

# Results from Runs 2-3 of the Muon $g-2$ Experiment at Fermilab

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SLAC FPD Seminar

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# The Standard Model: Great success, many open questions!

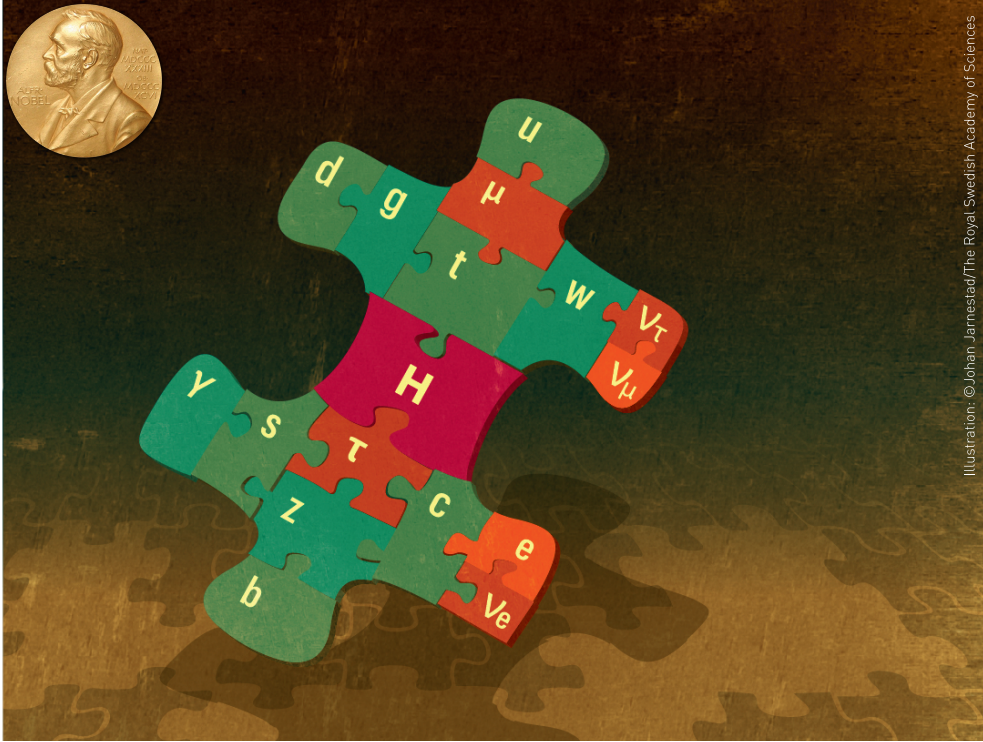
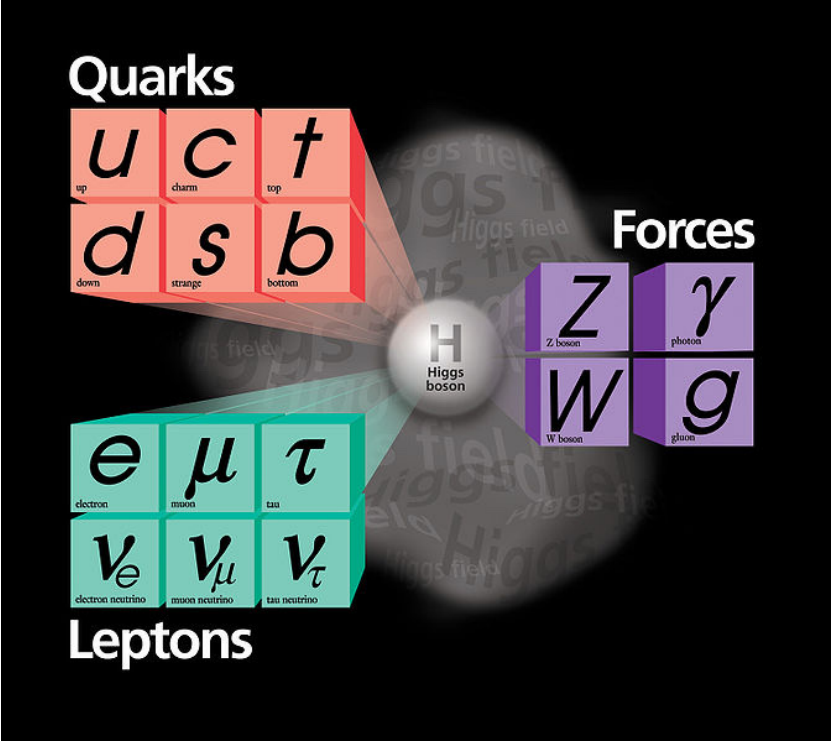


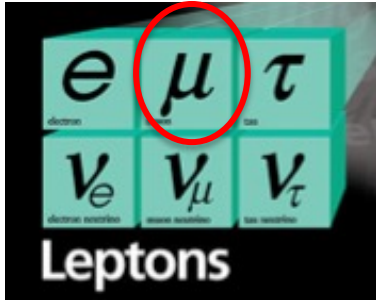
Illustration: © Johan Jarnestad/The Royal Swedish Academy of Sciences

# Outline



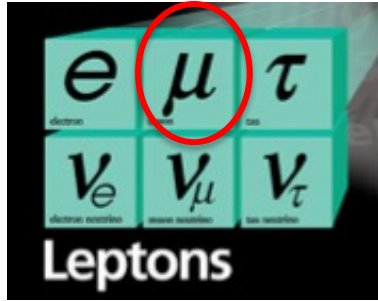
- Muon  $g-2$  Motivation
- Current Status
  - Theory
    - Dispersive Calculation
    - Updated  $e^+/e^-$  Measurements
    - Lattice QCD
  - Experimental status
- Fermilab Experimental Technique
- Runs 2-3
  - Hardware and analysis improvements
  - Crosschecks
- Outlook
  - General timeline: What comes next?

# Our favorite probe: The muon



- Fortuitous lifetime =  $2.2 \mu\text{s}$
- Spin 1/2 particle
- Encodes information about spin in its decay

# Our favorite probe: The muon

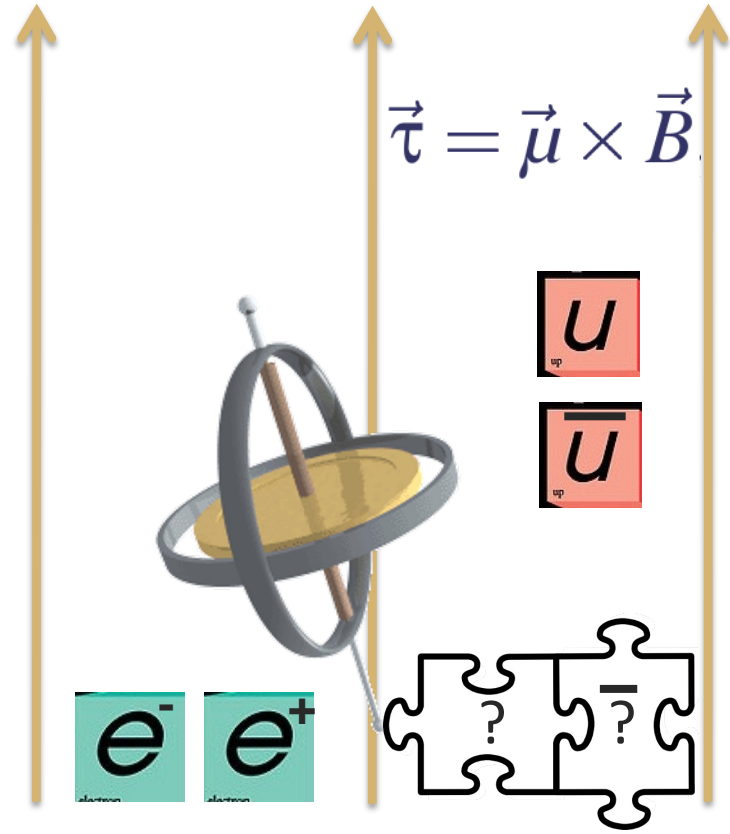


- Fortuitous lifetime =  $2.2 \mu\text{s}$
- Spin 1/2 particle
- Encodes information about spin in its decay

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

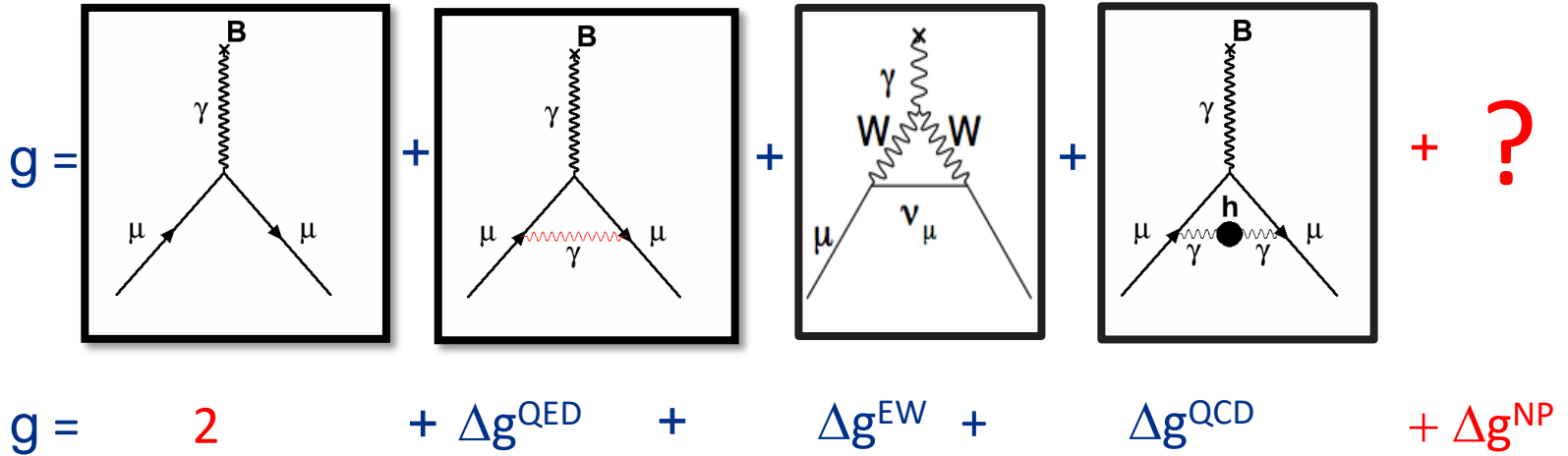
- This g-factor is the “g” in “g-2”
- $g = 2 +$  contributions from virtual particles

## Magnetic Field



# Muon g-2: The Basics

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

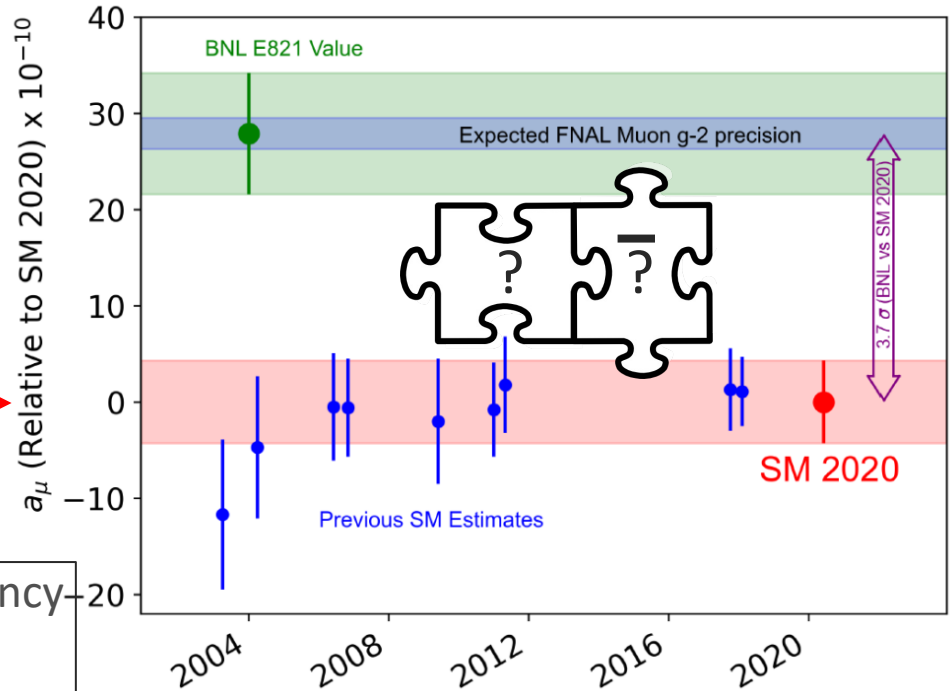
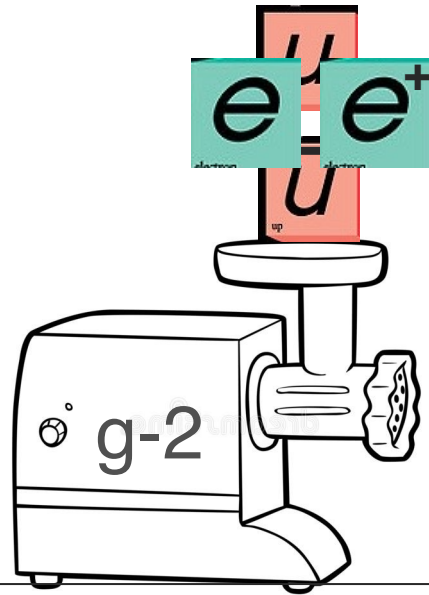


- $a_\mu$  is the **anomalous magnetic moment** (i.e the part that differs from 2)

$$a_\mu^{\text{SM}} = (g_\mu^{\text{SM}} - 2)/2 = a_\mu^{\text{QED}} + a_\mu^{\text{EW}} + a_\mu^{\text{QCD}}$$

$$a_\mu^{\text{NP}}$$

# Motivation: Theory vs Experiment in 2020



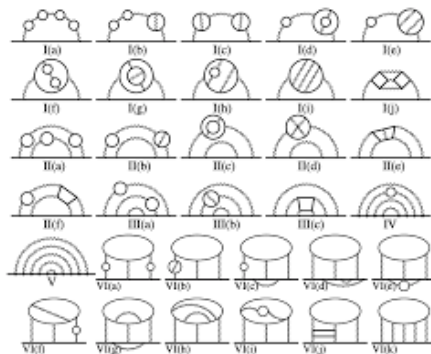
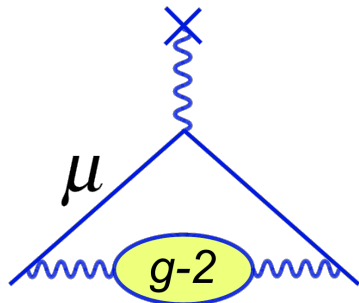
## Logical Possible Explanations for 3.7 $\sigma$ discrepancy

1. Theory calculation is wrong
2. Experimental determination is wrong
3. New Physics Explains the gap
4. Some combination of the above

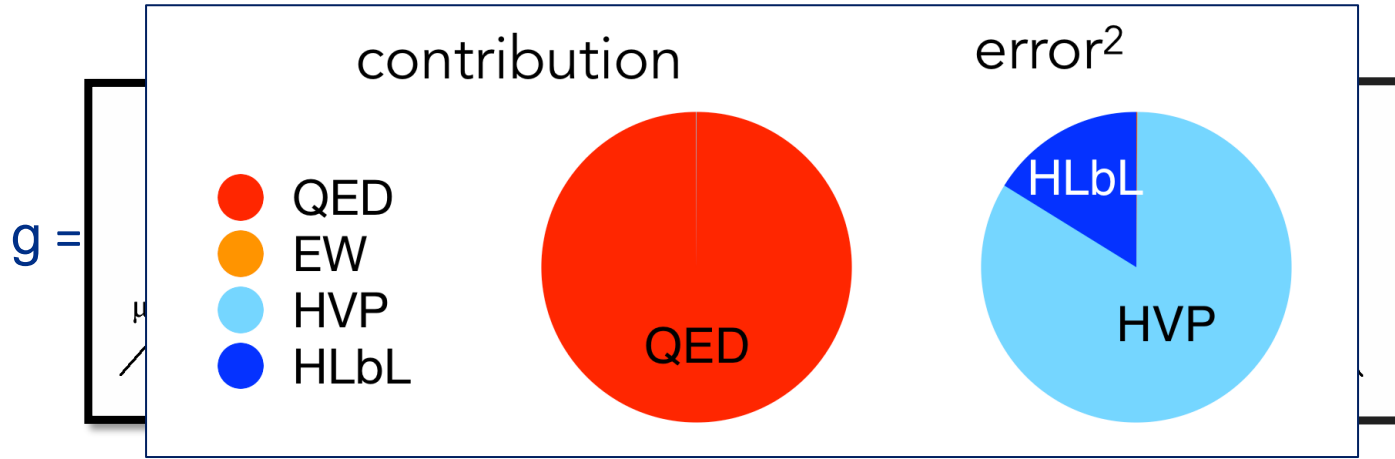
T. Aoyama, N. Asmussen, M. Benayoun et al., The anomalous magnetic moment of the muon in the Standard Model, Physics Reports (2020), <https://doi.org/10.1016/j.physrep.2020.07.006>.

# Theory

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# Muon g-2 calculation



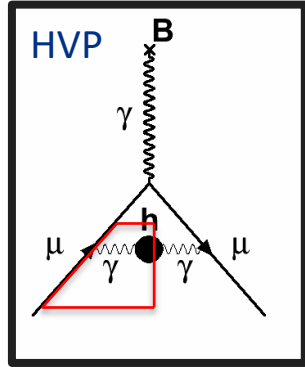
*Value*  $g = 2 + O(10^{-3})_{\text{QED}} + O(10^{-9})_{\text{EW}} + O(10^{-7})_{\text{QCD}}$

*Uncertainty* (ppm) 0.001 , 0.01 , 0.34 (HVP) & 0.15 (HLbL)

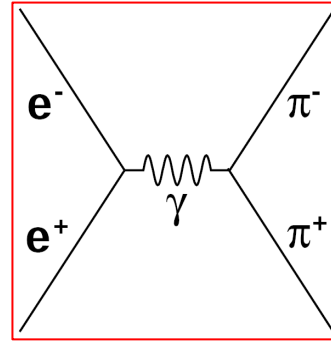
- Dominated by hadronic contributions → study those calculations in more detail

# Dispersive Theory Calculation is Driven by Experimental Input

Relates these terms



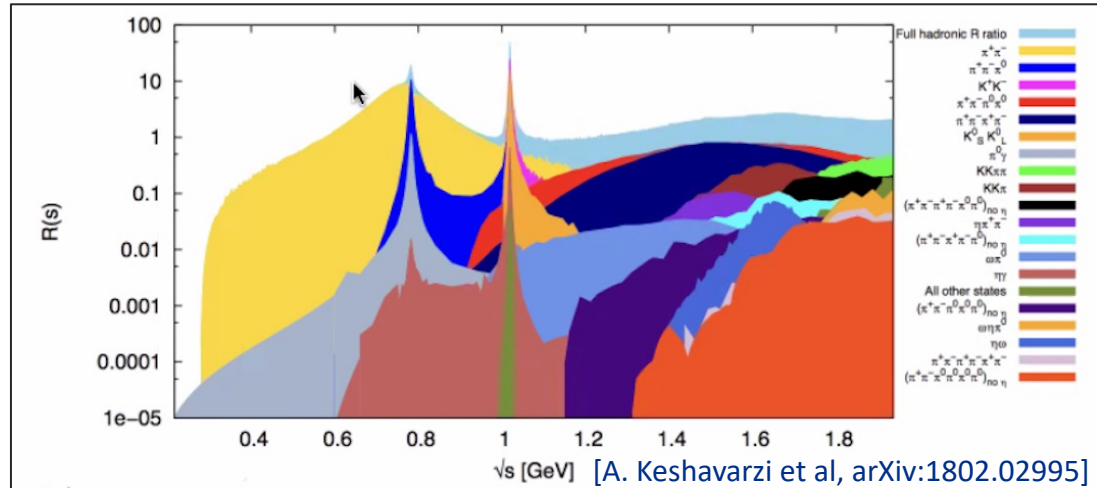
To observable processes like



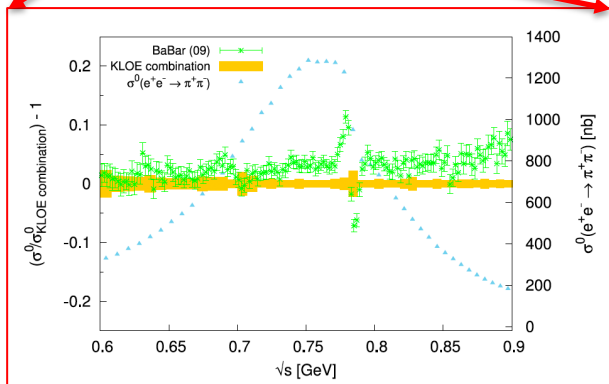
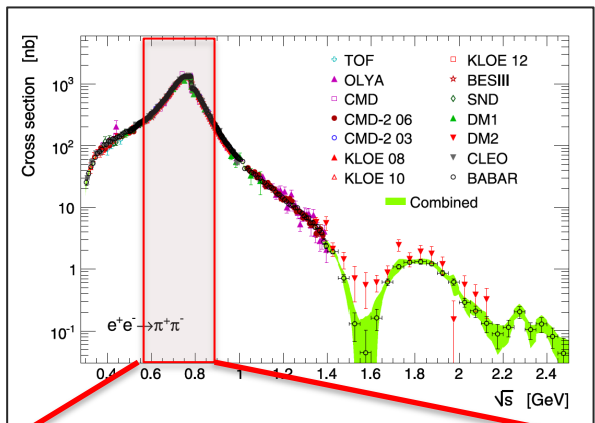
$$(a_\mu^{\text{HAD,LO}}) \propto \int_{4m_\pi^2}^{\infty} ds \frac{K(s)}{s} R(s)$$

$$R(s) \equiv \frac{\sigma_{\text{tot}}(e^+e^- \rightarrow \text{hadrons})}{\sigma_{\text{tot}}(e^+e^- \rightarrow \mu^+\mu^-)}$$

- Low-energy region dominates



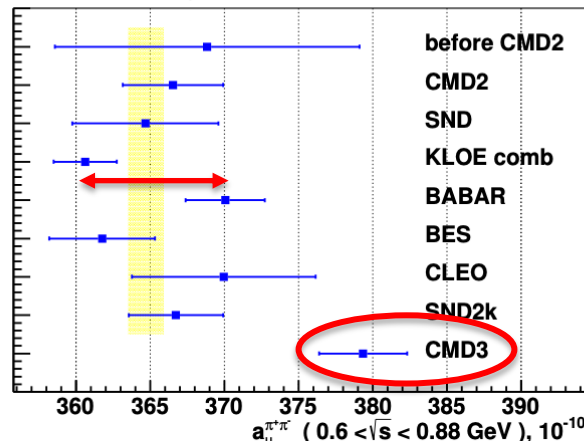
# Dispersive Theory Calculation is Driven by Experimental Input



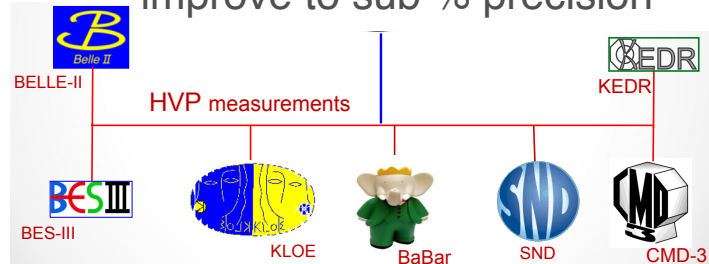
Many detailed measurements lead to precise theory calculation

The combination uncertainty is driven by tension in low-energy region

New: from CMD-3 [F. Ignatov et al, [arXiv:2302.08834](https://arxiv.org/abs/2302.08834)]



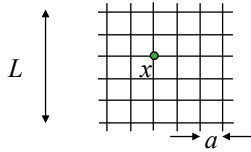
Many machines/exp pushing to improve to sub % precision



# Lattice QCD Introduction

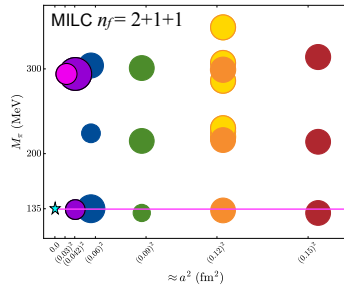
- Provides alternative method of calculating hadronic contributions
- Maps Minkowski spacetime  $\leftrightarrow$  Euclidean space

## Direct calculation using Euclidean Lattice QCD



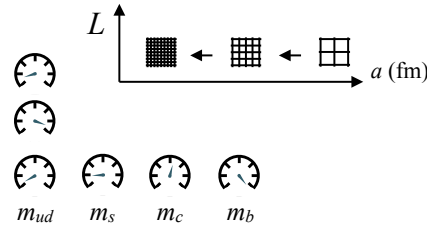
Approximations:  
 discrete space-time (spacing  $a$ )  
 finite spatial volume ( $L$ ), and time extent ( $T$ )  
 ...

Integrals are evaluated numerically using Monte Carlo methods.



### adjustable parameters

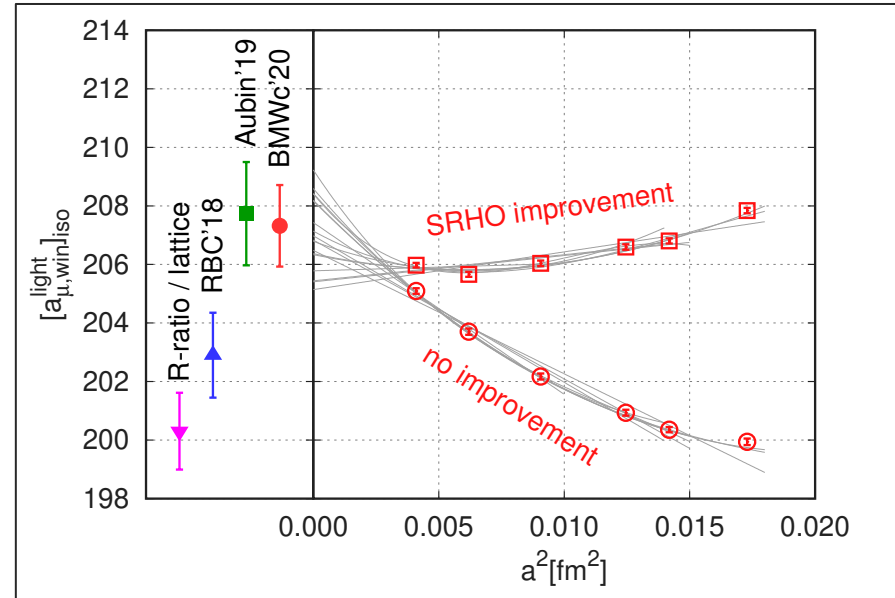
- ❖ lattice spacing:  $a \rightarrow 0$
- ❖ finite volume, time:  $L \rightarrow \infty, T > L$
- ❖ quark masses ( $m$ ):  $M_{H,lat} = M_{H,exp}$   
 tune using hadron masses  
 $m_f \rightarrow m_{f,phys}$   
 extrapolations/interpolations



# Lattice QCD Calculations

- Process
  - Perform calculations with different
    - lattice spacings
    - total volume
    - Particle masses
  - Use results to dis-entangle systematics and extrapolate to the physical, continuum limit
- Status
  - In 2020 WP, lattice HVP had 2.6% total uncertainty
  - In 2021, BMW first LQCD calculation, 0.8% uncertainty
  - $3.7\sigma$  tension with data-driven evaluation

Example of contribution in a subset of the lattice

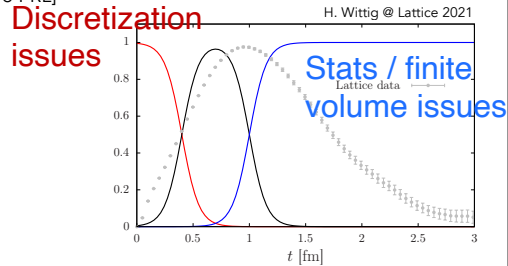


# Lattice QCD Windows

$$a_\mu^{\text{HVP,LO}} = \left(\frac{\alpha}{\pi}\right)^2 \int_0^\infty dt \tilde{w}(t) C(t)$$

- Use windows in Euclidean time to consider the different time regions separately. [T. Blum et al, arXiv:1801.07224, 2018 PRL]

Short Distance (SD)  $t : 0 \rightarrow t_0$   
 Intermediate (W)  $t : t_0 \rightarrow t_1$   
 Long Distance (LD)  $t : t_1 \rightarrow \infty$   
 $t_0 = 0.4 \text{ fm}, t_1 = 1.0 \text{ fm}$



- Internal cross check: compute each window separately (in continuum, infinite volume limits,...) and combine:

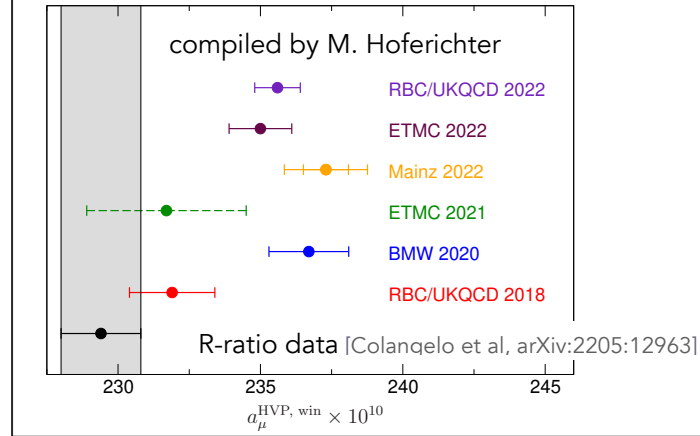
$$a_\mu = a_\mu^{\text{SD}} + a_\mu^{\text{W}} + a_\mu^{\text{LD}}$$

## • Intermediate window

- lattice uncertainties are smaller and the dispersive r-ratio data can be mapped to the Euclidean space for direct comparison
- Contributes 1/3 of the lowest order HVP contribution

- Work continues on other windows, multiple groups, 0.5% uncertainty goal by 2024

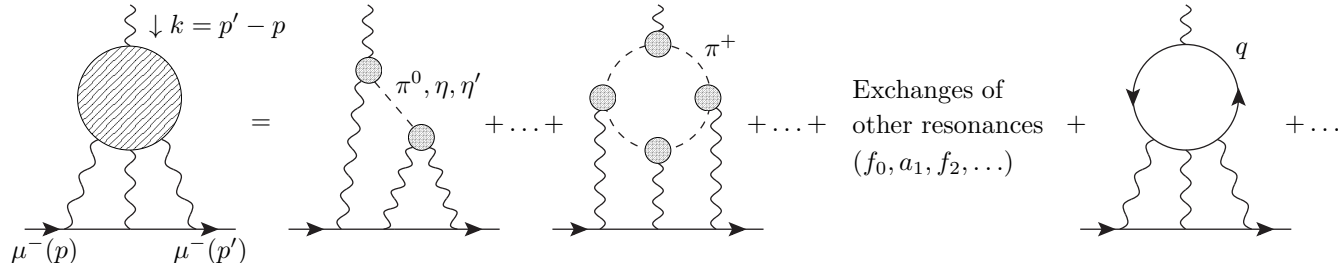
Further tensions for intermediate window:



**I** A. El-Khadra

P5

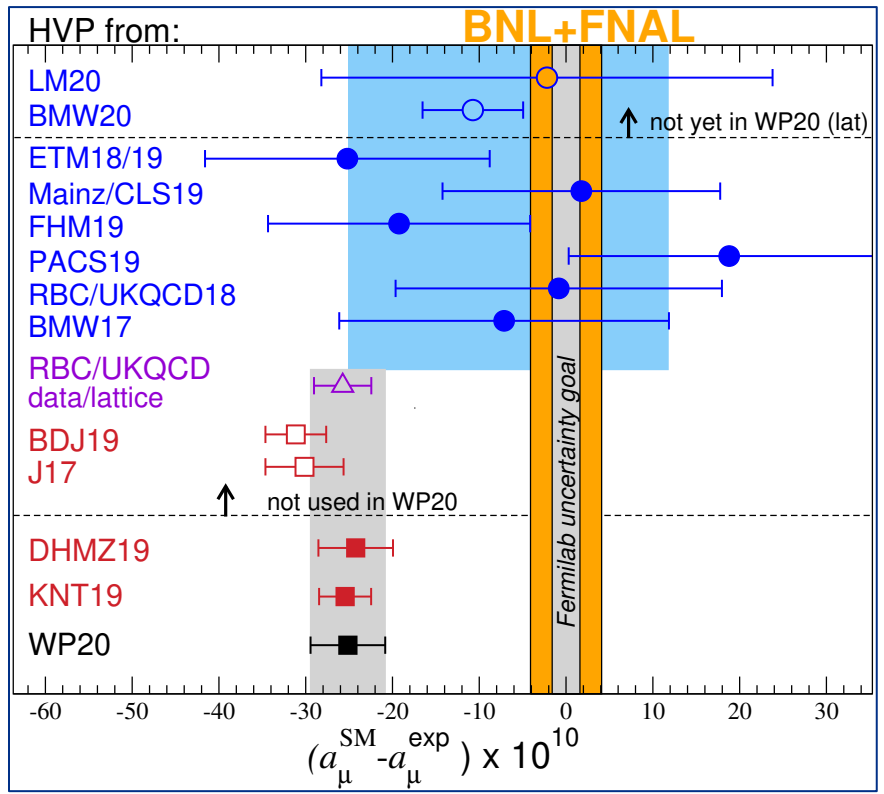
# Hadronic Light by Light



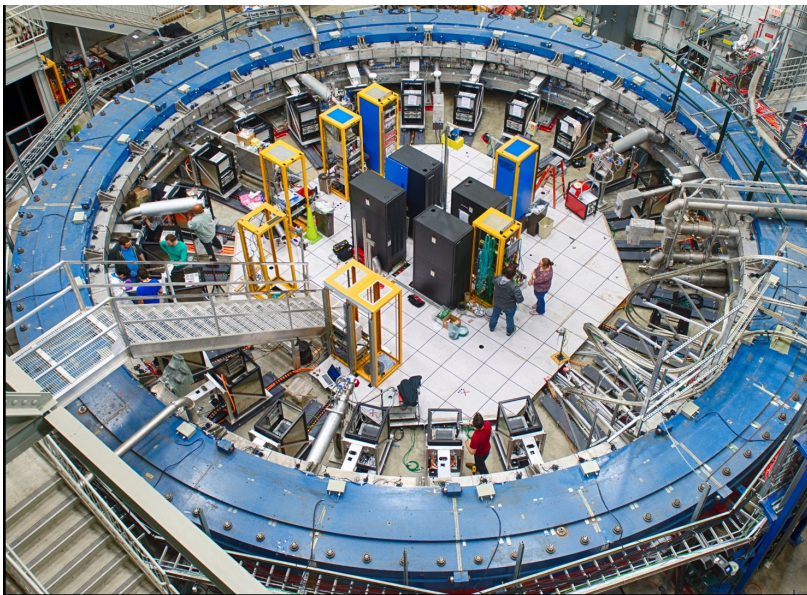
- HLBL has smaller contribution than HVP
- HLBL Dispersive calculation is more challenging than HVP
- The dominant pion-exchange contributes about 75% and is determined to 6%
- The subleading terms dominate the uncertainty for HLBL
- Multiple lattice groups performing complete calculation (at unphysical pion mass)
- Both dispersive and Lattice will approach target of  $\leq 10\%$  feasibly by 2024

# Summary: New Precise Lattice Calculations are in tension with Dispersive Calculations for $a_\mu$

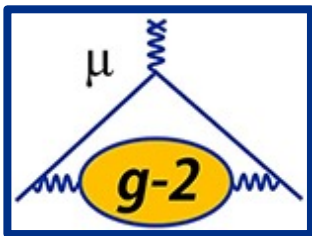
- Important to see how story evolves
  - Will need to see how other windows compares
  - There are several tensions within the dispersive calculations, within lattice and between dispersive and lattice contributions for HVP
- **Critical** to support efforts to understand these discrepancies and develop a firm theoretical calculation



# Outline



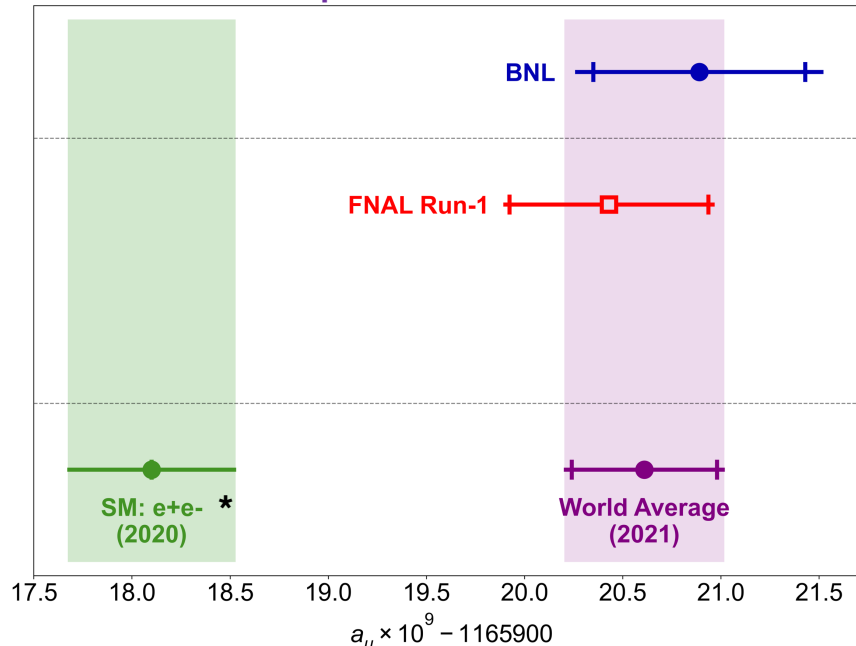
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# Starting Point: Run-1 Result

$$a_{\mu}(\text{FNAL; Run-1}) = 0.00\ 116\ 592\ 040(54) [463\ \text{ppb}]$$

$$a_{\mu}(\text{Exp}) = 0.00\ 116\ 592\ 061(41) [350\ \text{ppb}]$$

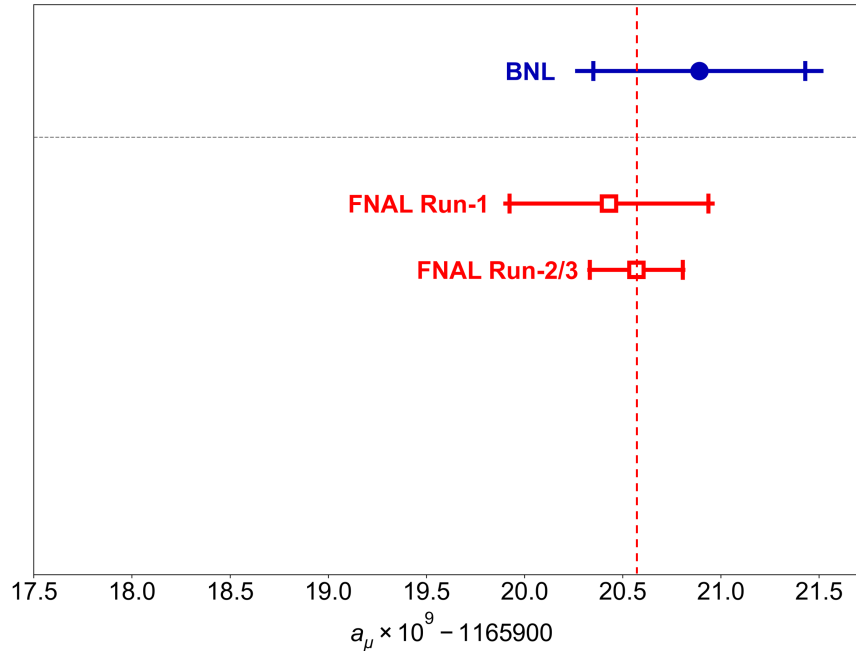


\* Muon g – 2 Theory Initiative white paper (WP) value  
<https://doi.org/10.1016/j.physrep.2020.07.006>

- Theoretical situation is complex and it is premature to interpret comparisons between theory and experiment
- $3.7\sigma$  discrepancy between BNL and WP 2020
- $4.2\sigma$  discrepancy between World Average 2021 and WP 2020

# Runs 2-3 Result: Measured Value

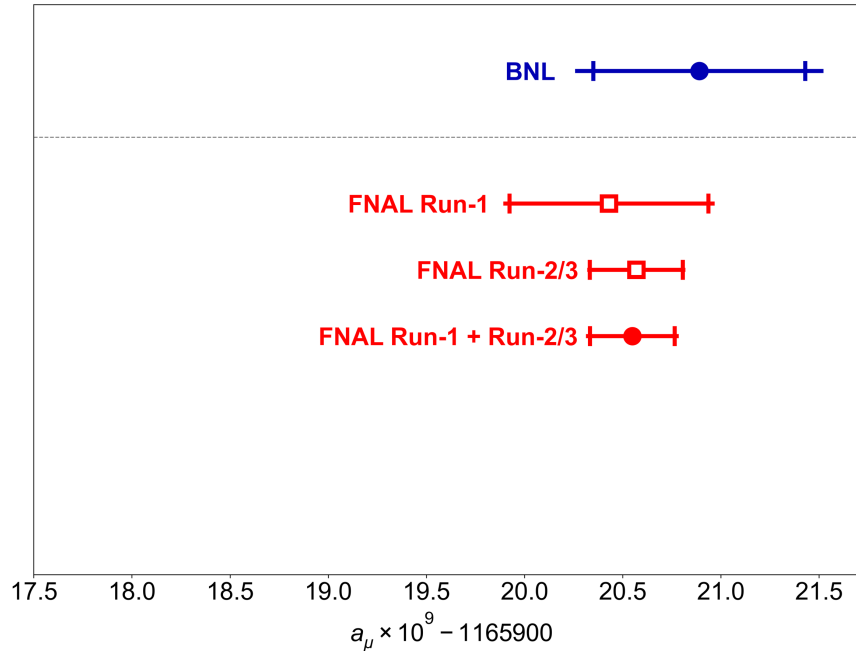
$$a_\mu(\text{FNAL}; \text{Run-2/3}) = 0.00\ 116\ 592\ 057(25) \text{ [215 ppb]}$$



- Experimental situation solidifying
  - Excellent agreement with both Run-1 and BNL!
  - Uncertainty more than halved to **215 ppb**
- Both FNAL values dominated by statistical error

# Runs 2-3 Result: FNAL Run-1 + Runs 2-3 Combination

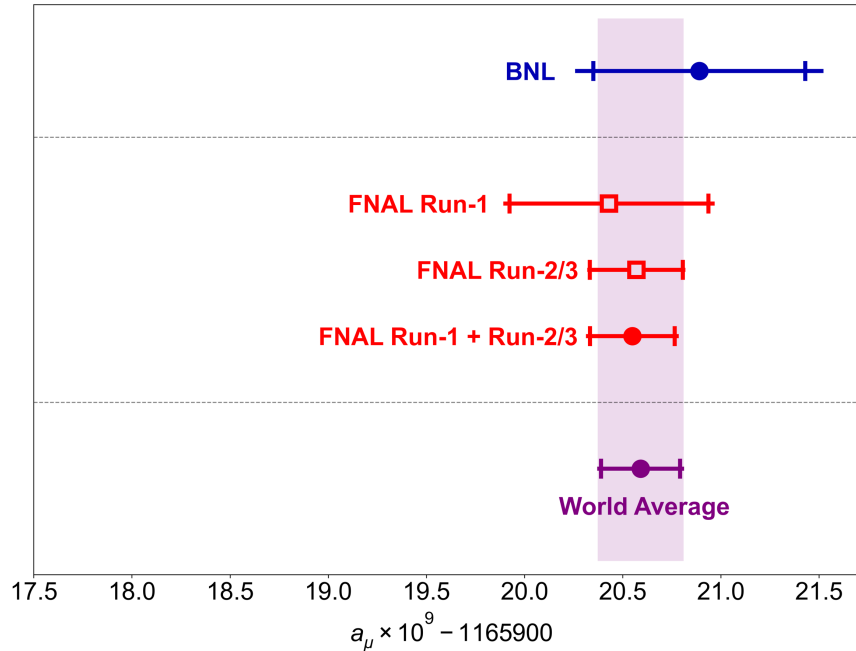
$$a_\mu(\text{FNAL}) = 0.00\ 116\ 592\ 055(24) \text{ [203 ppb]}$$



- FNAL combination: **203 ppb** uncertainty
- Both FNAL and BNL dominated by statistical error

# Run-2/3 Result: FNAL + BNL Combination

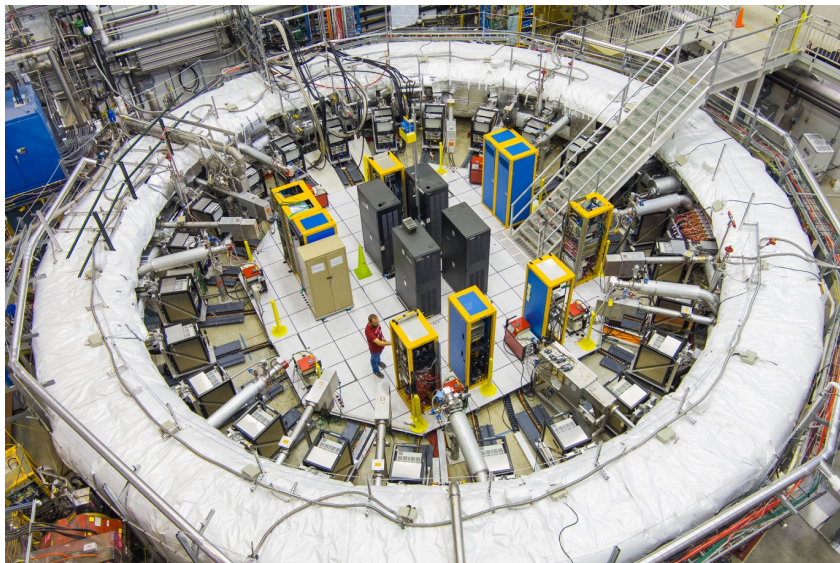
$$a_\mu(\text{FNAL}) = 0.00\ 116\ 592\ 055(24) [203\ \text{ppb}]$$



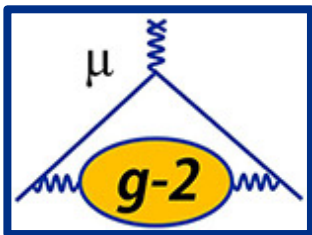
- FNAL combination: **203 ppb** uncertainty
- Both FNAL and BNL dominated by statistical error
- Combined world average **dominated by FNAL** values.

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

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# Muon g-2 basics in a storage ring

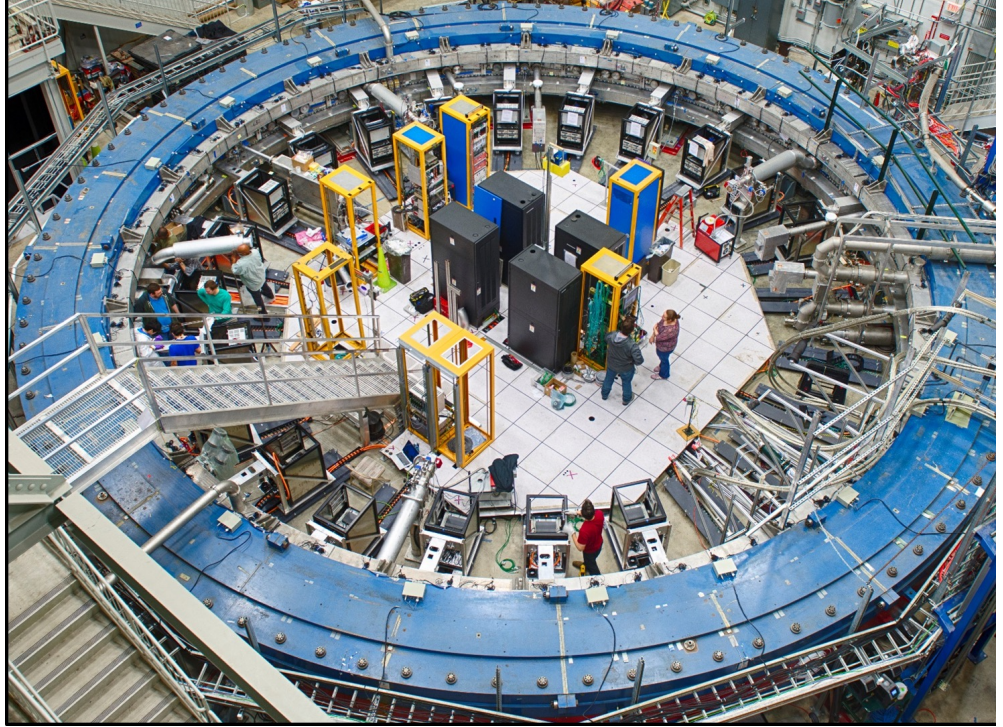
$$\omega_a = \frac{eB}{m} a_\mu$$

A precision measurement of the muon's anomalous spin-precession frequency in a well-measured magnetic field will tell us how muons see the universe.

# What are the main experimental steps to get $a_\mu$ ?

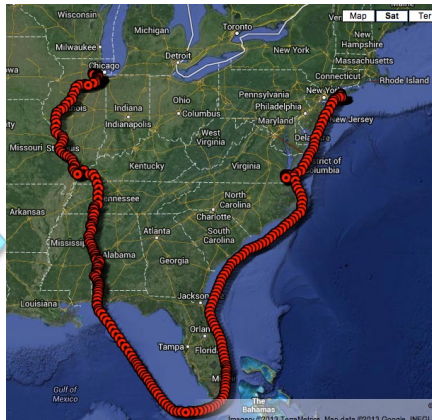
$$\omega_a = \frac{eB}{m} a_\mu$$

1. Build a racetrack for the muons
2. Inject and store polarized muons
3. Detect the decay positrons to determine the muons' properties
4. Map and track the magnetic field



# 1. Build a racetrack for the muons: Bring the magnet to Fermilab

2013

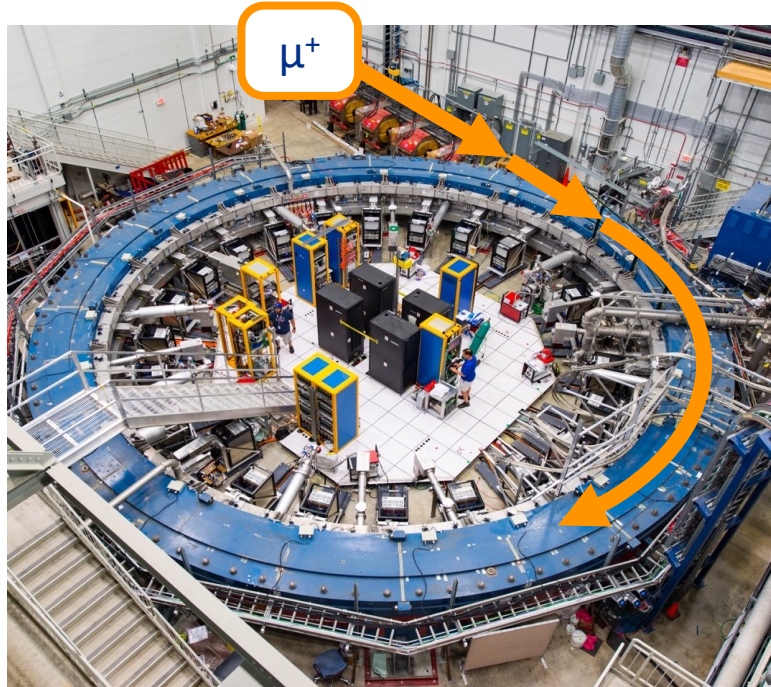


2014



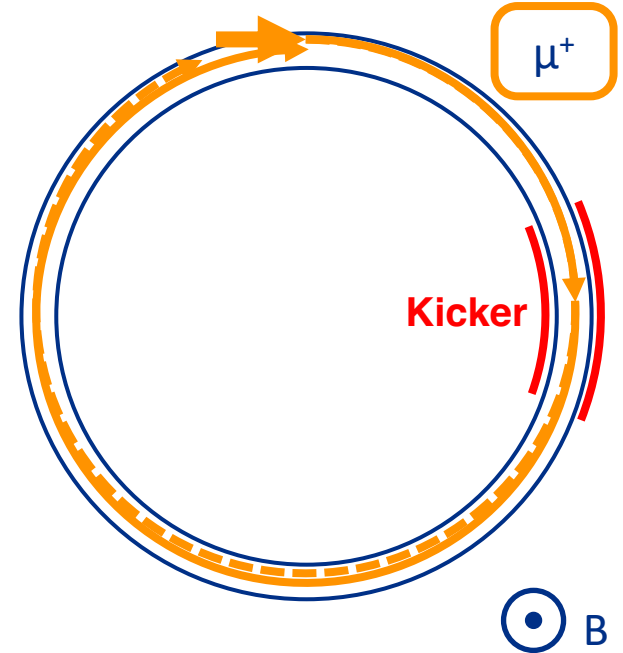
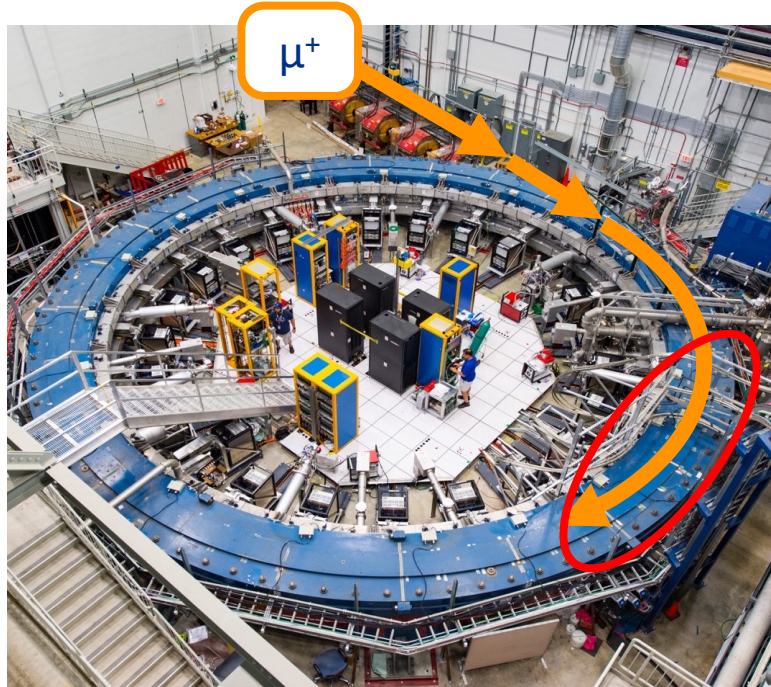
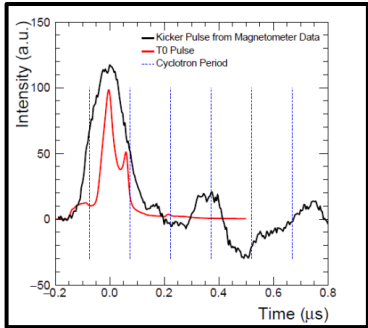
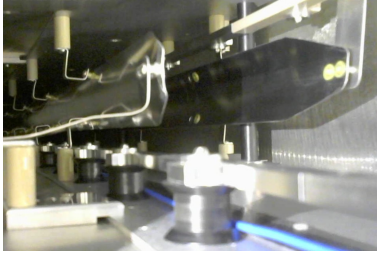
## 2. Inject and store polarized muons

- Muons are injected into storage ring & bend in the  $B$  field



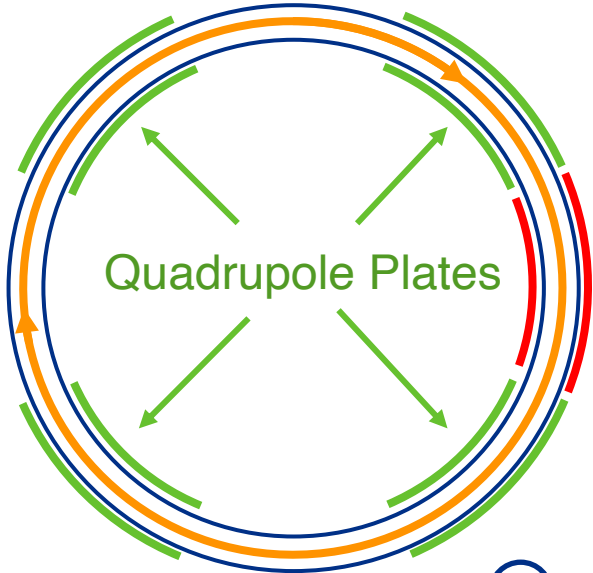
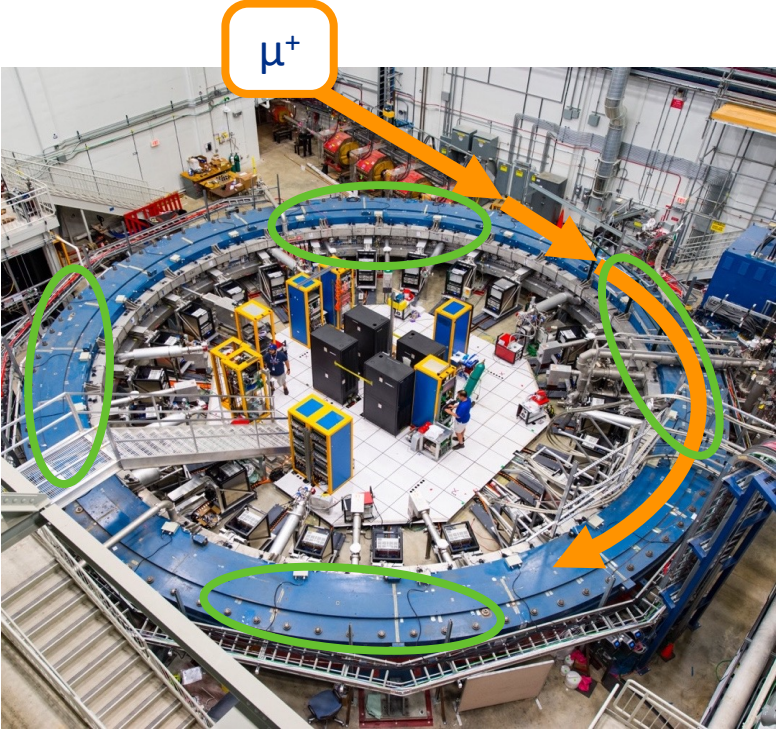
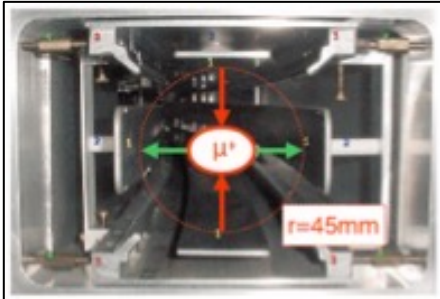
## 2. Inject and store polarized muons

- Fast **kicker** pulse transfers muons to central orbit



# 2. Inject and store polarized muons

- Pulsed **quads** provide vertical focusing (restoring force)



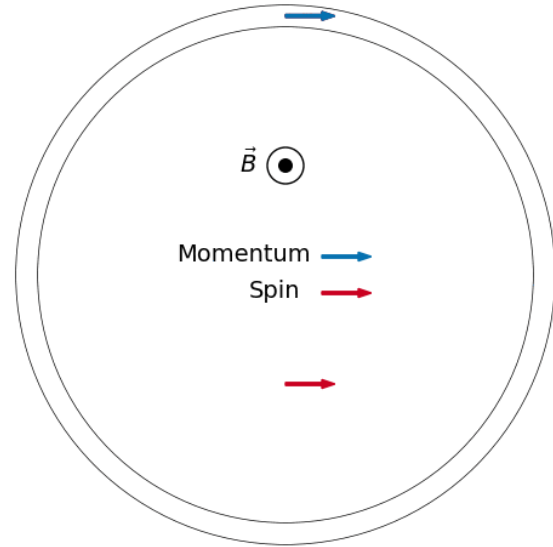
## 2. Inject and store polarized muons

1. Cyclotron frequency:

$$\omega_c = \frac{e}{m\gamma} B$$

2. Spin precession frequency

$$\omega_s = \frac{e}{m\gamma} B \left( 1 + \gamma \frac{g-2}{2} \right)$$



## 2. Inject and store polarized muons

1. Cyclotron frequency:

$$\omega_c = \frac{e}{m\gamma} B$$

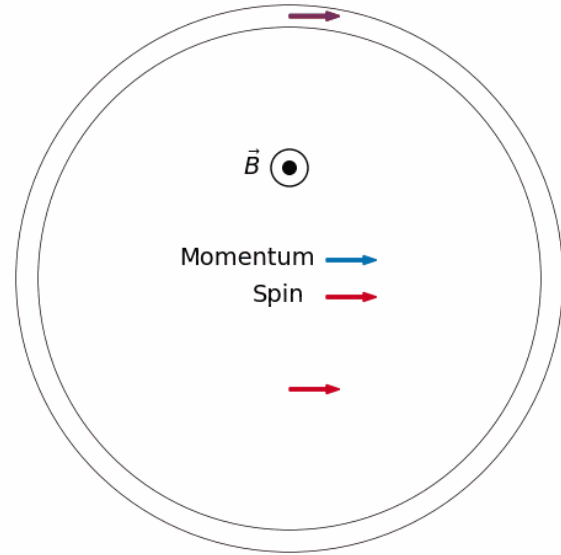
2. Spin precession frequency

$$\omega_s = \frac{e}{m\gamma} B \left( 1 + \gamma \frac{g-2}{2} \right)$$

3. **Spin rotates ahead of momentum** as muon orbits the ring

**Difference frequency**  $\omega_a$  is prop. to  $a_\mu$  (and B)

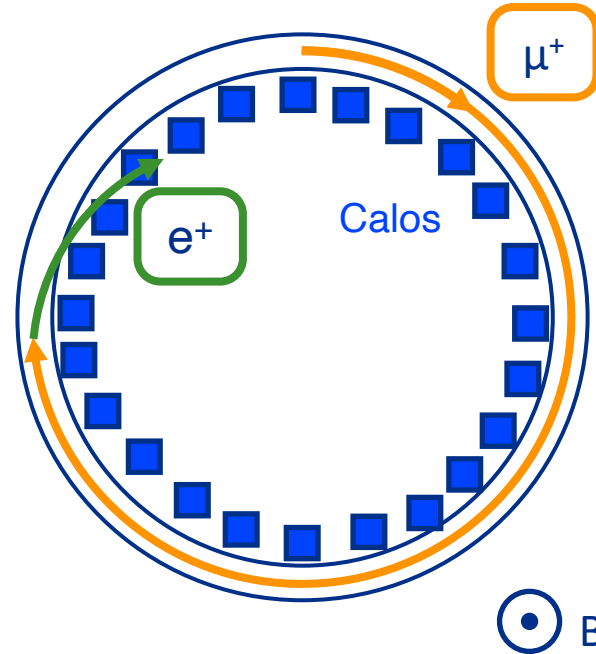
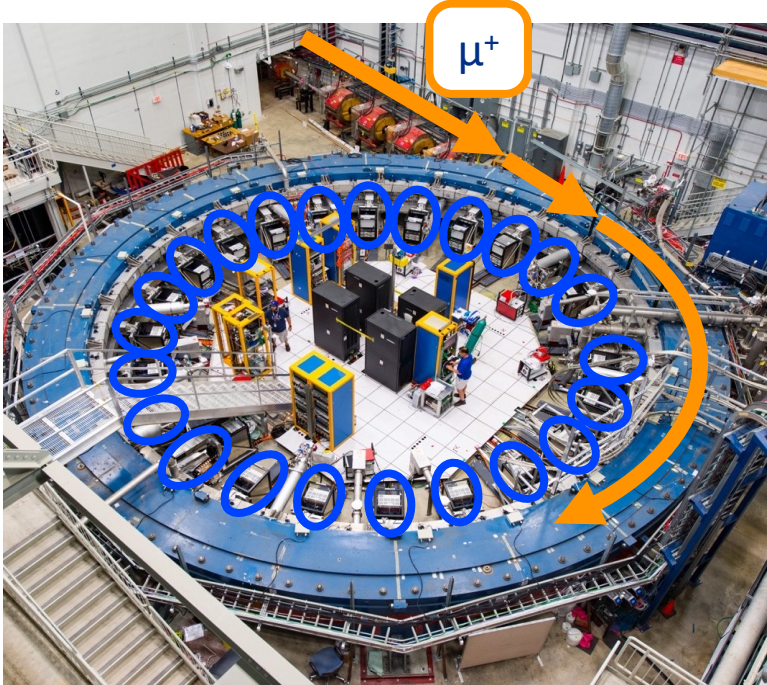
$$\omega_s - \omega_c \equiv \omega_a = \frac{eB}{m} \frac{g-2}{2} = \frac{eB}{m} a_\mu$$



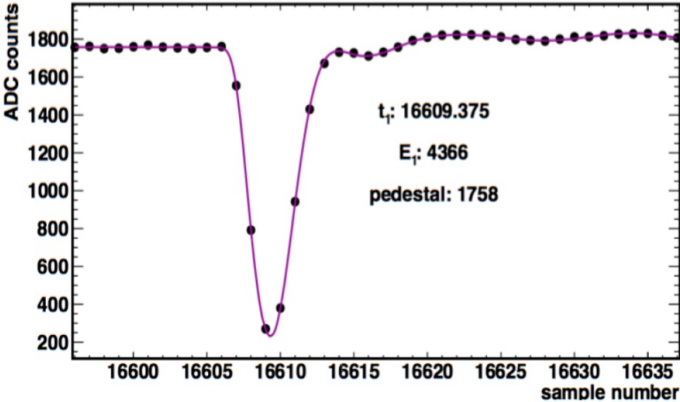
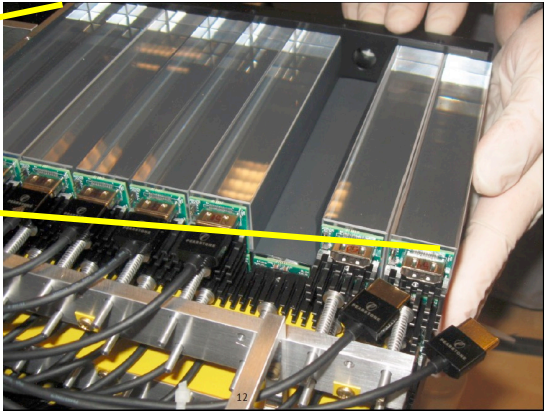
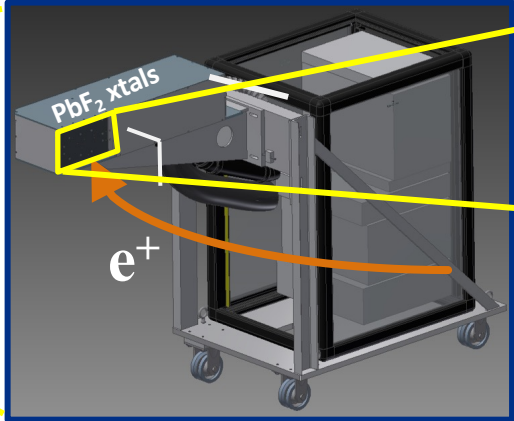
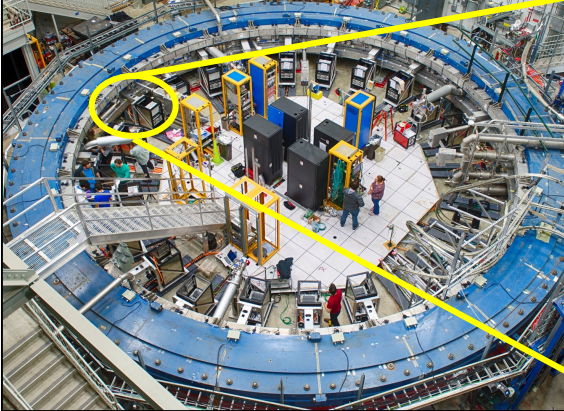
- At each point in the ring spin **rotates radially in & out** at  $\omega_a$

### 3. Detect decay positrons to determine the muons' properties

- Time & energy of decay  $e^+$  are measured by **24 calorimeters**

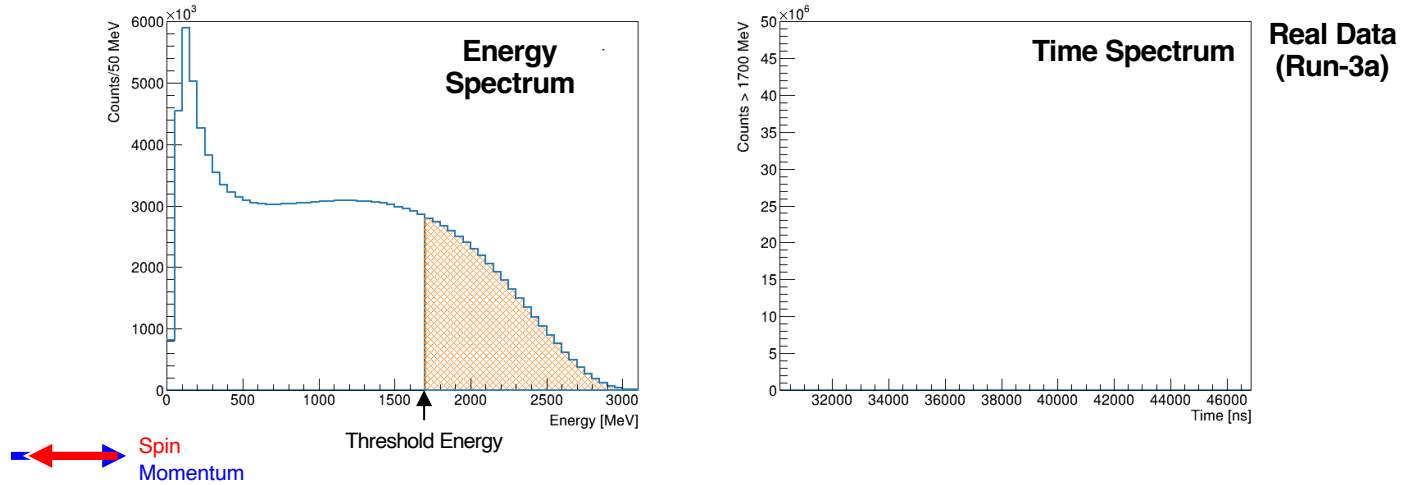


# 3. Detect decay positrons to determine the muons' properties



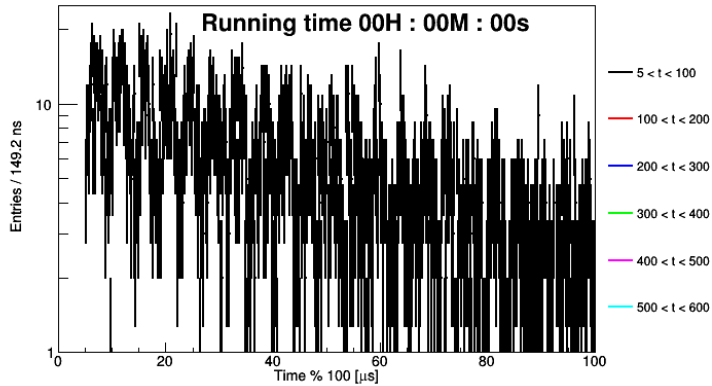
### 3. Detect decay positrons to determine the muons' properties

- Due to **parity violation**, as the  $\mu^+$  **spin** points towards & away from calos the number of **high energy  $e^+$  oscillates**

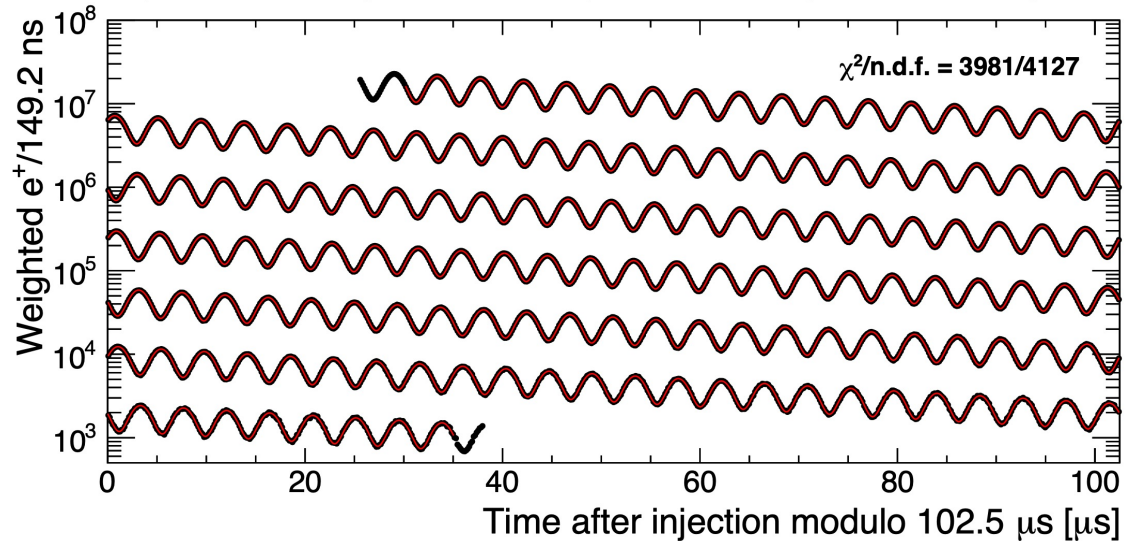


- **Count  $e^+$  hitting calos above threshold** (or weight the hits)
- We measure the oscillation frequency  $\omega_a$

# Muon Precession ( $\omega_a$ ): “Wiggle Plot”



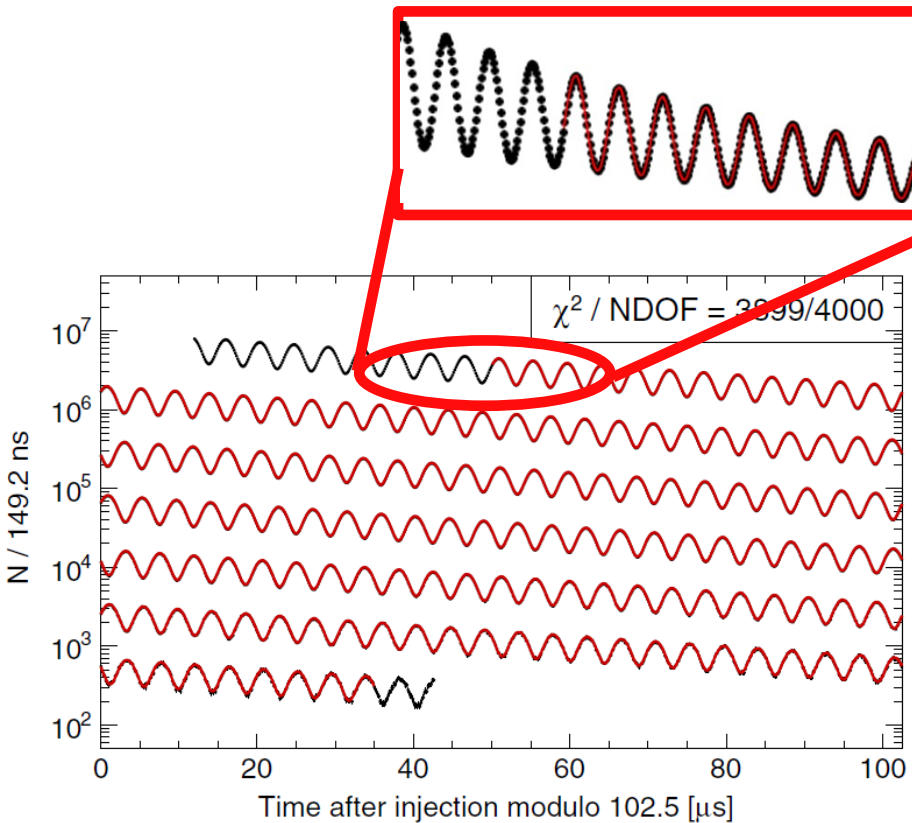
Run-3a: 33 B e<sup>+</sup>



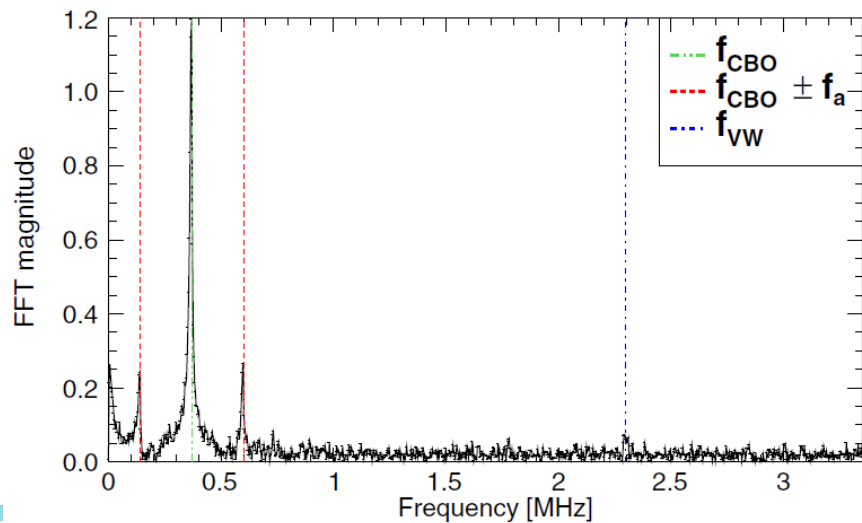
- Select decay positrons with  $E > 1.7$  GeV to maximize sensitivity
- Fit the time spectrum to **extract**  $\omega_a$

# Muon Precession ( $\omega_a$ ):

Start with simple 5 parameter fit:  $F(t) = N_0 e^{-t/\gamma\tau_\mu} [1 + A_0 \cos(\omega_a^m t + \phi_0)]$



FFT of fit residuals



# Muon Precession ( $\omega_a$ ):

- Actual fit has to account for:
  - Beam oscillations** – couple to acceptance & modulate signal
  - Muon losses** – decay isn't purely exponential

## 22 parameter fit

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

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

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

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

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

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

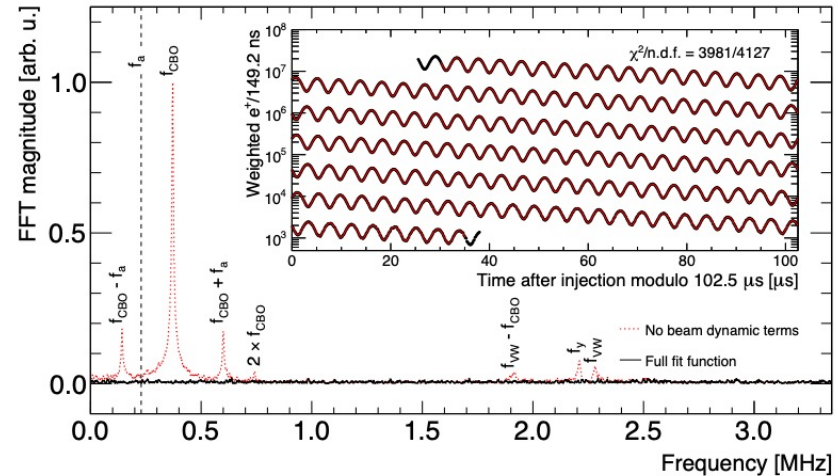
$$N_y(t) = 1 + A_y \cos(\omega_y(t) + \phi_y) e^{-\frac{t}{\tau_y}}$$

$$J(t) = 1 - k_{LM} \int_{t_0}^t \Lambda(t) dt$$

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

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

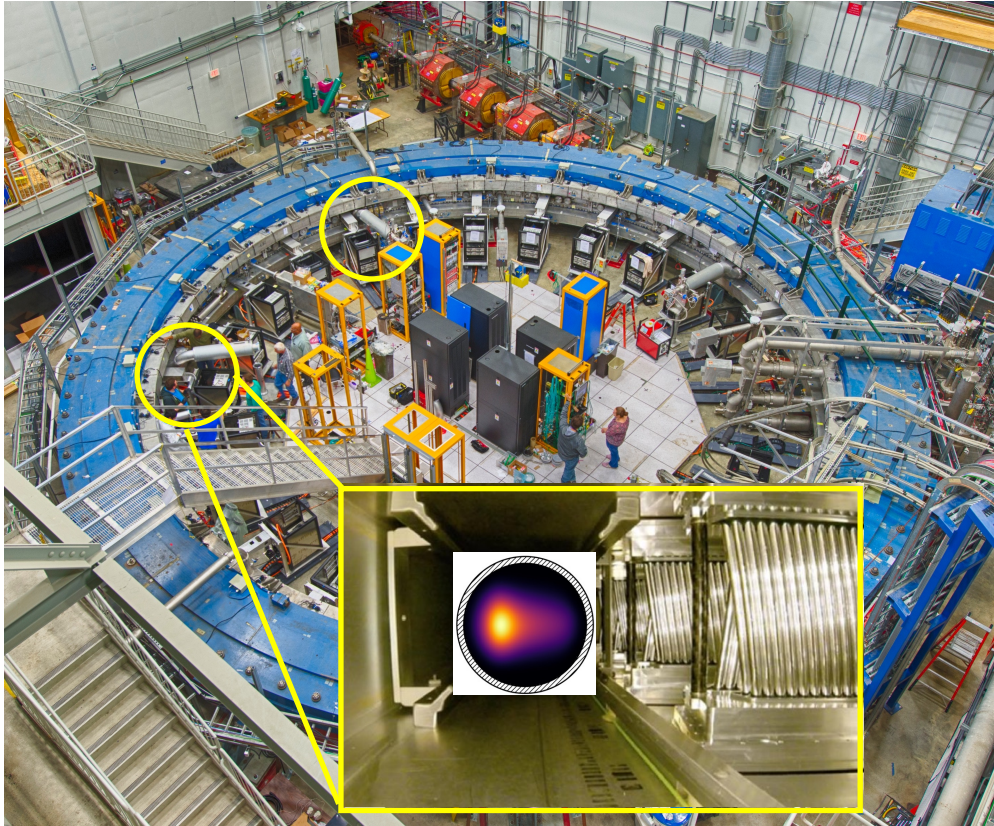
$$\omega_{VW}(t) = \omega_c - 2\omega_y(t)$$



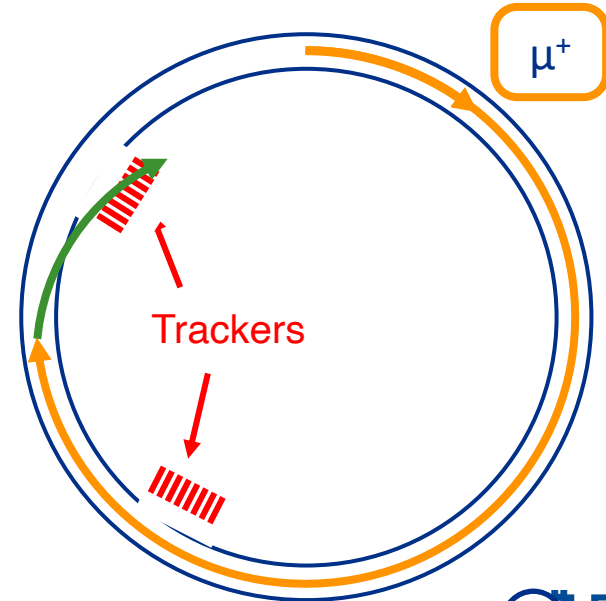
# 3. Measure decay positrons to determine the muons' properties

## Two Trackers

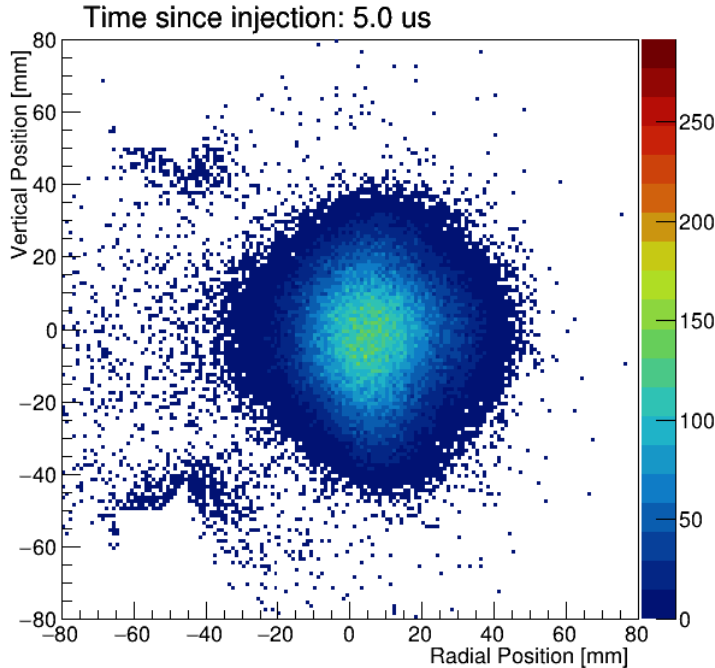
- Decay positron detected
- Reconstruction of muon beam distribution
- Measurement of beam dynamics properties



Muon's view of the storage region



### 3. Measure decay positrons to determine the muons' properties



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

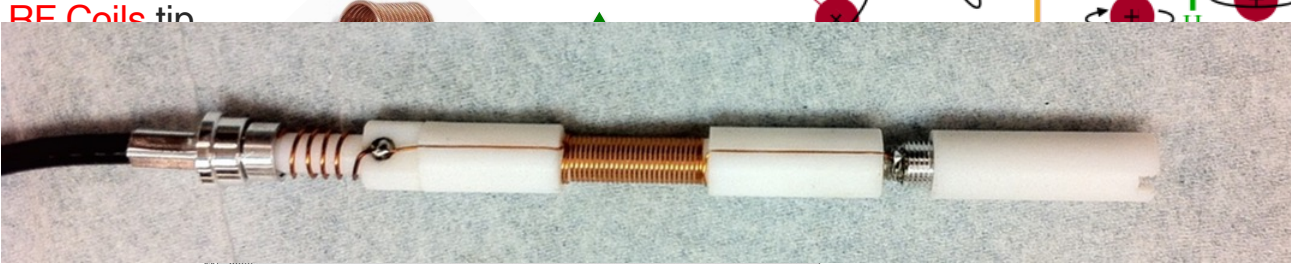
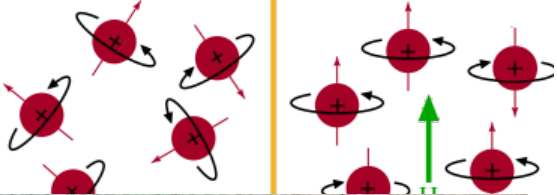
# 4. Map and Track the Magnetic Field

- Nuclear Magnetic Resonance (NMR)
  - Extremely Precise (~10 ppb)
  - Measures Total Field

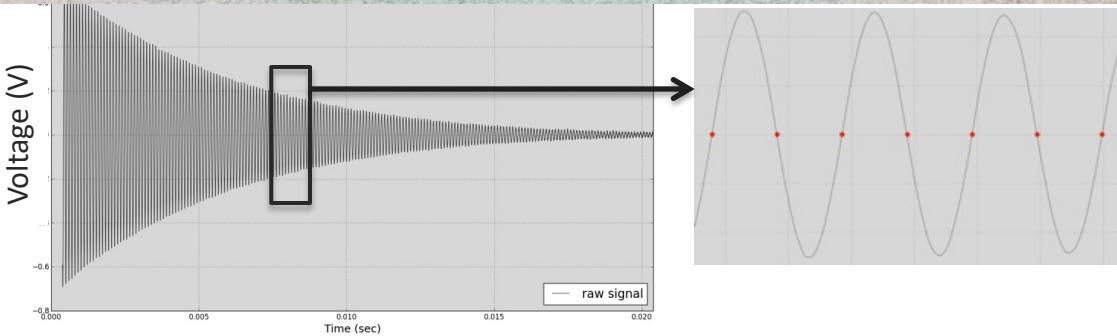
- Turn on magnetic field

Proton-rich sample

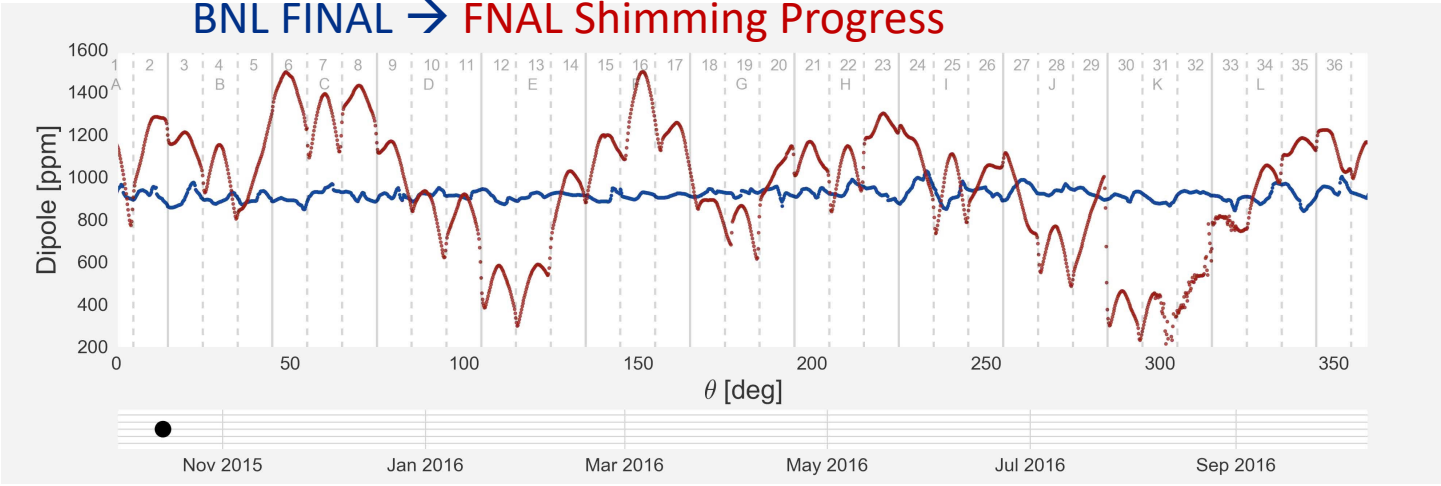
H



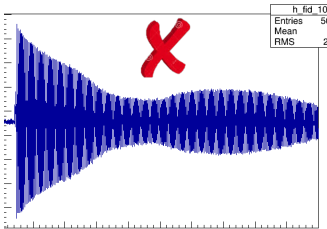
Digitize to extract  $\omega_p$



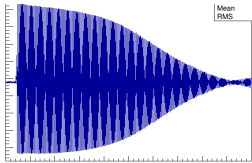
# 4. Map and Track the Magnetic Field: Start with a uniform field



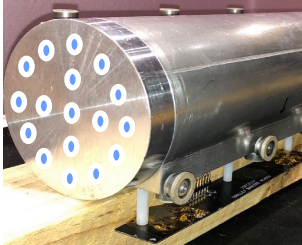
# 4. Map and Track the Magnetic Field: Start with a uniform field



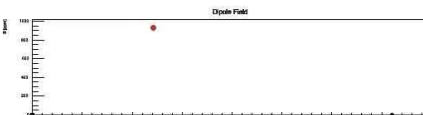
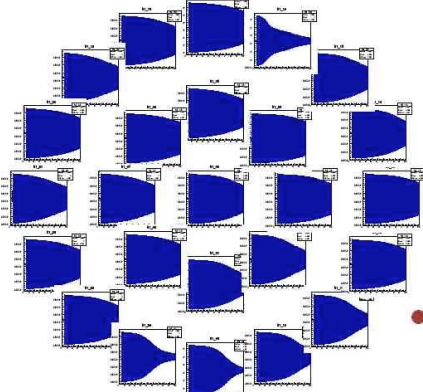
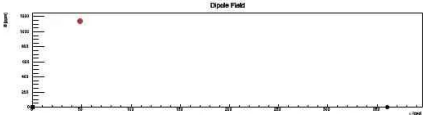
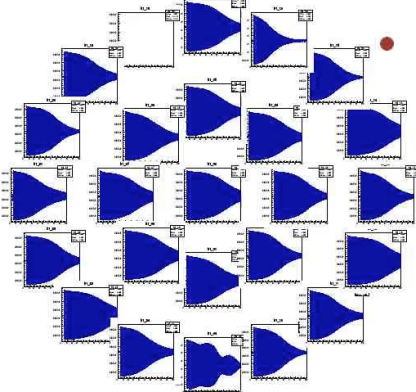
Large gradients



Small gradients



17 petroleum jelly NMR probes



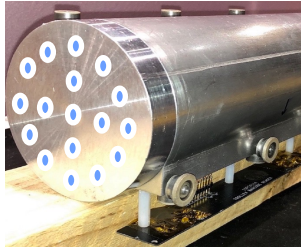
Nov 2015

Sep 2016

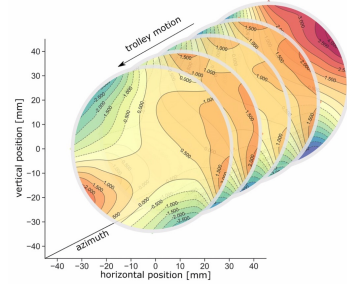


# 4. Map and track the magnetic field

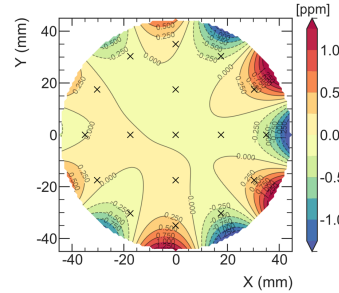
- In-vacuum NMR trolley maps field every ~3 days



17 petroleum jelly NMR probes



2D field maps (~8000 points)

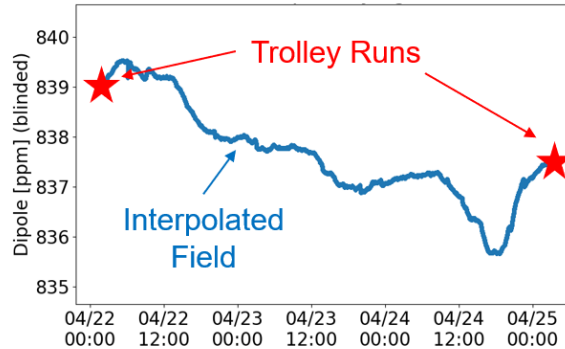


Azimuthally-Averaged Variation < 1 ppm

- 378 fixed probes monitor field during muon storage at 72 locations

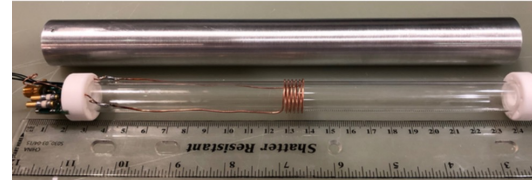
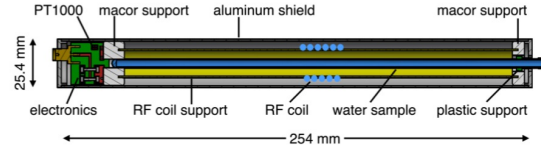
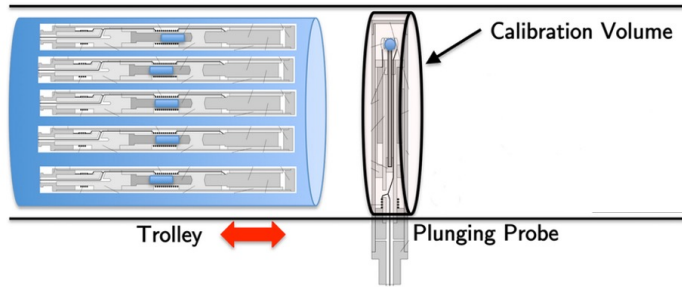


Fixed probes above/below muon storage region



## 4. Map and track the magnetic field

- Cross-calibrate using a cylindrical **plunging H<sub>2</sub>O probe** which repeatedly **changes places with trolley (petroleum jelly probes)**



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

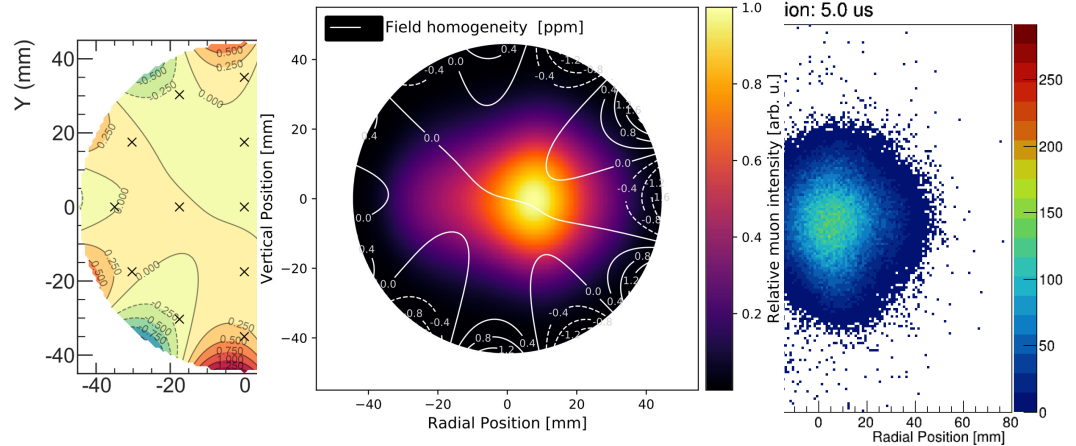
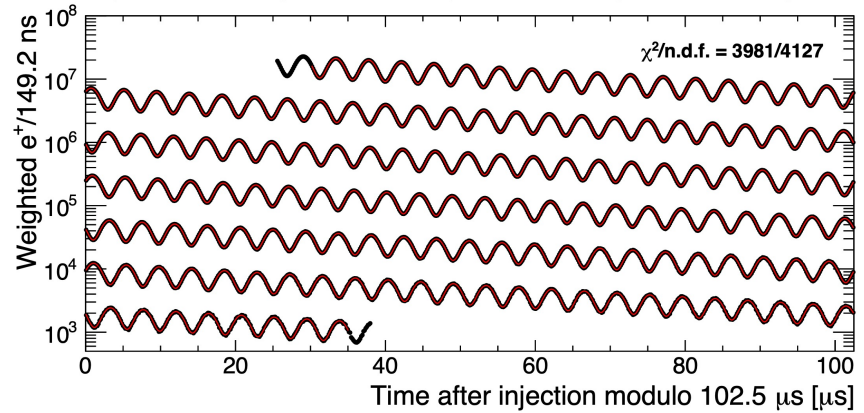


H<sub>2</sub>O Probe

<sup>3</sup>He Probe

# Putting it all together

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



# From ideal to reality

Measured anomalous  $\mu$  precession frequency

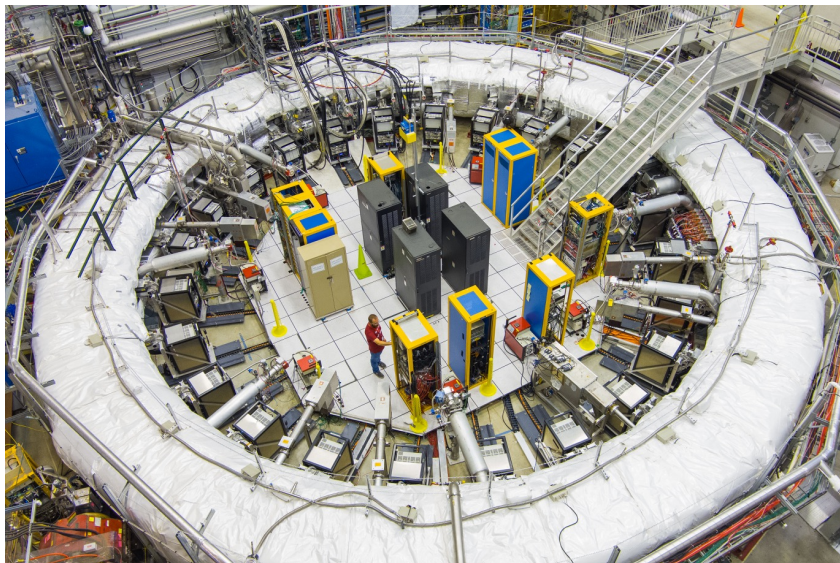
Beam dynamics effects that modify the observed  $\mu$  precession frequency

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

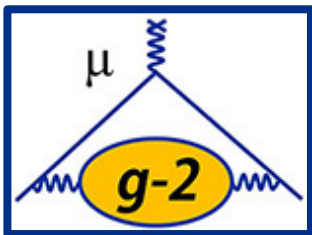
Calibrated proton precession frequency (NMR)

Transient magnetic fields only present when  $\mu$  circulate

# Outline

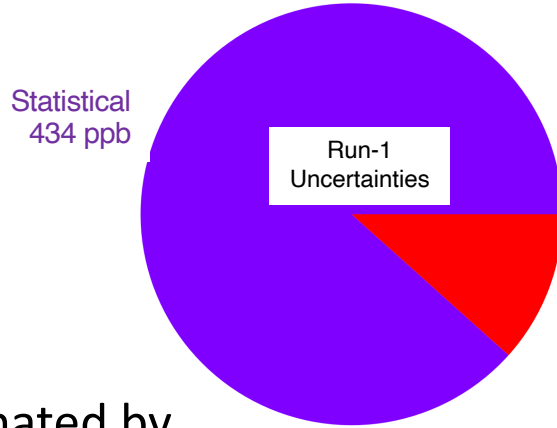


- Muon  $g-2$  Motivation
- Current Status
  - Theory
    - Dispersive Calculation
    - Updated  $e^+/e^-$  Measurements
    - Lattice QCD
  - Experimental status
- Fermilab Experimental Technique
- Runs 2-3
  - Hardware and analysis improvements
  - Crosschecks
- Outlook
  - General timeline: What comes next?



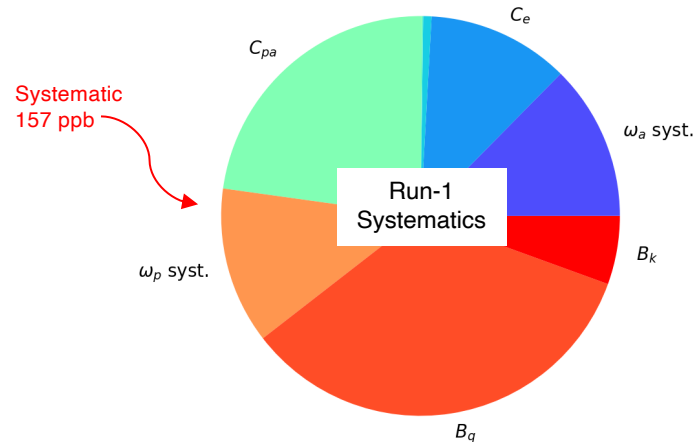
# Run 1 Uncertainties: Where can we improve?

Total Uncertainty: 462 ppb



Dominated by  
statistical error

Total Systematic: 157 ppb



Target: quadrupole transient field  $B_q$  and  
phase-acceptance effect  $C_{pa}$

# Systematic Errors

## Muon precession - $\omega_a$ (ppb)

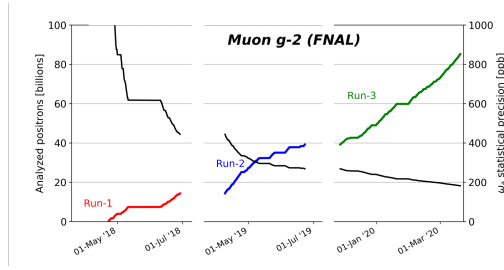
	BNL (E821)	Proposal	Run 1
Gain	120	20	10
Pileup	80	40	30
CBO	70	30	40
E & Pitch	50	30	55
Lost Muons	90	20	5
Phase Acceptance	*	*	75
<b>Total</b>	<b>180</b>	<b>70</b>	<b>108</b>

Numbers are approximate  
Category mapping is imperfect

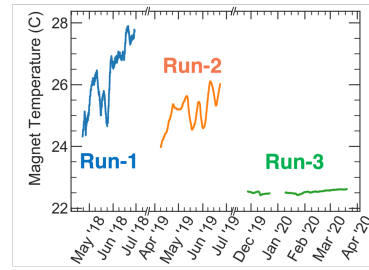
## B-Field (proton precession) $\omega_p$ (ppb)

	BNL 2001 (E821)	Proposal	Run 1
Absolute Calibration	50	35	19
Trolley Calibration	90	30	32
Trolley Baseline	50	30	40
Fixed Probe Baseline	70	30	23
Muon Weighting	30	10	18
Quad Transient	*	*	92
Kicker Transient	*	*	37
*Others	100	50	-
<b>Total</b>	<b>170</b>	<b>70</b>	<b>114</b>

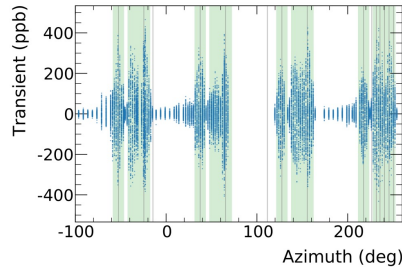
# Run-2/3 Uncertainty Improvement Categories



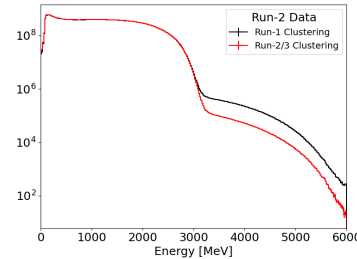
## Statistics



## Running Conditions

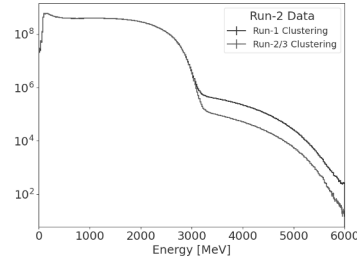
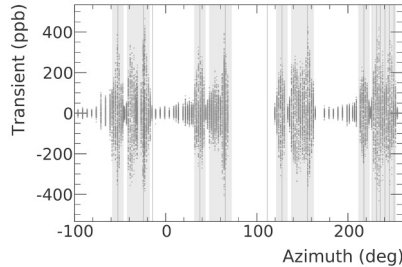
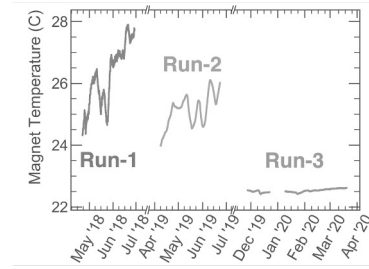
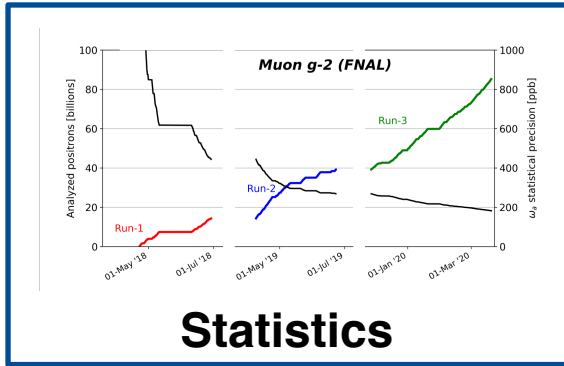


## Systematic Measurements & Studies



## Analysis Improvements

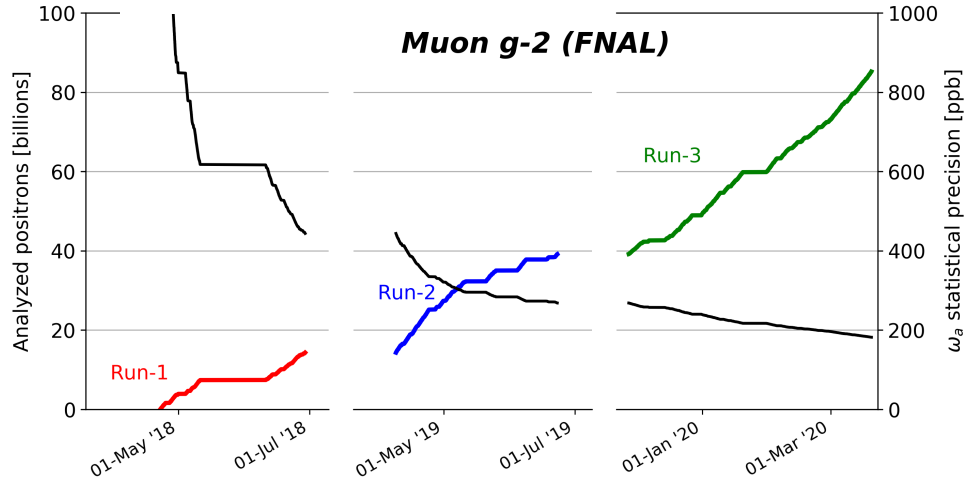
# Run-2/3 Uncertainty Improvement Categories



# Run-2/3 Improvement: Statistics

Weighted  $e^+$  in our final fit after quality control

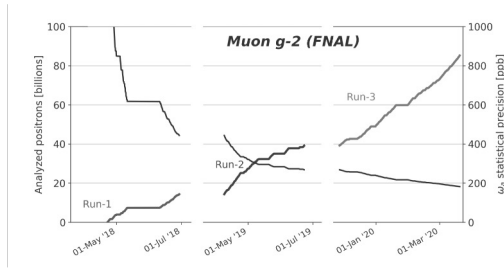
$E > 1 \text{ GeV}$   
 $t > 30 \text{ us}$



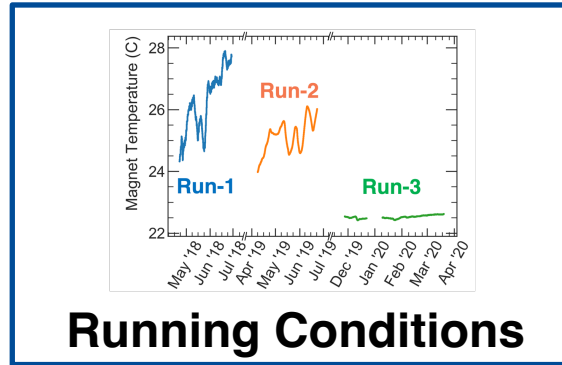
Factor 4.7 more data in Run-2/3 than Run-1

Dataset	Statistical Error [ppb]
Run-1	434
Run-2/3	201
Run-1 + Run-2/3	185

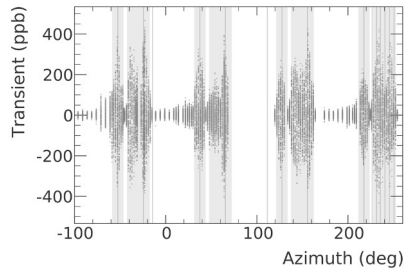
# Run-2/3 Uncertainty Improvement Categories



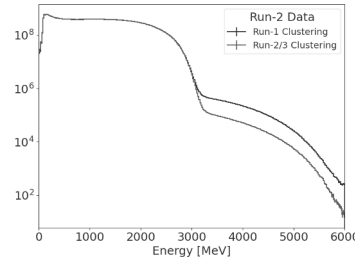
Statistics



Running Conditions



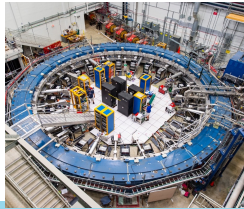
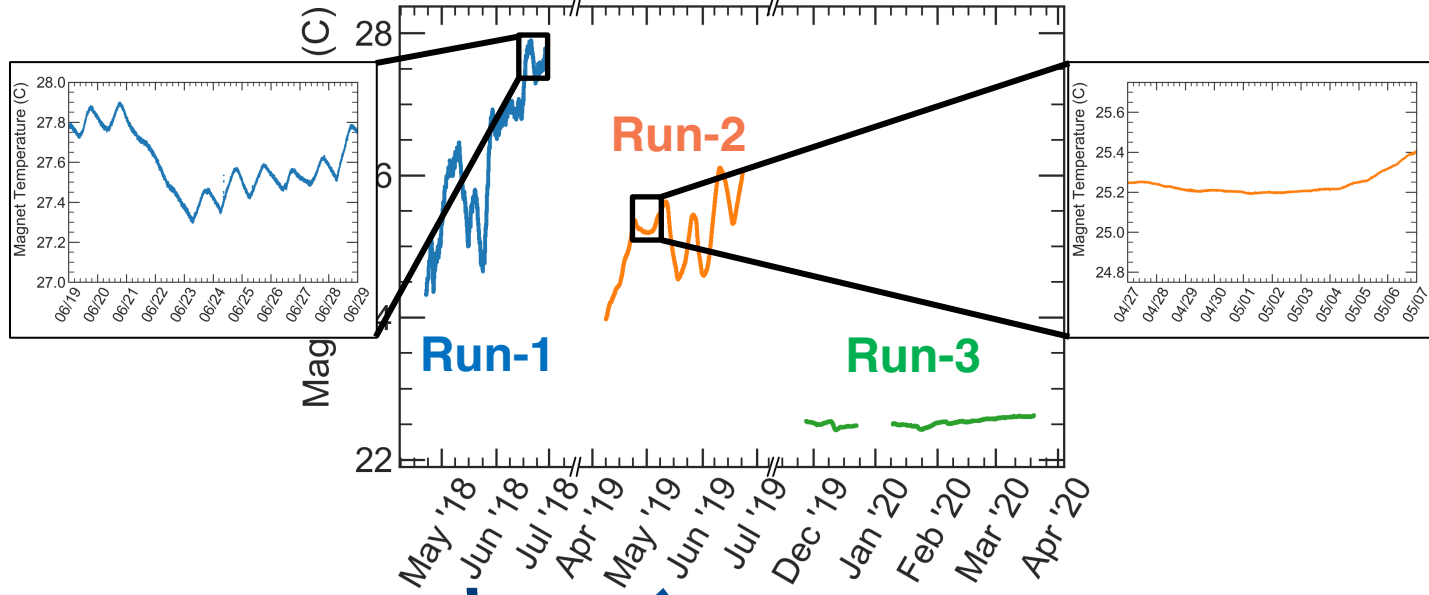
Systematic Measurements & Studies



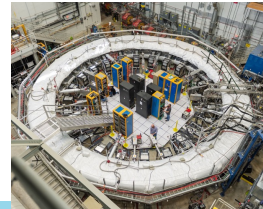
Analysis Improvements

# Running Conditions: Hall Temperature

- Temperature stability makes magnetic field less variable

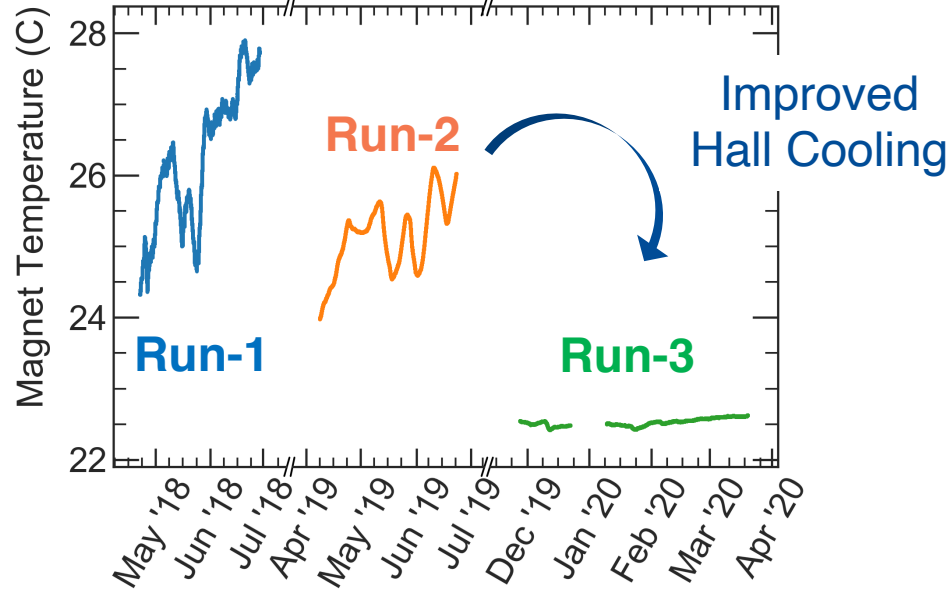


Added Insulation



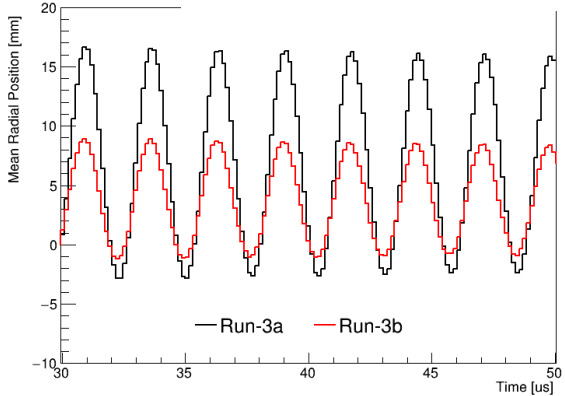
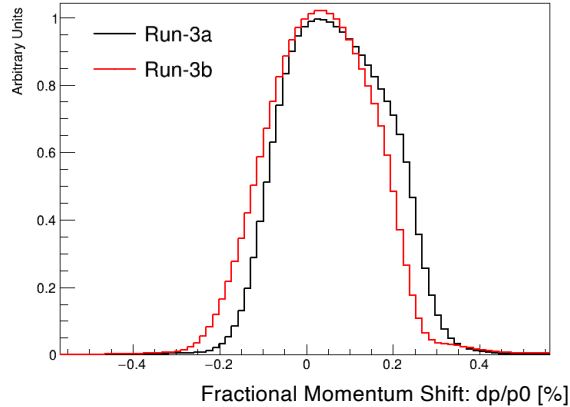
# Running Conditions: Hall Temperature

- Temperature stability makes magnetic field less variable



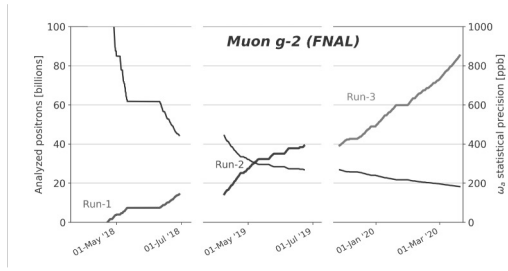
# Running Conditions: Kicker Strength

- Last 18% of Run-2/3 has upgraded, stronger kicker

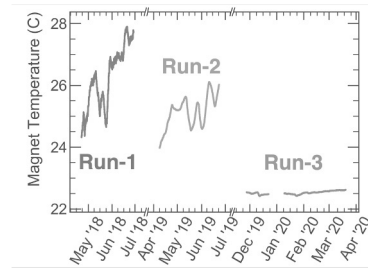


- Mom. distribution more centered
- **Lower E-field correction  $C_e$** 
  - (off-momentum muons whose electric field aren't cancelled by magic momentum technique)
- Phase space matching improved
- **Smaller beam oscillations**

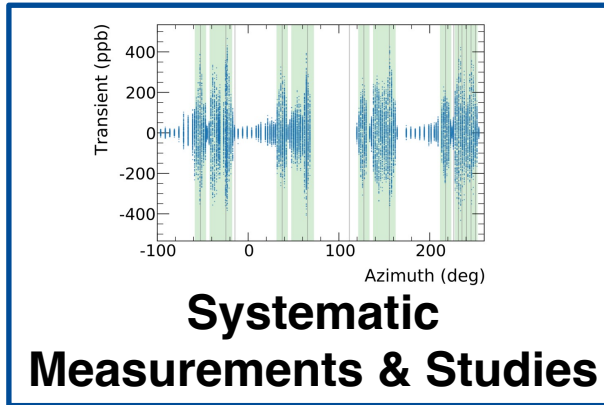
# Run-2/3 Uncertainty Improvement Categories



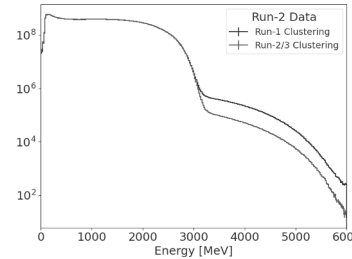
Statistics



Running Conditions



**Systematic  
Measurements & Studies**

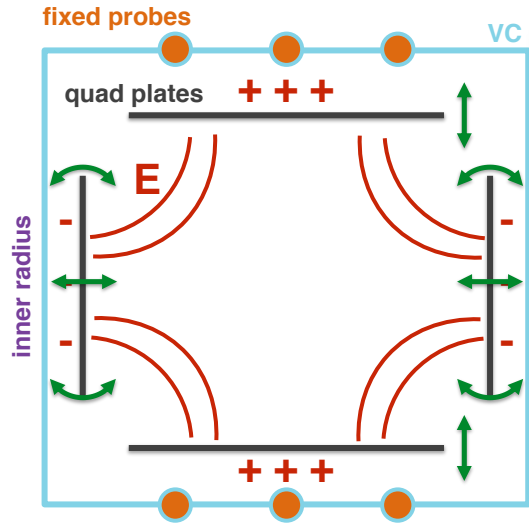


Analysis Improvements

# Transient Fields affect the muons

- Quads are pulsed synchronously with muons
- We observed a motion of the quad plates associated with these pulses
- Affects field observed by muons, but **not** the field mapped by trolley (quads off)

Quantity	Run 1	Correction terms (ppb)	Uncertainty (ppb)
$f_{\text{calib}} \langle \omega_p(x, y, \phi) \times M(x, y, \phi) \rangle$		...	56
$B_k$		-27	37
$B_q$		-17	92



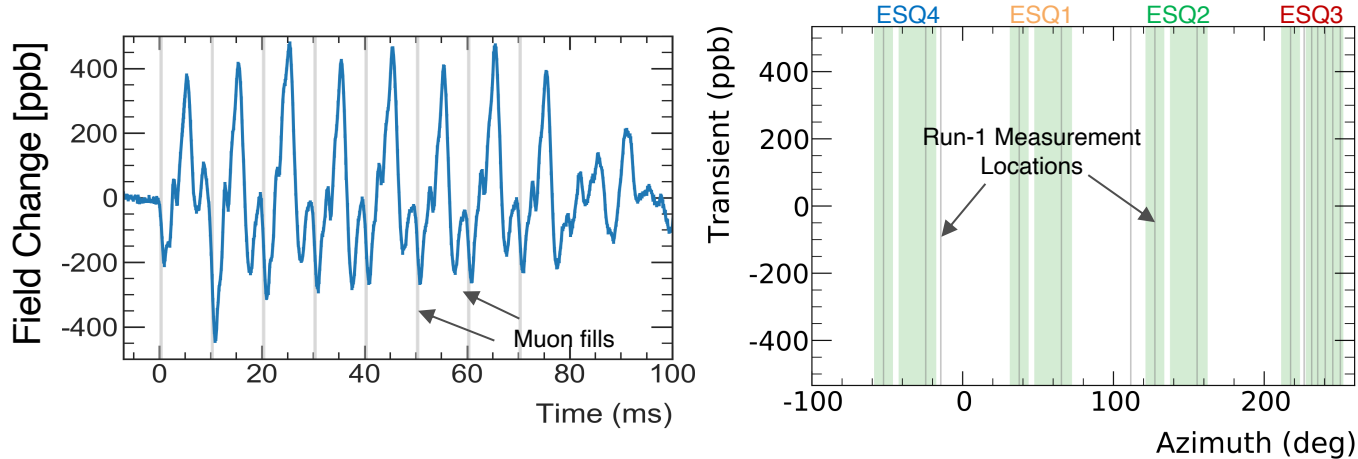
- ### Pulsing Quads
- Side plates oscillate radially
  - Oscillating conductor perturbs B-field
  - **Fixed probes** sensitive to oscillation

## Dedicated measurement



# Improved Measurements: Quad Transient Field

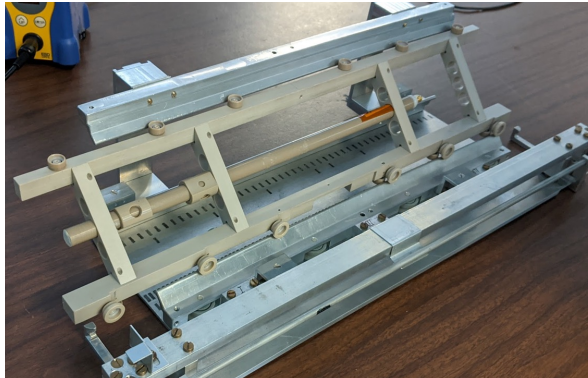
- Measured with a **new NMR probe** housed in insulator



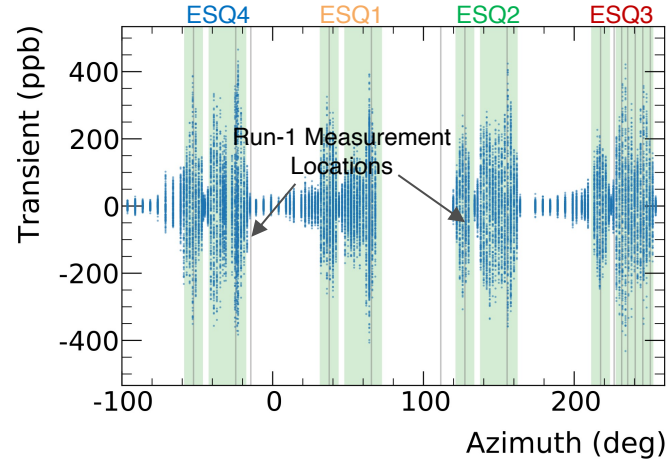
- For Run-1 analysis, we had **limited measurement positions around the ring**
- Largest Run-1 systematic: **92 ppb**

# Improved Measurements: Quad Transient Field

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

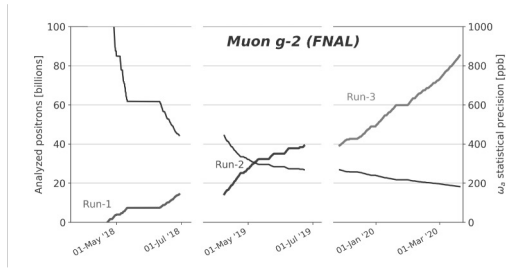


Measurement probe mounted  
on trolley rail train

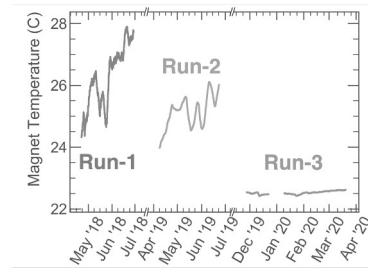


- Uncertainty is reduced to **20 ppb**

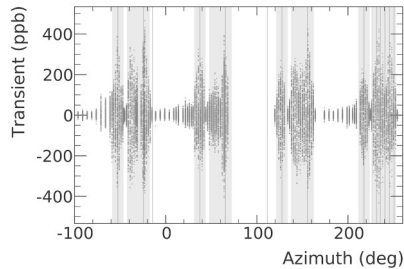
# Run-2/3 Uncertainty Improvement Categories



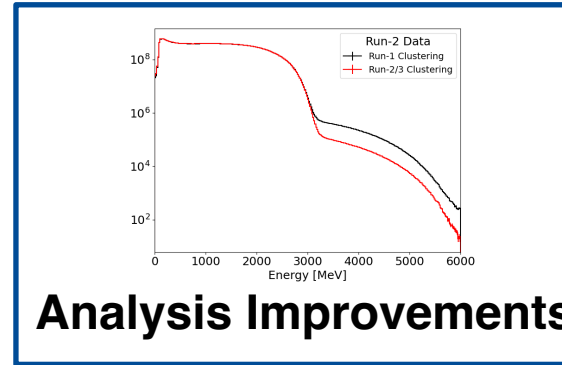
Statistics



Running Conditions



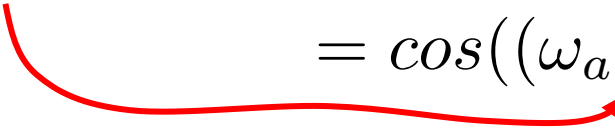
Systematic Measurements & Studies



Analysis Improvements

## $\omega_a$ Systematics: Phase Shifts

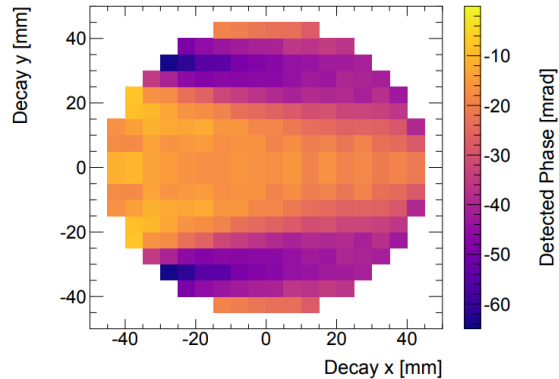
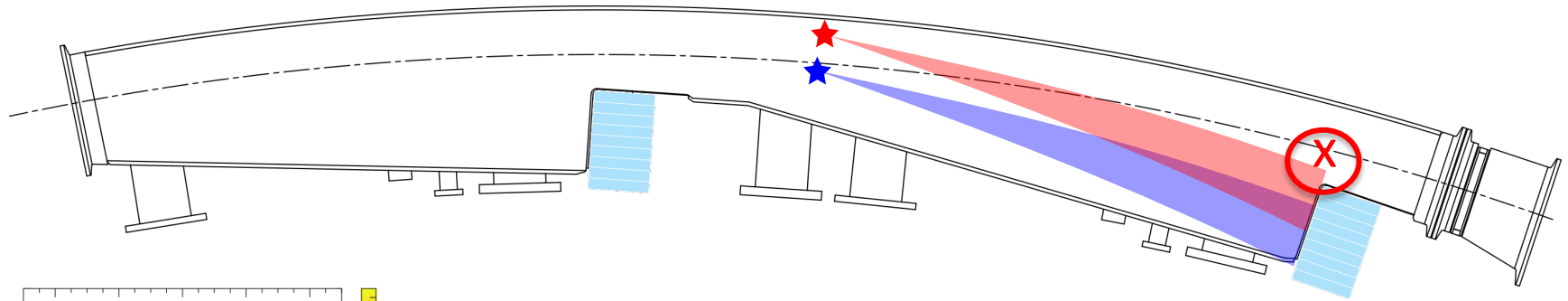
- Many systematics come from effects that **change the phase** of the detected  $e^+$  over time
- These make us mis-measure  $\omega_a$  with no other indications that we're getting it wrong

$$\begin{aligned} \cos(\omega_a t + \phi(t)) &= \cos(\omega_a t + \phi_0 + \phi' t + \dots) \\ &= \cos((\omega_a + \phi')t + \phi_0 + \dots) \end{aligned}$$


- 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 one particular effect ( $C_{PA}$ )

# $C_{PA}$ – Phase-Acceptance Correction

- The  $g - 2$  phase of the accepted positrons depends on the muon decay position  $(x, y, \phi)$  and energy.

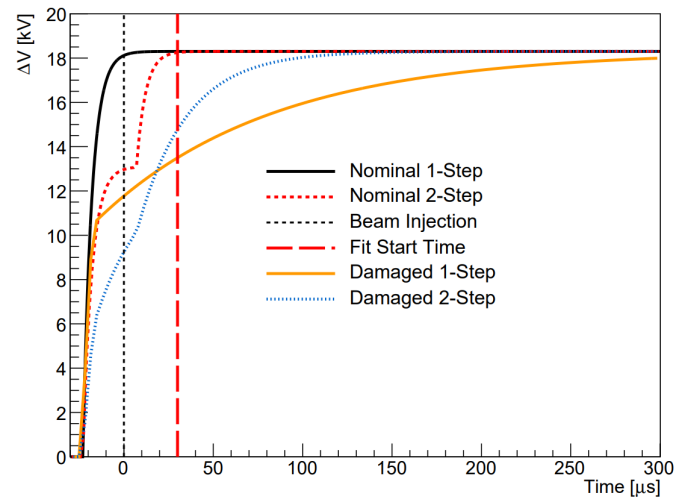


(Exaggerated) Example “decay cones” at the different radial positions.

Not an issue if the muon distribution doesn't change shape over a fill

# $C_{PA}$ – Phase Acceptance error in Run 1

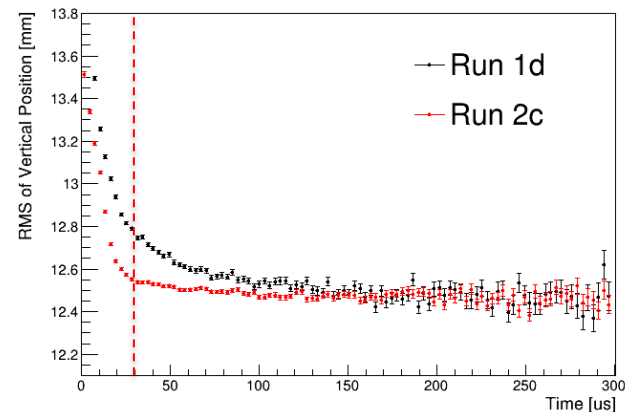
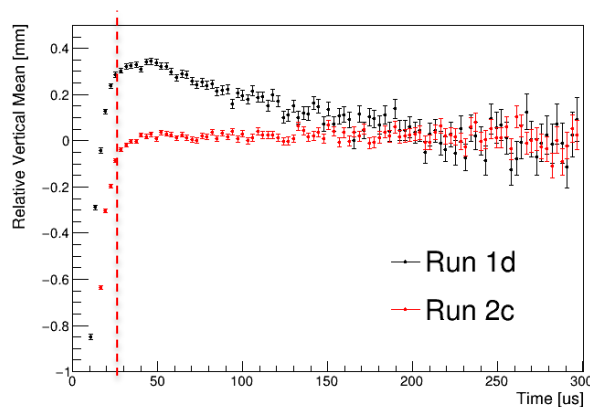
- The spatial muon distribution *should* be stable during the measurement period. However...
- 2 out of 32 Quad HV resistors were damaged which led to unstable beam conditions
  - The electric field changed during the measurement
  - The mean vertical position and width changed
  - Resulted in a -158 ppb correction with 75 ppb unc.
  - **Resistors fixed prior to Run2 → much more stable**



$C_{pa}$	Correction [ppb]	Unc. [ppb]
----------	------------------	------------

Run -1	-158	75
--------	------	----

Run -2/3	-27	13
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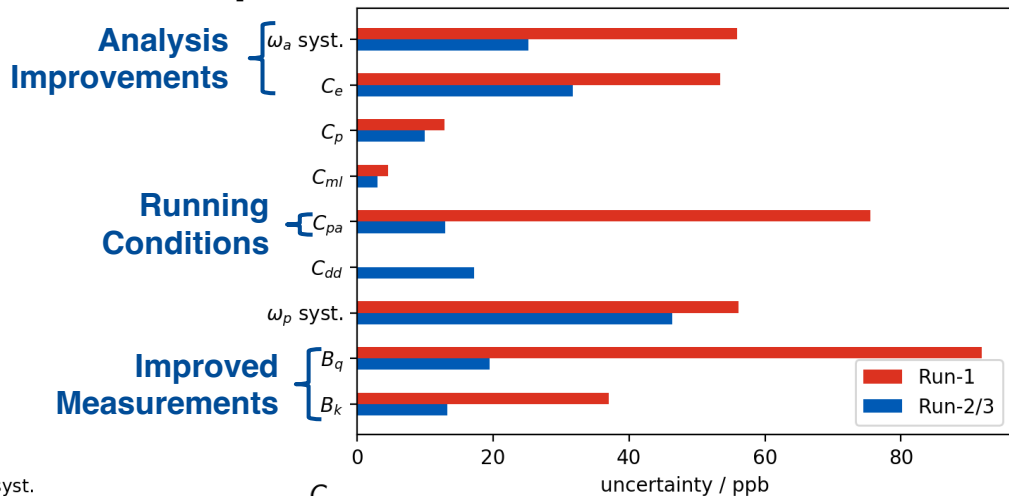
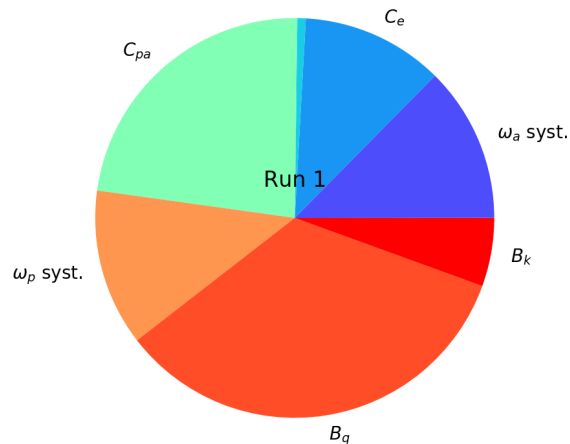


# Uncertainty Improvements Summary

- Systematic improvements in **all parameters**

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

Run-1 Systematics



- After improvements, total systematic comes from **multiple sources**

# Run-2/3 Uncertainties: Final Values

Quantity	Correction [ppb]	Uncertainty [ppb]
$\omega_a^m$ (statistical)	–	201
$\omega_a^m$ (systematic)	–	29
$C_e$	451	32
$C_p$	170	10
$C_{pa}$	-27	13
$C_{dd}$	-15	17
$C_{ml}$	0	3
$f_{\text{calib}} \langle \omega'_p(\vec{r}) \times M(\vec{r}) \rangle$	–	46
$B_k$	-21	13
$B_q$	-21	20
$\mu'_p(34.7^\circ)/\mu_e$	–	11
$m_\mu/m_e$	–	22
$g_e/2$	–	0
Total systematic	–	70
Total external parameters	–	1
Totals	622	215

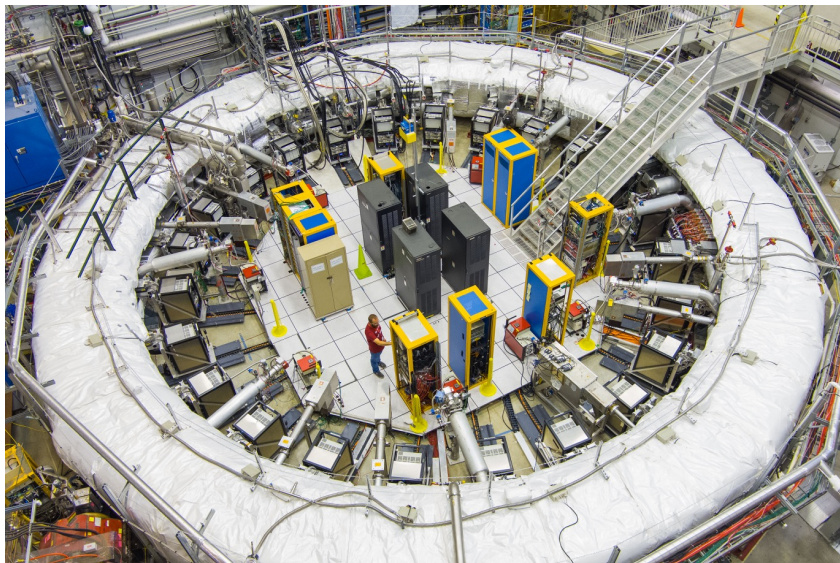
- Total uncertainty is **215 ppb**

[ppb]	Run-1	Run-2/3	Ratio
<b>Stat.</b>	<b>434</b>	<b>201</b>	<b>2.2</b>
<b>Syst.</b>	<b>157</b>	<b>70</b>	<b>2.2</b>

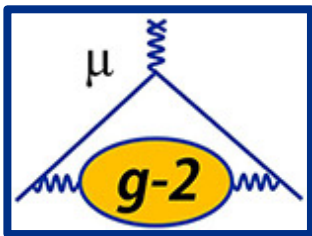
- Near-equal improvement: We're still **statistically dominated**

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

# Outline

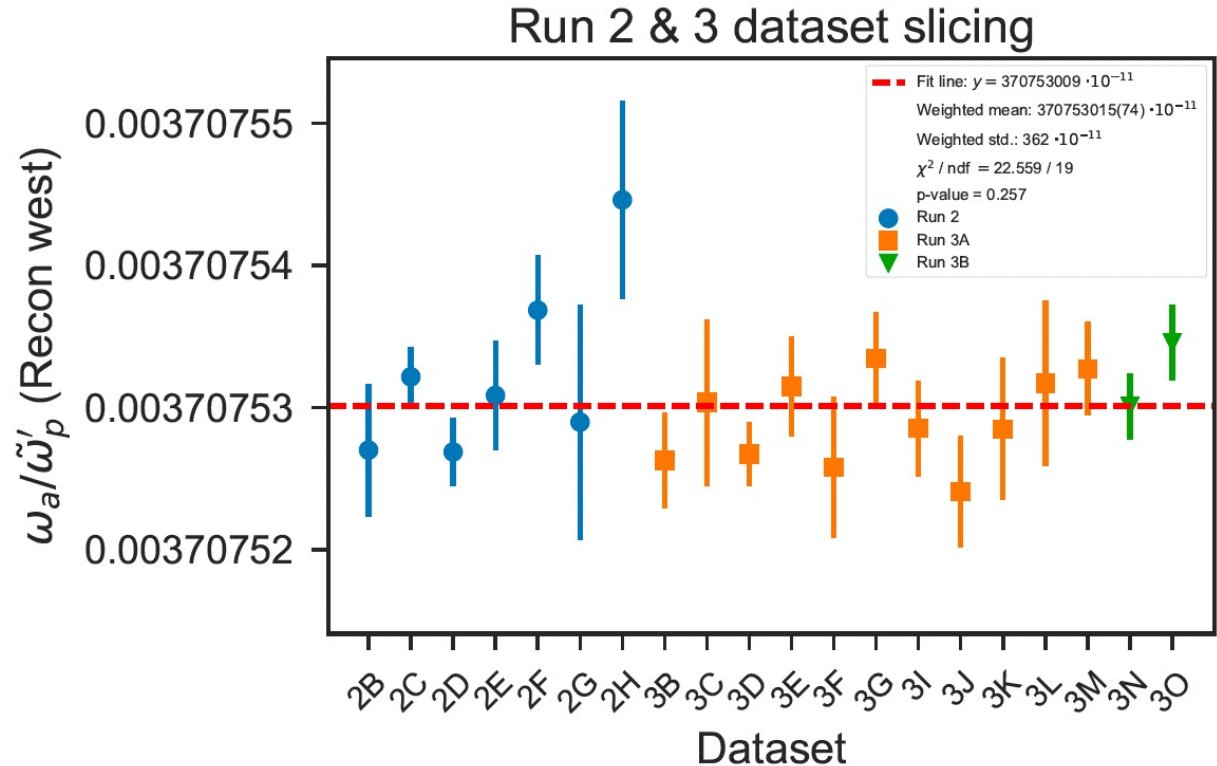


- Muon  $g-2$  Motivation
- Current Status
  - Theory
    - Dispersive Calculation
    - Updated  $e^+/e^-$  Measurements
    - Lattice QCD
  - Experimental status
- Fermilab Experimental Technique
- Runs 2-3
  - Hardware and analysis improvements
  - Crosschecks
- Outlook
  - General timeline: What comes next?



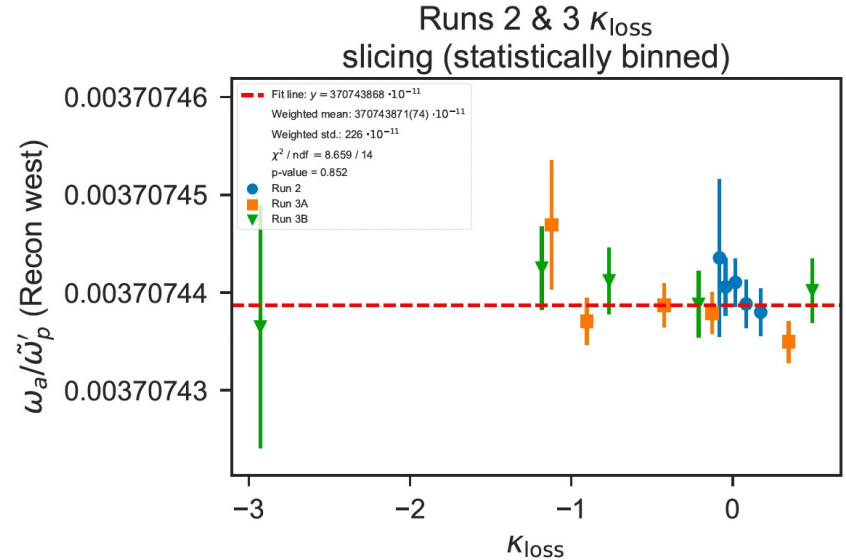
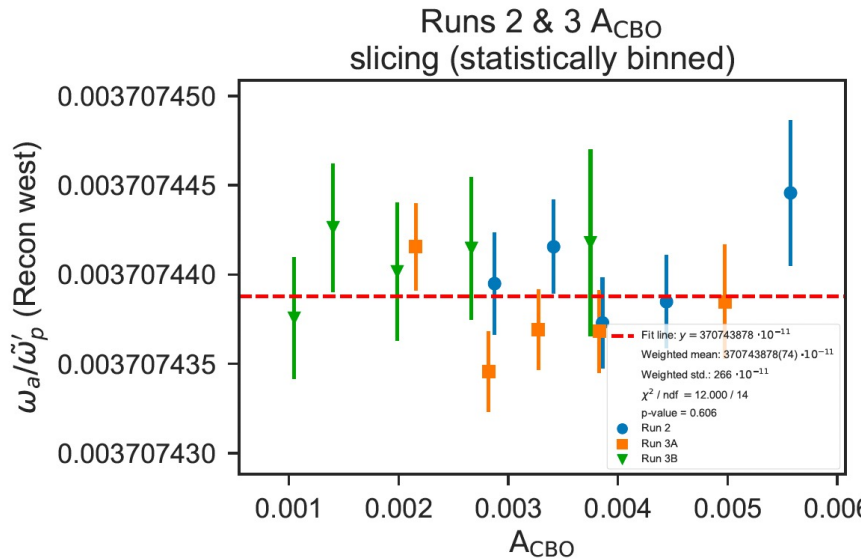
# Crosschecks: Run 2-3 sub-datasets sorted chronologically

- Identified many variables and subdivide run2-3 into ~5-10 subsets sorted on each variable
- Everything was consistent with expectations



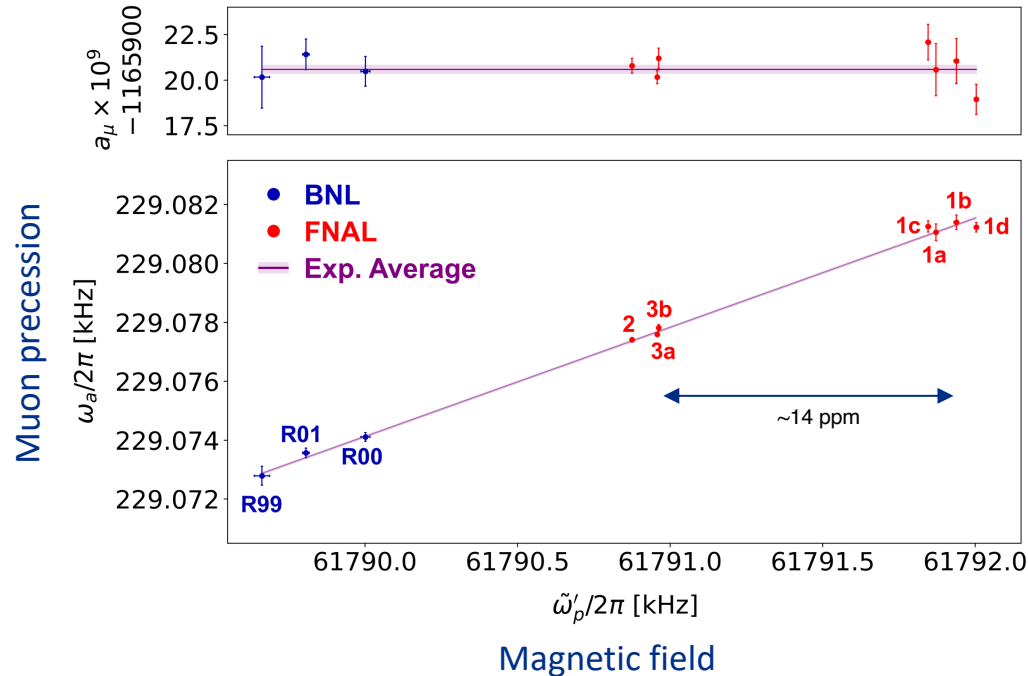
# Stability against different beam conditions

$A_{\text{cbo}}$  is the amplitude of beam oscillations,  
 $\kappa_{\text{loss}}$  is stored muon losses, which can shift phase

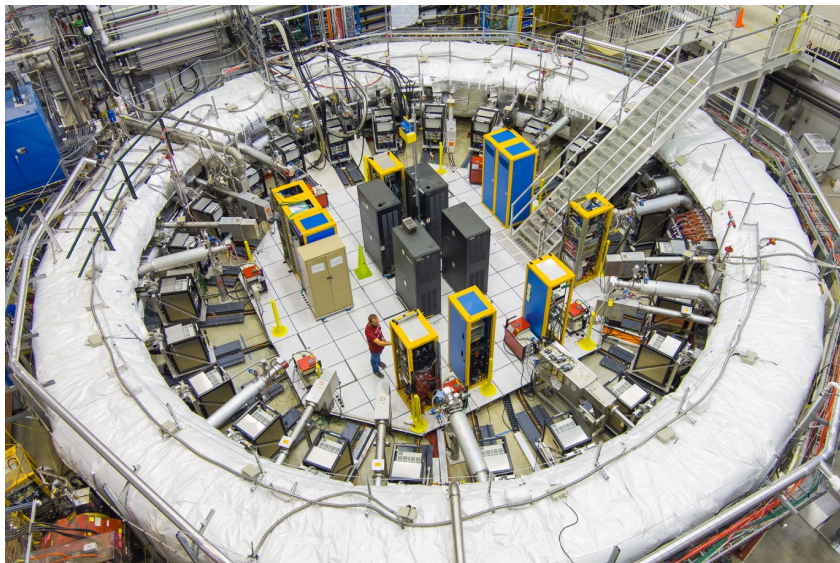


# Measurements at Different Magnetic Fields

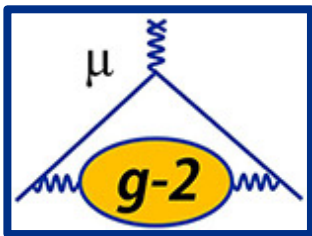
- Across BNL and Runs 1-3, datasets were taken at slightly different field settings
- Allows a simple cross-check of scaling between  $\mu$  and  $p$  precession frequency



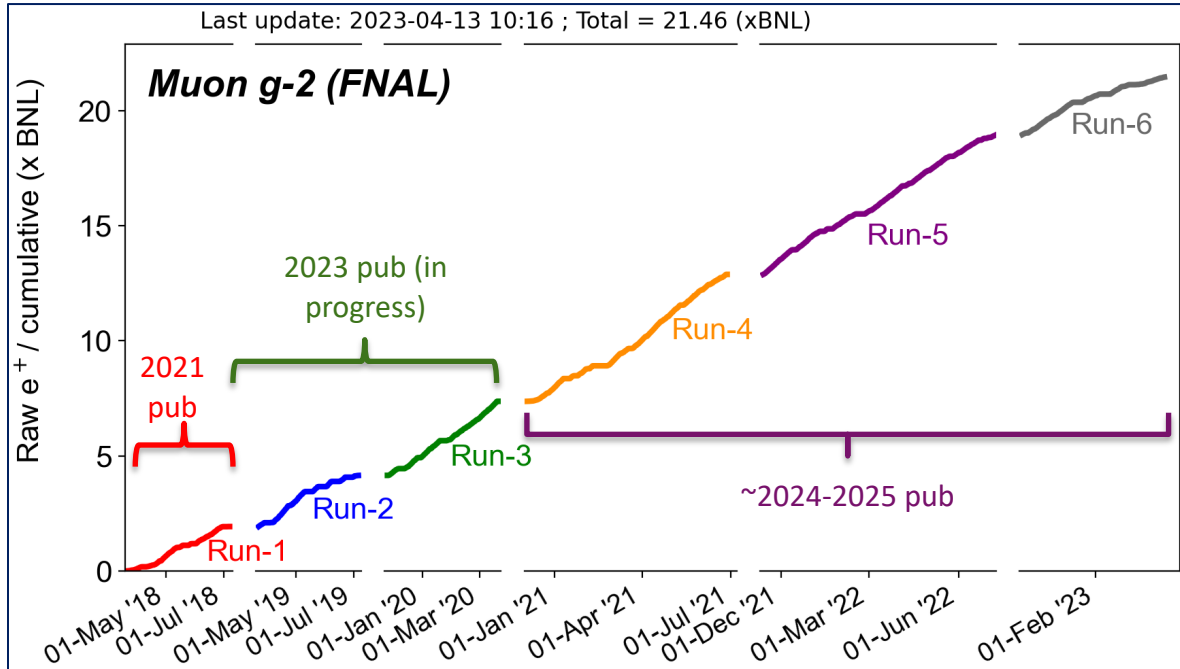
# Outline



- Muon  $g-2$  Motivation
- Current Status
  - Theory
    - Dispersive Calculation
    - Updated  $e^+/e^-$  Measurements
    - Lattice QCD
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  - Hardware and analysis improvements
  - Crosschecks
- Outlook
  - General timeline: What comes next?



# FNAL Data Summary



- Run-6 is final dataset collection ended in July 2023
  - Total integrated statistics reached the TDR goal of 21xBNL (actual = 21.9xBNL)
  - Systematic uncertainty ( $\sim 70$ ppb) should exceed the  $\sim 100$  ppb experimental goal
  - Experimental uncertainty should exceed  $\sim 140$  ppb

Additional magnet systematics ongoing for  $\sim 6$  months

Raw production on Runs 4-6 complete

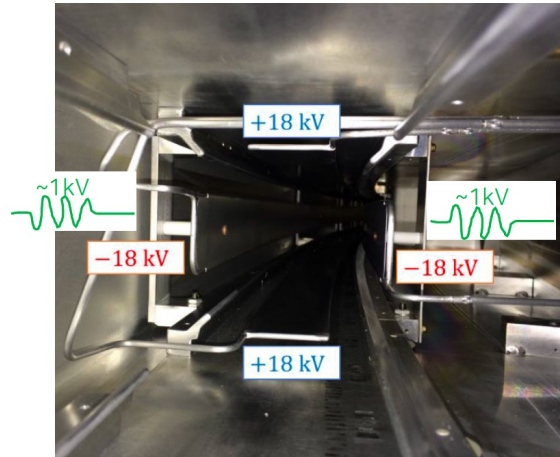
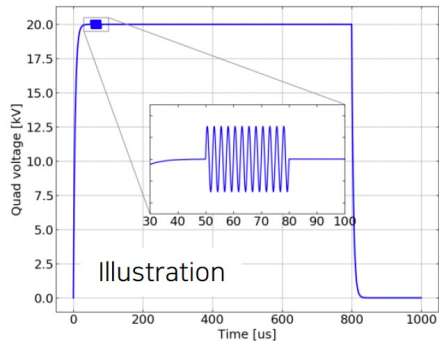
- Pushing into new regime, new puzzles

# Improved Operations in Run 4-5-6

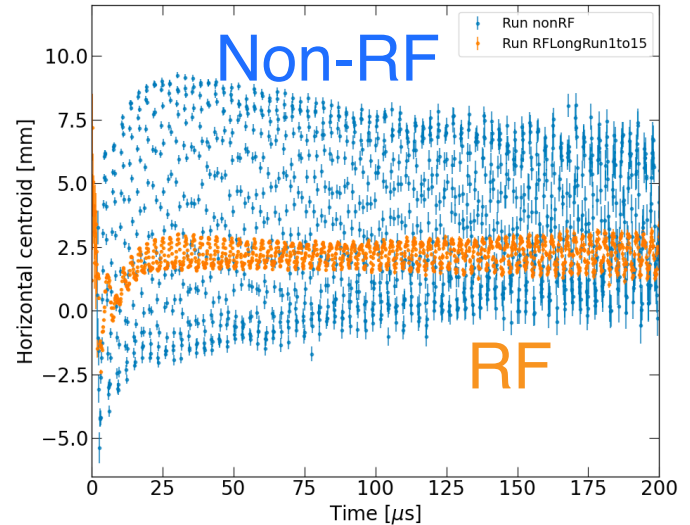
- Maintained temperature stability and pulsed system quality control near optimal parameters
- Reduced beam oscillations by augmenting quads with RF phase-space matching

## Quad-RF

RF HV on top of the Quad HV

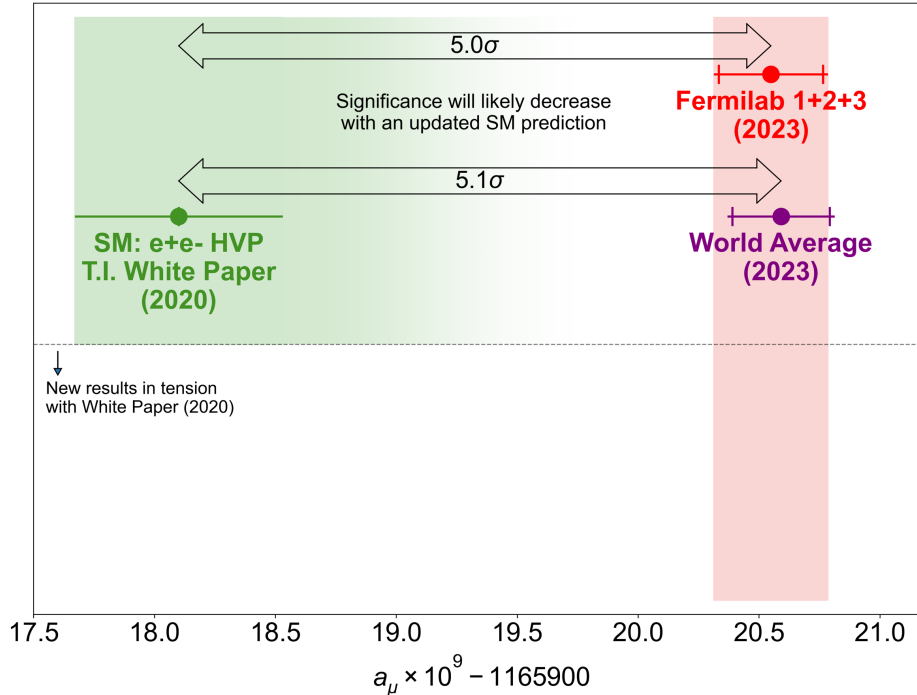


Beam center



# Experiment vs Theory Comparison

- Theory prediction is less clear now, but we can still make some comparisons

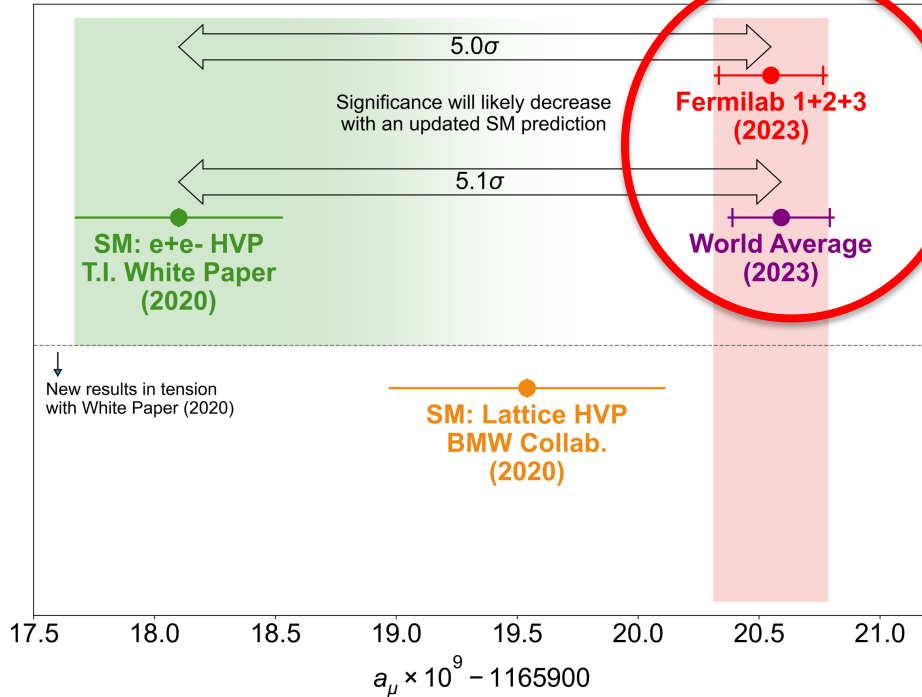


- $\sim 5\sigma$  wrt Theory Initiative WP (dispersive)  $\rightarrow$  will likely decrease
- Include **BMW** result by swapping HVP from WP with their value. Some caveats:
  - other lattice groups have checked intermediate window, which contributes less than 40% of the discrepancy with the dispersive calculation
  - Looking forward to seeing additional full lattice calculations in 2024
  - Ignores many dispersive results
  - As expected, BMW falls **in between** WP (2020) and experiment

# Runs 1-3 Results / Implications •

What can explain the difference?

- (a) Experimental Error
- (b) Theory Error
- (c) New Physics
- (d) Some combination of the above

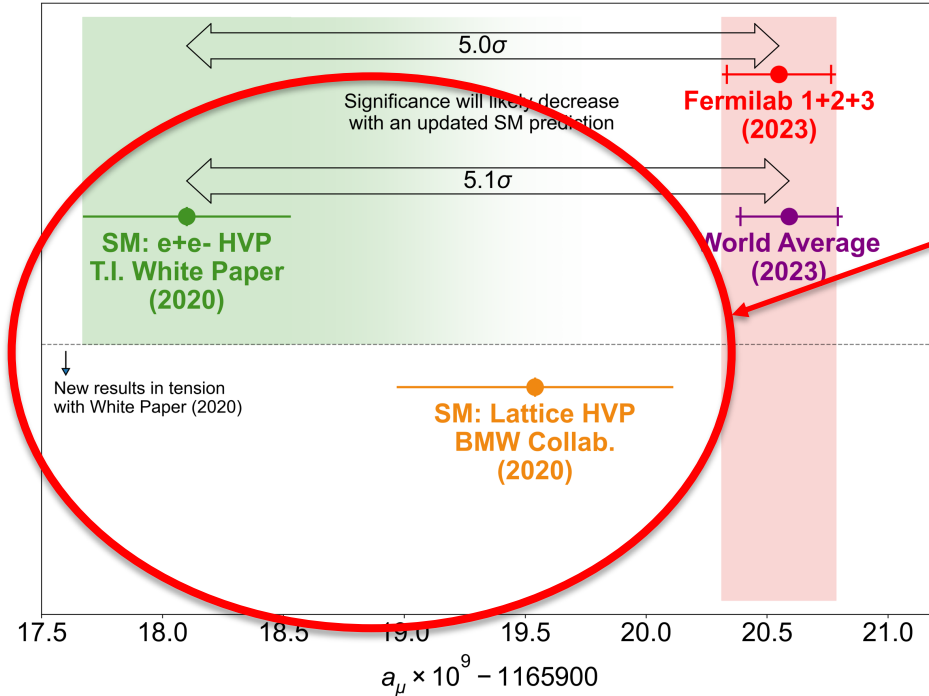


Excellent agreement between BNL and FNAL Run 1-3

This hypothesis is much less likely now

2025 FNAL result will reduce experimental uncertainty by ~30% and establish legacy target

# First Results / Implications



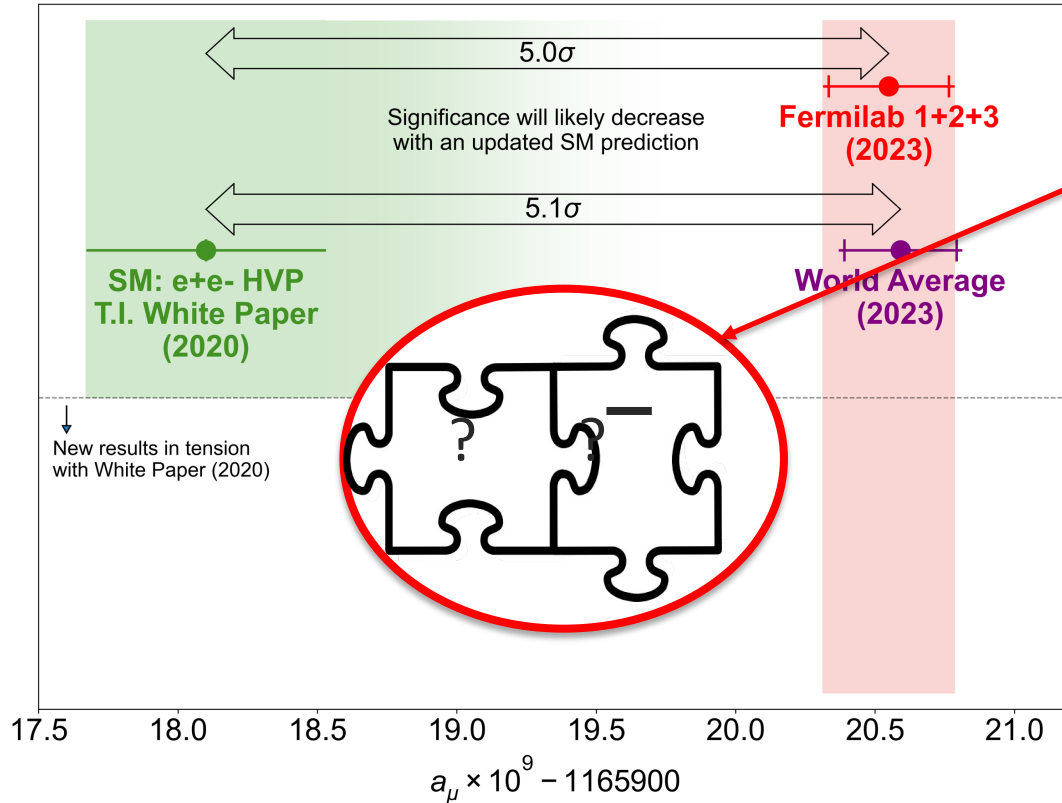
- What can explain the difference?
  - (a) Experimental Error
  - (b) Theory Error
  - (c) New Physics
  - (d) Some combination of the above

Longstanding dispersive calc  
- Investigating recent tension  
- What can CMD-3 tell us?

New lattice QCD approach suggests higher value

- Could new physics be lurking in e+/-e- measurements?
- Systematic e+/-e- experimental error?

# First Results / Implications



- What can explain the difference?
  - (a) Experimental Error
  - (b) Theory Error
  - (c) New Physics**
  - (d) Some combination of the above

**Many Exciting theory possibilities**

## Measurement of the Positive Muon Anomalous Magnetic Moment to 0.46 ppm

Muon g-2 Collaboration · B. Abi (Oxford U.) [Show All\(237\)](#)  
Apr 7, 2021

11 pages  
Published in: *Phys.Rev.Lett.* 126 (2021) 14, 141801  
Published: Apr 8, 2021  
e-Print: [2104.03281 \[hep-ex\]](#)  
DOI: [10.1103/PhysRevLett.126.141801](#) (publication)  
PDG:  $\mu(\mu)/(\hbar/2m(\mu))-1 = (g(\mu)-2)/2$   
Report number: FERMILAB-PUB-21-132-E  
Experiments: [FNAL-E-0989](#)

[Run1: link](#)

View in: [OSTI Information Bridge Server](#), [ADS Abstract Service](#)

[pdf](#)
[links](#)
[cite](#)
[claim](#)  
[reference search](#)
[↻ 1,445 citations](#)

# Physics possibilities (papers citing August arxiv paper, which has now been accepted for PRL)

## Probing chiral and flavored $Z'$ from cosmic bursts through neutrino interactions

ShivaSankar K. A., Arindam Das, Gaetano Lambiase, Takaaki Nomura, Yuta Orikasa (Aug 28, 2023)

e-Print: [2308.14483](#) [hep-ph]

[pdf](#) [cite](#) [claim](#) [reference search](#) [0 citations](#)

## Muon $g - 2$ and dark matter in Supersymmetric $SU(4)_c \times SU(2)_L \times SU(2)_R$

Qaisar Shafi (Delaware U.), Amit Tiwari (Delaware U.), Cem Salih Un (Aug 28, 2023)

e-Print: [2308.14682](#) [hep-ph]

[pdf](#) [cite](#) [claim](#) [reference search](#) [0 citations](#)

## Flavor physics in SU(5) GUT with a 45 scalar representation

Toru Goto (KEK, Tsukuba), Satoshi Mishima (KEK, Tsukuba and Saitama 2023)

e-Print: [2308.13329](#) [hep-ph]

[pdf](#) [cite](#) [claim](#)

## Searching for Heavy Leptophilic $Z'$ : from Lepton Colliders

Arnab Dasgupta (Pittsburgh U.), P.S. Bhupal Dev (McDonnell Ctr. Space Padhan (Pittsburgh U. and Bhubaneswar, Inst. Phys. and HBNI, Mumbai)

e-Print: [2308.12804](#) [hep-ph]

[pdf](#) [cite](#) [claim](#)

## Pion Transition Form Factor from Twisted-Mass Lattice QCD pole Contribution to the Muon $g - 2$

C. Alexandrou (Cyprus U. and Cyprus Inst.), S. Bacchio (Cyprus Inst.), G. Finkenrath (Cyprus Inst. and Wuppertal U.) et al. (Aug 23, 2023)

e-Print: [2308.12458](#) [hep-lat]

[pdf](#) [cite](#) [claim](#)

## Effective interactions for the SM fermion mass hierarchy and their possible UV realization

A.E. Cárcamo Hernández (Santa María U., Valparaíso and CCTVal, Valparaíso and Chile U., Santiago), Diego Restrepo (Antioquia U.), Ivan Schmidt (Santa María U., Valparaíso and CCTVal, Valparaíso and Chile U., Santiago), Óscar Zapata (Escuela de Ingeniería de Antioquia) (Aug 21, 2023)

e-Print: [2308.10946](#) [hep-ph]

[pdf](#) [cite](#) [claim](#) [reference search](#) [0 citations](#)

## Two-loop radiative corrections to $e^+e^- \rightarrow \gamma\gamma^*$ cross section

V.S. Fadin (Novosibirsk, IYF), R.N. Lee (Aug 18, 2023)

e-Print: [2308.09479](#) [hep-ph]

[pdf](#) [cite](#) [claim](#) [reference search](#) [0 citations](#)

## Current status on pair-produced muon-philic vectorlike leptons in multilepton channels at the LHC

Junichiro Kawamura (IBS, Daejeon, CTPU), Seodong Shin (IBS, Daejeon, CTPU and Jeonbuk Natl. U.) (Aug 15, 2023)

e-Print: [2308.07814](#) [hep-ph]

[pdf](#) [cite](#) [claim](#) [reference search](#) [0 citations](#)

## Handbook of the analytic and expansion formulae for the muon $g - 2$ anomaly

Shi-Ping He (APCTP, Pohang) (Aug 14, 2023)

e-Print: [2308.07133](#) [hep-ph]

[pdf](#) [cite](#) [claim](#) [reference search](#) [0 citations](#)

## Dark Coloured Scalars Impact on Single and Di-Higgs Production at the LHC

Pedro Gabriel (Lisbon U., CFTC and KIT, Karlsruhe, TP), Margarete Mühleitner (KIT, Karlsruhe, TP), Daniel Neacsu (LIP, Lisbon), Rui Santos (Lisbon U., CFTC and Lisbon, ISEL) (Aug 14, 2023)

e-Print: [2308.07023](#) [hep-ph]

[pdf](#) [cite](#) [claim](#) [reference search](#) [0 citations](#)

## Semi-visible dark photon in a model with vector-like leptons for the $(g - 2)_{e,\mu}$ and $W$ -boson mass anomalies

Waleed Abdallah, Mustafa Ashry, Junichiro Kawamura, Ahmad Moursy (Aug 10, 2023)

e-Print: [2308.05691](#) [hep-ph]

[pdf](#) [cite](#) [claim](#) [reference search](#) [2 cit](#)

## $(g - 2)_\mu$ and Stau coannihilation : Dark Matter and Collider Analysis

Manimala Chakraborti, Sven Heinemeyer, Ipsita Saha (Aug 10, 2023)

e-Print: [2308.05723](#) [hep-ph]

[pdf](#) [cite](#) [claim](#) [reference search](#) [1 c](#)

## Connecting $(g - 2)_\mu$ to neutrino mass in the extended neutrinophilic 2HDM

A.L. Cherchiglia (Campinas State U. and Granada U., Theor. Phys. Astrophys.), G. De Conto (ABC Federal U.), C.C. Nishi (ABC Federal U.) (Mar 31, 2023)

Published in: *JHEP* 08 (2023) 170 · e-Print: [2304.00038](#) [hep-ph]

[pdf](#) [DOI](#) [cite](#) [claim](#) [reference search](#) [0 cit](#)

## Accommodating Hints of New Heavy Scalars in the Framework of the Flavor-Aligned Two-Higgs-Doublet Model

Joseph M. Connell (UC, Santa Cruz, Inst. Part. Phys.), Pedro Ferreira (Lisbon U.), Howard E. Haber (UC, Santa Cruz, Inst. Part. Phys.) (Feb 27, 2023)

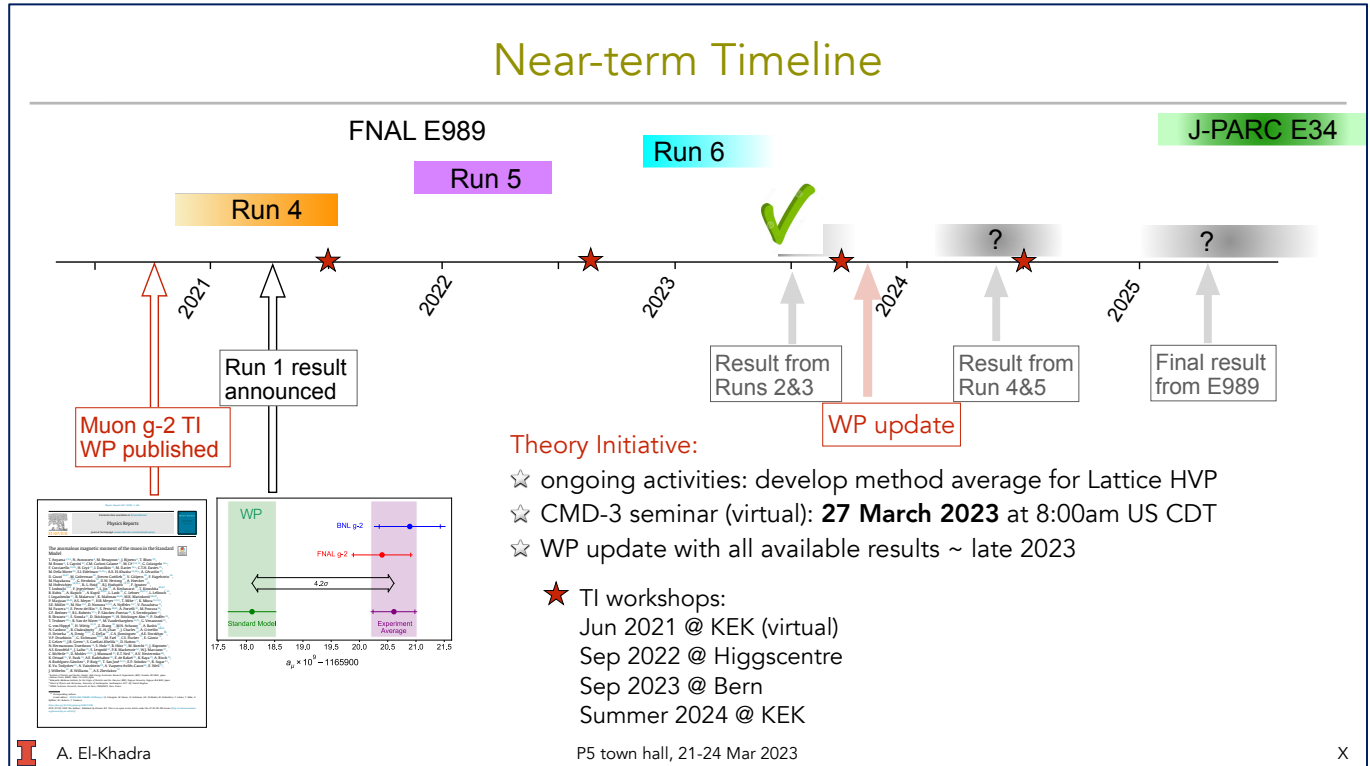
e-Print: [2302.13697](#) [hep-ph]

[pdf](#) [cite](#) [claim](#) [reference search](#) [3 cit](#)

# Overall Timeline & Summary

## A. El-Khadra's talk at P5 town hall, March 2023

- Major experimental result in 2023
- Theory planning significant updates in 2024
- Open questions on theory-theory & theory-exp anomalies will be addressed on this timeline





# Muon g-2 Collaboration



## USA

- Boston
- Cornell
- Illinois
- James Madison
- Kentucky
- Massachusetts
- Michigan
- Michigan State
- Mississippi
- North Central
- Northern Illinois
- Regis
- Virginia
- Washington

## USA National Labs

- Argonne
- Brookhaven
- Fermilab



## China

- Shanghai Jiao Tong



## Germany

- Dresden
- Mainz



## Italy

- Frascati
- Molise
- Naples
- Pisa
- Roma Tor Vergata
- Trieste
- Udine



## Korea

- CAPP/IBS
- KAIST



## Russia

- Budker/Novosibirsk
- JINR Dubna



## United Kingdom

- Lancaster/Cockcroft
- Liverpool
- Manchester
- University College London

181 collaborators

33 Institutions

7 countries

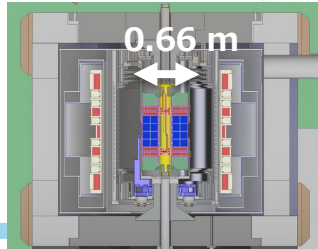
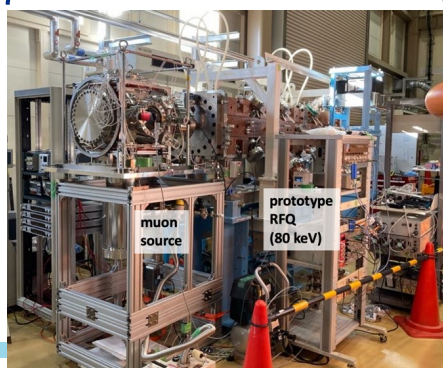
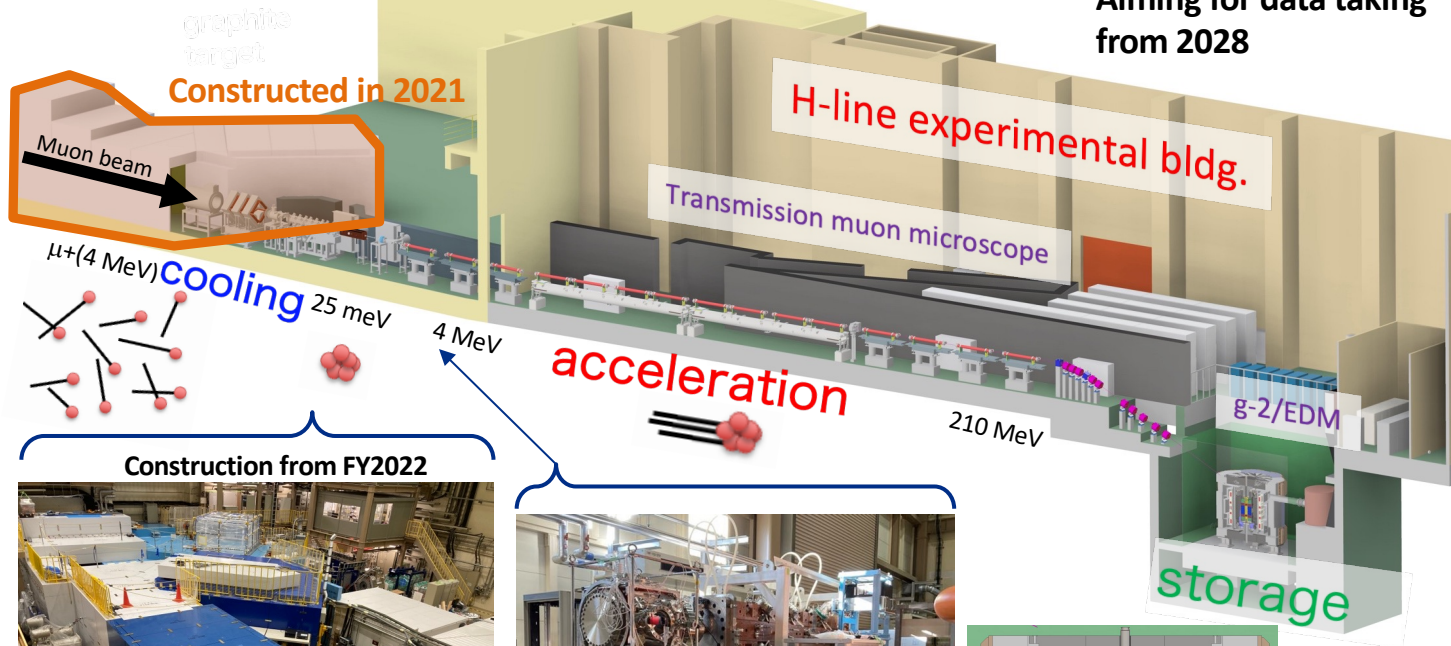


Muon g-2 Collaboration Meeting @ Elba, May 2019

# J-PARC Experiment & MUONE

# J-PARC muon g-2/EDM experiment

J-PARC MLF



Shields, area control (2022)  
B. Kiburg | Run 2-3 Result Muon g-2

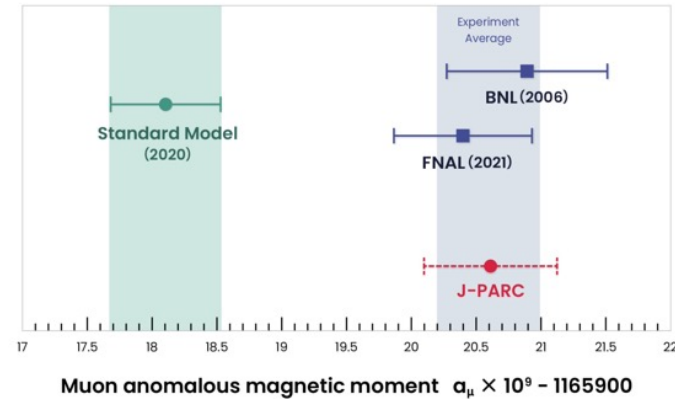
RF Acc. Test at S2 area (May 2023)

Muon storage ring (Sep 2, 2023)



# 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.

# Additional Experimental handle being pursued: MUonE at CERN

- A novel approach to determine the leading hadronic contribution via a very precise measurement of the shape of the differential cross section of  $\mu e$  elastic scattering

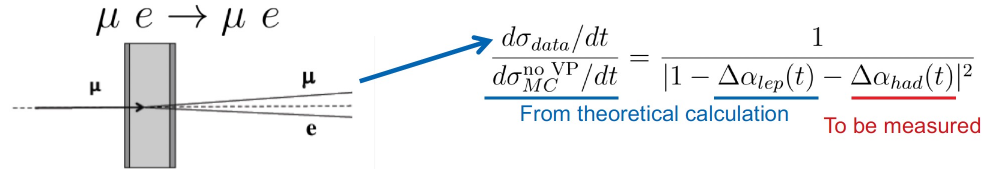
$$a_{\mu}^{HLO} = \frac{\alpha_0}{\pi} \int_0^1 dx (1-x) \Delta\alpha_{had}[t(x)]$$

- Be scattering target
- Tracking via silicon strip detectors
- Status
  - Scattering test beam studies 2017-2018
  - Test run in 2021/2022
- Goal: 3 years of running  $\rightarrow$  0.3% precision on  $a_{\mu}^{HLO}$

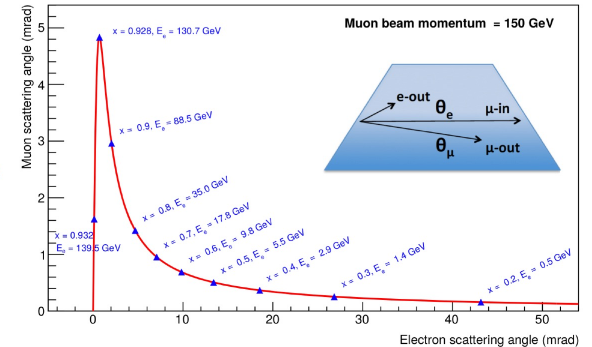
## The MUonE experiment



Extraction of  $\Delta\alpha_{had}(t)$  from the «shape» of the  $\mu^+ e^- \rightarrow \mu^+ e^-$  elastic differential cross section



- A beam of 160 GeV muons allows to cover the whole  $a_{\mu}^{HLO}$ .
- Correlation between muon and electron angles allows to select elastic events and reject background ( $e^+e^-$  pair production).
- Boosted kinematics:  
 $\theta_{\mu} < 5$  mrad,  $\theta_e < 32$  mrad.



G. Venanzoni, TI Meeting, KEK, 29 Jun 2021