Results and Perspectives on the Muon g-2 Experiment at Fermilab

A Muon g-2 storm seems to be brewing

Marco Incagli, INFN-Pisa
CERN seminar
5 September 2023
What is “g-2”? 

\[ \tilde{\mu}_P = -g_P \frac{e}{2m_P} \hat{S} \]

- \( g_P \): proportionality constant between spin and magnetic moment for particle P
- \( a_P \): magnetic anomaly
- \( a_P = 0 \) at tree level (purely Dirac particle)

Using modern language, the term \((g-2)/2\) reflects the magnitude of the Feynmann diagrams beyond leading order.

\[ a = 0 + \frac{\alpha}{2\pi} + \ldots \]
Standard Model Components of $g_\mu$

- **QED** dominates the value itself
- Uncertainty is dominated by **QCD**, in particular by the Hadronic Vacuum Polarization (**HVP**) term
- SM values taken from the **Muon g-2 Theory Initiative**
- Last compilation in 2020:
  
  https://doi.org/10.1016/j.physrep.2020.07.006

\[ a_\mu = 0 + 0.00116584719 + 0.00000000154 + 0.000000000092 + 0.000000006845 \]
HVP Calculation: Dispersive ($e^+e^-$) Method

$$a^{HLO} = \frac{1}{4} \left( \frac{3}{4m^2} \right) \int_{4m^2}^{\infty} e^+e^- \rightarrow \text{hadr} (s) K(s) ds$$

- Kernel function: $K(s) \propto \frac{1}{s}$
- Due to the $1/s$ term, the low energies most important

$$R = \frac{\text{had}}{0}$$

R-ratio
Standard Model Components of $g_\mu$

- Hadronic Light Equation
- QED
- Electroweak
- Hadronic Light-by-Light
- Hadronic Vacuum Polarization

$$a_\mu = 0 + 0.00116584719 + 0.00000000154 + 0.00000000092 + 0.000000006845$$

- Everything in SM needs to be included here: but are we sensitive to some **physics beyond the SM**?
- We can compare **experimental & predicted** values and ask:

  **“Is there some New Physics in our experiment that isn’t in the Standard Model?”**
A rich history of g-2 Theory and Experiment

Situation before Fermilab exp.: tension between theory and experiment

5/Sep/23  Marco Incagli - INFN Pisa
Fermilab Run-1 Result (2021)

- BNL E821 (2004) disagreed with SM prediction:
  
  - 7th April 2021, we released our Run-1 result
  - Using only 5% of our data, we confirmed BNL value
  - FNAL+BNL average stood 4.2σ from Theory Initiative White Paper (2020)

- Today’s talk is mostly about the new experimental result
- There have also been some new results from the SM prediction side of the plot…

https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.126.141801
https://doi.org/10.1016/j.physrep.2020.07.006
The Fundamental Experimental Principle

- Difference between spin precession and cyclotron revolution for a muon (charged particle with spin) in a magnetic field*:

\[ \omega_a = \omega_s - \omega_c = g \frac{e}{2m} B - \frac{e}{m} B = \frac{g - 2}{2} \frac{e}{m} B = a_\mu \frac{e}{m} B \]

*\( s \) and \( p \) are assumed to be in a plane perpendicular to \( B \)

- simple classical calculation
- the relativistic approach provides the same result
From single muon to *muon beam*

- The expression is more complicated when you add in $E$-field focusing and out of plane oscillations

\[
\omega_a = \frac{q}{m} a_\mu B
\]

- The motion is very nearly planar and the momentum is very nearly the ideal one, but both effects are not perfect and require corrections

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

0 if "in plane"

Term cancels at 3.094 GeV/c, the "Magic $\gamma$"
The *Cern3 g-2* experiment

- Emilio Picasso view of the *Cern3 g-2* experiment

[Video from CERN CDS Video Service](https://videos.cern.ch/record/43113)
Creating the Muon Beam for g-2:

- 8 GeV protons into the Recycler
- Target for pion production
- Long FODO channel to collect $\pi \rightarrow \mu \nu$
- Pions decay in ~2km channel
- $\mu$ enter storage ring
How do we measure the spin direction?

- Use V-A structure of weak decays to build a polarized beam...

![Pion Rest Frame Diagram](image1)

- ... and to measure the muon polarization looking for energetic positrons

![Muon Rest Frame Diagram](image2)
The number of observed positrons above a threshold energy oscillates with the \( \omega_x/2\pi \) frequency due to spin precession.

\[
N(t) = N_0 e^{t/\tau} \left[ 1 + A \cos(\omega_x t + \phi) \right]
\]

- exponential decay modulated by spin precession
- note that the x-axis "wraps up" every 100 \( \mu \text{sec} \) for a total of \( \sim 700 \mu \text{s} \) \( \rightarrow \sim 10 \) muon lifetimes
Extracting $a_\mu$ (simplified)

\[ \omega_a = a_\mu \left( \frac{e}{m} \right) B \rightarrow a_\mu = \frac{\omega_a}{B} \left( \frac{m}{e} \right) \]

by expressing $B$ in terms of the (shielded) proton precession frequency: $(B = \hbar \omega'_p / 2\mu'_p)$:

\[
a_\mu = \frac{\omega_a}{\tilde{\omega}'_p} \cdot \frac{\mu'_p m_\mu g_e}{\mu_e m_e 2}
\]

External data

\[
R'_\mu = \frac{\omega_a}{\tilde{\omega}'_p}
\]

ratio of muon to proton precessions in the same magnetic field

\[
\tilde{\omega}'_p = \text{(shielded) Proton angular velocity weighted for the muon distribution}
\]
The key ingredients

\[ R'_\mu = \frac{\omega_a}{\tilde{\omega}'_p} \]

\[ \tilde{\omega}'_p = \omega'_p \cdot M(x, y, \varphi) \]

muon precession

proton precession

muon distribution

\[ M(x, y, \varphi) \] magnetic field weighted by the muon distribution in the Storage Ring
24 Calorimeters + 2 trackers located all around the ring

NMR probes and electronics located all around the ring
Real World Experiment: Storage Ring

- 14 m diameter, 1.45 T C-shaped magnet stores muons
Measuring the Field: NMR Probes

- In-vacuum NMR trolley maps field every ~3 days

- 17 petroleum jelly NMR probes
- 2D field maps (~8000 points)
- Azimuthally-Averaged Variation < 1 ppm

- 378 fixed probes monitor field during muon storage at 72 locations
Calibration of Field Measurements

- Cross-calibrate using a cylindrical **plunging H$_2$O probe** which repeatedly **changes places with trolley** (petroleum jelly probes)

![Diagram of Calibration Volume with Trolley and Plunging Probe]

- This probe is **checked against a spherical probe** using an MRI magnet at ANL
- Both also cross-checked against a **$^3$He probe** (different systematics)

![Images of H$_2$O Probe and $^3$He Probe]
Real World Experiment: Muon Injection

- Muons are injected into storage ring & bend in the $B$ field
Real World Experiment: Kicker

- Fast kicker magnet tweaks direction from injection trajectory to center of aperture

μ⁺
Real World Experiment: Quads

Electrostatic quadrupoles vertically contain the beam.
Real World Experiment: Decay Positrons

- Experiment measures decay $e^+$ which curl inwards as they have lower momentum.
Real World Experiment: Trackers

- We measure the decay point with 2 trackers
Muon Distribution from Trackers:

- Measure **beam oscillations** directly
  - Beam-dynamics corrections
  - Tuning simulations
  - Optimizing experiment running
Muon Distribution from Trackers:

- Measure **beam oscillations** directly
  - Beam-dynamics corrections
  - Tuning simulations
  - Optimizing experiment running

- Use distribution to weight the field maps by where the muons live
Real World Experiment: Calorimeters

- Time & energy of decay $e^+$ are measured by 24 calorimeters
Measuring $\omega_a$ : 5 parameters fit function

- Fit with simple positron oscillation:
  \[ N_e(t) = N_0 \exp\left(-\frac{t}{\tau_\mu}\right) \left[1 + A \cos(\omega_a t + \varphi)\right] \]

- This simple fit is clearly not sufficient and well defined resonances are observed in the residuals

Muon lifetime: $\tau_\mu = \gamma \tau_{0\mu} = 64.33$ μsec

CBO = Coherent Betatron Oscillations
VW = Vertical Waist (oscillations)

RESIDUALS (in frequency space)
The complete 22 parameters fit function

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

\[ A_{BO}(t) = 1 + A_A \cos(\omega_{CBO}(t) + \phi_A) e^{-\frac{t}{\tau_{CBO}}} \]
\[ \phi_{BO}(t) = 1 + A_{\phi} \cos(\omega_{CBO}(t) + \phi_{\phi}) e^{-\frac{t}{\tau_{CBO}}} \]
\[ N_{CBO}(t) = 1 + A_{CBO} \cos(\omega_{CBO}(t) + \phi_{CBO}) e^{-\frac{t}{\tau_{CBO}}} \]
\[ N_{2CBO}(t) = 1 + A_{2CBO} \cos(2\omega_{CBO}(t) + \phi_{2CBO}) e^{-\frac{t}{2\tau_{CBO}}} \]
\[ N_{VW}(t) = 1 + A_{VW} \cos(\omega_{VW}(t) + \phi_{VW}) e^{-\frac{t}{\tau_{VW}}} \]
\[ N_y(t) = 1 + A_y \cos(\omega_y(t) t + \phi_y) e^{-\frac{t}{\tau_y}} \]
\[ J(t) = 1 - k_{LM} \int_{t_0}^{t} \Lambda(t) dt \]

\[ \omega_{CBO}(t) = \omega_0 t + A e^{-\frac{t}{\tau_A}} + B e^{-\frac{t}{\tau_B}} \]
\[ \omega_y(t) = F \omega_{CBO}(t) \sqrt{2\omega_c/F \omega_{CBO}(t)} - 1 \]
\[ \omega_{VW}(t) = \omega_c - 2\omega_y(t) \]

Red = free parameters
Blue = fixed parameters

Lost muons (μ hitting collimators)
Final fit to get $\omega_\alpha$
Real World Complications: Corrections

- We need to make corrections for several small effects:

\[
\frac{\omega_a}{\omega_p} = \frac{\omega_a^m}{\omega_p^m} \frac{1 + C_e + C_p + C_{pa} + C_{dd} + C_{ml}}{1 + B_k + B_q}
\]

- E-field & Up/Down motion: Spin precesses slower than in basic equation
- Phase changes over each fill: Phase-Acceptance, Differential Decay, Muon Losses

- Total correction is 622 ppb, dominated by E-field & Pitch…
Run-2/3 Uncertainty Improvement Categories

**Statistics**

**Running Conditions**

**Systematic Measurements & Studies**

**Analysis Improvements**
Run-2/3 Uncertainty Improvement Categories

Statistics

Running Conditions

Systematic Measurements & Studies

Analysis Improvements
Run-2/3 Improvement: Statistics

Weighted e\(^+\) in our final fit after quality control

E > 1 GeV
t > 30 us

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

<table>
<thead>
<tr>
<th>Dataset</th>
<th>Statistical Error [ppb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run-1</td>
<td>434</td>
</tr>
<tr>
<td>Run-2/3</td>
<td>201</td>
</tr>
<tr>
<td>Run-1 + Run-2/3</td>
<td>185</td>
</tr>
</tbody>
</table>
Run-2/3 Uncertainty Improvement Categories

Statistics

Systematic Measurements & Studies

Running Conditions

Analysis Improvements
Running Conditions: Hall Temperature

- Temperature stability makes magnetic field less variable

![Graph showing temperature stability and magnetic field variability over time with added insulation highlighted.](image-url)
Running Conditions: Hall Temperature

- Temperature stability makes magnetic field less variable
Running Conditions: Kicker Strength

- Last 18% of Run-2/3 has upgraded, stronger kicker
  - Mom. distribution more centered
  - Lower E-field correction $C_e$
  - Phase space matching improved
  - Smaller beam oscillations
Run-2/3 Uncertainty Improvement Categories

Statistics

Systematic Measurements & Studies

Running Conditions

Analysis Improvements
Improved Measurements: Quad Transient Field

- Pulsing quads vibrate ⇒ oscillating magnetic fields
- Measured with a new NMR probe housed in insulator

![Graph showing field change over time](image)

- For Run-1 analysis, we had **limited measurement positions**
- Largest Run-1 systematic: **92 ppb**
Improved Measurements: Quad Transient Field

- For Run-2/3 analysis, **probe runs on the trolley rails**
- Allows **full mapping** of all quad stations:

- Uncertainty is reduced to **20 ppb**
Improved Measurements: Kicker Transient Field

- Kicker creates eddy currents ⇒ transient magnetic field

- Run-2/3 has lower vibration noise vs. Run-1

- Uncertainty reduces from 37 ppb to 13 ppb
Run-2/3 Uncertainty Improvement Categories

Statistics

Running Conditions

Systematic Measurements & Studies

Analysis Improvements
Analysis Improvements: *Pile-up*

- *Pile-up*: 2 e\(^+\) arriving at same time $\rightarrow$ 1 cluster in ECAL
- Probability higher at injection (more muons): can bias $\omega_a$
- Clusters with E>3.1GeV are certainly *Pile-up*
- Reduced uncertainty by:
  - Improved reconstruction
  - Improved correction algorithms
Uncertainty Improvements Summary

- Systematic improvements in **all parameters**

\[
\frac{\omega_a}{\omega_p} = \frac{\omega_a^m}{\omega_p^m} \frac{1 + C_e + C_p + C_{pa} + C_{dd} + C_{ml}}{1 + B_k + B_q}
\]

- **Analysis Improvements**
  - \( \omega_a \) syst.
  - \( C_e \)
  - \( C_p \)
  - \( C_{ml} \)
  - \( C_{pa} \)
  - \( C_{dd} \)
  - \( \omega_p \) syst.

- **Running Conditions**
  - \( B_q \)
  - \( B_k \)

- **Improved Measurements**
Run-2/3 Uncertainties: Final Values

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Correction</th>
<th>Uncertainty [ppb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\omega_a^m$ (statistical)</td>
<td>–</td>
<td>201</td>
</tr>
<tr>
<td>$\omega_a^m$ (systematic)</td>
<td>–</td>
<td>20</td>
</tr>
<tr>
<td>$C_e$</td>
<td>451</td>
<td>32</td>
</tr>
<tr>
<td>$C_p$</td>
<td>170</td>
<td>10</td>
</tr>
<tr>
<td>$C_{pa}$</td>
<td>-27</td>
<td>13</td>
</tr>
<tr>
<td>$C_{dd}$</td>
<td>-15</td>
<td>17</td>
</tr>
<tr>
<td>$C_{ml}$</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>$f_{\text{calib}}(\omega_p(\tilde{r}) \times M(\tilde{r}))$</td>
<td>–</td>
<td>46</td>
</tr>
<tr>
<td>$B_k$</td>
<td>-21</td>
<td>13</td>
</tr>
<tr>
<td>$B_q$</td>
<td>-21</td>
<td>20</td>
</tr>
<tr>
<td>$\mu_p'(34.7^\circ)/\mu_e$</td>
<td>–</td>
<td>11</td>
</tr>
<tr>
<td>$m_{\mu}/m_e$</td>
<td>–</td>
<td>22</td>
</tr>
<tr>
<td>$g_e/2$</td>
<td>–</td>
<td>0</td>
</tr>
<tr>
<td>Total systematic</td>
<td>–</td>
<td>70</td>
</tr>
<tr>
<td>Total external parameters</td>
<td>–</td>
<td>20</td>
</tr>
<tr>
<td>Totals</td>
<td>622</td>
<td>215</td>
</tr>
</tbody>
</table>

- Total uncertainty is **215 ppb**

<table>
<thead>
<tr>
<th>[ppb]</th>
<th>Run-1</th>
<th>Run-2/3</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Stat.</strong></td>
<td>434</td>
<td>201</td>
<td>2.2</td>
</tr>
<tr>
<td><strong>Syst.</strong></td>
<td>157</td>
<td>70</td>
<td>2.2</td>
</tr>
</tbody>
</table>

- Near-equal improvement: We’re still statistically dominated

Systematic uncertainty of 70 ppb surpasses our proposal goal of 100 ppb!
Blind Analysis

• Perform analysis with **software & hardware blinding**
• Hardware blind comes from **altering our clock frequency**

Non-collaborators set frequency to \((40 - \delta) \text{ MHz}\)

• Clock is locked and **value kept secret** until analysis completed
July 24th 2023: Unblinding

- Physics week in Liverpool for unblinding meeting:
  - Unanimous vote from all collaborators to unblind!
  - Secret envelopes were finally opened to reveal the hidden clock frequencies and the result…

Photo credits: McCoy Wynne
... a moment of panic!

- two layers of unblinding: software and hardware
- first the software unblinding was removed and the following image appeared on screen: few seconds of panic!

![Graph](image.png)

- $\chi^2/\text{dof} = 21.52/1$
- $\chi^2/\text{dof} = 37.82/2$

- Unblinding: Run 3 blind clock $= 39988000$ Hz
  - DeltaR [ppb] = 14864.089, total RmupT shift $-0.000$ [ppb]
  - $= 0.0037072920774(7904)$ [213 ppb]

- 39,998,000 Hz

- 5/Sep/23
- Marco Incagli
- INFN Pisa

- $a_\mu \cdot 10^9 - 1165900$
- $+3.66 \sigma$, BNL 2006
- $1165920.893(629) \cdot 10^{-9}$
- $+3.38 \sigma$, FNAL Run 1
- $1165920.430(539) \cdot 10^{-9}$
- $-0.60 \sigma$, FNAL Run 2+3
- $1165917.800(250) \cdot 10^{-9}$
- $+0.17 \sigma$, FNAL Run 1+2+3
- $1165918.184(236) \cdot 10^{-9}$
- $+0.86 \sigma$, Exp. WA
- $1165918.515(221) \cdot 10^{-9}$
- Muon g-2 th. init. 2020
- $1165918.100(430) \cdot 10^{-9}$
After inserting the secret frequency ...

- The secret frequency, written in the two envelopes, was inserted in the program
Run-2/3 Result: Measured Value

\[ a_\mu(\text{FNAL; Run-2/3}) = 0.00\ 116\ 592\ 057(25) [215\ \text{ppb}] \]

- Excellent agreement with Run-1 and BNL!
- Uncertainty more than halved to 215 ppb
- Both FNAL values dominated by statistical error
- Assume systematics are 100% correlated and combine…
Run-2/3 Result: FNAL Run-1 + Run-2/3 Combination

\[ a_\mu(\text{FNAL}) = 0.00116592055(24) \, [203 \, \text{ppb}] \]

- FNAL combination: 203 ppb uncertainty
- Both FNAL and BNL dominated by statistical error
Run-2/3 Result: FNAL + BNL Combination

\[ a_\mu(\text{FNAL}) = 0.00 \ 116 \ 592 \ 055(24) \ [203 \ \text{ppb}] \]

- FNAL combination: 203 ppb uncertainty
- Both FNAL and BNL dominated by statistical error
- Combined world average dominated by FNAL values.

\[ a_\mu(\text{Exp}) = 0.00 \ 116 \ 592 \ 059(22) \ [190 \ \text{ppb}] \]
Measurements at Different Magnetic Fields

- Datasets were taken at slightly different field settings
- Allows a cross check with one of the most basic “handles”:

Also checked $a_\mu$ against temperature, day/night & others
Theory prediction is less clear now, but we can still compare experiment vs theory. Large discrepancy between experiment and WP (2020). Significance for Fermilab alone get to $5.0\sigma$. ... but the theoretical band is not as sharp as it was in the 2021 comparison!
HVP Calculation: Lattice QCD Method

- **Ab-initio** calculation of HVP on lattice
- Results **not included** in White Paper (2020)

- BMW collaboration reached the precision of 0.8%, comparable to R-ratio method
- Their calculation is closer to the experimental result
- Other groups are cross checking
- Intermediate stages agree, but no full HVP calculations to same precision.
Theory prediction is less clear now, but we can still compare

- Include **BMW** result by swapping HVP from WP with their value
- As expected, BMW falls in between WP (2020) and experiment
HVP Calculation: Dispersive (e⁺e⁻) Method

- Calculated from data for σ(e⁺e⁻→ hadrons)

\[ a_{\mu}^{\text{HVP,LO}} = \frac{\alpha^2}{3\pi^2} \int_{s_{\text{th}}}^{\infty} \frac{K(s)}{s} R(s) \, ds \]

- Analyticity & Unitarity

- Uses **data** from different experiments from **20+ years**
- **1/s weights low energy strongly:** 73% from π⁺π⁻ channel

**New results from SND2k and CMD-3 since White Paper**

- **CMD-3 is discrepant**
- **... what is going on?**
**Data Collection 2018 – 2023**

Last update: 2023-07-11 08:26; Total = 21.90 (xBNL)

- **Apr. 2021:** Run-1 Result (2018 data)
- **Aug. 2023:** Run-2/3 Result (2019-20 data)
- **~2025:** Run-4+5+6 Result (2021-23 data)
  - Reach our proposal goal for statistics (~21 BNL)

9 July 2023
Director Lia Merminga switches off the beam in **Muon g-2 control room**
The experimental landscape will improve …

1. FNAL Muon g-2:
   - \(a_\mu\) measured at 0.2 ppm
   - data already available to reduce error to < 0.14 ppm

2. A new type of experiment projected at J-Parc using low energy muons (p~300 MeV/c)
   - new technique
   - under construction
   - final goal ~0.4 ppm
The experimental landscape will improve …

Ongoing work in experimental inputs on $\sigma(e^+e^-\rightarrow \text{hadrons})$

- **Initial State Radiation technique:**
  - **BaBar:** new analysis of large $\pi\pi$ data set with better detector
  - **KLOE:** new analysis of 7x larger $\pi\pi$ set
  - **BESIII:** new results for $\pi\pi$ channel and $\pi\pi\pi$
  - **Belle II:** promising greater statistics than BaBar or KLOE and similar or better systematics for low-energy cross sections

- **Energy scan (VEPP-2000 machine in Novosibirsk)**
  - **SND:** new results for $\pi\pi$ channel
  - **CMD-3:** confirmation of their result on $\pi\pi$ channel; more channels to be analyzed
The theoretical landscape will improve …

1. close scrutiny of lattice calculations to establish its solidity
   – how to reconcile it with dispersion approach?

2. Use the dispersive approach with t-channel data (muon-electron scattering), instead of the standard s-channel
   – Letter Of Intents submitted at CERN: Muone (mu-on-e scattering)

\[ a_{\mu}^{\text{HLO}} = \frac{\alpha}{\pi} \int_0^1 dx \ (1 - x) \Delta \alpha_{\text{had}}[t(x)] \]

\[ t(x) = \frac{x^2 m_\mu^2}{x - 1} < 0 \]

\( \Delta \alpha_{\text{had}}(t) \) is the hadronic contribution to the running of \( \alpha \) in the spacelike region: \( a_{\mu}^{\text{HLO}} \) can be extracted from scattering data!
Conclusions

- We’ve determined $a_\mu$ to an unprecedented \textbf{203 ppb} precision
- New result is in \textbf{excellent agreement} with Run-1 & BNL
- More than \textbf{halved the total uncertainty} from Run-1
- Smashed our design goal with systematic uncertainty of \textbf{70 ppb}.
- There’s \textbf{more data} to analyze and we’ll squeeze uncertainty down further in our future results!
EXTRAS
Running Conditions: Damaged Quad Resistors

- Run-1 had damaged resistors in 2/32 quad plates leading to unstable beam storage
- Resistors re-designed & replaced before Run-2
- $C_{pa}$ uncertainty is reduced ($75 \text{ ppb} \rightarrow 13 \text{ ppb}$)
- Beam oscillation frequencies are also more stable
Experiment vs Theory Comparison

- Theory prediction is less clear now, but we can still compare

Following A. Keshavarzi at Lattice 2023...

- Substitute **CMD-3** data for HVP below 1 GeV
- Cherry-picking one experiment but gives a bounding case
- **SND2k** cannot be processed in this way, but would fall closer to WP (2020).
- Many parallel efforts are underway to resolve the theoretical ambiguity

Disclaimer from A. Keshavarzi’s Lattice 2023 talk:

**IMPORTANT: THIS PLOT IS VERY ROUGH!**
- TI White Paper result has been substituted by CMD-3 only for 0.33 → 1.0 GeV.
- The NLO HVP has not been updated.
- It is purely for demonstration purposes → should not be taken as final!

Fermilab
Theory Prediction
Lattice QCD
HVP Calculation: Lattice QCD Method Status

- Other groups are working to reproduce BMW result
- Start with “windowing” method and compare in easiest region

- Cut off effects suppressed
- No signal-to-noise problem
- Finite-volume effects small
3.8$\sigma$ tension between lattice QCD and data-driven evaluation [Colangelo et al., 2205.12963].

This accounts for 50% of the difference between BMW 20 and the White Paper average for $a_{\mu}^{\text{HV}}$. 
Simone Kuberski, Lattice 2023

The Intermediate-Distance Window

- 3.8 $\sigma$ tension between lattice QCD and data-driven evaluation [Colangelo et al., 2205.12963].

- This accounts for 50% of the difference between BMW 20 and the White Paper average for $a_\mu^{\text{hvp}}$.

- Agreement across many actions for the light-connected contribution (87%).

- Data-driven estimate: [Benton et al., 2306.16808] [Golterman]
Theory Prediction
Future Prospects
Dispersive Approach: Future Prospects for HVP

A. El-Khadra P5 town hall, 21-24 Mar 2023

Ongoing work on experimental inputs:
- BaBar: new analysis of large data set in $\pi\pi$ channel, also $\pi\pi\pi$, other channels, other channels
- KLOE: new analysis of large data in $\pi\pi$ channel, other channels
- SND: new results for $\pi\pi$ channel, other channels in progress
- BESIII: new results in 2021 for $\pi\pi$ channel, continued analysis also for $\pi\pi\pi$, other channels
- Belle II: arXiv:2207.06307 (Snowmass WP)
  Better statistics than BaBar or KLOE; similar or better systematics for low-energy cross sections
- STCF: arXiv:2203.06961
- Need blind analyses to resolve the tensions (esp. for $\pi\pi$ channel)

Ongoing work on theoretical aspects:
- Developing NNLO Monte Carlo generators (STRONG 2020 workshop https://agenda.infn.it/event/28089/) [appendix]
- radiative corrections using FsQED (scalar QED + pion form factor)
- charge asymmetry (CMD-3 measurement) vs radiative corrections [Ignatov + Lee, arXiv:2204.12235]
- development of new dispersive treatment of radiative corrections in $\pi\pi$ channel [Colangelo et al, arXiv:2207.03495]
- including $\tau$ decay data: requires nonperturbative evaluation of IIB correction [M. Bruno et al, arXiv:1811.00508]

If the differences between experiments are resolved:
data-driven evaluations of HVP with ~ 0.3% feasible by ~2025
Lattice QCD: Future Prospects for HVP

A. El-Khadra P5 town hall, 21-24 Mar 2023

HVP: lattice

Ongoing work:
- Evaluations of short-distance windows [ETMC, RBC/UKQCD]
- Proposals for computing more windows:
  - Use linear combinations of finer windows to locate the tension (if it persists) in $\sqrt{s}$ [Colangelo et al, arXiv:12963]
  - Use larger windows, excluding the long-distance region $t \gtrsim 2\,\text{fm}$ to maximize the significance of any tension [Davies at at, arXiv:2207.04765]

For total HVP:
- Independent lattice results at sub-percent precision: coming soon!
- Including $\pi\pi$ states for refined long-distance computation (Mainz, RBC/UKQCD, FNAL/MILC)
- Include smaller lattice spacings to test continuum extrapolations (needs adequate computational resources)

If results are consistent, Lattice HVP (average) with $\sim 0.5\%$ errors feasible by 2025
Theory vs Experiment
### Differences between $a_\mu$ values:

Sigma deviation between different predictions/measurements

<table>
<thead>
<tr>
<th></th>
<th>FNAL 2023 (World Ave)</th>
<th>WP 2020</th>
<th>BMW</th>
<th>CMD-3</th>
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<tr>
<td>Exp</td>
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<td>-</td>
<td></td>
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<tr>
<td>WP 2020</td>
<td>5.0 (5.1)</td>
<td>-</td>
<td></td>
<td></td>
</tr>
<tr>
<td>BMW</td>
<td>1.6 (1.7)</td>
<td>2.0</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>CMD-3</td>
<td>1.4 (1.5)</td>
<td>2.8</td>
<td>0.4</td>
<td>-</td>
</tr>
</tbody>
</table>

- Comparisons are taken from the whole $a_\mu$ value.
- They’re accurate when comparing to experiment.
- But e.g. WP (2020) & BMW both include same H-LbL components and error, so significance of difference between them is a little underestimated (2.0 vs 2.2σ).
BSM Physics
Discrepancy and New Physics:
(Experimentalist's (mis)Understanding)

D. Stöckinger:

\[ \text{discrepancy} \approx 2 \times a_{\mu}^{\text{SM,weak}} \]

but: expect \( a_{\mu}^{\text{NP}} \sim a_{\mu}^{\text{SM,weak}} \times \left( \frac{M_W}{M_{NP}} \right)^2 \times \text{couplings} \)

loop-induced, CP- and Flavor-conserving, chirality-flipping

compare:

\[ b \rightarrow s\gamma \quad \text{EDMs, } B \rightarrow \tau \nu \quad \mu \rightarrow e\gamma \quad \text{EWPO} \]
Discrepancy and New Physics: (Experimentalist’s (mis)Understanding)

Which models can still accommodate large deviation?

**SUSY:** MSSM, MRSSM
- MSugra... many other generic scenarios
- Bino-dark matter + some coannihil. + mass splittings
- Wino-LSP + specific mass patterns

Two-Higgs doublet model
- Type I, II, Y, Type X (lepton-specific), flavour-aligned

Lepto-quarks, vector-like leptons
- Scenarios with muon-specific couplings to $\mu_L$ and $\mu_R$

Simple models (one or two new fields)
- Mostly excluded
- Light N.P. (ALPs, Dark Photon, Light $L_\mu - L_\tau$)
Detectors
Calorimeter Location

- 24 EM calorimeters inside the ring to measure decay $e^+$
Calorimeter Design

• Array of 54 PbF$_2$ crystals - 2.5 x 2.5 cm$^2$ x 14 cm (15X$_0$)
• Readout by SiPMs to 800 MHz WFDs (1296 channels)
Calorimeter Performance

Energy Resolution

\[ \sigma_{E/E} \sim 2.8\% @ 2 \text{ GeV} \]

Timing Resolution

\[ \sigma_t \sim 25 \text{ ps} \]

Electron pile-up

Temporal separation at 5 ns

See NIMA 783 (2015), pp 12–21 for details
GAIN stability established to $\sim$few x $10^{-4}$

State-of-the-art Laser-based calibration system also allows for pseudo data runs for DAQ

10$^{-4}$ / h demonstrated (in Test Beam)
Muon Distribution $M_\mu$

- Want the **field actually experienced by muons**, so need to know **where muons are** in the field map.

- Measured with **two straw trackers** inside storage vacuum.
Tracker: Hawk-Eye with Muons

- Each tracker is made up of 8 modules inside vacuum chamber:
Tracker: Hawk-Eye with Muons

- A muon decays to a positron which travels through tracker
- $e^+$ position is recorded in tracker modules
- Hits are grouped and reconstructed into a track
- Track is extrapolated backwards to beam storage region
Corrections
E-field & Pitch Corrections:

- Non-simplified spin-motion is described by BMT equation:
  \[
  \frac{d(\hat{\beta} \cdot \vec{S})}{dt} = -\frac{q}{m} \vec{S}_T \cdot \left[ a_\mu \hat{\beta} \times \vec{B} + \beta \left( a_\mu - \frac{1}{\gamma^2 - 1} \right) \frac{\vec{E}}{c} \right]
  \]
  Jackson Eq. (11.171)

- Muons travel in E-field from focusing quadrupoles: experience a motional magnetic field in their rest frame

- Term vanishes at "magic" momentum (\(p_\mu = 3.094\) GeV)

- But not all muons are at \(p_\mu\) magic

- \(C_E\) comes from \(p_\mu\) distribution measured using timing data from calorimeters

- \(C_E = 489 \pm 53\) ppb
E-field & Pitch Corrections:

- Non-simplified spin-motion is described by BMT equation:

\[
\frac{d(\hat{\beta} \cdot \vec{S})}{dt} = -\frac{q}{m} \vec{S}_T \cdot \left[ a_\mu \hat{\beta} \times \vec{B} + \beta \left( a_\mu - \frac{1}{\gamma^2 - 1} \right) \frac{\vec{E}}{c} \right]
\]

- Jackson Eq. (11.171)

- Muons oscillate vertically (pitch) so \( \hat{\beta} \times \vec{B} \) term is reduced

- \( C_P \) is extracted from vertical width measured by the trackers

\[ C_P = 180 \pm 13 \text{ ppb} \]
E-field Correction: $C_E$

- Imagine injecting uniform momentum & time distributions:

  - Higher momentum muons have further to travel, so have lower cyclotron freq.

- Higher momentum muons have further to travel, so have lower cyclotron freq.
E-field Correction: $C_E$

- Over time, lower momentum will catch higher momentum:

- The way that the gaps are filled in is related to the momentum distribution of the stored beam.
E-field Correction: $C_E$

- Effect is a strong feature of the data at early times:
  - Less pronounced when all calos are added together
  - Either Fourier analysis or $\chi^2$ fit are used to get momentum distribution

![Cyclotron Period](image1)

- 4 – 10 µs

![g - 2](image2)

- 52 – 58 µs
Many systematics come from effects that change the phase of the detected $e^+$ over time.

These make us mis-measure $\omega_a$ with no other indications that we’re getting it wrong.

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

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

In general, anything that changes from early-to-late within each muon fill can be a cause of systematic error.

Most phase shifts are eliminated by design or before fitting the data, but we must correct for two effects ($C_{ML}$ & $C_{PA}$).
**C_{PA} – Phase-Acceptance Correction**

- Remember $\phi \rightarrow \phi(t)$ causes us to mis-measure $\omega_a$
  - Due to acceptance, $\phi$ depends on muon decay position $(x,y)$
  - Not an issue if the muon distribution doesn’t change shape over a fill

- But in Run 1, equipment failure led to beam instability
  - 2/32 quad HV resistors died
    → Focusing E-field changed
    → Beam width changed
• Beam width changes couples to phase “map” to cause $\phi(t)$
• -158 ppb correction with a 75 ppb uncertainty in Run 1
• Fixed by Run 2: majority of correction & uncertainty disappears
Why phase varies with decay position

- Average detected phase changes with decay position:
  - Origin is acceptance: if $e^+$ decays outwards then it will have a longer path length to a detector
  - We see fewer events from top/bottom of storage region as they miss the detectors vertically
$a_\mu$ from Measurement
What do we really measure?

\[ a_\mu \propto \frac{\omega_a}{B} \]

\[ a_\mu = \frac{\omega_a}{\tilde{\omega}_p'(T_r)} \frac{\mu'_p(T_r)}{\mu_e(H)} \frac{\mu_e(H)}{\mu_e(0)} \frac{m_\mu}{m_e} \frac{g_e}{2} \]

- \( \omega_a \): e\(^+\) oscillation frequency
- \( \tilde{\omega}_p'(T_r) \): magnetic field from precession of protons in H\(_2\)O, weighted by muon distribution

**Proposal Goal:**
- 140 ppb = 100 ppb (stat)
- \( \oplus 100 \) ppb (syst)

Measured to 10.5 ppb accuracy at \( T = 34.7^\circ \text{C} \)
- *Metrologia* 13, 179 (1977)

Bound-state QED (exact)

- Known to 22 ppb from muonium hyperfine splitting

Measured to 0.28 ppt

**Total < 25 ppb**
Systematics vs BNL
# Systematic Errors on $\omega_a$ (ppb)

<table>
<thead>
<tr>
<th>Category</th>
<th>BNL (E821)</th>
<th>Proposal</th>
<th>Run 1</th>
<th>Run-2/3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gain</td>
<td>120</td>
<td>20</td>
<td>10</td>
<td>5</td>
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<tr>
<td>Pileup</td>
<td>80</td>
<td>40</td>
<td>30</td>
<td>7</td>
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<td>CBO</td>
<td>70</td>
<td>30</td>
<td>40</td>
<td>20</td>
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<tr>
<td>E &amp; Pitch</td>
<td>50</td>
<td>30</td>
<td>55</td>
<td>33</td>
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<tr>
<td>Lost Muons</td>
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<td>20</td>
<td>5</td>
<td>3</td>
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<tr>
<td>Phase Acceptance</td>
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<td>-</td>
<td>75</td>
<td>15</td>
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<tr>
<td><strong>Total</strong></td>
<td><strong>180</strong></td>
<td><strong>70</strong></td>
<td><strong>108</strong></td>
<td><strong>42</strong></td>
</tr>
</tbody>
</table>

Numbers are approximate  
Category mapping is imperfect
Systematic Errors on $\omega_p$ (ppb)

<table>
<thead>
<tr>
<th>Category</th>
<th>BNL 2001 (E821)</th>
<th>Proposal</th>
<th>Run 1</th>
<th>Run-2/3</th>
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<tbody>
<tr>
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<td>Trolley Calibration</td>
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<tr>
<td>Fixed Probe Baseline</td>
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<td>23</td>
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<td>Muon Weighting</td>
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<td>18</td>
<td>10</td>
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<tr>
<td>Quad Transient</td>
<td>*</td>
<td>*</td>
<td>92</td>
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<tr>
<td>Kicker Transient</td>
<td>*</td>
<td>*</td>
<td>37</td>
<td>13</td>
</tr>
<tr>
<td>*Others</td>
<td>100</td>
<td>50</td>
<td>-</td>
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<tr>
<td><strong>Total</strong></td>
<td><strong>170</strong></td>
<td><strong>70</strong></td>
<td><strong>114</strong></td>
<td><strong>53</strong></td>
</tr>
</tbody>
</table>

Numbers are approximate
Category mapping is imperfect
Magnet Shimming Tools
Magnet Design & Shimming

• 14.2 m diameter “C”-shape magnet with 1.45 T vertical field
• **Shimming** campaign from 2015-16 resulted in very uniform field
• 14 ppm RMS across full azimuth & 3x better than at BNL

![Graph showing dipole field variation](image)

- Fermilab
- Brookhaven Typical

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</tbody>
</table>

- ρ = 7112 mm
Magnetic Shimming Tools

- Many “knobs” for shimming:
  - 72 Poles
  - Shaping & homogeneity
Magnetic Shimming Tools

• Many “knobs” for shimming:
  
  – 72 Poles
    • Shaping & homogeneity
  
  – 864 Wedges
    • Quadrupole asymmetry
Magnetic Shimming Tools

• Many “knobs” for shimming:
  – 72 Poles
    • Shaping & homogeneity
  – 864 Wedges
    • Quadrupole asymmetry
  – 48 Iron Top Hats
    • Change effective $\mu$

\[\text{g-2 Magnet in Cross Section}\]
Magnetic Shimming Tools

• Many “knobs” for shimming:
  – 72 Poles
    • Shaping & homogeneity
  – 864 Wedges
    • Quadrupole asymmetry
  – 48 Iron Top Hats
    • Change effective $\mu$
  – 144 Edge Shims
    • Quad/sextapole asymmetry
Many “knobs” for shimming:
- 72 Poles
  - Shaping & homogeneity
- 864 Wedges
  - Quadrupole asymmetry
- 48 Iron Top Hats
  - Change effective μ
- 144 Edge Shims
  - Quad/sextapole asymmetry
- 8000 Surface Iron Foils
  - Local changes of effective μ
- 100 Active Surface Coils
  - Control current to add ring-wide average field moments
Shimming the Magnet

- Progress towards a uniform field from Oct ‘15 to Sep ’16:

Dipole field (p-p & RMS) improved by factor 3 compared to BNL
$\omega_a$ Measurement
Why do decay $e^+$ tell us about muon spin?

- Muon spin information is encoded in **parity violating** decay

\[ \begin{align*}
  \mu^+ & \xrightarrow{p_{\nu_e}} e^+ \\
  \mu^+ & \xrightarrow{p_{\bar{\nu}_\mu}} e^+ 
\end{align*} \]

- Highest energy positrons are emitted back-to-back with neutrinos

- Neutrino helicity is fixed, so **high energy** positrons are emitted in **direction of muon spin**
Simple fit: residuals

- Simplest form for fit is an exponentially decaying oscillation:
  \[ N_0 e^{-t/\tau} (1 + A \cos(\omega_a t + \phi)) \]

CBO = Radial Mean Oscillations
VW = Vertical Width Oscillations

- Beam oscillations couple to acceptance & change number of e\(^+\) detected with time, and exponential isn’t perfect
Fit with beam dynamics terms

• Add terms to fit function to deal with complications:

\[ f(t) = N_0 e^{-t/\tau} \left( 1 + A \cos(\omega_a t + \phi) \right) \]

• Muons that are lost from storage ring before they decay:

\[ \Lambda(t) = 1 - \kappa_{loss} \int_{t_0}^{t} L(t') e^{(t'/\tau)} dt' \]

• Beam oscillations that modulate decay rate:

\[ N_{cbo}(t) = (1 + A_{cbo-N} \cdot e^{-t/\tau_{cbo}} \cdot \cos(\omega_{cbo}(t) \cdot t + \phi_{cbo-N})) \]
Fit with beam dynamics terms: residuals

- Adding terms tames the beast:

  ![Residuals FFT](image)

  Simple 5-parameter fit
  $\chi^2 / \text{ndf} = 8191 / 4149$

  Fit with extra terms
  $\chi^2 / \text{ndf} = 4005 / 4134$

- Important to get it right: $\omega_a$ changes by 2.2 ppm

- Good residuals & $\chi^2$ are necessary, but not sufficient condition.
Systematic Cause: Time-Dependent Phase

- If average phase of muon population changes over time then we can mis-measure $\omega_a$:

\[ N_0 e^{-t/\tau} (1 + A \cos(\omega_a t + \phi)) \]

But if $\phi \rightarrow \phi(t)$, then

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

- If higher order terms are small, then we measure $(\omega_a + \phi')$ instead of $\omega_a$ and still get good $\chi^2$
Main Systematic Issues

- 3 main systematics for $\omega_a$ measurement
- Variety of mitigation strategies
- Well under control – total is 56 ppb

Pile Up

- ~30 ppb

Gain Change

- ~10 ppb

Beam Oscillations

- ~40 ppb

Tracker data & beam dynamics

Empirical correction using calo data

Dedicated laser calibration system

Analysis starts here

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Systematic Issues: Gain

- Calorimeter gain takes time to recover from “flash” when beam first enters storage ring:

- Phase is energy dependent – so gain change generates another time-dependent phase & normalization issues

- Correct based on gain measurements from laser system and cross-check with tracker
Systematic Issues: Pile Up

- Pile up happens less often as the muons decay so phase changes with time and we get $\omega_a$ wrong

- Derive a pile up correction from data and check validity above 3.1 GeV

Two low energy $e^+$ can look like one high energy $e^+$
Muon EDM
Muon Electric Dipole Moment

- Muon EDM is essentially zero in SM.
- Any observation would be a sign of new physics:
  - Muon is the best option for a higher flavour gen. search
  - And it’s free of nuclear / molecular effects
  - But, needs non-mass-scaling BSM effects to see anything given $e^-$ EDM limit

EDMs: Theory & Experiment
Muon EDM: Tracker Search

• A non-zero muon EDM would modify the spin equation

\[ \tilde{\omega}_{a\eta} = a_\mu \frac{e}{m} \vec{B} + \eta \frac{e}{2m} \left[ \frac{\vec{E}}{c} + \vec{\beta} \times \vec{B} \right] \]

• \( \vec{\beta} \times \vec{B} \) dominates, so precession plane is tilted.

\[ \omega = \sqrt{\omega_a^2 + \omega_\eta^2} = \sqrt{\omega_a^2 + \left( \frac{e\eta\beta B}{2m} \right)^2} \]

• Search for an up-down oscillation, out of phase with \( \omega_a \).
**Muon EDM: Tracker Search**

- Search was done with tracker at BNL:
  - Previous tracker search was statistics limited
  - We’re aiming to improve this limit to $10^{-21}$ e cm

![Graph of # Tracks vs (time % $T_a$)](image)

![Graph of Average vertical angle vs (time % $T_a$)](image)

- **Tracker:** $|d_\mu| < 3.2 \times 10^{-19}$ e cm (95% CL)
- **Tracker & Calo:** $|d_\mu| < 1.8 \times 10^{-19}$ e cm (95% CL)
- **SM:** $|d_\mu| < 10^{-38}$ (World’s best for muon EDM)

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Electron Anomaly: $a_e$
Why $a_\mu$ and not $a_e$?

- Coupling of virtual loops goes as $m^2$ (dimensional analysis).
- Therefore, while $a_\mu$ is measured ~20x less precisely than the $a_e$, it has better sensitivity to heavy physics scales:

$$\left(\frac{m_\mu}{m_e}\right)^2 \approx 43,000$$

- E.g. lowest-order hadronic contribution to $a_e$ is $a^{\text{had,LO}} = (1.875 \pm 0.017) \times 10^{-12}$ (1.5 ppb of $a_e$).
- By comparison, the muon’s hadronic contribution is ~60 ppm.
**g_e and α:**

- New measurement of g_e in 2023:

  0.13 ppt on g_e

- Ability to compare with prediction hampered by disagreement in the value of α:

  ![Graph showing g_e measurements](image)

  **FIG. 5.** SM prediction of α using μ/μ_B from this Northwestern measurement (red), and from our 2008 Harvard measurement (blue), with solid and open points for slightly differing C_{10} [40,41]. The α measurements (black) were made with Cs at Berkeley [38] and Rb in Paris [39]. A ppb is 10^{-9}.
J-PARC Experiment
J-PARC muon g-2/EDM experiment

J-PARC MLF

Constructed in 2021

Muon beam

$\mu^+(4 \text{ MeV})$ cooling 25 meV

4 MeV

acceleration

Construction from FY2022

Transmission muon microscope

Aiming for data taking from 2028

H-line experimental bldg.

Muons storage ring

$0.66 \text{ m}$

RF Acc. Test at S2 area (May 2023)

Shields, area control (2022)

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Fermilab

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Shields, area control (2022)
J-PARC Experiment

- Complementary technique
  - $\mu$ beam accelerated from rest
  - no E fields
  - smaller magnet
- Aiming for a result comparable to Run-1 result towards the end of the decade

- Under construction aiming for data taking from 2028.
- Succeeded to deliver a surface muon beam to H-line.
- Constructed the experimental area for muon cooling and the first stage of the acceleration.
- Currently taking data to demonstrate the muon cooling by using the laser ionization of muonium, followed by RF acceleration tests.