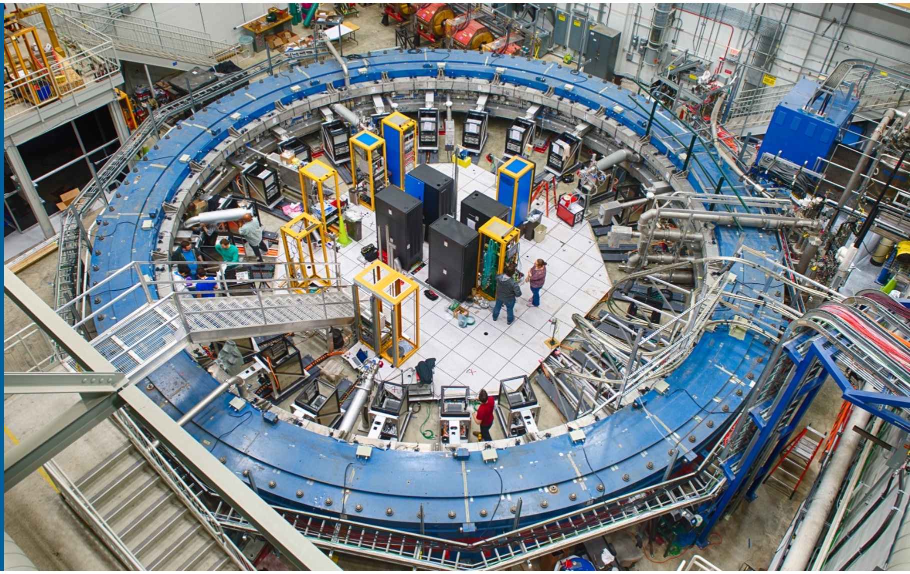
RESULTS FROM THE MUON G-2 EXPERIMENT IN THE LIGHT OF HADRONIC PHYSICS



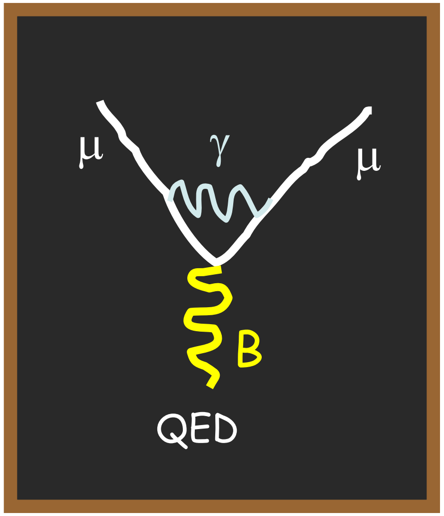
PETER WINTER
High Energy Physics Division
Argonne National Laboratory

SHORT INTRO & MOTIVATION FOR MUON g-2

A PRIMER: MAGNETIC MOMENTS

$$\vec{\mu} = g\frac{q}{2m}\vec{S} \qquad a = \frac{g-2}{2}$$

- Classical current loop in B field: $g = 1$
- Stern-Gerlach and atomic spectroscopy: $g_e \approx 2$
- Dirac theory of elementary spin-½ particle: $g \equiv 2$
- Kusch and Foley: $g_e = 2.00238(6) \neq 2$
- Schwinger's blackboard: $g_e = 2 + \alpha/\pi = 2.00232$
- Garwin (1957): $g_\mu = 2.00 \pm 0.10$ (±50,000 ppm)
- CERN I (1965): $a_\mu = 0.001\,162(5)$ (±4,300 ppm)



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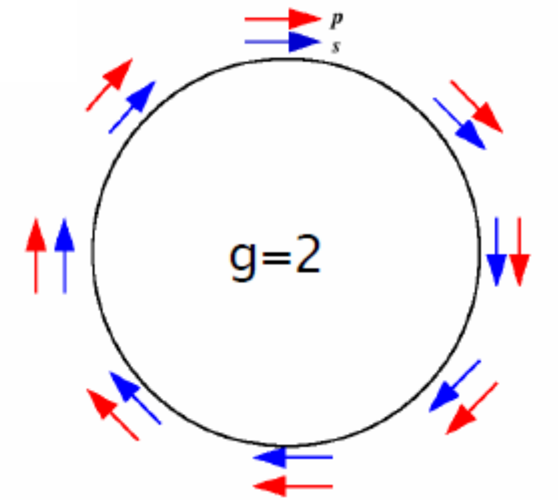
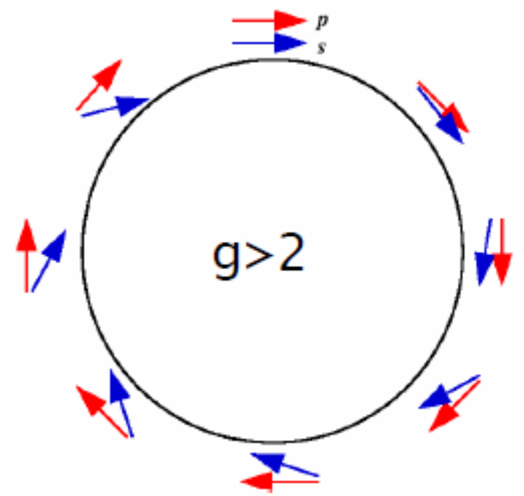
MUONS IN A STORAGE RING (NO E FIELD YET)

- Cyclotron frequency: $$\omega_c = \frac{e}{m\,\gamma} B$$
- Spin precession frequency: $$\omega_S = \frac{e}{m\,\gamma} B\,(1 + \gamma\, a_\mu)$$

Larmor + Thomas precession

$$\boxed{\vec{\omega}_a = \vec{\omega}_S - \vec{\omega}_c = \frac{e}{m}\left(a_\mu\,\vec{B}\,\right)}$$





MUONS IN B AND E FIELD

- In presence of additional E-field (neglecting $\beta \cdot B$ and EDM terms):

$$\vec{\omega}_a = \frac{e}{m}\left(a_\mu \vec{B} - \cancel{\left(a_\mu - \frac{1}{\gamma^2 - 1} \right)} \cancel{\frac{\vec{\beta} \times \vec{E}}{c}} \right)$$

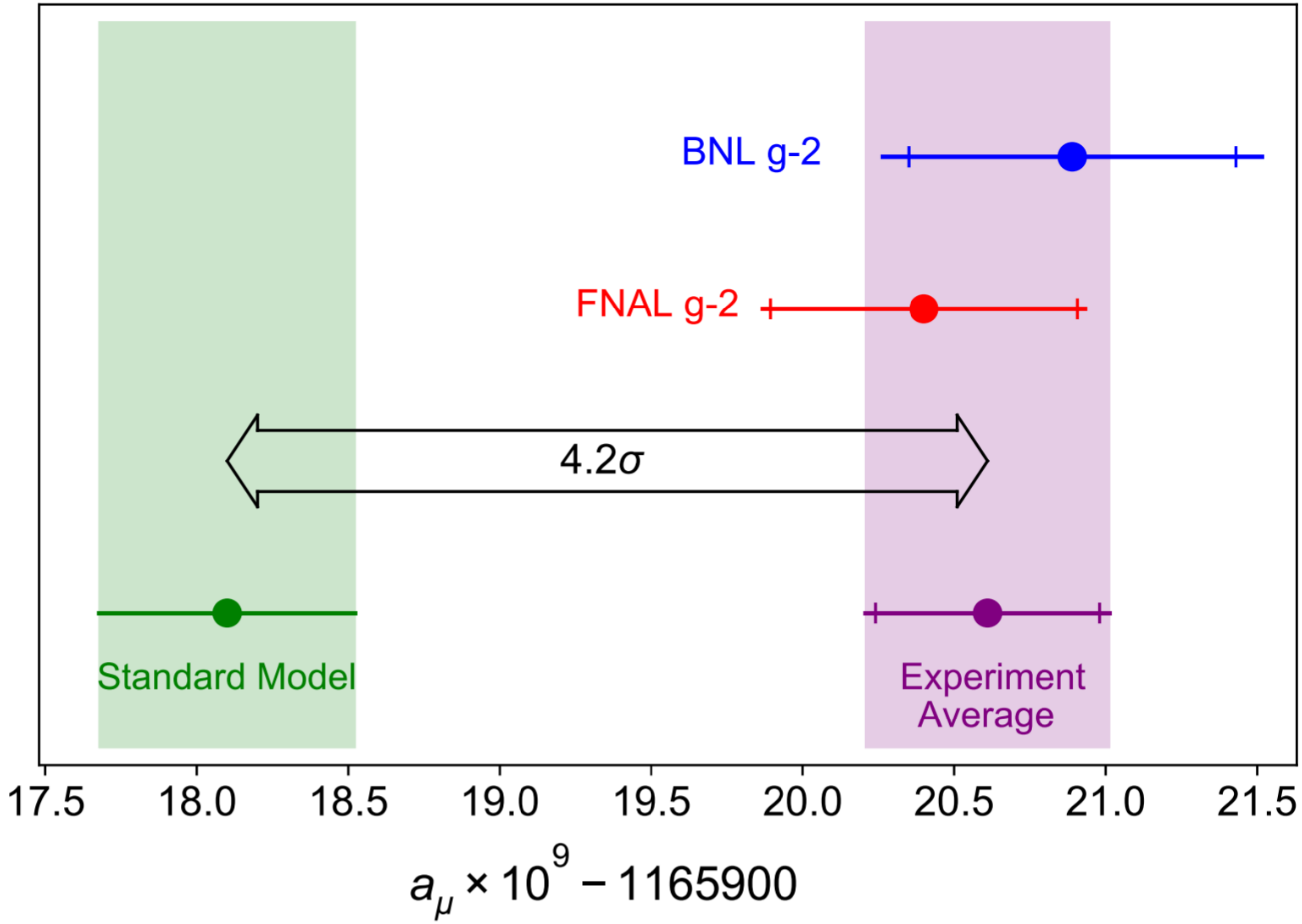
Magic momentum (γ = 29.3, p=3.094 GeV/c)
E field for vertical focusing
CERN-III, BNL E821, Fermilab E989

No E field: E = 0
Weak magnetic focusing
J-PARC E34

$$\omega_a = e/m\ a_\mu\ B$$

- Measuring the anomalous moment a_μ requires both
  1. the spin precession frequency ω_a
  2. the magnetic field **B**

THE BOTTOM LINE UPFRONT...



$$a_\mu(\mathrm{FNAL}) = 116\,592\,040(54) \times 10^{-11} \quad (0.46\,\mathrm{ppm})$$

$$a_\mu(\mathrm{Exp}) = 116\,592\,061(41) \times 10^{-11} \quad (0.35\,\mathrm{ppm})$$

HOW ABOUT THEORY?
A LOT OF PROGRESS OVER THE LAST YEARS...


JOHANNES GUTENBERG UNIVERSITÄT MAINZ

Theory Group
Institute for Nuclear Physics

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Second Plenary Workshop of the Muon g-2 Theory Initiative

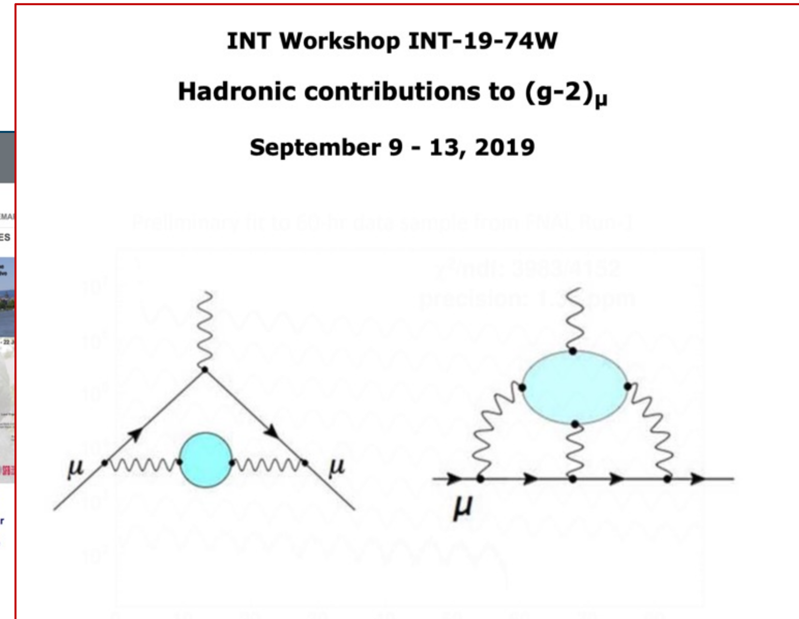
18 June 2018 - 22 June 2018

In the coming years, experiments at Fermilab and at J-PARC plan to reduce the uncertainties on the already very precisely measured anomalous magnetic moment of the muon by a factor of four. The goal is to resolve the current tantalizing tension between theory and experiment of three to four standard deviations. On the theory side the hadronic corrections to the anomalous magnetic moment are the dominant sources of uncertainty. They must be determined with better precision in order to unambiguously discover whether or not new physics effects contribute to this quantity.

There are a number of complementary theoretical efforts underway to better understand and quantify the hadronic corrections, including dispersive methods, lattice QCD, effective field theories, and QCD models. The Muon (g-2) Theory Initiative was formed in order to facilitate interactions between the different groups through organizing a series of workshops. The goal of this workshop is to bring together theorists from the different communities to discuss, assess, and compare the status of the various efforts, and to map out strategies for obtaining the best theoretical predictions for these hadronic corrections in advance of the experimental results.

First Circular
Second Circular
Indico website

Dates	June 18, 2018 - June 22, 2018
Timezone	GMT+2
Location	Helmholtz-Institut Mainz Staudinger Weg 18, 55128 Mainz, Ground Floor

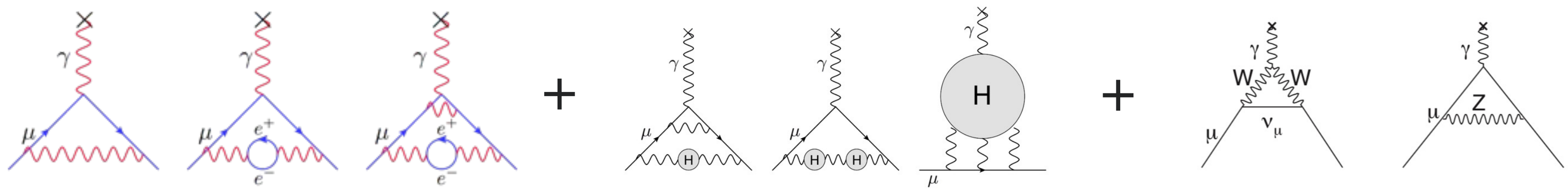


At the conference dinner in PhiPsi at BINP in Feb 2019

CURRENT DISCREPANCY BETWEEN SM PREDICTION AND EXPERIMENT

Schwinger | Vacuum polarization | Hadronic VP | Hadronic Light-by-Light

$a_\mu =$



QED **QCD** **EW**

$$a_\mu^{SM} = 0.00116591810\ (43)$$

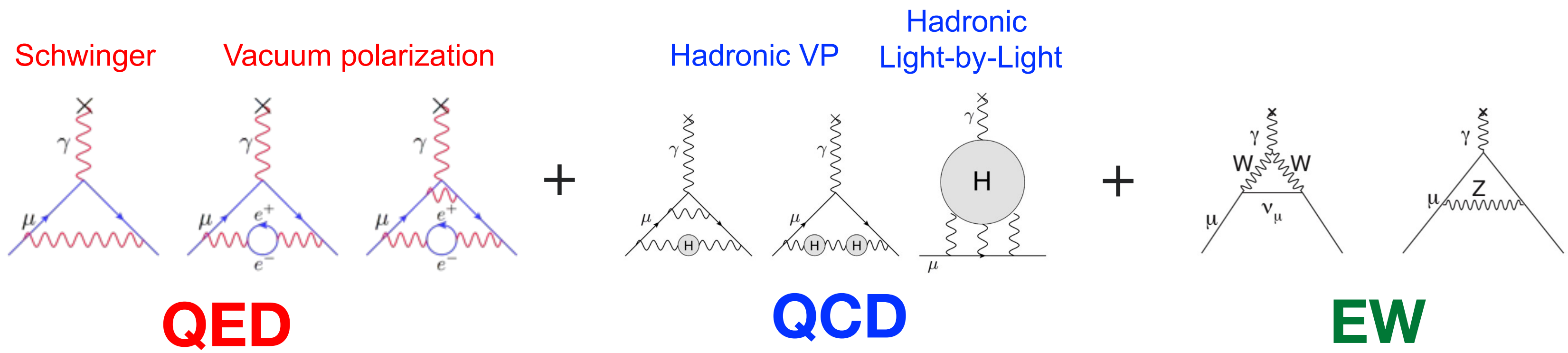
Theory Initiative: Phys. Rep. 887 (2020)

$$a_\mu^{Exp} = 0.00116592061\ (41)$$

Experimental value (FNAL + BNL)

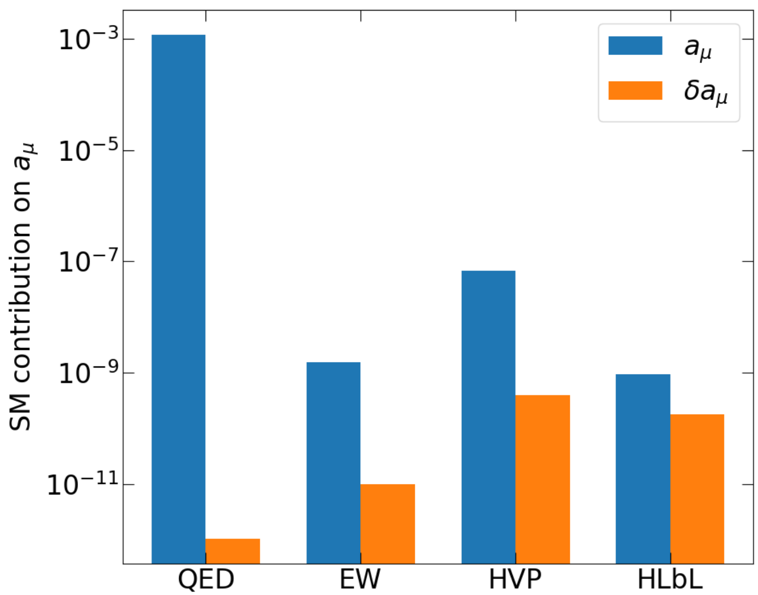
$$\boxed{\delta a_\mu = (251 \pm 59) \times 10^{-11}\ (4.2\sigma)}$$

CURRENT RECOMMENDED VALUE FROM THE THEORY INITIATIVE

$a_\mu =$ 

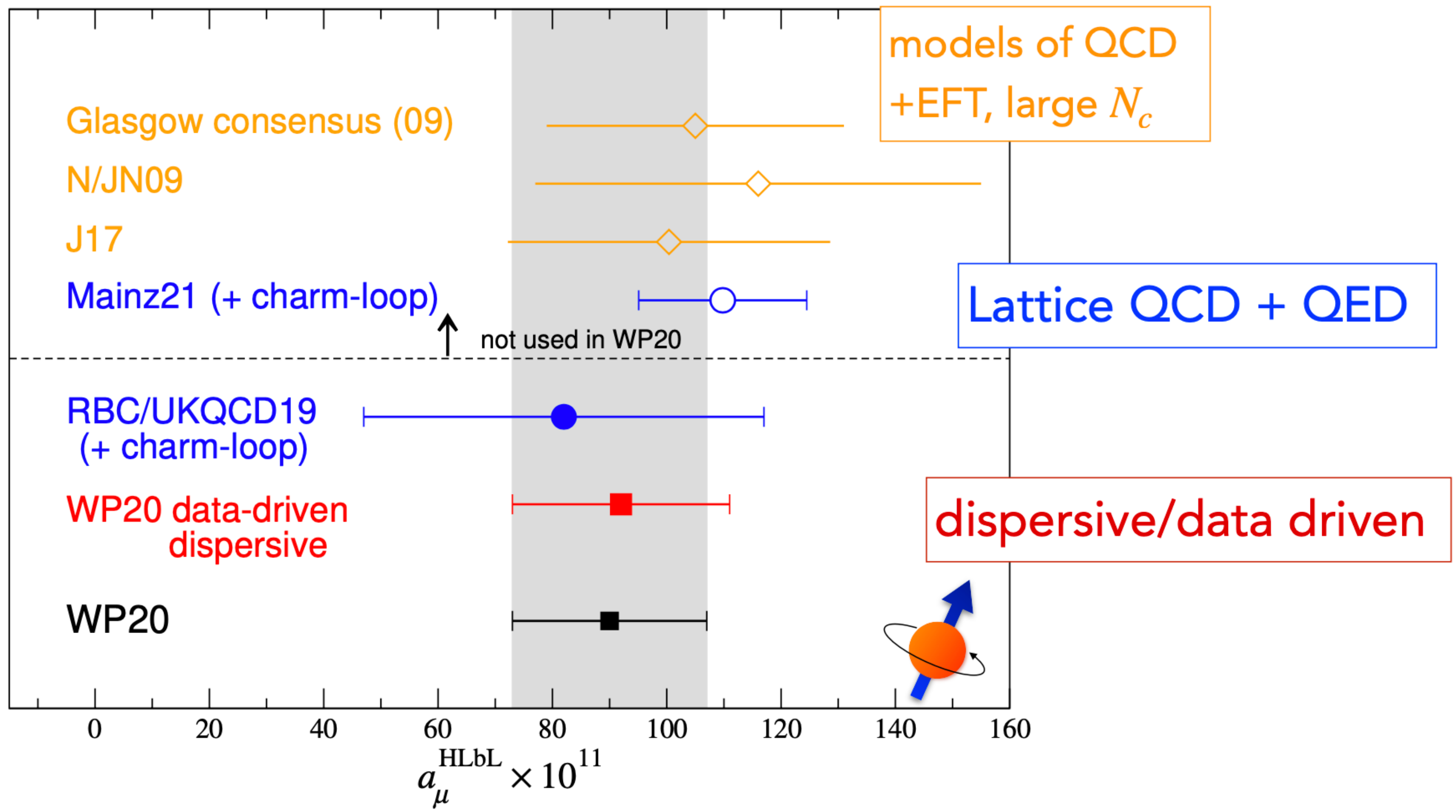
$$a_\mu^{SM} = 0.00116591810\,(43)$$

Theory Initiative: Phys. Rep. 887 (2020)



- Hadronic contributions dominate theory uncertainty
- Two main methods for HVP and HLbL:
  - Dispersive, data driven approach using experimental cross-sections
  - Lattice QCD calculations

HADRONIC LIGHT-BY-LIGHT



- Dominant contributions (~75% of total) well quantified with ~6% uncertainty
- Ongoing work on subleading contributions, which dominate current uncertainty
- Lattice QCD and new dispersive approach: <10% uncertainty by 2025 possible
- Hadronic light-by-light scattering not expected to solve overall discrepancy

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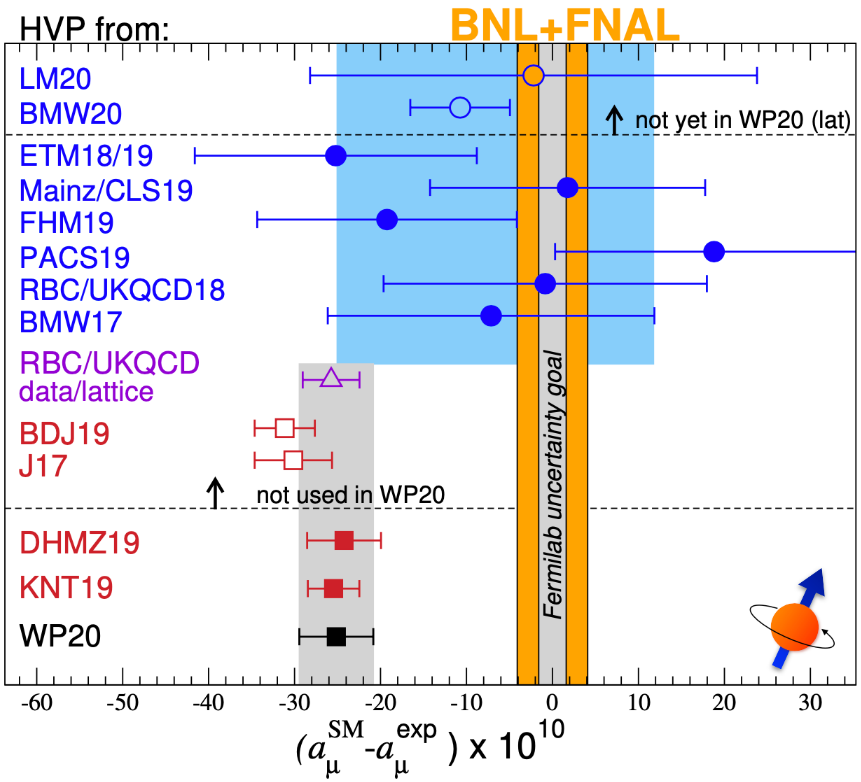
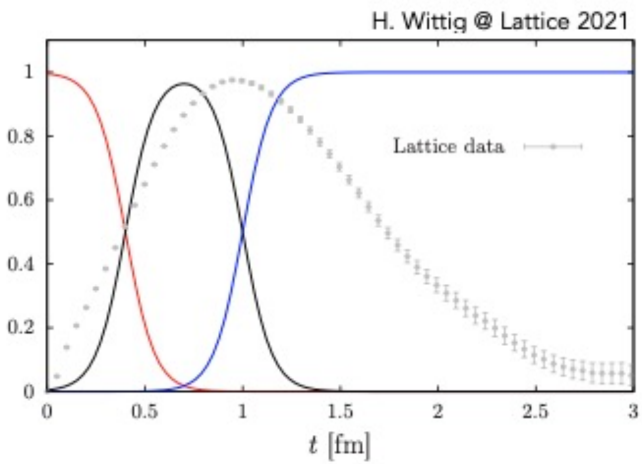
HADRONIC VACUUM POLARIZATION



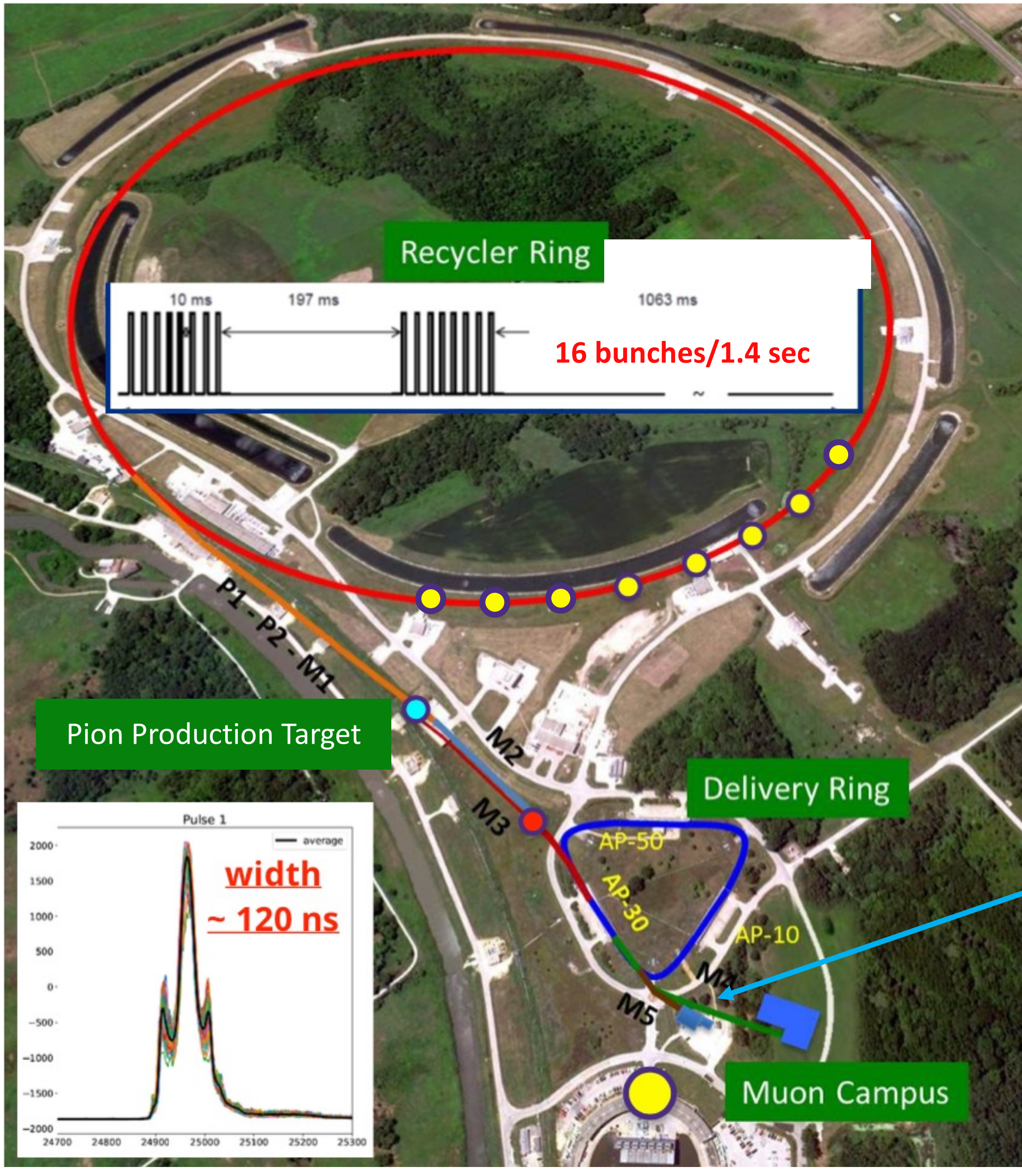
- Lattice calculations
- hybrid
- data driven approaches



- Theory WP 2020 used conservative merging procedure using data driven approaches only: $a_\mu^{\mathrm{hvp,LO}} = (693.1 \pm 4.0)\times 10^{-10}$ [0.6%]
- Lattice QCD average: $a_\mu^{\mathrm{hvp,LO}} = (711.6 \pm 18.5)\times 10^{-10}$ [2.6%]
- Lots of current work ongoing to understand possible discrepancy, comparison of intermediate time regions
- Data-driven approach can reach 0.3% by ~2025 (BaBar, SND, CMD-3, BESIII,…)
- If Lattice results are consistent, then <0.5% possible by 2025

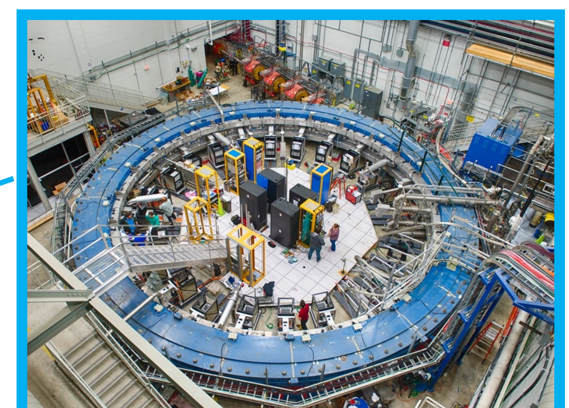
OVERVIEW OF THE E989 MUON g-2 EXPERIMENT AT FERMILAB

FERMILAB ACCELERATOR COMPLEX: 20 TIMES MORE MUONS

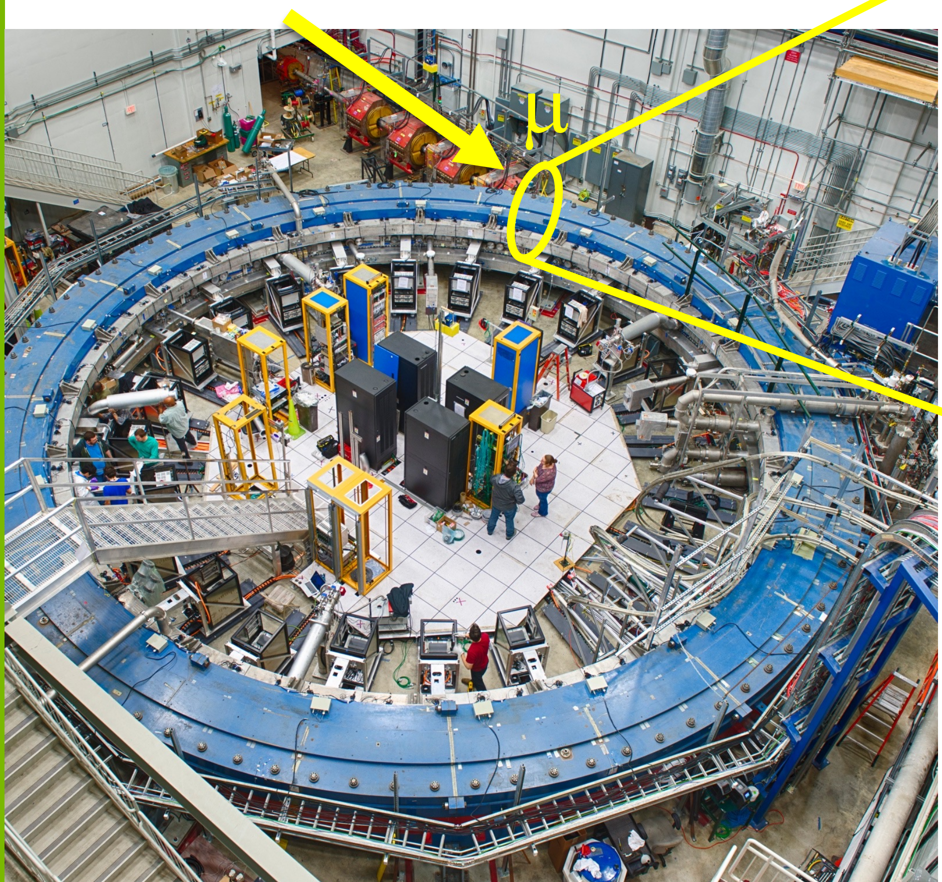


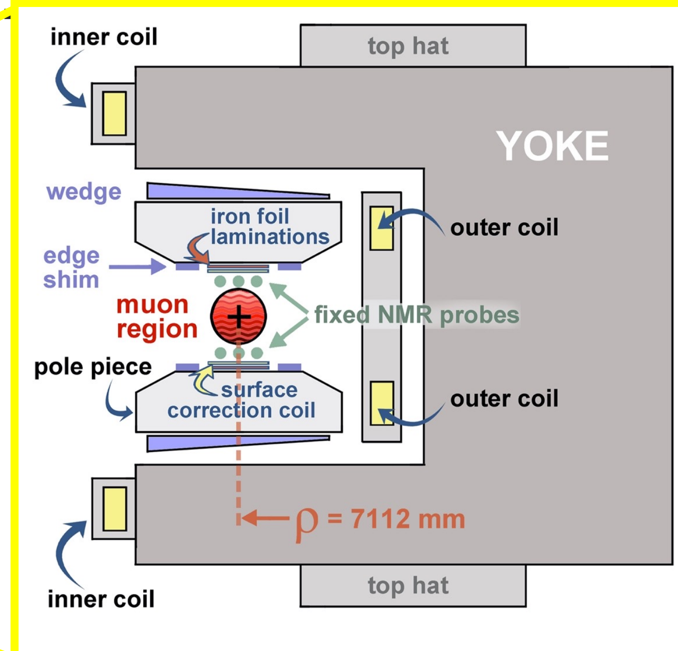
Some key ingredients:

- Long beamline to collect muons from pion decay
- Reduced hadronic flash
- 4x higher fill frequency than at BNL



MUON INJECTION & STORAGE: STORAGE RING MAGNET



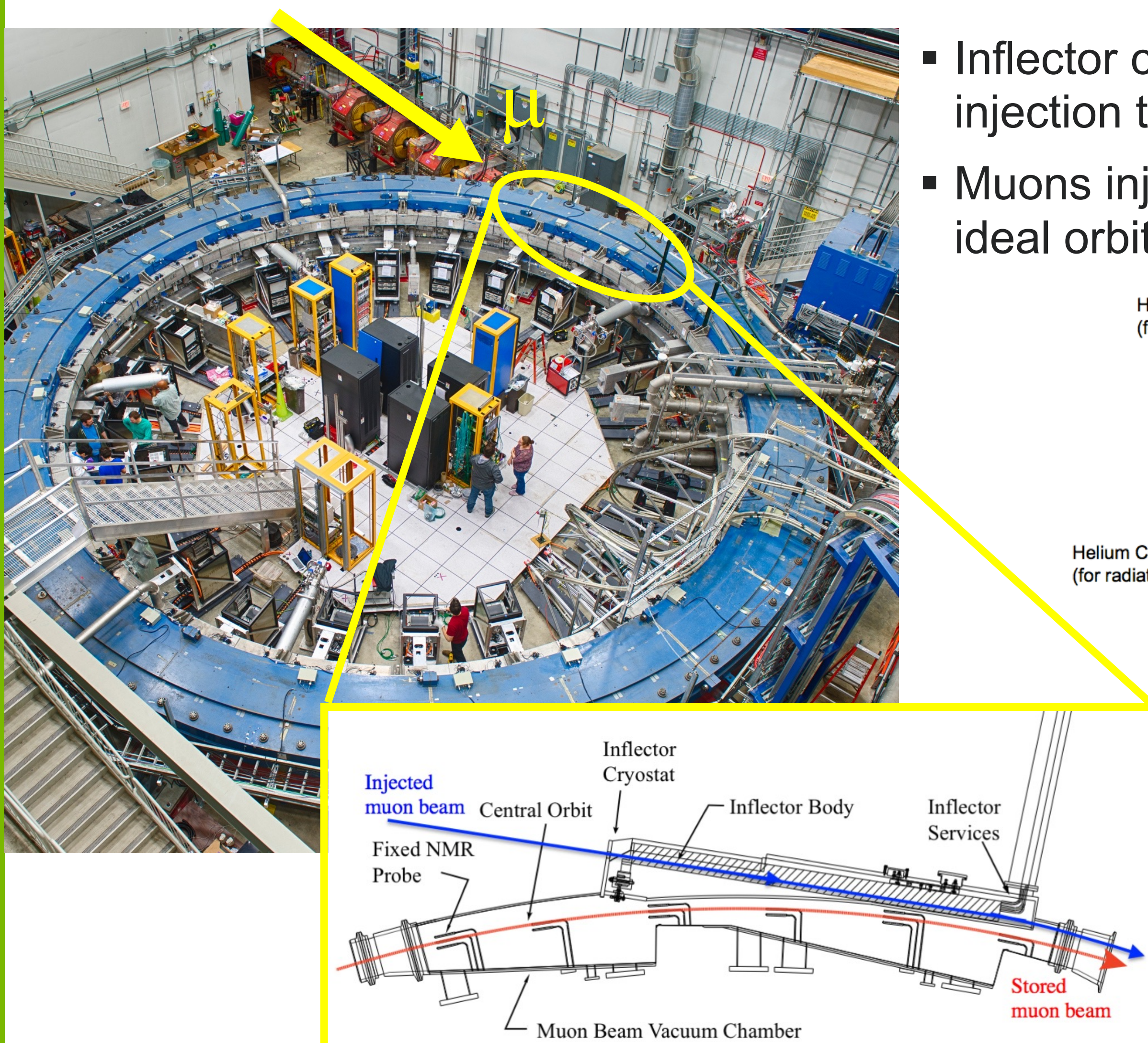


- Superconducting magnet at 1.45T
- Shim toolkit:
  - 48 top / bottom hats to tune dipole
  - 800 wedge shims to tune dipole
  - edge shims to tune quad and sextupole
  - About 9000 iron foils to fine tune field
- Power supply feedback to stabilize dipole
- 200 tunable coils to shim average multipoles

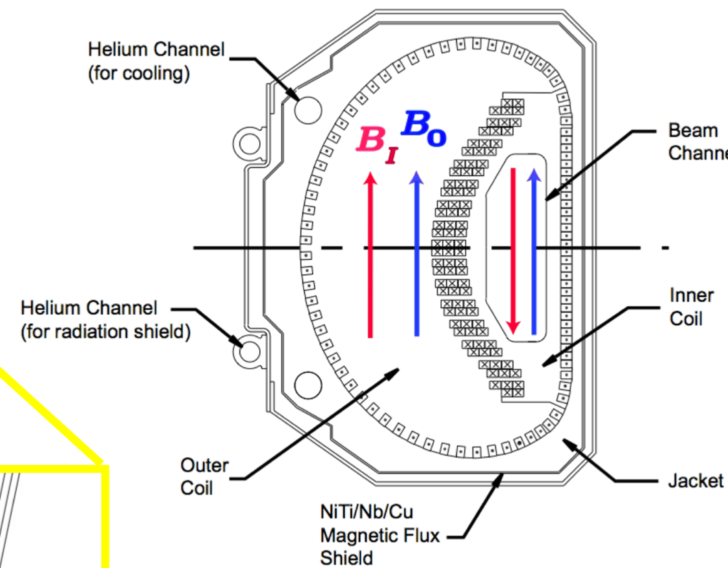
Achieved ~2.5 better homogeneity than BNL

MUON INJECTION & STORAGE: INFLECTOR MAGNET

- Inflector cancels main field for muon injection through yoke
- Muons injected with 77mm offset from ideal orbit



Inflector top view



Inflector cross section

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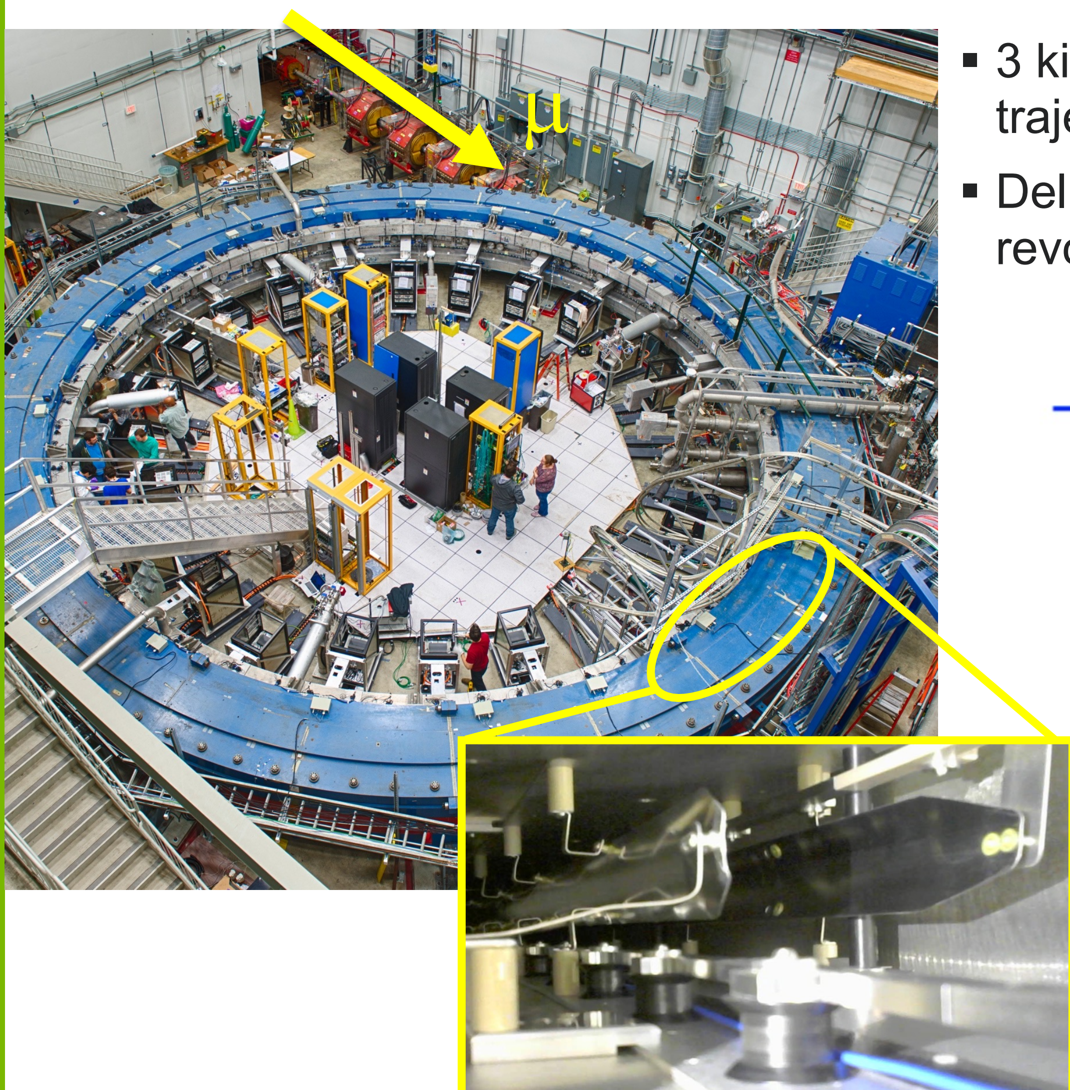
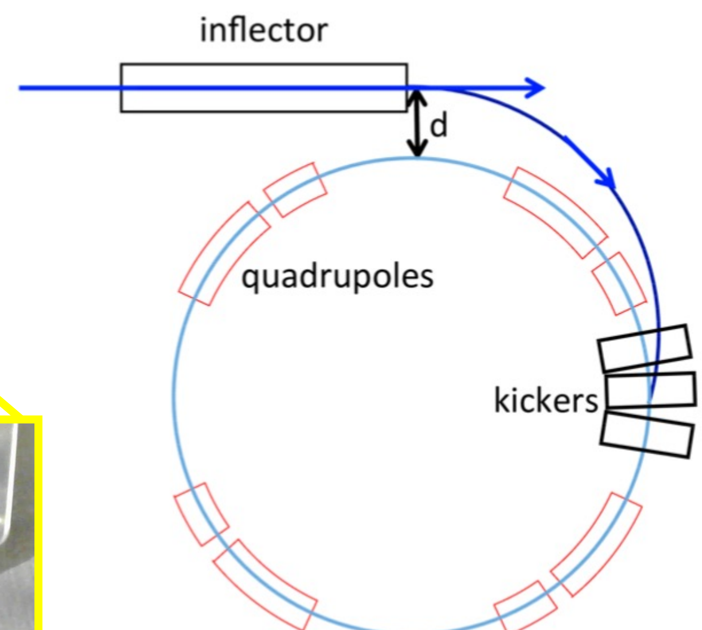
MUON INJECTION & STORAGE: KICKER MAGNET

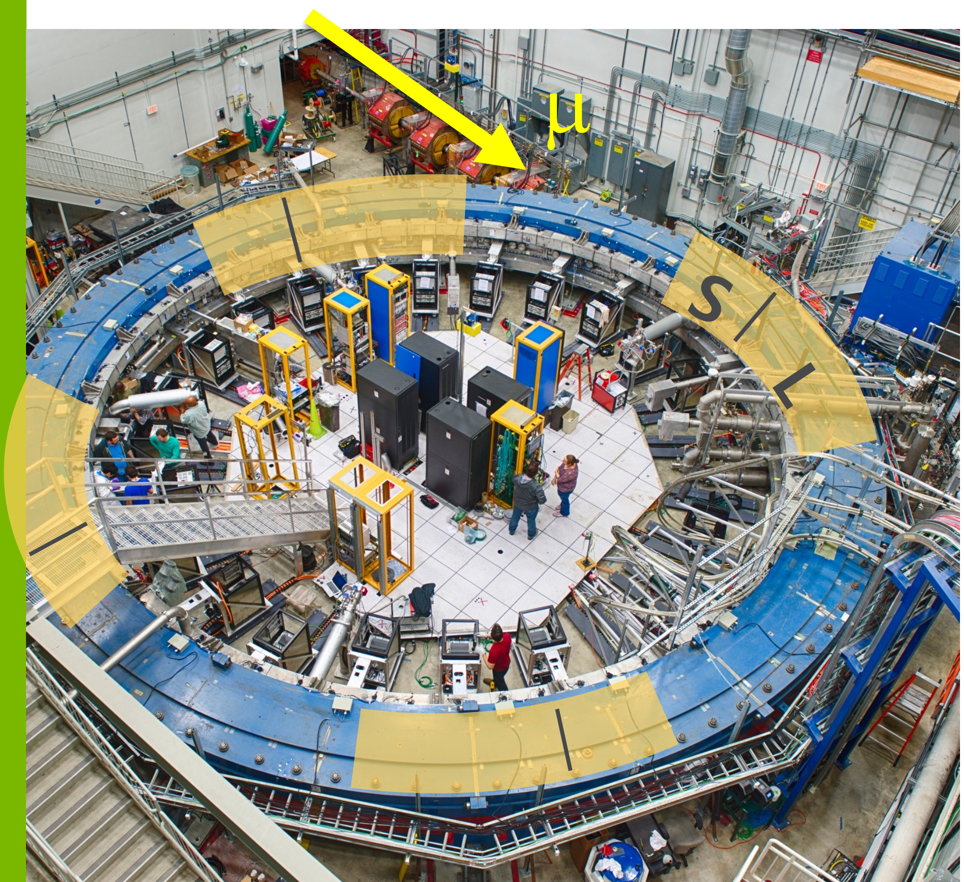


Kicker plates

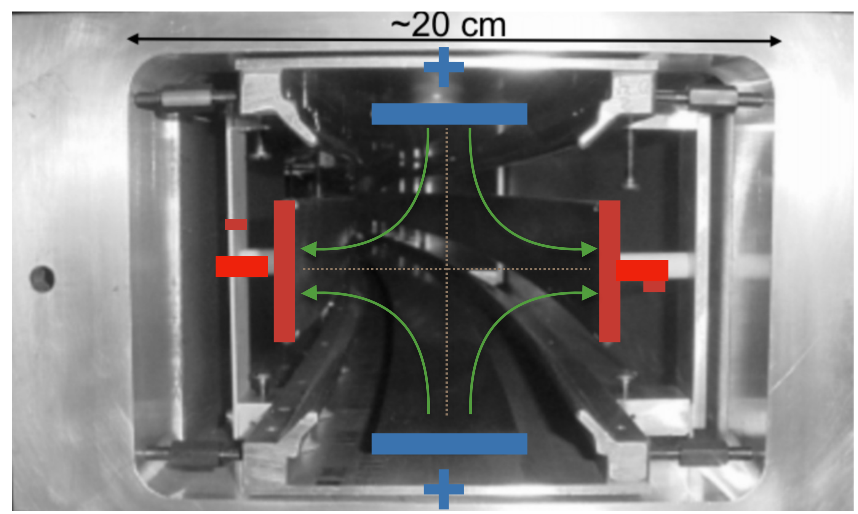
- 3 kicker magnets change muons' trajectories onto stored orbits
- Deliver pulse in <149 ns (muon revolution time)



MUON INJECTION & STORAGE: ELECTROSTATIC QUADRUPOLES

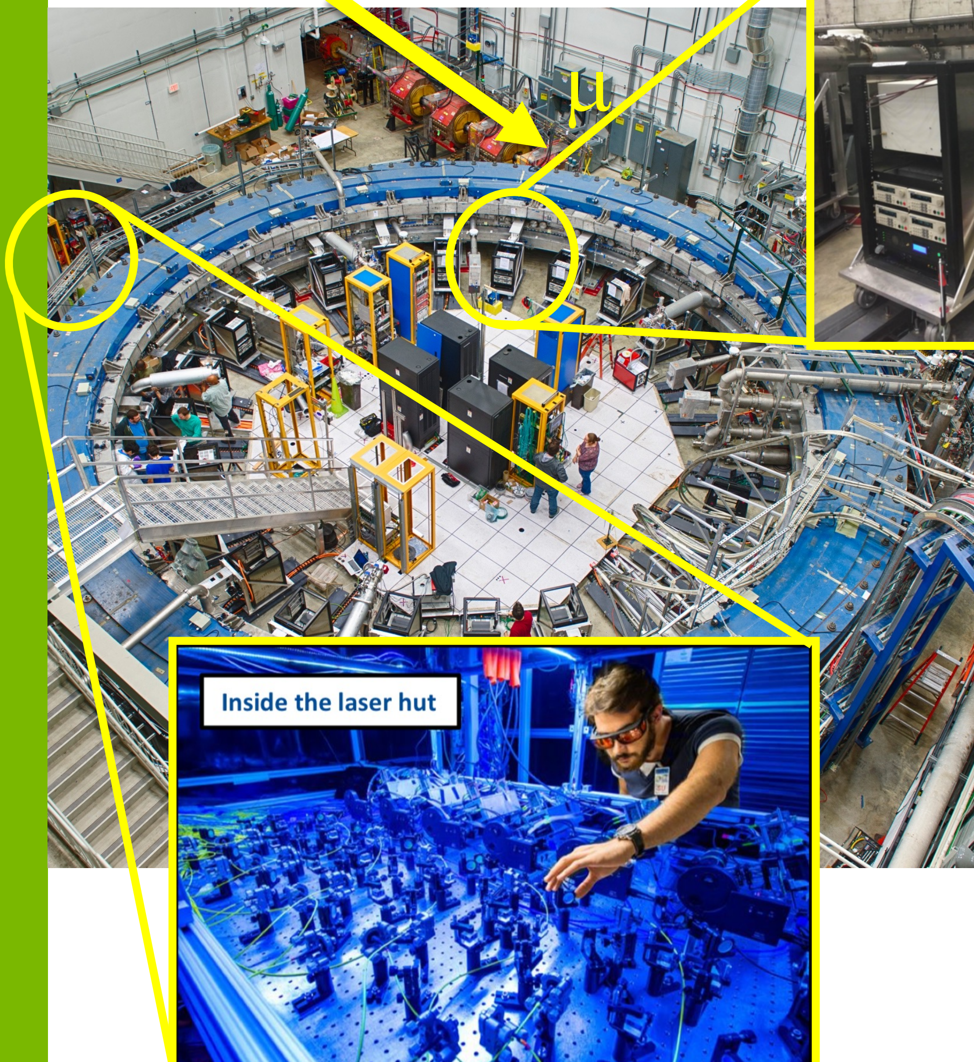


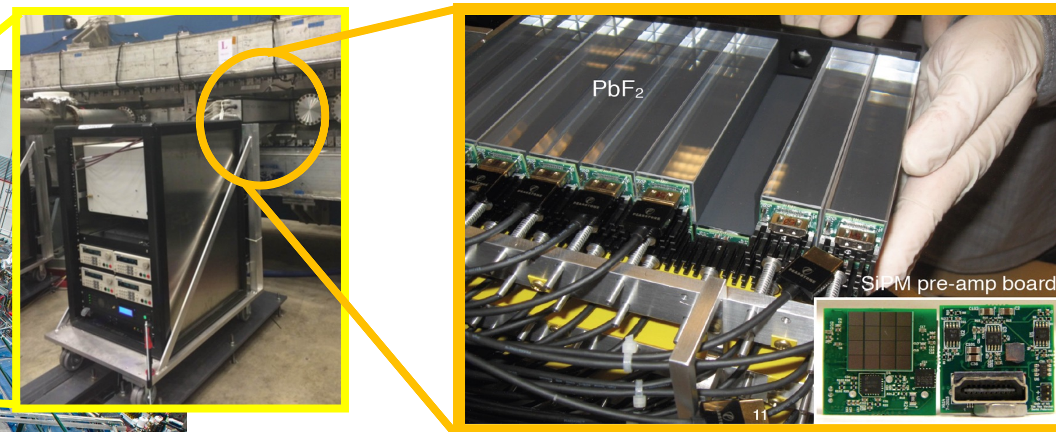
- Main B field provides radial focusing
- Four electrostatic quadrupoles for vertical focusing
- Also used to scrape the beam after injection
- Added a new RF system to reduce coherent betatron oscillation



Quadrupole plates

MEASURING THE MUON SPIN PRECESSION: CALORIMETER & LASER CALIBRATION

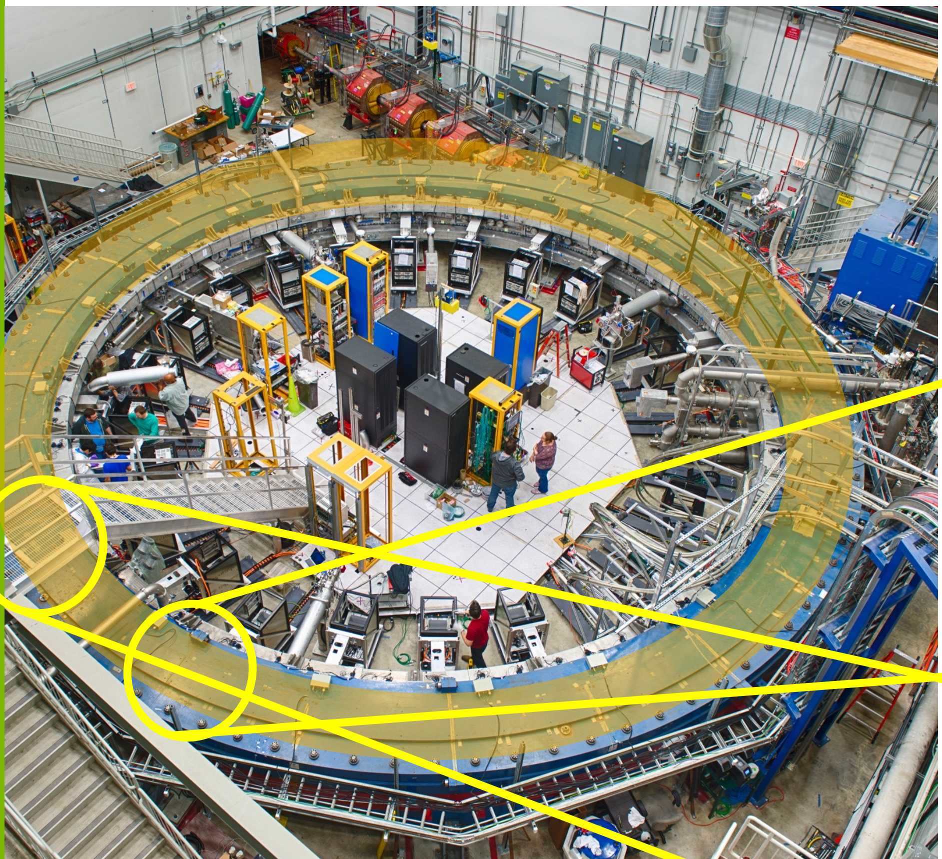




- 24 calorimeter stations detect the muon decay positrons:
  – 54 PbF2 crystals per station
  – SiPM readout
  – 800 MSPS digitization

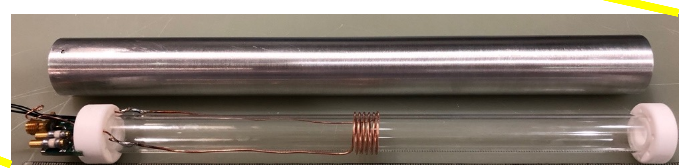
- Laser calibration system:
  – Each crystal receives laser pulse
  – Demonstrated gain corrected to 10^{-4}/h

MEASURING THE MAGNETIC FIELD: NUCLEAR MAGNETIC RESONANCE PROBES

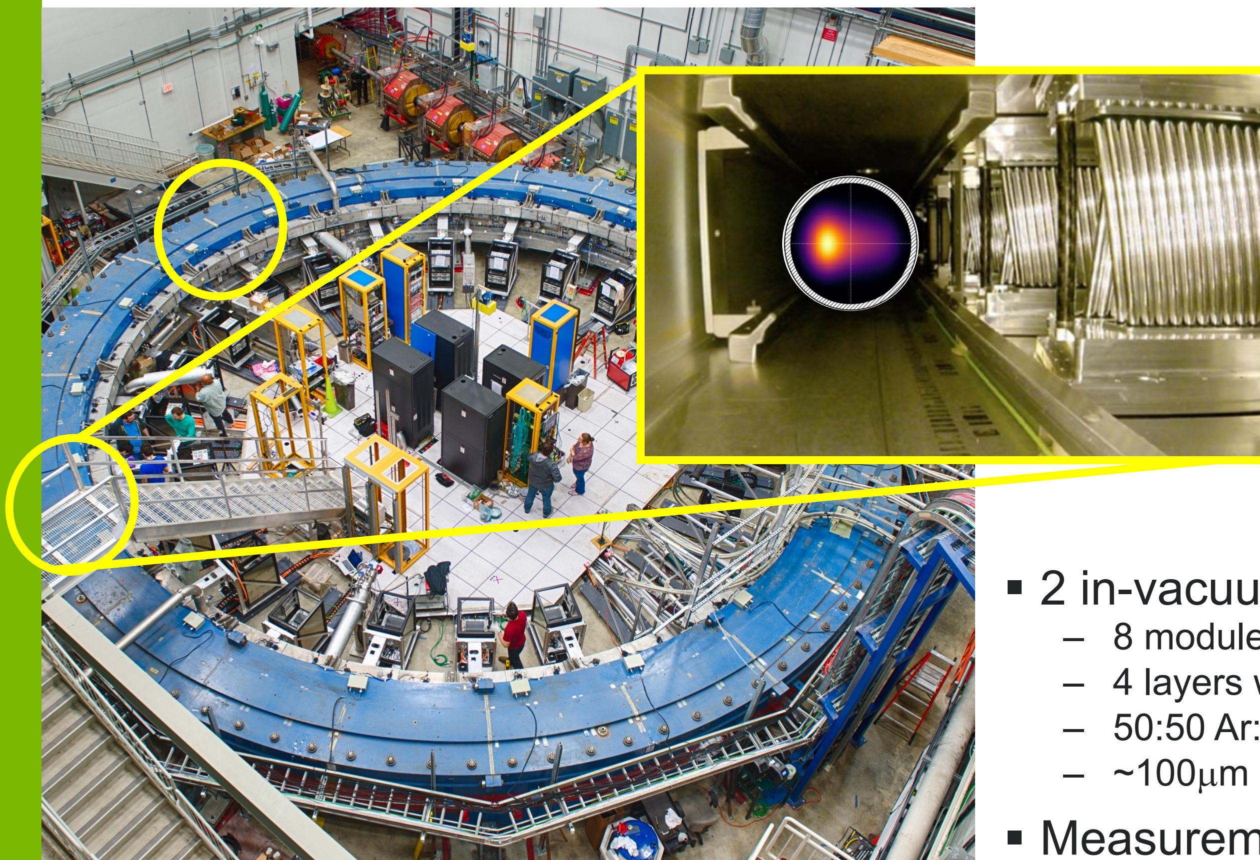


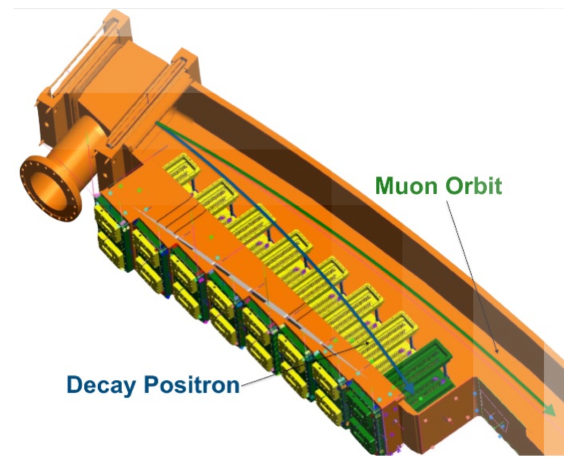
- 378 NMR probes in 72 stations track the field drift
- One field mapping trolley with 17 NMR probes to map field in storage region

- Water-based calibration probe to provide an absolute reference



MEASURING THE MUON DISTRIBUTION: STRAW TRACKERS





- 2 in-vacuum straw trackers:
  - 8 modules per tracker
  - 4 layers with 32 straws per module
  - 50:50 Ar:Ethane
  - ~100μm resolution
- Measurement of the muon distribution and handle on beam dynamics

A VIEW INSIDE THE VACUUM CHAMBERS

Video editing: Simon Corrodi

MEASURING ω_a AND $\tilde{\omega}'_p$: THE BIG PICTURE

MEASURING THE MAGNETIC FIELD USING PROTON NUCLEAR MAGNETIC RESONANCE

$$\boxed{\omega_a = e/m_\mu \, a_\mu \, B}$$

$$\mu_e = g_e \frac{e\hbar}{4m_e} \qquad B = \frac{\hbar\, \omega_p(T)}{2\, \mu_p(T)}$$

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

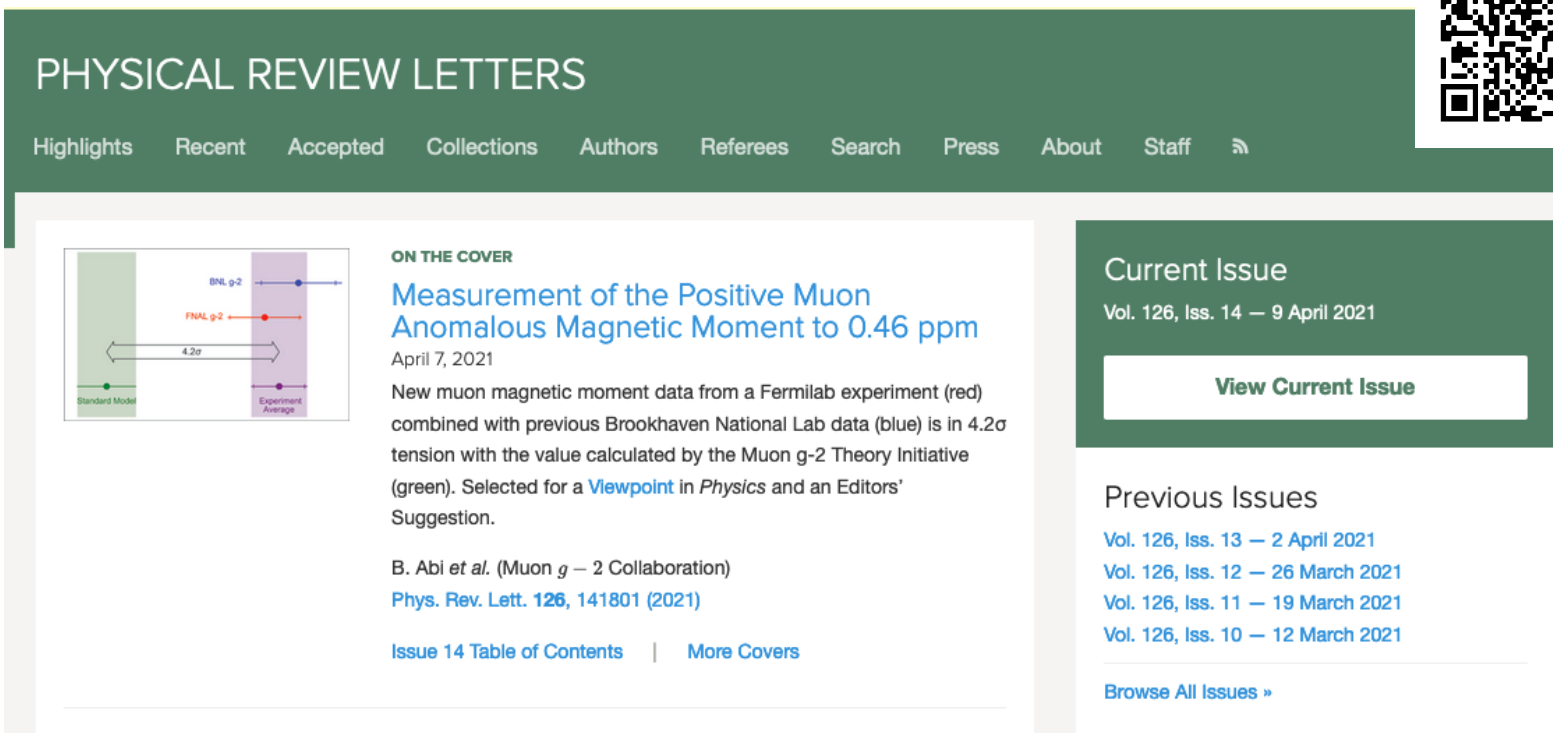
Determined by the experiment

ω_a Anomalous spin precession frequency

$\tilde{\omega}'_p(Tr)$ Larmor frequency of shielded proton in spherical water sample weighted by the muon distribution

$\frac{\mu'_p(Tr)}{\mu_e(H)}$	Magnetic moment ratio of proton in spherical water sample at T_r=34.7C and electron in hydrogen known to **10.5 ppb** [Metrologia 13, 179 (1977)]
$\frac{\mu_e(H)}{\mu_e}$	Bound-state QED correction (**exact**) [CODATA]
$\frac{m_\mu}{m_e}$	Mass ratio known from muonium hyperfine splitting experiment and QED to **22 ppb** [PRL 82, 711 (1999)]
$\frac{g_e}{2}$	Electron g-factor known from quantum cyclotron spectroscopy to **0.38 ppt** [PRA 83, 052122 (2011)]

SO HOW DO WE REALLY MEASURE $\frac{\omega_a}{\tilde{\omega}'_p(T_r)}$



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ON THE COVER

Measurement of the Positive Muon Anomalous Magnetic Moment to 0.46 ppm

April 7, 2021

New muon magnetic moment data from a Fermilab experiment (red) combined with previous Brookhaven National Lab data (blue) is in 4.2σ tension with the value calculated by the Muon g-2 Theory Initiative (green). Selected for a Viewpoint in *Physics* and an Editors' Suggestion.

B. Abi *et al.* (Muon $g-2$ Collaboration)

Phys. Rev. Lett. **126**, 141801 (2021)

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Vol. 126, Iss. 11 — 19 March 2021
Vol. 126, Iss. 10 — 12 March 2021

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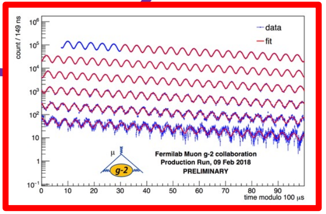
SO HOW DO WE REALLY MEASURE $\frac{\omega_a}{\tilde{\omega}'_p(T_r)}$

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

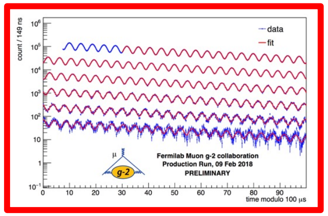
Measured g-2 frequency



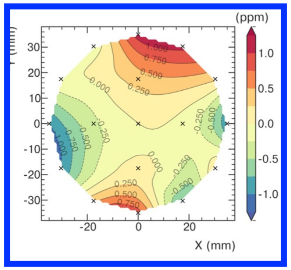
$$\frac{\omega_a}{\tilde{\omega}'_p(T_r)} \approx \frac{\omega_a^m}{\quad}$$

SO HOW DO WE REALLY MEASURE $\frac{\omega_a}{\tilde{\omega}'_p(T_r)}$

Measured g-2 frequency



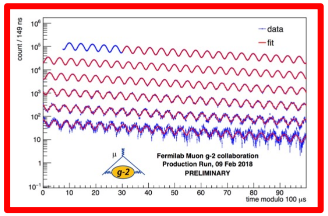
$$\frac{\omega_a}{\tilde{\omega}'_p(T_r)} \approx \frac{\omega_a^m}{< \omega_p(x, y, \phi)}$$



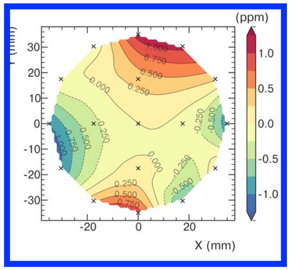
Magnetic field

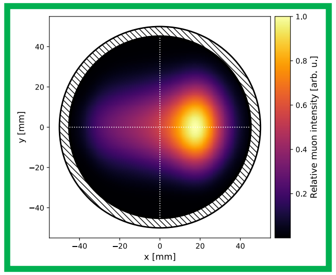
SO HOW DO WE REALLY MEASURE $\frac{\omega_a}{\tilde{\omega}'_p(T_r)}$

Measured g-2 frequency



$$\frac{\omega_a}{\tilde{\omega}'_p(T_r)} \approx \frac{\omega_a^m}{< \omega_p(x,y,\phi) \times M(x,y,\phi) >}$$

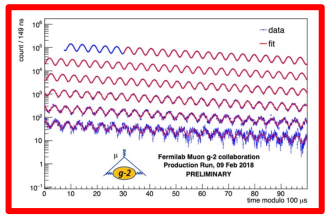




Magnetic field weighted by muon distribution

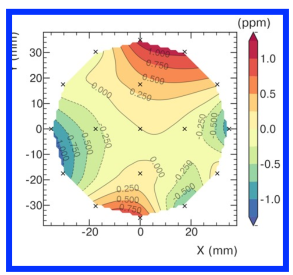
SO HOW DO WE REALLY MEASURE $\frac{\omega_a}{\tilde{\omega}'_p(T_r)}$

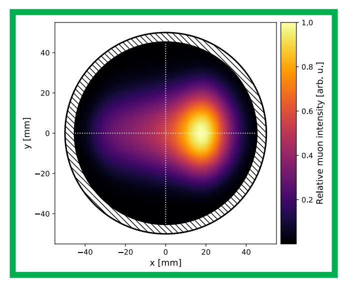
Measured g-2 frequency



Unblinding factor

$$\frac{\omega_a}{\tilde{\omega}'_p(T_r)} \approx \frac{f_{clock} \quad \omega_a^m}{< \omega_p(x,y,\phi) \times M(x,y,\phi) >}$$





Magnetic field weighted by muon distribution

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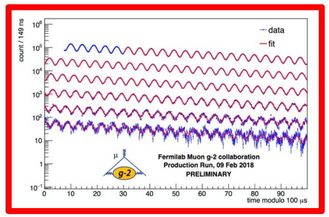
SO HOW DO WE REALLY MEASURE $\frac{\omega_a}{\tilde{\omega}'_p(T_r)}$

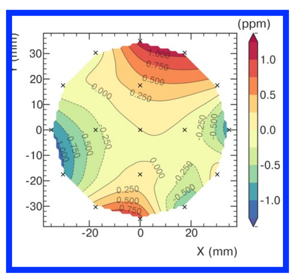
Measured g-2 frequency

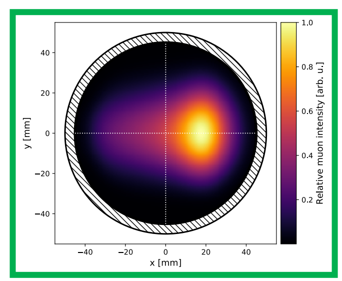


Beam dynamics related corrections

Unblinding factor

$$\frac{\omega_a}{\tilde{\omega}'_p(T_r)} \approx \frac{f_{clock} \quad \omega_a^m \quad (1 + C_e + C_p + C_{ml} + C_{pa})}{\langle\, \omega_p(x,y,\phi) \times M(x,y,\phi) \,\rangle}$$

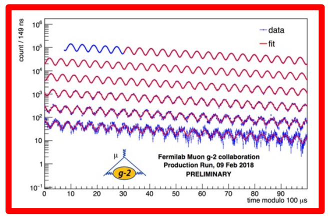




Magnetic field weighted by muon distribution

SO HOW DO WE REALLY MEASURE $\frac{\omega_a}{\tilde{\omega}'_p(T_r)}$

Measured g-2 frequency

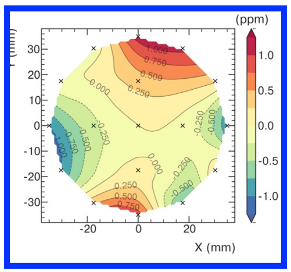


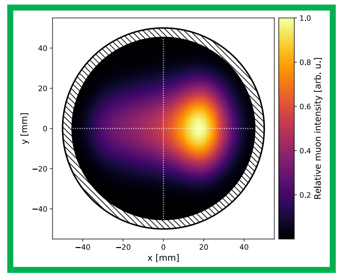
Beam dynamics related corrections

Unblinding factor

$$\frac{\omega_a}{\tilde{\omega}'_p(T_r)} \approx \frac{f_{clock} \quad \omega_a^m \quad (1 + C_e + C_p + C_{ml} + C_{pa})}{f_{calib} < \omega_p(x, y, \phi) \times M(x, y, \phi) >}$$

Field calibration

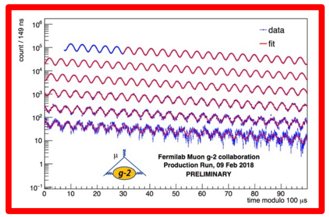




Magnetic field weighted by muon distribution

SO HOW DO WE REALLY MEASURE $\frac{\omega_a}{\tilde{\omega}'_p(T_r)}$

Measured g-2 frequency

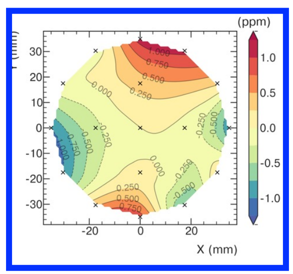


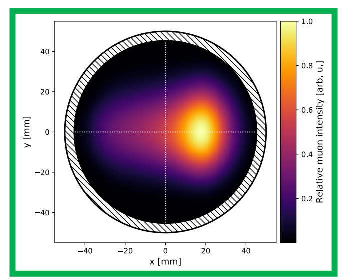
Beam dynamics related corrections

Unblinding factor

$$\frac{\omega_a}{\tilde{\omega}'_p(T_r)} \approx \frac{f_{clock} \quad \omega_a^m \quad (1 + C_e + C_p + C_{ml} + C_{pa})}{f_{calib} < \omega_p(x,y,\phi) \times M(x,y,\phi) > \ (1 + B_k + B_q)}$$

Field calibration





Corrections for transient magnetic fields

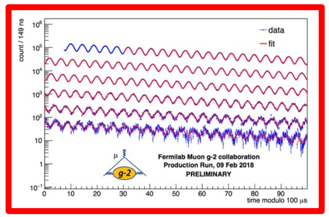
Magnetic field weighted by muon distribution

MEASURING ω_a AND $\tilde{\omega}'_p$:

THE RUN-1 ANALYSIS DETAILS AND RESULTS

DETAILS OF THE ANALYSIS

Measured g-2 frequency

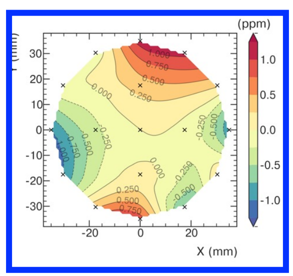


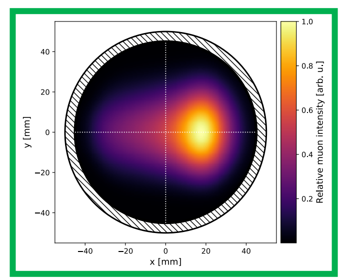
Beam dynamics related corrections

Unblinding factor

$$\frac{\omega_a}{\tilde{\omega}'_p(T_r)} \approx \frac{f_{clock} \quad \omega_a^m \quad (1 + C_e + C_p + C_{ml} + C_{pa})}{f_{calib} \langle \omega_p(x,y,\phi) \times M(x,y,\phi) \rangle \; (1 + B_k + B_q)}$$

Field calibration





Corrections for transient magnetic fields

Magnetic field weighted by muon distribution

DETAILS OF THE ANALYSIS

$$\frac{\omega_a}{\tilde{\omega}'_p(T_r)}$$

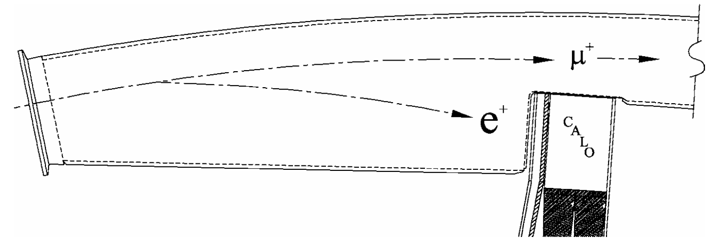
Quantity	Correction terms (ppb)	Uncertainty (ppb)
ω_a^m (statistical)	–	434
ω_a^m (systematic)	–	56
C_e	489	53
C_p	180	13
C_{ml}	-11	5
C_{pa}	-158	75
$f_{\mathrm{calib}}\langle\omega'_p(x,y,\phi)\times M(x,y,\phi)\rangle$	–	56
B_k	-27	37
B_q	-17	92
$\mu'_p(34.7^\circ)/\mu_e$	–	10
m_μ/m_e	–	22
$g_e/2$	–	0
Total systematic	–	157
Total fundamental factors	–	25
Totals	544	462

$$\ldots_{pa})$$
$$\ldots_k + B_q)$$

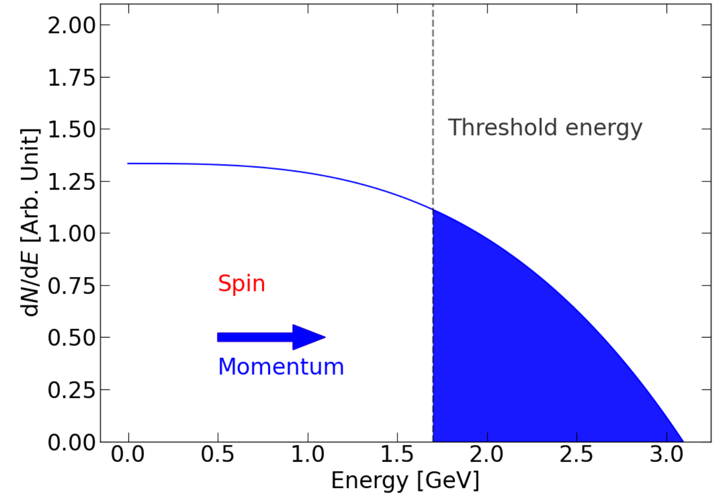
DETAILS OF THE ANALYSIS

$$\frac{\omega_a}{\tilde{\omega}'_p(T_r)} \approx \frac{f_{clock}\ \omega_a^m\ (1 + C_e + C_p + C_{ml} + C_{pa})}{f_{calib} < \omega_p(x, y, \phi) \times M(x, y, \phi) > (1 + B_k + B_q)}$$

MEASURING ω_a

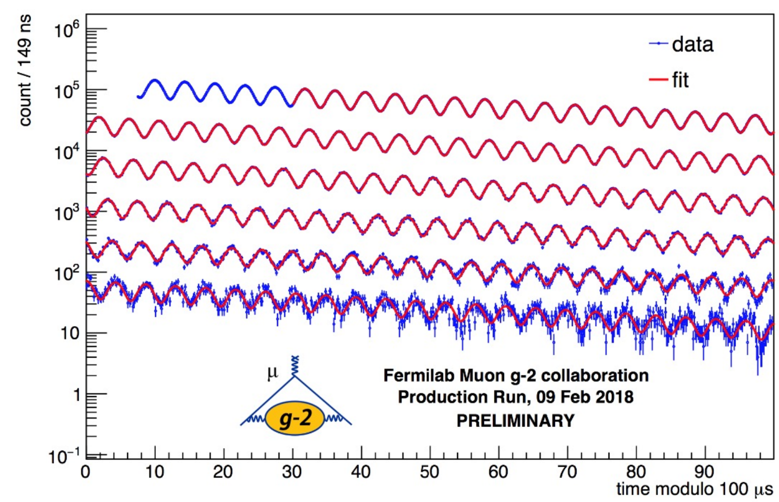


- Measure time and energy of decay positrons in the 24 calorimeters
- Due to parity violating weak decay, high energy positrons are emitted more along the direction of the spin



- Decay positron time distribution above an optimal energy threshold of E~1.7 GeV produces "wiggle" plot
- Main features of the "wiggle" plot from muon lifetime τ and spin precession ω_a, but actual fit way more complicated:

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



- Statistical uncertainty: $\sigma_{\omega_a} \propto 1/\sqrt{NA^2}$.

DETAILS OF THE ANALYSIS

$$\frac{\omega_a}{\tilde{\omega}'_p(T_r)} \approx \frac{f_{clock} \quad \omega_a^m \quad (1 + C_e + C_p + C_{ml} + C_{pa})}{f_{calib} \ < \omega_p(x,y,\phi) \times M(x,y,\phi) > \ (1 + B_k + B_q)}$$

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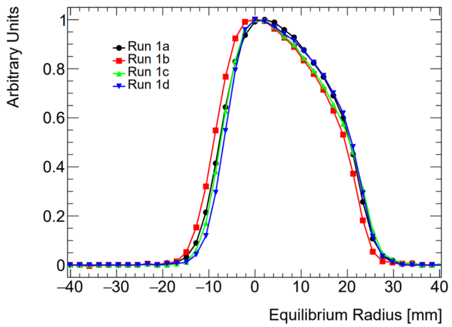
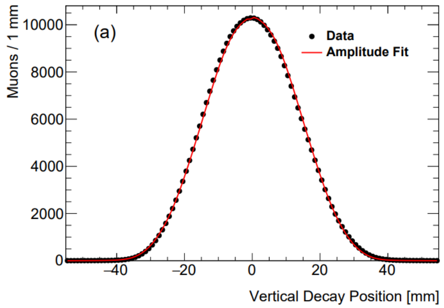
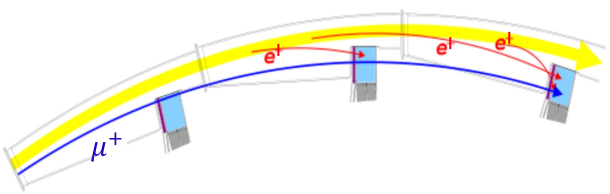
BEAM DYNAMICS CORRECTIONS



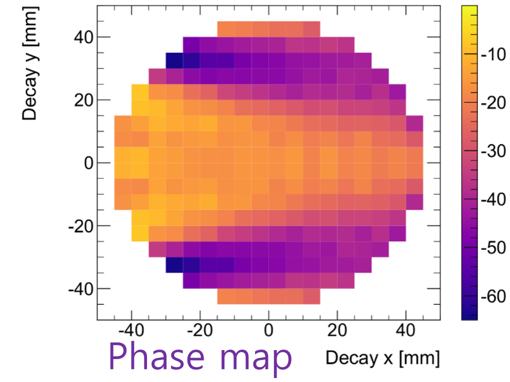
- **Electric field correction C_e:**
  - Electric field term cancels for magic momentum but stored muons have momentum spread Δp/p ~ 0.15%
  - Correction from measurement of equilibrium radius $\langle x_e^2 \rangle$



- **Pitch correction C_p:**
  - Vertical motion due to betatron oscillations reduces $\vec{\omega}_a$
  - Correction from vertical muon distribution $\langle y^2 \rangle$



- **Muon loss correction C_{ml}:**
  - Stored muons can be lost and can carry different phase
  - Detect and correct through coincidences in three neighboring calorimeters



- **Phase acceptance correction C_{pa}:**
  - In Run-1, damaged high-voltage resistors extended the charging time of the quadrupoles, introducing a time dependency over the fill
  - Correction from tracker data and simulated positron acceptance, asymmetry, and phase maps

DETAILS OF THE ANALYSIS

$$\frac{\omega_a}{\tilde{\omega}'_p(T_r)} \approx \frac{f_{clock} \quad \omega_a^m \quad (1 + C_e + C_p + C_{ml} + C_{pa})}{f_{calib} < \omega_p(x, y, \phi) \times M(x, y, \phi) > (1 + B_k + B_q)}$$

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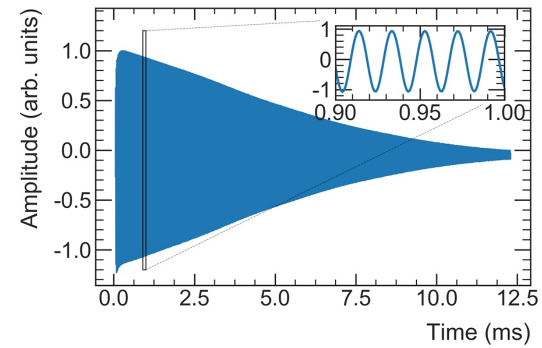
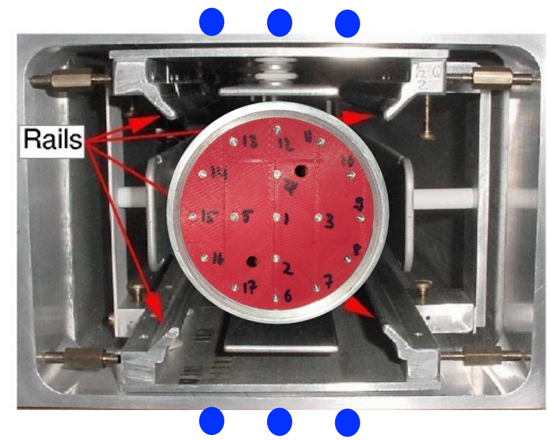
MEASURING < $\omega_p(x, y, \phi)$

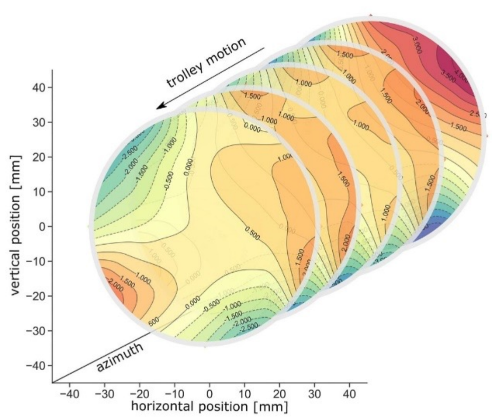
- Measurement of field amplitude via Nuclear Magnetic Resonance:
  - Frequency extracted from Free Induction Decay signal
  - Very good frequency precision (ppb level)
  - Good to track slow field changes

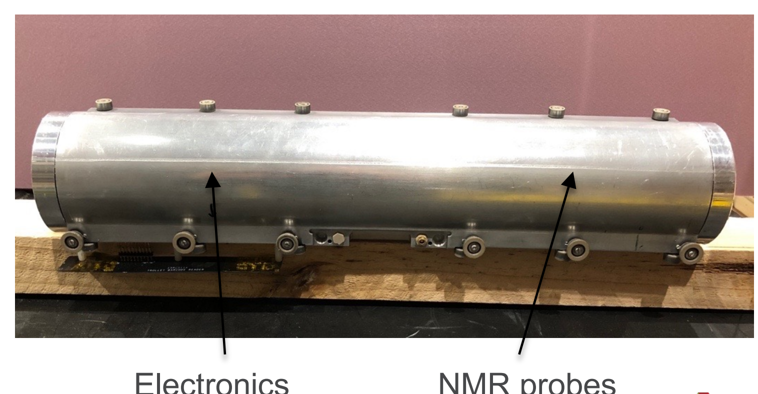


- 378 NMR probes installed in groups of 6 and 4 probes
  - Continuously track slow field drift every ~1 second
  - 72 azimuthal locations around the ring



- In-vacuum trolley maps the field every 3 to 5 days
  - 9000 measurements for each of the 17 probes
  - Detailed frequency maps where the muons are
  - Synchronizes the fixed probes to field maps



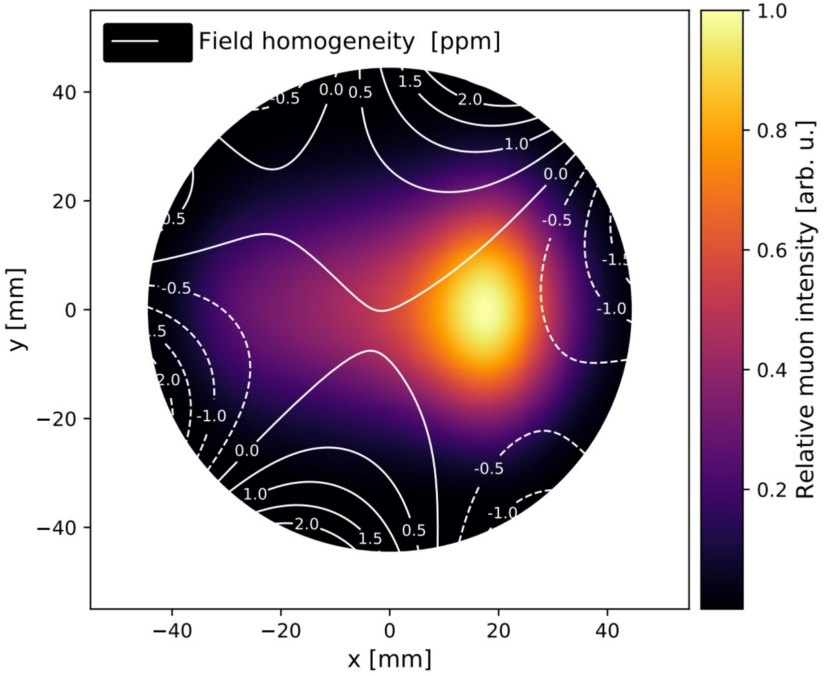


MEASURING $< \omega_p(x, y, \phi) \times M(x, y, \phi) >$

- The frequency maps $\omega_p(x, y, \phi)$ from trolley and fixed probe data need to be weighted by the muon distribution $M(x, y, \phi)$

$$\tilde{\omega}_p = \left\langle \frac{\int \omega_p(x, y, \phi)\ M(x, y, \phi)\ \mathrm{d}x\ \mathrm{d}y}{\int M(x, y, \phi)\ \mathrm{d}x\ \mathrm{d}y} \right\rangle$$

- The muon distribution $M(x, y, \phi)$ is extracted from the two straw-tracker stations
- $M(x, y, \phi)$ includes beam dynamics information (e.g. beta functions) and detector acceptances (calorimeter)

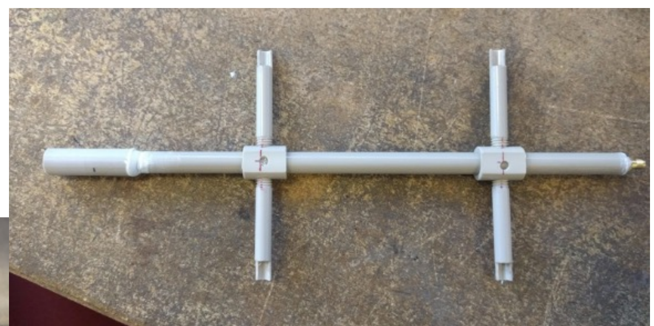


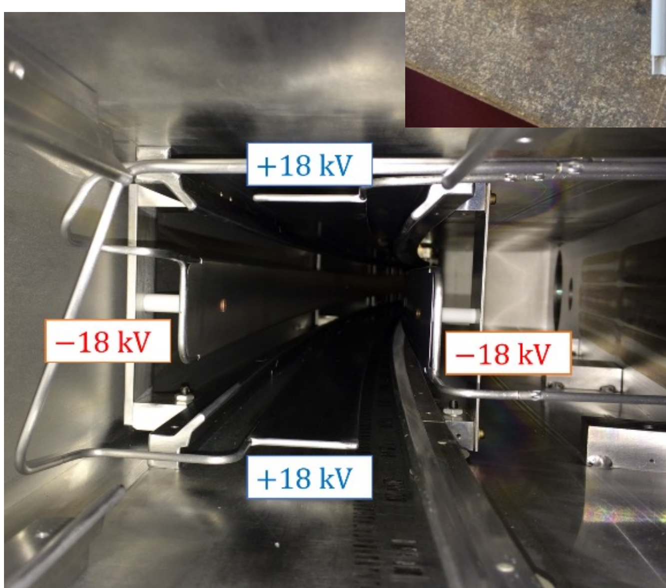
DETAILS OF THE ANALYSIS

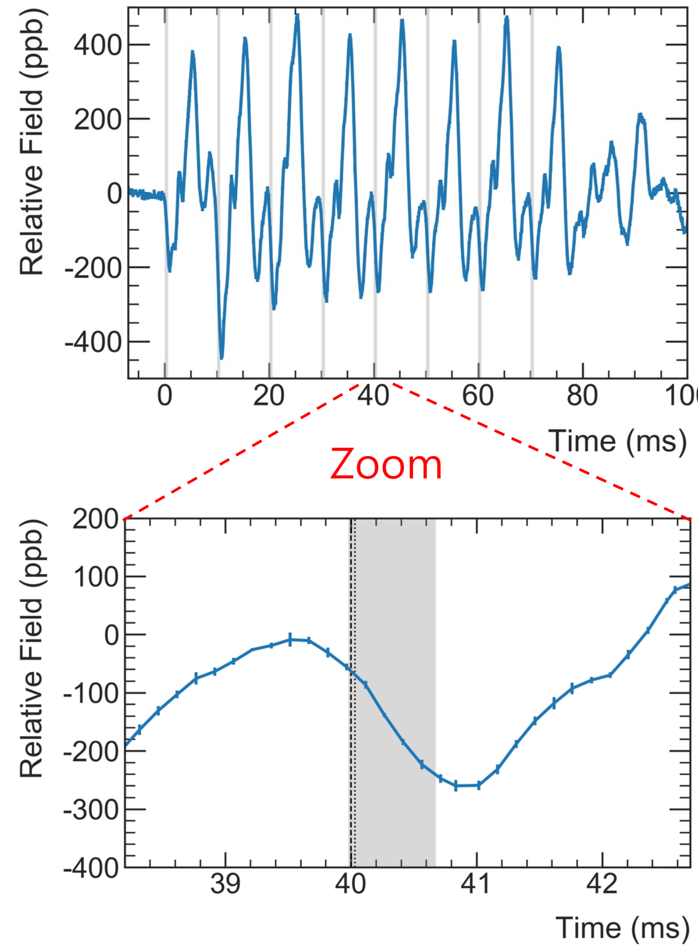
$$\frac{\omega_a}{\tilde{\omega}'_p(T_r)} \approx \frac{f_{clock} \quad \omega_a^m \quad (1 + C_e + C_p + C_{ml} + C_{pa})}{f_{calib} < \omega_p(x,y,\phi) \times M(x,y,\phi) > (1 + B_k + B_q)}$$

QUADRUPOLE TRANSIENT CORRECTION B_q

- Electrostatic quadrupoles have fast, pulsed currents
- Fixed probes have low bandwidth and shielded by vacuum chamber
- Built special vacuum compatible probe to measure any fast fields
- Measurement revealed fast magnetic field changes and led to largest systematic uncertainty in Run-1

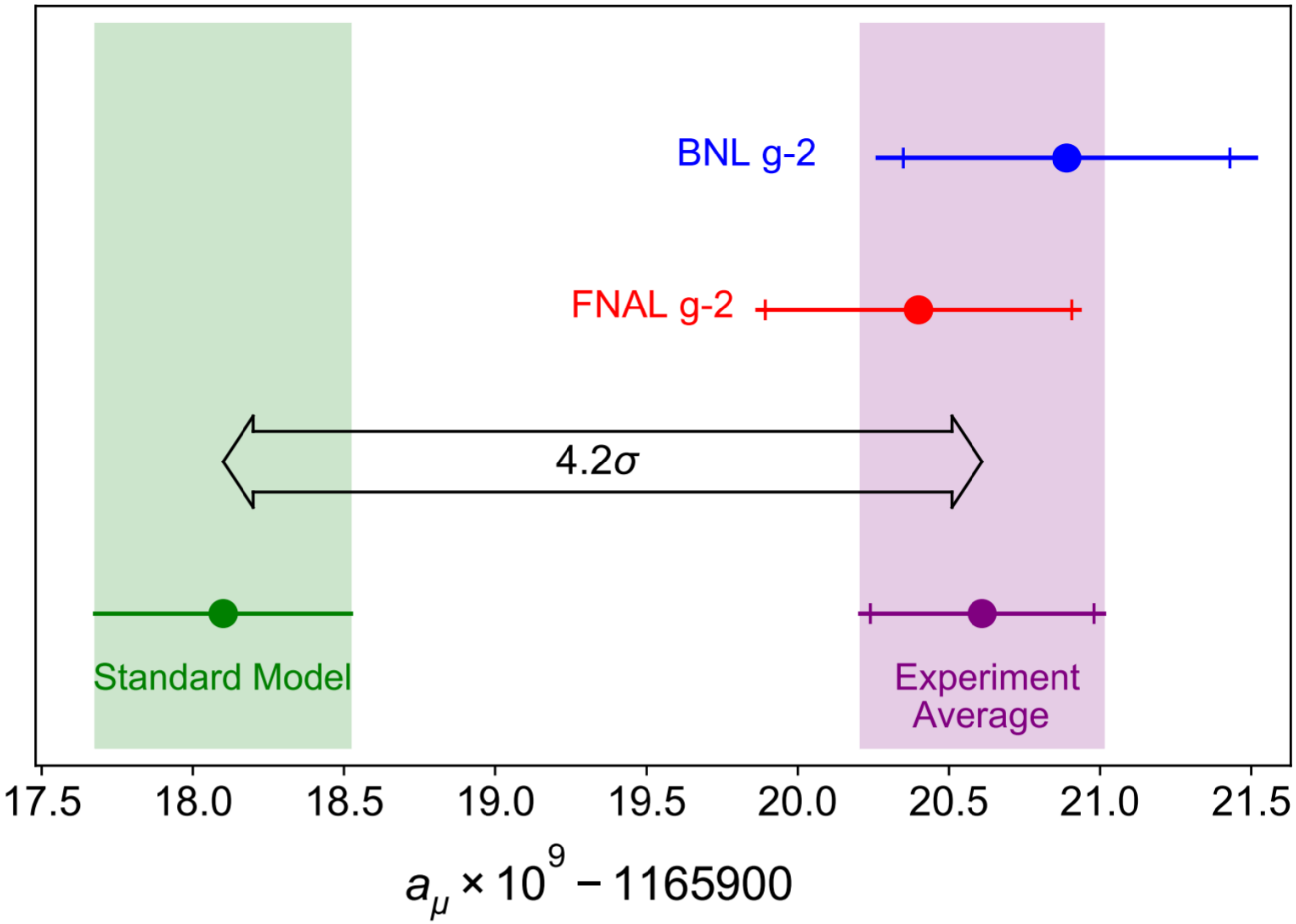






SUMMARY OF RUN-1 RESULT AND OUTLOOK

SUMMARY OF RUN-1 RESULT



$$a_\mu(\mathrm{FNAL}) = 116\,592\,040(54) \times 10^{-11} \quad (0.46\,\mathrm{ppm})$$

$$a_\mu(\mathrm{Exp}) = 116\,592\,061(41) \times 10^{-11} \quad (0.35\,\mathrm{ppm})$$

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SUMMARY AND OUTLOOK

- The Muon g-2 experiment measured a_μ to 460 ppb, consistent with BNL
- The combined experimental result differs from the SM value by 4.2σ
- This result is based on ~6% of our total statistical goal
- Already ~85% of the total statistics on tape (Run-1 to Run-5)
- Several key upgrades since Run-1 will further improve systematics:
  - New quad resistors reduces C_{pa}
  - Higher kicker voltage to center beam radially
  - Thermal magnet insulation and better hall cooling stabilize field drift
  - Improved quad transient measurement
  - New RF system to suppress CBO amplitude
- Upcoming final Run-6 should bring us to overall statistics goal
- ... stay tuned for more results to come (Run2/3 result ~Spring 2023)!

SUMMARY AND OUTLOOK