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# Doubling Down
# An Update from Run-2/3 of the Muon g-2 Experiment

Josh LaBounty

BNL Particle Physics Seminar

9/14/2023

# Outline

- Introduction
- Experiment
  - Experimental method
  - Systematics
  - This result
- Theory/Experiment Comparison
- Path forward

Hundreds of people from all around the world working together to calculate + measure “just” 1 value!

Summer Collaboration meeting at University of Liverpool  July 24-28, 2023

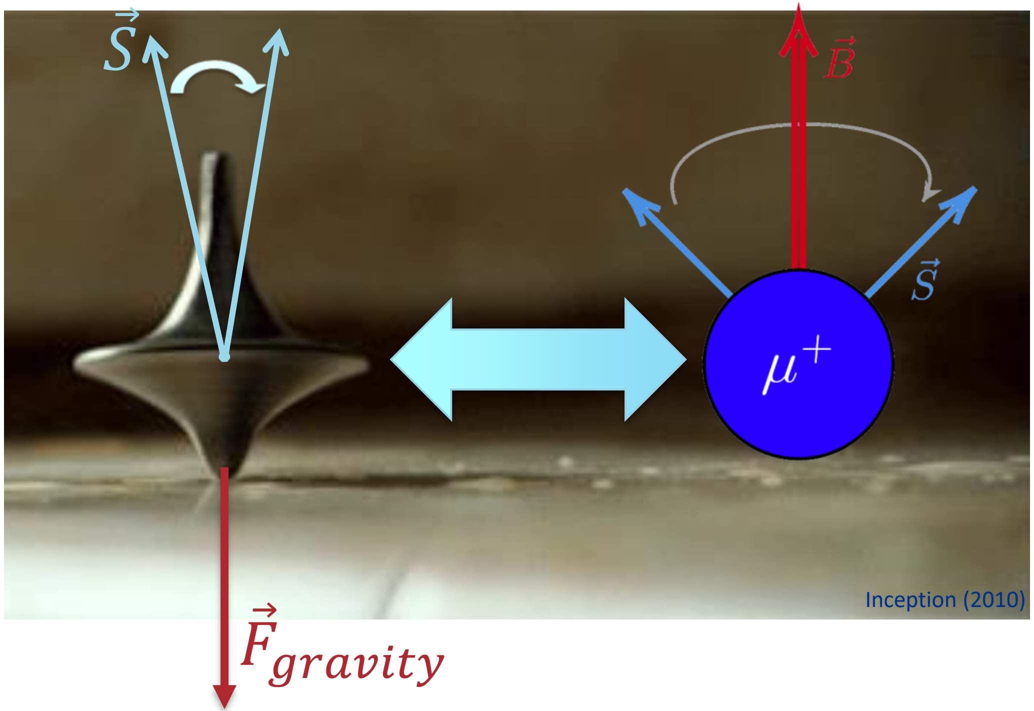
Muon g-2 Theory Initiative | Bern Workshop | September 2023

# Basics: Magnetic Moments

**The gyromagnetic ratio ('g'-factor) determines spin precession frequency in a magnetic field**

$$\vec{\tau} = \vec{\mu} \times \vec{B}$$

$$\vec{\mu} = g\frac{e}{2mc}\vec{s}$$



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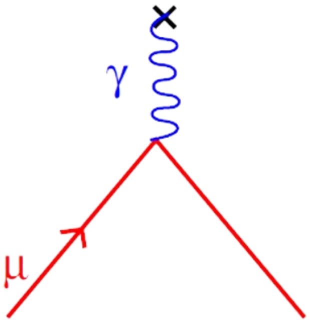
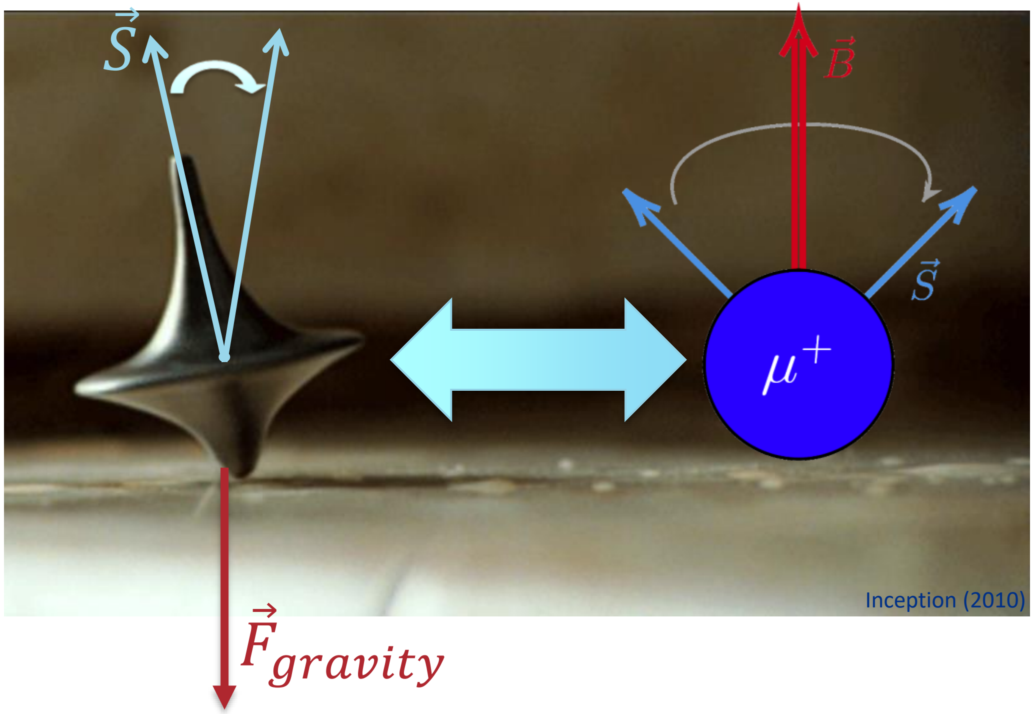
**Dirac's equation predicts, for a spin-1/2 charged fermion:**

$$g = 2$$



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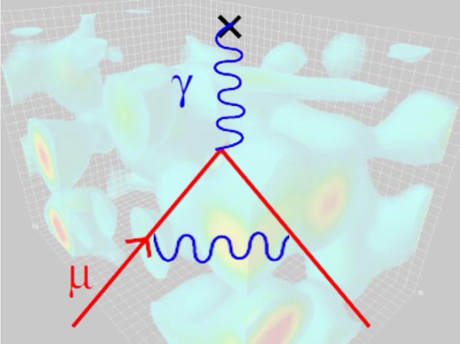
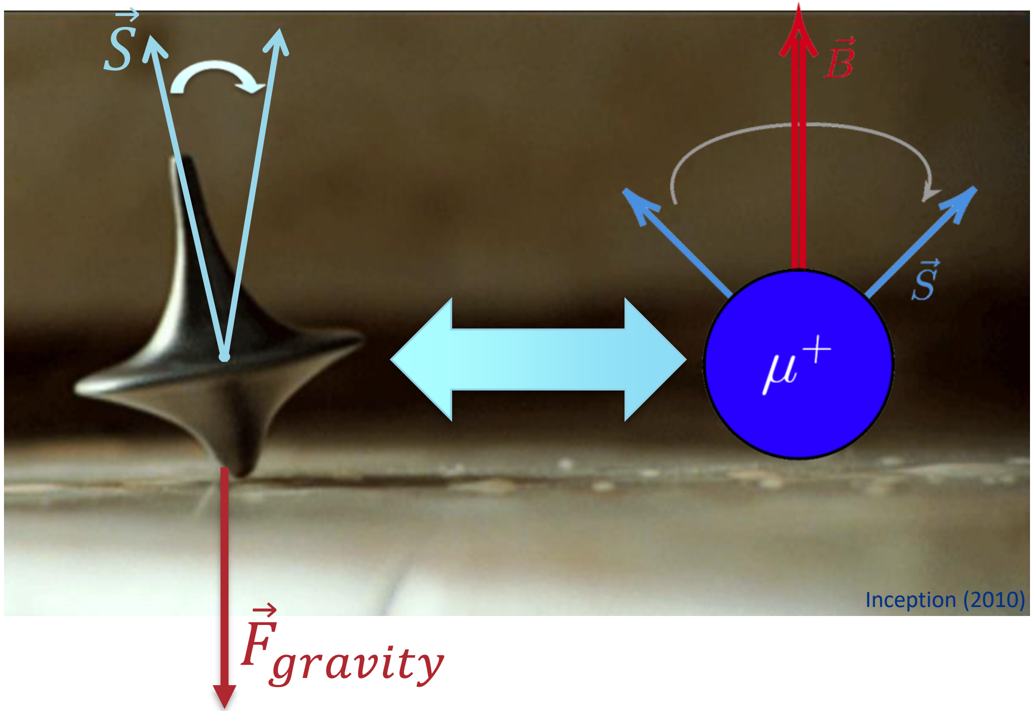
**Interactions with virtual particles alter the value, making it slightly greater than 2**

$$g > 2$$



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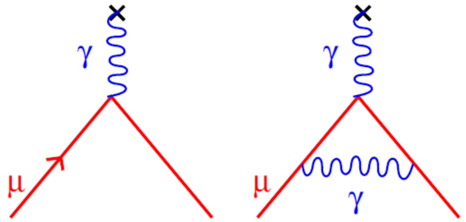
# Theoretical Calculation

| (2020 White Paper) Source | Value ($\times 10^{-11}$) | Error ($\times 10^{-11}$) | Error (ppb) |
|---|---|---|---|
| Schwinger | 116140973.30 | - | - |

**Schwinger calculated the first order correction to $a_\mu$ in the 1940's**

$$a \equiv \frac{g-2}{2} \rightarrow \frac{\alpha}{2\pi}$$

Tree Level QED




$g = 2( \quad 1 \quad + .00116 \ldots$

T. Aoyama et. al. The anomalous magnetic moment of the muon in the Standard Model (2020).

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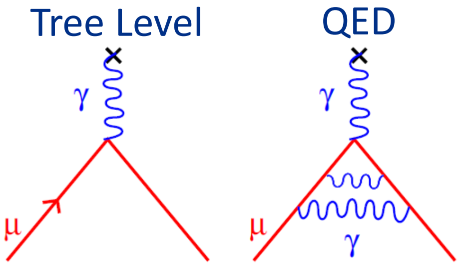
|---|---|---|---|
| Schwinger | 116140973.30 | - | - |
| QED | 116584718.93 | 0.1 | 0.9 |

***we'll talk about this again later

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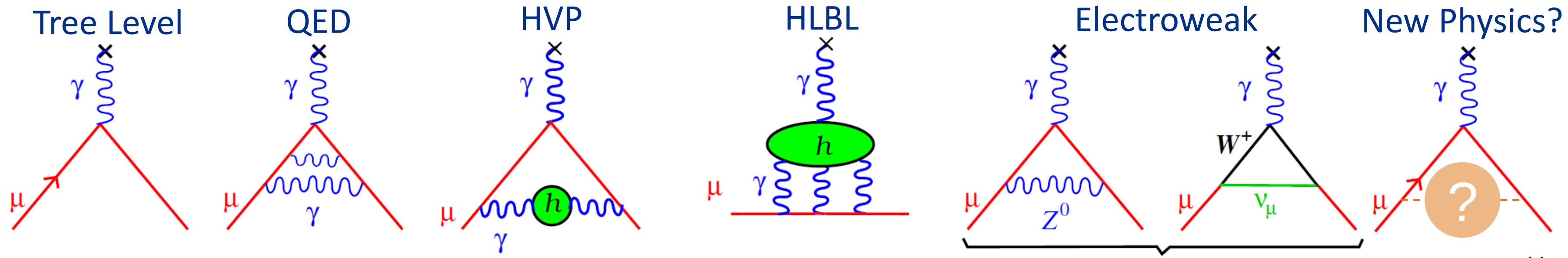
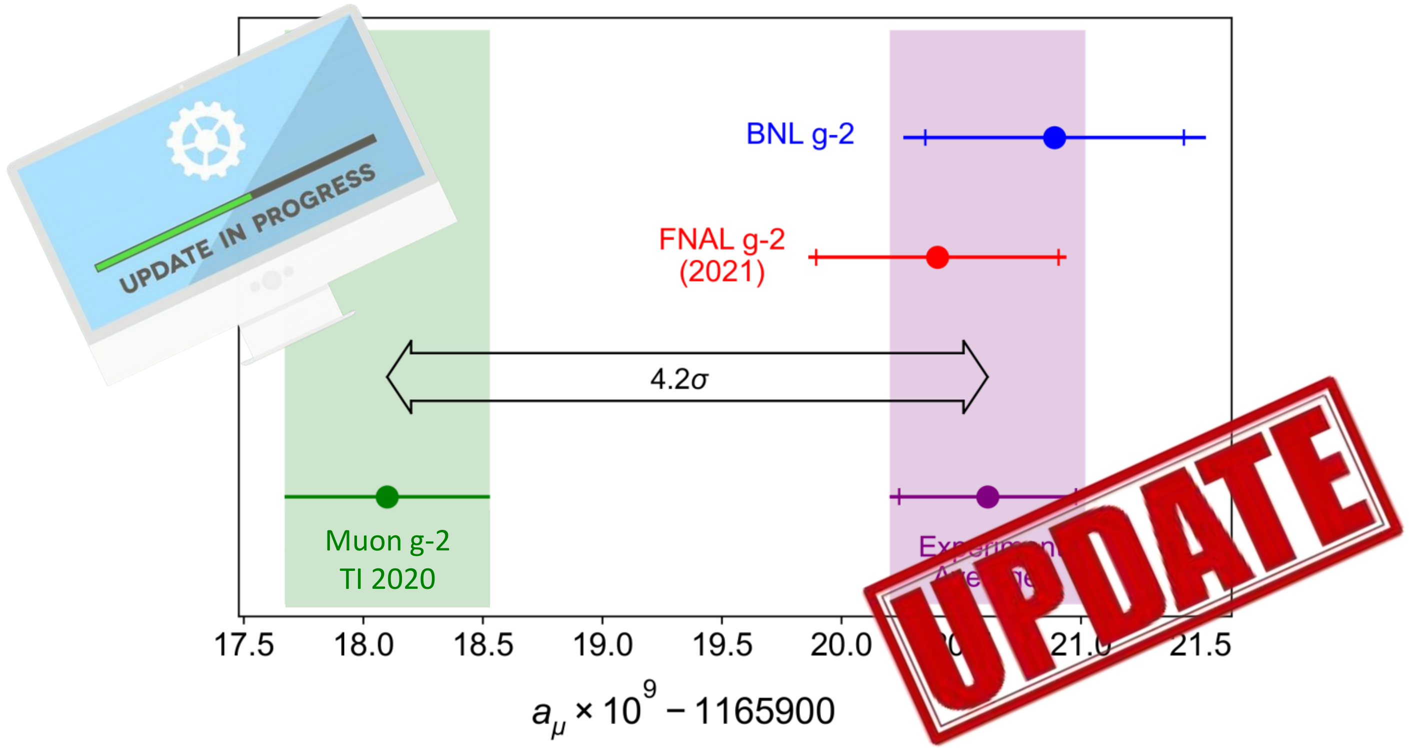
|---|---|---|---|
| Schwinger | 116140973.30 | - | - |
| QED | 116584718.93 | 0.1 | 0.9 |
| HVP*** | 6845 | **40** | **343** |
| HLbL | 92 | **18** | **154** |
| EW | 153.6 | 1.0 | 8.6 |
| Total | 116,591,810 | 43 | 368 |




$$g = 2( \quad 1 \quad + .00116\ldots \quad + .00000006845\ldots \quad + .00000000092\ldots \quad + .000000001536\ldots \quad + \mathcal{O}(100 * 10^{-11})\ )$$

T. Aoyama et. al. The anomalous magnetic moment of the muon in the Standard Model (2020).

# Where we were in 2021




The anomalous magnetic moment of the muon in the Standard Model
Physics Reports Volume 887, 3 December 2020, Pages 1-166
https://doi.org/10.1016/j.physrep.2020.07.006

Measurement of the Positive Muon Anomalous Magnetic Moment to 0.46 ppm
Phys. Rev. Lett. 126, 141801 – Published 7 April 2021

# Muon g-2 in a Storage Ring: $\omega_s$ vs. $\omega_c$

In a storage ring, the spin of a muon will precess to first order like:

$$\frac{d\vec{s}}{dt} = \vec{\mu} \times \left(\vec{B} - \vec{\beta} \times \vec{E}\right)$$

$$= \vec{\omega}_s = -\frac{ge}{2m}\vec{B} - (1-\gamma)\frac{e\vec{B}}{\gamma m}$$

and the momentum will precess like:

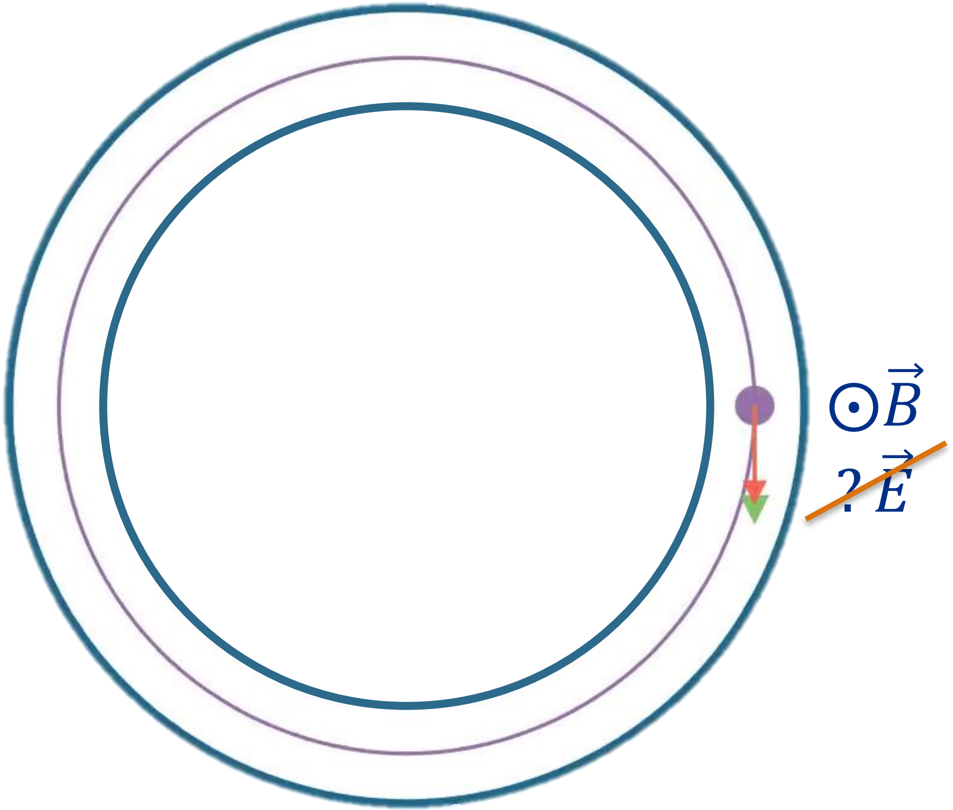
$$\frac{d\vec{p}}{dt} = \vec{\omega}_c = -\frac{e\vec{B}}{\gamma m}$$

The difference in these precession frequencies is:

$$\vec{\omega}_a \equiv \vec{\omega}_s - \vec{\omega}_c = a_\mu \frac{e\vec{B}}{m}$$

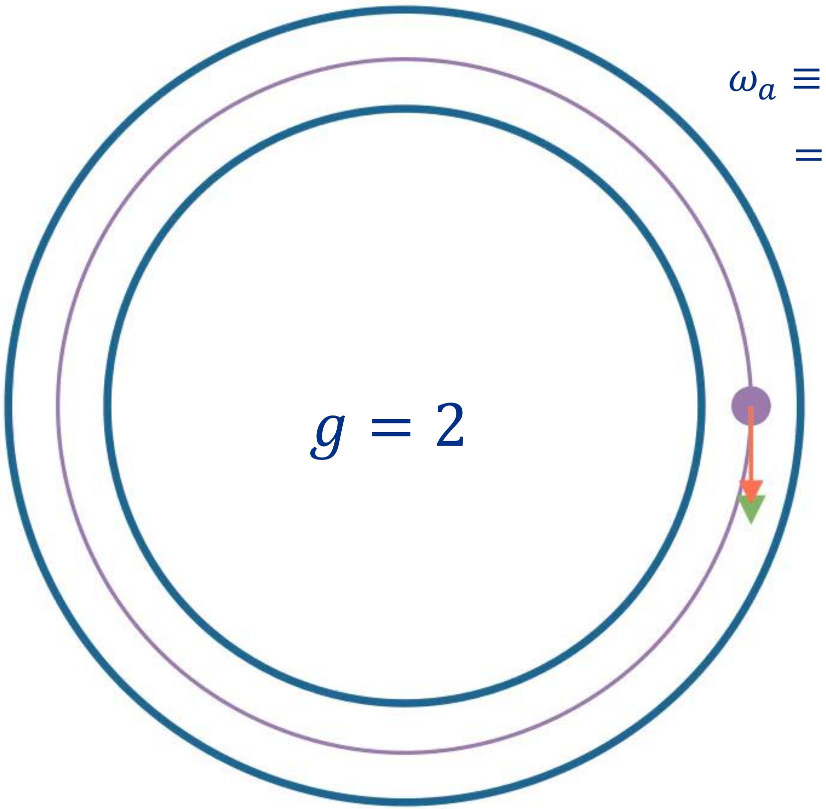
where

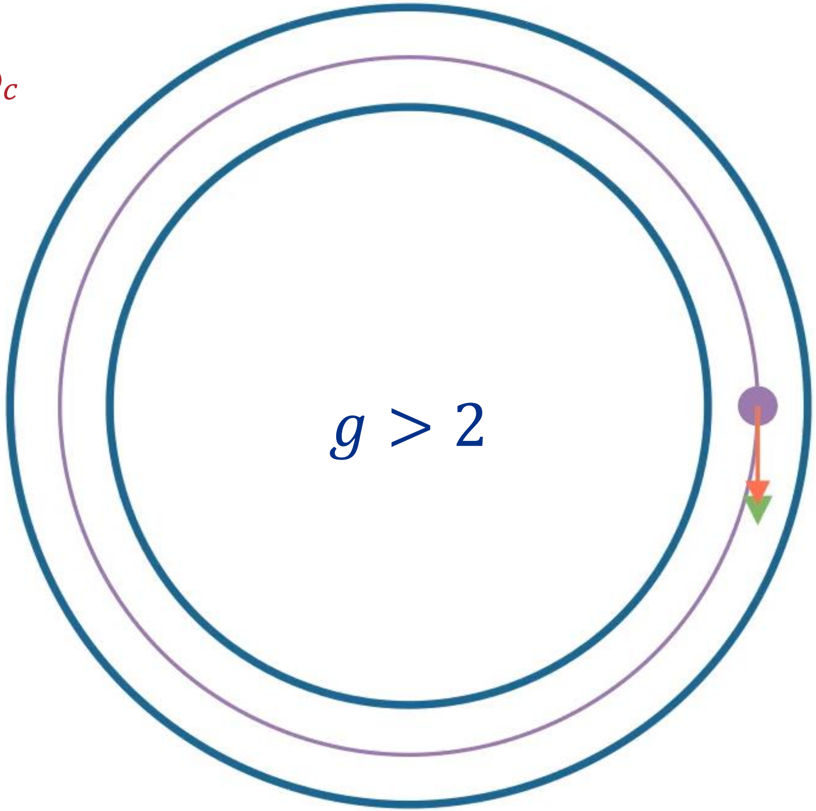
$$a_\mu \equiv \frac{g-2}{2}$$



# In a Storage Ring $\omega_a$ is Directly Sensitive to $a_\mu$

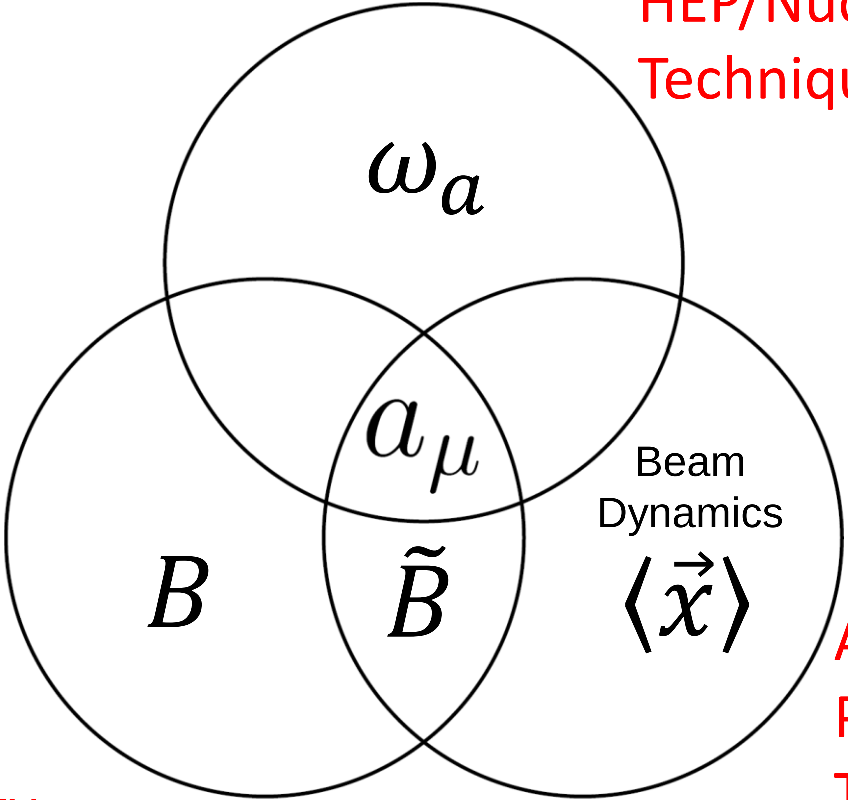
$$\omega_a \equiv \omega_s - \omega_c$$
$$= a_\mu \frac{eB}{m}$$



$$a_\mu = \frac{\omega_a}{\tilde{B}}\frac{m}{e} + \cdots$$

'Traditional' HEP/Nuclear Physics Techniques




Precise NMR Metrology

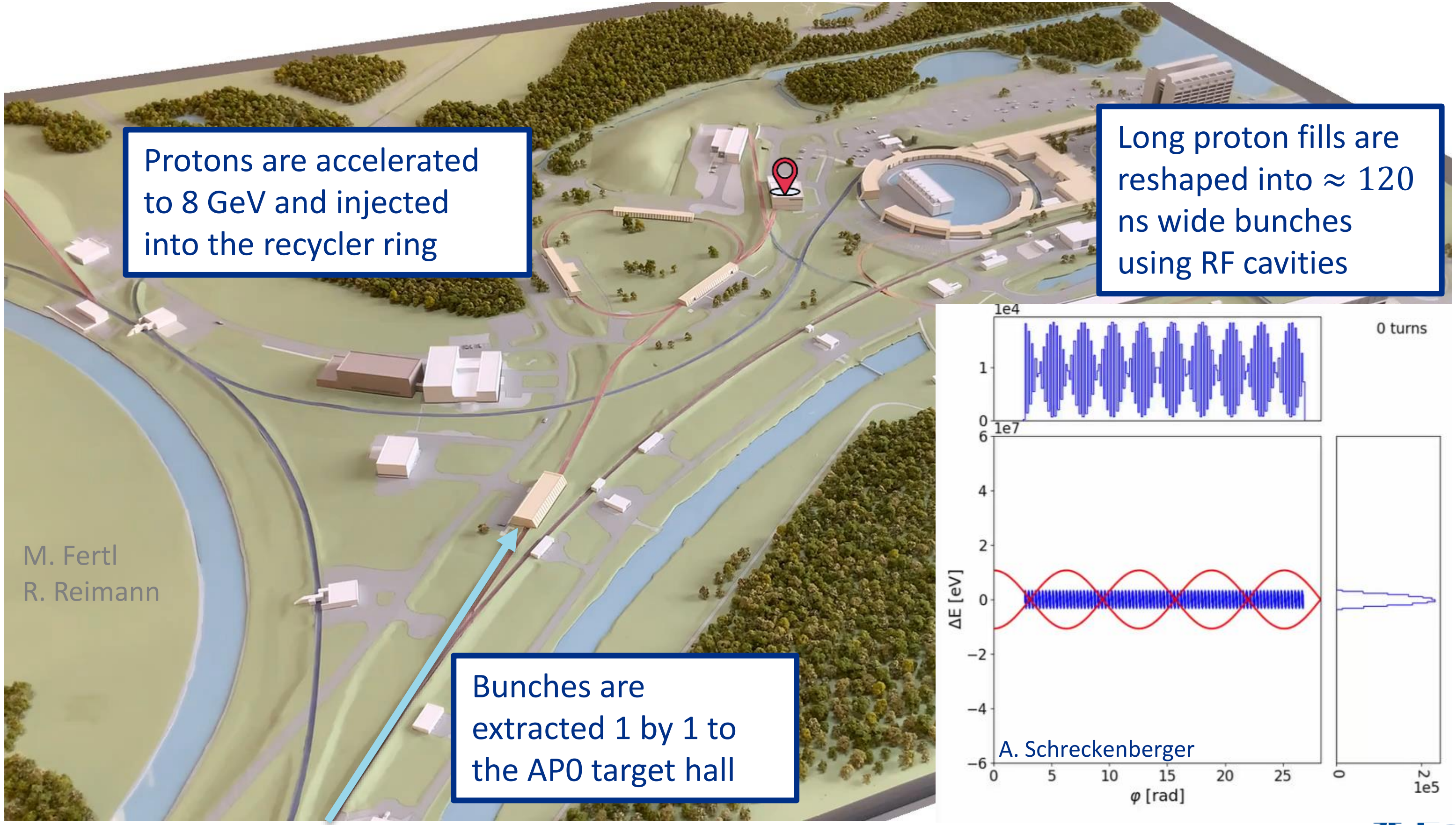
Accelerator Physics Techniques

# Muon Production and the Beamlines

Protons are accelerated to 8 GeV and injected into the recycler ring

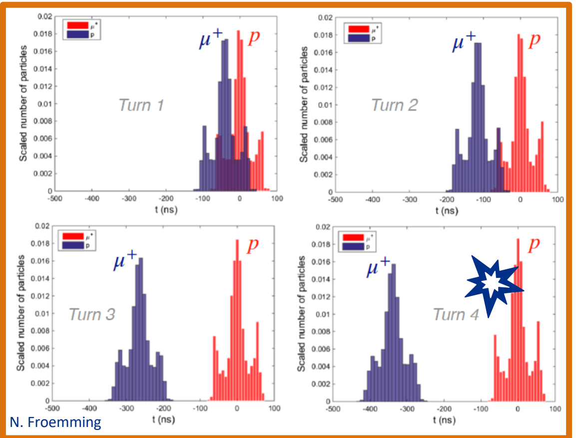
Long proton fills are reshaped into ≈ 120 ns wide bunches using RF cavities

Bunches are extracted 1 by 1 to the AP0 target hall

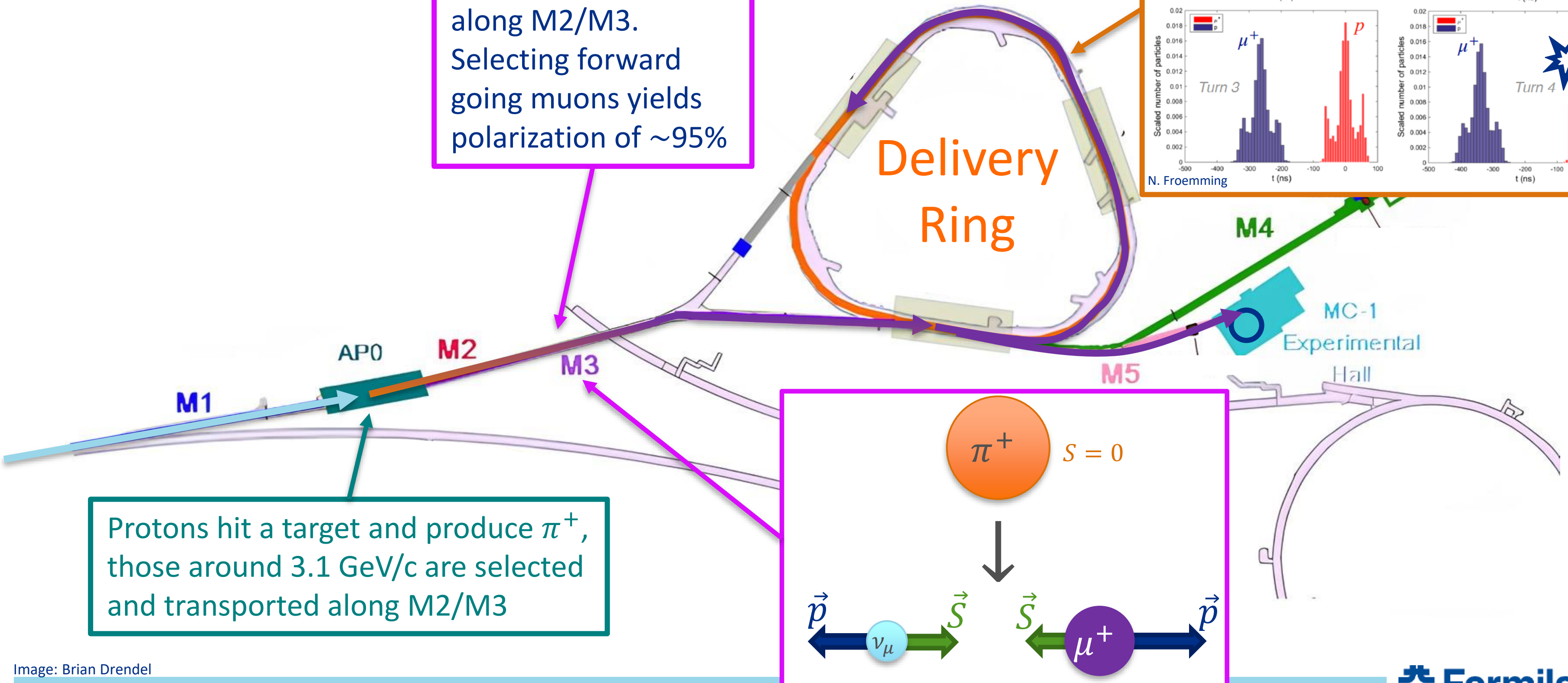


# How Muons are Made

Most remaining $\pi^+$ decay along the $\approx$ 2km DR detour. Protons can be separated from $\mu^+$




80% of $\pi^+$ decay along M2/M3. Selecting forward going muons yields polarization of ~95%




Protons hit a target and produce $\pi^+$, those around 3.1 GeV/c are selected and transported along M2/M3

Image: Brian Drendel



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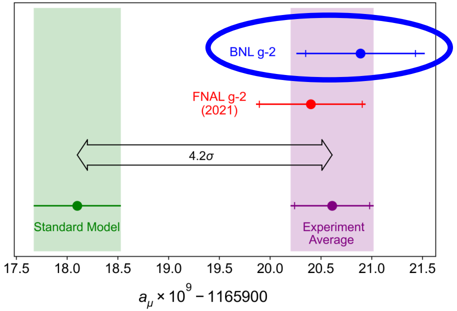
# Previous Generation: E821 at BNL



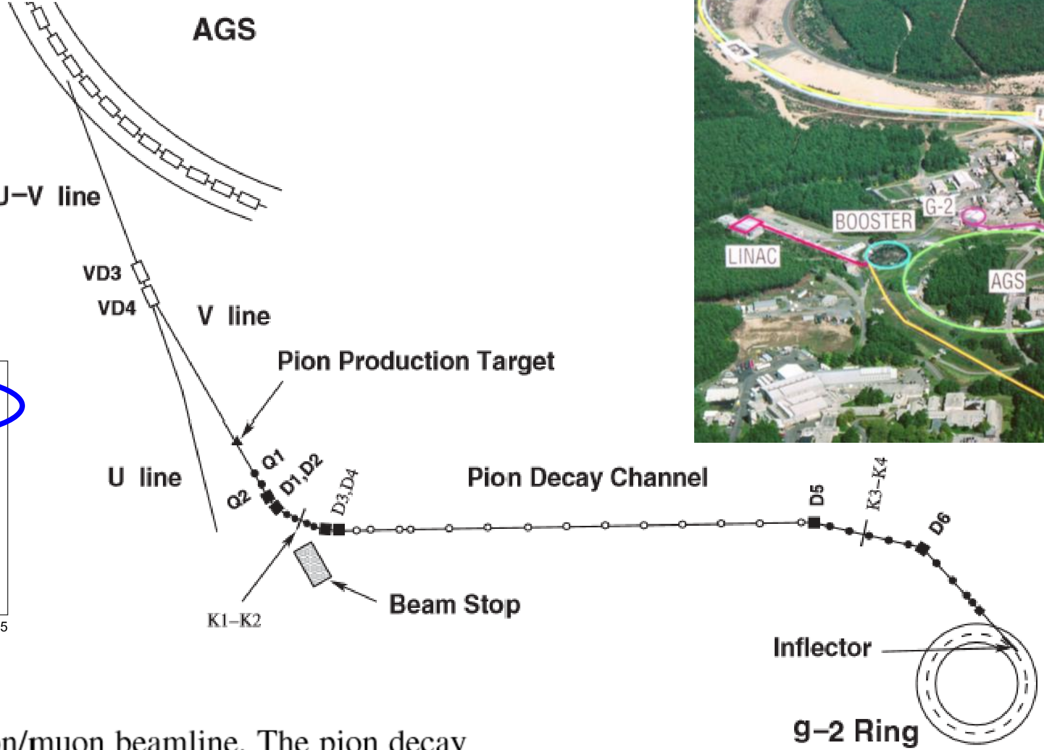
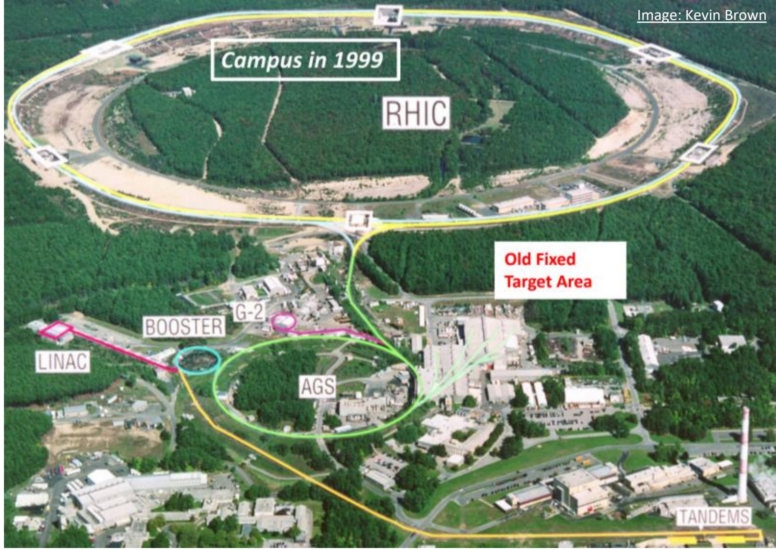




FIG. 3. Plan view of the pion/muon beamline. The pion decay channel is 80 m and the ring diameter is 14.1 m.





E821 Final Report
Phys. Rev. D 73, 072003

# In An Alternate Universe…

Upgrade to $\pi^+$ target for 5 GeV pions, use backward muon decays and eliminate pion flash

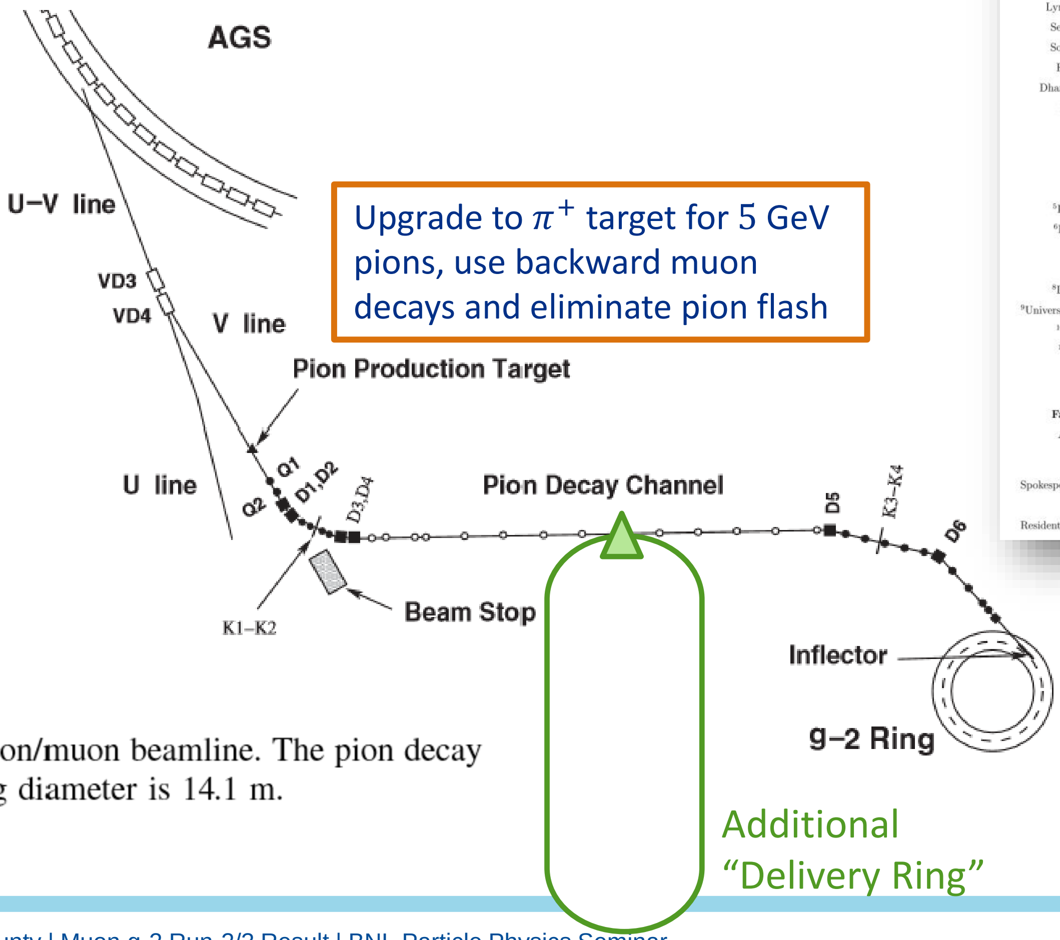



FIG. 3. Plan view of the pion/muon beamline. The pion decay channel is 80 m and the ring diameter is 14.1 m.

A $(g-2)_\mu$ Experiment to $\pm 0.2$ ppm Precision

BNL P969

**New $(g-2)_\mu$ Collaboration:** R.M. Carey[1], A. Gafarov[1], I. Logashenko[1], K.R. Lynch[1], J.P. Miller[1], B.L. Roberts[1], G. Bunce[2], W. Meng[2], W.M. Morse[2], Y.K. Semertzidis[2], D. Grigoriev[3], B.I. Khazin[3], S.I. Redin[3], Yuri M. Shatunov[3], E. Solodov[3], Y. Orlov[4], P. Debevec[5], D.W. Hertzog[5], P. Kammel[5], R. McNabb[5], F. Mülhauser[5], K.L. Giovanetti[6], K.P. Jungmann[7], C.J.G. Onderwater[7], S. Dhamija[8], T.P. Gorringe[8], W. Korsch[8], F.E. Gray[9], B. Lauss[9], E.P. Sichtermann[9], P. Cushman[10], T. Qian[10], P. Shagin[10], S. Dhawan[11], and F.J.M. Farley[11]

[1]Department of Physics, Boston University, Boston, MA 02215
[2]Brookhaven National Laboratory, Upton, NY 11973
[3]Budker Institute of Nuclear Physics, Novosibirsk, Russia
[4]Newman Laboratory, Cornell University, Ithaca, New York 14853
[5]Department of Physics, University of Illinois, Urbana-Champaign, IL 61801
[6]Department of Physics, James Madison University, Harrisonburg VA 22807
[7]Kernfysisch Versneller Instituut, Rijksuniversiteit, Groningen, NL 9747 AA Groningen, the Netherlands
[8]Department of Physics, University of Kentucky, Lexington, Kentucky 40506
[9]University of California, Berkeley and Lawrence Berkeley Laboratory, Berkeley, CA 94720
[10]Department of Physics, University of Minnesota, Minneapolis, MN 55455
[11] Department of Physics, Yale University, New Haven, Connecticut 06520

**Fast extracted proton beam to the V-target. 12 or 24 bunches per AGS cycle, 60 TP per cycle, minimum possible AGS cycle time.**

Spokespersons: B. Lee Roberts (roberts@bu.edu, 617-353-2187)
David W. Hertzog (hertzog@uiuc.edu, 217-333-3988)
Resident-spokesperson: William M. Morse (morse@bnl.gov, 631-344-3859)

E821 Final Report
Phys. Rev. D 73, 072003



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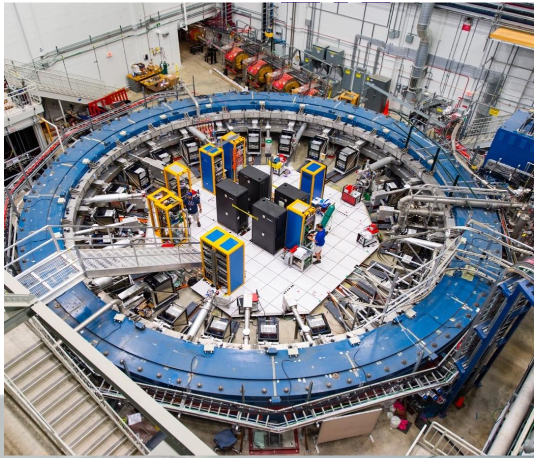
Brookhaven National Laboratory

## The Big Move: A Last Look at the Muon g-2 Ring's Departure from Brookhaven

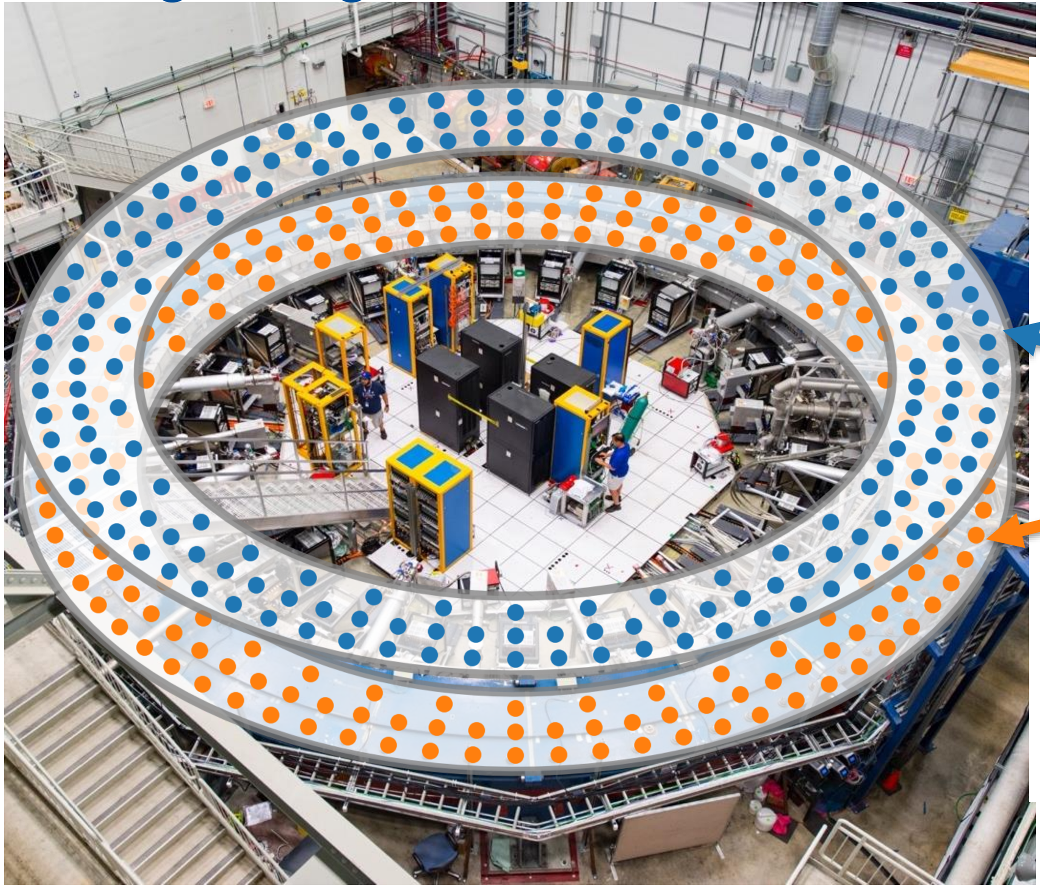
Brookhaven employees and expert engineers guided the massive electromagnet across Long Island in the first leg of its journey to Illinois

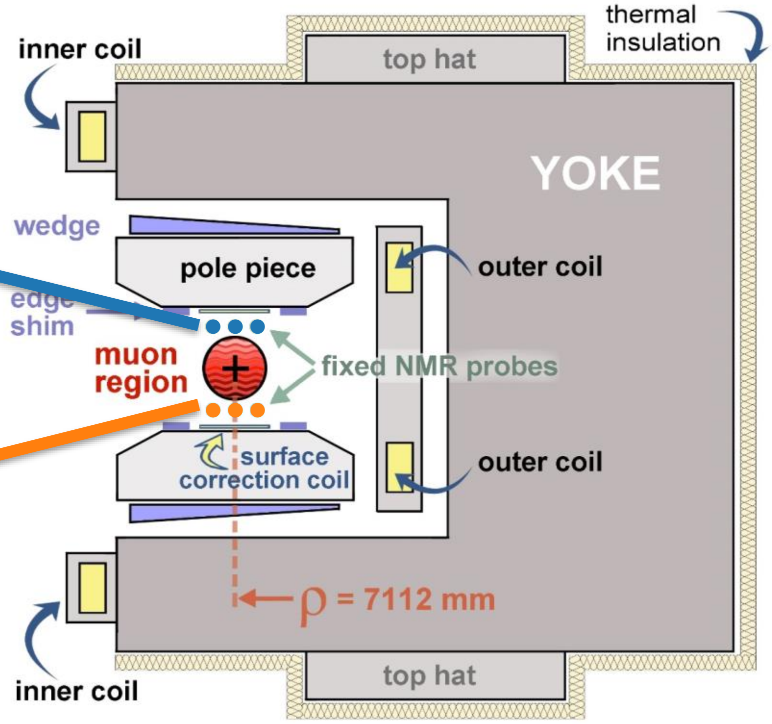
August 8, 2013


The massive electromagnetic muon storage ring can be seen here exiting the building where it gave Brookhaven Lab researchers a tantalizing glimpse of physics beyond the Standard Model.

# Storage Ring



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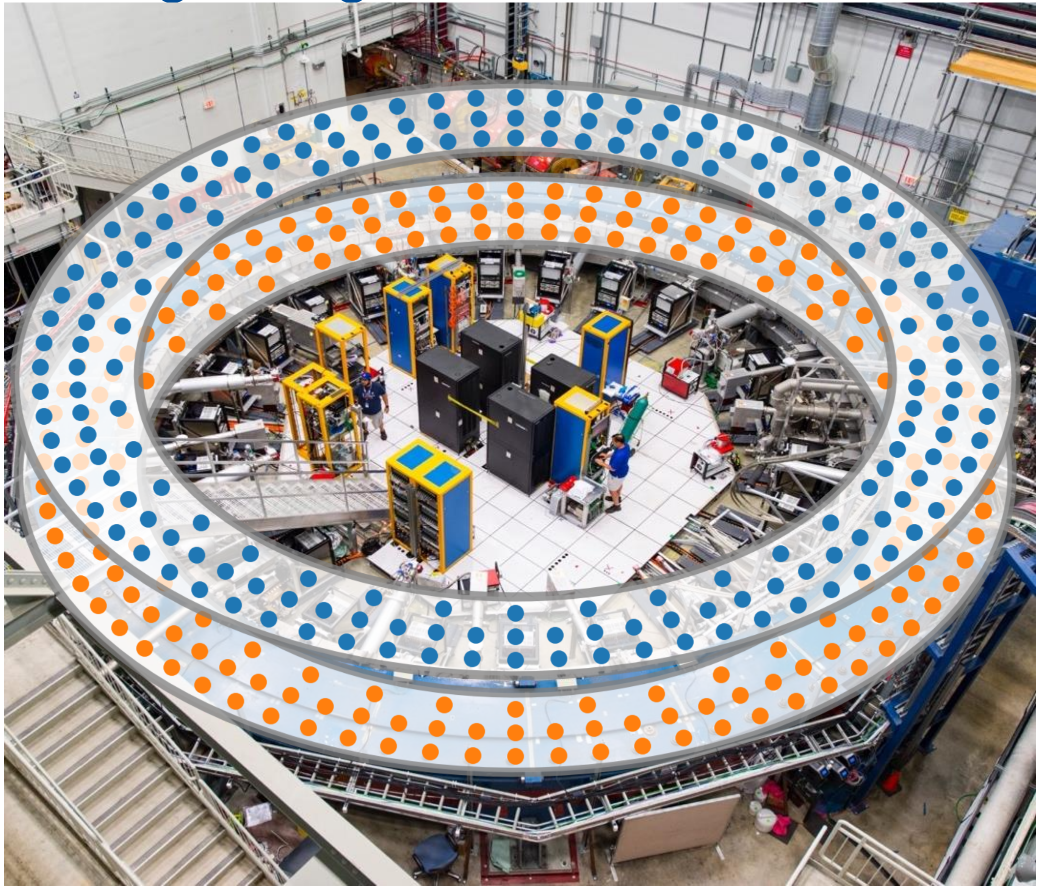
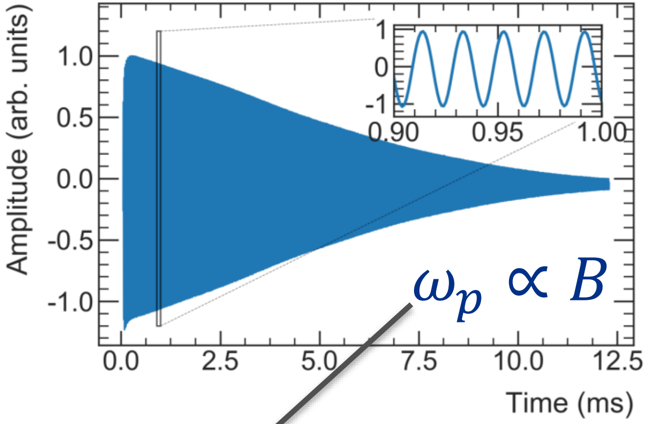
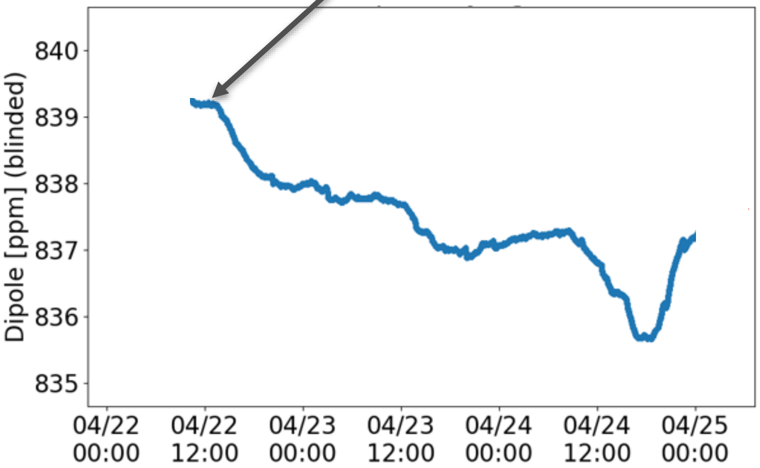





$\omega_p \propto B$

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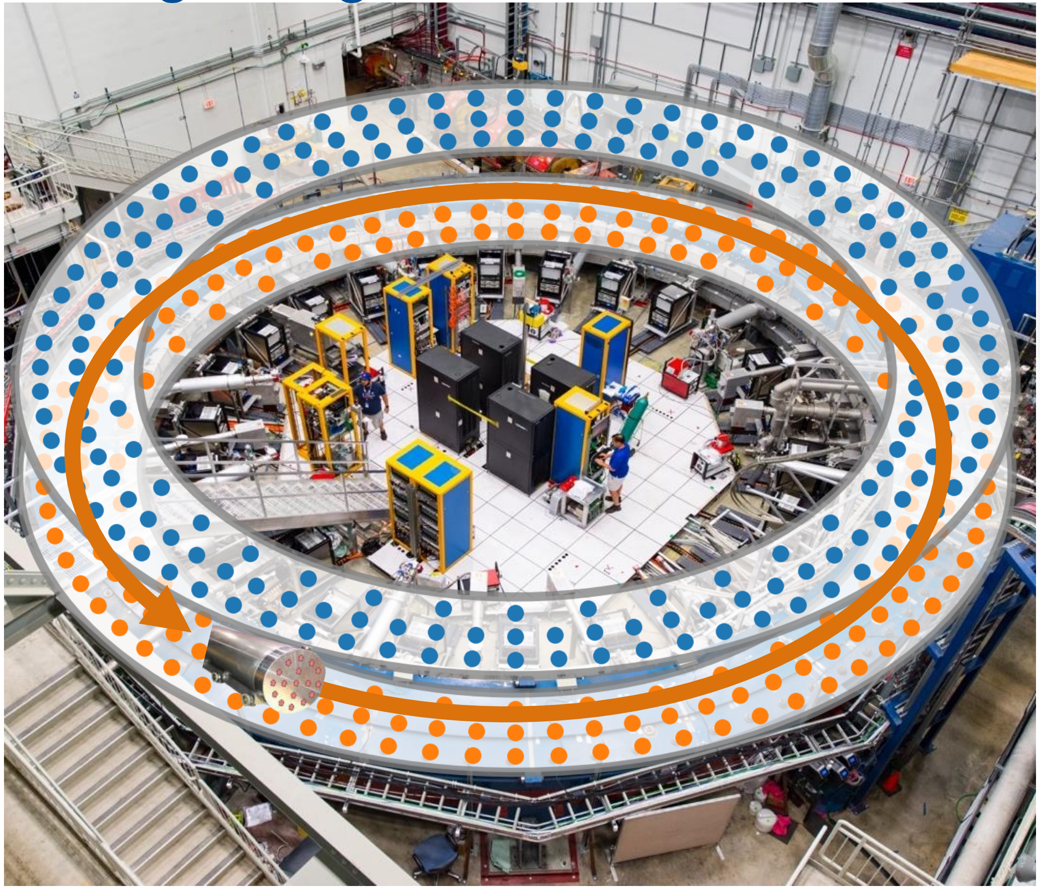
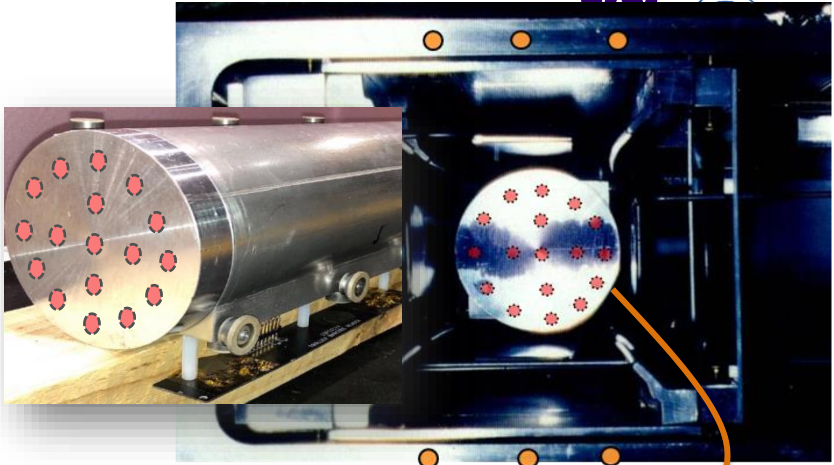
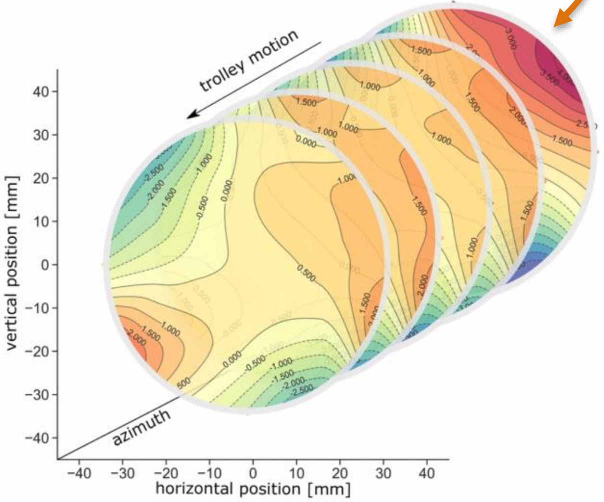
# Storage Ring







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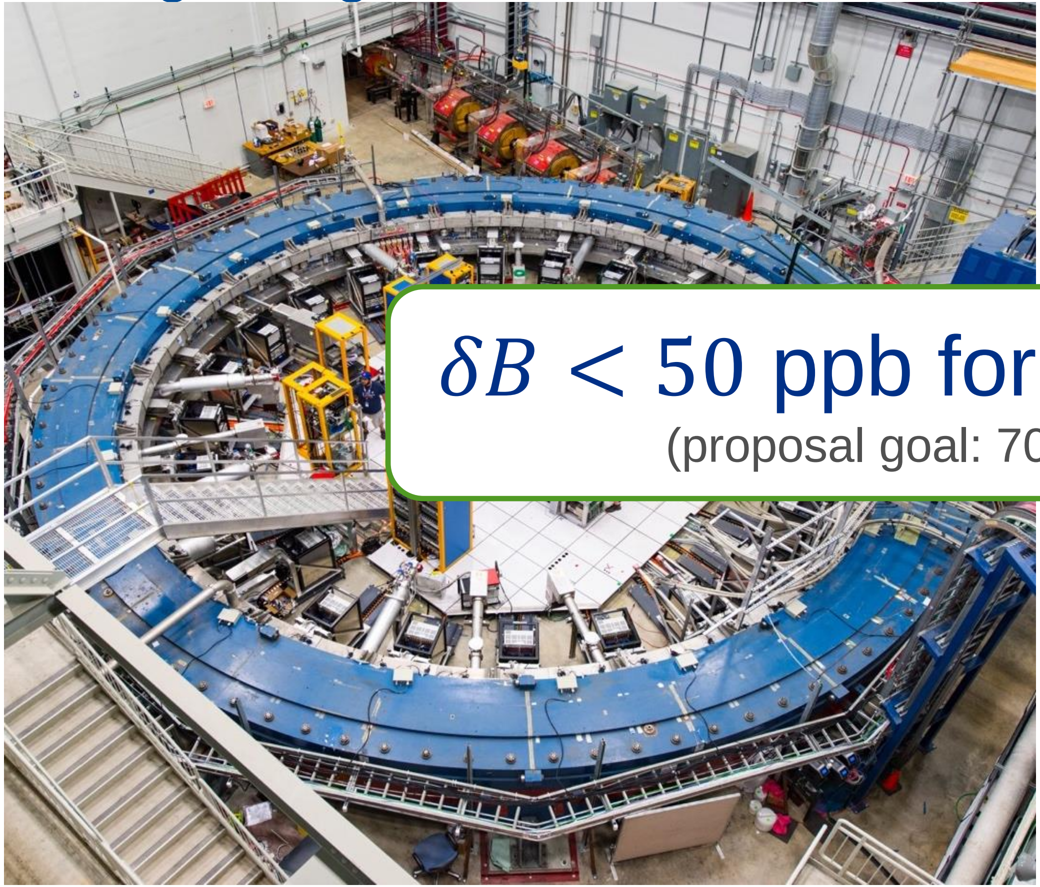
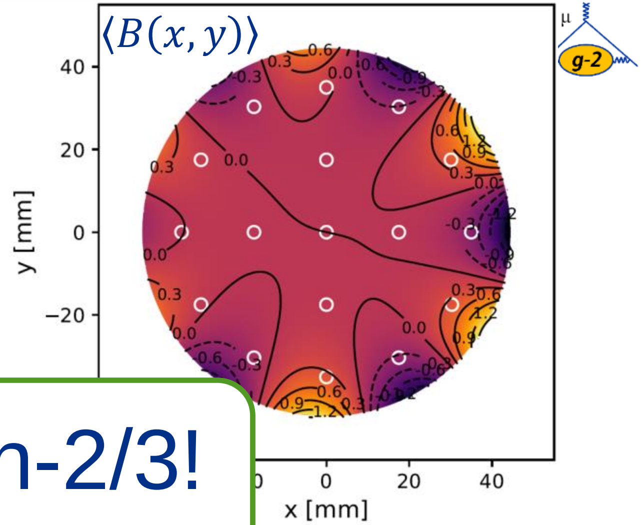
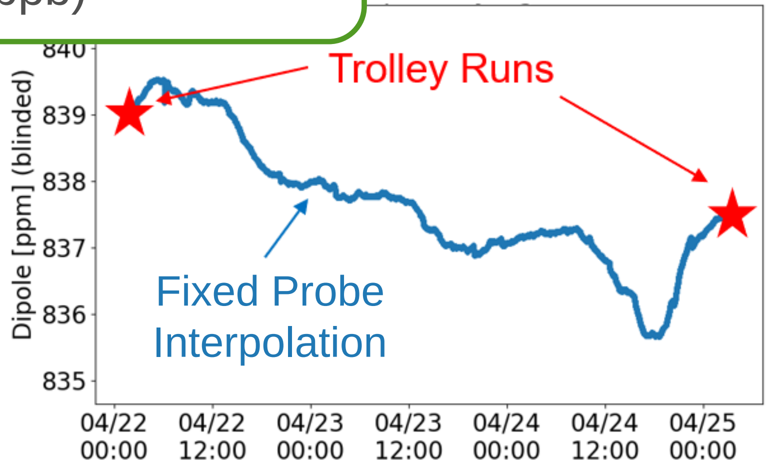


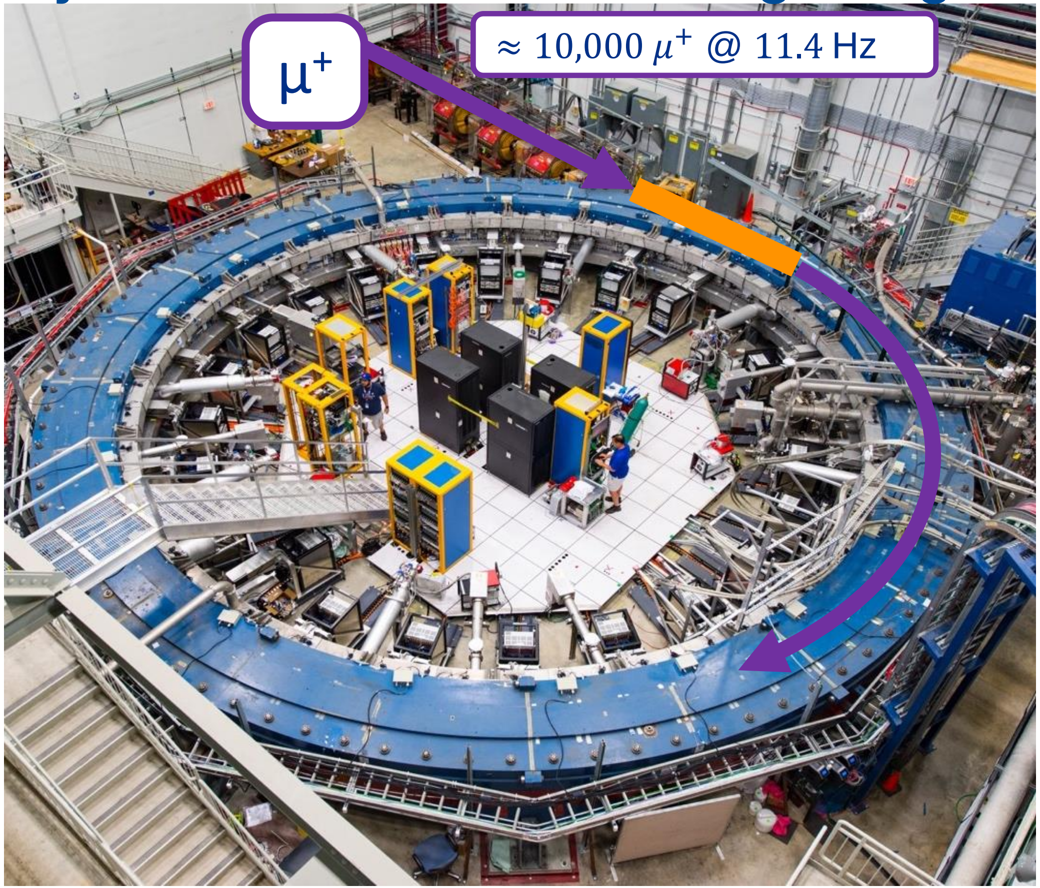



$\delta B < 50$ ppb for Run-2/3!

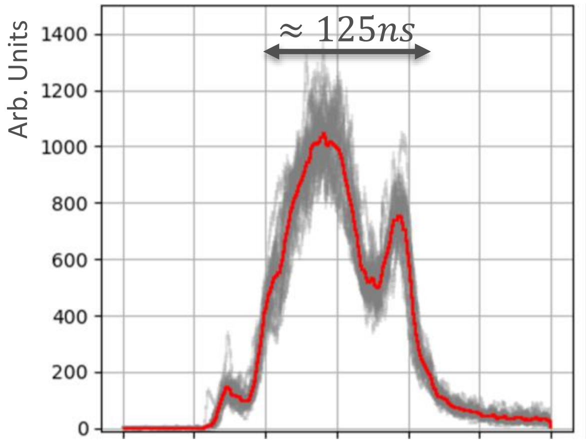
(proposal goal: 70 ppb)

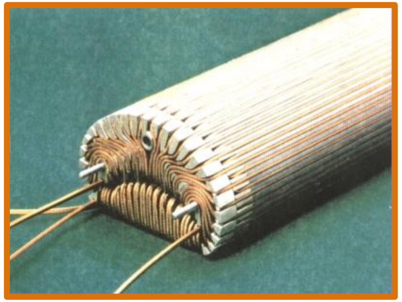


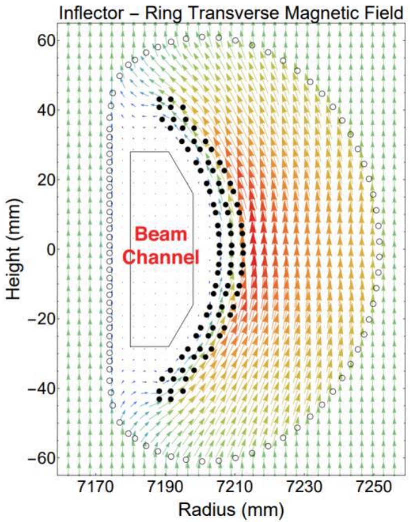
# Inject muons into the storage ring



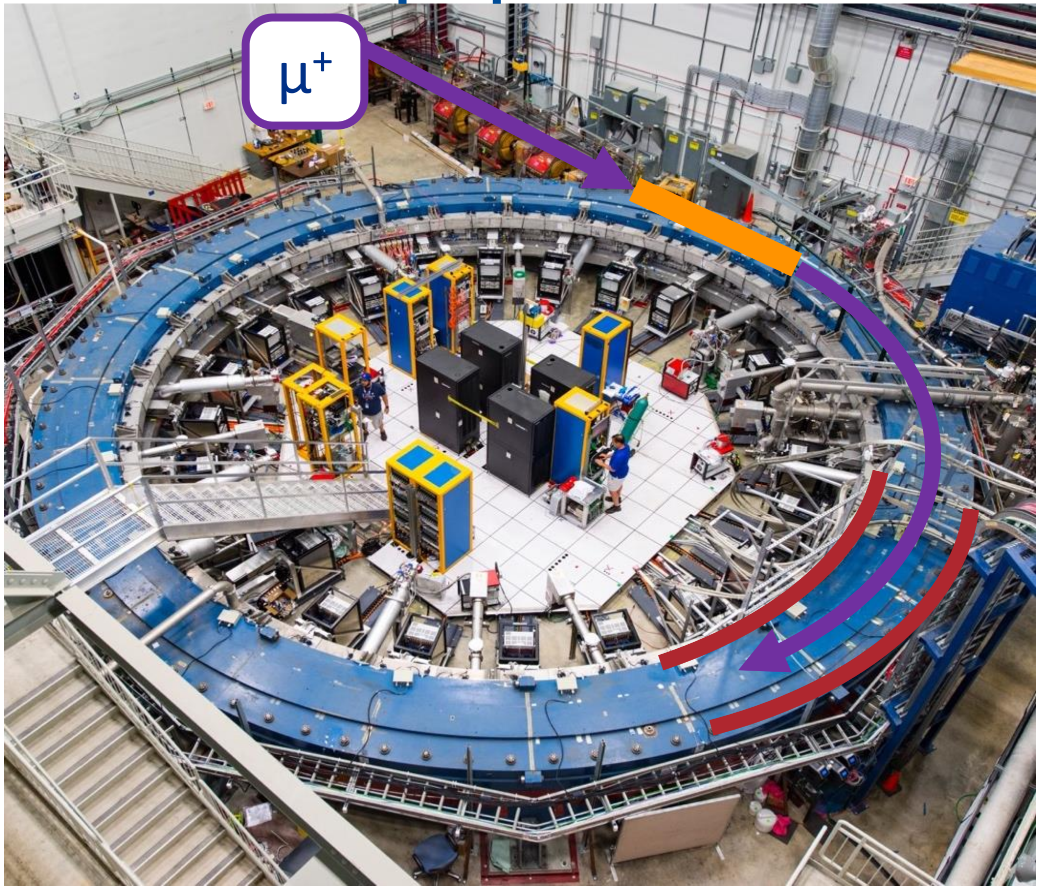

Beam Profile at Inflector Entrance

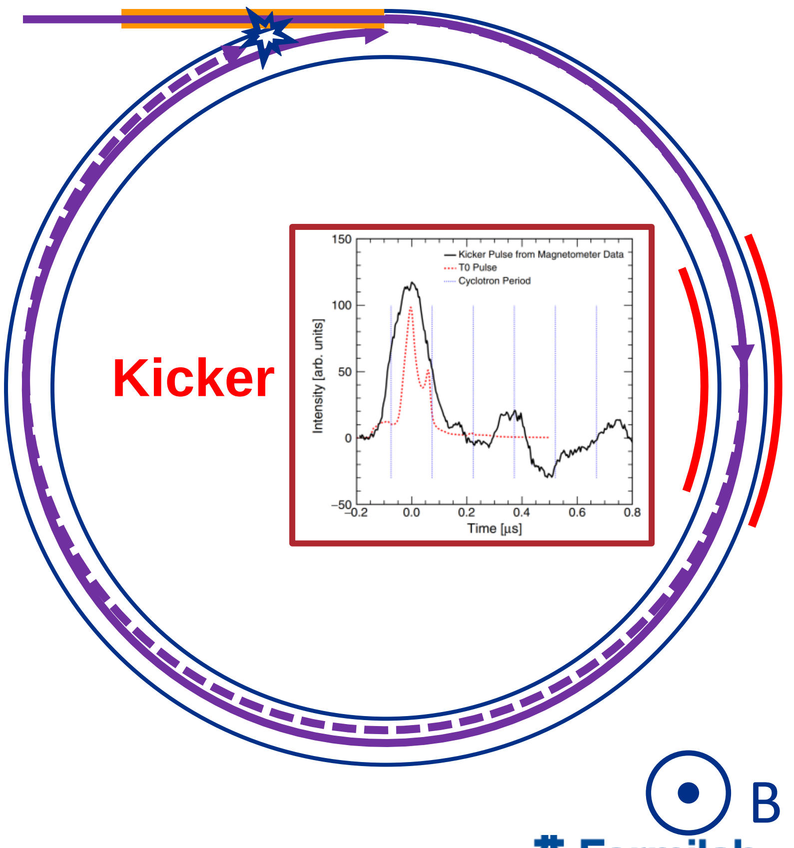




# Kick onto the proper orbit



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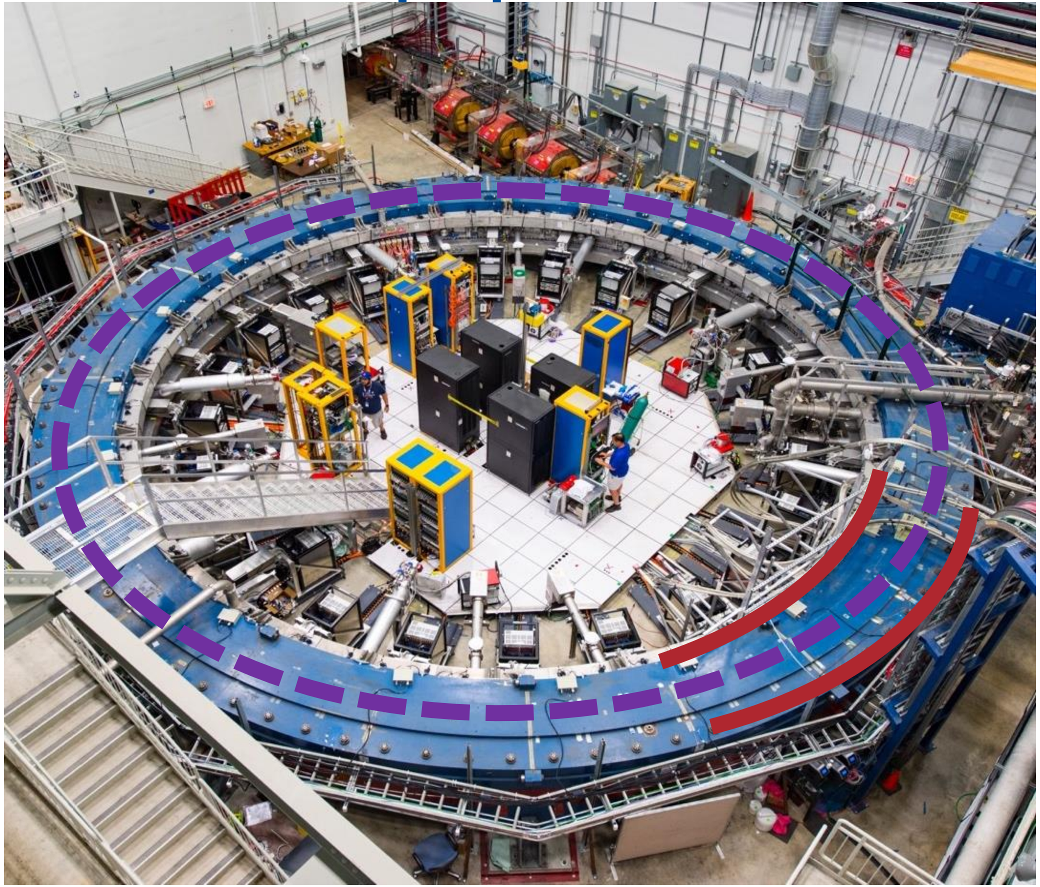
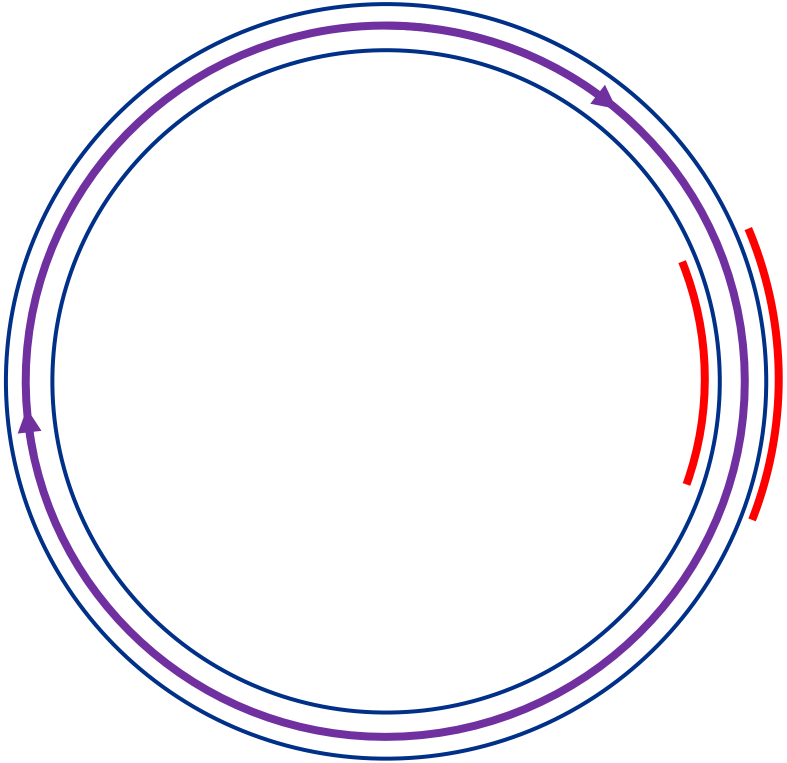
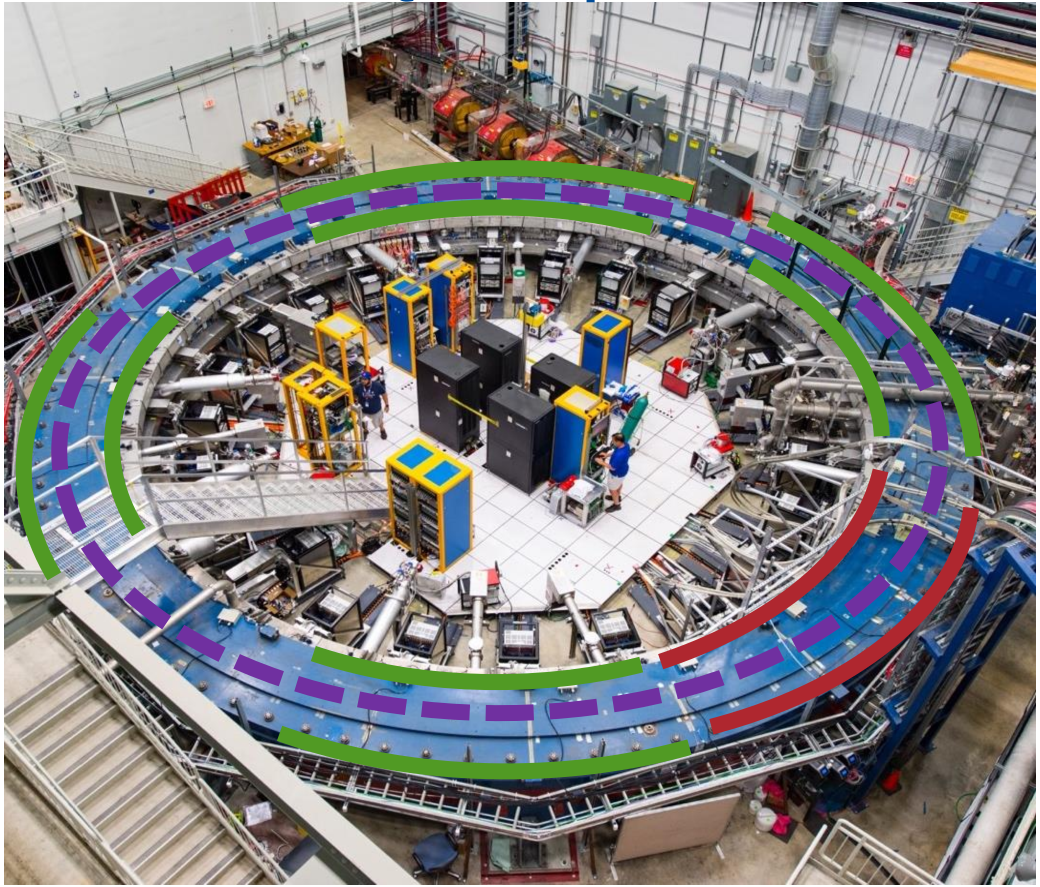
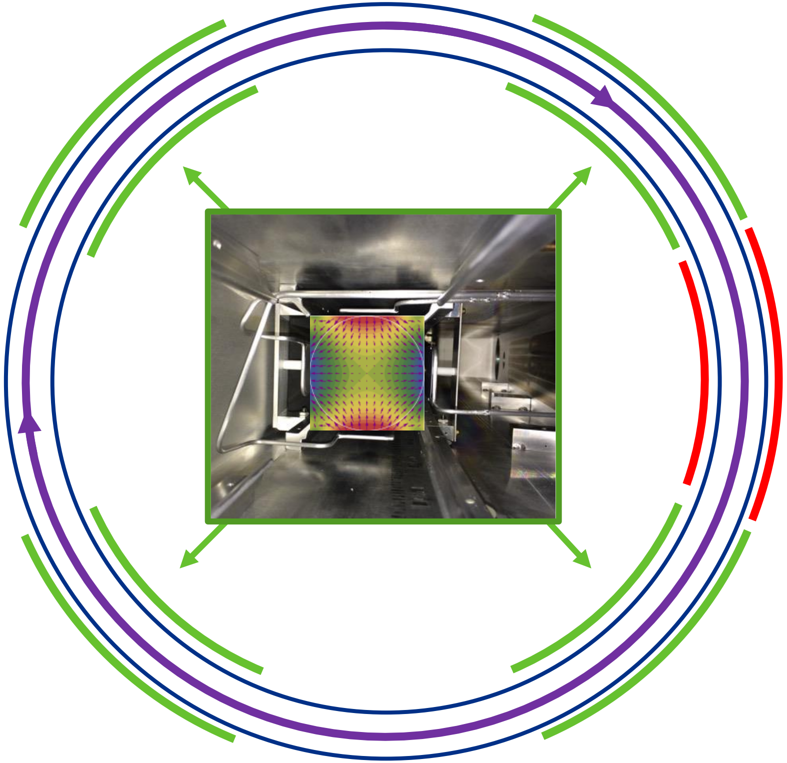


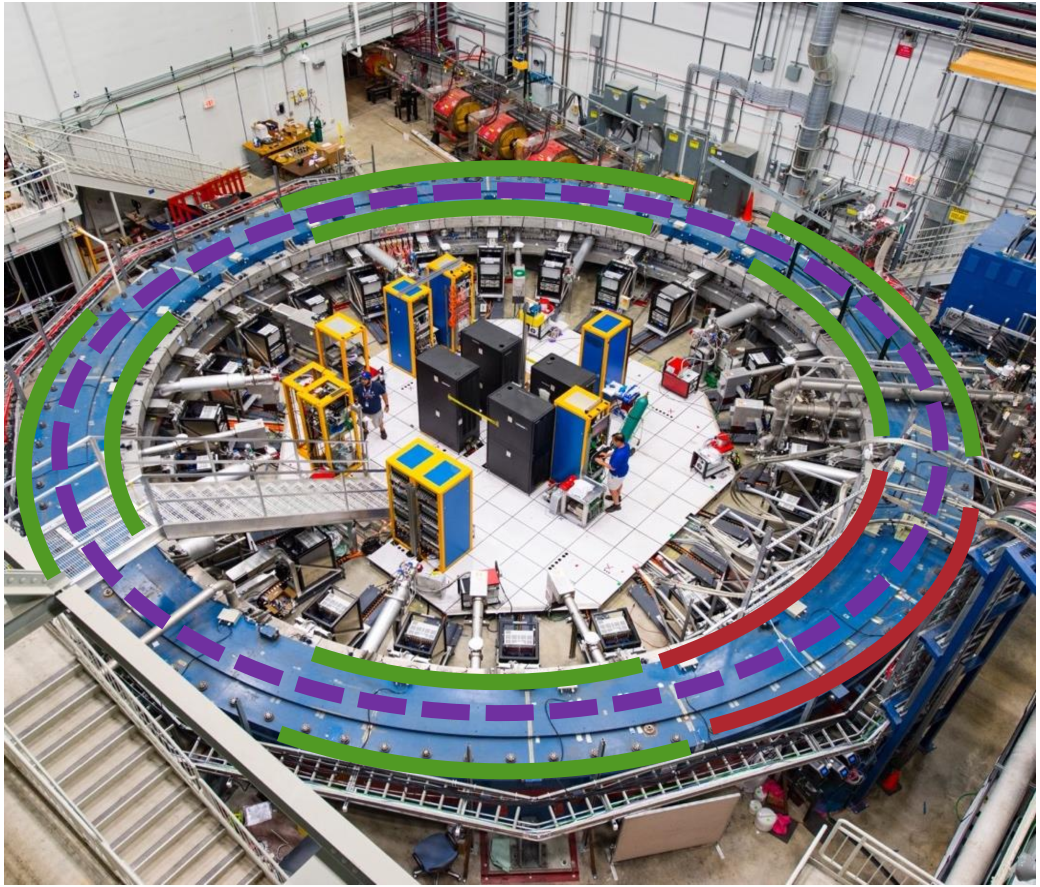


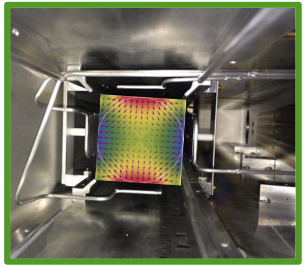
# Electrostatic Quadrupoles Focus Vertically



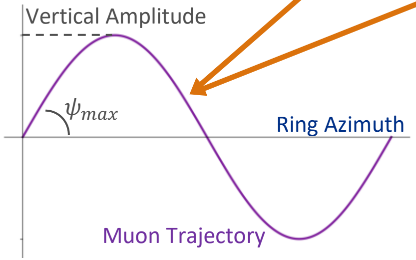


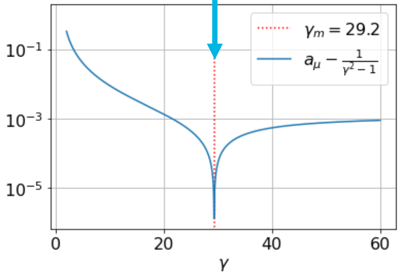
# Electric Field Requires Correction to $a_\mu$





$$\omega_a = \frac{eB}{mc}\left[a_\mu - a_\mu \frac{\gamma}{\gamma+1}\left(\beta\cdot\vec{B}\right)\vec{\beta} - \left(a_\mu - \frac{1}{\gamma^2-1}\right)\vec{\beta}\times\vec{E}\right]$$




Pitch Correction

$C_p \sim \mathcal{O}(200\ ppb)$

$\delta C_p \sim \mathcal{O}(5\ ppb)$

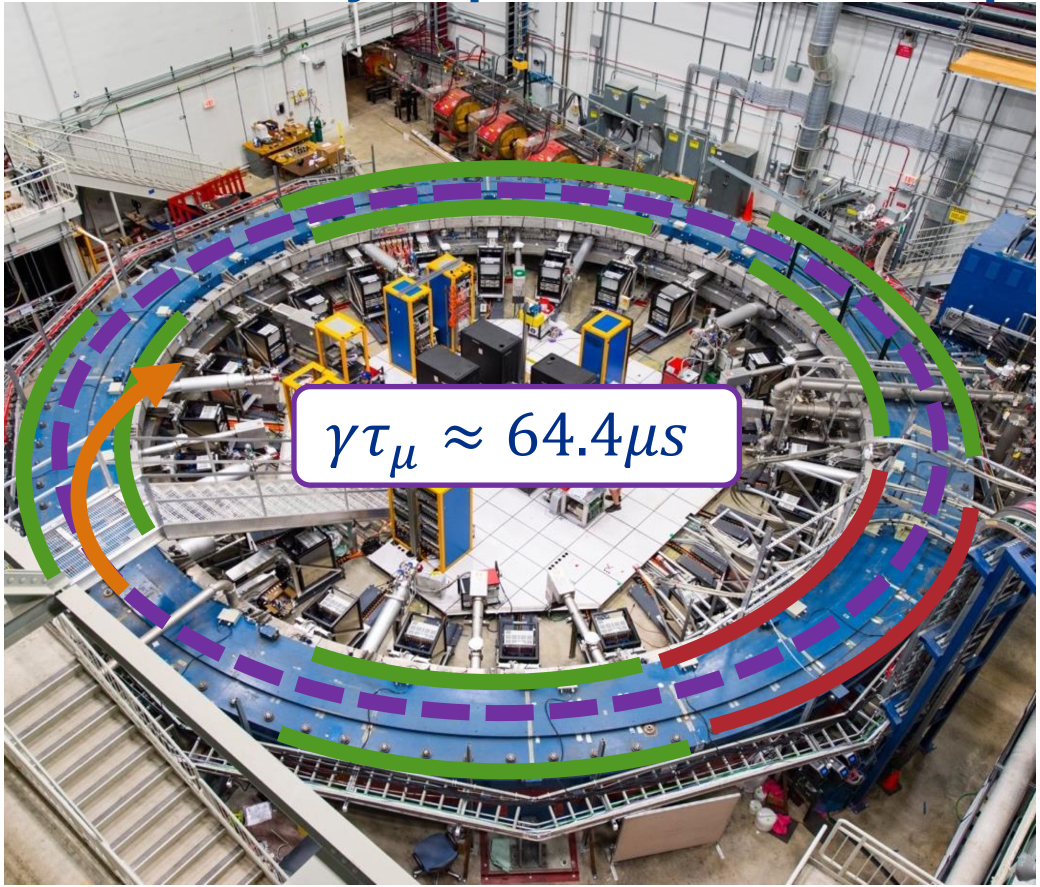
$E$ Field Correction

$C_e \sim \mathcal{O}(500\ ppb)$

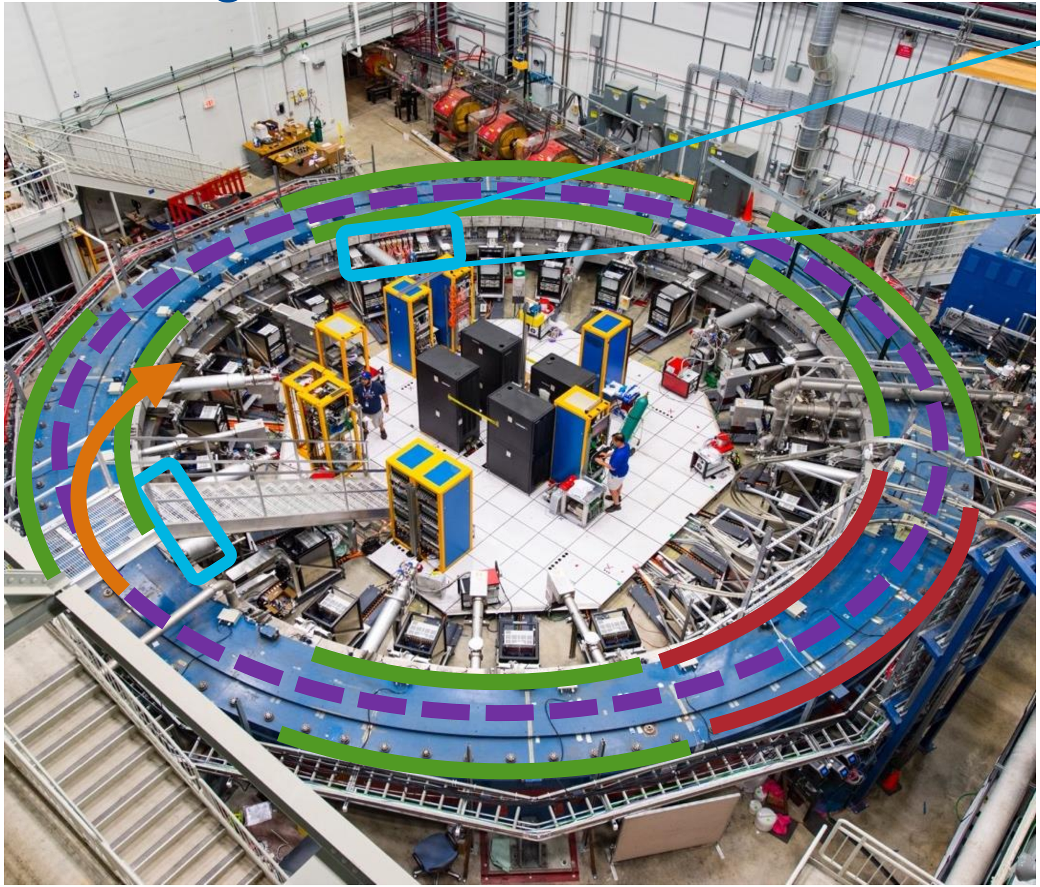
$\delta C_e \sim \mathcal{O}(30\ ppb)$

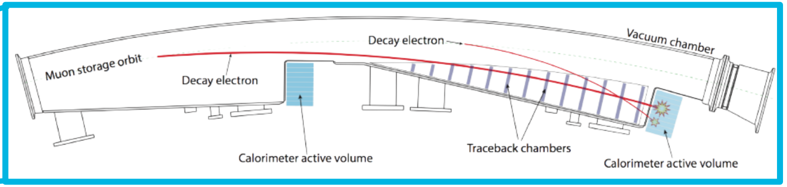
$$a_\mu = \omega_a \frac{mc}{eB}\left(1 + C_p + C_e + \cdots\right)$$

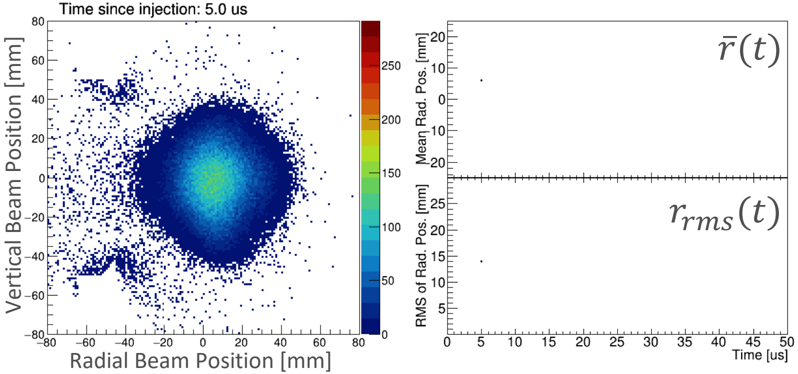
# Muons decay to positrons, which spiral inward



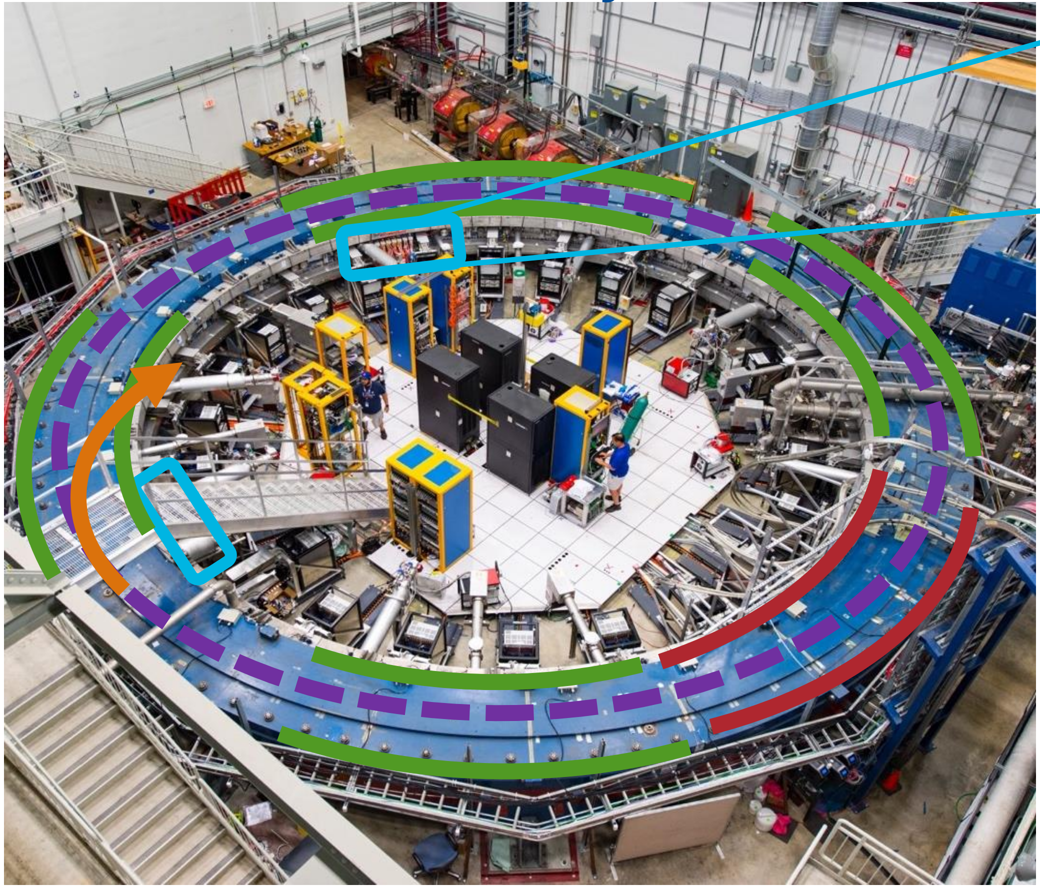
# Tracking Detectors can Reconstruct Decay Vertices

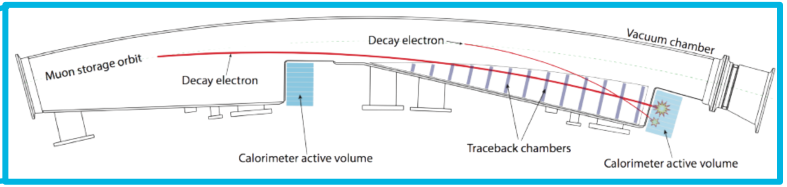




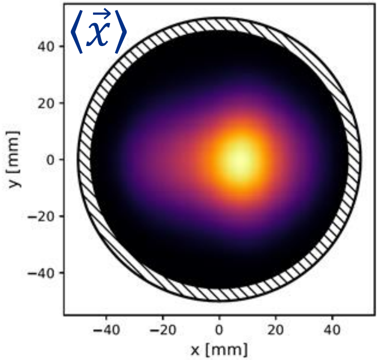



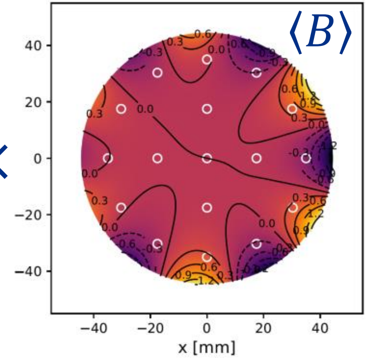
# Combined with Trolley Measurements, this Yields $\tilde{B}$






$$\left\langle \langle \vec{x} \rangle \times \langle B \rangle \right\rangle$$



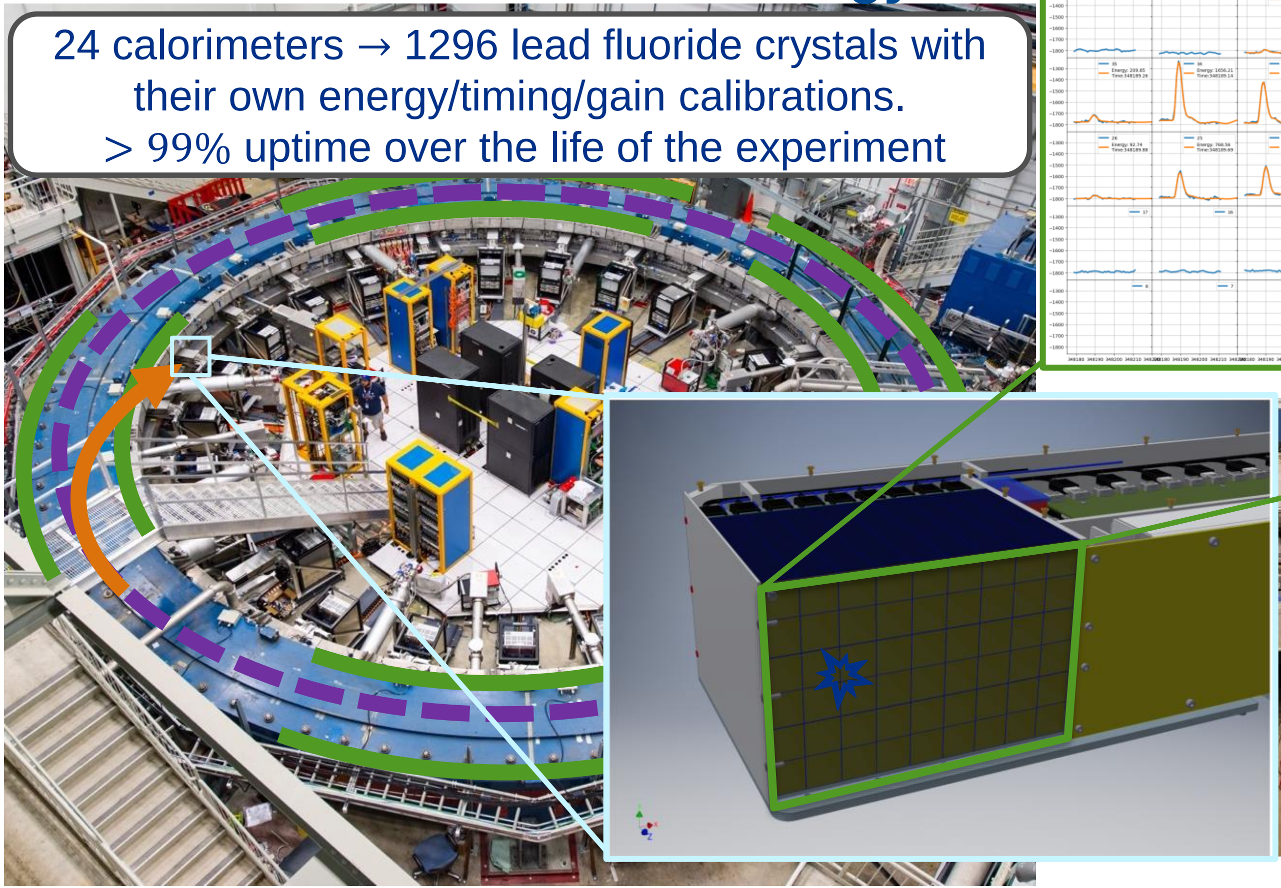



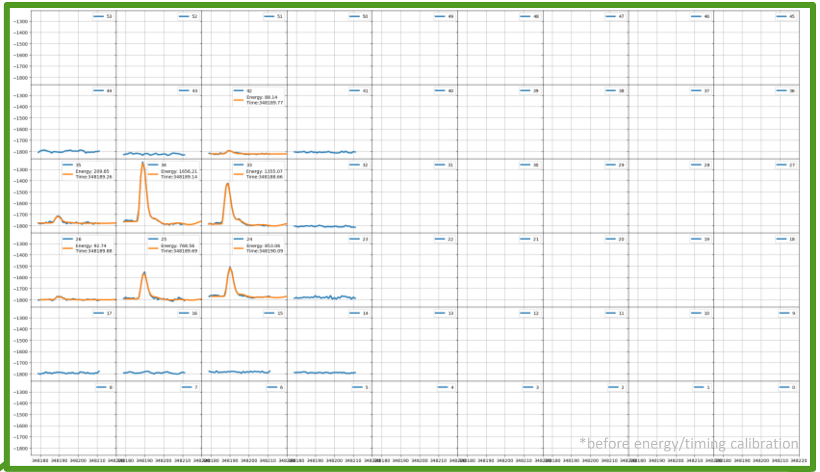

$$= \tilde{B}$$

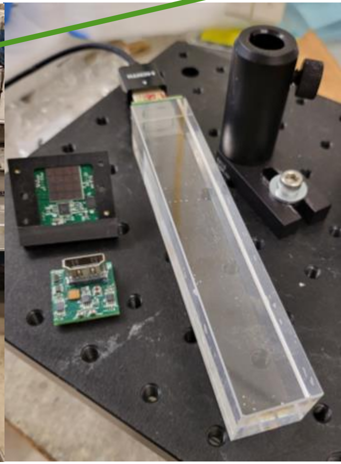
Time averaged beam position from trackers gives us the weighted $B$ field

# Calorimeters Measure $e^+$ Energy

24 calorimeters → 1296 lead fluoride crystals with their own energy/timing/gain calibrations.
$>$ 99% uptime over the life of the experiment



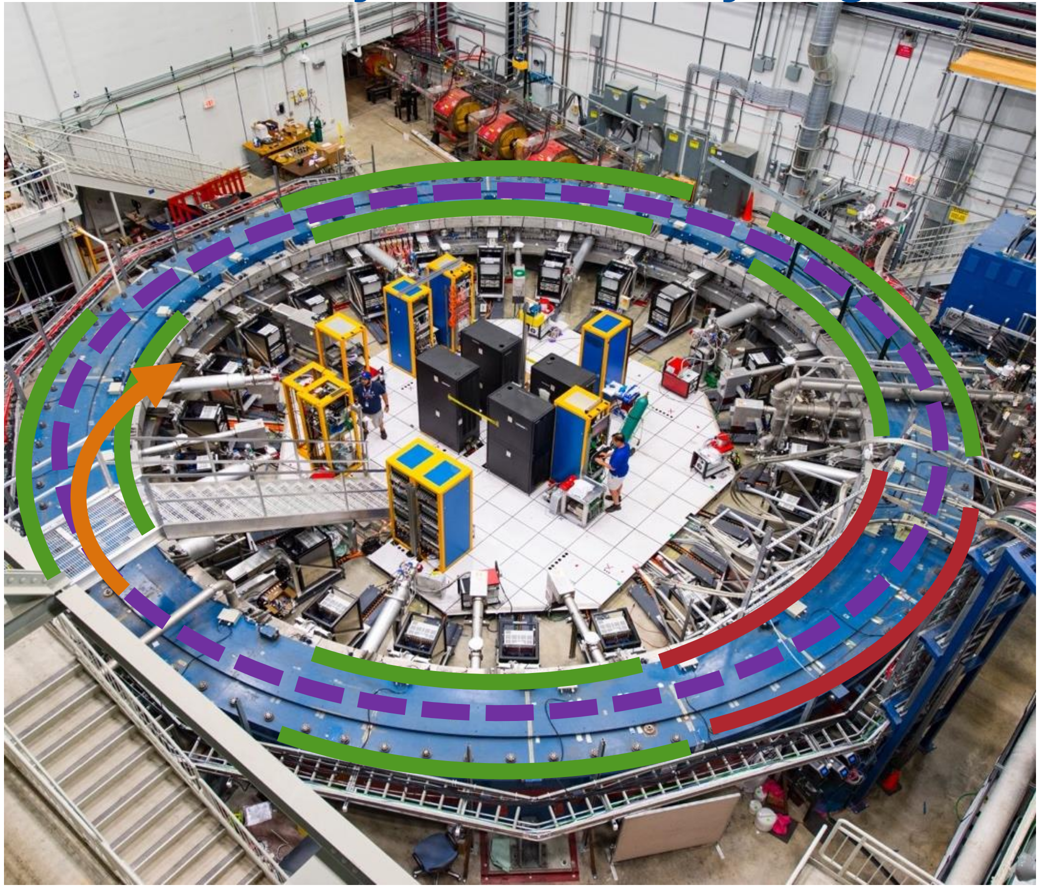


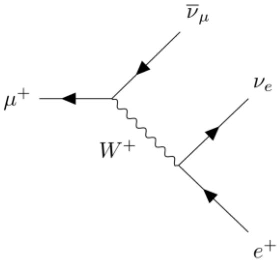



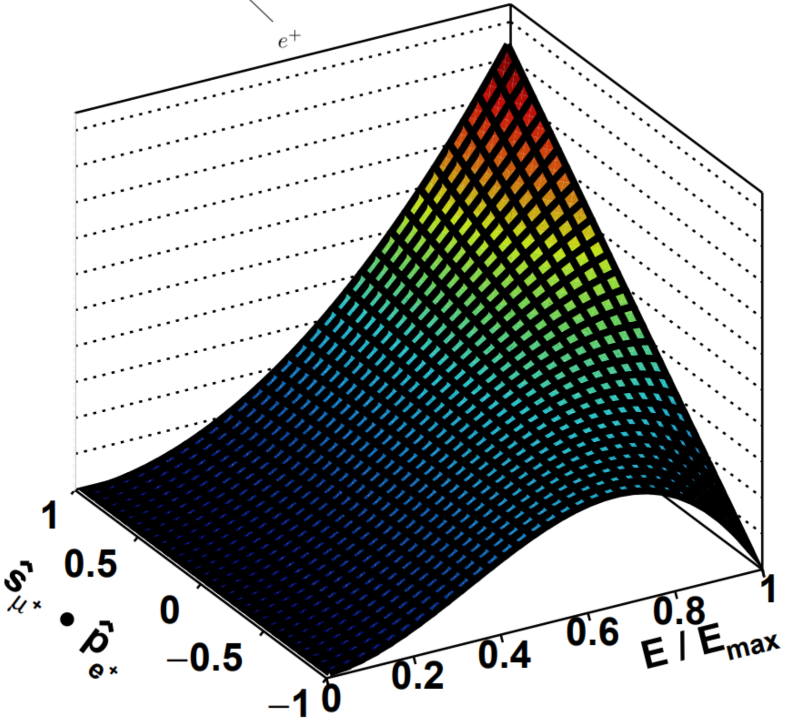


Fermilab

# Muons Decay is Self-Analyzing





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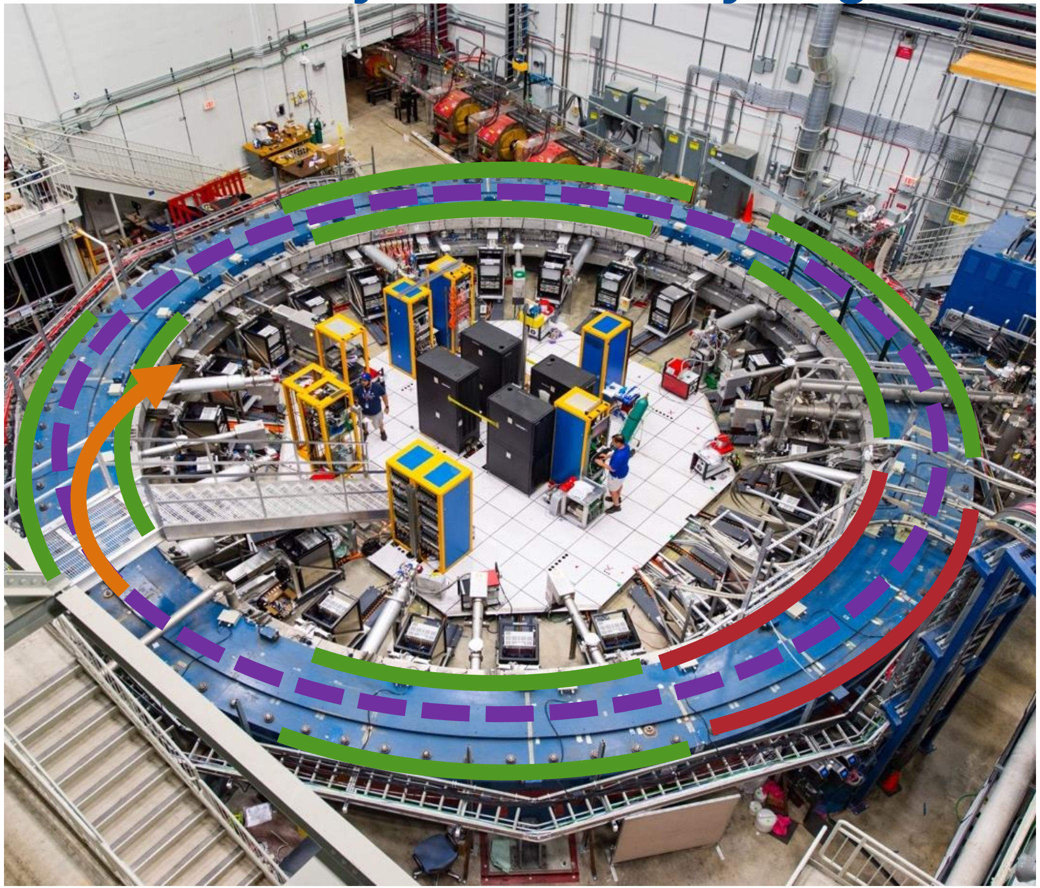
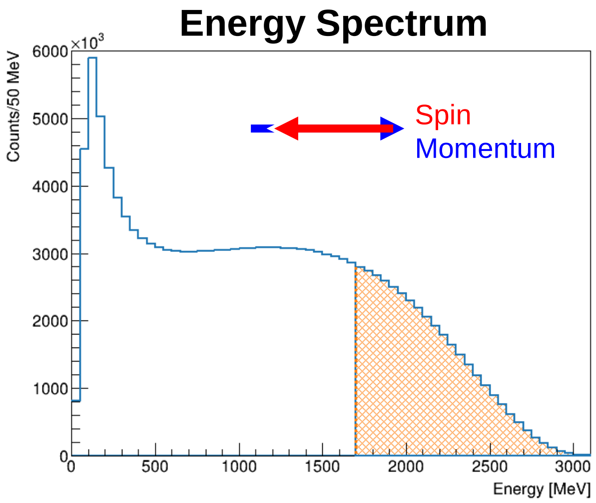
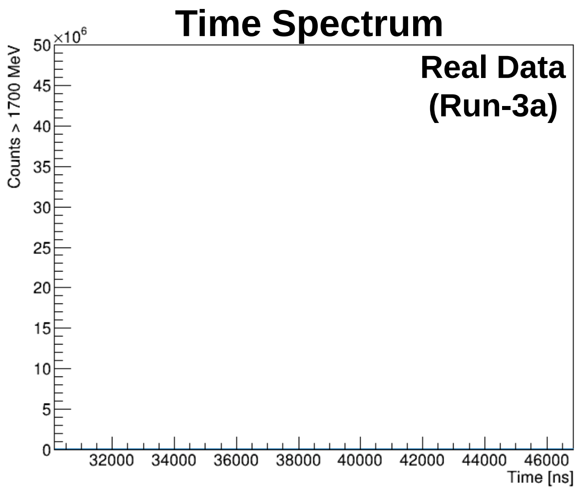




# Run-2/3 Dataset

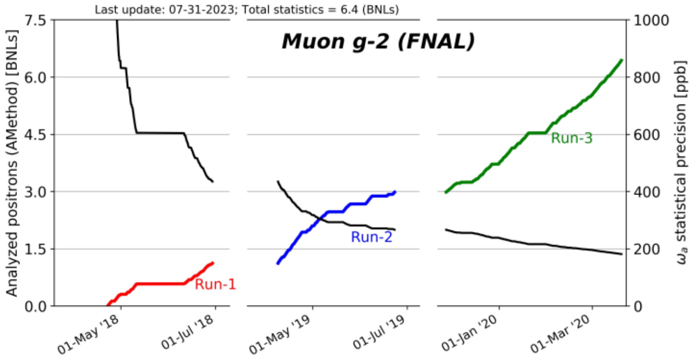
**This dataset: 5.3 x BNL, 4.7x Run-1**

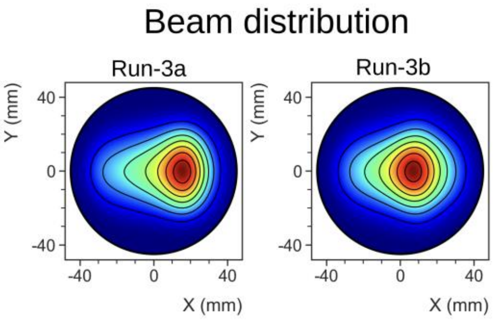
**Better running conditions**

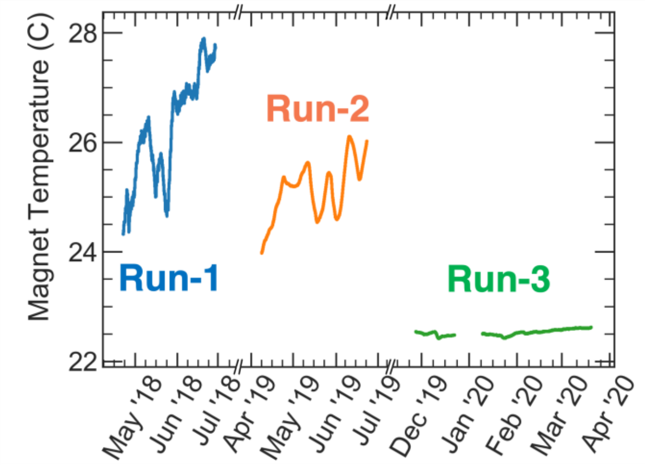
- **Improved quadrupole performance throughout**
- **Improved kick strength in the latter half of Run-3**
- **Improved magnet and detector stability**

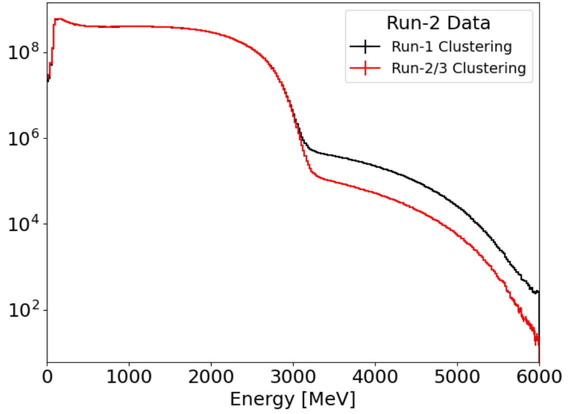
**Improved analysis techniques**

- **Pileup improved in one reconstruction algorithm by a factor or 2+**
- **Upgrades to how some systematics are handled, new measurement techniques incorporated as cross-checks**




+ many more improvements

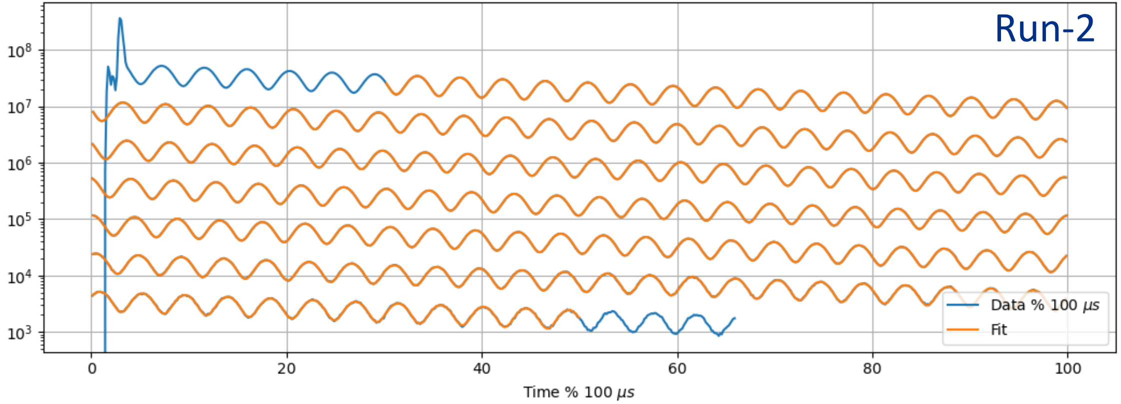
# Precession Frequency Analysis

**Simplest functional form:**

$$N(t) = N_0 e^{-t/\tau_\mu}\left(1 - A_0 \cos(\omega_a t - \phi_a)\right)$$

**However the fit to the data is relatively poor:**

$$\chi^2/NDF = 10.7$$



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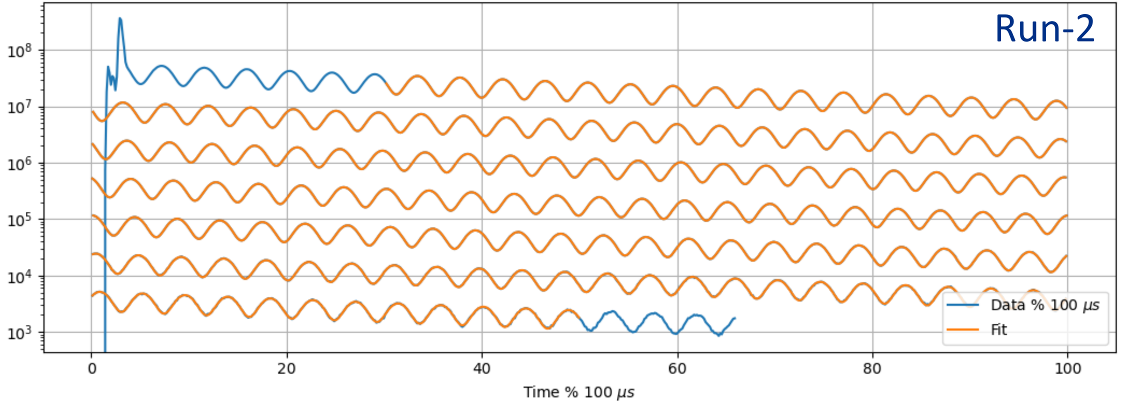
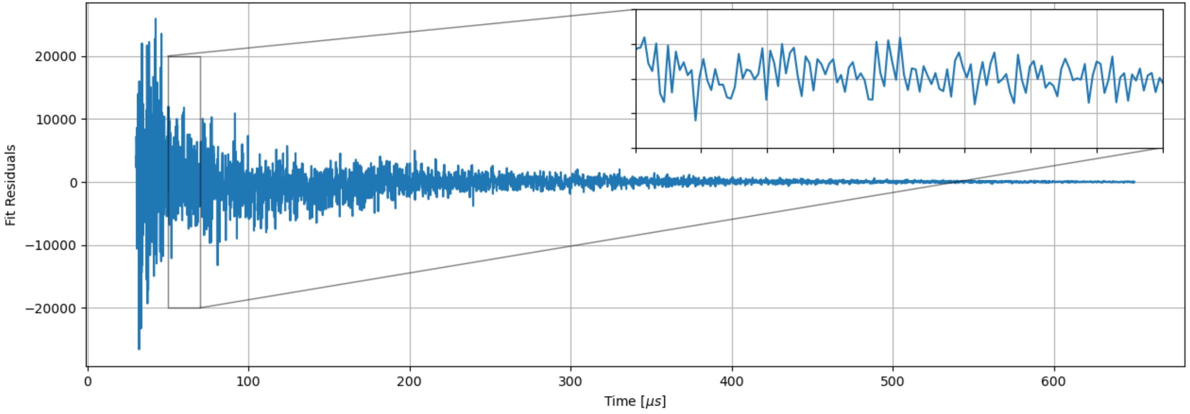
**Looking at the residuals, we see clear evidence of frequencies beyond the pure g-2 oscillation.**

**These are the beam oscillation frequencies, which if not accounted for can bias our extraction of $\omega_a$.**



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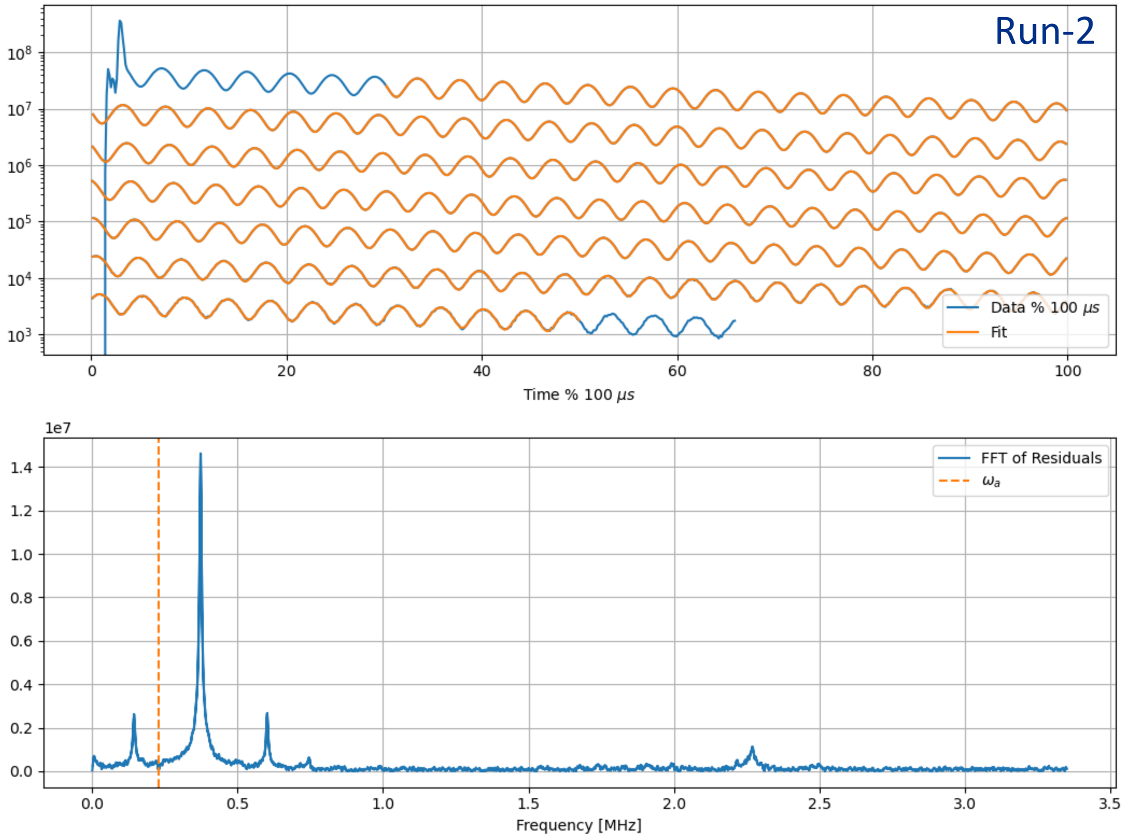
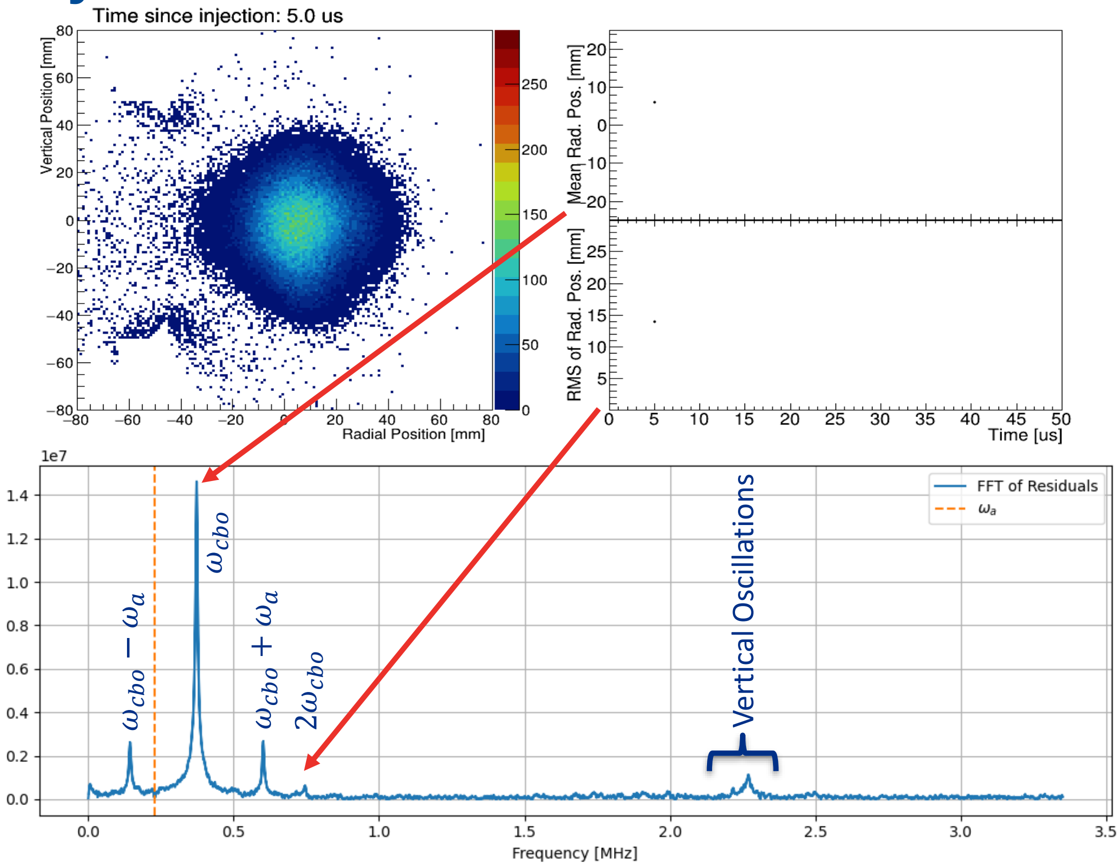


# Precession Frequency Analysis

**The largest beam oscillation frequency is the radial 'coherent betatron oscillation' [CBO].**

**This (and other beam motion frequencies) enter our fit due to detector acceptance difference for different decay positions.**



# Precession Frequency Analysis: Adding 1st Order CBO

**We can modify the fit function to incorporate these beam motion effects. The lowest order effect is the CBO motion, which we incorporate as:**

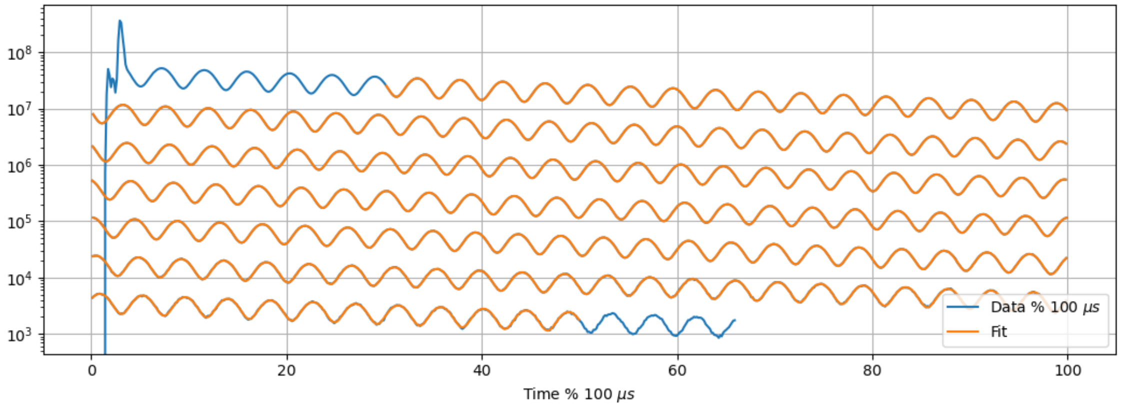
$$N(t) = N_0 N_x e^{-t/\tau_\mu}\left(1 - A_0\, cos(\omega_a t - \phi_a)\right)$$

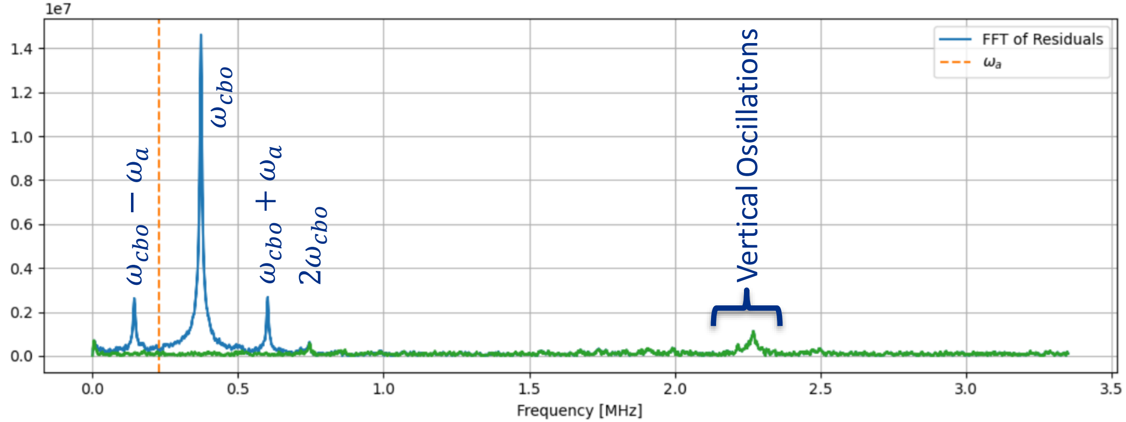
**where:**

$$N_x(t) = 1 + A_{cbo} e^{-t/\tau_{cbo}} cos(\omega_{cbo} t + \phi_{cbo})$$

**With this addition:**

$$\chi^2/NDF = 1.18$$



# Precession Frequency Analysis: Full Fit Function

$$N(t) = N_0 N_{loss}(t) N_x(t) N_y(t) N_{xy}(t)\, e^{-t/\tau} \left[1 + A\, A_x(t) \cos(R(\omega_a)t - \phi_a\, \phi_x(t))\right]$$

R ≡ blinded proxy for $\omega_a$

$$N_{loss}(t) = 1 - K_{loss}\Lambda(t)$$

$$N_x(t) = 1 + e^{-2t/\tau_{cbo}} A_{NX22} \cos(\omega_{cbo}(t)t + \phi_{NX22})$$

$$N_y(t) = 1 + e^{-t/\tau_y} A_{NY11} \cos(\omega_y(t)t + \phi_{NY11})$$

$$A_x(t) = e^{-t/\tau_{cbo}} A_{AX11} \cos(\omega_{cbo}(t)t + \phi_{AX11})$$

$$\phi_x(t) = 1 + e^{-t/\tau_{cbo}} A_{\phi X11} \cos(\omega_{cbo}(t)t + \phi_{\phi X11})$$

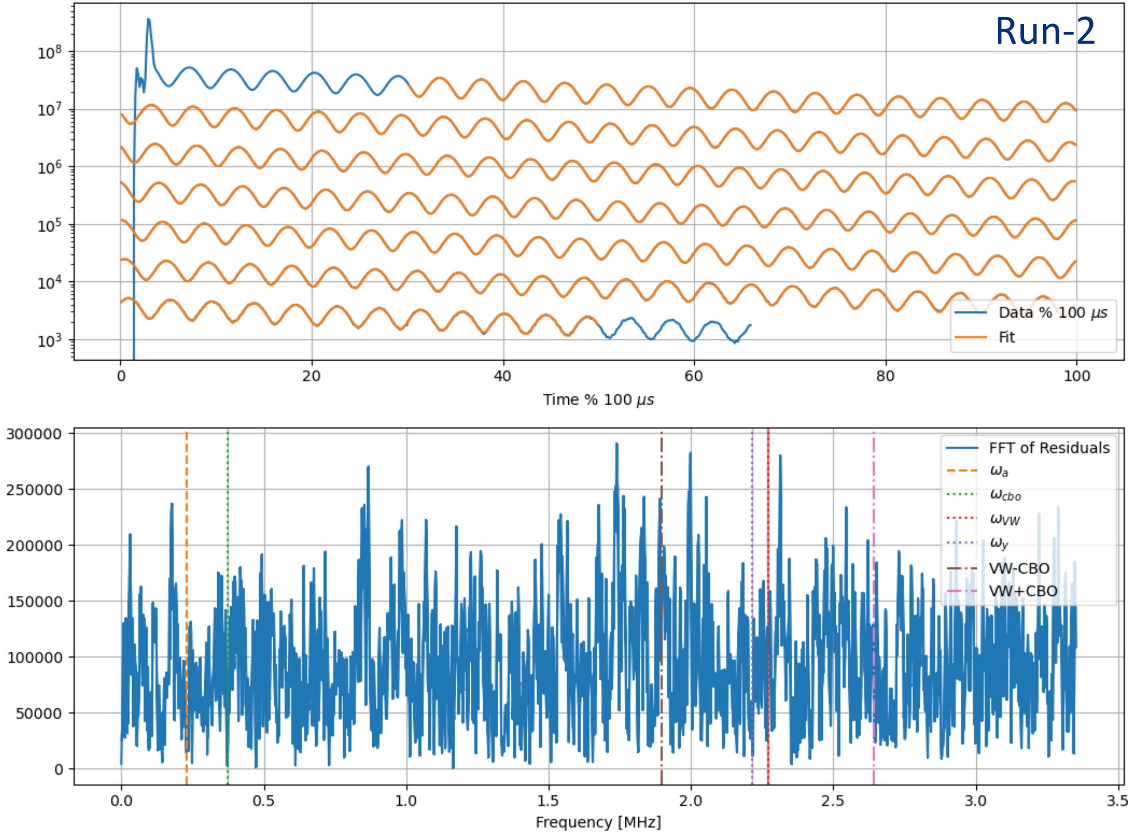
$$N_{xy}(t) = 1 + e^{-t/\tau_{cbo}} A_{NX11} \cos(\omega_{cbo}(t)t + \phi_{NX11}) + e^{-t/\tau_{vw}} A_{NY22} \cos(\omega_{VW}(t)t + \phi_{NY22}) + e^{-t/\tau_{cbo} - t/\tau_{vw}} * \left[A_{xy+} \cos\left((\omega_{VW} + \omega_{cbo})t + \phi_{xy+}\right) + A_{xy-} \cos\left((\omega_{VW} - \omega_{cbo}) + \phi_{xy-}\right)\right]$$

Revealed with higher statistics Run-2+3.
More expected in Run-4+

# Precession Frequency Analysis

**After the addition of terms accounting for vertical and horizontal beam motions and Muon losses, we arrive at a final fit.**

**No more peaks are seen in the residuals, and the fit converges to a stable minimum.**

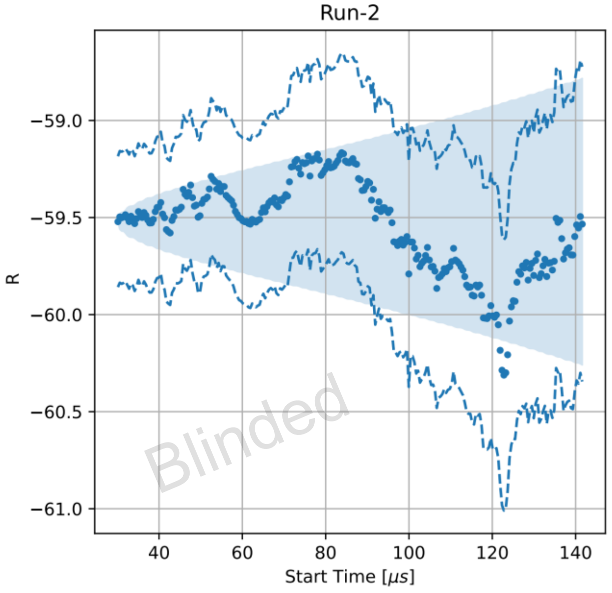


# Precession Frequency Analysis: Cross Checks

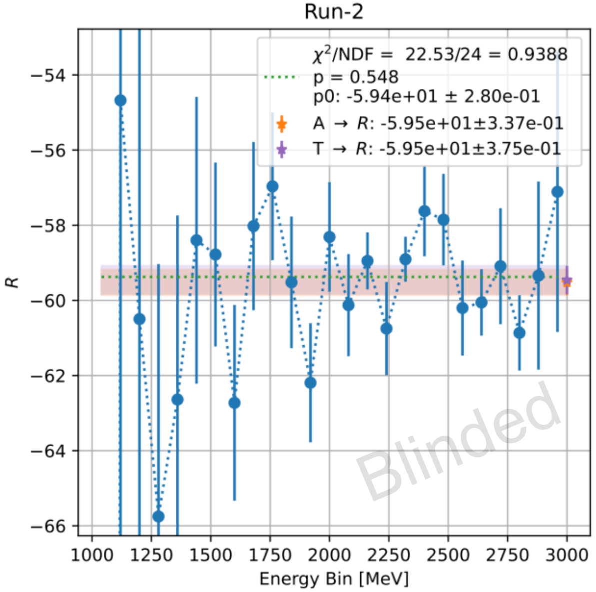
R ≡ blinded proxy for $\omega_a$

## $R(\omega_a)$ stability vs:

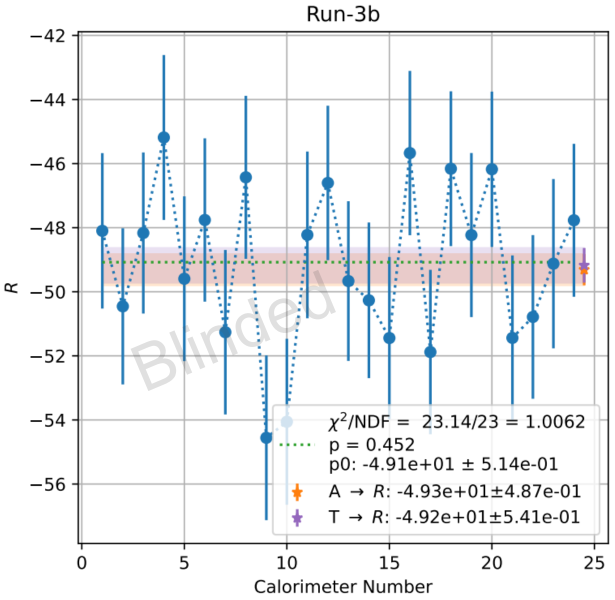
### Start time




### Energy Bin

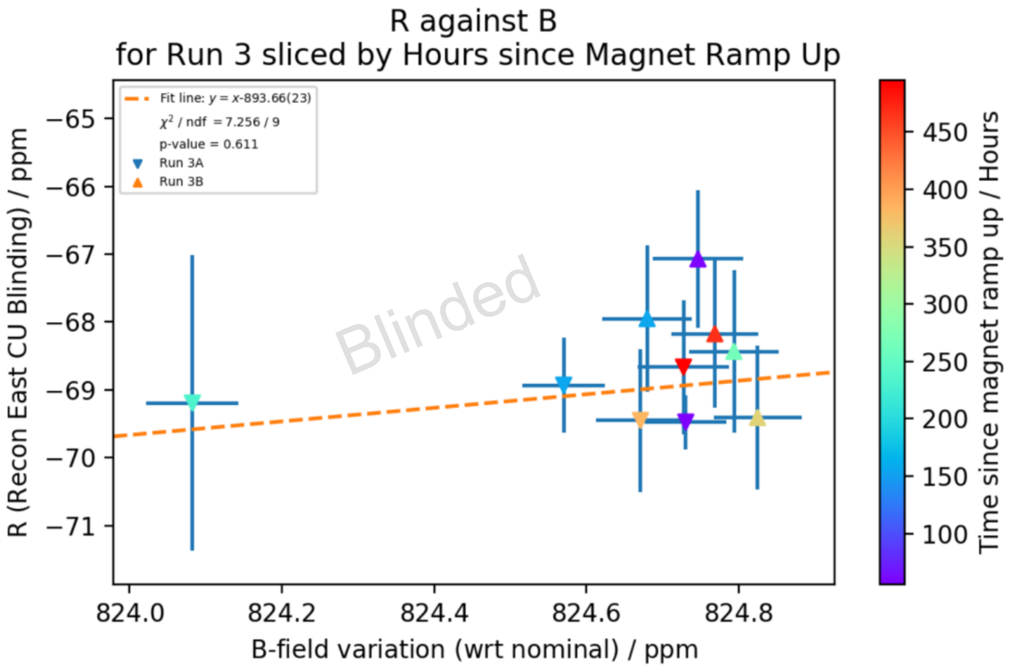


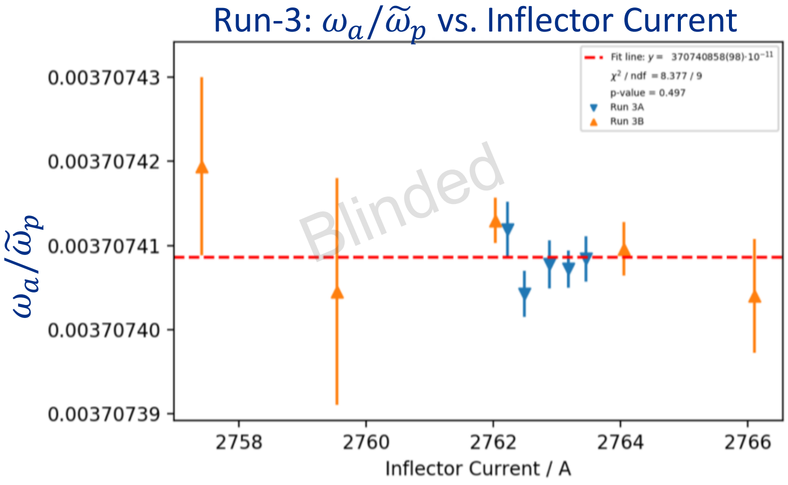

### Calorimeter

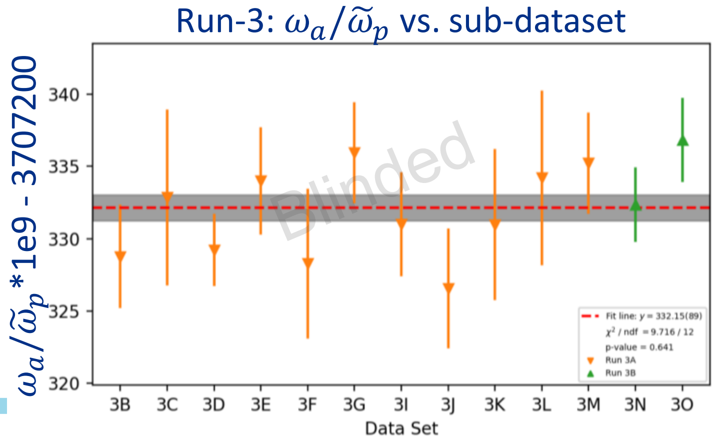



Fermilab

# Precession Frequency Analysis: Cross Checks




+ many, many more cross checks

# Putting it all together… with corrections

$$a_\mu = \frac{\omega_a}{\tilde{B}} \frac{m_\mu}{e}$$

Changes in $\omega_a$ | Changes in $\phi_a$

$$\frac{f_{clock}\,\omega_a^{meas}(1 + C_e + C_p + C_{ml} + C_{pa} + C_{dd})}{f_{calib}\langle \vec{x}(x,y,\phi) \times \omega_p(x,y,\phi)\rangle (1 + B_k + B_q)}$$

Transient magnetic fields

## External Constants

| | |
|---|---|
| $\frac{\mu_p'(T_r)}{\mu_e(H)}$ | 10.5 ppb uncertainty at $T_r = 34.7°C$ <br> Metrologia 13, 179 (1977) |
| $\frac{\mu_e(H)}{\mu_e}$ | Bound state QED calculation “Exact” <br> CODATA 2018 |
| $\frac{m_\mu}{m_e}$ | Muonium hyperfine splitting + QED\| 22 ppb uncertainty <br> CODATA 2018 |
| $\frac{g_e}{2}$ | Electron g-2 (2023) 0.13 ppt uncertainty <br> Phys. Rev. Lett. 130, 071801 (2023). |

# Systematic Improvements: $C_{pa}$

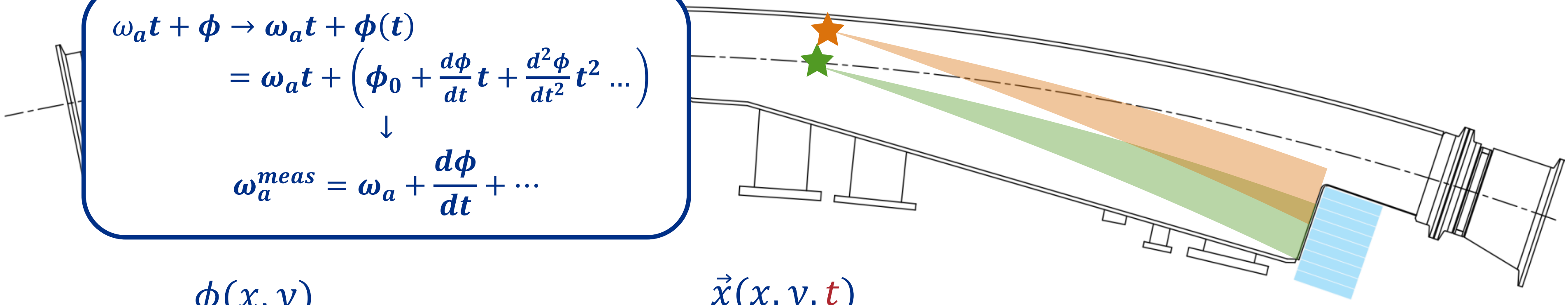
$$\frac{f_{clock}\,\omega_a^{meas}(1 + C_e + C_p + C_{ml} + C_{pa} + C_{dd})}{f_{calib}\langle \vec{x}(x,y,\phi) \times \omega_p(x,y,\phi)\rangle(1 + B_k + B_q)}$$

$$\omega_a t + \phi \rightarrow \omega_a t + \phi(t)$$

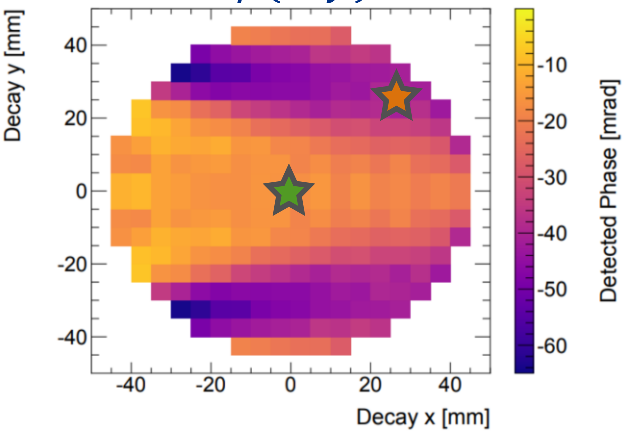
$$= \omega_a t + \left(\phi_0 + \frac{d\phi}{dt}t + \frac{d^2\phi}{dt^2}t^2 \ldots\right)$$

$$\downarrow$$

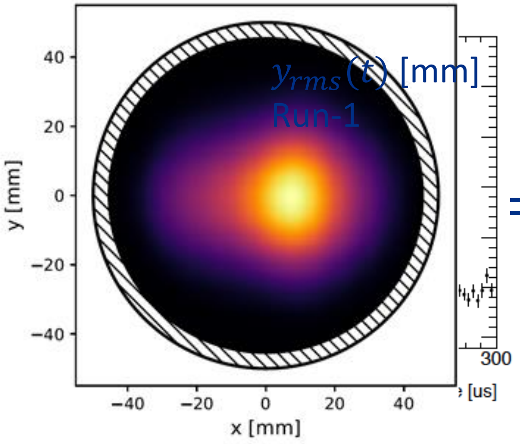
$$\omega_a^{meas} = \omega_a + \frac{d\phi}{dt} + \cdots$$



$\phi(x,y)$




$\otimes$ $\vec{x}(x,y,t)$

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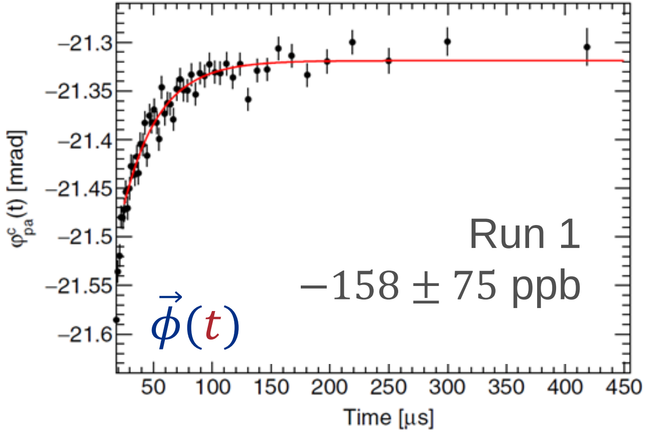

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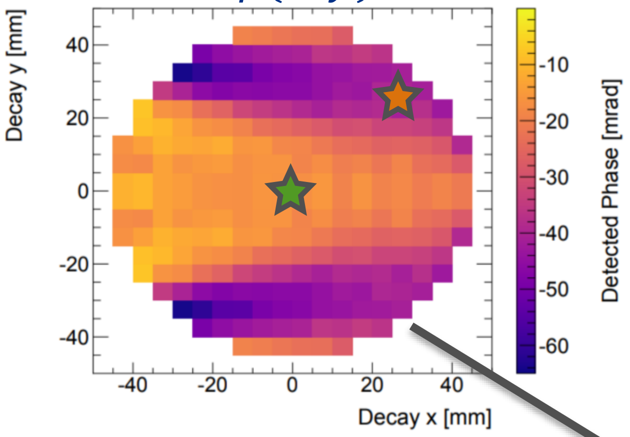
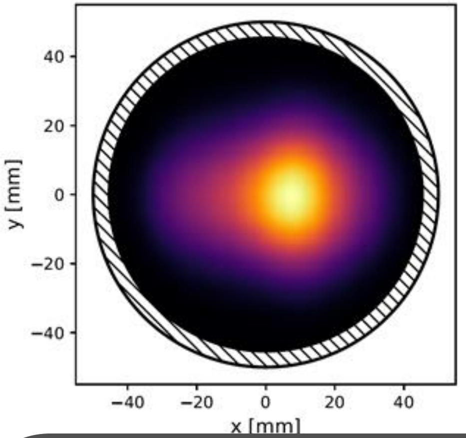
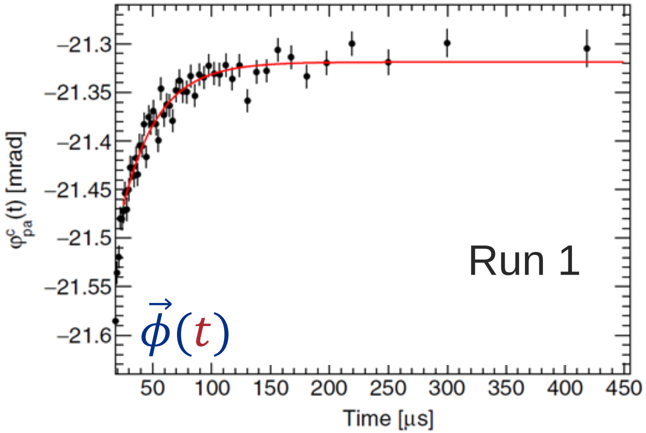
$$\frac{f_{clock}\,\omega_a^{meas}(1 + C_e + C_p + C_{ml} + C_{pa} + C_{dd})}{f_{calib}\langle\vec{x}(x,y,\phi)\times\omega_p(x,y,\phi)\rangle(1 + B_k + B_q)}$$

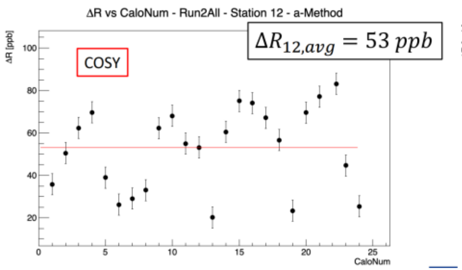
$\phi(x,y)$ $\otimes$ $\vec{x}(x,y,t)$ $=$ $\vec{\phi}(t)$

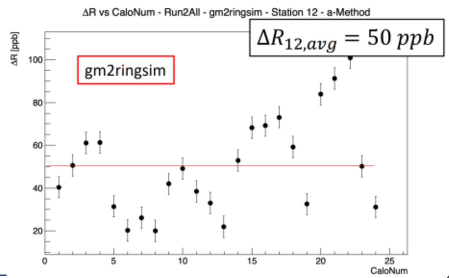



Additional systematic studies done to verify phase/ acceptance maps. Cross checks between different simulation programs to ensure consistent results.



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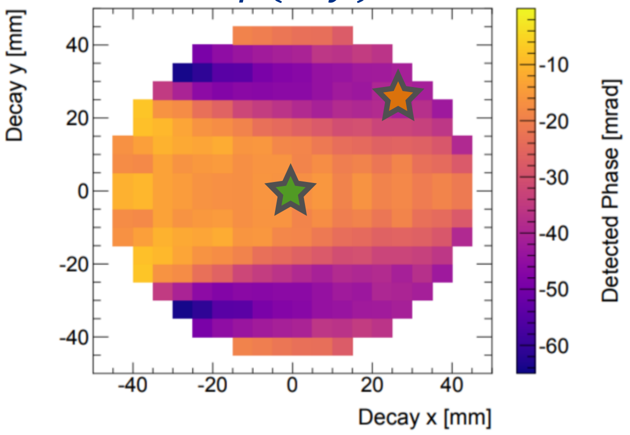
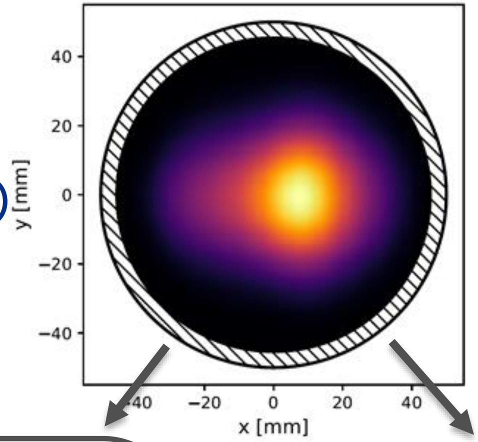
$\phi(x,y)$

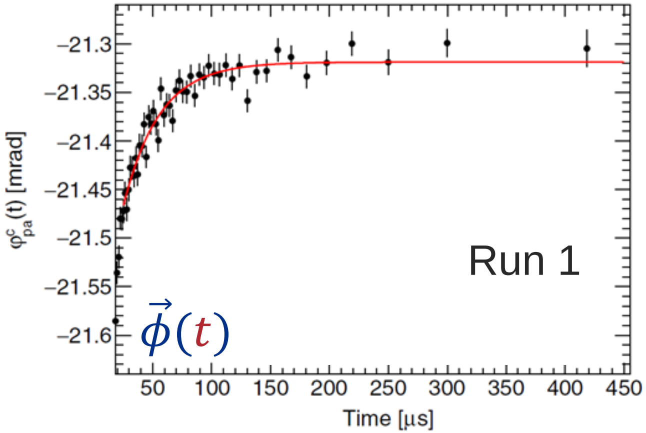


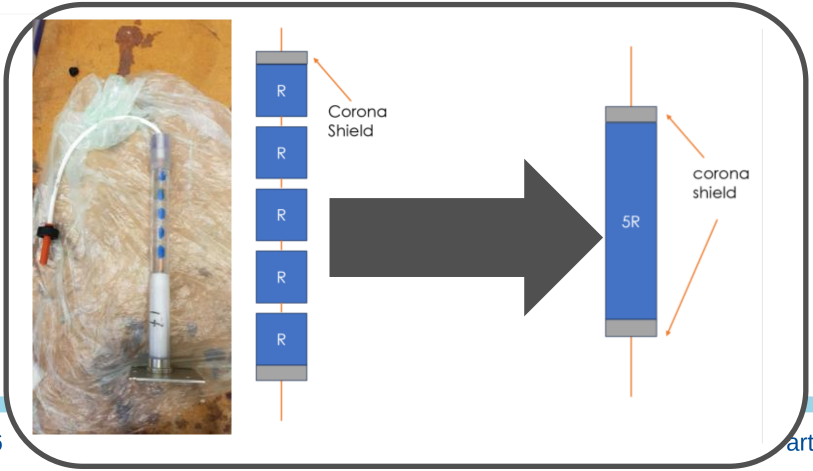

$\otimes$

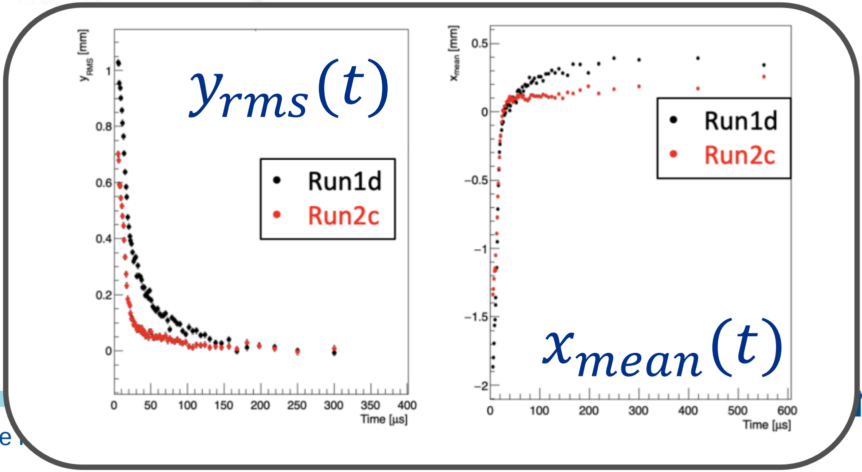
$\vec{x}(x,y,t)$




$=$




article

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# Systematic Improvements: $C_{pa}$

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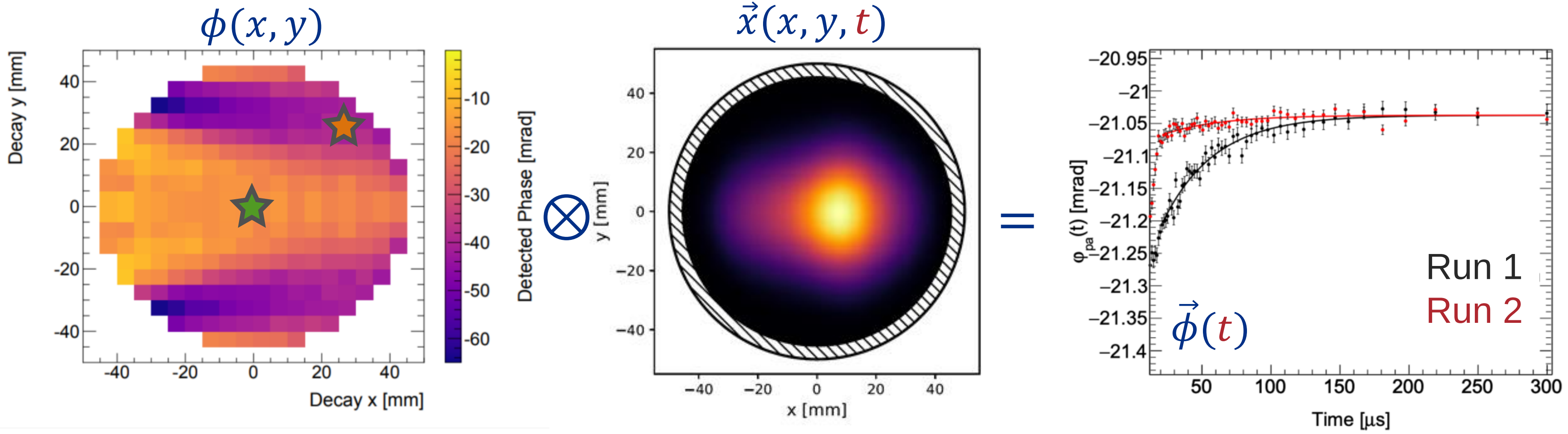
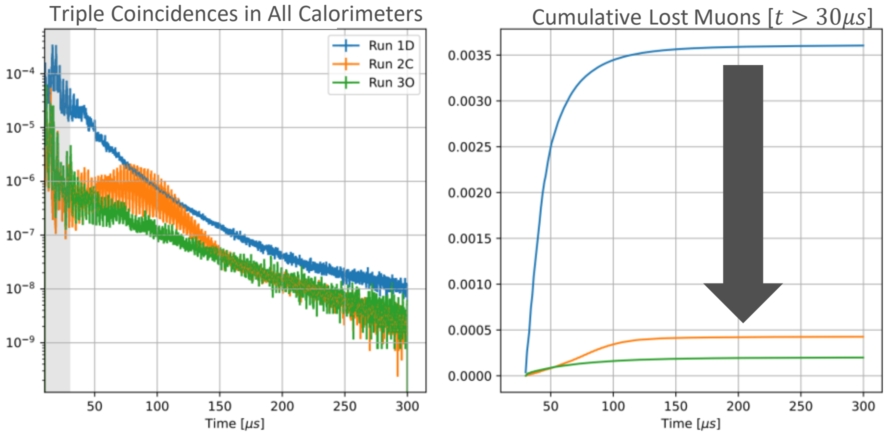
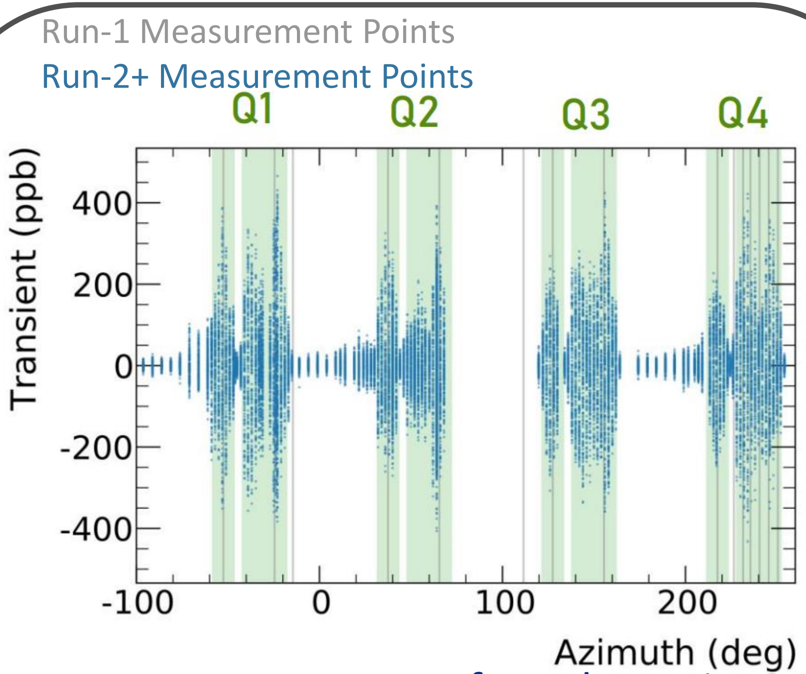



| $C_{pa}$ | Correction [ppb] | Uncertainty [ppb] |
|---|---|---|
| Run-1 | $-158$ | 75 |
| Run-2/3 | $-27$ | 13 |

# Selected Systematic Improvements




Better running conditions reduced muon losses: $C_{ml}$ is now negligible




More measurements of quad transient: $B_q$ is now much better understood

# Run-2/3 Systematics

| Quantity | Correction [ppb] | Uncertainty [ppb] (Run-1) | Uncertainty [ppb] |
|---|---|---|---|
| $\omega_a^m$ (statistical) | – | 434 | 201 |
| $\omega_a^m$ (systematic) | – | 56 | 25 |
| $C_e$ | 451 | 53 | 32 |
| $C_p$ | 170 | 13 | 10 |
| $C_{pa}$ | -27 | 75 | 13 |
| $C_{dd}$ | -15 | - | 17 |
| $C_{ml}$ | 0 | 5 | 3 |
| $f_{\text{calib}} \langle \omega'_p(\vec{r}) \times M(\vec{r}) \rangle$ | – | 56 | 46 |
| $B_k$ | -21 | 37 | 13 |
| $B_q$ | -21 | 92 | 20 |
| $\mu'_p(34.7^\circ)/\mu_e$ | – | 10 | 11 |
| $m_\mu/m_e$ | – | 22 | 22 |
| $g_e/2$ | – | 0 | 0 |
| Total systematic | – | 157 | 70 |
| Total external parameters | – | 25 | 25 |
| Totals | 622 | 462 | 215 |

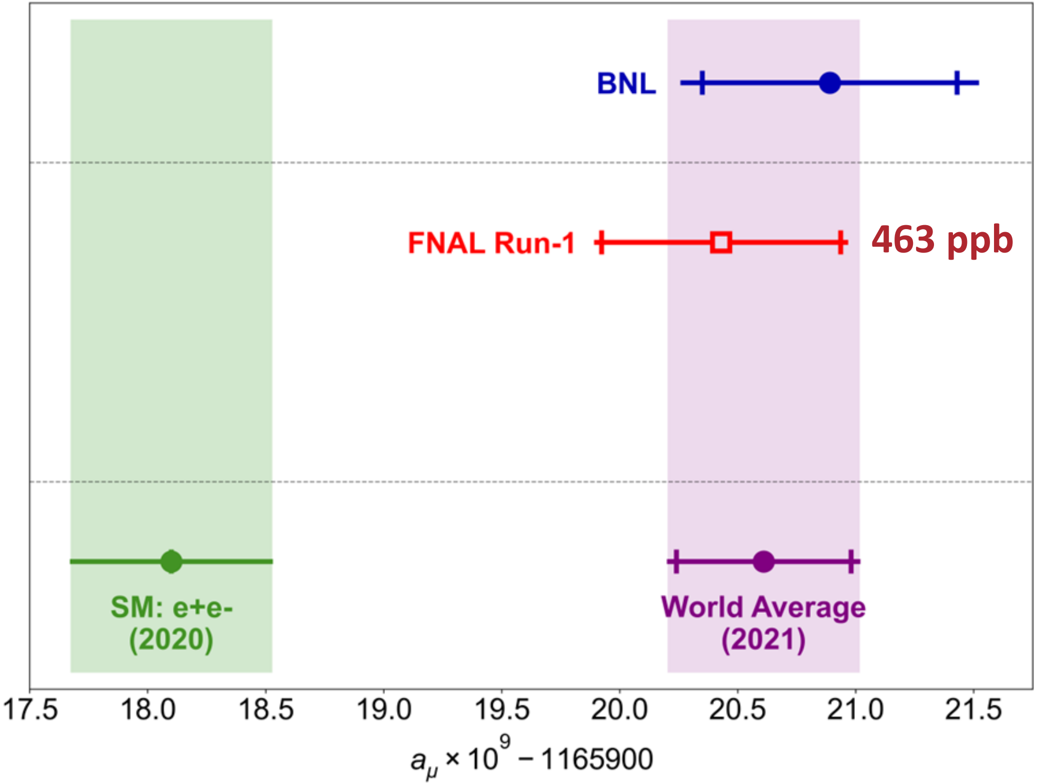
| [ppb] | Run-1 | Run-2/3 | Ratio |
|---|---|---|---|
| **Stat.** | 434 | **201** | 2.2 |
| **Syst.** | 157 | **70** | 2.2 |

**Systematic uncertainty of 🎉 70 ppb surpasses our 🎉 proposal goal of 100 ppb!**



Fermilab

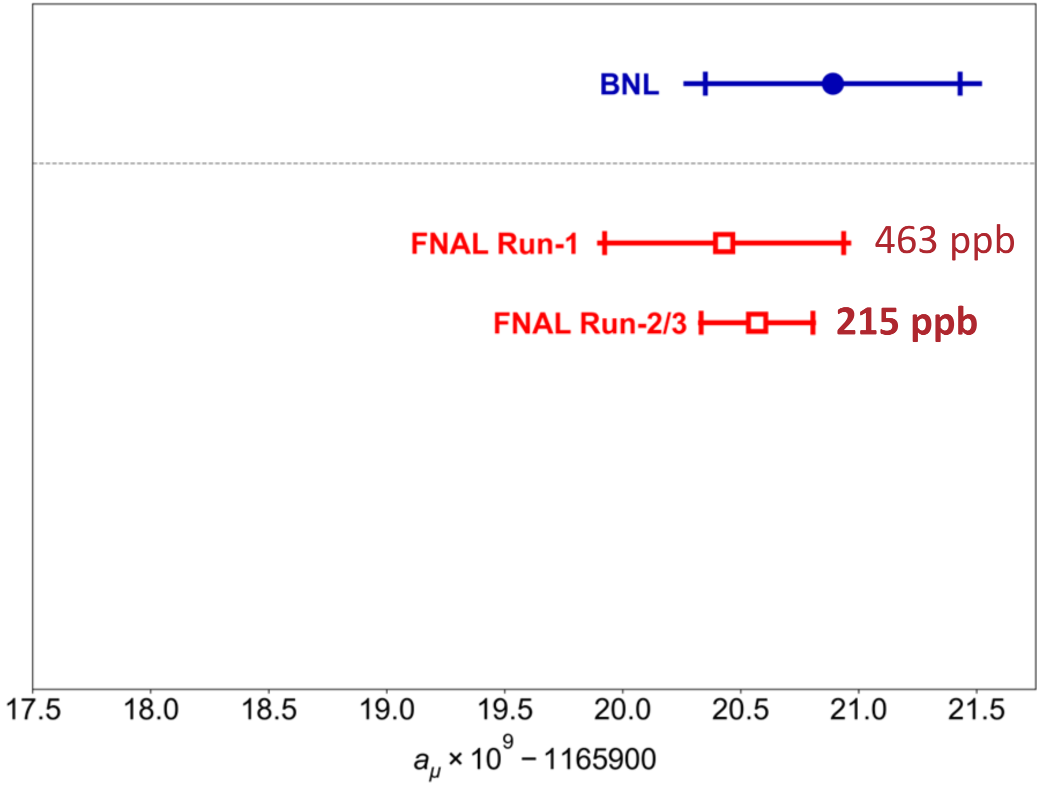
# Where we stand now




460 ppb

463 ppb

# Where we stand now

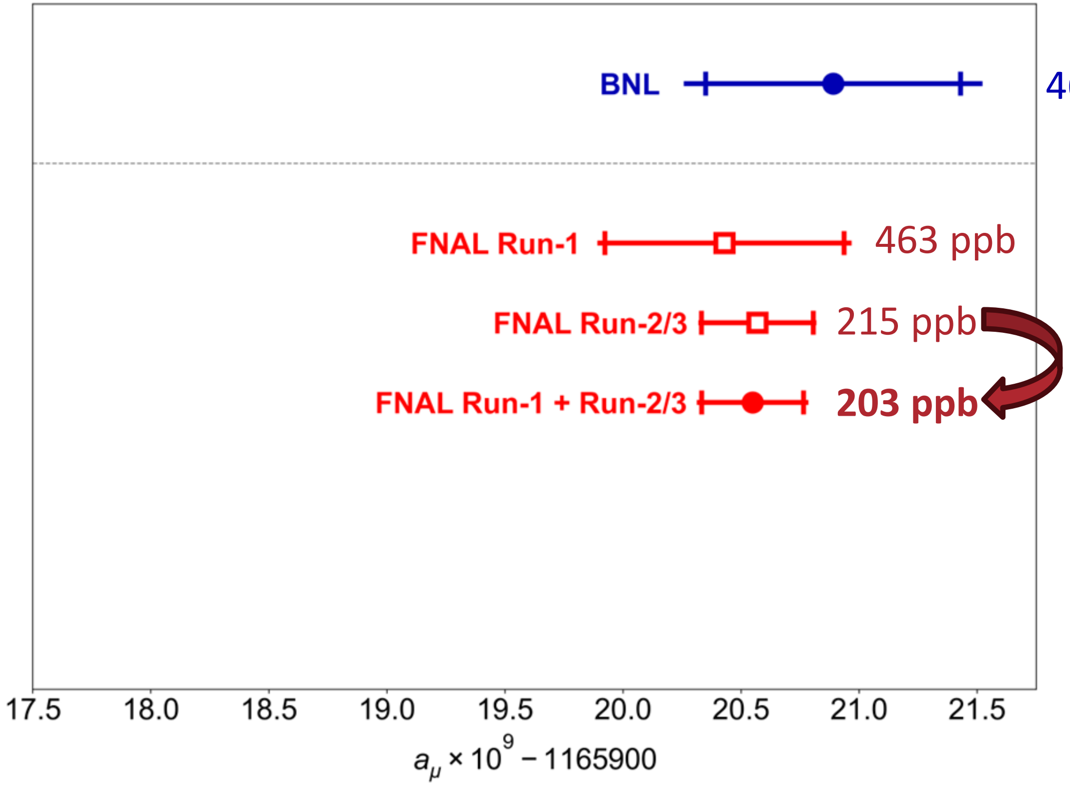



460 ppb

463 ppb

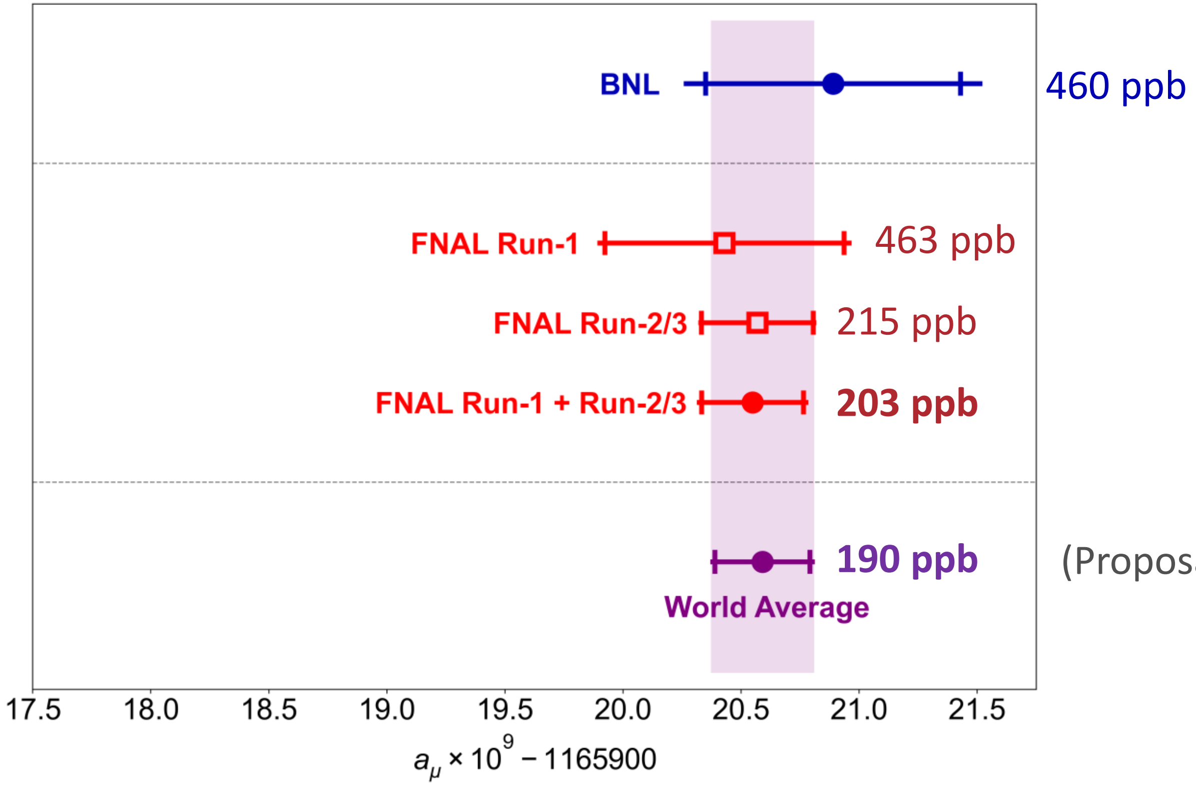
**215 ppb**

# Where we stand now



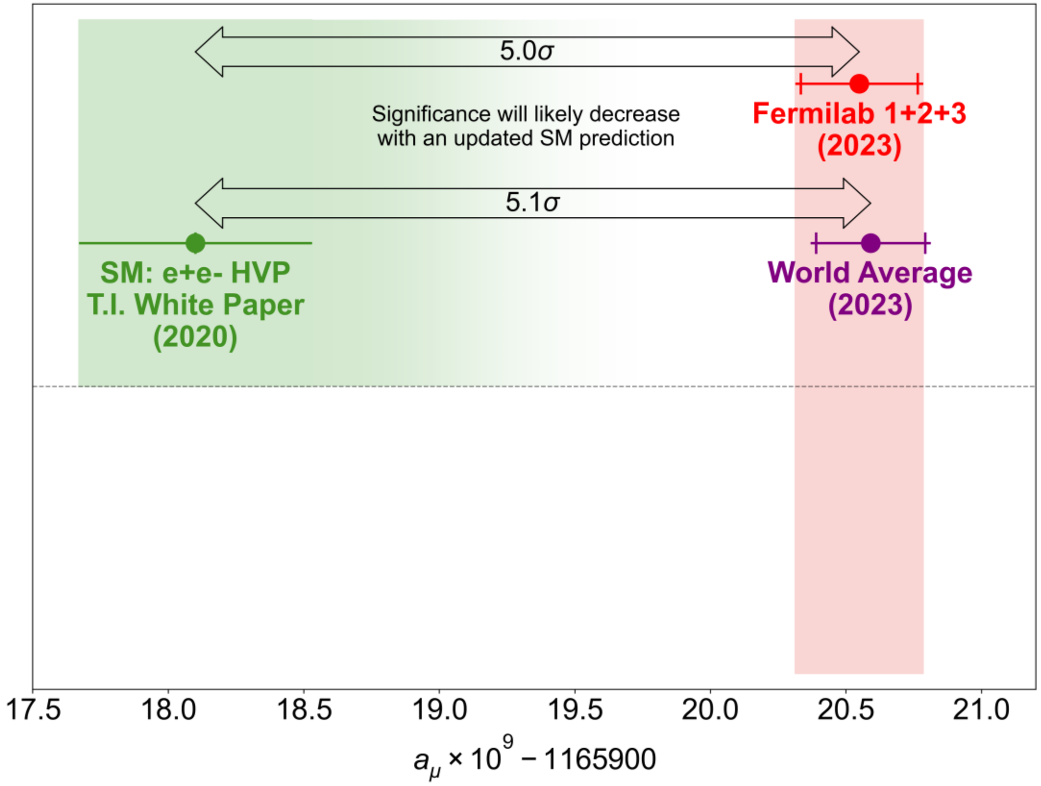

(Assuming systematics are 100% correlated)

# Where we stand now



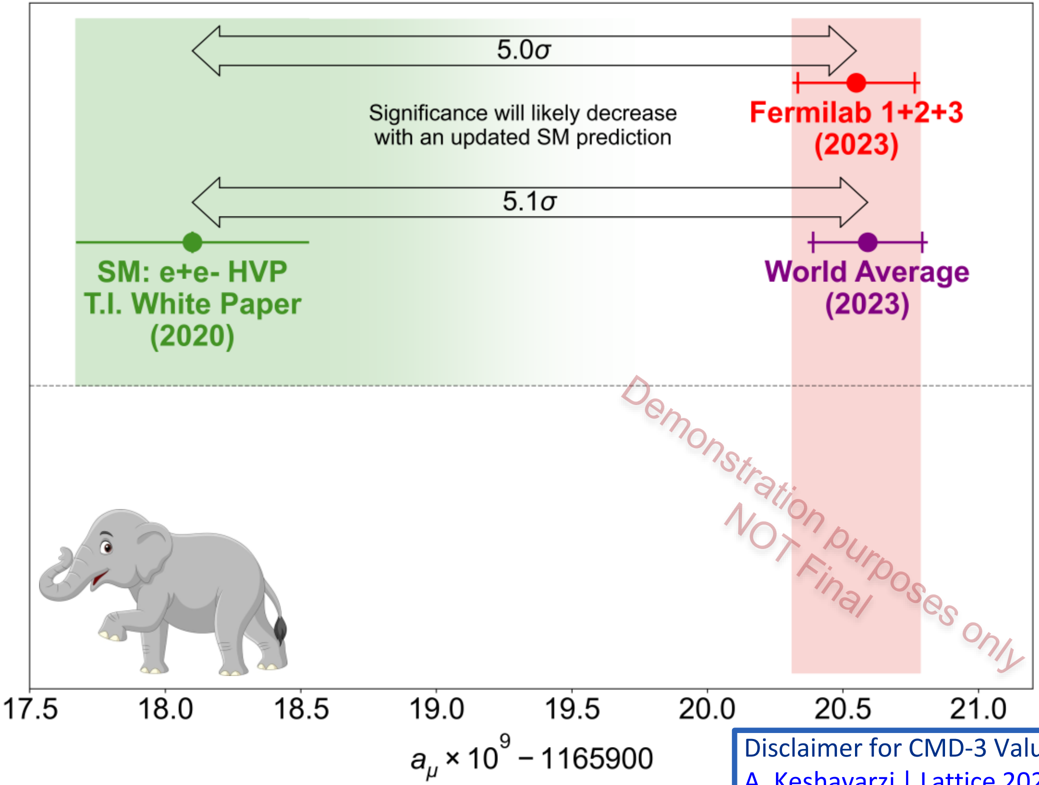

(Proposal goal: 140 ppb)

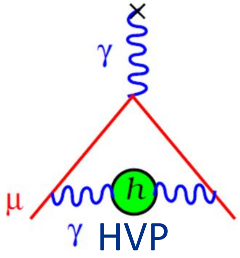
# Where we stand now




## Were there no updates to the theory side, I could end the talk here…

# Where we stand now




Disclaimer for CMD-3 Values

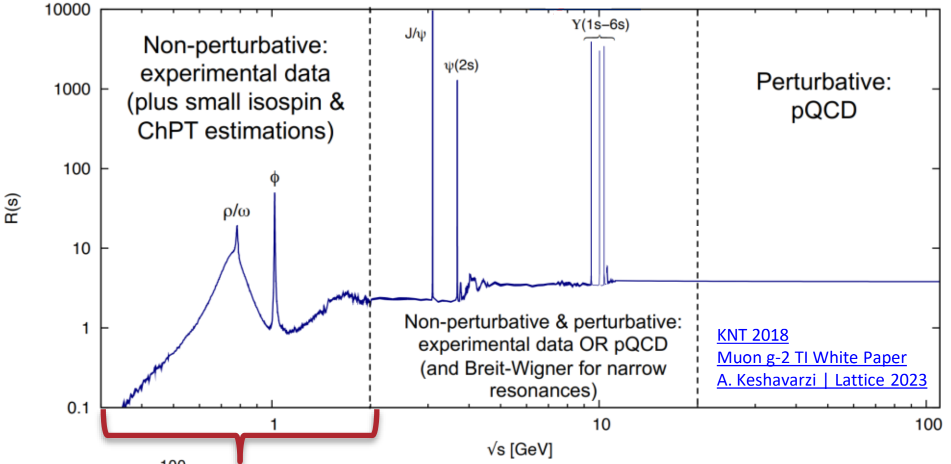
A. Keshavarzi | Lattice 2023

IMPORTANT: THIS PLOT IS VERY ROUGH!

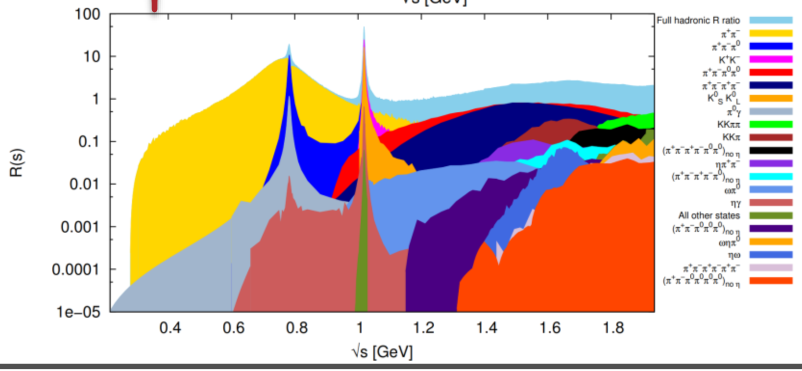
- TI White Paper result has been substituted by CMD-3 only for 0.33 → 1.0 GeV.
- The NLO HVP has not been updated.
- It is purely for demonstration purposes → should not be taken as final!


WARNING
You're about to hear an experimentalist talk about theory…

# Theoretical Tensions: Dispersive vs. Lattice

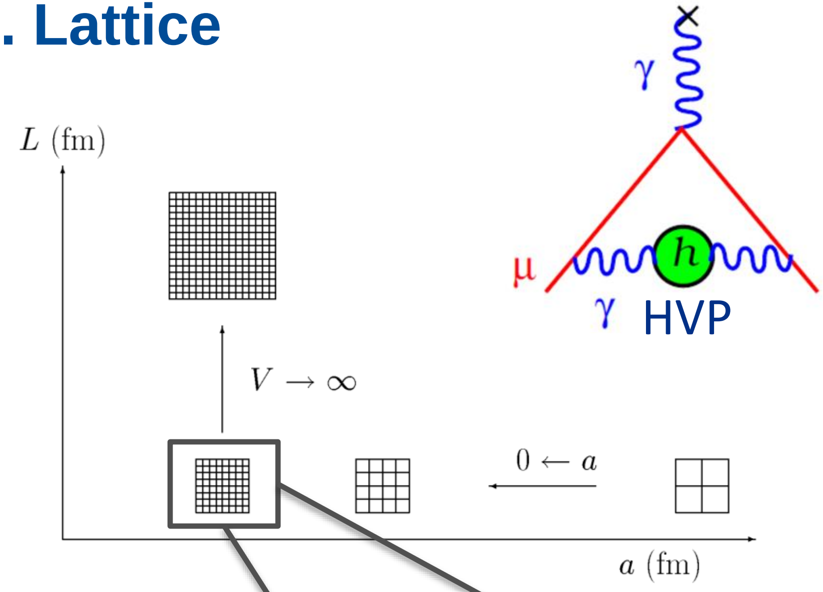



KNT 2018
Muon g-2 TI White Paper
A. Keshavarzi | Lattice 2023

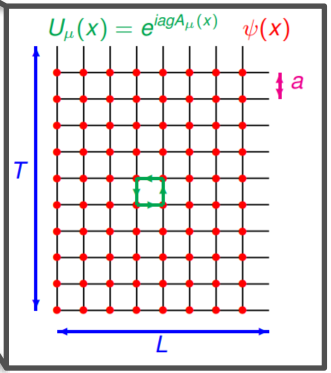




$$a_\mu^{HVP,LO} = \frac{\alpha^2}{3\pi^3}\int_s^\infty \frac{ds}{s} R(s)K(s)$$








Aida X. El-Khadra | Lattice QCD
Laurent Lellouch

Fermilab

# Theoretical Tensions: Dispersive vs. Lattice

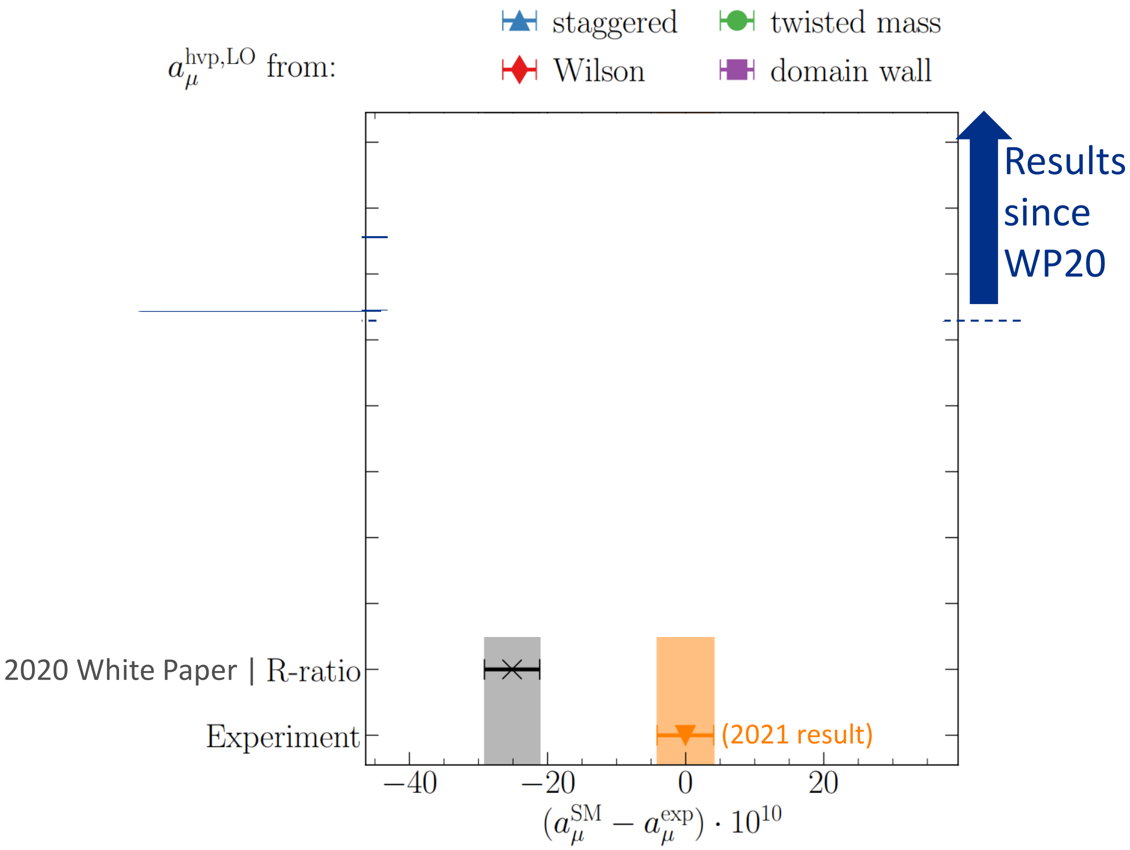
**Only one sub-percent evaluation of $a_\mu^{HVP}$ on the lattice [[BMW 20](#)]**

**Goal: many 0.5% lattice calculations**

- **Limited supercomputer time**
- **Timescale: 1.5-2 years**

**Goal: comparisons of lattice with dispersive results**

- **Tools developed to make intermediate comparisons**
- **Timescale: right now!**




Simon Kuberski | Lattice 2023

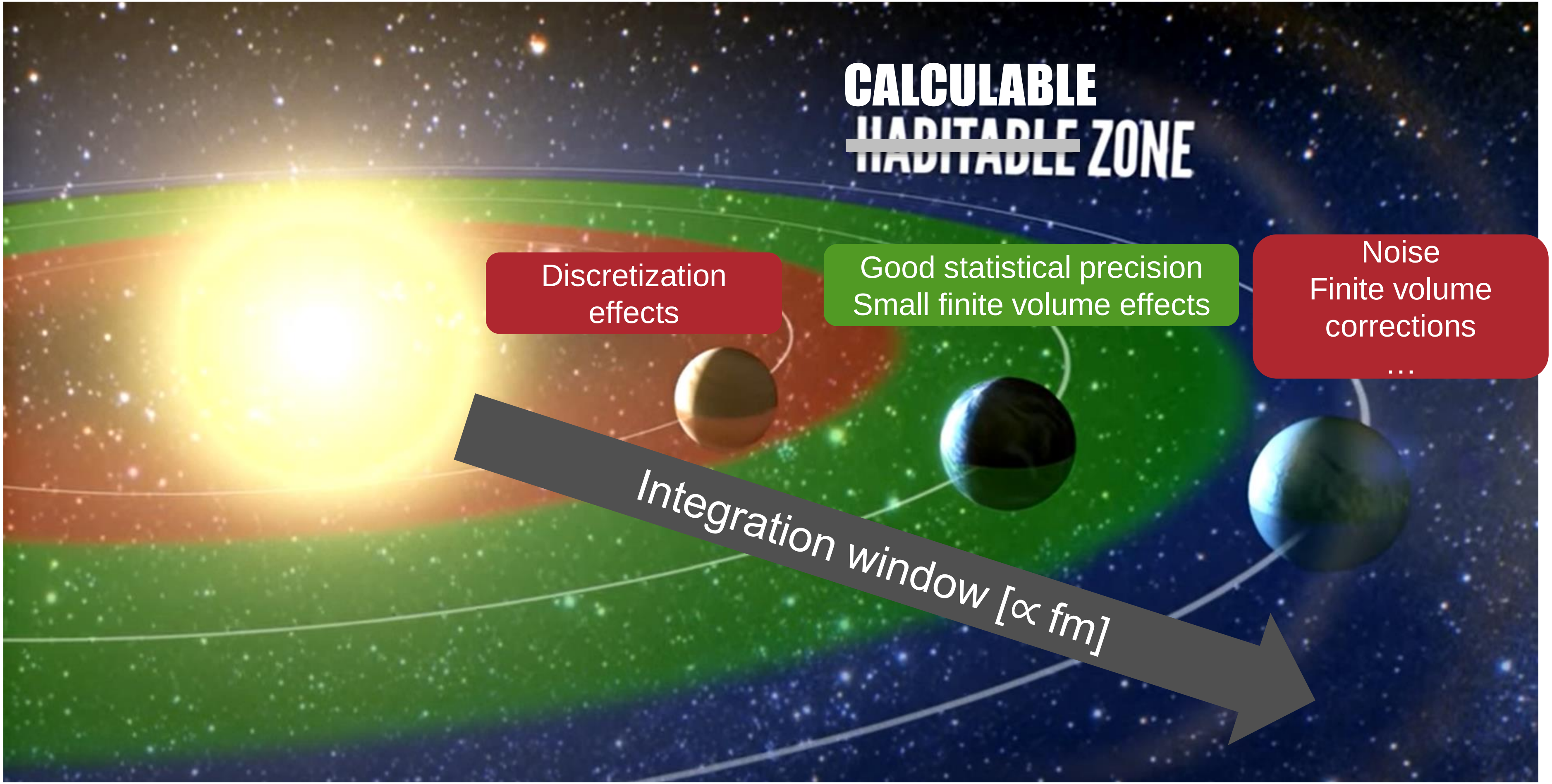



Image: UC Berkeley/UH-Manoa/Illumina Studios

# Lattice: Euclidean Time Windows

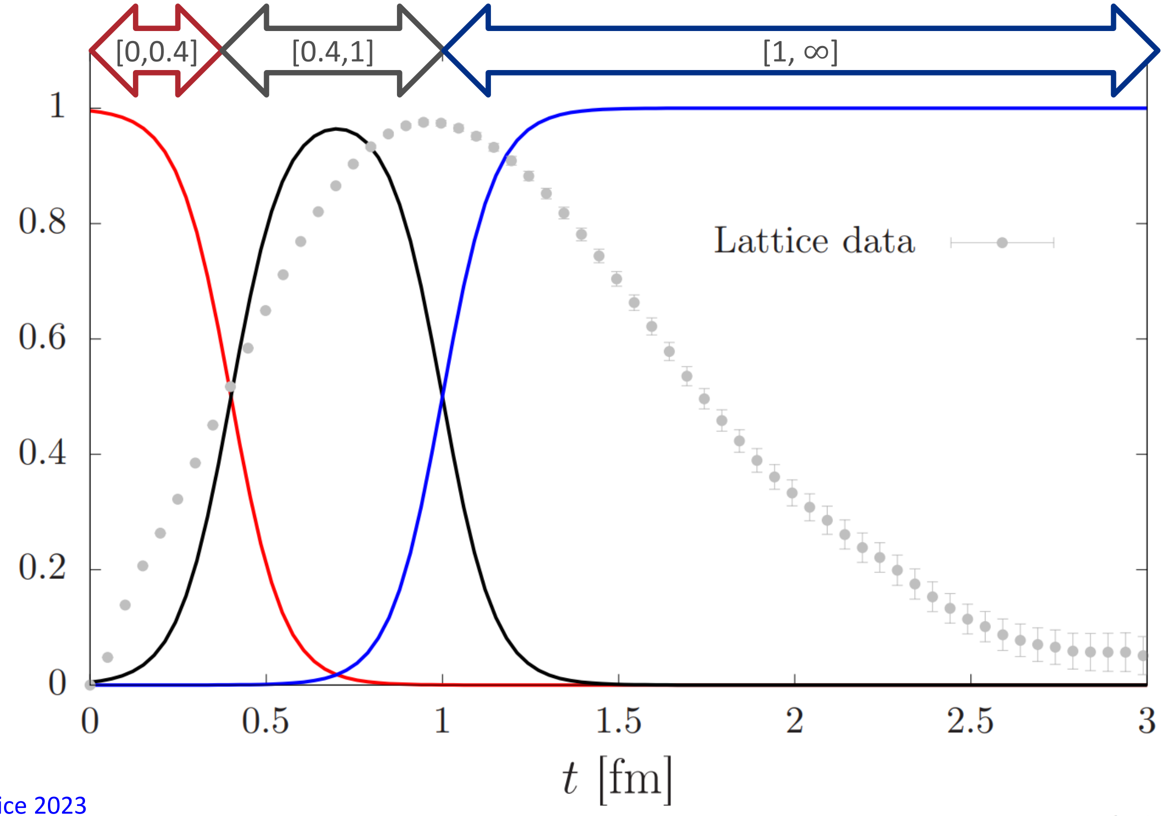



Image: Antoine Gérardin | Lattice 2023

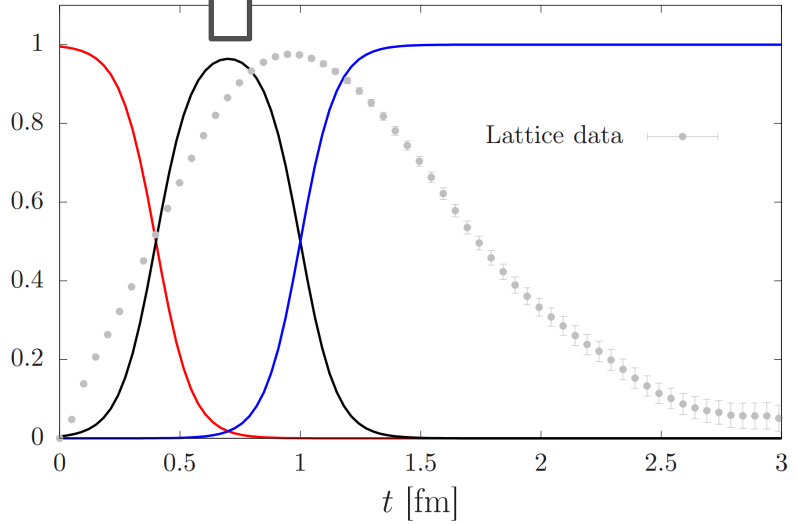
Equation: Phys. Rev. D 106, 114502 (2022)

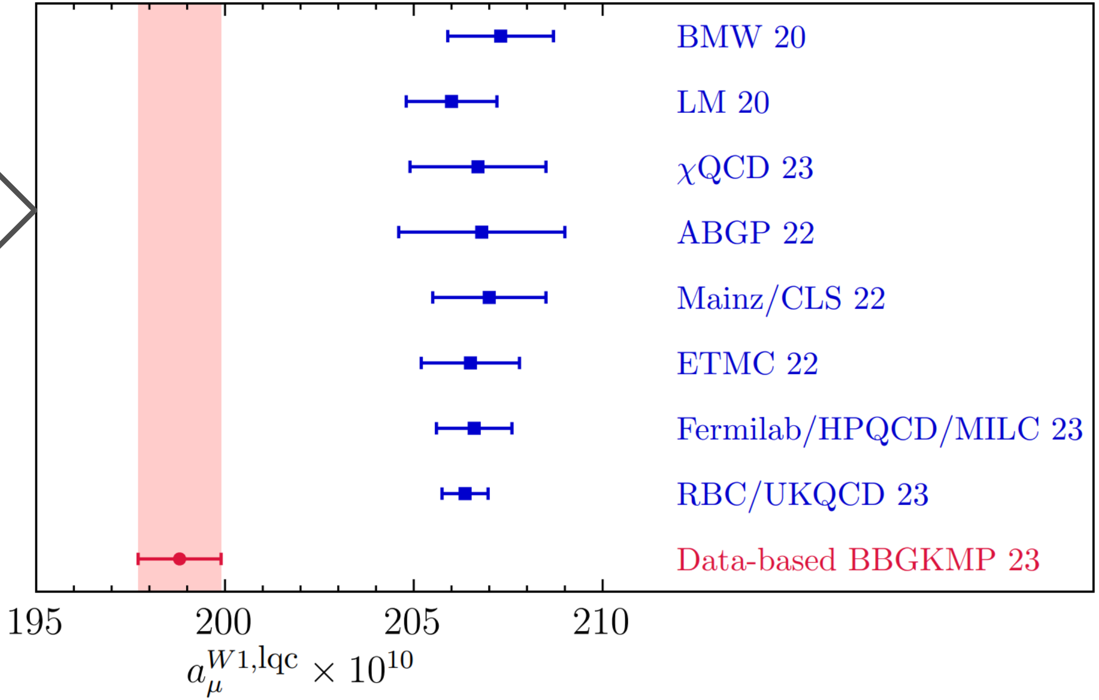
$$\Theta(t, t', \Delta) \equiv \frac{1}{2}\left(1 + \tanh[(t - t')/\Delta]\right).$$

$$t_0 = 0.4\,\text{fm}, \quad t_1 = 1.0\,\text{fm} \quad \text{and} \quad \Delta = 0.15\,\text{fm}.$$

# Theoretical Tensions: Intermediate Window

Light quark connected contribution to intermediate window

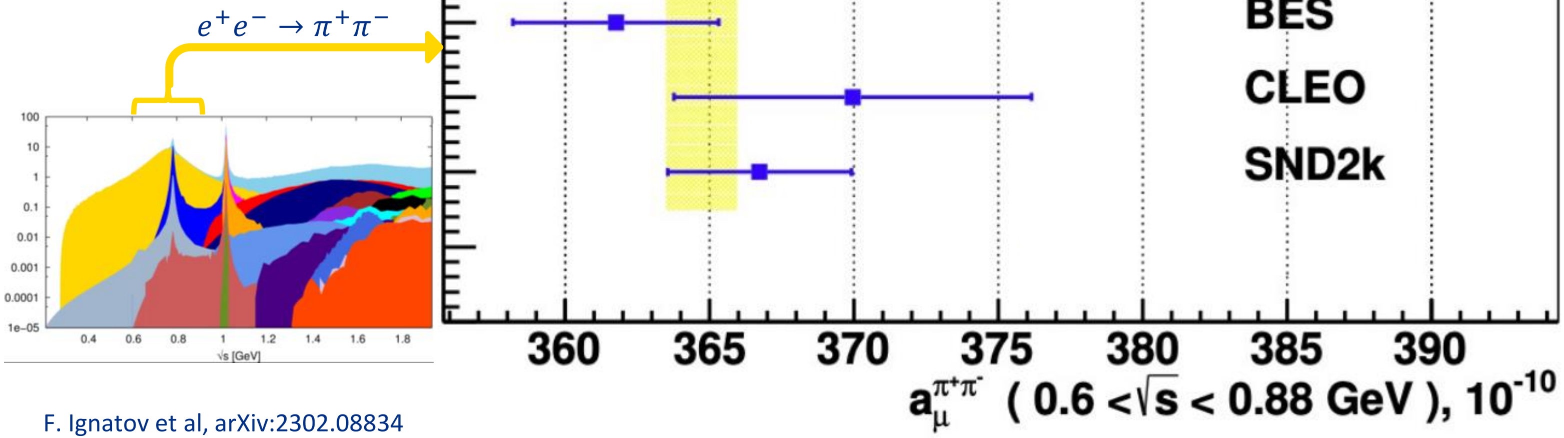



Left: [Antoine Gérardin | Lattice 2023]
Right: [Maarten Golterman | Lattice 2023]

**Tensions between dispersive and lattice calculations persist even where lattice extrapolation effects are sub-dominant**

# Theoretical (Input) Tensions: Babar, KLOE, and CMD-3

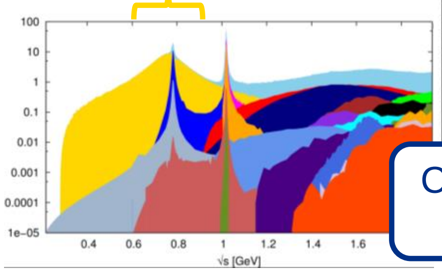



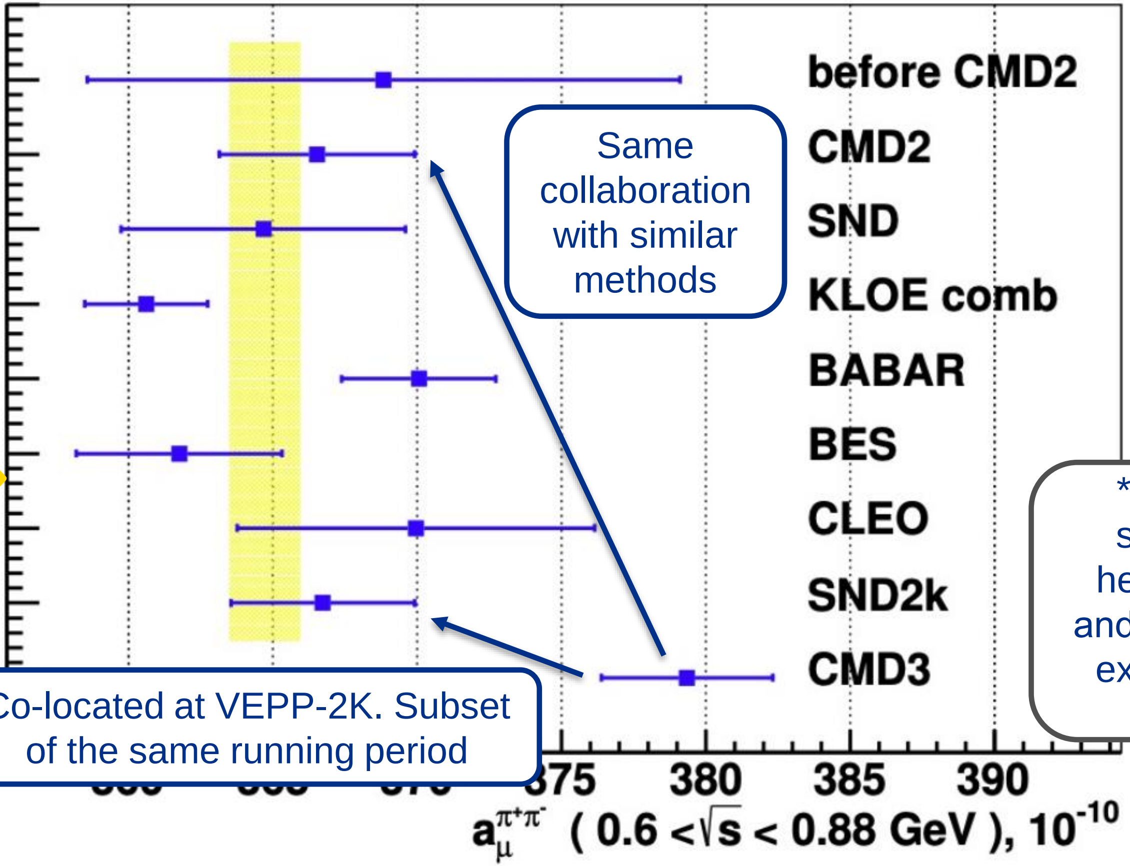

For 2020 WP, known tensions between KLOE and BABAR were incorporated into systematic error

F. Ignatov et al, arXiv:2302.08834

# Theoretical (Input) Tensions: Babar, KLOE, and CMD-3


$e^+e^- \to \pi^+\pi^-$



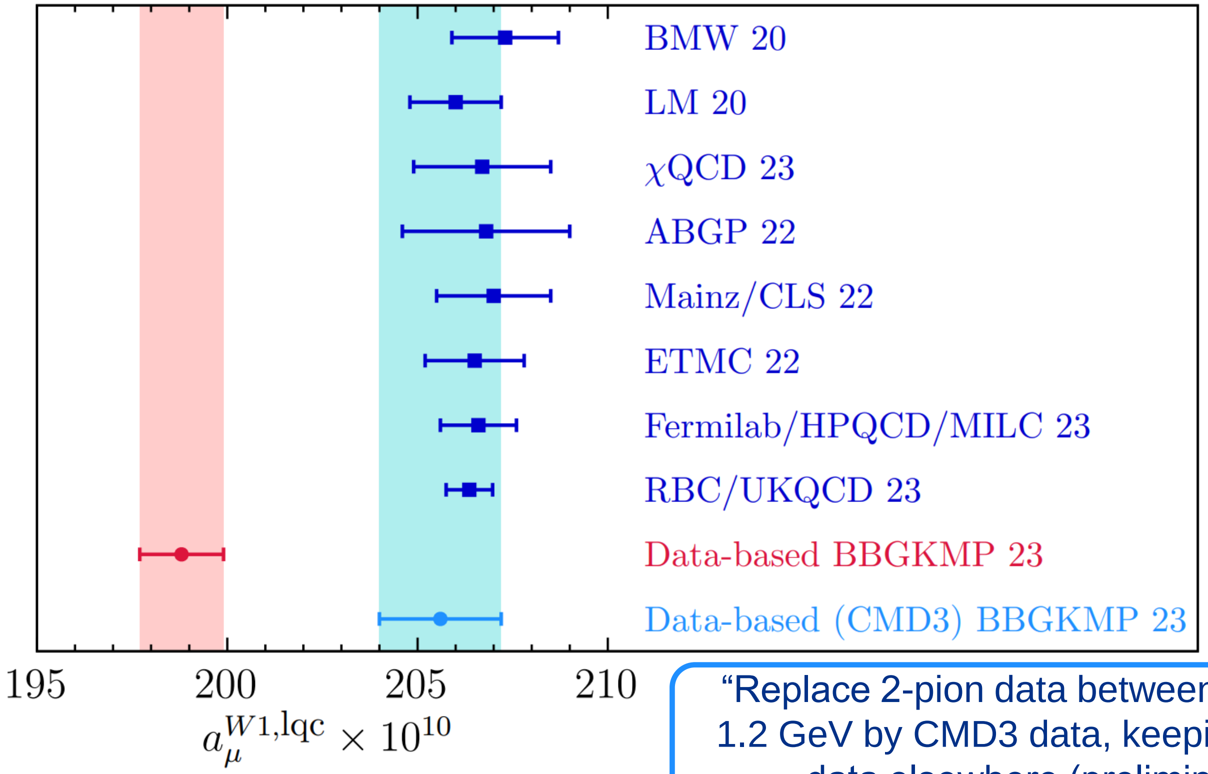




Same collaboration with similar methods

Co-located at VEPP-2K. Subset of the same running period

*Still in pre-print stage, but being heavily scrutinized and no 'smoking gun' explanation for the difference yet

F. Ignatov et al, arXiv:2302.08834




"Replace 2-pion data between 0.33 and 1.2 GeV by CMD3 data, keeping KNT19 data elsewhere (preliminary)"

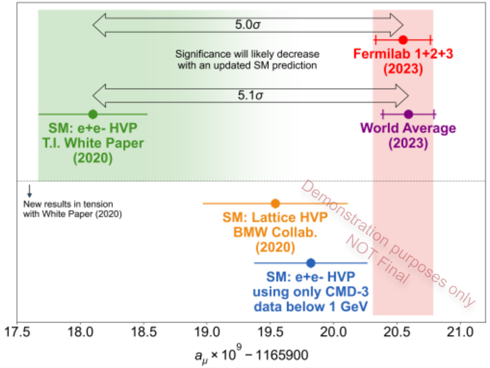
Light quark connected contribution to intermediate window

[Maarten Golterman | Lattice 2023]

# What does it all mean?

<u>Assuming</u>

The Experiment Correctly Measures Nature




## "Old dispersive inputs are right"

- $5\sigma$ signal of new physics!
- Difference between dispersive and lattice results needs to be understood.

## "Lattice calculations are right"

- Standard model lives to fight another day
- Still need more independent (blinded) calculations to confirm the results
- $\approx 4\sigma$ tension (in some energy ranges) between lattice and dispersive evaluations to solve. Do dispersive calculations get the right inputs?

## "CMD-3 cross sections are right"

- Assuming CMD-3 is gives the 'truest' value of the low-energy $e^+/e^-$ cross section, the lattice and dispersive calculations can agree
- How did 20+ years of experiments get the wrong $e^+/e^-$ cross sections?
- What did CMD-3 do different? No 'smoking gun' yet.
- Does this cause tensions elsewhere?

# What does it all mean?

**Physics**

## Mismatch with Standard-Model Predictions Reaches 5 Sigma

August 10, 2023 • *Physics* 16, 139

**The Muon g-2 Collaboration has doubled the precision of their 2021 measurement of the muon's magnetic moment, strengthening a tension with predictions based on the standard model.**

M. Wynne

On Monday, July 24, members of the Muon g-2 Collaboration gathered at the University of Liverpool, UK, to "unblind" their latest experimental results. This photo shows Fermi National Accelerator Laboratory scientist James Mott reading out one of the ... **Show more**

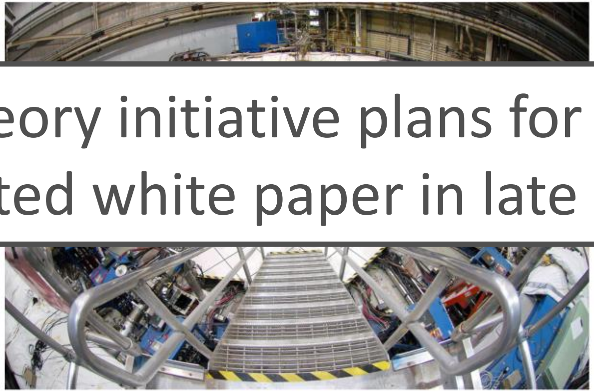
**nature**

NEWS | 10 August 2023

## Dreams of new physics fade with latest muon magnetism result

**Precision test of particle's magnetism confirms earlier shocking findings – but theory might not need a rethink after all.**

Davide Castelvecchi



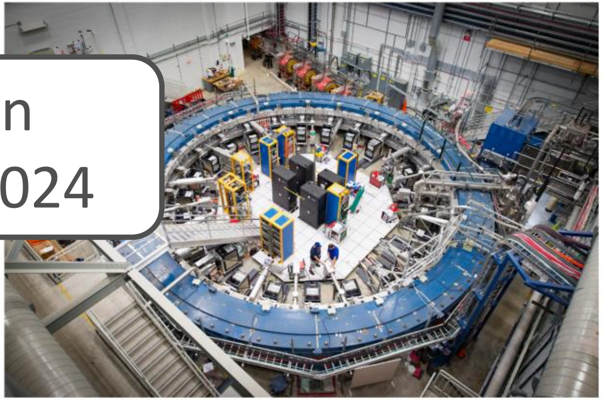
The Muon *g* – 2 experiment at the Fermi National Accelerator Laboratory near Chicago, Illinois, has made the best measure of the muon's magnetic moment. Credit: Science History Images/Alamy

**The New York Times**

## *Physicists Move One Step Closer to a Theoretical Showdown*

The deviance of a tiny particle called the muon might prove that one of the most well-tested theories in physics is incomplete.

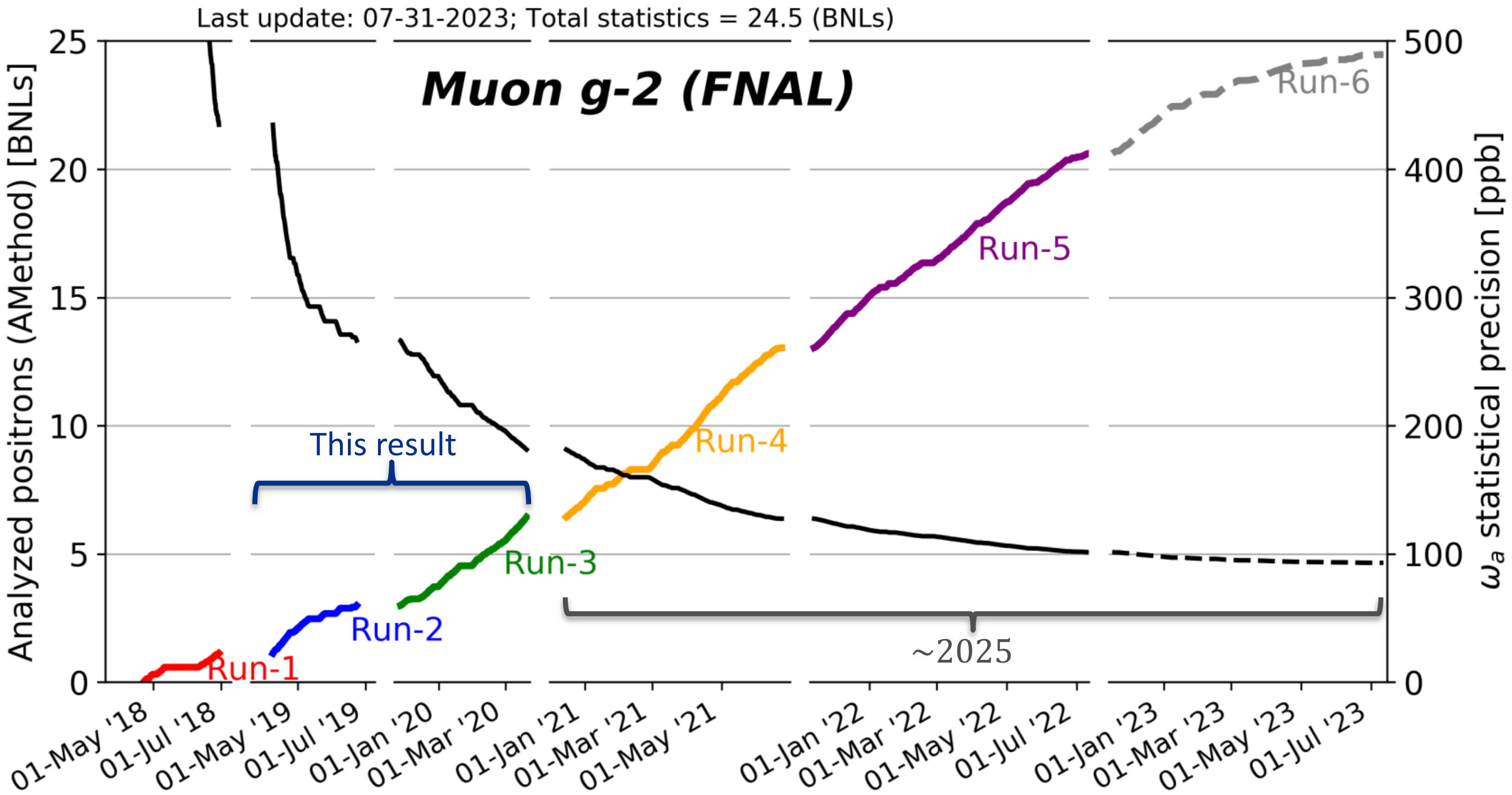
Share full article | 480



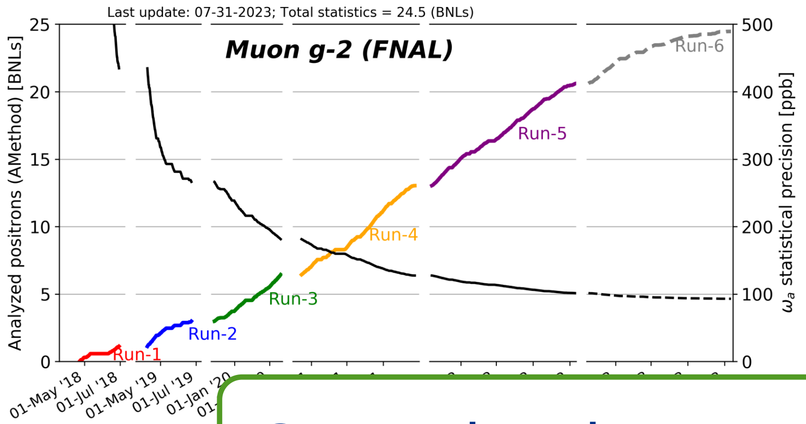
The Muon g-2 ring at the Fermilab particle accelerator complex in Batavia, Ill. Reidar Hahn/Fermilab, via US Department of Energy

**Theory initiative plans for an updated white paper in late 2024**

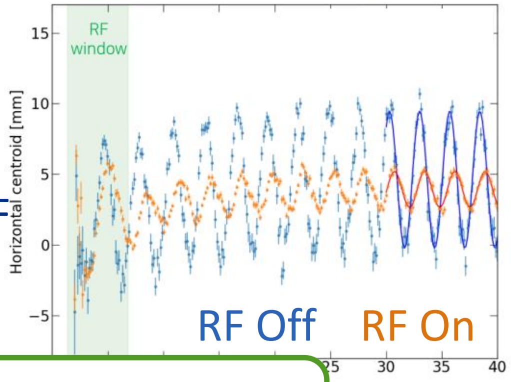
# Experimental outlook: The best is yet to come!



# Improvements for Run-4+

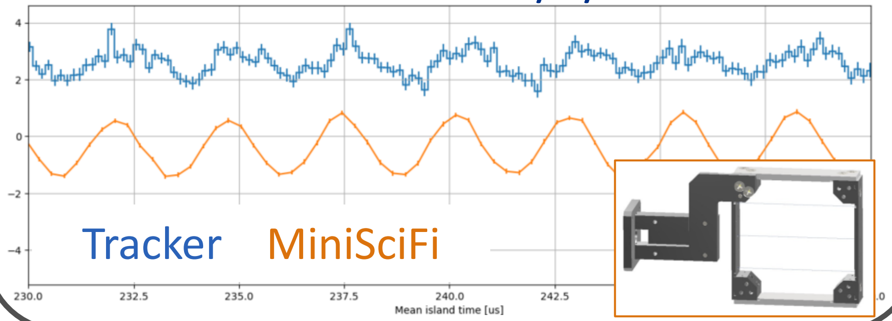



Experimental conditions continue to improve. Quad RF in Run-5 reduces CBO amplitude

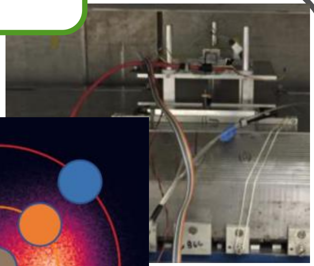


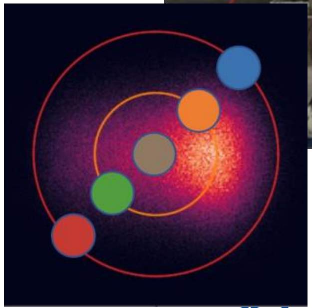

**On track to beat our proposal goal of 140ppb!**

Additional ...
new detectors in Run-4/5/6



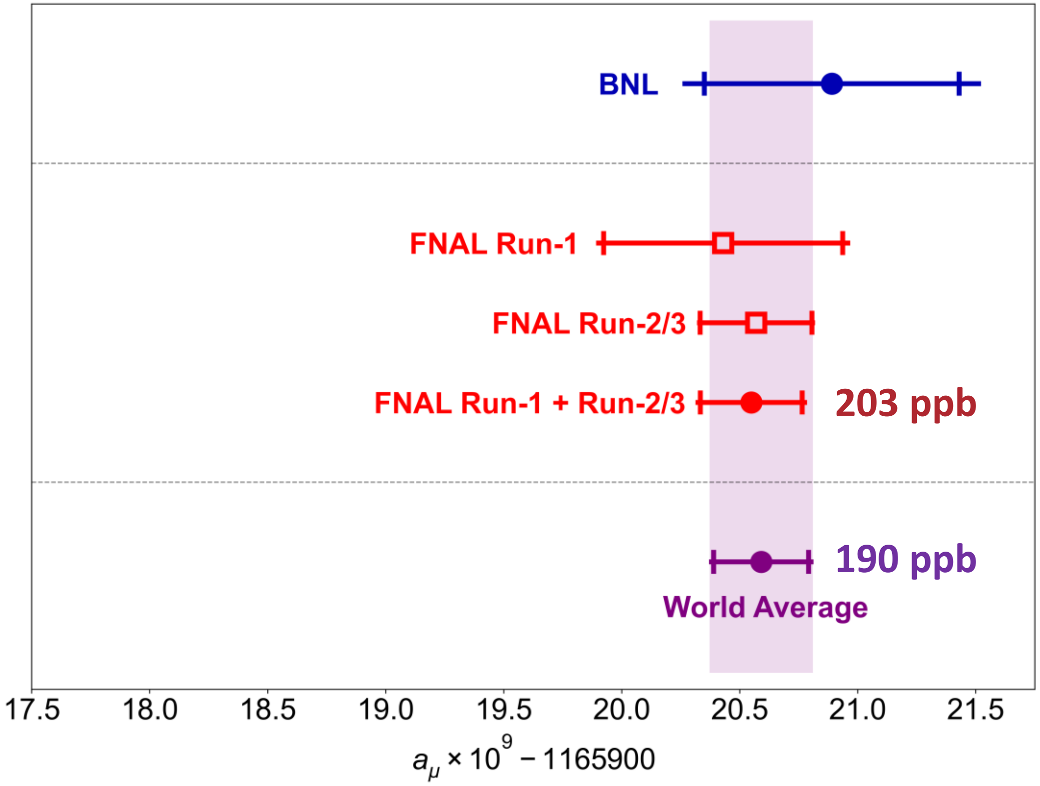

Measurements of the magnetic field (main field + transients) continue post-Run-6



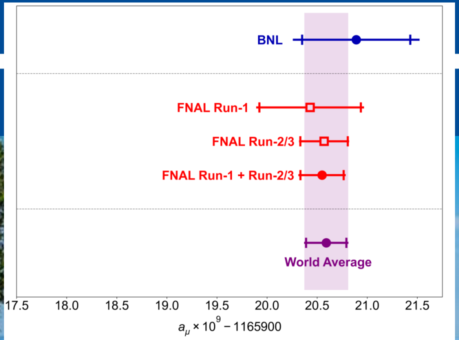


# Conclusions

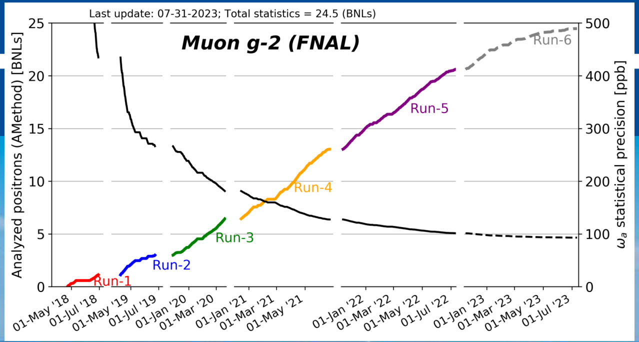
- The Muon g-2 Experiment at Fermilab has measured $a_\mu$ to 0.2 ppm
- Theoretical calculations of $a_\mu$ remain in flux → Updated white paper in 2024
- Run-4+ promises more improvements in statistical and systematic uncertainties




It's an exciting time for muons!



BNL
FNAL Run-1
FNAL Run-2/3
FNAL Run-1 + Run-2/3
World Average
17.5
18.0
18.5
19.0
19.5
20.0
20.5
21.0
21.5
$a_\mu \times 10^9 - 1165900$

Last update: 07-31-2023; Total statistics = 24.5 (BNLs)
Muon g-2 (FNAL)
Analyzed positrons (AMethod) [BNLs]
$\omega_a$ statistical precision [ppb]
Run-1
Run-2
Run-3
Run-4
Run-5
Run-6
01-May '18
01-Jul '18
01-May '19
01-Jul '19
01-Jan '20
01-Mar '20
01-Jan '21
01-Mar '21
01-May '21
01-Jan '22
01-Mar '22
01-May '22
01-Jul '22
01-Jan '23
01-Mar '23
01-May '23
01-Jul '23


Muon g-2 Collaboration Meeting — Elba 2019


# Thank you!