FERMILAB-SLIDES-23-317-V


# Overview of the Muon *g*–2 Experiment Results

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Università di Pisa
INFN
Fermilab

DMNet

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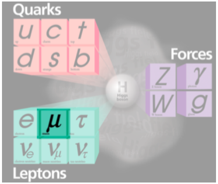
INFN Istituto Nazionale di Fisica Nucleare
INFN Padova
Dipartimento di Fisica e Astronomia Galileo Galilei

# Introduction: the muon anomaly

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

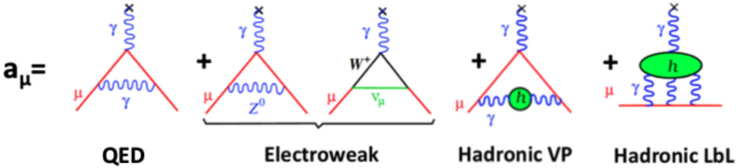
$$\vec{\mu} = \mathbf{g}\frac{q}{2m_\mu}\vec{S}$$




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

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

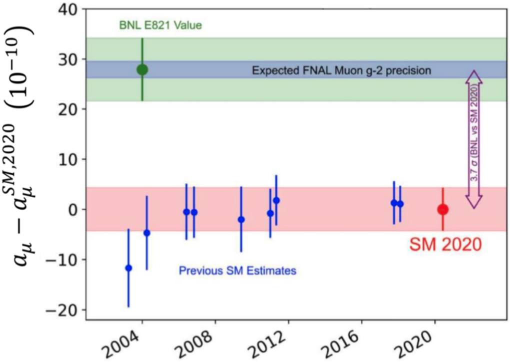
–> Theoretically calculated using the Standard Model (SM) :




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

# Experimental measurement vs. SM calculation in 2020

- 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:

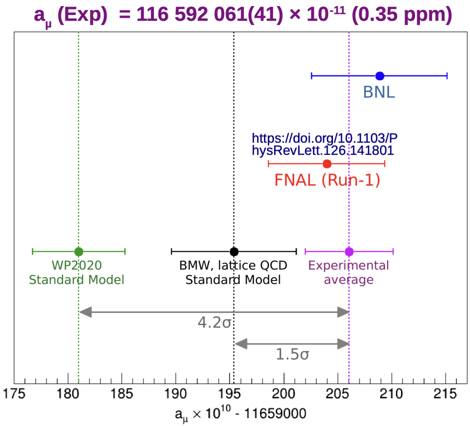
$$a_\mu^{SM,2020} = 116591810(43) \times 10^{-11}$$

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

- In the meantime: **FNAL Exp**. was built and is collecting data since 2018 aiming to improve uncertainty with 140 ppb goal

# Experimental measurement vs. SM calculation (2021)

- In April 2021 were published:




- a new measurement from **FNAL Muon g − 2 Exp. Run-1 data** that confirmed result from BNL:

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

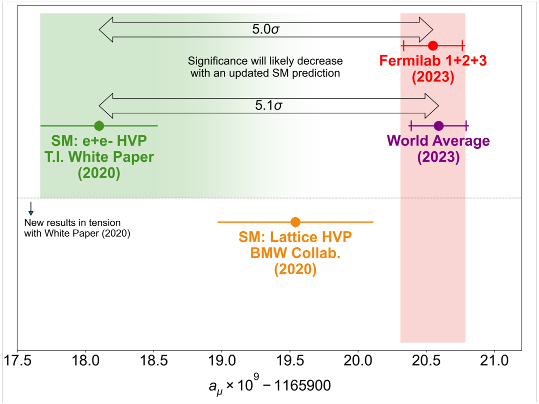
[Phys. Rev. Lett. **126**, no.14, 141801 (2021)]

- 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 this talk:
  review of the FNAL Run-1 measurement and...

# New Experimental Measurement vs. SM calculation

- Adding the **new FNAL Muon g-2 result from Run-2/3 data**:




- **Dark Matter (DM)** may be responsible for the potential discrepancy between experimental measurement and SM prediction
- In this tak: overview of the **first-ever direct DM search with muons in a storage ring** using the data collected by the Muon *g*–2 experiment

# Experimental technique

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

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

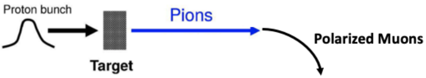
3. Muon spin precession frequency (Larmor) is given by:

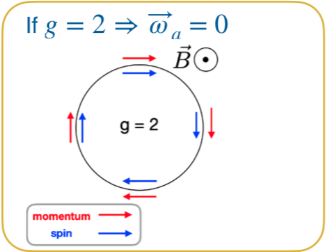
$$\vec{\omega}_S = \frac{q}{\gamma m_\mu}\vec{B}(1 + \gamma a_\mu)$$

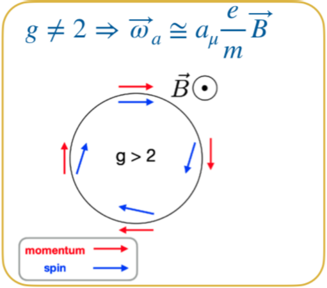
4. Muon anomaly is related to **anomalous precession frequency**:

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

5. Measure $B$ and $\omega_a$ to extract the anomaly



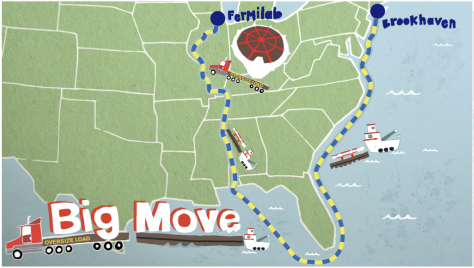



# Production of the muon beam

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

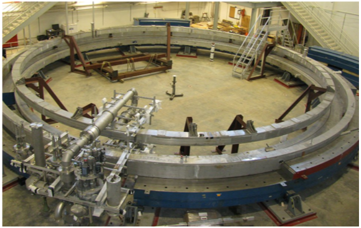

# The storage ring journey: from BNL to FNAL in Summer 2013

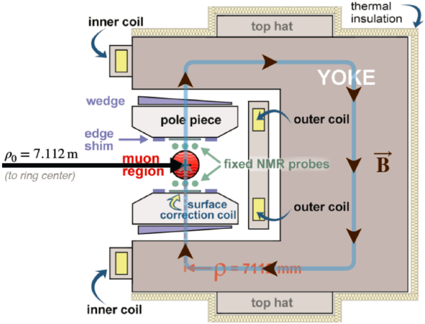


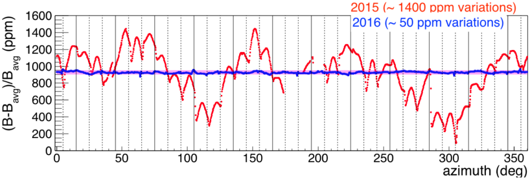


# Storage ring magnet

- 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**



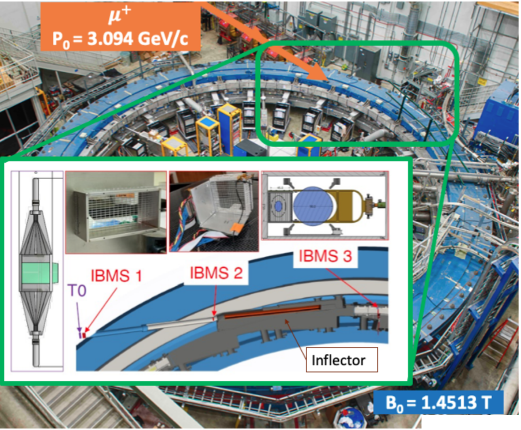


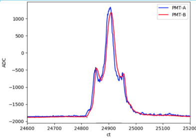

final field ~ 3 times more uniform than at BNL

# Injection of the muons into the ring

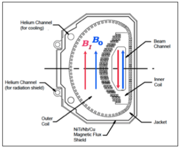
- Beam enters the ring through a 2.2 m-long 10 cm hole in the iron yoke

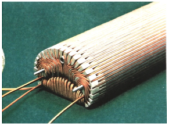



- **T0 Counter** (thin scintillator read out by PMTs) to measure **beam time profile**

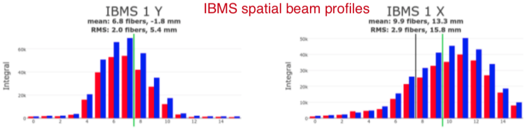



- **Inflector magnet** provides nearly field free region for muons to enter the storage region



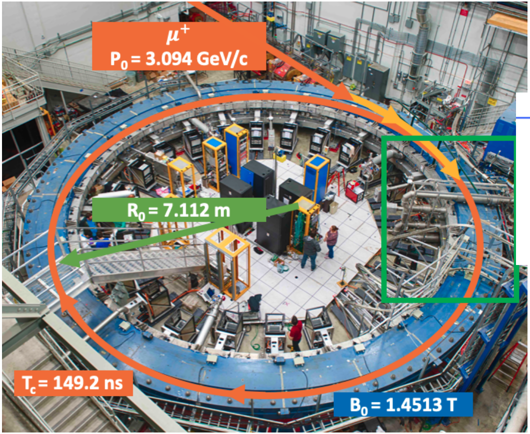



- **Inflector Beam Monitoring System** (scintillator fiber grids) to measure **beam spatial profile**



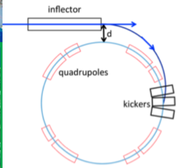
# Muon storage

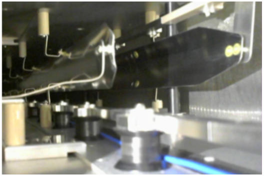
- Injected beam is 77 mm off from storage region center

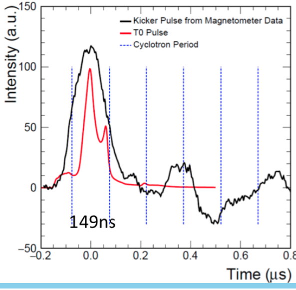



**Kicker Magnets**

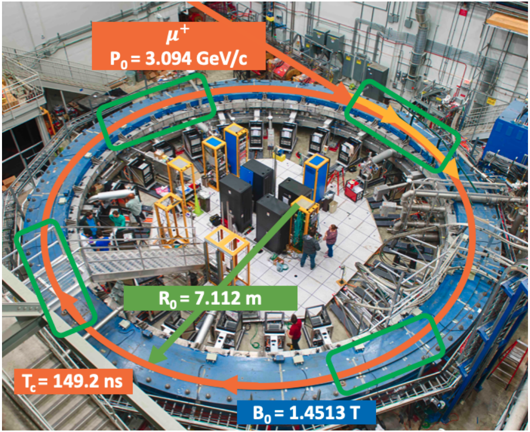
- 3 pulsed magnets deflect beam ~10 mrad onto the closed storage orbit in less than 150 ns



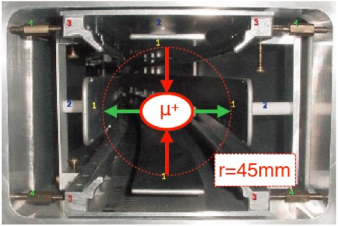


# Vertical focusing




**Electrostatic Quadrupoles**

- 4 sets of quads provide vertical beam focusing

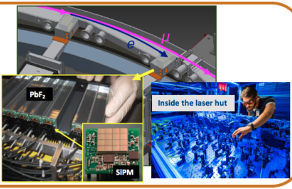



- $E$–field component cancels out (at first order) when muons at *magic momentum*:

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

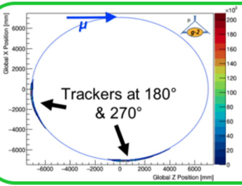
~0 if $\gamma$=29.3 *i.e.*, $p_\mu$=3.094 GeV/c

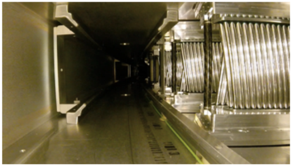
# Detectors and field probes




## 24 Calos around the ring

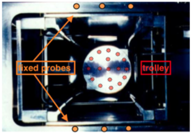
- Each made of 6×9 $PbF_2$ crystals read out by large-area SiPMs
- 1296 channels individually calibrated by 405nm-laser system

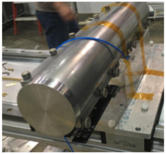


## 2 in-vacuum straw trackers

- 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:

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

ratio of frequencies ($R_\mu$) 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)]

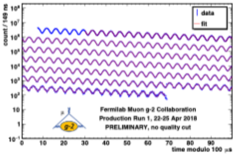
$m_\mu/m_e$ from [Phys. Rev. Lett. **82**, 711 (1999)]

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

$\omega_a$: muon anomalous precession frequency

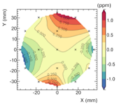
Extract from decay positron time spectra

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

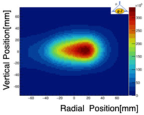



$\widetilde{\omega}'_p(T_r)$: magnetic field B in terms of (shielded) proton precession frequency (proton NMR $\hbar\omega_P = 2\mu_p B$) **and** weighted by the muon distribution

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



Map the magnetic field




Muon distribution in the storage ring

# 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
$\omega_a^{meas}$ : measured precession frequency

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

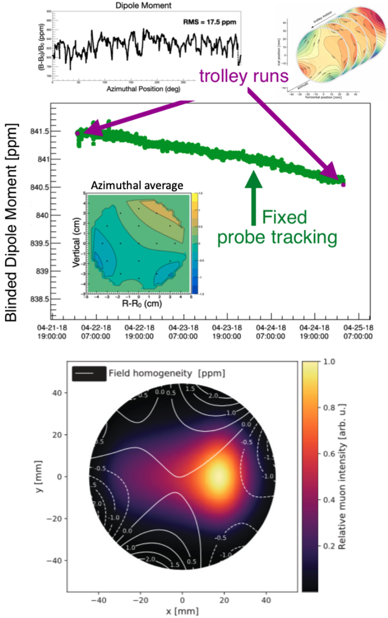
$C_e$ : electric field correction
$C_p$ : pitch correction
$C_{ml}$ : muon loss correction
$C_{pa}$ : phase-acceptance correction
$C_{dd}$ : differential-decay correction

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

# Measuring the magnetic field seen by the muons

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

- $\omega'_p$ 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)

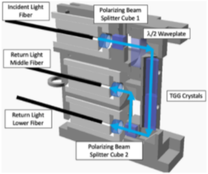


# Magnetic field corrections

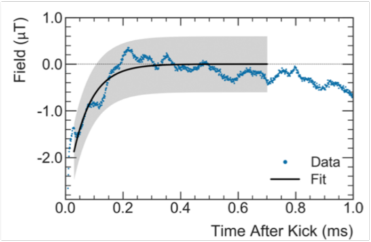
$$R_\mu = \left( \frac{f_{clock} \cdot \omega_a^{meas} \cdot (1 + C_e + C_p + C_{ml} + C_{pa} + C_{dd})}{f_{calib} \cdot \omega'_p(x,y,\phi) \otimes M(x,y,\phi) \cdot (1 + B_k + B_q)} \right)$$

## Kicker transient field

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

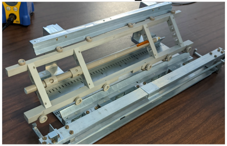


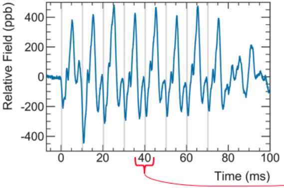
(a)

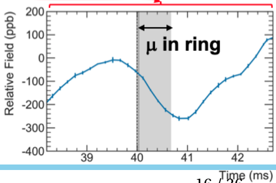



## Quads transient field

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





# Measuring $\omega_a$

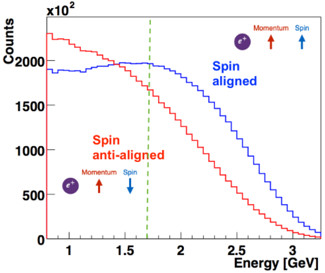
$$R_\mu = \left( \frac{f_{clock} \cdot \omega_a^{meas} \cdot (1 + C_e + C_p + C_{ml} + C_{pa} + C_{dd})}{f_{calib} \cdot \omega'_p(x,y,\phi) \otimes M(x,y,\phi) \cdot (1 + B_k + B_q)} \right)$$

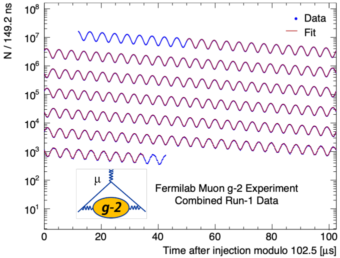
- Polarized muon decay:

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

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

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

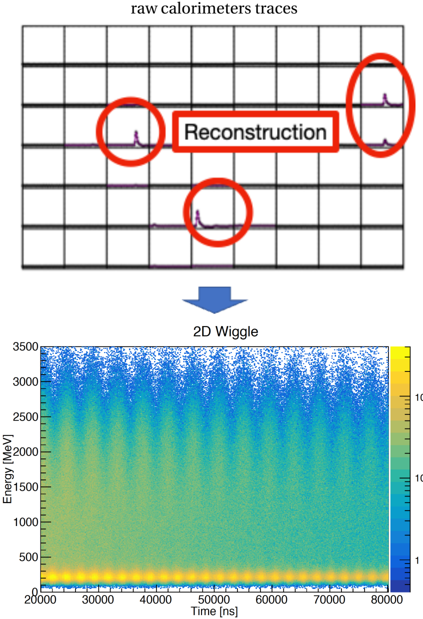



**$E_{e^+}$ and t are measured by the calorimeters with a blinding factor applied to the digitization rate**

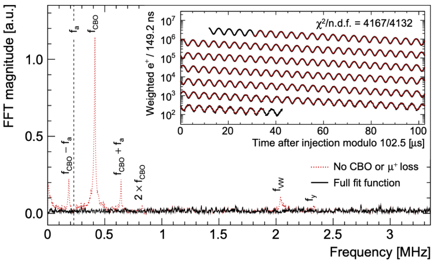
# Wiggle plot

- Calorimeters data is reconstructed into energies and times
  –> Two independent reconstruction routines
- Different analysis techniques used to reduce systematic errors :
  - **Threshold (T) Method**
    – only energy threshold applied to select positrons
  - **Asymmetry-Weighted (A) Method:**
    – positrons divided into energy bins and weighted by g-2 asymmetry
  - **Ratio (R) Method**
    – exponential decay due to muon lifetime is removed before fitting
  - **Integrated Charge (Q) Method:**
    – sum of raw calorimeter traces (unique method independent of reconstruction)



# 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 22-parameter fit function that includes beam dynamics effects




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

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

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

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

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

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

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

$\omega_y$, $\omega_{VW}$ 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

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

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

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

# Fitting procedure

- Fit → Residuals → Fast Fourier Transform (FFT)
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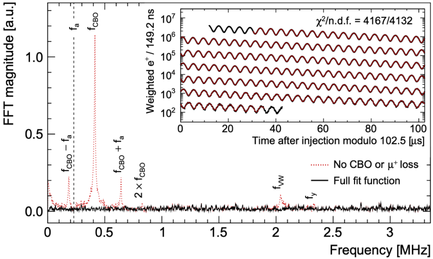



$$N_0\, e^{-\frac{t}{\gamma\tau}}\left(1 + A \cdot A_{BO}(t)\cos(\omega_a t + \phi \cdot \phi_{BO}(t))\right)\cdot N_{CBO}(t)\cdot N_{VW}(t)\cdot N_y(t)\cdot N_{2CBO}(t)\cdot J(t)$$

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

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

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

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

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

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

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

$\omega_y$, $\omega_{VW}$ vertical oscillations

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

Lost muons

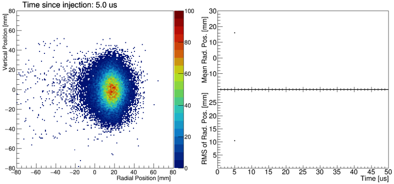
$$\omega_{CBO}(t) = \omega_0 t + Ae^{-\frac{t}{\tau_A}} + Be^{-\frac{t}{\tau_B}}$$

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

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

Red = free parameters
Blue= fixed parameters

The muon beam oscillates and breathes:



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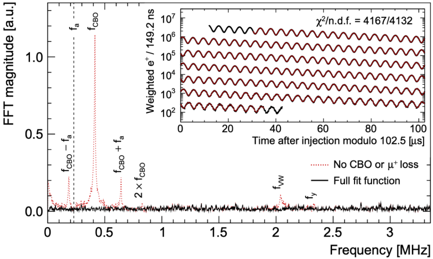


$$N_0 e^{-\frac{t}{\tau_\mu}}\left(1 + A \cdot A_{BO}(t)\cos(\omega_a t + \phi \cdot \phi_{BO}(t))\right) \cdot N_{\rm CBO}(t) \cdot N_{\rm VW}(t) \cdot N_y(t) \cdot N_{\rm 2CBO}(t) \cdot J(t)$$

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

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

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

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

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

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

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

$\omega_y$, $\omega_{VW}$ vertical oscillations

Red = free parameters
Blue= fixed parameters

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

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

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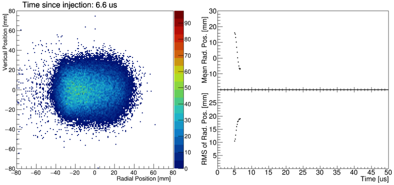

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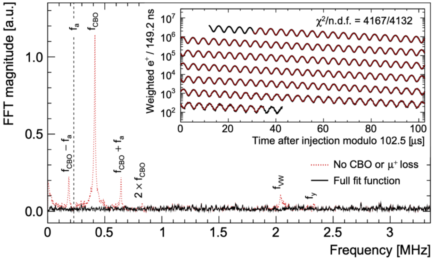


$$\boxed{N_0 e^{-\frac{t}{\gamma\tau}} \left(1 + A \cdot A_{BO}(t)\cos(\omega_a t + \phi \cdot \phi_{BO}(t))\right) \cdot N_{\rm CBO}(t) \cdot N_{\rm VW}(t) \cdot N_y(t) \cdot N_{\rm 2CBO}(t) \cdot J(t)}$$

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

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

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

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

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

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

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

$\omega_y$, $\omega_{VW}$ vertical oscillations

Red = free parameters
Blue= fixed parameters

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

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

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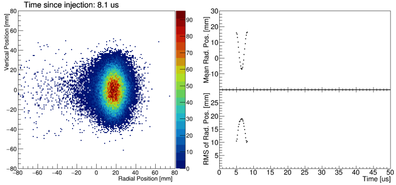
The muon beam oscillates and breathes:



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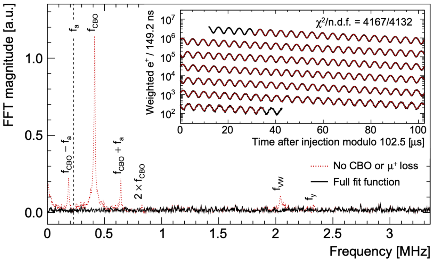


$$N_0\, e^{-\frac{t}{\gamma\tau}}\left(1 + A \cdot A_{BO}(t)\cos(\omega_a t + \phi \cdot \phi_{BO}(t))\right) \cdot N_{\rm CBO}(t) \cdot N_{\rm VW}(t) \cdot N_y(t) \cdot N_{\rm 2CBO}(t) \cdot J(t)$$

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

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

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

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

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

$\omega_y$, $\omega_{VW}$ vertical oscillations

Red = free parameters
Blue= fixed parameters

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

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

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

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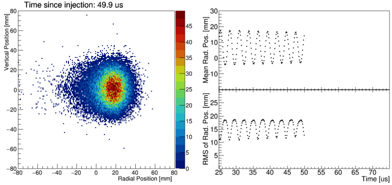
The muon beam oscillates and breathes:



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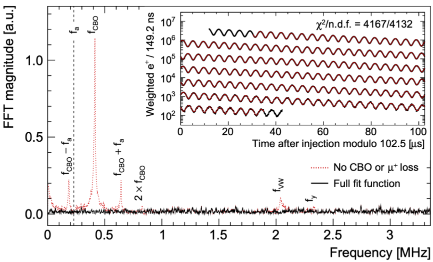


$$\boxed{N_0\, e^{-\frac{t}{\gamma\tau}}\left(1 + A \cdot A_{BO}(t)\cos(\omega_a t + \phi \cdot \phi_{BO}(t))\right) \cdot N_{\mathrm{CBO}}(t) \cdot N_{\mathrm{VW}}(t) \cdot N_y(t) \cdot N_{2\mathrm{CBO}}(t) \cdot J(t)}$$

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

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

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

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

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

$\omega_y$, $\omega_{VW}$ 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

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

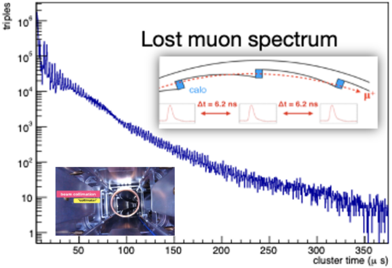
Lost muons

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

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

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

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



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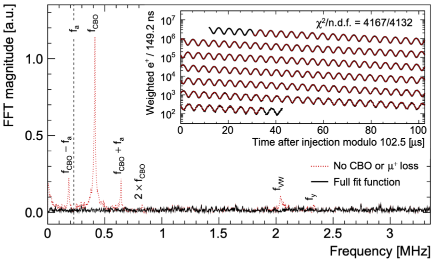


$$N_0 e^{-\frac{t}{\gamma\tau}} (1 + A \cdot A_{BO}(t) \cos(\omega_a t + \phi \cdot \phi_{BO}(t))) \cdot N_{\mathrm{CBO}}(t) \cdot N_{\mathrm{VW}}(t) \cdot N_y(t) \cdot N_{\mathrm{2CBO}}(t) \cdot J(t)$$

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

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

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

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

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

$\omega_y, \omega_{VW}$ vertical oscillation

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

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Lost muons

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

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

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

+ 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 Effect on Spin Precession

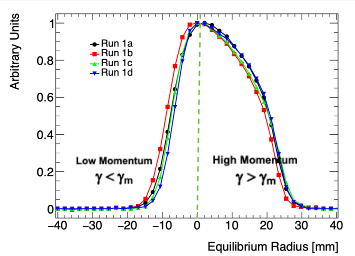
$$R_\mu = \left(\frac{f_{clock} \cdot \omega_a^{meas} \cdot (1 + C_e + C_p + C_{ml} + C_{pa} + C_{dd})}{f_{calib} \cdot \omega'_p(x,y,\phi) \otimes M(x,y,\phi) \cdot (1 + B_k + B_q)}\right)$$

## Electric Field

- due to momentum spread around $p_{magic}$

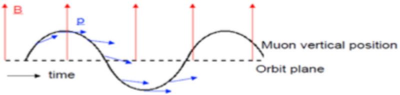
$$\vec{\omega}_a \cong -\frac{e}{m}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta} \times \vec{E}}{c}\right]$$

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

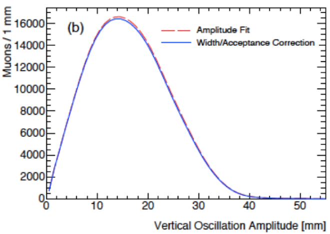



## Pitch

- due to vertical beam oscillation




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

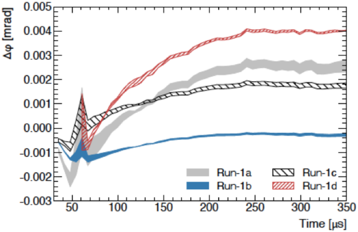


# Corrections for Phase-Changing Effects

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

## Muon losses

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

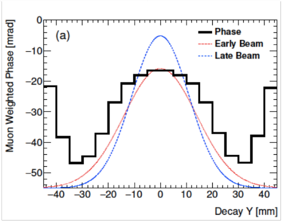


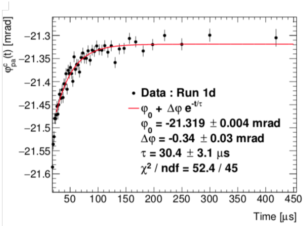

## Differential Decay

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

## Phase acceptance

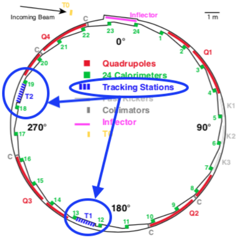
- phase changes due to early to late variations of the beam
- measured using tracker data and simulations

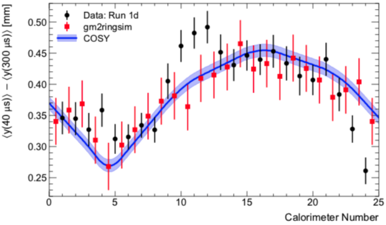


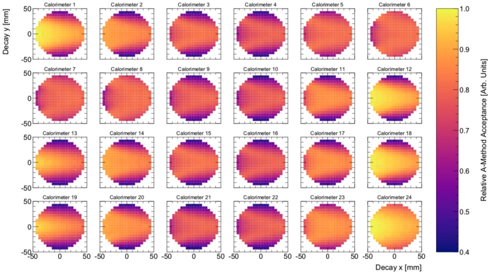



# Simulations for phase-acceptance

- 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

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

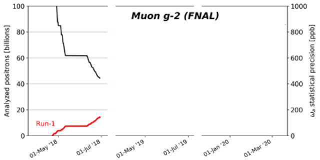
**Clock frequency** ($f_{clock}$):

- frequency that our DAQ clock ticks
- **stable** at ppt level
- hardware-blinded to have (40 - $\varepsilon$) MHz
  - –> $\varepsilon$ 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

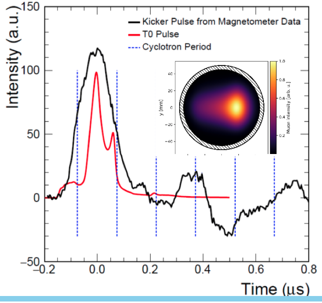
## Statistics:

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

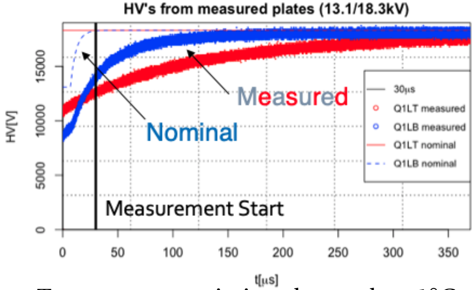



## Main challenges:

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

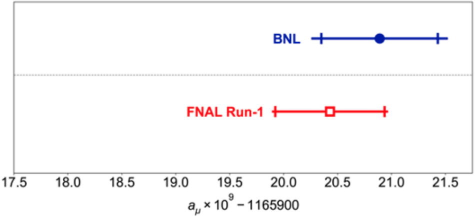



- 2 of 32 HV Quad resistors were damaged
  - $\longrightarrow$ slow recovery time, enhanced $C_{pa}$




- Temperature variations larger than 1°C

# Run-1 Result




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

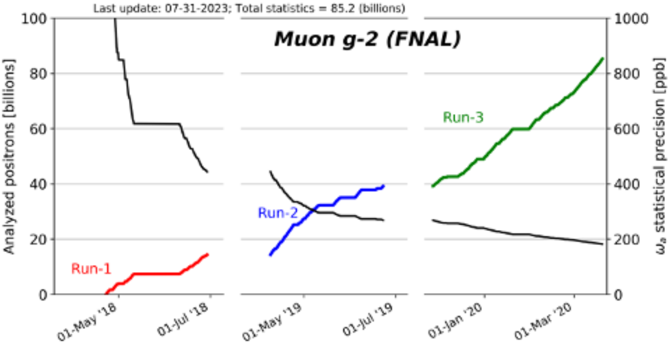
$$a_\mu = 116592040(54) \times 10^{-11} \ (462 \text{ ppb})$$

- Good agreement with BNL $g-2$

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

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

# Run-2 and Run-3 Statistics Improvement



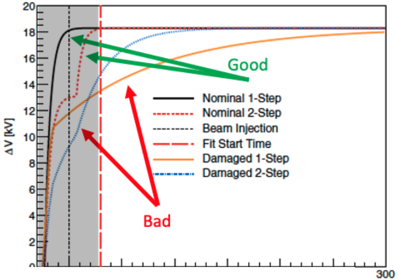

**Statistics:**

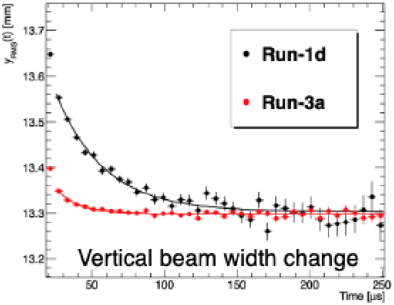
- ~ 4.7 more data in Run-2/3 than Run-1

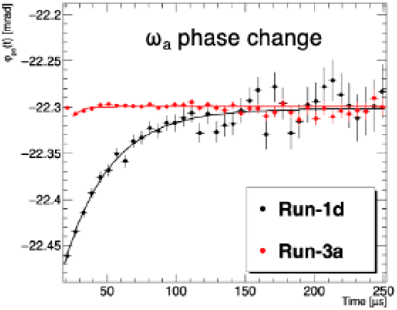
| Dataset | Stat. Unc. |
|---|---|
| Run-1 | 434 ppb |
| Run-2/3 | 201 ppb |
| Run-1+Run-2/3 | 185 ppb |

# Run-2 and Run-3 Hardware Improvements

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

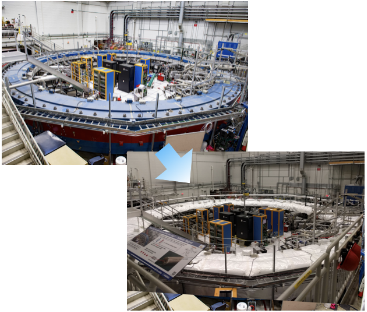


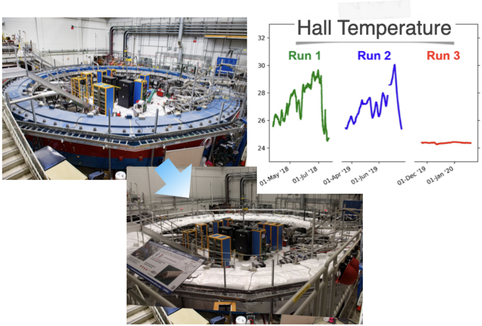
# Run-2 and Run-3 Hardware Improvements

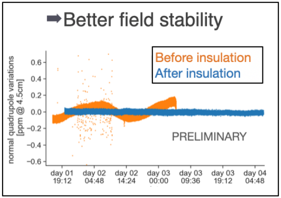
- **Before Run-2:**
  –> Replaced bad quads HV resistors
  –> Magnet covered with a thermal blanket

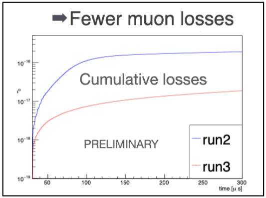


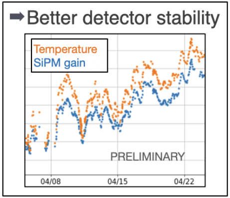
# Run-2 and Run-3 Hardware Improvements

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



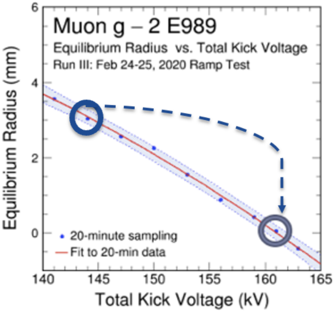



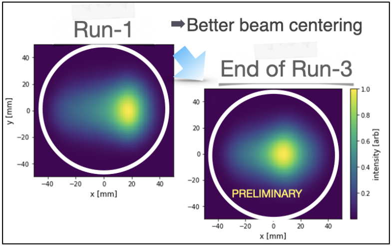



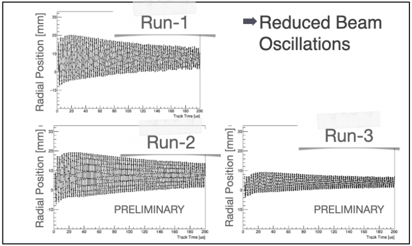



# Run-2 and Run-3 Hardware Improvements

- **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



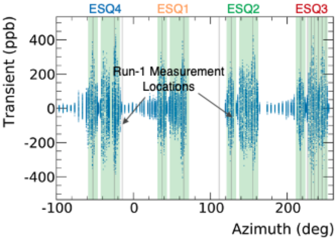



# Run-2 and Run-3 Measurement Improvements

- Improved **quadrupole field transient** ($B_q$) by measuring both time and space

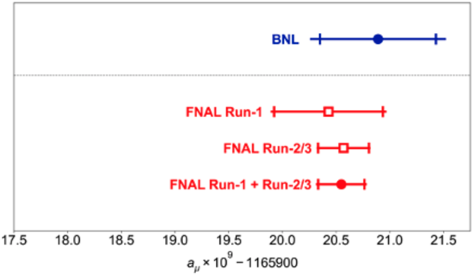
$$\delta_{B_q} \sim 92\,\text{ppb} \rightarrow \sim 20\,\text{ppb}$$




- Improved **kicker field transient** ($B_k$) by performing cross-check of the measurement also with a new magnetometer

$$\delta_{B_k} \sim 37\,\text{ppb} \rightarrow \sim 13\,\text{ppb}$$

# Run-2/3 Result




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

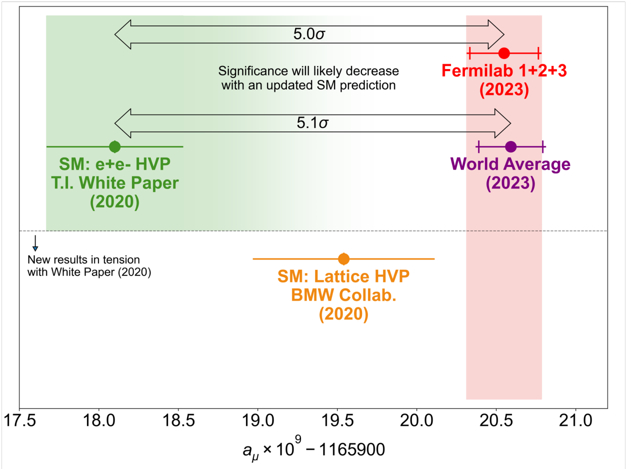
$$a_\mu = 116592057(25) \times 10^{-11}\ (215\ \text{ppb})$$

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

| Quantity | Correction [ppb] | Uncertainty [ppb] |
|---|---|---|
| $\omega_a^m$ (statistical) | – | 201 |
| $\omega_a^m$ (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 |
| $m_\mu/m_e$ | – | 22 |
| $g_e/2$ | – | 0 |
| Total systematic | – | 70 |
| Total external parameters | – | 25 |
| Totals | 622 | 215 |

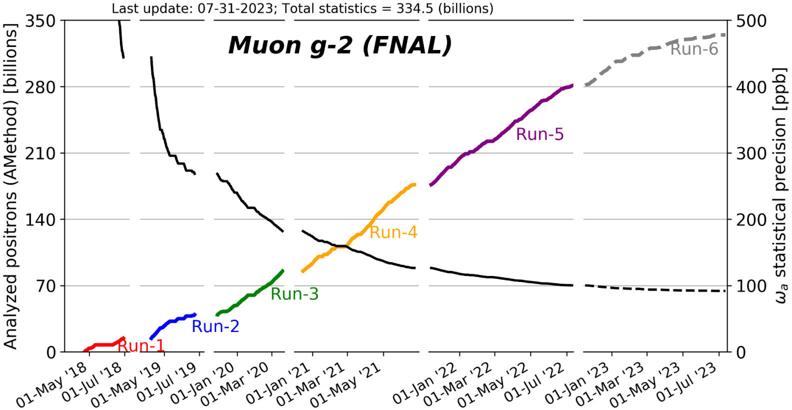
- Both Run-1 and Run-2/3 results uncertainties are **statistics dominated**
- Run-2/3 systematic uncertainty of 70 ppb is lower than our TDR goal of 100 ppb!
- Combination assuming systematics 100% correlated with final uncertainty of 203 ppb

# Experimental measurement vs. SM calculation




- $5.1\sigma$ discrepancy between 2023 World average and WP (2020)
- BMW result (*i.e.*, changing in WP (2020) result the HVP term from dispersion with lattice-QCD calculation) falls in between WP (2020) and the experiment

# What’s next?




- Completed Run-6 before summer: there is more data still to analyze!
- Not only Muon g-2 measurement: there are other analysis: EDM, CPT/LV and **Dark Matter** searches.

# Dark Matter Searches

Muon $g$-2 experiment enables the **direct search for two ultralight DM candidates** that primarily interact with muons:

- **Scalar DM (signature: Parallel perturbation)**

- **Scalar DM perturbs the muon's mass:**

$$\omega_a(\mathrm{t}) = a\frac{q}{m(t)}B, \text{ where}$$

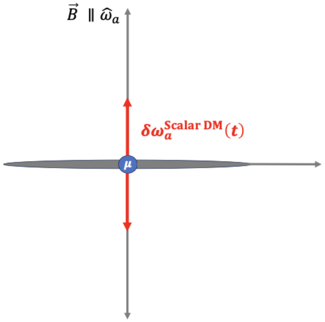
$$\left(m(t) \rightarrow m_0(1 + A'_{\mathrm{DM}}\cos m_{\mathrm{DM}})\right)$$

$$= a\frac{q}{m_0(1+A'_{\mathrm{DM}}\cos m_{\mathrm{DM}}t)}B$$

$$\approx a\frac{q}{m_0}B(1 - A'_{\mathrm{DM}}cos\, m_{\mathrm{DM}}t)$$

$$\therefore \delta\omega_a^{\mathrm{Scalar\ DM}}(t) = A_{\mathrm{DM}}\cos(m_{\mathrm{DM}}\,t + \varphi_{\mathrm{DM}})$$

- **Therefore, it causes modulation of $\omega_a$ at $m_{\mathrm{DM}}$**

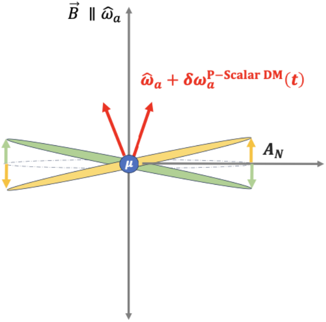



Slide courtesy of Byungchul Yu (University of Mississippi)

Muon $g$-2 experiment enables the **direct search for two ultralight DM candidates** that primarily interact with muons:

- **Scalar DM (signature: Parallel perturbation)**
- **PseudoScalar DM (signature: Perpendicular perturbation)**

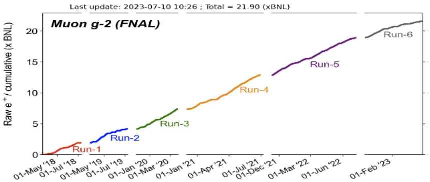
- **Pseudoscalar DM works as an anomalous magnetic field that interacts only with the muon spin, making the muon's spin precession plane swing.**
- Up-down number asymmetry refers to a difference in the number of decay positrons accepted at the crystals in a calorimeter's upper and lower parts.
- The decay positron is preferentially emitted to the spin direction, leading to the up-down number asymmetry.
- **Therefore, it causes the modulation of $A_N$ (Amplitude of up-down number asymmetry) at $m_{DM}$**




Slide courtesy of Byungchul Yu (University of Mississippi)

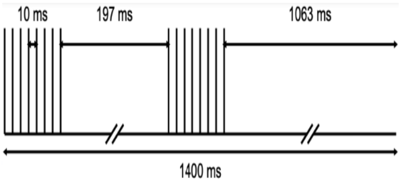
# Estimation of Dark Matter mass sensitivity

**Maximum time scale**




**Whole experiment lifetime (5 years)**

**Minimum time scale**




**Bunch separation (10 ms)**

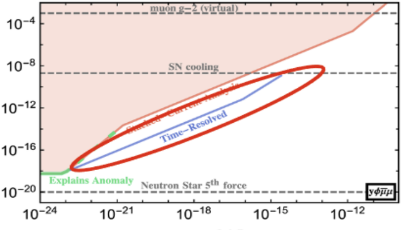
| | | | |
|---|---|---|---|
| **DM Mass** | $10^{-23}$eV | $m_{DM}$ | $10^{-13}$eV |
| **DM Freq** | $10^{-8}$Hz | | $10^{2}$ Hz |

Targeted Dark Matter mass range with its corresponding frequency

Slide courtesy of Byungchul Yu (University of Mississippi)

# Dark Matter Model sensitivity

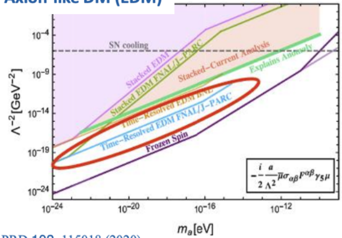
## Scalar DM model sensitivity plot




Ryan Janish, Harikrishnan Ramani
PRD **102**, 115018 (2020)

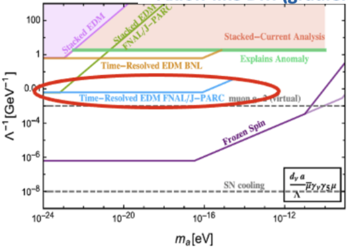
## Pseudoscalar DM model projected sensitivity plots

Axion-like DM (EDM)




Ryan Janish, Harikrishnan Ramani PRD **102**, 115018 (2020)

Axion-like DM (gradient)




Projected sensitivity of “direct” DM search using the Muon $g-2$ data is beyond the astronomical bounds.

Slide courtesy of Byungchul Yu (University of Mississippi)

# Summary and Conclusions

- FNAL $g-2$ Experiment goal is to measure $a_\mu$ 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
- **Run-2 and Run-3 data** measurement achieved a factor 2 uncertainty reduction both in statistics and systematics!
- With **Run-4, Run-5 and Run-6** we expect to achieve the uncertainty goal and other analysis including **dark matter searches** are been developed.

# Thanks!