FERMILAB-SLIDES-24-0120-PPD

Muon *g*–2: experimental status

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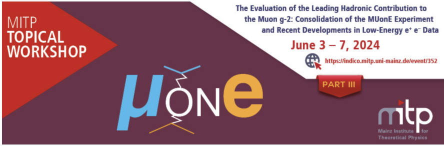
on behalf of the Muon *g*–2 Collaboration

Università di Pisa

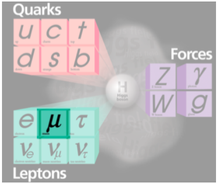
INFN

Fermilab



Introduction: the muon anomaly

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

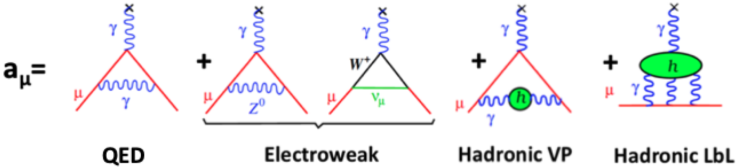


$$\vec{\mu} = \mathbf{g}\frac{q}{2m_\mu}\vec{S}$$

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

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

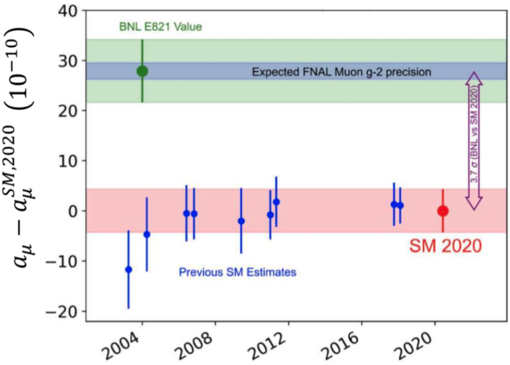
–> Theoretically calculated using the Standard Model (SM) :



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

Experimental measurement vs. SM calculation (before 2021)

- Long-standing $> 3\sigma$ discrepancy



- **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:

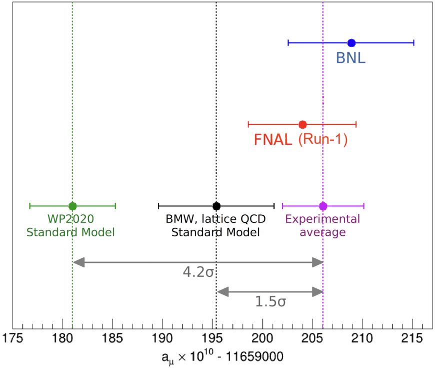
$$a_\mu^{SM,2020} = 116591810(43) \times 10^{-11}$$

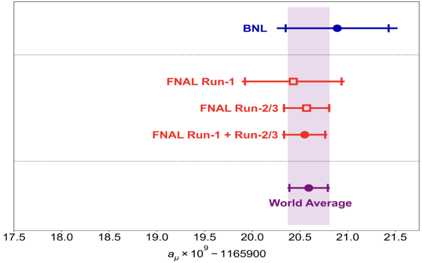
[Phys. Rept. **887**, 1 (2020)]

- 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 measurement vs. SM calculation (after 2021)





– In April 2021 were published:

- the first measurement from **FNAL Muon g – 2 Exp. Run-1 data** that confirmed result from BNL:

$$\mathbf{a}_\mu(\mathbf{FNAL}) = 116592040(54) \cdot 10^{-11} \ (460\,\text{ppb})$$
$$\mathbf{a}_\mu(\mathbf{BNL}) = 116592089(63) \cdot 10^{-11} \ (540\,\text{ppb})$$
$$\mathbf{a}_\mu(\mathbf{Exp}) = 116592061(41) \cdot 10^{-11} \ (350\,\text{ppb})$$

[Phys. Rev. Lett. **126**, no.14, 141801 (2021)]

- a new theoretical calculation $\mathbf{a}_\mu(\mathbf{BMW, HVP-LO})$ based on Lattice QCD in tension with $\mathbf{a}_\mu(\mathbf{WP, HVP-LO})$ calculation based on e^+e^- data

[Nature **593** (2021) 51-55]

– In August 2023 was presented:

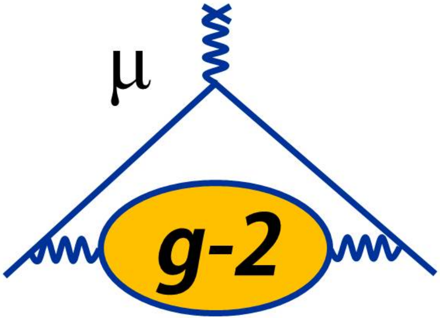
- the second measurement from **FNAL Muon g – 2 Exp. Run-2/3 data**

$$\mathbf{a}_\mu(\mathbf{FNAL}) = 116592055(24) \cdot 10^{-11} \ (203\,\text{ppb})$$

[Phys. Rev. Lett. **131**, 161802 (2023)]

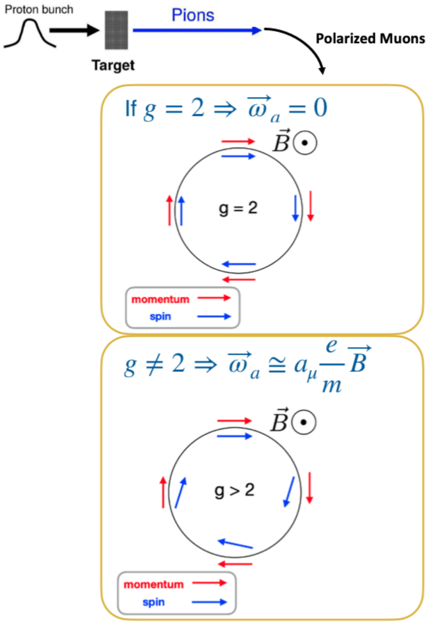
Outline of the talk

- Experimental Technique
- Run-1 measurement
- Run-2/3 measurement
- Experimental world average
- Improvements in Run-4/5/6 measurement



Experimental technique

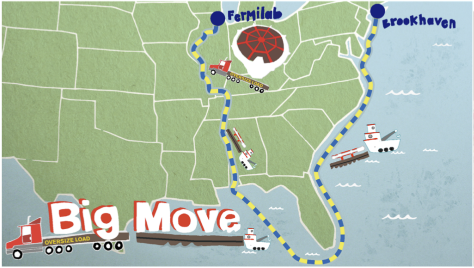
1. Inject polarized muons into a magnetic storage ring
2. Muons circulate around the ring at the cyclotron frequency:
$$\vec{\omega}_C = \frac{q}{\gamma m_\mu}\vec{B}$$
3. Muon spin precession frequency (Larmor) is given by:
$$\vec{\omega}_S = \frac{q}{\gamma m_\mu}\vec{B}(1+\gamma a_\mu)$$
4. Muon anomaly 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

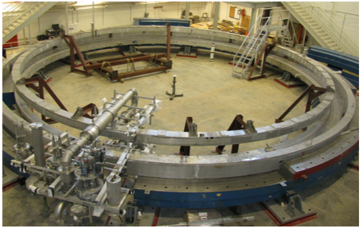
- **Recycler Ring:** 8 GeV protons from Booster are divided in 4 bunches
- **Target Station:** p-bunches are collided with target and π^+ with 3.1 GeV/c ($\pm$10%) are collected
- **Beam Transport and Delivery Ring:** magnetic lenses select μ^+ from $\pi^+ \rightarrow \mu^+ \nu_\mu$ then μ^+ are separated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

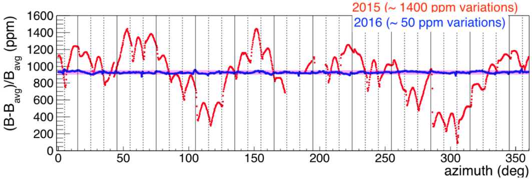
The storage ring journey: from BNL to FNAL in Summer 2013

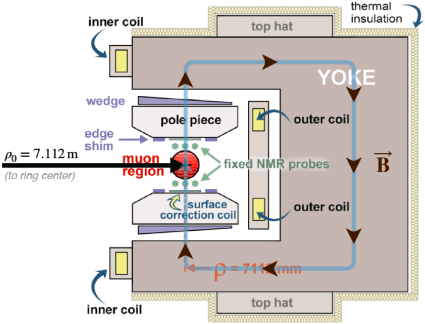


Storage ring magnet

- 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**



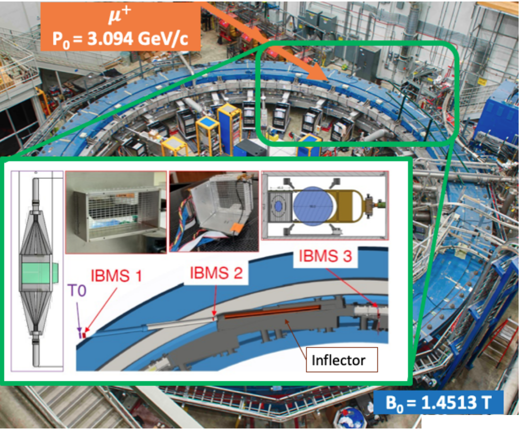




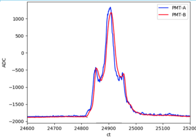
final field ~ 3 times more uniform than at BNL

Injection of the muons into the ring

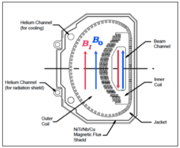
- Beam enters the ring through a 2.2 m-long 10 cm hole in the iron yoke

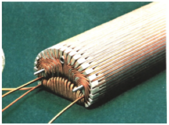


- **T0 Counter** (thin scintillator read out by PMTs) to measure **beam time profile**

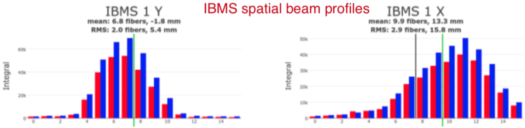


- **Inflector magnet** provides nearly field free region for muons to enter the storage region



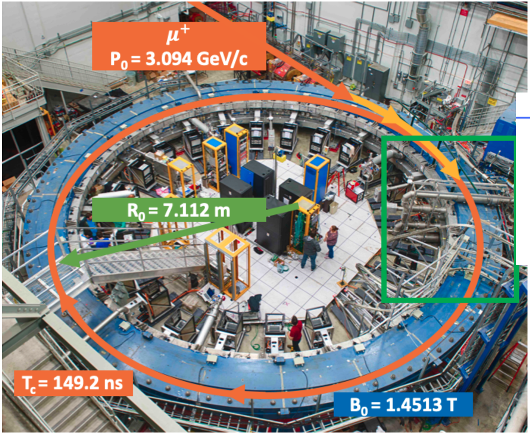


- **Inflector Beam Monitoring System** (scintillator fiber grids) to measure **beam spatial profile**



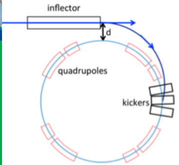
Muon storage

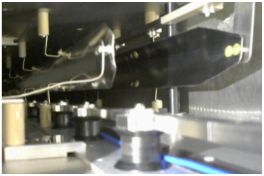
- Injected beam is 77 mm off from storage region center

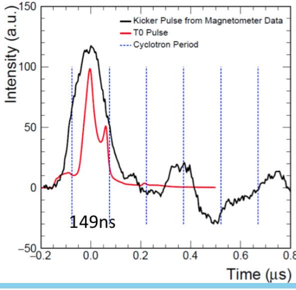


Kicker Magnets

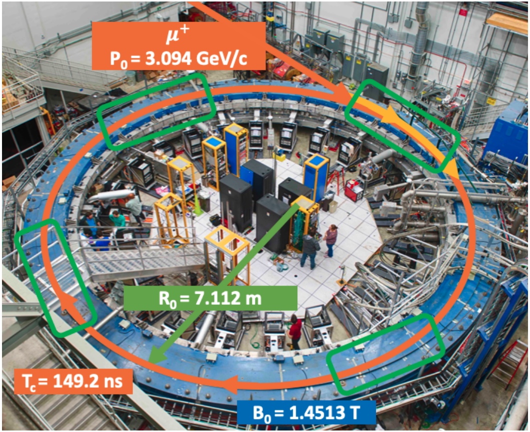
- 3 pulsed magnets deflect beam ~10 mrad onto the closed storage orbit in less than 150 ns





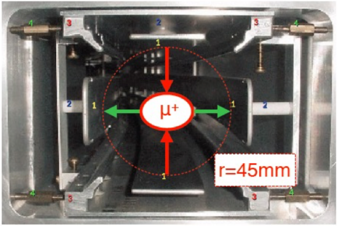


Vertical focusing



Electrostatic Quadrupoles

- 4 sets of quads provide vertical beam focusing

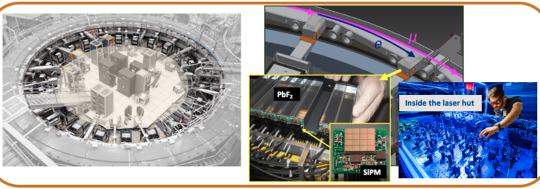


- E–field component cancels out (at first order) when muons at *magic momentum* :

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

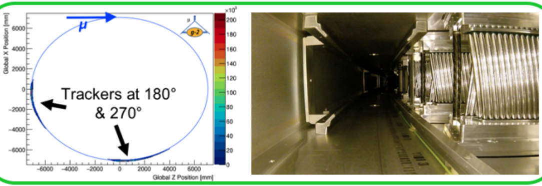
~0 if γ=29.3 *i.e.*, p_μ=3.094 GeV/c

Detectors and field probes



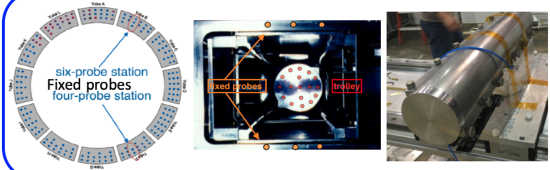
24 Calos around the ring

- 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

Final formula

Muon anomaly is determined with:

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

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)]

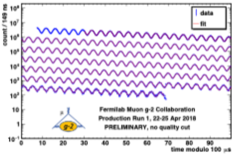
m_μ/m_e from [2018 CODATA (Web Version 8.1)]

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

ω_a: muon anomalous precession frequency

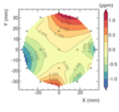
Extract from decay positron time spectra

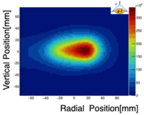
$N(t) = N_0 e^{-t/\tau_\mu}[1 + A\cos(\omega_a t + \phi)]$



$\widetilde{\omega}'_p(T_r)$: 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

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

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

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

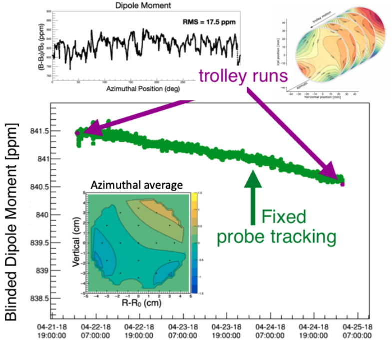
C_e : electric field correction
C_p : pitch correction
C_{ml} : muon loss correction
C_{pa} : phase-acceptance correction
C_{dd} : differential-decay correction

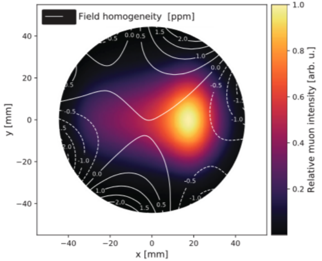
B_k : transient field from eddy current in kicker
B_q : transient field from quad vibration

Measuring the magnetic field seen by the muons

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

- 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)



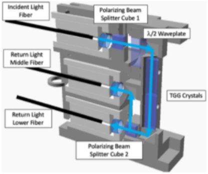


Magnetic field corrections

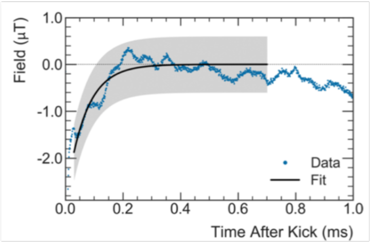
$$R_\mu = \left(\frac{f_{clock} \cdot \omega_a^{meas} \cdot (1 + C_e + C_p + C_{ml} + C_{pa} + C_{dd})}{f_{calib} \cdot \omega'_p(x,y,\phi) \otimes M(x,y,\phi) \cdot (1 + B_k + B_q)} \right)$$

Kicker transient field

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

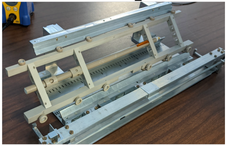


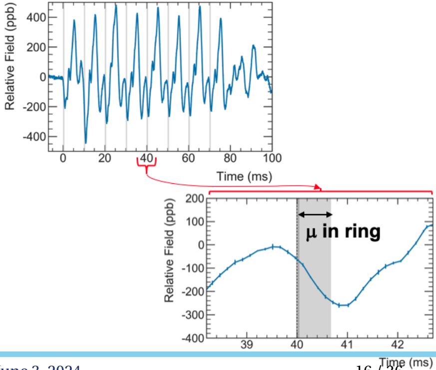
(a)



Quads transient field

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





Measuring ω_a

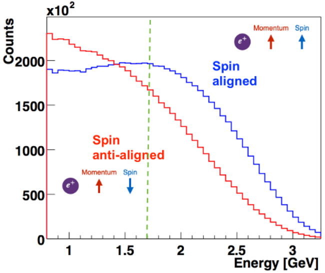
$$R_\mu = \left(\frac{f_{clock} \cdot \omega_a^{meas} \cdot (1 + C_e + C_p + C_{ml} + C_{pa} + C_{dd})}{f_{calib} \cdot \omega'_p(x,y,\phi) \otimes M(x,y,\phi) \cdot (1 + B_k + B_q)} \right)$$

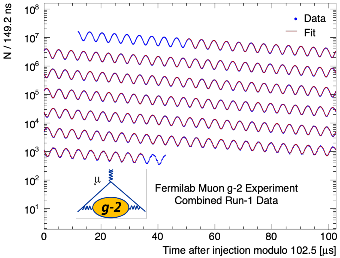
- Polarized muon decay:

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

- 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 $\underline{\omega_a}$:

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



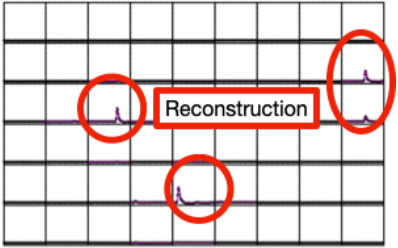


E_{e^+} and t are measured by the calorimeters with a blinding factor applied to the digitization rate

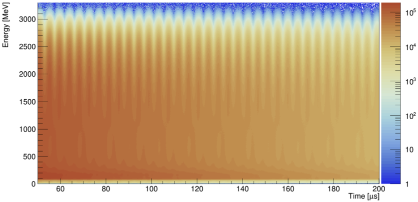
Wiggle plot

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

raw calorimeters traces



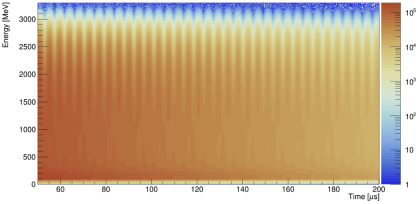
Energy-Time Wiggle Plot



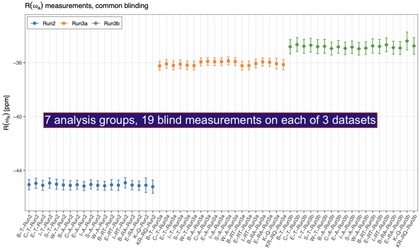
Wiggle plot

- 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

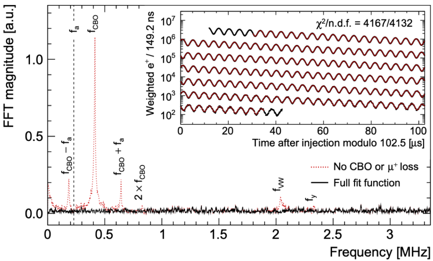


Different Analysis (e.g., Run-2/3)



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



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

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

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

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

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

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

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

Fitting procedure

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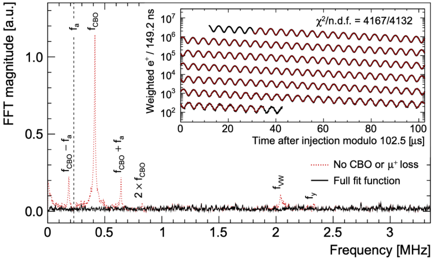
- Analyses of FFT fit residuals shows that simple 5-parameter model is inadequate
- Flat FFT of residuals using a (typical) 22-parameter fit function that includes beam dynamics effects



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

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

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

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ω_{CBO}, ω_{2CBO} radial oscillations

ω_y, ω_{VW} vertical oscillations

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

$$\omega_{\rm CBO}(t) = \omega_0 t + Ae^{-\frac{t}{\tau_A}} + Be^{-\frac{t}{\tau_B}}$$

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

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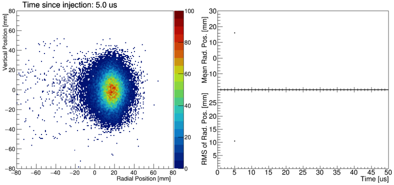
Red = free parameters
Blue= fixed parameters

The muon beam oscillates and breathes:



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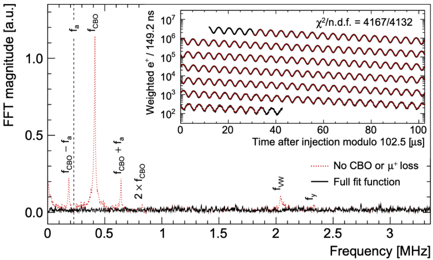

$$N_0 e^{-\frac{t}{\gamma\tau}} \left(1 + A \cdot A_{BO}(t) \cos(\omega_a t + \phi \cdot \phi_{BO}(t))\right) \cdot N_{\mathrm{CBO}}(t) \cdot N_{\mathrm{VW}}(t) \cdot N_y(t) \cdot N_{\mathrm{2CBO}}(t) \cdot J(t)$$

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

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

ω_{CBO}, ω_{2CBO} radial oscillations

ω_y, ω_{VW} vertical oscillations

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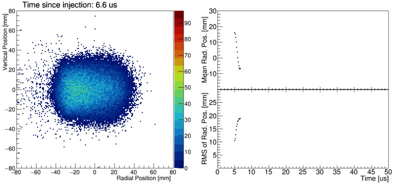

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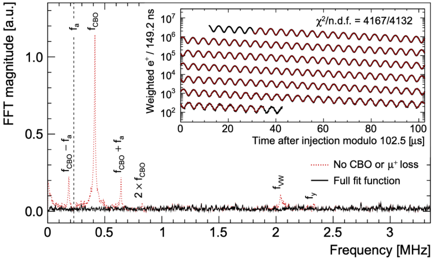

$$N_0 e^{-\frac{t}{\gamma\tau}} \left(1 + A \cdot A_{BO}(t)\cos(\omega_a t + \phi \cdot \phi_{BO}(t))\right) \cdot N_{CBO}(t) \cdot N_{VW}(t) \cdot N_y(t) \cdot N_{2CBO}(t) \cdot J(t)$$

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ω_{CBO}, ω_{2CBO} radial oscillations

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

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ω_y, ω_{VW} vertical oscillations

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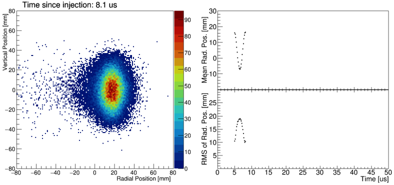

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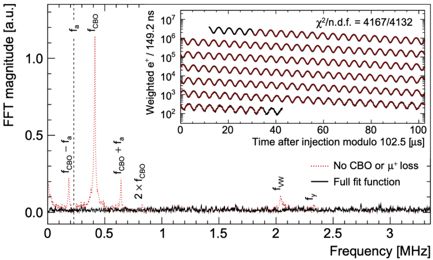

$$N_0\, e^{-\frac{t}{\gamma\tau}}\,(1 + A \cdot A_{BO}(t)\cos(\omega_a t + \phi \cdot \phi_{BO}(t))) \cdot N_{\rm CBO}(t) \cdot N_{\rm VW}(t) \cdot N_y(t) \cdot N_{\rm 2CBO}(t) \cdot J(t)$$

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ω_{CBO}, ω_{2CBO} radial oscillations

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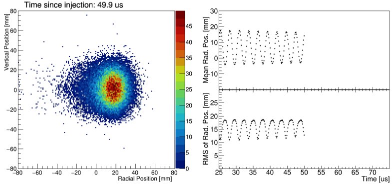

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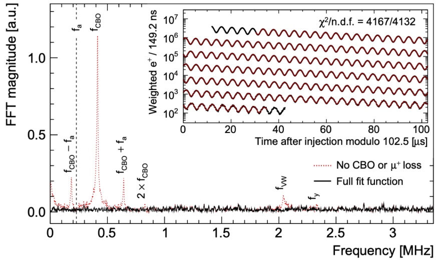

$$N_0\, e^{-\frac{t}{\gamma\tau}} \left(1 + A \cdot A_{BO}(t) \cos(\omega_a t + \phi \cdot \phi_{BO}(t))\right) \cdot N_{\mathrm{CBO}}(t) \cdot N_{\mathrm{VW}}(t) \cdot N_y(t) \cdot N_{2\mathrm{CBO}}(t) \cdot J(t)$$

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ω_y, ω_{VW} vertical oscillations

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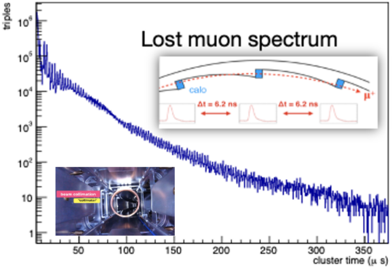
Additional term to account for muons that hit the collimators and are lost:



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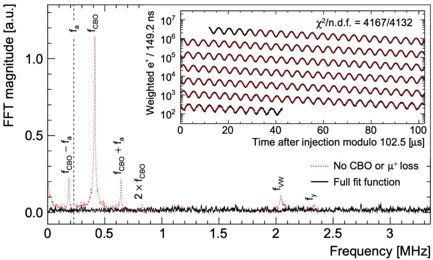

$$\boxed{N_0\, e^{-\frac{t}{\gamma\tau}} \left(1 + A \cdot A_{BO}(t) \cos(\omega_a t + \phi \cdot \phi_{BO}(t))\right) \cdot N_{\mathrm{CBO}}(t) \cdot N_{\mathrm{VW}}(t) \cdot N_y(t) \cdot N_{\mathrm{2CBO}}(t) \cdot J(t)}$$

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+ 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)
differential decay

Correction for Effects on Spin Precession

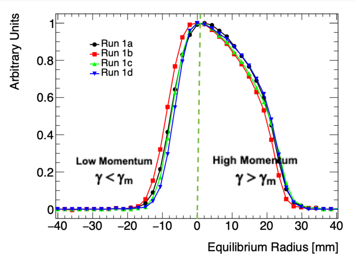
$$R_\mu = \left(\frac{f_{clock} \cdot \omega_a^{meas} \cdot (1 + C_e + C_p + C_{ml} + C_{pa} + C_{dd})}{f_{calib} \cdot \omega'_p(x,y,\phi) \otimes M(x,y,\phi) \cdot (1 + B_k + B_q)} \right)$$

Non-simplified spin-motion is described by:

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

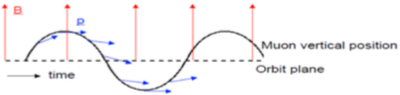
Electric Field

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

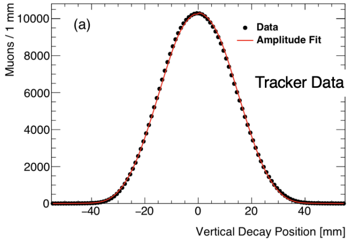


Pitch

- due to vertical beam oscillation



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

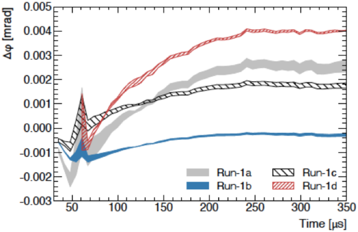


Corrections for Phase-Changing Effects

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

Muon losses

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



Differential Decay

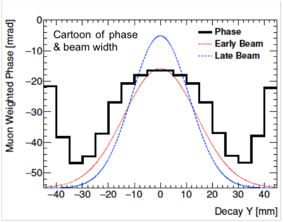
- correction to account for high momentum muons having a longer lifetime

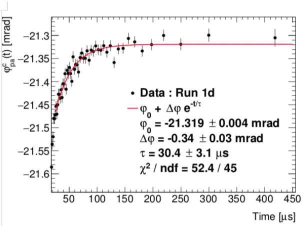
Phase acceptance

- phase changes due to early to late variations of the beam

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

- measured using tracker data and simulations





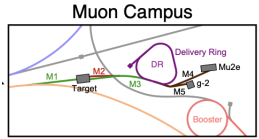
Simulation Tools

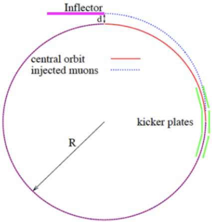
- Beam dynamics from simulations:
  - for beam dynamics corrections
  - to propagate the muon distribution around the ring

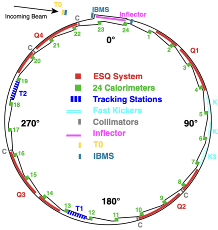
- Main simulation tools:
  - MARS
  - G4BEAMLINE
  - BMAD
  - COSY
  - GM2RINGSIM

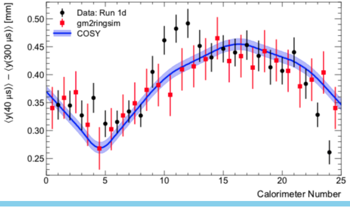
Muon Campus Simulation

Storage Ring Simulation









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

Blinding/Unblinding

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

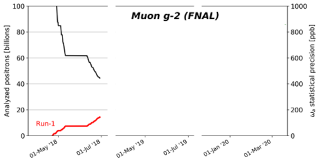
Clock frequency (f_{clock}):

- 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

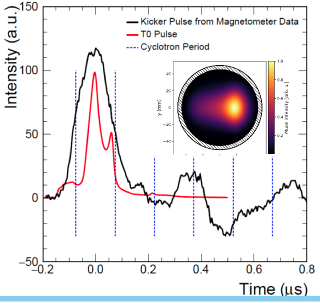
Statistics:

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

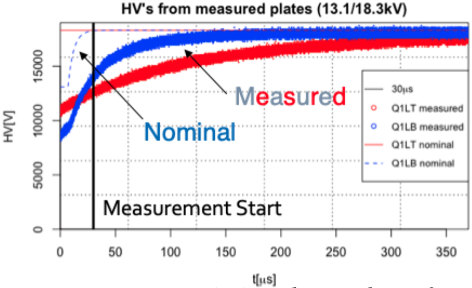


Main challenges:

- Non-ideal kick
  - $\longrightarrow$ low amplitude and ringing
  - $\longrightarrow$ beam not centered in storage region

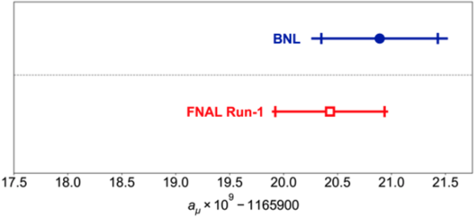


- 2 of 32 HV Quad resistors were damaged
  - $\longrightarrow$ slow recovery time, enhanced C_{pa}



- Temperature variations larger than 1°C

Run-1 Result



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

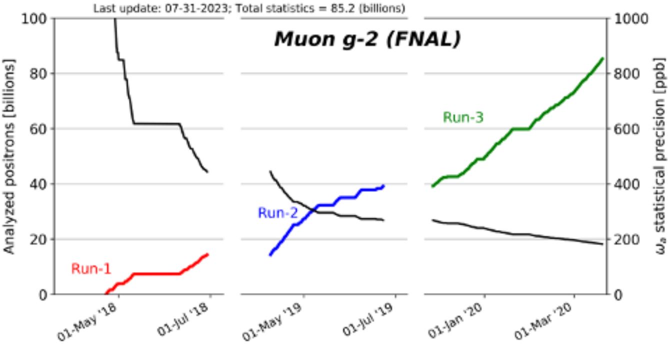
$$a_\mu = 116592040(54) \times 10^{-11} \ (462 \text{ ppb})$$

- 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
$f_{\rm calib}\langle\omega'_p(x,y,\phi)\times M(x,y,\phi)\rangle$	–	56
B_k	-27	37
B_q	-17	92
$\mu'_p(34.7°)/\mu_e$	–	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

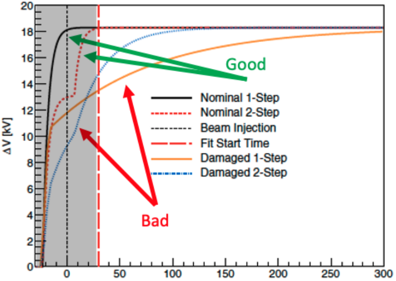
Statistics:

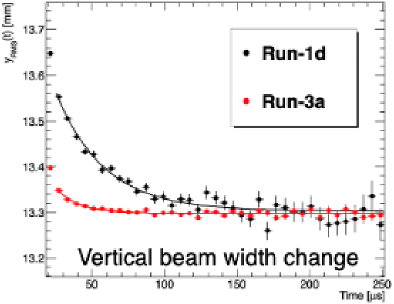
- ~ 4.7 more data in Run-2/3 than Run-1

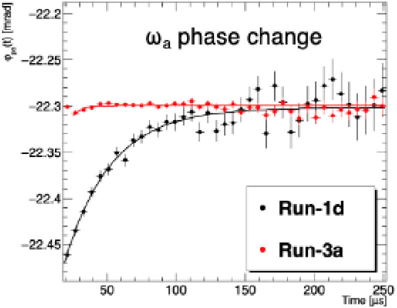
Run-2 and Run-3 Hardware Improvements

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

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

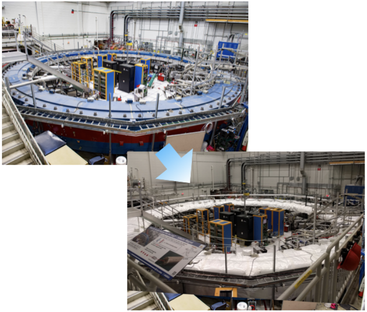






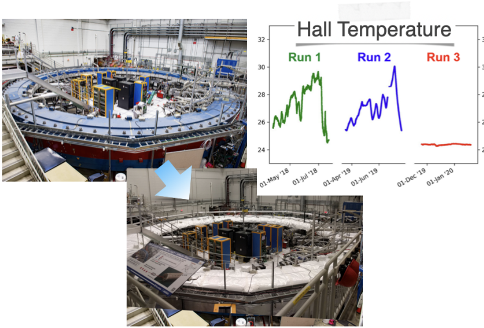
Run-2 and Run-3 Hardware Improvements

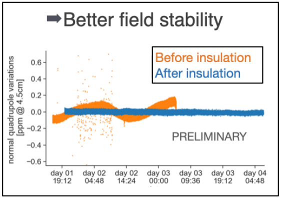
- **Before Run-2:**
  - –> Replaced bad quads HV resistors
  - –> Magnet covered with a thermal blanket

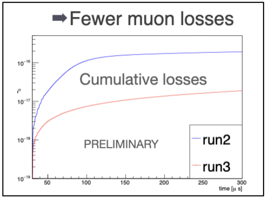


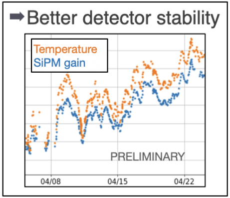
Run-2 and Run-3 Hardware Improvements

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



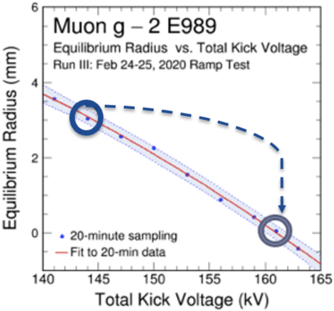


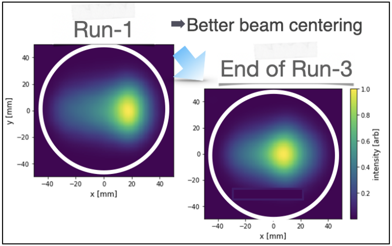


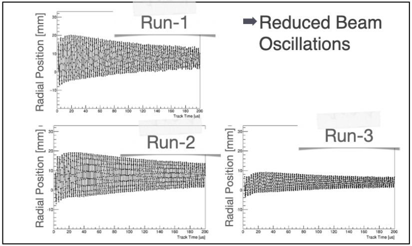


Run-2 and Run-3 Hardware Improvements

- **Before Run-2:**
  - –> Replaced bad 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







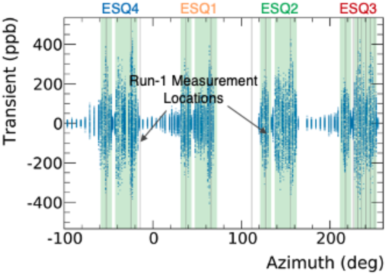
Run-2 and Run-3 Measurement Improvements

- 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

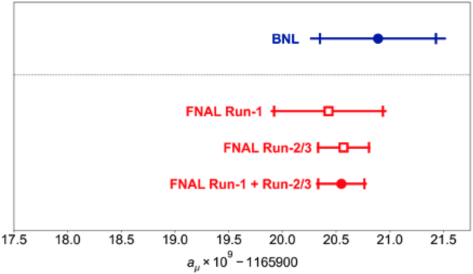
$$\delta_{B_q} : 92\,\text{ppb} \rightarrow 20\,\text{ppb}$$

- 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 $g-2$

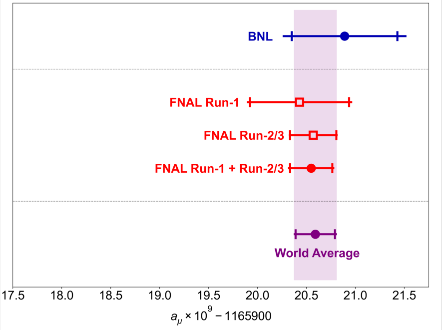
Quantity	Correction [ppb]	Uncertainty [ppb]
ω_a^m (statistical)	–	201
ω_a^m (systematic)	–	25
C_e	451	32
C_p	170	10
C_{pa}	-27	13
C_{dd}	-15	17
C_{ml}	0	3
$f_{\text{calib}} \langle \omega'_p(\vec{r}) \times M(\vec{r}) \rangle$	–	46
B_k	-21	13
B_q	-21	20
$\mu'_p(34.7^\circ)/\mu_e$	–	11
m_μ/m_e	–	22
$g_e/2$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

- 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)

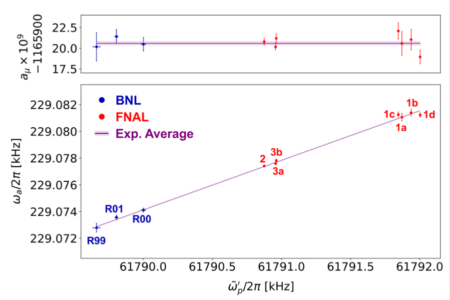
Experimental world average and field dependence

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

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

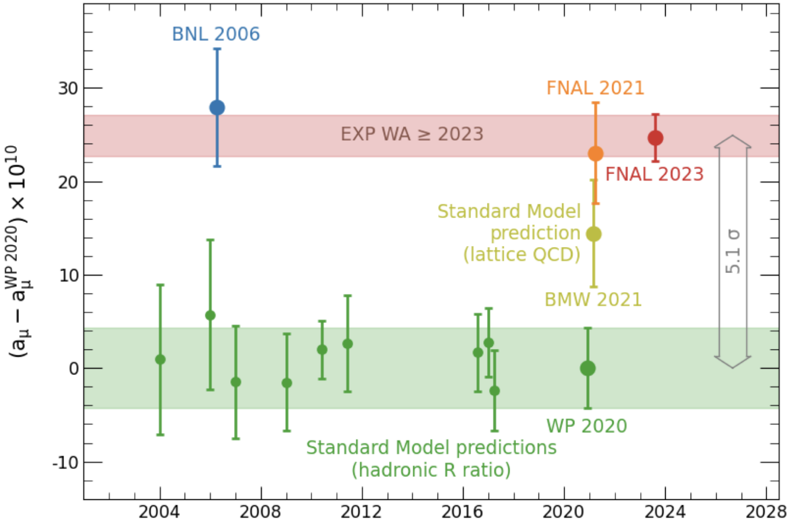


- Measurements were taken at different Magnetic Fields:



- Also checked a_μ against temperature, day/night & others

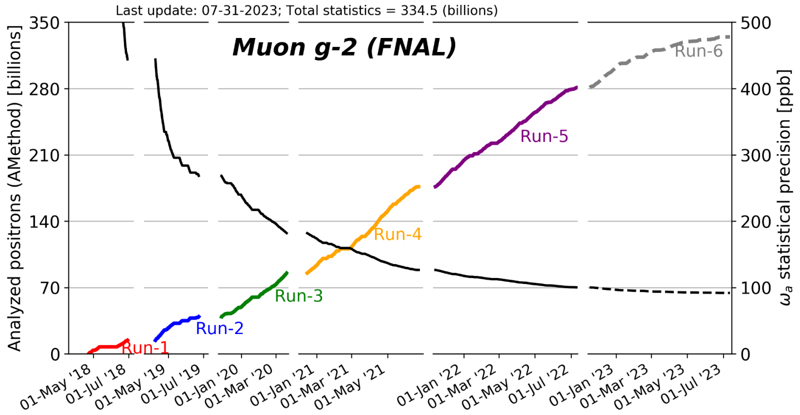
Experimental measurement vs. SM calculation



How precisely can we predict the muon g-2 in the standard model?

see previous talk by Marc Knecht about the SM prediction.

What's next?

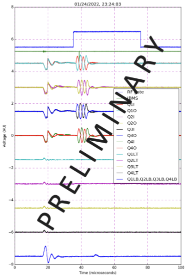


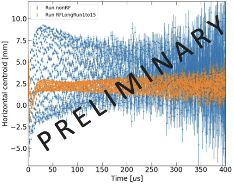
- Completed all runs (collected > 21×BNL): there is **more data still to analyze**!
- Not only statistical improvement (see next slide):
  - **improved running conditions**
  - **extensive systematic measurements & Studies**
- After beam running ended in July 2023, we focused on magnetic field systematic studies

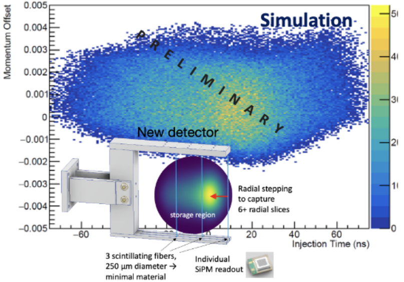
Run-4 and beyond Improvements

- 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)

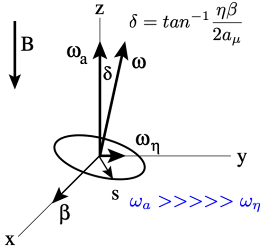
- Improved knowledge of the **time-momentum correlation** with simulation and a new detector
  - scintillating fibers (miniSciFi) for direct beam measurements





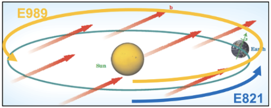


Not only Muon g-2 measurement

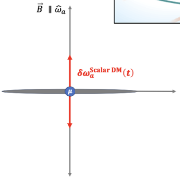


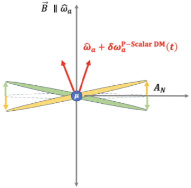
EDM previous searches statistical limited ($10^{-19}e$ cm), goal to reach $10^{-21}e$ cm. Search for an up-down oscillation, out of phase with ω_a.

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 (scalar and pseudoscalar) ultralight dark matter candidates that primarily interact with muons.





Summary and Conclusions

- FNAL $g-2$ Experiment goal is to measure a_μ with a **precision of 140 ppb** (4×BNL precision)
- The result from the analysis of the Run-1/2/3 data **confirmed** result from BNL experiment
- With **Run-2 and Run-3 data** measurement achieved a factor 2 uncertainty reduction both in statistics and systematics!
- Next: analysis of **Run-4, Run-5 and Run-6** (expect to achieve the uncertainty goal), also other analysis EDM, CPT/LV and Dark Matter searches are been developed.

Thanks!

Enjoy the
PRL **131**, 161802 (2023)
and the new paper:
arXiv:2402.15410
and stay tuned for the
next result!