New Results from the Muon $g-2$ Experiment at Fermilab

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Warwick Seminar
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UNIVERSITY OF LIVERPOOL

LEVERHULME TRUST

New Results from the Muon $g-2$ Experiment at Fermilab

- Introduction
- Analysis
- Result
- Outlook & Summary

New Results from the Muon $g-2$ Experiment at Fermilab

Muon $g-2$

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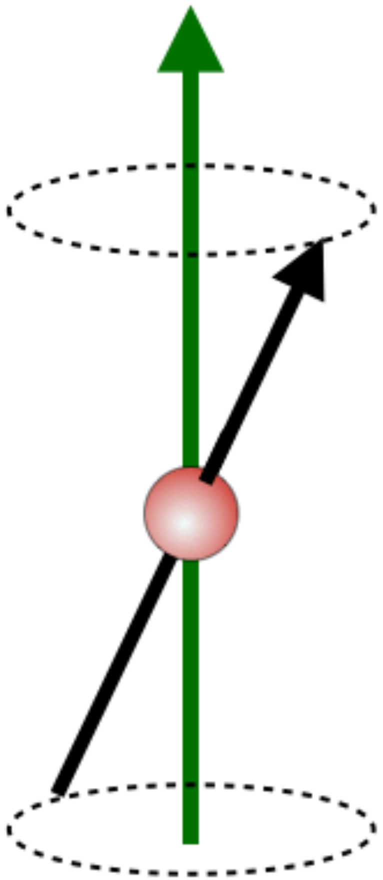
- The anomalous magnetic moment of the muon:
  - Magnetic moments **precess** in a magnetic field $\vec{\mu} = g\frac{e}{2m}\vec{S}$
  - g - factor quantifies interaction strength



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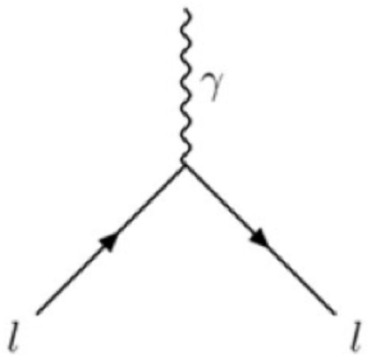

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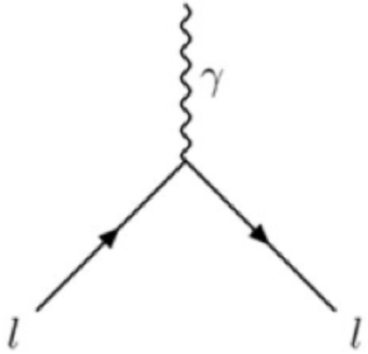
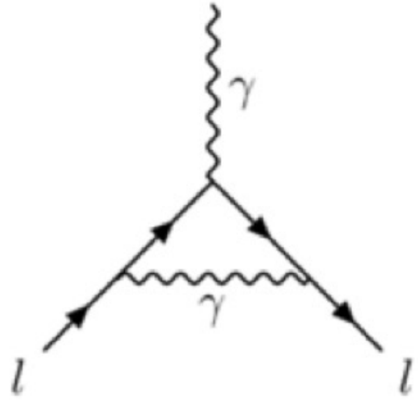


- Interactions with virtual particles cause g to deviate from 2 ($g > 2$). **Muon magnetic anomaly** is defined as:

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

First order QED correction by Schwinger:

$$a_l = \frac{g_l - 2}{2} = \frac{\alpha}{2\pi} + O(\alpha^2)$$
$$= 0.001\,161\,40\,.$$



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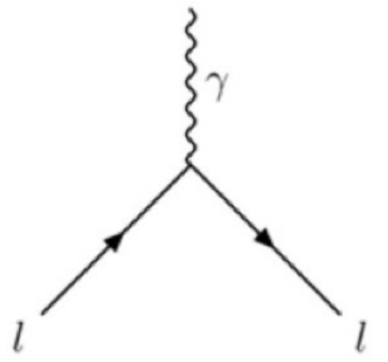

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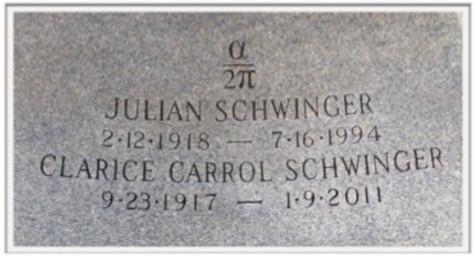
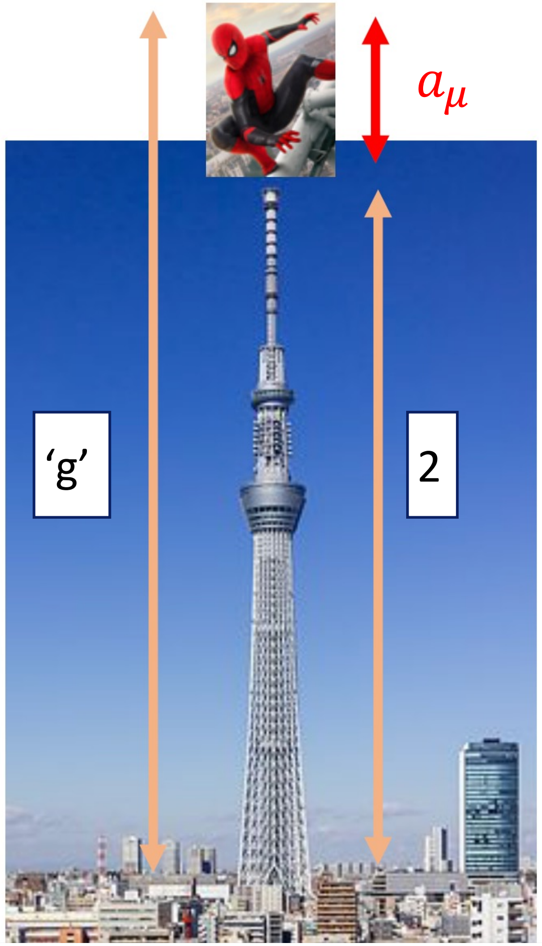


Why $g-2$

- An experimental trick:

$$g = 2\times(1+a_\mu) \approx 2 + 0.002$$

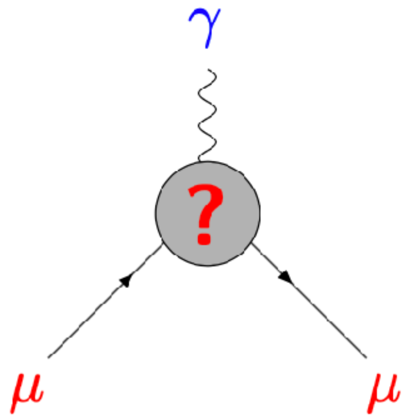
~1000 gain by measuring a_μ instead of g-factor !



Credit to X. Fan

Why Muon $g-2$

- Muon as a probe to **New Physics:**
  - For possible new physics $a_\mu = a_\mu^{\mathrm{SM}} + a_\mu^{\mathrm{NP}}$
  - Its effects is enhanced by $a_\mu^{NP} \propto (\frac{m_l}{\Lambda_{NP}})^2$



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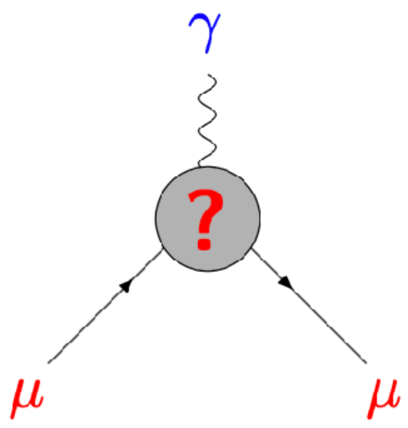
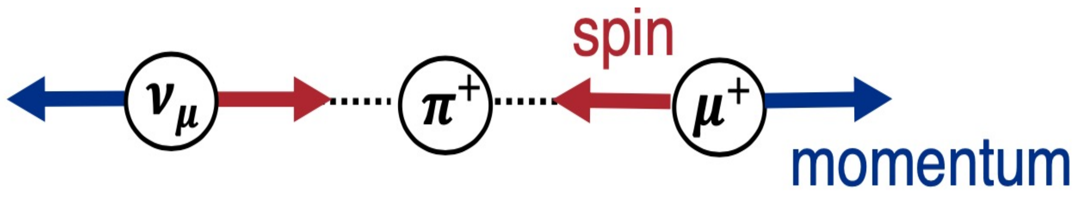
  - Muon is more sensitive by a factor of $(\frac{m_\mu}{m_e})^2 \approx 4.3\times10^4$



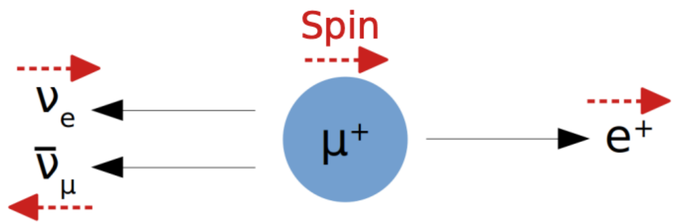
Why Muon $g-2$

- Muon as a probe to **New Physics**

- A great tool for experimentalists
  - Can be produced copiously in proton collisions and **pion decays**
  - Can select momentum and polarization
  - Decays are very simple (Michel distribution due to weak decay)



Pion decay to generate polarized muon



Muon decay

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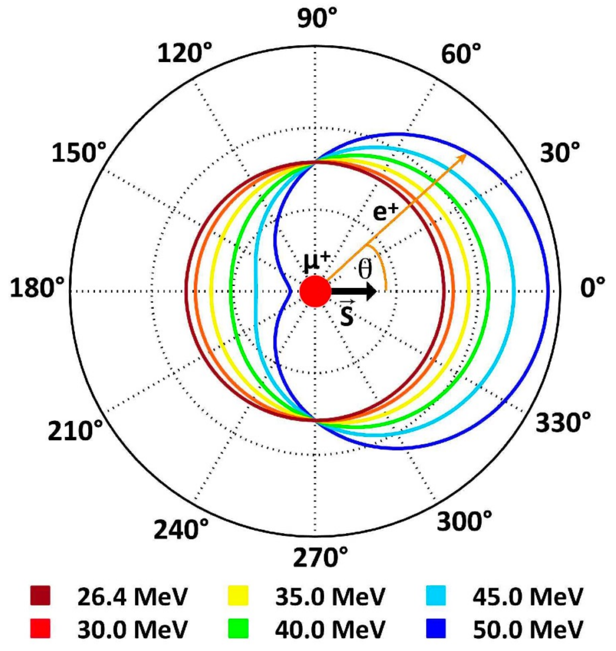
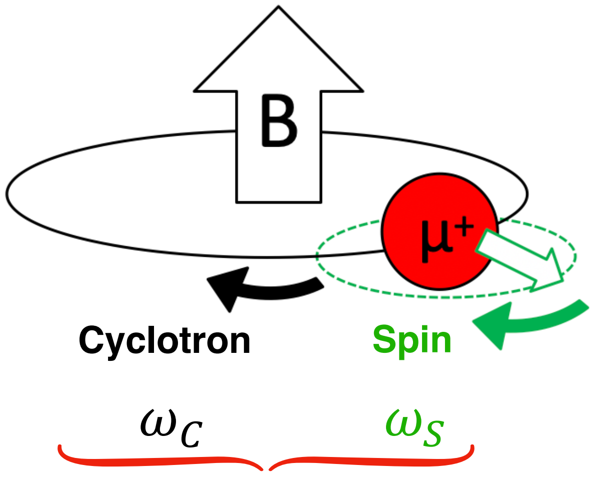


Michel spectrum:
highest energy positrons are aligned with muon's spin

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:



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

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

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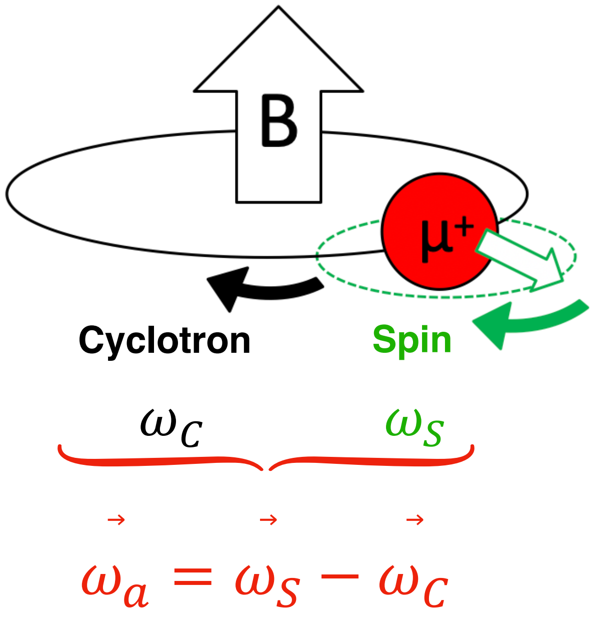

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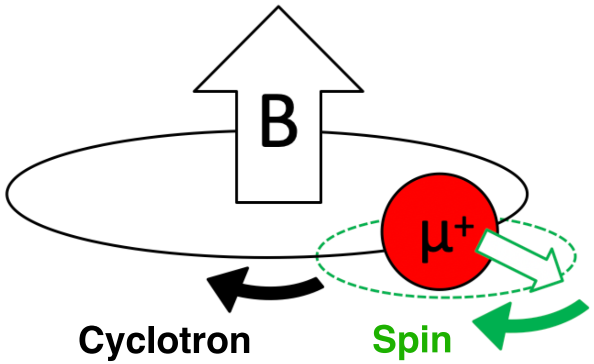

ω_C ω_S

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Magic "γ": $\gamma^2 = \frac{1}{a_\mu} + 1$

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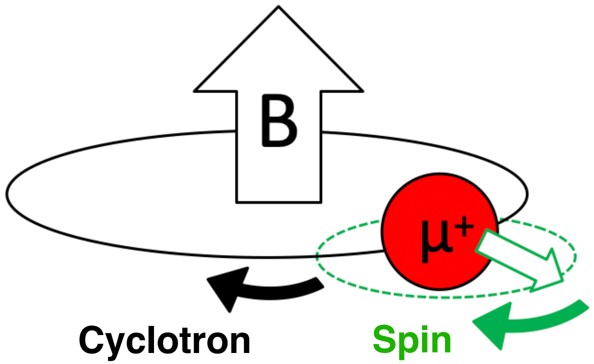

$$\omega_C \quad \omega_S$$

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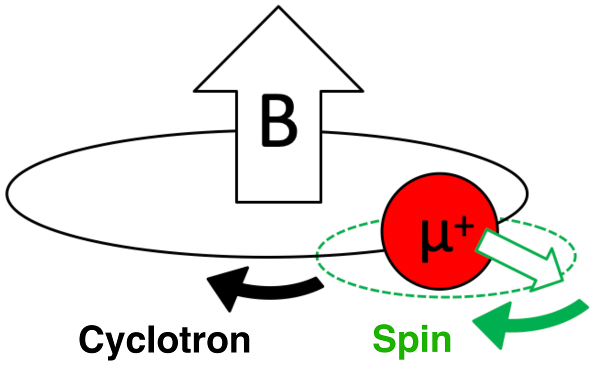

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Measure

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

Extract

Muon $g-2$ Experiment at Fermilab

Experimental Principle

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

1. Measure ω_a^m: modulation of decay positron time spectrum
2. Measure B: proton nuclear magnetic resonance (NMR) $\longrightarrow$ $2\mu'_p B = \hbar\omega'_p(\text{vacuum})$
3. Extract a_μ

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A real-world equation:

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

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Corrections from Beam Dynamics

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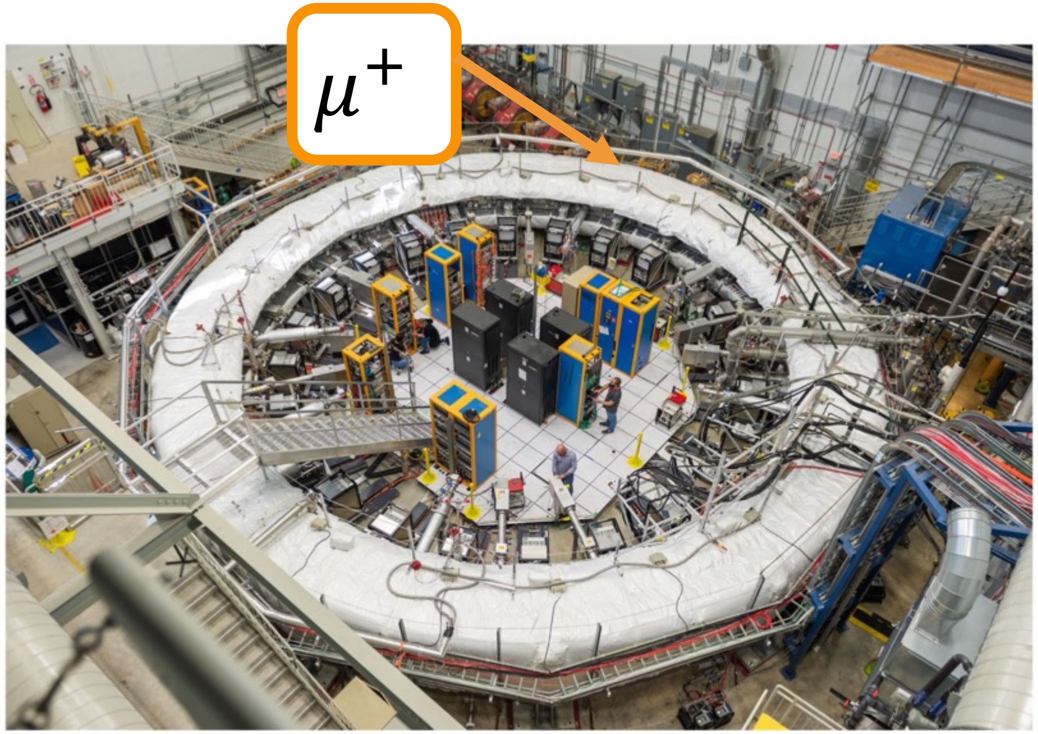
Corrections from Magnetic Field Transient

External constants precisely known (to 25 ppb)

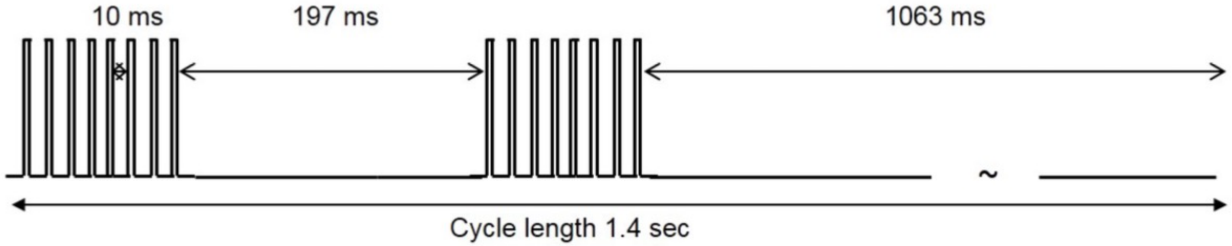
Muon $g-2$ Experiment at Fermilab

Setups: Injecting, Kicking, and Storing the Muon Beam

- Injecting polarized muons into a storage ring



- **3.1 GeV/c** μ^+ enter the ring
- Cyclotron period: 149.2 ns
- A cycle of 16 bunches repeating every 1.4 seconds
- ~4000 μ^+/bunch in the storage ring in Run-2/3



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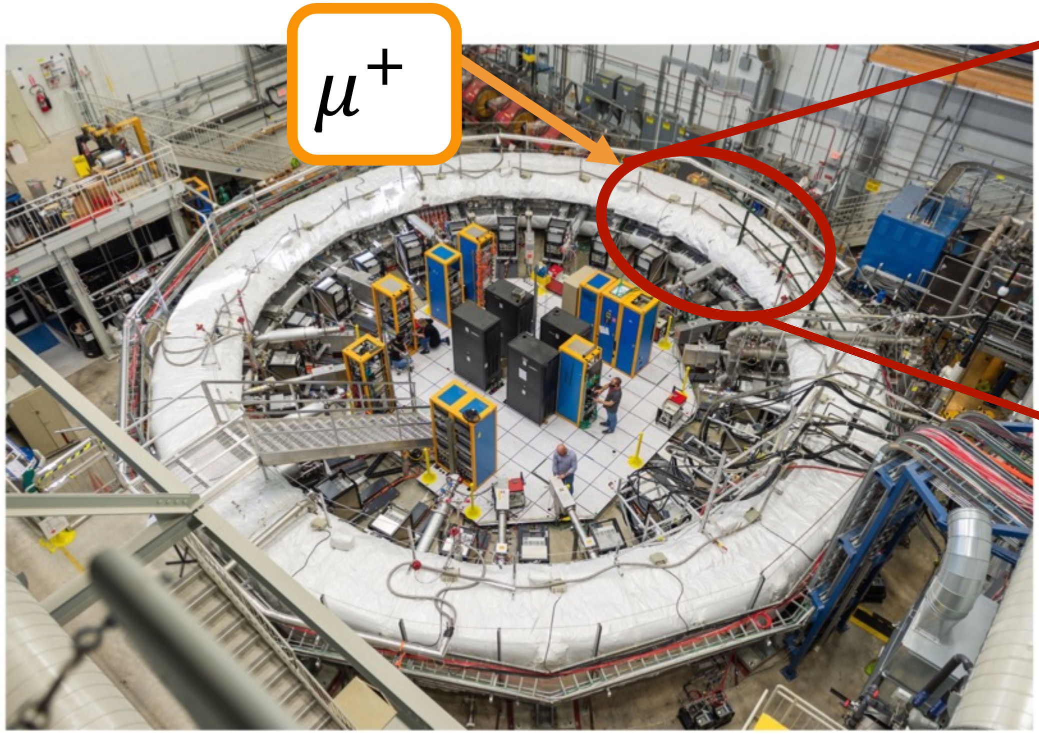
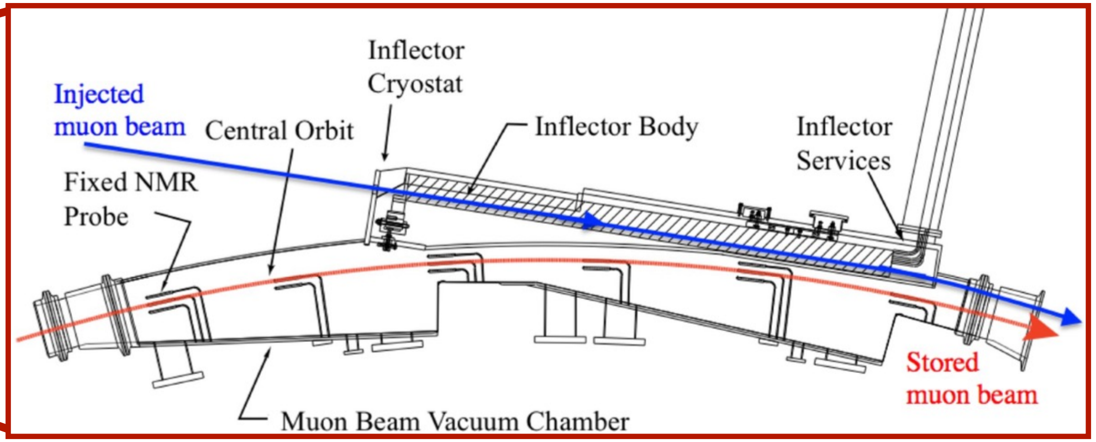
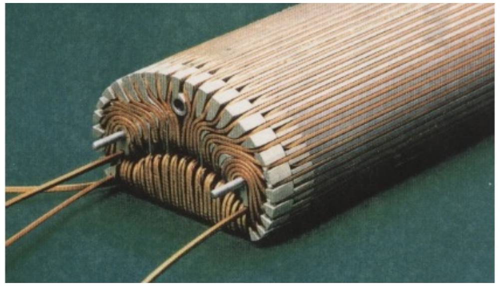
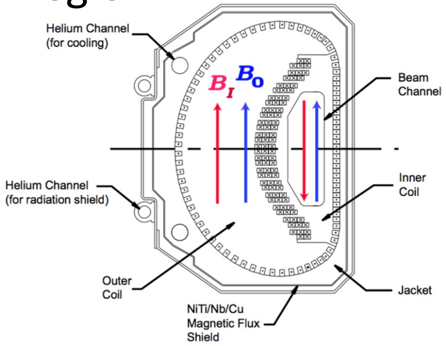




- Inflector creates a "field-free" region

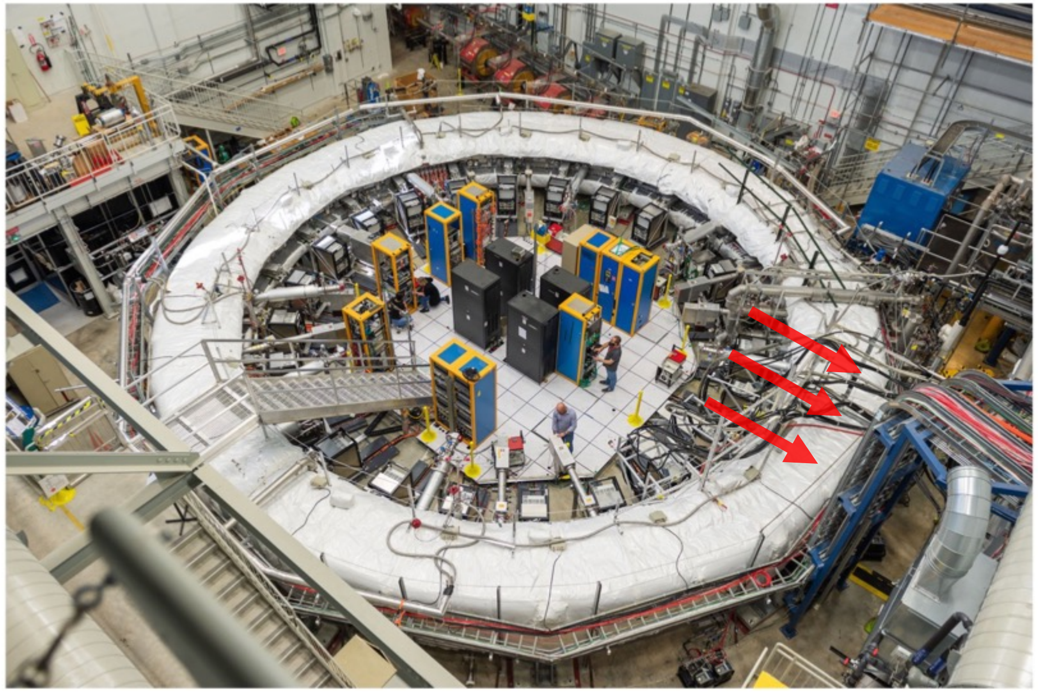


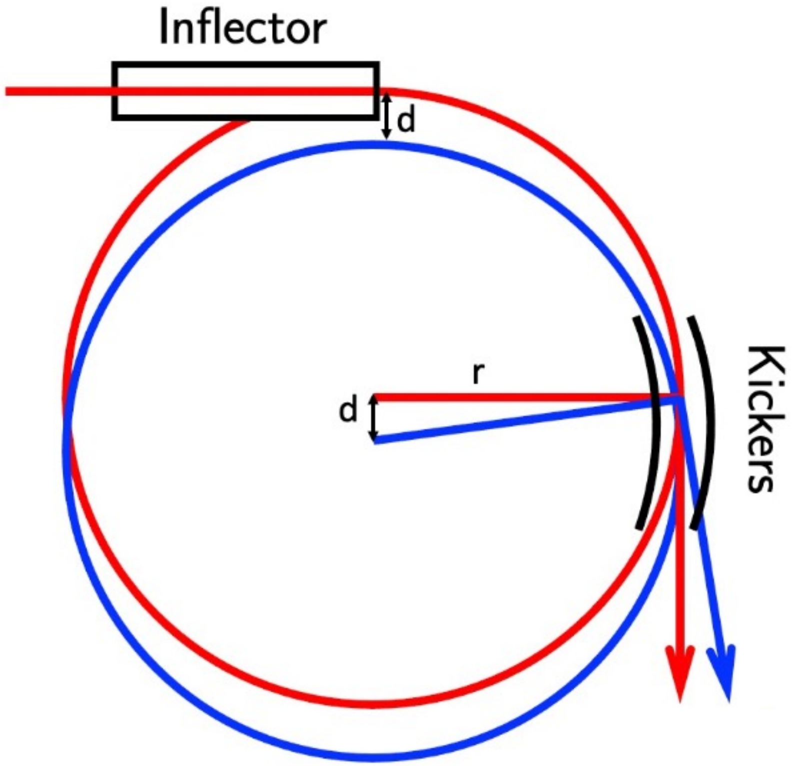


Muon $g-2$ Experiment at Fermilab

Setups: Injecting, Kicking, and Storing the Muon Beam

- 3 pulses magnets changes muon angle onto the good orbit (~10 mrad)

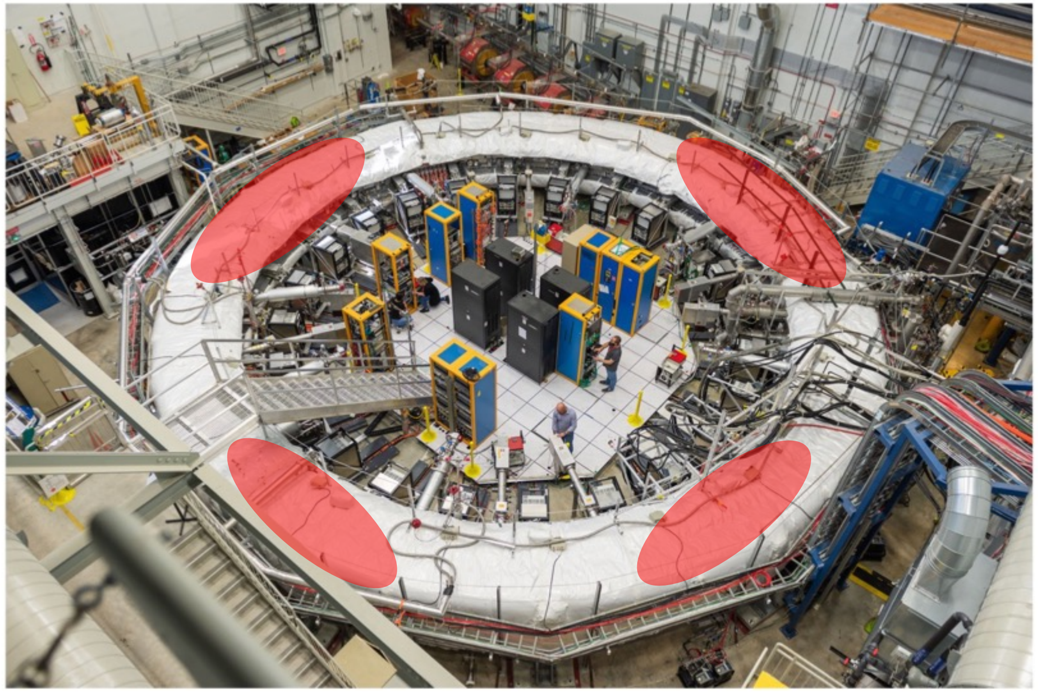


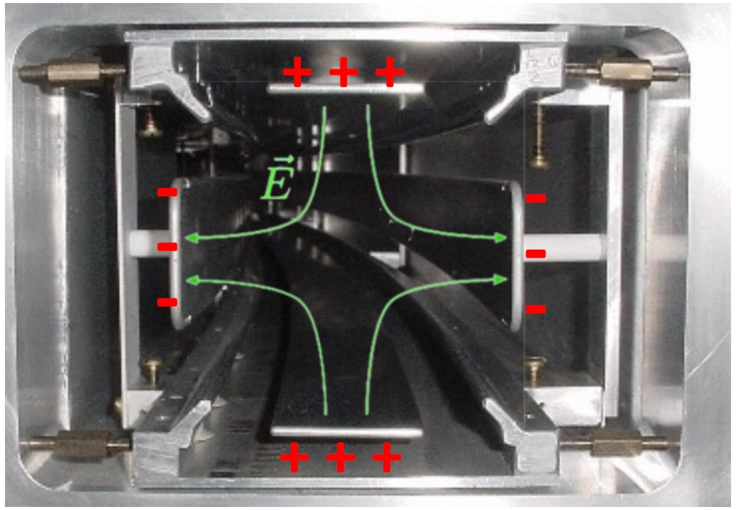


Muon $g-2$ Experiment at Fermilab

Setups: Injecting, Kicking, and Storing the Muon Beam

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



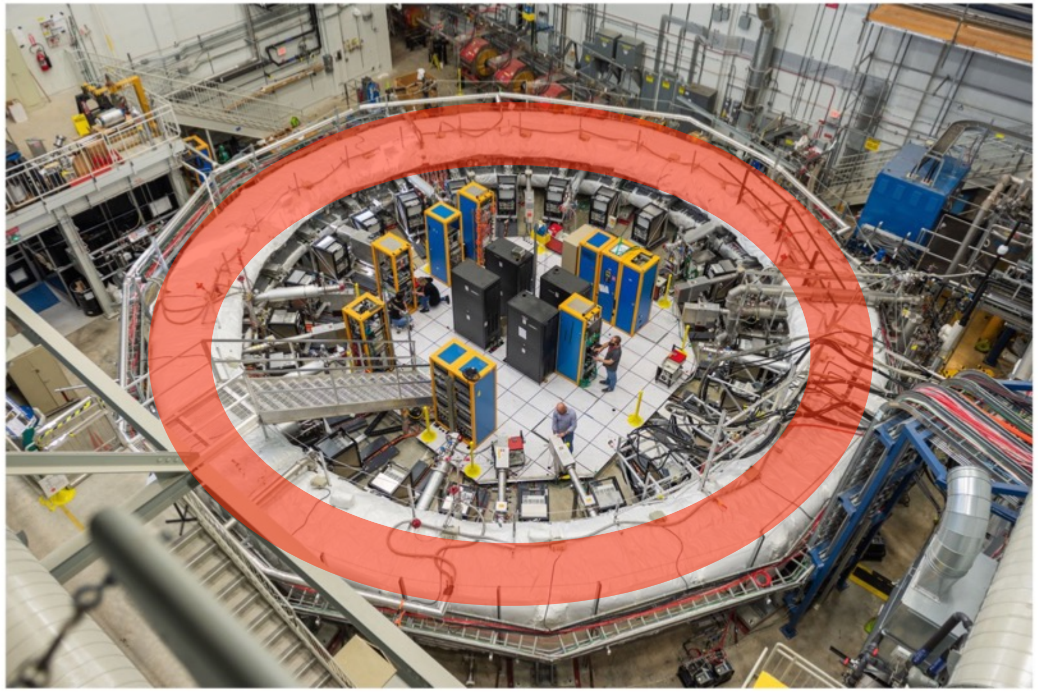


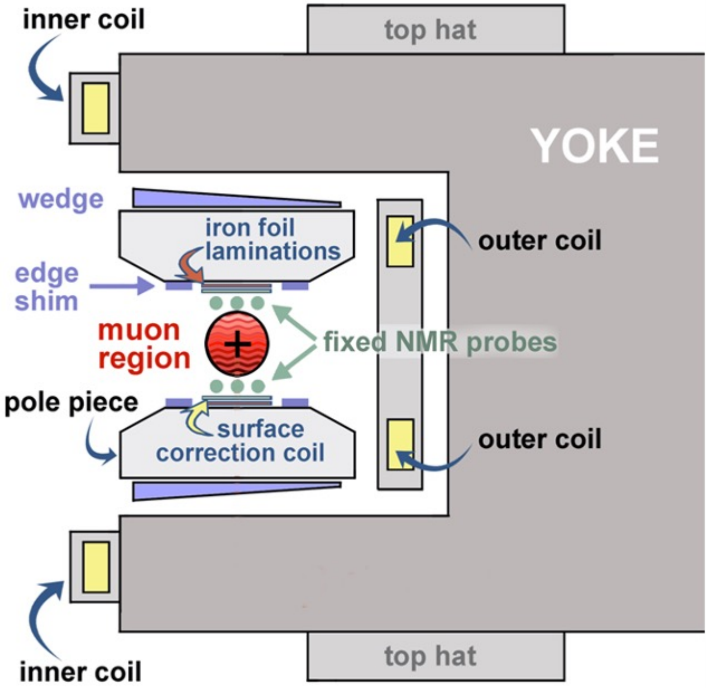
- Quads cover 43% of azimuth
- Focus beam to a simple harmonic motion about closed orbit

Muon $g-2$ Experiment at Fermilab

Setups: Injecting, Kicking, and Storing the Muon Beam

- 1.45T superferric magnet shimmed to 50 ppm uniformity (~3x uniformity)

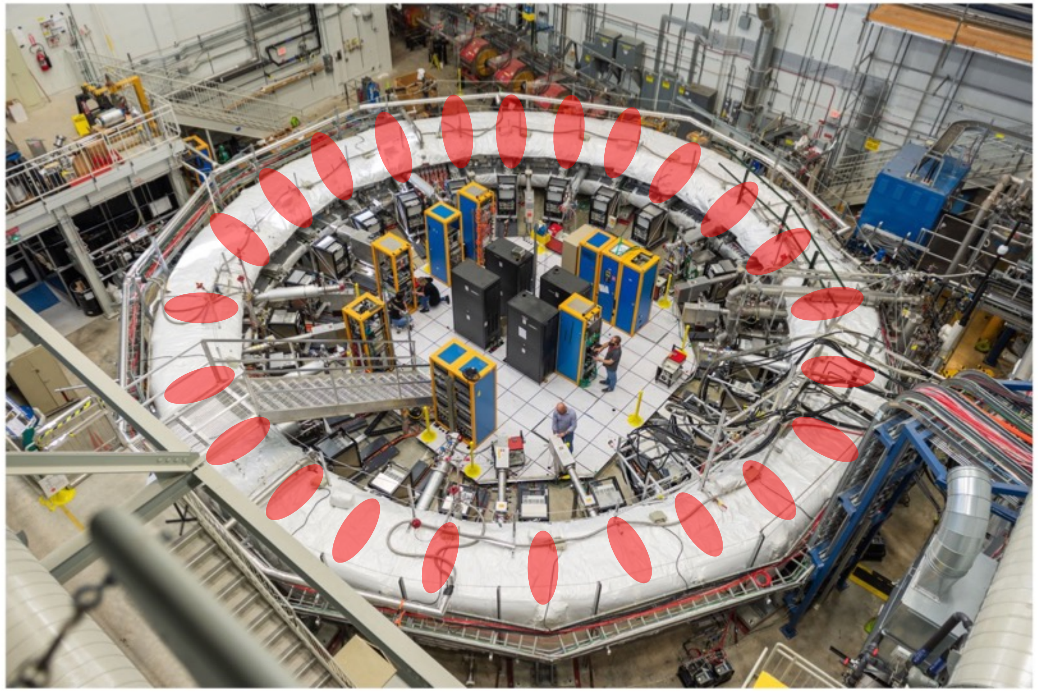


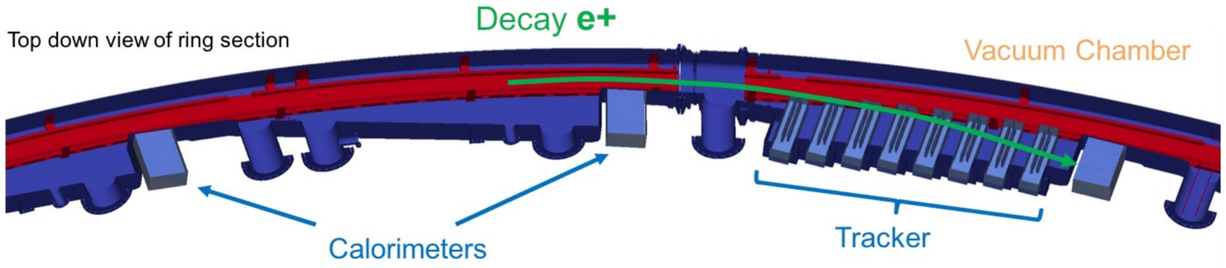


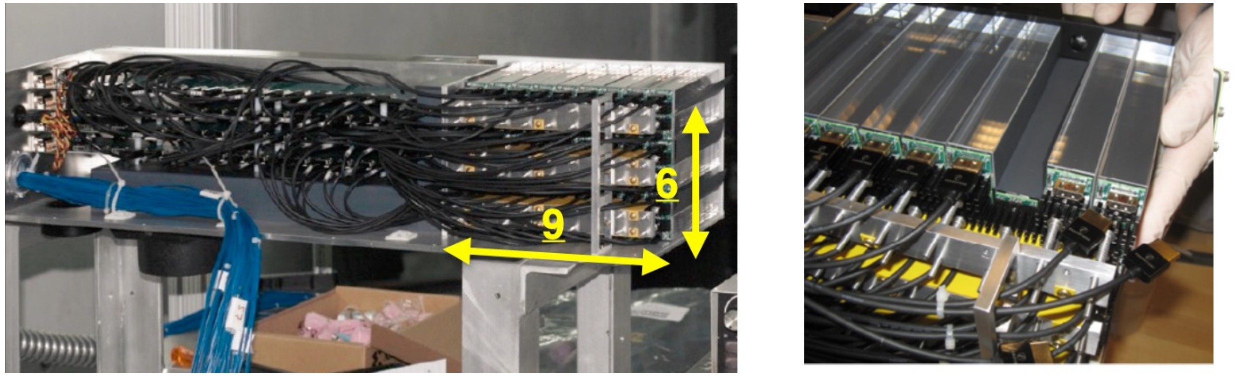
Muon $g-2$ Experiment at Fermilab

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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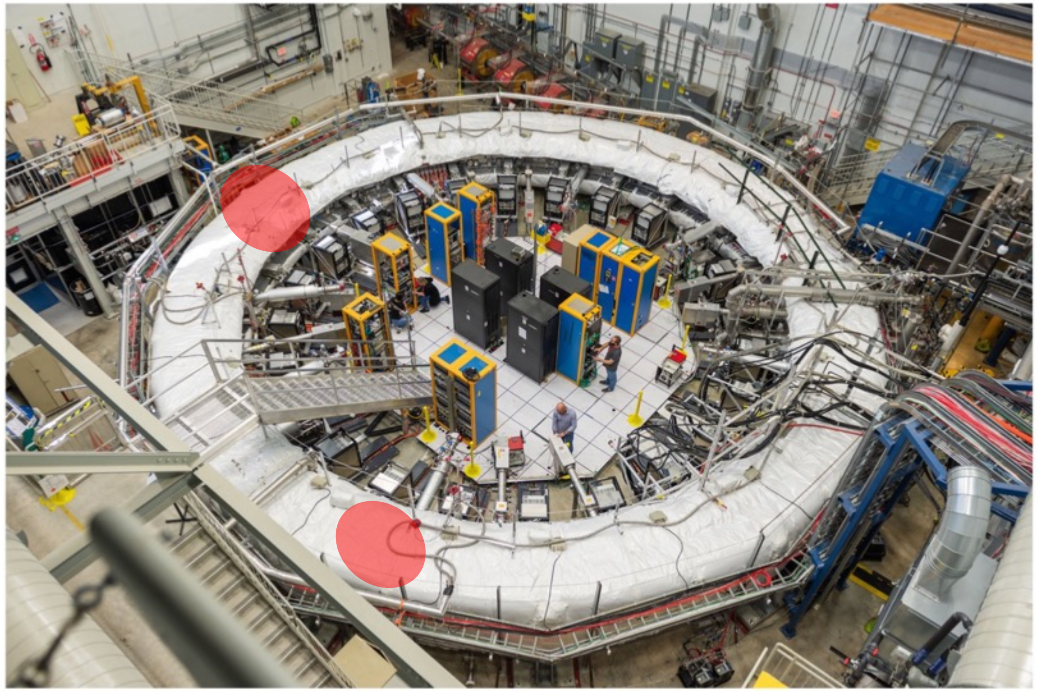

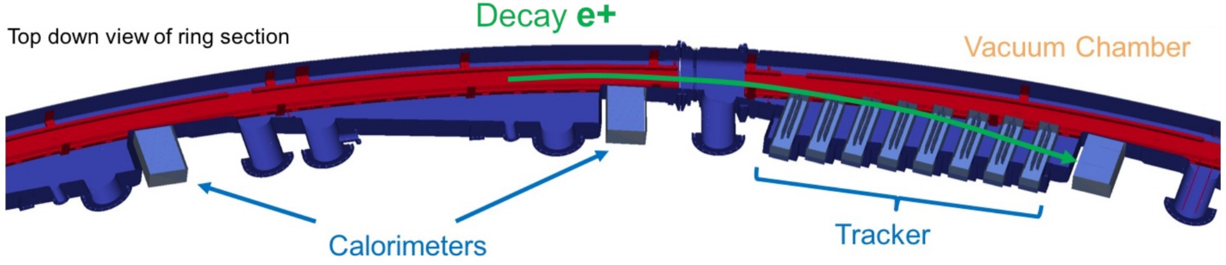

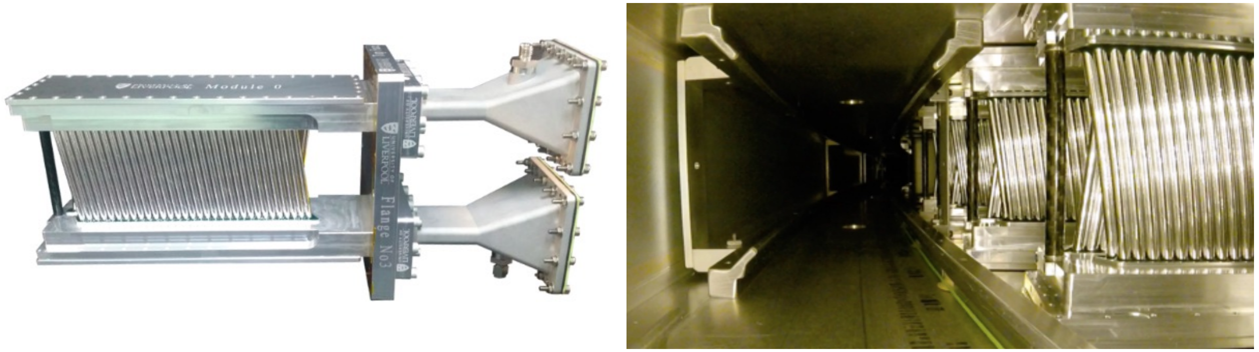

Straw tracker developed in Liverpool

New Results from the Muon $g - 2$ Experiment at Fermilab

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- Introduction
- **Analysis**
  - Precession frequency
  - Beam dynamics
  - Field
  - Blinding, combination, etc.
- Result
- Outlook & Summary

Precession frequency

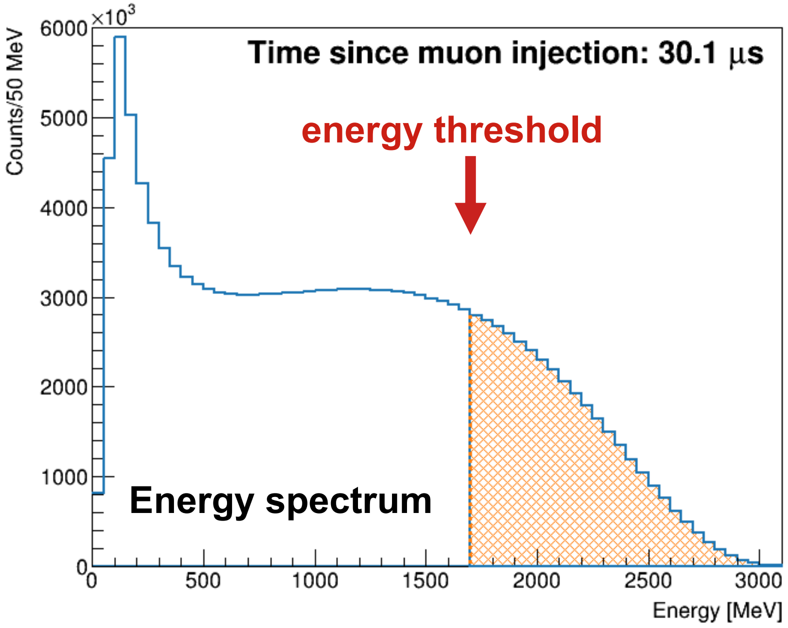
Corrections from Beam Dynamics

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

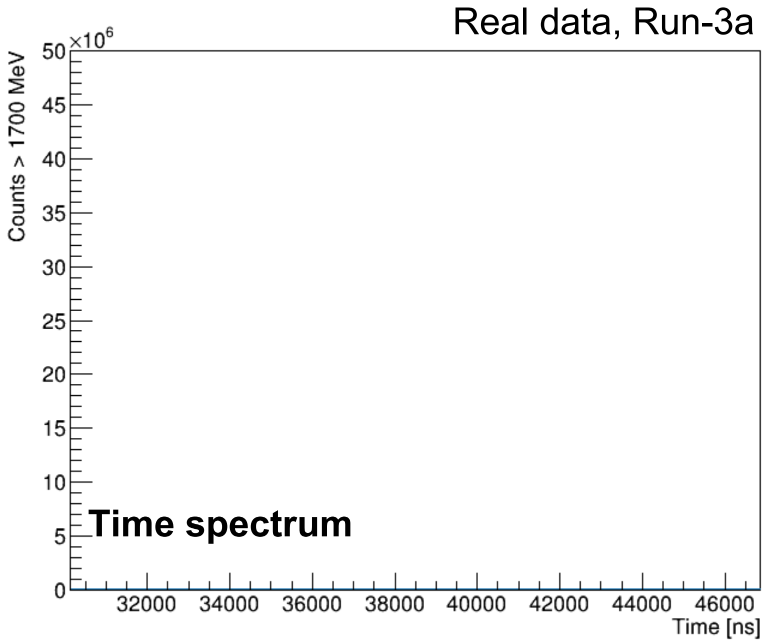
B-field and its corrections

Muon Precession Frequency

- The number of detected high-energy positrons oscillating above an energy threshold is **modulated** by the anomalous precession frequency ω_a



Count **positrons** above an energy threshold



spin

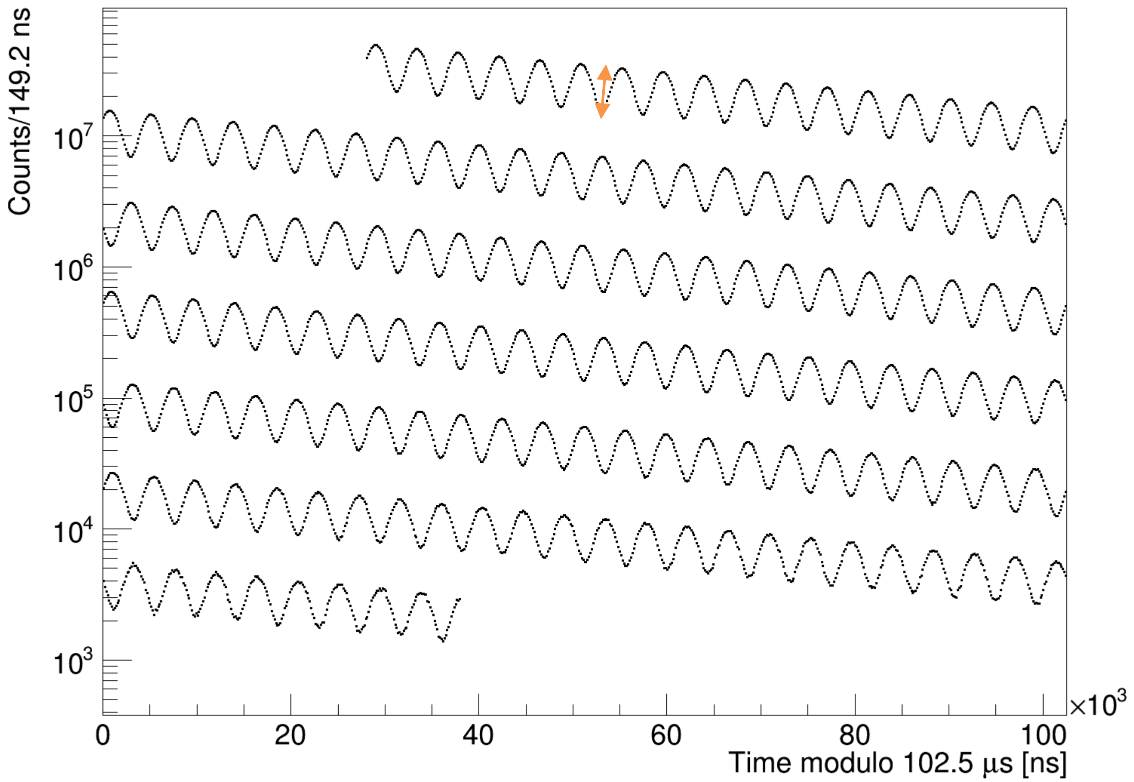
momentum

Counts **oscillate at ω_a** and extract frequency from time spectrum

Muon Precession Frequency

The "Wiggle Plot"

Run-3a: $\delta\omega_a(stat) = 329$ ppb, 15.3B positrons (~50% of Run-2/3)



relative size of wiggle:
asymmetry ≈ 0.35

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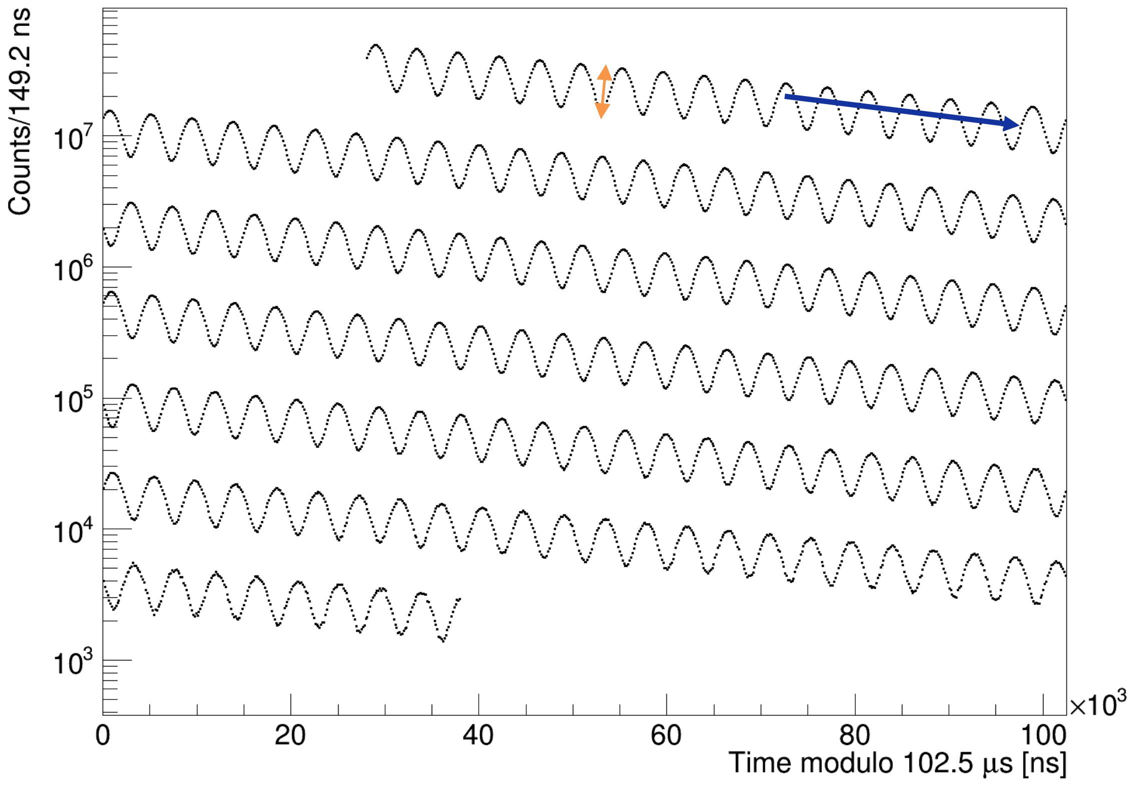

relative size of wiggle:
asymmetry ≈ 0.35

exponential decay:
boosted lifetime $\approx 64.4\ \mu s$

Muon Precession Frequency

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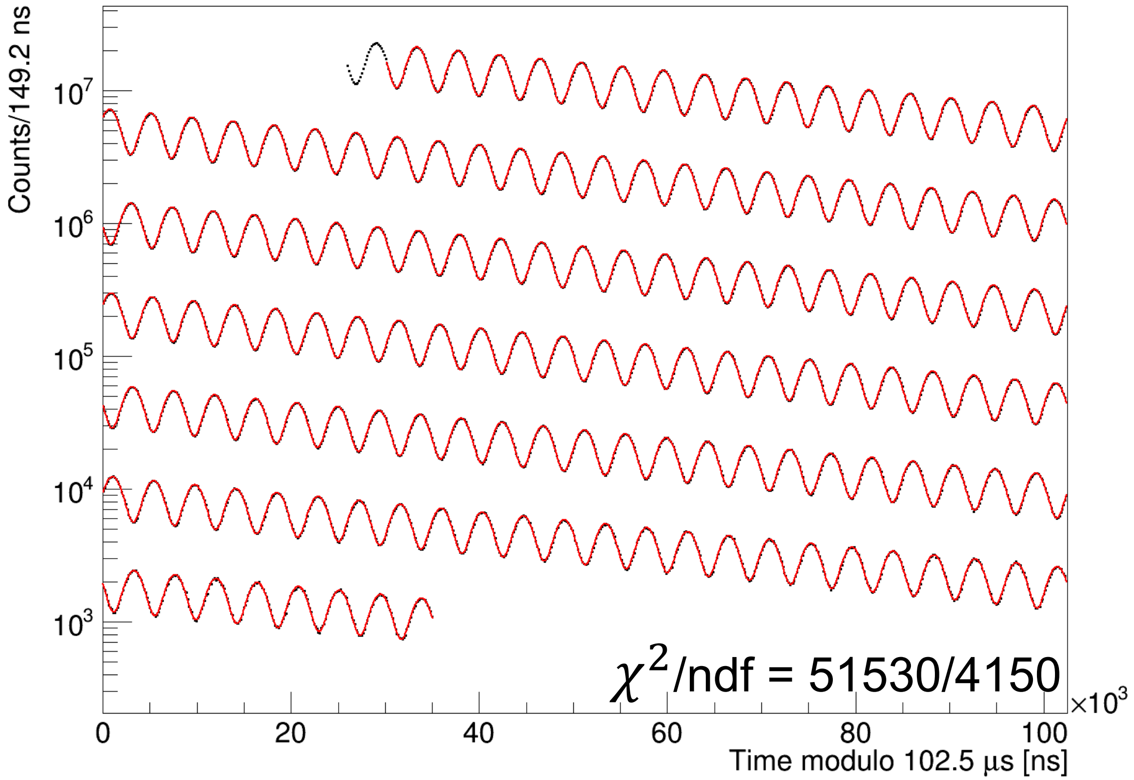


Simple fit to extract the frequency:

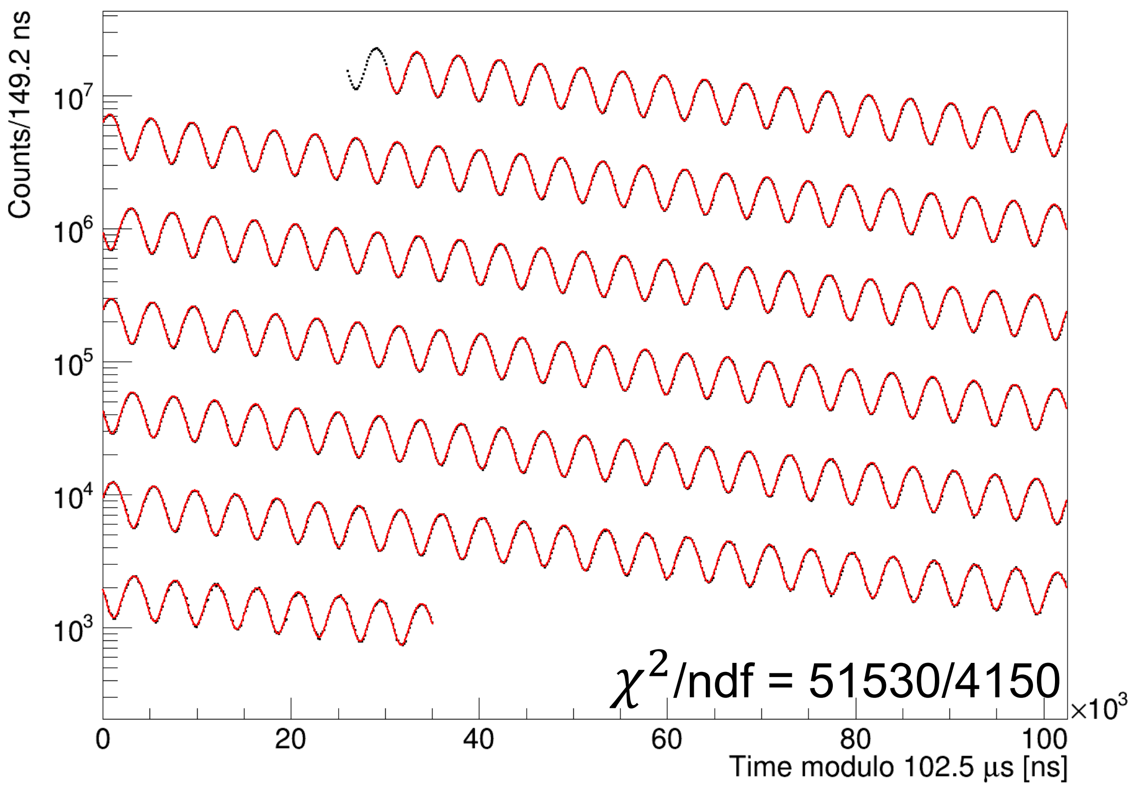
an exponentially decaying oscillation at g-2

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

Muon Precession Frequency

The “Wiggle Plot”

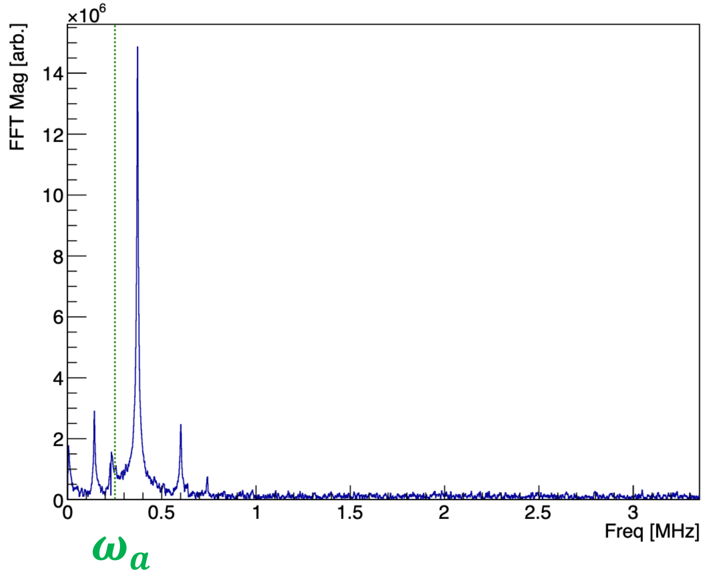
Run-3a: $\delta\omega_a(stat) = 329$ ppb, 15.3B positrons



Simple fit to extract the frequency:

an exponentially decaying oscillation at g-2

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

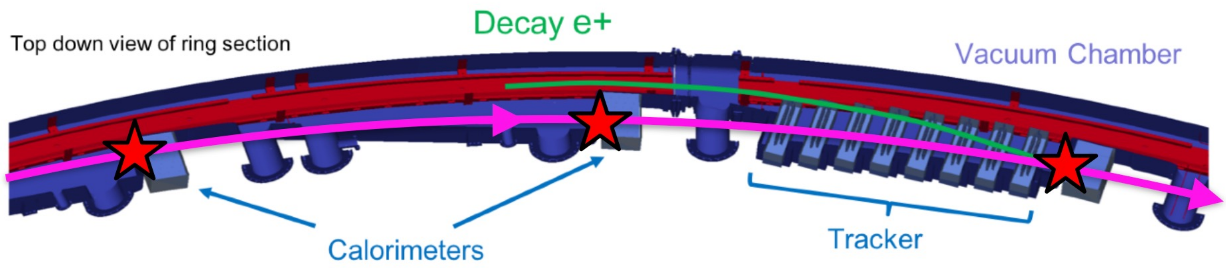


Peaks on the Fast Fourier Transform (FFT) of fit residuals:
simple fit is not sufficient; need a better model

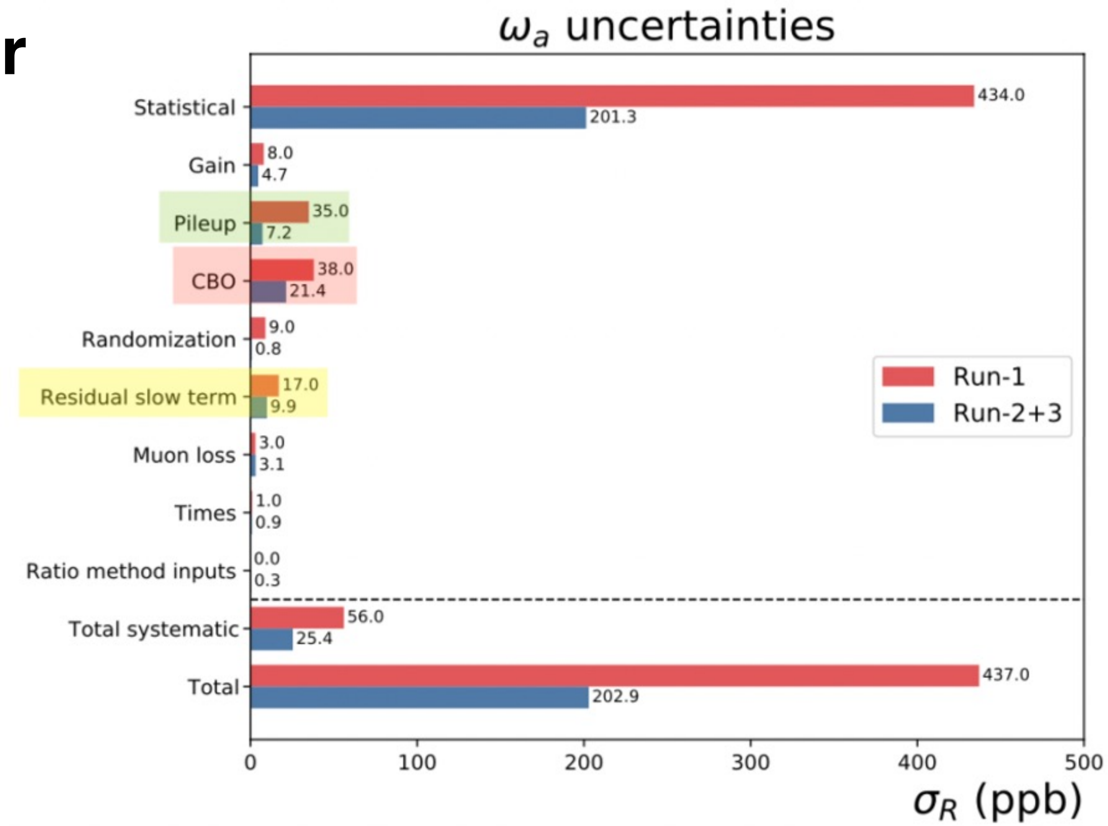
Muon Precession Frequency

Extra terms in the Fitting Function

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



Some muons are lost before they decay

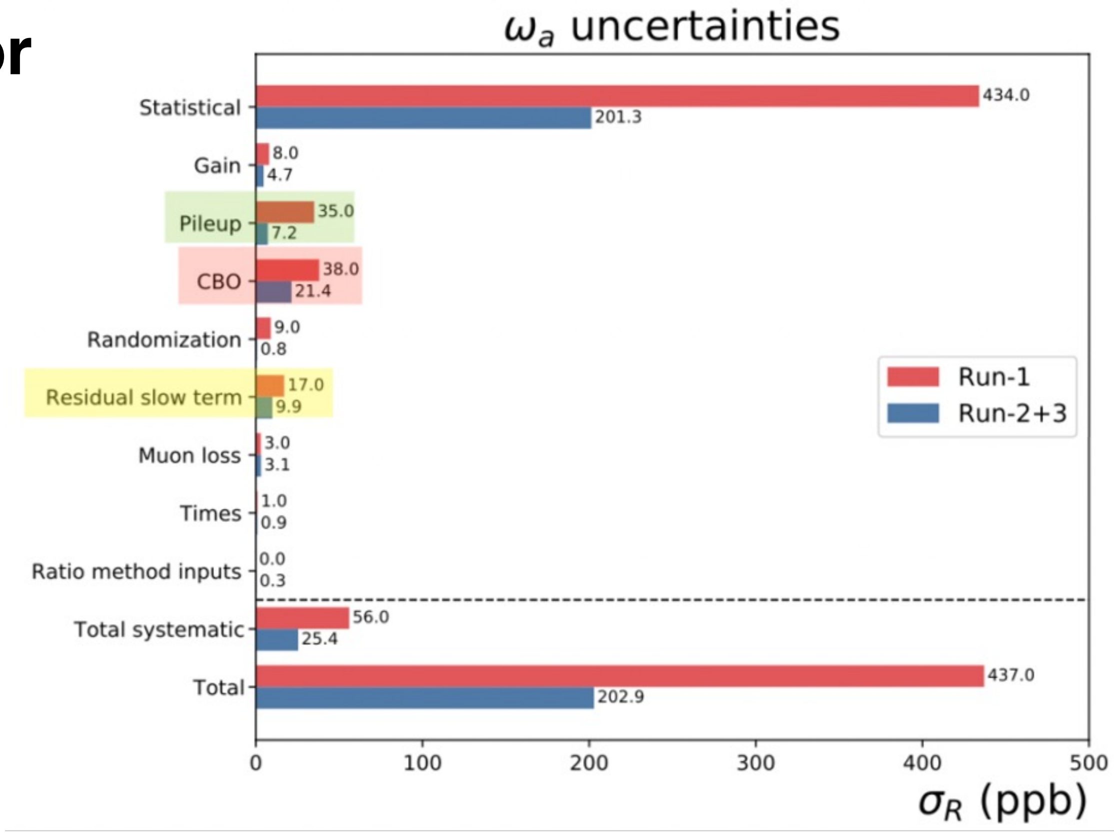


Muon Precession Frequency

Extra terms in the Fitting Function

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

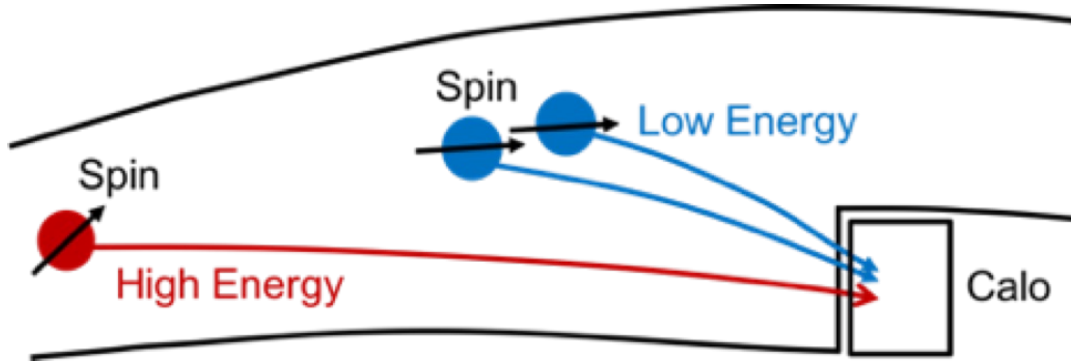
- I will elaborate two major systematic sources:
  - **Pileup**
  - Coherent betatron oscillations **(CBO)**

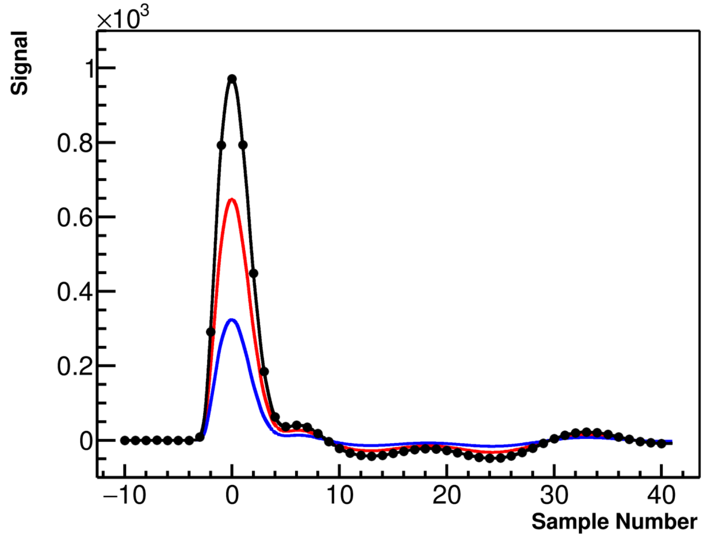


Muon Precession Frequency

Pileup

- Two or more positrons are misidentified as a single positron due to arriving too close in time/space





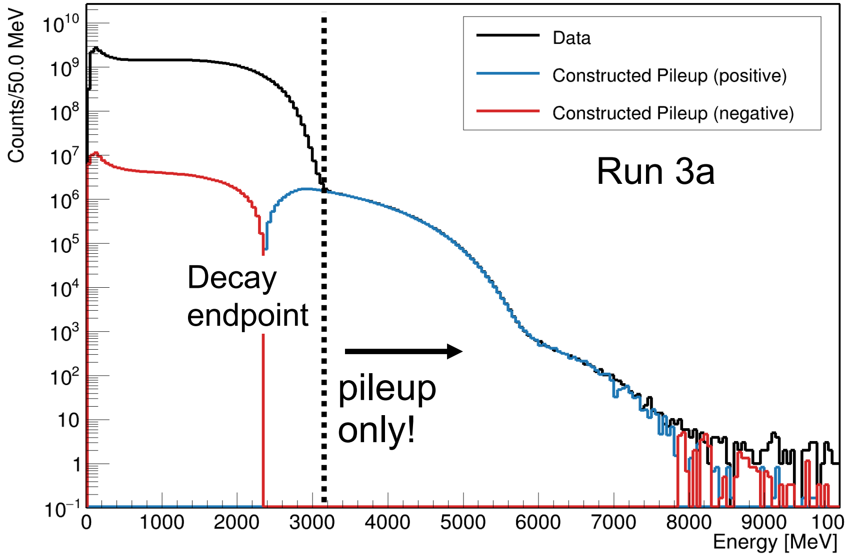
- Two low energy positrons fake a high energy positron signal
- Probability of pileup decreases over fill

Muon Precession Frequency

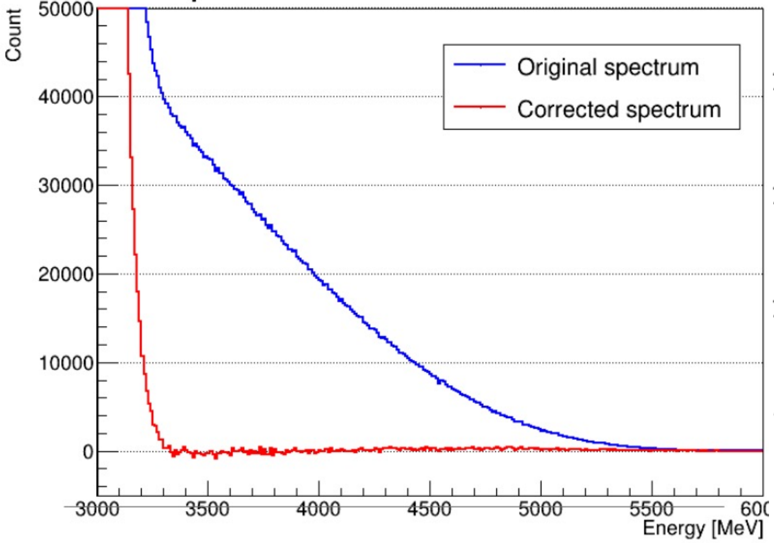
Pileup Correction

- Correct data with empirically determined pileup spectrum
- Improved clustering algorithm for a pileup reduction

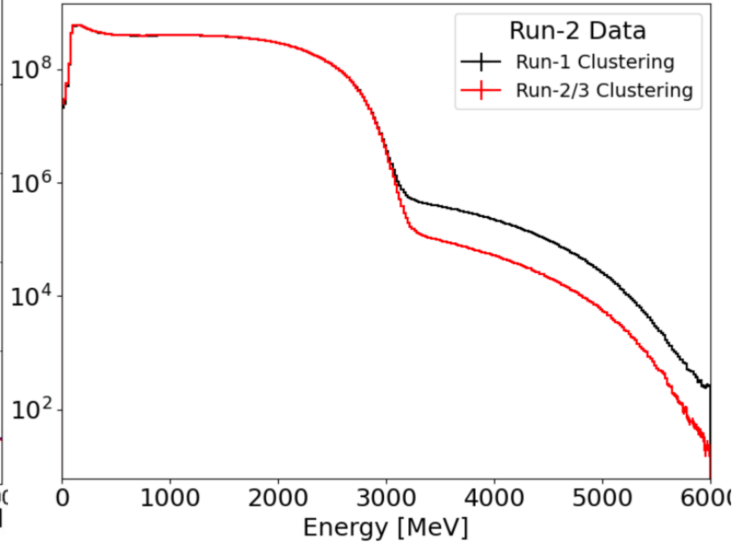
Energy spectrum



Spectrum before/after correction

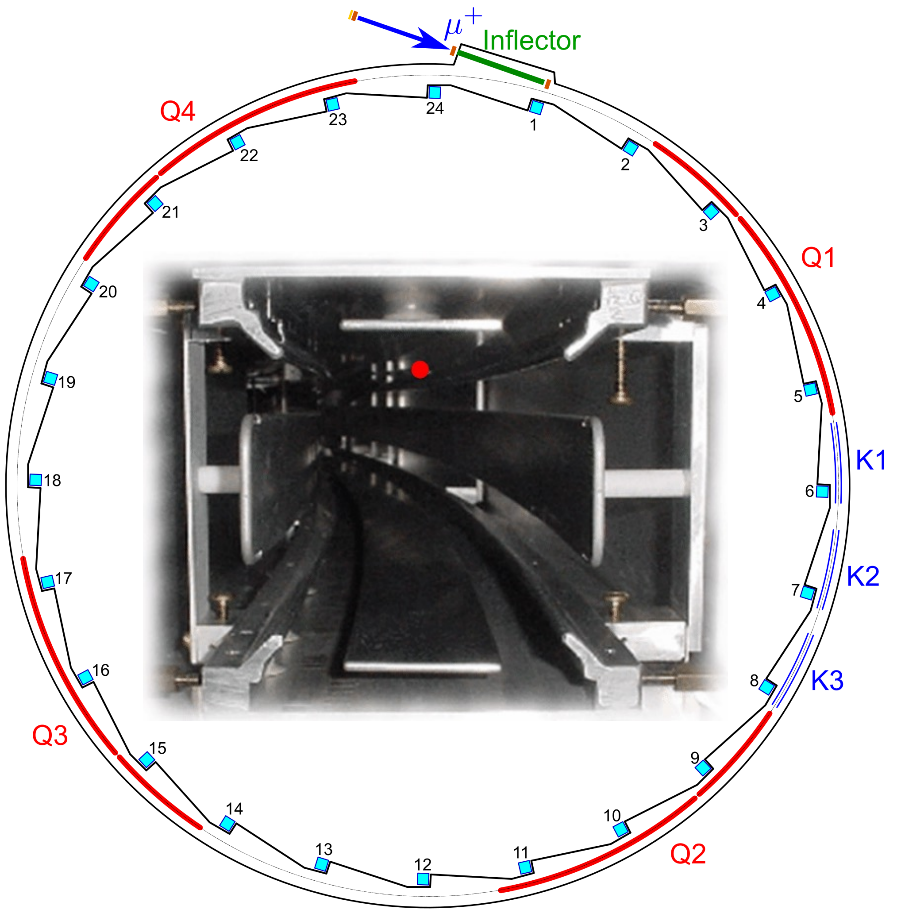


Reduced pileup in Run-2/3 spectrum

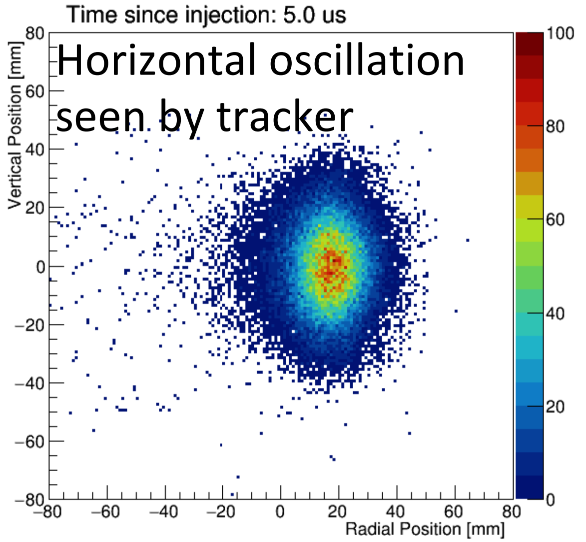


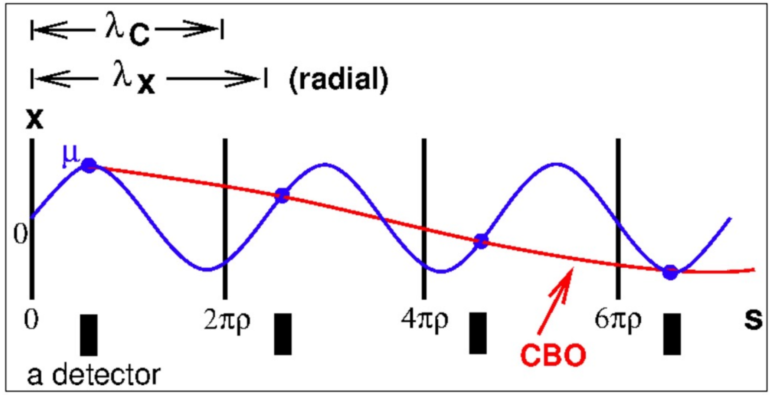
Muon Precession Frequency

Coherent Betatron Oscillations (CBO)



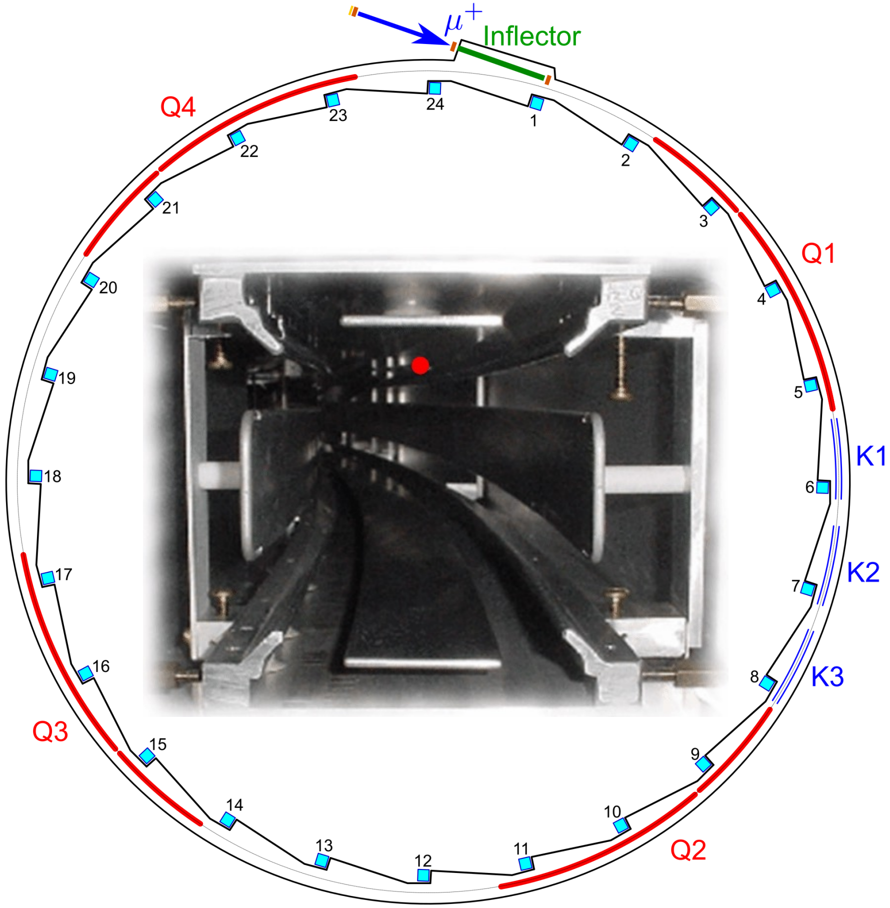
- As muons circulate around the storage ring, they slowly oscillate between the plates
- Coherent betatron oscillations (CBO) horizontally couples to **detector acceptance** and modulate signal





Muon Precession Frequency

Coherent Betatron Oscillations (CBO)



- As muons circulate around the storage ring, they slowly oscillate between the plates
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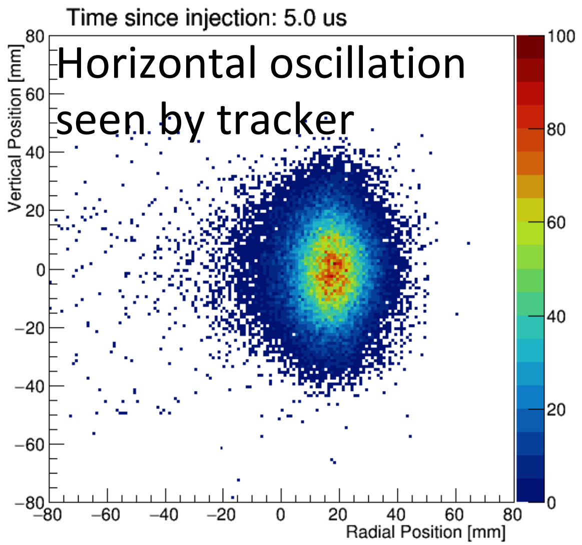
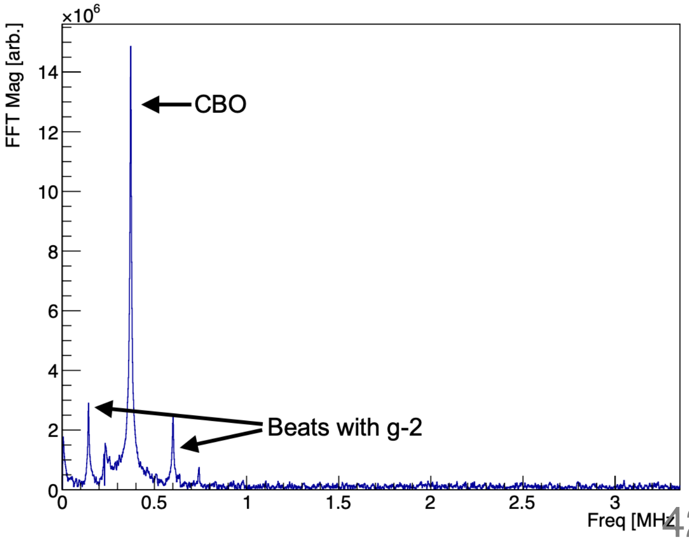
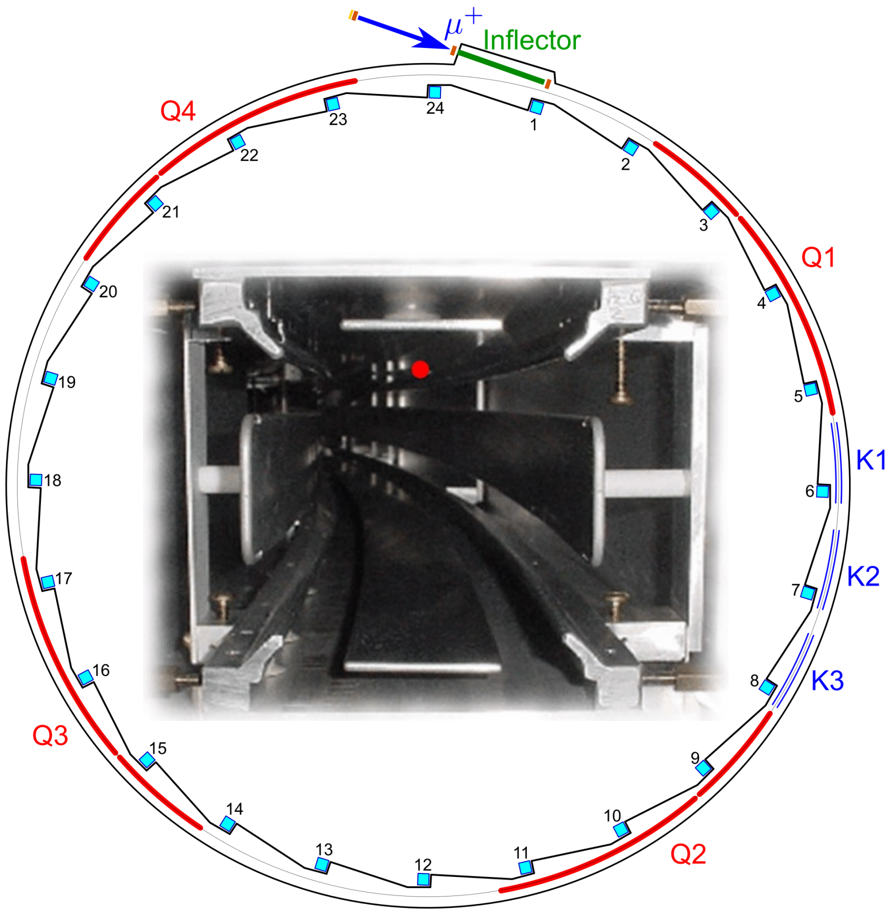


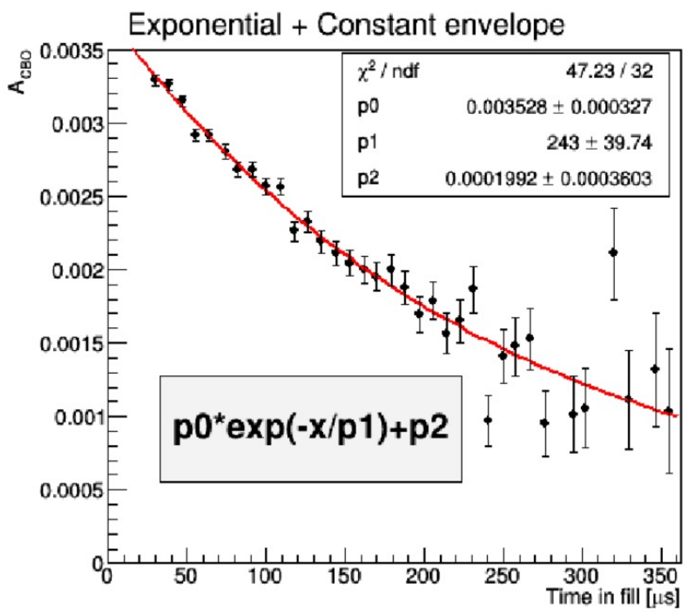


Muon Precession Frequency

Coherent Betatron Oscillations (CBO)



- The amplitude of CBO decreases over time because of the **decoherence of muons**

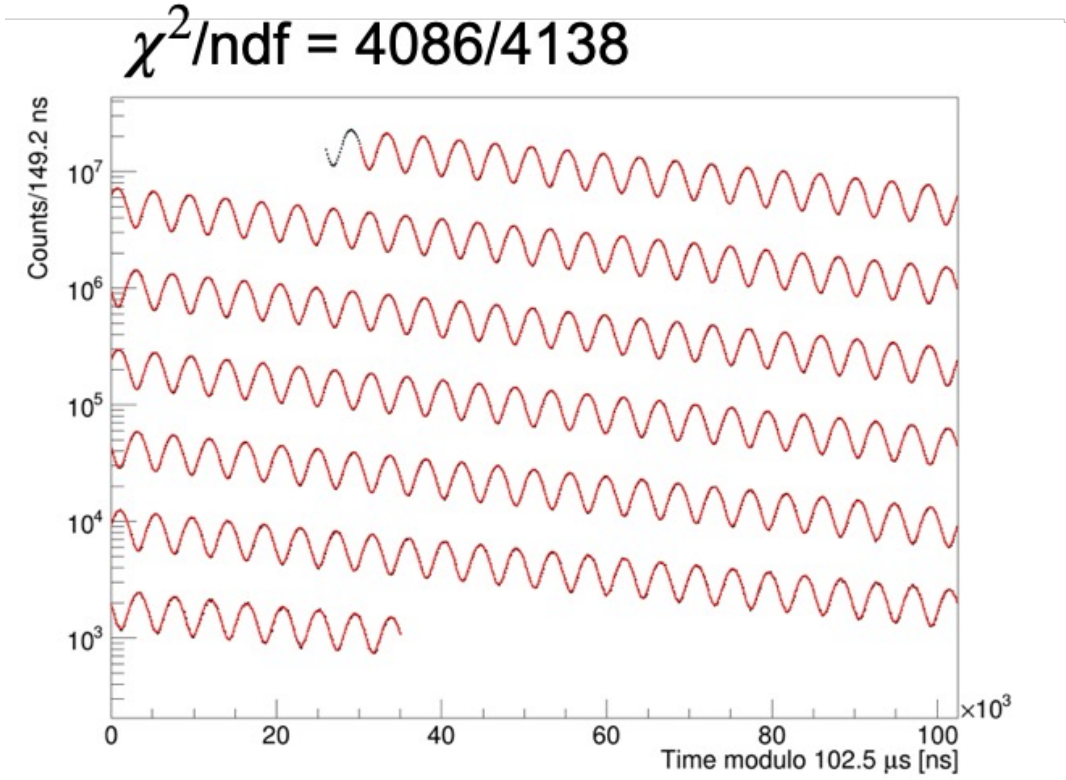


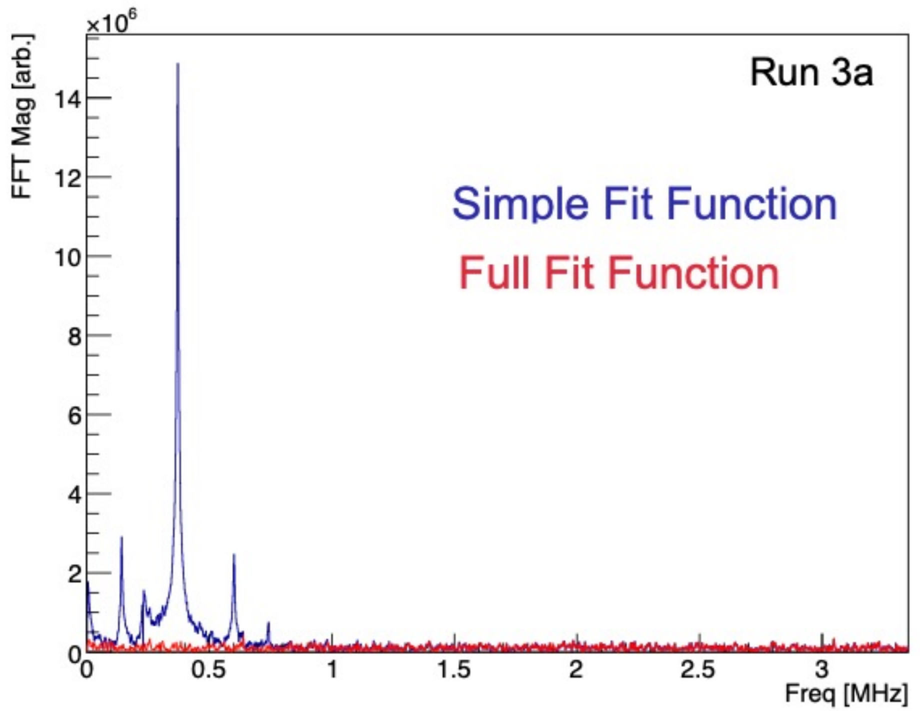
- Time-dependence is modelled
- Assess uncertainty by testing many different models

Muon Precession Frequency

Full Fit and Uncertainty improvements

- Modified fit function for beam dynamics effects gives good fit quality



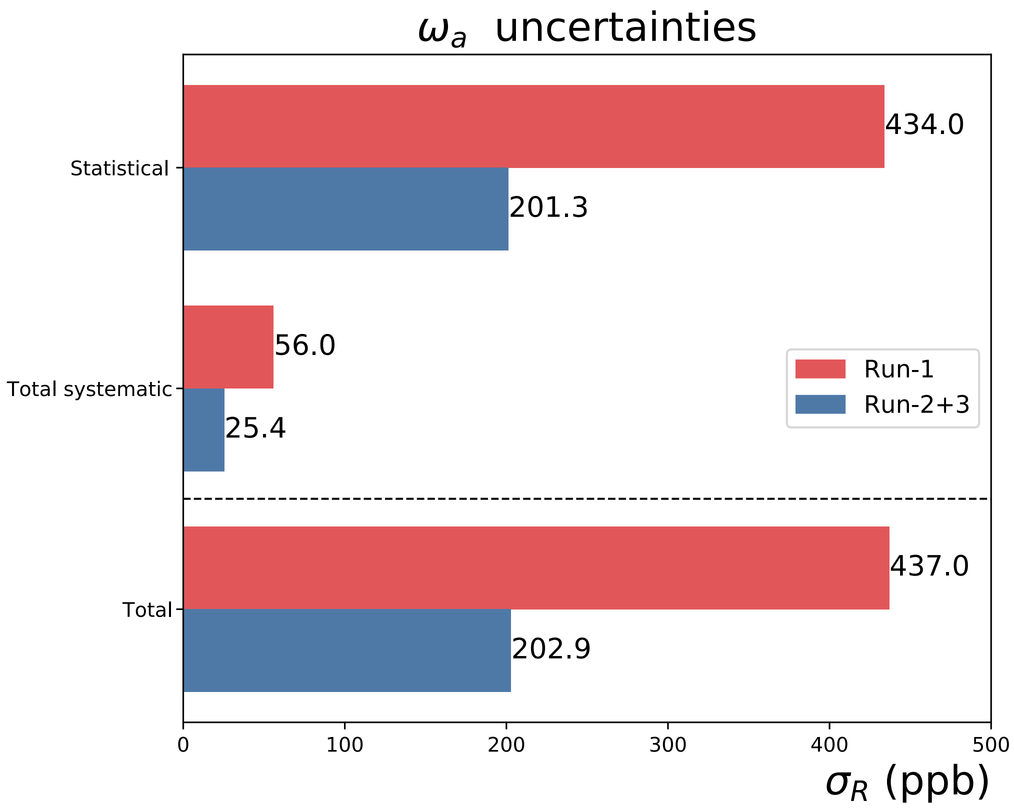


Muon Precession Frequency

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



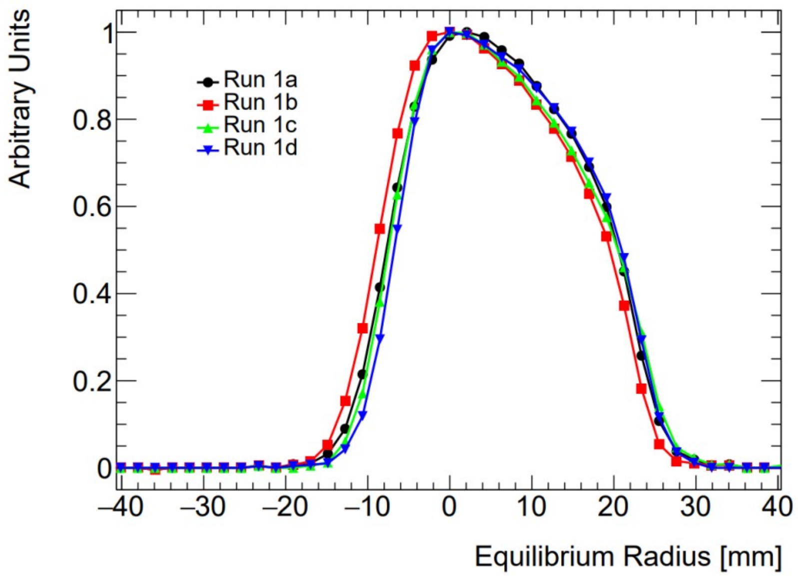
Beam Dynamic Corrections

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

$$\omega_a = -\frac{q}{m}[\ldots + (a_\mu - \frac{1}{\gamma^2 - 1})\frac{\beta \times \mathbf{E}}{c}]$$

C_e	**E-field** correction (**momentum dispersion** from 'magic' γ)

$$\frac{\Delta p}{p_0} = (1-n)\frac{x_e}{R_0}$$



- The correction depends on the muon **radius distribution** **$\langle X_e^2 \rangle$** wrt the 'magic' radius. This distribution can be measured with either calo or tracker data:

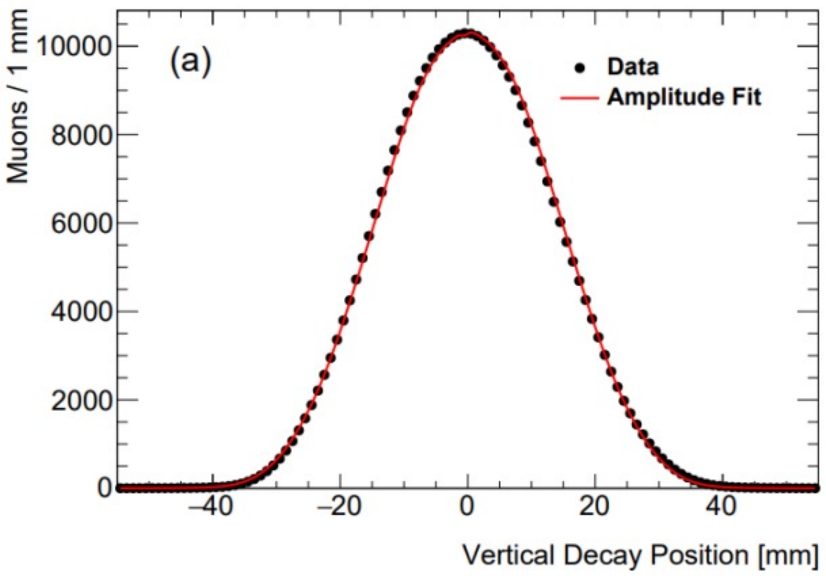
$$C_e \approx 2n(1-n)\beta_0^2 \frac{\langle x_e^2 \rangle}{R_0}$$

Beam Dynamic Corrections

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

C_p	**Pitch correction** from muon's small vertical momentum component

$$\omega_a = -\frac{q}{m}[\dots + \frac{\gamma}{\gamma+1}(\beta \cdot B)\beta]$$



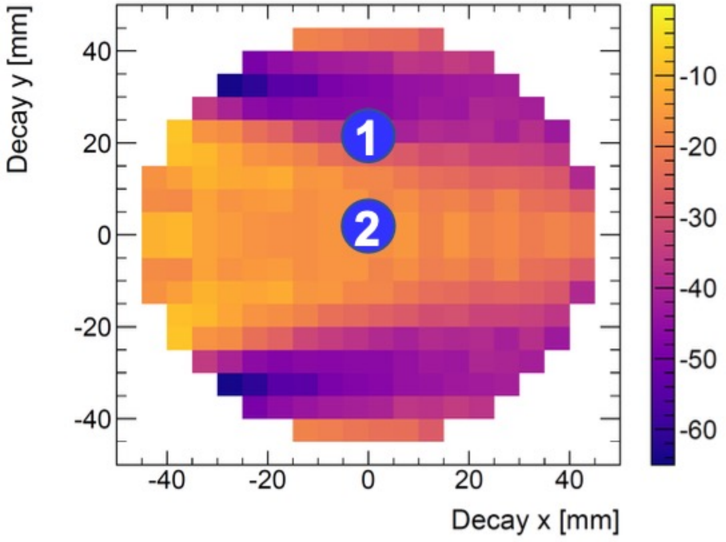
- Calculated by measuring (or reconstructing) **vertical position distribution**:

$$C_p = \frac{1}{2}\langle\psi^2\rangle = \frac{n}{4R_0^2}\langle A^2\rangle = \frac{n}{2R_0^2}\langle (y-\bar{y})^2 \rangle$$

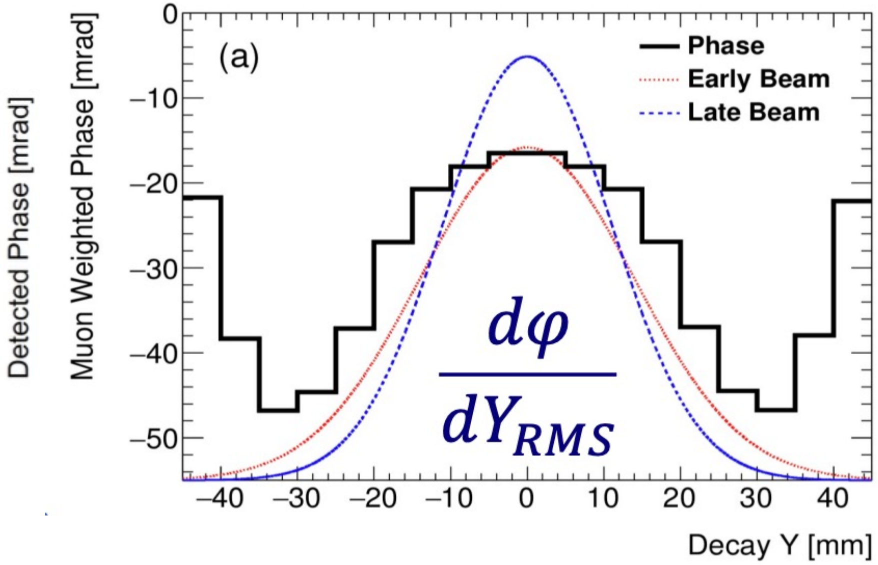
Beam Dynamic Corrections

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

C_{pa}	**Phase acceptance** correction by decay-position dependence of positron phase



Wiggle plots for (1) ≠ (2)



- Early-to-late beam motion modulation leads to time-dependent phase

Beam Dynamic Corrections

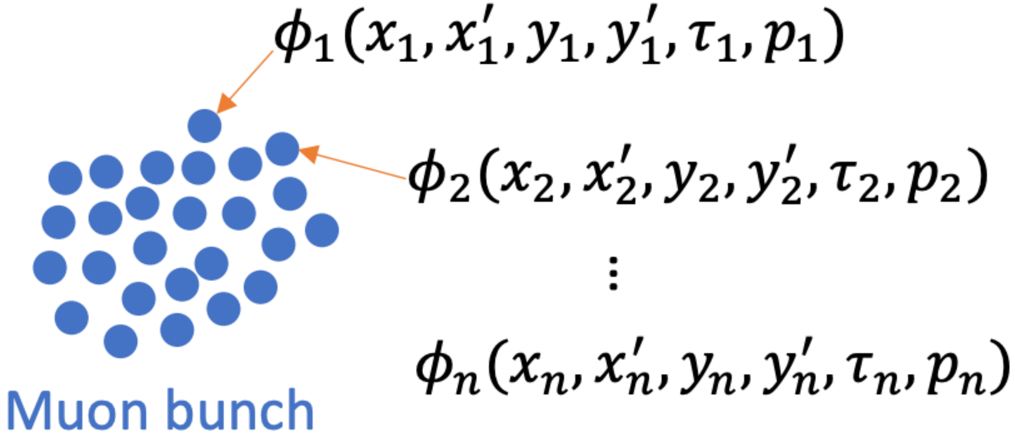
$$a_\mu = \frac{\omega_a^m}{\omega_p^m} \times \frac{(1 + C_e + C_p + C_{pa} + C_{dd} + C_{ml})}{(1 + B_k + B_q)} \times [\ldots]$$

C_{dd}	**Differential decay** correction as high momentum muons have longer lifetime

- Coherent **time dependence of $\boldsymbol{\varphi_0}$** over fill could bias measured ω_a :

$$\frac{\Delta\omega_a}{\omega_a} = -\frac{1}{\omega_a}\frac{d\phi_0}{dt}$$

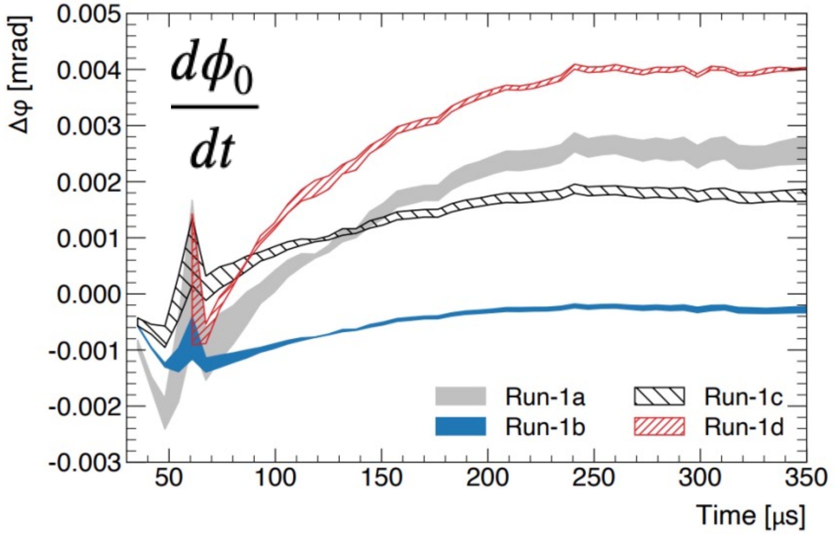
- New correction in Run-2/3



Beam Dynamic Corrections

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

C_{ml}	**Muon loss** correction from initial phase-momentum correlation in muons



- Muons are lost in time, there is time-dependent change in phase:

$$\frac{d\phi_0}{dt} = \frac{d\phi_0}{d<p>}\frac{d<p>}{dt}$$

Beam Dynamic Corrections

Uncertainty Summary

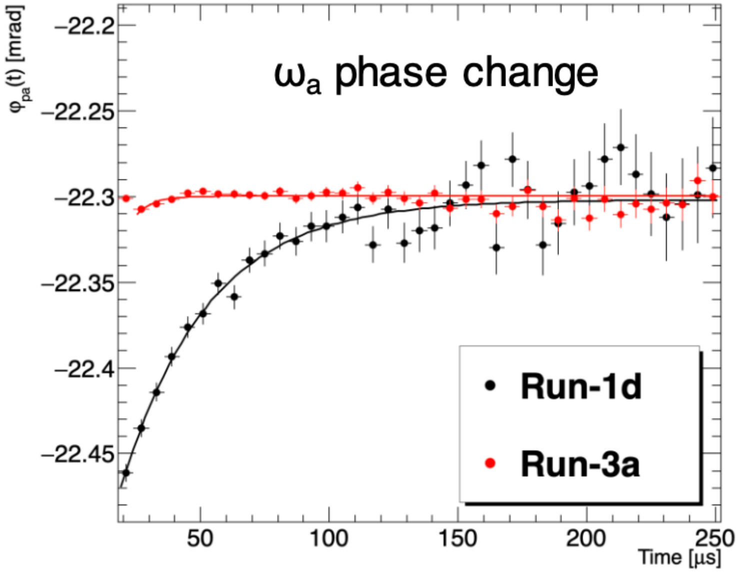
	Corrections [ppb]	Uncertainty [ppb]	Uncertainty in Run-1 [ppb]
C_e	451	**32**	53
C_p	170	10	13
C_{pa}	-27	**13**	75
C_{dd}	-15	17	-
C_{ml}	0	3	5
Total	580	40	93

Beam Dynamic Corrections

Uncertainty Summary

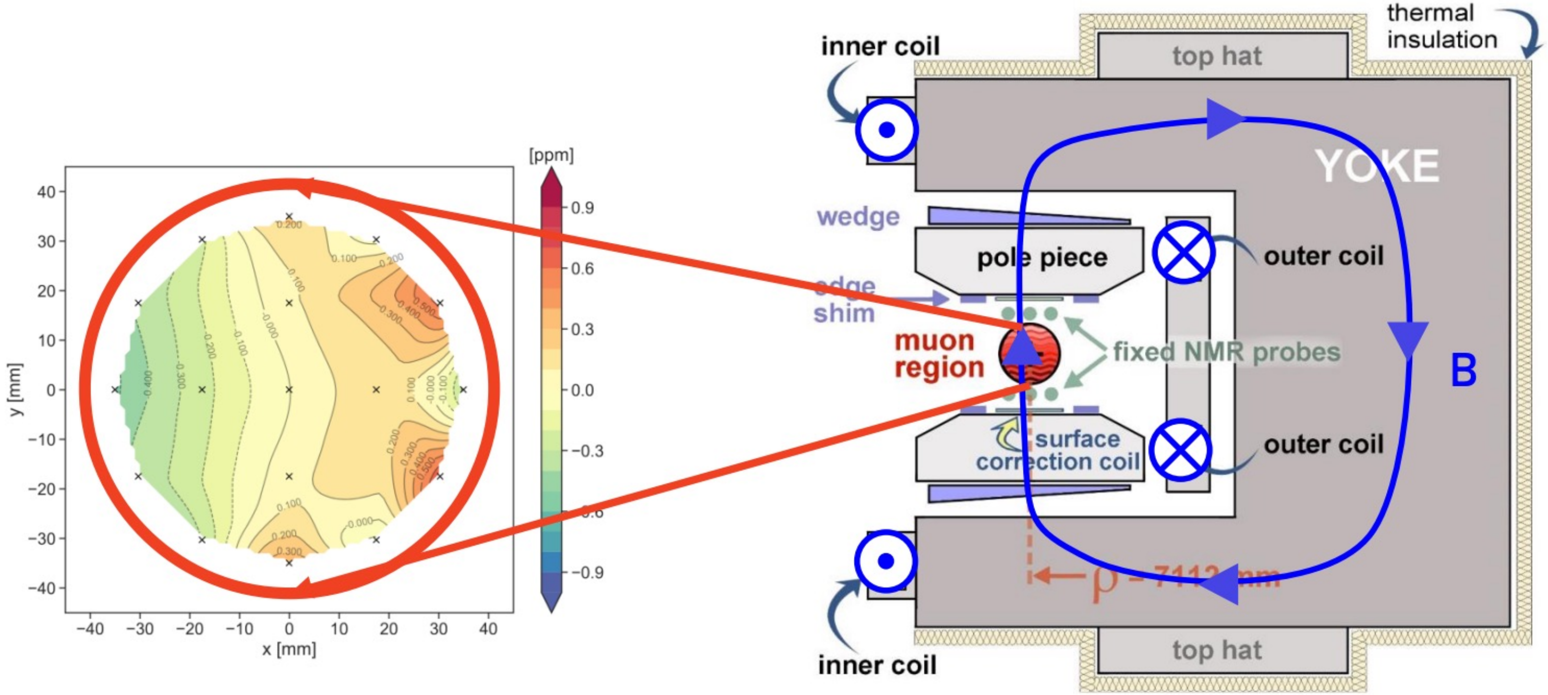
	Corrections [ppb]	Uncertainty [ppb]	Uncertainty in Run-1 [ppb]
C_e	451	**32**	53
C_p	170	10	13
C_{pa}	-27	**13**	75
C_{dd}	-15	17	-
C_{ml}	0	3	5
Total	580	40	93

- 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

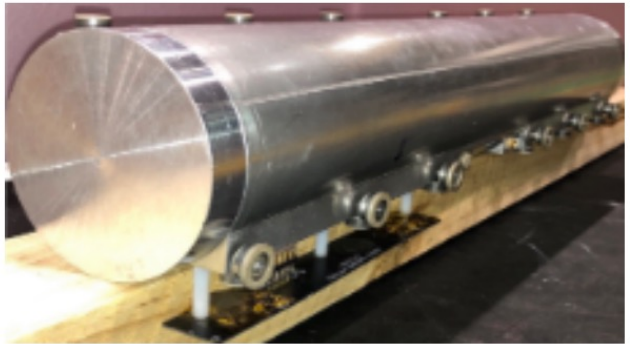


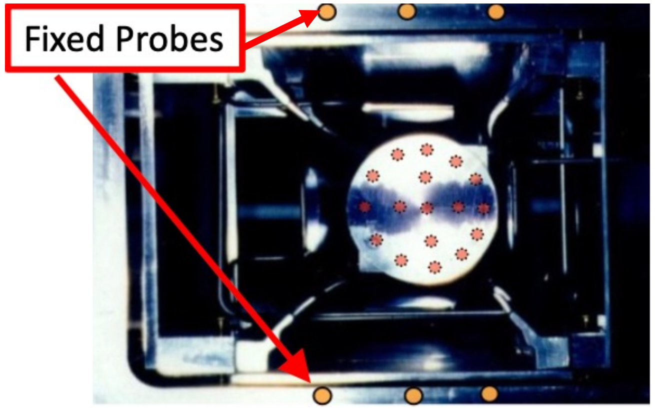
7.112 m radius ‘C’-shape magnet with vertically-aligned field
B = 1.45 T

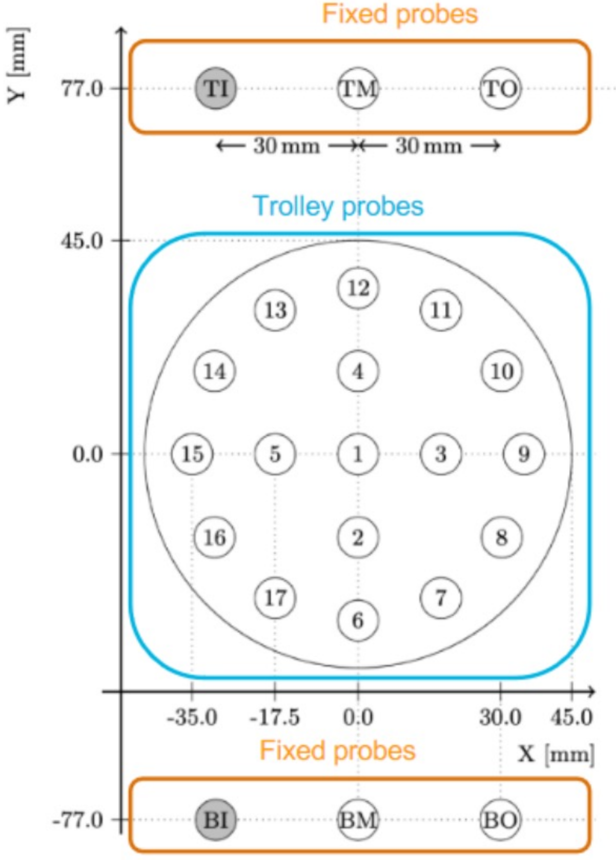
- Dipole field has ppm-level uniformity (<20 ppm RMS across the full azimuth)
- Shimming devices (active and passive) minimise gradients and keep field uniform

Magnetic Field Measurement

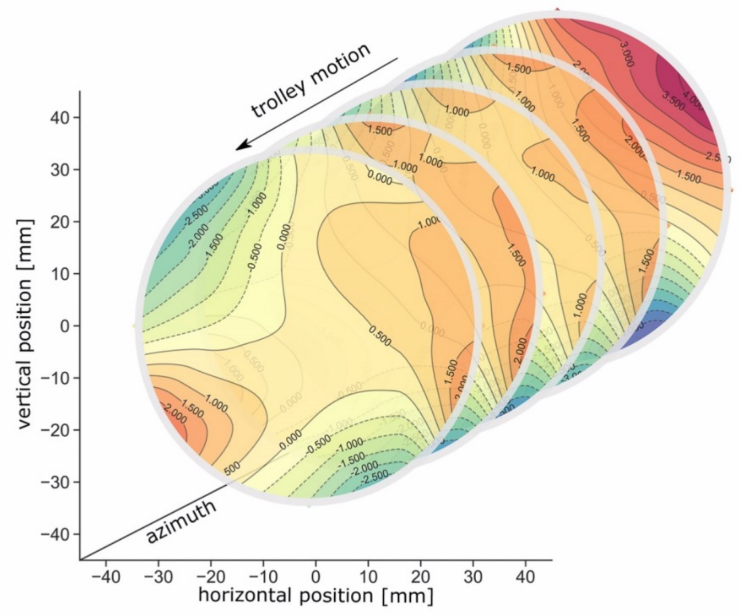
NMR: Trolley and Fixed Probes







- **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

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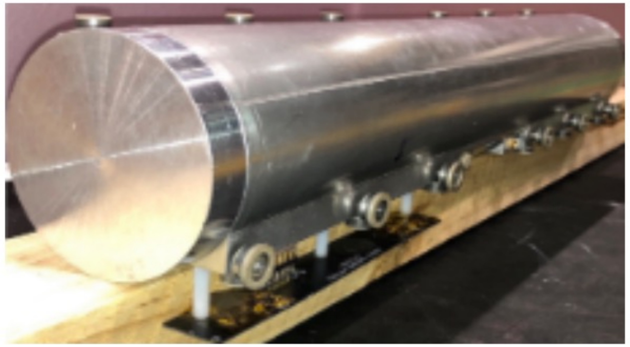
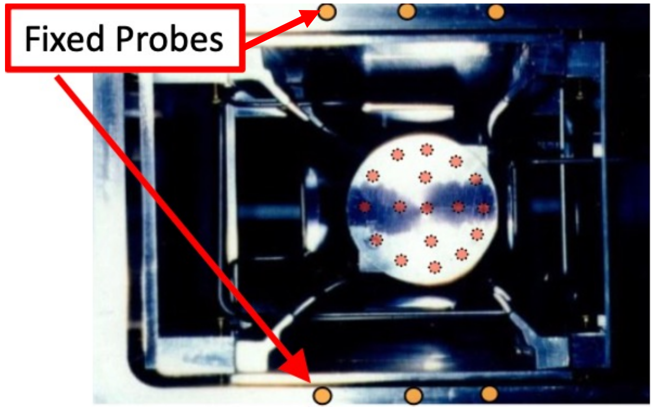
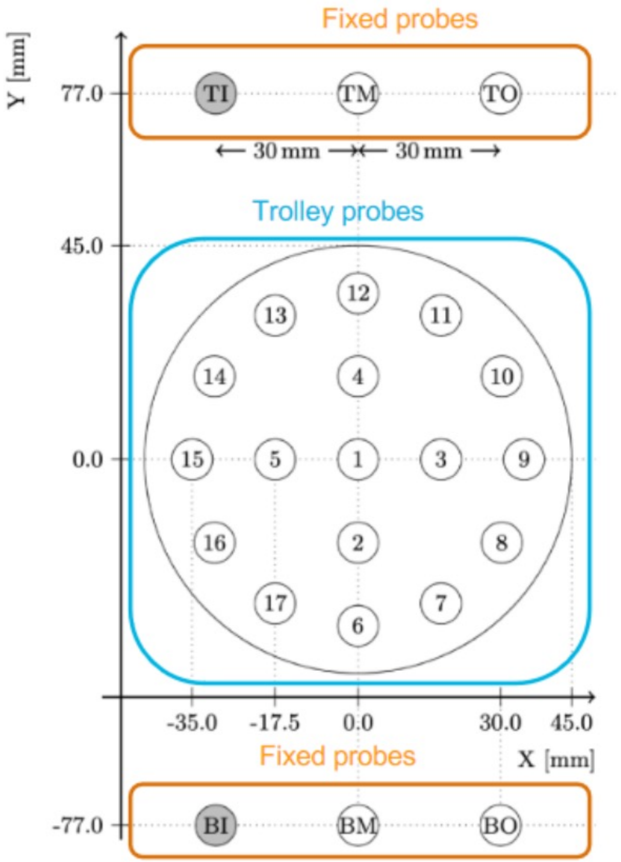
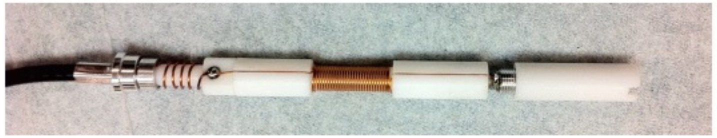
NMR: Trolley and Fixed Probes







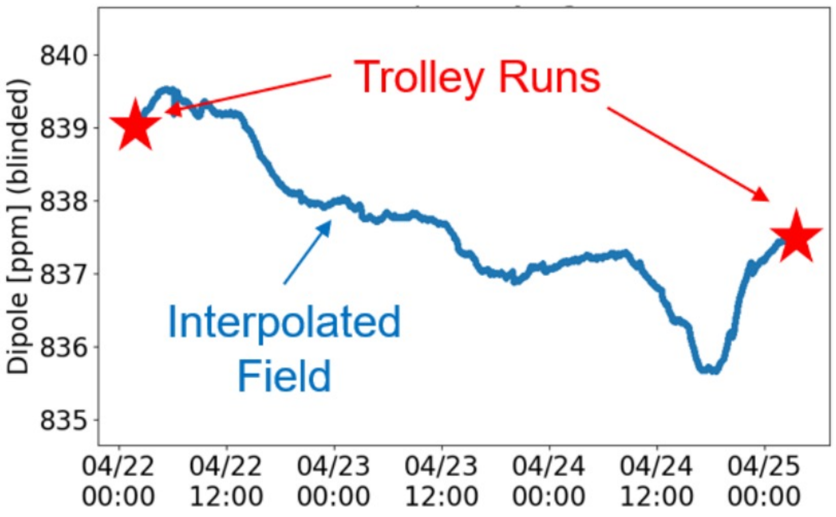
- **378 fixed NMR probes,** above or below storage volume permanently installed ("fixed") at 72 locations around the ring (every ~5°)
- Track changes in the field continuously during muon storage

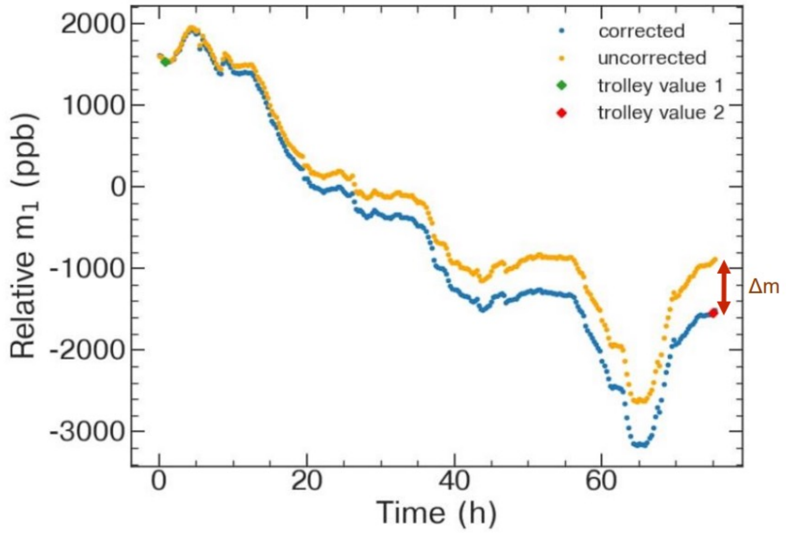


Magnetic Field Measurement

Field Interpolation

- Need to know the precise field at the times when muons are present in the ring
- Fixed probes don't measure storage region directly – need to calibrate it with trolley measurement
- Offset driven by small changes in the field regions with low FP sensitivity





Run-2/3 uncertainty ~17 ppb

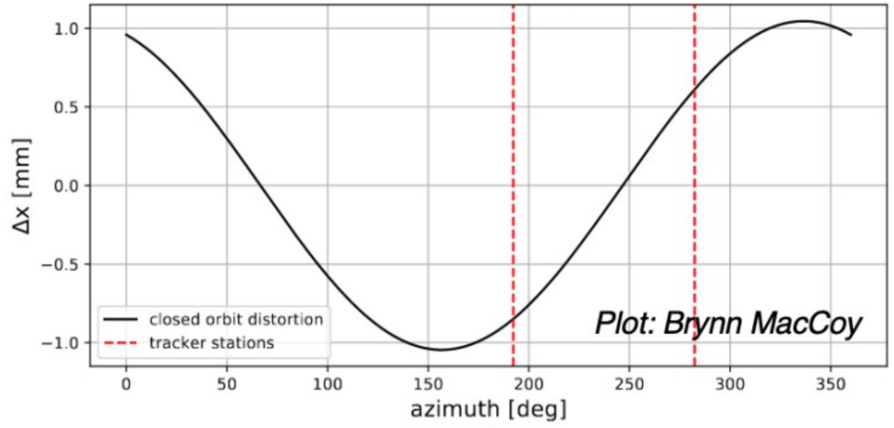
Magnetic Field Measurement

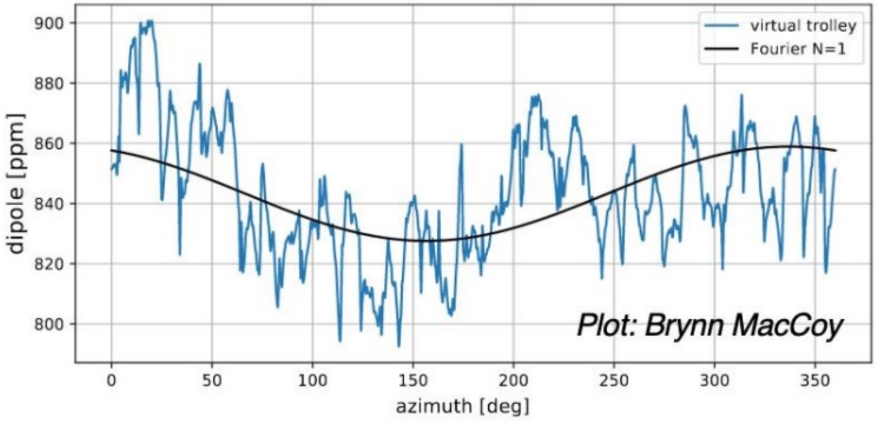
Muon Weighting

$$a_\mu = \frac{\omega_a^m}{< \omega_p \otimes \rho_\mu >} \times \cdots$$

- Magnetic field maps weighted by muon distribution determined by trackers
- Use beam dynamics simulations to extrapolate distribution around ring

Average radial beam position





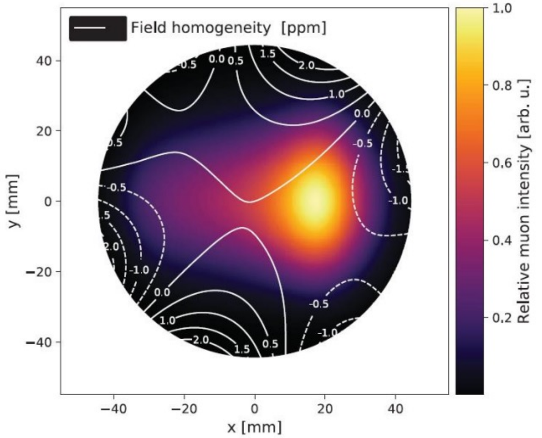
Azimuthal dependence of field moments

Magnetic Field Measurement

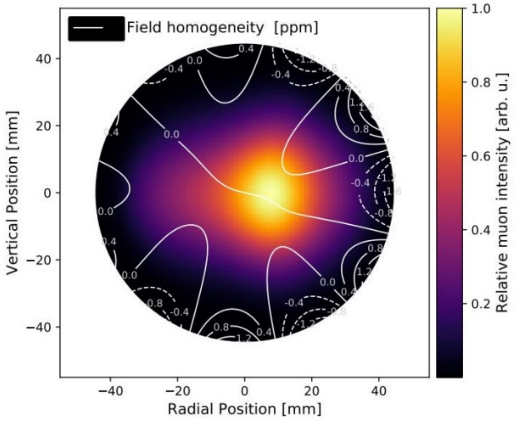
Muon Weighting

$$a_\mu = \frac{\omega_a^m}{< \omega_p \otimes \rho_\mu >} \times \cdots$$

- Magnetic field maps weighted by muon distribution determined by trackers
- Use beam dynamics simulations to extrapolate distribution around ring
- Improvement in Run-2/3: better centred beam



Run-1



Run-2/3

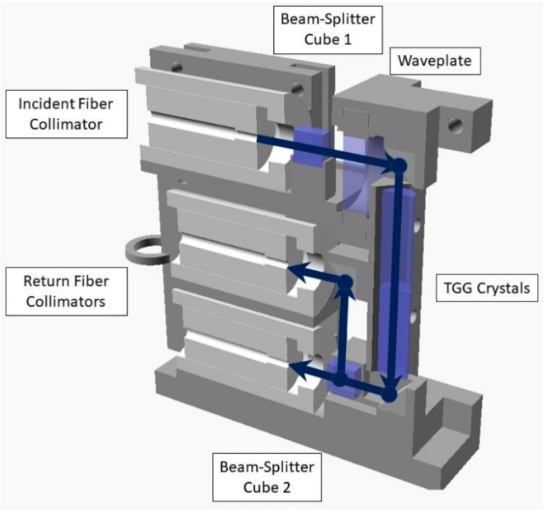
Run-2/3 uncertainty: 7 – 13 ppb

Magnetic Field Measurement

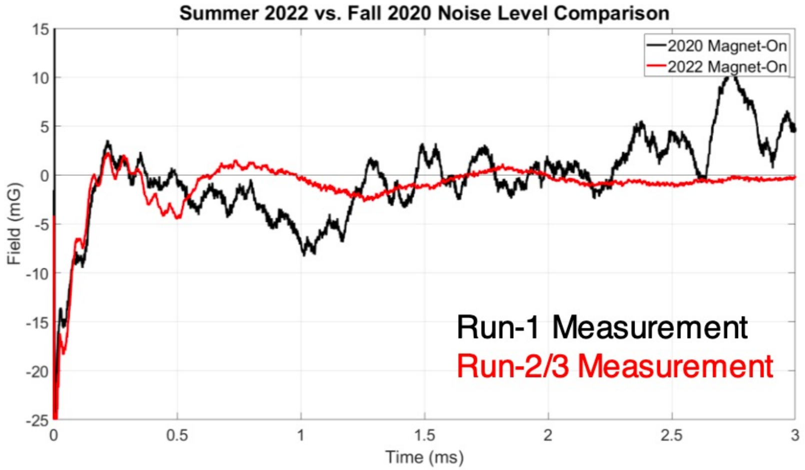
Quad Transient Fields Correction: B_k

$$a_\mu = \frac{\omega_a^m}{<\omega_p^m>} \times \frac{(1 + C_e + \cdots)}{(1 + B_k + B_q)} \times \cdots$$

- Kicker creates **eddy currents ⇒ transient magnetic field**



Faraday magnetometer



- Run-2/3 has **lower vibration noise** vs. Run-1
- Uncertainty reduces from **37 ppb to 13 ppb**

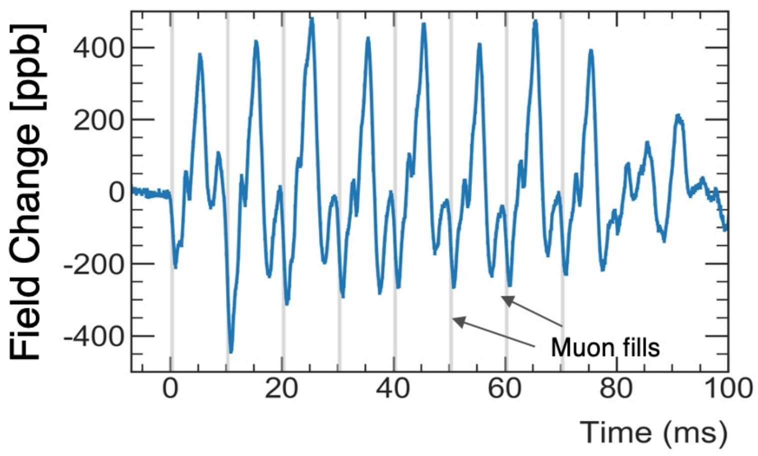
Release talk by James Mott, 10th August 2023

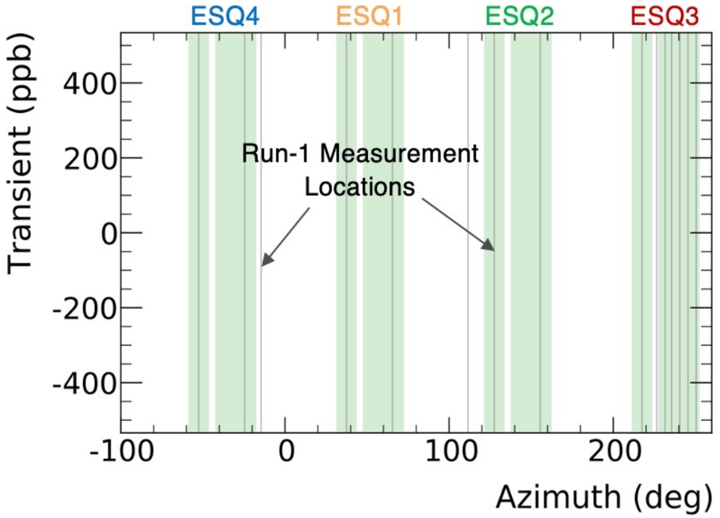
Magnetic Field Measurement

Quad Transient Fields Correction: B_q

$$a_\mu = \frac{\omega_a^m}{<\omega_p^m>} \times \frac{(1 + C_e + \cdots)}{(1 + B_k + B_q)} \times \cdots$$

- Pulsing **quads' plates vibrate ⇒ oscillating magnetic fields**
- Measured with a **new NMR probe** housed in insulator





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

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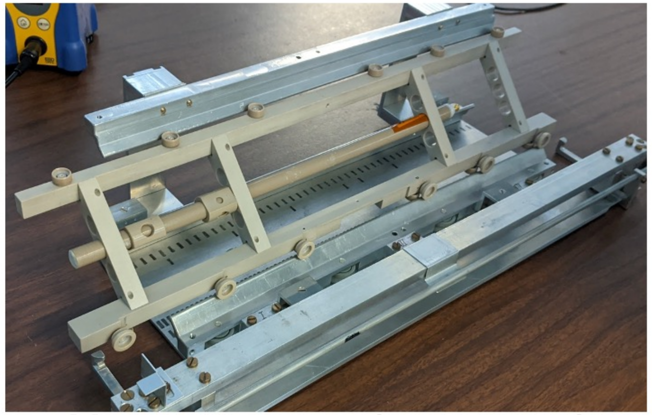
Magnetic Field Measurement

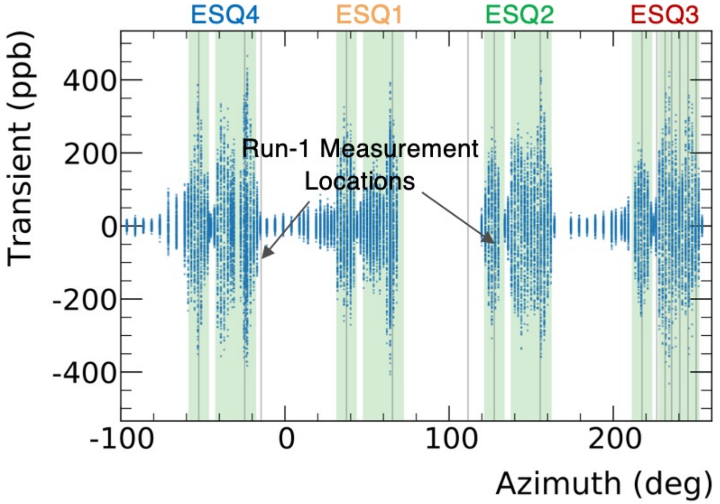
Quad Transient Fields Correction: B_q

$$a_\mu = \frac{\omega_a^m}{< \omega_p^m >} \times \frac{(1 + C_e + \cdots)}{(1 + B_k + B_q)} \times \cdots$$

- 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**

Release talk by James Mott, 10th August 2023

Magnetic Field Measurement

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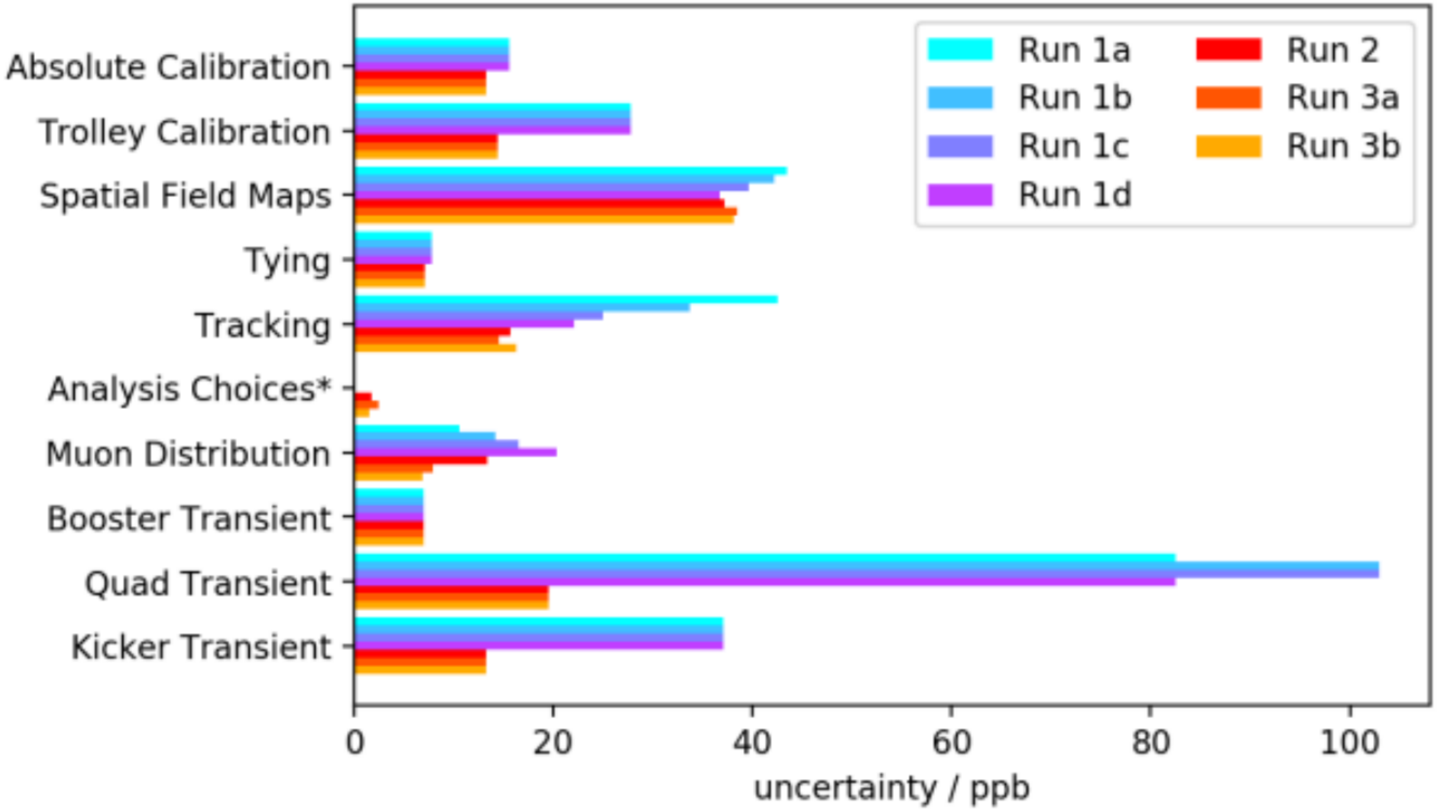
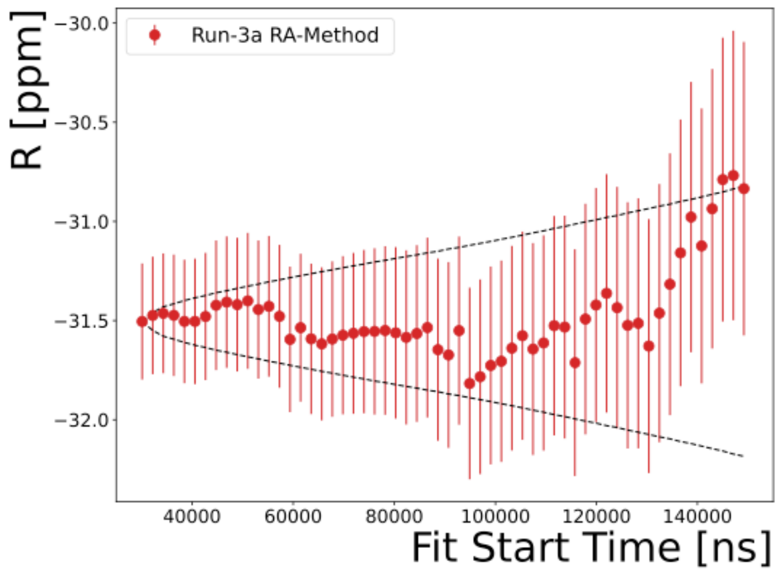
Uncertainty Summary



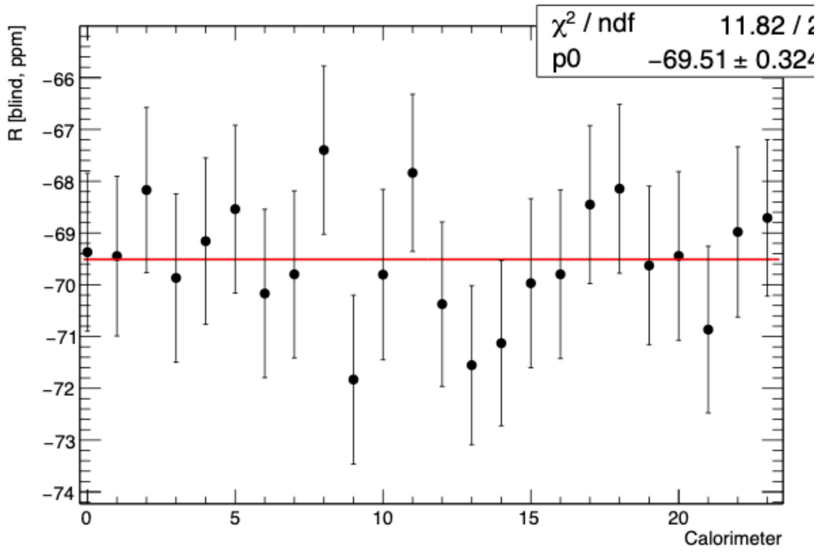
- Main reduction in the uncertainty comes from better understanding of the **transient field effects** (B_k and B_q)
- Interpolation uncertainty also reduced with increased trolley runs
- **TDR goal already achieved**

Consistency Check

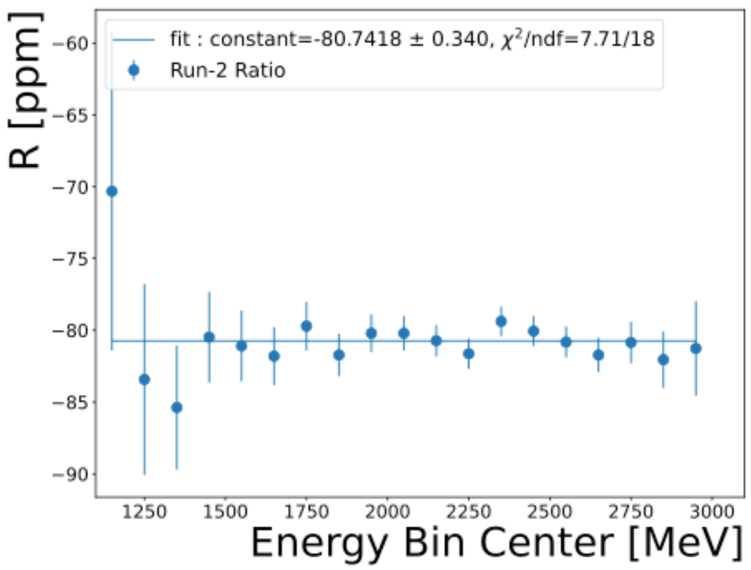
- We perform many consistency checks: fit residual FFTs, fit start time scans, fits by calorimeter, fits by positron energy, etc.



Fit start time scan



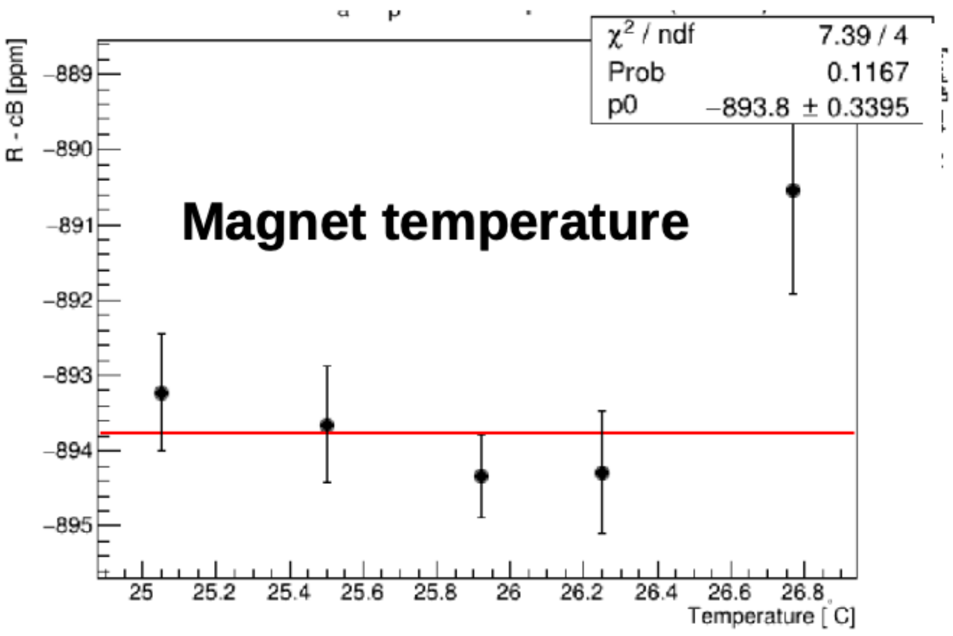
Per-calorimeter fits

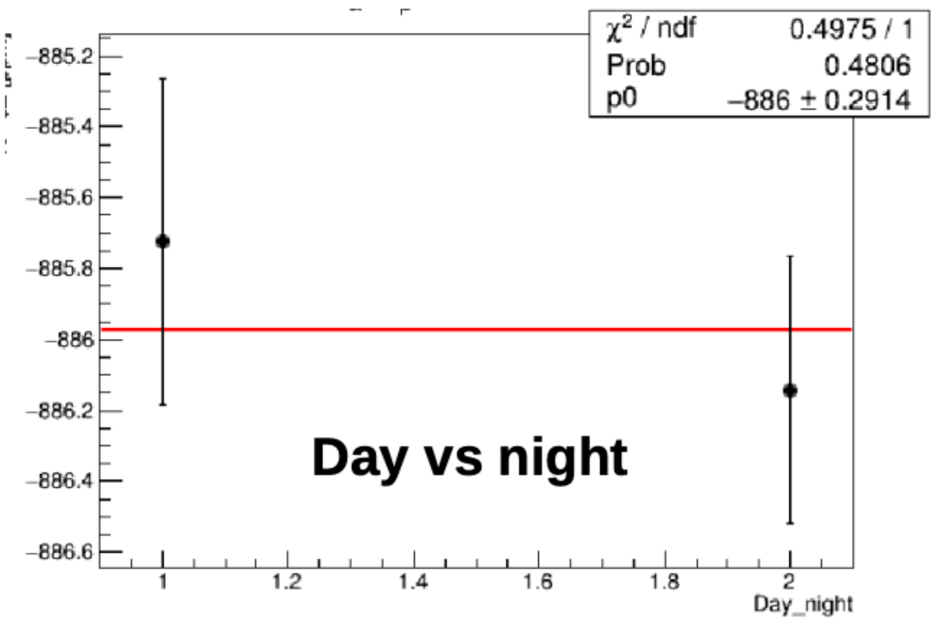


Energy-bin fits

Consistency Check

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





Datasets and Combination

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- Three datasets based on different running configurations (Run-2; Run-3a; Run-3b)
- 7 analysis groups for a total of 19 analysis methods (results)
  - Final combination only considers 6 of them (asymmetry-weighted methods)
- Assuming 100% correlated systematics across datasets

dataset	quad HV [kV]	index n	kicker HV [kV]	beam $< x >$ [mm]	magnet temp, ΔT	fills $\times 10^6$	ω_a statistical uncertainty [ppm]
Run 2	18.3	0.108	142	5-6	$\sim 3\ ^oC$	18	0.34
Run 3a	18.2	0.107	142	4-5	$\sim 0.2\ ^oC$	33	0.29
Run 3b	18.2	0.107	165	0-1	$\sim 0.2\ ^oC$	12	0.47

Datasets and Combination

- Three datasets based on different running configurations (Run-2; Run-3a; Run-3b)
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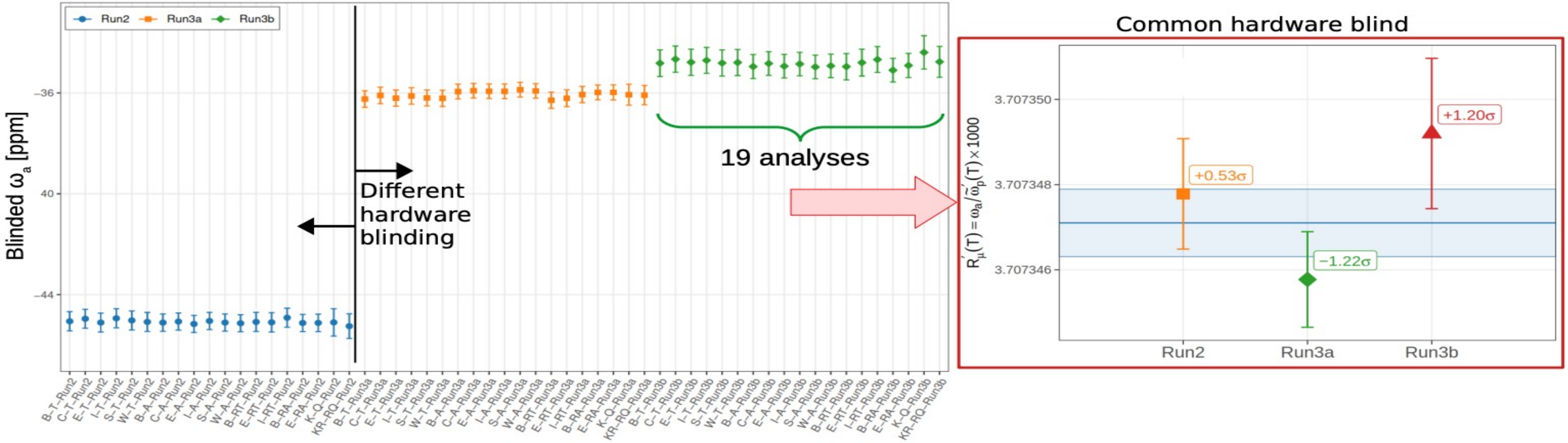
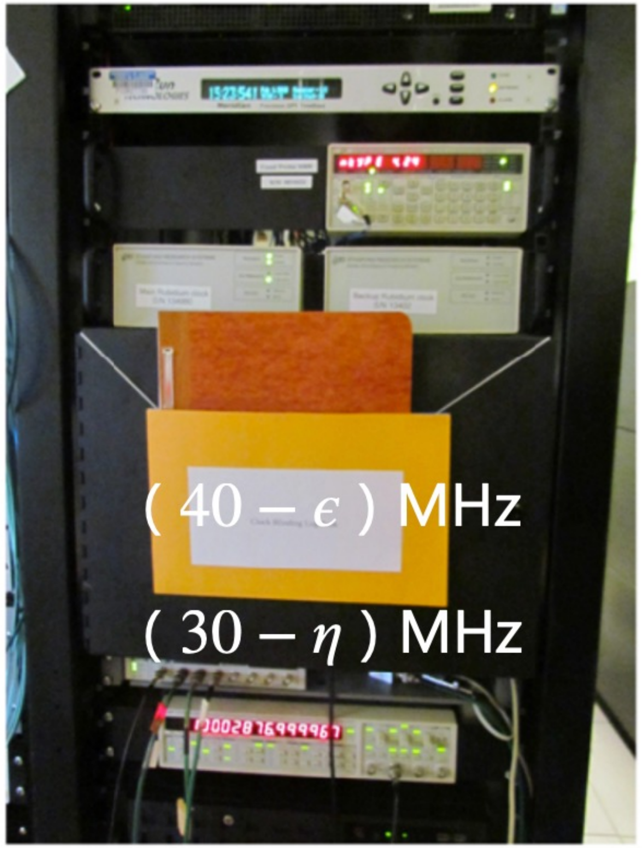


Blinding Analysis

Locked Clock Panel



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

- 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

New Results from the Muon $g - 2$ Experiment at Fermilab

- Introduction
- Analysis
- Result
  - Unblinding
  - Discrepancies with SM prediction(s)
- Outlook & Summary

Unblinding

24th of July, 2023

- Muon g-2 analysis has **software & hardware blinding**
- Unblinding meeting in Liverpool:

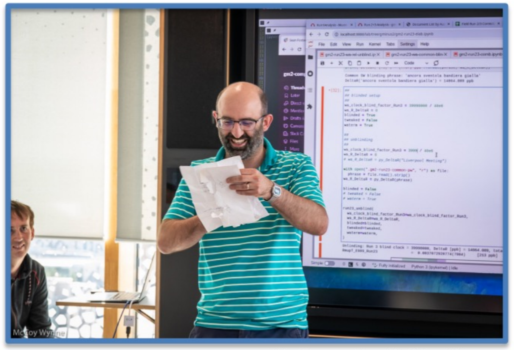



Photo credits: McCoy Wynne

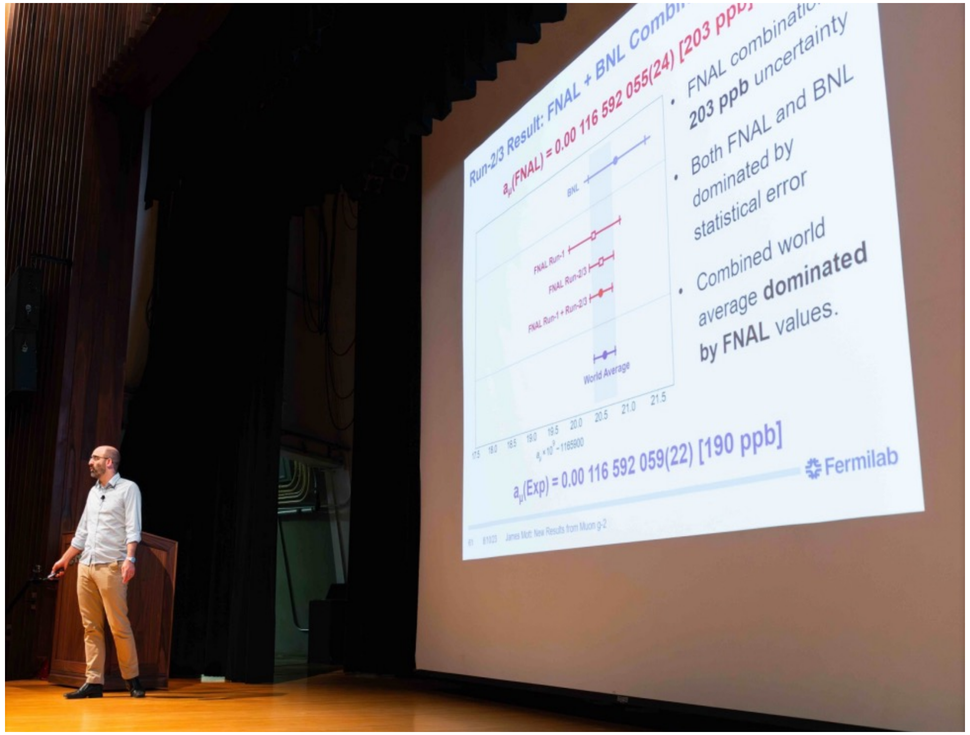
- Unanimous vote from all collaborators to unblind!
- Secret envelopes were finally opened to reveal the hidden clock frequencies and the result…

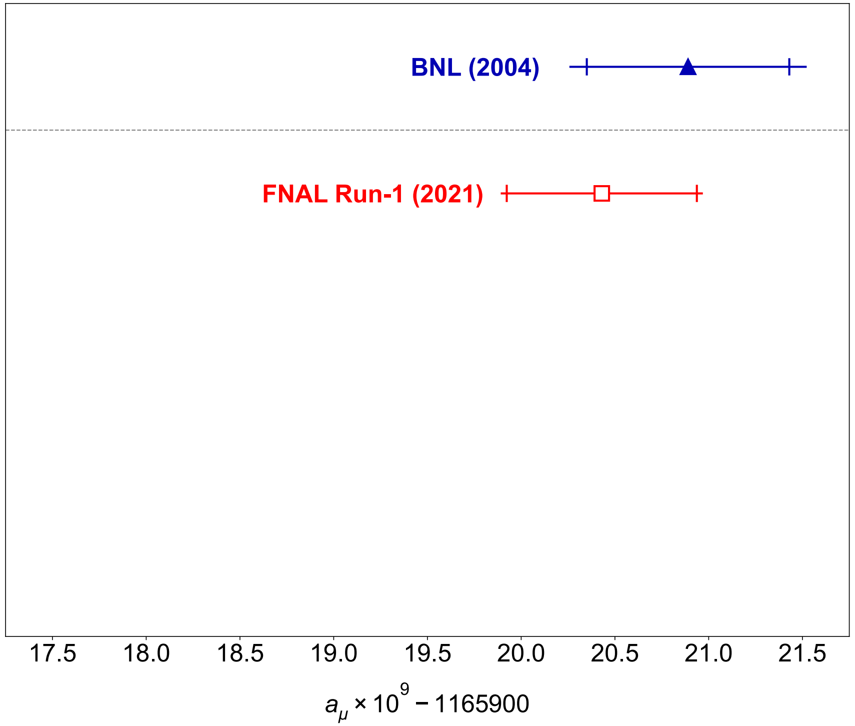
Summer Collaboration meeting at University of Liverpool July 24-28, 2023

New Result

Released on 10th of Aug 2023

- PRL (…) has been accepted



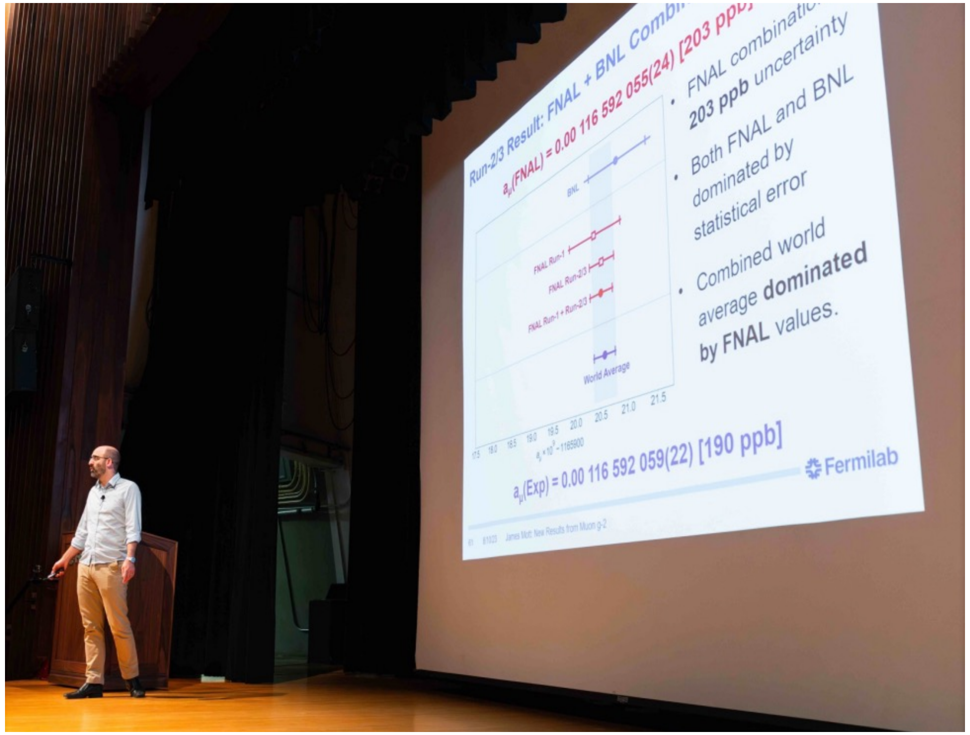


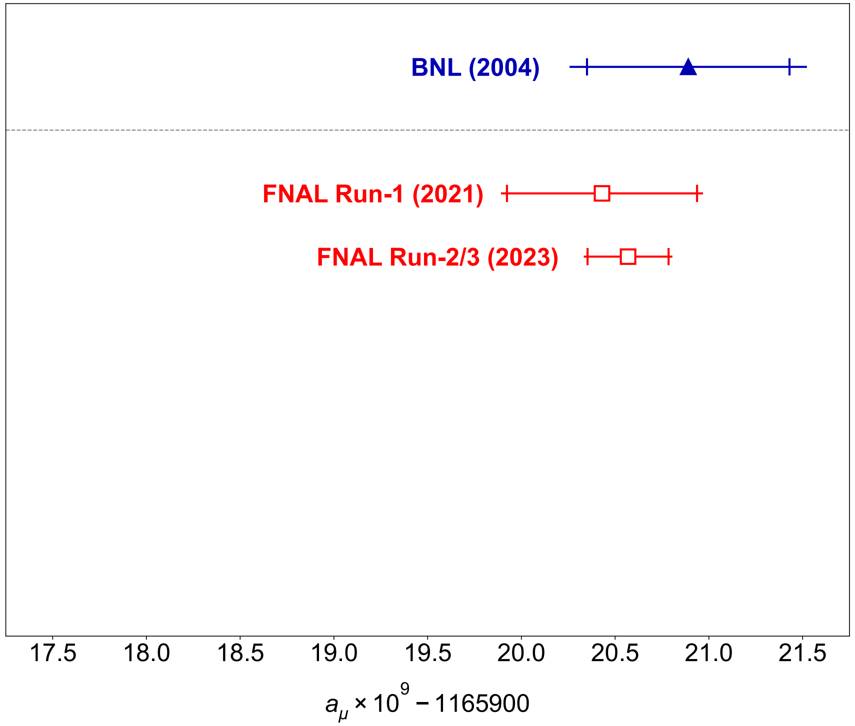
- FNAL Run-1 (2021) confirmed BNL (Brookhaven, 2004) measurement

New Result

Released on 10th of Aug 2023

- PRL (…) has been accepted



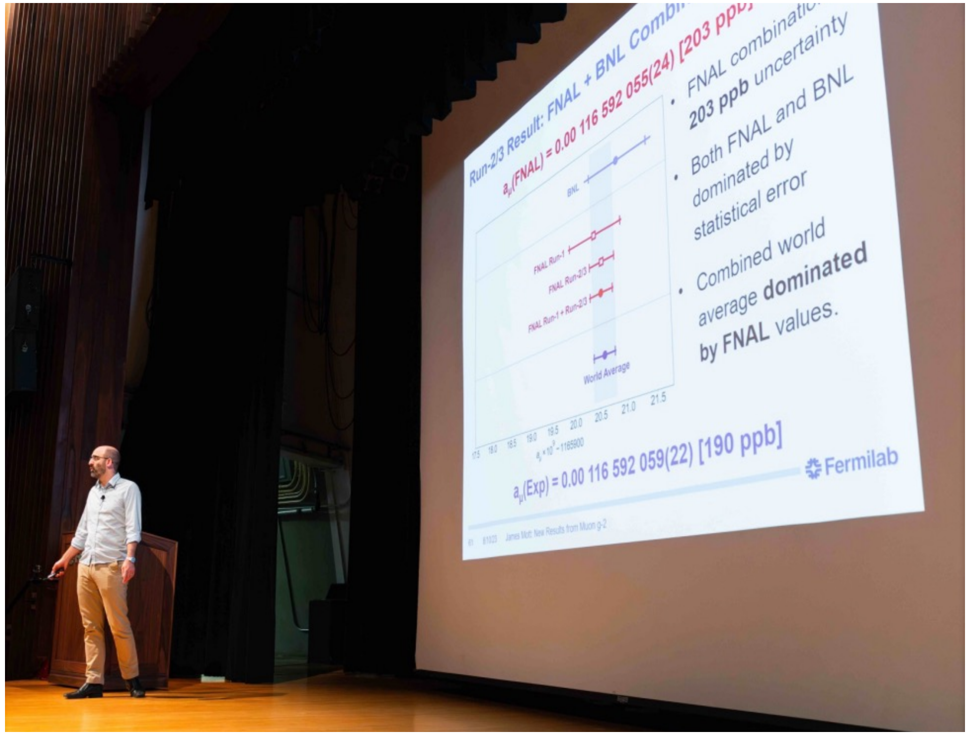


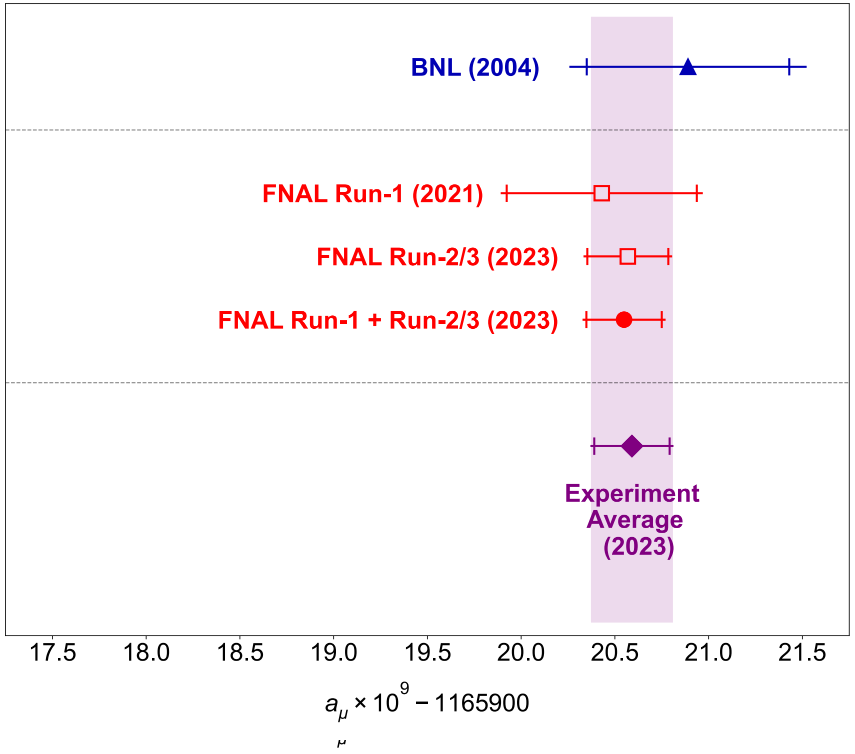
- FNAL Run-1 (2021) confirmed BNL (Brookhaven, 2004) measurement
- FNAL (2023): **Excellent agreement** with BNL and Run-1; Uncertainty more than halved to **215 ppb**

New Result

Released on 10th of Aug 2023

- PRL (…) has been accepted

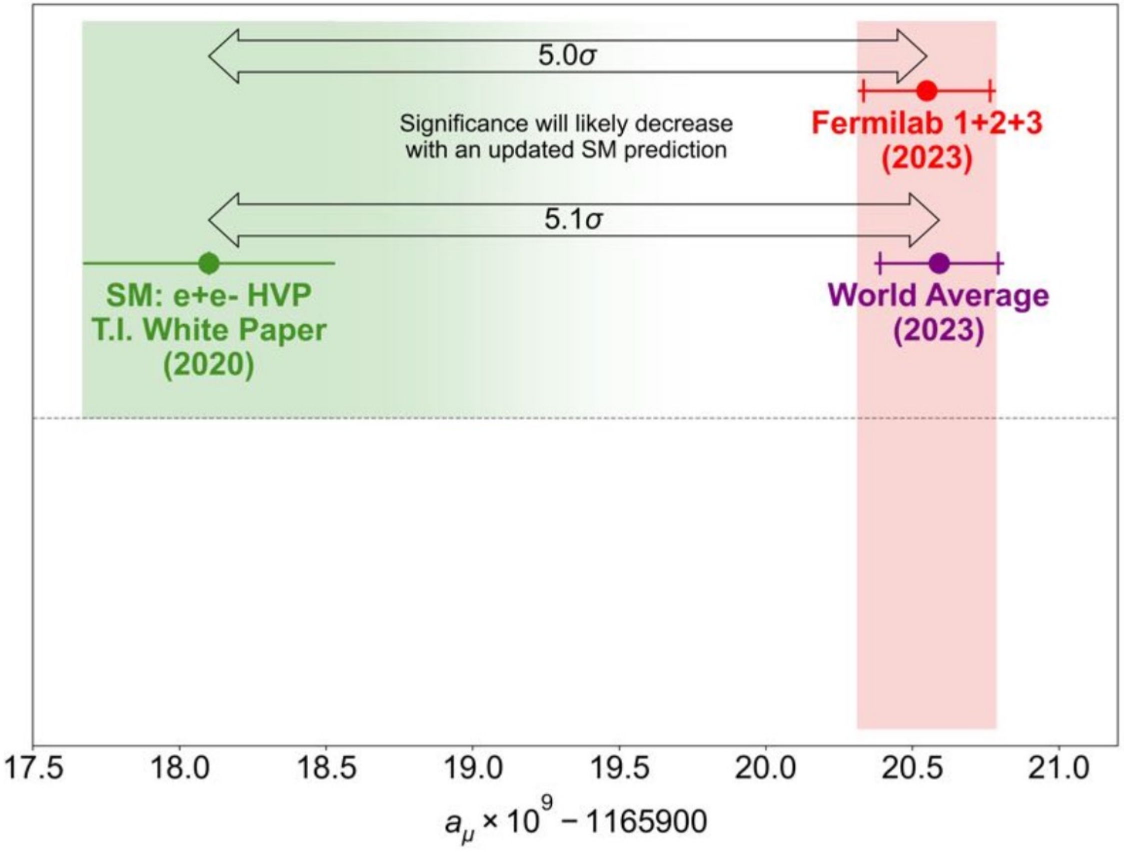




- Combined FNAL result uncertainty: **203 ppb**
- Combined world average uncertainty is **190 ppb**
- Average is **dominated by FNAL** value

The Current Puzzle

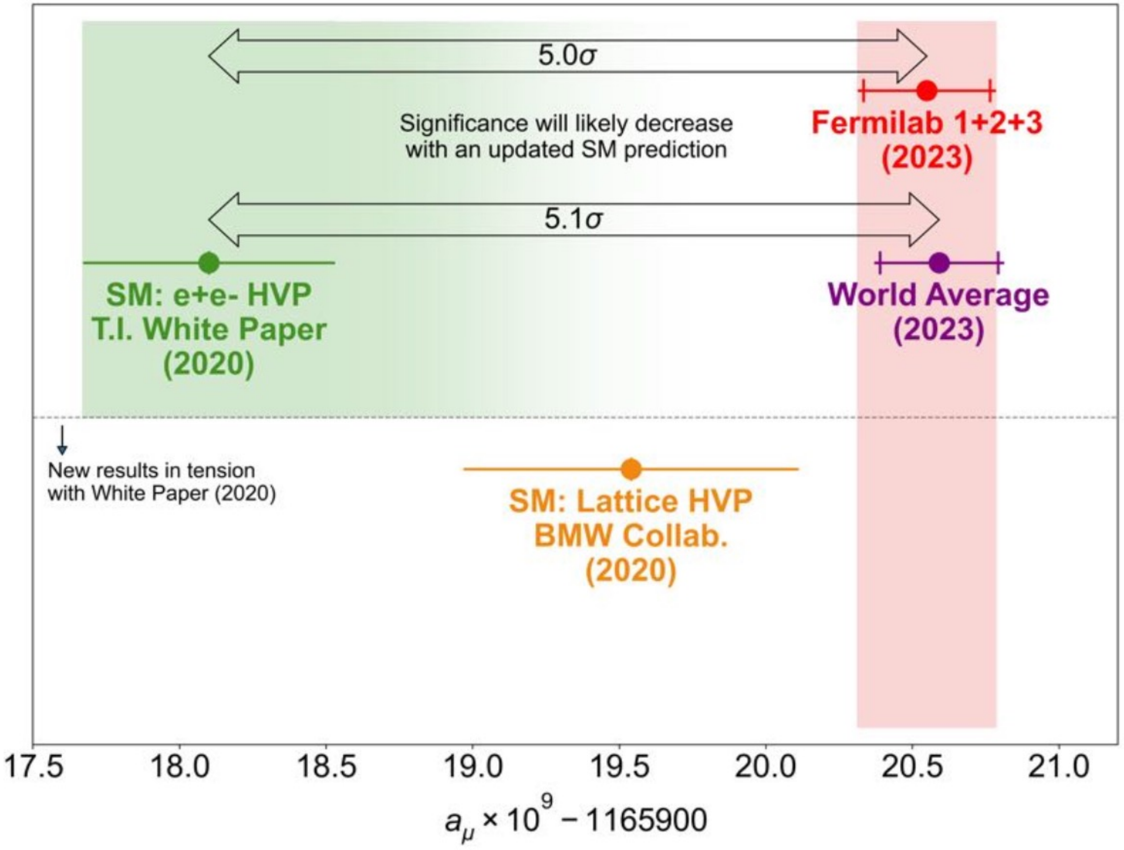
Discrepancy between Experiments & Theories



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

The Current Puzzle

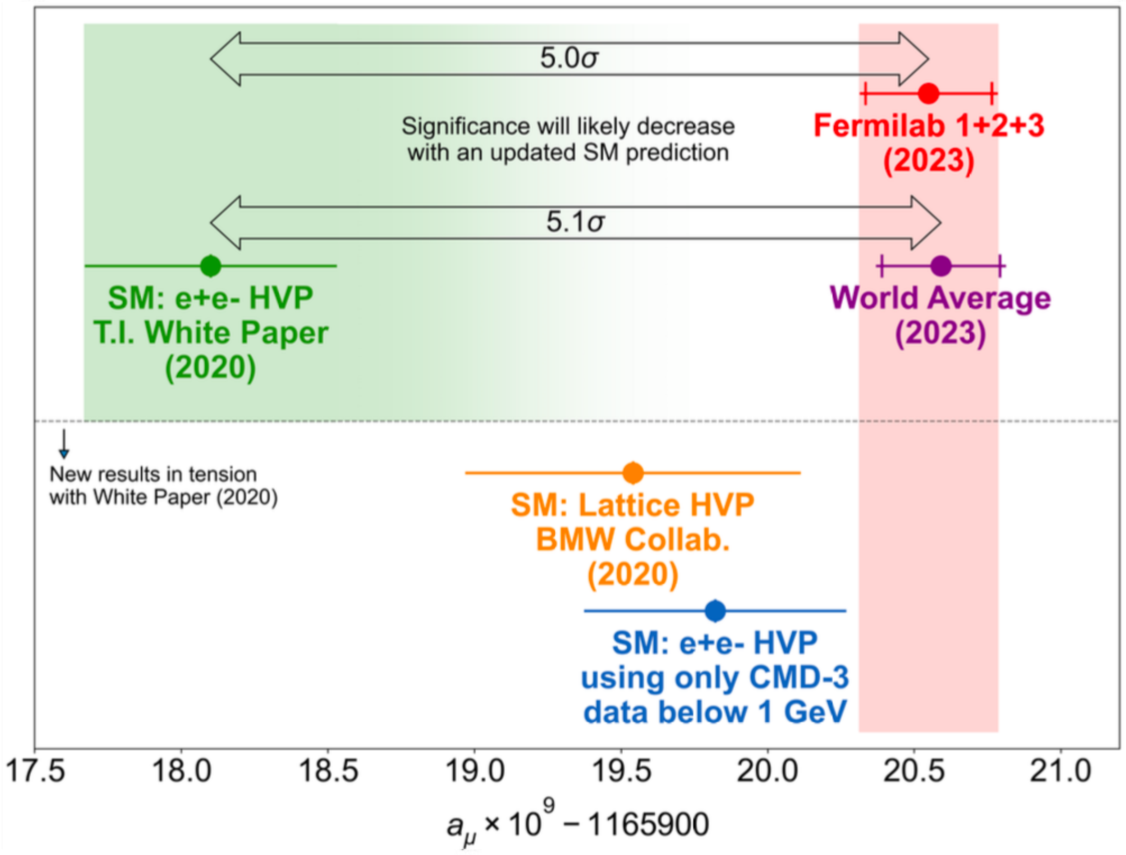
Discrepancy between Experiments & Theories



- New experimental average with SM prediction (WP-2020) gives > 5σ
- Since then, two important developments on SM prediction:
  - Lattice QCD from the BMW (2020)

The Current Puzzle

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 $e^+e^- \to \pi^+\pi^-$ cross section from CMD-3 (2023)

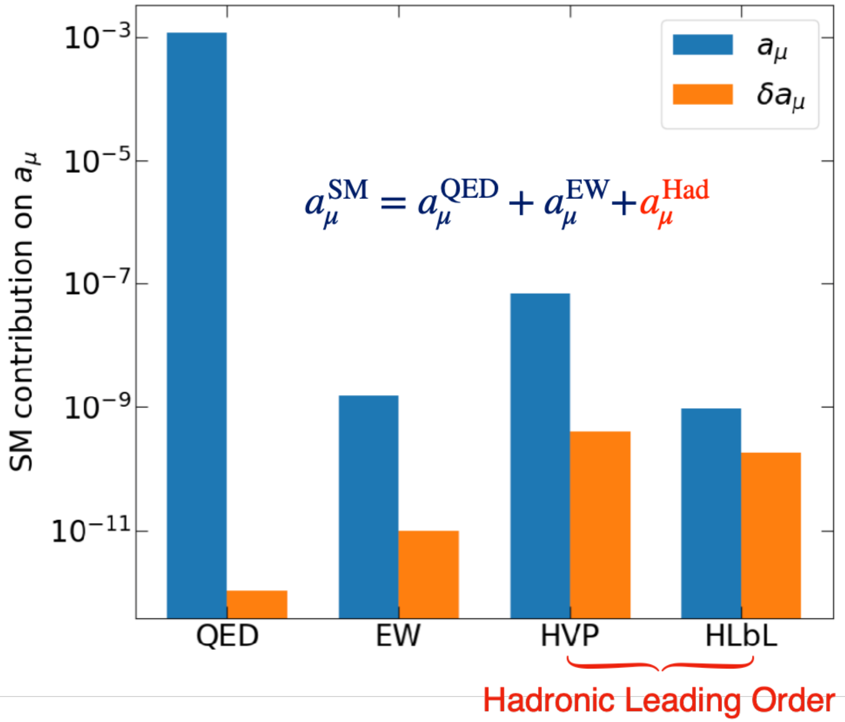
➢ **Disclaimer:**
The CMD-3 point is a visual exercise. It is not a fully updated SM prediction!

- 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 → <u>should not be taken as final!</u>

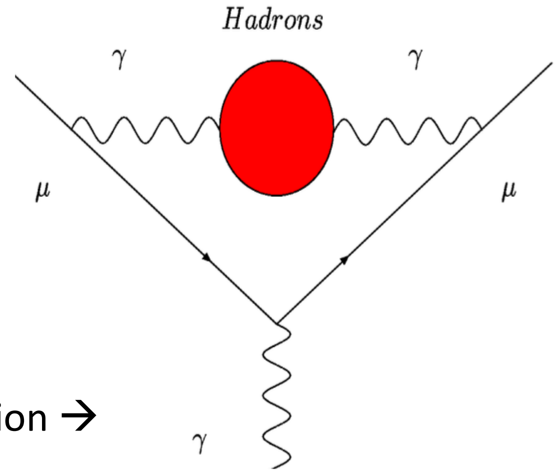
The Current Puzzle

Standard Model (SM) predictions

- The uncertainty in the SM prediction of a_μ is **entirely limited** by our knowledge of the hadronic leading order contribution a_μ^{HLO} $(a_\mu^{\mathrm{HVP,LO}})$



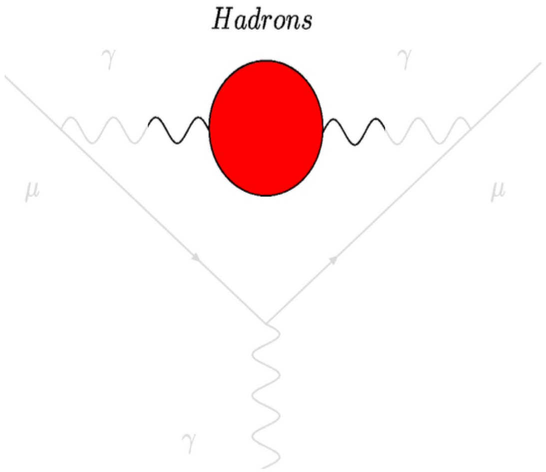
- HVP: hadronic vacuum polarization →
- HLbL: hardronic light-by-light

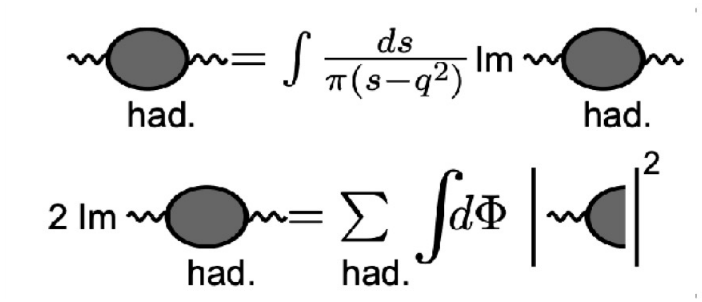


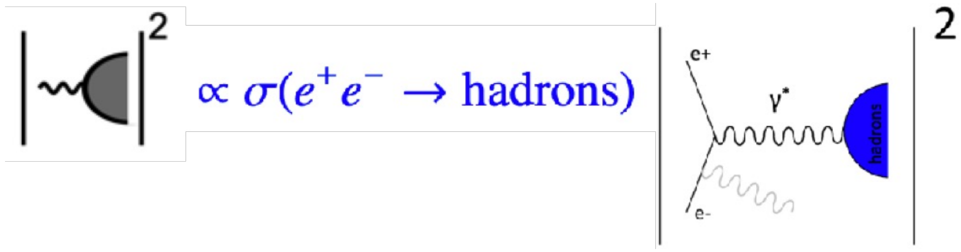
The Current Puzzle

Standard Model (SM) predictions

- The uncertainty in the SM prediction of a_μ is **entirely limited** by our knowledge of the hadronic leading order contribution a_μ^{HLO} $(a_\mu^{\mathrm{HVP,LO}})$
- Approaches (at low-E; pQCD doesn't work):
    1) Lattice QCD Method: Ab-initio calculation on lattice
    2) Dispersive Method: using $\sigma(e^+e^- \to$ hadrons) data



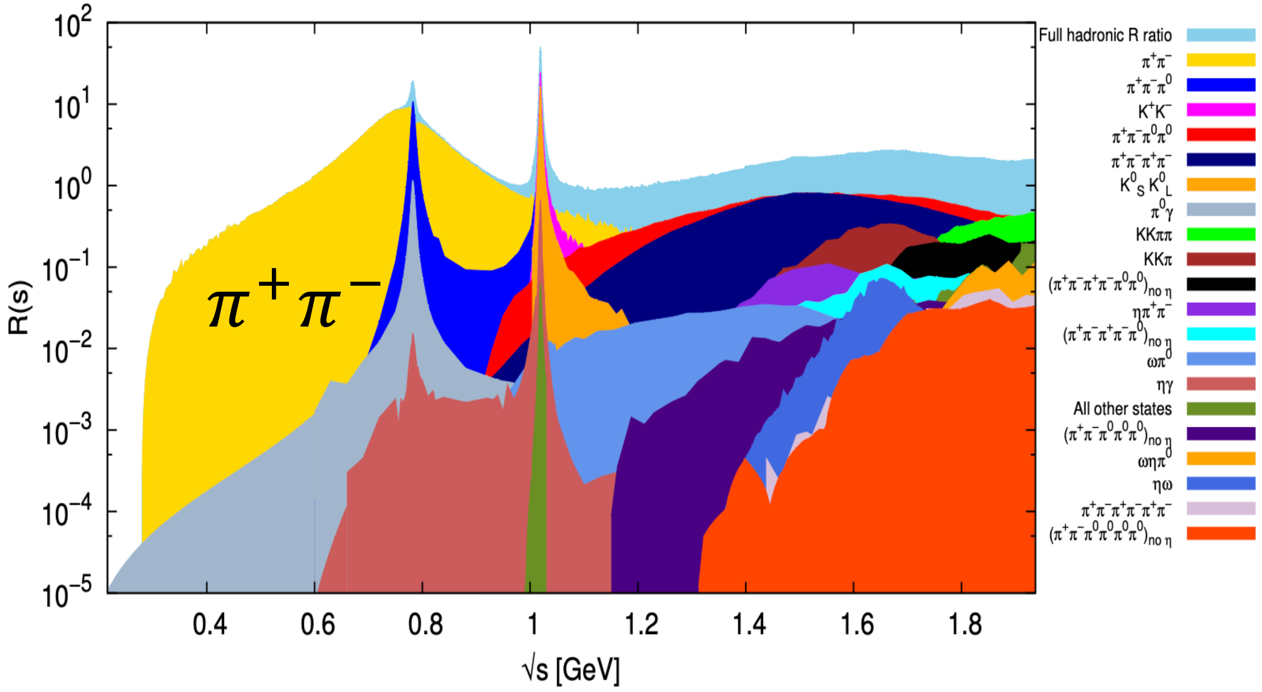


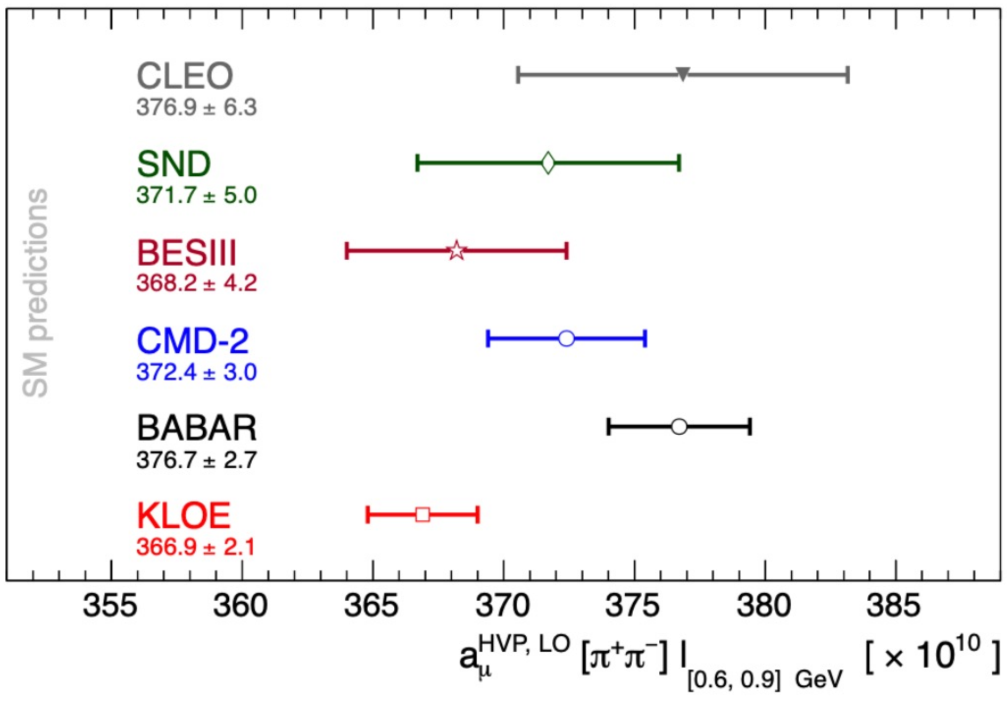


The Current Puzzle

Dispersive Method Using Collider Data

- $e^+e^- \to \pi^+\pi^-$ **channel** is the major source of uncertainty





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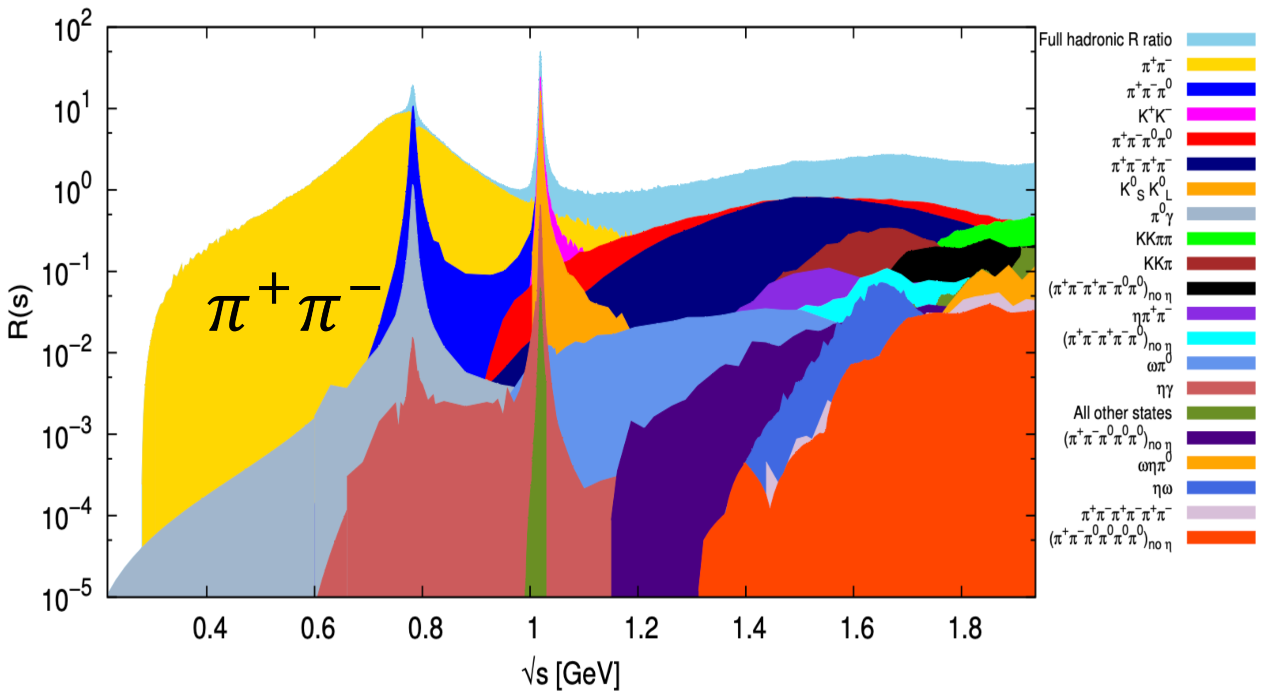

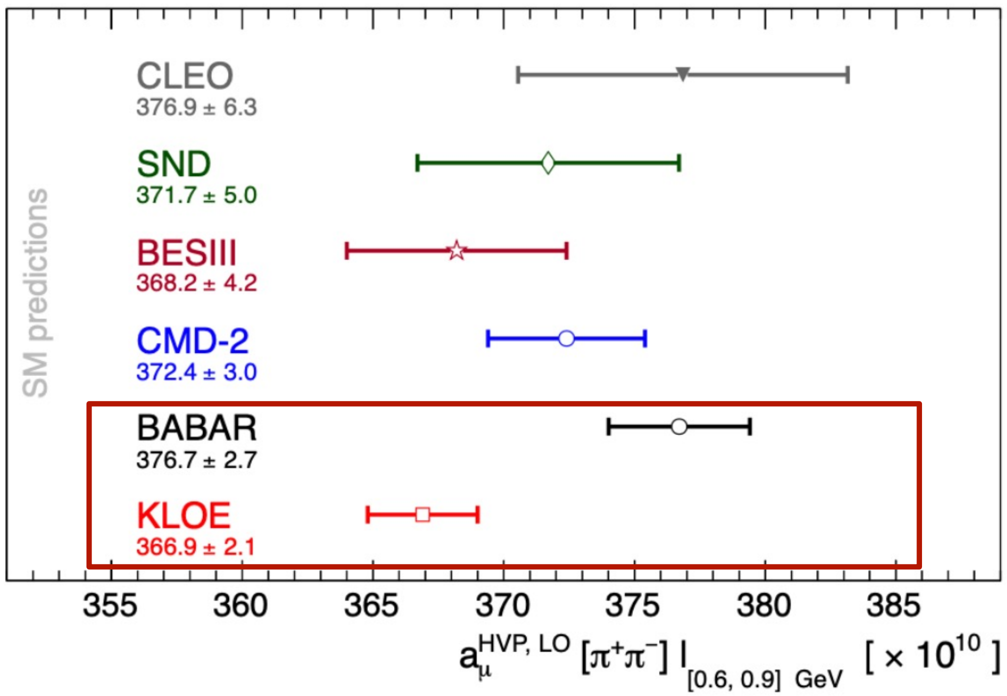

The discrepancy between **BABAR** and **KLOE** needs to be understood

The Current Puzzle

Dispersive Method Using Collider Data

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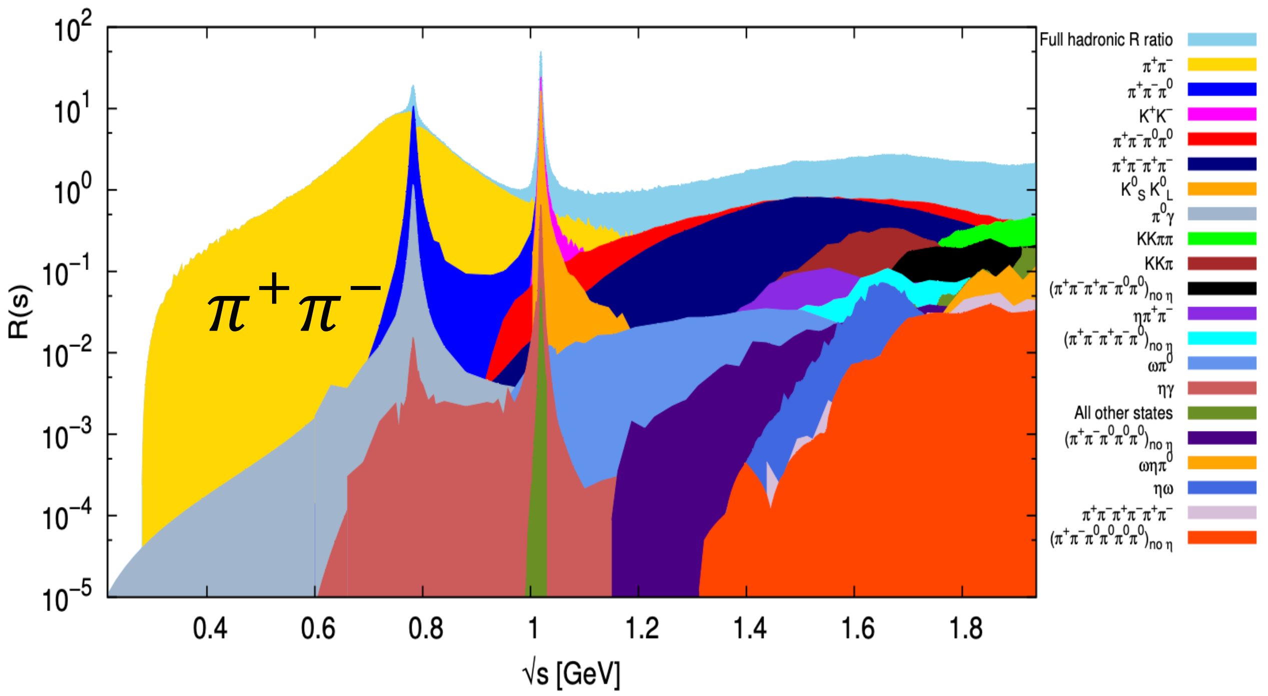

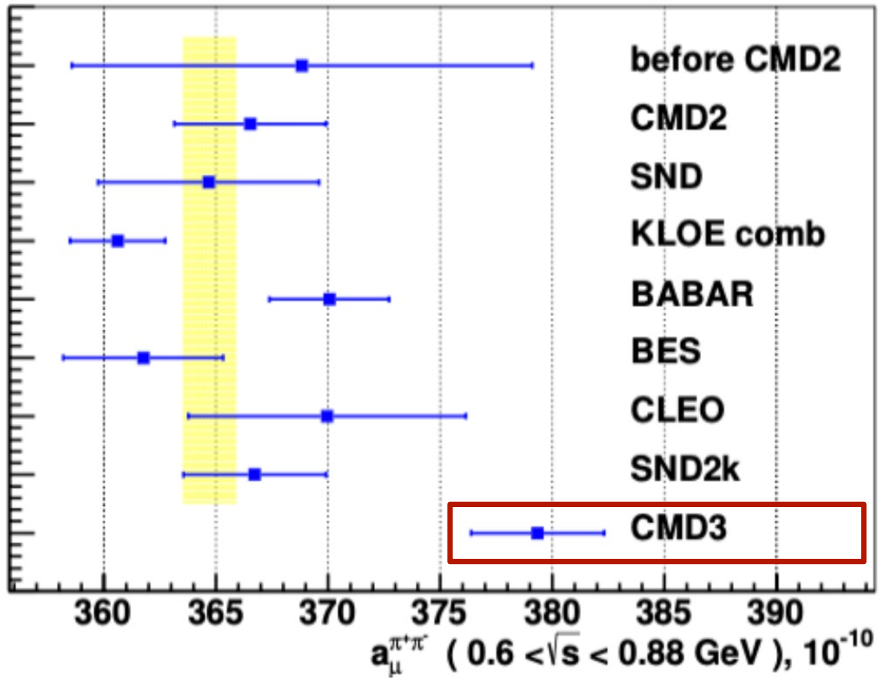

A **recent CMD-3 result** is different from all the previous data → more puzzles!

Outlook

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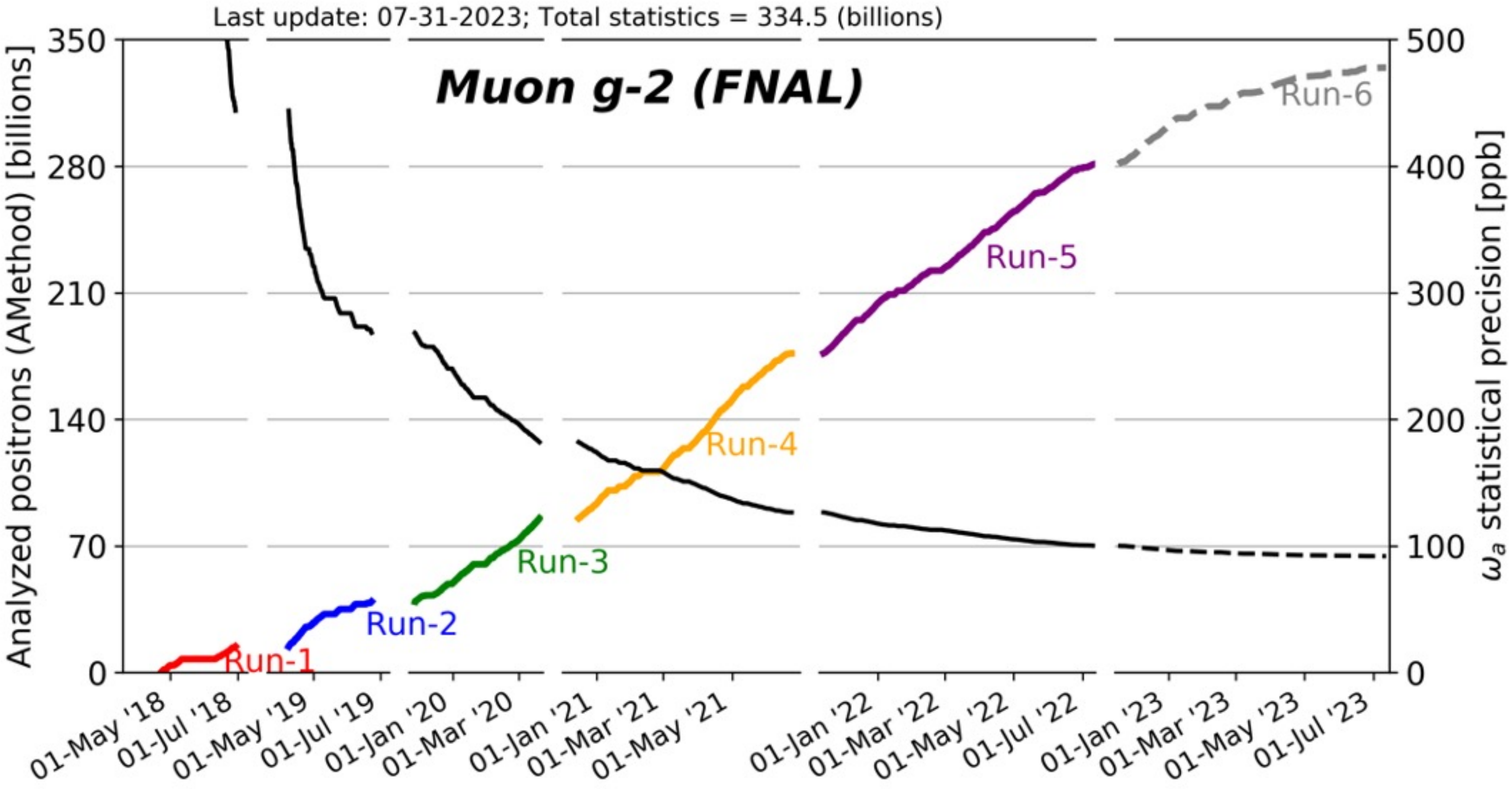
- Towards solving SM prediction ($a_\mu^{HVP,LO}$) inconsistencies:
  - **KLOE & BABAR** discrepancy (MC generator, …)
  - Outstanding **CMD-3** result
  - **MUonE** to better understand $a_\mu^{HVP,LO}$

Outlook

- Towards solving SM prediction ($a_{\mu}^{HVP,LO}$) inconsistencies:
  - **KLOE & BABAR** discrepancy (MC generator, …)
  - Outstanding **CMD-3** result
  - **MUonE** to better understand $a_{\mu}^{HVP,LO}$
- Experimental updates:
  - Final result from Fermilab (Run-4/5/6)
  - New Muon $g-2$/EDM experiment at J-PARC

Outlook

Final Result from Fermilab (Run-4/5/6)



- With data in Runs 4,5,6, we can **double our sensitivity again** and likely surpass our goal of **140ppm** total uncertainty
- Expected ~ 2025

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

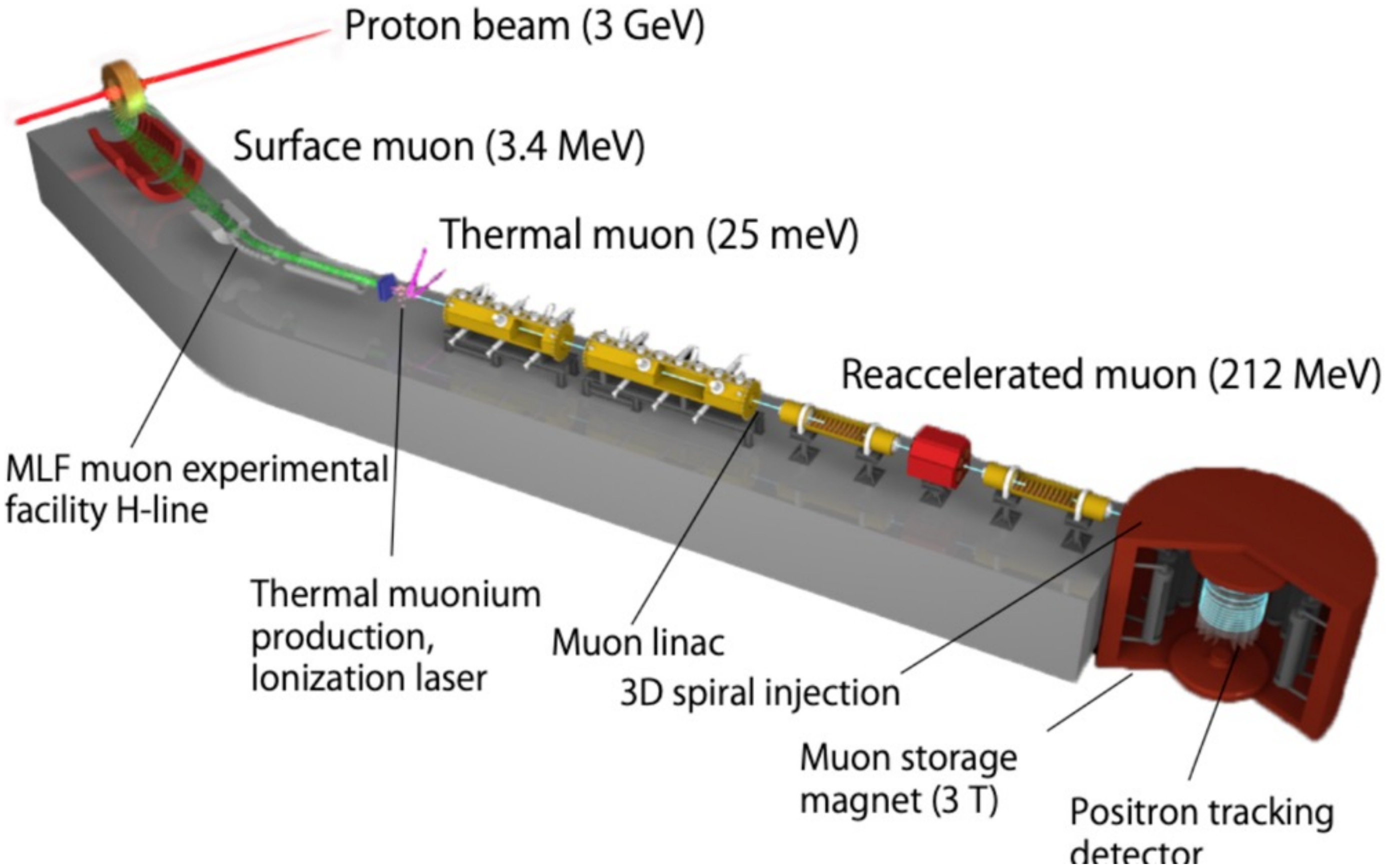
- Muon acceleration to 212 MeV

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)

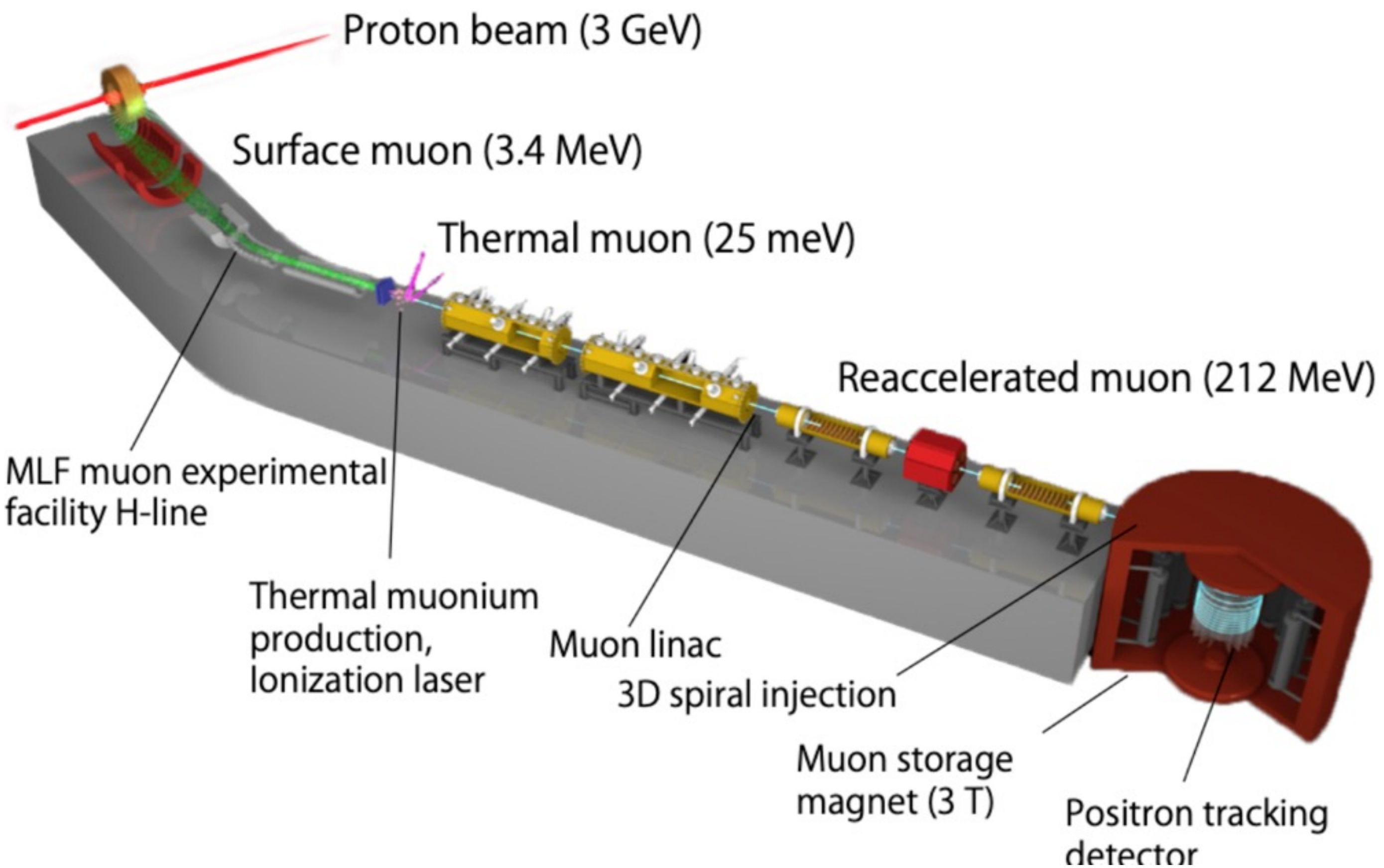
Muon EDM (sensitivity)

- $1.5 \times 10^{-21}\ e \cdot \mathrm{cm}$ (×70 better)

Schedule:

First data taking phase

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



Summary

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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.		

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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

Summary

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↕ Up to 5-sigma discrepancy

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Summary

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Precession Frequency	Beam Dynamics Corrections	Magnetic Field

Consistency Check; Blinding; Combination etc.

Up to 5-sigma discrepancy

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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)

Summary

UNIVERSITY OF LIVERPOOL

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

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

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- 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

Thank you!

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

Muon g-2 Collaboration

Muon g-2

UNIVERSITY OF LIVERPOOL

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

181 collaborators
33 Institutions
7 countries

China
- Shanghai Jiao Tong

Germany
- Dresden
- Mainz

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

Korea
- CAPP/IBS
- KAIST

Ru
- Budker/Novosibirsk
- JINR Dubna

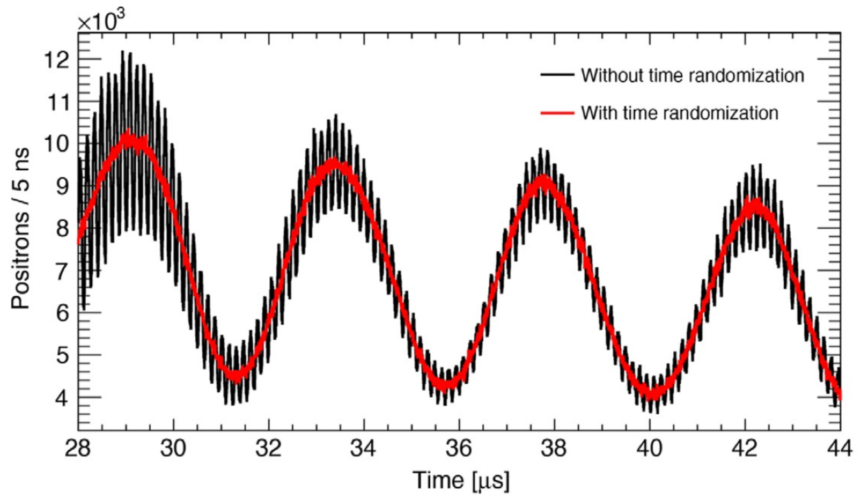
United Kingdom
- Lancaster/Cockcroft
- Liverpool
- Manchester
- University College London

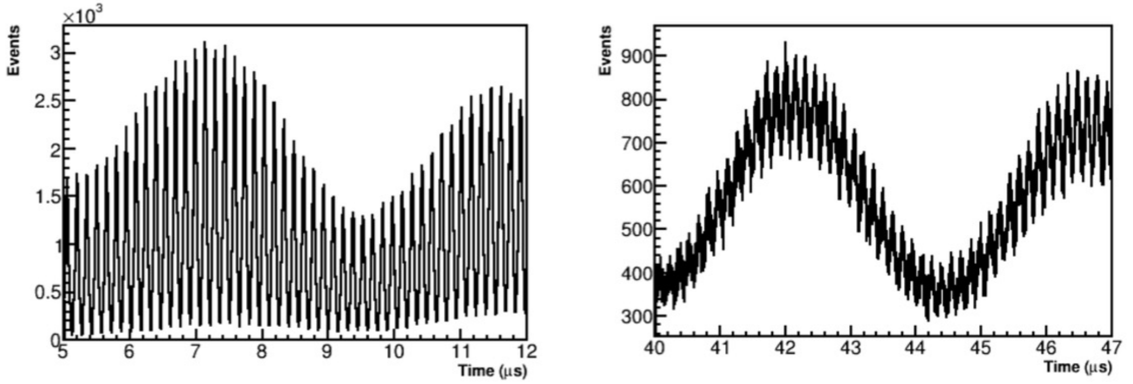
Muon g-2 Collaboration Meeting @ Elba, May 2019

Muon Precession Frequency

Fast Rotation Effect

- Each individual detector can only sample the muon beam at a particular phase of the cyclotron period.
- In terms of the debunching effect, this sampling implies that the positron data will contain a modulation at the cyclotron period (**149 ns << 4.3 us**) that decoheres over the measurement period.





(a) Fast rotation signal in the positron data for calorimeter 1, at early times when the signal is strong.

(b) Fast rotation signal in the positron data for calorimeter 1, at later times when the signal is reduced.

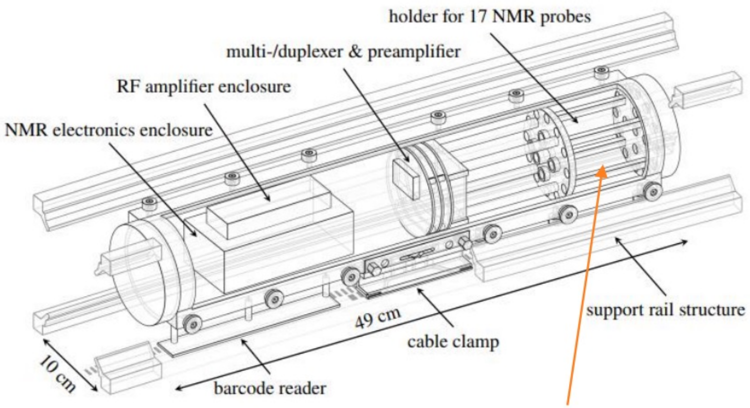
Magnetic Field Measurement

Absolute Calibration

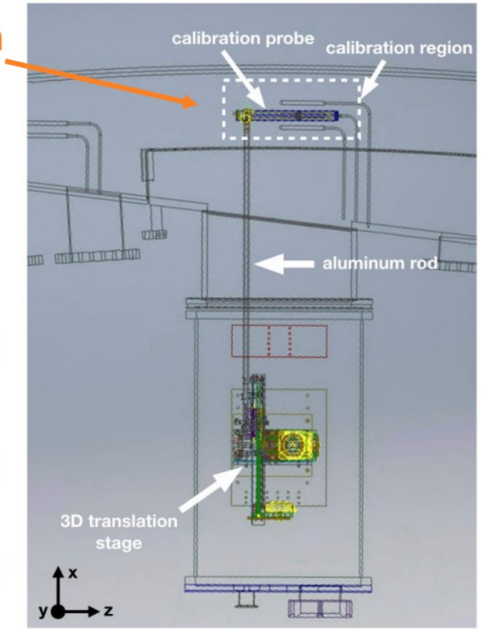
- Trolley and fixed NMR probes use petroleum jelly as the proton sample – low volatility
- Need to measure protons in H_2O (measurement standard) → calibration
- Trolley and cylindrical H_2O calibration probe switch places to repeatedly measure the same field in the same place. Calibration performed ~once per year.

Uncertainty
17 ppb

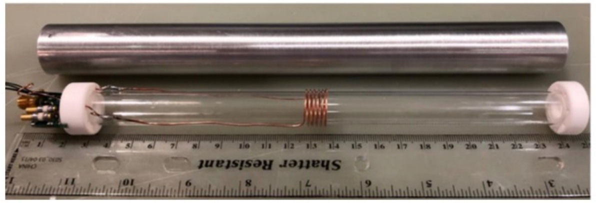
Calibration region



Trolley probes



Cylindrical H_2O probe



Spherical H_2O

Spherical ^3He

Cross-check with spherical probes
Uncertainty: 9 ppb

EPS talk by Saskia Charity, 21st August 2023

Muon $g-2$ Experiment at Fermilab

Experimental Principle

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

1. Measure ω_a^m: modulation of decay positron time spectrum
2. Measure B: proton nuclear magnetic resonance (NMR) $\longrightarrow$ $B = \frac{\hbar\omega_p}{2} \cdot \frac{\mu_e(\mathrm{H})}{\mu'_p(\mathrm{H_2O})} \cdot \frac{\mu_e}{\mu_e(\mathrm{H})} \cdot \frac{1}{\mu_e}$
3. Extract a_μ

A real-world equation:

Corrections from Beam Dynamics

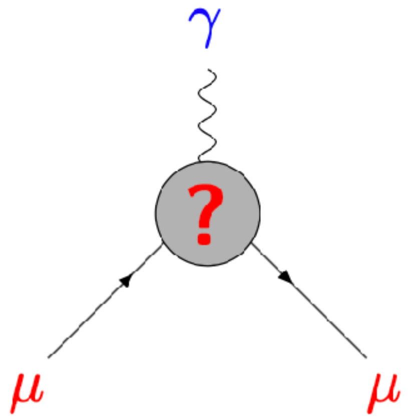
$$a_\mu = \frac{\omega_a^m}{\omega_p^m} \times \frac{(1 + C_e + C_p + C_{pa} + C_{dd} + C_{ml})}{(1 + B_k + B_q)} \times \left[\frac{g_e}{2}\frac{\mu'_p(\mathrm{H_2O})}{\mu_e(\mathrm{H})}\frac{\mu_e(\mathrm{H})}{\mu_e}\frac{m_\mu}{m_e}\right]$$

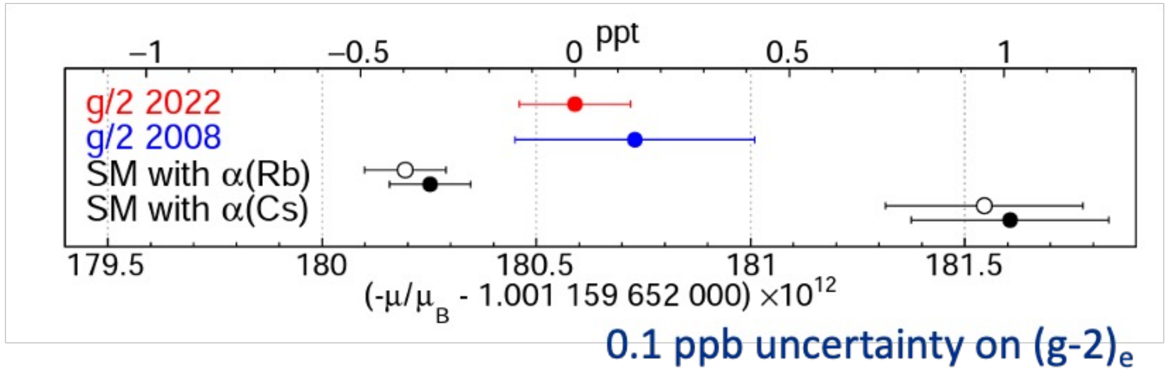
Corrections from Magnetic Field Transient

External constants precisely known (to 25 ppb)

Why Muon $g-2$

- Muon as a probe to **New Physics**
  - For any new physics $a_\mu = a_\mu^{\mathrm{SM}} + a_\mu^{\mathrm{NP}}?$
  - Its effects is enhanced by $a_\mu^{NP} \propto (\frac{m_l}{\Lambda_{NP}})^2$
  - Muon is more sensitive by a factor of $(\frac{m_\mu}{m_e})^2 \approx 4.3\times10^4$





Gabrielse, PRL 130, 071801 (2023)

- Trapped electrons allow the most precise measurement of g-2
- **A factor of 40** improved measurements on $(g\text{-}2)_e$ is needed to provide a compatible crosscheck with the muon (with a factor of 2 improved α measurement)

Beam Dynamic Corrections

UNIVERSITY OF LIVERPOOL

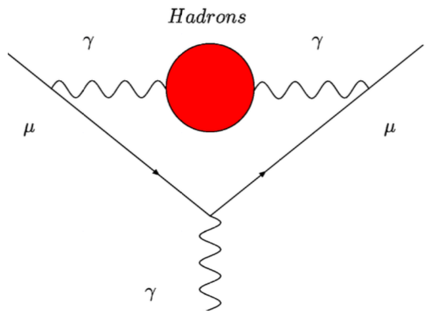
$$a_\mu = \frac{\omega_a^m}{\omega_p^m} \times \frac{(1 + C_e + C_p + C_{pa} + C_{dd} + C_{ml})}{(1 + B_k + B_q)} \times [\ldots]$$

C_e	**E-field** correction (**momentum dispersion** from magic γ)
C_p	**Pitch correction** from muon's small vertical momentum component
C_{pa}	**Phase acceptance** correction by decay-position dependence of positron phase
C_{dd}	**Differential decay** correction as high momentum muons have longer lifetime
C_{ml}	**Muon loss** correction from initial phase-momentum correlation in muons

MUonE Experiment

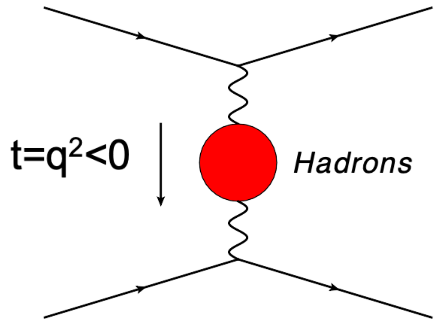
A New Approach towards a_μ^{HVP} with running of $\Delta\alpha_{\mathrm{had}}$

- The dispersive approach to compute $a_\mu^{\mathrm{HVP,LO}}$ is via the **time-like** formula:



$$a_\mu^{\mathrm{HVP}} = \left(\frac{\alpha m_\mu}{3\pi}\right)^2 \int_{m_{\pi^0}^2}^{\infty} ds \frac{R_{\mathrm{had}}(s)\boldsymbol{K(s)}}{s^2}, \quad K(s) = \int_0^1 dx \frac{x^2(1-x)}{x^2 + (1-x)(s/m_\mu^2)}$$

- Alternatively, exchanging the x and s integrations → **space-like** formula:



$$a_\mu^{\mathrm{HVP}} = \frac{\alpha}{\pi}\int_0^1 dx\,(1-x)\Delta\alpha_{\mathrm{had}}[t(x)], \quad t(x) = \frac{x^2 m_\mu^2}{x-1} < 0$$

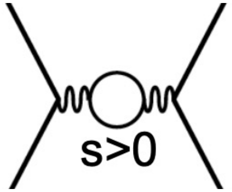
- $\Delta\alpha_{\mathrm{had}}$ is the hadronic contribution to the **running α** (electromagnetic coupling constant)

MUonE Experiment

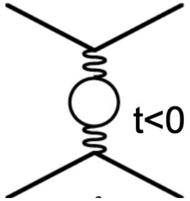
Running of $\Delta\alpha_{\text{had}}$: Time-like vs Space-like

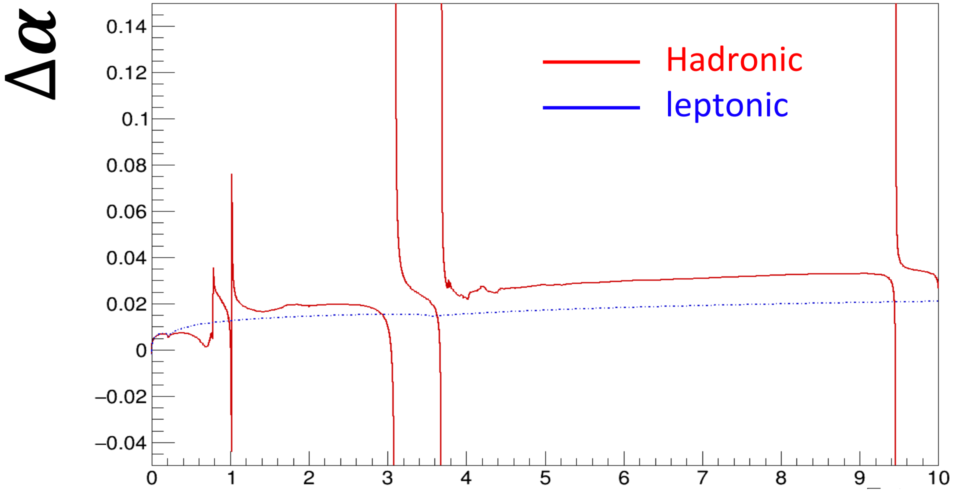
$$\Delta\alpha_{had}^{(5)}(q^2) = -\frac{\alpha}{3\pi}\, q^2 \int_{m_{\pi^0}^2}^{\infty} ds' \frac{R(s')}{s'(s'-q^2)}$$

- **Time-like:** characterized by the opening of resonances

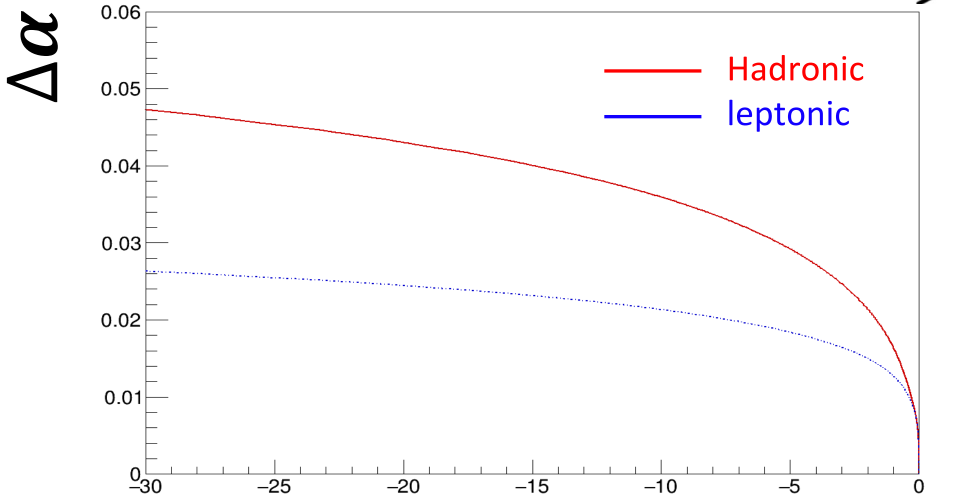


- **Space-like**: very smooth behaviour





$E = \sqrt{s}$ [GeV]

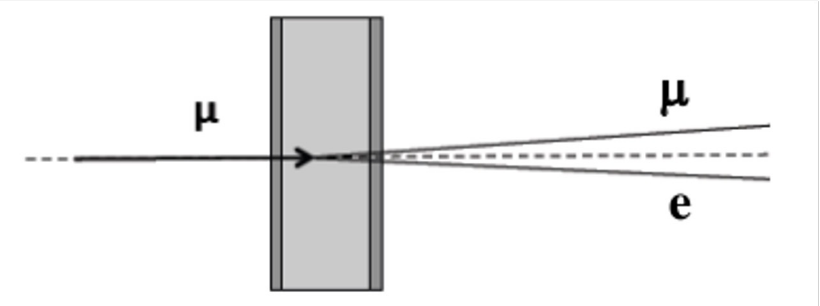


$E = \sqrt{-t}$ [GeV]

MUonE Experiment

$\Delta\alpha_{\text{had}}$ via Muon-electron Scattering

- $\Delta\alpha_{\text{had}}[t(x)]$ can be extracted from the shape of the differential cross-section of muon-electron scattering $\mu^+ e^- \rightarrow \mu^+ e^-$



$$R_{\text{had}} = \frac{d\sigma_{\text{data}}(\Delta\alpha_{\text{had}})}{d\sigma_{\text{MC}}(\Delta\alpha_{\text{had}} = 0)} \sim 1 + 2\Delta\alpha_{\text{had}}(t)$$

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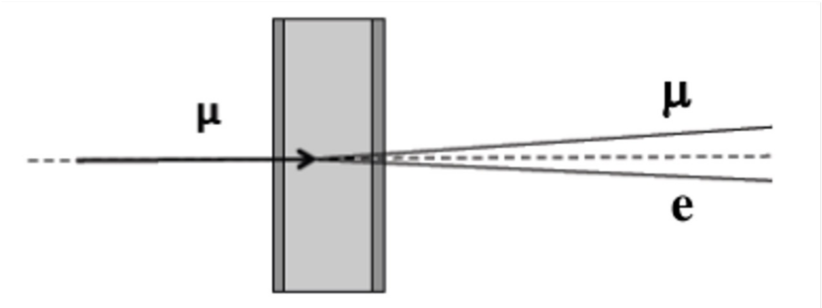

Shape of this is measured

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The NNLO differential cross section from **theoretical calculation**

To be determined in this experiment

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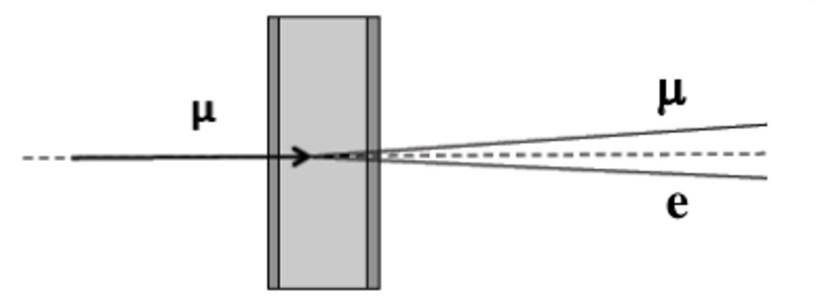

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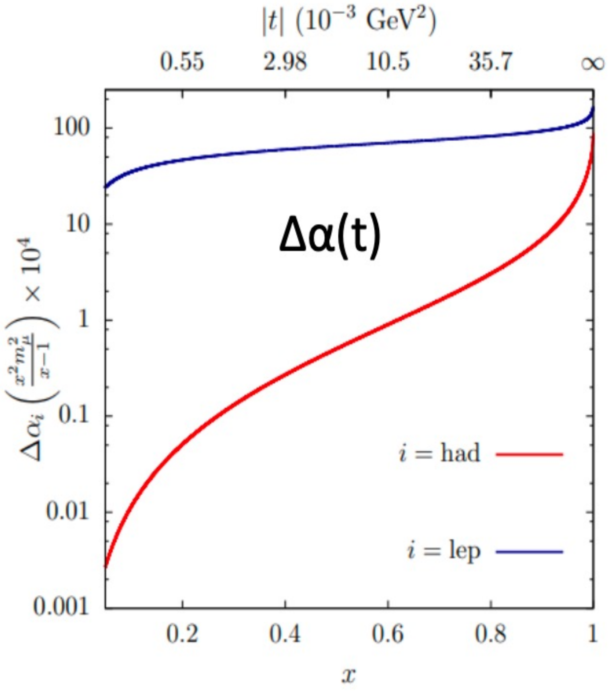

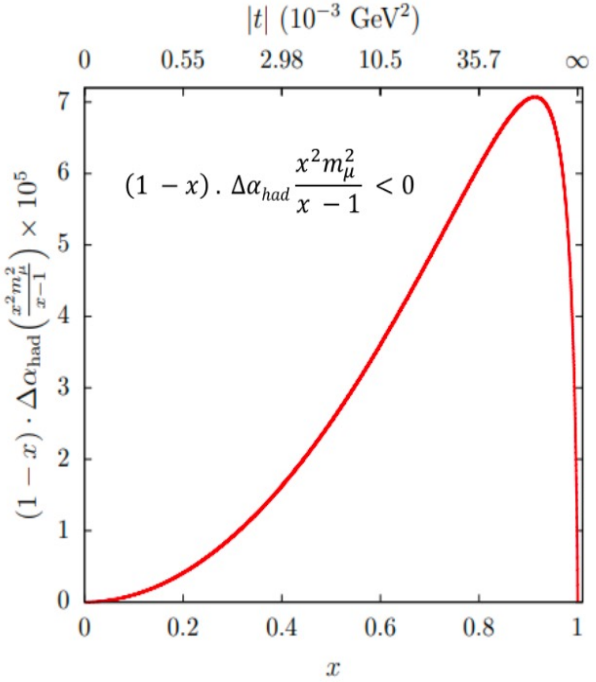

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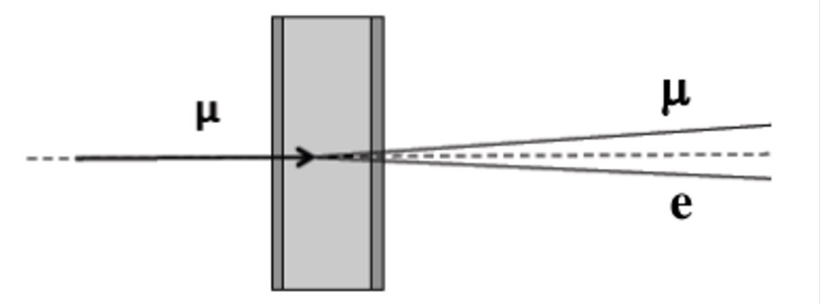

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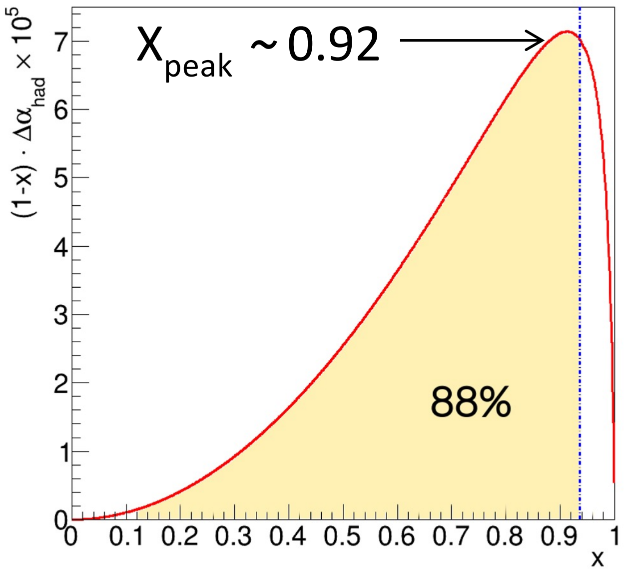
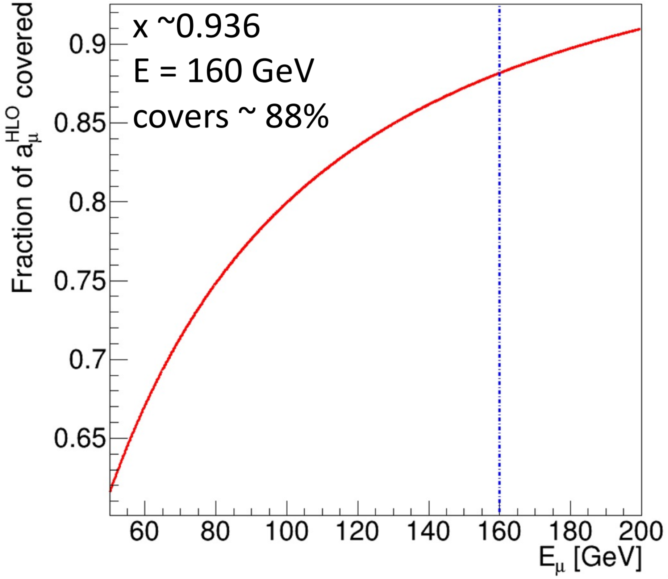
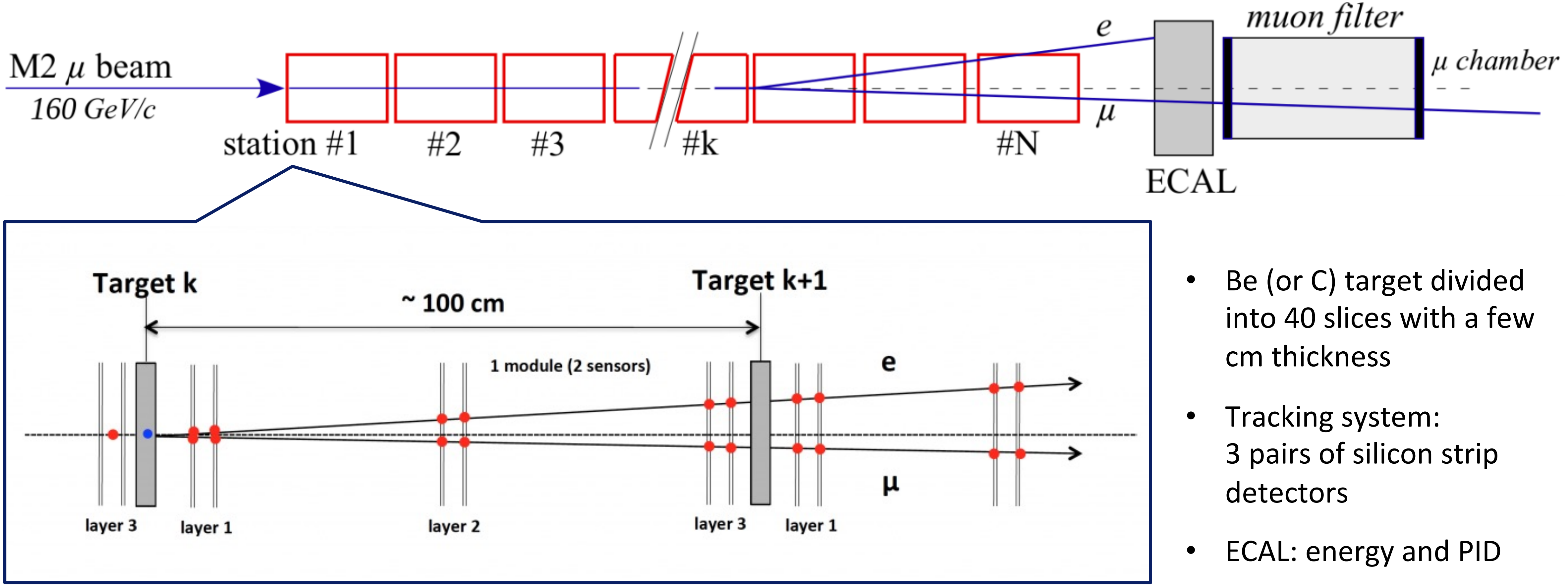




MUonE Experiment

Setup Overview



- Be (or C) target divided into 40 slices with a few cm thickness
- Tracking system:
  3 pairs of silicon strip detectors
- ECAL: energy and PID

MUonE Experiment

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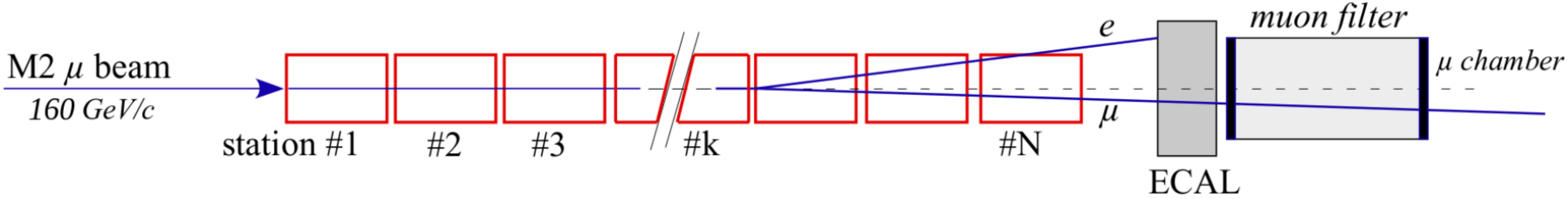

- Correlation between muon and electron angles allows to select elastic events and reject background ($\mu\ N \rightarrow \mu\ N\ e^+e^-$).
- Boosted kinematics:
  - Single detector to cover full acceptance
  - $\theta_\mu < 5$ mrad, $\theta_e < 32$ mrad.