Measurement of the anomalous spin precession frequency in the Muon $g - 2$ experiment at Fermilab

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INFN Sezione Roma Tor Vergata

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Sections

1. Introduction
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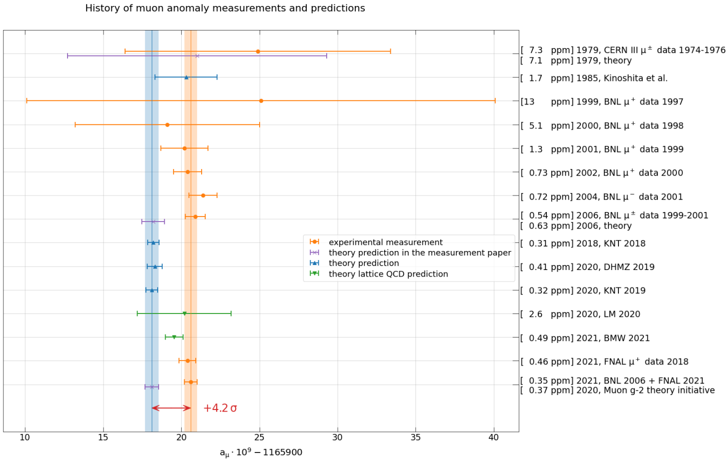
3. Muon g-2 at Fermilab
4. Precession Frequency Analysis
5. Conclusions and Future Perspective

Introduction

The Muon Anomalous Magnetic Moment

Long history (not complete) of g-2 measurements and theory predictions updated in 2021 with the FNAL measure



Spin Precession in a Magnetic Field

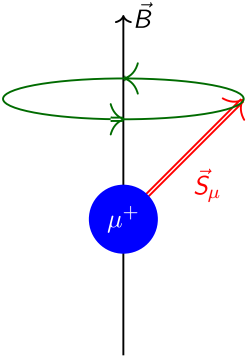
A particle's spin in a magnetic field experience a torque and a precession motion proportional to it's magnetic moment,for generic leptons defined as

$$\vec{\mu}_\ell = g_\ell \frac{e}{2m_\ell} \vec{S}_\ell$$

The spin precession frequency is given by:

$$\omega_s = g \frac{e}{2m} B$$

- Dirac equation predicts naturally $g = 2$ for elementary particles
- Radiative corrections give a positive contribution. Schwinger: $a_\mu \sim \frac{\alpha}{2\pi} \approx 0.00116$ (at first order)



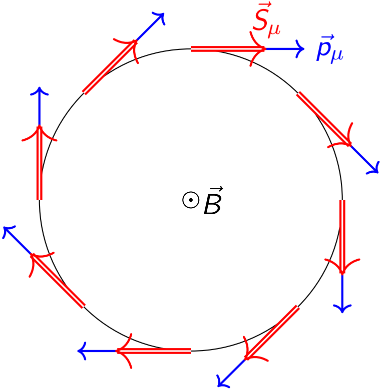
Measuring a_μ

Spin Precession in a Magnetic Field

The measurement is based on the anomalous spin precession frequency:

$$\vec{\omega}_a = \vec{\omega}_{spin} - \vec{\omega}_{cyclotron} = a_\mu \frac{e\vec{B}}{mc}$$

- $a_\mu = 0$ spin and momentum precess at the same rate



Spin Precession in a Magnetic Field

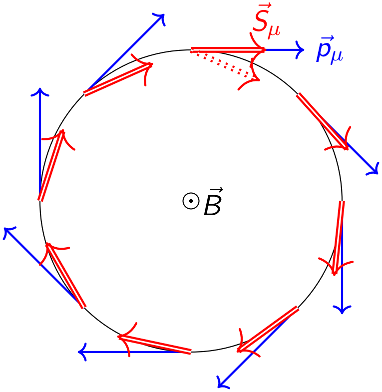
The measurement is based on the anomalous spin precession frequency:

$$\vec{\omega}_a = \vec{\omega}_{spin} - \vec{\omega}_{cyclotron} = a_\mu \frac{e\vec{B}}{mc}$$

- $a_\mu = 0$ spin and momentum precess at the same rate
- $a_\mu > 0$ the spin has a precession motion around the momentum direction

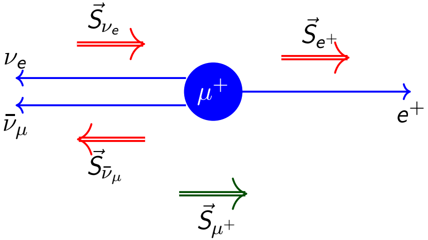
a_μ can be extracted by measuring ω_a and B:

$$a_\mu = \frac{\omega_a}{B} \cdot \frac{mc}{e}$$



How to measure the spin precession frequency

The muon polarization is measured using the parity-violating decay



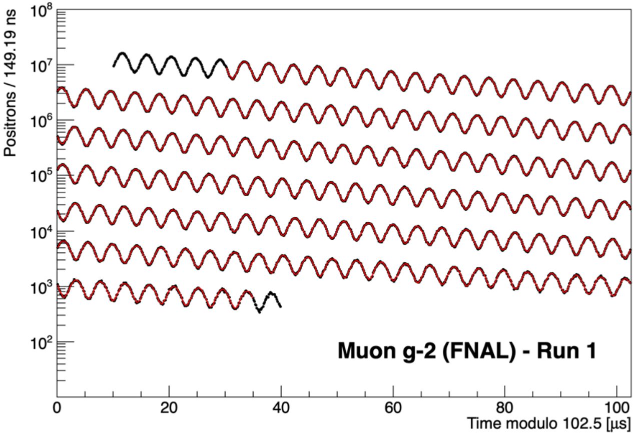
High momentum e^+ are emitted preferentially in the muon's spin direction

Just count the number of high energy positrons in a given direction to extract the precession frequency

Wiggle Plot

The result is the muon exponential decay modulated by the anomalous precession frequency:

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



From ω_a to a_μ

The final formula for a_μ, without electric fields and with a beam perpendicular to the magnetic field is:

$$a_\mu = \frac{\omega_a}{\tilde{\omega}'_p(T)} \underbrace{\frac{\mu'_p(T)}{\mu_e} \frac{m_\mu}{m_e} \frac{g_e}{2}}_{\text{External}}$$

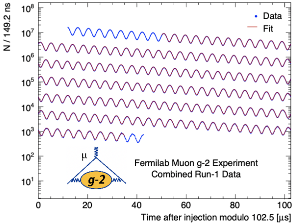
where the B-field is expressed in term of the shielded proton precession frequency in the NMR probes. External factors are known to very high precision. We extract the ratio:

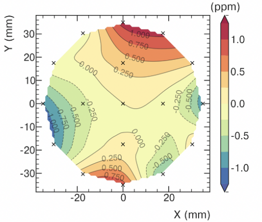
$$R'_\mu = \frac{\omega_a}{\tilde{\omega}'_p(T)}$$

From ω_a to a_μ

$$R'_\mu = \frac{\omega_a}{\tilde{\omega}'_p(T)} =$$

$\boldsymbol{\omega_a}$





$\boldsymbol{\omega_p(x, y, \varphi)}$

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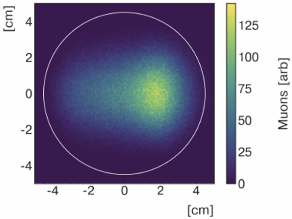


$\boldsymbol{M(x, y, \varphi)}$

From ω_a to a_μ (for real)

The final formula for R'_μ, with all the corrections is:

$$R'_\mu = \frac{\omega_a}{\tilde{\omega}'_p(T)} = \frac{f_{clock} \cdot \omega_a^{meas} \cdot \overbrace{(1 + C_e + C_p + C_{ml} + C_{pa})}^{\text{Beam Dynamics}}}{f_{calib} \cdot \langle \omega'_p(x, y, \phi) \cdot M(x, y, \phi) \rangle \cdot \underbrace{(1 + B_k + B_q)}_{\text{Transient Fields}}}$$

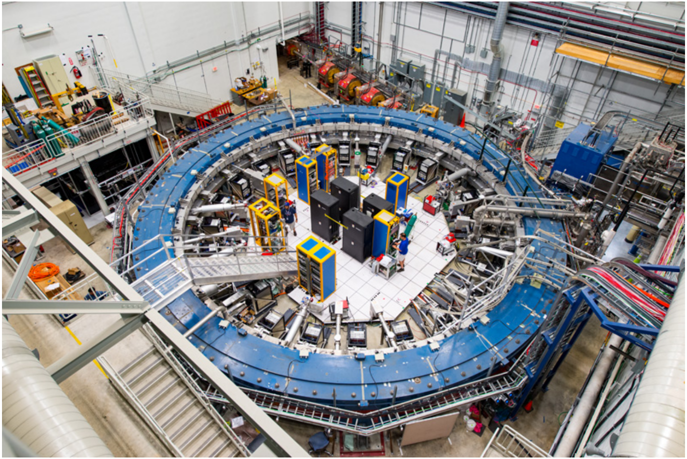
- ω_a^{meas} is the the measured precession frequency (this talk)
- $\tilde{\omega}'_p(T)$ is the the magnetic field magnitude (in term of NMR frequency) around the ring (Peter Winter's talk)
- $C_e + C_p + C_{ml} + C_{pa}$ are beam dynamics corrections (On Kim's talk)
- B_k and B_q are magnetic field transients (David Kessler's talk)

A contribution from the beam simulation is included in $M(x, y, \phi)$ and in the beam dynamic terms. This will be presented in Anna Driutti's talk.

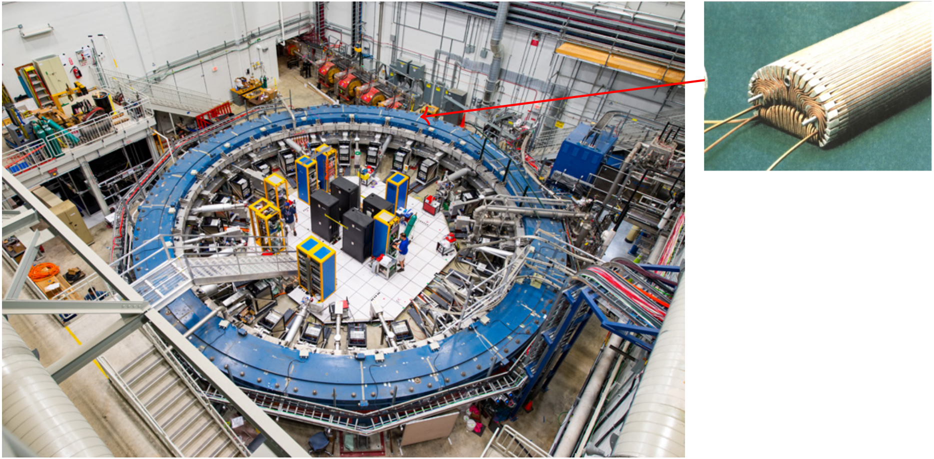
Muon g-2 at Fermilab

Fermilab Muon Campus

One Ring To Rule Them All...

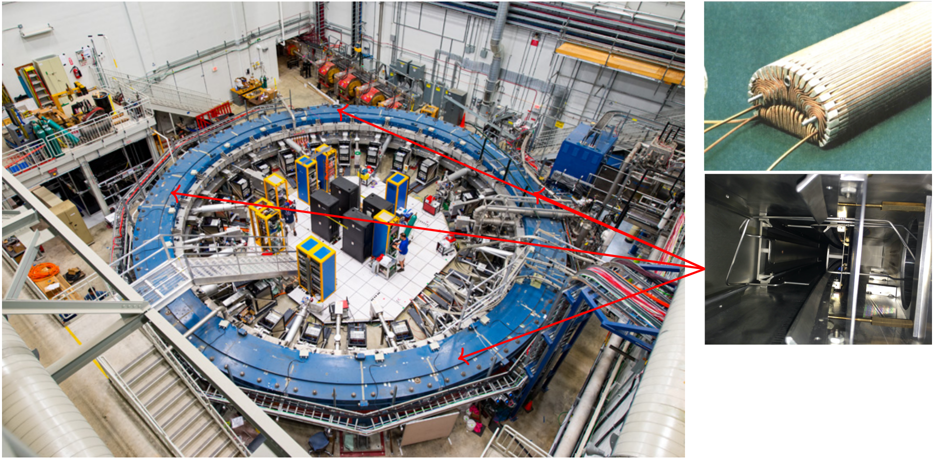


One Ring To Rule Them All...



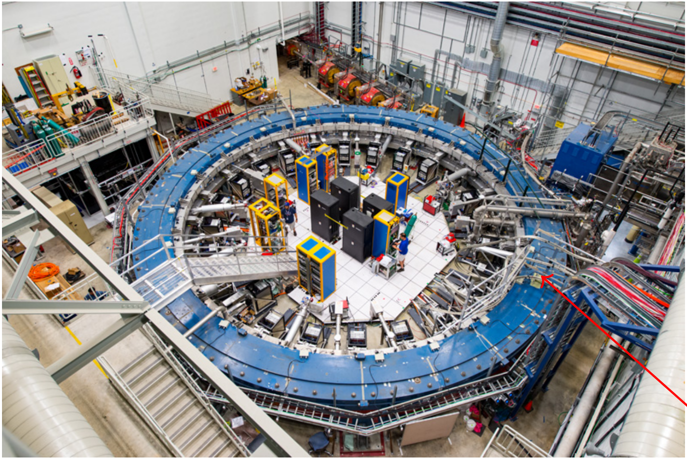
Inflector

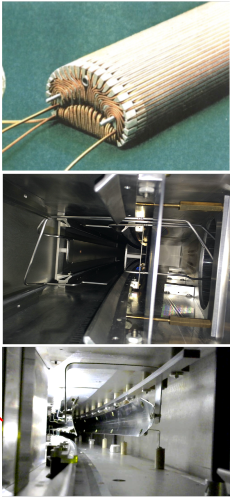
One Ring To Rule Them All...



Quadrupoles

One Ring To Rule Them All...

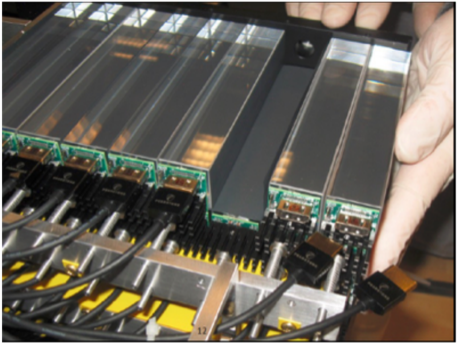


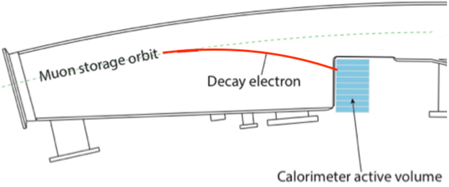


Kickers

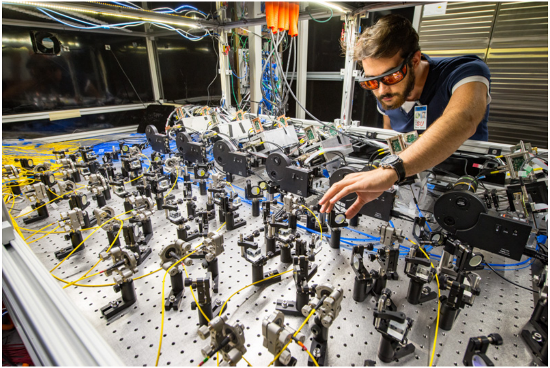
Calorimeters

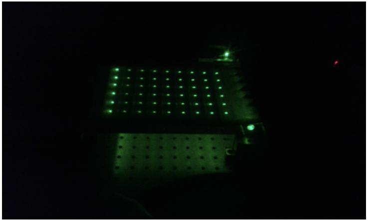
- 24 calorimeters along the inner circumference (out of vacuum)
- 54 PbF_2 crystals ($n = 1.82$) in a 6×9 matrix
- Each crystal is $2.5 \times 2.5 \times 14\ \mathrm{cm}^3 \sim 15\ X_0$ for PbF_2
- Čerenkov light is read by large area SiPM
- Gain is monitored at a 10^{-4} level of stability by state of the art Laser Calibration System

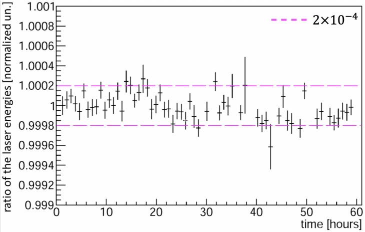




Laser Calibration System







Calibration of the 1296 crystals for Short Term $\mathcal{O}(1\text{ ns})$, Measurement Window $\mathcal{O}(1\text{ ms})$ and Long Term $\mathcal{O}(1\text{ day})$

Precession Frequency Analysis

The Analysis Method

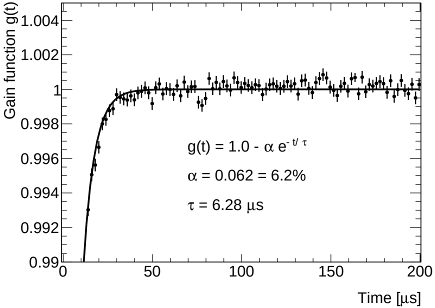
To measure the anomalous precession frequency the following procedure has been adopted:

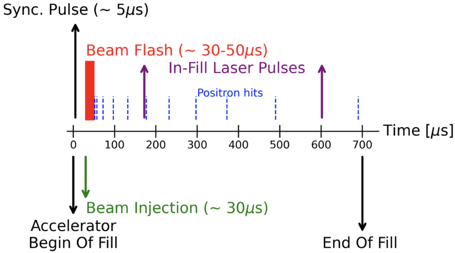
1- Positron hit reconstruction (local or global approach):
  a- Crystal waveforms fitting to extract time and energy
  b- Clustering to identify single positron events
2- Calorimeter gain correction
3- Data correction
4- Anomalous precession frequency fitting
5- Systematic evaluation
6- Result combination of the 6 independent analyses (including this one)

Calorimeter Gain Corrections

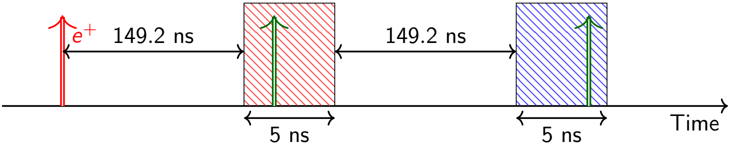
- At beam injection a large flux of particles hit the calorimeters
- SiPMs gain drops due to the high number of hits
- $\mathcal{O}(10\ \mu s)$ recovery time
- Laser system measures the calorimeter response as a function of time
- Positron energy is corrected:

$$E_{true} = E_{SiPM} \cdot \frac{1}{1 - \alpha e^{-t/\tau}}$$

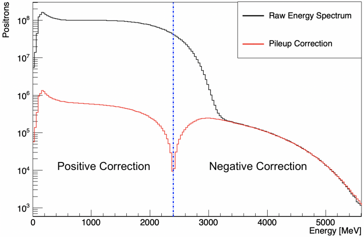




Pileup Subtraction



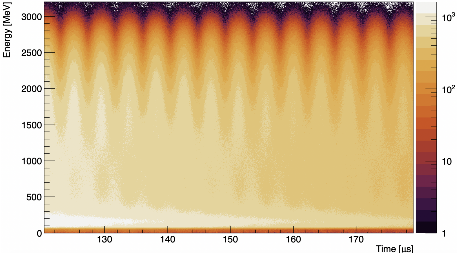
- Reconstruction algorithm cannot resolve close-in-time positrons
- The pileup probability depends on the squared positron rate biasing the ω_a measurement
- Shadow window method:
  - For every positron event look for another cluster in a shadow window
  - Combine the two clusters into an artificial pileup event
  - Subtract pileup

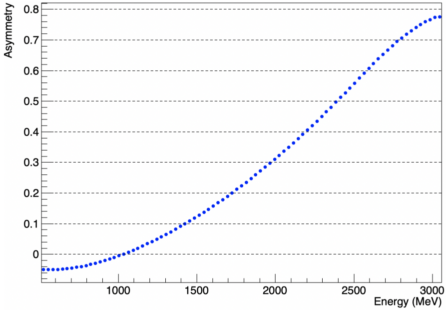


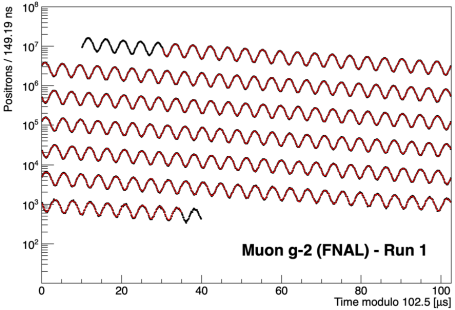
ω_a Analysis

Analysis methods:

- T: integrate all positrons above 1.7 GeV
- A: weight the positrons with asymmetry function and integrate above 1.1 GeV







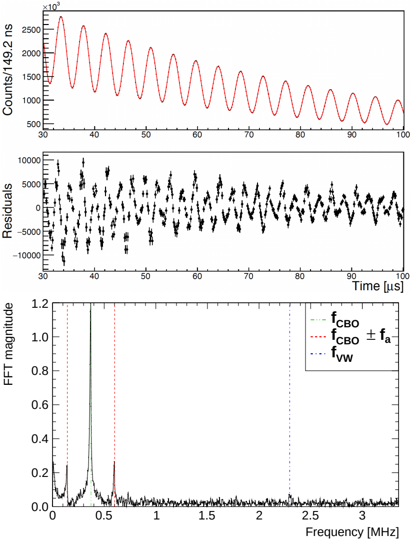
Fitting ω_a - 5 Parameters Function

In principle simple fit:

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

from $\sim 30\ \mu$s to $\sim 650\ \mu$.
Beam dynamic effects appear in the residuals FFT:

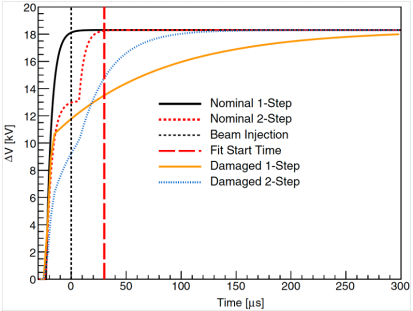
- Slow terms: Beam Losses
- $f \sim 0.4$ MHz: Coherent Betatron Oscillations (CBO)
- $f \sim 2.3$ MHz: Vertical Width Oscillations (VW)

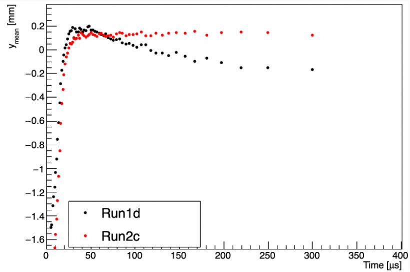


Variable Beam Frequencies

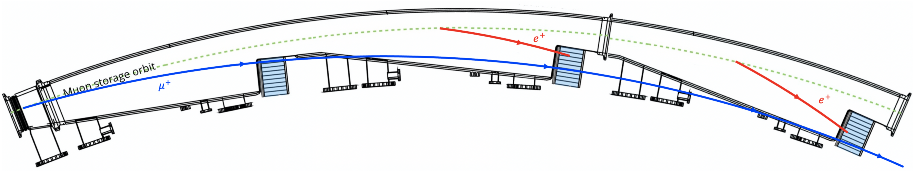
- Faulty resistors in one quadrupole: slower charge lead to unexpected beam vertical motion
- Beam mean vertical position drifting down during the fill
- The beam instabilities induced a change in the beam frequencies accounted in the fitting function

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

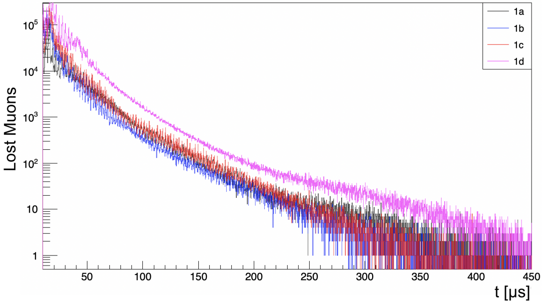




Lost Muons



- Muons can hit the collimators and exit the storage region before decay
- Distort the decay exponential during the measurement window
- Search for: Coincidences between calorimeters ($\Delta t = 6.25$ ns) with $E \sim 170$ MeV



Fitting ω_a - 22 Parameters Function

$$N(t) = N_0\, e^{-\frac{t}{\gamma\tau}}\, \left[1 + A \cdot A_{BO}(t) \cos(\omega_a\, t + \phi + \phi_{BO}(t))\right] \cdot$$

$$\cdot\, N_{\mathrm{CBO}}(t) \cdot N_{\mathrm{VW}}(t) \cdot N_y(t) \cdot N_{2\mathrm{CBO}}(t) \cdot \Lambda(t)$$

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

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

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

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

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

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

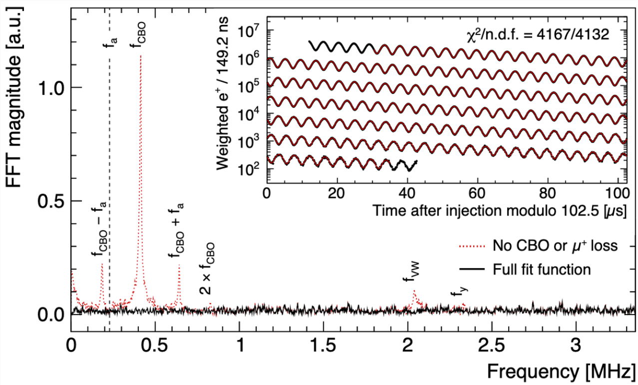
$$\omega_{\mathrm{CBO}}(t) = \omega_0^{CBO} + \frac{A}{t} e^{-\frac{t}{\tau_A}} + \frac{B}{t} e^{-\frac{t}{\tau_B}}$$

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

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

$$\Lambda(t) = 1 - k_{LM} \int_{t_0}^{t} L(t') e^{t'/\tau}\, dt'$$

Fit Result



The residuals FFT doesn't show any resonance. All the beam dynamic terms are handled correctly in the fitting function

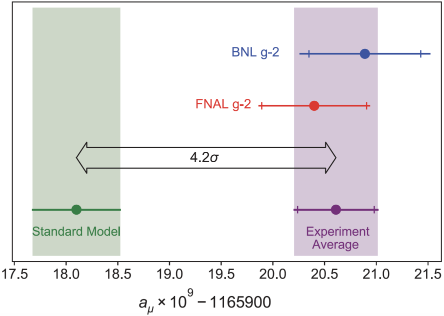
Conclusions and Future Perspective

Conclusions

- The muon anomalous precession frequency measurement is based on the detection of high energy positrons in a storage ring
- Data is corrected for detector effects such as the calorimeters gain and pileup
- Wiggle plot histogram is fitted including the beam motion
- The ω_a measurement is combined with the Magnetic Field and Beam Distribution measurements to get a_μ

Run 1 Result

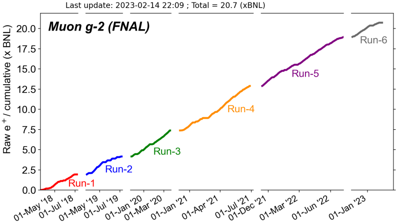
$$a_\mu^{FNAL} = 116\ 592\ 040(54) \times 10^{-11}$$



Future Perspectives

- Run 1 represents ∼ 6% of the total statistics
- Run 2+3 publication expected by next summer:
  - A factor 2 improvement in the statistical precision is expected
  - Improvements to the beam dynamics systematics (better storage conditions)
  - Improvement on the analysis technique (better positron hit reconstruction, pileup subtraction, fitting...)

- Run 4 and 5 are being reconstructed and are almost ready to be analyzed
- A final Run 6 data taking is ongoing



Muon g-2 Collaboration

BACKUP

References

- B. Abi et al. (Muon $g-2$ Collaboration) - *Measurement of the Positive Muon Anomalous Magnetic Moment to 0.46 ppm*, Phys. Rev. Lett. 126, 141801
- T. Albahri et al. (Muon $g-2$ Collaboration) - *Measurement of the anomalous precession frequency of the muon in the Fermilab Muon* $g-2$ *Experiment*, Phys. Rev. D 103, 072002
- T. Albahri et al. (Muon $g-2$ Collaboration) - *Magnetic-field measurement and analysis for the Muon* $g-2$ *Experiment at Fermilab*, Phys. Rev. A 103, 042208
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