Precision Measurement of the Muon Anomalous Magnetic Moment: Status, Challenges, and Implications

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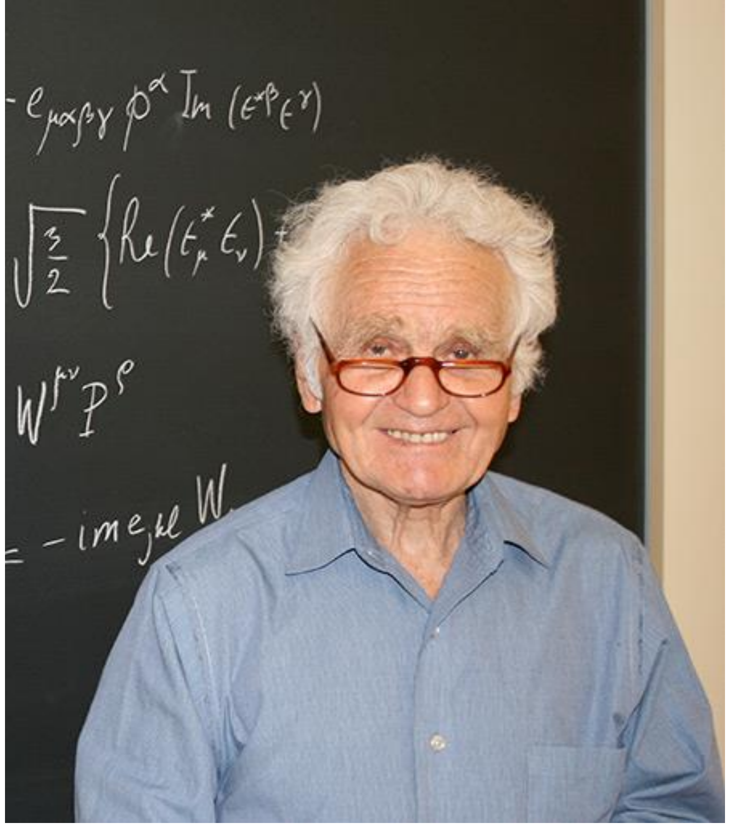
Huizhou, China

Yang Cheng-zhong Forum
April 3, 2026

- Muon g-2: A Window into the Quantum Vacuum
- Stern/Gerlach, CERN → BNL → FNAL
- The four miracles that make the modern muon g-2 experiment possible
  - Production of longitudinally polarized muons (parity violating pion decays)
  - Parity violating muon decays probes the muon spin direction by detecting the electron energy
  - The g-2 precession is independent of the muon momentum
  - The “magic” muon momentum: 3.09 GeV/c, g-2 freq. independent of electric focusing field
- Status of the experimental and theoretical results; future options

Yuri F. Orlov (1924-2020)



- Recipient of the APS Wilson Prize 2020 for his invaluable and numerous contributions to muon g-2 experiment.
- First complete analysis of storage-ring EDM systematic errors in 1996 and with a contribution to AGS-2000 workshop. He set us on the right path.
- Non-linear analysis of beam and spin dynamics
  - Spin coherence time (SCT) estimation including three independent parameters (hor., vert., and longitudinal oscillations)
  - In electric rings with RF set the correct analysis of conserved parameters-verified by benchmarked simulations

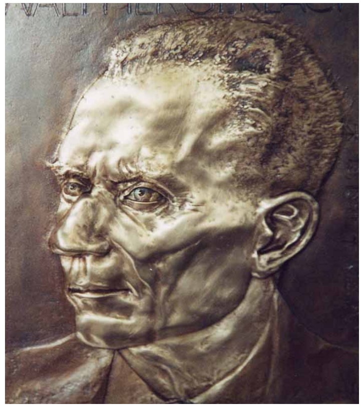
Cornell University

- Geometrical phases, establishing superiority over neutron EDM case due to special geometry
- Wien-filter with partially frozen spin method
- Resonance EDM method for the deuteron case
- Comprehensive study of gravitational effects

Space quantization (spin)

Quantization of space by Walter Gerlach and Otto Stern

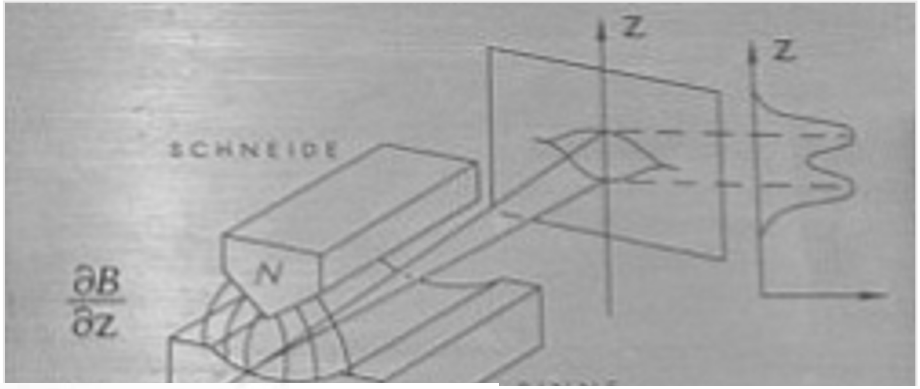
Z. Phys. 8, 110 (1922)

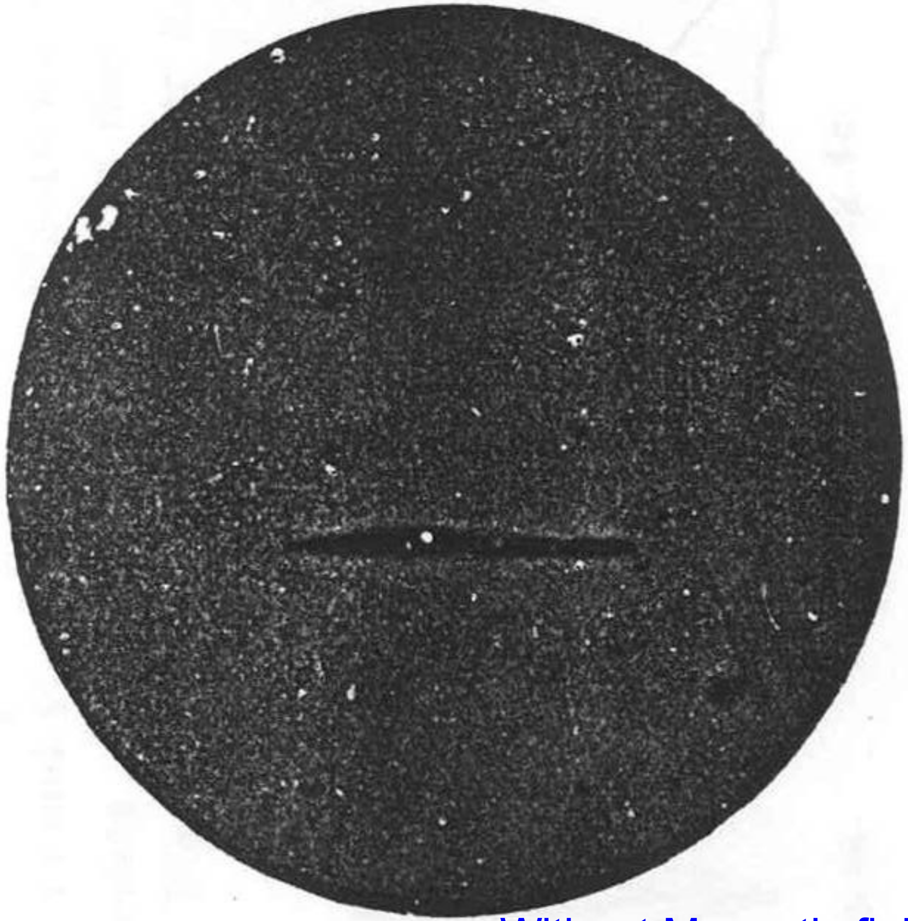


- They guided a beam of silver atoms through an inhomogeneous magnetic field.

- Surprise: the beam split in two distinct lines (non-continuous distribution)

Fig. 20 Plaque at the entrance of the former *Physikalisches Institut* of the University of Frankfurt, Robert-Mayer Str. 2–4. Photo H. Schmidt-Böcking, 2002





Without Magnetic field

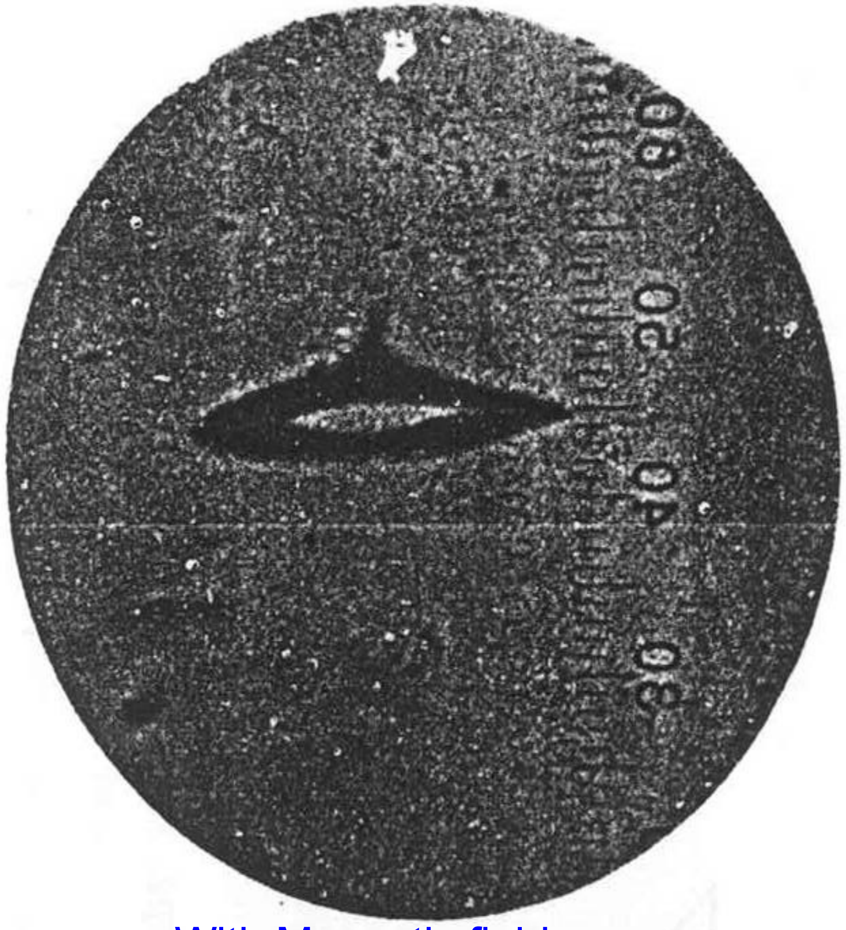


Fig. 3.

With Magnetic field

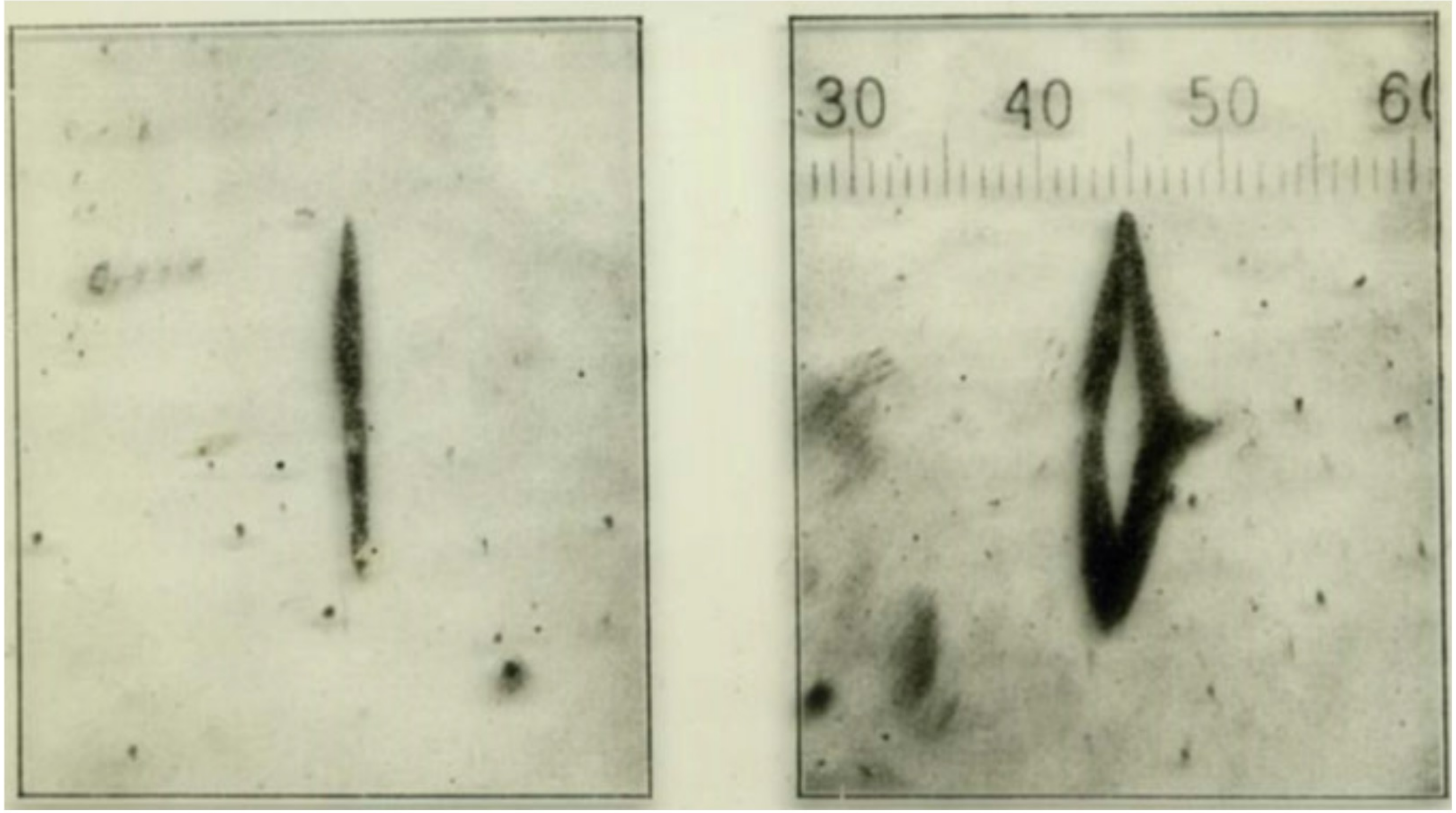
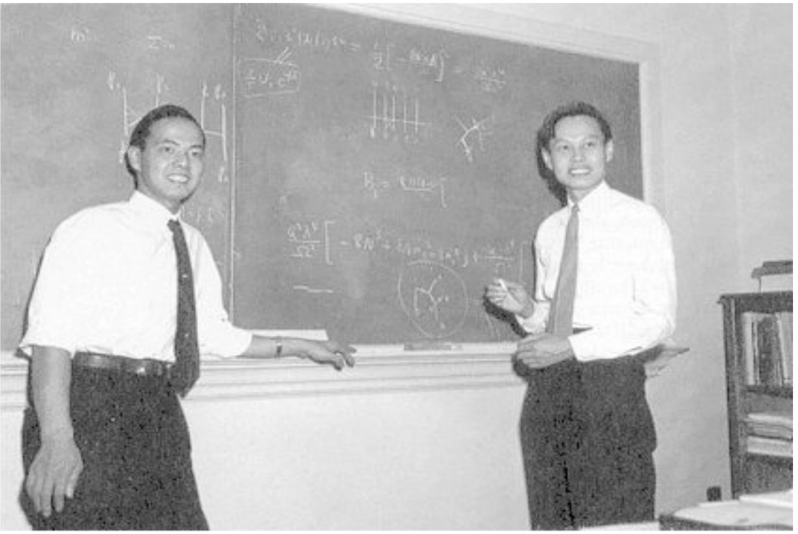


Fig. 7 Silver sulfide (Ag_2S) deposits obtained in the SGE. The microphotographs are from Otto Stern's personal collection, published images were included in (Gerlach and Stern 1922b). Left side: Ag beam deposit obtained in the absence of the magnetic field (deposit length about 1.1 mm, width about 0.06 to 0.1 mm). Right: Beam deposit with the magnetic field switched on; the deposit is split into two components broadened due to the beam velocity distribution. The asymmetry of the magnetic field strength between the two magnetic pole pieces is reflected by the shape of the deposit as atoms passing near the tip of the *S* pole are more strongly deflected

Symmetries (parity)

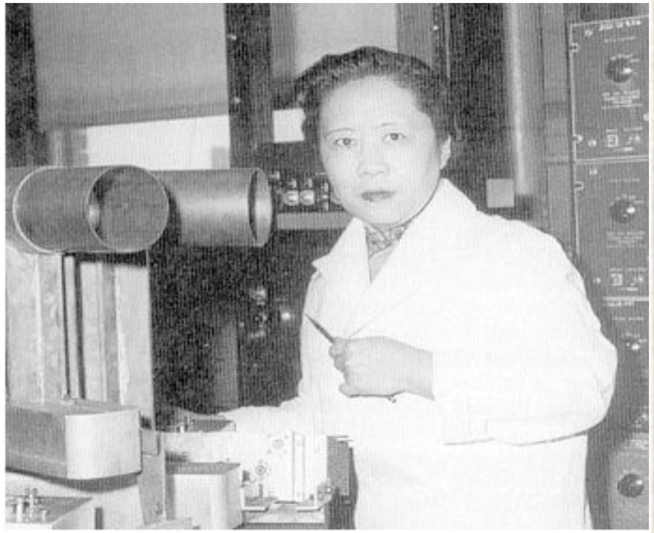
Parity violation in weak interactions



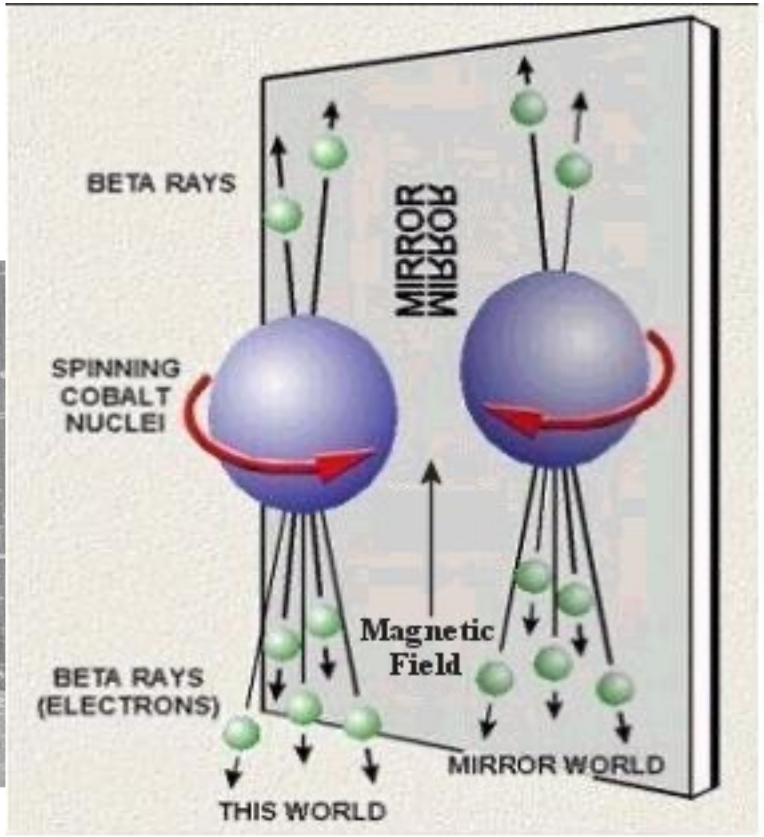
T. D. Lee　　　　C. N. Yang

The θ-τ problem resolved: seemingly, two particles with same mass and lifetime decayed to states with opposite parity

Weak interactions don't conserve parity! θ-τ → same particle K^+ positive kaon.



C. S. Wu



The ellipsoid on the left represents a large number of cobalt-60 nuclei, all with their spins in the same direction, and all emitting beta rays. (In reality, any one cobalt nucleus emits only on beta ray - transforming itself thereby into a nickel nucleus). On the right this process is seen in a mirror. The direction of spin is reversed, while the direction in which most beta rays are emitted remains unchanged. The mirror world is thus distinguishable from the real world.

The parity transformation of (x,y,z) to (-x,-y,-z) is completed by turning the mirror image upside down. The spins of the cobalt nuclei are thus returned to their original direction, but most beta rays are now emitted upward - contrary to experimental fact. The parity-transformed world is not identical with the real world; parity is not conserved.

Note that the asymmetry would be perfect with the beta rays emitting in one direction only (and none in the other direction), if all the cobalt nuclei are aligned perfectly with the magnetic field. In the actual experiment, the requirements of high vacuum and low temperature (~ 1/100 °K) is very difficult to achieve.

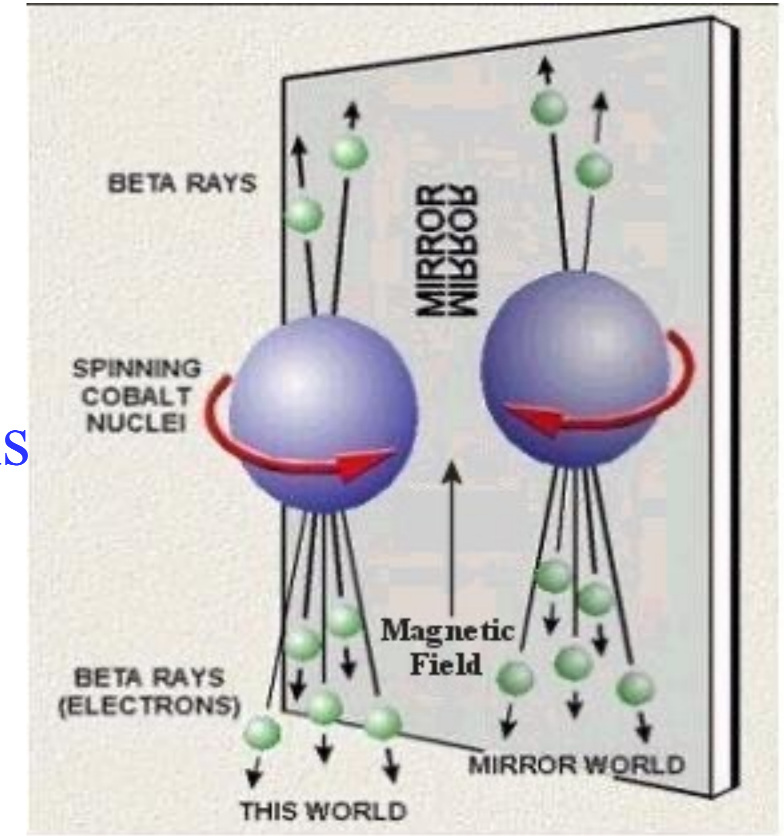
Parity Violation in Weak Interaction

Parity violation in weak interactions

$$^{60}_{27}\mathrm{Co} \rightarrow {}^{60}_{28}\mathrm{Ni} + e^- + \bar{\nu}_e$$

- Electrons and neutrinos come out left-handed
- Positrons and antineutrinos right handed

- In beta decay, a neutron transforms into a proton, an electron and an antineutrino.



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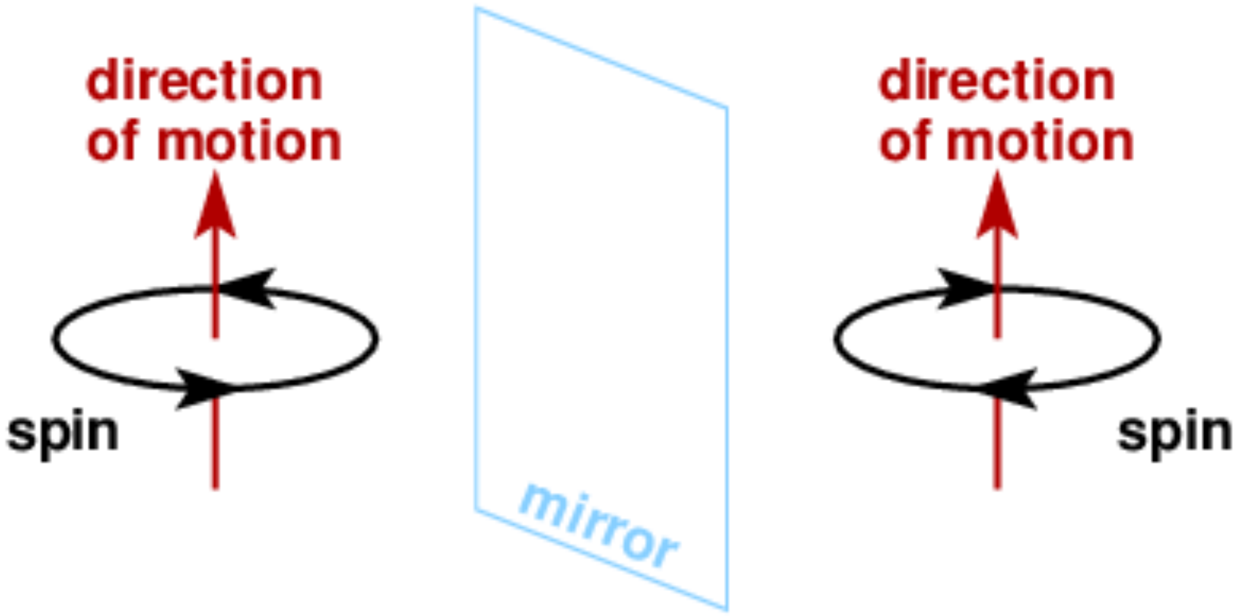


right handed

left handed

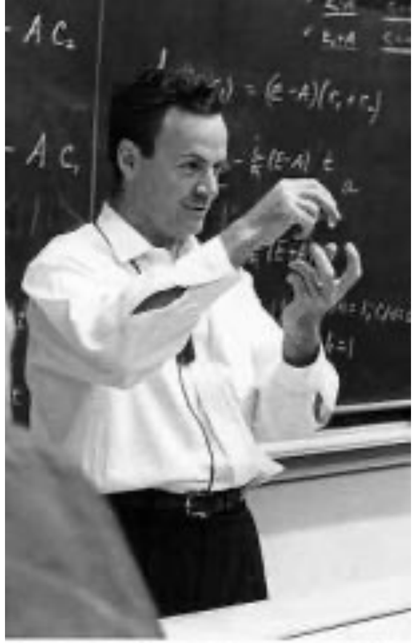
Definition of g-Factor

$$g \equiv \frac{\dfrac{\text{magnetic moment}}{e\hbar/2m}}{\dfrac{\text{angular momentum}}{\hbar}}$$

g-2 measures the difference between the charge and mass distribution. g-2=0 when they are the same all the time…

From Dirac equation g-2=0 for point-like, spin ½ particles, e.g leptons.

MDM can also tell us about Quantum Field Fluctuations



- A “soup” of virtual particles is coming in and out of existence affecting the MDM interaction of particles with B-fields.
- The interaction is estimated using Feynman diagrams.
- It is expressed with the so-called g-2 factor: $a = (g\text{-}2)/2$, the anomaly.

g-factors:

- Proton (g_p=+5.586) and the neutron (g_n=-3.826) are composite particles.
- The ratio g_p/g_n=-1.46 close to the predicted –3/2 was the first success of the constituent quark model.

- The g_e-2 (of the electron) is non-zero mainly due to quantum field fluctuations involving QED. A "soup" of virtual particles coming in and out of existence…
- The anomalous magnetic moment of leptons can be estimated with high accuracy

Electron Magnetic Dipole Moment

D. Hanneke, S. Fogwell, and G. Gabrielse, PRL **100**, 120801 (2008)

$$\vec{\mu} = -g\left(\frac{e}{2m}\right)\vec{s} \qquad \frac{d\vec{s}}{dt} = \vec{\mu} \times \vec{B}$$

$$g/2 = 1.001\ 159\ 652\ 180\ 73\ (28)\ [0.28\ \text{ppt}]$$

$$\frac{g}{2} = 1 + C_2\left(\frac{\alpha}{\pi}\right) + C_4\left(\frac{\alpha}{\pi}\right)^2 + C_6\left(\frac{\alpha}{\pi}\right)^3 + C_8\left(\frac{\alpha}{\pi}\right)^4 + C_{10}\left(\frac{\alpha}{\pi}\right)^5 + \ldots + a_{\mu\tau} + a_{\text{hadronic}} + a_{\text{weak}}, \quad (4)$$

It's a triumph of QED!

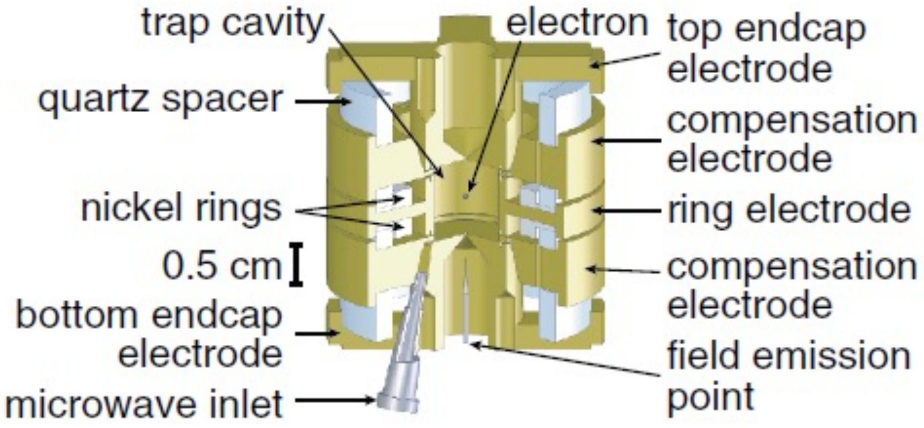


FIG. 2 (color). Cylindrical Penning trap cavity used to confine a single electron and inhibit spontaneous emission.

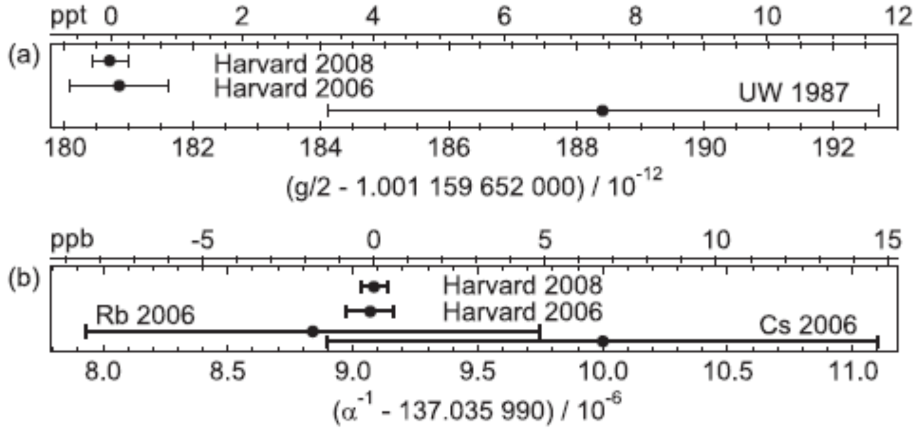
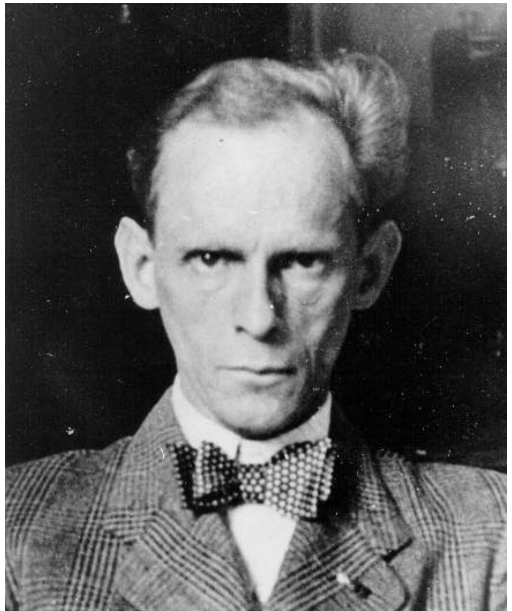


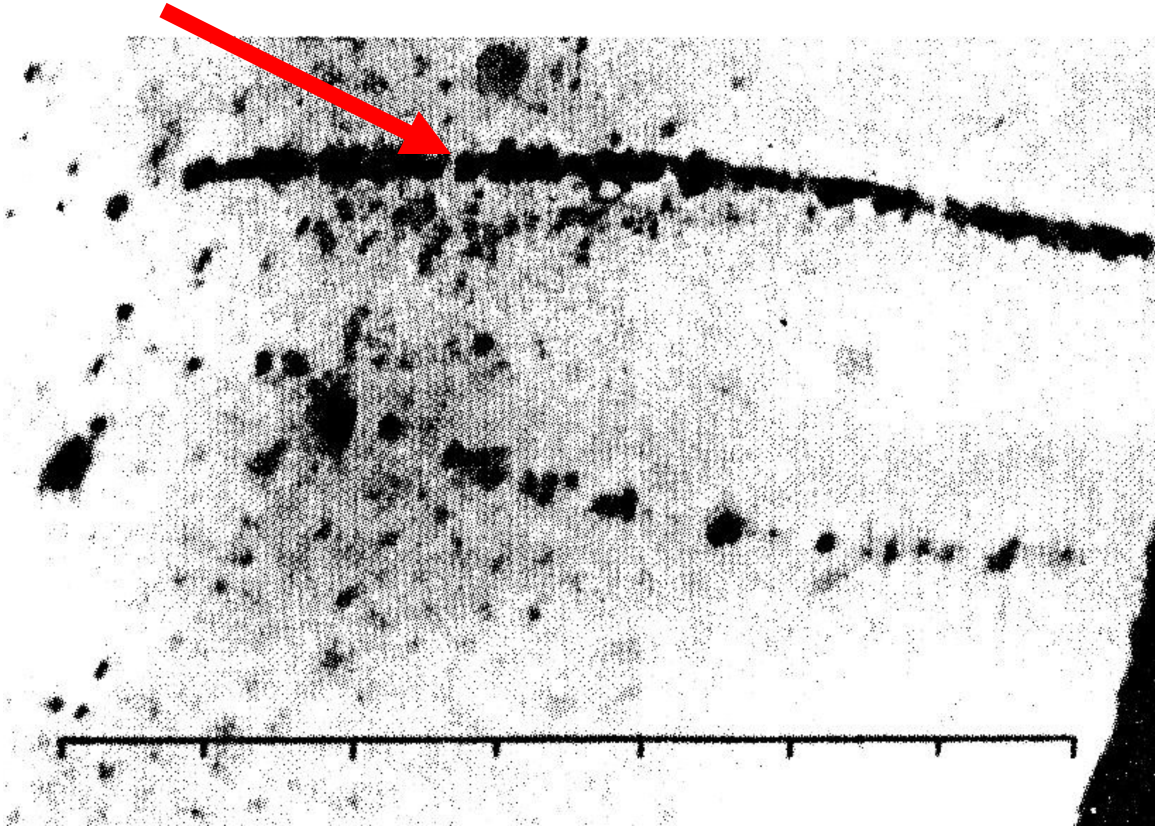
FIG. 1. Most accurate measurements of the electron $g/2$ (a), and most accurate determinations of α (b).

The Muon

Paul Kunze,
Z. Phys. 83, 1 (1933)



“a particle of uncertain nature”



Identified in 1936

Study of cosmic rays by Seth Neddermeyer and Carl Anderson

MAY 15, 1937 PHYSICAL REVIEW VOLUME 51

Note on the Nature of Cosmic-Ray Particles

SETH H. NEDDERMEYER AND CARL D. ANDERSON
California Institute of Technology, Pasadena, California

(Received March 30, 1937)

MEASUREMENTS[1] of the energy loss of particles occurring in the cosmic-ray showers have shown that this loss is proportional massive than protons but more penetrating than electrons obeying the Bethe-Heitler theory, we have taken about 6000 counter-tripped photo-

Confirmed by: Street & Stevenson, Nishina, Tekeuchi & Ichimiya

NOVEMBER 1, 1937 PHYSICAL REVIEW VOLUME 52

LETTERS TO THE EDITOR

Prompt publication of brief reports of important discoveries in physics may be secured by addressing them to this department. Closing dates for this department are, for the first issue of the month, the eighteenth of the preceding month, for the second issue, the third of the month. Because of the late closing dates for the section no proof can be shown to authors. The Board of Editors does not hold itself responsible for the opinions expressed by the correspondents.

Communications should not in general exceed 600 words in length.

New Evidence for the Existence of a Particle of Mass Intermediate Between the Proton and Electron

Anderson and Neddermeyer[1] have shown that, for energies

between those of the proton and electron. If this is true, it should be possible to distinguish clearly such a particle from an electron or proton by observing its track density

J. C. STREET
E. C. STEVENSON

Research Laboratory of Physics,
Harvard University,
Cambridge, Massachusetts,
October 6, 1937.

[1] Anderson and Neddermeyer, Phys. Rev. **50**, 263 (1936).
[2] Street and Stevenson, Phys. Rev. **51**, 1005 (1937).

It took 10 years to conclude that the muon interacted too weakly with matter to be the "Yukawa" particle which was postulated to carry the nuclear force

DECE

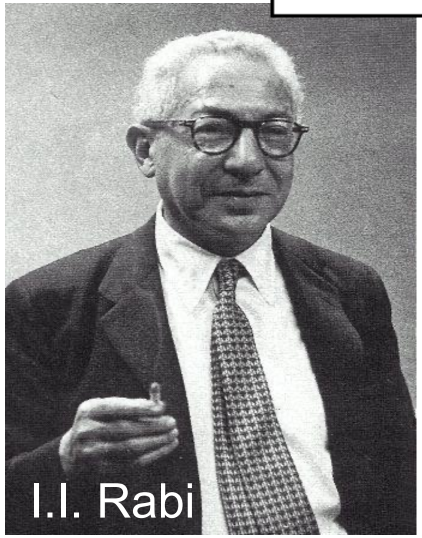
On the Nature of Cosmic-Ray Particles

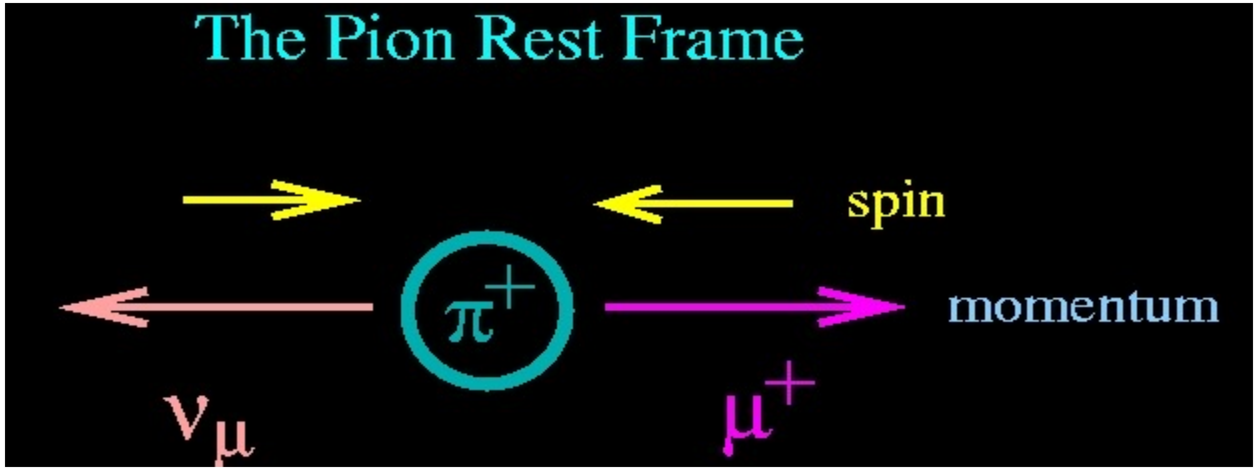
Y. NISHINA, M. TAKEUCHI, AND T. ICHIMIYA
Institute of Physical and Chemical Research, Tokyo

(Received August 28, 1937)

Properties of the Muon

- Lifetime ~2.2 μs, practically forever
- m_μ/m_e = 206.768 277(24)
- produced polarized (first miracle)
  - in-flight decay: both "forward" and "backward" muons are highly polarized





The Standard Model (Our Periodic Table)

Leptons

e	μ	τ
ν_e	ν_μ	ν_τ

Interact weakly through the

Electroweak gauge bosons

γ	Z^0	$W^\pm$

Quarks

u	c	t
d	s	b

Interact strongly through the gluons g

Latest addition: the Higgs boson

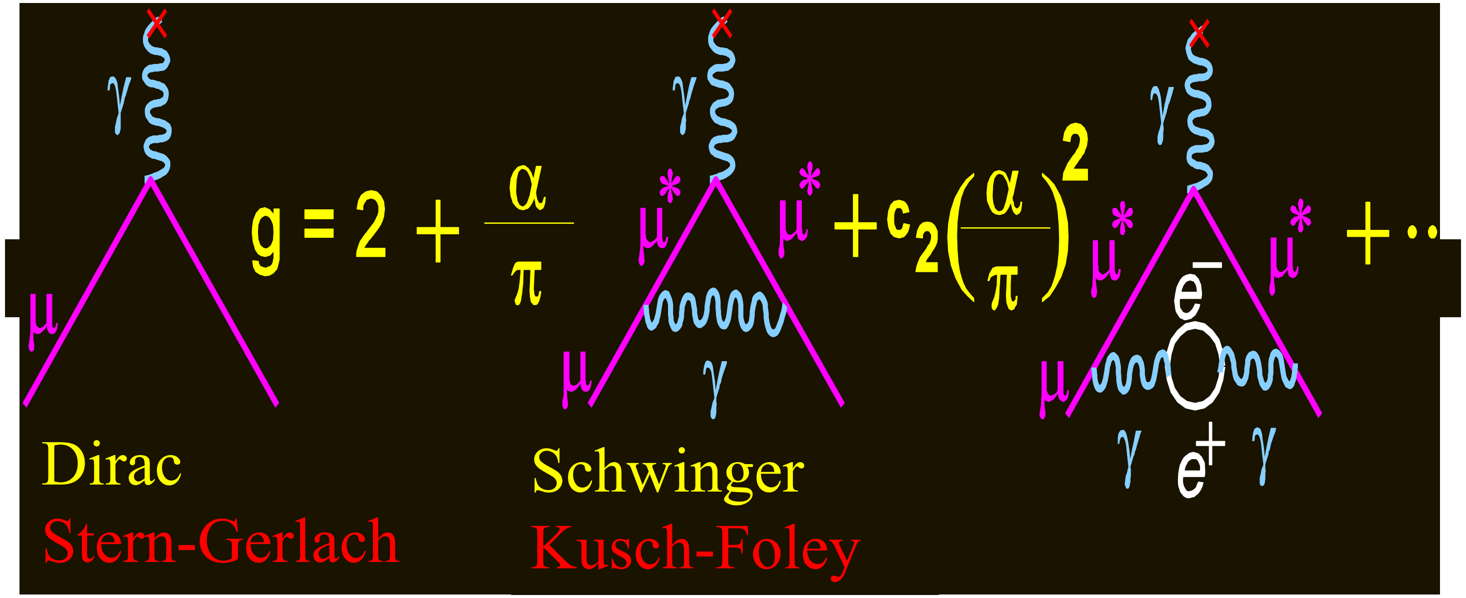
g-factors: Muon acts as an amplifier of Quantum Vacuum

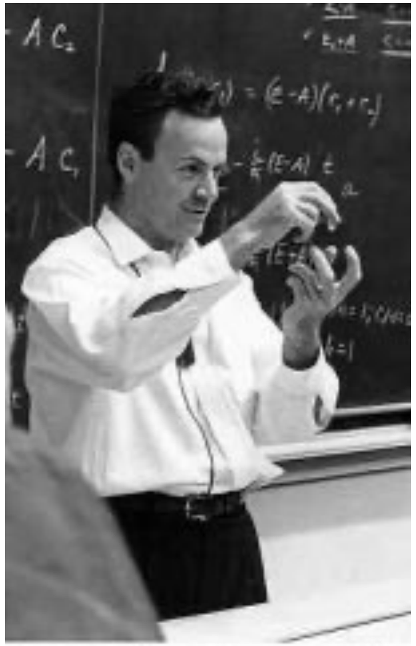
- The g_μ-2 is more sensitive to a class of particles than the g_e-2 by $(m_\mu/m_e)^2$~40,000. A thicker "soup" of virtual particles coming in and out of existence…

- Muons are sensitive to W, Z, and new physics, e.g. SUSY: neutralino

Radiative corrections change g from its Dirac value of 2. We symbolically express these corrections as Feynman diagrams

Lee B. Roberts



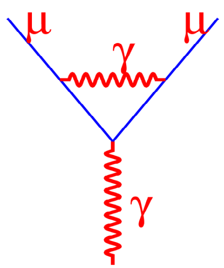


We have a pertubation expansion:

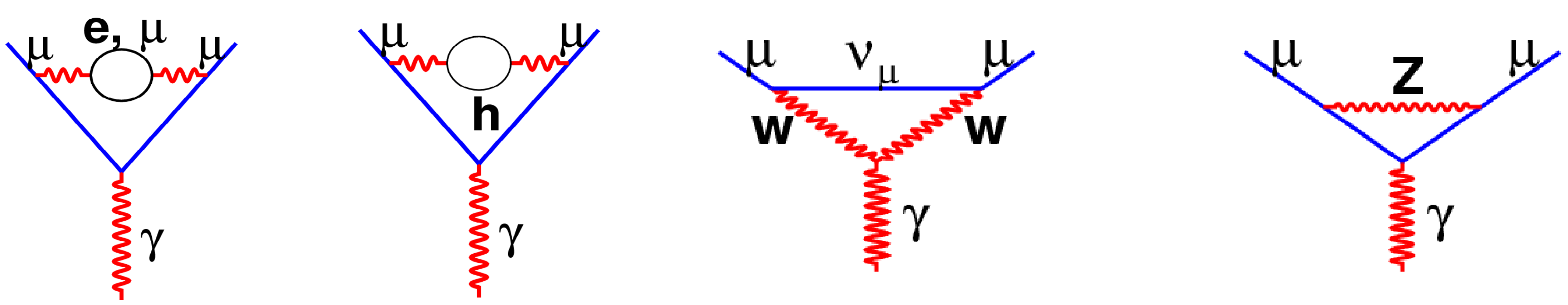
$$a(\mathrm{QED}) = \frac{1}{2}\frac{\alpha}{\pi} + C_2\left(\frac{\alpha}{\pi}\right)^2 + C_3\left(\frac{\alpha}{\pi}\right)^3 + C_4\left(\frac{\alpha}{\pi}\right)^4 + C_5\left(\frac{\alpha}{\pi}\right)^5 + \cdots$$

g - 2 for the muon, SM contributions

Largest contribution : $$a_\mu = \frac{\alpha}{2\pi} \approx \frac{1}{800}$$



Other standard model contributions :



QED hadronic weak

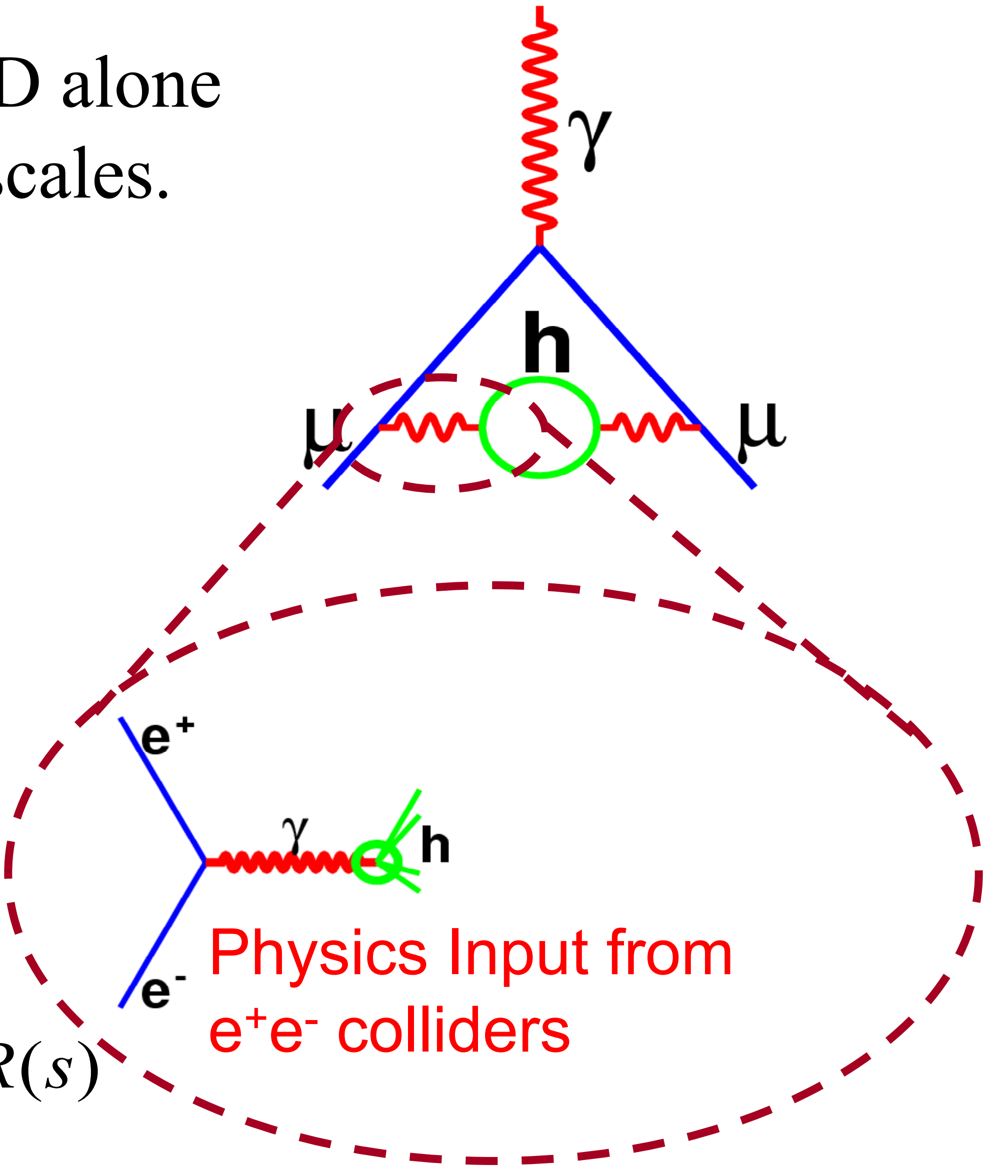
Muons (heavier than electrons) are more sensitive to weak interaction forces (standard model (SM))

Muons become (sometimes) 10^3 times heavier!

Weak interactions

Hadronic contribution (had1)

Cannot be calculated from pQCD alone because it involves low energy scales.



However, by dispersion theory, this a_μ(had1) can be related to

$$R = \frac{\sigma(e^+e^- \rightarrow hadrons)}{\sigma(\mathrm{e}^+e^- \rightarrow \mu^+\mu^-)}$$

measured in e^+e^- collisions.

$$a_\mu(had,1) = \left(\frac{\alpha m_\mu}{3\pi}\right)^2 \int_{4m_\pi^2}^{\infty} \frac{ds}{s^2} K(s) R(s)$$

A brief history of the CERN muon g-2 experiments

Review

The 47 years of muon $g - 2$

F.J.M. Farley[a,*], Y.K. Semertzidis[b]

[a] Yale University, New Haven, CT 06520, USA
[b] Brookhaven National Laboratory, Upton, NY 11973, USA

Received 30 October 2003

Fig. 10. The first experimental magnet in which muons were stored at CERN for up to 30 turns. Left to right: Georges Charpak, Francis Farley, Bruno Nicolai, Hans Sens, Antonio Zichichi, Carl York and Richard Garwin.

CERN I, 1958-1962

- Top view of first magnet

With 100 MeV/c muons

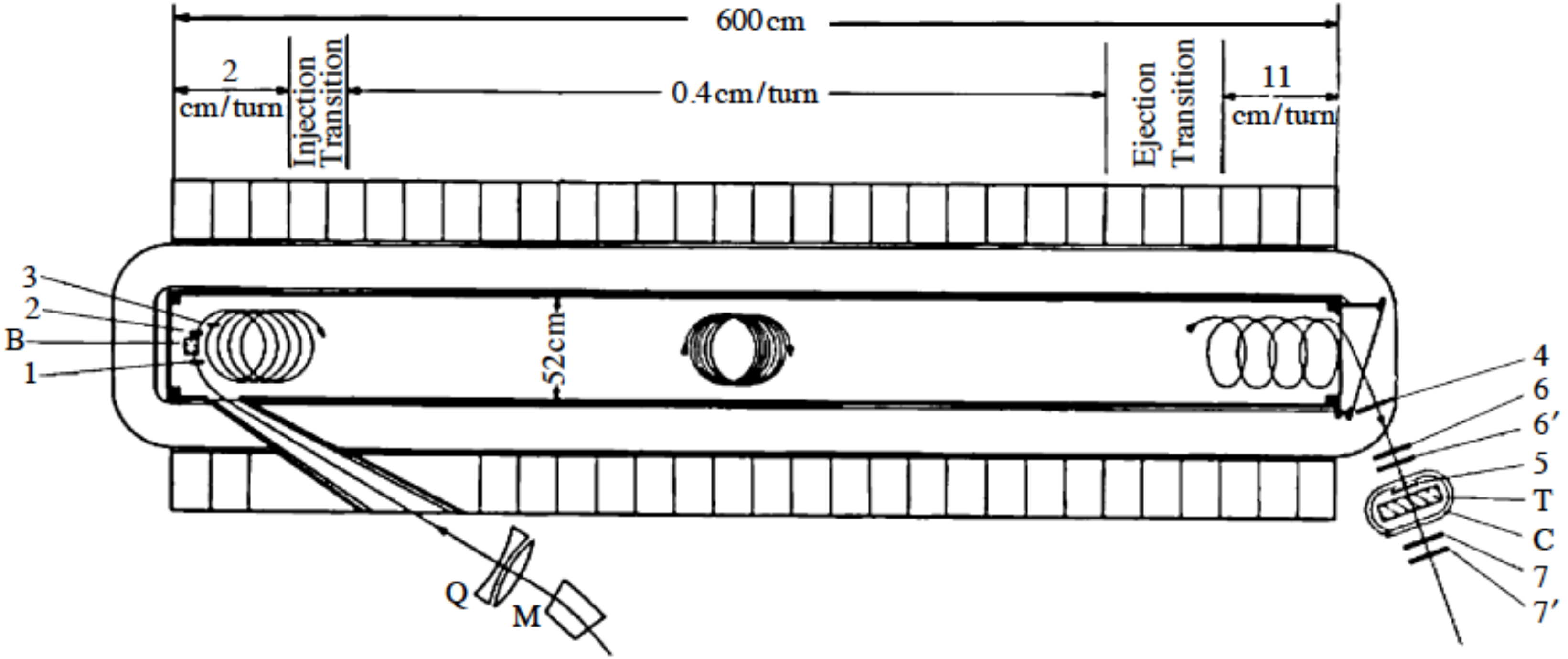


Fig. 12. The 6 m bending magnet used for storing of muons for up to 2000 turns. A transverse field gradient makes the orbit walk to the right. At the end a very large gradient is used to eject the muons which stop in the polarization analyzer. Coincidences 123 and $466'5\bar{7}$ signal an injected and ejected muon respectively. The coordinates used in the text are x (the long axis of the magnet), y (the transverse axis in the plane of the paper) and z (the axis perpendicular to the paper).

CERN I, 1958-1962

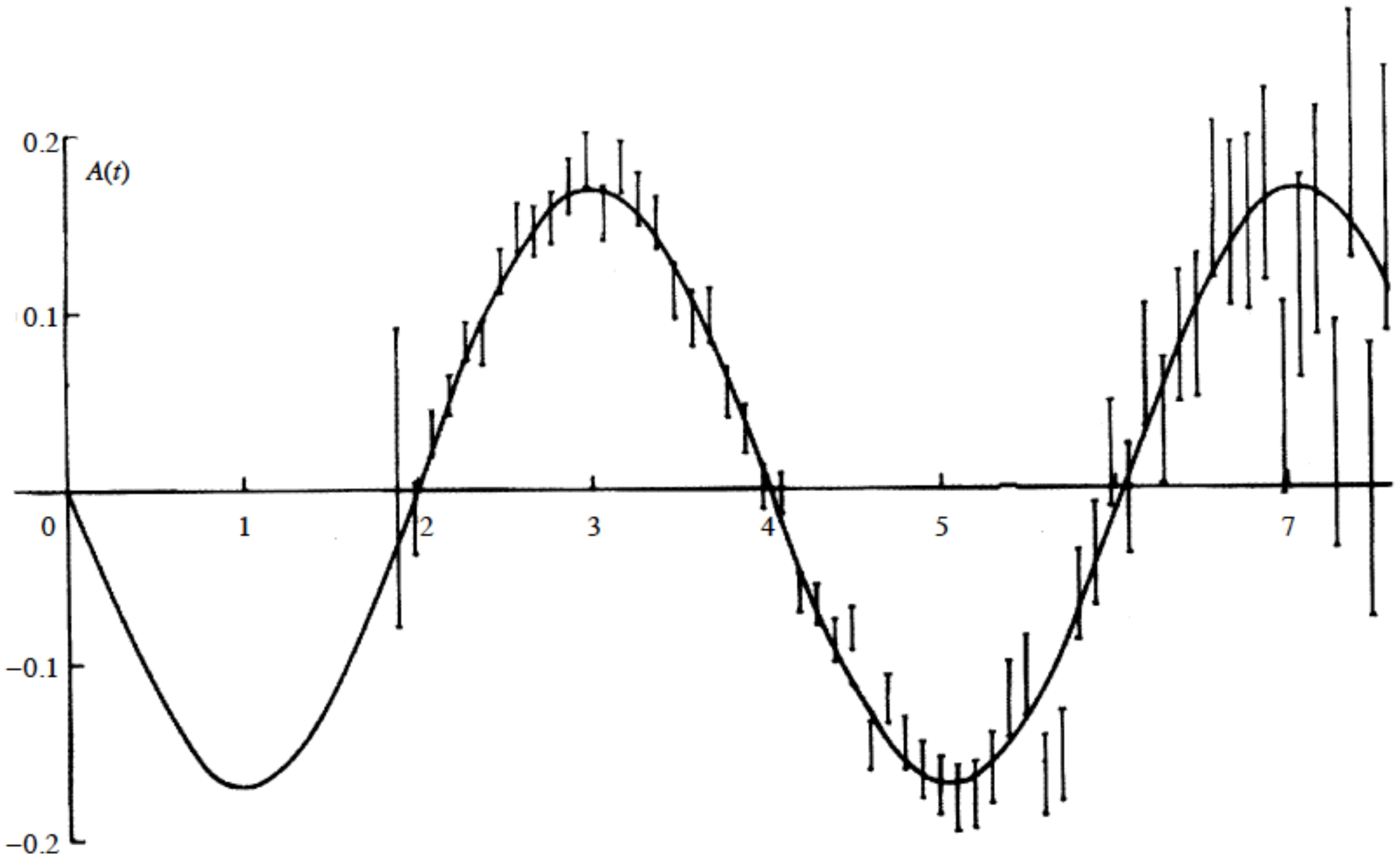


Fig. 14. Asymmetry A of observed decay electron counts as a function of the storage time t. The time t spent in the magnet depended on the transverse position of the orbit on the parabolic magnetic field (45). The muons that were stored for 7.5 μs made 1600 turns in the magnet and then emerged spontaneously at the far end. The sinusoidal variation results from the $(g-2)$ precession; the frequency is measured to $\pm 0.4\%$.

CERN II, 1962-1968

- Top view of the second magnet. Proton injection.

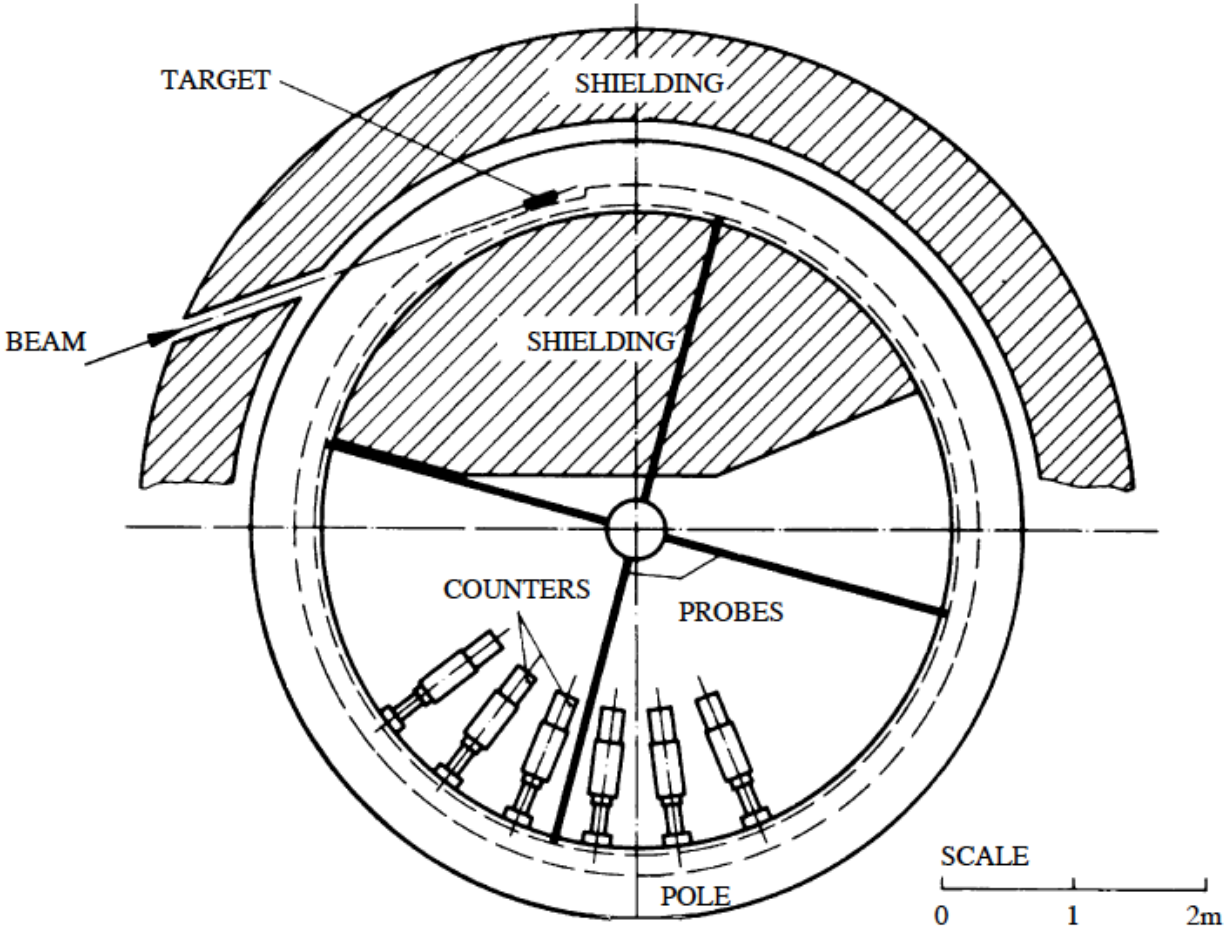


Fig. 17. The first muon storage ring: diameter 5 m, muon momentum 1.3 GeV/c, time dilation factor 12. The injected pulse of 10.5 GeV protons produces pions at the target, which decay in flight to give muons.

CERN II, 1962-1968
270ppm in *a*.

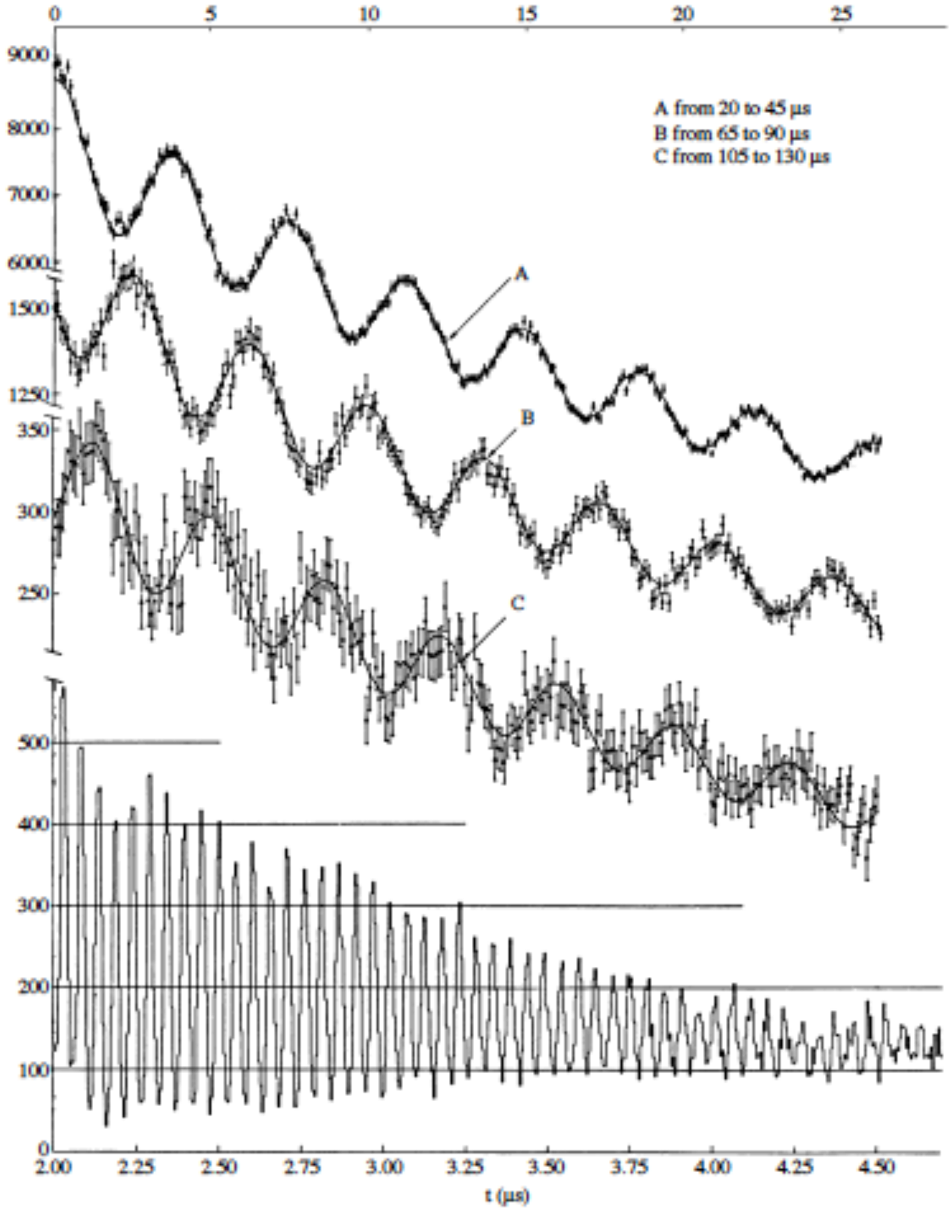


Fig. 19. The first muon storage ring: decay electron counts as a function of time after the injected pulse. The lower curve 1.5–4.5 μs (lower timescale) shows the 19 MHz modulation due to the rotation of the bunch of muons around the ring. As it spreads out the modulation dies away. This is used to determine the radial distribution of muon orbits. Curves A, B and C are defined by the legend (upper time scale); they show various sections of the experimental decay (lifetime 27 μs) modulated by the $(g-2)$ precession. The frequency is determined to 215 ppm, $\bar{B}$ to 160 ppm leading to 270 ppm in a.

CERN III, 1969-1976

- The third magnet, second storage ring. Pion injection, E-field focusing, Magic momentum

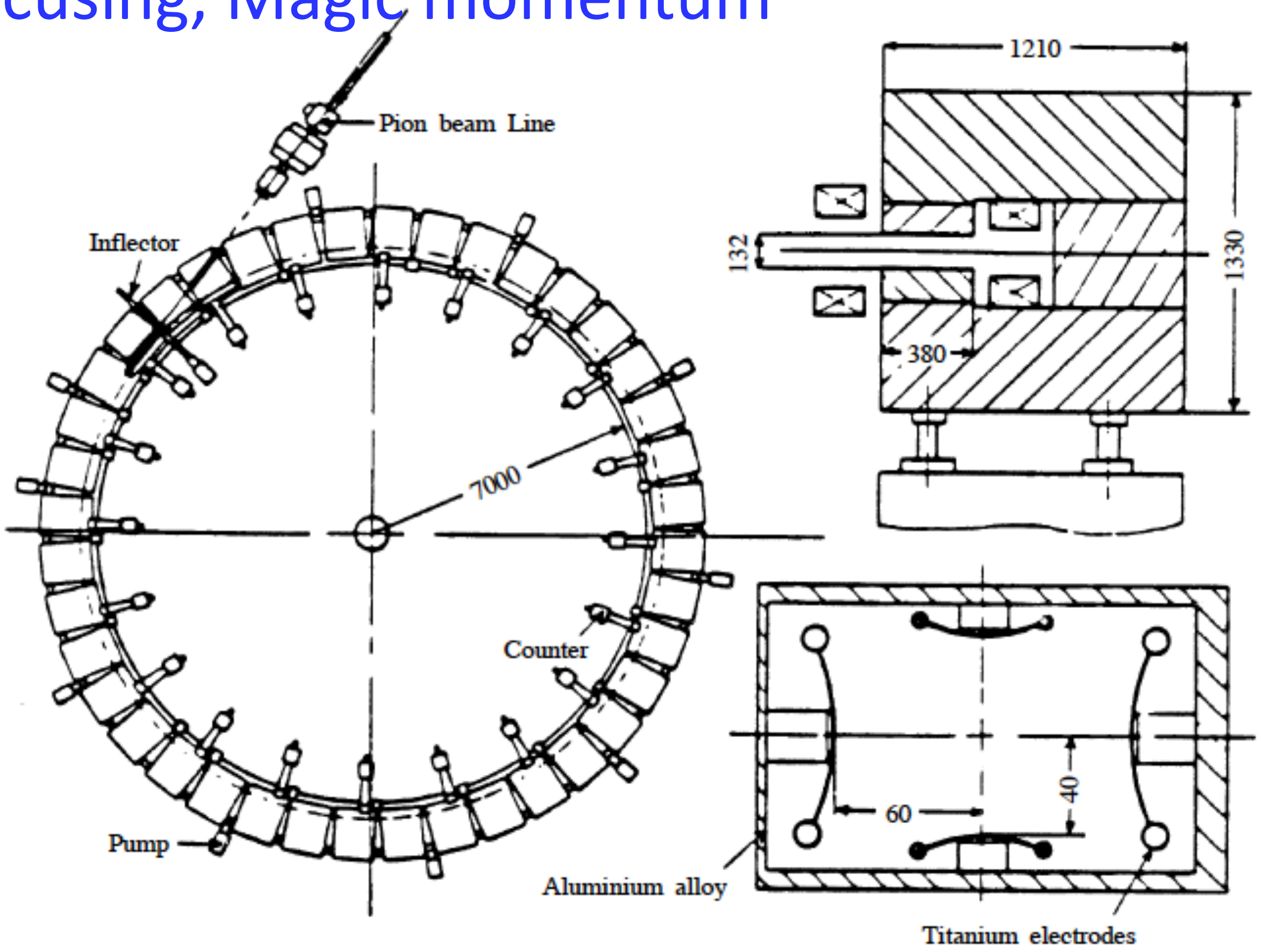


Fig. 21. The second muon storage ring, which consisted of 40 contiguous magnet blocks. The open side of the C-shaped yoke (upper right) faces the centre of the ring. The cross-section of the vacuum chamber and electric quadrupole is shown bottom right. The decay electrons are detected by 20 counters. Dimensions are in mm.

CERN III, 1969-1976. 7.3ppm in *a*.

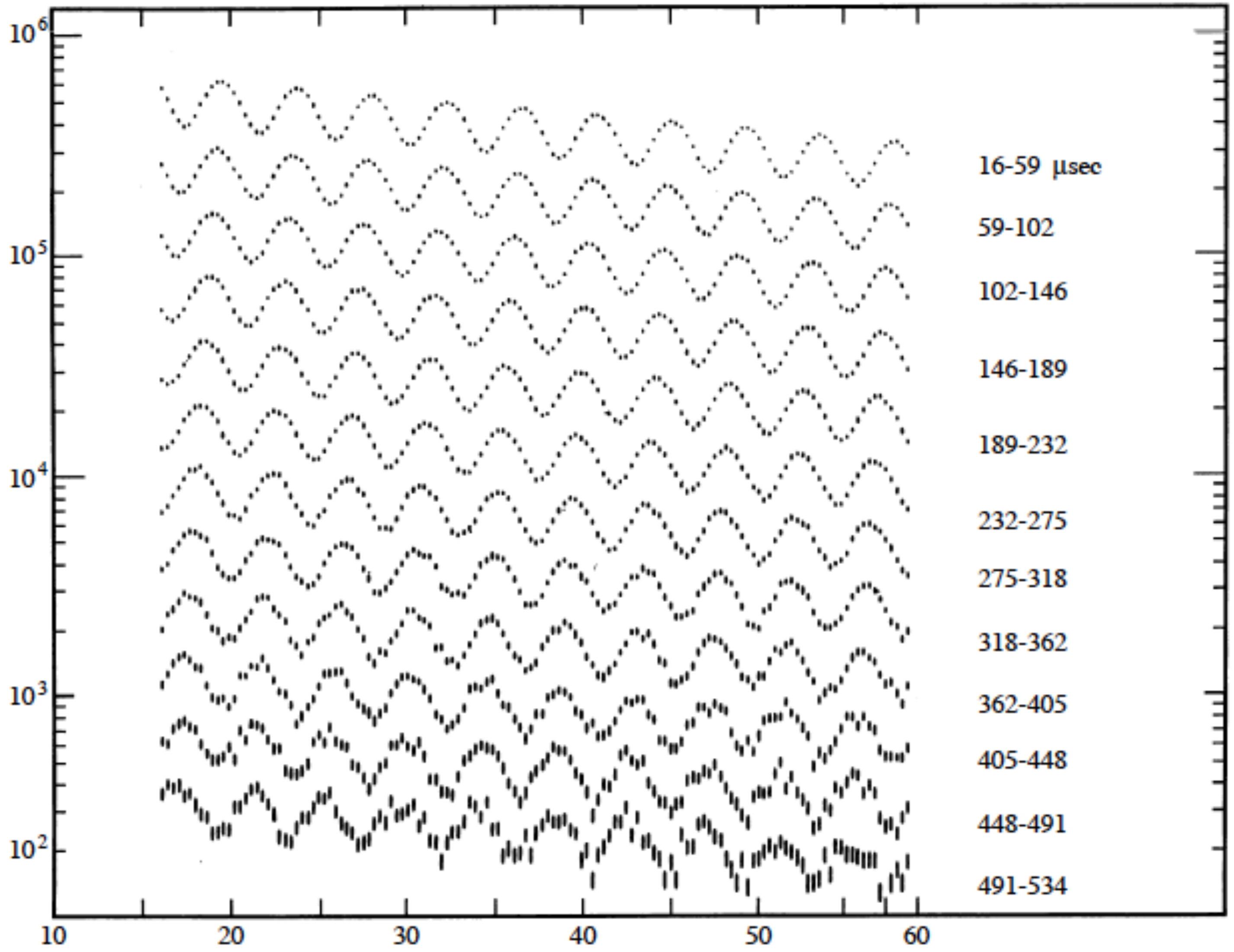
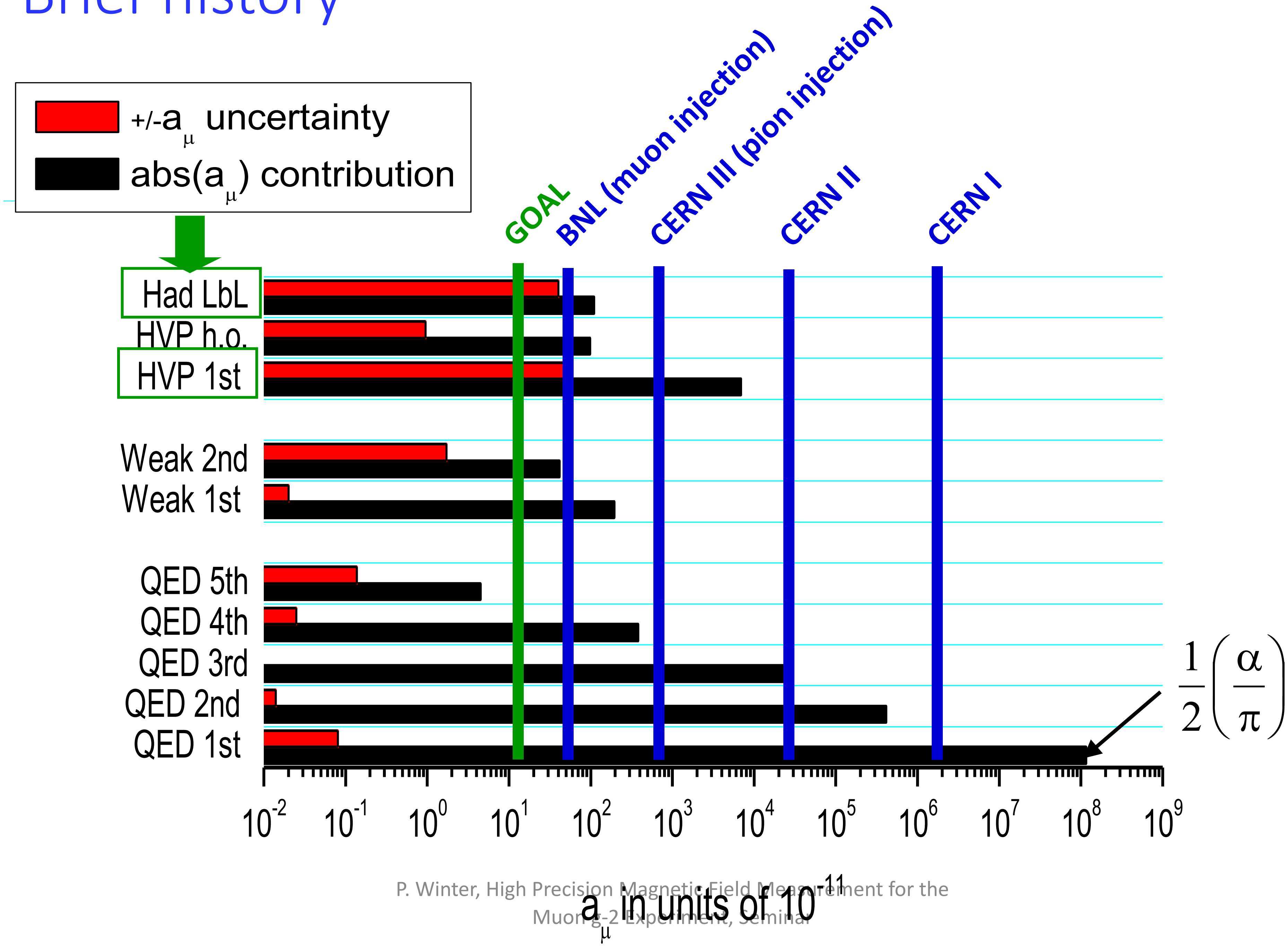


Fig. 25. The second muon storage ring: decay electron counts versus time (in microseconds) after injection. The range of time for each line is shown on the right (in microseconds).

Brief history



From CERN to BNL (1987)

- Much higher proton → pion → muon intensity
- One, large diameter (15m) superconducting magnet (1.5T)

- Direct muon injection (x10 more efficient), fast kicker (200 Gauss, ~200ns), measurement of eddy currents using Faraday effect on top of 1.5T main field.
- DC inflector magnet, uniform B-field to 1ppm, NMR trolley
- Electro-static quadrupoles with x2 field gradient and measure it.

- High-precision beam & spin simulation program for systematic error studies
- Continuous signal recording around signal → data-based pileup subtraction
- Study Coherent betatron oscillations

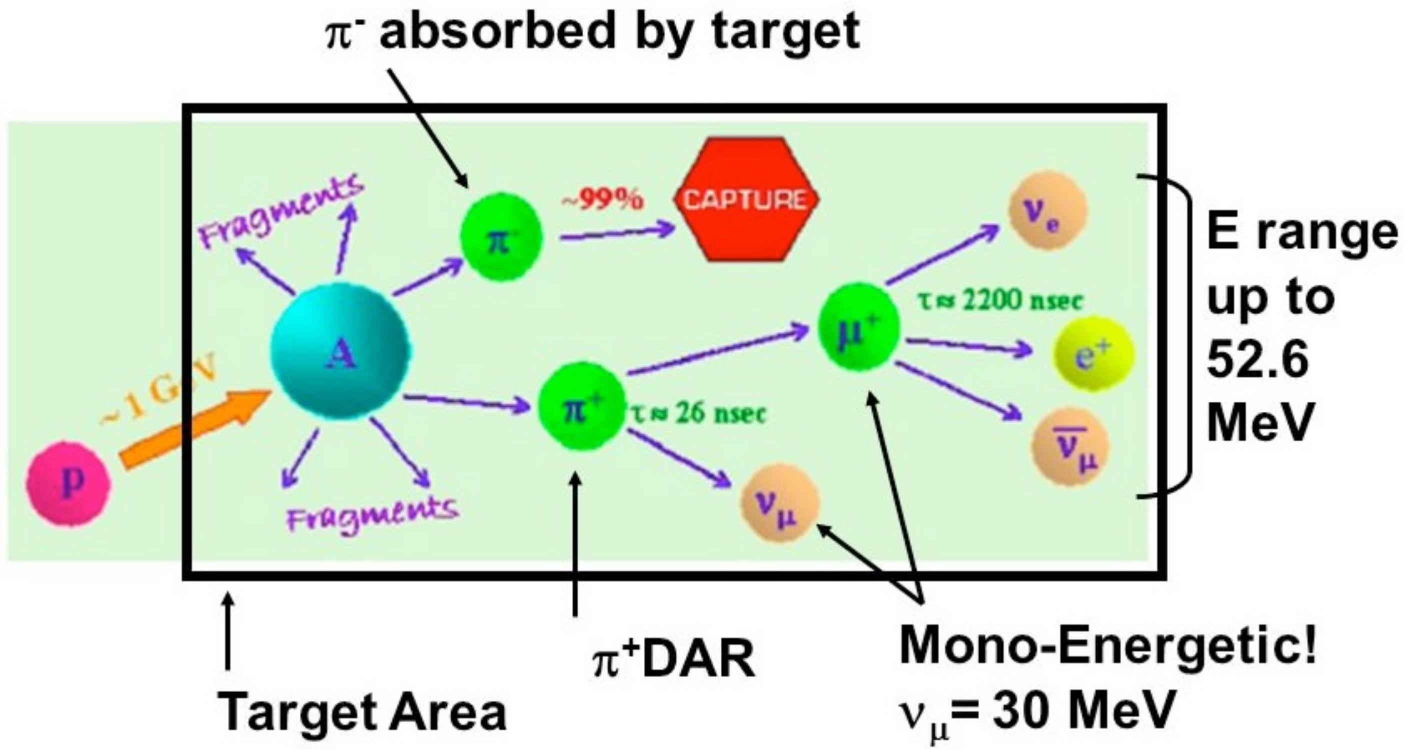
Pion vs. muon injections

Injection method	**Pion**	**Muon**
Light flash on detectors (neutrons, etc.)	Large! Some dets did not gate on but after 140micro-sec!	Down by alpha~1/137
Statistics	Limited	>10 improvement
Phase-space	Uniform	Large CBO*
Kicker needed?	No, kinematics assisted	Pulsed magnet needed (300Gauss, 100ns)

* CBO: Coherent betatron oscillations

Storage Ring Muon g-2:
Rigorous Test of the Standard Model

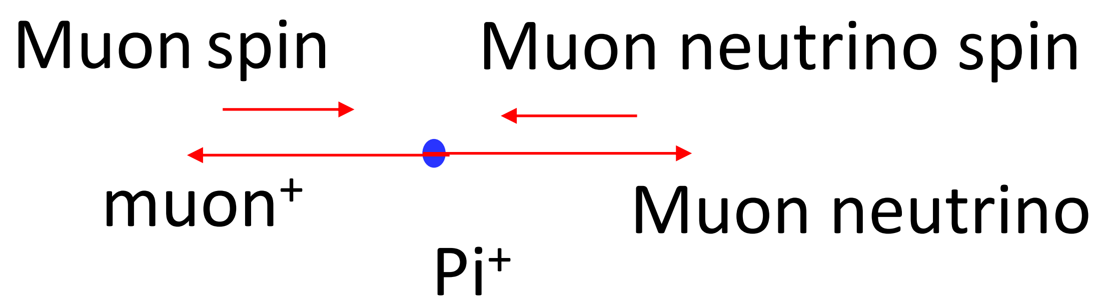
Producing pions and muons



Charged pion and muon stop in << 1 ns

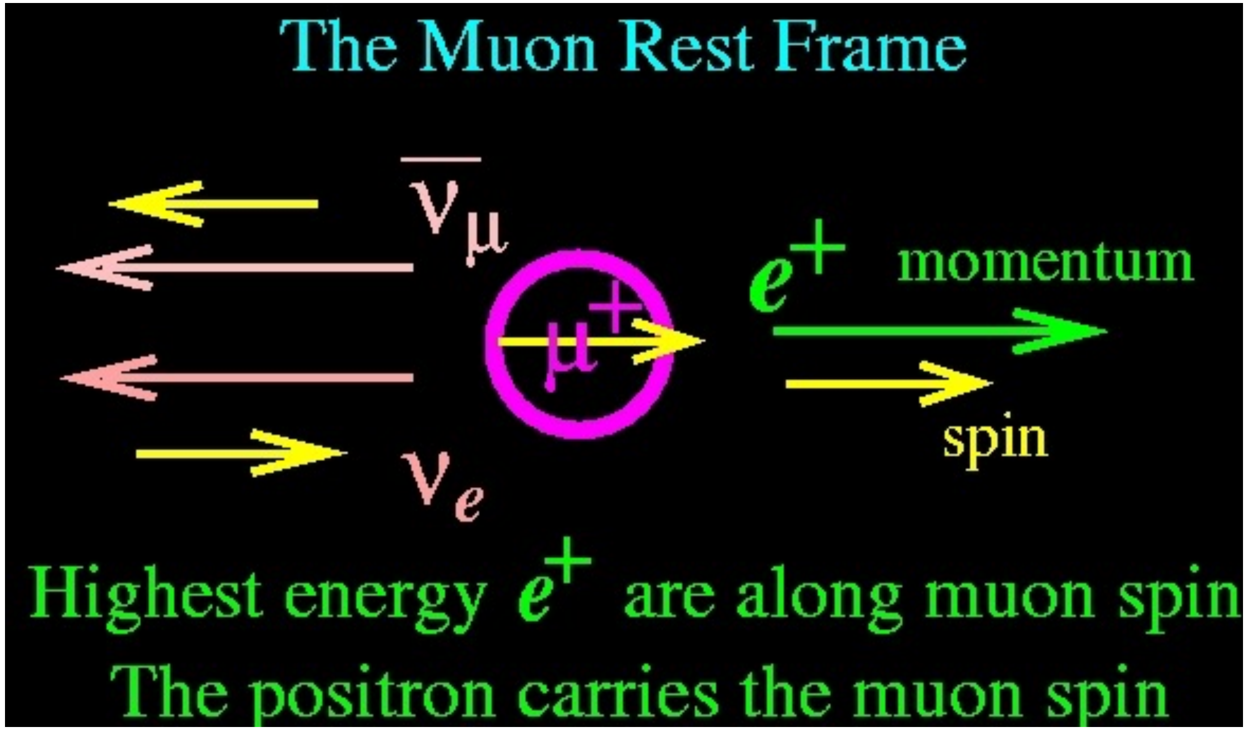
Polarized muon production (1st miracle)

1. Pion decays via weak (parity violating) interactions to a muon plus a muon neutrino.
2. A muon neutrino is left-handed, having its spin opposite to its momentum
3. Therefore, the muon, also has its spin opposite to its momentum to conserve momentum and angular momentum. (Note: muon neutrino is a particle, while the mu+ is an anti-particle.)



Muon decay (2nd miracle)

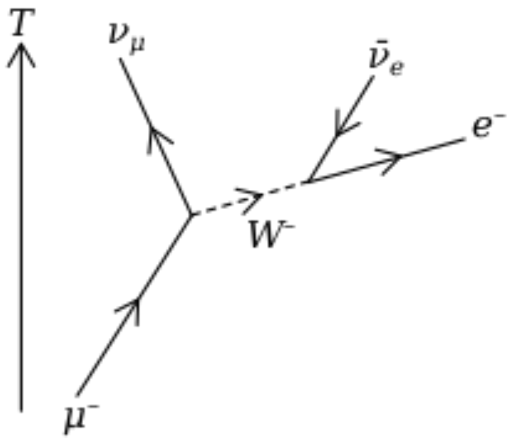
- Decay is self analyzing

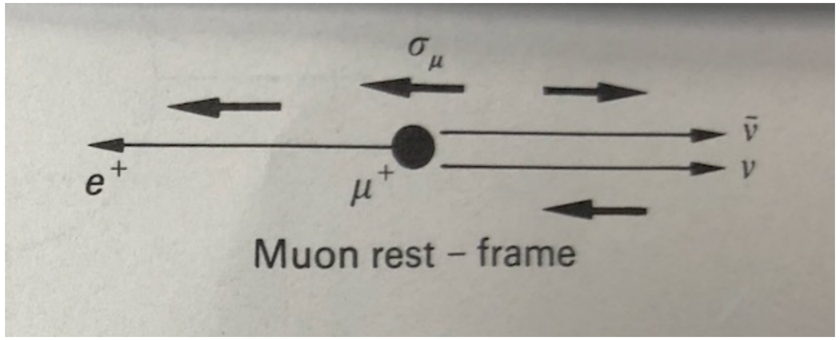


- The highest energy $e^{\pm}$ from $\mu^{\pm}$ decay carry information of the muon spin direction.

Muon decay

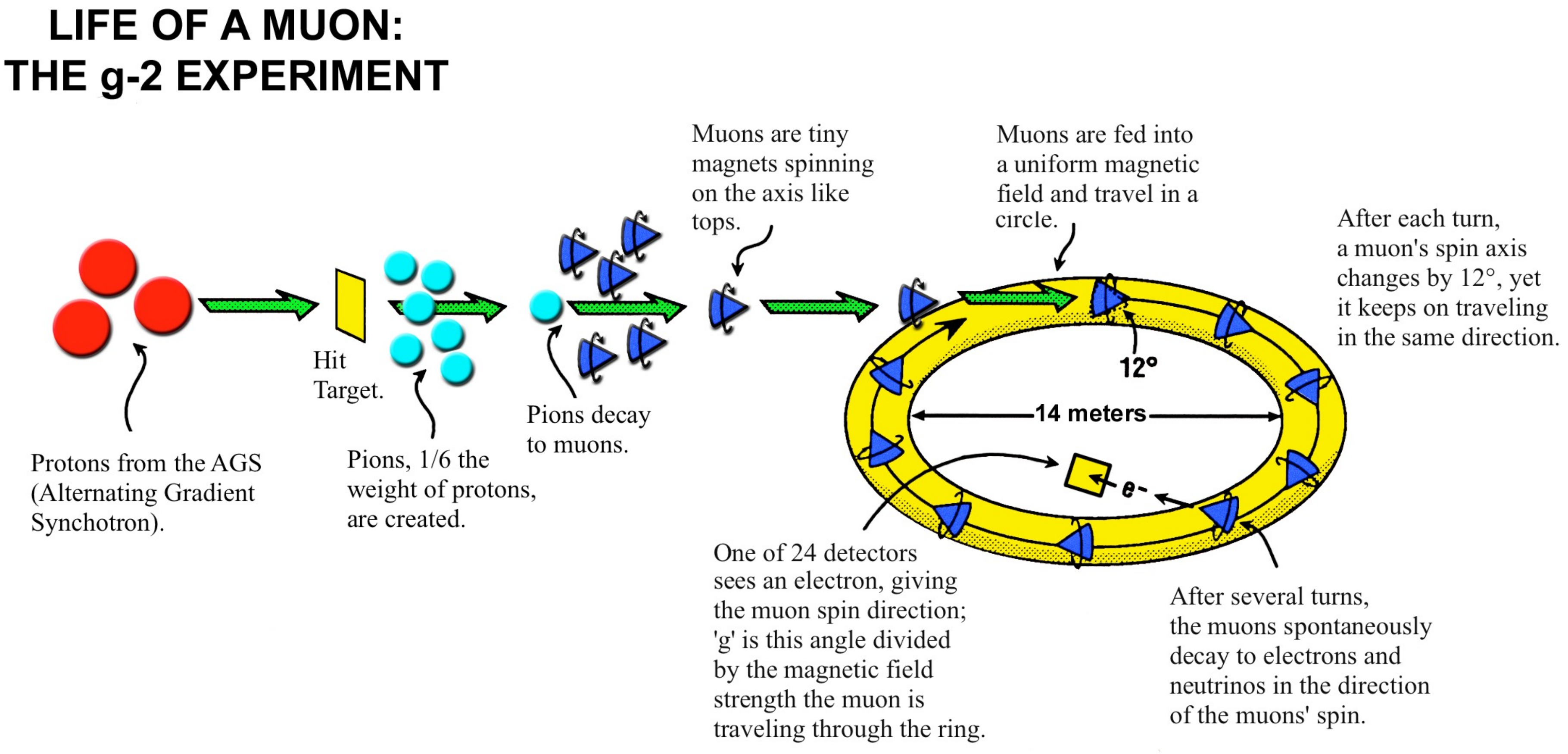
1. Muons decay via weak-interactions, violating Parity (P) symmetry. The electron spectrum from muon decays confirms the V-A theory, which predicts the helicity of the electron.





Muon g-2 experiment: major challenge to the Standard Model

- E821 at BNL: 1997-2004
- E989 at FNAL: first data in 2017



Spin Precession Rate at Rest

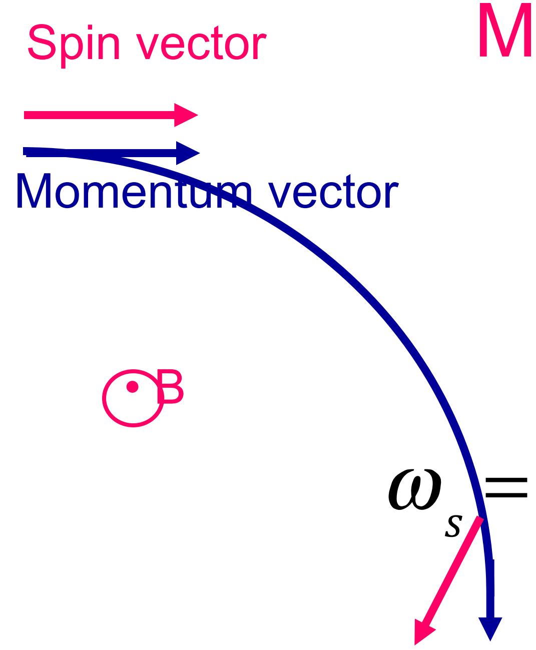
$$\frac{d\vec{s}}{dt} = \vec{\mu} \times \vec{B} + \vec{d} \times \vec{E}$$

There is a large asymmetry in this equation: μ is relatively large, d is compatible with zero

The Principle of g-2

$$\text{At rest}: \quad \frac{d\vec{s}}{dt} = \vec{\mu} \times \vec{B}$$

Moving: Thomas precession!



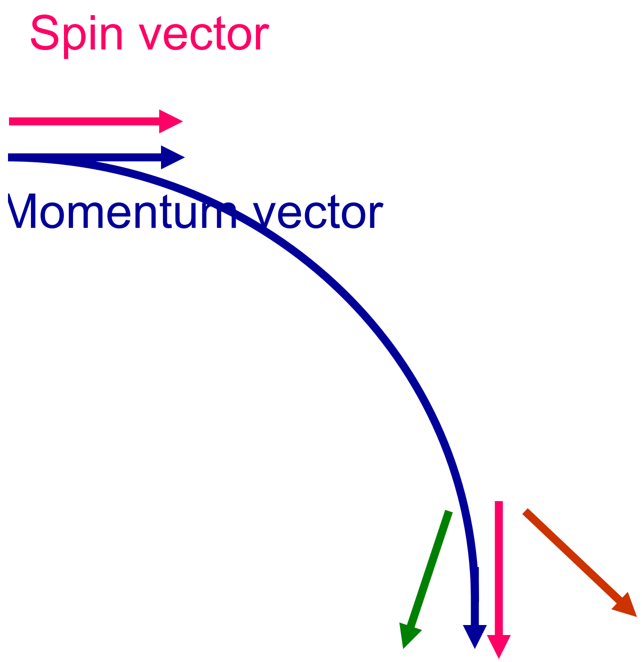
$$\omega_c = \frac{eB}{m\gamma}$$

$$\omega_s = \frac{g}{2}\frac{eB}{m} + (1-\gamma)\frac{eB}{m\gamma}$$

$$\omega_a = \omega_s - \omega_c = \left(\frac{g-2}{2}\right)\frac{eB}{m} \Rightarrow \boxed{\omega_a = a\frac{eB}{m}}$$

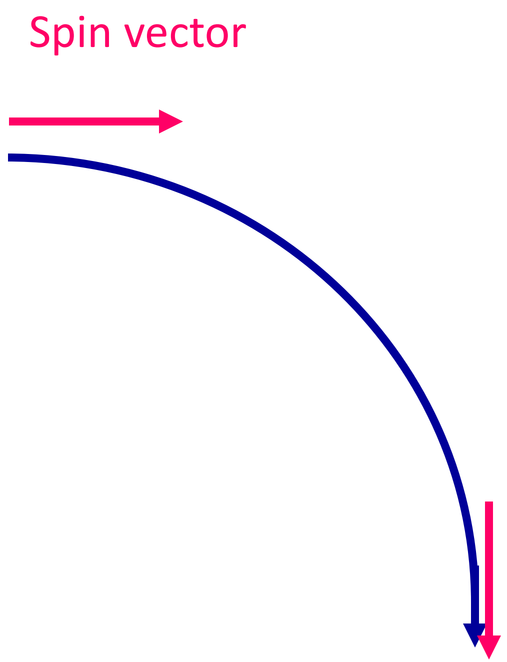
Independent of velocity (3rd miracle)!

Effect of Radial Electric Field



- Low energy particle
- …just right
- High energy particle

Effect of Radial Electric Field



- …just right

, γ~29.3

for muons,
"magic"
momentum

(~3GeV/c)

g-2 precession independent of electric fields (4th miracle)!

Breakthrough concept: Freezing the horizontal spin precession due to E-field

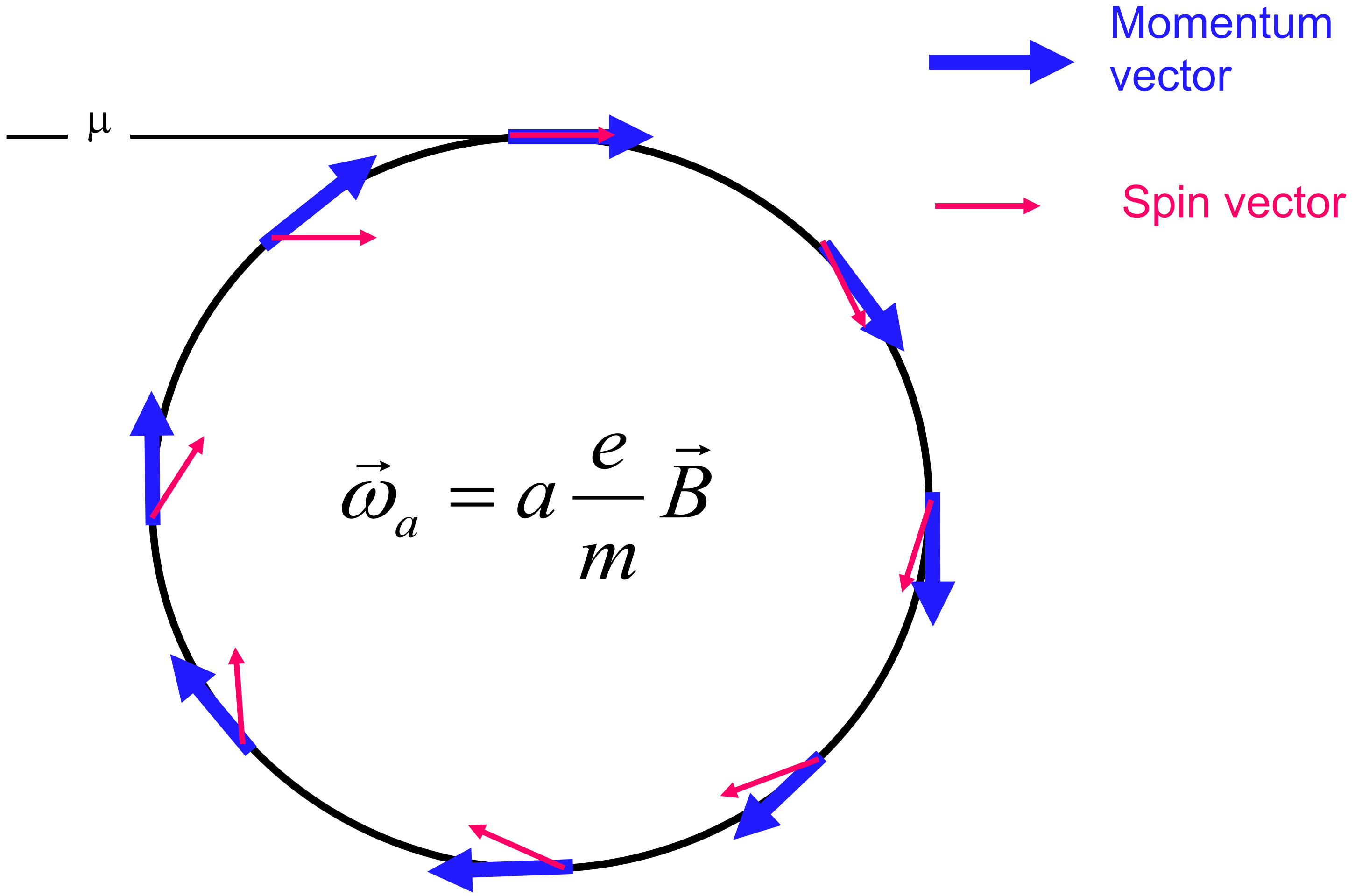
$$\vec{\omega}_a = -\frac{q}{m}\left\{ a\vec{B} - \left[a - \left(\frac{mc}{p}\right)^2 \right] \frac{\vec{\beta}\times\vec{E}}{c} \right\}$$

Muon g-2 focusing is electric: The spin precession due to E-field is zero at "magic" momentum (3.1GeV/c for muons, 0.7 GeV/c for protons,…)

$$p = \frac{mc}{\sqrt{a}}, \text{ with } G = a = \frac{g-2}{2}$$

The "magic" momentum concept was used in the muon g-2 experiments at CERN, BNL, and now at FNAL.

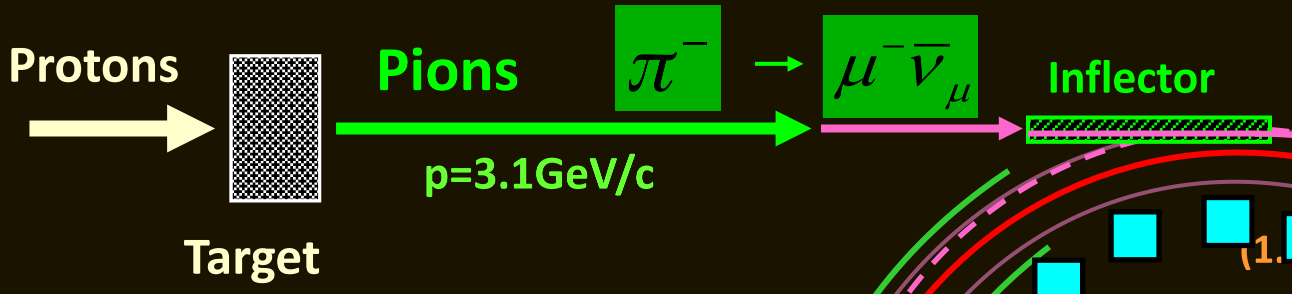
Spin Precession in g-2 Ring (Top View)

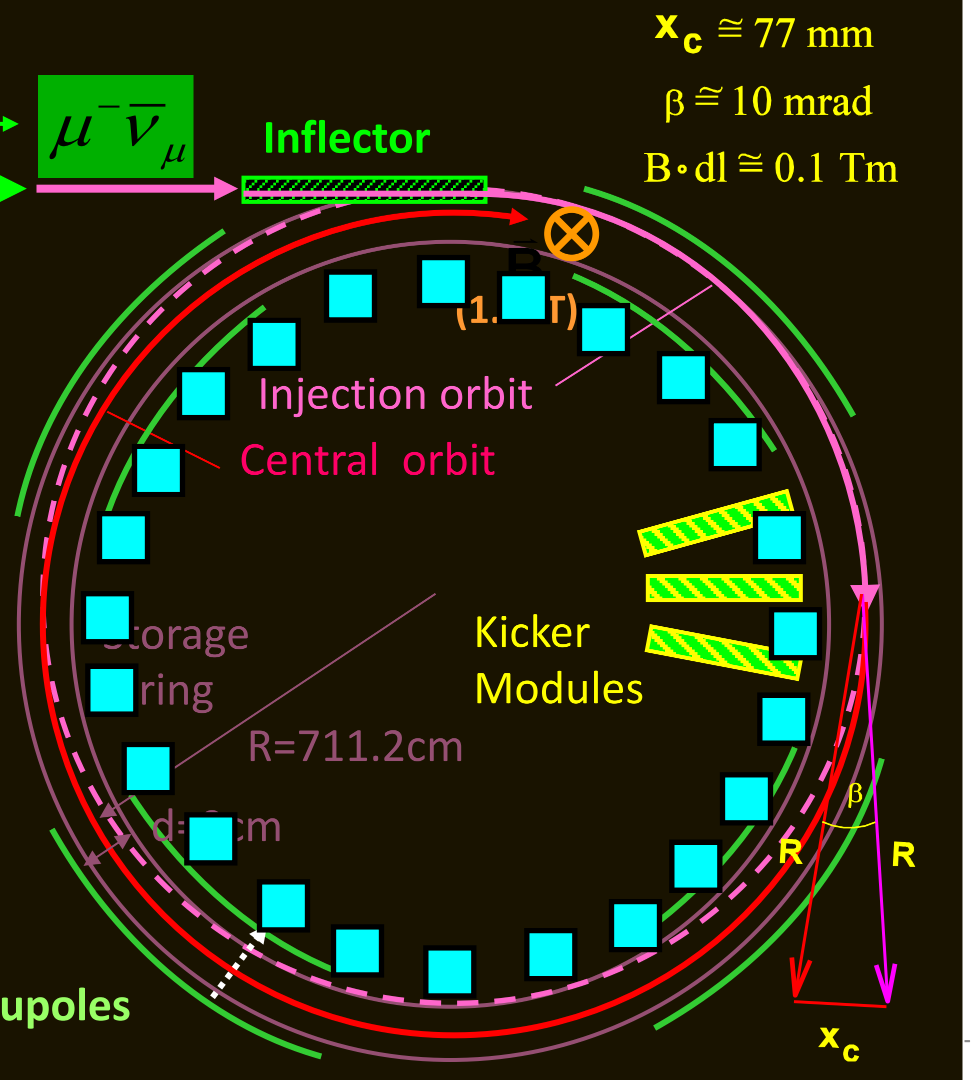


$$\vec{\omega}_a = a\frac{e}{m}\vec{B}$$

The electric focusing does not influence the g-2 precession rate

Experimental Technique



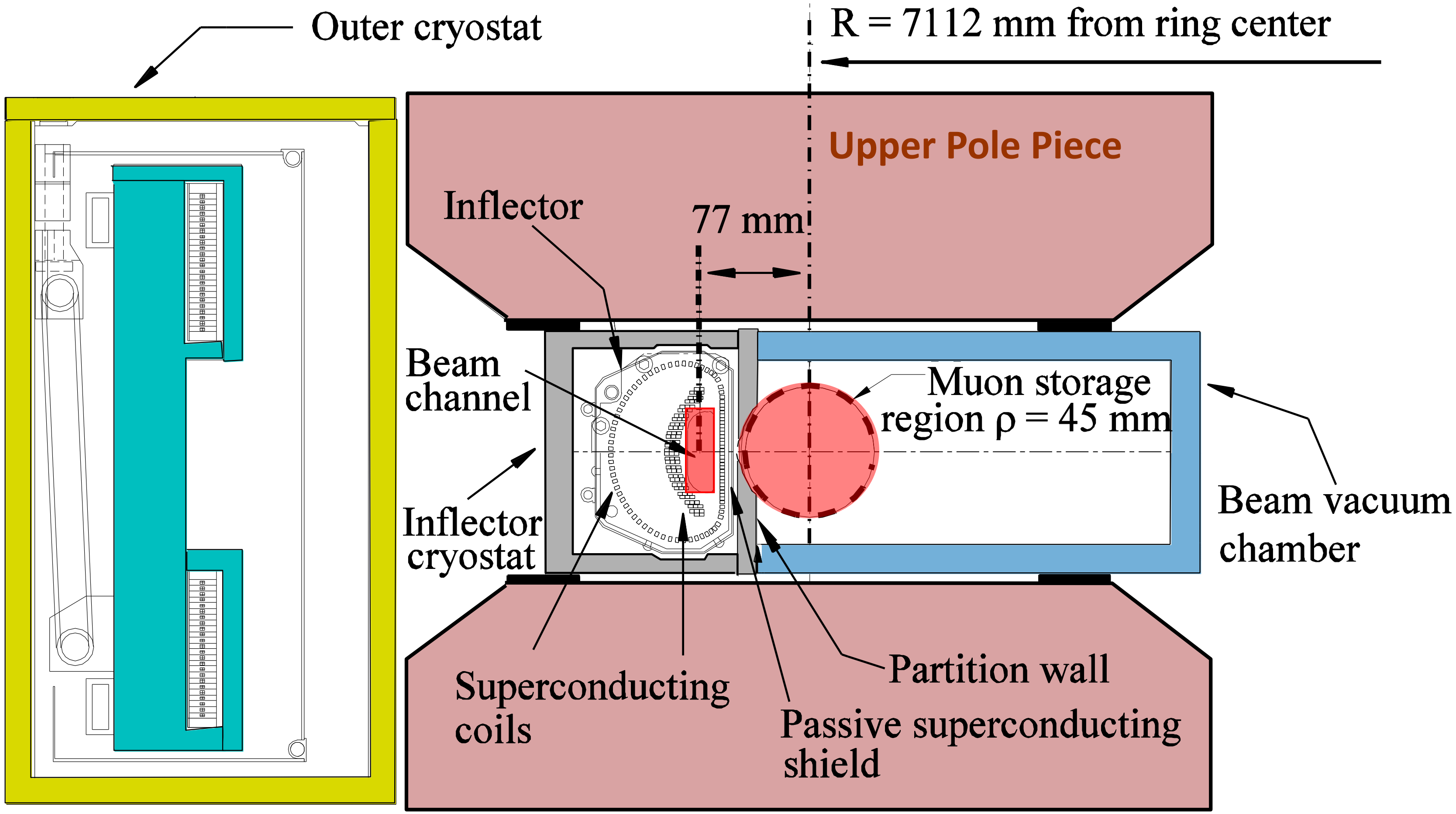


slide by B. Lee Roberts

- Muon polarization
- Muon storage ring
- injection & kicking
- focus by Electric Quadrupoles
- 24 electron calorimeters

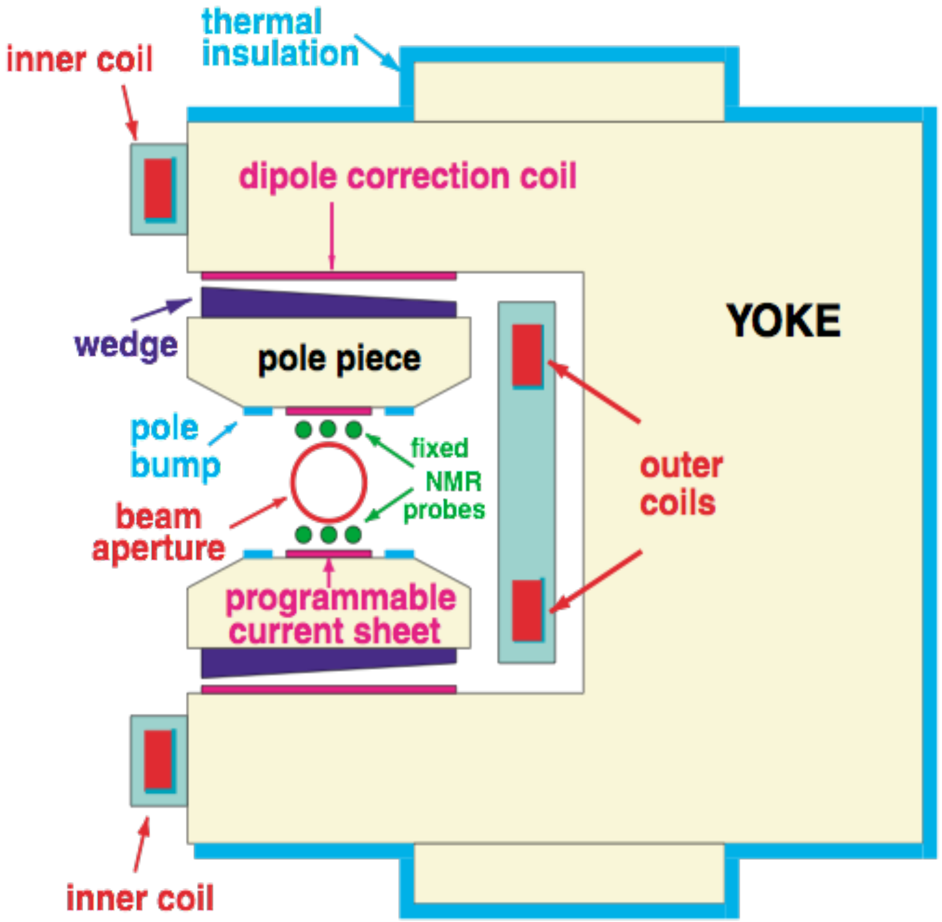
$$\vec{\omega}_a = -\frac{e}{m} a_\mu \vec{B}$$

Space limitations prevent matching the inflector exit to the storage aperture

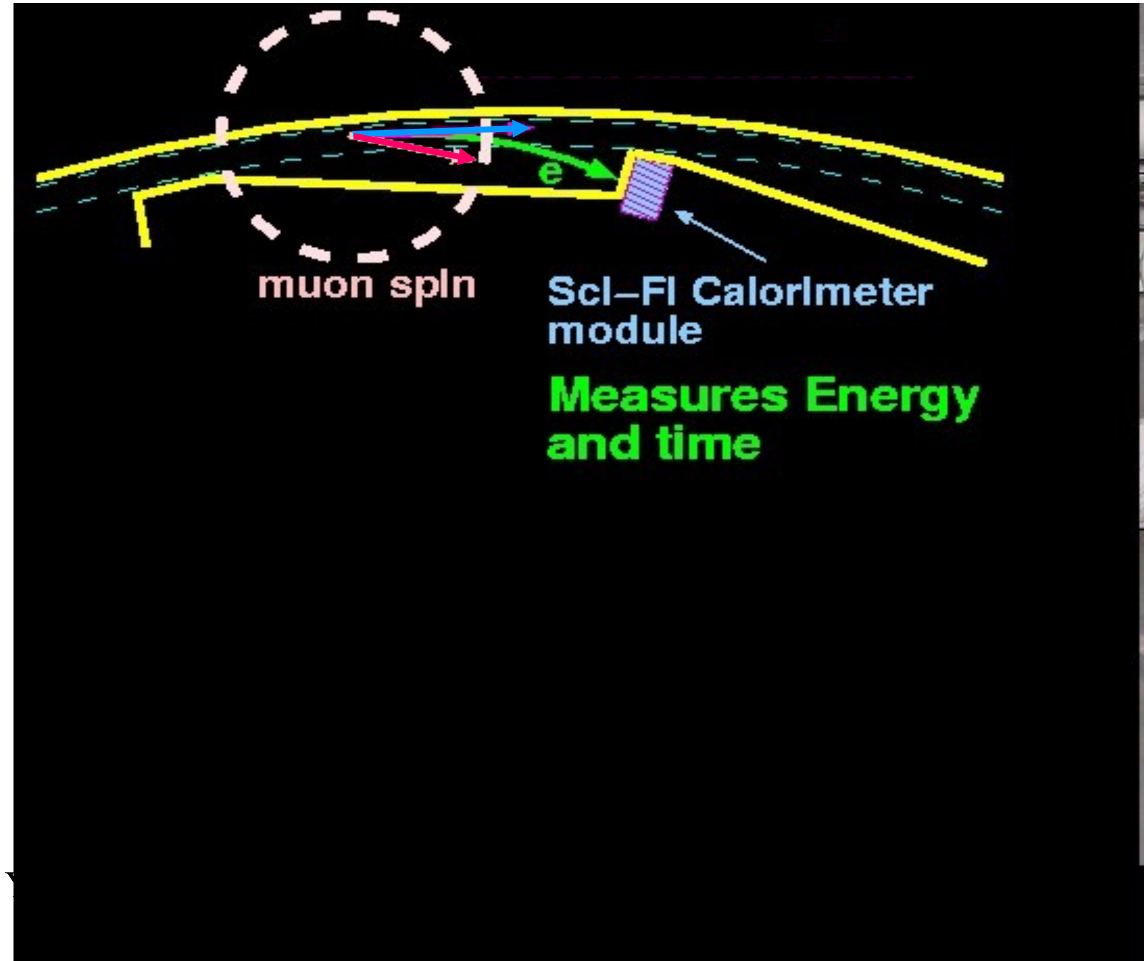


Inflector magnet shielding design by W. Meng (BNL)

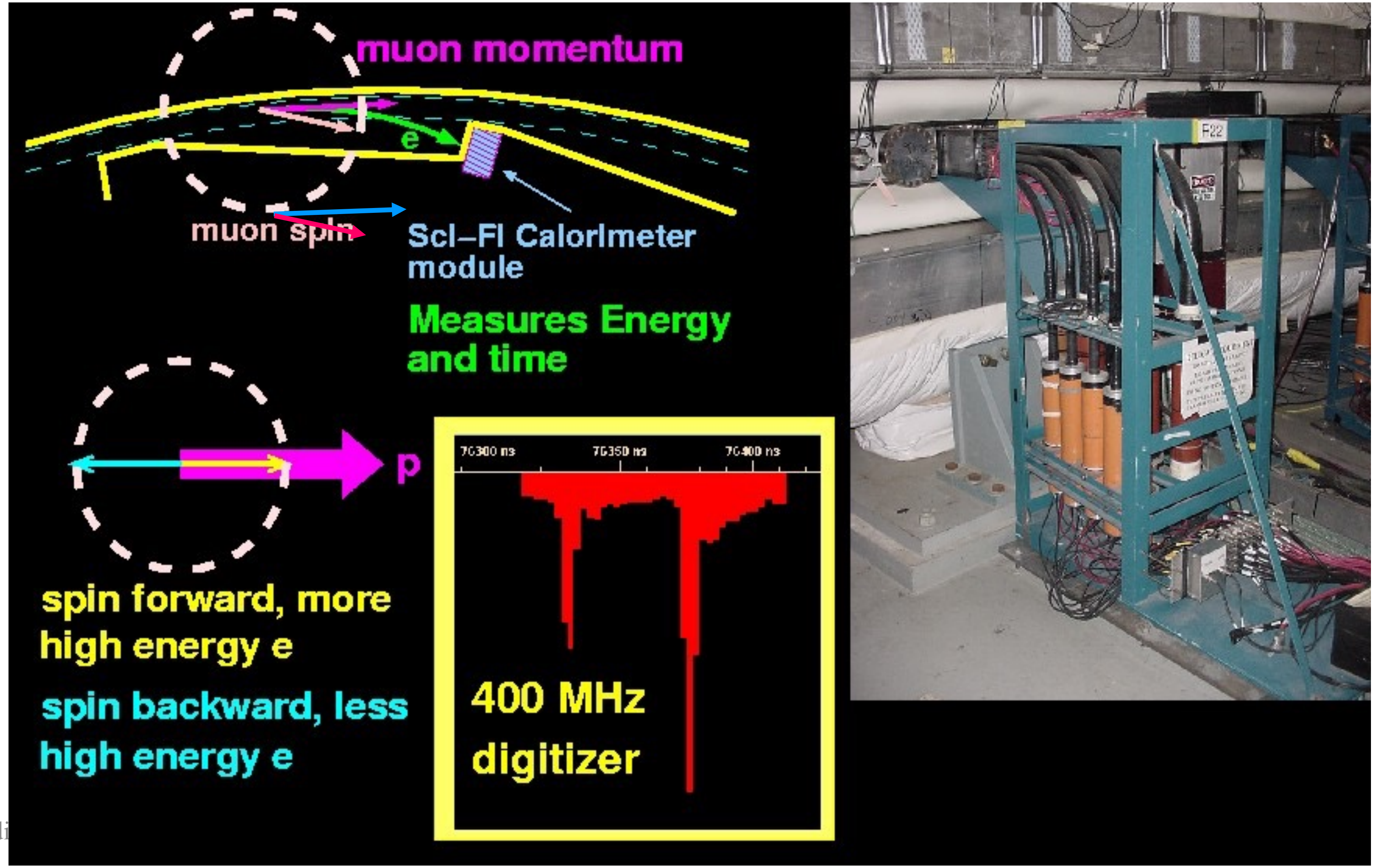
Cross section of the storage ring magnet



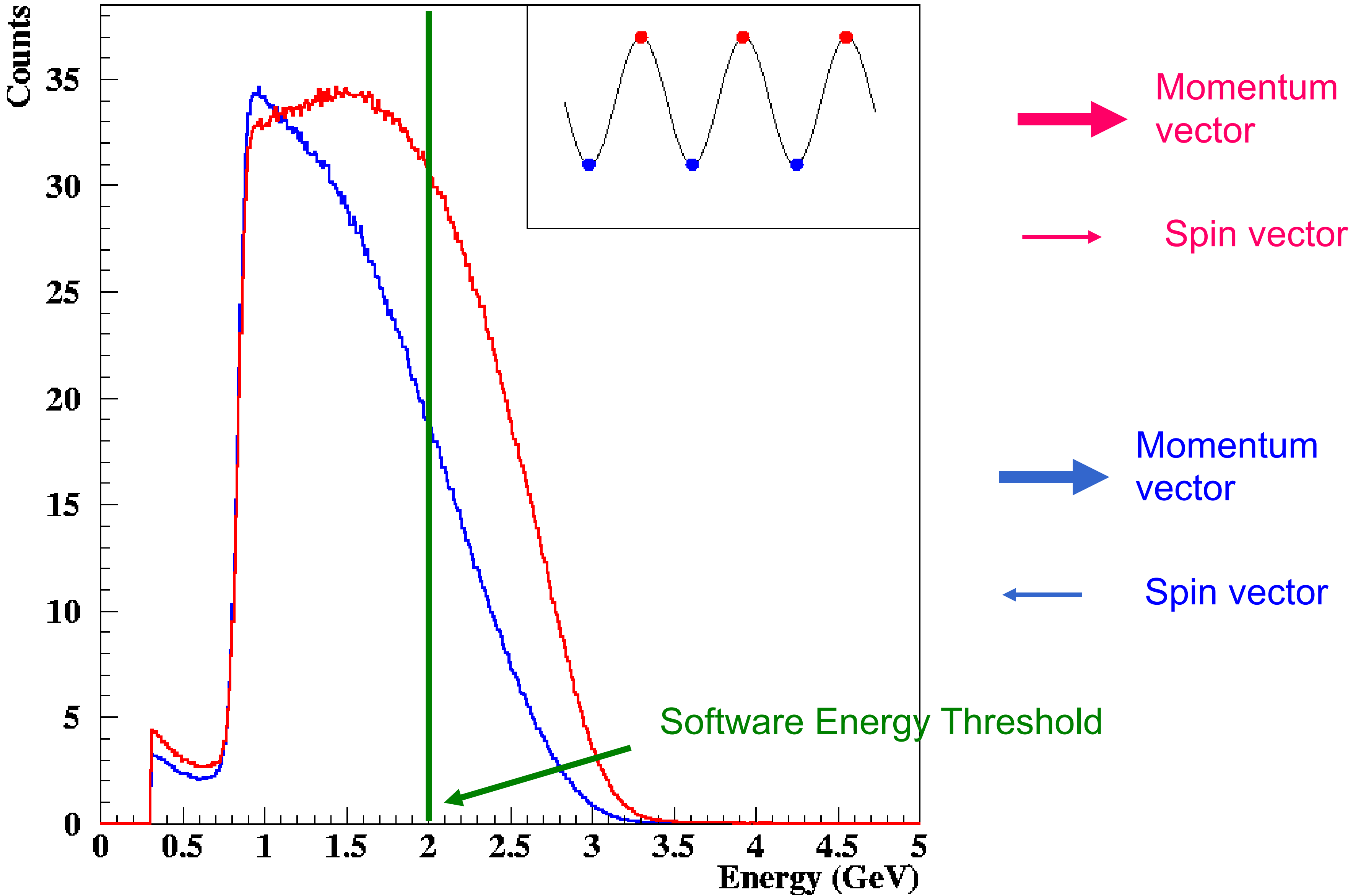
Detectors and vacuum chamber



Detectors and vacuum chamber



Energy Spectrum of Detected Positrons depends on spin direction

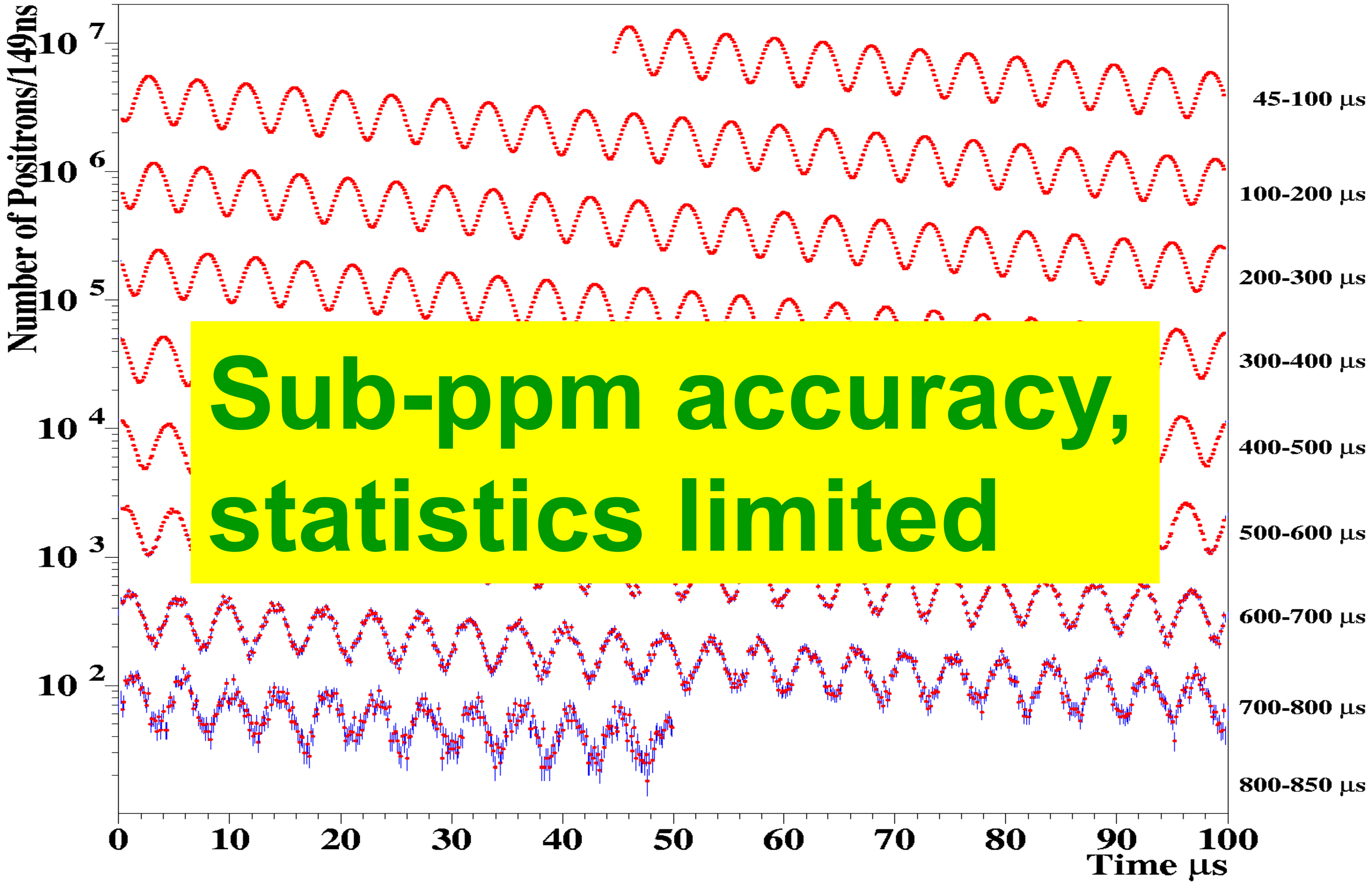


- Muon g-2: Precision physics in a Storage Ring

- Statistics limited… to improve sensitivity by a factor of 4 at Fermilab

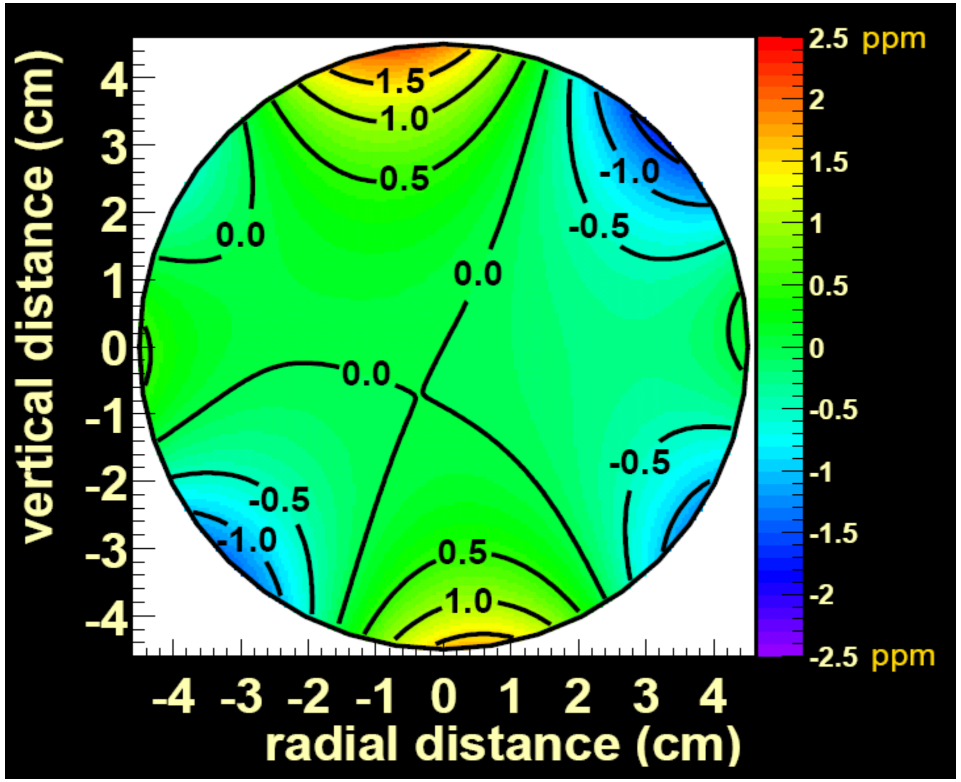
Muon g-2: 4 Billion e⁺ with E>2GeV

$$dN/dt = N_0 e^{-\frac{t}{\tau}}\left[1 + A\cos(\omega_a t + \phi_a)\right]$$



Sub-ppm accuracy, statistics limited

The ± 1 ppm uniformity in the average field is obtained with special shimming tools.

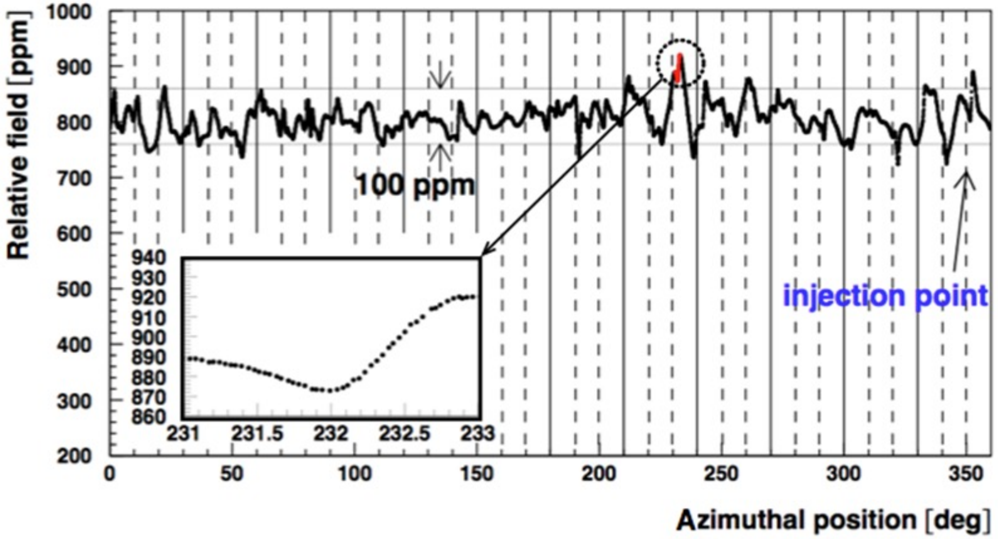


$\langle B \rangle_{\text{azimuth}}$

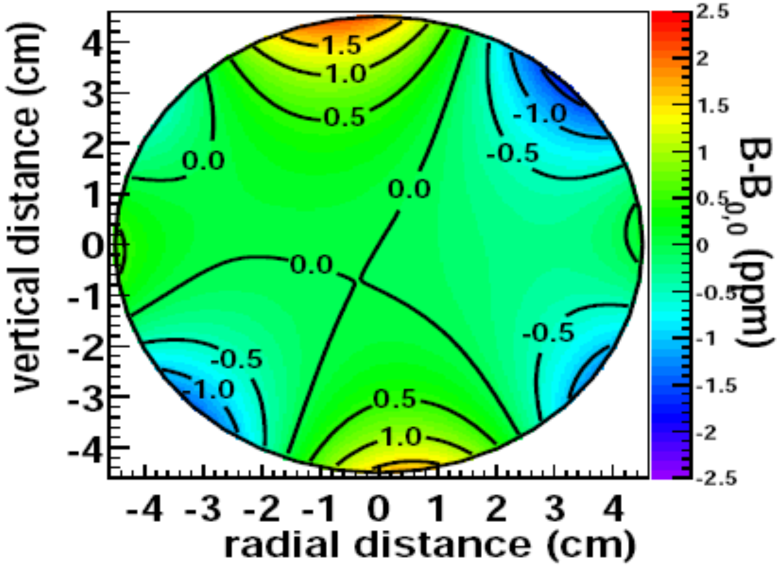
σ_{syst} on $\langle B \rangle_{\mu-\text{dist}} = \pm 0.03$ ppm

Goal for the shimming of the storage ring magnet

Field vs. Azimuth



Azimuthally Averaged
Field vs r,z



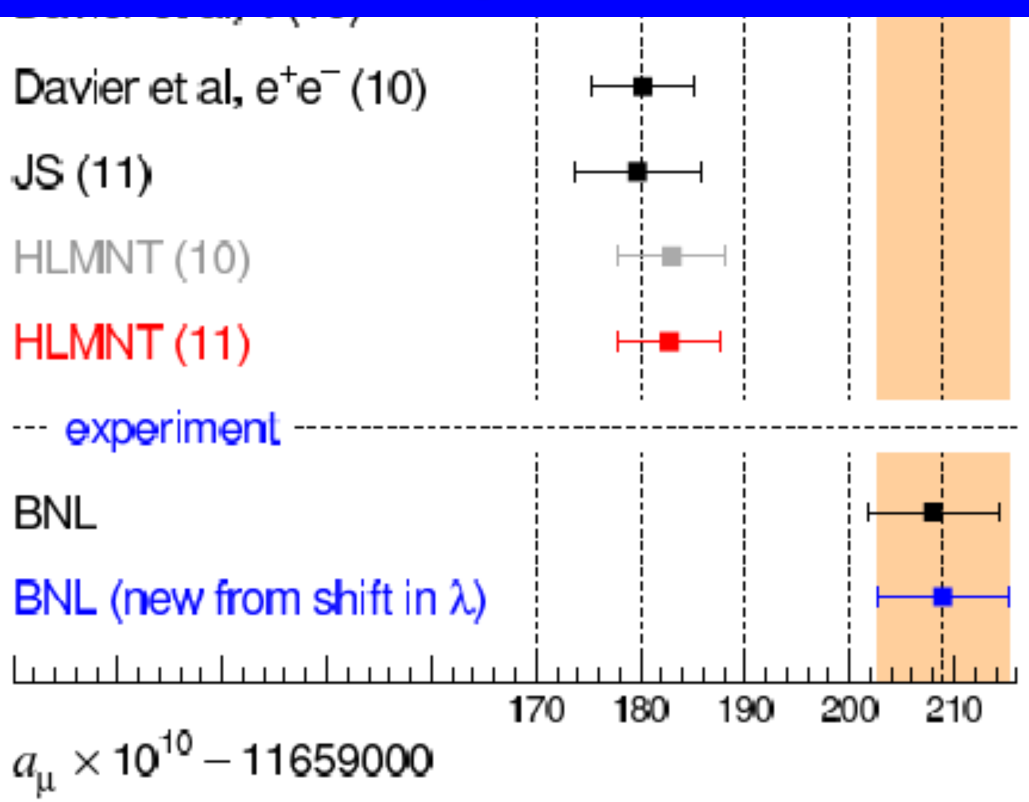
Bennett et al. 10.1103/PhysRevD.73.072003

Goal: +/- 25 ppm

Goal: +/- 0.5 ppm

Comparison of Theory/Experiment

The result is 3.5 s.d. away from theory! What is it?

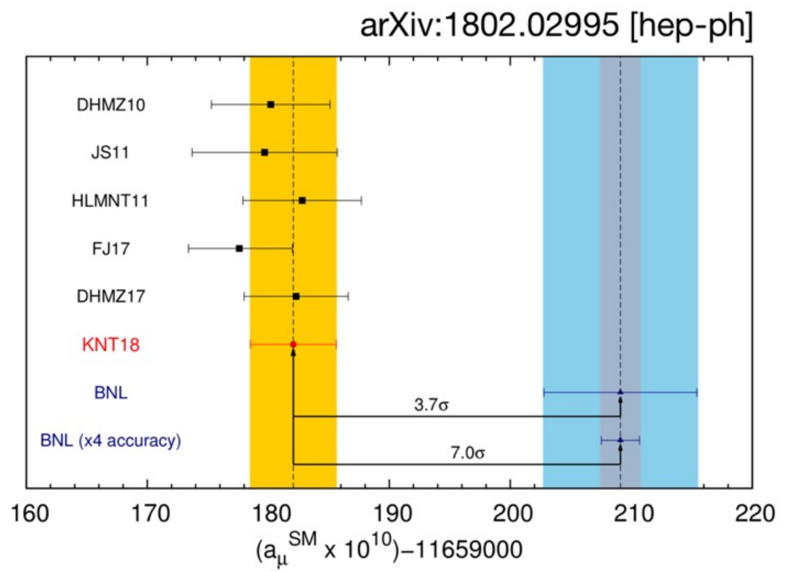


Yannis Semertzidis

Figure 1: Standard model predictions of a_μ by several groups compared to the measurement from BNL

Current status of a_μ in Standard Model

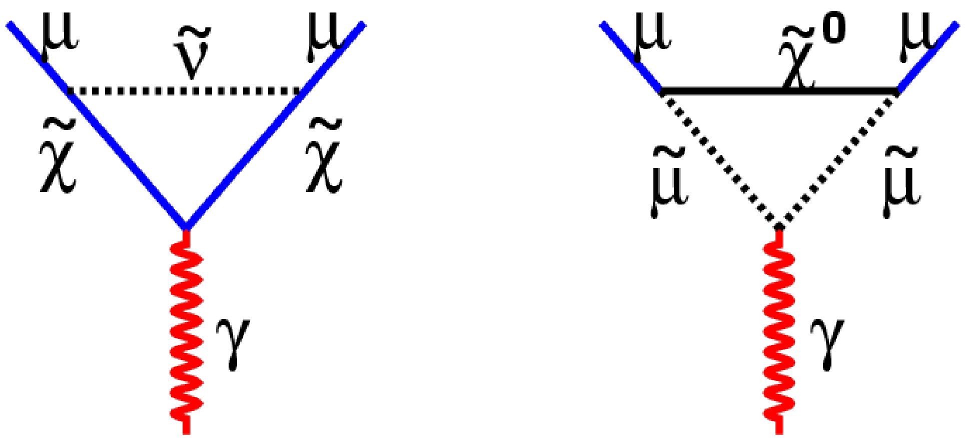
	Value (x 10^{-11})
QED	116 584 718.951 ± 0.009 ± 0.019 ± 0.007 ± 0.077
HVP (lo)	6949 ± 34
HVP (ho)	-98.4 ± 0.7
HLBL	105 ± 26
EQ	154 ± 1
Total SM	116 591 818 ± 43



$$a_\mu^{Expt.} - a_\mu^{SM} = (271 \pm 73) \times 10^{-11} \quad (3.7\,\sigma)$$

- New E989 experiment will reduce experimental uncertainty by a factor of 4 to 16 x 10^{-11} (140 ppb)
- If current discrepancy remains this would yield $>7\sigma$
- Together with theory improvements could give $>9\sigma$

Beyond standard model, e.g. SUSY



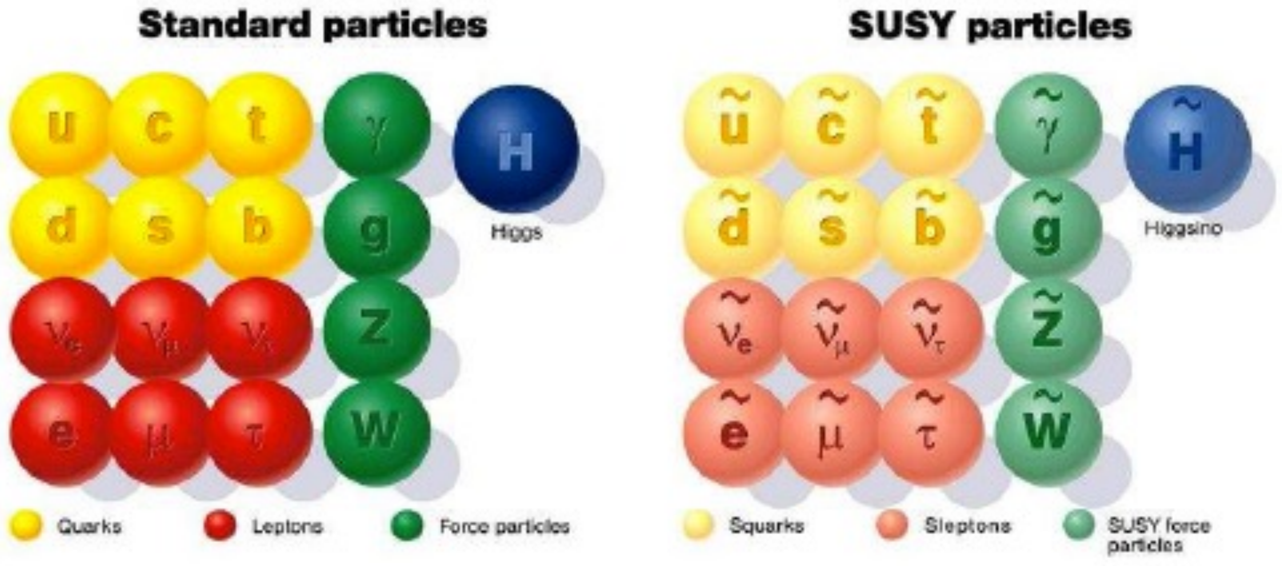
$$a_\mu^{\mathrm{susy}} \cong \mathrm{sgn}(\mu) \times 13 \times 10^{-10} \left(\frac{100\mathrm{GeV}}{m_{\mathrm{susy}}} \right)^2 \tan\beta$$

W. Marciano, J. Phys. G29 (2003) 225

Muon g-2 sensitivity to the "image world" of SUSY

$$a_\mu^{\mathrm{SUSY}} \approx 13\times 10^{-10} \tan\beta \; \mathrm{sign}(\mu) \left(\frac{100\mathrm{GeV}}{M_{\mathrm{SUSY}}} \right)^2$$

Mass of Neutralino!



The muon g-2 coil moved to Fermilab for more intense beam

Contacts: C. Polly – Project Manager (polly@fnal.gov)
K.W. Merritt – Deputy Project Manager (wyatt@fnal.gov)
D. Hertzog – Co-Spokesperson (hertzog@uw.edu)
B. L. Roberts – Co-Spokesperson (roberts@bu.edu)

From BNL to FNAL (2012)

- Higher proton and more pulses/cycle & segmented calorimeters → higher muon intensity with ~same pileup rate

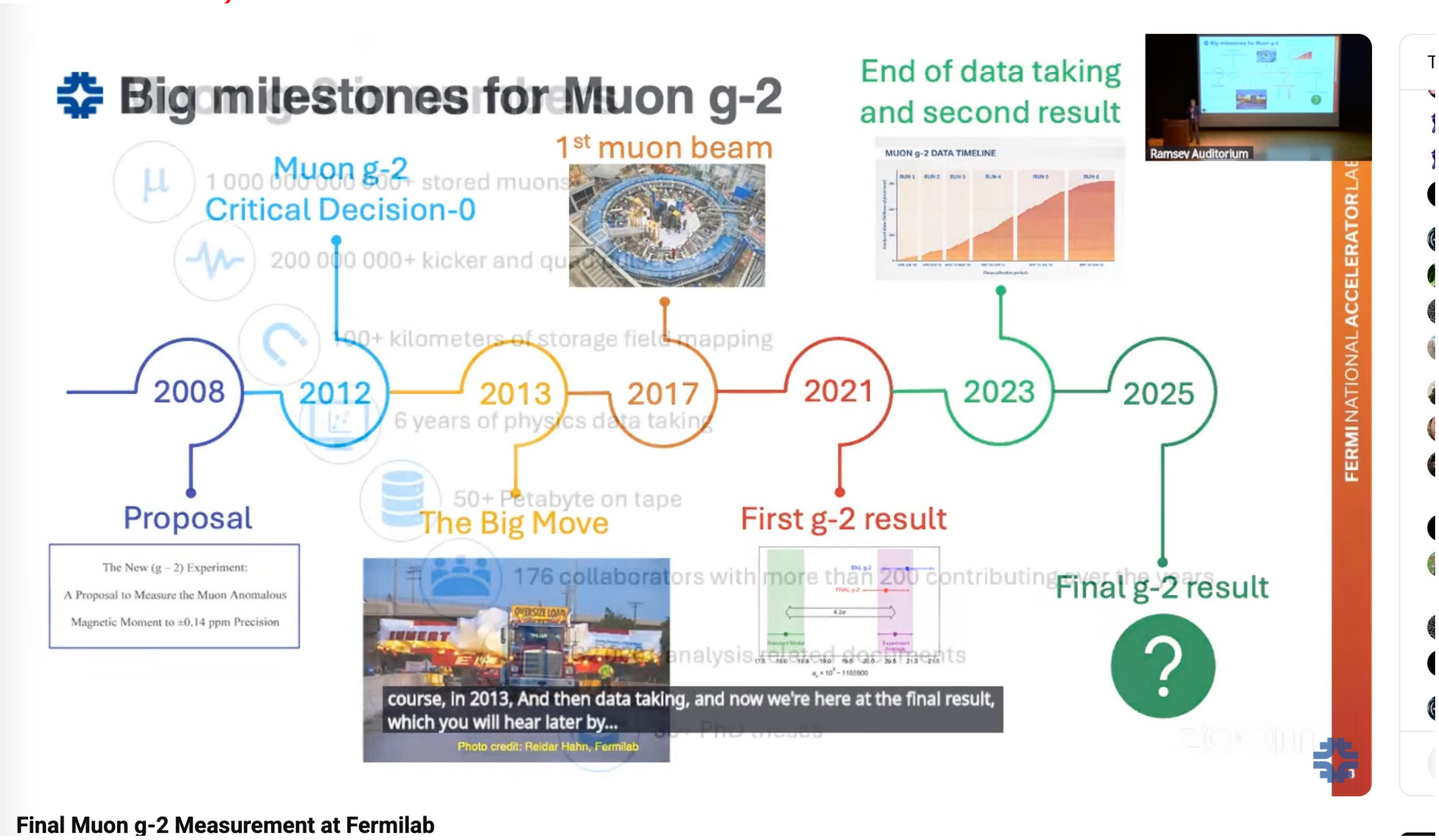
- High resolution tracker for real time muon position monitoring

- More B-field uniformity (x3)

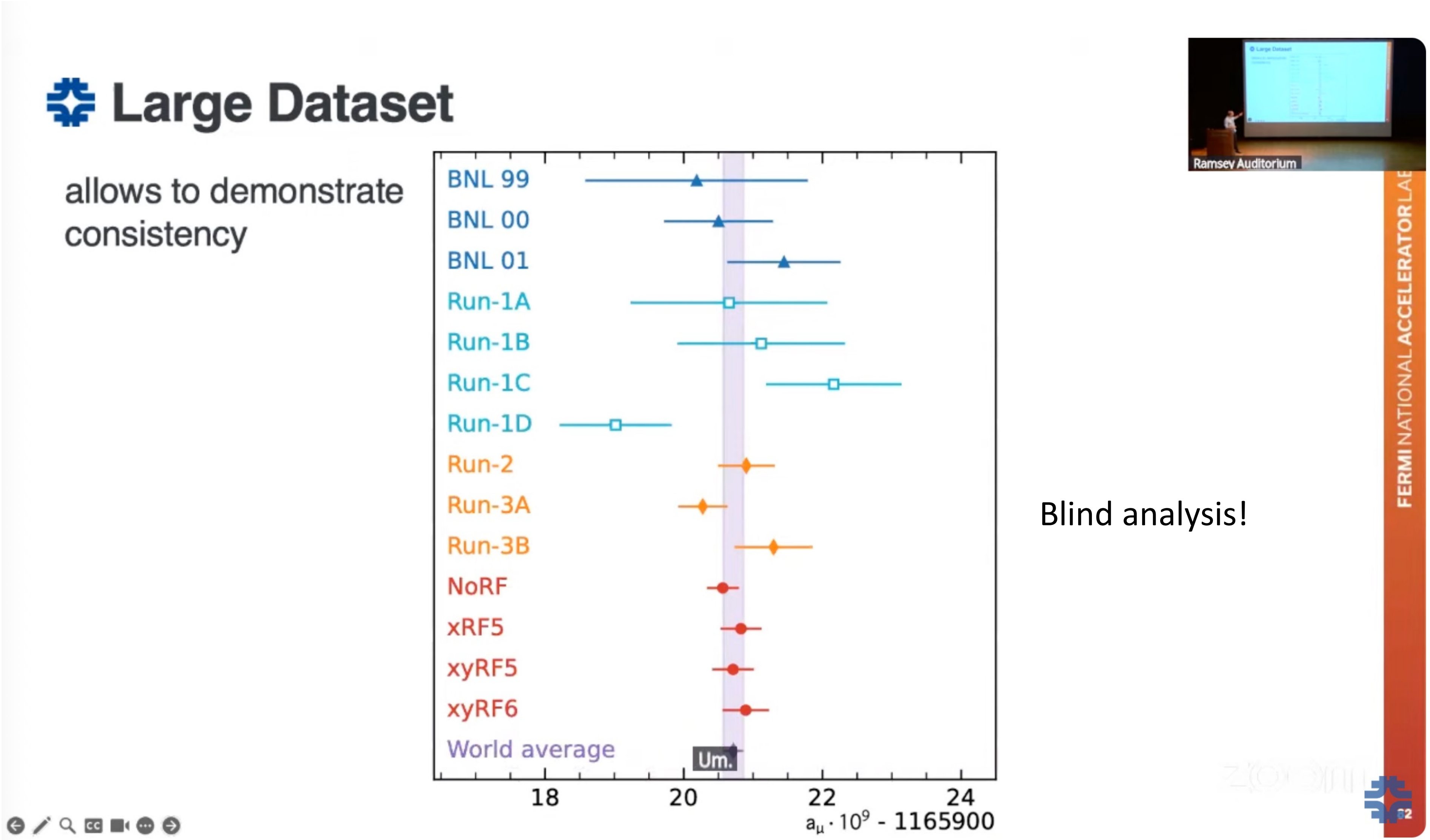
- Several high precision beam/spin dynamics simulations

- Reduced CBO amplitude by an order of magnitude
- Reduced muon losses during storage by x5

Slide by Peter Winter, co-spokesperson Fermilab, June 3



Announcement talk by Simon Corrodi, June 3, 2025



Blind analysis!

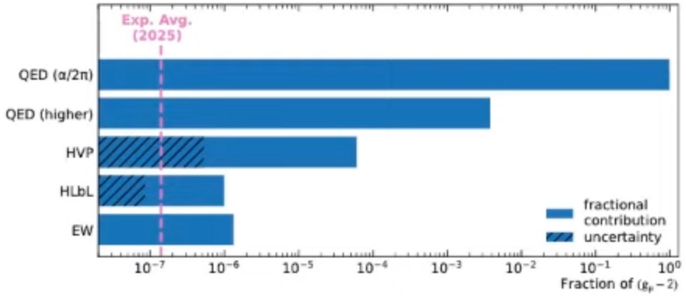
Beautiful experimental results (High-precision in storage rings)

Slide by Simon Corrodi

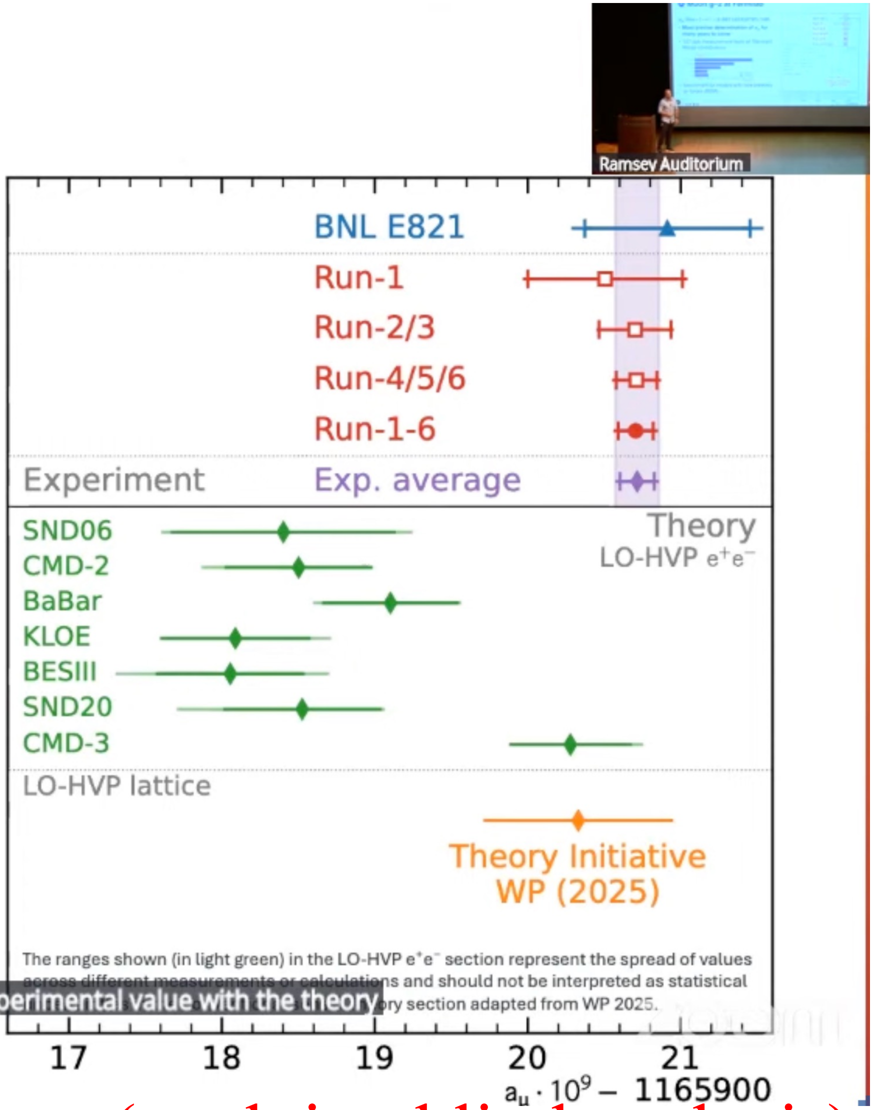
Muon g–2 at Fermilab

$$a_\mu(\text{Run}-1-6) = 0.001165920705(148)$$

- **Most precise determination of a_μ for many years to come**
- 127 ppb measurement tests all Standard Model contributions



- benchmark for models with new particles or forces (BSM)

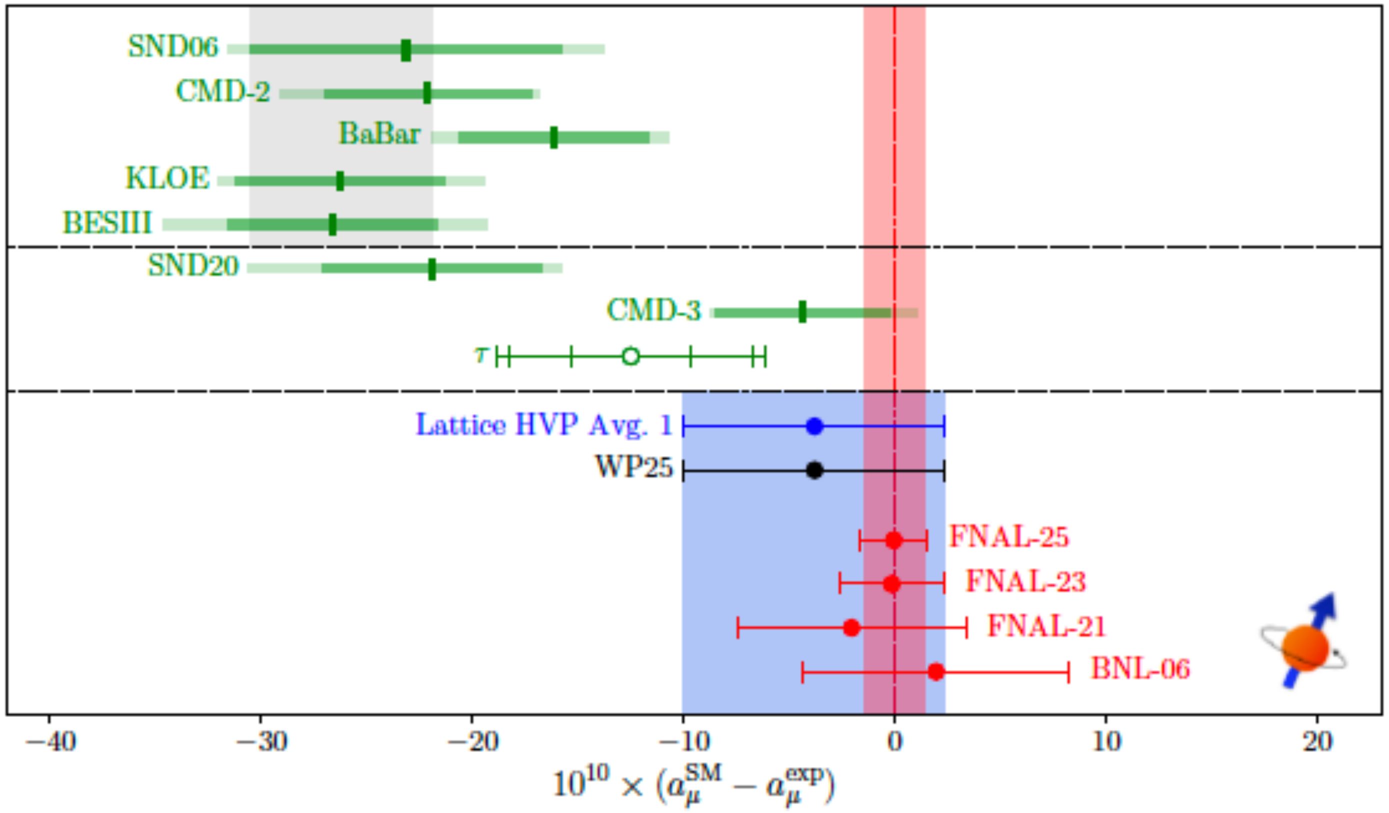


Summer or anything? If you compare the experimental value with the theory

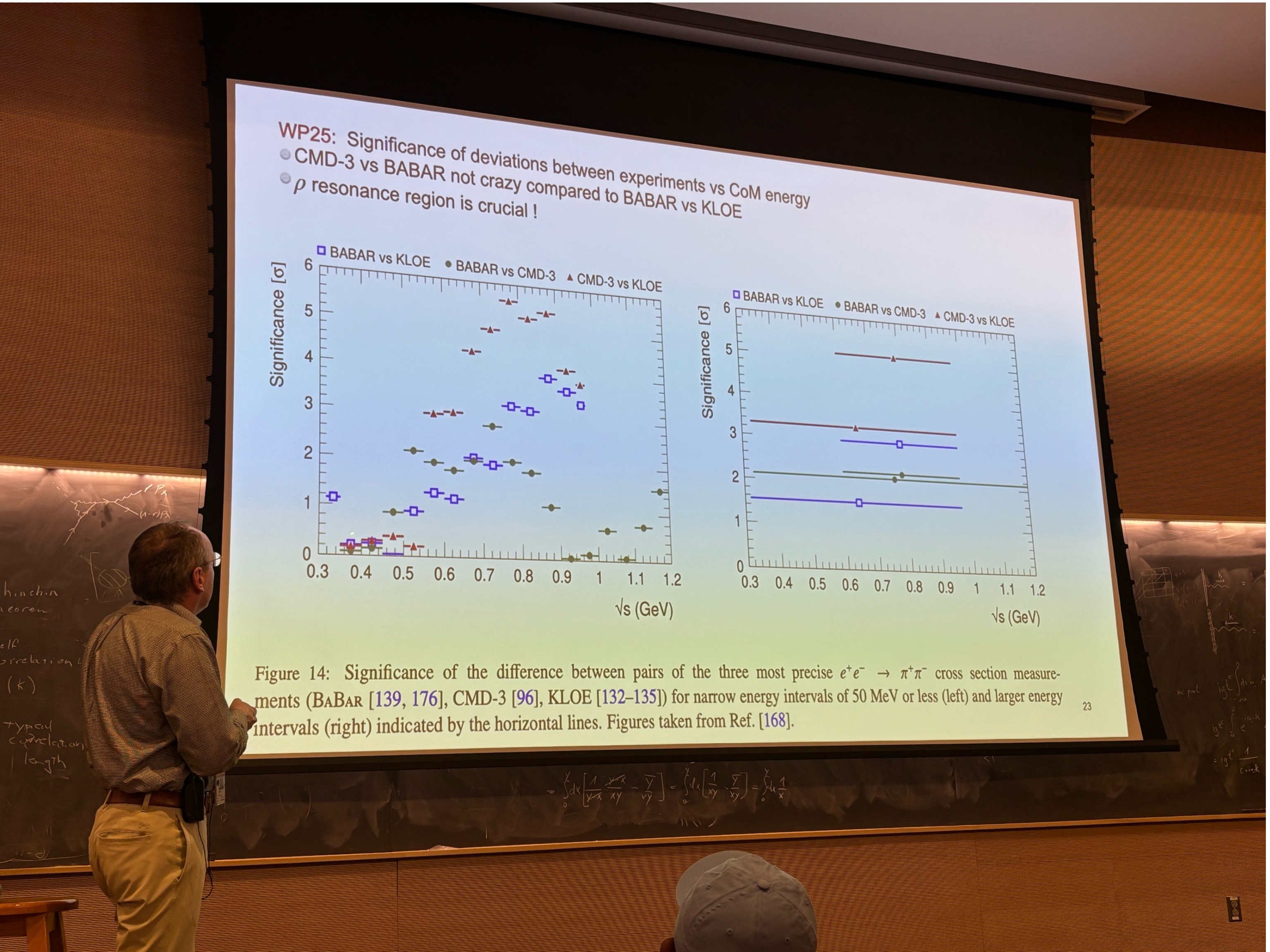
Theory results under intense progress (applying blind analysis)

Status of theory and experiment of Muon g–2

[White Paper '25]



Peter Boyle, colloquium on the theory of muon g-2; BNL, July 22, 2025

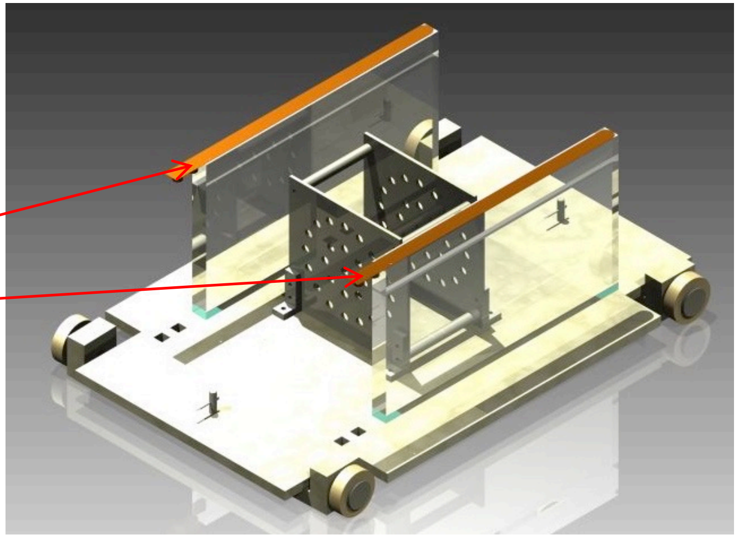


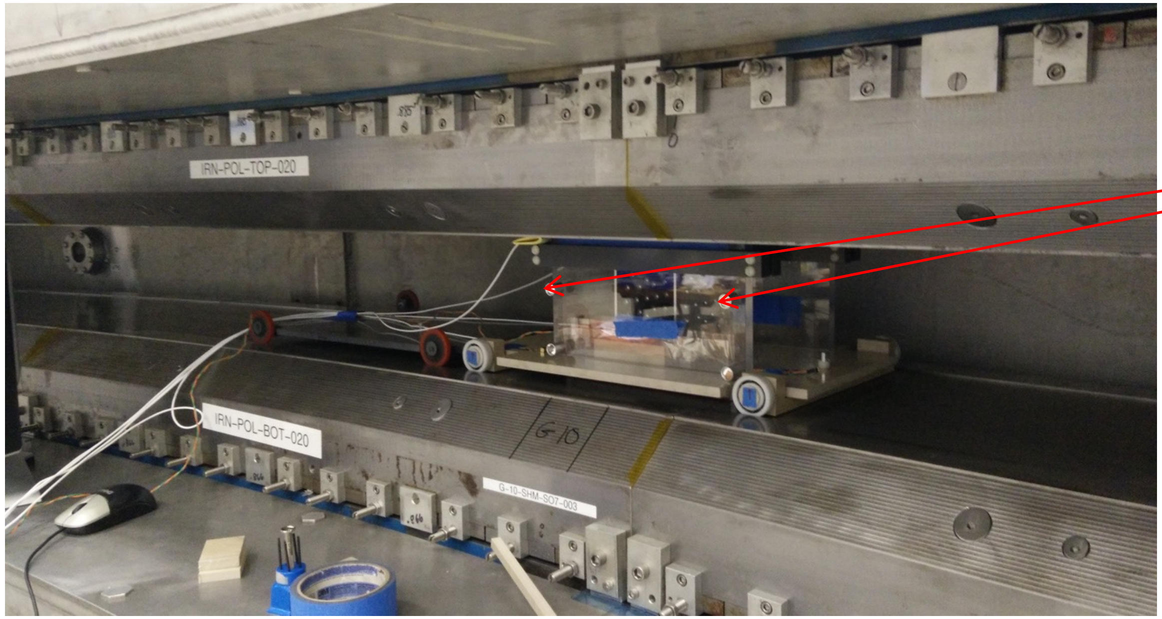
- He predicted that lattice QCD will match the experimental error within five years!
- It may be possible to do better by a factor of ~2 in the experiment with mostly present equipment, significantly more with muon collider technology. It would be fun to design an upgrade!

The ring has been reassembled and fully powered to 1.45T! First data taken: 2017

Shimming tool

- Multipurpose instrument
  - 25 **NMR Probes** for field
  - 4 **capacitive gap sensors**
    - Measure pole alignment
    - 70 nm resolution
    - Few micron reproducibility
- Laser tracked position with μm resolution



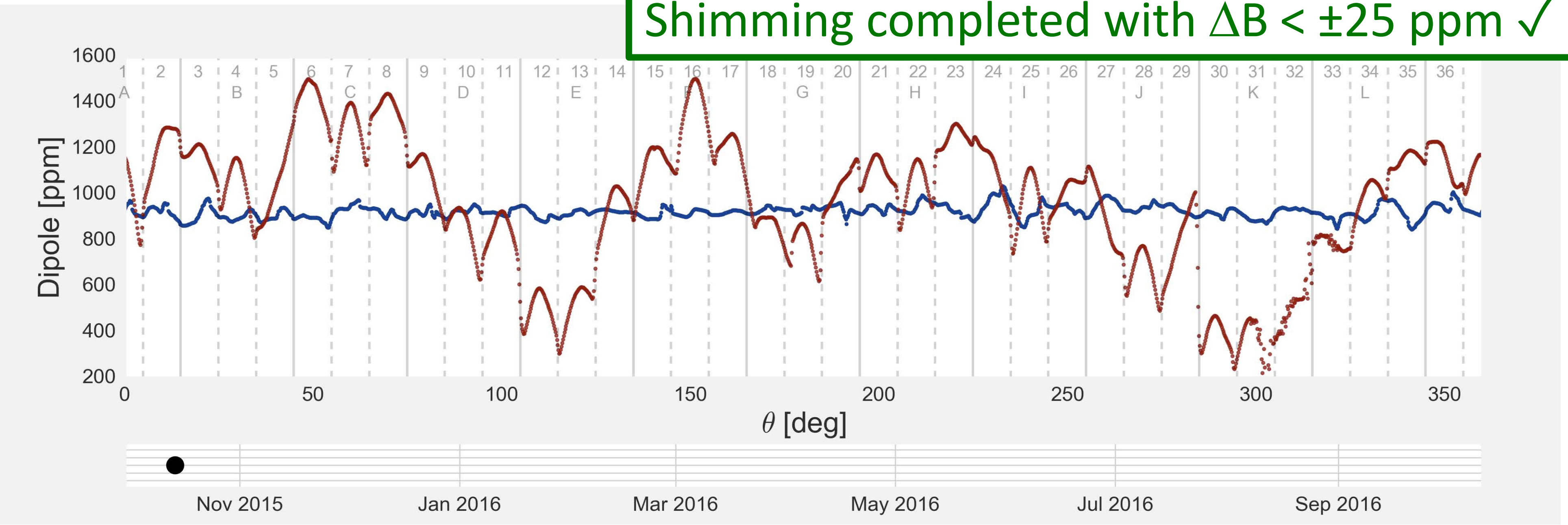


Shimming goal achieved as of September 2016:

- Many improvements on entire experiment to reach 140 ppb
- Precision alignment to reach dipole gradients of $\Delta B < \pm 25$ ppm
  - 72 poles
  - 840 wedge shims
  - 9000 thin iron foils

10 months of improving the dipole field in 1 minute...

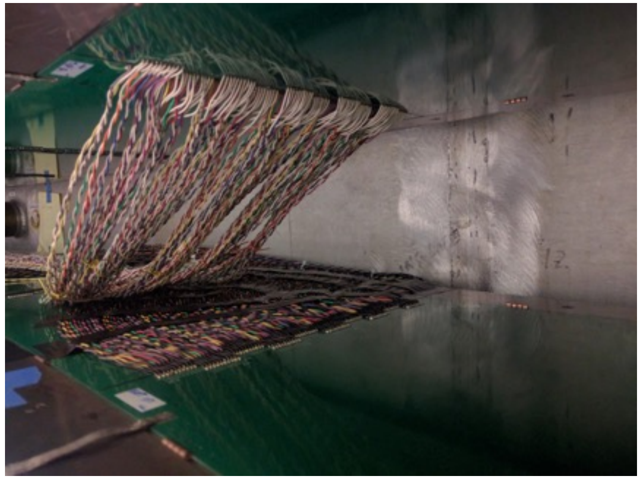
Shimming completed with $\Delta B < \pm 25$ ppm ✓

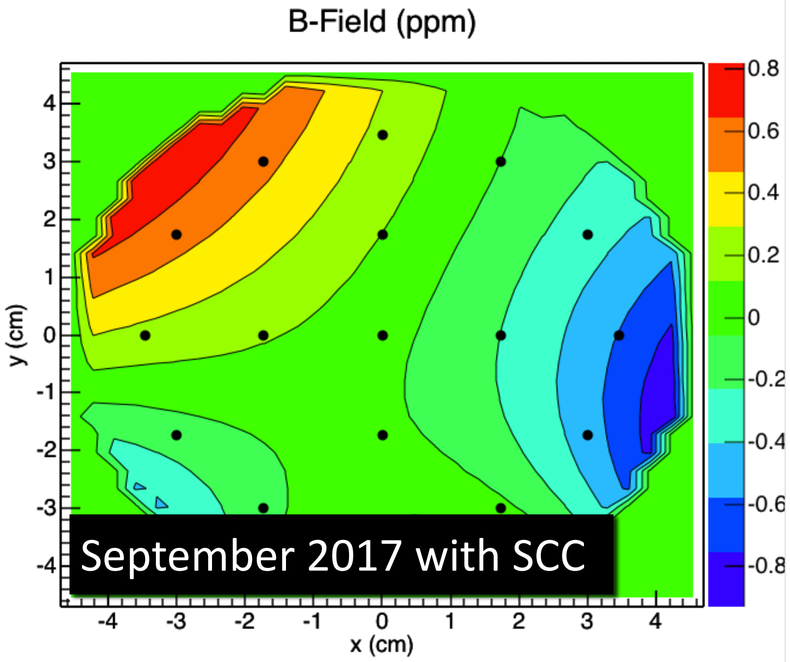


Calibrations Poles Wedges Laminations

Surface coils and power supply feedback

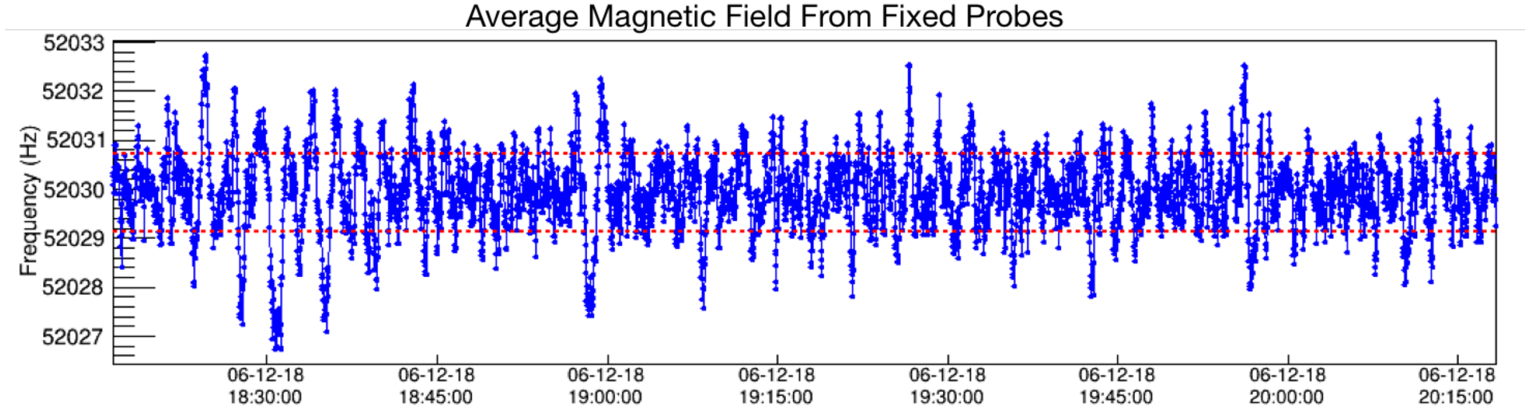
- 200 continuous current traces around the ring individual tunable between +-2A
- Used to cancel higher multipoles





	Norm	Skew
Quad	-0.46	0.22
Sext	-0.32	-0.29
Octu	-0.13	0.28
Decu	0.05	0.07
Dipole	-0.0	

- Power supply feedback stabilizes main dipole field to ±15 ppb

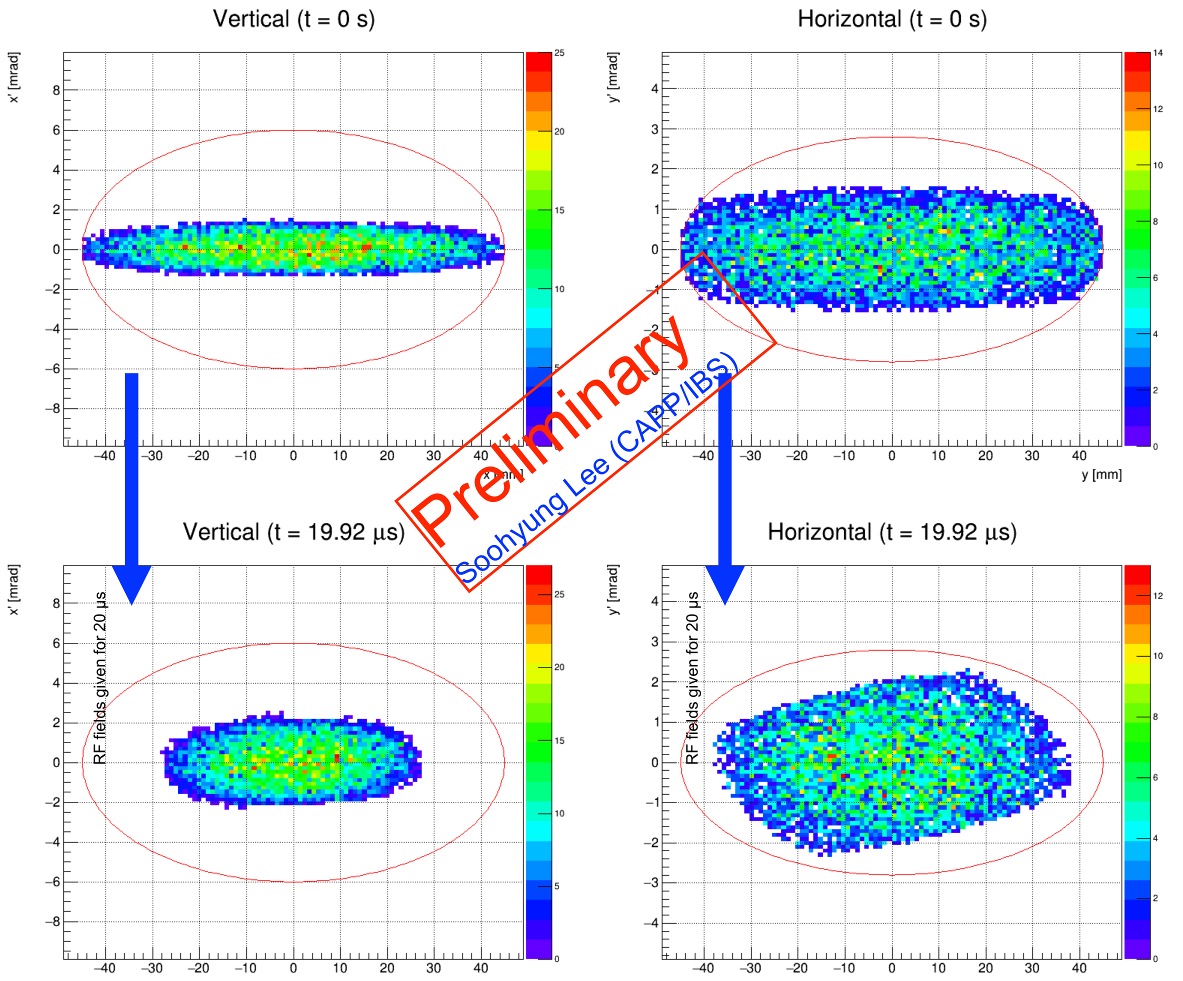


Systematic errors for the muon g-2 exp. at BNL and at FNAL (projections)

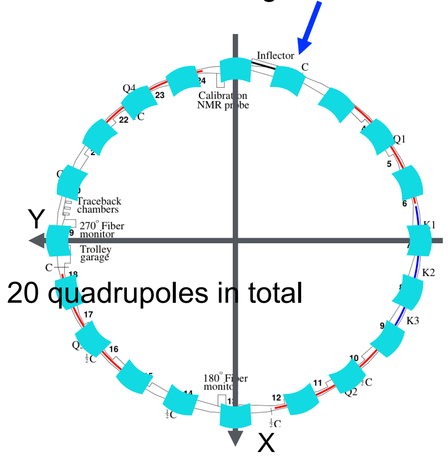
Category	E821 [ppb]	E989 Improvement Plans	Goal [ppb]
Gain changes	120	Better laser calibration	
		low-energy threshold	20
Pileup	80	Low-energy samples recorded	
		calorimeter segmentation	40
Lost muons	90	Better collimation in ring	20
CBO	70	Higher n value (frequency)	
		Better match of beamline to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

RF-Phase Matching: Tracking Simulation

- Muon phase-space matching with RF quads. Korean contribution

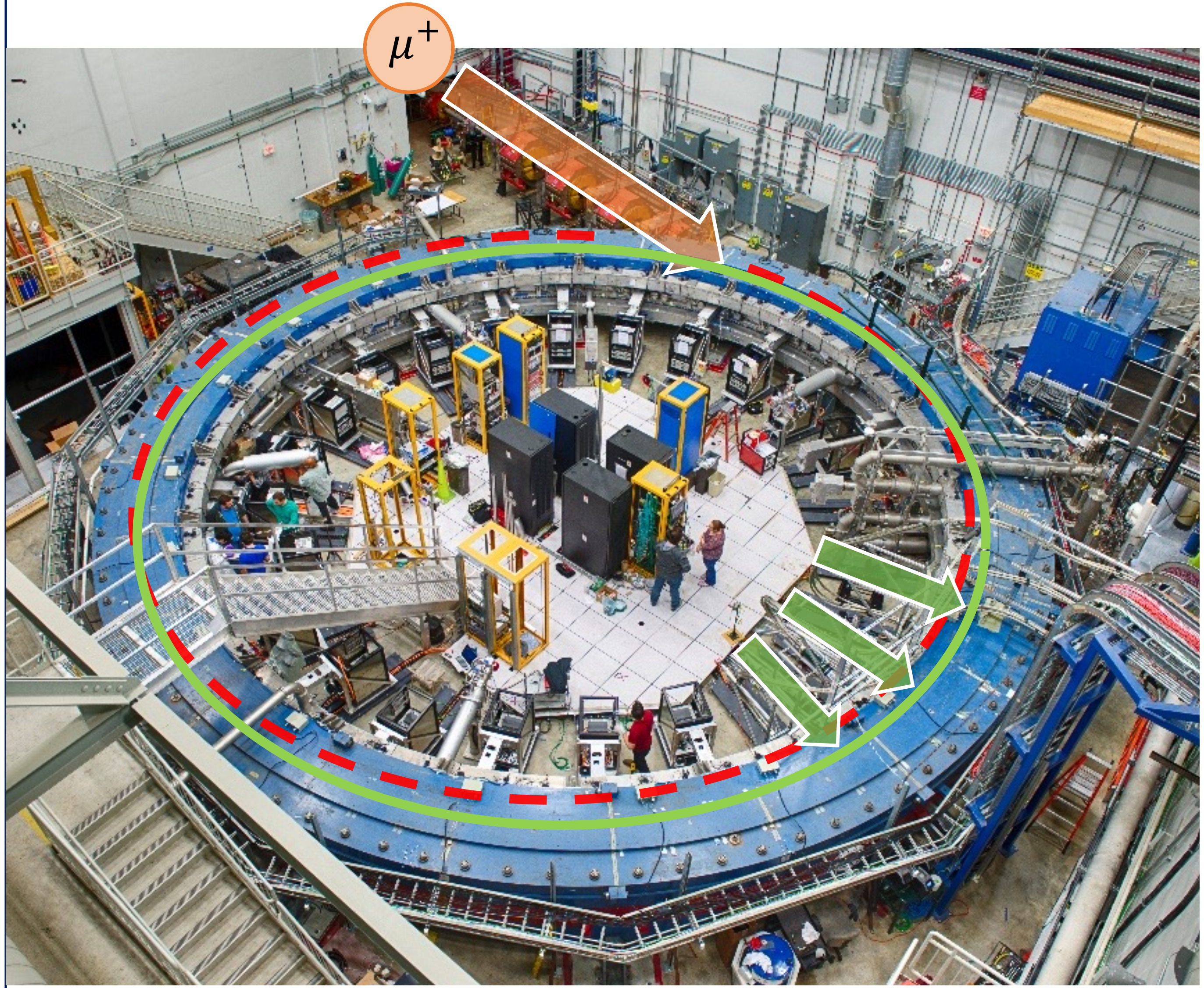


10,000 muons, ideal beam



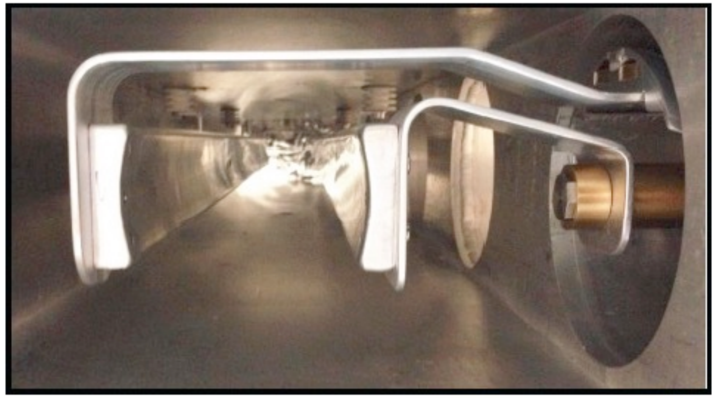
Voltages of V_x=375 V and V_y=125 V are applied to horizontal and vertical plates in each quadrupoles

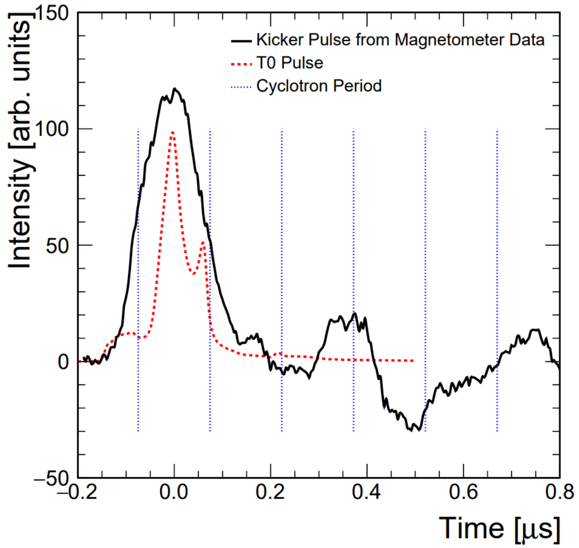
Overview of Muon $g-2$ Experiment at Fermilab (E989)



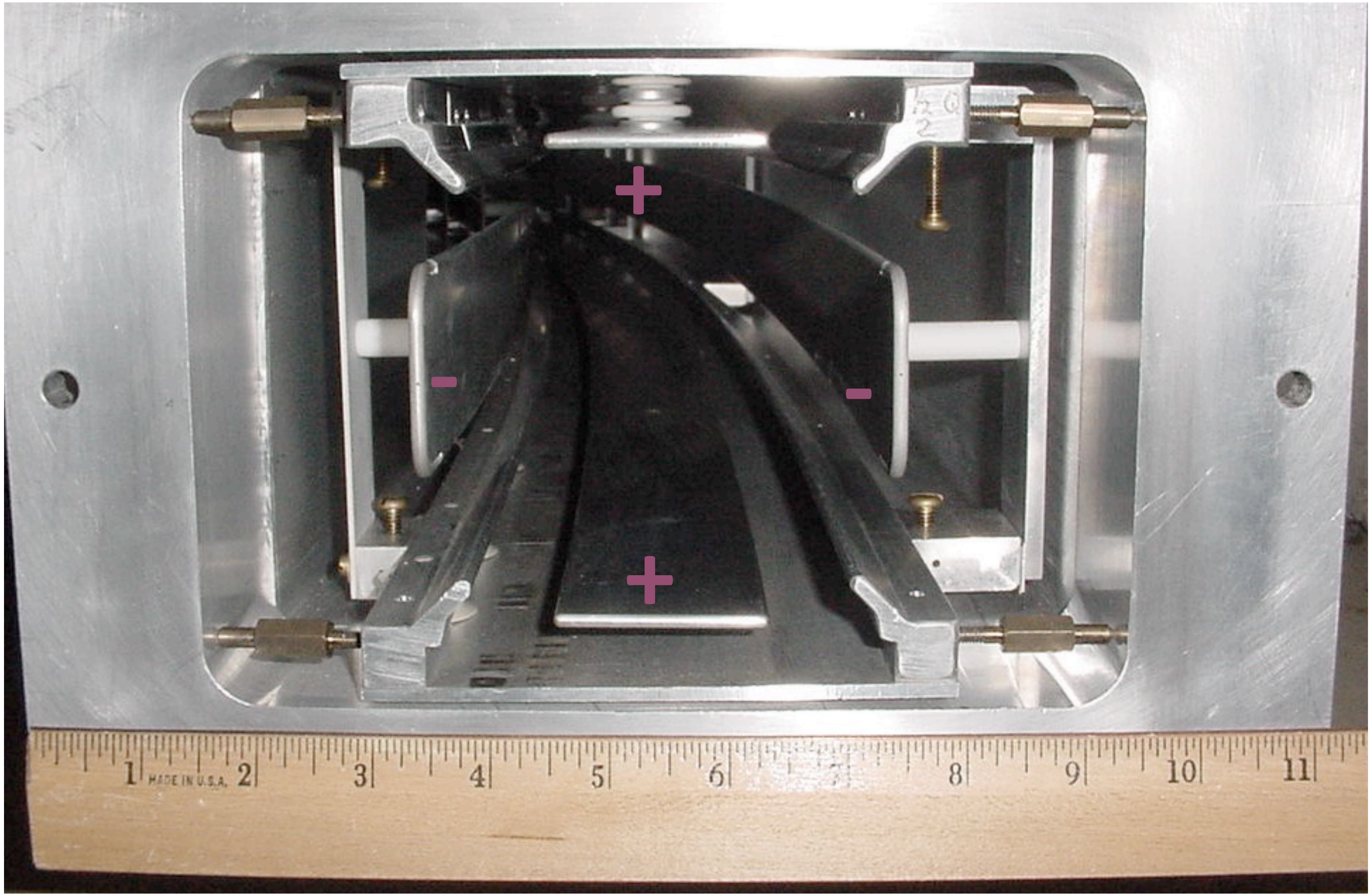
▶ Kick

- Muons are kicked onto the design orbit by the fast non-ferric **kicker magnet** system.

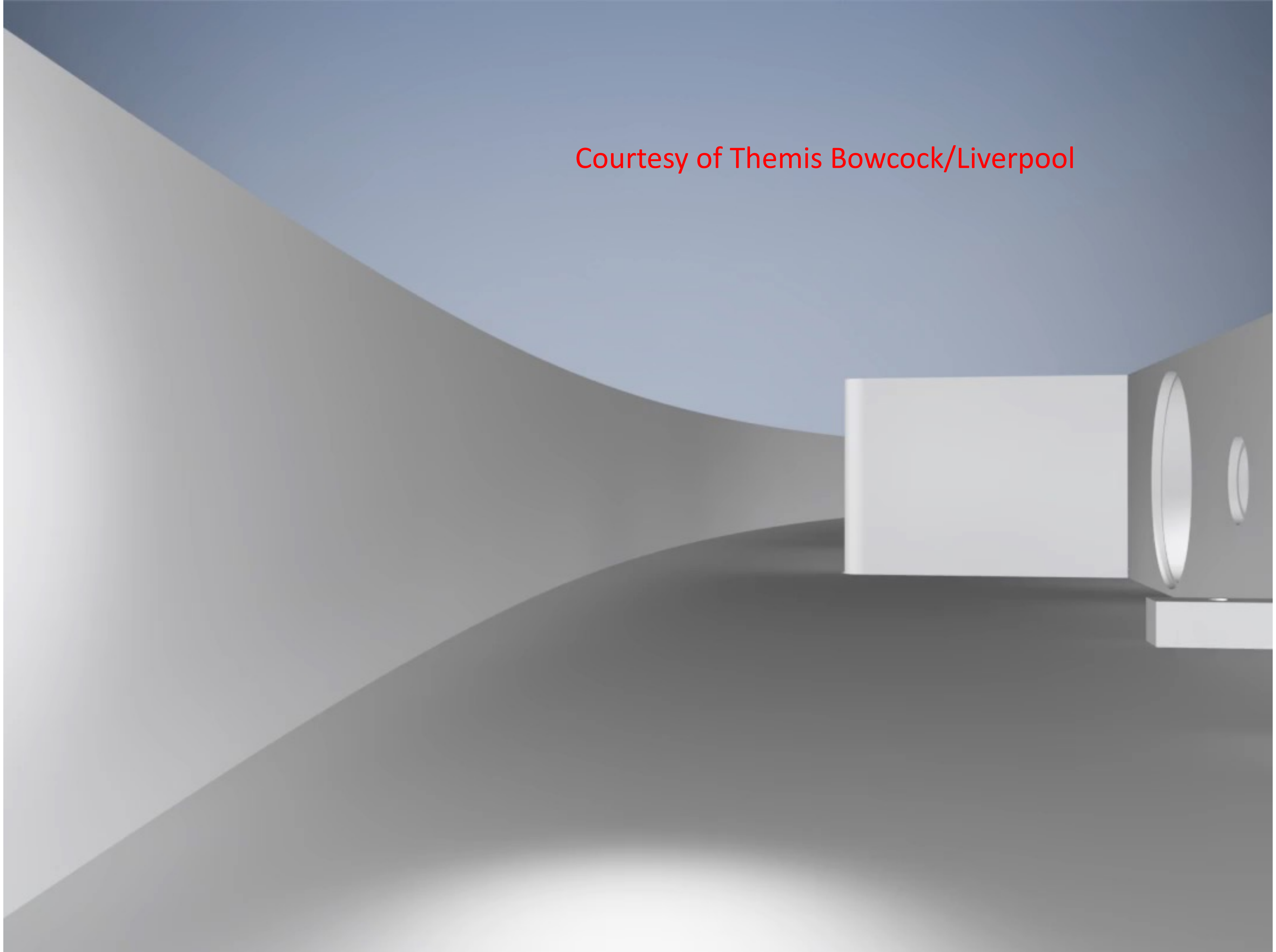




The Electrostatic Quadrupoles: μ^+ polarity

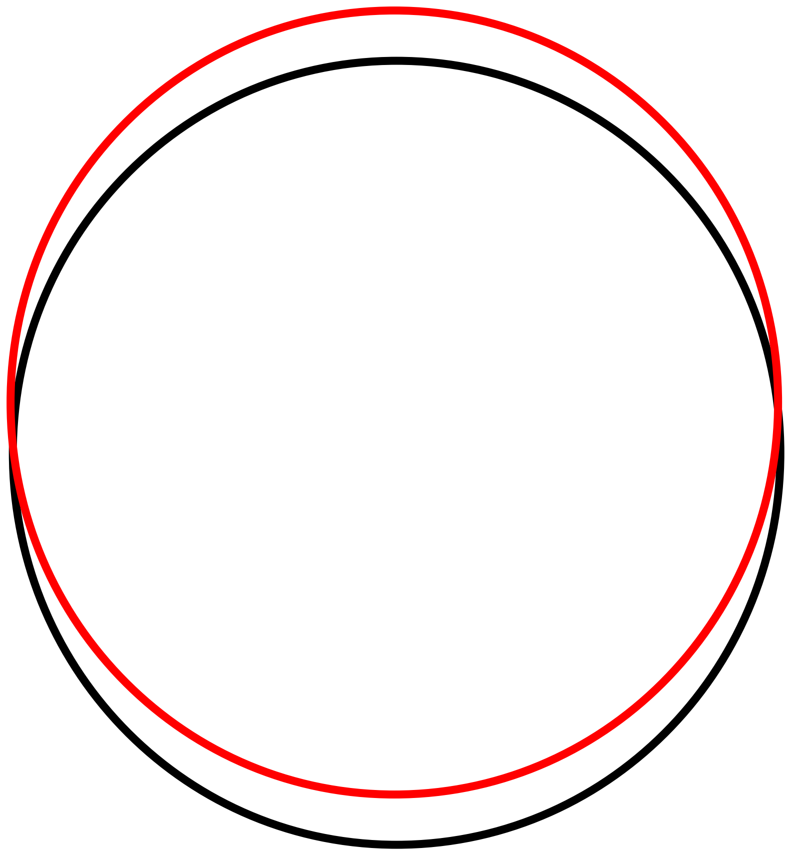


~ ± 24 kV at full power,   17 kV for beam scraping after injection


Courtesy of Themis Bowcock/Liverpool

Coherent betatron oscillations influence the g-2 phase

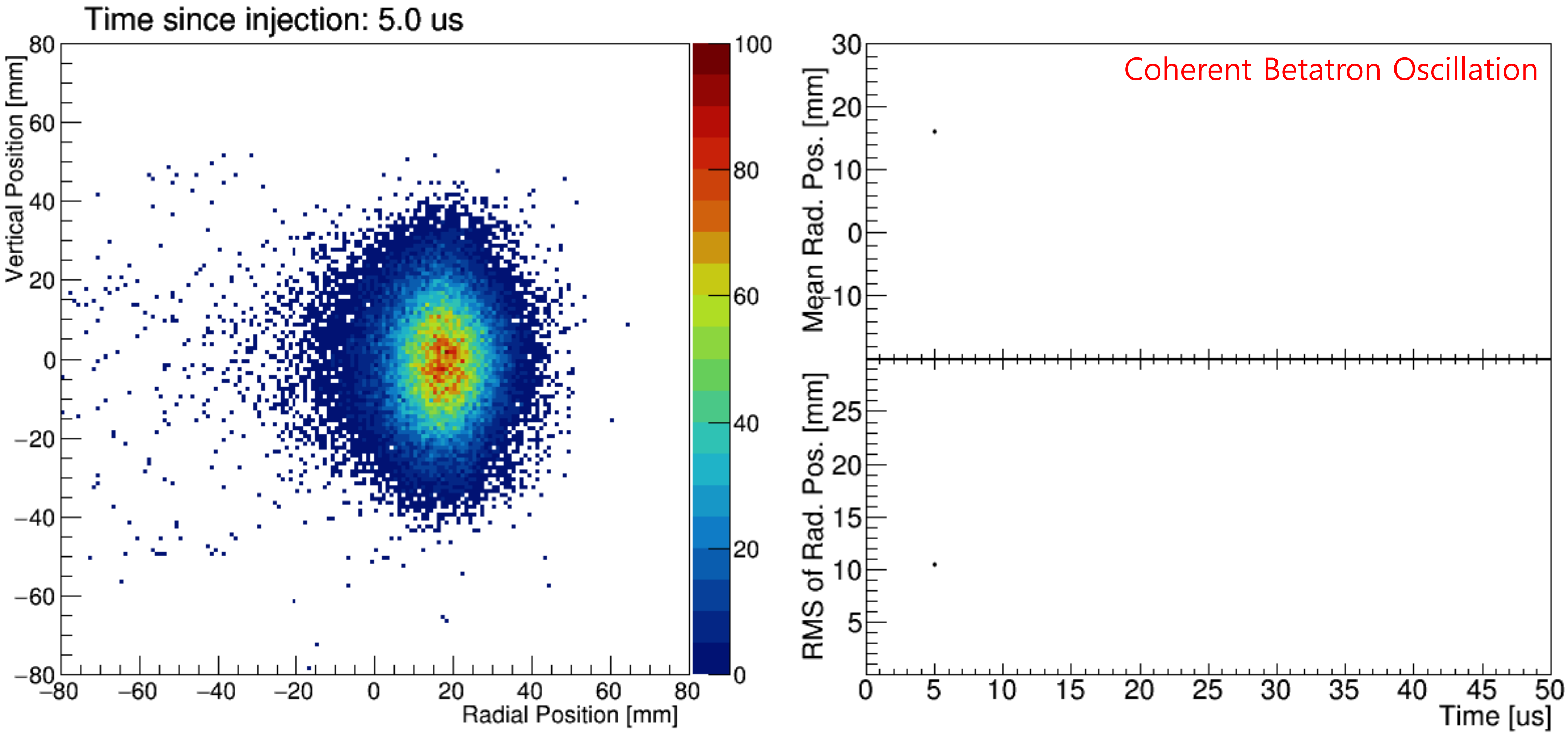
- CBO frequency $f_{cbo} = f_c\left(1 - \sqrt{1-n}\right)$. Radial oscillations, through aliasing, became a problem
- A very high-frequency, cascaded through various effects down to g-2 frequency



Straw trackers

▶ Straw trackers

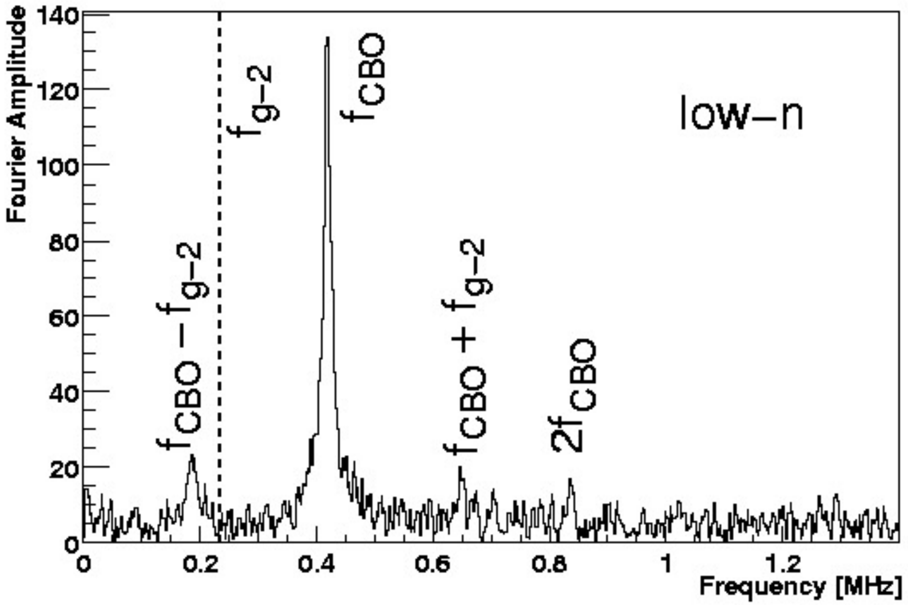
- Measures trajectories of the decay positrons and extrapolates to find the muon distribution.

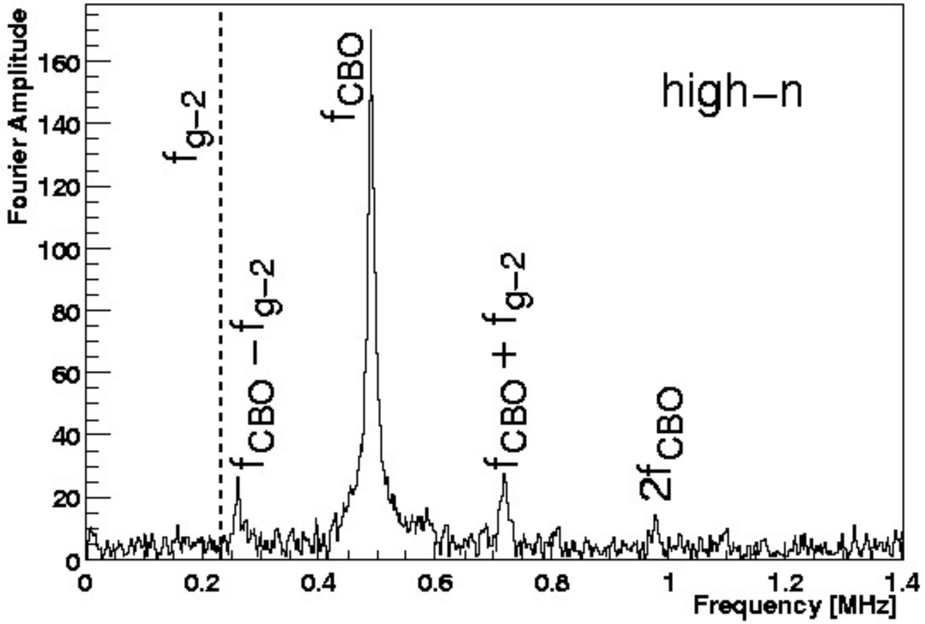


CBO in the 2001 Data Set

$$f(t) = N_0 e^{-\lambda t}[1 + A\cos(\omega_a t + \phi)]$$

Residuals from fitting the 5-parameter function





CBO in the Data Set

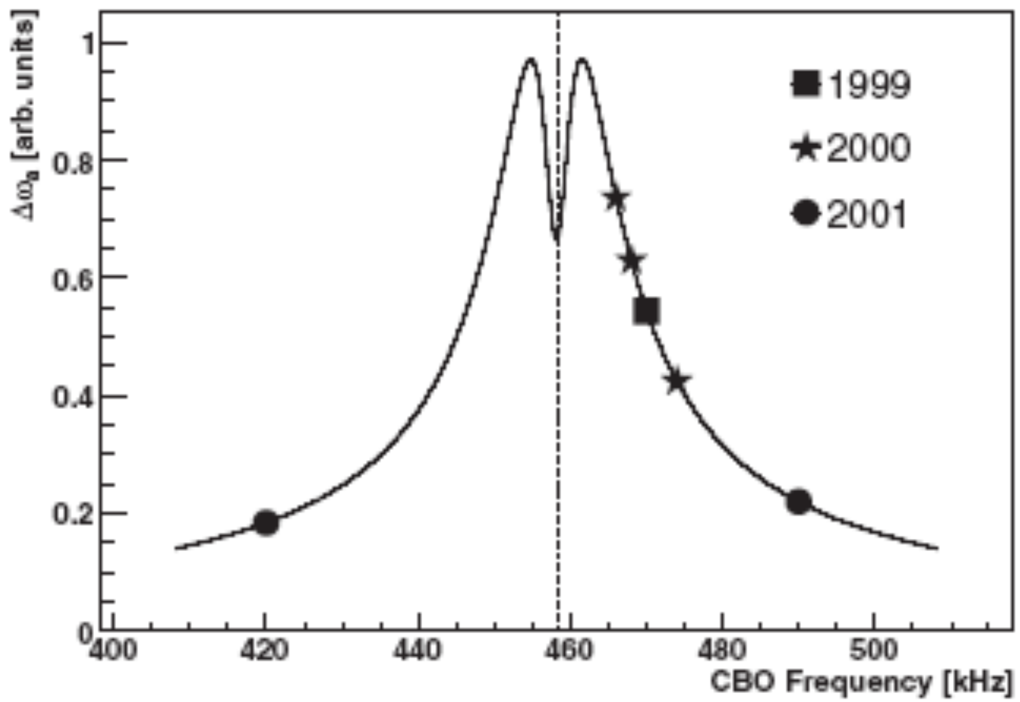
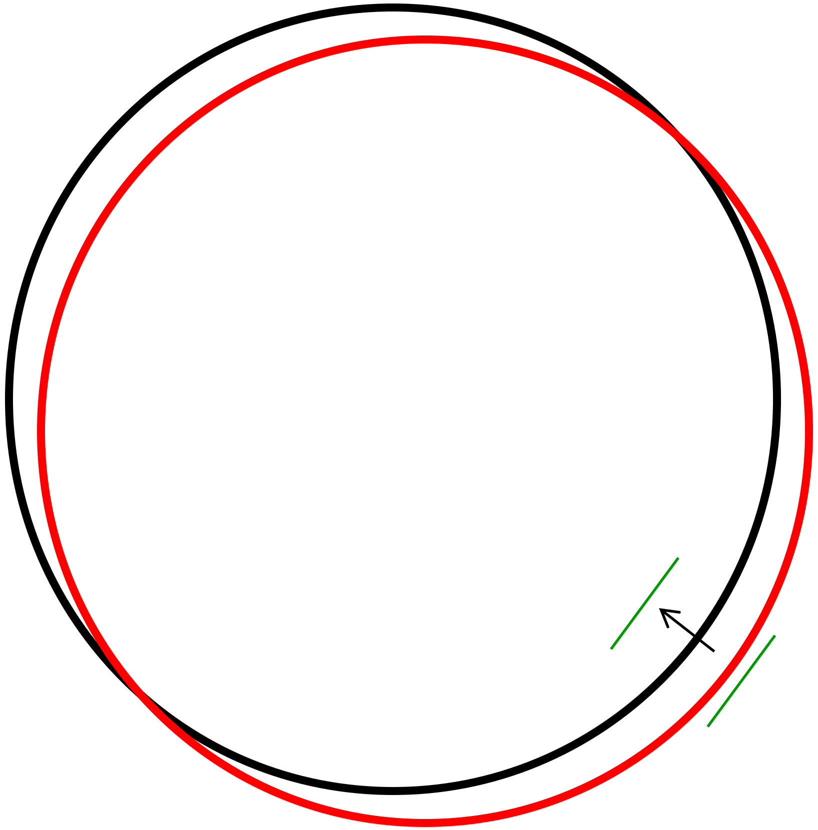


FIG. 36. The relative pull ($\Delta\omega$) versus the CBO modulation frequency *if not* addressed by the fitting function. A typical full vertical scale is several ppm; the actual scale depends on the specifics of the fit and the data set used. The R00 data were acquired under run conditions in which ω_a was very sensitive to CBO. This sensitivity was minimized in the R01 period where low- and high-n subperiods, each having CBO frequencies well below or above twice the $(g-2)$ frequency, were employed.

The effect depends on the CBO frequency

Yuri Orlov suggested to fix it by using a pair of plates (PE) as mini-kicker: We tried his method at Fermilab; it worked.



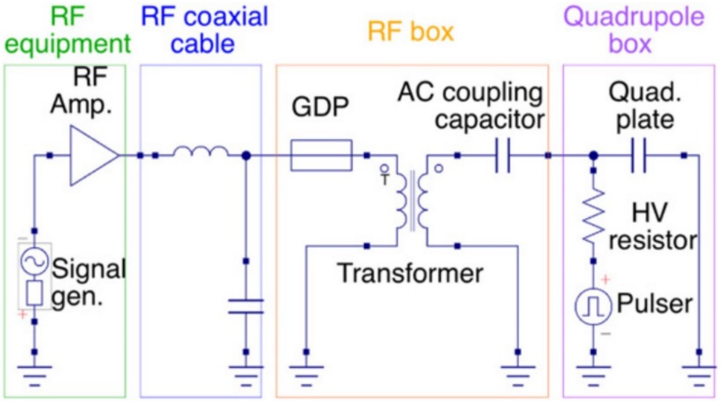
PE plates are 1m long
Apply rf E-field 470KHz

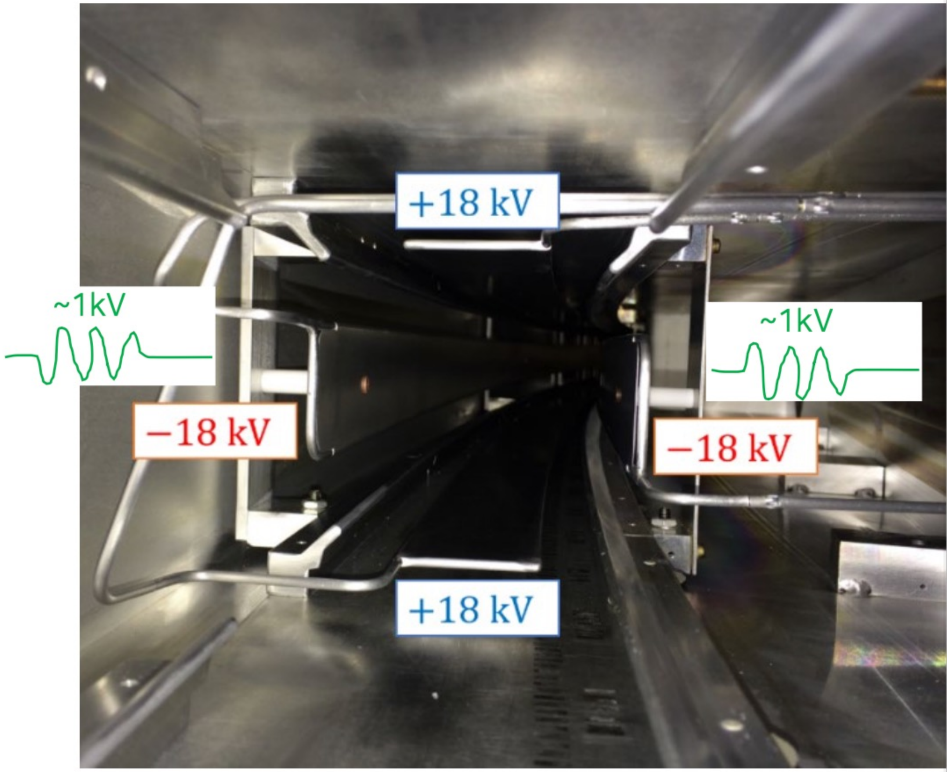
QUAD-RF SYSTEM

On Kim's slide

RF rack
- Generates and amplifies RF signals.

Quad-RF feedthrough
- Couples to existing quad HV system.



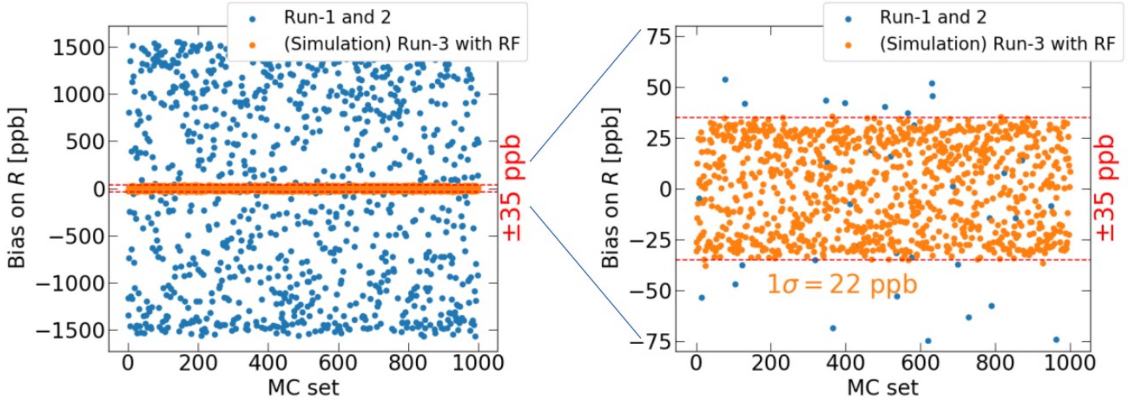


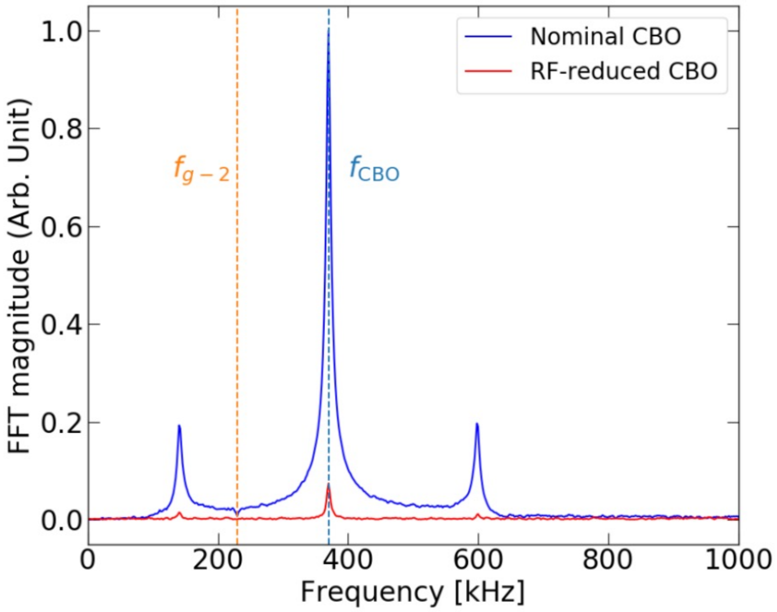
Quad HV + RF
- ~1 kV RF signals are superposed to Quad HV.
- Only applied during the early storage < 30 us.
- Typically applied to inner/outer plates to reduce the CBO amplitude, but can be applied to top/bottom plates as well to reduce muon losses more.

On Kim's slide

Simulation

Parameter	Run-1d	Run-2	(Projected) RF CBO reduction
$\tau_{\rm CBO}$ [μs]	190 ± 11	259.8 ± 9.3	-
$A^N_{\rm CBO} \times 10^4$	32.4 ± 1.0	32.7 ± 0.4	1.8
$A^A_{\rm CBO} \times 10^4$	5.9 ± 1.4	3.4 ± 0.7	0.3
$A^\phi_{\rm CBO} \times 10^4$	1.1 ± 0.7	0.4 ± 0.7	0.1



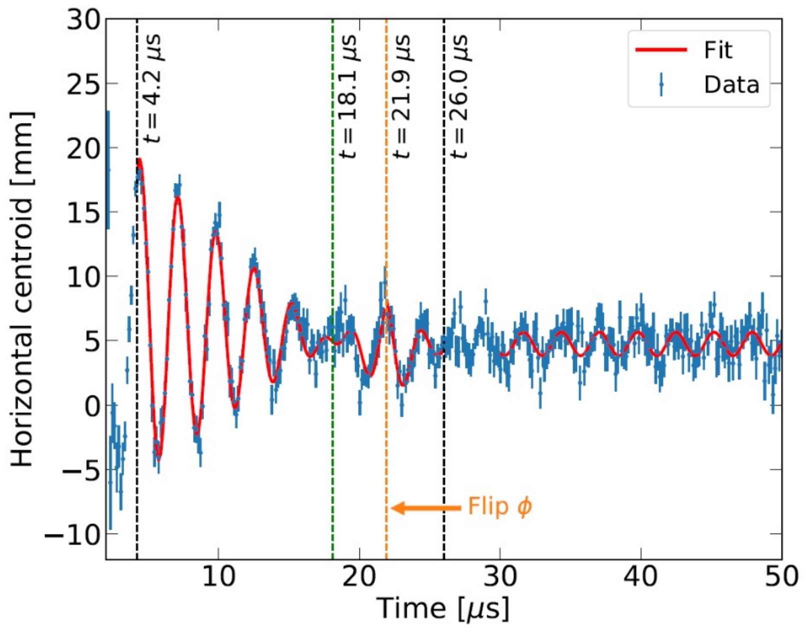


Estimated reduction of the CBO systematic uncertainty

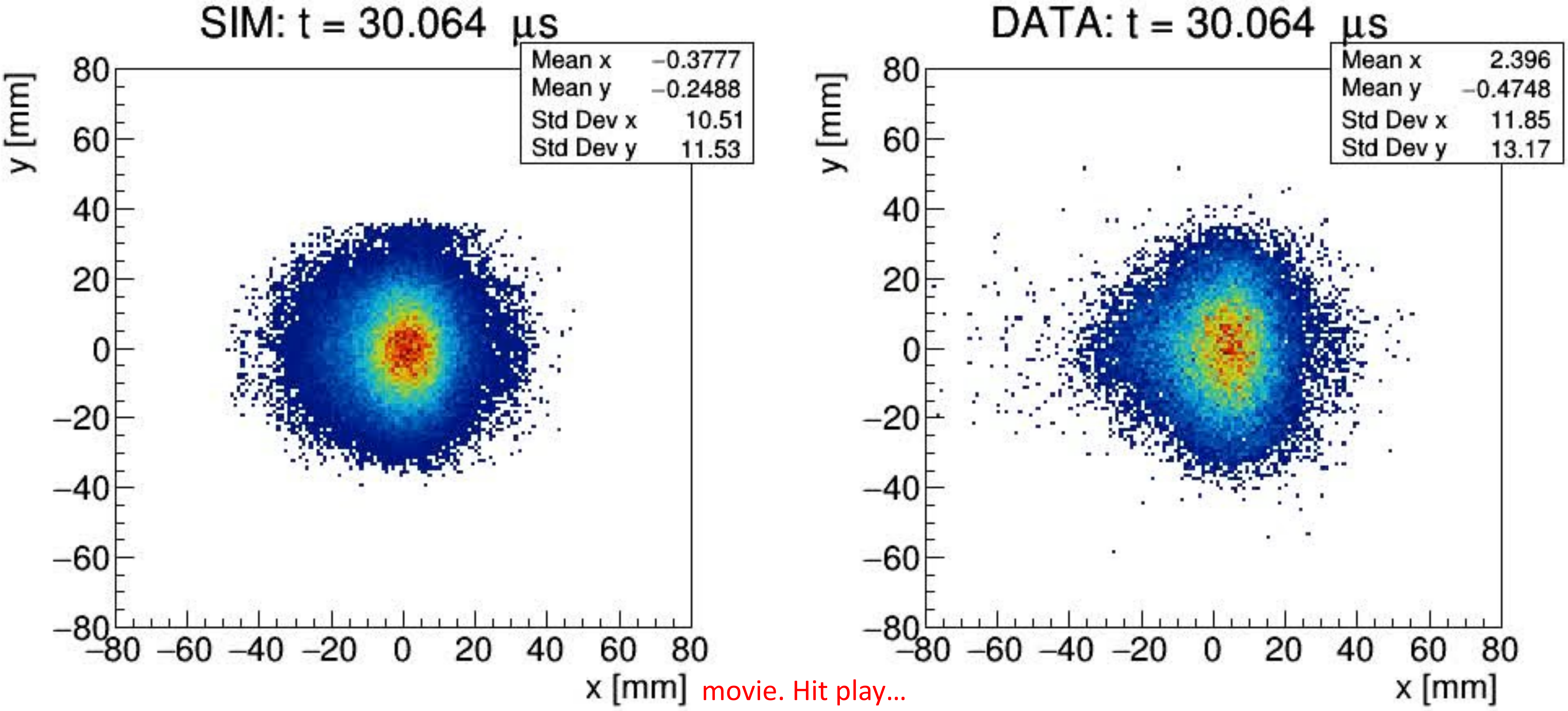
- Details can be found in DocDB 24590.
- Dominant CBO fit parameters would be reduced by an order of magnitude (see Table left).
- Estimated reduction in the CBO systematic uncertainty: by a factor of 50.
- Final CBO uncertainty would've been < 1 ppb.

Data

- When focused only on the CBO reduction.
- CBO amplitude was reduced by an order of magnitude.
- Final CBO amplitude after 30 us: < 1 mm.



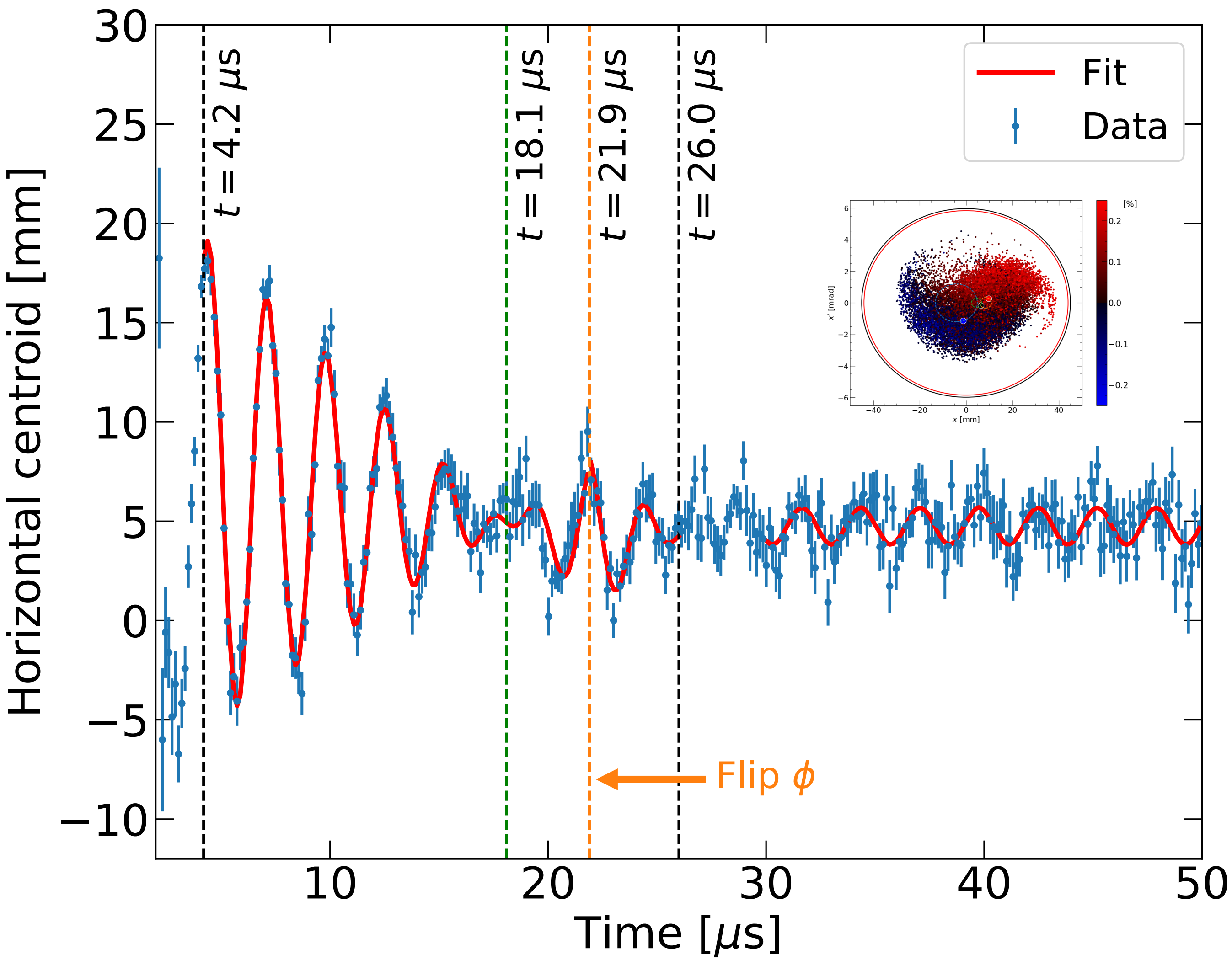
Linear simulation from reconstructed beam (SIM) versus tracker data (DATA)

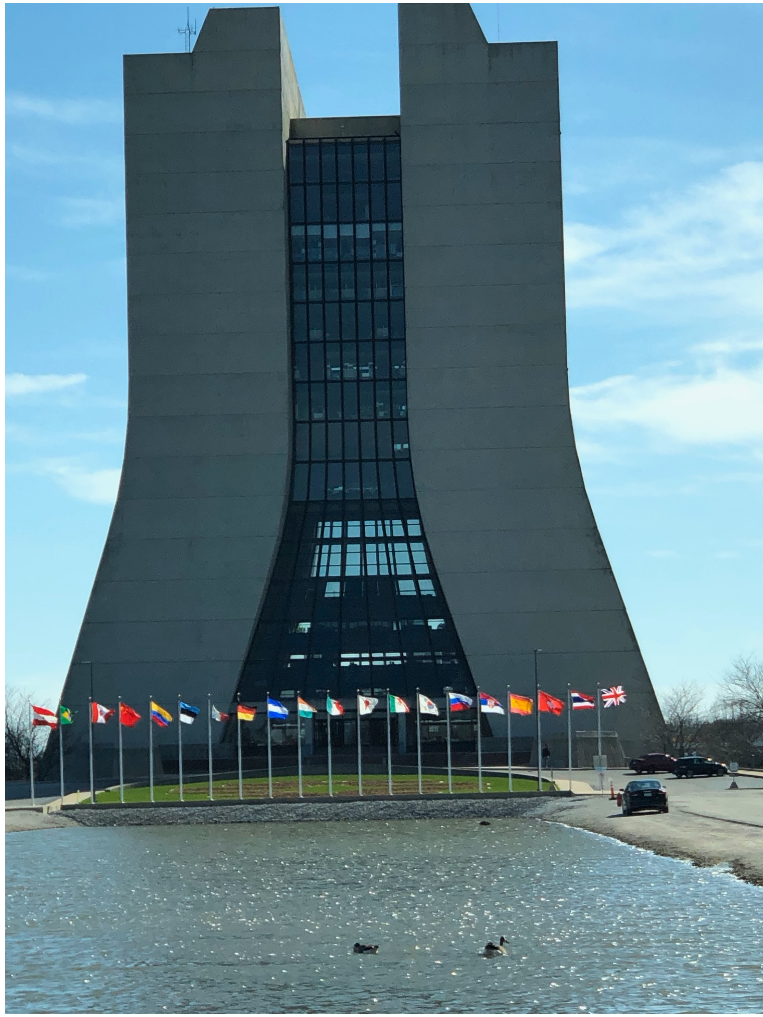


movie. Hit play…

- Good agreement. Thus, the reconstruction reproduces observed beam.
- Ignore tiny time gap in video between SIM and DATA. It's from the reconstruction with 0.149us-wide bins.

RF CBO amplitude reduction (data from muon g-2 experiment)

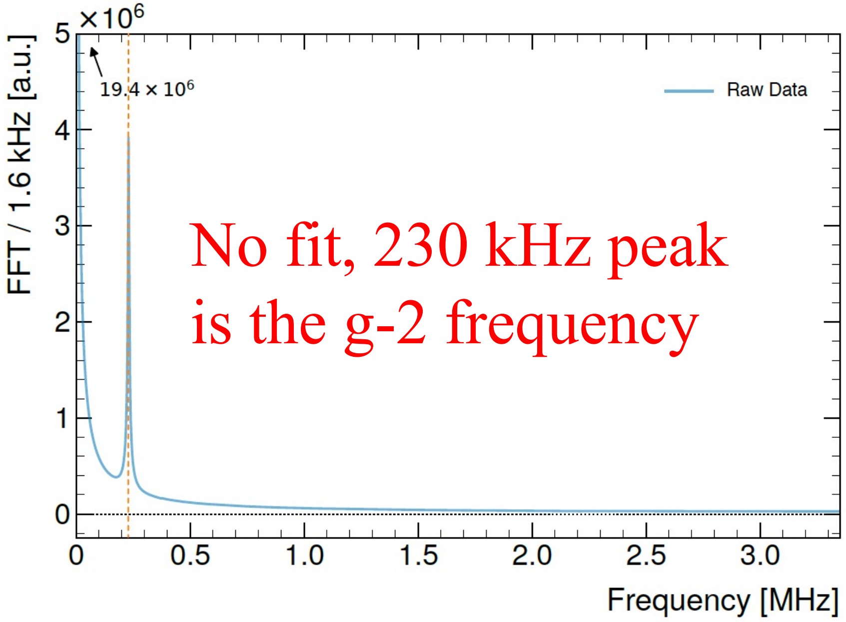


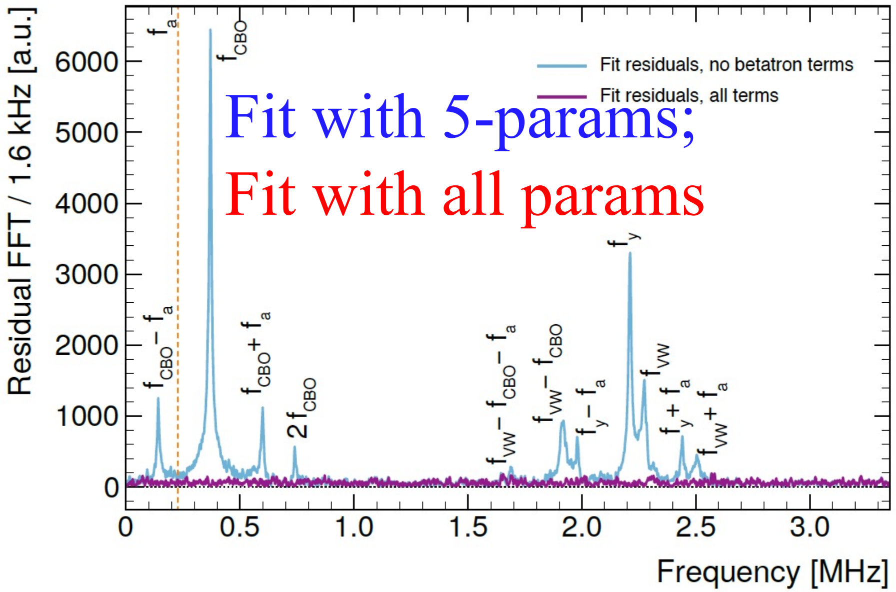


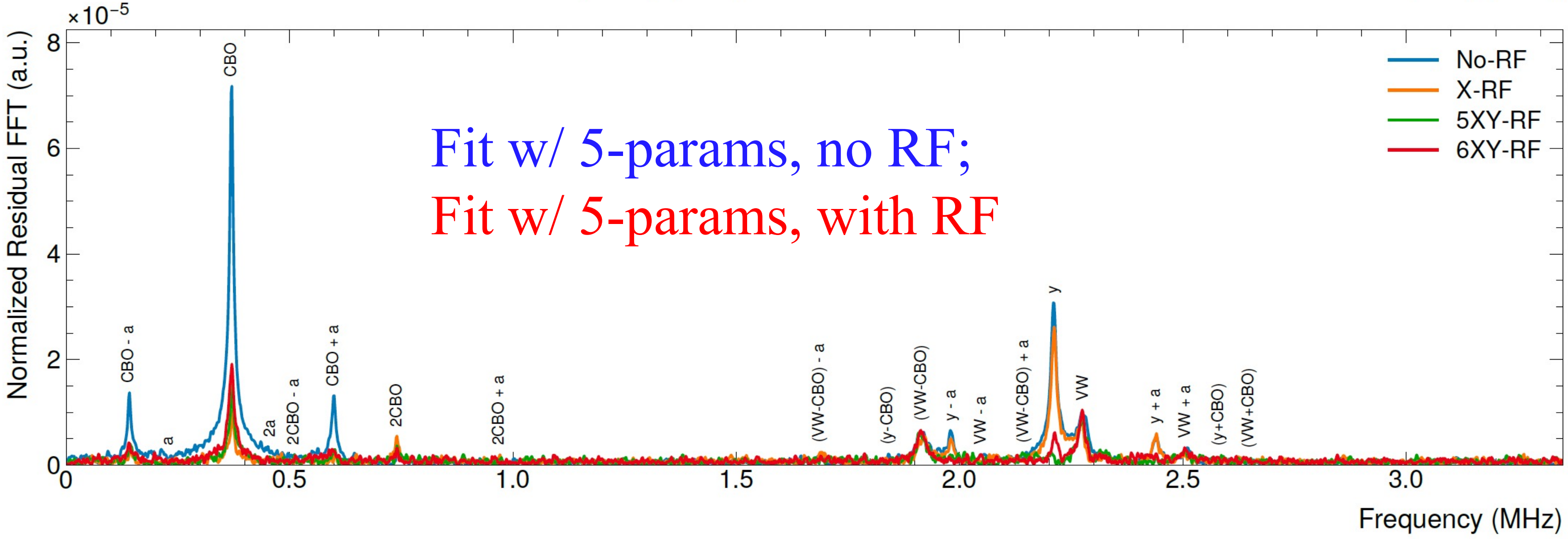
On Kim *et al*, New J. Phys. **22** (2020) 063002

CBO in the Fermilab Data Set, Fourier results

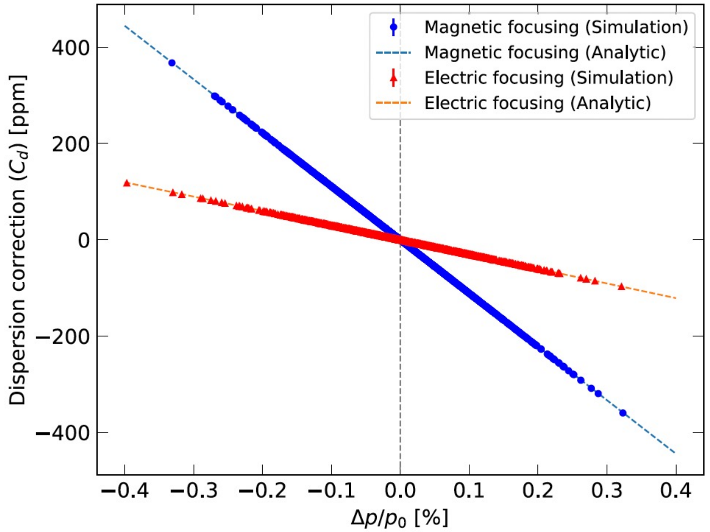
Fourier analysis of original data or after fits

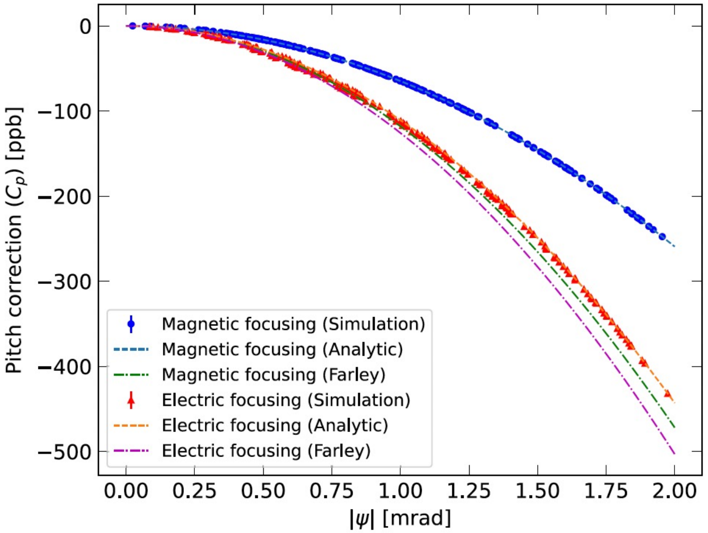






Comparison of analytical estimations of systematic corrections and simulations

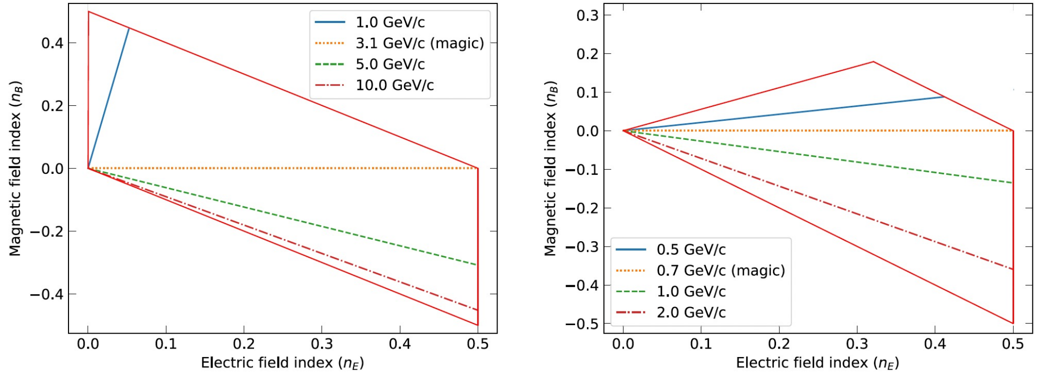




Vertical angle (pitch) effect

Momentum dispersion

On Kim: Extending the "magic" for future g-2 experiments

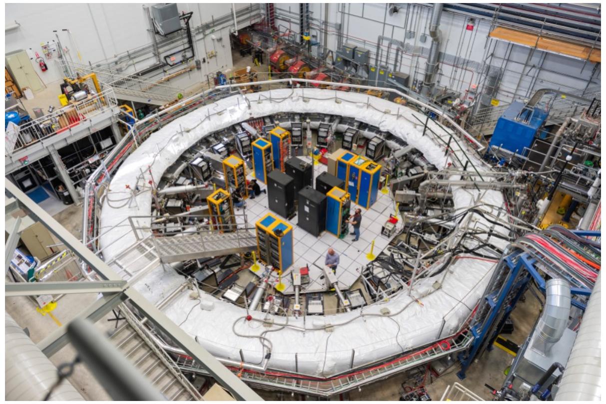


(a) (b)

FIG. 6. The relation between the magnetic and electric field indices (n_B and n_E) to cancel out the dispersion correction for given momenta of the muon and the proton. The field indices must lie within a region enclosed by the red solid lines, to obtain the net vertical focusing and positive momentum. The magic momentum case for each particle is shown for validation, where it needs only the electric focusing to be present ($n_B = 0$). (a) Muon. (b) Proton.

Muon g-2 experiment

- Successful demonstration of high-precision physics in storage rings.
- The collaboration developed several new tools for systematic error probing.
- High-precision numerical integrators for beam/spin dynamics simulations,…
- Bill Morse and Lee Roberts are the recipients of the APS 2023 Panofsky Prize.



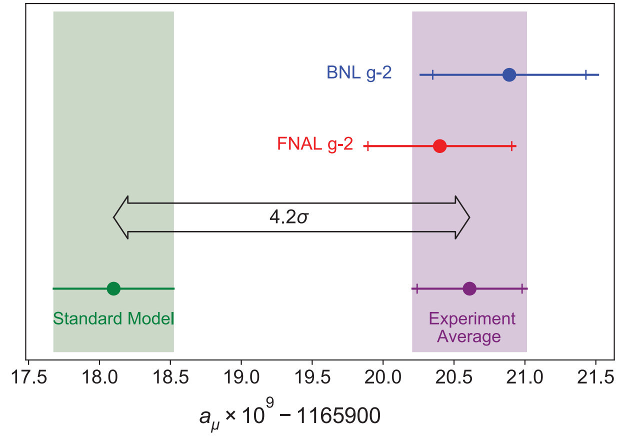


FIG. 4. From top to bottom: experimental values of a_μ from BNL E821, this measurement, and the combined average. The inner tick marks indicate the statistical contribution to the total uncertainties. The Muon $g-2$ Theory Initiative recommended value [13] for the standard model is also shown.

Yuri Orlov: 2020 Wilson Prize; Bill Morse & Lee Roberts: 2023 Panofsky Prize

- We built the largest single diameter (15m) superconducting magnet coil at the time. Moved it across the country to repeat the experiment.
- Uniformity of B-field (1.5T) in cross-section to better than 10^{-6} measured it (absolute) to better than 10^{-7} calibrated with two independent methods
- Developed a trolley system measuring the B-field in situ (>5000 points)
- Introduced a new DC inflector with innovative B-field shield at 3T without being detectable at storage region <10 cm away
- Built a fast (200ns, 300G) magnet (kicker) without ferrite, measured the pulsed B-field eddy currents to 10^{-8} requiring enormous dynamic range
- Developed electrostatic quads with twice the CERN gradient; measured the Electric field gradient.
- Our calorimeter detectors had to have time stability, early to late in storage, of <20ps, measured it <2ps; gain stability to 10^{-4}
- Used combinatorics to remove pileup pulses; segmented calo detectors
- Traceback system monitoring motion in real time, without affecting muons
- Used RF, riding on the quads, for 30 us to adjust coherent beam motion and reduce muon losses, both by an order of magnitude
- …
- Project manager (Chris Polly, Fermilab) received DOE management Prize

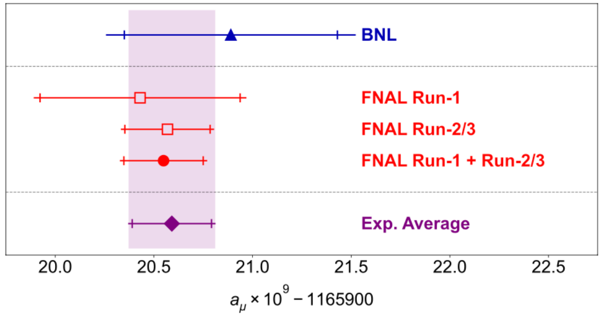


FIG. 3. Experimental values of a_μ from BNL E821 [8], our Run-1 result [1], this measurement, the combined Fermilab result, and the new experimental average. The inner tick marks indicate the statistical contribution to the total uncertainties.

On time, on budget

Yuri Orlov: 2020 Wilson Prize; Bill Morse & Lee Roberts: 2023 Panofsky Prize

- We built the largest single diameter (15m) superconducting magnet coil at the time. Moved it across the country to repeat the experiment.
- Uniformity of B-field (1.5T) in cross-section to better than 10^{-6} measured it (absolute) to better than 10^{-7} calibrated with two independent methods
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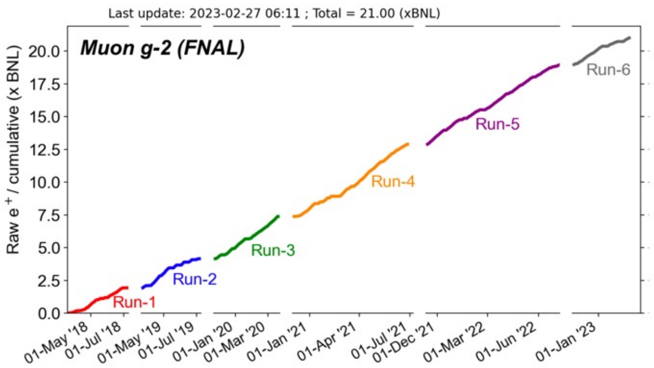
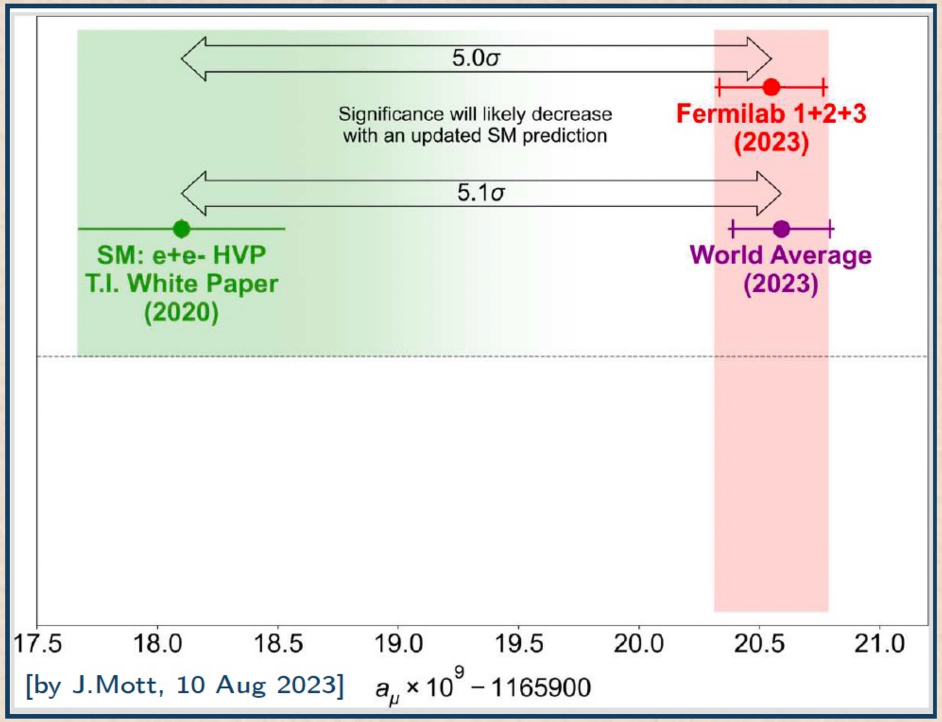


On time, on budget, delivered!

Muon g-2 theory status

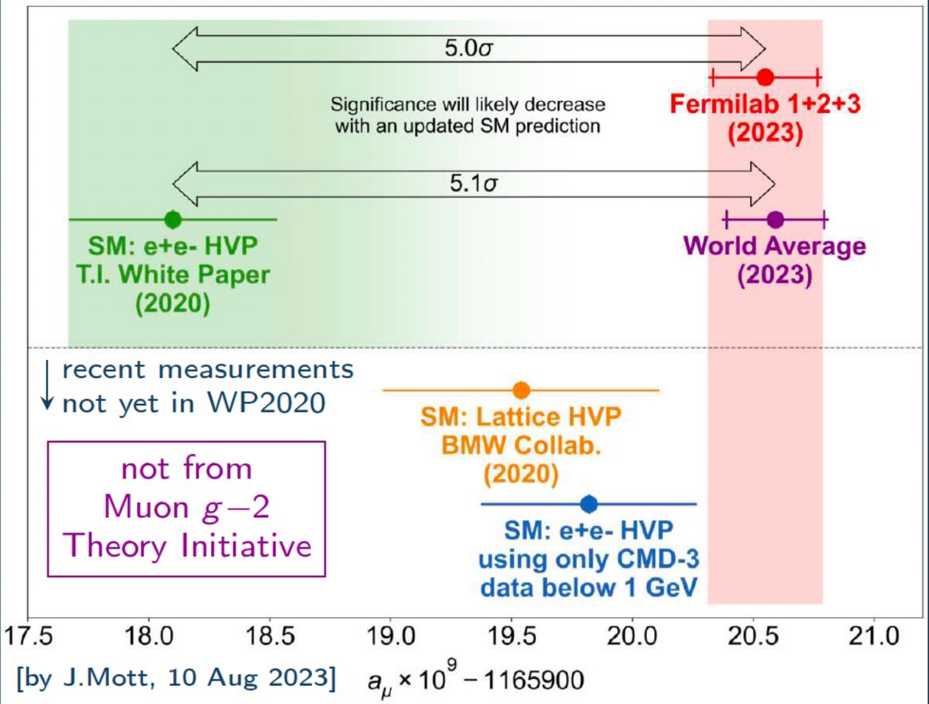
Comparison with theory



- large discrepancy with WP2020 prediction
- but new measurements not included in WP2020 expected to decrease significance of discrepancy

Muon g-2 theory status

Comparison with theory



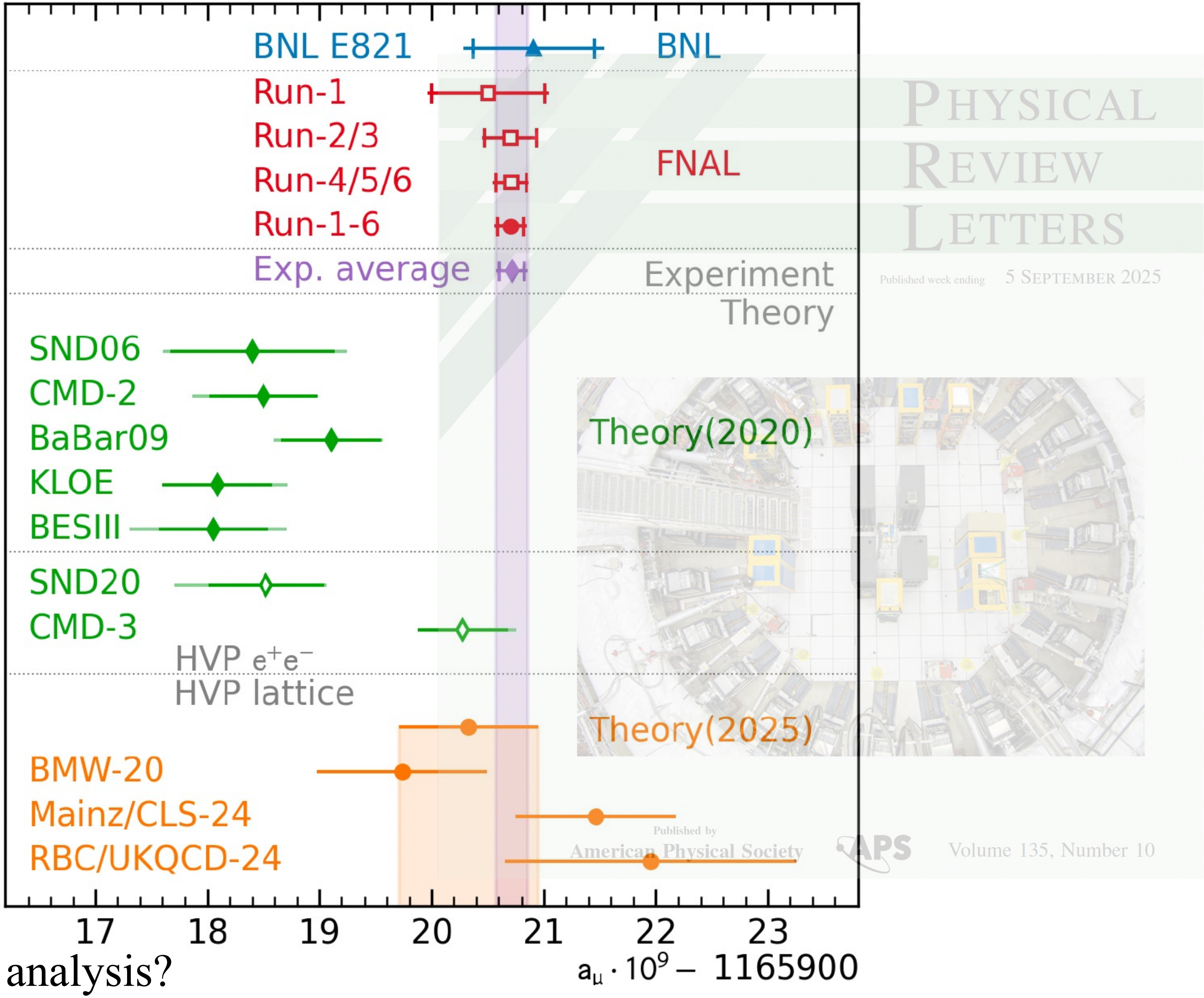
- large discrepancy with WP2020 prediction
- but new measurements not included in WP2020 expected to decrease significance of discrepancy

- replace WP2020 $a_\mu^{\text{HVP,LO}}$ estimate with BMW2020 lattice QCD calculation [A. Keshavarzi, Lattice 2023]
- replace WP2020 $a_\mu^{\text{HVP,LO}}(\pi^+\pi^-)$ in [0.33, 1.0] GeV interval with CMD-3 $\sigma(e^+e^- \to \pi^+\pi^-)$ measurement [A. Keshavarzi, Lattice 2023] (this is a visual exercise, not an updated SM prediction)

- also new SND2k $\sigma(e^+e^- \to \pi^+\pi^-)$ measurement, less precise than CMD-3, consistent with previous measurements used in WP2020

- large ongoing effort to understand present poor consistency of theory predictions based on different inputs

Muon g-2 experiment and theory status



Boxing Gou: Is electron beam polarization playing a role in this analysis?

Muon g-2 theory status

Muon $g-2$ test prospects

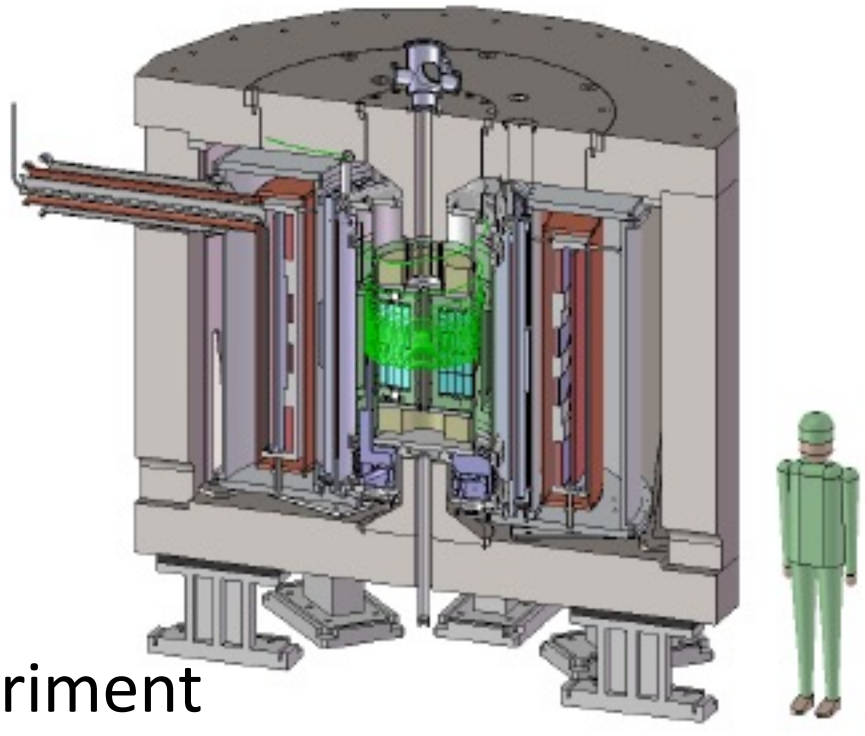
experimental measurement

- a_μ to 0.12,ppm from FNAL-E989 complete dataset analysis by 2025
- a_μ to 0.45 ppm from J-PARC E34 with cold slow ($E = 300$ MeV) muons in small 4 T NMR magnet
- a_μ to 3 ppm from Muonium spectroscopy PRL 127 (2021) 251801

theory prediction

- energy-scan scan $\sigma(e^+e^- \to \text{hadrons})$
  - CMD-3, SND
  - BES-III
- ISR technique $\sigma(e^+e^- \to \text{hadrons})$
  - *BABAR* $\sigma(e^+e^- \to \pi^+\pi^-(\gamma))$
  - Belle II (asymmetric-energy super *B*-factory)
  - BES-III, possibly Super Charm-Tau factories
  - analysis of KLOE data (Liverpool)
- MUonE: 160 GeV muons on e^- t-channel scattering, $a_\mu^{\text{HVP,LO}}$ to 0.5%
- Lattice QCD community will test and reproduce the BMW 2021 HVP contribution calculation
  - partial replications all confirmed BMW calculation
- Muon $g-2$ Theory Initiative group will verify and combine available measurement and calculations

J-PARC Muon g-2 experiment: Under construction



- Totally independent experiment
- Very different systematic errors
- Much more uniform B-field
- Accepting all muon decays

New proposal?

- For an experiment at HIAF: 2512.11486 [hep-ex]
- Phase I: 2-4 GeV muons with ~0.1 ppm precision (similar to FNAL)
- Phase II: 10-20 GeV muons with ~0.05 ppm precision (3x better than FNAL)

CANTON-μ Proposal: A Next-Generation Muon $g-2$ Measurement at Sub-0.1 ppm Precision

Ce Zhang,[1,*] Yu Xu,[2,3,†] On Kim,[4,‡] Bingzhi Li,[5] Guodong Shen,[2,3,6] Liangwen Chen,[2,3,6] Fedor Ignatov,[1] Liang Li,[7] Qiang Li,[8] Xueheng Zhang,[2,3,6] and Zhiyu Sun[2,3,6]

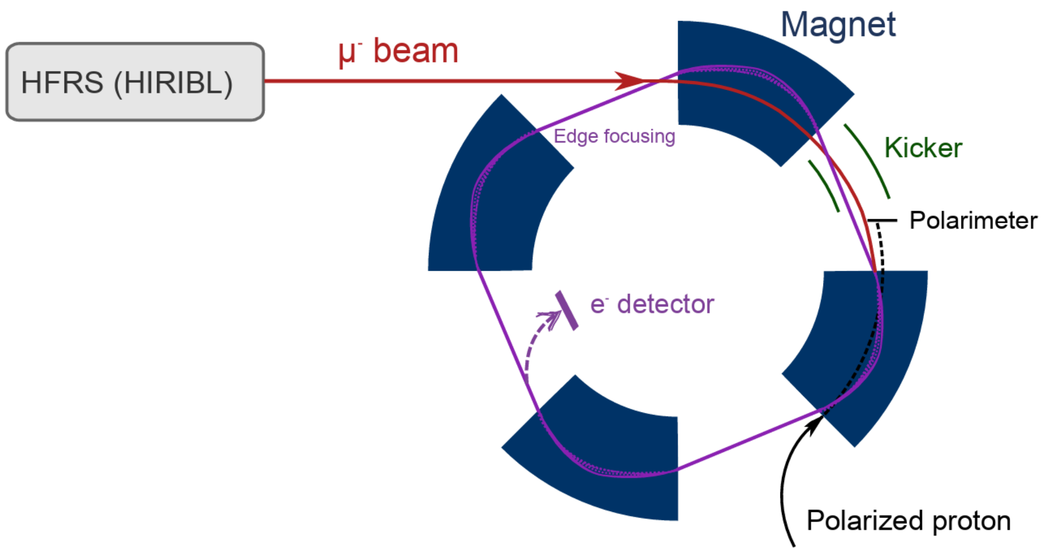


FIG. 6. Schematic design of Concept A with a polarized-proton co-magnetometer.

Summary

- Space quantization and the four miracles made the muon g-2 experiments at BNL and Fermilab possible
- We have achieved our experimental target to collect data for reaching 0.14ppm precision, published in 2025
- The theory needs to improve in order to guide the New-Physics discovery
- Lattice QCD and additional experimental efforts are well underway.

g - 2 for the muon, SM contributions

Miller et al., 2012)[4] of quantum electro-dynamics (QED) up to five loops for the muon anomaly, $a_\mu^{\mathrm{QED}} = (116\,584\,718.09 \pm 0.15) \times 10^{-11}$,[5–13] then of the hadronic "content" of the photon $a_\mu^{\mathrm{HVP+HLbyL}} = (6929.6 \pm 49.4) \times 10^{-11}$,[14–18] the weak interaction contributions[19–21] $a_\mu^{\mathrm{EW(1+2\,loop)}} = (153 \pm 1.0) \times 10^{-11}$, and beyond the standard model (SM) new physics (NP), as, e.g., super-symmetry (SUSY). The SM total theoretical estimation of the muon $(g-2)$ value is given by[4]

$$a_\mu^{\mathrm{SM}} = 116\,591\,801(49)_{\mathrm{tot}} \times 10^{-11} (\pm 0.42\,\mathrm{ppm}) \quad (1)$$

compared to the experimental value

$$a_\mu^{\mathrm{BNLexp}} = 116\,592\,089(54)_{\mathrm{stat}}(33)_{\mathrm{syst}}(63)_{\mathrm{tot}} \times 10^{-11} (\pm 0.54\,\mathrm{ppm}) \quad (2)$$

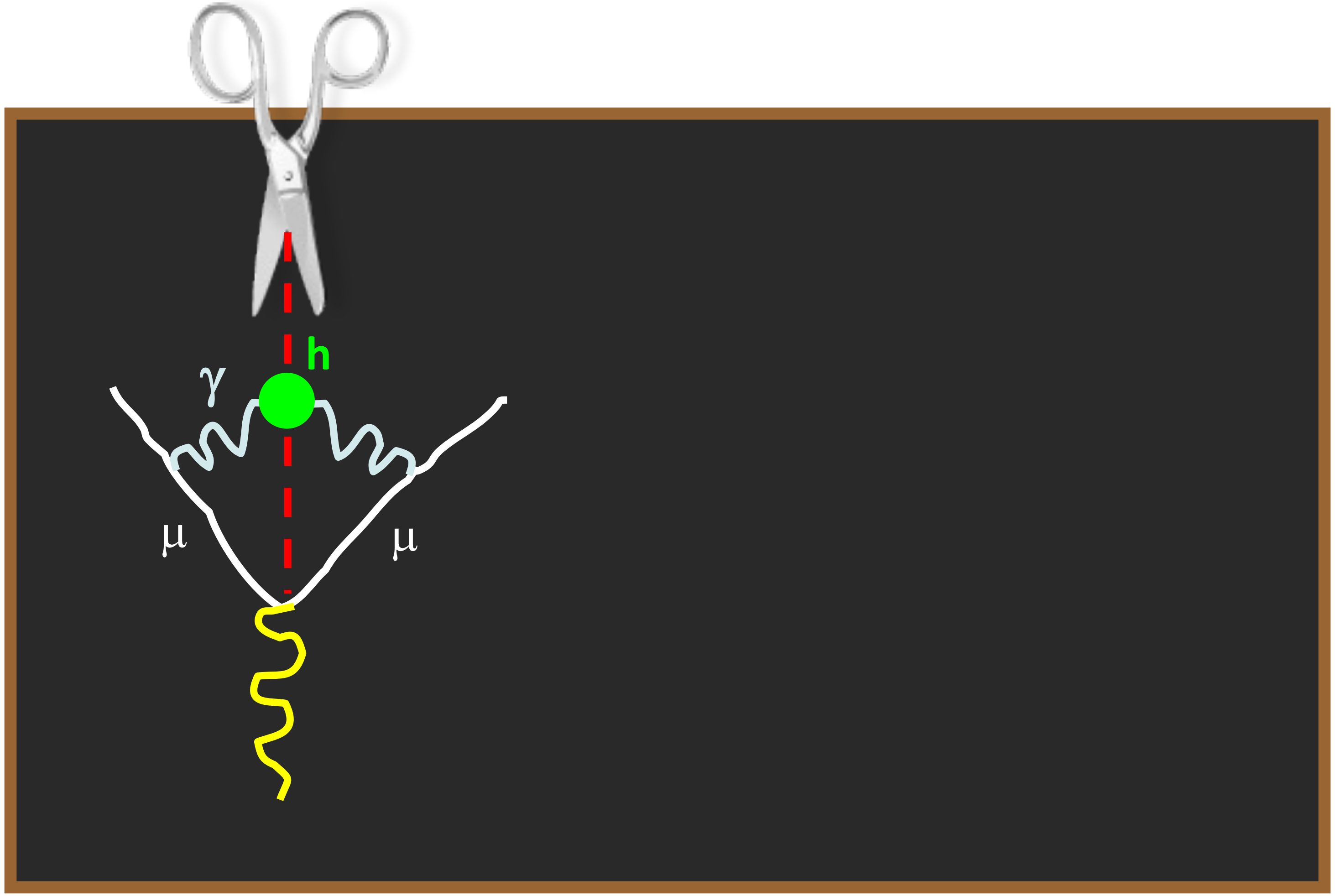
indicating a difference of

$$\Delta a_\mu^{\mathrm{BNL-SM}} = a_\mu^{\mathrm{BNLexp}} - a_\mu^{\mathrm{SM}} = (287 \pm 80) \times 10^{-11} \quad (3)$$

which is 2.5 ppm with a total uncertainty of 0.7 ppm or roughly 3.4 standard deviations.

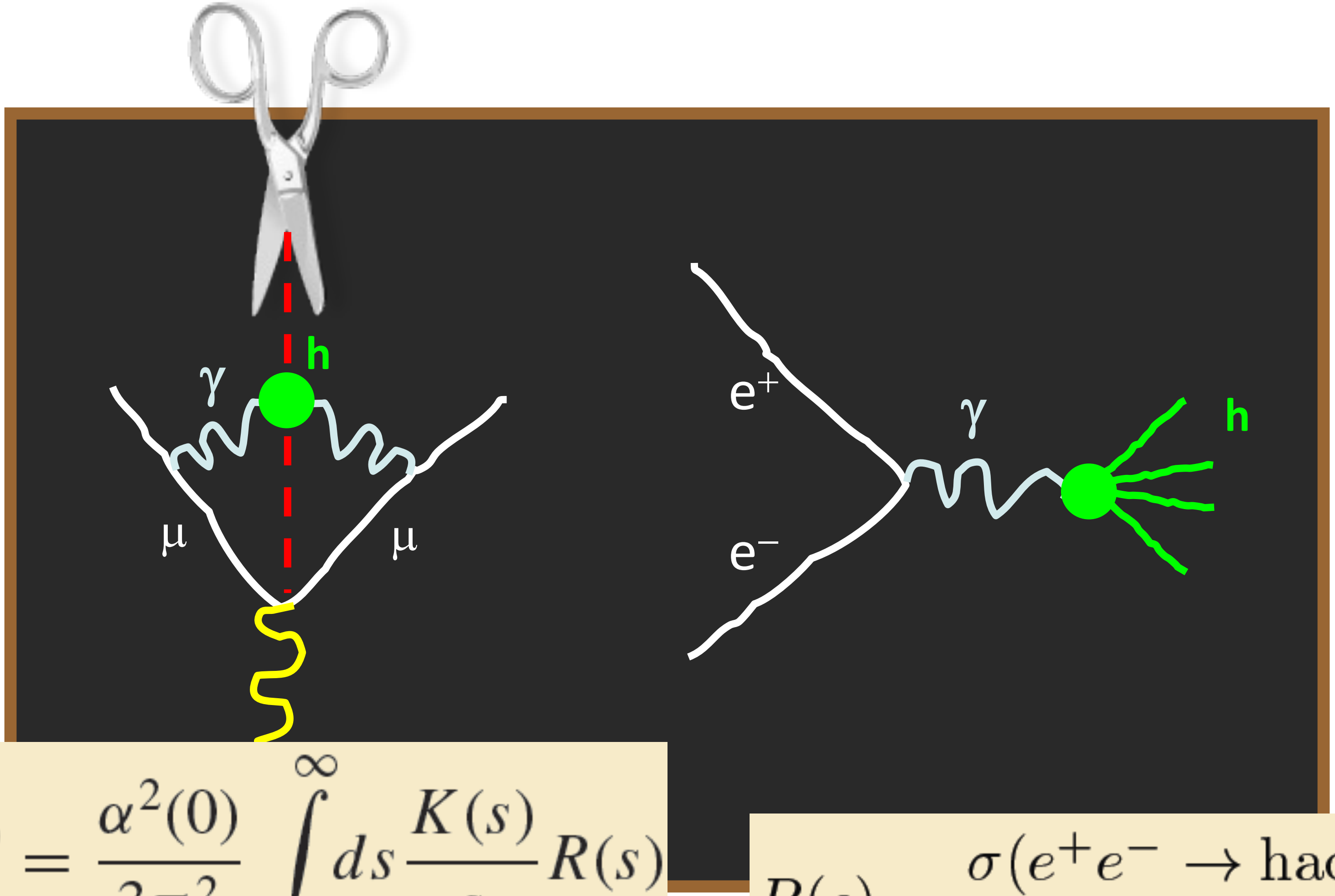
Hadronic vacuum polarization

Challenging but can link to experimental data!



Hadronic vacuum polarization

Challenging but can link to experimental data!



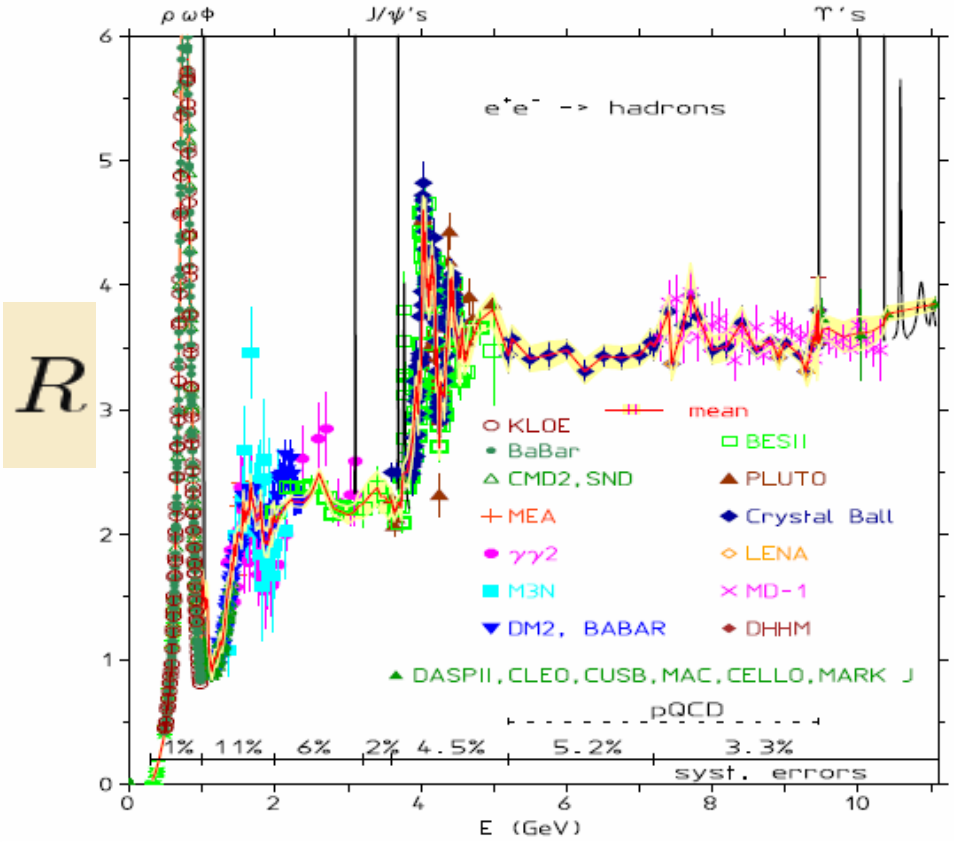
$$a_\mu^{\text{had,LO}} = \frac{\alpha^2(0)}{3\pi^2} \int_{4m_\pi^2}^{\infty} ds \frac{K(s)}{s} R(s)$$

$$R(s) = \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \text{muons})}$$

P. Winter

Hadronic vacuum polarization

$$a_\mu^{\mathrm{had,LO}} = \frac{\alpha^2(0)}{3\pi^2} \int_{4m_\pi^2}^{\infty} ds \frac{K(s)}{s} R(s)$$



- A lot of precision data already available from many experiments
- Future improvements from VEP-2000, KLOE, BaBar, Belle, BES-III, ...

P. Winter

Muon g-2 Collaboration

US Universities
- Boston
- Cornell
- UIUC
- James Madison
- Kentucky
- Massachusetts
- Michigan
- Michigan State
- Mississippi
- North Central College
- Regis
- Virginia
- Washington

US National Labs
- Argonne
- Brookhaven
- Fermilab

181 collaborators
33 Institutions
7 countries

China
- Shanghai Jiao Tong

Germany
- Dresden
- Mainz

Italy
- Frascati
- Molise
- Naples
- Pisa
- Roma Tor Vergata
- Trieste
- Udine

Korea
- CAPP/IBS/KAIST

Russia
- Budker/Novosibirsk
- JINR Dubna

United Kingdom
- Lancaster/Cockcroft
- Liverpool
- Manchester
- University College London

Muon g-2 Collaboration Meeting @ Elba
May 2019