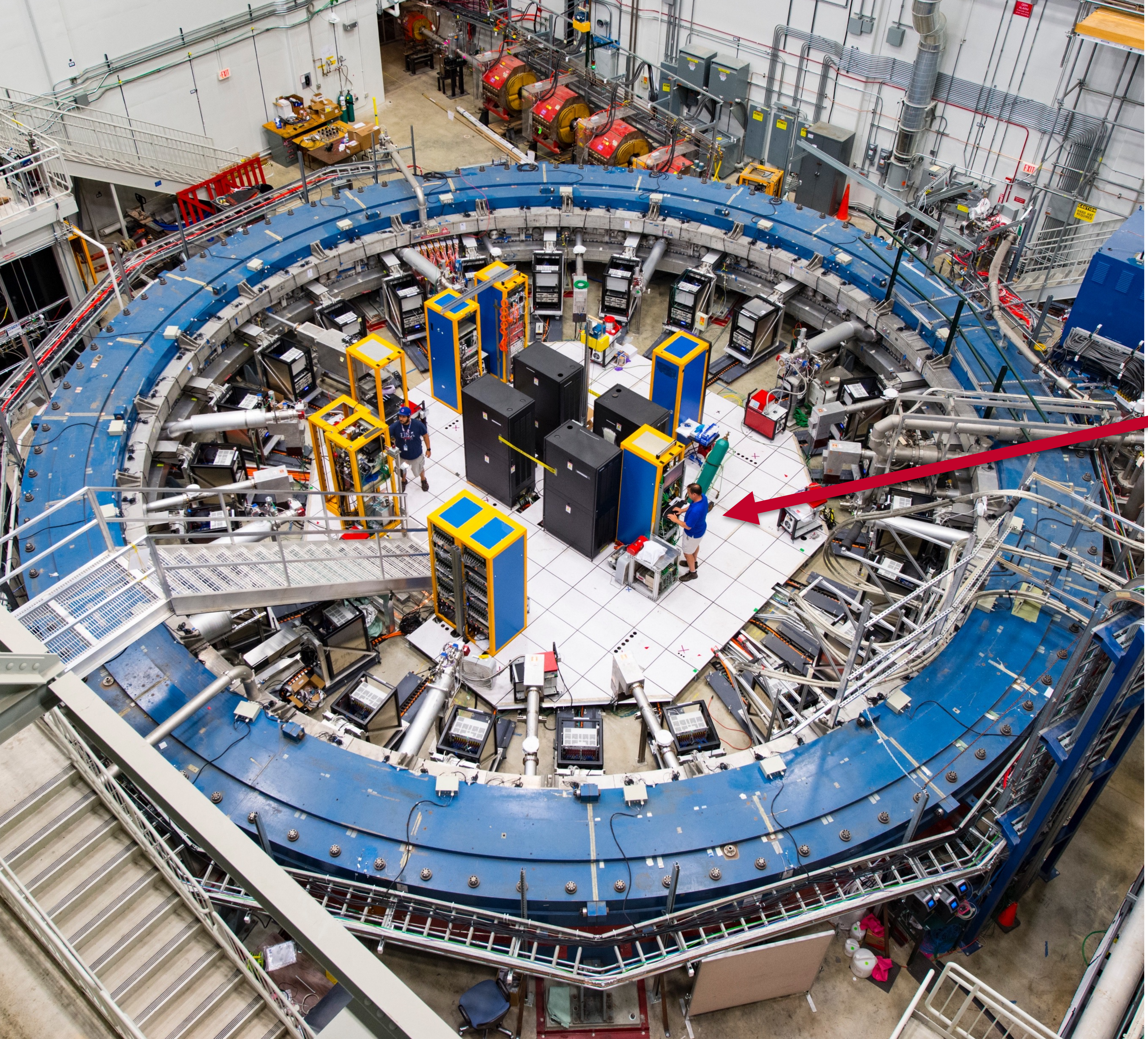


Breaking Walls To The Unknown:
The 18th Particle?

Dr. Chris Polly

Fermi National Accelerator Laboratory

substituted by

Prof. Dr. Martin Fertl

Johannes Gutenberg University Mainz

Falling Walls Circle – Wilhelm and Else Heraeus Symposium for Breakthroughs in Physical Sciences

November 8th, 2021

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

The 17 Elementary Particles of the Standard Model

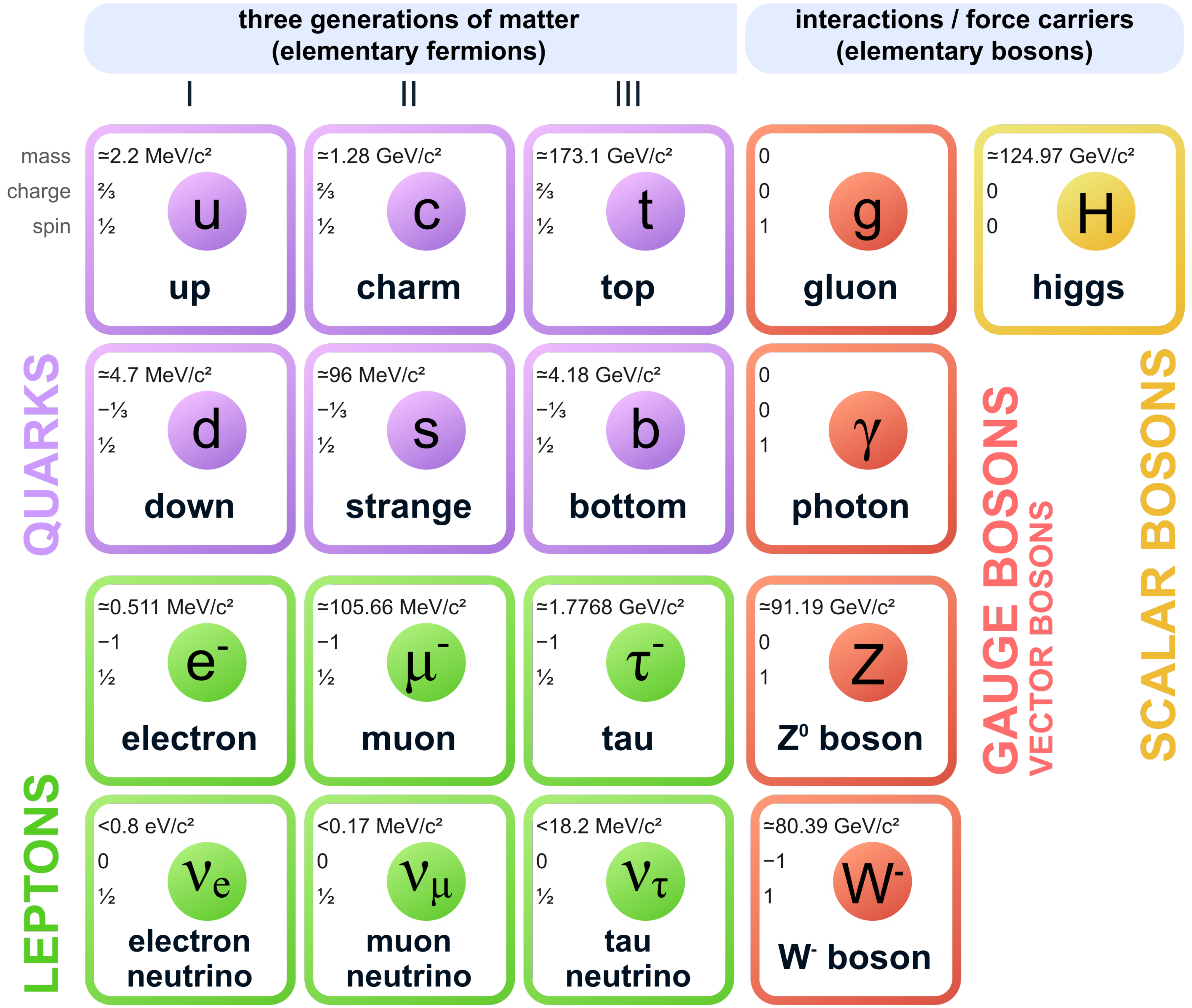
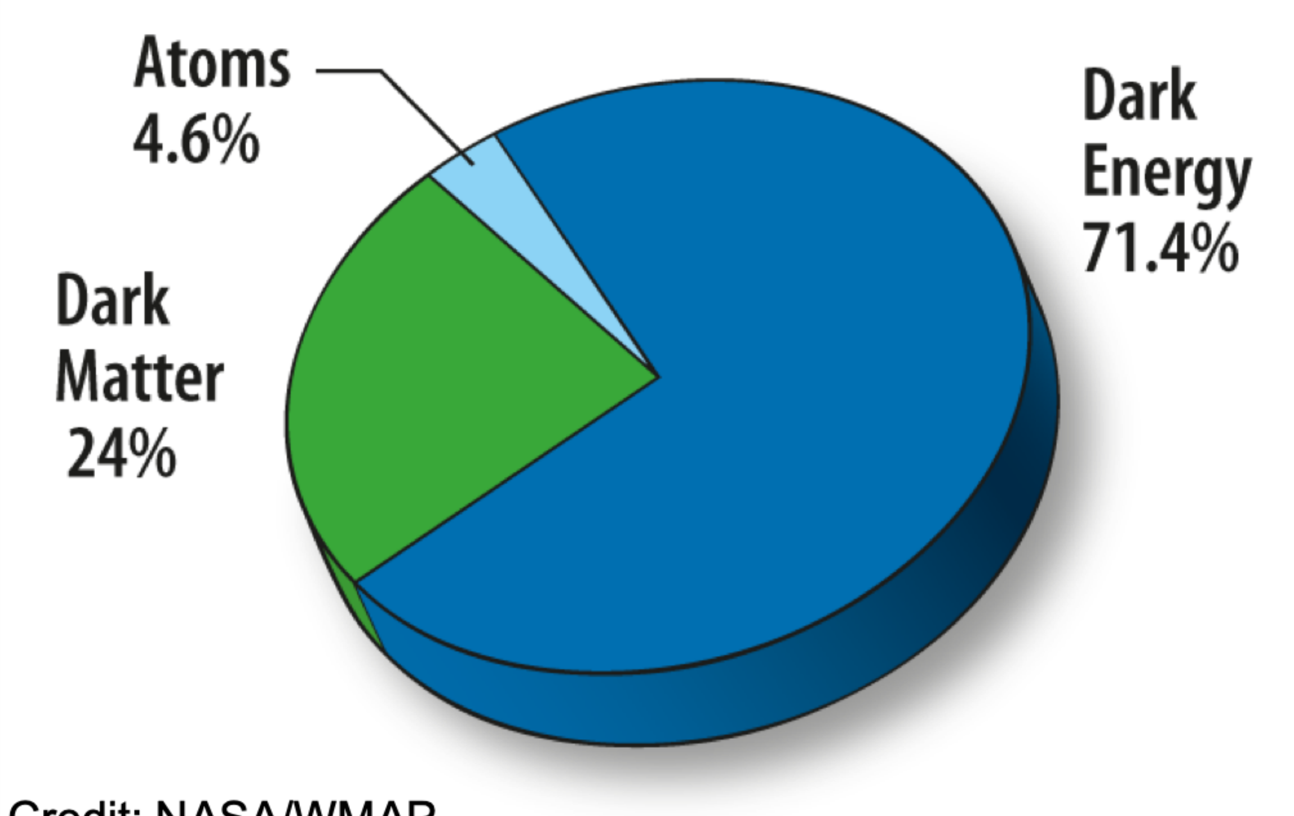


Figure adapted and updated from https://commons.wikimedia.org/wiki/File:Standard_Model_of_Elementary_Particles_Anti.svg

Fundamental Questions

Baryon asymmetry of the Universe:
Why is there not more anti-matter?
Why are we even here?



Credit: NASA/WMAP Science Team

Dark energy:
What is it?

What is Dark Matter made of ?

How does gravity fit into a common framework with the other three forces?

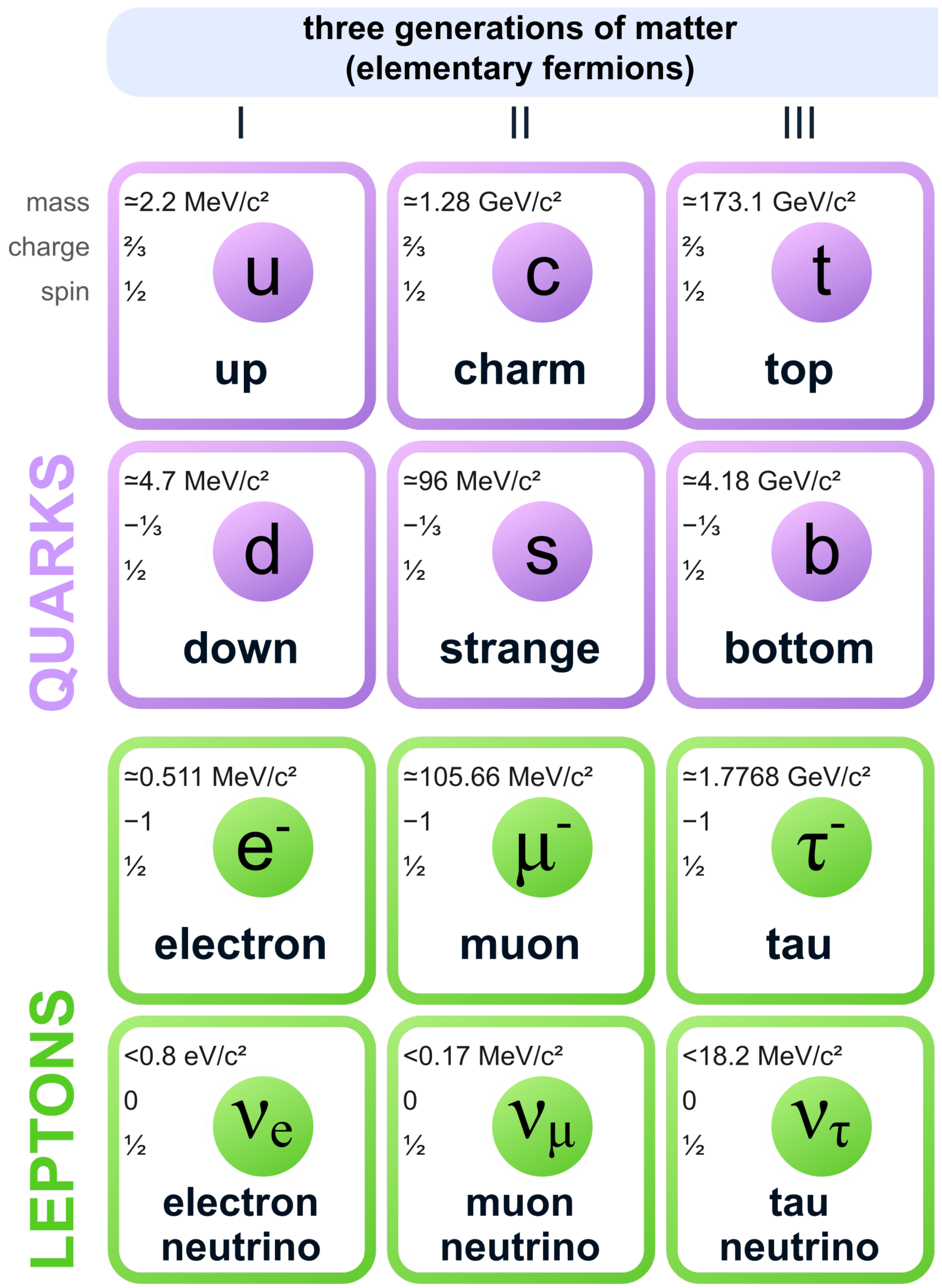
Neutrinos do have mass!
How heavy are they?
How do they obtain mass?

The Standard Model of Particle Physics does not provide any answers to these fundamental questions!

Andromeda galaxy, WISE space telescope, 3.4 μm, Credit: NASA/JPL-Caltech/UCLA


THE MUON g–2 ANOMALY EXPLAINED
μ
THE MUON IS THE ELECTRON'S HEAVIER COUSIN.
'Sup, cuz!
e
μ
JUST LIKE THE ELECTRON, IT HAS A MAGNETIC MOMENT THAT COMES FROM ITS CHARGE AND QUANTUM SPIN.
LIKE ALL CHARGED PARTICLES, IT TENDS TO INTERACT WITH ITSELF IN A MAGNETIC FIELD, AND IN THE PROCESS IT CREATES OTHER PARTICLES THAT EXIST FOR A BRIEF MOMENT IN TIME.
Whoa.
IT DOES THIS IN A QUANTUM MECHANICAL WAY, WHICH MEANS IT CREATES MANY COMBINATIONS OF PARTICLES ALL THE TIME, AND ALL AT THE SAME TIME.
THAT MEANS THAT WHEN YOU LOOK AT A MUON, YOU DON'T JUST SEE THE MUON; YOU ALSO SEE THE INFINITE NUMBER OF VIRTUAL PARTICLES IT IS CONSTANTLY CREATING.
I don't know who you are any more.
EACH OF THESE PARTICLES AFFECTS THE MUON'S MAGNETIC MOMENT IN A MEASURABLE WAY, CHANGING ITS VALUE.
g = 2
g ≠ 2
BY USING OUR CATALOG OF KNOWN PARTICLES, WE CAN PREDICT WHAT THIS CHANGE SHOULD BE...
g?
...AND COMPARE IT TO EXPERIMENTAL MEASUREMENTS OF IT.
g?
BUT WHAT IF THOSE TWO NUMBERS ARE NOT THE SAME?
g = 2.000001!
g = 2.000002!
COULD WE BE WRONG ABOUT WHICH PARTICLES THE MUON CAN CREATE? OR IS OUR WHOLE FORMULATION OF PHYSICS INCORRECT?
You're wrong!
No, you're wrong!
THAT IS THE MYSTERY OF THE MUON'S MAGNETIC MOMENT.
g Brookhaven =
2.00233184178
±0.00000000126
IT IS ONE OF THE MOST PRECISELY TESTED PHYSICAL QUANTITIES IN HUMAN HISTORY.
20 YEARS AGO, BROOKHAVEN NATIONAL LAB MEASURED IT, AND FOUND IT TO BE DIFFERENT THAN THE THEORETICAL VALUE BY 2.7σ.
2.7σ
g Theoretical
g Experimental
SINCE THEN, THE THEORETICAL VALUE HAS GOTTEN MORE PRECISE, AND NOW FERMI NATIONAL LAB HAS MADE AN EVEN MORE ACCURATE MEASUREMENT OF IT:
MUONS SPIN AROUND INSIDE A STORAGE RING.
DETECTORS CATCH THE MUONS AS THEY DECAY INTO ELECTRONS.
THE ENERGY OF THE ELECTRONS DEPENDS ON THE DIRECTION OF THE MUONS' MAGNETIC MOMENT.
g
e
t
THE FLUCTUATIONS IN THE ENERGY OF THE ELECTRONS COMING OFF THE RING TELL YOU THE VALUE OF THE MUON'S MAGNETIC MOMENT.
...AND WHEN IT'S POINTING BACKWARDS, THEY HAVE LESS ENERGY.
WHEN THE MOMENT IS POINTING FORWARDS, THE DECAYING ELECTRONS HAVE MORE ENERGY...
FERMILAB SHIPPED THE GIANT MAGNET FROM BROOKHAVEN, NEW YORK TO CHICAGO, UPGRADED THE EXPERIMENT SIGNIFICANTLY, AND REPEATED IT WITH MORE MUONS.
WITH THIS NEW MEASUREMENT, THE DIFFERENCE IN g IS NOW 4.2σ, PROVIDING STRONGER EVIDENCE THAT SOMETHING IS AMISS.
Maybe we're both right...
COULD IT BE THAT THE MUON IS CREATING PARTICLES WE DON'T KNOW ANYTHING ABOUT, BUT WHICH MIGHT SOLVE OTHER MYSTERIES IN PHYSICS?
DARK MATTER?
NEW FORCES?
IT'S ALL PART OF OUR SEARCH TO DISCOVER HOW THE UNIVERSE WORKS.
WE ALL LOOK AROUND AND WONDER: HOW CAN THIS ALL BE? WHY DO WE EXIST?
ONE THING IS FOR SURE: THE HUNT IS ON, AND NEW DISCOVERIES ARE ON THE HORIZON.
APS physics
Written and drawn by Jorge Cham
For Physics Magazine physics.aps.org
Thanks to Chris Polly and Fermilab!

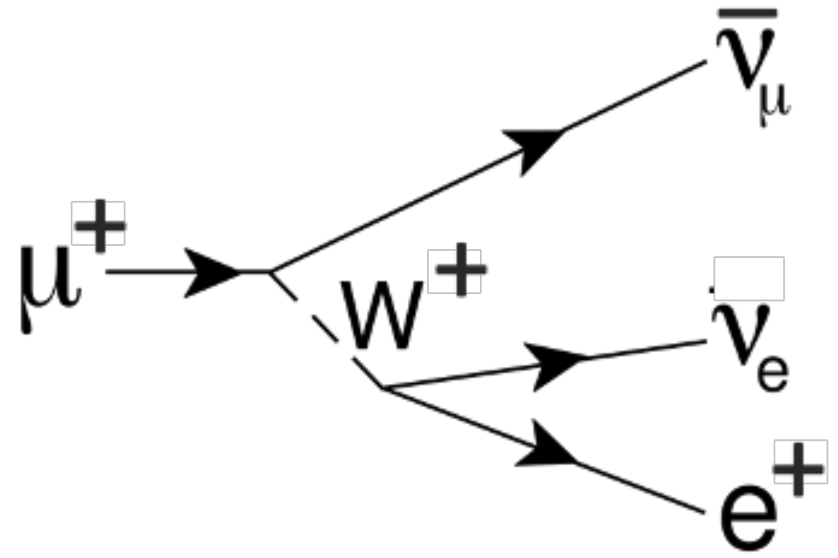
What are muons?

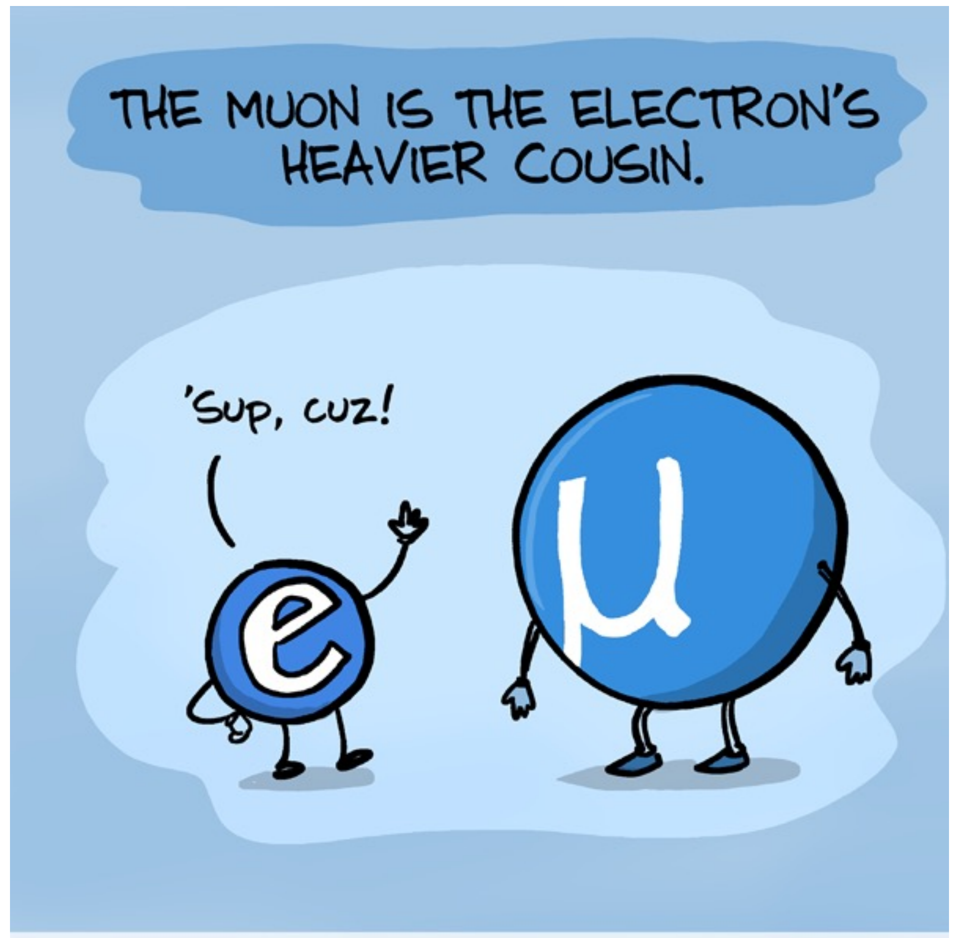


The heavier cousin of the electrons:

- 200 x heavier than an electron
- Same “spin” (intrinsic angular momentum)
- Same electric charge than e

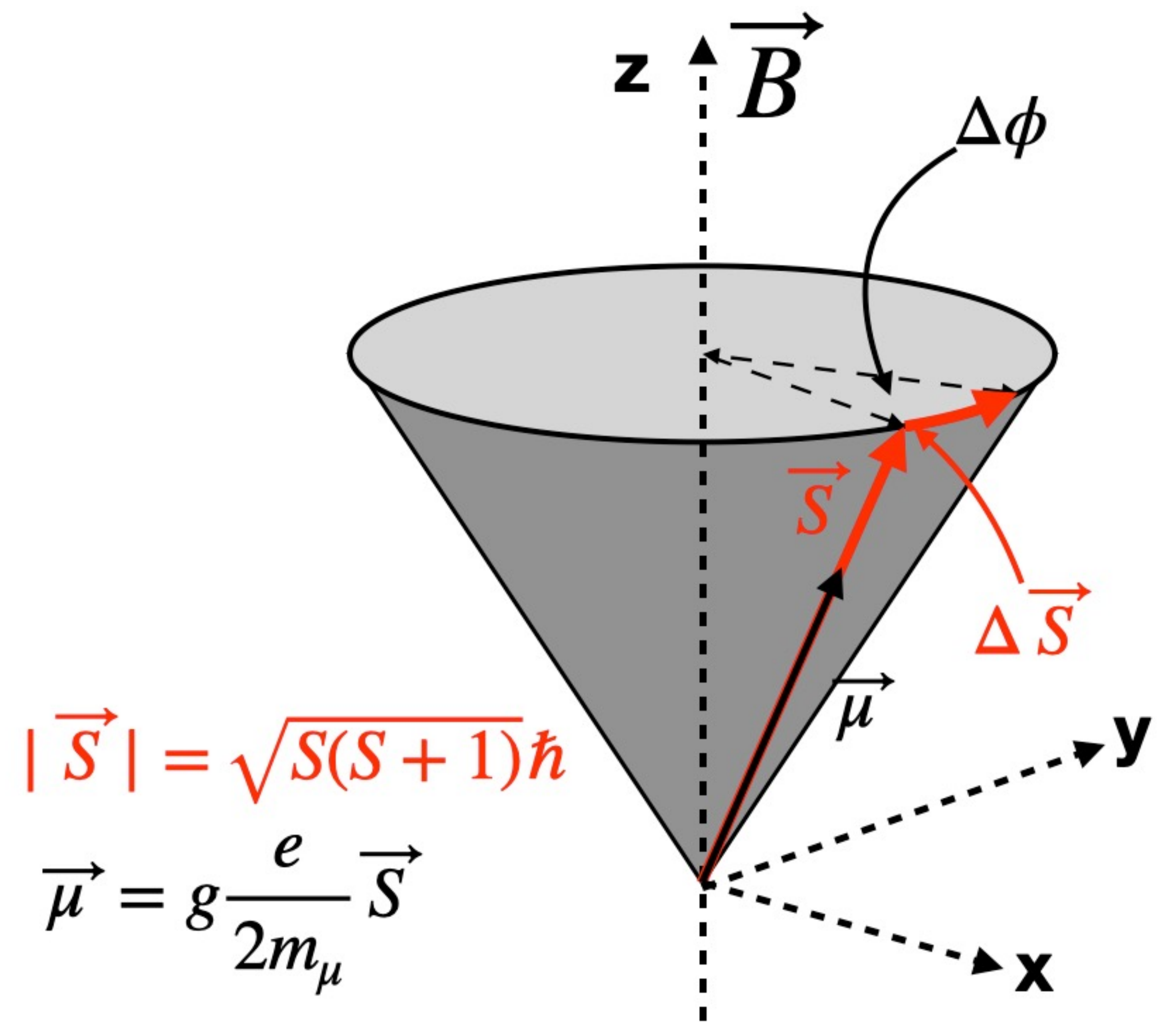
- Unstable: lifetime ≈ 2 μs
- Production in large numbers at accelerators
- Decay: Prototype of weak interaction





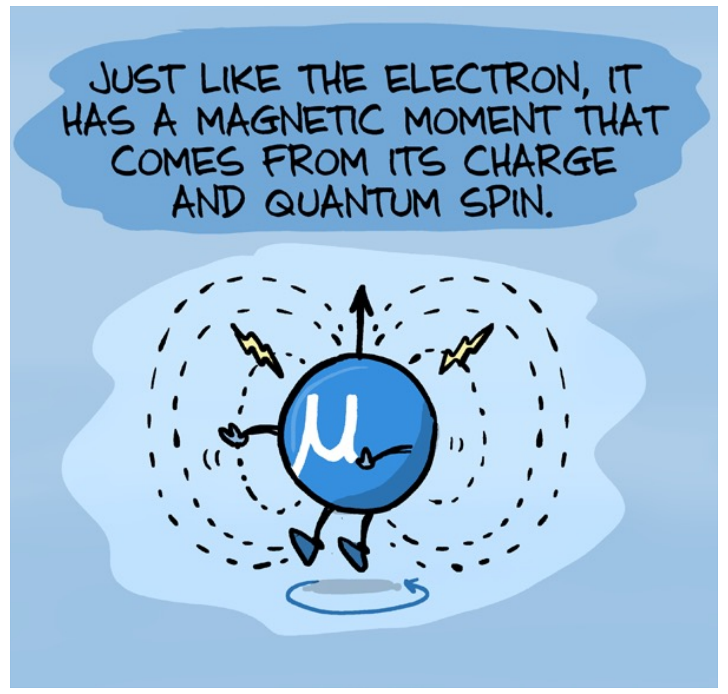
JG|U

The g factor of a charged lepton



Charged particle with magnetic dipole moment and spin

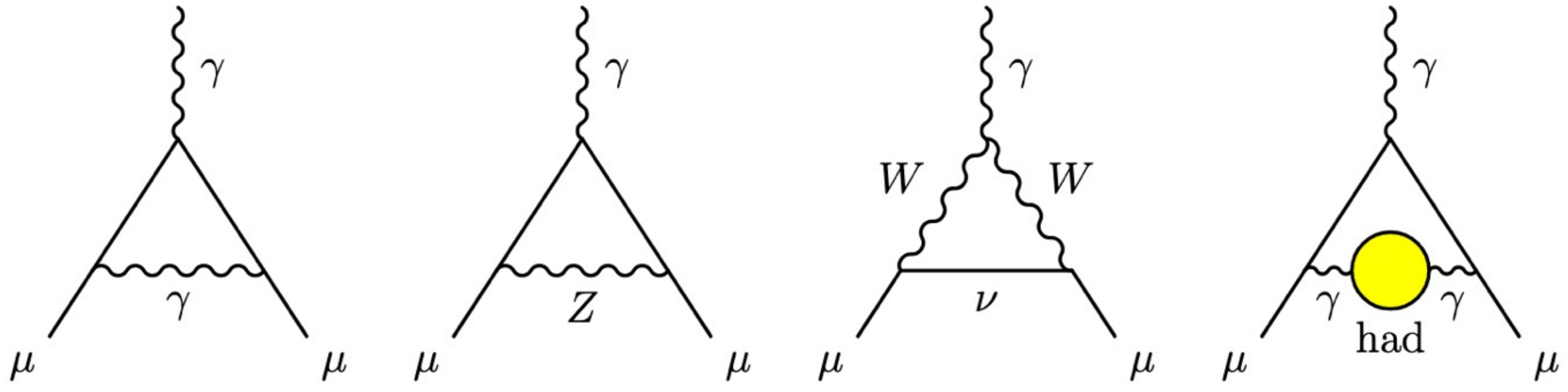
$$\vec{\mu} = g\frac{q}{2m}\vec{s}$$



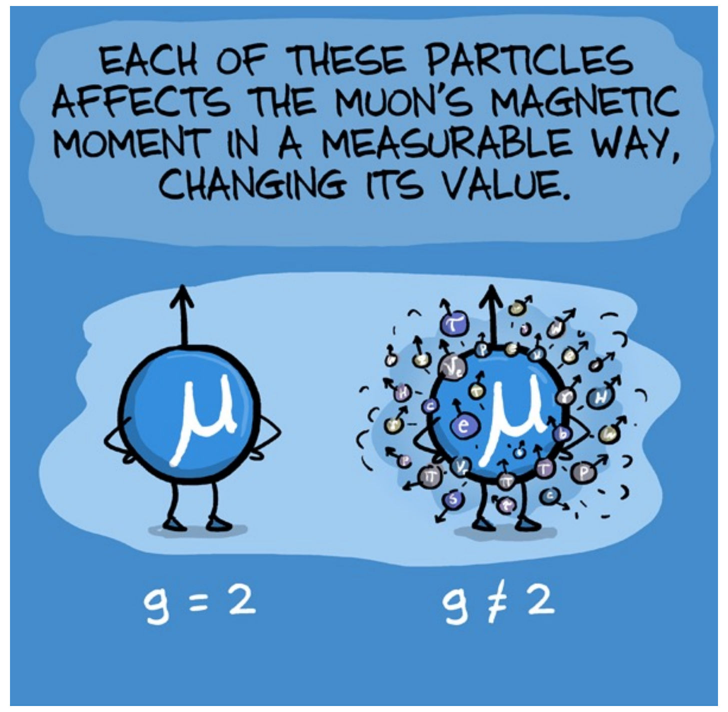
For a point-like charged lepton with spin 1/2 Dirac predicts $g = 2$

(P. Dirac, The Quantum Theory of the Electron, Proc. R. Soc. Lond. A 1928 **117**)

Interactions with virtual particles cause the “anomalous magnetic moment”

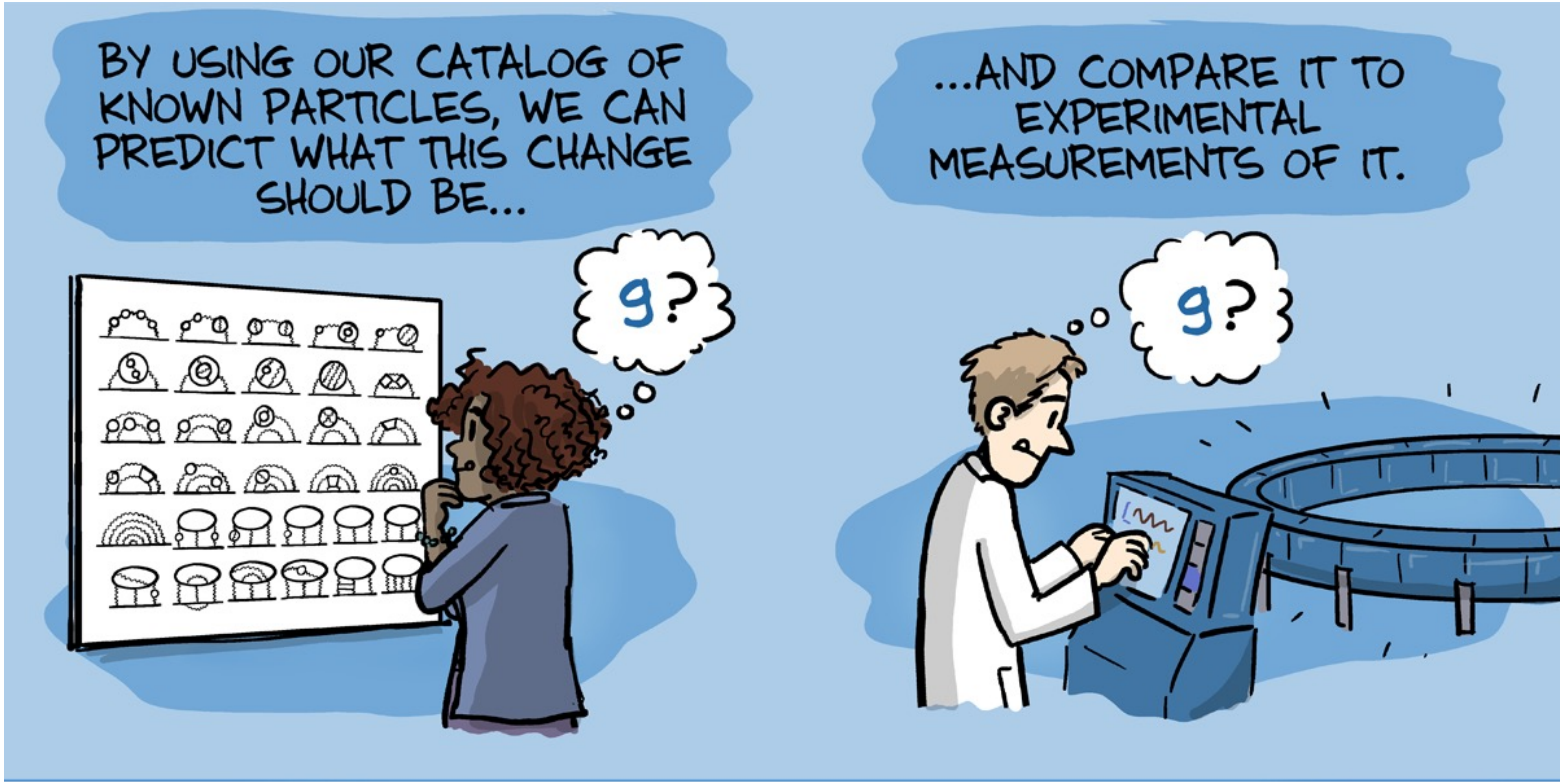


$$a_\mu = \frac{g_\mu - 2}{2} = a_{\text{QED}} + a_{\text{weak}} + a_{\text{had}}(+a_{\text{BSM}})$$

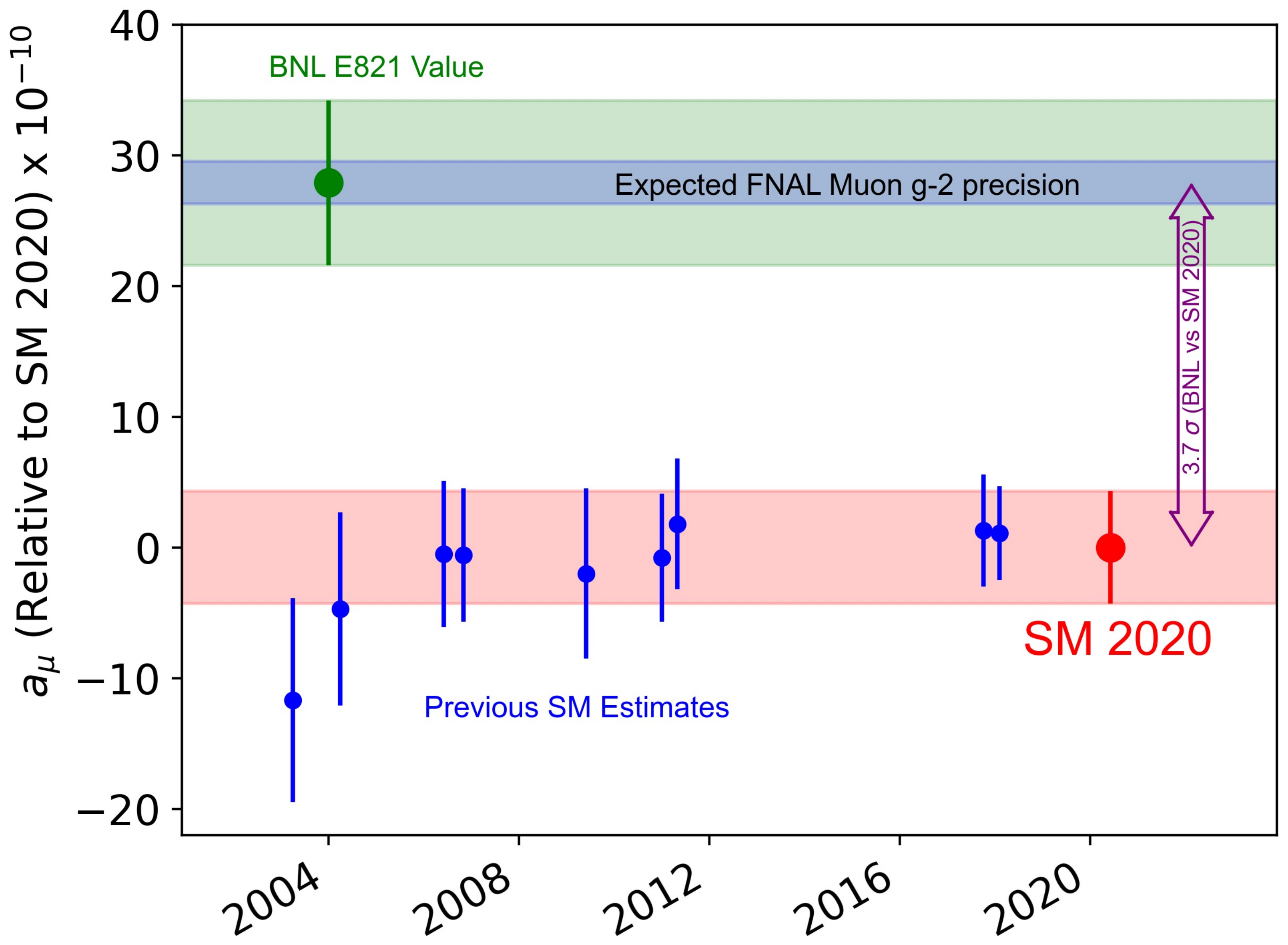


Feynman diagrams: M. Tanabashi et al. (Particle Data Group), Phys. Rev. D98, 030001 (2018)

Prediction meets the experiment !?



Prediction meets the experiment



Total SM prediction: $a_\mu^{SM} = 116591810 \pm 43$ (368 ppb)

Phys. Rept. 887 (2020) 1-166

Experiment (BNL E821): $a_\mu^{BNL} = 116592089 \pm 63$ (540 ppb)

Phys. Rev. D 73, 072003, 2006

Discrepancy: $\Delta a_\mu = a_\mu^{exp} - a_\mu^{SM} = (279 \pm 76)\times 10^{-11}$

3.7 σ deviation

Check the experiment:
Reduce uncertainty by a factor of 4 @ FNAL with 20x more muons!

Check the prediction:
Are all interactions and particles accounted for?

Or is this a hint for #18 lurking to be discovered?

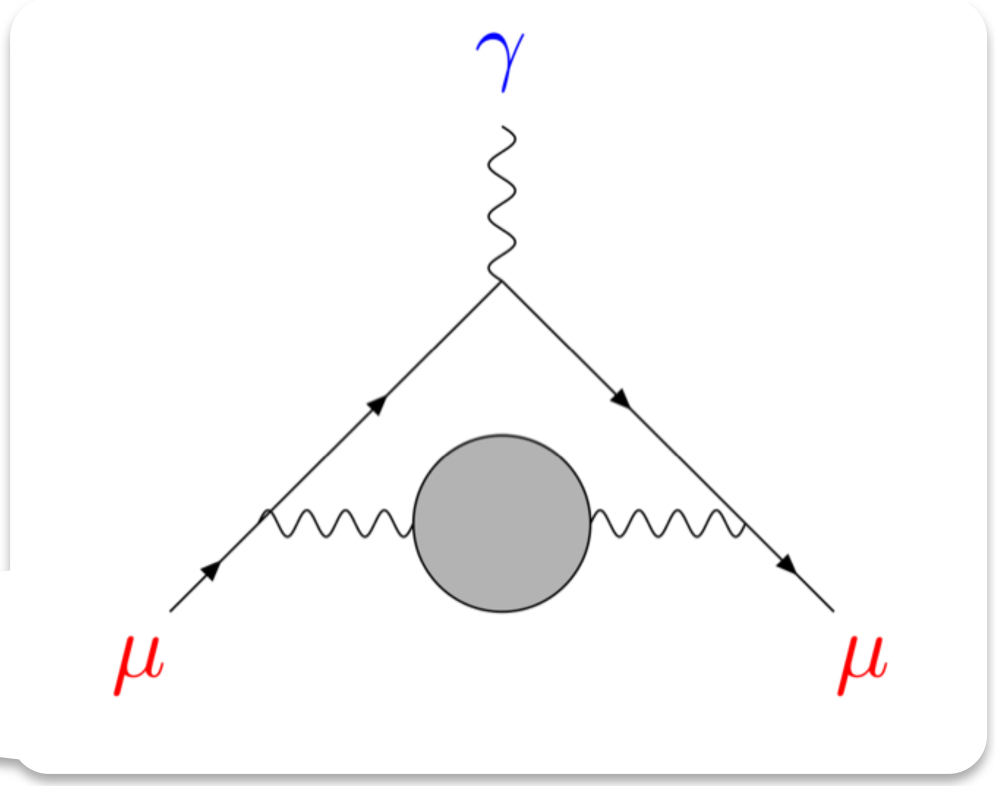
Recent evaluations of the SM prediction of a_μ

Units: xxx 10^{-11}

QED ($\mathcal{O}(\alpha^5)$, > 12000 digrams): 116584718.931 ± 0.104

Electroweak: 153.6 ± 1.0

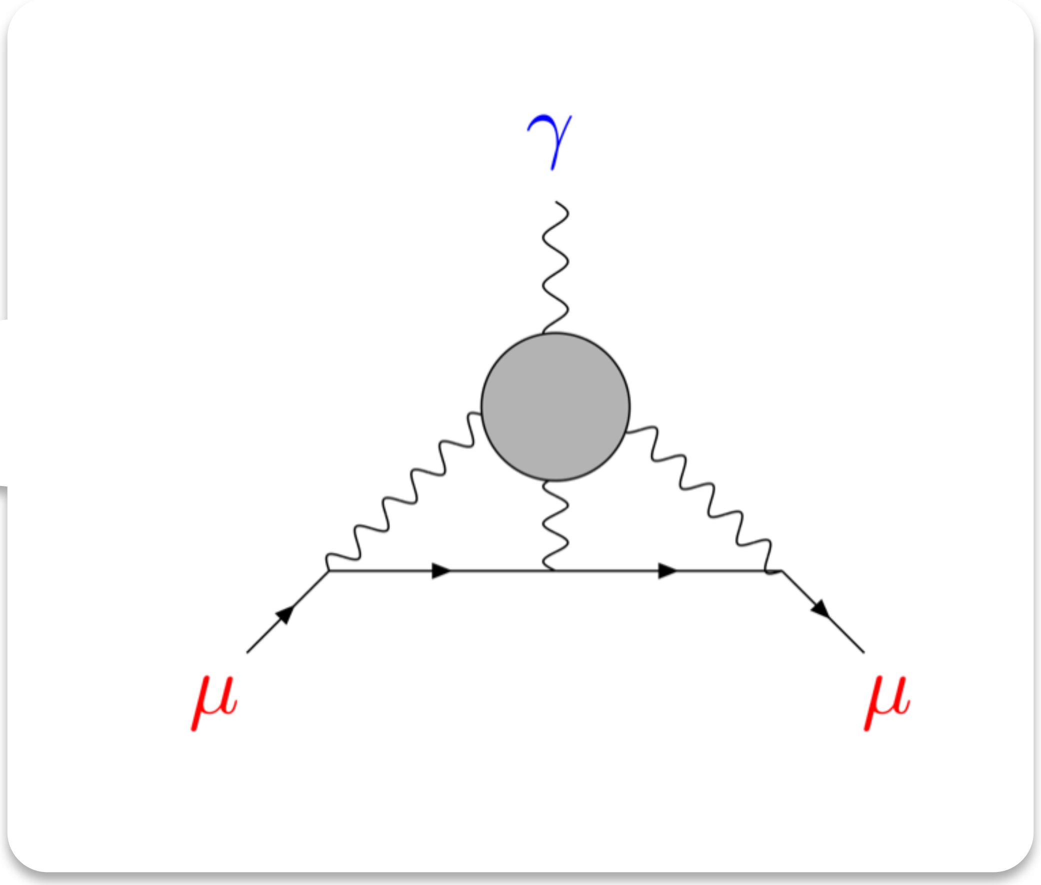
LO hadronic vacuum polarization: 6931 ± 40



NLO HVP: -98.3 ± 0.7

NNLO HVP: 12.4 ± 0.1

LO hadronic light-by-light scattering: 92 ± 19



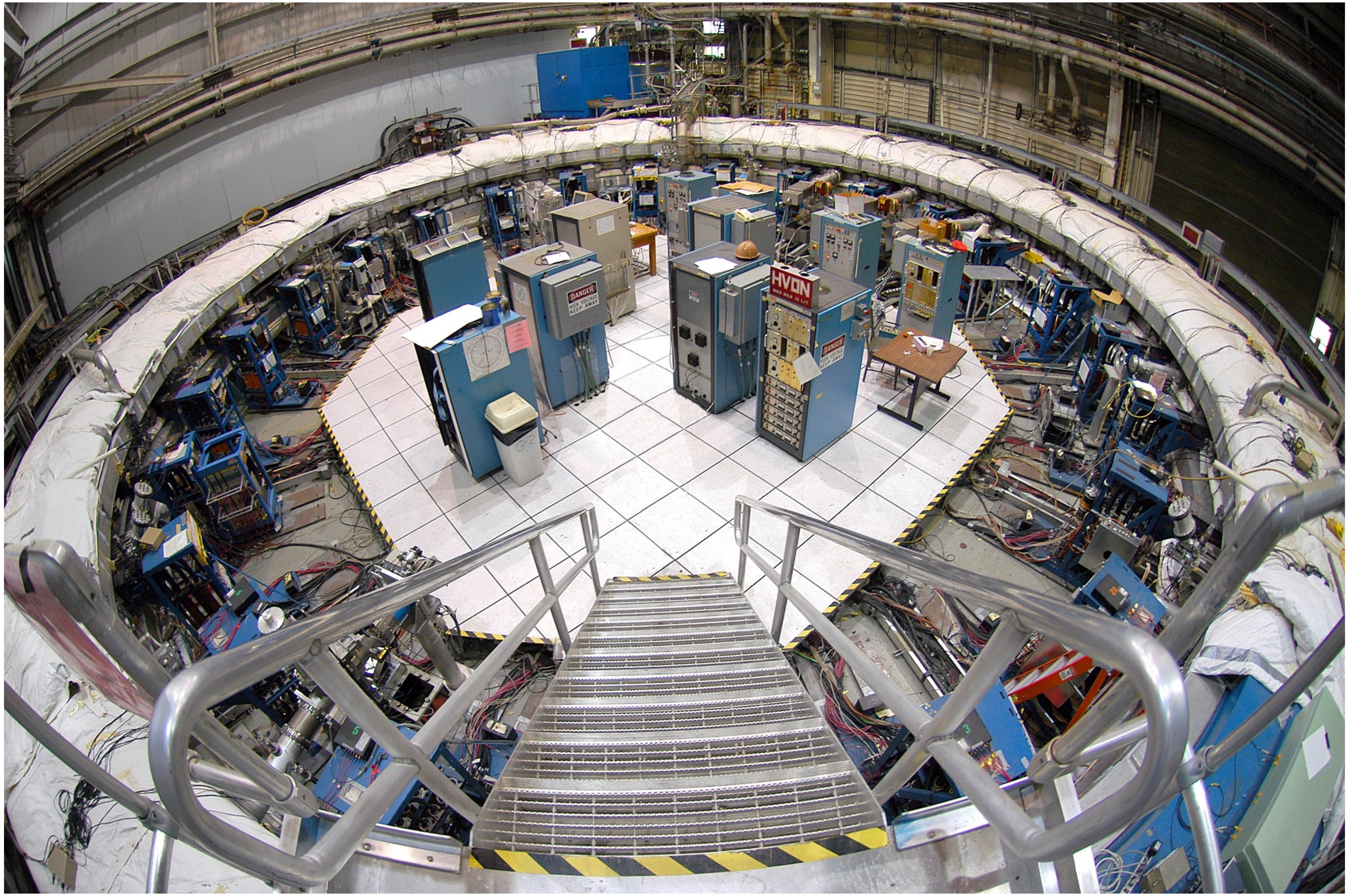
NLO hLbL scattering: 2 ± 1

Uncertainty dominated by hadronic physics contributions!

Total SM prediction: $a_\mu^{\text{SM}} = 116591810 \pm 43$ (368 ppb)

Numbers taken from "Muon g-2 Theory Initiative White Paper": Phys. Rept. 887 (2020) 1-166

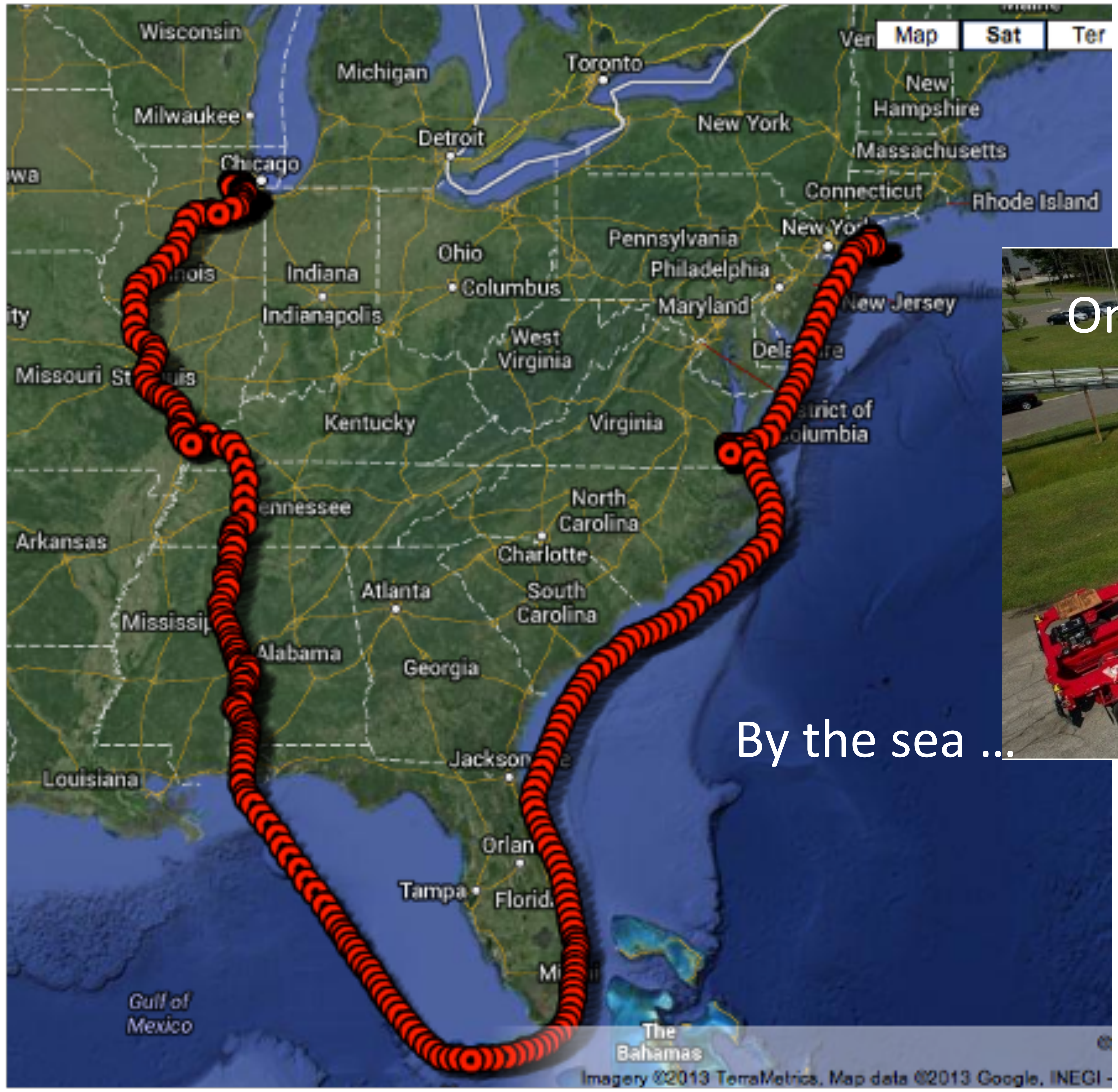
The muon g-2 experiment at Brookhaven



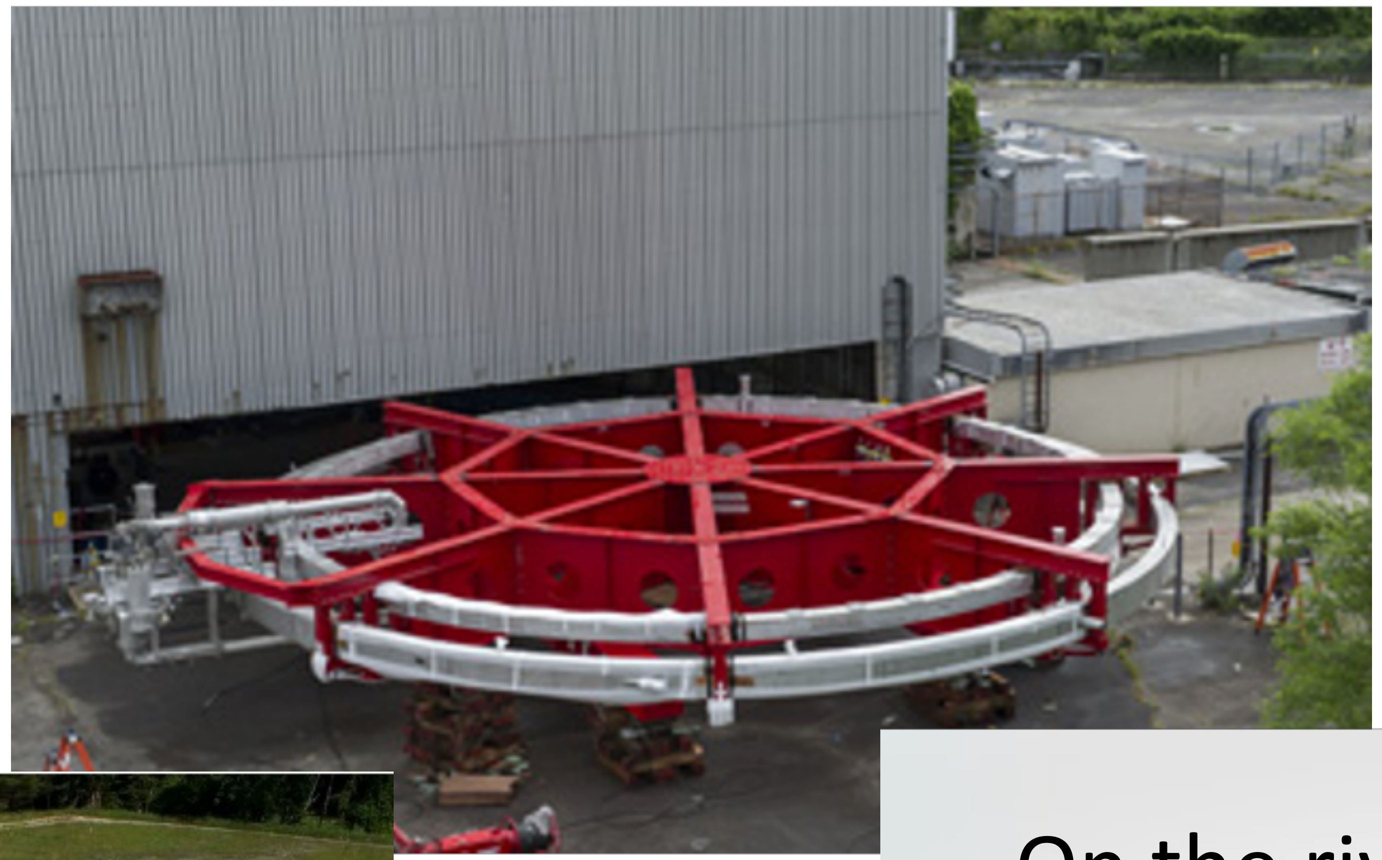
The long journey from Brookhaven to Fermilab (2013) !

If the short route isn't feasible…

… a little detour is needed!



By the sea …



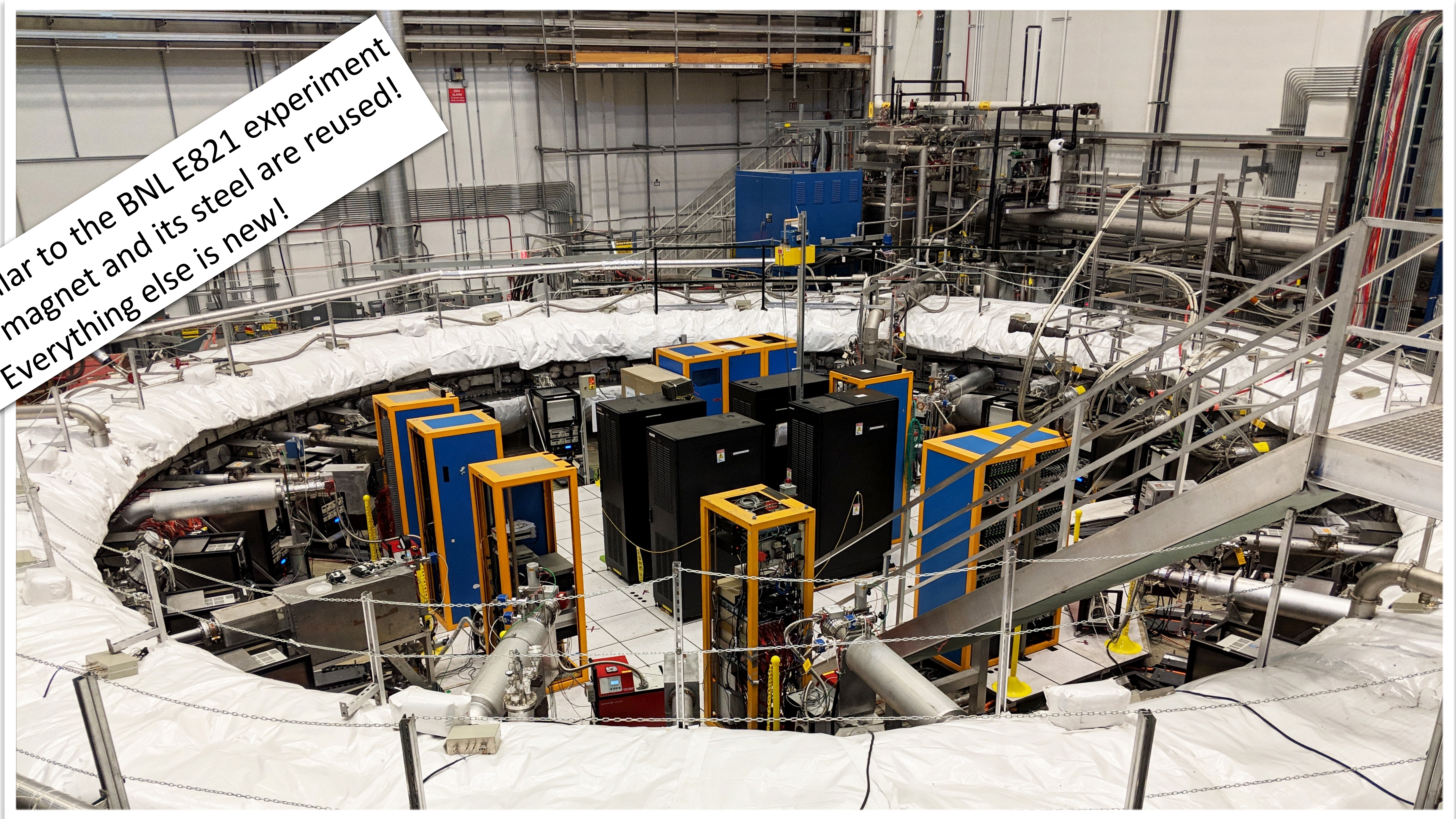
On the road …

On the river …

Making friends in Chicago!

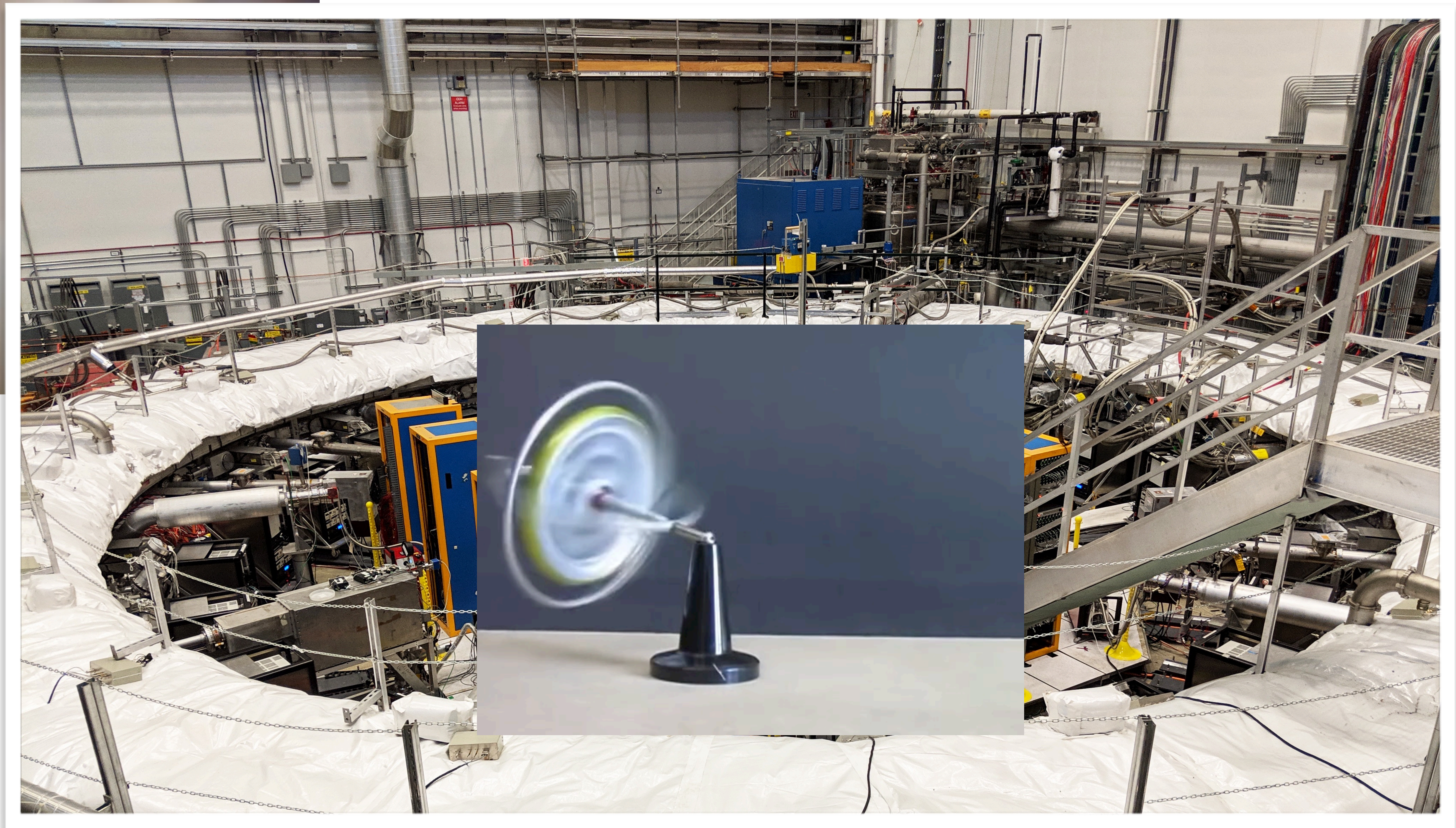
FNAL muon campus: the new home base!

The muon g-2 experiment at Fermilab



Looks very similar to the BNL E821 experiment
But only the magnet and its steel are reused!
Everything else is new!

Muons spin like elementary tops in the storage ring



Precessing top: cropped from Hill Science videos
https://www.youtube.com/watch?v=cquvA_IpEsA

The two clocks of a charged lepton

A *relativistic* charged lepton circulating a homogenous magnetic field experiences two effects:

Cyclotron motion

Equilibrium between centrifugal and Lorentz force

Cyclotron frequency

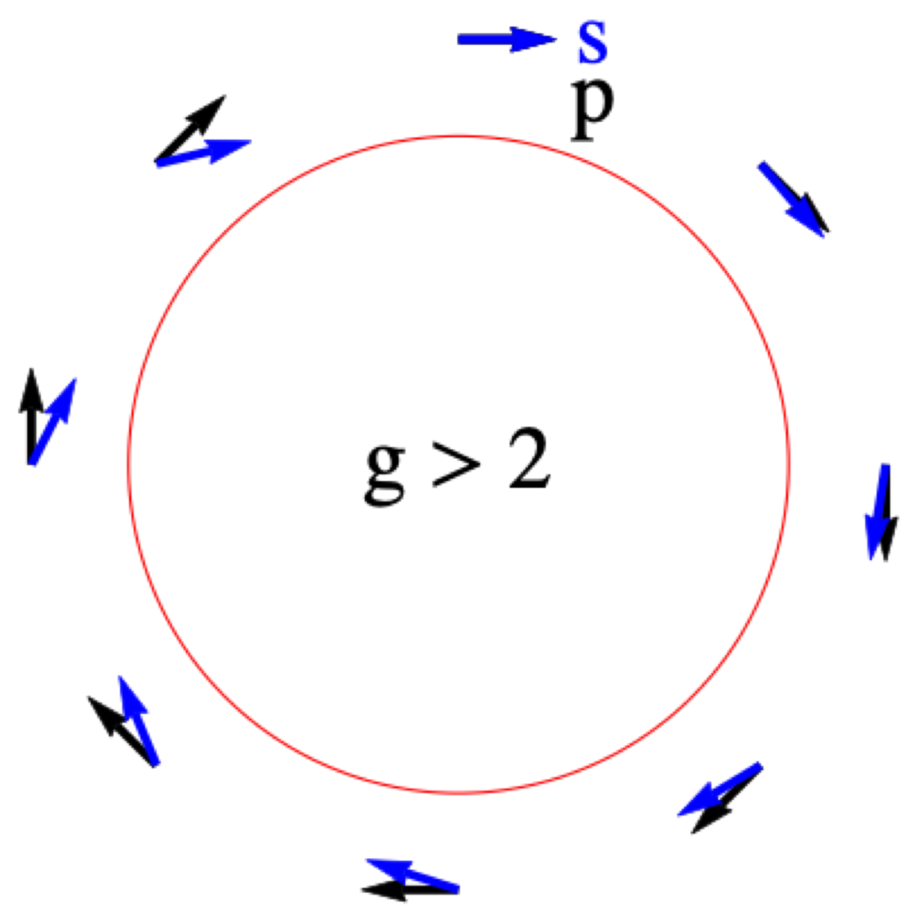
$$\vec{\omega}_c = -\frac{Qe}{m\gamma}\vec{B}$$

Spin precession

Coupling of magnetic moment and field

Larmor frequency

$$\vec{\omega}_s = -g\frac{Qe}{2m}\vec{B} - (1-\gamma)\frac{Qe}{\gamma m}\vec{B}$$



Anomalous spin precession frequency:

$$\vec{\omega}_a = \vec{\omega}_s - \vec{\omega}_c = -\left(\frac{g-2}{2}\right)\vec{B} = -a\frac{Qe}{m}\vec{B}$$

Independent of particle momentum!

Clock frequency shifts for muons in motion

Evolution of muon's longitudinal polarization in a superposition of electric and magnetic fields

$$\frac{d}{dt}P_{\mathrm{L}} = \frac{d}{dt}\left(\hat{\beta}\cdot\vec{s}\right) = -\frac{e}{m}\vec{s_{\perp}}\cdot\left[a_{\mu}\hat{\beta}\times\vec{B} + \left(a_{\mu} - \frac{1}{\gamma^2 - 1}\right)\beta\vec{E}\right]$$

By virtue of
the parity violation
of weak interactions

Spin component
perpendicular to
velocity

Non-relativistic and
circular motion limit

Relativistically generated magnetic fields
"electric field correction"
"pitch correction"

Accurate reconstruction
of decay positrons
for frequency extraction

Magnetic field
maps and temporal
interpolation

Reconstruction
of complex beam
dynamics

FNAL E989: $E \neq 0$
suppressed at $\gamma = 29.3$
"magic momentum"

Extracting a_μ - the external ingredients

Anchor B, e and m_μ to other high-precision measurements and calculations

$$a_\mu = \frac{\omega_a}{\tilde{B}}\frac{m_\mu}{e} = \frac{\omega_a}{\tilde{\omega}'_p(T_r)}\frac{\mu'_p(T_r)}{\mu_e(H)}\frac{\mu_e(H)}{\mu_e}\frac{m_\mu}{m_e}\frac{g_e}{2}$$

Extracting a_μ - the external ingredients

Anchor B, e and m_μ to other high-precision measurements and calculations

$$\frac{\mu'_p(T_r)}{\mu_e(H)}$$

10.5 ppb uncertainty
at T_r = 34.7°C

Metrologia 13, 179 (1977)

$$\frac{\mu_e(H)}{\mu_e}$$

Bound state QED calculation
exact

Rev. Mod. Phys. 88, 035009 (2016)

$$a_\mu = \frac{\omega_a}{\tilde{B}}\frac{m_\mu}{e} = \frac{\omega_a}{\tilde{\omega}'_p(T_r)}\frac{\mu'_p(T_r)}{\mu_e(H)}\frac{\mu_e(H)}{\mu_e}\frac{m_\mu}{m_e}\frac{g_e}{2}$$

Total uncertainty
from external quantities:
24 ppb

$$\frac{m_\mu}{m_e}$$

Muonium hyperfine splitting
22 ppb uncertainty

Phys. Rev. Lett. 82, 11 (1999)

$$\frac{g_e}{2}$$

Measurement with
0.28 ppt uncertainty

Phys. Rev. A 83, 052122 (2011)

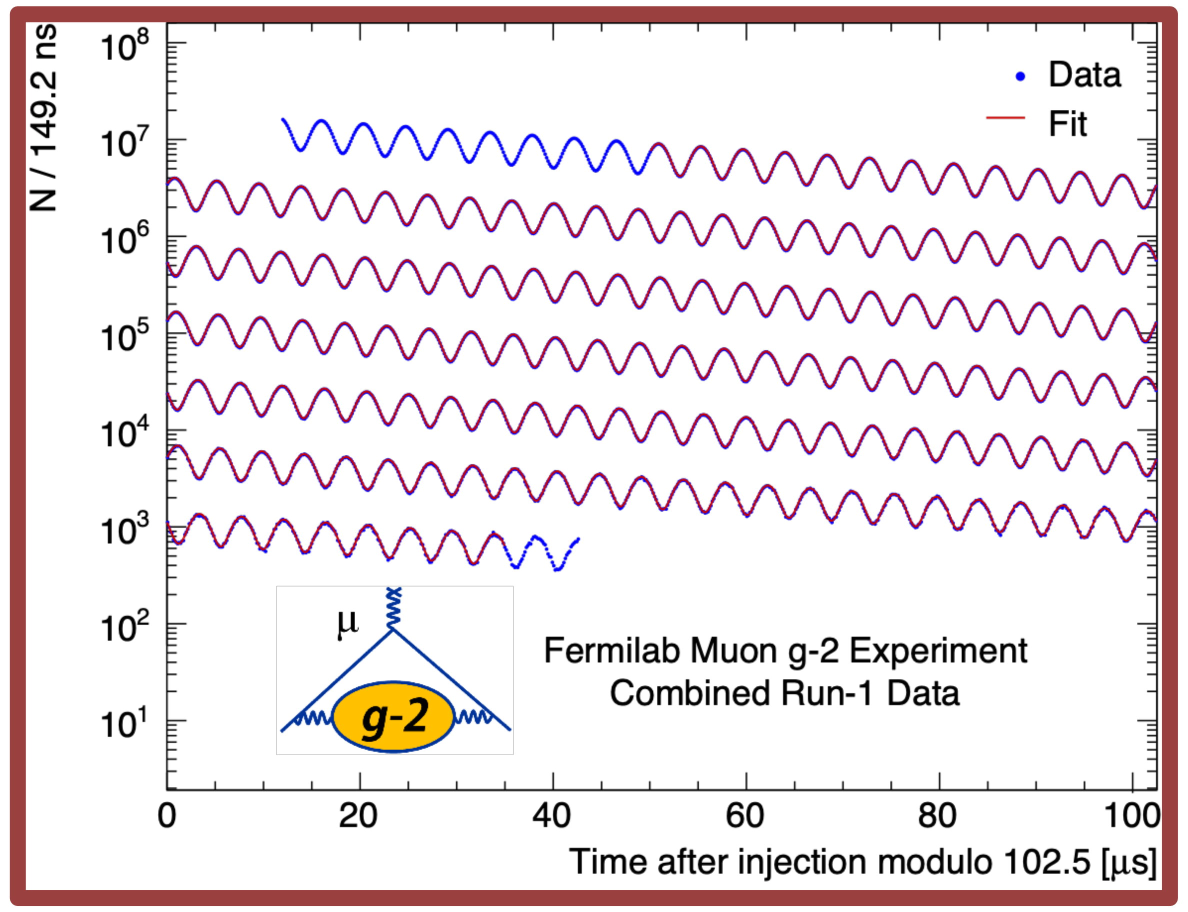
Extracting a_μ - our challenge

$$a_\mu = \frac{\omega_a}{\tilde{B}} \frac{m_\mu}{e} = \frac{\omega_a}{\tilde{\omega}'_p(T_r)} \frac{\mu'_p(T_r)}{\mu_e(H)} \frac{\mu_e(H)}{\mu_e} \frac{m_\mu}{m_e} \frac{g_e}{2}$$

$$R' = \frac{\omega_a}{\tilde{\omega}'_p} = \frac{f_{\mathrm{clock}}\, \omega_a^{\mathrm{meas}} \left(1 + C_e + C_p + C_{ml} + C_{pa}\right)}{f_{\mathrm{calib}} \langle M(x, y, \phi)\, \omega_p(x, y, \phi) \rangle \left(1 + B_k + B_q\right)}$$

JG|U

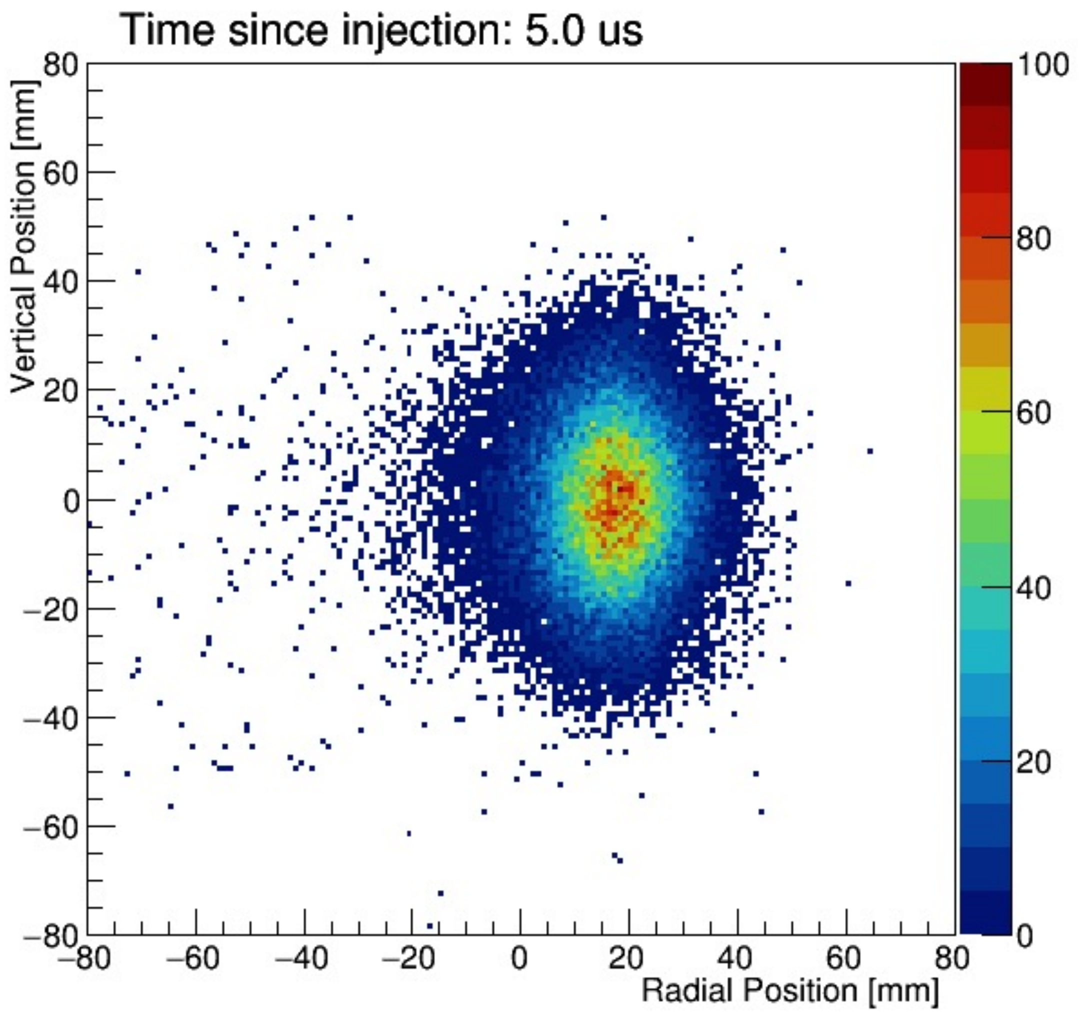
Extracting a_μ - our tools



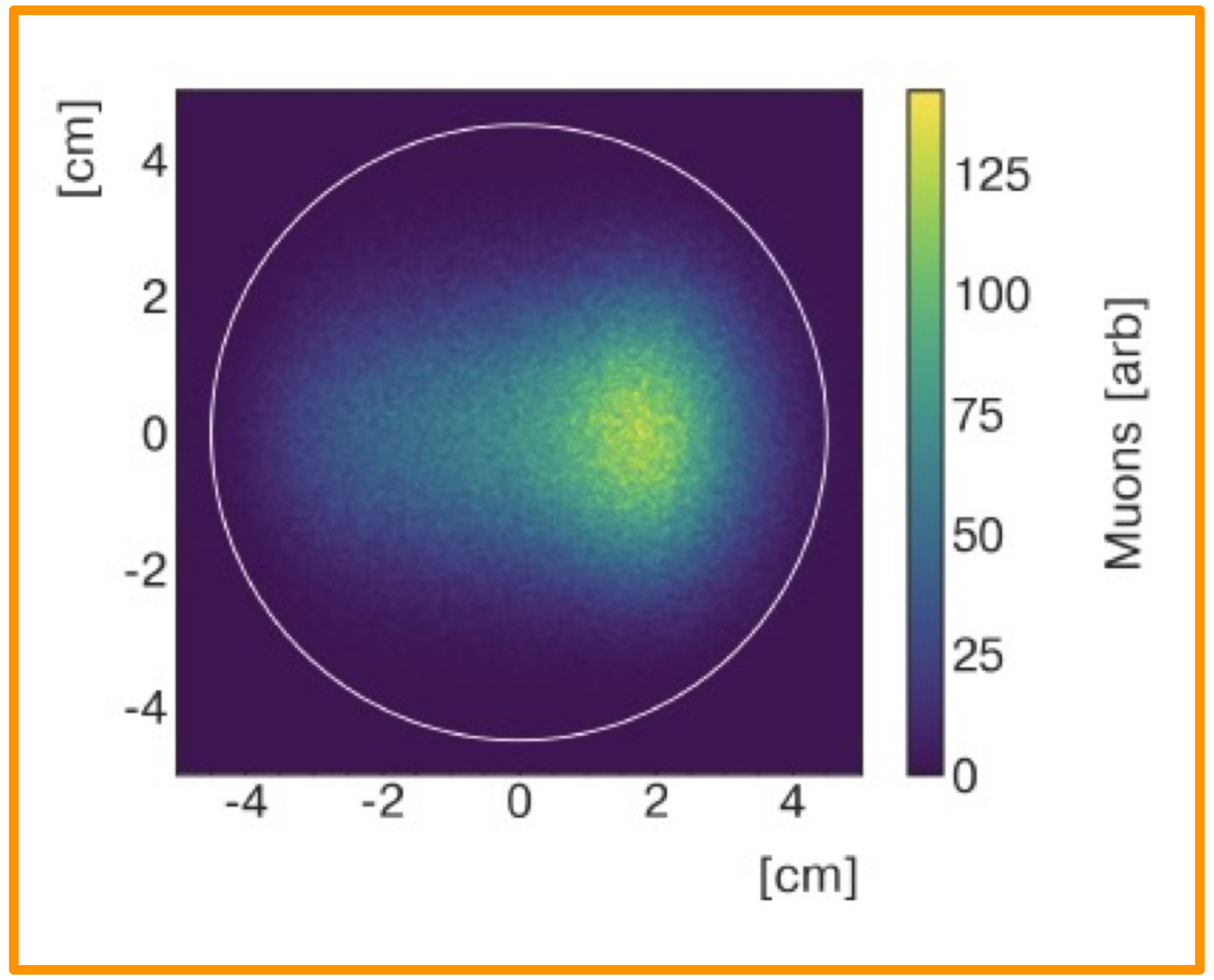
Anomalous spin precession frequency

Muon beam dynamics corrections

Clock blinding



$$R' = \frac{\omega_a}{\tilde{\omega}'_p} = \frac{f_{\mathrm{clock}}\, \omega_a^{\mathrm{meas}} \left(1 + C_e + C_p + C_{ml} + C_{pa}\right)}{f_{\mathrm{calib}} \langle M(x, y, \phi)\, \omega_p(x, y, \phi)\rangle \left(1 + B_k + B_q\right)}$$

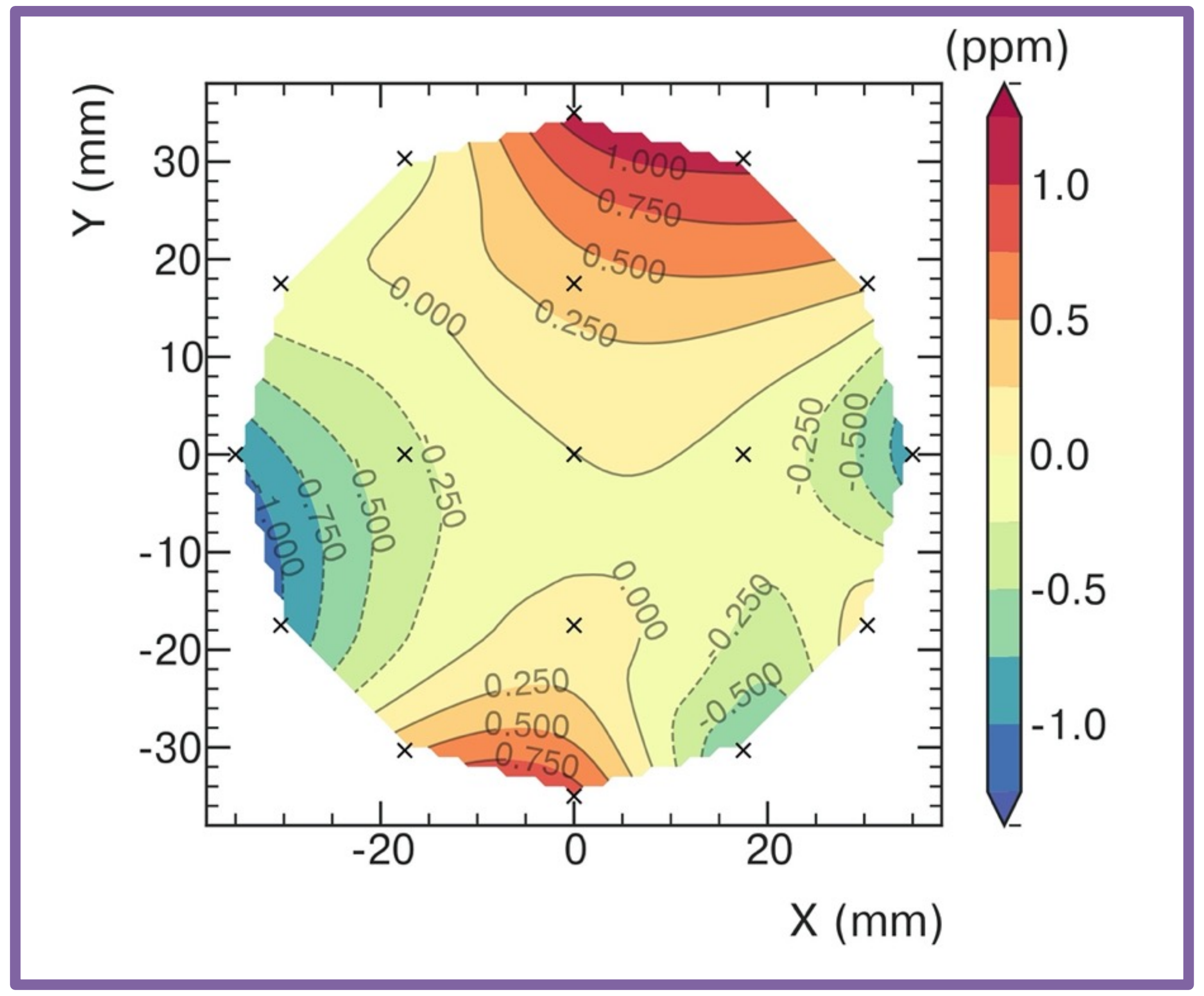


Spatial muon distribution

Spatial distribution of magnetic field

Transient magnetic fields

Calibration



M. Fertl – Falling Walls Circle, November 8th 2021

JG|U

The Muon g-2 collaboration ready to unblind …

Domestic Universities
- Boston
- Cornell
- Illinois
- James Madison
- Kentucky
- Massachusetts
- Michigan
- Michigan State
- Mississippi
- Northern Illinois
- Regis
- UT Austin
- Virginia
- Washington

National Labs
- Argonne
- Brookhaven
- Fermilab

China
- Shanghai Jao Tong University

United Kingdom
- Lancaster
- Liverpool
- University College London

Italy
- Frascati
- Molise
- Naples
- Pisa
- Roma 2
- Trieste
- Udine

Germany
- JGU Mainz
- TU Dresden

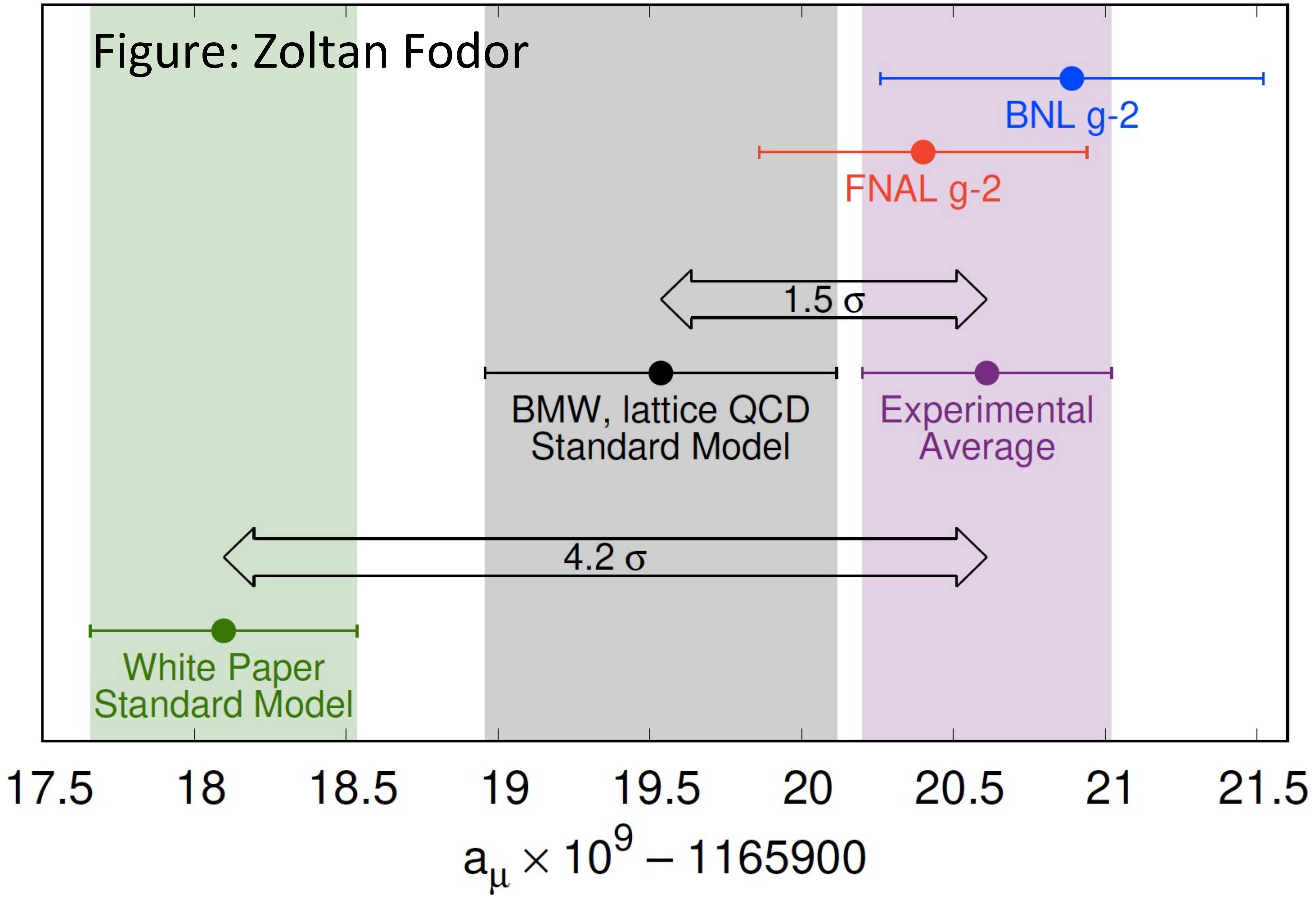
Russia
- JINR/Dubna
- Novosibirsk

South Korea
- CAPP/IBS
- KAIST

… on February 25th, 2021!

The 40 MHz clock was really set to:
39 997 784 MHz

Result from combined Run 1 datasets



a_μ(BNL) = 0.00116592089(63) → 540 ppb

a_μ(FNAL, R1) = 0.00116592040(54) → 463 ppb

Both experiments uncertainty dominated by statistics:

a_μ(Exp) = 0.00116592061(41) → 350 ppb

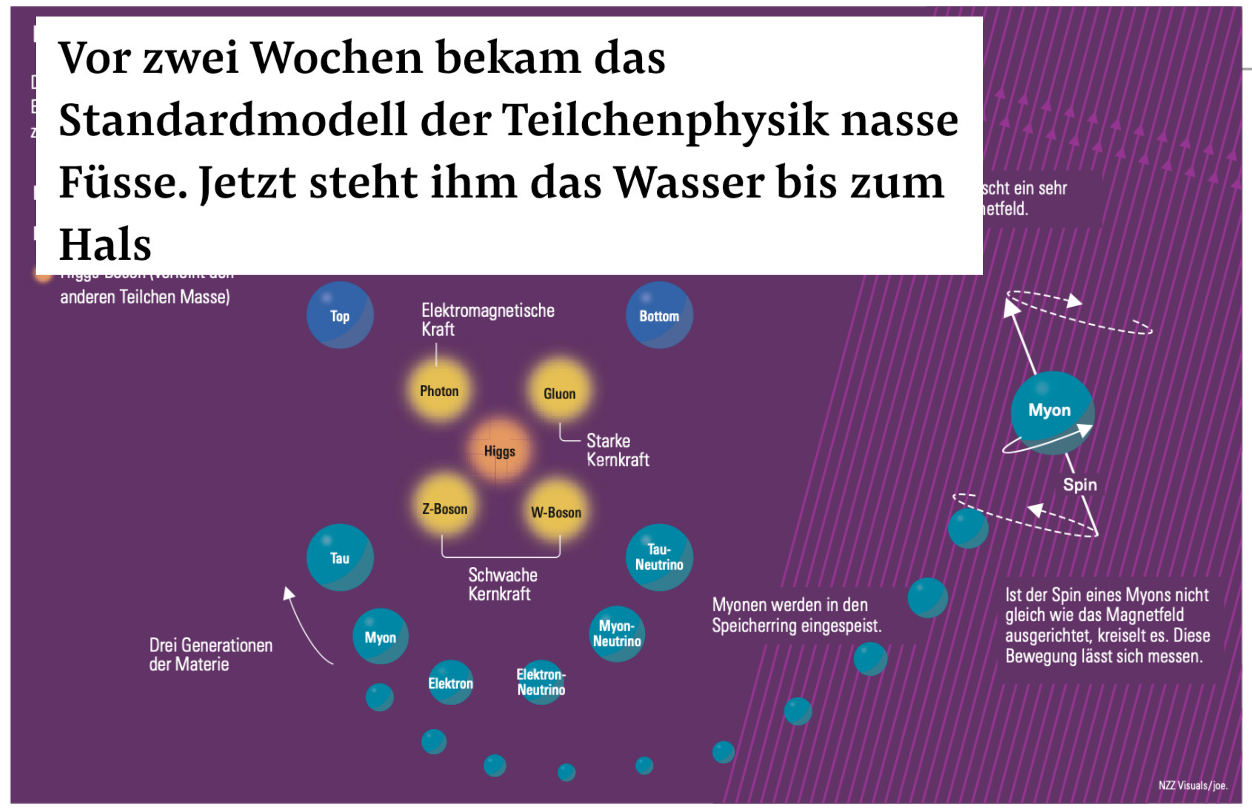
a_μ(SM) = 0.00116591810(43) → 350 ppb

4.2 σ discrepancy between experiment and community approved SM prediction

BUT: the very recent results from lQCD vor HVP would reduce the tension to 1.5 σ!
*Borsányi et al., Nature **593**, 51–55, 2021*
and arXiv:2002.12347

16 NZZ Panorama
Neue Zürcher Zeitung
Donnerstag, 8. April 2021

Vor zwei Wochen bekam das Standardmodell der Teilchenphysik nasse Füsse. Jetzt steht ihm das Wasser bis zum Hals



Im Gebälk der Teilchenphysik kracht es

Eine Präzisionsmessung liefert die bisher überzeugendsten Hinweise auf «neue Physik»

Show mit Lava und Nordlicht

Vulkanausbruch auf Island wird zum Besuchermagnet

RUDOLF HERMANN

Shuttlebus und Imbissbude

"All the News That's Fit to Print"

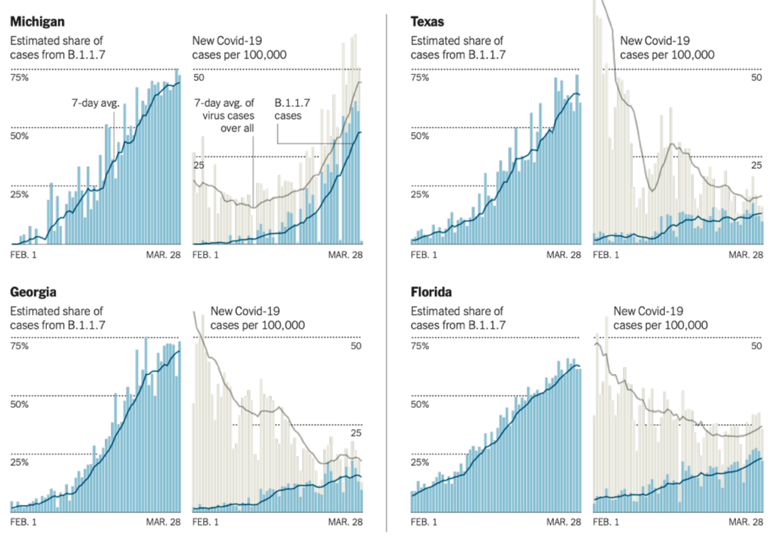
The New York Times

VOL. CLXX . . . No. 59,022 — NEW YORK, THURSDAY, APRIL 8, 2021

Biden Tax Plan Aims to Curtail Use of Havens

Loophole Has Enriched Global Corporations

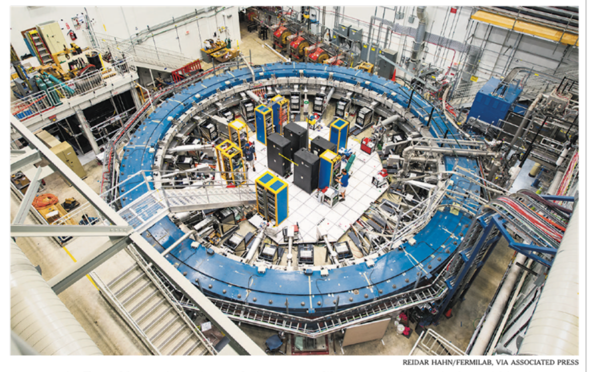
Contagious Variant Is Fueling Surge in Infections Across the U.S.



ISIS and African Militants Join In a Marriage of Convenience

New York to Provide $2.1 Billion For Undocumented Immigrants

A Particle's Tiny Wobble Could Upend the Known Laws of Physics



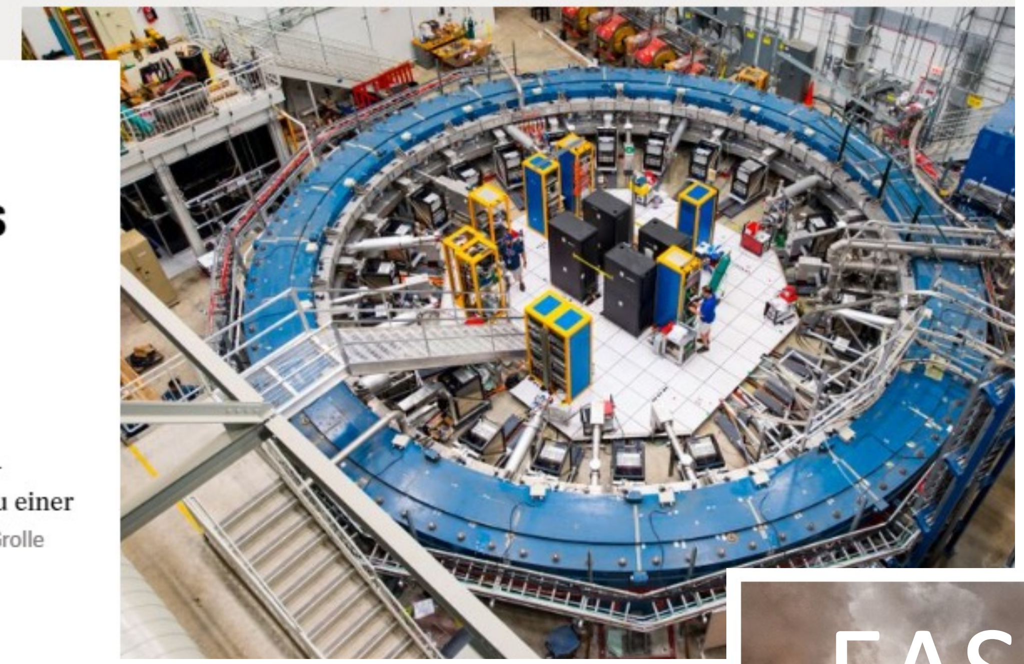
A ring at the Fermi National Accelerator Laboratory in Illinois is used to study the wobble of muons.

Adventurers Strain the W

DER SPIEGEL

Kryptowährung Vor 4 Min — Kindesmissbrauch vor Vor 8 Min — Europäer Vor 30 Min

SPIEGEL+ Alle Artikel & digitales Magazin — 1,- € im ersten Monat



Neue Erkenntnisse in der Teilchenphysik

Kundschafter ins Unbekannte

Seit 50 Jahren ersehnen Forscher Einblicke in die Welt jenseits der bekannten Naturgesetze. Mit den Erkenntnissen aus dem Myon-g-2-Experiment könnte sich das Tor zu einer neuen Physik öffnen. Von Johann Grolle

---

Le Monde
VENDREDI 9 AVRIL 2021

Une particule élémentaire polarise le monde de la physique

Une anomalie dans le comportement

FAS

Braut sich da was zusammen? Im Sommer 2013 wurde der Myonen-Speicherring (auf dem Lastwagen) am Fermilab nahe Chicago angeliefert. Jetzt wurden erste Ergebnisse verkündet.

Die Macht der Myonen

Ein Teilchen schickt sich an, eine beispiellos erfolgreiche Theorie zu sprengen. Viele Physiker freuen sich wie Bolle. Andere warnen, dazu sei es noch zu früh.

ZEIT ONLINE

Teilchenphysik

Neue Erkenntnisse stellen Standardmodell der Physik infrag

Datenauswertungen am Chicagoer Fermilab zeigen eine Abv Drehmoment des Myons, eines Elementarteilchens. Das könı Verständnis von Physik verändern.

8. April 2021, 7:47 Uhr / Aktualisiert am 8. April 2021, 8:50 Uhr / Quelle: ZEIT ONLIN
296 Kommentare

4/9/2021 Starker Hinweis auf bisher unbekannte Kräfte oder Teilchen - Technik - derStandard.at › Wissenschaft

DERSTANDARD

Startseite › Wissenschaft › **Technik**

NEUE PHYSIK

Starker Hinweis auf bisher unbekannte Kräfte oder Teilchen

Erneut lässt ein hochpräzises Experiment auf eine Physik abseits des gültigen Standardmodells schließen

9. April 2021, 06:00 80 Postings

F+ PODCASTS BLOGS THEMEN TICKER ARCHIV STELLENMARKT
Wissen Physik & Mehr Das magnetische Moment des Myons ist größer als erwartet. Frühere Messungen bestätigt.

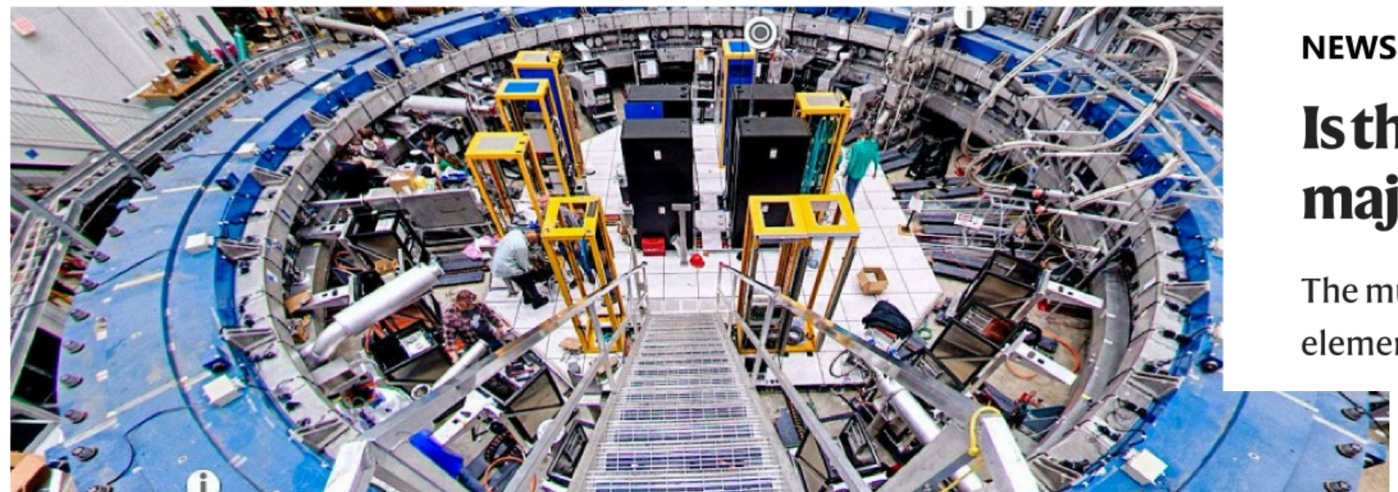
Sonderseite: Coronavirus

Frankfurter Allgemeine
HERAUSGEGEBEN VON GERALD BRAUNBERGER, JÜRGEN KAUBE, CARSTEN KNOP, BERTHOLD KOHLER

RÄTSELHAFTE MYONEN

Abschied vom Standardmodell?

VON MANFRED LINDINGER · AKTUALISIERT AM 07.04.2021 · 18:55



4/8/2021 Is the standard model broken? Physicists cheer major muon result

nature — View all journals

Content ⌄ Journal info ⌄ Publish ⌄ Sign up for alerts

nature › news › article

NEWS · 07 APRIL 2021

Is the standard model broken? Physicists cheer major muon result

The muon's magnetic moment is larger than expected — a hint that new elementary particles are waiting to be discovered.

Science — Contents News Careers Journals

Read our COVID-19 research and news.

SHARE 486

Muons twirl as they circulate in this ring-shaped accelerator at Fermilab, like race cars perpetually spinning out.
REIDAR HAHN/FERMILAB

Particle mystery deepens, as physicists confirm that the muon is more magnetic than predicted

By Adrian Cho | Apr. 7, 2021, 11:00 AM

Süddeutsche Zeitung

SZ.de Zeitung Magazin

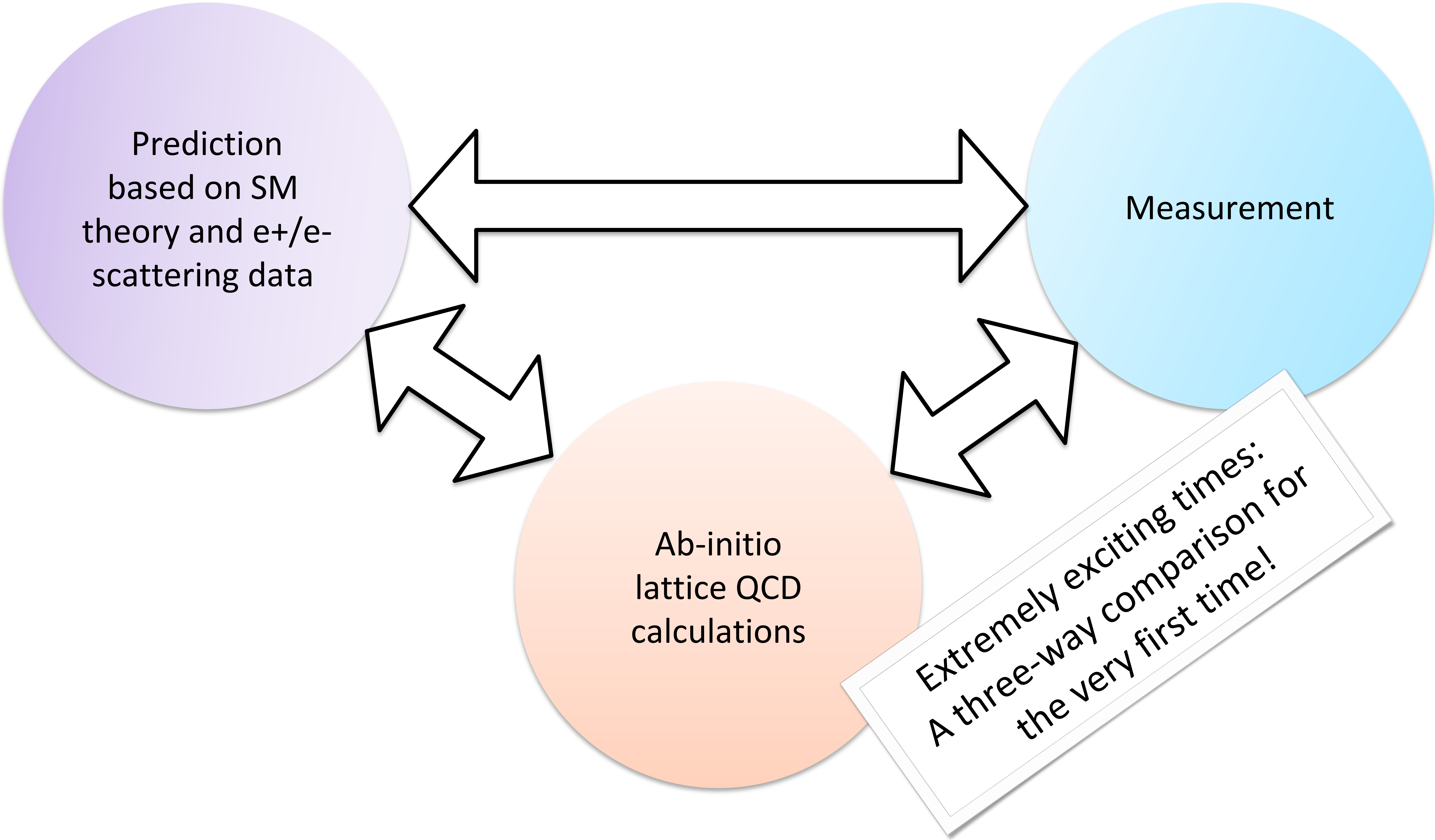
Politik Wirtschaft Meinung Panorama Sport München Bayern Kultur Gesellschaft

sik > Myonen-Experiment stellt Standardmodell der Physik infrage

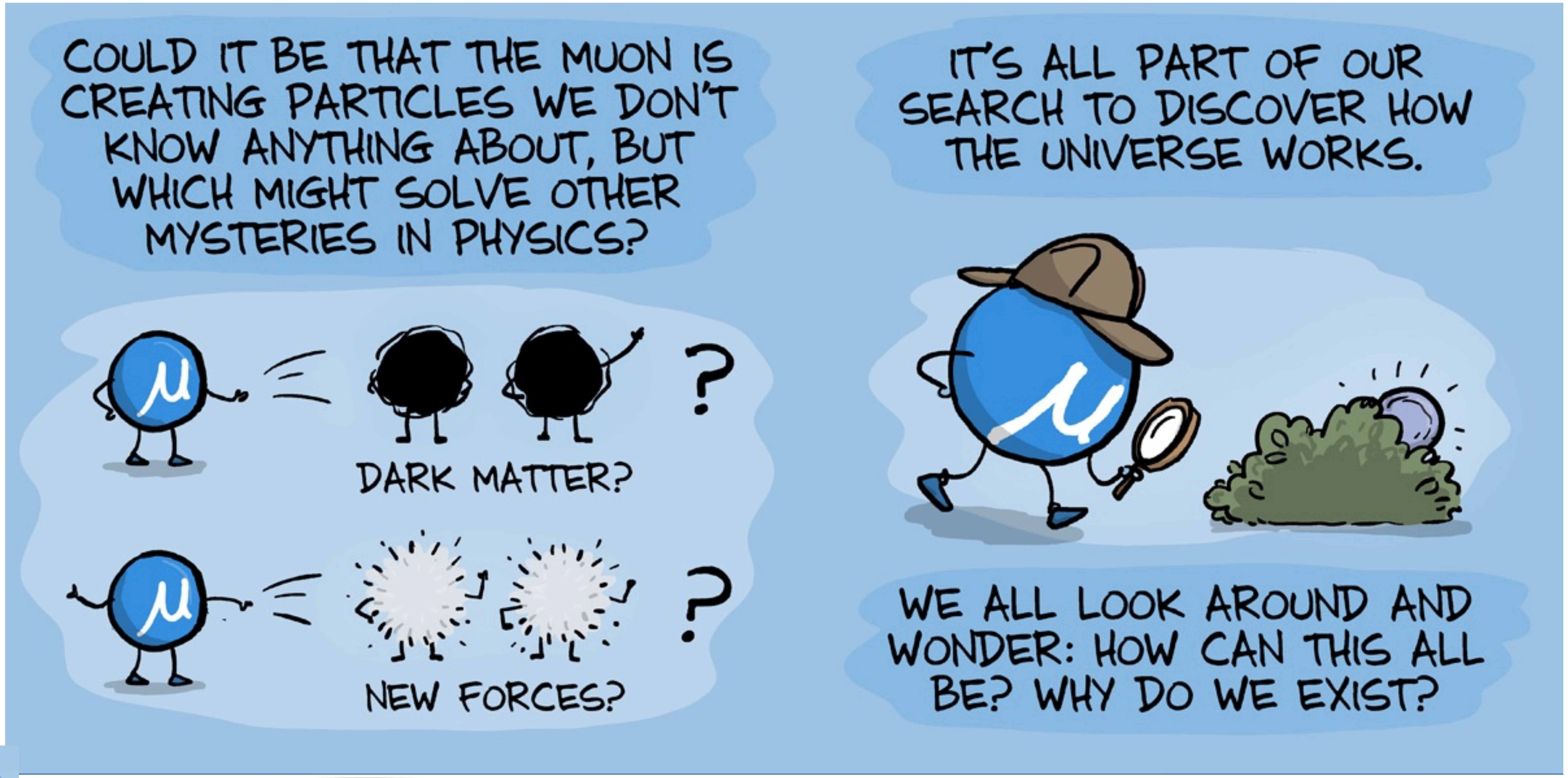
8. April 2021, 15:54 Uhr Physik

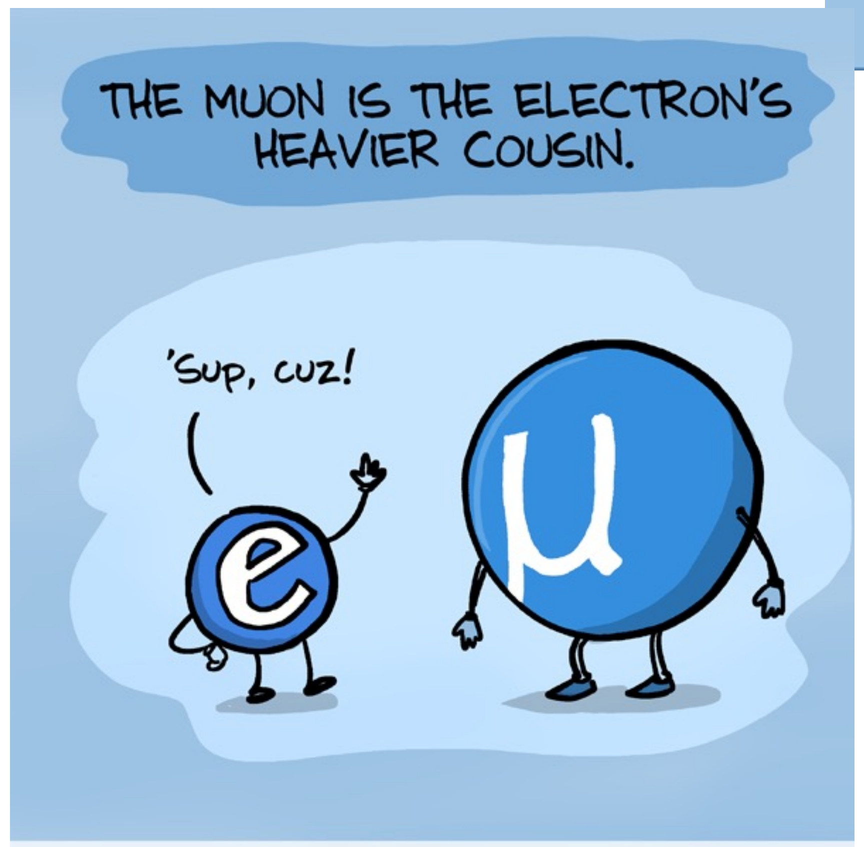
Myonen-Experiment stellt Standardmodell infrage

A new era of a_μ comparisons



Particle #18: are you out there?

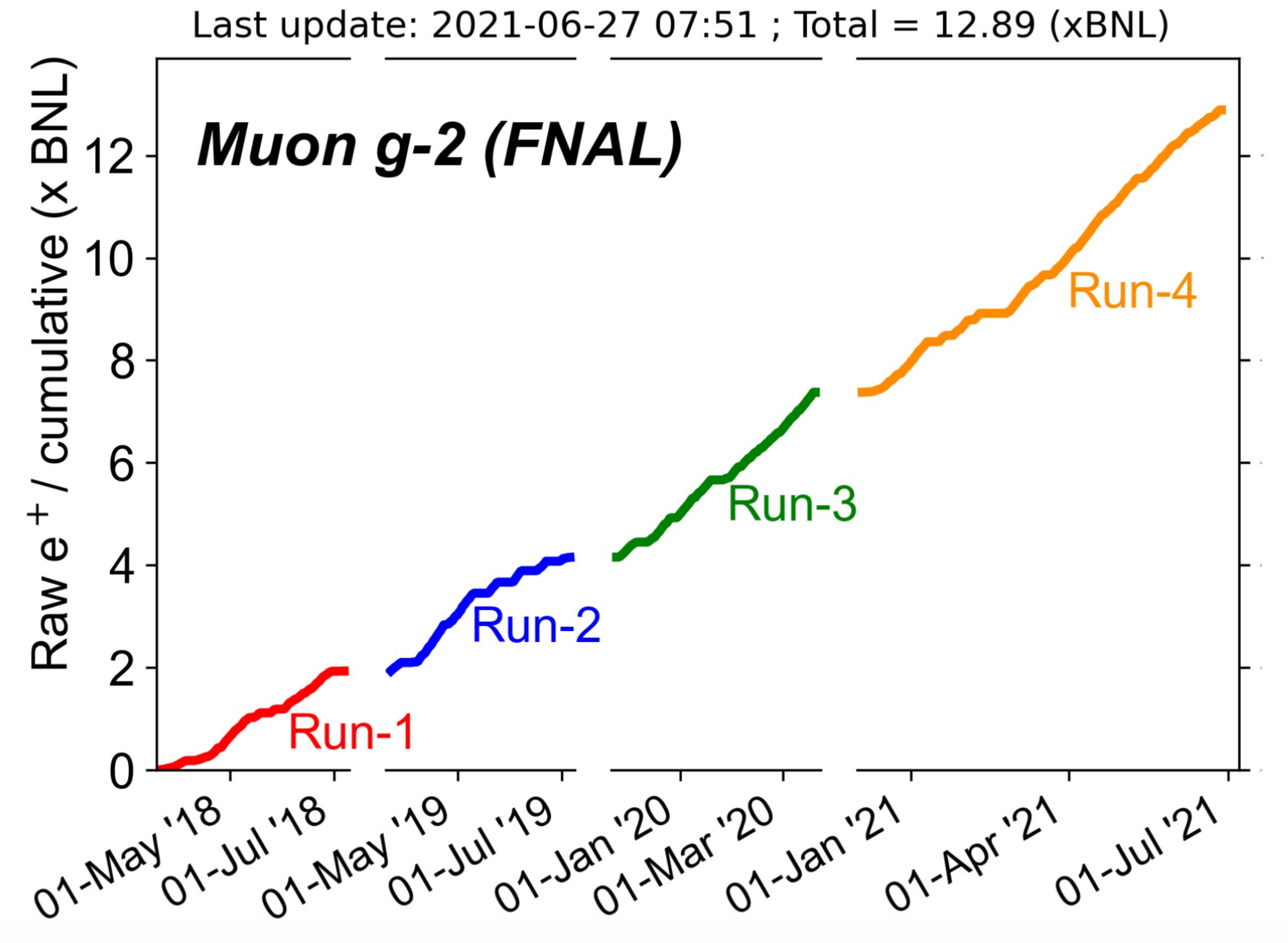




Other mysteries: Hints for lepton flavour universality violation b→sμμ, Cabibbo angle anomaly

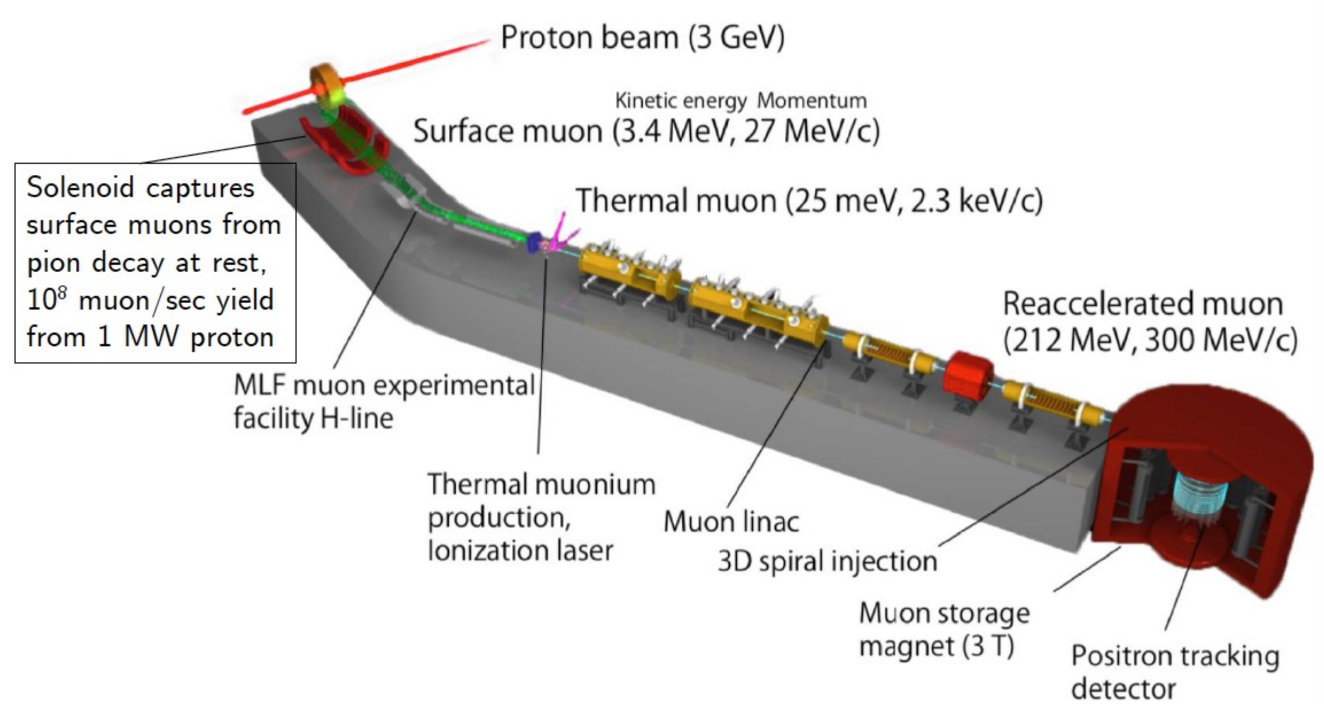
Muon really just the heavier cousin?

Extremely exciting times…



The near future:

- Fermilab experiment ongoing with much improved conditions → Factor 2 uncertainty reduction next year
- Intense scrutinizing of the lQCD calculation ongoing



The intermediate future:

- Independent measurement of muon g-2 at J-PARC
  - Different experimental technique
  - Different beam energy → Different magnetic field
- Proposed new data-driven HVP determination: MUonE at CERN

Thank you Chris for your leadership and congratulations!

Chris Polly is new Muon g-2 co-spokesperson

January 16, 2018 | Tom Barratt

Share Tweet Email

Chris Polly

LAS VEGAS REVIEW-JOURNAL

SUBSCRIBE SIGN IN

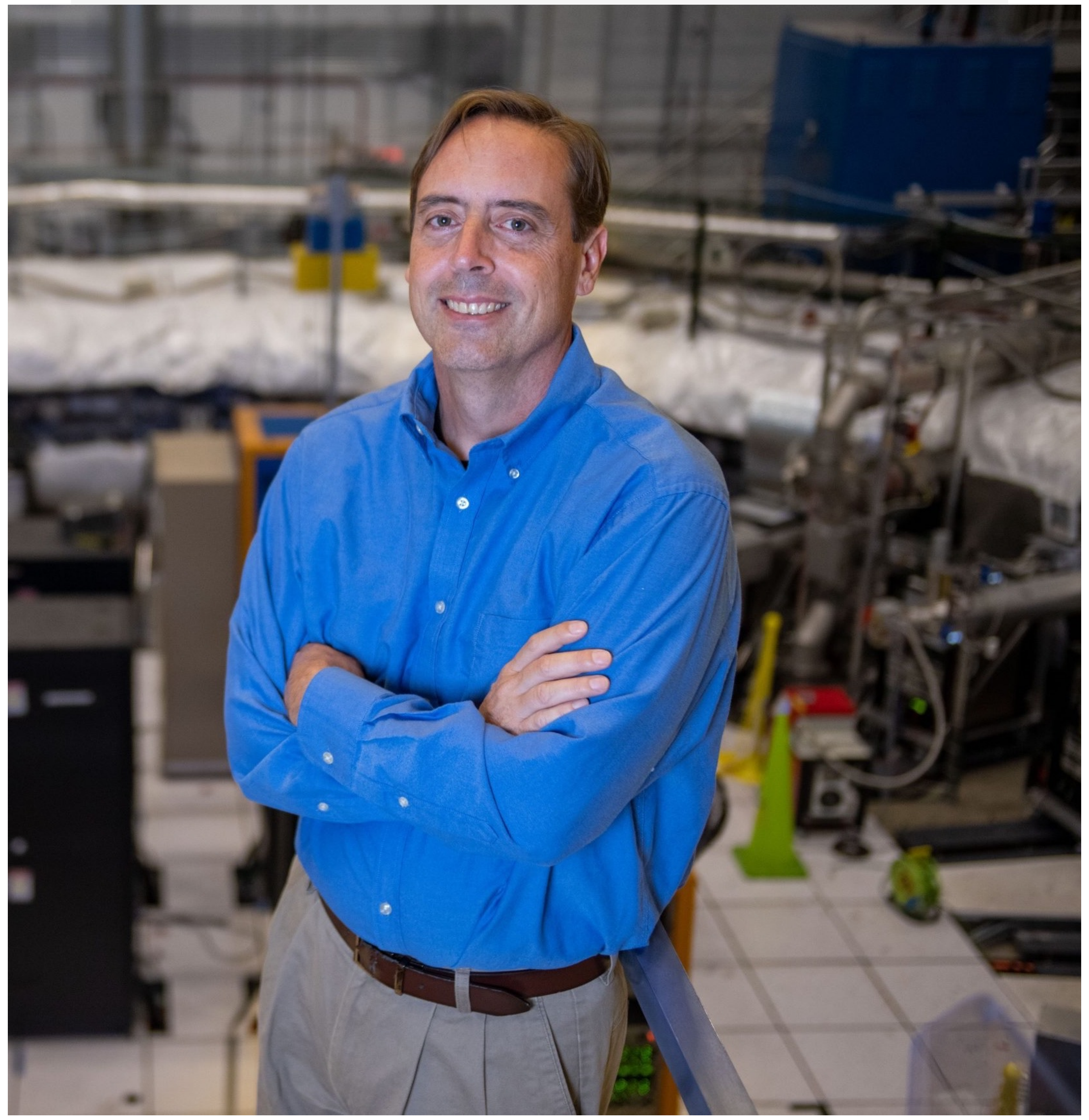
79°F NEWS LOCAL SPORTS BUSINESS OPINION CRIME ENTERTAINMENT INVESTIGATIONS VIDEOS OBITS

Chris Polly, center, project director for Fermilab, speaks during a safety briefing in Glen Ellyn, Ill., Thursday, July 25 before the final move of the electromagnet. The electromagnet is 50 feet ...

FERMILAB

CHRIS POLLY

WINNER 2021 | 2021 | PHYSICAL SCIENCES



Thanks to the various funding agencies, in particular DOE, the excellence cluster PRISMA+ at JGU, and the WE Heraeus Foundation