

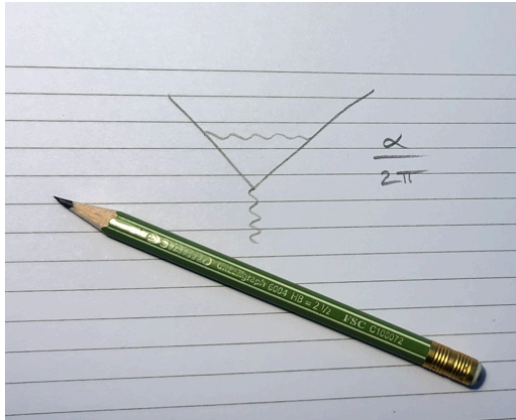
# Muon $g-2 \Leftrightarrow \Delta\alpha$ connection

Massimo Passera  
INFN Padova

ANOMALIES 2021  
10-12 November 2021  
Hyderabad, India

## Theory

## Experiment



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- Incredibly high precision: like measuring the length of a soccer field with an uncertainty smaller than the width of a human hair!
- If  $SM \neq EXP$ , then there must be new undiscovered physics!

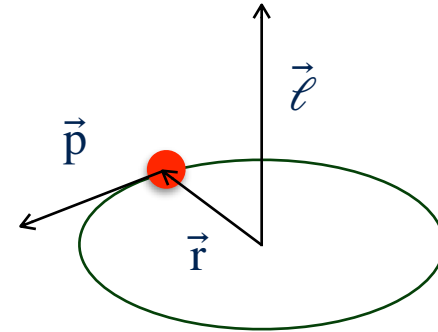
## The magnetic moment of the muon

The motion of a classical particle of mass **m** and charge **e** with angular momentum

$$\vec{\ell} = \vec{r} \times \vec{p}$$

generates the (orbital) magnetic moment :

$$\vec{\mu}_\ell = \frac{e}{2m} \vec{\ell}$$



In 1925 Goudsmit & Uhlenbeck propose that the electron has an “internal rotation” characterised by a “spin”  $\vec{s}$  and an associated magnetic moment, like a tiny bar magnet:

$$\vec{\mu}_s = g \frac{e}{2m} \vec{s}$$

with **g = 2**, not 1! Very strange, but worked.

JUST LIKE THE ELECTRON, IT HAS A MAGNETIC MOMENT THAT COMES FROM ITS CHARGE AND QUANTUM SPIN.



## $g = 2$ (or not?)

- 1928: Dirac's equation unifies the two fields that revolutionized XX<sup>th</sup> century physics: special relativity and quantum mechanics.

The Dirac equation predicts that a unit of spin interacts with a magnetic field twice as much as a unit of orbital angular momentum:  $g=2!$

Great triumph for the Dirac equation, but not the end of the story...



- 1948: With improvements in experimental techniques, Kusch & Foley measure  $g \neq 2!$  The electron “magnetic moment anomaly” is:

$$a = (g-2)/2 = 0.00119(5)$$

What happened?? A relativistic **quantum field theory** of electromagnetism, ie Quantum ElectroDynamics (QED), is needed!

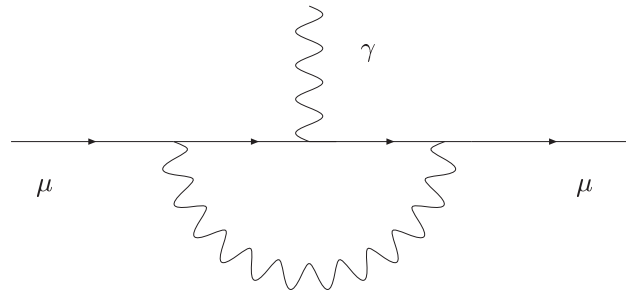
## The QED prediction

- 1948: Schwinger, using Quantum ElectroDynamics (QED), predicts

$$a = (g-2)/2 = \alpha/(2\pi) = 0.00116$$

in perfect agreement with Kusch & Foley's measurement

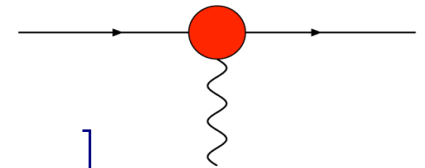
$$a = (g-2)/2 = 0.00119(5)$$



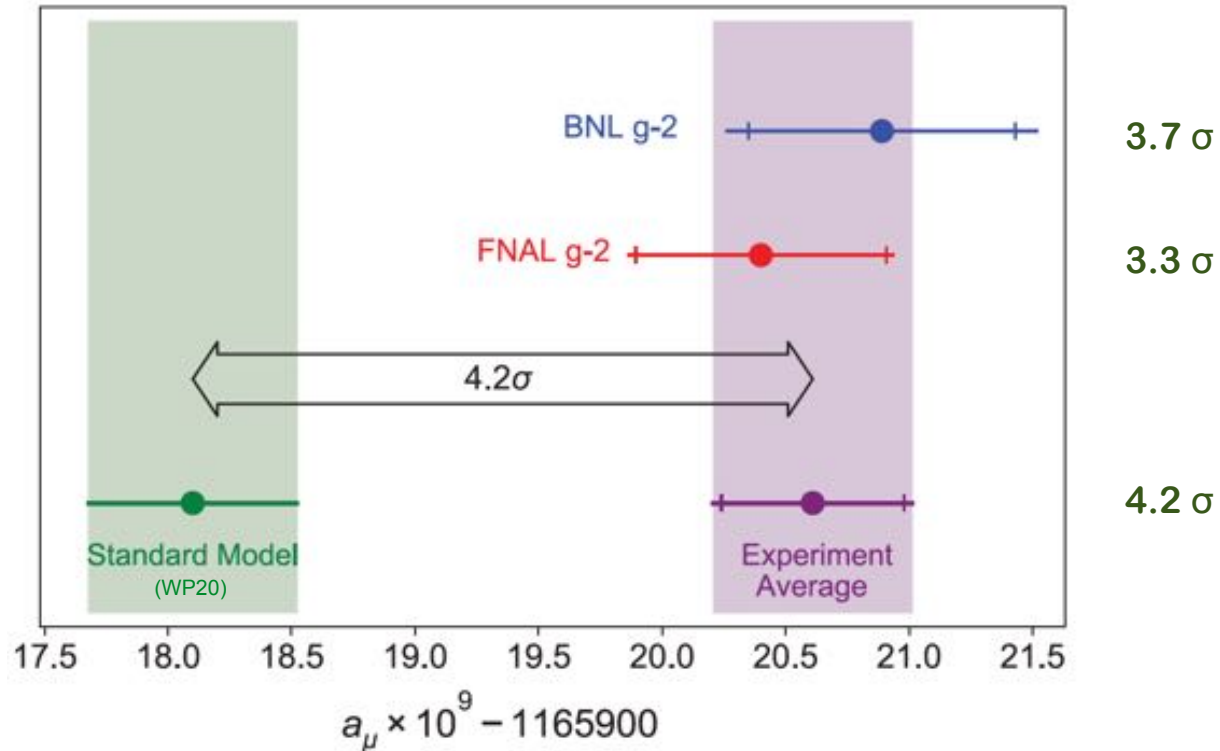
- Tremendous quantitative triumph for relativistic QFT (QED).
- Today we keep studying the lepton-photon vertex:

$$\Gamma^\mu = ie[\gamma^\mu F_1(q^2) + \frac{i\sigma^{\mu\nu} q_\nu}{2m} F_2(q^2) + \dots]$$

$$F_1(0) = 1 \quad F_2(0) = a$$



See Lee Roberts' talk



$$a_{\mu}^{\text{EXP}} = (116592089 \pm 63) \times 10^{-11} [0.54\text{ppm}] \quad \text{BNL E821}$$

$$a_{\mu}^{\text{EXP}} = (116592040 \pm 54) \times 10^{-11} [0.46\text{ppm}] \quad \text{FNAL E989 Run 1}$$

$$a_{\mu}^{\text{EXP}} = (116592061 \pm 41) \times 10^{-11} [0.35\text{ppm}] \quad \text{WA}$$

- FNAL aims at  $16 \times 10^{-11}$ . First 4 runs completed, 5th just started.
- Muon g-2 proposal at J-PARC: Phase-1 with  $\sim$  BNL precision.

- **Muon g-2: the Standard Model prediction**
- **Muon g-2  $\iff \Delta\alpha$  connection**
- **The MUonE project**

# Muon $g-2$ : the Standard Model prediction

**WP20 = White Paper of the Muon  $g-2$  Theory Initiative: [arXiv:2006.04822](https://arxiv.org/abs/2006.04822)**



# Muon g-2: the QED contribution



$$a_{\mu}^{\text{QED}} = (1/2)(\alpha/\pi) \quad \text{Schwinger 1948}$$

$$+ 0.765857426 (16) (\alpha/\pi)^2$$

Sommerfield; Petermann; Suura&Wichmann '57; Elend '66; MP '04

$$+ 24.05050988 (28) (\alpha/\pi)^3$$

Remiddi, Laporta, Barbieri ... ; Czarnecki, Skrzypek '99; MP '04;  
Friot, Greynat & de Rafael '05, Ananthanarayan, Friot, Ghosh 2020

$$+ 130.8780 (60) (\alpha/\pi)^4$$

Kinoshita & Lindquist '81, ... , Kinoshita & Nio '04, '05;  
Aoyama, Hayakawa, Kinoshita & Nio, 2007, Kinoshita et al. 2012 & 2015;  
Steinhauser et al. 2013, 2015 & 2016 (all electron &  $\tau$  loops, analytic);

Laporta, PLB 2017 (mass independent term) **COMPLETED!**

$$+ 750.86 (88) (\alpha/\pi)^5 \quad \text{COMPLETED!}$$

Kinoshita et al. '90, Yelkhovsky, Milstein, Starshenko, Laporta, ...

Aoyama, Hayakawa, Kinoshita, Nio 2012, 2015, 2017 & 2019.

Volkov 1909.08015:  $A_1^{(10)}$ [no lept loops] at variance, but negligible  $\delta a_{\mu} \sim 6 \times 10^{-14}$

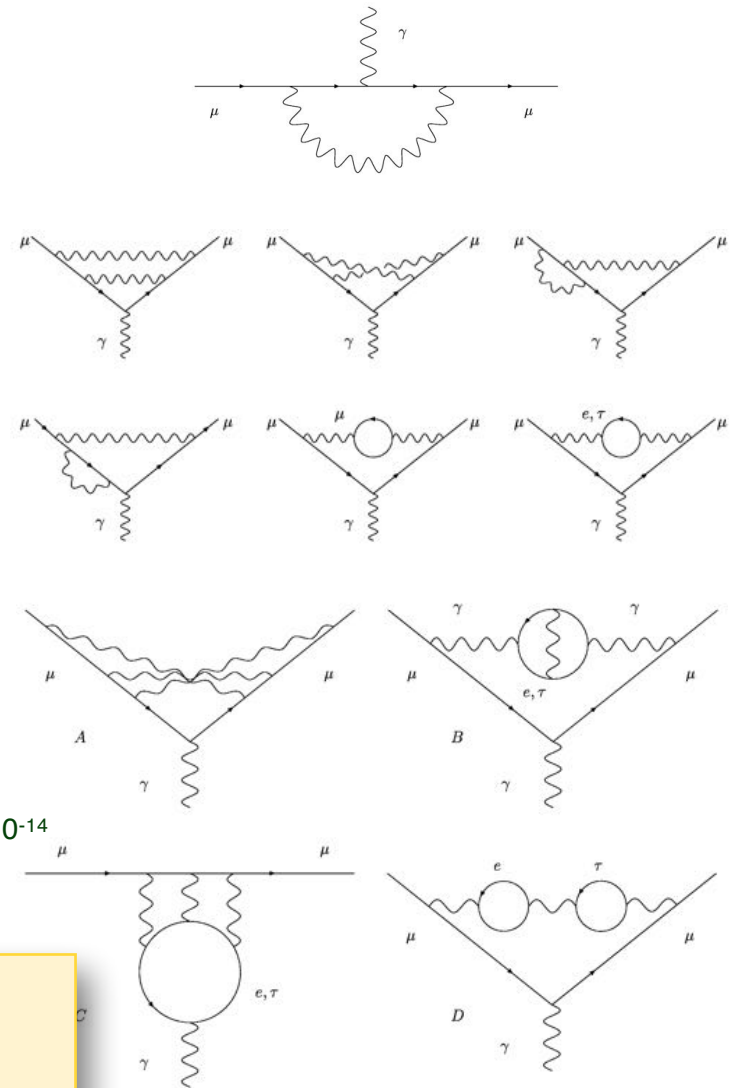
**Adding up, we get:**

$$a_{\mu}^{\text{QED}} = 116584718.931 (19)(100)(23) \times 10^{-11}$$

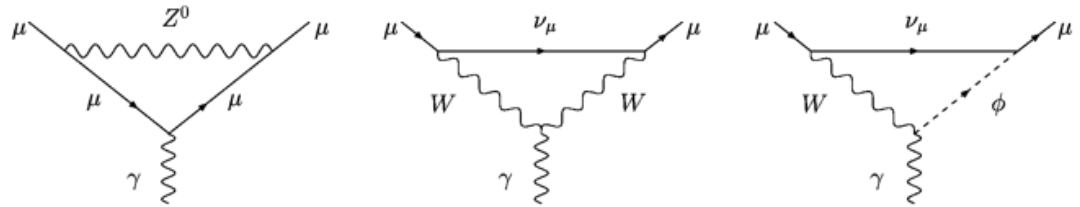
mainly from 4-loop coeff. unc. 6-loop from  $\alpha(\text{Cs})$

$\alpha = 1/137.035999046(27)$  [0.2ppb] Parker et al 2018

WP20 value



● One-loop term:



$$a_{\mu}^{\text{EW}}(1\text{-loop}) = \frac{5G_{\mu}m_{\mu}^2}{24\sqrt{2}\pi^2} \left[ 1 + \frac{1}{5} (1 - 4\sin^2\theta_W)^2 + O\left(\frac{m_{\mu}^2}{M_{Z,W,H}^2}\right) \right] \approx 195 \times 10^{-11}$$

1972: Jackiv, Weinberg; Bars, Yoshimura; Altarelli, Cabibbo, Maiani; Bardeen, Gastmans, Lautrup; Fujikawa, Lee, Sanda; Studenikin et al. '80s

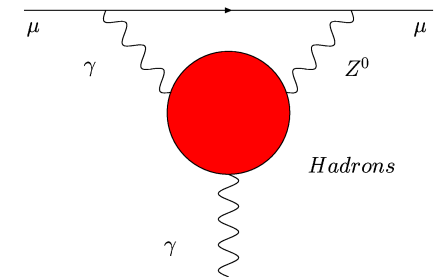
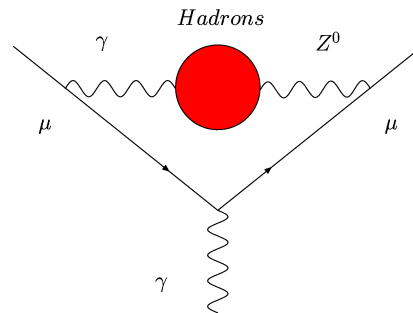
● One-loop plus higher-order terms:

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

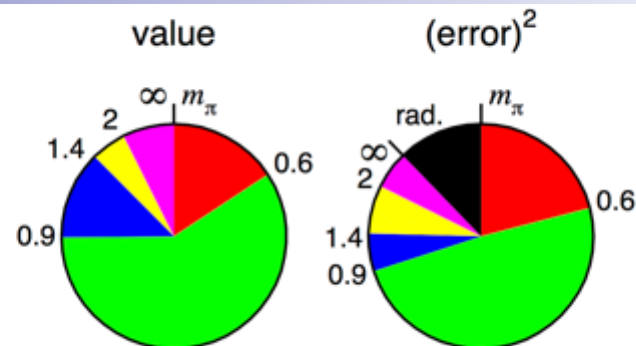
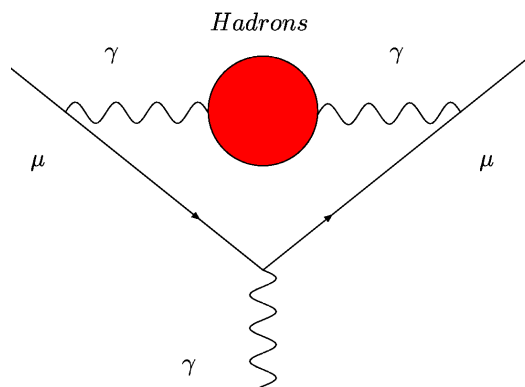
Kukhto et al. '92; Czarnecki, Krause, Marciano '95; Knecht, Peris, Perrottet, de Rafael '02; Czarnecki, Marciano and Vainshtein '02; Degrassi and Giudice '98; Heinemeyer, Stockinger, Weiglein '04; Gribov and Czarnecki '05; Vainshtein '03; Gnendiger, Stockinger, Stockinger-Kim 2013, Ishikawa, Nakazawa, Yasui, 2019.

Hadronic loop uncertainties (and 3-loop nonleading logs).

WP20 value



# The hadronic LO contribution



Keshavarzi, Nomura, Teubner 2018

$$a_{\mu}^{\text{HLO}} = \frac{1}{4\pi^3} \int_{m_{\pi}^2}^{\infty} ds K(s) \sigma_{\text{had}}^{(0)}(s)$$

$$K(s) = \int_0^1 dx \frac{x^2 (1-x)}{x^2 + (1-x)(s/m_{\mu}^2)}$$

$$a_{\mu}^{\text{HLO}} = 6895 (33) \times 10^{-11}$$

F. Jegerlehner, arXiv:1711.06089

$$= 6939 (40) \times 10^{-11}$$

Davier, Hoecker, Malaescu, Zhang, arXiv:1908.00921

$$= 6928 (24) \times 10^{-11}$$

Keshavarzi, Nomura, Teubner, arXiv:1911.00367

$$= 6931 (40) \times 10^{-11} (0.6\%)$$

WP20 value



**WP20 value obtained merging conservatively DHMZ + KNT + constraints from CHHKS**

Colangelo, Hoferichter, Hoid, Kubis, Stoffer 2018-19

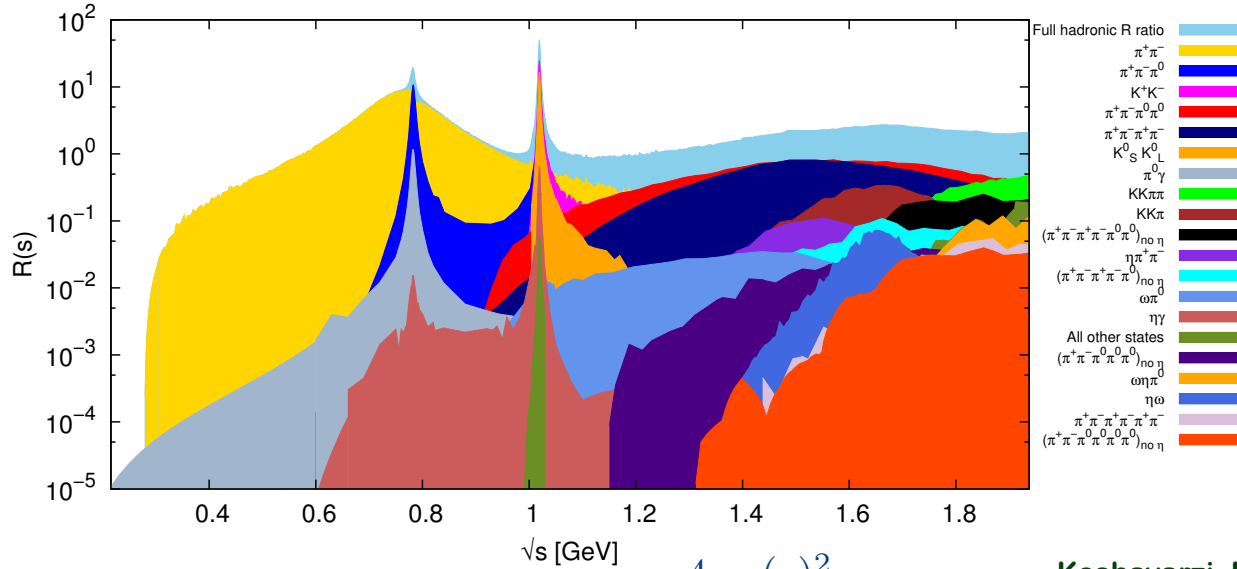


**Radiative Corrections to  $\sigma(s)$  are crucial.**

S. Actis et al, Eur. Phys. J. C66 (2010) 585

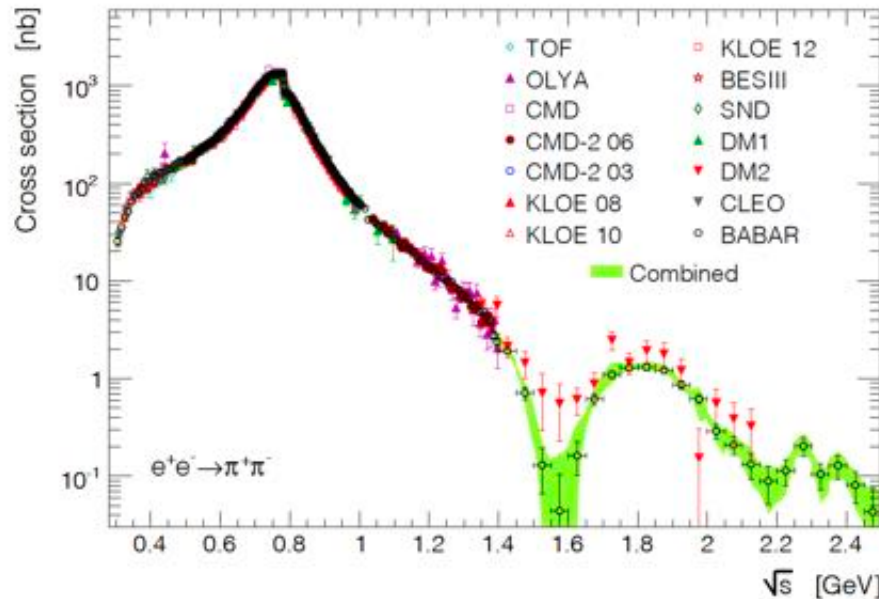
**See Martin  
Hoferichter's talk**

# The low-energy hadronic cross section



$$R(s) = \sigma(e^+e^- \rightarrow \text{hadrons}) / \frac{4\pi\alpha(s)^2}{3s}$$

Keshavarzi, Nomura Teubner  
PRD 2018

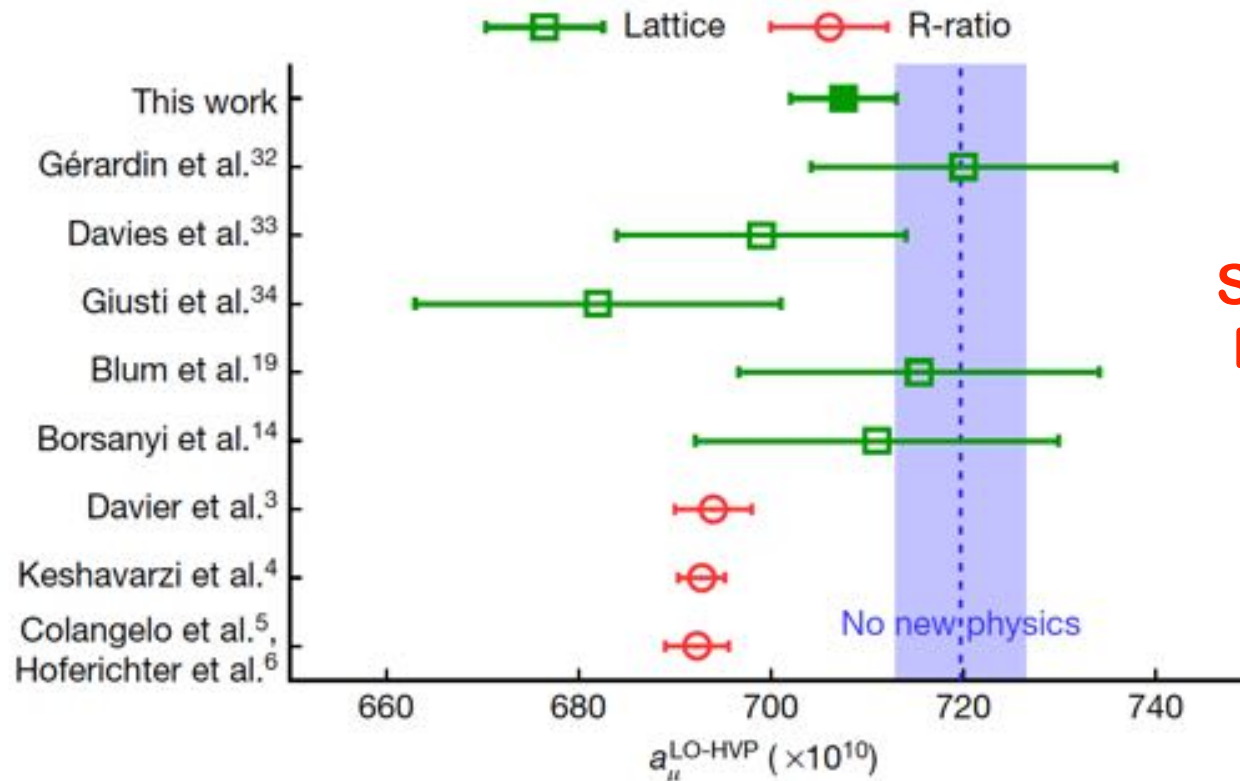


Davier, Hoecker, Malaescu, Zhang  
EPJC 2020

- Great progress in lattice QCD results. The BMW collaboration reached 0.8% precision:

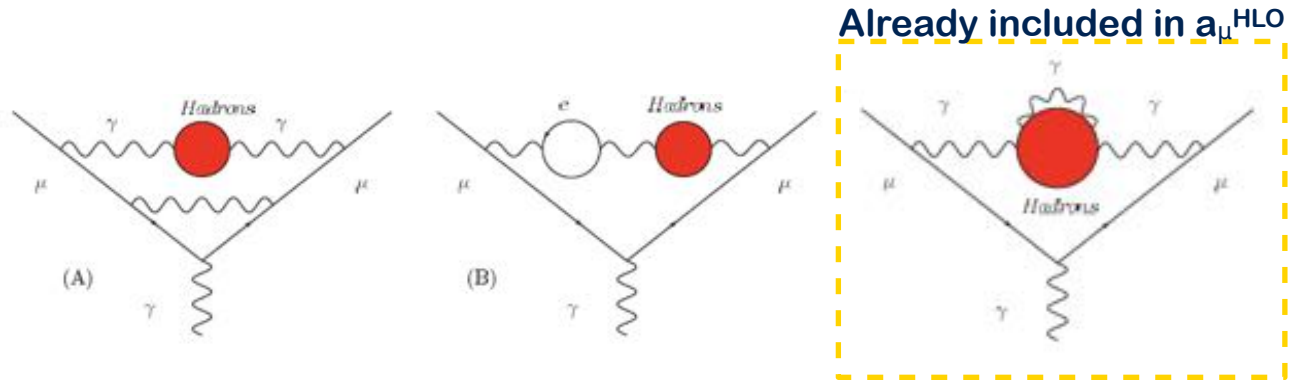
$$a_{\mu}^{\text{HLO}} = 7075(23)_{\text{stat}}(50)_{\text{syst}} [55]_{\text{tot}} \times 10^{-11}$$

- 2–2.5 $\sigma$  tension with the dispersive evaluations. BMW collaboration 2021



See Christoph Lehner's talk

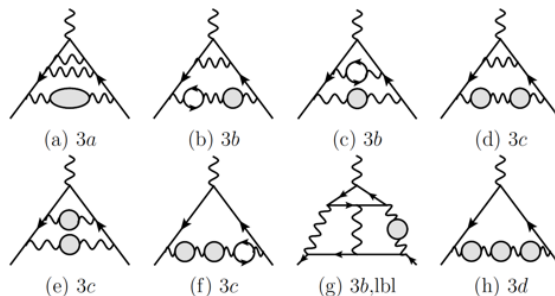
- $O(\alpha^3)$  contributions of diagrams containing HVP insertions:



$$a_{\mu}^{\text{HNLO}}(\nu p) = -98.3 (7) \times 10^{-11}$$

Krause '96; Keshavarzi, Nomura, Teubner 2019; WP20.

- $O(\alpha^4)$  contributions of diagrams containing HVP insertions:

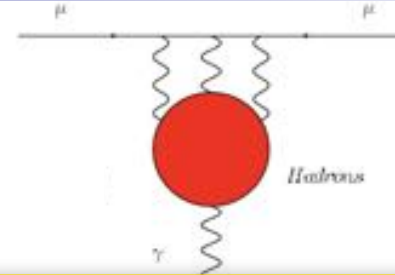


$$a_{\mu}^{\text{HNNLO}}(\nu p) = 12.4 (1) \times 10^{-11}$$

Kurz, Liu, Marquard, Steinhauser 2014

- **Hadronic light-by-light at  $O(\alpha^3)$**

This term had a troubled life! But nowadays:



**See Martin Hoferichter's talk**

$a_\mu^{\text{HNLO}}( b ) =$	<b>80 (40) <math>\times 10^{-11}</math></b>	Knecht & Nyffeler '02
	<b>= 136 (25) <math>\times 10^{-11}</math></b>	Melnikov & Vainshtein '03
	<b>= 105 (26) <math>\times 10^{-11}</math></b>	Prades, de Rafael, Vainshtein '09
	<b>= 100 (29) <math>\times 10^{-11}</math></b>	Jegerlehner, arXiv:1705.00263
	<b>= 92 (19) <math>\times 10^{-11}</math></b>	WP20 (phenomenology)

**Significant improvements due to data-driven dispersive approach.**

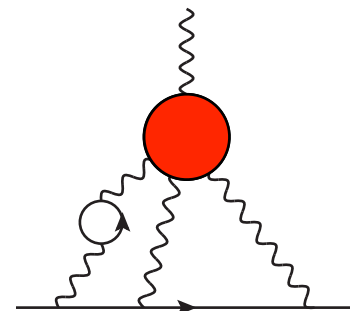
Colangelo, Hoferichter, Procura, Stoffer, 2014–17; Pauk, Vanderhaeghen 2014.

**Lattice: RBC: 82(35) $\times 10^{-11}$**  1911.08123 **Mainz: 110(15) $\times 10^{-11}$**  2104.02632

- **Hadronic light-by-light at  $O(\alpha^4)$**

$$a_\mu^{\text{HNNLO}}(|b|) = 2 (1) \times 10^{-11}$$

Colangelo, Hoferichter, Nyffeler, MP, Stoffer 2014; WP20



- Comparing the SM prediction with the measured muon g-2 value:

$$a_{\mu}^{\text{EXP}} = 116592061 (41) \times 10^{-11}$$

BNL+FNAL

$$a_{\mu}^{\text{SM}} = 116591810 (43) \times 10^{-11}$$

WP20

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

4.2  $\sigma$

If BMW 2021 HLO instead of WP20, EXP & SM differ only by **1.6 $\sigma$**

- Is  $\Delta a_{\mu}$  due to **new physics** beyond the SM? Could be due to:
  - NP at the weak scale and weakly coupled to SM particles
  - NP very heavy and strongly coupled to SM particles
  - NP very light ( $\Lambda \lesssim 1$  GeV) and feebly coupled to SM particles



# Muon $g-2 \iff \Delta a$ connection

**Marciano, MP, Sirlin 2008 & 2010**  
**Keshavarzi, Marciano, MP, Sirlin 2020**

- Can  $\Delta a_\mu$  be due to **missing contributions** in the hadronic  $\sigma(s)$ ?
- An upward shift of  $\sigma(s)$  also induces an increase of  $\Delta\alpha_{\text{had}}^{(5)}(M_Z)$ .
- Consider:

$$a_\mu^{\text{HLO}} \rightarrow a = \int_{4m_\pi^2}^{s_u} ds f(s) \sigma(s), \quad f(s) = \frac{K(s)}{4\pi^3}, \quad s_u < M_Z^2,$$

$$\Delta\alpha_{\text{had}}^{(5)} \rightarrow b = \int_{4m_\pi^2}^{s_u} ds g(s) \sigma(s), \quad g(s) = \frac{M_Z^2}{(M_Z^2 - s)(4\alpha\pi^2)},$$

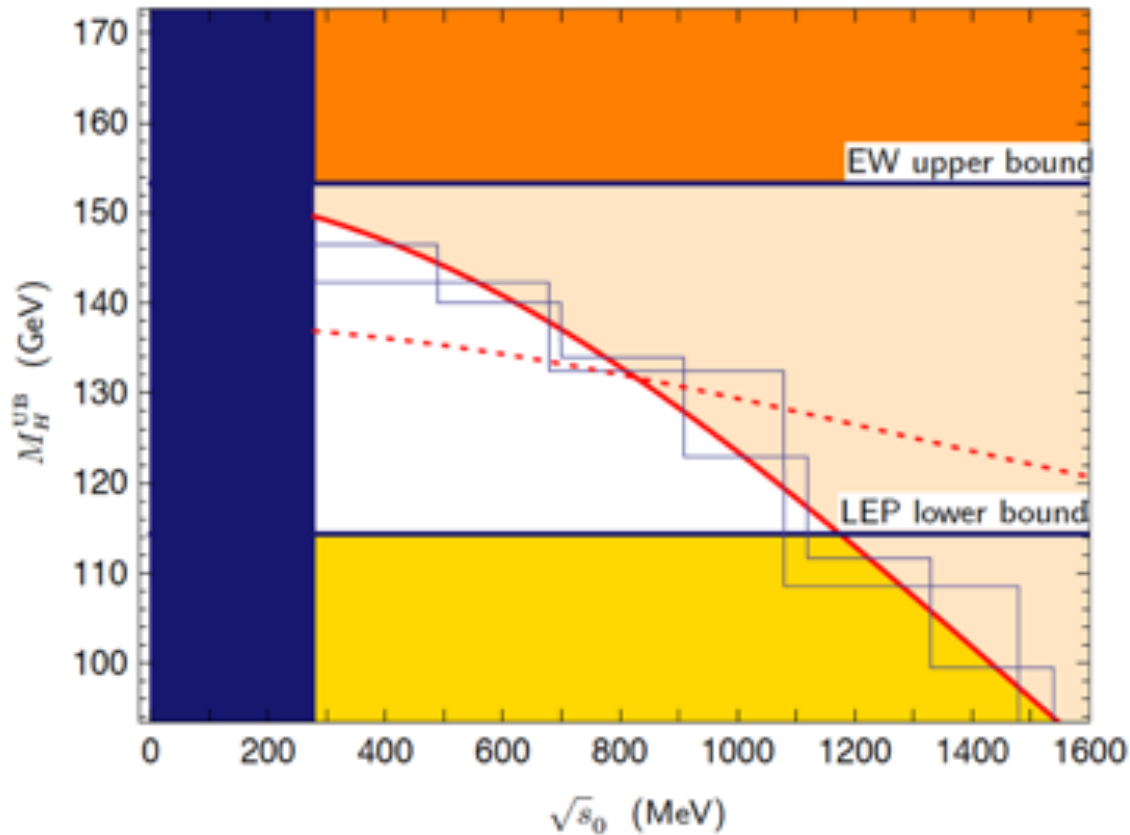
and the increase

$$\Delta\sigma(s) = \epsilon\sigma(s)$$

$\epsilon > 0$ , in the range:

$$\sqrt{s} \in [\sqrt{s_0} - \delta/2, \sqrt{s_0} + \delta/2] \quad \longrightarrow$$

How much does the  $M_H$  upper bound from the EW fit change when we shift up  $\sigma(s)$  by  $\Delta\sigma(s)$  [and thus  $\Delta\alpha_{\text{had}}^{(5)}(M_Z)$ ] to fix  $\Delta a_\mu$  ?

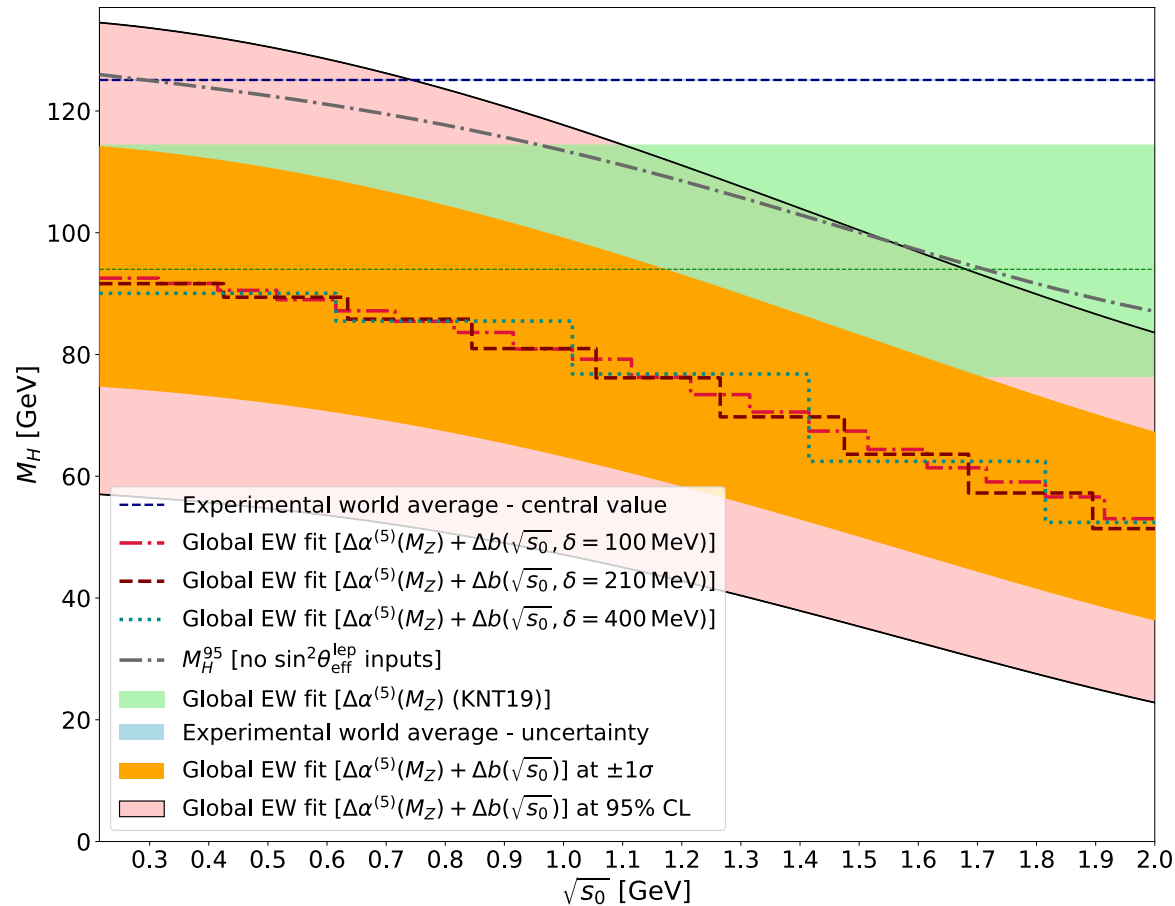


Marciano, MP, Sirlin, PRD 2008

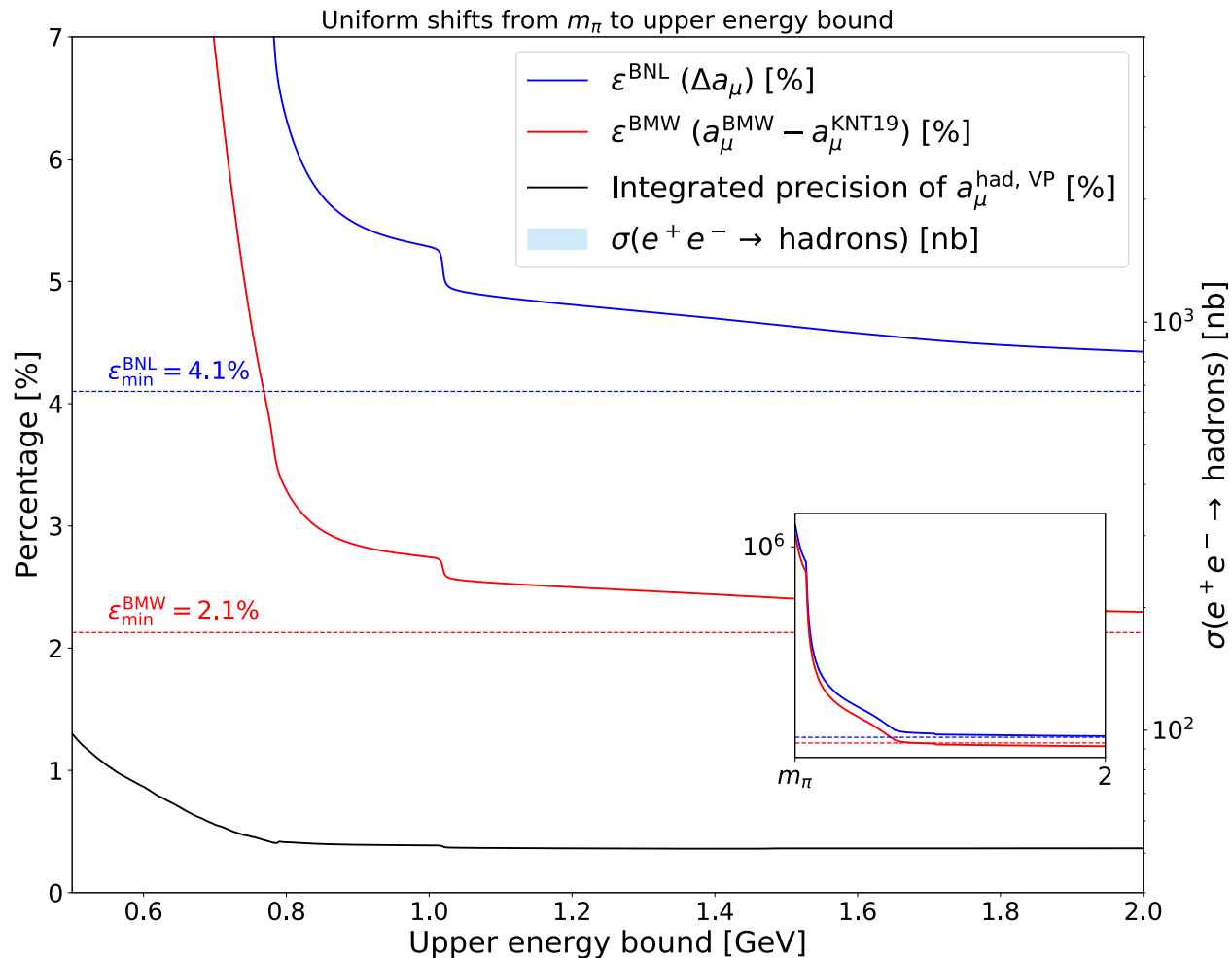
Major update: Higgs discovered, improved EW observables ( $M_W$ ,  $\sin^2\theta$ ,  $M_{\text{top}}$ , ...), updates to  $\sigma(s)$ , theory improvements, global fit, ...

Parameter	Input value	Reference	Fit result	Result w/o input value
$M_W$ (GeV)	80.379(12)	[5]	80.359(3)	80.357(4)(5)
$M_H$ (GeV)	125.10(14)	[5]	125.10(14)	$94^{+20+6}_{-18-6}$
$\Delta\alpha_{\text{had}}^{(5)}(M_Z^2) \times 10^4$	276.1(1.1)	[23]	275.8(1.1)	272.2(3.9)(1.2)
$m_t$ (GeV)	172.9(4)	[5]	173.0(4)	...
$\alpha_s(M_Z^2)$	0.1179(10)	[5]	0.1180(7)	...
$M_Z$ (GeV)	91.1876(21)	[5]	91.1883(20)	...
$\Gamma_Z$ (GeV)	2.4952(23)	[5]	2.4940(4)	...
$\Gamma_W$ (GeV)	2.085(42)	[5]	2.0903(4)	...
$\sigma_{\text{had}}^0$ (nb)	41.541(37)	[108]	41.490(4)	...
$R_l^0$	20.767(25)	[108]	20.732(4)	...
$R_c^0$	0.1721(30)	[108]	0.17222(8)	...
$R_b^0$	0.21629(66)	[108]	0.21581(8)	...
$\bar{m}_c$ (GeV)	1.27(2)	[5]	1.27(2)	...
$\bar{m}_b$ (GeV)	$4.18^{+0.03}_{-0.02}$	[5]	$4.18^{+0.03}_{-0.02}$	...
$A_{\text{FB}}^{0J}$	0.0171(10)	[108]	0.01622(7)	...
$A_{\text{FB}}^{0,c}$	0.0707(35)	[108]	0.0737(2)	...
$A_{\text{FB}}^{0,b}$	0.0992(16)	[108]	0.1031(2)	...
$A_e$	0.1499(18)	[75,108]	0.1471(3)	...
$A_c$	0.670(27)	[108]	0.6679(2)	...
$A_b$	0.923(20)	[108]	0.93462(7)	...
$\sin^2\theta_{\text{eff}}^{l\text{op}}(Q_{\text{FB}})$	0.2324(12)	[108]	0.23152(4)	0.23152(4)(4)
$\sin^2\theta_{\text{eff}}^{l\text{op}}(\text{Had Coll})$	0.23140(23)	[100]	0.23152(4)	0.23152(4)(4)

Keshavarzi, Marciano, MP, Sirlin, PRD 2020 (using Gfitter)



**Shifts  $\Delta\sigma(s)$  to fix  $\Delta a_\mu$  are possible,  
but conflict with the EW fit if they occur above  $\sim 1$  GeV**



Shifts below  $\sim 1$  GeV conflict with the quoted exp. precision of  $\sigma(s)$

Keshavarzi, Marciano, MP, Sirlin, PRD 2020 (updated 2021)

- Crivellin, Hoferichter, Manzari and Montull, “Hadronic vacuum polarization:  $(g-2)_\mu$  versus global electroweak fits,” arXiv:2003.04886.
- Eduardo de Rafael, “On Constraints Between  $\Delta\alpha_{\text{had}}(M_Z^2)$  and  $(g_\mu-2)_{\text{HVP}}$ ,” arXiv:2006.13880.
- Malaescu and Schott, “Impact of correlations between  $a_\mu$  and  $\alpha_{\text{QED}}$  on the EW fit,” arXiv:2008.08107.
- Colangelo, Hoferichter and Stoffer, “Constraints on the two-pion contribution to hadronic vacuum polarization,” arXiv:2010.07943.

# What happens to the electron $g-2$ ?



- The 2008 measurement of the electron g-2 is:

$$a_e^{\text{EXP}} = 11596521807.3 (2.8) \times 10^{-13} \quad \text{Hanneke et al, PRL100 (2008) 120801}$$

vs. old (factor of 15 improvement,  $1.8\sigma$  difference):

$$a_e^{\text{EXP}} = 11596521883 (42) \times 10^{-13} \quad \text{Van Dyck et al, PRL59 (1987) 26}$$

- Equate  $a_e^{\text{SM}}(\alpha) = a_e^{\text{EXP}}$  → “g<sub>e</sub>-2” determination of alpha:

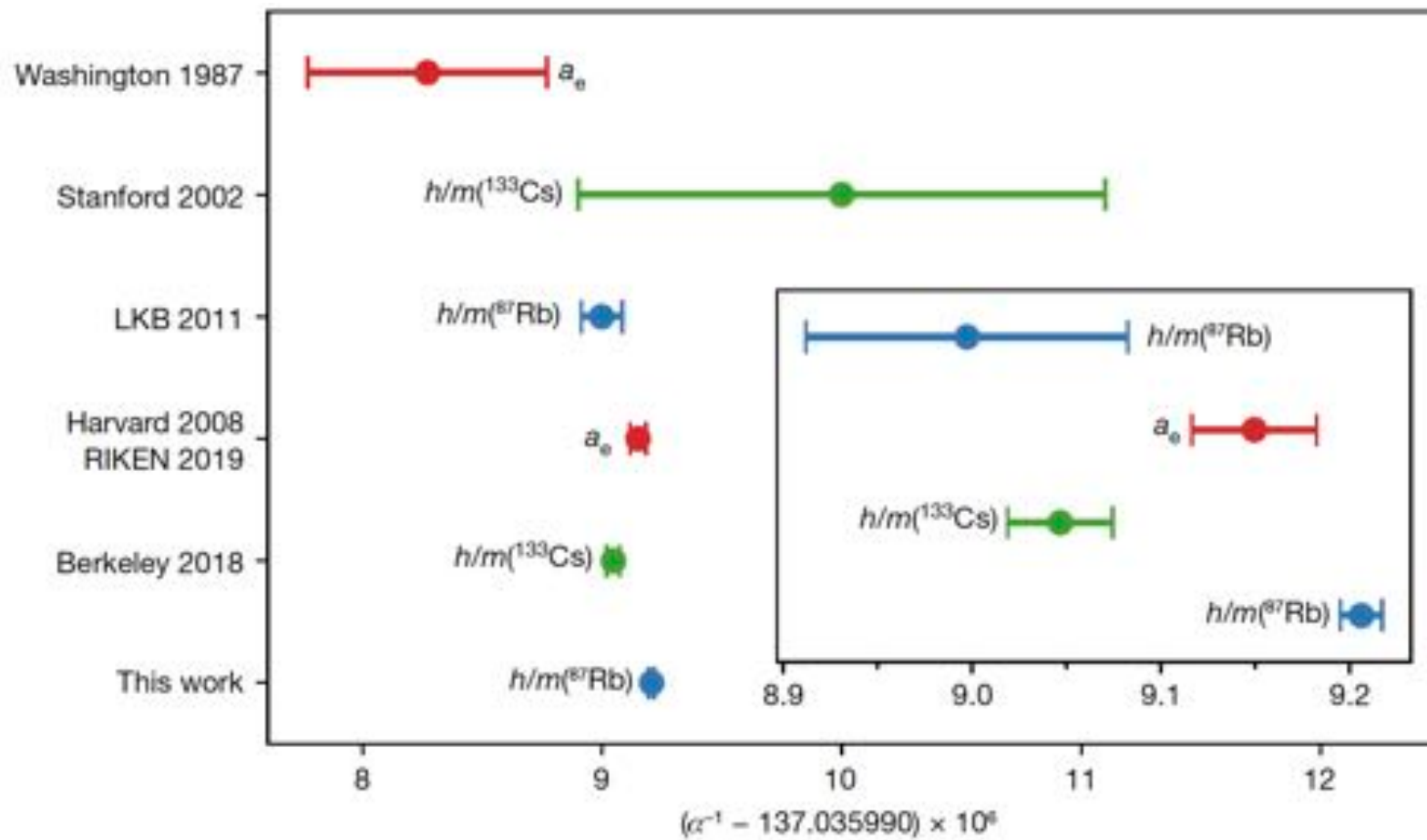
$$\alpha^{-1} = 137.035\,999\,151 (33) \quad [0.24 \text{ ppb}]$$

- The best determination of  $\alpha$  is obtained via atomic interferometry:

$$\alpha^{-1} = 137.035\,999\,046 (27) [0.20 \text{ ppb}] \quad \text{Parker et al, Science 360 (2018) 192 (Cs)}$$

$$\alpha^{-1} = 137.035\,999\,206 (11) [0.08 \text{ ppb}] \quad \text{Morel et al, Nature 588 (2020) 61 (Rb)}$$

**2018→2020: improvement in precision, but  $5.4\sigma$  difference!**



Morel et al, Nature 588 (2020) 61

- Using the best determinations of  $\alpha$  (which differ by  $5.4\sigma$ ):

$$\alpha = 1/137.035\,999\,046\,(27) \text{ [Cs 2018]}$$

$$\alpha = 1/137.035\,999\,206\,(11) \text{ [Rb 2020]}$$

$$a_e^{\text{SM}} = 115\,965\,218\,16.16\,(0.11)\,(0.08)\,(2.28) \times 10^{-13} \text{ [Cs18]}$$

$$= 115\,965\,218\,02.64\,(0.11)\,(0.08)\,(0.93) \times 10^{-13} \text{ [Rb20]}$$

$\delta C_5^{\text{qed}}$

$\delta a_e^{\text{had}}$

from  $\delta\alpha$

$$a_e^{\text{EXP}} = 115\,965\,218\,07.3\,(2.8) \times 10^{-13} \text{ Hanneke et al, PRL 2008}$$

- The (EXP – SM) difference is:

$$\Delta a_e = a_e^{\text{EXP}} - a_e^{\text{SM}} = -8.9\,(3.6) \times 10^{-13} \text{ [2.5}\sigma\text{] [Cs18]}$$

$$= +4.7\,(3.0) \times 10^{-13} \text{ [1.6}\sigma\text{] [Rb20]}$$

QED 5-loop:  $a_e^{\text{QED5}} = 4.6 \times 10^{-13}$

- NP sensitivity limited only by the experimental errors in  $\alpha$  and  $a_e$ .  
May soon play a pivotal role in probing NP in the leptonic sector.

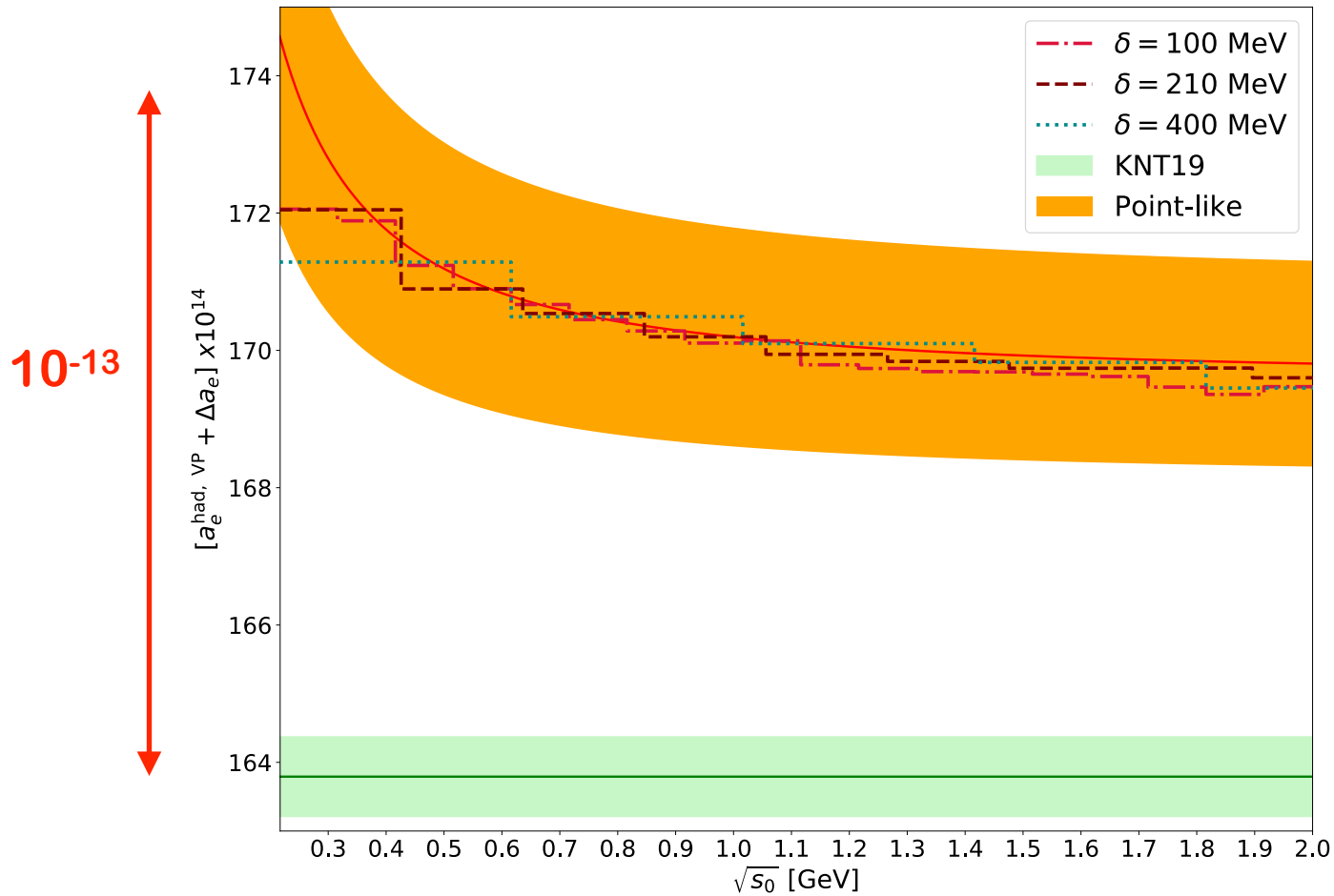
- Using  $\alpha(\text{Rb2020})$ , the sensitivity is  $\delta\Delta a_e = 3.0 \times 10^{-13}$ , ie ( $\times 10^{-13}$ ):

$$\underbrace{(0.1)_{\text{QED5}}, (0.1)_{\text{HAD}}, (0.9)_{\delta\alpha}, (2.8)_{\delta a_e^{\text{EXP}}}}_{(0.2)_{\text{TH}}}$$

- The  $(g-2)_e$  experimental error may soon drop below  $10^{-13} \rightarrow$   
 **$a_e$  sensitivity below  $10^{-13}$  may soon be reached!**
- In a broad class of BSM theories, contributions to  $a_l$  scale as

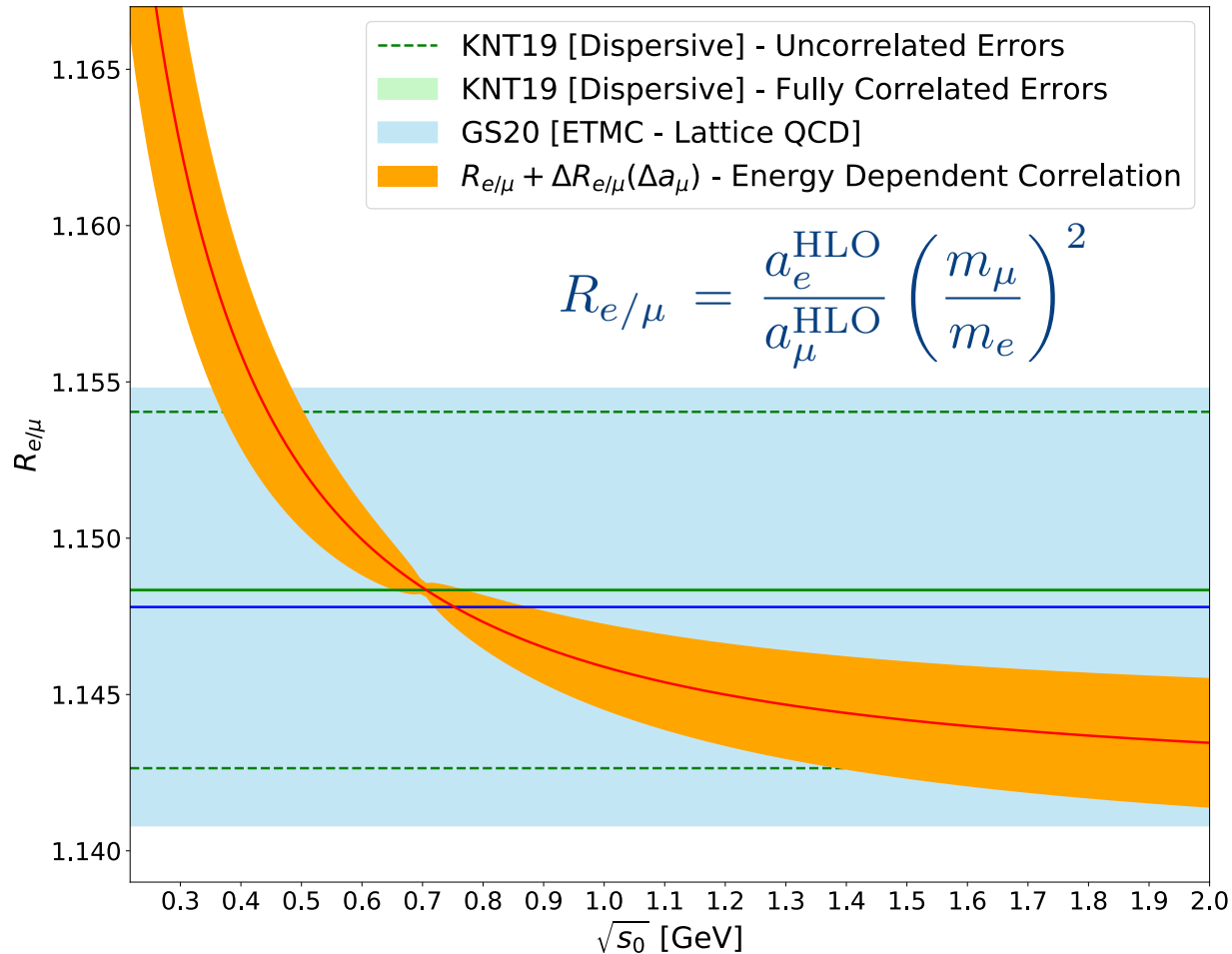
$$\frac{\Delta a_{l_i}}{\Delta a_{l_j}} = \left( \frac{m_{l_i}}{m_{l_j}} \right)^2 \quad \text{This Naive Scaling leads to:}$$

$$\Delta a_e = \left( \frac{\Delta a_\mu}{3 \times 10^{-9}} \right) 0.7 \times 10^{-13}; \quad \Delta a_\tau = \left( \frac{\Delta a_\mu}{3 \times 10^{-9}} \right) 0.8 \times 10^{-6}$$



Shifts  $\Delta\sigma(s)$  to fix  $\Delta a_\mu$  only slightly change  $\Delta a_e$

Keshavarzi, Marciano, MP, Sirlin, PRD 2020



**Good agreement between lattice [Giusti & Simula 2020] and KNT19.  
 Possible future bounds on very low energy shifts  $\Delta\sigma(s)$ ?**

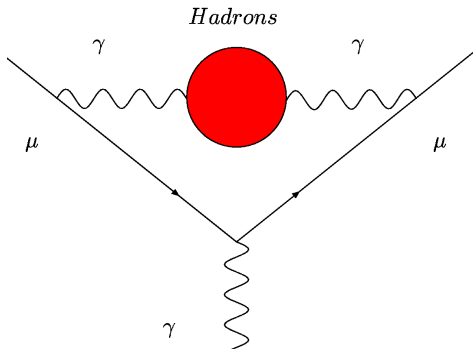
Keshavarzi, Marciano, MP, Sirlin, PRD 2020

# The MUonE project



## The space-like method for $a_\mu^{\text{HLO}}$

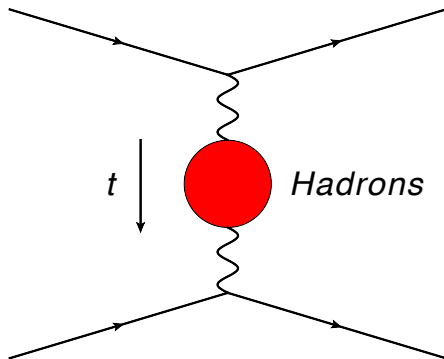
- Leading hadronic contribution computed via the usual dispersive (timelike) formula:



$$a_\mu^{\text{HLO}} = \frac{1}{4\pi^3} \int_{m_\pi^2}^{\infty} ds K(s) \sigma_{\text{had}}^{(0)}(s)$$

$$K(s) = \int_0^1 dx \frac{x^2 (1-x)}{x^2 + (1-x) (s/m_\mu^2)}$$

- Alternatively, simply exchanging the  $x$  and  $s$  integrations:



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

$$t(x) = \frac{x^2 m_\mu^2}{x-1} < 0$$

Lautrup, Peterman, de Rafael, 1972

$\Delta\alpha_{\text{had}}(t)$  is the hadronic contribution to the space-like running of  $\alpha$ : **proposal to measure  $a_\mu^{\text{HLO}}$  via scattering data!**

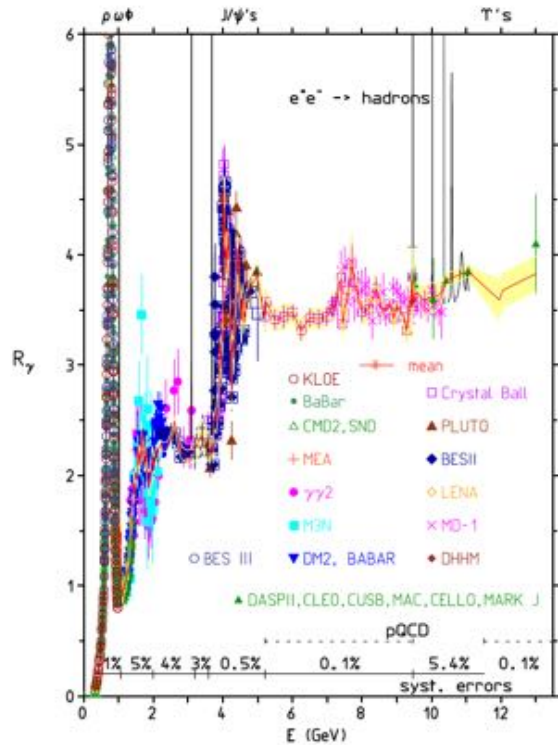


# $a_\mu^{\text{HLO}}$ : time-like vs space-like method

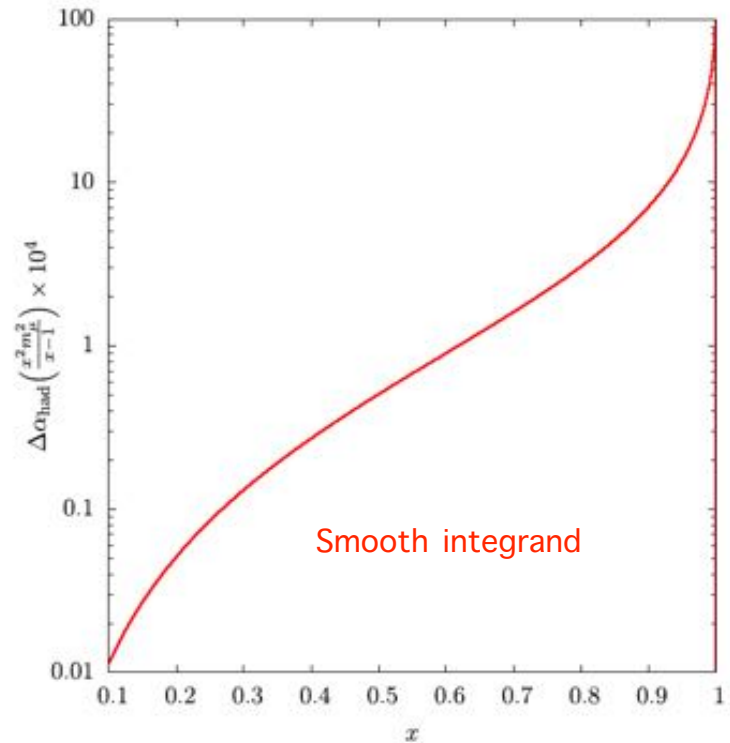
Timelike



Spacelike



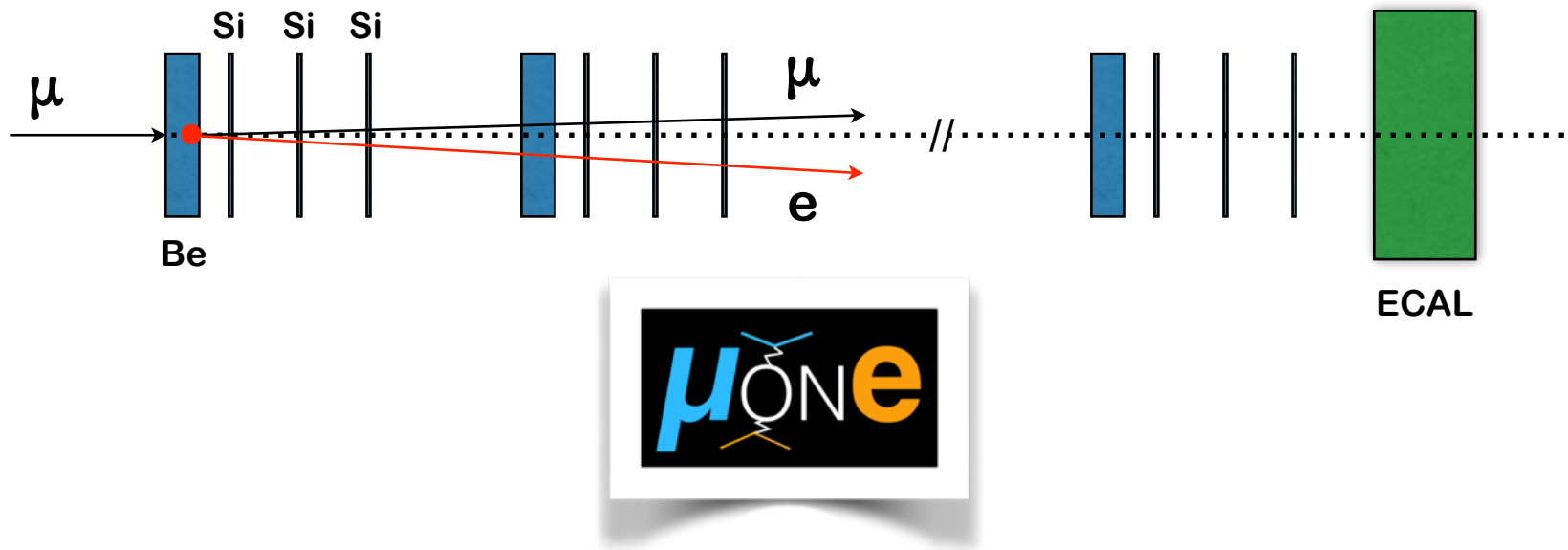
F. Jegerlehner, arXiv:1511.04473



Carloni Calame, MP, Trentadue, Venanzoni, PLB 2015

- Inclusive measurement
- Smooth integrand
- Direct interplay with lattice QCD

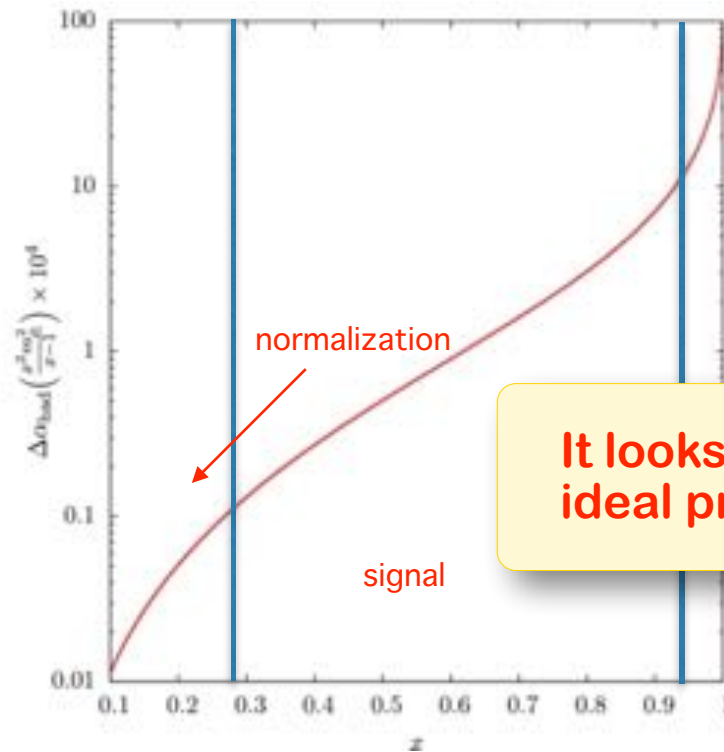
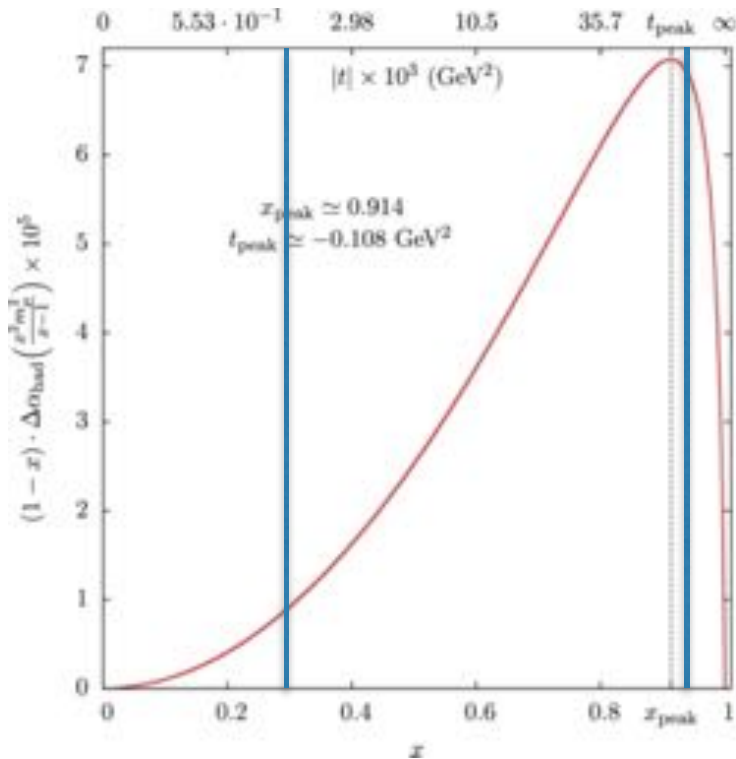
- $\Delta\alpha_{\text{had}}(t)$  can be measured via the **elastic scattering**  $\mu e \rightarrow \mu e$ .
- We propose to scatter a 150 GeV muon beam, available at CERN's North Area, on a fixed electron target (Beryllium). Modular apparatus: each station has one layer of Beryllium (target) followed by several thin Silicon strip detectors.



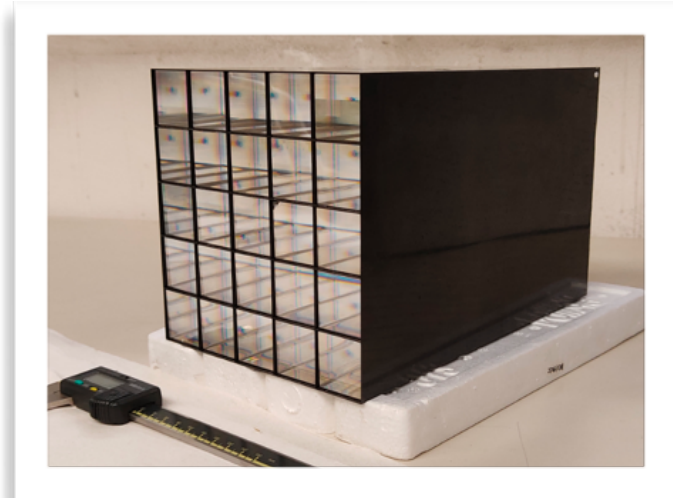
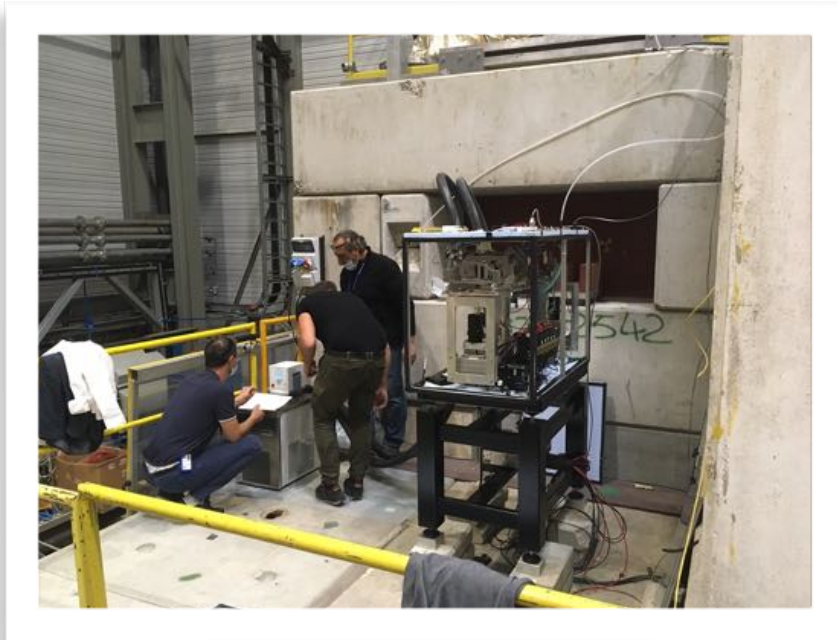
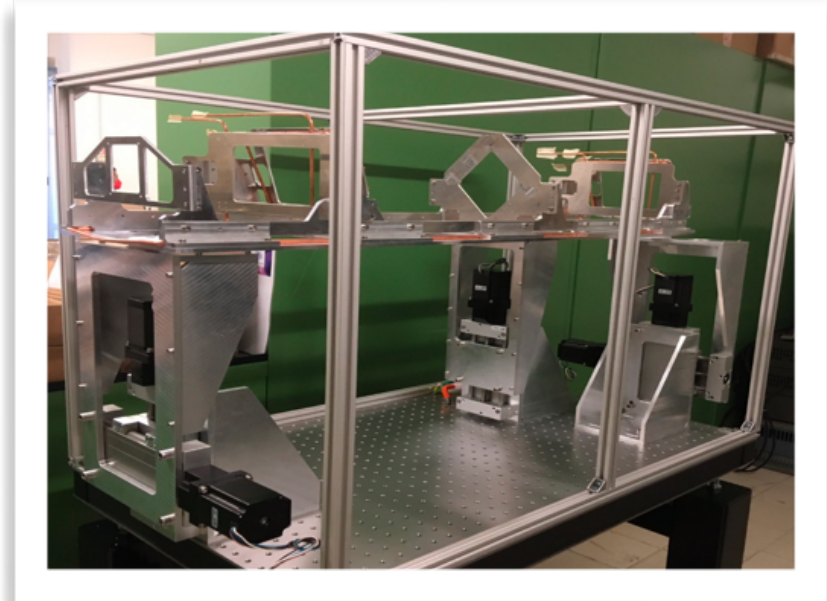
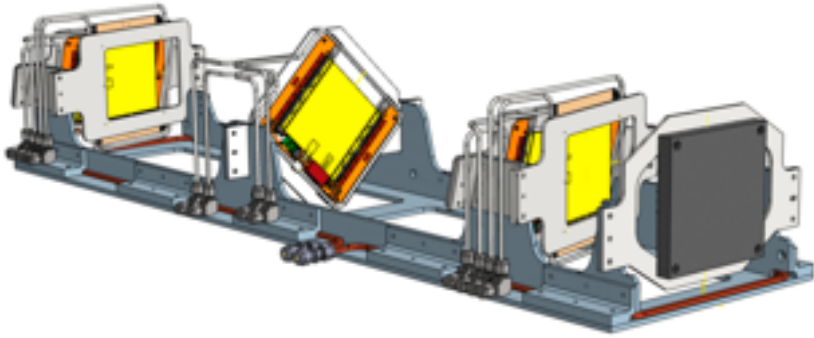
Abbiendi, Carloni Calame, Marconi, Matteuzzi, Montagna,  
Nicosini, MP, Piccinini, Tenchini, Trentadue, Venanzoni

EPJC 2017 - arXiv:1609.08987

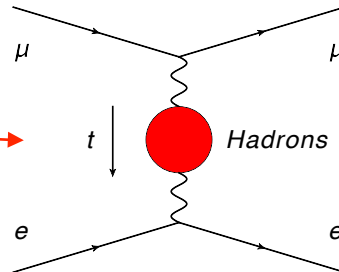
- For a 150 GeV muon beam ( $\sqrt{s} \sim 400$  MeV), MUonE's scan region extends up to  $x=0.932$ , ie beyond the  $x=0.914$  peak!



- **Statistics:** With CERN's 150 GeV muon beam M2 ( $1.3 \times 10^7 \mu/s$ ), incident on 40 15mm Be targets (total Be thickness: 60cm), 2-3 years of data taking ( $2 \times 10^7$  s/yr)  $\rightarrow \mathcal{L}_{\text{int}} \sim 1.5 \times 10^7 \text{ nb}^{-1}$ .
- With this  $\mathcal{L}_{\text{int}}$  we estimate that measuring the shape of  $d\sigma/dt$  we can reach a statistical sensitivity of  **$\sim 0.3\%$  on  $a_\mu^{\text{HLO}}$** , ie  $\sim 20 \times 10^{-11}$ .
- **Systematic** effects must be known at  $\leq 10\text{ppm}$ !
- Test beams performed at CERN in 2017 & 2018 arXiv:1905.11677, 2102.11111
- Lol submitted to CERN SPSC in 2019: **Test run approved for 2021, delayed to 2022.**
- If test run successful, intermediate run in 2022-23.



- To extract  $\Delta\alpha_{\text{had}}(t)$  from MUonE's measurement, the ratio of the SM cross sections in the signal and normalisation regions must be known at  $\leq 10\text{ppm}$ !



- Fully differential fixed-order MC @ NLO ready Pavia and PSI 2018-19
- NNLO QED: Master Integrals for 2-loop box diagrams computed. Full 2-loop amplitude completed! ( $m_e=0$ ) Padova 2017 - 2021
- Two MC built including partial subsets of the NNLO QED corrections due to electron and muon radiation Pavia and PSI 2020
- NNLO hadronic effects computed Padova and KIT 2019
- Extraction of the leading electron mass effects from the massless muon-electron scattering amplitudes PSI 2019 - 2021
- New Physics extracting  $\Delta\alpha_{\text{had}}(t)$  at MUonE? Padova and Heidelberg 2020
- ...

Theory for muon-electron scattering @ 10 ppm:  
A report of the MUonE theory initiative. arXiv:2004.13663



## Muon-electron scattering: Theory kickoff workshop

4-5 September 2017

Padova  
Europe/Rome timezone

- Overview
- Venue
- Timetable
- Logistic
- Map

Support



**MUonE theory workshops: Padova 2017, Mainz 2018, Zurich 2019**  
**Next MUonE theory workshop: MITP Mainz 2020-21 postponed to 2022**

# Conclusions

- Fermilab's Muon  $g-2$  experiment confirms BNL's result: the discrepancy between experiment and SM increases to  $4.2\sigma$ .
- The BMWc lattice QCD result weakens the exp-SM discrepancy. It must be confirmed or refuted by other lattice calculations.
- Is  $\Delta a_\mu$  due to missed contributions in the hadronic cross section? Shifts above 1 GeV to fix  $\Delta a_\mu$  conflict with the electroweak fit.
- Leading hadronic contribution to  $a_\mu$ : dispersive vs lattice. MUonE will provide a new independent & alternative determination.