Latest Results of the Muon g-2 Experiment at Fermilab

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on Behalf of the Muon g-2 Collaboration

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Sections

1. Muon g-2
2. The Experiment
3. The Result
4. Conclusions and Future Perspectives

Muon g-2

Spin Precession in a Magnetic Field

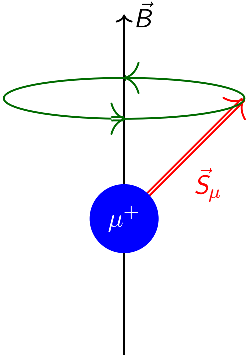
A particle's spin in a magnetic field experience a torque and a precession motion proportional to it's magnetic moment, defined as

$$\vec{\mu} = g\frac{e}{2m}\vec{S}$$

The spin precession frequency is given by:

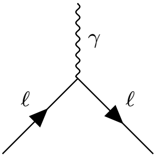
$$\omega_s = g\frac{e}{2m}B$$

- Dirac equation predicts naturally $g = 2$ for a spin $\frac{1}{2}$ elementary particle
- Define the anomaly as $a_\mu := \frac{g-2}{2}$
- Radiative corrections give a positive contribution. Schwinger: $a_\mu \sim \frac{\alpha}{2\pi} \approx 0.00116$ (at first order)



Standard Model Prediction of a_μ

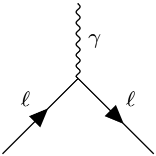
$a_\mu = 0$



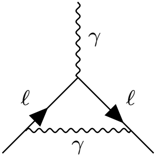
Dirac

Standard Model Prediction of a_μ

$$a_\mu = 0 + a_\mu^{QED}$$



Dirac



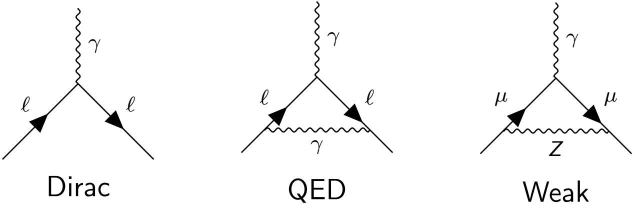
QED

- Highest and most precise contribution to a_μ
- Computed perturbatively

$$a_\mu^{QED} = \sum_{n\geq 1} c^{(2n)} \left(\frac{\alpha}{\pi}\right)^n$$

Standard Model Prediction of a_μ

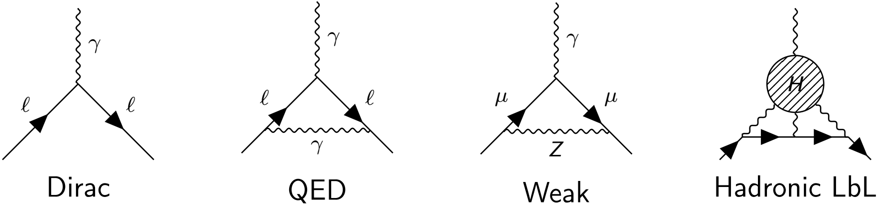
$$a_\mu = 0 + a_\mu^{QED} + a_\mu^{W}$$



- Contribution due to the $Z,\ W,\ H$ exchange
- Computed at 2 loops level
- Well known and with small uncertainty

Standard Model Prediction of a_μ

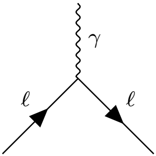
$$a_\mu = 0 + a_\mu^{QED} + a_\mu^{W} + a_\mu^{HLbL}$$



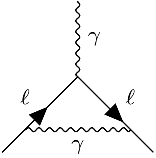
- Second dominant uncertainty source
- At low energies:
  - Data driven
  - Lattice QCD
- Perturbative QCD for c-quark loops

Standard Model Prediction of a_μ

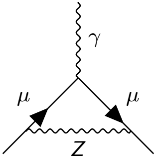
$$a_\mu = 0 + a_\mu^{QED} + a_\mu^{W} + a_\mu^{HLbL} + a_\mu^{HVP}$$



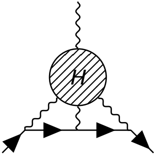
Dirac



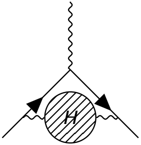
QED



Weak



Hadronic LbL



Hadronic Vacuum Polarization

- Dispersive (data driven):

$$a_\mu^{HVP,LO} = \frac{1}{4\pi^3} \int_{m_\pi^2}^{\infty} ds\ K(s)\ \sigma^0_{e^+e^- \to had}$$

- Lattice QCD calculation shows a discrepancy with the dispersive approach

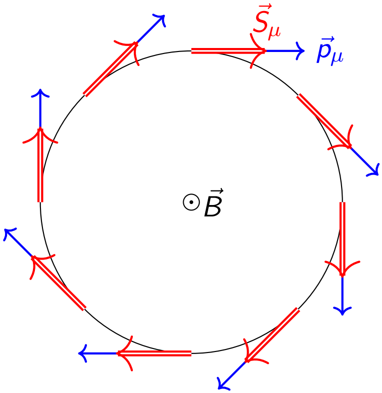
The Experiment

How to measure a_μ

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



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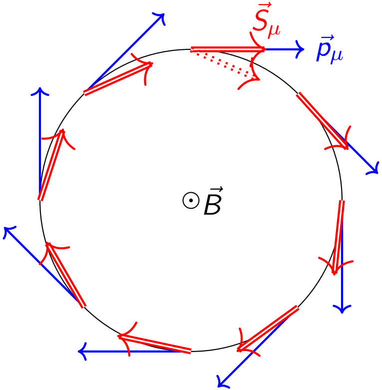
- $a_\mu = 0$ spin and momentum precess at the same rate
- $a_\mu > 0$ the spin has a precession motion around the momentum direction

a_μ can be extracted from a polarized muon beam by measuring ω_a and B:

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



How to measure a_μ (for real)

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

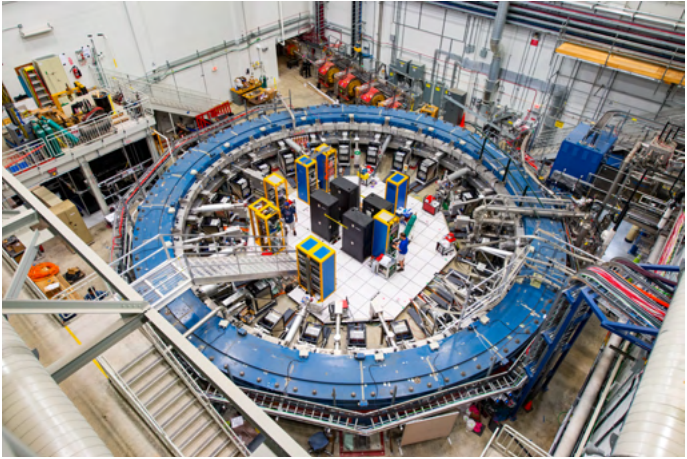
Magnetic field is expressed in term of the shielded proton precession frequency (ω'_p). External factors are known to very high precision (22 ppb uncertainty).

We extract the ratio:

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

- ω_a^{meas} is the the measured precession frequency
- $\tilde{\omega}'_p(T)$ is the the magnetic field magnitude averaged around the ring
- $M(x, y, \phi)$ is the beam distribution along the ring

One Ring To Store Them All...



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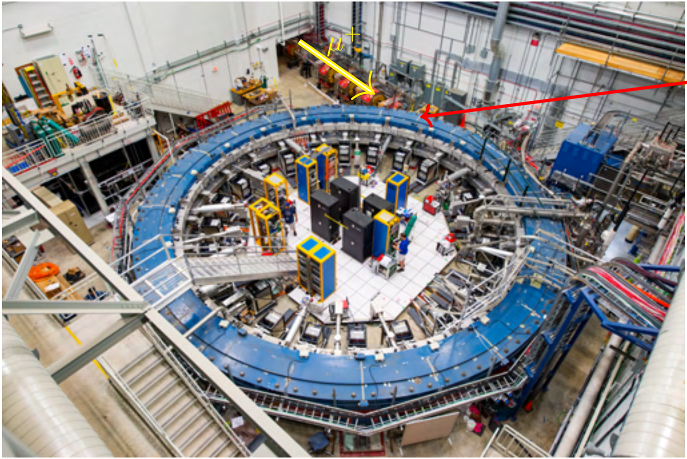
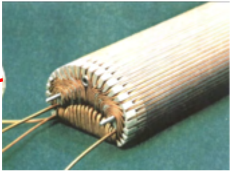
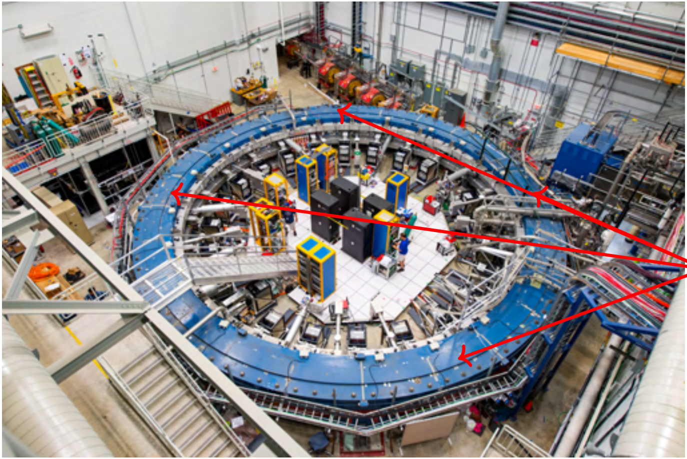
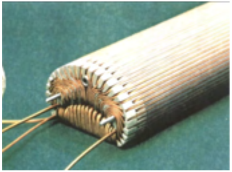


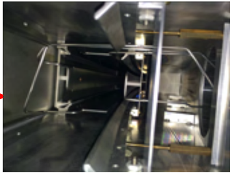


Inflector

One Ring To Store Them All...

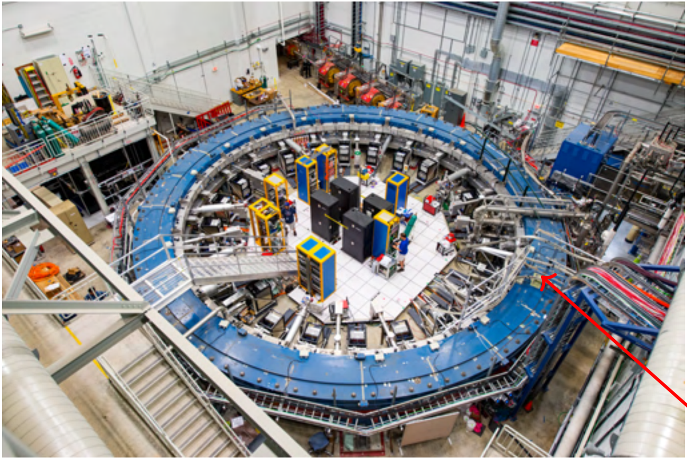




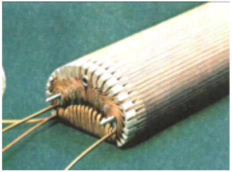


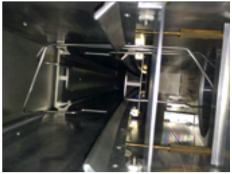
Quadrupoles

One Ring To Store Them All...



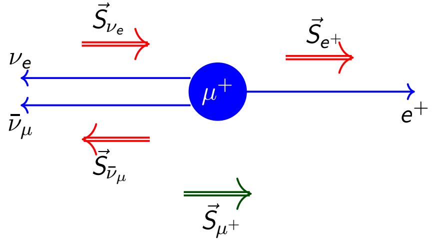
Kickers





How to measure the spin precession frequency

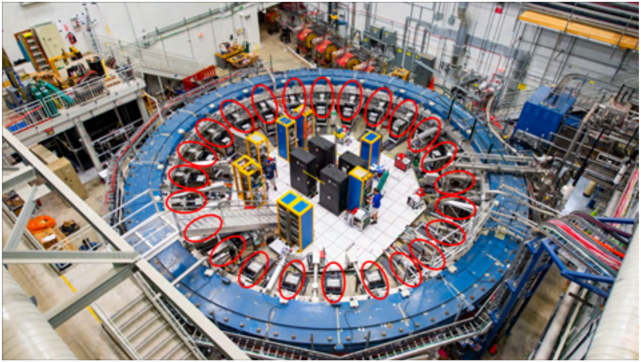
The muon polarization is measured using the parity-violating decay

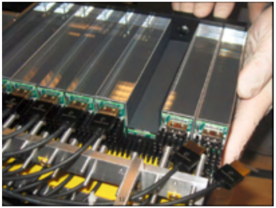


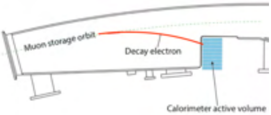
High momentum e^+ are emitted preferentially in the muon's spin direction

Count the number of high energy positrons in a given direction as a function of time to extract the precession frequency

Detect decay positrons







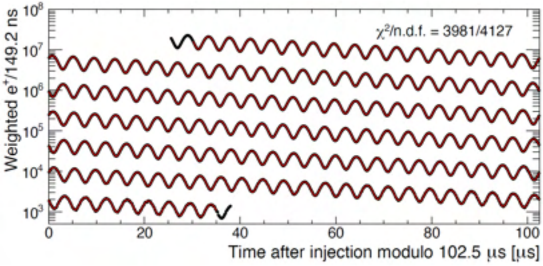
- 24 PbF2 calorimeters along the inner circumference (out of vacuum)
- Čerenkov light is read by large area SiPM
- Gain is monitored at a 10^{-4} level of stability by state of the art Laser Calibration System

Wiggle Plot

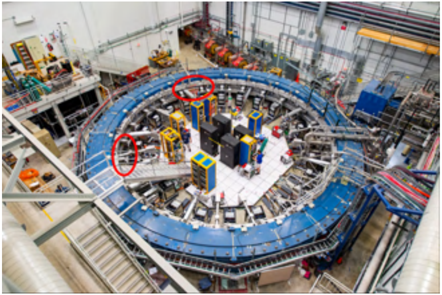
The time distribution of the high energy positrons shows the muons exponential decay modulated by the anomalous precession frequency.

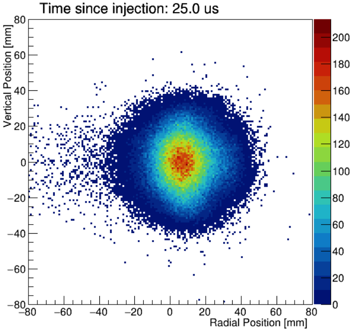
The distribution is fitted to extract ω_a, including:

- Beam Dynamic terms to account for beam oscillations that distort the modulation signal
- Muon Losses that distort the exponential shape of the distribution



Measure Beam Distribution

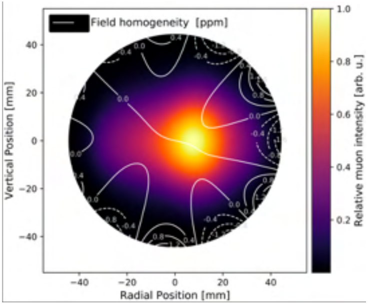




- Two tracker stations monitor the beam profile back-tracking decay positrons
- Provides a non-destructive reconstruction of the beam position over time

Weighted Magnetic Field

- A set of NMR fixed probes measure the field coninuously around the storage region
- Trolley runs to measure the magnetic field inside the storage region
- Dedicated trolley runs every 2/3 days and whenever the magnet is turned on/off
- A field map in the storage region is interpolated using fixed probes and trolley data
- The field map is then weighted with the muon distribution obtained from the tracker

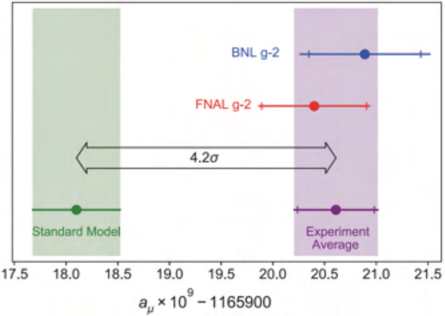


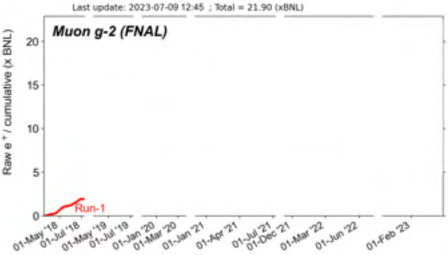
The Result

Run 1 result

On April 2021 we published our first result:

- Based on 5% of the data collected
- Confirmed BNL experiment result (20 years before)
- Increased the discrepancy with the Theory Initiative White Paper to 4.2σ

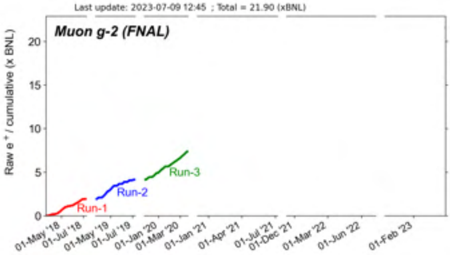




Run 2-3 improvements

After Run 1 many efforts were done to improve the uncertainties:

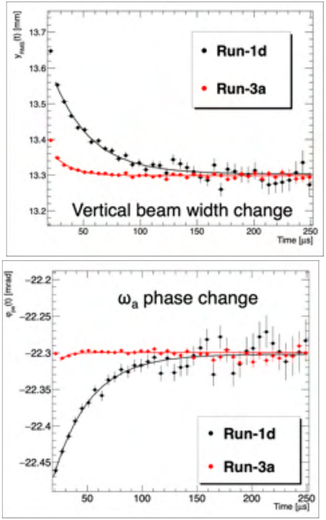
- Statistics
  - Factor 4.7 in the number of analyzed positrons (weighted, $E > 1$ GeV, $t > 30$ μs)
  - Statistical uncertainty decreased from 434 ppb (Run 1) to 201 ppb (Run 2-3)



Run 2-3 improvements

After Run 1 many efforts were done to improve the uncertainties:

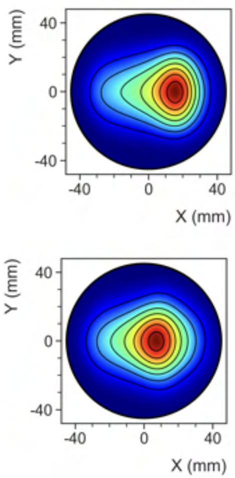
- Statistics
- Beam Storage - Quadrupoles
    - Damaged resistors in Run 1 caused beam motion during the fill; re-designed for Run 2 to reduce beam motion
    - Reduced uncertainty on C_{pa} from 75 ppb to 13 ppb



Run 2-3 improvements

After Run 1 many efforts were done to improve the uncertainties:

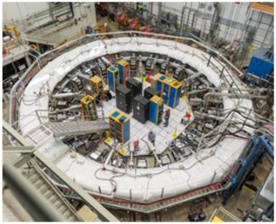
- Statistics
- Beam Storage - Quadrupoles
- Beam Storage - Kickers
    - Kickers strength improved to design value at the end of Run 3
    - Beam more centered, reduced oscillations

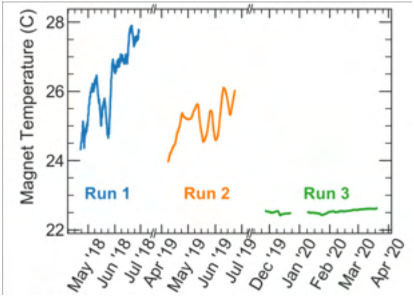


Run 2-3 improvements

After Run 1 many efforts were done to improve the uncertainties:

- Statistics
- Beam Storage - Quadrupoles
- Beam Storage - Kickers
- Temperature stability
    - Thermal insulation added to the ring between Run 1 and Run 2 to improve thermal stability of the magnet
    - A/C hall cooling after Run 2 further improved the stability
    - Reduced magnetic field and SiPM gain variations due to temperature

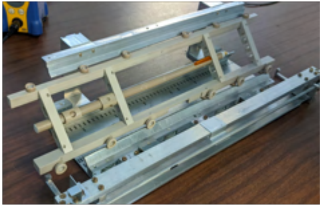


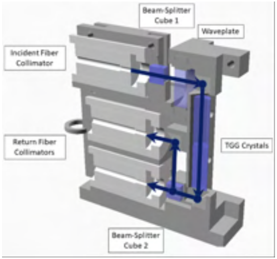


Run 2-3 improvements

After Run 1 many efforts were done to improve the uncertainties:

- Statistics
- Beam Storage - Quadrupoles
- Beam Storage - Kickers
- Temperature stability
- Field Transient Measurement
    - Quadrupoles transient field B_q measured all around the ring (only 2 locations in Run 1)
    - Improved Kicker transient field measurement with fiber magnetometer

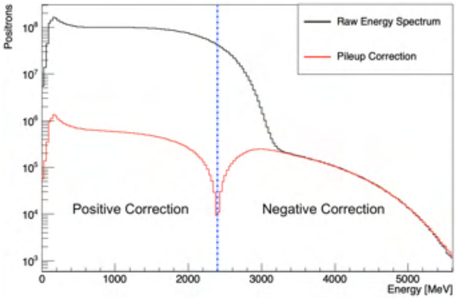




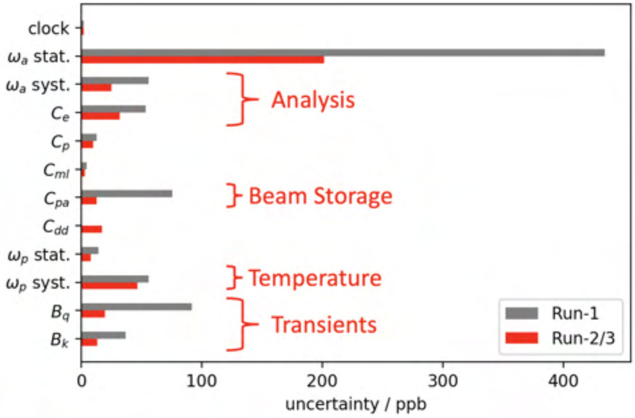
Run 2-3 improvements

After Run 1 many efforts were done to improve the uncertainties:

- Statistics
- Beam Storage - Quadrupoles
- Beam Storage - Kickers
- Temperature stability
- Field Transient Measurement
- Analysis Technique Improvements
    - New positron reconstruction algorithms
    - Improved Pile-Up subtraction technique



Run 2-3 improvements



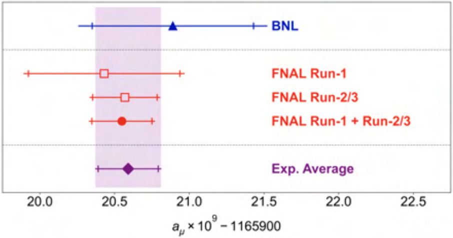
Total Uncertainty:

$$\sigma^{Run1} = 434^{\text{Stat}} + 157^{\text{Syst}} \text{ ppb}$$
$$\sigma^{Run2-3} = 201^{\text{Stat}} + 70^{\text{Syst}} \text{ ppb}$$

Run 2 and 3 result

New result released on the 10th of August 2023

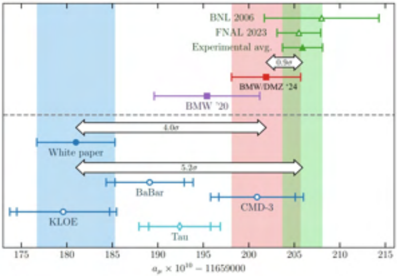
- Result paper: **Phys.Rev.Lett. 131 (2023) 16, 161802**; Analysis Details: **Phys.Rev.D 110 (2024) 3, 032009**
- In excellent agreement with both BNL and Run 1 result
- Reduced by a factor 2.2 statistical and systematic uncertainty



$$
\begin{aligned}
a_\mu^{Run2-3} &= 116\ 592\ 057(25) \times 10^{-11} \quad [0.21\ \text{ppm}] \\
a_\mu^{Run1-2-3} &= 116\ 592\ 055(24) \times 10^{-11} \quad [0.20\ \text{ppm}] \\
a_\mu^{ExpAvg} &= 116\ 592\ 059(22) \times 10^{-11} \quad [0.19\ \text{ppm}]
\end{aligned}
$$

Theory Comparison

- Fermilab result alone yelds to a $> 5\sigma$ discrepancy with the 2020 Theory Initiative calculation



BMW/DMZ24 Collaborations arXiv: 2407.10913

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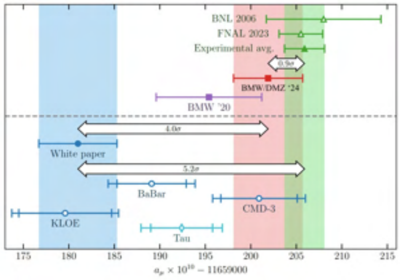
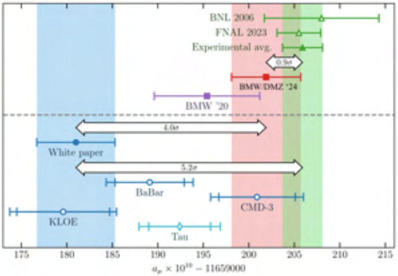
- HVP value from lattice calculations reduces the discrepancy with the experimental value



BMW/DMZ24 Collaborations arXiv: 2407.10913

Theory Comparison

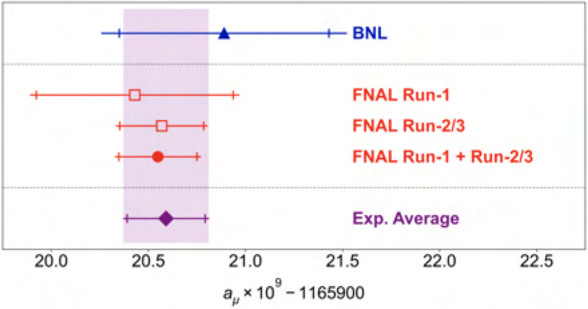
- Fermilab result alone yelds to a $> 5\sigma$ discrepancy with the 2020 Theory Initiative calculation
- HVP value from lattice calculations reduces the discrepancy with the experimental value
- Recent results on $e^+e^- \to \pi^+\pi^-$ cross section from CMD-3 (below 1 GeV) further reduces the discrepancy
- Many efforts on the theory side to resolve theoretical ambiguities



BMW/DMZ24 Collaborations arXiv: 2407.10913

Conclusions and Future Perspectives

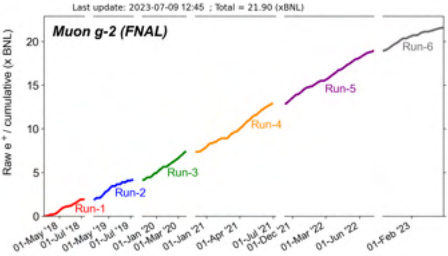
Conclusions



- Presented the result for the measurement of a_μ with the Run 2 and 3 data
- Result is in good agreement with both the Run 1 and the BNL results
- Improved by a factor 2.2 both on statistical and systematic uncertainties
- Reached the systematic goal of 70 ppb from the TDR
- Achieved precision of 0.19 ppm on the combined a_μ measurement

Future Perspectives

- On the 9th of July 2023 concluded the data-taking of the experiment reaching the statistical goal of 21 times the BNL dataset
- Run6 dedicated to systematic studies to better understand the beam related corrections
- Between 2023 and 2024 conducted an intensive campaign of systematic measurements on the magnet
- Run 4-5-6 under analysis, full result expected to be completed in 2025
- Same datasets analyzed for Muon EDM, Dark Matter and Lorentz-CPT violation searches



Thanks for all the Muons