

**Award for Excellence 2023**



# Predictions for low-energy particle physics experiments

**Yannick Ulrich**

**IPPP, University of Durham**

5 SEPTEMBER 2023

you might have seen some of these headlines

BBC Home News Sport Weather iPlayer Sounds

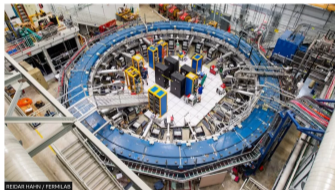
NEWS

Home Cost of Living War in Ukraine Climate UK World Business Politics Culture Tech More

Science & Environment

### Scientists at Fermilab close in on fifth force of nature

10 August



RECAR HAHN / FERMI LAB

The findings come from the US muon g-2 experiment

The BBC (10 Aug)

you might have seen some of these headlines



you might have seen some of these headlines

The image shows a screenshot of a Daily Mail article. At the top, the 'MailOnline' logo is visible, along with navigation links for Home, News, Royals, U.S., Sport, TV&Showbiz, Femal, Health, Science, Money, Travel, Best Buys, and Discounts. A secondary row of links includes Latest Headlines, Blue Origin, SpaceX, NASA, Apple, Google, Twitter, and Microsoft. The main headline reads: 'A new force of nature? Scientists close in on a fifth force as they discover a mysterious subatomic particle disobeying the laws of physics'. Below the headline is a bulleted list of three points: 'Physicists observed the 'peculiar wobble' of subatomic particle called a muon', 'Modern understanding of physics may be missing an 'unknown particle or force'', and 'The new findings replicate earlier results from 2021 but with four times the data'. The article is attributed to 'By JONATHAN CHADWICK FOR MAILONLINE' and is dated 'UPDATED: 14:13, 11 August 2023'. A '699 View comments' button is also present. At the bottom of the article, a partial sentence reads: 'Scientists are closing in on identifying a new force of nature after observing the peculiar 'wobble' of a subatomic particle.' Below the article screenshot, there is a blue text overlay that says 'The Daily Mail (11 Aug) and winner of the best use of quotes'.

MailOnline

Home | News | Royals | U.S. | Sport | TV&Showbiz | Femal | Health | Science | Money | Travel | Best Buys | Discounts | Login

Latest Headlines | Blue Origin | SpaceX | NASA | Apple | Google | Twitter | Microsoft

### A new force of nature? Scientists close in on a fifth force as they discover a mysterious subatomic particle disobeying the laws of physics

- Physicists observed the 'peculiar wobble' of subatomic particle called a muon
- Modern understanding of physics may be missing an 'unknown particle or force'
- The new findings replicate [earlier results from 2021](#) but with four times the data

By JONATHAN CHADWICK FOR MAILONLINE  
UPDATED: 14:13, 11 August 2023

699 View comments

Scientists are closing in on identifying a new force of nature after observing the peculiar 'wobble' of a subatomic particle.

The Daily Mail (11 Aug)  
and winner of the best use of quotes

- magnetic moment of a charged lepton:

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

- Dirac:  $g_{\mu}^{\text{Dirac}} = 2$

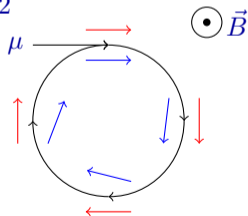
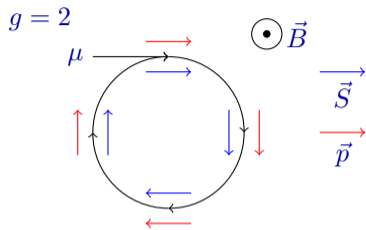
- in the full **Standard Model**

$$g^{\text{SM}} = (2 \times 1 + a_{\mu}) > 2$$

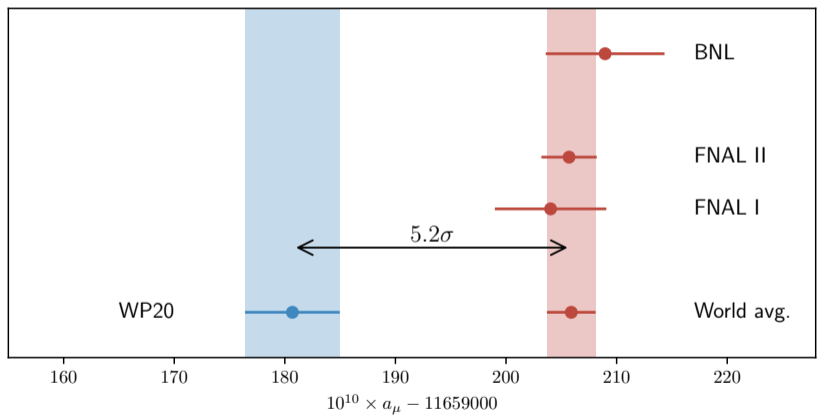
- measure  $a_{\mu}$  by comparing cyclotron and Larmor  $g > 2$

$$\text{frequency } \omega_s - \omega_c = a_{\mu} \times \frac{qB}{m_{\mu}}$$

- if  $a_{\mu}^{\text{th}} \neq a_{\mu}^{\text{exp}} \Rightarrow$  physics **Beyond Standard Model**

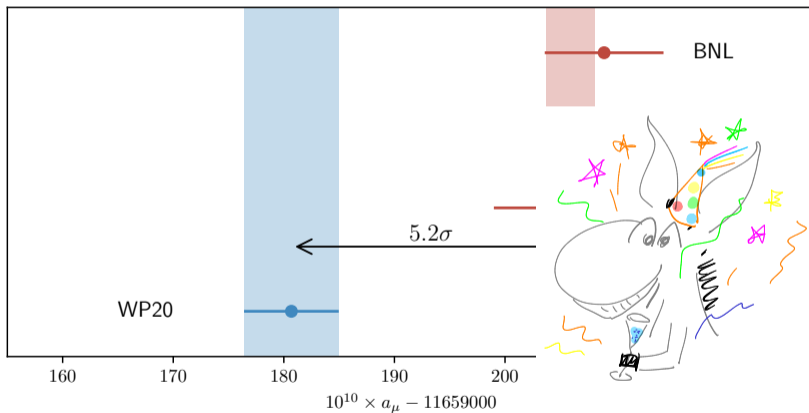


most precise measurement of  $g - 2$  [FNAL 23]













$5.2\sigma \Rightarrow 2 \times 10^{-7}$  chance of a statistical fluke

most precise measurement of  $g - 2$  [FNAL 23]



$5.2\sigma \Rightarrow 2 \times 10^{-7}$  chance of a statistical fluke  
a discovery?

|            | $10^{11} \times$ value        | diagrams   |
|------------|-------------------------------|--|
| QED 1-loop | $\alpha/2\pi = 116\,140\,973$ |    |
| QED 2-loop | -177 231                      |   |
| QED 3-loop | 1 480                         |   |
| more QED   | -5                            | + 70 others  |
| EW         | 153                           |   |
| HVP        | 6 845(40)                     |   |
| HLbL       | 92(17)                        |    |
| total      | 116 591 810(43)               | [g - 2 white paper 20]   |
| FNAL+BNL   | 116 592 059(22)               |  |

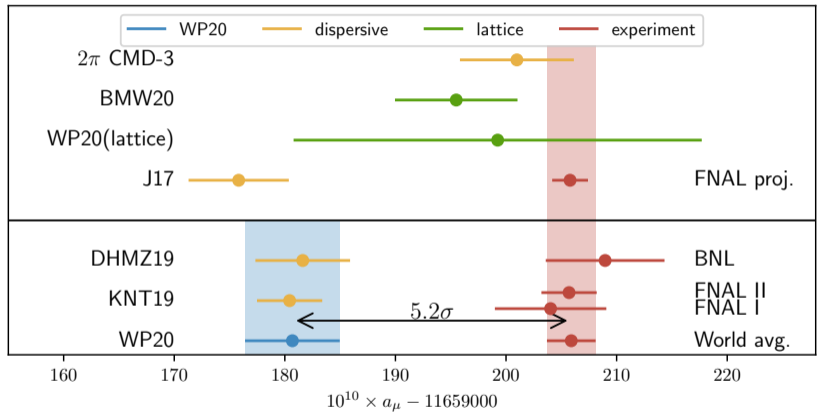
+ 3 others

+ 1 conspiracy theory

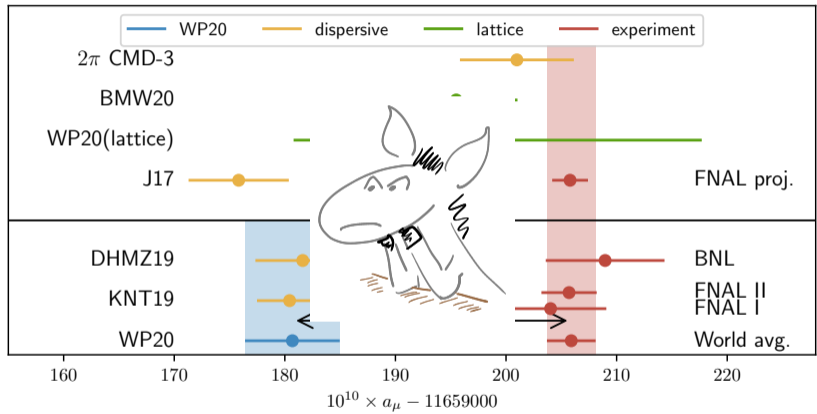
+ 70 others

+ others





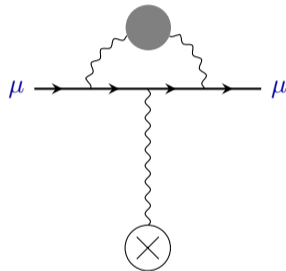
need a third way of doing this to pin down  $a_{\mu}^{\text{HVP}}$ ! [CMD-3 23] [BMW 20]



need a third way of doing this to pin down  $a_\mu^{\text{HVP}}$ ! [CMD-3 23] [BMW 20]

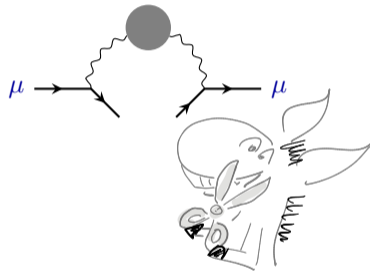
how to you measure part of  $a_{\mu}$ ?

- cannot calculate this diagram
- normally done in  $ee \rightarrow \text{hadrons}$  which is really messy
- a new proposal:



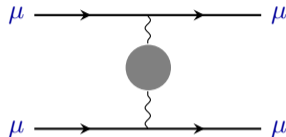
how to you measure part of  $a_{\mu}$ ?

- cannot calculate this diagram
- normally done in  $ee \rightarrow \text{hadrons}$  which is really messy
- a new proposal:



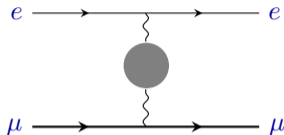
how to you measure part of  $a_{\mu}$ ?

- cannot calculate this diagram
- normally done in  $ee \rightarrow \text{hadrons}$  which is really messy
- a new proposal:



how to you measure part of  $a_\mu$ ?

- cannot calculate this diagram
- normally done in  $ee \rightarrow \text{hadrons}$  which is really messy
- a new proposal:
- measure  $e\mu \rightarrow e\mu$

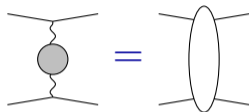


## the MUonE experiment

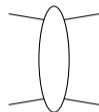
- completely independent of previous extraction
- much cleaner but also much smaller  
(signal  $\sim 10^{-3} \times$  background)
- competitive extraction @  $10^{-2}$

$\Rightarrow$  goal for MUonE: measure  $e\mu \rightarrow e\mu$  @  $10^{-5}$

[MUonE 19]



=



-



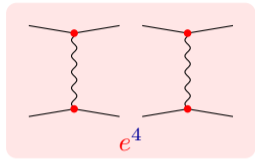
textbook QED

-

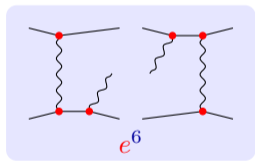
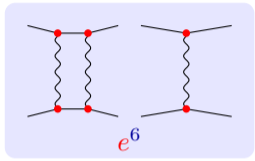
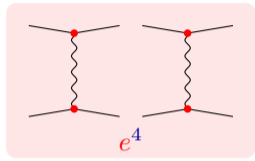
QED

5+ years,  
4+ workshops,  
34+ authors

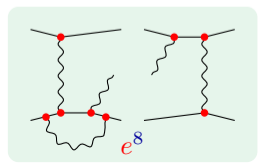
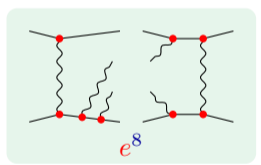
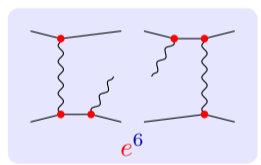
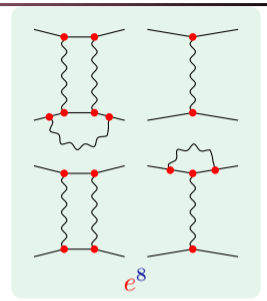
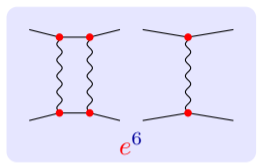
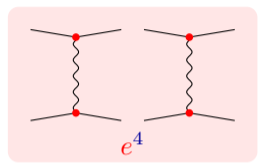
$\sigma_{LO} \supset$



$\sigma_{\text{NLO}} \supset$



$\sigma_{\text{NNLO}} \supset$



- in Dec 22 we published the first full NNLO calculation for  $\mu$ - $e$  scattering
- the first NNLO calculation with two different internal & external masses
- 11 authors, 12 institutes, 6 countries
- in the works for 5+ years
- run for 2.5 CPU yr (290 kWh energy / 1300 kettles / 3.5 kgCO<sub>2</sub>e)

all results and data:

[mule-tools.gitlab.io/user-library/mu-e-scattering/muone-full-legacy](https://mule-tools.gitlab.io/user-library/mu-e-scattering/muone-full-legacy)



PUBLISHED FOR SISSA BY SPRINGER

RECEIVED: December 23, 2022

ACCEPTED: January 3, 2023

PUBLISHED: January 20, 2023

## Muon-electron scattering at NNLO

A. Broggio,<sup>a</sup> T. Engel,<sup>b,c,d</sup> A. Ferroglio,<sup>e,f</sup> M.K. Mandal,<sup>g,h</sup> P. Mastrolia,<sup>i,o</sup>  
M. Rocco,<sup>b</sup> J. Ronca,<sup>j</sup> A. Signer,<sup>k,o</sup> W.J. Torres Bobadilla,<sup>l</sup> Y. Ulrich<sup>†</sup> and M. Zoller<sup>‡</sup>

<sup>a</sup>Faculty of Physics, University of Vienna, Boltzmannsgasse 5, A-1090 Vienna, Austria

<sup>b</sup>Paul Scherrer Institut, CH-5232 Villigen PSI, Switzerland

<sup>c</sup>Physik-Institut, Universität Zürich, Winterthurerstrasse 190, CH-8057 Zürich, Switzerland

<sup>d</sup>Albert-Ludwigs-Universität Freiburg, Physikalisches Institut, Hermann-Herder-Strasse 3, D-79104 Freiburg, Germany

<sup>e</sup>Physics Department, New York City College of Technology, The City University of New York, 300 Jay Street, Brooklyn, NY 11201, U.S.A.

<sup>f</sup>The Graduate School and University Center, The City University of New York, 365 Fifth Avenue, New York, NY 10016, U.S.A.

<sup>g</sup>INFN, Sezione di Padova,

Via Marzolo 8, I-35131 Padova, Italy

<sup>h</sup>Mam L. Bhasini Institute for Theoretical Physics, UCLA Department of Physics and Astronomy, Los Angeles, CA 90095, U.S.A.

<sup>i</sup>Dipartimento di Fisica e Astronomia, Università degli Studi di Padova, Via Marzolo 8, I-35131 Padova, Italy

<sup>j</sup>Dipartimento di Matematica e Fisica, Università di INFN, Sezione di Roma Tre, Via della Vasca Navale 84, I-00146 Roma, Italy

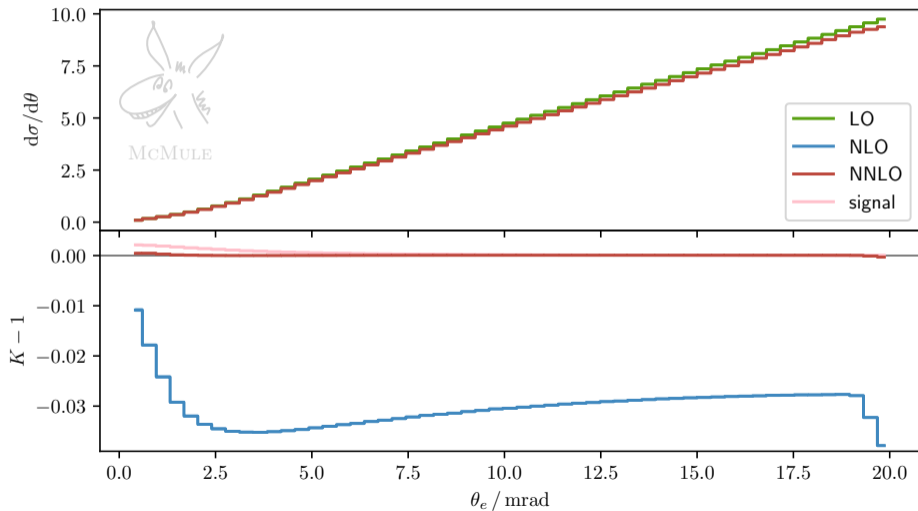
<sup>k</sup>Max-Planck-Institut für Physik, Werner-Heisenberg Föhlinger Ring 6, D-80805 München, Germany

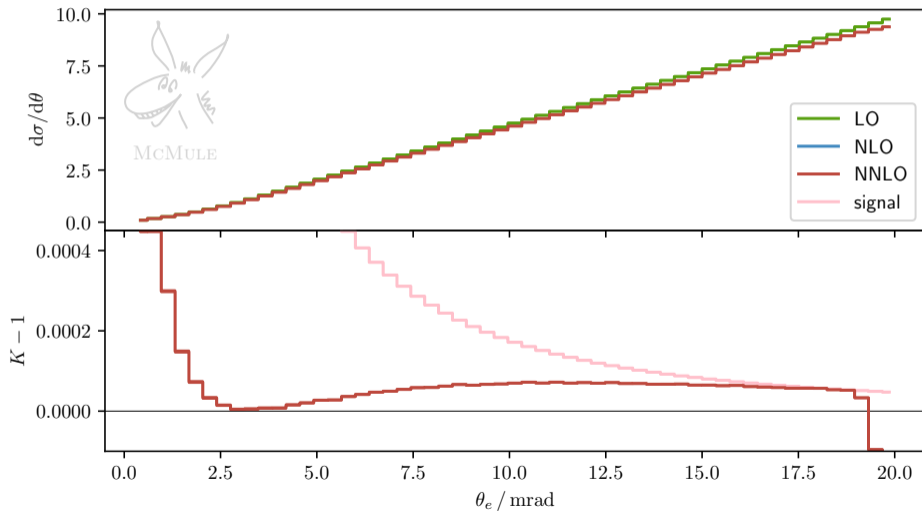
<sup>l</sup>Institute for Particle Physics Phenomenology, Unto South Road, Durham DH1 3LE, U.K.

<sup>o</sup>E-mail: [alessandro.broggio@uniroma1.it](mailto:alessandro.broggio@uniroma1.it), [tin.aferroglio@citytech.cuny.edu](mailto:tin.aferroglio@citytech.cuny.edu), [tpmanoja@gmail.com](mailto:tpmanoja@gmail.com), [pierpaolo.mastrolia@pd.infn.it](mailto:pierpaolo.mastrolia@pd.infn.it), [marco.ronca@johannes.it](mailto:marco.ronca@johannes.it), [adrian.signer@psi.ch](mailto:adrian.signer@psi.ch), [torres@mpg.de](mailto:torres@mpg.de), [yannick.ulrich@durham.ac.uk](mailto:yannick.ulrich@durham.ac.uk), [max.zoller@psi.ch](mailto:max.zoller@psi.ch)

<sup>†</sup>[yannick.ulrich@durham.ac.uk](mailto:yannick.ulrich@durham.ac.uk), <sup>‡</sup>[max.zoller@psi.ch](mailto:max.zoller@psi.ch)









McMULE

[mule-tools.gitlab.io](https://mule-tools.gitlab.io)

f.l.t.r.: F.Hagelstein (Mainz), A.Coutinho (IFIC), N.Schalch (Bern), L.Naterop (Zurich & PSI), S.Kollatzsch (Zurich & PSI), A.Signer (Zurich & PSI), M.Rocco (PSI), T.Engel (Freiburg), V.Sharkovska (Zurich & PSI), Y.Ulrich (Durham), A.Gurgone (Pavia)  
not pictured: P.Banerjee (IIT Guwahati), D.Moreno (PSI), D.Radic (Tubingen)