Status of the Fermilab Muon $g-2$ Experiment

Ce Zhang

University of Liverpool

IOP Joint APP, HEPP and NP Annual Conference 2024

UNIVERSITY OF LIVERPOOL

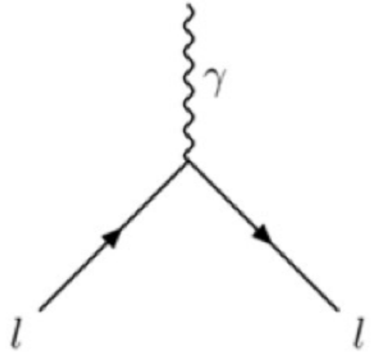
LEVERHULME TRUST

Status of the Fermilab Muon $g-2$ Experiment

- Introduction
  - Experimental principles
  - Run 2/3 improvements & results
- Improvements in Run 4/5/6
- Conclusion

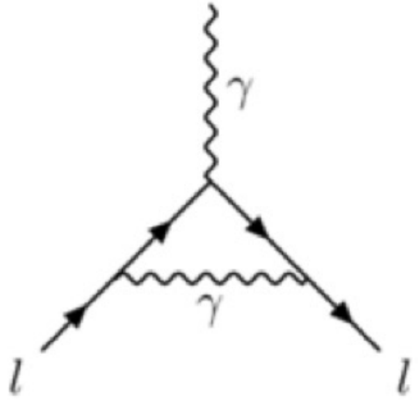
Muon $g-2$

- The anomalous magnetic moment of the muon:
  - Magnetic moments **precess** in a magnetic field $\vec{\mu} = g\frac{e}{2m}\vec{S}$
  - g - factor quantifies interaction strength
  - Dirac predicted $\boldsymbol{g = 2}$ for spin-1/2 fermions



- Interactions with virtual particles cause g to deviate from 2 ($g > 2$). **Muon magnetic anomaly** is defined as:

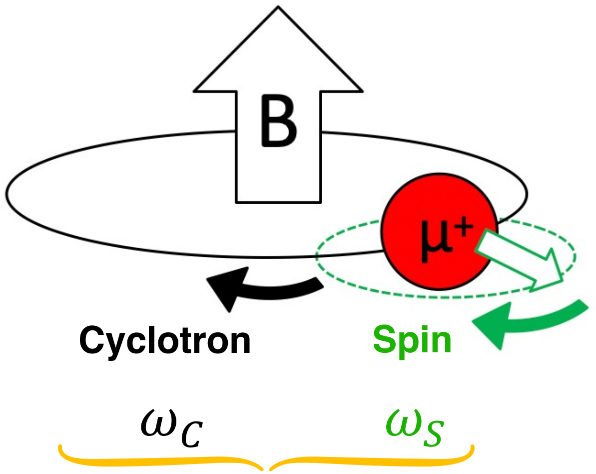
$$a_\mu = \frac{g-2}{2}$$



Muon $g-2$ Experiment at Fermilab

Experimental Principle

- The **muon precession frequency** is the rate at which the muon's spin and momentum accumulate relative angle:



$$\vec{\omega}_a = \vec{\omega}_S - \vec{\omega}_C$$

Measure

$$\omega_a = -\frac{q}{m_\mu} a_\mu B$$

Extract

ω_a^m: modulation of decay positron time spectrum

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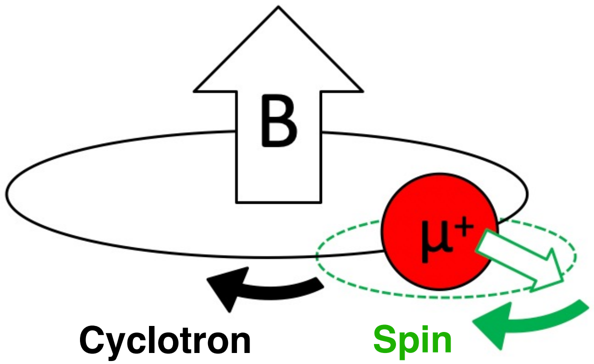

ω_C ω_S

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Measure

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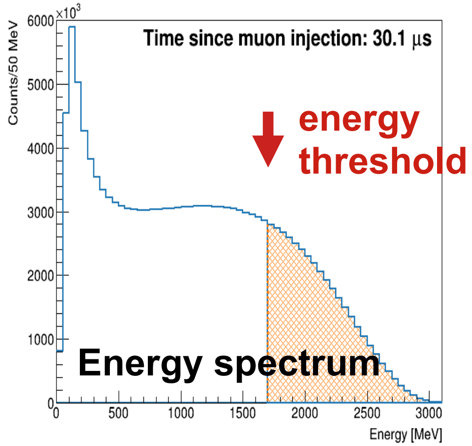
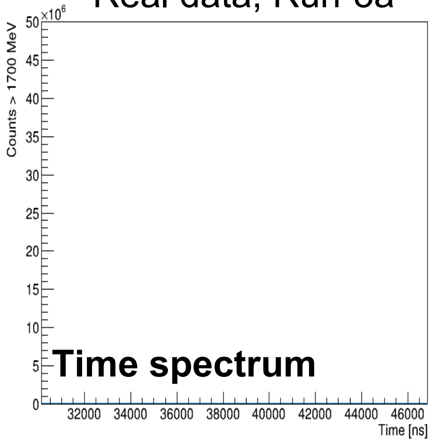
Extract

Real data, Run-3a





ω_a^m: modulation of decay positron time spectrum

Muon $g-2$ Experiment at Fermilab

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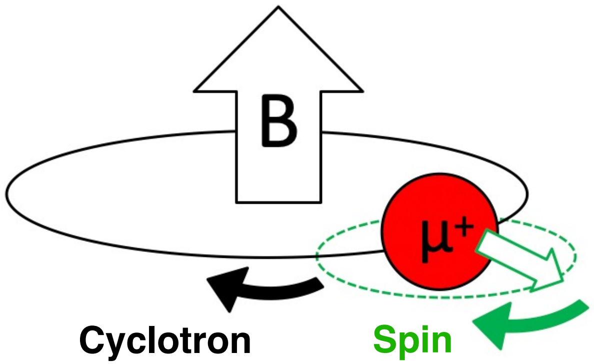

$$\underbrace{\omega_C}\;\underbrace{\omega_S}$$

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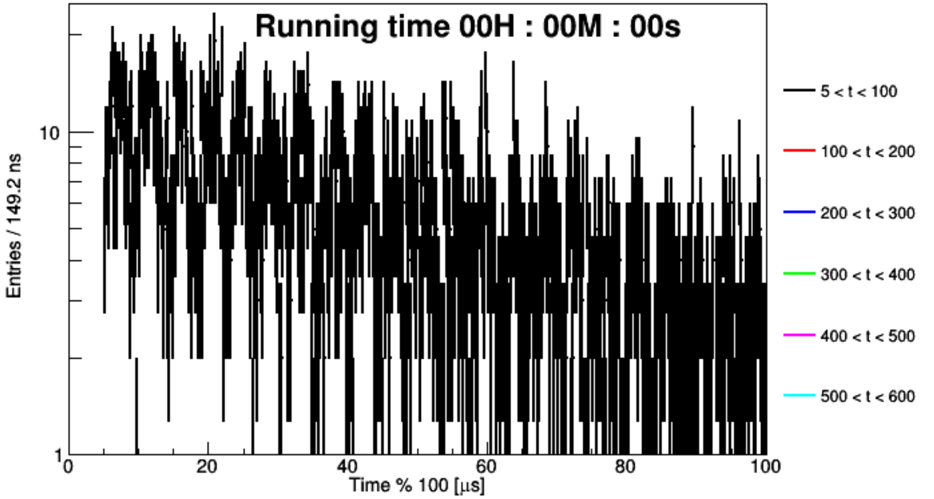

ω_a^m: modulation of decay positron time spectrum

More details in the next talk!

09:15 **Measurement of the anomalous spin precession frequency ω_a in the Muon g-2 experiment at Fermilab (12'+3')**

Speaker: Lorenzo Cotrozzi (University Of Liverpool)

Muon $g-2$ Experiment at Fermilab

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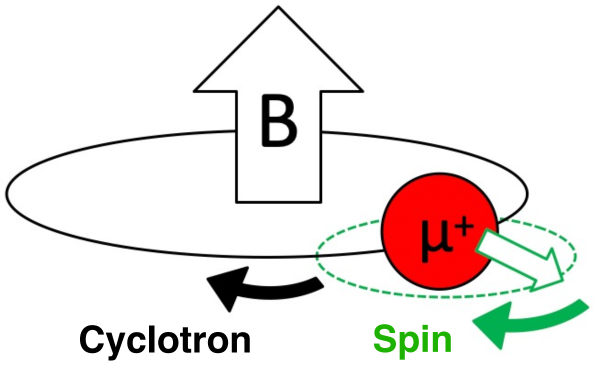

ω_C ω_S

$$\vec{\omega}_a = \vec{\omega}_S - \vec{\omega}_C$$

Measure

$$\omega_a = -\frac{q}{m_\mu} a_\mu B$$

Extract

$$2\mu'_p(\mathrm{H_2O}, T_r)B = \hbar\omega'_p(\mathrm{H_2O}, \mathrm{T}_r)$$

→ we essentially measure muon spin precession relative to proton spin precession

ω_a^m: modulation of decay positron time spectrum

B: Magnetic field measured via proton spin precession

Muon $g-2$ Experiment at Fermilab

Experimental Principle

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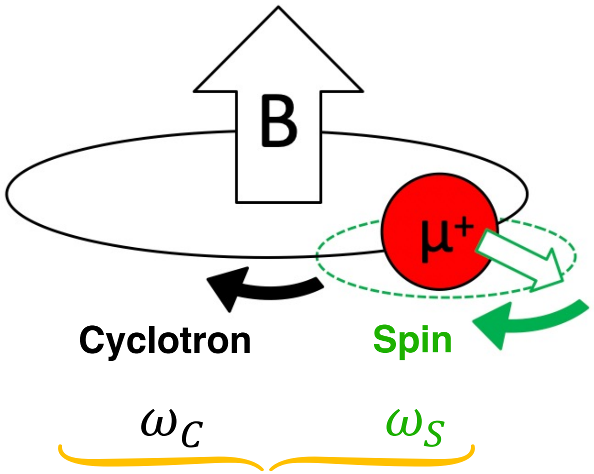


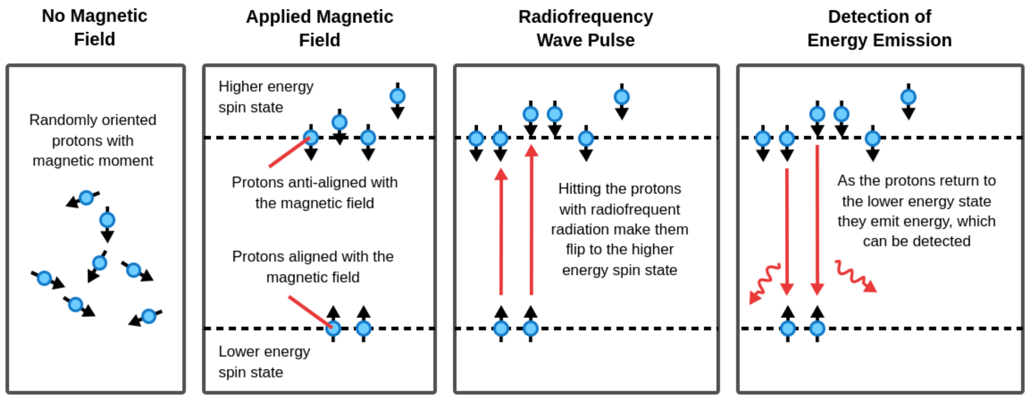
$$\vec{\omega}_a = \vec{\omega}_S - \vec{\omega}_C$$

Measure

$$\omega_a = -\frac{q}{m_\mu} a_\mu B$$

Extract

Measure B with nuclear magnetic resonance **(NMR)**



Labster.com

ω_a^m: modulation of decay positron time spectrum

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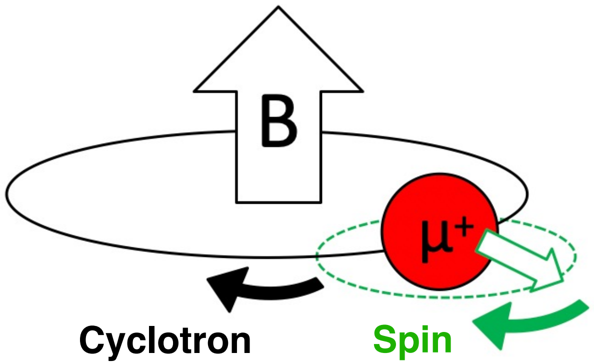
Muon $g-2$ Experiment at Fermilab

Experimental Principle

- The **muon precession frequency** is the rate at which the muon's spin and momentum accumulate relative angle:



$$\underbrace{\omega_C \qquad \omega_S}$$

$$\vec{\omega}_a = \vec{\omega}_S - \vec{\omega}_C$$

A 'real-world' equation:

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

$$\times \left[\frac{\mu_p'(T_r)}{\mu_e(H)} \frac{\mu_e(H)}{\mu_e} \frac{m_\mu}{m_e} \frac{g_e}{2} \right]$$

Muon $g-2$ Experiment at Fermilab

Experimental Principle

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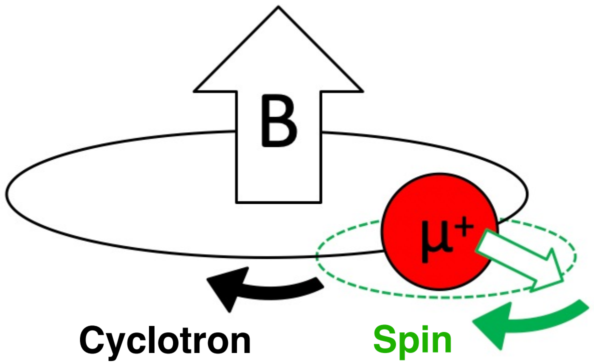


ω_C ω_S

$$\vec{\omega}_a = \vec{\omega}_S - \vec{\omega}_C$$

Corrections from Beam Dynamics

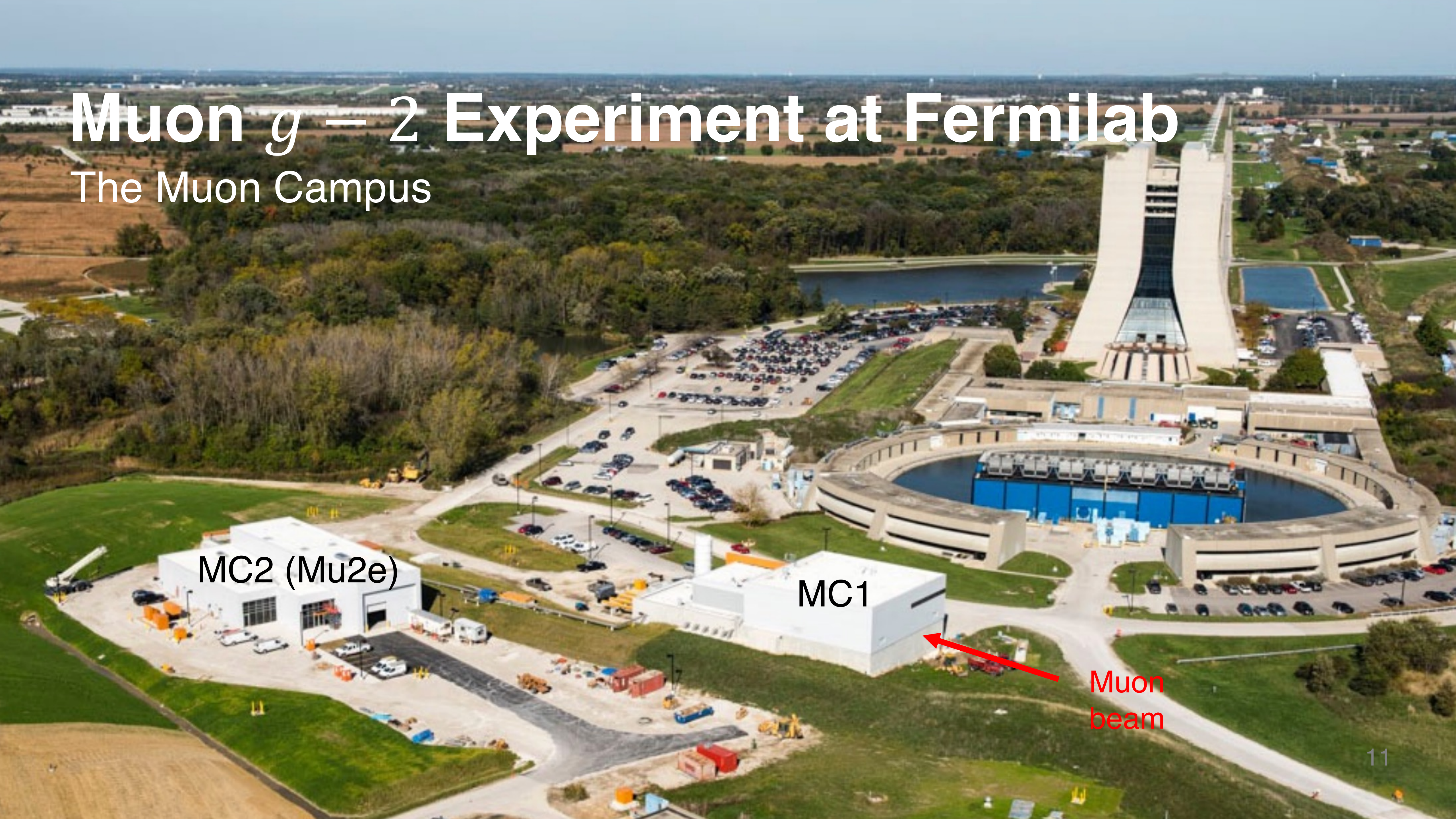
$$a_\mu = \frac{\omega_a^m}{\omega_p^m} \times \frac{(1 + C_e + C_p + C_{pa} + C_{dd} + C_{ml})}{(1 + B_k + B_q)} \times \left[\frac{\mu_p'(T_r)}{\mu_e(H)} \frac{\mu_e(H)}{\mu_e} \frac{m_\mu}{m_e} \frac{g_e}{2} \right]$$

Corrections from Magnetic Field Transient

External constants precisely known (to 25 ppb)

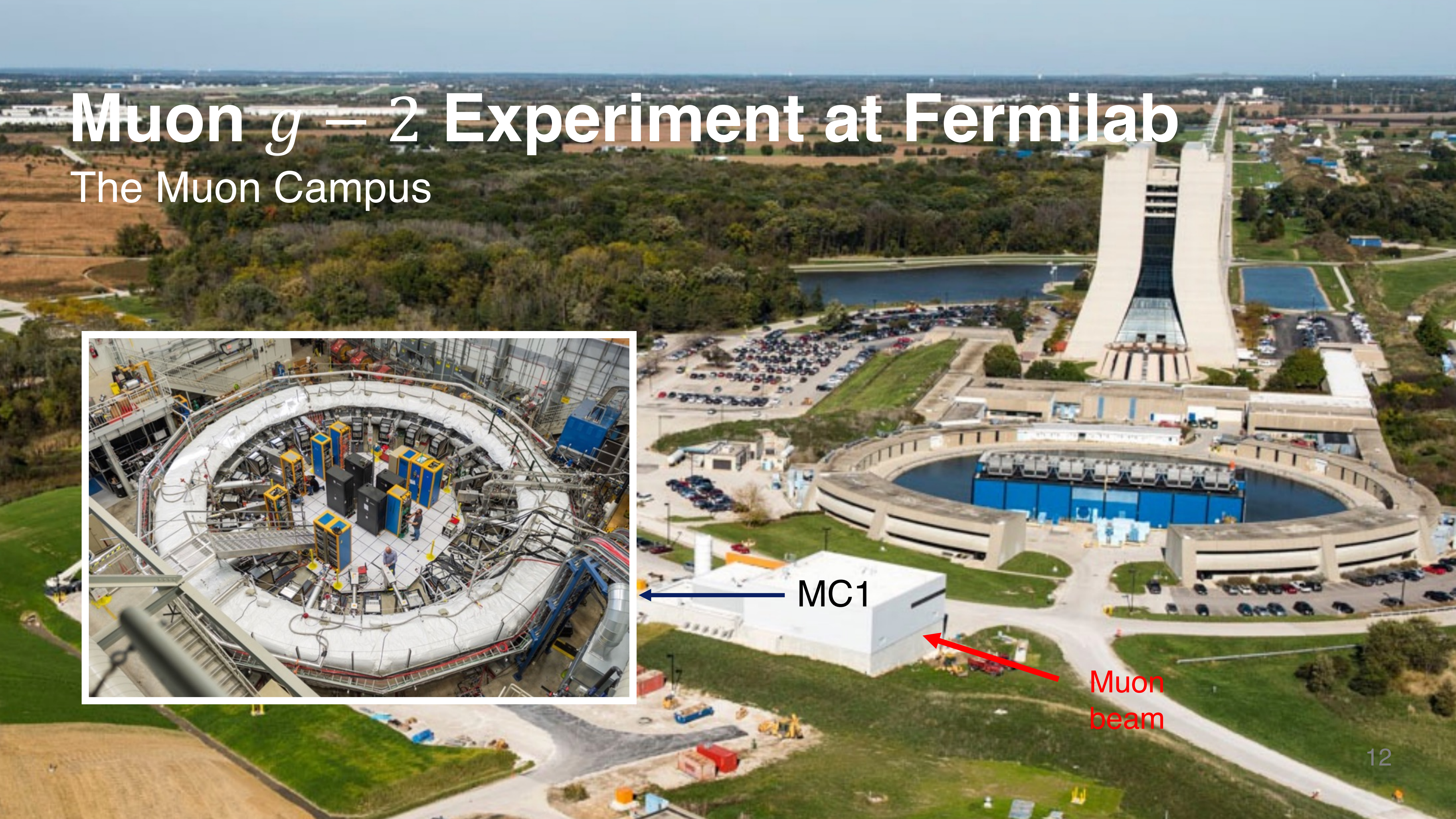
Muon $g-2$ Experiment at Fermilab

The Muon Campus



Muon $g-2$ Experiment at Fermilab

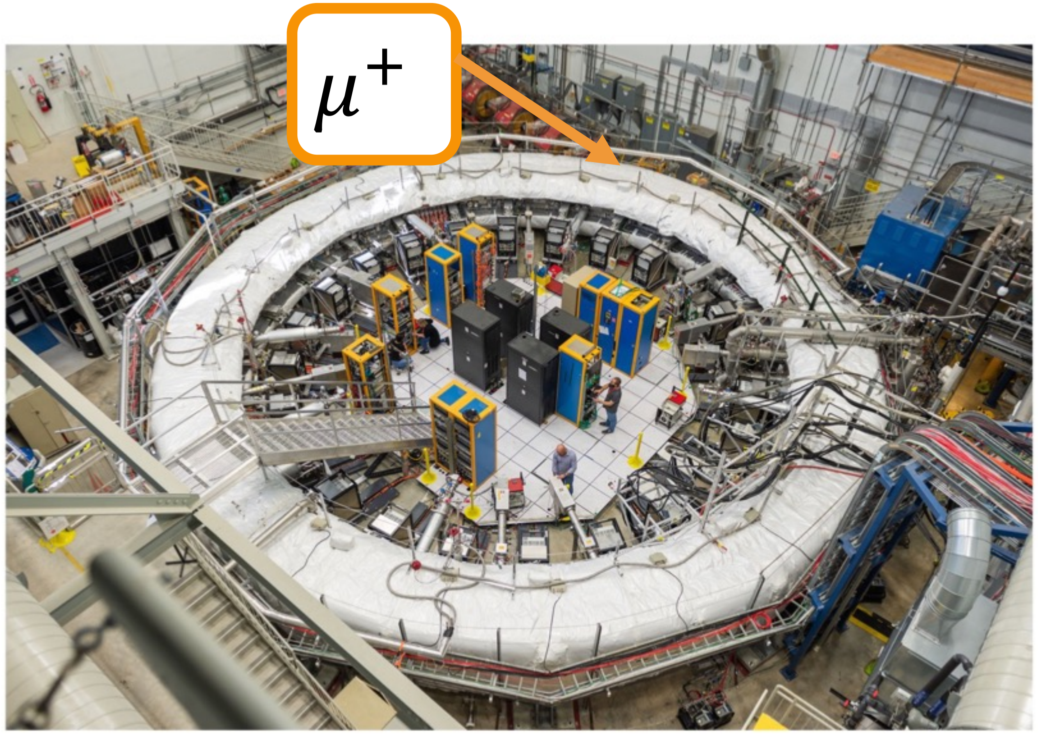
The Muon Campus



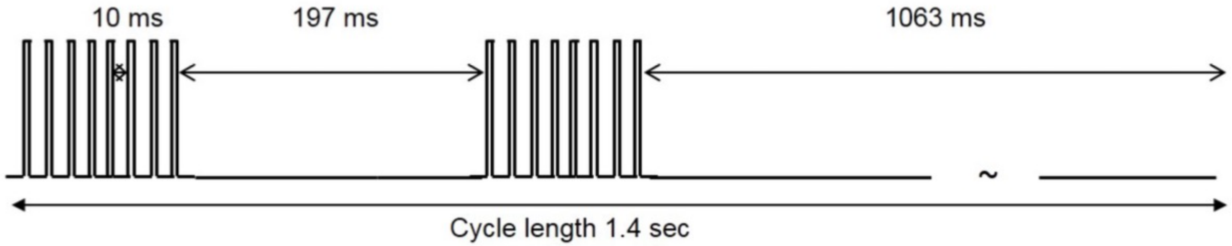
Muon $g-2$ Experiment at Fermilab

Setups: Injecting, Kicking, and Storing the Muon Beam

- **Polarized muon beam** from Fermilab accelerator



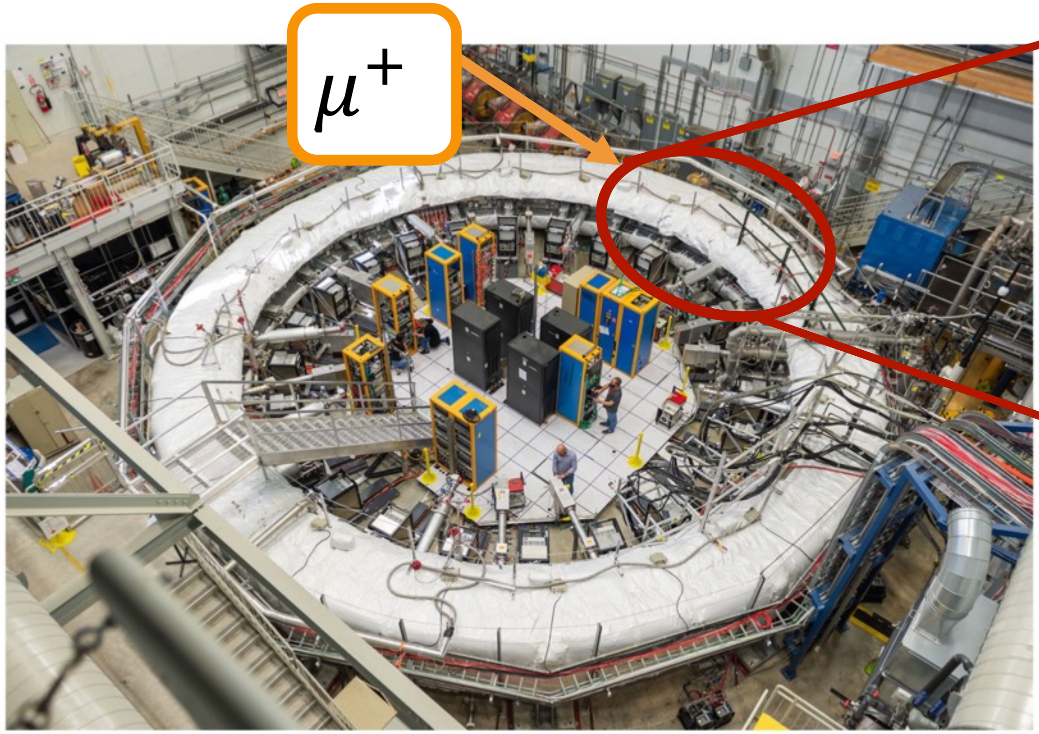
- **3.1 GeV/c** μ^+
- Cyclotron period: 149.2 ns
- A cycle of 16 bunches repeating every 1.4 seconds

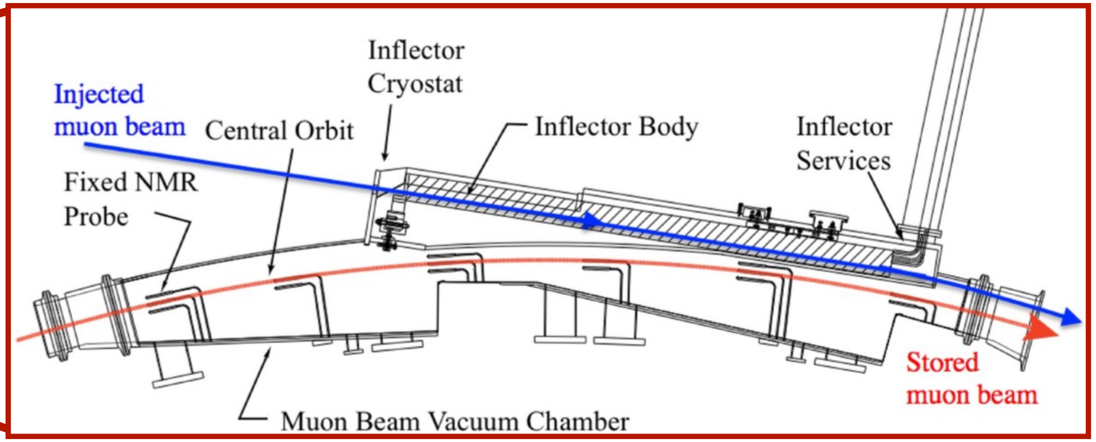


Muon $g - 2$ Experiment at Fermilab

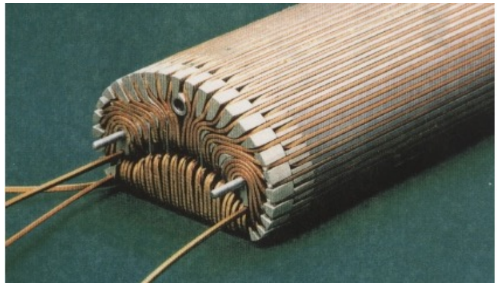
Setups: Injecting, Kicking, and Storing the Muon Beam

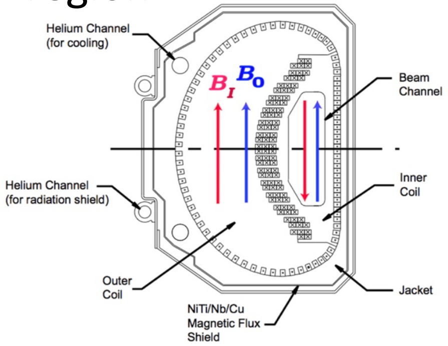
- **Inflector** helps injecting polarized muons into a storage ring





- Inflector creates a “field-free” region

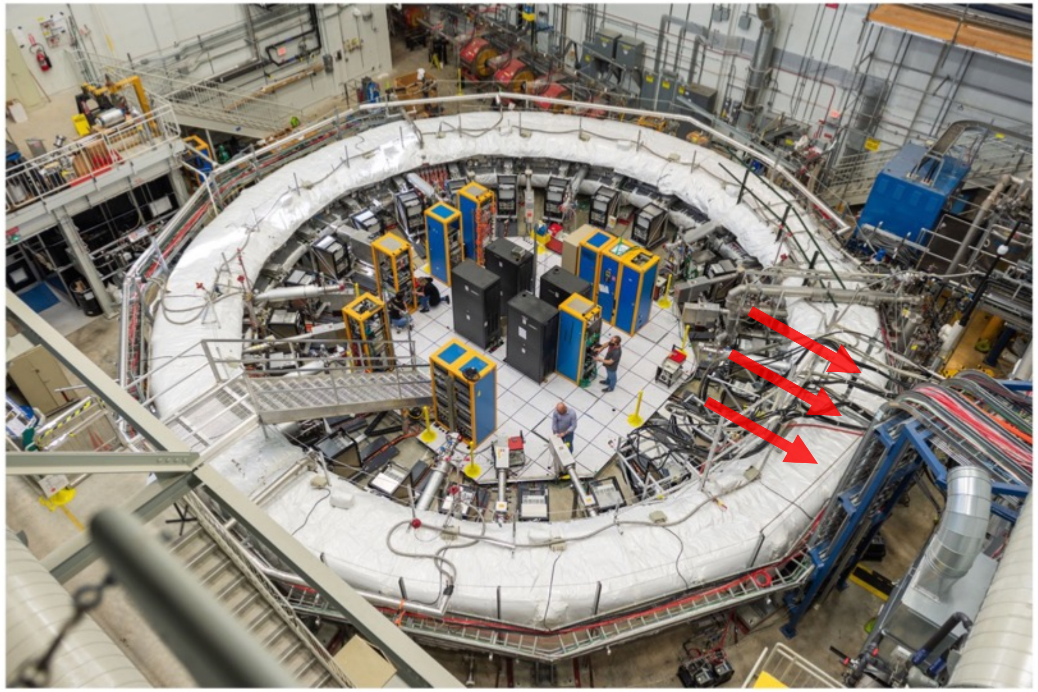


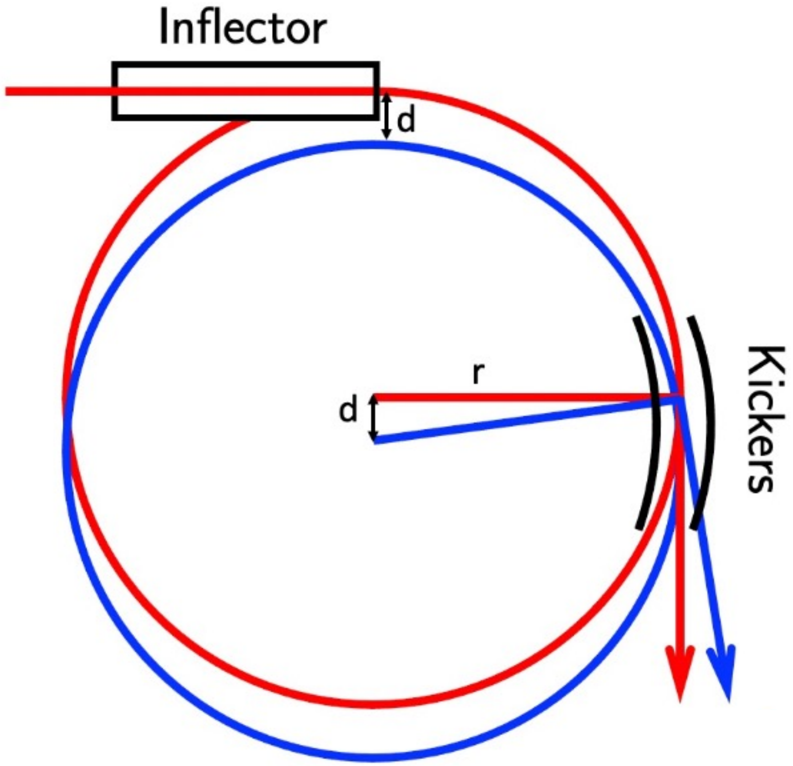


Muon $g - 2$ Experiment at Fermilab

Setups: Injecting, Kicking, and Storing the Muon Beam

- **Pulsed magnets kicker** changes muon angle to the good orbit (~10 mrad)

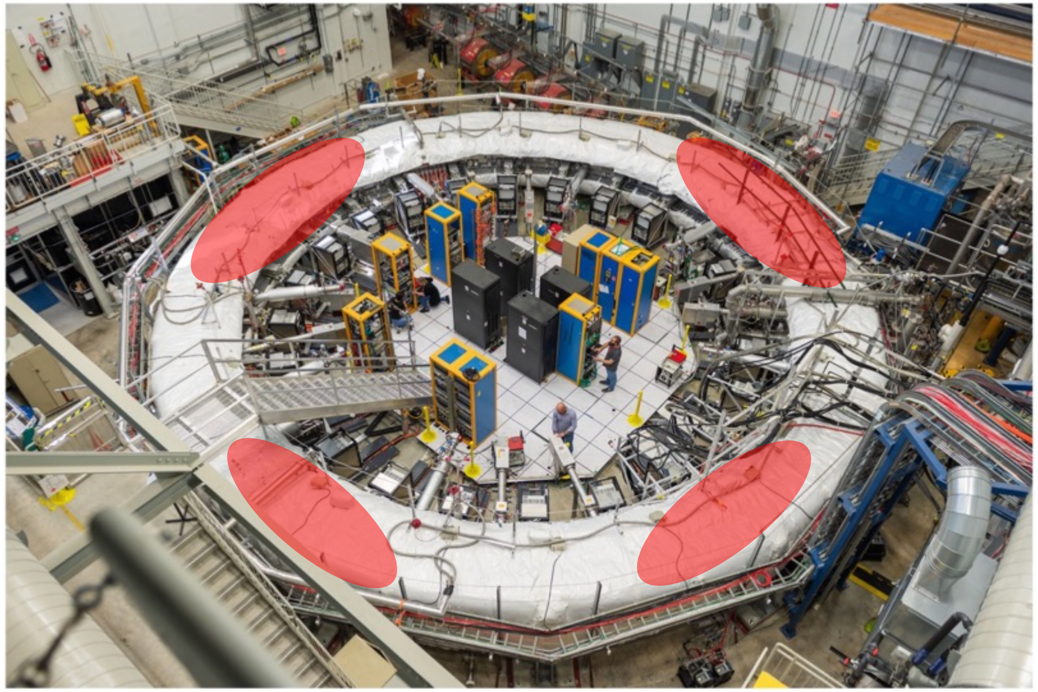


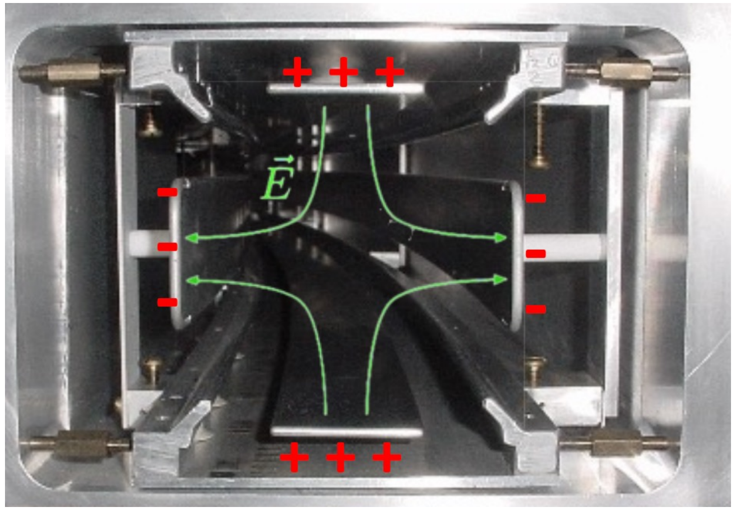


Muon $g-2$ Experiment at Fermilab

Setups: Injecting, Kicking, and Storing the Muon Beam

- **Electrostatic Quadrupoles (ESQ)** provide vertical focusing of the beam



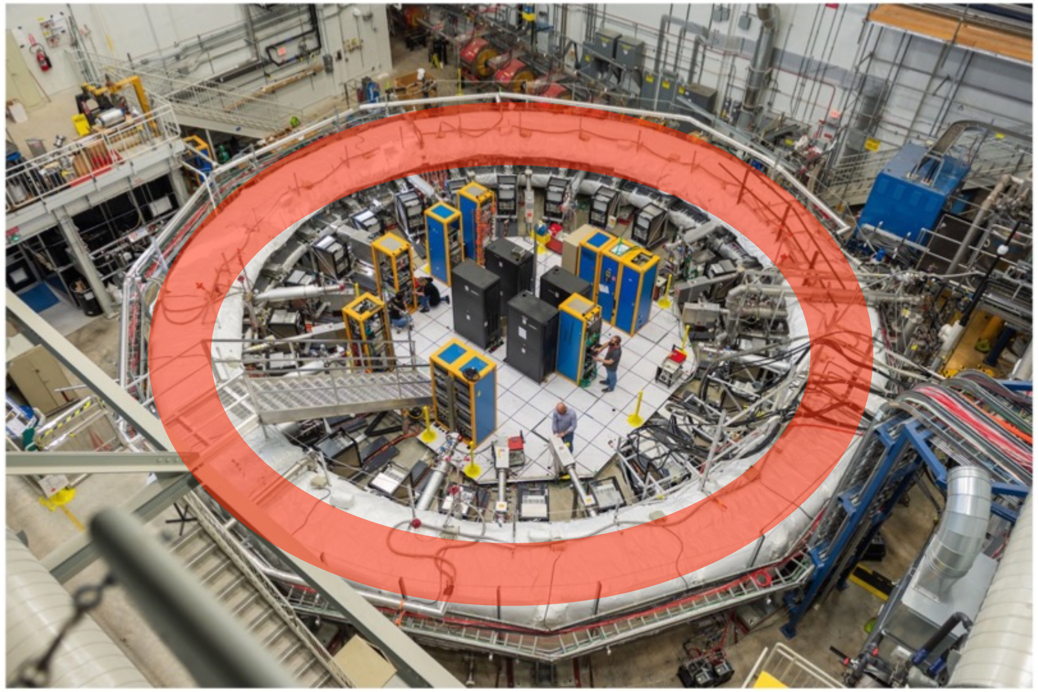


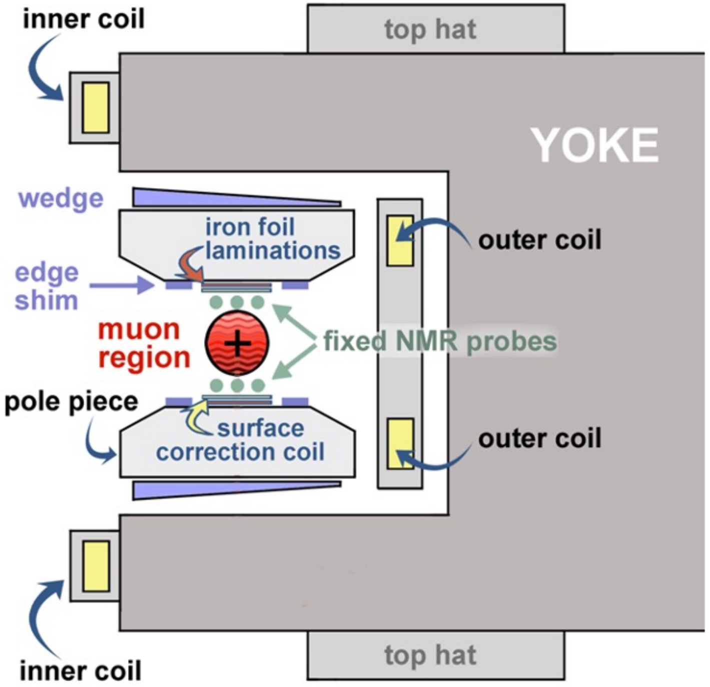
- Quads cover 43% of azimuth
- Focus beam to a simple harmonic motion about closed orbit

Muon $g-2$ Experiment at Fermilab

Setups: Injecting, Kicking, and Storing the Muon Beam

- **1.45T super-ferric magnet** shimmed to 50 ppm uniformity

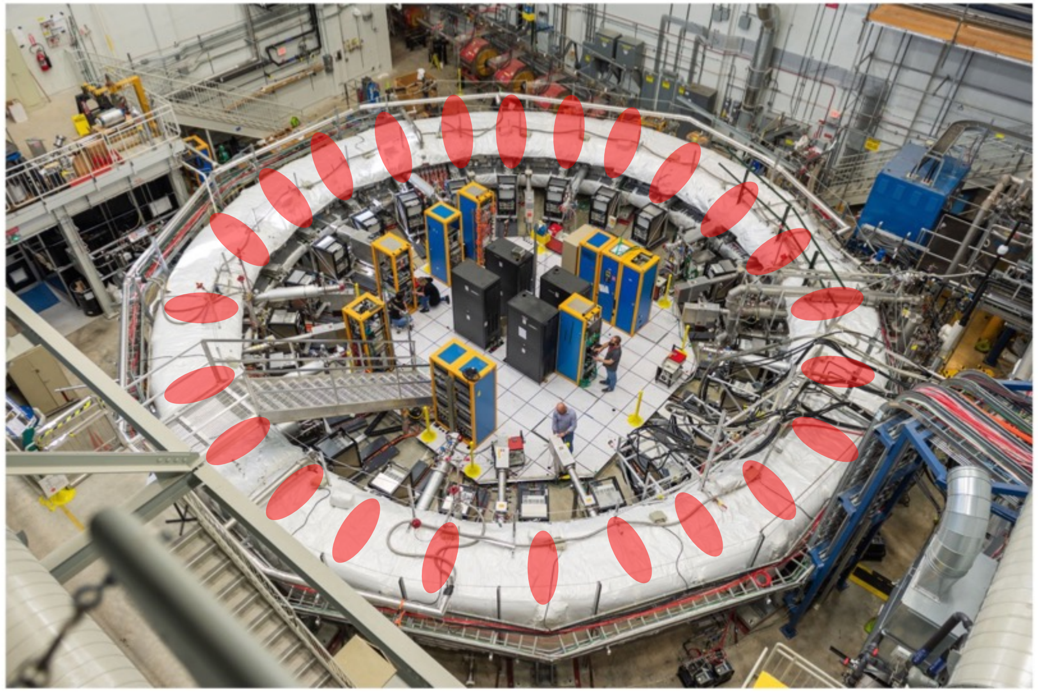


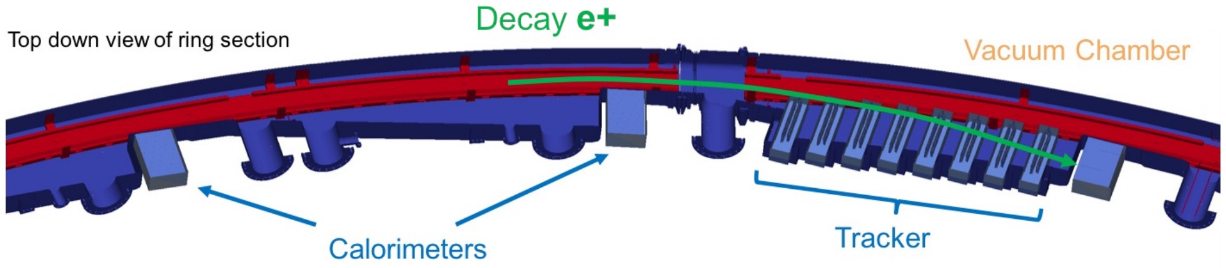


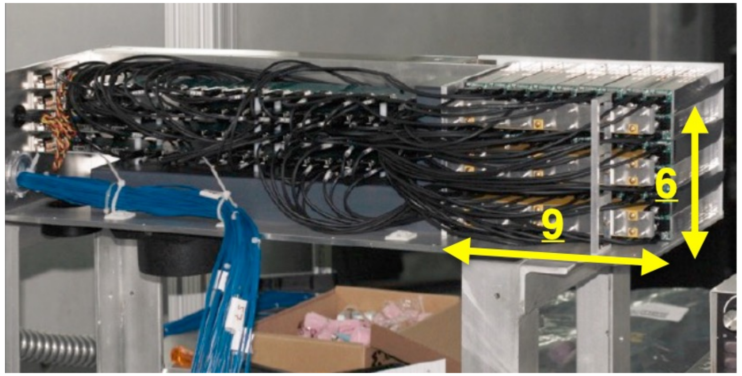
Muon $g-2$ Experiment at Fermilab

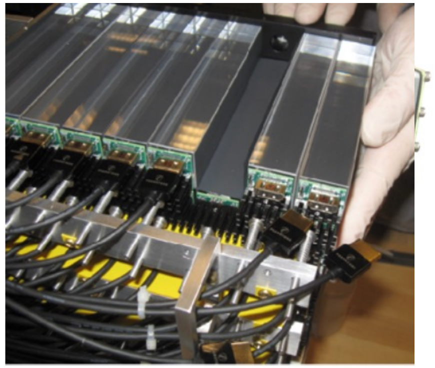
Setups: Detectors

- Detect decay positrons with 24 **calorimeters** and 2 **tracker** stations









PbF_2 crystals

Muon $g-2$ Experiment at Fermilab

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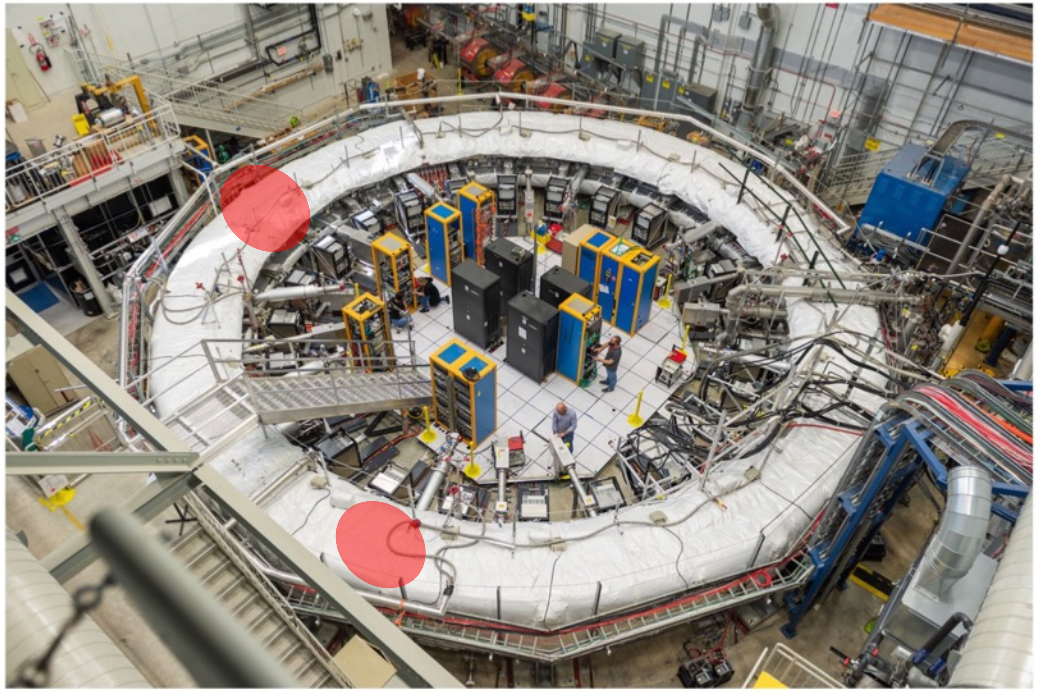
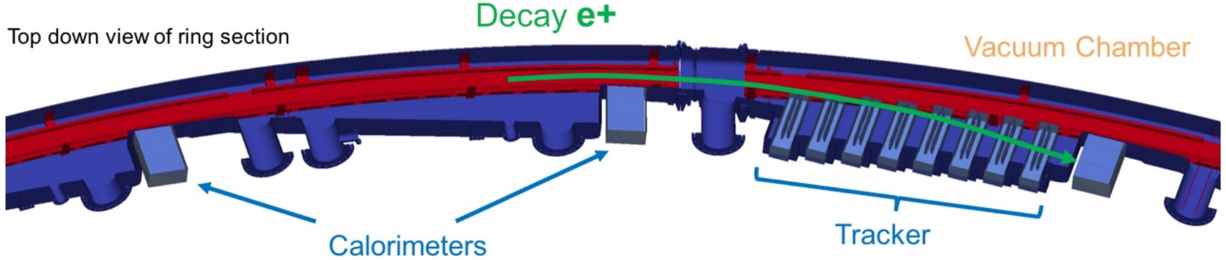
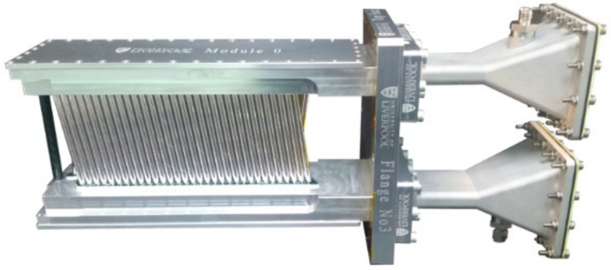
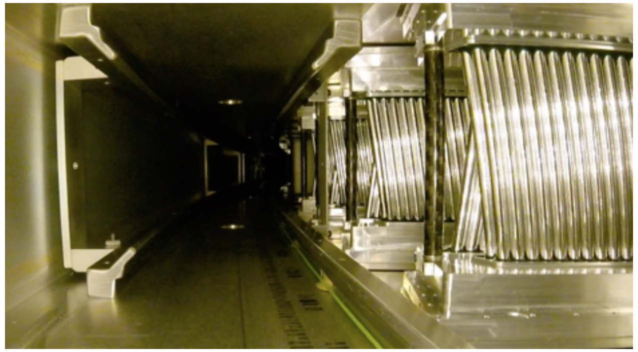




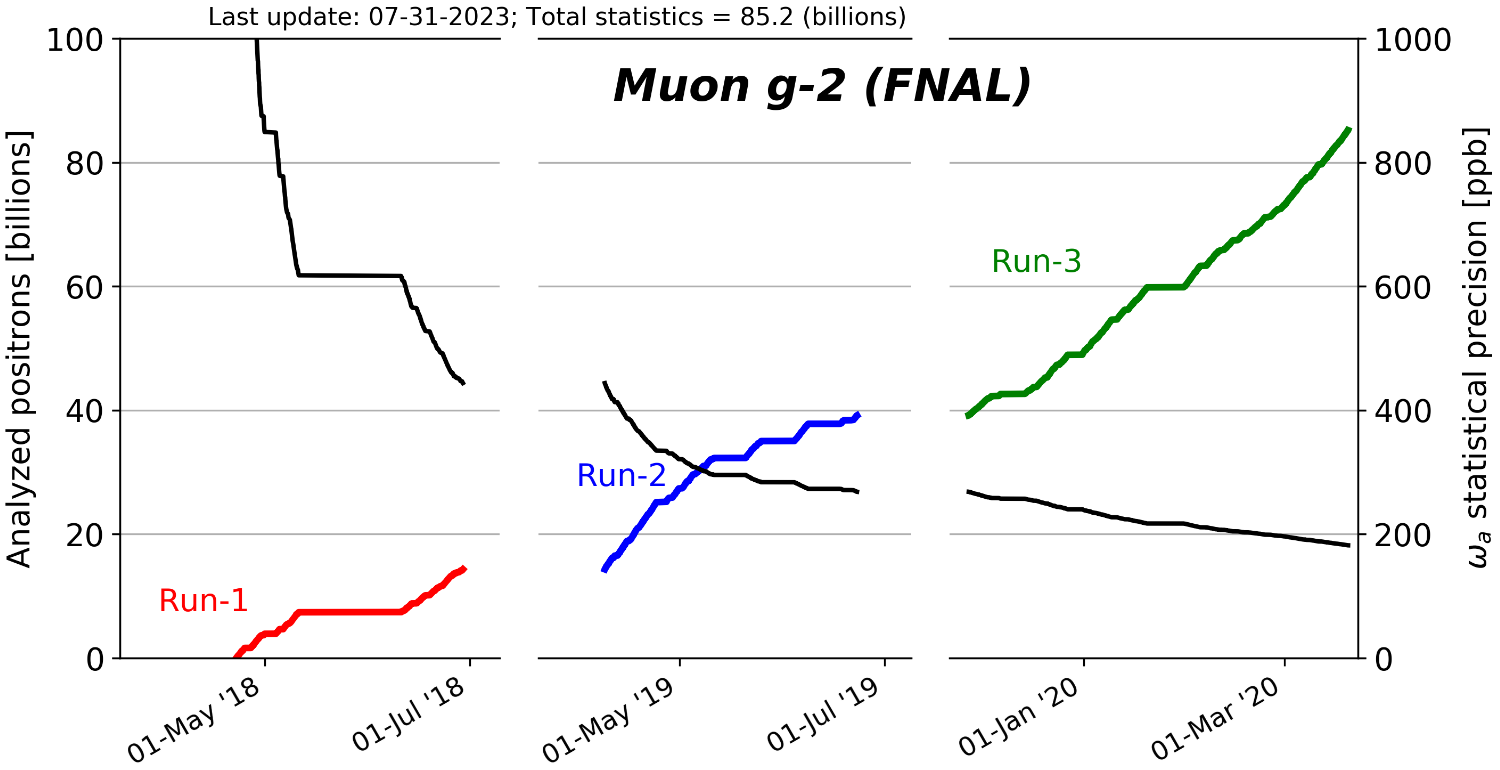




Straw tracker developed in Liverpool

Improvements in Run 2&3

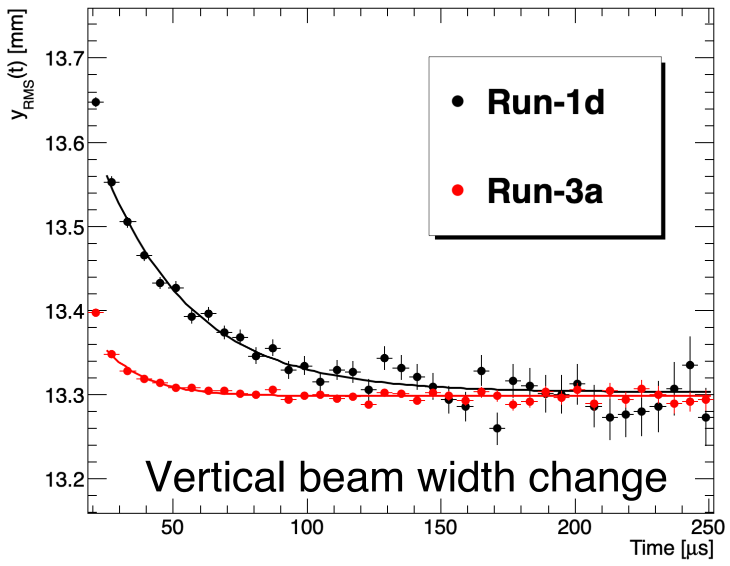
- Statistics: 4.7x more data in Run-2/3 than Run-1

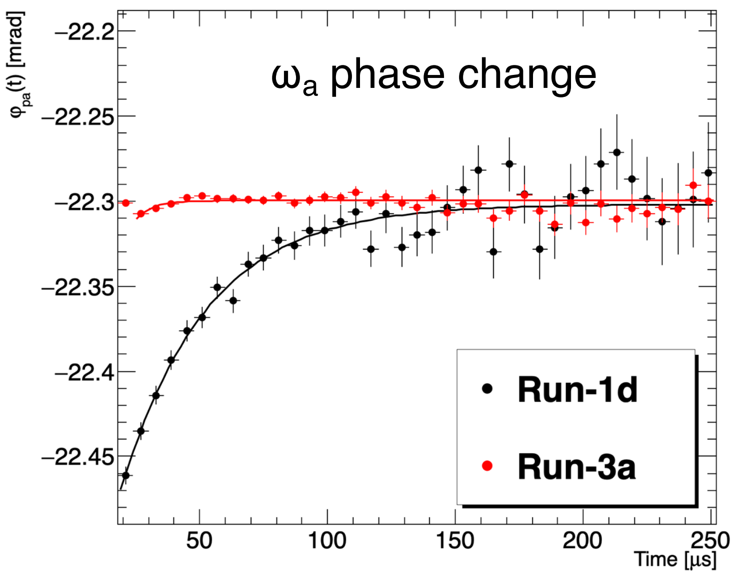


RUN	σ_{STAT} [ppb]
1	434
2+3	201
1+2+3	185

Improvements in Run 2&3

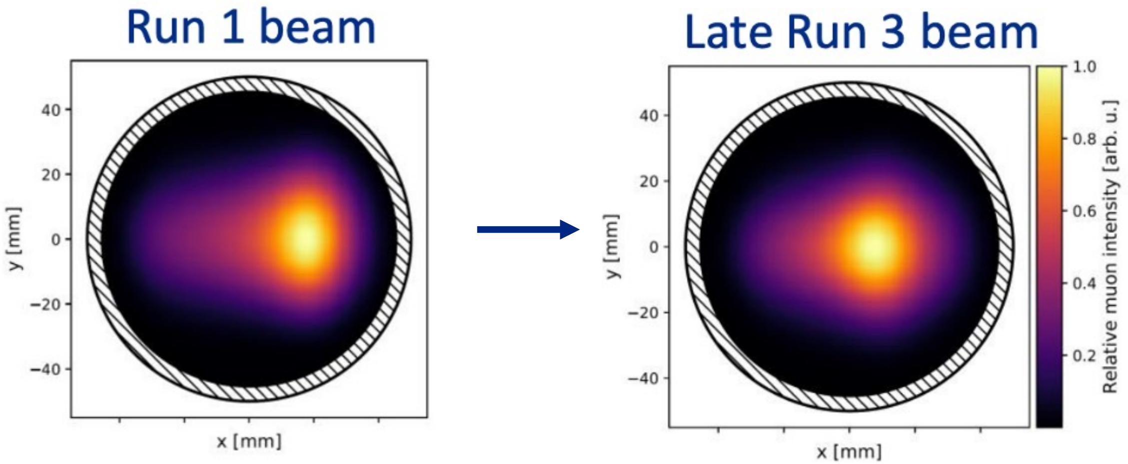
- Statistics: 4.7x more data in Run-2/3 than Run-1
- Running conditions
  1) **Re-designed resistors** lead to stable beam storage





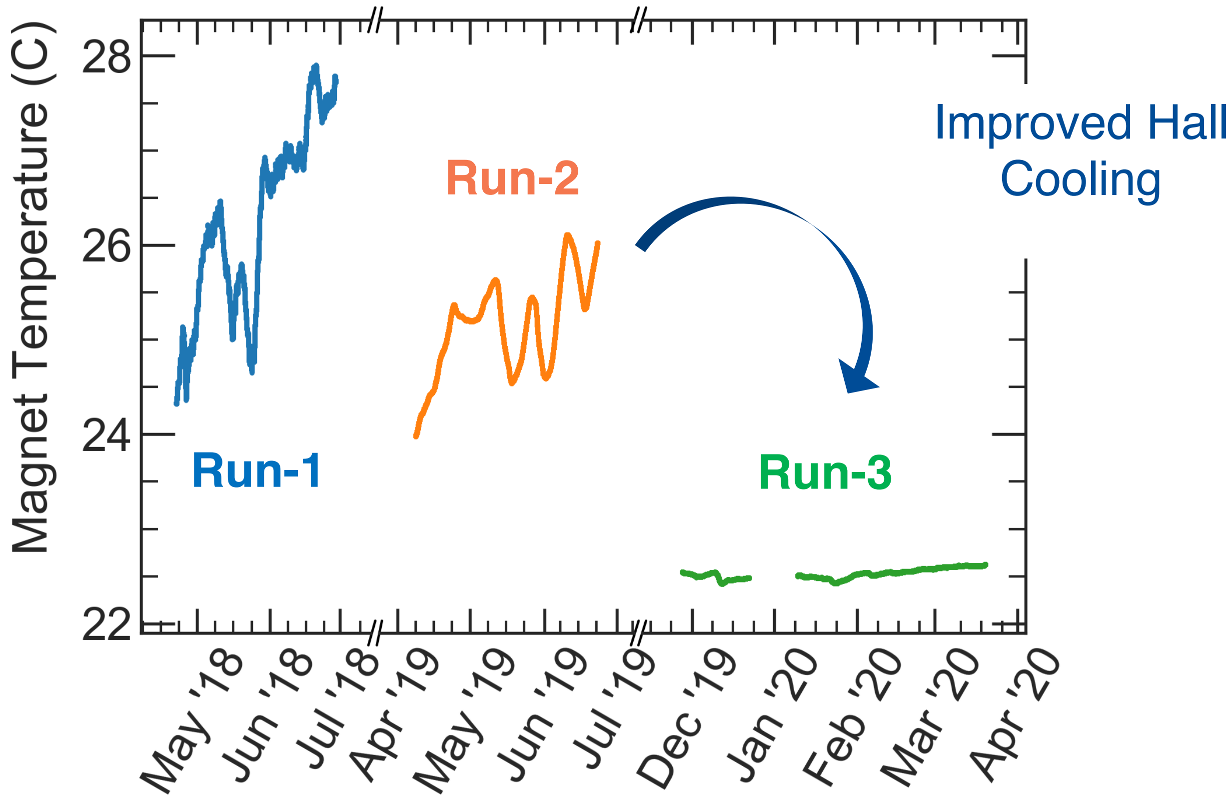
Improvements in Run 2&3

- Statistics: 4.7x more data in Run-2/3 than Run-1
- Running conditions
  1) **Re-designed resistors**
  2) **Stronger kicker strength** moved the beam closer to the center, reduce beam oscillation and E-field correction



Improvements in Run 2&3

- Statistics: 4.7x more data in Run-2/3 than Run-1
- Running conditions
  1) **Re-designed resistors**
  2) **Stronger kicker strength**
  3) **Improved hall temperature** stability makes the magnetic field less variable



Improvements in Run 2&3

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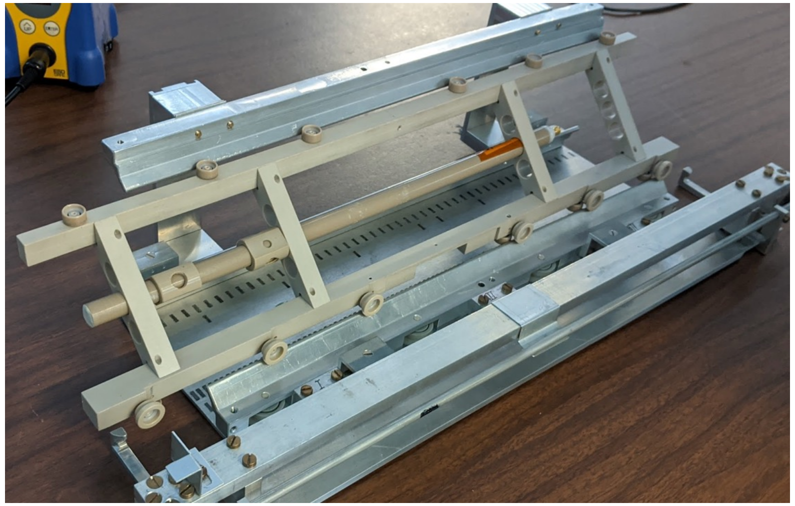
- Measurements on:
  1) **Quad Transient Field** with a new NMR probe in an insulator



Measurement probe mounted on trolley rail train allows full mapping of all quad stations

Improvements in Run 2&3

- Statistics: 4.7x more data in Run-2/3 than Run-1
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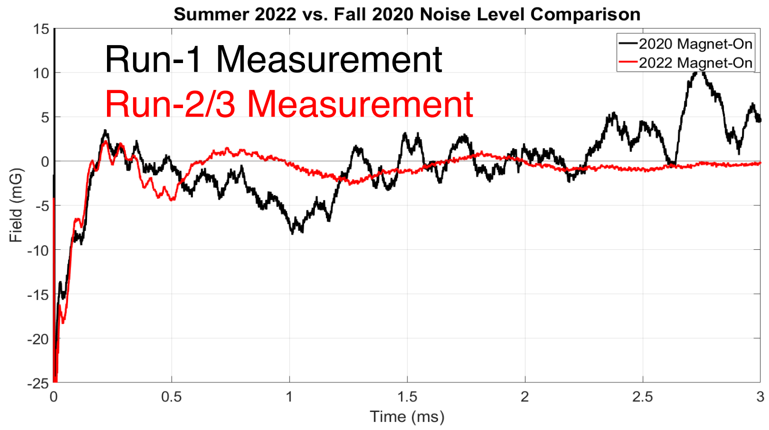
- Measurements on:
  1) **Quad Transient Field** with a new NMR probe in an insulator
  2) **Kicker Transient Field** has lower vibration noise in Run 2/3



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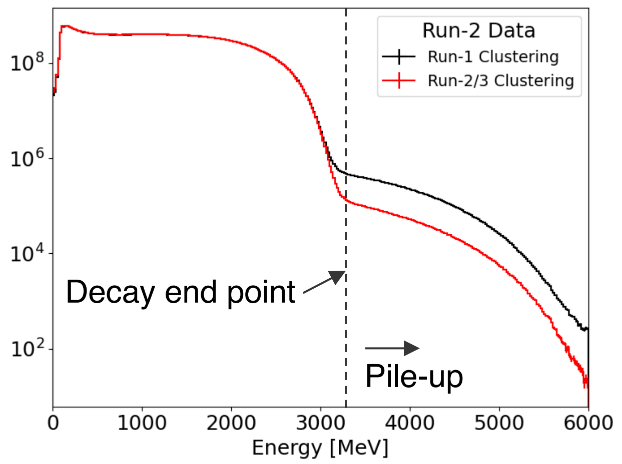
- Analysis:
  - **Pile-up** with improved algorithm



Improvements in Run 2&3

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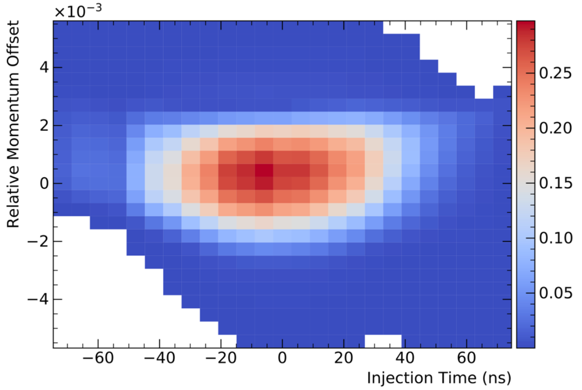
    - **E-field correction** includes Time-momentum correlation



Improvements in Run 2&3

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- Analysis:
  - **Pile-up** with improved algorithm
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Systematic uncertainty of 70 ppb surpasses our proposal goal of 100 ppb!

Putting it all together

24th of July, 2023

- Unblinding meeting in Liverpool:

Putting it all together

24th of July, 2023

- Unblinding meeting in Liverpool:

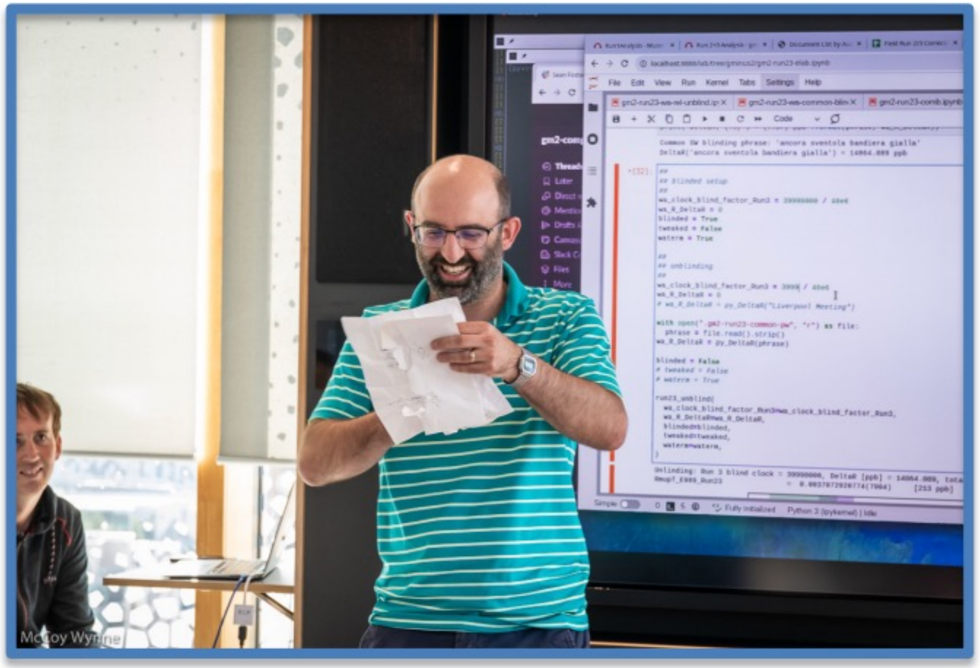
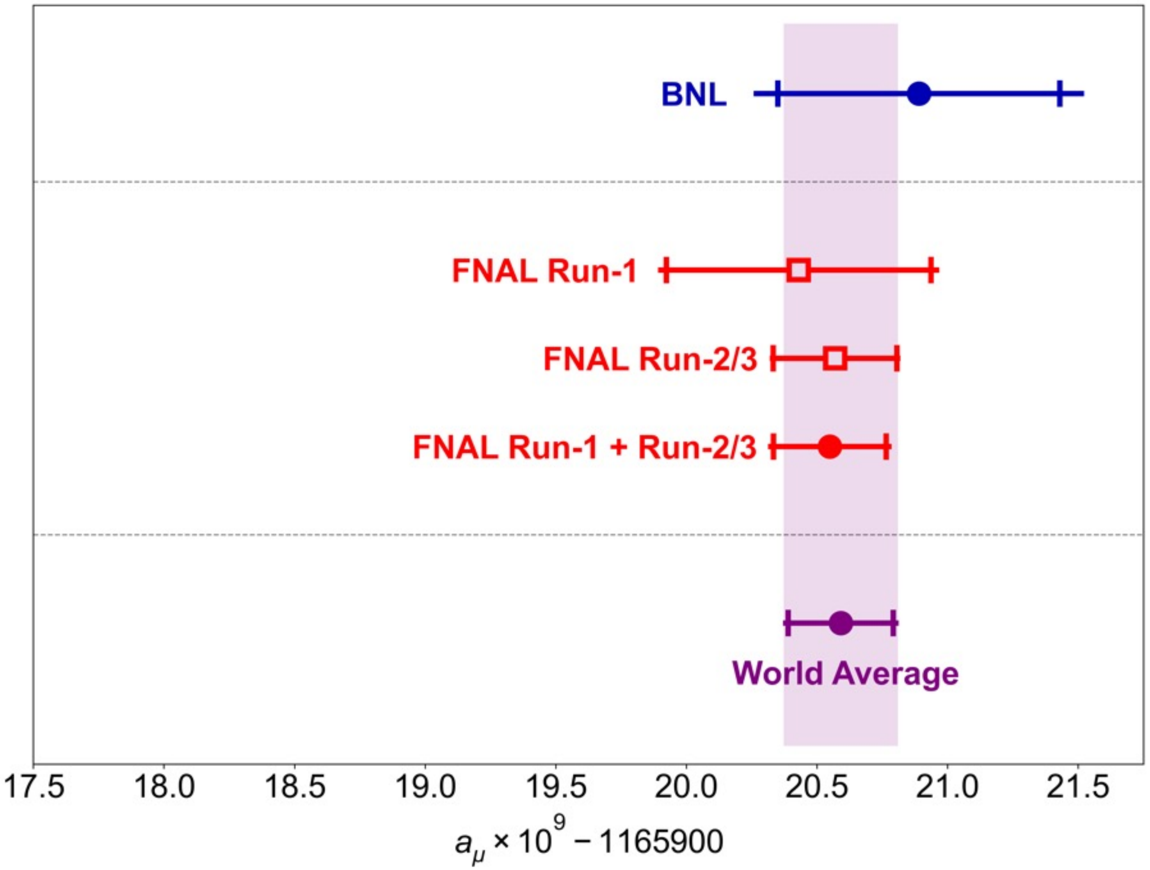


Photo credits: McCoy Wynne

Right here! We were at the spine building ↑

Run 2+3 Result

FNAL + BNL Combination



a_μ(FNAL; Run-2/3) = 0.00 116 592 057(25) [215 ppb]

a_μ(FNAL) = 0.00 116 592 055(24) [203 ppb]

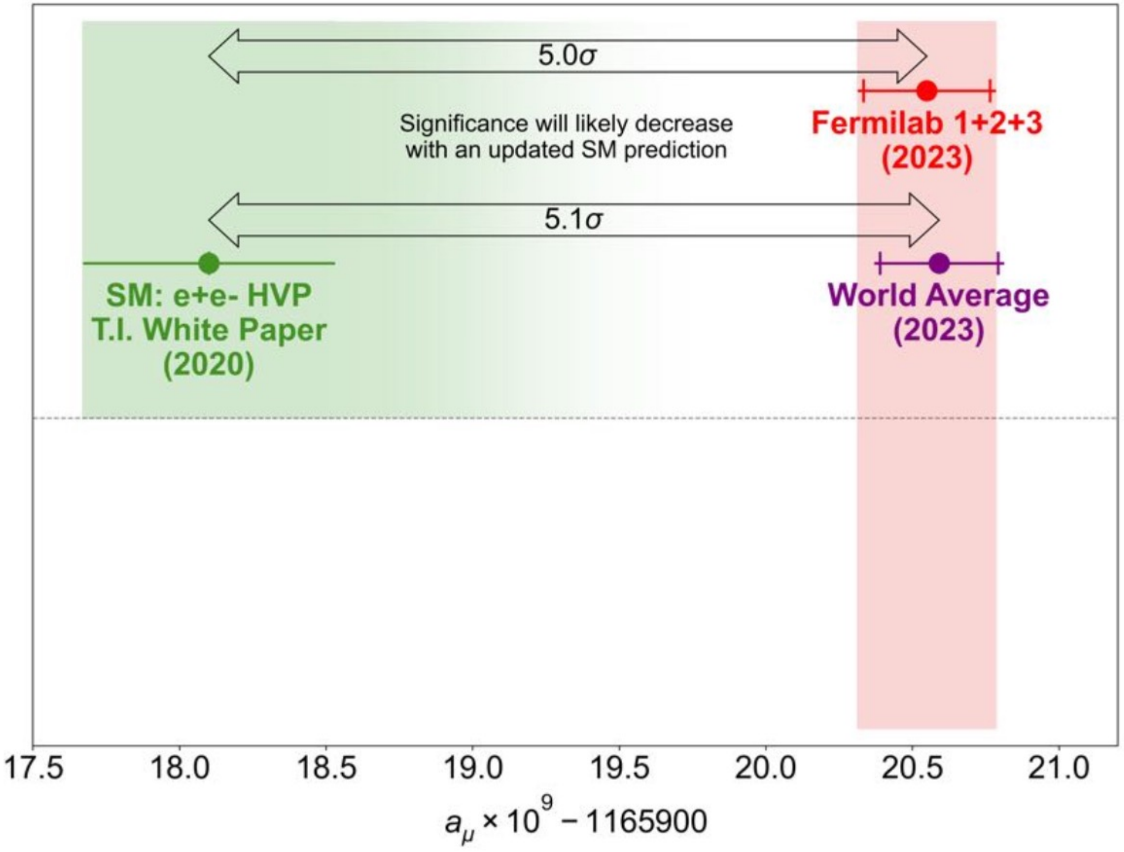
- **Excellent agreement with Run-1 and BNL**
- Uncertainty more than halved to **215 ppb**
- FNAL combination: **203 ppb** uncertainty

a_μ(Exp) = 0.00 116 592 059(22) [190 ppb]

Phys. Rev. Lett 131.161802 (October 2023)
Detailed Report: arXiv 2402.15410 (February 2024)

Run 2+3 Result

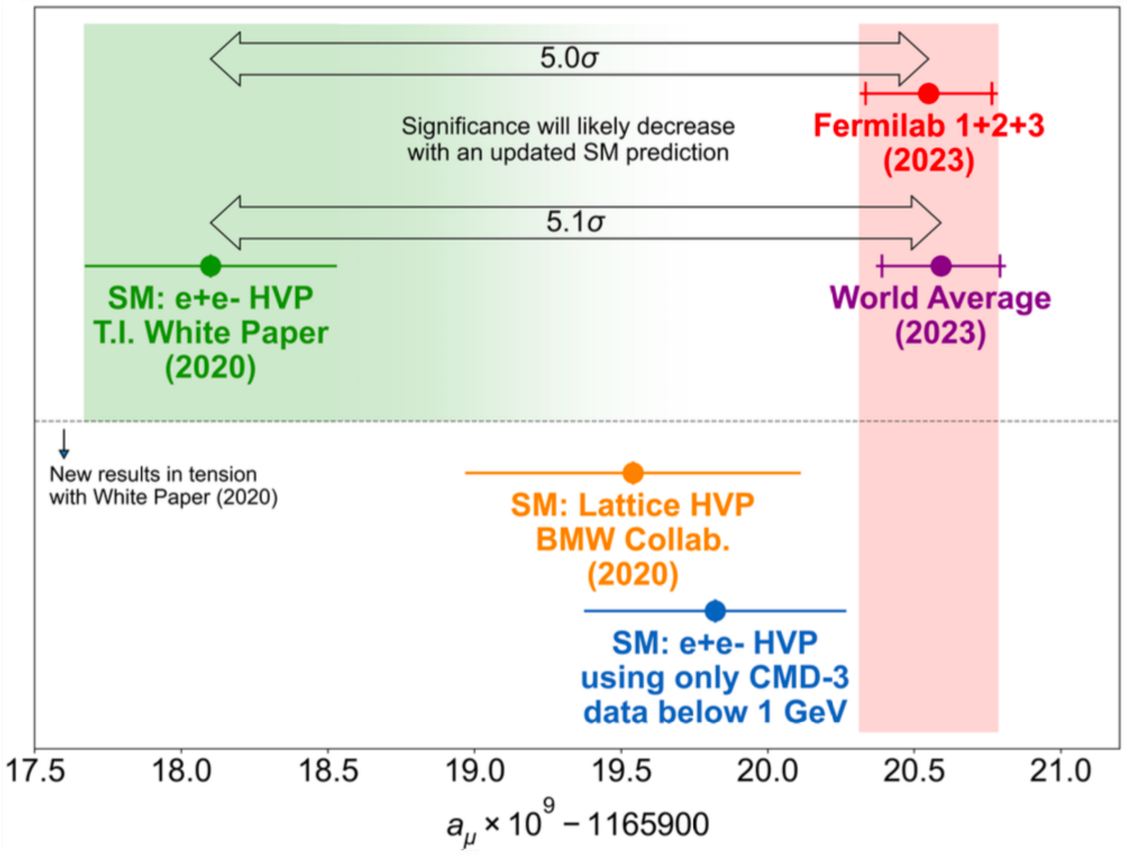
Discrepancy between Experiments & Theories



- New experimental average with SM prediction (WP-2020) gives > 5σ

Run 2+3 Result

Discrepancy between Experiments & Theories



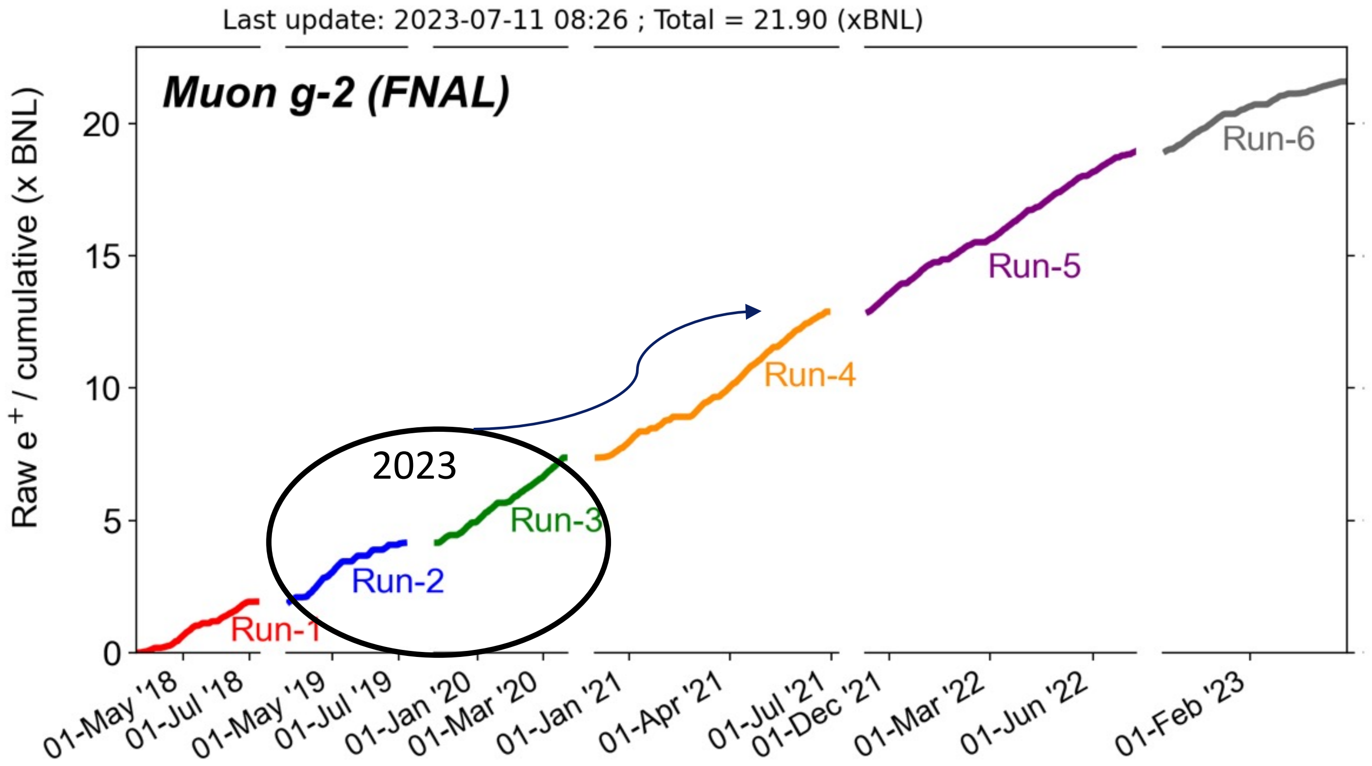
- New experimental average with SM prediction (WP-2020) gives > 5σ
- Since then, two important developments on SM prediction:
  - Lattice QCD from the BMW (2020)
  - New $e^+e^- \rightarrow \pi^+\pi^-$ cross section from CMD-3 (2023)

> **Disclaimer:**
> The CMD-3 point is a visual exercise. It is not a fully updated SM prediction!

- 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!

Even More Improvements in Run 4/5/6

- With Run4+5+6 data, we can **double our sensitivity again** and likely surpass our goal of 140ppm total uncertainty

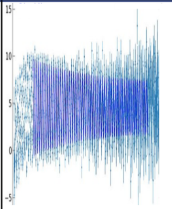
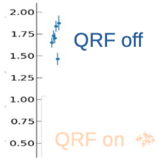
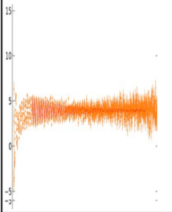
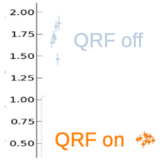
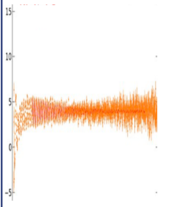
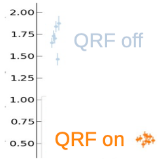


RUN	σ_{STAT} [ppb]
1	434
2+3	201
4+5+6	107 (est.)
1+2+3+4+5+6	90 (est.)

Even More Improvements in Run 4/5/6

- In addition to statistics, lots of improvements are made to move to the next level, in particular:

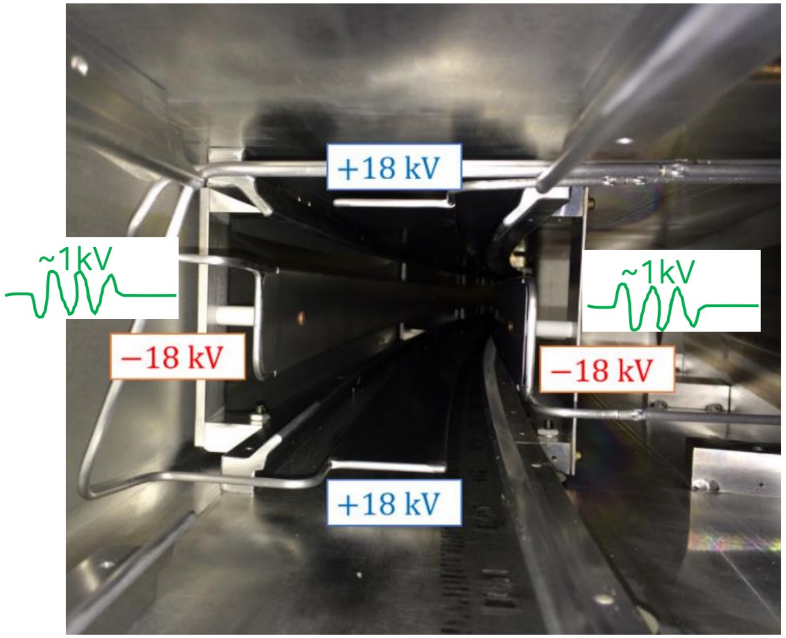
1) Quad RF system
2) New detector ('mini sci-fi')
3) Analysis techniques

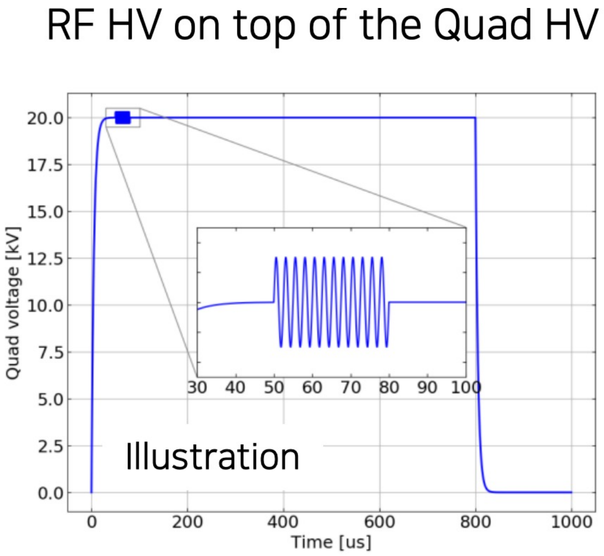
	kickers	quadrupoles	CBO	muon loss	typical ctags
Run4	165 kV	18.2 kV, n= 0.108, RF off			~500
Run5	165 kV	18.2 kV, n= 0.108, RF on			~400
Run6	165 kV	18.2 kV, n= 0.108, RF on			~350

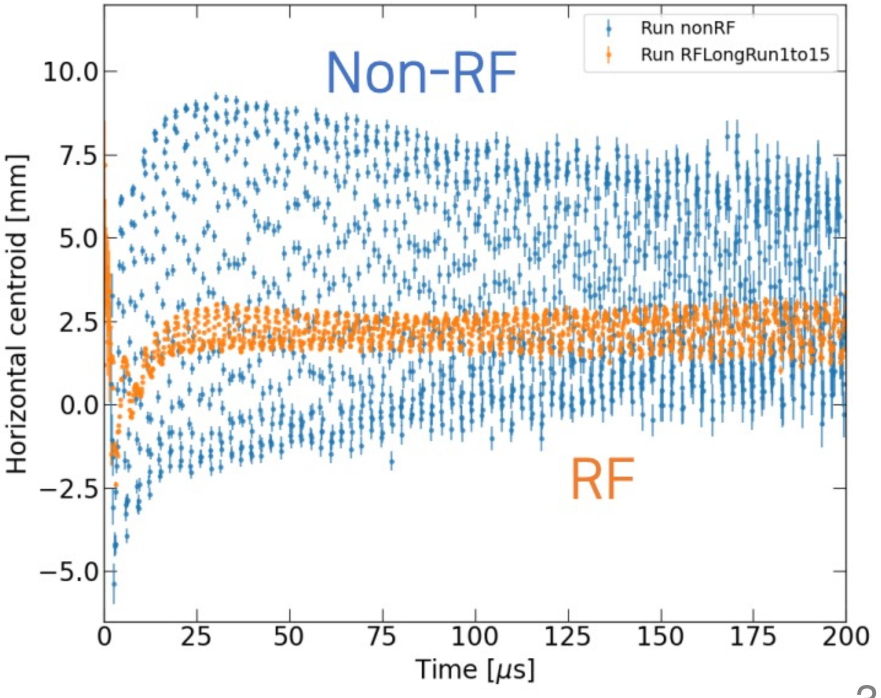
Even More Improvements in Run 4/5/6

1) Quad RF system

- Quadrupole radio frequency (RF) system from Run 5 helps reduced horizontal beam oscillations



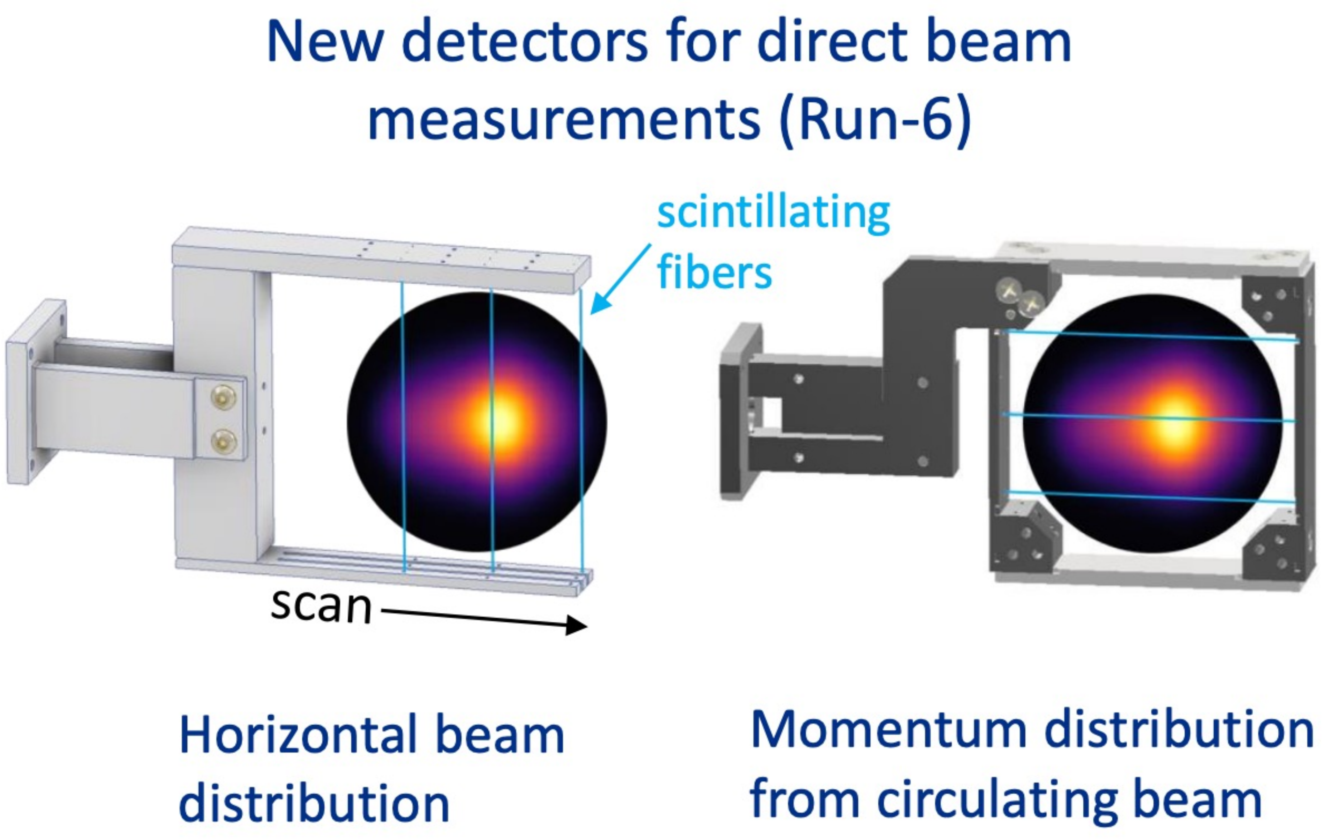




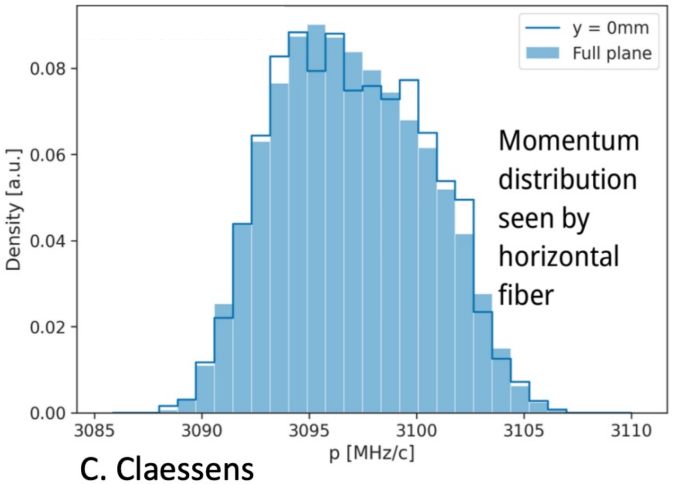
On Kim et. al, New J. Phys. 22, 063002 (2020)

Even More Improvements in Run 4/5/6

2) New ‘mini sci-fi’ detector



- 3 Fibers with 250 μm diameter measure circulating beam fast rotation intensity
- Better understanding & modeling of beam dynamics → improve the systematics

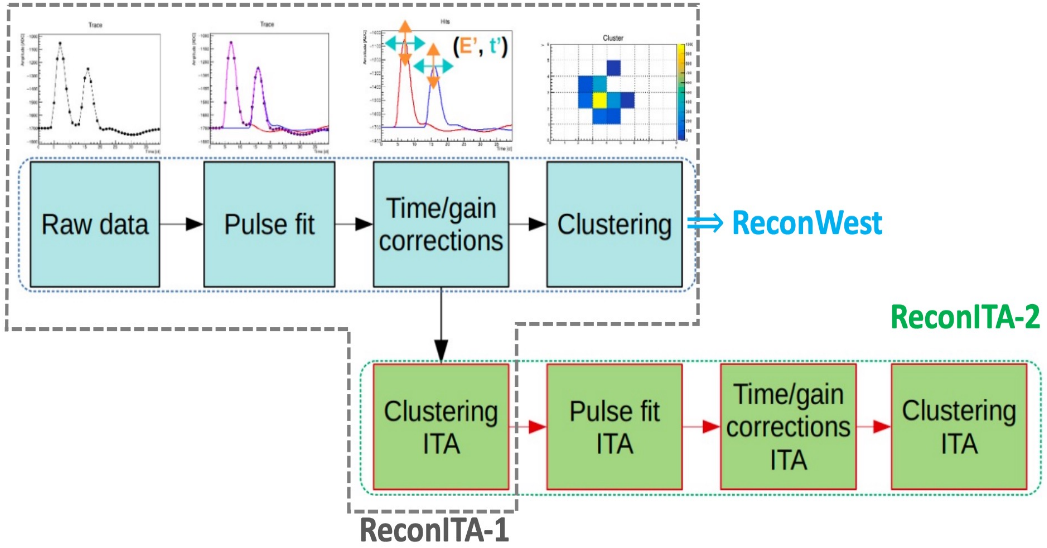


C. Claessens

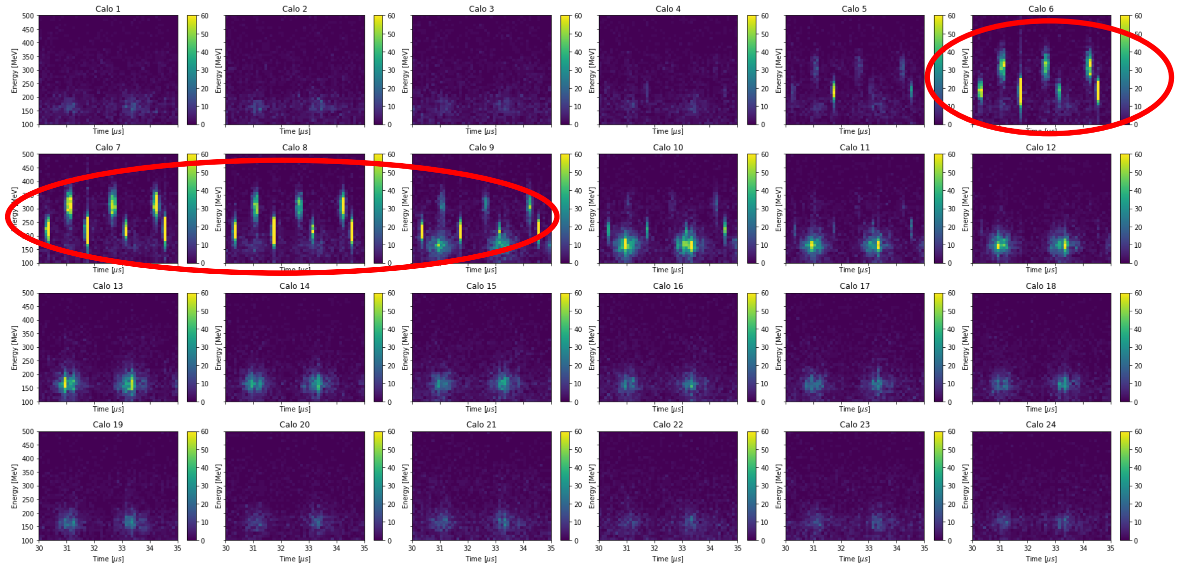
Even More Improvements in Run 4/5/6

3) Improved analysis technique

- Clustering algorithm and improved lost muon selection help to reduce hadronic contamination



New clustering algorithm ('RITA2') to be implemented in the analysis in the Europa group



Energy-time spectrum in 24 calorimeters see proton/deuteron leakage (Run-4)

Conclusions

- In Run-2/3, we have determined muon $g - 2$ to an unprecedented **203 ppb** precision:
  - In excellent agreement with Run-1 & BNL
  - With more than halved the total uncertainty from Run-1, we have surpassed our TDR goals in statistics and systematics

- For Run-4/5/6, more improvements have been made:
  - Statistical reduction by another factor of 2 and further improved systematics
  - The final result in 2025 → stay tuned!

Thanks!

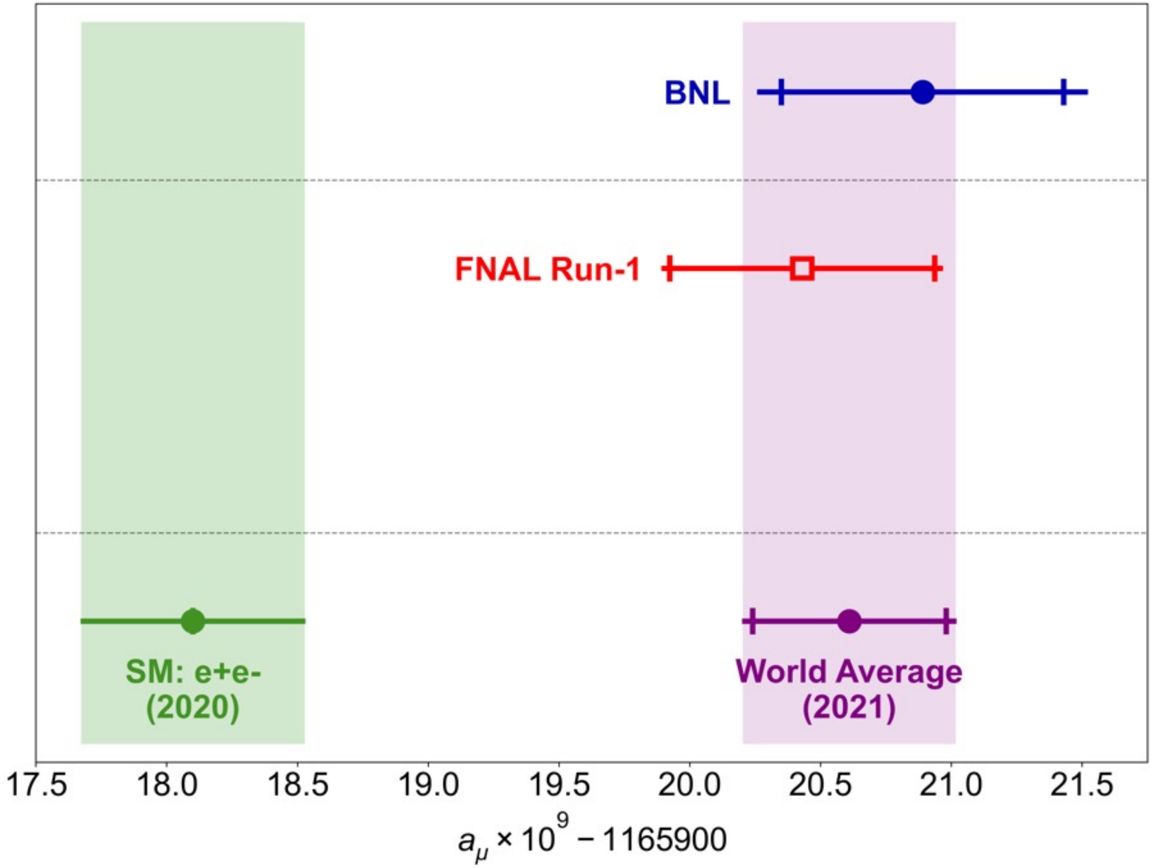
Acknowledgements

- 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)

Backup

Run 2&3 Result

Starting Point: Run-1 Result, 2020



SM: Muon g – 2 Theory Initiative white paper value
https://doi.org/10.1016/j.physrep.2020.07.006

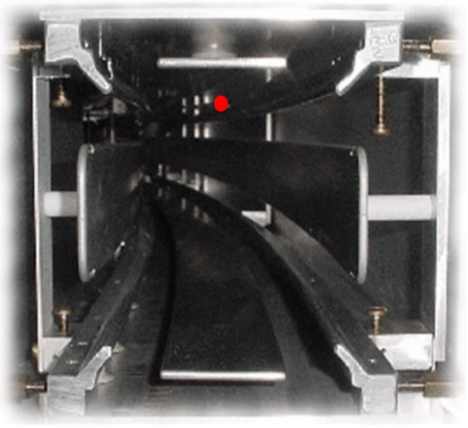
a_μ(FNAL; Run-1) = 0.00 116 592 040(54) [463 ppb]

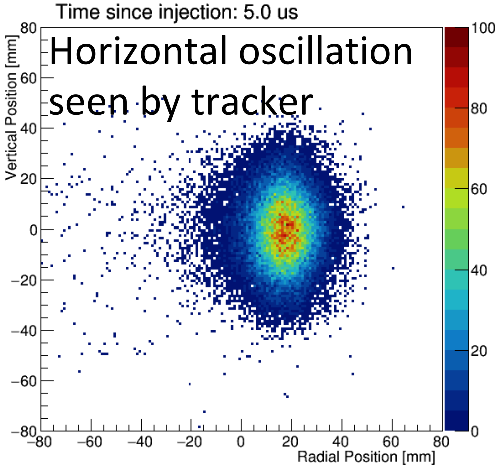
a_μ(Exp) = 0.00 116 592 061(41) [350 ppb]

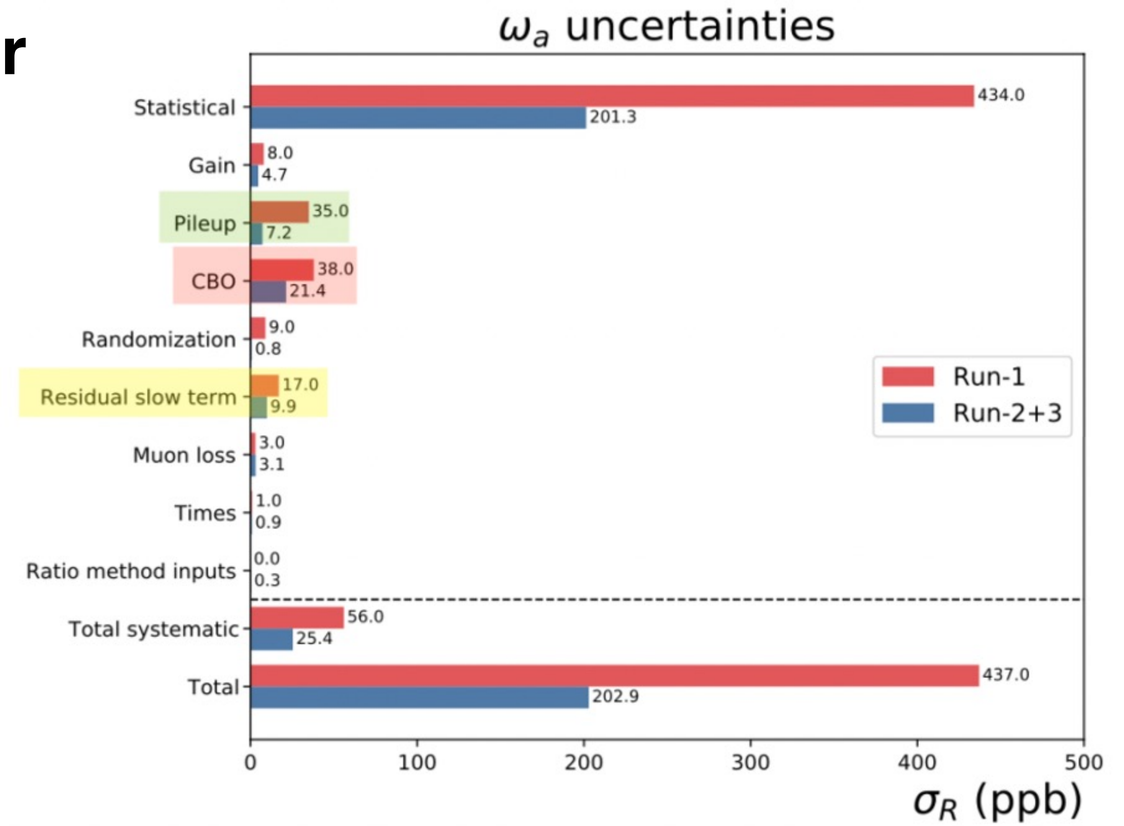
Muon Precession Frequency

Extra terms in the Fitting Function

- A better model must account for **detector effects**, **beam oscillations** coupled to acceptance, **lost muons** and **fast rotations** effects





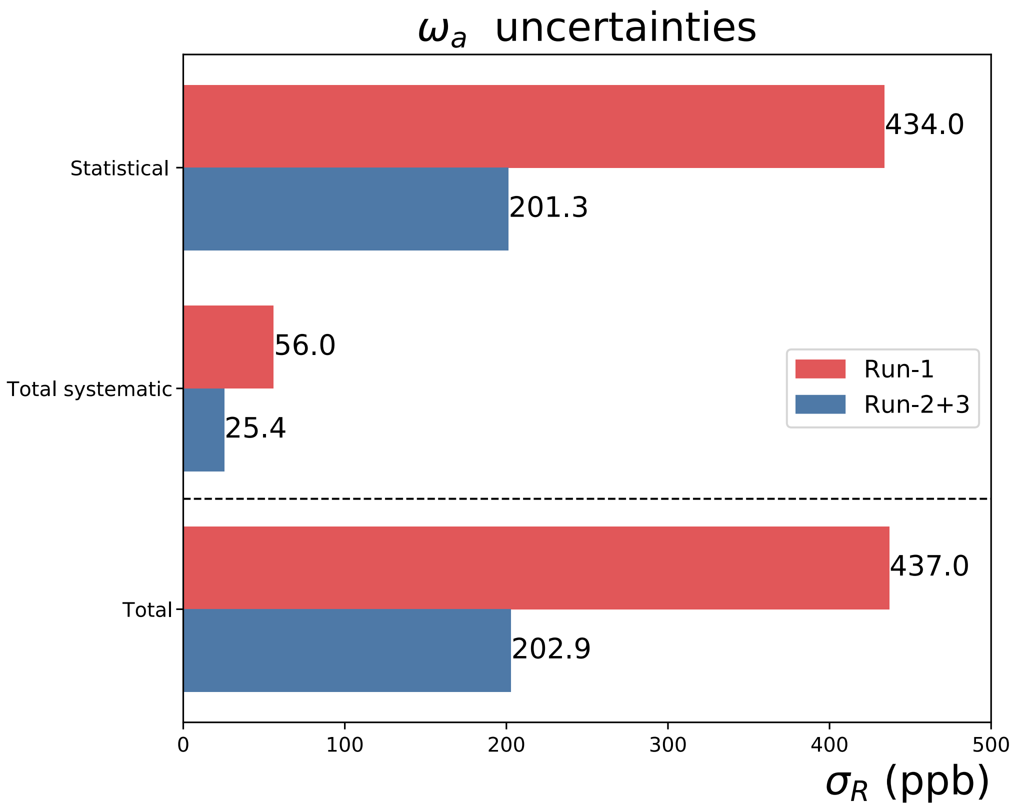


Muon Precession Frequency

Full Fit and Uncertainty improvements

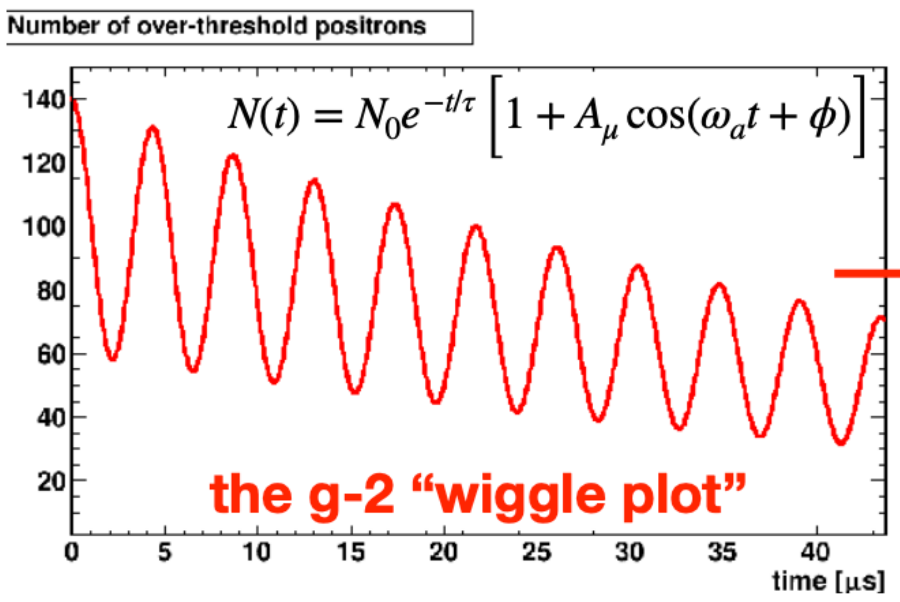
- Run-2/3 uncertainty is **2.2 times** smaller than Run-1

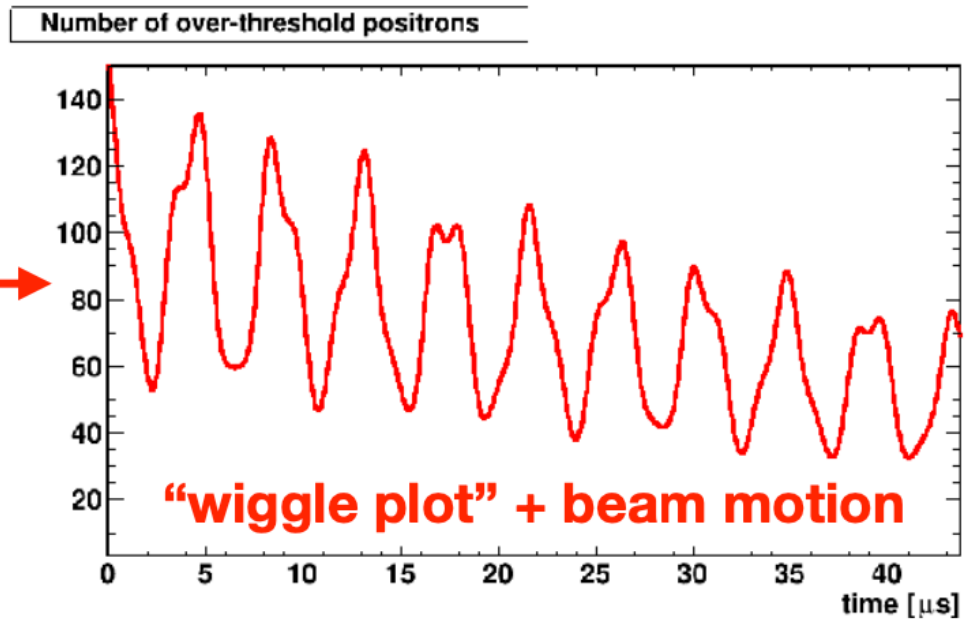
Quantity	Correction [ppb]	Uncertainty [ppb]
ω_a^m (statistical)	–	201
ω_a^m (systematic)	–	25
C_e	451	32
C_p	170	10
C_{pa}	-27	13
C_{dd}	-15	17
C_{ml}	0	3
$f_{\text{calib}} \langle \omega'_p(\vec{r}) \times M(\vec{r}) \rangle$	–	46
B_k	-21	13
B_q	-21	20
$\mu'_p(34.7°)/\mu_e$	–	11
m_μ/m_e	–	22
$g_e/2$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



Beam Dynamic Corrections

$$a_\mu = \frac{\omega_a^m}{\omega_p^m} \times \frac{(1 + C_e + C_p + C_{pa} + C_{dd} + C_{ml})}{(1 + B_k + B_q)} \times [\ldots]$$



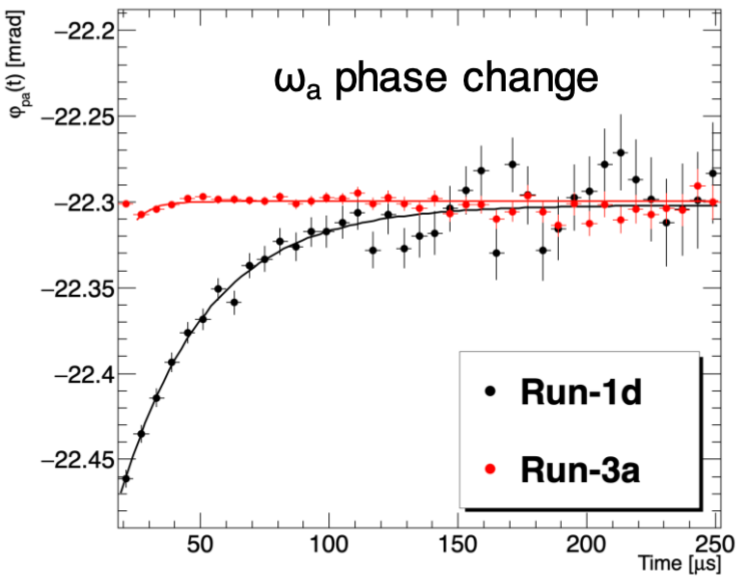


Beam Dynamic Corrections

Uncertainty Summary

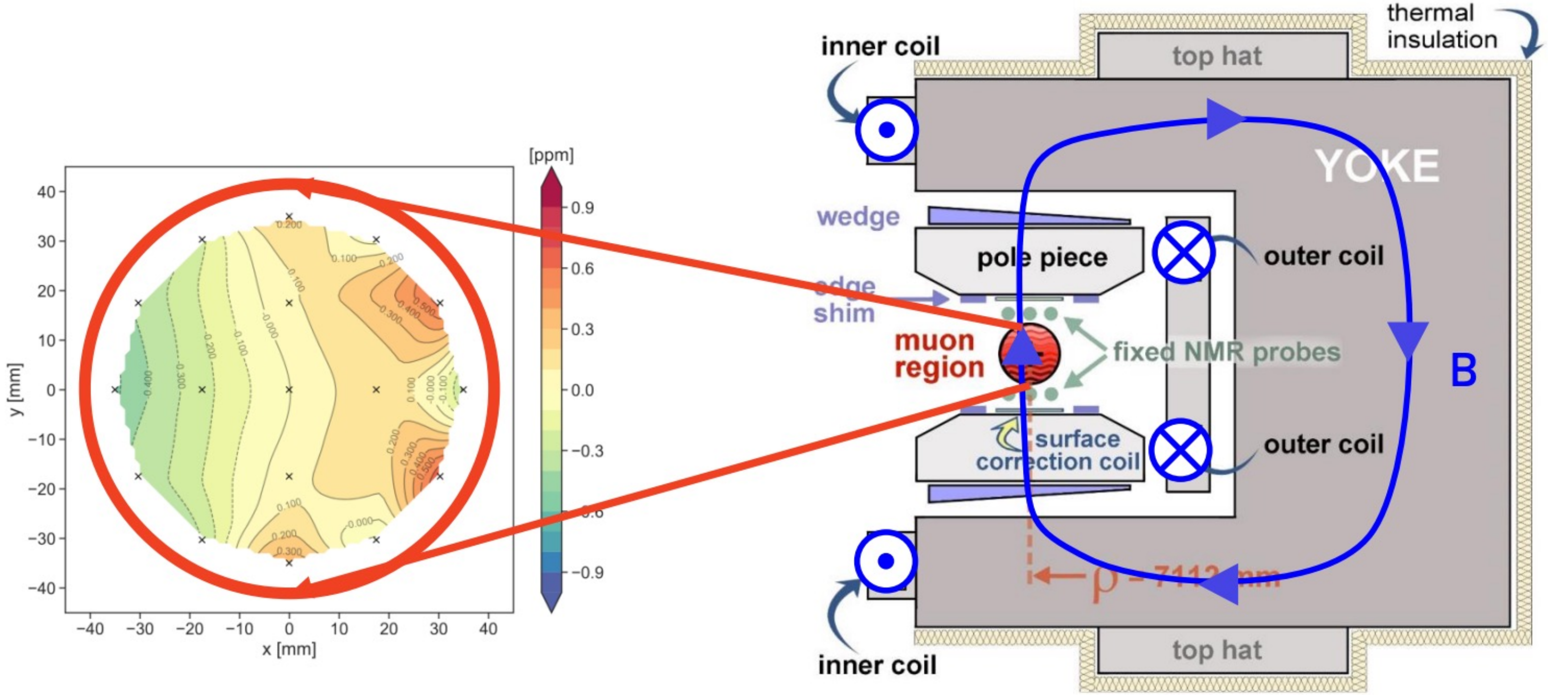
	Corrections [ppb]	Uncertainty [ppb]	Uncertainty in Run-1 [ppb]
C_e	451	**32**	53
C_p	170	10	13
C_{pa}	-27	**13**	75
C_{dd}	-15	17	-
C_{ml}	0	3	5
Total	580	40	93

- C_{pa} etc have been greatly reduced after fixing the 2 **broken HV resistors** in Run-1



Magnetic Field Measurement

Field in Muon Storage Region

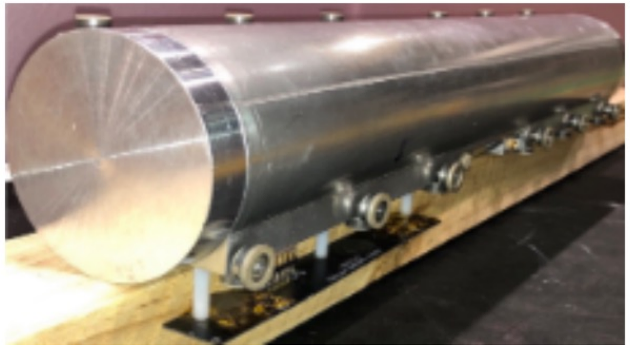


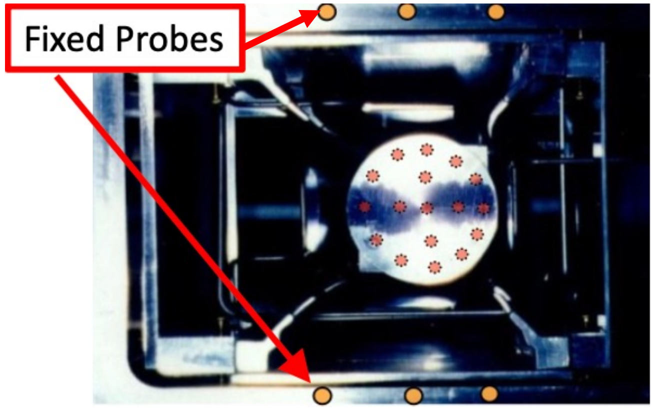
7.112 m radius 'C'-shape magnet with vertically-aligned field
B = 1.45 T

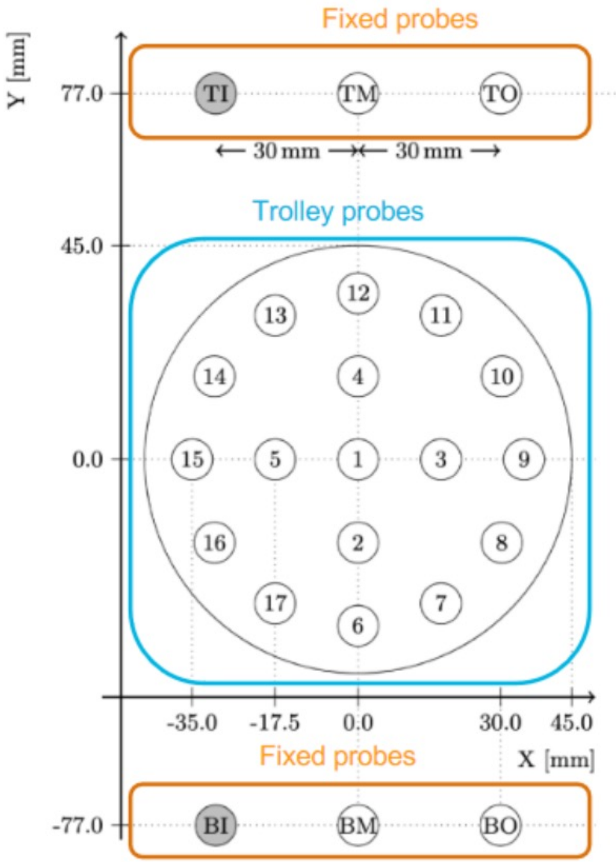
- Dipole field has ppm-level uniformity (<20 ppm RMS across the full azimuth)
- Shimming devices (active and passive) minimise gradients and keep field uniform

Magnetic Field Measurement

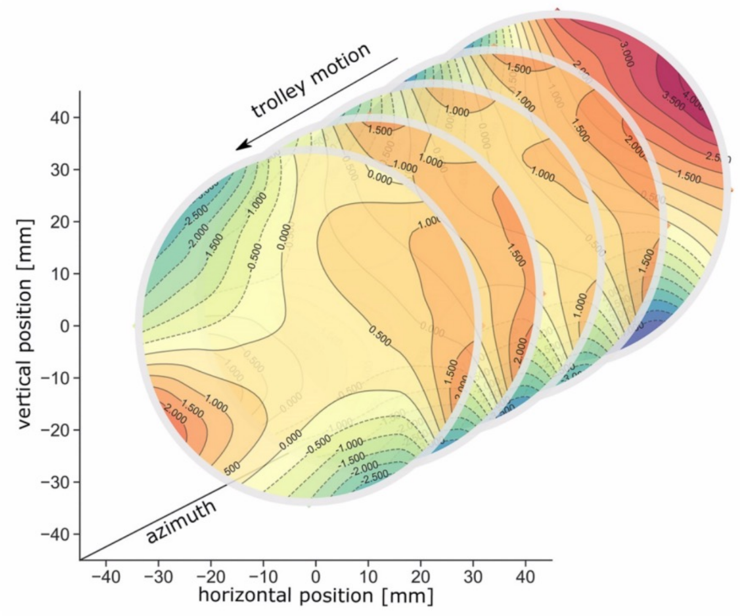
NMR: Trolley and Fixed Probes





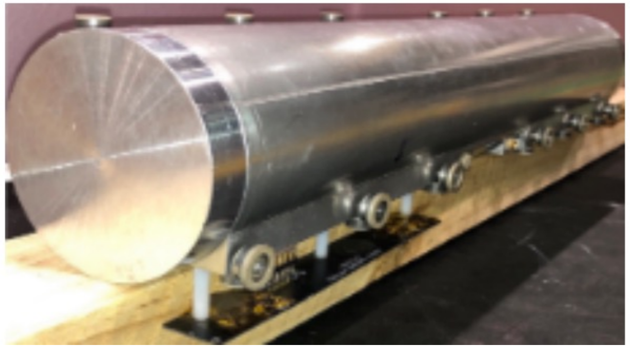


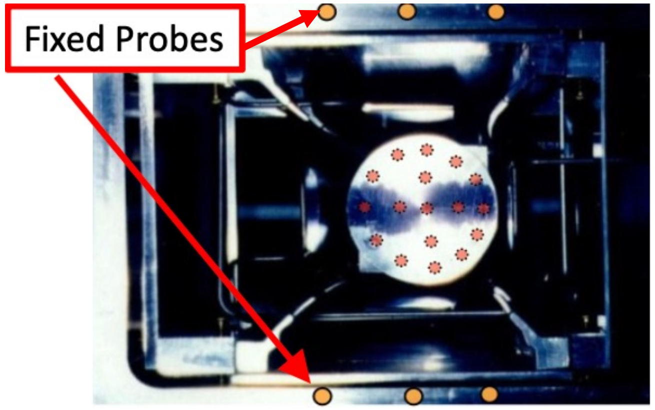
- **A trolley** with 17 NMR probes maps the magnetic field in muon storage volume every ~3 days
- Run-1: **14** trolley maps; Run-2/3: **69** maps

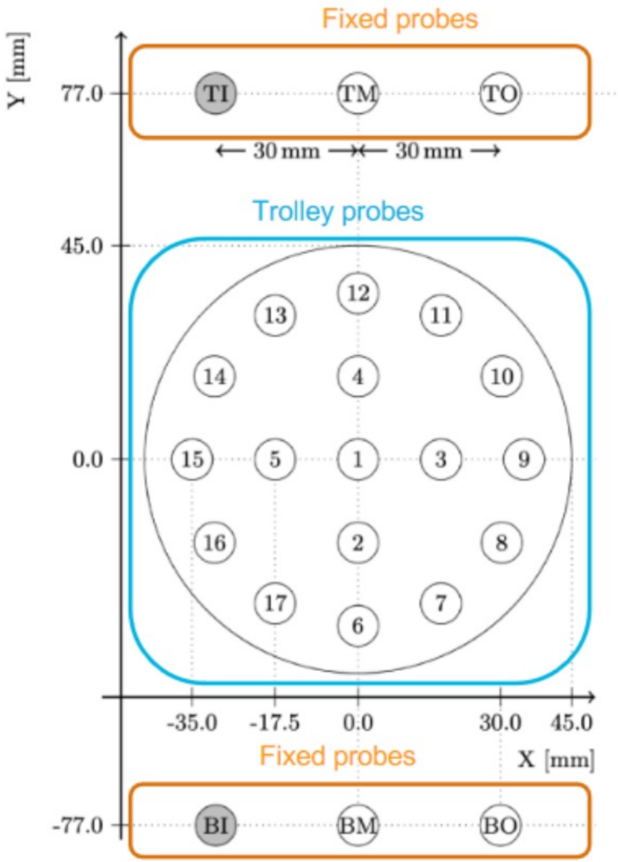


Magnetic Field Measurement

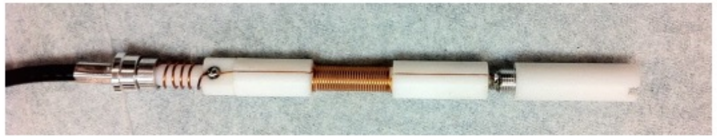
NMR: Trolley and Fixed Probes





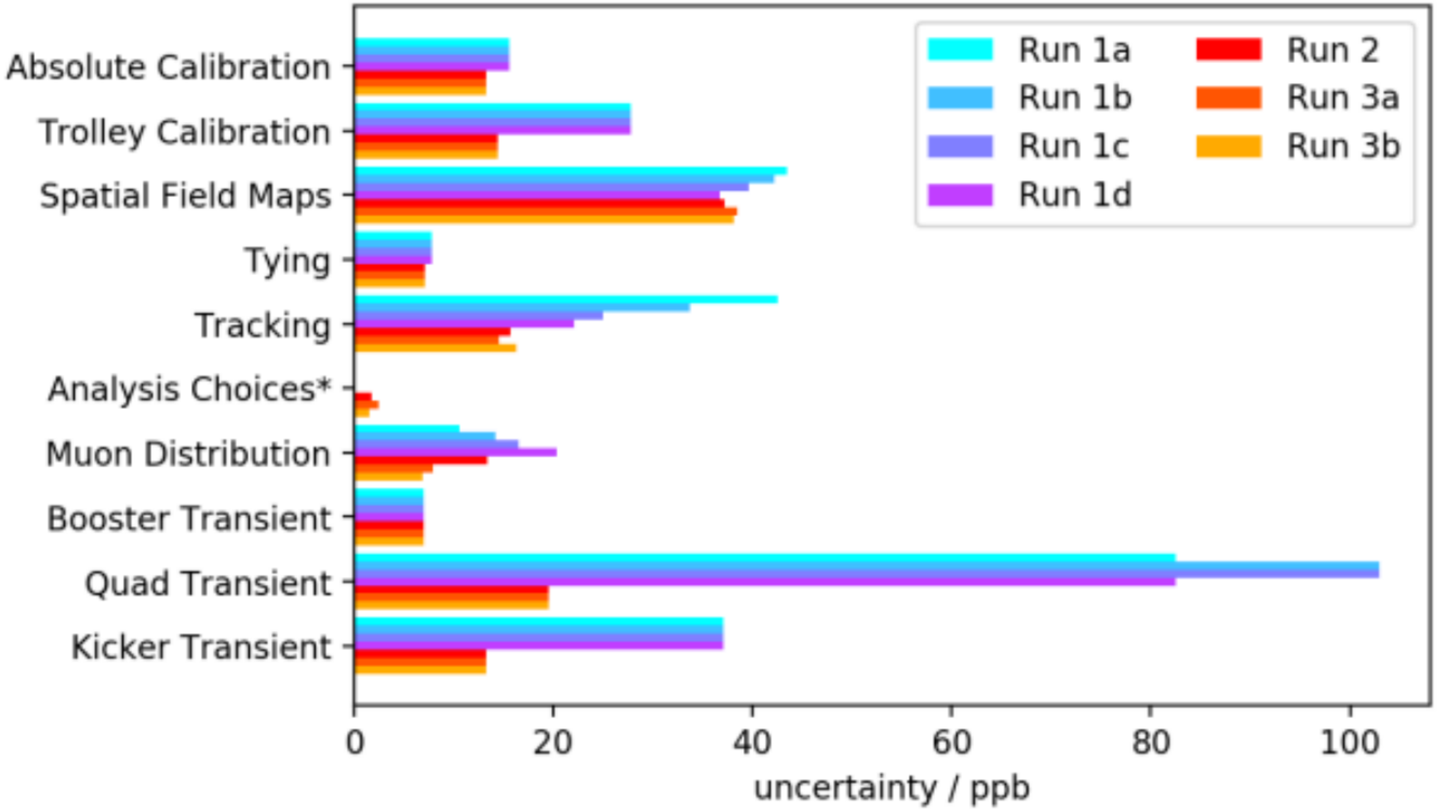


- **378 fixed NMR probes,** above or below storage volume permanently installed ("fixed") at 72 locations around the ring (every ~5^o)
- Track changes in the field continuously during muon storage



Magnetic Field Measurement

Uncertainty Summary

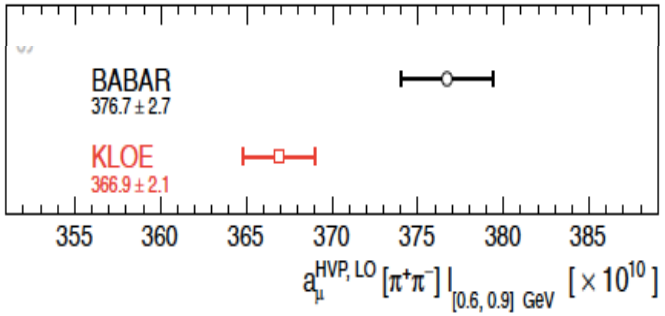


- Main reduction in the uncertainty comes from better understanding of the **transient field effects** (B_k and B_q)
- Interpolation uncertainty also reduced with increased trolley runs
- **TDR goal already achieved**

Outlook

- Towards solving SM prediction ($a_\mu^{HVP,LO}$) inconsistencies:
  - **KLOE & BABAR** discrepancy
  - Outstanding **CMD-3** result
  - **MUonE** project @ CERN to better understand $a_\mu^{HVP,LO}$

Almost 3 sigma tension between these two measurements



09:45 **Status of the MUonE experiment (12'+3')**

Speaker: Riccardo Pilato (University of Liverpool (GB))

Outlook

Muon $g-2$/EDM Experiment at J-PARC

Features:

Muon cooling

- Surface muon (3.4 MeV, large emittance)

➜ thermal muon (0.2 eV, low emittance)

Muon LINAC

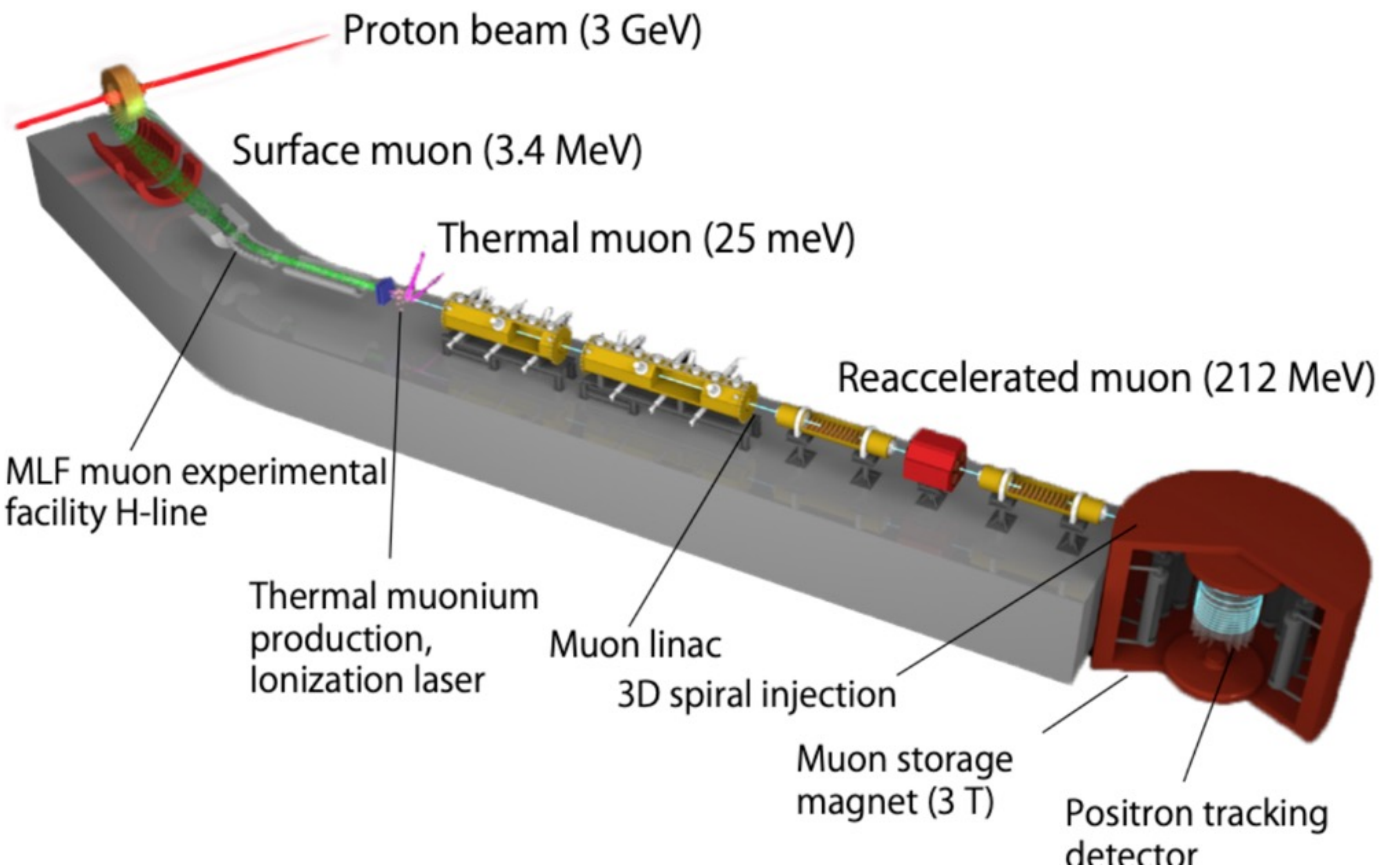
- Muon acceleration to 212 MeV

3D spiral injection

- Large kick angle within a few ns
- Good injection efficiency

Storage ring

- Compact storage ring
- Tracking detector



Outlook

Muon $g-2$/EDM Experiment at J-PARC

Goals:

a_μ (statistically limited)

- **0.45 ppm (phase-1, ~ BNL/FNAL Run-1)**
- **0.10 ppm (phase-2, ~ FNAL Final)**

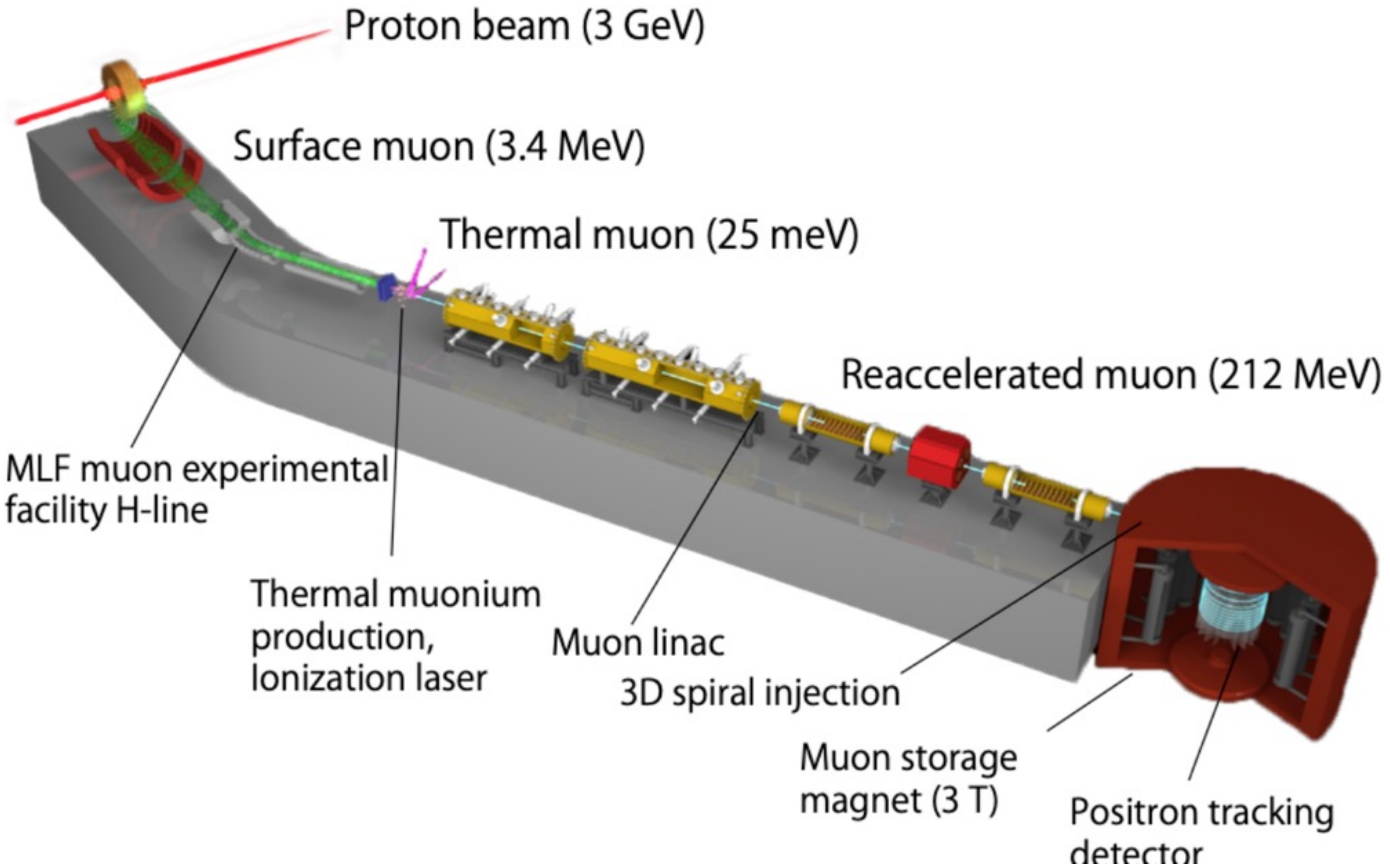
Muon EDM (sensitivity)

- $1.5\times10^{-21}\ e\cdot\mathrm{cm}$ **(×70 better)**

Schedule:

First data taking phase

- **Start from 2028 and beyond**
- **Running time of 2×10^7s (240 days)**



Summary

Muon $g-2$ Experiment at Fermilab

Better than **200 ppb precision** achieved in Run-2/3

Precession Frequency	Beam Dynamics Corrections	Magnetic Field

Consistency Check; Blinding; Combination etc.

Up to 5-sigma discrepancy

SM prediction(s)

Data-driven method (WP2020) conflicts with the **LQCD**

Discrepancies within the data-driven method:

- KLOE – BABAR
- CMD-3 with all previous results

Future experimental results

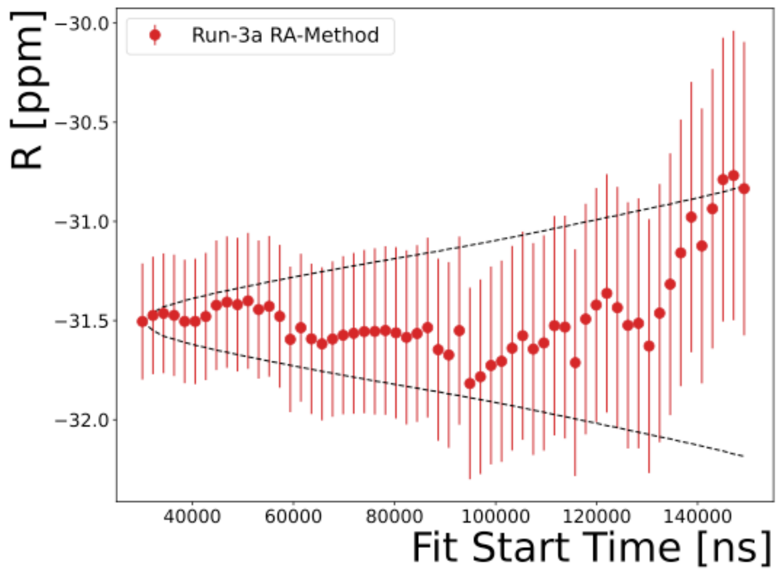
- Final result (Run-4/5/6) from Fermilab (~2025)
- New Experiment at J-PARC (2028)

Future SM update

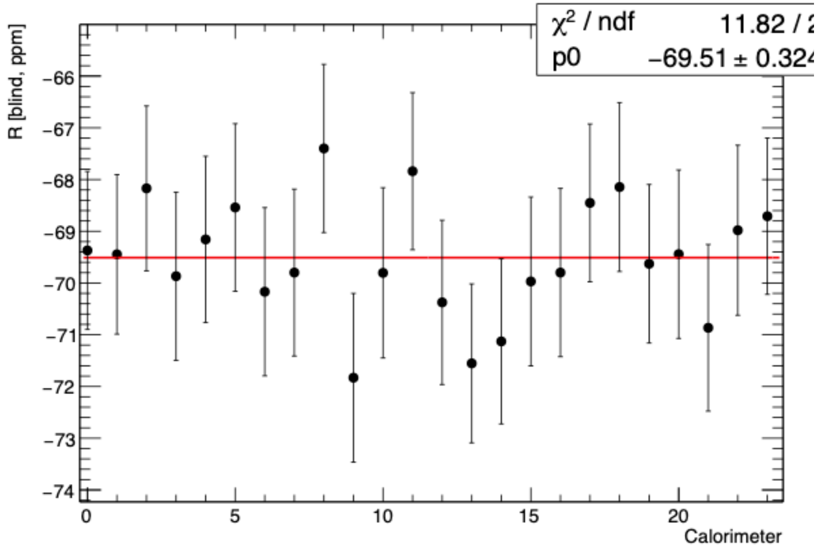
- **The Muon $g-2$ Theory Initiative** is coordinating the SM prediction update
- **MUonE Project** at CERN to directly measure HVP

Consistency Check

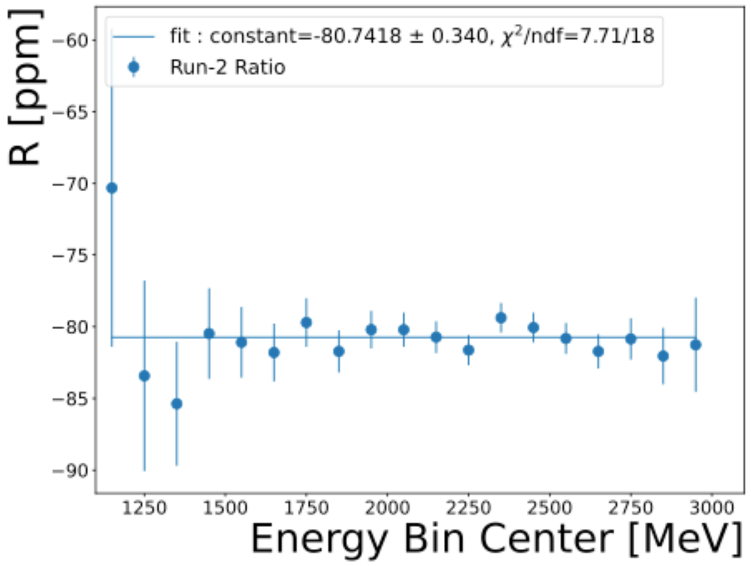
- We perform many consistency checks: fit residual FFTs, fit start time scans, fits by calorimeter, fits by positron energy, etc.



Fit start time scan



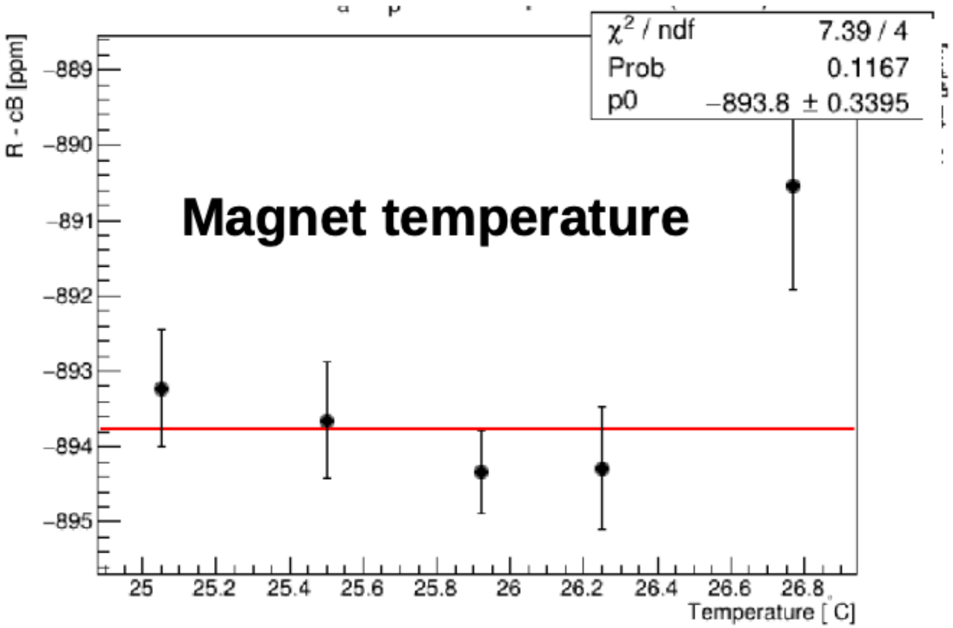
Per-calorimeter fits

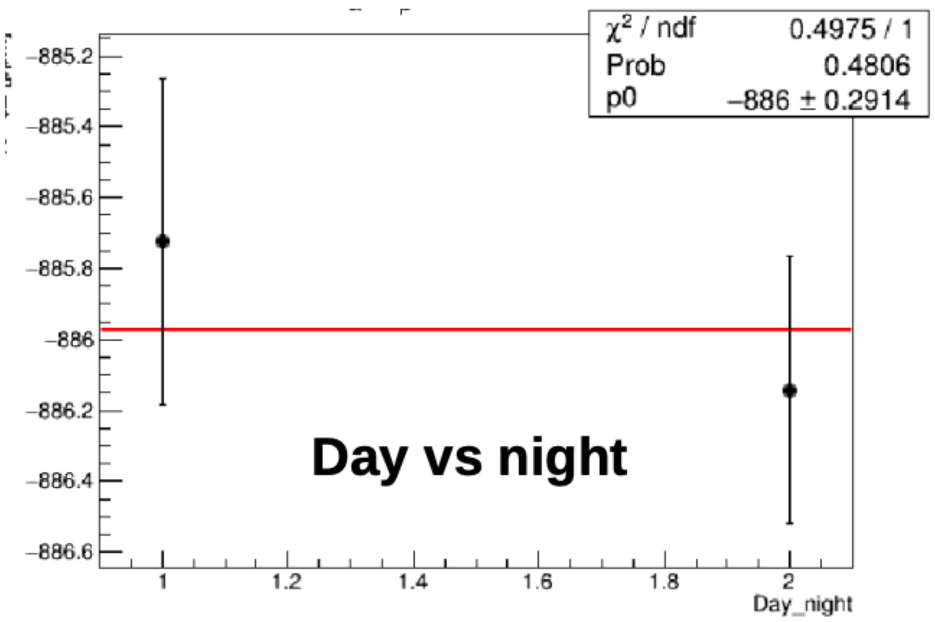


Energy-bin fits

Consistency Check

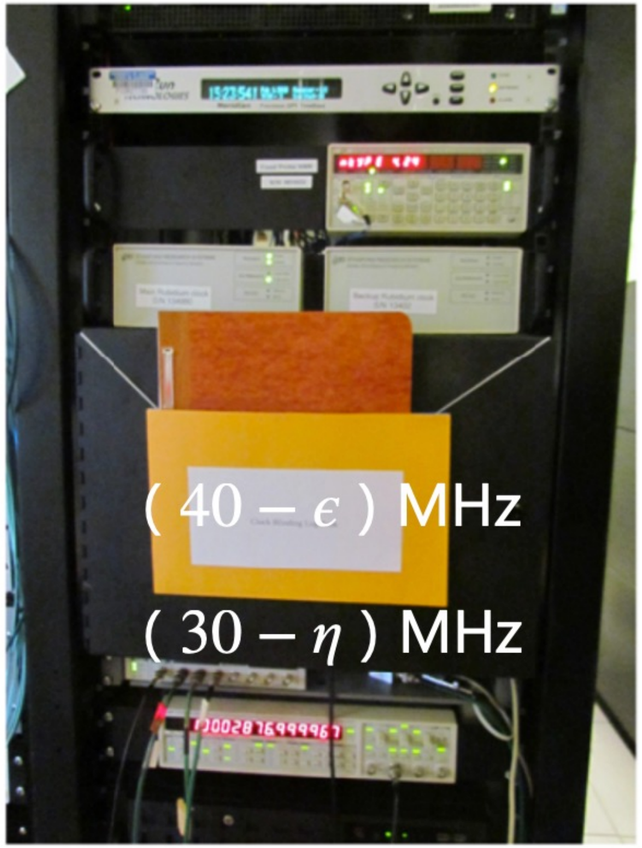
- We perform many consistency checks: fit residual FFTs, fit start time scans, fits by calorimeter, fits by positron energy, etc.





Blinding Scheme

Locked Clock Panel



$$\frac{\omega_a}{\tilde{\omega}'_p} = \frac{f_{\text{clock}}\ \omega_{a,\text{meas}}\ (1 + c_e + c_p + c_{ml} + c_{pa})}{f_{\text{field}}\ \left\langle \omega_p \bigotimes \rho_\mu \right\rangle\ (1 + B_{qt} + B_{kick})}$$

- Perform analysis with **software & hardware** blinding
- Hardware blind comes from altering our clock frequency
  - Non-collaborators set frequency to **(40 – ϵ) MHz**
- Clock is locked and value kept secret until analysis completed