Fermilab
U.S. DEPARTMENT OF ENERGY
Office of Science

FERMILAB-SLIDES-20-071-E

Standing on The Shoulders of Giants

Past, Present, and Future of Muon $g-2$

Josh LaBounty, on behalf of the Muon $g-2$ Collaboration

New Perspectives 2020

07/21/2020

Background: What is $g-2$?

The spin of a muon (or any similarly charged fermion) will precess about an external magnetic field like:

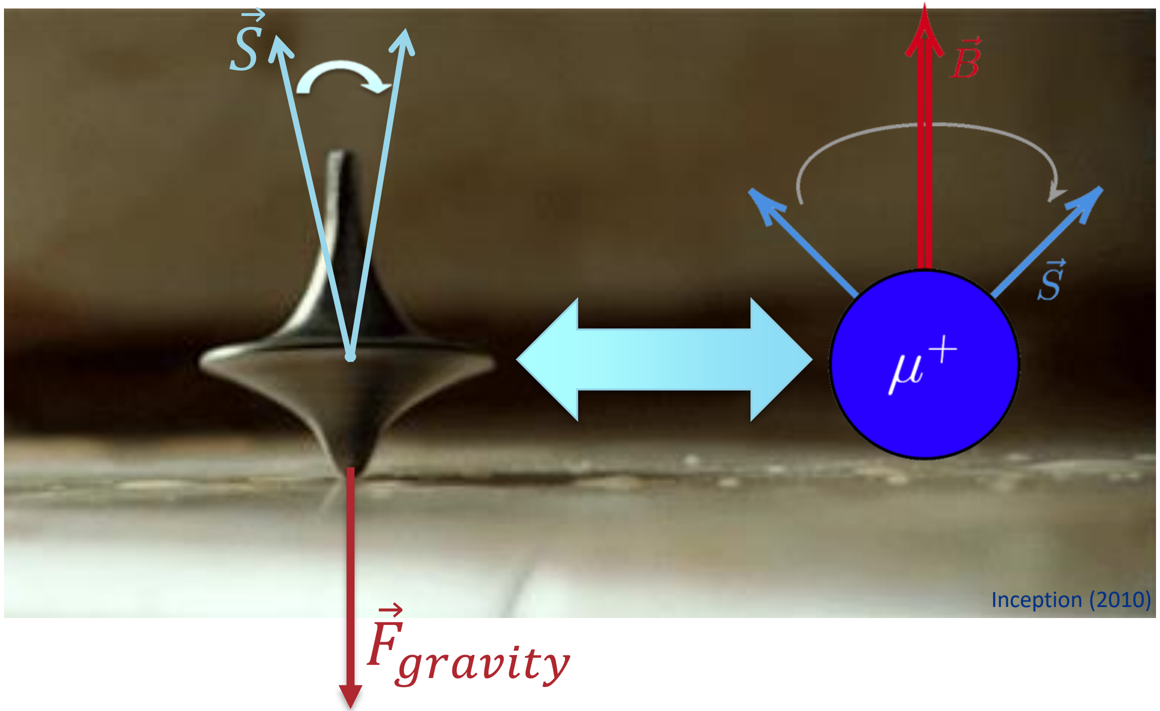
$$\frac{d\vec{s}}{dt} = \vec{\mu} \times \vec{B} = \frac{gq}{2mc}\vec{s} \times \vec{B}$$

Dirac (in 1928) calculated (for a Spin-½ charged particle) that $g = 2$

$$H = \frac{\vec{p}^2}{2m} + V(r) + \frac{e}{2m}\vec{B} \cdot \left(\vec{L} + 2\vec{S}\right)$$

By the late 1940's, there was substantial evidence that this was not exactly true, and so the search was on for the deviation from the 0th order prediction:

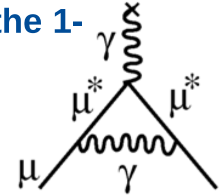
$$a_\mu \equiv \frac{g_\mu - 2}{2}$$



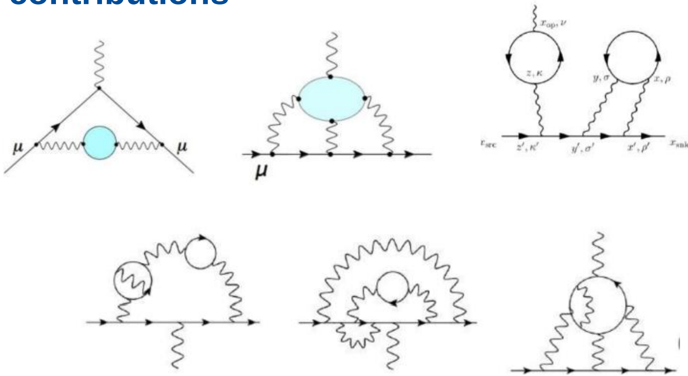
Initial Calculations

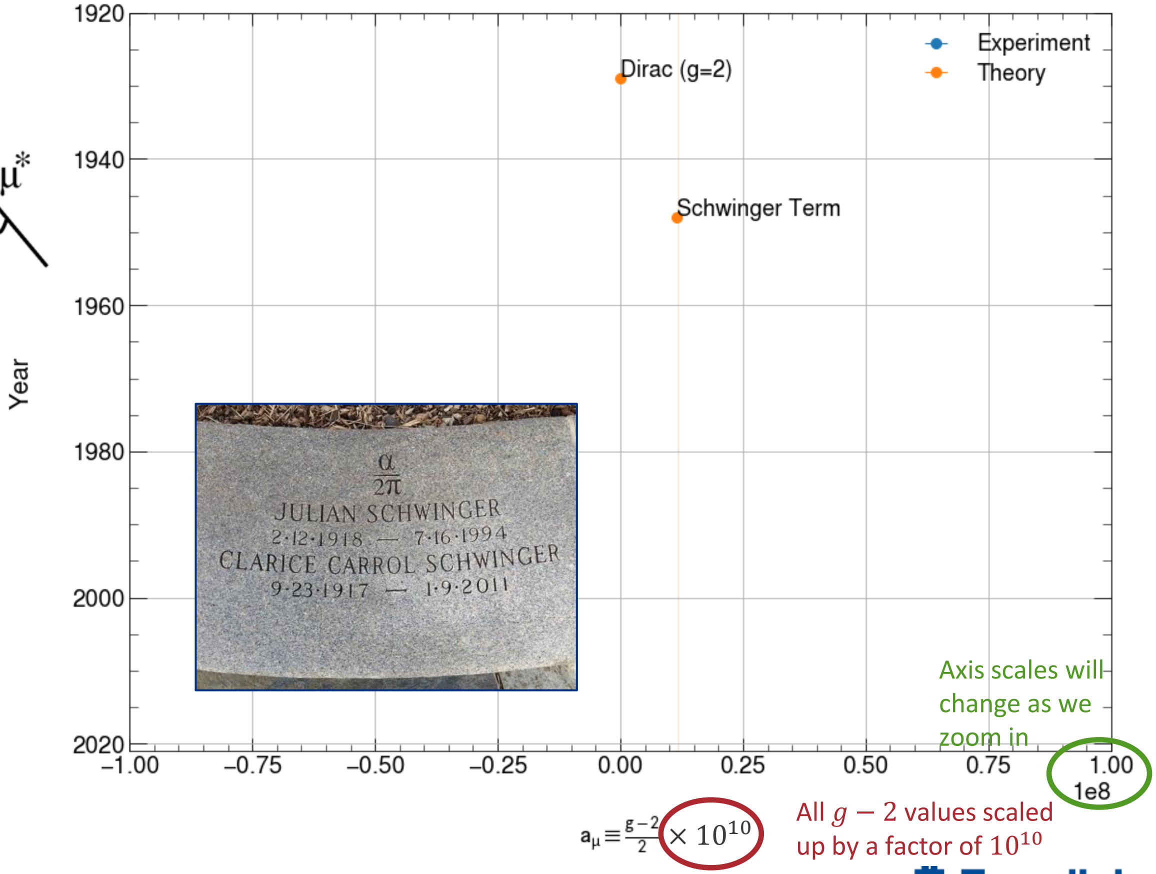
Julian Schwinger, in 1948, calculated the first correction to g due to the 1-photon loop:

$$a_\mu^{\text{Schwinger}} = \frac{\alpha}{2\pi}$$



Since then, over 12,000 QED diagrams have been computed (complete out to 5th order) as well as many other contributions

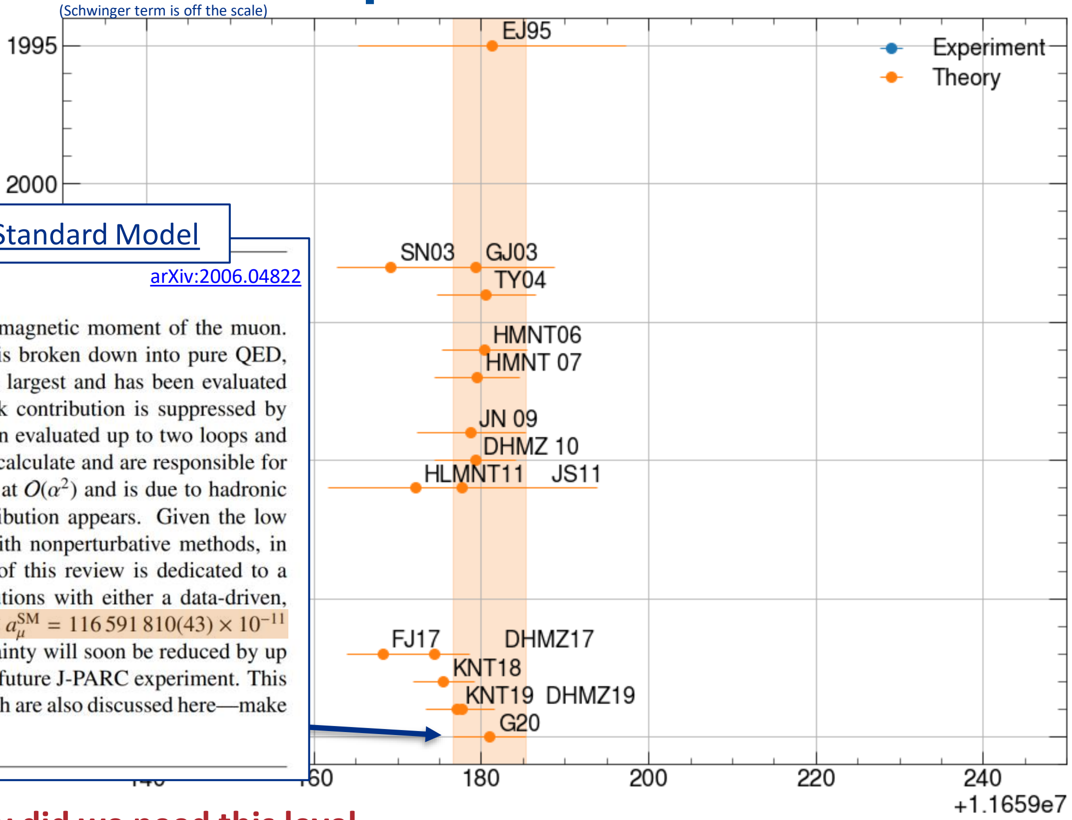




Present: Theory Whitepaper Released April 2020

Theory whitepaper just released!

Wonderful talk by Prof. Aida El-Khadra given at Fermilab summarizing the results



The anomalous magnetic moment of the muon in the Standard Model

arXiv:2006.04822

Abstract

We review the present status of the Standard Model calculation of the anomalous magnetic moment of the muon. This is performed in a perturbative expansion in the fine-structure constant α and is broken down into pure QED, electroweak, and hadronic contributions. The pure QED contribution is by far the largest and has been evaluated up to and including $\mathcal{O}(\alpha^5)$ with negligible numerical uncertainty. The electroweak contribution is suppressed by $(m_\mu/M_W)^2$ and only shows up at the level of the seventh significant digit. It has been evaluated up to two loops and is known to better than one percent. Hadronic contributions are the most difficult to calculate and are responsible for almost all of the theoretical uncertainty. The leading hadronic contribution appears at $\mathcal{O}(\alpha^2)$ and is due to hadronic vacuum polarization, whereas at $\mathcal{O}(\alpha^3)$ the hadronic light-by-light scattering contribution appears. Given the low characteristic scale of this observable, these contributions have to be calculated with nonperturbative methods, in particular, dispersion relations and the lattice approach to QCD. The largest part of this review is dedicated to a detailed account of recent efforts to improve the calculation of these two contributions with either a data-driven, dispersive approach, or a first-principle, lattice-QCD approach. The final result reads $a_\mu^{\rm SM} = 116\,591\,810(43) \times 10^{-11}$ and is smaller than the Brookhaven measurement by 3.7σ. The experimental uncertainty will soon be reduced by up to a factor four by the new experiment currently running at Fermilab, and also by the future J-PARC experiment. This and the prospects to further reduce the theoretical uncertainty in the near future—which are also discussed here—make this quantity one of the most promising places to look for evidence of new physics.

- **Uncertainty on the theoretical result is now $\mathcal{O}(300\ ppb)$**

Why did we need this level of precision?

$a_\mu \equiv \frac{g-2}{2} \times 10^{10}$

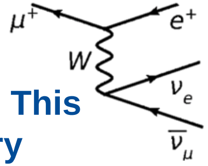
Past: Nevis

The Nevis and Liverpool experiments in 1957 showed that g_μ was consistent with the Dirac prediction:

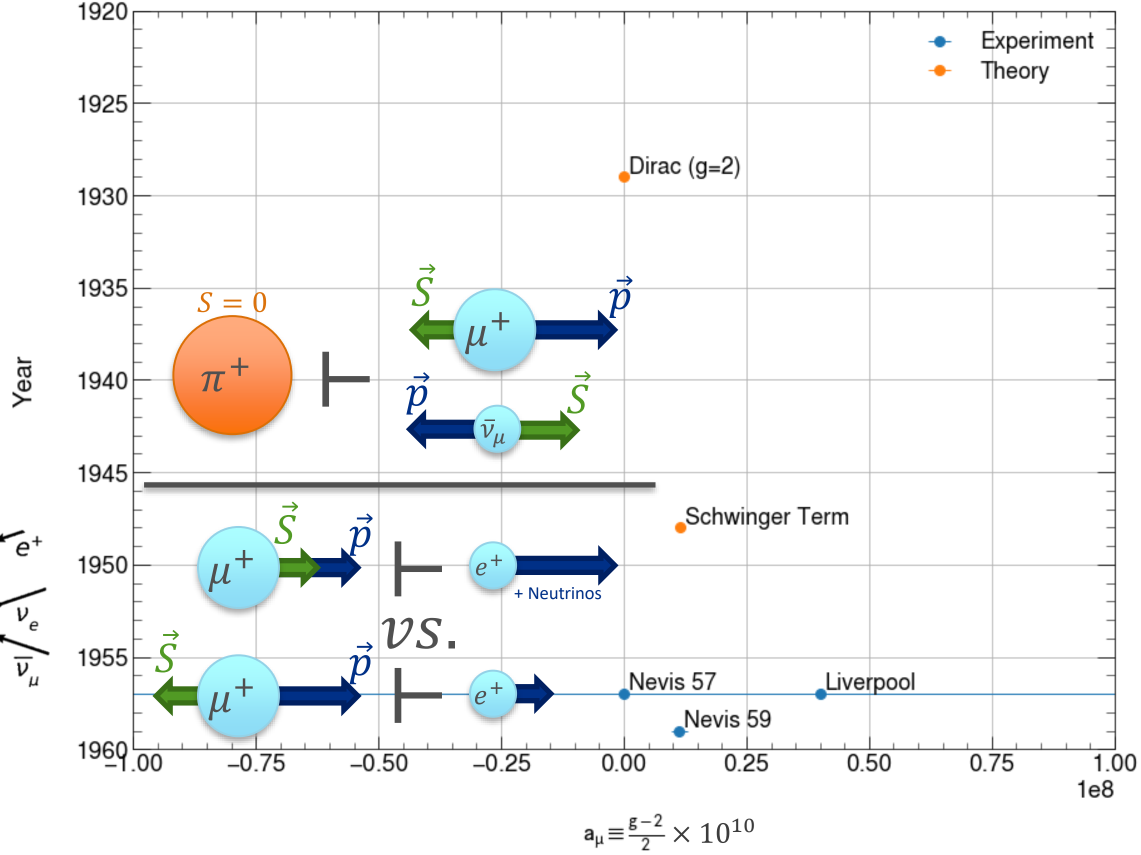
$$g_\mu = 2 \pm 10\%$$

These experiments both stopped muons in a target and rotated their spins with a changing magnetic field.

- Polarized muons come 'free' with pion decay
- Most importantly, they showed parity violation in the weak decay of the muon (decay $e^{+/-}$ preferentially emitted in the direction of the spin vector). This has formed the basis of every measurement of $g - 2$.



A refinement of the technique in 1959 showed a result consistent with the Schwinger correction



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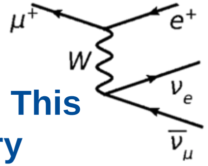

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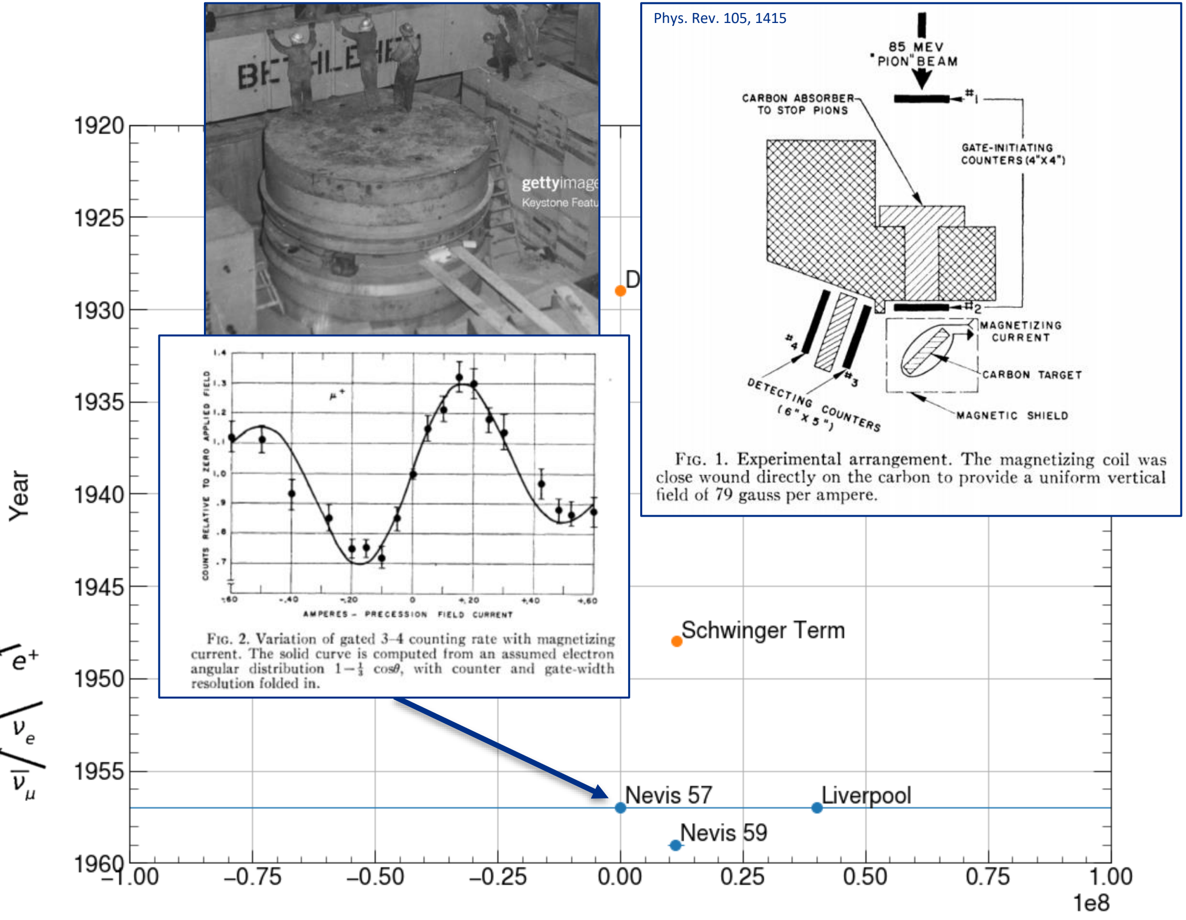

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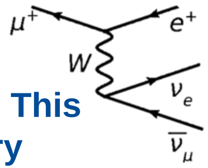
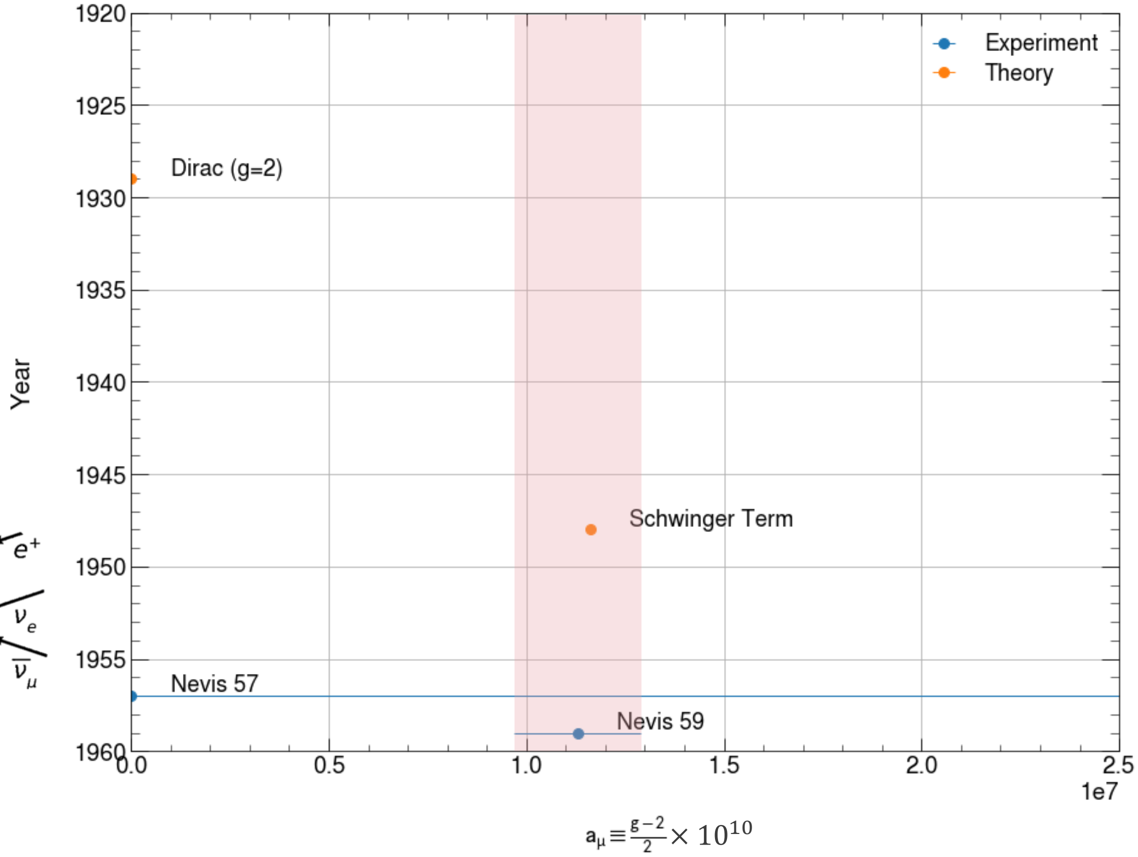




A refinement of the technique in 1959 showed a result consistent with the Schwinger correction

Past: CERN I and II

Seeing the results from Nevis/Liverpool, groups at CERN started to show interest in measuring a_μ for themselves.

- **Learning from Nevis: use the relative precession of the spin and cyclotron frequencies → directly proportional to a_μ (to first order):**

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

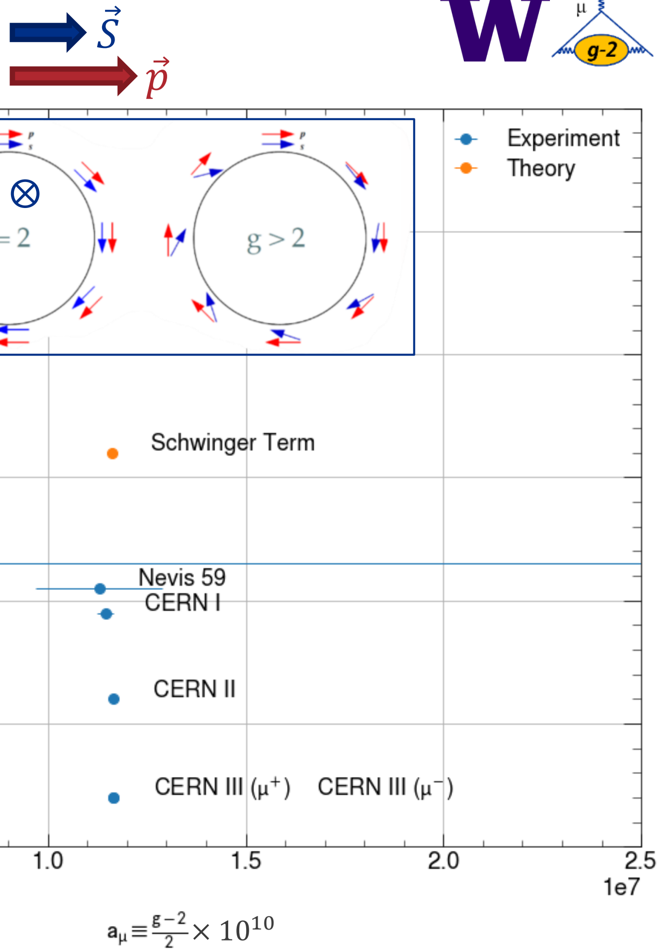
$$\omega_c = \frac{eB}{\gamma m}$$

$$\downarrow$$

$$\omega_a \equiv \omega_s - \omega_c = -\left(\frac{g-2}{2}\right)\frac{e}{m_\mu}B$$

$$= -a_\mu \frac{e}{m_\mu} B$$

Measure ω_a, B and you have a_μ



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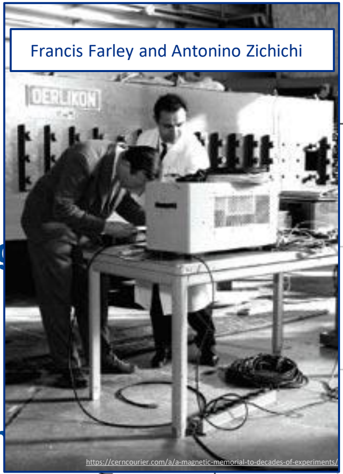

https://doi.org/10.1016/0370-1573(81)90028-4

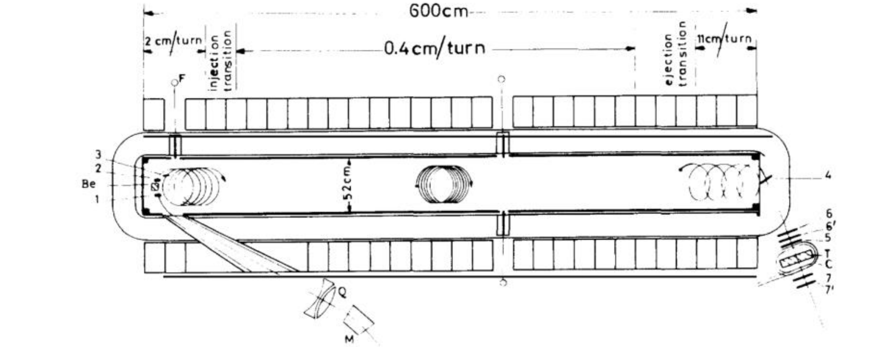

Fig. 2. The storage of muons in the 6 m bending magnet used in the first CERN (g-2) experiment. The field gradient makes the orbits walk to the right and at the end a large gradient is used to eject the particles so that they are stopped in the polarization analyser. Injected and ejected muons which stopped in the analyser were signalled by a coincidence between detectors 123 and 466′5$\bar{7}$, respectively. The decay electrons were separated into forward [77′$\bar{4}$(6$\bar{6}$′)] and backward [66′4(7$\bar{7}$′)] events and collected in 0.1 μs time bins as a function of storage time.

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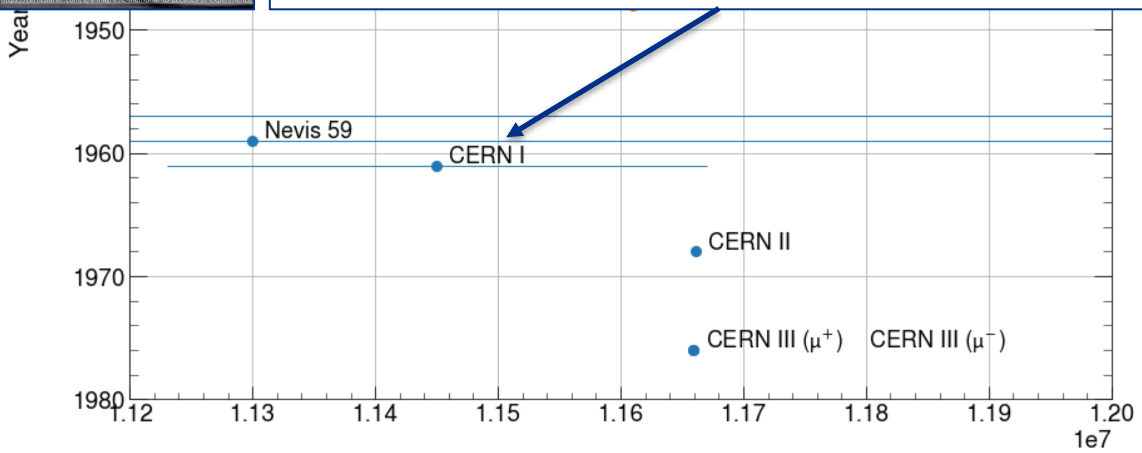

$a_\mu \equiv \frac{g-2}{2} \times 10^{10}$

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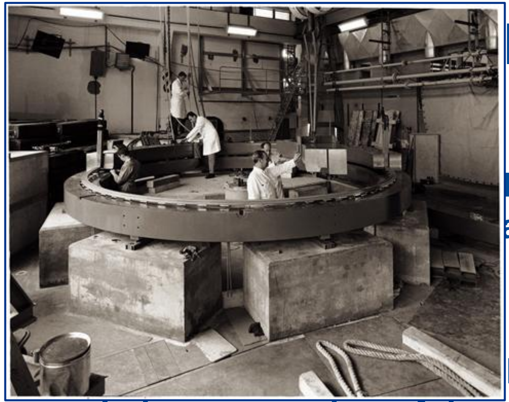

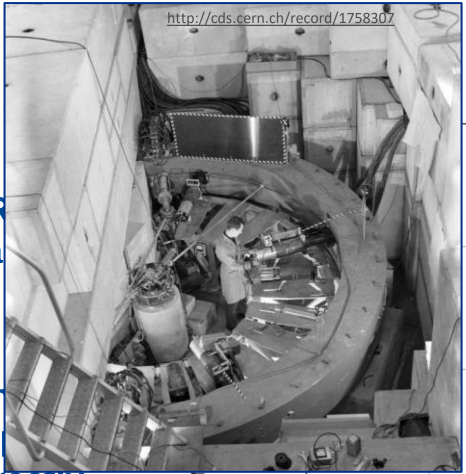

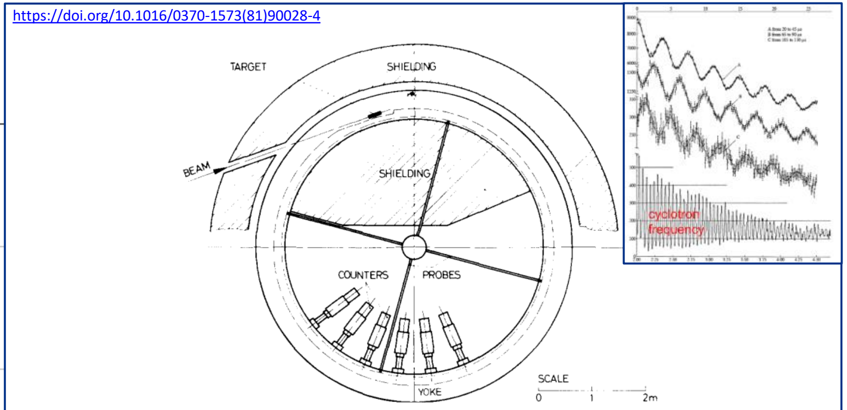

Fig. 5. Plan view of the 5 m diameter magnet used in the first muon storage ring at CERN. The momentum of the muons was 1.3 GeV/c and these particles were derived from a pulse of 10 GeV protons which produced pions at the target. A fraction of the latter subsequently decayed in flight inside the storage region. The proton beam and target are indicated in the figure as is the shielding needed to protect the decay electron counters.

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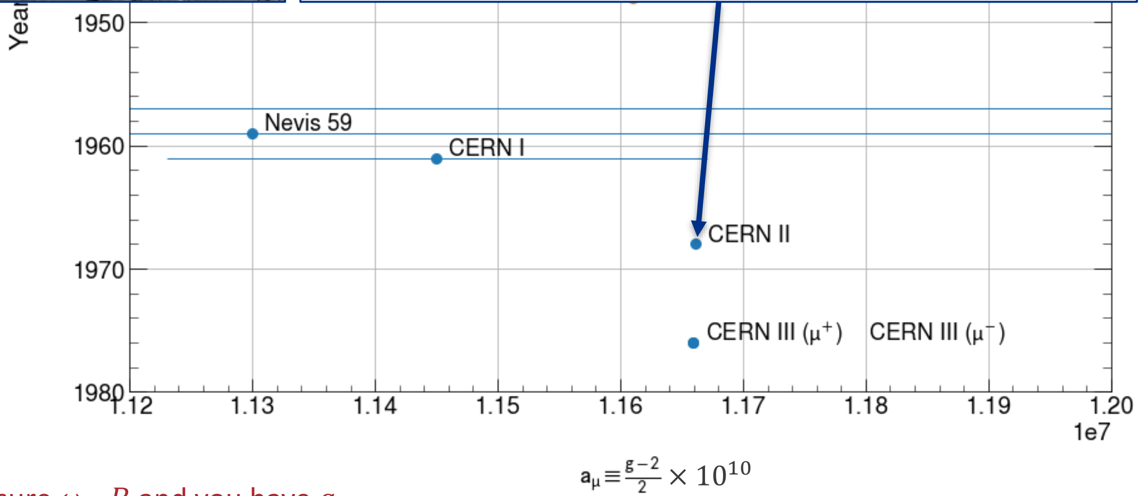


Past: CERN III

The equations on the previous slide are only valid to first order. A fuller version is:

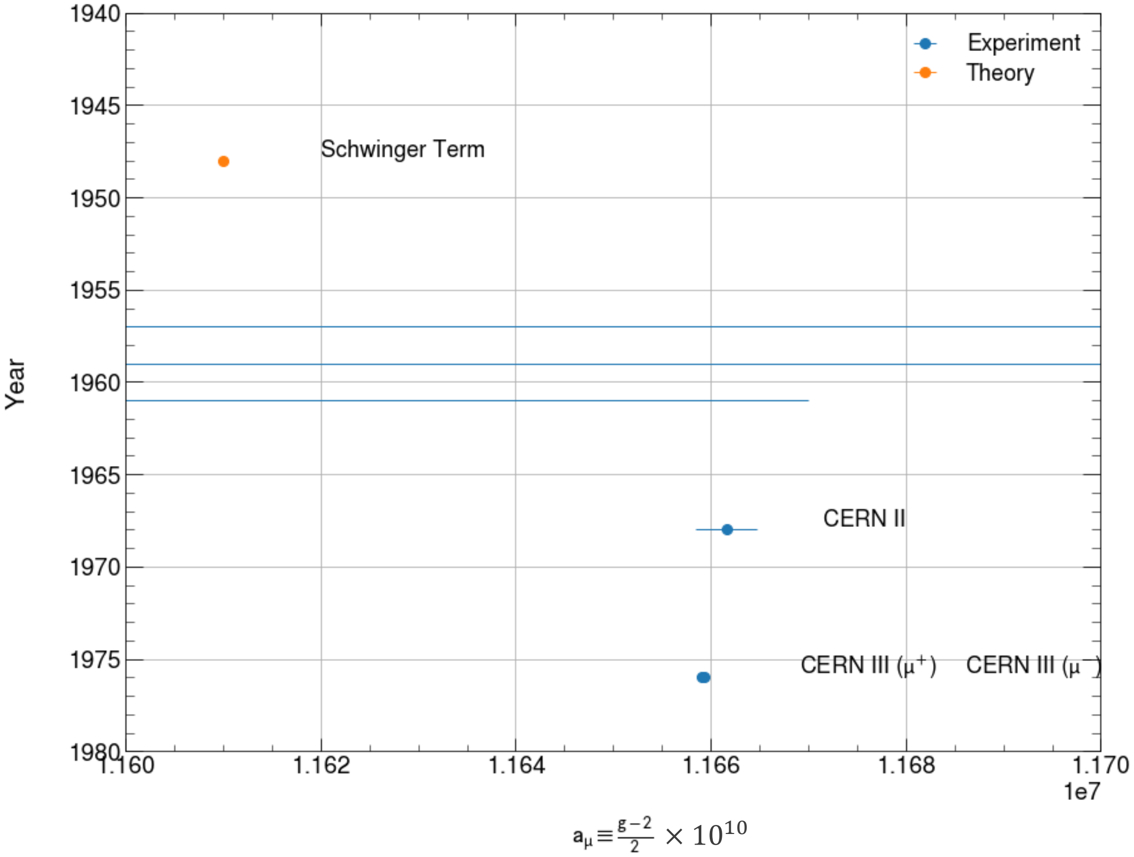
$$\omega_a = \frac{e}{m}\left[a_\mu \vec{B} + \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right] + \cdots$$

Electrostatic focusing → More uniform $\vec{B}$… at the cost of adding $\vec{E}$

CERN-III featured a $14.1\ m$ diameter storage ring to allow for storing muons at the 'magic momentum' (which minimizes the $\vec{\beta}\times\vec{E}$ term):

- $\gamma = \sqrt{\frac{1}{a_\mu} + 1} \approx 29.3 \rightarrow p = 3.09\,\frac{GeV}{c}$

π injection (rather than a proton target in the ring) helped reduce initial splash and increase storage



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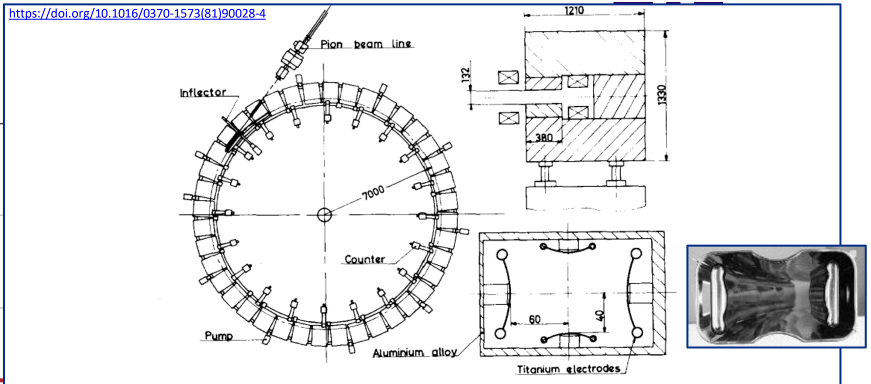

Fig. 7. Plan view of the 14 m diameter magnet which formed the second muon storage ring at CERN. Cross-sections of the magnet and electric quadrupoles are also shown. The muon momentum was 3.098 GeV/c. The line of the 3.1 GeV/c pion beam is shown entering the ring through the pulsed inflector.

Electrostatic focusing → M... $\vec{B}$… at the cost of adding $\vec{E}$...

CERN-III featured a $14.1\ m$ ... storage ring to allow for st... muons at the 'magic mome... (which minimizes the $\vec{\beta} \times \vec{E}$...

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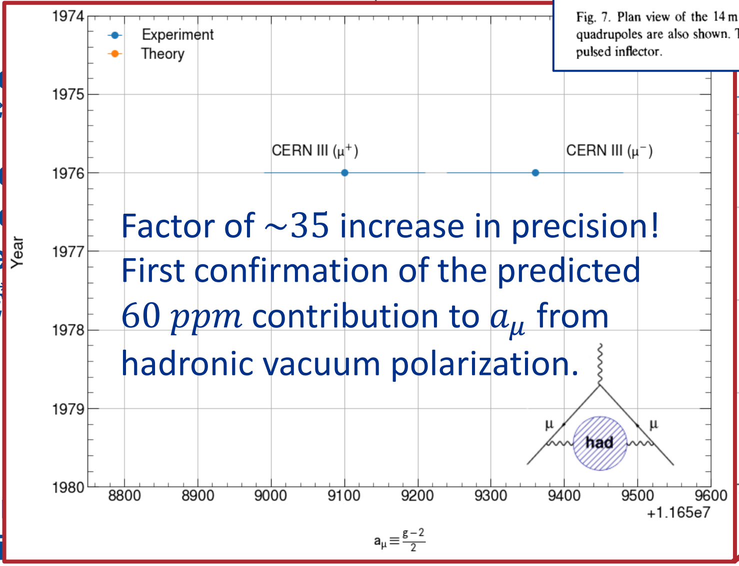

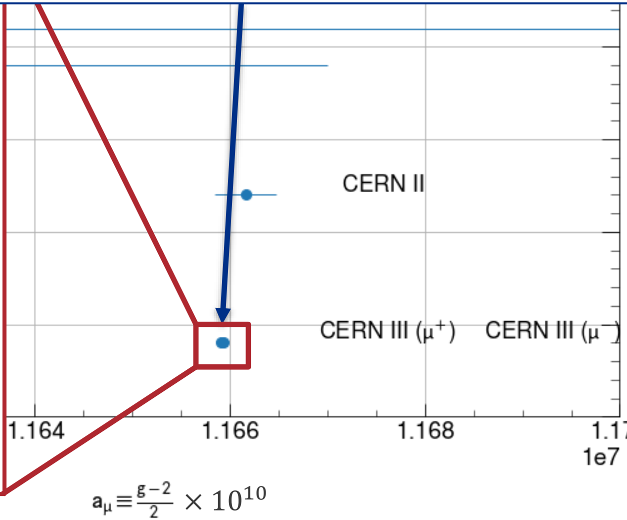

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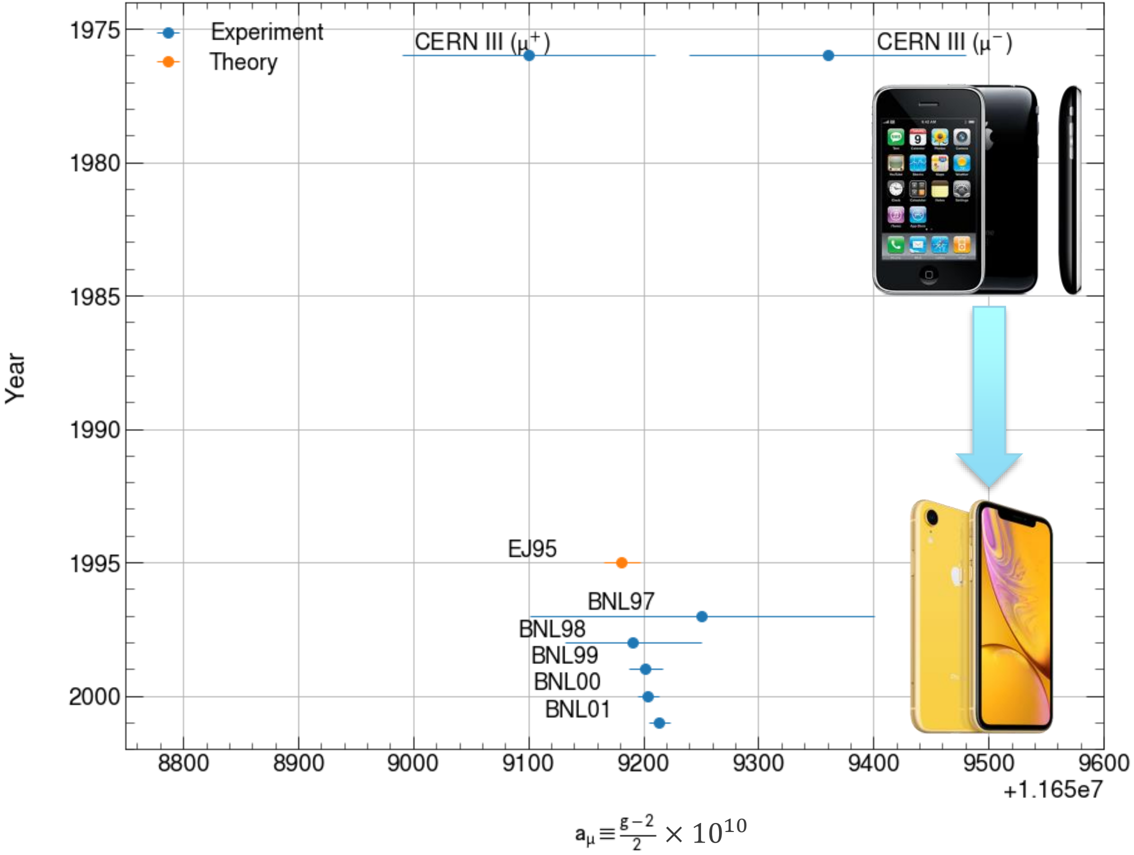
Past: E821 Brookhaven Measurement

E821 kept the fundamentals of the CERN-III measurement but improved upon it in pretty much every way.

- 20 years of hardware/software advances.
- **Transition from pion injection to muon injection further reduced the initial splash of particles.**
- Electromagnetic kicker puts muons onto correct orbits
- Transition from 14 separate magnets to a single ring meant that the magnetic field is much more uniform
- Magnetic field can be mapped/tracked in situ using trolley / fixed NMR probes

About a factor of 14 improvement over CERN-III's final result.



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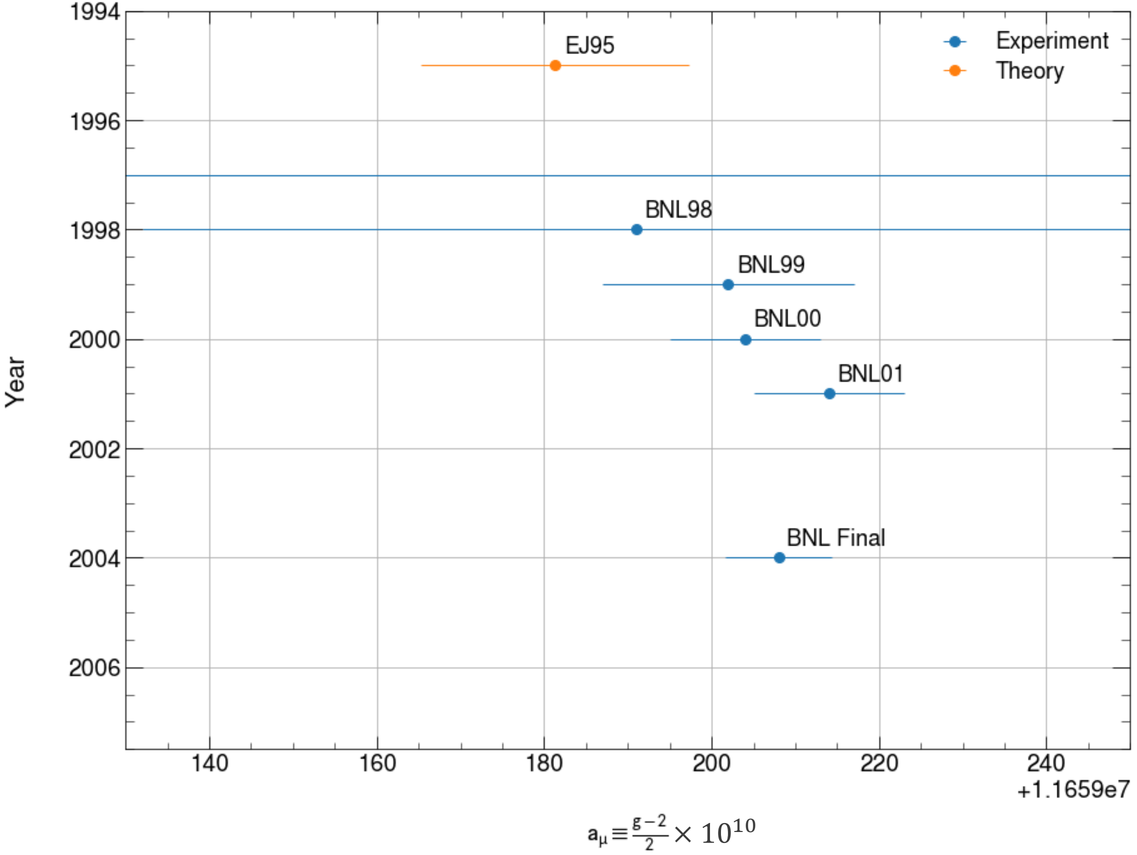

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E821 Final Report

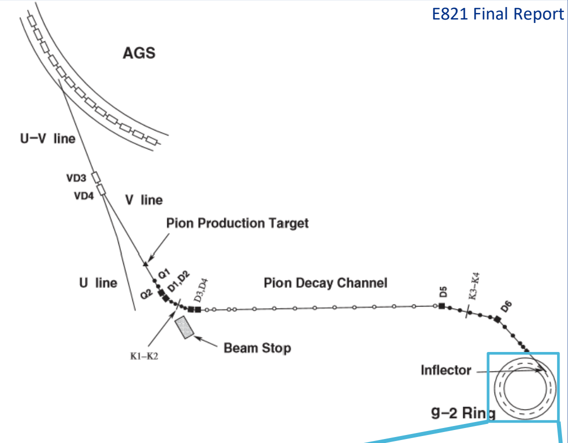
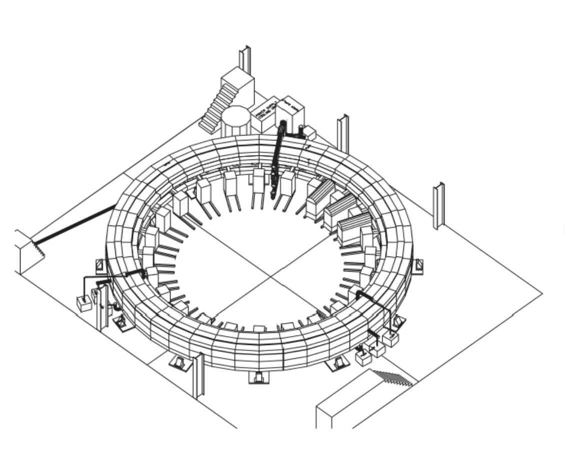
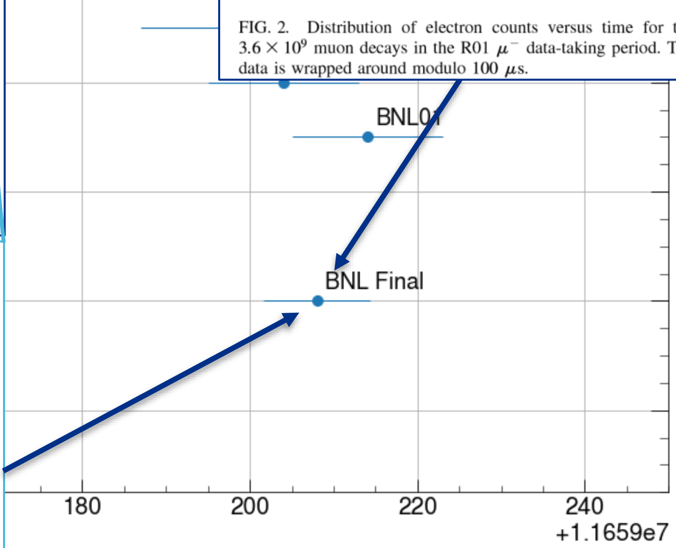


FIG. 3. Plan view of the pion/muon beamline. The pion decay channel is 80 m and the ring diameter is 14.1 m.





$a_\mu \equiv \frac{g-2}{2} \times 10^{10}$

G. W. BENNETT *et al.*

E821 Final Report

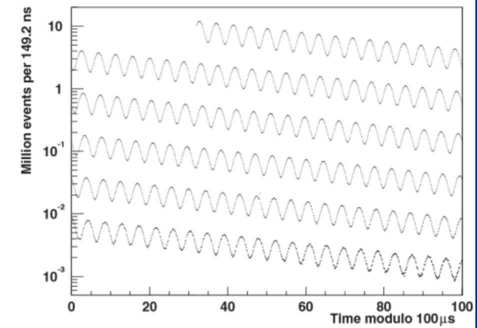


FIG. 2. Distribution of electron counts versus time for the 3.6×10^9 muon decays in the R01 μ^- data-taking period. The data is wrapped around modulo 100 μs.

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Present: E989

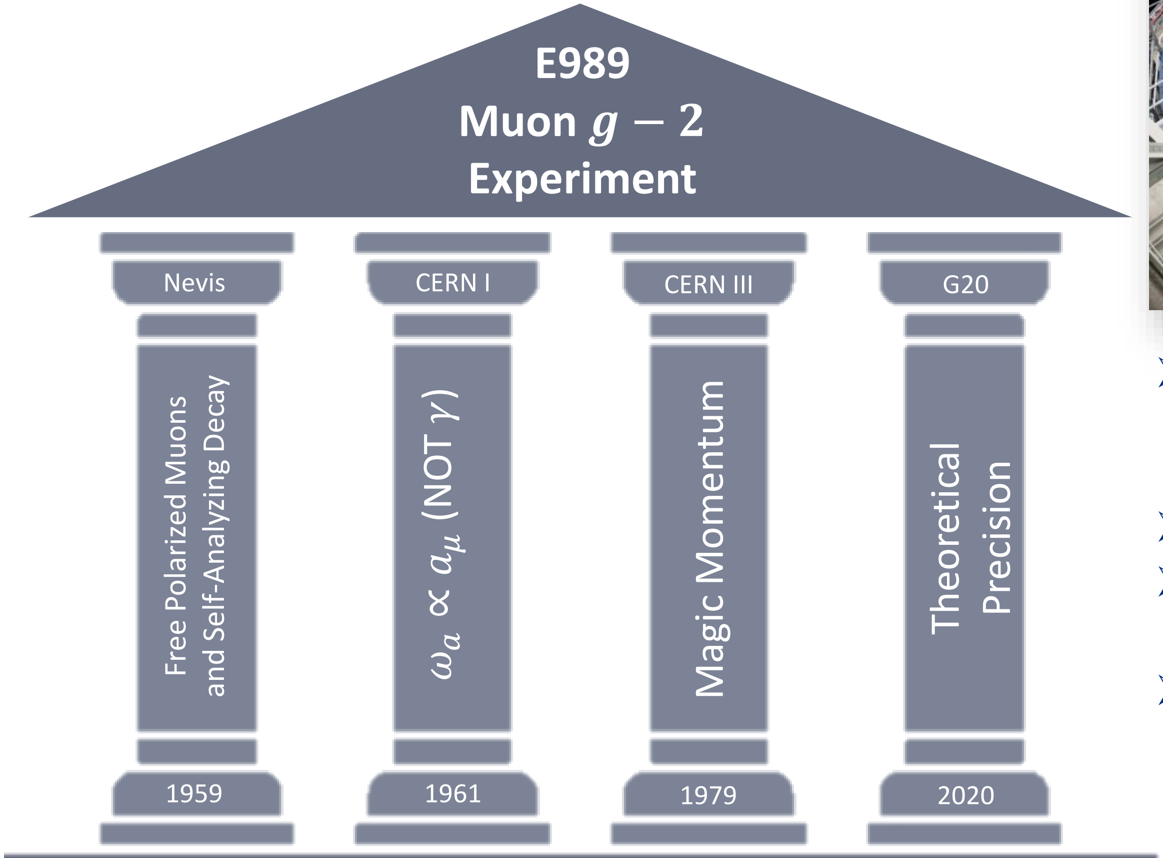
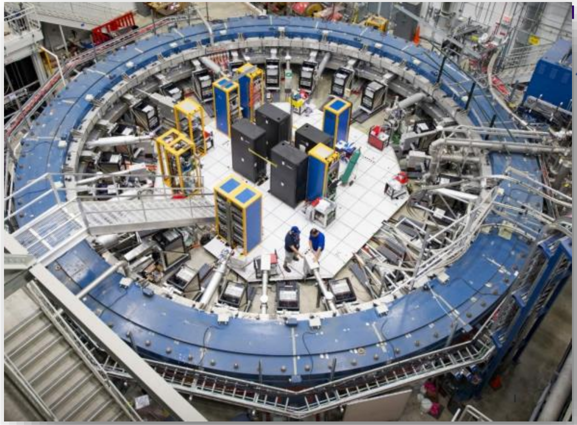


Image: https://www.drlinkcheck.com/blog/modern-seo



- Muons are special: Free polarization and a self-analyzing decay
- $\omega_a \propto a_\mu$ (not γ!)
- Magic momentum cancels $\vec{E} \times \vec{B}$ term
- Theory can be calculated as precisely as measurements

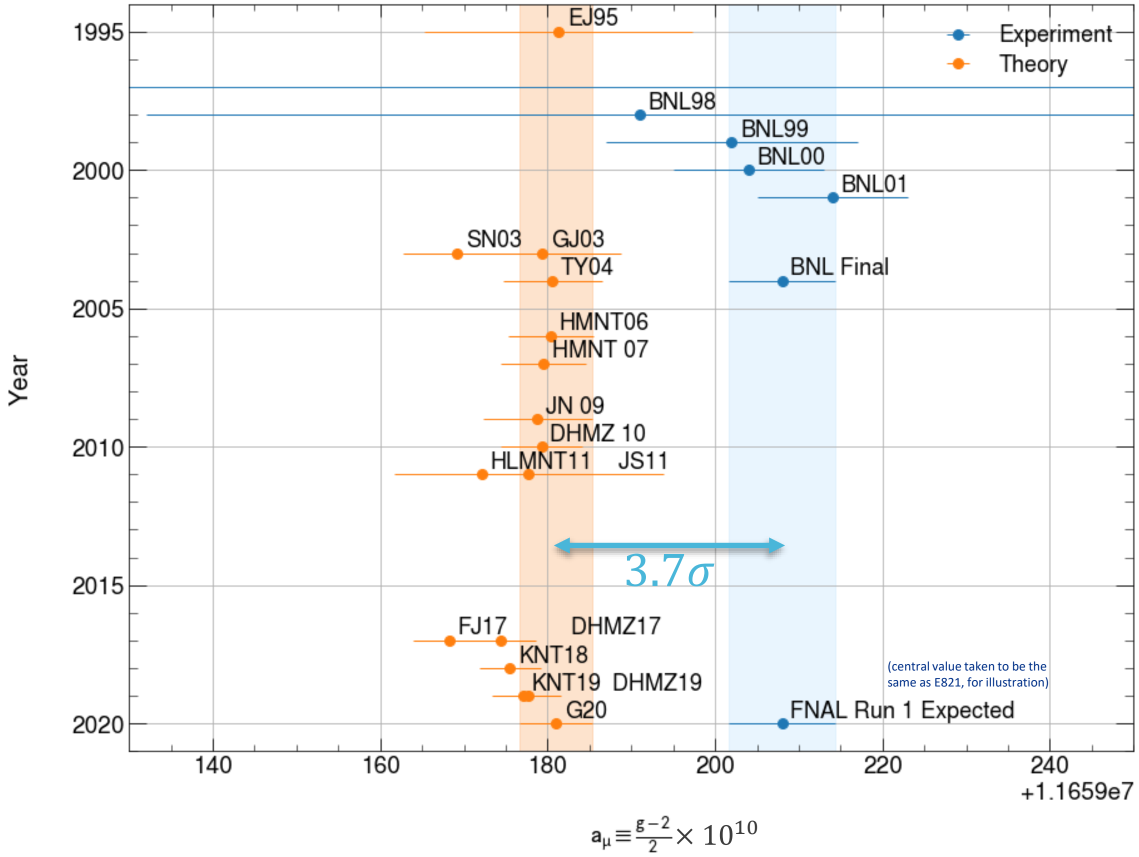
Present: E989

The first run of the Fermilab Muon g-2 experiment is expected to match the final BNL result in precision.

Overall, the goal is to reduce the experimental uncertainty from $540\ ppb \rightarrow 140\ ppb$

Like the transition from CERN III → E821, the transition from E821 → E989 is a refinement of the technique

- Better detector systems reduce pileup
- Better shimming / mapping of the magnetic field
- Fermilab DR allows for a cleaner beam, reduced π^{+} contamination
- 20 years of hardware/software improvements



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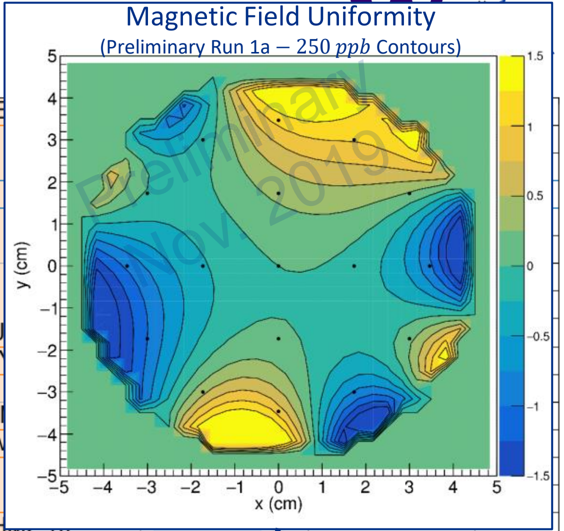

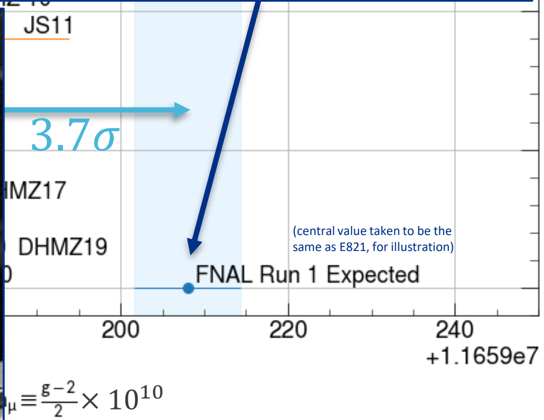

Fermilab

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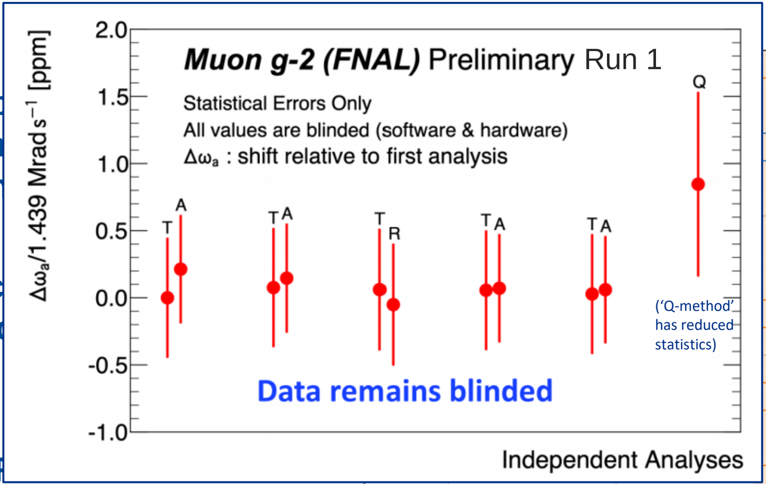
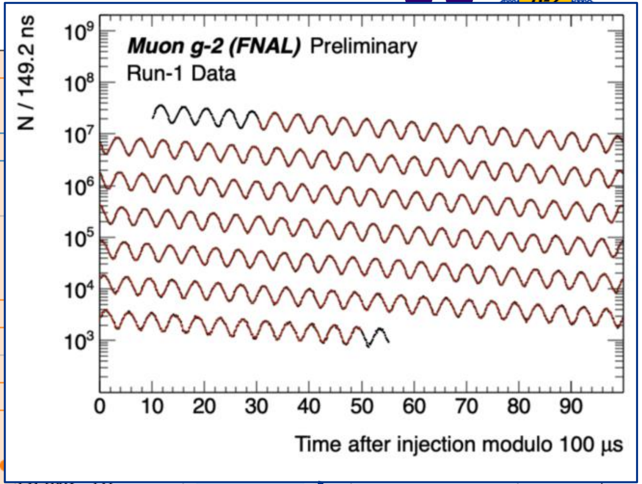
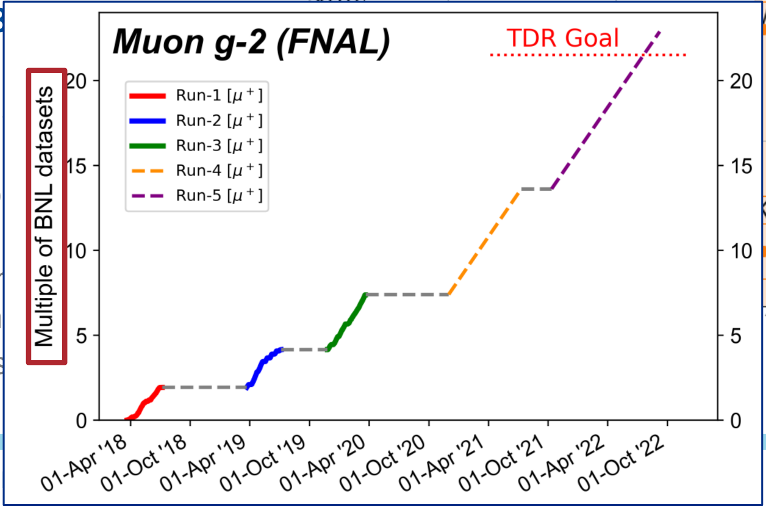
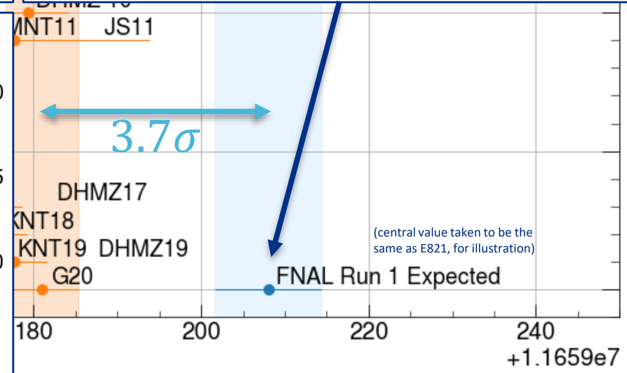








$a_\mu \equiv \frac{g-2}{2} \times 10^{10}$

Future: Outlook

If the central value from E821 is maintained and we reach our goal of $140\ ppb$ precision, we will be able to show a 5σ discrepancy with the standard model calculation.

This has huge implications for many BSM physics models, ruling out some (e.g. MSSM, Dark Photon) and supporting others (Two-Higgs doublet models, Axion, Leptoquarks).

J-PARC Measurement will provide an independent confirmation of a_μ.

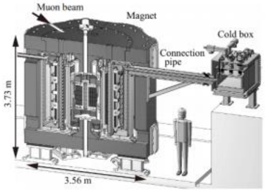
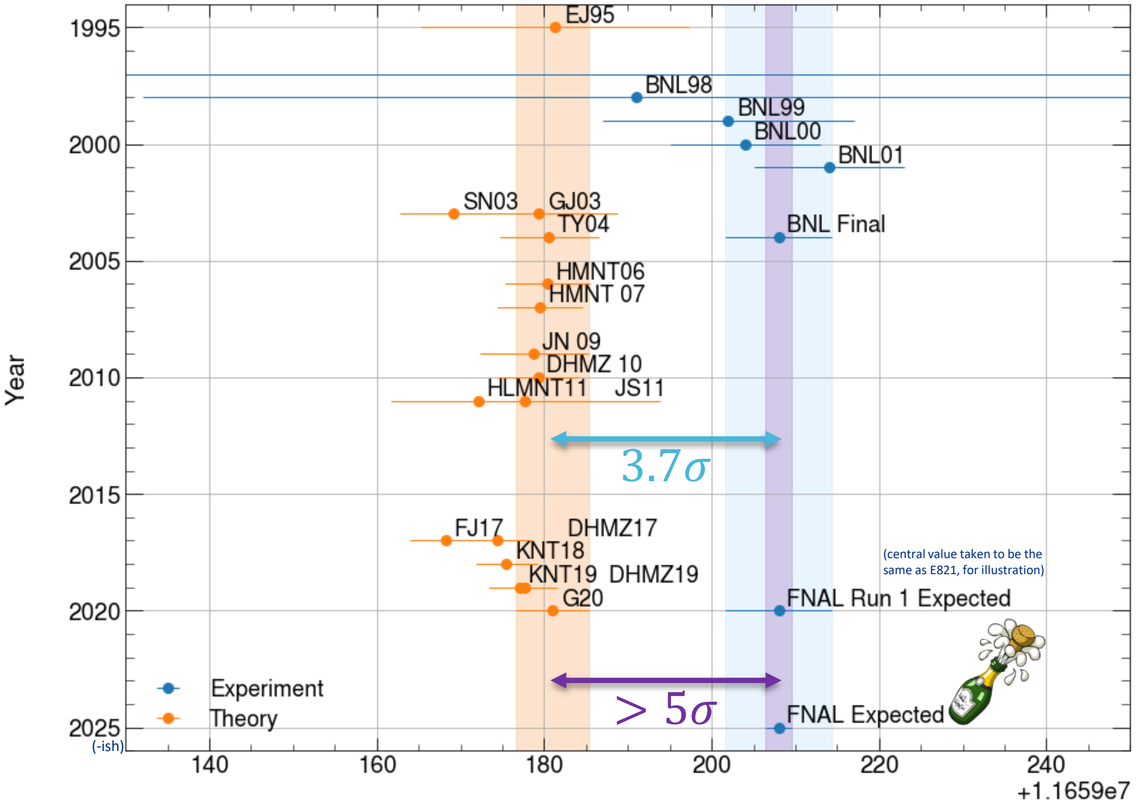
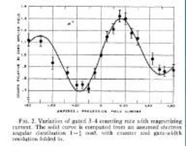
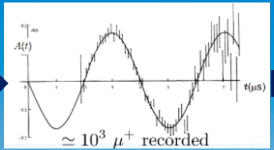


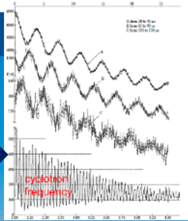
Fig. 8 Overview of the muon storage magnet. arXiv:1901.03047

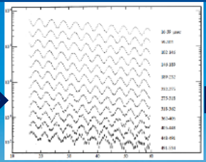


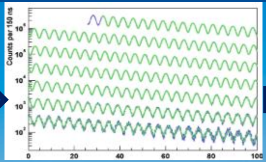
$a_\mu \equiv \frac{g-2}{2} \times 10^{10}$

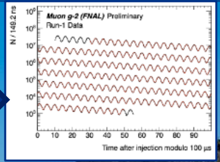




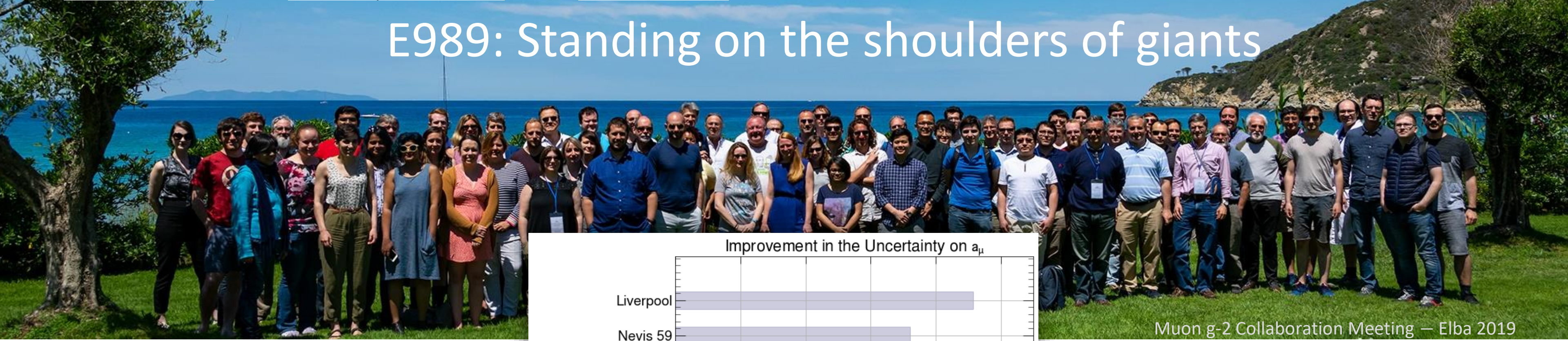




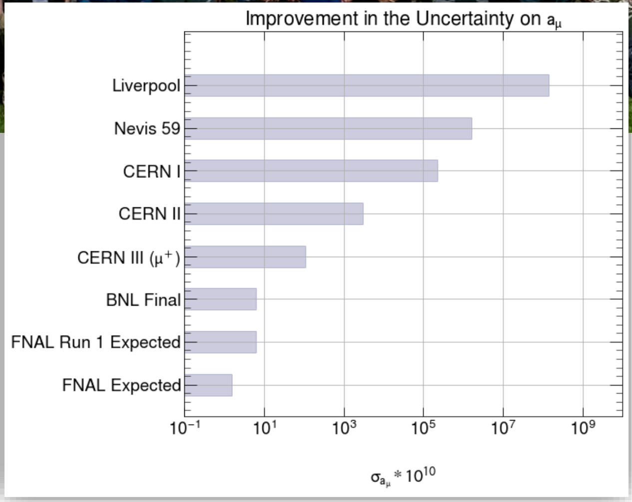




E989: Standing on the shoulders of giants



Muon g-2 Collaboration Meeting — Elba 2019



Thank you!

Questions?

Bonus Slides!

My Contributions

Detector Operations

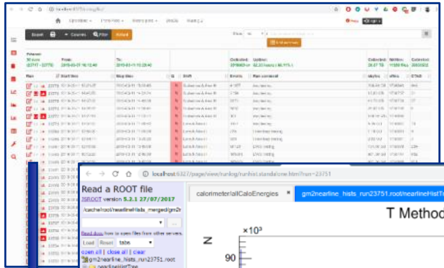
- **Maintaining and improving the detector systems, focusing on the electromagnetic calorimeters**
- **Supported by Fermilab URA**

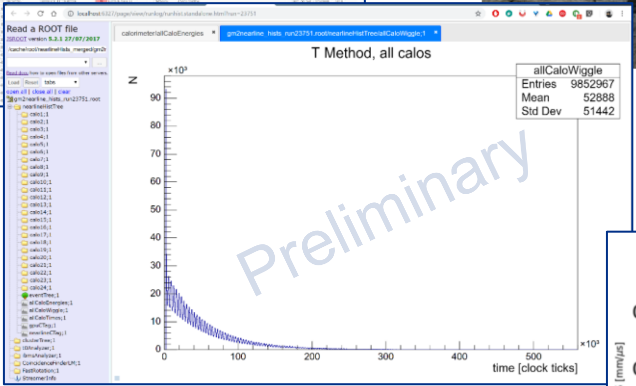
Data Processing

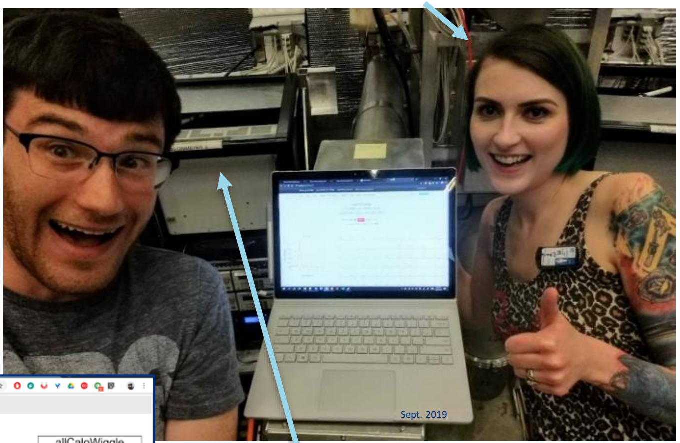
- **Manager of ‘Nearline’ data analysis system, which can process ~30% of the data from the experiment within 2 hours of it being taken. Provided first look at Run 2+ data.**
- **Web interface for live monitoring**
- **Useful for systematic studies / live optimization of beam parameters**

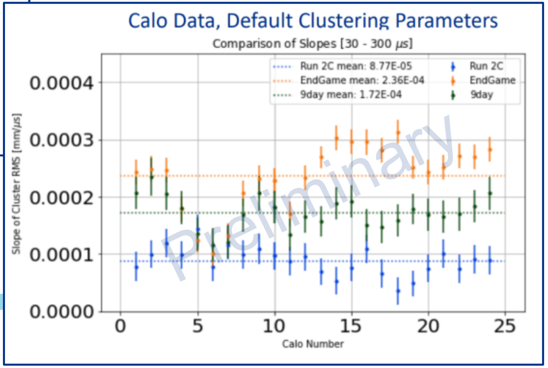
ω_a Analysis

- **Systematic studies related to the extraction of ω_a**









E989 vs. E821 Systematic Errors

E989 TDR

Table I: Uncertainties on the quantities used to determine a_μ^{Exp} and a_μ^{SM}. Experimental errors from Ref [6]. CODATA ratio uncertainties from the 2014 online update.

Quantity	Present Uncertainty ppb	E989 Goal ppb
Total ω_a Statistical	460	100
Final ω_a Systematic	210	70
Final $\tilde{\omega}_p$ Systematic	170	70
CODATA m_μ/m_e	22	–
CODATA μ_p/μ_e	3.0	NA
Electron g factor, g_e	0.000035	NA
Final E821	630	–
Goal Fermilab E989	–	140

Source of uncertainty	R99 [ppb]	R00 [ppb]	R01 [ppb]	E989 [ppb]	Section
Absolute calibration of standard probe	50	50	50	35	15.4.1
Calibration of trolley probes	200	150	90	30	15.4.1
Trolley measurements of B_0	100	100	50	30	15.3.1
Interpolation with fixed probes	150	100	70	30	15.3
Uncertainty from muon distribution	120	30	30	10	15.3
Inflector fringe field uncertainty	200	–	–	–	–
Time dependent external B fields	–	–	–	5	15.6
Others †	150	100	100	30	15.7
Total systematic error on ω_p	400	240	170	70	–
Muon-averaged field [Hz]: $\tilde{\omega}_p/2\pi$	61 791 256	61 791 595	61 791 400	–	–

Table 15.1: Systematic errors for the magnetic field for the different run periods in E821. R99 refers to data taken in 1999, R00 to 2000, R01 to 2001. The last two columns refer to anticipated uncertainties for E989, and the section in this chapter where the uncertainty is discussed in detail. †Higher multipoles, trolley temperature and its power supply voltage response, and eddy currents from the kicker.

Table 16.1: Detector-specific systematic uncertainties in E821 and proposed upgrade actions and projected future uncertainties for E989.

E821 Error	Size [ppb]	Plan for the New $g-2$ Experiment	Goal [ppb]
Gain changes	120	Better laser calibration; low energy threshold; temperature stability; segmentation to lower rates	20
Pileup	80	low energy samples recorded; calorimeter segmentation; Fast Cherenkov light; improved analysis techniques	40

Summary

Nevis 57

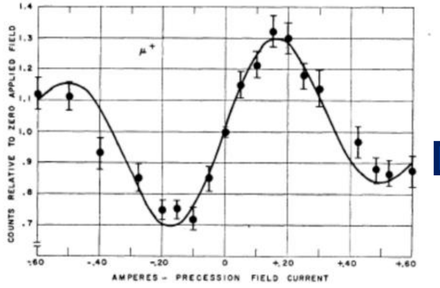
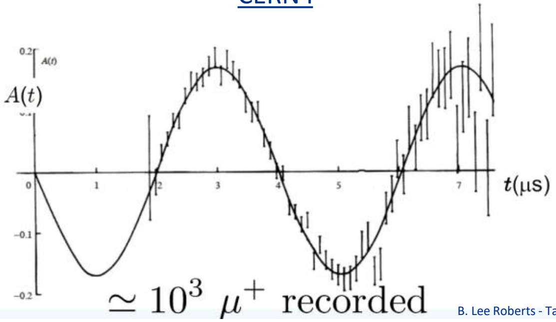


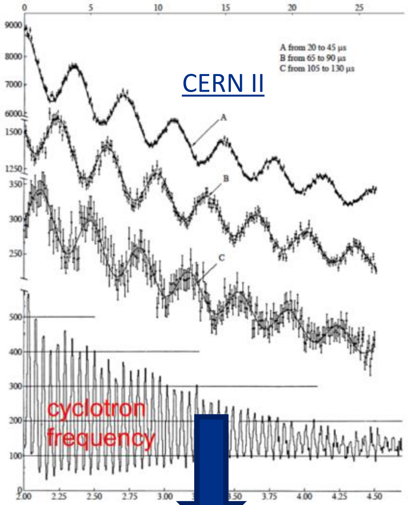
FIG. 2. Variation of gated 3–4 counting rate with magnetizing current. The solid curve is computed from an assumed electron angular distribution $1-\frac{1}{3}\cos\theta$, with counter and gate-width resolution folded in.

CERN I

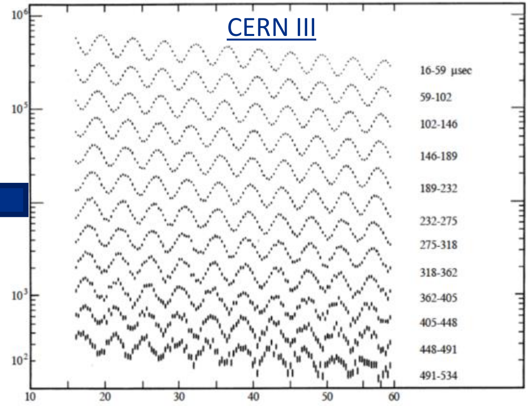


B. Lee Roberts - Tau2018

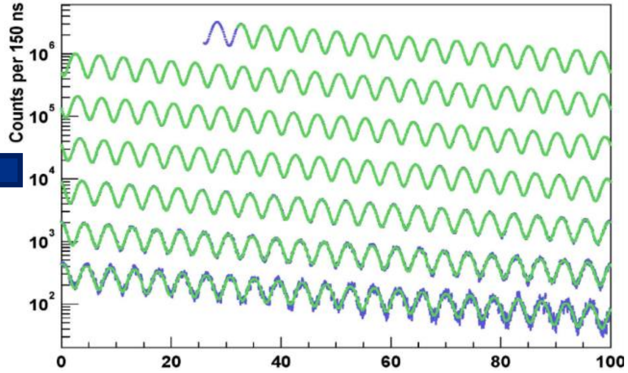
CERN II



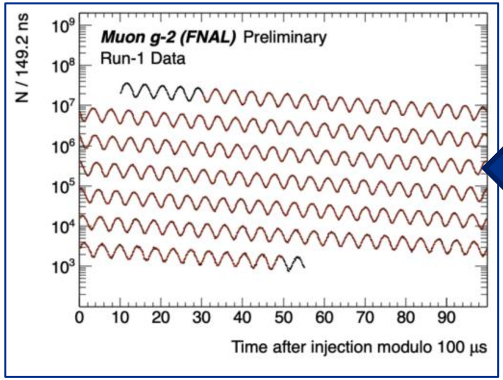
CERN III



BNL (E821)



FNAL (E989)



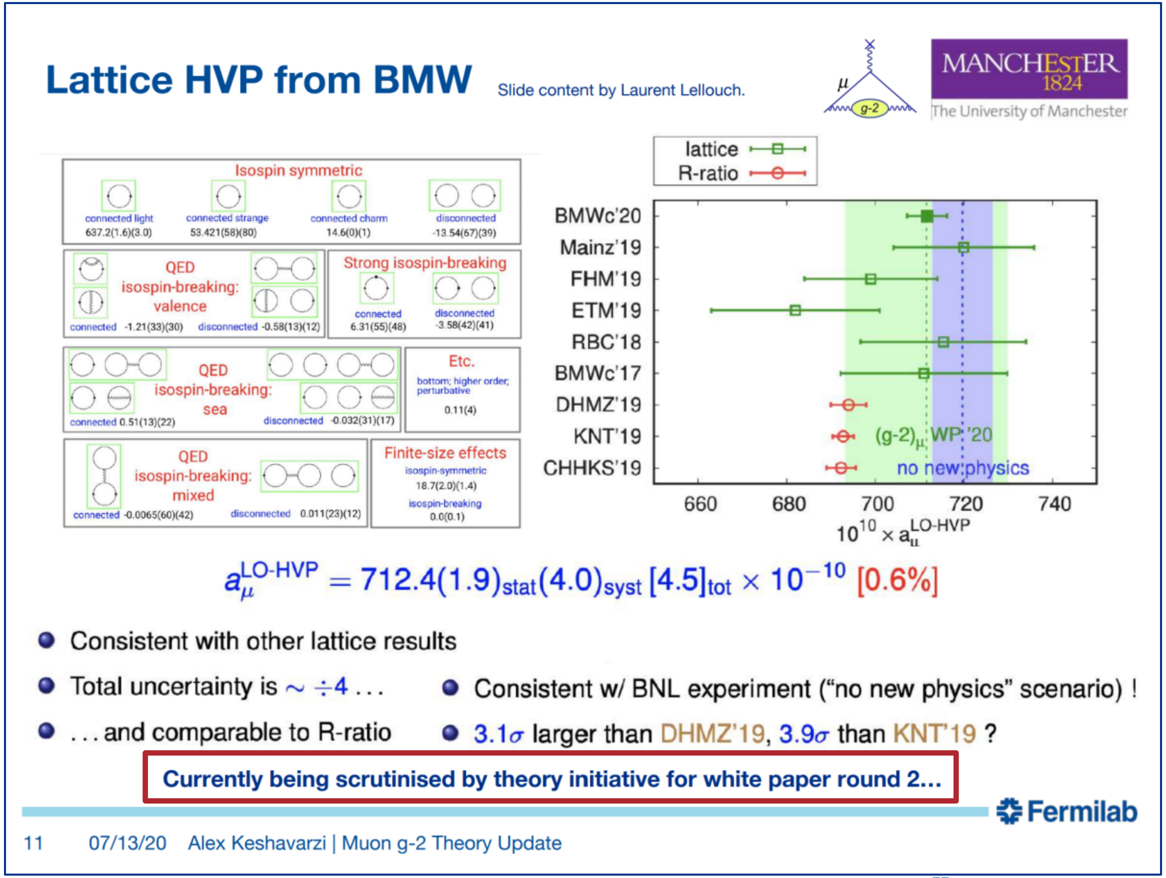
What if we’re just wrong?

New Lattice HVP result from BMW (not the car company) gives a value of a_μ which is consistent with the standard model.

Currently under scrutiny

- New technique
- Well-vetted techniques for doing the same calculation differ by $> 3\,\sigma$
- Fixes g_μ anomaly, but causes tension in some well-established electroweak fits
- No confirmation by other groups with the same level of uncertainty

Results of this scrutiny will be included in updated theoretical predictions.



Past: Theory Push for E821

A number of mistakes in the QED calculations for $g-2$ were realized during the CERN I-III years and corrected.

PhysRevLett.23.441

PHOTON-PHOTON SCATTERING CONTRIBUTION TO THE SIXTH-ORDER MAGNETIC MOMENT OF THE MUON*

Janis Aldins† and Toichiro Kinoshita
Laboratory of Nuclear Studies, Cornell University, Ithaca, New York 14850

and

Stanley J. Brodsky and Andrew J. Dufner
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305

(Received 25 July 1969)

We report a calculation of the three-photon—exchange (electron-loop) contribution to the sixth-order anomalous magnetic moment of the muon. Our result, which contains a logarithmic dependence on the muon-to-electron mass ratio, brings the theoretical prediction into agreement with the CERN measurements, within the 1—standard-deviation experimental accuracy.

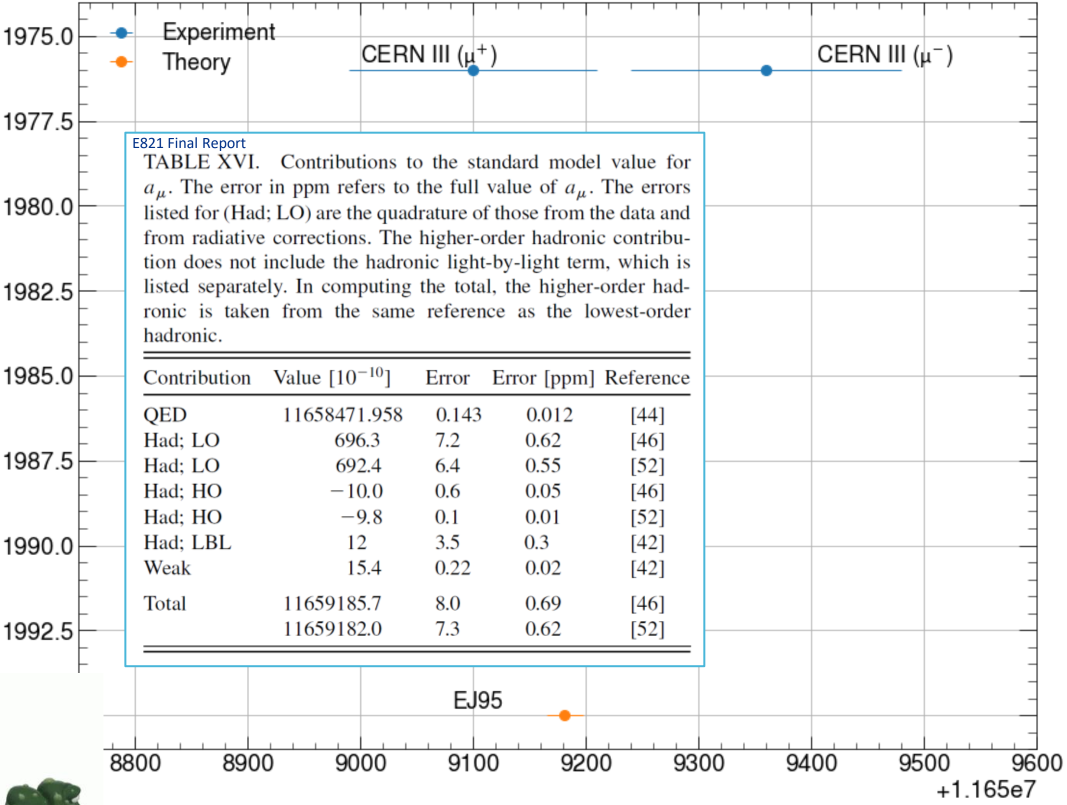
This leads us to a revised theoretical prediction

$$a_{\text{theo}} = (116\,587 \pm 3) \times 10^{-8} \quad (7)$$

and

$$a_{\text{expt}} - a_{\text{theo}} = (29 \pm 34) \times 10^{-8} = (250 \pm 290)\ \text{ppm}. \quad (8)$$

PhysRevLett.23.441



E821 Final Report

TABLE XVI. Contributions to the standard model value for a_μ. The error in ppm refers to the full value of a_μ. The errors listed for (Had; LO) are the quadrature of those from the data and from radiative corrections. The higher-order hadronic contribution does not include the hadronic light-by-light term, which is listed separately. In computing the total, the higher-order hadronic is taken from the same reference as the lowest-order hadronic.

Contribution	Value $[10^{-10}]$	Error	Error [ppm]	Reference
QED	11658471.958	0.143	0.012	[44]
Had; LO	696.3	7.2	0.62	[46]
Had; LO	692.4	6.4	0.55	[52]
Had; HO	−10.0	0.6	0.05	[46]
Had; HO	−9.8	0.1	0.01	[52]
Had; LBL	12	3.5	0.3	[42]
Weak	15.4	0.22	0.02	[42]
Total	11659185.7	8.0	0.69	[46]
	11659182.0	7.3	0.62	[52]

$$a_\mu \equiv \frac{g-2}{2} \times 10^{10}$$

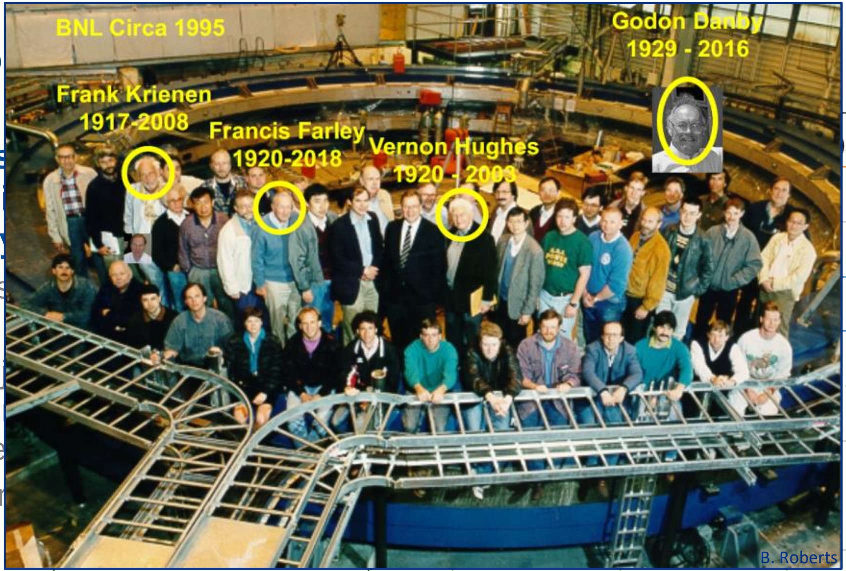
Error on the theoretical result was reduced to be comparable with the expected E821 experimental limits

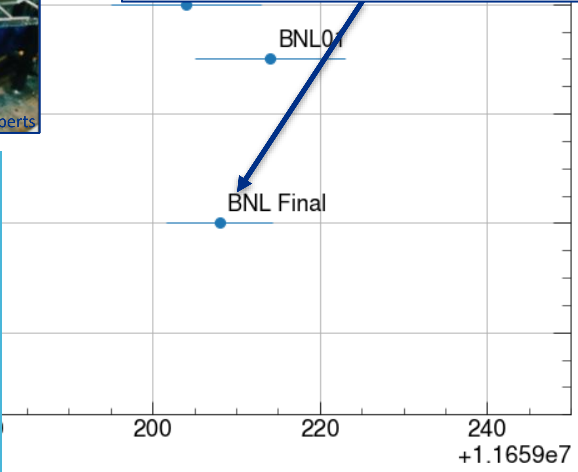
Past: E821 Broo

E821 kept the fundamentals
CERN-III measurement but
upon it in pretty much every

- 20 years of hardware/s advances.
- Transition from pion inj muon injection further initial splash of particle
- Electromagnetic kicker onto correct orbits
- Transition from 14 separate magnets to a single ring the magnetic field is much uniform
- Magnetic field can be mapped/tracked in situ us / fixed NMR probes

About a factor of 14 improven over CERN-III's final result.





$a_\mu \equiv \frac{g-2}{2} \times 10^{10}$

E821 Final Report

G. W. BENNETT *et al.*

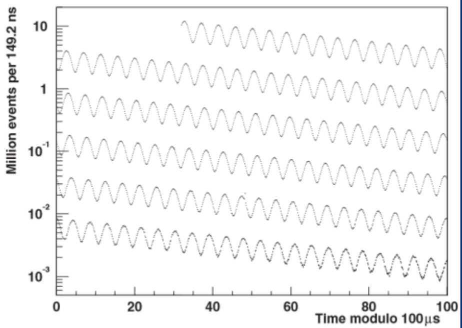
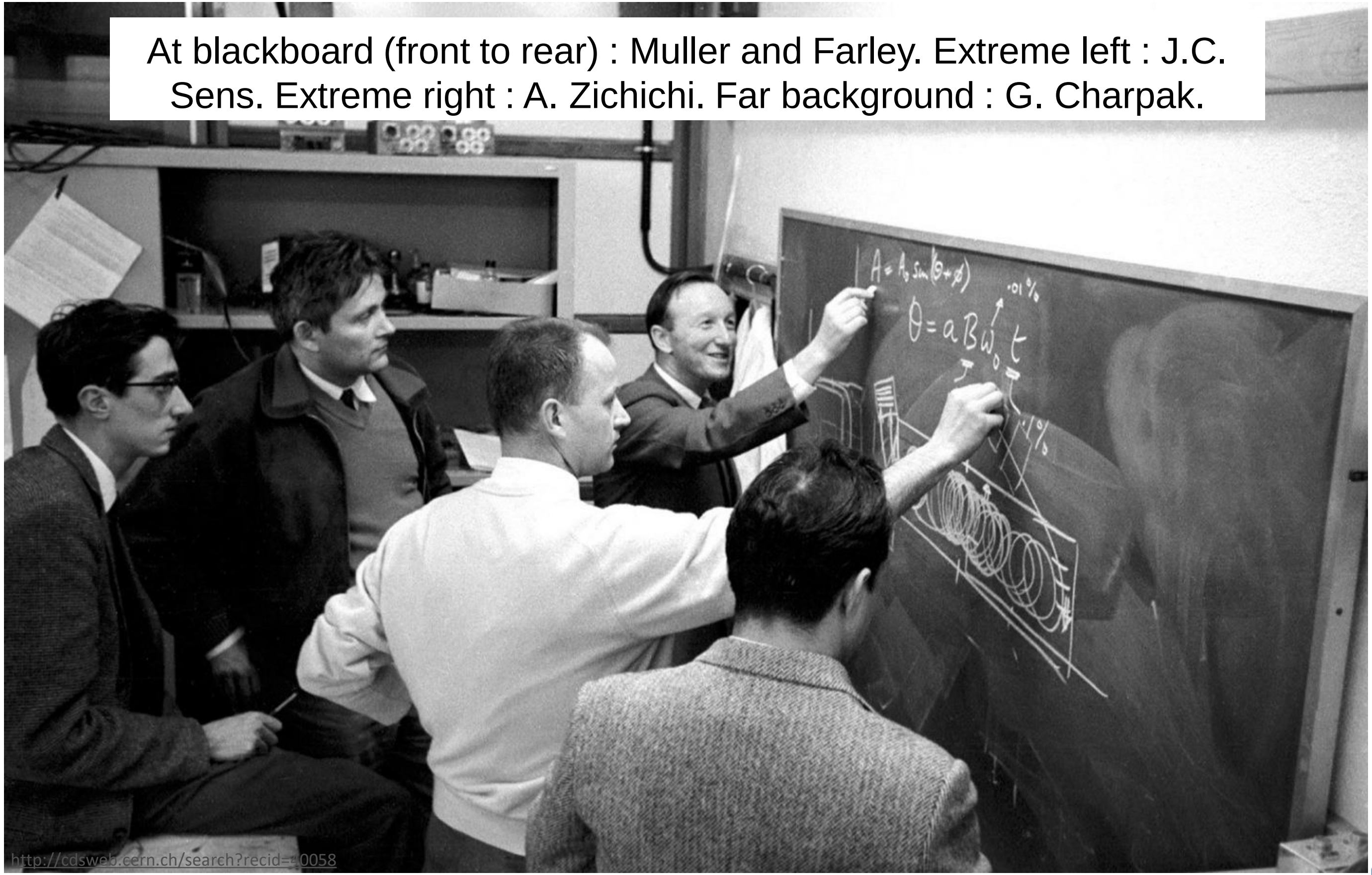


FIG. 2. Distribution of electron counts versus time for the 3.6×10^9 muon decays in the R01 μ^- data-taking period. The data is wrapped around modulo 100 μs.

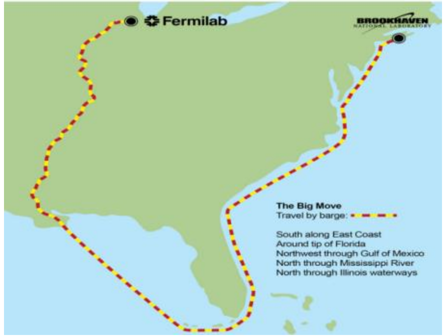
Fermilab

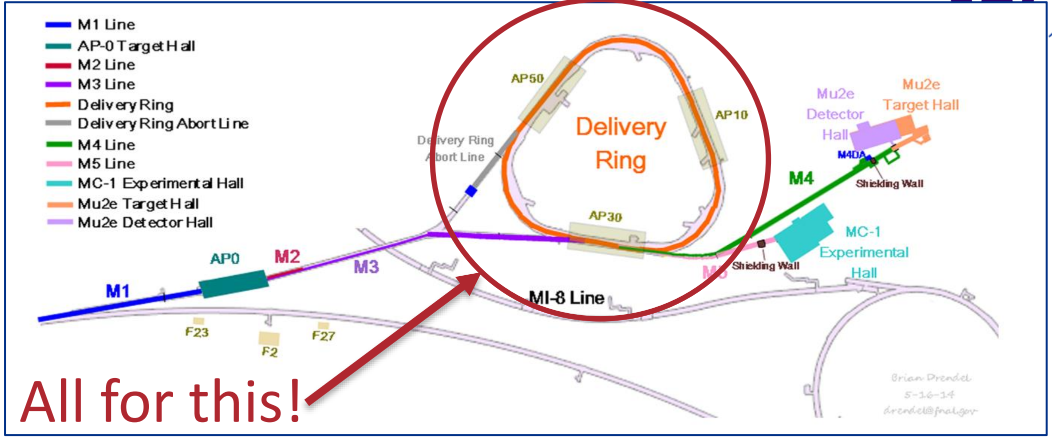
Blackboard Interpretations of CERN I

At blackboard (front to rear) : Muller and Farley. Extreme left : J.C. Sens. Extreme right : A. Zichichi. Far background : G. Charpak.

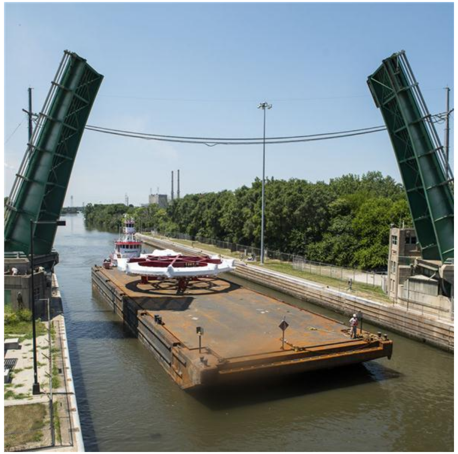


"The Big Move"





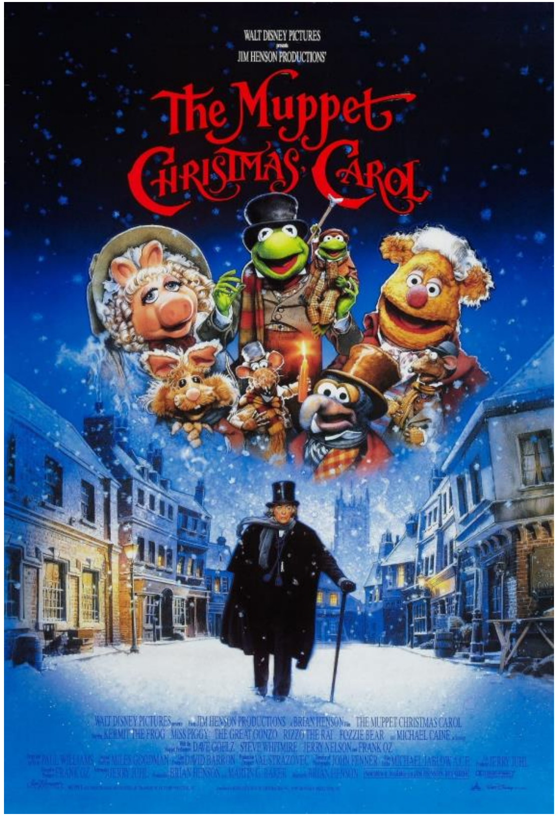
All for this!



https://muon-g-2.fnal.gov/bigmove/gallery.shtml

Fermilab

Outline



- Past

- Present

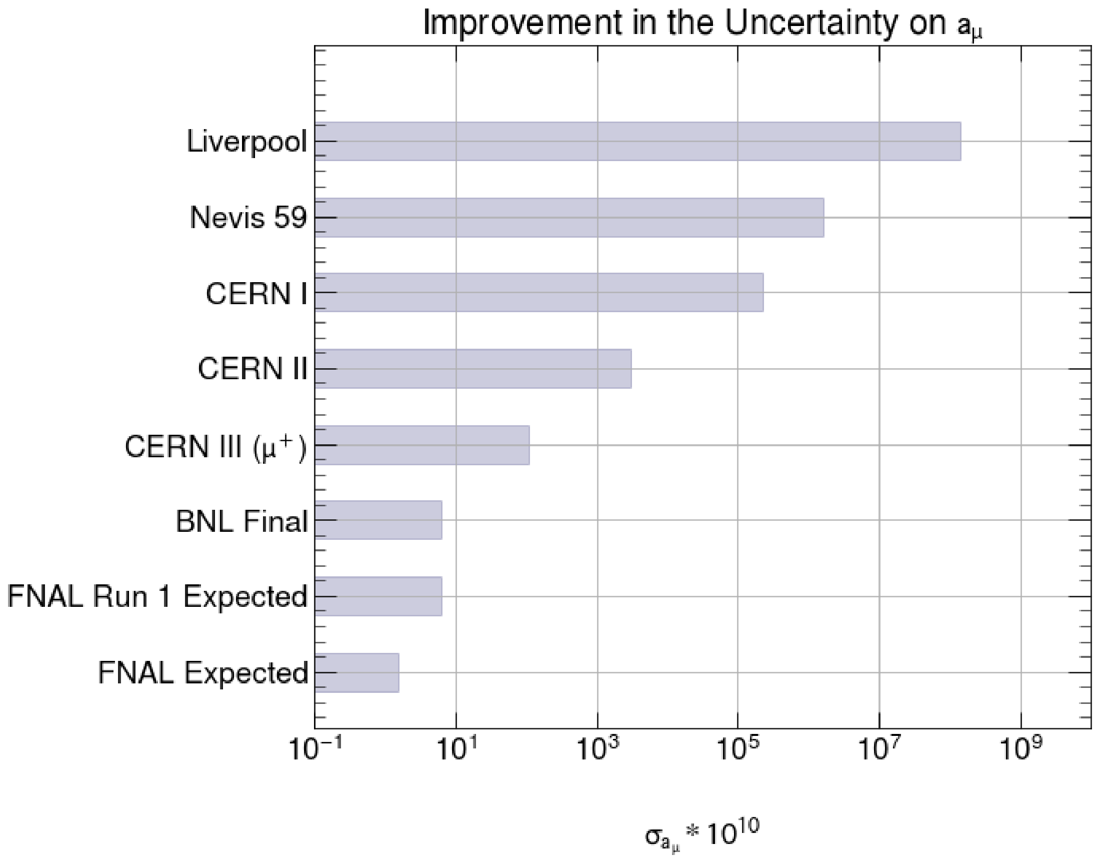
- Future

As we go through, we'll touch on the 4 pillars that make our measurement of $g-2$ possible (and viable as a test of the SM)

- ➢ Muons are special: Free polarization and a self-analyzing decay
- ➢ $\omega_a \propto a_\mu$ (not γ!)
- ➢ Magic momentum cancels $\vec{E} \times \vec{B}$ term
- ➢ Theory can be calculated as precisely as measurements

Throughout the talk, these bullets will denote the 'pillars'

g-2 Throughout The Years



g-2 Throughout The Years

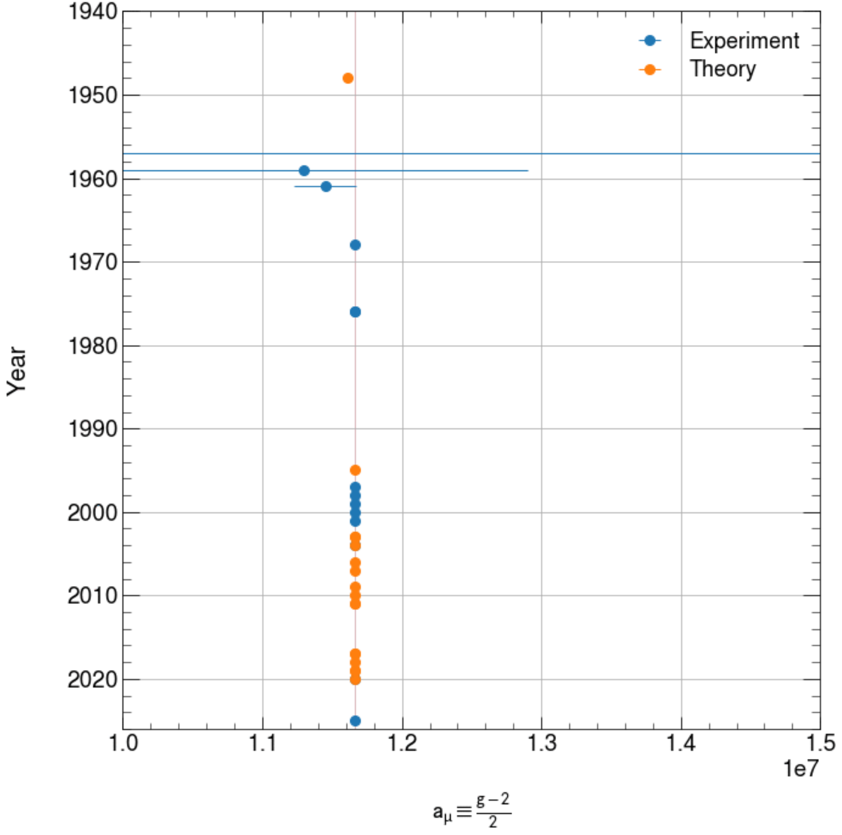
808 J P Miller *et al*

Table 1. Measurements of the muon anomalous magnetic moment. When the uncertainty on the measurement is the size of the next term in the QED expansion, or the hadronic or weak contributions, the term is listed under 'sensitivity'. The '?' indicates a result that differs by greater than two standard deviations from the Standard Model. For completeness, we include the experiment of Henry *et al* [46], which is not discussed in the text.

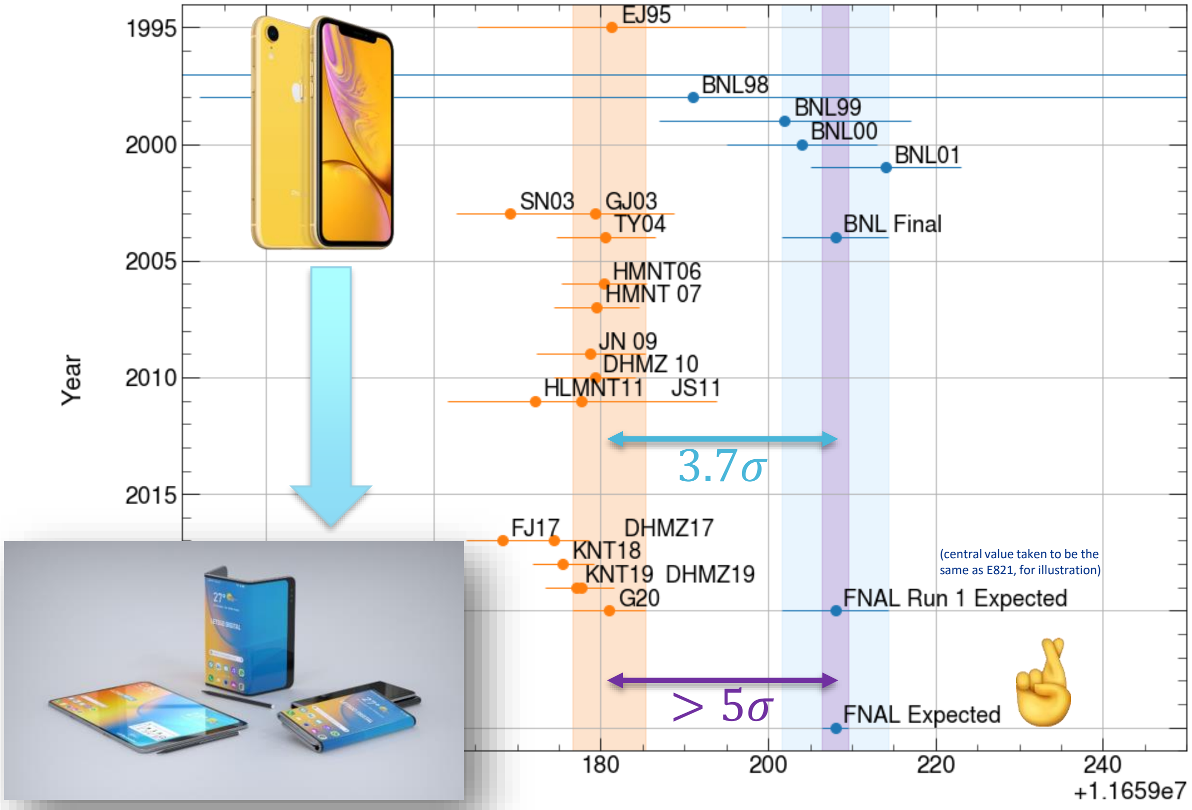
$\pm$	Measurement	σ_{a_μ}/a_μ	Sensitivity	References
μ^+	$g = 2.00 \pm 0.10$		$g = 2$	Garwin *et al* [30], Nevis (1957)
μ^+	$0.001\,13^{+0.000\,16}_{-0.000,12}$	12.4%	$\frac{\alpha}{\pi}$	Garwin *et al* [33], Nevis (1959)
μ^+	0.001 145(22)	1.9%	$\frac{\alpha}{\pi}$	Charpak *et al* [34] CERN 1 (SC) (1961)
μ^+	0.001 162(5)	0.43%	$\left(\frac{\alpha}{\pi}\right)^2$	Charpak *et al* [35] CERN 1 (SC) (1962)
$\mu^\pm$	0.001 166 16(31)	265 ppm	$\left(\frac{\alpha}{\pi}\right)^3$	Bailey *et al* [36] CERN 2 (PS) (1968)
μ^+	0.001 060(67)	5.8%	$\frac{\alpha}{\pi}$	Henry*et al* [46] solenoid (1969)
$\mu^\pm$	0.001 165 895(27)	23 ppm	$\left(\frac{\alpha}{\pi}\right)^3$ + Hadronic	Bailey *et al* [37] CERN 3 (PS) (1975)
$\mu^\pm$	0.001 165 911(11)	7.3 ppm	$\left(\frac{\alpha}{\pi}\right)^3$ + Hadronic	Bailey *et al* [38] CERN 3 (PS) (1979)
μ^+	0.001 165 919 1(59)	5 ppm	$\left(\frac{\alpha}{\pi}\right)^3$ + Hadronic	Brown *et al* [48] BNL (2000)
μ^+	0.001 165 920 2(16)	1.3 ppm	$\left(\frac{\alpha}{\pi}\right)^4$ + Weak	Brown *et al* [49] BNL (2001)
μ^+	0.001 165 920 3(8)	0.7 ppm	$\left(\frac{\alpha}{\pi}\right)^4$ + Weak + ?	Bennett *et al* [50] BNL (2002)
μ^-	0.001 165 921 4(8)(3)	0.7 ppm	$\left(\frac{\alpha}{\pi}\right)^4$ + Weak + ?	Bennett *et al* [51] BNL (2004)
$\mu^\pm$	0.001 165 920 80(63)	0.54 ppm	$\left(\frac{\alpha}{\pi}\right)^4$ + Weak + ?	Bennett *et al* [51, 26] BNL WA (2004)

https://iopscience.iop.org/article/10.1088/0034-4885/70/5/R03

g-2 Throughout The Years



Future: Outlook



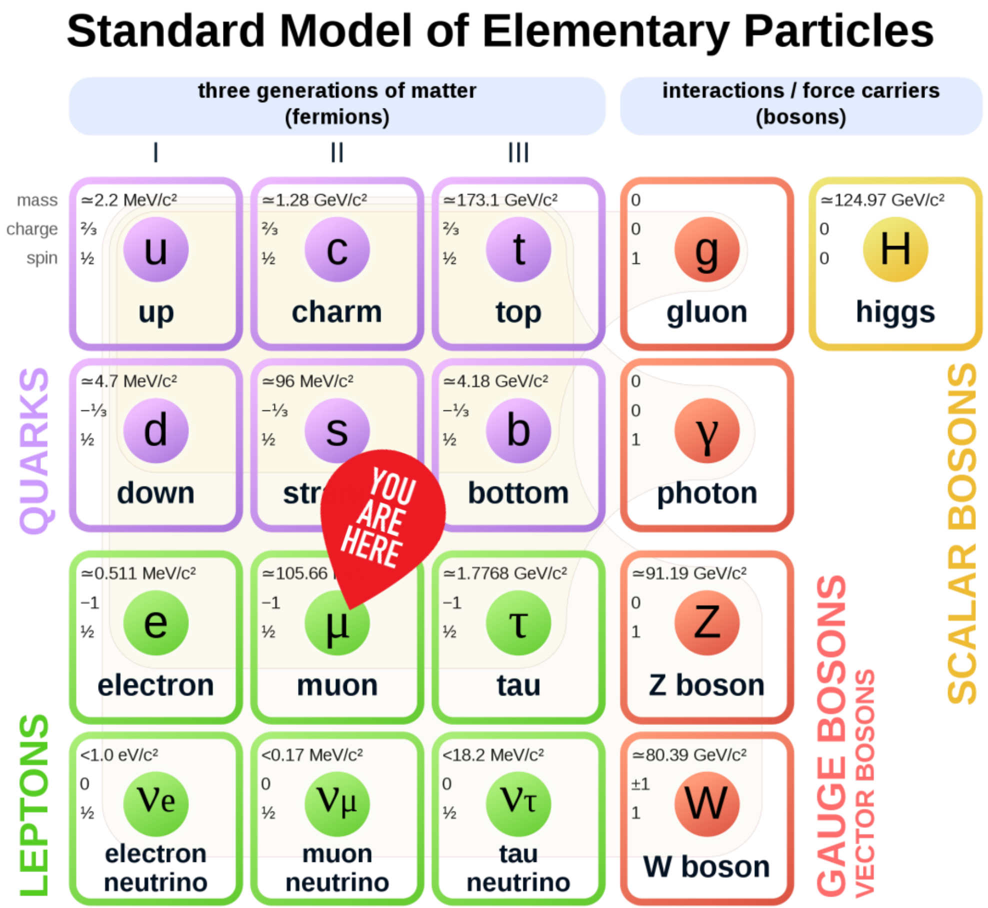
$a_\mu \equiv \frac{g-2}{2} \times 10^{10}$

Table of Errors (from E821 Final Report, 2004)

TABLE I. Summary of a_μ results from CERN and BNL, showing the evolution of experimental precision over time. The average is obtained from the 1999, 2000 and 2001 data sets only.

Experiment	Years	Polarity	$a_\mu \times 10^{10}$	Precision [ppm]	Reference
CERN I	1961	μ^+	11450000(220000)	4300	[2]
CERN II	1962–1968	μ^+	11661600(3100)	270	[3]
CERN III	1974–1976	μ^+	11659100(110)	10	[5]
CERN III	1975–1976	μ^-	11659360(120)	10	[5]
BNL	1997	μ^+	11659251(150)	13	[6]
BNL	1998	μ^+	11659191(59)	5	[7]
BNL	1999	μ^+	11659202(15)	1.3	[8]
BNL	2000	μ^+	11659204(9)	0.73	[9]
BNL	2001	μ^-	11659214(9)	0.72	[10]
Average			11659208.0(6.3)	0.54	[10]

Background



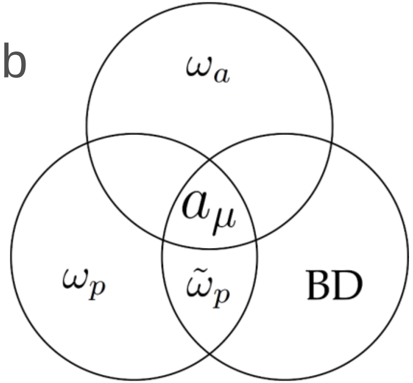
$$m_\mu \approx 200\, m_e$$

$$\downarrow$$

$$\mathrm{NP}_\mu \approx 200^2 \mathrm{NP}_e$$

Overview

- Goal of the experiment is to measure $a_\mu \equiv (g-2)/2$ to 140 ppb
- In order to do this, we measure three quantities:
  - ω_a: anomalous spin precession frequency of the muon
  - ω_p: free proton precession frequency ($\propto B$)
  - Beam Dynamics: the path the muons travel in a magnetic field
    - $\omega_p \otimes BD = \tilde{\omega}_p$



- We then combine these values with others measured by other experiments

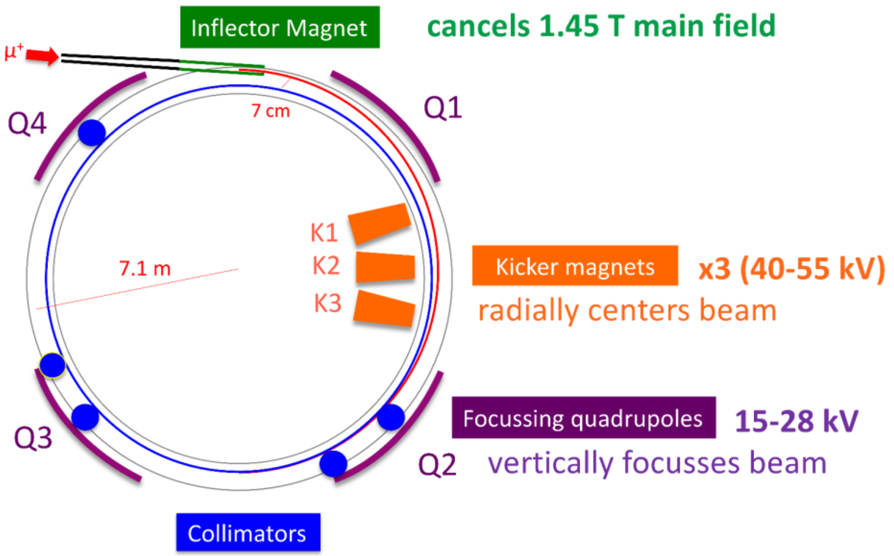
$$a_\mu = \frac{\boldsymbol{\omega_a}}{\boldsymbol{\tilde{\omega}_p}} \frac{\mu_p}{\mu_e} \frac{m_\mu}{m_e} \frac{g_e}{2}$$

0.3 ppt

22 ppb

3 ppb

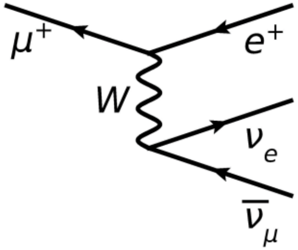
Experimental setup



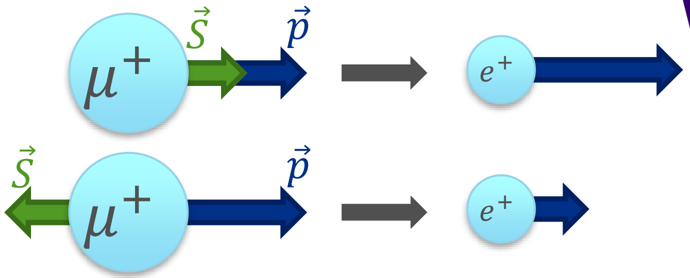
A beam of polarized muons is brought into the storage ring through the inflector magnet, which cancels the field from the main storage ring in a small area. They are placed onto the correct orbit by 3 kicker magnets and then allowed to precess as they orbit in the uniform magnetic field.

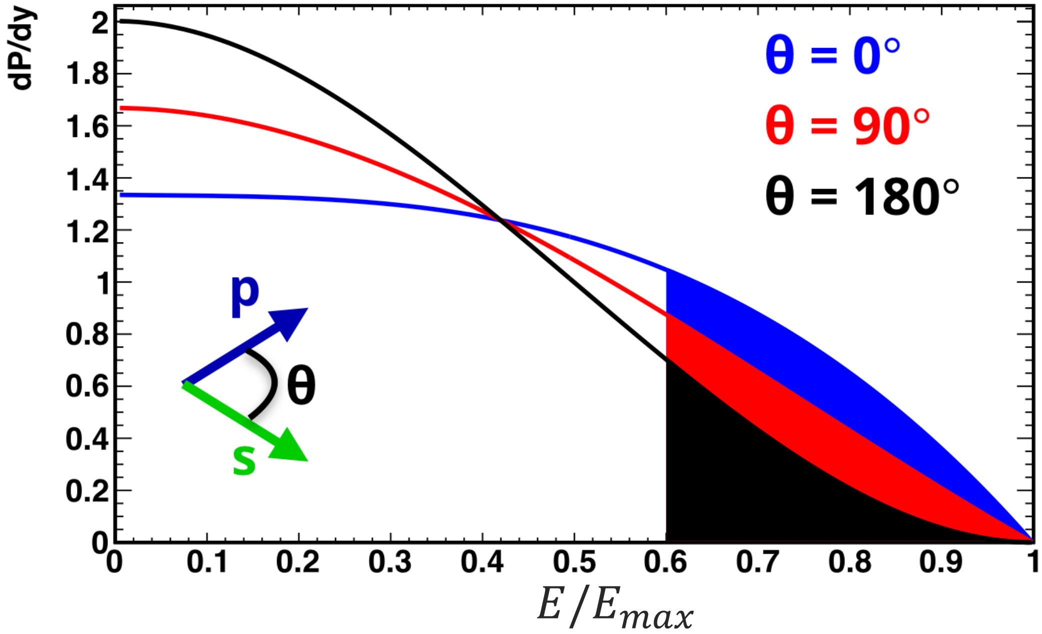
How do we measure ω_a?

Conveniently, nature does it for us. Decay positrons are preferentially emitted in the direction of the muons spin.



This imprints ω_a onto the energy vs. time spectrum of the decay positrons, which we can measure.





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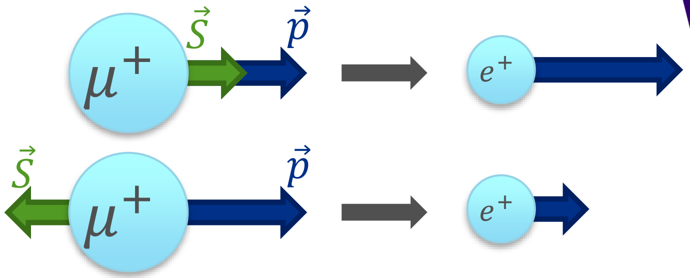
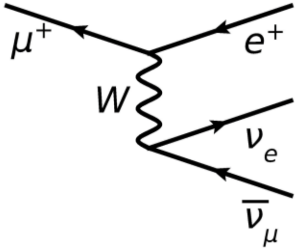
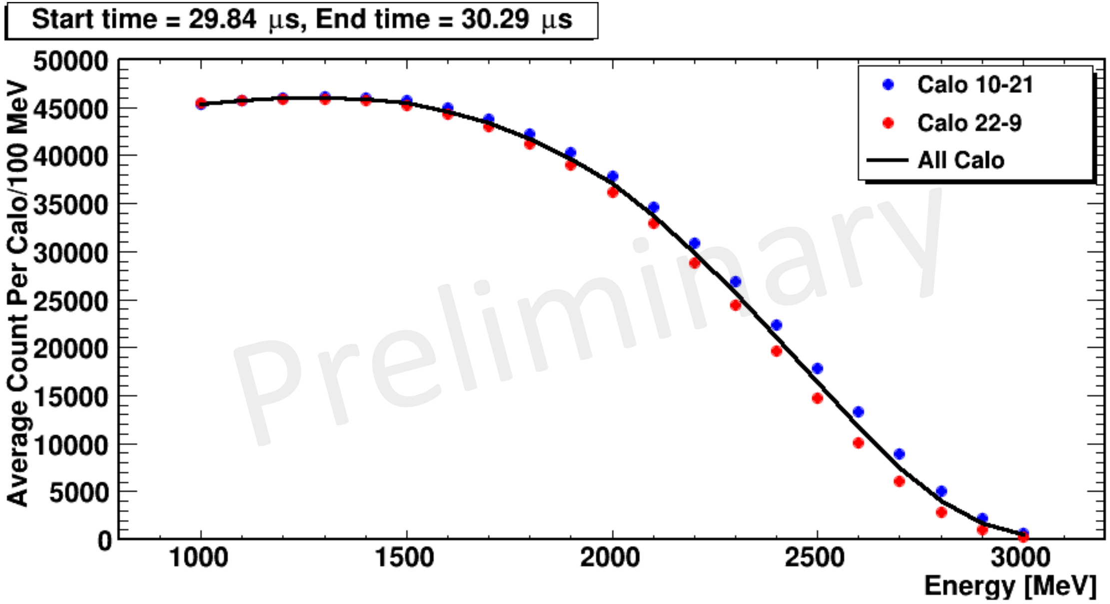
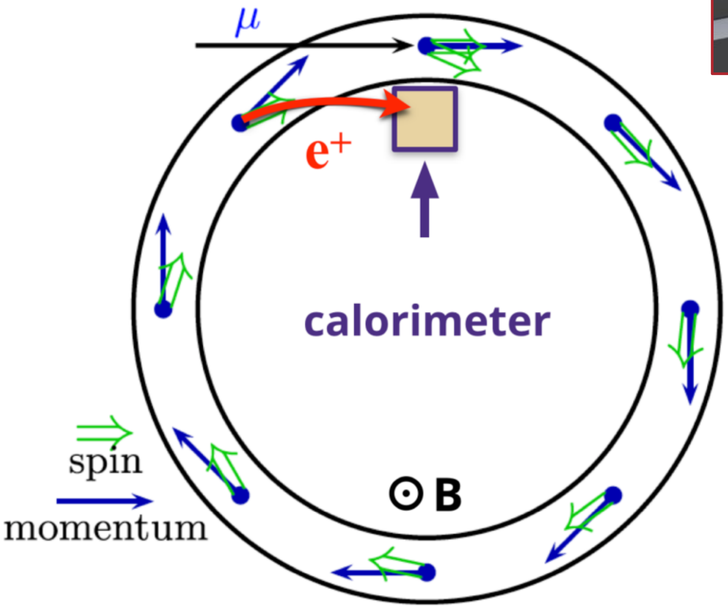


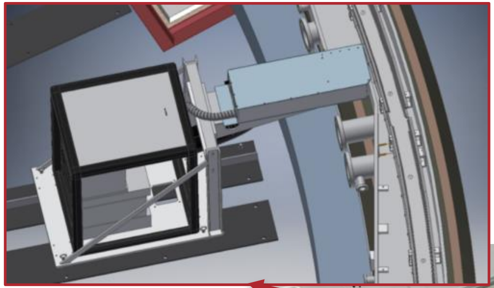


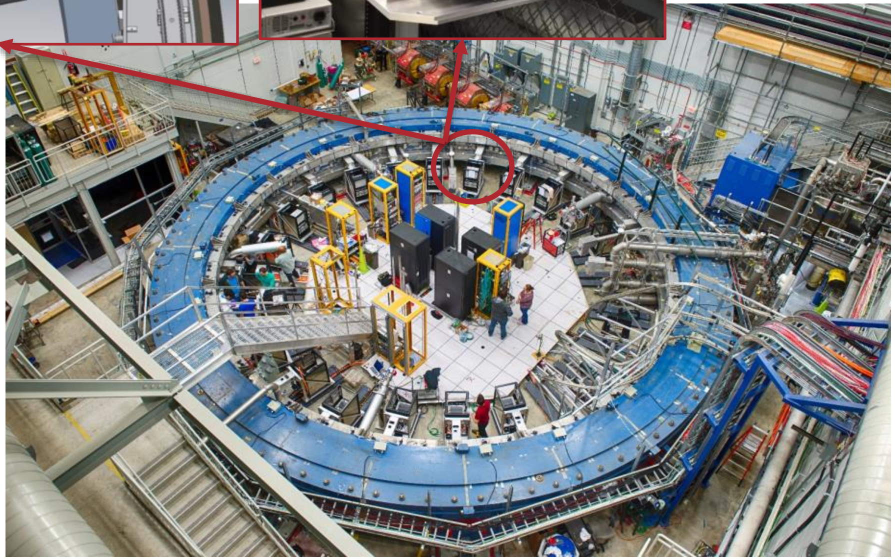


This imprints ω_a onto the energy vs. time spectrum of the decay positrons, which we can measure.

Experimental setup

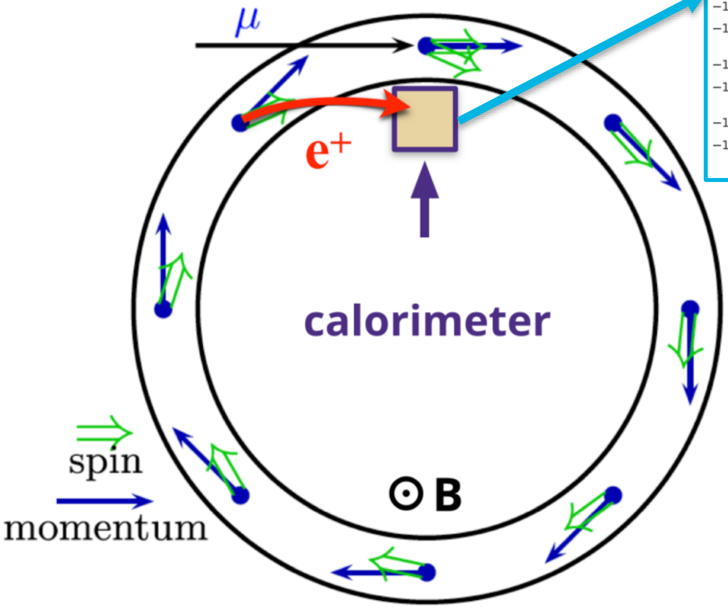


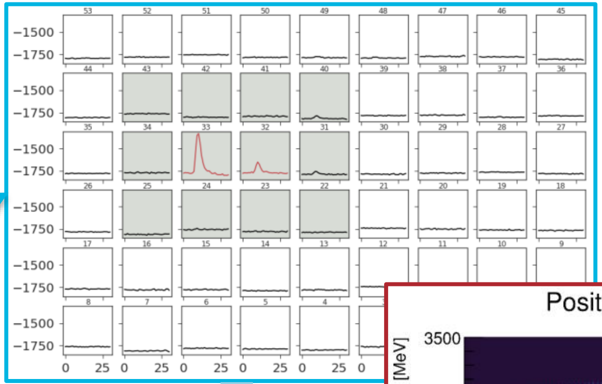


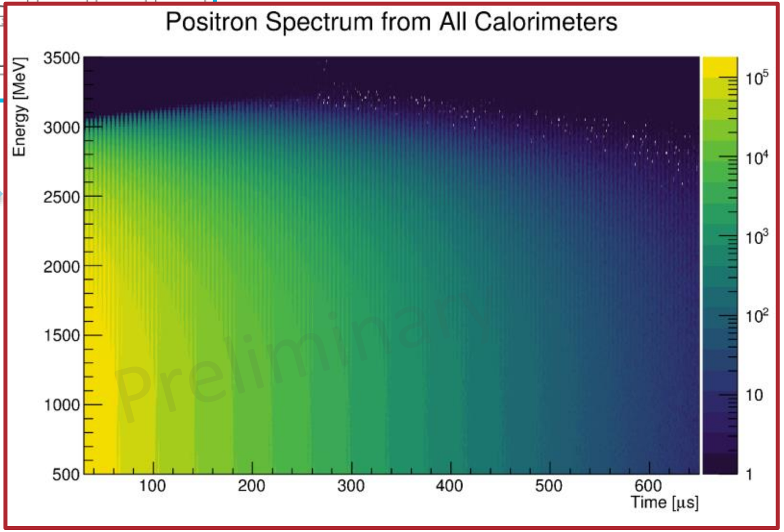


After some time, each muon decays into a positron which then spirals inward and strikes a calorimeter. Each of the 24 calorimeters consists of 54 $\mathrm{PbF_4}$ crystals, which emit Čerenkov light when a decay positron passes through them. The energy of the positron is recorded in the calorimeter as well as the time of impact.

Experimental setup

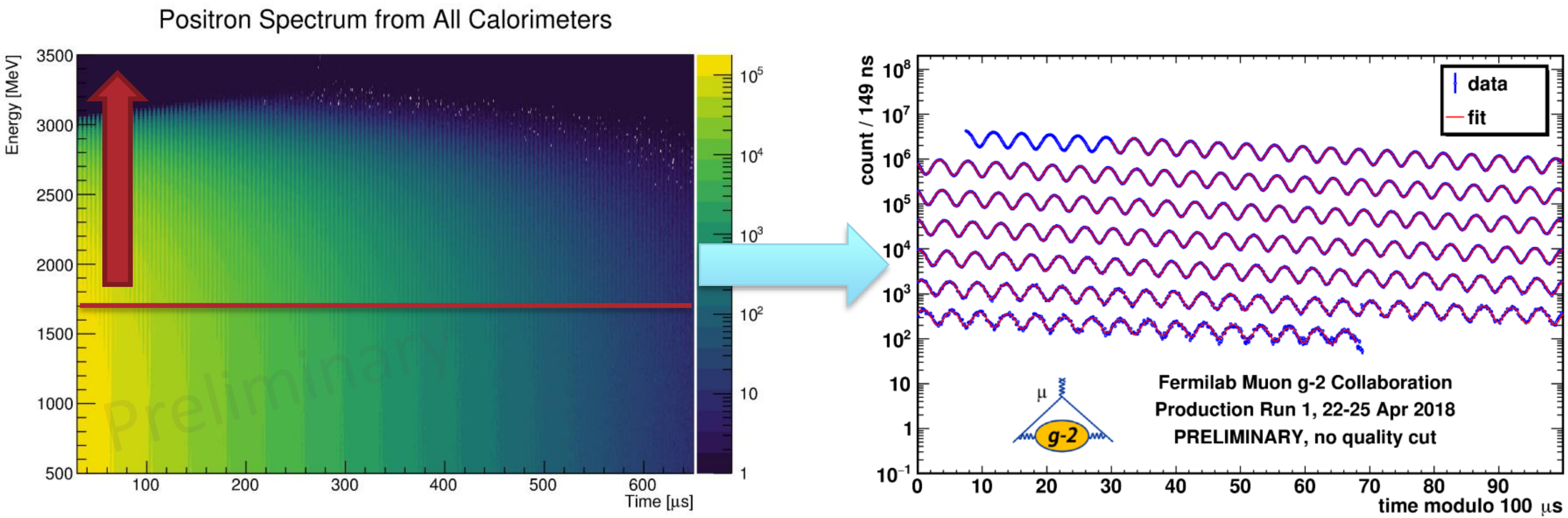






From each of these positron signals, we construct the right plot of energy vs. time.

Creating the 'Wiggle Plot'

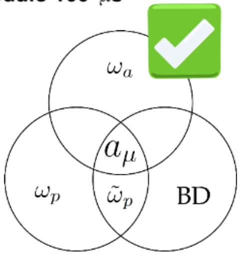


We can create a plot of the energy vs. time spectrum of the decay positrons. Integrating all of the counts above a certain energy threshold allows us to capture the 'wiggle' which is embedded in this spectrum.

We fit this plot with a function such as

$$N(t) = N_0\, e^{-t/\tau_\mu}(1 + A\, cos(\omega_a t + \phi_a)) + \text{[Higher order terms]}$$

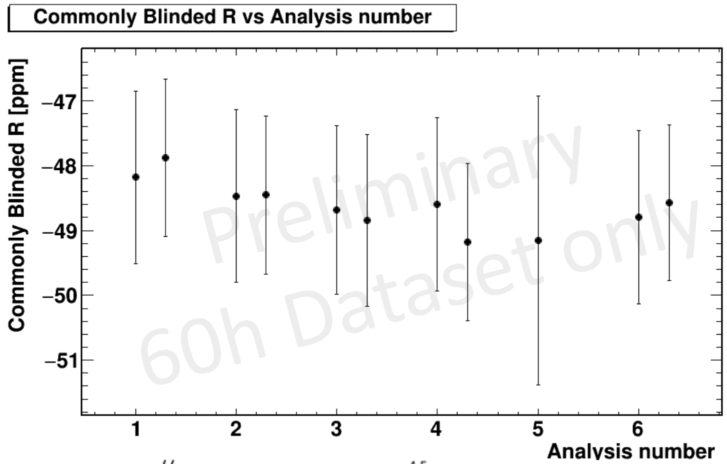
In order to extract ω_a.

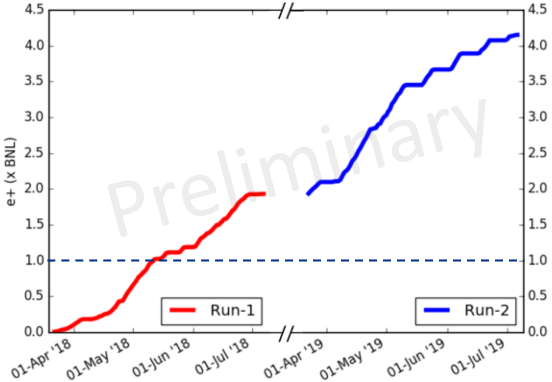


Results

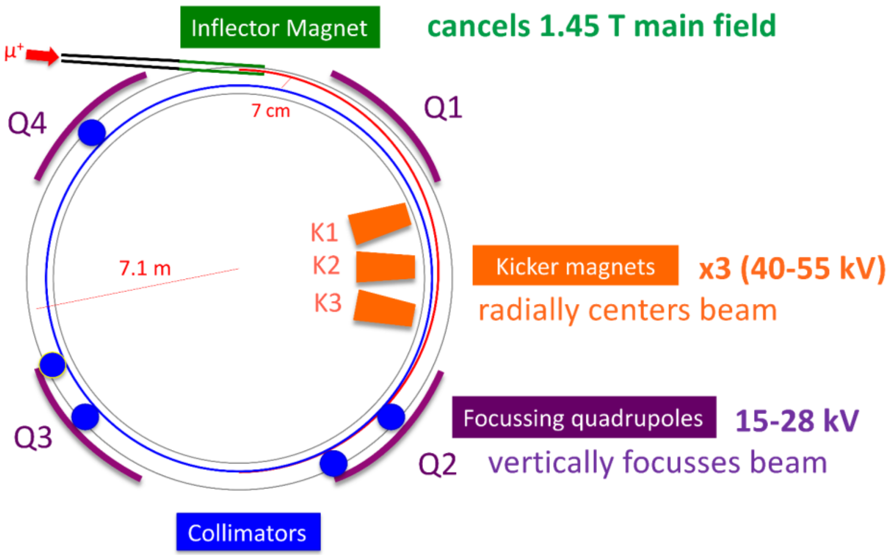
- A relative (but not absolute) comparison of the ω_a analyses has been performed, and all analyzers agree on the result to within statistical + systematic errors.
- Final analysis of the first run is nearly complete, and we expect to have a result published in the coming months
  - The first run is expected to have a total error comparable to the 2003 BNL final result, with 3+ runs to follow.
- Run 2 analysis is underway and Run 3 data collection started yesterday(!!!).

$R = \omega_a$ (ppm from reference value) + [Unknown offset]





Experimental setup



A beam of polarized muons is brought into the storage ring through the inflector magnet, which cancels the field from the main storage ring in a small area. They are placed onto the correct orbit by 3 kicker magnets and then allowed to precess as they orbit in the uniform magnetic field.

Higher Order Terms

$$N(t) = N_0 \cdot \left(1 - K_{loss} \int_0^t e^{t'/\tau} L(t')\, dt'\right) \cdot N_{CBO}(t) \cdot N_{VW}(t) \cdot e^{-t/\tau} \cdot [1 + A(t) \cos(\omega_a(R) - \phi(t))]$$

Parameter	Meaning
R	Blinded ω_a
N_0	Normalization
τ	Muon lifetime
A	$g-2$ asymmetry
ϕ	$g-2$ phase
$\omega_{CBO,0}$	CBO frequency
τ_{CBO}	CBO decoherence time
$A_{CBO,N}$	CBO N_0 modulation
$\phi_{CBO,N}$	Phase of CBO N_0 modulation
$A_{CBO,A}$	CBO A modulation
$\phi_{CBO,A}$	Phase of CBO A modulation
$A_{CBO,\phi}$	CBO ϕ modulation
$\phi_{CBO,\phi}$	Phase of CBO ϕ modulation
ω_{VW}	VW frequency
τ_{VW}	VW decoherence lifetime
A_{VW}	VW N_0 modulation
ϕ_{VW}	Phase of VW N_0 modulation
K_{loss}	Muon loss correction amplitude

$$N_{CBO}(t) = 1 + A_{CBO,N} \cdot e^{-t/\tau_{CBO}} \cos(\omega_{CBO} \cdot t - \phi_{CBO,N})$$

$$N_{VW}(t) = 1 + A_{VW,N} \cdot e^{-t/\tau_{VW}} \cos(\omega_{VW} \cdot t - \phi_{VW,N})$$

$$\phi(t) = \phi_0 + A_{CBO,\phi} \cdot e^{-t/\tau_{CBO}} \cos(\omega_{CBO} \cdot t - \phi_{CBO,\phi})$$

$$A(t) = A_0 \left[1 + A_{CBO,A} \cdot e^{-t/\tau_{CBO}} \cos(\omega_{CBO} \cdot t - \phi_{CBO,A})\right]$$

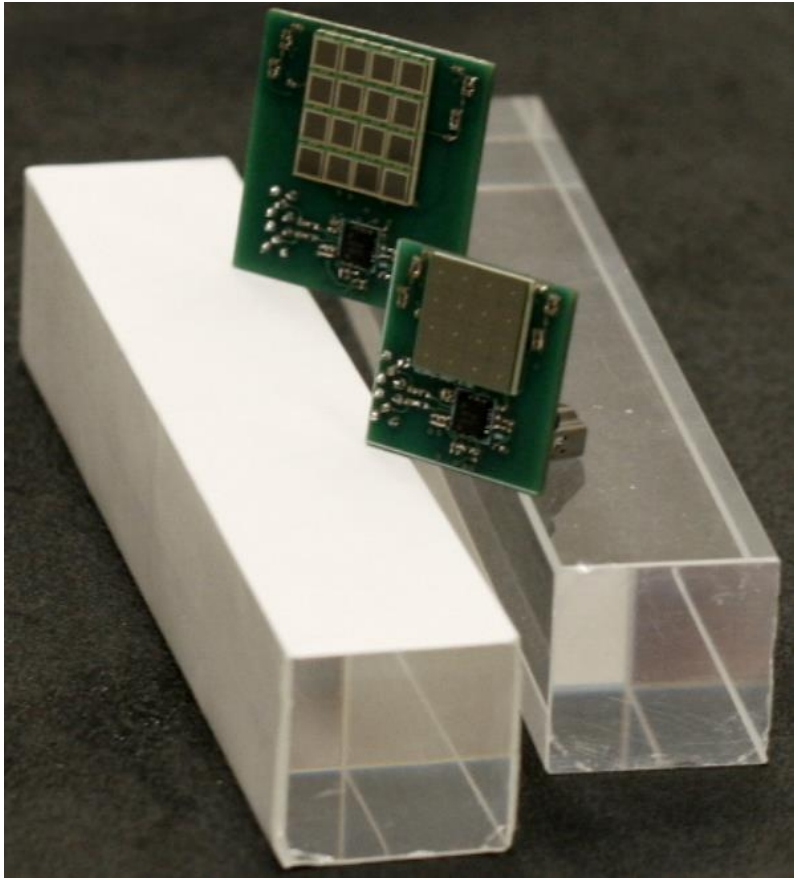
$$\omega_{CBO}(t) = \omega_{CBO,0} \left[1 + \delta_{CBO}(t)\right].$$

$\boldsymbol{\delta_{CBO}(t)}$ fixed from tracker measurements

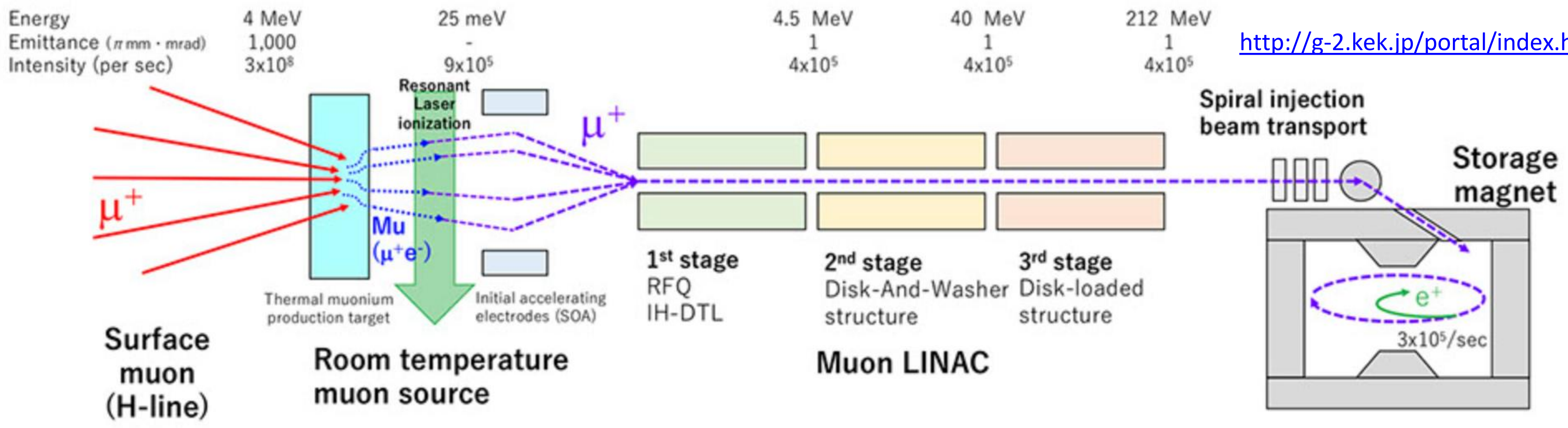
Who's who.


Muon g-2 Collaboration
7 Countries, 33 Institutions, 203 Collaborators

Calorimeter Crystals



J-PARC Muon $g - 2$



http://g-2.kek.jp/portal/index.html

Our experiment introduced here is intended to measure a_μ and d_μ with a very different technique, using a 300 MeV/c reaccelerated thermal muon beam with 50% polarization, vertically injected into an Magnetic Resonance Imaging (MRI)-type solenoid storage ring with 1 ppm local magnetic field uniformity for the muon storage region with an orbit diameter of 66 cm.

arXiv:1901.03047v2

Some References

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