

Muon g-2

Gavin Hesketh, with thanks to Mark Lancaster



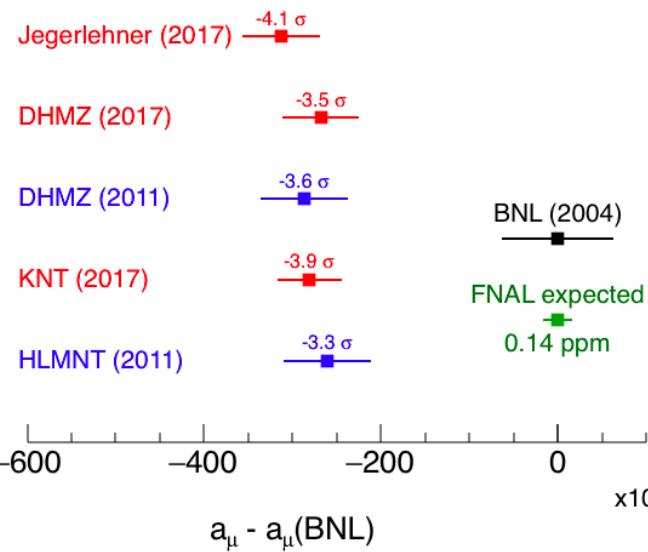
Anomalous contribution to the magnetic moment

- exactly 2 at tree level (Dirac prediction)
- shifted away from 2 by loops
 - QCD, EM, ... & New Physics?



$$a_\mu = \left(\frac{g - 2}{2} \right)$$

Comparison of SM
& BNL Measurement



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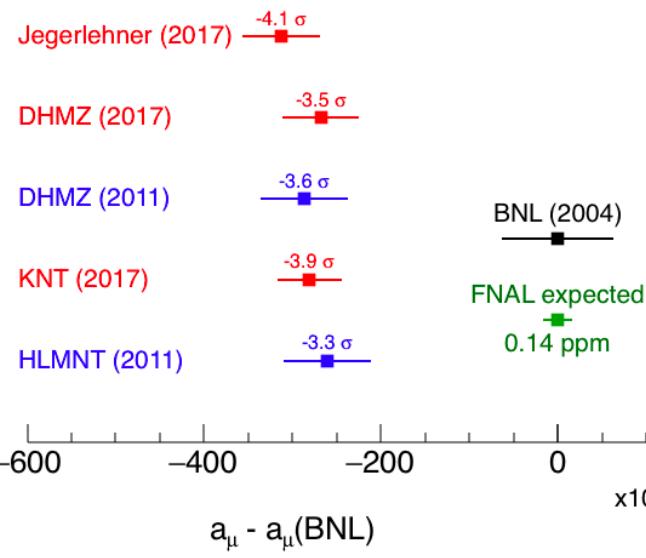


Fermilab  @Fermilab · 3h
"If I were to put my money on something that would signal new physics, it's the g-2 experiment at Fermilab."



We Asked Celeb Physicist Brian Cox About Flat Earth Conspiracies, the ...
gizmodo.com

Comparison of SM & BNL Measurement

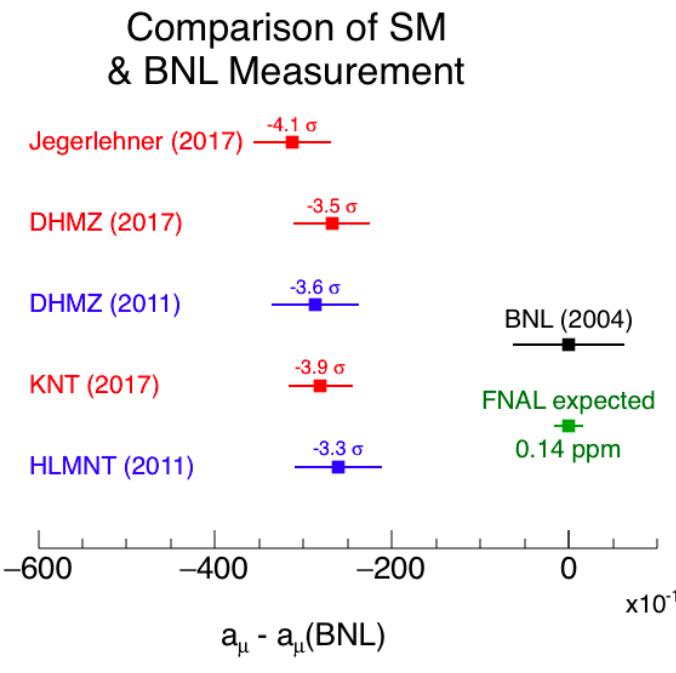
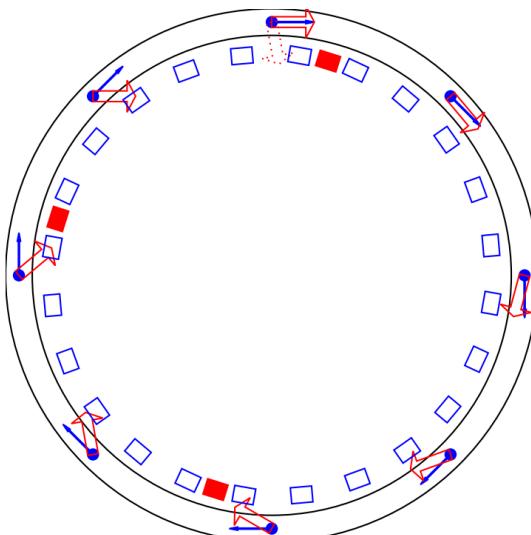


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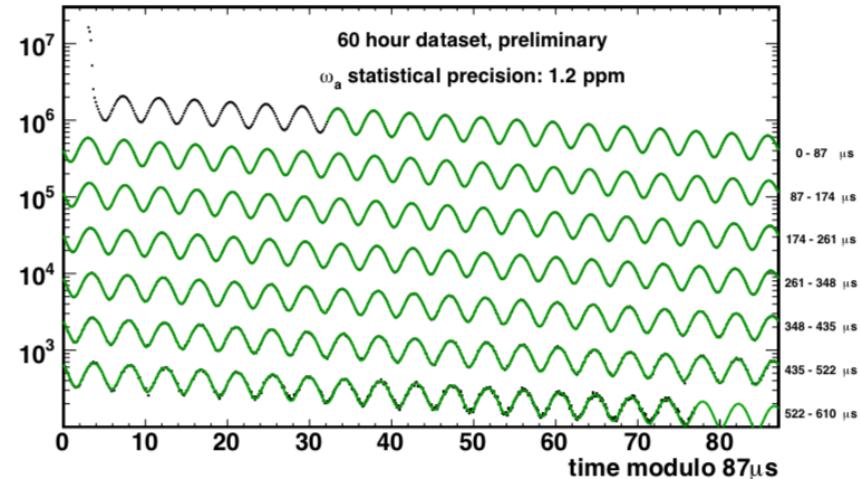
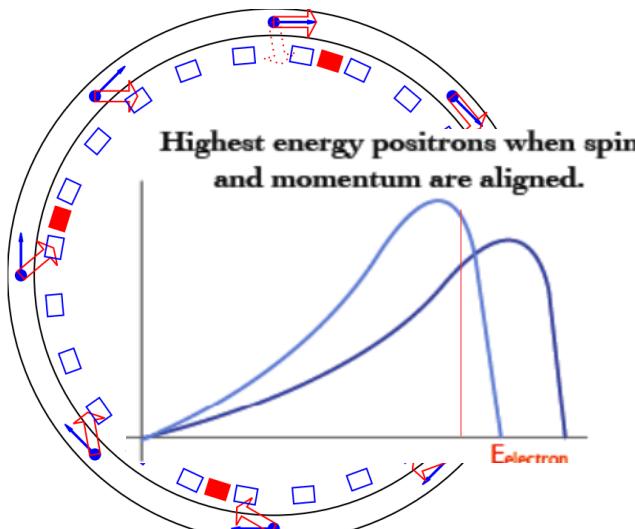


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Comparison of SM & BNL Measurement

Jegerlehner (2017) -4.1σ

DHMZ (2017) -3.5σ

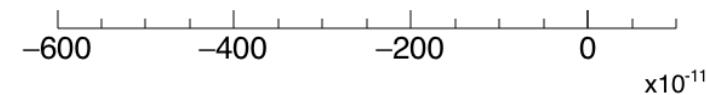
DHMZ (2011) -3.6σ

KNT (2017) -3.9σ

HLMNT (2011) -3.3σ

BNL (2004)

FNAL expected
0.14 ppm



$a_\mu - a_\mu(\text{BNL})$

Ground breaking: May 2013

STFC PPPR funding: April 2014 – April 2017

STFC PPGP funding: Oct 2016 -

Commissioning Run: June 2017

Project delivered on time and on budget!

(\$50M DoE, £1M UK)

First year of production data: Feb – July 2018

UK leadership

- Co spokesperson
- Detector Ops. Coordinator
- DAQ/Online Coordinator
- R-method Coordinator

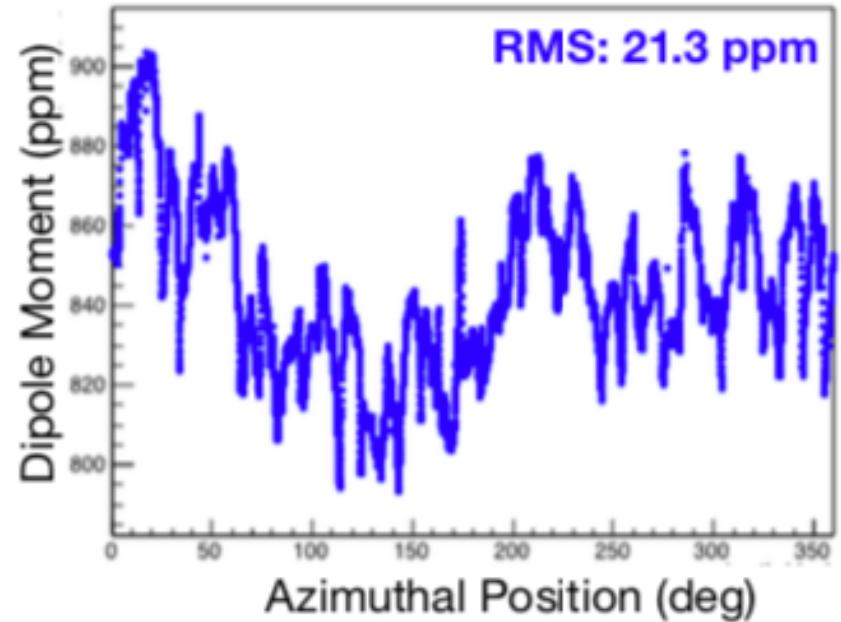
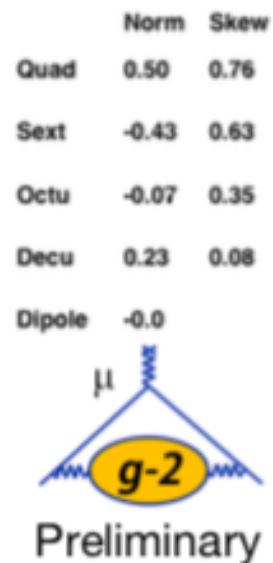
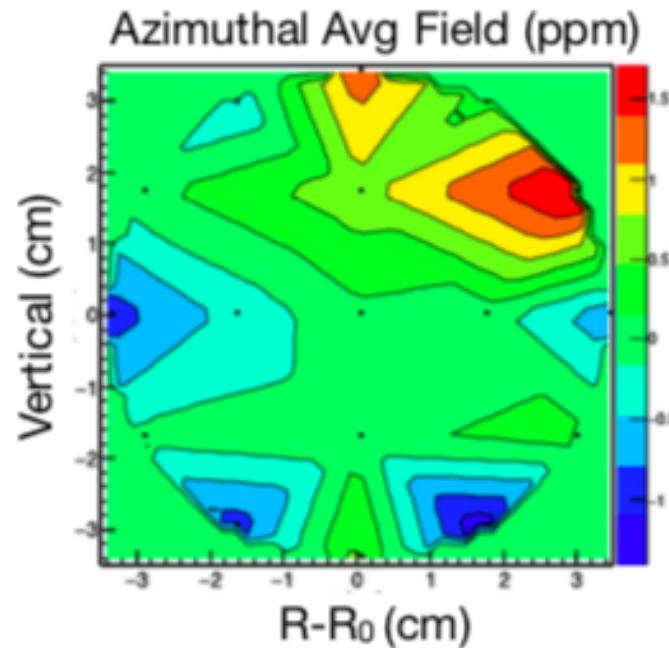
May 2013



May 2017

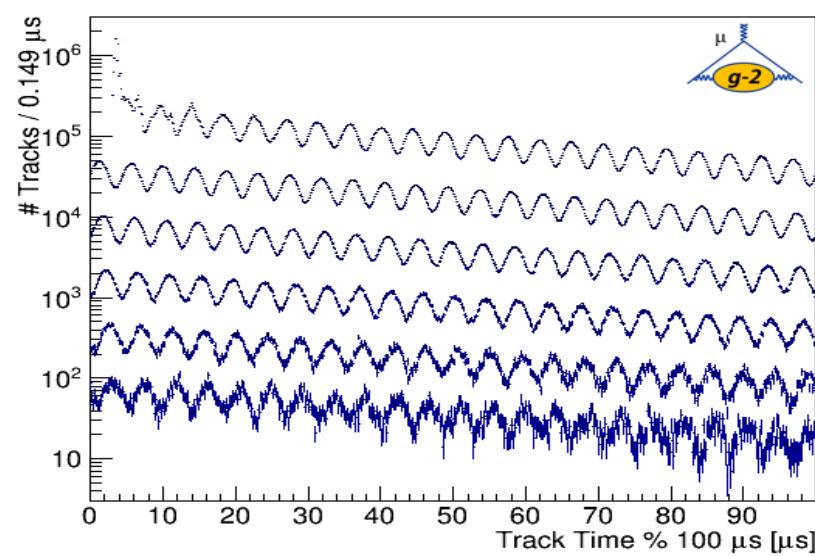
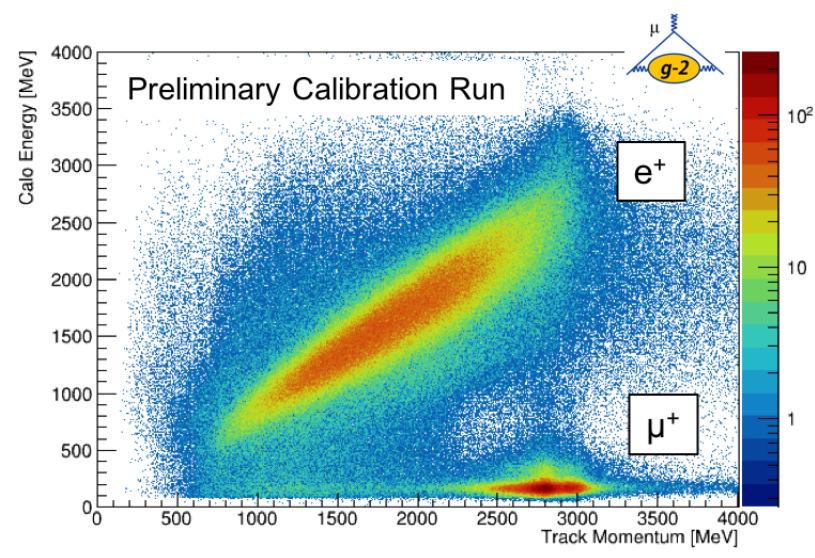
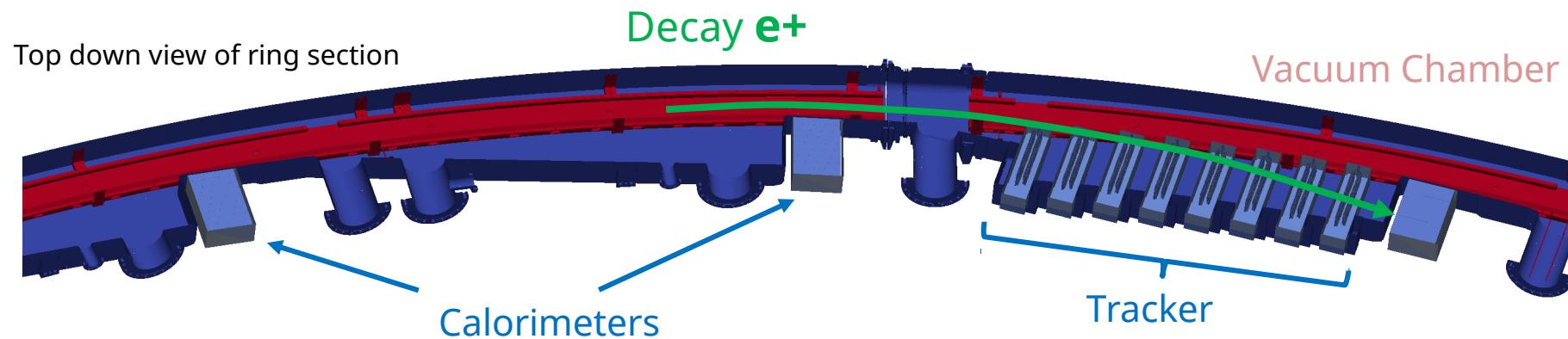


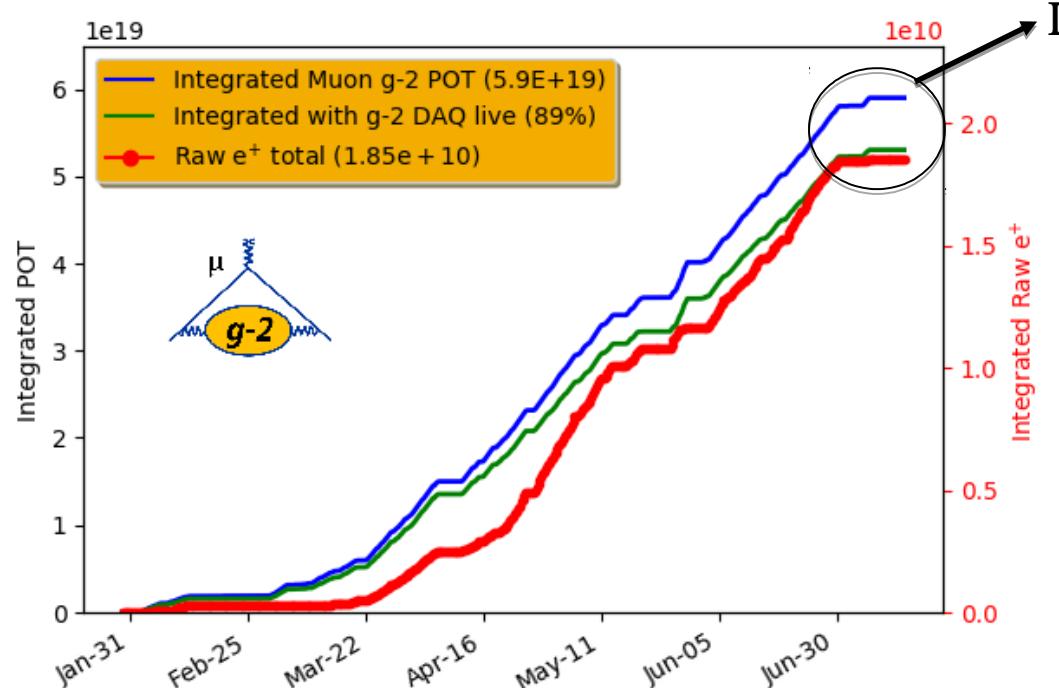
B field



Have achieved a B-field uniformity 3x better than BNL (x2 was goal)

UK deliverable: straw trackers





Dedicated systematic study runs

BNL recorded 9B e^+/e^- in 5 years

FNAL has recorded 18.5B e^+ in 5 months
- publish this dataset in 2019

Combining these could establish $>5\sigma$

Current e^+ rate is 50% design. Upgrades to kicker + new inflector magnet, with minor accelerator modifications will give x2 for 2018/19 run (starting Nov)

Runs in 2019/20 will accumulate $\sim 20x$ BNL

- could push significance to $\sim 10\sigma$

g-2 theory, and MUonE

| | VALUE ($\times 10^{-11}$) UNITS |
|-------------------------|--|
| QED ($\gamma + \ell$) | $116\,584\,718.951 \pm 0.009 \pm 0.019 \pm 0.007 \pm 0.077_\alpha$ |
| HVP(lo) [20] | $6\,923 \pm 42$ |
| HVP(lo) [21] | $6\,949 \pm 43$ |
| HVP(ho) [21] | -98.4 ± 0.7 |
| HLbL | 105 ± 26 |
| EW | 154 ± 1 |
| Total SM [20] | $116\,591\,802 \pm 42_{\text{H-LO}} \pm 26_{\text{H-HO}} \pm 2_{\text{other}} (\pm 49_{\text{tot}})$ |
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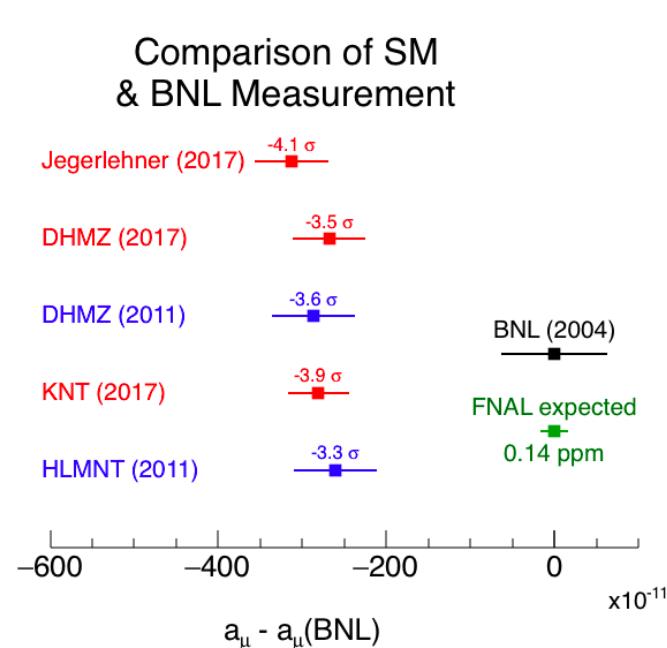
[T. Blum et al., arXiv:1311.2198]

Limited by LO hadronic vacuum pol. corrections

- input from ee->hadrons
- new input also from lattice (prominent UK role)
 - need x2 improvement to keep up with experiment

Muon g-2 Theory Initiative underway

<https://indico.fnal.gov/event/13795/>



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MUonE experiment @ CERN:

- space-like (free of resonances) e-mu scattering
 - basically a 150 GeV muon structure-function experiment
 - > new, independent input to HVP calculations

Schedule:

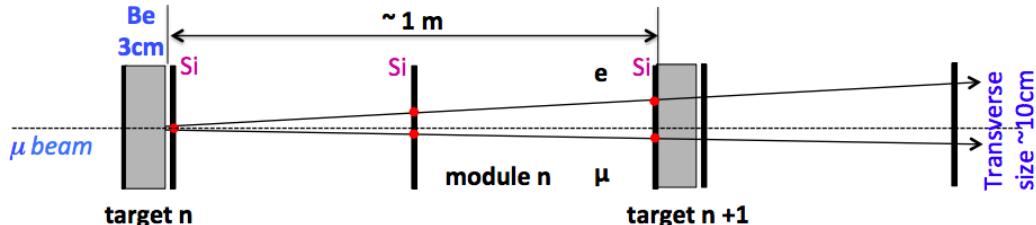
2018: 2 modules in CERN M2 Beam Line

2019: LOI to SPSC

2020/1: construction & installation

2021/2: start data taking (for 2 years)

Up to 20 Be targets + Si detectors downstream calorimeters + muon PID



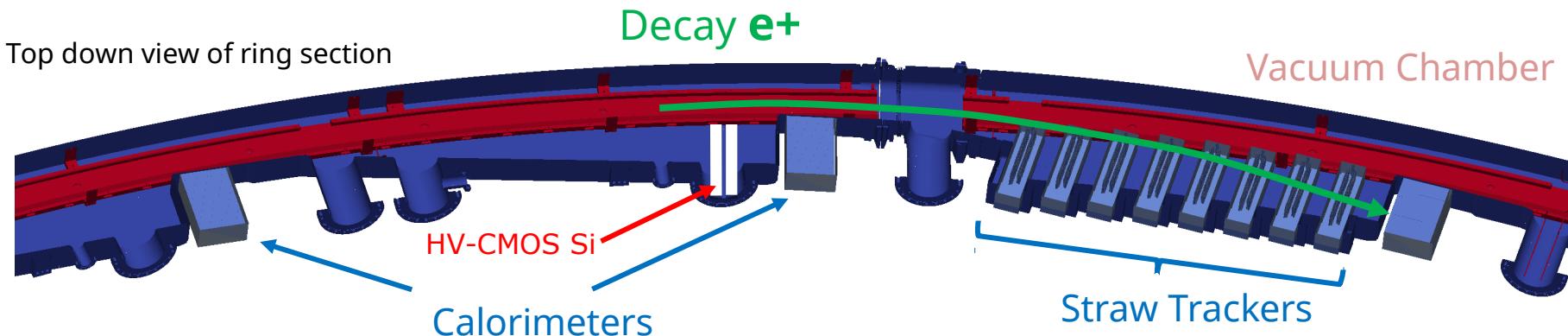
g-2 runs for 2 more years with μ^+

Share beam with Mu2e in 2021: 3 months would give 4xBNL μ^-

- CPT check of g-2
- world's best μ^- lifetime measurement

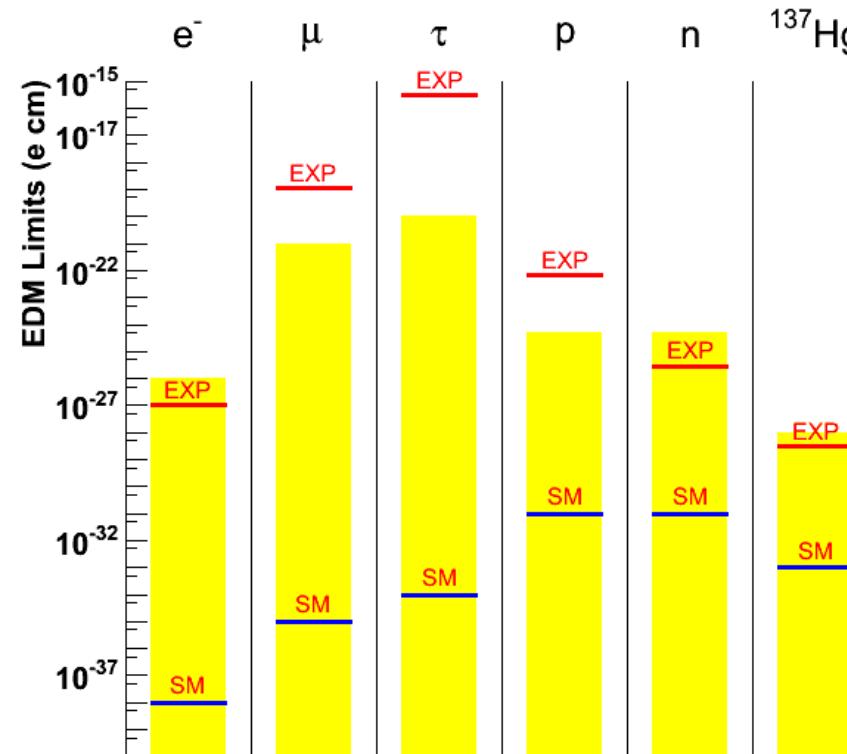
In 2020, deploy HV-CMOS detectors (Mu3e sensors/readout)

- prototype for future, dedicated mu-EDM experiment



In SM, EDMs of fundamental particles ~zero -> any observation = new physics!

-> access PeV-scale (CP-violating) physics



Muon EDM is the only 2nd gen. measurement
- and free of nuclear/molecular effects

Limit from BNL: 1.8×10^{-19}

Present g-2 will extend by x100
- straw trackers critical

Dedicated silicon detectors in front of 24 calorimeters at g-2 -> further factor x10
- pushing into the realm of BSM predictions.

Proposed E-field storage ring at CERN

- push sensitivity by 10^5 , down to 10^{-29} (mass scaling equivalent of 10^{-30} e-EDM)

Probe new physics up to 3000 TeV for CP-violating phase of $\pi/4$

- or a CP-violating phase down to 10^{-7} for electroweak-scale NP

 θ_{gCD} to 10^{-13} :

- 10^3 below current bound from neutron-EDM

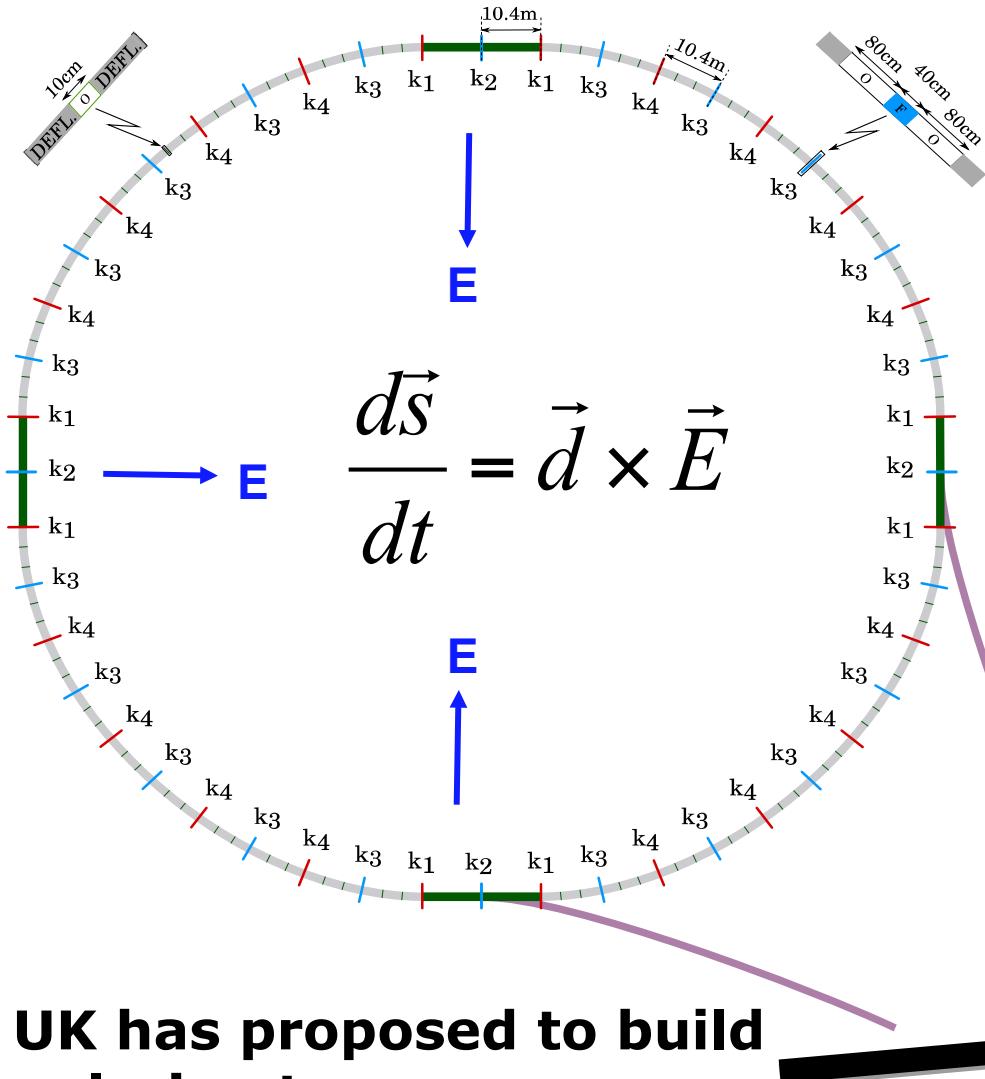
Pseudo-scalar Higgs couplings at 10^{-3}

- 10^2 below current bound from electron-EDM

Proton-EDM at this sensitivity may be our only means of accessing H-u/d/e coupling

A variant experiment (see arXiv:1710.05271 and 1708.06367: Sussex/RAL/KCL) can also probe for axions (axion field induces oscillating EDM)

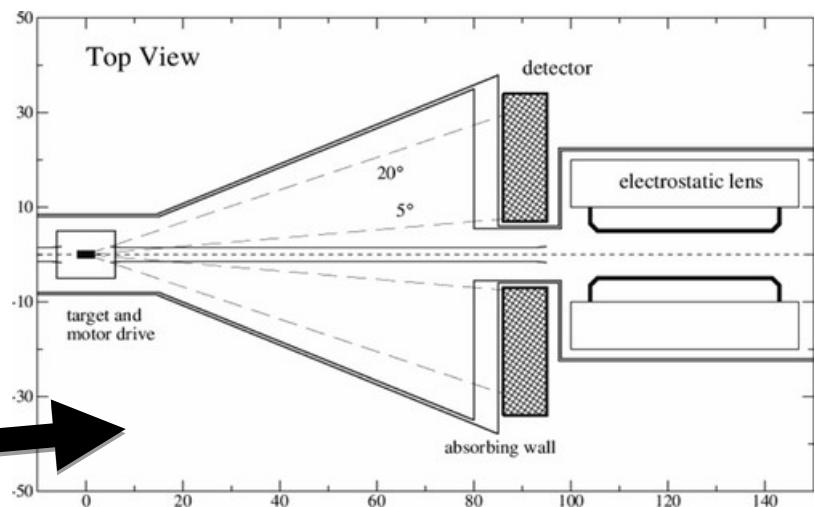
Future programme: proton-EDM



UK has proposed to build polarimeters.

**~700 MeV proton beam
- could fit in ISR tunnel**

Straight sections are instrumented with quads, BPMs, polarimeters, injection points.



10 year programme, with g-2, CLFV (Mu2e-II & Mu3e-II) & p-EDM

- probe CP-conserving/violating & flavour-violating BSM physics
- to PeV scale, complementing and extending LHC searches
 - *an important part of the diversity of the UK & European programme*

- g-2, & g-2 (mu) @FNAL

- mu-EDM @FNAL

- MUonE @CERN

- Mu2e-II @FNAL and Mu3e-II @PSI

- p-EDM @CERN

Each of these experiments will produce world's best measurements

These experiments build on UK leadership in EDM, MDM & HV-CMOS

- and opportunity to build, run and publish within a few years

The programme represents a new cost to STFC of O(£3.5M)

- 80% of capital expenditure before 2024.

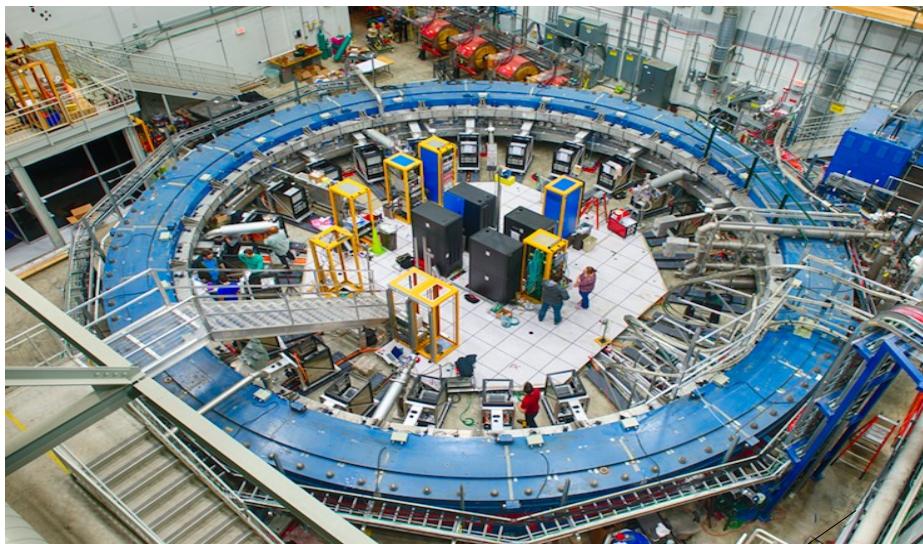
We have prepared a document with more details ready for PPAP consideration

| | 2019 | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 |
|-----------------------------|---------|-----------|-----------|-----------|------|-----------------------|------|-----------|-----------|-------------------|
| g-2 running | STFC-CG | (STFC-CG) | (STFC-CG) | | | | | | | |
| MuonE R&D | | (STFC-CG) | | | | | | | | |
| MuonE construction | | | | | | | | | | |
| MuonE exploitation | | | | | | | | | | |
| mu-EDM prototype | | | | | | | | | | |
| mu-EDM construction | | | | | | | | | | |
| mu-EDM exploitation | | | | | | | | | | |
| pEDM R&D | | (STFC-CG) | | | | | | | | |
| pEDM construction | | | | | | | | | | |
| pEDM exploitation | | | | | | | | | | |
| Mu2e construction | STFC | (STFC-CG) | | | | | | | | |
| Mu2e exploitation | | | (STFC-CG) | (STFC-CG) | | | | | | |
| Mu2e-II R&D | | | | | | | | | | |
| Mu2e-II Construction | | | | | | | | | | |
| Mu3e-I exploitation | STFC | (STFC-CG) | (STFC-CG) | | | | | | | |
| Mu3e-II construction | | | | | | | | | | |
| Mu3e-II exploitation | | | | | | | | | | |
| Science | | muon g-2* | muon EDM* | muon LFV* | | muon g-2 theory check | | muon LFV* | muon EDM* | muon LFV* |
| Worlds best limits=* | | | | | | | | | | pEDM* to SM limit |

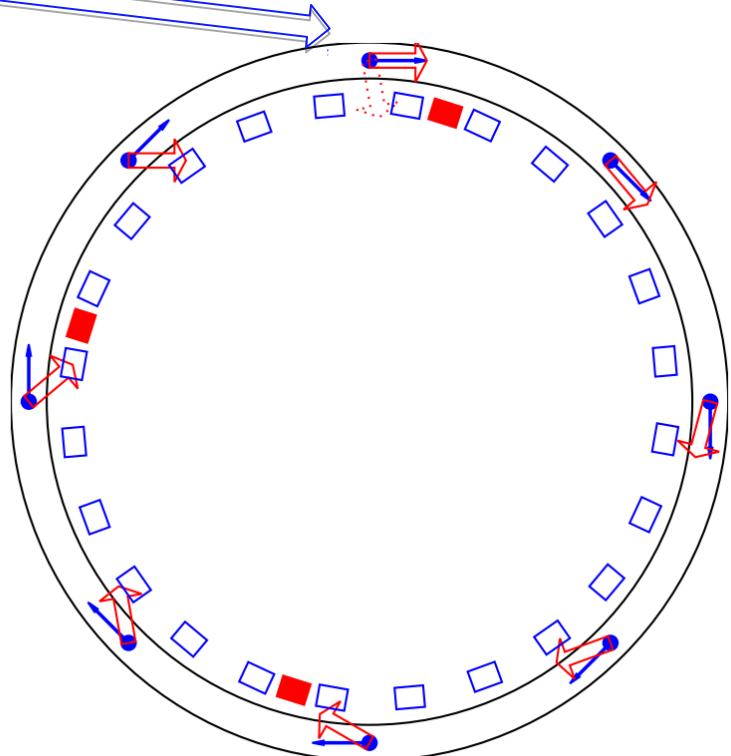
Thanks for your attention!

~~ fin ~~

Muon g-2



**Inject muons
at 3.09 GeV**



$$\omega = -\frac{q}{m} \left[a_\mu B - \left(a_\mu - \frac{1}{\gamma^2 - 1} \right) \frac{\beta \times E}{c} \right]$$

Use of “magic momentum” 3.09 GeV
 → direct access to ω from precession freq.

Graphics from Themis Bowcock, PPAP 2017

24 calorimeters and 3 straw-strackers (UK) measure e^+ for $O(1 \text{ ms})$ for spills separated by 10ms.
 16,000 stored 3.09 GeV muons from 10^{12} protons per spill.

Muon g-2

$\text{BNL} \rightarrow \text{FNAL}$
 $[50 \text{ (stat)} + 33 \text{ (syst)} \rightarrow 11 \text{ (stat)} + 11 \text{ (syst)}] \times 10^{-11}$

Improvements:

- muon muons per proton, cleaner delivery
- detectors & modelling
- stored muon beam dynamics
- field uniformity & calibration

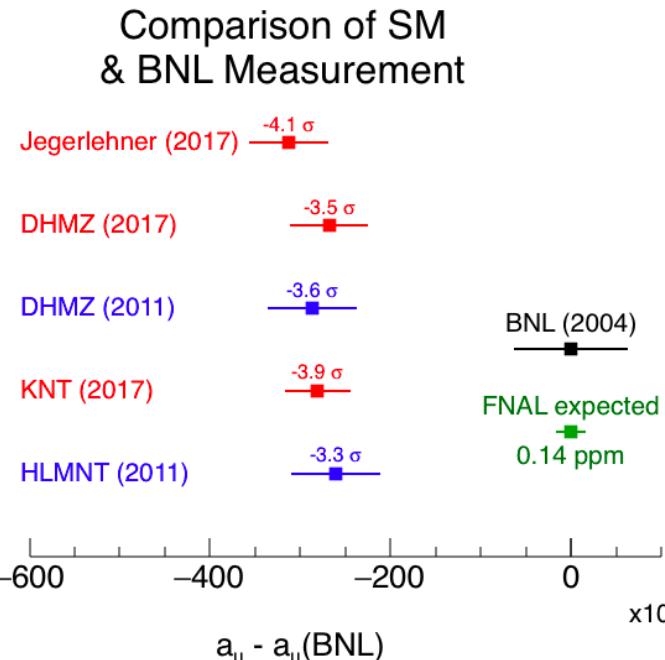
Recorded 2 x Brookhaven stats this year.

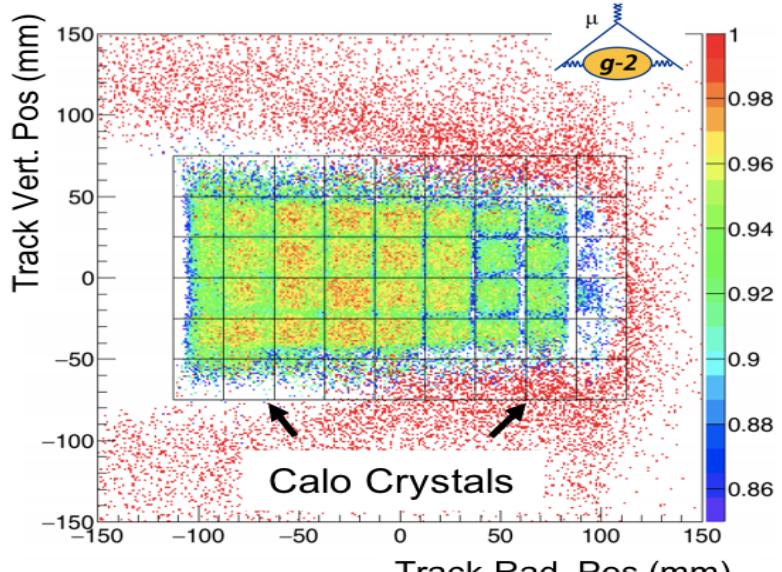
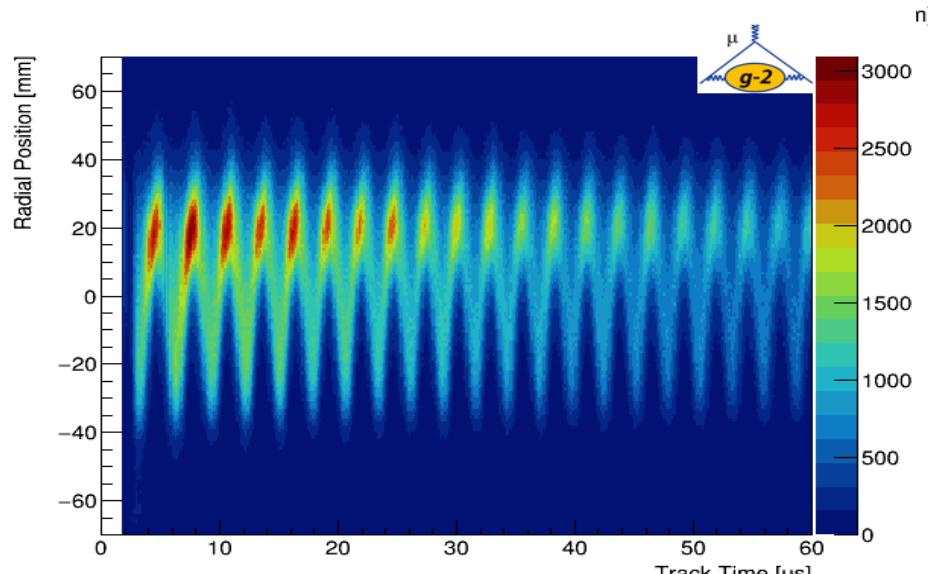
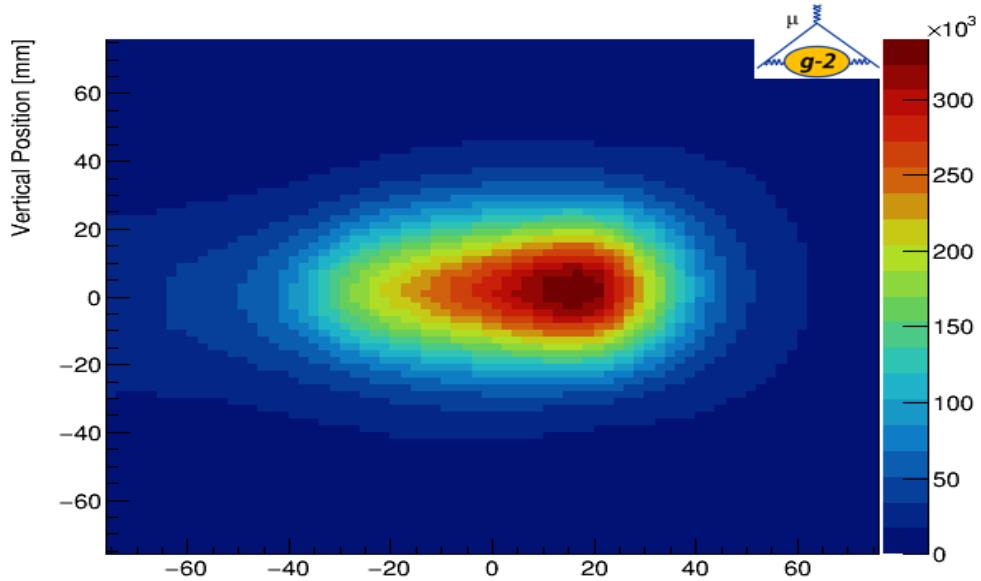
$$\vec{\omega} = -\frac{e}{m} \left\{ a \vec{B} + \left(\frac{1}{1-\gamma^2} - a \right) \frac{\vec{\beta} \times \vec{E}}{c} + \frac{\eta}{2} \left(\frac{\vec{E}}{c} + \vec{\beta} \times \vec{B} \right) \right\}$$

$\vec{\omega}_a$
 $\vec{\omega}_e$

Can also access muon EDM by looking for vertical oscillation

- zero in the SM (EDMs only possible with violation of PT)
- expect to surpass Brookhaven limit very soon, then $\times 100$.





Considerable recent theory progress : with prominent UK role

PHYSICAL REVIEW LETTERS 121, 022003 (2018)

Editors' Suggestion

Calculation of the Hadronic Vacuum Polarization Contribution to the Muon Anomalous Magnetic Moment

T. Blum,¹ P. A. Boyle,² V. Gülpers,³ T. Izubuchi,^{4,5} L. Jin,^{1,5} C. Jung,⁴ A. Jüttner,³ C. Lehner,^{4,*} A. Portelli,² and J. T. Tsang²

Lattice + e⁺e⁻ data

(RBC and UKQCD Collaborations)

692.5 (2.7) × 10⁻¹⁰

PHYSICAL REVIEW D 97, 114025 (2018)

Editors' Suggestion

Featured in Physics

693.3 (2.5) × 10⁻¹⁰

Muon g - 2 and $\alpha(M_Z^2)$: A new data-based analysis

Alexander Keshavarzi,^{1,*} Daisuke Nomura,^{2,3,†} and Thomas Teubner^{1,‡}

¹*Department of Mathematical Sciences, University of Liverpool, Liverpool L69 3BX, United Kingdom*

²*KEK Theory Center, Tsukuba, Ibaraki 305-0801, Japan*

Institute for Theoretical Physics, Kyoto University, Kyoto 606-8502, Japan

Only e⁺e⁻ data



(Received 6 April 2018; published 25 June 2018)

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

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HVP calculated using dispersion relation plus experimental data from ee->hadrons

Lattice calculations starting to contribute

[T. Blum et al., arXiv:1801.07224]

See Phiala Shanahan's talk at ICHEP

<https://indico.cern.ch/event/686555/timetable/#20180711>

