FERMILAB-SLIDES-25-0114-PPD-V

Status of the Muon *g*-2 and muonEDM measurements at Fermilab

Anna Driutti
INFN Sezione di Pisa
on behalf of the Muon $g-2$ Collaboration

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μ g-2
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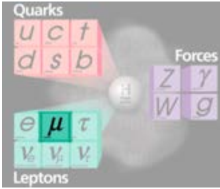
Magnetic moments: g-factor and the muon anomaly



- The **magnetic moment** proportional to spin through the **g-factor**:

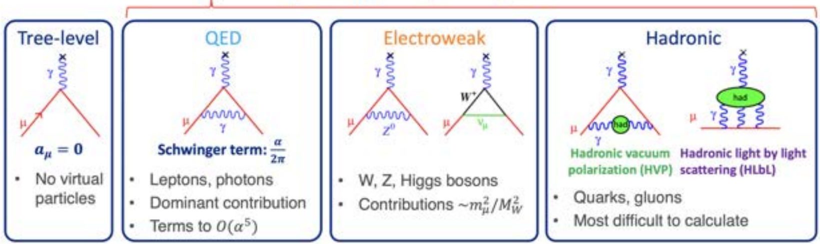
$$\vec{\mu} = \mathbf{g}\frac{q}{2m_\mu}\vec{S}$$

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

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

–> a_μ can be calculated with the SM (all particles contribute):

$$a_\mu^{SM} = a_\mu^{QED} + a_\mu^{EW} + a_\mu^{HVP} + a_\mu^{HLbL} \approx 0.0012$$



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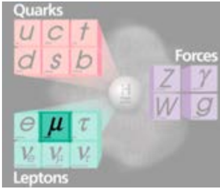

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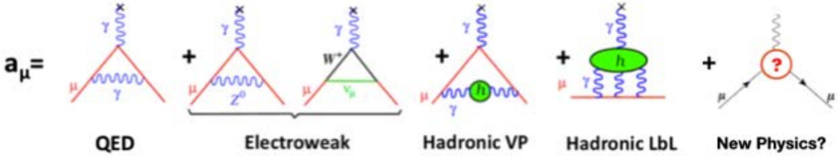


–> If unknown particles contribute the SM will disagree with measurement: **a_μ precise test of the SM and look for new physics**

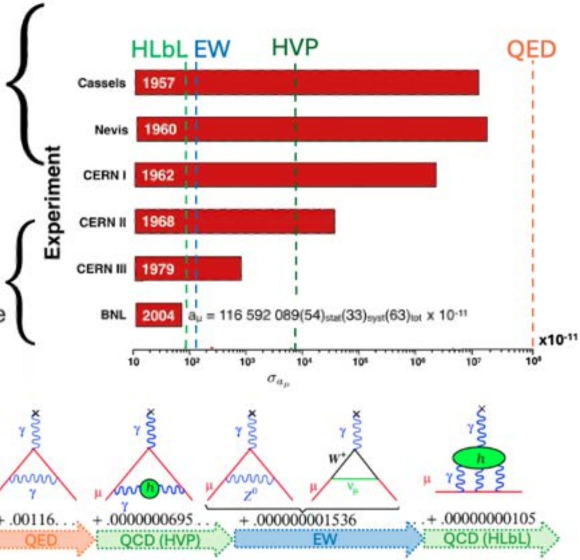
History of the Muon *g-2* Experiments

Stopped Muons

Stop muons in a magnetic field measurement of g_μ directly

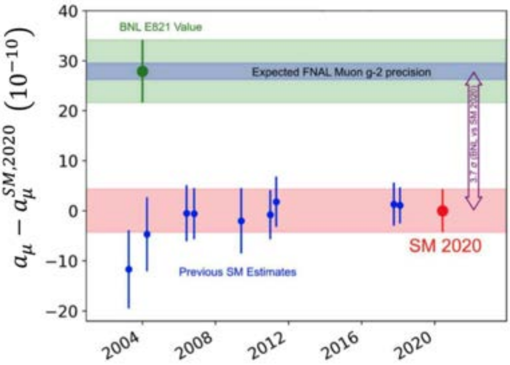
Storage Ring

Dilated lifetime measurement of a_μ, more precise



The BNL Results

- BNL measurement appears to be larger than the Standard Model value by $> 3\sigma$



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

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

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

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

$$a_\mu^{SM,2020} = 116591810(43) \times 10^{-11}$$

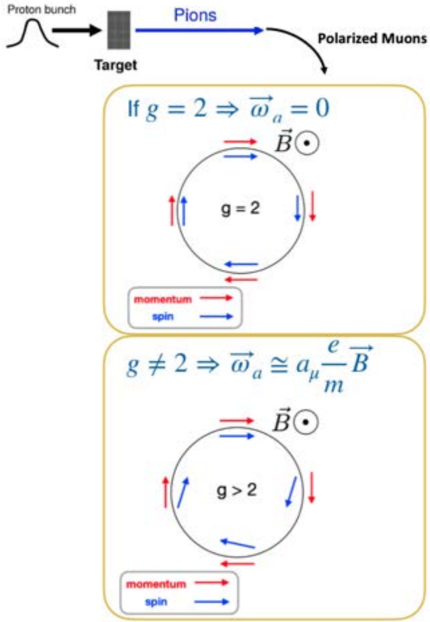
[Phys. Rept. **887**, 1 (2020)]

- In the meantime: **FNAL Exp**. was constructed and began collecting data in 2018, continuing operations until 2023 aiming to improve uncertainty with 140 ppb goal

[E821, BNL uncertainty: 540 ppb; SM, 2020 uncertainty: 370 ppb]

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 (Larmor) 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



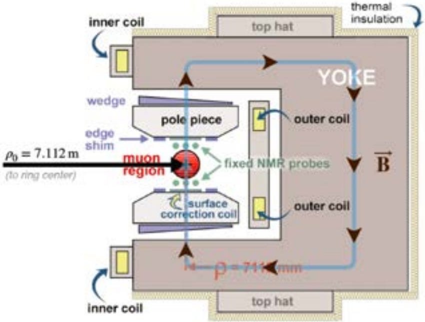
Production of the muon beam

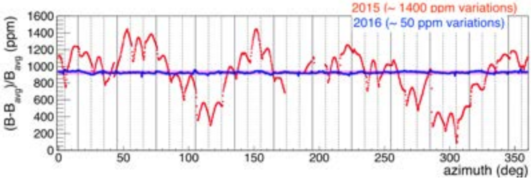
- **Recycler Ring:** 8 GeV protons from Booster are divided in 4 bunches
- **Target Station:** p-bunches are collided with target and π^+ with 3.1 GeV/c (±10%) are collected
- **Beam Transport and Delivery Ring:** magnetic lenses select μ^+ from $\pi^+ \to \mu^+ \nu_\mu$ then μ^+ are separated from p 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**

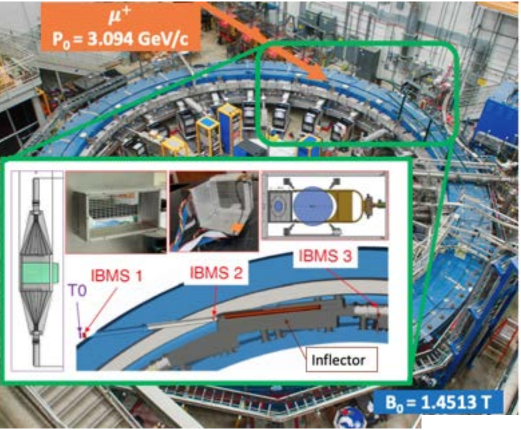




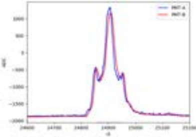
final field ~ 3 times more uniform than at BNL

Injection of the muons into the ring

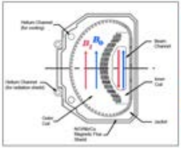
- Beam enters the ring through a 2.2 m-long 10 cm hole in the iron yoke



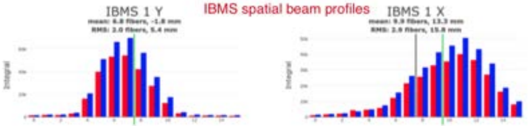
- **T0 Counter** (thin scintillator read out by PMTs) to measure **beam time profile**



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

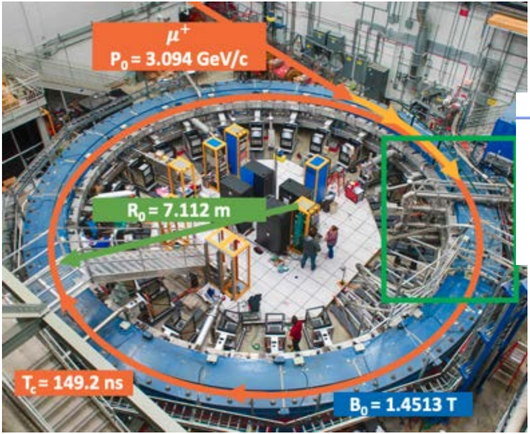


- **Inflector Beam Monitoring System** (scintillator fiber grids) to measure **beam spatial profile**



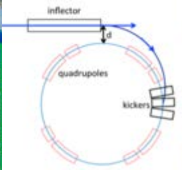
Muon storage

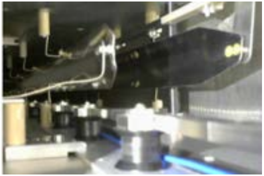
- Injected beam is 77 mm off from storage region center

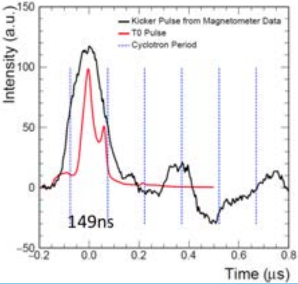


Kicker Magnets

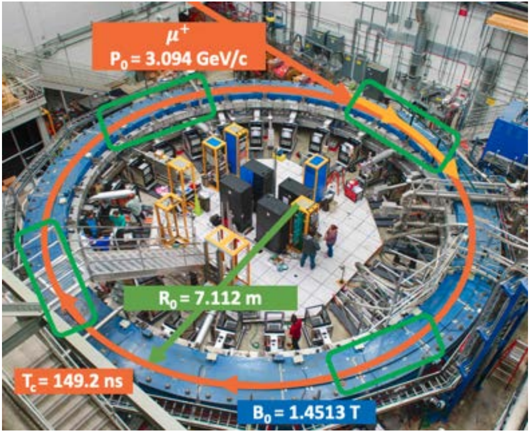
- 3 pulsed magnets deflect beam ~10 mrad onto the closed storage orbit in less than 150 ns





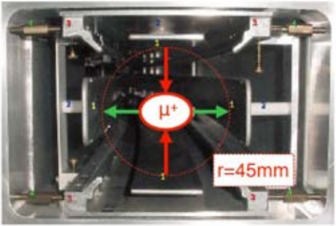


Vertical focusing



Electrostatic Quadrupoles

- 4 sets of quads provide vertical beam focusing



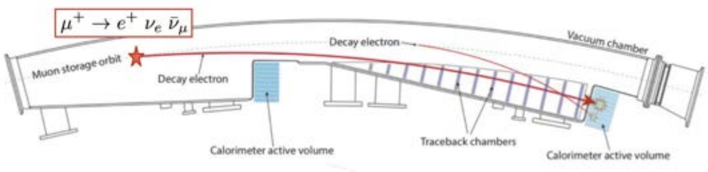
- E–field component cancels out (at first order) when muons at *magic momentum*:

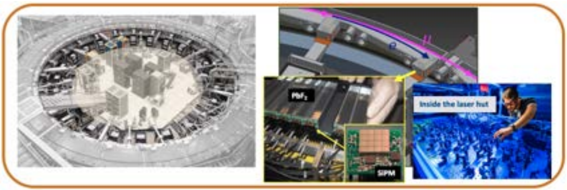
$$\vec{\omega}_a \cong -\frac{e}{m}\left[a_\mu \vec{B} - \left(a_\mu - \underbrace{\frac{1}{\gamma^2 - 1}}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right]$$

~0 if γ=29.3 *i.e.*, p_μ=3.094 GeV/c

Detectors

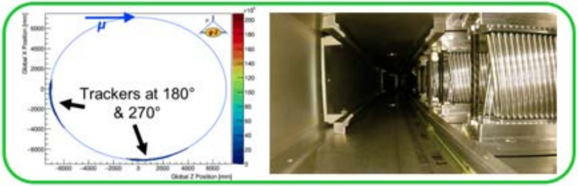
e^+ from μ decays curve inside the ring and hit the detectors:





24 Calos around the ring

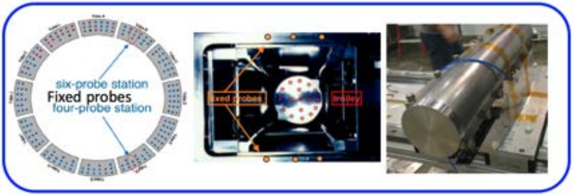
- Each made of 6×9 PbF_2 crystals read out by large-area SiPMs
- 1296 channels individually calibrated by 405nm-laser system



2 in-vacuum straw trackers

- Each with 8 modules consisting of 128 gas filled straws

Field probes



2 types of field probes

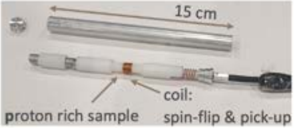
- 378 fixed NMR probes above and below storage region
  - ⟶ measure B-field 24/7
- Trolley with 17-probe NMR
  - ⟶ 2D profile of B over the entire azimuth when beam is OFF

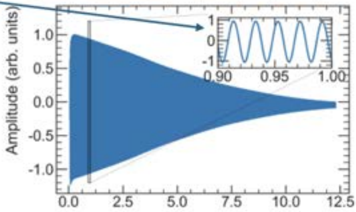
Nuclear Magnetic Resonance (NMR)

- NMR probes measure magnetic fields via proton precession.
  - Like what we do with muons.
  - But much easier. Protons are plentiful and stable, with precisely-known g_p.

$$\omega_p = -\frac{g_p q}{2m_p} B$$

- NMR probes have many aligned protons precessing at ω_p
  - Electrically induces "Free Induction Decay" (FID) signal in a coil.

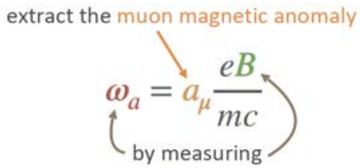




Sample FID signal: Frequency is proportional to field strength.

Towards 140 ppb

1) **Consolidated method:** storage ring (same ring of the BNL experiment):



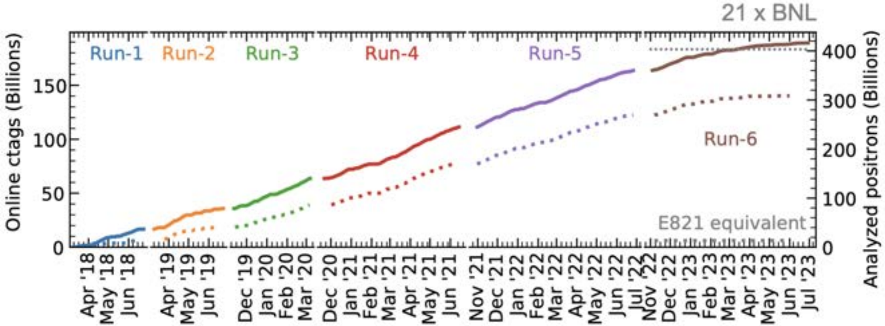
δa_μ	BNL (ppb)	FNAL goal (ppb)
ω_a statistic	480	100
ω_a systematic	180	70
ω_p systematics	170	70
Total	540	140

2) **Polarized muon beam** more intense and “pure” (statistical goal: 21 times more than BNL) thanks to the FNAL Accelerator Complex;

3) improved **magnetic field and detectors** to reduced systematics;

4) new collaboration *i.e.* **new ideas**;

Summary of the data-taking



- 6 years of data taking, passed the TDR goal 21 x BNL statistics
- Post-Run-6 with magnet on but no muons (magnetic field syst.)

The muon anomaly E989 final formula

Muon anomaly is determined with:

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

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)]

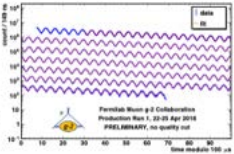
m_μ/m_e from [2018 CODATA (Web Version 8.1)]

$g_e/2$ from [Phys. Rev. Lett. **130**, 071801 (2023), Prog. Theor. Exp. Phys. 2022, 083C01 (2022), and 2023 update]

ω_a: muon anomalous precession frequency

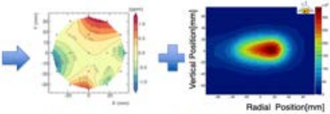
Extract from decay positron time spectra

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



$\tilde{\omega}'_p(T_r)$: magnetic field B in terms of (shielded) proton precession frequency (proton NMR $\hbar\omega_P = 2\mu_p B$) **and** weighted by the muon distribution

(shielded = measured in spherical water sample at $T_r = 34.7\,°C$)



Master formula for Muon g-2 analysis

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

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

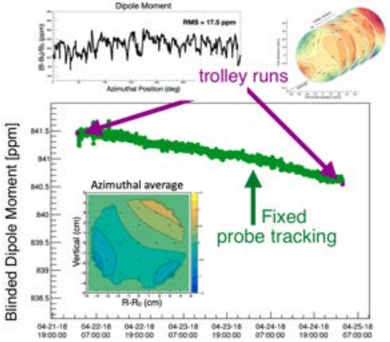
C_e	: electric field correction
C_p	: pitch correction
C_{ml}	: muon loss correction
C_{pa}	: phase-acceptance correction
C_{dd}	: differential-decay correction

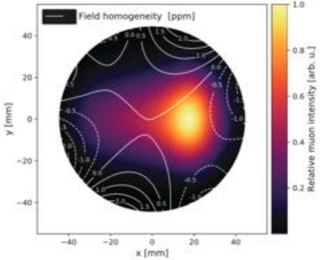
B_k	: transient field from eddy current in kicker
B_q	: transient field from quad vibration

Measuring the magnetic field seen by the muons

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

- 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)



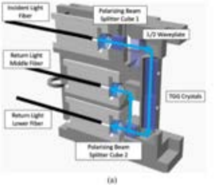


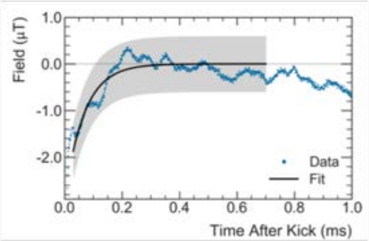
Magnetic field corrections

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

Kicker transient field

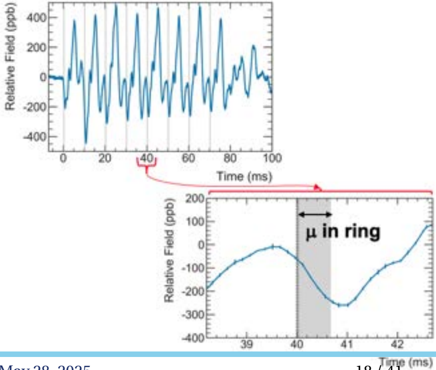
- due to eddy currents produced by kicker pulses
- measured using Faraday magnetometers





Quads transient field

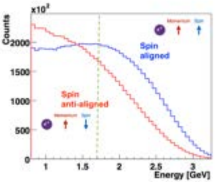
- due to mechanicals vibrations from pulsing the quads
- mapped using special NMR probes



Measuring ω_a

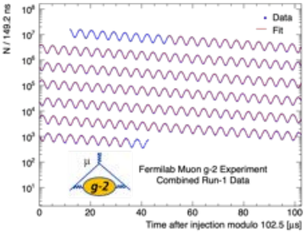
$$R_\mu = \left(\frac{f_{clock} \cdot \omega_a^{meas} \cdot (1 + C_e + C_p + C_{ml} + C_{pa} + C_{dd})}{f_{calib} \cdot \omega'_p(x,y,\phi) \otimes M(x,y,\phi) \cdot (1 + B_k + B_q)}\right)$$

- Polarized muon decay: $\mu^+ \to e^+ + \nu_e + \overline{\nu}_\mu$
- due to angular momentum conservation μ^+ and e^+ spins are in the same direction
- So, high energy e^+ are preferentially emitted in direction of μ^+ spin
- With the Lorentz boost, the high energy e^+ are emitted when the μ^+ momentum and spin are aligned.



- Energy spectrum modulates at ω_a frq.
- Counting the number of e^+ with $E_{e^+} > E_{\text{threshold}}$ as a function of time (wiggle plot) leads to $\underline{\omega_a}$:

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

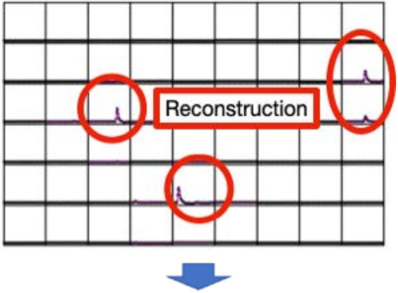


E_{e^+} and t are measured by the calorimeters with a blinding factor applied to the digitization rate

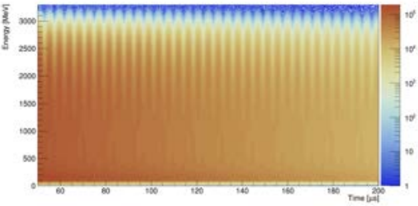
Wiggle plot

- Calorimeters data is reconstructed into energies and times
  –> 2 (Run-1) or 3 (Run-2/3) independent reconstruction routines

raw calorimeters traces



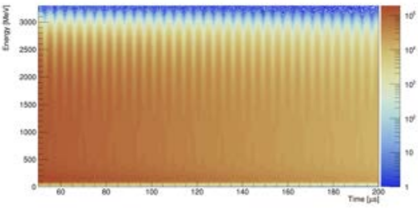
Energy-Time Wiggle Plot



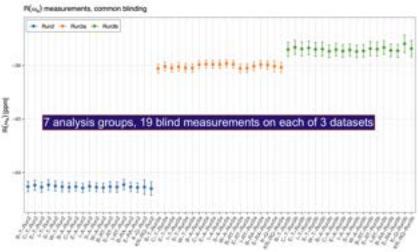
Wiggle plot

- Calorimeters data is reconstructed into energies and times
  –> 2 (Run-1) or 3 (Run-2/3) independent reconstruction routines
- Different and software independently blind analysis techniques:
  - **Threshold (T) Method**
    – only positrons above energy threshold
  - **Asymmetry-Weighted (A) Method:**
    – positrons divided into energy bins and weighted by g-2 asymmetry
  - **Ratio (R) Method**
    – muon lifetime exponential decay removed before fitting
  - **Ratio Asymmetry-Weighted (RA) Method**
  - **Integrated Charge (Q) Method:**
    – sum of raw calorimeter traces (unique method independent of reconstruction)

Energy-Time Wiggle Plot

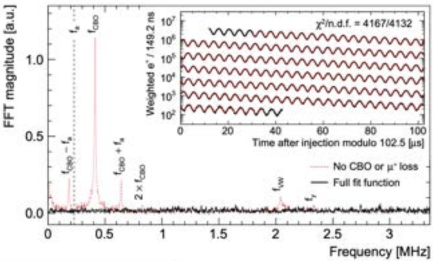


Different Analysis (e.g., Run-2/3)



Fitting procedure

- Fit → Residuals → Fast Fourier Transform (FFT)
- Analyses of FFT fit residuals shows that simple 5-parameter model is inadequate
- Flat FFT of residuals using a (typical) 22-parameter fit function that includes beam dynamics effects



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

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

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

$\omega_{CBO}, \omega_{2CBO}$ radial oscillations

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

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

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

ω_y, ω_{VW} vertical oscillations

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

Red = free parameters
Blue= fixed parameters

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

Lost muons

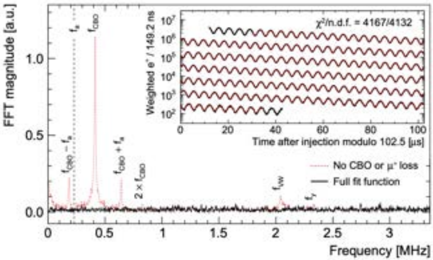
$$\omega_{CBO}(t) = \omega_0 t + A e^{-\frac{t}{\tau_A}} + B e^{-\frac{t}{\tau_B}}$$

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

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

Fitting procedure

- Fit → Residuals → Fast Fourier Transform (FFT)
- Analyses of FFT fit residuals shows that simple 5-parameter model is inadequate
- Flat FFT of residuals using a (typical) 22-parameter fit function that includes beam dynamics effects



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

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

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

$\omega_{CBO}, \omega_{2CBO}$ 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

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

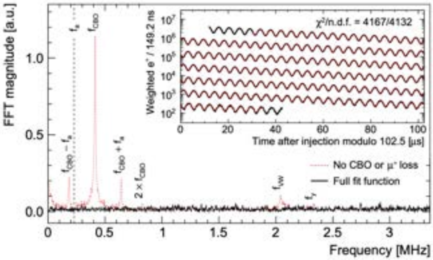
$$\omega_y(t) = F \omega_{CBO(t)} \sqrt{2\omega_c / F \omega_{CBO}(t) - 1}$$

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

The muon beam oscillates and breathes:

Fitting procedure

- Fit → Residuals → Fast Fourier Transform (FFT)
- Analyses of FFT fit residuals shows that simple 5-parameter model is inadequate
- Flat FFT of residuals using a (typical) 22-parameter fit function that includes beam dynamics effects



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

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

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

ω_{CBO}, ω_{2CBO} radial oscillations

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

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

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

ω_y, ω_{VW} vertical oscillations

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

Red = free parameters
Blue= fixed parameters

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

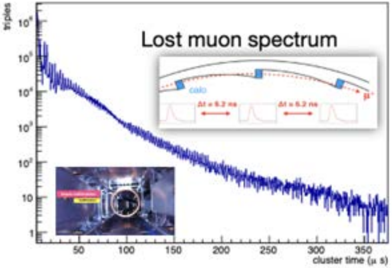
Lost muons

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

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

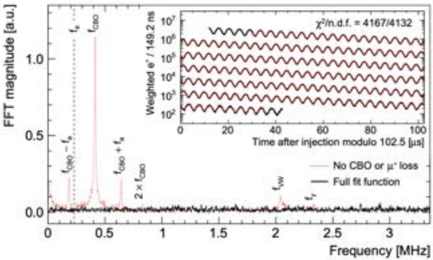
$$\omega_{VW}(t) = \omega_c - 2\omega_y(t)$$

Additional term to account for muons that hit the collimators and are lost:



Fitting procedure

- Fit → Residuals → Fast Fourier Transform (FFT)
- Analyses of FFT fit residuals shows that simple 5-parameter model is inadequate
- Flat FFT of residuals using a (typical) 22-parameter fit function that includes beam dynamics effects



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

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

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

ω_{CBO}, ω_{2CBO} radial oscillations

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

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

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

ω_y, ω_{VW} vertical oscillation

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

Red = free parameters
Blue= fixed parameters

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

Lost muons

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

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

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

+ beam dynamics corrections:

Electric Field, Pitch, Muon Loss, Phase Acceptance

$$\omega_a = \omega_a^{meas} \cdot (1 + C_e + C_p + C_{ml} + C_{pa})$$

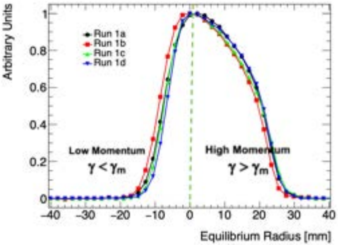
$+ C_{dd}$ (in Run-2/3)

Correction for Effects on Spin Precession

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

Non-simplified spin-motion is described by:

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

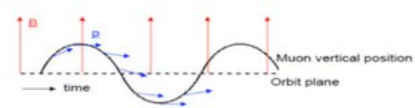


Electric Field

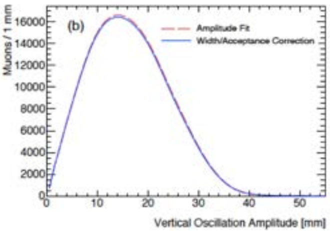
- due to momentum spread around p_{magic}
- measured using momentum distribution provided by the calorimeters in terms of equilibrium radius

Pitch

- due to vertical beam oscillation



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



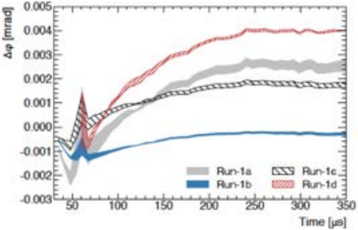
Corrections for Phase-Changing Effects

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

$$\cos(\omega_a t + \phi(t)) = \cos(\omega_a t + \phi_0 + \phi' t + \ldots)$$
$$= \cos((\omega_a + \phi')t + \phi_0 + \ldots)$$

Muon losses

- cause a phase shift because muon-phase and muon loss rate are momentum-dependent
- measured using data-driven technique

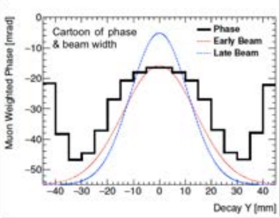


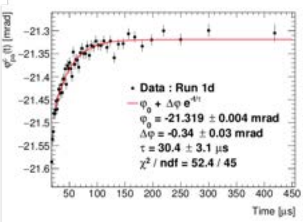
Differential Decay

- correction to account for high momentum muons having a longer lifetime

Phase acceptance

- phase changes due to early to late variations of the beam
- measured using tracker data and simulations





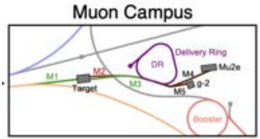
Simulation Tools

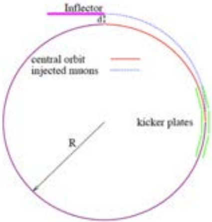
- Beam dynamics from simulations:
    - for beam dynamics corrections
    - to propagate the muon distribution around the ring
- Main simulation tools:
    - MARS
    - G4BEAMLINE
    - BMAD
    - COSY
    - GM2RINGSIM

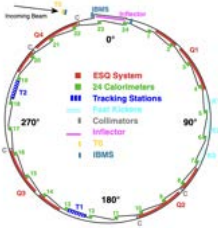
Muon Campus Simulation

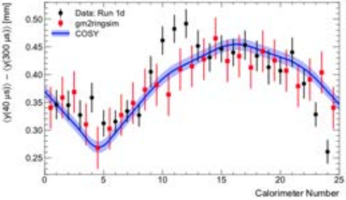
Storage Ring Simulation

- simulation tools are cross-checked against benchmarks and against each other.









Blinding/Unblinding

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

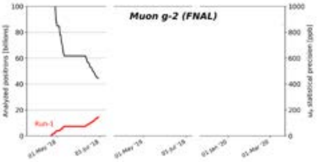
Clock frequency (f_{clock}):

- frequency that our DAQ clock ticks
- **stable** at ppt level
- hardware-blinded to have (40 - ε) MHz
  - –> ε kept **secret** from all collaborators
- **revealed** only when physics analysis is completed:
  - –> Run-1 result unblinded on Feb 25, 2021 during a virtual meeting
  - –> Run-2/3 result unblinded on Jul 24, 2023 during the collaboration meeting

First production run

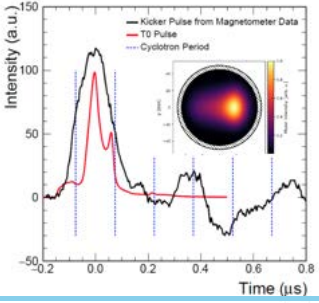
Statistics:

- March 26 – July 7 2018 : **Run1**
- **1.2** × **BNL** after data quality selection

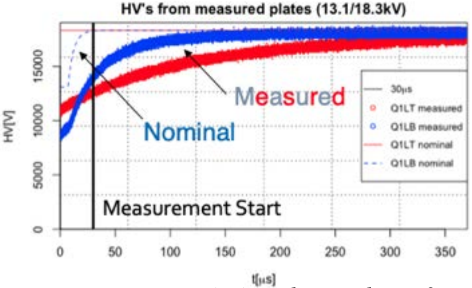


Main challenges:

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

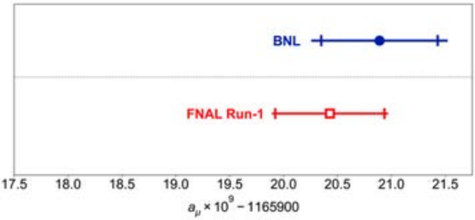


- 2 of 32 HV Quad resistors were damaged
  - ⟶ slow recovery time, enhanced C_{pa}



- Temperature variations larger than 1°C

Run-1 Result



- First **FNAL $g-2$** result :

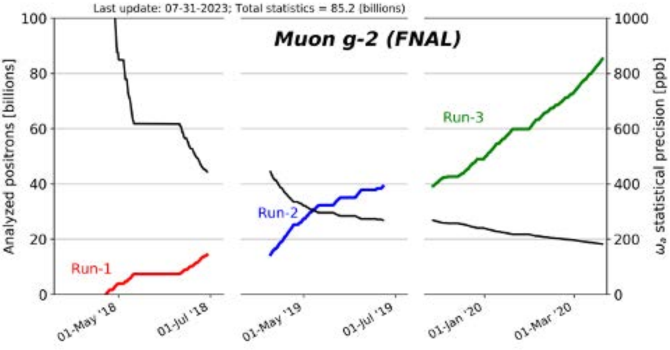
$$a_\mu = 116592040(54) \times 10^{-11} \; (462 \text{ ppb})$$

- Good agreement with BNL $g-2$

- Run-1 result uncertainty is **statistics dominated**
- Major systematic uncertainties: **Phase Acceptance and Quad field transients**
- **Next**: reduce as much as possible the experimental uncertainty on g-2 !

Quantity	Correction Terms (ppb)	Uncertainty (ppb)
ω_a (statistical)	–	434
ω_a (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

Run-2 and Run-3 Statistics Improvement



Dataset	Stat. Unc.
Run-1	434 ppb
Run-2/3	201 ppb
Run-1+Run-2/3	185 ppb

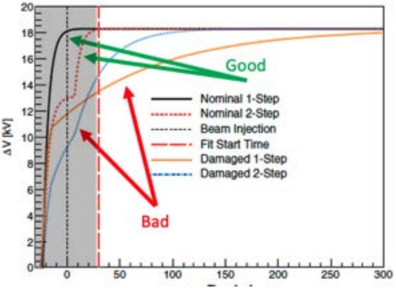
Statistics:

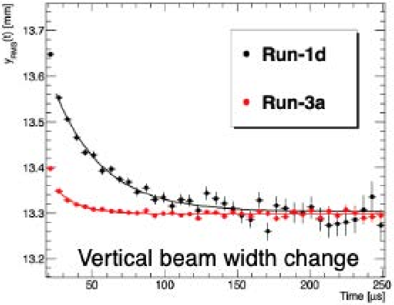
- ~ 4.7 more data in Run-2/3 than Run-1

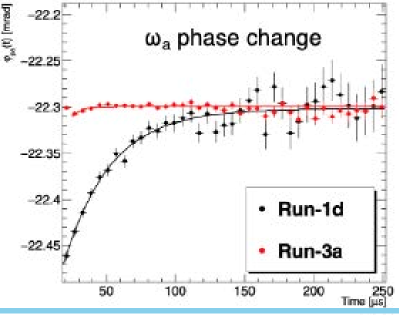
Run-2 and Run-3 Hardware Improvements

- **Before Run-2:**
  - –> Replaced faulty quads HV resistors Less beam motion and reduced C_{pa}

$$C_{pa} : -158 \pm 75\,\text{ppb} \rightarrow -27 \pm 13\,\text{ppb}$$

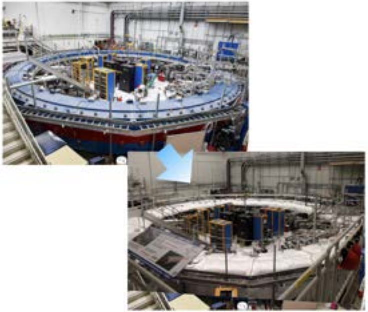






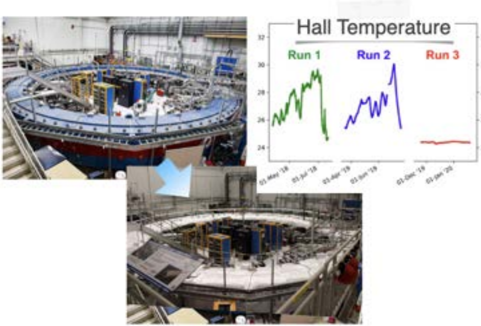
Run-2 and Run-3 Hardware Improvements

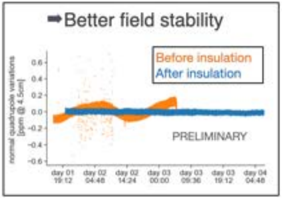
- **Before Run-2:**
  - –> Replaced faulty quads HV resistors
  - –> Magnet covered with a thermal blanket

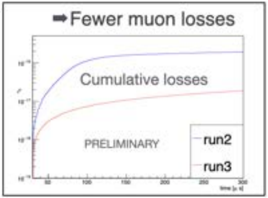


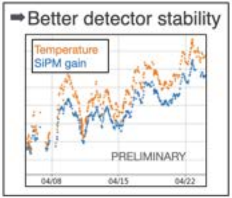
Run-2 and Run-3 Hardware Improvements

- **Before Run-2:**
  - –> Replaced faulty quads HV resistors
  - –> Magnet covered with a thermal blanket
- **Before Run-3:**
  - –> Hall temperature control improved



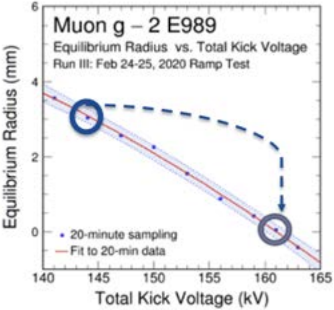


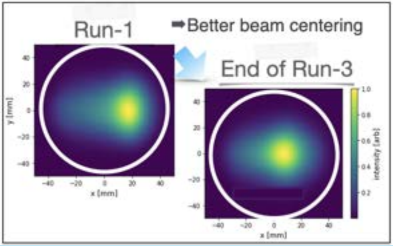


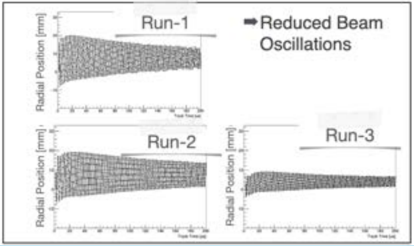


Run-2 and Run-3 Hardware Improvements

- **Before Run-2:**
  - –> Replaced faulty quads HV resistors
  - –> Magnet covered with a thermal blanket
- **Before Run-3:**
  - –> Hall temperature control improved
- **During Run-2 and Run-3:**
  - –> Replaced kicker cables ⇒ kickers at HV design value







Run-2 and Run-3 Measurement Improvements

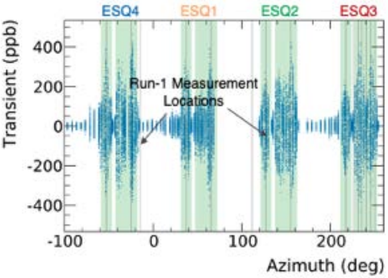
- Improved ω_a **analysis technique**:
  - added new positron reconstruction algorithms
  - improved pile-up subtraction technique

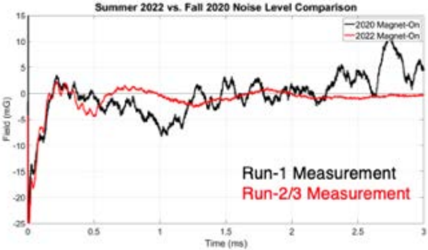
- Improved **quadrupole field transient** (B_q) uncertainty by measuring all azimuthal locations

$$\delta_{B_q} : 92 \text{ ppb} \rightarrow 20 \text{ ppb}$$

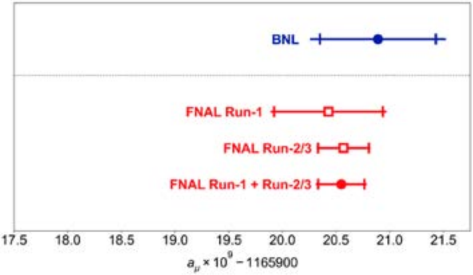
- Improved **kicker field transient** (B_k) uncertainty by performing new measurements and a cross-check with a new magnetometer

$$\delta_{B_k} : 37 \text{ ppb} \rightarrow 13 \text{ ppb}$$





Run-2/3 Result



- **New (2023) FNAL $g-2$** result :

$$a_\mu = 116592057(25) \times 10^{-11}\ (215\ \text{ppb})$$

- Good agreement with FNAL Run-1 BNL $g-2$

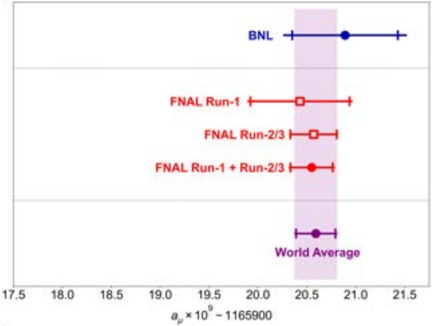
- Both Run-1 and Run-2/3 results uncertainties are **statistics dominated**
- **Run-2/3 systematic uncertainty** of 70 ppb is **lower than our TDR goal** of 100 ppb!
- Run-1+ Run-2/3 **combination uncertainty of 203 ppb** (assuming systematics 100% correlated)

Quantity	Correction [ppb]	Uncertainty [ppb]
ω_a^m (statistical)	–	201
ω_a^m (systematic)	–	25
C_e	451	32
C_p	170	10
C_{pa}	-27	13
C_{dd}	-15	17
C_{ml}	0	3
$f_{\text{calib}} \langle \omega'_p(\vec{r}) \times M(\vec{r}) \rangle$	–	46
B_k	-21	13
B_q	-21	20
$\mu'_p(34.7^\circ)/\mu_e$	–	11
m_μ/m_e	–	22
$g_e/2$	–	0
Total systematic	–	70
Total external parameters	–	25
Totals	622	215

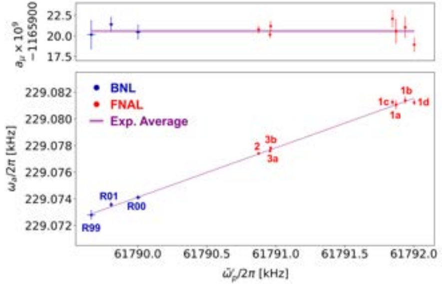
Experimental world average and field dependence

- Combined world average dominated by **FNAL value**:

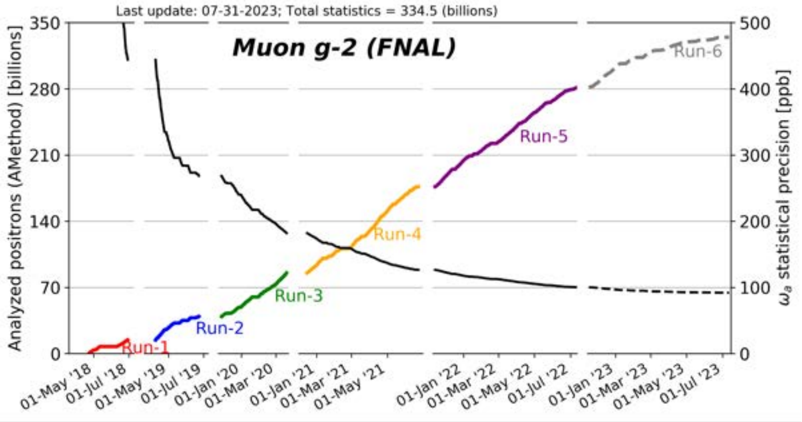
$\mathbf{a}_\mu(\mathbf{Exp}) = 116592059(22)\cdot 10^{-11}$ (190 ppb)



- Measurements were taken at different Magnetic Fields:



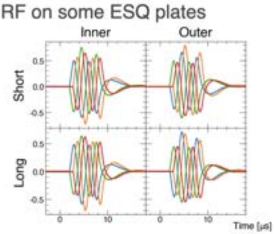
Run-4 Run-5 and Run-6

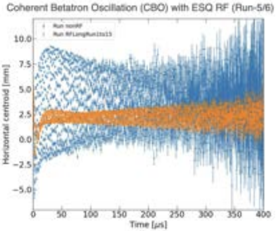


- In Run-4/5/6 not only statistical improvement:
  - **improved running conditions** (quad RF in Run-5/6 reduced horizontal beam oscillations)
  - **extensive systematic measurements & Studies** in Run-6 for better understanding and modeling of beam dynamics also with new detectors (scintillating fibers) for direct beam measurements

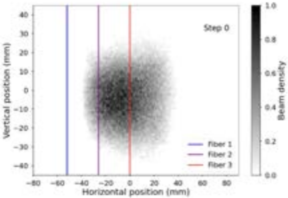
Run-4 and beyond Improvements

- New **Radio Frequency System** mounted on quadrupoles which reduces Beam Betatron oscillations (and lost muons)
  - damps beam oscillations in the first 10 μs
  - tested during Run-4 and in use during Run-5 (and Run-6)





- Improved knowledge of the **time-momentum correlation** with simulation and a new detector
  - scintillating fibers (miniSciFi) for direct beam measurements



Minimally **In**trusive **Sci**ntillating **Fi**ber

The final Muon g-2 result will be announced next week!

Analysis of Runs-4/5/6 completed! Result will be unveiled in a seminar next week on June 3, 2025 10 a.m. CT (FNAL Time)

https://muon-g-2.fnal.gov/index.html


Muon g-2

The Muon g-2 experiment at Fermilab released measurements of the magnetic moment of the muon in 2021 and 2023. The 2023 result was the world's most precise measurement yet of the anomalous magnetic moment of the muon. It improved the precision of the experiment's previous result by a factor of 2 and set up a showdown between theory and experiment over 20 years in the making.

The final result from the Muon g-2 experiment at Fermilab will be unveiled in a scientific seminar at 10 a.m. CT on June 3, 2025. The seminar will be streamed live on Fermilab's YouTube.

If your research institution is interested to request a post-release presentation of the new Muon g-2 result, please use this Google form to contact the speaker's committee.

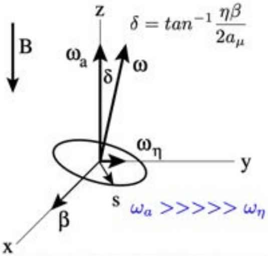
Link to the Muon g-2 experiment webpage

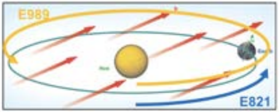
Not only Muon g-2 measurement

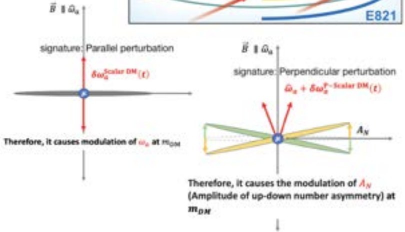
EDM previous searches statistical limited ($10^{-19}e$ cm), goal to reach $10^{-21}e$ cm
Search for an up-down oscillation, out of phase with ω_a.

CPT/LV using long period of data collected we can look if the spin precession rate changes over a sidereal day (as predicted by Standard-Model Extension).

DM Muon $g-2$ experiment enables the direct search for two ultralight dark matter candidates (scalar and pseudoscalar) that primarily interact with muons.

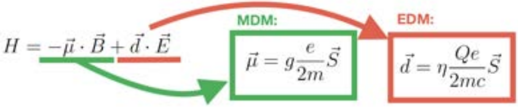






Muon EDM

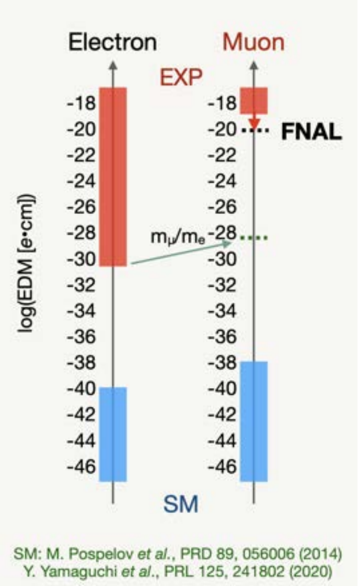
- Just as charged particles have a magnetic dipole moment (MDM), they could also have an **intrinsic electric dipole moment (EDM)**:



- **SM expectation is** 10^{-36} ***e*** **cm**, observation is sion of physics beyond SM and means presence of CP violation in the lepton sector
- Historically muon EDM has been measured alongside the g-2 value. **Current best limit** from Muon g-2 experiment at BNL:

$d_\mu < 1.8 \times 10^{-19}\ e\cdot\text{cm}$ (95% C. L.)
G. W. Bennett *et al.*, PRD 80, 052008 (2009)

- **FNAL Goal:** 10^{-21} *e* cm ~ two orders of magnitude improvement



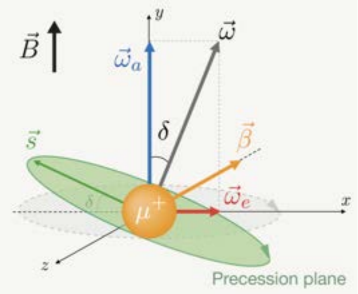
Measuring the Muon EDM at Fermilab

- An EDM tinily increases the precession frequency and tilts the spin precession plane

0 for $\gamma = 29.3$ (p = 3.09 GeV/c)　　$d_\mu = \eta \frac{e\hbar}{4mc} \neq 0$

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

$\vec{\omega}_a$: horizontal precession　　$\vec{\omega}_e$: vertical precession

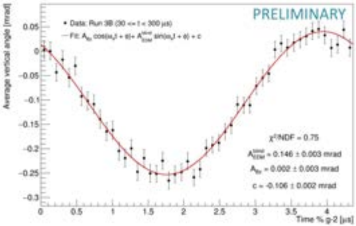


- Search for an EDM by looking at the average vertical angle:
  - directly using the trackers
  - analysis blinded injecting a fake signal of unknown amplitude
  - Plot modulo the g-2 period, fix phase and frequency and fit simultaneously:

oscillation in phase with g− 2　　EDM oscillation amplitude　　constant

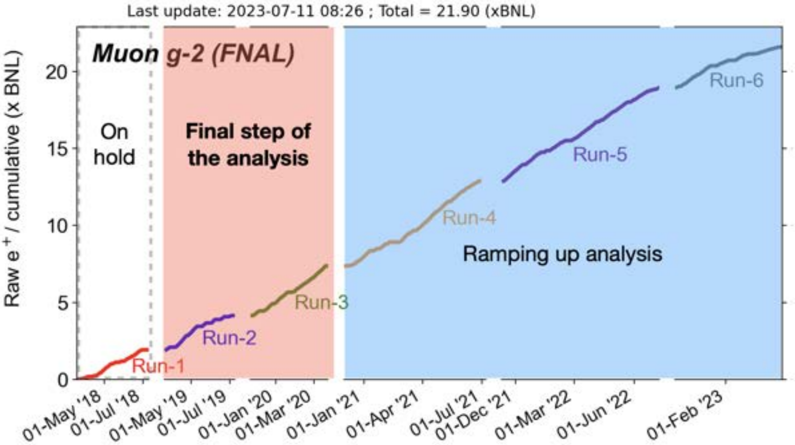
$$\langle\theta_y\rangle(t) = \frac{A_{g-2}\cos(\omega_a t + \phi_a) + A_{\mathrm{EDM}}\sin(\omega_a t + \phi_a)}{\left(1 + A_N\cos(\omega_a t + \phi_a^p)\right)\left(1 + A_{\mathrm{CBO}}\cos(\omega_{\mathrm{CBO}} t + \phi_{\mathrm{CBO}})\right)} + C$$

number of positrons



  - Add corrections for radial field and tracker acceptance (momentum dependent)

FNAL Muon EDM Analysis Plan



- **Run-1:** analysis is completed but still blinded;
- **Run-2/3:** nearly completing (collaboration review started), results is expected for this year!
- **Run-4/5/6:** analysis just started

Summary and Conclusions

- FNAL $g-2$ Experiment goal is to measure a_μ with a **precision of 140 ppb** (4×BNL precision) and its **final result will be presented next week**!
- The result from the analysis of the Run-1 andRun-2/3 data **confirmed** the result from BNL experiment and reach 200 ppb precision.
- The **FNAL muon EDM** search aims to improve the current limit (from BNL exp.) by two orders of magnitude (first result expected this year)
- Other analysis: **CPT/LV and Dark Matter searches** are been developed.

Thanks!

The final result from the FNAL Muon g-2 experiment will be unveiled in a seminar on June 3, 2025 10 a.m. CT (streamed live on Fermilab's YouTube)