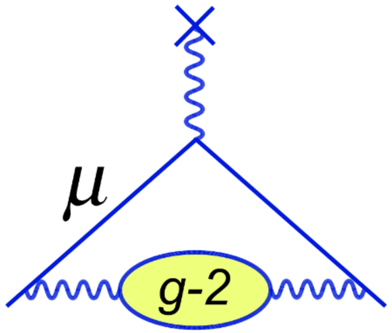
Anomalous Spin Precession Frequency (ω_a) Analysis in the Muon $g-2$ Experiment at Fermilab

On Kim (University of Mississippi)
On behalf of the Muon $g-2$ Collaboration

NuFact2024

2024 Sep. 16th



Other Muon $g - 2$ Talks in NuFact2024

- Theory
  - (Thu) Muon CLFV and g-2 theories, Aida El-Khadra

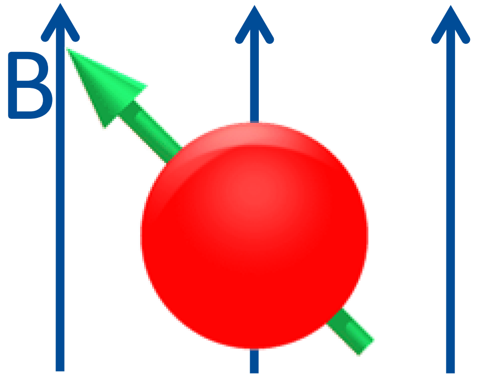
- Experiment
  - (This) Anomalous Spin Precession Frequency Analysis in the Muon g-2 Experiment at Fermilab, On Kim
  - (Next) Magnetic Field Analysis in the Muon g-2 Experiment, David Kessler
  - (NNext) Beam dynamics corrections of the Muon g-2 Experiment at Fermilab, David Tarazona
  - (Mon) A Dedicated Period of Magnetic Field Systematics Studies in the Muon g-2 Experiment at Fermilab, Matt Bressler
  - (Tue) The Status of the Muon EDM Search with the Muon g-2 Experiment at Fermilab, Gavin Hesketh
  - (Wed) Dark Matter Search in the Muon g-2 Experiment at Fermilab, Byungchul Yu
  - (Thu) Muon CLFV and g-2 experiments, Sophie Middleton

- J-PARC g-2/EDM
  - (Mon) Status and prospect of the J-PARC muon g-2/EDM experiment, Kazuhito Suzuki

Motivation

- More precise measurements of the magnetic moment of the muon can be a window to new BSM physics.

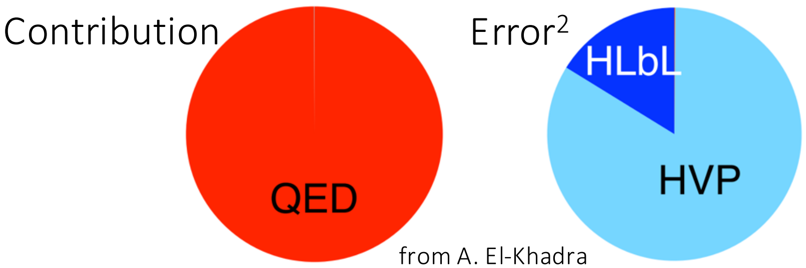
Muon magnetic anomaly $a_\mu = \frac{g_\mu - 2}{2}$, $\quad \boldsymbol{\mu} = g\frac{q}{2m}\mathbf{s}$



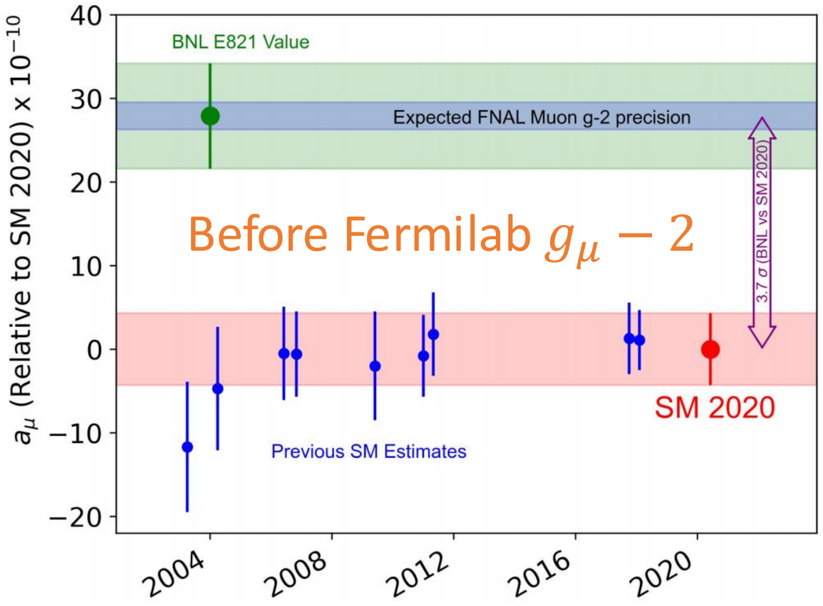
- $a_\mu(\text{Dirac}) = 0$, but in reality, due to all the contributions from the quantum vacuum,

$$a_\mu = a_\mu(\text{QED}) + a_\mu(\text{EW}) + a_\mu(\text{QCD}) \neq 0$$

- There have been strong hints of new physics in a_μ for decades (now in a somewhat vague situation – see in a couple of slides).
- The SM uncertainty is completely dominated by hadronic contributions, because evaluating them is notoriously hard.

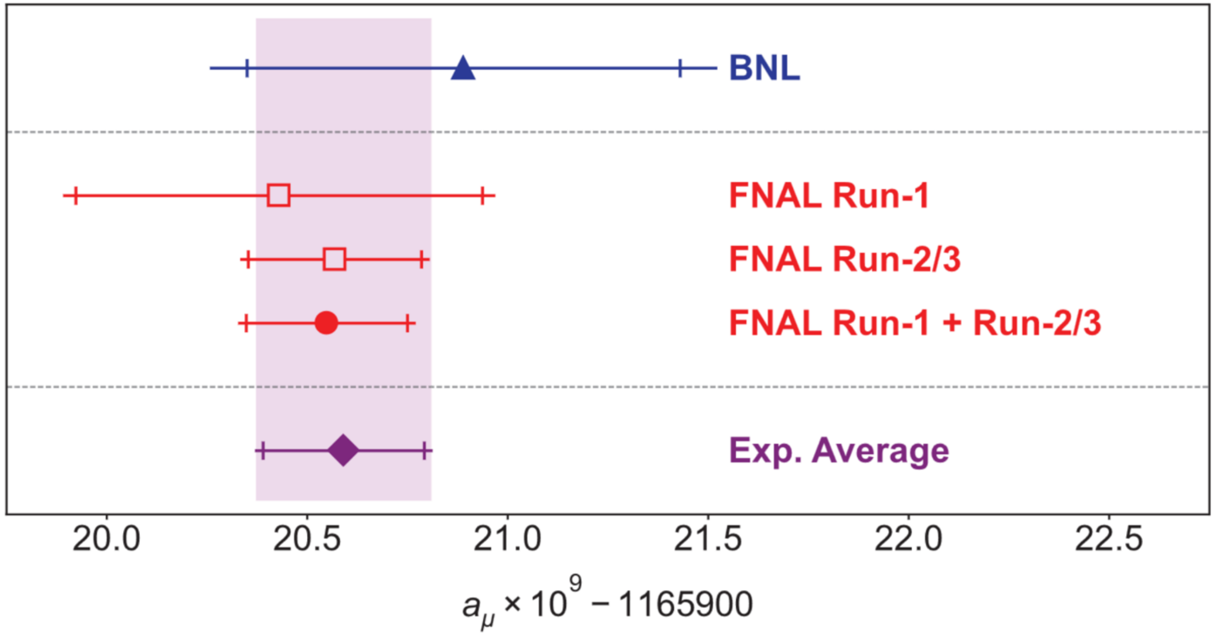


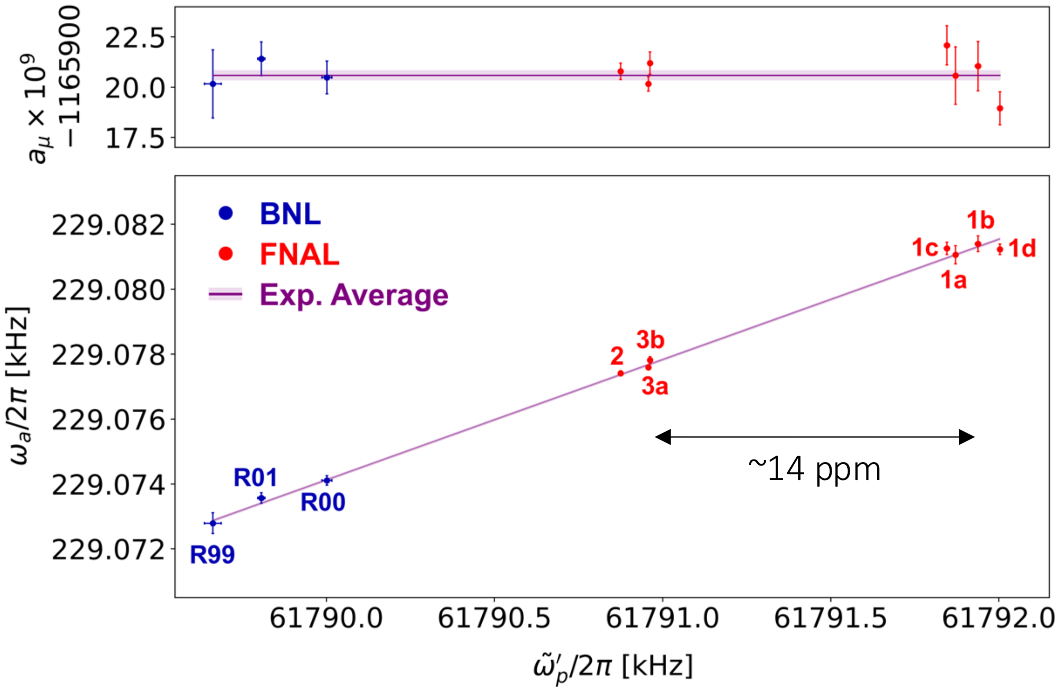
from A. El-Khadra



First (2021) and Second (2023) Results

- Run-1 result (2018 data) and Run-2/3 result (2019/2020 data) were consistent.
  Both renewed the most precise measurement of muon magnetic anomaly.





$$a_\mu(\mathrm{Exp}) = 0.00\,116\,592\,059\,(22)\ [190\ \mathrm{ppb}]$$

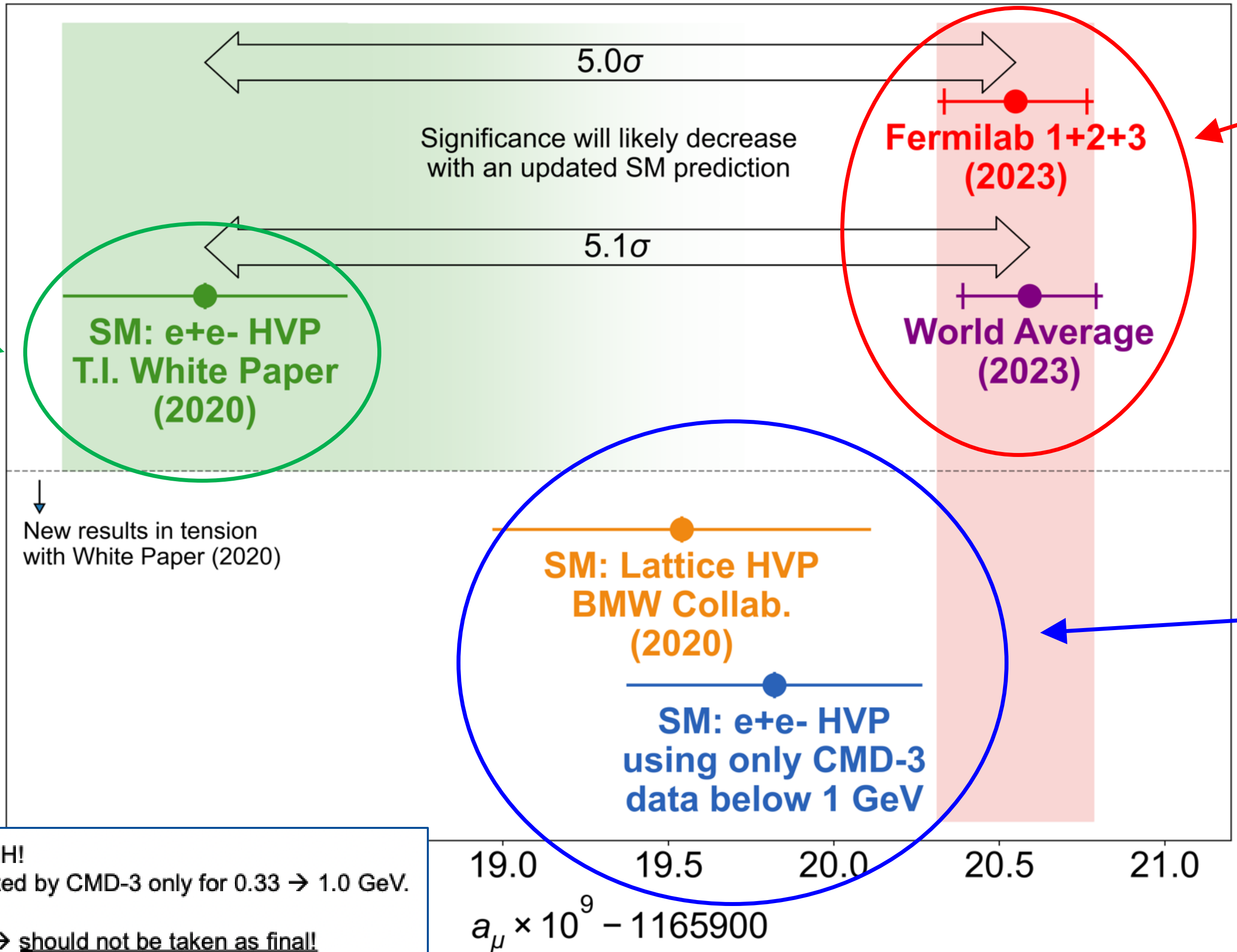
PRL **126**, 141801 (2021)
PRL **131**, 161802 (2023)

Experiment vs. Theory (SM)

- Theory predictions from different approaches (for $a_\mu(\mathrm{HVP})$, hadronic vacuum polarization) **don't agree!**

Muon $g-2$ Theory Initiative compiled the SM estimation primarily using the dispersive method for the hadronic vacuum polarization (HVP).

It uses 20+ years of e^+e^- data (contribution dominated by $e^+e^- \to \pi^+\pi^-$) from various collaborations (BaBar, KLOE, SND, BESIII, etc.)



*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!

We have $> 5\sigma$ significance by comparing the experiment average and 2020 WP, but this is an indefinite conclusion because…

There are new puzzles on HVP. Ab-initio lattice QCD calculation favors the measured value much better than the dispersive method.

A new dispersive approach result from the CMD-3 that came out recently has a strong tension with the other dispersive method results (even with the previous themselves: CMD-2).

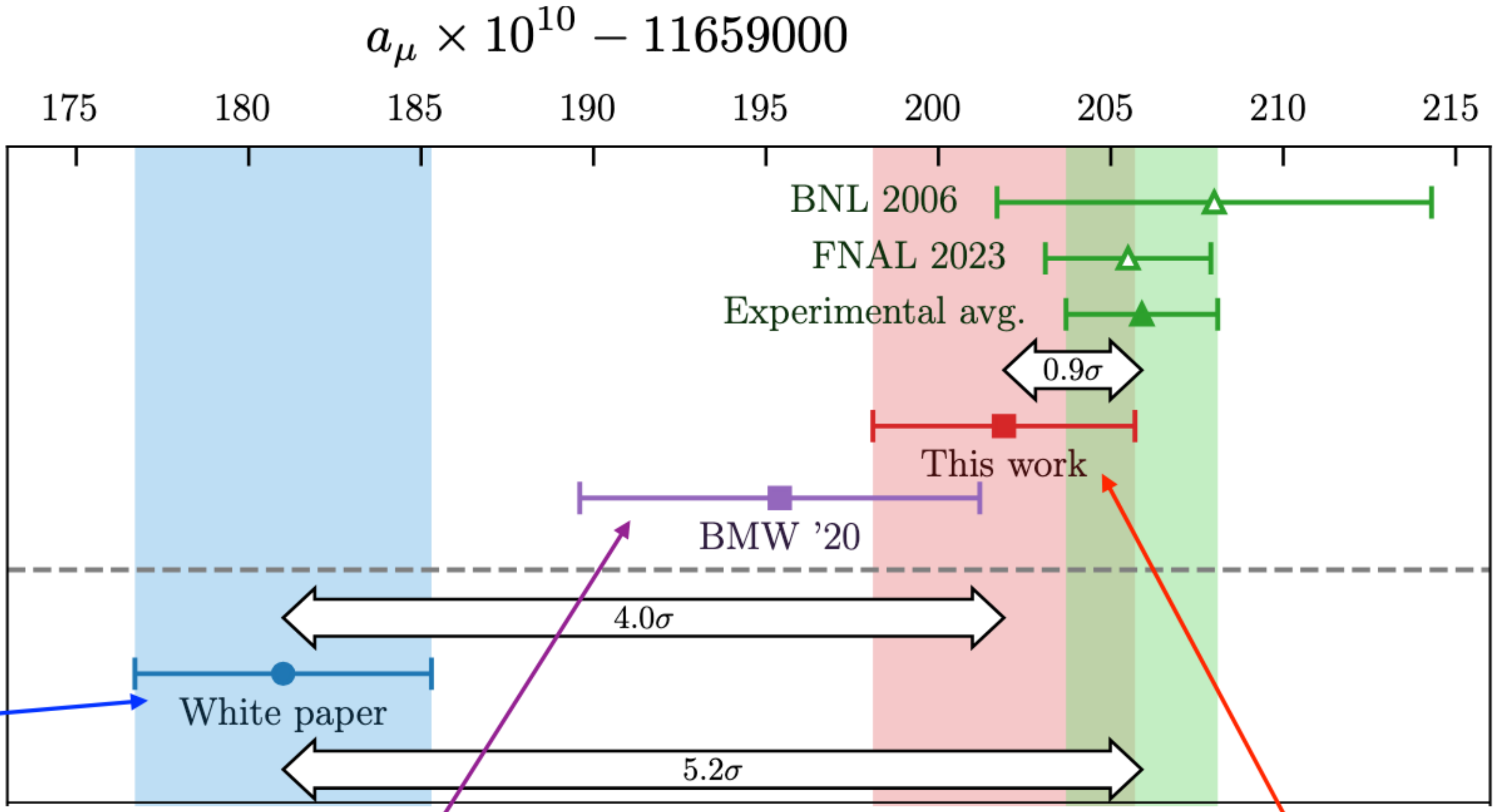
New Lattice Update

Slide from Christine Davies (University of Glasgow)

2024 update

BMW/DMZ24, 2407.10913

adds 0.048fm ensemble, reduces finite L/T error. Uses data-driven for large-t tail. Blinded analysis.



WP20 data-driven: 693.1(4.0)

7

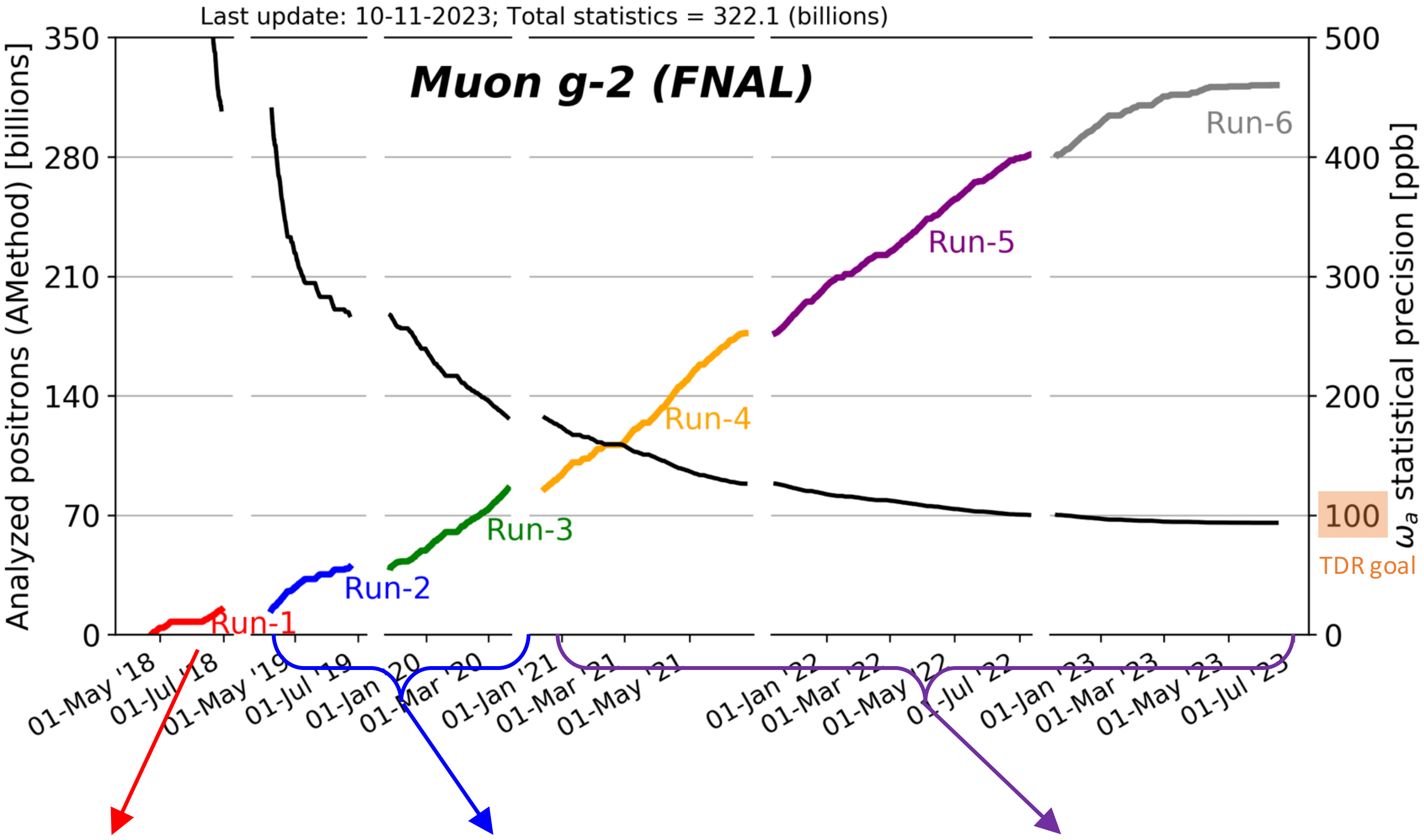
BMW20: $10^{10} a_\mu^{\mathrm{LOHVP}} = 707.5(5.5)$

BMW/DMZ24: $10^{10} a_\mu^{\mathrm{LOHVP}} = 714.1(3.3)$

But this is not a theory talk; listen to Aida's talk on Muon CLFV and g-2 theories on Thursday.

Status

- Notwithstanding, we continue our analysis; ~x3 more data are being analyzed!



First result (Run-1)
(published 2021)

Second result (Run-2/3)
(published 2023)

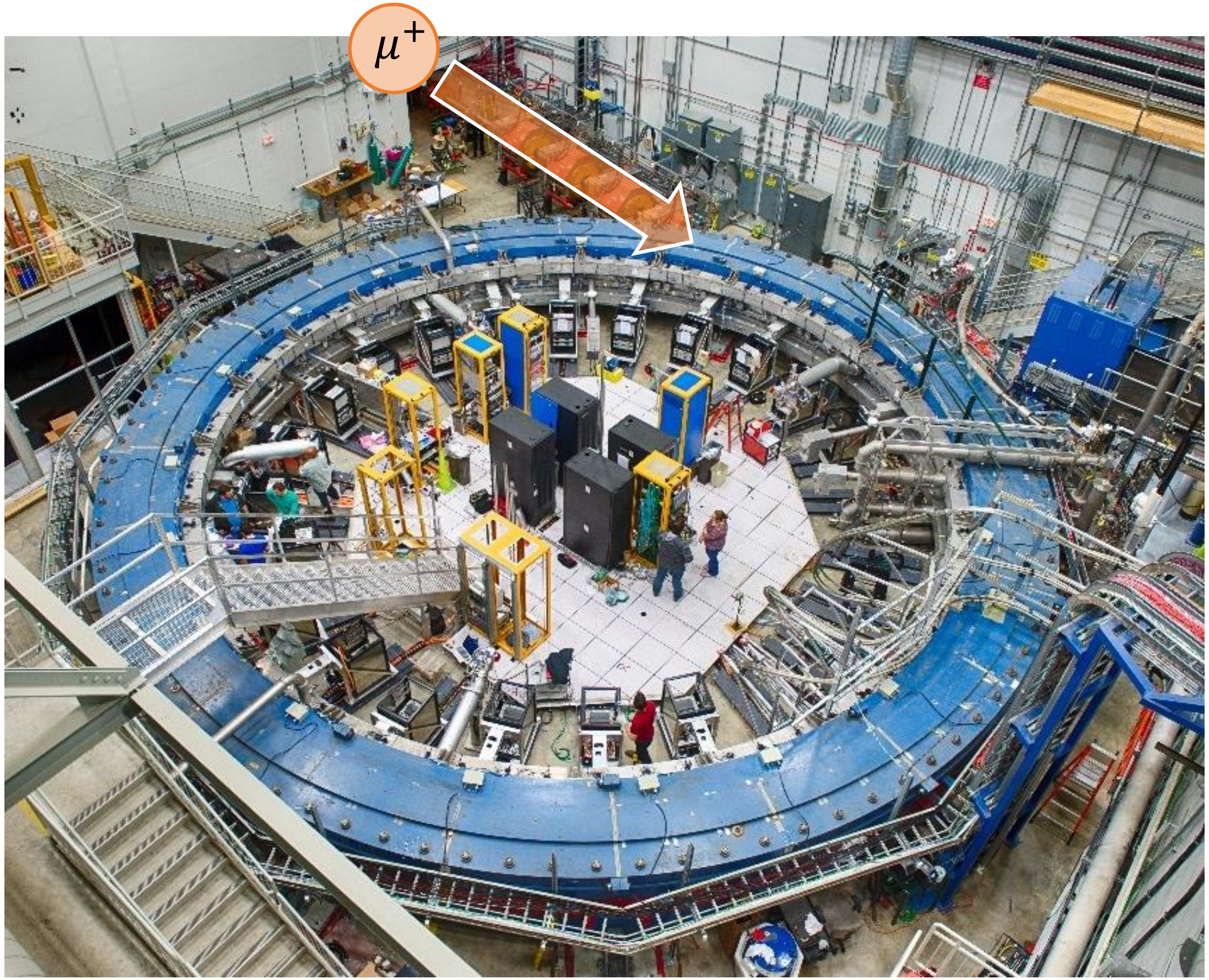
Final result (Run-4/5/6)
(anticipated 2025)

Our physics operation terminated in June 2023.

We met the TDR statistics goal! 
And surpassed the systematics goal in the Run-2/3 analysis! 

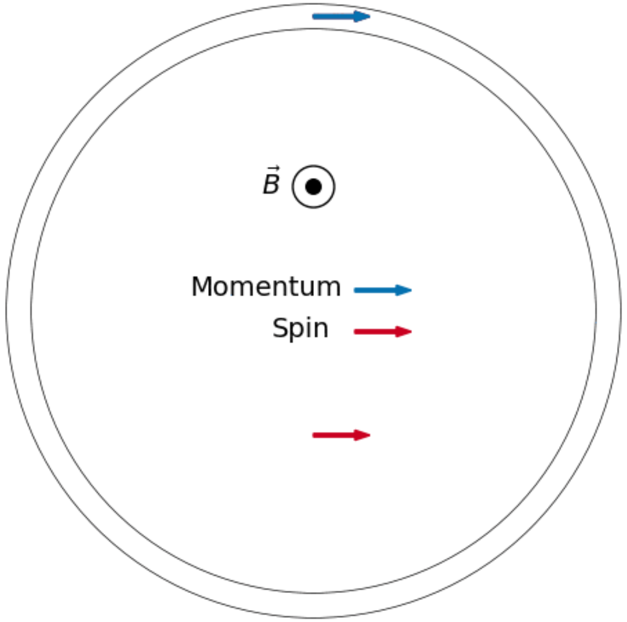
Stay tuned for the final result! (2025)

Experimental Overview

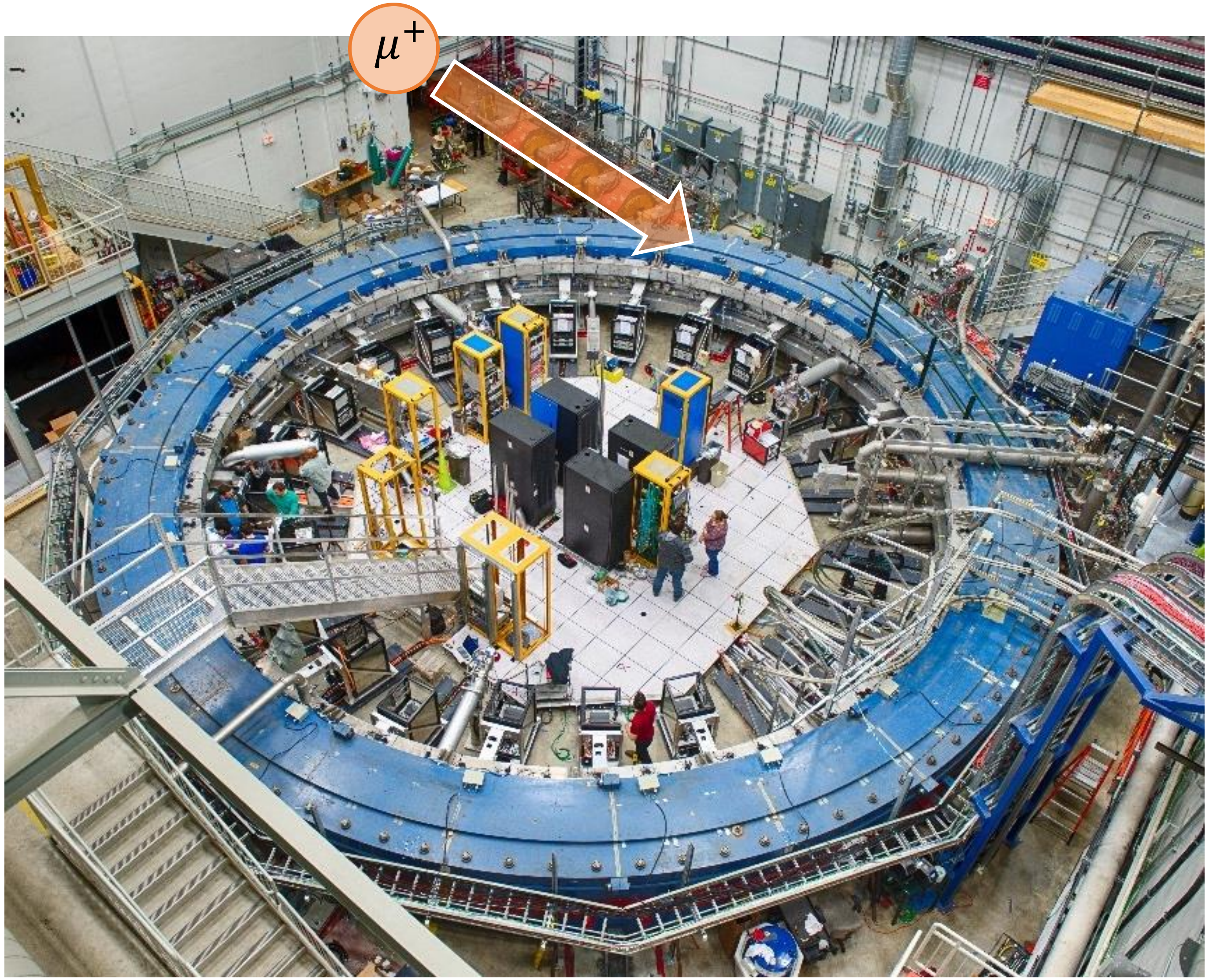


- Muons are stored in the storage ring (∼15 m diameter) under a 1.5 T homogeneous magnetic field.

- Muon spins precess under the magnetic field:



Experimental Overview



- Muons are stored in the storage ring (~15 m diameter) under a 1.5 T homogeneous magnetic field.
- Muon spins precess at a rate: ω_a with respect to momentum.

Measure

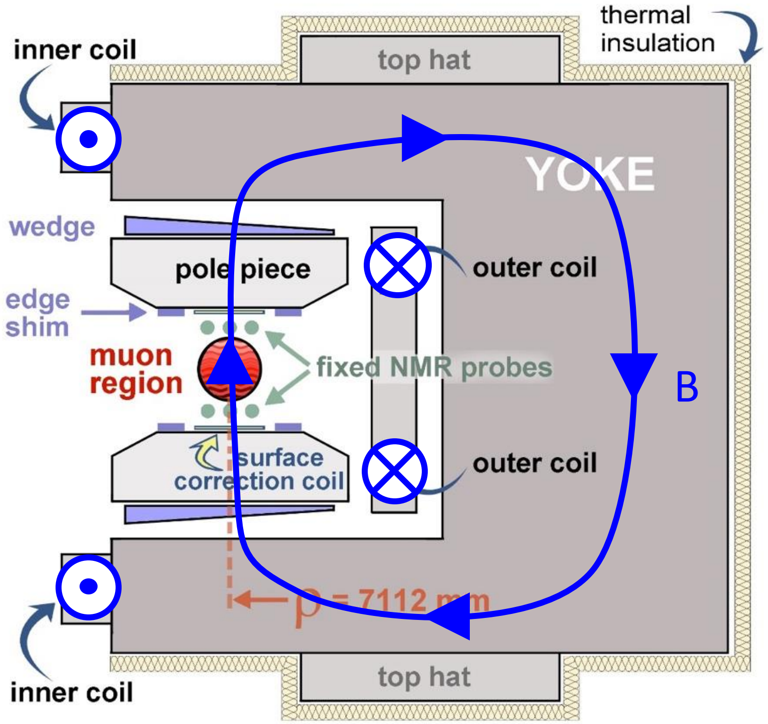
$$\omega_a = \omega_s - \omega_c = a_\mu \frac{eB}{mc}$$

Extract

Magnetic Field

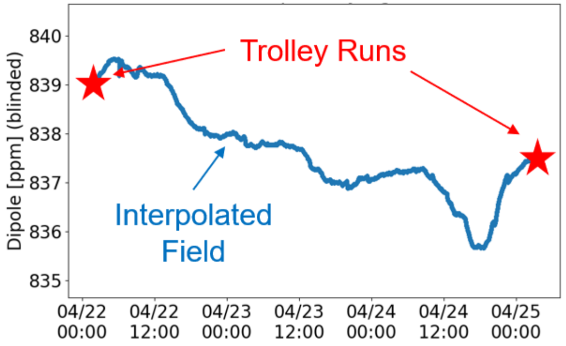
More details in the magnetic field talks!
(Next) Magnetic Field Analysis in the Muon g-2 Experiment, David Kessler
(Mon) A Dedicated Period of Magnetic Field Systematics Studies in the Muon g-2 Experiment at Fermilab, Matt Bressler

- Homogeneous 1.5 T magnetic field by superconducting C-shaped magnet (sub-ppm in 9 cm diameter muon storage region).

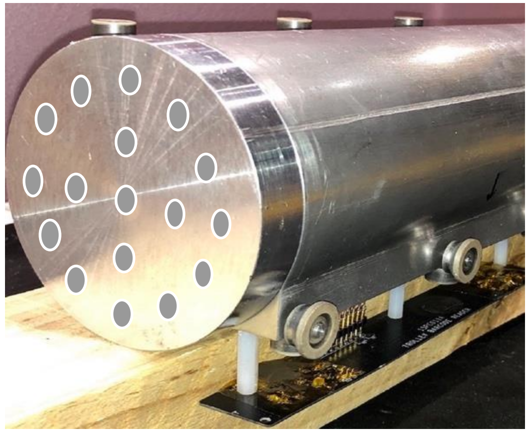


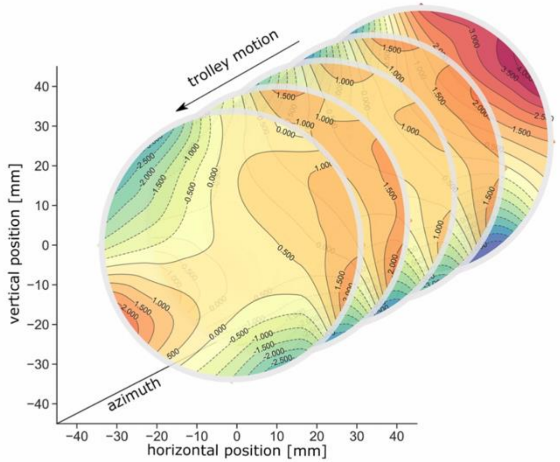
- Use NMR probes to measure the field.
  1. Fixed probes: 24/7

Fixed probes above/below muon storage region



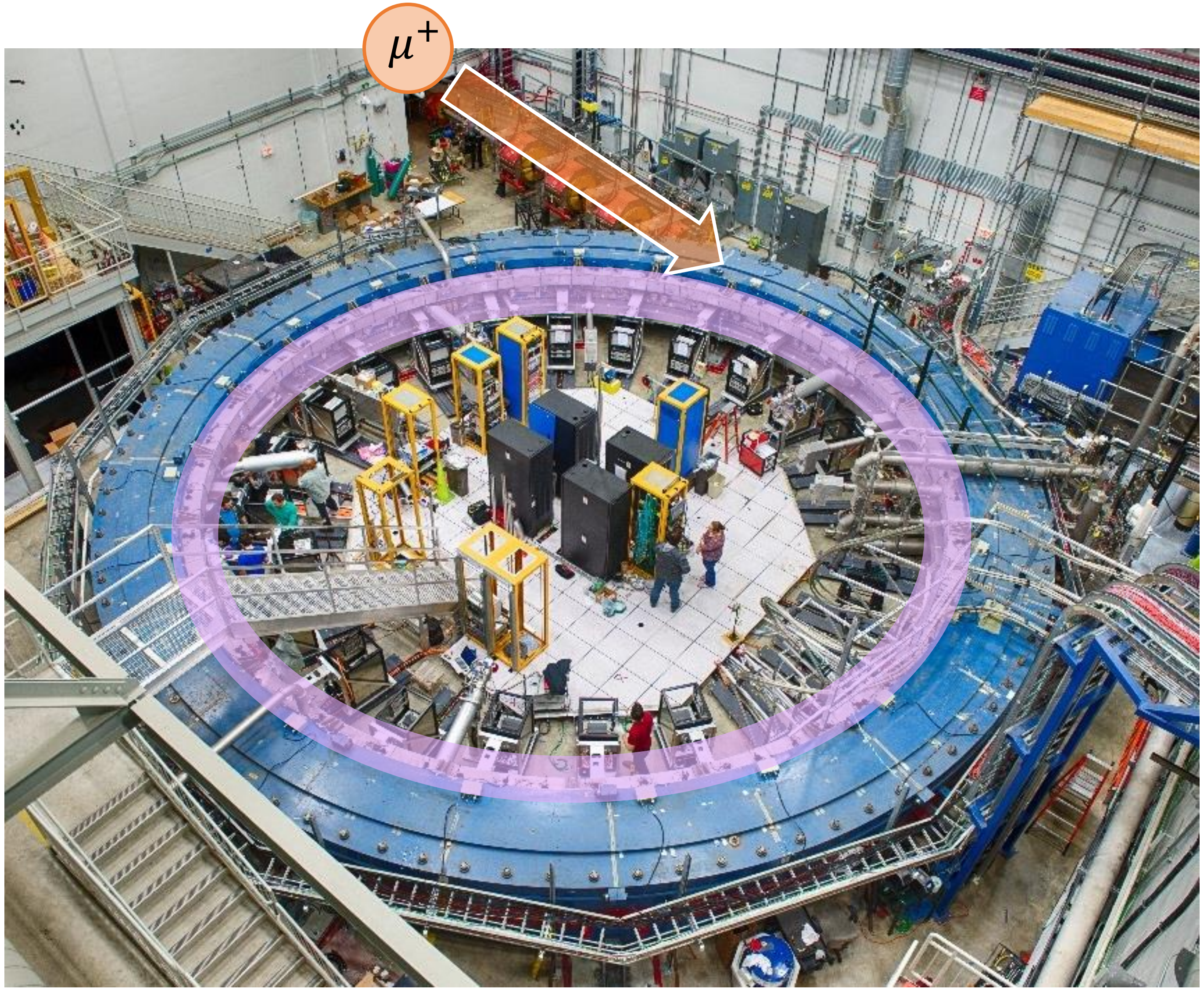
  2. Trolley (in vacuum): every 3-4 days



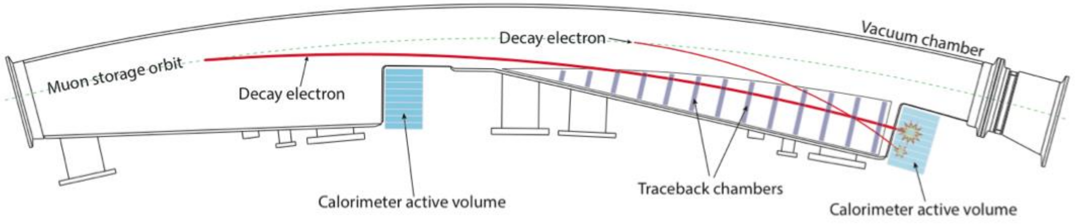


17 petroleum jelly NMR probes.
Maps the field as it goes around the storage ring

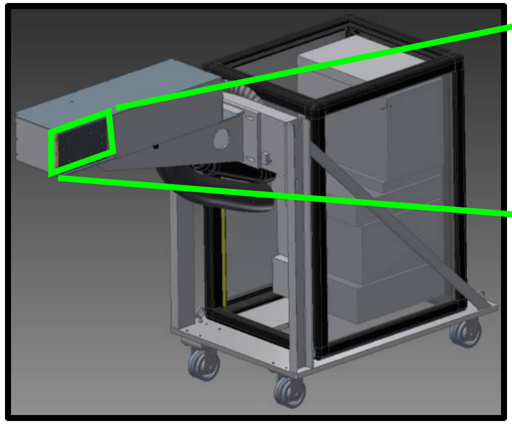
Muon Decay



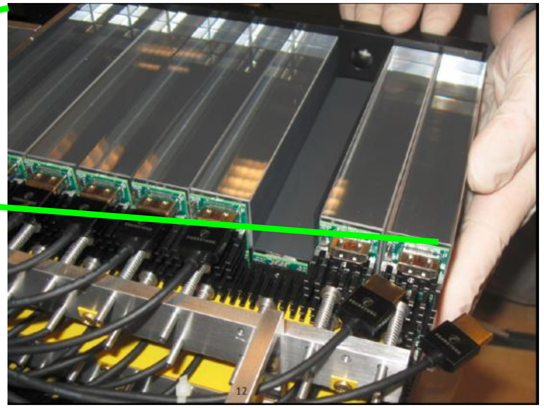
- Detection
  - Decay positrons curl into 24 electromagnetic calorimeters surrounding the storage ring.



Calorimeter station

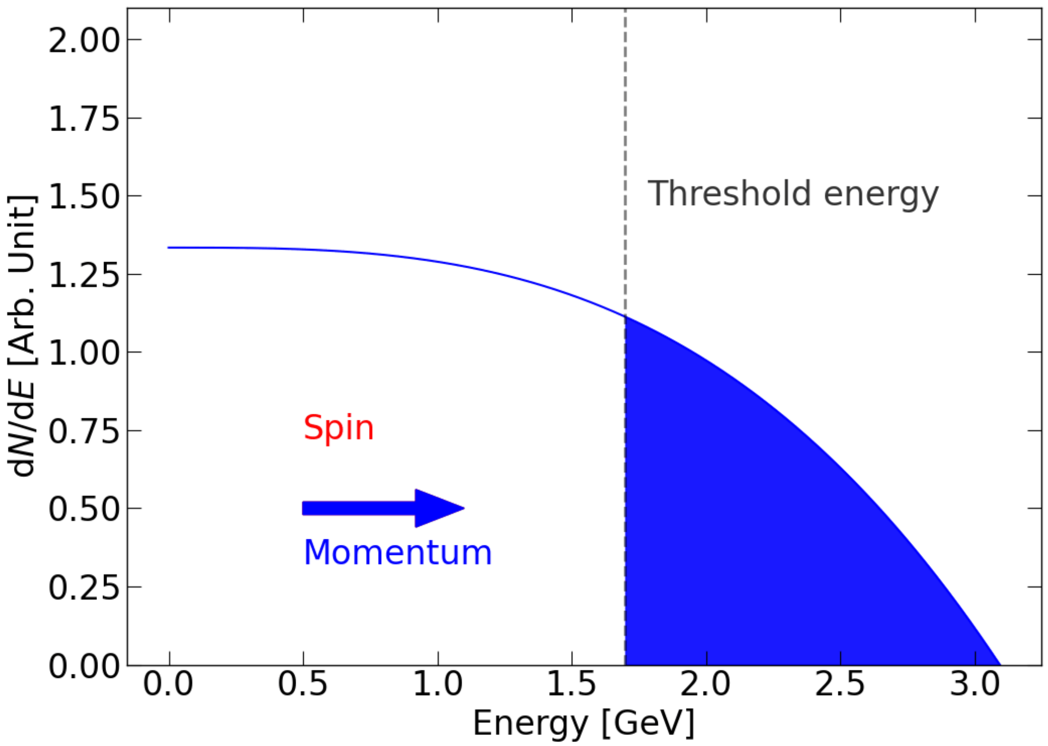


PbF_2 crystals + SiPM

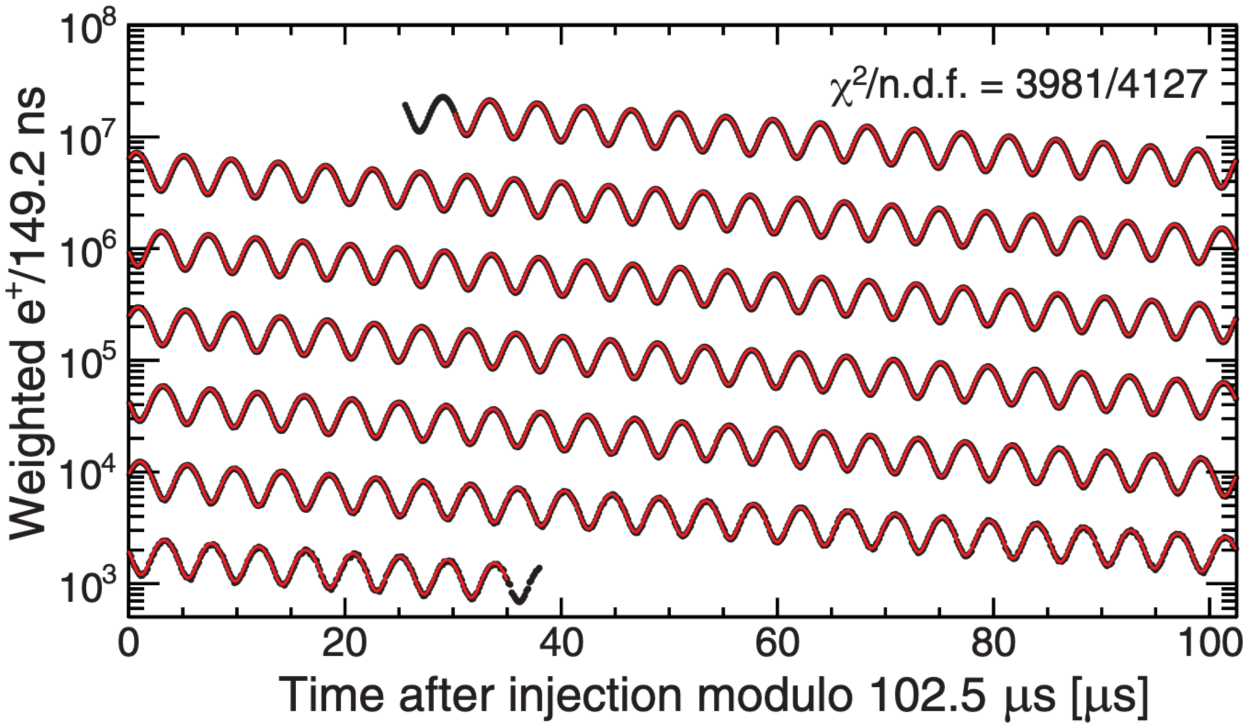


Anomalous Spin Precession of Muon

- Parity-violating weak decay: $\mu^+ \rightarrow e^+\nu_e\bar{\nu}_\mu$:
  high energy decay e^+ are preferentially emitted to the muon spins.



- Resulting "Wiggle plot"



- Fit the wiggle plot to extract ω_a (simplified function).

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

Measurement Quantity Anatomy

$$\omega_a = a_\mu \frac{qB}{m} \Rightarrow a_\mu = \underbrace{\boxed{\frac{\omega_a}{\tilde{\omega}'_p(T_r)}}}_{\text{What we measure.}} \overbrace{\frac{\mu'_p(T_r)}{\mu_e(H)} \frac{\mu_e(H)}{\mu_e} \frac{m_\mu}{m_e} \frac{g_e}{2}}^{\text{Known to 24 ppb}}$$

What we measure.

Known to 24 ppb

Omega-a Team

Measured $g-2$ frequency

Beam Dynamics Team

Beam dynamics corrections

Unblinding conversion factor

$$\mathcal{R}'_\mu = \frac{\omega_a}{\tilde{\omega}'_p(T_r)} = \frac{f_{\text{clock}}\, \omega_a^m \,(1 + \overbrace{C_e + C_p + C_{ml} + C_{pa}}^{\text{Beam dynamics corrections}})}{f_{\text{calib}} \underbrace{\langle \omega_p(x,y,\phi) \times M(x,y,\phi) \rangle}_{\text{Magnetic field weighted over the muon distribution}} (1 + \underbrace{B_k + B_q}_{\text{Corrections from the transient magnetic field}})}$$

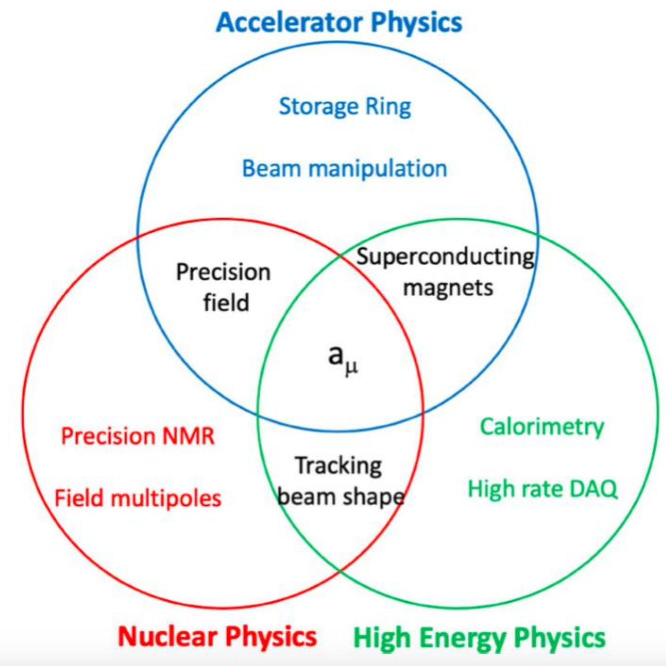
Field Team

NMR probe calibration factor

Magnetic field weighted over the muon distribution

Corrections from the transient magnetic field

Category	TDR Target Uncertainty [ppb]
Statistical (ω_a)	100
Systematic (ω_a)	70
Systematic ($\tilde{\omega}_p$)	70
Total	**140**



Analysis Chain for ω_a

Stage	Options		
Data Acquisition	Time slices with 50 MeV threshold	Full waveform (combined into 37.5 ns bin width)	
Reconstruction	Local fitting	Global fitting	Energy-integrated (Q)
Data Weighting	No weighting (T)	Asymmetry-weighted (A)	
Histogramming	Ratio	Stroboscopic	
Correction	Pileup	Fast Rotation	
Systematics	Beam Dynamics	Pileup, Gain	Slow Effects

6 independent ω_a analysis groups (involved institutions: BU, CU, UIUC, Ole Miss, INFN, UPisa, ULiverpool, UCL, SJTU, UW, Uky)

Analysis Chain for ω_a

Data Acquisition

Reconstruction

Data Weighting

Histogramming

Correction

Systematics

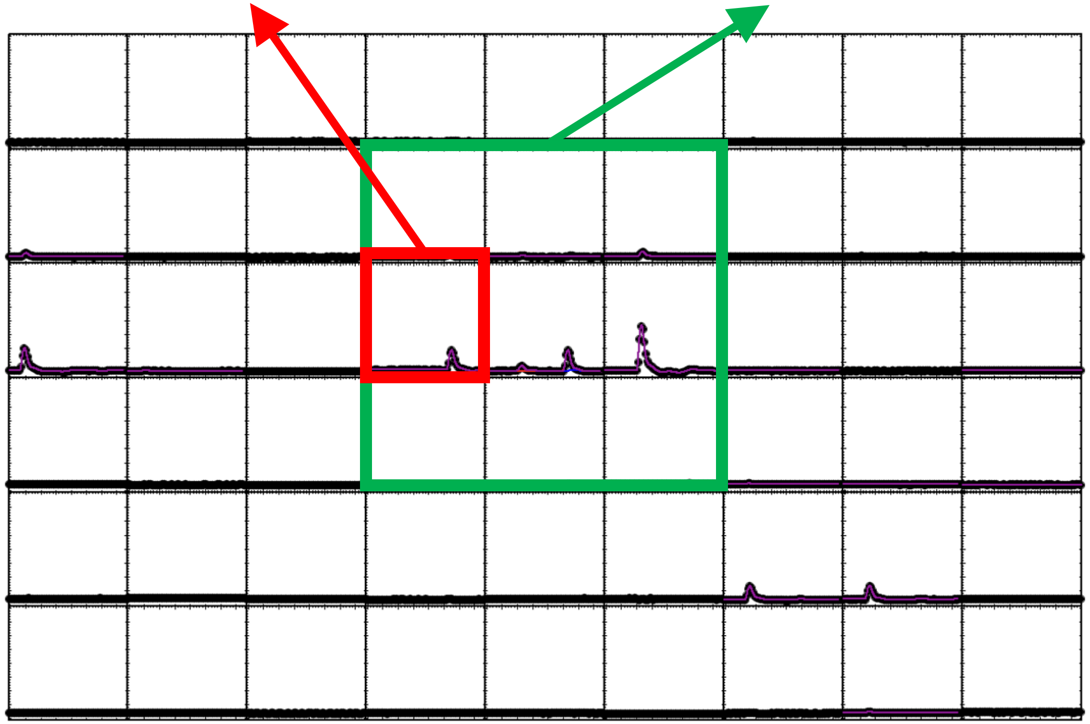
Time slices with 50 MeV threshold

Full waveform (combined into 37.5 ns bin width)

Local fitting

Global fitting

Energy-integrated (Q)

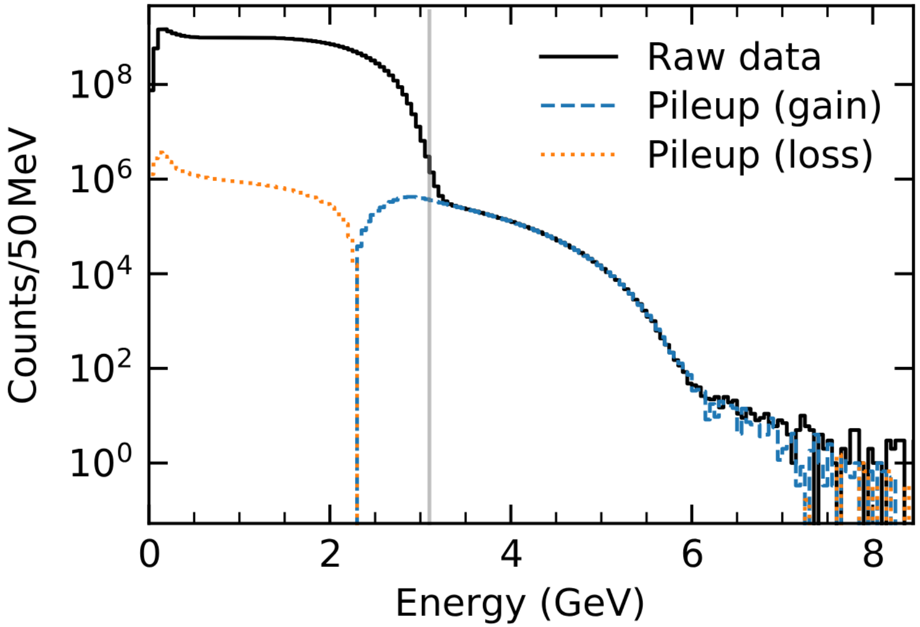


Waveform time slices in 9×6 PbF_2 crystals.

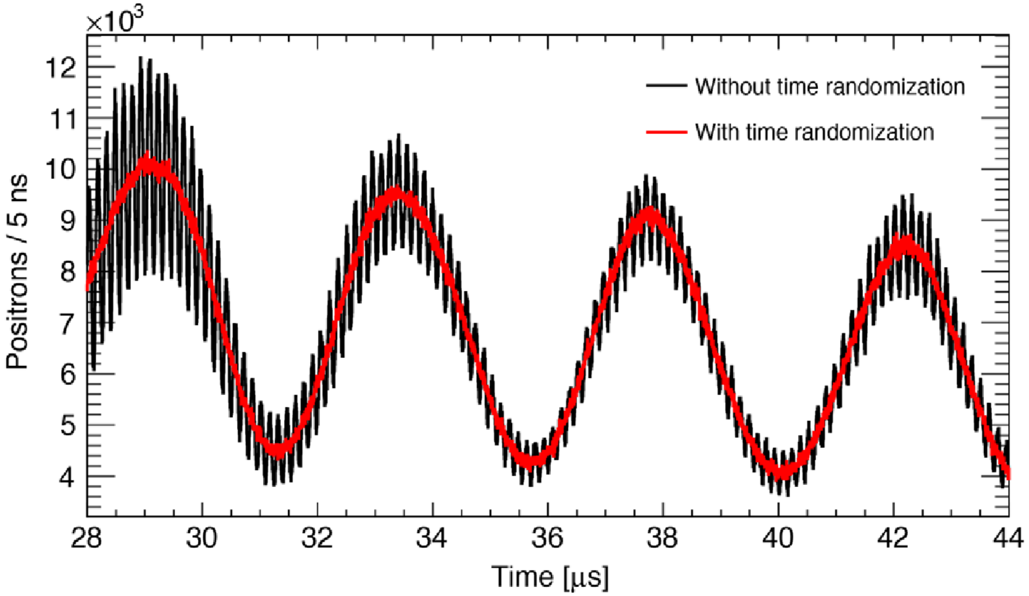
Fit and reconstruct "clusters" = positron hits.

Analysis Chain for ω_a

- Data Acquisition
- Reconstruction
- Data Weighting
- Histogramming
- Correction
- Systematics



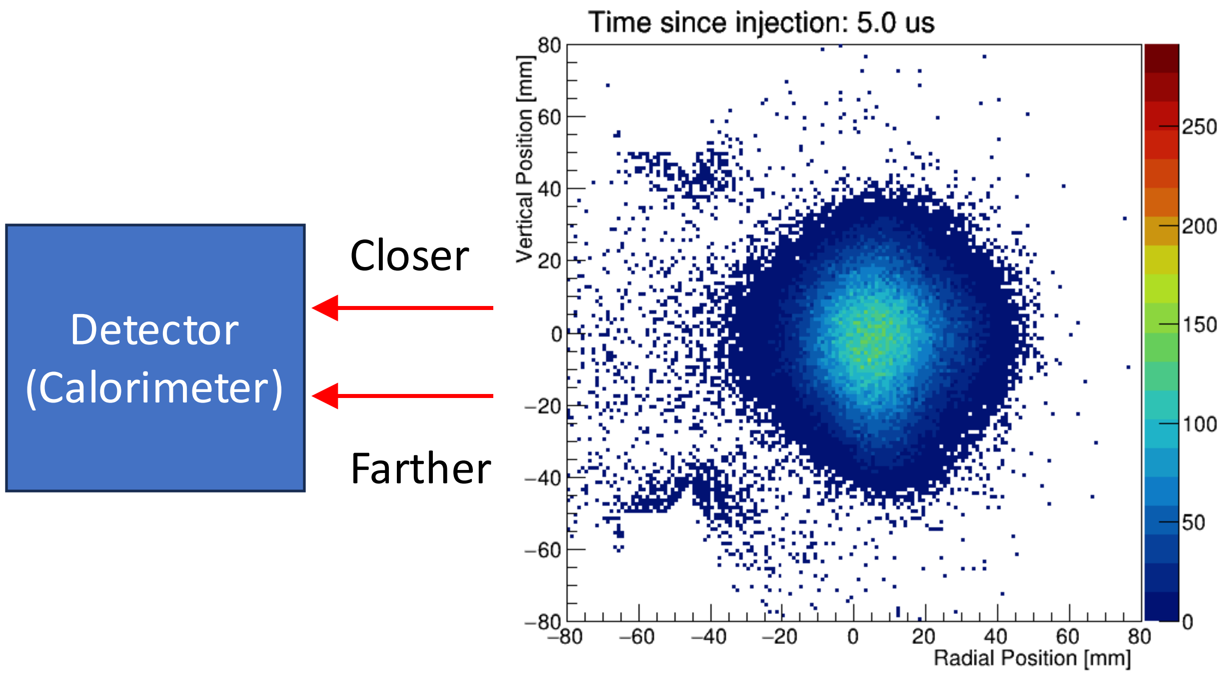
Pileup



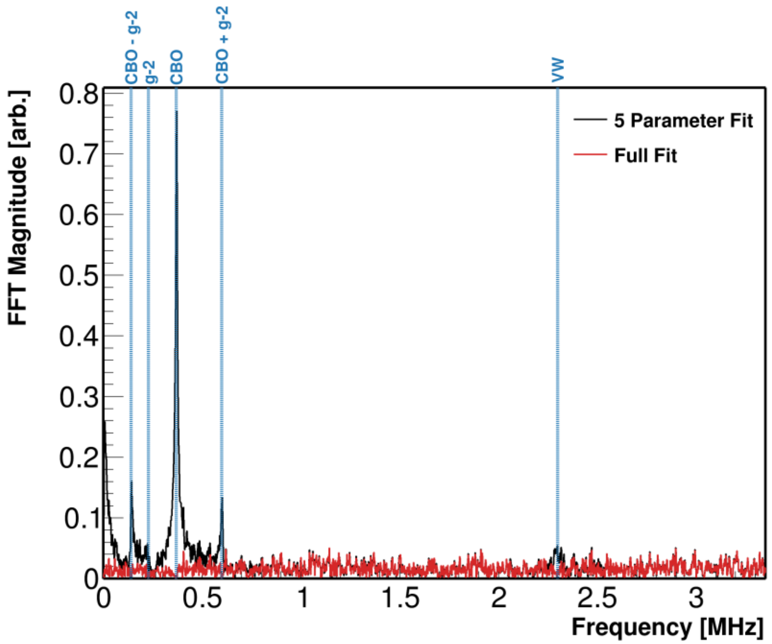
Fast Rotation

Analysis Chain for ω_a

$$f(t) = N_0 \cdot N_x(t) \cdot N_y(t) \cdot N_{xy}(t) \cdot \Lambda(t) \cdot e^{-t/\gamma\tau_\mu}$$
$$(1 + A_0 \cdot A_x(t)\cos(\omega_a^m t - (\phi_0 + \phi_x(t)))).$$



FFT of fit residuals of the wiggle plot



Systematics

Beam Dynamics → Coherent Betatron Oscillations (CBO)

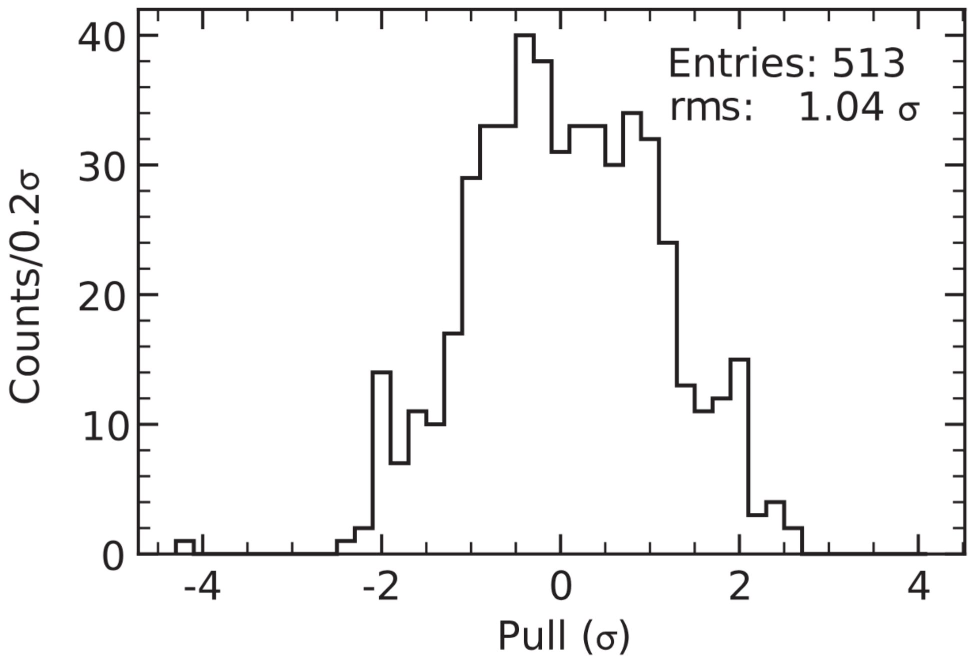
Uncertainty [ppb]	BNL	FNAL Run-1	FNAL Run-2/3
CBO	70	38	21
ω_a syst. (ω_a^m syst.)	180	108 (56)	47 (25)
ω_a stat.	460	434	201

Combination

- There were 7 independent groups (now 6) analyzed ω_a in slightly different methods.

Group	Recon	Method	Number of free parameters 2, 3a/3b	τ_μ handling	Run-2 k_{loss}	Run-3 k_{loss}	$f_{\text{CBO}}(t)$ term	CBO env. $e^{-t/\tau}+C$	VW – CBO term
I	Local	A, T	28/28	Free	Free, +	Free, −		r3b ✓	✓
II	Local	A, T	25/26	Free	Free, +	Fix, 0	✓	r3b ✓	✓
III	Local	A, T	28/28	Free	Free, +	Free, −	✓, fixed τ_d	✓	✓
III	Local	AR, TR	14/14	Fix	Free, +	Free, −	✓, fixed τ_d	✓	
IV	Local	A, T	18/18	Free	Free, +	Fix, 0	✓, fixed τ_d	✓	
IV	Local	AR, TR	15/15	Fix	Fix, +	Fix, 0	✓, fixed τ_d	✓	
V	Global	A, T	30/30	Free	Free, +	Free, −	✓	✓	✓
V	Global	TR	19/19	Fix	Fix, +	Fix, −	✓	✓	
VI	Global	A, T	27/28	Penalize	Free, +	Free −	✓, fixed τ_d	r3b ✓	✓
VII	Energy	Q	34/38	Free	Free, +	Free, −	✓	✓	r3 ✓
VII	Energy	QR	26/24	Fix	Fix, +	Fix, −	✓	✓	r3 ✓

Pull of ω_a between 513 pairs



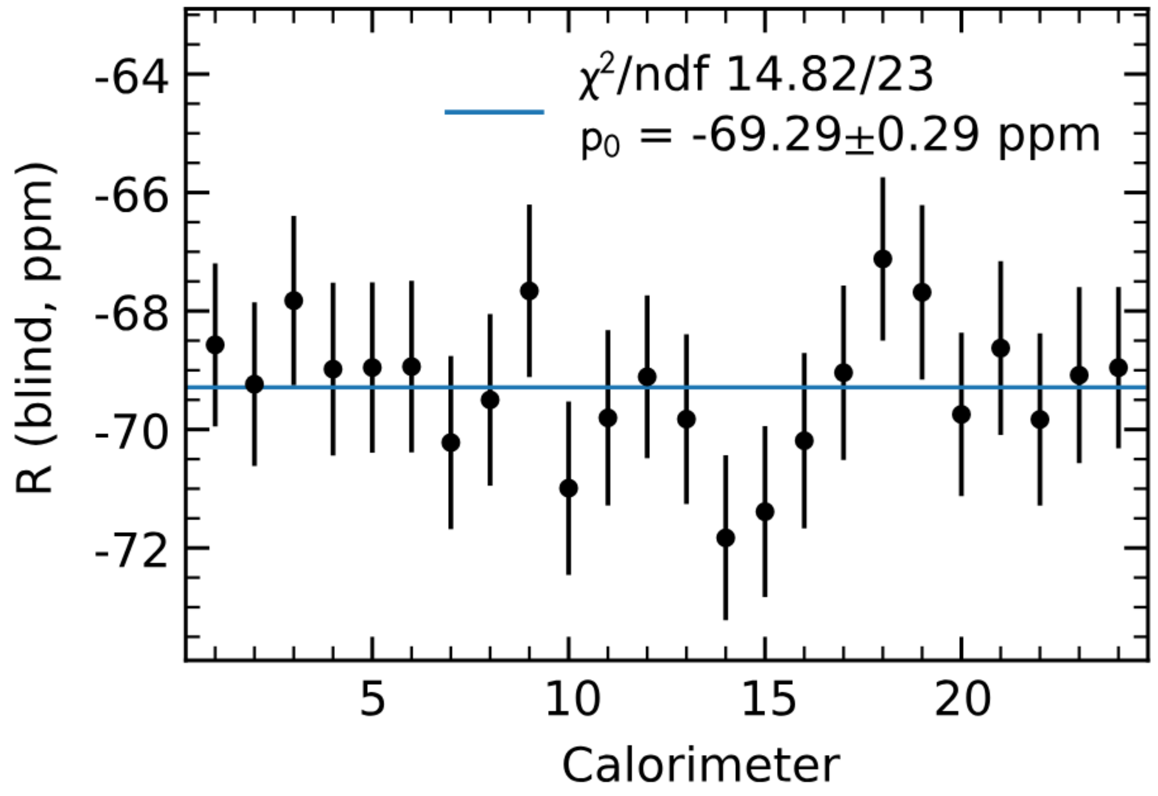
- Estimated the analysis-to-analysis correlations by dedicated Monte-Carlo simulation studies.

Consistency Checks

- Check if the fit parameters (especially blinded ω_a $(= R)$) are consistent in different knobs.

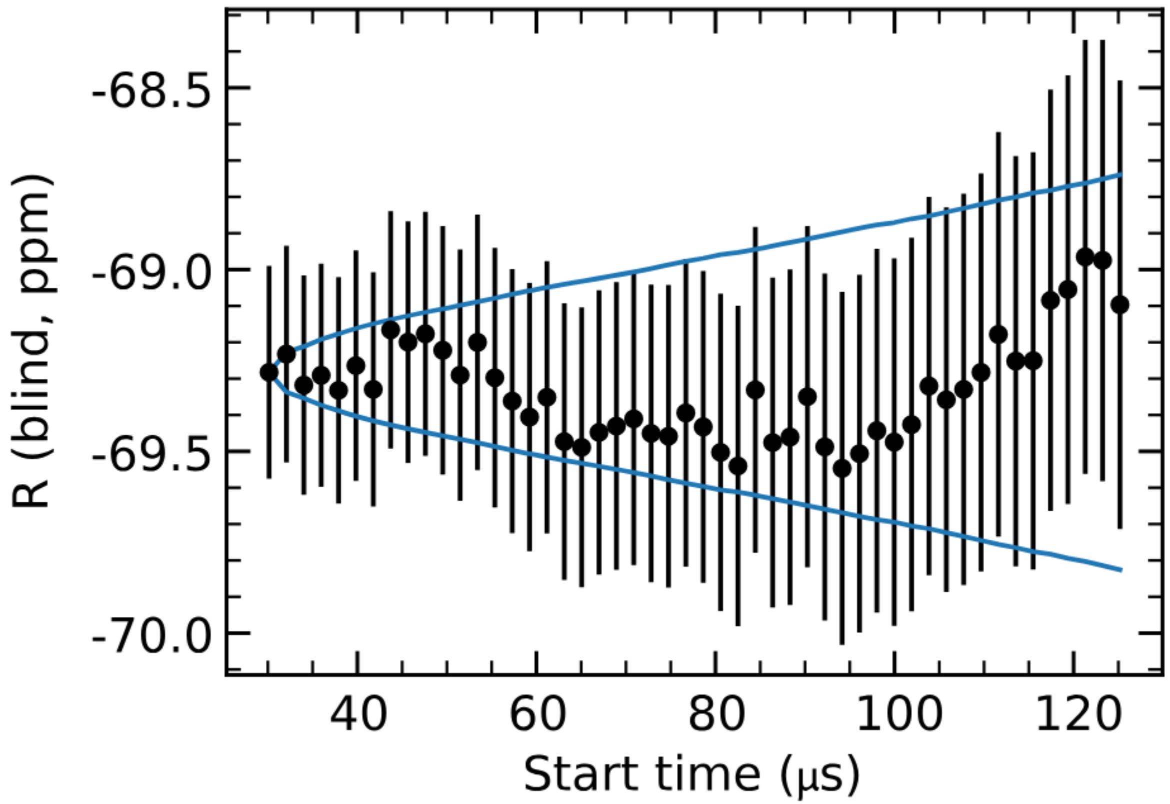
Per detector

*A wave can appear if any beam dynamics effects that go around the ring were mistreated.



Fit start time

*It may diverge from the statistically allowed band if any slow-varying effects were mistreated.



Prospect – Systematics Improvement

Run-2/3 Result: PRL **131**, 161802 (2023)

TABLE I. Values and uncertainties of the $\mathcal{R}'_\mu$ terms in Eq. (2), and uncertainties due to the external parameters in Eq. (1) for a_μ. Positive C_i increases a_μ; positive B_i decreases a_μ [see Eq. (2)]. The ω_a^m uncertainties are decomposed into statistical and systematic contributions. All values are computed with full precision and then rounded to the reported digits.

	Quantity	Correction (ppb)	Uncertainty (ppb)
ω_a	ω_a^m (statistical)	...	201
	ω_a^m (systematic)	...	25
BD	C_e	451	32
	C_p	170	10
	C_{pa}	−27	13
	C_{dd}	−15	17
	C_{ml}	0	3
ω_p	$f_{\text{calib}} \cdot \langle \omega'_p(\vec{r}) \times M(\vec{r}) \rangle$	...	46
	B_k	−21	13
	B_q	−21	20
	$\mu'_p(34.7°)/\mu_e$	...	11
	m_μ/m_e	...	22
	$g_e/2$	...	0
	Total systematic for $\mathcal{R}'_\mu$	...	70
	Total external parameters	...	25
	Total for a_μ	622	215

$$\mathcal{R}'_\mu = \frac{\omega_a}{\tilde{\omega}'_p(T_r)} = \frac{f_{\text{clock}}\, \omega_a^m\, (1 + C_e + C_p + C_{ml} + C_{pa})}{f_{\text{calib}}\, \langle \omega_p(x,y,\phi) \times M(x,y,\phi) \rangle (1 + B_k + B_q)}$$

Run-4/5/6 improvements

(No real estimates on systematics yet)

- ~100 (in total Runs 1-6), ~x4 stats
- ~x10 reduction of CBO with the RF system (Run-5/6).
- New signal processing algorithm to suppress backgrounds/sidebands. Verification with the new beam-monitoring system (miniSciFi).
- New tracker-based analysis method for cross-checking.
- More calibrations performed in more consistent ways + cross-calibrations. Better understanding and handling of magnet drift.
- Significantly more and better measurements (spatial dependence, etc.).

We have already surpassed the TDR systematics goal of 100 ppb.
And possibly even less for Run-4/5/6!

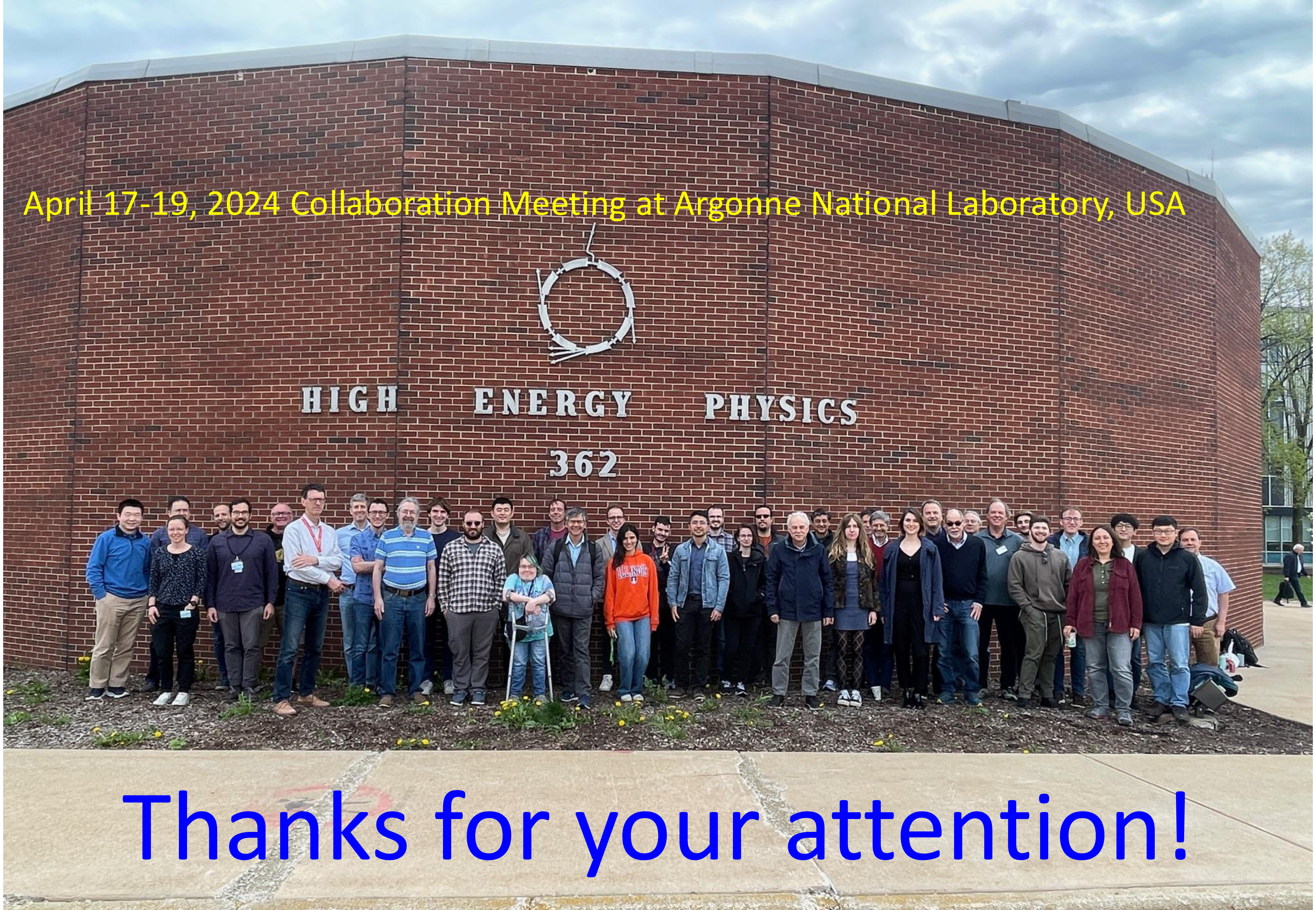
Take-Home Messages

- Fermilab Muon $g-2$ finished data taking in June 2023.
- Comparison to the Standard Model is in a vague state at the moment. Many ongoing efforts are being made in HVP communities to scrutinize the calculations.
- The final result (Run-4/5/6 data taken in 2021-2023) analysis is underway. It is anticipated that the result will be published in 2025 with $\sim$140 ppb precision.
  - We met the TDR target statistics goal and likely will surpass the systematics goal.
  - Many improvements have been made in systematics. For instance, Run-5/6 data was taken with the RF system, and CBO (one of the main systematic sources for ω_a) was dramatically reduced.
- BSM searches are underway using our data – EDM, CPT/LIV and DM.
  - Don't miss the talks about those in NuFACT2024:
    - (Tue) The Status of the Muon EDM Search with the Muon g-2 Experiment at Fermilab, Gavin Hesketh
    - (Wed) Dark Matter Search in the Muon g-2 Experiment at Fermilab, Byungchul Yu
- Run-2/3 detailed analysis report: arXiv:2402.15410 (PRD**110**, 032009).

Acknowledgement

- Department of Energy (USA)
- National Science Foundation (USA)
- Istituto Nazionale di Fisica Nucleare (Italy)
- Science and Technology Facilities Council (UK)
- Royal Society (UK)
- Leverhulme Trust (UK)
- European Union's Horizon 2020
- Strong 2020 (EU)
- German Research Foundation (DFG)
- National Natural Science Foundation of China
- MSIP, NRF and IBS-R017-D1 (Republic of Korea)

April 17-19, 2024 Collaboration Meeting at Argonne National Laboratory, USA



Thanks for your attention!

Backups

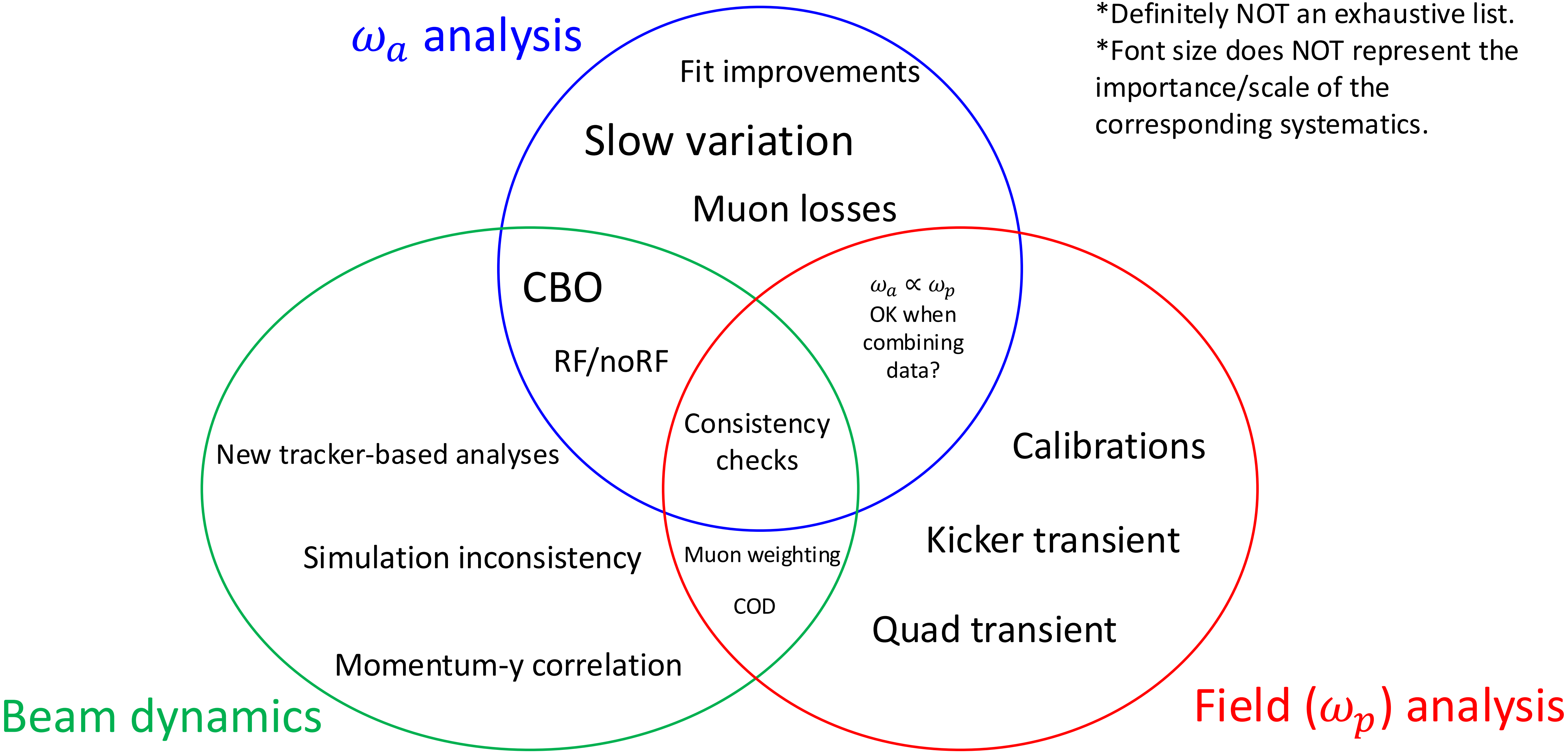
Progress – Analysis Focus

"You already published two results for Run-1 and 2/3, so all the analysis tools must have been already established. Isn't it like now you just put 4/5/6 data into the machinery and get the results out right away?"

- Nope, that's not really what it looks like.
  - More data gives us a better resolution for investigating systematics. We always try to comprehend the data as best as we can. It's worthwhile to put more time/resources into understanding better!
  - We also have newly introduced systems/techniques used in Run-4/5/6 data-taking and analysis. Those are supposed to improve our analysis, but they definitely need scrutiny.
  - Processing more data (>5 PB of raw data for Runs-4/5/6) takes significantly more time, too. Not just for reconstructing/validating/analyzing the data, but we want to carefully do all consistency checks, e.g., across various external parameters (temperature, pressure, etc.), beam/detector parameters (energy, time, beam-condition, etc.), consistency among various simulation programs, analyzer groups, analysis methods, etc. We also undergo intense reviews on all analyses to gain more confidence.

Progress – Analysis Focus

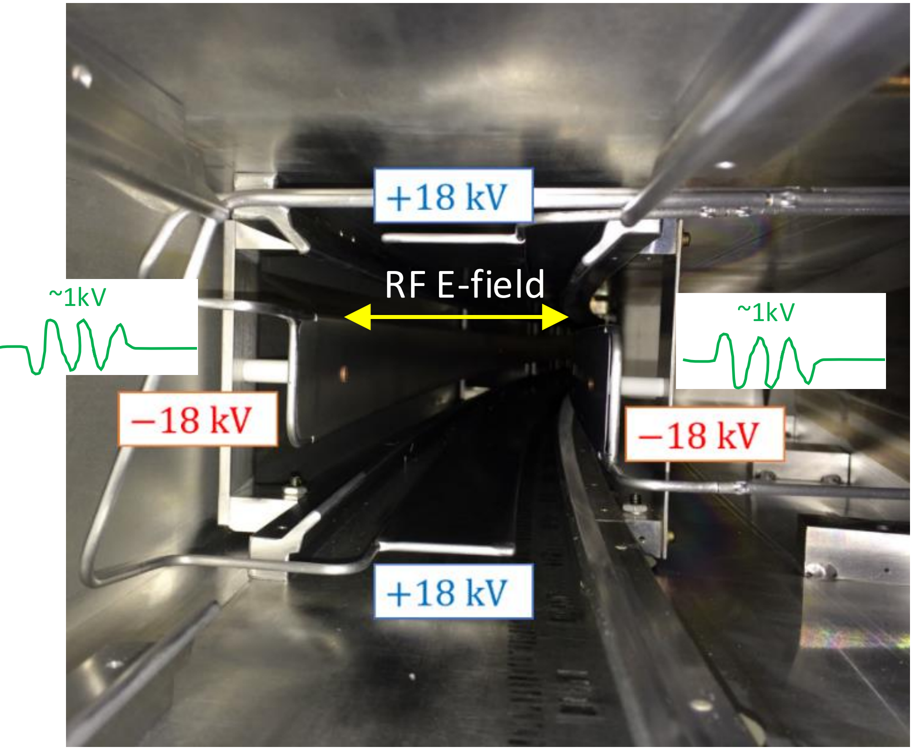
*Definitely NOT an exhaustive list.
*Font size does NOT represent the importance/scale of the corresponding systematics.



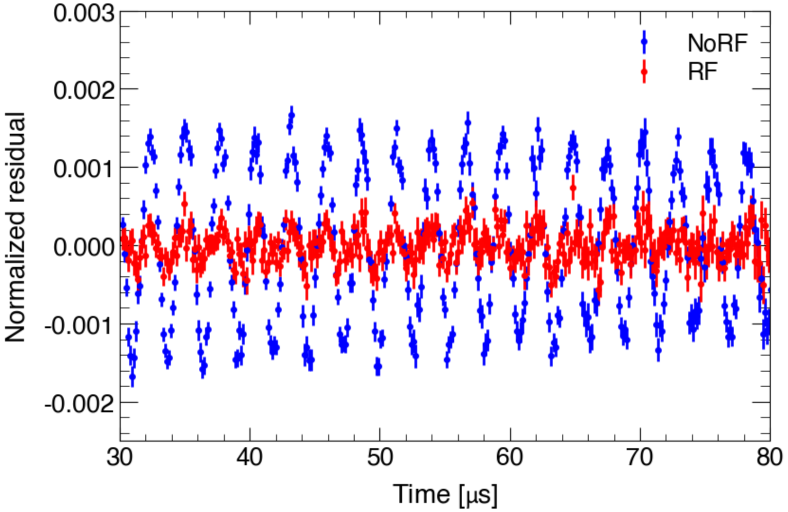
Prospect – Systematics Improvement

- Implemented the RF system to reduce the CBO significantly.
- Run-5/6 data (almost half of the entire data) was taken with the RF system.

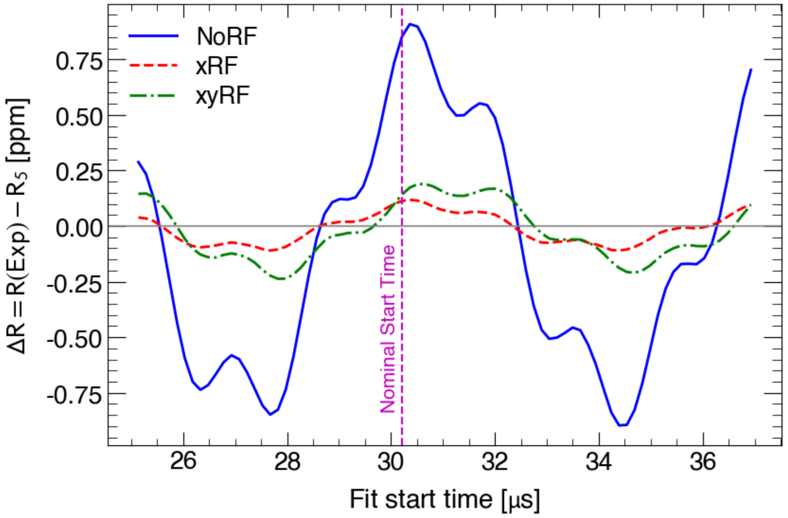
Electrostatic Quadrupole + RF



CBO

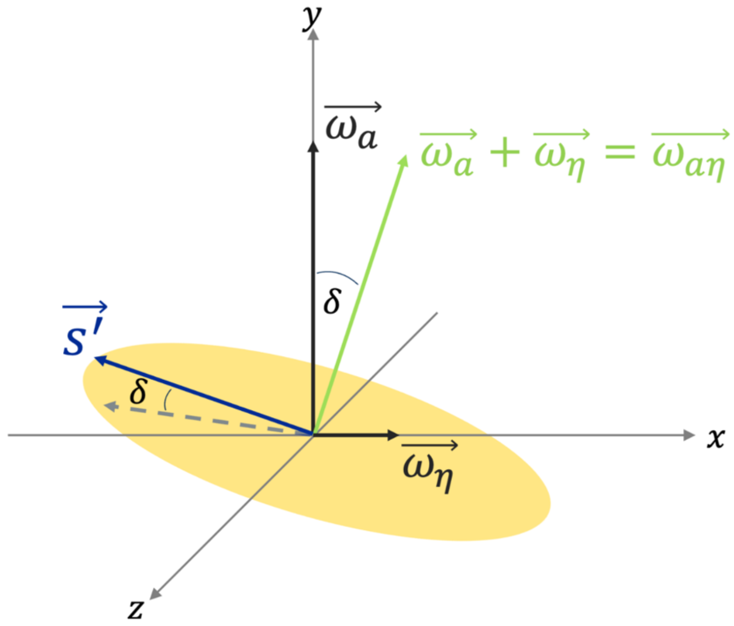


CBO systematics proxy



BSM Searches

- Electric Dipole Moment (EDM)
  - The spin precession plane is tilted in the presence of the EDM.
  - Run-1 in review, Run-2/3 in progress
  - Current limit (BNL): 1.8×10^{-19} e $\cdot$ cm $\rightarrow$ Projected limit: $\lesssim 3 \times 10^{-20}$ e $\cdot$ cm



- CPT and Lorentz Invariance Violation
  - ω_a modulated at the sidereal motion.
  - Run-2/3 in review.
  - Current limit (BNL): 1.4×10^{-24} GeV $\rightarrow$ Projected limit (FNAL Run-2/3): $\mathcal{O}(10^{-25})$ GeV

- Ultralight Muonic Dark Matter (scalar)
  - ω_a modulated at the DM Compton frequency.
  - Run-2/3 in progress.

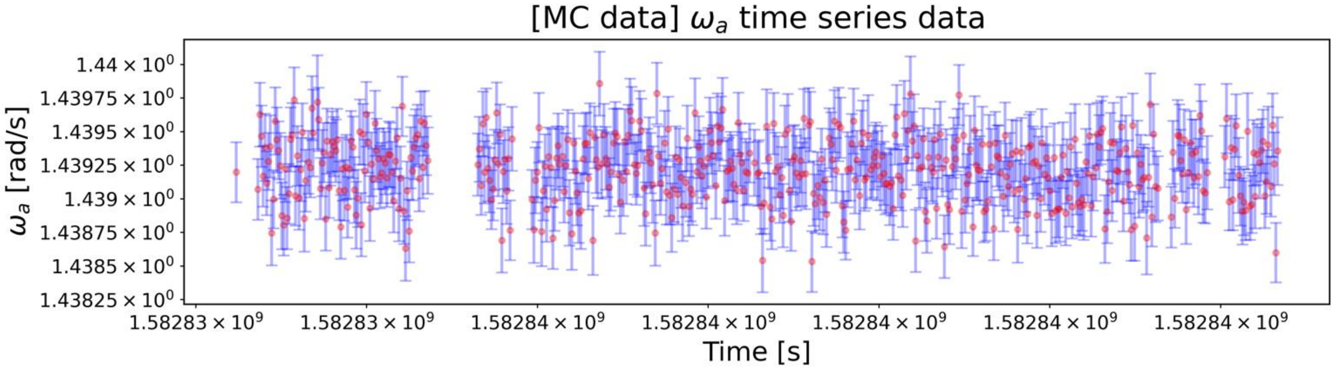
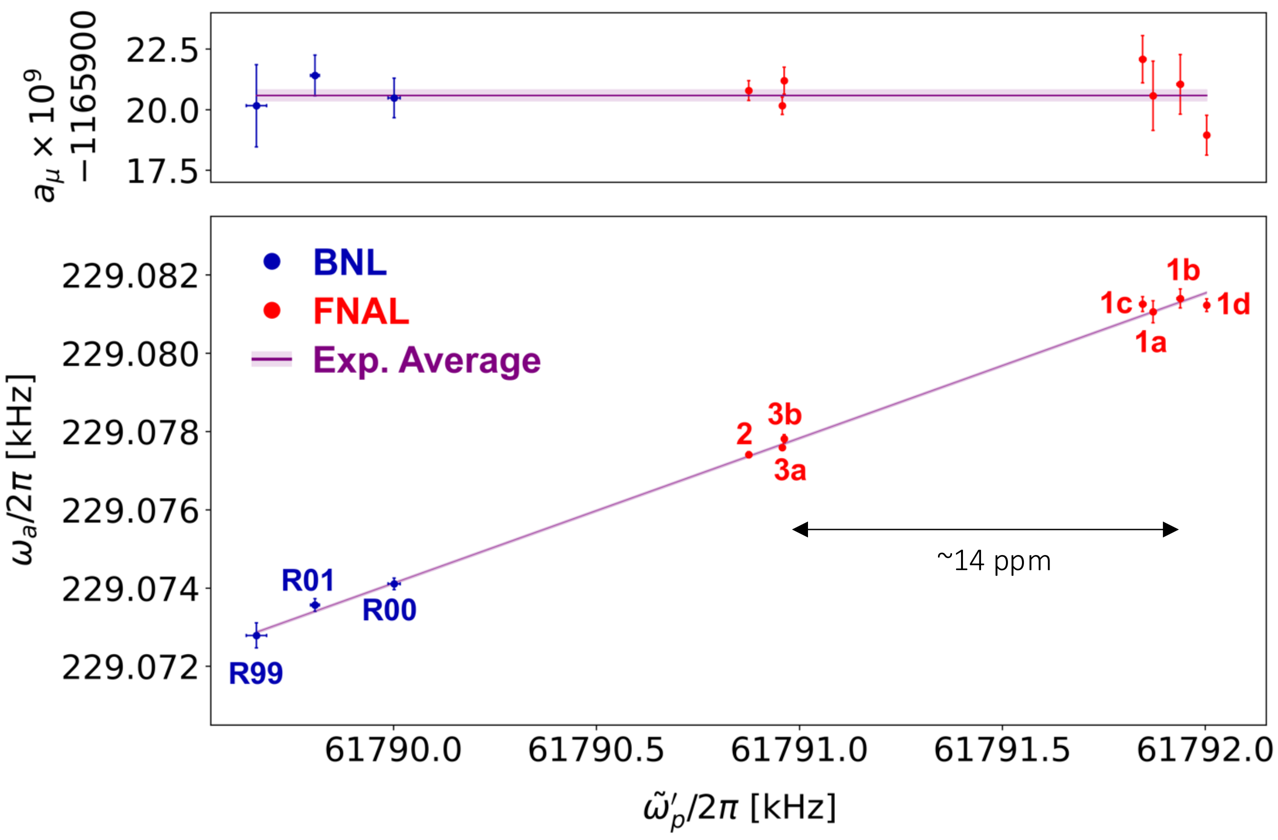


TABLE II. Values and uncertainties of the $\mathcal{R}'_\mu$ correction terms in Eq. (4), and uncertainties due to the constants in Eq. (2) for a_μ. Positive C_i increase a_μ and positive B_i decrease a_μ.

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

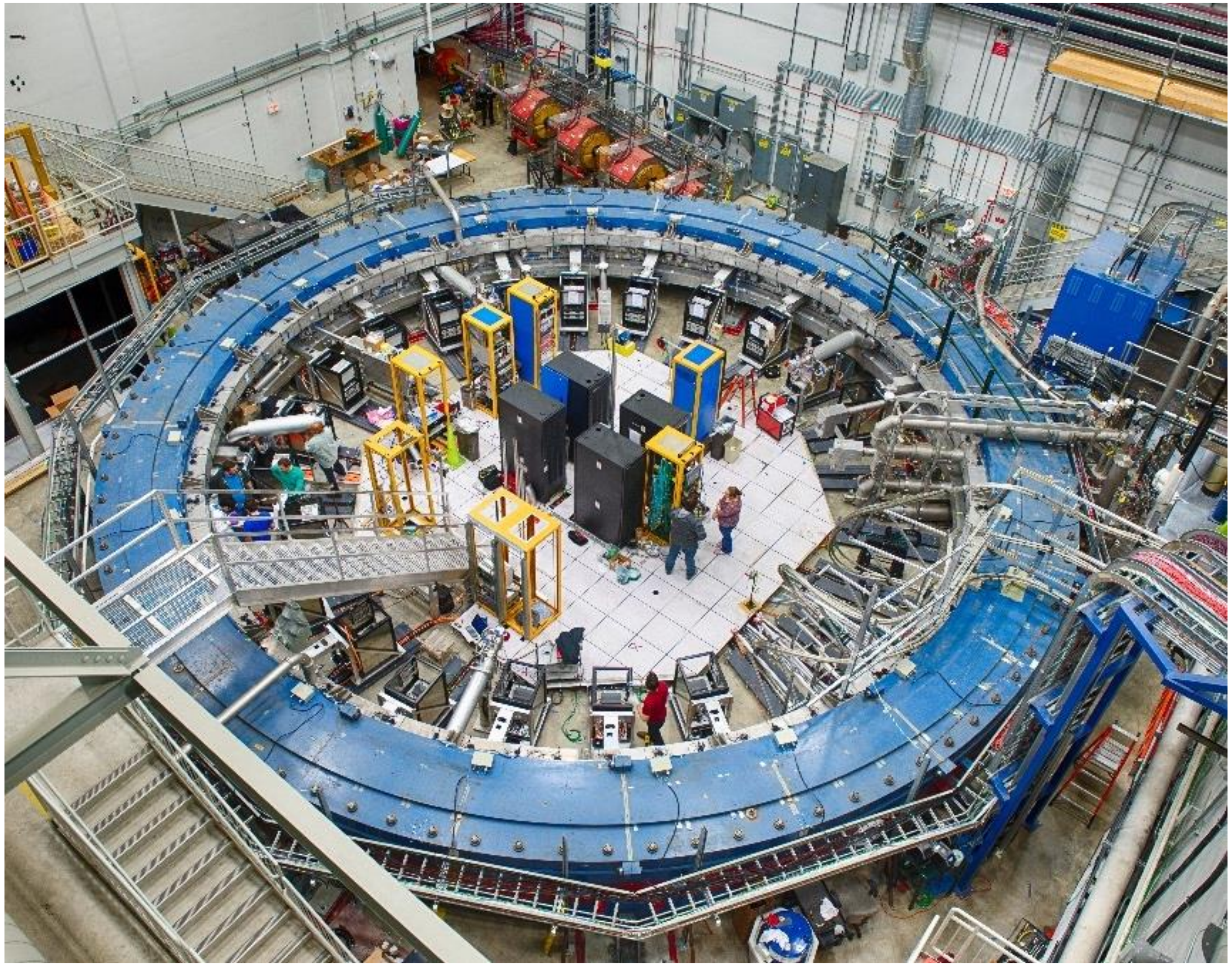
TABLE I. Values and uncertainties of the $\mathcal{R}'_\mu$ terms in Eq. (2), and uncertainties due to the external parameters in Eq. (1) for a_μ. Positive C_i increases a_μ; positive B_i decreases a_μ [see Eq. (2)]. The ω_a^m uncertainties are decomposed into statistical and systematic contributions. All values are computed with full precision and then rounded to the reported digits.

Quantity	Correction (ppb)	Uncertainty (ppb)
ω_a^m (statistical)	⋯	201
ω_a^m (systematic)	⋯	25
C_e	451	32
C_p	170	10
C_{pa}	−27	13
C_{dd}	−15	17
C_{ml}	0	3
$f_{\text{calib}}\cdot\langle\omega'_p(\vec{r})\times M(\vec{r})\rangle$	⋯	46
B_k	−21	13
B_q	−21	20
$\mu'_p(34.7°)/\mu_e$	⋯	11
m_μ/m_e	⋯	22
$g_e/2$	⋯	0
Total systematic for $\mathcal{R}'_\mu$	⋯	70
Total external parameters	⋯	25
Total for a_μ	622	215

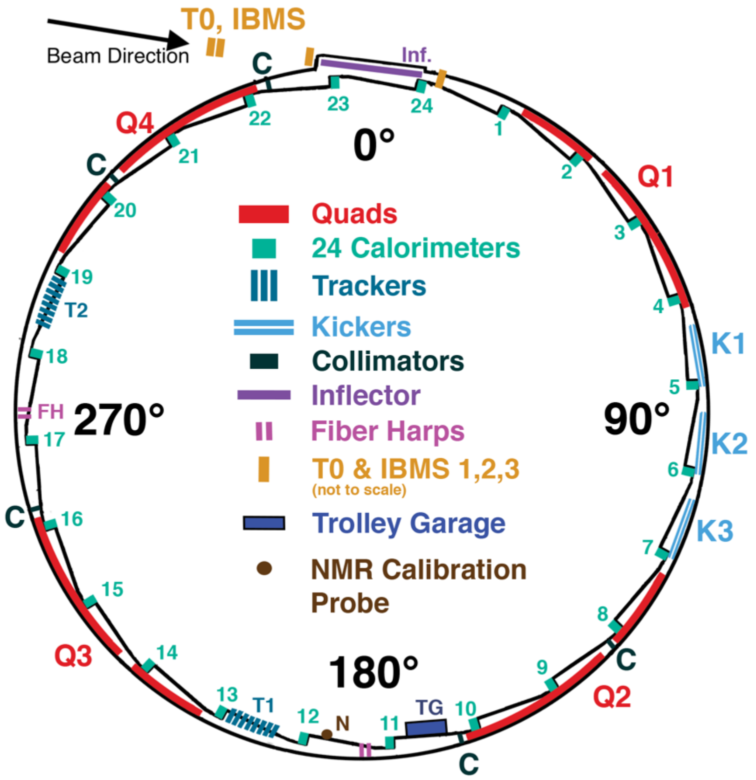


$a_\mu \times 10^9 - 1165900$
22.5
20.0
17.5
BNL
FNAL
Exp. Average
229.082
229.080
229.078
229.076
229.074
229.072
$\omega_a/2\pi$ [kHz]
1b
1c
1d
1a
2
3b
3a
~14 ppm
R01
R00
R99
61790.0
61790.5
61791.0
61791.5
61792.0
$\tilde{\omega}'_p/2\pi$ [kHz]

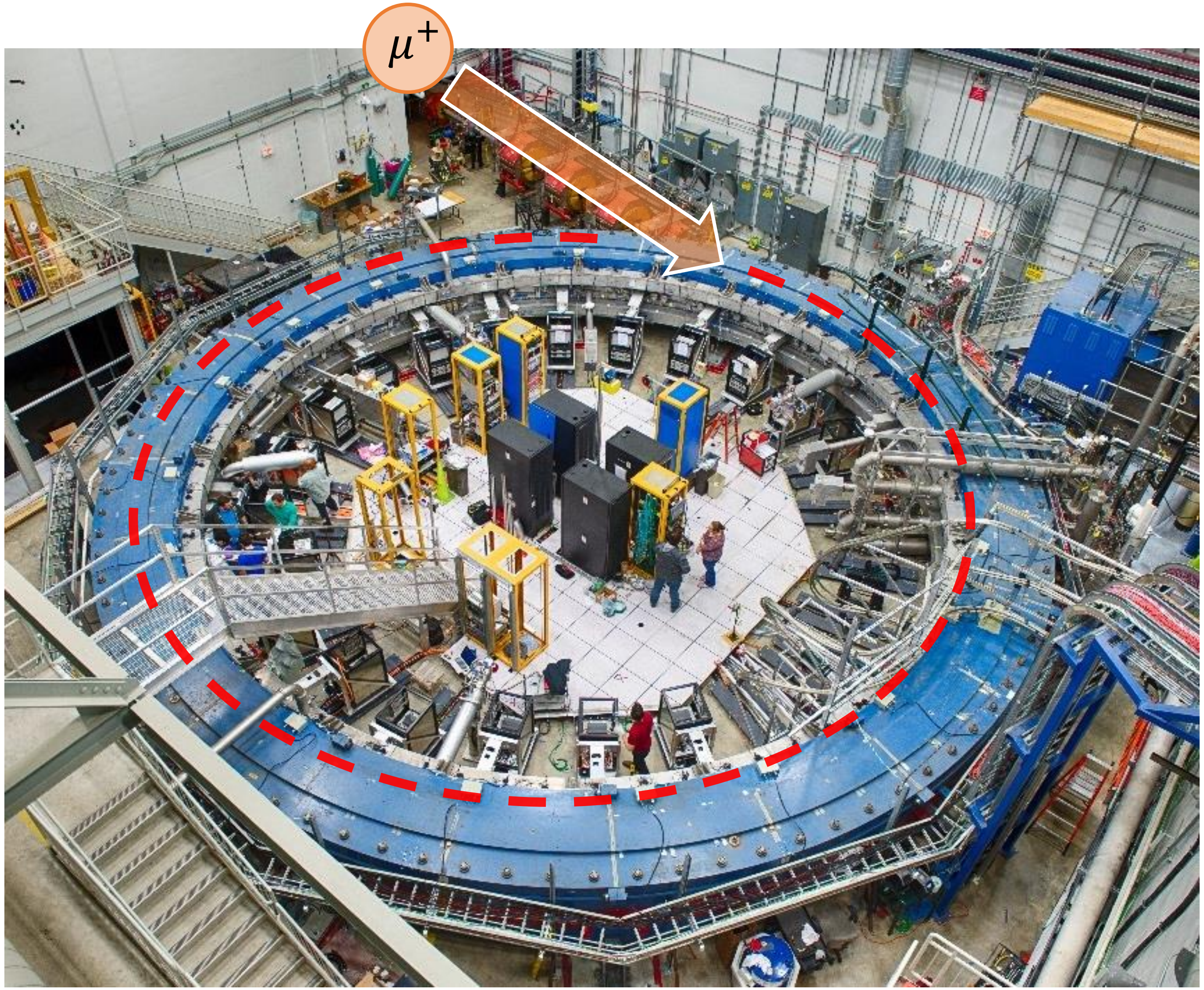
Experimental Overview



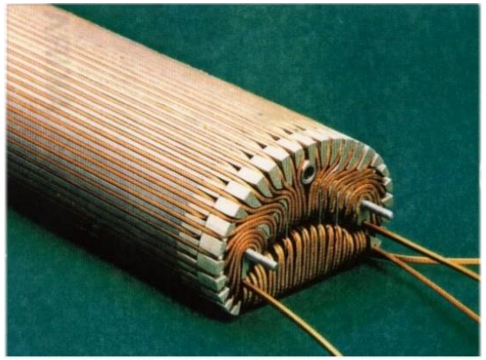
- Muon $g-2$ Storage Ring
  - Radius: 7.112 m.
  - Homogeneous magnetic field: 1.45 T.

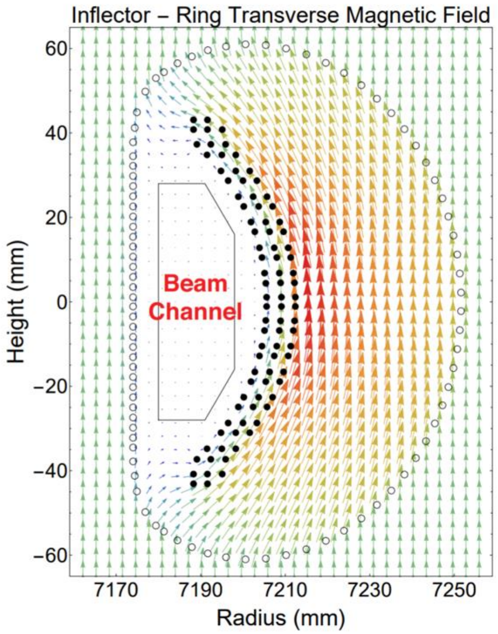


Experimental Overview

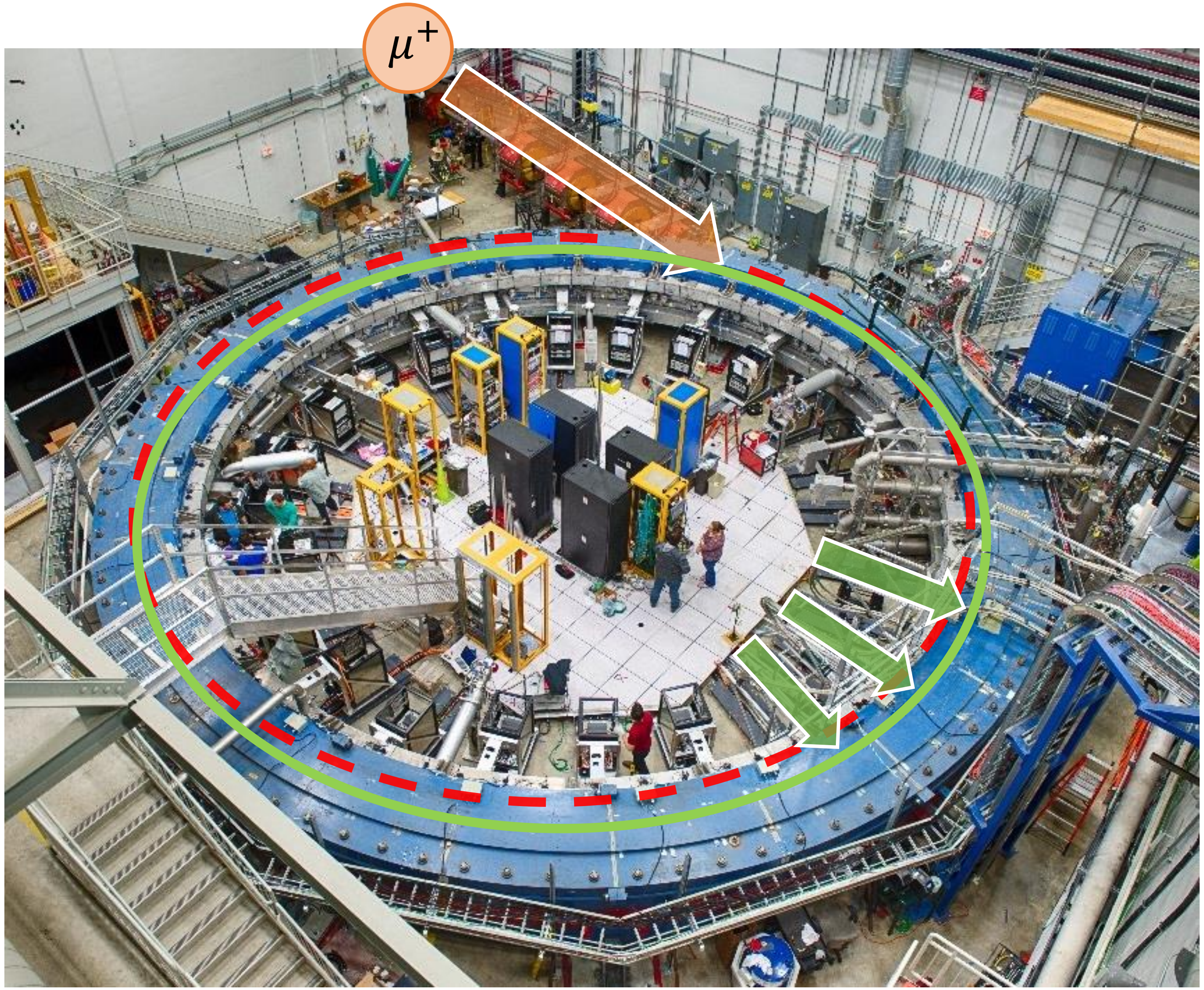


- Injection
  - A polarized anti-muon beam (3.1 GeV) is injected into the storage ring through a superconducting inflector magnet.
  - It cancels the main magnetic field to inject the beam tangentially.

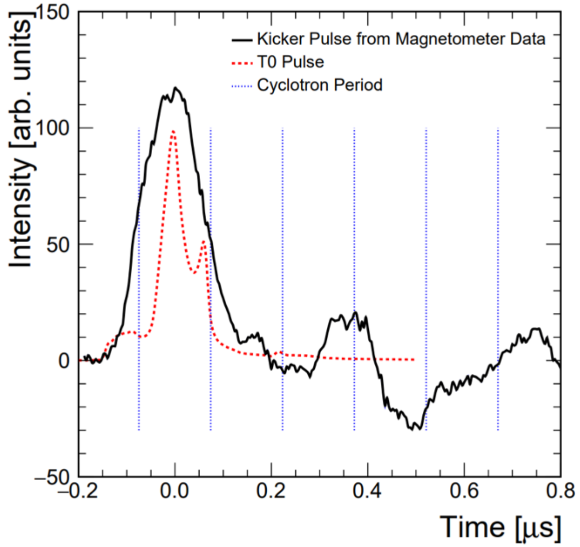




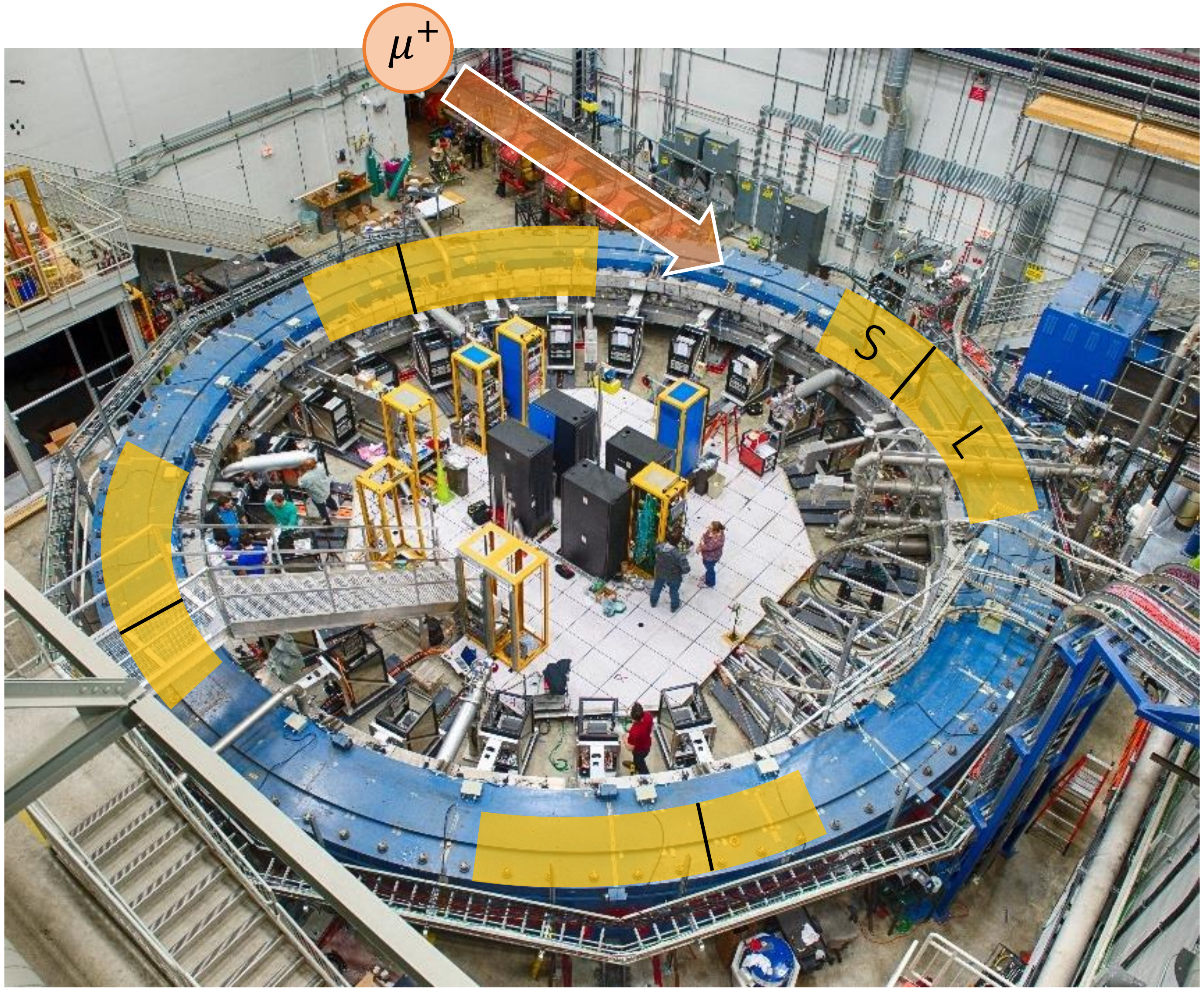
Experimental Overview



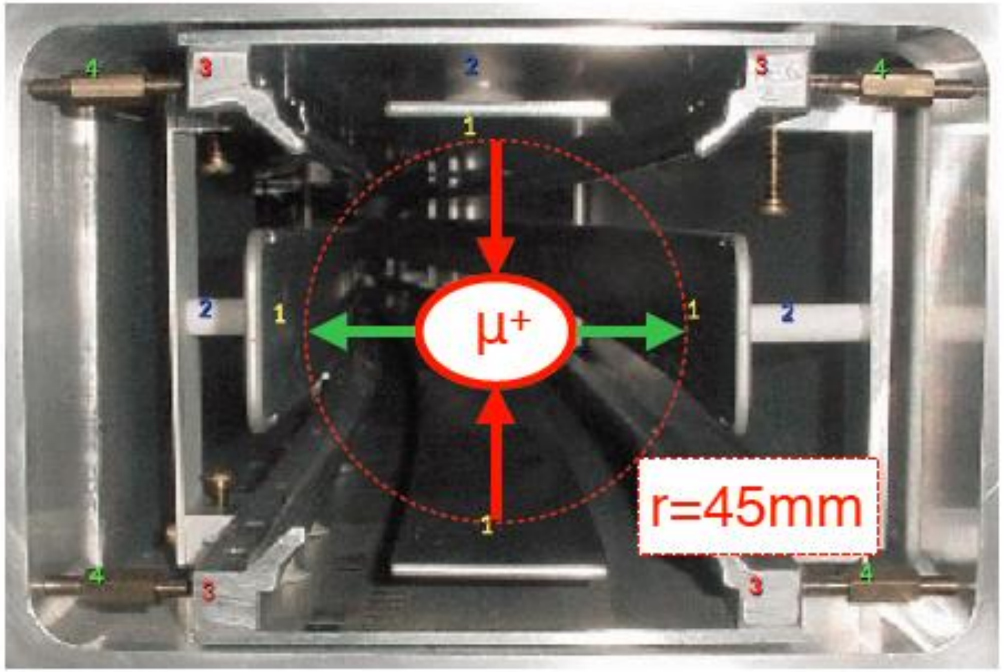
- Kick
  - The fast non-ferric kicker magnet system kicks the muons onto the design orbit.



Experimental Overview

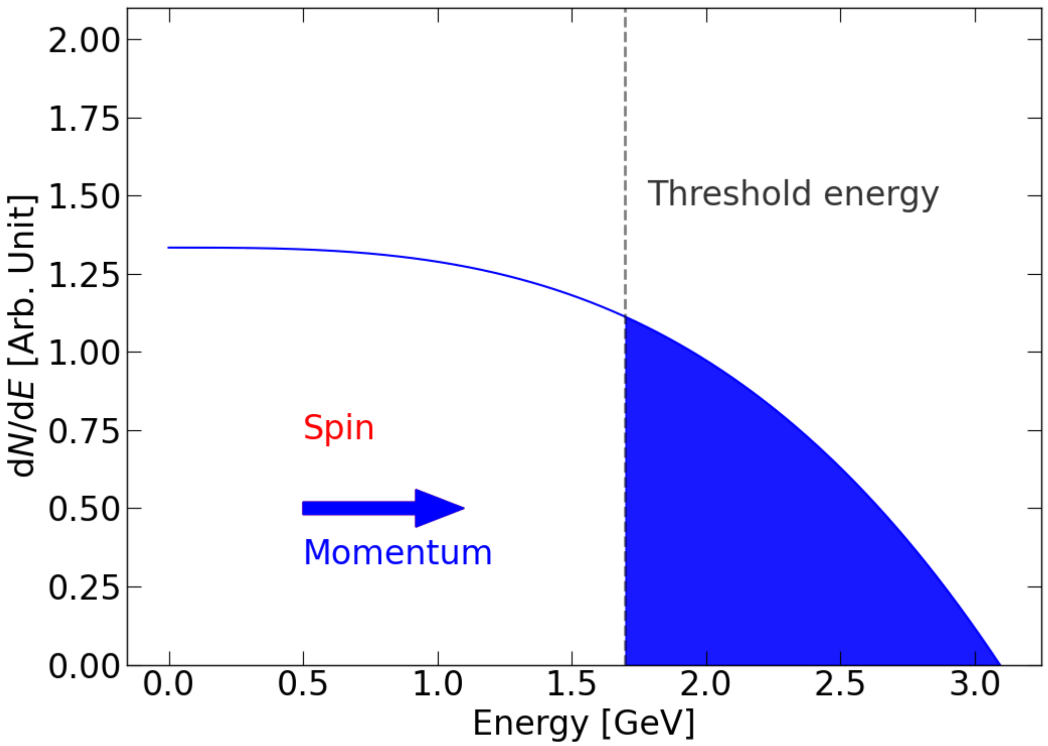


- Vertical Focusing
  - The Electrostatic Quadrupoles (ESQ) focuses the beam vertically.
  - Four Quadrupole sections cover 43% of the circumference.

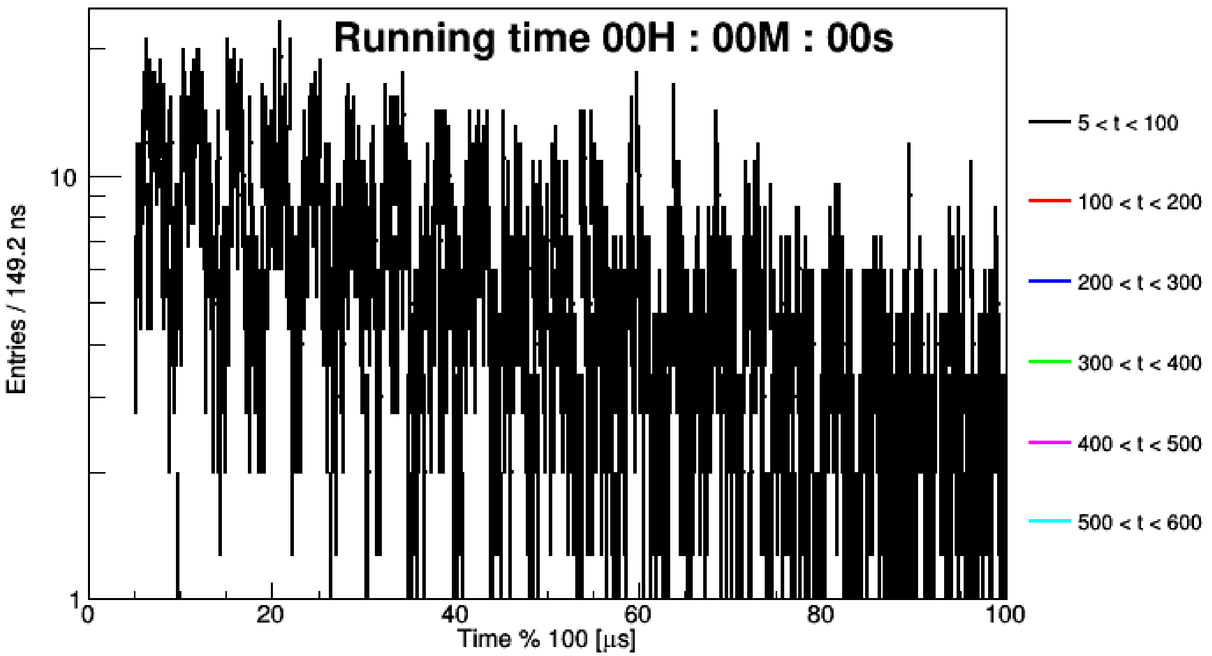


Anomalous Spin Precession of Muon

- Parity-violating weak decay: $\mu^+ \to e^+ \nu_e \bar{\nu}_\mu$: high energy decay e^+ are preferentially emitted to the muon spins.



- Resulting "Wiggle plot"



- Fit the wiggle plot to extract ω_a.

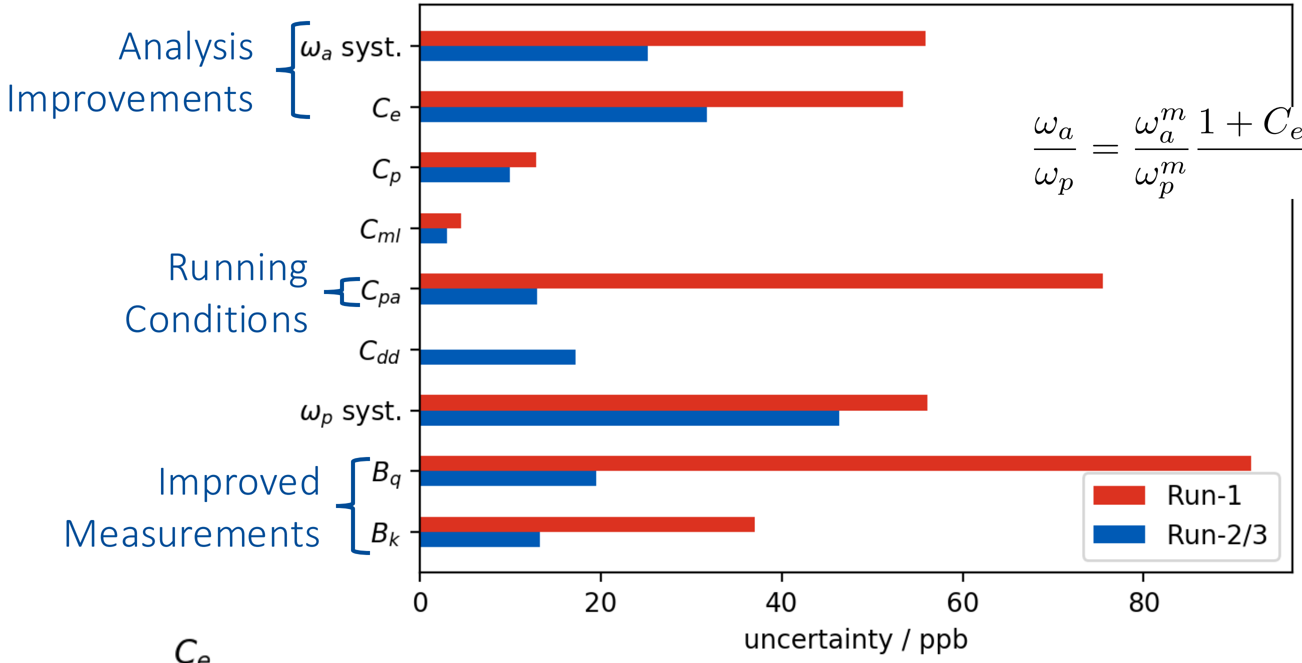
$$N(t) = N_0 e^{-t/\tau}\left[1 + A\cos(\omega_a t - \phi)\right]$$

$$\frac{\omega_a}{\omega_p} = \frac{\omega_a^m}{\omega_p^m}\,\frac{1+\overbrace{C_e+C_p}^{\text{E-field \& Up/Down motion: Spin precesses slower than in basic equation}}+\overbrace{C_{pa}+C_{dd}+C_{ml}}^{\text{Phase changes over each fill: Phase-Acceptance, Differential Decay, Muon Losses}}}{1+\underbrace{B_k+B_q}_{\text{Transient Magnetic Fields: Quad Vibrations, Kicker Eddy Current,}}}$$

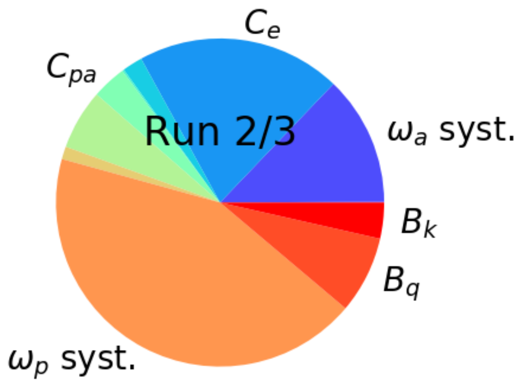
Measured Values

Uncertainty Improvements Summary

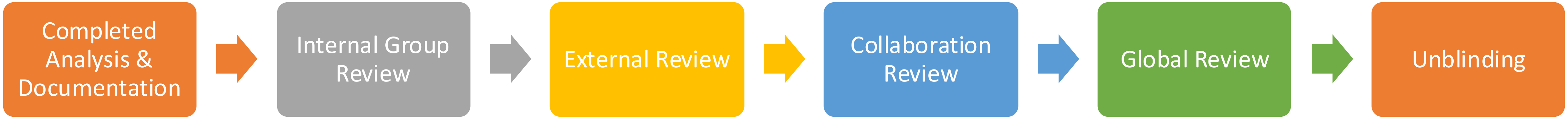
- Systematic improvements in **all parameters**



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



- After improvements, total systematic comes from multiple sources


Completed Analysis & Documentation
Internal Group Review
External Review
Collaboration Review
Global Review
Unblinding