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

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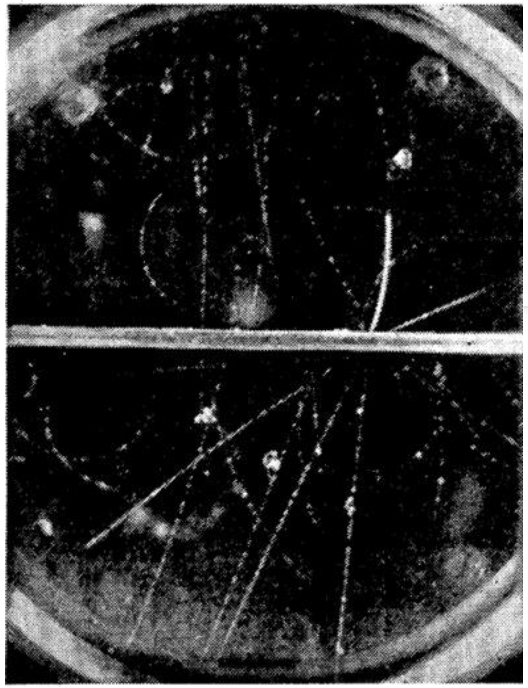
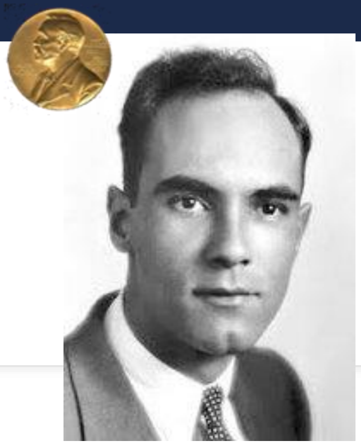
Sezione di Trieste



Muon

- Discovered 1936



Carl Anderson
Seth Neddermeyer

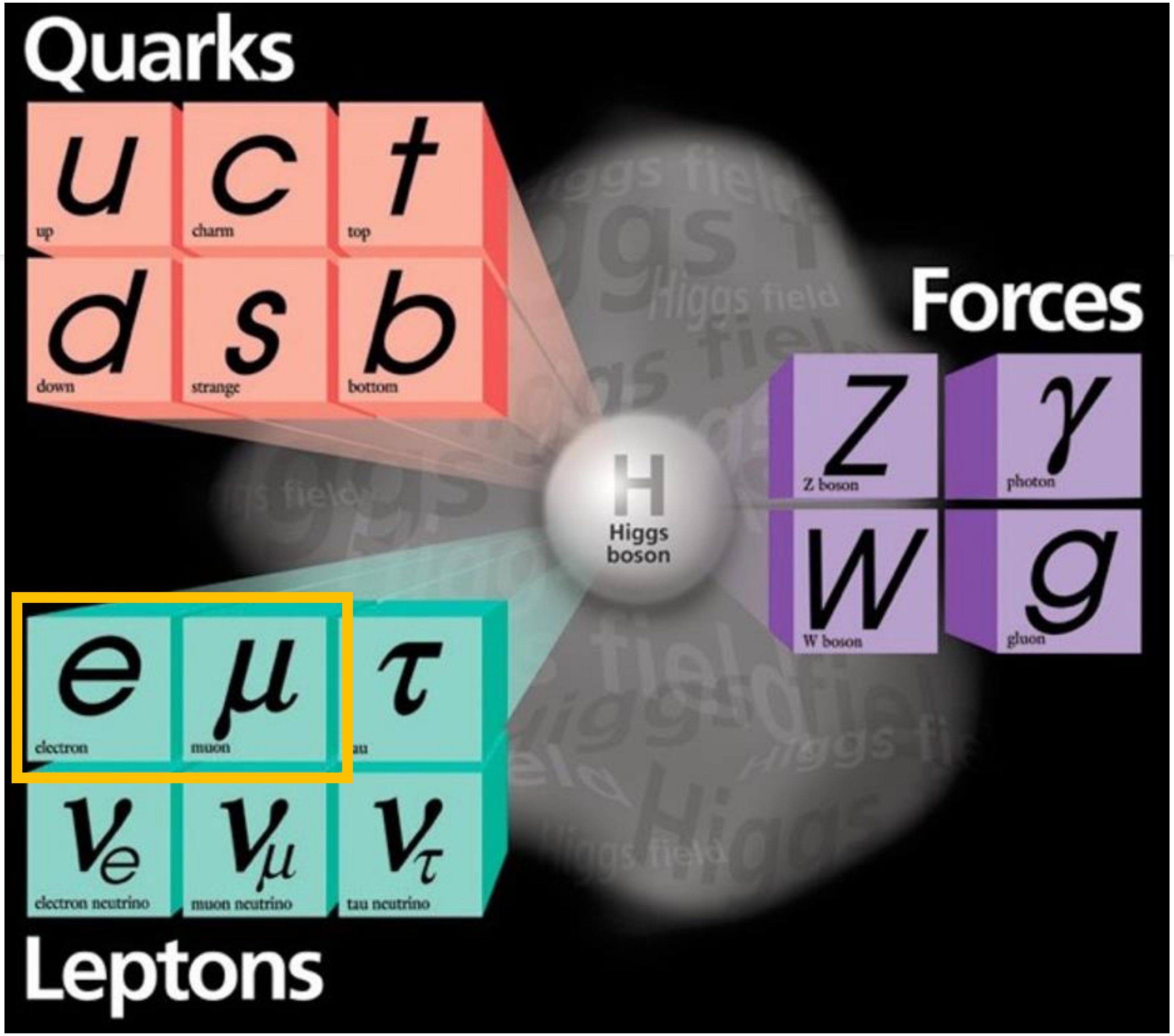
VOL. 50, NO. 4 AUGUST 15, 1936 SECOND SERIES

Cloud Chamber Observations of Cosmic Rays at 4300 Meters Elevation and Near Sea-Level

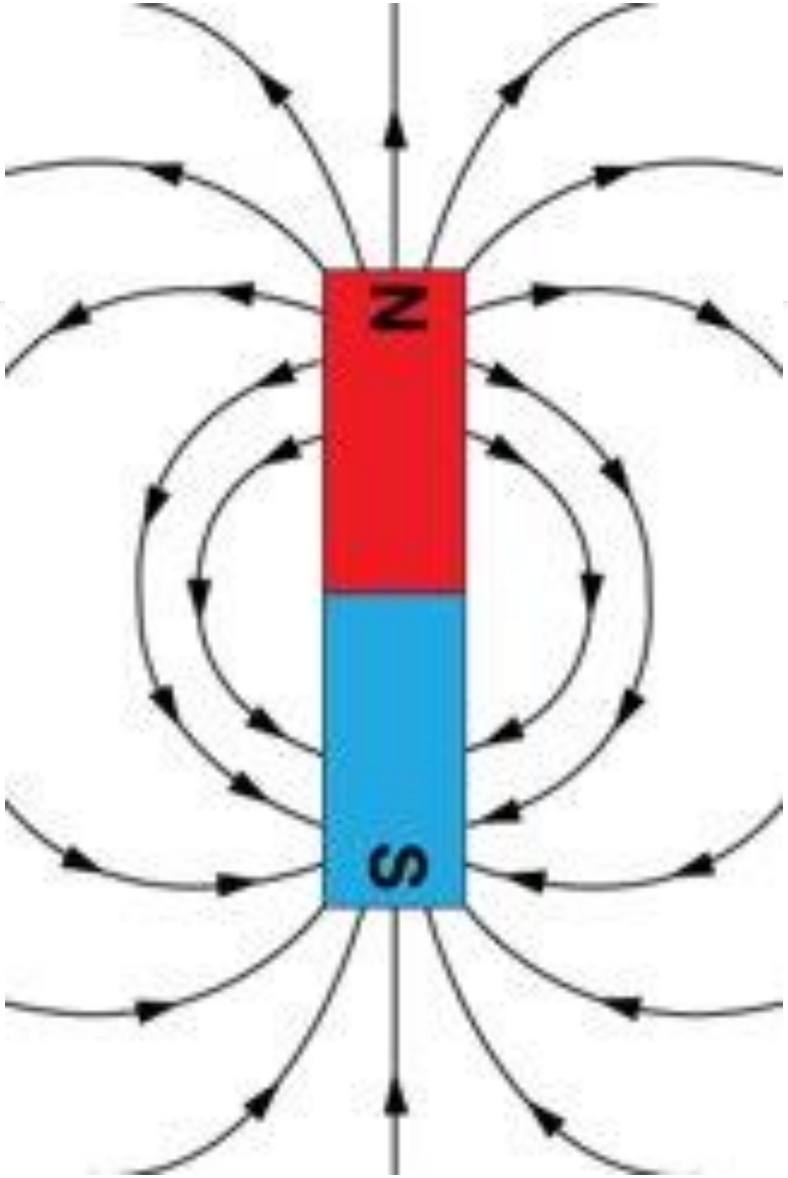
CARL D. ANDERSON AND SETH H. NEDDERMEYER, *Norman Bridge Laboratory of Physics, California Institute of Technology*
(Received June 9, 1936)

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

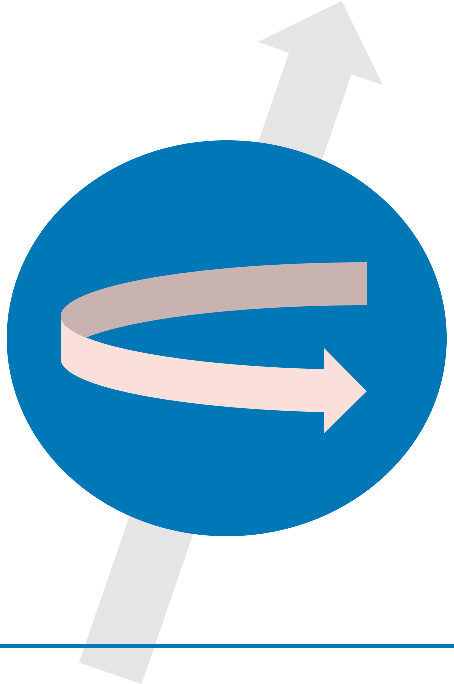
Standard model



Magnetic dipole moment

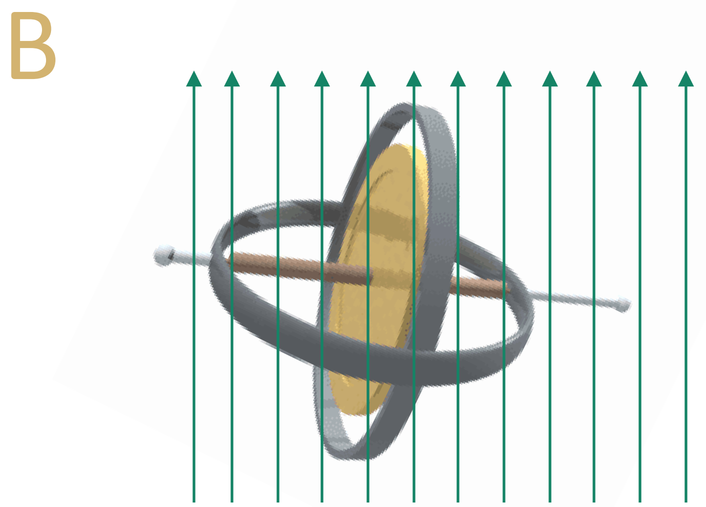


- Bar magnet, current loop ...
- Charged particle (electron, muon, ...)
- Angular momentum



Spin precession (in a magnetic field)

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

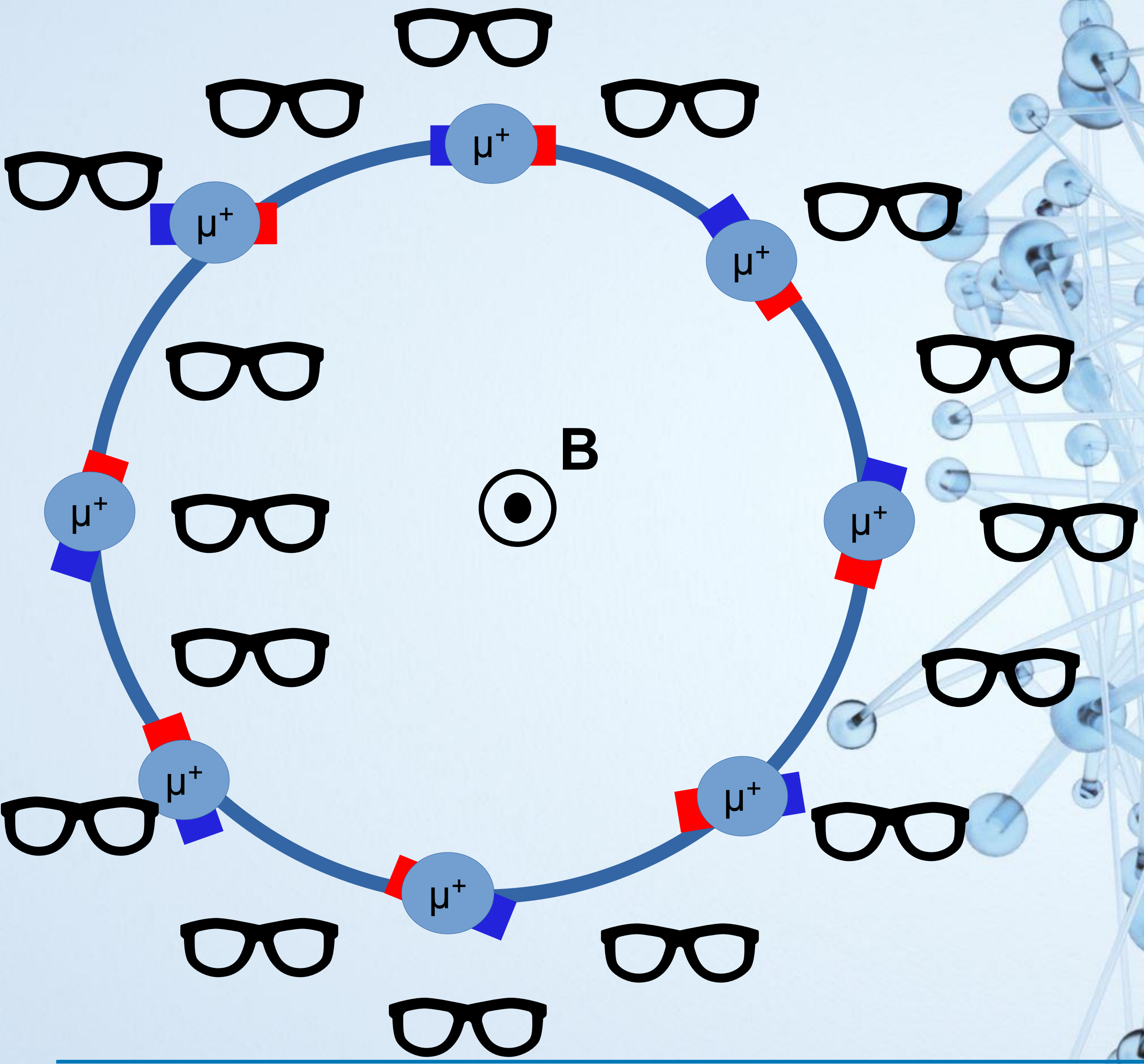


Quantum mechanics (Dirac) $g = 2$

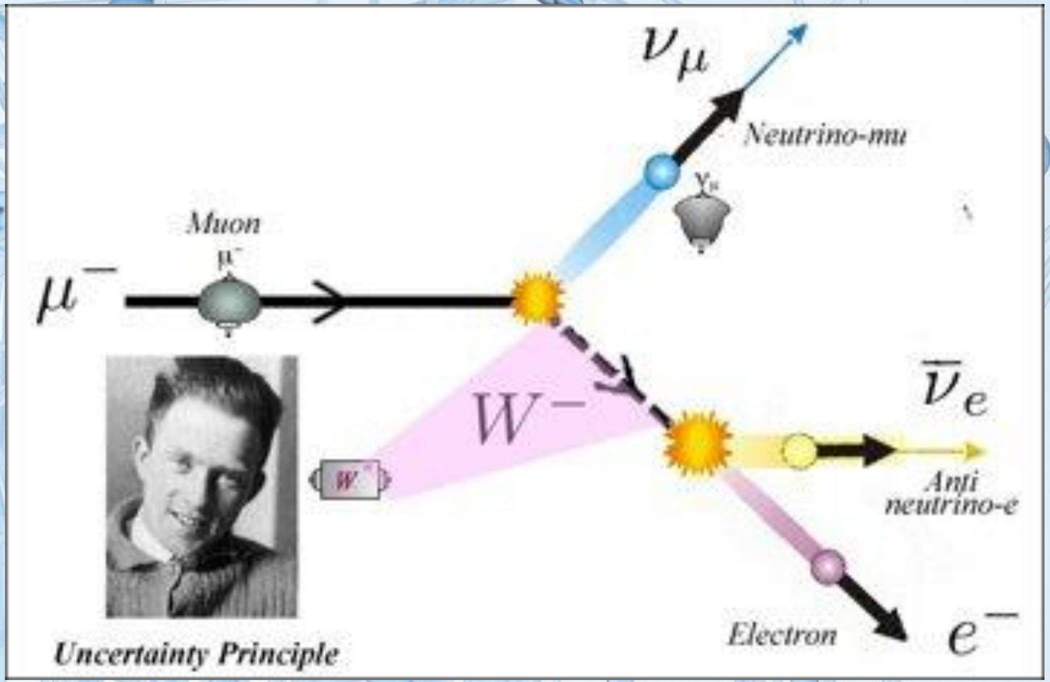
1948 Foley & Kusch measure $g_e > 2$ **(electron)**

$g_e = 2.00238$

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

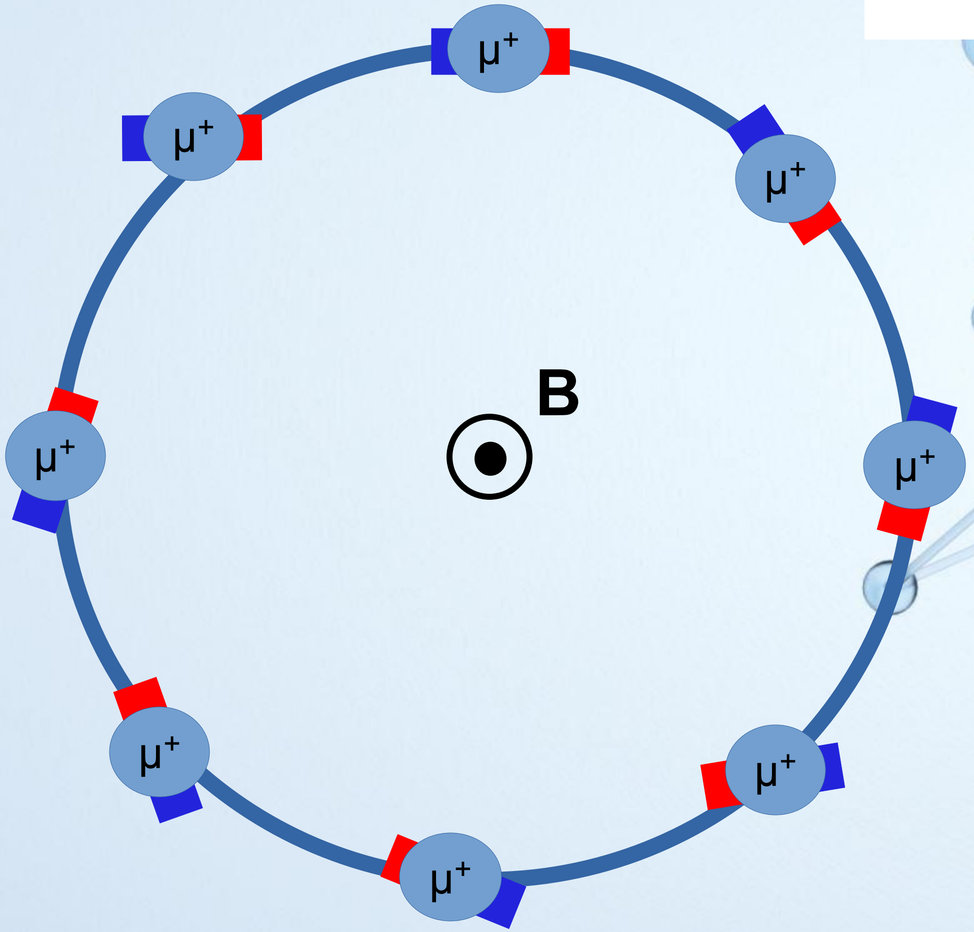


E > E_threshold



- *Long lived*
- *"Goldilocks mass"*

• What do we actually measure?

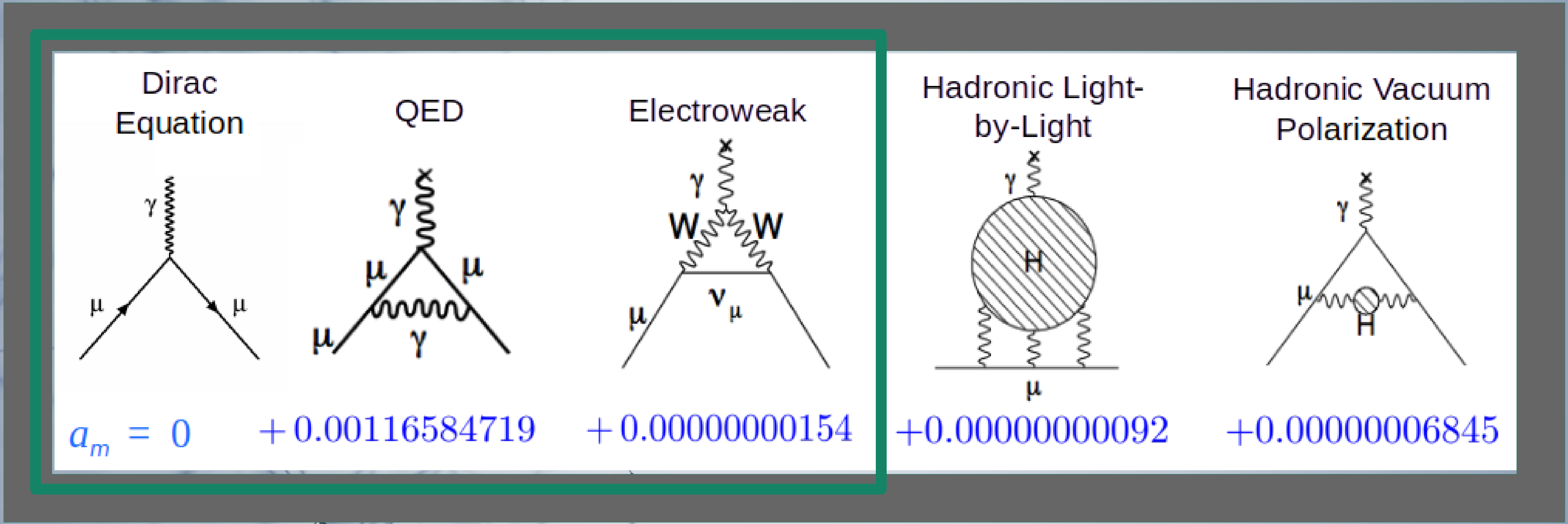


$$\vec{\omega}_a \equiv \vec{\omega}_s - \vec{\omega}_c = -\frac{q}{m_\mu}\left[a_\mu \vec{B} - a_\mu\left(\frac{\gamma}{\gamma+1}\right)(\vec{\beta}\cdot\vec{B})\vec{\beta} - \left(a_\mu - \frac{1}{\gamma^2-1}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right]$$

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?

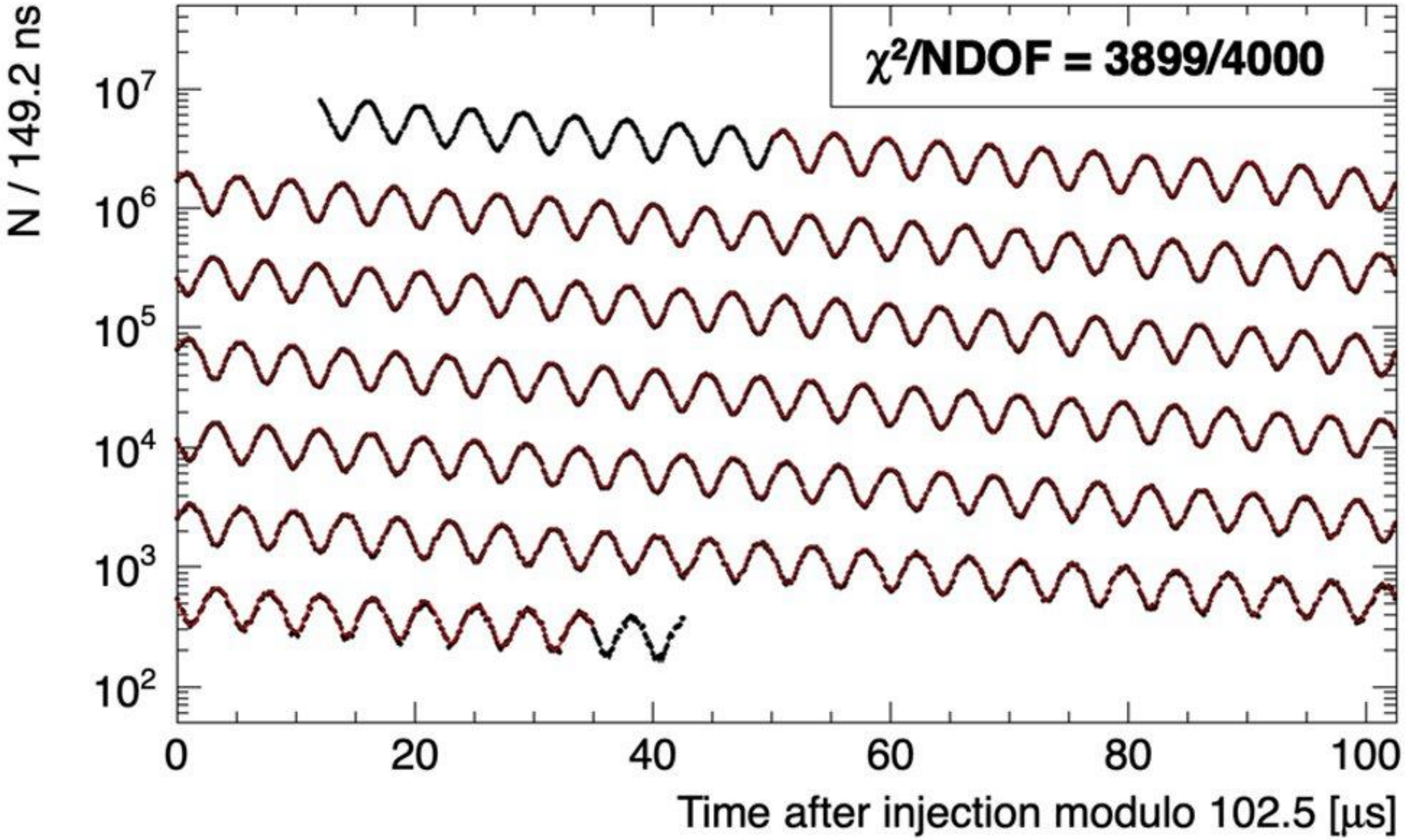


- **Information about vacuum properties**

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

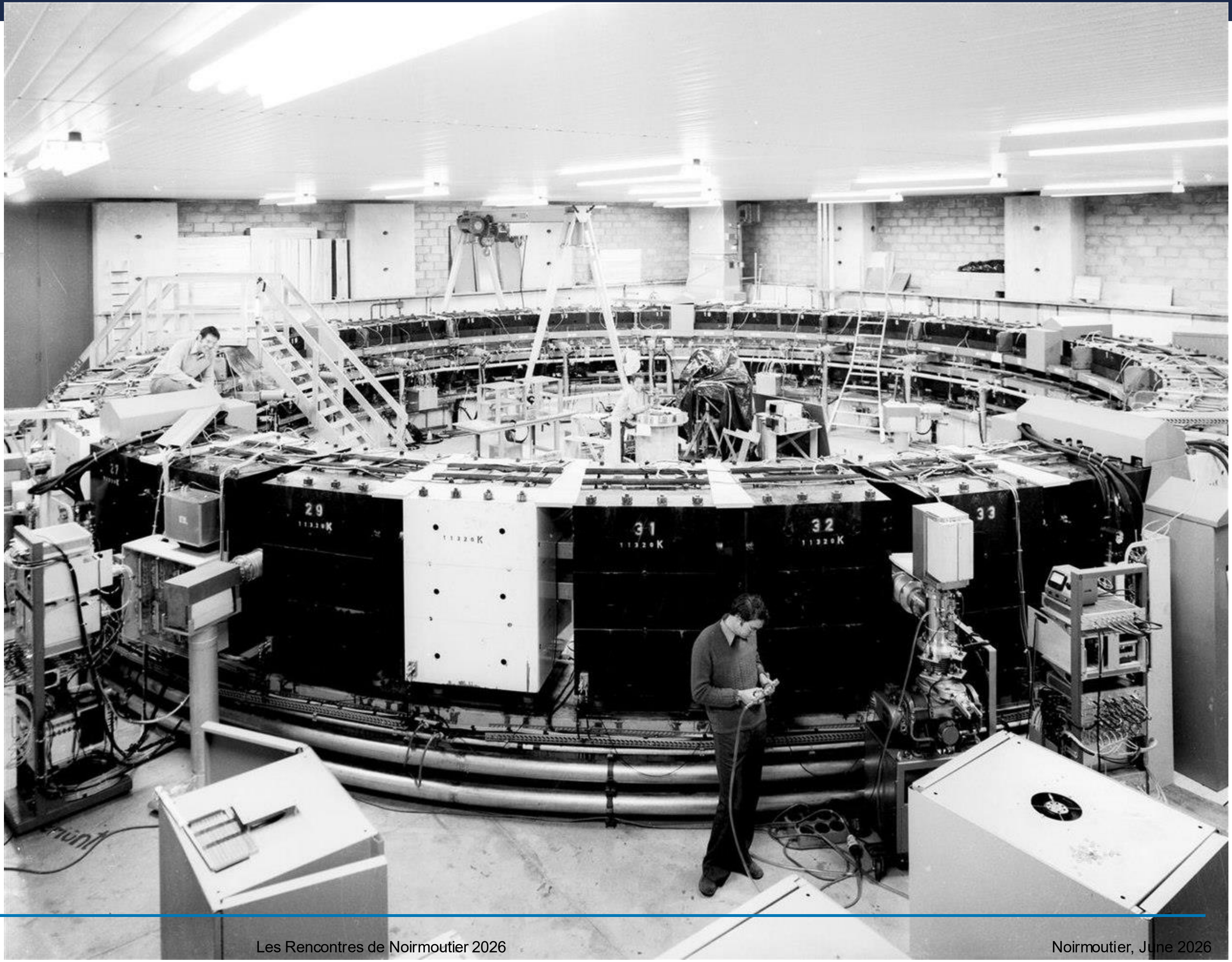
T. Aoyama et al., "The anomalous magnetic moment of the muon in the Standard Model," *Phys. Rept.* 1143 (2025) 1–158, arXiv:2505.21476

Number of decay positrons



CERN
1960

Confirmation of QED
Precision 1%



BNL E821
1990

Precision 1 ppm
Is there a problem with the SM?

Faculty of Physics
University of Rijeka

INFN
Istituto Nazionale
di Fisica Nucleare

E989
MUON g-2 experiment

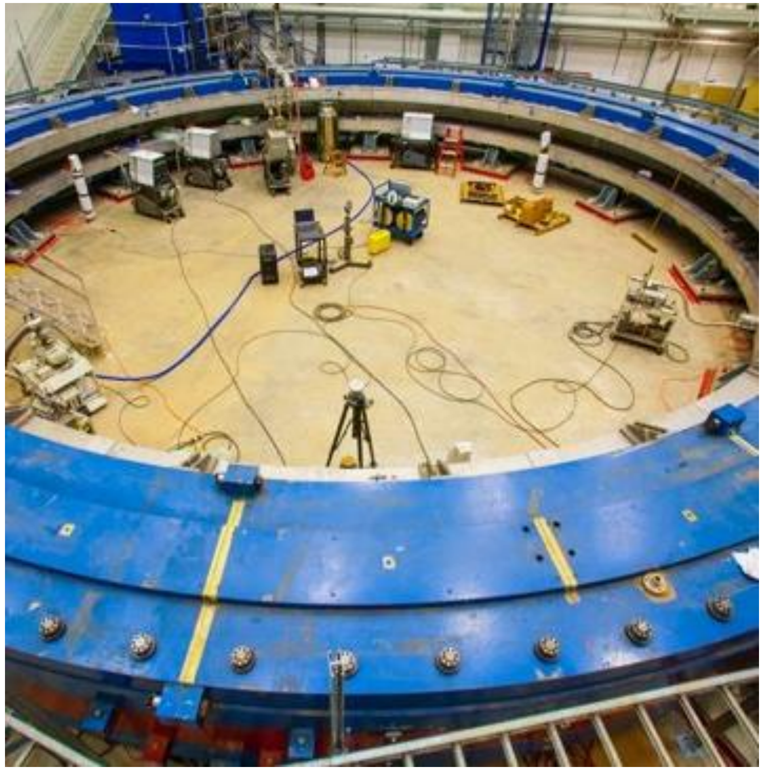
Arrival


EMMERT
EMMERT

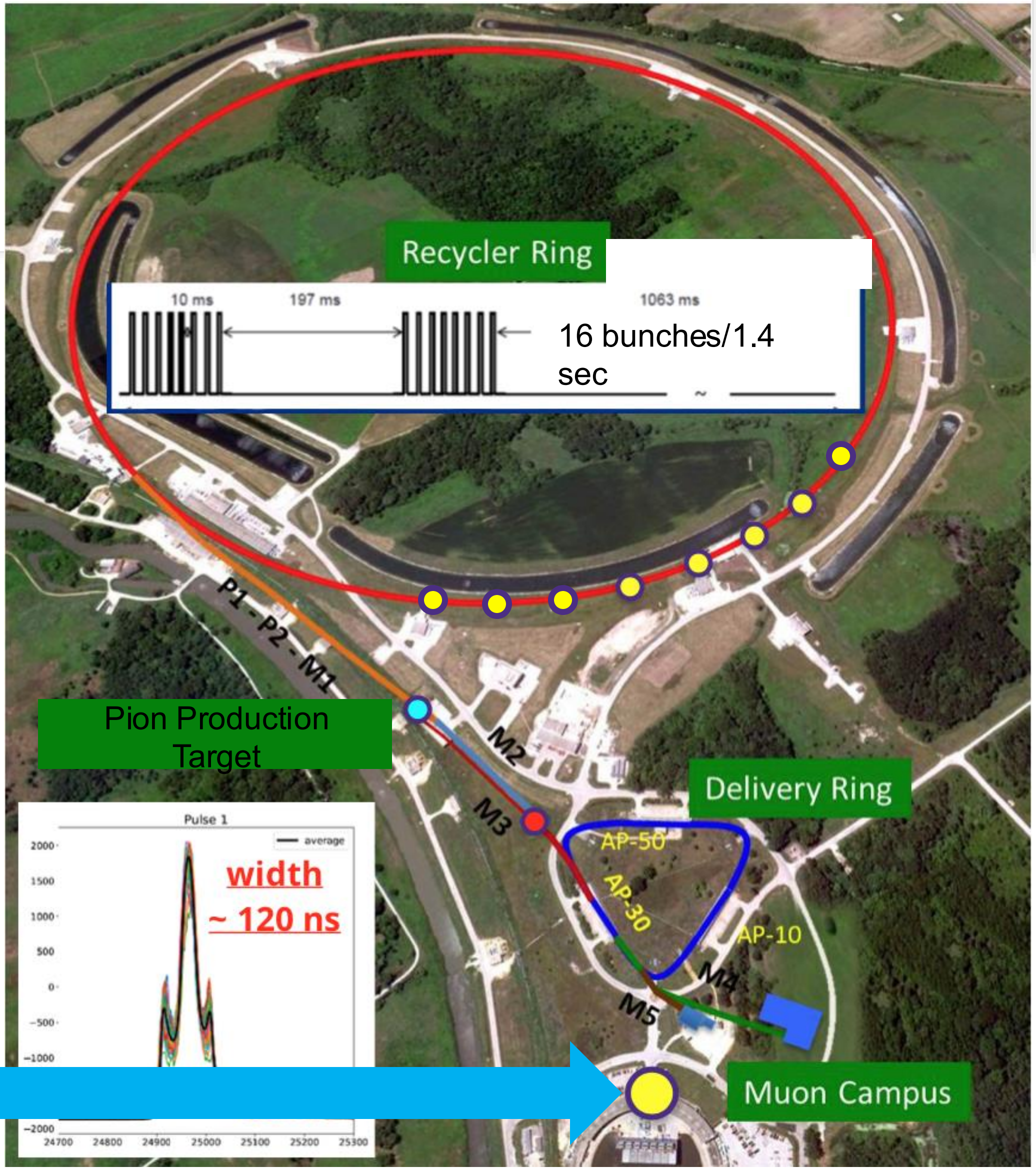

53
294
94
90
94
355
290
Butterfield Road
55
Midway Airport
Costco, Bollingbrook
355
294
87th Street
Lemont Road
Lemont Port

Reassembly

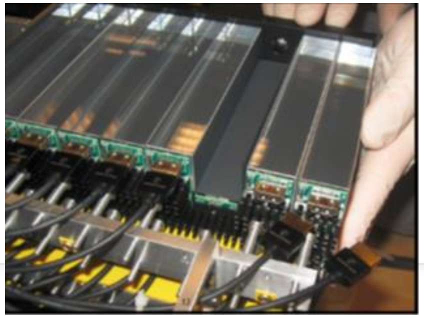
- Superconducting ring travelled in one piece

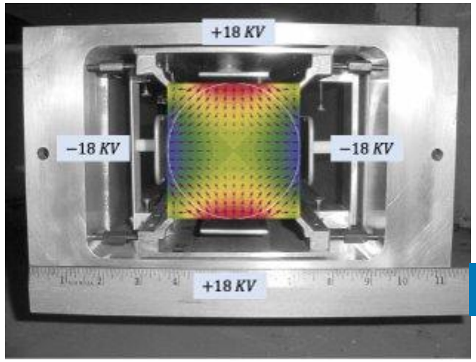


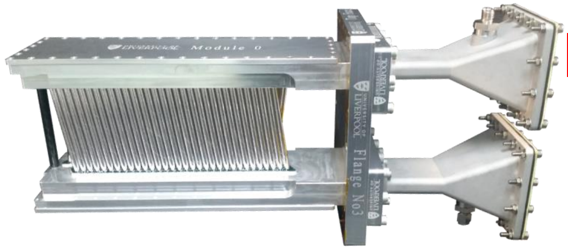
Muon g-2 experiment

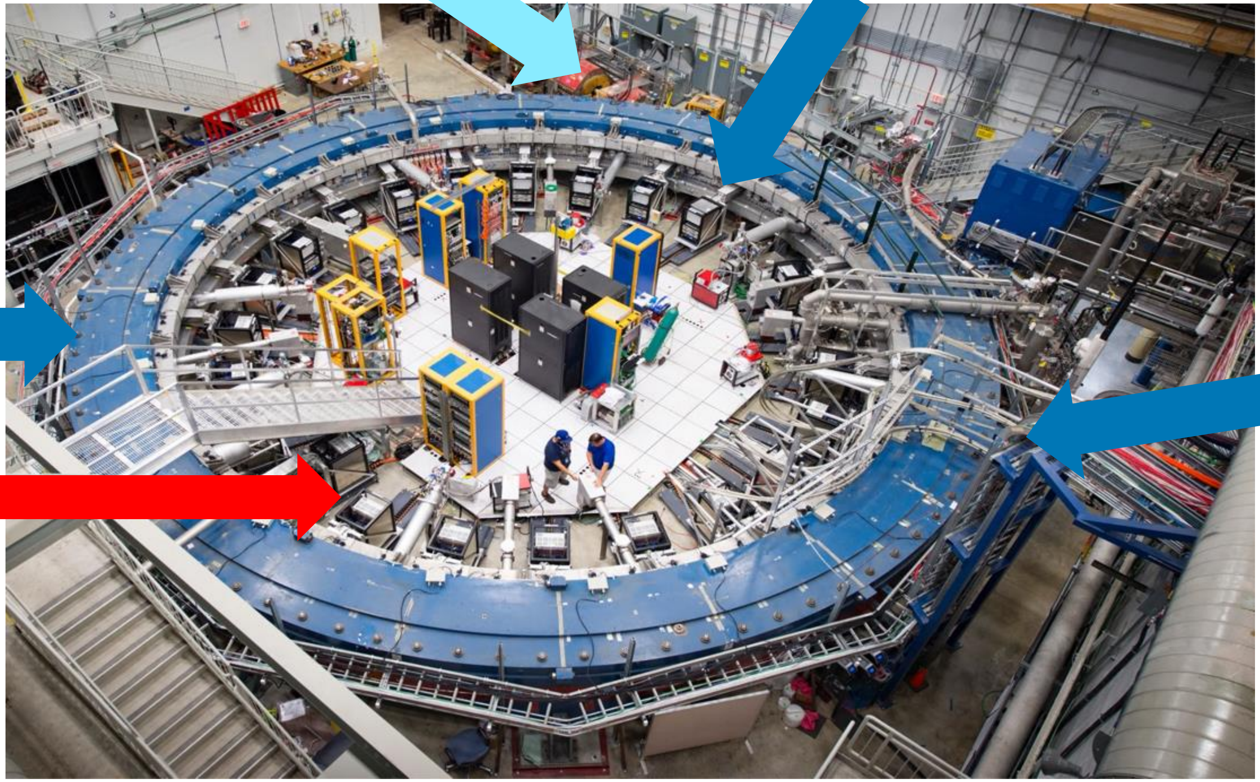


Experiment







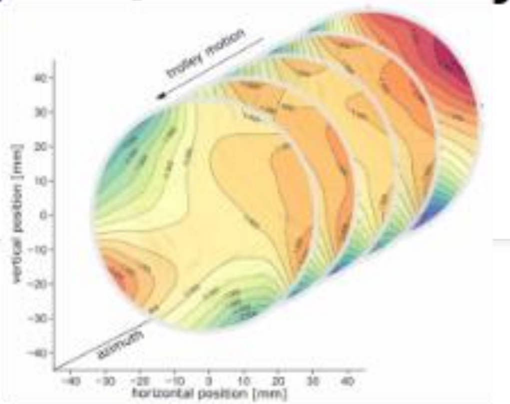


Measuring the Field: NMR Probes

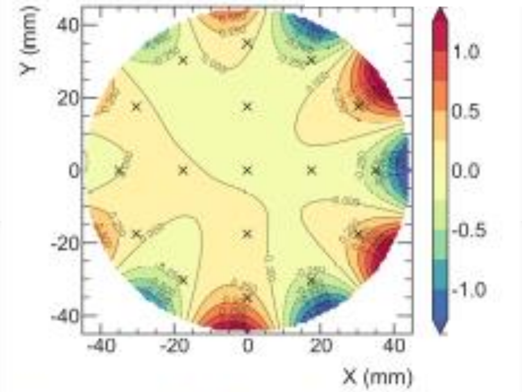
$$\tilde{\omega}'_p(t) = \frac{1}{2\pi}\int_0^{2\pi} \tilde{\omega}'_p(\phi, t)\,\mathrm{d}\phi,$$

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

17 petroleum jelly NMR probes

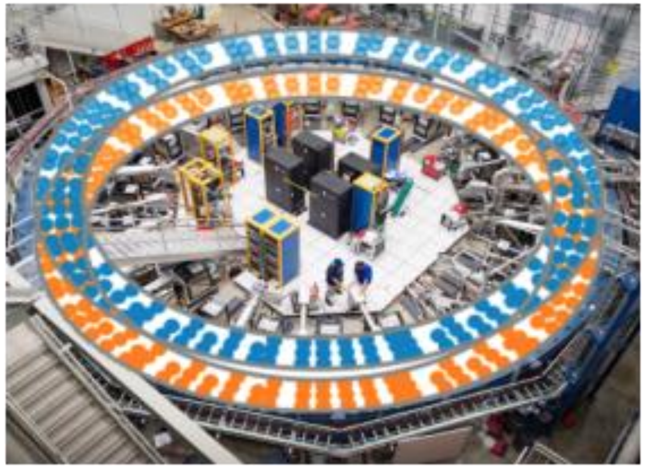


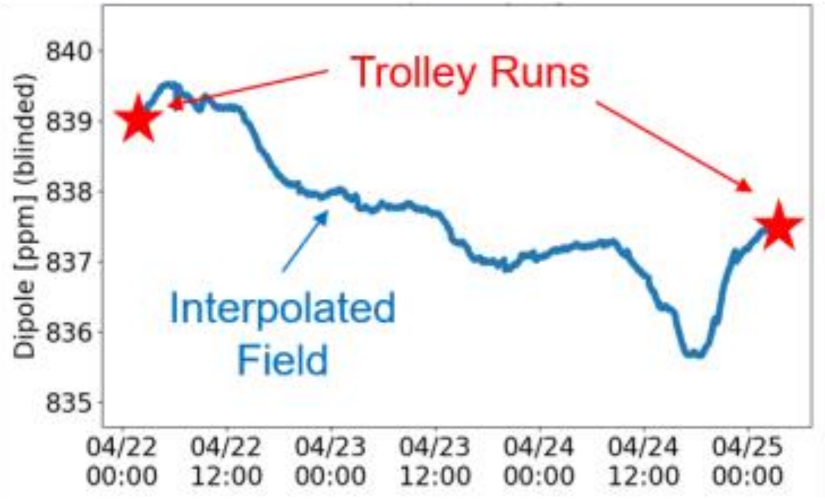
2D field maps (~8000 points)



Azimuthally-Averaged **Variation < 1 ppm**

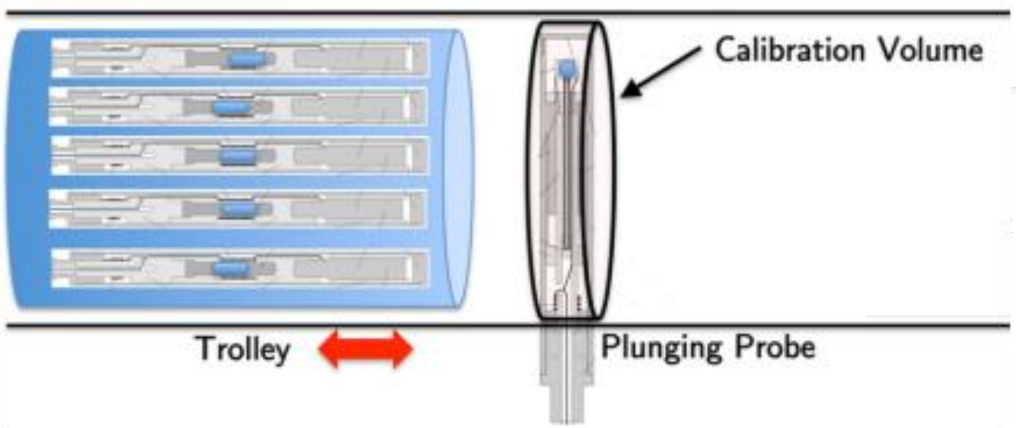
- **378 fixed probes** monitor field during muon storage at 72 locations

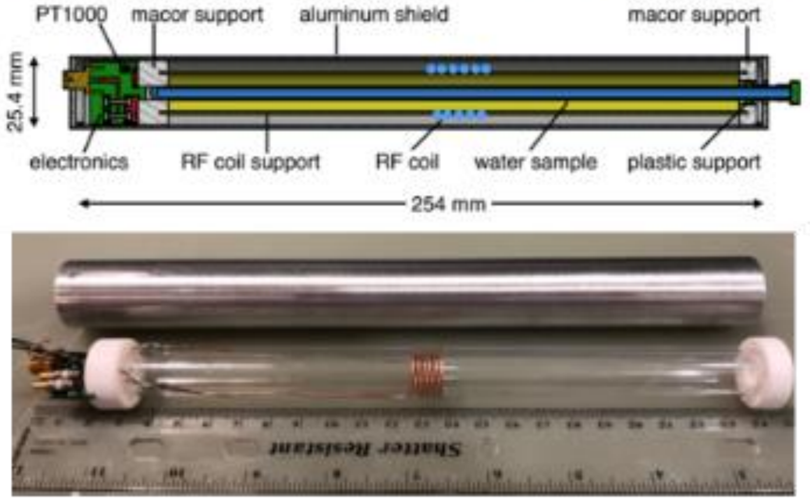




Calibration of Field Measurements

- Cross-calibrate using a cylindrical **plunging H_2O probe** which repeatedly **changes places with trolley (petroleum jelly probes)**





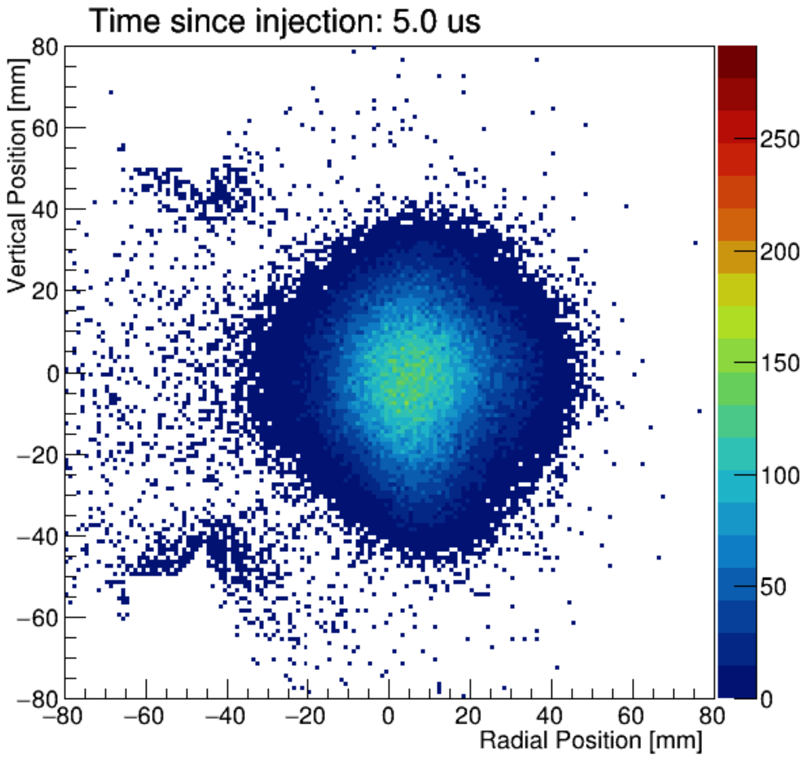
- This probe is **checked against a spherical probe** using an MRI magnet at ANL
- Both also cross-checked against a **^{3}He probe** (different systematics)

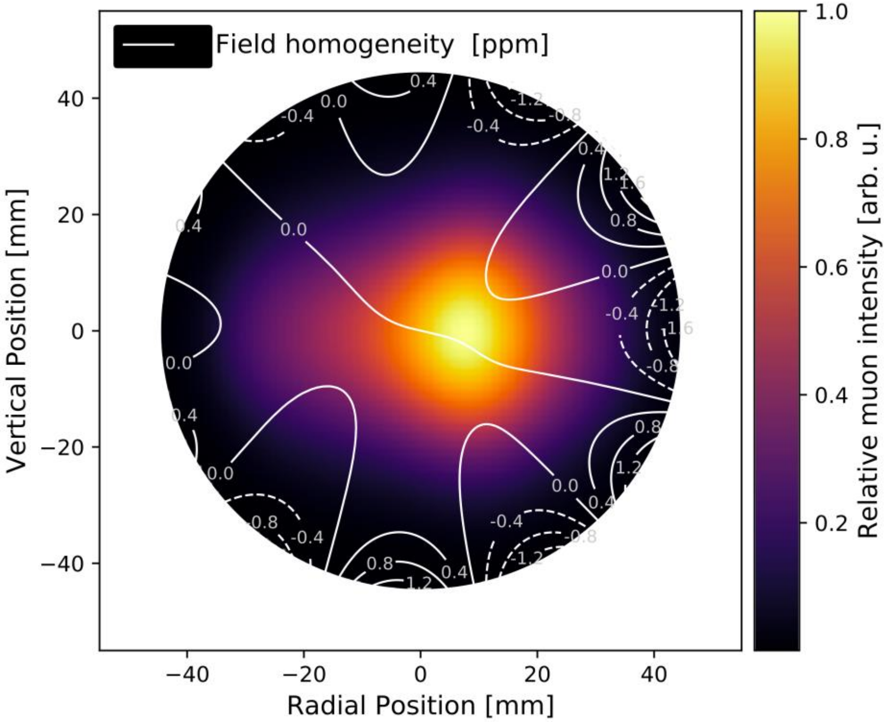
H_2O Probe

^{3}He Probe

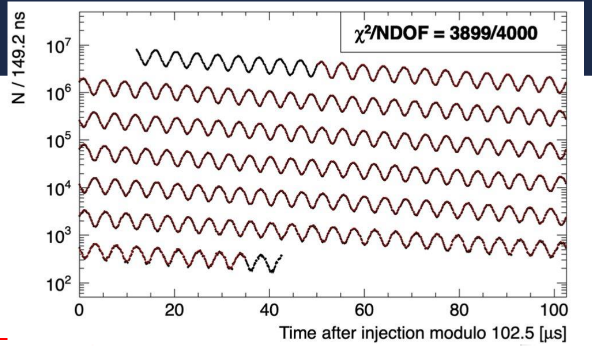
Beam (from trackers) and field

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





Life is complicated



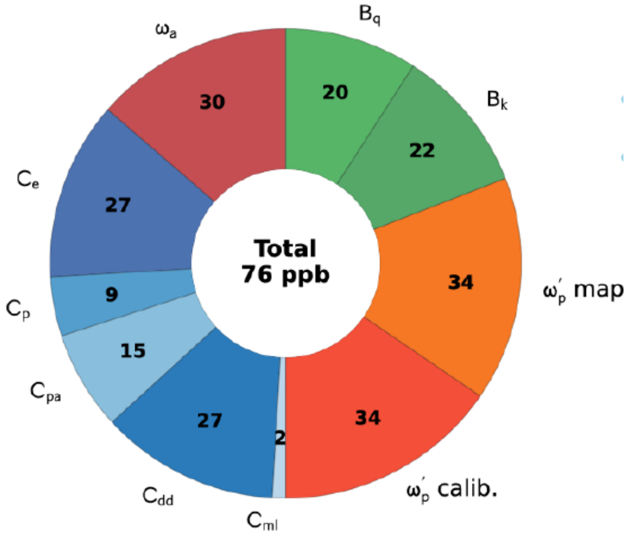
E-field & Up/Down motion: Spin precesses slower than in basic equation

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

$$\frac{\omega_a}{\omega_p} = \frac{\omega_a^m}{\omega_p^m} \frac{1 + C_e + C_p + C_{pa} + C_{dd} + C_{ml}}{1 + B_k + B_q}$$

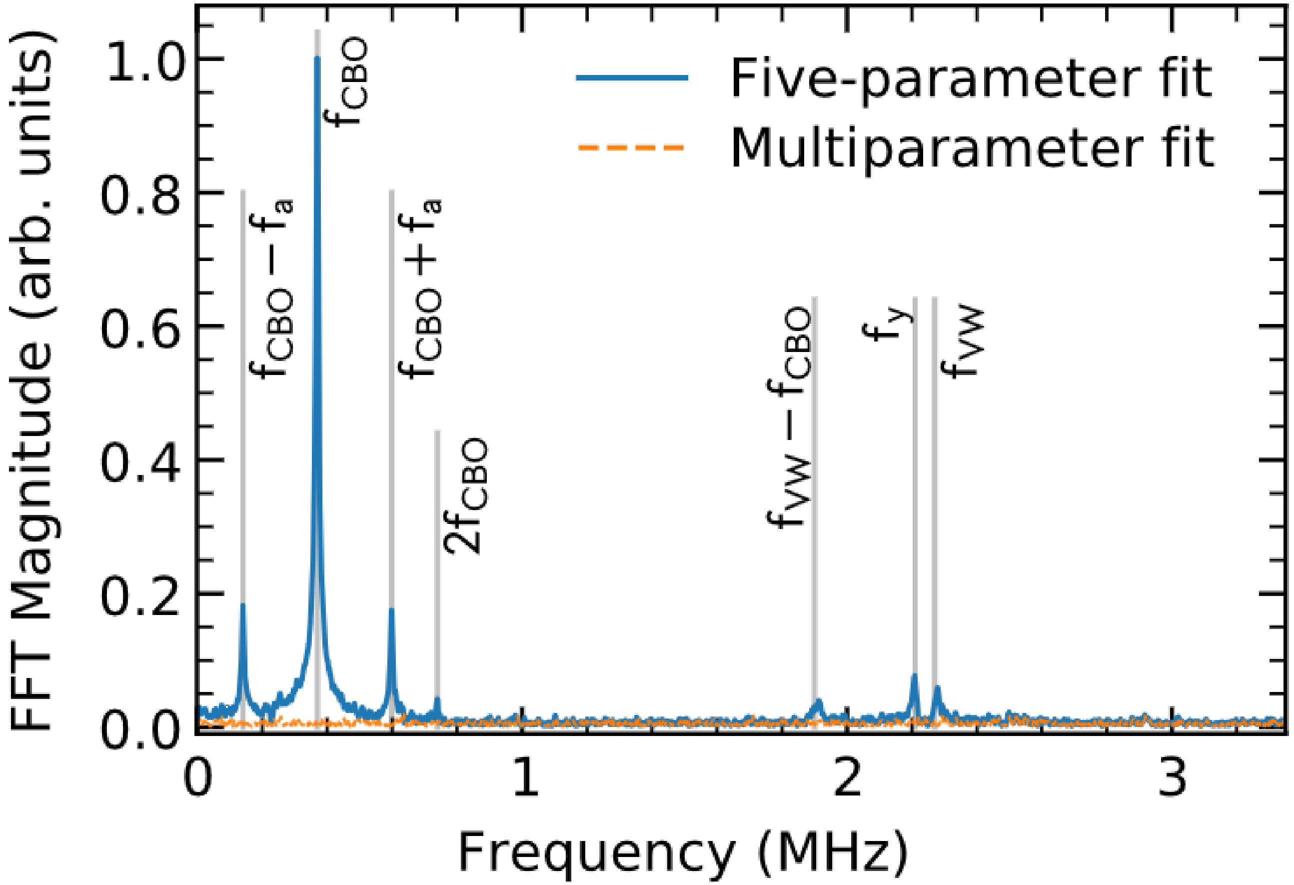
Measured Values

Transient Magnetic Fields: Quad Vibrations, Kicker Eddy Current,

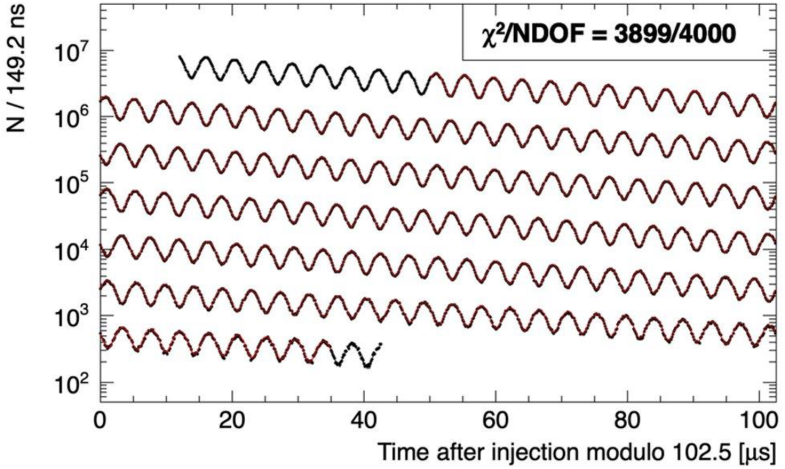


Analysis

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



Group	Method	Run-2 R	Run-2 σ_R	Run-3a R	Run-3a σ_R	Run-3b R	Run-3b 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



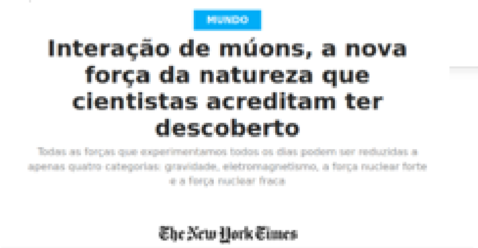
Blind analysis

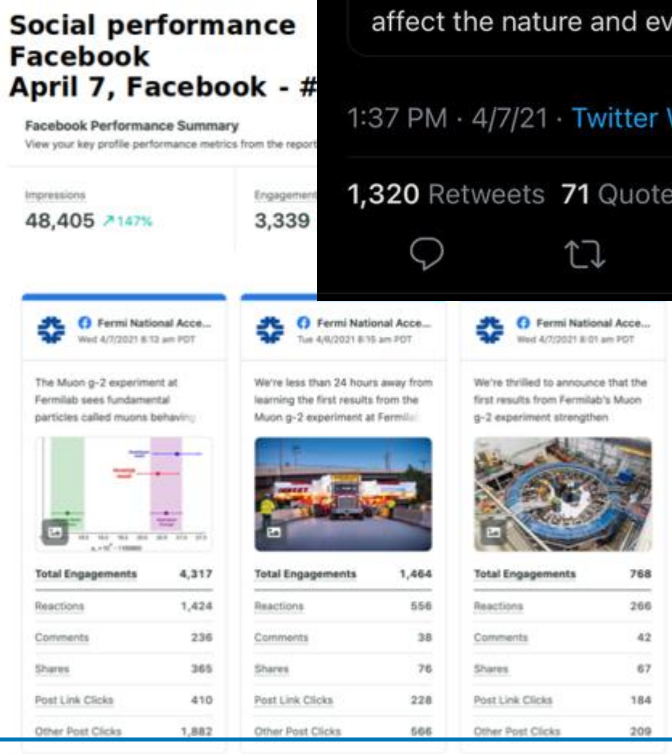
Unblinding


McCoy Wynne

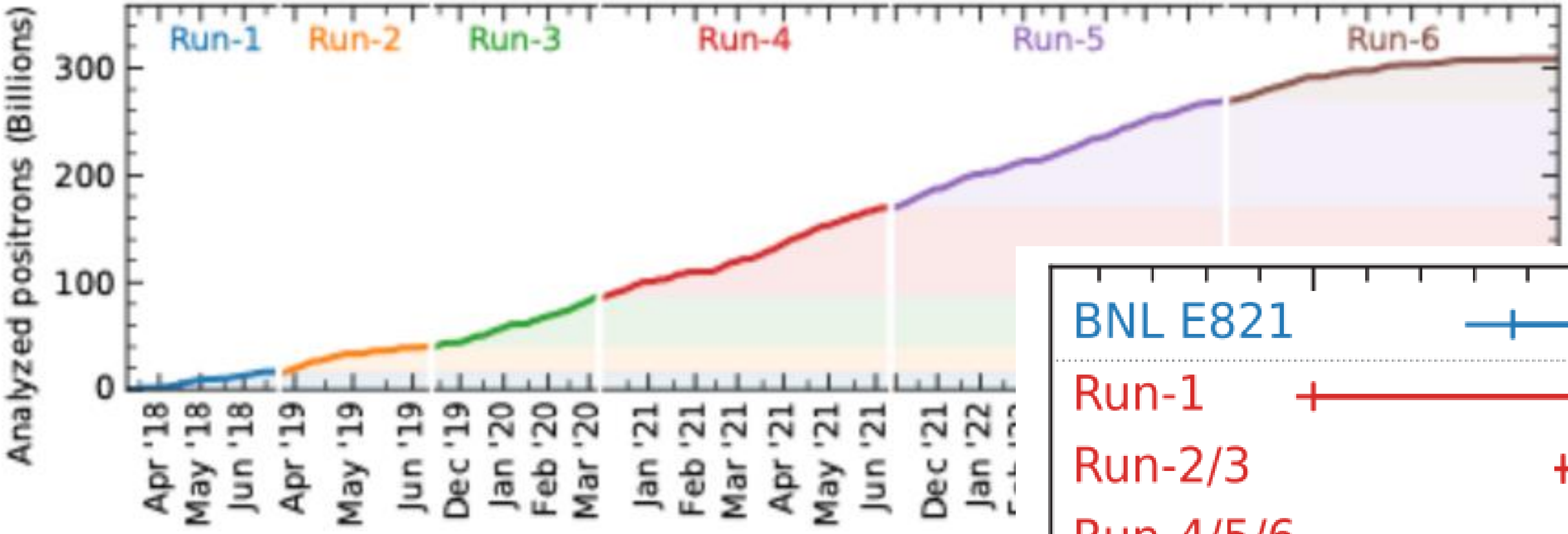

Emil Frlez
Adrian Weisskopf
Soohyung Lee
Giovanni Maria Piac...
Eremey Valetov
Seongtae Park
Erik Swanson
T
Dikai Li
David Sim
Kyun Woo Chris Ho...
Kevin Pitts
F
Vladimir Baranov

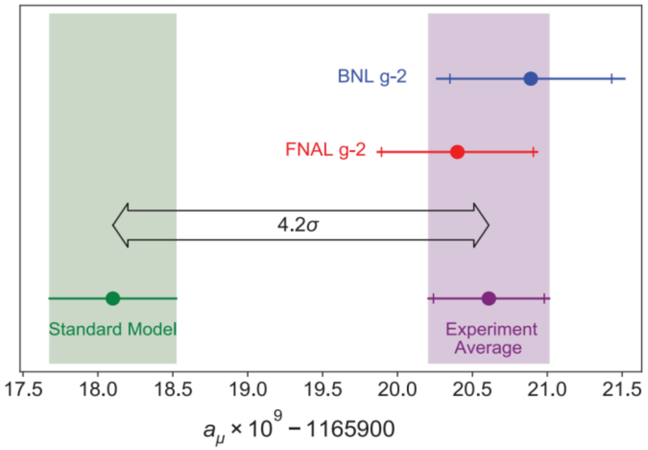
2021 – first result

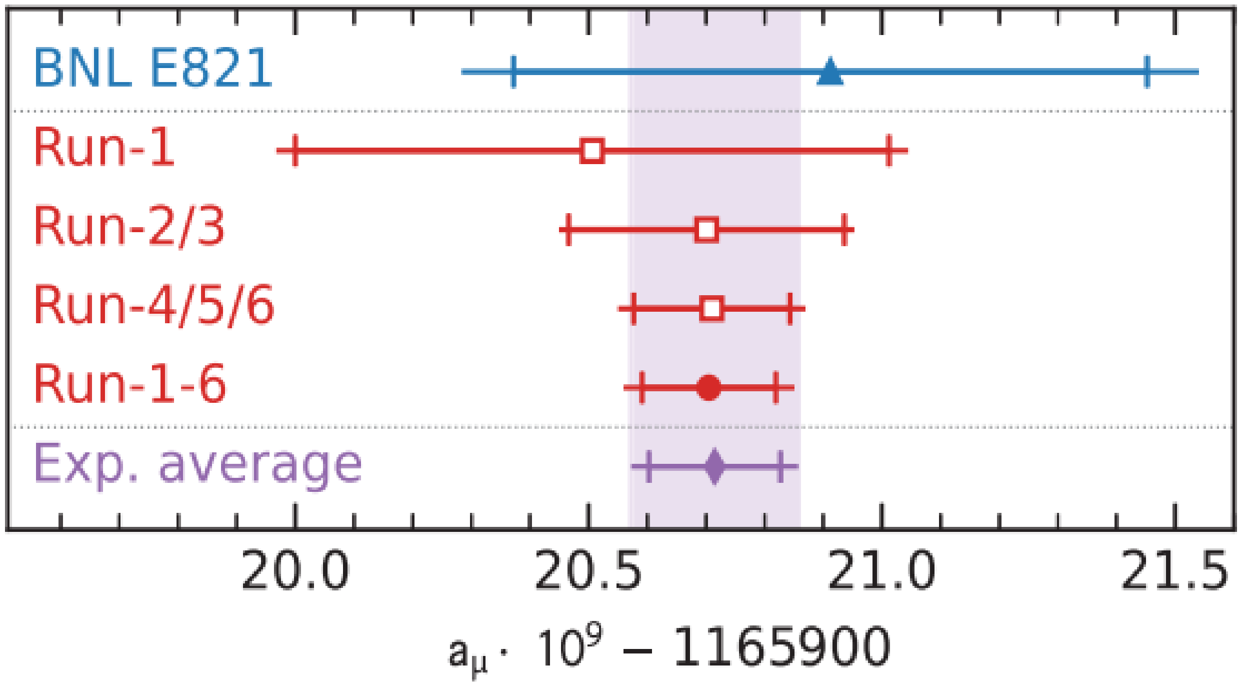




Final Result - Run 1-6







- 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	
		low-energy threshold	20
Pileup	80	Low-energy samples recorded	
		calorimeter segmentation	40
Lost muons	90	Better collimation in ring	20
CBO	70	Higher n value (frequency)	
		Better match of beamline to ring	< 30
E and pitch	50	Improved tracker	
		Precise storage ring simulations	30
Total	180	Quadrature sum	70

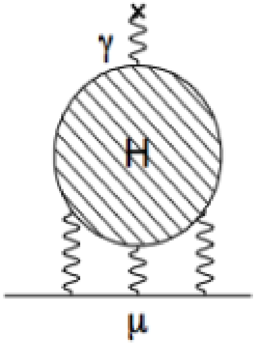
Component	Uncertainty (ppb)
Statistical	98
Systematic	78
External parameters	~22
Total (quadrature)	**127**

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

Comparison with theory

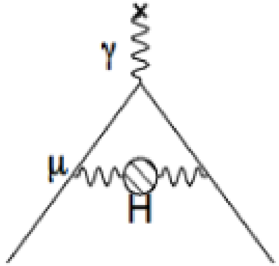
- Lattice QCD
- CMD – 3, data driven approach

Hadronic Light-by-Light

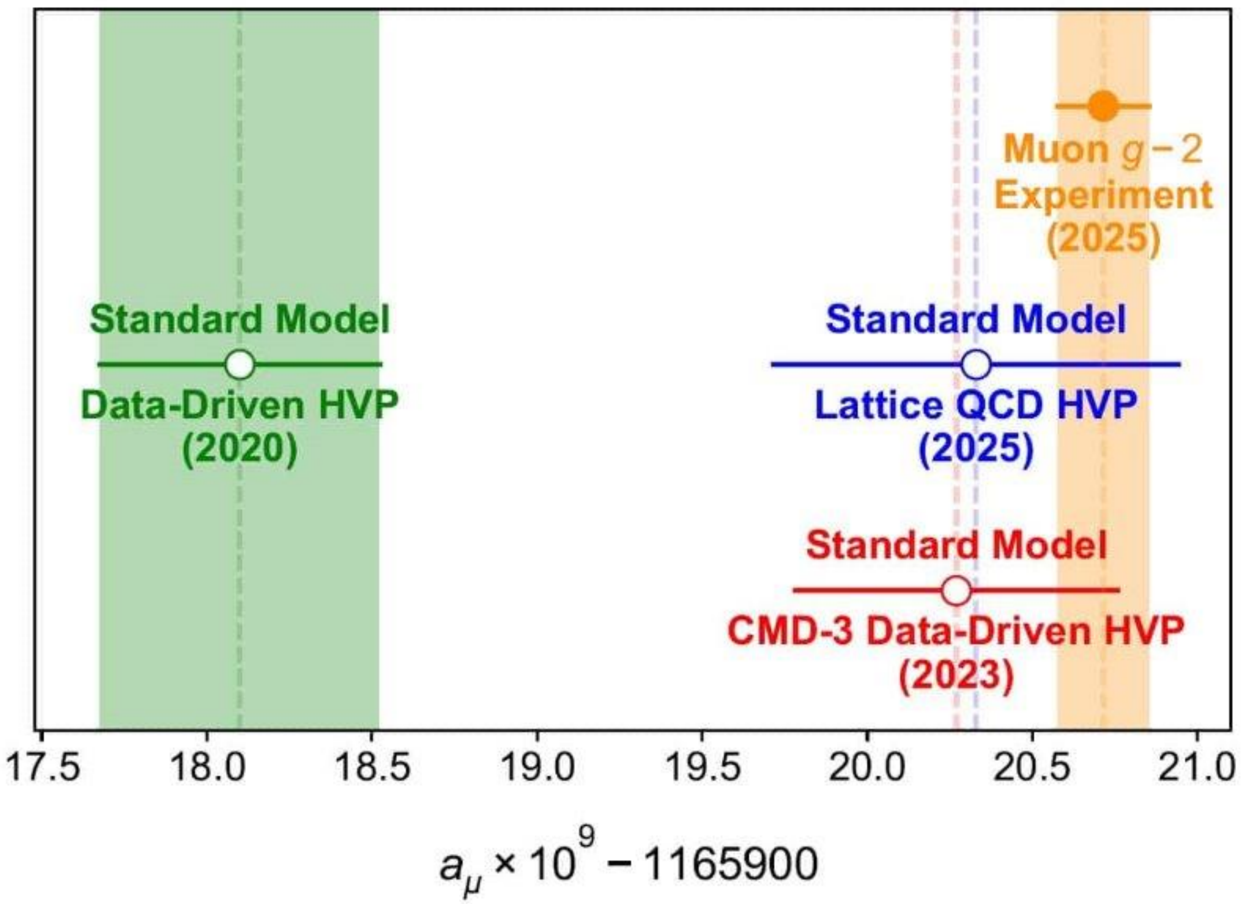


$+0.00000000092$

Hadronic Vacuum Polarization



$+0.00000006845$



Conclusion

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

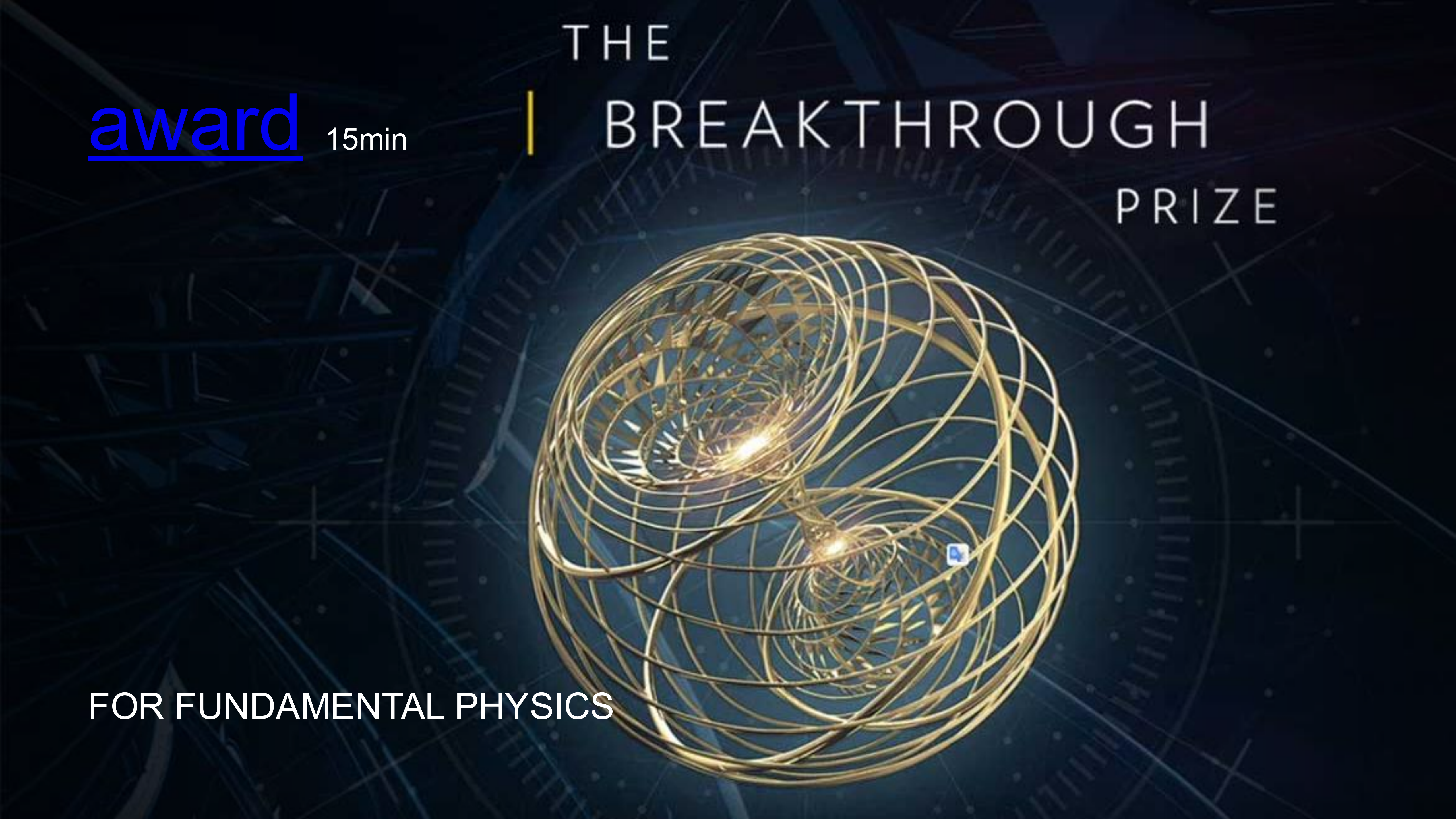
PHYSICAL REVIEW LETTERS **135,** 101802 (2025)

Editors' Suggestion **Featured in Physics**

Measurement of the Positive Muon Anomalous Magnetic Moment to 127 ppb

The end?

[award](#) 15min



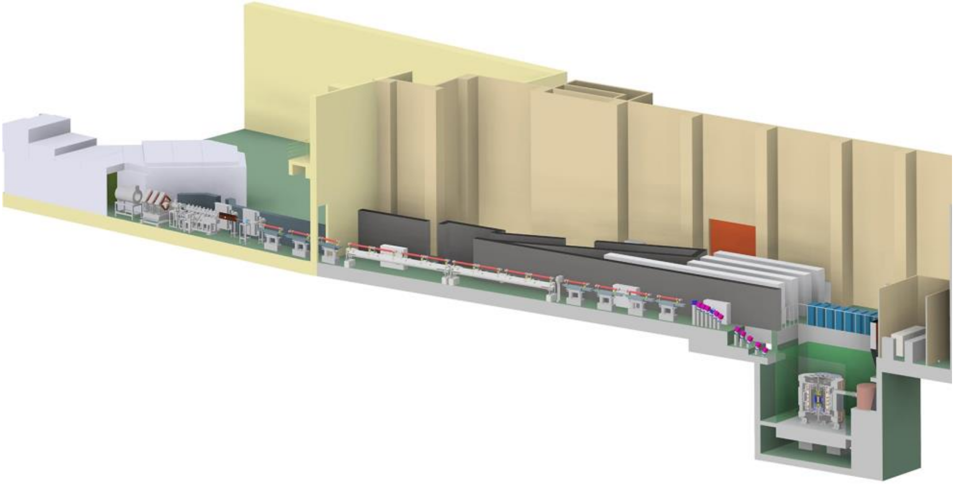
FOR FUNDAMENTAL PHYSICS

No!

J-PARC

Low energy muons

No electric field



MUonE

Space-like measurement of HVP