Workshop on Muon Science Technology and Industry (MELODY 2023)

Muon g-2 = New Physics?

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Experimental Principle

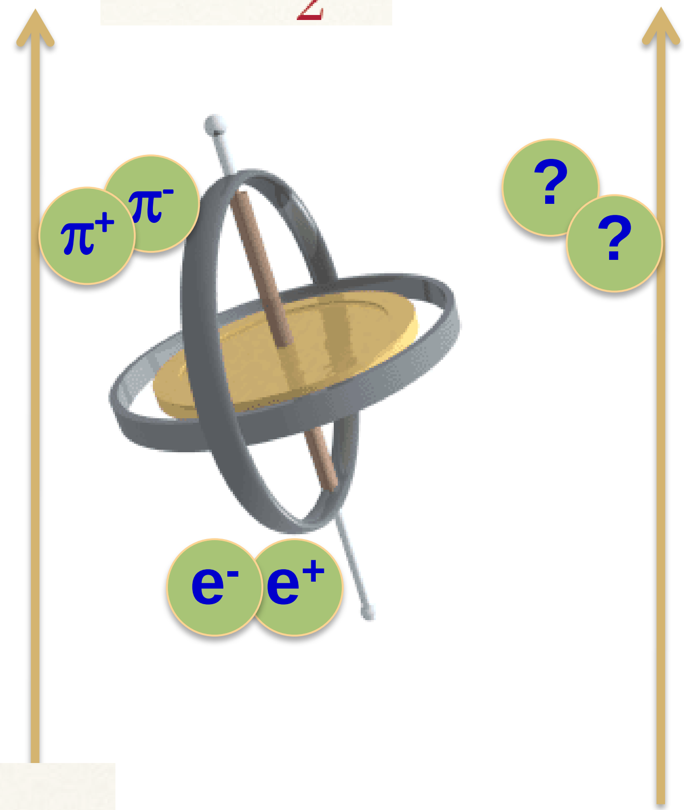
The name of game: measure frequency

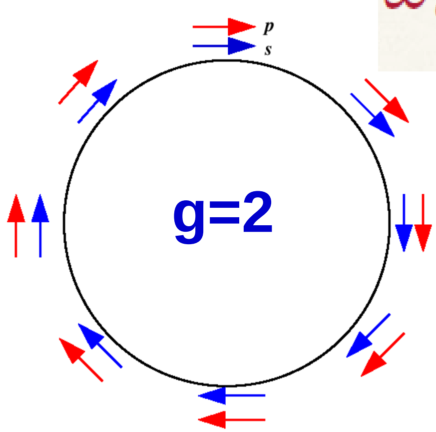
$$a = \frac{g-2}{2}$$

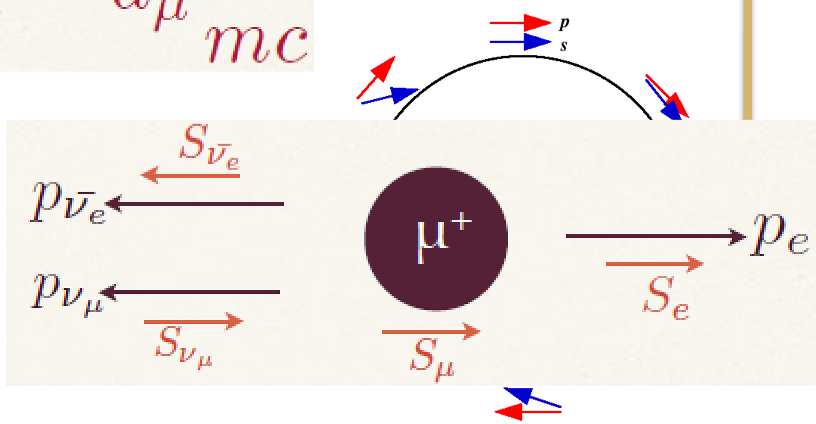
- **Put (polarized) muons in a magnetic field and measure precession f.q.**
- **Get muon spin direction from decayed electrons**
- **a_μ ~ difference between precession frequency and cyclotron frequency**

$$\omega_a = \omega_s - \omega_c$$

$$\omega_a = a_\mu \frac{eB}{mc}$$







$$\omega_s = g \frac{eB}{2mc}$$

Frequency Measurements

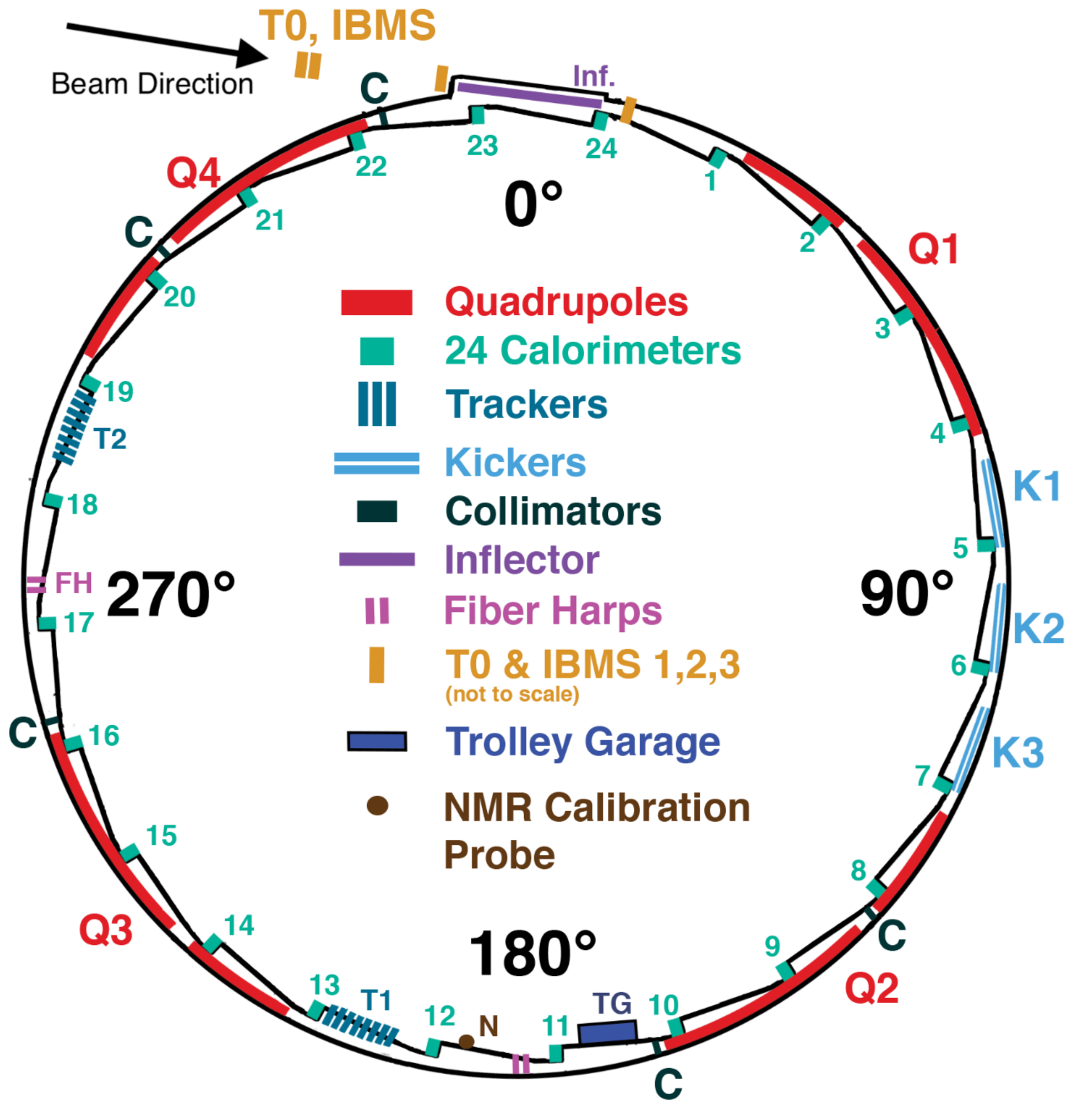
Frequency measurements can be done in very high precision

- **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**

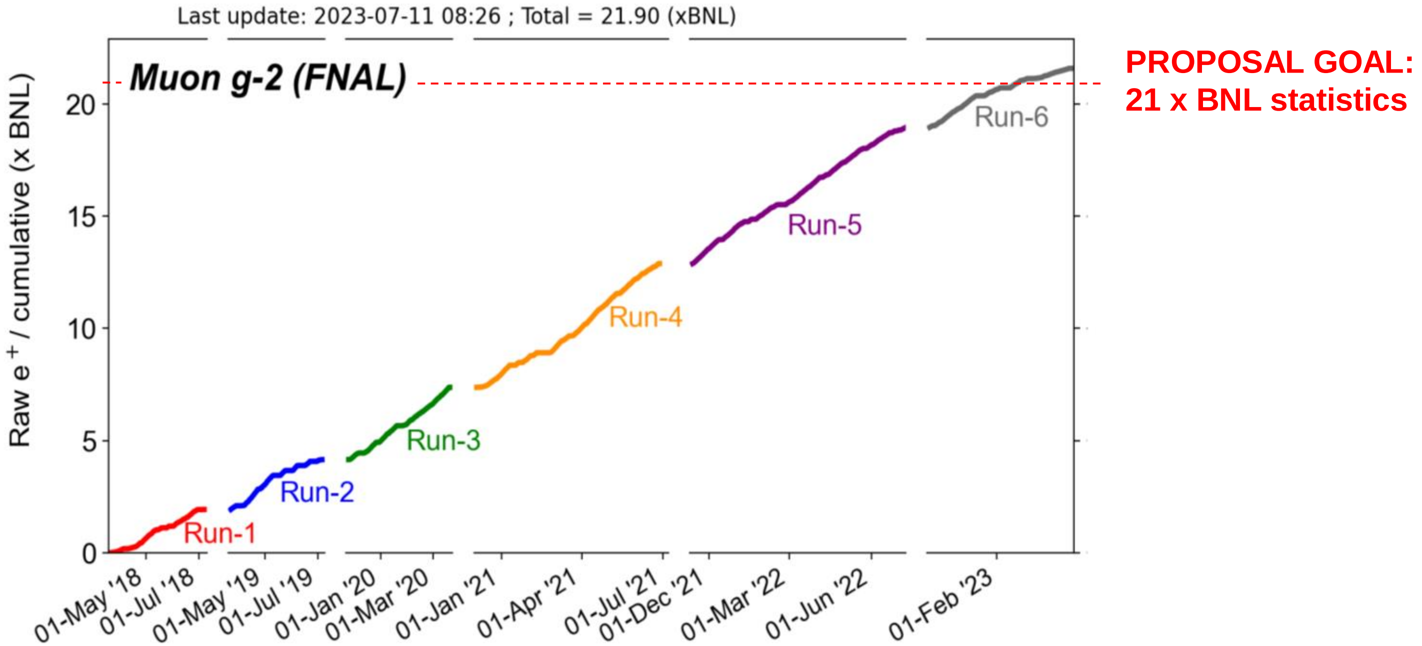
Detector System



- 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

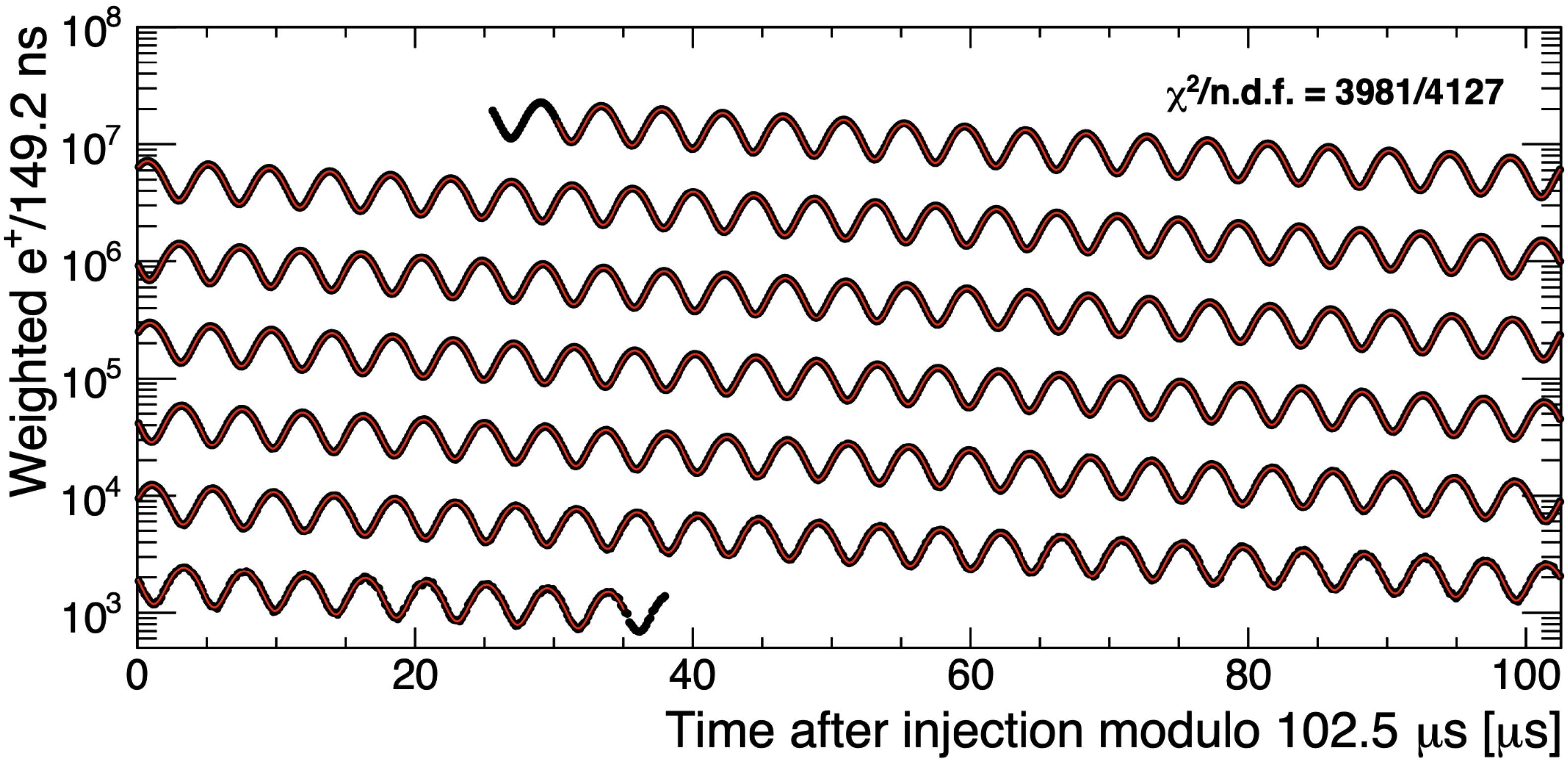
9 PB of Raw Data!

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

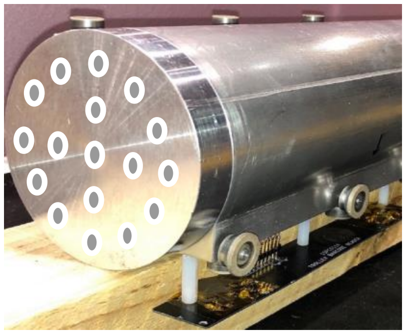


- Energetic e+ oscillates as μ+ spin direction aligns or anti-aligns with momentum direction
- Count e+ hitting calos above threshold (or weight the hits)
- Extract the oscillation frequency ω_a via fitting time spectrum

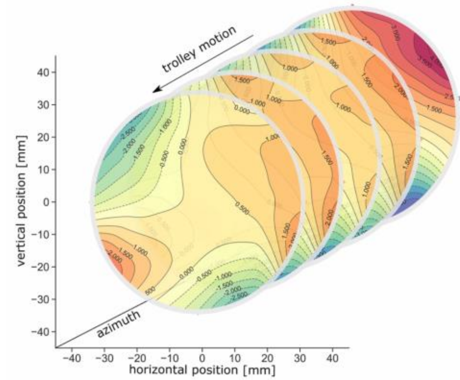
More in Kim-Siang's talk

ω_p Measurement

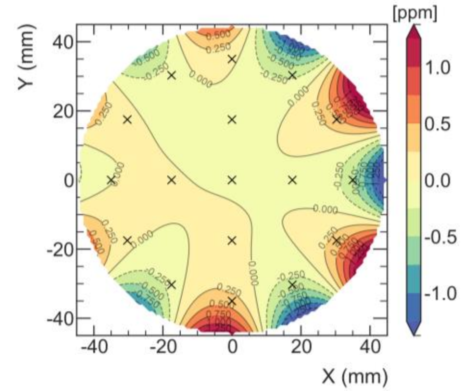
- **In-vacuum NMR trolley maps field every few days**



17 petroleum jelly NMR probes

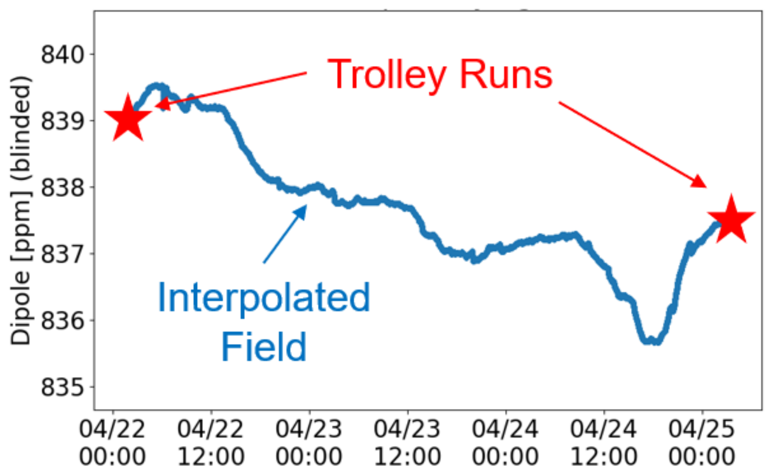


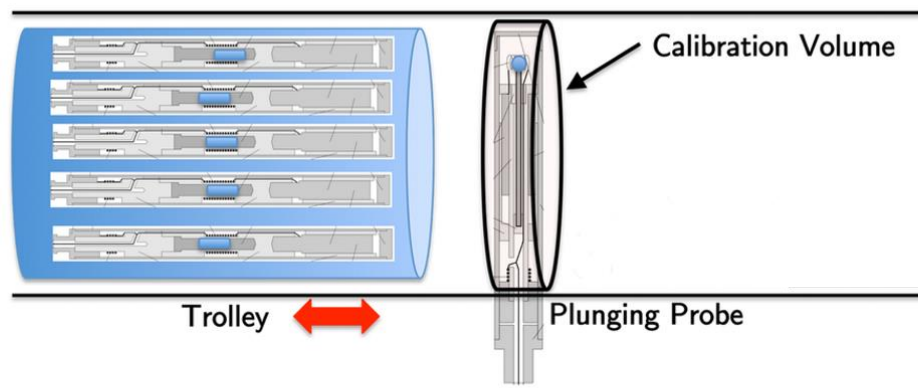
2D field maps (~8000 points)



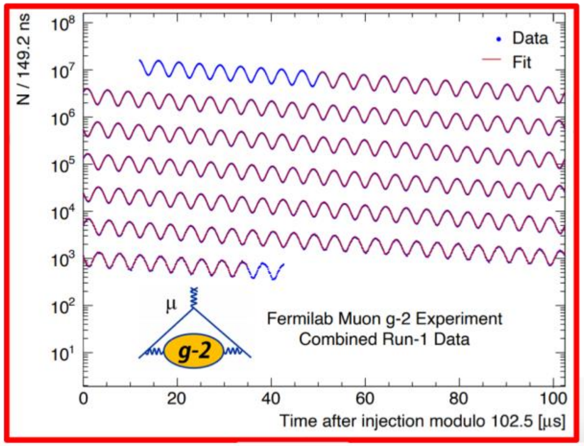
Azimuthally-Averaged Variation < 1 ppm

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

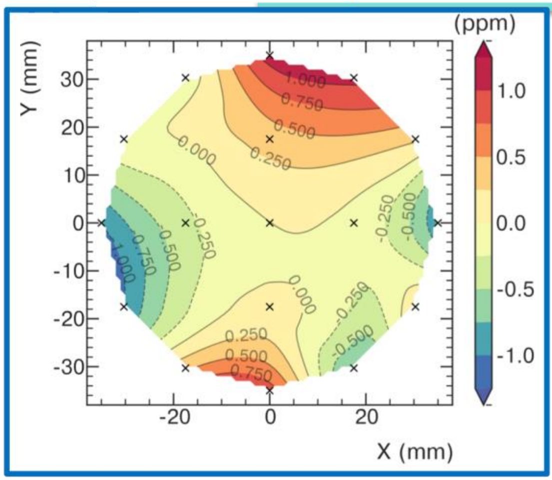




Full Measurement with Corrections



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



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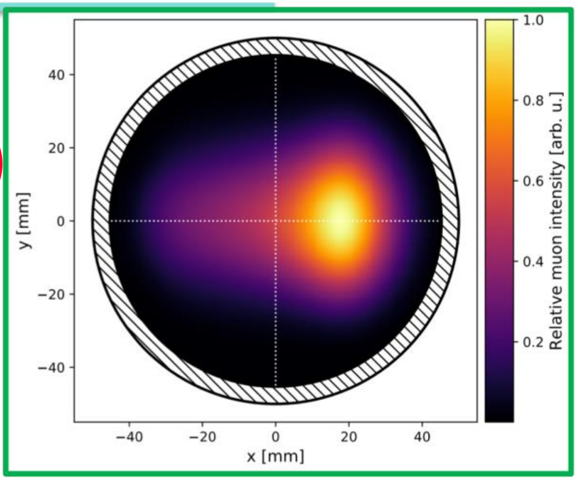
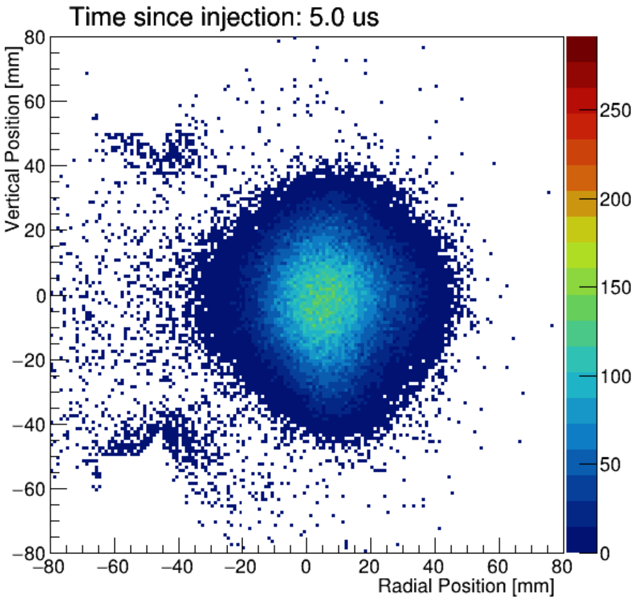
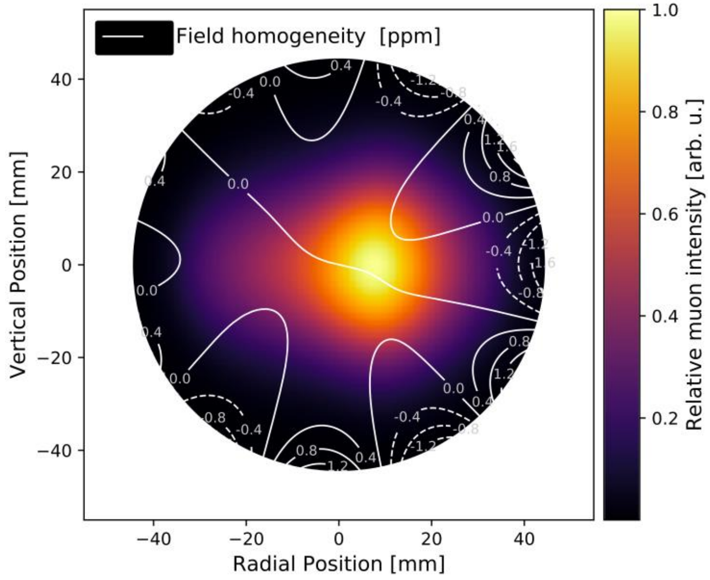


Muon Distribution Measurement





- **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

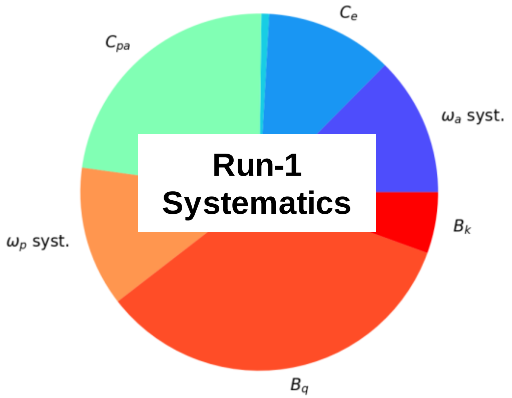
$$\frac{\omega_a}{\omega_p} = \frac{\omega_a^m}{\omega_p^m} \frac{1 + C_e + C_p + C_{pa} + C_{dd} + C_{ml}}{1 + B_k + B_q}$$

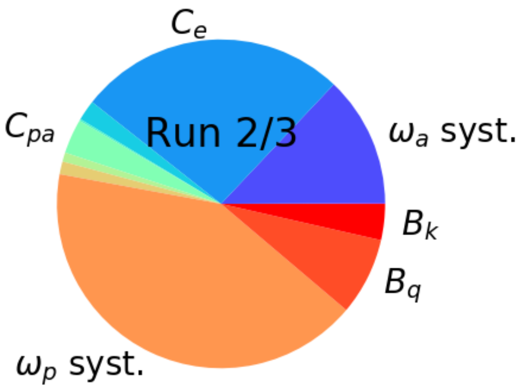
Measured Values

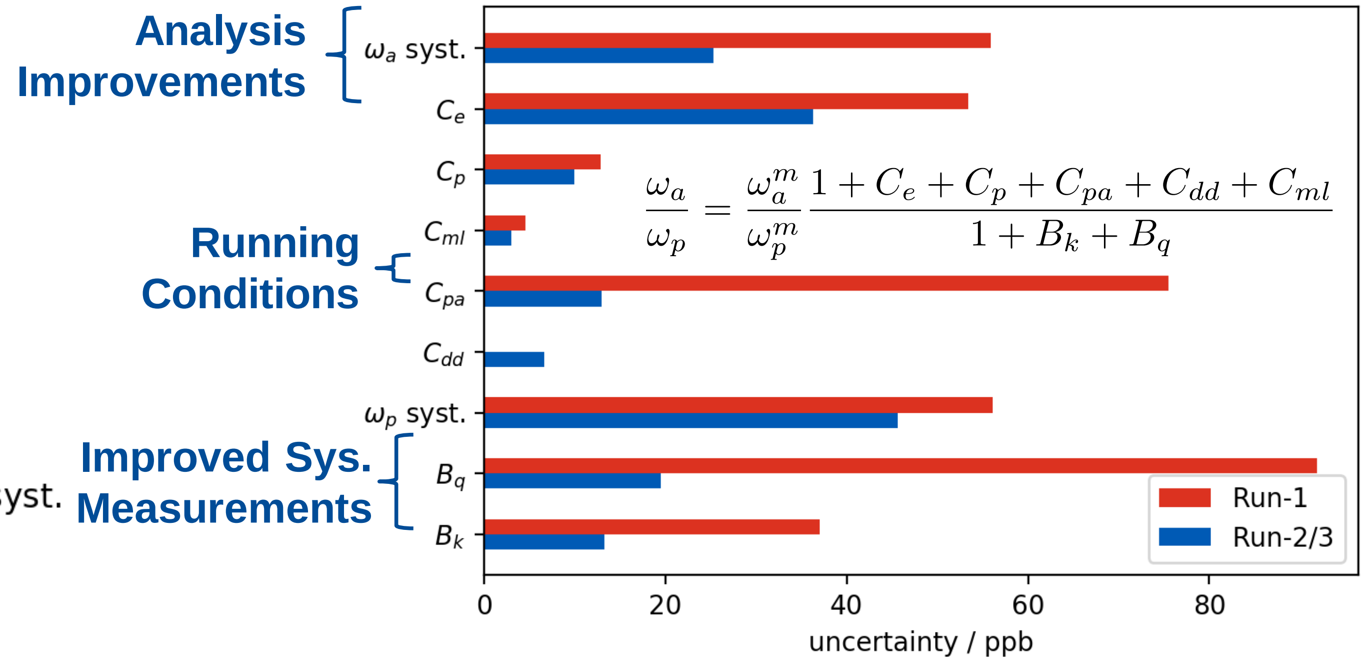
Transient Magnetic Fields: Quad Vibrations, Kicker Eddy Current

- **Total correction 622 ppb, dominated by E-field & Pitch**
- **Corrections are small, but dominated Run-1 systematics**
- **How/where to improve?**

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 measurement positions, B_q 92ppb → 20ppb**
- **Pileup background: improved reconstruction/algorithm, ω_{a_p} 30ppb → 7ppb**

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
$\mu'_p(34.7^\circ)/\mu_e$	–	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

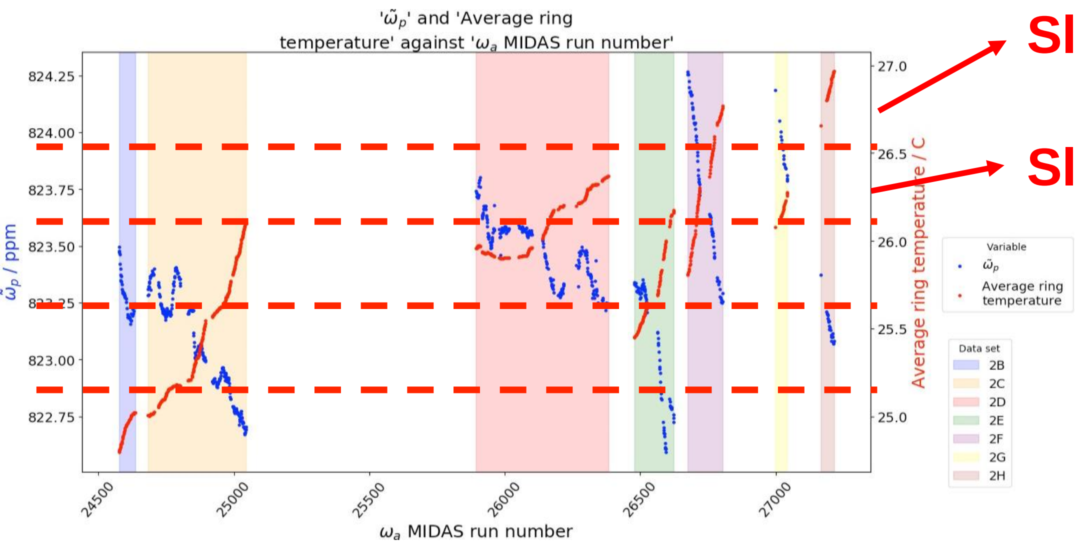
- **Near-equal improvement**
- **Still statistically dominated**

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

Blind Analysis

- **Perform analysis with software & hardware blinding**
  - **Hardware blind comes from altering our clock frequency**
  - **Clock is locked and value kept secret until analysis completed**
  - **Non-collaborators set frequency to (40 – δ) MHz**
- **Unblinding meeting (on July 24th 2023)**
  - **Unanimous vote from all collaborators to unblind**
  - **Secret envelopes were finally opened to reveal the hidden clock frequencies and the result…**

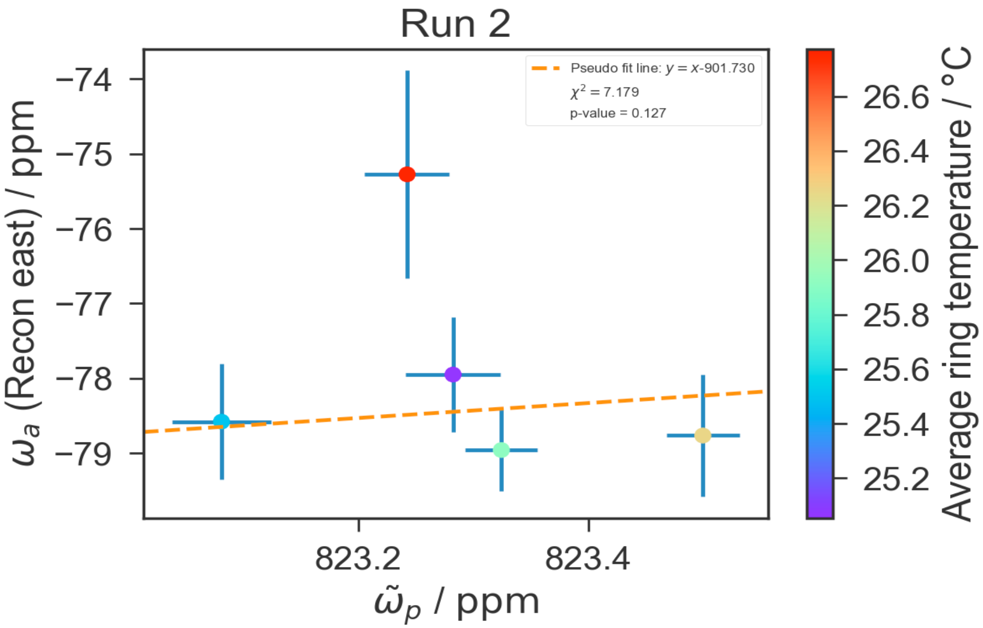
Data Consistency Check

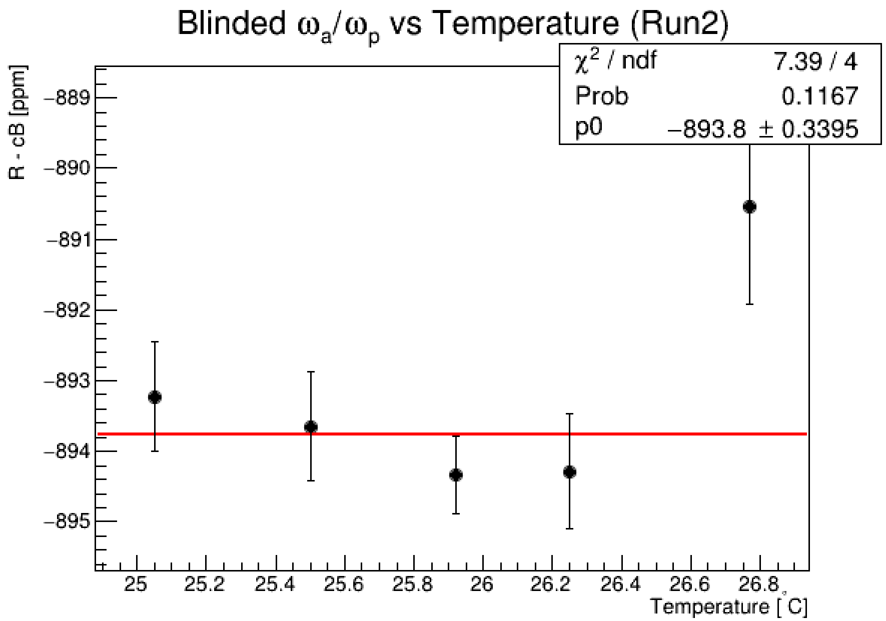


Sliced dataset 1

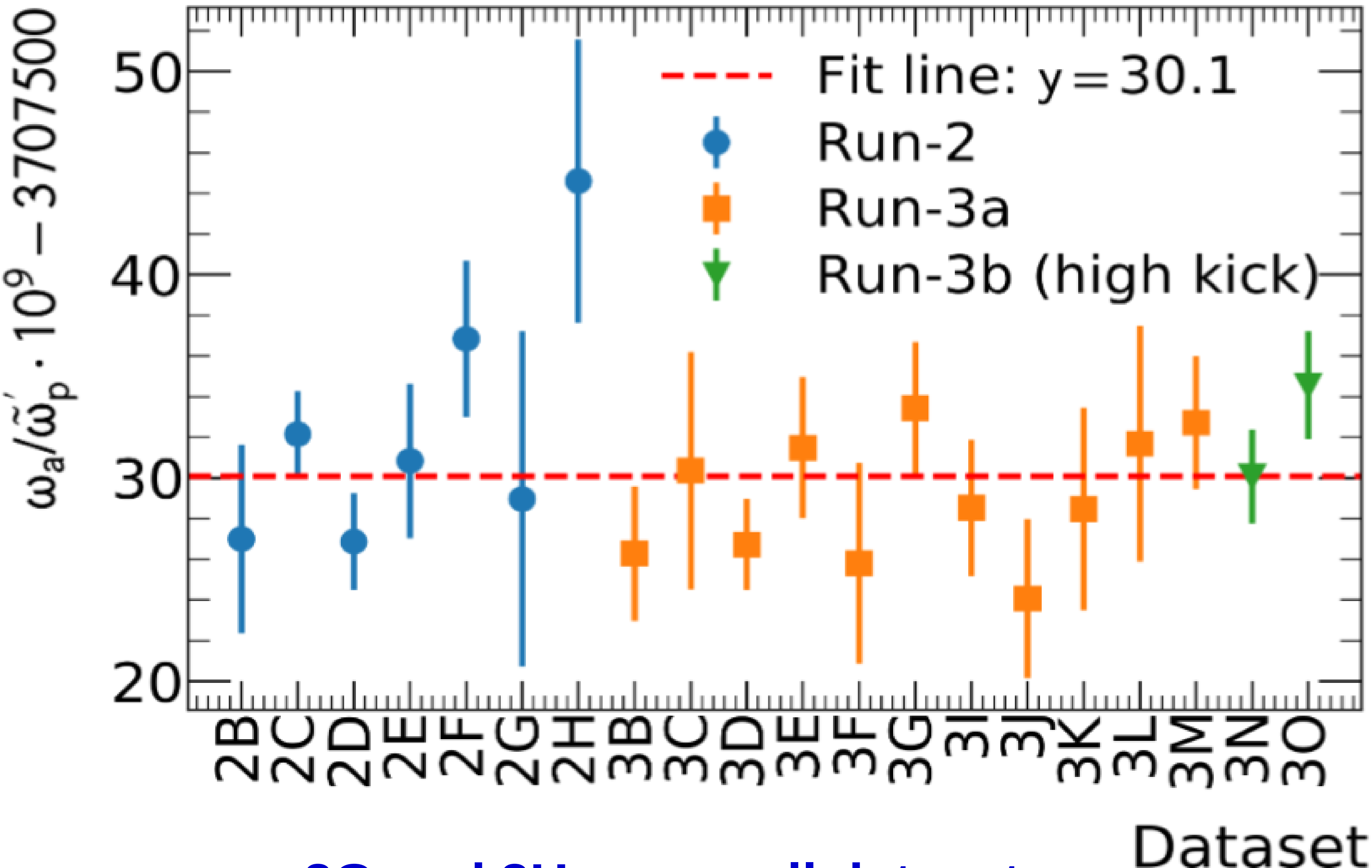
Sliced dataset 2

Perform sliced dataset analysis





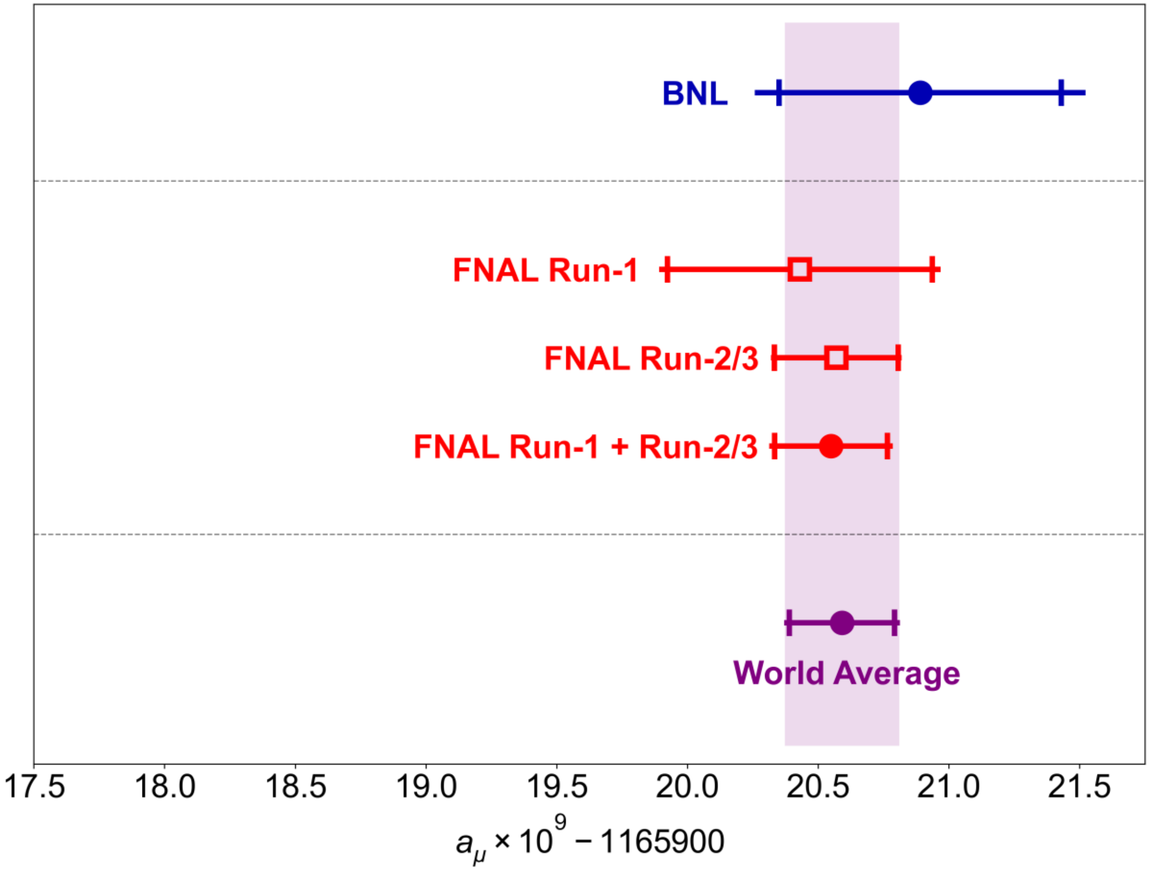
Data Consistency Check



- **2G and 2H are small datasets**

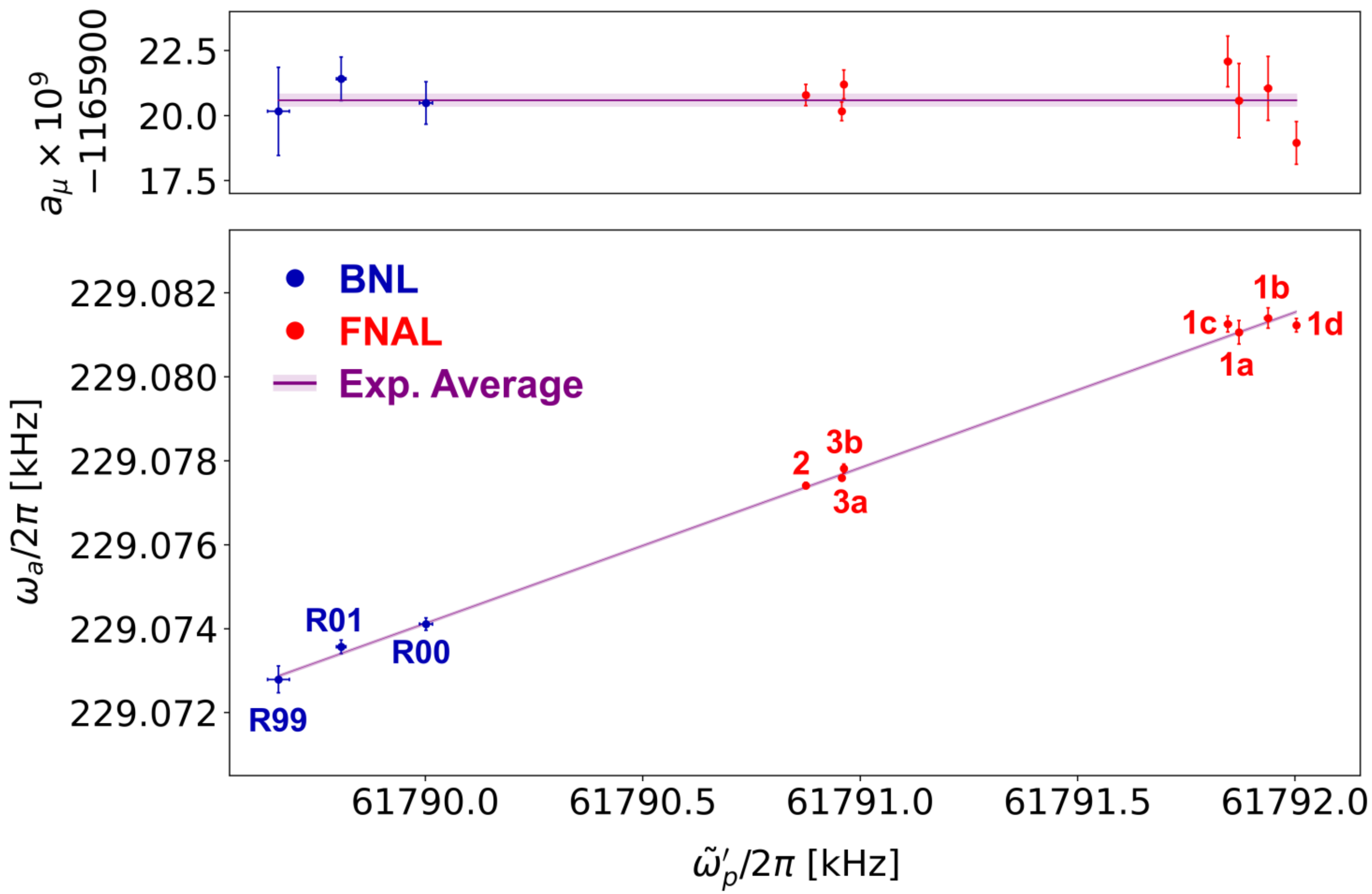
Run2/3 Result & New World Average

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



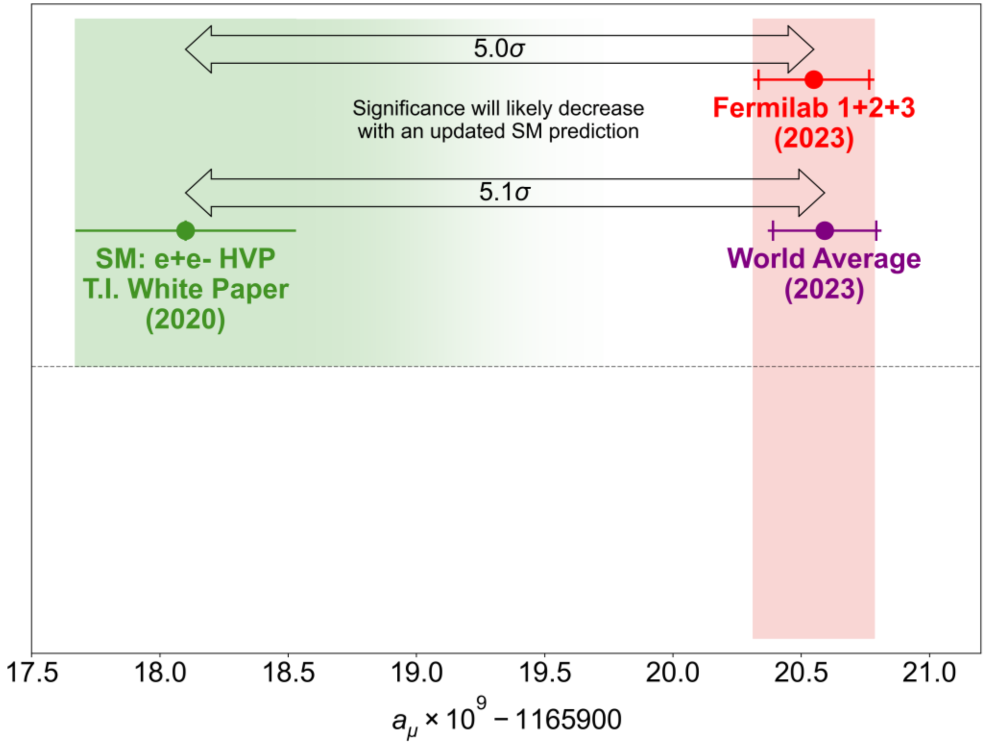
a_μ(Exp) = 0.00 116 592 059(22) [190 ppb]

Data Consistency Check



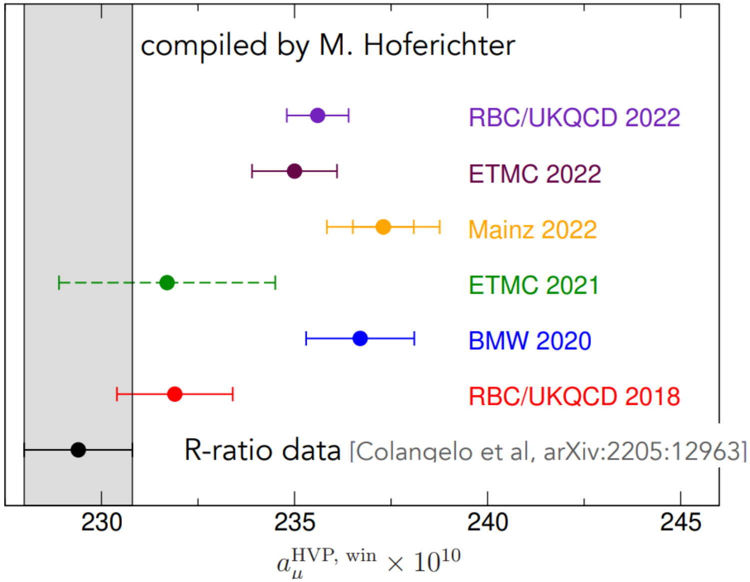
- Cross checked with BNL results as well
- Datasets taken with slightly different fields

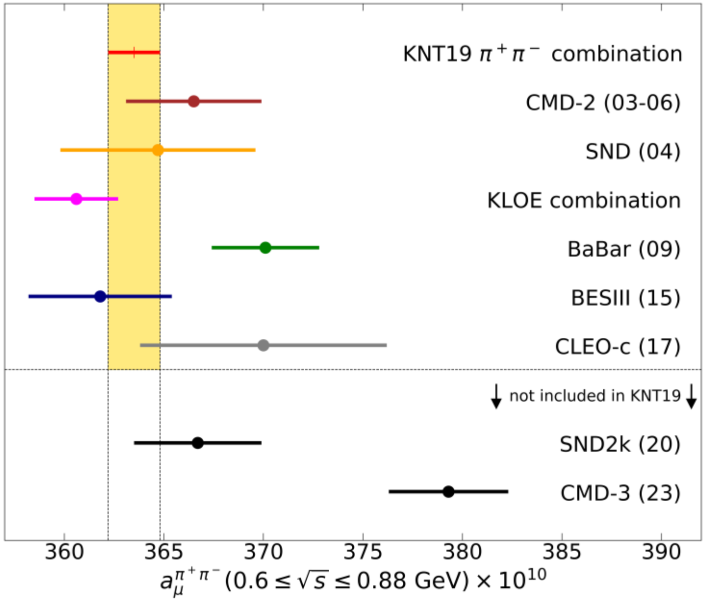
Experiment vs. Theory Saga



- **Large discrepancy between experiment results and theory calculations (WP) from 2020**
- **>5 sigma discovery?!**
- **New Physics?!**
- **But there are new developments …**

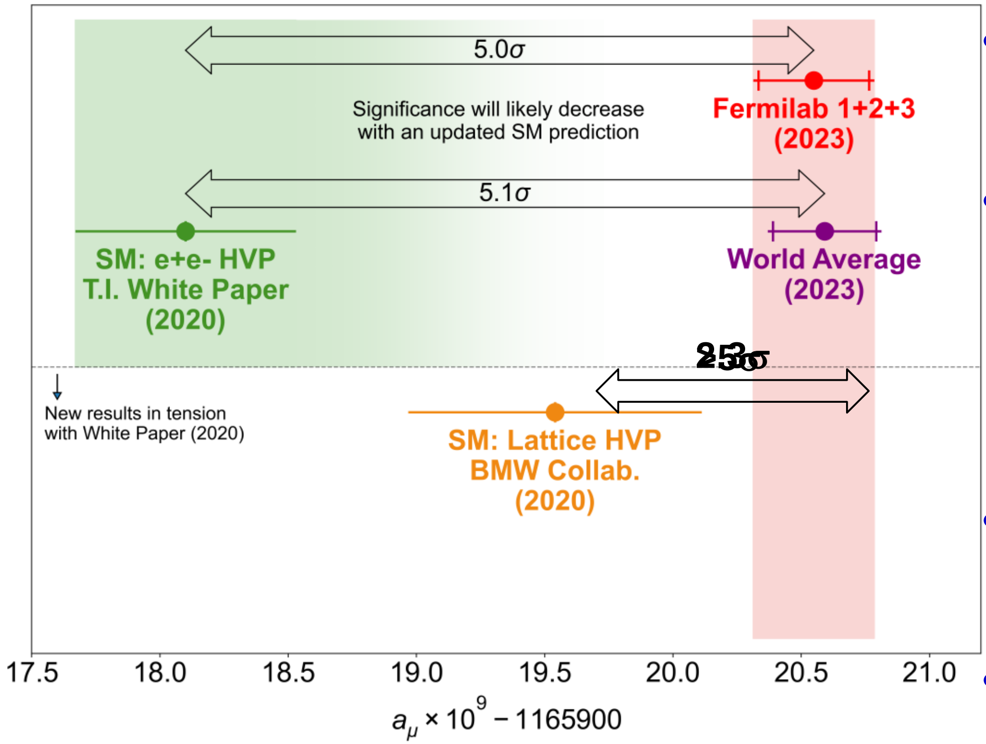
Hadronic Vacuum Polarization Update





- **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**
  - **Arxiv: 2308.05233 [SJTU contributions]**
  - **Possible explanation for tensions with other experiments**
- **MuonE: a_{μ_Had} from experiment!**

Experiment vs. Theory Saga



- **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 soon**
- **a_μ(Exp) Run1-6 uncertainty:**
  - **<120ppb 50% reduction**
- **a_μ(SM) 2025 uncertainty:**
  - **<120-150ppb? 50% reduction?**

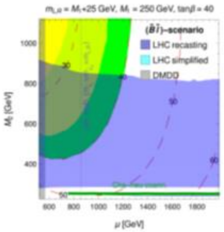
New Physics Explanation

Dominik Stöckinger, arxiv: 2104.03691

Which models can still accommodate large deviation?

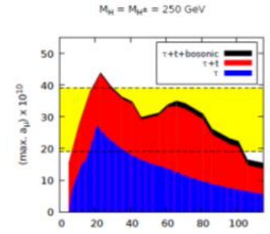
SUSY: MSSM, MRSSM

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



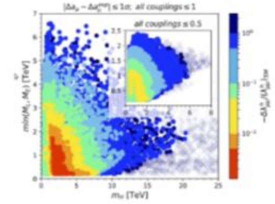
Two-Higgs doublet model

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



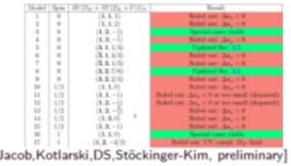
Lepto-quarks, vector-like leptons

- scenarios with muon-specific couplings to μ_L and μ_R



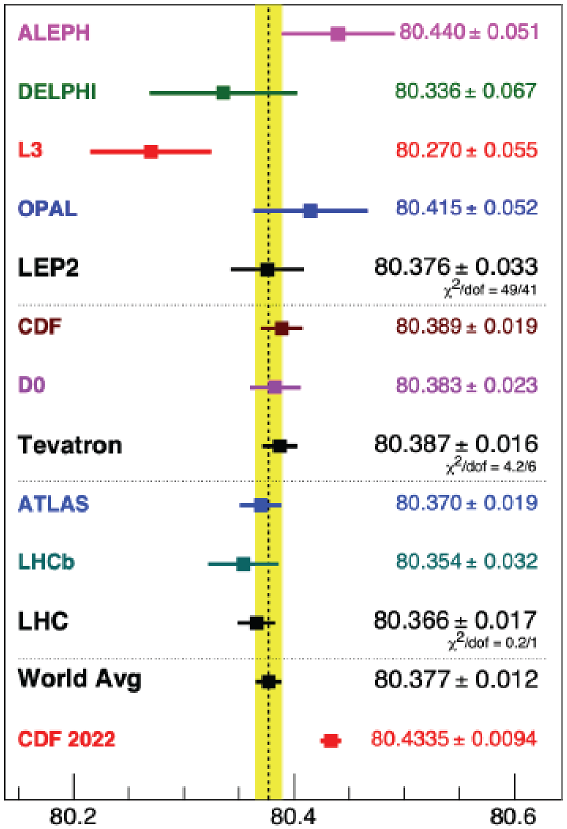
Simple models (one or two new fields)

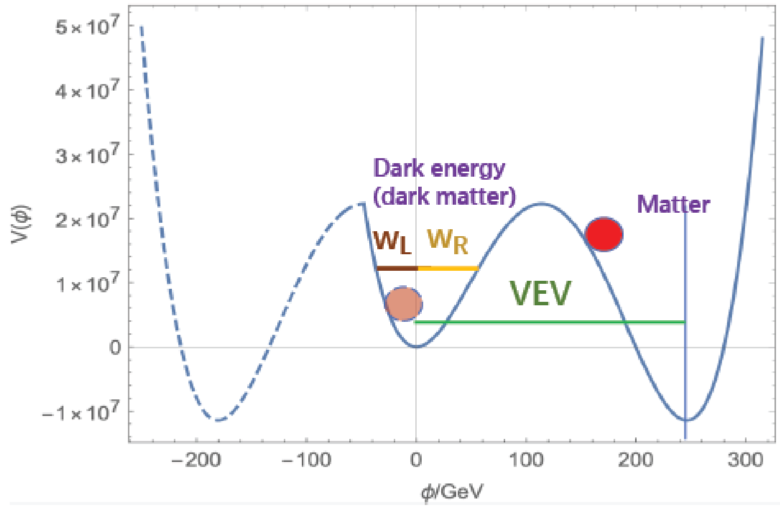
- Mostly excluded
- light N.P. (ALPs, Dark Photon, Light $L_\mu - L_\tau$)



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

Sensitive Test for New Physics Model





arxiv: 2308.16412

Y. Fang

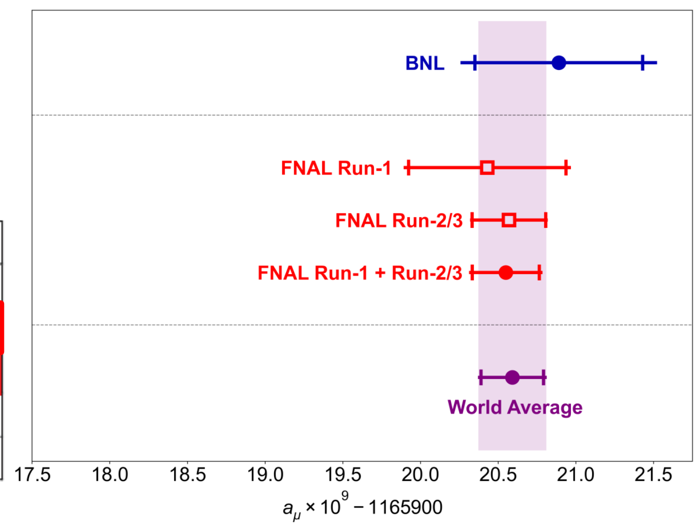
$$m = \alpha V$$

$$\frac{\Delta m}{m} = \frac{\Delta V}{V}$$

$$a_\mu^{\text{had,LO}} = \frac{m_\mu^2}{12\pi^3}\int_{s_{\text{th}}}^{\infty} ds\, \frac{1}{s}\hat{K}(s)\sigma_{\text{had}}(s)$$

$$a_\mu = \frac{g_e}{2}\frac{\omega_a}{\omega_p}\frac{m_\mu}{m_e}\frac{\mu_p}{\mu_e}$$

Particle	α	Δm/GeV	
		deviation	current uncertainty [9]
W	0.327	8.04×10^{-3}	1.2×10^{-2}
Z	0.371	9.12×10^{-3}	2.1×10^{-3}
H	0.509	1.25×10^{-2}	0.17
top	0.702	1.73×10^{-2}	0.30



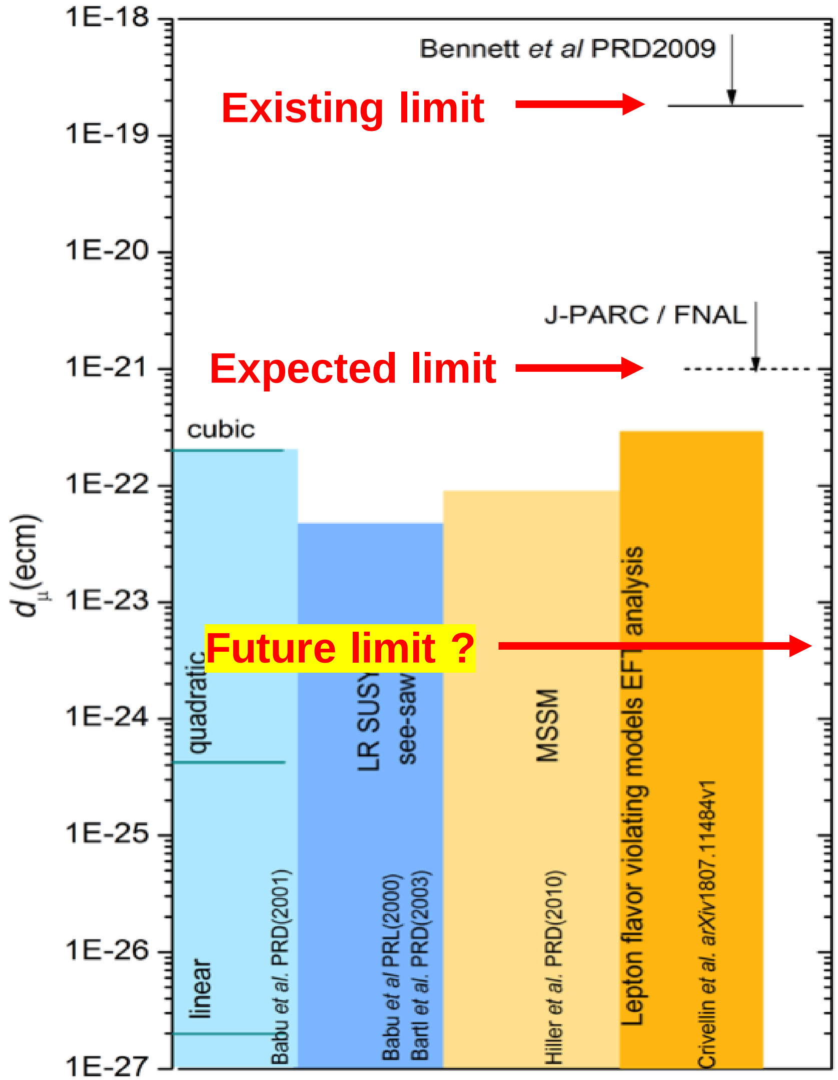
Theory:

Dilation effect on m_μ

Experiment:

Mass ratio $\frac{m_\mu}{m_e}$ cancels

Muon Electric Dipole Moment (EDM)

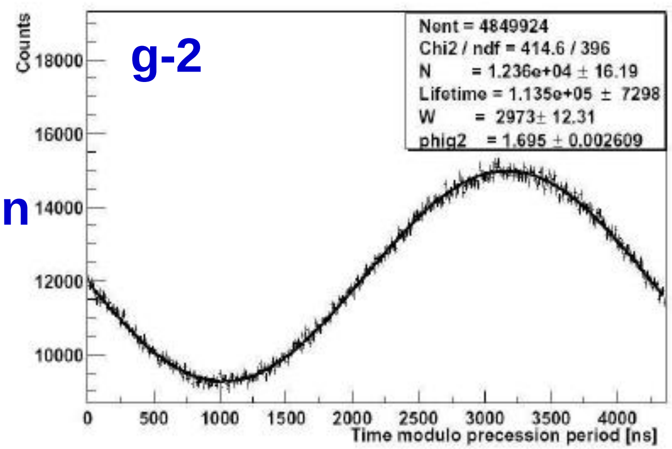


- **SM prediction for muon EDM is almost 0: $d_\mu < 10^{-38}$ e·cm**
- **Unambiguous new physics signal**
- **Muon is the best option**
  - **Direct measurement**
  - **Free of nuclear / molecular effects**
- **Note that $d_e \sim 10^{-29}$ e·cm**
  - **Current best result $d_\mu \sim 10^{-18}$ e·cm**
  - **10^3-10^4 improvement expected**
  - **Still need BSM effect >> $(m_\mu/m_e)^2$**
- **Big discovery potential**

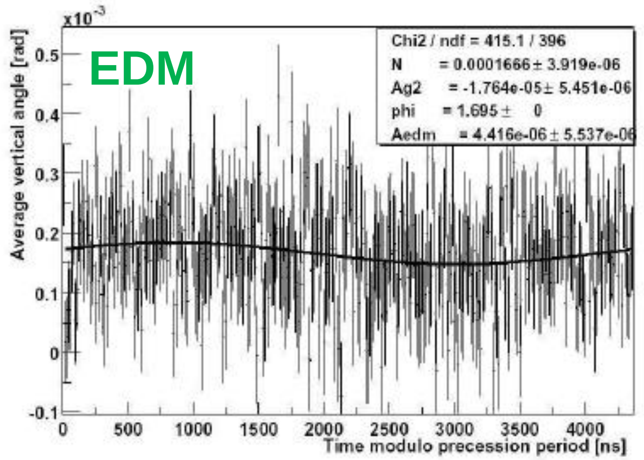
Muon Electric Dipole Moment (EDM)

BNL μ_{EDM} search was done with tracker data

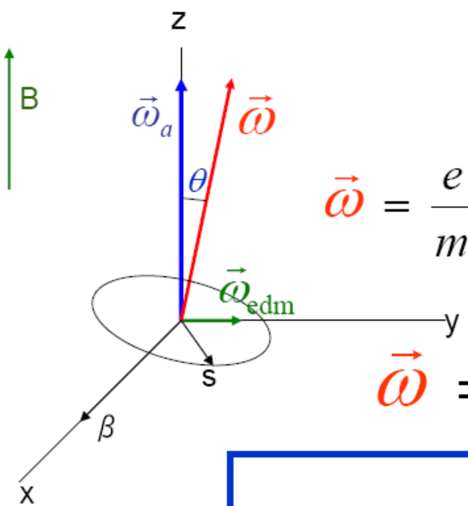
- ✓ **Improved further when combing calo data**



 # Tracks vs (time % T_a)



Average vertical angle vs (time % T_a)



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

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

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

Tracker:

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

Tracker & Calo:

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

Statistically limited search

- ✓ **Expect to reach 10^{-21} e·cm soon**

CPT and Lorentz Invariance Violation

Standard Model Extension (SME) Allows for CPT/LV

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

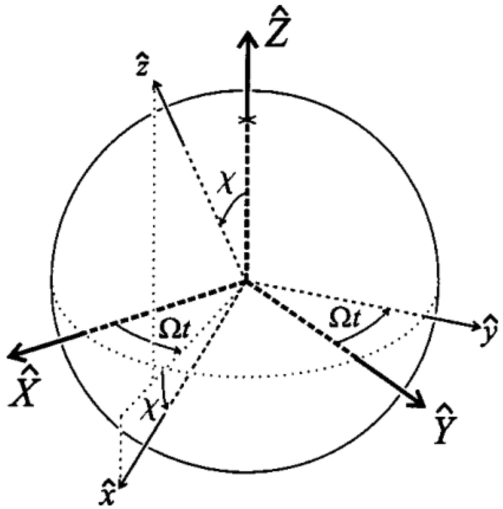
$$L' = -a_\kappa \bar{\psi}\gamma^\kappa\psi - b_\kappa\bar{\psi}\gamma_5\gamma^\kappa\psi - \tfrac{1}{2}H_{\kappa\lambda}\bar{\psi}\sigma^{\kappa\lambda}\psi + \tfrac{1}{2}ic_{\kappa\lambda}\bar{\psi}\gamma^\kappa \overleftrightarrow{D}^\lambda\psi + \tfrac{1}{2}id_{\kappa\lambda}\bar{\psi}\gamma_5\gamma^\kappa\overleftrightarrow{D}^\lambda\psi,$$

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

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

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

- **Sidereal oscillation in $\mathcal{R} = \omega_a/\tilde{\omega}_p'$**
  - ω_a is 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 < ~10^{-24} GeV
  - Dimensionless FOM < ~10^{-23}
- **Improvement from FNL g-2 coming soon**



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

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**
  - ✓ **>5σ discovery potential**
- ✓ **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 physics 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

China

- Shanghai Jiao Tong

Germany

- Dresden

Italy

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

Korea

- CAPP/ISB
- KAIST

Russia

- Budker/Novosibirsk
- JINR Dubna

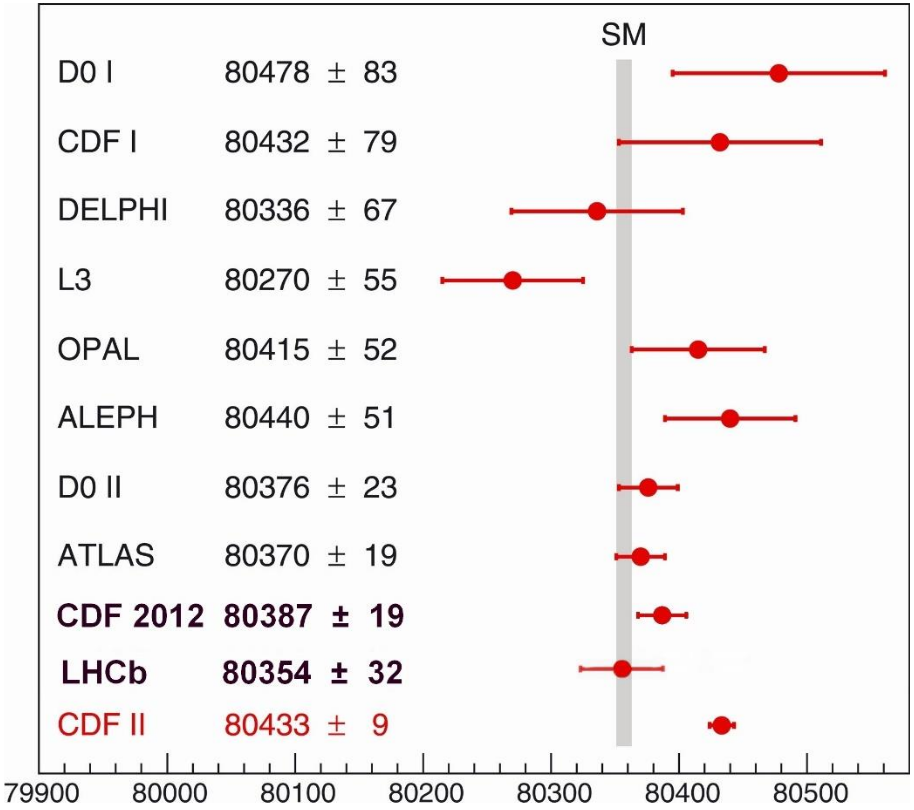
United Kingdom

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

181 collaborators
33 Institutions
7 countries

Muon g-2 Collaboration Meeting @ Elba
May 2019

What about W Mass?



$$\Delta\alpha_{\text{had}}^{(5)}(q^2) = \frac{q^2}{4\pi\alpha^2}\int_{m_\pi}^{\infty} ds\ \sigma_{\text{had}}(s)\frac{q^2}{(q^2-s)}$$

Global EW fits: predict M_W, M_H,…

$$a_\mu^{\text{had, VP}} = \frac{1}{4\pi^3}\int_{m_\pi}^{\infty} ds\ \sigma_{\text{had}}(s)\,K(s)$$

A. Keshavarzi:

The new CDF M_W measurement makes the situation worse:

- It pushes $\Delta\alpha_{had}^{(5)}(M_Z^2)$ even further away from FNAL g-2 and lattice HVP.
- From EW fit predictions, it results in 4.9σ discrepancy for $\Delta\alpha_{had}^{(5)}(M_Z^2)$, 9.5σ discrepancy for M_H.
- There is no scenario that accommodate Muon g-2 discrepancy and CDF CDF M_W.