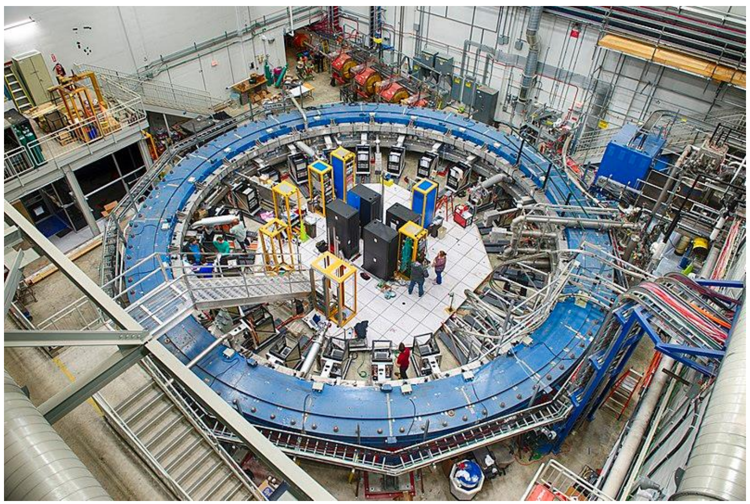
Outlook for Muon g-2 Experiment

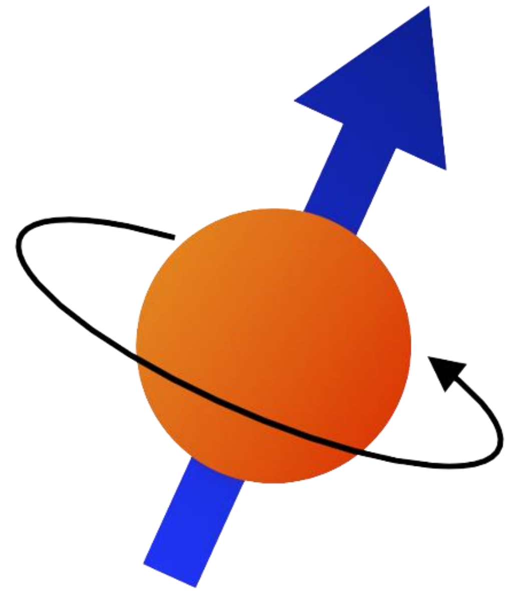


V.S.

~~Round 1~~

~~Round 2~~

Round 3



Liang Li
Shanghai Jiao Tong University

Frequency Measurements

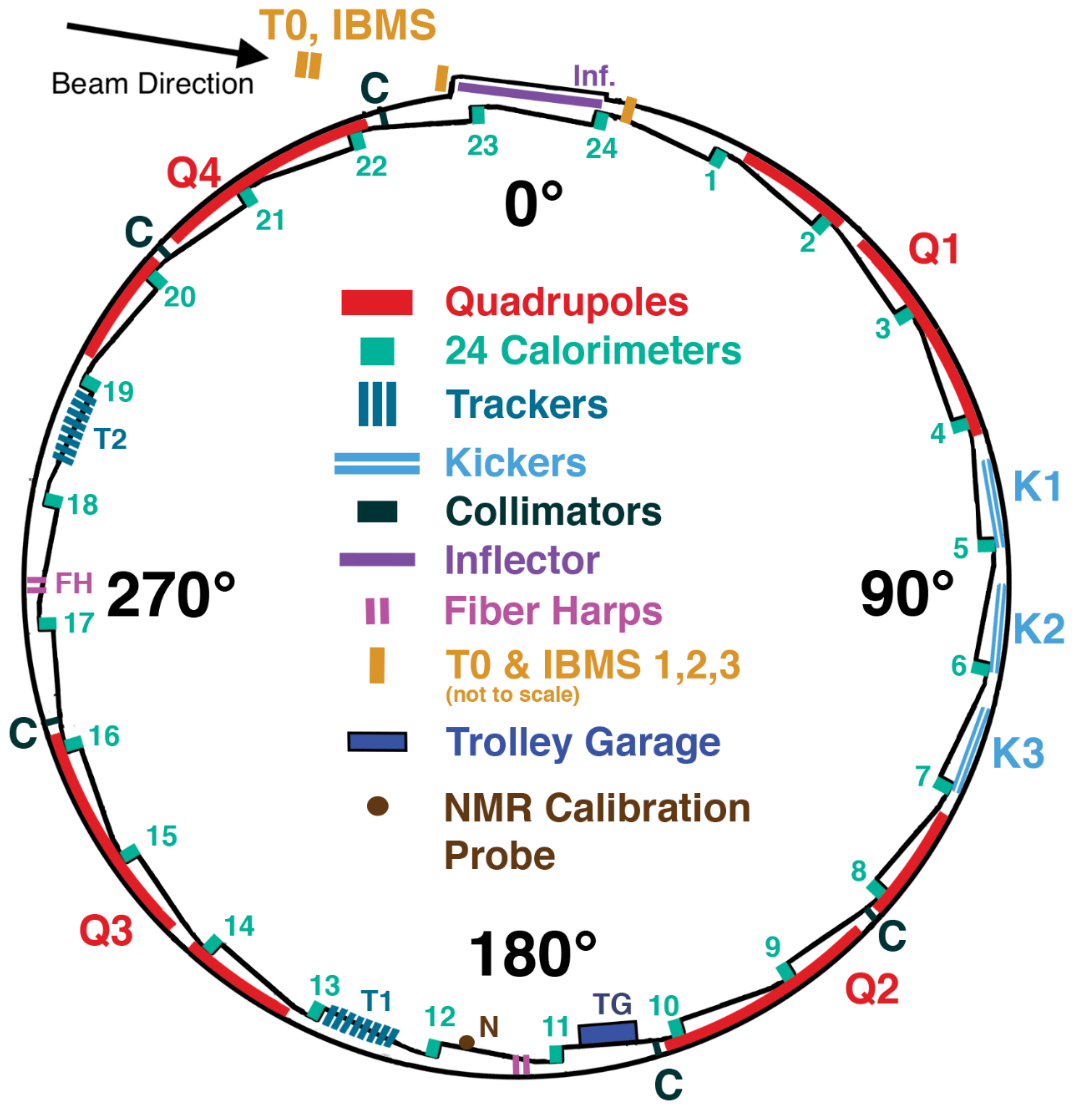
Frequency measurements can be done in very high precision

- **Measure frequency ratio and extract from several measurements**

$$a_\mu \sim \frac{\omega_a}{<B>} = \frac{g_e}{2}\frac{\omega_a}{\varpi_p}\frac{m_\mu}{m_e}\frac{\mu_p}{\mu_e}$$

  - **ω_p is proton Larmor precession frequency in water sample (ω_p ~ |B|)**
  - **ϖ_p is the weighted magnetic field folded with muon distribution**
  - **All other values from Committee on Data for Science and Technology (CODATA), uncertainty < 25 ppb**
    - **E.g. muon-to-electron mass ratio by muonium hyperfine structure experiment**
- **Final measurements done in three steps**
  - **Inject muons into a ring with uniform magnetic field**
  - **Measure muon frequency difference ω_a**
  - **Measure proton precession frequency ω_p and muon distribution**
  - **Blind analyses: measurements and correction factors done *independently* before final answer**

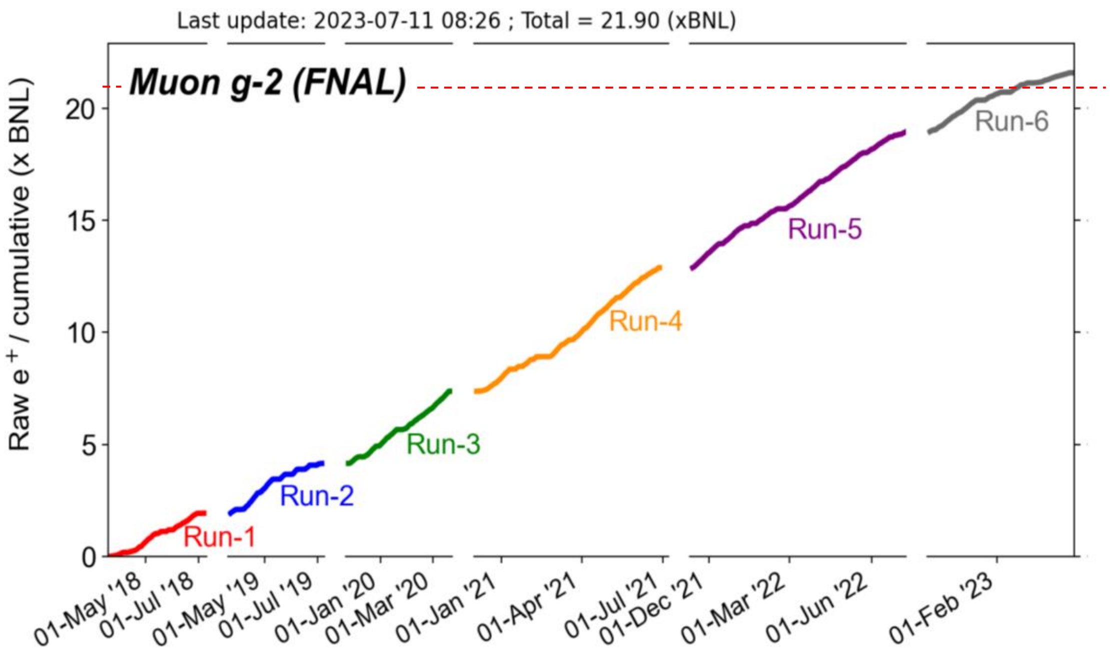
Detector System



- 15 meter wide dipole superconducting magnet
- Inflector, kickers, quadrupoles, collimators for beam insertion
- 386 NMR probes
- Moving trolley with 17 probes
- 24 calorimeters
- Laser calibration system
- 2 tracker stations
- Auxiliary detectors: T0, IBMs, Fiber harps

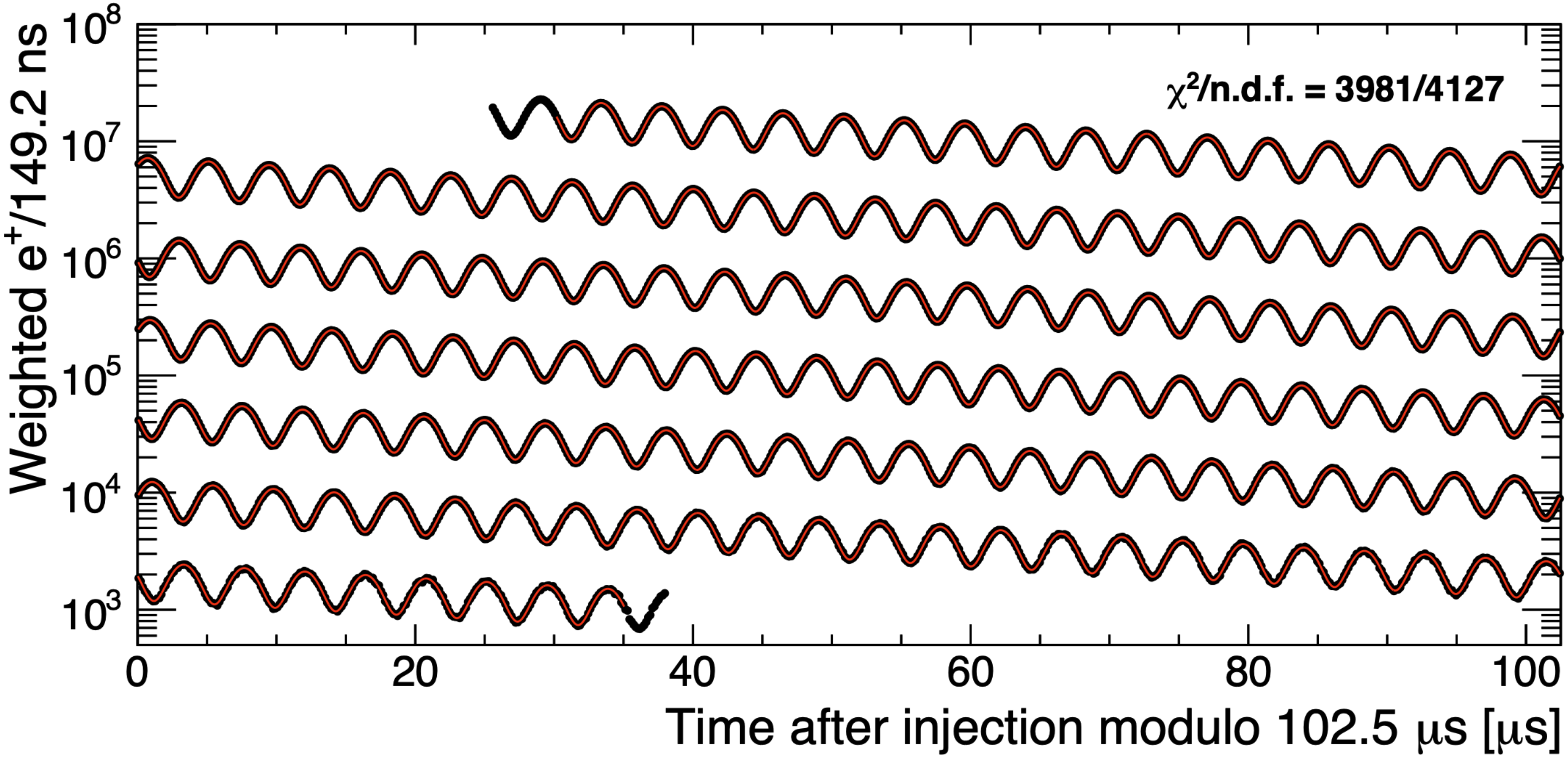
9 PB of Raw Data!

Data Collection



- ✓ **Apr. 2021: Run-1 Result (2018 data) Stat. 434ppb**
- ✓ **Aug. 2023: Run-2/3 Result (2019-20 data) Stat. 201ppb**
- ✓ **Circa 2025: Run-4/5/6 Result (2021-23 data) Stat. ~100ppb**
- ✓ **Run-2/3 ~ 4 times larger than Run-1**
- ✓ **Run-4/5/6 ~ 4 times larger than Run-2/3**

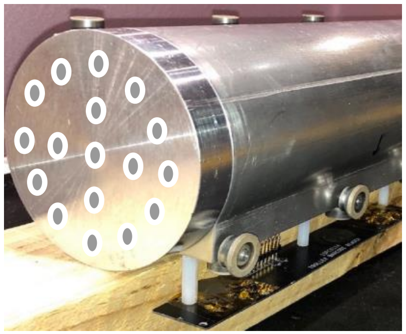
ω_a Measurement



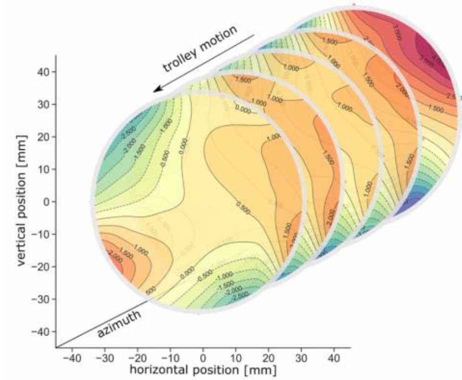
- **Energetic e+ oscillates as μ+ spin direction aligns or anti-aligns with momentum direction**
- **Count e+ hitting calos above threshold (or weight the hits)**
- **Extract the oscillation frequency ω_a via fitting time spectrum**

ω_p Measurement

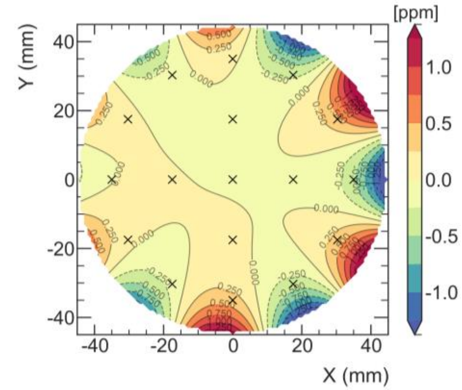
- **In-vacuum NMR trolley maps field every few days**



17 petroleum jelly NMR probes

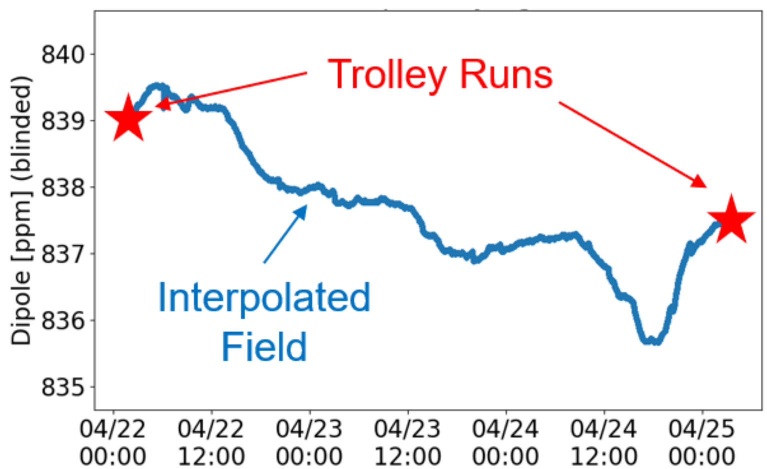


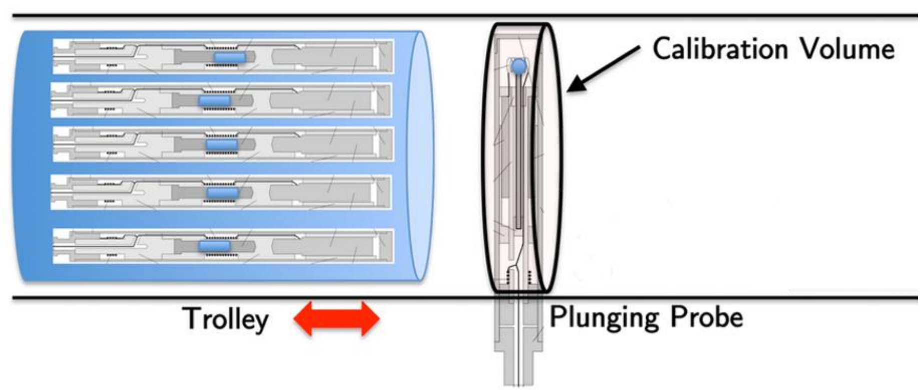
2D field maps (~8000 points)



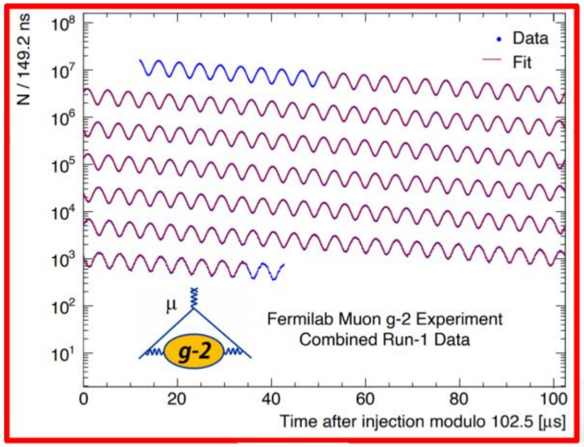
Azimuthally-Averaged Variation < 1 ppm

- **378 fixed probes monitor field during muon storage at 72 locations**
- **Cross-calibrate using a cylindrical plunging H_2O probe**

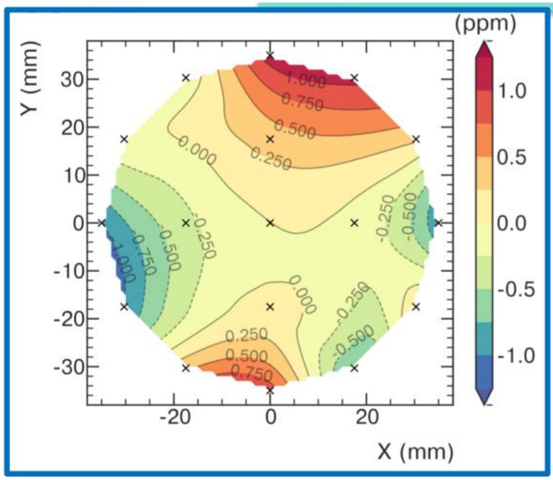




Full Measurement with Corrections



$$\mathcal{R}'_\mu = \frac{\omega_a}{\tilde{\omega}'_p(T_r)} = \frac{f_{\text{clock}}\, \omega_a^m (1 + C_e + C_p + C_{ml} + C_{pa})}{f_{\text{calib}} \langle\, \omega_p(x,y,\phi) \times M(x,y,\phi)\, \rangle (1 + B_k + B_q)}$$



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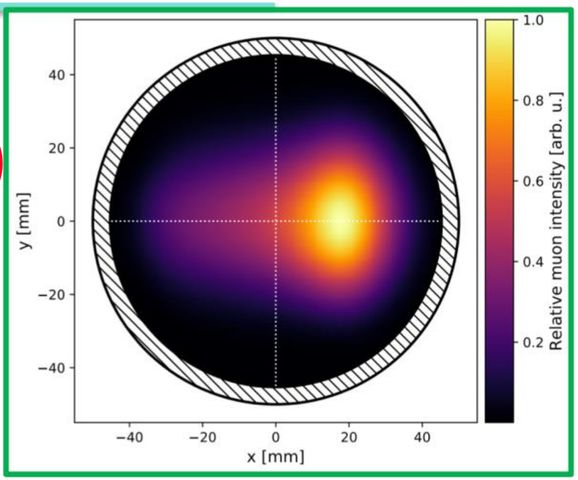
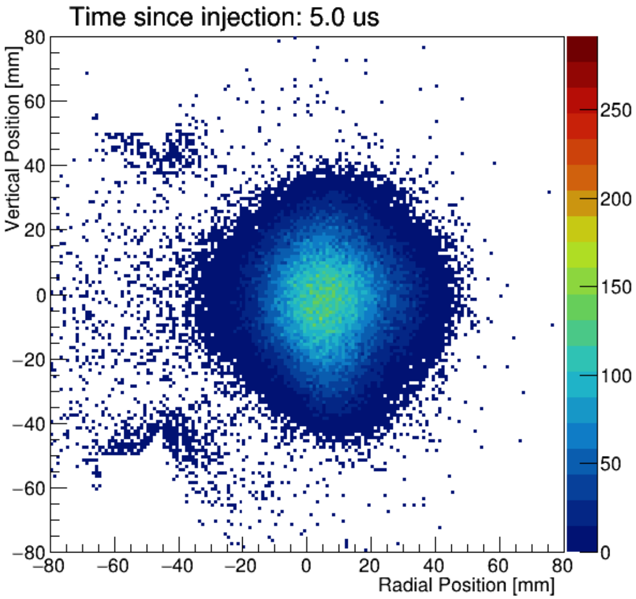
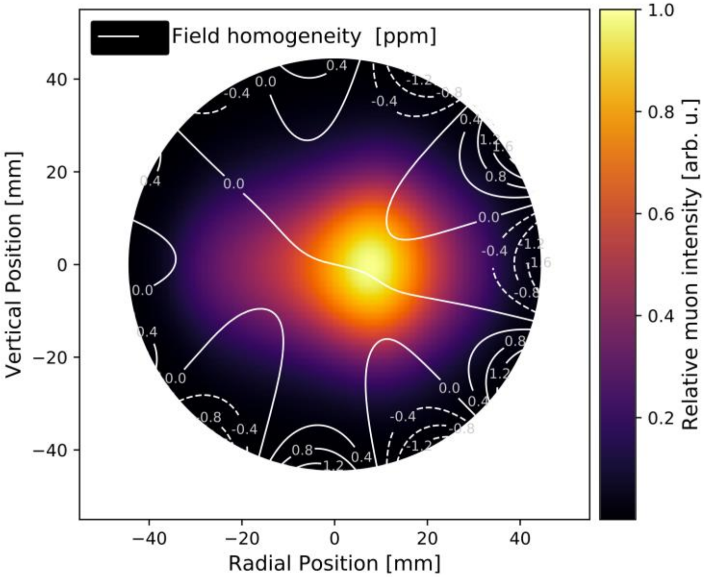


Muon Distribution Measurement



- Trackers can measure beam oscillations directly
  - Beam-dynamics corrections
  - Tuning simulations
  - Optimizing experiment running conditions
- Use muon distribution to weight field maps by where the muons live



Full Measurement with Corrections

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

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

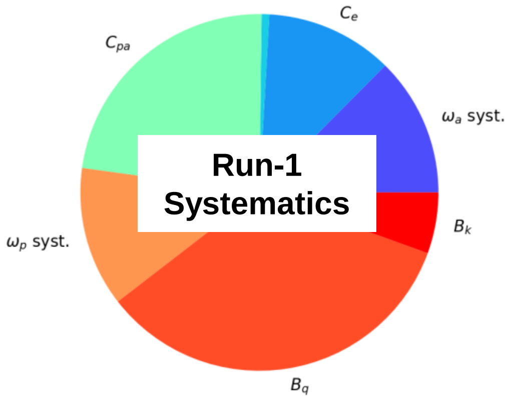
$$\frac{\omega_a}{\omega_p} = \frac{\omega_a^m}{\omega_p^m} \frac{1 + C_e + C_p + C_{pa} + C_{dd} + C_{ml}}{1 + B_k + B_q}$$

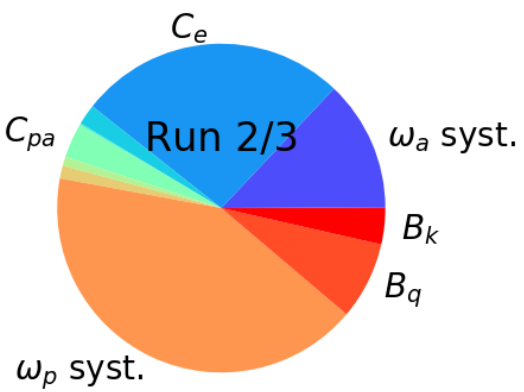
Measured Values

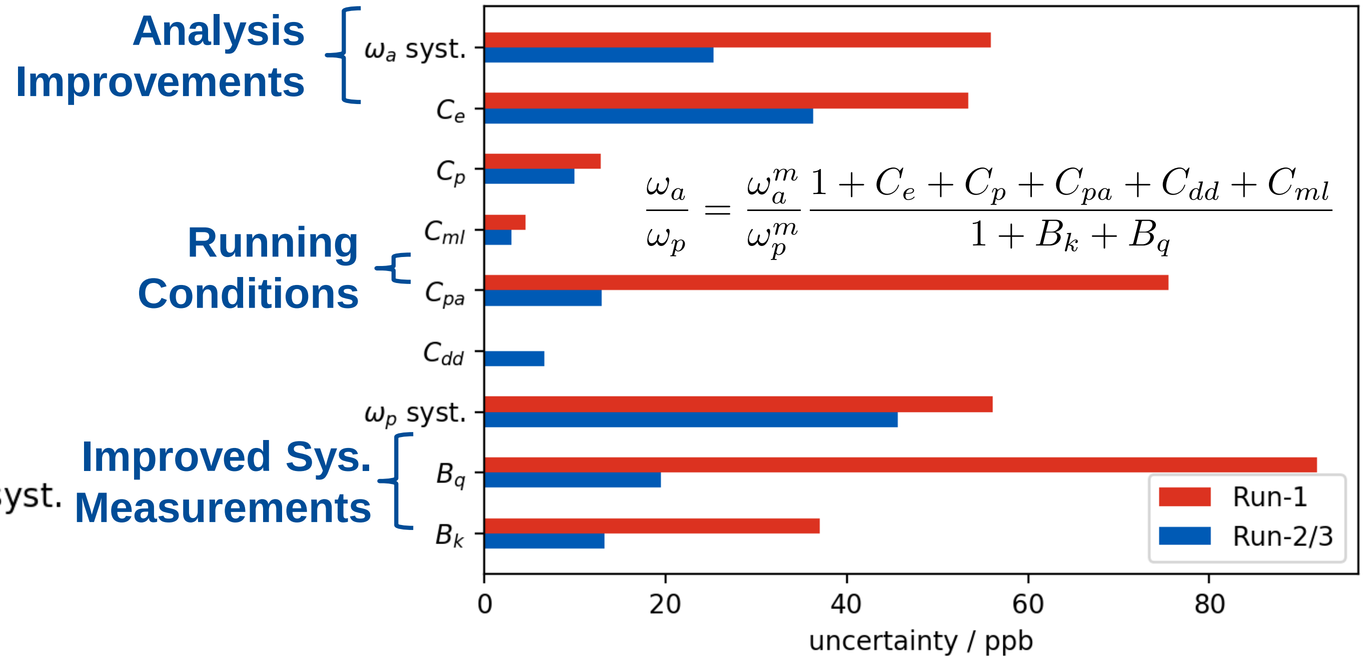
Transient Magnetic Fields: Quad Vibrations, Kicker Eddy Current

- **Total correction 622 ppb, dominated by E-field & Pitch**
- **Corrections are small, but dominated Run-1 systematics**
- **Ultimate goal of precision experiment:**
  - **Correction uncertainties understood and minimized**

Improving Systematic Uncertainties







Major improvements came from:

- **Repaired damaged resistors: improved beam storage, C_{pa} 75ppb→13ppb**
- **Stronger kicker: centered muon distribution, C_e 53ppb→32ppb**
- **Beam effects: smaller oscillations, ω_{a_cbo} 40ppb → 20ppb**
- **Quad vibrations: more measurements, B_q 92ppb → 20ppb**
- **Pileup background: improved reconstruction/algorithm, ω_{a_p} 30ppb → 7ppb**

Run5 Quad-RF reduce CBO

Run4+ continuous measurements

Improving Systematic Uncertainties

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: 215 ppb

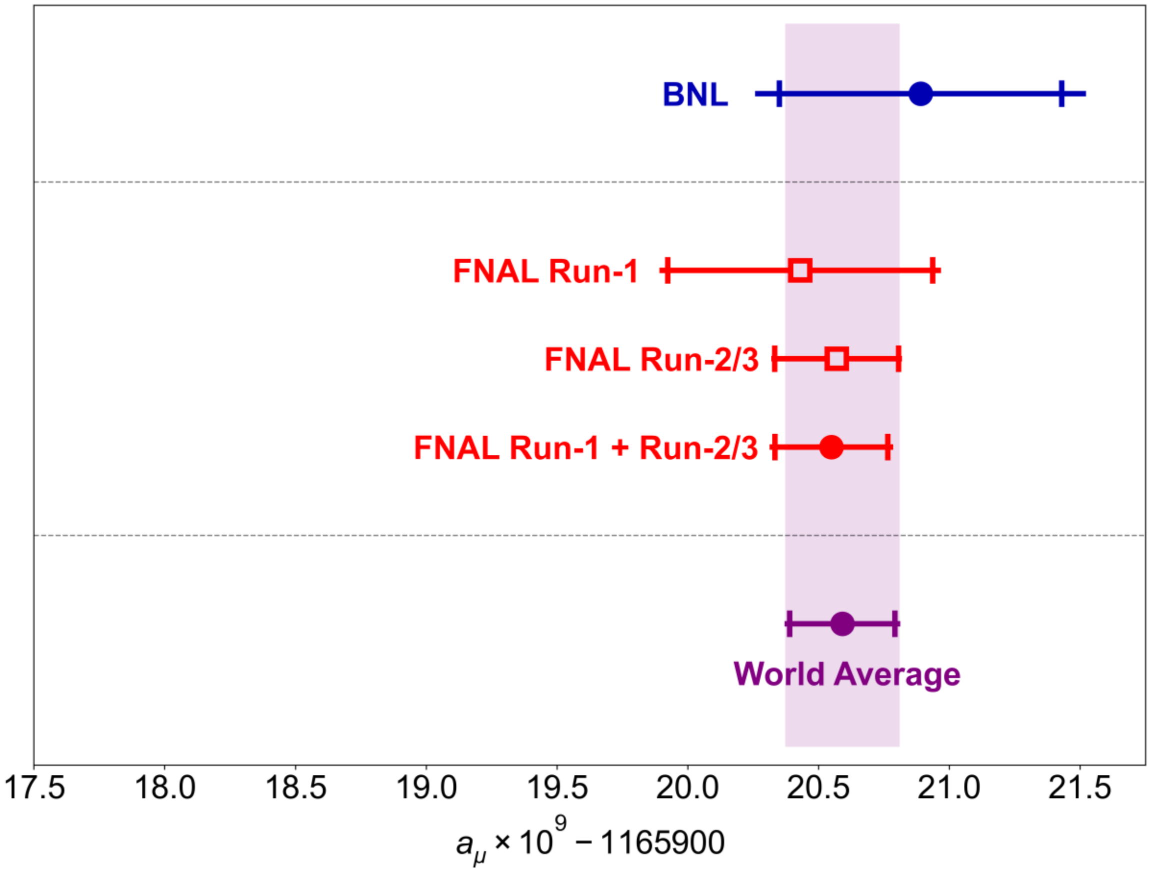
[ppb]	Run-1	Run-2/3	Ratio
Stat.	434	**201**	2.2
Syst.	157	**70**	2.2

- **Near-equal improvement**
- **Still statistically dominated**

- **Total systematic uncertainty: 70 ppb**
- **Surpasses the proposal goal of 100 ppb!**

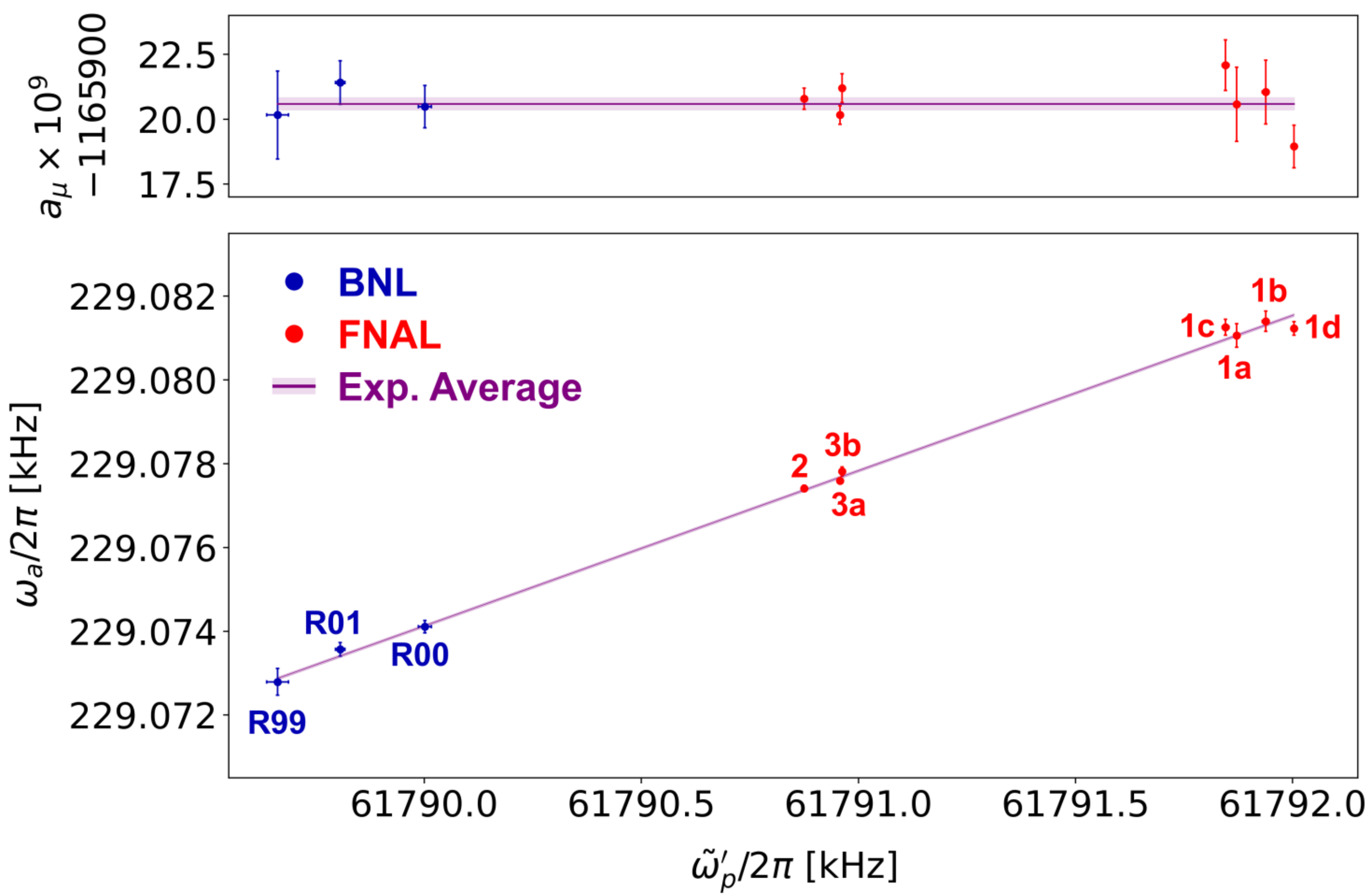
Run2/3 Result & New World Average

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



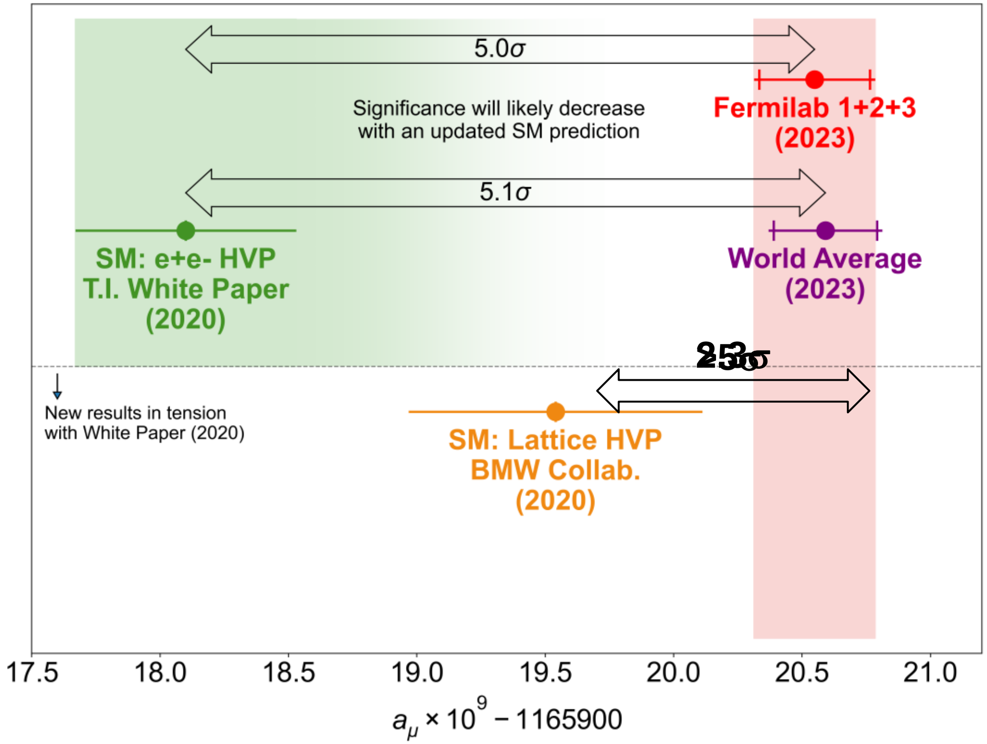
a_μ(Exp) = 0.00 116 592 059(22) [190 ppb]

Data Consistency Check



- **One of many cross checks done**
- **Cross checked with BNL results as well**
- **Datasets taken with slightly different fields**

Experiment vs. Theory Saga



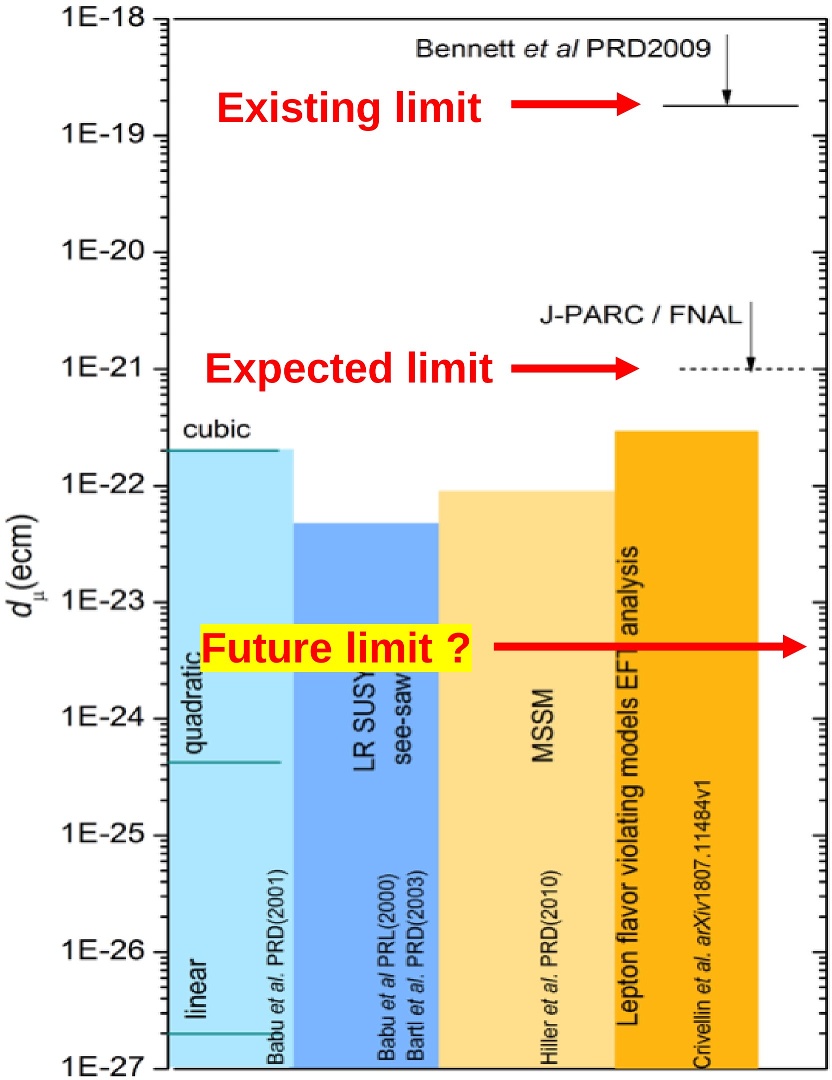
✓ All the more reason to further improve precision measurements!

✓ Round 3 or more are very welcome

✓ New physics potential beyond g-2

- Expect to solve theoretical ambiguity in the next 1-2 years
- Muon g-2 Theory Initiative latest summary
  - https://muon-gm2-theory.illinois.edu/
- More results from BaBar, KLOE, SND, BESIII, Belle II to come
- a_μ(Exp) Run1-6 uncertainty:
  - < 120ppb, 50% reduction
- a_μ(SM) 2025 uncertainty:
  - < 50% reduction possible?

Muon Electric Dipole Moment (EDM)

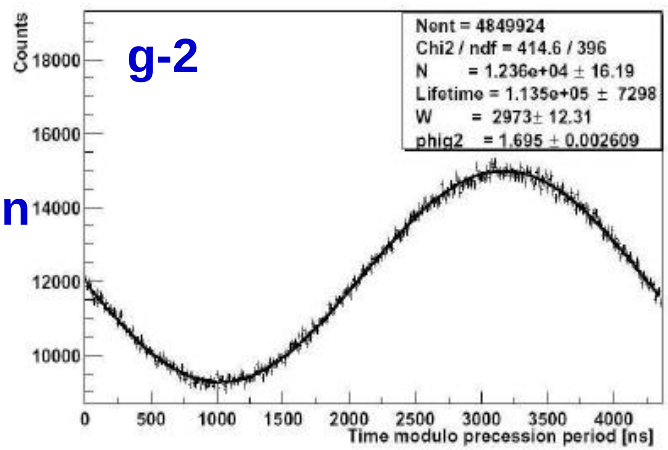


- SM prediction for muon EDM is almost 0: $d_\mu < 10^{-38}$ e·cm
- Unambiguous new physics signal
- Muon is the best option
  - Direct measurement
  - Free of nuclear / molecular effects
- Note that $d_e \sim 10^{-29}$ e·cm
  - Current best result $d_\mu \sim 10^{-19}$ e·cm
  - $10\text{-}10^2$ improvement expected
  - Still need BSM effect >> $(m_\mu/m_e)^2$
- Big discovery potential

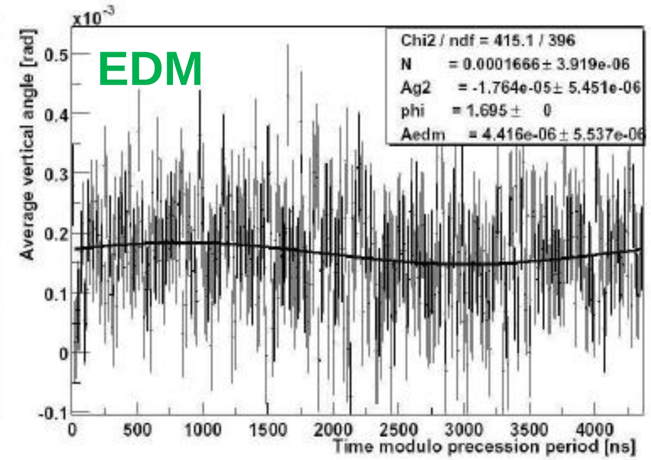
Muon Electric Dipole Moment (EDM)

BNL μ_{EDM} search was done with tracker data

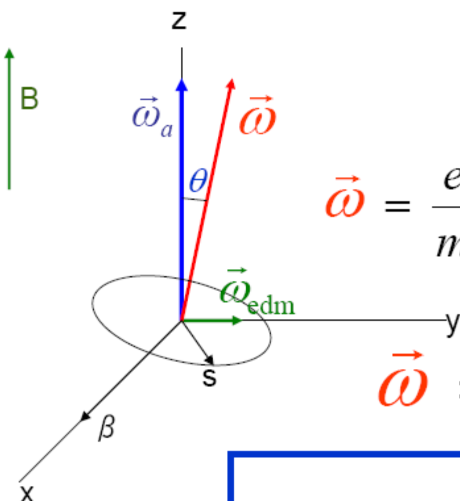
- ✓ **Improved further when combing calo data**



 # Tracks vs (time % T_a)



Average vertical angle vs (time % T_a)



$$\vec{\omega} = \frac{e}{m}\left\{a\vec{B} + \frac{\eta}{2}\left(\vec{\beta}\times\vec{B}\right)\right\}$$

$$\vec{\omega} = \vec{\omega}_a + \vec{\omega}_{\mathrm{edm}}$$

$$\tan\theta = \frac{\omega_{edm}}{\omega_a}$$

Single Tracker [BNL]:

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

Two Trackers + Calo [FNAL]:
(Expected from Run-1 data)

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

Statistically limited search

- ✓ **10^{-21} e·cm reachable with full data and improved tracking, calo may also help**

CPT and Lorentz Invariance Violation

Standard Model Extension (SME) Allows for CPT/LV

- **Muon anomalous frequency would be changed by CPT/LV terms**

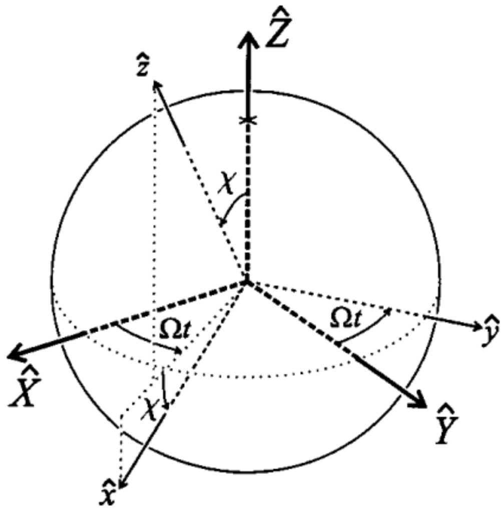
$$L' = -a_\kappa \bar{\psi}\gamma^\kappa\psi - b_\kappa \bar{\psi}\gamma_5\gamma^\kappa\psi - \tfrac{1}{2}H_{\kappa\lambda}\bar{\psi}\sigma^{\kappa\lambda}\psi + \tfrac{1}{2}ic_{\kappa\lambda}\bar{\psi}\gamma^\kappa \overleftrightarrow{D}^\lambda\psi + \tfrac{1}{2}id_{\kappa\lambda}\bar{\psi}\gamma_5\gamma^\kappa \overleftrightarrow{D}^\lambda\psi,$$

$$\delta\omega_a^{\mu^\pm} \approx 2\check{b}_Z^{\mu^\pm}\cos\chi + 2(\check{b}_X^{\mu^\pm}\cos\Omega t + \check{b}_Y^{\mu^\pm}\sin\Omega t)\sin\chi$$

$$\check{b}_J^{\mu^\pm} \equiv \pm\frac{b_J}{\gamma} + m_\mu d_{J0} + \frac{1}{2}\varepsilon_{JKL}H_{KL} \qquad (J = X, Y, Z)$$

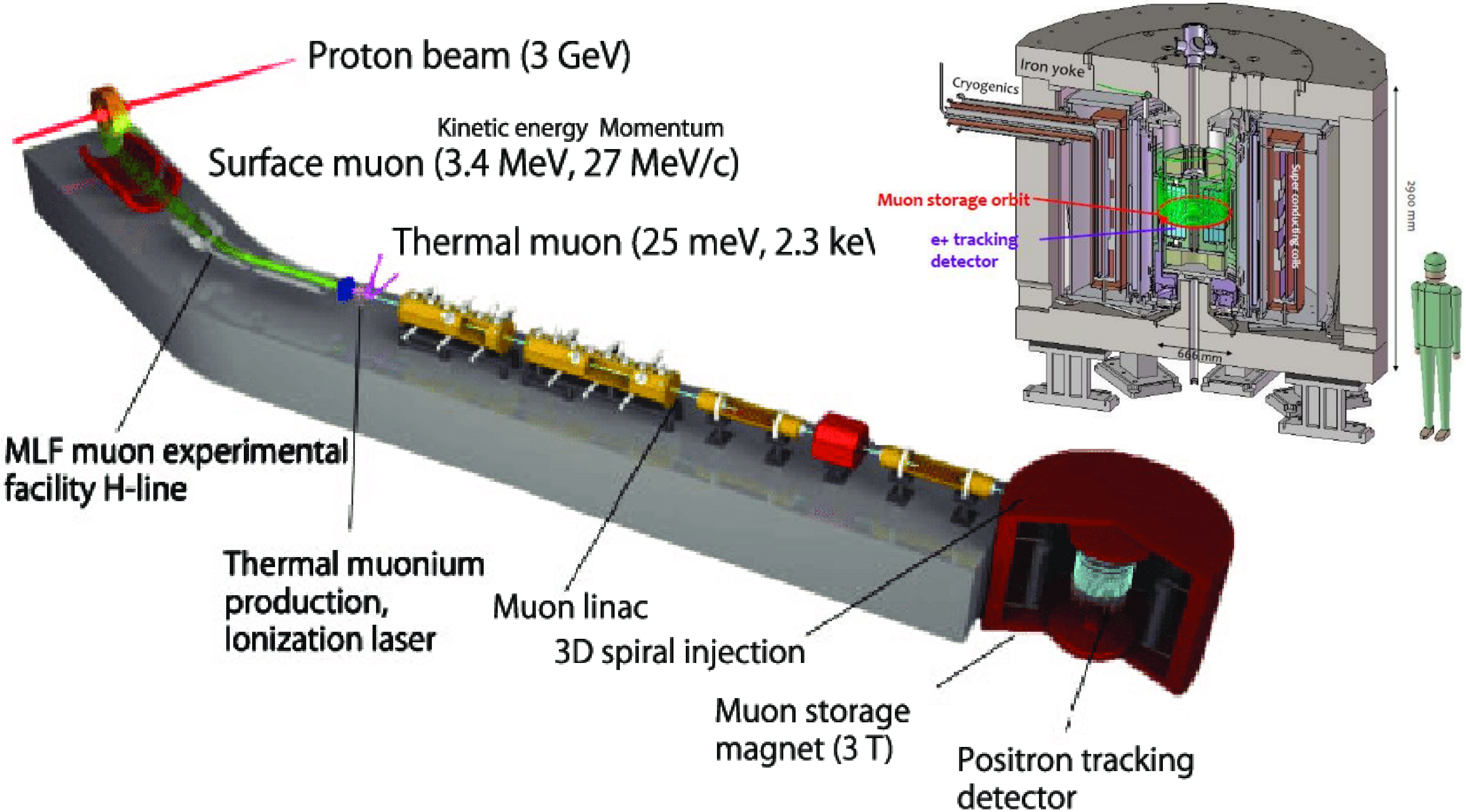
a_k, b_k are CPT- odd; others are CPT- even $\quad \Omega = 2\pi/T_{Earth}; \chi = 90° - latitude$

- **Sidereal oscillation in $\mathcal{R} = \omega_a/\tilde{\omega}'_p$**
  - **ω_a proportional to magnetic field**
- **Two kinds of CPT/LV signals**
  - **Difference between average R_{μ^+} and R_{μ^-}**
  - **Sidereal modulations in R_{μ^+} and R_{μ^-}**
- **Previous BNL result put sharp bound on CPT**
  - **CPT/LV coefficients < 1.4 X 10^{-24} GeV**
  - **Dimensionless FOM < ~10^{-23}**
- **Improvement from FNL**
  - **Run-2 data < 1.2 x 10^{-24} GeV**
  - **Run-2/3 data < O(10^{-25}) GeV (expected)**



Nonrotating Celestial Equatorial Frame ($\hat{X},\hat{Y},\hat{Z}$)

J-PARC g-2/EDM



$$\vec{\omega}_a = \frac{e}{mc}\left[a\vec{B} - \left(a - \frac{1}{\gamma^2 - 1}\right)\vec{\beta}\times\vec{E}\right] + \frac{e\eta}{2mc}\left(\vec{E} + \vec{\beta}\times\vec{B}\right)$$

g-2 **E=0** **EDM**

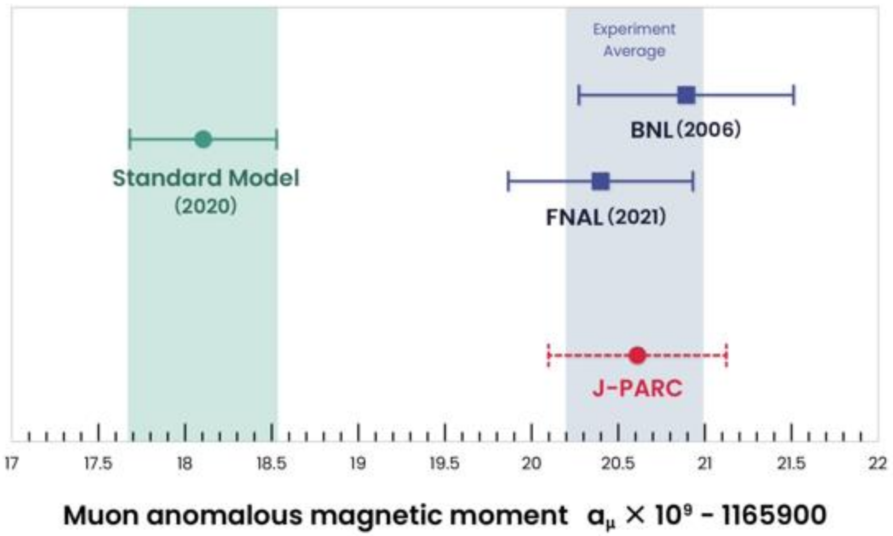
J-PARC g-2/EDM

Comparison of various parameters for the Fermilab and J-PARC $(g-2)$ Experiments

Parameter	Fermilab E989	J-PARC E24
Statistical goal	100 ppb	400 ppb
Magnetic field	1.45 T	3.0 T
Radius	711 cm	33.3 cm
Cyclotron period	149.1 ns	7.4 ns
Precession frequency, ω_a	1.43 MHz	2.96 MHz
Lifetime, $\gamma\tau_\mu$	64.4 μs	6.6 μs
Typical asymmetry, A	0.4	0.4
Beam polarization	0.97	0.50
Events in final fit	1.8×10^{11}	8.1×10^{11}

No magic momentum!

- **No strong focusing**
- **Super-low emittance muon beam**
- **Compact storage ring**
- **Full tracking detector**



Aim to have comparable precision with FNAL Run-1 result

- **Statistical uncertainty dominated**
- **$\delta\omega_a = 0.45$ ppm, $\delta\omega_{a_sys} < 0.1$ppm**
- **$\delta EDM = 1.5{\cdot}10^{-21} e{\cdot}cm$**

TDR: 2017
KEK approval: 2021
Data taking: 2028

Next talk from Yoshioka-san!

Conclusion and Outlook

- ✓ **Most precise Muon g-2 experiment result so far: 0.20ppm**
- ✓ **Final release expected in 2025**
  - ✓ **Expect significant improvements from both experiment and theory side**
  - ✓ **Discovery potential with improved precisions**
- ✓ **New physics potential in many aspects**
  - ✓ **Test BSM models, Muon EDM, CPT/LV and Dark Matter search**
- ✓ **J-PARC Muon g-2/EDM experiment expected to take data in ca. 2028**
- ✓ **More exciting results from Muon g-2 underway, stay tuned!**

Backup

Muon g-2 Collaboration

US Universities
- Boston
- Cornell
- UIUC
- James Madison
- Kentucky
- Massachusetts
- Michigan
- Michigan State
- Mississippi
- North Central College
- Northern Illinois
- Regis
- Virginia
- Washington

US National Labs
- Argonne
- Brookhaven
- Fermilab

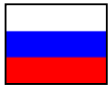
181 collaborators
33 Institutions
7 countries

China
- Shanghai Jiao Tong

Germany
- Dresden

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

Korea
- CAPP/ISB
- KAIST

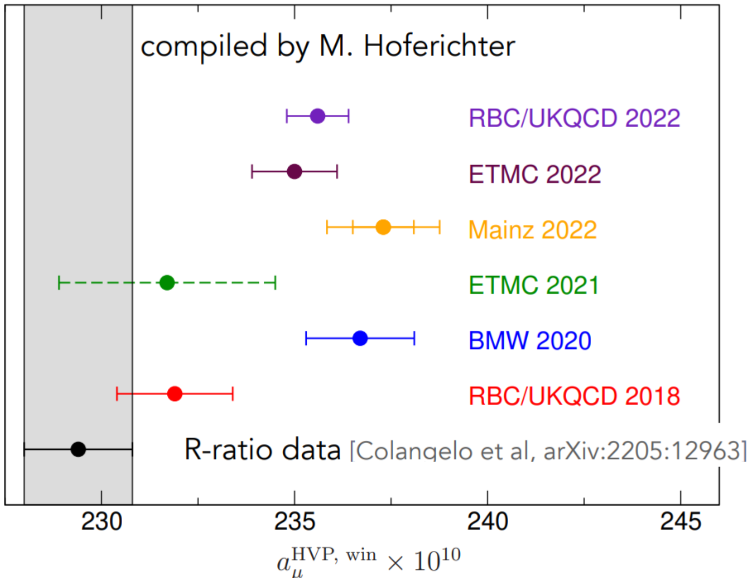


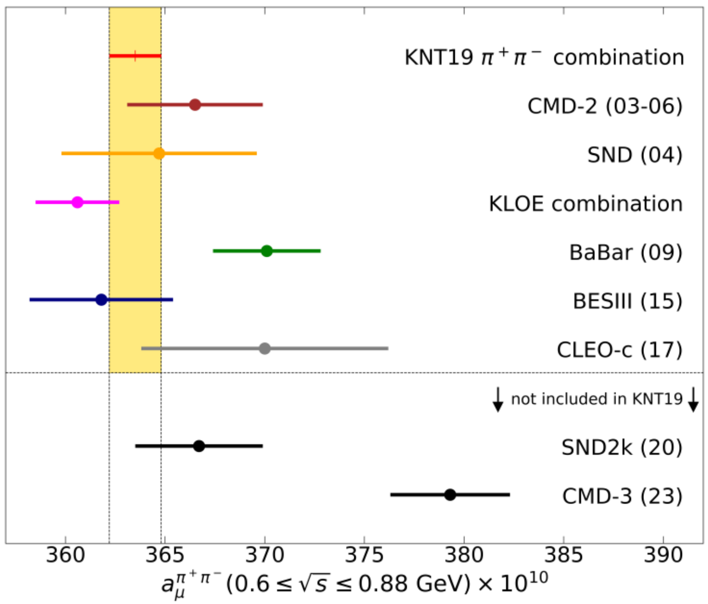
Russia
- Budker/Novosibirsk
- JINR Dubna

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

Muon g-2 Collaboration Meeting @ Elba
May 2019

Hadronic Vacuum Polarization Update





- **LQCD Intermediate window: BMW 2020 claimed 0.8% precision, closer to experimental value but 2.1σ with data-driven HVP**
- **Need full LQCD HVP calculations for all windows**

- **Data-driven results from SND2k and CMD-3 since 2020 White Paper**
- **SND2k agrees with 2020 results**
- **CMD-3 deviates from all others >3σ**
- **New paper from Babar**
  - **Phys. Rev. D 108, L111103 (2023) Possible explanation for tensions with other experiments**

- **MuonE: a_{μ_Had} from experiment!**