Results from the Muon *g*–2 Experiment at Fermilab

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on behalf of the Muon g–2 Collaboration

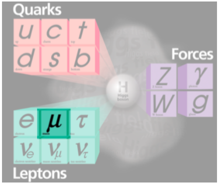
μ

g-2

Fermilab

Introduction: the muon anomaly

- **Muon:** elementary particle with spin-1/2 and magnetic moment proportional to spin through the **g-factor**:

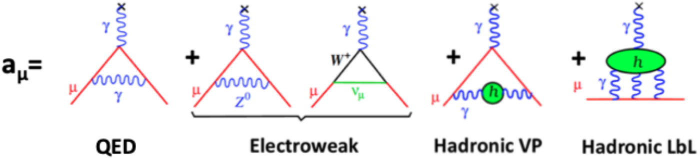


$$\vec{\mu} = \mathbf{g}\frac{q}{2m_\mu}\vec{S}$$

- At first order (Dirac theory for $s = 1/2$ particles) $g = 2$ but with higher order corrections $g > 2$:

$$\underbrace{g_\mu = 2}_{\text{Dirac}}(1 + a_\mu) \quad \Rightarrow \quad \boxed{a_\mu = \frac{g-2}{2}} \quad \textbf{muon anomaly}$$

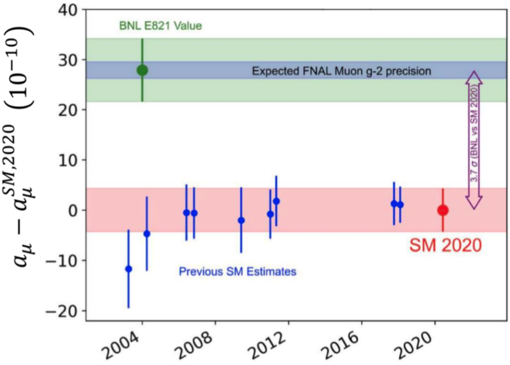
–> Theoretically calculated using the Standard Model (SM):



–> Comparison to measurement allows for a **precise test of the SM and to look for new physics**

Experimental measurement vs. SM calculation

- FNAL Experiment motived by long-standing $> 3\sigma$ discrepancy



- **E821 (BNL)** experimental value:

$$a_\mu^{\text{E821,BNL}} = 116592080(63) \times 10^{-11}$$

[Phys. Rev. D, **73** (2006) 072003]

- **SM value** re-evaluated in 2020 by Muon g-2 Theory Initiative (WP20):

$$a_\mu^{\text{SM, WP20}} = 116591810(43) \times 10^{-11}$$

[Phys. Rept. **887**, 1 (2020)]

- **FNAL Exp**. is collecting data aiming to improve uncertainty with 140 ppb goal
- In this talk:
  - **first result from FNAL Muon g-2 Exp.** with $\delta(a_\mu) = 462$ ppb
  - summary and outlook of the Physics Runs

Status of the SM calculation

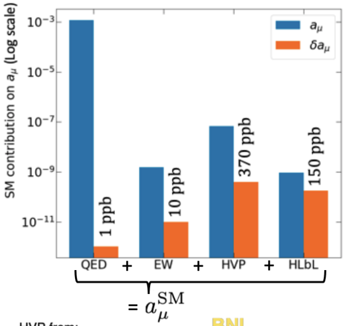
- Calculation is continuously updated
- Largest contribution from QED (well known)
- Uncertainty dominated by HVP

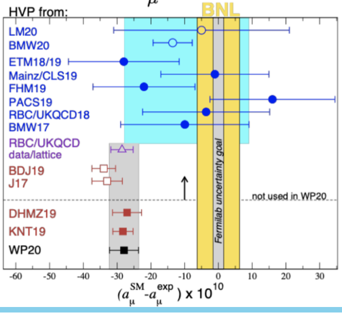
–> WP20 result relies on **HVP data-driven calculations**

  - uses experimental inputs from e^+e^- cros section data

–> Alternative approach: **HVP lattice calculations**

  - BMW20 is first result with precision competitive with data-driven calculations
  - tension with HVP data-driven but potentially explains exp. results
  - looking forward to see further developments





Experimental technique

1. Inject polarized muons into a magnetic storage ring
2. Muons circulate around the ring at the cyclotron frequency:

$$\vec{\omega}_C = \frac{q}{\gamma m_\mu}\vec{B}$$

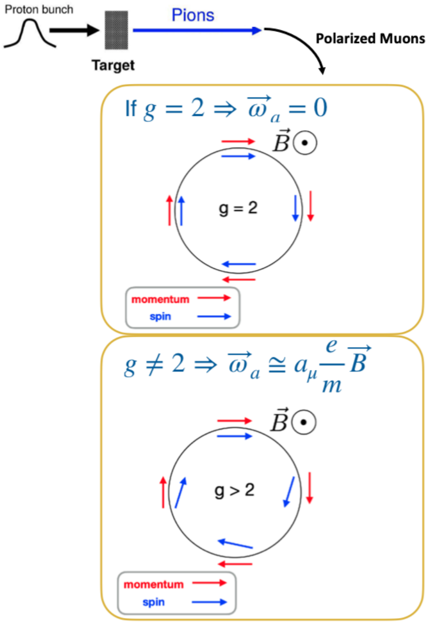
3. Muon spin precession frequency is given by:

$$\vec{\omega}_S = \frac{q}{\gamma m_\mu}\vec{B}(1 + \gamma a_\mu)$$

4. Muon anomaly is related to **anomalous precession frequency**:

$$\vec{\omega}_a \cong \vec{\omega}_S - \vec{\omega}_C \cong a_\mu \frac{q}{m_\mu}\vec{B}$$

5. Measure B and ω_a to extract the anomaly



Final formula

Muon anomaly is determined with:

$$a_\mu = \underbrace{\boxed{\frac{\omega_a}{\tilde{\omega}'_p(T_r)}}}_{\text{ratio of frequencies } (R_\mu) \text{ measured by us}} \underbrace{\frac{\mu'_p(T_r)}{\mu_e(H)} \frac{\mu_e(H)}{\mu_e} \frac{m_\mu}{m_e} \frac{g_e}{2}}_{\text{fundamental factors}}$$

ratio of frequencies (R_μ) measured by us

fundamental factors (combined uncertainty 25 ppb):

$\mu'_p(T_r)/\mu_e(H)$ from [Metrologia **13**, 179 (1977)]

$\mu_e(H)/\mu_e$ from [Rev. Mod. Phys. **88** 035009 (2016)]

m_μ/m_e from [Phys. Rev. Lett. **82**, 711 (1999)]

$g_e/2$ from [Phys. Rev. A **83** 052122 (2011)]

ω_a: muon anomalous precession frequency

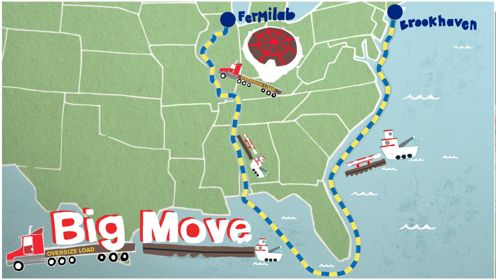
$\tilde{\omega}'_p(T_r)$: magnetic field B in terms of (shielded) proton precession frequency **and** weighted by the muon distribution

(shielded = measured in a spherical water sample at the reference temperature $T_r = 34.7\ ^\circ$C)

Production of the muon beam

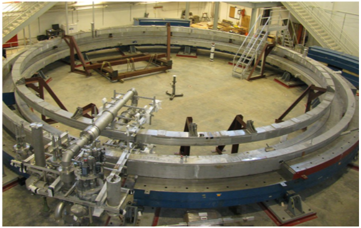
- **Recycler Ring:** 8 GeV protons from Booster are divided in 4 bunches
- **Target Station:** p-bunches are collided with target and π^+ with 3.1 GeV/c ($\pm 10\%$) are collected
- **Beam Transport and Delivery Ring:** magnetic optics select μ^+ from $\pi^+ \rightarrow \mu^+ \nu_\mu$ then μ^+ are separated from p and π^+ in circular ring
- **Muon Campus:** polarized μ^+ are ready to be injected into the **storage ring**

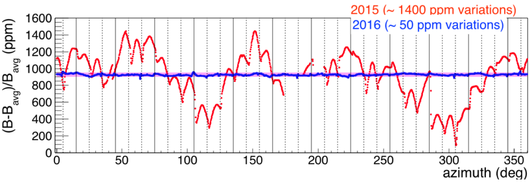
The storage ring journey: from BNL to FNAL in Summer 2013

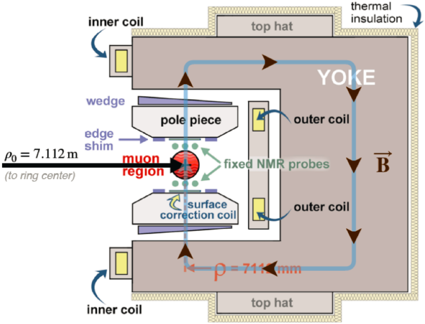


Storage ring magnet

- Three superconducting coils provide 1.45 T vertical magnetic field
- Vacuum chambers surrounded by a cryosystem and C-shaped **yokes** to allow the decay positrons to reach the detectors.
- Achieved 50 ppm on field uniformity thanks to low-carbon steel **poles**, **edge shims**, **steel wedges**, **surface correction coil**



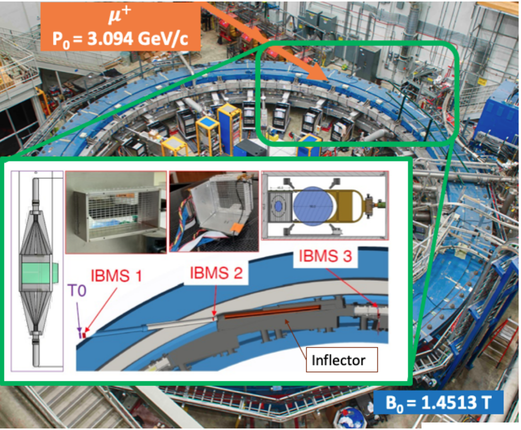




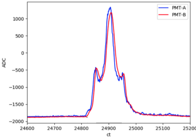
final field ~ 3 times more uniform than at BNL

Injection of the muons into the ring

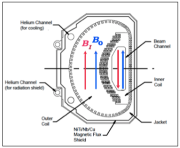
- Beam enters the ring through a 2.2 m-long 10 cm hole in the iron yoke

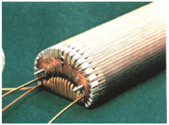


- **T0 Counter** (thin scintillator read out by PMTs) to measure **beam time profile**

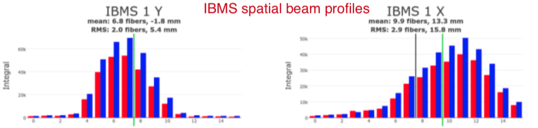


- **Inflector magnet** provides nearly field free region for muons to enter the storage region



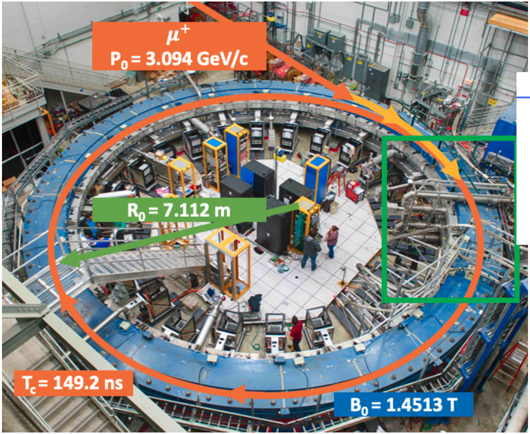


- **Inflector Beam Monitoring System** (scintillator fiber grids) to measure **beam spatial profile**



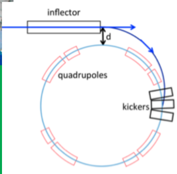
Muon storage

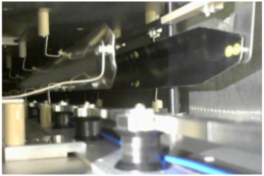
- Injected beam is 77 mm off from storage region center

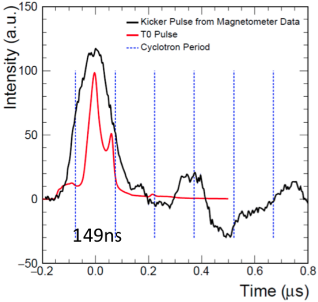


Kicker Magnets

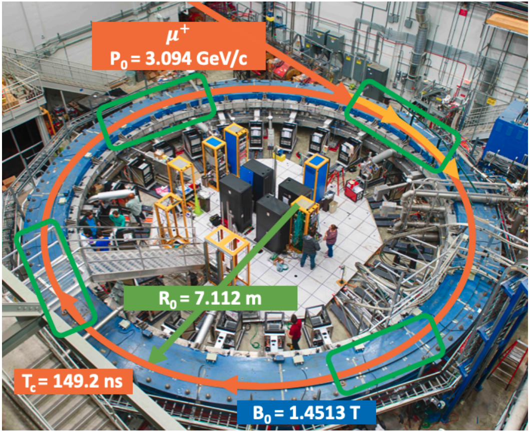
- 3 pulsed magnets deflect beam ~10 mrad onto the storable orbit in less than 150 ns





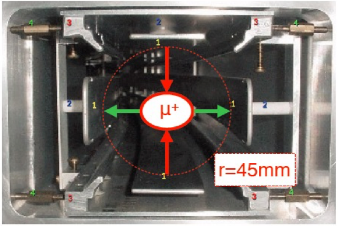


Vertical focusing



Electrostatic Quadrupoles

- 4 sets of quads provide vertical beam focusing

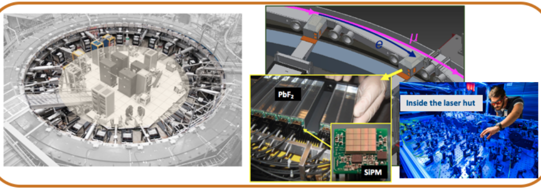


- E–field component cancels out (at first order) when muons are at *magic momentum* :

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

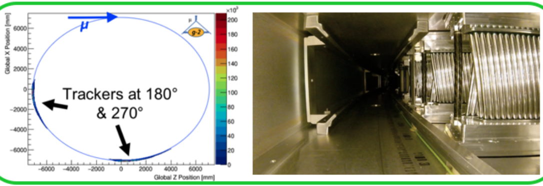
~0 if γ=29.3 *i.e.*, p_μ=3.094 GeV/c

Detectors and field probes



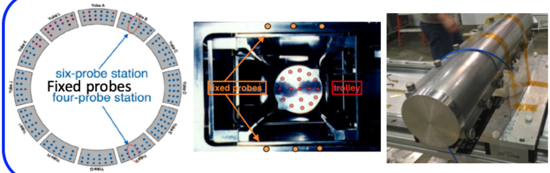
24 Calos around the ring

- Each made of 6×9 PbF_2 crystals read out by large-area SiPMs
- 1296 channels individually calibrated by 405nm-laser system



2 in-vacuum straw trackers

- Each with 8 modules consisting of 128 gas filled straws



2 types of field probes

- 378 fixed NMR probes above and below storage region
  - → measure B-field 24/7
- Trolley with 17-probe NMR
  - → 2D profile of B over the entire azimuth when beam is OFF

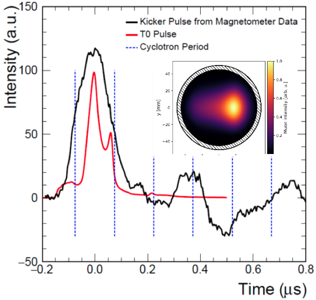
First production Run

Statistics:

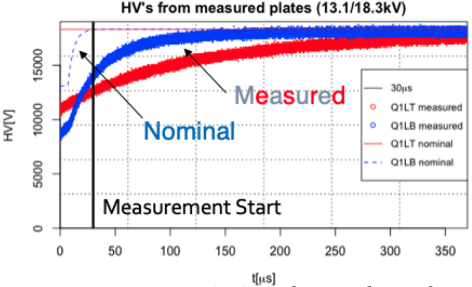
- March 26 – July 7 2018 : **Run-1**
- **1.2 × BNL** after data quality selection

Main challenges:

- Non-ideal kick
  - ⟶ low amplitude and ringing
  - ⟶ beam not centered in storage region



- few HV Quad resistors were damaged
  - ⟶ slow recovery time



- Temperature variations larger than 1°C

Master formula for analysis of Run-1

$$R_\mu = \left(\frac{\overbrace{f_{clock} \cdot \omega_a^{meas}}^{\omega_a} \cdot (1 + \overbrace{C_e + C_p + C_{ml} + C_{pa}}^{\text{beam dynamics corrections}})}{\underbrace{f_{calib} \cdot \omega'_p(x,y,\phi) \otimes M(x,y,\phi)}_{\tilde{\omega}'_p(T_r)} \cdot (1 + \underbrace{B_k + B_q}_{\text{field corrections}})} \right)$$

- f_{clock} : blinded clock
- ω_a^{meas} : measured precession frequency

- f_{calib} : absolute magnetic field calibration
- $\omega'_p(x,y,\phi)$: field maps
- $M(x,y,\phi)$: muon beam distribution

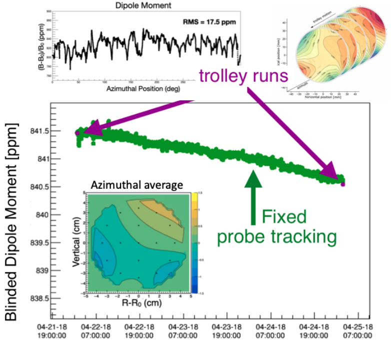
- C_e : electric field correction
- C_p : pitch correction
- C_{ml} : muon loss correction
- C_{pa} : phase-acceptance correction

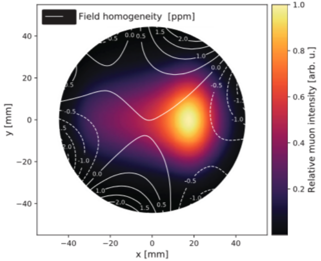
- B_k : transient field from eddy current in kicker
- B_q : transient field from quad vibration

Measuring the magnetic field seen by the muons

$$R_\mu = \left(\frac{f_{clock} \cdot \omega_a^{meas} \cdot (1 + C_e + C_p + C_{ml} + C_{pa})}{\boxed{f_{calib} \cdot \omega'_p(x,y,\phi) \otimes M(x,y,\phi)} \cdot (1 + B_k + B_q)} \right)$$

- ω'_p is proportional to the magnetic field and it is mapped every 3 days using 17 NMR probes on a trolley
- During data taking fixed NMR probes located above and below the storage region monitor the field
- Fixed probes to interpolate the field between trolley runs
- Field maps are weighted by beam distribution (extrapolated from the decay e^+ trajectory measured by the trackers and simulations)





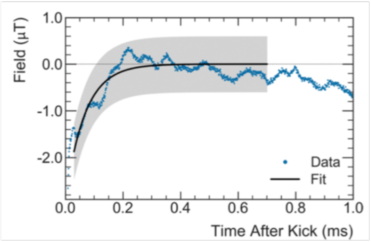
Magnetic field corrections

$$R_\mu = \left(\frac{f_{clock} \cdot \omega_a^{meas} \cdot (1 + C_e + C_p + C_{ml} + C_{pa})}{f_{calib} \cdot \omega'_p(x,y,\phi) \otimes M(x,y,\phi) \cdot (1 + B_k + B_q)} \right)$$

Kicker transient field

- due to eddy currents produced by kicker pulses
- measured using Faraday magnetometers

$$B_k \sim 30\ \text{ppb} \quad \delta_{B_k} \sim 40\ \text{ppb}$$



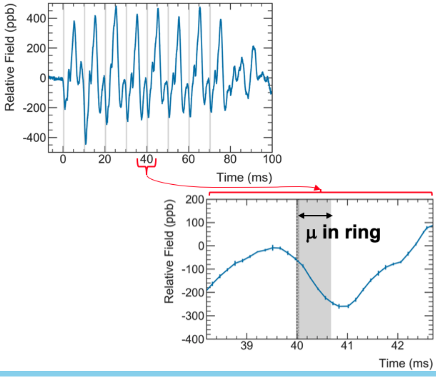
Quads transient field

- due to mechanicals vibrations from pulsing the quads
- mapped using special NMR probes

$$B_q \sim 17\ \text{ppb} \quad \delta_{B_q} \sim 92\ \text{ppb}$$

→ δ_{B_q} dominated by incomplete map

→ expected to be reduced by factor 2 for Run-2 and after



Measuring ω_a

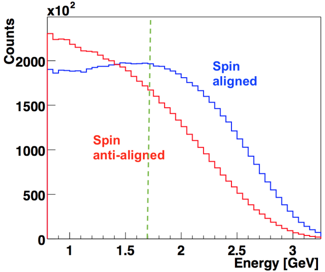
$$R_\mu = \left(\frac{f_{clock} \cdot \omega_a^{meas} \cdot (1 + C_e + C_p + C_{ml} + C_{pa})}{f_{calib} \cdot \omega'_p(x,y,\phi) \otimes M(x,y,\phi) \cdot (1 + B_k + B_q)} \right)$$

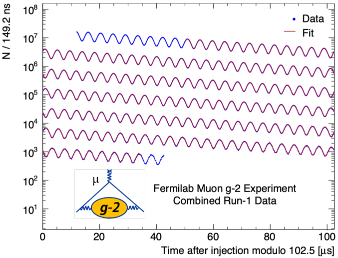
- Polarized muon decay:

$$\mu^+ \rightarrow e^+ + \nu_e + \overline{\nu}_\mu$$

- High energy e^+ are preferentially emitted in direction of μ^+ spin (parity violation of the weak decay)
- Energy spectrum modulates at the ω_a frequency
- Counting the number of e^+ with $E_{e^+} > E_{\text{threshold}}$ as a function of time (wiggle plot) leads to $\underline{\omega_a}$:

$$N(t) = \underbrace{N_0}_{\text{normalization}} e^{\overbrace{-t/\tau}^{\text{muon lab-frame lifetime}}} [1 + \underbrace{A}_{\text{g-2 asymmetry}} \cos(\omega_a t + \overbrace{\varphi}^{\text{g-2 phase}})]$$

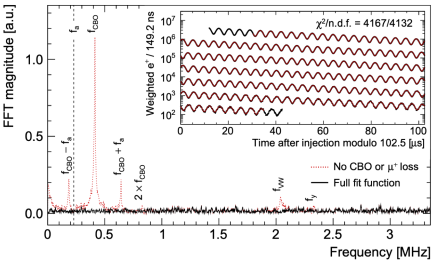




E_{e^+} and t are measured by the calorimeters with a blinding factor applied to the digitization rate

Fitting procedure

- FFT analysis of fit residuals shows that simple 5-parameter model is inadequate
- Fit result improves using a 22-parameter fit function:



$$N_0 e^{-\frac{t}{\gamma\tau}} \left(1 + A \cdot A_{BO}(t) \cos(\omega_a t + \phi \cdot \phi_{BO}(t))\right) \cdot N_{CBO}(t) \cdot N_{VW}(t) \cdot N_y(t) \cdot N_{2CBO}(t) \cdot J(t)$$

$$A_{BO}(t) = 1 + A_A \cos(\omega_{CBO}(t) + \phi_A) e^{-\frac{t}{\tau_{CBO}}}$$

$$\phi_{BO}(t) = 1 + A_\phi \cos(\omega_{CBO}(t) + \phi_\phi) e^{-\frac{t}{\tau_{CBO}}}$$

ω_{CBO}, ω_{2CBO} radial oscillations

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

$$N_{2CBO}(t) = 1 + A_{2CBO} \cos(2\omega_{CBO}(t) + \phi_{2CBO}) e^{-\frac{t}{2\tau_{CBO}}}$$

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

$$N_y(t) = 1 + A_y \cos(\omega_y(t)t + \phi_y) e^{-\frac{t}{\tau_y}}$$

ω_y, ω_{VW} vertical oscillations

Red = free parameters
Blue= fixed parameters

$$J(t) = 1 - k_{LM} \int_{t_0}^{t} \Lambda(t) dt$$

Lost muons

$$\omega_{CBO}(t) = \omega_0 t + A e^{-\frac{t}{\tau_A}} + B e^{-\frac{t}{\tau_B}}$$

$$\omega_y(t) = F \omega_{CBO(t)} \sqrt{2\omega_c / F \omega_{CBO}(t) - 1}$$

$$\omega_{VW}(t) = \omega_c - 2\omega_y(t)$$

Electric field and pitch corrections

$$R_\mu = \left(\frac{f_{clock} \cdot \omega_a^{meas} \cdot (1 + C_e + C_p + C_{ml} + C_{pa})}{f_{calib} \cdot \omega'_p(x,y,\phi) \otimes M(x,y,\phi) \cdot (1 + B_k + B_q)} \right)$$

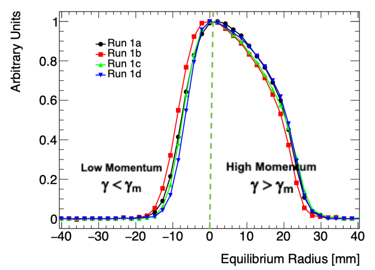
Electric Field

- due to momentum spread around p_{magic}

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

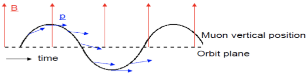
- measured using momentum distribution provided by the calorimeters in terms of equilibrium radius

$C_e \sim 450$ ppb $\quad \delta_{C_e} \sim 50$ ppb



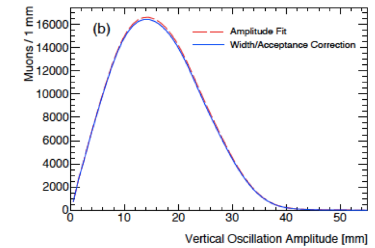
Pitch

- due to vertical beam oscillation



- measured using the beam vertical amplitude from the trackers, calorimeter data, and simulations

$C_p \sim 200$ ppb $\quad \delta_{C_p} \sim 20$ ppb



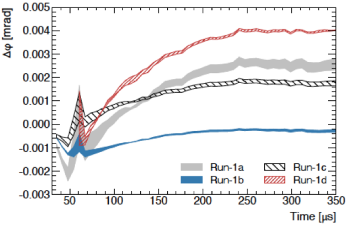
Muon loss and phase acceptance corrections

$$R_\mu = \left(\frac{f_{clock} \cdot \omega_a^{meas} \cdot (1 + C_e + C_p + \boxed{C_{ml}} + \boxed{C_{pa}})}{f_{calib} \cdot \omega'_p(x, y, \phi) \otimes M(x, y, \phi) \cdot (1 + B_k + B_q)} \right)$$

Muon losses cause a phase shift

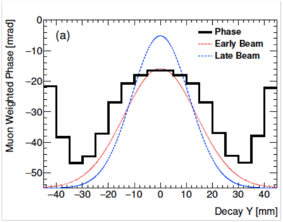
- because muon-spin-phase and muon loss rate are momentum-dependent
- measured using data-driven technique

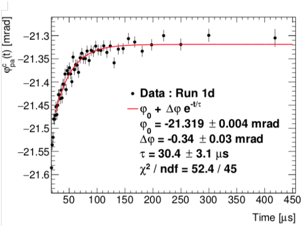
$$C_{ml} < 20\,\text{ppb} \quad \delta_{C_{ml}} \sim 5\,\text{ppb}$$



Phase acceptance

- phase changes due to early to late variations of the beam
- worsened by damaged quads resistors
- measured using tracker data and simulations

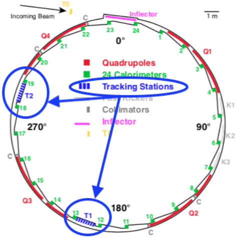


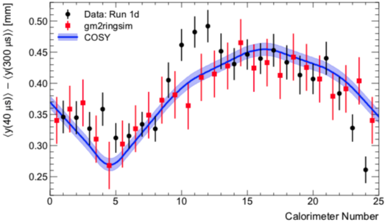


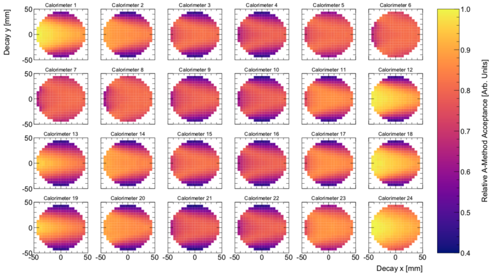
$$C_{pa} \sim 200\,\text{ppb} \quad \delta_{C_{pa}} \sim 80\,\text{ppb}$$

Simulations for phase-acceptance

- Time-dependence of beam spatial distributions are measured by trackers in two locations
- Two independent **simulations** are used to extrapolate beam profile from tracker locations around the ring
  - based on **COSY-INFINITY** and **GEANT-4**
  - cross-checked against data
- The beam profiles in the ring are then folded with calorimeter acceptance maps produced with the **GEANT-4** based simulation







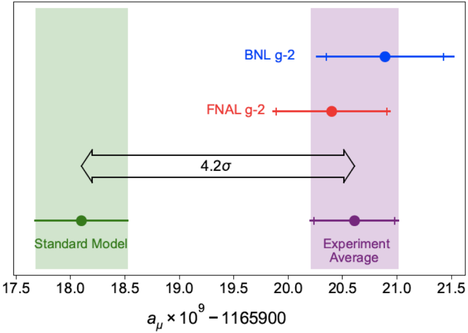
Unblinding

$$R_\mu = \left(\frac{f_{clock} \cdot \omega_a^{meas} \cdot (1 + C_e + C_p + C_{ml} + C_{pa})}{f_{calib} \cdot \omega'_p(x,y,\phi) \otimes M(x,y,\phi) \cdot (1 + B_k + B_q)} \right)$$

Clock frequency (f_{clock}) is:

- the frequency that our DAQ clock ticks
- **stable** at ppt level
- kept **secret** from all collaborators
  - –> for Run-1 it was chosen and weekly monitored by Joe Lykken and Greg Bock (FNAL Directorate)
- **revealed** only when physics analysis is completed
  - –> 25 Feb 2021: Run-1 result was unblinded

Run-1 Result



- Run-1 result uncertainty is statistics dominated but we only analyzed 6% of data we plan to collect
- Major systematic uncertainties will be reduced after Run-2 thanks to hardware upgrades and further studies

- After unblinding we obtain the first FNAL $g-2$ result :

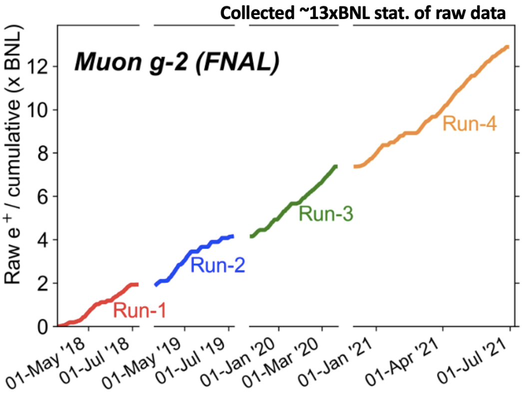
$$a_\mu = 116592040(54) \times 10^{-11} \quad (462\,\text{ppb})$$

- Good agreement with BNL
- 4.2σ tension with SM prediction when combining the two experiments

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
$f_{\text{calib}} \langle \omega_p(x,y,\phi) \times M(x,y,\phi) \rangle$	...	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

Status of Data-Collection & Outlook

Much more data to analyze!

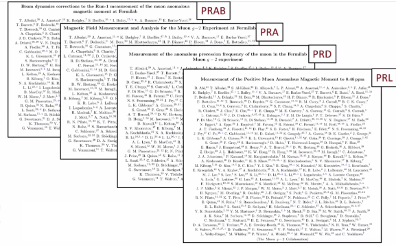


- Currently preparing for **Run-5**
- Successfully completed **Run-4**:
  - collected ~5.5× BNL, the largest data set so far!
  - performed studies to understand Run-2, Run-3 and Run-4 syst., and for Run-5 configuration
  - transitioned to fully remote shifts
- **Run-2** / **Run-3**: analysis in progress, expecting to reduce combined exp. unc. by another factor of 2 by next summer. Systematics on track for < 100 ppb
- **Run-1**: results ~ 6% of full stats, 434 ppb stat ⊕ 157 ppb syst unc.

Summary and Conclusions

- FNAL $g-2$ Experiment goal is to measure a_μ with a precision of 140 ppb (4×BNL precision)
- Run-1 result confirmed BNL Experiment measurement and the combination of the two shows a 4.2σ tension with the SM calculation
- Run-2 and Run-3 measurement in progress: expected to achieve a factor 2 improvement
- Just completed Run-4 and preparing for Run-5!

More details in the papers!



Thanks!