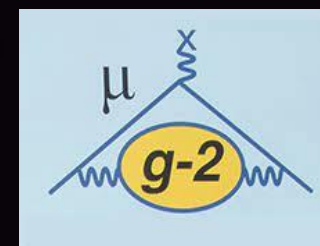
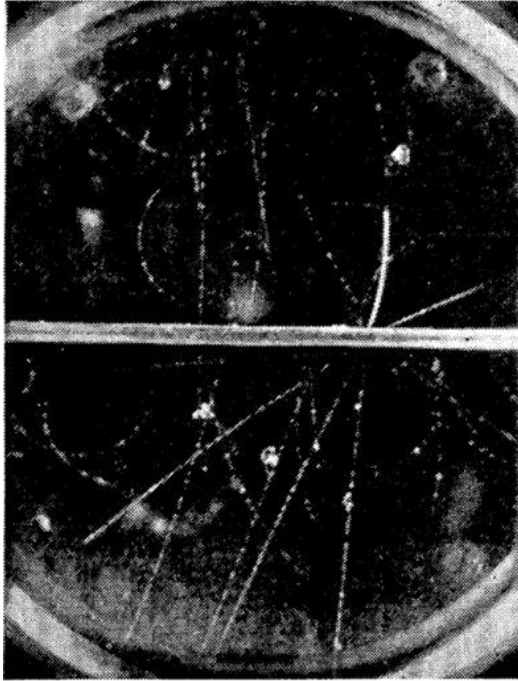


The muon ($g-2$) experiment: Final result from Fermilab

MARIN KARUZA

University of Rijeka and INFN
Sezione di Trieste



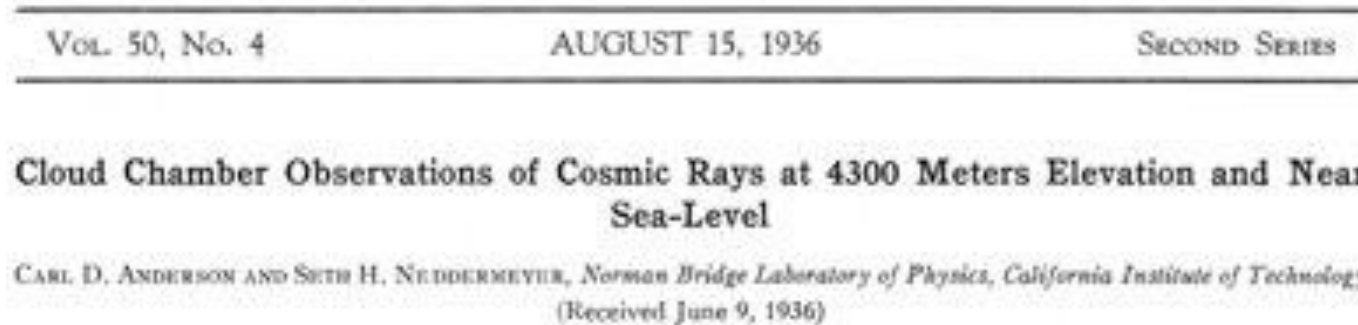


Muon

- Discovered 1936



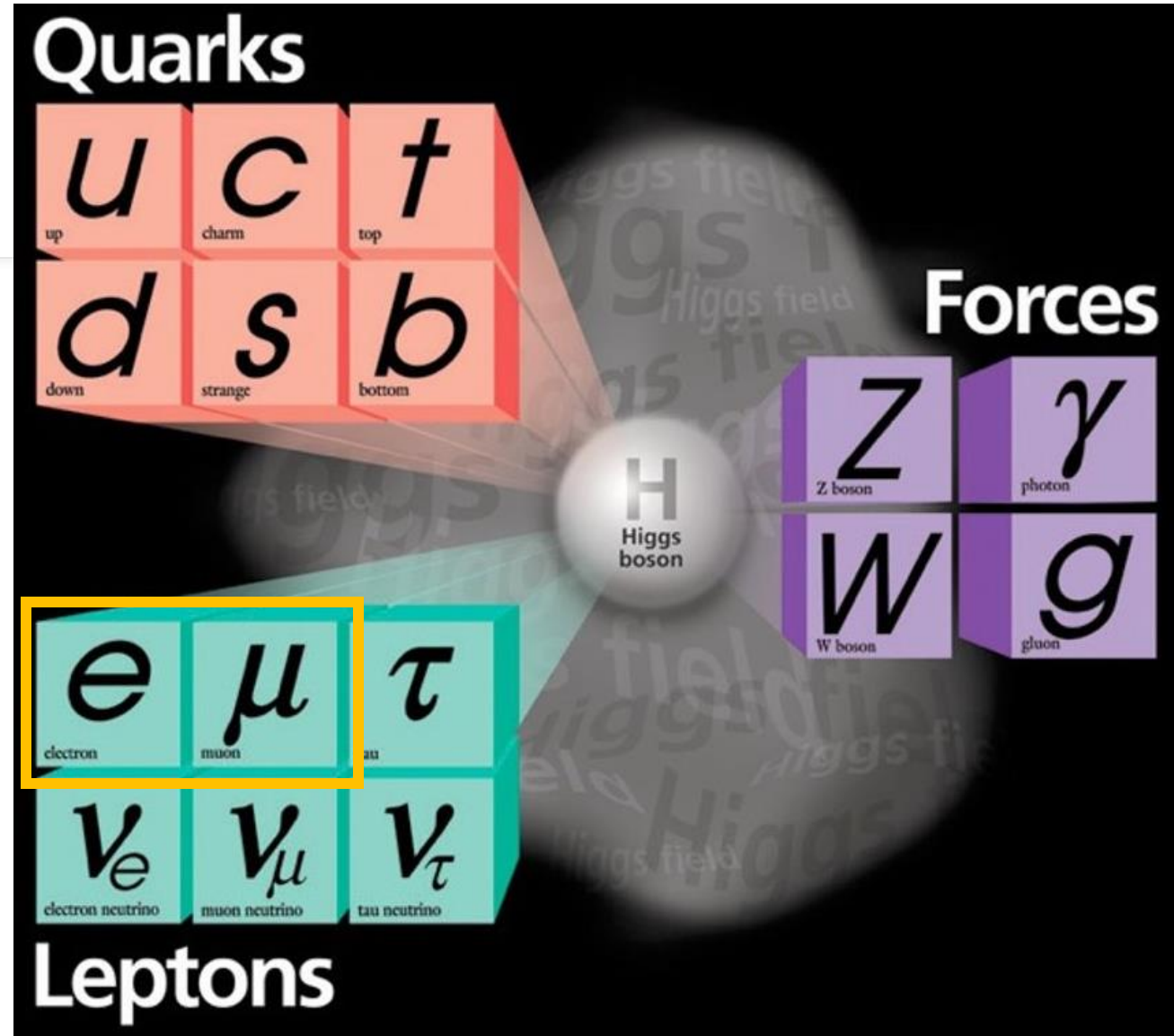
**Carl Anderson
Seth Neddermeyer**



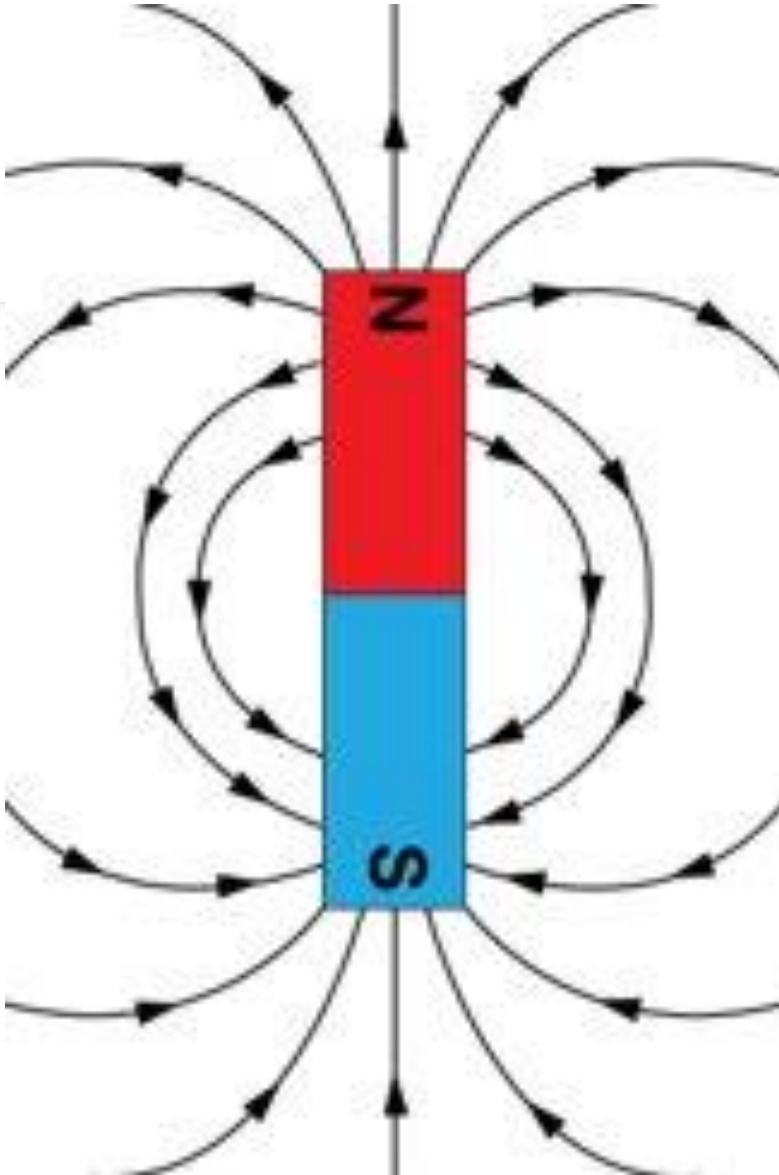
Atop Pike's Peak at 14,000 ft Observing Cosmic Rays



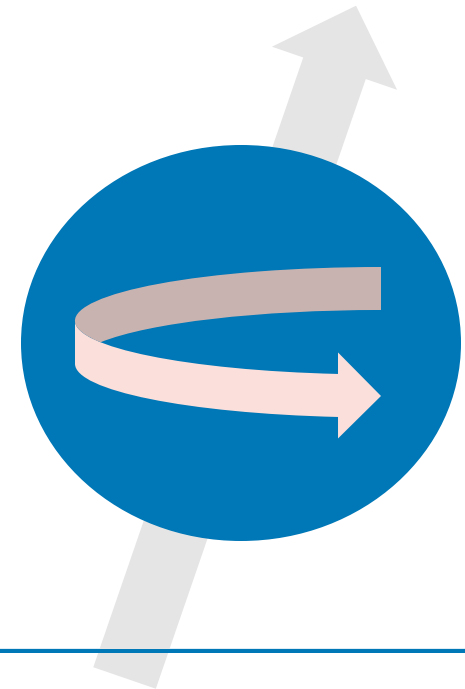
Standard model



Magnetic dipole moment

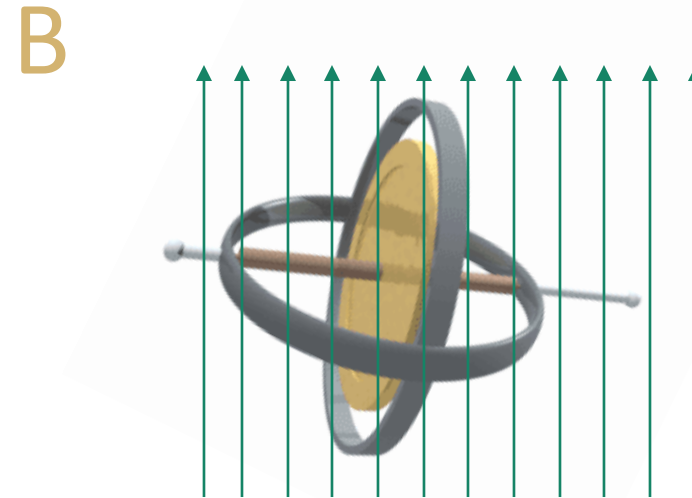


- Bar magnet, current loop ...
- Charged particle (electron, muon, ...)
- Angular momentum



Spin precession (in a magnetic field)

$$\omega_s = g \frac{eB}{2m}$$



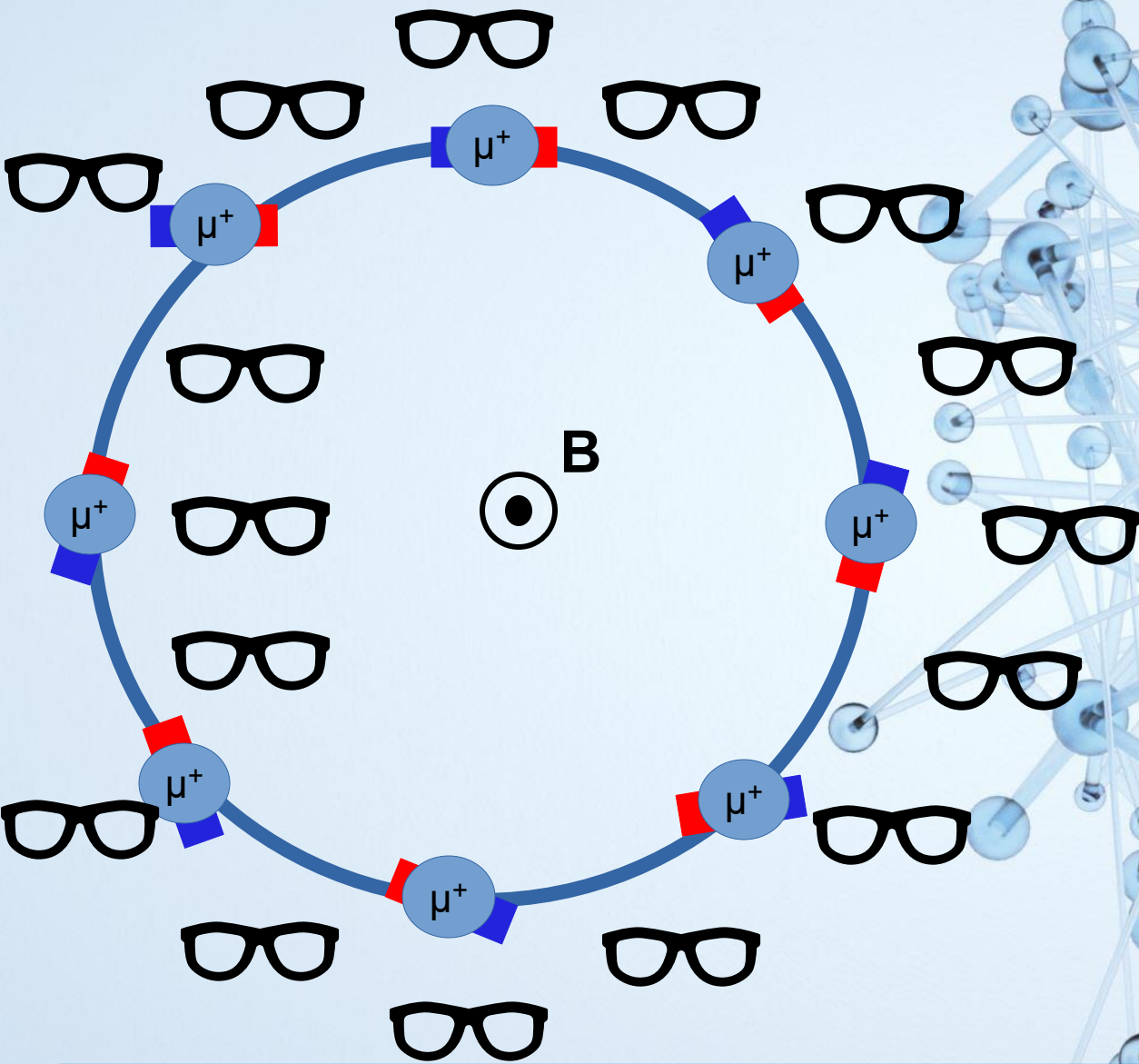
Quantum mechanics (Dirac)

$$g = 2$$

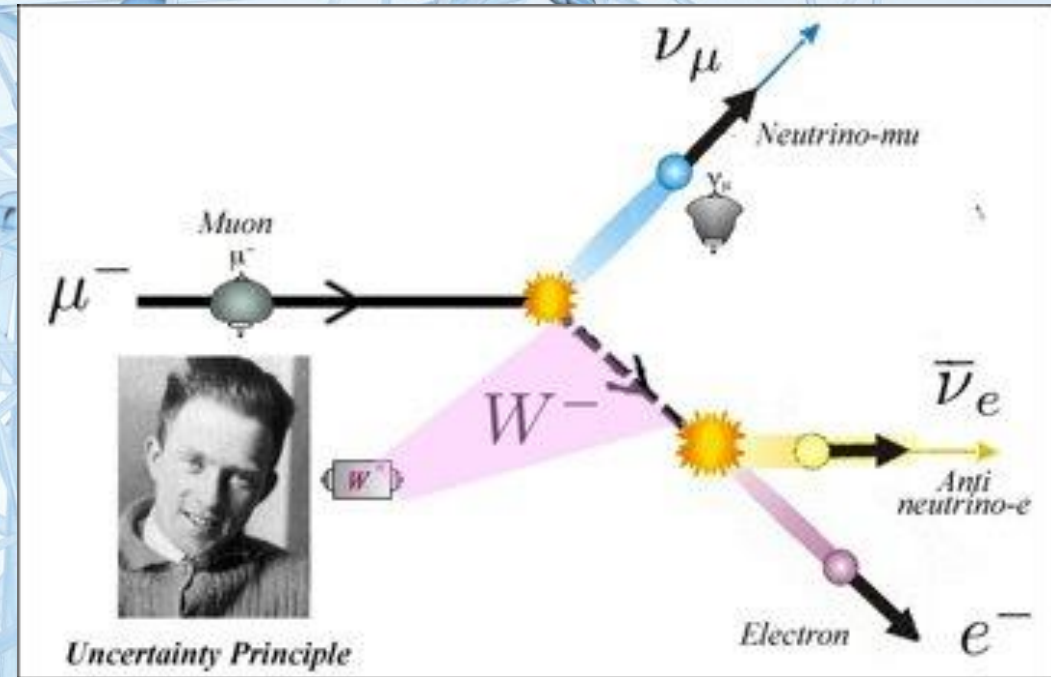
1948 Foley & Kusch measure $g_e > 2$ (electron)

$$g_e = 2.00238$$

• What do we measure (muons stored in a magnetic field)?

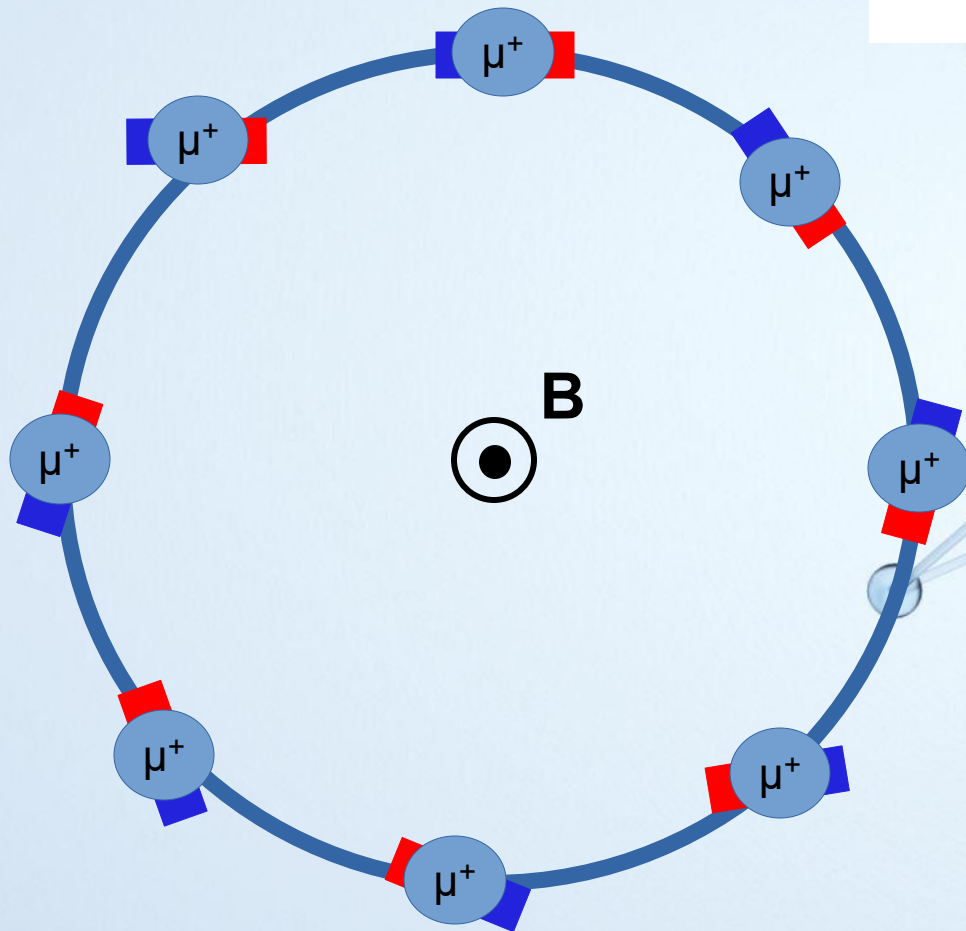


$$E > E_{\text{threshold}}$$



- Long lived
- "Goldilocks mass"

- What do we actually measure?



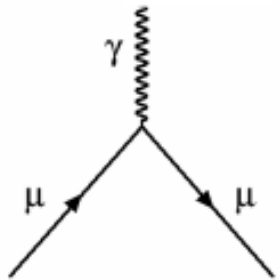
$$\vec{\omega}_a \equiv \vec{\omega}_s - \vec{\omega}_c = -\frac{q}{m_\mu} \left[a_\mu \vec{B} - a_\mu \left(\frac{\gamma}{\gamma + 1} \right) (\vec{\beta} \cdot \vec{B}) \vec{\beta} - \left(a_\mu - \frac{1}{\gamma^2 - 1} \right) \frac{\vec{\beta} \times \vec{E}}{c} \right]$$

At "magic"
momentum

$$\vec{\omega}_a \equiv \vec{\omega}_s - \vec{\omega}_c = -a_\mu \frac{q \vec{B}}{m_\mu}$$

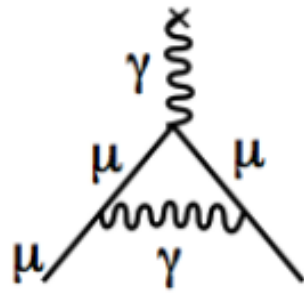
What is it all about?

Dirac
Equation



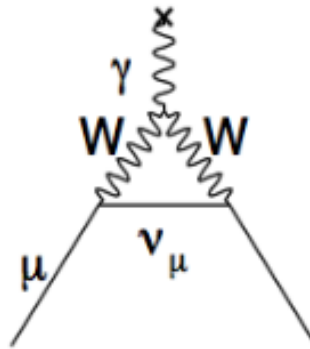
$$a_m = 0$$

QED



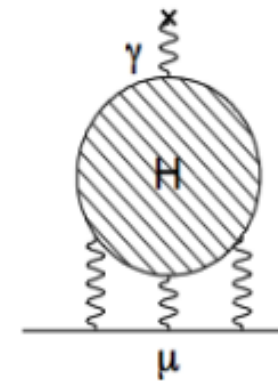
$$+0.00116584719$$

Electroweak



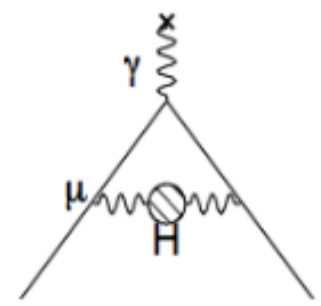
$$+0.00000000154$$

Hadronic Light-
by-Light



$$+0.00000000092$$

Hadronic Vacuum
Polarization



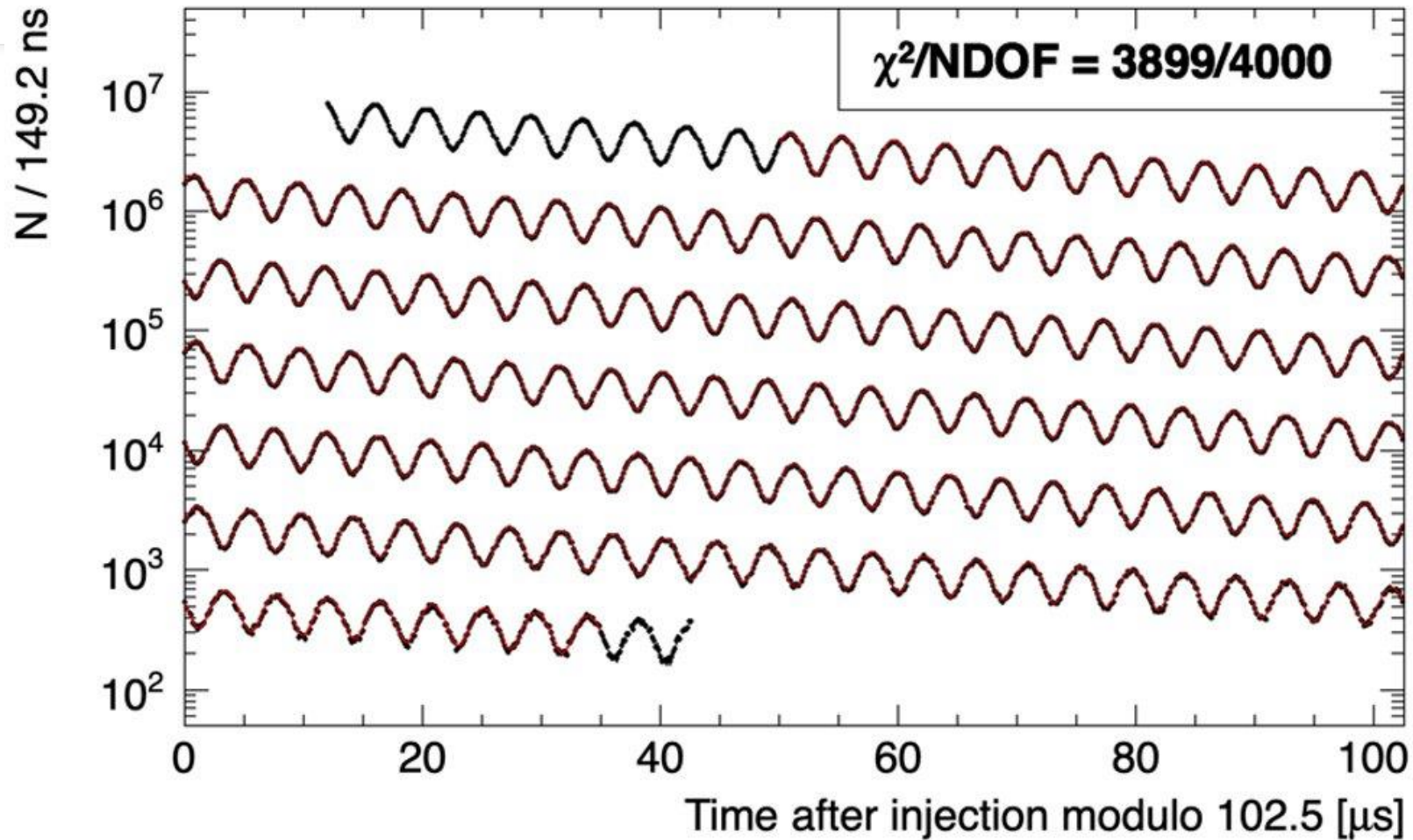
$$+0.00000006845$$

- Information about vacuum properties

White Paper: Phys. Rept. 887 (2020) 1-166
<https://doi.org/10.1016/j.physrep.2020.07.006>

T. Aoyama et al., "The anomalous magnetic moment of the muon in the Standard Model," *Phys. Rept.* 1143 (2025) 1–158, [arXiv:2505.21476](https://arxiv.org/abs/2505.21476)

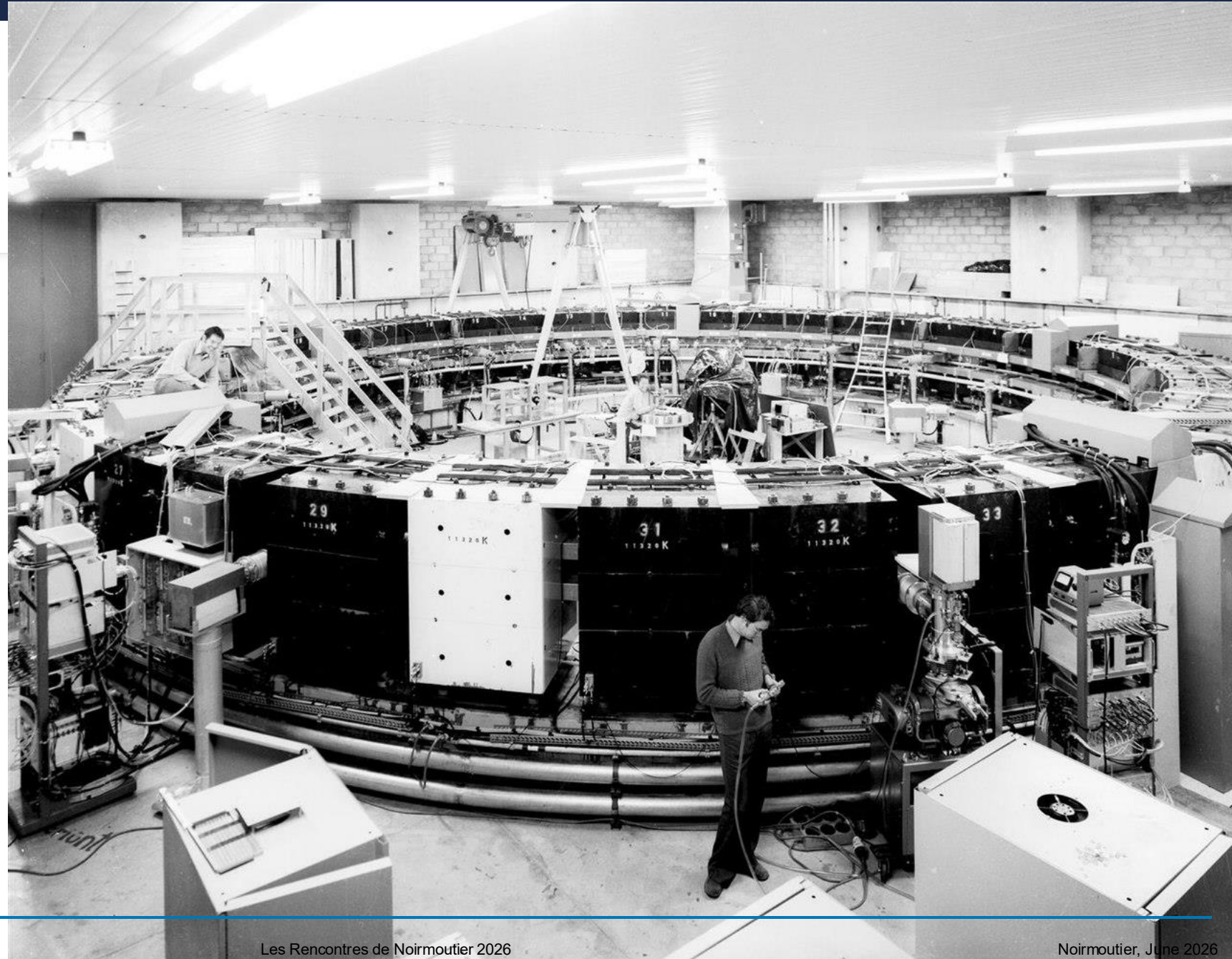
Number of decay positrons



CERN 1960

Confirmation of QED
Precision 1%

By CERN - <https://cds.cern.ch/record/41876>, CC BY 4.0,
<https://commons.wikimedia.org/w/index.php?curid=70982470>



BNL E821 1990

Precision 1 ppm
Is there a problem with
the SM?



E989 MUON $g-2$ experiment



Arrival

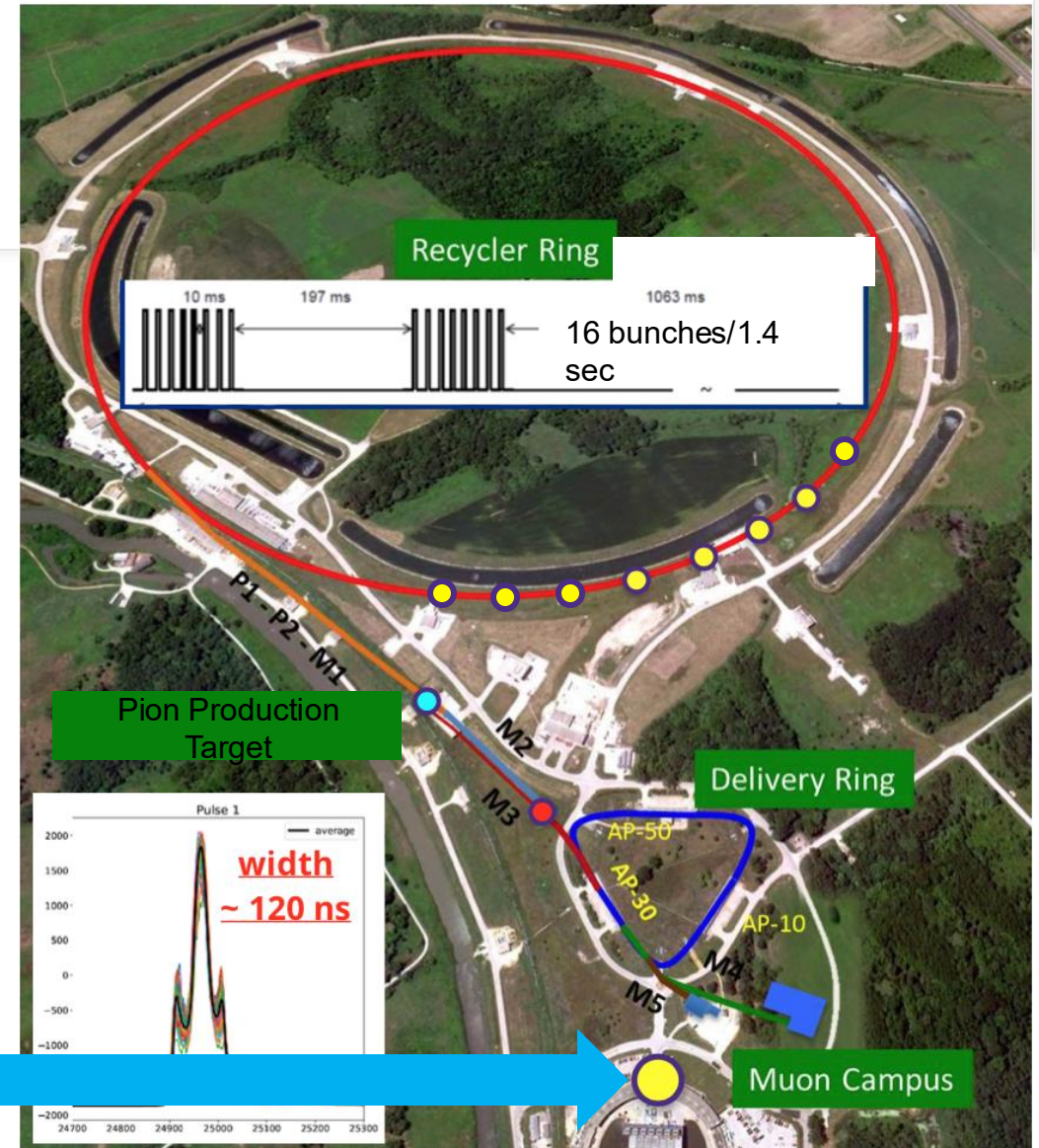


Reassembly

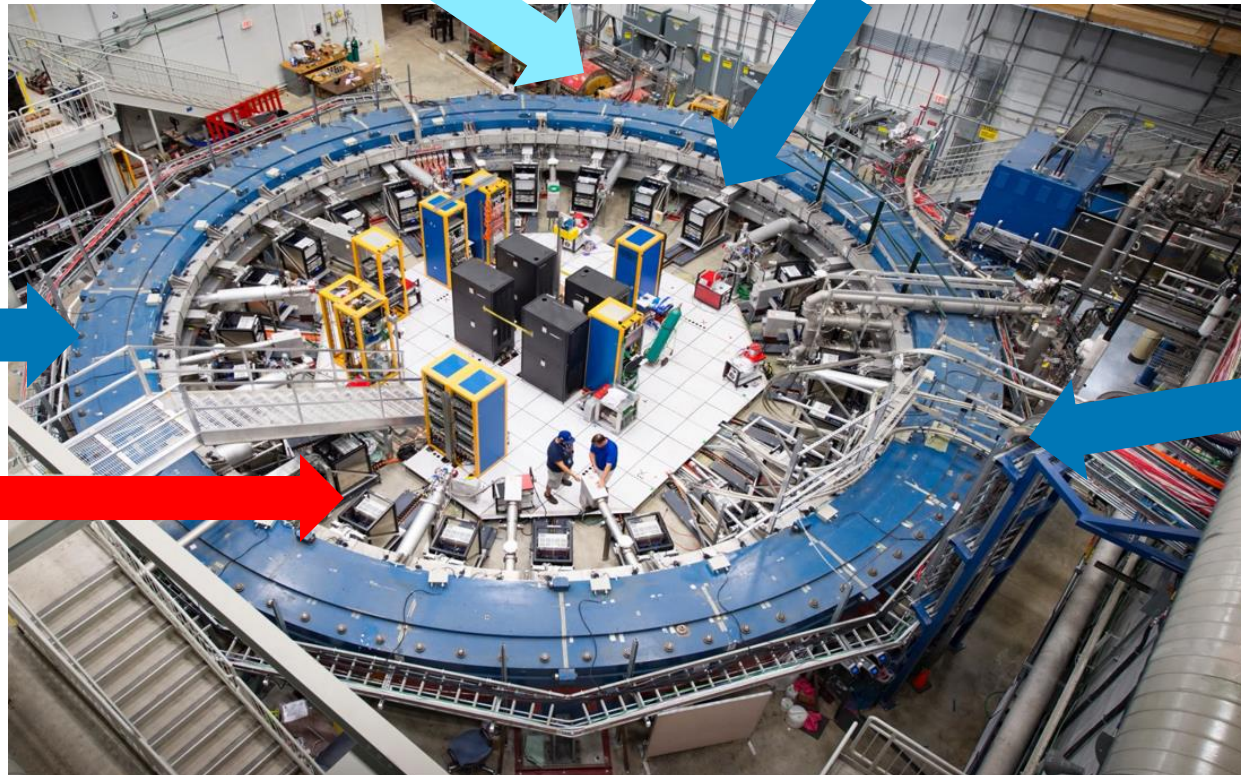
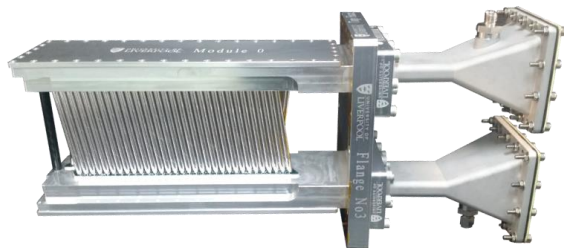
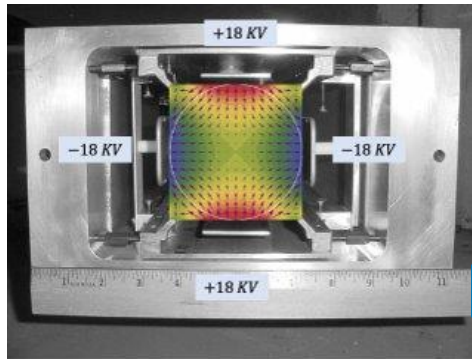
- Superconducting ring travelled in one piece



Muon g-2 experiment



Experiment



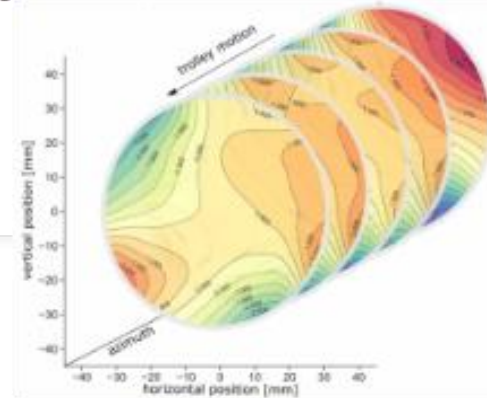
Measuring the Field: NMR Probes

$$\tilde{\omega}'_p(t) = \frac{1}{2\pi} \int_0^{2\pi} \tilde{\omega}'_p(\phi, t) d\phi,$$

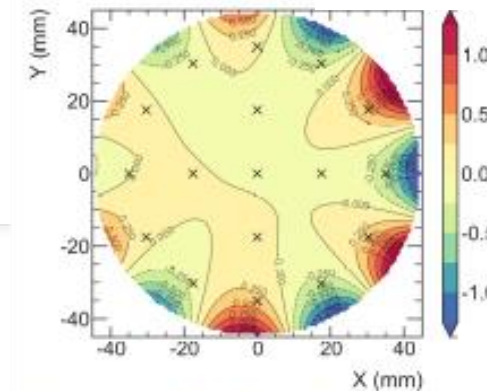
- In-vacuum NMR trolley maps field every ~3 days



17 petroleum jelly
NMR probes

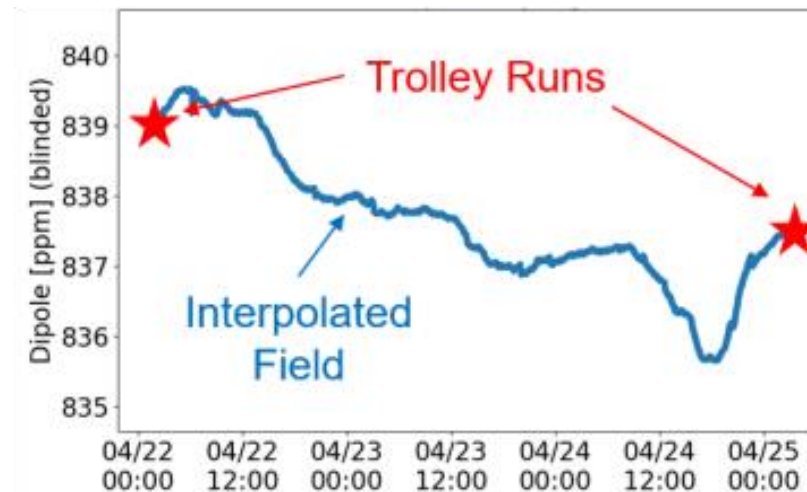
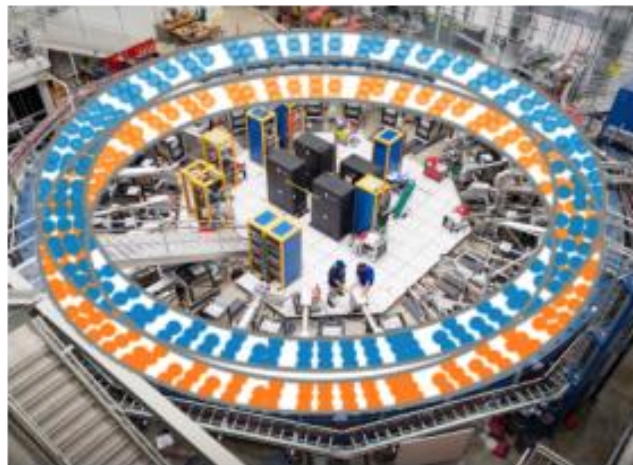


2D field maps
(~8000 points)



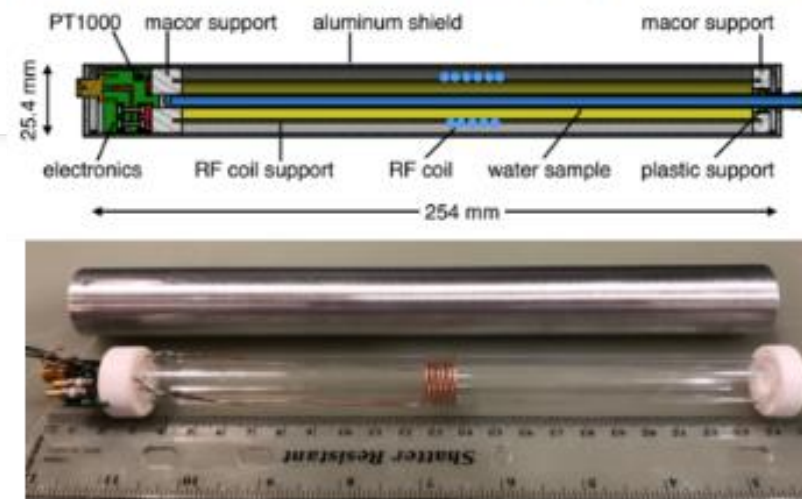
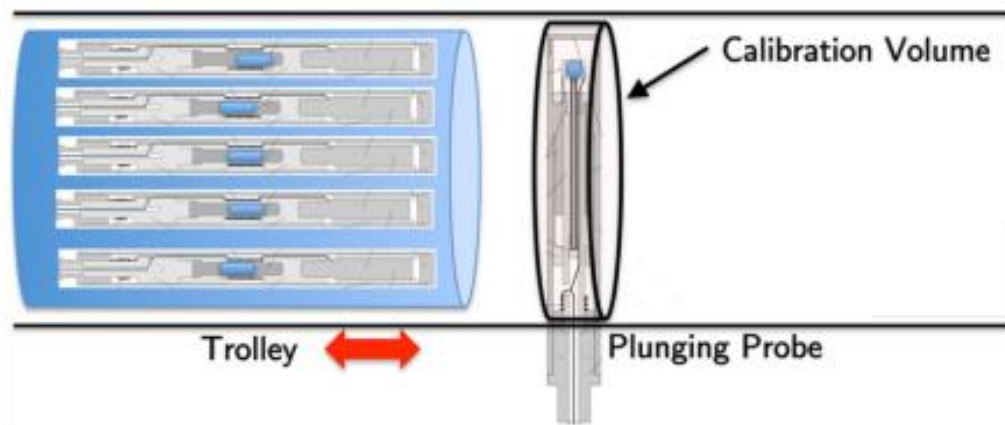
Azimuthally-Averaged
Variation < 1 ppm

- 378 fixed probes** monitor field during muon storage at 72 locations

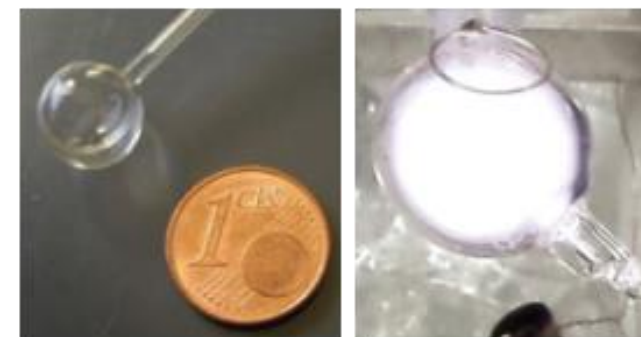


Calibration of Field Measurements

- Cross-calibrate using a cylindrical **plunging H₂O probe** which repeatedly **changes places with trolley (petroleum jelly probes)**



- This probe is **checked against a spherical probe** using an MRI magnet at ANL
- Both also cross-checked against a **³He probe** (different systematics)

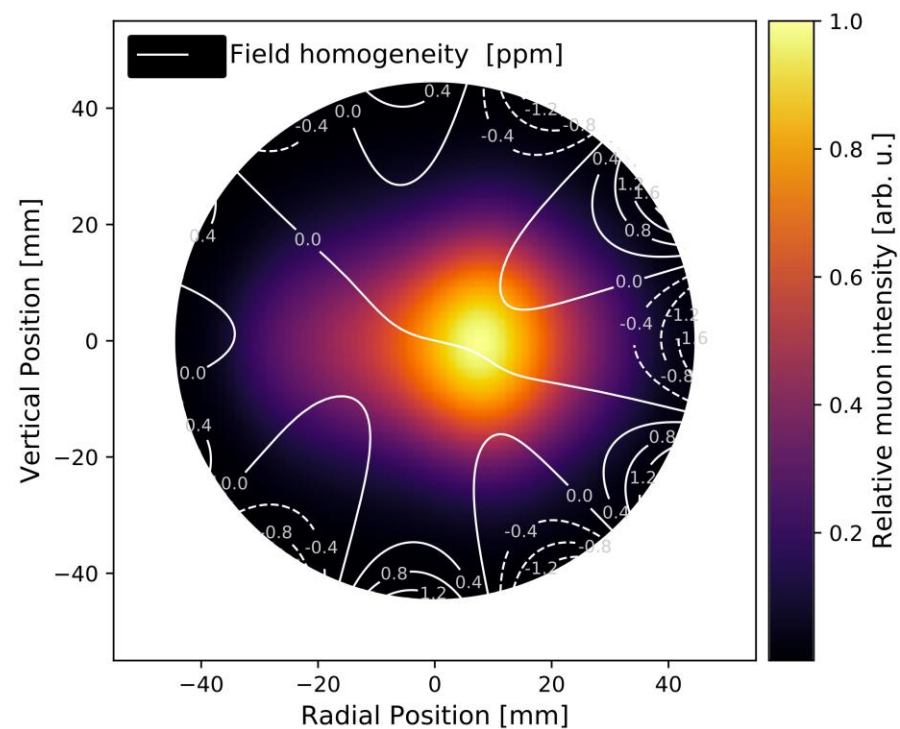
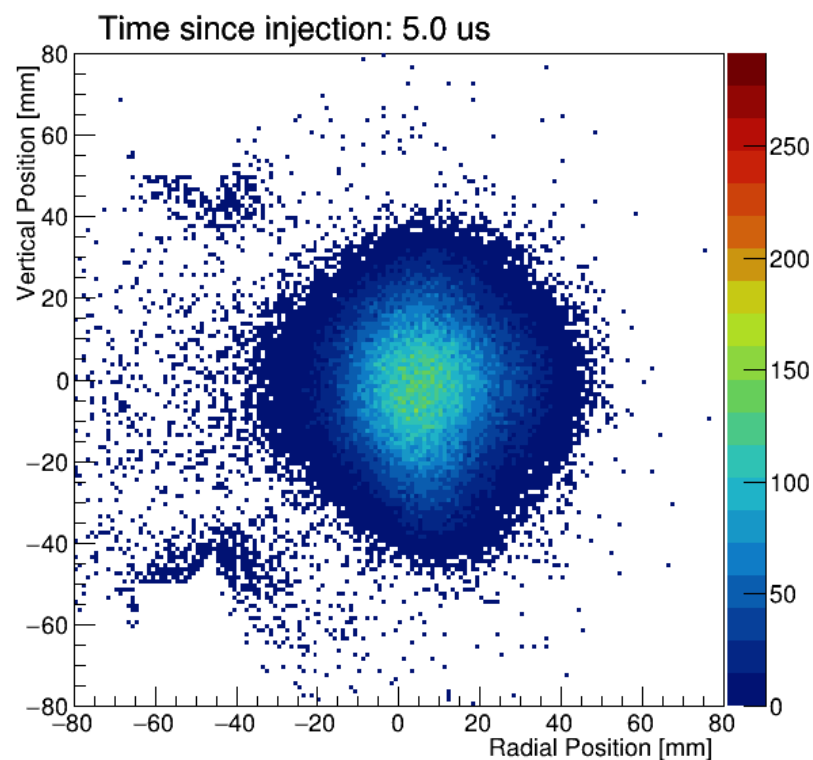


H₂O Probe

³He Probe

Beam (from trackers) and field

$$\omega_s = g \frac{eB}{2m}$$



Life is complicated

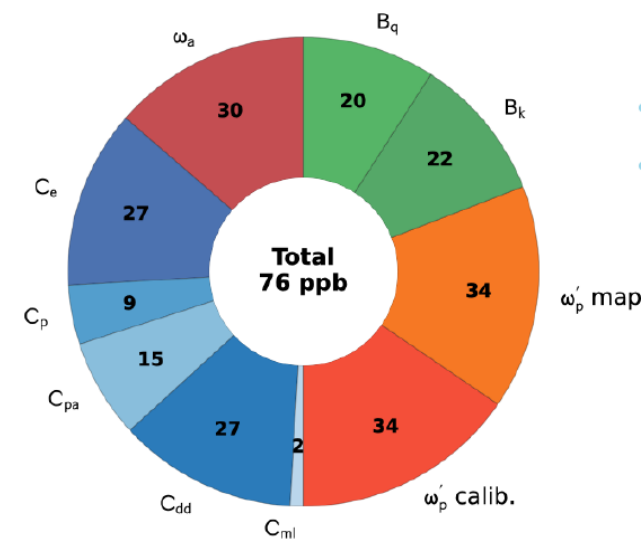
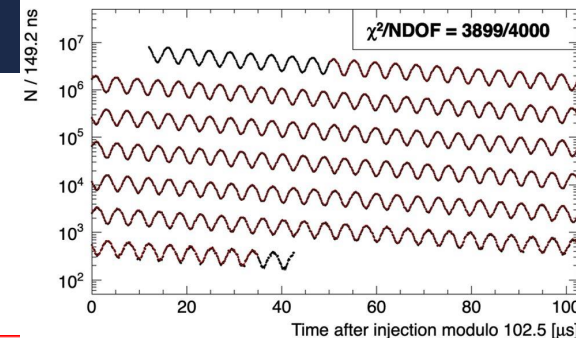
**E-field & Up/Down motion:
Spin precesses slower than
in basic equation**

**Phase changes over each fill:
Phase-Acceptance, Differential
Decay, Muon Losses**

$$\frac{\omega_a}{\omega_p} = \frac{\omega_a^m}{\omega_p^m} \frac{1 + \overbrace{C_e + C_p + C_{pa} + C_{dd} + C_{ml}}^{1 + \underbrace{B_k + B_q}_{\text{Transient Magnetic Fields: Quad Vibrations, Kicker Eddy Current,}}}}{1 + B_k + B_q}$$

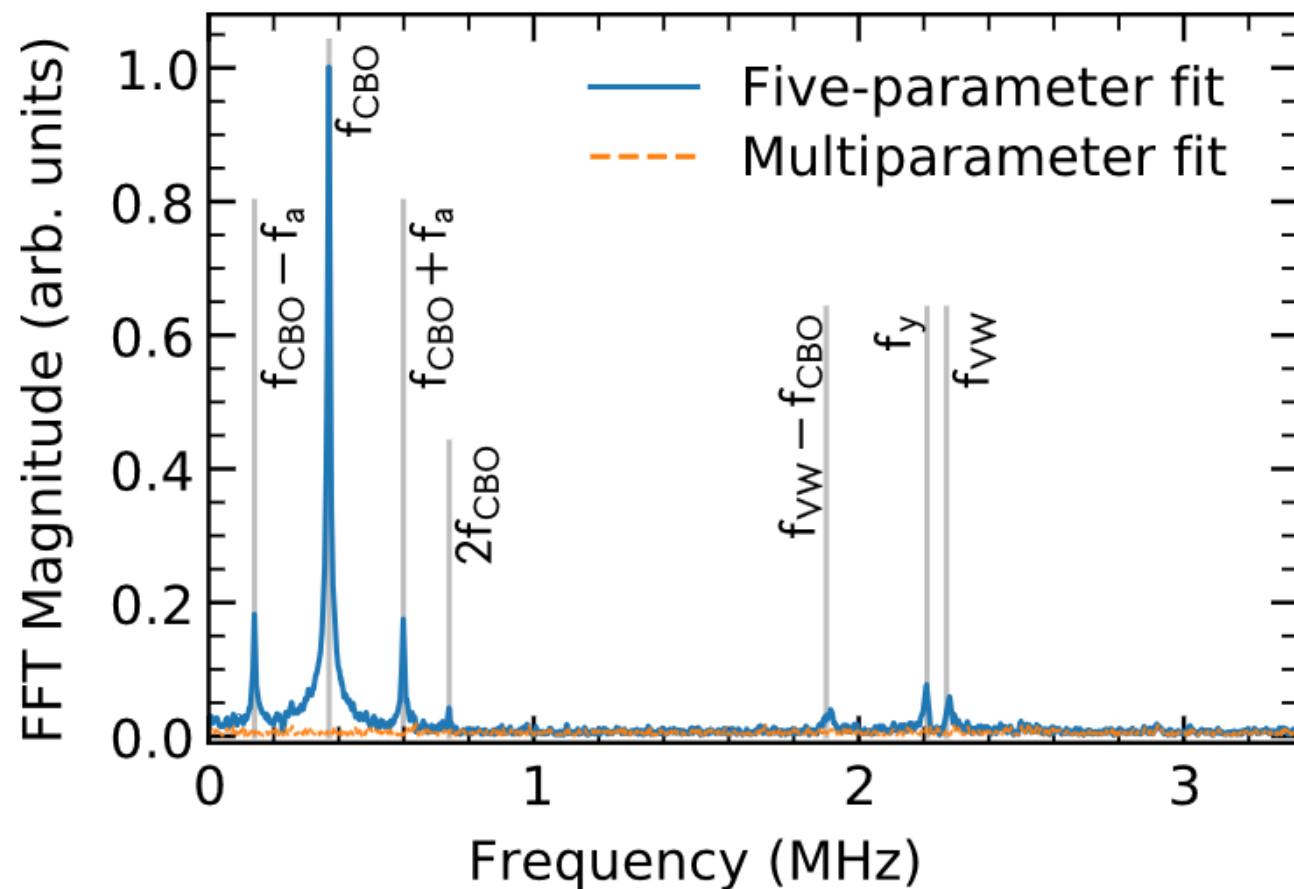
Measured Values

**Transient Magnetic Fields:
Quad Vibrations,
Kicker Eddy Current,**

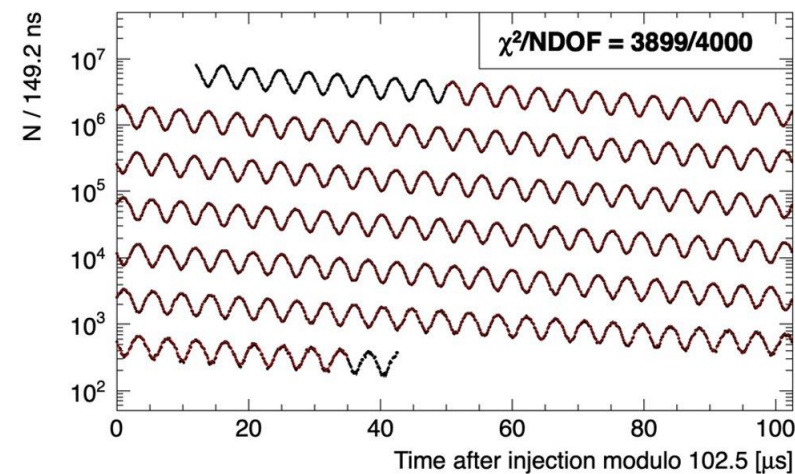


Analysis

$$f(t) = N_0 \cdot N_x(t) \cdot N_y(t) \cdot N_{xy}(t) \cdot \Lambda(t) \cdot e^{-t/\tau_\mu} \\ (1 + A_0 \cdot A_x(t) \cos(\omega_a^m t - (\phi_0 + \phi_x(t))))$$



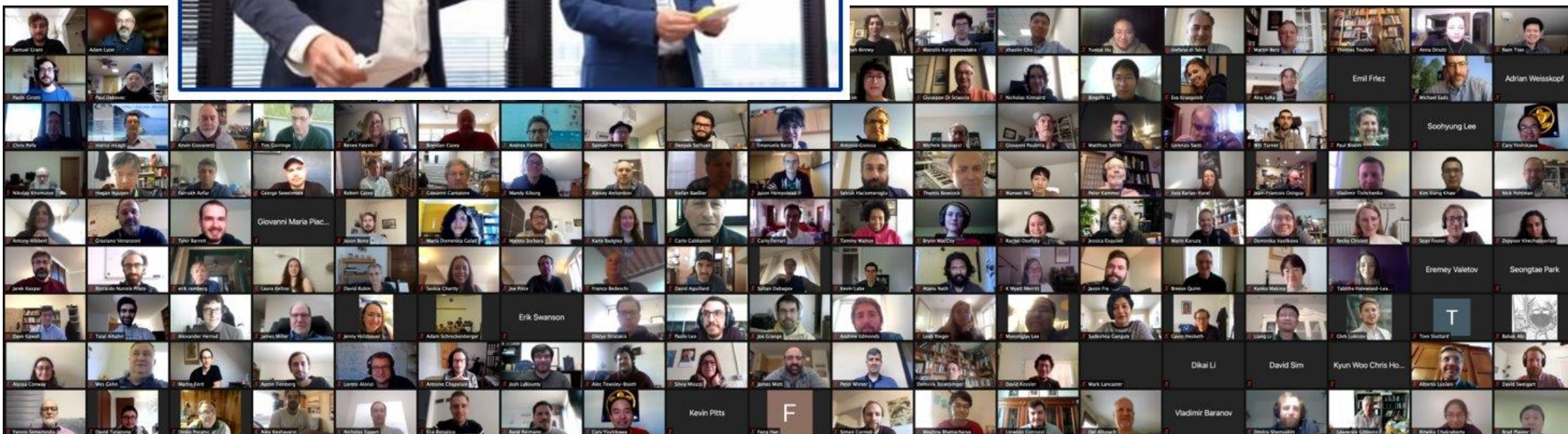
Group	Method	Run-2		Run-3a		Run-3b	
		R	σ_R	R	σ_R	R	σ_R
I	T	-99.112	0.377	-98.682	0.320	-97.298	0.520
II	T	-99.171	0.376	-98.700	0.323	-97.274	0.519
III	T	-99.198	0.377	-98.690	0.323	-97.267	0.520
IV	T	-99.147	0.382	-98.726	0.329	-97.304	0.528
V	T	-99.029	0.378	-98.603	0.325	-97.191	0.513
VI	T	-99.047	0.378	-98.581	0.325	-97.145	0.522
I	A	-99.197	0.339	-98.355	0.290	-97.453	0.468
II	A	-99.232	0.338	-98.408	0.290	-97.407	0.467
III	A	-99.253	0.337	-98.416	0.291	-97.422	0.468
IV	A	-99.199	0.344	-98.430	0.295	-97.438	0.476
V	A	-99.134	0.340	-98.416	0.291	-97.337	0.466
VI	A	-99.157	0.340	-98.397	0.293	-97.316	0.470
III	RT	-99.189	0.383	-98.693	0.334	-97.279	0.533
IV	RT	-99.160	0.383	-98.710	0.329	-97.244	0.529
V	RT	-99.006	0.384	-98.549	0.325	-97.158	0.513
III	RA	-99.222	0.345	-98.458	0.301	-97.402	0.480
IV	RA	-99.180	0.345	-98.432	0.297	-97.372	0.477
VII	Q	-99.191	0.543	-98.555	0.414	-96.875	0.663
VII	RQ	-99.300	0.491	-98.638	0.386	-97.239	0.616



Blind analysis



Unblinding



2021 – first result

MUNDO Interação de múons, a nova força da natureza que cientistas acreditam ter descoberto

Todas as forças que experimentamos todos os dias podem ser reduzidas a apenas quatro categorias: gravidade, eletromagnetismo, a força nuclear forte e a força nuclear fraca.

The New York Times

OUT THERE

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

Experiments with particles known as muons suggest that there are forms of matter and energy vital to the nature and evolution of the cosmos that are not yet known to science.



This result could change physics forever

20:24 news - Apr 8, 2021



Muons: 'Strong' evidence found for a new force of nature

No YouTube video
Screenshot captured

nature

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NEWS • 27 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.

David Castelnuovo



Dipartimento di Fisica
Seminario Generale

Risultati dell'esperimento Muon g-2 al Fermilab

Programma
15:00 G. Di Sciascio: Introduzione
15:10 F. Fucito & N. Tantalò, modera M. Bianchi: Il calcolo di g-2
15:50 M. Sorbara: L'esperimento Muon g-2 al Fermilab.
16:30 discussione

21/04/21 15:00 CET
On-line Webinar



SCIENCE & NATURE

'Tantalizing' Results of 2 Experiments Defy Physics Rulebook

Associated Press | April 8, 2021 8:42 pm



Social performance Facebook April 7, Facebook -

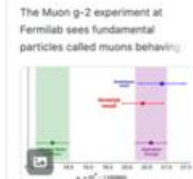
Facebook Performance Summary

View your key profile performance metrics from the report

Impressions
48,405 ▲147%

Engagement
3,339

Fermi National Acce...
Wed 4/7/2021 8:12 am PDT



The Muon g-2 experiment at Fermilab sees fundamental particles called muons behaving...

Metric	Value
Total Engagements	4,317
Reactions	1,424
Comments	236
Shares	365
Post Link Clicks	410
Other Post Clicks	1,882

Fermi National Acce...
Tue 4/6/2021 8:15 am PDT



We're less than 24 hours away from learning the first results from Fermilab's Muon g-2 experiment at Fermilab.

Metric	Value
Total Engagements	1,464
Reactions	556
Comments	38
Shares	76
Post Link Clicks	228
Other Post Clicks	566

Fermi National Acce...
Wed 4/7/2021 8:01 am PDT



We're thrilled to announce that the first results from Fermilab's Muon g-2 experiment strengthen.

Metric	Value
Total Engagements	768
Reactions	266
Comments	42
Shares	67
Post Link Clicks	184
Other Post Clicks	209



Mark Hamill
@HamillHimself

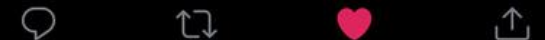
Evidence is mounting that The Force
has been with us...
ALWAYS.

The New York Times @nytimes · 3h

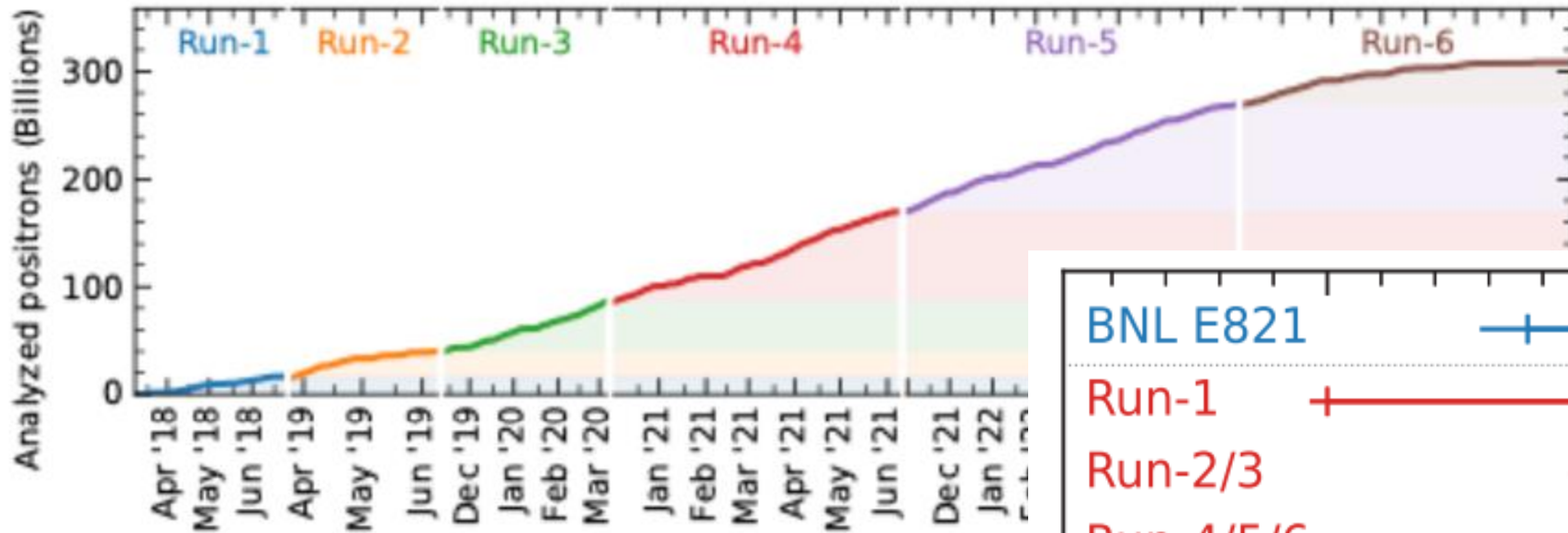
Breaking News: Evidence is mounting that a tiny subatomic particle is being influenced by forms of matter and energy that are not yet known to science but which may nevertheless affect the nature and evolution of the univer...

1:37 PM · 4/7/21 · Twitter Web App

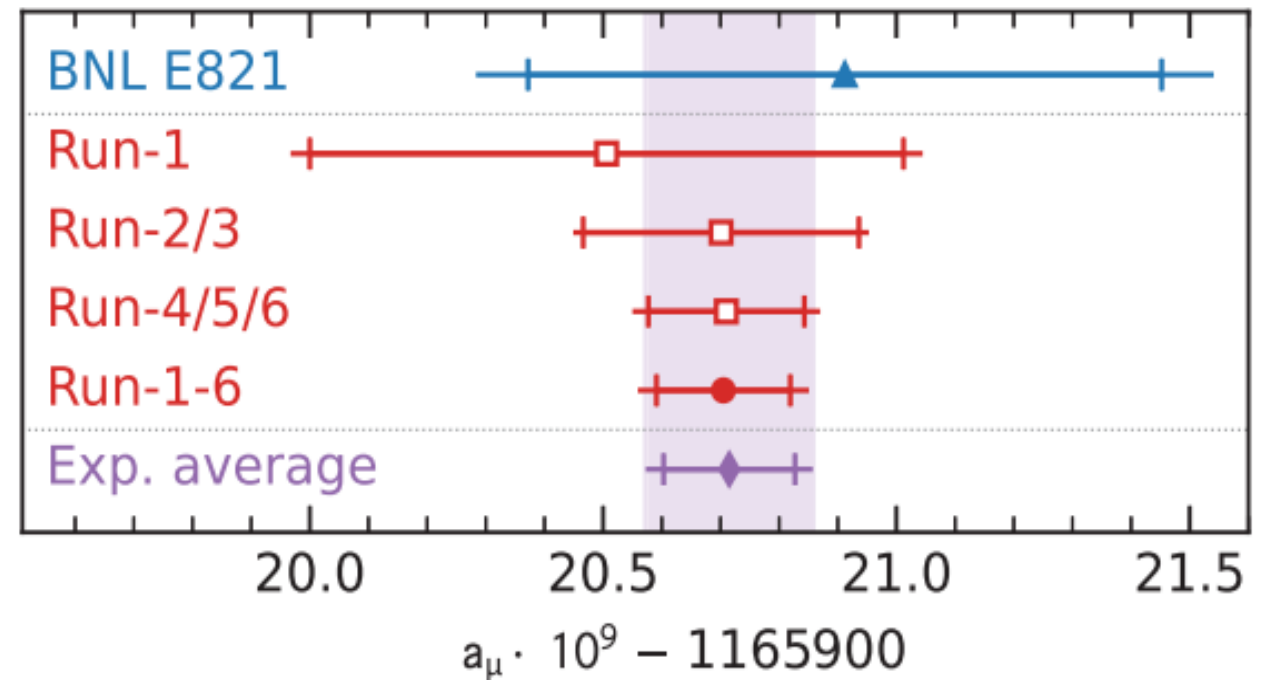
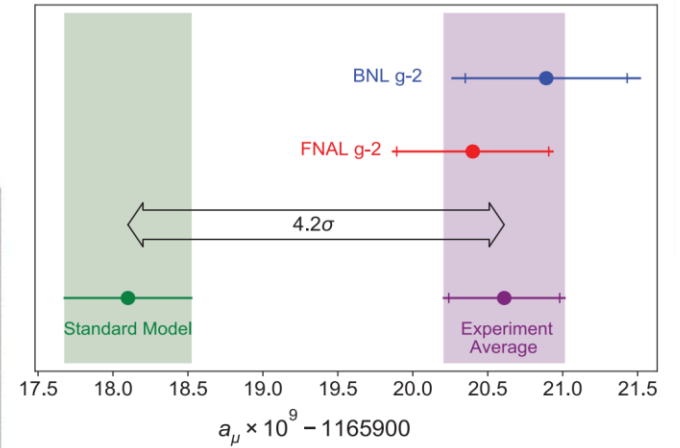
1,320 Retweets 71 Quote Tweets 8,695 Likes



Final Result - Run 1-6



- Final precision: 127 ppb
- Full dataset Run 1-6, 21 x BNL statistics
- Surpassed design goal of 140 ppb



Reality check vs TDR (140 ppb)

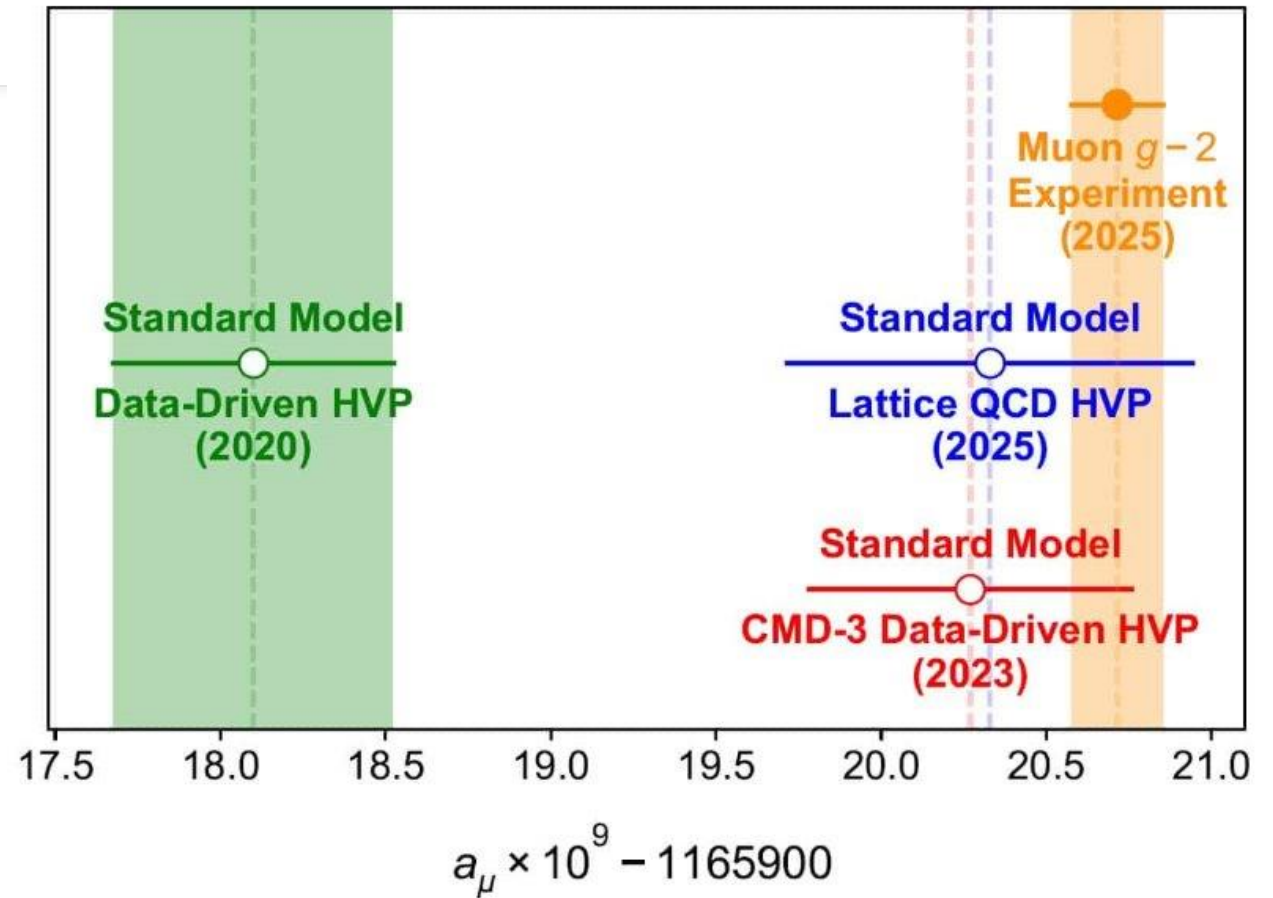
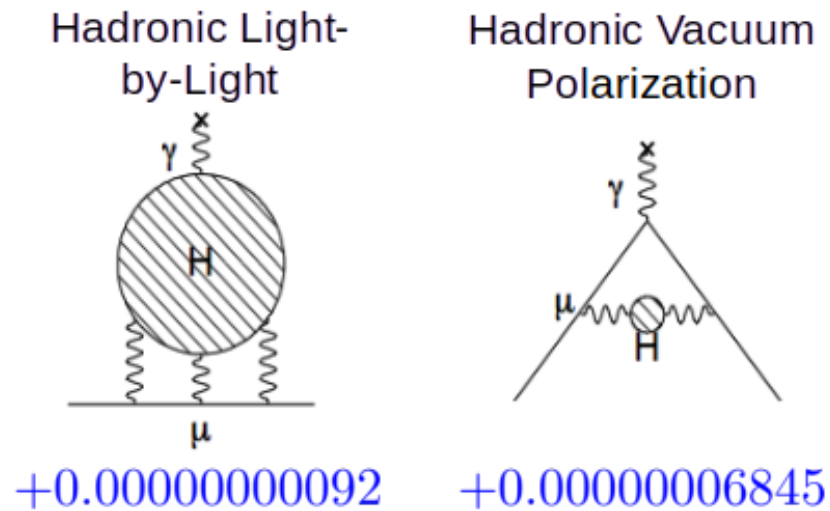
Category	E821 [ppb]	E989 Improvement Plans	Goal [ppb]
Gain changes	120	Better laser calibration	20
		low-energy threshold	
Pileup	80	Low-energy samples recorded	40
		calorimeter segmentation	
Lost muons	90	Better collimation in ring	20
CBO	70	Higher n value (frequency)	< 30
		Better match of beamline to ring	
E and pitch	50	Improved tracker	30
		Precise storage ring simulations	
Total	180	Quadrature sum	70

Component	Uncertainty (ppb)
Statistical	98
Systematic	78
External parameters	~22
Total (quadrature)	127

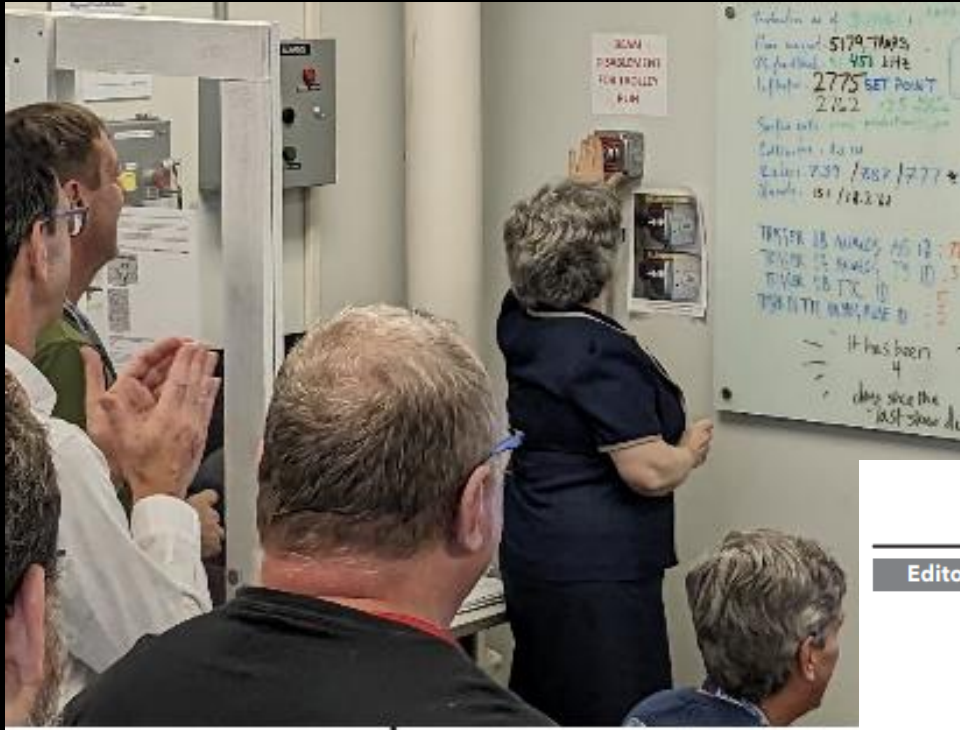
Quantity	Correction (ppb)	Uncertainty (ppb)
ω_a^m (statistical)	...	114
ω_a^m (systematic)	...	30
C_e	347	27
C_p	175	9
C_{pa}	-33	15
C_{dd}	26	27
C_{ml}	0	2
$\langle \omega_p' \times M \rangle$	...	48
B_k	-37	22
B_q	-21	20
μ_p' / μ_B	...	4
m_μ / m_e	...	22
Total systematic for $\mathcal{R}'_\mu$	...	76
Total for a_μ	572	139

Comparison with theory

- Lattice QCD
- CMD – 3, data driven approach



Conclusion



- Experimental results in excellent agreement
- Final result: 127 ppb precision, surpassing 140 ppb design goal

PHYSICAL REVIEW LETTERS **135**, 101802 (2025)

Editors' Suggestion

Featured in Physics

Measurement of the Positive Muon Anomalous Magnetic Moment to 127 ppb

The end?

award 15min

THE BREAKTHROUGH PRIZE

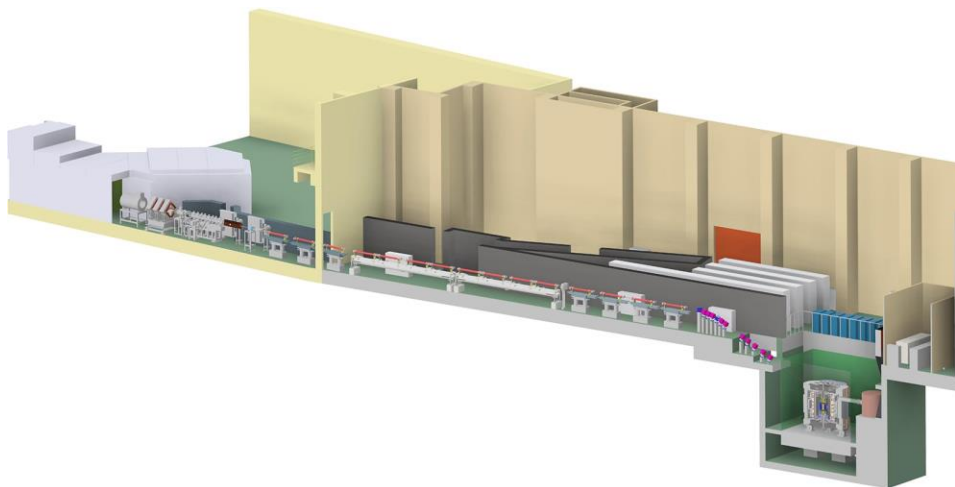


FOR FUNDAMENTAL PHYSICS

No!

J-PARC

Low energy muons
No electric field



MUonE

Space-like measurement of HVP

