Final Muon $g - 2$ Result at Fermilab

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on behalf of the Fermilab Muon g-2 collaboration

NuFact 2025

UNIVERSITY OF LIVERPOOL
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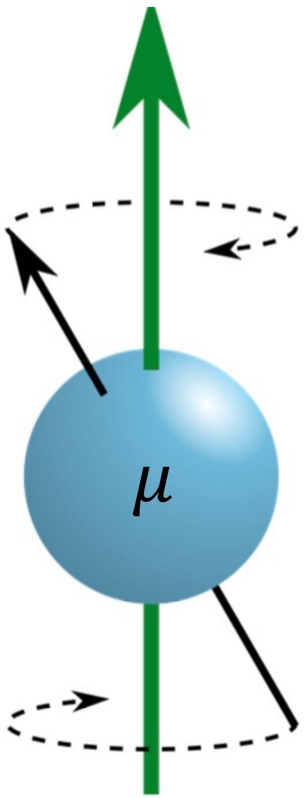
Final Muon $g-2$ Result at Fermilab

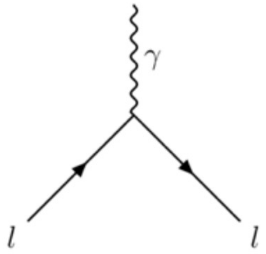
- Magnetic anomaly of the muon – concept, history, and limitations
- A Journey to 127 ppb at Fermilab
  - Techniques, setup, and results from Runs 1–3
  - Runs 4/5/6: notable Improvements and final results
- Are we done?

Magnetic anomaly of the muon



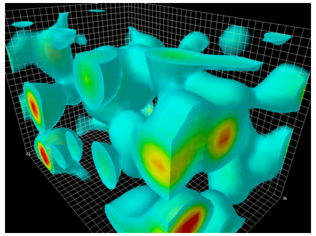
- A magnetic moment ($\boldsymbol{\mu}$) arising from intrinsic spin angular momentum ($\boldsymbol{S}$) via a g-factor:

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

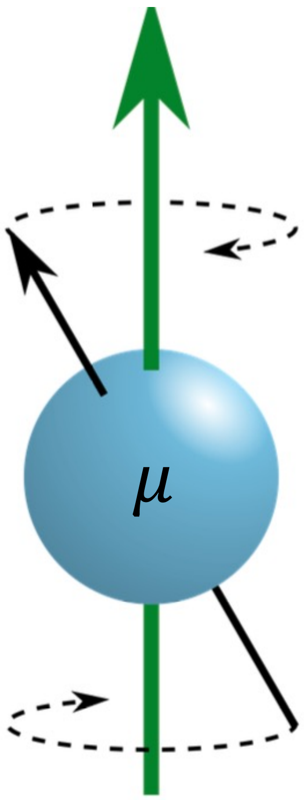


- Dirac equation (1928) predicted $\boldsymbol{g \equiv 2}$ for elementary particles of spin =1/2 like electron and muon.
- A higher order quantum fluctuations makes the g factor deviated from 2.
- **The magnetic anomaly** is defined as

$$a = \frac{(g-2)}{2}$$



Magnetic anomaly of the muon



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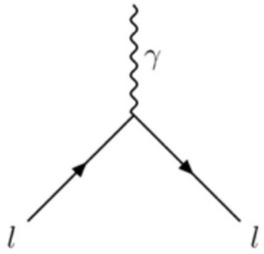

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- A higher order quantum fluctuations makes the g factor deviated from 2.
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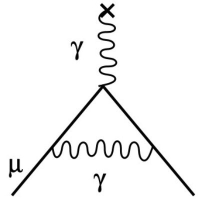
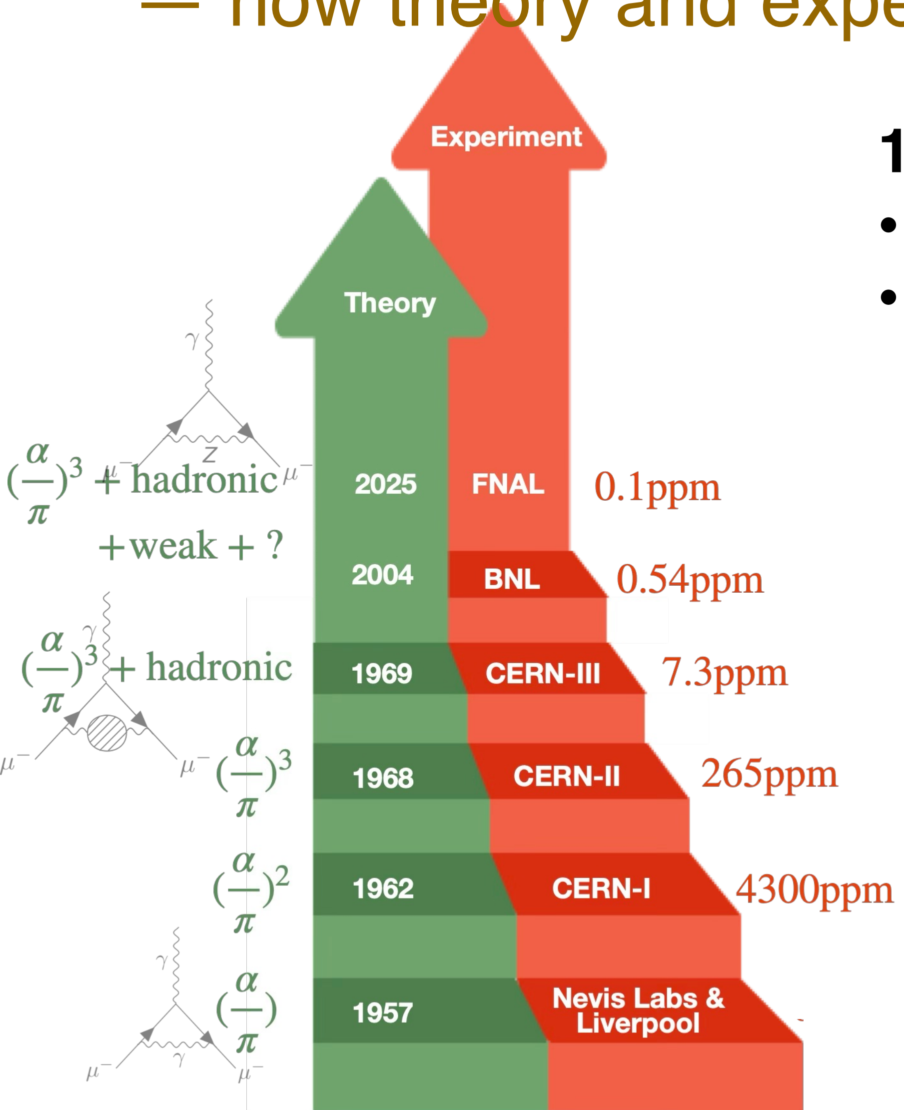
$$a = \frac{(g-2)}{2} = \frac{\alpha}{2\pi} = 0.001161$$



1948: Triumph of QED by Schwinger

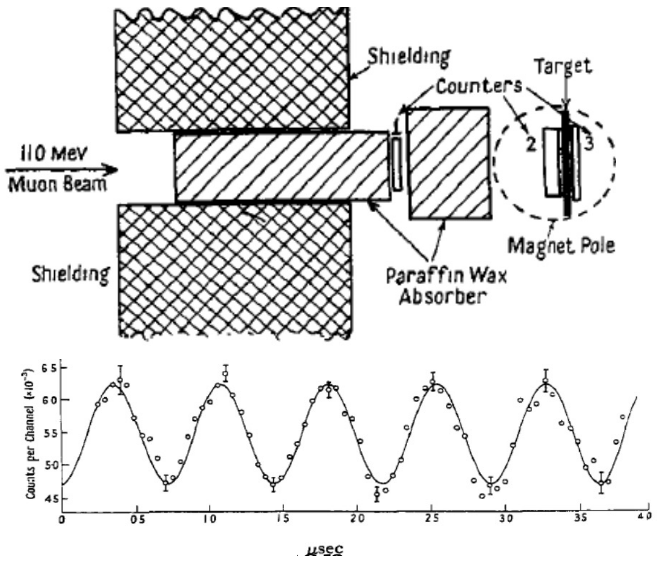
Magnetic anomaly of the muon

— how theory and experiments shape each other



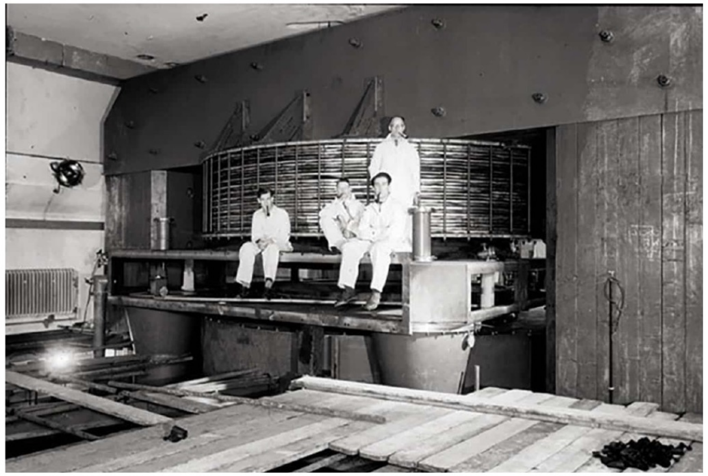
1957 marked the first direct measurements of muon g-2:

- Garwin, Lederman, Weinrich at Nevis
- Cassels, et al. at Liverpool



$$g_\mu = 2.004 \pm 0.014$$

0.7% uncertainty



156 inch Cyclotron in Liverpool

Magnetic anomaly of the muon

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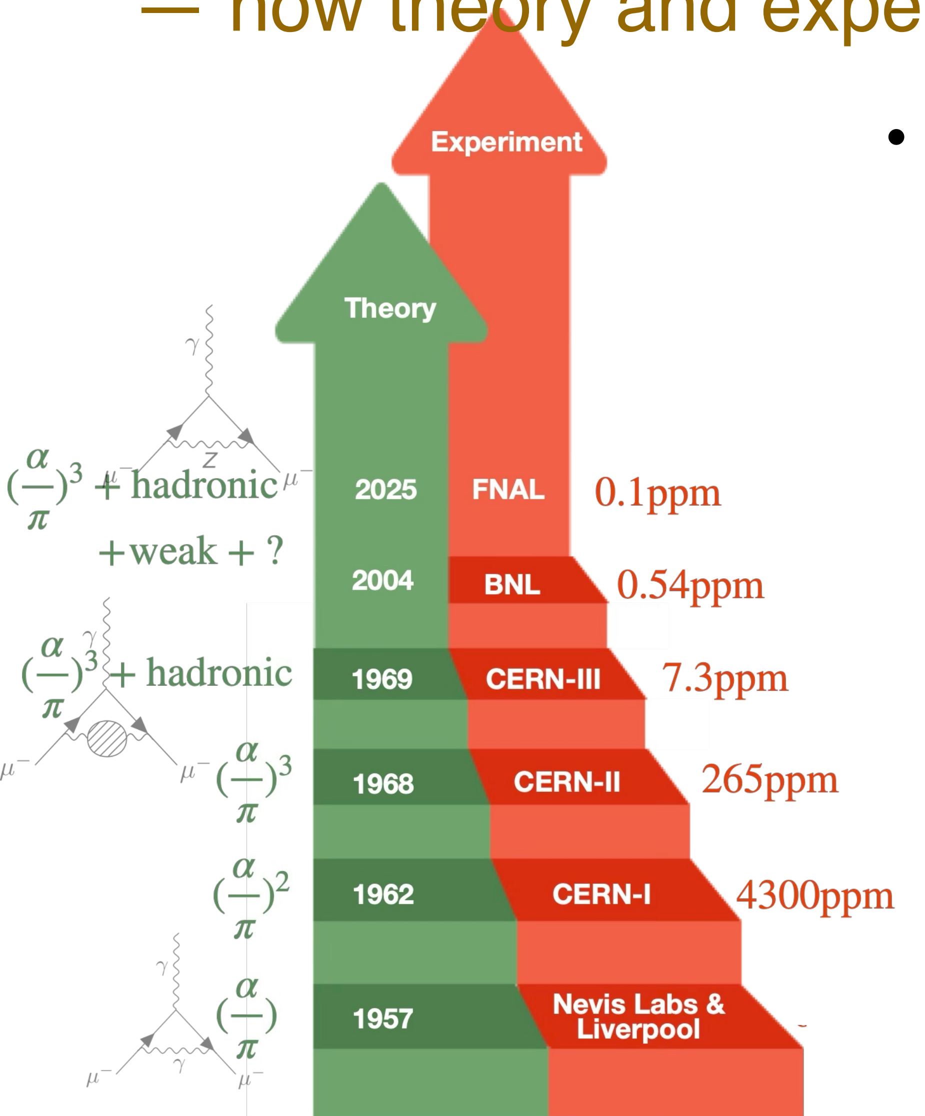
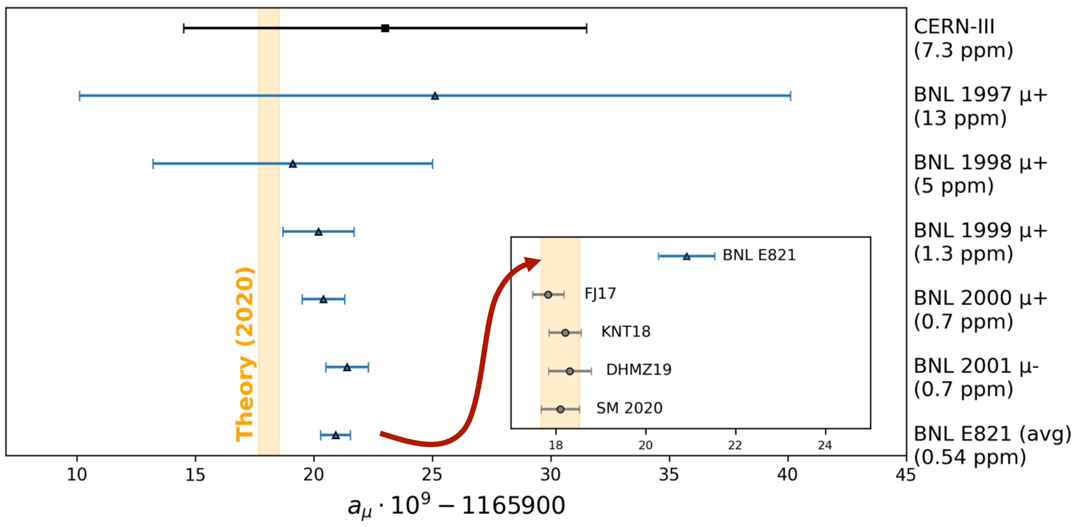


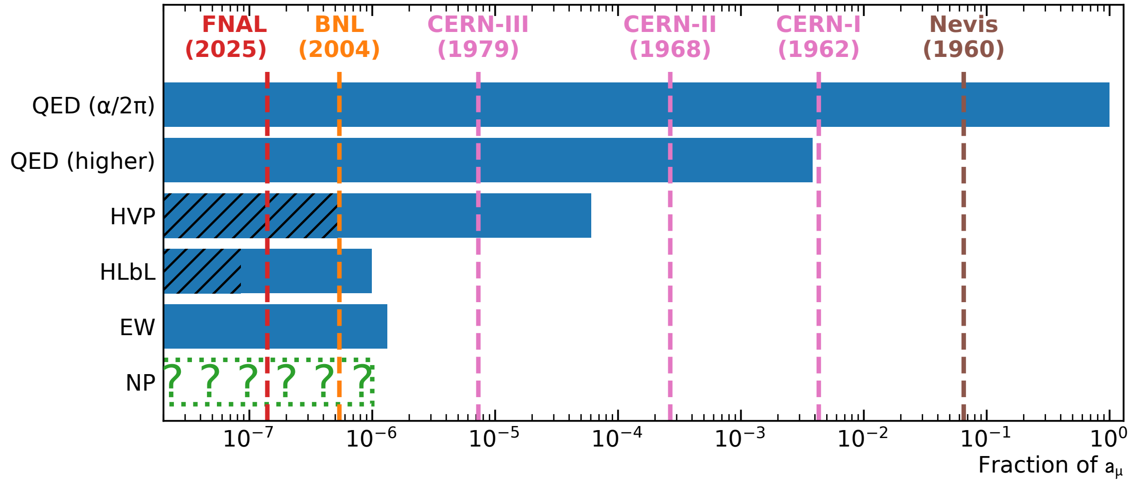
- Both theory and experiments evolve toward greater accuracy in a feedback loop
  - Improved SM predictions define targets for experiments;
  - Experiment results & discrepancies challenge the theory.



Magnetic anomaly of the muon

— precision as a path to New Physics

- Muon with $(m_\mu/m_e)^2 \sim 43000$ enhanced sensitivity to **New Physics** particles. In this way, precision becomes a high-energy probe, reaching energy scales beyond current collider limits. ($\Delta a_\mu \sim 2.5\times10^{-9}$ → O(10–1000 TeV))
- As precision improves, the tiniest deviations from the SM become detectable. The bounds on new physics are tightened such as DM, heavy z boson.



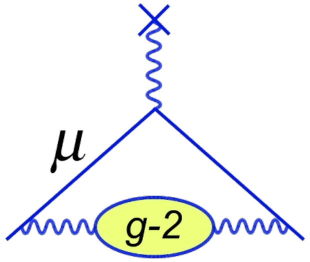
Magnetic anomaly of the muon

— statistical vs. systematic limits in experiments

- Technology shapes the precision limits and defines what's possible:
  - **Higher muon yield** thanks to accelerator facility dev → smaller statistical errors
  - **Better detectors, field calibration, etc.** → lower systematic errors
- Fermilab's result has reached ~100 ppb in both statistical and systematic;
  - When systematics match statistics, new methods are required, not just more data!
- Further gains using the same approach would be extremely difficult.

$\frac{\omega_a}{\tilde{\omega}'_p}$	Stat. Uncertainty (ppb)	Syst. Uncertainty (ppb)	Total Uncertainty (ppb)
Run-1-6	**98**	**78**	**127**
	TDR goal 100 ppb ✓	TDR goal: 100 ppb ✓	TDR goal: 140 ppb ✓

A Journey to 127 ppb at Fermilab



2002 — BNL final measurement

2009 — Proposal

The New (g − 2) Experiment:

A Proposal to Measure the Muon Anomalous

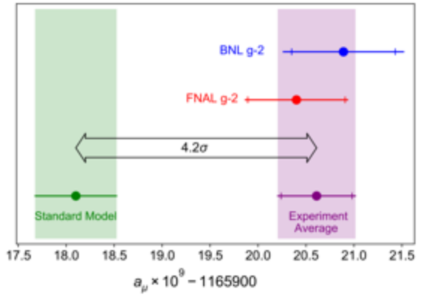
Magnetic Moment to ±0.14 ppm Precision

2012 — Muon g-2 Critical Decision-0

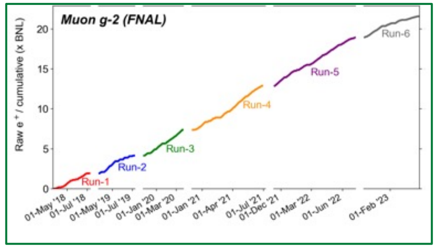
2013 — The Big Move

2017 — 1^{st} muon beam

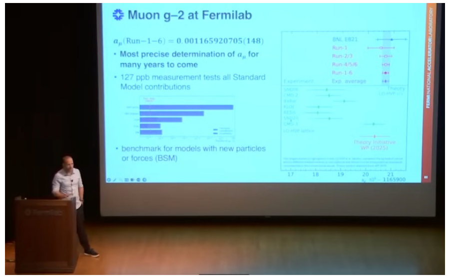
2021 — First a_μ result



2023 — End of data taking and second result

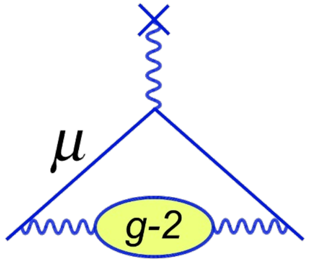


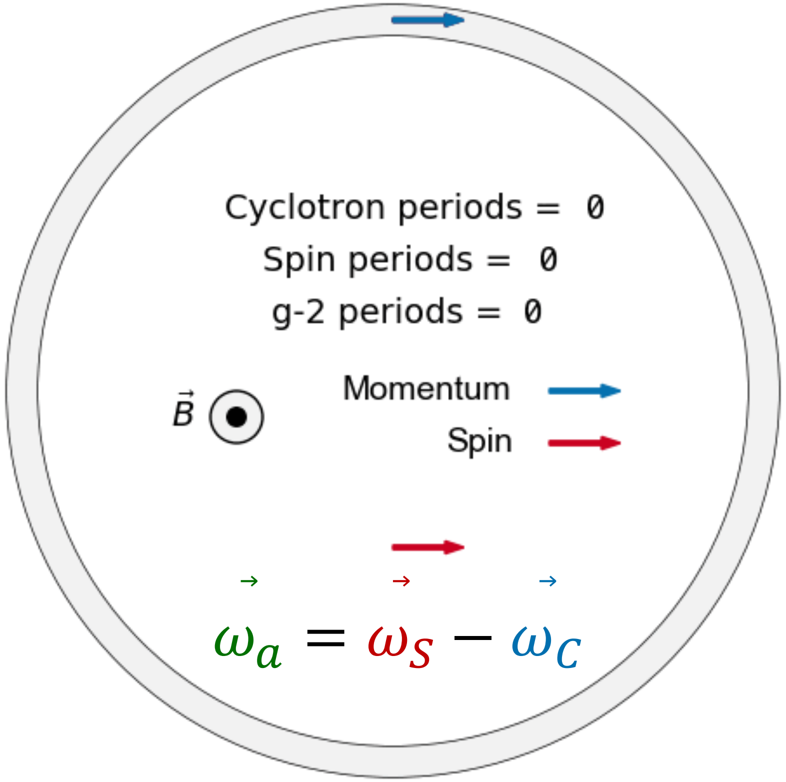
2025 — **Final a_μ result at Fermilab**



Measurement at Fermilab

Store spin-polarized muons in a uniform magnetic field





- **Spin rotates ahead of momentum** as muon orbits the storage ring.
- Frequency difference $\boldsymbol{\omega_a}$ is prop. to a_μ and B:

Measure

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

Extract

$\boldsymbol{\omega_a}$: measuring decay positron time spectrum

(High-energy positrons preferentially follow the spin)

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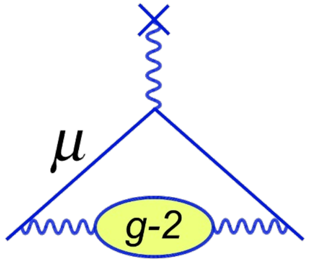

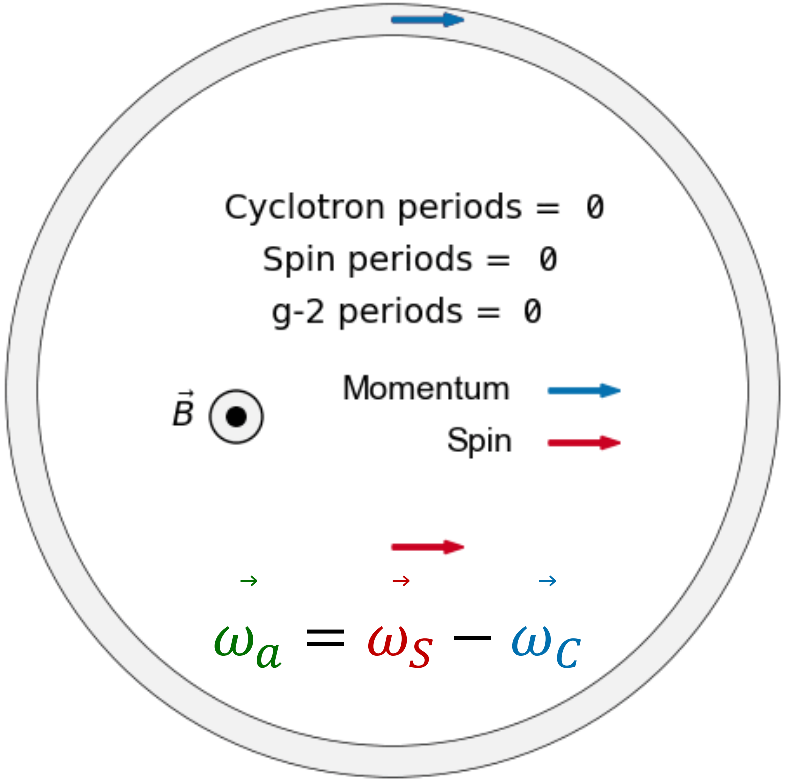

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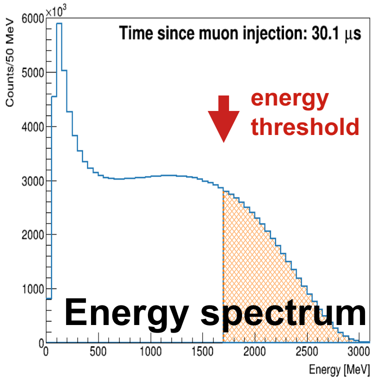

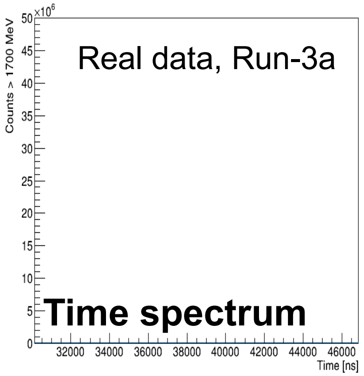

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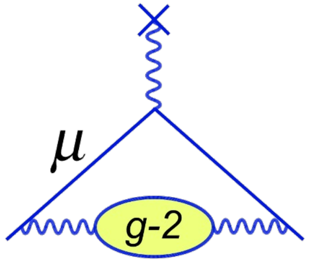

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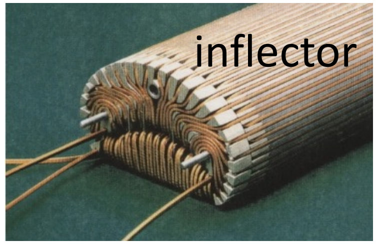

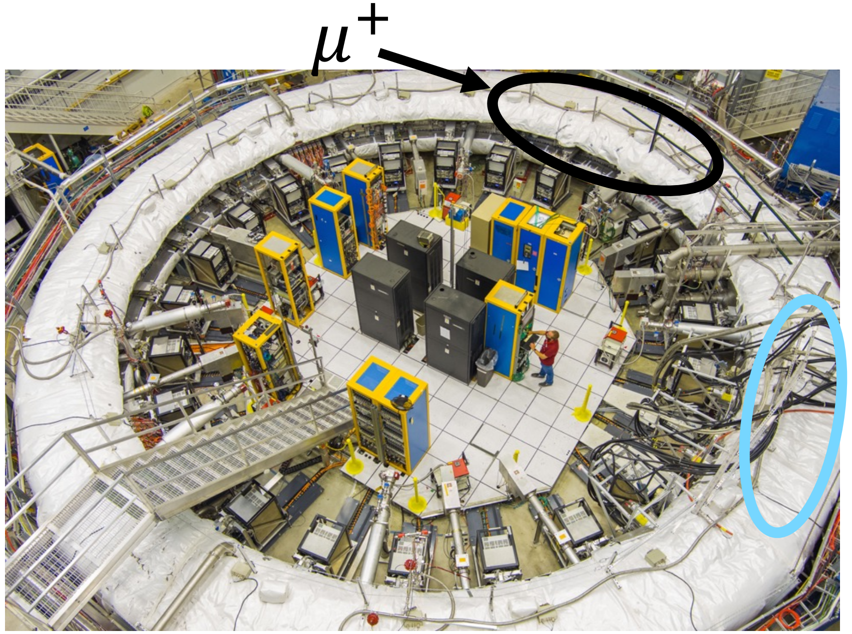

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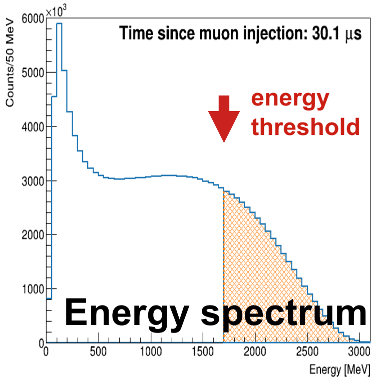

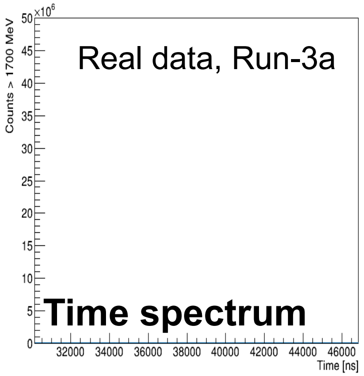

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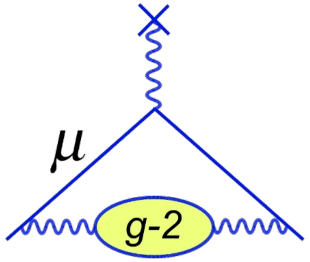

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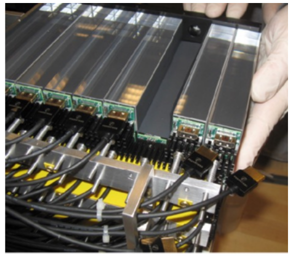
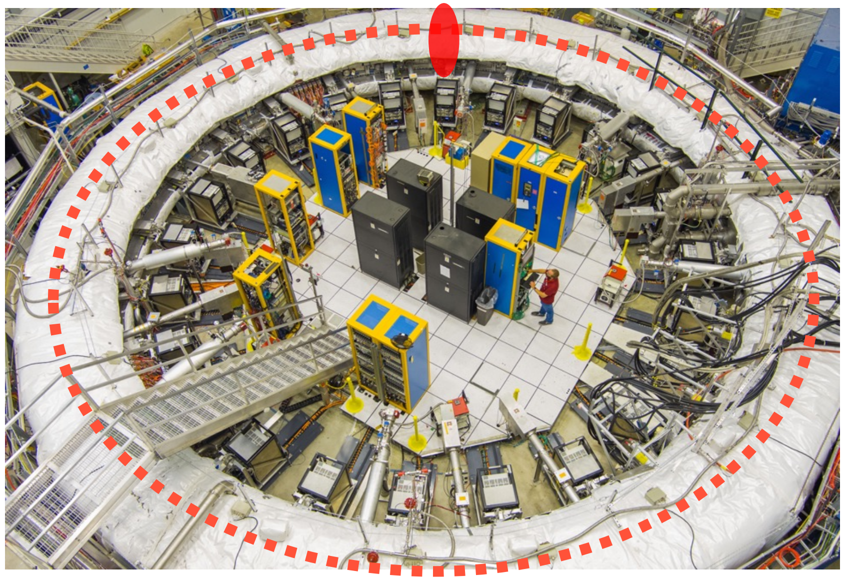


24 calorimeters made of PbF_2 crystals



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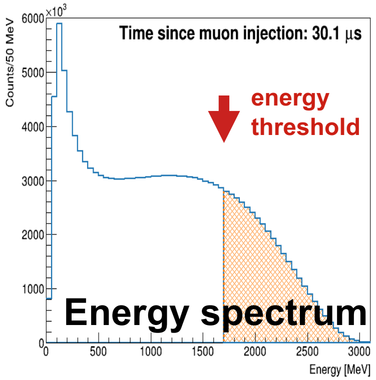

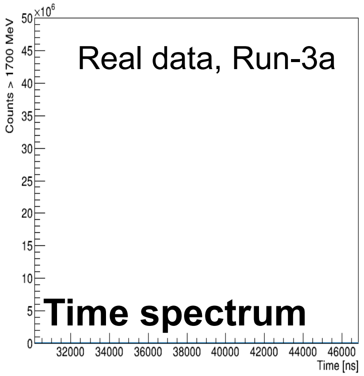

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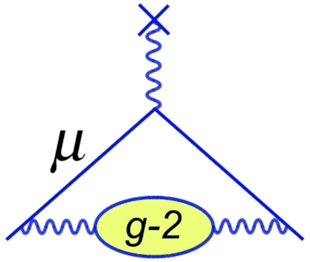
Measurement at Fermilab



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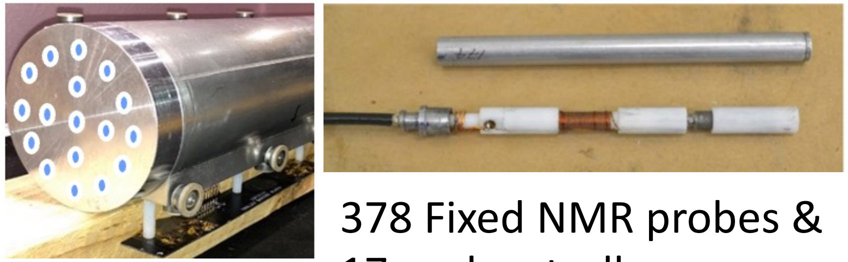
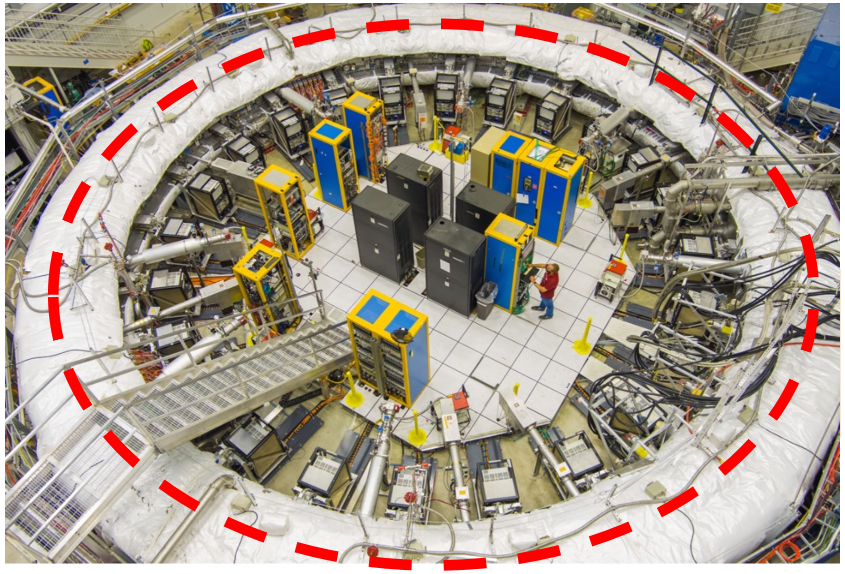


378 Fixed NMR probes & 17 probes trolley



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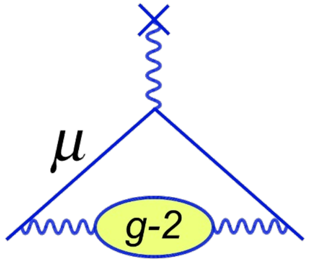
$\boldsymbol{\omega_a}$: measuring decay positron time spectrum

$\boldsymbol{B}$: Magnetic field measured via proton spin precession

Measurement at Fermilab



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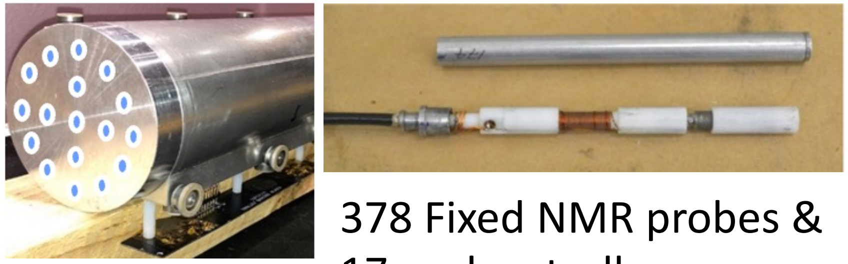

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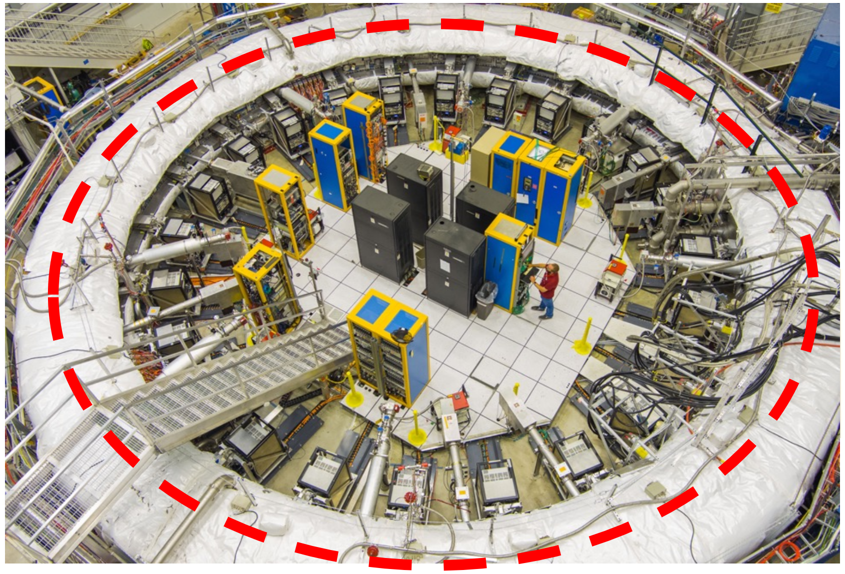

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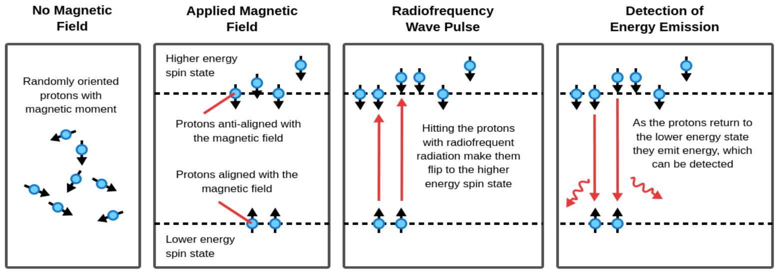
Extract

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

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

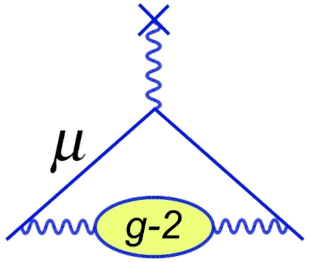


$\boldsymbol{\omega_a}$: measuring decay positron time spectrum

$\boldsymbol{B \rightarrow \omega'_p}$ **; essentially, we measure two frequencies**

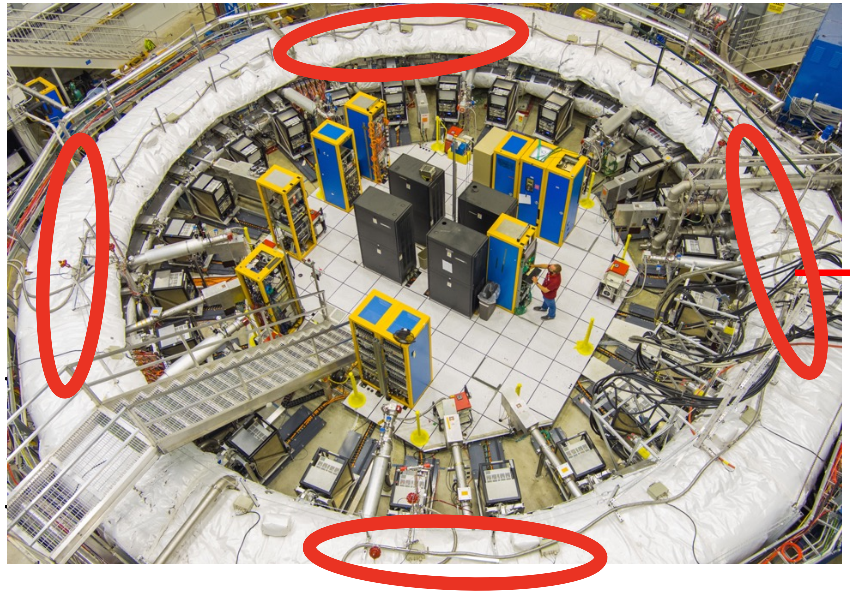
Measurement at Fermilab

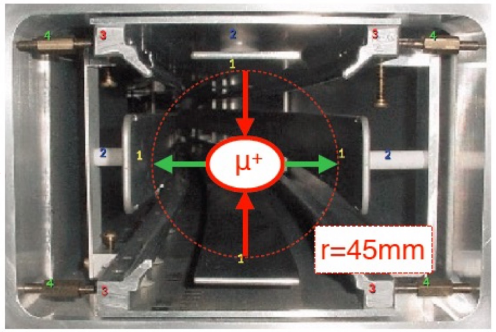
‘Corrections’ in the real-world



- The full formula is complicated by beam dynamics

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

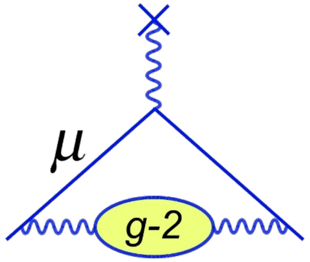




Electrostatic quadrupoles in four sections provide 43% azimuthal coverage and focus the muon beam vertically

Measurement at Fermilab

'Corrections' in the real-world



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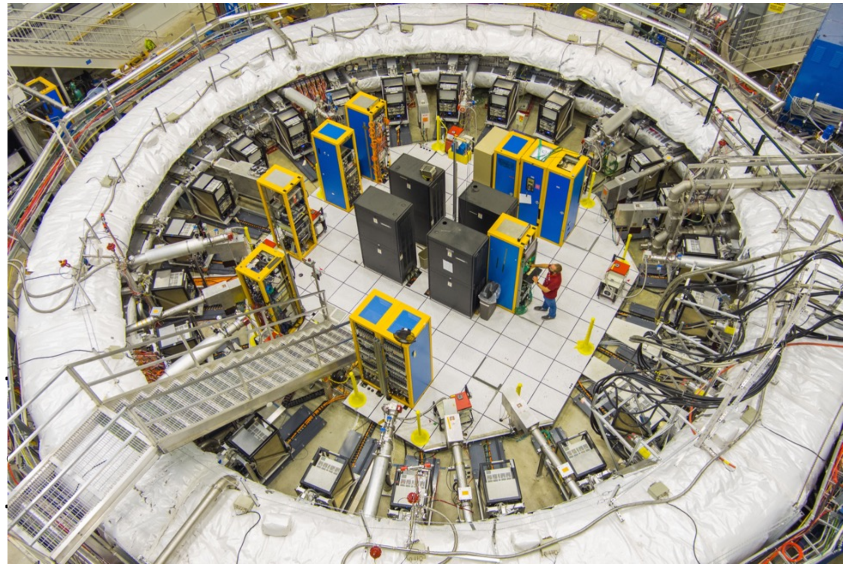
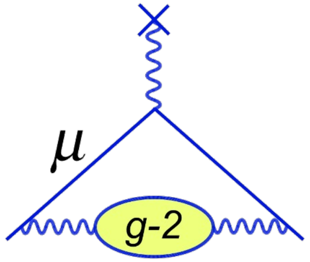


- **'Magic'** γ (~ 29.3, p = 3.09 GeV/c**)** leads to a substantial reduction (~0) in this term, but due to muon's momentum dispersion, we still need **an E-field correction.**

Measurement at Fermilab

'Corrections' in the real-world



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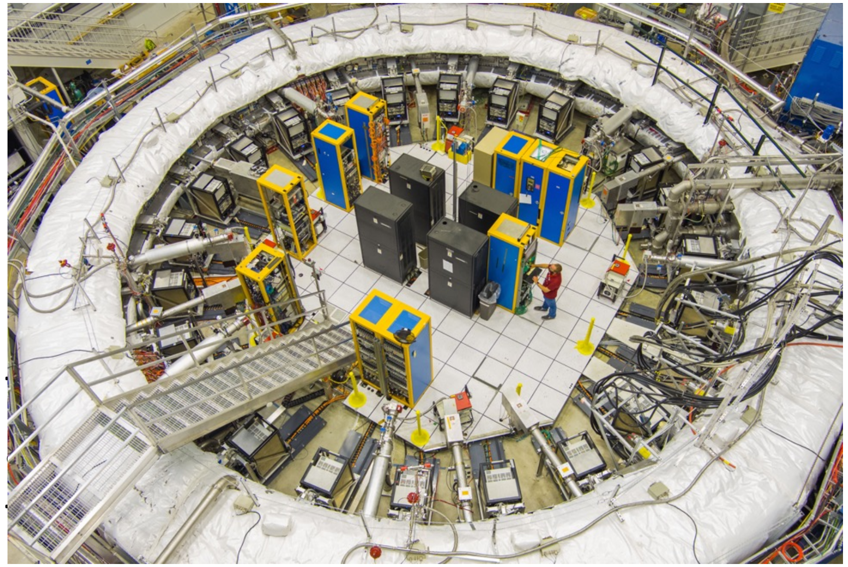
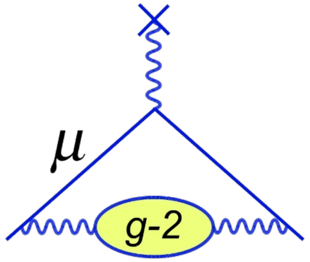


- **'Magic'** γ (~ 29.3, p = 3.09 GeV/c**)** leads to a substantial reduction (~0) in this term, but due to muon's momentum dispersion, we still need **an E-field correction.**
- Vertical motion of the muon makes $\vec{\beta}\cdot\vec{B} \neq 0$, adding a **pitch correction.**

Measurement at Fermilab

An actual computation expression



Corrections from Beam Dynamics:

① Spin dynamics ② Varying phase

$$a_\mu = \frac{\omega_a^m}{< \omega_p^m \otimes M(x,y,\phi) >} \times \frac{(1 + C_e + C_p + C_{pa} + C_{dd} + C_{ml})}{(1 + B_k + B_q)}$$

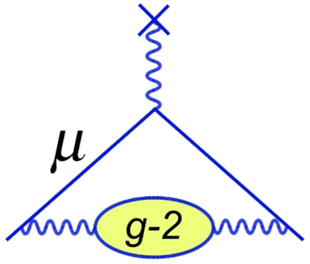
field weighted by muon

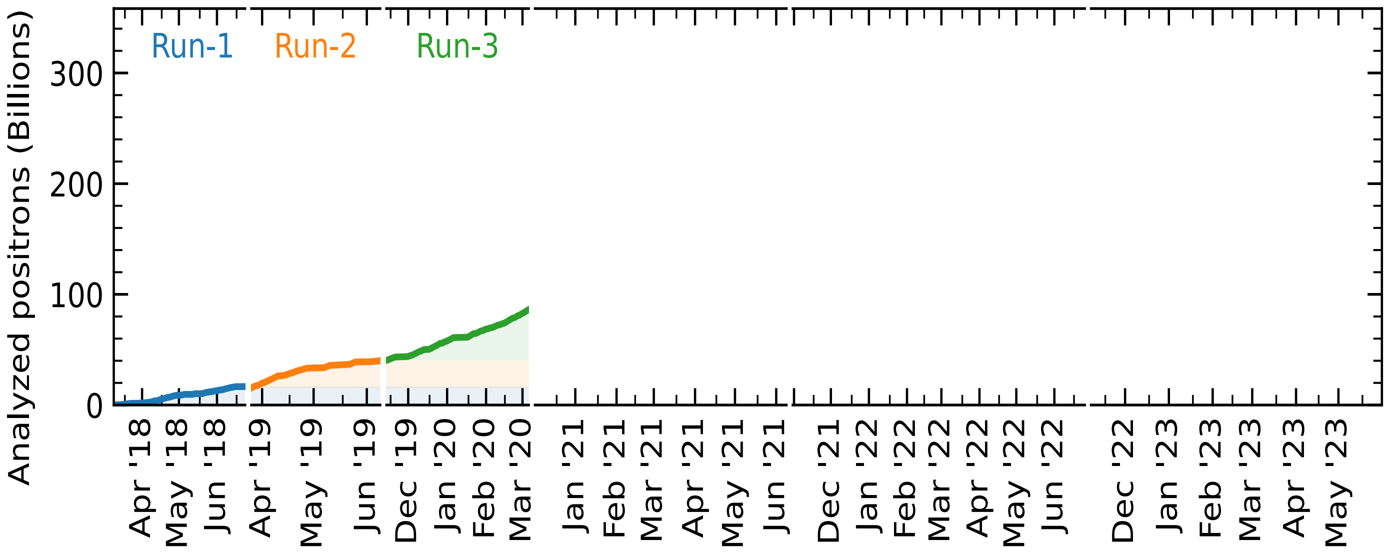
Corrections from Magnetic Field Transient

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

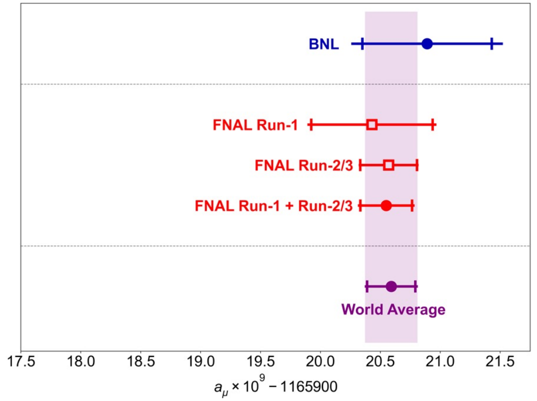
External constants precisely known (to 25 ppb)

From Runs 1/2/3 to Runs 4/5/6





Run-1 (2021) and Run-2&3 releases show a very good agreement



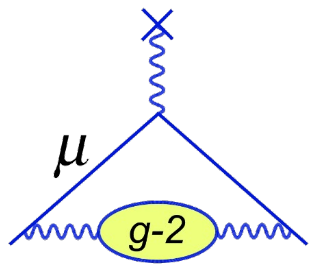
Our unblinding meeting in Liverpool (2023) for Run2&3:

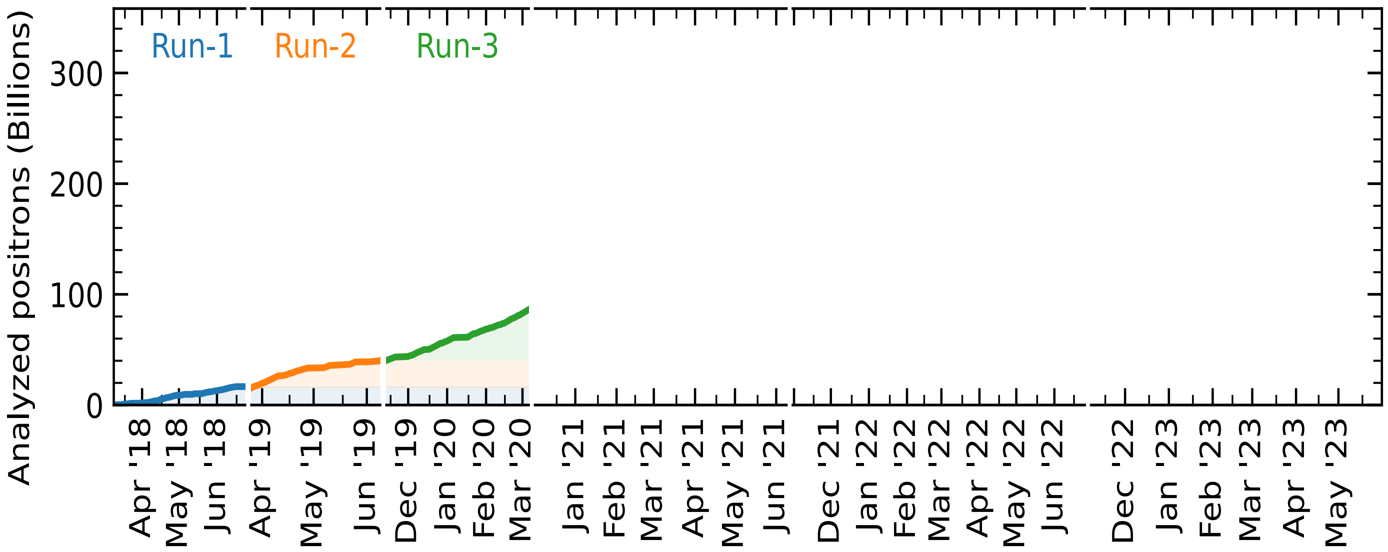
Photo credits: McCoy Wynne

April 2021: **Run-1** results, roughly matching the BNL data

August 2023: **Run-2/3** results, 4.6 times more than Run-1

From Runs 1/2/3 to Runs 4/5/6





April 2021: **Run-1** results, roughly matching the BNL data

August 2023: **Run-2/3** results, 4.6 times more than Run-1

Key Improvements

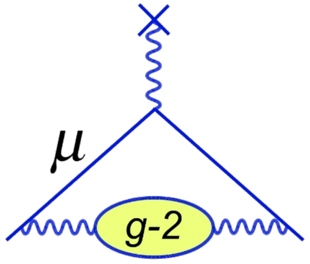
from Run1 to Run2&3:

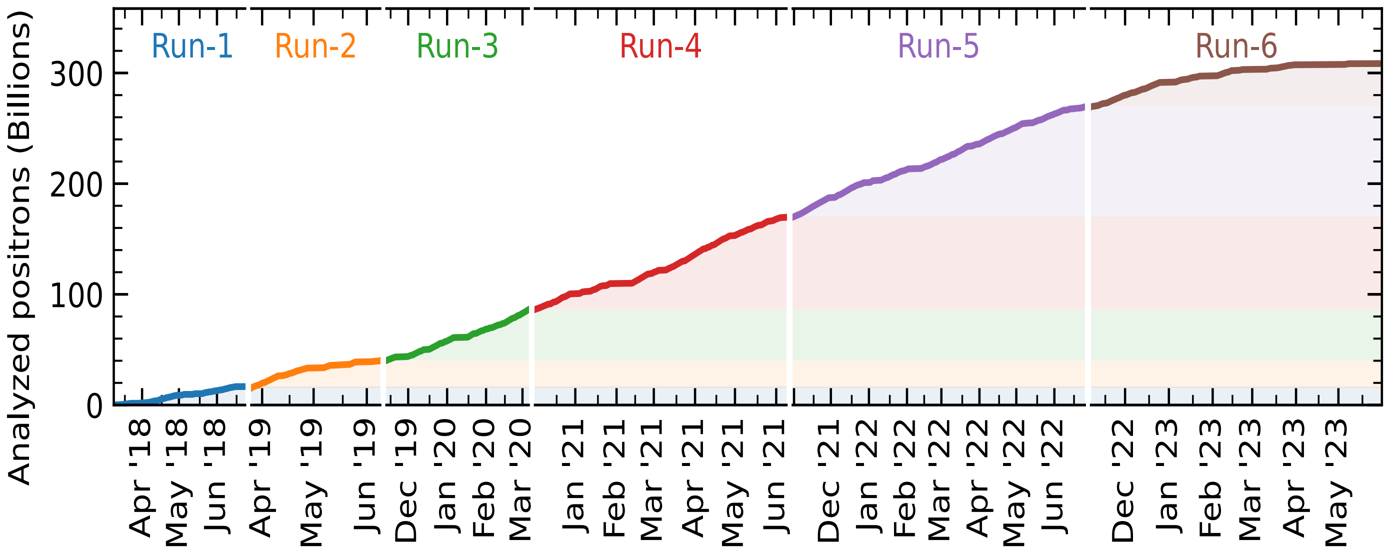
1) Running conditions
   - **Damaged resistors** were replaced, leading to **a more stable beam**
   - **A stronger kicker** improved the center beam position and smaller oscillation
   - Improved **hall cooling** makes the magnetic field less variable

2) Improved measurements
   - **A new NMR probe** in an insulator with more field measurement positions.

3) Analysis improvements
   - **An improved reconstruction algorithm** reduced the pile-up effect
   - **Tracker method** for E-field correction
   - …

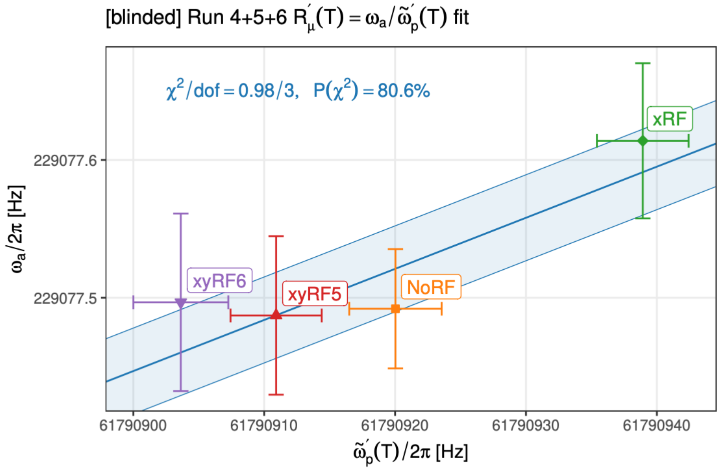
From Runs 1/2/3 to Runs 4/5/6





Runs 4/5/6:

- From early Run5 we add an additional **Quad RF system;**
- The dataset is split into 4 sets: **noRF**, **xRF** (horizontal RF only), **xyRF5** (horizontal and vertical RF in Run5) and **xyRF6** (horizontal and vertical RF in Run6).



April 2021: **Run-1** results, roughly matching the BNL data

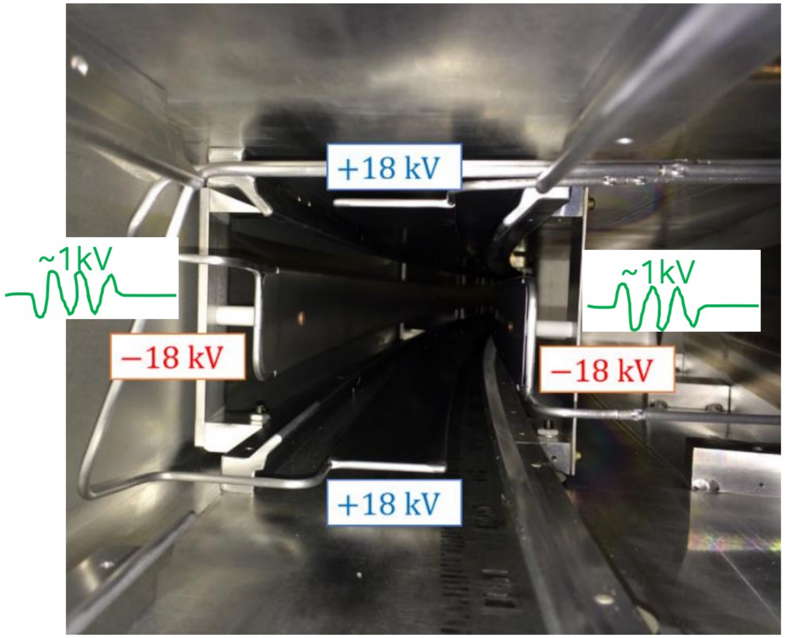
August 2023: **Run-2/3** results, 4.6 times more than Run-1

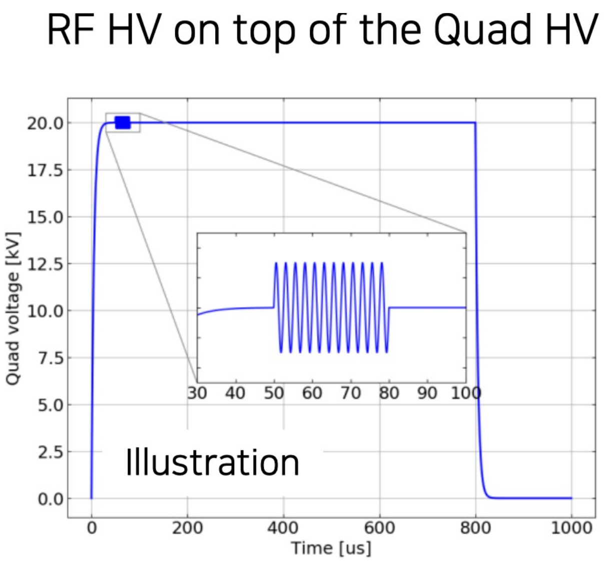
Final release 2025: **Run-4/5/6** results; **2.6 x Run-1/2/3**

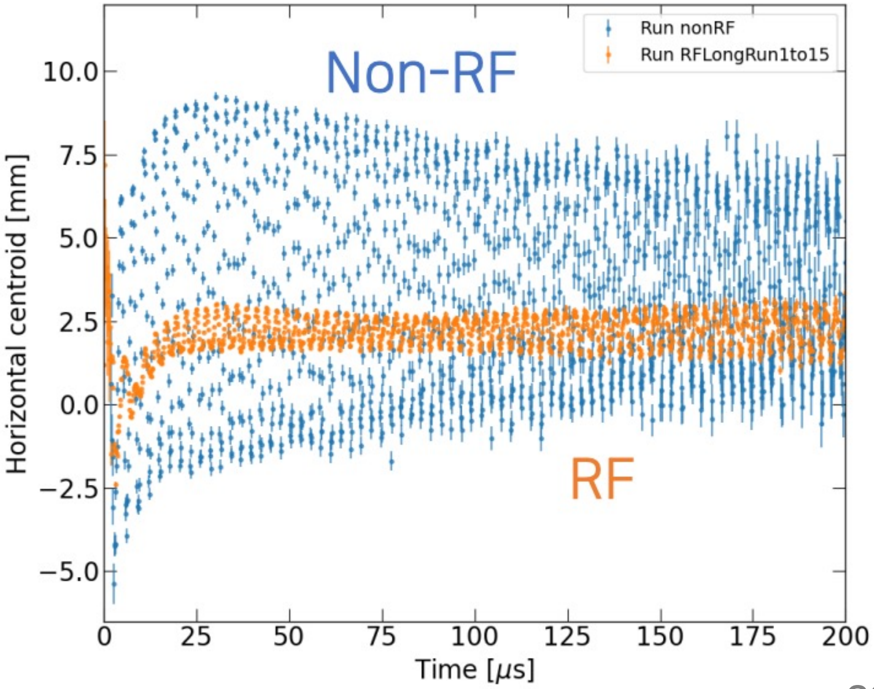
Notable Improvements in Runs 4/5/6

1) Quad RF system

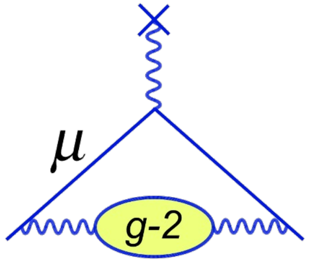
- RF acts like a forced harmonic oscillator. Muon phase shifts partially cancel each other out, which helps reduce the overall oscillation of the beam oscillations.







Notable Improvements in Runs 4/5/6



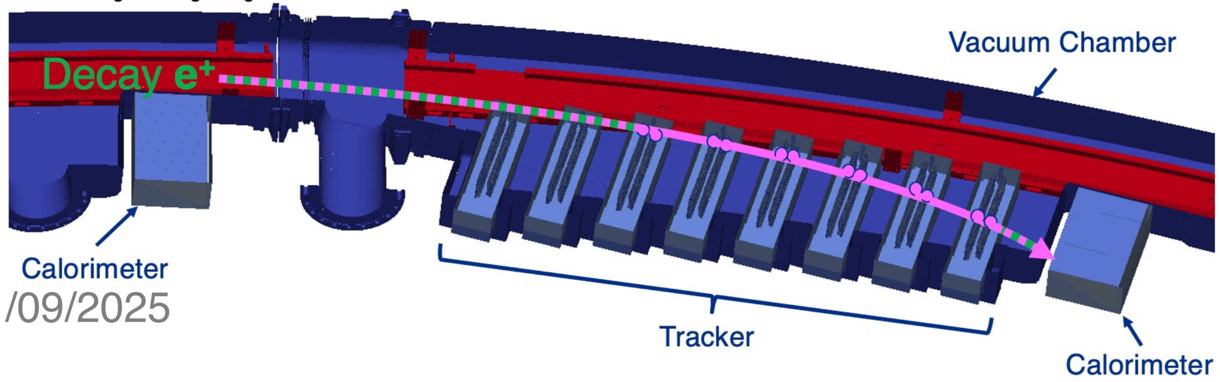
1) Quad RF system

- RF acts like a forced harmonic oscillator. Muon phase shifts partially cancel each other out, which helps reduce the overall oscillation of the beam oscillations.

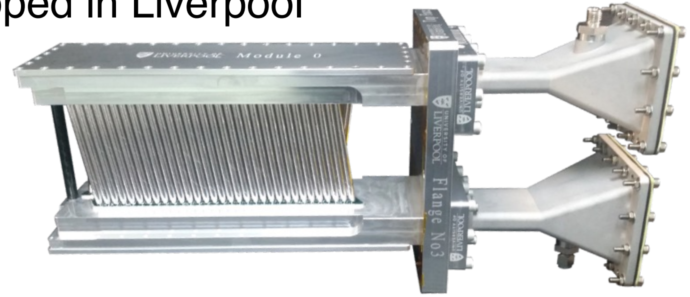
2) Expanded use of tracker data

- Straw tube tracking detectors allow us to “see” the beam. In Run 4/5/6, we expanded the use of the tracker data in many beam dynamics analyses, such as E-field (C_e) and Differential decay (C_{dd}).

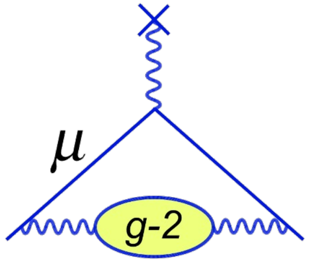
Section through storage ring



Straw Tracker Module developed in Liverpool



Notable Improvements in Runs 4/5/6



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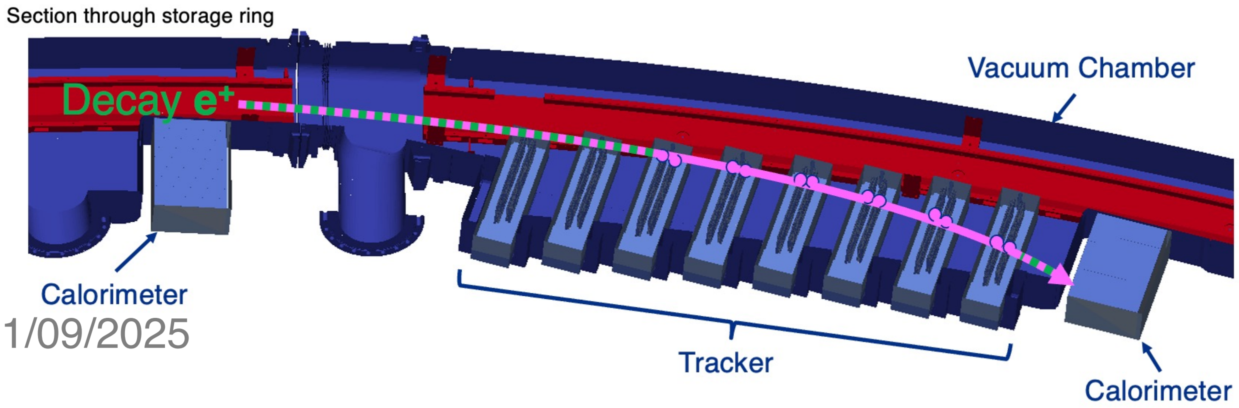
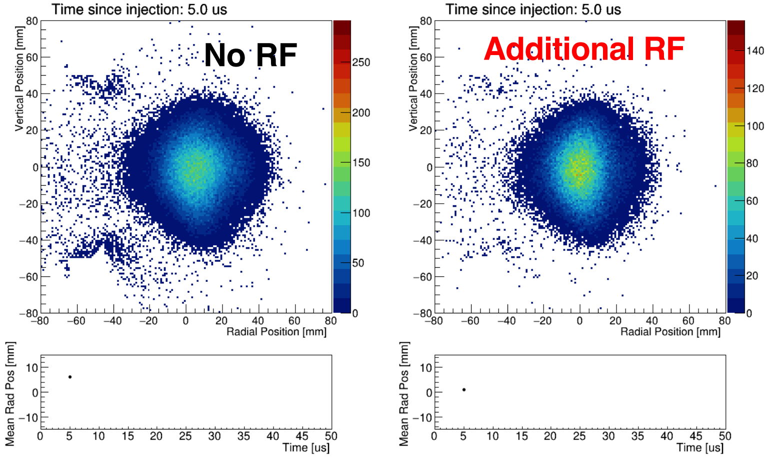
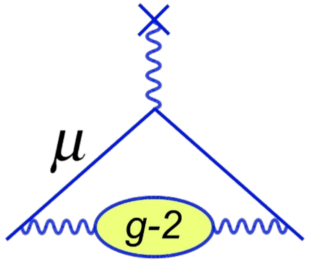




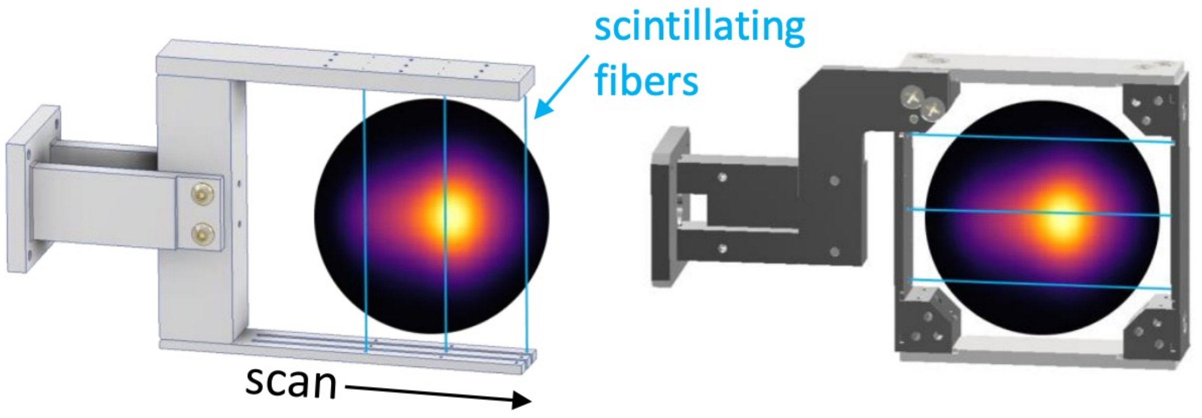
Significant reduction in oscillation amplitude

Notable Improvements in Runs 4/5/6



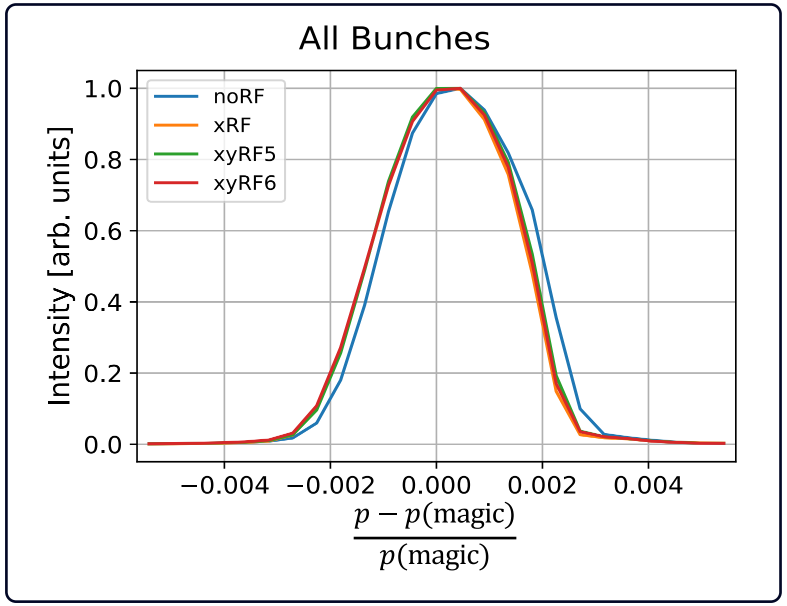
3) New 'mini sci-fi' detector

- Minimally Intrusive Scintillating Fiber Detector for both Vertical and Horizontal versions was applied in the later Run6 for cross-checks and uncertainty analysis
- 3 Fibers with 250 μm diameter measure circulating beam fast rotation intensity



Horizontal beam distribution

Momentum distribution from circulating beam

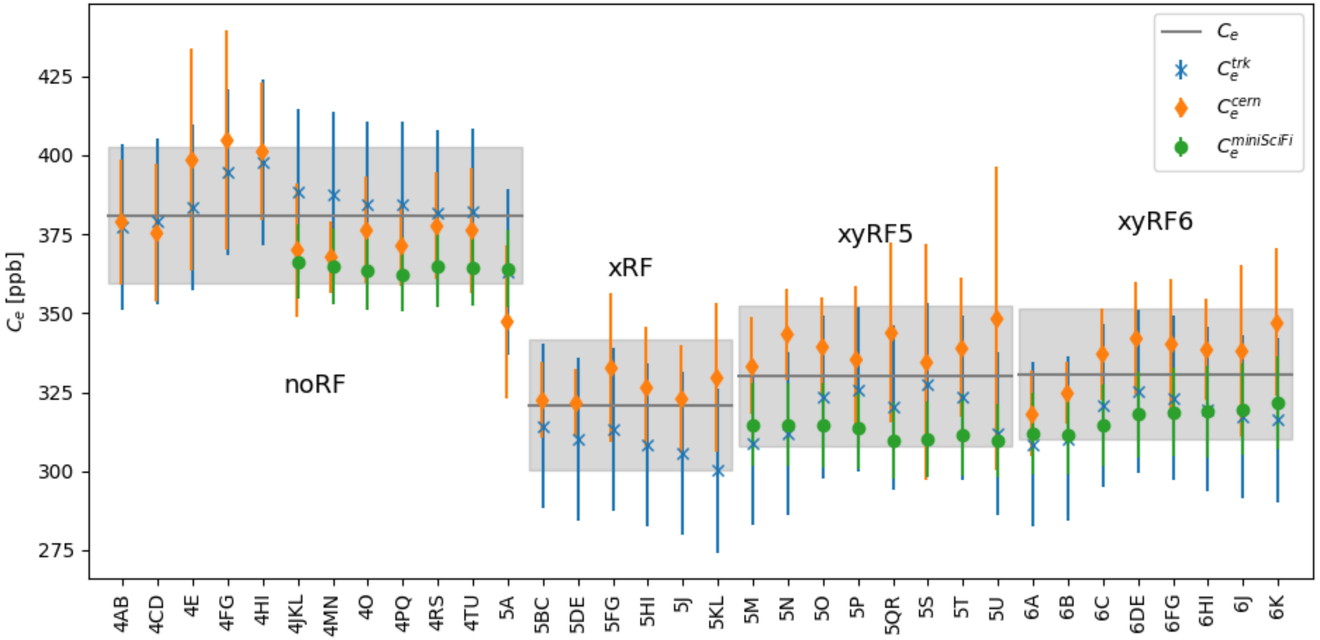


Notable Improvements in Runs 4/5/6

An integrated example: The E-field Correction

- E-field correction — the largest uncertainty in the beam dynamics — was analyzed via three methods in Runs4/5/6: calorimeter approach (Runs1/2/3), updated tracker method and mini-scifi cross-checks.

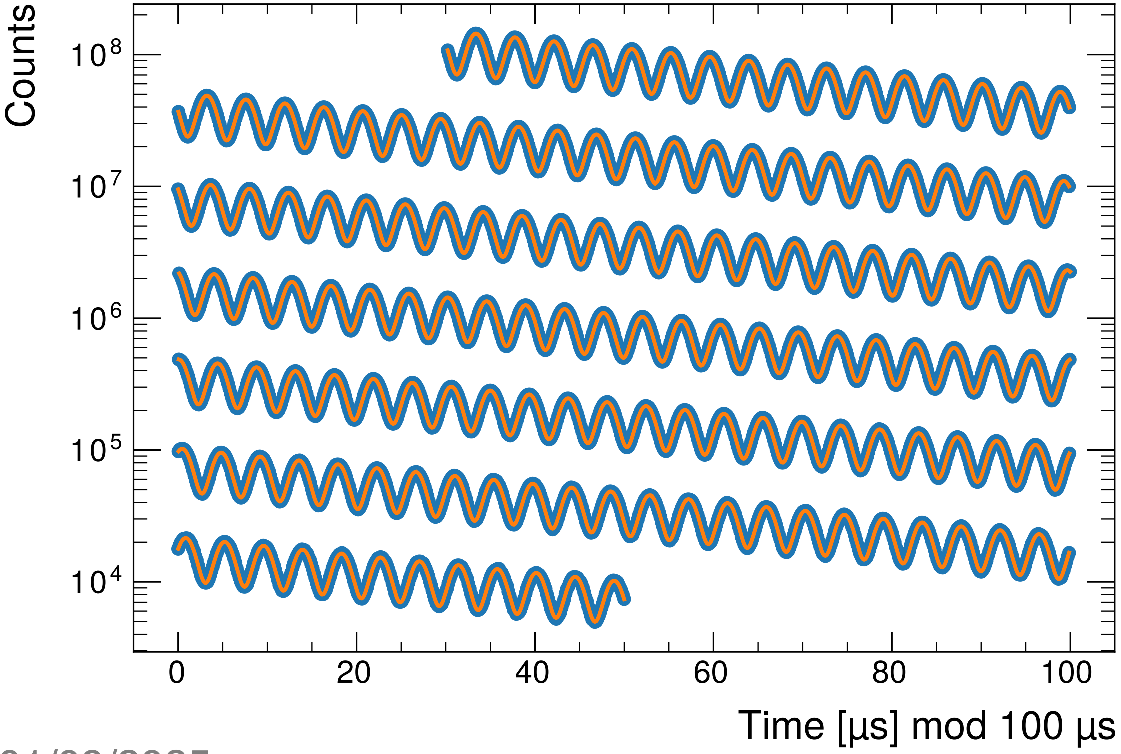
- Altogether, they increased confidence and a small reduction of uncertainties to a total of **27 ppb!**



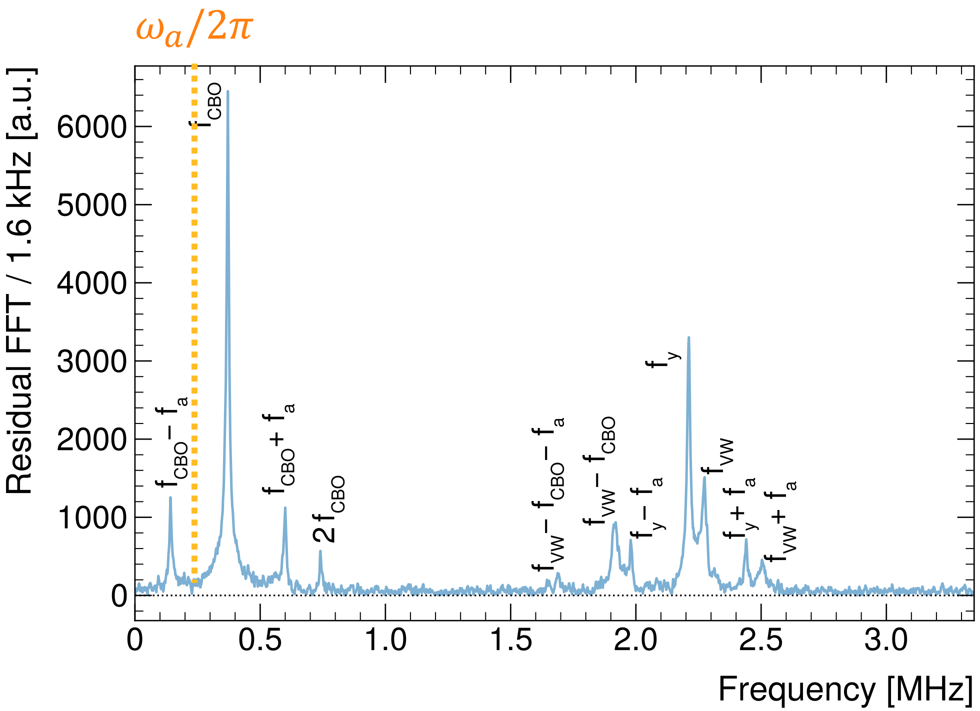
Notable Improvements in Runs 4/5/6

4) ω_a analysis: new models, and discoveries

- Larger statistics revels even more prominent frequency components



$$N(t) = N_0\, e^{-t/\tau}\,[1 + A\cos(\omega_a t\ - \phi_0)]$$



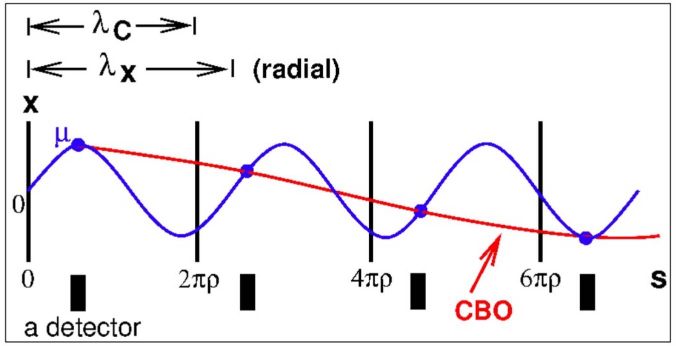
Notable Improvements in Runs 4/5/6

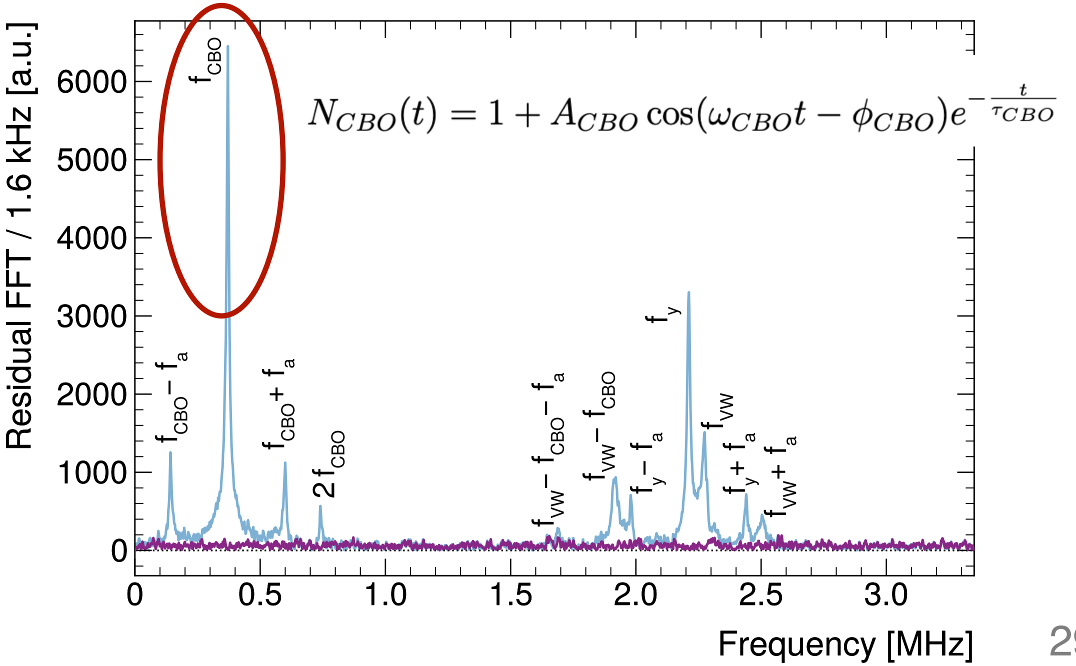
4) ω_a analysis: new models, and discoveries

- Larger statistics revels even more prominent frequency components
- In Runs-4/5/6, 5 groups with 8 method using up to **50 parameters** in the fit model to account for beam oscillations, muons losses, and detector effects ...

Example:

Beam dynamics modeling, such as the **Coherent Betatron Oscillation (CBO)**





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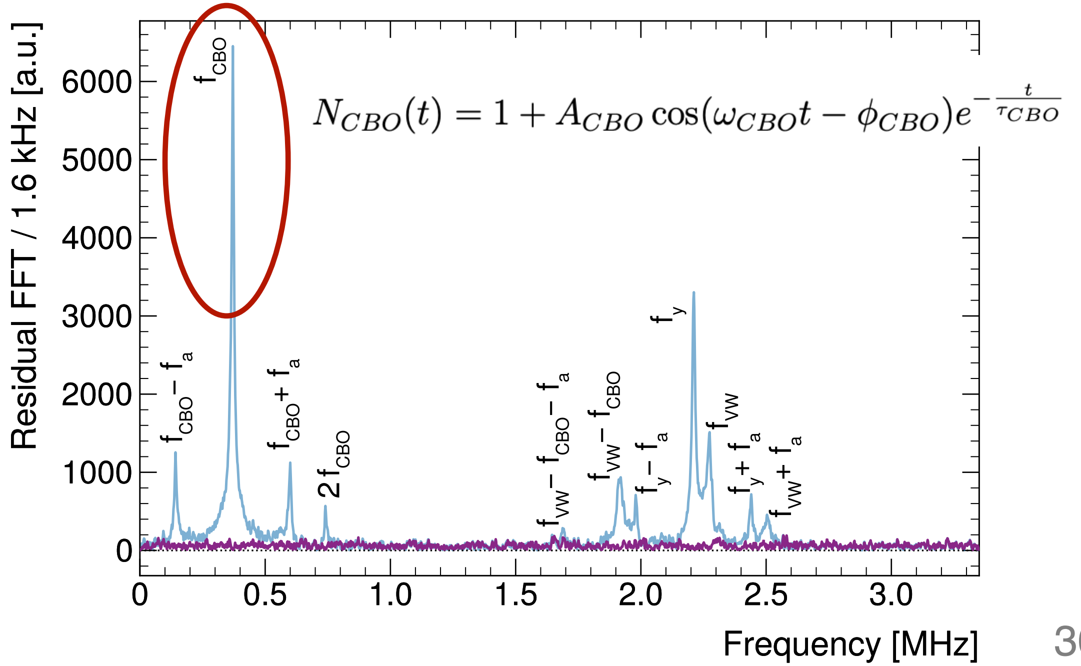
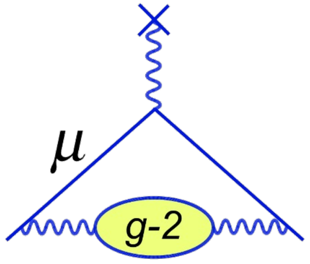
Example:

Beam dynamics modeling, such as the **Coherent Betatron Oscillation (CBO)**

- if not accounted for: **~800** ppb effect without the additional RF
- if not accounted for: **~80** ppb effect with the additional RF

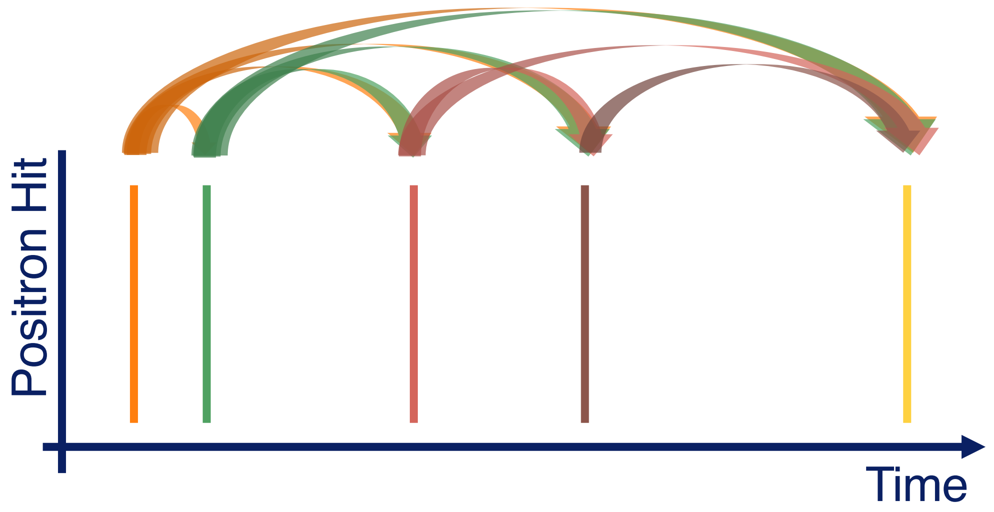


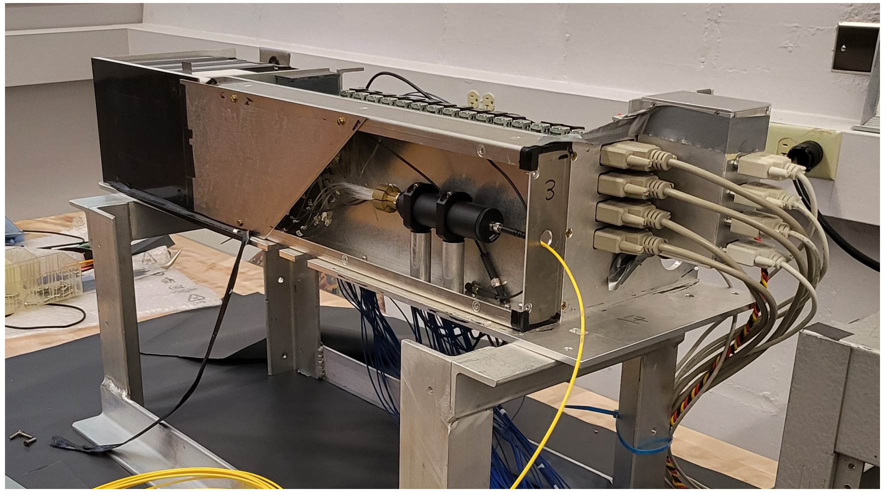
Notable Improvements in Runs 4/5/6



4) ω_a analysis: new models, and discoveries

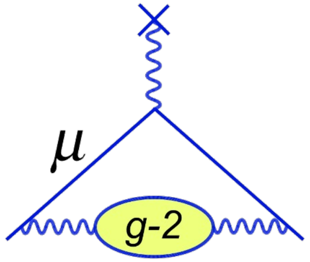
- A mysterious "early-to-late effect" has been identified with a physical explanation.
- Detector effects from preceding positron hits, with rate dependence at the μs scale; estimated impact 20–40 ppb with ~25 ppb uncertainty.





- Calorimeter in lab for dedicated measurements

Notable Improvements in Runs 4/5/6



4) ω_a analysis: new models, and discoveries

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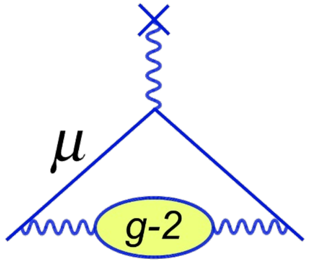
More details on the ω_a analysis – presentation on Tuesday in WG4:

14:10 **Precision Measurement of the Muon Anomalous Precession Frequency Using Run-4/5/6 Data of the Muon g-2 Experiment at Fermilab** 25m

The Muon g-2 Experiment at Fermilab has achieved a significant milestone by measuring the muon anomalous magnetic moment with a precision of 127 parts per billion (ppb), surpassing its original design goal of 140 ppb. This presentation provides an overview of the analysis of the anomalous precession frequency using the Run-4/5/6 dataset, which is crucial for the Muon g-2 measurement. We will discuss the analysis workflow and the determination of systematic uncertainties that contributed to this achievement. Special attention will be given to the modeling of coherent betatron oscillations (CBO) in the presence of the newly introduced radiofrequency (RF) field, as well as the identification and correction of residual slow effects observed in the time spectrum. These advancements are of vital importance for enhancing the accuracy of anomalous frequency measurement.

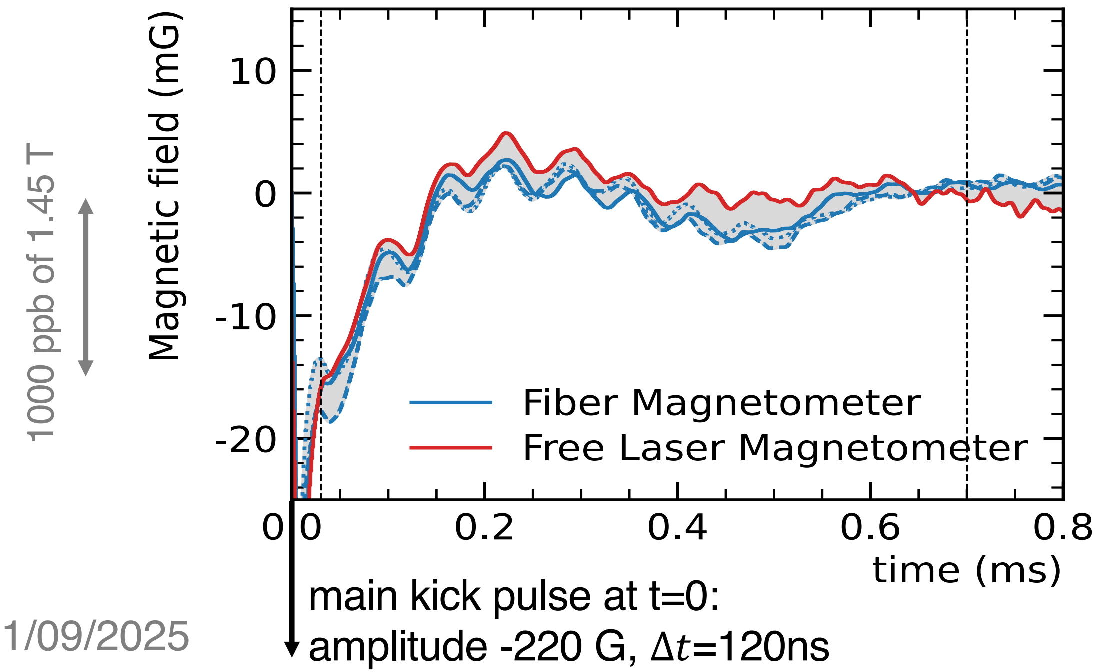
Speaker: Zejia Lu

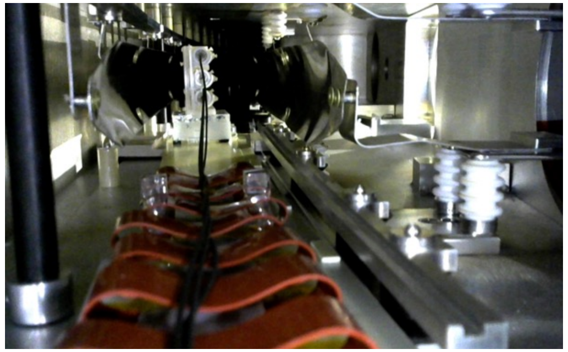
Notable Improvements in Runs 4/5/6



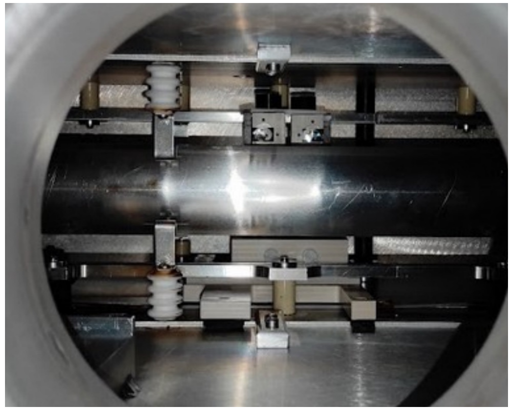
5) $\boldsymbol{B}$ field: newly measured kicker transient effect (B_k)

- Kick field causes eddy currents and introduces a transient magnetic field.
- In Runs 4/5/6, we newly developed two different magnetometers, both based on Faraday effect in TGG crystals





- Fiber magnetometer



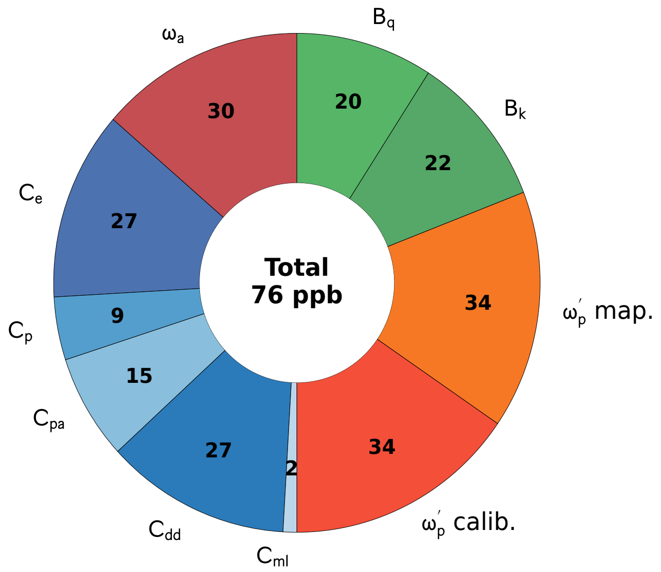
- Free laser magnetometer

Final Results

$$\frac{\omega_a}{\tilde{\omega}'_p} = \frac{\omega_a^m(1+C_e+C_p+C_{pa}+C_{dd}+C_{ml})}{\langle\omega'_p \times M\rangle(1+B_k+B_q)}$$

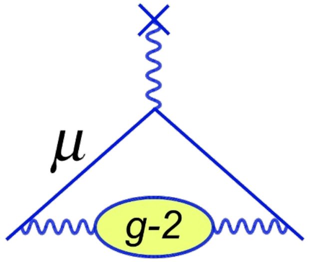
Run-4/5/6

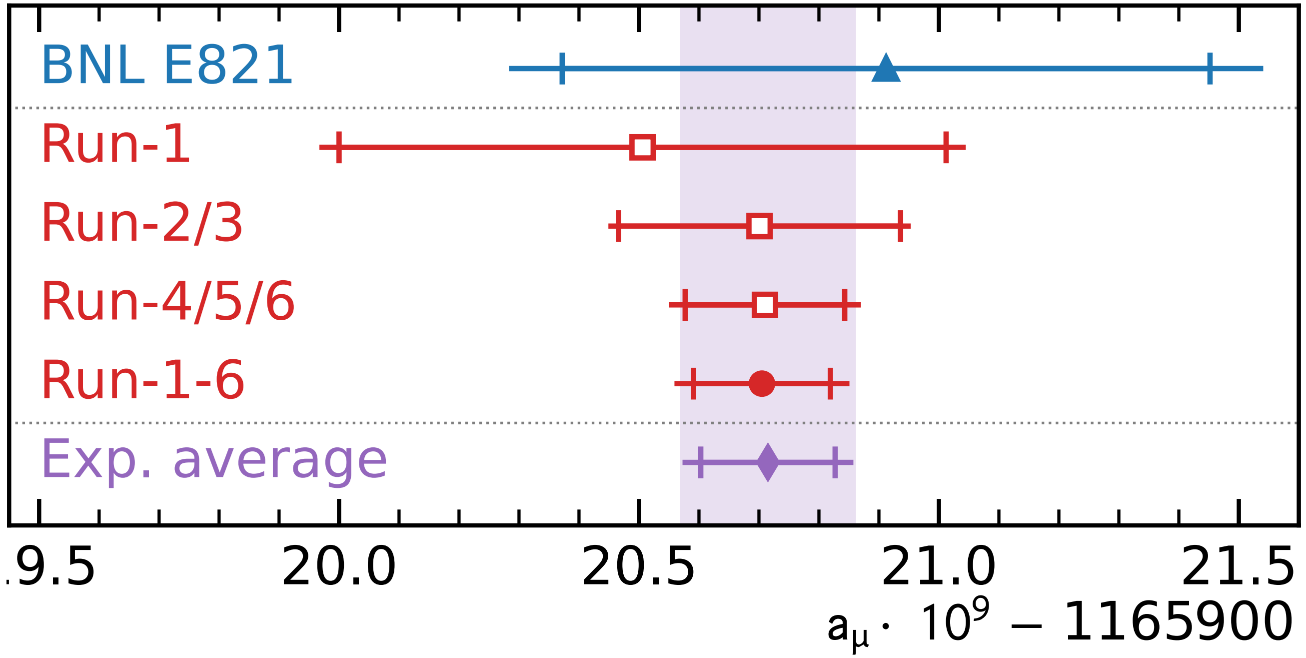
Quantity		Correction (ppb)	Uncertainty (ppb)
ω_a^m (statistical)		···	114
ω_a^m (systematic)		···	30
C_e	Electric Field	347	27
C_p	Pitch	175	9
C_{pa}	Phase Acceptance	-33	15
C_{dd}	Differential Decay	26	27
C_{ml}	Muon Loss	0	2
$\langle\omega'_p \times M\rangle$ (mapping, tracking)		···	34
$\langle\omega'_p \times M\rangle$ (calibration)		···	34
B_k	Transient Kicker	-37	22
B_q	Transient ESQ	-21	20
μ'_p/μ_B		···	4
m_μ/m_e		···	22
Total systematic for $\mathcal{R}'_\mu$		···	76
Total for a_μ		572	139



- TDR goal: 100 ppb ✓
- Systematics are “evenly” distributed:
  - No dominant source
  - Further improving would require to reduce in many categories

Final Results





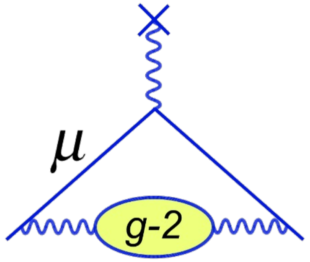
$$a_\mu(\text{Run}-4/5/6) = 0.001165920710(162)$$

$$a_\mu(\text{Run}-1-6) = 0.001165920705(148)$$

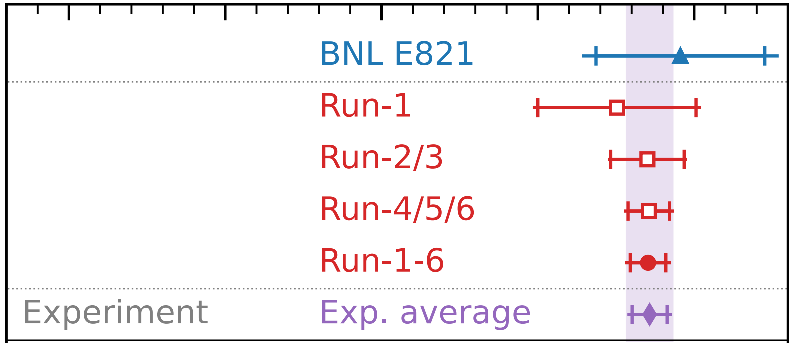
$$a_\mu(\text{exp}) = 0.001165920715(145)$$

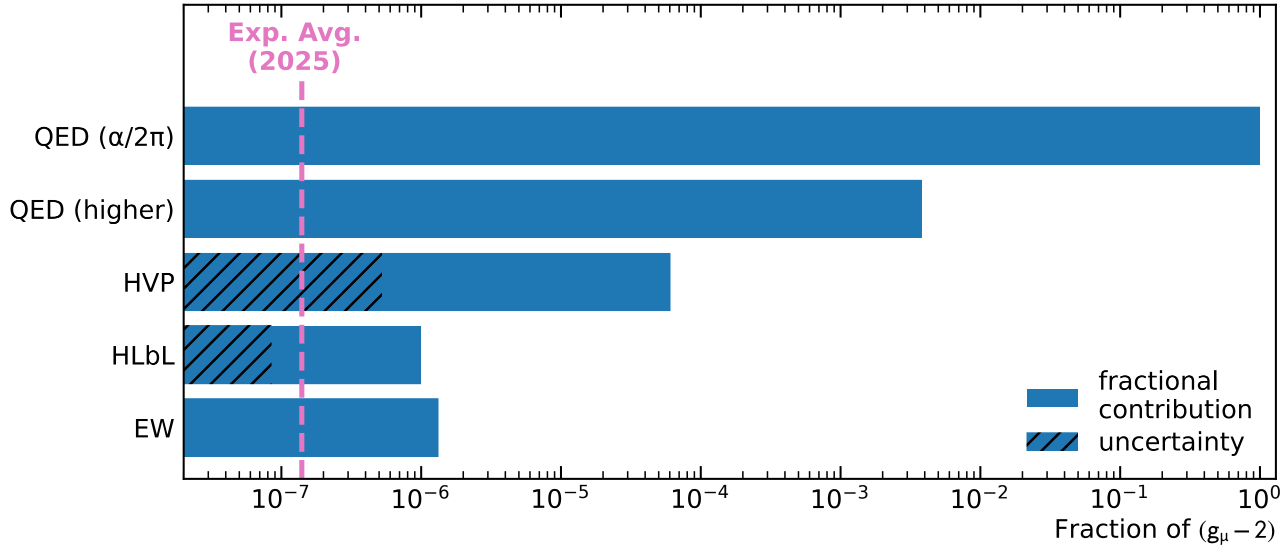
- Runs 4-6 uncertainty reduced by 1.8 times over Runs 1-3;
- Combined Fermilab Runs 1-6 reduces BNL uncertainty by a **factor of 4.3**

Are we done?



- Yes –
  - Most precise determination of a_μ - a 127-ppb measurement probing all SM contributions





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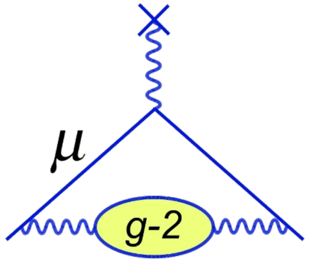
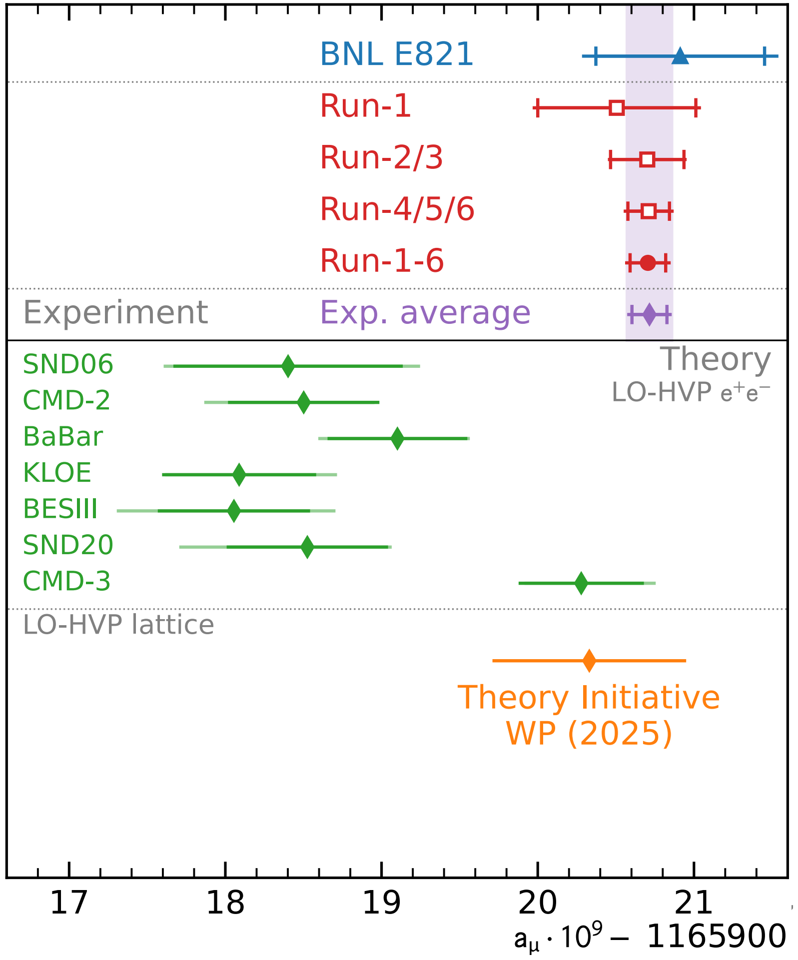


- Yes –
  - Most precise determination of a_μ - a 127-ppb measurement probing all SM contributions
- and No –
  - The overall picture still remains unsettled;
  - What's next from our collaboration:
    - Muon EDM
    - CPT/Lorenz-violating
    - Dark Matter
    - ...
  - Other related projects: J-PARC, MUonE, ...



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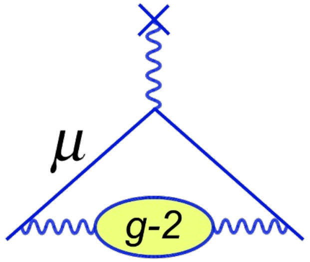


- Related talks (all in Tuesday's WG4 session)

13:45 **J-PARC muon g-2/EDM experiment** 25m

The J-PARC muon g-2/EDM experiment aims to precisely measure the anomalous magnetic moment and electric dipole moment based on a novel low-emittance muon beam. Such a beam is realized by a muon linear accelerator following a cooled muon source, which allows to employ different techniques than the BNL and FNAL experiments such as a compact storage ring without electric focusing and track detection of decay positr
The experiment is curren
data taking in 2030. In th

Speaker: Masato Kimura

14:35 **Status of the MUonE experiment** 25m

The MUonE experiment at CERN aims to determine the leading-order hadronic contribution to the muon by an innovative approach, using elastic scattering of 160 GeV muons on atomic electrons in a low-Z target. The M2 beam line at CERN provides the necessary intensity needed to reach the statistical goal in few years of data taking. The experimental challenge relies in the precise control of the systematic effects. A first run with a minimal prototype setup was carried out in 2023. A pilot run is in preparation to be held in 2025 with a reduced setup of the full detector components. We will present the status of the experiment, first preliminary results and the future plans.

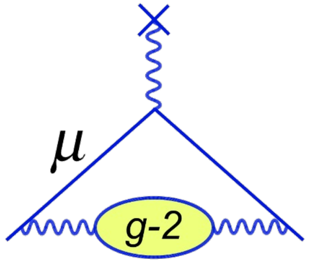
Speaker: Dr Saskia Charity

15:00 **Searching for a muon EDM at the Fermilab Muon g-2 experiment** 25m

The new Muon g-2 experiment at Fermilab, while primarily designed to measure the muon's anomalous magnetic moment, also offers the unique opportunity to perform a world-leading search for the muon's electric dipole moment (EDM). Within the Standard Model, the muon EDM is predicted to be vanishingly small, orders of magnitude smaller than the reach of current experiments. However, some BSM models predict different mass scaling, or decouple the EDM from the lepton masses altogether, allowing for much larger EDMs. As such, any observed signal would provide direct evidence of new physics and a new source of CP violation in the lepton sector. Even in the absence of a discovery, improving the experimental limits on the muon EDM provides valuable constraints on BSM theories. This talk will present the experimental strategies employed at Fermilab to search for a muon EDM, with a focus on using data from the straw trackers, and will give an update on the current status and future prospects of the analysis.

Speaker: Dominika Vasilkova

Summary



- We provide the final result from the Fermilab muon g-2 measurement

$$\boldsymbol{a_\mu}(\text{Run}-1-6) = \mathbf{0.001165920705(148)}$$

– a benchmark for many years to come;

- Despite very different conditions in Runs 1-6, the remarkable consistency of the results further reinforces the robustness of our outcome;
- Further projects and BSM analyses are underway. Muon g-2 remains far from complete, continuing to play a central role in the pursuit of New Physics.

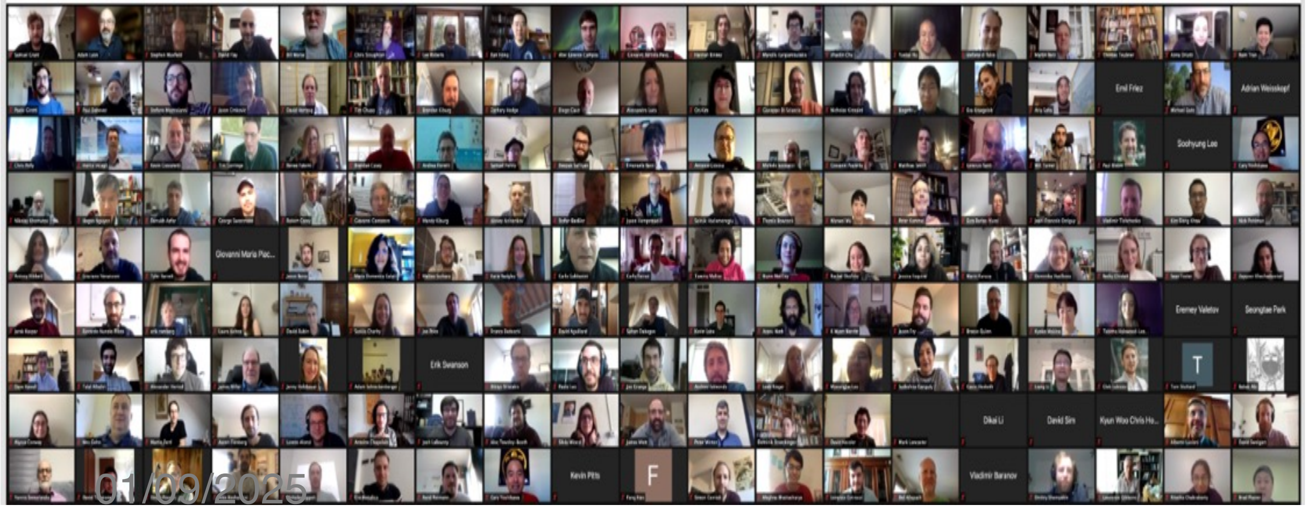
Thank you for the attention!

Collaboration meeting at Fermilab, March 2017

Collaboration meeting at Elba, Italy, May 2019

Collaboration meeting at Liverpool, UK, July 2023

Online Collaboration Meeting during Covid-19 period, April 2022



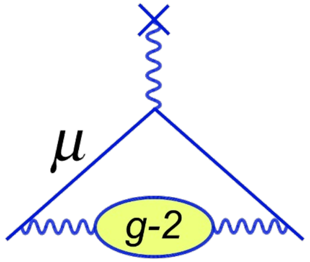
Final unblinding, May 2025

Thank you for the attention!

Acknowledgements

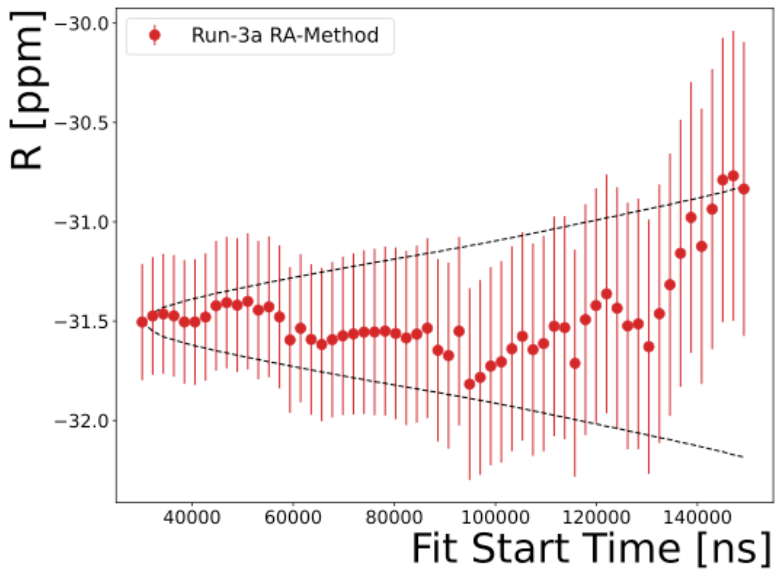
- Department of Energy (USA),
- National Science Foundation (USA),
- Istituto Nazionale di Fisica Nucleare (Italy),
- Science and Technology Facilities Council (UK),
- Royal Society (UK),
- Leverhulme Trust (UK),
- European Union's Horizon 2020,
- Strong 2020 (EU),
- German Research Foundation (DFG),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

Backup

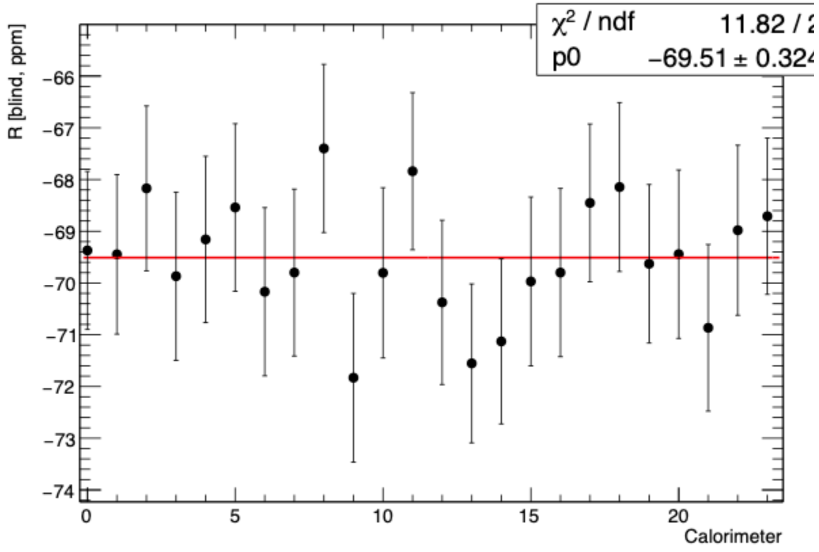


Consistency Check

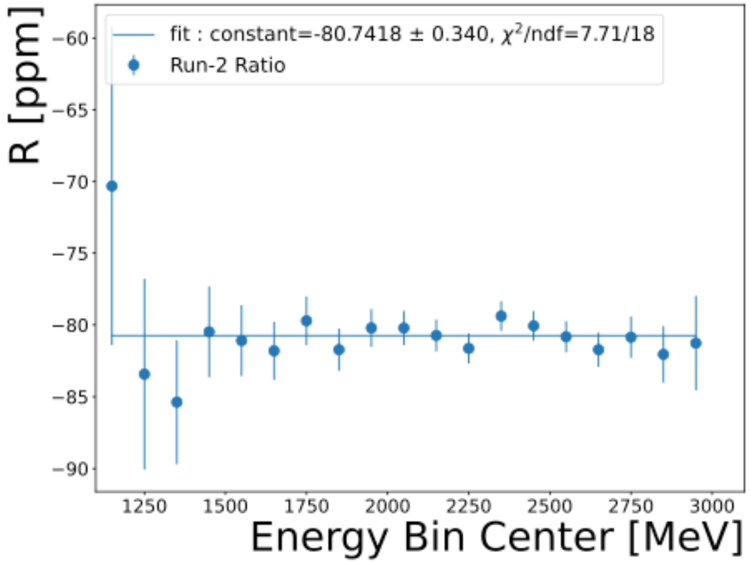
- We perform many consistency checks: fit residual FFTs, fit start time scans, fits by calorimeter, fits by positron energy, etc.



Fit start time scan



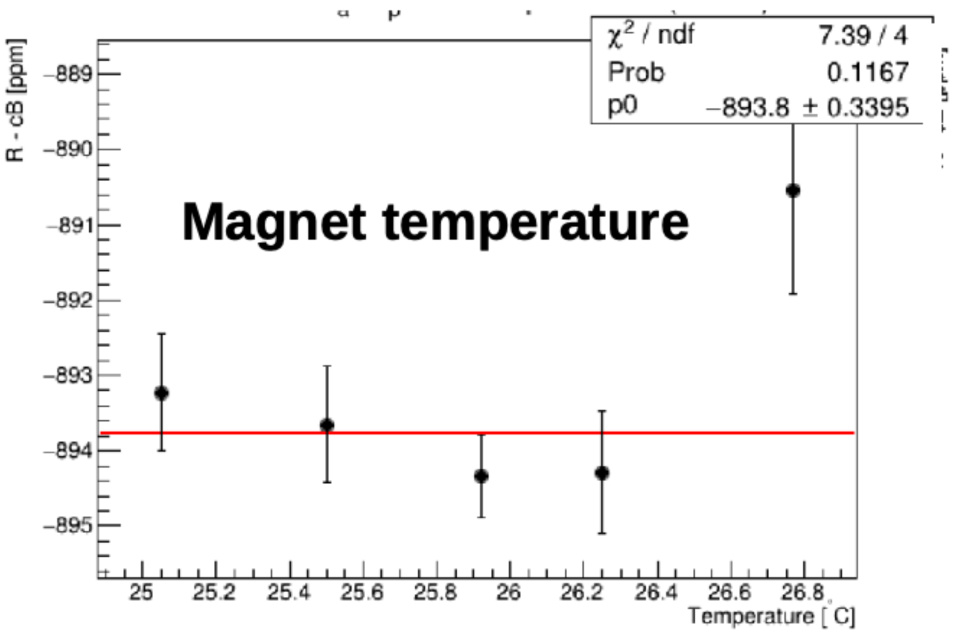
Per-calorimeter fits

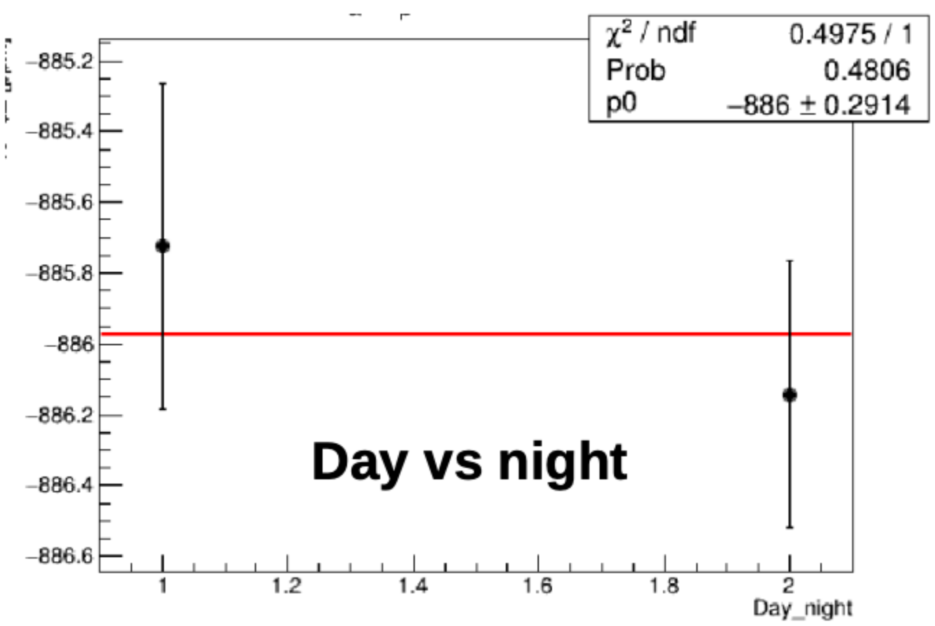


Energy-bin fits

Consistency Check

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

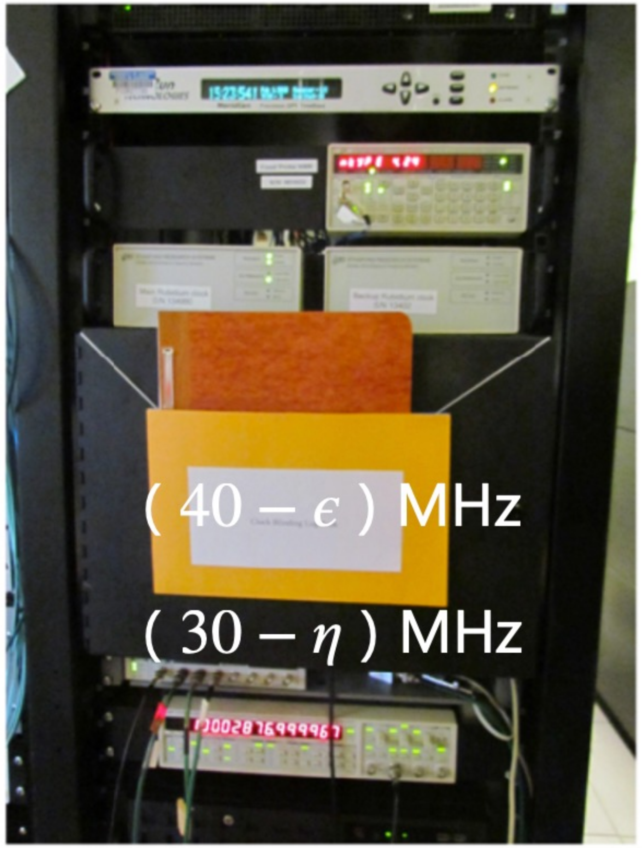




Blinding Scheme

University of Liverpool

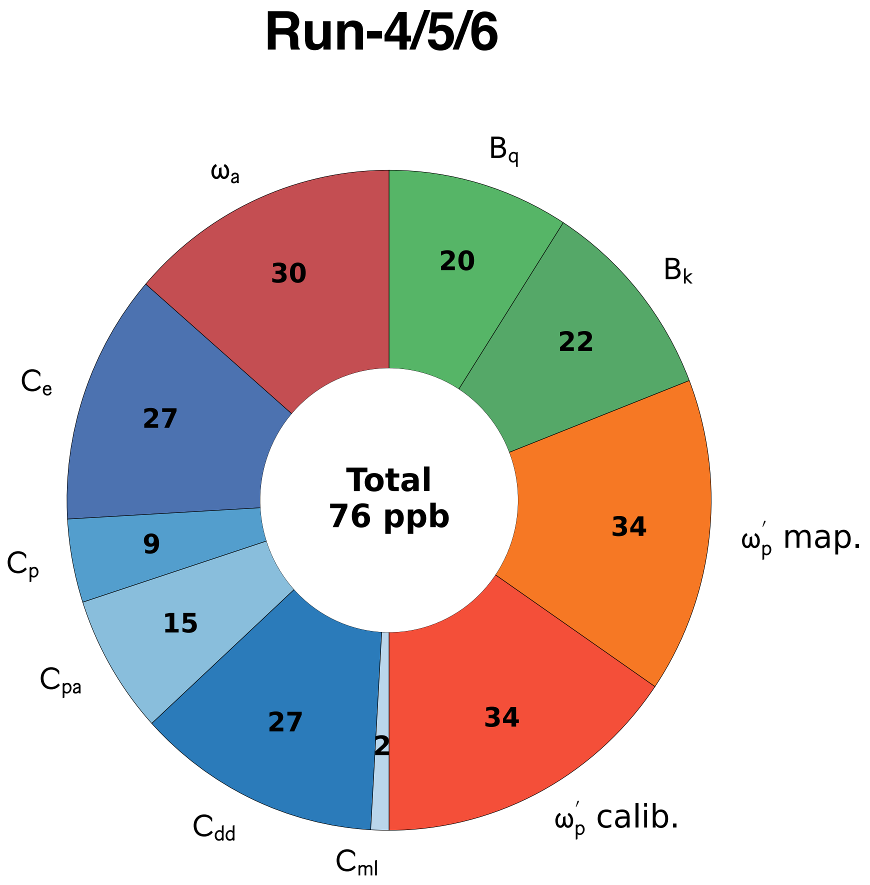
Locked Clock Panel



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

- 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

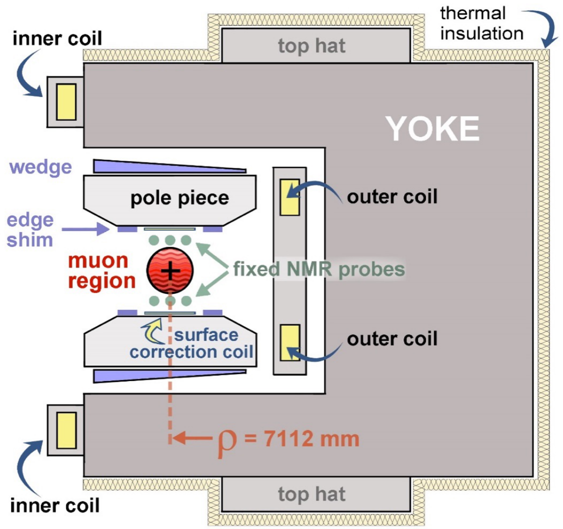
Systematics

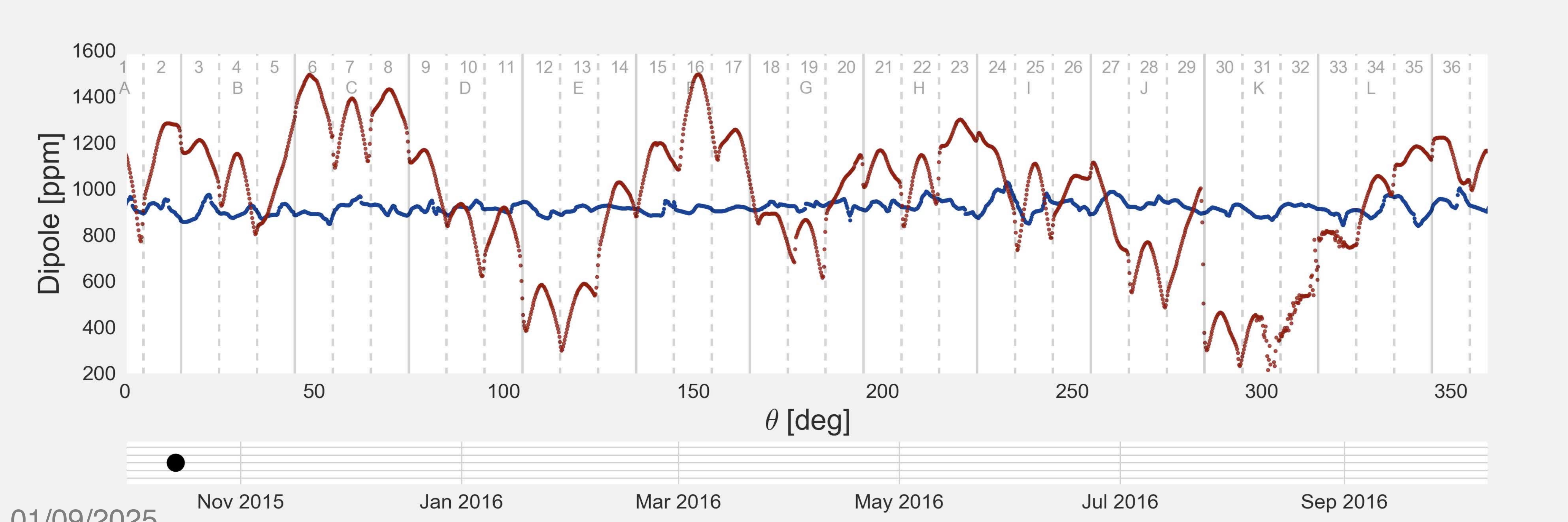


- Run-2/3 with Run-4/5/6 knowledge
- Identified physical source for residual slow term effects
- Dedicated MiniSciFi detector and further improved methods
- Improved understanding, leading to more conservative uncertainty (sign error correction in one component)
- More conservative uncertainty motivated by additional cross-calibration
- Reduction of uncertainties due to additional measurement
- Additional measurement lead to refined spatial model

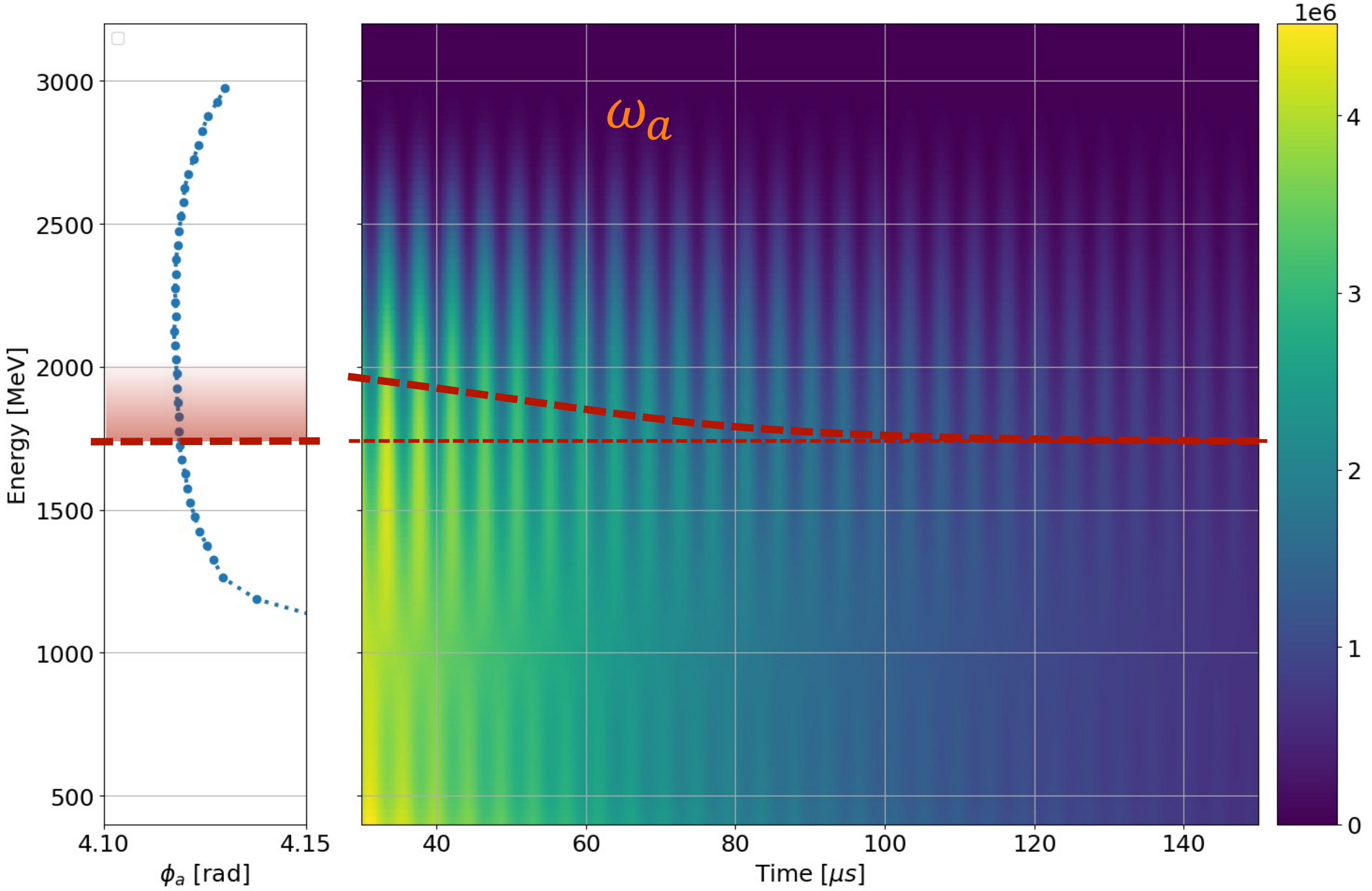
Magnetic Field Shimming

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



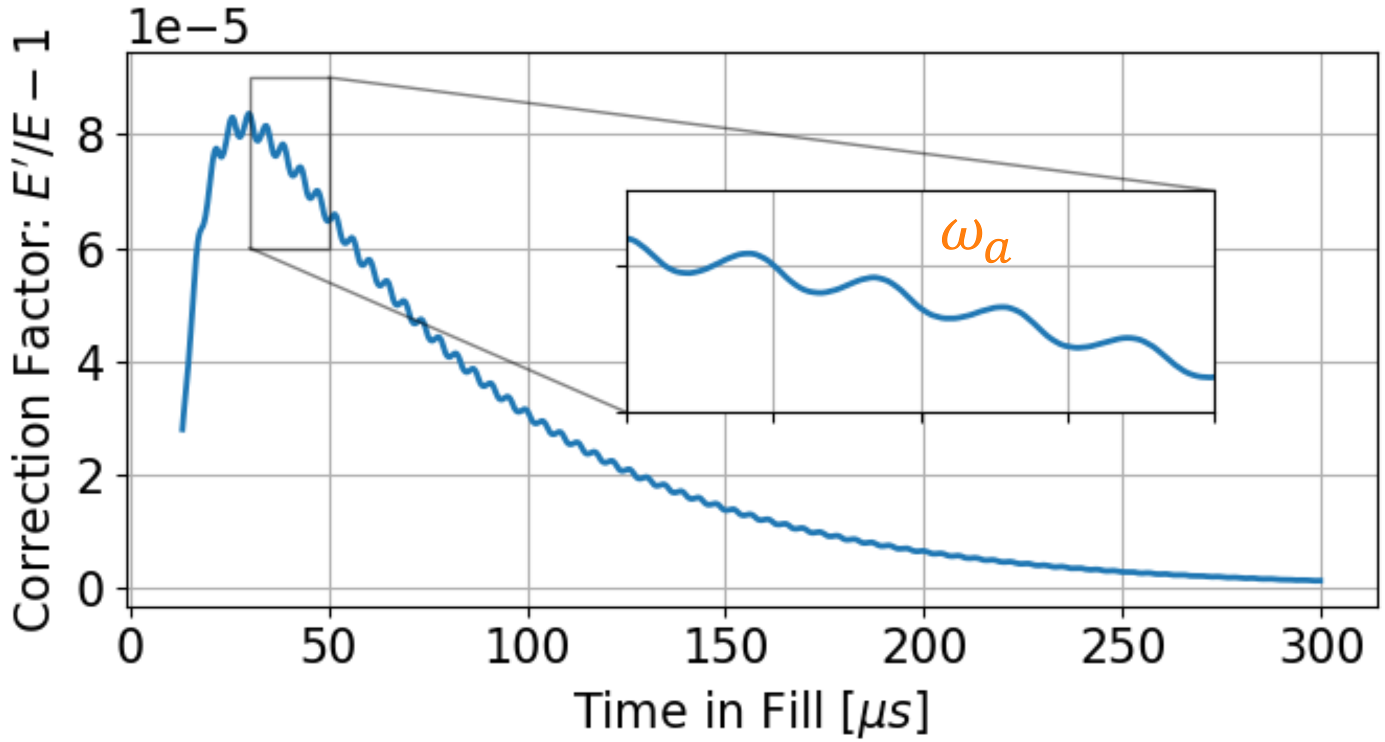


Gain-Like Detector Effects



Effective **threshold changes** over time

Gain-Like Detector Effects



*noRF dataset

New! Sensitive also below 10^{-4} if

- Rate & Energy dependent
- Time constant $\sim 1/\omega_a$
- Correction shows ω_a-behavior but **out of phase**
- Time-dependent phase-change
- Fitted ω_a sensitive to such effects

Run-4/5/6: Superior Statistics, Additional Measurements

and simulation efforts allowed for many **cross-checks and gain new insights**

To combine our results: use this Run-4/5/6 knowledge for Run-1/2/3

Identified an **Intensity-Dependent Gain Sag**

- with a magnitude below our stability design goal (10^{-4})
- however, **phase-shifted** oscillation at ω_a leads to **larger sensitivity** than orig. estimated
- **Resolved puzzle** of residual slow terms in ω_a-fits
- Run-2/3: +47 ppb $\pm$ 24 ppb
  (Run-1: +50 ppb $\pm$ 29 ppb)

Improved spatial-model of Kicker-Transients

- Additional, dedicated measurement after muon storage periods
- similar cross-checks for transient fields from ESQ (B_Q), confirmed used model
- Run-2/3: +19 ppb $\pm$ 23 ppb

*on a_μ, correction on B_k has opposite sign

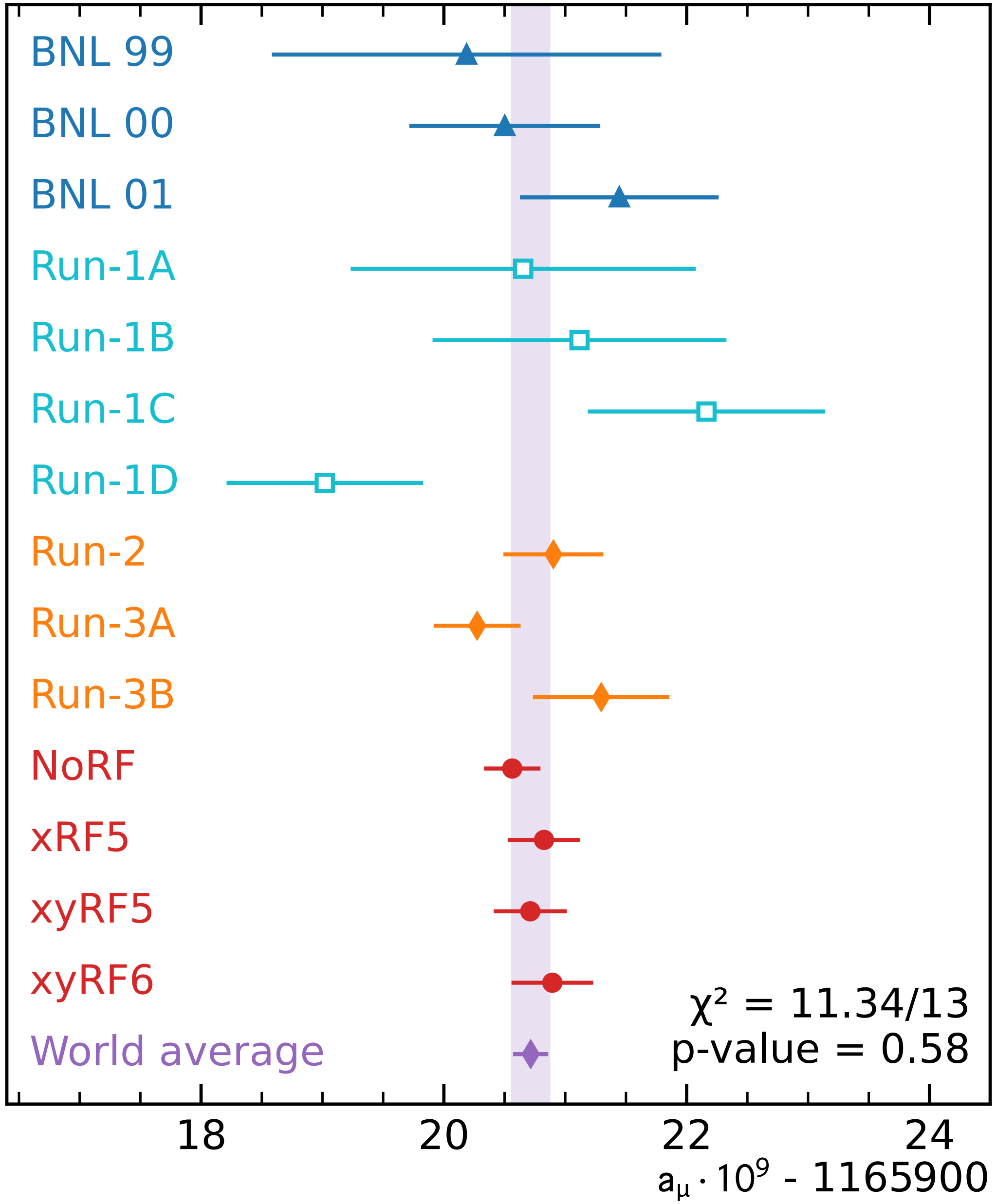
Identified and corrected a **sign error**

- in one (of three) contribution to the Differential Decay Correction ($C_{dd}^{beamline}$)
- Run-2/3: magnitude of $C_{dd}^{beamline}$: 12 ppb to 20 ppb
- Run-2/3: +32 ppb $\pm$17 ppb
  *uncertainty due to method not sign error

All these correction have the same sign. Run-2/3 total +89 ppb
Total Run-2/3 uncertainty: from 70 ppb to 78 ppb

Large Dataset

allows to demonstrate consistency



CERN Experiments – what a difference!

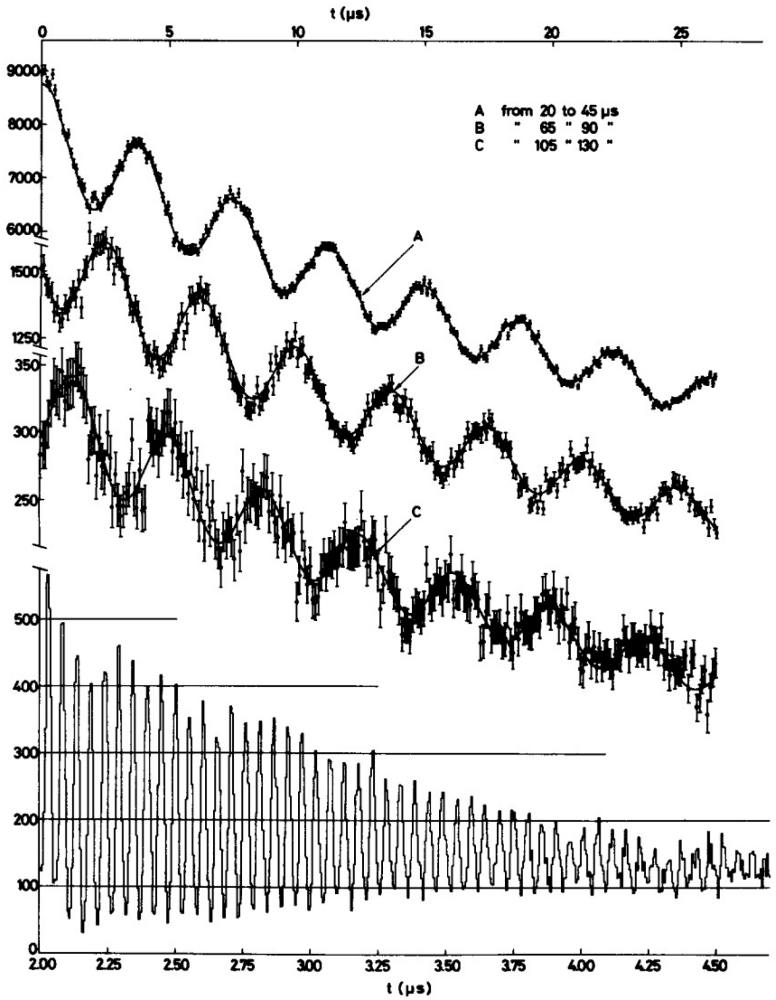
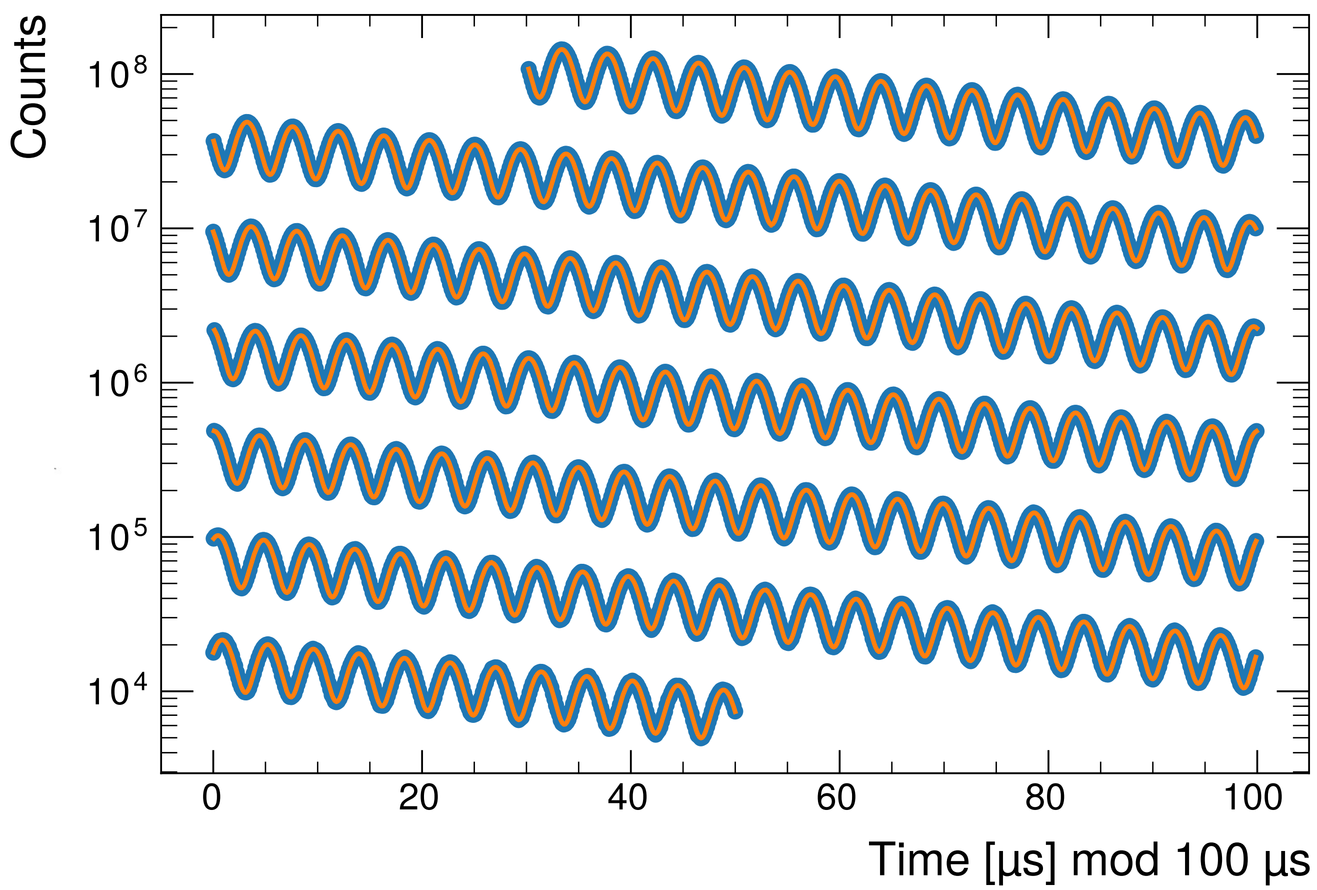


Fig. 2. Distribution of decay-electron events as a function of time. Lower curve shows rotation frequency of muon at early time. A, B, C: late time data, 20 - 130 µsec showing (g - 2)-precession. Data are fitted from 21 to 190 µsec.

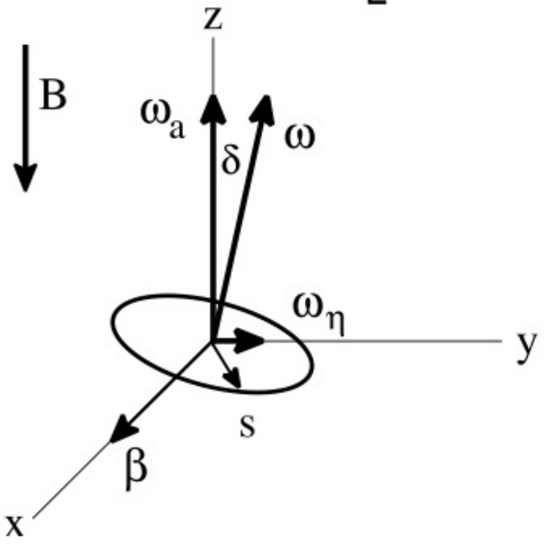


Muon EDM

Muon EDM

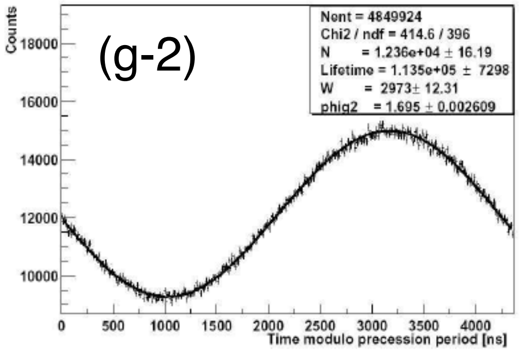
non-zero EDM (η) modifies the spin equation

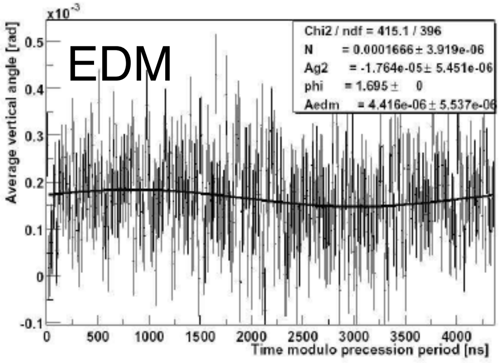
$$\vec{\omega}_{a\eta} = a_\mu \frac{e}{m}\vec{B} + \eta\frac{e}{2m}\left[\frac{\vec{E}}{c} + \vec{\beta}\times\vec{B}\right]$$



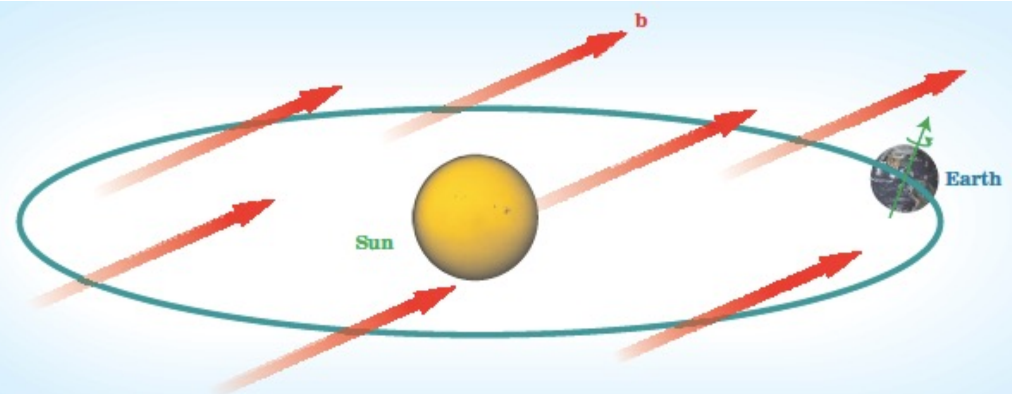
Search for an up/down asymmetry out of phase with ω_a

BNL: tracker-based analysis





CPT and Lorentz Violations



Lorentz Violation –
existence of a preferred direction

- Uniform background vector, *b*
- What could it come from?
  Spontaneous Symmetry Breaking,
  - **SM**: In EWSB, scalar field gets non-zero vacuum expectation value, filling vacuum with *Lorentz Symmetric quantities*
  - **SME**: Can have Lorentz SB, where vector field gets non-zero vev, filling vacuum with *4-dimensionally oriented quantities* → preferred direction in space → LV!
  - Possibilities: string theory, loop-quantum gravity, etc.

CPT Violation

- LV *allows* but does not *require* CPTV, because CPT Theorem no longer holds (but CPTV does require LV)

Dark Matter - Physics Signature

Muon $g-2$ has a competitive sensitivity to the **ultralight (thus bosonic and wave-like field) muonic DM**. It is the first direct DM search with muons in a storage ring.

- Scalar field (Yukawa coupling) $\phi = \phi_0 \cos(m_\phi t)$
  - It induces oscillating m_μ.

$$\mathcal{L} \supset -g\phi\bar{\mu}\mu - g'\phi^2\bar{\mu}\mu \quad \Rightarrow \quad m_\mu \to m_\mu + g\phi + g'\phi^2$$

  - It leads ω_a to oscillate: $\omega_a \to \omega_a(1 + A_\phi \cos m_\phi t)$

- Pseudoscalar axion-like field $a = a_0 \cos(m_a t)$
  - EDM coupling induces oscillating EDM (d_μ).

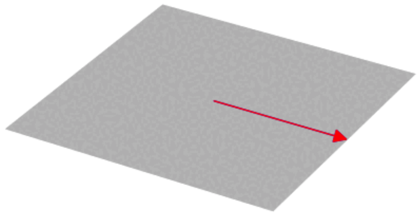
$$\mathcal{L} \supset -ig_{\mathrm{EDM}} a\bar{\mu}\sigma^{\lambda\nu}\gamma_5\mu F_{\lambda\nu} \;\Rightarrow\; d_\mu \to d_\mu + g_{\mathrm{EDM}} a$$

  - Gradient coupling induces oscillating spin along the axis of the muon's motion.

$$\mathcal{L} \supset g_{a\mu}\partial_\lambda a\bar{\mu}\gamma^\lambda\gamma_5\mu \;\Rightarrow\; \mathcal{H} \supset \mathrm{g}_{a\mu}\nabla a \cdot \mathbf{S}$$

  - Both lead to oscillating $\delta\boldsymbol{\omega}_a$ components perpendicular to $\boldsymbol{\omega}_a$.

Spin precession



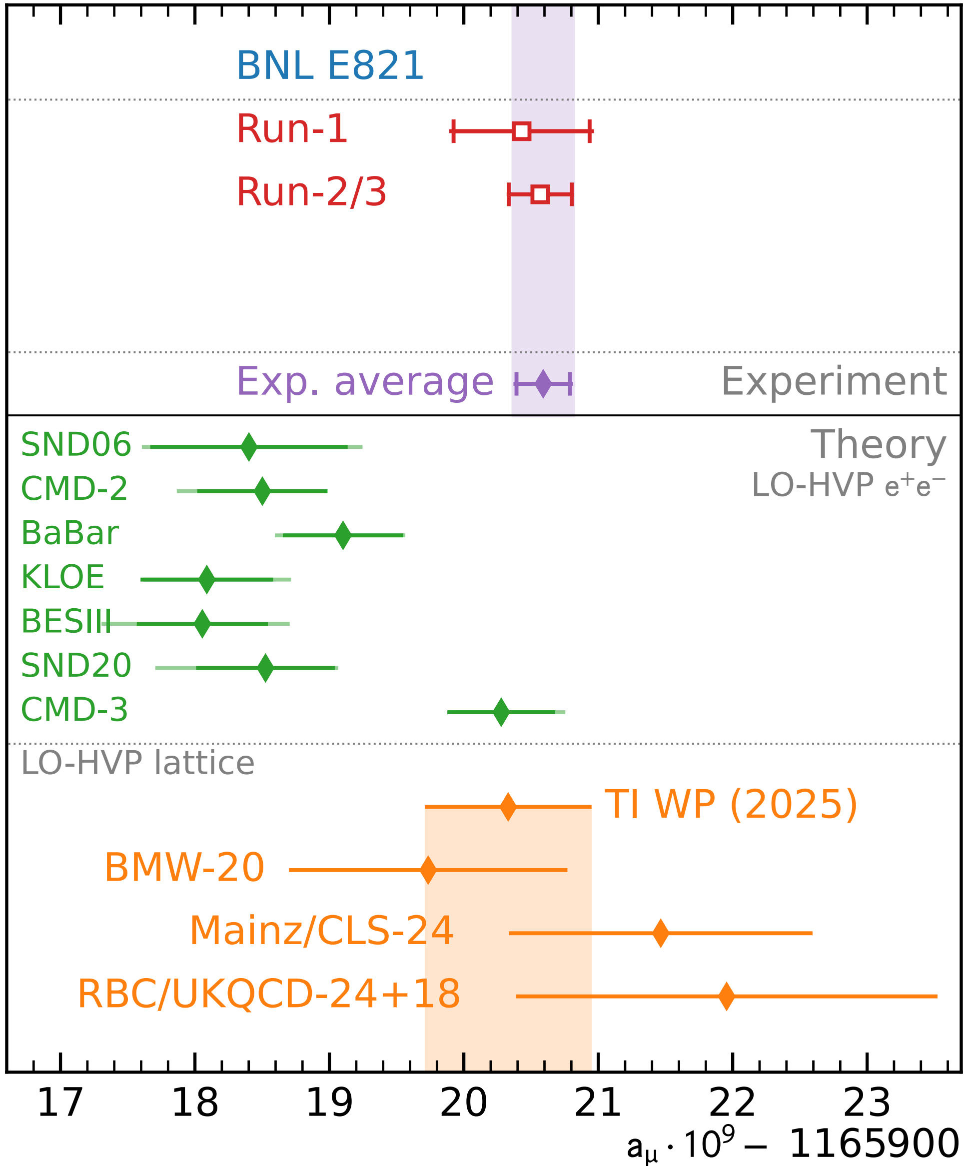
No DM

Gradient coupling (10% of ω_a)

TI White Paper 2025

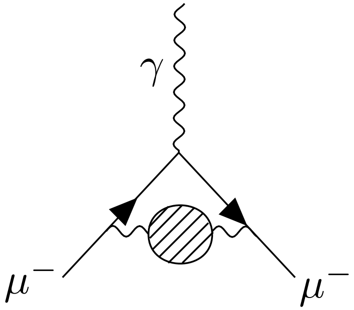
Last week:

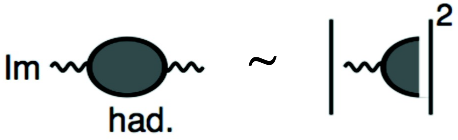
New **TI White Paper (2025)** using only lattice-QCD based LO-HVP determination



All the details in
TI White Paper 2025
arXiv:2505.21476

LO-HVP: dispersive e^+e^-





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

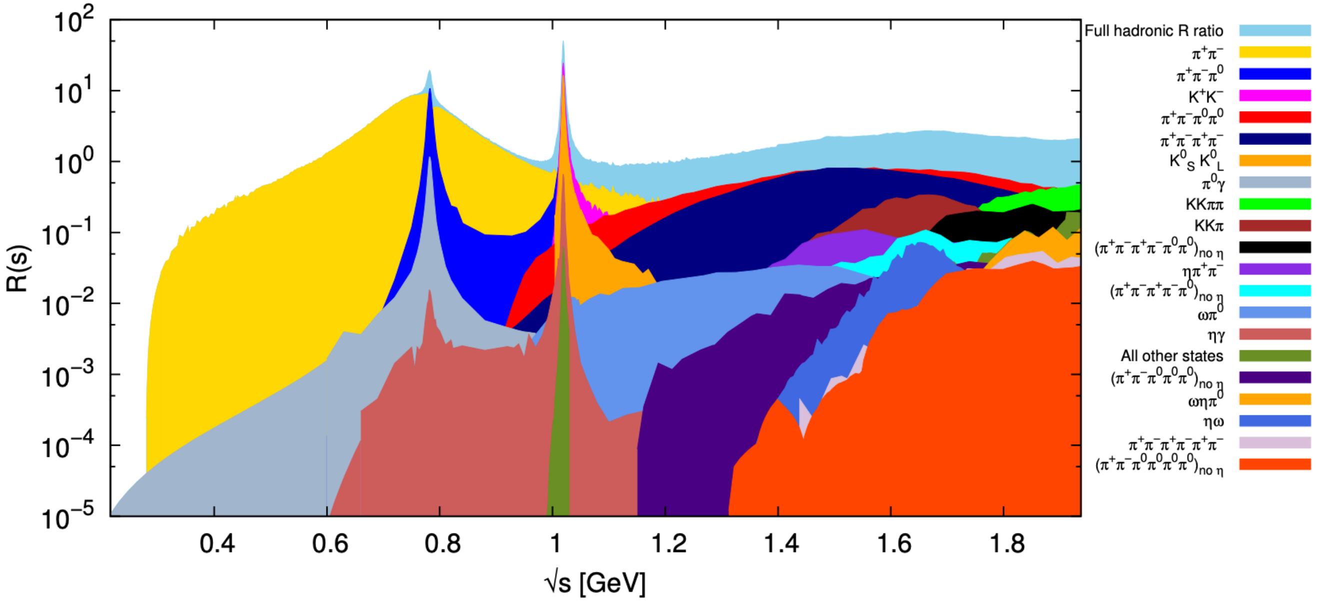


Figure 16: Contributions to the KNT data compilation of the total hadronic R-ratio from the different hadronic final states below 1.937 GeV [30, 265]. The full R-ratio is shown in light blue. Each final state is included as a new layer on top in decreasing order of the size of its contribution to $a_\mu^{\text{HVP, LO}}$.

https://arxiv.org/pdf/2505.21476

WP 2025 – Dispersive LO-HVP [pipi]

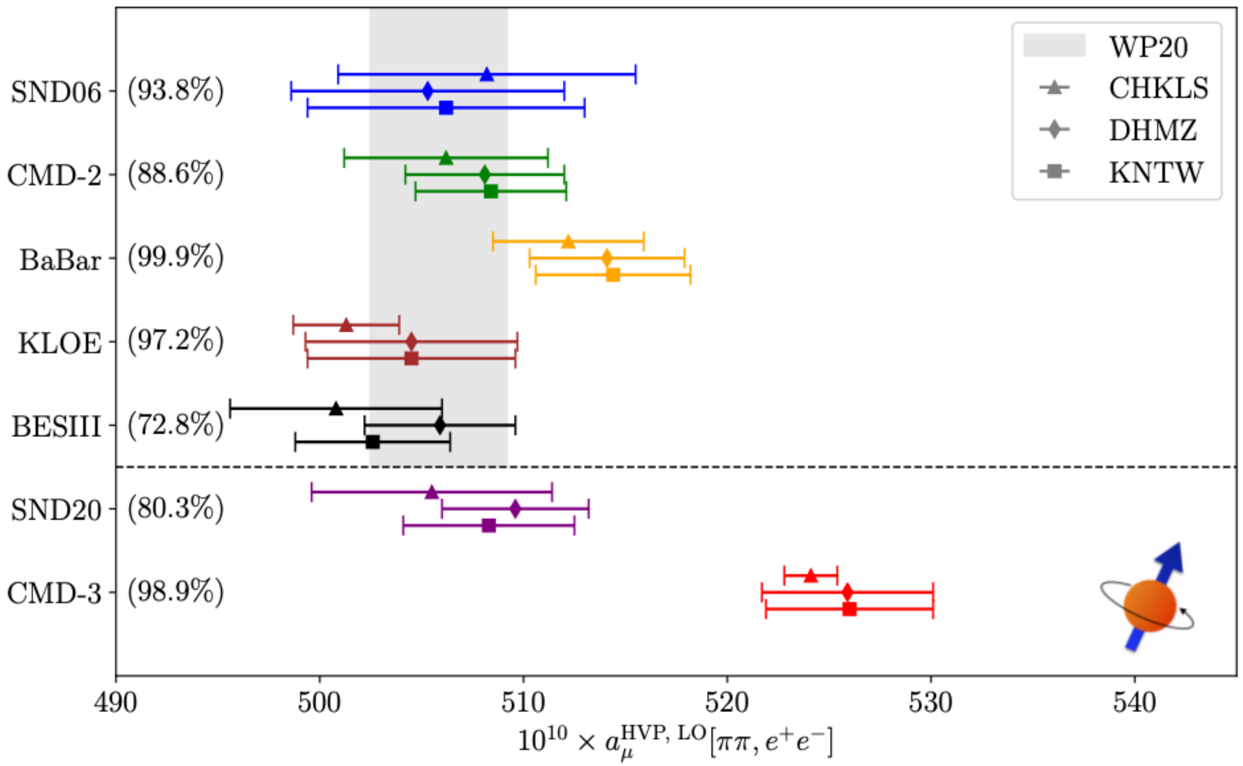


Figure 26: Dispersive theoretical predictions for $a_\mu^{\text{HVP, LO}}[\pi\pi]$, based on various measurements of $e^+e^- \to \pi^+\pi^-$, fit/interpolated and complemented for the uncovered mass ranges (percentages of the integral covered by each measurement are shown), for the three approaches "CHKLS," "DHMZ," and "KNTW" as detailed in the main text. The gray band indicates the result from WP20, including the error inflation due to the BaBar–KLOE tension. The experiments above the dashed line entered the result for WP20, whilst those below are new measurements since then. The numerical values shown are reproduced in Table 5.

https://arxiv.org/pdf/2505.21476

WP 2025 – Dispersive a_μ

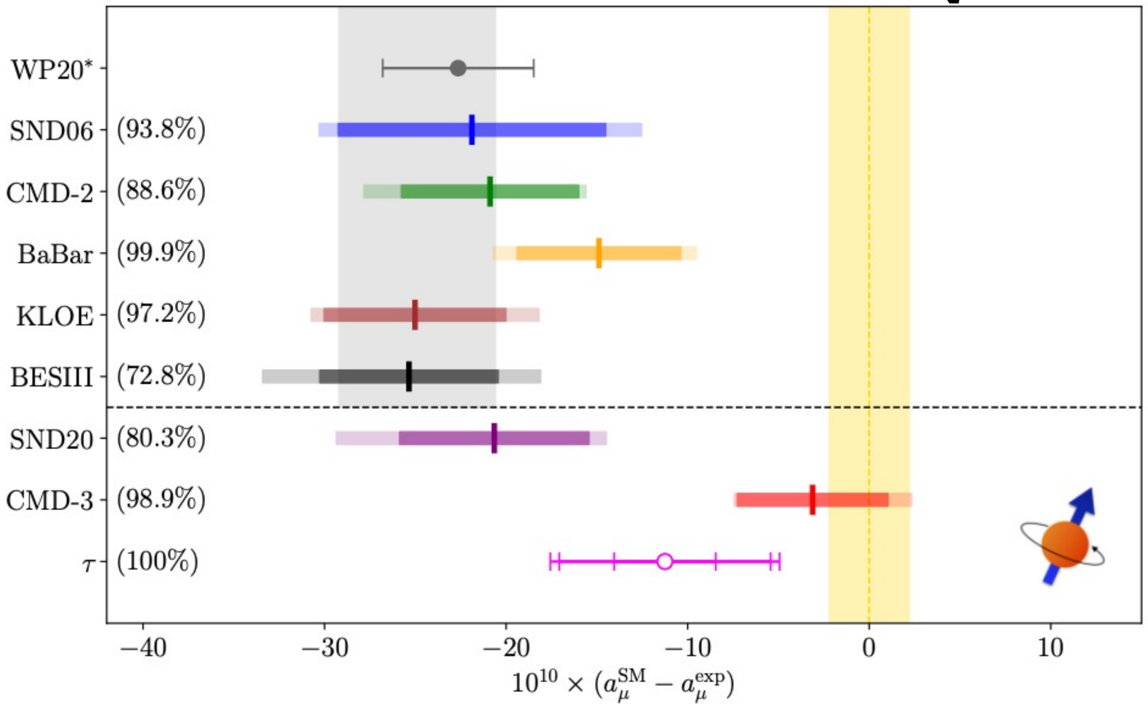


Figure 27: Summary of current data-driven evaluations of HVP, propagated to a_μ^{SM} (the yellow band indicates a_μ^{exp}, the gray band the WP20 SM prediction based on the e^+e^- data sets above the dashed line and the remainder from WP20, in particular, the WP20 HLbL value; the data point labeled WP20* indicates the shift upon using WP25 input for the other contributions besides LO HVP). The τ point corresponds to WP25 in Fig. 13, with the third, outmost error including the additional uncertainties beyond the 2π channel (the remainder of HVP is taken from WP20, the other contributions from WP25). The other points use input from the various $e^+e^- \to \pi^+\pi^-$ experiments according to Fig. 26 (again with HVP remainder from WP20 and the other contributions from WP25), where for each experiment the central values are obtained as simple average of the three combination methods, the inner ranges as simple average of the uncertainties obtained in each method, and the outer ranges reflect the maximal range covered by all methods (the percentages indicate how much of the 2π contribution to the HVP integral is covered by each measurement). We emphasize that these ranges are merely meant to illustrate the current spread, they cannot be interpreted as uncertainties with a proper statistical meaning. The numerical values follow from Tables 1 and 5.

https://arxiv.org/pdf/2505.21476