Results and Perspectives on the Muon g-2 Experiment at Fermilab

A Muon g-2 storm seems to be brewing

Marco Incagli, INFN-Pisa

CERN seminar

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What is *"g-2"* ?

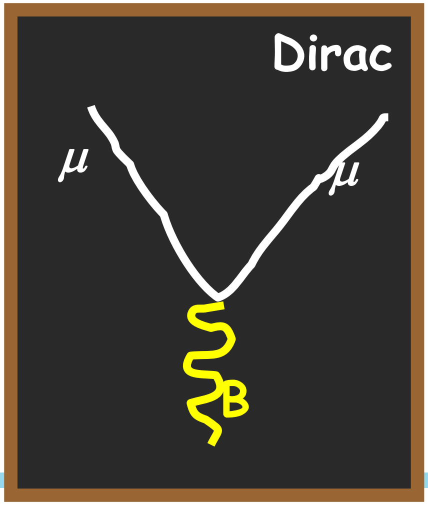
$$\vec{\mu}_p = -g_p \frac{e}{2m_p} \vec{S}$$

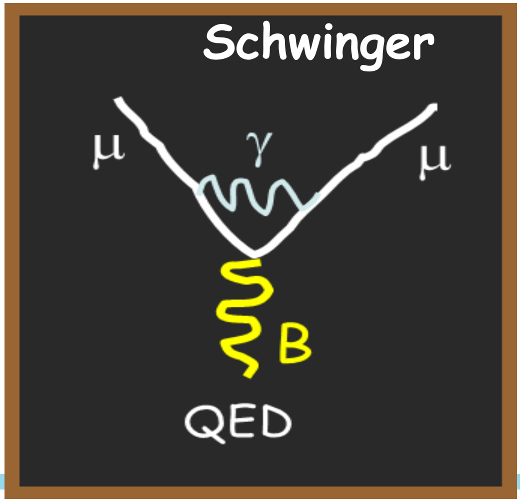
$$a_p = \frac{g_p - 2}{2}$$

- ***g_P*** : proportionality constant between spin and magnetic moment for particle P
- ***a_P*** : magnetic anomaly
- ***a_P*** = 0 at tree level (*purely Dirac particle*)

- Using modern language, the term (g-2)/2 reflects the magnitude of the Feynmann diagrams beyond leading order

a = *0* + $\alpha/2\pi$ + ...





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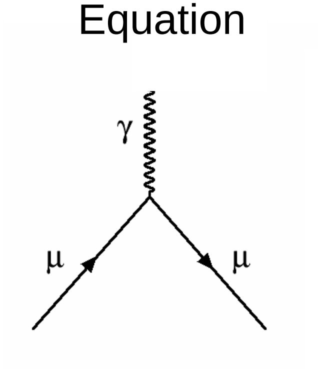
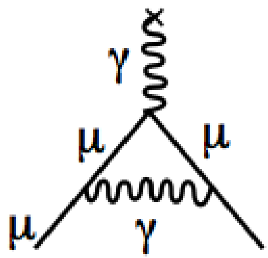
Standard Model Components of g_μ

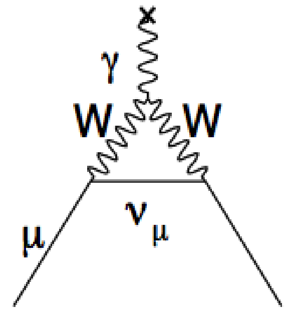
Dirac Equation



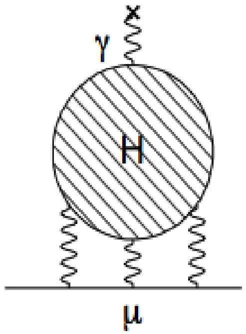
QED



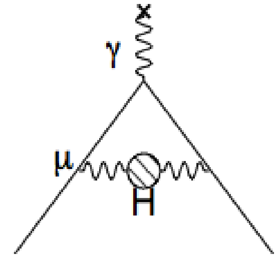
Electroweak



Hadronic Light-by-Light



Hadronic Vacuum Polarization



$$a_\mu = 0 \quad + 0.00116584719 \quad + 0.00000000154 \quad +0.00000000092 \quad +0.00000006845)$$

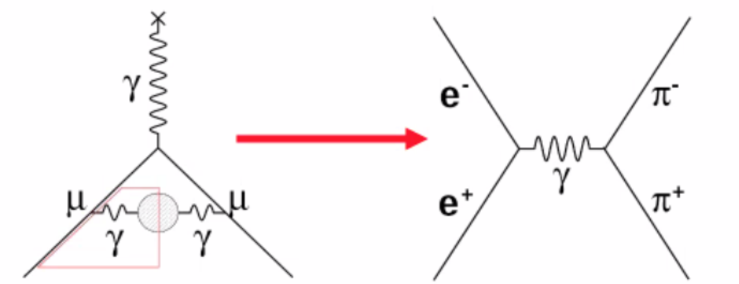
- **QED** dominates the value itself
- Uncertainty is dominated by **QCD**, in particular by the Hadronic Vacuum Polarization (**HVP**) term
- SM values taken from the **Muon g-2 Theory Initiative**
- Last compilation in **2020**:

White Paper: Phys. Rept. 887 (2020) 1-166
https://doi.org/10.1016/j.physrep.2020.07.006

https://muon-gm2-theory.illinois.edu/

HVP Calculation: Dispersive (e^+e^-) Method

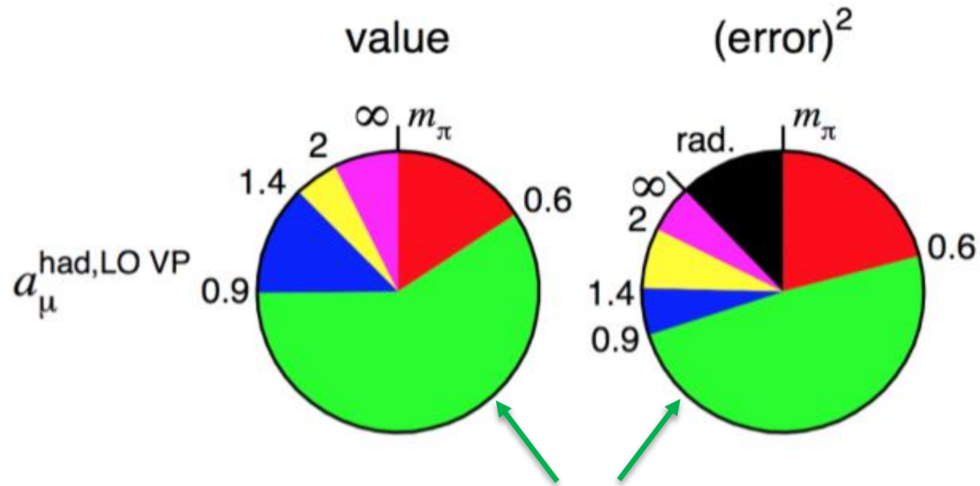
$$a_m^{HLO} = \frac{1}{4p^3}\int_{4m_p^2}^{\infty} s_{e^+e^-\to hadr}(s)K(s)\,ds$$



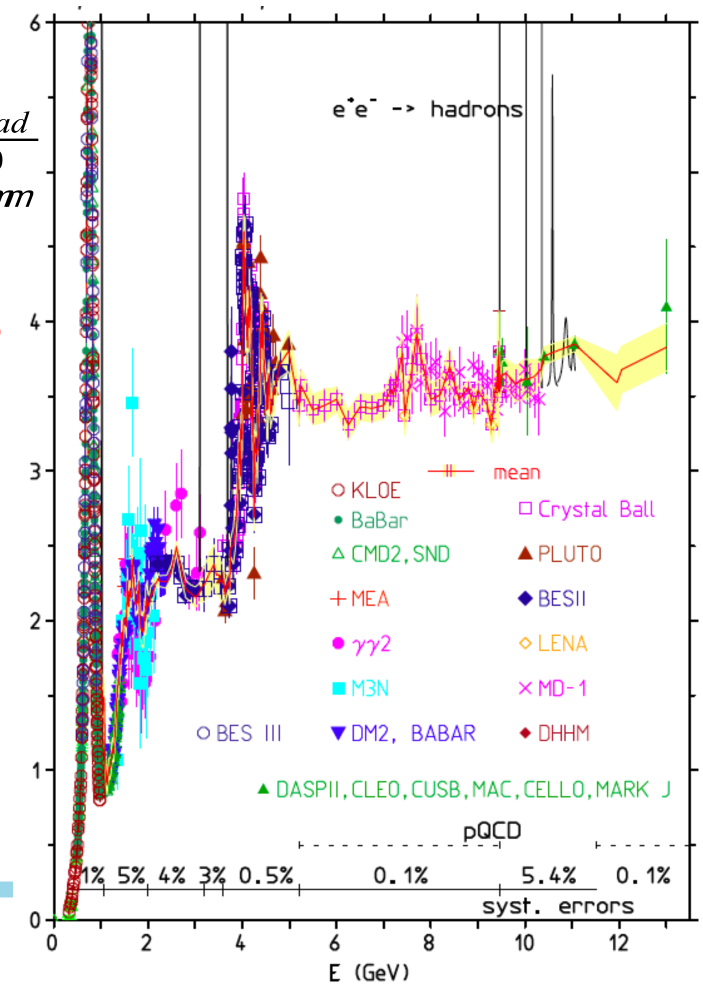
- Kernel function: $K(s) \propto {}^{1}/_{s}$
- Due to the 1/s term, the low energies most important

$$R = \frac{s_{had}}{s^0_{mm}}$$

R-ratio

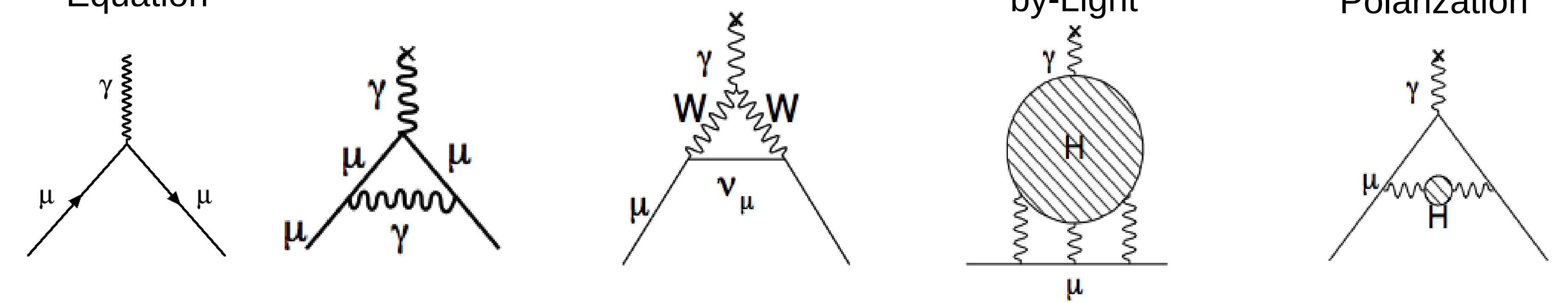


rho resonance region



Standard Model Components of g_μ

Dirac Equation | QED | Electroweak | Hadronic Light-by-Light | Hadronic Vacuum Polarization

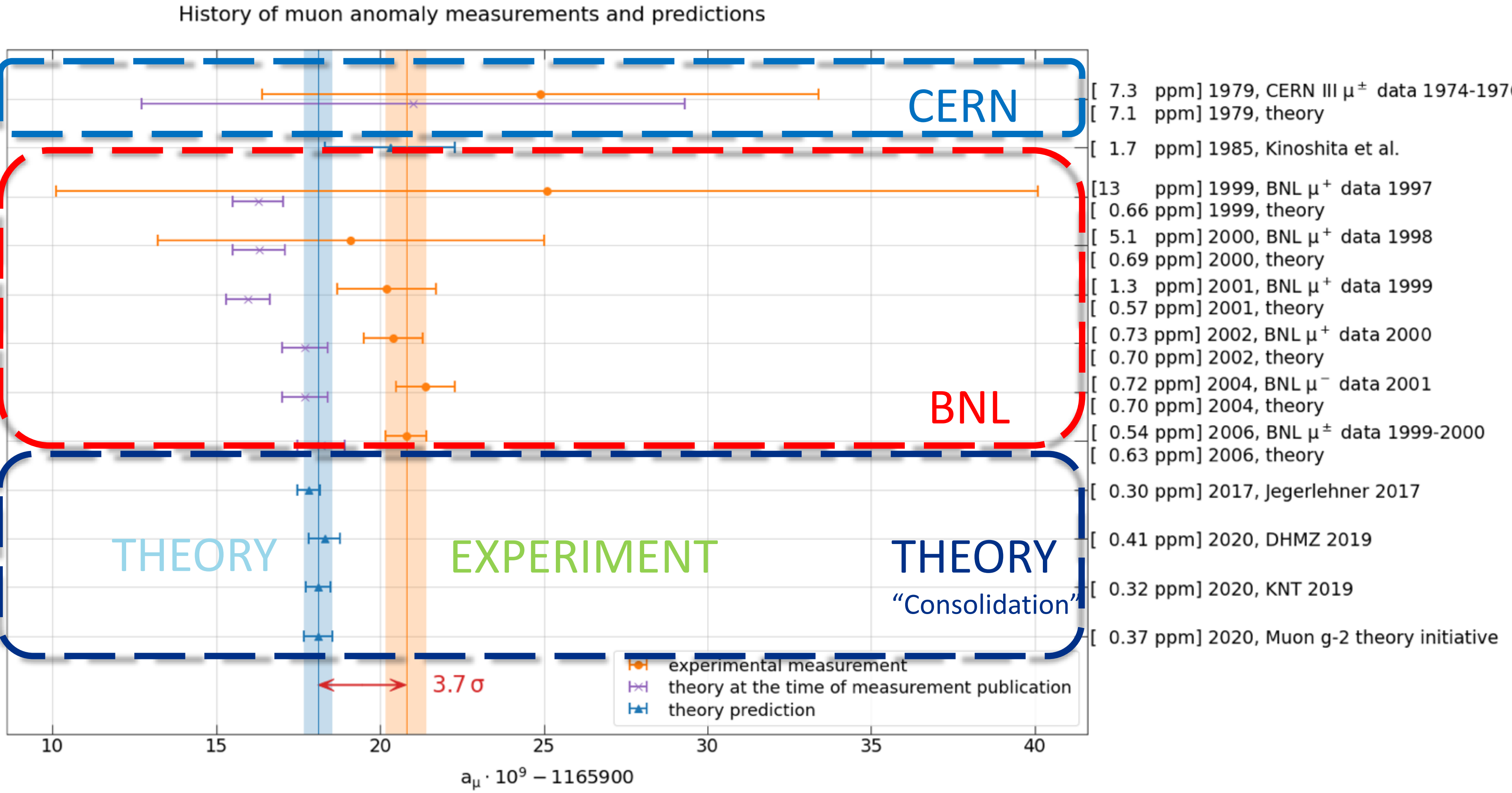


$$a_\mu = 0 \quad + 0.00116584719 \quad + 0.00000000154 \quad + 0.00000000092 \quad + 0.00000006845)$$

- Everything in SM needs to be included here: but are we sensitive to some **physics beyond the SM**?
- We can compare **experimental & predicted** values and ask:

"Is there some New Physics in our experiment that isn't in the Standard Model?"

A rich history of g-2 Theory and Experiment

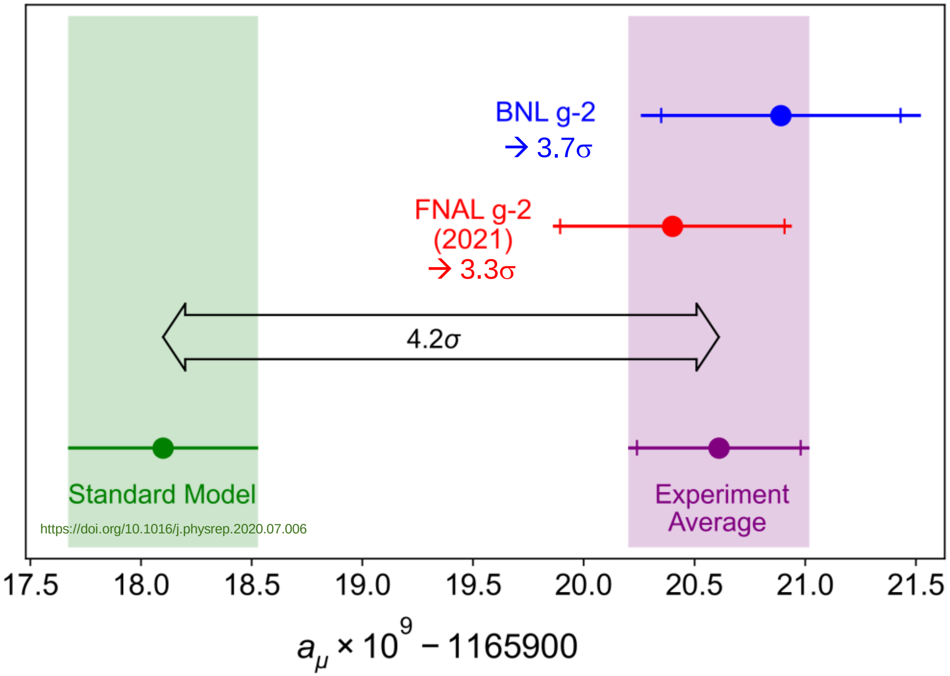


Situation before Fermilab exp.: tension between theory and experiment

Fermilab Run-1 Result (2021)

- BNL E821 (2004) disagreed with SM prediction:

https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.126.141801



- 7th April 2021, we released our **Run-1** result
- Using only 5% of our data, we **confirmed BNL** value
- FNAL+BNL average stood **4.2σ** from Theory Initiative White Paper (2020)

- Today's talk is mostly about the new experimental result
- There have also been some new results from the SM prediction side of the plot…

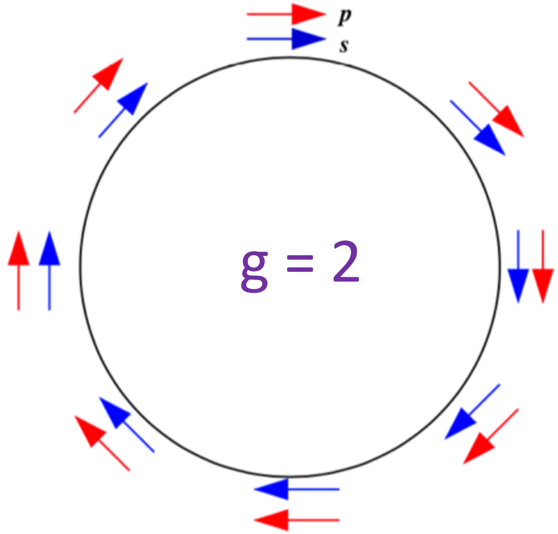
The Fundamental Experimental Principle

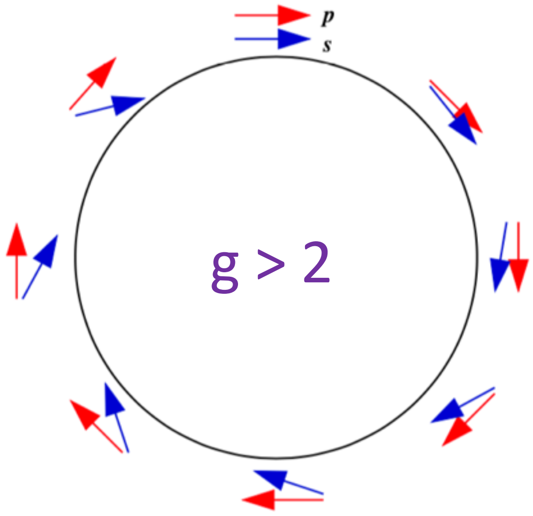
- Difference between spin precession and cyclotron revolution for a muon (charged particle with spin) in a magnetic field*:

$$\omega_a = \omega_s - \omega_c = g\frac{e}{2m}B - \frac{e}{m}B = \frac{g-2}{2}\frac{e}{m}B = a_\mu\frac{e}{m}B$$

*__s__ and __p__ are assumed to be in a plane perpendicular to __B__

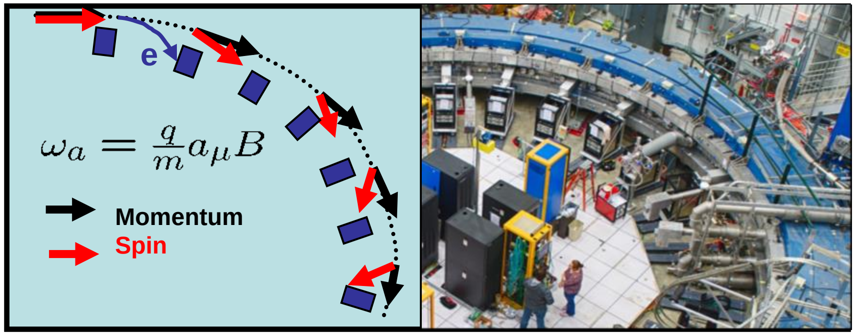
- simple classical calculation
- the relativistic approach provides the same result





From single muon to *muon beam*

- The expression is more complicated when you add in *E*-field focusing and out of plane oscillations



- **The motion is very nearly planar and the momentum is very nearly the ideal one, but both effects are not perfect and require corrections**

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

0 if "in plane"

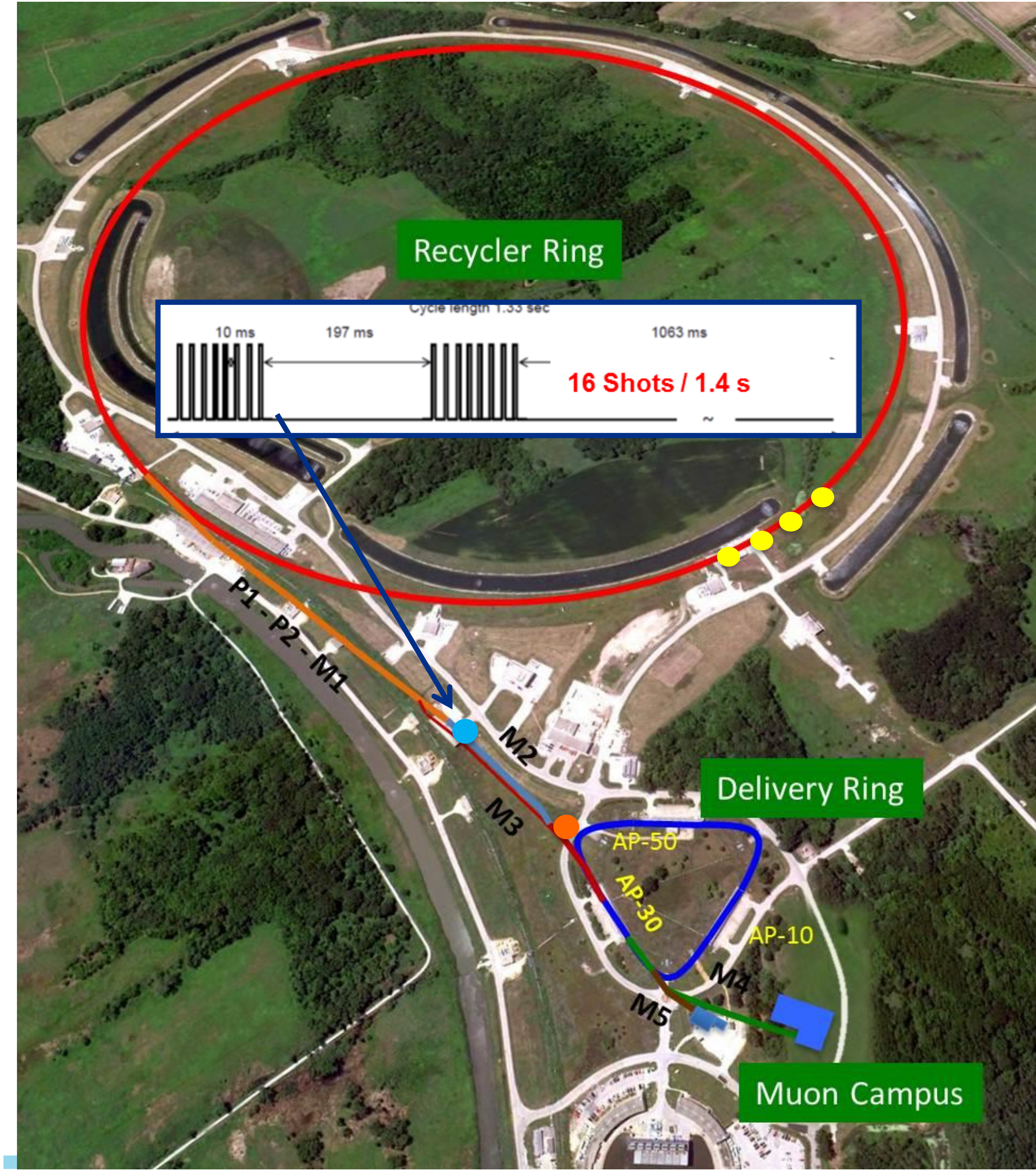
Term cancels at 3.094 GeV/c, the "Magic γ"

The *Cern3 g-2* experiment

- Emiliio Picasso view of the *Cern3 g-2* experiment

Video from CERN CDS Video Service
https://videos.cern.ch/record/43113

Fermilab

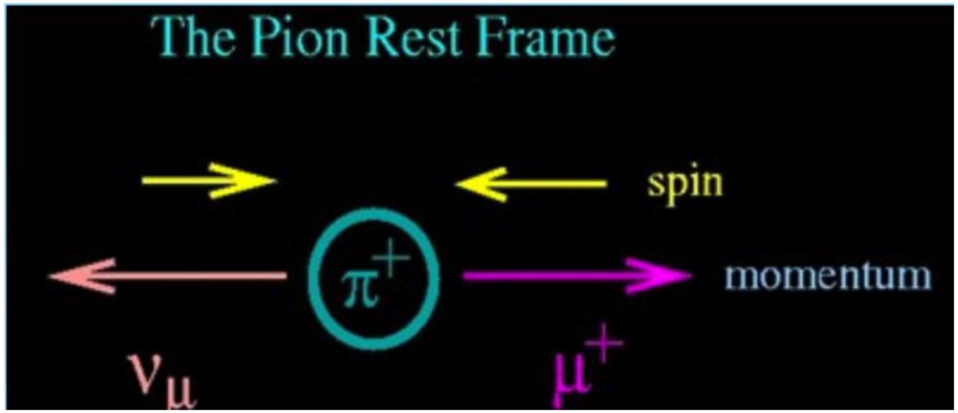


Creating the Muon Beam for g-2:

- 8 GeV protons into the Recycler
- Target for pion production
- Long FODO channel to collect $\pi \rightarrow \mu\nu$
- pions decay in ~2km channel
- μ enter storage ring

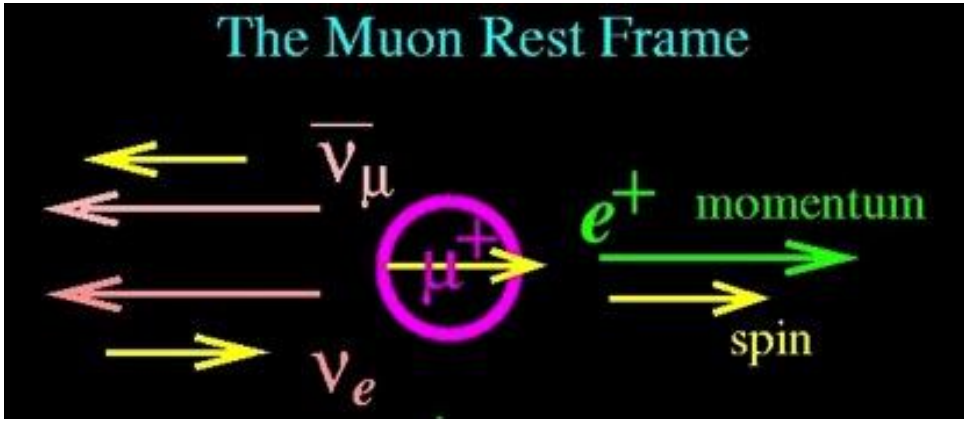
How do we measure the spin direction?

- Use V-A structure of weak decays to build a polarized beam...



spin anti-parallel to muon momentum

- ... and to measure the muon polarization looking for **energetic positrons**



high momentum positrons emitted preferentially along muon spin

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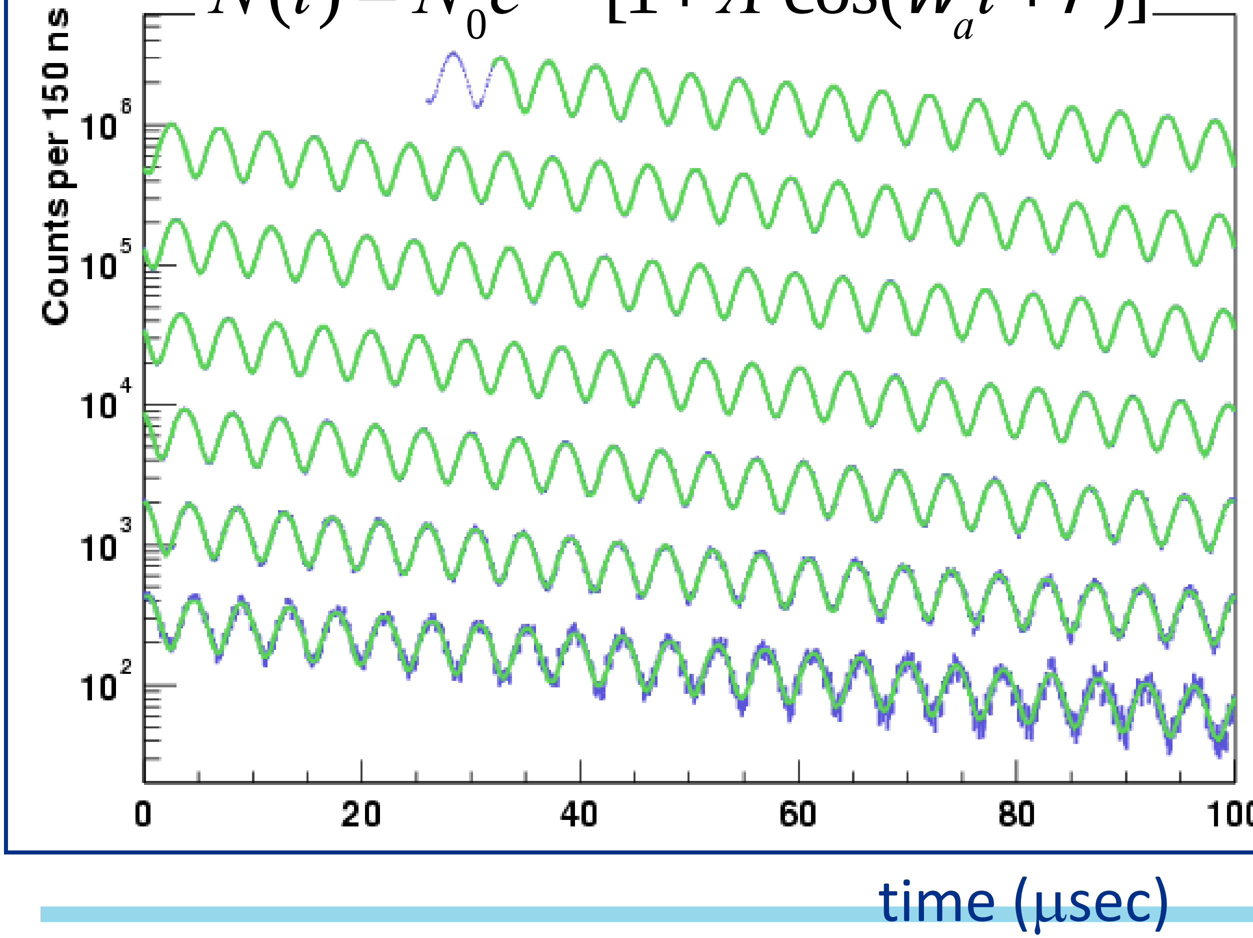
Measuring the spin precession

- The number of observed positrons above a threshold energy oscillates with the $\omega_a/2\pi$ frequency due to spin precession

$$N(t) = N_0 e^{-t/t}[1 + A\cos(w_a t + f)]$$



- exponential decay modulated by spin precession
- *note that the x-axis "wraps up" every 100 μsec for a total of ~700 μs → ~10 muon lifetimes*

Extracting a_μ(simplified)

$$\boldsymbol{\omega_a = a_\mu\,(e/m)\,B} \;\rightarrow\; \boldsymbol{a_\mu = \omega_a/B\,(m/e)}$$

by expressing B in terms of the (shielded) proton precession frequency:
$(B = \hbar\omega'_p/2\mu'_p)$:

$$a_\mu = \frac{\omega_a}{\tilde{\omega}'_p} \cdot \frac{\mu'_p}{\mu_e}\frac{m_\mu}{m_e}\frac{g_e}{2}$$

External data

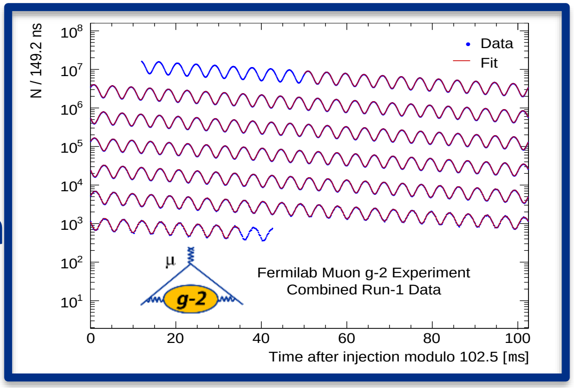
$$R'_\mu = \frac{\omega_a}{\tilde{\omega}'_p}$$

ratio of muon to proton precessions in the same magnetic field

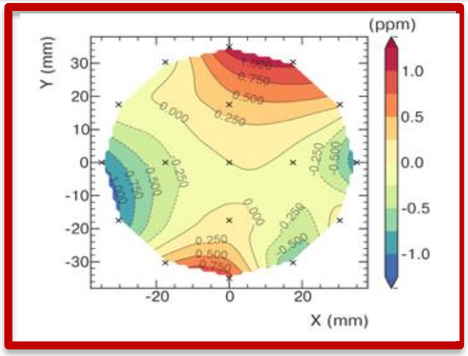
$\tilde{\omega}'_p$ = (shielded) Proton angular velocity **weighted for the muon distribution**

The key ingredients

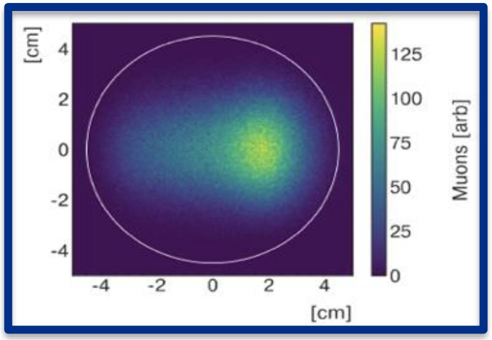
ω_a
muon precession



$$R'_\mu = \frac{\omega_a}{\widetilde{\omega'}_p} \sim \frac{\omega_a}{\omega'_p \cdot M(x,y,\varphi)}$$



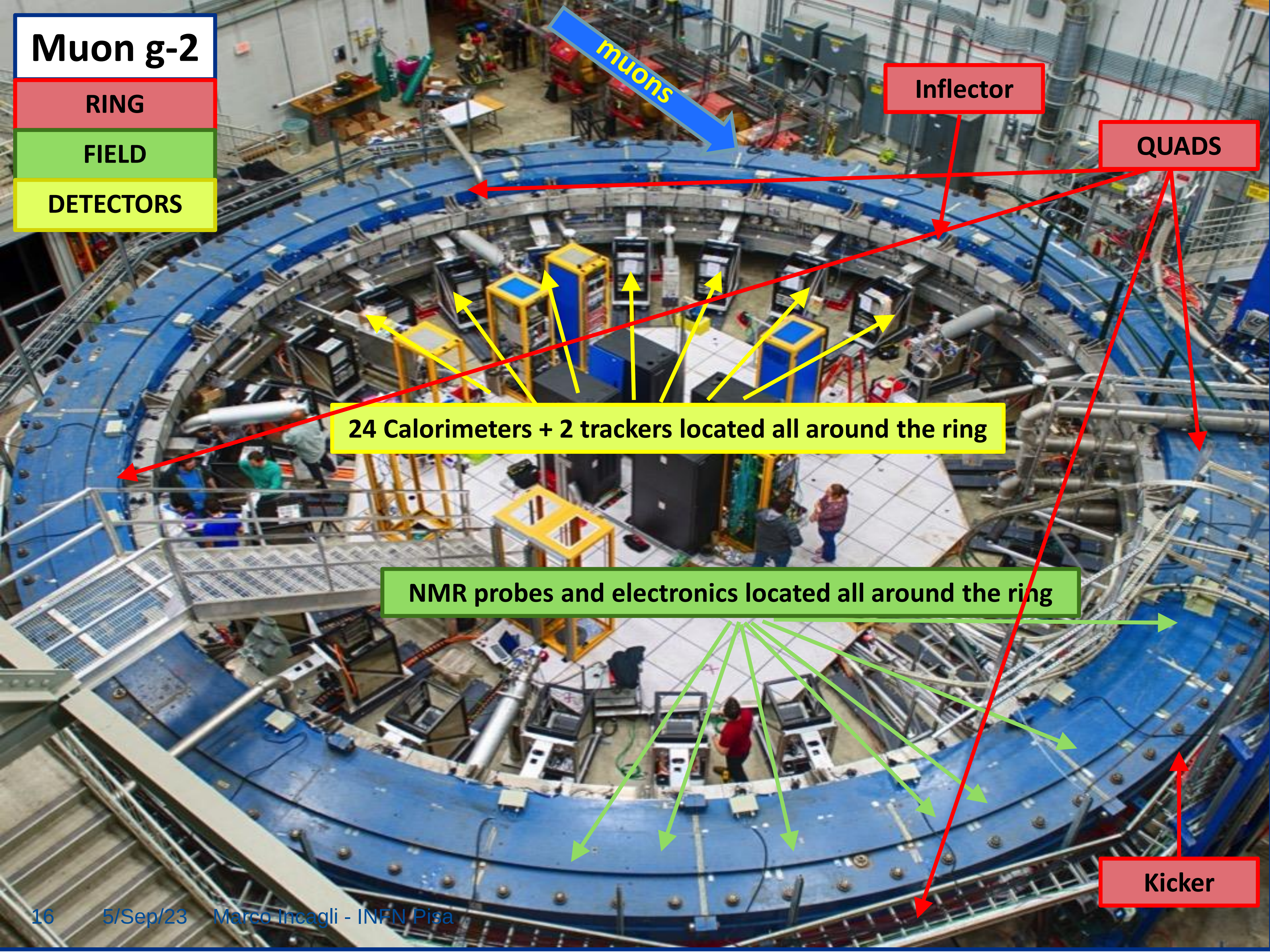
ω'_p
proton precession



$M(x, y, \varphi)$
muon distribution

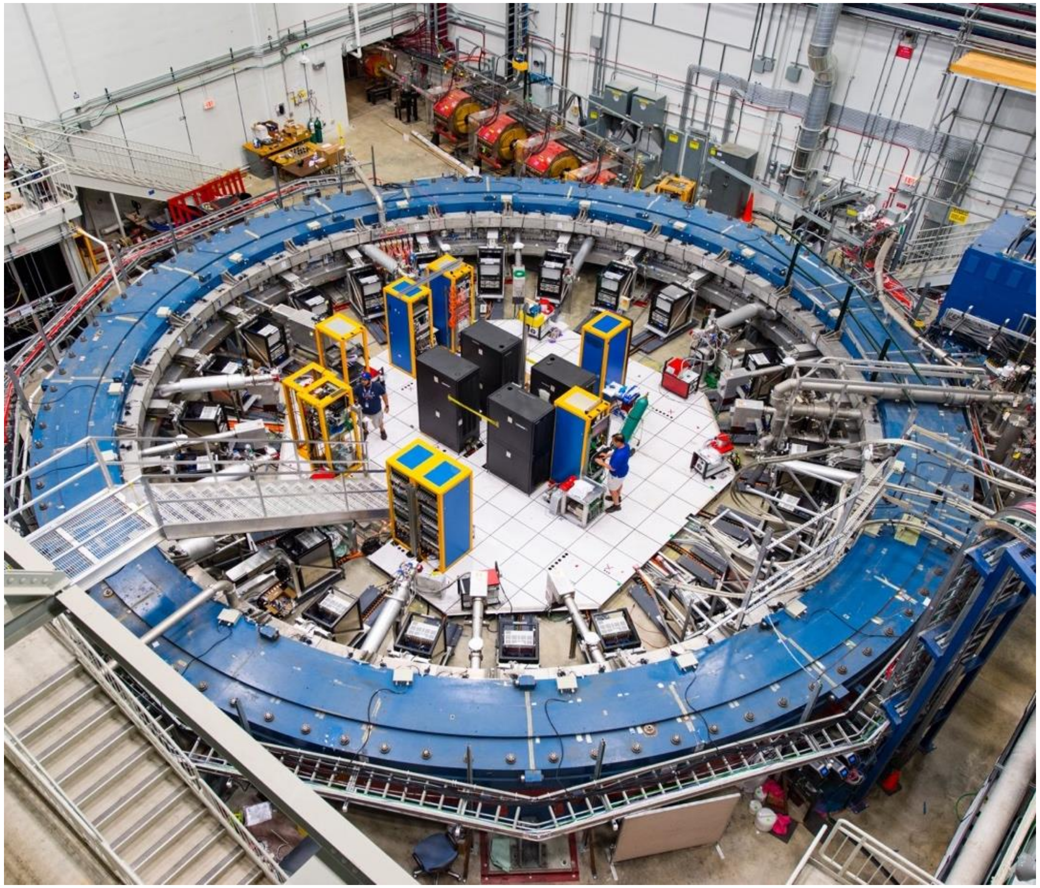
- $\widetilde{\omega'}_p = \omega'_p \cdot M(x, y, \varphi)$ magnetic field weighted by the muon distribution in the Storage Ring

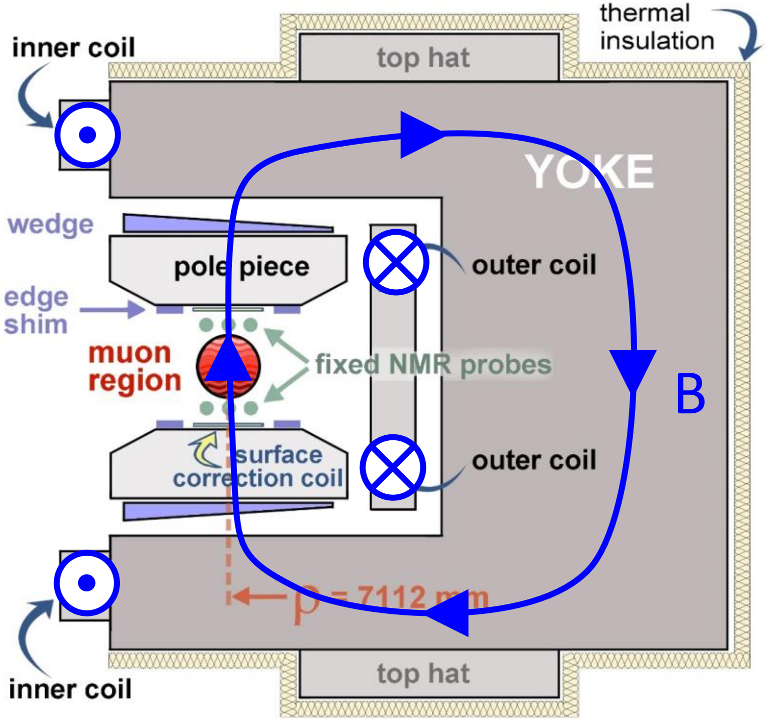
Muon g-2


RING
FIELD
DETECTORS
muons
Inflector
QUADS
24 Calorimeters + 2 trackers located all around the ring
NMR probes and electronics located all around the ring
Kicker

Real World Experiment: Storage Ring

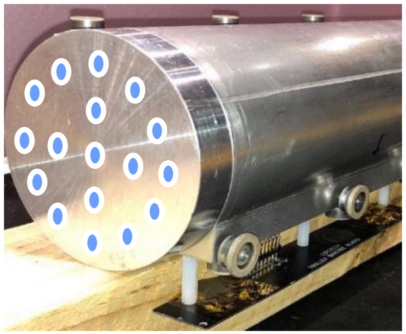
- 14 m diameter, 1.45 T C-shaped magnet stores muons



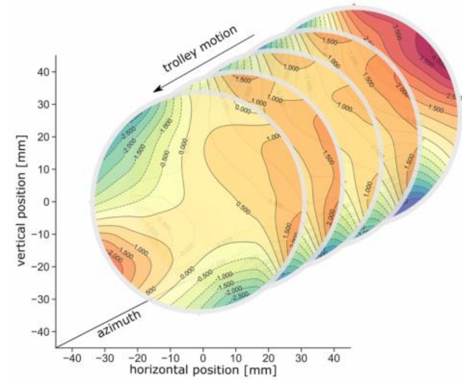


Measuring the Field: NMR Probes

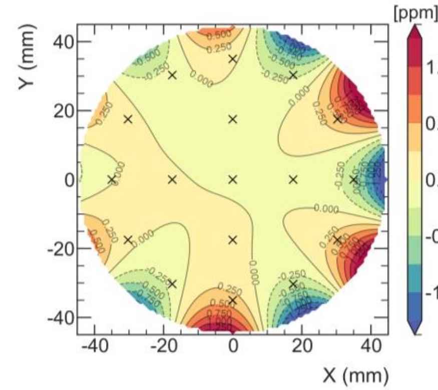
- In-vacuum NMR trolley **maps field every ~3 days**



17 petroleum jelly NMR probes

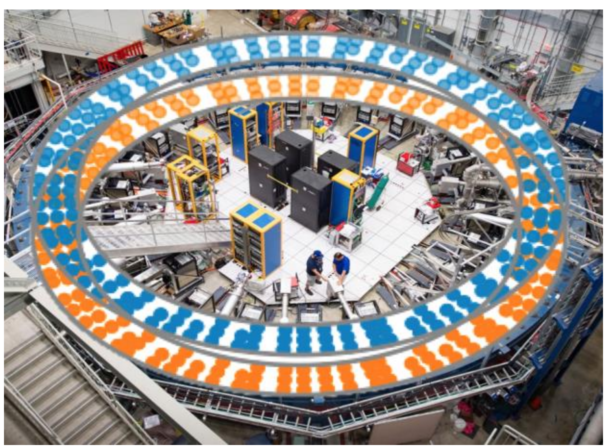


2D field maps (~8000 points)

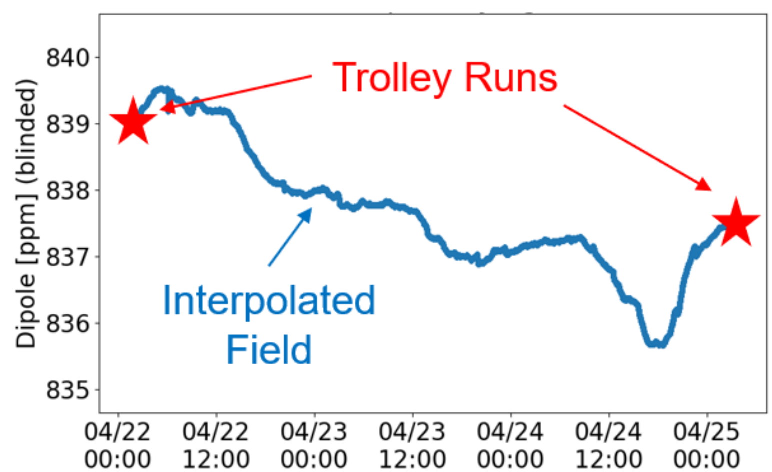


Azimuthally-Averaged **Variation < 1 ppm**

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

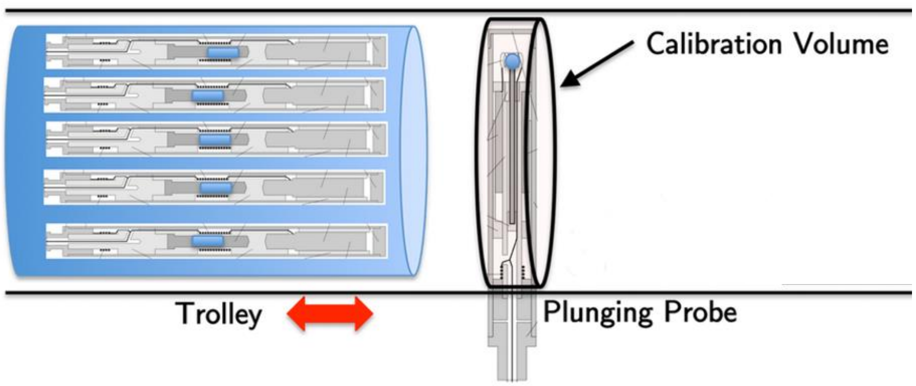


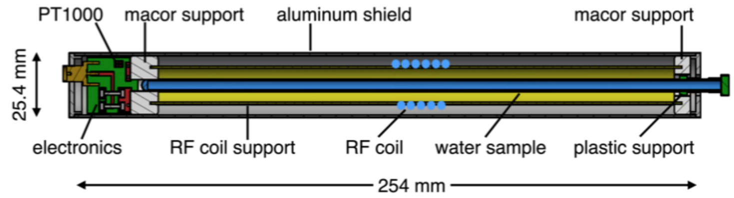
Fixed probes above/below muon storage region

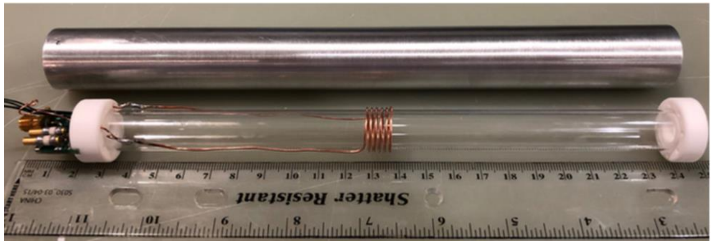


Calibration of Field Measurements

- Cross-calibrate using a cylindrical **plunging H_2O probe** which repeatedly **changes places with trolley (petroleum jelly probes)**







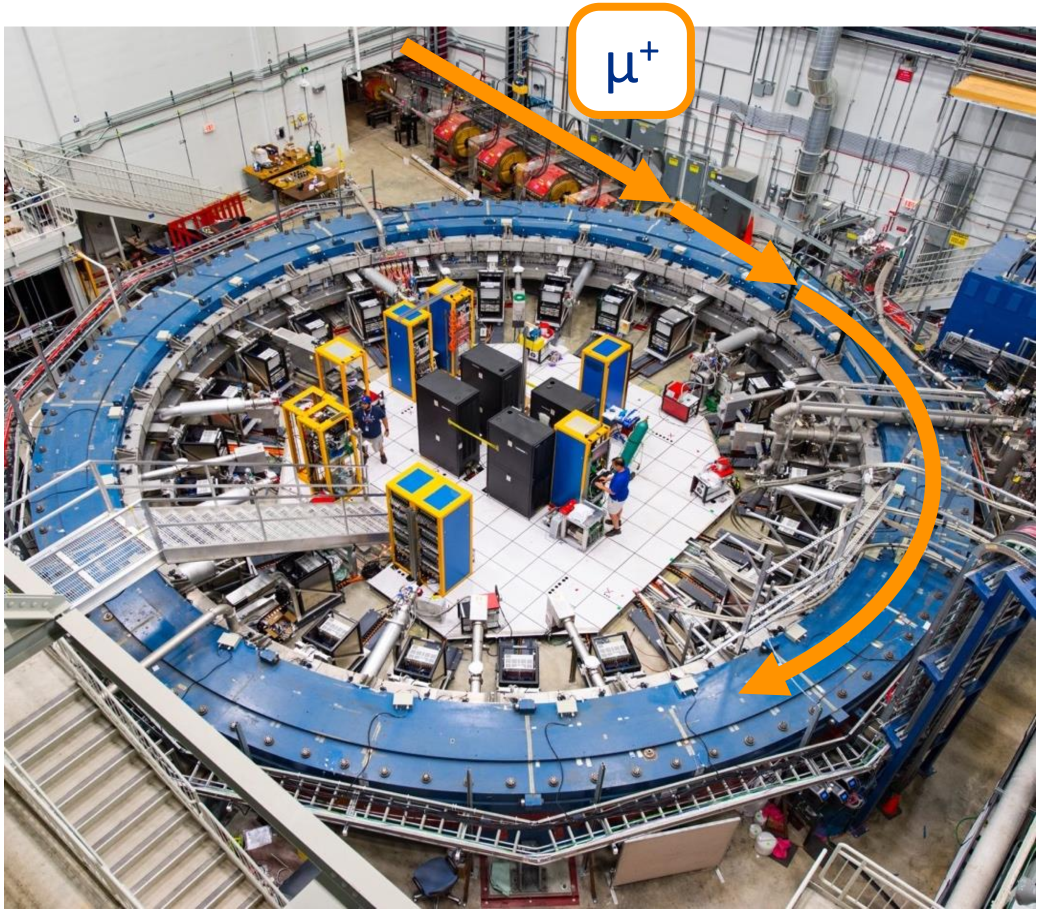
- This probe is **checked against a spherical probe** using an MRI magnet at ANL
- Both also cross-checked against a **^{3}He probe** (different systematics)

H_2O Probe

^{3}He Probe

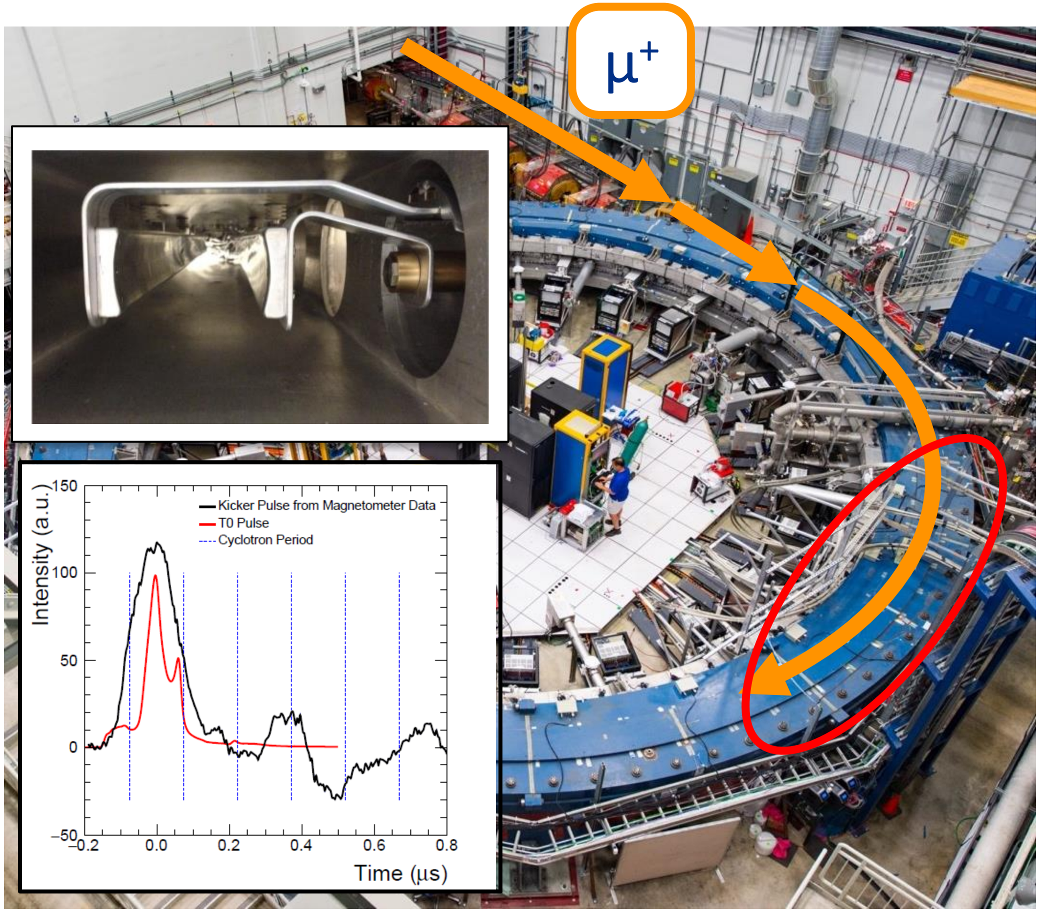
Real World Experiment: Muon Injection

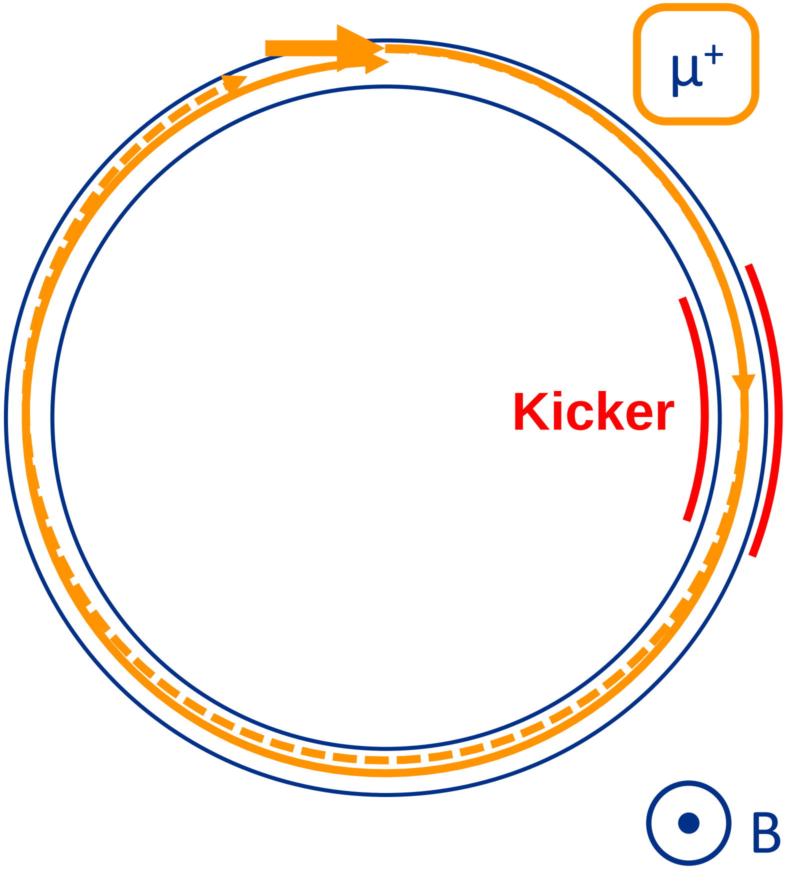
- Muons are injected into storage ring & bend in the *B* field



Real World Experiment: Kicker

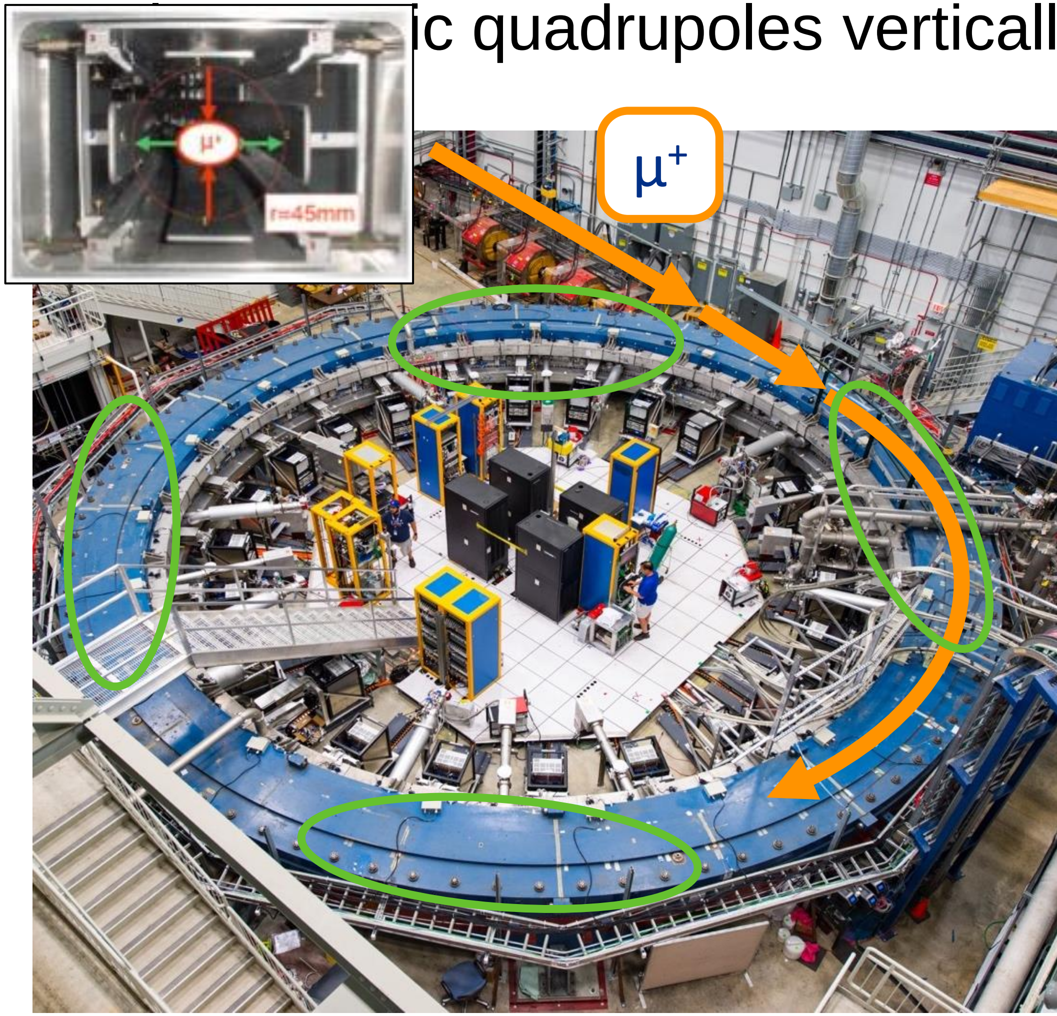
- Fast kicker magnet tweaks direction from injection trajectory to center of aperture

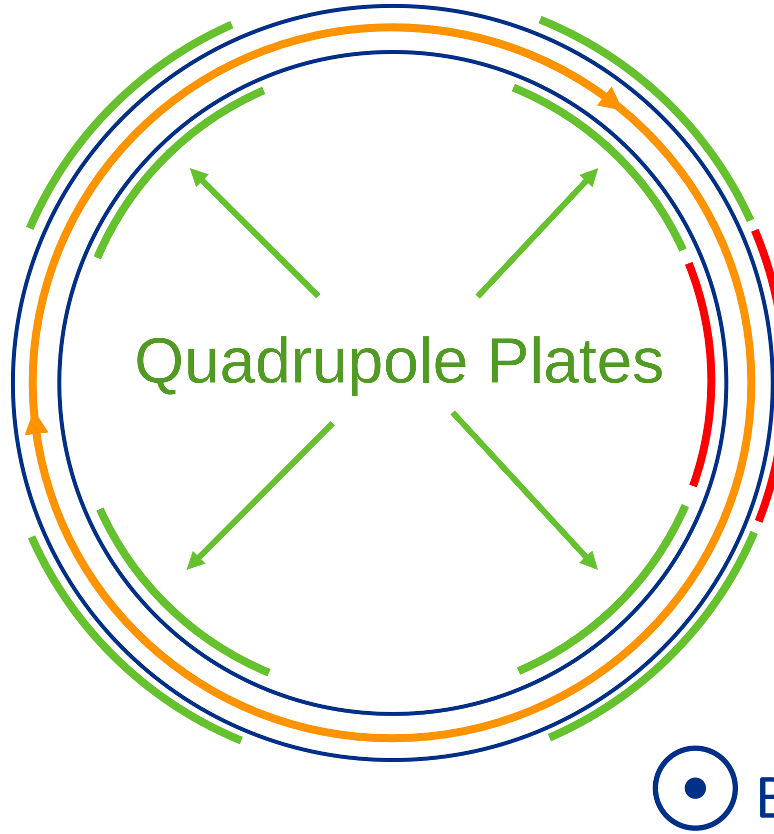




Real World Experiment: Quads

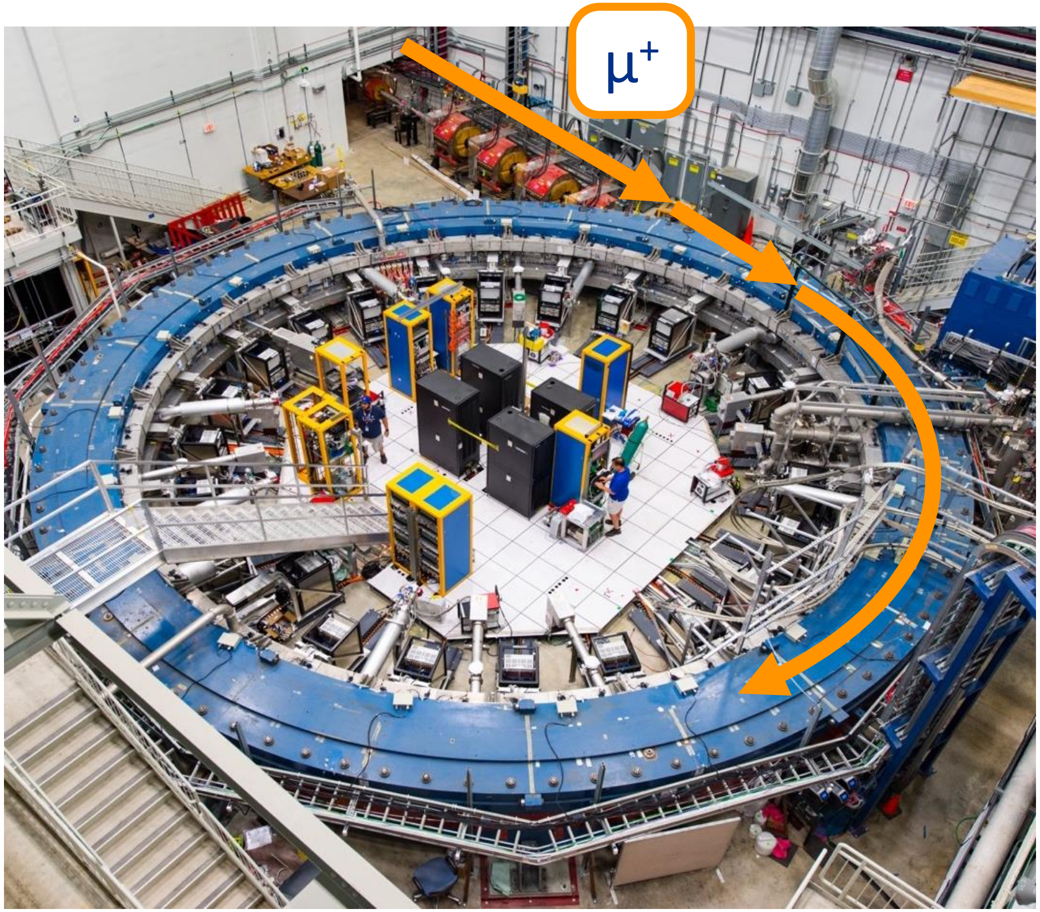
ic quadrupoles vertically contain the beam

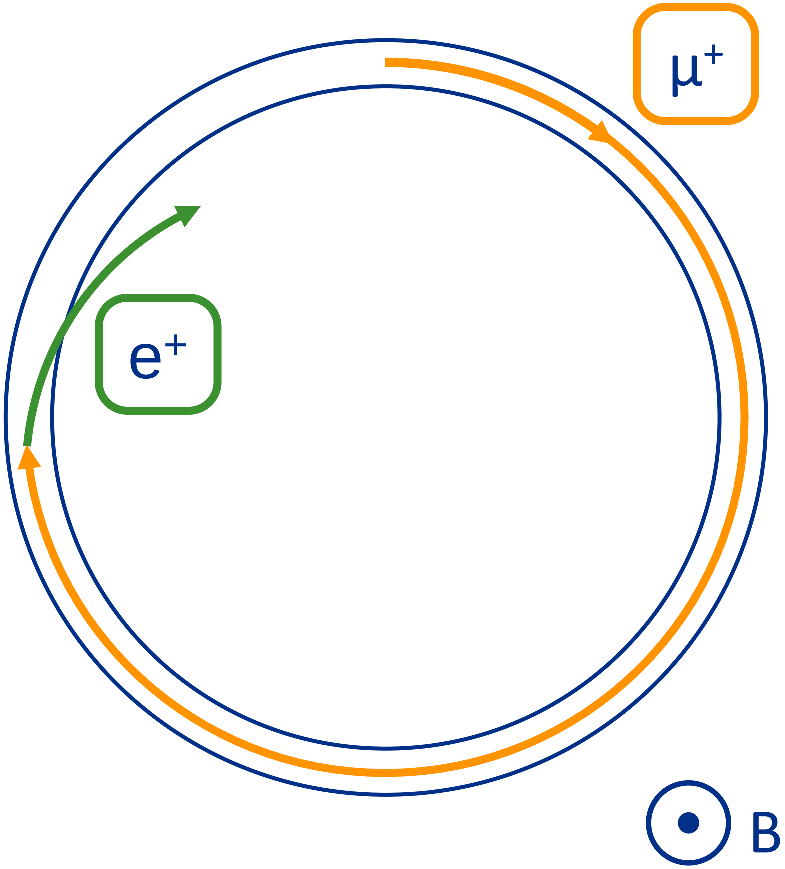




Real World Experiment: Decay Positrons

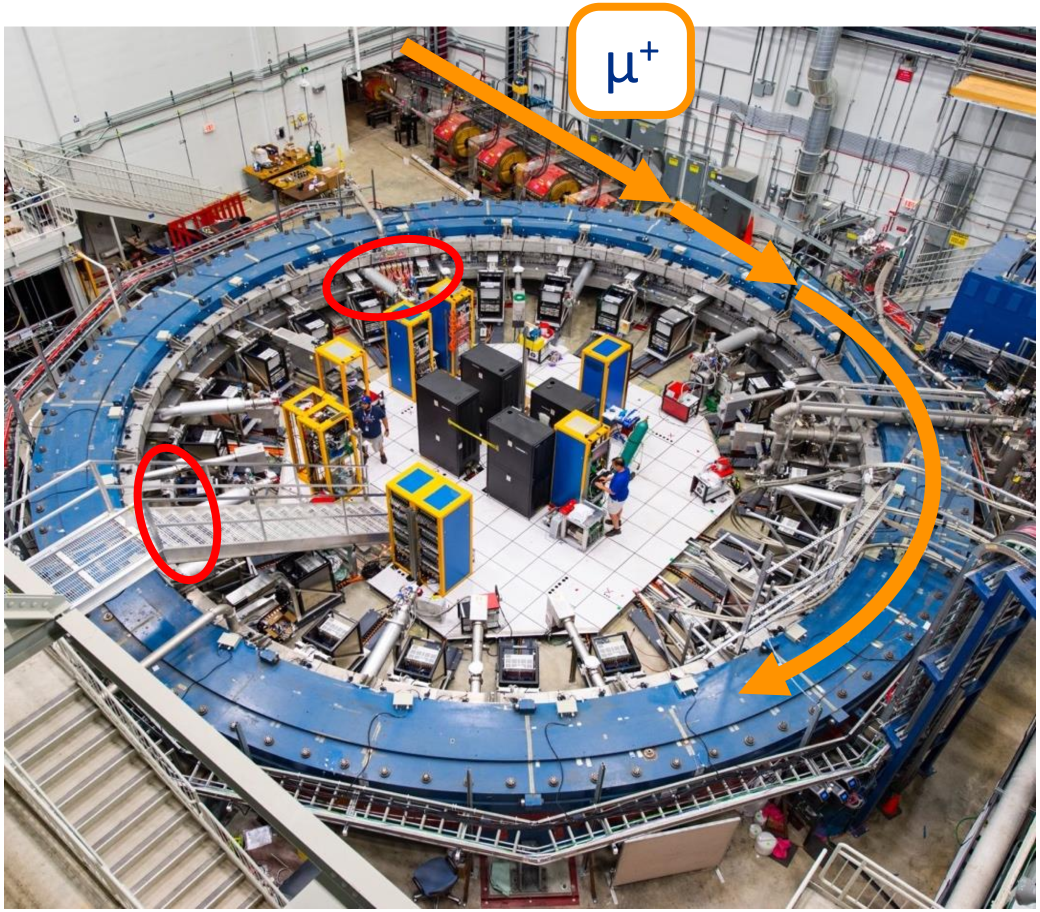
- Experiment measures decay e^+ which curl inwards as they have lower momentum

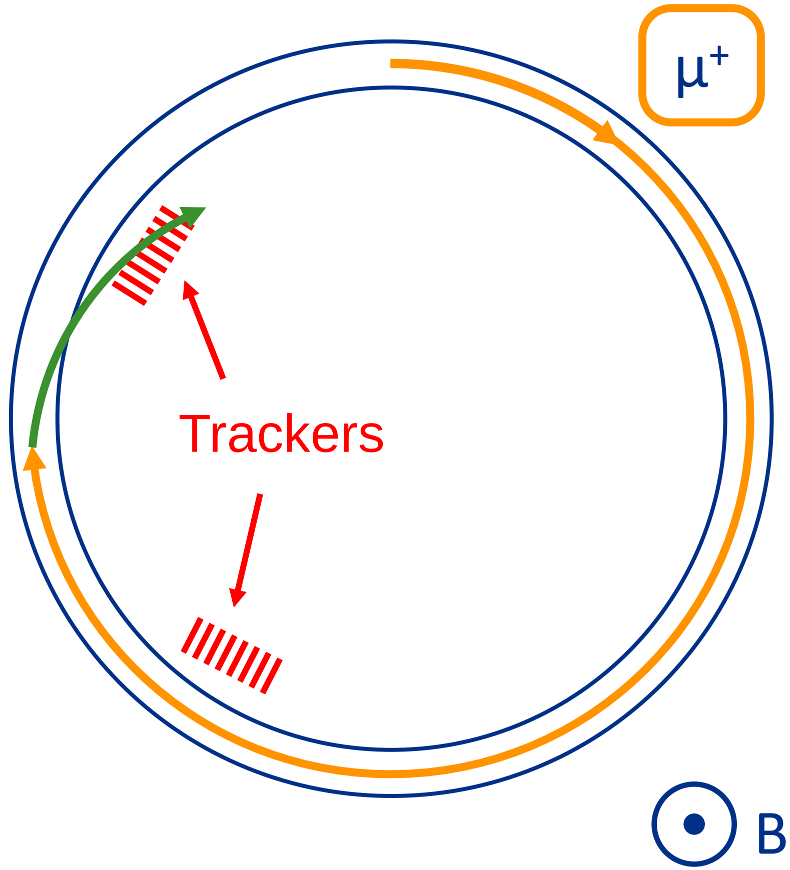




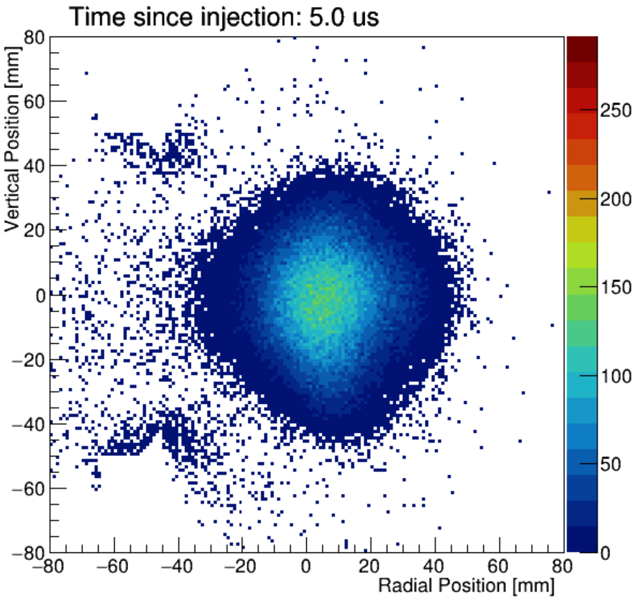
Real World Experiment: Trackers

- We measure the decay point with **2 trackers**





Muon Distribution from Trackers:



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

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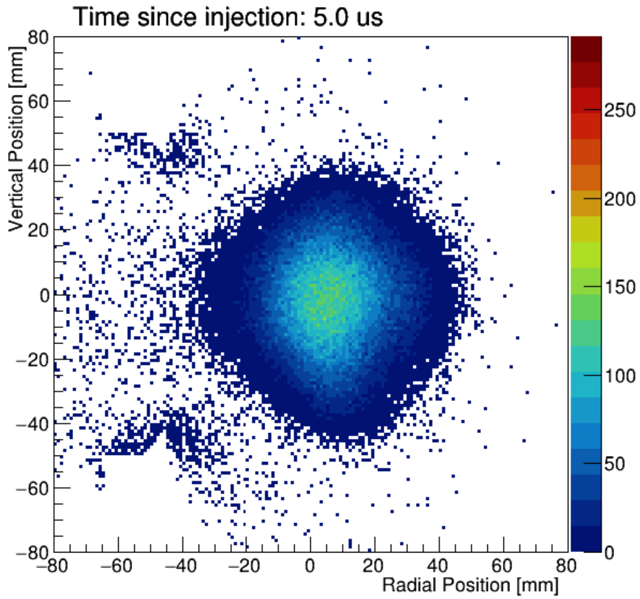
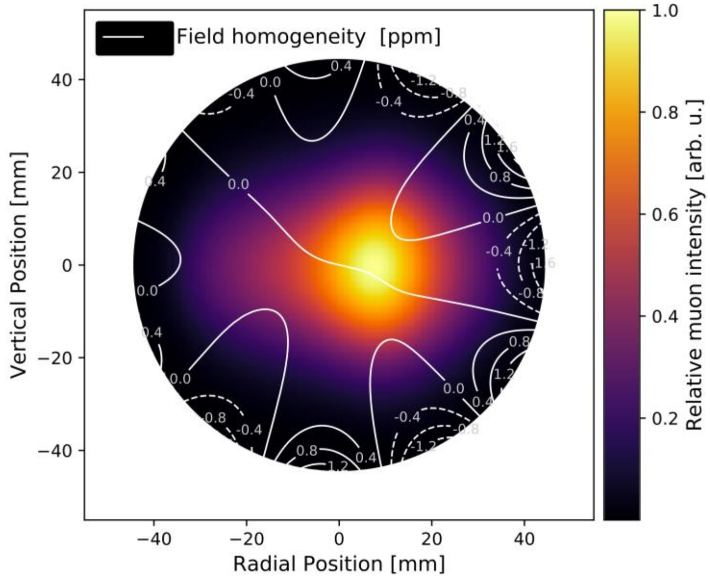


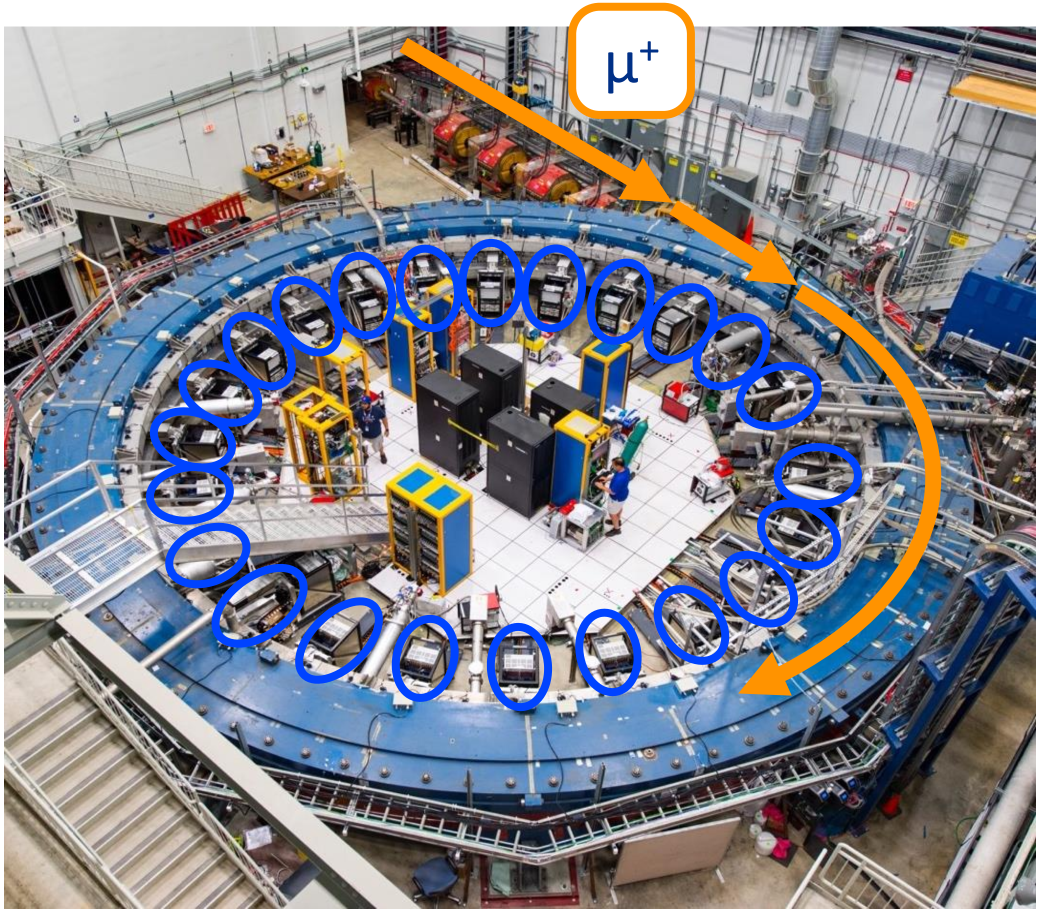


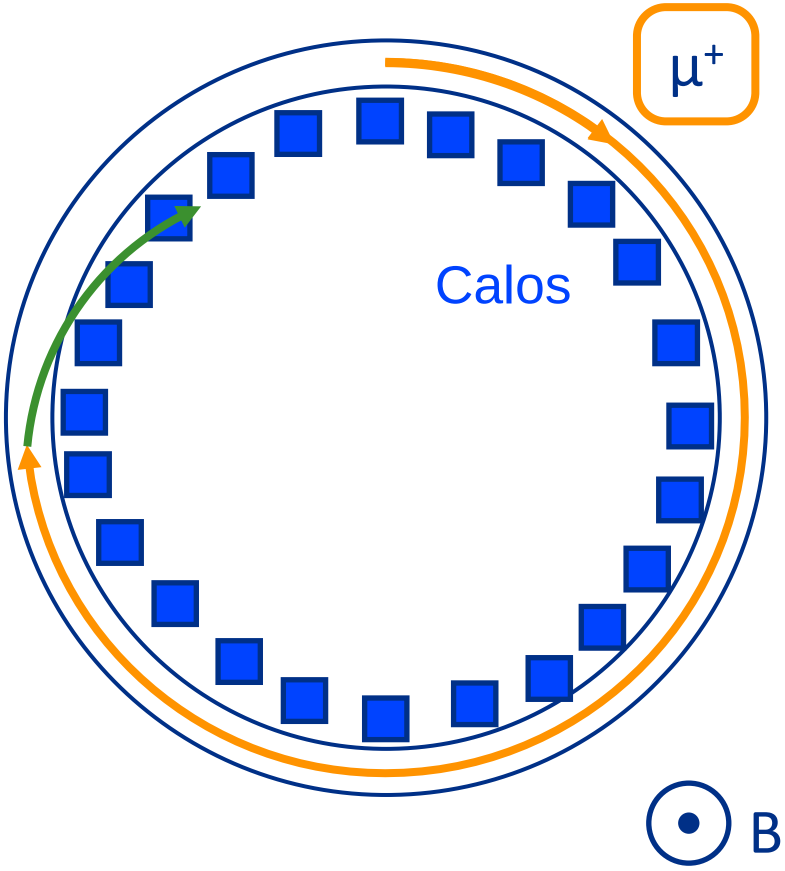
- Measure **beam oscillations** directly
  - Beam-dynamics corrections
  - Tuning simulations
  - Optimizing experiment running

- Use distribution to weight the field maps by where the muons live

Real World Experiment: Calorimeters

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



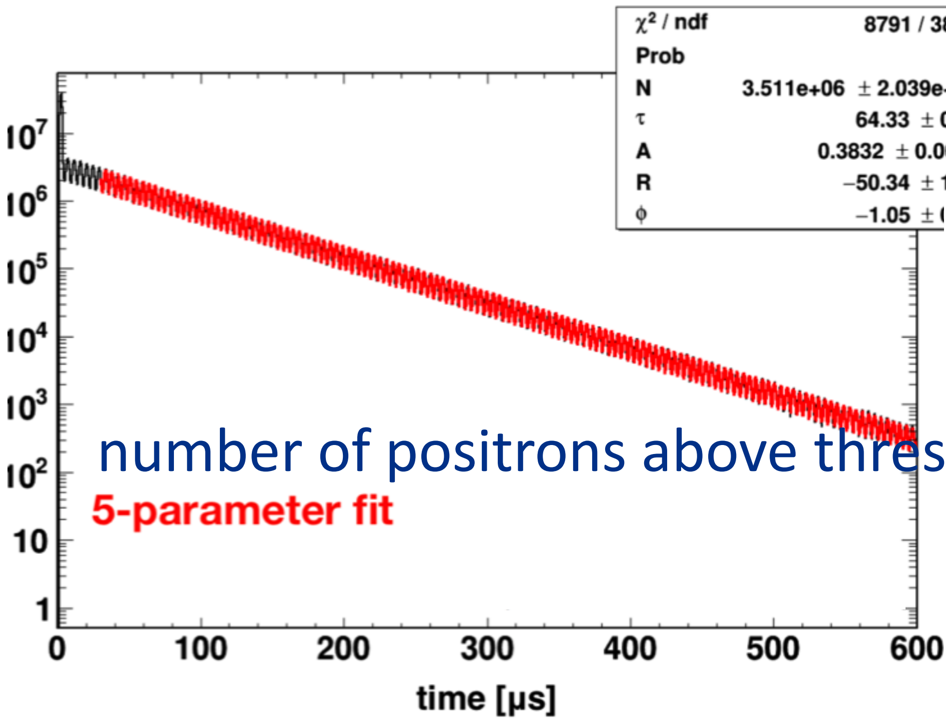


Measuring ω_a : 5 parameters fit function

- Fit with simple positron oscillation:

$$N_e(t) = N_0 \exp\left(-t/\tau_{\mu}\right)\left[1 + A\cos(\omega_a t + \varphi)\right]$$

- This simple fit is clearly not sufficient and well defined resonances are observed in the residuals

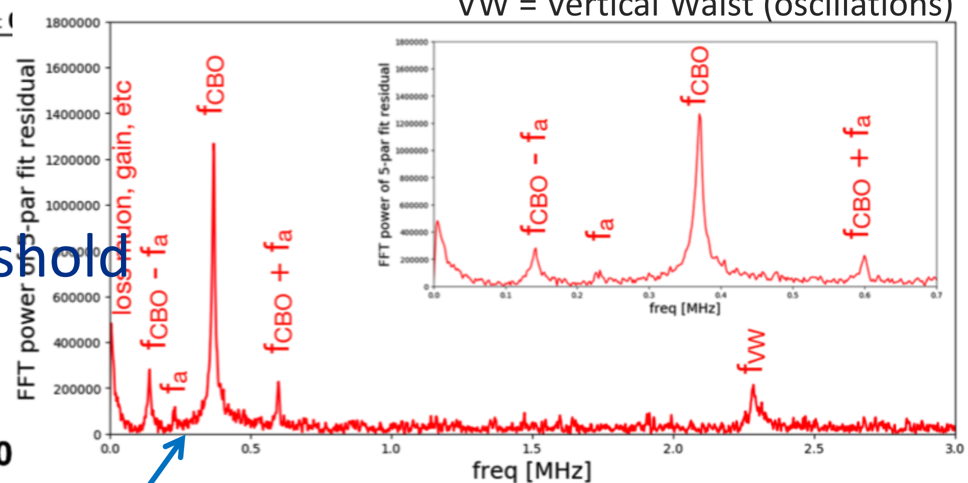


muon lifetime: $\tau_\mu = \gamma\tau_{0\mu}$ = 64.33 μsec

number of positrons above threshold

CBO = Coherent Betatron Ocillations

VW = Vertical Waist (oscillations)



RESIDUALS (in frequency space)

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The complete 22 parameters fit function

ω_y, ω_{VW} vertical oscillations

ω_{CBO}, ω_{2CBO} radial oscillations

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

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

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

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

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

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

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

Red = free parameters

Blue= fixed parameters

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

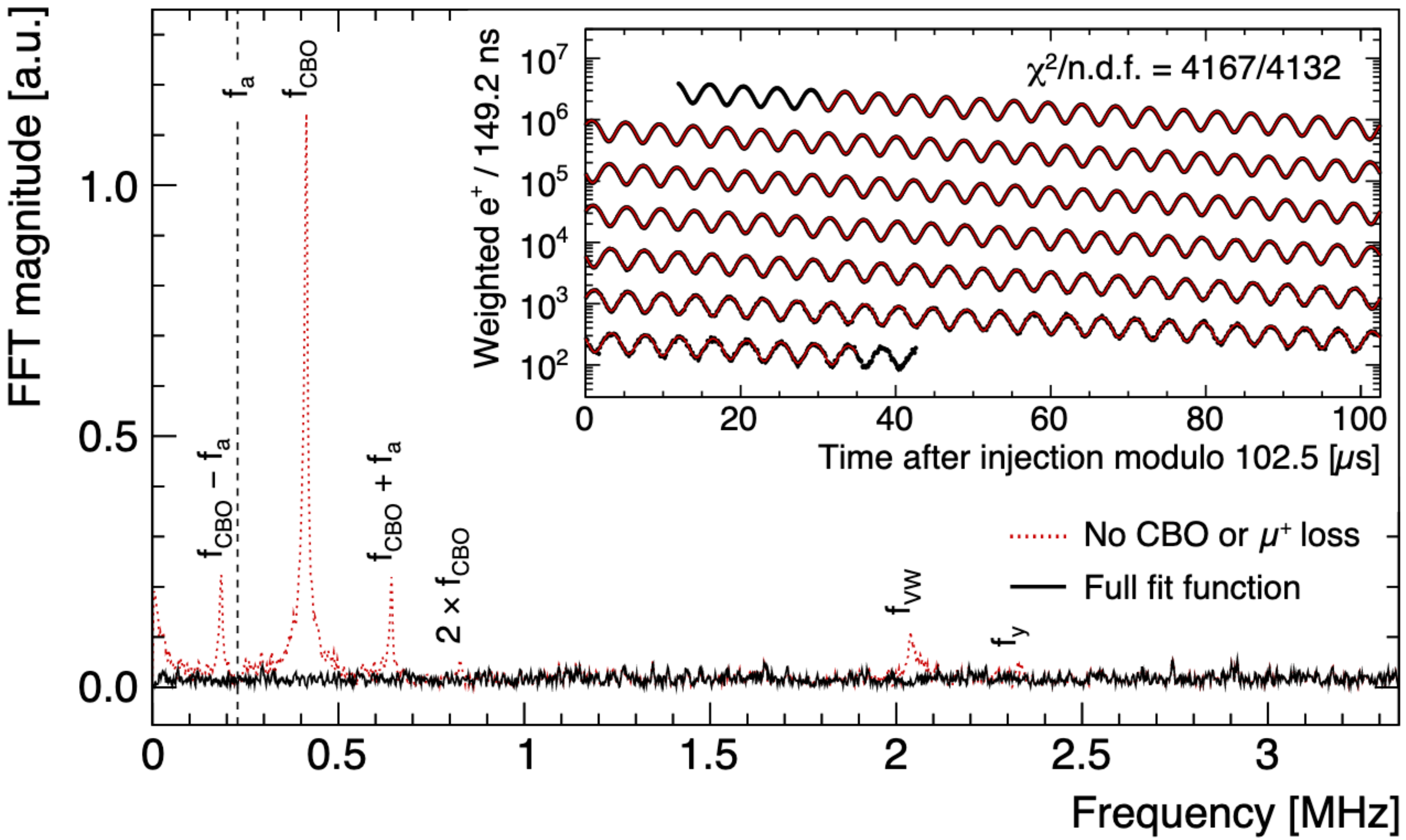
Lost muons (μ hitting collimators)

$$\omega_{\rm CBO}(t) = \omega_0 t + Ae^{-\frac{t}{\tau_A}} + Be^{-\frac{t}{\tau_B}}$$

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

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

Final fit to get ω_a



Real World Complications: Corrections

- We need to make corrections for several small effects:

E-field & Up/Down motion: Spin precesses slower than in basic equation

Phase changes over each fill: Phase-Acceptance, Differential Decay, Muon Losses

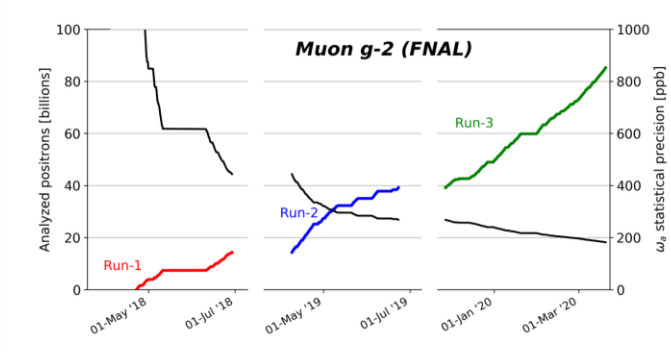
$$\frac{\omega_a}{\omega_p} = \frac{\omega_a^m}{\omega_p^m} \frac{1 + C_e + C_p + C_{pa} + C_{dd} + C_{ml}}{1 + B_k + B_q}$$

Measured Values

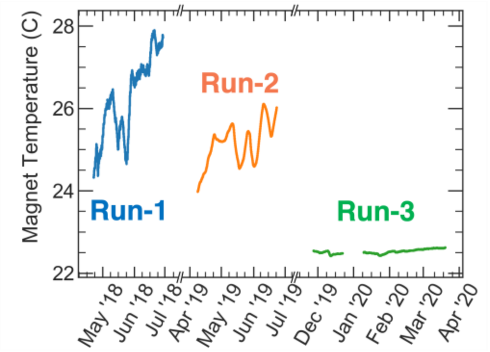
Transient Magnetic Fields: Quad Vibrations, Kicker Eddy Current,

- Total correction is **622 ppb**, dominated by **E-field & Pitch**…

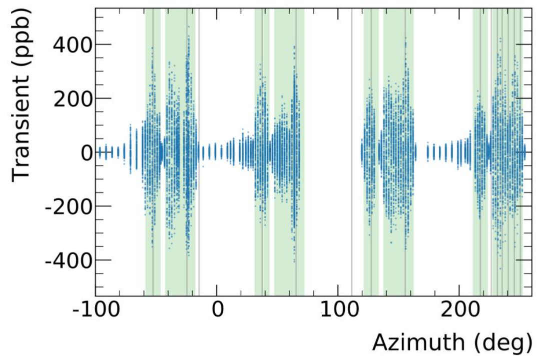
Run-2/3 Uncertainty Improvement Categories



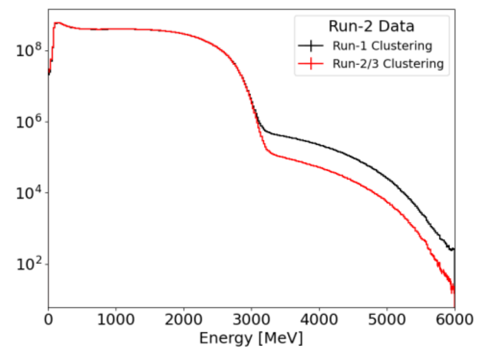
Statistics



Running Conditions



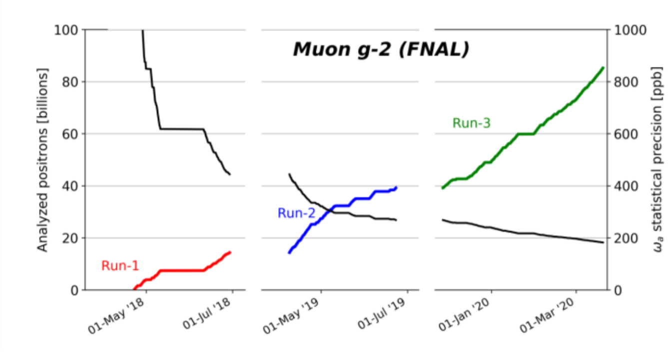
Systematic Measurements & Studies



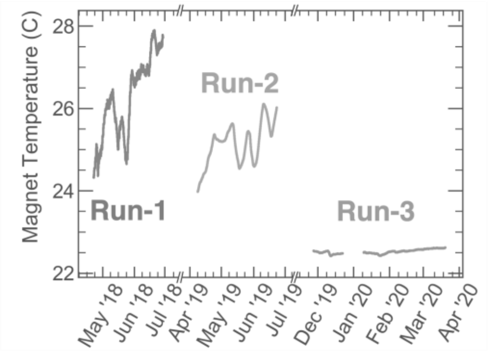
Analysis Improvements

Fermilab

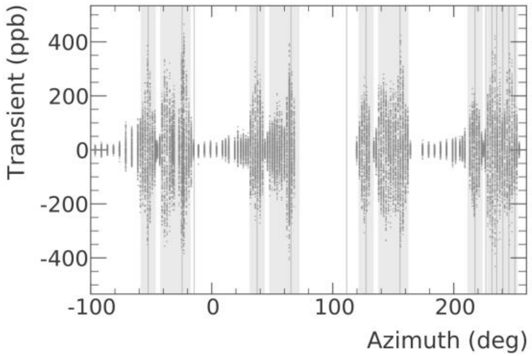
Run-2/3 Uncertainty Improvement Categories



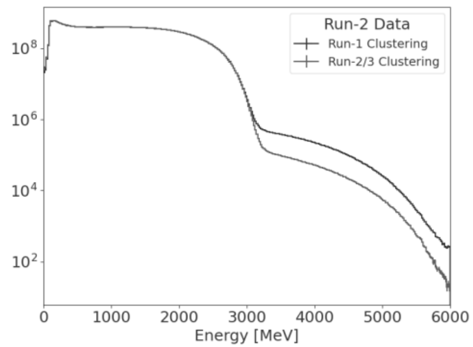
Statistics



Running Conditions



Systematic Measurements & Studies

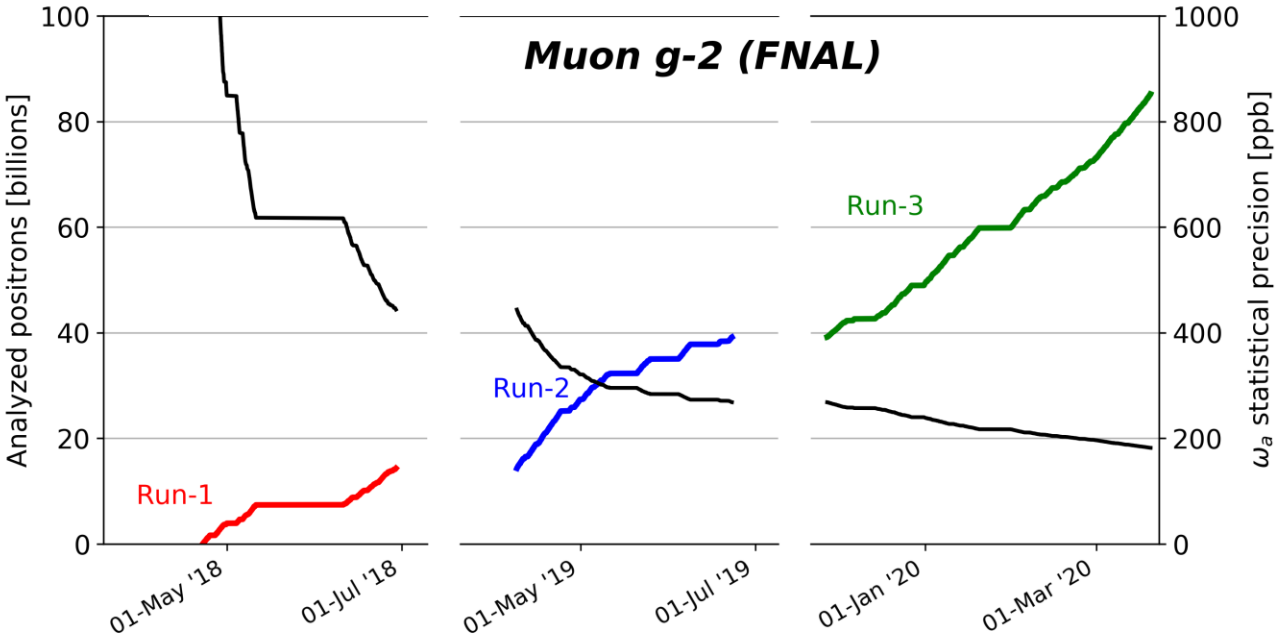


Analysis Improvements

Run-2/3 Improvement: Statistics

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

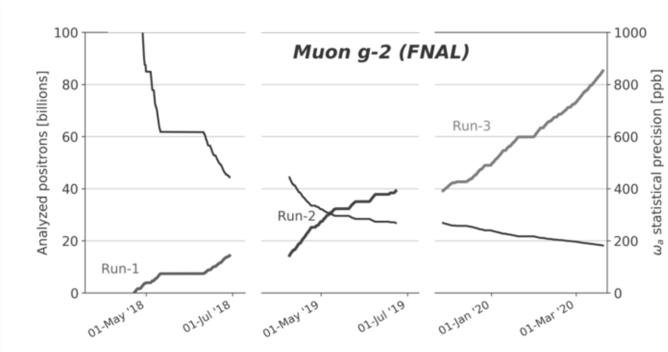
E > 1 GeV
t > 30 us



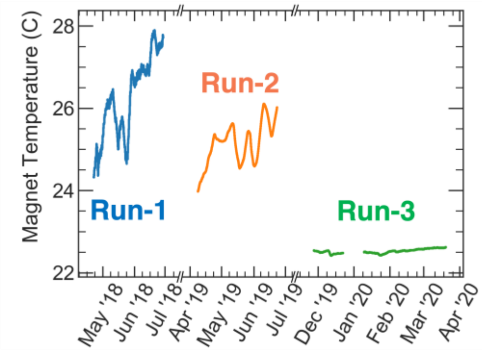
- Factor 4.7 more data in Run-2/3 than Run-1

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

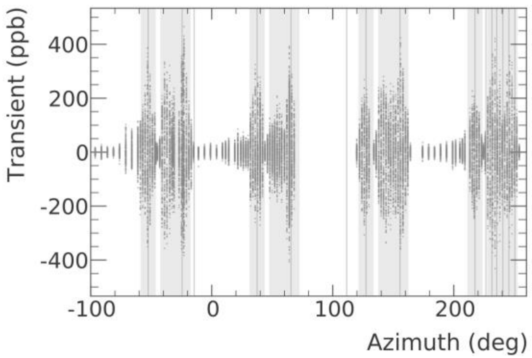
Run-2/3 Uncertainty Improvement Categories



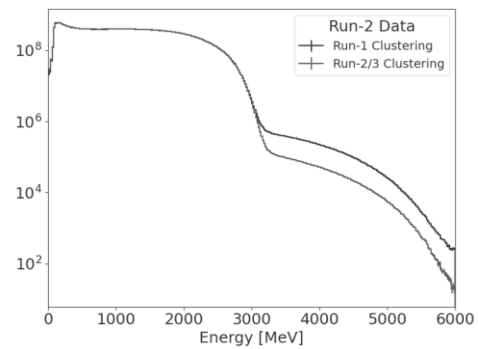
Statistics



Running Conditions



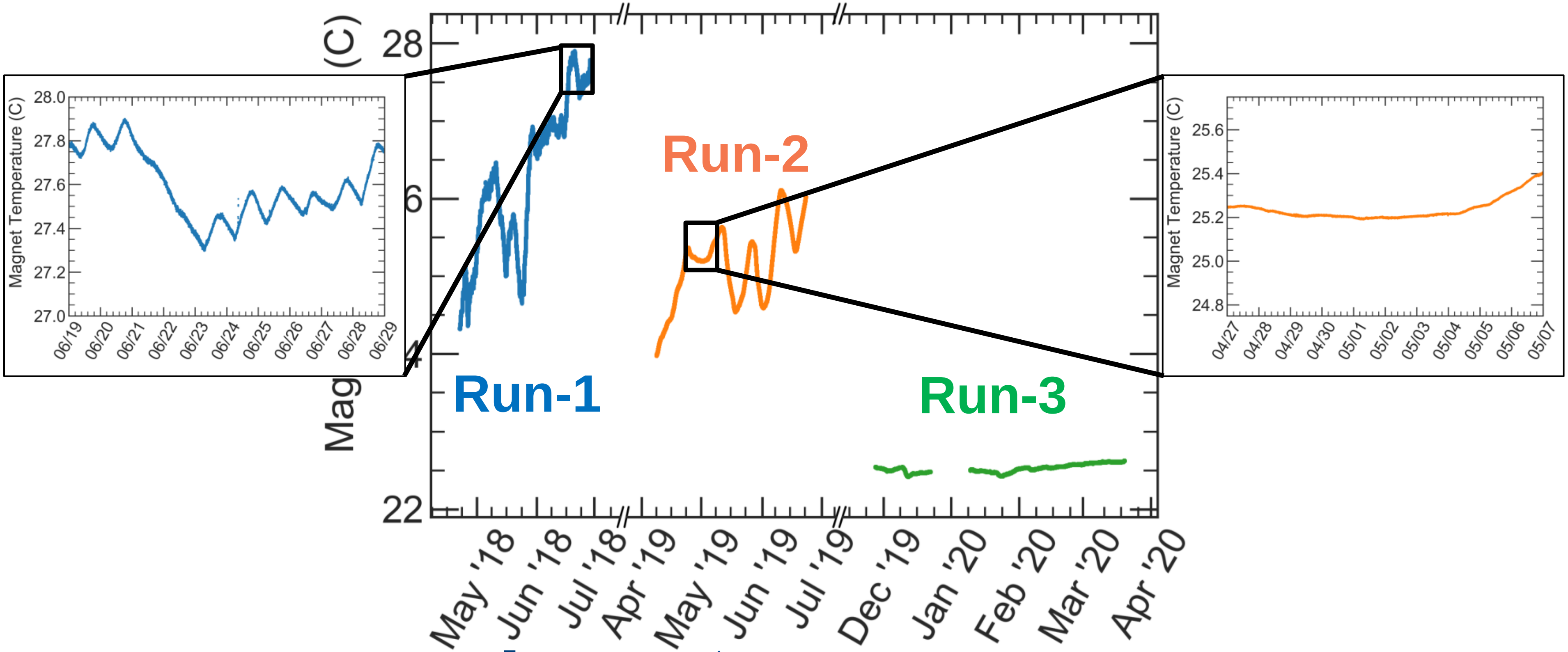
Systematic Measurements & Studies

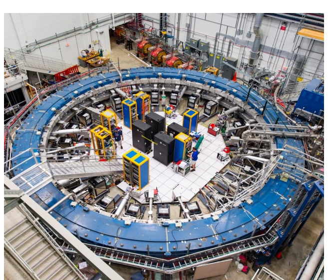


Analysis Improvements

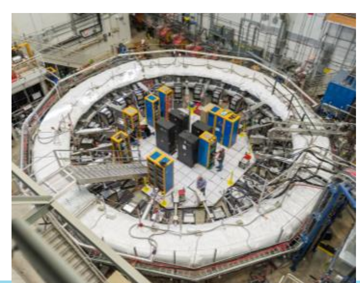
Running Conditions: Hall Temperature

- Temperature stability makes magnetic field less variable





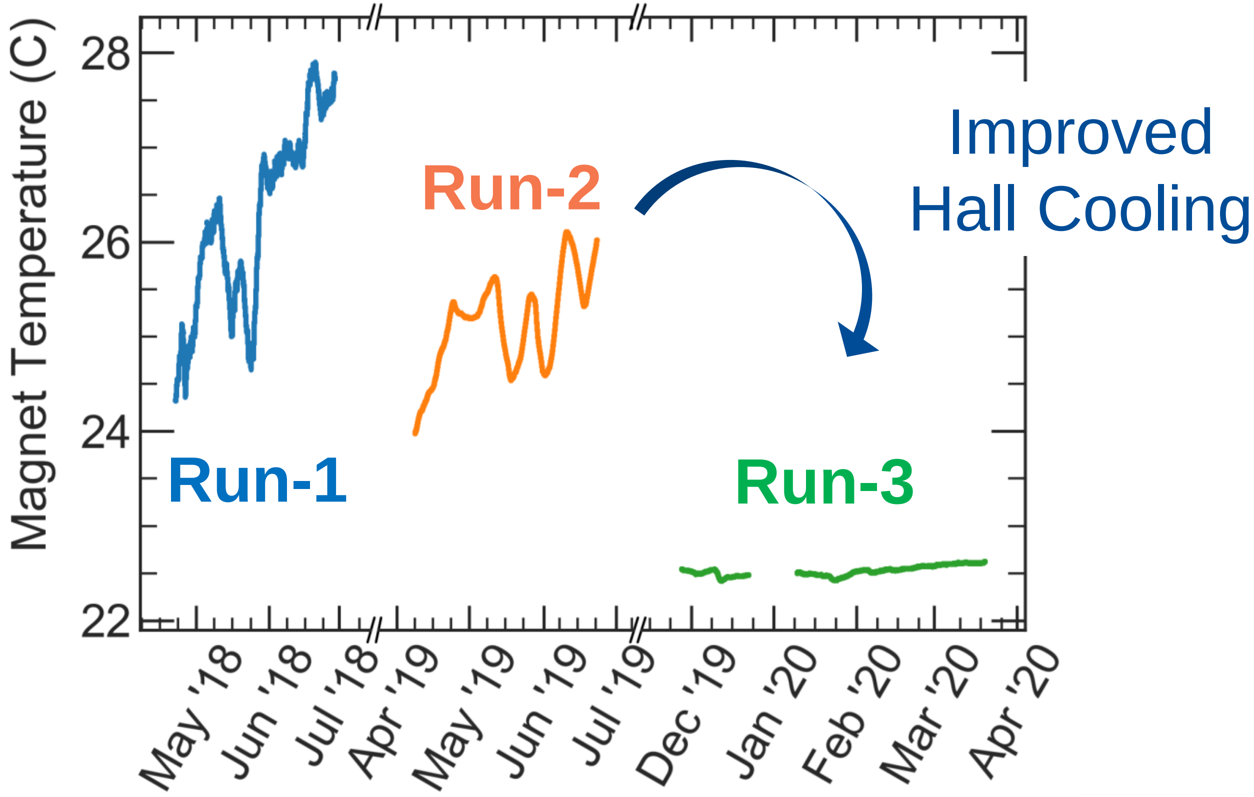
Added Insulation



Fermilab

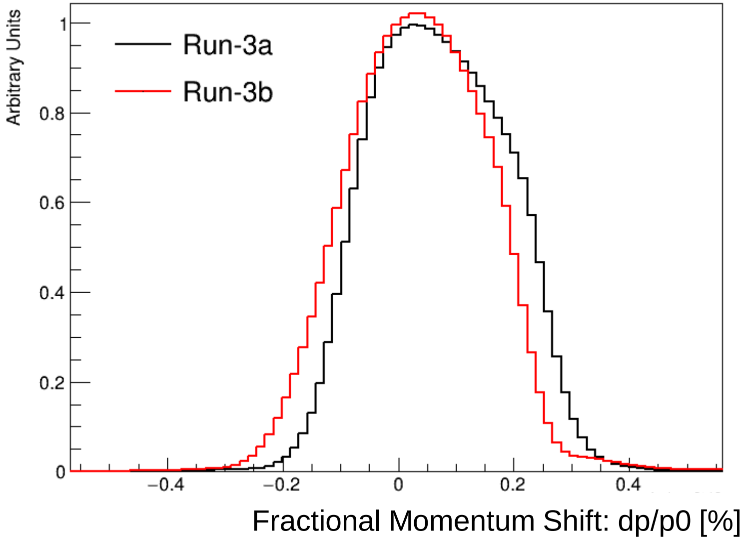
Running Conditions: Hall Temperature

- Temperature stability makes magnetic field less variable

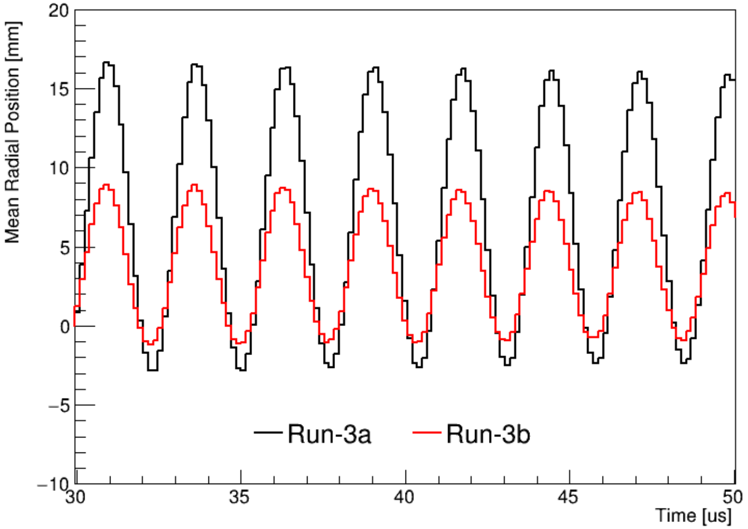


Running Conditions: Kicker Strength

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

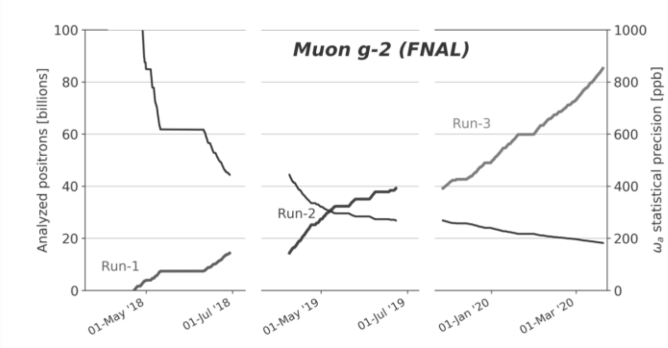


- Mom. distribution more centered
- **Lower E-field correction C_e**

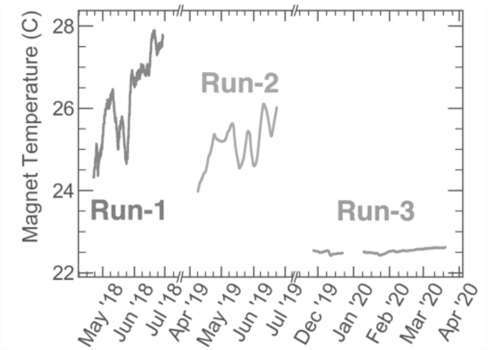


- Phase space matching improved
- **Smaller beam oscillations**

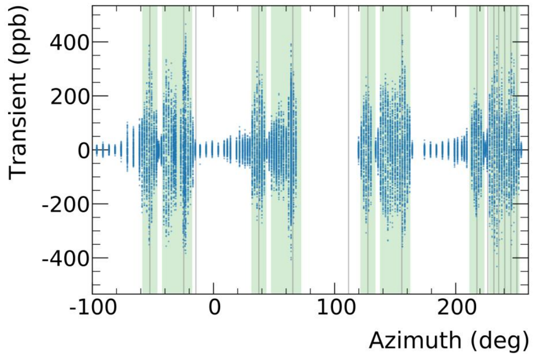
Run-2/3 Uncertainty Improvement Categories



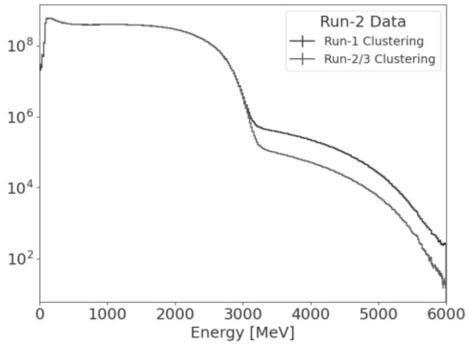
Statistics



Running Conditions



Systematic Measurements & Studies

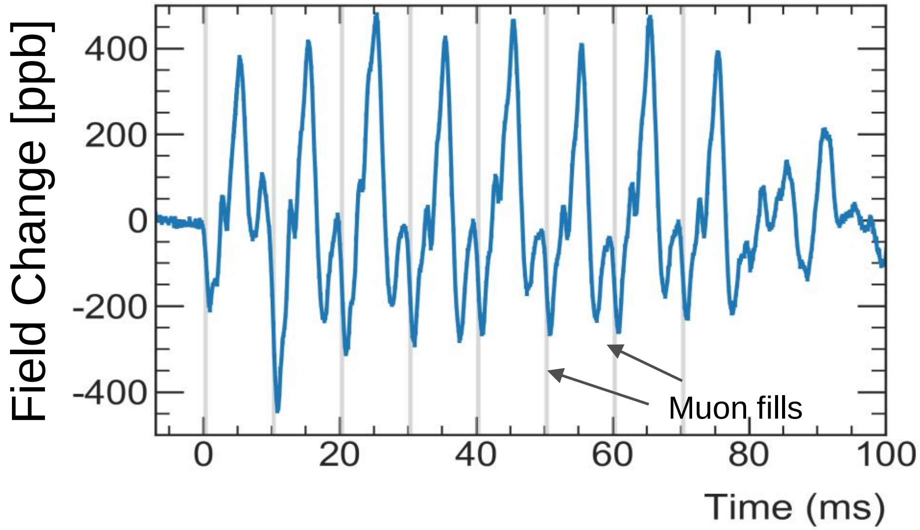


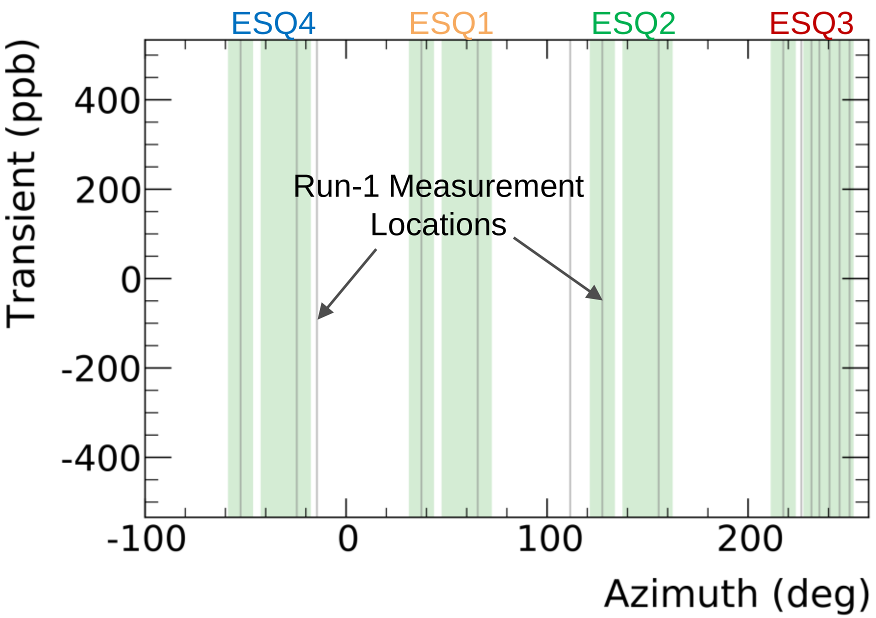
Analysis Improvements

Fermilab

Improved Measurements: Quad Transient Field

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

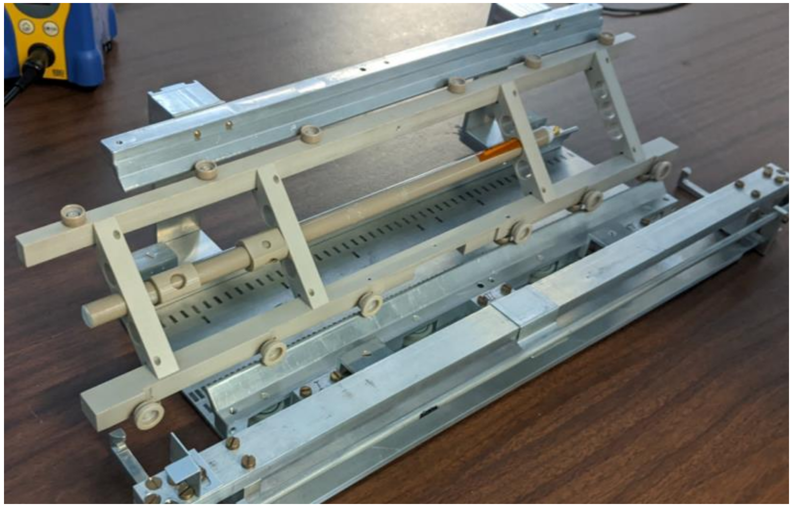




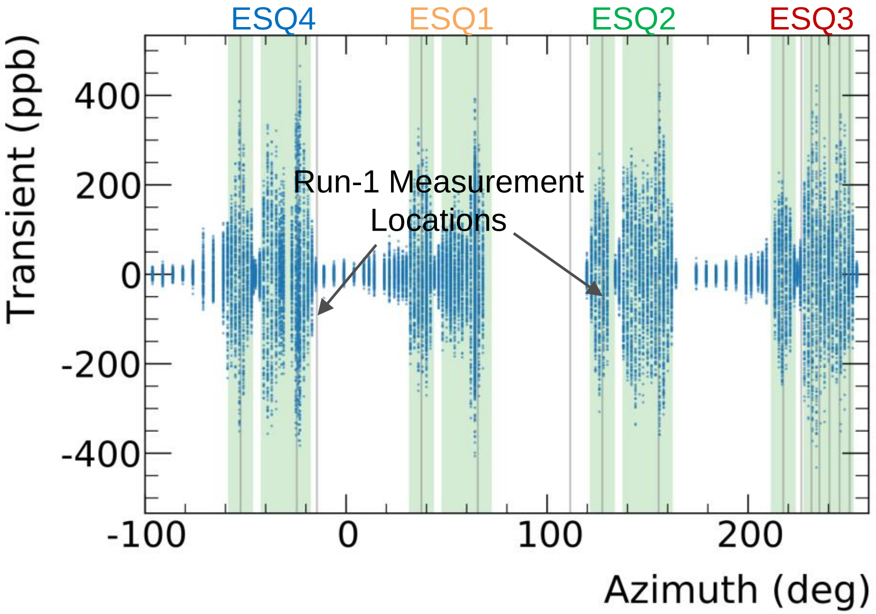
- For Run-1 analysis, we had **limited measurement positions**
- Largest Run-1 systematic: **92 ppb**

Improved Measurements: Quad Transient Field

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



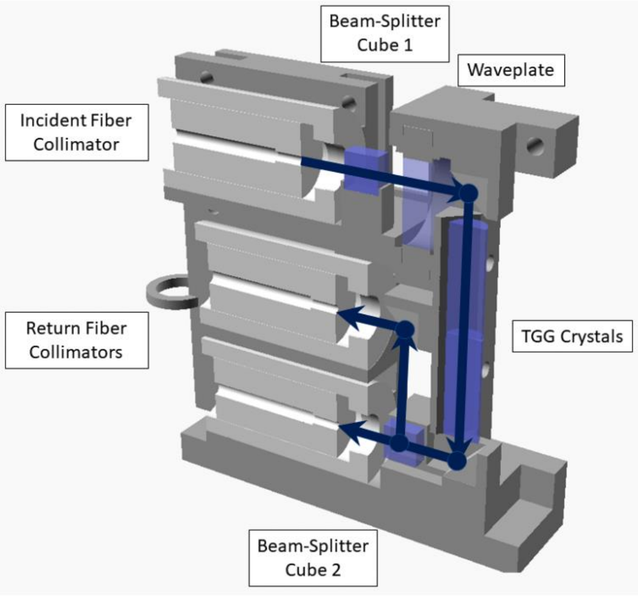
Measurement probe mounted
on trolley rail train



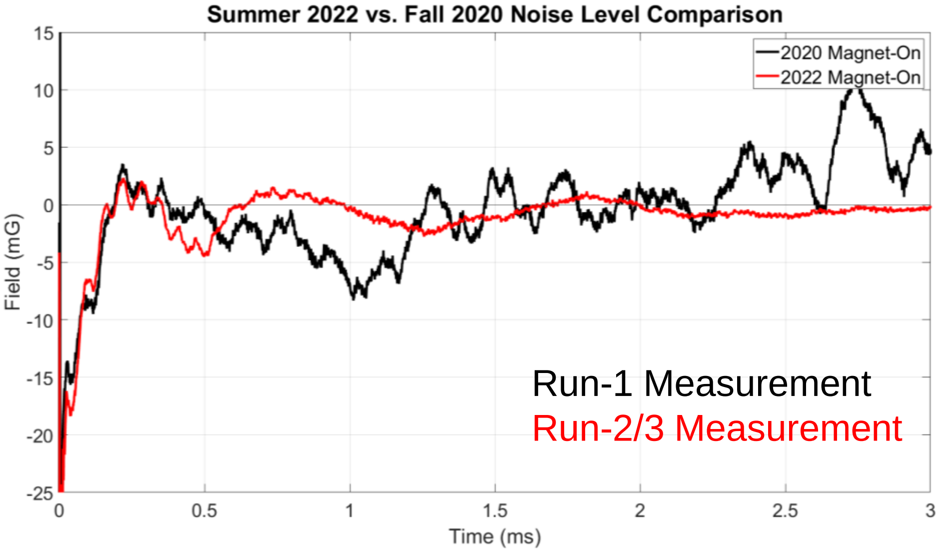
- Uncertainty is reduced to **20 ppb**

Improved Measurements: Kicker Transient Field

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

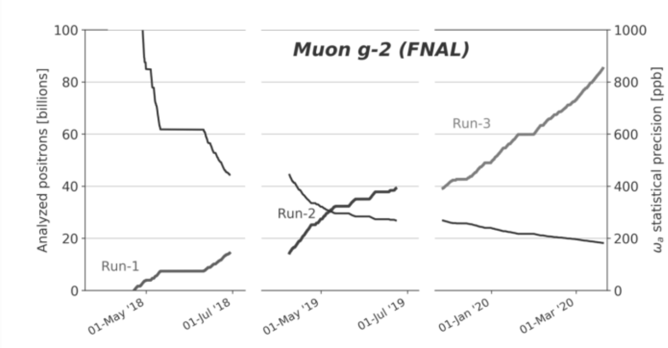


Faraday magnetometer

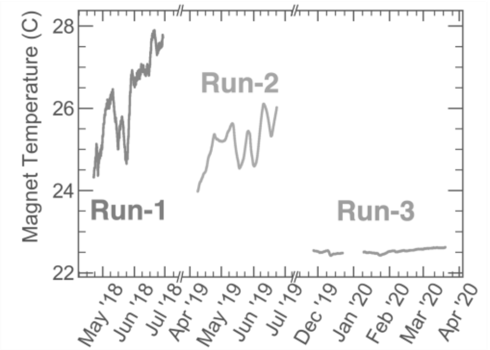


- Run-2/3 has **lower vibration noise** vs. Run-1
- Uncertainty reduces from **37 ppb to 13 ppb**

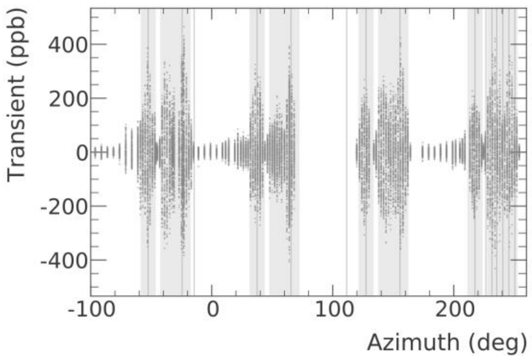
Run-2/3 Uncertainty Improvement Categories



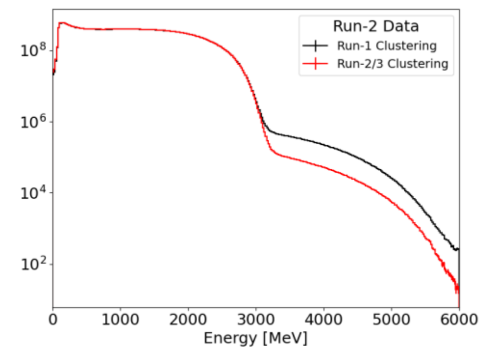
Statistics



Running Conditions

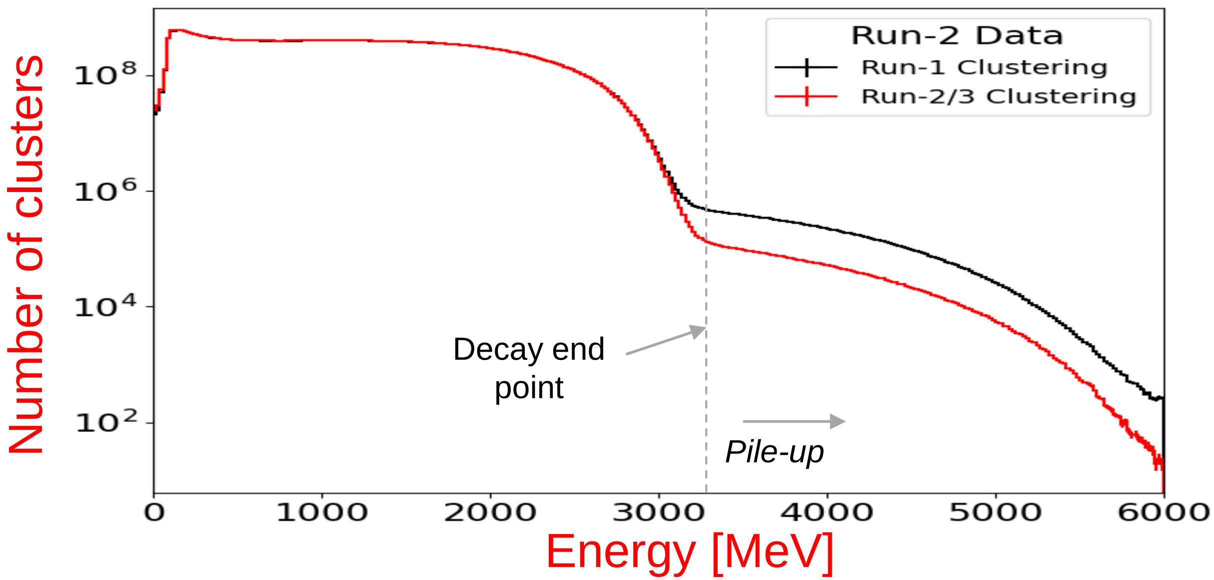


Systematic Measurements & Studies



Analysis Improvements

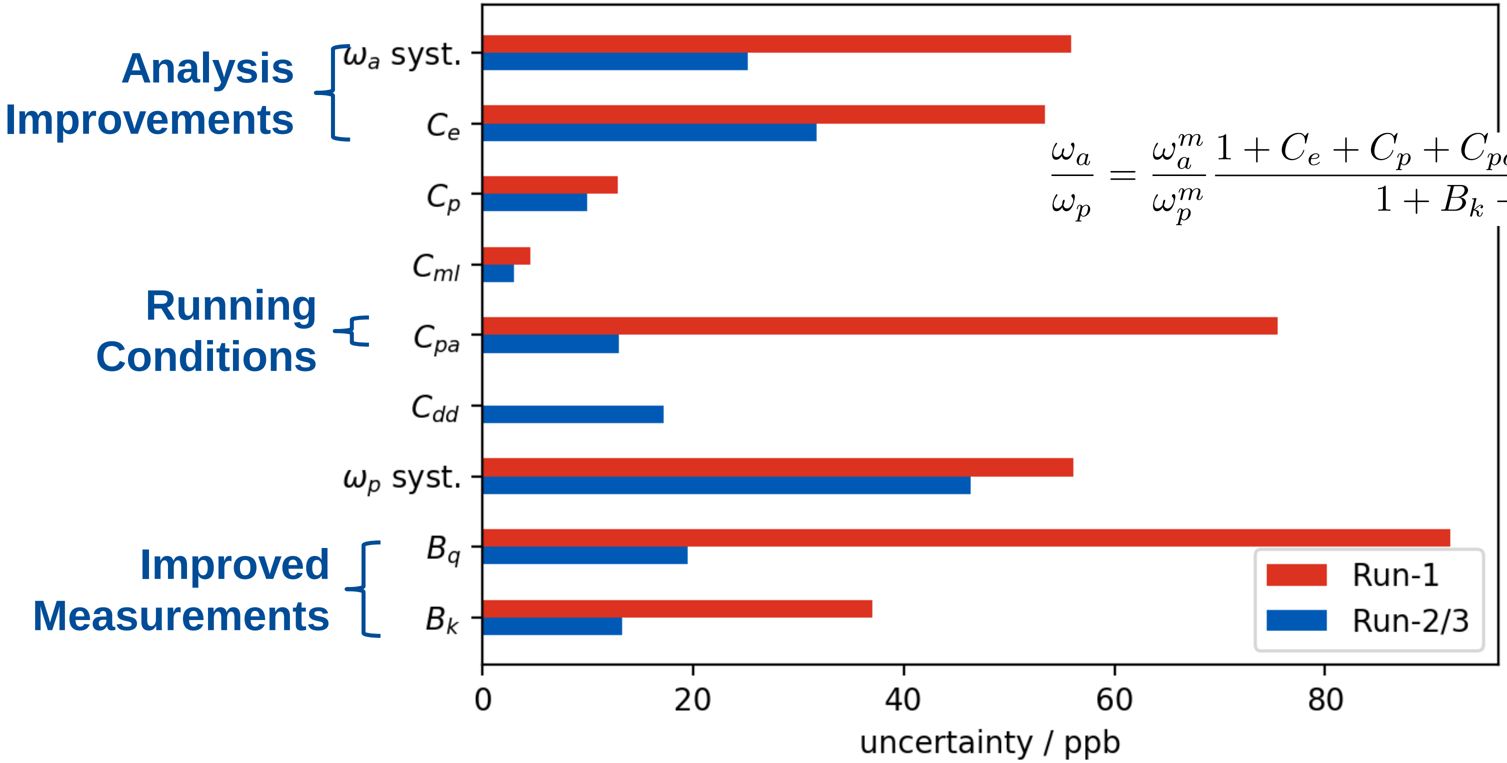
Analysis Improvements: *Pile-up*



- *Pile-up*: 2 e^+ **arriving at same time** → 1 cluster in ECAL
- Probability higher at injection (more muons): can **bias ω_a**
- Clusters with E>3.1GeV are certainly *Pile-up*
- Reduced uncertainty by:
  - Improved **reconstruction**
  - Improved **correction algorithms**

Uncertainty Improvements Summary

- Systematic improvements in **all parameters**



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

Fermilab

Run-2/3 Uncertainties: Final Values

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

- Total uncertainty is **215 ppb**

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

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

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

Blind Analysis

- Perform analysis with **software & hardware blinding**
- Hardware blind comes from **altering our clock frequency**

Greg Bock & Joe Lykken

Non-collaborators set frequency to **(40 – δ) MHz**

- Clock is locked and **value kept secret** until analysis completed

July 24th 2023: Unblinding

- Physics week in Liverpool for unblinding meeting:

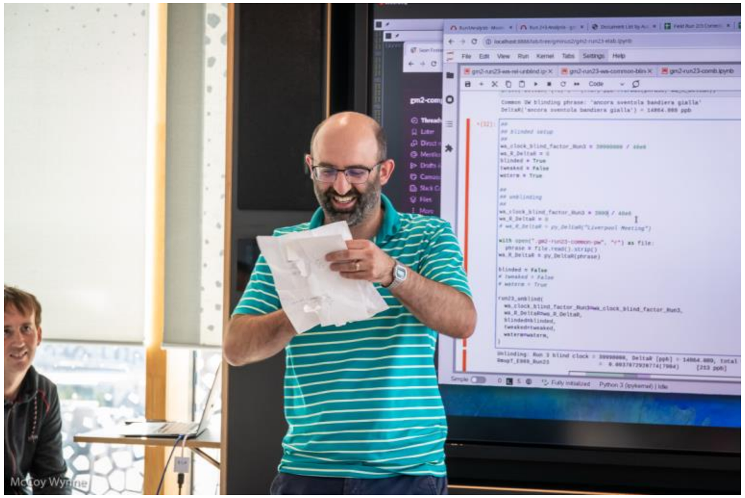


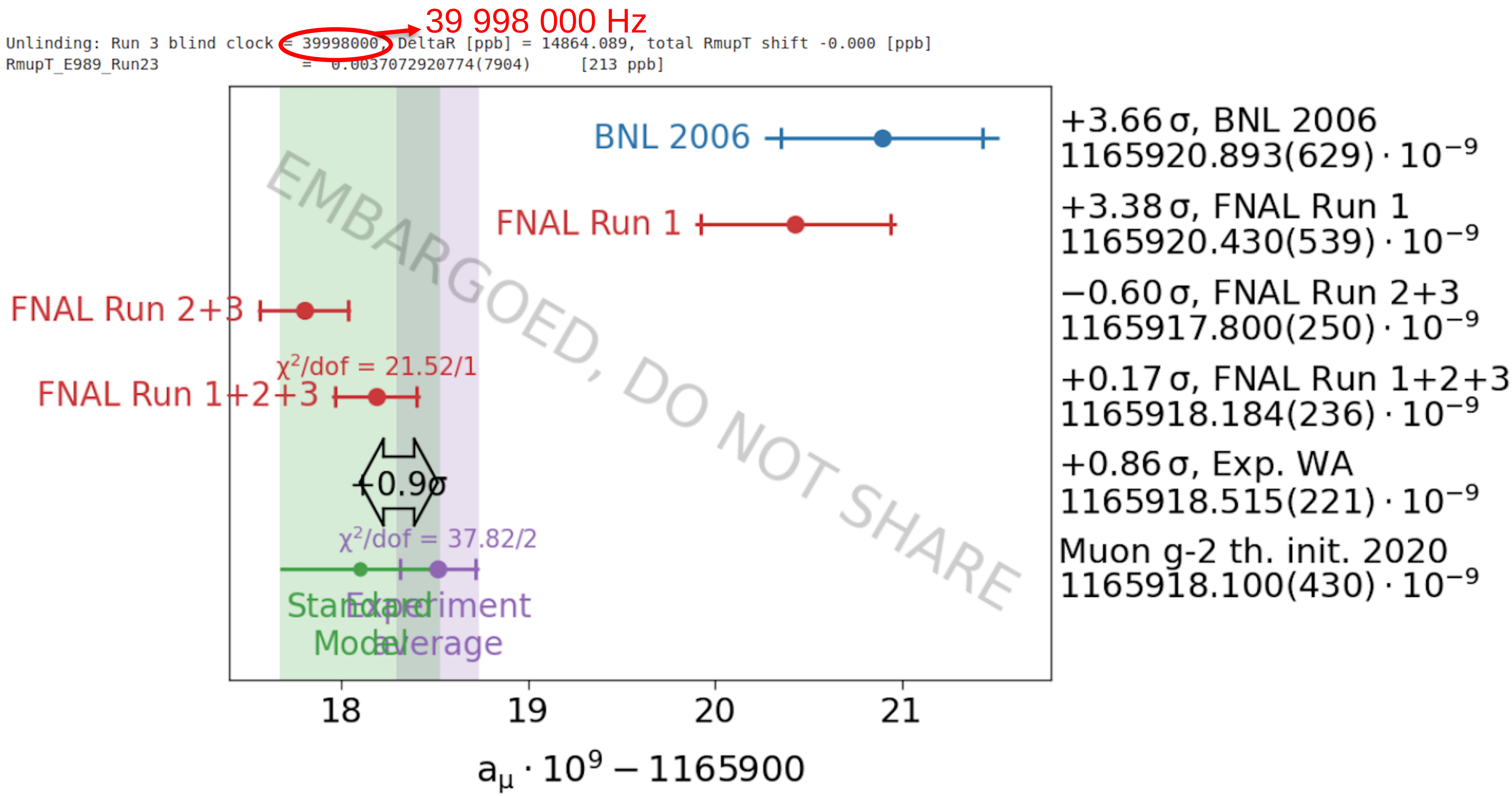
Photo credits: McCoy Wynne

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

Fermilab

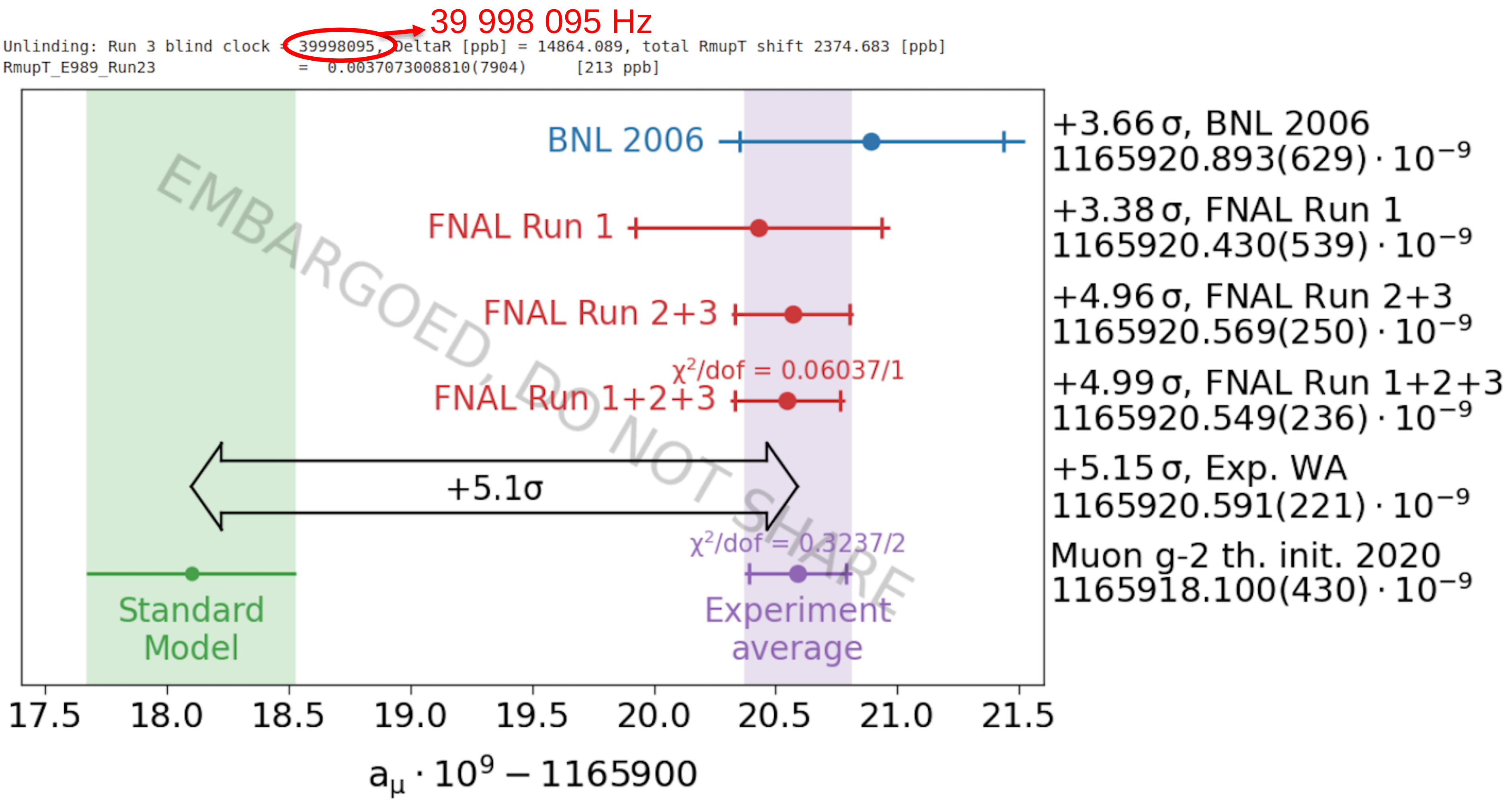
... a moment of panic!

- two layers of unblinding: software and hardware
- first the software unblinding was removed and the following image appeared on screen: few seconds of panic!



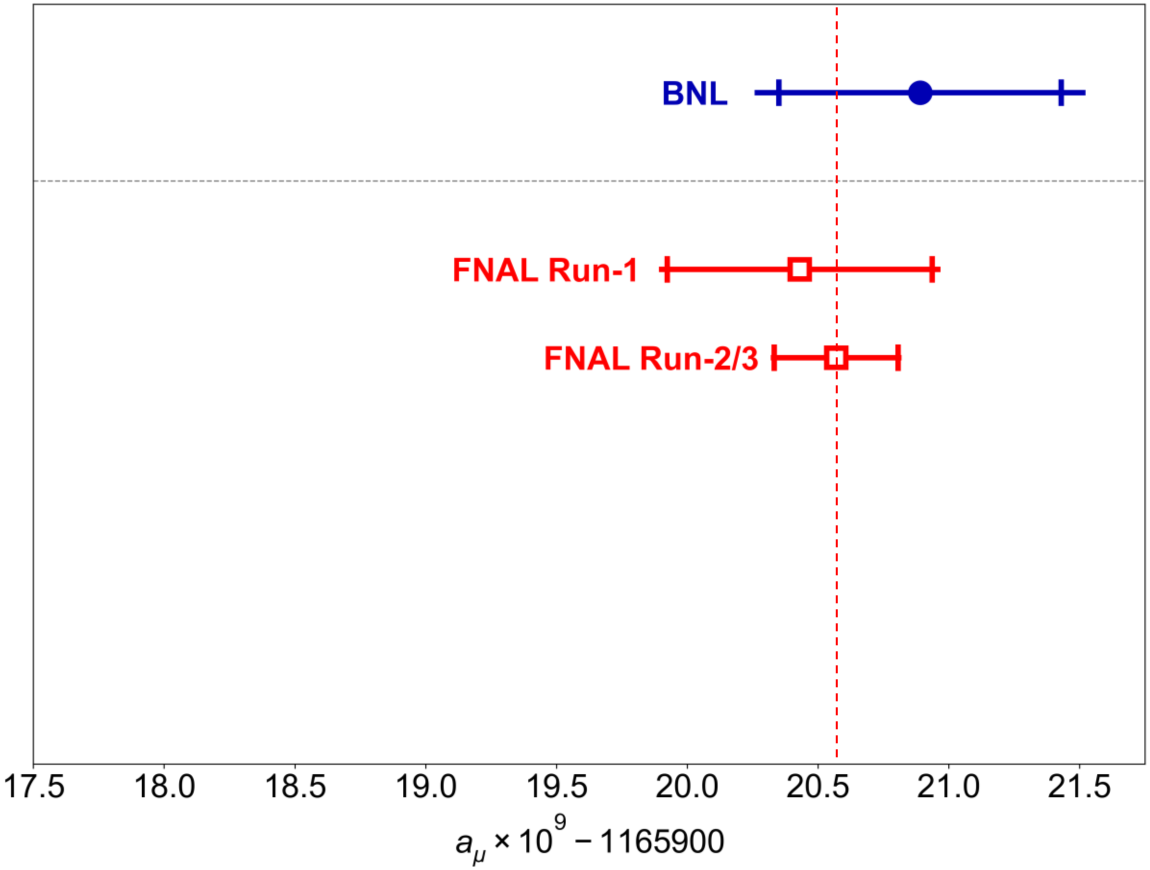
After inserting the secret frequency ...

- The secret frequency, written in the two envelopes, was inserted in the program



Run-2/3 Result: Measured Value

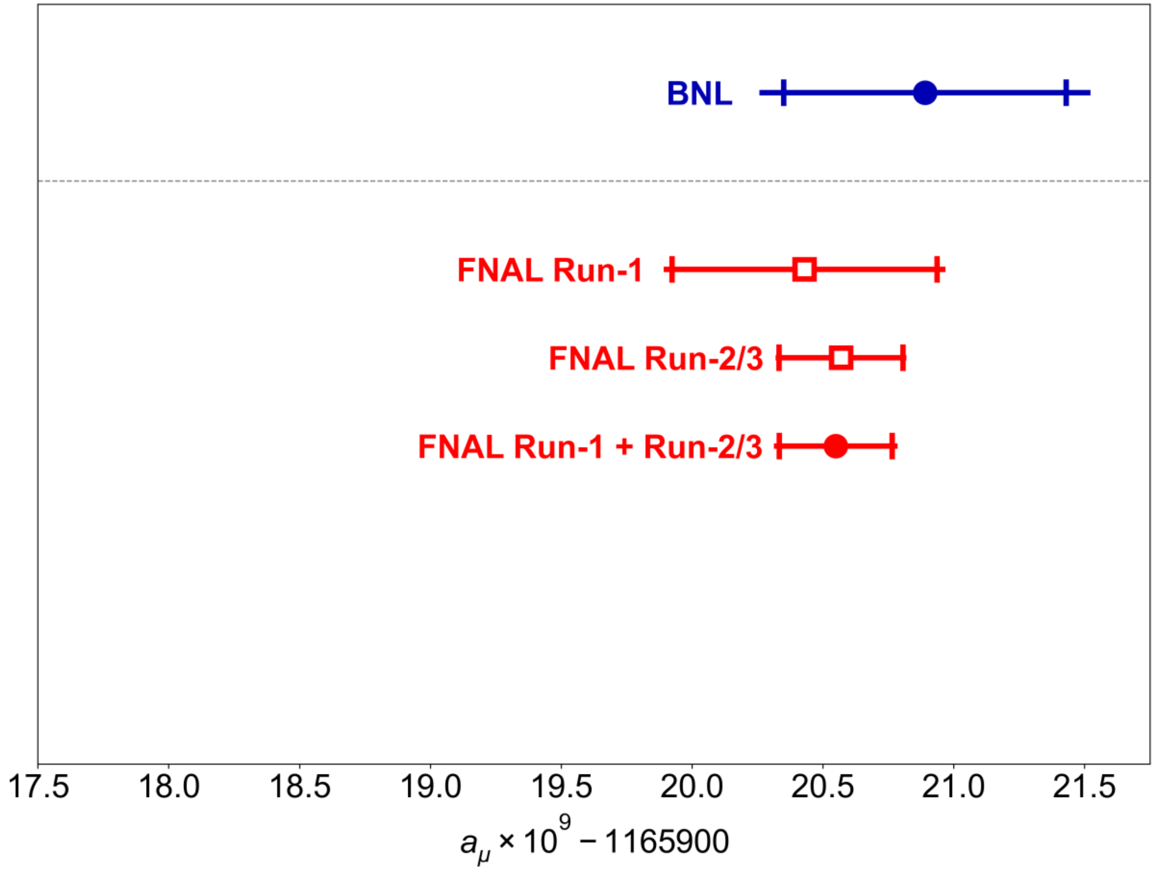
a_μ(FNAL; Run-2/3) = 0.00 116 592 057(25) [215 ppb]



- **Excellent agreement with Run-1 and BNL!**
- Uncertainty more than halved to **215 ppb**
- Both FNAL values dominated by statistical error
- Assume systematics are 100% correlated and combine…

Run-2/3 Result: FNAL Run-1 + Run-2/3 Combination

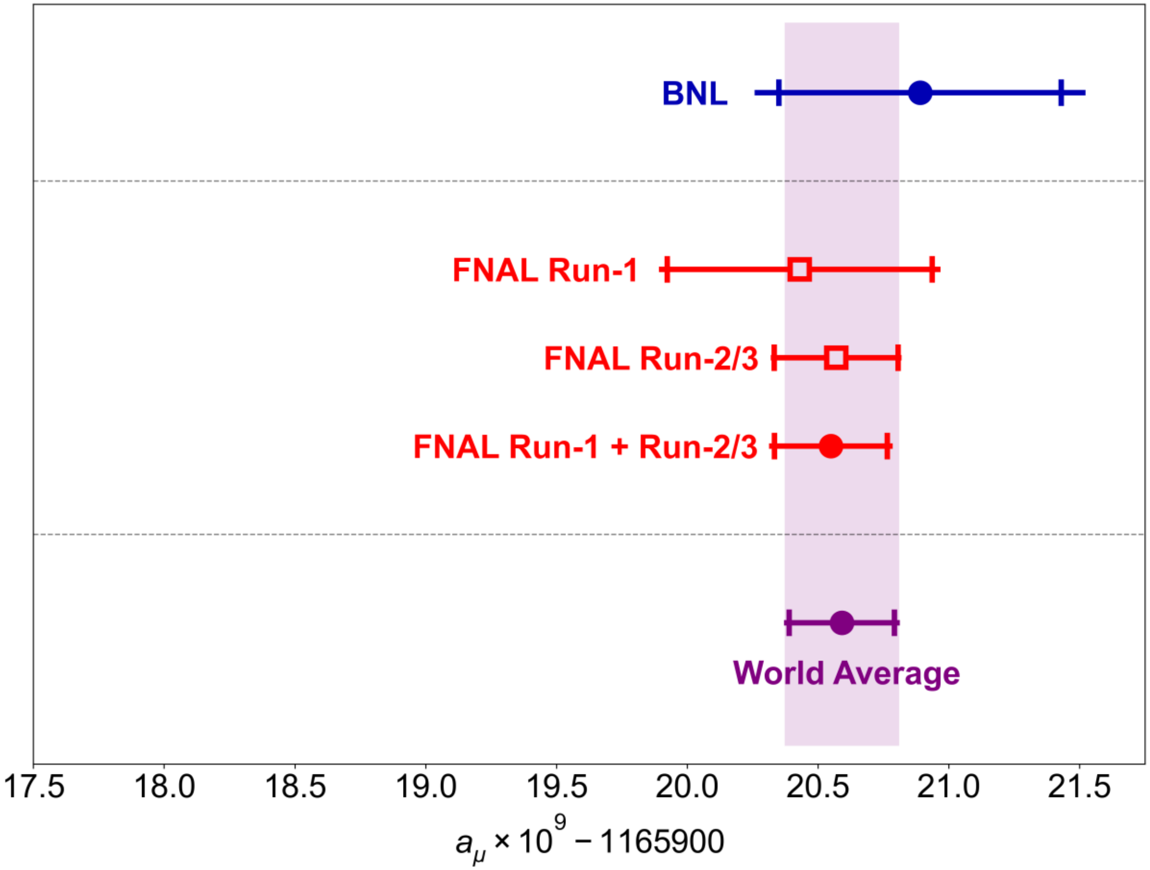
a_μ(FNAL) = 0.00 116 592 055(24) [203 ppb]



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

Run-2/3 Result: FNAL + BNL Combination

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

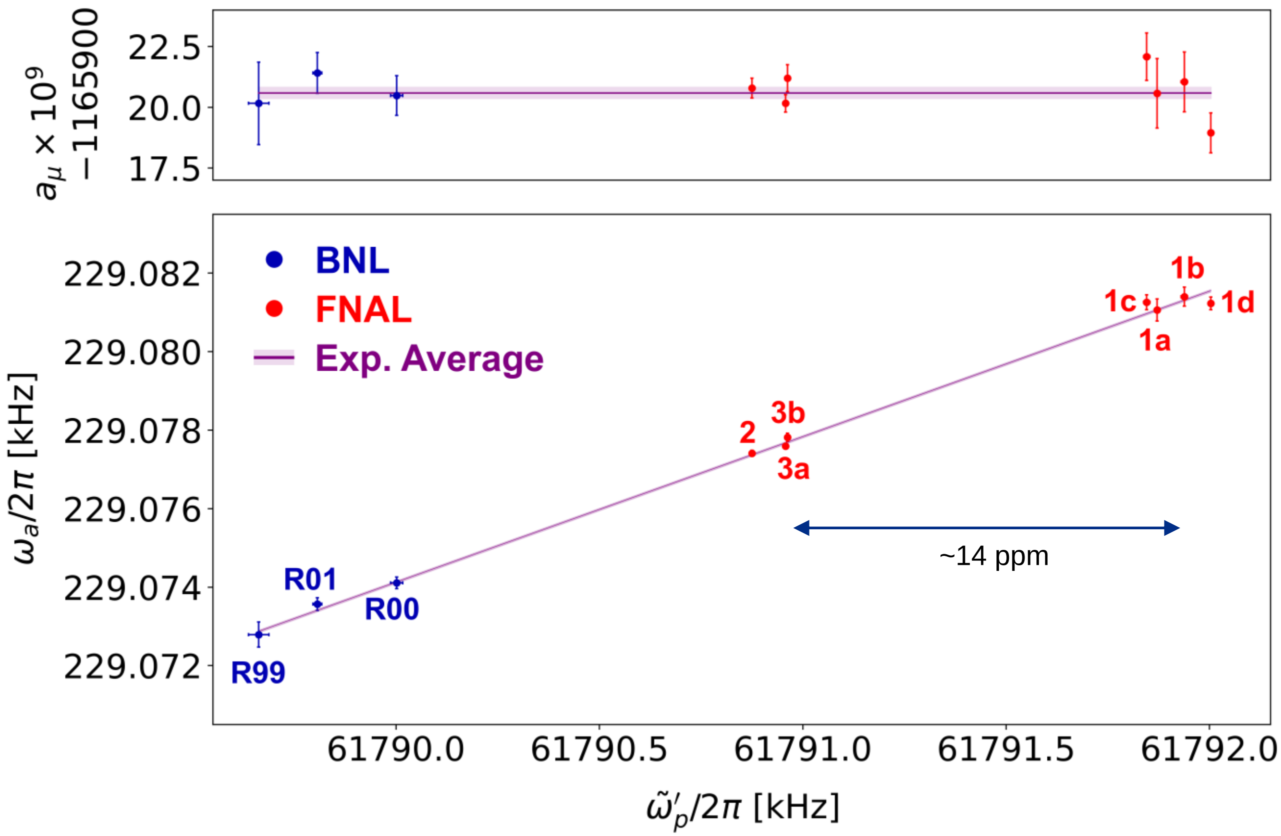


- FNAL combination: **203 ppb** uncertainty
- Both FNAL and BNL dominated by statistical error
- Combined world average **dominated by FNAL** values.

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

Measurements at Different Magnetic Fields

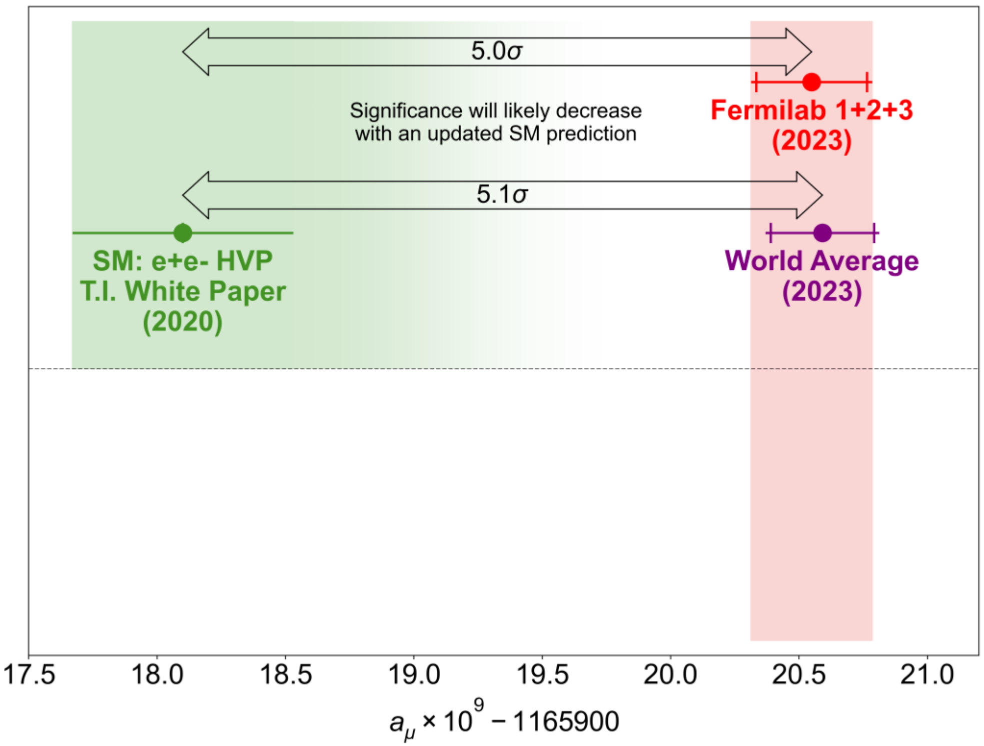
- Datasets were taken at slightly different field settings
- Allows a cross check with one of the most basic “handles”:



- Also checked a_μ against temperature, day/night & others

Experiment vs Theory Comparison

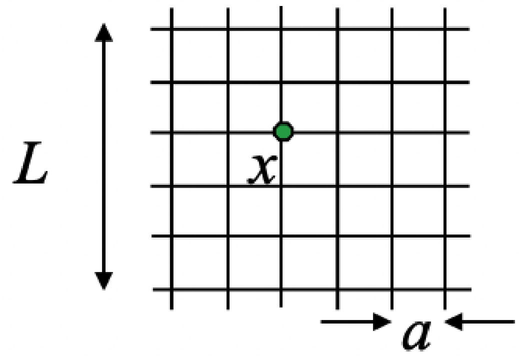
- Theory prediction is less clear now, but we can still compare

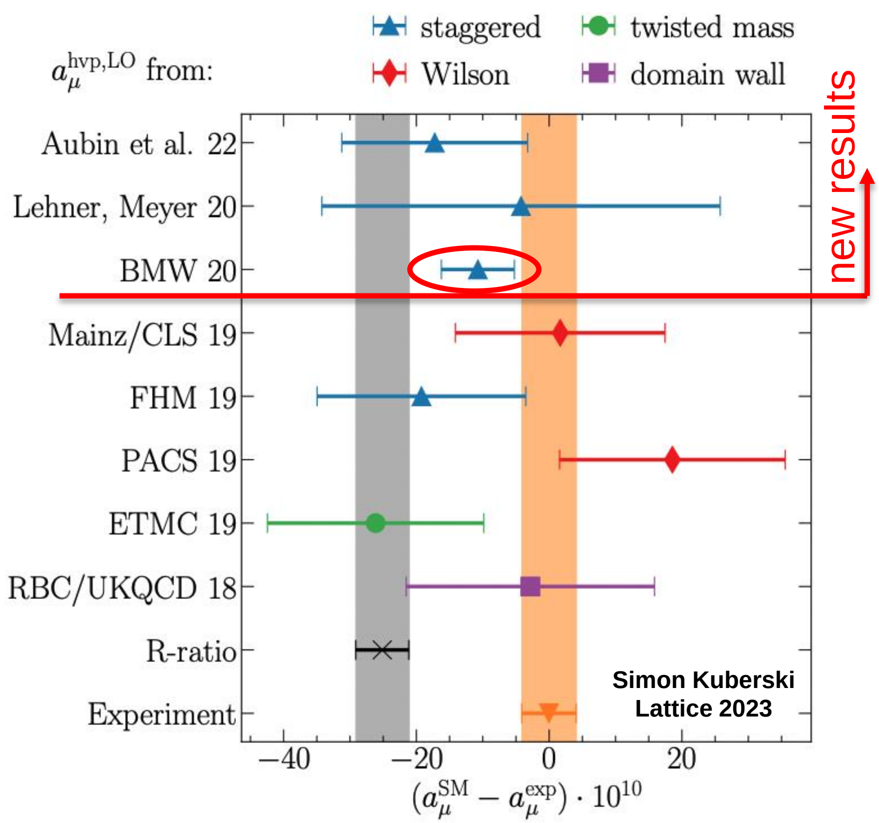


- Large discrepancy between experiment and WP (2020)
- Significance for **Fermilab alone** get to **5.0σ**
- ... but the theoretical band is not as sharp as it was in the 2021 comparison!

HVP Calculation: Lattice QCD Method

- ***Ab-initio*** calculation of HVP on lattice
- Results **not included** in White Paper (2020)

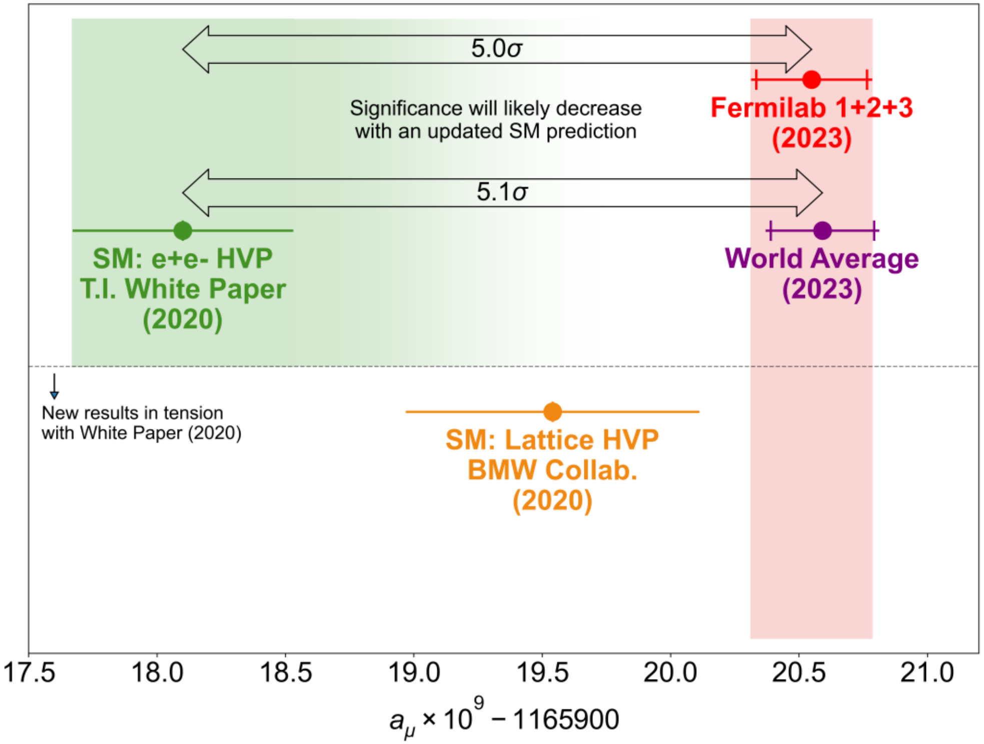




- **BMW** collaboration reached the precision of 0.8%, comparable to R-ratio method
- Their calculation is closer to the experimental result
- Other groups are cross checking
- Intermediate stages agree, but no full HVP calculations to same precision.

Experiment vs Theory Comparison

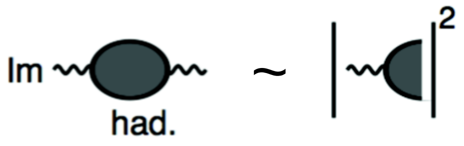
- Theory prediction is less clear now, but we can still compare



- Include **BMW** result by swapping HVP from WP with their value
- As expected, BMW falls **in between** WP (2020) and experiment

HVP Calculation: Dispersive (e^+e^-) Method

- Calculated from data for $\sigma(e^+e^- \rightarrow \text{hadrons})$



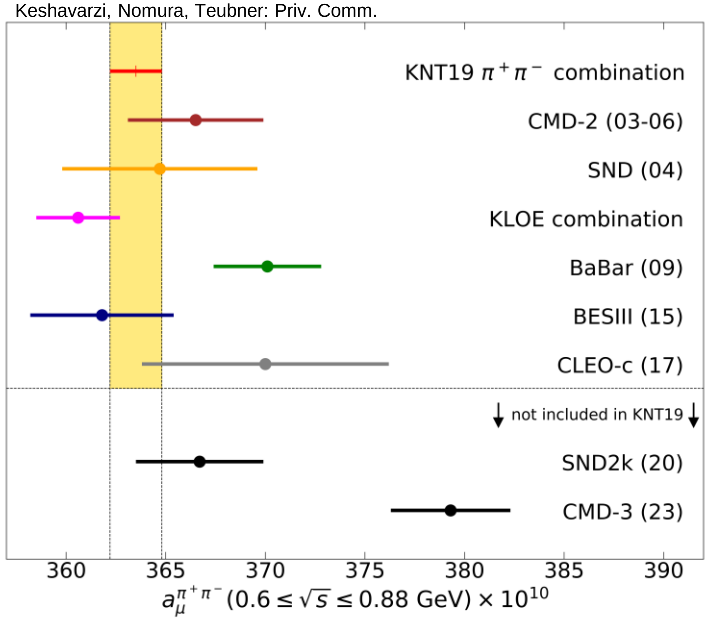
Analyticity & Unitarity

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

Hadronic R-ratio (Data Driven)

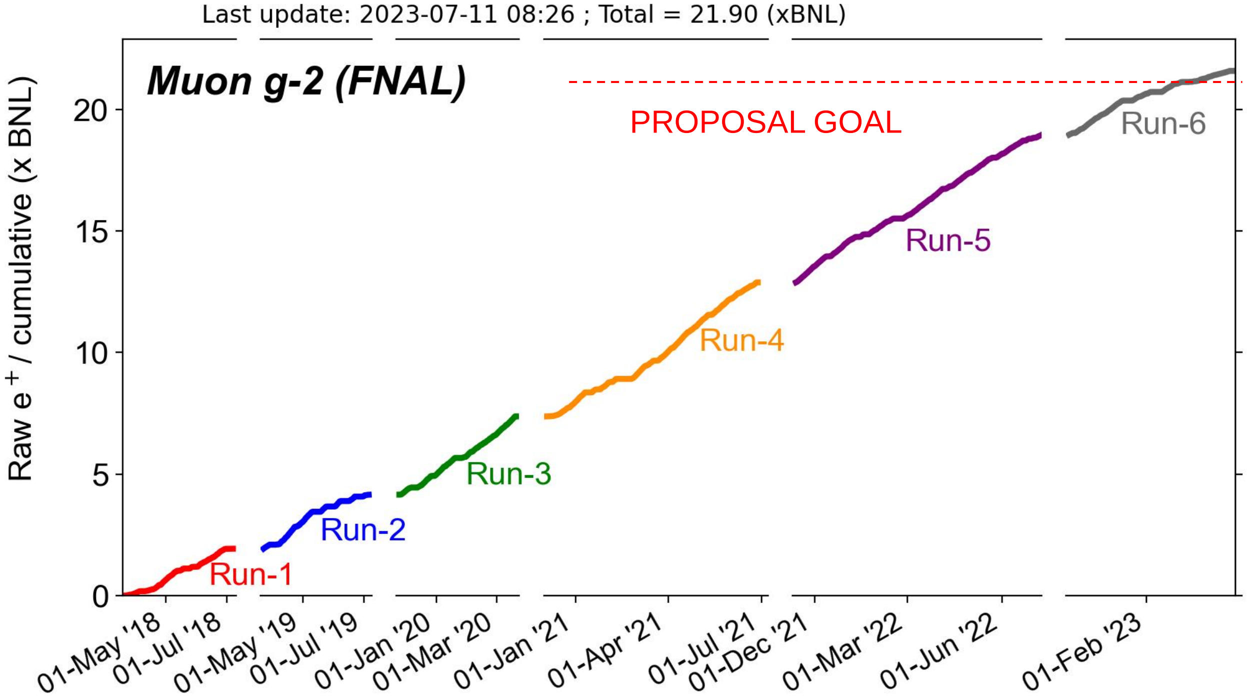
- Uses **data** from different experiments from **20+ years**
- 1/s weights low energy strongly: 73% from **$\pi^+\pi^-$ channel**

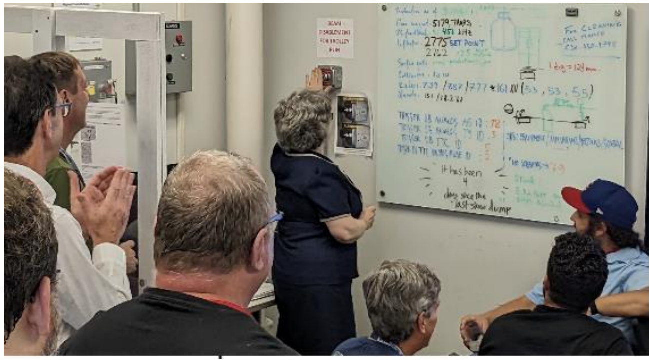
Keshavarzi, Nomura, Teubner: Priv. Comm.



- New results from **SND2k** and **CMD-3** since White Paper
- **CMD-3 is discrepant**
- ... what is going on?

Data Collection 2018 – 2023





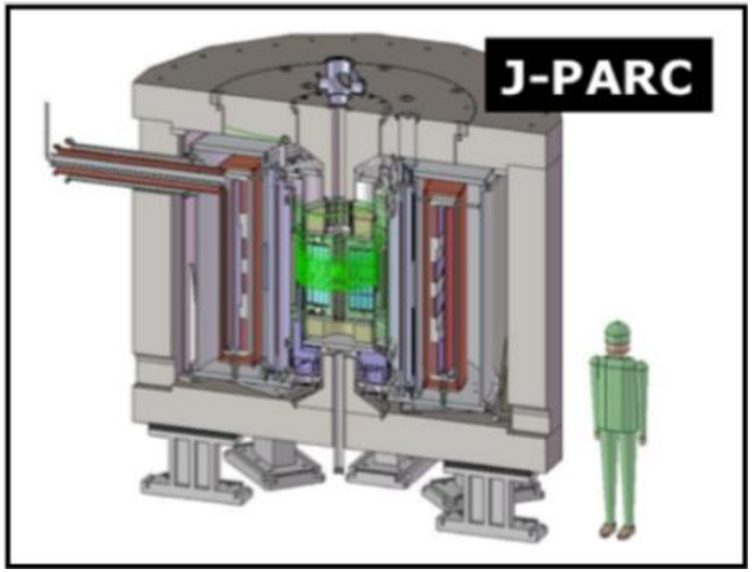
9 July 2023
Director Lia Merminga switches off the beam in *Muon g-2* control room

- **Apr. 2021:** **Run-1 Result** (2018 data)
- **Aug. 2023:** **Run-2/3 Result** (2019-20 data)
- **~2025:** **Run-4+5+6 Result** (2021-23 data)
  - Reach our proposal goal for statistics (~21 BNL)

The experimental landscape will improve …

1. FNAL Muon g-2 :
   - **a_μ measured at 0.2 ppm**
   - data already available to reduce error to < 0.14 ppm

2. A new type of experiment projected at J-Parc using low energy muons (p~300 MeV/c)
   - new technique
   - under construction
   - final goal ~0.4 ppm



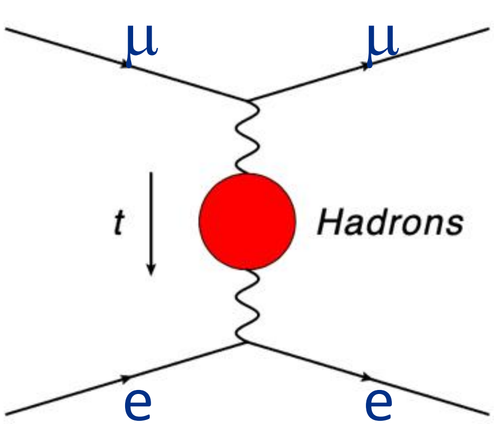
The experimental landscape will improve …

Ongoing work in experimental inputs on $\sigma(e^+e^- \rightarrow \text{hadrons})$

- Initial State Radiation technique:
  - BaBar: new analysis of large $\pi\pi$ data set with better detector
  - KLOE: new analysis of 7x larger $\pi\pi$ set
  - BESIII: new results for $\pi\pi$ channel and $\pi\pi\pi$
  - Belle II: promising greater statistics than BaBar or KLOE and similar or better systematics for low-energy cross sections
- Energy scan (VEPP-2000 machine in Novosibirsk)
  - SND: new results for $\pi\pi$ channel
  - CMD-3: confirmation of their result on $\pi\pi$ channel; more channels to be analyzed

The theoretical landscape will improve …

1. close scrutiny of lattice calculations to establish its solidity
   – how to reconcile it with dispersion approach?
2. Use the dispersive approach with t-channel data (*muon-electron* scattering), instead of the standard s-channel
   – Letter Of Intents submitted at CERN: *Muone (mu-on-e scattering)*



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

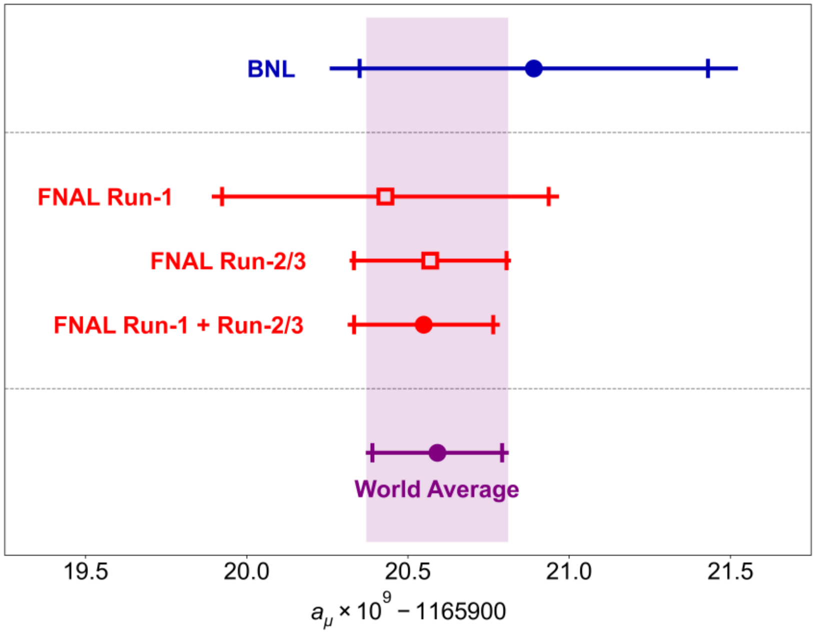
$$t(x) = \frac{x^2 m_\mu^2}{x-1} < 0$$

Lautrup, Peterman, de Rafael, 1972

$\Delta\alpha_{had}(t)$ is the hadronic contribution to the running of α in the spacelike region: a_μ^{HLO} can be extracted from scattering data!

Conclusions

- We've determined a_μ to an unprecedented **203 ppb** precision



- New result is in **excellent agreement** with **Run-1 & BNL**

- More than **halved the total uncertainty** from Run-1

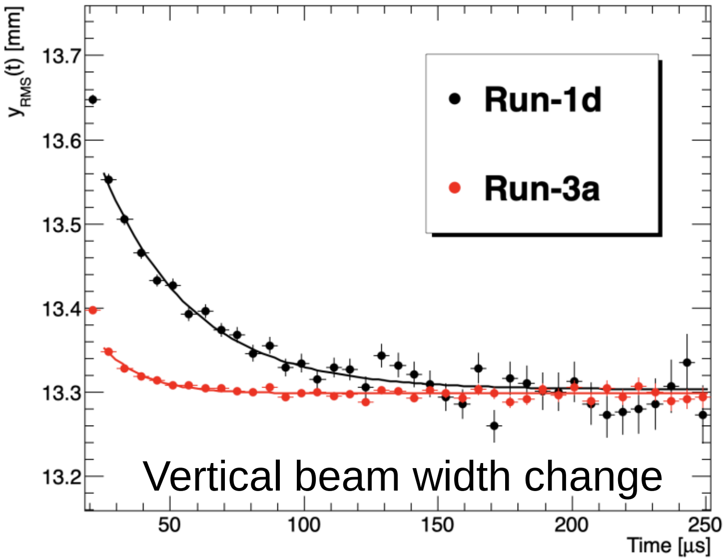
- **Smashed our design goal** with systematic uncertainty of **70 ppb**.

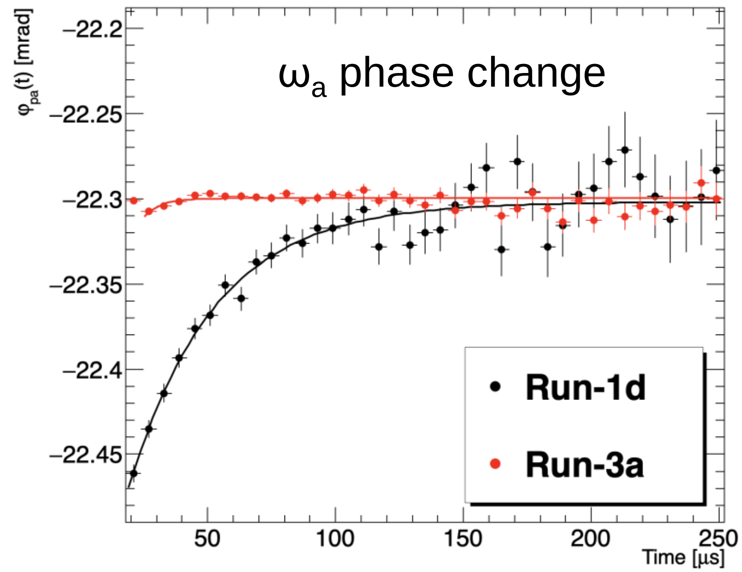
- There's **more data** to analyze and we'll squeeze uncertainty down further in our future results!

EXTRAS

Running Conditions: Damaged Quad Resistors

- Run-1 had **damaged resistors** in 2/32 quad plates leading to **unstable beam storage**
- Resistors re-designed & **replaced before Run-2**

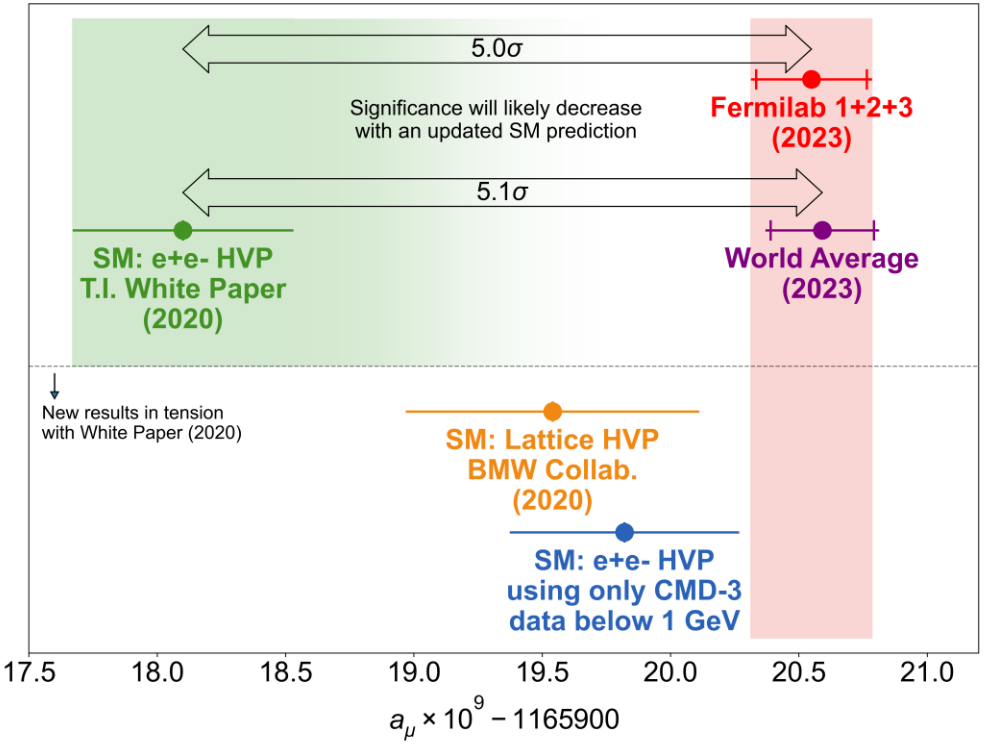




- $\mathbf{C_{pa}}$ uncertainty is reduced (**75 ppb → 13 ppb**)
- Beam **oscillation frequencies** are also **more stable**

Experiment vs Theory Comparison

- Theory prediction is less clear now, but we can still compare



Disclaimer from A. Keshavarzi's Lattice 2023 talk:

IMPORTANT: THIS PLOT IS VERY ROUGH!
- TI White Paper result has been substituted by CMD-3 only for 0.33 → 1.0 GeV.
- The NLO HVP has not been updated.
- It is purely for demonstration purposes → should not be taken as final!

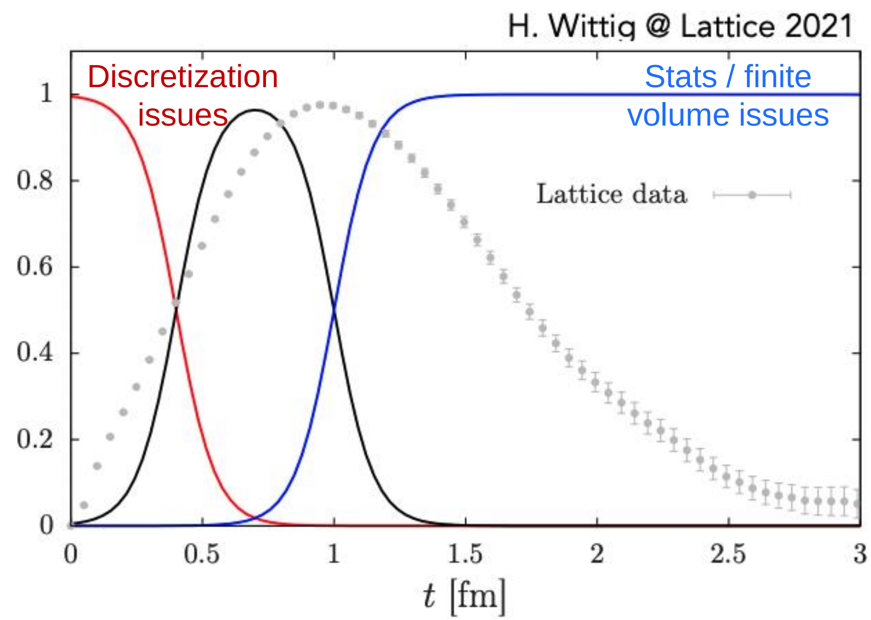
Following A. Keshavarzi at Lattice 2023…

- Substitute **CMD-3** data for HVP below 1 GeV
- Cherry-picking one experiment but gives a bounding case
- **SND2k** cannot be processed in this way, but would fall closer to WP (2020).
- Many **parallel efforts are underway** to resolve the theoretical ambiguity

Theory Prediction
Lattice QCD

HVP Calculation: Lattice QCD Method Status

- Other groups are working to reproduce BMW result
- Start with “windowing” method and compare in easiest region

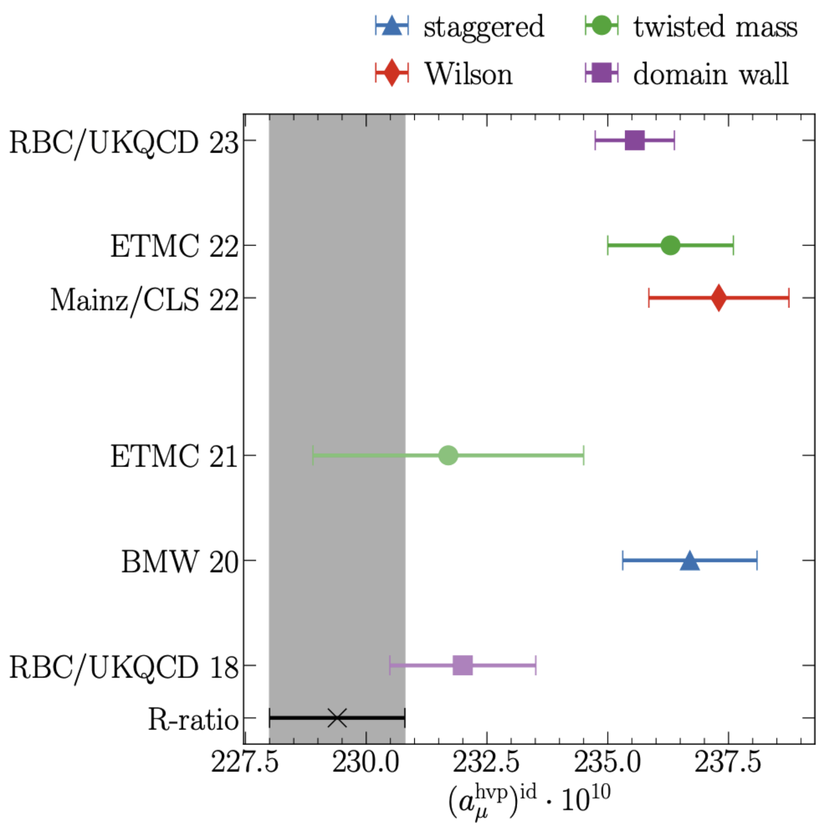


- Cut off effects suppressed
- No signal-to-noise problem
- Finite-volume effects small

HVP Calculation: Lattice QCD Method Status

Simon Kuberski, Lattice 2023

The intermediate-distance window



- $3.8\,\sigma$ tension between lattice QCD and data-driven evaluation [Colangelo et al., 2205.12963].
- This accounts for 50% of the difference between BMW 20 and the White Paper average for a_μ^{hvp}.

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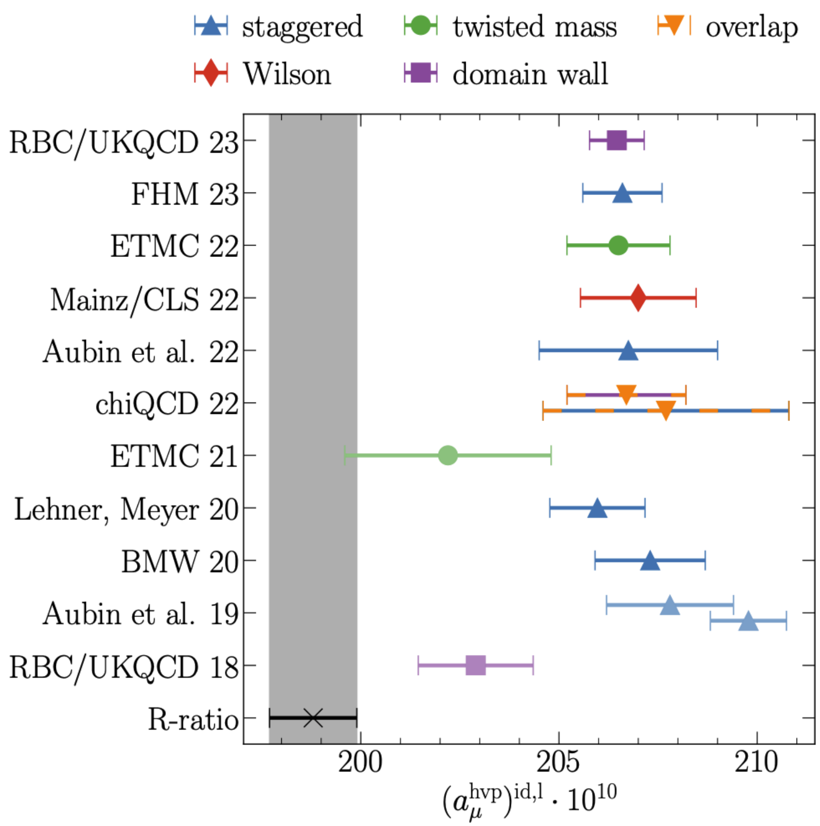
HVP Calculation: Lattice QCD Method Status

Simon Kuberski, Lattice 2023

The intermediate-distance window



- $3.8\,\sigma$ tension between lattice QCD and data-driven evaluation [Colangelo et al., 2205.12963].
- This accounts for 50% of the difference between BMW 20 and the White Paper average for $a_\mu^{\rm hvp}$.
- Agreement across many actions for the light-connected contribution (87%).
- Data-driven estimate: [Benton et al., 2306.16808] [Golterman]

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Theory Prediction
Future Prospects

Dispersive Approach: Future Prospects for HVP

A. El-Khadra P5 town hall, 21-24 Mar 2023

Ongoing work on experimental inputs:

- BaBar: new analysis of large data set in $\pi\pi$ channel, also $\pi\pi\pi$, other channels, other channels
- KLOE: new analysis of large data in $\pi\pi$ channel, other channels
- SND: new results for $\pi\pi$ channel, other channels in progress
- BESIII: new results in 2021 for $\pi\pi$ channel, continued analysis also for $\pi\pi\pi$, other channels
- Belle II: arXiv:2207.06307 (Snowmass WP)
  Better statistics than BaBar or KLOE; similar or better systematics for low-energy cross sections
- STCF: arXiv:2203.06961
- Need blind analyses to resolve the tensions (esp. for $\pi\pi$ channel)

Ongoing work on theoretical aspects:

- Developing NNLO Monte Carlo generators (STRONG 2020 workshop https://agenda.infn.it/event/28089/) [➠ appendix]
- radiative corrections using FsQED (scalar QED + pion form factor)
- charge asymmetry (CMD-3 measurement) vs radiative corrections [Ignatov + Lee, arXiv:2204.12235]
- development of new dispersive treatment of radiative corrections in $\pi\pi$ channel [Colangelo at al, arXiv2207.03495]
- including τ decay data: requires nonperturbative evaluation of IB correction [M. Bruno et al, arXiv:1811.00508]

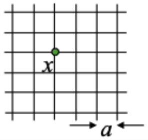
If the differences between experiments are resolved:
data-driven evaluations of HVP with $\sim 0.3\,\%$ feasible by ~2025

Fermilab

Lattice QCD: Future Prospects for HVP

A. El-Khadra P5 town hall, 21-24 Mar 2023

HVP: lattice



Ongoing work:

Evaluations of short-distance windows [ETMC, RBC/UKQCD]

Proposals for computing more windows:

- Use linear combinations of finer windows to locate the tension (if it persists) in $\sqrt{s}$ [Colangelo et al, arXiv:12963]
- Use larger windows, excluding the long-distance region $t \gtrsim 2\,\mathrm{fm}$ to maximize the significance of any tension [Davies at at, arXiv:2207.04765]

For total HVP:

- independent lattice results at sub-percent precision: coming soon!
- Including $\pi\pi$ states for refined long-distance computation (Mainz, RBC/UKQCD, FNAL/MILC)
- include smaller lattice spacings to test continuum extrapolations (needs adequate computational resources)

If results are consistent, Lattice HVP (average) with $\sim 0.5\,\%$ errors feasible by 2025

Theory vs Experiment

Differences between a_μ values:

Sigma deviation between different predictions/measurements

	FNAL 2023 (World Ave)	WP 2020	BMW	CMD-3
Exp	-			
WP 2020	5.0 (5.1)	-		
BMW	1.6 (1.7)	2.0	-	
CMD-3	1.4 (1.5)	2.8	0.4	-

- Comparisons are taken from the whole a_μ value.
- They're accurate when comparing to experiment
- But e.g. WP (2020) & BMW both include same H-LbL components and error, so significance of difference between them is a little underestimated (2.0 vs 2.2σ).

BSM Physics

Discrepancy and New Physics:

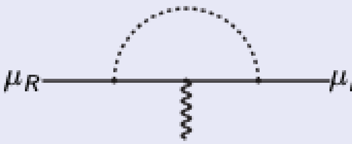
(Experimentalist's (mis)Understanding)

D. Stöckinger:

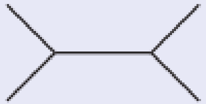
discrepancy $\approx 2 \times a_\mu^{\mathrm{SM,weak}}$

but: expect $a_\mu^{\mathrm{NP}} \sim a_\mu^{\mathrm{SM,weak}} \times \left(\frac{M_W}{M_{\mathrm{NP}}}\right)^2 \times$ couplings

loop-induced, CP- and Flavor-conserving, chirality-flipping



compare:



EDMs, $b \to s\gamma$, $B \to \tau\nu$, $\mu \to e\gamma$

EWPO

Fermilab

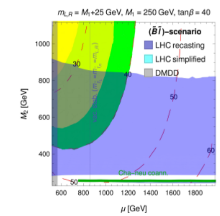
Discrepancy and New Physics:
(Experimentalist's (mis)Understanding)

D. Stöckinger: https://arxiv.org/abs/2104.03691

Which models can still accommodate large deviation?

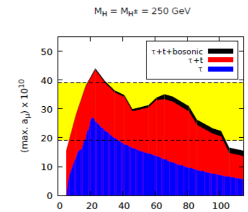
SUSY: MSSM, MRSSM

- MSugra... many other generic scenarios
- Bino-dark matter+some coannihil.+mass splittings
- Wino-LSP+specific mass patterns



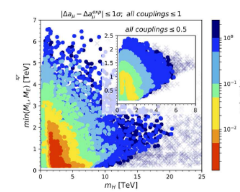
Two-Higgs doublet model

- Type I, II, Y, Type X(lepton-specific), flavour-aligned



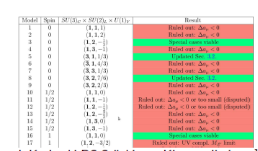
Lepto-quarks, vector-like leptons

- scenarios with muon-specific couplings to μ_L and μ_R



Simple models (one or two new fields)

- Mostly excluded
- light N.P. (ALPs, Dark Photon, Light $L_\mu - L_\tau$)

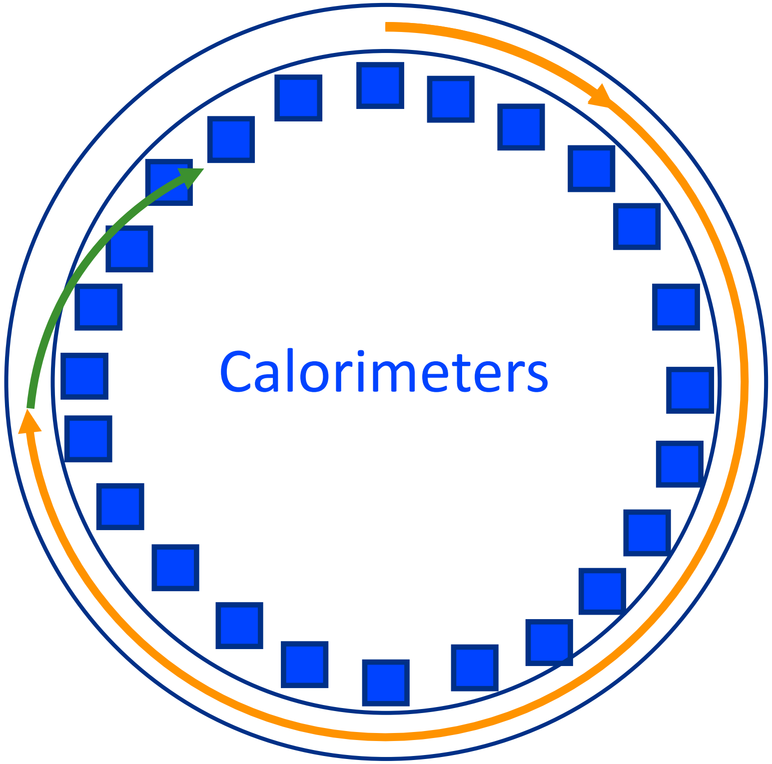


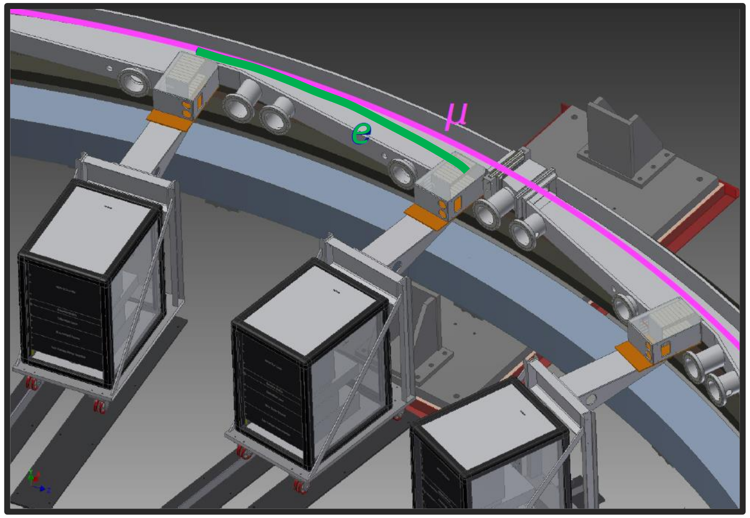
[Athron,Balazs,Jacob,Kotlarski,DS,Stöckinger-Kim, preliminary]

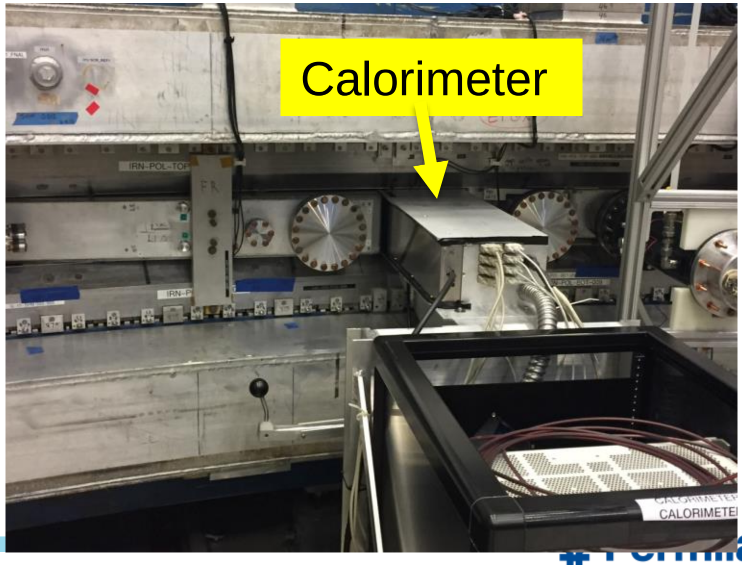
Detectors

Calorimeter Location

- 24 EM calorimeters inside the ring to measure decay e^+

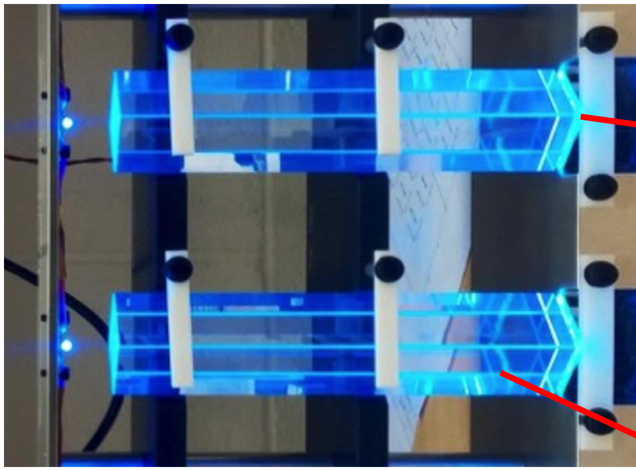


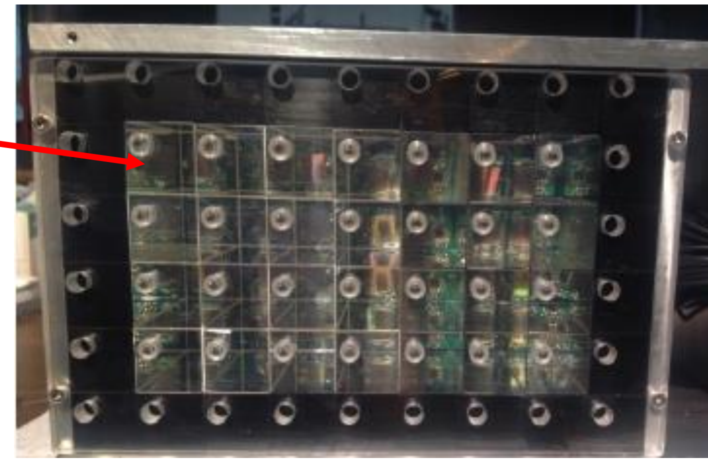




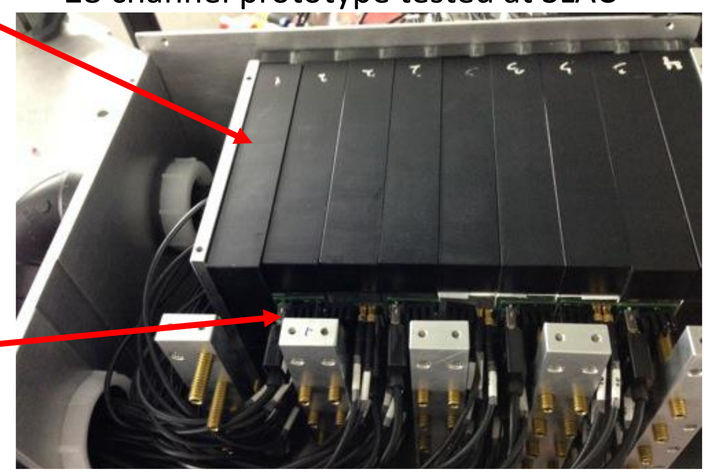
Calorimeter Design

- Array of 54 PbF_2 crystals - 2.5 x 2.5 cm^2 x 14 cm ($15X_0$)
- Readout by SiPMs to 800 MHz WFDs (1296 channels)



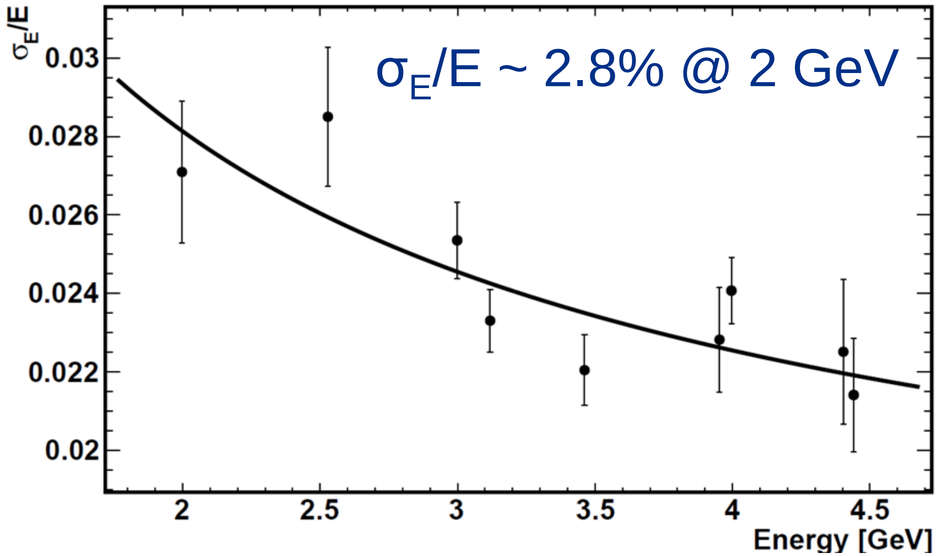


28 channel prototype tested at SLAC

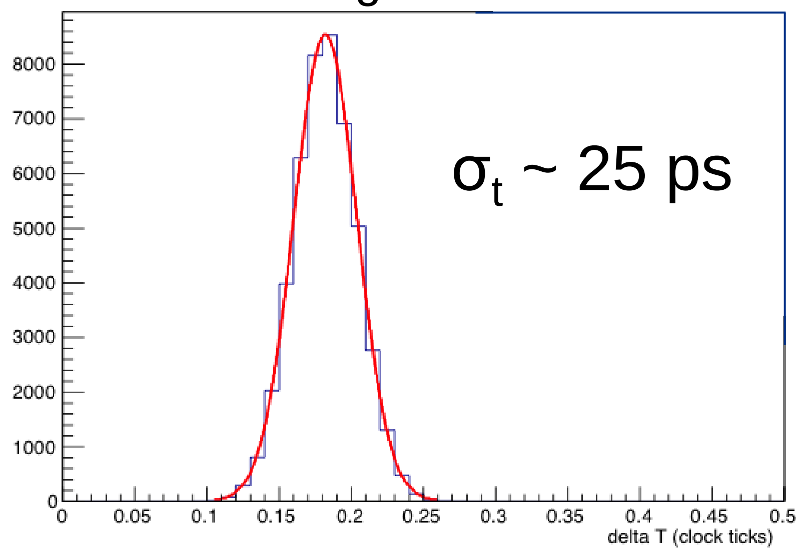


Calorimeter Performance

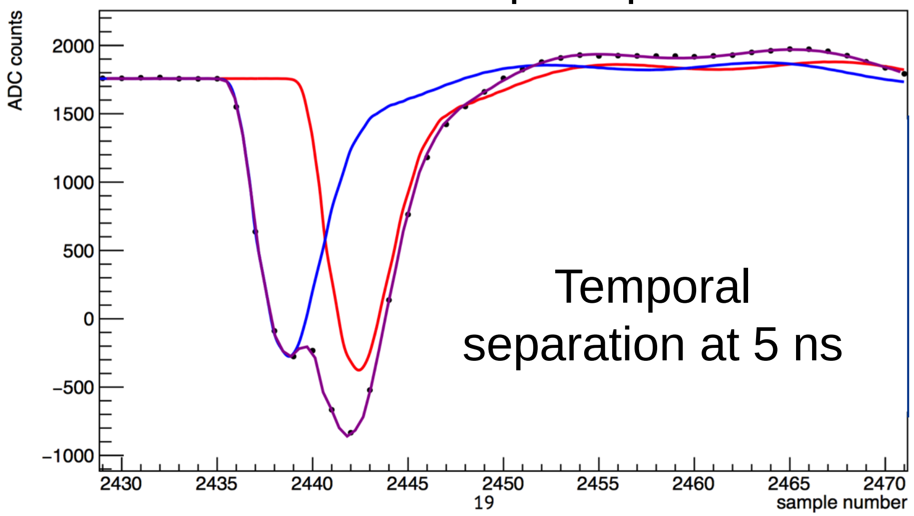
Energy Resolution



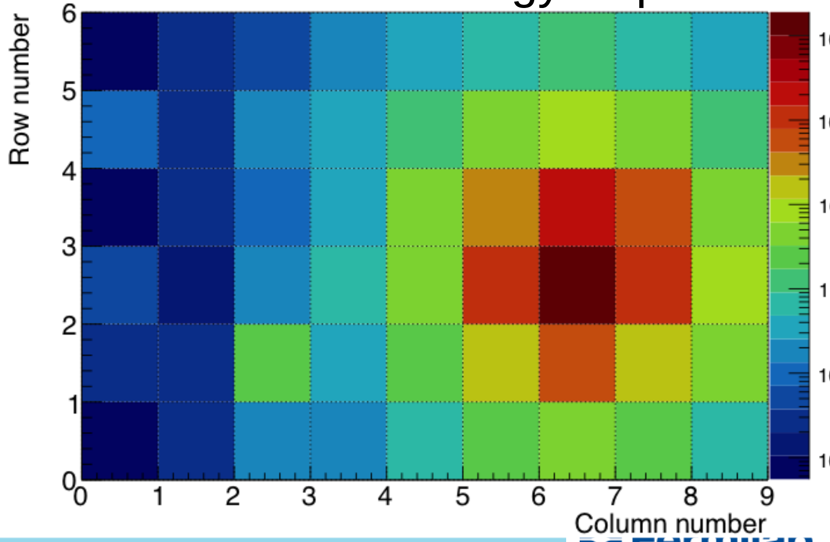
Timing Resolution



Electron pile-up



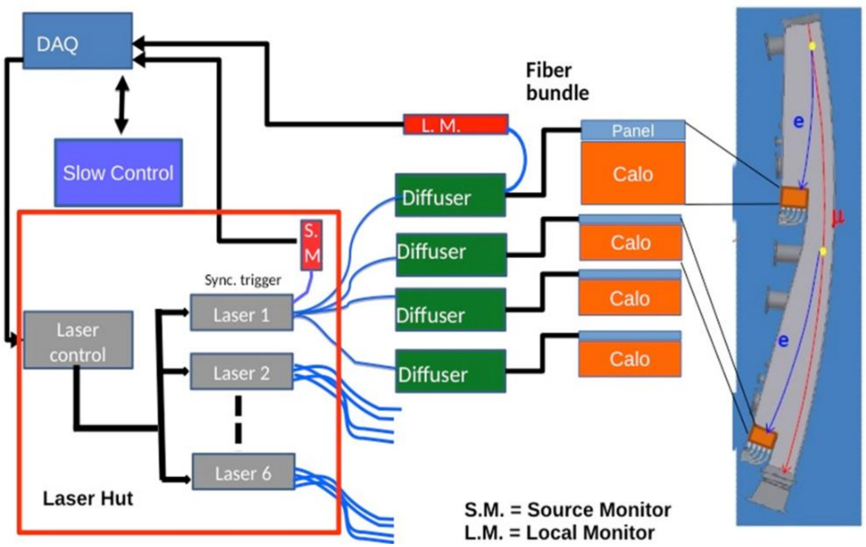
Position from Energy Deposit

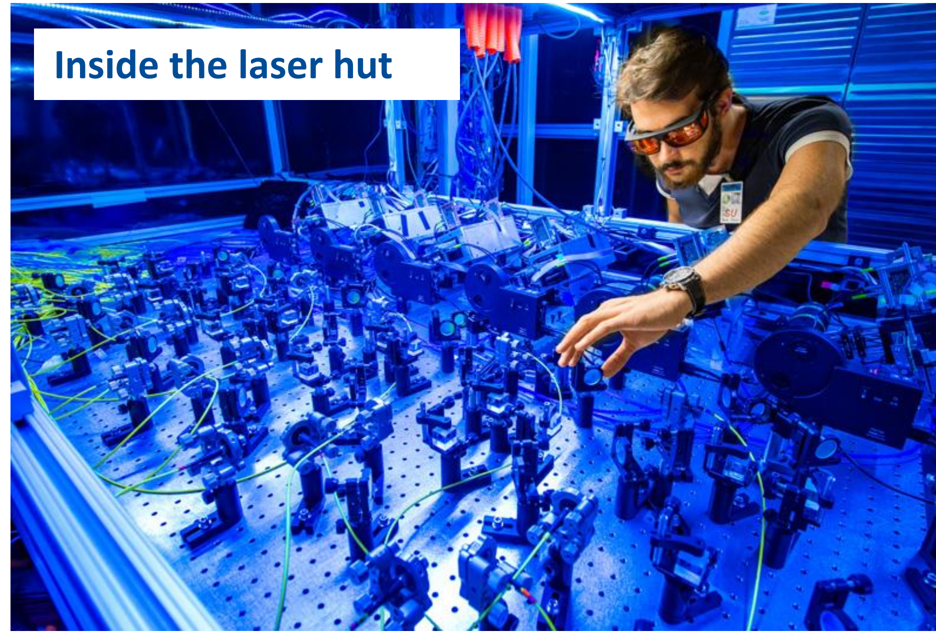


See NIM A 783 (2015), pp 12–21 for details

GAIN stability established to ~few x 10^{-4}

State-of-the-art Laser-based calibration system also allows for pseudo data runs for DAQ





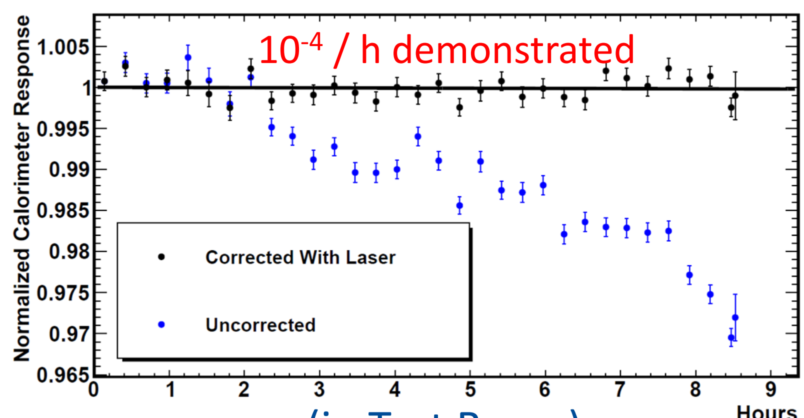
Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

Test of candidate light distributors for the muon (g – 2) laser calibration system

A. Anastasi [a,c], D. Babusci [a], F. Baffigi [b], G. Cantatore [d,g], D. Cauz [d,i], G. Corradi [a], S. Dabagov [a], G. Di Sciascio [f], R. Di Stefano [e,j], C. Ferrari [a,b], A.T. Fienberg [l], A. Fioretti [a,b], L. Fulgentini [b], C. Gabbanini [a,b,*], L.A. Gizzi [b], D. Hampai [a], D.W. Hertzog [l], M. Iacovacci [e,h], M. Karuza [d,k], J. Kaspar [l], P. Koester [b], L. Labate [b], S. Mastroianni [l], D. Moricciani [f], G. Pauletta [d,i], L. Santi [d,i], G. Venanzoni [a]

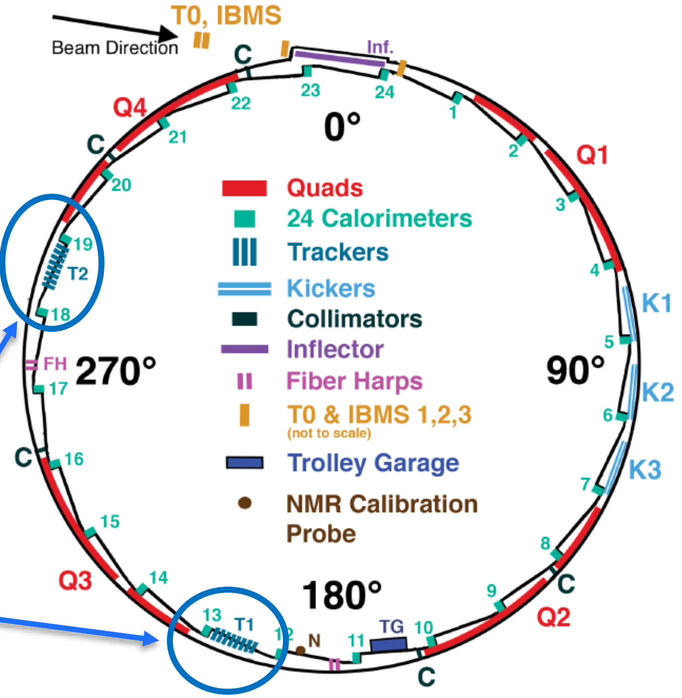


(in Test Beam)

Muon Distribution M_μ

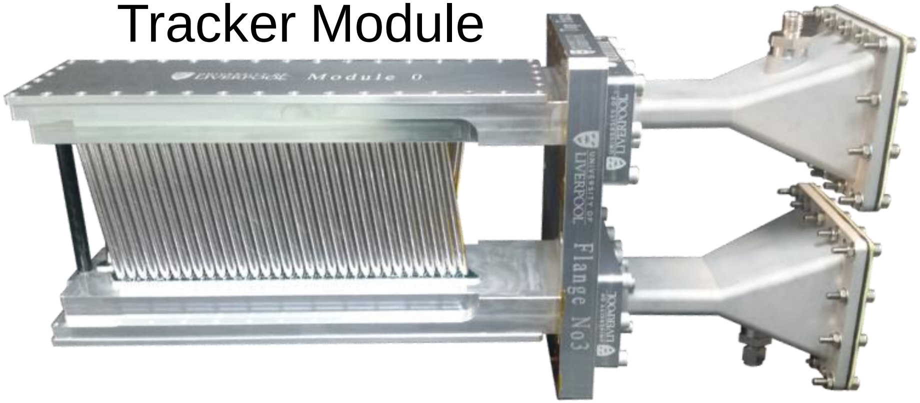
- Want the **field actually experienced by muons**, so need to know **where muons are** in the field map

- Measured with **two straw trackers** inside storage vacuum



Trackers

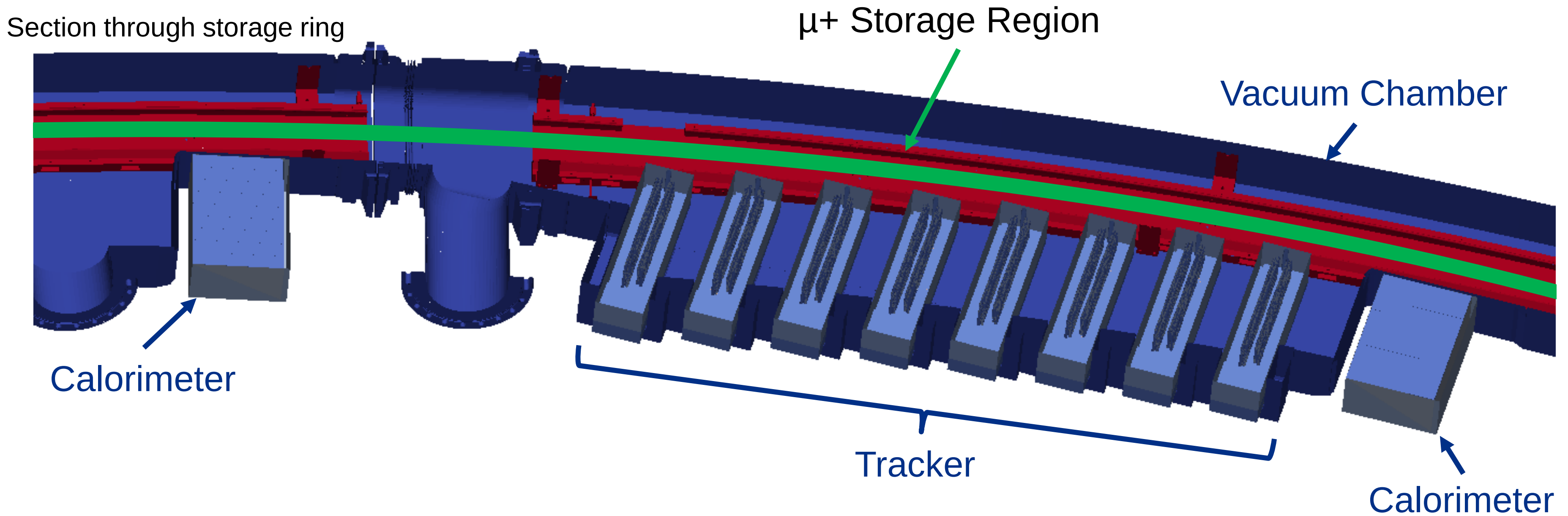
Tracker Module



Muon's view of a tracker

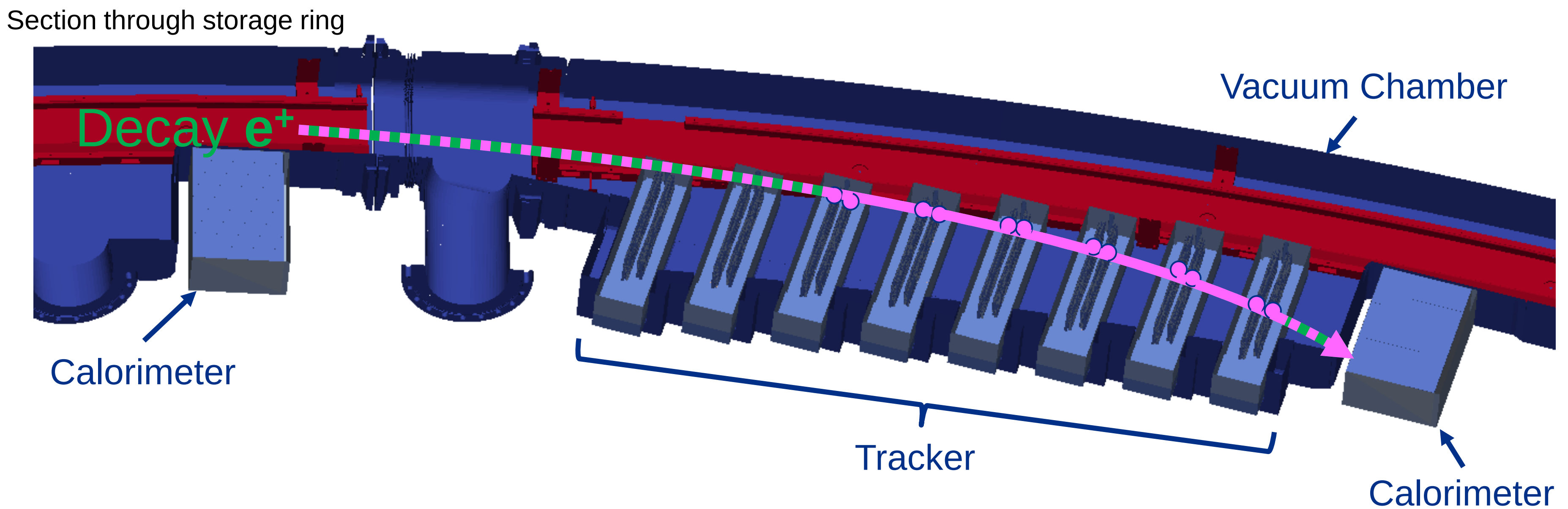
Tracker: Hawk-Eye with Muons

- Each tracker is made up of 8 modules inside vacuum chamber:



Tracker: Hawk-Eye with Muons

- A muon decays to a positron which travels through tracker



- e^+ position is recorded in tracker modules
- Hits are grouped and reconstructed into a track
- Track is extrapolated backwards to beam storage region

Corrections

E-field & Pitch Corrections:

- Non-simplified spin-motion is described by BMT equation:

Jackson Eq. (11.171)

$$\frac{d(\hat{\beta}\cdot\vec{S})}{dt} = -\frac{q}{m}\vec{S}_T\cdot\left[a_\mu\hat{\beta}\times\vec{B} + \beta\left(a_\mu - \cancel{\frac{1}{\gamma^2-1}}\right)\frac{\vec{E}}{c}\right]$$

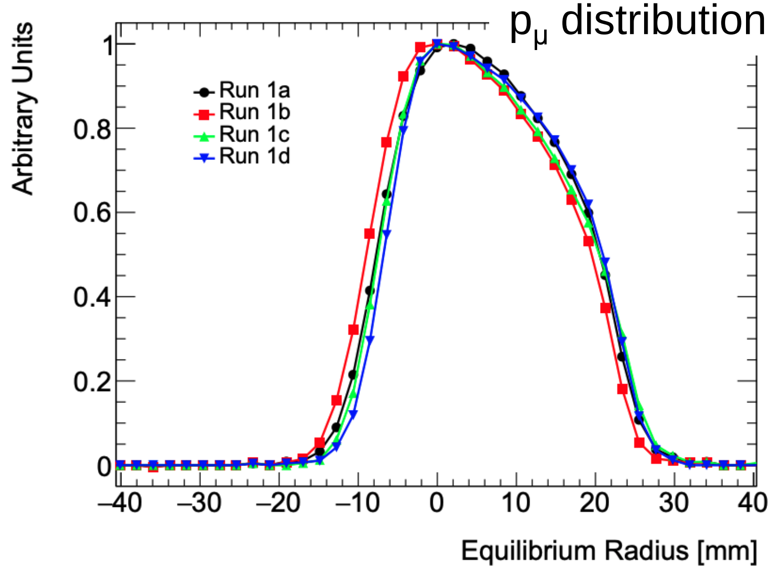
p_μ = 3.094 GeV

$\omega_a \propto a_\mu B$

- Muons travel in **E-field** from focusing quadrupoles: experience a **motional magnetic field** in their rest frame
- Term vanishes at "magic" momentum (p_μ = 3.094 GeV)
- But not all muons are at p_{magic}
- C_E comes from p_μ distribution measured using timing data from calorimeters

C_E = 489 ± 53 ppb

p_μ distribution



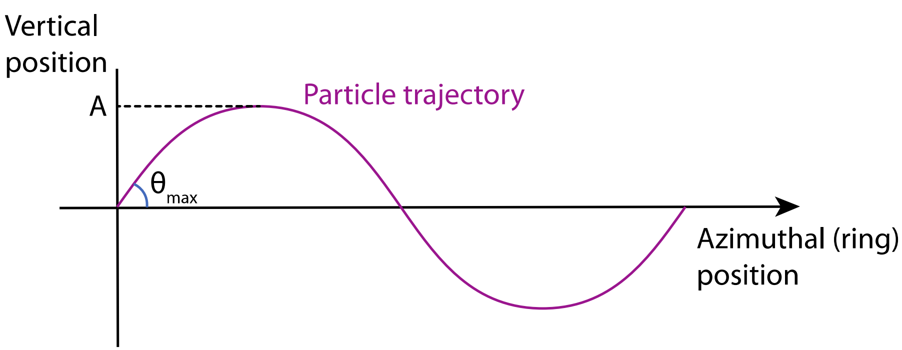
E-field & Pitch Corrections:

- Non-simplified spin-motion is described by BMT equation:

Jackson Eq. (11.171)

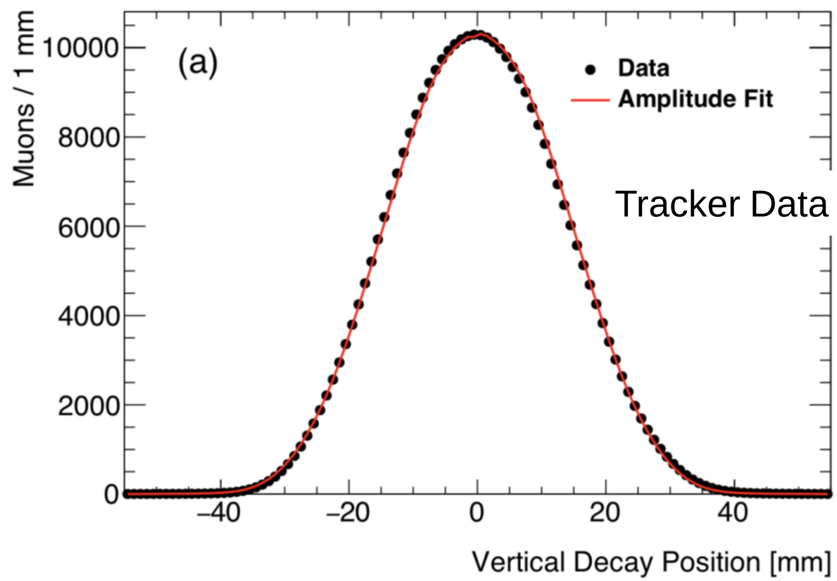
$$\frac{d(\hat{\beta}\cdot\vec{S})}{dt} = -\frac{q}{m}\vec{S}_T \cdot \left[a_\mu \hat{\beta}\times\vec{B} + \beta\left(a_\mu - \frac{1}{\gamma^2-1}\right)\frac{\vec{E}}{c}\right]$$

- Muons oscillate vertically **(pitch)** so $\hat{\beta}\times\vec{B}$ term is reduced



- C_P is extracted from vertical width measured by the trackers

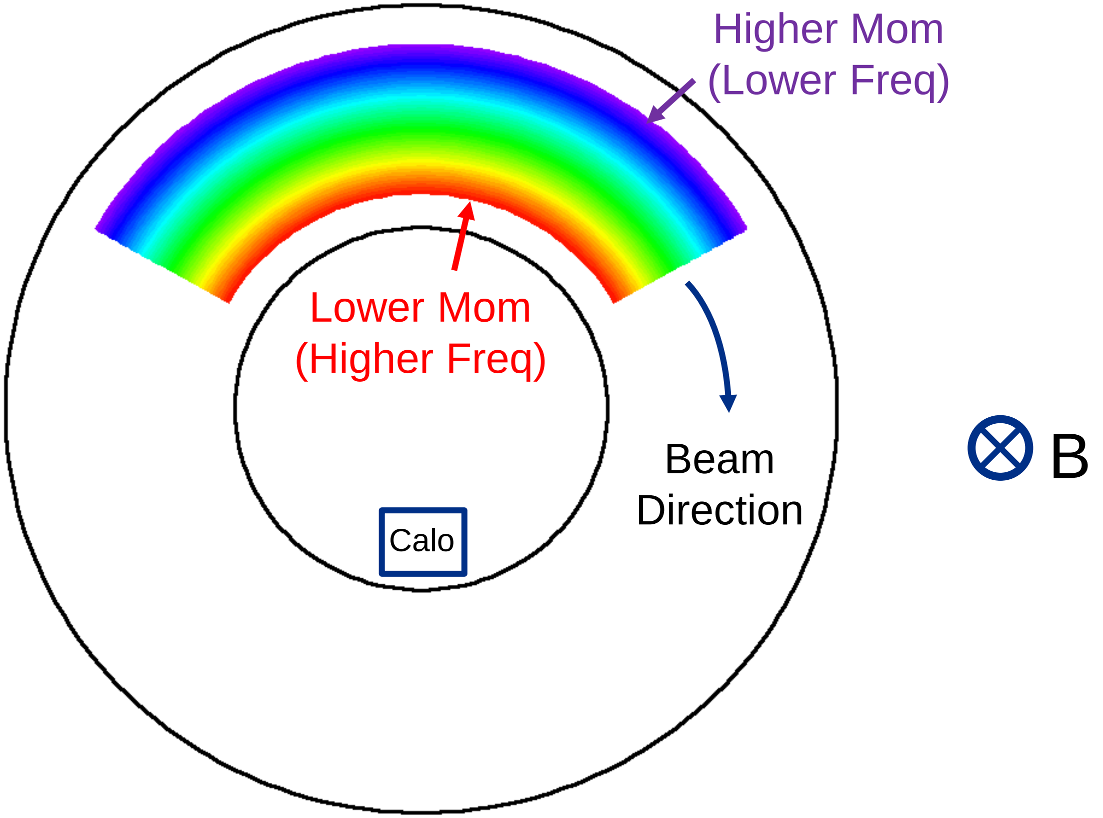
C_P = 180 ± 13 ppb



E-field Correction: C_E

- Imagine injecting uniform momentum & time distributions:

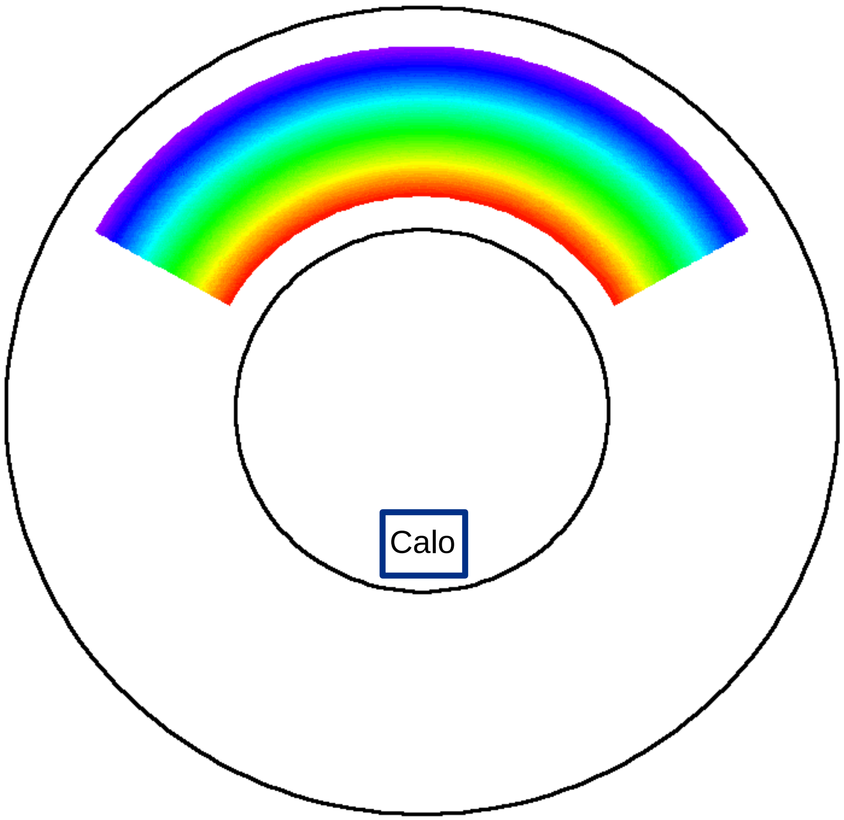
v ~ c for all muons



- Higher momentum muons have further to travel, so have lower cyclotron freq.

E-field Correction: C_E

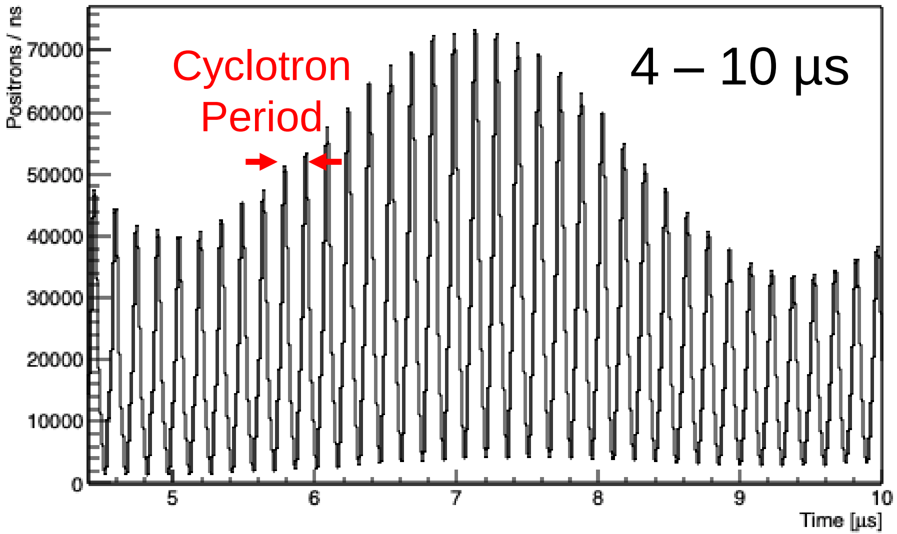
- Over time, lower momentum will catch higher momentum:

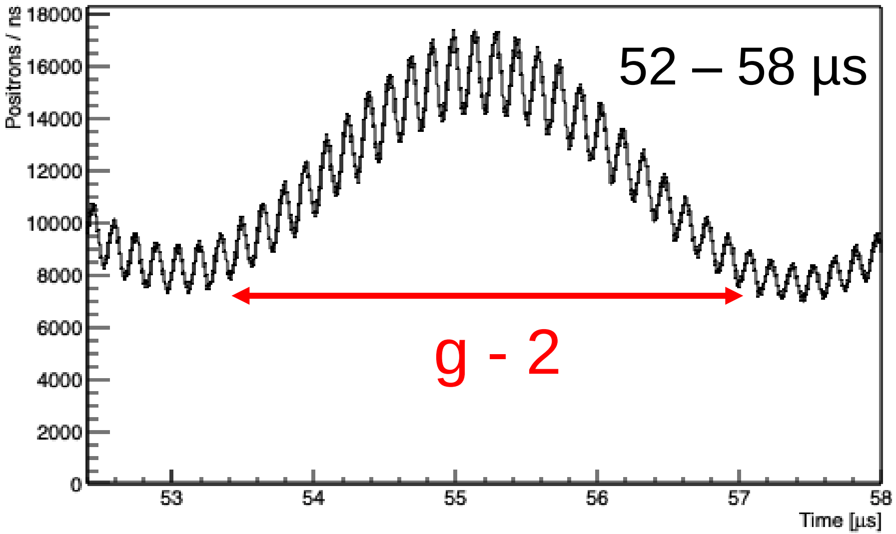


- The way that the gaps are filled in is related to the momentum distribution of the stored beam

E-field Correction: C_E

- Effect is a strong feature of the data at early times:





- Less pronounced when all calos are added together
- Either Fourier analysis or χ^2 fit are used to get momentum distribution

ω_a Systematics: Phase Shifts

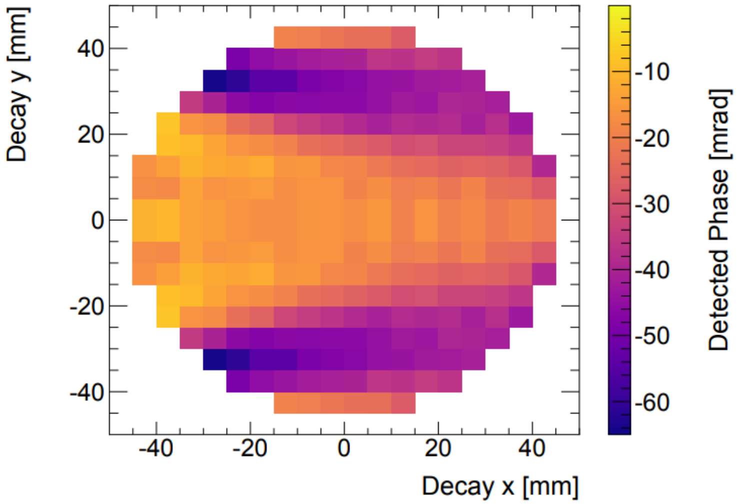
- Many systematics come from effects that **change the phase** of the detected e^+ over time
- These make us mis-measure ω_a with no other indications that we're getting it wrong

$$cos(\omega_a t + \phi(t)) = cos(\omega_a t + \phi_0 + \phi' t + ...)$$
$$= cos((\omega_a + \phi')t + \phi_0 + ...)$$

- In general, anything that changes from **early-to-late** within each muon fill can be a cause of systematic error.
- Most phase shifts are eliminated by design or before fitting the data, but we must correct for two effects (C_{ML} & C_{PA})

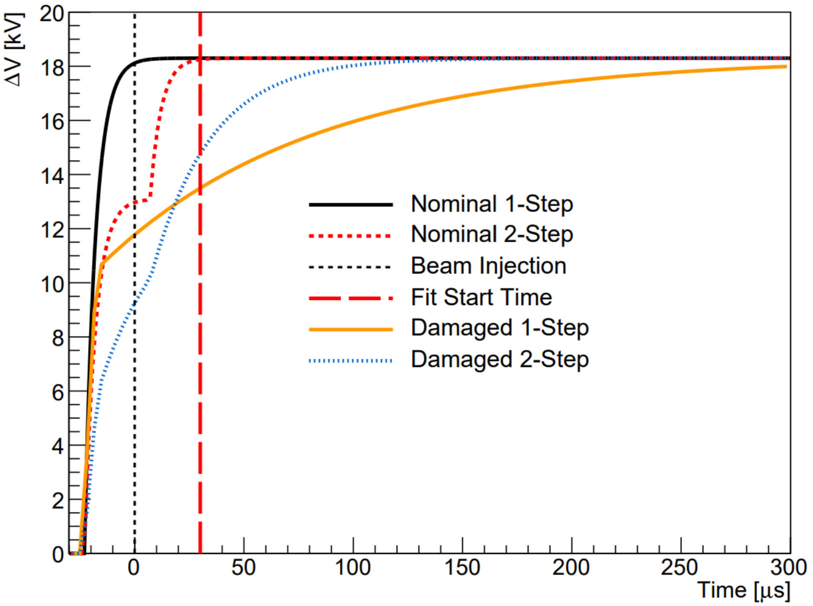
C_{PA} – Phase-Acceptance Correction

- Remember $\phi \rightarrow \phi(t)$ causes us to mis-measure ω_a

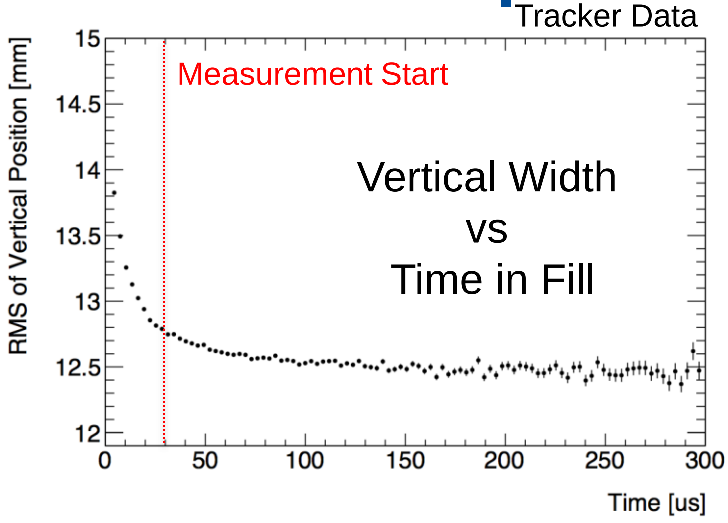


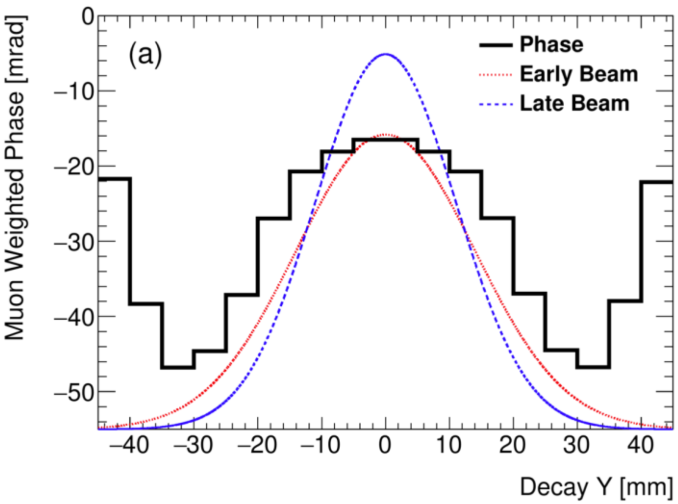
- Due to acceptance, ϕ depends on muon decay position (x,y)
- Not an issue if the muon distribution doesn't change shape over a fill

- But in Run 1, equipment failure led to beam instability
- 2/32 quad HV resistors died
  → Focusing E-field changed
  → Beam width changed



C_{PA} – Phase-Acceptance Correction



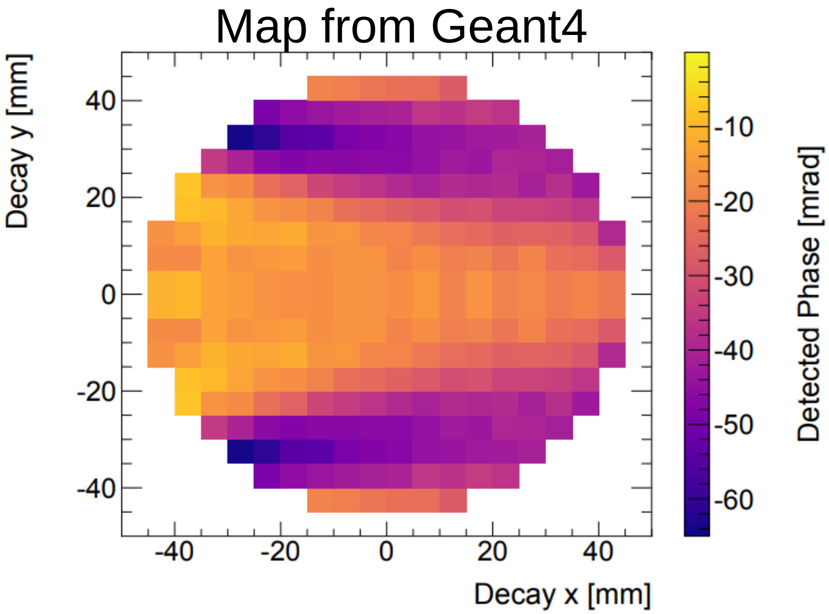


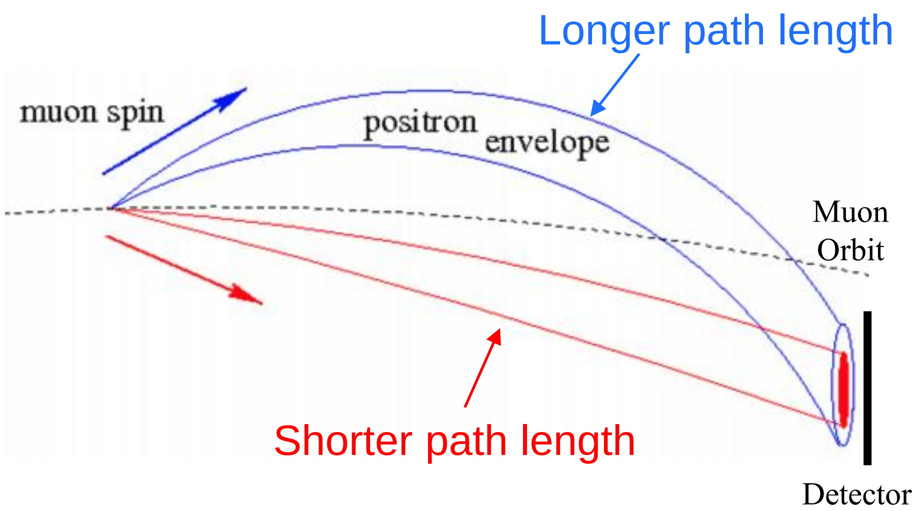
Cartoon of phase & beam width

- Beam width changes couples to phase “map” to cause $\phi(t)$
- -158 ppb correction with a 75 ppb uncertainty in Run 1
- Fixed by Run 2: majority of correction & uncertainty disappears

Why phase varies with decay position

- Average detected phase changes with decay position:





- Origin is acceptance: if e^+ decays outwards then it will have a longer path length to a detector
- We see fewer events from top/bottom of storage region as they miss the detectors vertically

a_μ from Measurement

What do we really measure?

$$a_\mu \propto \frac{\omega_a}{B}$$

Us | Others

$$a_\mu = \frac{\omega_a}{\tilde{\omega}'_p(T_r)} \frac{\mu'_p(T_r)}{\mu_e(H)} \frac{\mu_e(H)}{\mu_e} \frac{m_\mu}{m_e} \frac{g_e}{2}$$

ω_a: e^+ oscillation frequency

$\tilde{\omega}'_p(T_r)$: magnetic field from precession of protons in $H_2$0, weighted by muon distribution

Proposal Goal:
140 ppb = 100 ppb (stat) $\oplus$ 100 ppb (syst)

$\frac{\mu_e(H)}{\mu'_p(T)}$ Measured to 10.5 ppb accuracy at T = 34.7°C
Metrologia **13**, 179 (1977)

$\frac{\mu_e}{\mu_e(H)}$ Bound-state QED (exact)
Rev. Mod. Phys. **88** 035009 (2016)

$\frac{m_\mu}{m_e}$ Known to 22 ppb from muonium hyperfine splitting
Phys. Rev. Lett. **82**, 711 (1999)

$\frac{g_e}{2}$ Measured to 0.28 ppt
Phys. Rev. A **83**, 052122 (2011)

Total < 25 ppb

Systematics vs BNL

Systematic Errors on ω_a (ppb)

	BNL (E821)	Proposal	Run 1	Run-2/3
Gain	120	20	10	5
Pileup	80	40	30	7
CBO	70	30	40	20
E & Pitch	50	30	55	33
Lost Muons	90	20	5	3
Phase Acceptance	-	-	75	15
Total	**180**	**70**	**108**	**42**

Numbers are approximate
Category mapping is imperfect

Systematic Errors on ω_p (ppb)

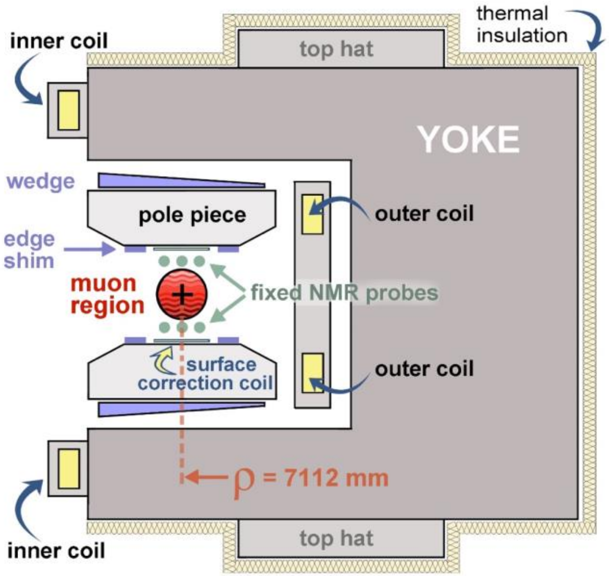
	BNL 2001 (E821)	Proposal	Run 1	Run-2/3
Absolute Calibration	50	35	19	13
Trolley Calibration	90	30	32	14
Trolley Baseline	50	30	40	38
Fixed Probe Baseline	70	30	23	16
Muon Weighting	30	10	18	10
Quad Transient	*	*	92	20
Kicker Transient	*	*	37	13
*Others	100	50	-	-
Total	**170**	**70**	**114**	**53**

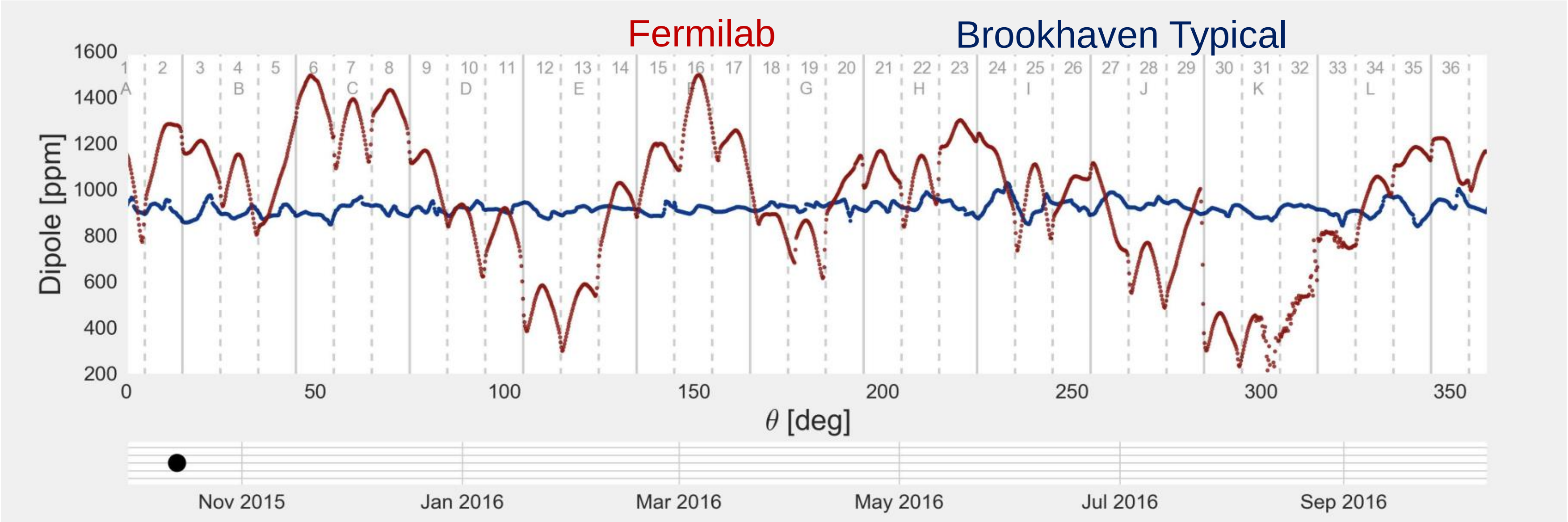
Numbers are approximate
Category mapping is imperfect

Magnet Shimming Tools

Magnet Design & Shimming

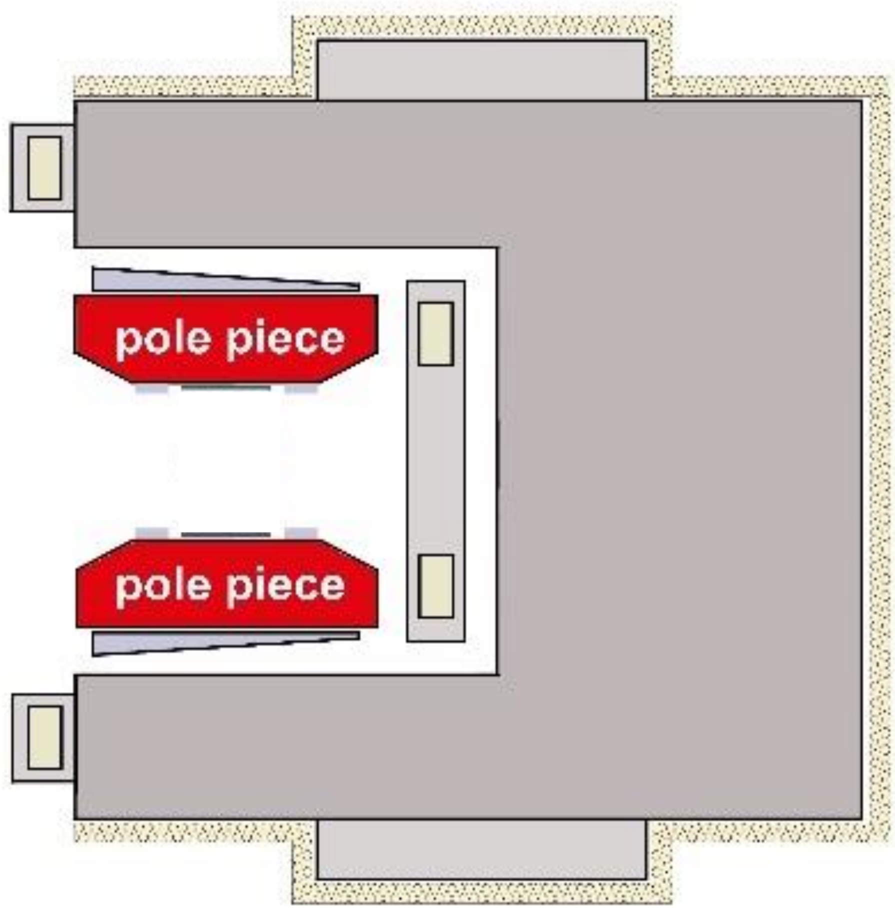
- 14.2 m diameter "C"-shape magnet with 1.45 T vertical field
- **Shimming** campaign from **2015-16** resulted in very uniform field
- 14 ppm RMS across full azimuth & 3x better than at BNL





Magnetic Shimming Tools

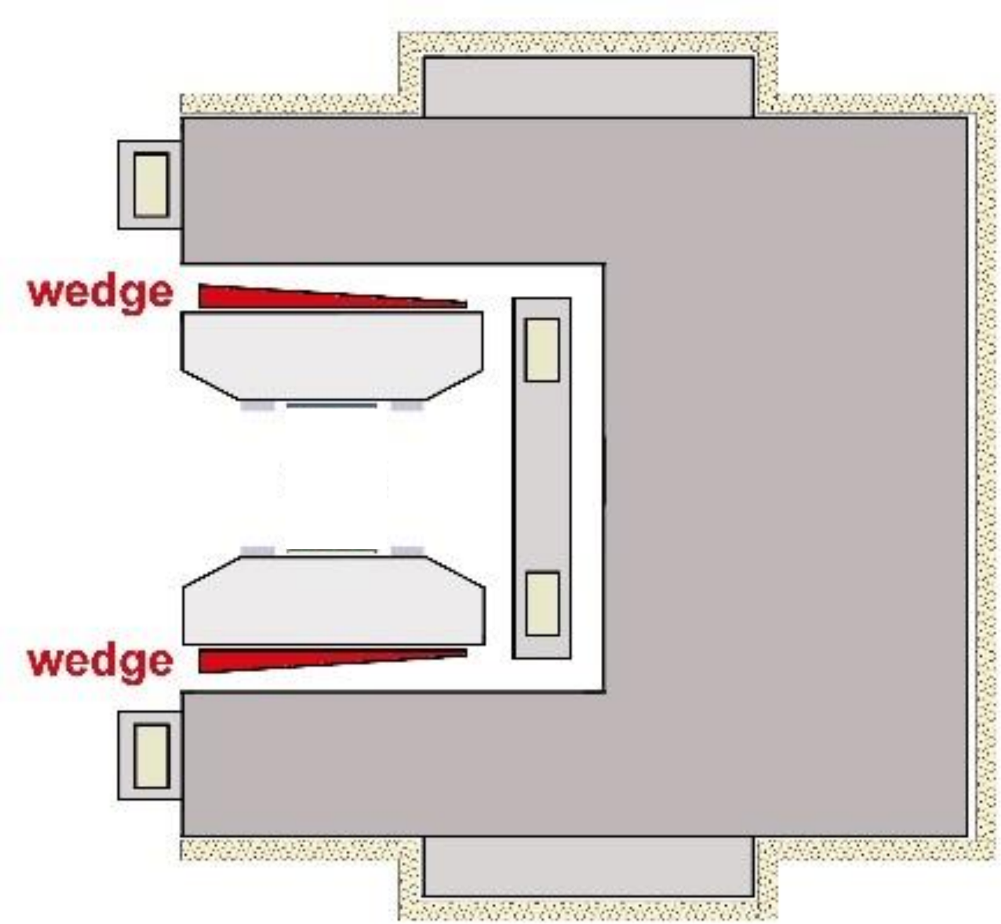
- Many "knobs" for shimming:
  - 72 Poles
    - Shaping & homogeneity



g-2 Magnet in Cross Section

Magnetic Shimming Tools

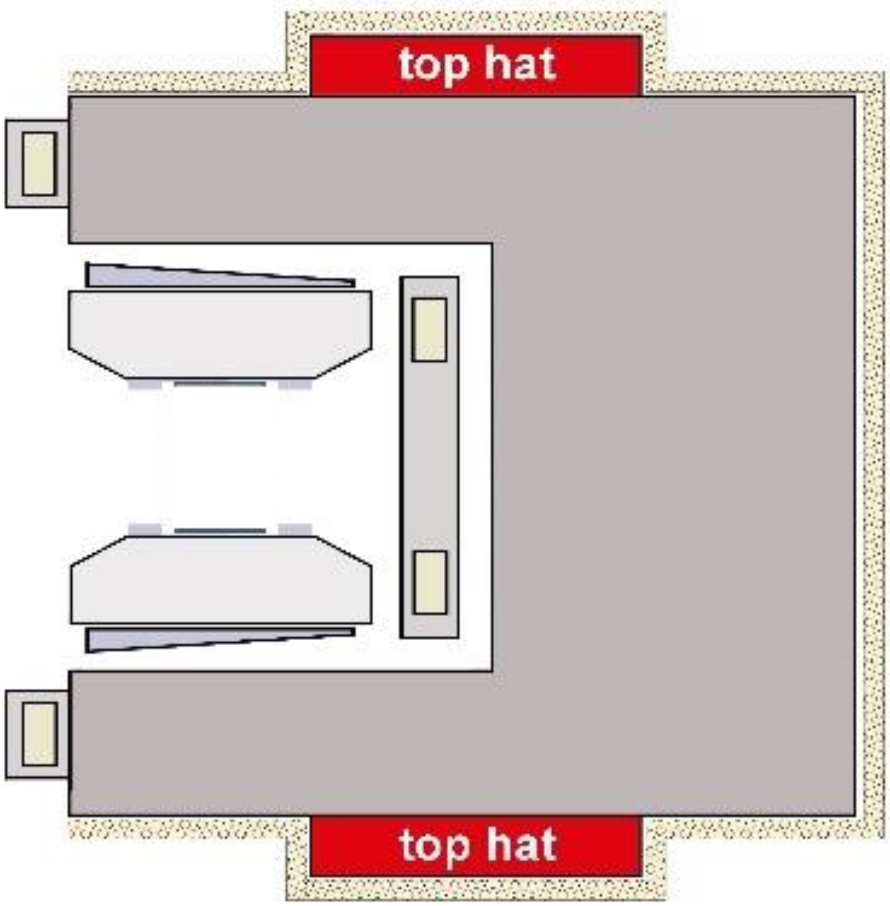
- Many "knobs" for shimming:
  - 72 Poles
    - Shaping & homogeneity
  - 864 Wedges
    - Quadrupole asymmetry



g-2 Magnet in Cross Section

Magnetic Shimming Tools

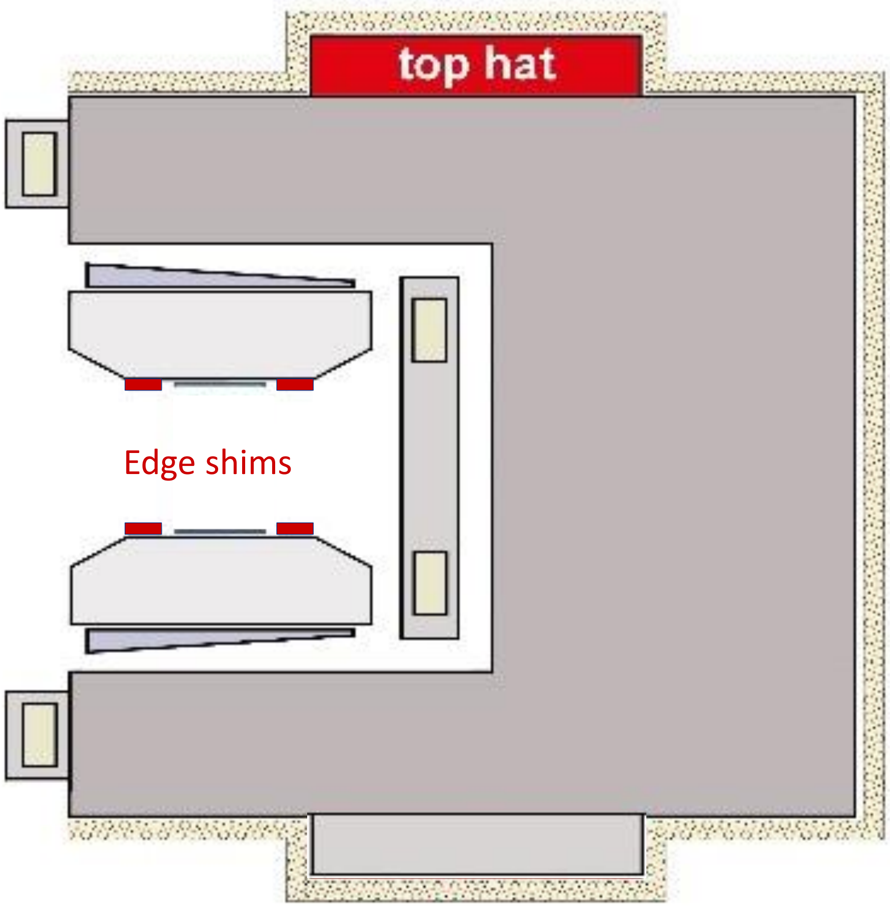
- Many "knobs" for shimming:
  - 72 Poles
    - Shaping & homogeneity
  - 864 Wedges
    - Quadrupole asymmetry
  - 48 Iron Top Hats
    - Change effective μ



g-2 Magnet in Cross Section

Magnetic Shimming Tools

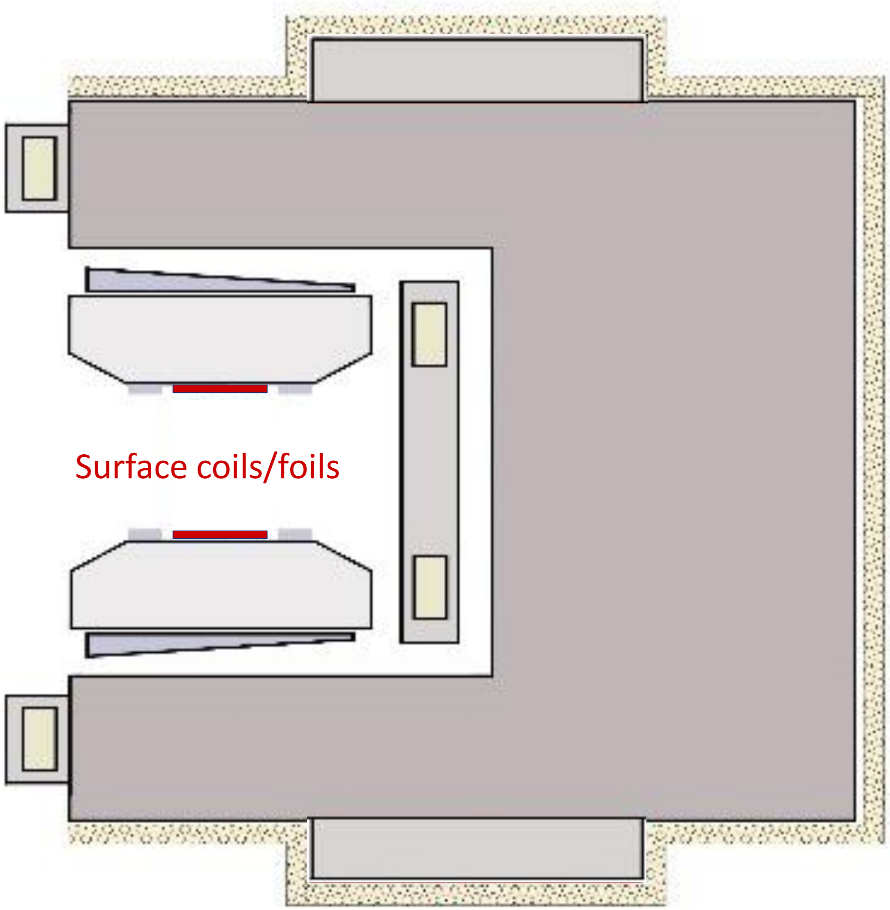
- Many “knobs” for shimming:
  - 72 Poles
    - Shaping & homogeneity
  - 864 Wedges
    - Quadrupole asymmetry
  - 48 Iron Top Hats
    - Change effective μ
  - 144 Edge Shims
    - Quad/sextapole asymme



g-2 Magnet in Cross Section

Magnetic Shimming Tools

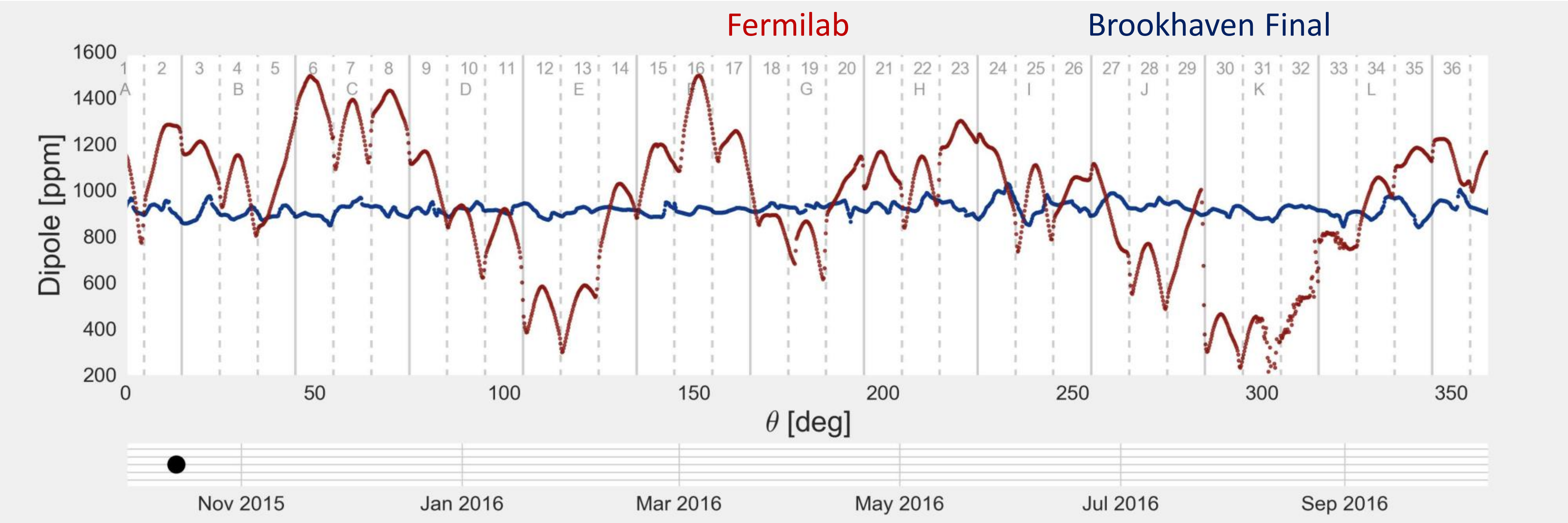
- Many "knobs" for shimming:
  - 72 Poles
    - Shaping & homogeneity
  - 864 Wedges
    - Quadrupole asymmetry
  - 48 Iron Top Hats
    - Change effective μ
  - 144 Edge Shims
    - Quad/sextapole asymme
  - 8000 Surface Iron Foils
    - Local changes of effectiv
  - 100 Active Surface Coils
    - Control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

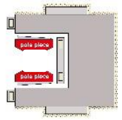


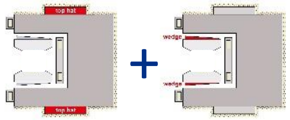
g-2 Magnet in Cross Section

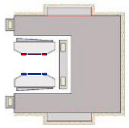
Shimming the Magnet

- Progress towards a uniform field from Oct ‘15 to Sep ’16:







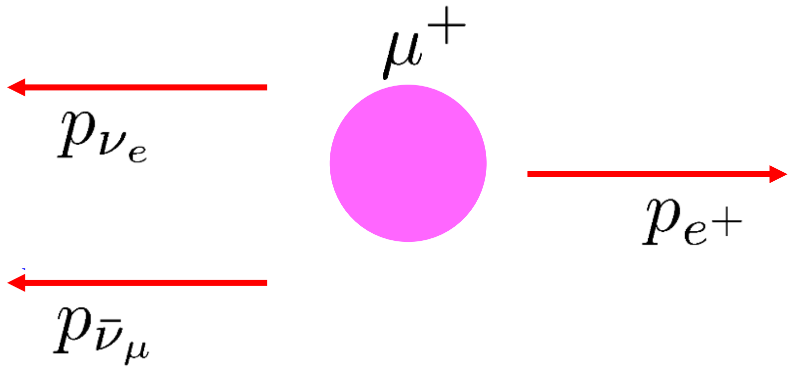


Dipole field (p-p & RMS) improved by factor 3 compared to BNL

ω_a Measurement

Why do decay e^+ tell us about muon spin?

- Muon spin information is encoded in **parity violating** decay



- Highest energy positrons are emitted back-to-back with neutrinos

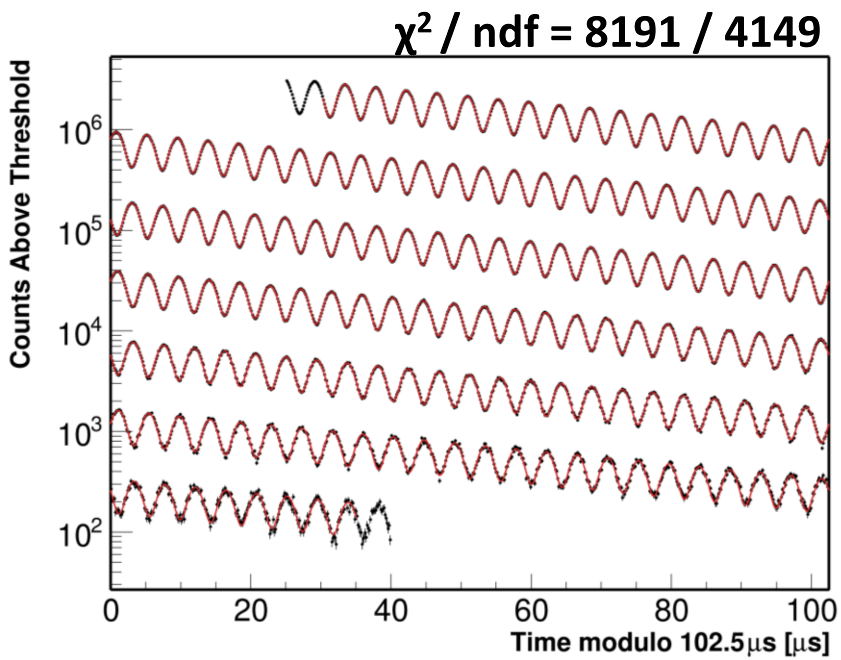
- Neutrino helicity is fixed, so **high energy** positrons are emitted in **direction of muon spin**

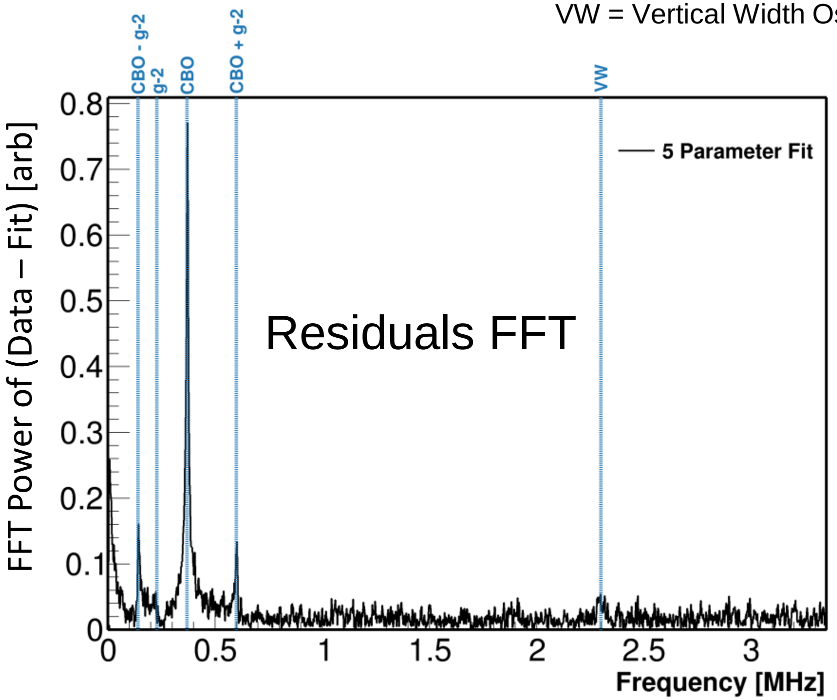
Simple fit: residuals

- Simplest form for fit is an exponentially decaying oscillation:

$$N_0 e^{-t/\tau}(1 + A\cos(\omega_a t + \phi))$$

CBO = Radial Mean Oscillations
VW = Vertical Width Oscillations





- Beam **oscillations couple to acceptance** & change number of e^+ detected with time, and **exponential isn't perfect**

Fit with beam dynamics terms

- Add terms to fit function to deal with complications:

$$N_0 e^{-t/\tau}(1 + A\cos(\omega_a t + \phi))$$

⬇

$$f(t) = N_0 e^{-t/\tau}\, \Lambda(t)\, N_{cbo}(t)\, N_{2cbo}(t)\, (1 + A_{cbo}(t) cos(\omega_a t + \phi_{cbo}(t))$$

- Muons that are lost from storage ring before they decay:

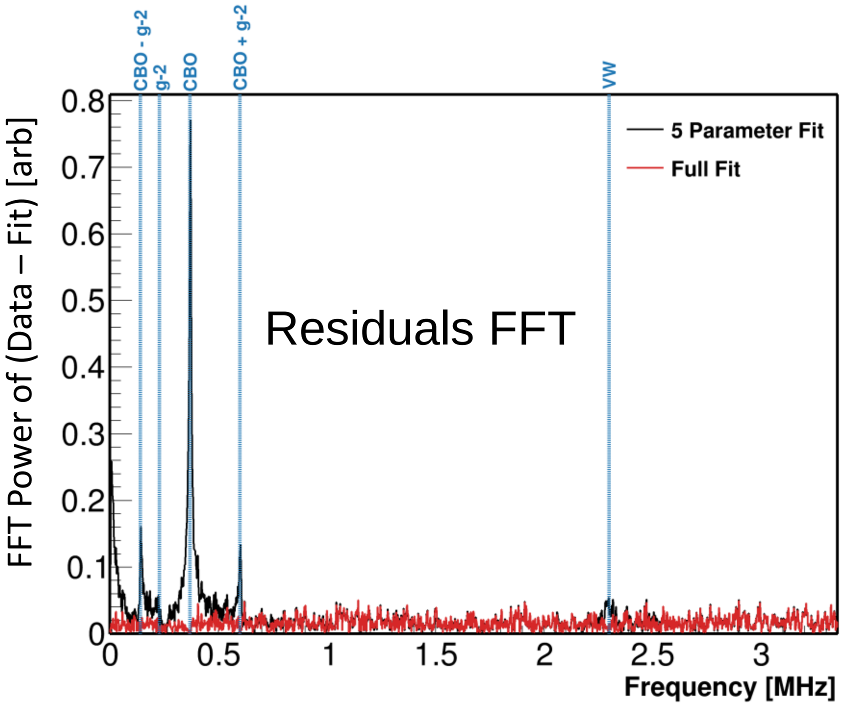
$$\Lambda(t) = 1 - \boldsymbol{\kappa_{loss}} \int_{t_0}^{t} L(t') e^{(t'/\tau)} dt'$$

- Beam oscillations that modulate decay rate:

e.g. $N_{cbo}(t) = (1 + \boldsymbol{A_{cbo-N}} \cdot e^{-t/\boldsymbol{\tau_{cbo}}} \cdot \cos(\omega_{cbo}(t) \cdot t + \boldsymbol{\phi_{cbo-N}}))$

Fit with beam dynamics terms: residuals

- Adding terms tames the beast:



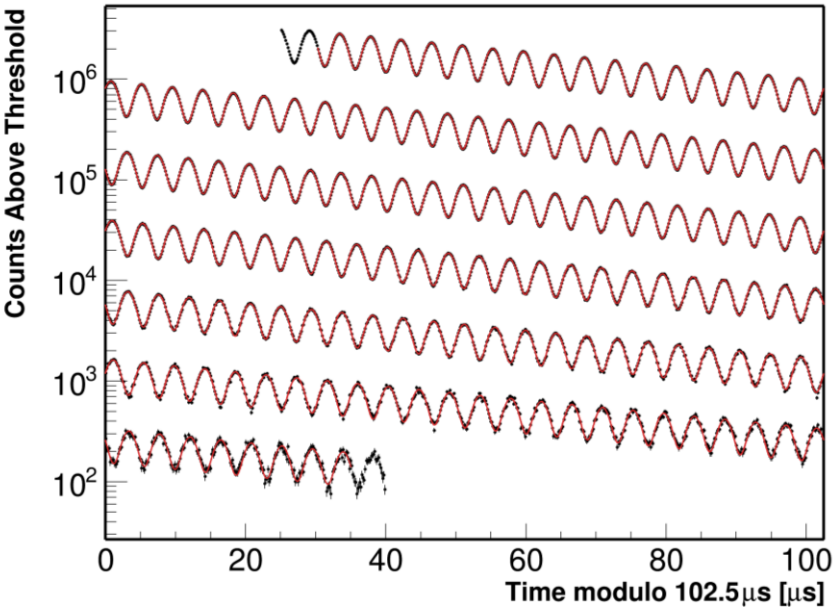
Simple 5-parameter fit
χ^2 / ndf = 8191 / 4149

Fit with extra terms
χ^2 / ndf = 4005 / 4134

- Important to get it right: ω_a changes by **2.2 ppm**
- Good residuals & χ^2 are necessary, but not sufficient condition.

Systematic Cause: Time-Dependent Phase

- If average phase of muon population changes over time then we can mis-measure ω_a:



$$N_0 e^{-t/\tau}(1 + A\cos(\omega_a t + \phi))$$

But if $\boldsymbol{\phi} \rightarrow \boldsymbol{\phi}(\mathbf{t})$, then

$$cos(\omega_a t + \phi(t)) = cos(\omega_a t + \phi_0 + \phi' t + ...)$$
$$= cos((\omega_a + \phi')t + \phi_0 + ...)$$

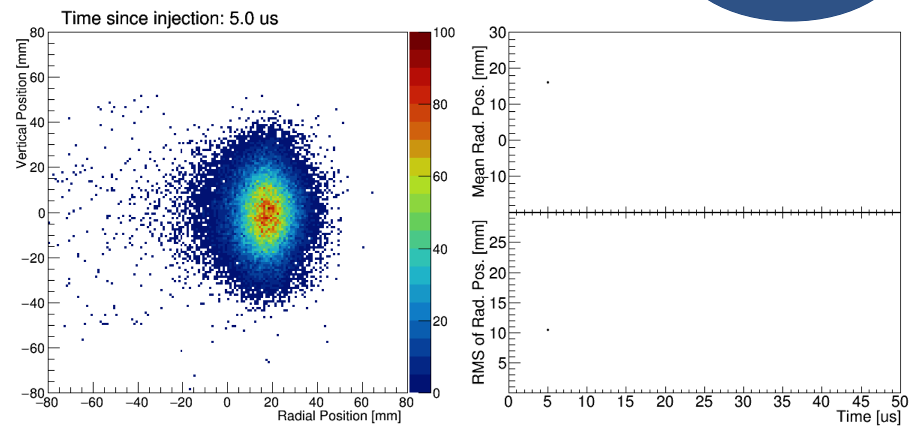
- If higher order terms are small, then we measure (ω_a + ϕ') instead of ω_a and still get good χ^2

Main Systematic Issues

- 3 main systematics for ω_a measurement
- Variety of mitigation strategies
- Well under control – total is **56 ppb**

Beam Oscillations

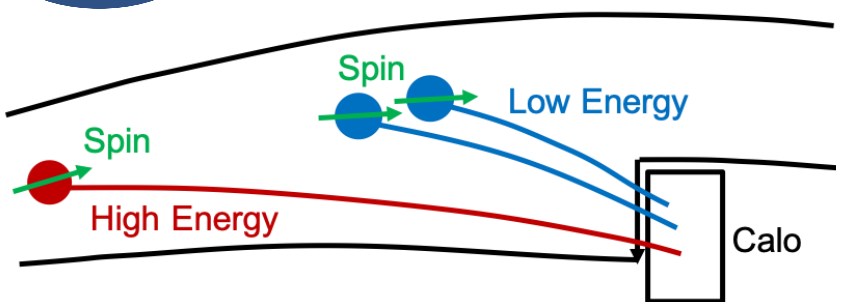
~40 ppb



Tracker data & beam dynamics

Pile Up

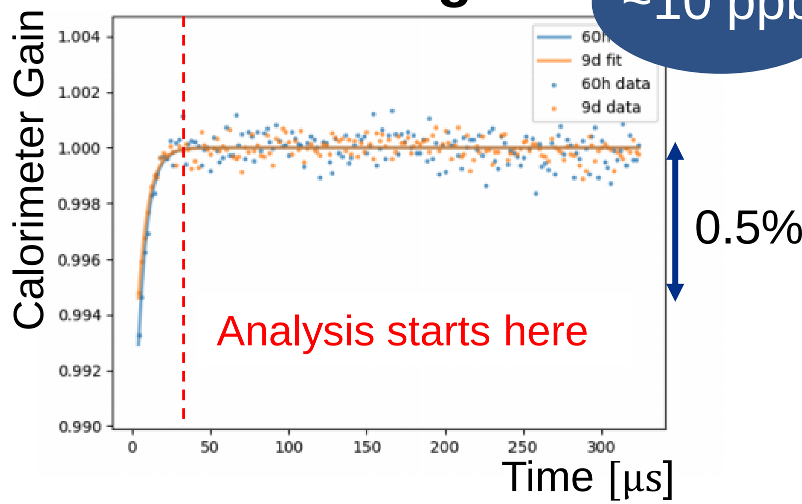
~30 ppb



Empirical correction using calo data

Gain Change

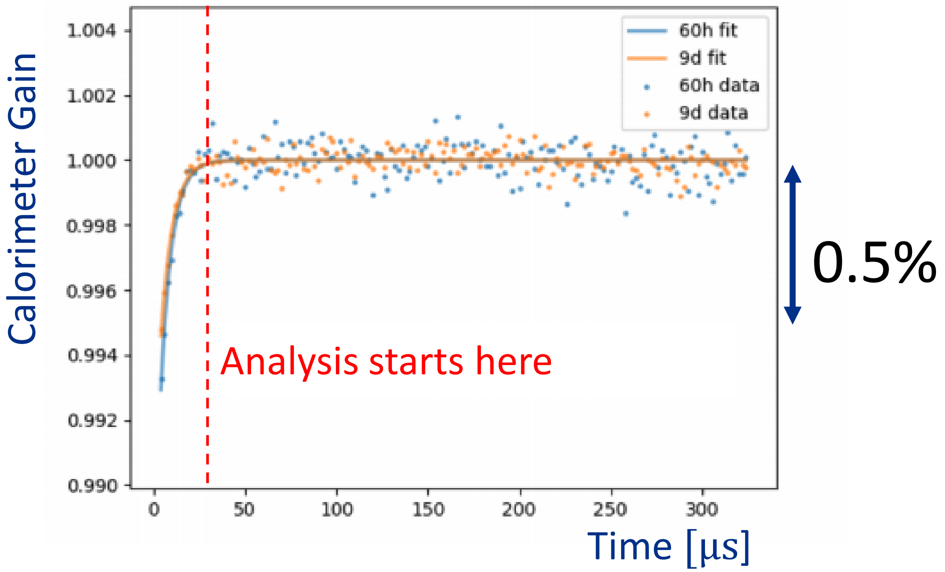
~10 ppb



Dedicated laser calibration system

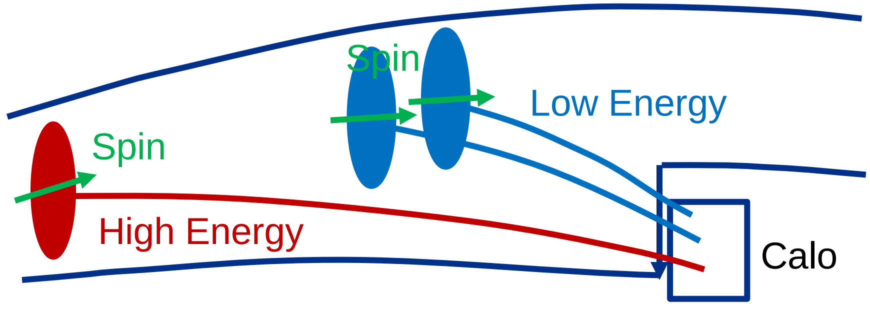
Systematic Issues: Gain

- Calorimeter gain takes time to recover from “flash” when beam first enters storage ring:

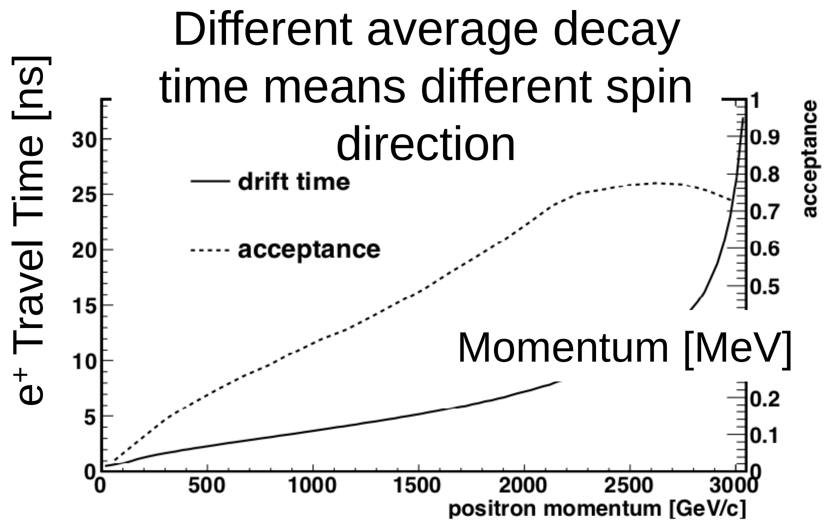


- Phase is energy dependent – so gain change generates another time-dependent phase & normalization issues
- Correct based on gain measurements from laser system and cross-check with tracker

Systematic Issues: Pile Up

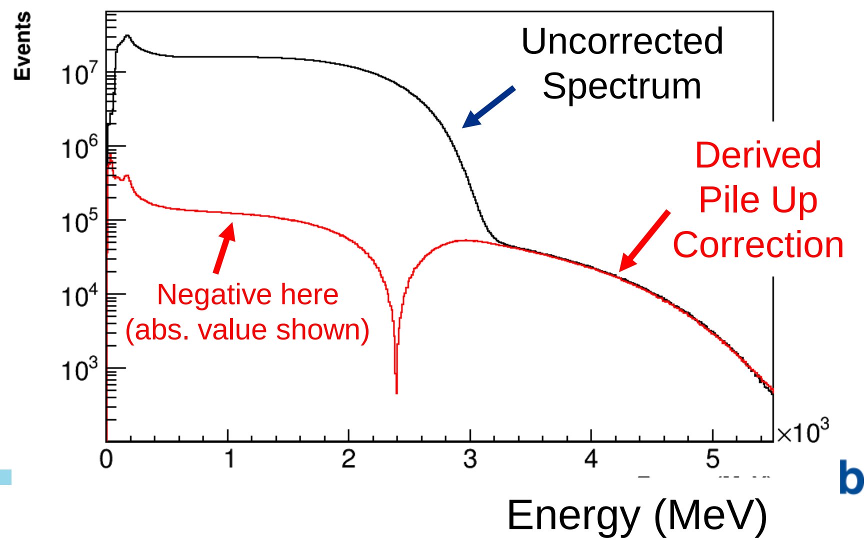


Two low energy e⁺ can look like one high energy e⁺



- Pile up happens less often as the muons decay so phase changes with time and we get ω_a wrong

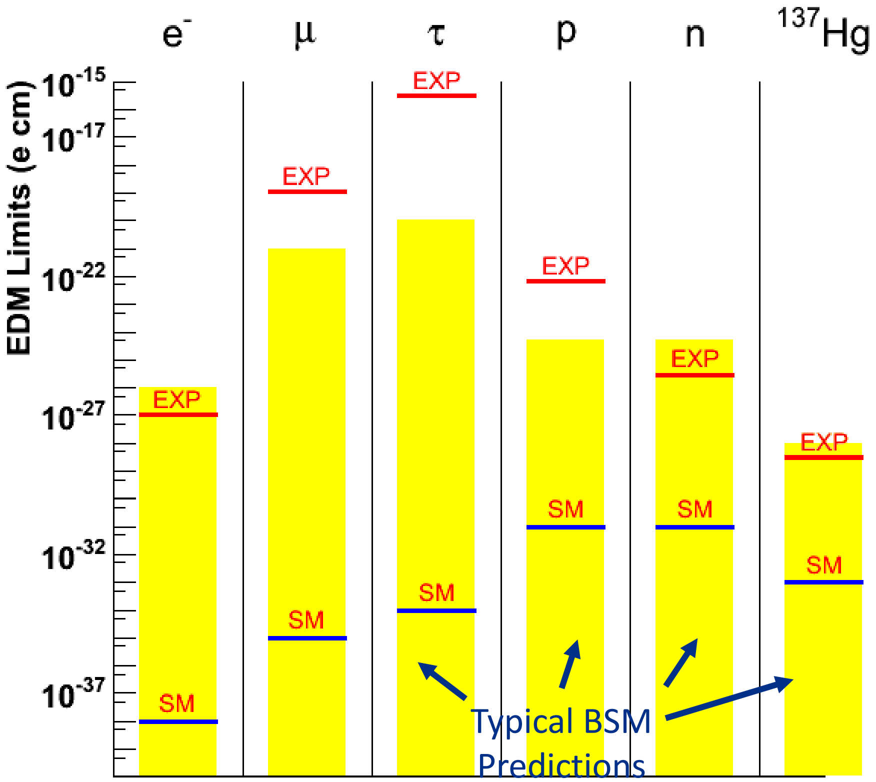
  - Derive a pile up correction from data and check validity above 3.1 GeV



Muon EDM

Muon Electric Dipole Moment

- Muon EDM is essentially zero in SM.
- Any observation would be a sign of new physics:



EDMs: Theory & Experiment

- Muon is the best option for a higher flavour gen. search
- And it's free of nuclear / molecular effects
- But, needs non-mass-scaling BSM effects to see anything given e^- EDM limit

Muon EDM: Tracker Search

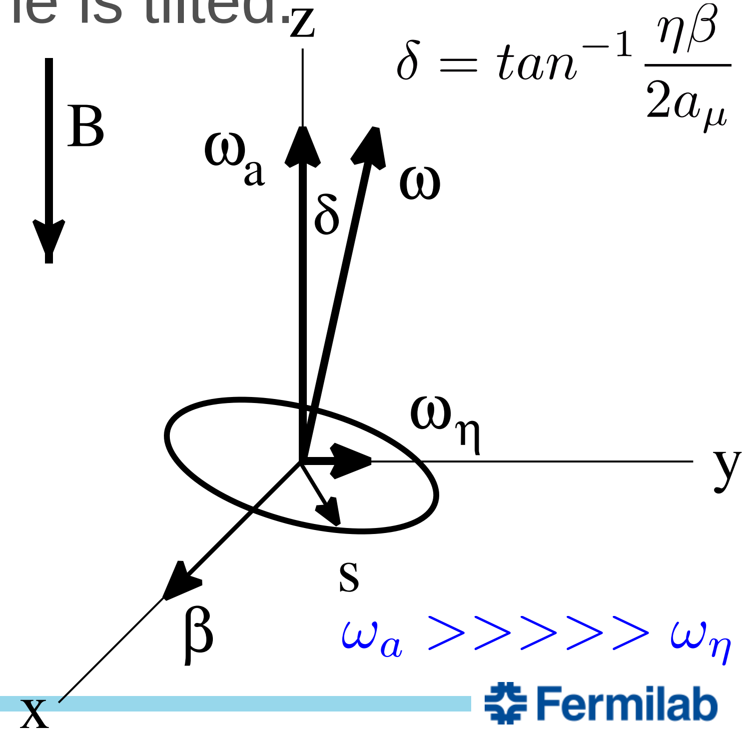
- A non-zero muon EDM would modify the spin equation

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

- $\vec{\beta}\times\vec{B}$ dominates, so precession plane is tilted.

$$\delta = tan^{-1}\frac{\eta\beta}{2a_\mu}$$

$$\omega = \sqrt{\omega_a^2 + \omega_\eta^2} = \sqrt{\omega_a^2 + \left(\frac{e\eta\beta B}{2m}\right)^2}$$

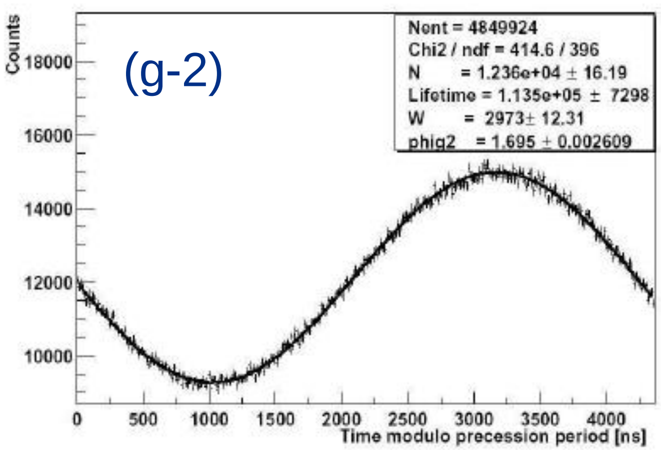


- Search for an up-down oscillation, out of phase with ω_a.

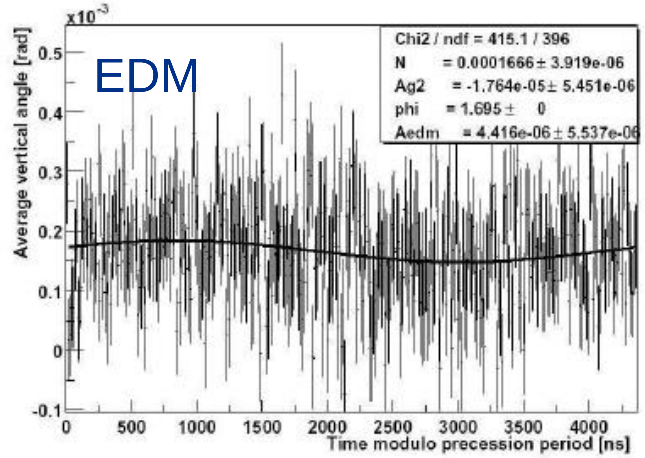
$\omega_a >>>>> \omega_\eta$

Muon EDM: Tracker Search

- Search was done with tracker at BNL:



Tracks vs (time % T_a)



Average vertical angle vs (time % T_a)

- Previous tracker search was statistics limited

Tracker: $|d_\mu| < 3.2 \times 10^{-19}\, e\,\mathrm{cm}\,(95\%\mathrm{CL})$

Tracker & Calo: $|d_\mu| < 1.8 \times 10^{-19}\, e\,\mathrm{cm}\,(95\%\mathrm{CL})$

SM: $|d_\mu| < 10^{-38}$

(World's best for muon EDM)

- We're aiming to improve this limit to 10^{-21} e cm

Electron Anomaly: a_e

Why a_μ and not a_e?

- Coupling of virtual loops goes as m^2 (dimensional analysis)
- Therefore, while a_μ is measured ~20x less precisely than the a_e, it has better sensitivity to heavy physics scales:

$$\left(\frac{m_\mu}{m_e}\right)^2 \simeq 43,000$$

- E.g. lowest-order hadronic contribution to a_e is $a^{had,LO} = (1.875 \pm 0.017) \times 10^{-12}$ (1.5 ppb of a_e)
- By comparison, the muon's hadronic contribution is ~60 ppm.

g_e and α:

- New measurement of g_e in 2023: 0.13 ppt on g_e

Measurement of the Electron Magnetic Moment

X. Fan, T. G. Myers, B. A. D. Sukra, and G. Gabrielse
Phys. Rev. Lett. **130**, 071801 – Published 13 February 2023

https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.130.071801

- Ability to compare with prediction hampered by disagreement in the value of α:

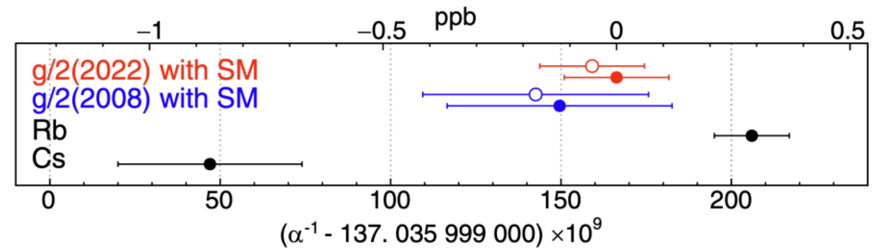


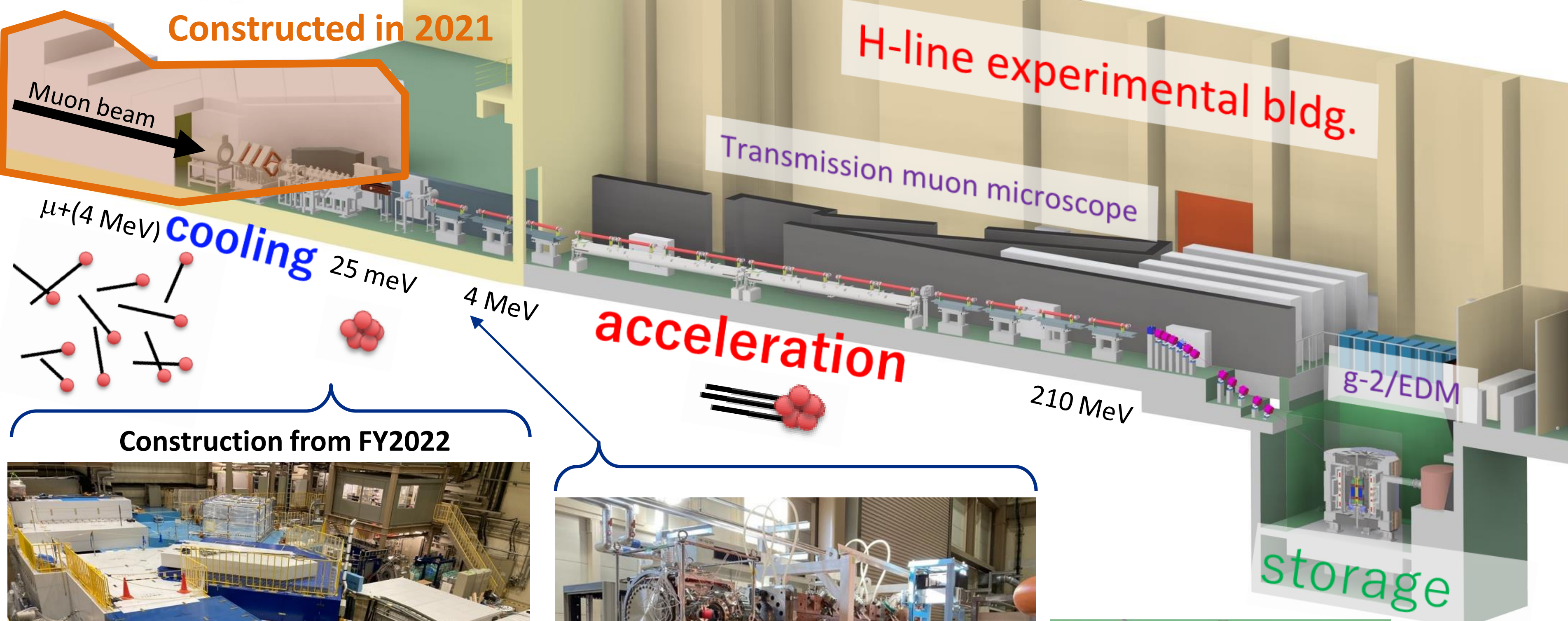
FIG. 5. SM prediction of α using μ/μ_B from this Northwestern measurement (red), and from our 2008 Harvard measurement (blue), with solid and open points for slightly differing C_{10} [40,41]. The α measurements (black) were made with Cs at Berkeley [38] and Rb in Paris [39]. A ppb is 10^{-9}.

J-PARC Experiment

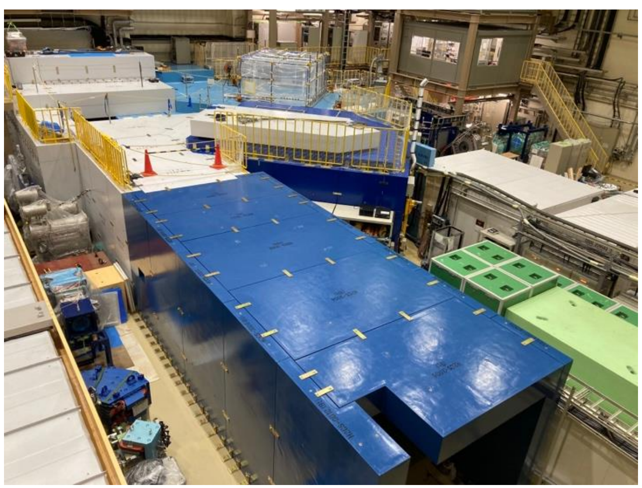
J-PARC muon g-2/EDM experiment

J-PARC MLF

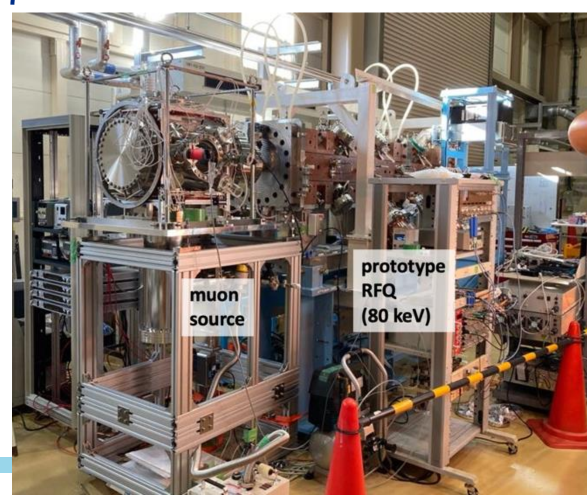
Aiming for data taking from 2028



Construction from FY2022



Shields, area control (2022)

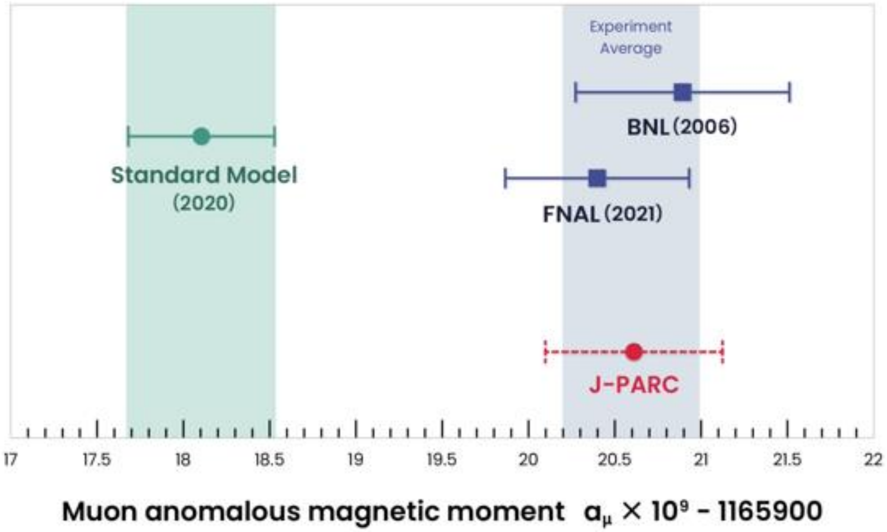


RF Acc. Test at S2 area (May 2023)

Fermilab

J-PARC Experiment

- Complementary technique
  - μ beam accelerated from rest
  - no E fields
  - smaller magnet
- Aiming for a result comparable to Run-1 result towards the end of the decade



- Under construction aiming for data taking from 2028.
- Succeeded to deliver a surface muon beam to H-line.
- Constructed the experimental area for muon cooling and the first stage of the acceleration.
- Currently taking data to demonstrate the muon cooling by using the laser ionization of muonium, followed by RF acceleration tests.