Current status of the muon *g*–2 measurement at Fermilab

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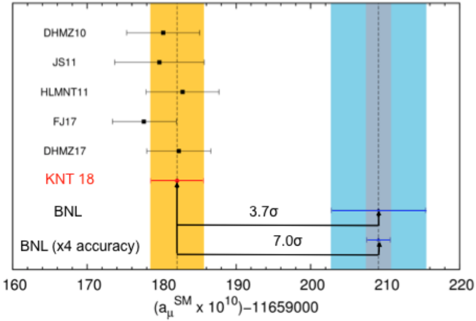
Motivation

Comparison of the measurement to the calculation of $\mathbf{a}_\mu = (\mathbf{g}_\mu - \mathbf{2})/\mathbf{2}$ allows for a precise test of the Standard Model and to look for new physics.



arXiv:1802.02995v1 [hep-ph]

BNL $g-2$ experiment (E821) found a discrepancy $> 3\sigma$ w.r.t. theoretical prediction.

Fermilab $g-2$ experiment (E989) aims for a reduction of the experimental uncertainty by a factor of 4 with respect to BNL result:

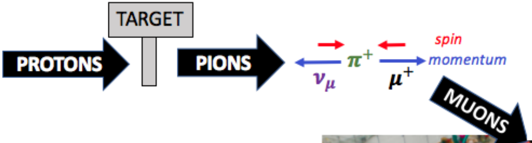
$$\boxed{\delta(a_\mu)^{\text{exp.}} : 540 \text{ ppb} \rightarrow 140 \text{ ppb}}$$

If a_μ value is confirmed (using latest a_μ^{SM}), the new $g-2$ result has the potential to confirm the discrepancy and claim discovery:

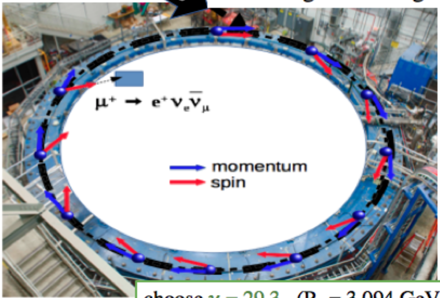
$$\boxed{\mathbf{a}_\mu^{\mathbf{FNAL}} - \mathbf{a}_\mu^{\mathbf{SM}} \sim \mathbf{7}\sigma}$$

Experimental Technique

1. Muon production



2. Polarized muons are injected into a magnetic storage ring



3. Measure B and the "anomalous precession frequency" *i.e.*, the Spin precession frequency relative to the Cyclotron frequency:

choose $\gamma = 29.3$ $(P_\mu = 3.094 \text{ GeV/c})$

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

Measure these

Final formula

In the final analysis the anomaly is extracted with:

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

Get from CODATA[3]:

g_e = -2.002 319 304 361 82(52) (0.00026 ppb)

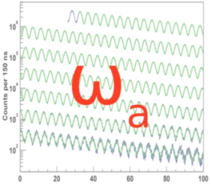
m_μ/m_e = 206.768 2826(46) (22 ppb)

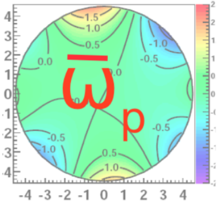
μ_e/μ_p = -658.210 6866(20) (3.0 ppb)

[3] Rev. Mod. Phys. 88, no. 3, 035009 (2016) [arXiv:1507.07956]

- ω_a anomalous spin precession frequency is extracted from decay positron time spectra
- $\overline{\omega}_p$ average magnetic field seen by the muons is measured by NMR
- δa_μ is determined by precision of ω_a and ω_p measurements:

δa_μ	BNL (ppb)	FNAL goal (ppb)
ω_a statistic	480	100
ω_a systematic	180	70
ω_p systematics	170	70
Total	**540**	**140**





Requirements for a 140 ppb measurement

δa_μ	BNL (ppb)	FNAL goal (ppb)
ω_a statistic	480	100
ω_a systematic	180	70
ω_p systematics	170	70
Total	**540**	**140**

- **20 × BNL statistics**
  - more muons/second, higher quality beam, store more muons, ...
- **3 × more uniform magnetic field and improve the ω_p measurement**
  - optimize shimming procedure, precise pNMR probes, ...
- **Improve the ω_a measurement**
  - new instrumentation: segmented and fast EM calorimeters, higher bit-depth WFDs, laser calibration system, tracker system, ...

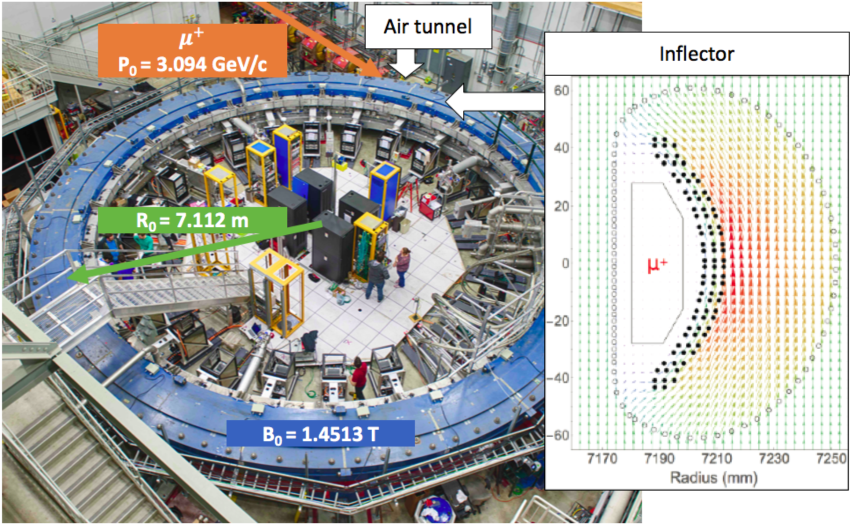
Production of the muon beam

- **Recycler Ring:** 8 GeV protons from Booster are rebunched
- **Target Station:** p are collided with target and π^+ with $p = 3.1$ GeV/c ($\pm10\%$) are collected
- **Beam Transfer and Delivery Ring:** in decay line magnetic lenses select μ^+ from $\pi^+ \to \mu^+\nu_\mu$, while in circular ring the μ are separated from p and π^+
- **Muon Campus:** a beam of μ^+ polarize is ready to be injected into the storage ring. We expect 20 times BNL statistics!

Journey of the storage ring: from BNL to FNAL

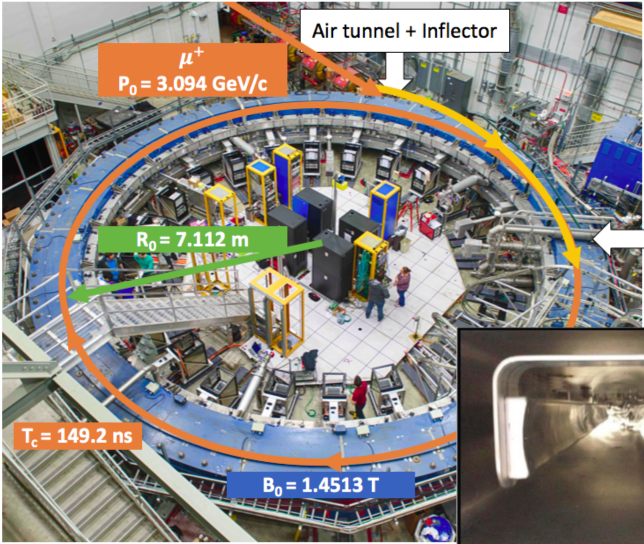
Injection of the Muons in the ring

μ^+ injected first through a air **tunnel** in the iron yoke and then a field-cancelling **Inflector** magnet



Muon Storage

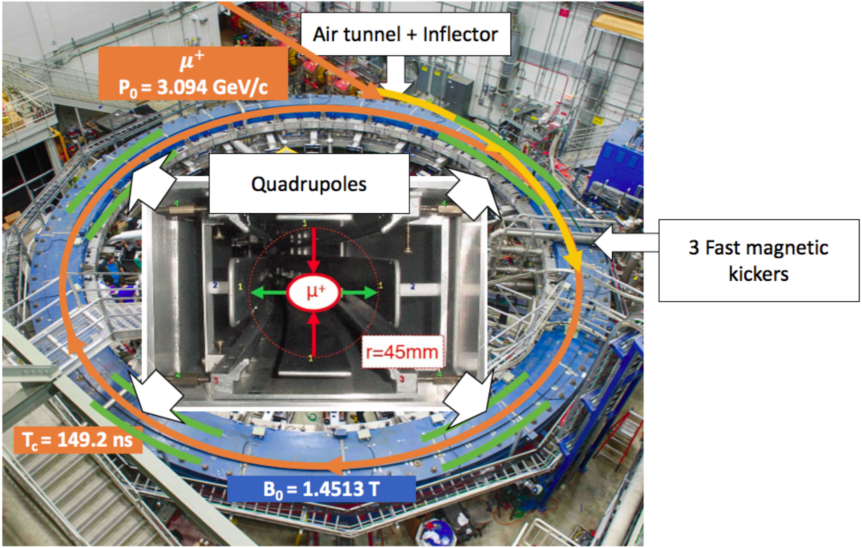
3 magnetic kickers to deflect the beam outward
by ~10.8 mrad at 90° to put beam onto a centered orbit



Fast kickers:
Off before the
beam returns!

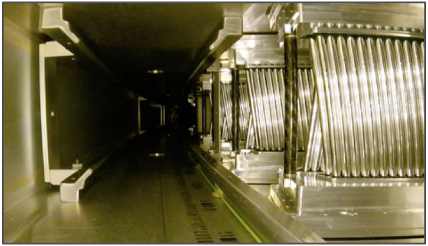
Vertical Focusing

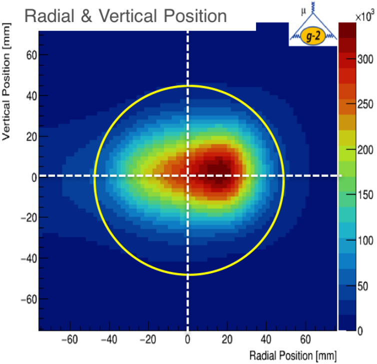
4 Sets of Electrostatic Quadrupole plates for vertical focusing



Storage Profile

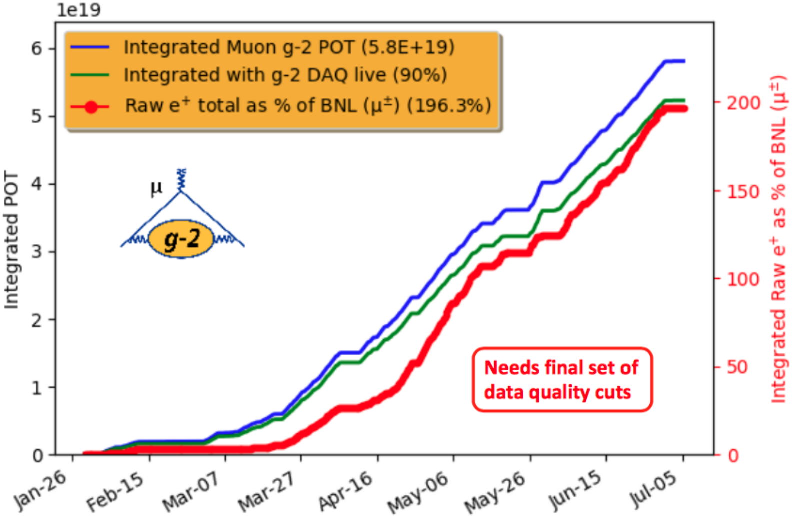
- ring equipped with two in-vacuum straw tracker detectors.
- trackers used to extrapolate decay e^+ trajectory back to muon decay position $\rightarrow$ they provide an image of the store muon beam profile
- final alignment and calibration not yet complete: beam not centred!
- tracker detectors essential for $g-2$ systematics and EDM search





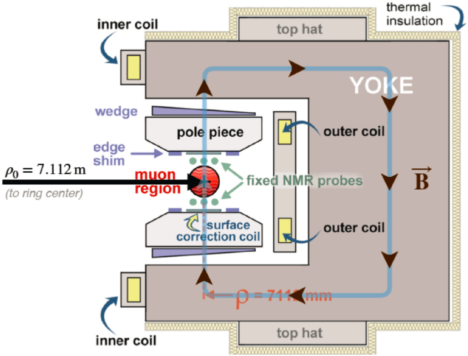
Run 1 Statistics

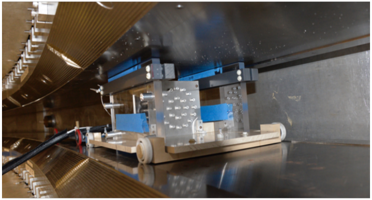
In FY18 collected ~ 2×BNL statistics of raw data (no quality selection):



How we measure ω_P

- ω_P is proportional to the magnetic field;
- magnetic field is created as uniform as possible (shimming procedure) and kept mechanically and thermally stable
- during data-taking the field is monitored by fixed NMR probes
- periodically ($\sim$ 1 run every days) field is mapped by a trolley that runs around the inside of the ring and calibrates the stationary probes

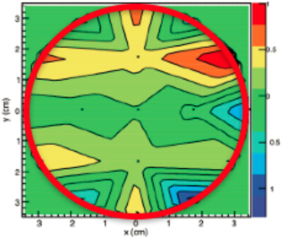




ω_P Measurement

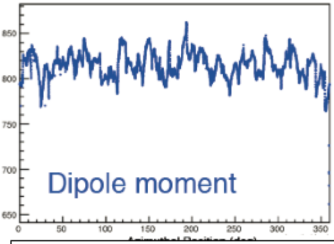
RMS ~ 15 ppm (vs 40 at BNL)

March 18



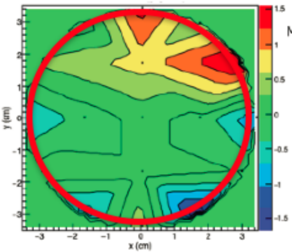
Multipole Moments (ppm)

	Norm	Skew
Quad	-0.19	0.28
Sext	0.05	0.27
Octu	-0.07	0.25
Decu	0.23	0.07



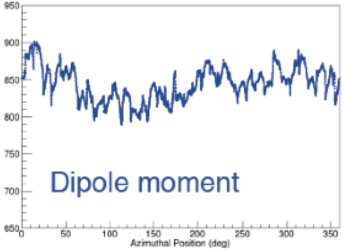
0 180° 360°

June 25



Multipole Moments (ppm)

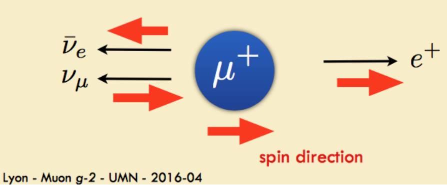
	Norm	Skew
Quad	0.14	0.87
Sext	-0.46	0.67
Octu	-0.06	0.36
Decu	0.24	0.08



Averaged around azimuth

How we mesure ω_a

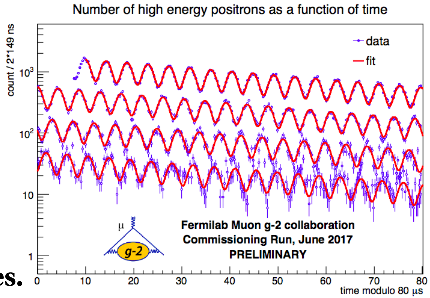
Injected polarized muons decay: $\mu^+ \rightarrow e^+ + \nu_e + \nu_\mu$:



$\Rightarrow$ high energy e^+ are emitted preferentially with electron momentum direction strongly correlated with μ^+ spin (parity violation of the weak decay)

Counting the number of e^+ with $E_{e^+} > E_{\text{threshold}}$ as a function of time (wiggle plot) leads to $\underline{\omega_a}$:

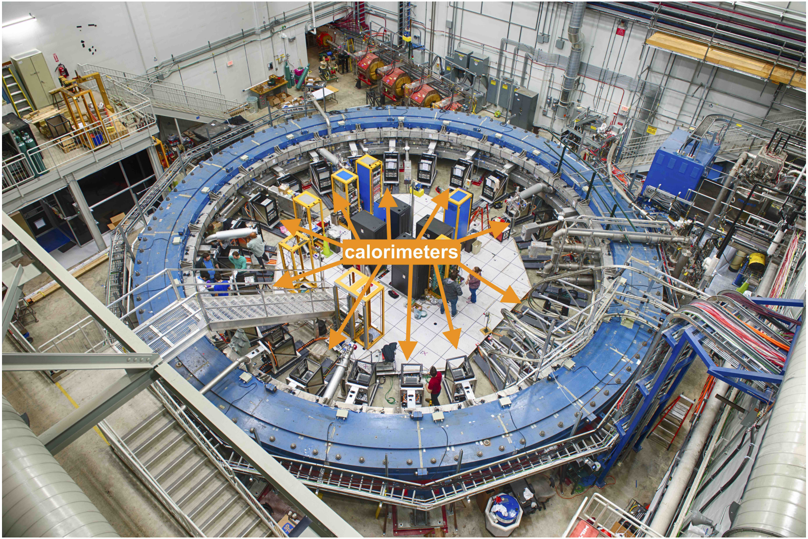
$$N(t) = N_0 e^{-t/\tau}[1 + A\cos(\omega_a t + \phi)]$$



E_{e^+} and t are the measured observables.

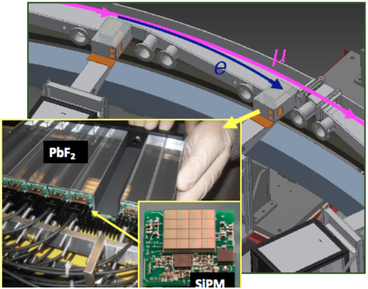
Detectors for ω_a Measurement

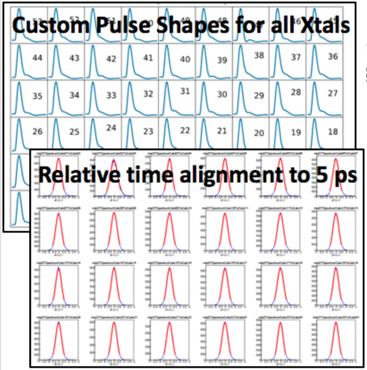
- The energy and hit time of the e^+ from the μ decay are measured by the 24 calorimeters positioned inside the ring.

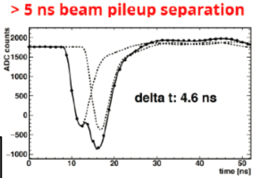


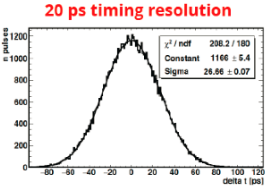
Calorimeters

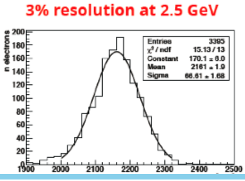
- each calorimeter is composed of 6×9 PbF_2 crystals read out individually by large-area SiPMs
- calibration, time alignment and gain stability for each of 1296 channels is provided by the laser calibration system











Methods to obtain ω_a

- Multiple analysis techniques

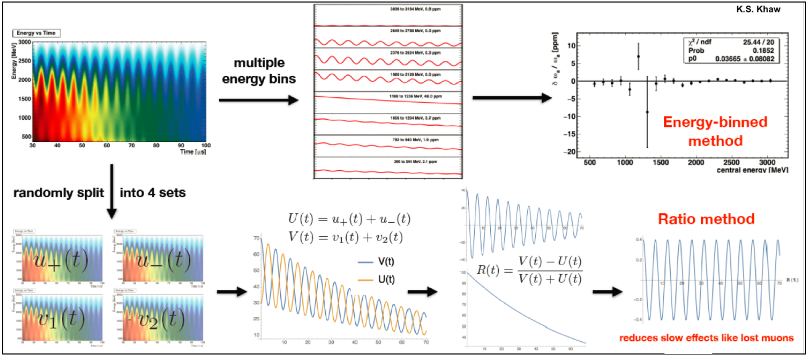
Threshold (T) Method

Integrated Charge (Q) Method

Asymmetry Method

Energy-binned Method

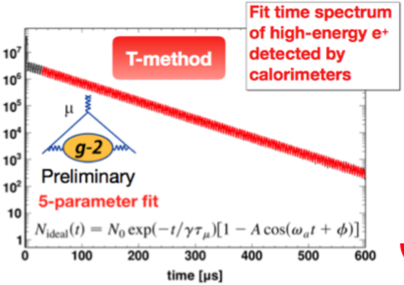
Ratio (R) Method

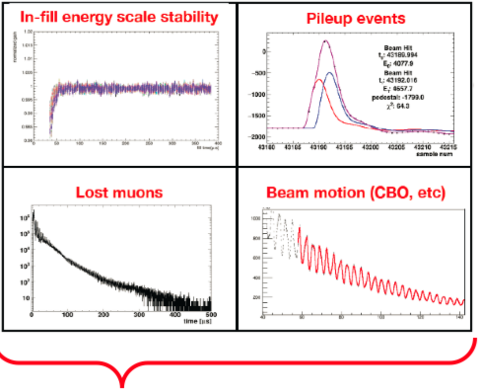


- two independent reconstruction routines to turn raw waveforms into energies and times
- results hardware and software blinded

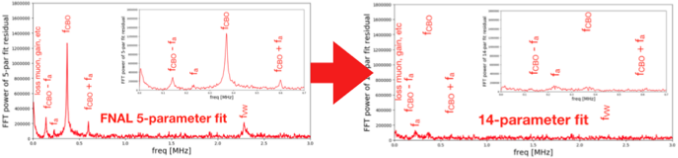
ω_a Analysis Highlights

- Advanced fitting algorithms accounting for systematics





T-method: FFT of fit residuals: Big improvements when accounting for CBO, lost muons,...



Summary and Conclusions

- The experiment just finished the 1^{st} physics data taking: $\sim 2\times$BNL statistics (raw data) has already been collected!
- Measurements of ω_a and ω_p are becoming more mature: **goal of publishing in 2019** ($\sim$ 400 ppb)!
- The ultimate goal is to measure a_μ with a precision of 140 ppb (4×BNL precision).