Muon g-2 Experiment and SM

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on behalf of the Muon g-2 Collaboration

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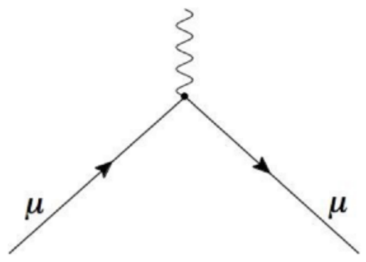
Muon Magnetic Moment and Defining the Anomaly

Magnetic Moment of Muon

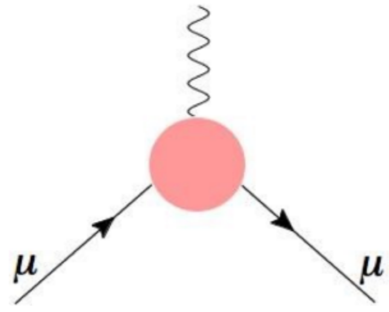
$$\vec{\mu} = g_\mu \frac{e}{2m}\vec{s}$$

g: Proportionality constant between spin and magnetic moment

Dirac: g=2



Quantum effects : g>2



Anomalous Magnetic Moment of Muon

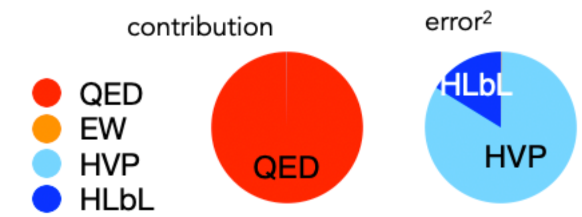
$$a_\mu = \frac{g_\mu - 2}{2}, \qquad \vec{\mu} = (1 + a_\mu)\frac{e}{m}\vec{s}$$

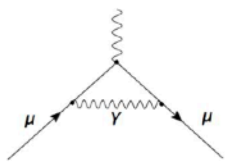
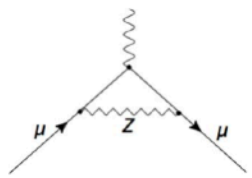
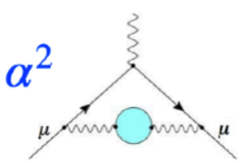
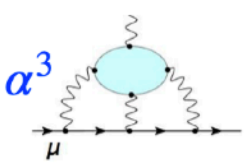
Shows how much g differs fractionally from 2!

Measuring this anomaly could tell us if there are new particles or even forces that contribute to a_μ

Standard Model Contribution: Calculating the Anomaly

$$a_\mu = a_\mu(QED) + a_\mu(EW) + a_\mu(hadronic)$$



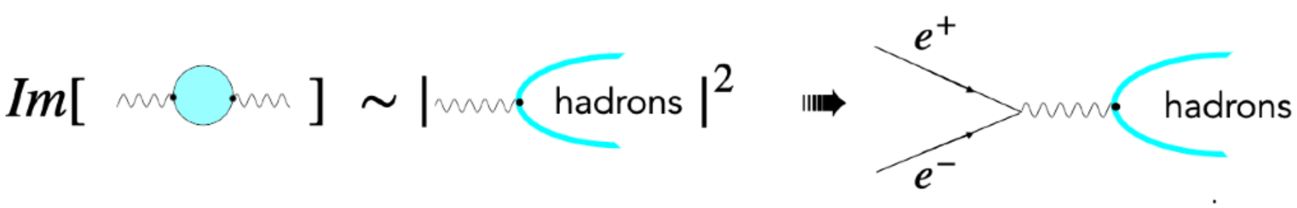
QED		+… (5 loops)	$116\,584\,718.9\,(1) \times 10^{-11}$	0.001 ppm	Well-known
EW		+… x	$153.6\,(1.0) \times 10^{-11}$	0.01 ppm	
HVP	α^2 	+… (NNLO)	$6845\,(40) \times 10^{-11}$ [0.6%]	0.34 ppm	Non-perturbative (Data-driven & lattice QCD)
HLbL	α^3 	+… (NLO)	$92\,(18) \times 10^{-11}$ [20%]	0.15 ppm	

- QED and EW contributions are very well-known with small uncertainties
- Hadronic contribution error dominates the uncertainty budget
- HVP needs to be on the 0.5% precision to keep up with the experiment uncertainties
- HLBL precision demand is less thank HVP, only 10% would be good enough
- Refining the SM calculations means refining the HVP calculation
- **Muon g-2 Theory Initiative** was formed to determine SM value of a_μ. Produce a single consensus theoretical value which is comparable to the experimental value.

Standard Model Contribution: Calculating the Anomaly

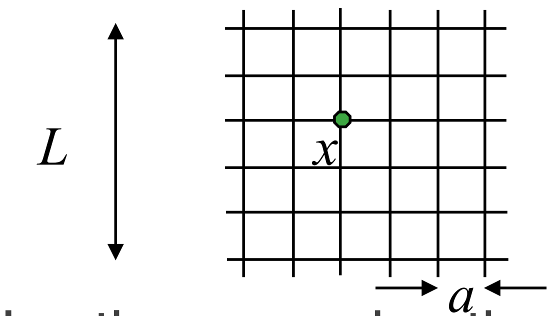
Independent Strategies to Evaluate Hadronic Contributions

Dispersive + Data-driven



- HVP: Use dispersion relations and re-write the integrals in terms of hadronic cross sections
  - Many experiments have measured positron-electron cross sections for different channels over the needed energy range with a decent uncertainty
- HLbL: A new dispersive approach
  - Model Independent
  - Significantly more complicated than HVP

Lattice QCD



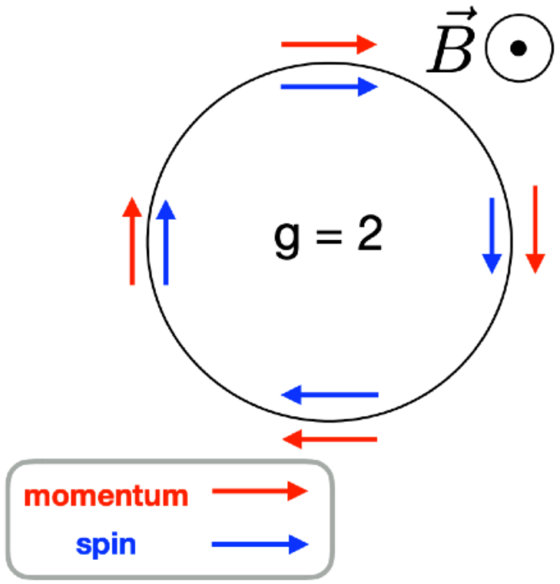
- Use the approximation of discrete space-time (a), finite spatial volume (L), time extent (T) to quantify the QCD effects
- Integrals are evaluated numerically using MC methods
- Already used to calculate simple hadronic quantities with high precision
- Heavily depends on computation resources
- Allows for the SM theory-based evaluations

Courtesy of A. El-Khadra

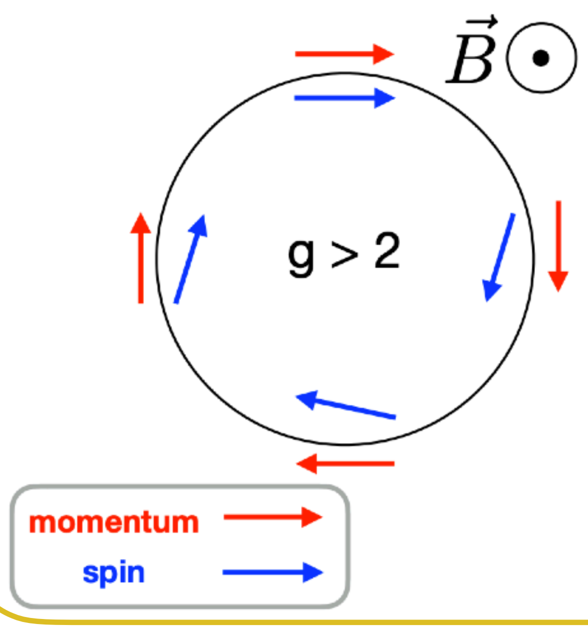
Muon Magnetic Moment and Measuring the Anomaly

polarized muons in a magnetic field

If $g = 2 \Rightarrow \overrightarrow{\omega}_a = 0$



$g \neq 2 \Rightarrow \overrightarrow{\omega}_a \cong a_\mu \frac{e}{m} \overrightarrow{B}$



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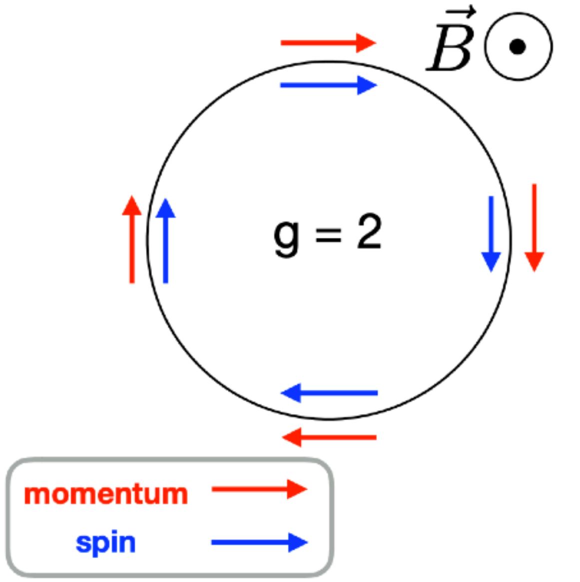

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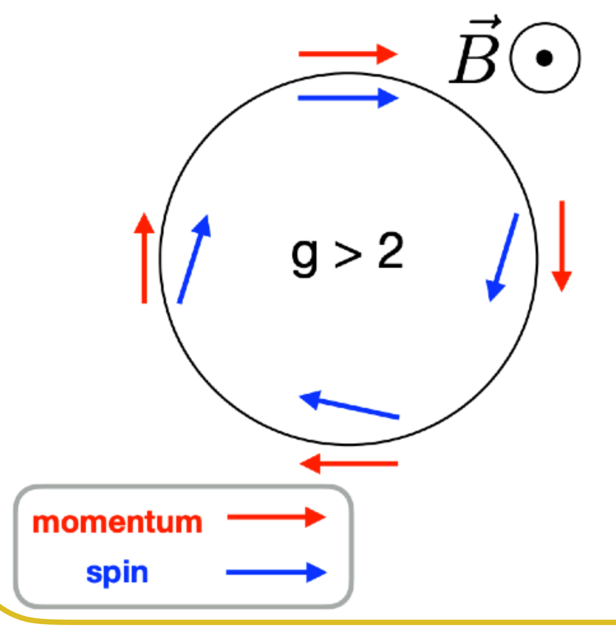

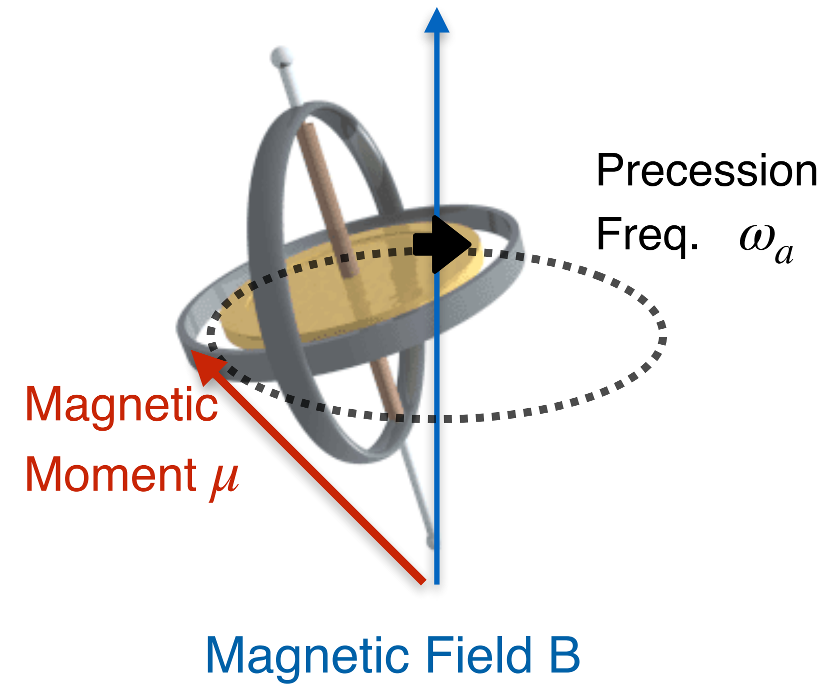

$\overrightarrow{\omega}_c = -\frac{e}{\gamma m} \overrightarrow{B}$, cyclotron frequency (freq. of charged particle under magnetic field)

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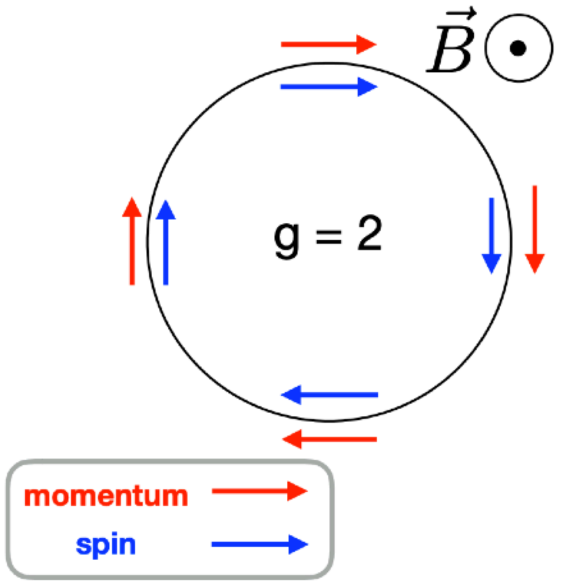

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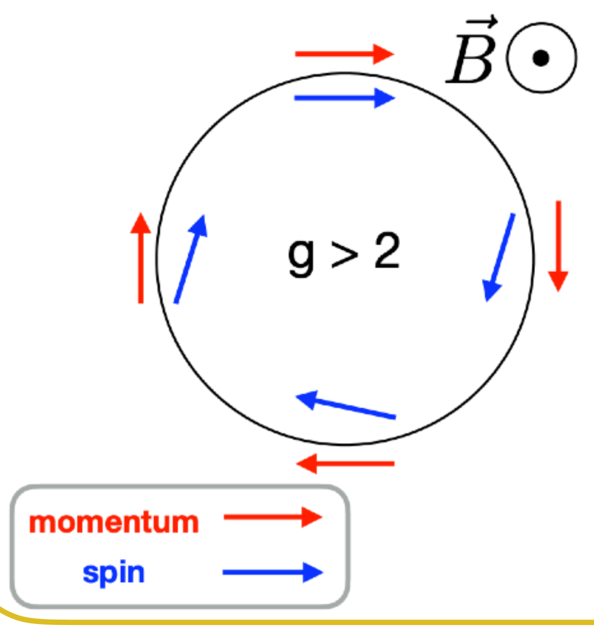

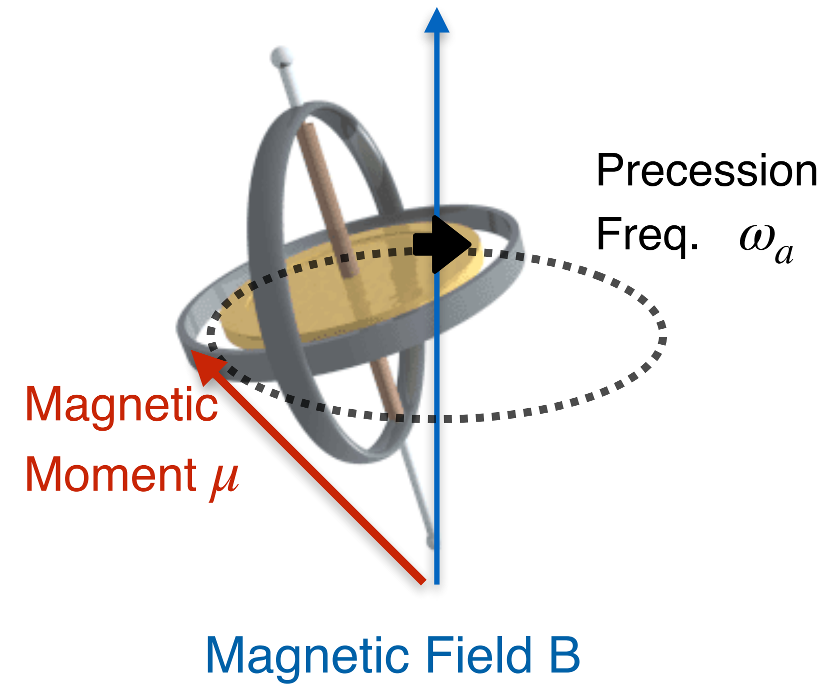

$\overrightarrow{\omega}_c = -\frac{e}{\gamma m}\overrightarrow{B}$, cyclotron frequency (freq. of charged particle under magnetic field)

$\overrightarrow{\omega}_s = -\frac{e}{\gamma m}\overrightarrow{B}(1 + \gamma a_\mu)$, Larmor precession frequency(total spin precession freq.)

Muon Magnetic Moment and Measuring the Anomaly

polarized muons in a magnetic field

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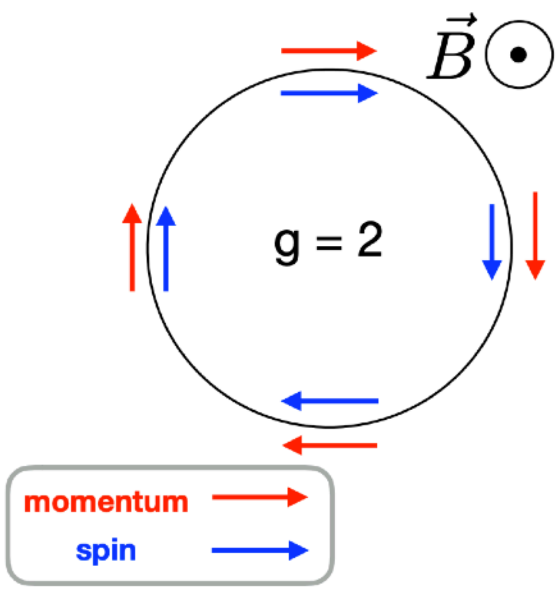

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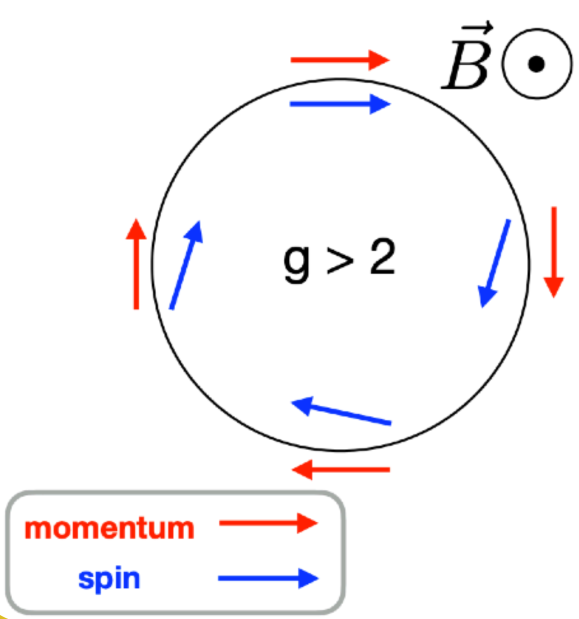
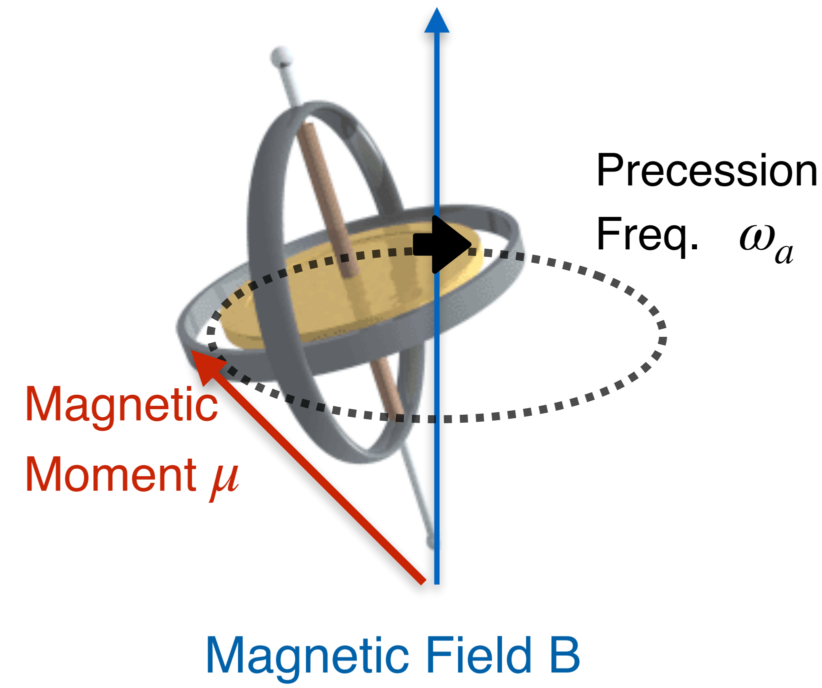




$\vec{\omega}_c = -\frac{e}{\gamma m}\vec{B}$, cyclotron frequency (freq. of charged particle under magnetic field)

$\vec{\omega}_s = -\frac{e}{\gamma m}\vec{B}(1 + \gamma a_\mu)$, Larmor precession frequency(total spin precession freq.)

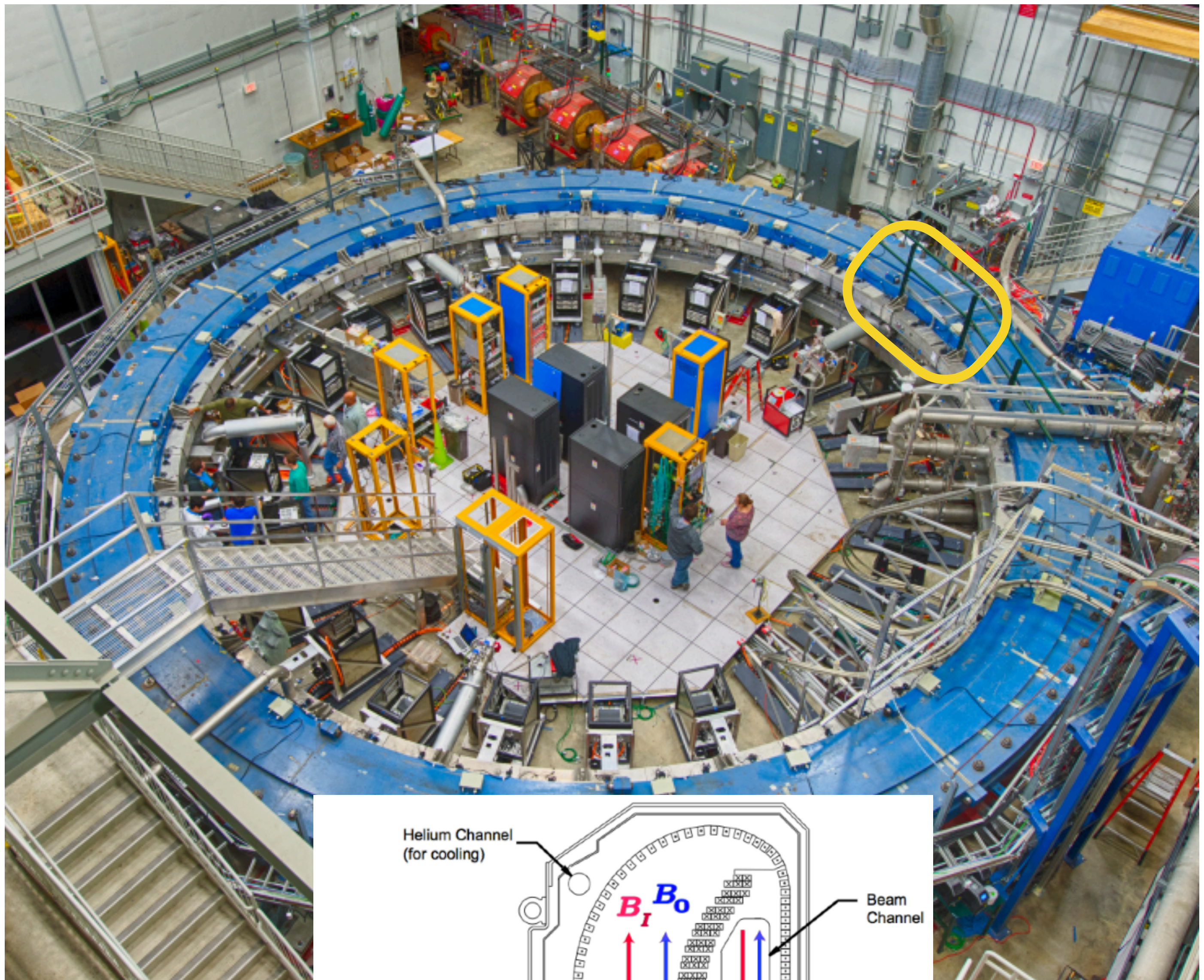
$\vec{\omega}_a \cong \vec{\omega}_s - \vec{\omega}_c$, anomalous precession frequency

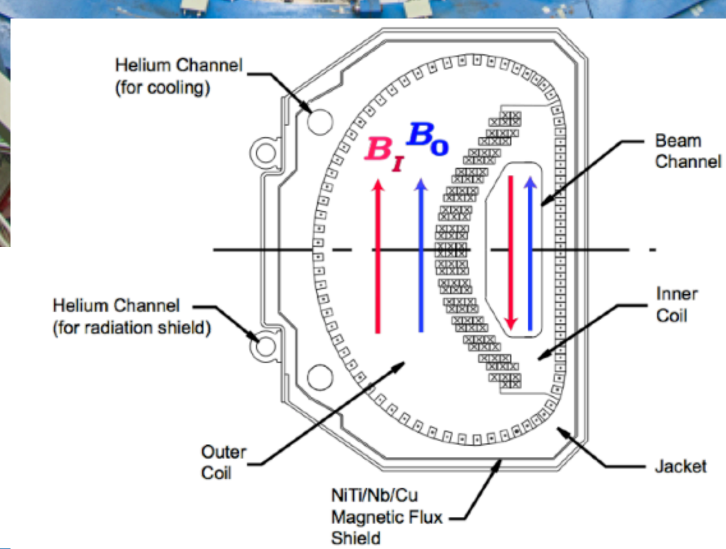
$$\vec{\omega}_a \cong a_\mu \frac{e}{m}\vec{B}$$

Measure them to extract anomaly

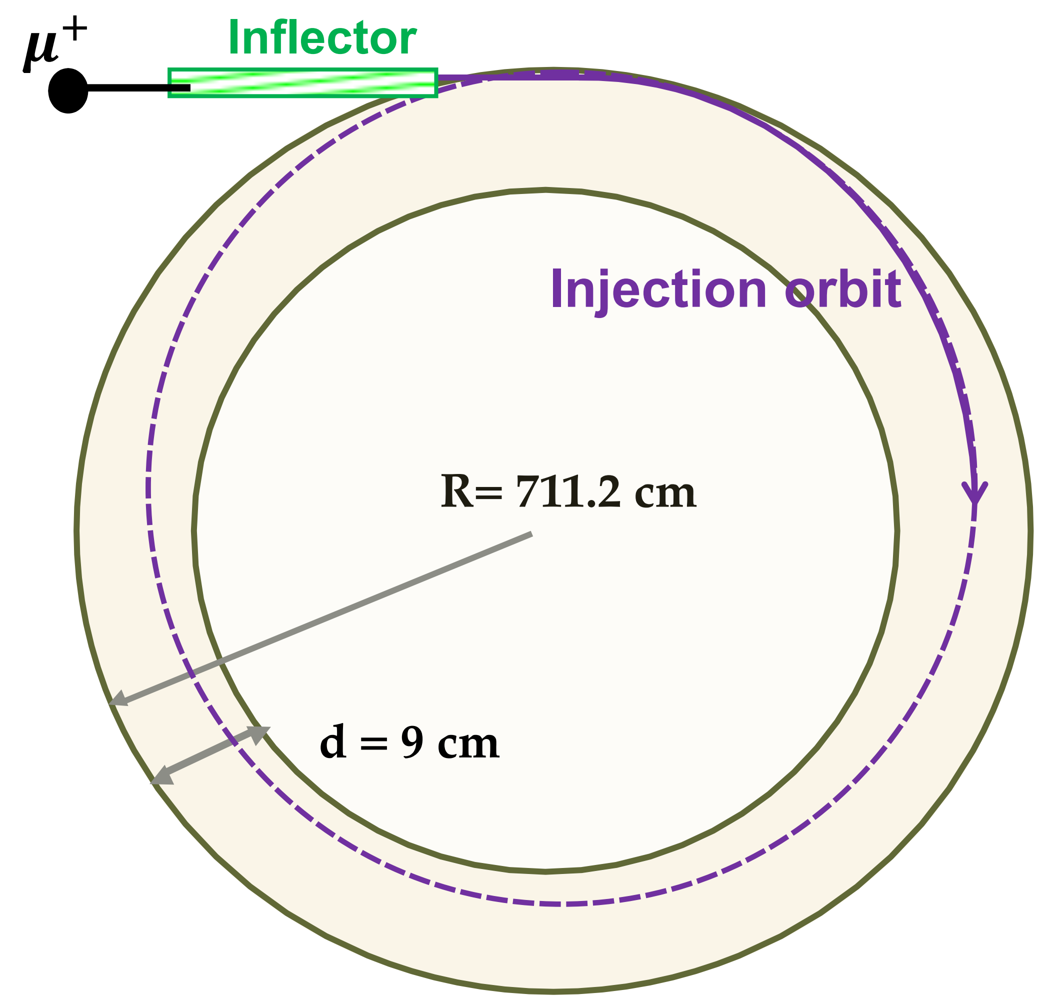
Muon g-2 Experiment

Storing the Muons : Inflector and Kickers



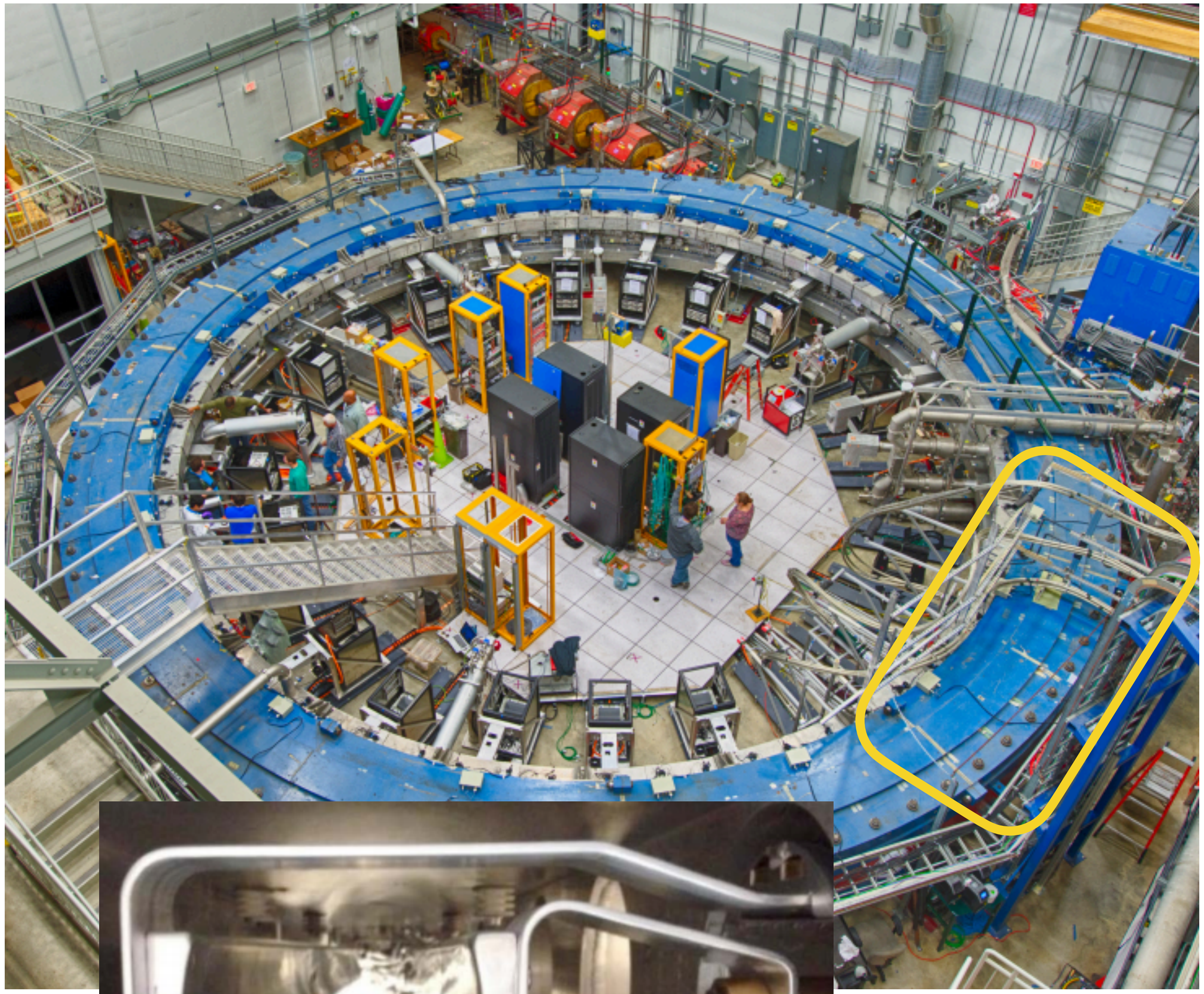


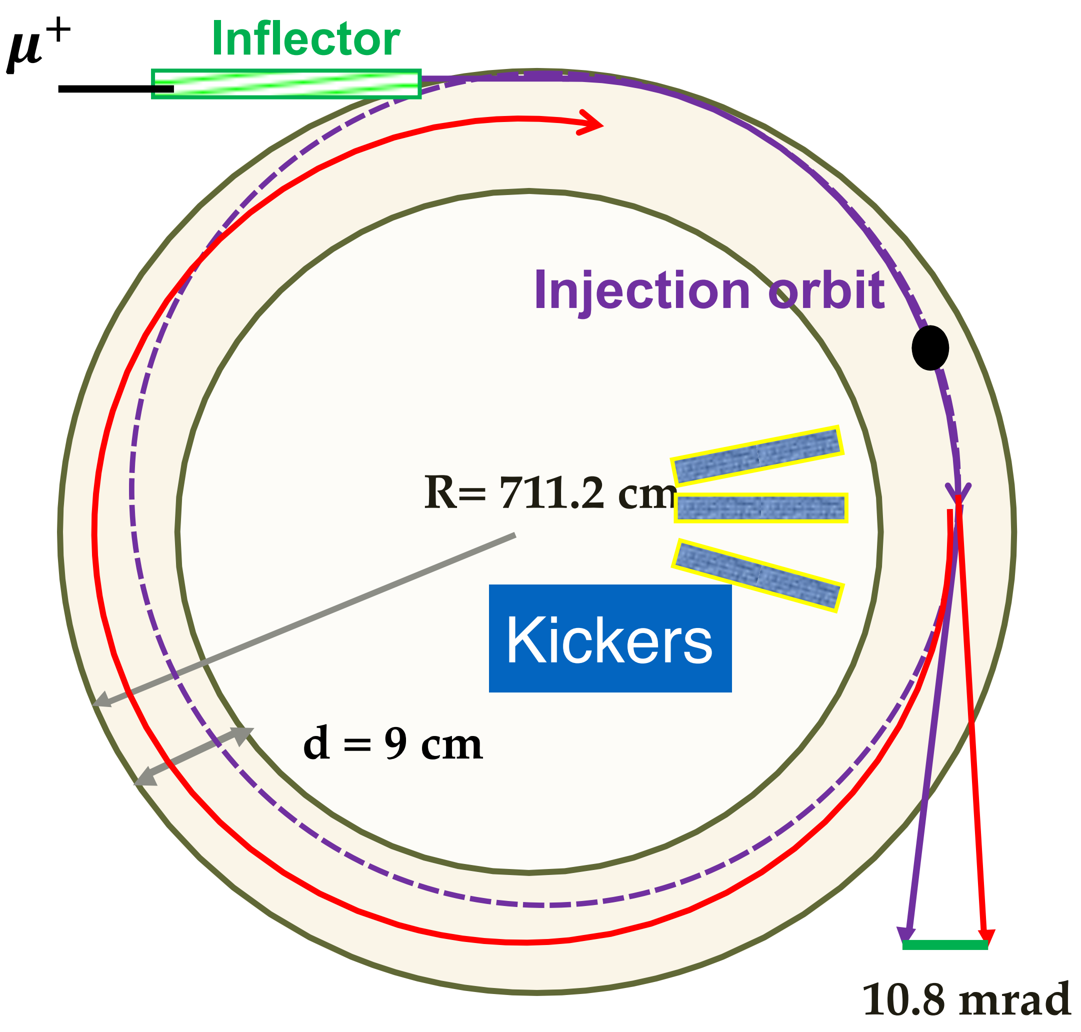
- **Inflector**
  - Super conducting magnet
  - Cancels B field(1.45T) in the magnet gap and let the beam enter the storage ring without being deflected.
  - They are at r=77mm outside central closed orbit



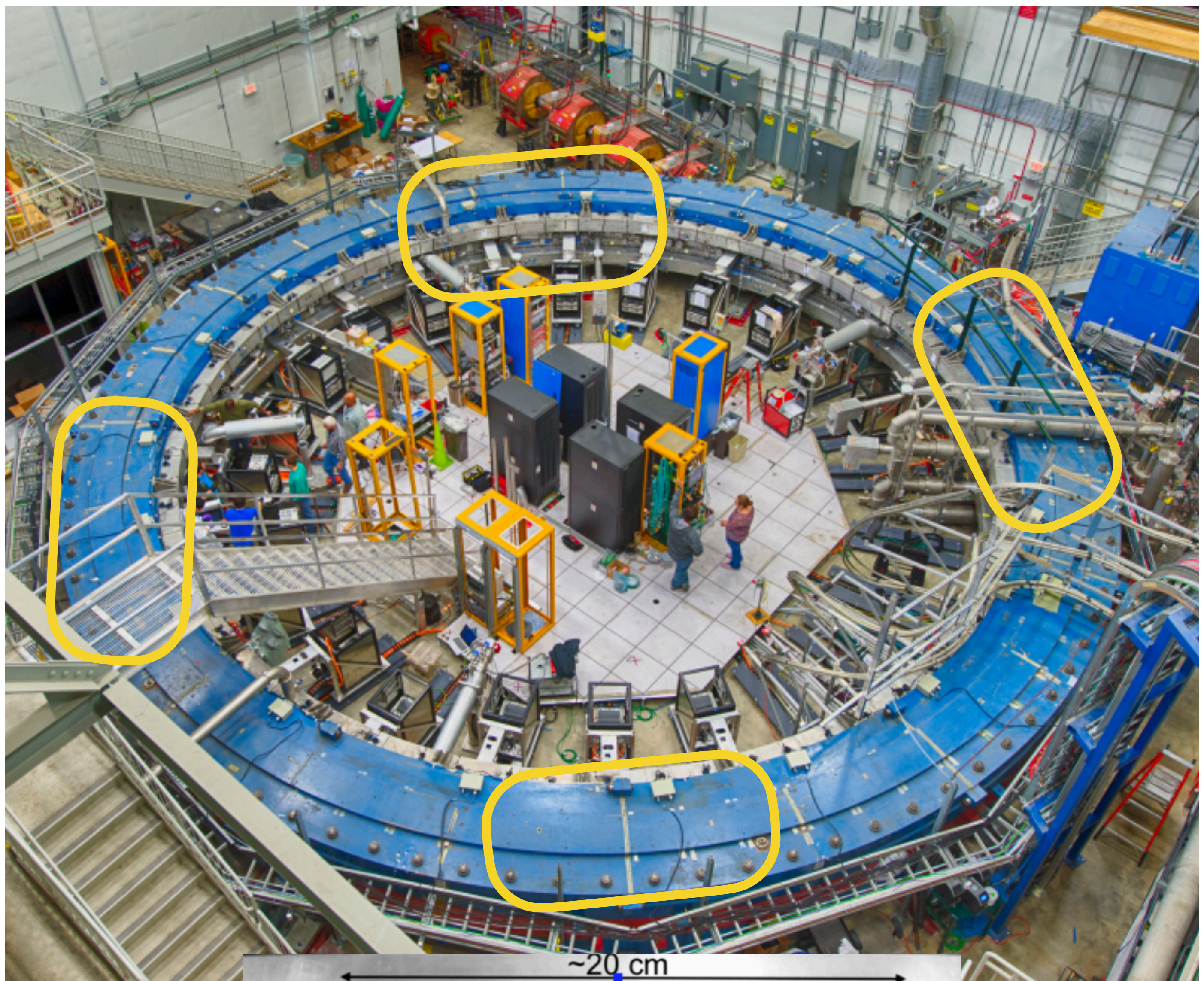
Storing the Muons : Inflector and Kickers

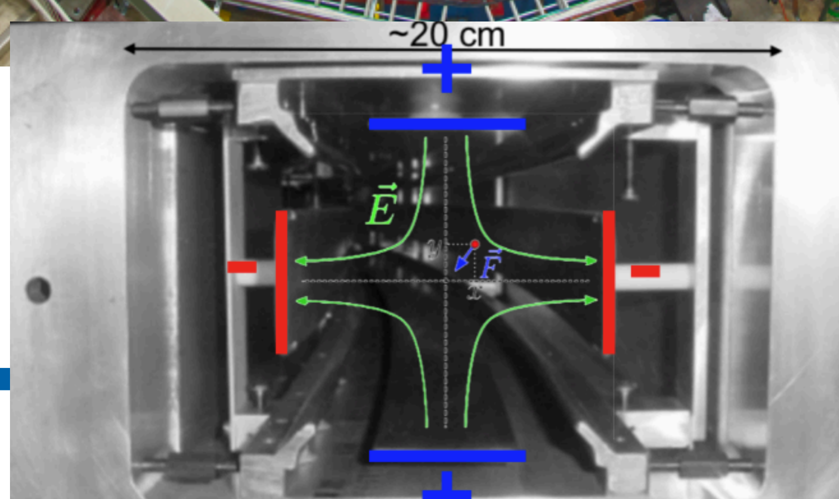
- **Magnetic Kickers**
  - Kick some more to direct the muons into ideal orbit.
  - Use 10.8 mrad pulsed kicks (<149 ns)



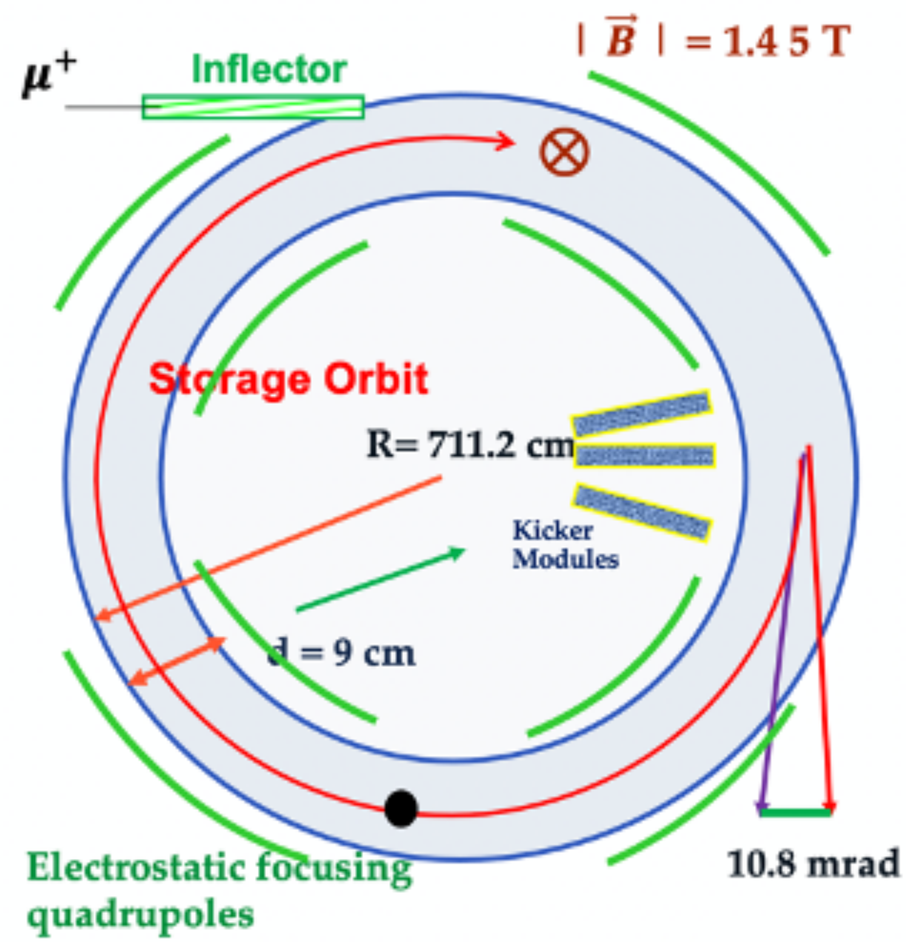


Storing the Muons: Electrostatic Quadrupoles





- **Electrostatic Quadrupoles**
  - **Electrostatic quadrupoles are used to focus the beam vertically while the storage ring field provides horizontal focusing**
  - Cancels out leading order of electric field contribution running at magic momentum p = 3.094 GeV/c



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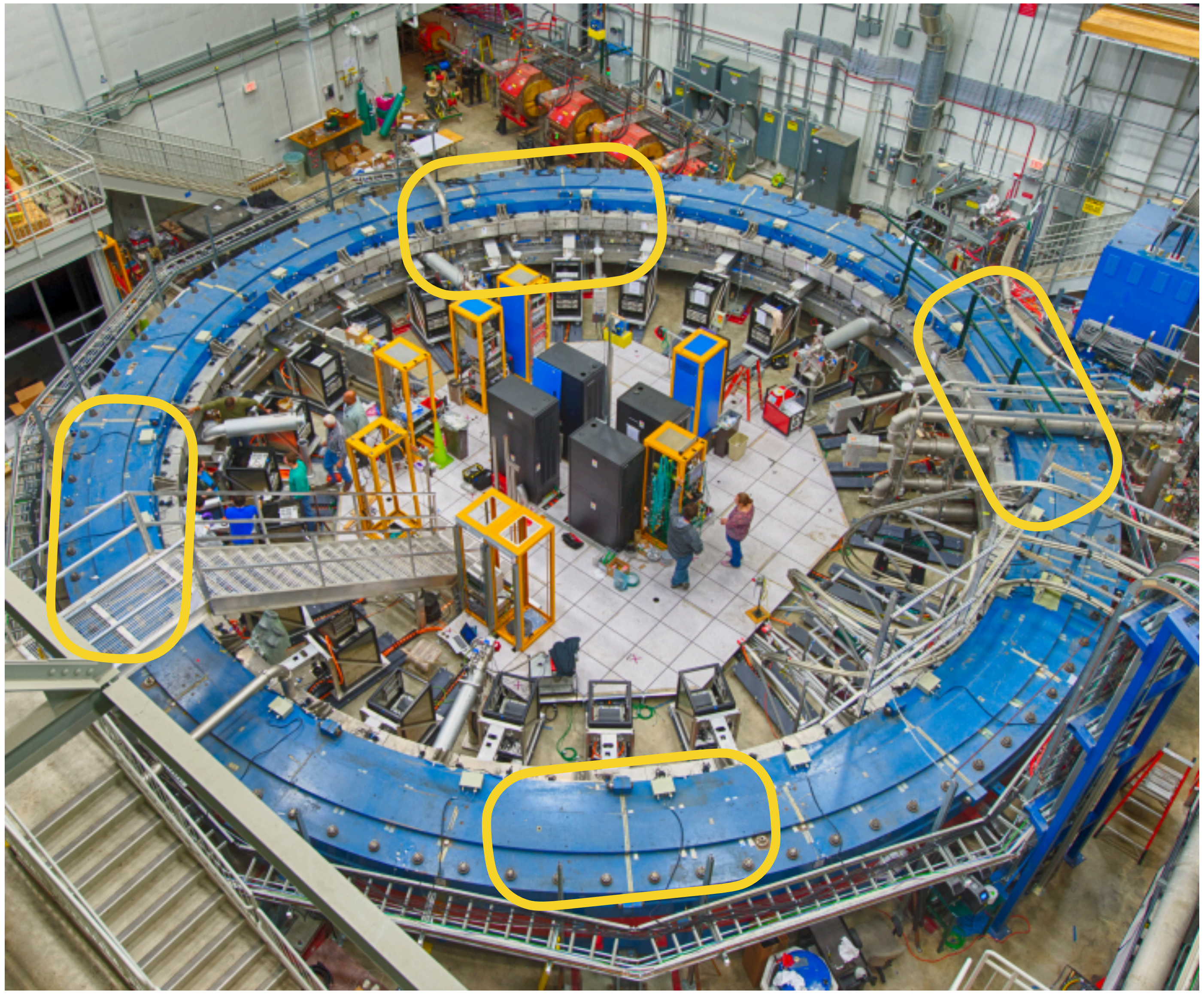


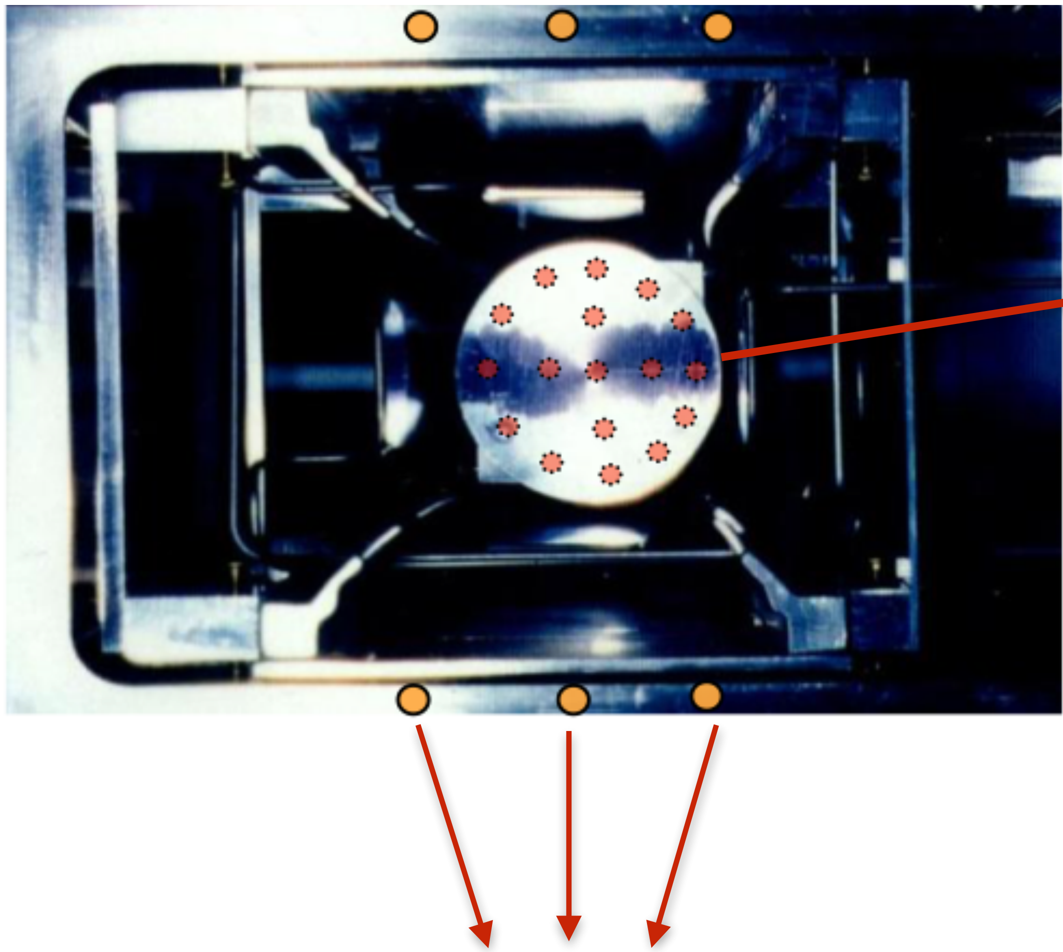
- **Electrostatic Quadrupoles**
  - 4 sets of quads which cover 43% of the ring
  - Electrostatic quadrupoles are used to focus the beam vertically while the storage ring field provides horizontal focusing
  - **Cancels out leading order of electric field contribution running at magic momentum p = 3.094 GeV/c**

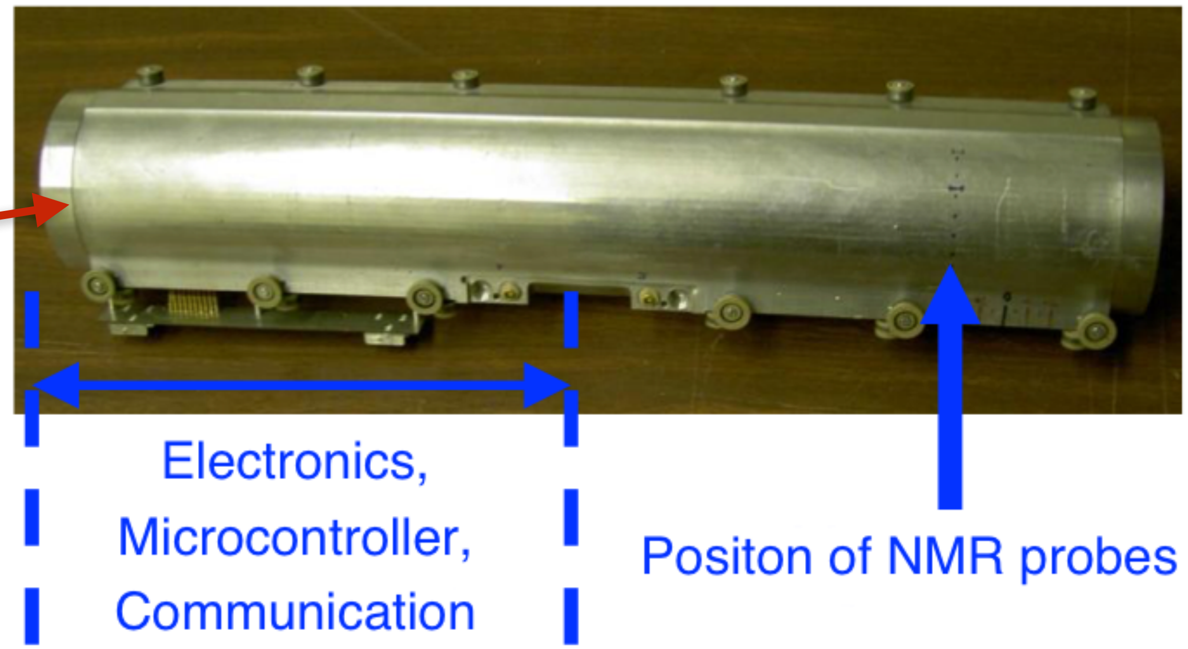
$$\vec{\omega}_a = \frac{e}{m}\left[a_\mu \vec{B} - a_\mu \frac{\gamma}{\gamma+1}\left(\vec{\beta}\cdot\vec{B}\right)\vec{\beta} - \left(a_\mu - \frac{1}{\gamma^2-1}\right)\vec{\beta}\times\vec{E} \right]$$

0 if in plane

Term cancels at the magic momentum

Measuring ω_p: Monitoring and Measuring the Magnetic Field

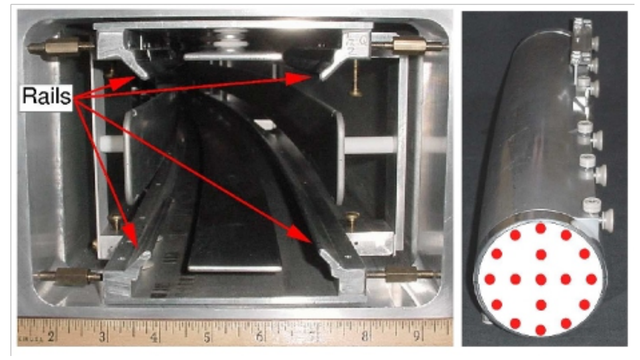


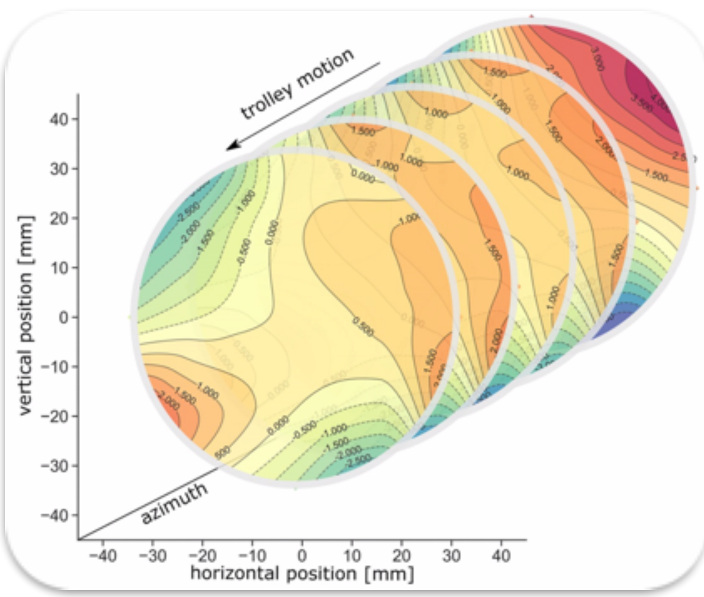


- **Fixed probes:**
  - 378 probes located on vacuum chamber
  - Measure the magnetic field while muons are inside the storage ring

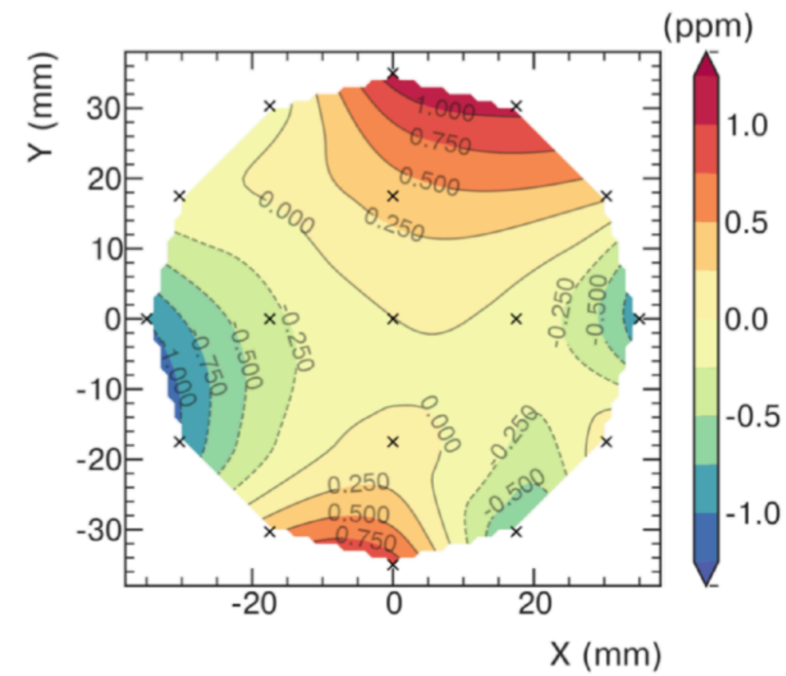
- **Trolley(Motorized cart):**
  - 17 NMR probes
  - Circles around the ring on periodically
  - Measures the magnetic field in the storage region
  - Used to calibrate FP measurements

Measuring ω_p: Monitoring and Measuring the Magnetic Field





azimuthally averaged field

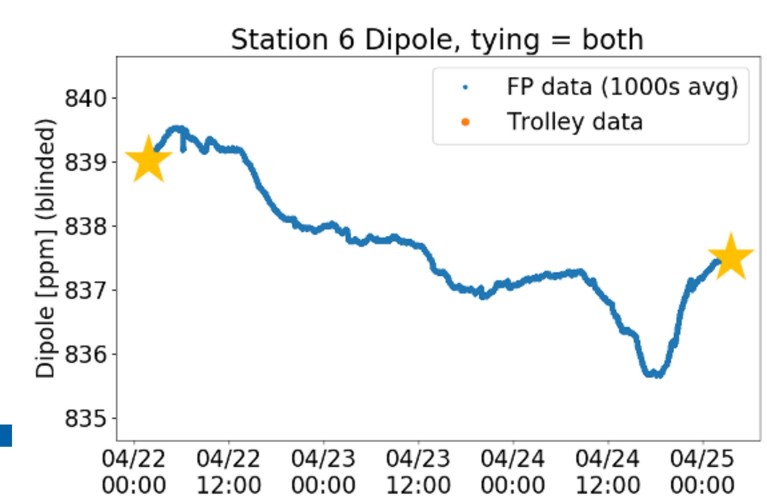


To determine ω_p at all times:

- Map the magnetic field in the storage region with trolley runs every 3 days
- Use fixed probes to interpolate the field between trolley runs

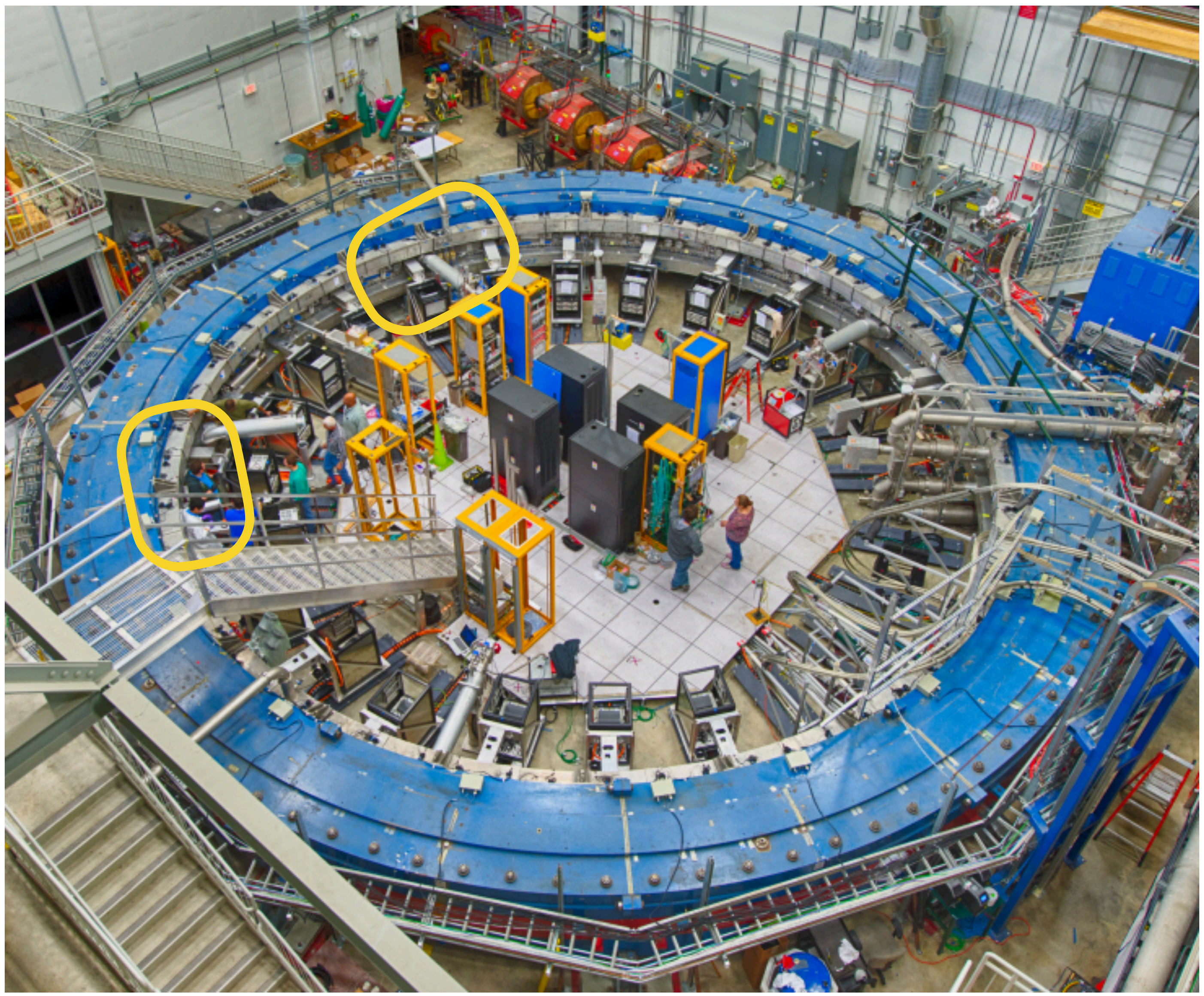
$$a_\mu = \left(\frac{g_e}{2}\right)\left(\frac{\omega_a}{\langle\omega_p\rangle}\right)\left(\frac{\mu_p}{\mu_e}\right)\left(\frac{m_\mu}{m_e}\right)$$

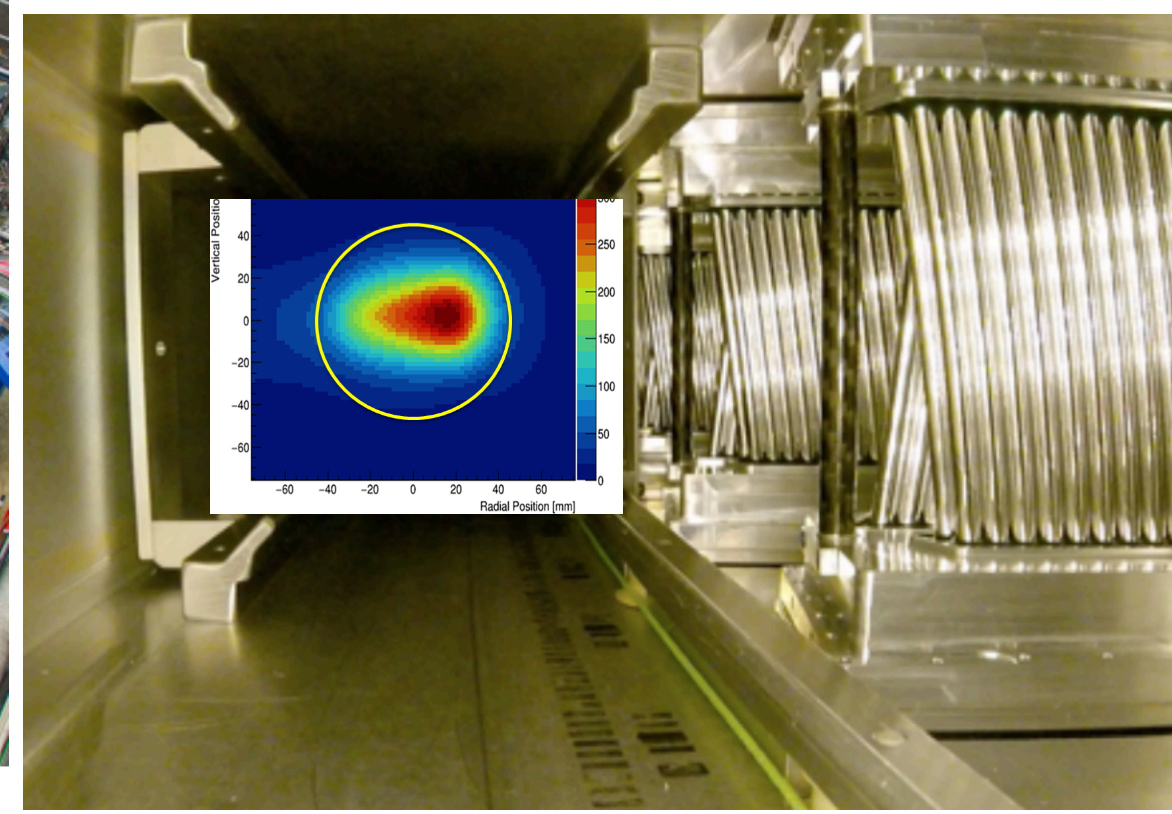
$$\langle\omega_p\rangle \approx \omega_p \otimes \rho(r)$$



Detectors: Trackers for Reconstructing the Beam Profile

- **Trackers**
  - 2 straw-tracker stations
  - 8 modules per station each with 128 straws
  - Reconstruct muon beam profile from positron trajectories



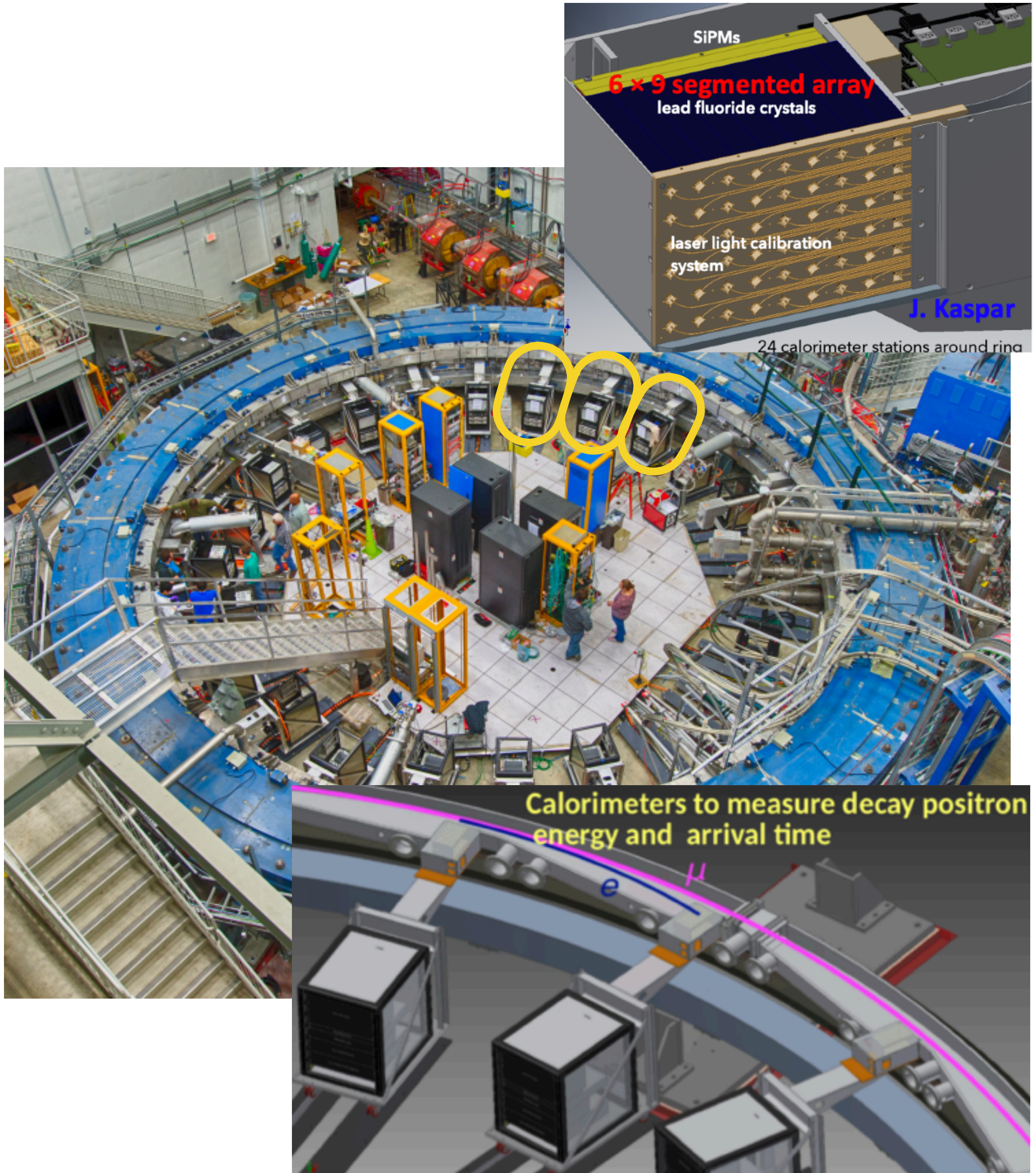


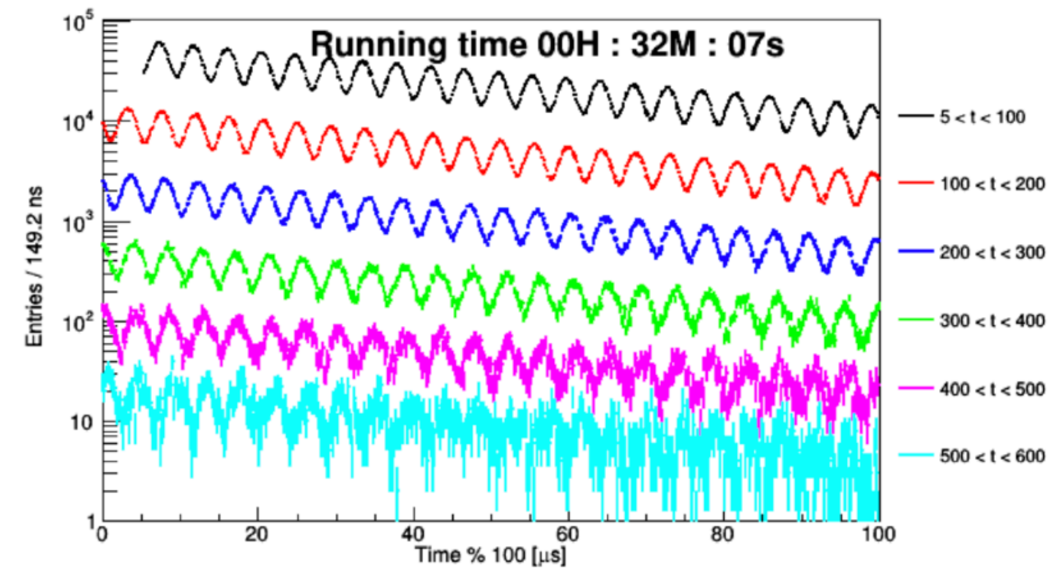
$$a_\mu = \left(\frac{g_e}{2}\right)\left(\frac{\omega_a}{\langle\omega_p\rangle}\right)\left(\frac{\mu_p}{\mu_e}\right)\left(\frac{m_\mu}{m_e}\right)$$

$$\langle\omega_p\rangle \approx \omega_p \otimes \rho(r)$$

Detectors : Calorimeters

- **Calorimeters**
  - 24 segmented PbF_2 crystal calorimeters stationed around the ring
  - Detects energy and arrival time of e^+ decayed from muons: $\mu^+ \rightarrow e^+ \bar{\nu}_\mu \nu_e$



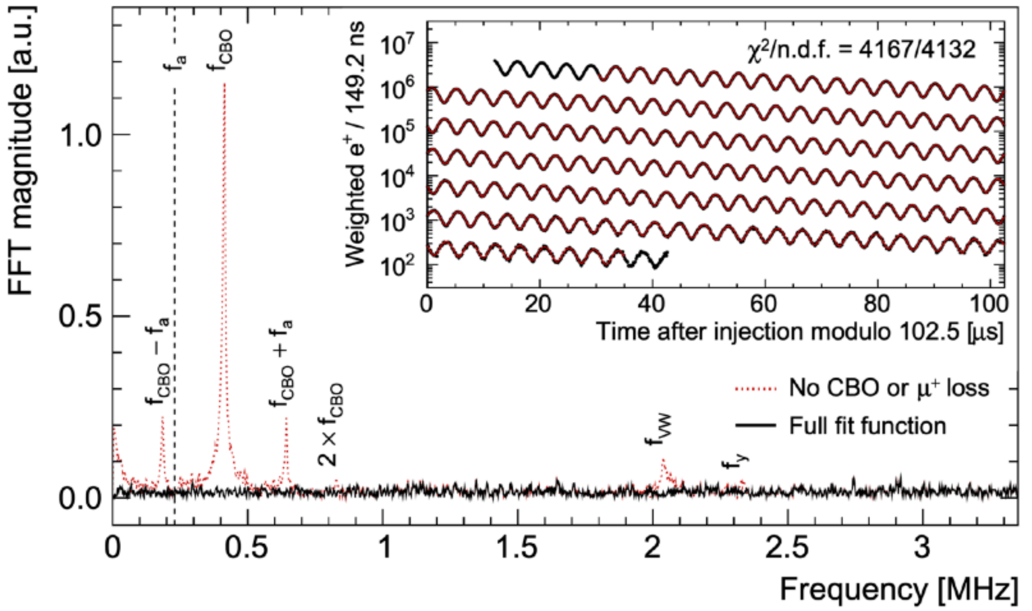


$$N(t) = N_0 e^{-t/\tau}[1 + A\cos(\omega_a t + \phi)]$$

$$a_\mu = \left(\frac{g_e}{2}\right)\left(\frac{\omega_a}{\langle\omega_p\rangle}\right)\left(\frac{\mu_p}{\mu_e}\right)\left(\frac{m_\mu}{m_e}\right)$$

Calculating ω_a: Hidden information in the wiggle plot

FFT analysis of fit residuals



Calculating ω_a: Hidden information in the wiggle plot

Underling Physics

5 parameter fit function

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

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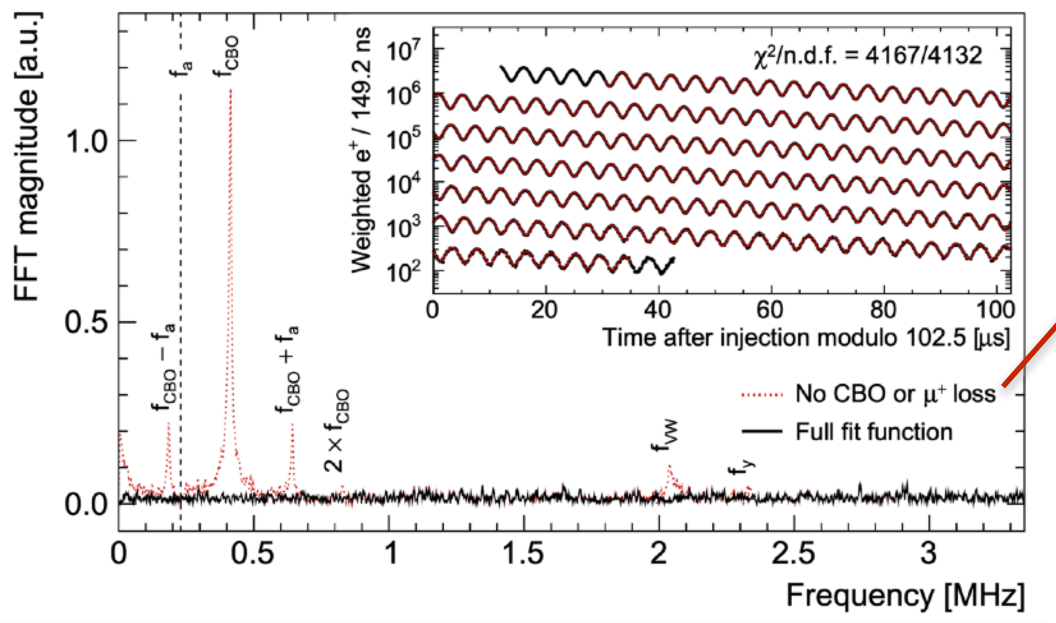

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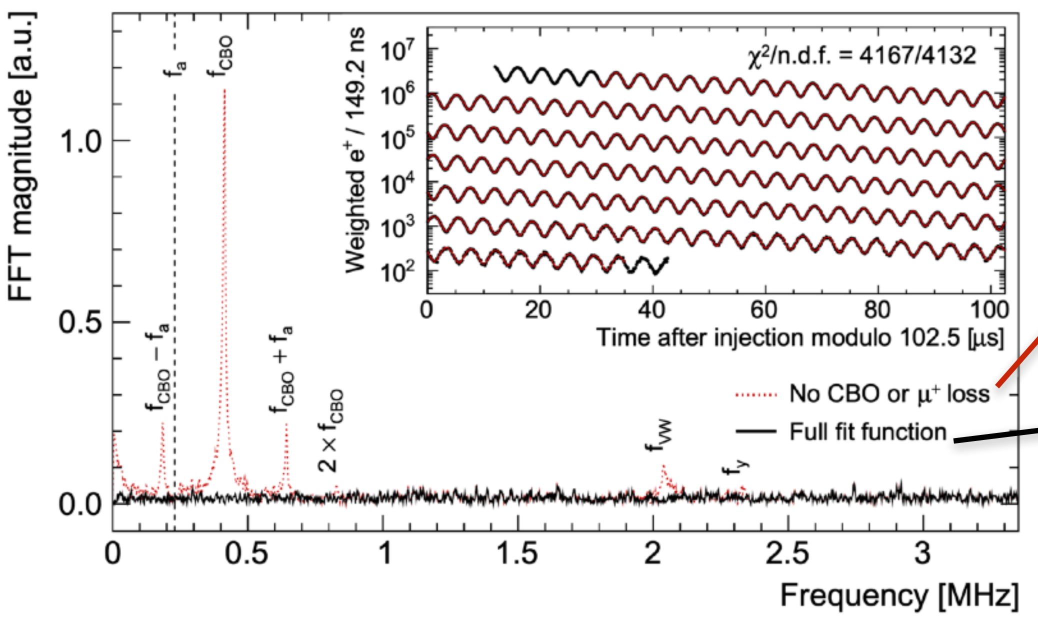

Underling Physics

5 parameter fit function

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

Systematic Effects

Including CBO, lost muon,
other beam dynamics related parameters
improve the fit results

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

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

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

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

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

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

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

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

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

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

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

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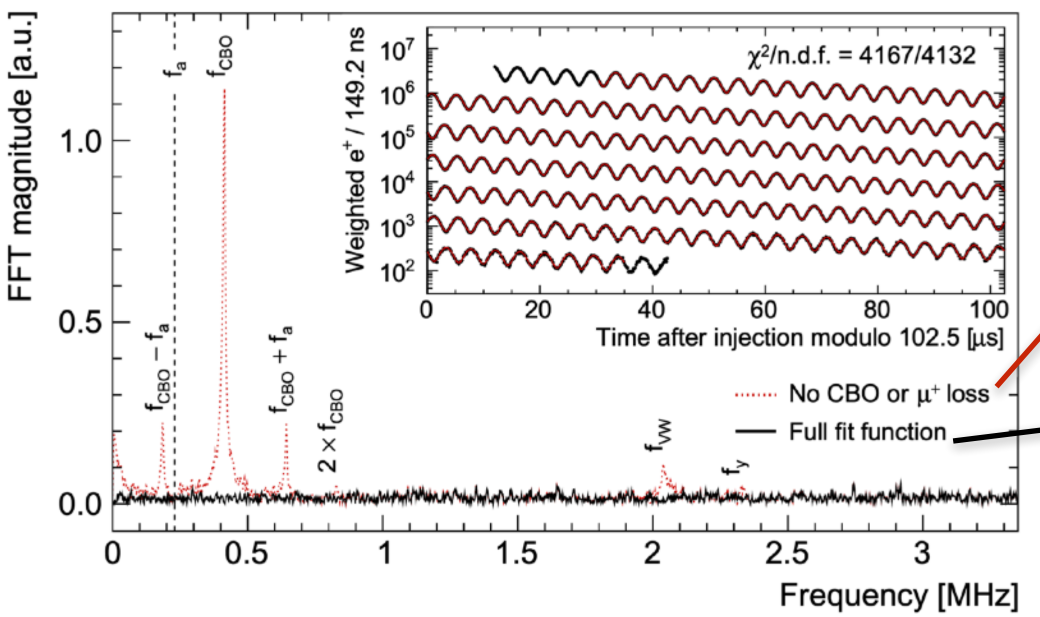

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5 parameter fit function

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

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improve the fit results

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

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

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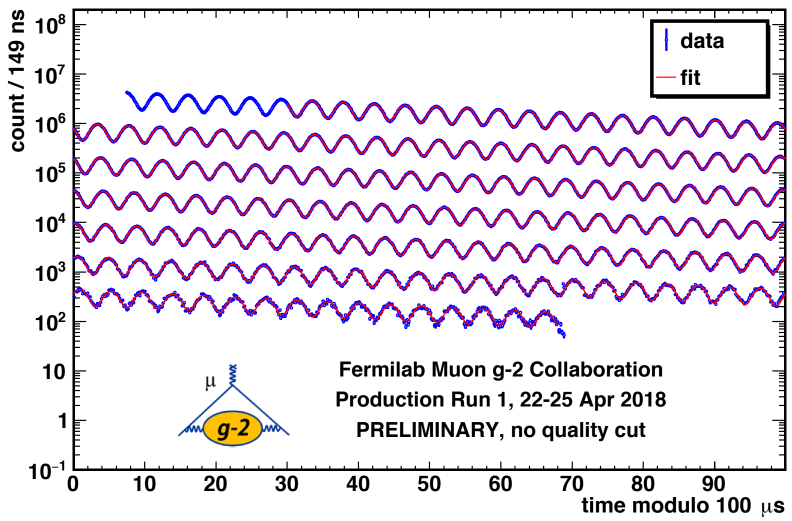
$$\omega_{\text{CBO}}(t) = \omega_0 t + A e^{-\frac{t}{\tau_A}} + B e^{-\frac{t}{\tau_B}}$$

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

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

See Lorenzo Cotrozzi's talk: Wednesday, Low Energy Session

Measuring the Muon Anomaly



ω_a

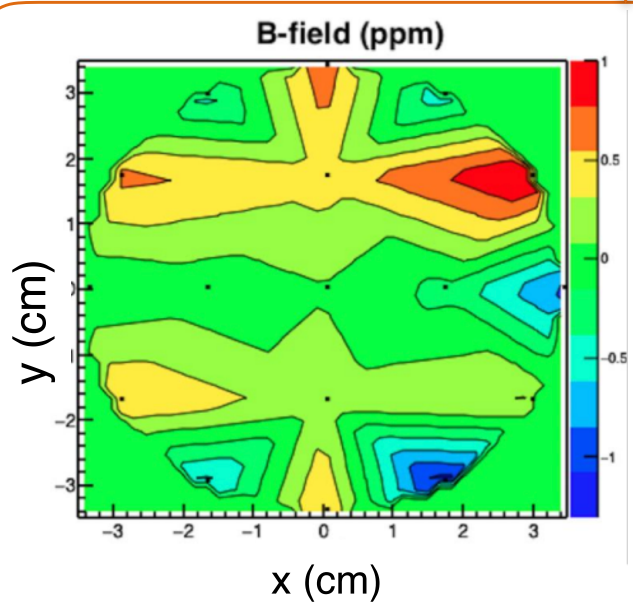
Extract from decay positron time spectra

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

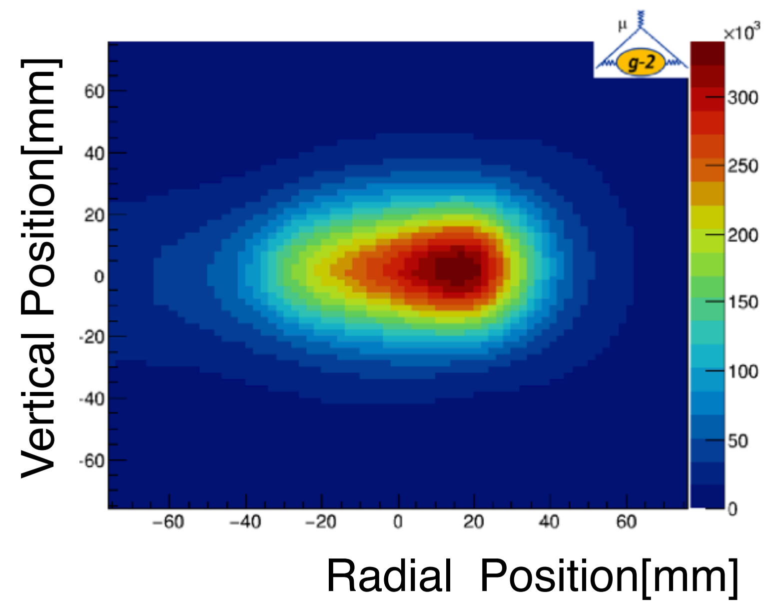
$$a_\mu = \left(\frac{g_e}{2}\right)\left(\frac{\omega_a}{\langle\omega_p\rangle}\right)\left(\frac{\mu_p}{\mu_e}\right)\left(\frac{m_\mu}{m_e}\right)$$

	Relative error (ppb)	Experiment
g_e	0.000 26	Quantum electron cyclotron. Hanneke et al. 2008.
μ_e/μ_p	3.0	Hydrogen spectroscopy. Winkler et al. 1972.
m_μ/m_e	22	Muonium hyperfine splitting. Liu et al. 1999.

0.26 ppt 3 ppb 22 ppb ⇨ 2017 CODATA



Map the magnetic field



Obtain muon distribution In the storage ring

$$\langle\omega_p\rangle \approx \omega_p \otimes \rho(r)$$

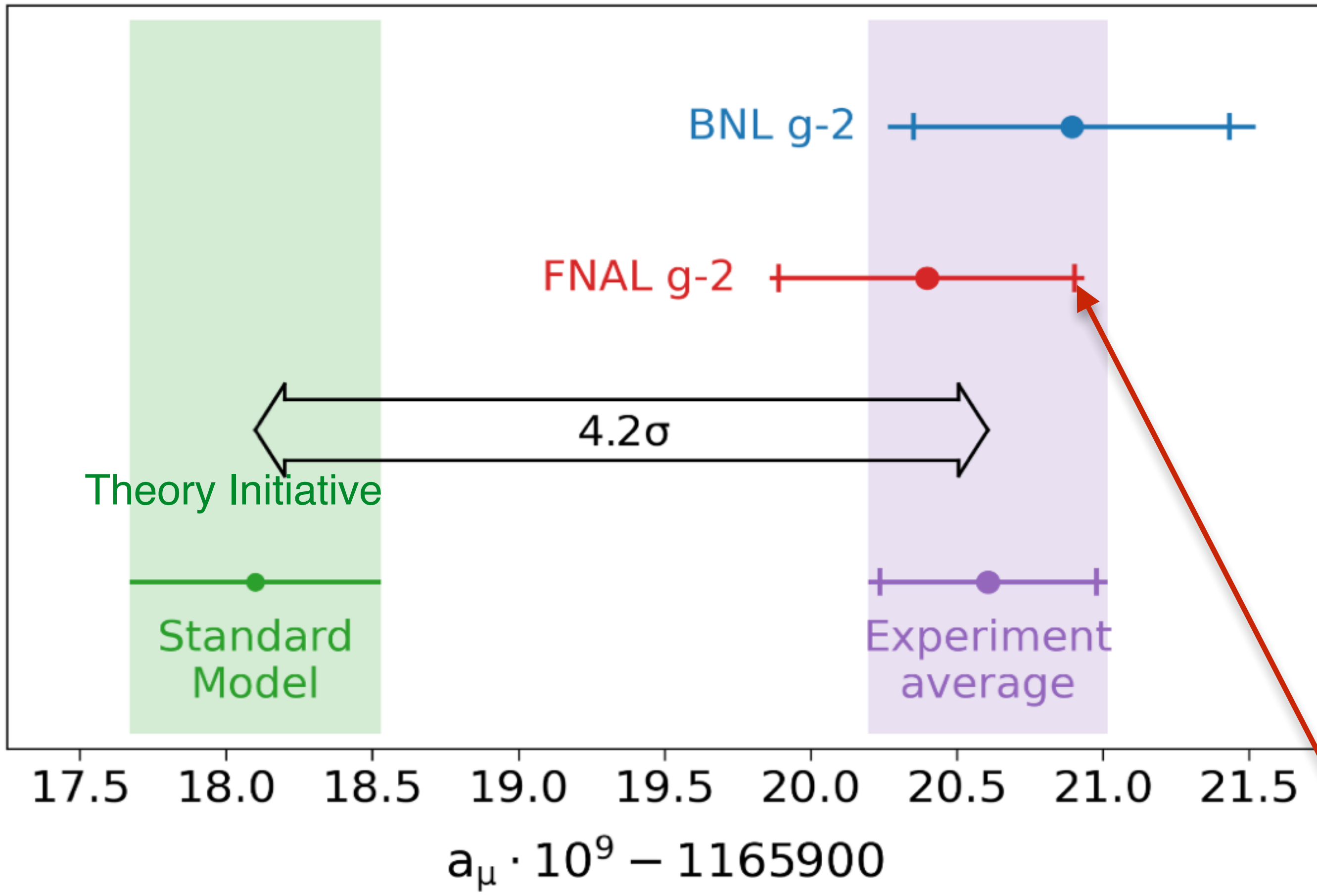
Average magnetic field weighted by muon distribution

ω_p: free proton precession frequency

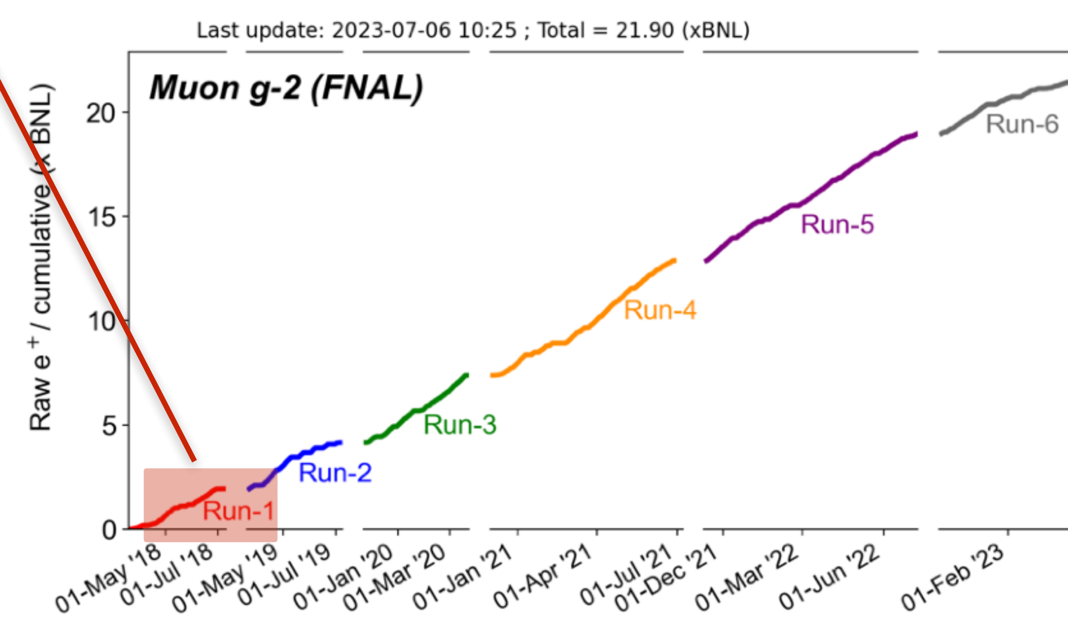
Using proton NMR $\hbar\omega_p = 2\mu_p B$

First Measurement from Fermilab Muon g-2 Experiment

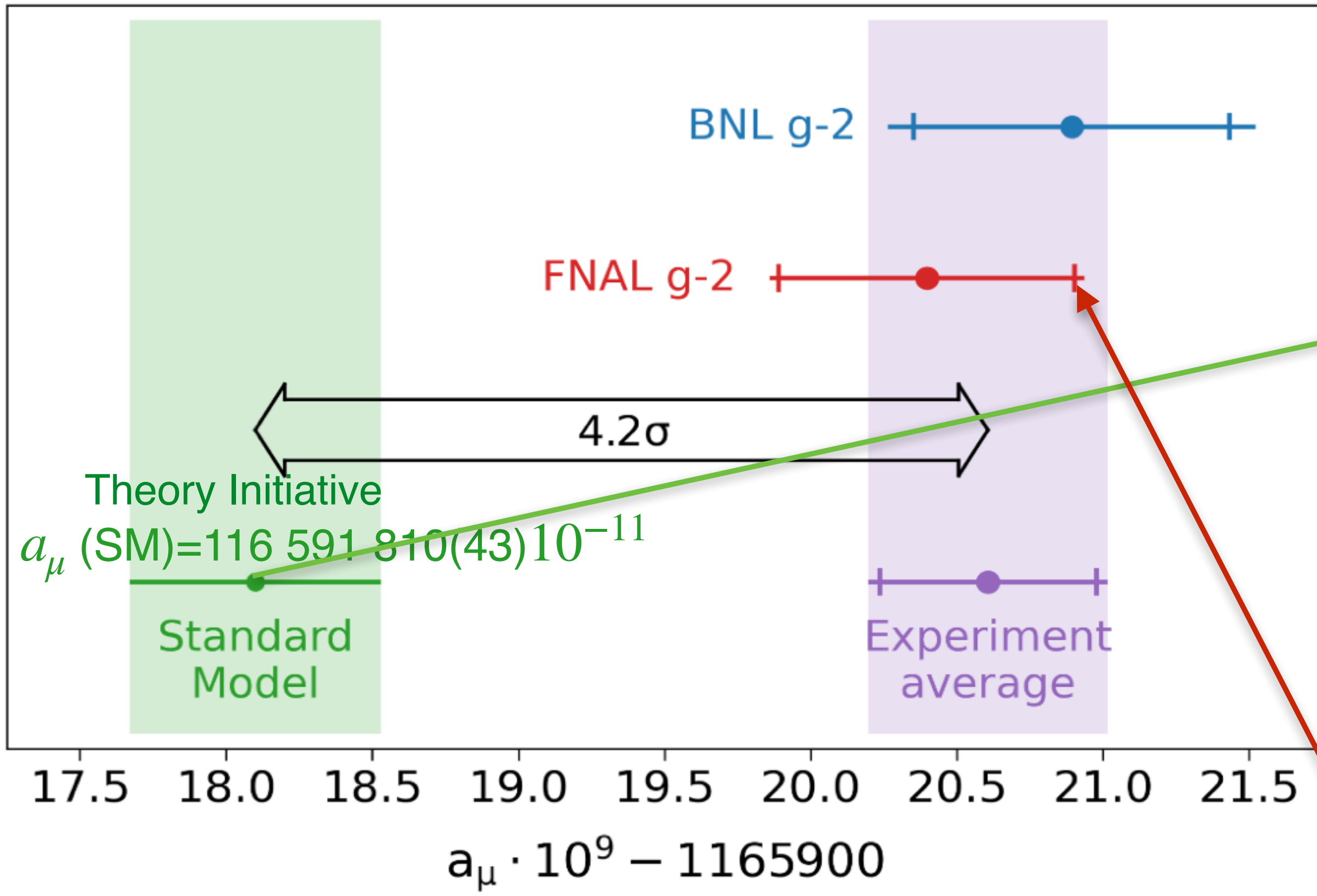
Fermilab Muon g-2 Experiment Result: Run-1 Analysis



- ✓FNAL determined anomaly with 460 ppb precision (statistical 434 ppb, systematics 159 ppb)
- ✓Nothing was found that indicated contradiction with BNL results
- ✓Run-1 result represents only 5% of Fermilab Muon g-2 data
- ✓15% smaller error

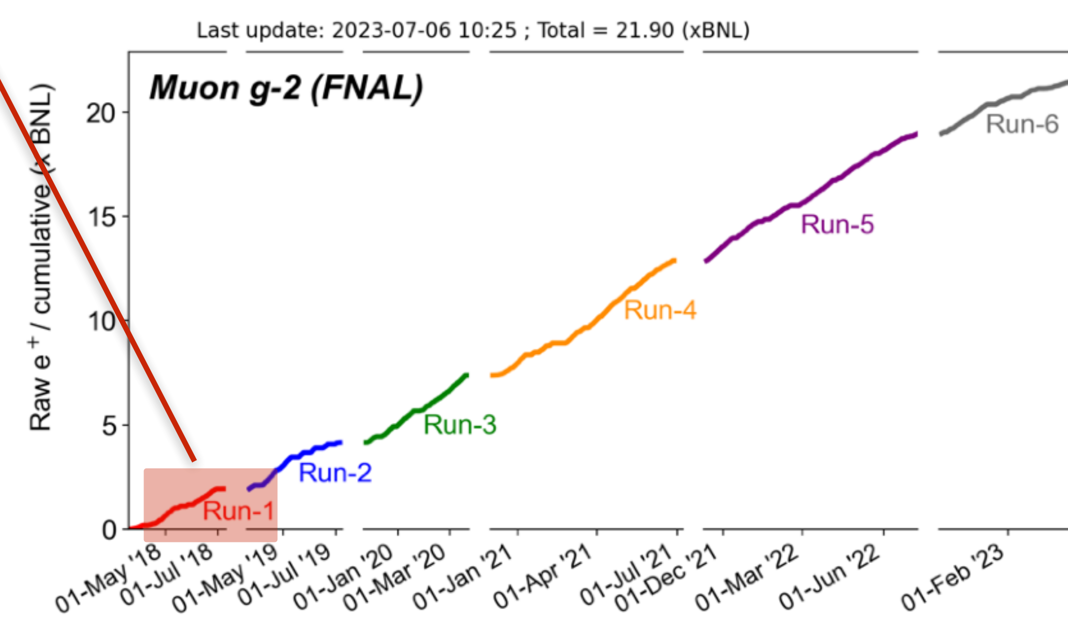


Theory Initiative SM Calculation



- ✓2020 Muon g-2 Theory Initiative
- ✓Net uncertainty is 368 ppb
- ✓HLbL incorporates both data-driven and lattice calculations, HVP is contribution is coming from only data-driven method

- ✓FNAL determined anomaly with 460 ppb precision (statistical 434 ppb, systematics 159 ppb)
- ✓Nothing was found that indicated contradiction with BNL results
- ✓Run-1 result represents only 5% of Fermilab Muon g-2 data
- ✓15% smaller error



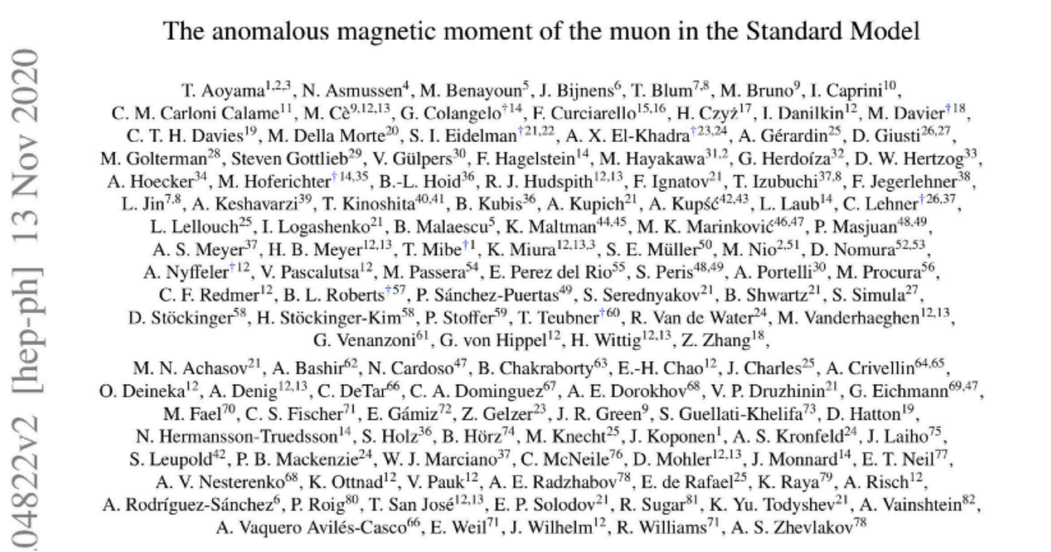
Close look at the SM calculations

Lattice

Data-based Dispersive

Lattice and Data

Official WP20

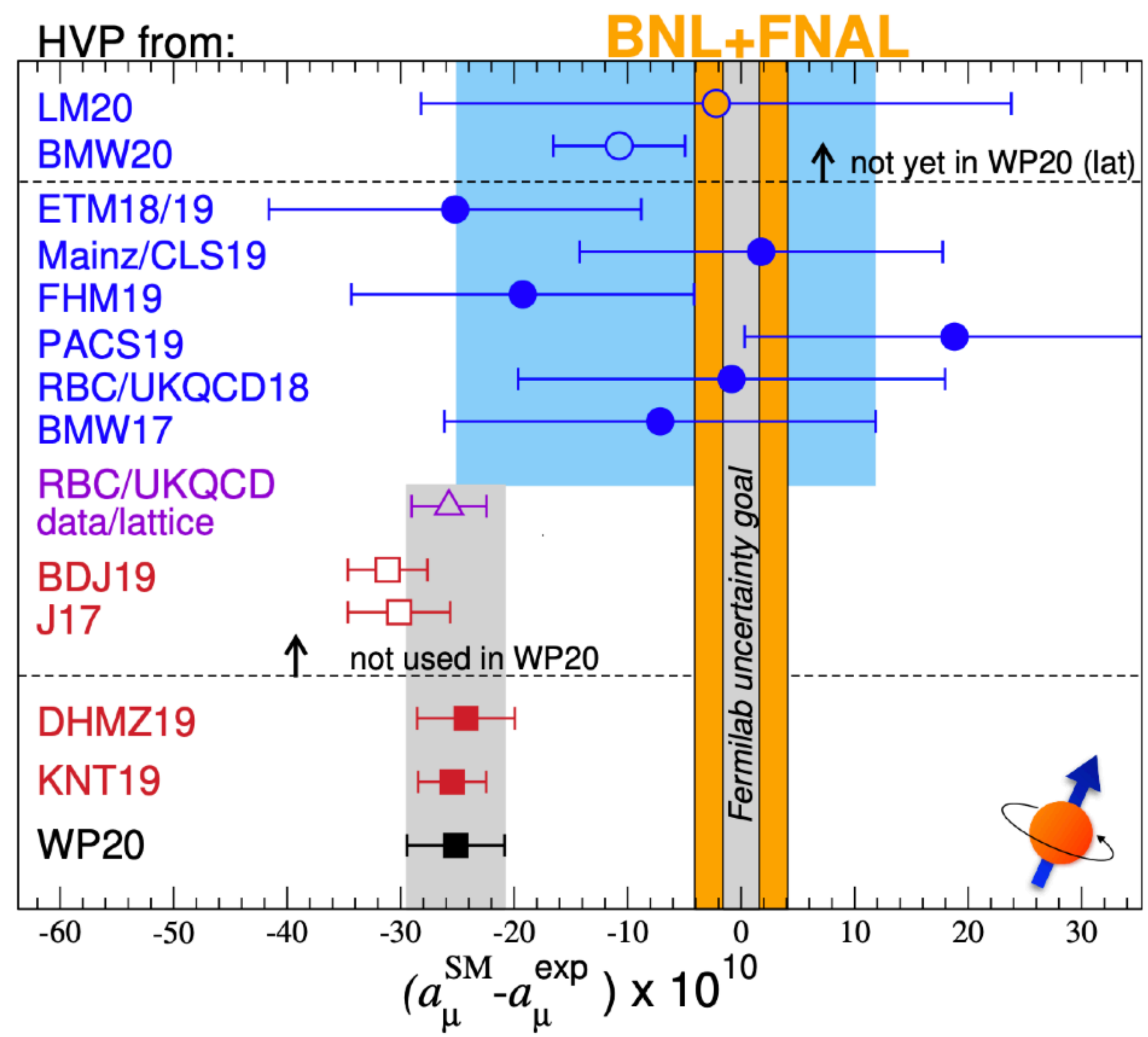


The anomalous magnetic moment of the muon in the Standard Model

T. Aoyama[1,2,3], N. Asmussen[4], M. Benayoun[5], J. Bijnens[6], T. Blum[7,8], M. Bruno[9], I. Caprini[10], C. M. Carloni Calame[11], M. Cè[9,12,13], G. Colangelo[†14], F. Curciarello[15,16], H. Czyż[17], I. Danilkin[12], M. Davier[†18], C. T. H. Davies[19], M. Della Morte[20], S. I. Eidelman[†21,22], A. X. El-Khadra[†23,24], A. Gérardin[25], D. Giusti[26,27], M. Golterman[28], Steven Gottlieb[29], V. Gülpers[30], F. Hagelstein[14], M. Hayakawa[31,2], G. Herdoíza[32], D. W. Hertzog[33], A. Hoecker[34], M. Hoferichter[†14,35], B.-L. Hoid[36], R. J. Hudspith[12,13], F. Ignatov[21], T. Izubuchi[37,8], F. Jegerlehner[38], L. Jin[7,8], A. Keshavarzi[39], T. Kinoshita[40,41], B. Kubis[36], A. Kupich[21], A. Kupść[42,43], L. Laub[14], C. Lehner[†26,37], L. Lellouch[25], I. Logashenko[21], B. Malaescu[5], K. Maltman[44,45], M. K. Marinković[46,47], P. Masjuan[48,49], A. S. Meyer[37], H. B. Meyer[12,13], T. Mibe[†1], K. Miura[12,13,3], S. E. Müller[50], M. Nio[2,51], D. Nomura[52,53], A. Nyffeler[†12], V. Pascalutsa[12], M. Passera[54], E. Perez del Rio[55], S. Peris[48,49], A. Portelli[30], M. Procura[56], C. F. Redmer[12], B. L. Roberts[†57], P. Sánchez-Puertas[49], S. Serednyakov[21], B. Shwartz[21], S. Simula[27], D. Stöckinger[58], H. Stöckinger-Kim[58], P. Stoffer[59], T. Teubner[†60], R. Van de Water[24], M. Vanderhaeghen[12,13], G. Venanzoni[61], G. von Hippel[12], H. Wittig[12,13], Z. Zhang[18],

M. N. Achasov[21], A. Bashir[62], N. Cardoso[47], B. Chakraborty[63], E.-H. Chao[12], J. Charles[25], A. Crivellin[64,65], O. Deineka[12], A. Denig[12,13], C. DeTar[66], C. A. Dominguez[67], A. E. Dorokhov[68], V. P. Druzhinin[21], G. Eichmann[69,47], M. Fael[70], C. S. Fischer[71], E. Gámiz[72], Z. Gelzer[23], J. R. Green[9], S. Guellati-Khelifa[73], D. Hatton[19], N. Hermansson-Truedsson[14], S. Holz[36], B. Hörz[74], M. Knecht[25], J. Koponen[1], A. S. Kronfeld[24], J. Laiho[75], S. Leupold[42], P. B. Mackenzie[24], W. J. Marciano[37], C. McNeile[76], D. Mohler[12,13], J. Monnard[14], E. T. Neil[77], A. V. Nesterenko[68], K. Ottnad[12], V. Pauk[12], A. E. Radzhabov[78], E. de Rafael[25], K. Raya[79], A. Risch[12], A. Rodríguez-Sánchez[6], P. Roig[80], T. San José[12,13], E. P. Solodov[21], R. Sugar[81], K. Yu. Todyshev[21], A. Vainshtein[82], A. Vaquero Avilés-Casco[66], E. Weil[71], J. Wilhelm[12], R. Williams[71], A. S. Zhevlakov[78]

04822v2 [hep-ph] 13 Nov 2020



- Theory Initiative HVP contribution
  - Two independent data-driven compilations
  - 6 independent LQCD calculations with HVP average at 2.6% total uncertainty
  - BMW20 is the first LQCD calculation with sub-percent error (in 2021)

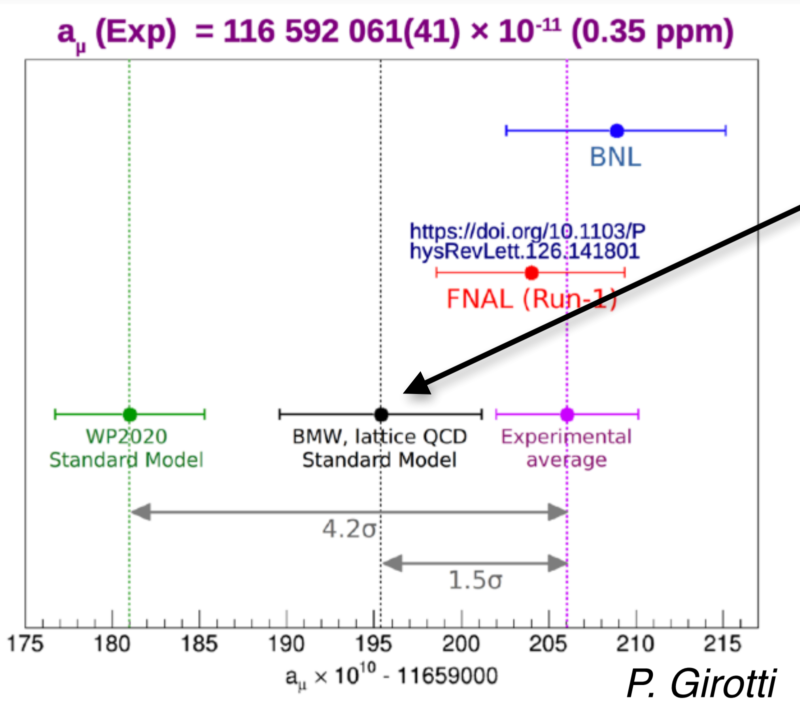
Close look at the SM calculations

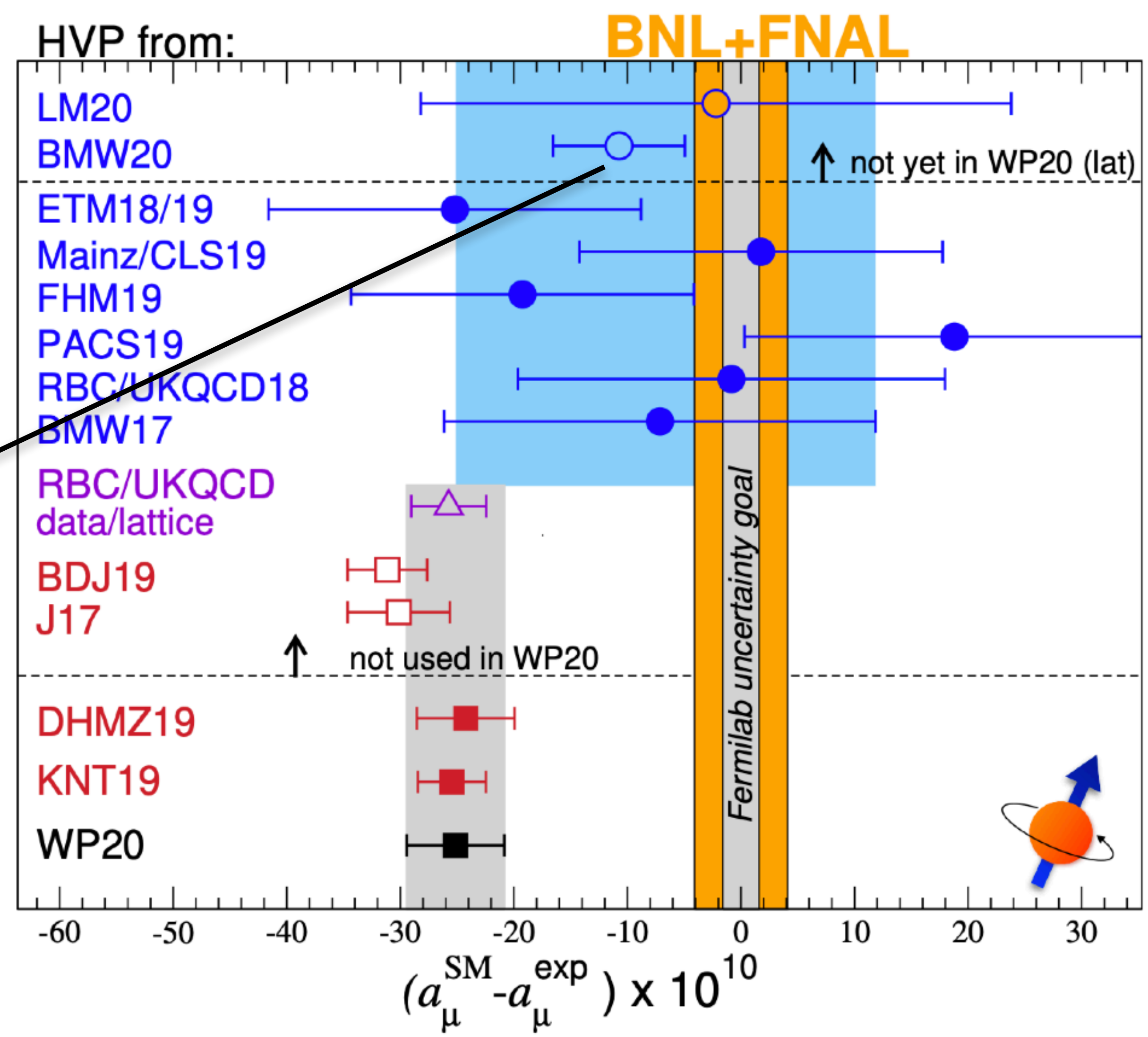
Lattice

Data-based Dispersive

Lattice and Data

Official WP20

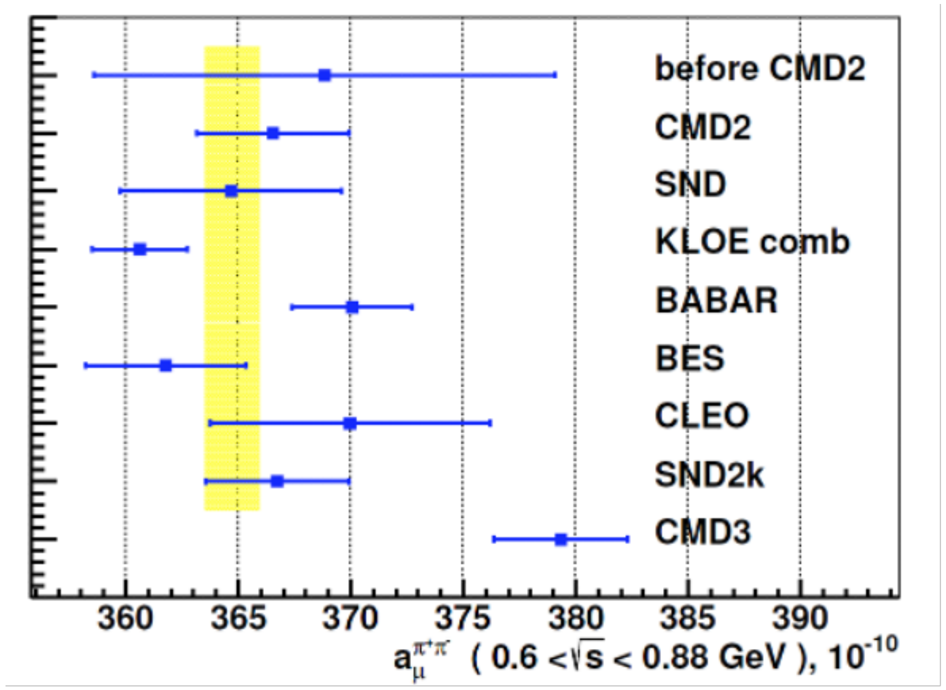




- BMW20 reduced the tension with experimental average to 1.5σ
- BMW20 is also in tension with data-based dispersive result(2.1σ)
- Needs to be confirmed by other lattice QCD groups
- Will be interested to see how it evolves in future but lattice QCD calculations requires a huge amount of computing resource. All groups are working on defining intermediate results (simpler way to compare things)

CMD3 Result

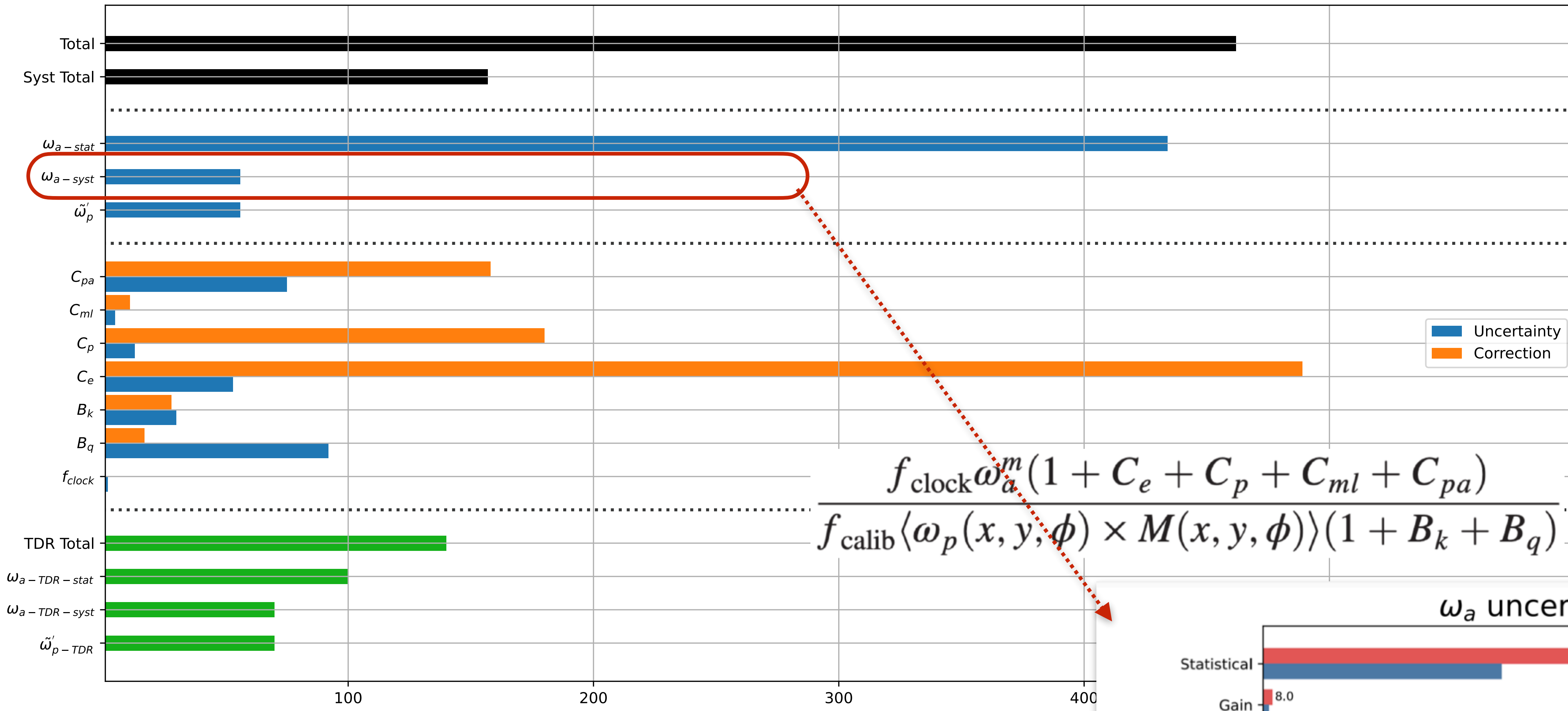
F. Ignatov et al, March 2023



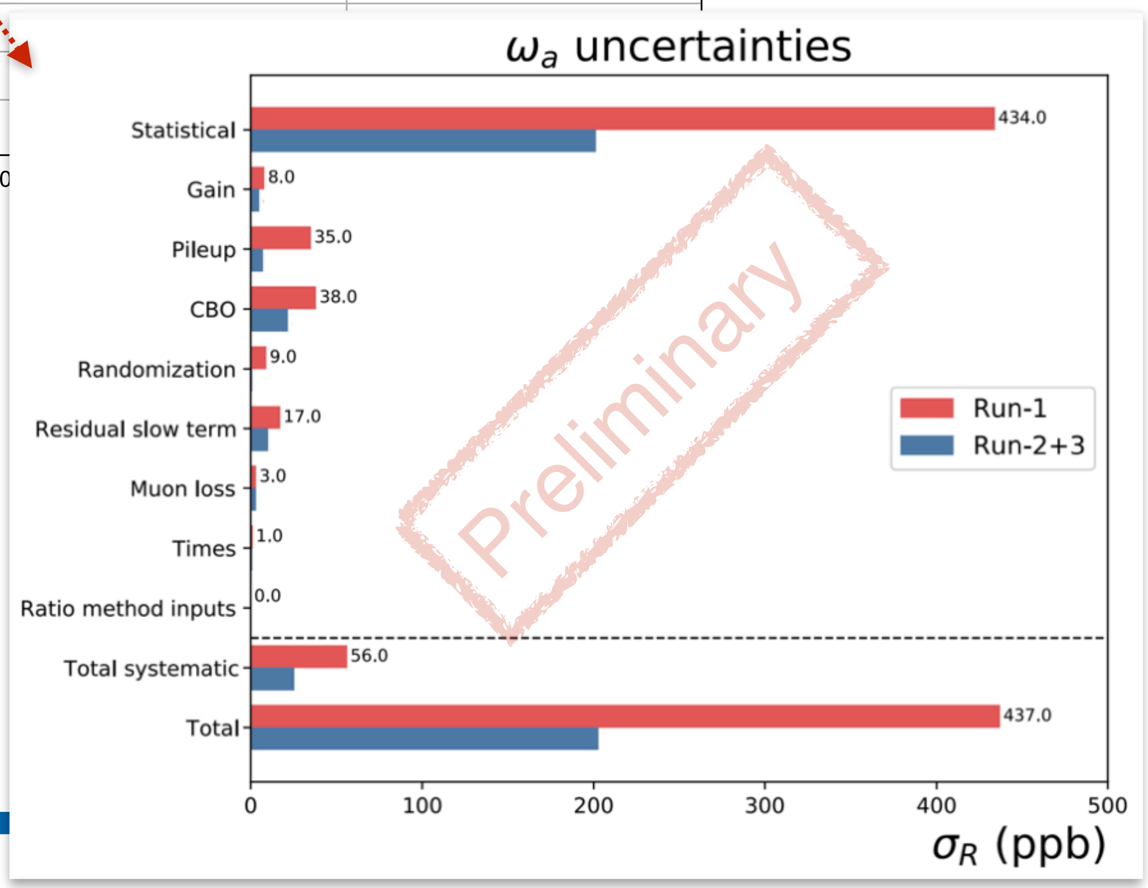
- Measurement of $e^+e^- \to \pi^+\pi^-$ cross section contributes to HVP
- Tension with previous measurements (>3 to 5 σ)
- Close to the experimental measurement
- A panel with muon g-2 collaboration showed no obvious problem
- There is no simple answer! Big puzzle to be resolved
- Electron-positron collider community is investigating the reason
- New results to come from BaBar, KLOE, SND, BesIII, Belle II

Improvements on the Experiment

Improvements on the Muon g-2 Experiment Uncertainty:
Analysis Methods(after Run-1)



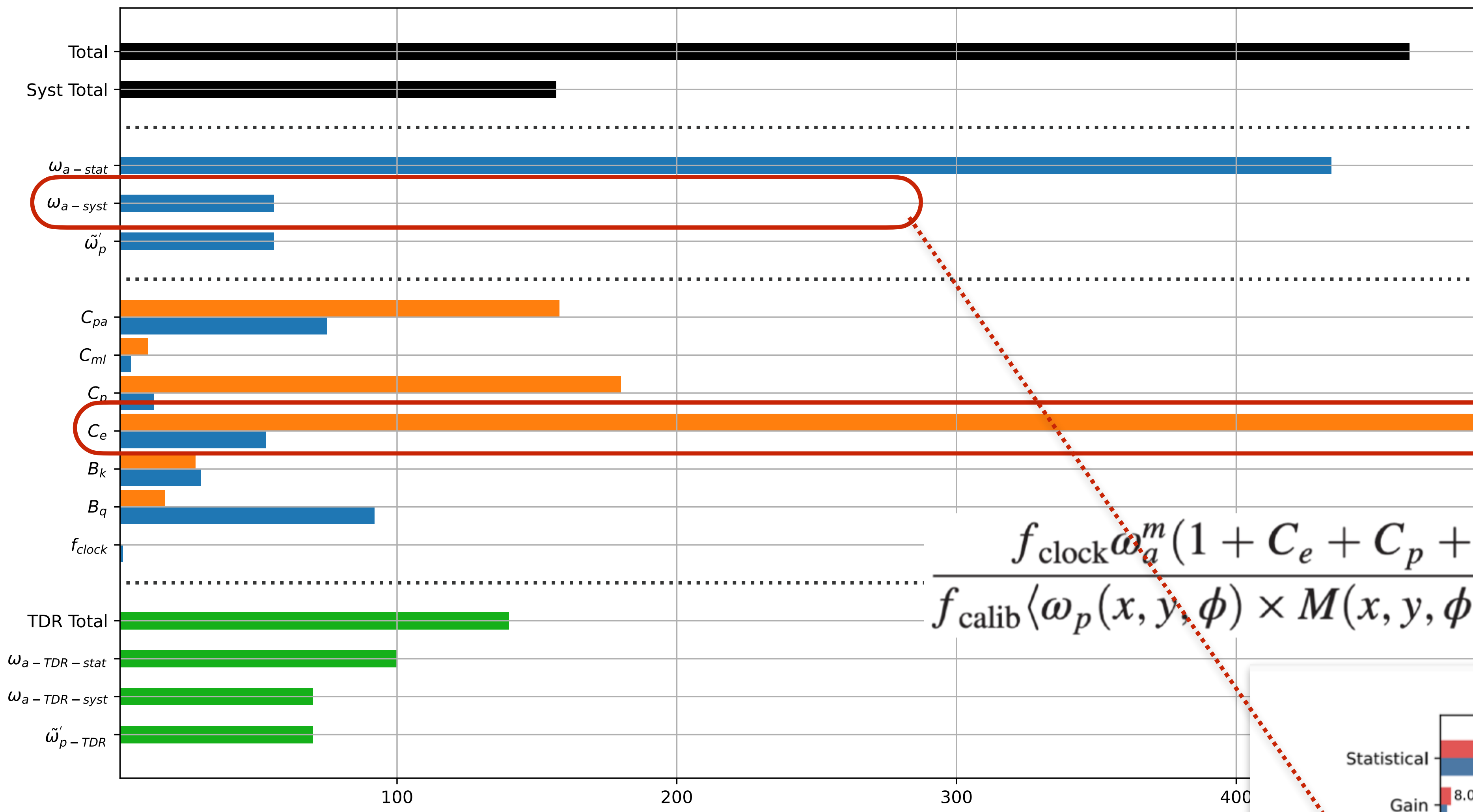
$$\frac{f_{\text{clock}}\,\omega_a^m(1+C_e+C_p+C_{ml}+C_{pa})}{f_{\text{calib}}\langle\omega_p(x,y,\phi)\times M(x,y,\phi)\rangle(1+B_k+B_q)}$$

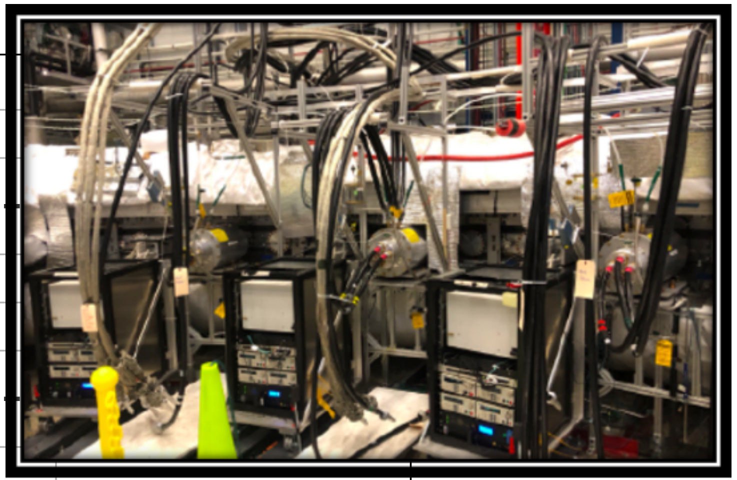


- Improved reconstruction method and reduced pileup
- Improved models to define the data
- Run-2/3 ω_a systematics is expected to go down by half

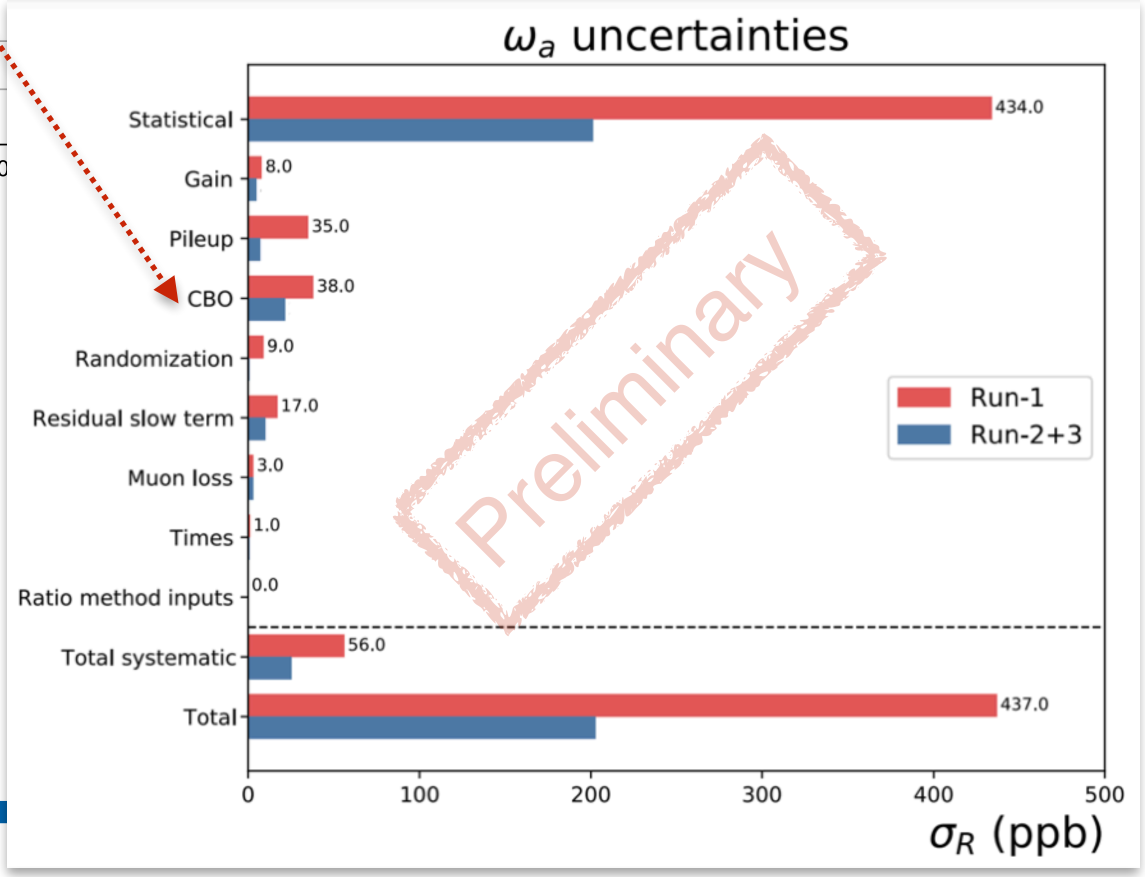
Improvements on the Muon g-2 Experiment Uncertainty:

Improved Kick(during Run-3)



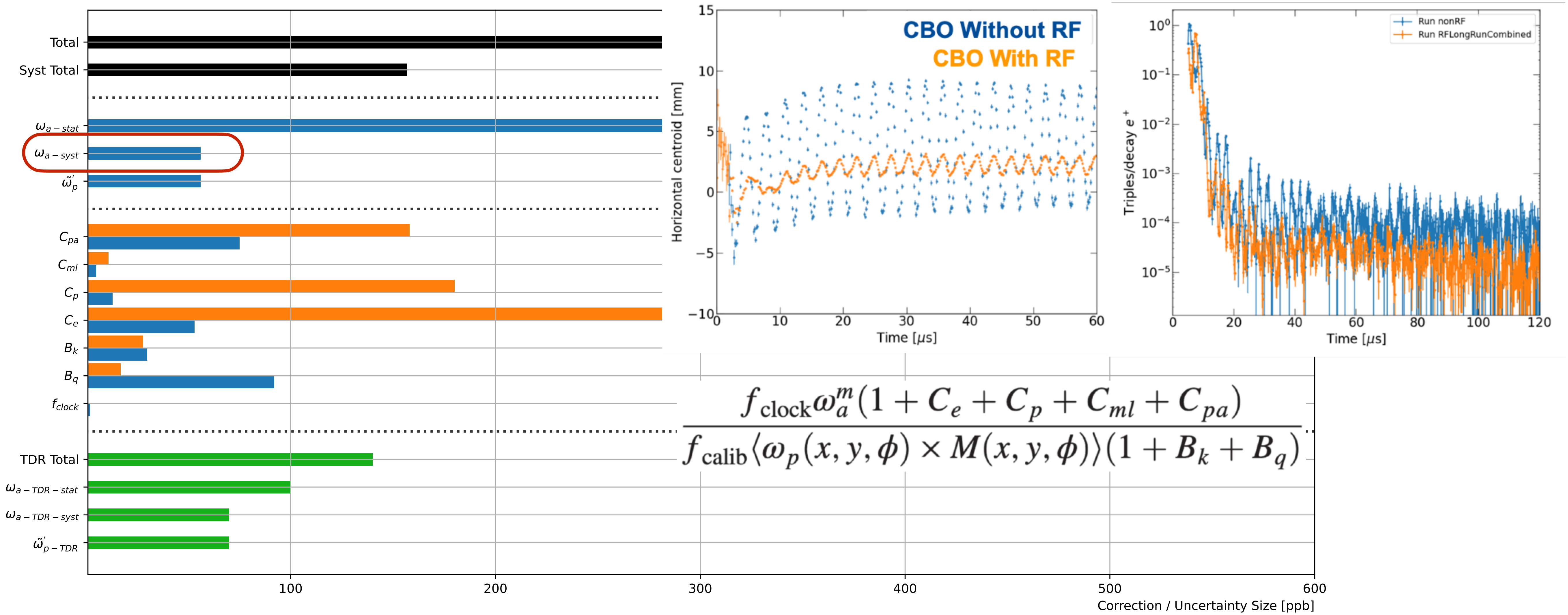


$$\frac{f_{\text{clock}}\,\omega_a^m(1+C_e+C_p+C_{ml}+C_{pa})}{f_{\text{calib}}\langle\omega_p(x,y,\phi)\times M(x,y,\phi)\rangle(1+B_k+B_q)}$$



- Improved kick: Most recent part of Run-3 had a perfectly centered beam owing to improved kicker system.
  - Reduced CBO amplitude
  - Centered muons means less C_e uncertainty

Improvements on the Muon g-2 Experiment Uncertainty:
Quad-RF System (during Run-5/6)



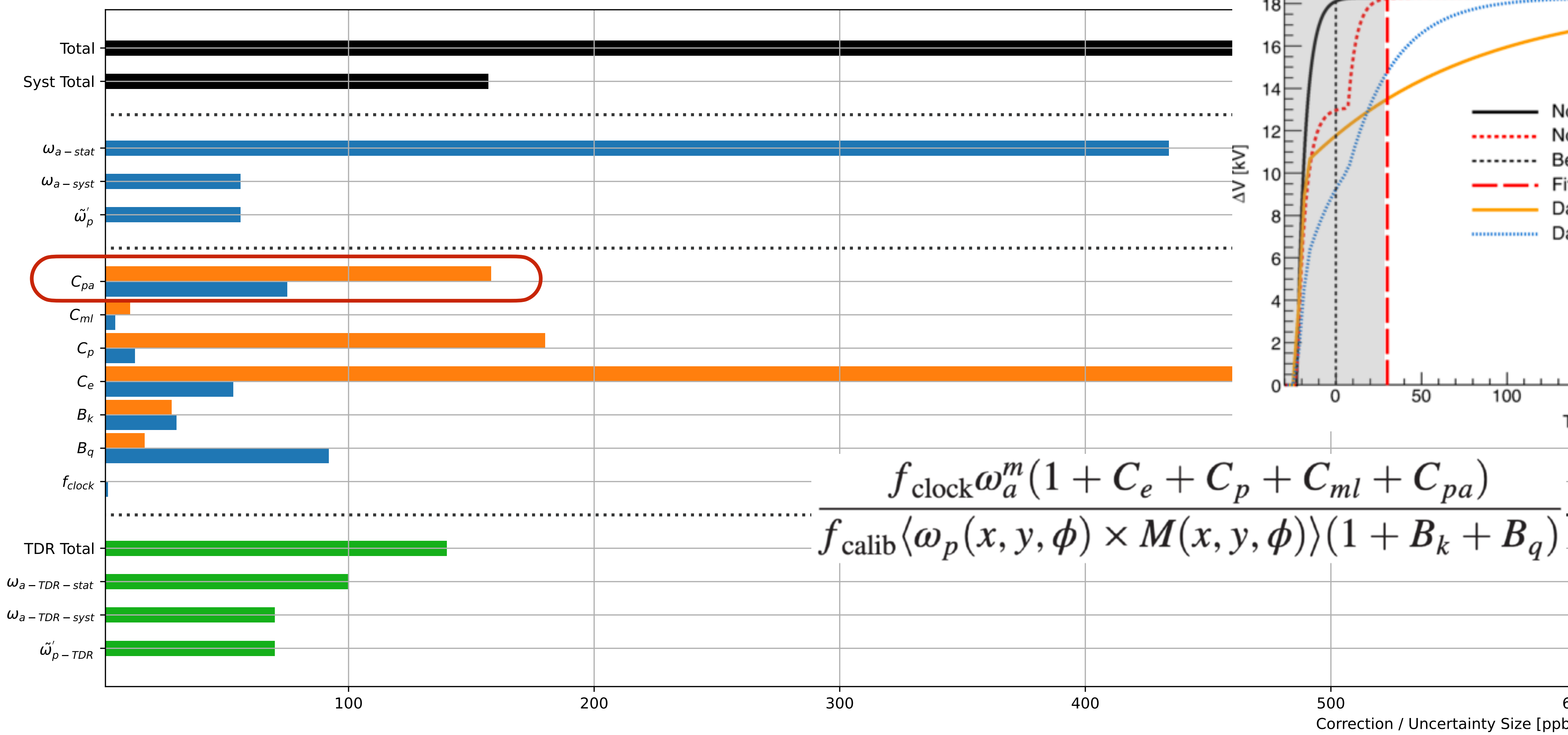
$$\frac{f_{\text{clock}}\,\omega_a^m(1 + C_e + C_p + C_{ml} + C_{pa})}{f_{\text{calib}}\langle\omega_p(x,y,\phi) \times M(x,y,\phi)\rangle(1 + B_k + B_q)}$$

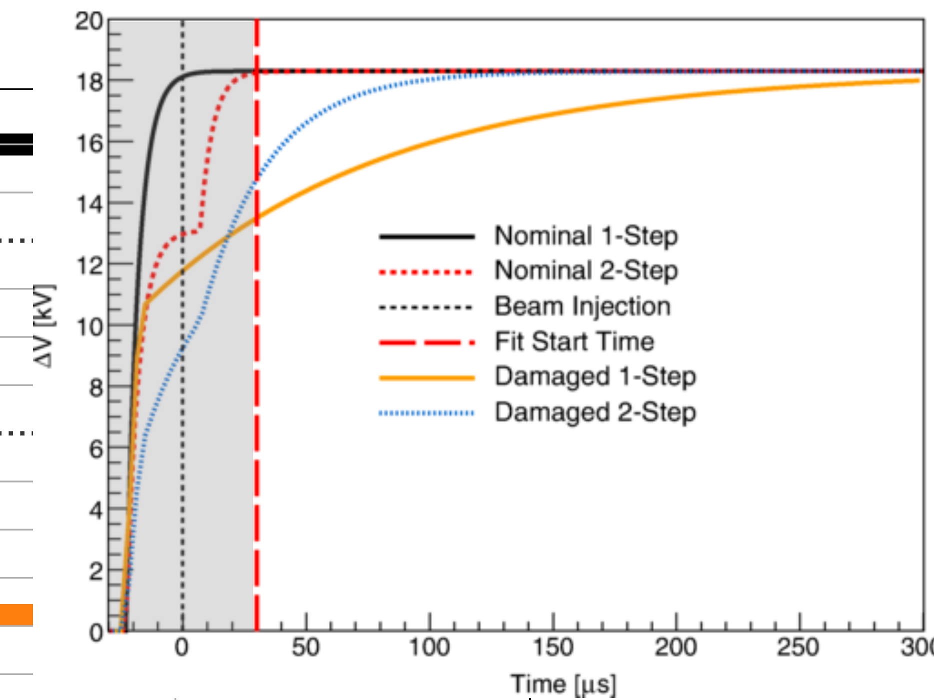
Apply RF dipole or quadrupole electric field; (by kicking the beam out of phase with CBO)

- Reduce CBO Amplitude which is caused by an imperfect kicker system (factor of 5 reduction)
- Reduce muon loss by scraping the beam (factor of 4 reduction)

Improvements on the Muon g-2 Experiment Uncertainty:

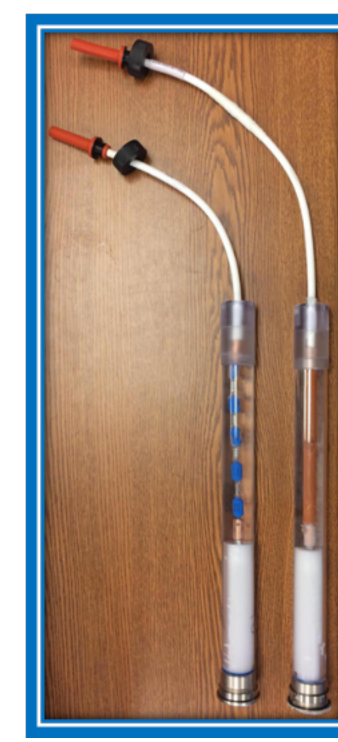
Fixed the damaged resistors (after Run-1)



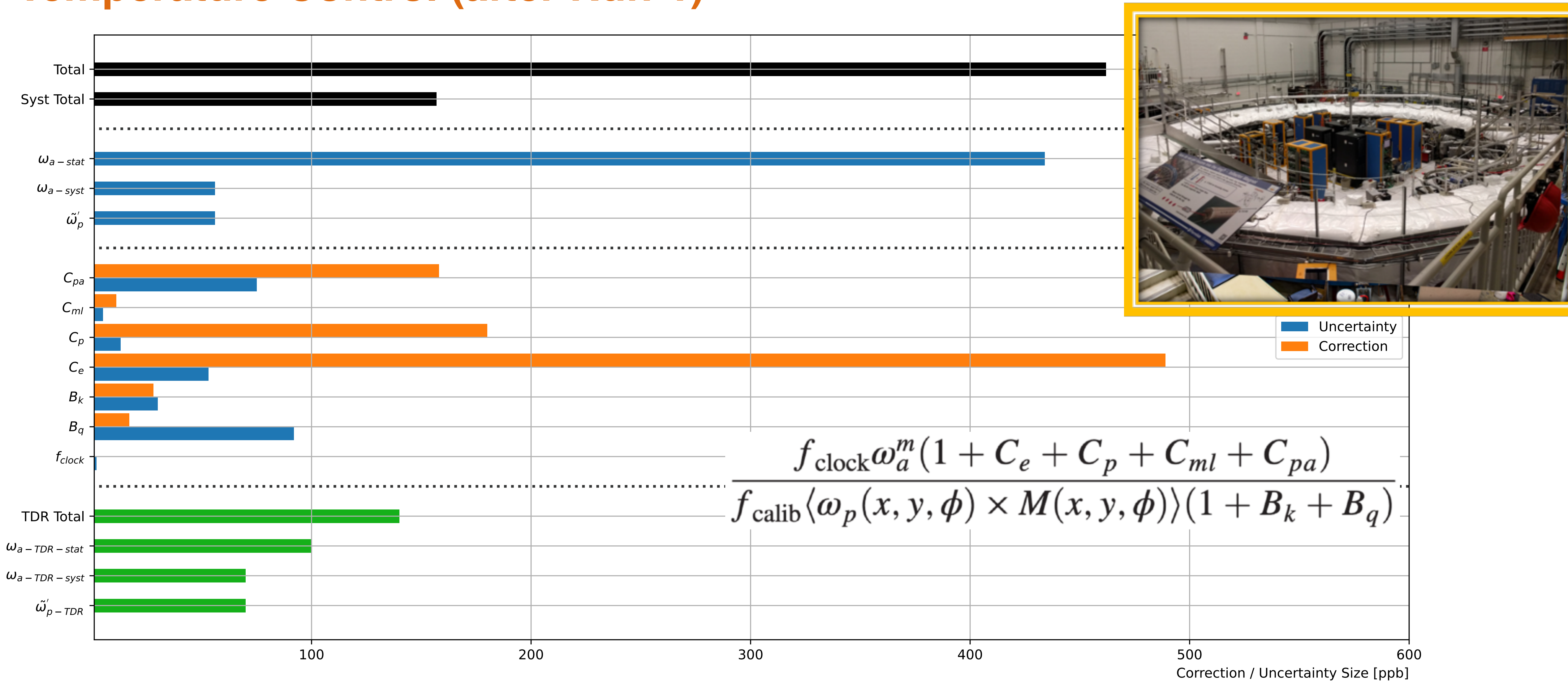


$$\frac{f_{\text{clock}}\,\omega_a^m(1 + C_e + C_p + C_{ml} + C_{pa})}{f_{\text{calib}}\langle\omega_p(x,y,\phi) \times M(x,y,\phi)\rangle(1 + B_k + B_q)}$$

- 3 of the quad resistors got damaged towards the end of Run-1 which caused:
  - A time dependent phase
  - Unstable beam motion (beam mean and width)
- Convolution between beam motion and initial phase of the beam generated an early-to-late effect on ω_a
- PA was second largest uncertainty in Run-1 result
- Phase Acceptance is going to be **greatly** reduced for Run-2/3 and beyond

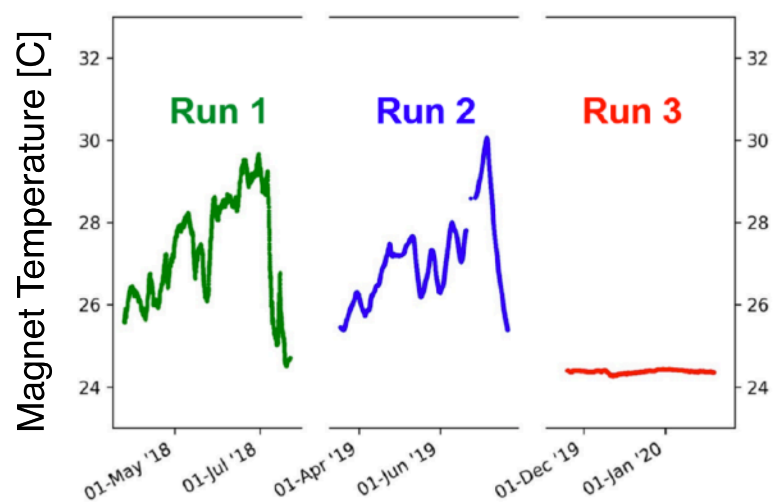


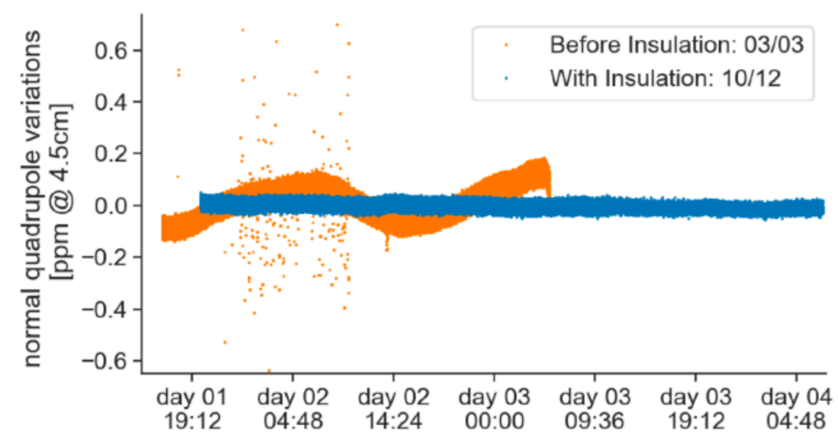
Improvements on the Muon g-2 Experiment Uncertainty:
Temperature Control (after Run-1)



$$\frac{f_{\text{clock}}\,\omega_a^m(1+C_e+C_p+C_{ml}+C_{pa})}{f_{\text{calib}}\langle\omega_p(x,y,\phi)\times M(x,y,\phi)\rangle(1+B_k+B_q)}$$

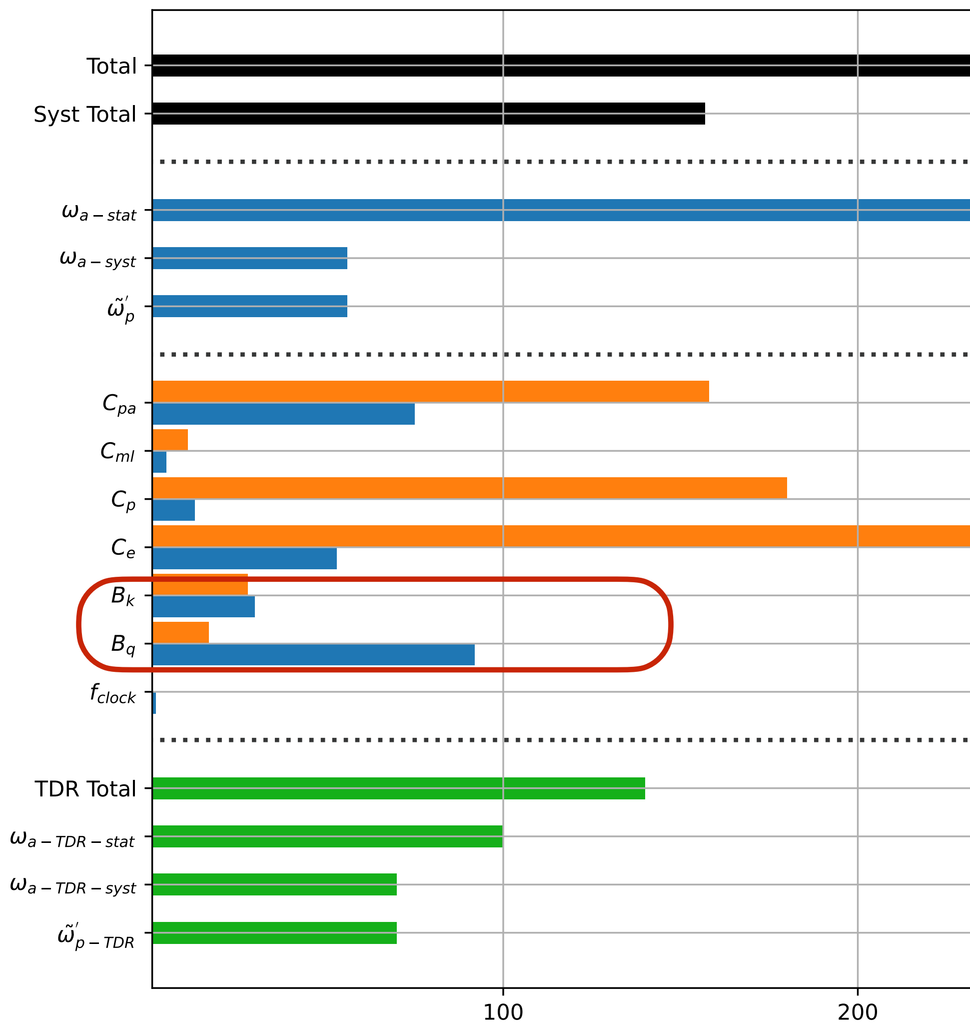
- Magnet insulation was improved
- Temperature control was improved
  - Better field stability
  - Fewer muon loss
  - Better detector stability



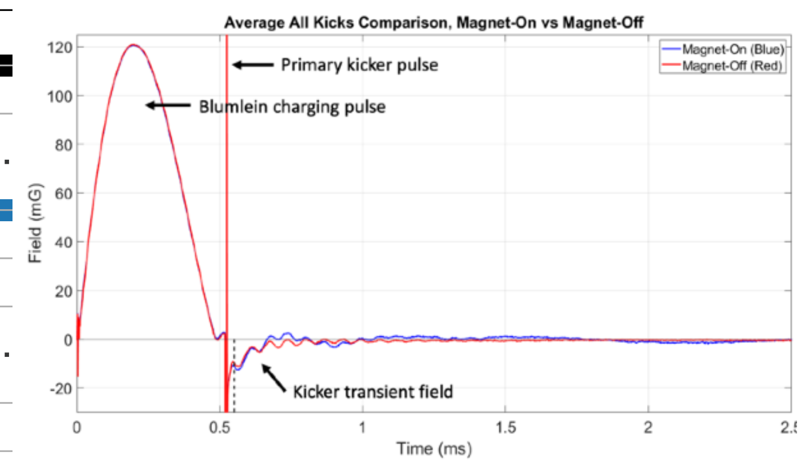


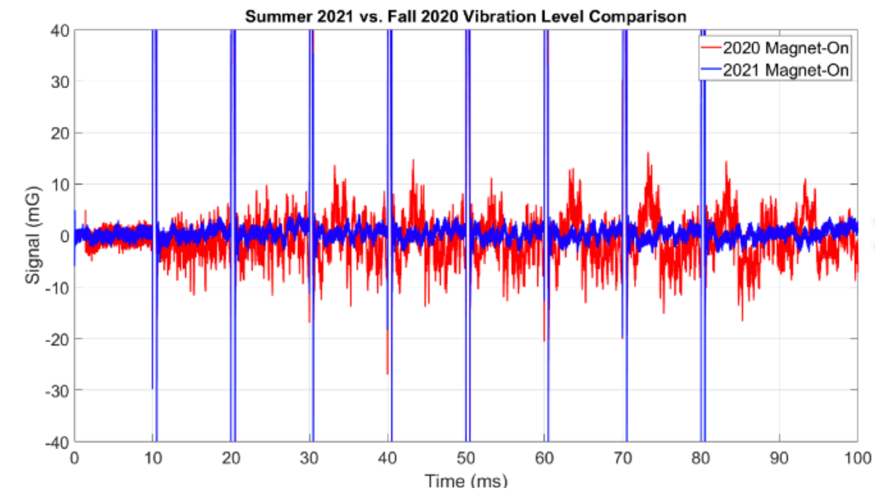
Improvements on the Muon g-2 Experiment Uncertainty:

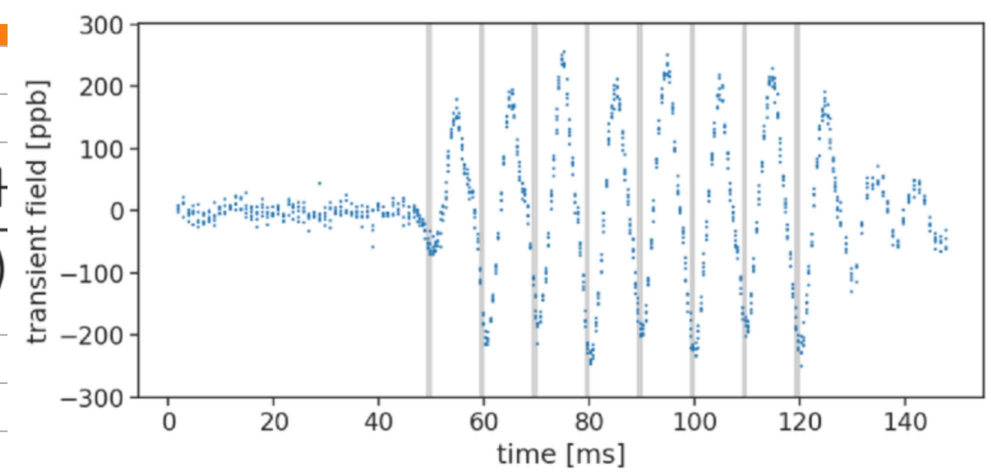
Field Systematics (after Run-1)

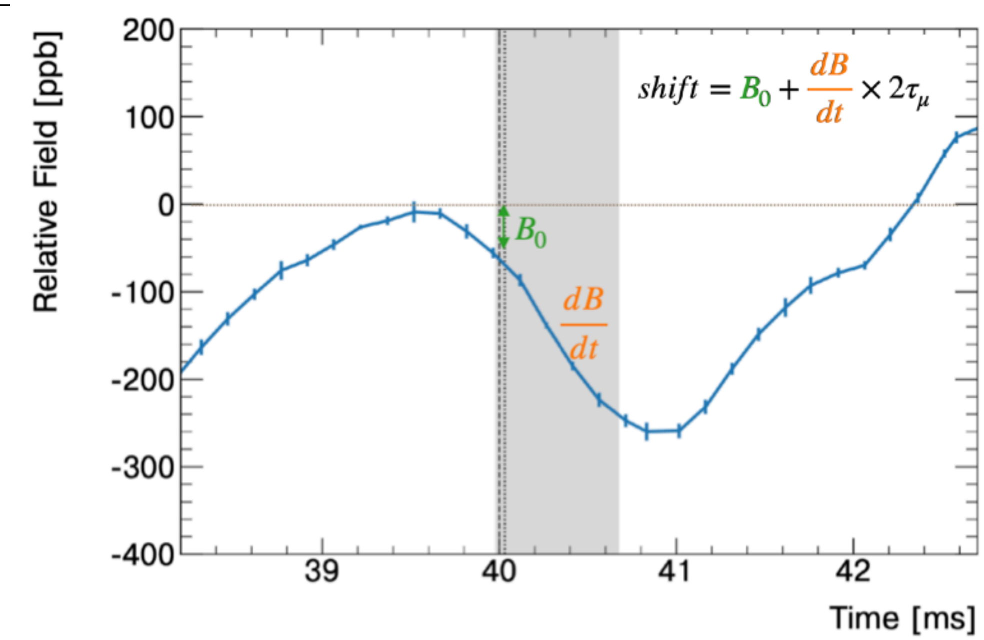


$$\frac{f_{\text{clock}}\,\omega_a^m(1+}{f_{\text{calib}}\langle\omega_p(x,y,\phi)}$$



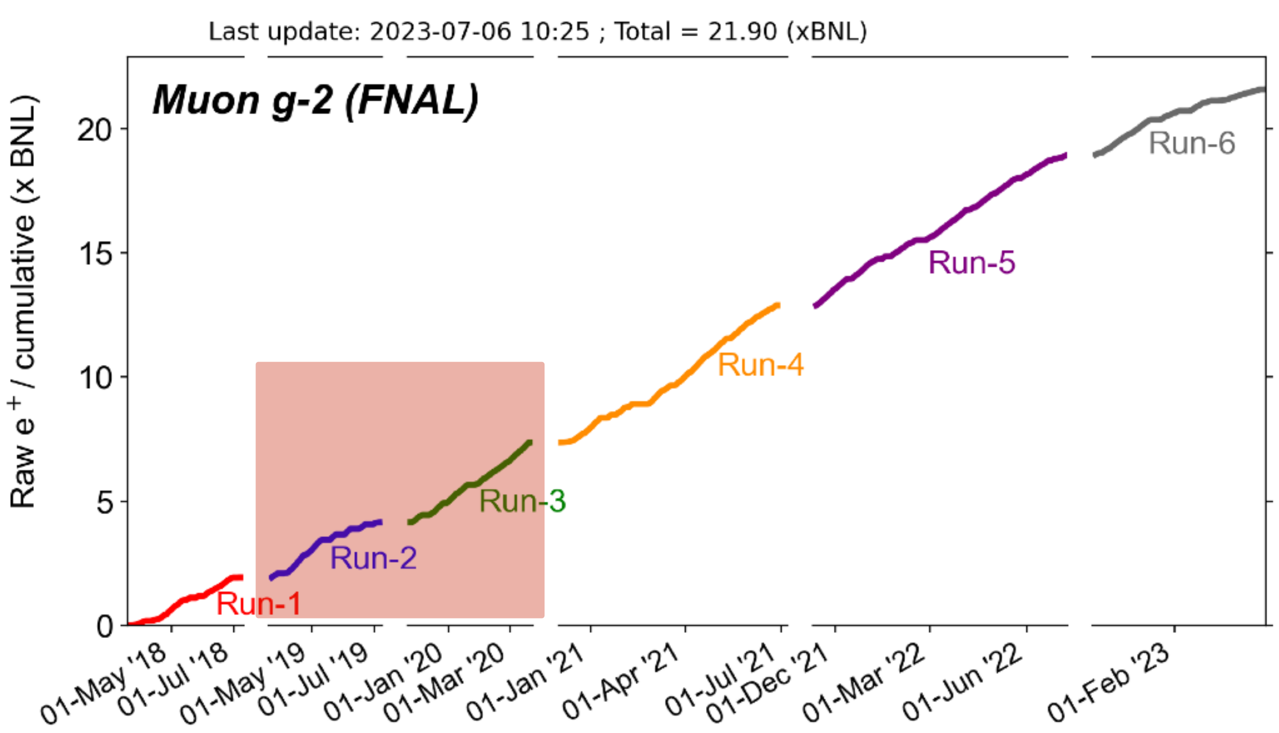






- Kicker Transient Measurements
  - Kickers pulsing created influence on the average field seen by beam
  - That created a field perturbation
  - Used a magnetometer to measure the transient
  - B_k will be reduced by 3 times beyond Run-2/3
- Quad Transient Measurements (Largest uncertainty in Run-1)
  - Quads charging and discharging cause mechanical vibration
  - That causes a field perturbation
  - Used special NMR probes to map the effect
  - Run-1 measurements were dominated by the spread of the effect, Run-2/3 mapping is more detailed
  - Run-2/3 uncertainty (B_q) will be 4 times less than Run-1

Muon g-2 Experiment Status

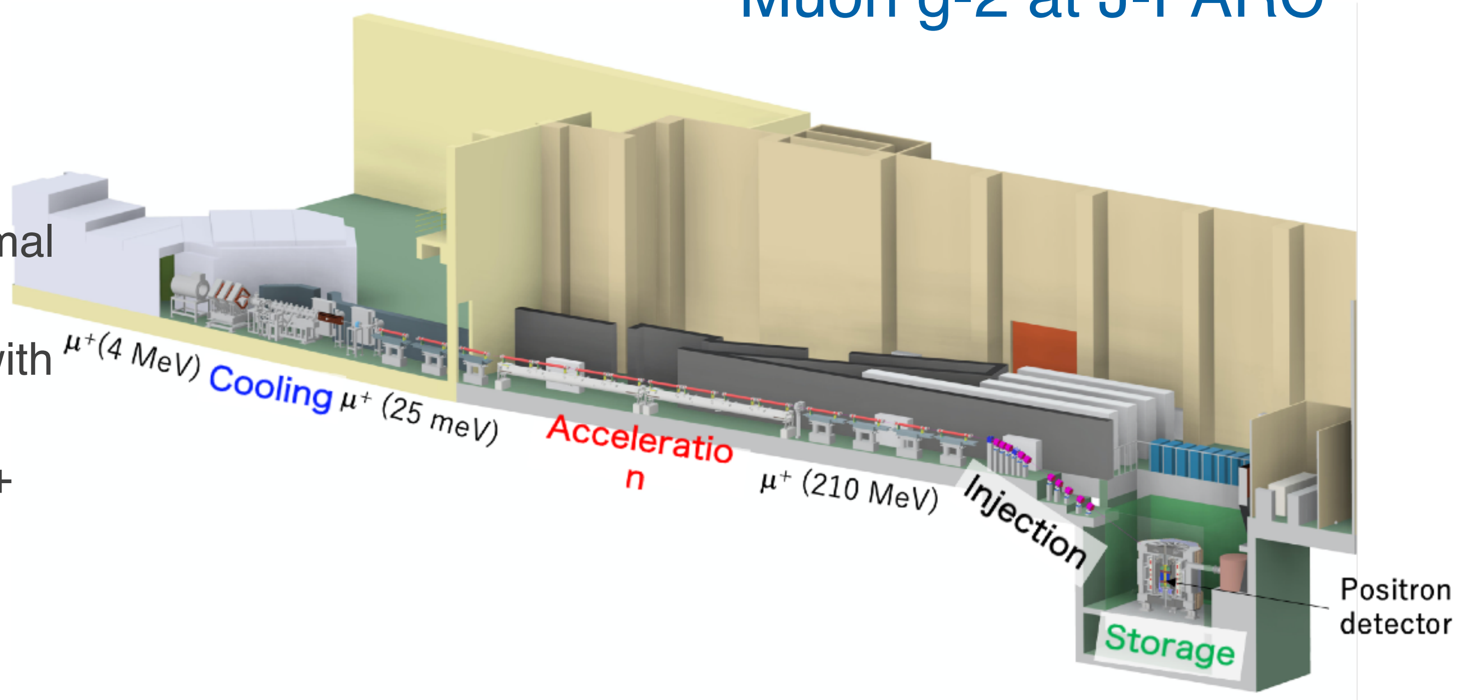


Muon g-2 at Fermilab

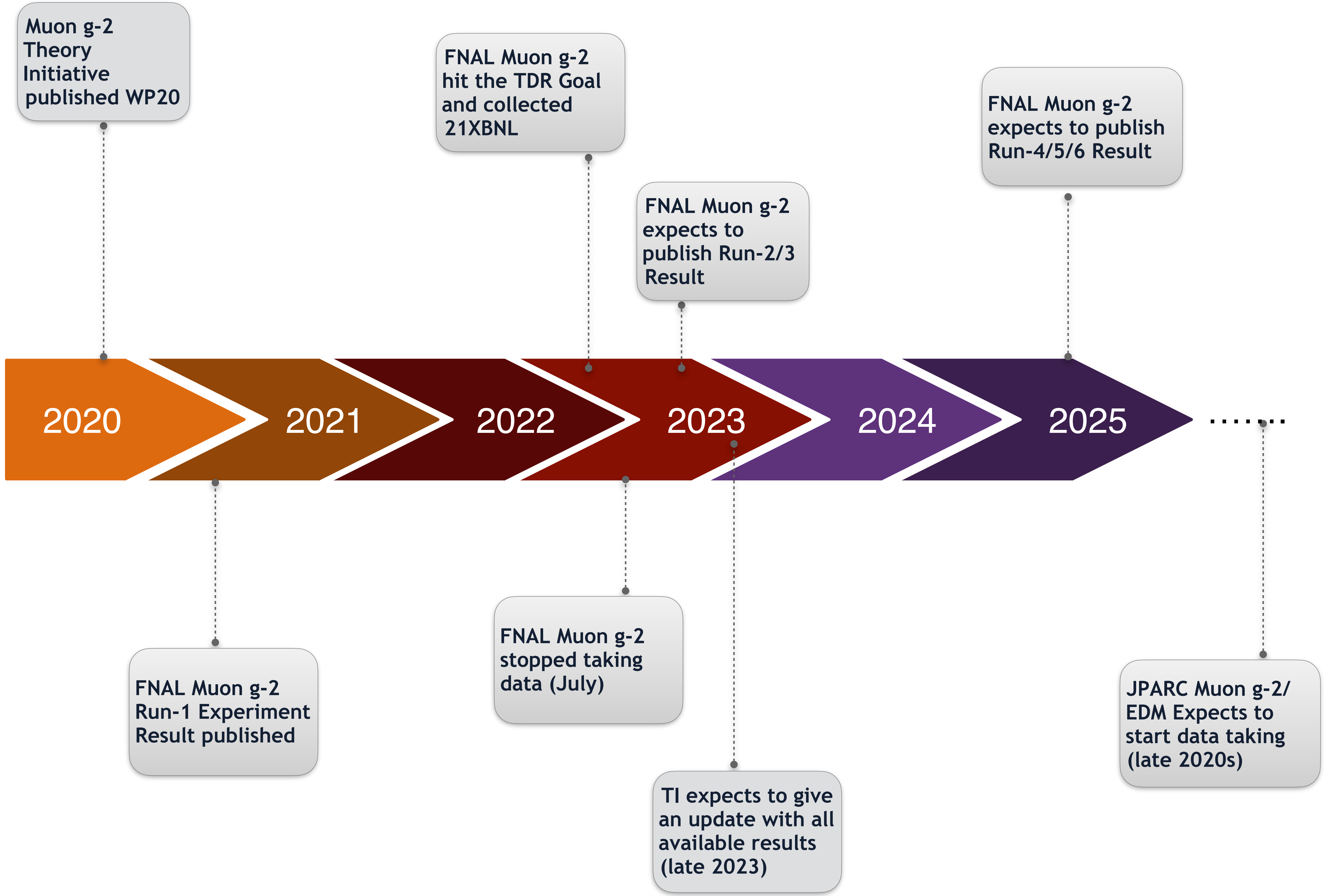
- Run-6 has ended in July 2023 (Final year)
- Hit the TDR Goal of 21 X BNL data
- Run-2/3 analysis is wrapping up
  - 4.5 times the statistics of Run-1
  - Expect statistical error ~ 2 times improvement
  - Expect systematic error ~ 1.5 times improvement
- Run-4/5/6 analysis has launched

Muon g-2 at J-PARC

- A new different approach to measure muon g-2 at J-PARC
- Low emittance muon beam
- No strong focusing, E=0
- Positron tracking detector (silicon strip sensors)
- Electric field will be eliminated by using reaccelerated thermal muon beam
- Lower momentum muon beam + compact storage region with highly uniform magnetic field
- Tracking detector for decay positrons —> reduced pile-up + able to measure the momentum direction of positrons.
- Expects to start late 2020s



Timeline for Muon g-2



Outlook and Summary

- FNAL Muon g-2 experiment will publish second batch of data (Run-2/3) with twice as precise of previous result **soon**. Third and last batch of dataset is expected to be published in 2025
  - FNAL Muon g-2 experiment has reached the statistical TDR goal
  - Run-2/3 will have reduced systematic uncertainties thanks to many hardware and software improvements
  - Experiment goal is to eventually reach to 140 ppb precision
- Lattice Gauge Theory Community is working around the clock to confirm the lattice prediction with other groups/techniques
  - More computational resource in future
  - Better methods and algorithms
- Theory Initiative is working on figuring out the differences between LQCD and data-driven methods. Final average number will finally match FNAL precision goal. Next update in September 2023!
  - Lattice HVP by 2025-> 0.5% (if no tension)
  - Dispersive+lattice LbL by 2025 -> 10%
- e^-e^+ collider community working to understand the difference of CMD-3 results from previous experiments.
  - Might have a chance of repeating the measurements with larger datasets.
  - New results to come from BaBar, KLOE, SND, BesIII, Belle II (reduced uncertainty).
  - Data-driven HVP by 2025 -> 0.3% (if no tension)
- 2025 is expected to be the year to resolve many puzzles…

Thanks!

Backup Slides

Systematics from Run-1

$$a_\mu \propto \frac{f_{\rm clock}\ \ \omega_a^m\,(1 + C_e + C_p + C_{ml} + C_{pa})}{f_{\rm calib}\ \langle \omega_p'(x,y,\phi) \times M(x,y,\phi)\rangle\ (1 + B_k + B_q)}$$

$f_{\rm clock}$	•Blinded clock
ω_a^m	•Measured precession frequency
C_e	•Electric field correction
C_p	•Pitch correction
C_{ml}	•Muon loss correction
C_{pa}	•Phase-acceptance correction
$f_{\rm calib}$	•Absolute magnetic field calibration
$\omega_p'(x,y,\phi)$	•Field tracking multipole distribution
$M(x,y,\phi)$	•Muon weighted multipole distributed
B_k	•Transient field from the eddy current in kicker
Bq	•Transient field from the quad charging

Phase acceptance and transient field corrections are the largest systematics!

Run-1 Systematics

Quantity	Correction Terms (ppb)	Uncertainty (ppb)
ω_a (statistical)	–	434
ω_a (systematic)	–	56
C_e	489	53
C_p	180	13
C_{ml}	-11	5
C_{pa}	-158	75
$f_{\text{calib}}\langle\omega'_p(x,y,\phi)\times M(x,y,\phi)\rangle$	–	56
B_k	-27	37
B_q	-17	92
$\mu'_p(34.7^\circ)/\mu_e$	–	10
m_μ/m_e	–	22
$g_e/2$	–	0
Total systematic	–	157
Total fundamental factors	–	25
Totals	544	462

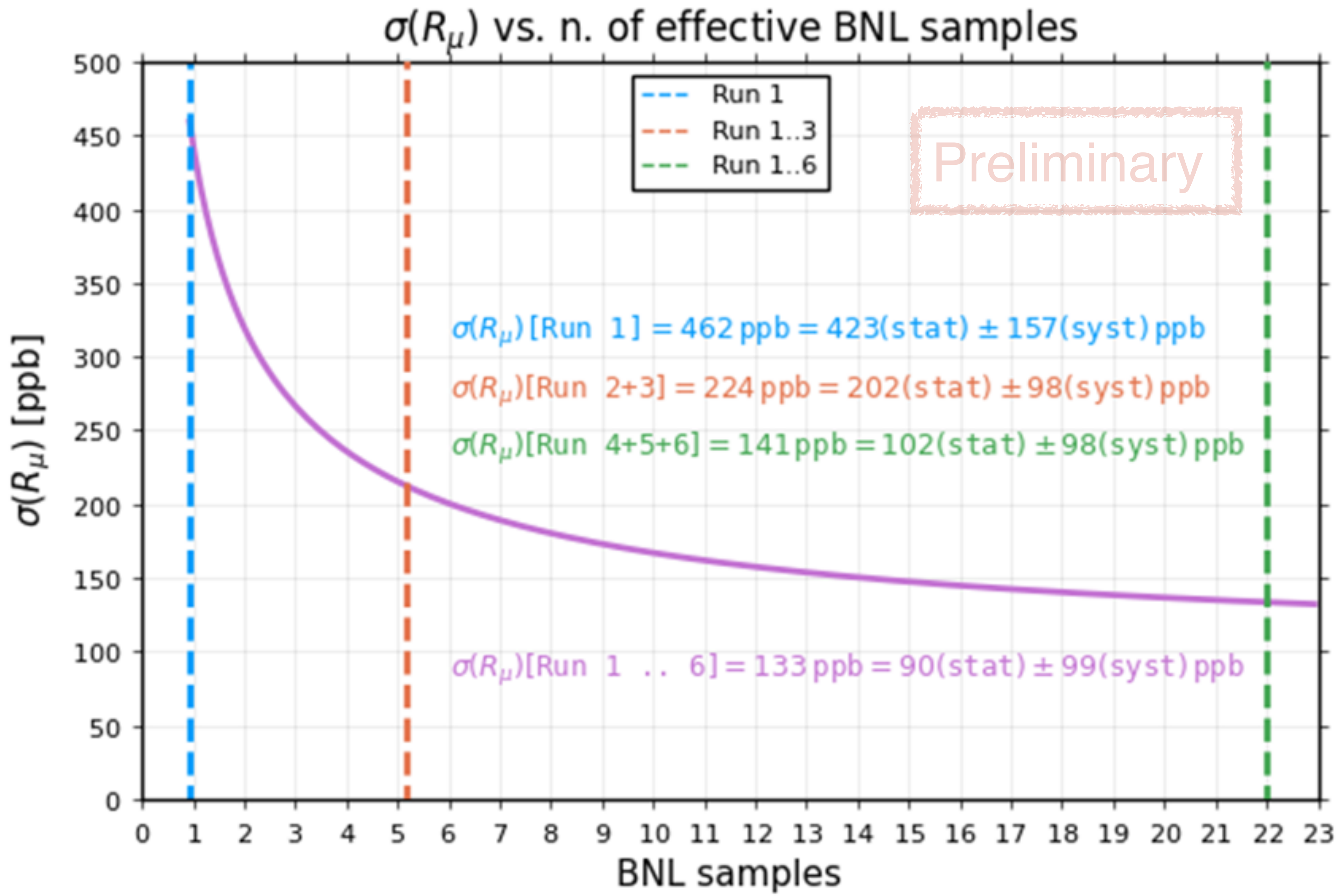
Dominated by statistical uncertainty

Systematics dominated by PA and Field Transients

*Nearly half of BNL

*Will be even better for Run-2 and beyond

Estimation for future dataset uncertainties



Most promising models to explain the discrepancy

- Muon g-2 can indicate if there is a CP-conserving, lepton-flour conserving or BSM chirality-flipping interaction but can't tell which one is the most promising.
- Possible explanations:
  - SUSY models (while evading LHC limits)
  - Leptoquark models (if leptoquark masses are above all LHC limits)
  - 2-Higgs doublet models

Establishing a g-2 discrepancy from SM would place a strict limit on BSM scenarios

Muon g-2 Theory Initiative

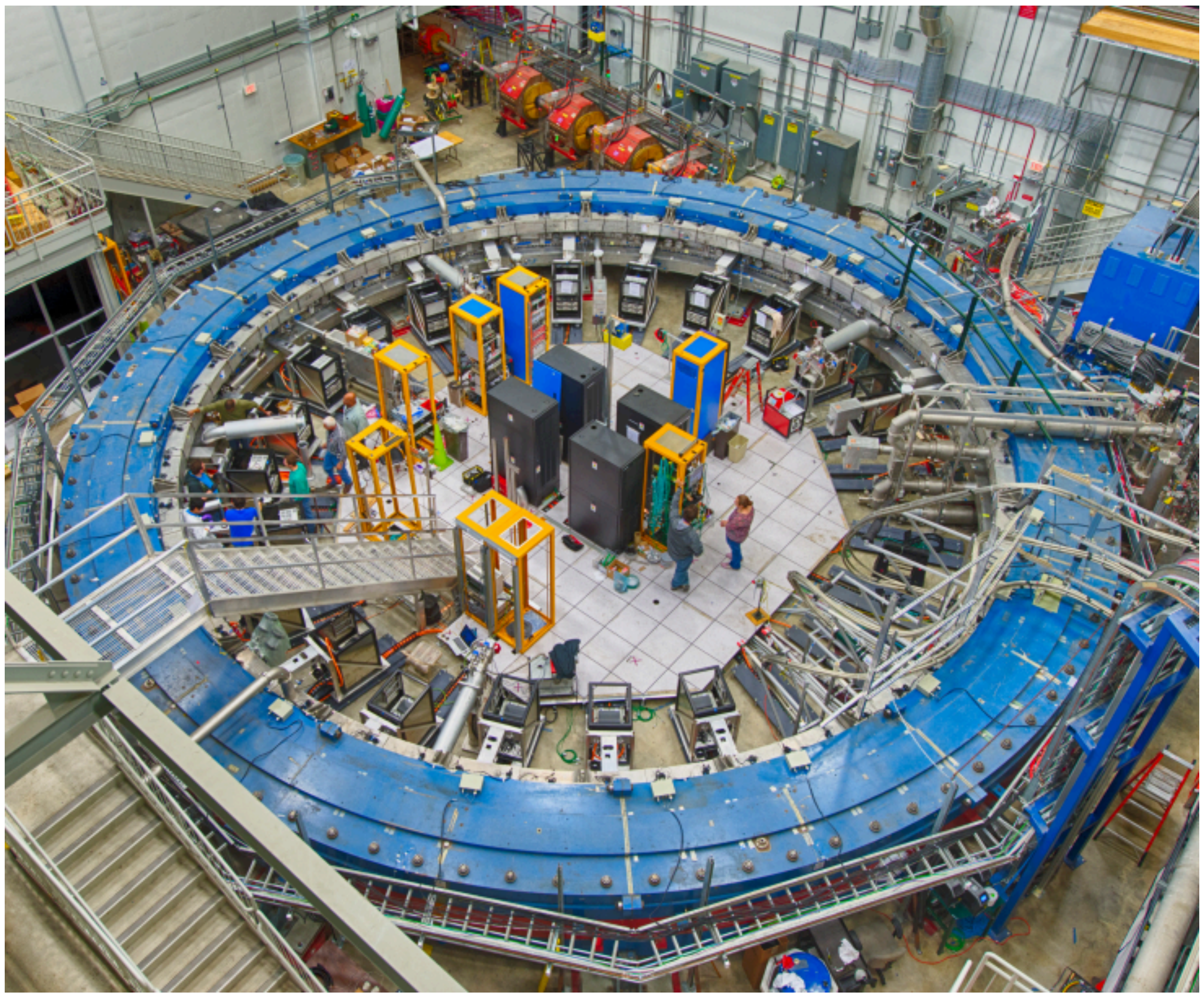
Steering Committee

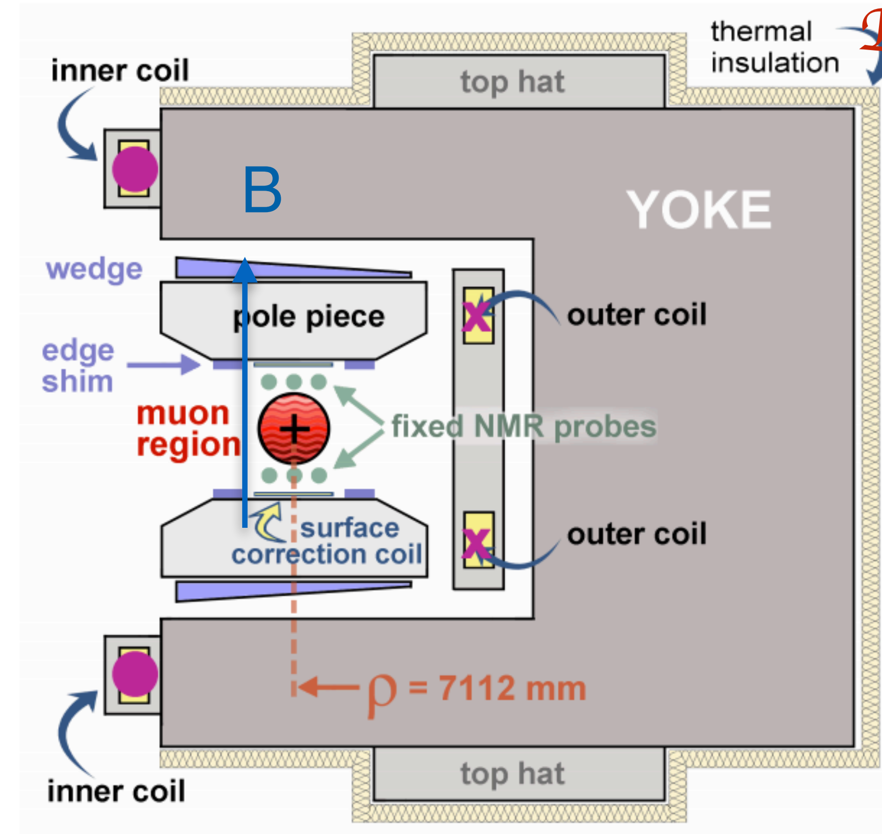
- Gilberto Colangelo (Bern)
- Michel Davier (Orsay) co-chair
- Aida El-Khadra (UIUC & Fermilab) chair
- Martin Hoferichter (Bern)
- Christoph Lehner (Regensburg University & BNL) co-chair
- Laurent Lellouch (Marseille)
- Tsutomu Mibe (KEK)
  J-PARC Muon g-2/EDM experiment
- Lee Roberts (Boston)
  Fermilab Muon g-2 experiment
- Thomas Teubner (Liverpool)
- Hartmut Wittig (Mainz)

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

- Maximize the impact of the Fermilab and J-PARC experiments
  ➠ quantify and reduce the theoretical uncertainties on the hadronic corrections
- summarize the theory status and assess reliability of uncertainty estimates
- organize workshops to bring the different communities together:
  First plenary workshop @ Fermilab: 3-6 June 2017
  HVP workshop @ KEK: 12-14 February 2018
  HLbL workshop @ U Connecticut: 12-14 March 2018
  Second plenary workshop @ HIM (Mainz): 18-22 June 2018
  Third plenary workshop @ INT (Seattle): 9-13 September 2019
  Lattice HVP at high precision workshop (virtual): 16-20 November 2020
  Fourth plenary workshop @ KEK (virtual): 28 June - 02 July 2021
  Fifth plenary workshop @ Higgs Centre (Edinburgh): 5-9 September 2022
- 1st White Paper published in 2020 (132 authors, 82 institutions, 21 countries) [T. Aoyama et al, arXiv:2006.04822, Phys. Repts. 887 (2020) 1-166.]
- 2nd White Paper: First discussions @ KEK meeting in June 2021
  expect to develop a concrete plan @ Higgs Centre workshop

Storing the Muons: Magnet





g-2 Magnet in Cross Section

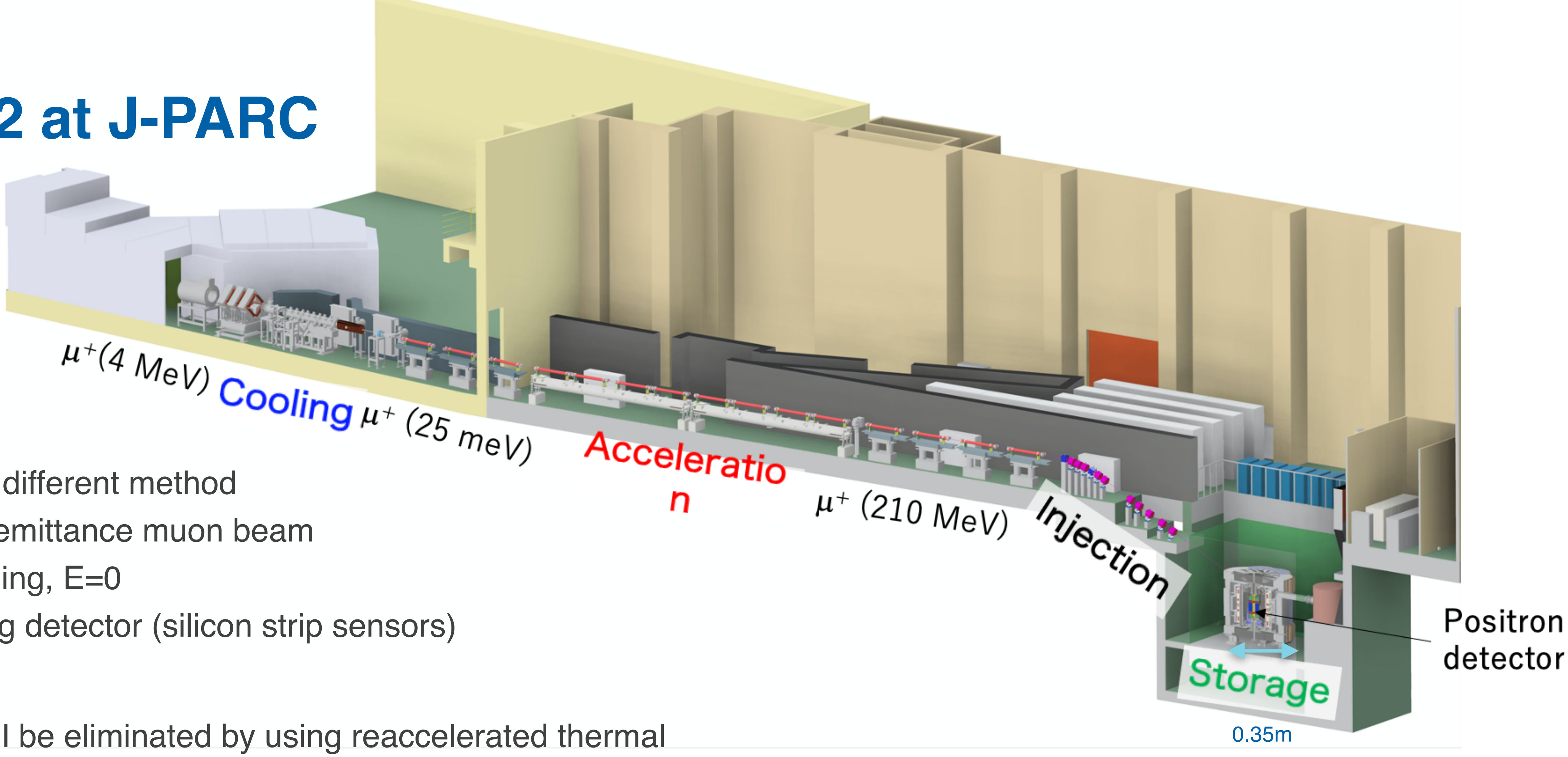
Superconducting C shaped magnet

Provides 1.45T B field(vertical and uniform)

- **12 Yokes**:Open on the inside, allows the decay positrons to reach to the detectors.
- **72 poles:**Low-carbon steel to minimize the impurity
- **144 Edge shims:** Minimize the local sextupole field by changing edge shim thickness
- **864 Steel wedges:** Angle adjustment (compensate quadrupole component), radial adjustment (shim local dipole field).
- **Surface correction coil:** Reduces non-uniformities on higher moment of field.

Achieved 25 ppm on field uniformity

Muon g-2 at J-PARC



- J-PARC uses a different method
- They have low emittance muon beam
- No strong focusing, E=0
- Positron tracking detector (silicon strip sensors)

- Electric field will be eliminated by using reaccelerated thermal muon beam
- Lower momentum muon beam + compact storage region with highly uniform magnetic field
- Tracking detector for decay positrons —> reduced pile-up + able to measure the momentum direction of positrons.
- Final Goal is to reach **0.46ppm—> 0.1ppm** on a_μ
- Beam line construction has started and commissioning is expected to start in 2027

Comparison of Experiment Parameters

Table 1. Comparison of BNL-E821, FNAL-E989, and our experiment.

	BNL-E821	Fermilab-E989	Our experiment
Muon momentum	3.09 GeV/c		300 MeV/c
Lorentz γ	29.3		3
Polarization	100%		50%
Storage field	$B = 1.45$ T		$B = 3.0$ T
Focusing field	Electric quadrupole		Very weak magnetic
Cyclotron period	149 ns		7.4 ns
Spin precession period	4.37 μs		2.11 μs
Number of detected e^+	5.0×10^9	1.6×10^{11}	5.7×10^{11}
Number of detected e^-	3.6×10^9	–	–
a_μ precision (stat.)	460 ppb	100 ppb	450 ppb
(syst.)	280 ppb	100 ppb	<70 ppb
EDM precision (stat.)	0.2×10^{-19} $e\cdot$cm	–	1.5×10^{-21} $e\cdot$cm
(syst.)	0.9×10^{-19} $e\cdot$cm	–	0.36×10^{-21} $e\cdot$cm

J-PARC E34

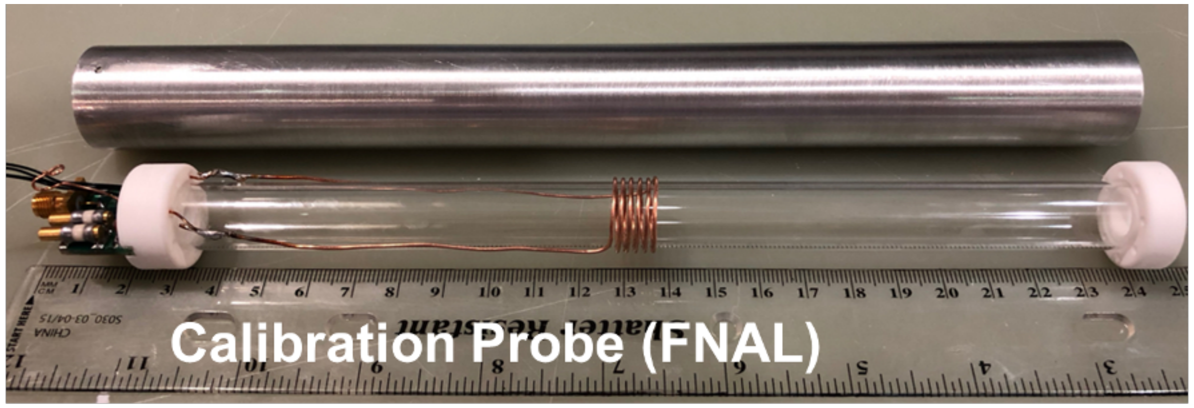
Radius of cyclotron motion: 7.1 m

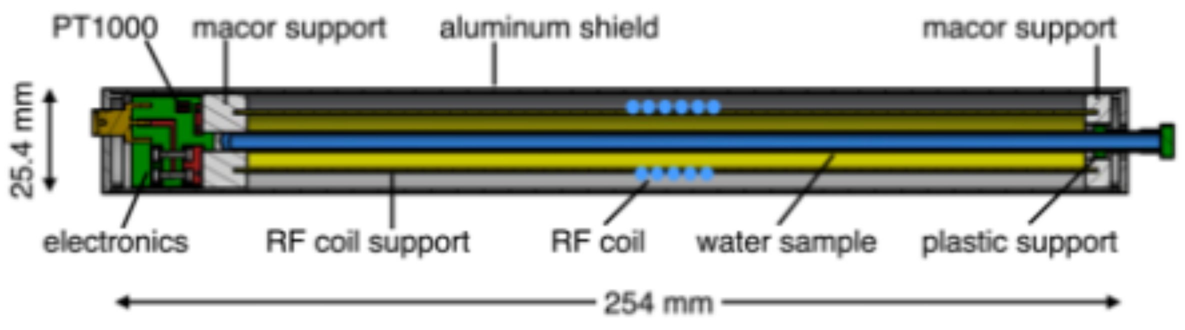
Radius of cyclotron motion: 333 mm

PTEP 2019 (2019), 053C02

NMR Probes
Calibration Uncertainty

$$a_\mu \propto \frac{f_{\mathrm{clock}} \;\; \omega_a^m \, (1 + C_e + C_p + C_{ml} + C_{pa})}{f_{\mathrm{calib}} \; \langle \omega'_p(x,y,\phi) \times M(x,y,\phi) \rangle (1 + B_k + B_q)}$$





Absolute field calibration:

- Absolute probes were used to calibrate NMR probes
- Proton NMR, calibrated in terms of $\omega_p(T_r)$ of a proton shielded in a spherical sample of water at an exact temperature.

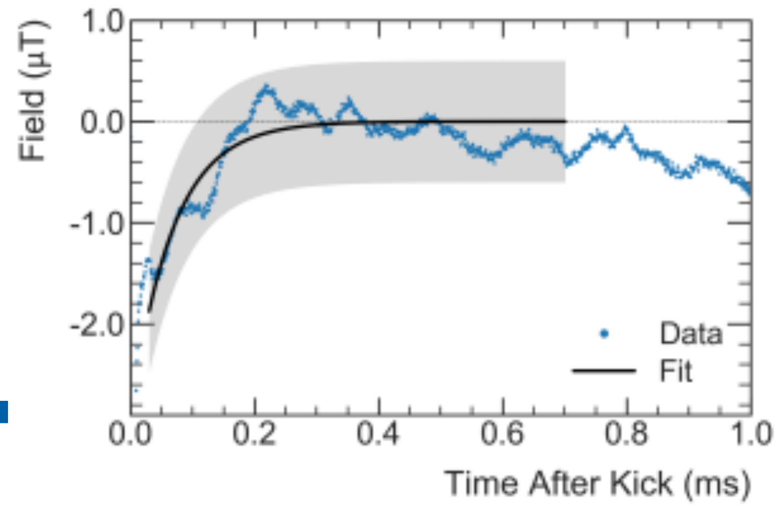
Kicker Transients

$$a_\mu \propto \frac{f_{\text{clock}} \quad \omega_a^m \, (1 + C_e + C_p + C_{ml} + C_{pa})}{f_{\text{calib}} \, \langle \omega'_p(x,y,\phi) \times M(x,y,\phi) \rangle \, (1 + B_k + B_q)}$$

Kickers pulsing created influence on the average field seen by beam

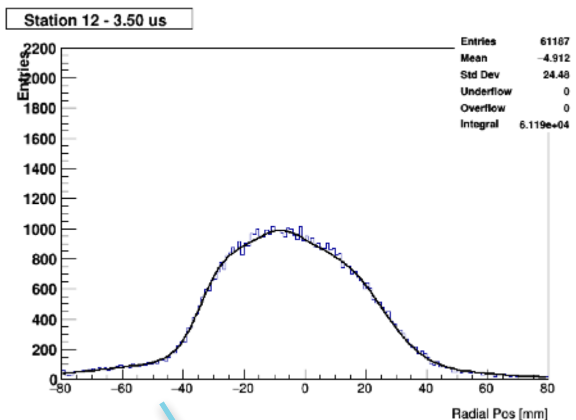
Field Perturbation

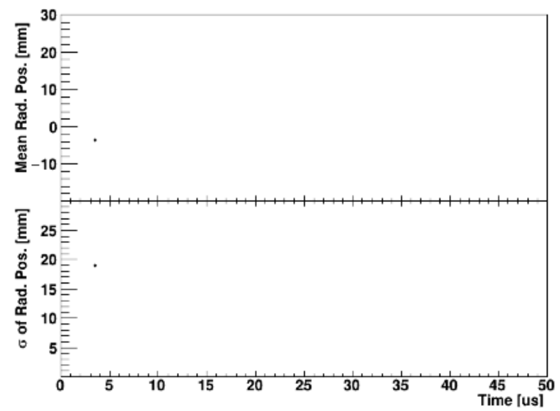
Used a magnetometer to measure the transient



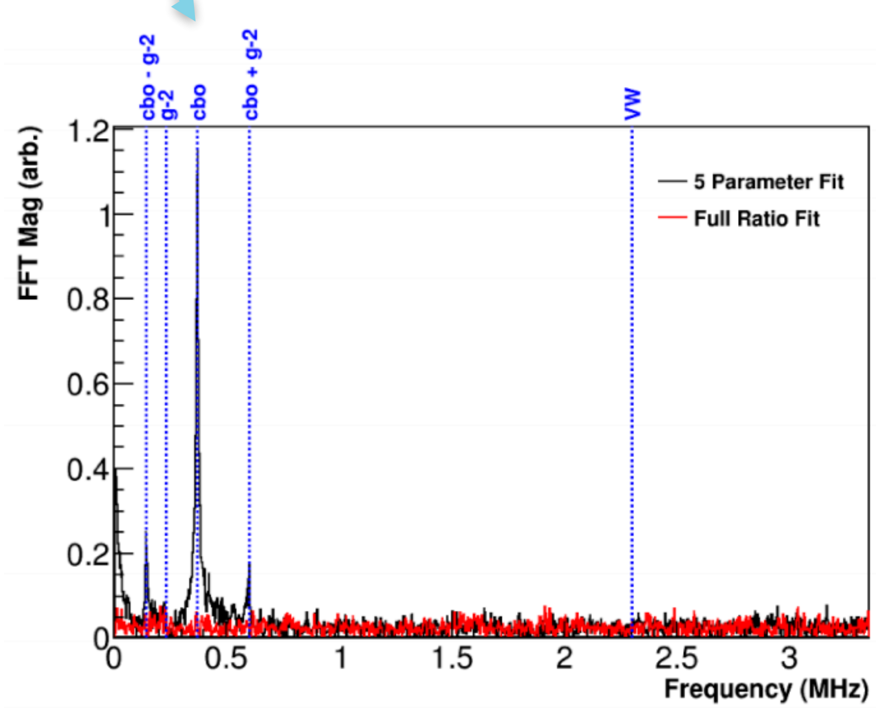
Beam Dynamics

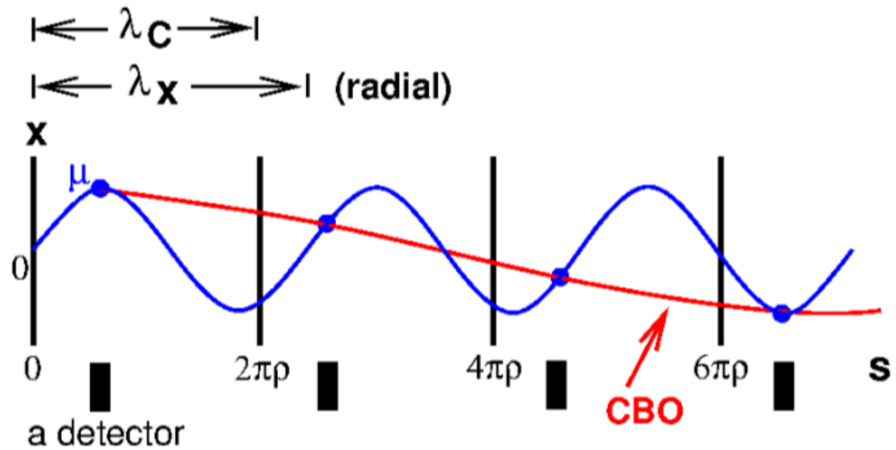
- CBO - Coherent Beam Oscillation





Radial CBO movement





λ_x - radial wavelength

λ_C - cyclotron wavelength

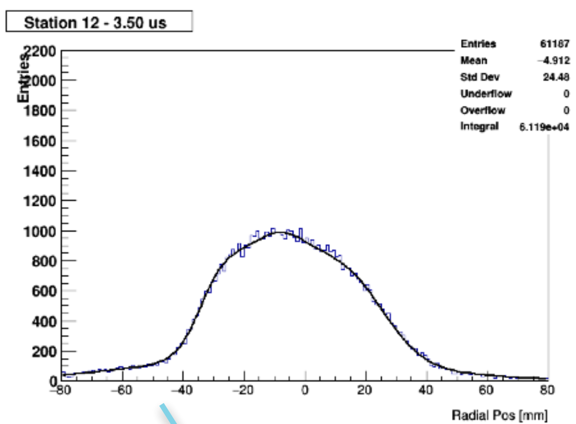
Frequency from detector point of view = $f_c - f_x$

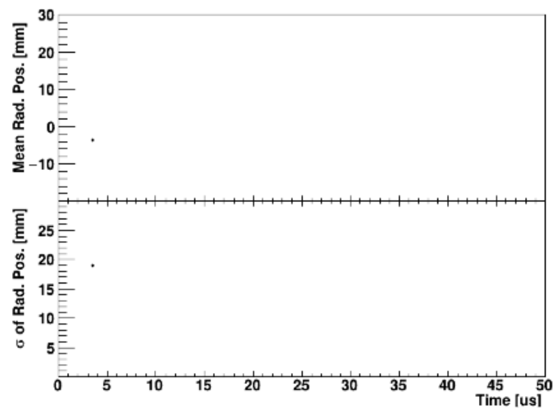
$$x = x_e + A_x cos(f_x t + \delta_x) \qquad y = A_y cos(f_y t + \delta_y)$$

Simple Harmonic Motion

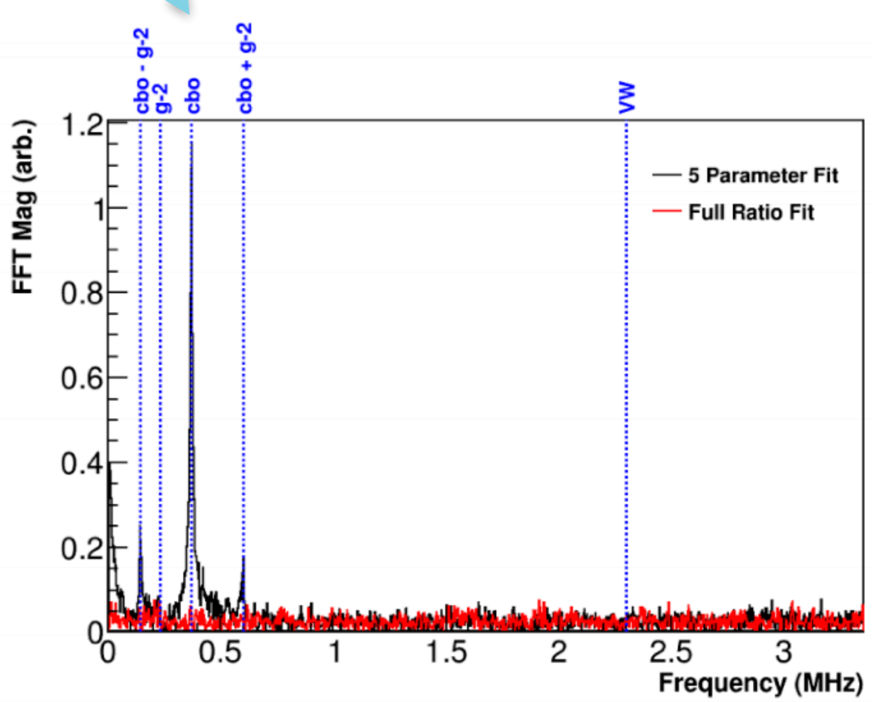
Beam Dynamics

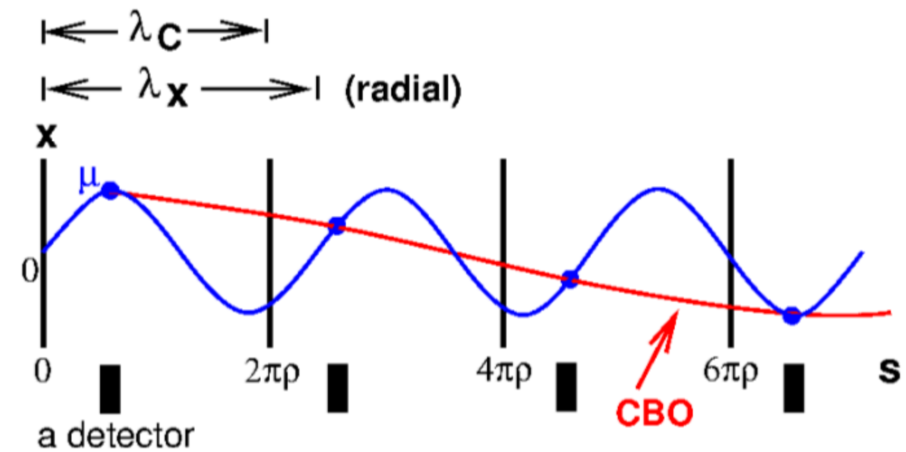
- CBO - Coherent Beam Oscillation





Radial CBO movement





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Frequency from detector point of view = $f_c - f_x$

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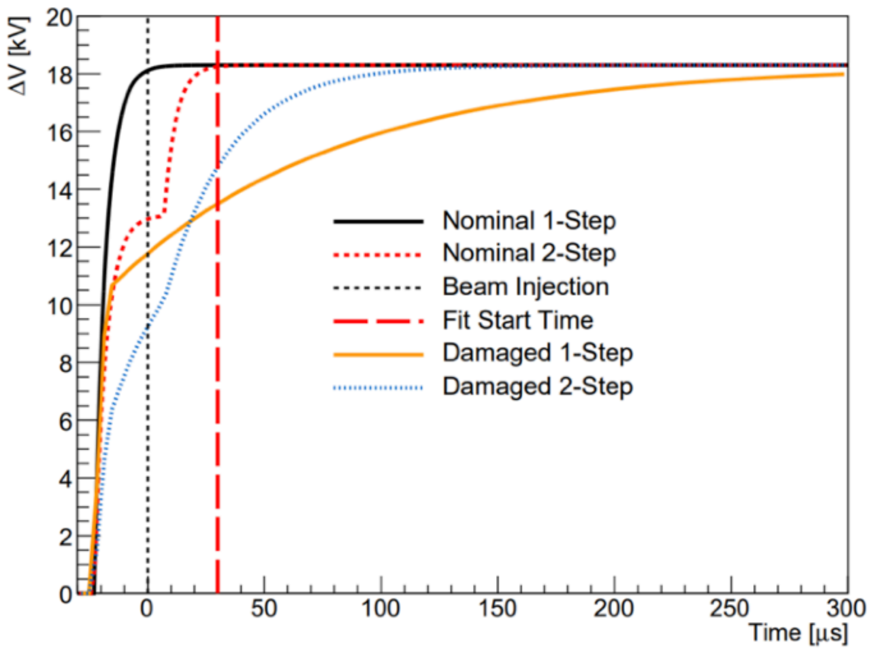
Simple Harmonic Motion

Phase Acceptance

$$a_\mu \propto \frac{f_{\text{clock}} \;\; \omega_a^m \, (1 + C_e + C_p + C_{ml} + C_{pa})}{f_{\text{calib}} \; \langle \omega_p'(x,y,\phi) \times M(x,y,\phi) \rangle \; (1 + B_k + B_q)}$$

When there is a time dependent phase,

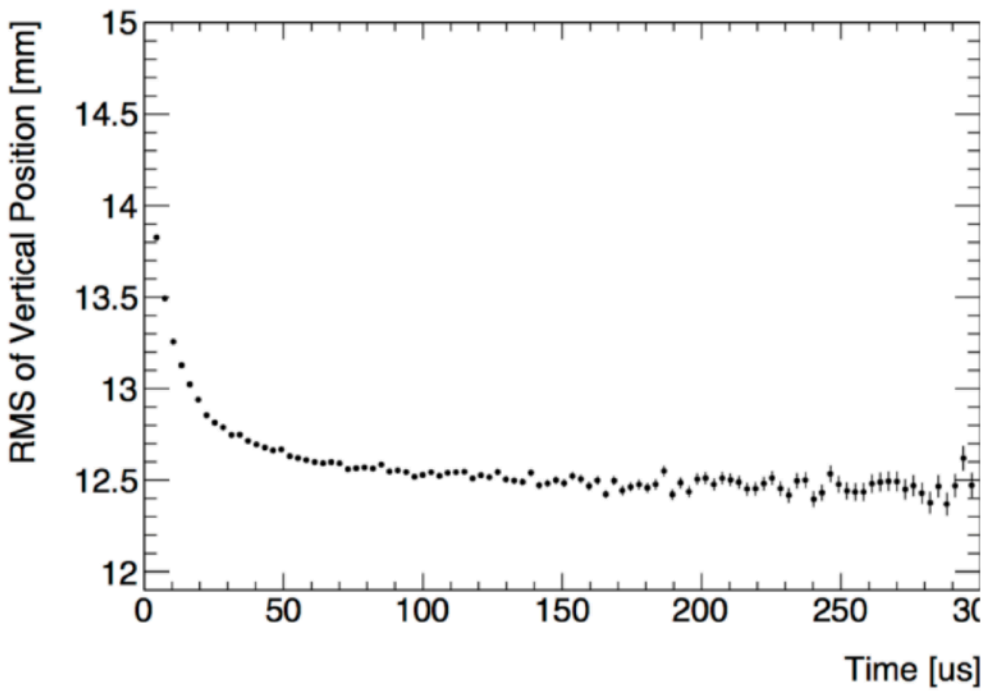
It shifts the ω_a !

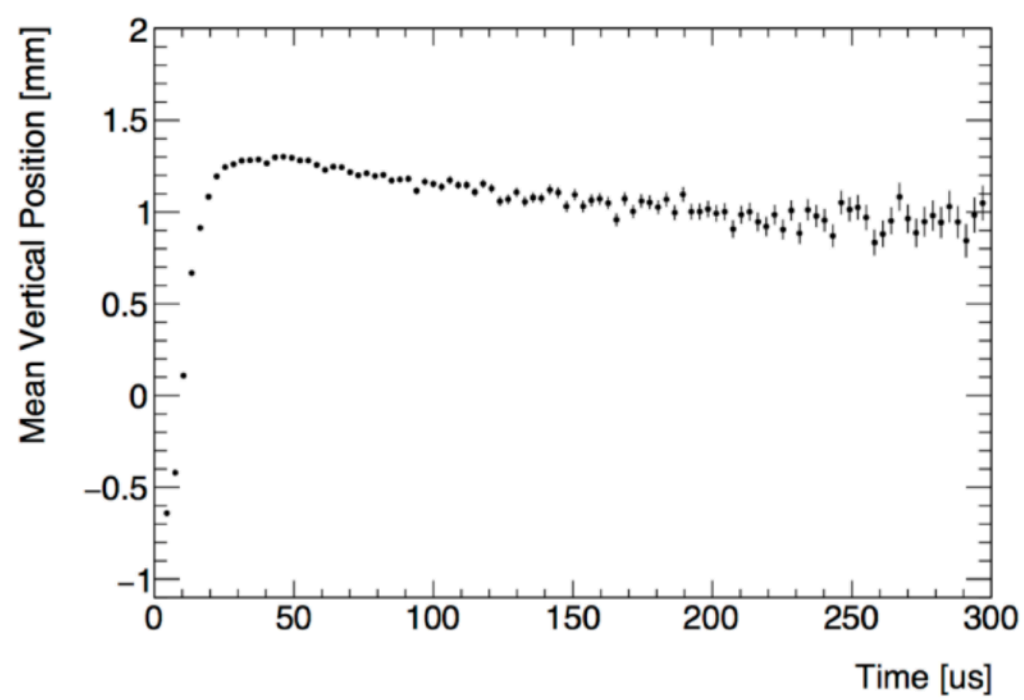


Due to damaged HV resistors; stored beam distribution was unstable.

It caused a time dependent phase

Beam vertical mean and width changed

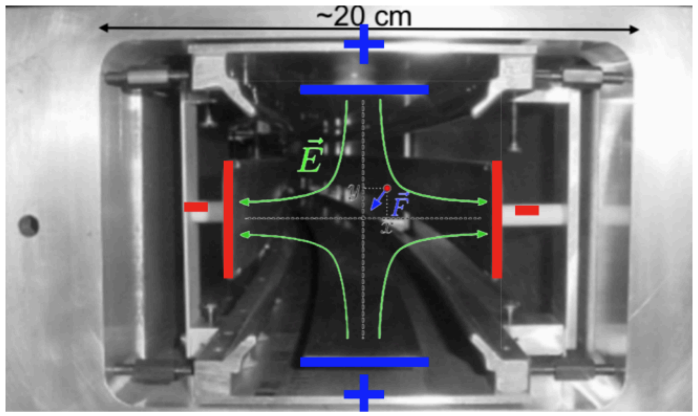


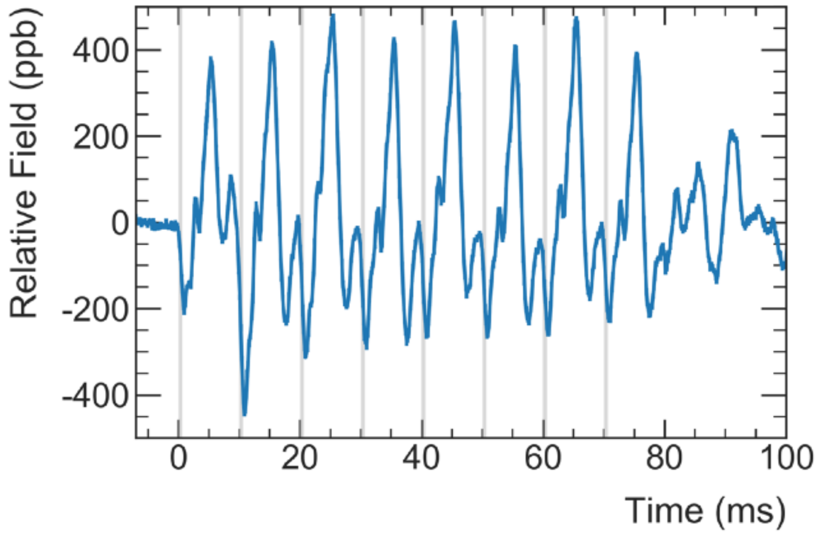


ESQ Transients

$$a_\mu \propto \frac{f_{\text{clock}} \;\; \omega_a^m \, (1 + C_e + C_p + C_{ml} + C_{pa})}{f_{\text{calib}} \, \langle \omega'_p(x,y,\phi) \times M(x,y,\phi) \rangle \, (1 + B_k + B_q)}$$

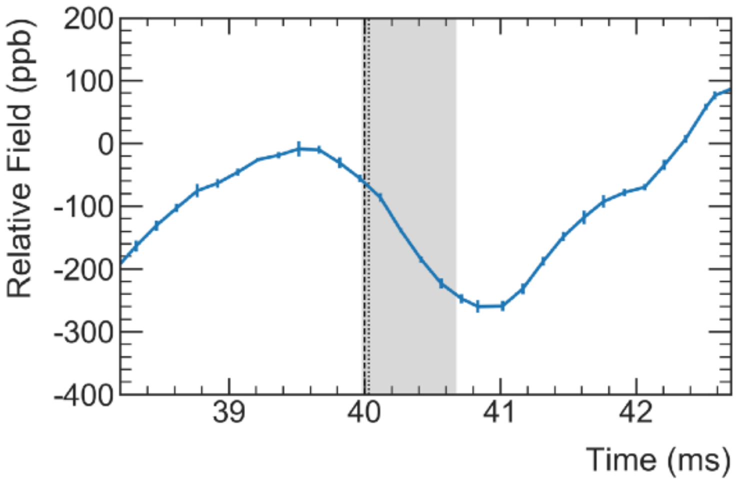
Quads charging and discharging cause mechanical vibration





Field Perturbation

Measure the field with special NMR probes and map the effect!



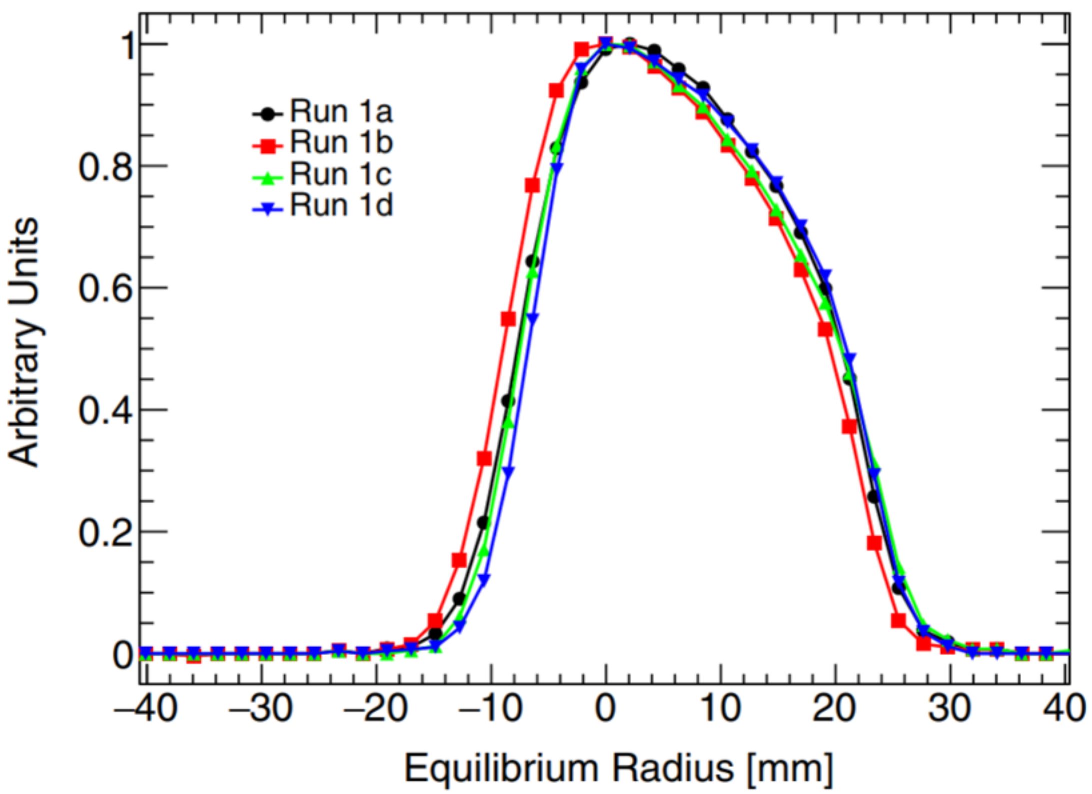
E-field and Pitch Correction

$$a_\mu \propto \frac{f_{\text{clock}} \quad \omega_a^m \, (1 + C_e + C_p + C_{ml} + C_{pa})}{f_{\text{calib}} \, \langle \omega_p'(x,y,\phi) \times M(x,y,\phi) \rangle \, (1 + B_k + B_q)}$$

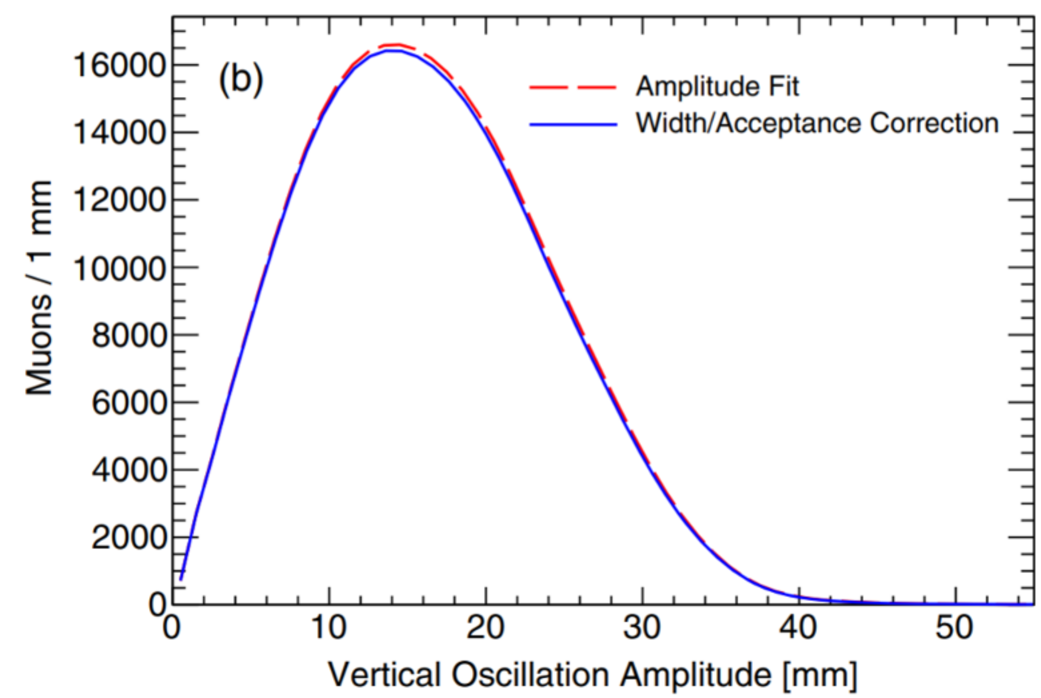
Not all of the muons are at magic momentum!

There is a 0.5% momentum acceptance

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



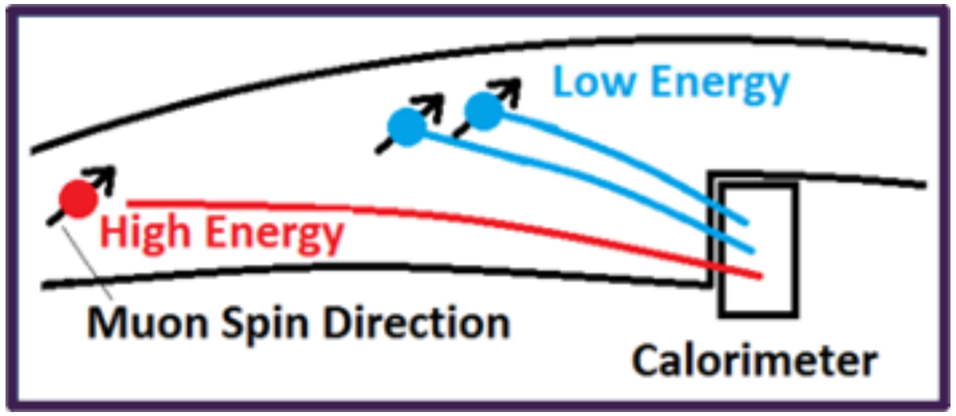
Vertical betatron oscillations cause non-zero average value for $\vec{\beta} \cdot \vec{B}$

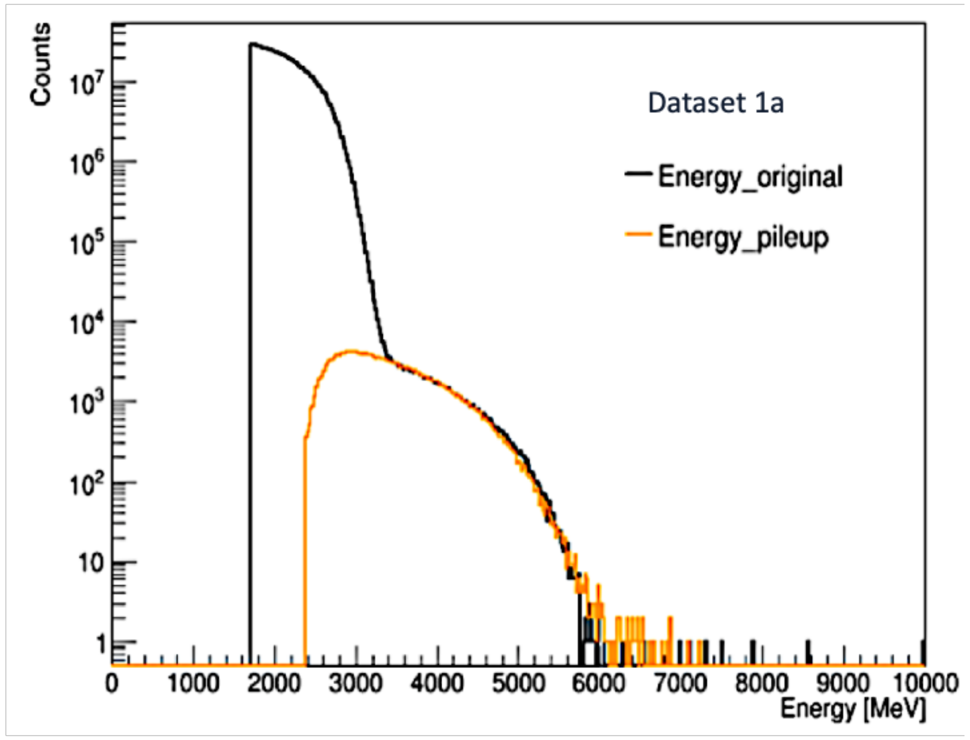


Pileup

$$a_\mu \propto \frac{f_{\mathrm{clock}}\ \omega_a^m (1 + C_e + C_p + C_{ml} + C_{pa})}{f_{\mathrm{calib}}\ \langle \omega'_p(x,y,\phi) \times M(x,y,\phi) \rangle\ (1 + B_k + B_q)}$$

- Pileup is one of the systematics that modulated precession frequency.
- When more than two positrons hit the detector at the same time and place, they could be treated as a single pulse.
- That distorts the time and energy spectrum!

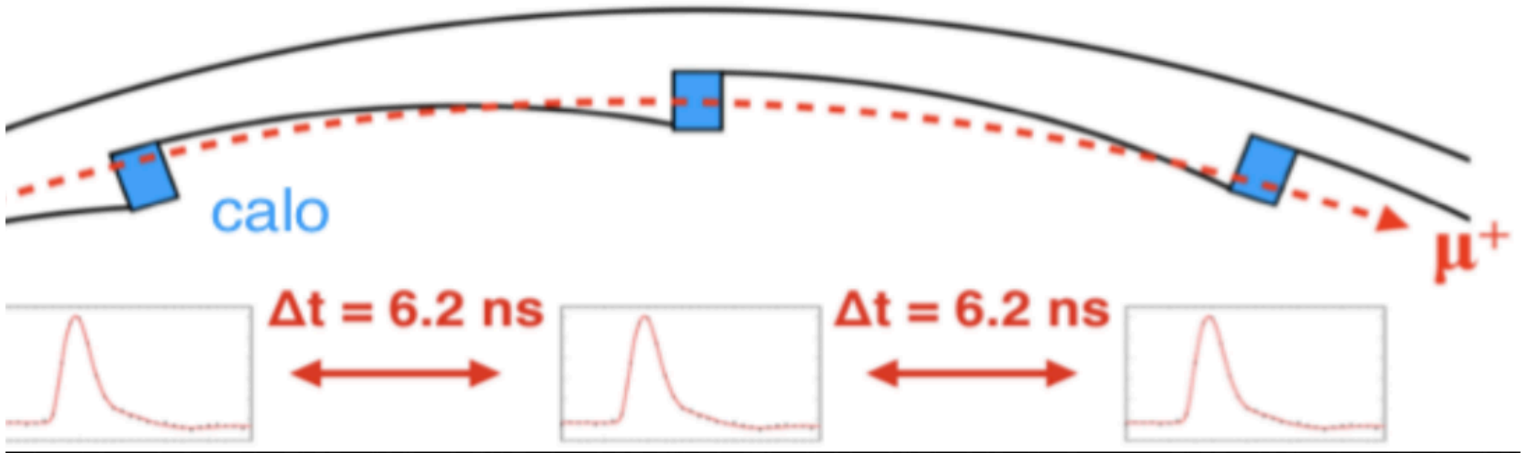




Run-1 data set	1a	1b	1c	1d
Gain changes (ppb)	12	9	9	5
Pileup (ppb)	39	42	35	31
CBO (ppb)	42	49	32	35
Time randomization (ppb)	15	12	9	7
Early-to-late effect (ppb)	21	21	22	10
total systematic uncertainty (ppb)	64	70	54	49

Muon Loss

$$a_\mu \propto \frac{f_{\text{clock}} \;\; \omega_a^m \, (1 + C_e + C_p + C_{ml} + C_{pa})}{f_{\text{calib}} \; \langle \omega_p'(x,y,\phi) \times M(x,y,\phi) \rangle \; (1 + B_k + B_q)}$$



- Muons that were scattered from different materials before decaying and then punch through multiple calorimeters.
- They have different phase than stored muons so they modulate ω_a, producing a systematic error.
- We need to identify them in the data!