morning of Monday, March 25th (room 222-R-01, Filtration Plan) and it will finish on Tuesday 26th (room 32-1-A24 followed by 6-R-012) early afternoon.

Starts 25 Mar 2019, 09:00
Ends 26 Mar 2019, 19:00
Europe/Zurich

CERN
6/R-012 - Salle conference BE

CERN Physics Beyond Colliders

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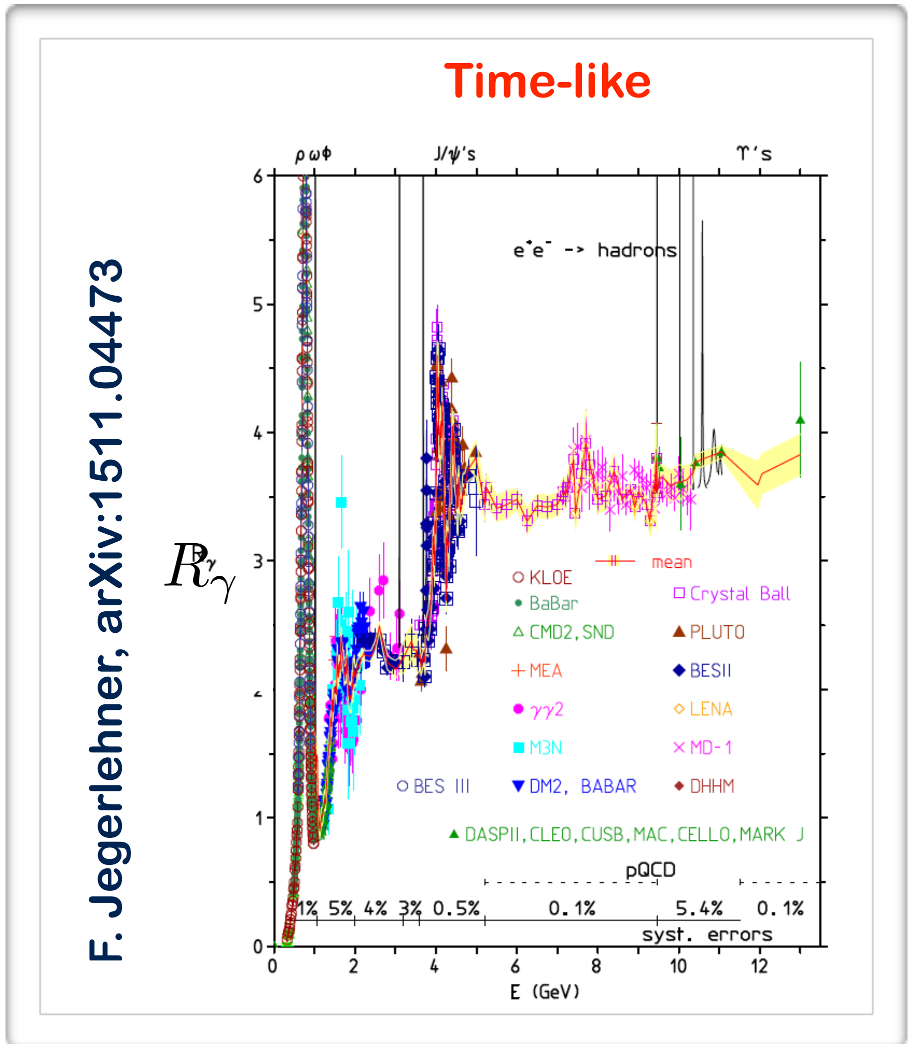
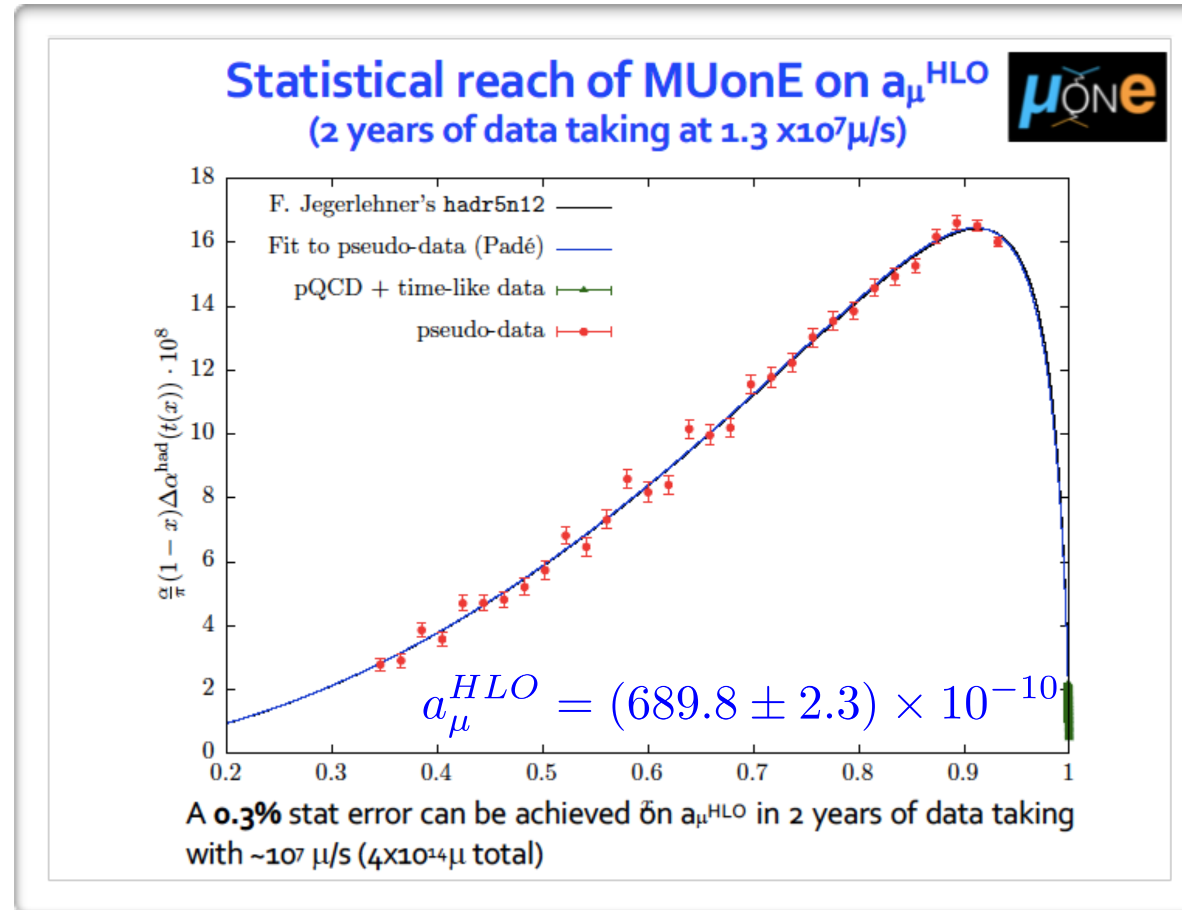
MUonE: space-like evaluation of $a_\mu^{HVP,\,LO}$

[Lautrup, de Rafael '69]

[T. Blum '03]





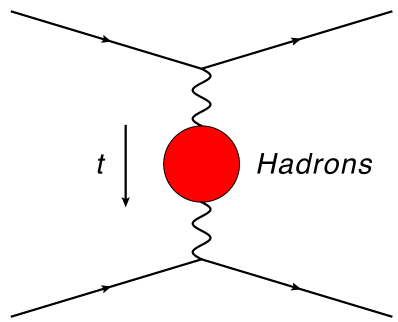
➡ combination of many exp. data sets

➡ smooth integrand

➡ single experiment enough - **but high accuracy needed (one-loop effect)**

MUonE: theoretical effort underway

➡ **Theory in low-Q^2 [dominating HVP integral]: To extract $\Delta\alpha_{had}(t)$ from this measurement, the ratio of the SM cross sections in the signal and normalisation regions must be known at ≲ 10ppm!**



[NNLO amp.: Mastrolia, Passera, Primo, Schubert JHEP1711(2017), Di Vita, Laporta, Mastrolia, Primo, Schubert JHEP09(2018)016]

[NNLO had. contributions Fael JHEP1902(2019)027, Fael, Passera Phys. Rev. Lett. 122(2019) 19, 192001]

[MC@QED NLO+weak Alacevich, Carloni Calame, Chiesa, Montagna, Nicrosini, Piccinini, JHEP1902 (2019)155]

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

[Fixed-order NNLO+ Resumation Broggio; Banerjee Engel, Gnendiger, Signer, Ulrich JHEP02(2019)118]

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[0.001,0.14] GeV^2

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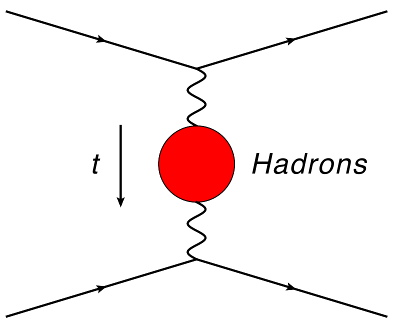

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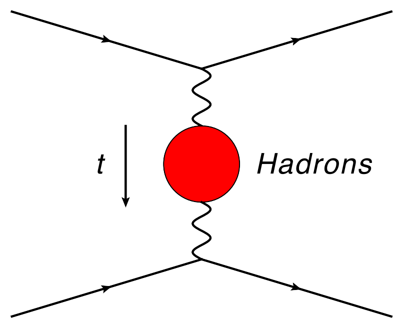

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[4, ∞] GeV²

➡ **Theory in high-Q^2: PT** √

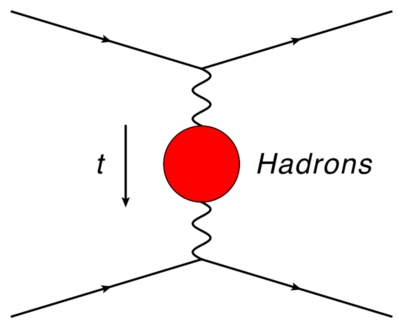
[Chetyrkin et al. '96]

[Harlander&Steinhauser '02]

MUonE: theoretical effort underway

[0.001,0.14] GeV^2

➡ Theory in low-Q^2 [dominating HVP integral]: To extract $\Delta\alpha_{had}(t)$ from this measurement, the ratio of the SM cross sections in the signal and normalisation regions must be known at $\lesssim$ 10ppm!



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[0.14,4] GeV^2

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

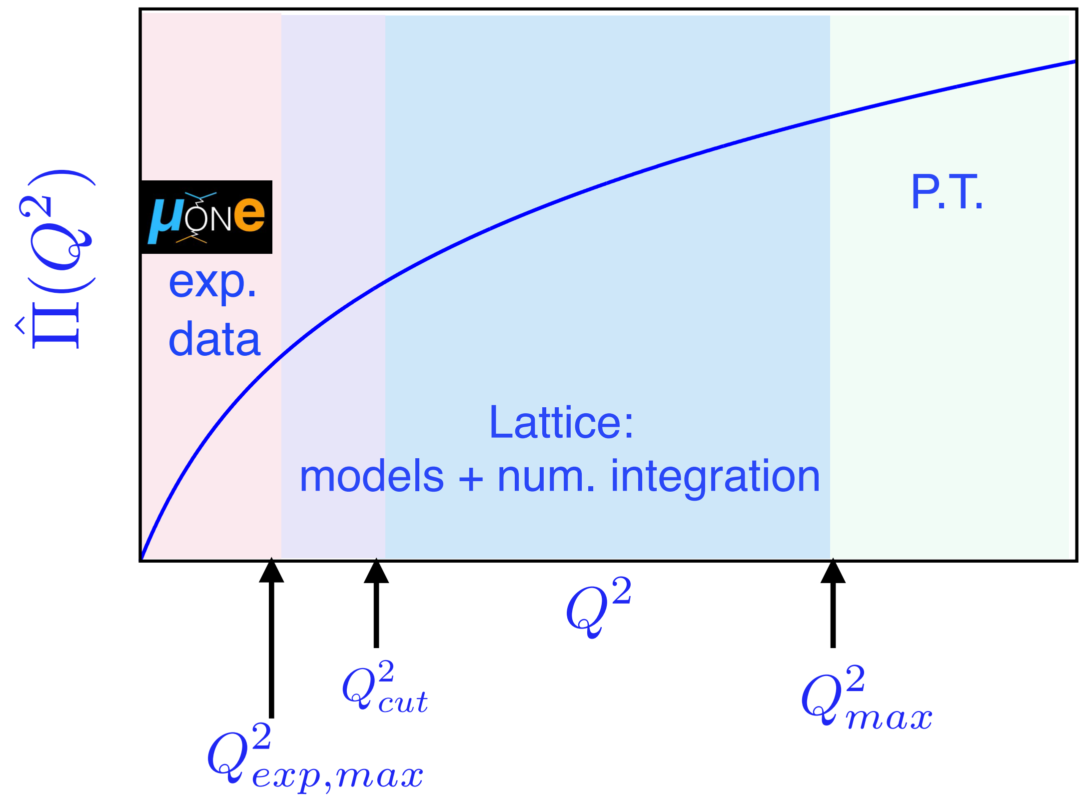
[4, ∞] GeV^2

➡ Theory in high-Q^2: PT √

[Chetyrkin et al. '96]

[Harlander&Steinhauser '02]

Hybrid method: MUonE experiment +lattice

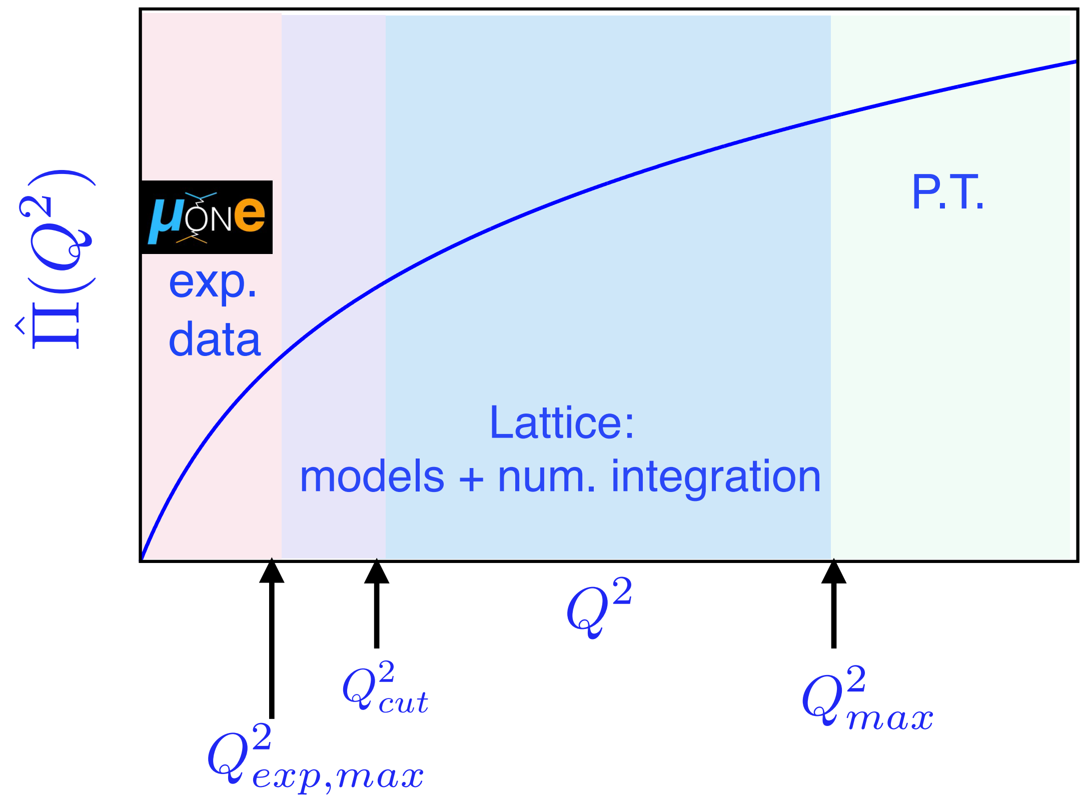


$$a_\mu^{had,LO} = \underbrace{\frac{\alpha}{\pi}\int_0^{0.93\ldots} dx(1-x)\Delta\alpha_{had}[Q^2(x)]}_{I_0} + \underbrace{\left(\frac{\alpha}{\pi}\right)^2\int_{0.14}^{Q^2_{max}} dQ^2 f(Q^2)\times\hat{\Pi}(Q^2)}_{I_1} + \underbrace{\left(\frac{\alpha}{\pi}\right)^2\int_{Q^2_{max}}^{\infty} dQ^2 f(Q^2)\times\hat{\Pi}_{pert.}(Q^2)}_{I_2}$$

- **lattice QCD**
- **R-ratios**

[Chetyrkin et al. '96]
[Harlander&Steinhauser '02]

Hybrid method: MUonE experiment +lattice



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- **lattice QCD**
- **R-ratios**

- I_1 **contribution to the HVP from the lattice:**

HVP: Intermediate-Q^2 range integration [MKM & N. Cardoso ’18]

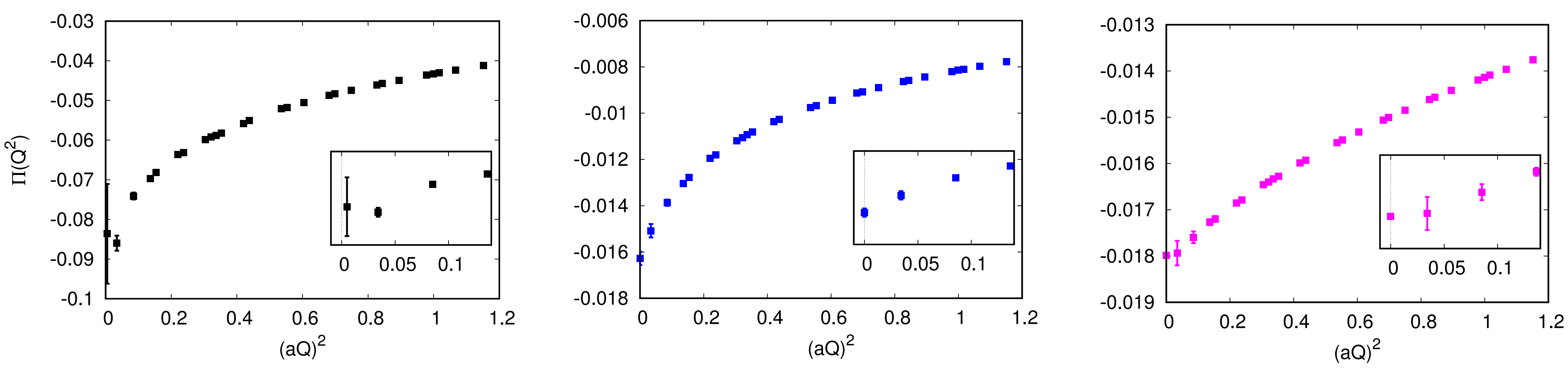
$$a_\mu^{had,LO} = \underbrace{\frac{\alpha}{\pi}\int_0^{0.93\ldots} dx(1-x)\Delta\alpha_{had}[Q^2(x)]}_{I_0} + \underbrace{\left(\frac{\alpha}{\pi}\right)^2 \int_{0.14}^{Q^2_{max}} dQ^2 f(Q^2)\times\hat{\Pi}(Q^2)}_{I_1} + \underbrace{\left(\frac{\alpha}{\pi}\right)^2 \int_{Q^2_{max}}^{\infty} dQ^2 f(Q^2)\times\hat{\Pi}_{pert.}(Q^2)}_{I_2}$$

- ➡ I_1 on CLS ensembles with N_f=2 O(a) improved Wilson fermions (A5,E5,F6,G8,N6,O7)
- ➡ m_π≈180-440MeV, continuum extrapolation (0.05-0.09fm), chiral extrapolation to $m_{\pi,phys}$
- ➡ Partially quenched: s, c (κ_s,κ_c taken from [CLS/Mainz, JHEP 1710 (2017)])
- ➡ Neglecting isospin breaking effects ($m_u \neq m_d$ and $\alpha_{em} \neq 0$)
- ➡ $m_\pi L \geq 4$, long-distance effects effects in I_1 not yet explored explicitly

HVP: Intermediate-Q^2 range integration [MKM & N. Cardoso ’18]

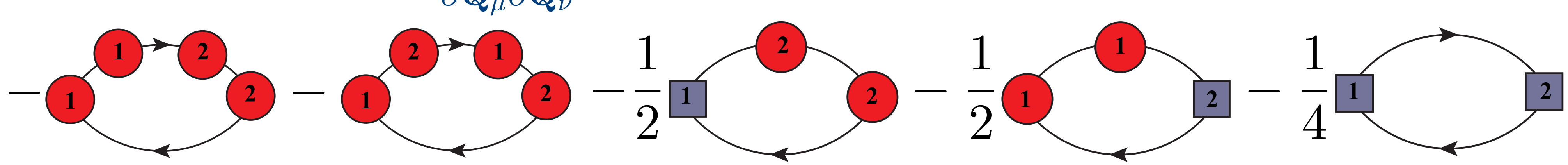
light (u/d) — strange — charm

m_π = 311 MeV



- ➡ Statistical precision in I_1 (still) determined by $\Pi(0)$ $\hat{\Pi}(Q^2) = 4\pi^2(\Pi(Q^2) - \Pi(0))$
- ➡ Expansion of the quark propagator around zero spatial momentum “derivative method”/“Rome method”
- ➡ 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)]

$\Pi(0) =$



- ➡ Light contribution: $Q^2 \to 0$ extrapolation

HVP: Intermediate-Q^2 range integration [ETMC ’18 and ETMC ’19]

light (u/d)

[D. Giusti, F. Sanfilippo, S. Simula, Phys. Rev. D 98, 114504 (2018)]

Using the (dual + π-π) repr.

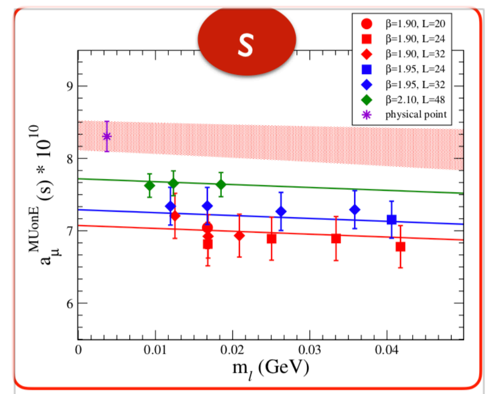
$$\left[a_\mu^{\text{LO-HVP}}\right]_>(ud) = 81.2(1.7)\cdot 10^{-10}$$

quark-connected terms only

[Talk by D. Giusti, Fri. 9.00]

strange

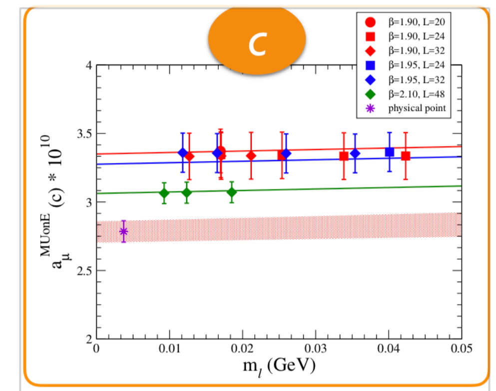
[D. Giusti @ Lattice 2019]



$$\left[a_\mu^{\text{LO-HVP}}\right]_>(s) = 8.30(21)_{stat}(32)_{syst}\cdot 10^{-10}$$

charm

[D. Giusti @ Lattice 2019]



$$\left[a_\mu^{\text{LO-HVP}}\right]_>(c) = 2.785(78)_{stat}(68)_{syst}\cdot 10^{-10}$$

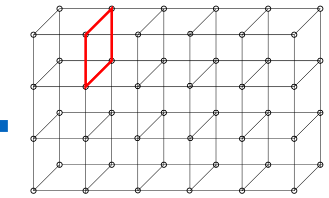
$$\left[a_\mu^{\text{LO-HVP}}\right]_>(s) = 8.30(21)_{stat}(32)_{syst}\cdot 10^{-10}$$

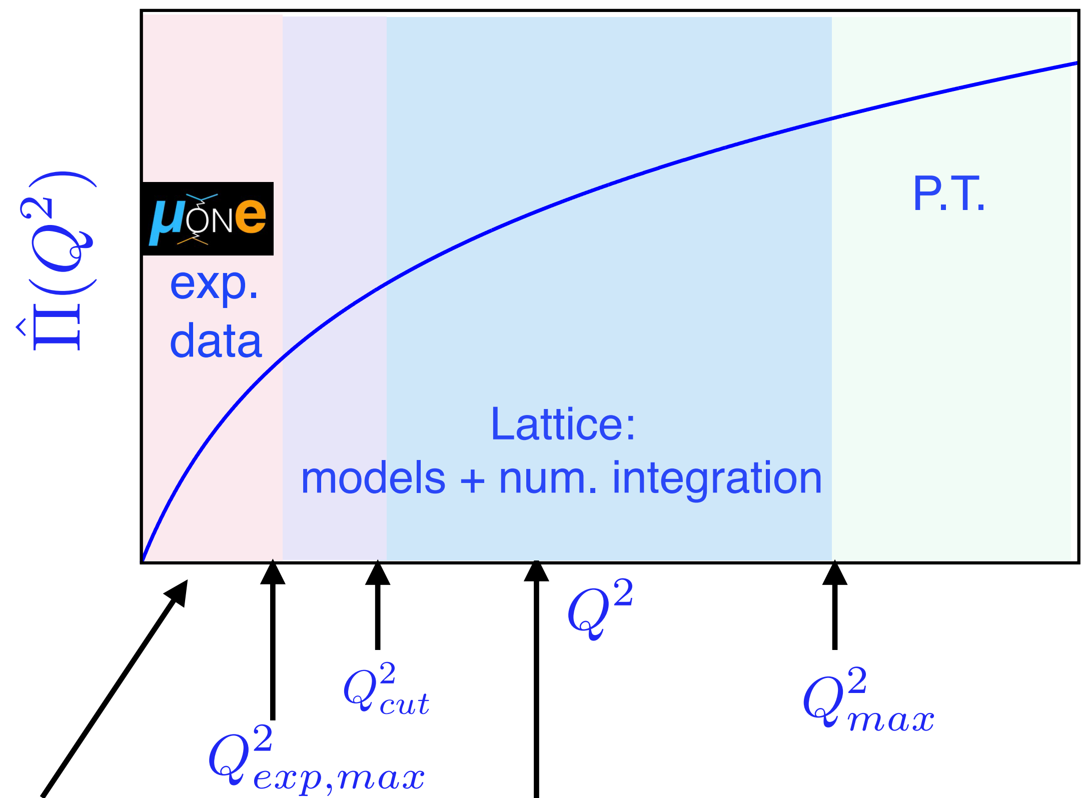
$$\left[a_\mu^{\text{LO-HVP}}\right]_>(c) = 2.785(78)_{stat}(68)_{syst}\cdot 10^{-10}$$

f	$[\delta a_\mu^{\text{HVP}}]_>(f)\cdot 10^{10}$
ud	0.9 (0.3)
s	−0.0005 (0.0004)
c	0.0034 (0.0007)
total	0.9 (0.3)

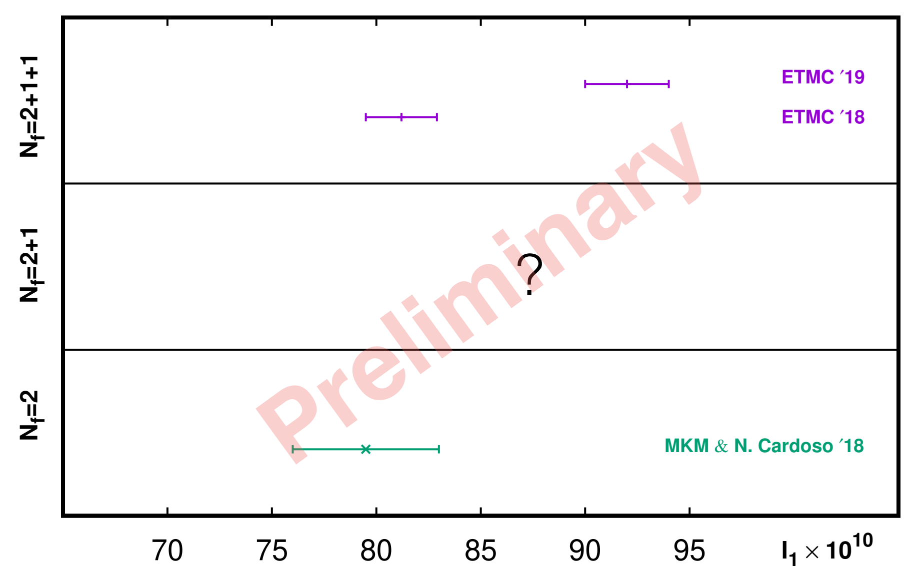
$$\left[a_\mu^{\text{HVP}}\right]_> = 92(2)\cdot 10^{-10}$$

preliminary

Hybrid strategy for the HVP: MUonE +  + P.T.



- **Low momentum region**
  - ➡ **Experiment (NLO, NNLO, radiative corrections …)**



[Talk by D. Giusti, Fri. 9.00]
[D. Giusti et al., Phys. Rev. D 98, 114504]

$$[\delta I_1 / a_\mu^{had,LO}] \simeq 0.3 - 0.5\%$$

MUonE after 2 yrs of data taking:

$$[\delta a_\mu^{had,LO} / a_\mu^{had,LO}] \simeq 0.3$$

HVP: Intermediate-Q² range integration

$$a_\mu^{had,LO} = \underbrace{\frac{\alpha}{\pi}\int_0^{0.93\ldots} dx(1-x)\Delta\alpha_{had}[Q^2(x)]}_{I_0} + \underbrace{\left(\frac{\alpha}{\pi}\right)^2 \int_{0.14}^{Q^2_{max}} dQ^2 f(Q^2)\times\hat{\Pi}(Q^2)}_{I_1} + \underbrace{\left(\frac{\alpha}{\pi}\right)^2 \int_{Q^2_{max}}^{\infty} dQ^2 f(Q^2)\times\hat{\Pi}_{pert.}(Q^2)}_{I_2}$$

- A recent proposal [https://cds.cern.ch/record/2677471] where I_1 and I_2 are evaluated directly from MUonE data [see talk by C. Carloni Calame, Tue. 16.00]

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

- "Fermion-like" parametrization ansatz for $\Delta\alpha_{had}[Q^2(x)]$

$$\Delta\alpha_{had}[Q^2(x)] = KM\left\{-\frac{5}{9} - \frac{4M}{3Q^2} + \left(\frac{4M^2}{3Q^4} + \frac{M}{3Q^2} - \frac{1}{6}\right)\frac{2}{\sqrt{1-\frac{4M}{Q^2}}}\log\left|\frac{1-\sqrt{1-\frac{4M}{Q^2}}}{1+\sqrt{1-\frac{4M}{Q^2}}}\right|\right\}$$

- Recursively used for the NNLO contribution [see talk by M. Fael, Tue. 16.50]
- Systematics estimate: conventional wisdom of lattice QCD calculations

Summary & Outlook

- In the 2-3 years, 0.3% statistical uncertainty in HVP expected from MUonE
- Measuring the running of α_{QED} in the $Q^2 \in [0.001, 0.14]$ GeV^2 which dominates the HVP
- Hybrid method (Exp.+Lat.+P.T.): $I = I_0 + I_1 + I_2$, first cross-checks with different lattice discretisations in progress
- Outlook: use $m_{\pi,phys}$, revisit strategy for a_μ^{light} (TMR), isospin breaking corrections, estimate discr. effects

- MUonE: L.O.I. to SPSC@CERN submitted in June 2019!
- MUonE strategy to utilize low energy data for the entire Q^2 range [Talk by C. Carloni Calame, Tue. 16.00]
- Lattice invaluable for estimating the systematics of this approach [Sections IVA and IVC of the Muon g-2 Theory Initiative white paper: Lattice QCD calculations of the HVP]

- Open postdoctoral position at the University of Munich, Germany available from 1.1.2020: MUonE-related topics and lattice QCD(+QED) conceptual developments. Please share with potential candidates: https://labs.inspirehep.net/jobs/1751820

LMU LUDWIG-MAXIMILIANS-UNIVERSITÄT MÜNCHEN

Thank you!

MUonE Timeline

[LOI submitted to SPSC@CERN in June 2019]
https://cds.cern.ch/record/2677471

Planned activities and MUonE timescale

We expect a first feedback from SPSC in the next months, and hopefully have a pilot run approved for 2021.

- **2019-2020:**
  - prepare for a pilot run in 2021 (2 working modules)
  - theory development, systematics studies (beam momentum scale, detector resolution, MS), design optimization, data analysis development, establish an "official" collaboration.
- **2021:** pilot run.
- **2022:** add stations in sync with CMS production plan (50% by spring, 50% by end of the year).
- **2023-2024:** data taking with full apparatus.

[Talk by C. Carloni Calame, Tue. 16.00]