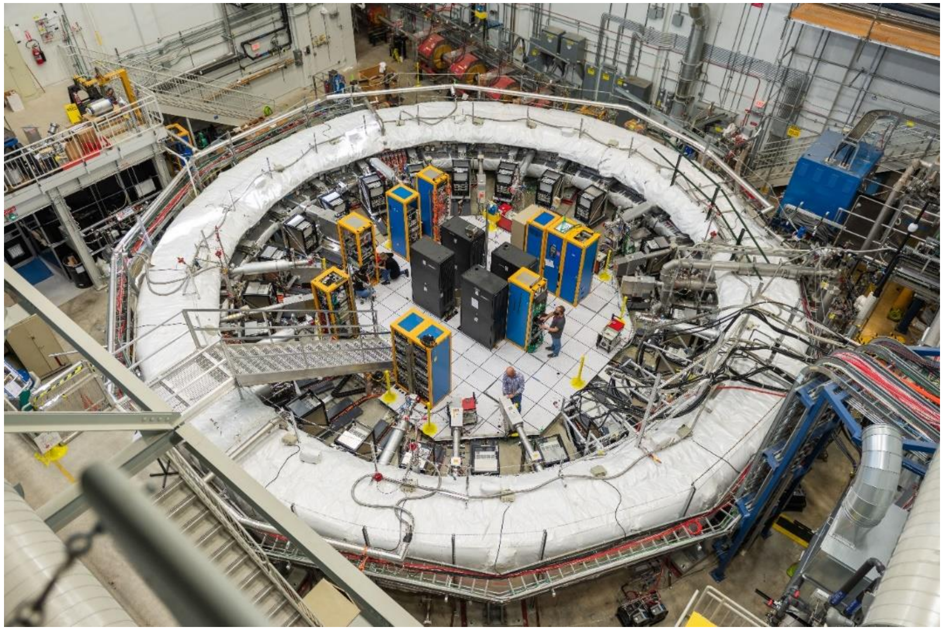
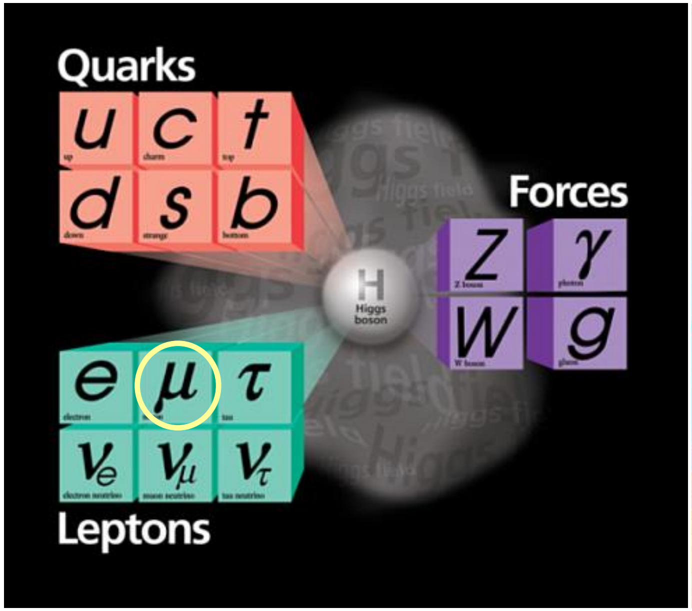
见微学术沙龙

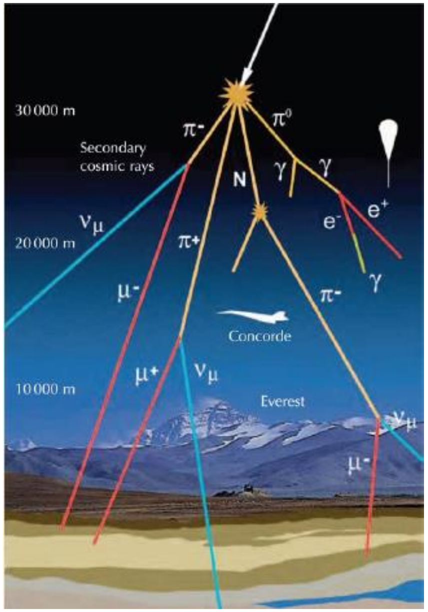
缪子反常磁矩距离诺奖还有多远？

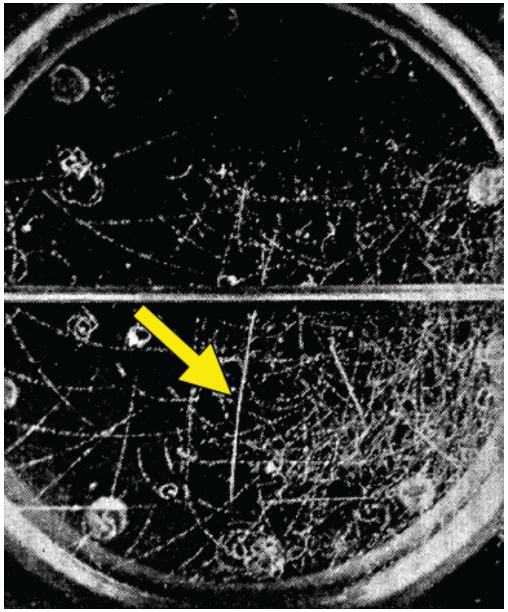


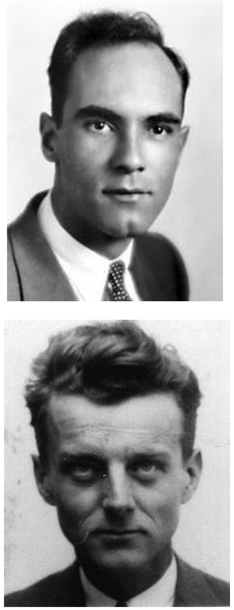
李亮
上海交通大学

神奇的缪子





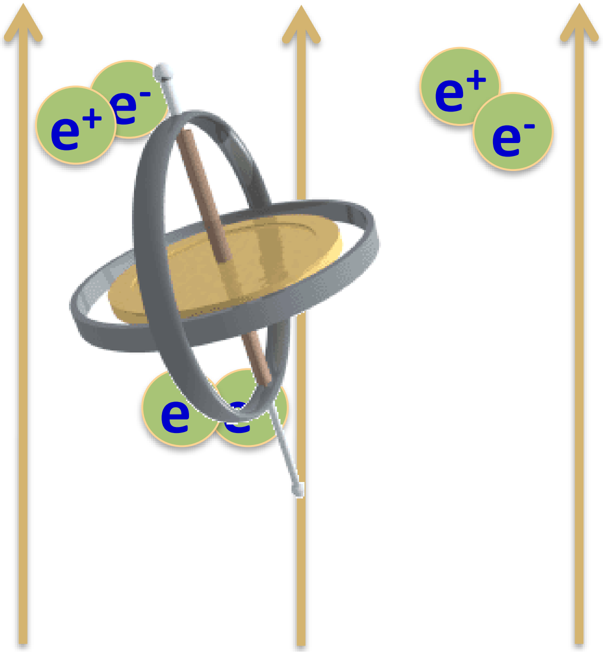




缪子在粒子物理世界中有着独特的特性

- 宇宙射线与大气作用后产生大量缪子
- 与电子电量相同但重200倍，电离作用小，穿透力很强
- 有自旋，是基本粒子但是会衰变
- **1936年安德森和学生尼德迈耶共同发现了缪子**
  - 认为发现的是汤川秀树已预言的参与强相互作用的介子，很快发现并不是
  - 拉比的名言：**Who ordered that?** 这是谁点的菜?
- **1956年李政道和杨政宁指出缪子衰变中宇称不守恒！**

什么是自旋?



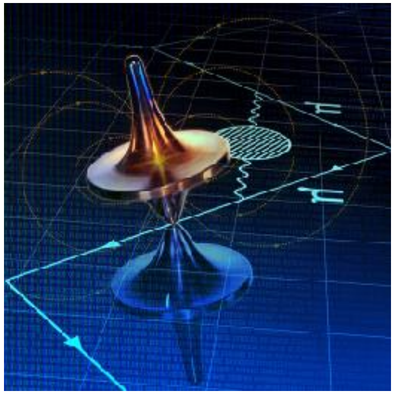
自旋是量子微观世界的独有特性

- 与宏观世界中的转动角动量类比，但是不同：基本粒子自旋为量子化
- 费米子自旋为半整数，玻色子自旋为整数
- 通过测量粒子的自旋磁矩可以深入研究自旋、粒子结构、磁矩之间的复杂关系
- 缪子在垂直磁场中旋转并产生进动(**precession**)
  - 其他粒子与缪子的相互作用将影响缪子的进动频率
  - 产生缪子反常磁矩

与理论值不符的反常磁矩意味着新物理！

- 基本粒子不基本或是发现新粒子、新理论

Muon g-2 Experiment at Fermilab



$$\vec{\mu_S} = g\frac{q}{2m}\vec{S}$$

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

Science

BREAKTHROUGH OF THE YEAR

2021

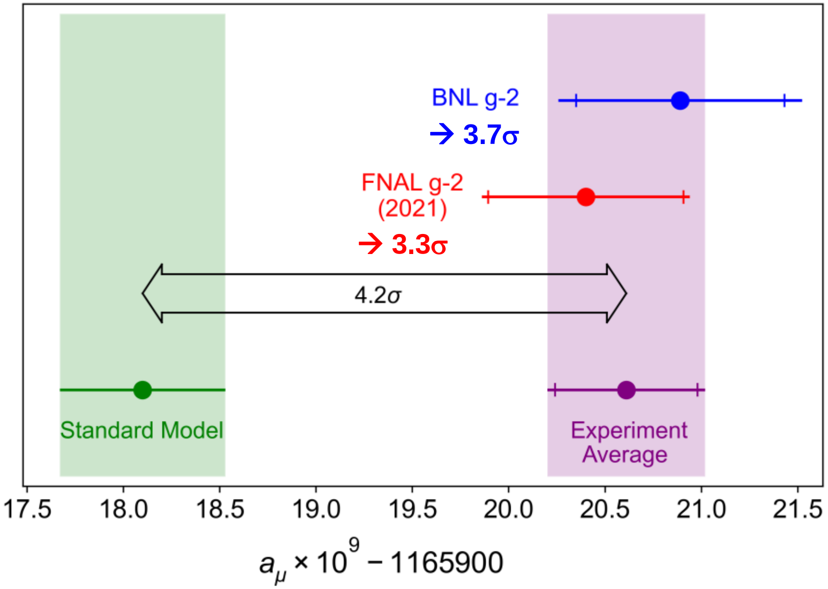
Runners-up

At last, a crack in particle physics' standard model?

2021年《科学》十大进展
诺贝尔物理奖的有力竞争者！

斯德哥尔摩给诺奖委员会邀请做专题报告

上一次粒子物理领域获此类邀请为2013年，希格斯粒子被发现并于当年获诺奖！



Experimental Principle

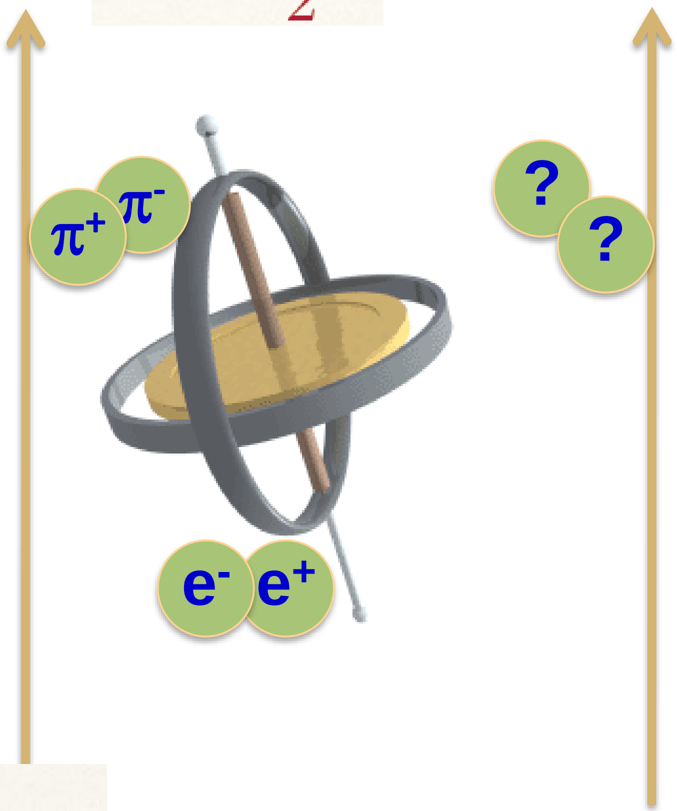
The name of game: measure frequency

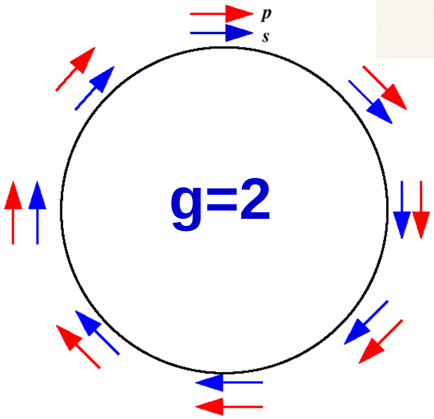
$$a = \frac{g-2}{2}$$

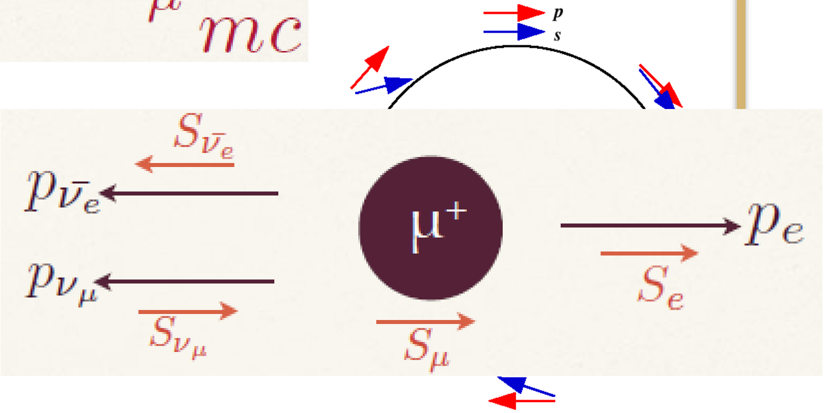
- **Put (polarized) muons in a magnetic field and measure precession f.q.**
- **Get muon spin direction from decayed electrons**
- **a_μ ~ difference between precession frequency and cyclotron frequency**

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

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







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

Frequency Measurements

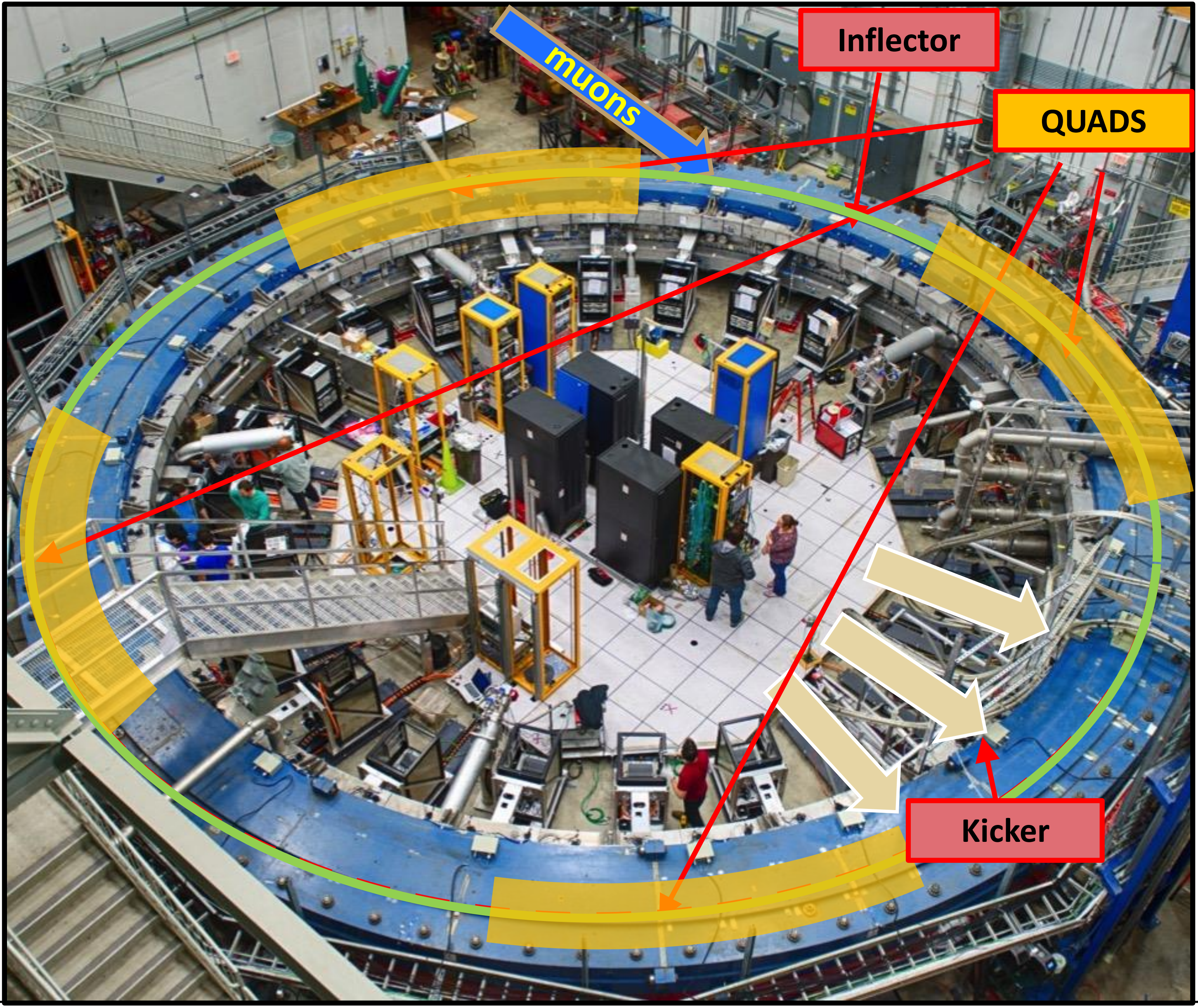
Frequency measurements can be done in very high precision

- Measure frequency ratio and extract from several measurements

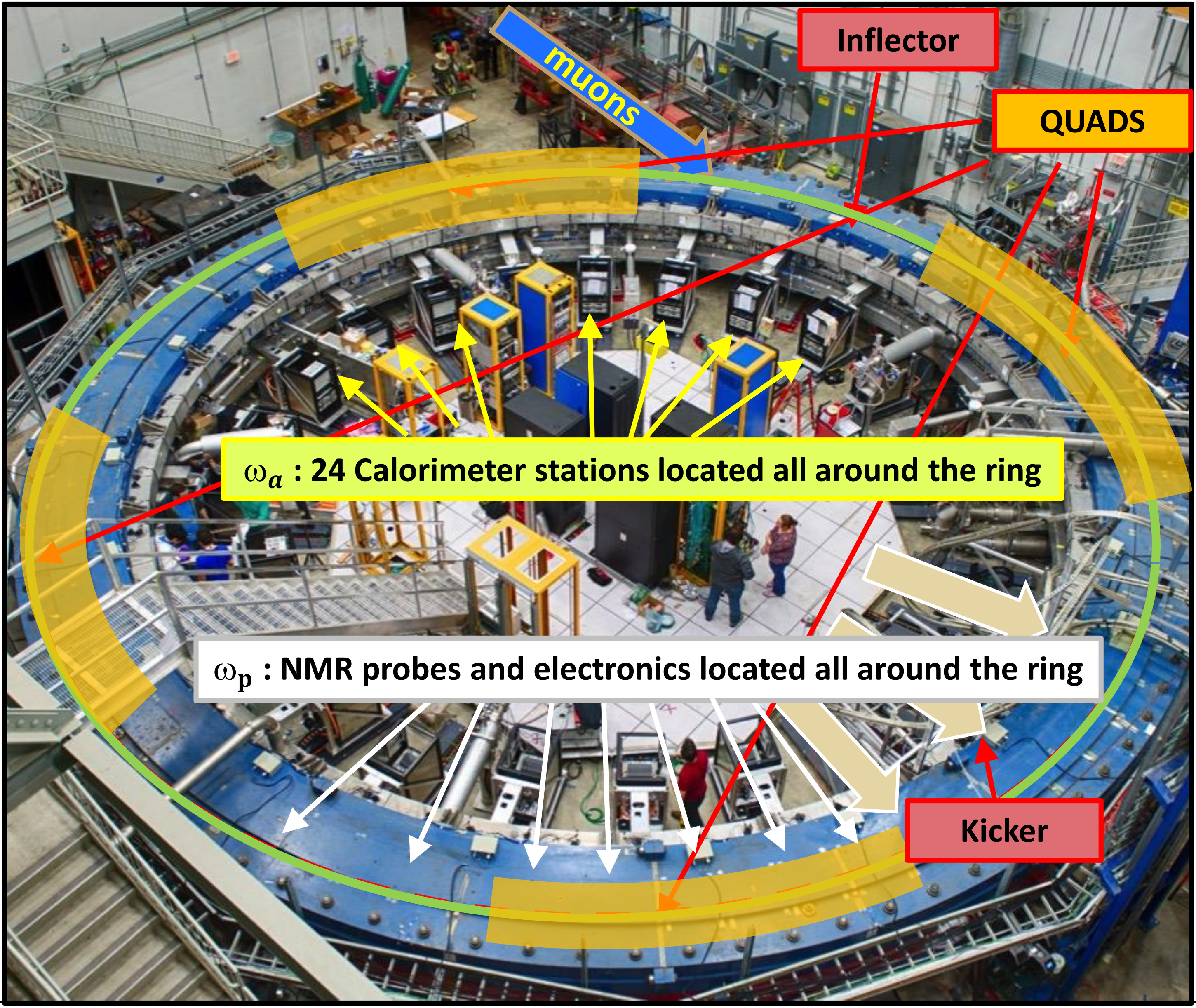
$$a_{\mu} \sim \frac{\omega_a}{<B>} = \frac{g_e}{2}\frac{\omega_a}{\varpi_p}\frac{m_{\mu}}{m_e}\frac{\mu_p}{\mu_e}$$

  - ω_p is the proton precession frequency ($\omega_p \sim |B|$)
  - 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

Experimental Setup



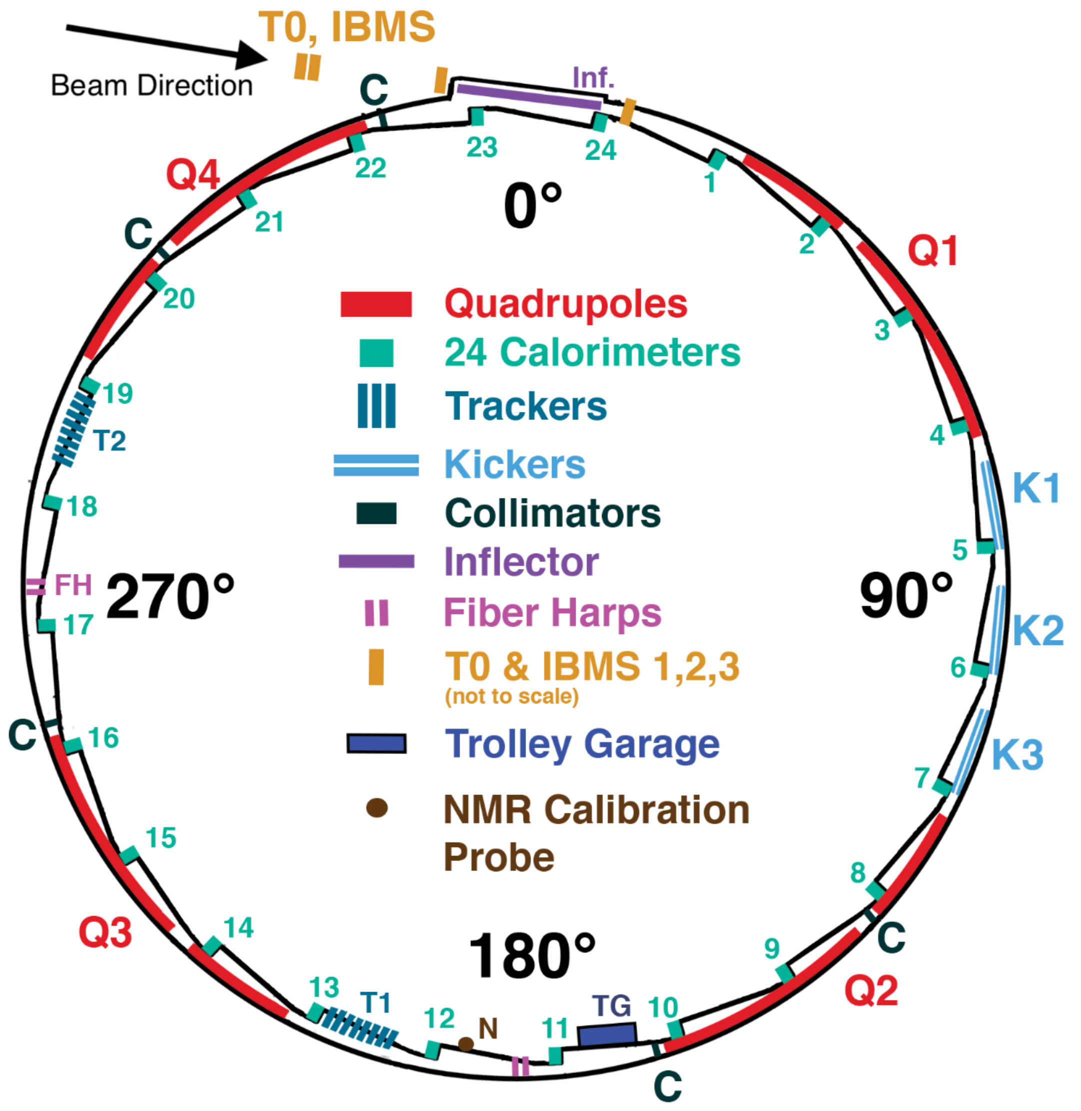
Experimental Setup



ω_a : 24 Calorimeter stations located all around the ring

ω_p : NMR probes and electronics located all around the ring

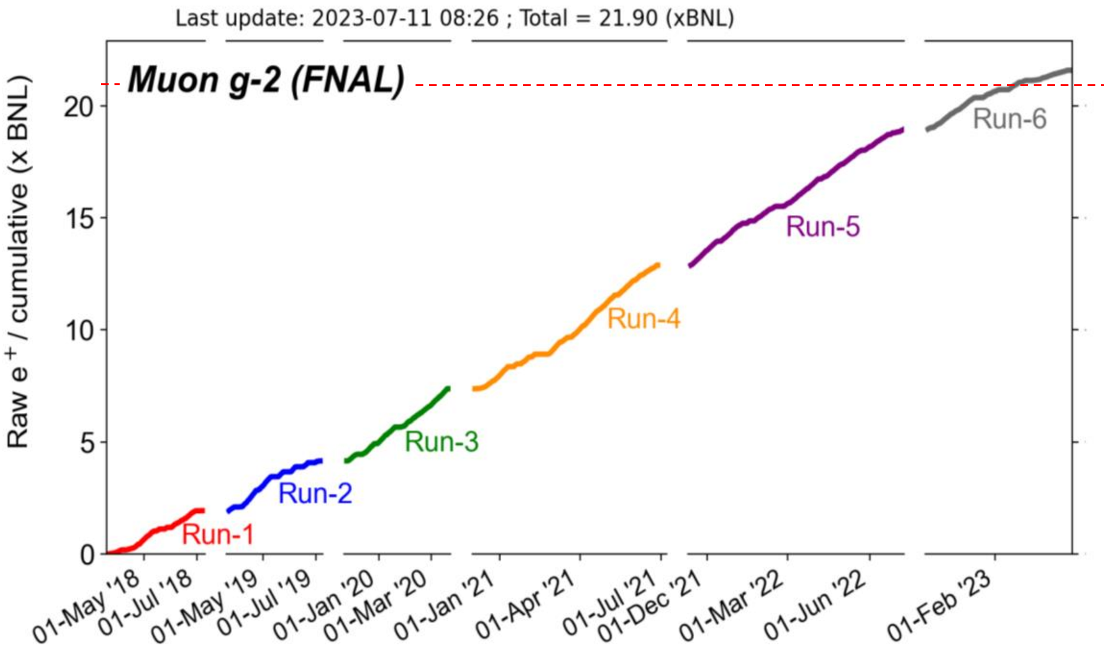
Detector System



- 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

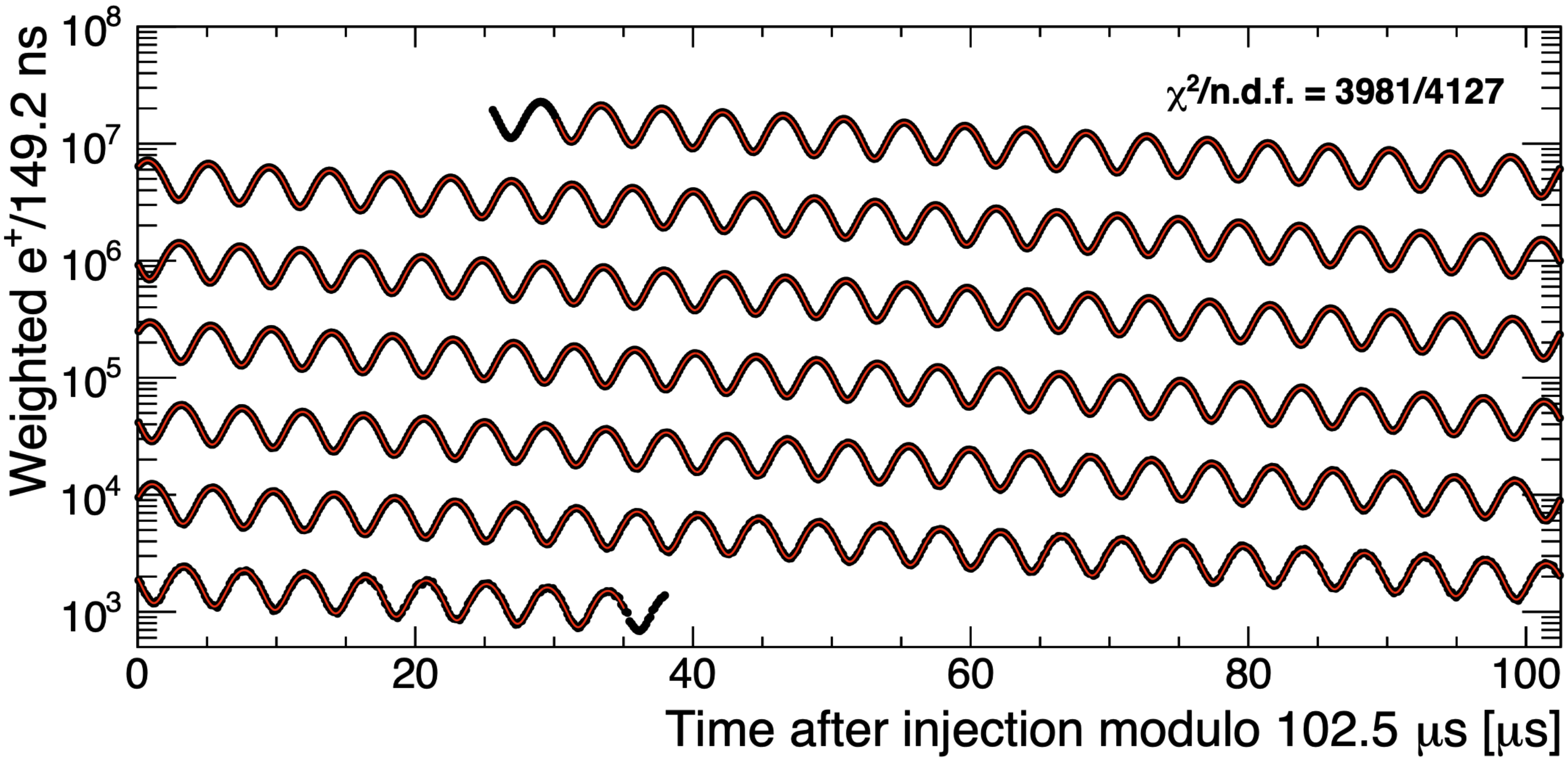
Data Collection



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**

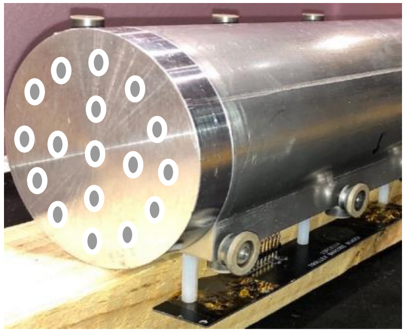
ω_a Measurement



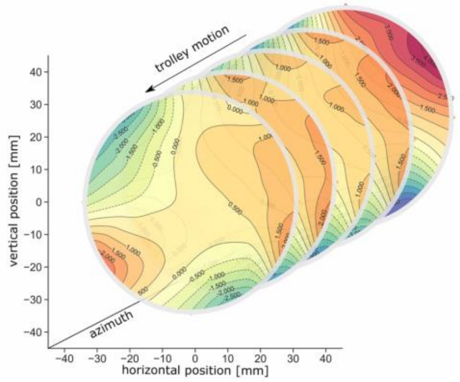
- Energetic e+ oscillates as μ+ spin direction aligns or anti-aligns with momentum direction
- Count e+ hitting calos above threshold (or weight the hits)
- Extract the oscillation frequency ω_a via fitting time spectrum

ω_p Measurement

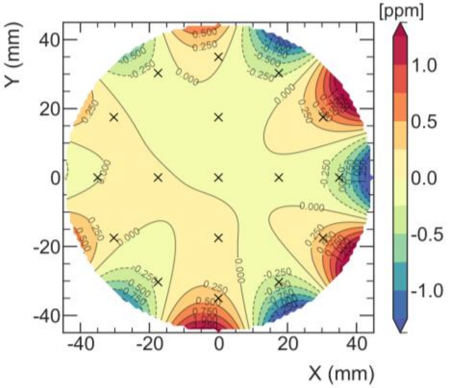
- **In-vacuum NMR trolley maps field every few days**



17 petroleum jelly NMR probes

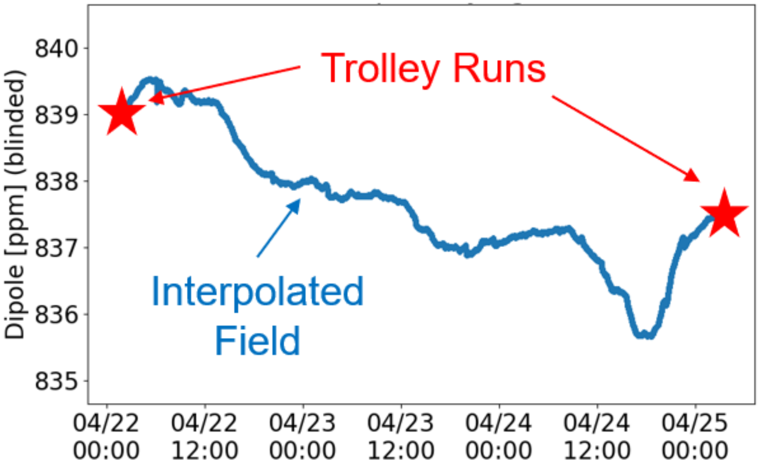


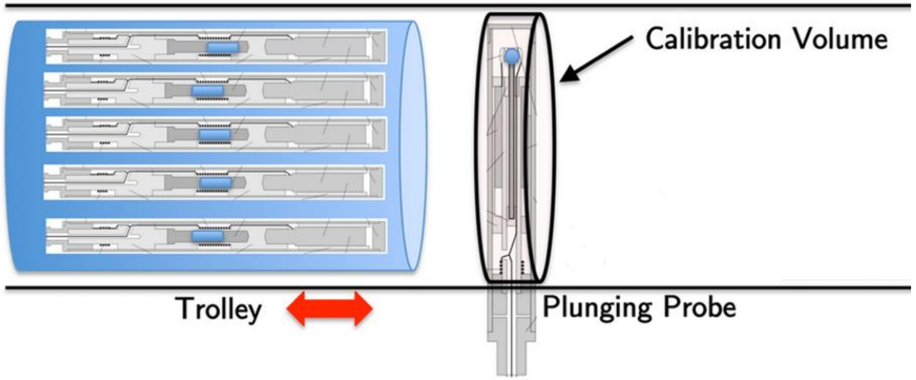
2D field maps (~8000 points)



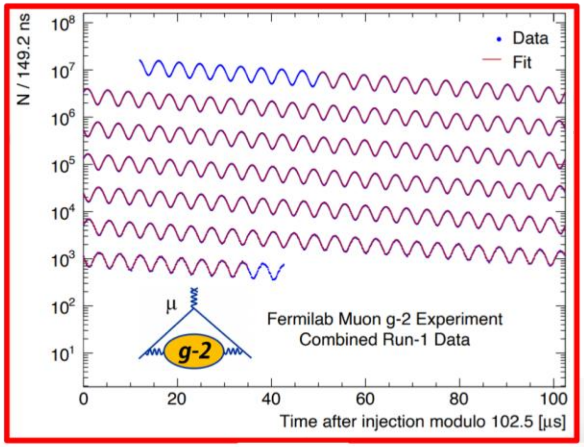
Azimuthally-Averaged Variation < 1 ppm

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

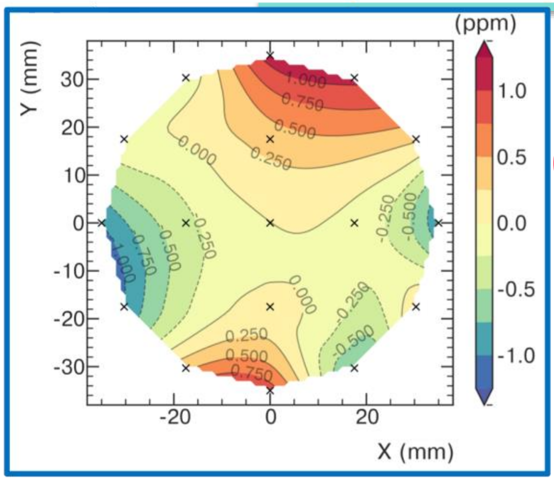




Full Measurement with Corrections



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



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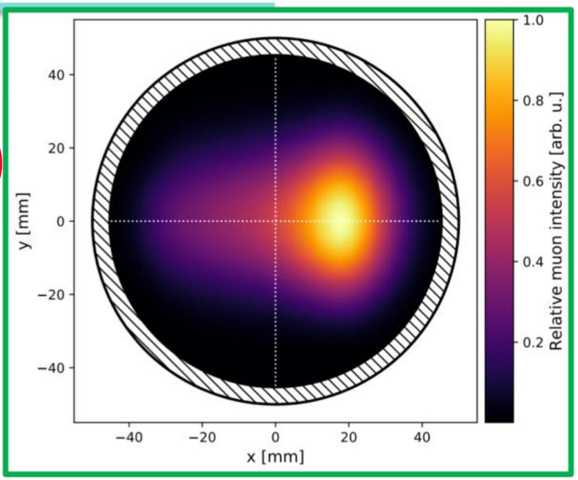
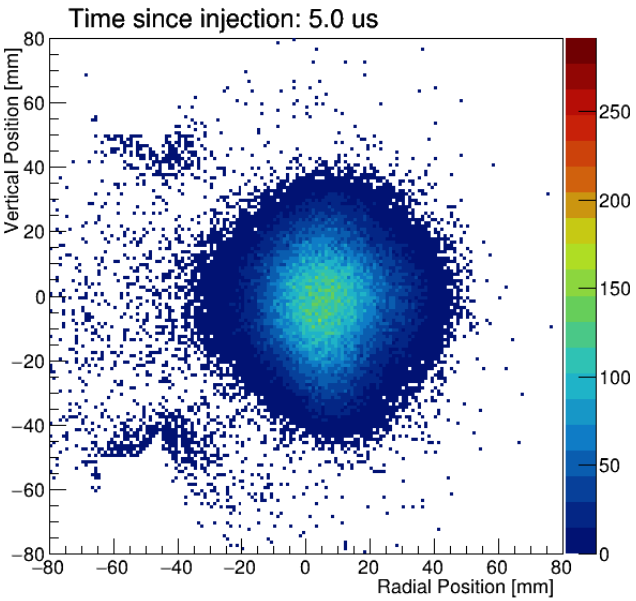
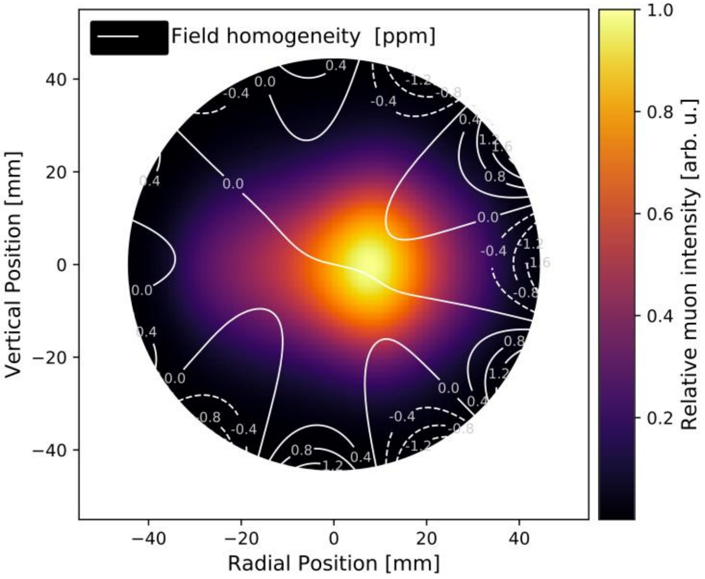


Muon Distribution Measurement





- 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?**

E-Field and Pitch Correction

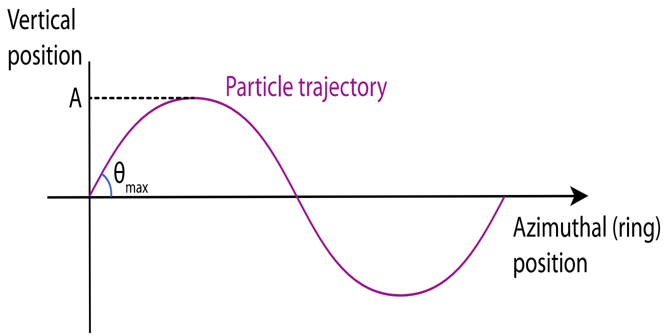
- **Muons make horizontal circular movement under influence of magnetic field B, what about vertical movement?**
  - **Use electrostatic quadruples to confine muons vertically, this brings additional complication**

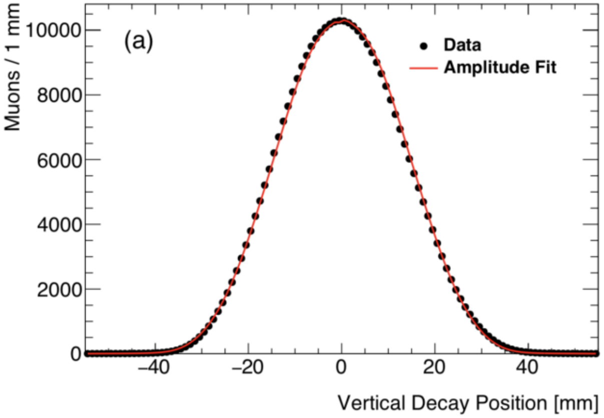
$$\frac{d(\hat{\beta}\cdot\vec{S})}{dt} = -\frac{q}{m}\vec{S}_T \cdot \left[\boxed{a_\mu \hat{\beta}\times\vec{B}} + \beta\cancel{\left(a_\mu - \frac{1}{\gamma^2-1}\right)\frac{\vec{E}}{c}}\right]$$

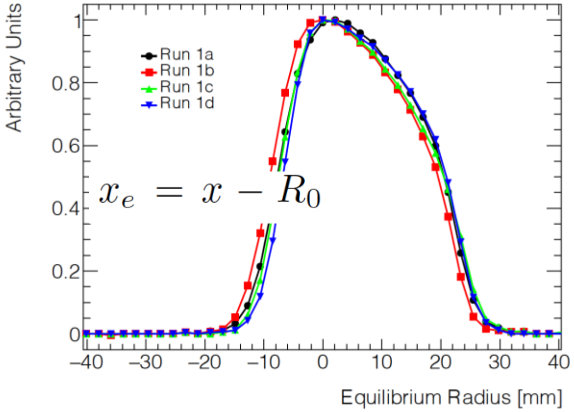
BMT Eq.

Minimized if $\gamma = 29.3$ (magic momentum, P_{magic})

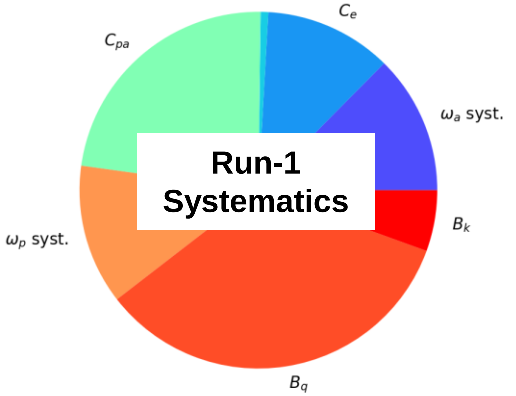
  - **Pitch Correction: muons oscillate vertically (pitch)**
  - **Residual Electric field correction: Not all muons at P_{magic}**

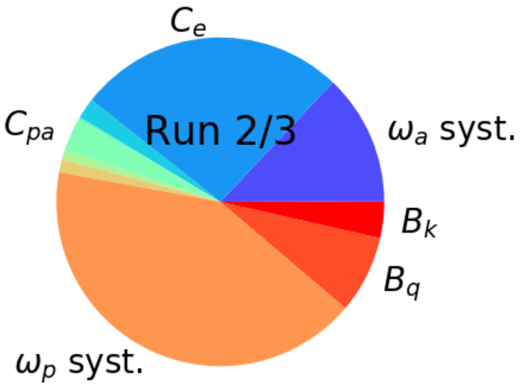






Improving Systematic Uncertainties

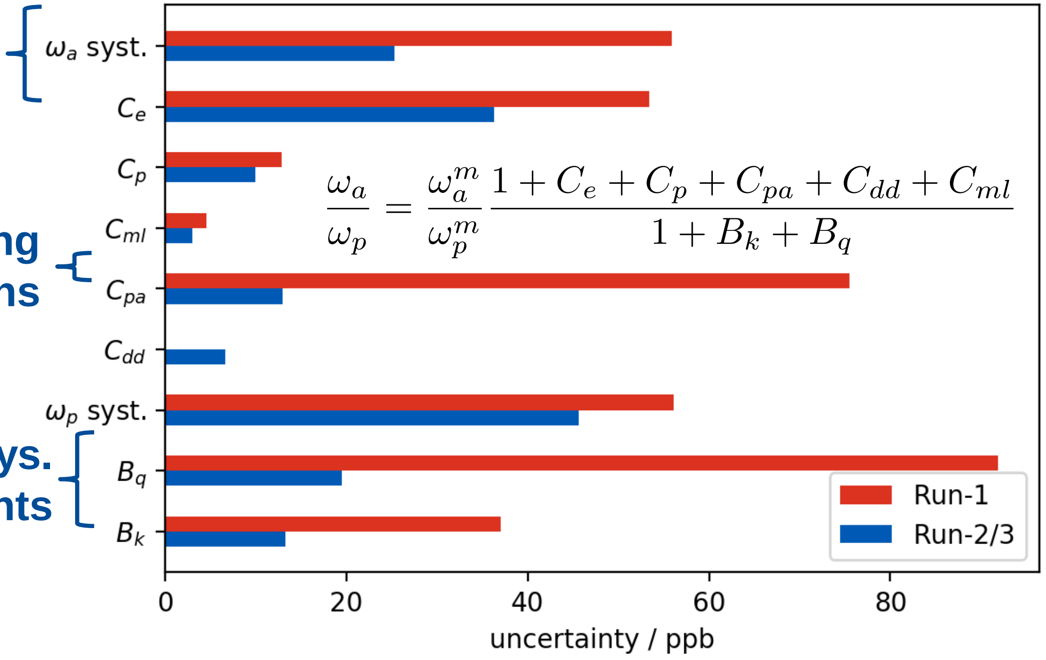




Analysis Improvements

Running Conditions

Improved Sys. Measurements

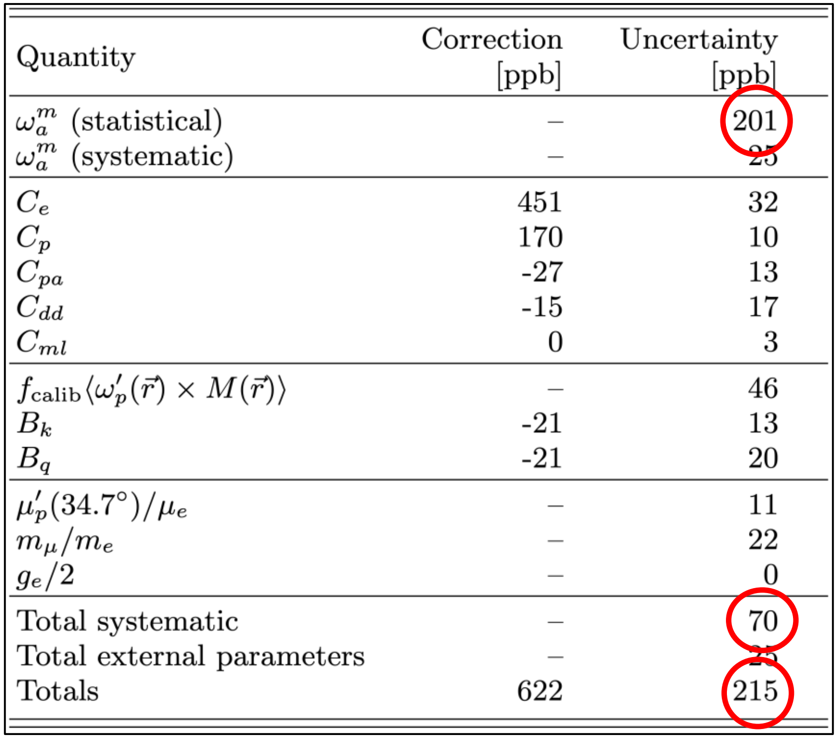


$$\frac{\omega_a}{\omega_p} = \frac{\omega_a^m}{\omega_p^m} \frac{1 + C_e + C_p + C_{pa} + C_{dd} + C_{ml}}{1 + B_k + B_q}$$

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
$\mu'_p(34.7^\circ)/\mu_e$	–	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**

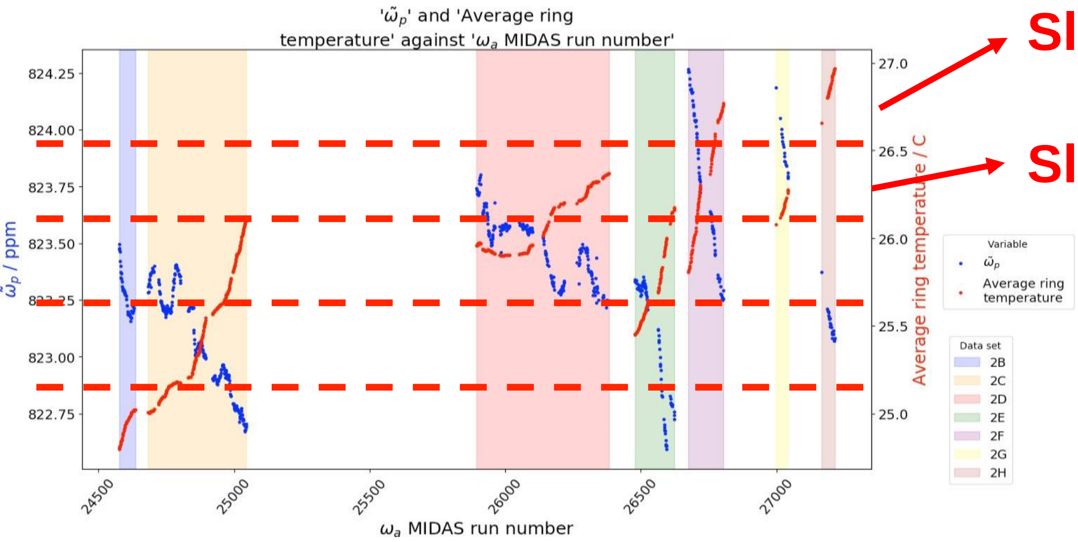
- **Total systematic uncertainty: 70 ppb**
- **Surpasses the proposal goal of 100 ppb!**

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…

McCoy Wynne

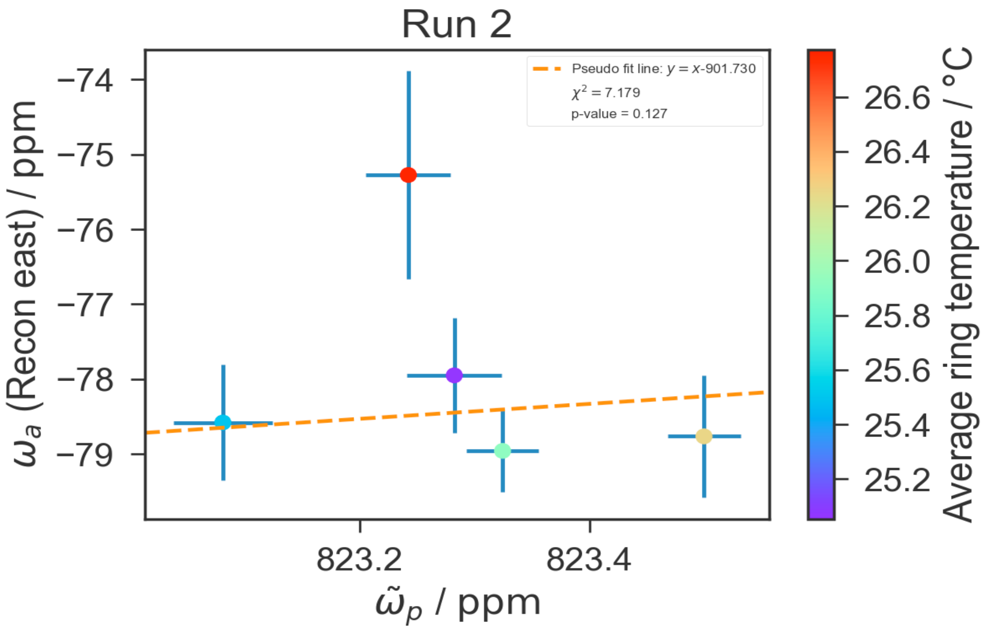
Data Consistency Check

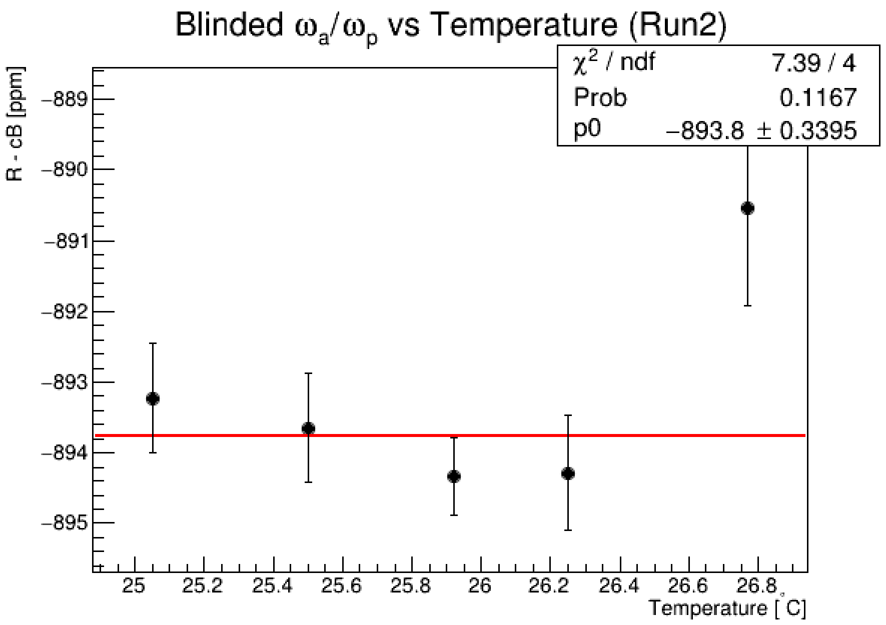


Sliced dataset 1

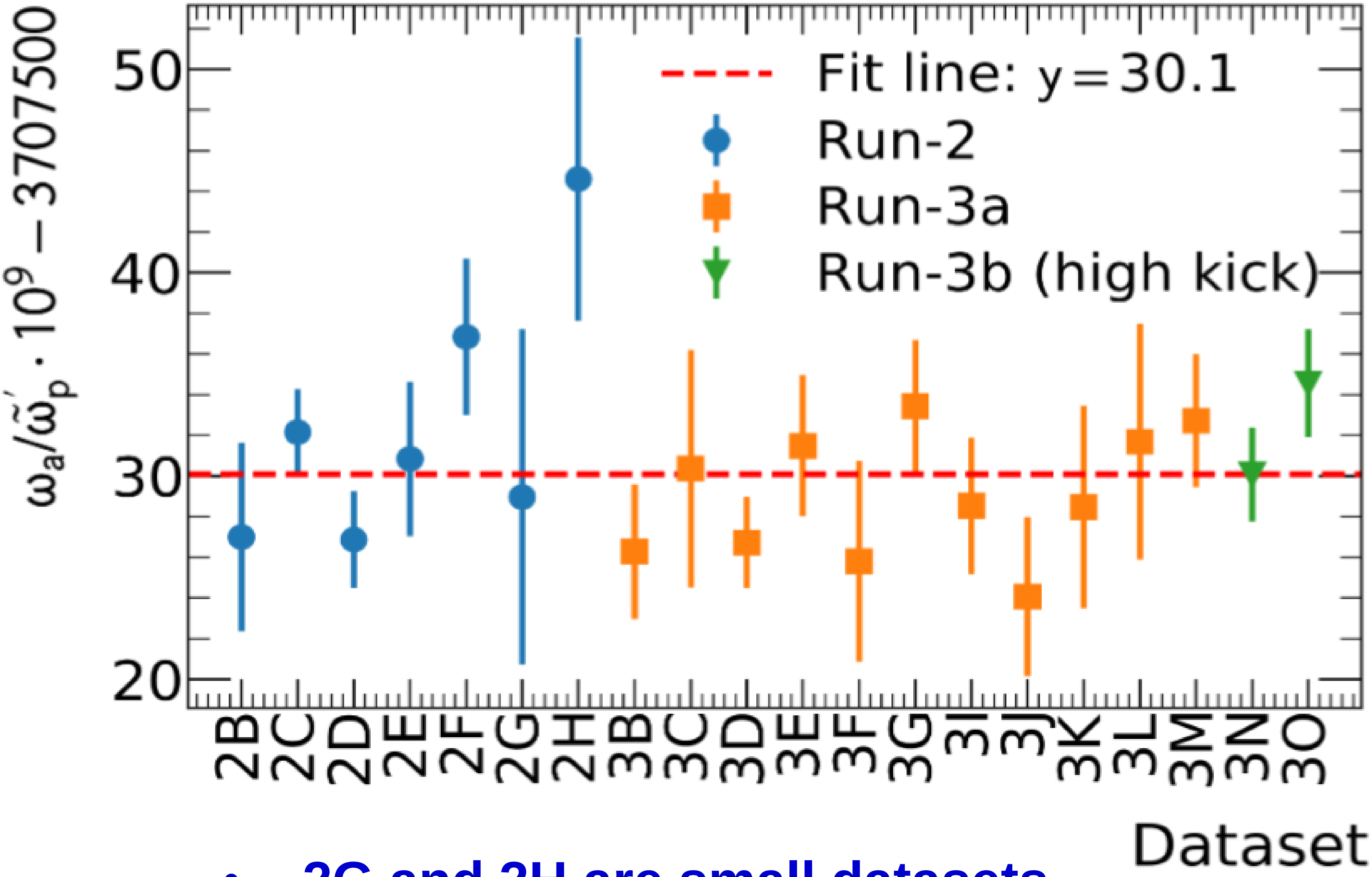
Sliced dataset 2

Perform sliced dataset analysis





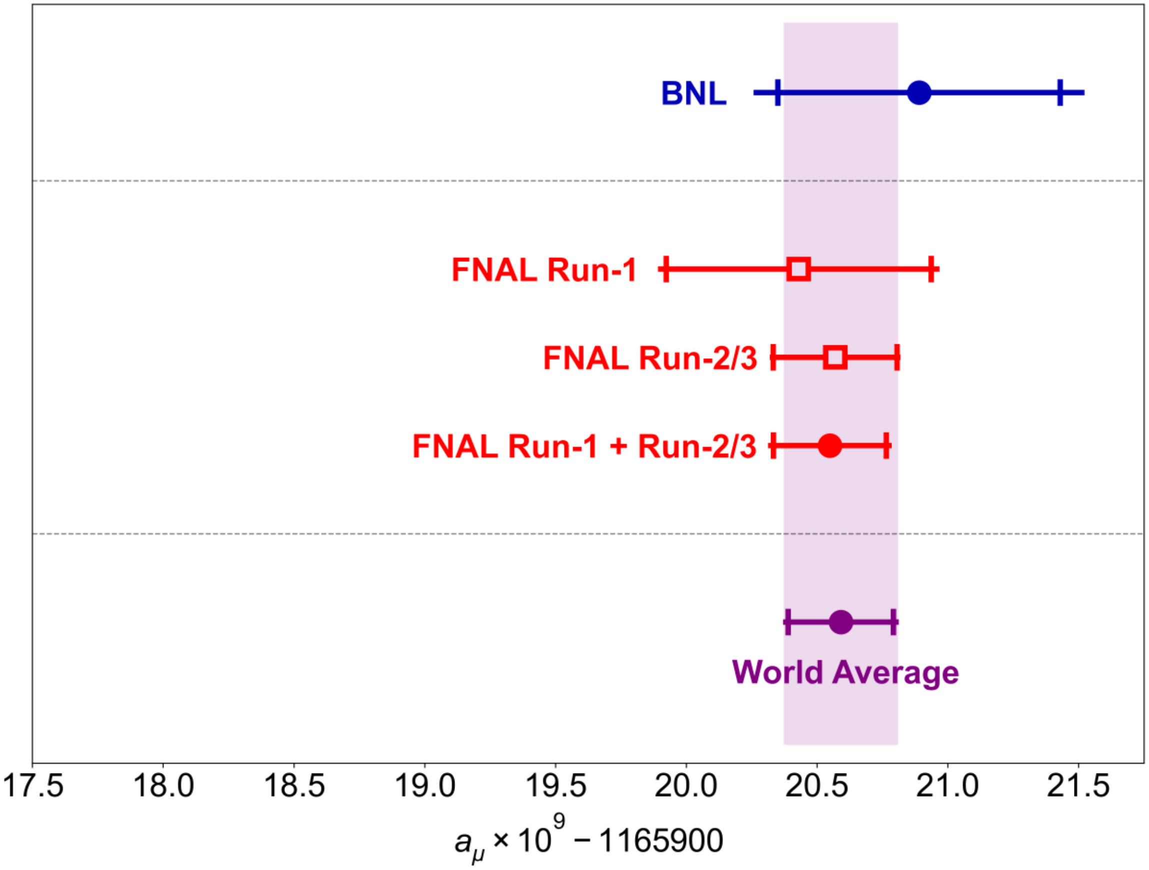
Data Consistency Check



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

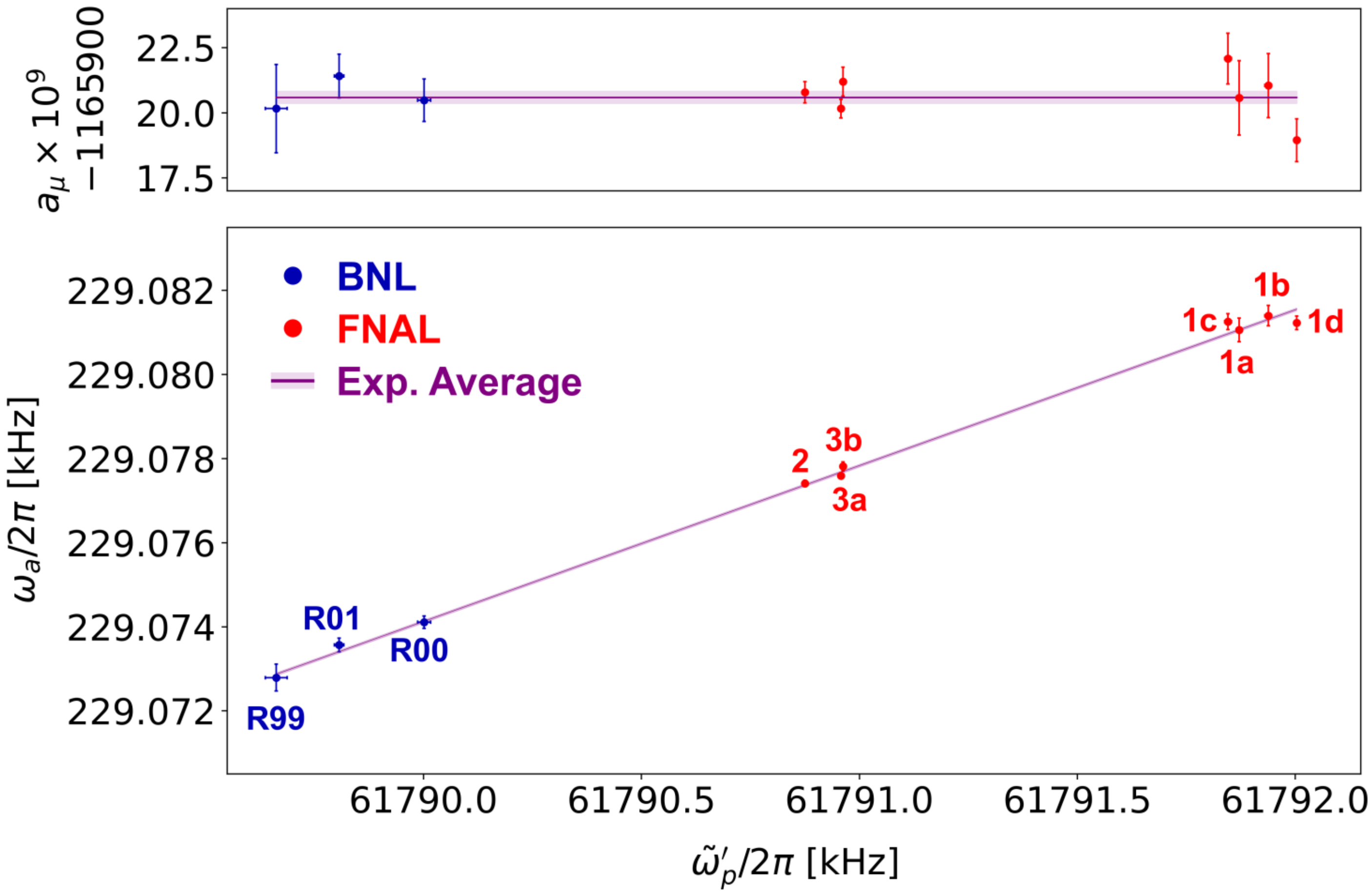
Run2/3 Result & New World Average

$a_\mu(\text{FNAL}) = 0.00\ 116\ 592\ 055(24)\ [203\ \text{ppb}]$



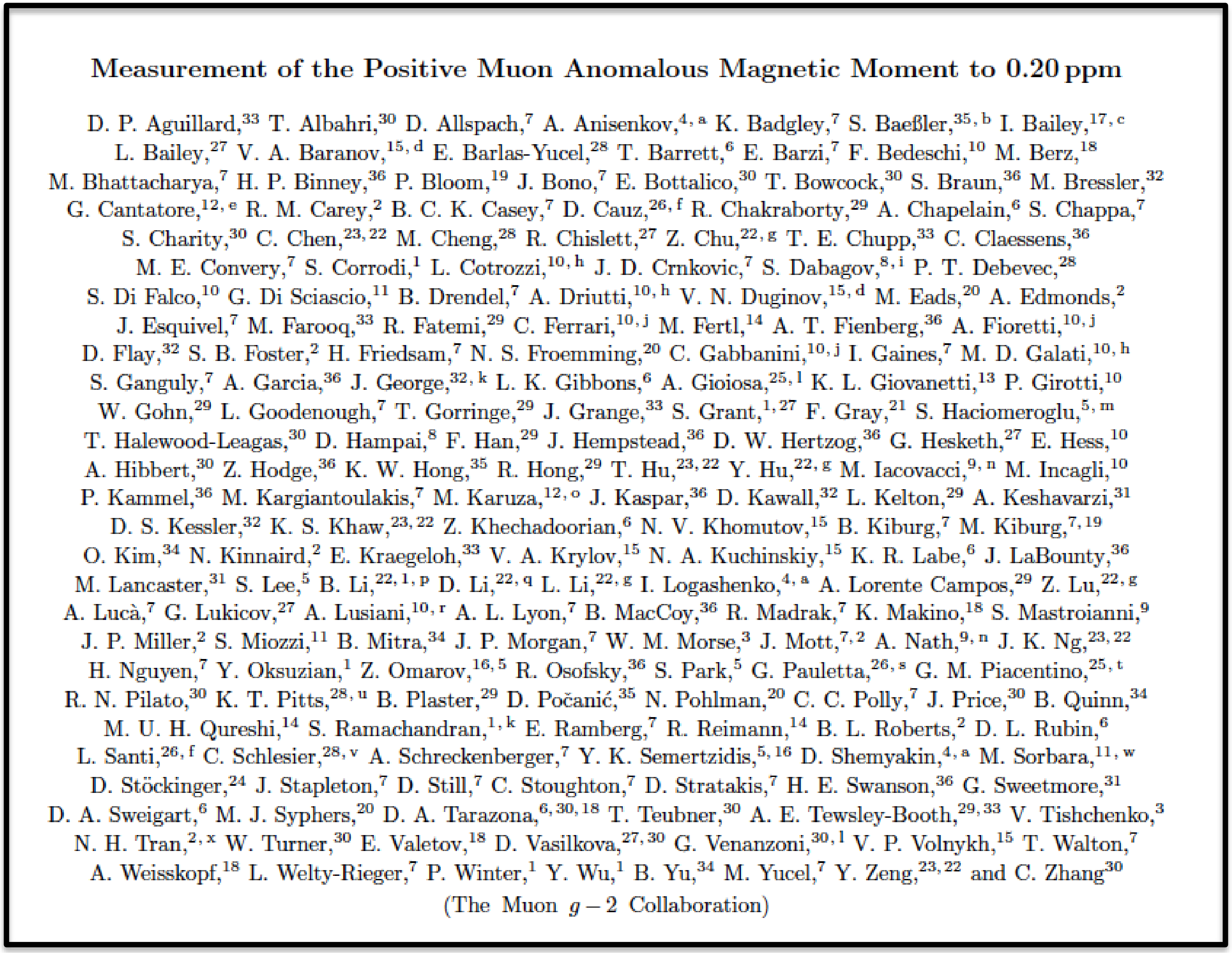
$a_\mu(\text{Exp}) = 0.00\ 116\ 592\ 059(22)\ [190\ \text{ppb}]$

Data Consistency Check



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

Paper Submission on August 10th



Measurement of the Positive Muon Anomalous Magnetic Moment to 0.20 ppm

D. P. Aguillard,[33] T. Albahri,[30] D. Allspach,[7] A. Anisenkov,[4,a] K. Badgley,[7] S. Baeßler,[35,b] I. Bailey,[17,c]
L. Bailey,[27] V. A. Baranov,[15,d] E. Barlas-Yucel,[28] T. Barrett,[6] E. Barzi,[7] F. Bedeschi,[10] M. Berz,[18]
M. Bhattacharya,[7] H. P. Binney,[36] P. Bloom,[19] J. Bono,[7] E. Bottalico,[30] T. Bowcock,[30] S. Braun,[36] M. Bressler,[32]
G. Cantatore,[12,e] R. M. Carey,[2] B. C. K. Casey,[7] D. Cauz,[26,f] R. Chakraborty,[29] A. Chapelain,[6] S. Chappa,[7]
S. Charity,[30] C. Chen,[23,22] M. Cheng,[28] R. Chislett,[27] Z. Chu,[22,g] T. E. Chupp,[33] C. Claessens,[36]
M. E. Convery,[7] S. Corrodi,[1] L. Cotrozzi,[10,h] J. D. Crnkovic,[7] S. Dabagov,[8,i] P. T. Debevec,[28]
S. Di Falco,[10] G. Di Sciascio,[11] B. Drendel,[7] A. Driutti,[10,h] V. N. Duginov,[15,d] M. Eads,[20] A. Edmonds,[2]
J. Esquivel,[7] M. Farooq,[33] R. Fatemi,[29] C. Ferrari,[10,j] M. Fertl,[14] A. T. Fienberg,[36] A. Fioretti,[10,j]
D. Flay,[32] S. B. Foster,[2] H. Friedsam,[7] N. S. Froemming,[20] C. Gabbanini,[10,j] I. Gaines,[7] M. D. Galati,[10,h]
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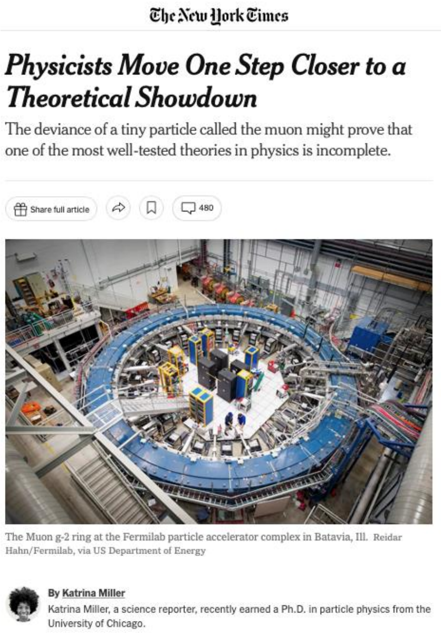
T. Halewood-Leagas,[30] D. Hampai,[8] F. Han,[29] J. Hempstead,[36] D. W. Hertzog,[36] G. Hesketh,[27] E. Hess,[10]
A. Hibbert,[30] Z. Hodge,[36] K. W. Hong,[35] R. Hong,[29] T. Hu,[23,22] Y. Hu,[22,g] M. Iacovacci,[9,n] M. Incagli,[10]
P. Kammel,[36] M. Kargiantoulakis,[7] M. Karuza,[12,o] J. Kaspar,[36] D. Kawall,[32] L. Kelton,[29] A. Keshavarzi,[31]
D. S. Kessler,[32] K. S. Khaw,[23,22] Z. Khechadoorian,[6] N. V. Khomutov,[15] B. Kiburg,[7] M. Kiburg,[7,19]
O. Kim,[34] N. Kinnaird,[2] E. Kraegeloh,[33] V. A. Krylov,[15] N. A. Kuchinskiy,[15] K. R. Labe,[6] J. LaBounty,[36]
M. Lancaster,[31] S. Lee,[5] B. Li,[22,1,p] D. Li,[22,q] L. Li,[22,g] I. Logashenko,[4,a] A. Lorente Campos,[29] Z. Lu,[22,g]
A. Lucà,[7] G. Lukicov,[27] A. Lusiani,[10,r] A. L. Lyon,[7] B. MacCoy,[36] R. Madrak,[7] K. Makino,[18] S. Mastroianni,[9]
J. P. Miller,[2] S. Miozzi,[11] B. Mitra,[34] J. P. Morgan,[7] W. M. Morse,[3] J. Mott,[7,2] A. Nath,[9,n] J. K. Ng,[23,22]
H. Nguyen,[7] Y. Oksuzian,[1] Z. Omarov,[16,5] R. Osofsky,[36] S. Park,[5] G. Pauletta,[26,s] G. M. Piacentino,[25,t]
R. N. Pilato,[30] K. T. Pitts,[28,u] B. Plaster,[29] D. Počanić,[35] N. Pohlman,[20] C. C. Polly,[7] J. Price,[30] B. Quinn,[34]
M. U. H. Qureshi,[14] S. Ramachandran,[1,k] E. Ramberg,[7] R. Reimann,[14] B. L. Roberts,[2] D. L. Rubin,[6]
L. Santi,[26,f] C. Schlesier,[28,v] A. Schreckenberger,[7] Y. K. Semertzidis,[5,16] D. Shemyakin,[4,a] M. Sorbara,[11,w]
D. Stöckinger,[24] J. Stapleton,[7] D. Still,[7] C. Stoughton,[7] D. Stratakis,[7] H. E. Swanson,[36] G. Sweetmore,[31]
D. A. Sweigart,[6] M. J. Syphers,[20] D. A. Tarazona,[6,30,18] T. Teubner,[30] A. E. Tewsley-Booth,[29,33] V. Tishchenko,[3]
N. H. Tran,[2,x] W. Turner,[30] E. Valetov,[18] D. Vasilkova,[27,30] G. Venanzoni,[30,l] V. P. Volnykh,[15] T. Walton,[7]
A. Weisskopf,[18] L. Welty-Rieger,[7] P. Winter,[1] Y. Wu,[1] B. Yu,[34] M. Yucel,[7] Y. Zeng,[23,22] and C. Zhang[30]
(The Muon $g-2$ Collaboration)

Paper Acceptance on September 5th

Media Reach: ~7.1B Audience



The New York Times

Physicists Move One Step Closer to a Theoretical Showdown

The deviance of a tiny particle called the muon might prove that one of the most well-tested theories in physics is incomplete.

The Muon g-2 ring at the Fermilab particle accelerator complex in Batavia, Ill. Reidar Hahn/Fermilab, via US Department of Energy

By **Katrina Miller**
Katrina Miller, a science reporter, recently earned a Ph.D. in particle physics from the University of Chicago.

NEWS INFN

10 AGOSTO 2023

MUON g-2 RADDOPPIA LA PRECISIONE E SI PREPARA AL CONFRONTO FINALE CON LA TEORIA

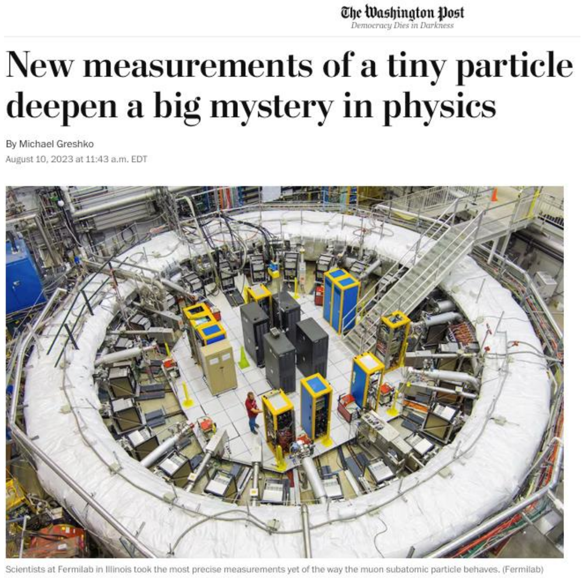
Una nuova e ancora più precisa misura di una particolare proprietà magnetica del muone, il cosiddetto *momento magnetico anomalo* (indicato con la lettera g), è stata presentata oggi, 10 agosto, nel corso di un seminario, dalla Collaborazione scientifica dell'esperimento Muon g-2 del Fermi National Accelerator Laboratory (FermiLab) di Batavia, vicino Chicago, Stati Uniti. La nuova

Scientists at Fermilab close in on fifth force of nature

4 days ago

The findings come from the US muon g-2 experiment

By Pallab Ghosh



The Washington Post
Democracy Dies in Darkness

New measurements of a tiny particle deepen a big mystery in physics

By Michael Greshko
August 10, 2023 at 11:43 a.m. EDT

Scientists at Fermilab in Illinois took the most precise measurements yet of the way the muon subatomic particle behaves. (Fermilab)

停滞100年的物理学，终于迎来全新的突破？第五种力要被发现了？

2023-08-24 10:08:03 来源: 科学认识论 湖北 举报

最近，美国费米国家实验室宣布对μ子g-2的测量精度提高1倍，可能暗示发现新的粒子，也可能是第五种基本作用力。

Muon g-2 加大最新测量力度，探索未知领域寻找新物理

2023 年 8 月 10 日

媒体联系
- 特雷西·马克，费米实验室，media@fnal.gov，224-290-7803

物理学家现在对 μ 子的一种称为反常磁矩的特性有了全新的测量，该测量将之前结果的精度提高了 1 倍。

美国能源部费米国家加速器实验室从事 Muon g-2 实验的科学家国际合作于8 月 10 日宣布了备受期待的更新测量结果。这一新值支持了他们在 2021 年 4 月宣布的第一个结果，并建立了理论与实验之间酝酿了20多年的对决。

"我们确实在探索新领域。我们正在以前所未有的精度确定 μ 子磁矩，"费米实验室高级科学家 Brendan Casey 自 2008 年以来一直致力于 μ 子 g-2 实验。

2023 年 8 月 10 日公布的结果是费米实验室实验的第二个结果，其精确度是 2021 年 4 月 7 日公布的第一个结果的两倍。照片：Ryan Postel，费米实验室

동아사이언스

과학

기본입자 '뮤온'의 일탈 재확인…흔들리는 물리학 '표준모형'

2023.08.11 16:10

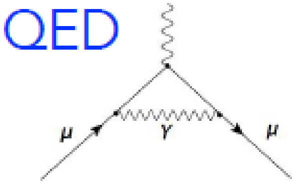
| 미국 페르미국립연구소

두 번째 뮤온 실험에서 표준모형이 예측한 g값과 미세하게 벗어나는 값이 측정됐다. Fermilab 제공

Muon g-2 Theory Prediction

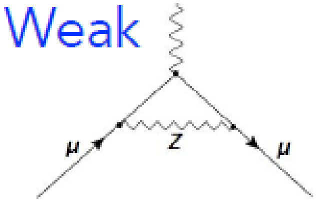
$$\boxed{a_\mu = a_\mu(\mathrm{QED}) + a_\mu(\mathrm{Weak}) + a_\mu(\mathrm{Hadronic})}$$

QED



$+\ldots$ $\quad 116\,584\,718.9\,(1) \times 10^{-11}$ $\quad 0.001$ ppm

Weak



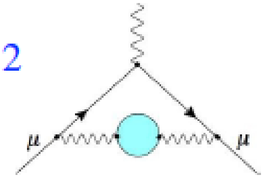
$+\ldots$ $\quad 153.6\,(1.0) \times 10^{-11}$ $\quad 0.01$ ppm

Hadronic…

Muon g-2 Theory Initiative: Phys. Rept. 887 (2020) 1-166 (WP2020)

…Vacuum Polarization (HVP)

α^2

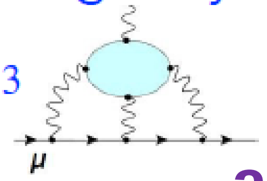


$+\ldots$ $\quad 6845\,(40) \times 10^{-11}$ $\quad 0.37$ ppm

[0.6%]

…Light-by-Light (HLbL)

α^3



$+\ldots$ $\quad 92\,(18) \times 10^{-11}$ $\quad 0.15$ ppm

[20%]

a_μ(SM) = 0.00 116 591 810(43) [370 ppb]

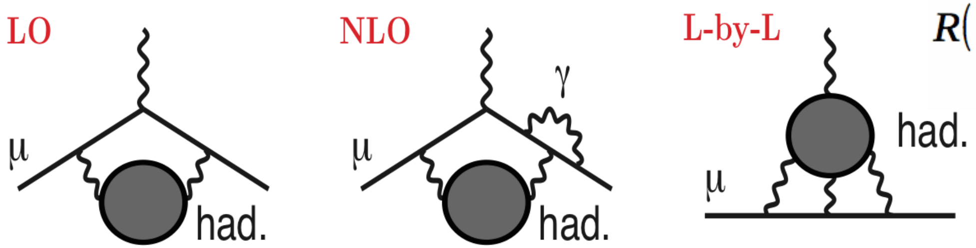
Muon g-2 Theory Prediction: HVP

$$a_m^{SM} = a_m^{QED} + a_m^{EW} + a_m^{Had}$$

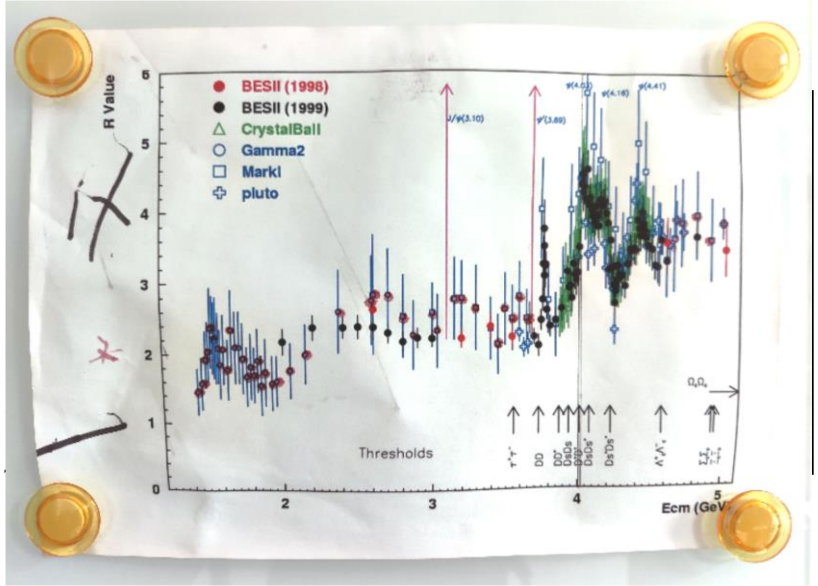
$$a_\mu^{had,1} \propto \int_{2m_\pi}^{\infty} ds \frac{K(s)}{s} R(s)$$

$$R(s) = \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \text{muons})}$$

Hadronic Vacuum Polarization (HVP)

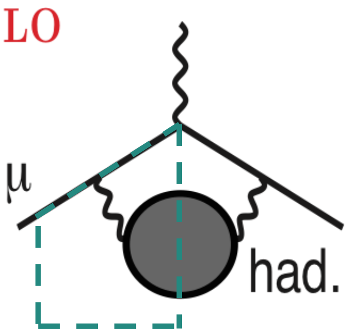


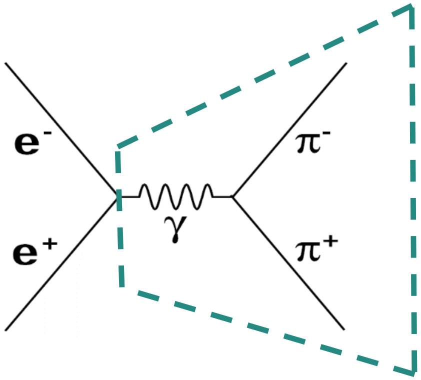
- Includes quark and gluon loops
- Small contribution with dominant source of theoretical uncertainties *R*
- Hadronic Vacuum Polarization
- Two approaches
  - Dispersion relationships
  - Lattice



1/s weights low energy strongly: 73% from π + π − channel

Muon g-2 Theory Prediction: HVP

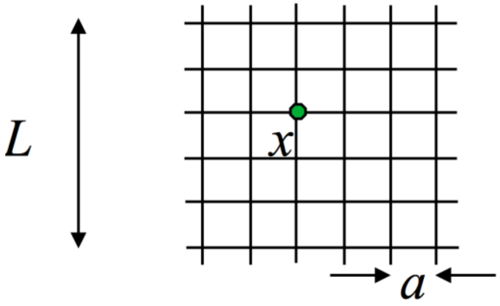




$$a_\mu^{had,1} \propto \int_{2m_\pi}^{\infty} ds \frac{K(s)}{s} R(s)$$

$$R(s) = \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \text{muons})}$$

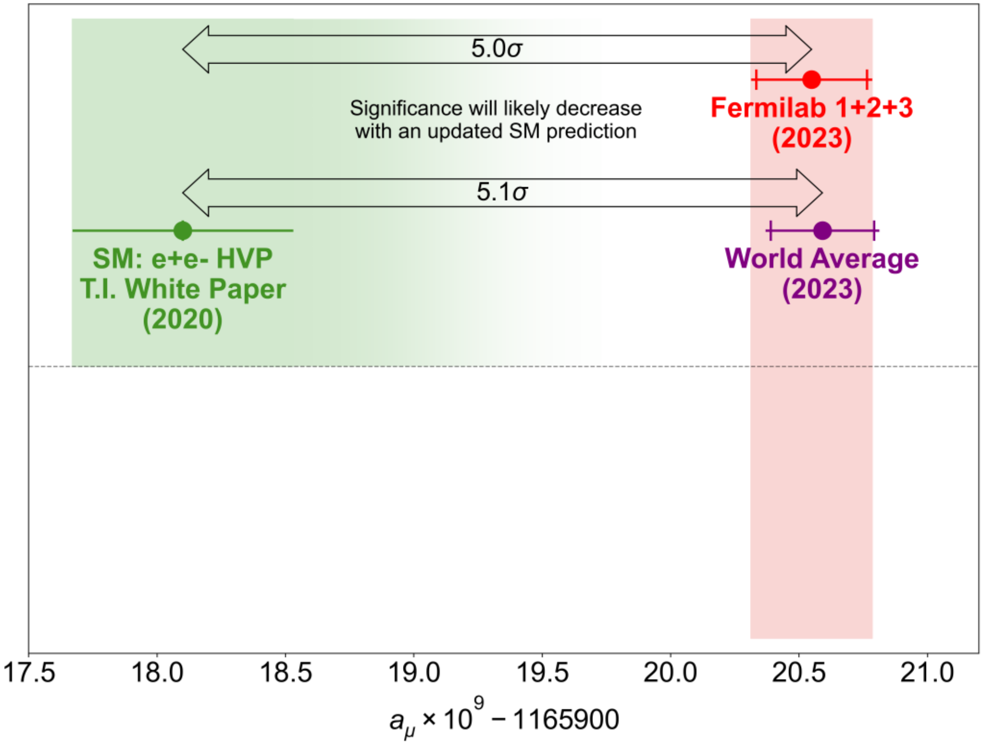
- **Dispersion relation connects rate of e^+e^-→hadrons to HVP**
- **More experimental data across the energy spectrum, better understanding of the data determines the uncertainty.**



- **Lattice HVP determinations improving with more computing time**
- **Fast progress but only intermediate window**
- **Still need full HVP calculations**

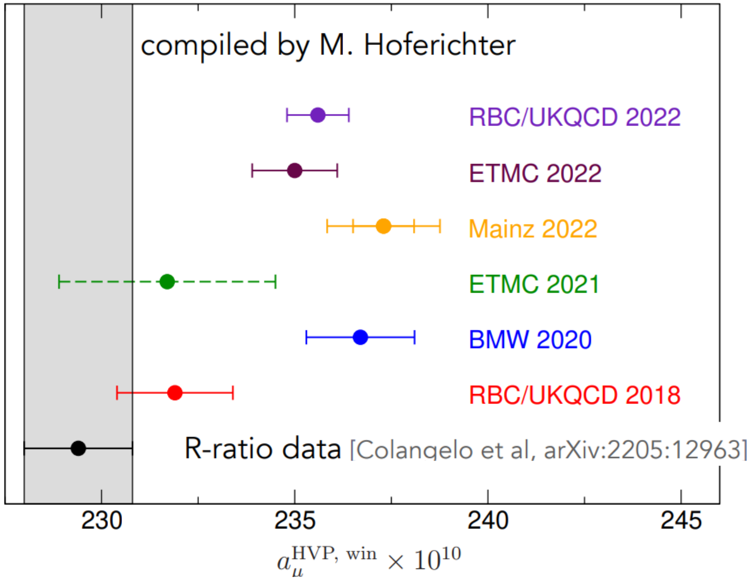
$$a_\mu^{\mathrm{had,\,LO\,VP}} = \frac{\alpha^2}{\pi^2}\int \mathrm{d}q^2 w(q^2)\hat{\Pi}(q^2)$$

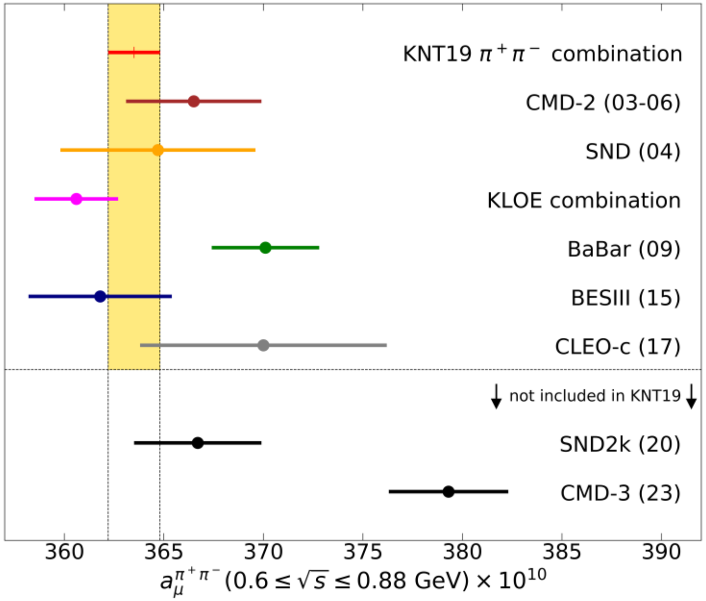
Experiment vs. Theory Saga



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

Hadronic Vacuum Polarization Update



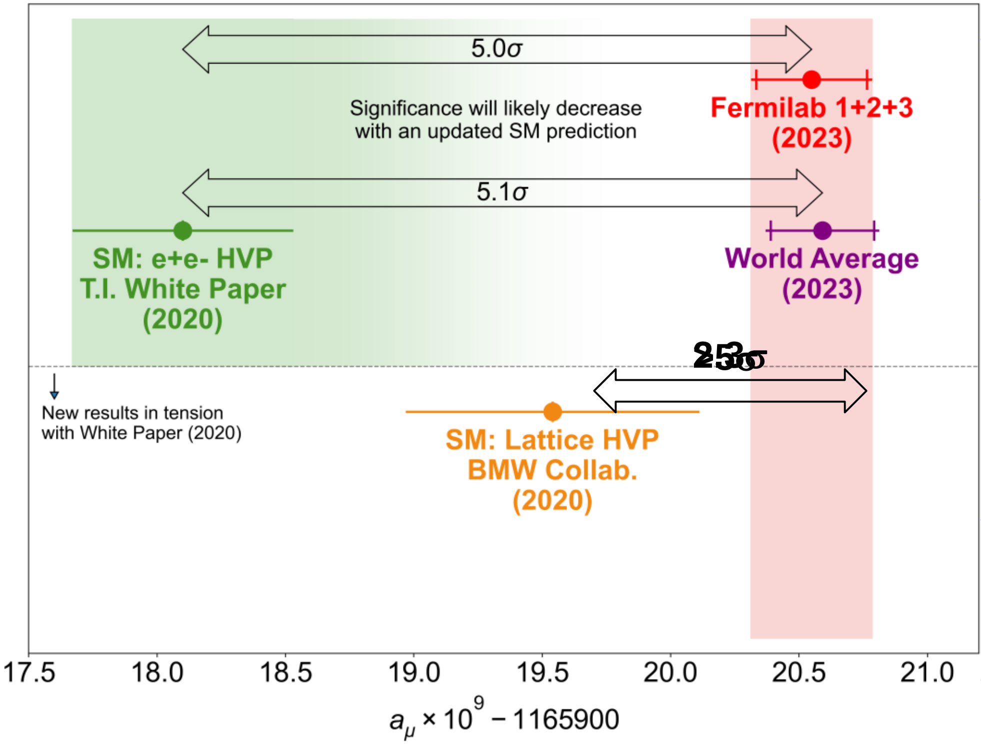


- **LQCD Intermediate window: BMW 2020 claimed 0.8% precision, closer to experimental value but 2.1σ with data-driven HVP**
- **Need full LQCD HVP calculations for all windows**

- **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?

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

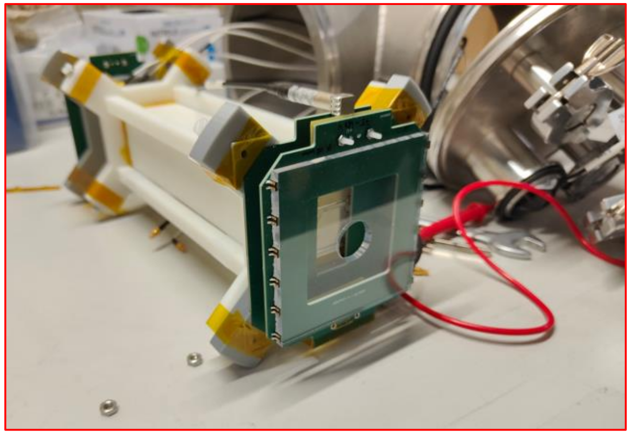
Muon g-2 Collaboration

7 countries, 33 institutions, 181 collaborators

Muon g-2 Collaboration Meeting @ Elba
May 2019

交大缪子物理团队

交大、KEK团队交流

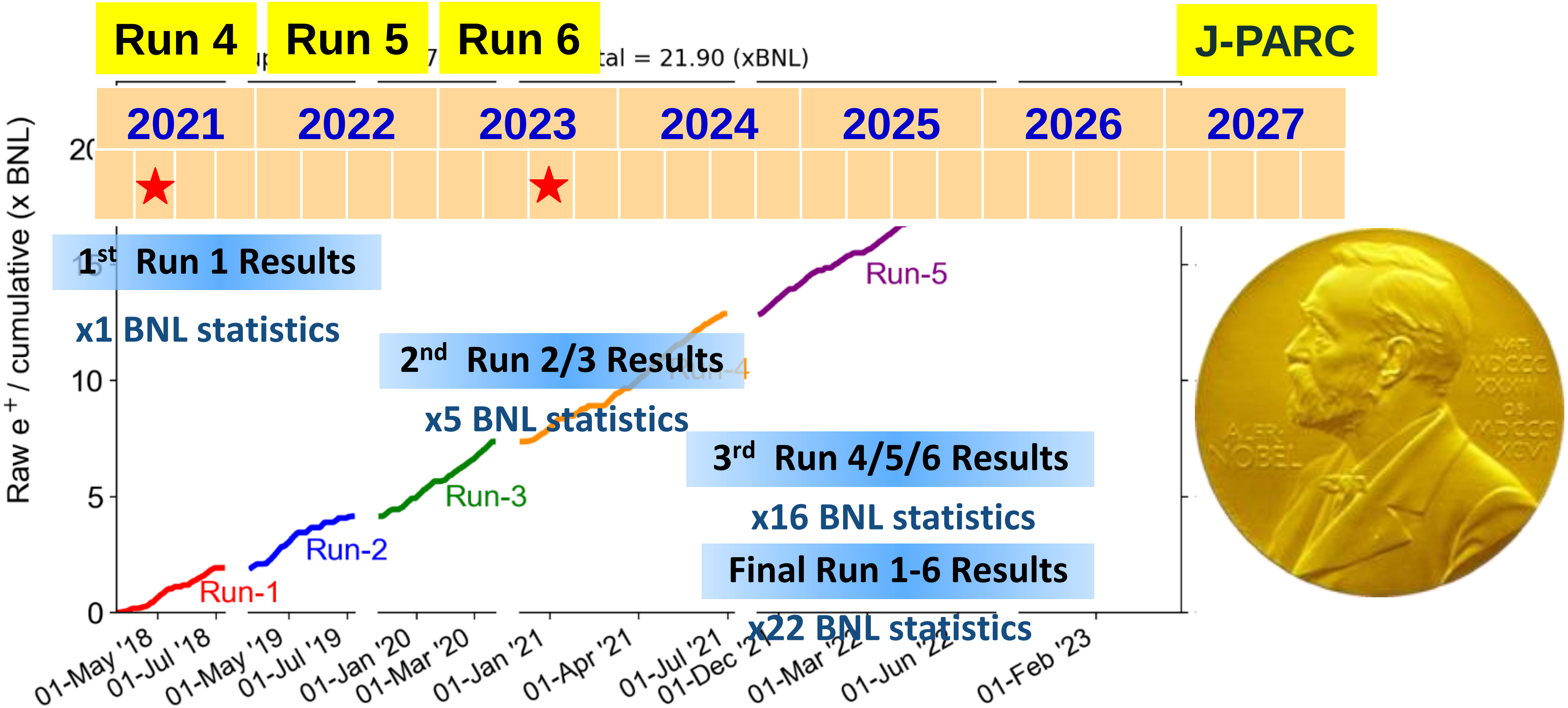


J-PARC

PAUL SCHERRER INSTITUT

PSI

总结和展望



1st Run 1 Results

x1 BNL statistics

2nd Run 2/3 Results

x5 BNL statistics

3rd Run 4/5/6 Results

x16 BNL statistics

Final Run 1-6 Results

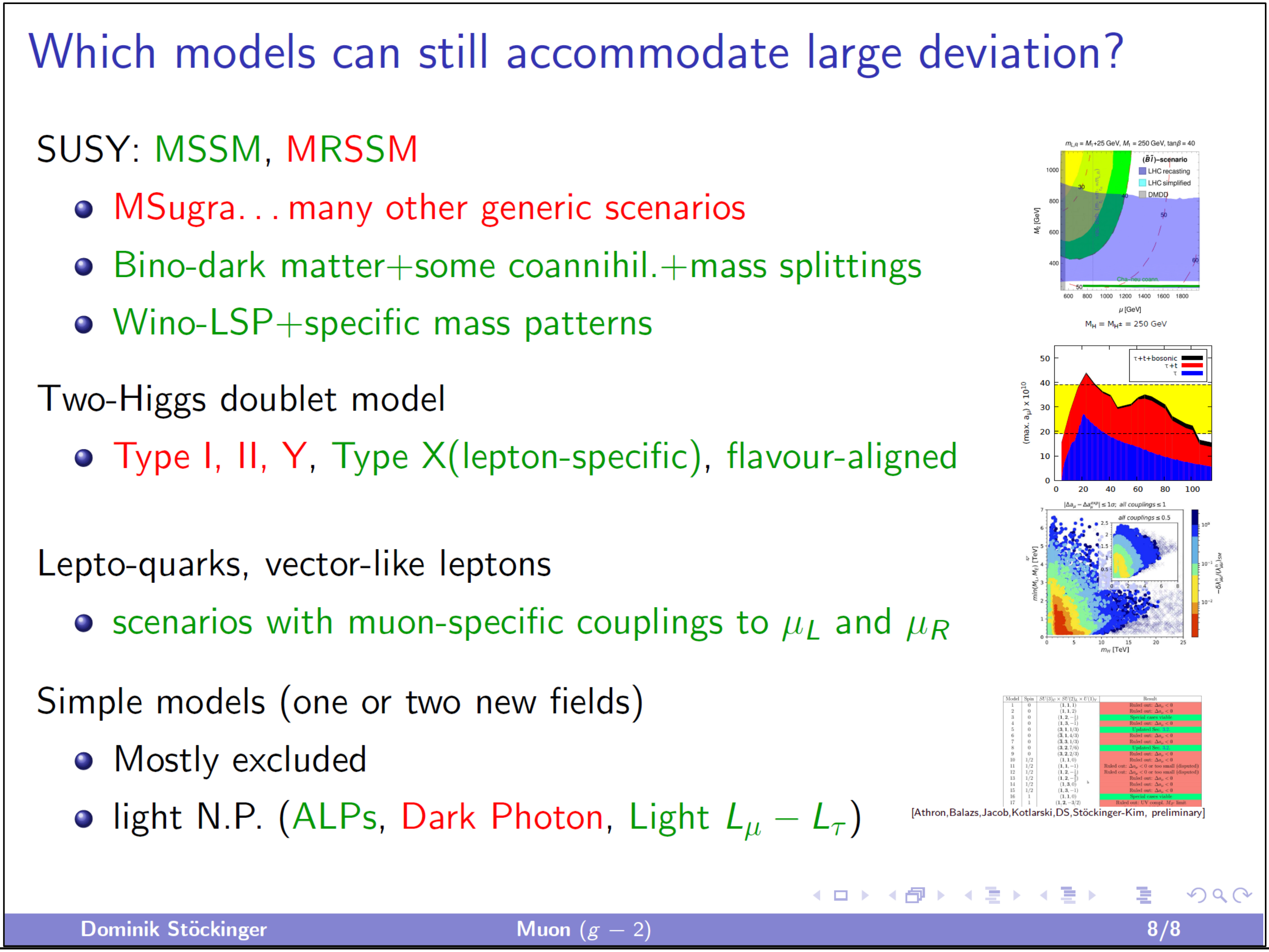
x22 BNL statistics

- ✓ 迄今为止最精确的缪子反常磁矩测量：千万分之二 （0.20ppm)
- ✓ 更精确的最终测量结果预计将于2025年发表
  - ✓ 实验测量值和理论预测值的精度同步提高, 大于5倍标准差的终极发现将吹响新物理革命的号角！
- ✓ 在多个方向对新物理敏感: 电偶极矩EDM, 对称性破缺CPT/LV以及暗物质的寻找
- ✓ 日本的J-PARC缪子反常磁矩实验预计于2028年取数
- ✓ 中国的首个强流缪子源正在建设（东莞），预计2030年左右完成

Backup

BSM Physics

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 $L_\mu - L_\tau$)

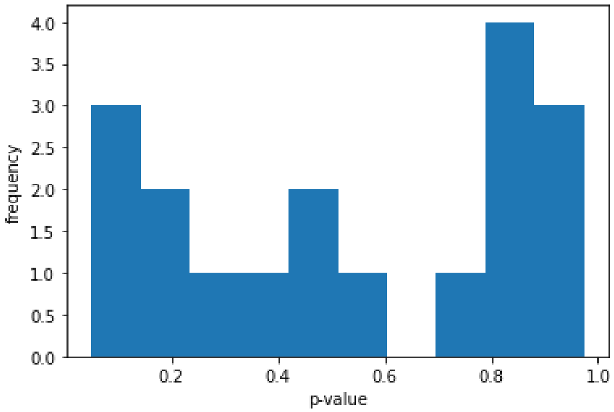
Model	Spin	$SU(3)_C \times SU(2)_L \times U(1)_Y$	Result
1	0	$(\mathbf{1},\mathbf{1},1)$	Ruled out: $\Delta a_\mu < 0$
2	0	$(\mathbf{1},\mathbf{1},2)$	Ruled out: $\Delta a_\mu < 0$
3	0	$(\mathbf{1},\mathbf{2},-\frac{1}{2})$	Special cases viable
4	0	$(\mathbf{1},\mathbf{3},-1)$	Ruled out: $\Delta a_\mu < 0$
5	0	$(\mathbf{3},\mathbf{1},1/3)$	Updated Sec. 3.2.
6	0	$(\overline{\mathbf{3}},\mathbf{1},4/3)$	Ruled out: $\Delta a_\mu < 0$
7	0	$(\overline{\mathbf{3}},\mathbf{3},1/3)$	Ruled out: $\Delta a_\mu < 0$
8	0	$(\mathbf{3},\mathbf{2},7/6)$	Updated Sec. 3.2.
9	0	$(\mathbf{3},\mathbf{2},2/3)$	Ruled out: $\Delta a_\mu < 0$
10	1/2	$(\mathbf{1},\mathbf{1},0)$	Ruled out: $\Delta a_\mu < 0$
11	1/2	$(\mathbf{1},\mathbf{1},-1)$	Ruled out: $\Delta a_\mu < 0$ or too small (disputed)
12	1/2	$(\mathbf{1},\mathbf{2},-\frac{1}{2})$	Ruled out: $\Delta a_\mu < 0$ or too small (disputed)
13	1/2	$(\mathbf{1},\mathbf{2},-\frac{3}{2})$	Ruled out: $\Delta a_\mu < 0$
14	1/2	$(\mathbf{1},\mathbf{3},0)$	Ruled out: $\Delta a_\mu < 0$
15	1/2	$(\mathbf{1},\mathbf{3},-1)$	Ruled out: $\Delta a_\mu < 0$
16	1	$(\mathbf{1},\mathbf{1},0)$	Special cases viable
17	1	$(\mathbf{1},\mathbf{2},-3/2)$	Ruled out: UV compl. $M_{Z'}$ limit

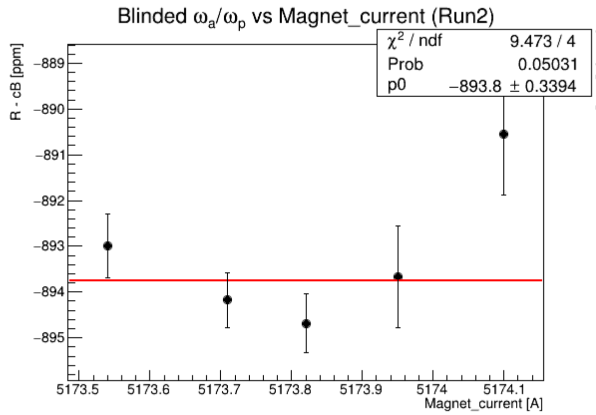
[Athron,Balazs,Jacob,Kotlarski,DS,Stöckinger-Kim, preliminary]

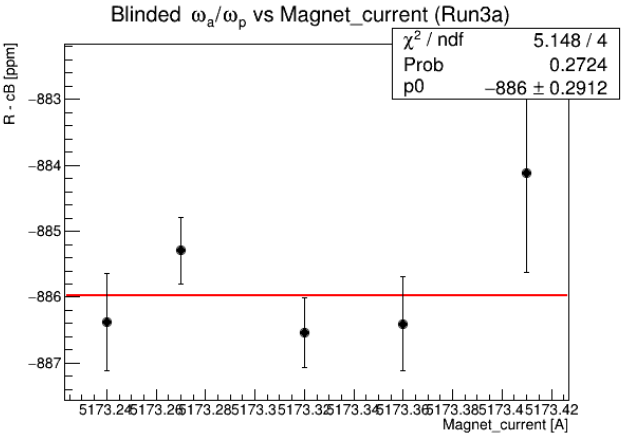
Dominik Stöckinger Muon $(g-2)$ 8/8

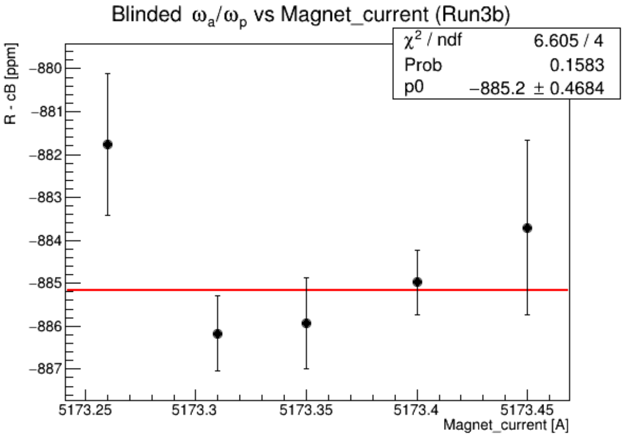
Data Consistency Check: Overall Results

	Run 2	Run 3a	Run 3b
Ring temperature	0.12	0.97	0.22
Time since magnet ramp up	0.80	0.82	0.47
Inflector current	0.76	0.38	0.59
Magnet current	0.05	0.27	0.16
Vacuum pressure	0.11	0.93	0.91
Day/Night split	0.85	0.48	0.82

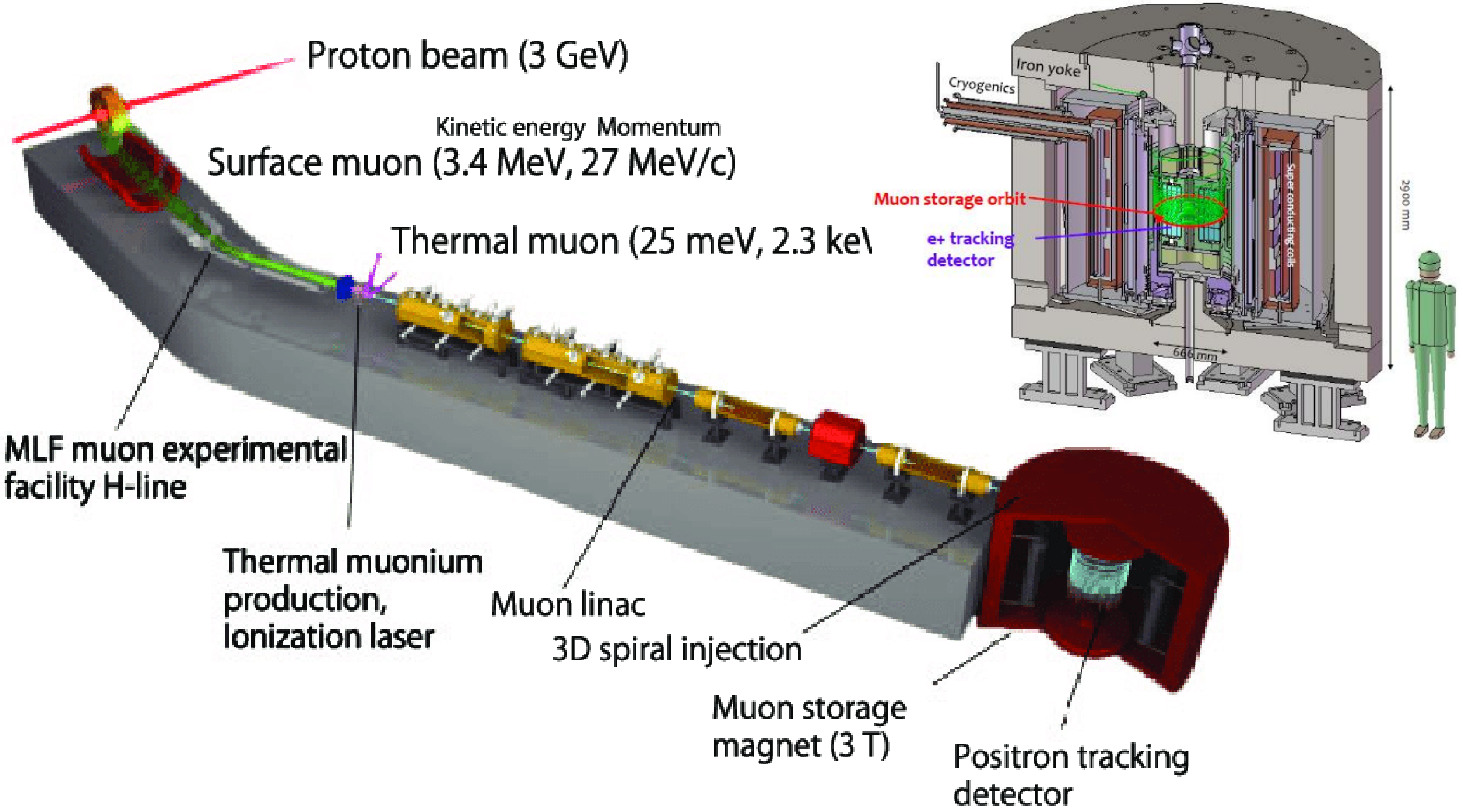








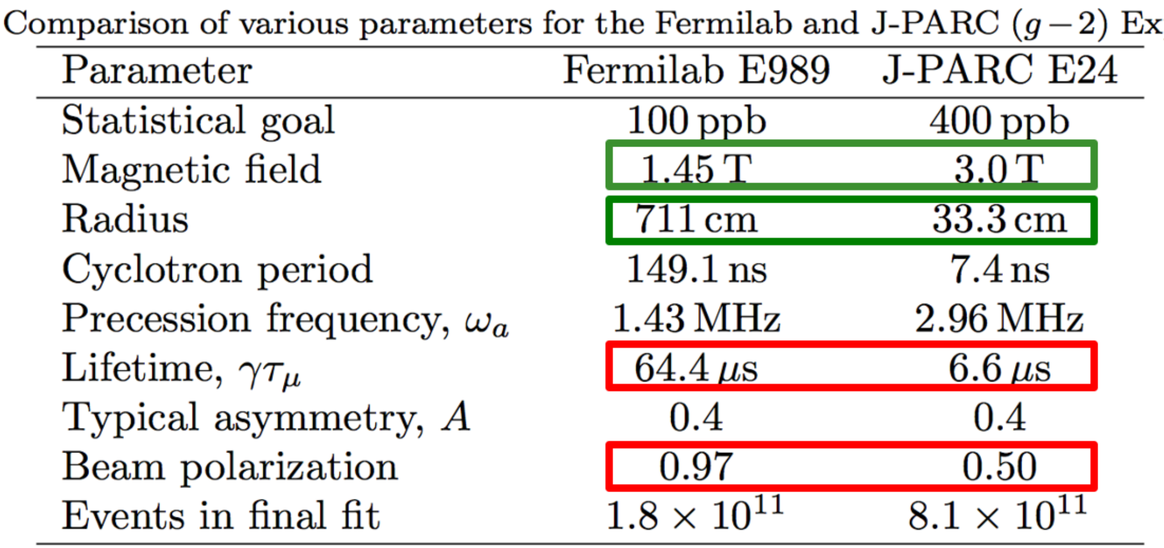
J-PARC g-2/EDM



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

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

J-PARC g-2/EDM

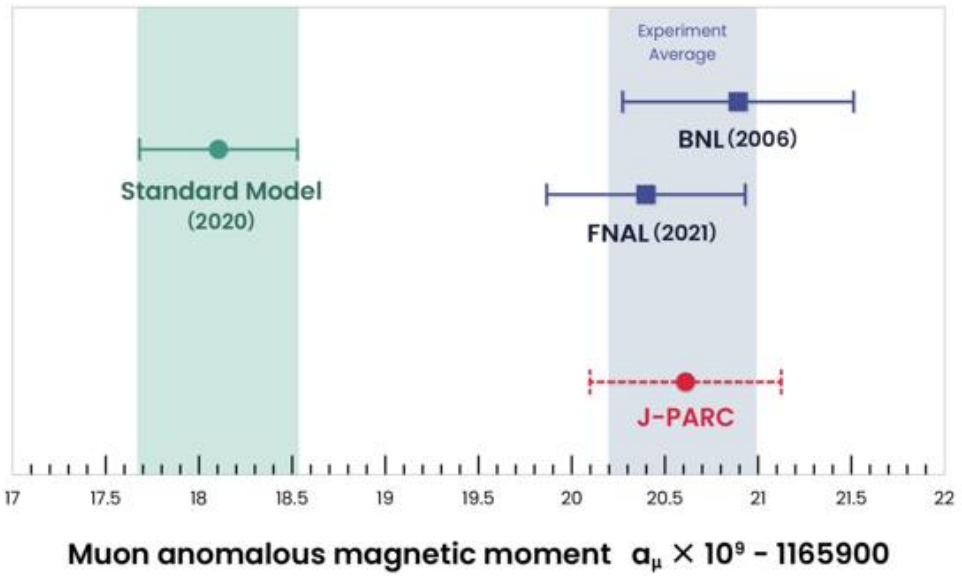


Comparison of various parameters for the Fermilab and J-PARC $(g-2)$ Experiments

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 including $\delta\omega_{a\_sys}$ < 0.1ppm**
- **δEDM = $1.5\cdot10^{-21}$e·cm**

TDR: 2017

KEK approval: 2021

Data taking: 2028?