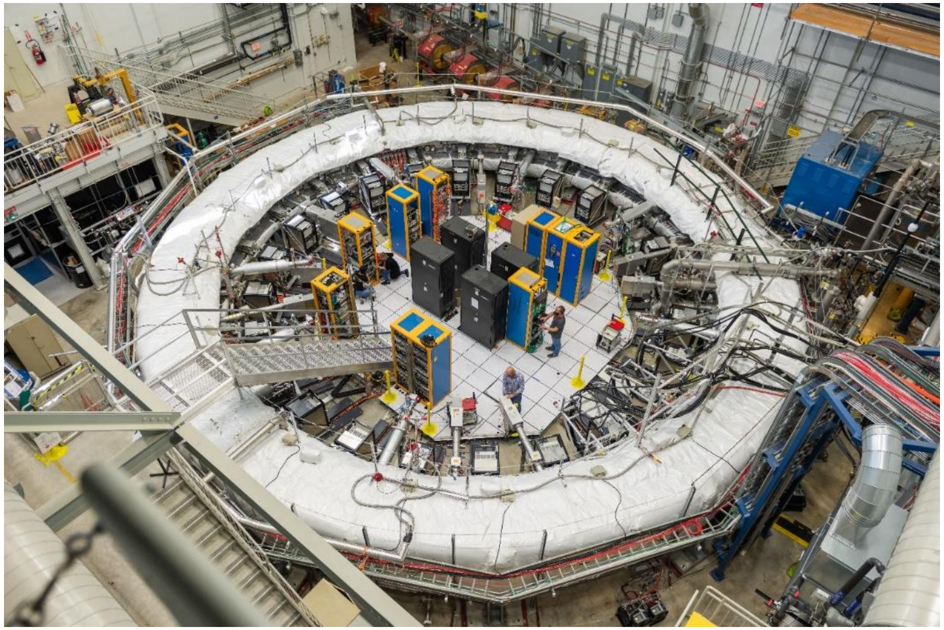
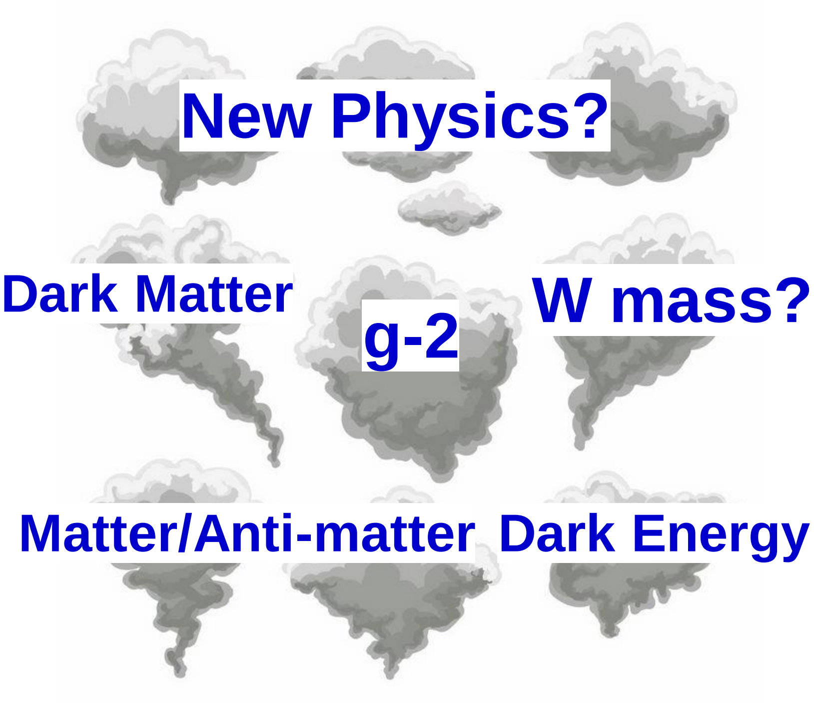
Workshop on Multi-front Exotic phenomena in Particle and Astrophysics (MEPA 2023)

New Physics Potential from Muon g-2 Experiment at Fermilab





New Physics?

Dark Matter

g-2

W mass?

Matter/Anti-matter

Dark Energy

Liang Li

Shanghai Jiao Tong University

Experimental Principle

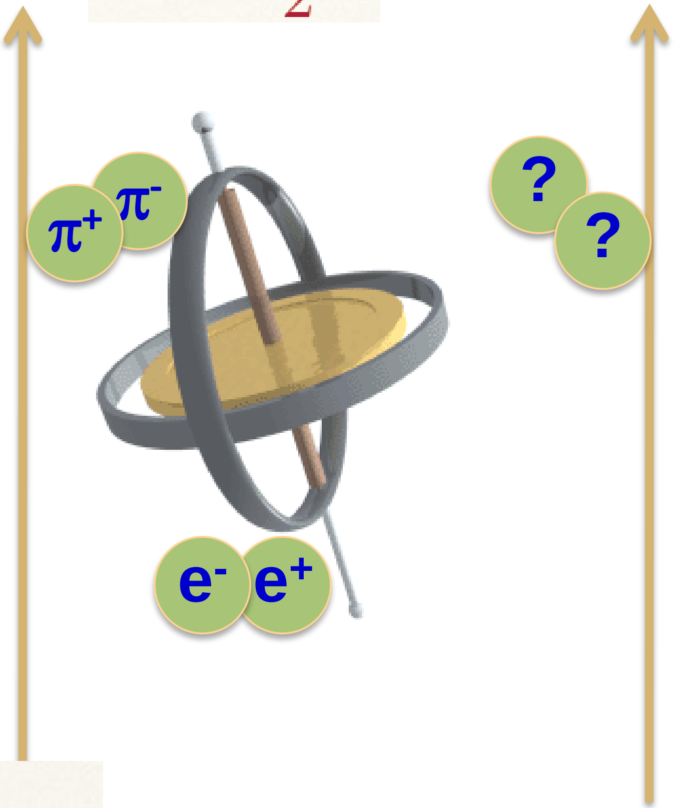
The name of game: measure frequency

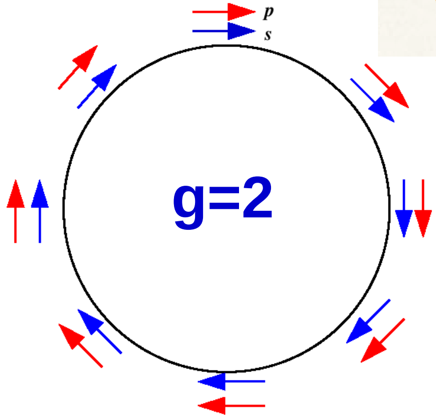
- **Put (polarized) muons in a magnetic field and measure precession f.q.**
- **Get muon spin direction from decayed electrons**
- **a_μ ~ difference between precession frequency and cyclotron frequency**

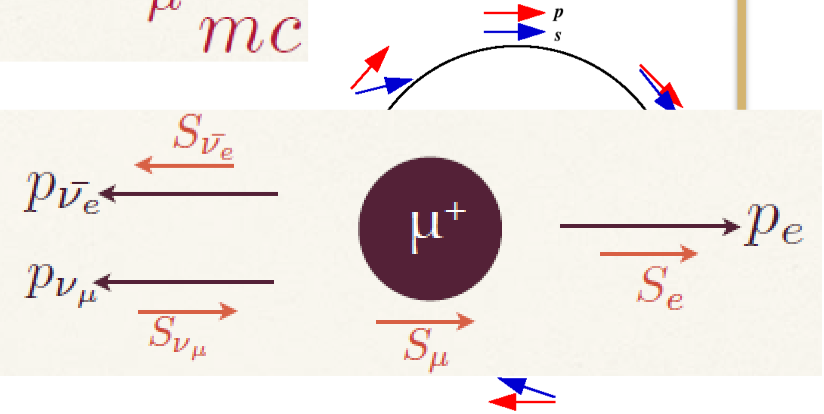
$$\omega_a = \omega_s - \omega_c$$

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

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







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

Frequency Measurements

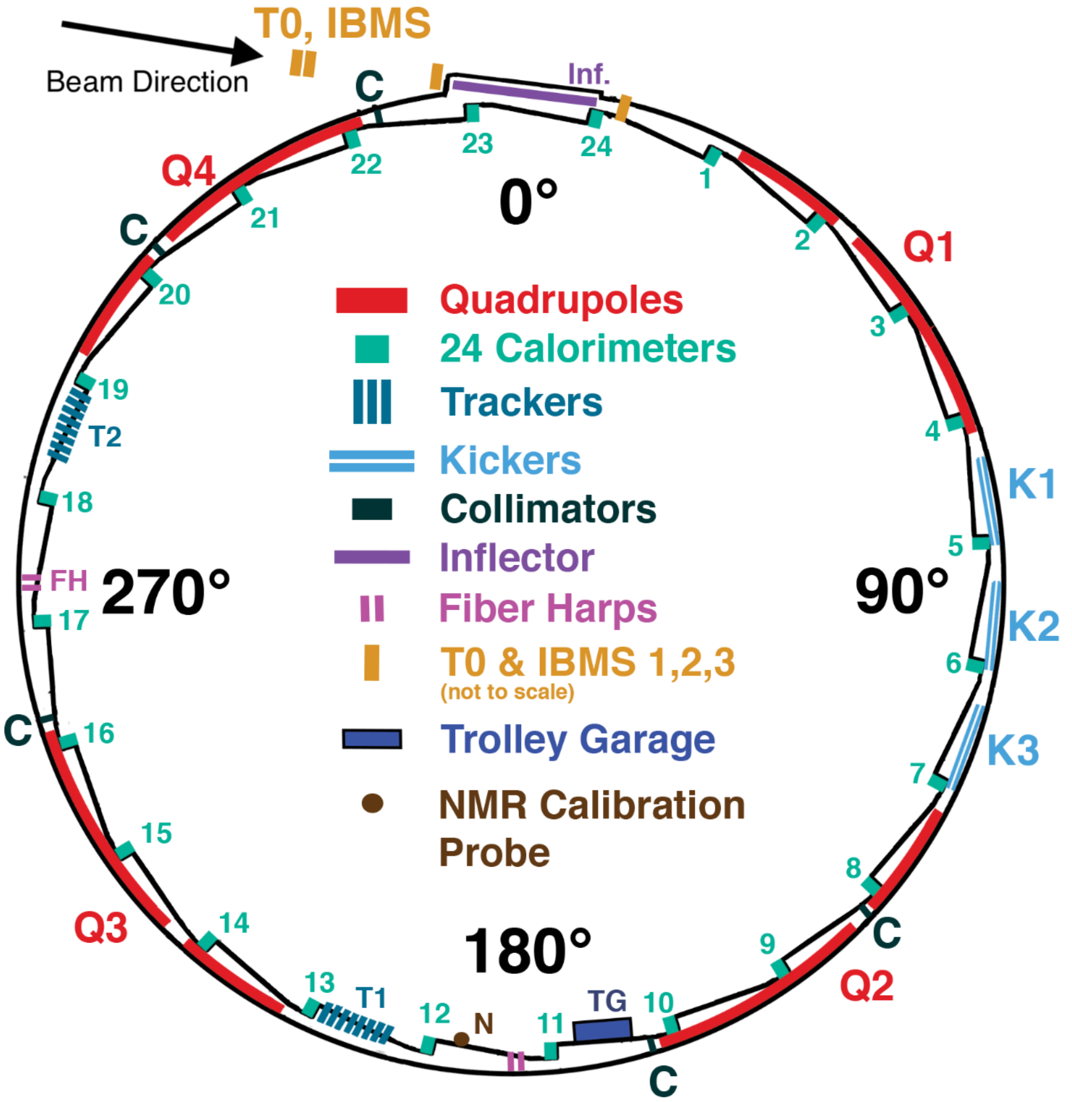
Frequency measurements can be done in very high precision

- **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 the proton precession frequency (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**

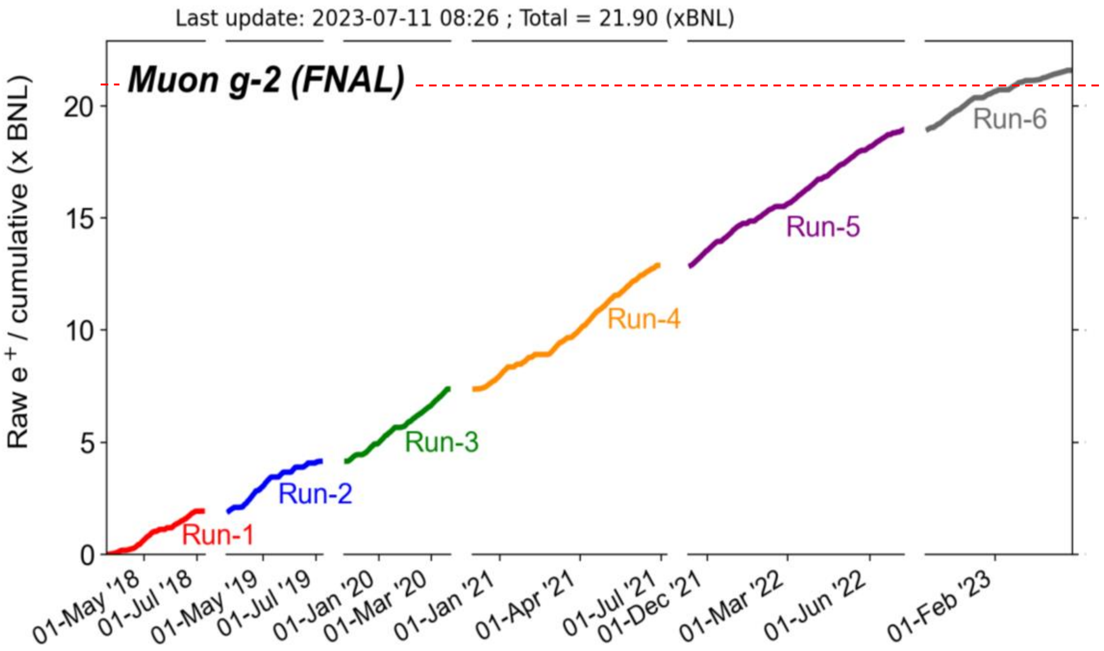
Detector System



- 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

Collecting data from all detector components

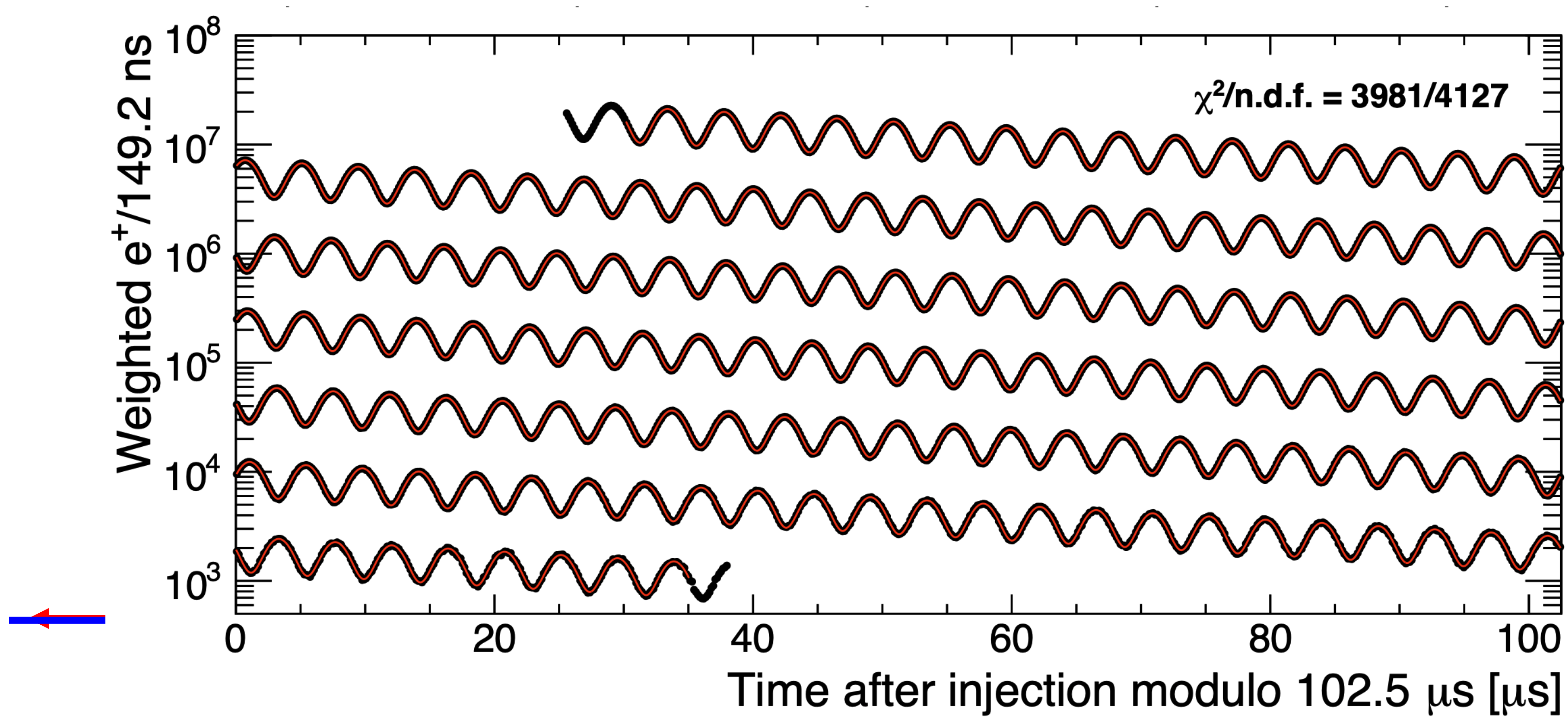
Data Collection



PROPOSAL GOAL:
21 x BNL statistics

- ✓ **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**

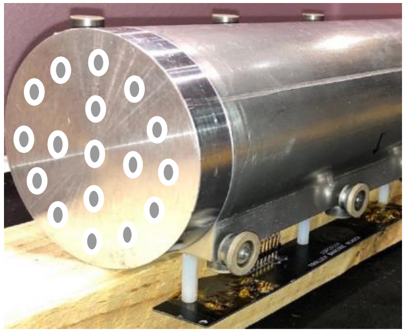
ω_a Measurement



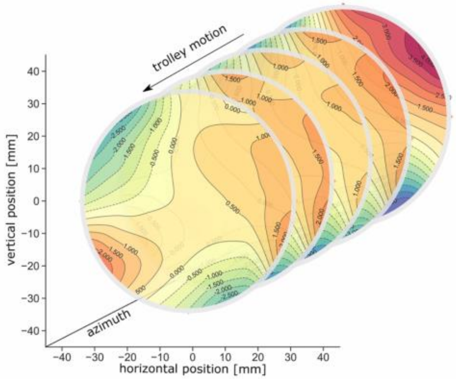
- **Energetic e+ oscillates as μ+ spin direction aligns or anti-aligns with momentum direction**
- **Count e+ hitting calos above threshold (or weight the hits)**
- **Extract the oscillation frequency ω_a via fitting time spectrum**

ω_p Measurement

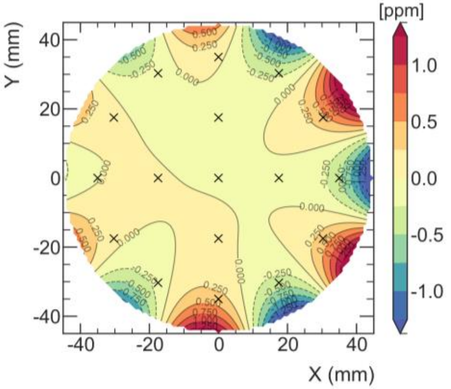
- In-vacuum NMR trolley maps field every few days



17 petroleum jelly NMR probes

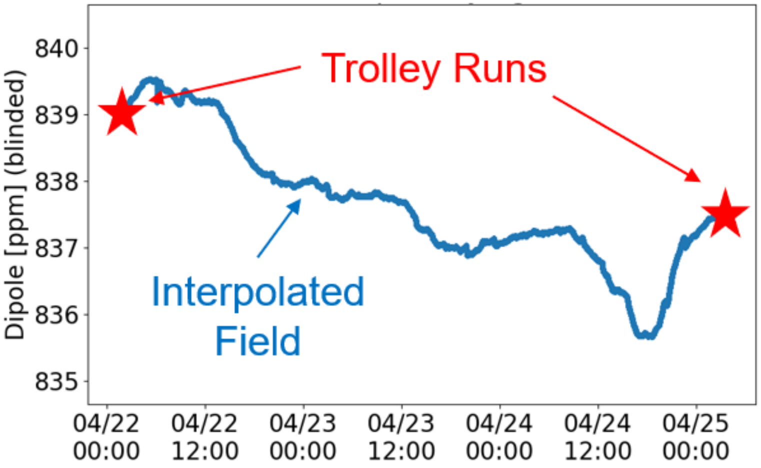


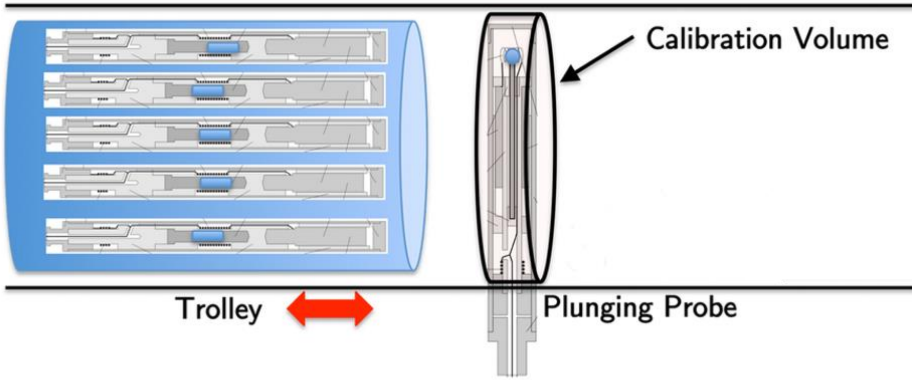
2D field maps (~8000 points)



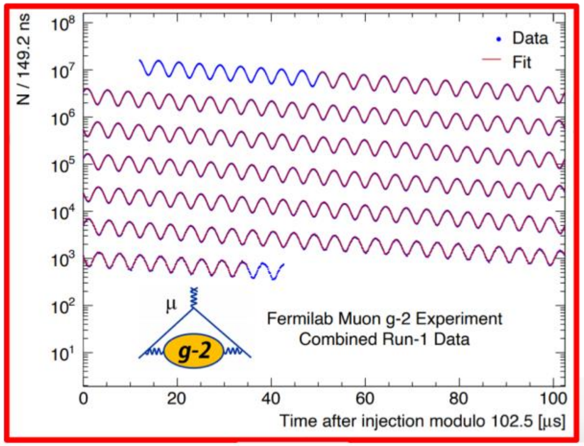
Azimuthally-Averaged Variation < 1 ppm

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

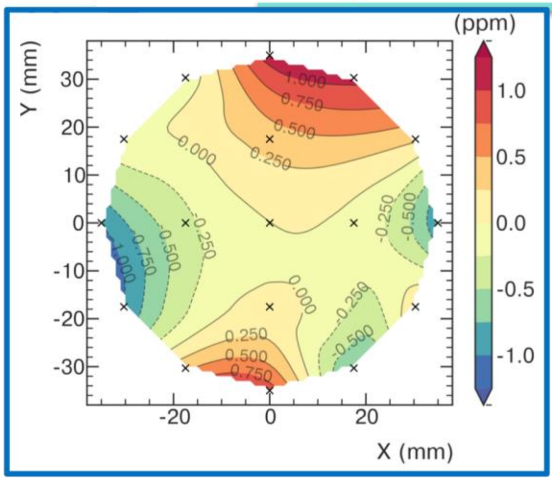




Full Measurement with Corrections



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



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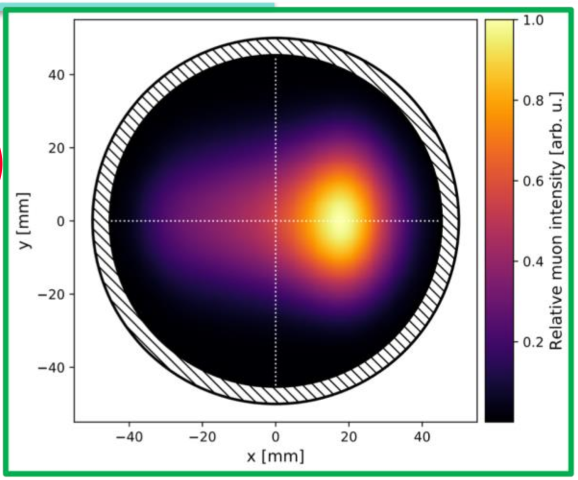
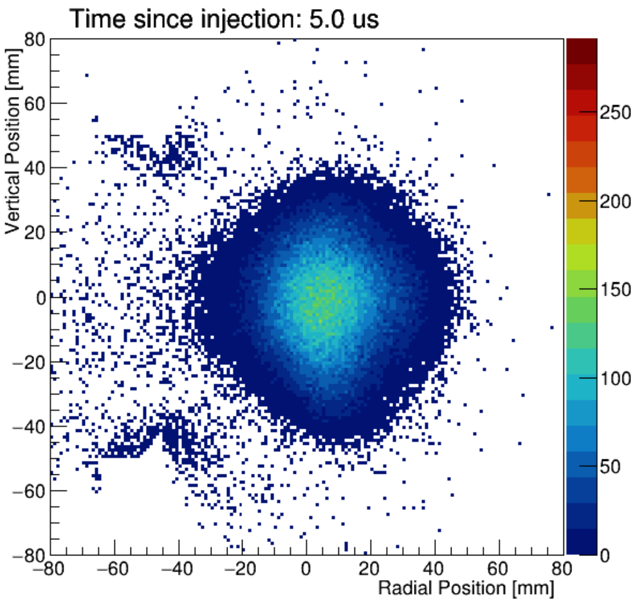
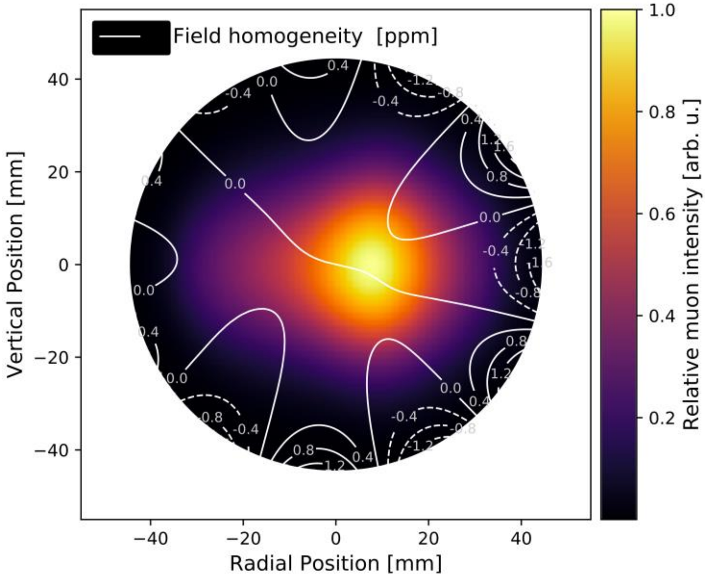


Muon Distribution Measurement





- 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

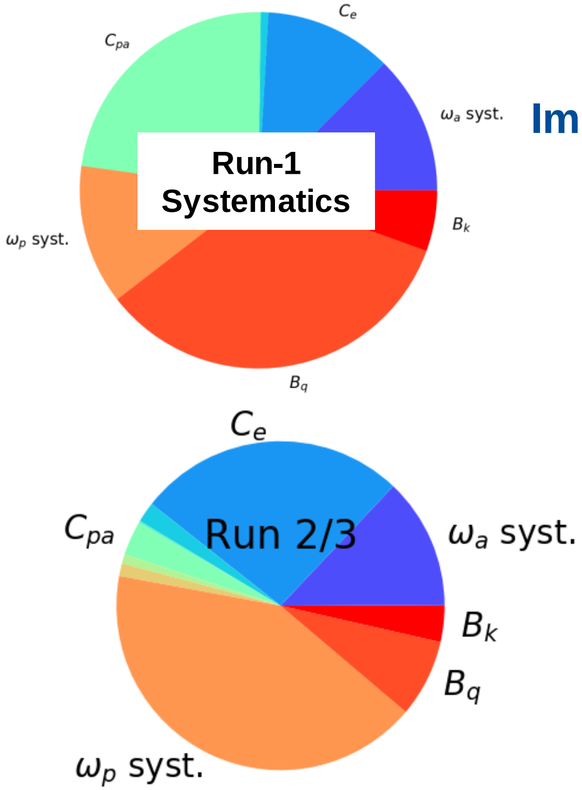
$$\frac{\omega_a}{\omega_p} = \frac{\omega_a^m}{\omega_p^m}\,\frac{1+\overbrace{C_e+C_p}+\overbrace{C_{pa}+C_{dd}+C_{ml}}}{1+\underbrace{B_k+B_q}}$$

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?**

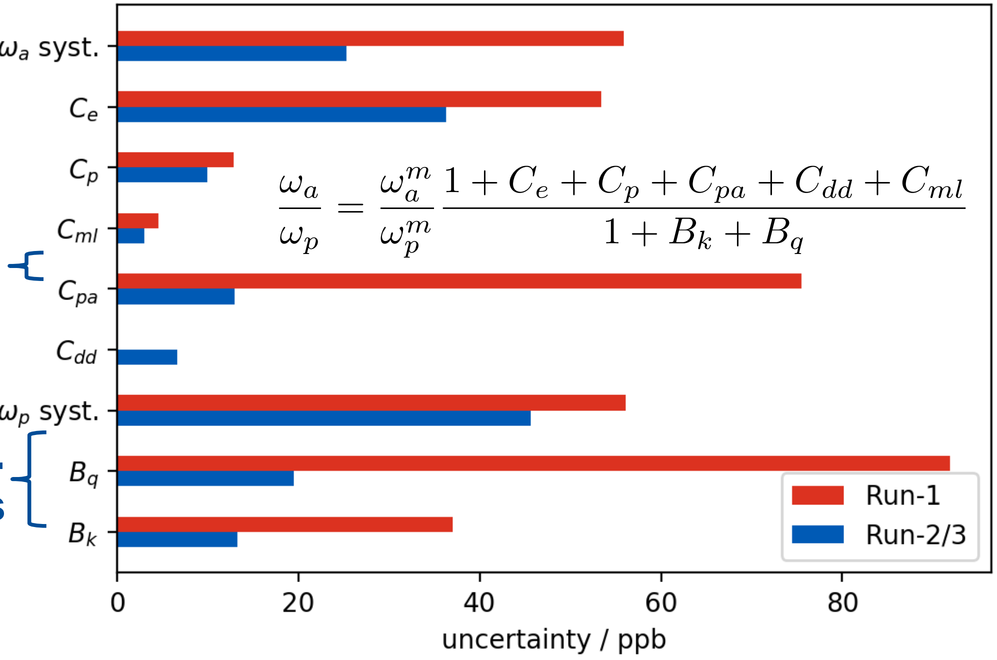
Improving Systematic Uncertainties



Analysis Improvements

Running Conditions

Improved Sys. Measurements

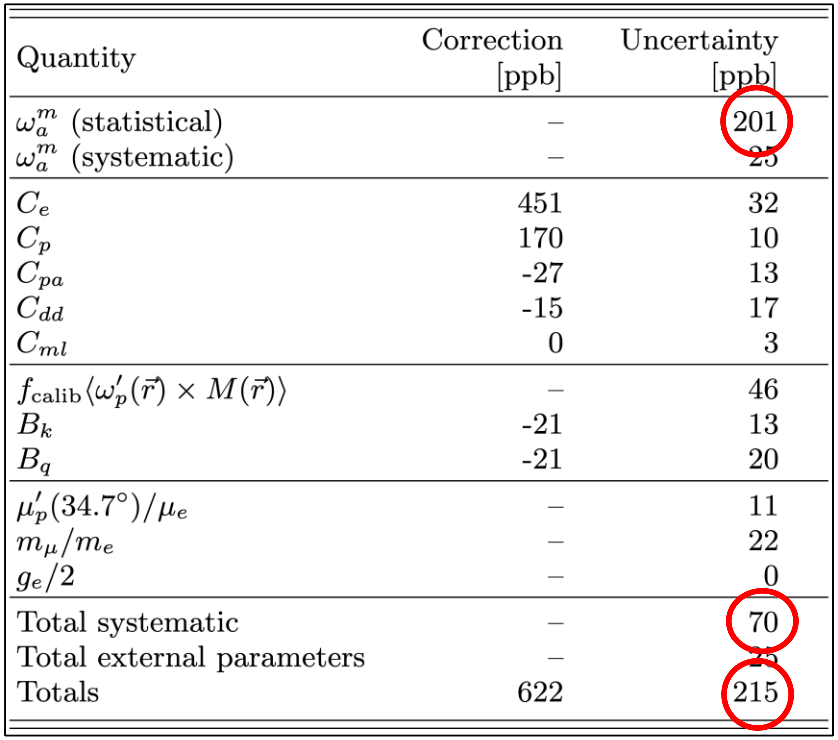


$$\frac{\omega_a}{\omega_p} = \frac{\omega_a^m}{\omega_p^m} \frac{1 + C_e + C_p + C_{pa} + C_{dd} + C_{ml}}{1 + B_k + B_q}$$

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
$\mu'_p(34.7°)/\mu_e$	–	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

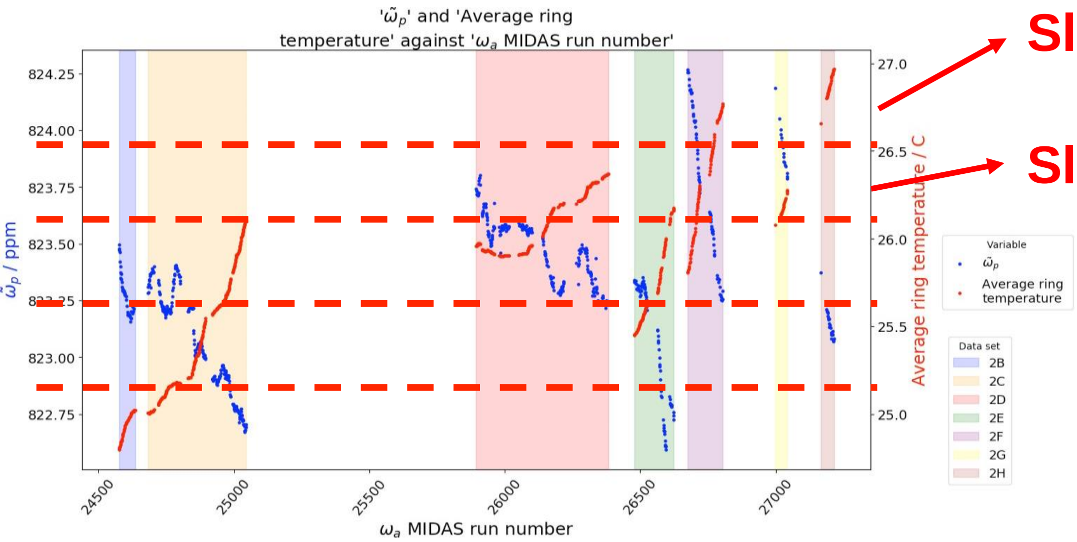
- **Near-equal improvement**
- **Still statistically dominated**

- **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…**

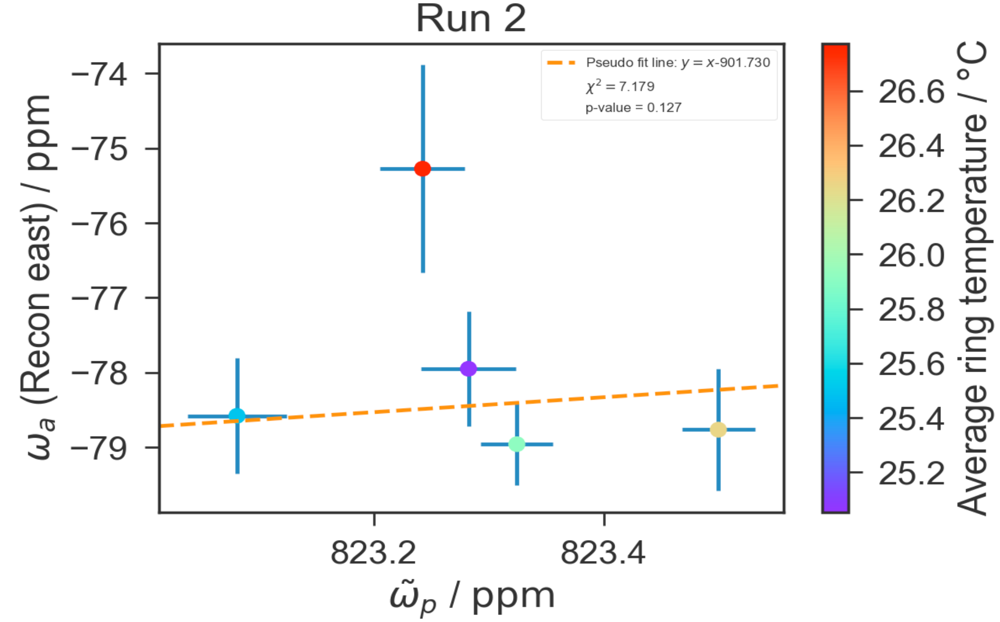
Data Consistency Check

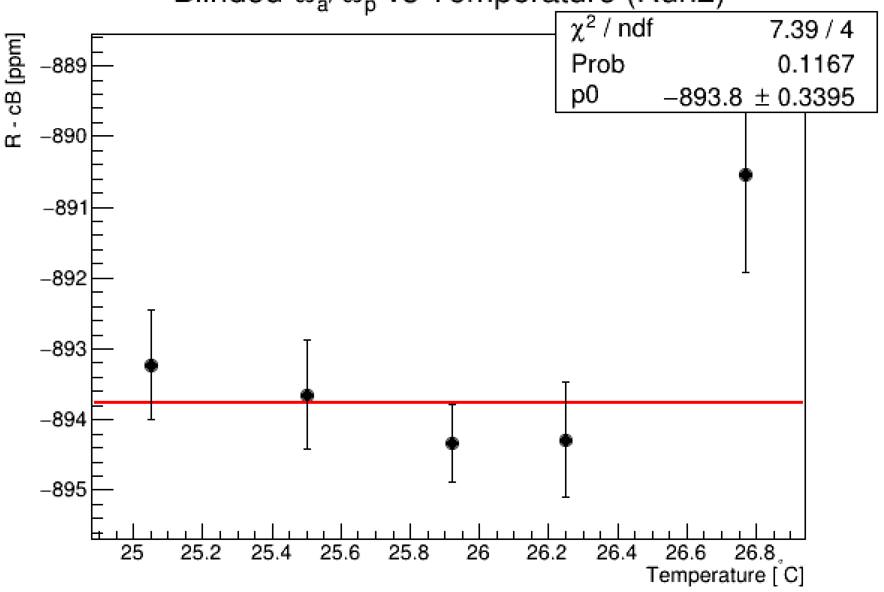


Sliced dataset 1

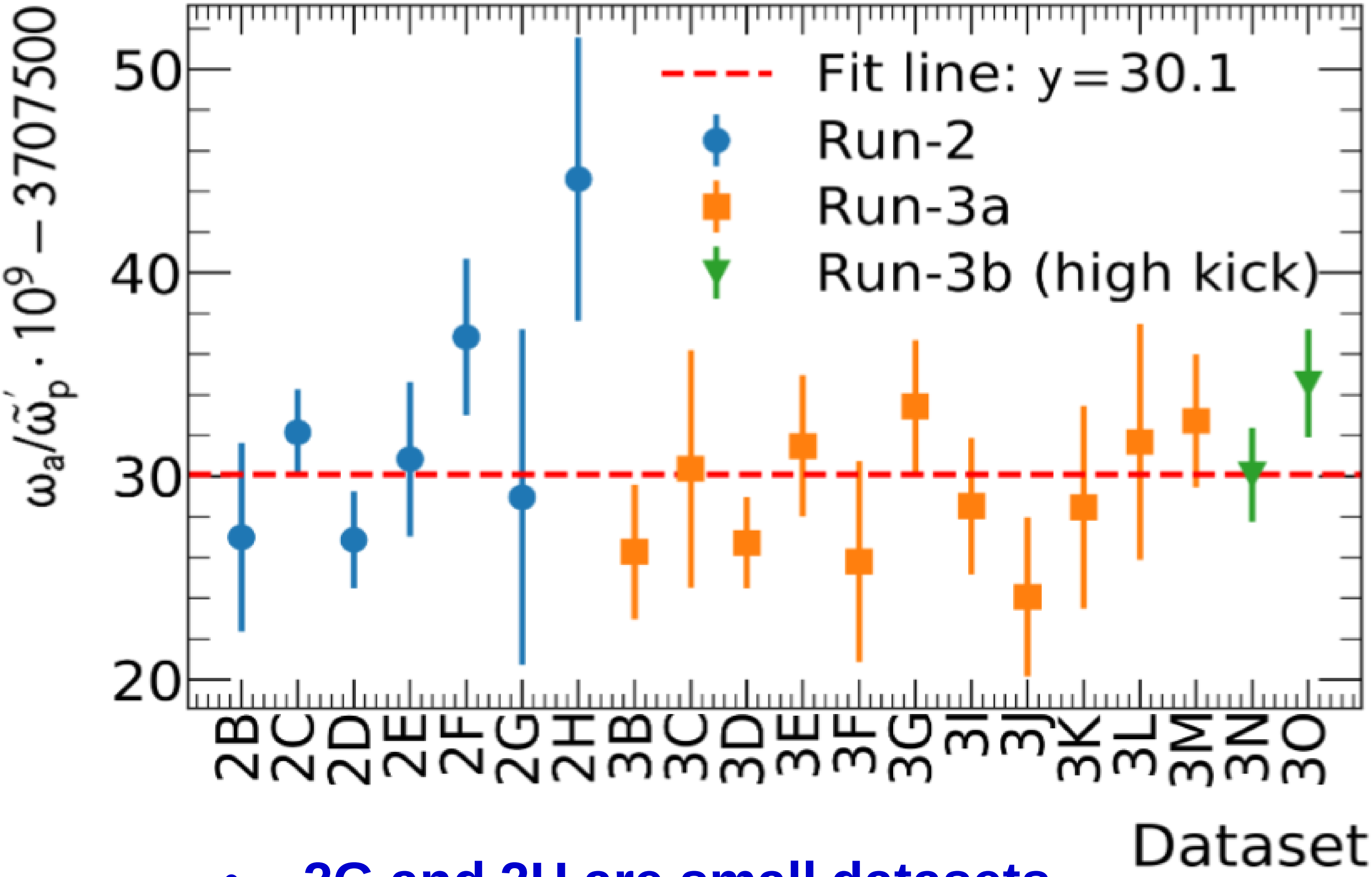
Sliced dataset 2

Perform sliced dataset analysis





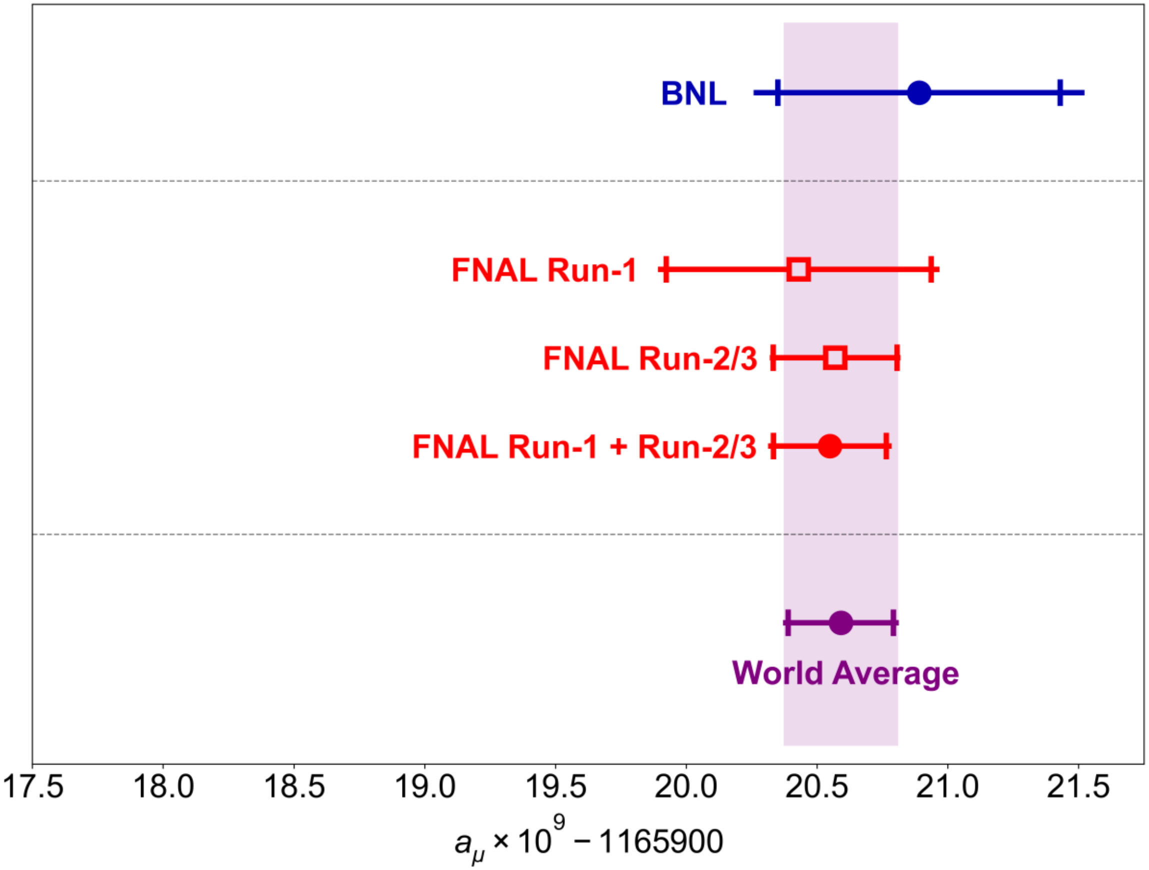
Data Consistency Check



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

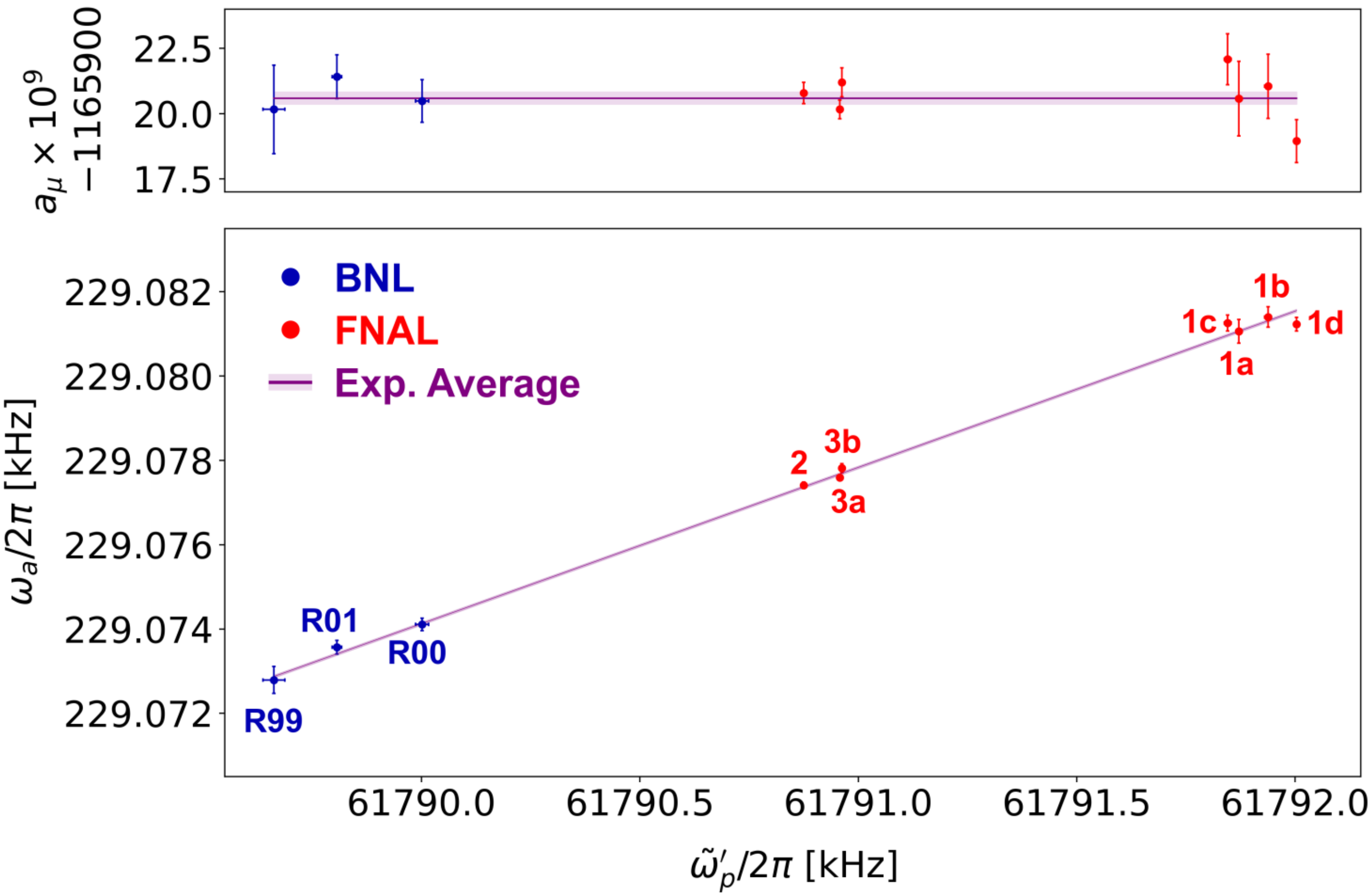
Run2/3 Result & New World Average

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



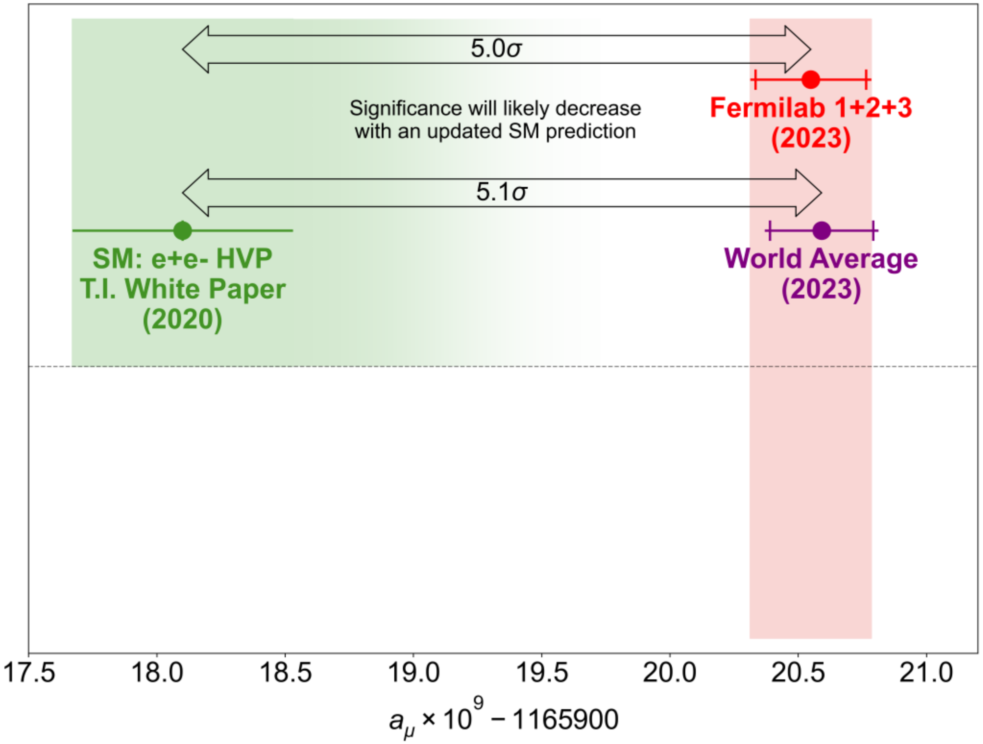
a_μ(Exp) = 0.00 116 592 059(22) [190 ppb]

Data Consistency Check



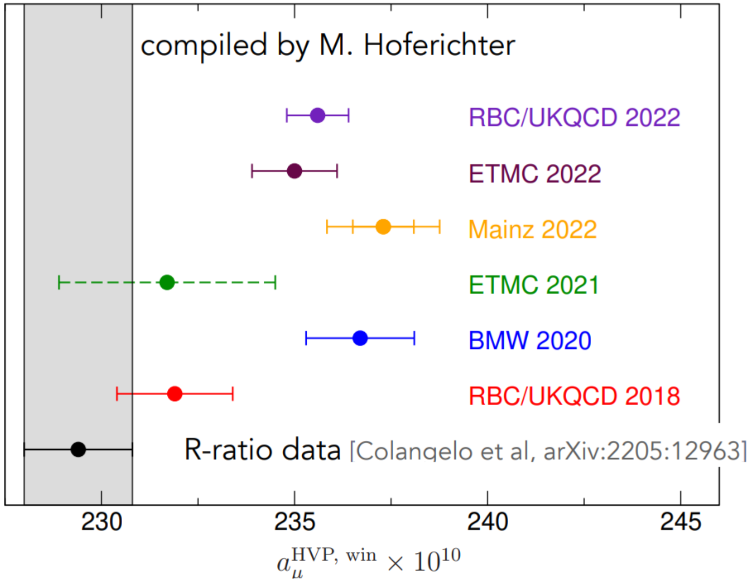
- **Cross checked with BNL results as well**
- **Datasets taken with slightly different fields**

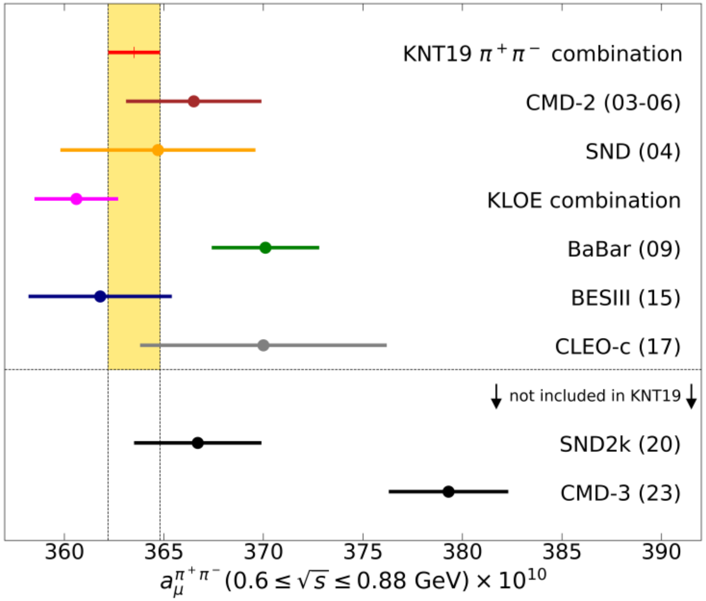
Experiment vs. Theory Saga



- 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



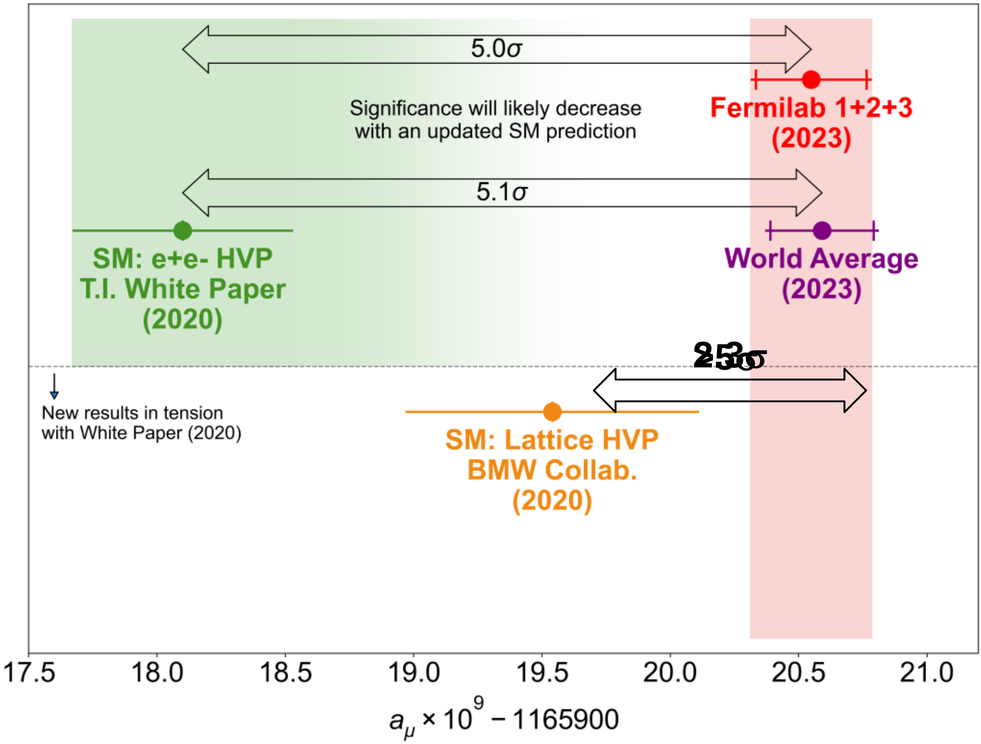


- **LQCD Intermediate window: BMW 2020 claimed 0.8% precision, closer to experimental value but 2.1σ with data-driven HVP**
- **Need full LQCD HVP calculations for all windows**

- **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!**

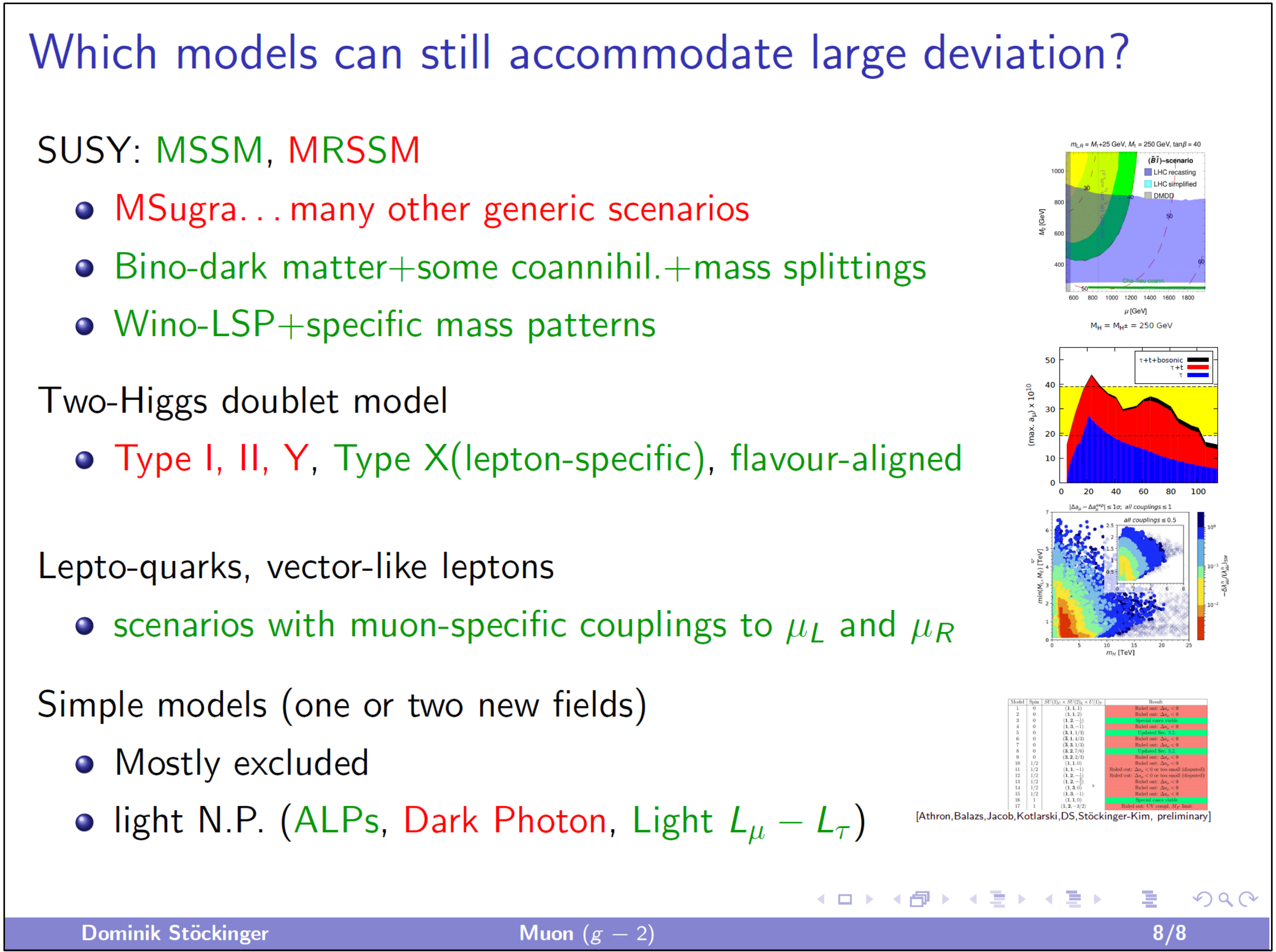
Experiment vs. Theory Saga



- **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

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

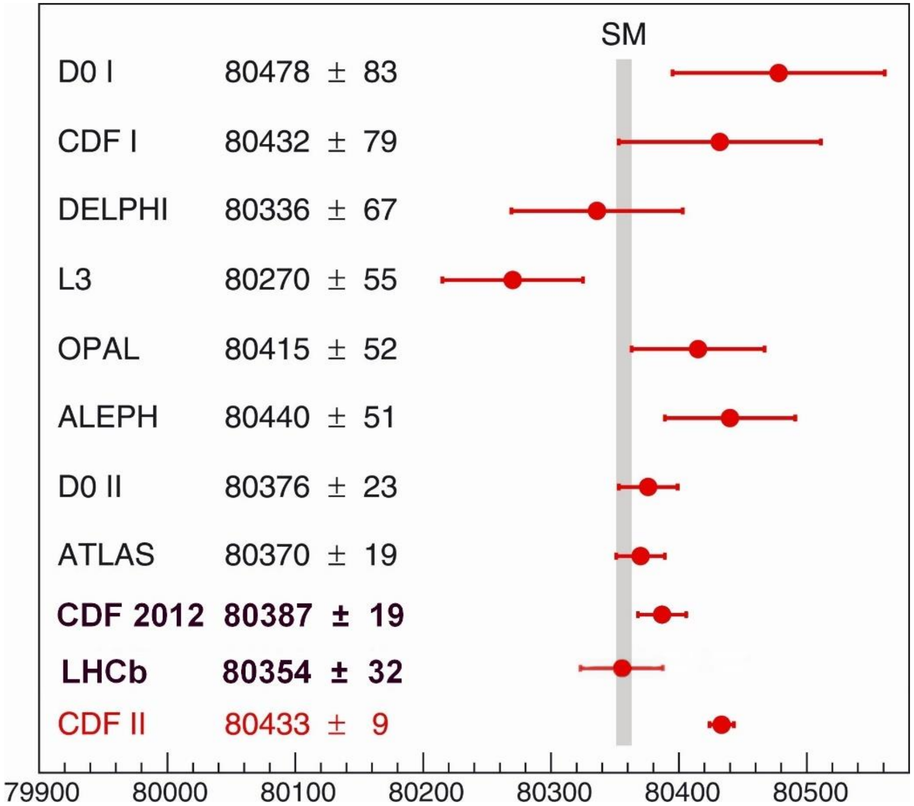
Simple models (one or two new fields)

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

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

Dominik Stöckinger Muon $(g-2)$ 8/8

What about W Mass?



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

Global EW fits: predict M_W, M_H,…

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

From A. Keshavarzi:

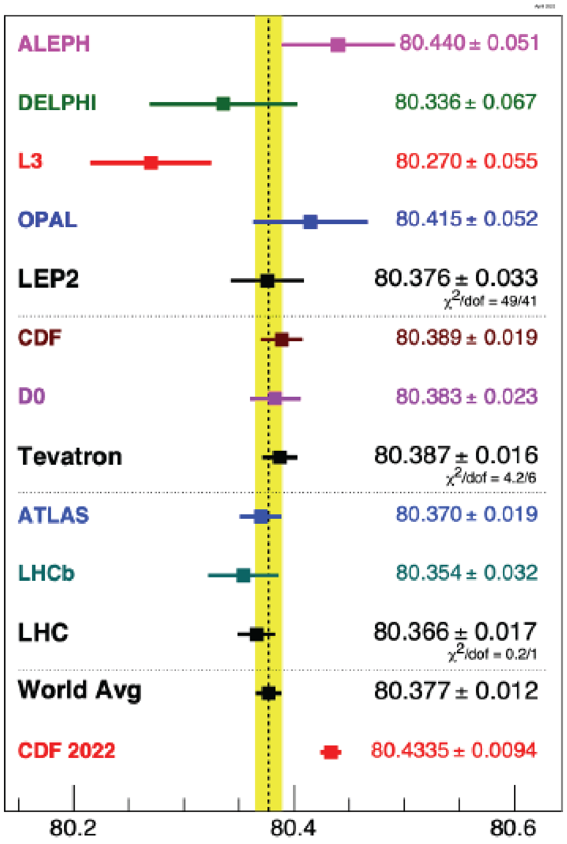
The new CDF M_W measurement makes the situation worse:

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

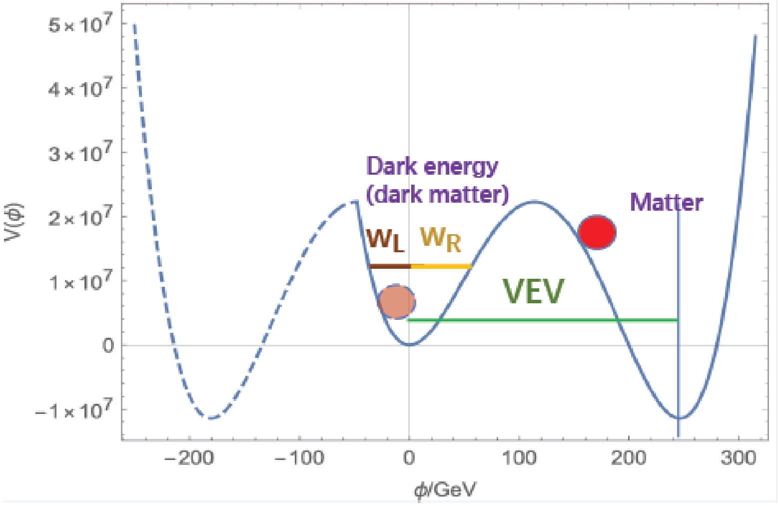
Sensitive Test for New Physics Model

Arxiv: 2308.16412

Y. Fang



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

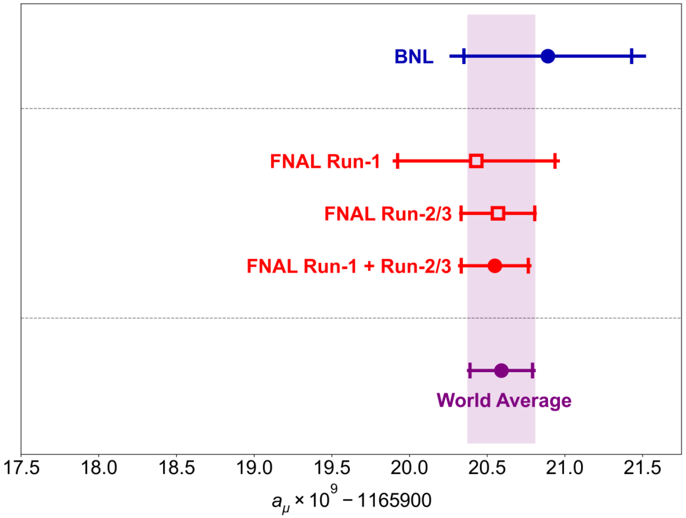


$$m = \alpha V$$

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

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

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



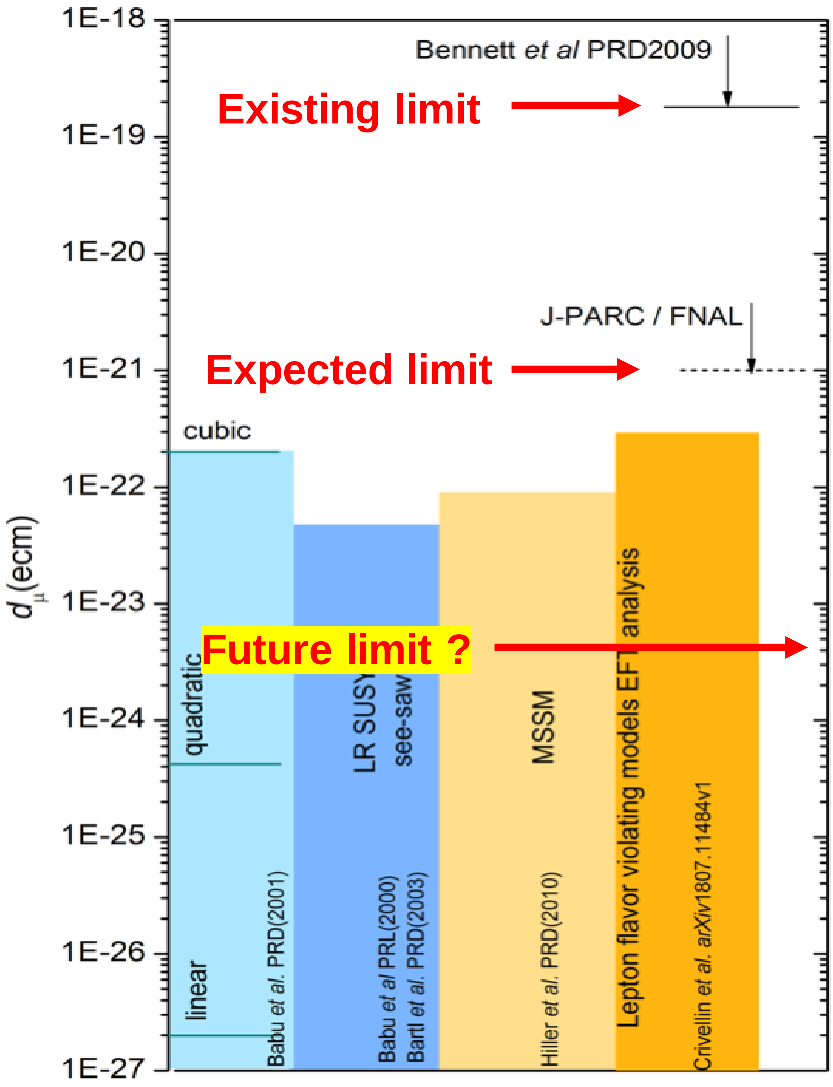
Theory:

Dilation effect on m_μ

Experiment:

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

Muon Electric Dipole Moment (EDM)

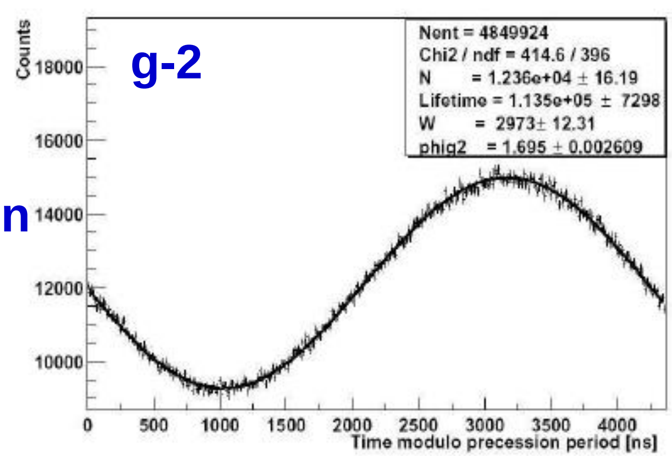


- **SM prediction for muon EDM is almost 0: $d_\mu < 10^{-38}$ e·cm**
- **Unambiguous new physics signal**
- **Muon is the best option**
  - **Direct measurement**
  - **Free of nuclear / molecular effects**
- **Note that $d_e \sim 10^{-29}$ e·cm**
  - **Current best result $d_\mu \sim 10^{-18}$ e·cm**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

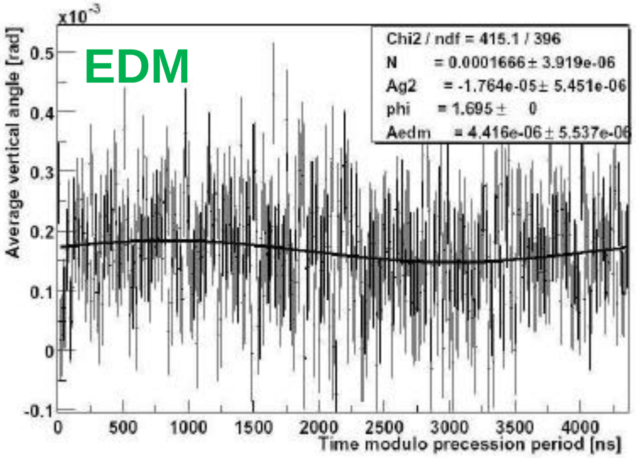
Muon Electric Dipole Moment (EDM)

BNL μ_{EDM} search was done with tracker data

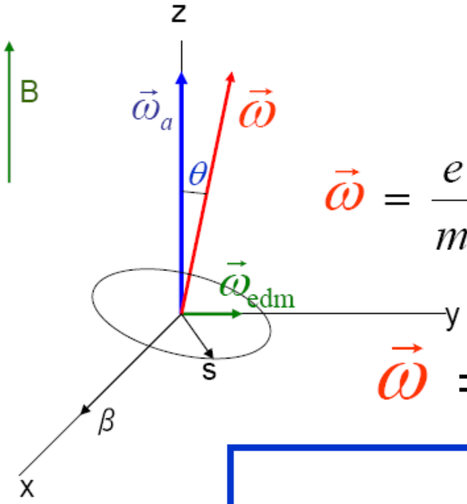
- ✓ **Improved further when combing calo data**



 # Tracks vs (time % T_a)



Average vertical angle vs (time % T_a)



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

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

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

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**

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

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

7 countries, 33 institutions, 181 collaborators

Muon g-2 Collaboration Meeting @ Elba
May 2019