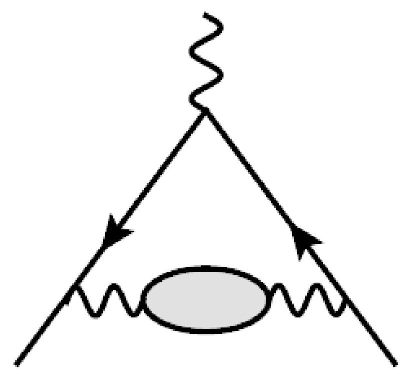
Muon轻子的反常磁矩

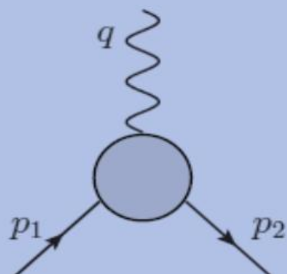
刘涛（高能所理论室）



中国高能物理非加速器战略研讨会
2021年5月15日

轻子反常磁矩

$$V_{int} = -\vec{\mu} \cdot \vec{B}, \quad \vec{\mu} = g\left(\frac{e}{2m}\right)\vec{s}.$$



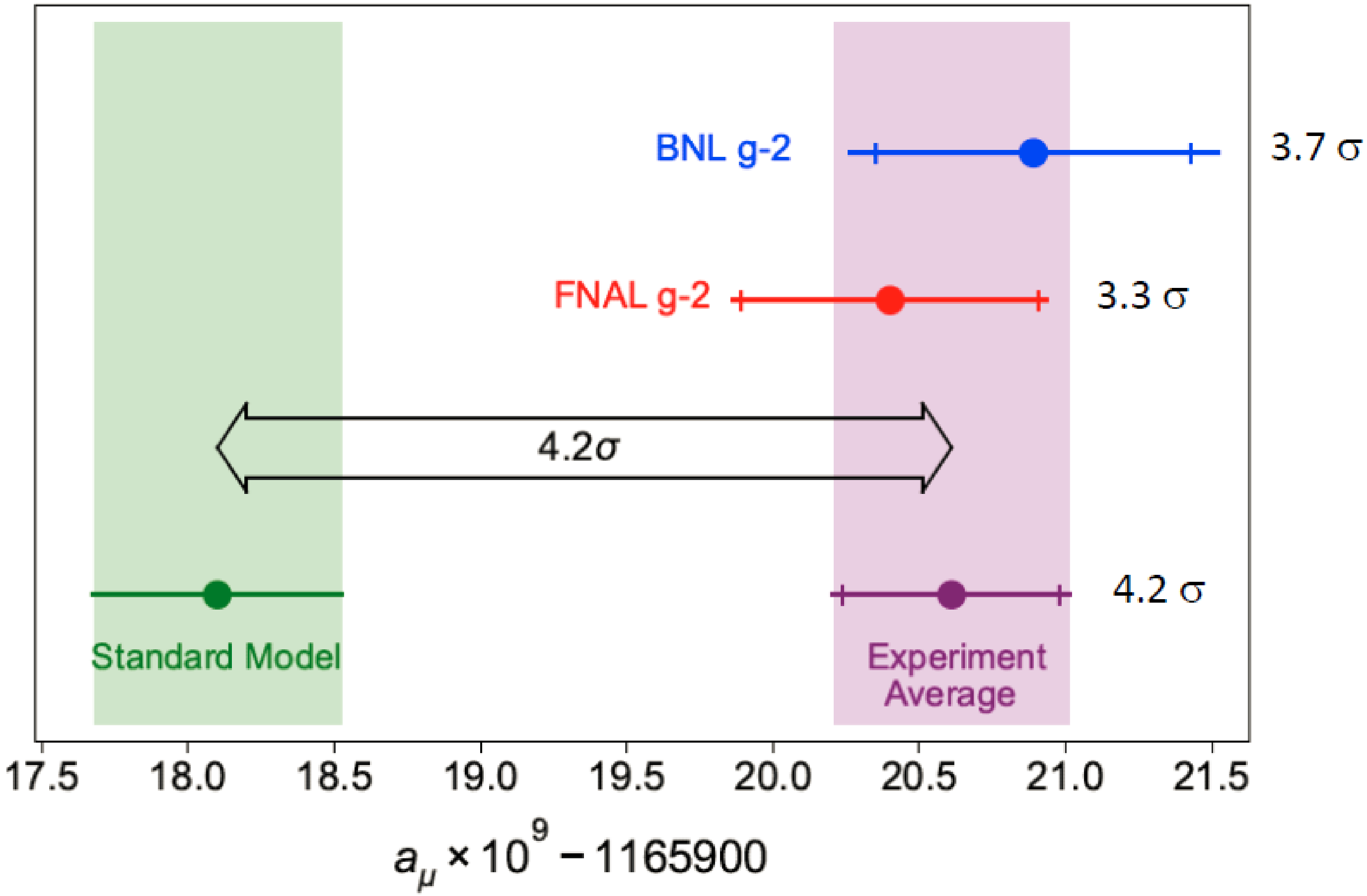
$$= -ie\,\bar{\psi}(p_2)\left(\gamma^\mu F_1(q^2) + i\frac{\sigma^{\mu\nu}q_\nu}{2m}F_2(q^2)\right)\psi(p_1)$$

$$F_1(0) = 1 \quad F_2(0) = \frac{g-2}{2} \equiv a_l$$

反常磁矩是迄今物理学中测量的最精确的物理量之一。

Muon轻子的质量大概为电子的200倍左右，对可能的新物理效应更敏感。

费米实验室的最新结果



$$a_\mu(\text{Exp}) - a_\mu(\text{SM}) = (251 \pm 59) \times 10^{-11}$$

$a_\mu(\text{Exp}) = 116\,592\,061(41) \times 10^{-11} \quad (0.35\ \text{ppm}).$

Muon g-2 Experiment

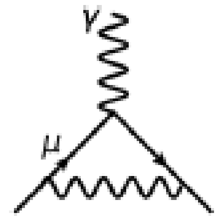
Newsroom

- First results from the Muon g-2 Experiment seminar April 7, 2021
- Physicists publish worldwide consensus of muon magnetic moment calculation June 11, 2020
- Muon g-2 receives DOE project management achievement award May 8, 2019
- Muon g-2 begins second run March 26, 2019
- Theorist publish highest precision prediction July 13, 2018
- Beam off, hard hats on July 12, 2018
- Mark Lancaster elected as co-spokesperson May 9, 2018
- Muon g-2 scientist Tammy Walton receives Brookhaven Lectureship award April 25, 2018
- Muon g-2 experiment officially starts up February 6, 2018
- Muon machine makes milestone magnetic map January 29, 2018
- Chris Polly is new Muon g-2 co-spokesperson January 16, 2018
- Muon g-2 ring receives first beam June 5, 2017
- Press release: Muon magnet's moment has arrived May 31, 2017
- Frontier Science Result: Muon g-2: New detectors for the Muon g-2 experiment Jan 23, 2015
- Digging begins for Muon g-2 and Mu2e beamlines Dec. 9, 2014
- High school students advance particle physics and their own science education at Fermilab Sept. 30, 2014
- Giant electromagnet completes its journey, moves into its new home at Fermilab July 31, 2014
- g-2 receives Mission Need approval from DOE Sept. 19, 2012
- Muon g-2 off to a running start May 3, 2012
- Fermilab's Muon Department at edge of Intensity Frontier March 29, 2012
- New Fermilab experiment to take muons out for a spin Aug. 19, 2011

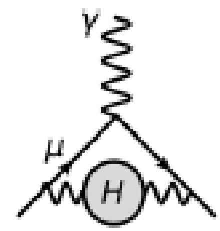
https://muon-g-2.fnal.gov/news.html

标准模型理论预言（10^{-11} ）：

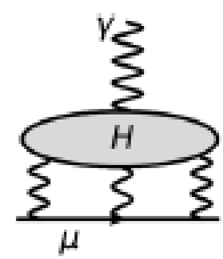
$$a_\mu = a_\mu^{\text{QED}} + a_\mu^{\text{had}} + a_\mu^{\text{EW}}$$



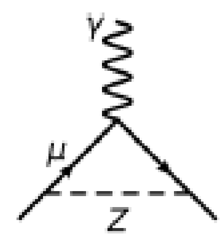
116 584 718.931(104)



6845(40)



92(18)



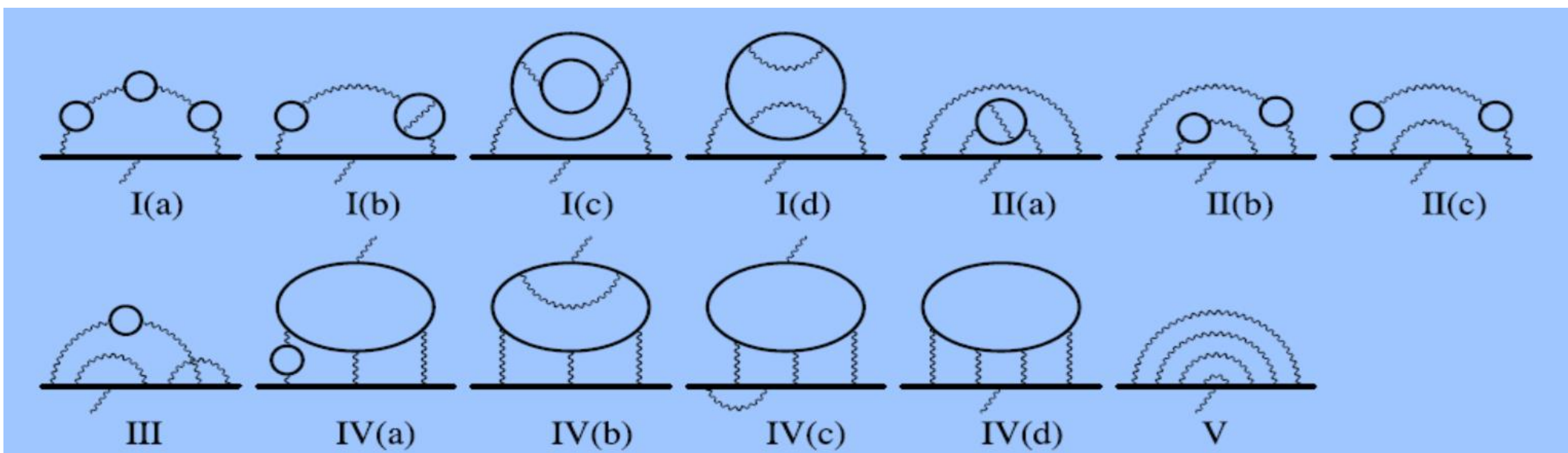
153.6(1.0)

[white paper， 2020]

QED修正

$$a_\mu(\text{Exp}) - a_\mu(\text{SM}) = (251 \pm 59) \times 10^{-11}$$

Order	with $\alpha(\text{Cs})$	with $\alpha(a_e)$
2	116 140 973.321(23)	116 140 973.233(28)
4	413 217.6258(70)	413 217.6252(70)
6	30 141.90233(33)	30 141.90226(33)
8	381.004(17)	381.004(17)
10	5.0783(59)	5.0783(59)
$a_\mu(\text{QED})$	116 584 718.931(30)	116 584 718.842(34)



QED部分的独立检验

Anomalous magnetic moment with heavy virtual leptons

Alexander Kurz (KIT, Karlsruhe, TTP and DESY, Zeuthen), Tao Liu (KIT, Karlsruhe, TP), Peter Marquard (DESY, Zeuthen), Matthias Steinhauser (KIT, Karlsruhe, TTP) (Nov 11, 2013)

Published in: *Nucl.Phys.B* 879 (2014) 1-18 • e-Print: 1311.2471 [hep-ph]

Light-by-light-type corrections to the muon anomalous magnetic moment at four-loop order

Alexander Kurz (DESY, Zeuthen and KIT, Karlsruhe, TTP), Tao Liu (KIT, Karlsruhe, TTP), Peter Marquard (DESY, Zeuthen), Alexander V. Smirnov (Moscow, ITEP), Vladimir A. Smirnov (SINP, Moscow) et al. (Aug 4, 2015)

Published in: *Phys.Rev.D* 92 (2015) 7, 073019 • e-Print: 1508.00901 [hep-ph]

Electron contribution to the muon anomalous magnetic moment at four loops

Alexander Kurz (DESY, Zeuthen and KIT, Karlsruhe, TTP), Tao Liu (Alberta U.), Peter Marquard (DESY, Zeuthen), Alexander Smirnov (Moscow State U.), Vladimir Smirnov (SINP, Moscow and Humboldt U., Berlin and Humboldt U., Berlin, Inst. Math.) et al. (Feb 8, 2016)

Published in: *Phys.Rev.D* 93 (2016) 5, 053017 • e-Print: 1602.02785 [hep-ph]

High-precision calculation of the 4-loop contribution to the electron g-2 in QED

Stefano Laporta (INFN, Bologna and Bologna U.) (Apr 23, 2017)

Published in: *Phys.Lett.B* 772 (2017) 232-238 • e-Print: 1704.06996 [hep-ph]

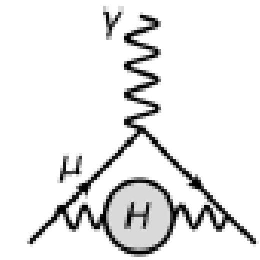
QED检验结果

$$a_\mu(\text{Exp}) - a_\mu(\text{SM}) = (251 \pm 59) \times 10^{-11}$$

	universal	e^-	τ	$e^- + \tau$
Steinhauser:	$-5.44(35)$	$+386.77(1.40)$	$+0.12371(15)$	$+0.182592(29)$
Kinoshita:	$-5.56894(245)$	$+386.264(17)$	$+0.12326(35)$	$+0.18259(12)$
Laporta:	$-5.56679893738506\ldots$			

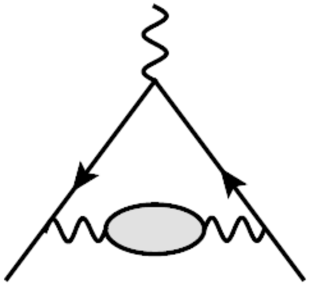
1. 四圈图贡献每部分至少有**两个**组用**不同**的方法计算过
2. 最大的理论误差比费米实验室预期的实验误差小**一个量级**

QCD修正： HVP



$6845(40) \times 10^{-11}$

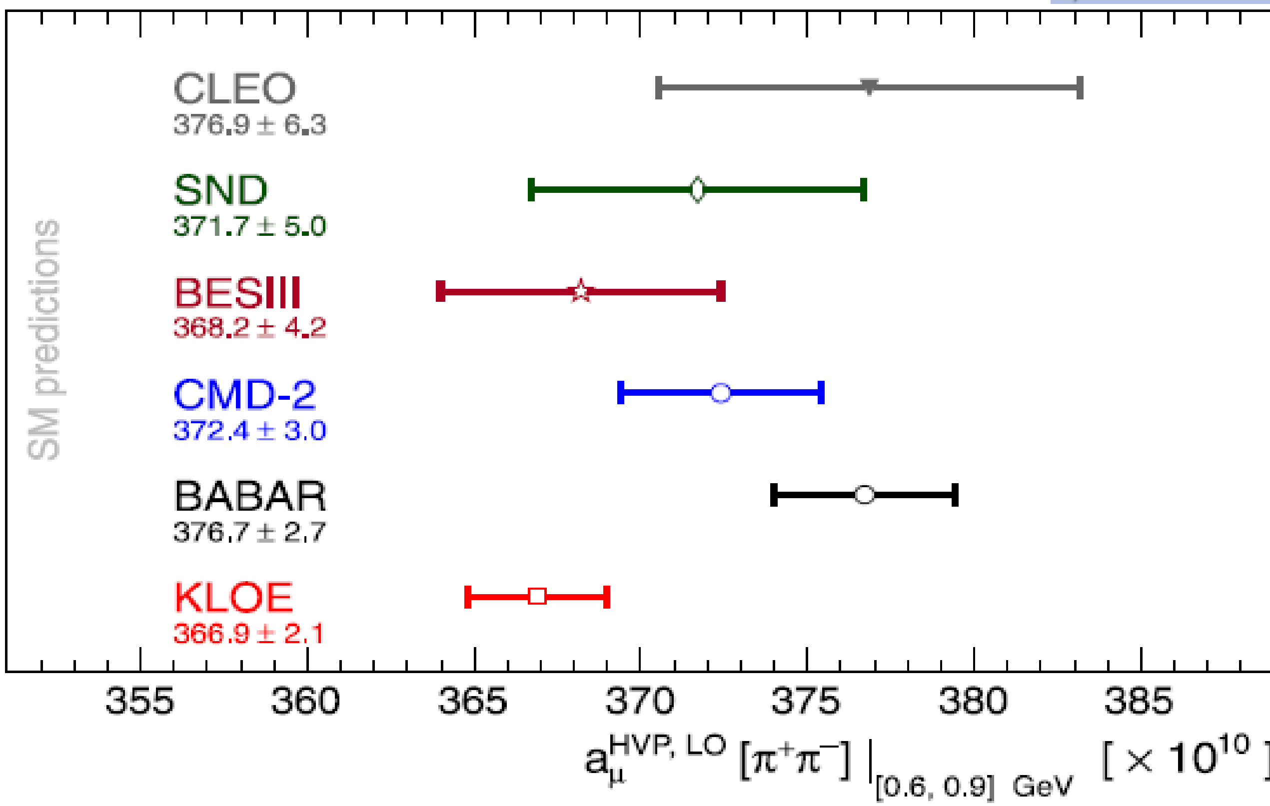
[LO+NLO+NNLO]



$$\Pi(q^2) = -\frac{q^2}{\pi}\int_{m_\pi^2}^{\infty}\frac{ds}{s}\frac{\mathrm{Im}\Pi(s)}{q^2-s}$$

$$R(s) = \frac{\sigma(e^+e^-\to hadrons)}{\sigma_0(e^+e^-\to\mu^+\mu^-)} = 12\pi\mathrm{Im}\Pi(s)$$

$a_\mu(\mathrm{FNAL}) = 116\,592\,040(54)\times 10^{-11}$ (0.46 ppm)



[white paper]

QCD修正：HVP

Workshop summary and concluding remarks

Hartmut Wittig

PRISMA+ Cluster of Excellence, Institute for Nuclear Physics and Helmholtz Institute Mainz

thanks to
A. El-Khadra, C. Lehner, D. Giusti, M. Golterman, V. Gülpers, L. Lellouch, C. McNeile, K. Szabo,...

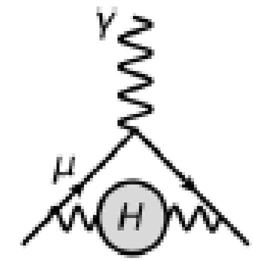
The hadronic vacuum polarization from l
Topical Workshop — Muon g – 2 Theory
16 – 20 November 2020

格点计算！

Workshop sessions

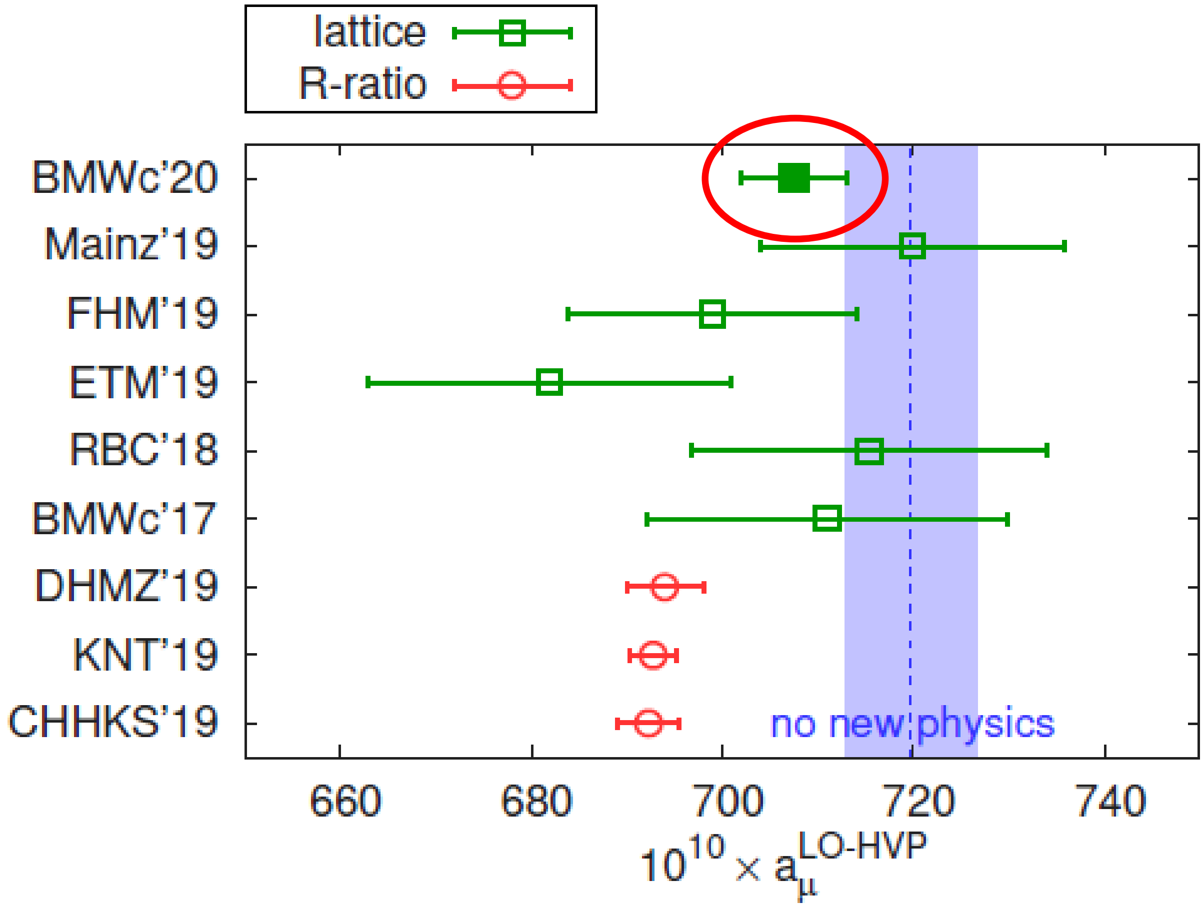
- **Quark-disconnected contributions** (H.B. Meyer)
- **Discretisation effects and continuum extrapolation** (R. Van de Water)
- **Scale setting** (K. Szabo)
- **Isospin breaking effects** (V. Gülpers)
- **Finite-size effects** (M. Golterman)
- **Long-distance regime of the vector correlator** (D. Mohler)
- **Lattice crosschecks** (L. Lellouch)
- **Comparison with e^+e^- / R-ratio data** (M. Hoferichter)

QCD修正：HVP



$6931(40) \times 10^{-11}$

[LO, white paper**]**



[Nature 592, 333-334 **(2021)]**

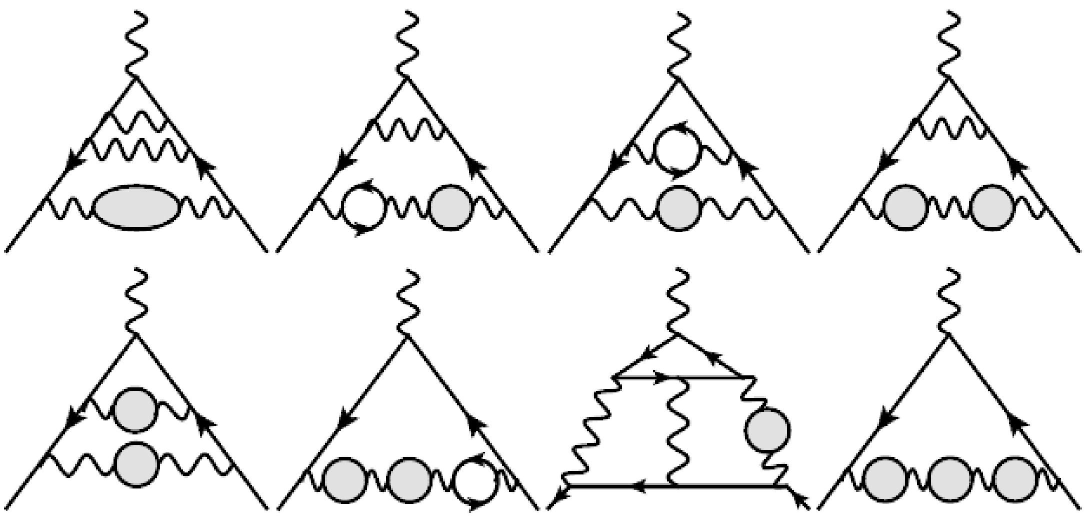
NNLO HVP

$$a_\mu(\text{FNAL}) = 116\,592\,040(54) \times 10^{-11} \quad (0.46 \text{ ppm})$$

Hadronic contribution to the muon anomalous magnetic moment to next-to-next-to-leading order

Alexander Kurz (DESY, Zeuthen and KIT, Karlsruhe, TTP), Tao Liu (KIT, Karlsruhe, TTP), Peter Marquard (DESY, Zeuthen), Matthias Steinhauser (KIT, Karlsruhe, TTP) (Mar 25, 2014)

Published in: *Phys.Lett.B* 734 (2014) 144-147 • e-Print: 1403.6400 [hep-ph]

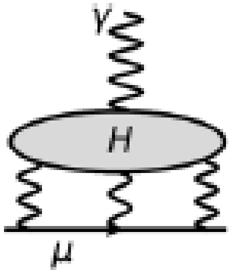


NNLO贡献：

$12.4 \pm 0.1 \times 10^{-11}$

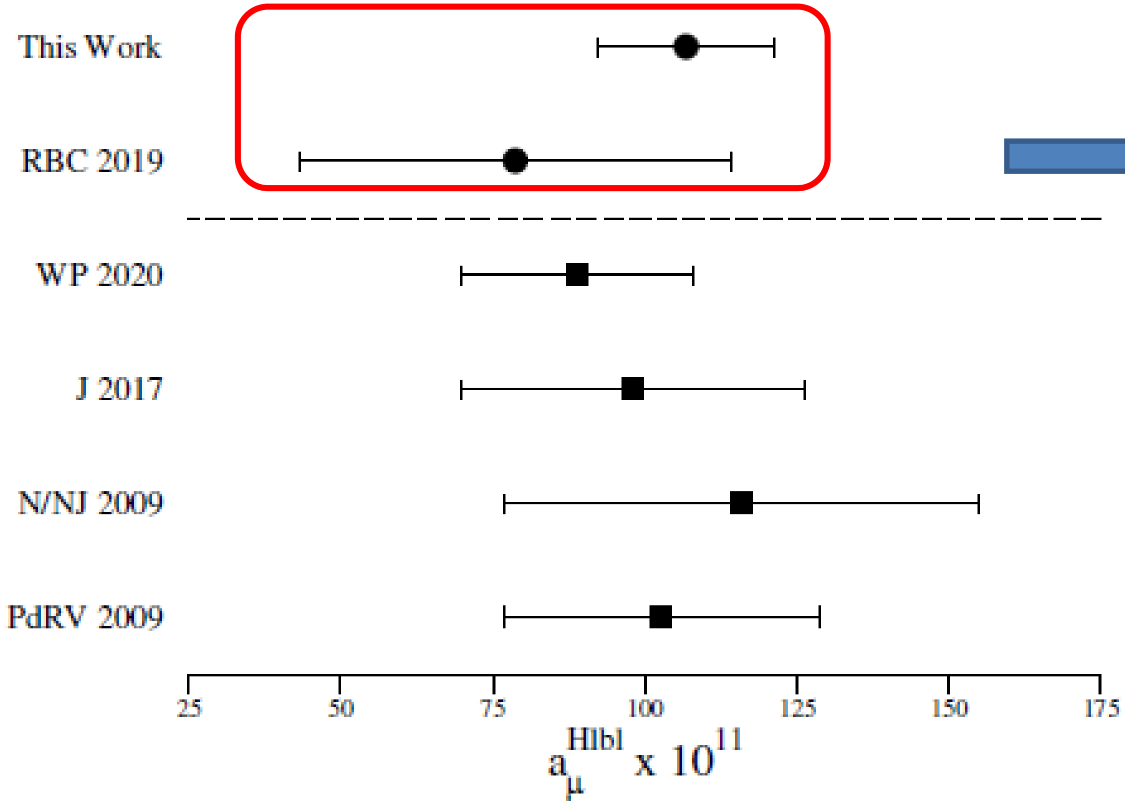
与将来预期的实验误差在同一个量级上

QCD HLBL



$92(18) \times 10^{-11}$

[LO, white paper]



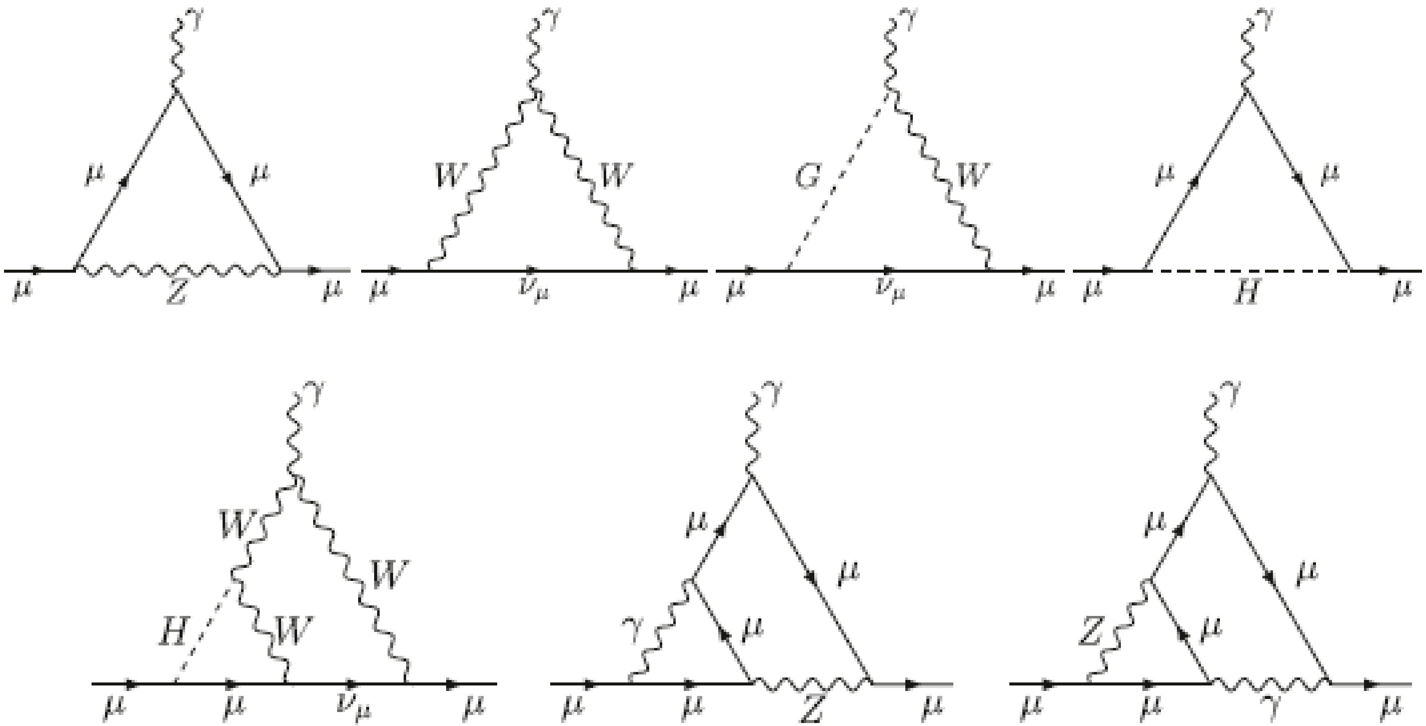
格点计算结果：

$106.8(14.7) \times 10^{-11}$

与实验值更接近。

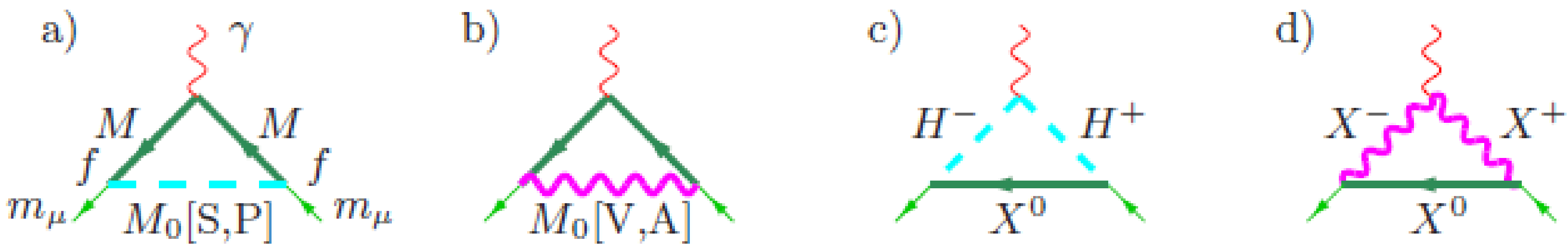
[arXiv: 2104.02632]

弱修正



$$a_\mu^{\mathrm{EW}} = 153.6(1.0) \times 10^{-11}$$

新物理效应

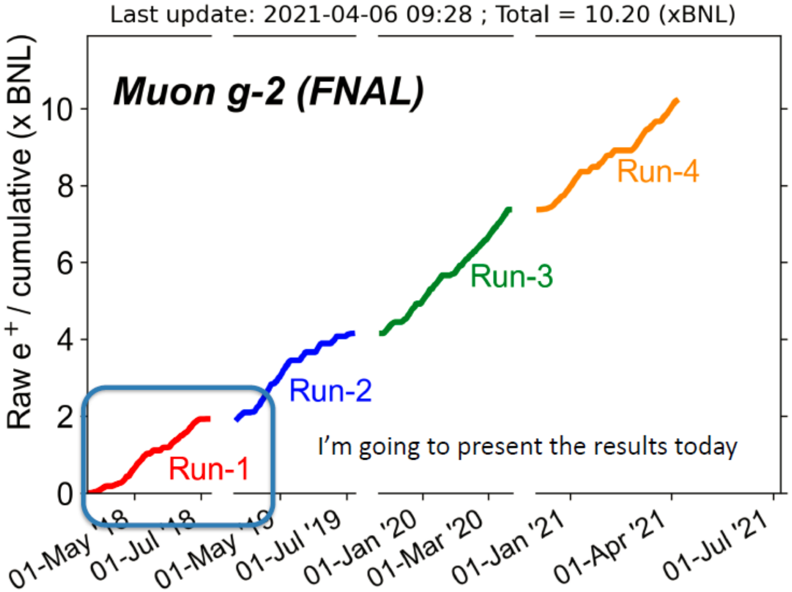


[Phys.Rept. 477 (2009) 1-110]

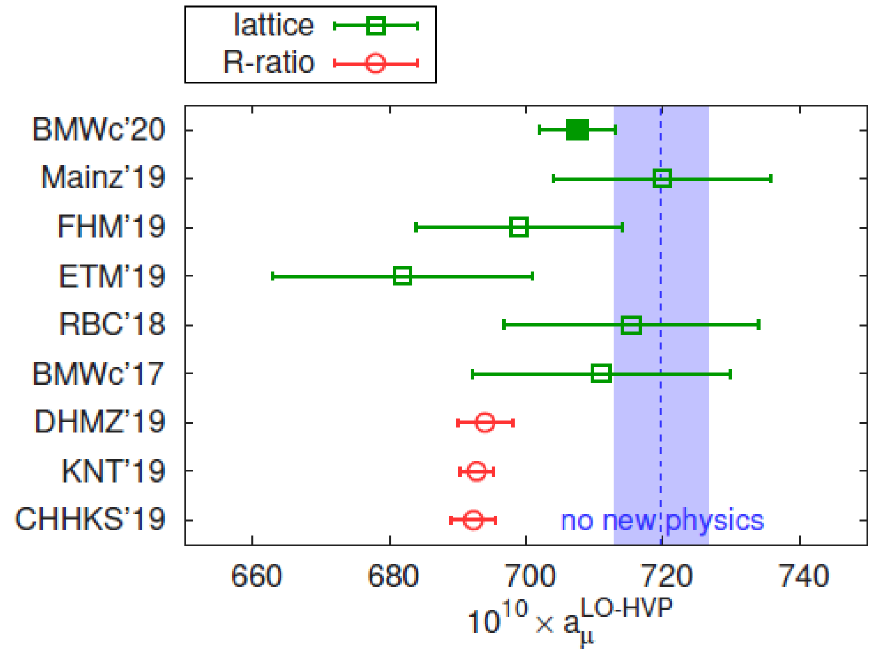
常见的新物理模型：Supersymmetry
Extra gauge bosons
Extra dimension
Leptoquarks
THDMs
Axion-like particles
…

伴随的其他方向的物理：中微子，暗物质，对撞机，新物理双圈修正等

实验与理论



Venanzoni, CERN Seminar, 8 April 2021



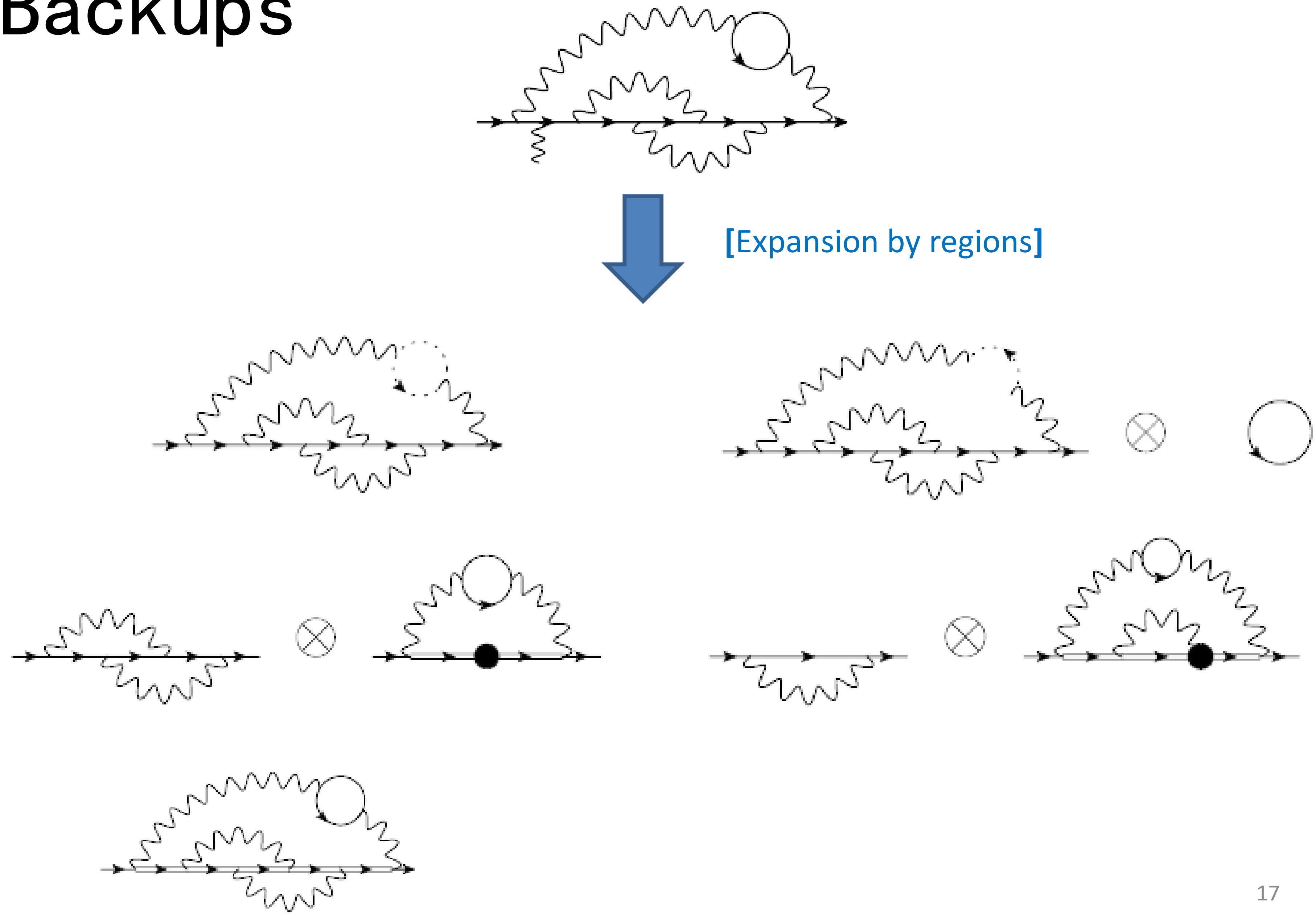
$$a_\mu(\text{FNAL}) = 116\,592\,040(54) \times 10^{-11} \quad (0.46\text{ ppm})$$

$$a_\mu(\text{Exp}) - a_\mu(\text{SM}) = (251 \pm 59) \times 10^{-11}$$

Order	with α(Cs)
2	116 140 973.321(23)
4	413 217.6258(70)
6	30 141.90233(33)
8	381.004(17)
10	5.0783(59)
a_μ(QED)	116 584 718.931(30)

谢谢各位老师！

Backups



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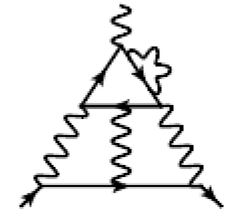
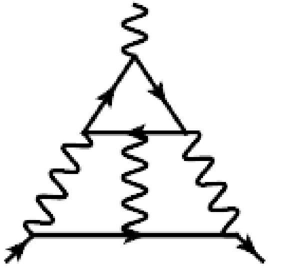


$$x = m_e/m_\mu \simeq 1/206.7682843$$

$$=27.395 \pm 0.014 + (4.93482 \pm 0.00003)\ell_x$$
$$+ x\left[-0.81 \pm 1.22 + 59.0235\ell_x\right]$$
$$+ x^2\left[142.5 \pm 7.6 + 40.6546\ell_x + 20.5582\ell_x^2 - 9.6167\ell_x^3 + 0.8333\ell_x^4\right]$$

$$=27.395 \pm 0.014 + (-26.3105 \pm 0.0002)$$
$$+ [-0.0039 \pm 0.0059 - 1.5219]$$
$$+ [0.003334 \pm 0.0001769 - 0.005070 + 0.01367 + 0.03409 + 0.01575]$$
$$= [1.084 \pm 0.014] + [-1.5259 \pm 0.0059] + [0.06177 \pm 0.00018]$$
$$= -0.380 \pm 0.016$$

$$= (20.52801865 + 0.42645778 + 0.00655695 + \ldots)$$



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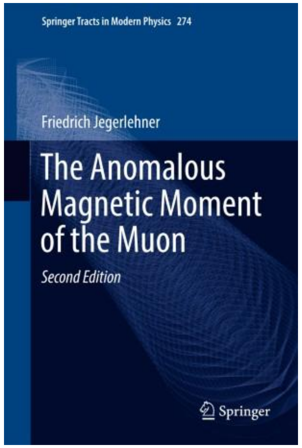

[white paper]

Beyond NLO, it was pointed out in Ref. [8] that even NNLO insertions are not negligible, as their combined effect

$$a_\mu^{\text{HVP, NNLO}} = 1.24(1) \times 10^{-10} \tag{2.35}$$

is of a similar size as the final accuracy goal of the Fermilab $g-2$ experiment. We will adopt this value for the NNLO contribution, which agrees well with the subsequent evaluation from Ref. [27], $a_\mu^{\text{HVP, NNLO}} = 1.22(1) \times 10^{-10}$.

4. Data-driven and dispersive approach to HLbL

J. Bijnens, G. Colangelo, F. Curciarello, H. Czyż, I. Danilkin, F. Hagelstein, M. Hoferichter, B. Kubis, A. Kupść, A. Nyffeler, V. Pascalutsa, E. Perez del Rio, M. Procura, C.F. Redmer, P. Sánchez-Puertas, P. Stoffer, M. Vanderhaeghen

Our final estimates for HLbL from Table 15 and HLbL at NLO [31] from Eq. (4.91) read as follows:

$$\begin{aligned} a_\mu^{\text{HLbL}} &= (69.3(4.1) + 20(19) + 3(1)) \times 10^{-11} \\ &= 92(19) \times 10^{-11}, \end{aligned} \tag{4.92}$$

$$a_\mu^{\text{HLbL, NLO}} = 2(1) \times 10^{-11}, \tag{4.93}$$

[31] G. Colangelo, M. Hoferichter, A. Nyffeler, M. Passera, P. Stoffer, Phys. Lett. B 735 (2014) 90, http://dx.doi.org/10.1016/j.physletb.2014.06.012, arXiv:1403.7512 [hep-ph].