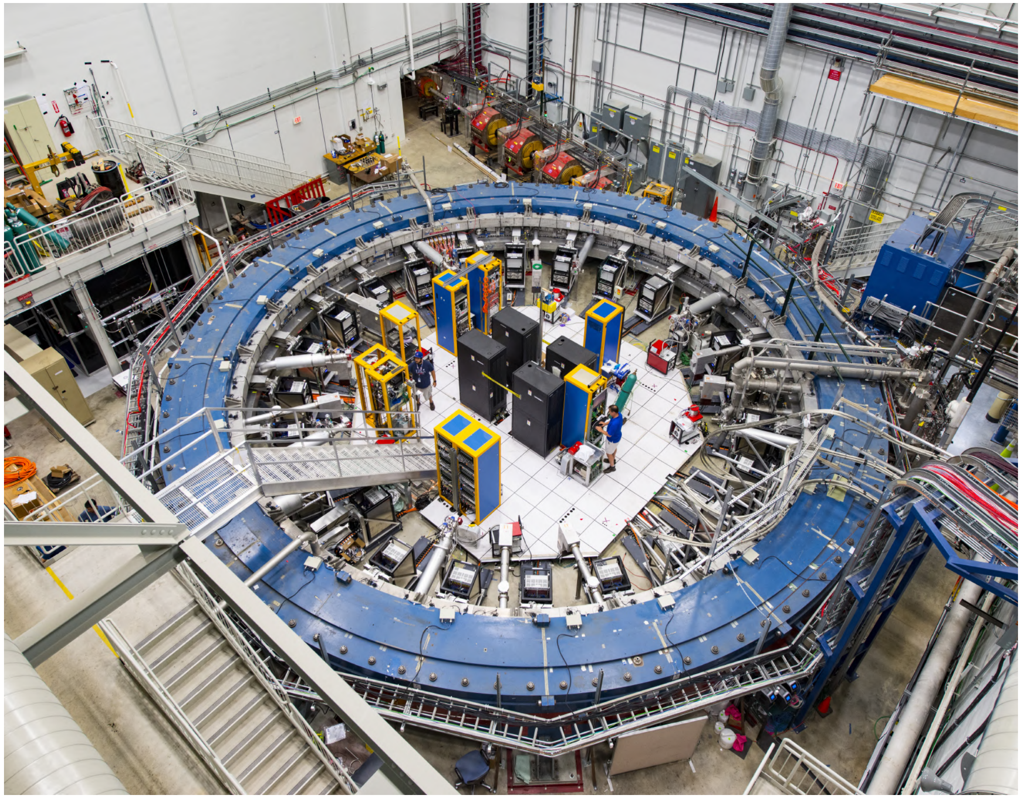


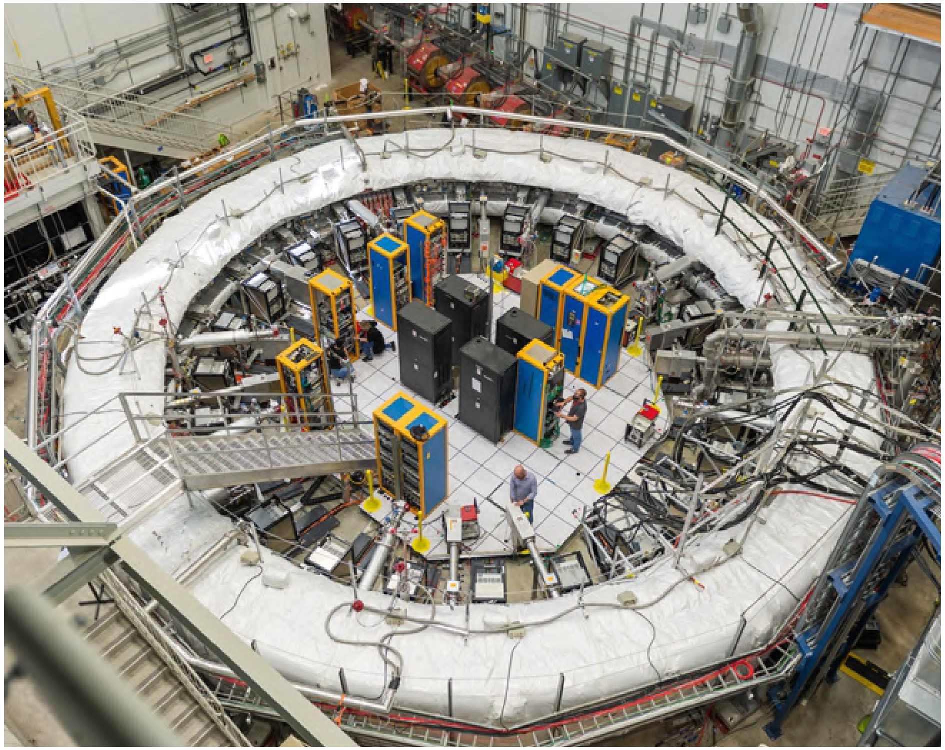
WP1: Muon g-2 overview

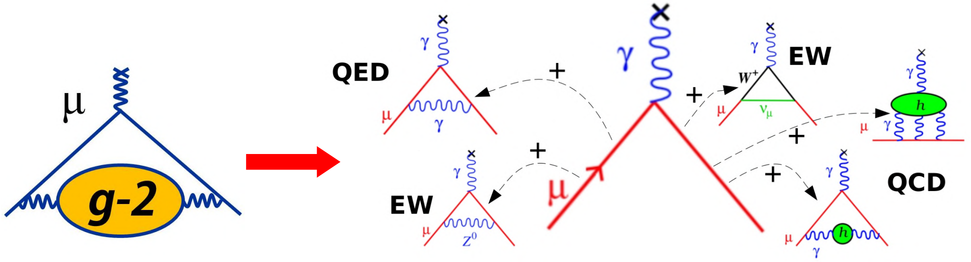
2024 aMUSE General Meeting
Padova, 17 Sep 2024

Paolo Girotti (INFN Pisa)
Dominik Stoeckinger (TU Dresden)

Muon g-2

- The muon anomaly **a_μ** encodes all the possible virtual interations
- E989: measure the muon anomaly to 140 parts per billion
- A discrepancy with the value predicted by the Standard Model would be a sign of new physics

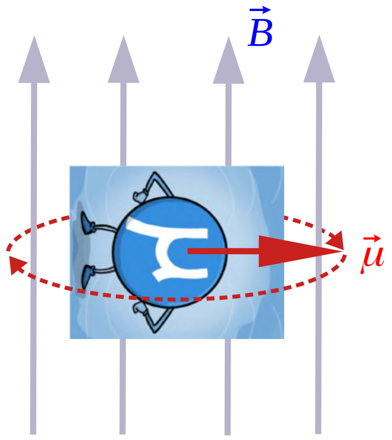




- BNL experiment found 3.7σ discrepancy with theory
- Repurposed the magnetic ring, upgraded everything else
- Took data from 2018 to 2023

Experimental technique

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

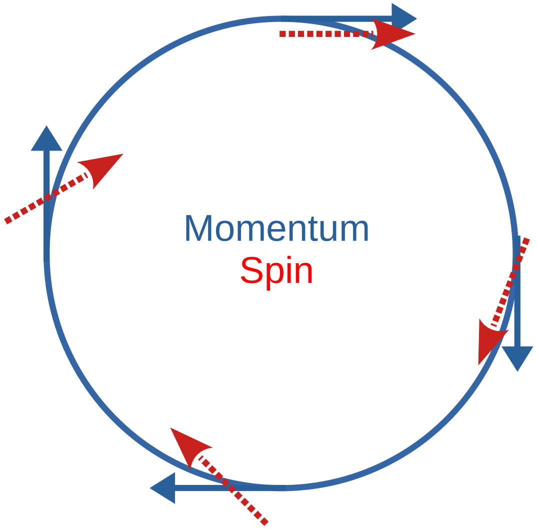


- In a magnetic storage ring, the muon spin precesses slightly faster than its cyclotron frequency

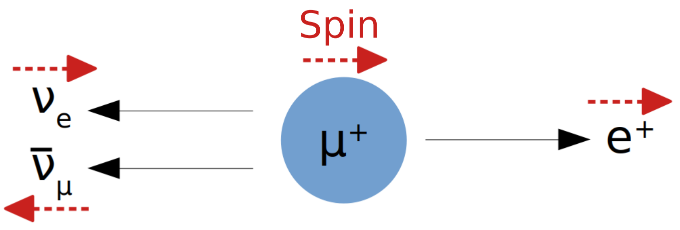
$$\vec{\omega}_s = -\frac{ge\vec{B}}{2m} - (1-\gamma)\frac{e\vec{B}}{m\gamma} > \vec{\omega}_c = -\frac{e\vec{B}}{m\gamma}$$

$$\vec{\omega}_a = \underline{\vec{\omega}_s} - \underline{\vec{\omega}_c} = -\left(\frac{g-2}{2}\right)\frac{e\vec{B}}{m} \equiv -\boxed{a_\mu}\frac{e\vec{B}}{m}$$

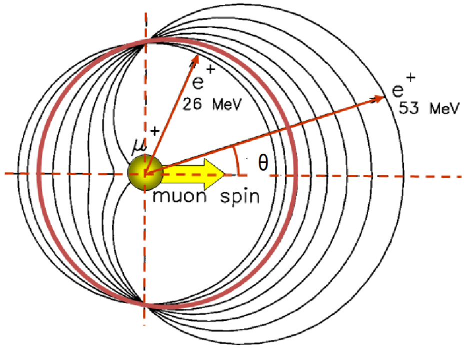
- This “anomalous” precession frequency is proportional to g-2 and to the magnetic field
- <u>ω_a is entirely due to the virtual interactions between the muon and the field</u>
- Measure $\boldsymbol{\omega_a}$ and **B** → obtain $\boxed{\mathbf{a_\mu}}$



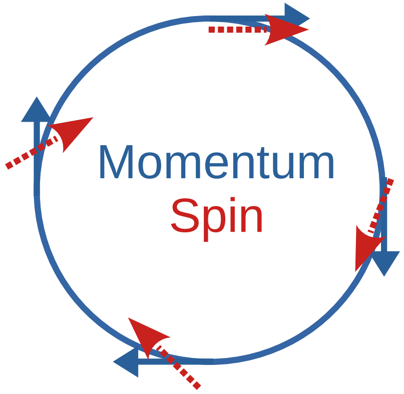
Measurement principle



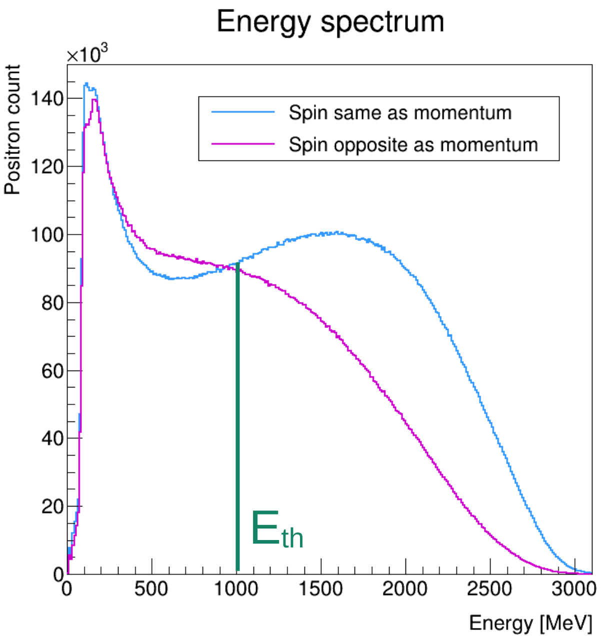
Muon decays in a positron and 2 neutrinos



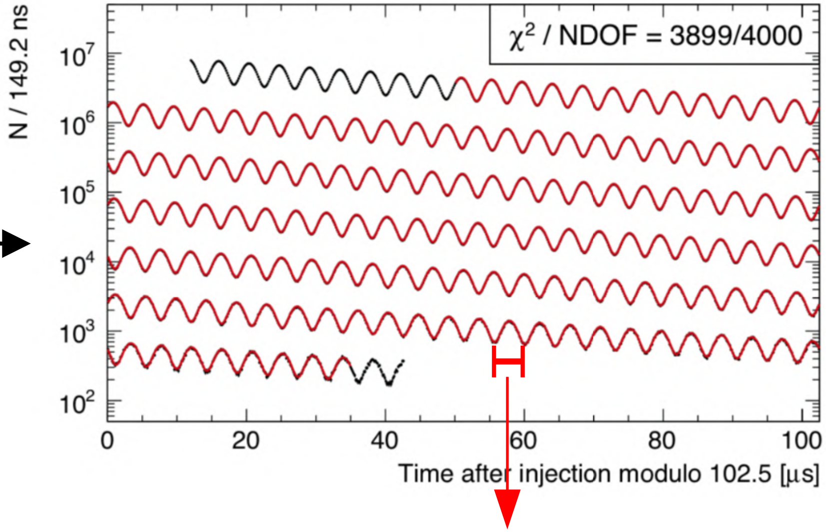
Parity violation → positrons emitted preferably in the direction of the muon spin



Spin precession → the e^+ spectrum in the lab frame **oscillates** through time



Integral above E_{th}



g-2 frequency

Formula

$$\vec{\omega}_a = a_\mu \frac{e\vec{B}}{m} \longrightarrow a_\mu = \frac{\omega_a}{\underbrace{\tilde{\omega}'_p(T_r)}}\boxed{\frac{\mu'_p(T_r)}{\mu_e}\frac{m_\mu}{m_e}\frac{g_e}{2}}$$

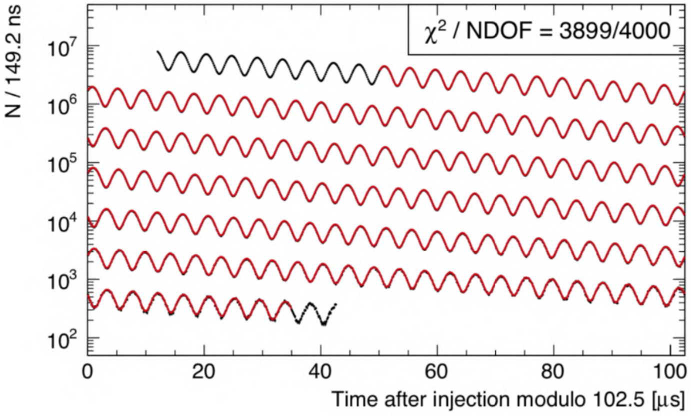
Constants known from other experiments with high precision (25 ppb)

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

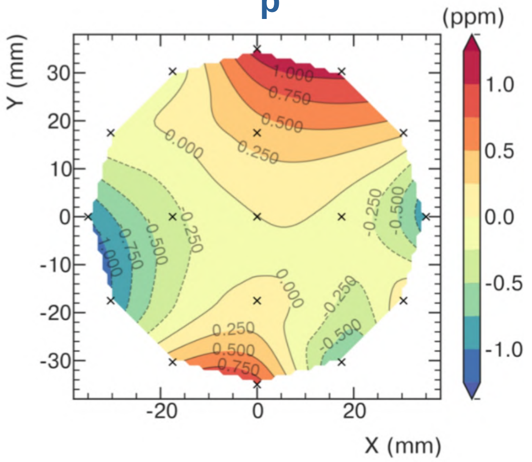
Three key measurements:

- **ω_a**: Muon anomalous precession frequency
- **ω_p**: Larmor precession frequency of protons (B field)
- **ρ_r**: Muon distribution

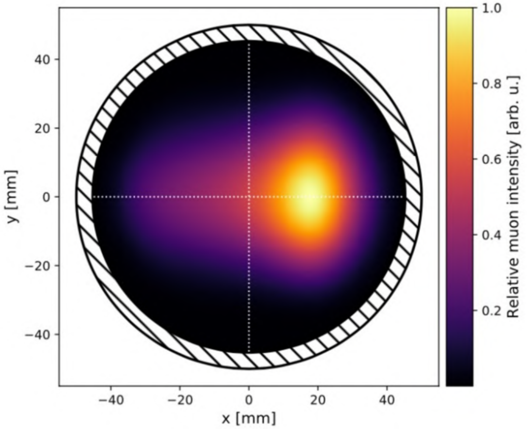
ω_a



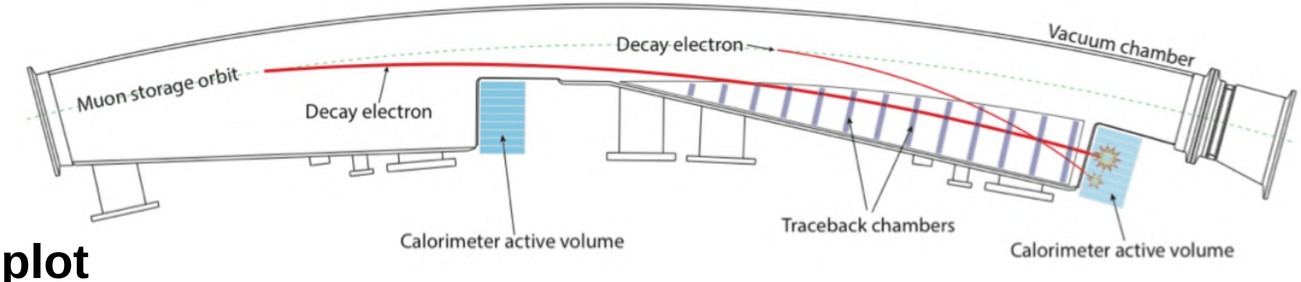
ω_p



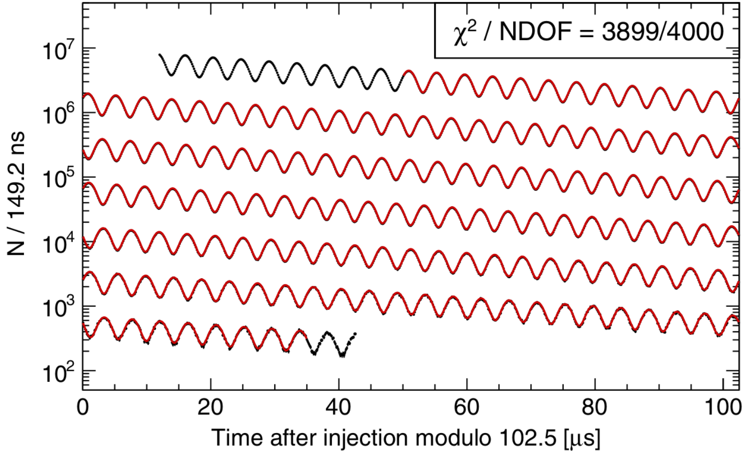
ρ(r)



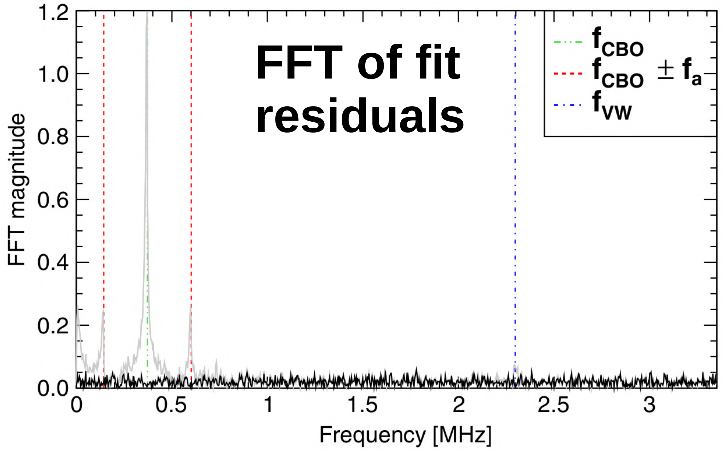
Measuring ω_a



Run-1 wiggle plot



- Positrons above 1 GeV are counted vs time and weighted by their asymmetry A(E)
- Histogram fitted with 27-parameter function
  - Muon precession and beam oscillations
- 7 independent blinded analyses to extract the muon anomalous precession frequency ω_a

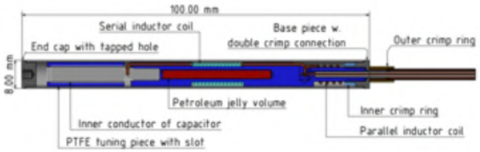


$$
\begin{aligned}
N(t) = {} & Ne^{-t/\tau_\mu}\left[1 + A\cdot\cos(\boxed{\omega_a} t - \phi + \phi_{BO}(t))\right]\cdot \\
& \cdot\left(1 + A_{CBO}\cos(\omega_{CBO}t - \phi_{CBO})e^{-\frac{t}{\tau_{CBO}}}\right)\cdot \longrightarrow \text{Horizontal betatron oscillation} \\
& \cdot\left(1 + A_{VW}\cos(\omega_{VW}t - \phi_{VW})e^{-\frac{t}{\tau_{VW}}}\right)\cdot \longrightarrow \text{Vertical waist} \\
& \cdot\left(1 + A_{2CBO}\cos(\omega_{2CBO}t - \phi_{2CBO})e^{-\frac{t}{\tau_{2CBO}}}\right)\cdot \longrightarrow \text{Horizontal breathing} \\
& \cdot\left(1 + A_y\cos(\omega_y t - \phi_y)e^{-\frac{t}{\tau_y}}\right)\cdot \longrightarrow \text{Vertical oscillation} \\
& \cdot\left(1 - k_{LM}\int_0^t L(t')e^{t'/\tau_\mu}dt'\right)\cdot \longrightarrow \text{Lost muons} \\
& \cdot\left(1 + [A_+\cos(\omega_+(t)t - \phi_+) + A_-\cos(\omega_-(t)t - \phi_-)]\,e^{-\frac{t}{\tau_{CBOVW}}}\right)
\end{aligned}
$$

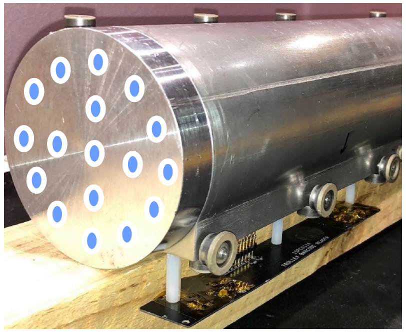
Measuring the field

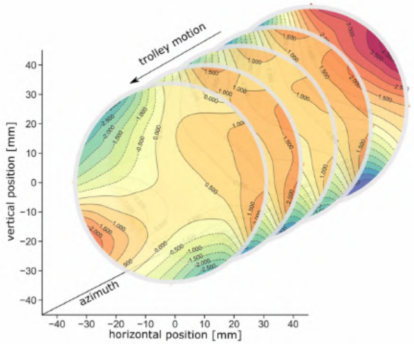
- Field intensity measured with Nuclear Magnetic Resonance (NMR) probes in terms of proton precession frequency ω_p
- Continuously monitored around the storage region and periodically measured inside the storage region

378 fixed probes continuous monitoring

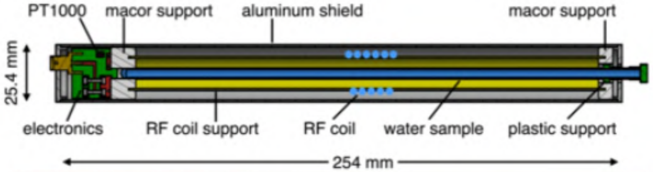


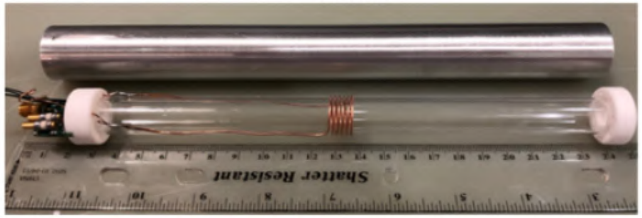
17 probes on a trolley to 3D map every ~3 days



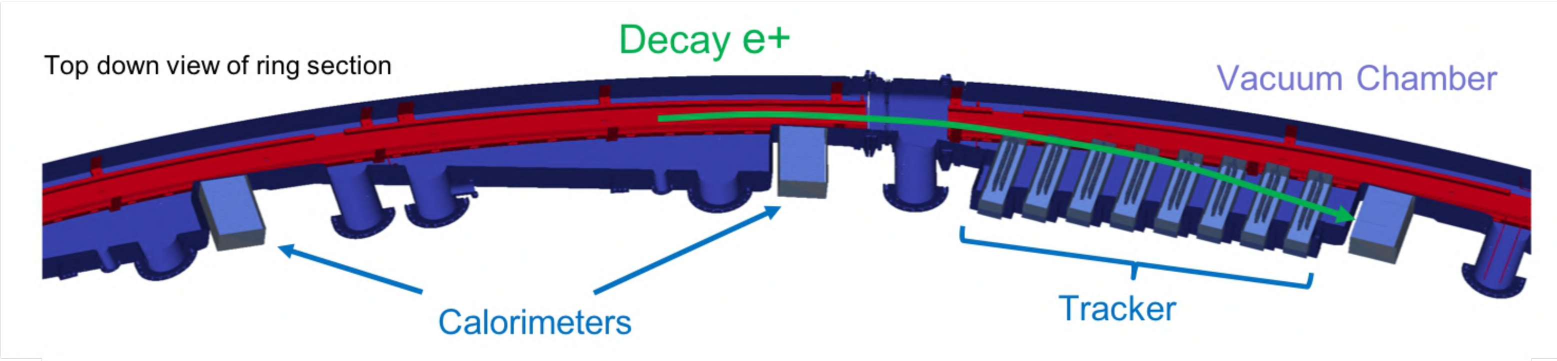


Trolley cross-calibrated to absolute probes

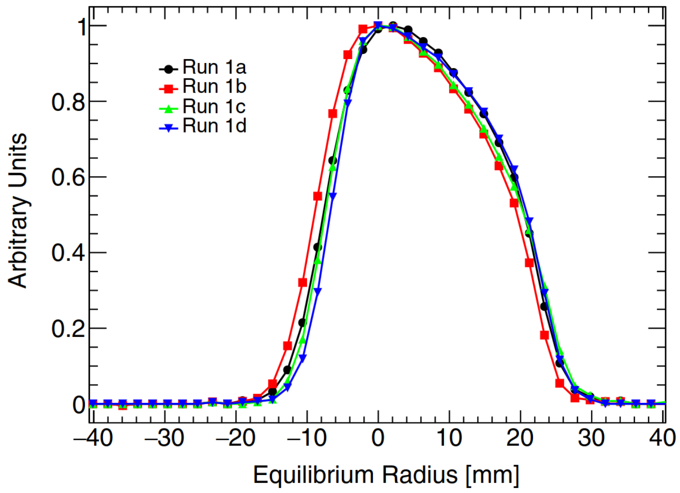


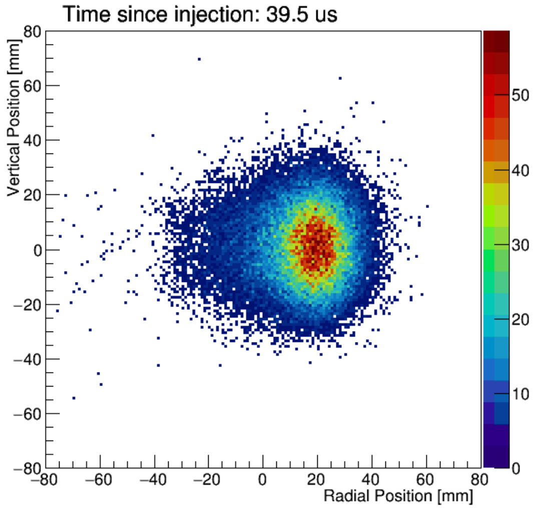


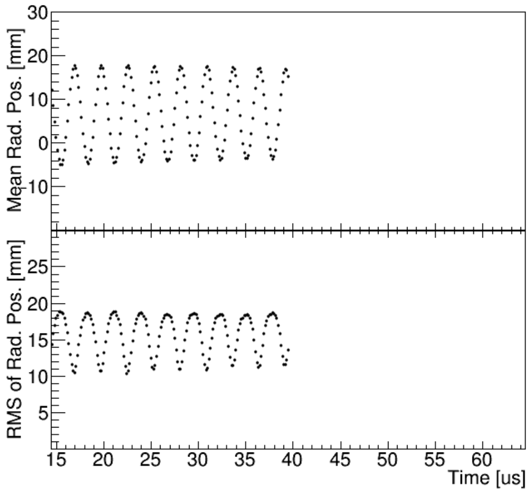
Measuring the beam



- Trackers at 180° and 270° reconstruct the positron trajectory to extrapolate the decay vertex in the storage region
- Muon distribution maps extrapolated to the entire ring azimuth with Geant4 simulation (gm2ringsim)
- Calorimeter hit energy matching to perform particle identification



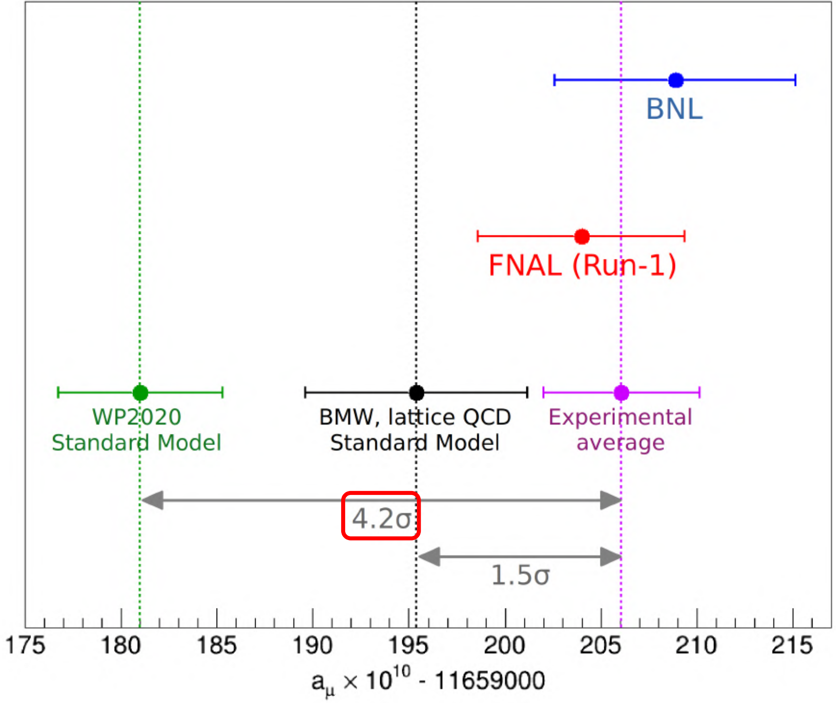




Run-1 result (2021)

- First **a_μ** measurement, 462 ppb, from 2018 data
- In agreement with BNL and increased tension with 2020 theory
- Great success and paved the way for subsequent analyses

https://doi.org/10.1103/PhysRevLett.126.141801



a_μ (FNAL) = 0.00116 592 040(54) [460 ppb]

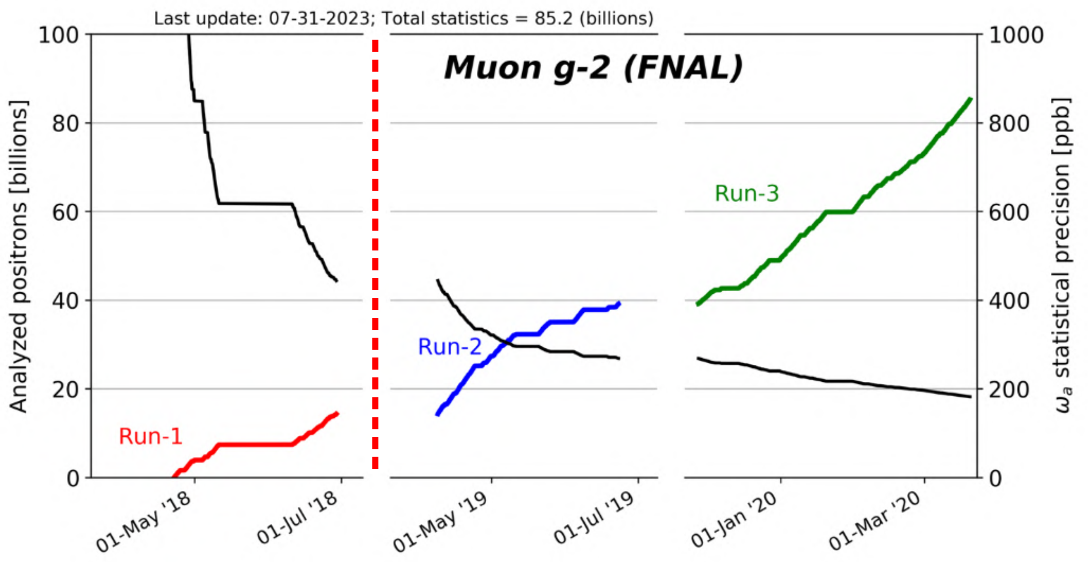
a_μ (World avg) = 0.00116 592 061(41) [350 ppb]

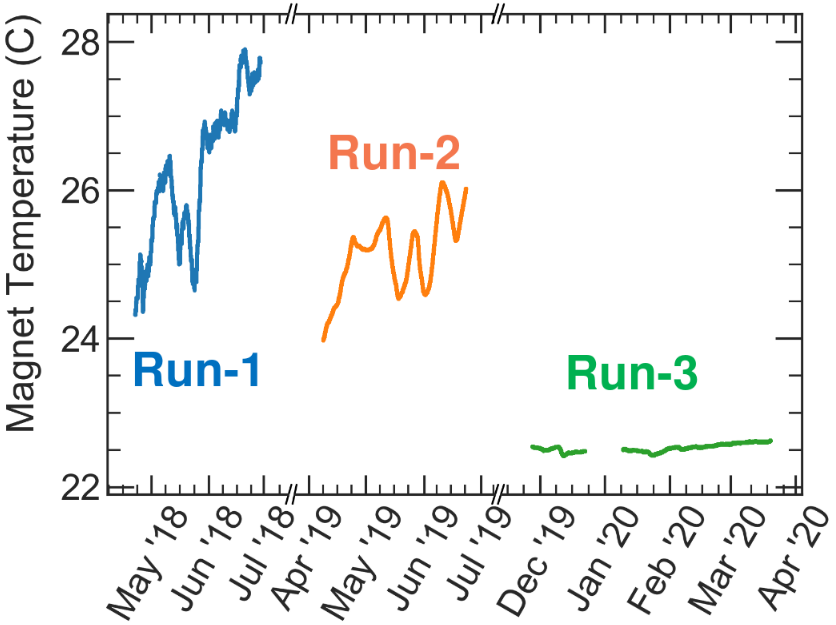
$$a_\mu \propto \frac{f_{clock}\,\omega_a^m\,(1 + C_e + C_p + C_{ml} + C_{pa})}{f_{calib}\,\langle\omega'_p(x,y,\phi) \times M(x,y,\phi)\rangle\,(1 + B_k + B_q)}$$

Quantity	Correction [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
$f_{calib}\langle\omega'_p(x,y,\phi) \cdot M(x,y,\phi)\rangle$	-	56
B_q	-17	92
B_k	-27	37
μ'_p/μ_e	-	10
m_μ/m_e	-	22
g_e	-	0
Total systematic	-	157
Total external factors	-	25
Total	544	462

Run-2/3

- 4.7x more data wrt Run-1
- Statistical error reduced from 434 ppb in Run-1 to 201 ppb in Run-2/3
- 185 ppb when combined

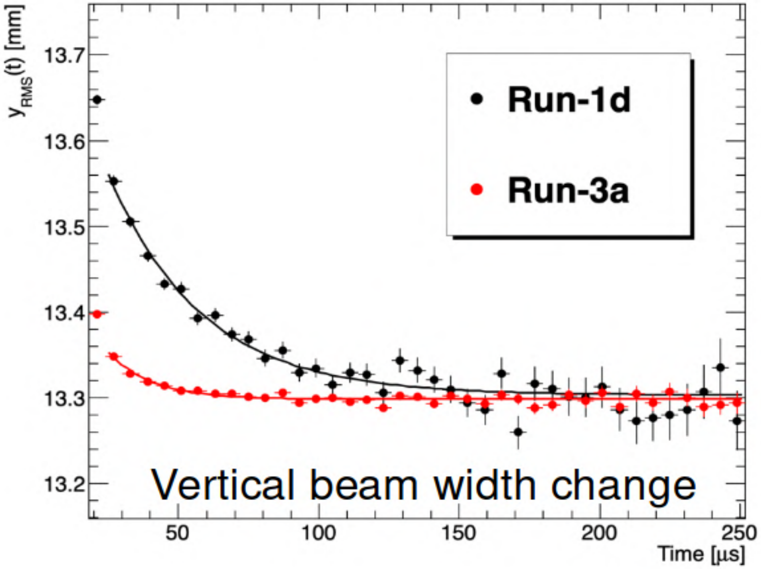


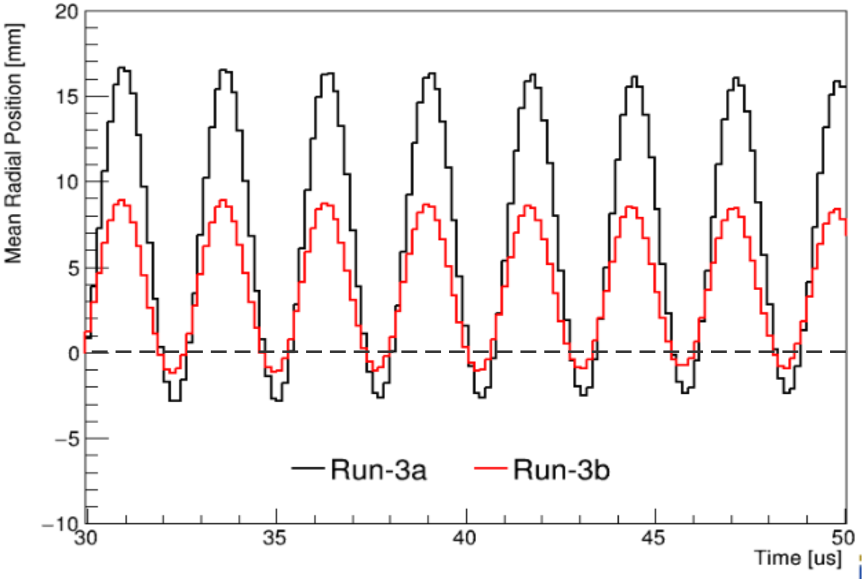


- Magnet blanket installed after Run-1 to mitigate day-night temperature fluctuations
- AC unit installed in experiment hall after Run-2 for complete temperature stability
- AC unit installed for laser hut too

Run-2/3

- Damaged quadrupole resistors in Run-1 have been re-designed and replaced before Run-2
- More stable beam storage
- C_{pa} uncertainty reduced by ~6x

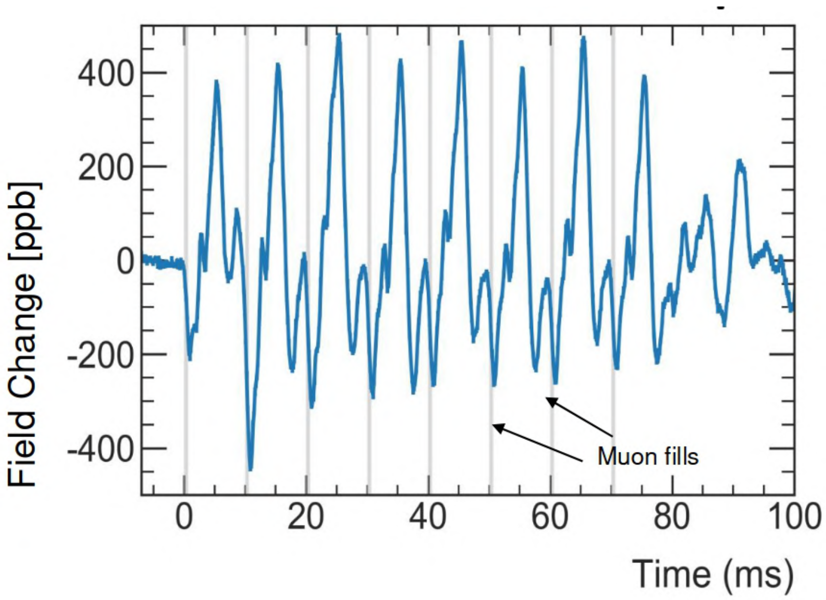


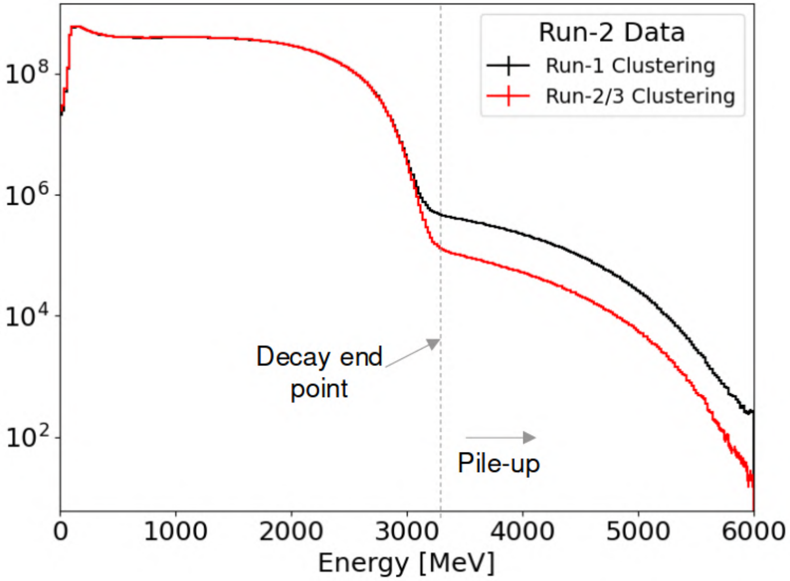


- Kicker upgraded and operated at nominal voltage toward the end of Run-3
- Beam distribution much more centered
- Smaller beam oscillations
- Lower beam dynamics corrections

Run-2/3

- Pulsing quadrupoles vibrate, generating an oscillating magnetic field
- New NMR probe to measure these oscillations at more locations
- 5x reduction of uncertainty with respect to Run-1

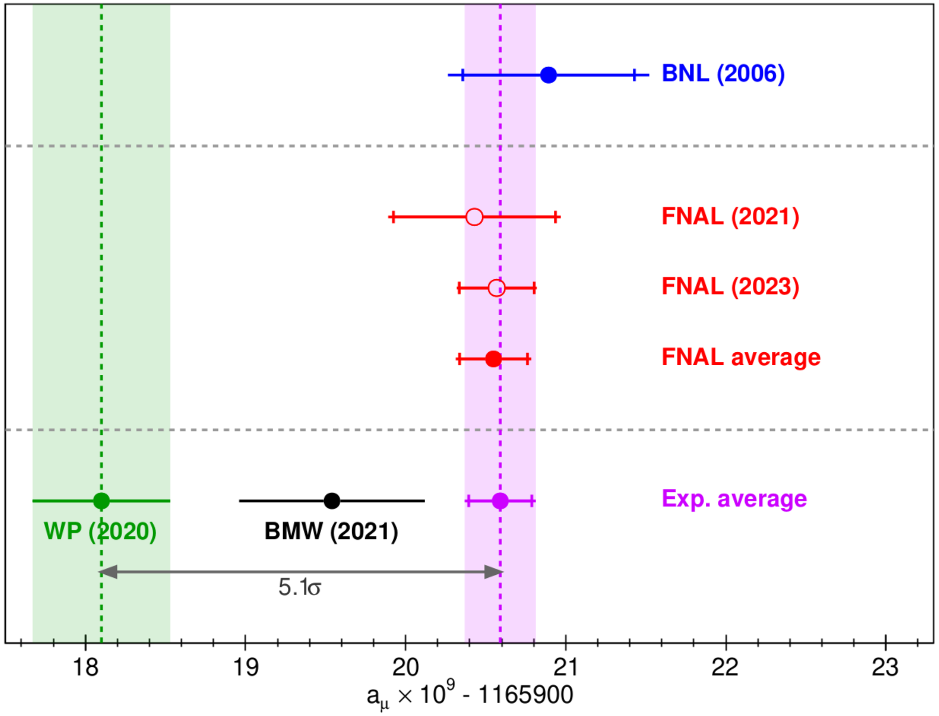




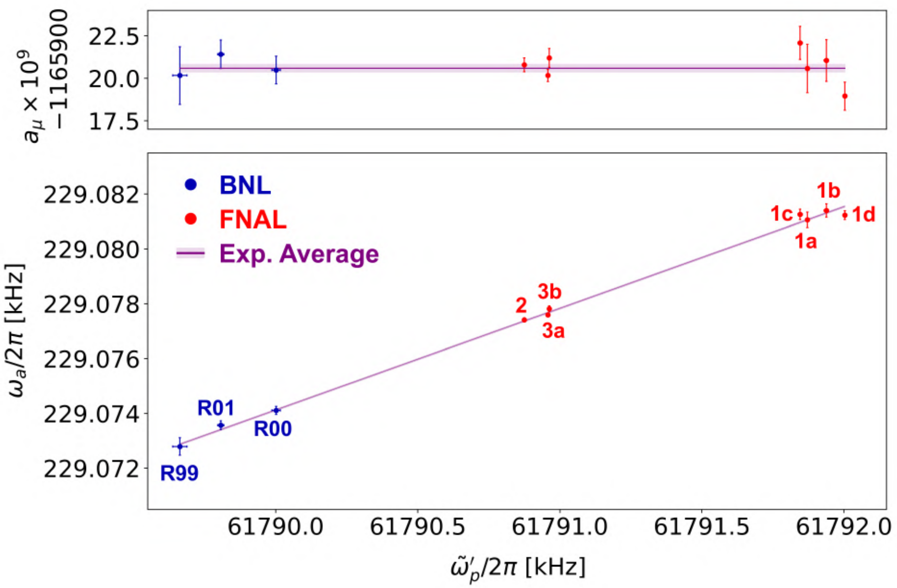
- Pileup is a major uncertainty for ω_a determination
- Improved positron reconstruction in calorimeter
- Improved pileup correction algorithms
- Uncertainty reduced by 5x

Run-2/3 result

- Run-2/3 measurement published on 10 Aug 2023
- Excellent **a_μ** agreement with Run-1
- Tension with data-driven theory (2020) at 5.1σ level



Measurements at different magnetic fields



a_μ (FNAL) = 0.00116 592 055(24) [203 ppb]

a_μ (World Avg) = 0.00116 592 059(22) [190 ppb]

Run-2/3 papers

PHYSICAL REVIEW LETTERS **131,** 161802 (2023)

Editors' Suggestion

Measurement of the Positive Muon Anomalous Magnetic Moment to 0.20 ppm

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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]
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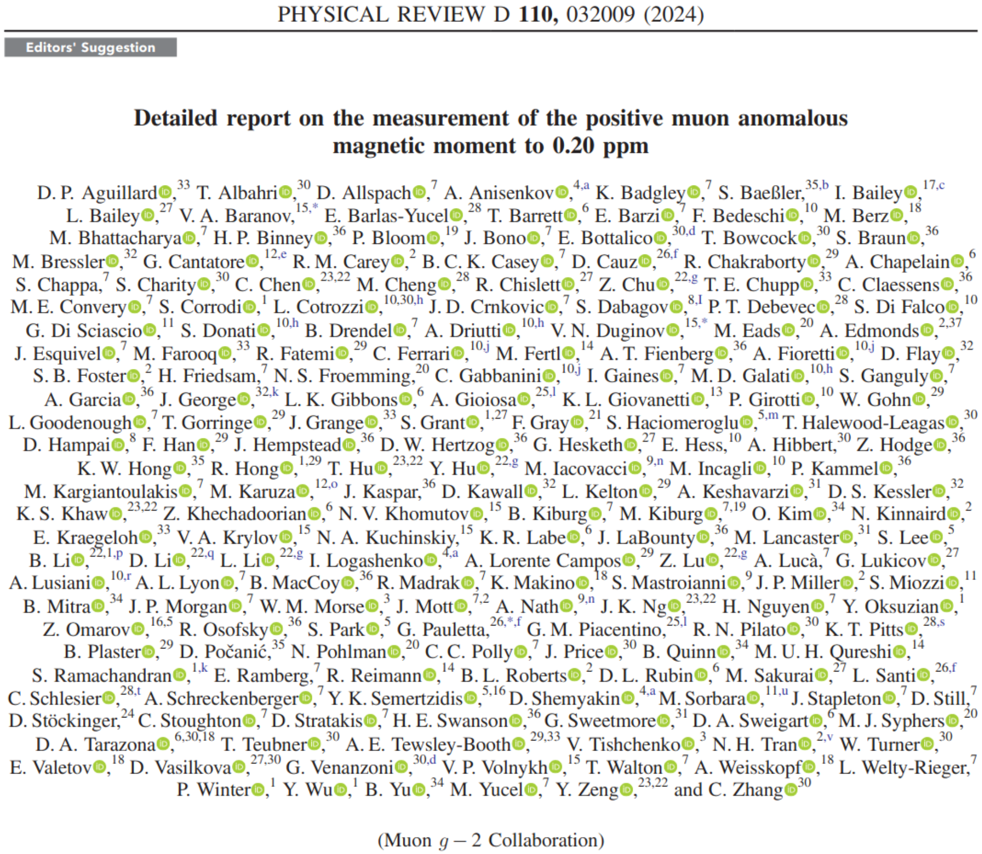
T. Gorringe,[29] J. Grange,[33] S. Grant,[1,27] F. Gray,[21] S. Haciomeroglu,[5,m] T. Halewood-Leagas,[30] D. Hampai,[8]
F. Han,[29] J. Hempstead,[36] D. W. Hertzog,[36] G. Hesketh,[27] E. Hess,[10] A. Hibbert,[30] Z. Hodge,[36] K. W. Hong,[35]
R. Hong,[29,1] T. Hu,[23,22] Y. Hu,[22,g] M. Iacovacci,[9,n] 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)



PHYSICAL REVIEW D **110,** 032009 (2024)

Editors' Suggestion

Detailed report on the 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]
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G. Di Sciascio,[11] S. Donati,[10,h] B. Drendel,[7] A. Driutti,[10,h] V. N. Duginov,[15,*] M. Eads,[20] A. Edmonds,[2,37]
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] S. Ganguly,[7]
A. Garcia,[36] J. George,[32,k] L. K. Gibbons,[6] A. Gioiosa,[25,l] K. L. Giovanetti,[13] P. Girotti,[10] W. Gohn,[29]
L. Goodenough,[7] T. Gorringe,[29] J. Grange,[33] S. Grant,[1,27] F. Gray,[21] S. Haciomeroglu,[5,m] 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,[1,29] 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]
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C. Schlesier,[28,t] A. Schreckenberger,[7] Y. K. Semertzidis,[5,16] D. Shemyakin,[4,a] M. Sorbara,[11,u] J. Stapleton,[7] D. Still,[7]
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D. A. Tarazona,[6,30,18] T. Teubner,[30] A. E. Tewsley-Booth,[29,33] V. Tishchenko,[3] N. H. Tran,[2,v] W. Turner,[30]
E. Valetov,[18] D. Vasilkova,[27,30] G. Venanzoni,[30,d] 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]

(Muon $g-2$ Collaboration)

https://doi.org/10.1103/PhysRevLett.131.161802

17 October 2023

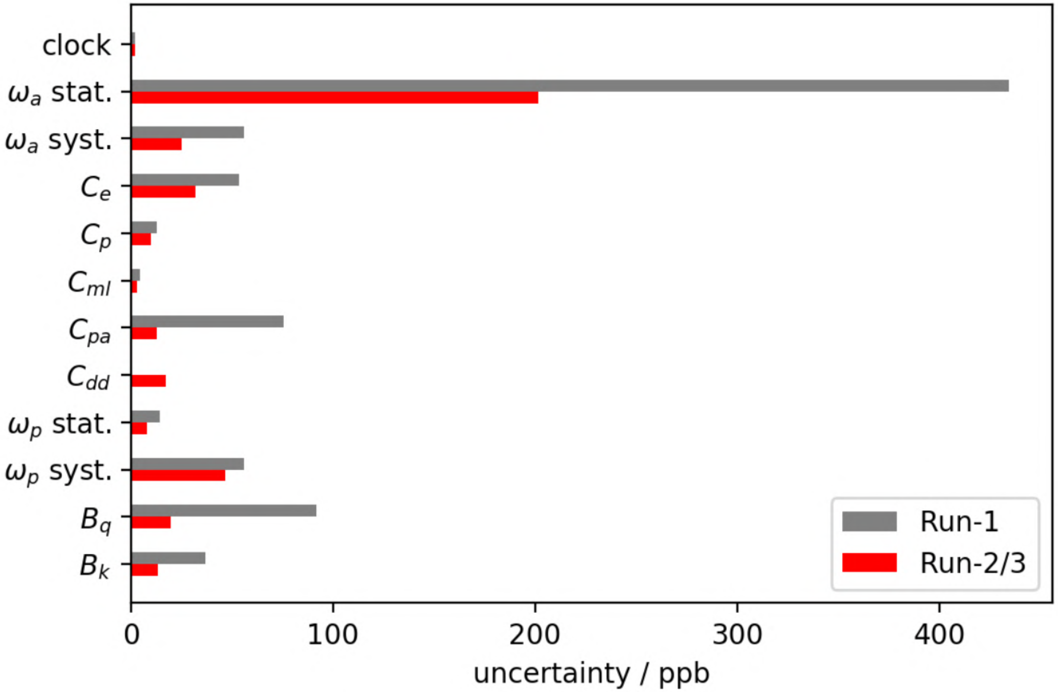
https://doi.org/10.1103/PhysRevD.110.032009

8 August 2024

Uncertainties

- Published results are still statistically limited
- Both statistical and systematic uncertainties have been halved from Run-1 to Run-23
- Total systematic uncertainty (70 ppb) exceeded design goal of 100 ppb
- Excellent performance of the apparatus

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



Uncertainties

ω_a systematics	BNL	FNAL TDR	FNAL Run-1	FNAL Run-2/3
Gain + residuals	120	20	19	11 *
Pileup	80	40	37	7 *
Lost muons	90	20	5	<4
CBO	70	30	40	21 *
E-field/pitch	50	30	55	34 *
Phase acceptance	-	-	75	13 *
Total ω_a	**180**	**70**	**108**	**41**

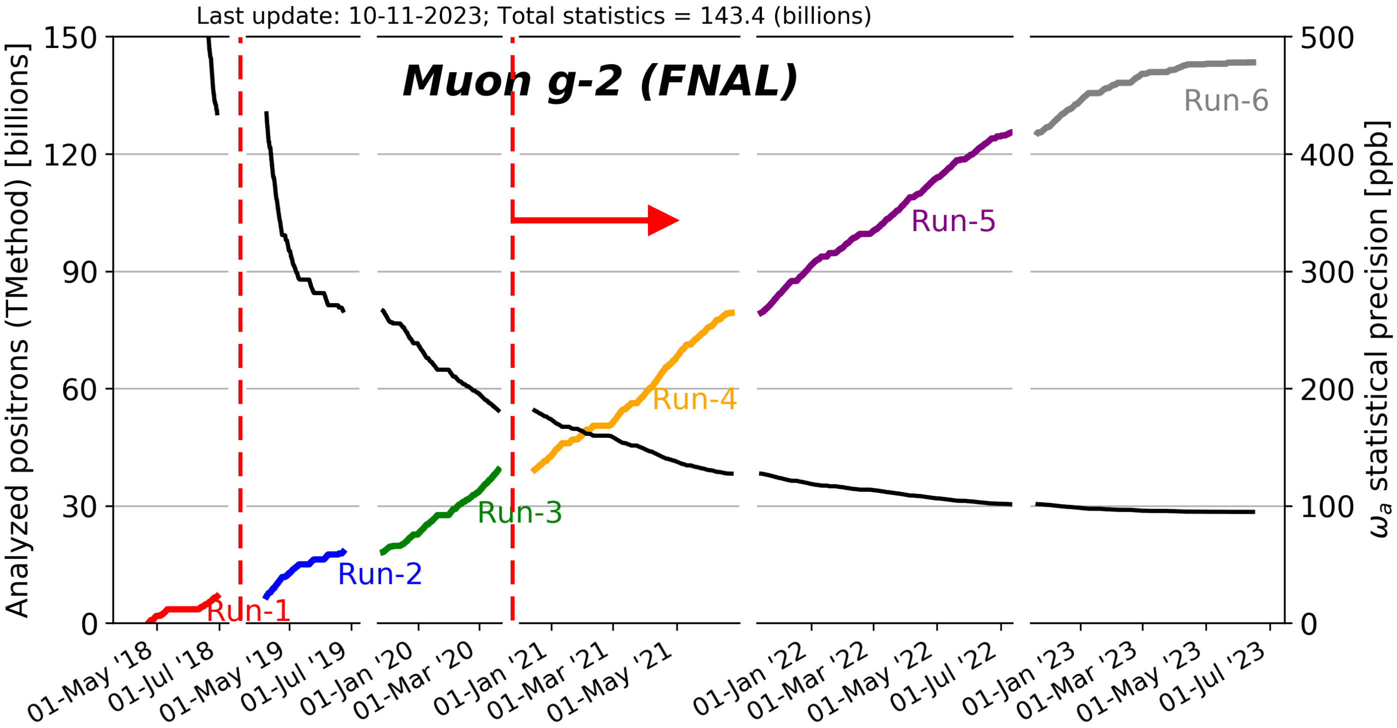
- Enourmous effort from the entire collaboration
- Crucial contribution from aMUSE researchers (*)

- All systematic uncertainties are now at or below the TDR level

ω_p systematics	BNL	FNAL TDR	FNAL Run-1	FNAL Run-2/3
Trolley calibration	90	30	32	18 *
Trolley meas	50	30	40	38
Fixed probes	70	30	23	17 *
Muon weighting	30	10	20	9
Absolute calib	50	35	19	9
Configuration	-	-	23	22 *
Kicker transients	-	-	37	13 *
Quad transients	-	-	92	20
Other	100	50	-	-
Total ω_p	**170**	**70**	**114**	**52**

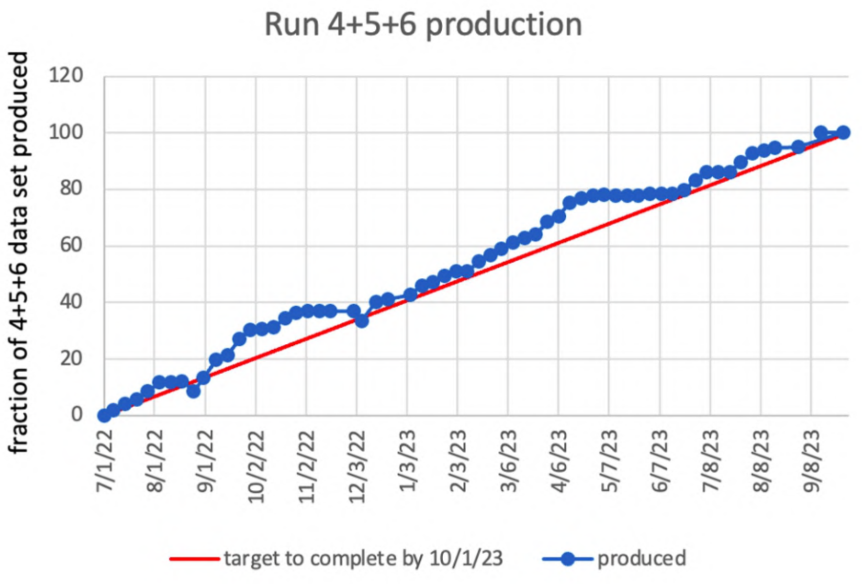
Run-4/5/6

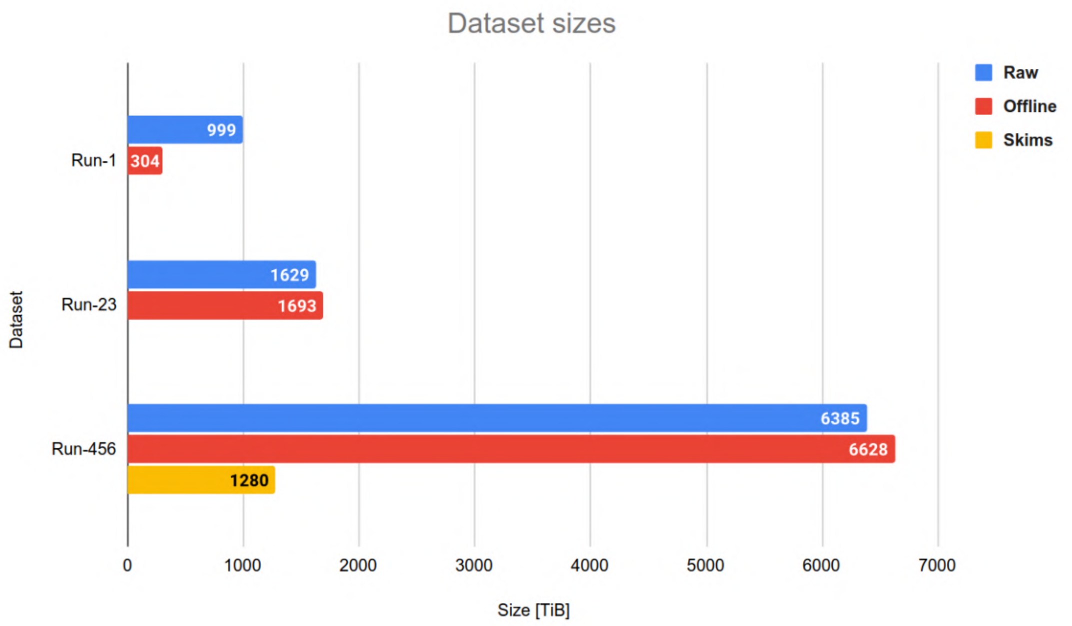
- Three more datasets taken from 2020 to 2023
- They account for ~70% of total statistics
- TDR goal achieved in February 2023
- Second half of Run-6 mostly dedicated to systematic studies
- Analysis in progress, final publication expected in 2025



Data production

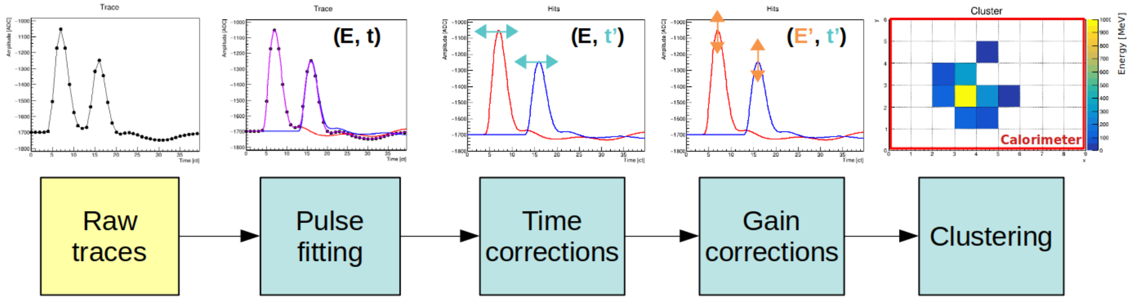
- Collaboration-wide effort to increase the production speed and efficiency and produce the large Run-456 datasets in time for analysis and publication schedule
- Production increased by ~5x with respect to Run-2
- Run-6 pre-produced in parallel with data acquisition (new!)
- New compact data skims to reduce the reconstructed output from 7 PB to 1.3 PB for faster and easier data analysis





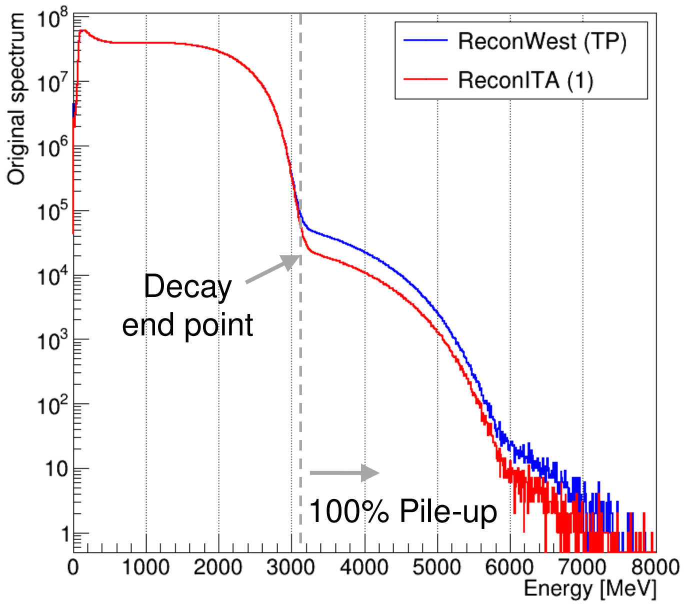
Reconstruction

- Three positron reconstructions techniques – a new one by INFN added since Run-4
- All have been upgraded to further improve pulse fitting and positron cluster separation
- Pileup has been reduced by 2x or more, and is no longer a dominant systematic
- Improved energy reconstruction accuracy



Raw traces → Pulse fitting → Time corrections → Gain corrections → Clustering

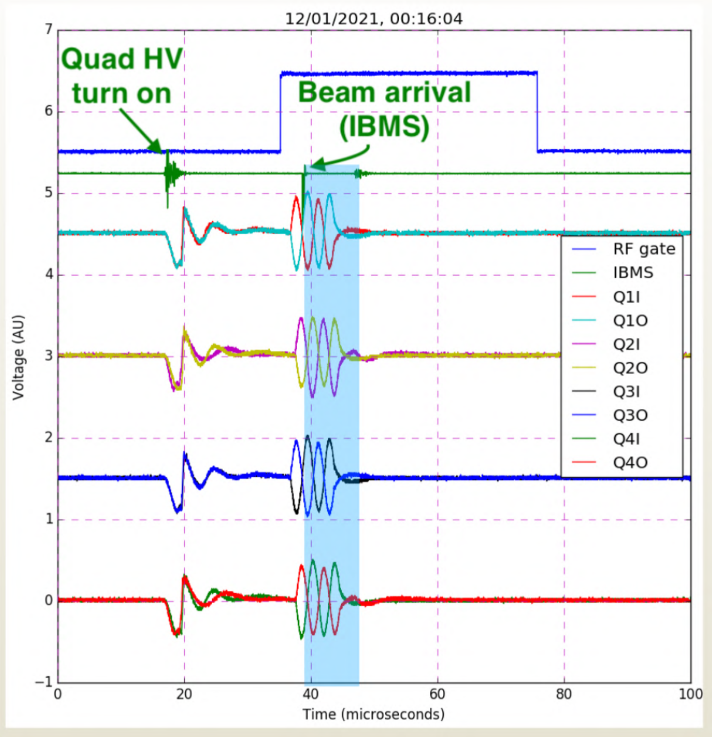
$$a_\mu \propto \frac{f_{clock}\,\boxed{\omega_a^m}\,(1 + C_e + C_p + C_{ml} + C_{pa})}{f_{calib}\,\langle \omega_p'(x,y,\phi) \times M(x,y,\phi)\rangle\,(1 + B_k + B_q)}$$

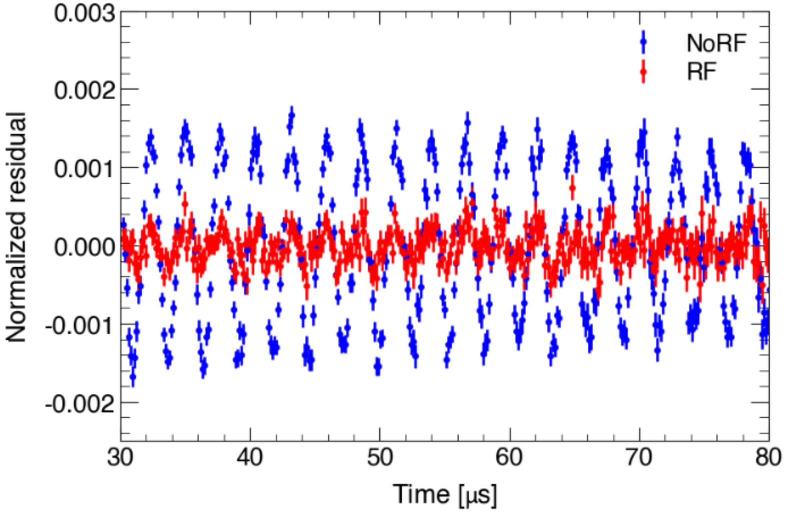


Quadrupole RF

- A quadrupole radio-frequency dampening system has been installed and tuned at the end of Run-4
- The RF pulsing scheme reduces the radial and vertical oscillations of the beam
- Turned on starting from Run-5
- Coherent Betatron Oscillation (CBO) amplitude reduced by factor ~9
- CBO systematic uncertainties, among the largest ones in Run-23, will be reduced
- However, analysis is slightly more complicated to fully characterize CBO frequencies

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

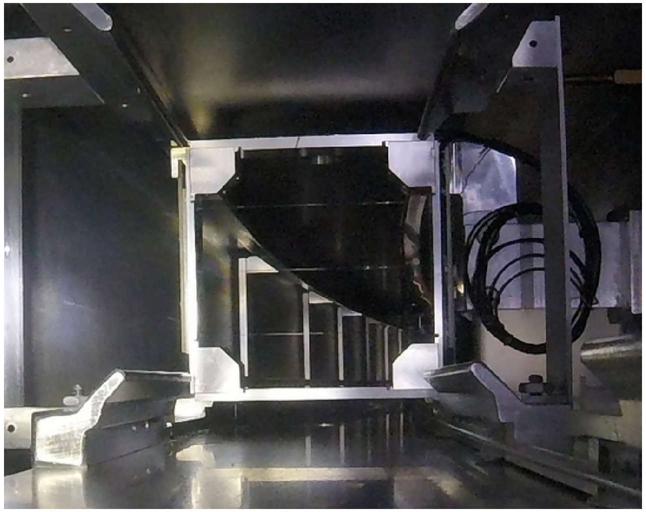


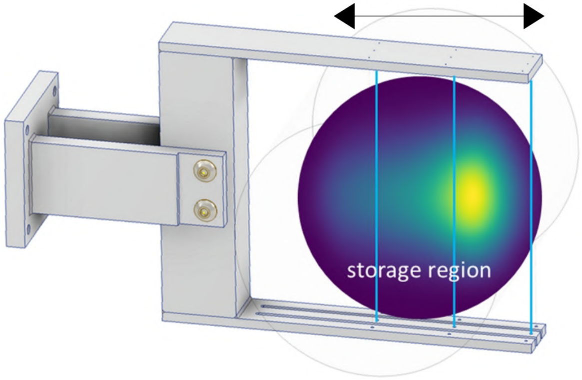


Mini-SciFi detector

- Two **Mini**mally intrusive **Sci**ntillating **Fi**ber detectors have been installed before Run-6 to measure the beam distribution distructively
- Fibers can be mechanically moved to scan the entire storage region
- Horizontal fibers to measure the decay time – momentum correlation and compare with calorimeter data
- Vertical fibers to measure the CBO envelope and phase, and measure the momentum distribution and compare with calorimeters/trackers
- Many successful campaigns during Run-6
- Analysis in progress…

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

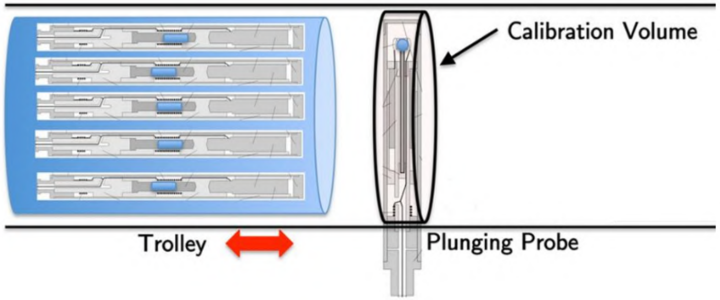


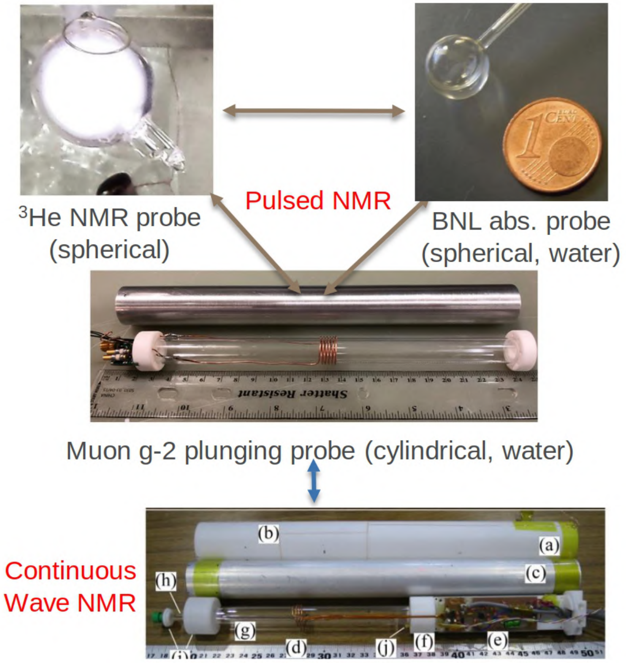


Field calibrations

- Excellent performance of field determinations in Run-23, already exceeding TDR goals
- Some improvements and cross checks in Run-456 analysis to increase trust in methods
- New test on absolute calibration with ^{3}He probe
- Cross calibration measurements with Japan collaboration
- Improved trolley position algorithms
- More systematic studies on time and configuration changes

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





Pulsed NMR

^{3}He NMR probe (spherical)

BNL abs. probe (spherical, water)

Muon g-2 plunging probe (cylindrical, water)

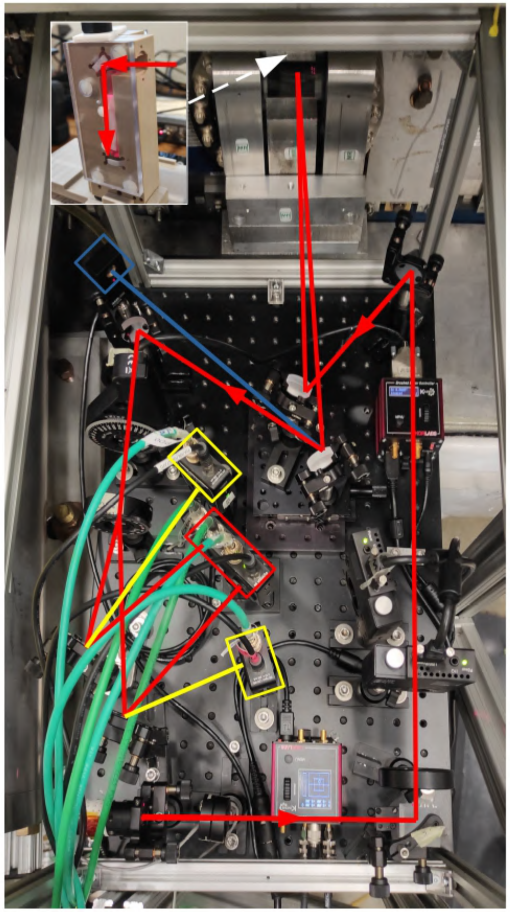
Continuous Wave NMR

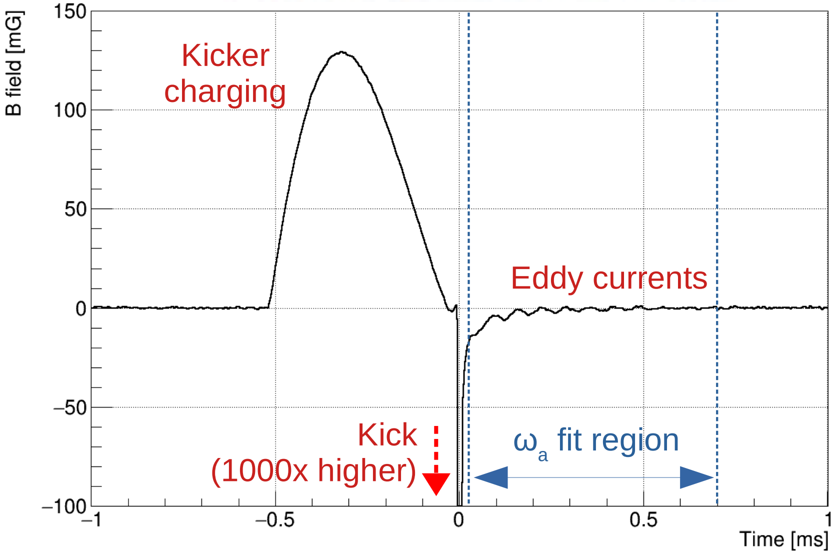
J-PARC NMR probe
Muon g-2/EDM and MuSEUM
(cylindrical, water)

Kicker transient

- The three kickers produce a 120 ns pulse to correct the injection orbit during the first turn
- However, they induce slowly decaying eddy currents in the surrounding aluminum
- Two Faraday magnetometers to measure the effect, one designed and operated by INFN since end of Run-5
- New studies on mechanical vibrations and measurements at multiple radial positions to improve estimate of Bk term

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





Projected uncertainties

- Run-4/5/6 statistics is ~3 times higher with respect to Runs 1-3
- Run-4/5/6 analysis is ongoing on all thrusts
- Systematic uncertainties are being evaluated right now
- What we can expect:

Run-23

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

~100 ppb for entire Runs 1-6

~10x reduction of CBO systematics
Pileup systematics reduced

New algorithms and new MiniSciFi detectors

New tracker-based analysis for cross checking

Improved analysis, calibration, and cross-checks

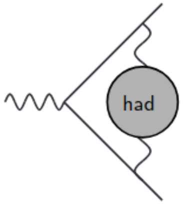
Improved measurements, cross checks, and spatial models

Already below TDR, possibly even better in Run-456!

Slide from Dominik S.

a_μ theory

Background: a_μ predicted in SM: all particles/all interactions relevant!

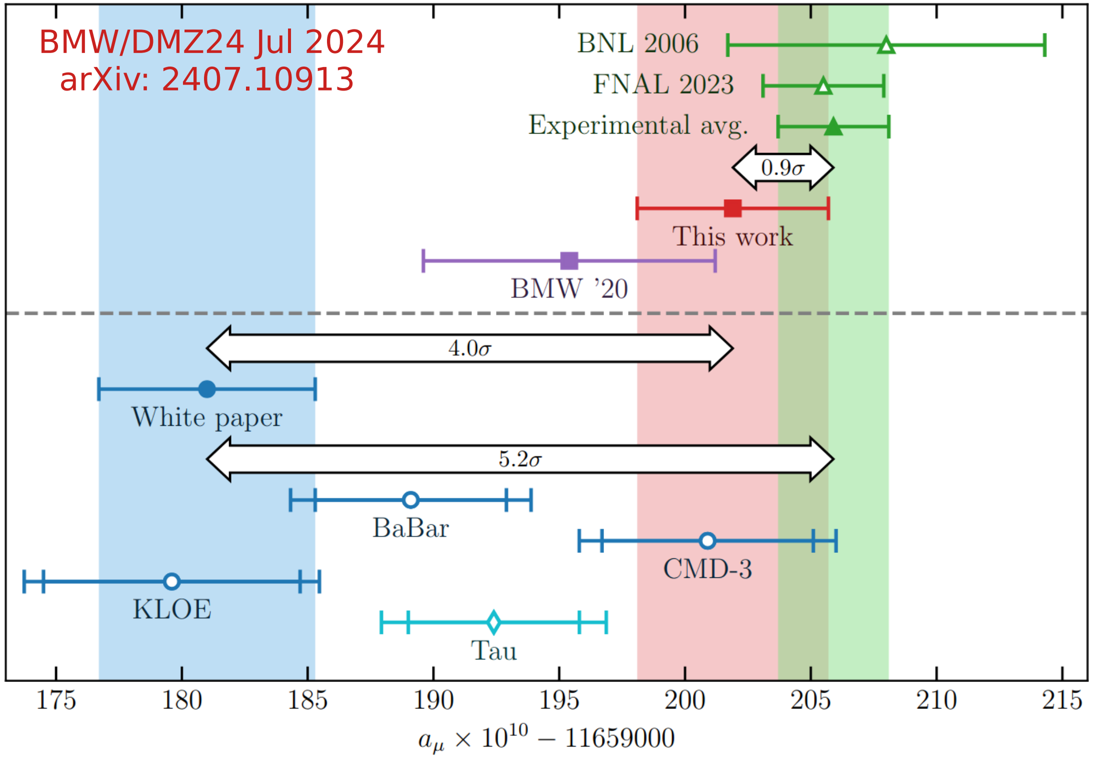


Critical:

hadronic vacuum polarization.

past: e^+e^- data (KLOE, Babar etc)

now also: lattice QCD


BMW/DMZ24 Jul 2024
arXiv: 2407.10913

Slide from Dominik S.

a_μ theory

Background: a_μ is crucial, unique constraint on new physics — complementary to LHC, flavour, dark matter physics

Given recent SM theory developments, we can ask: “What if. . . ”

. . . Δa_μ remains/comes back to 2021-value 25×10^{-10}:

strong BSM constraints

. . . Δa_μ reduces to 10×10^{-10}:

strong BSM constraints

. . . discrepancy with HVP remains:

BSM within HVP???

. . . Δa_μ reduces to 0:

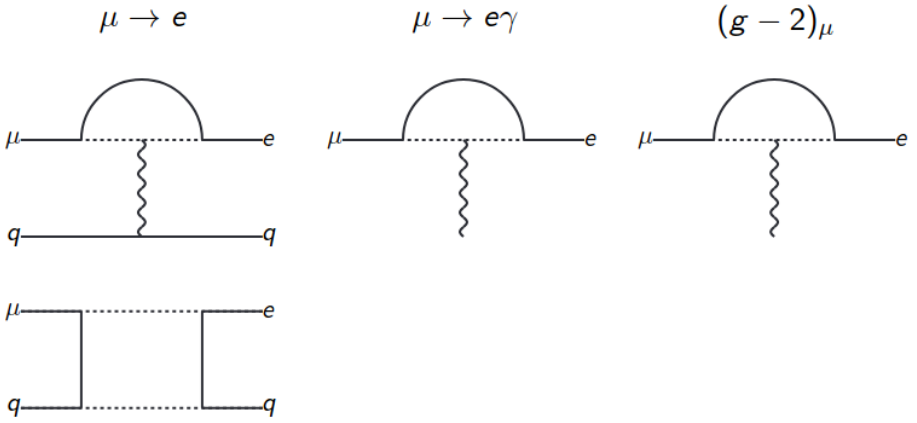
different kinds of BSM constraints

aMUSE Theorists contribute in all these respects:

Slide from Dominik S.

$\mu \to e$ and combined theory

Background: cLFV would be unambiguous sign for new physics — origin of flavour/generations, neutrino masses?

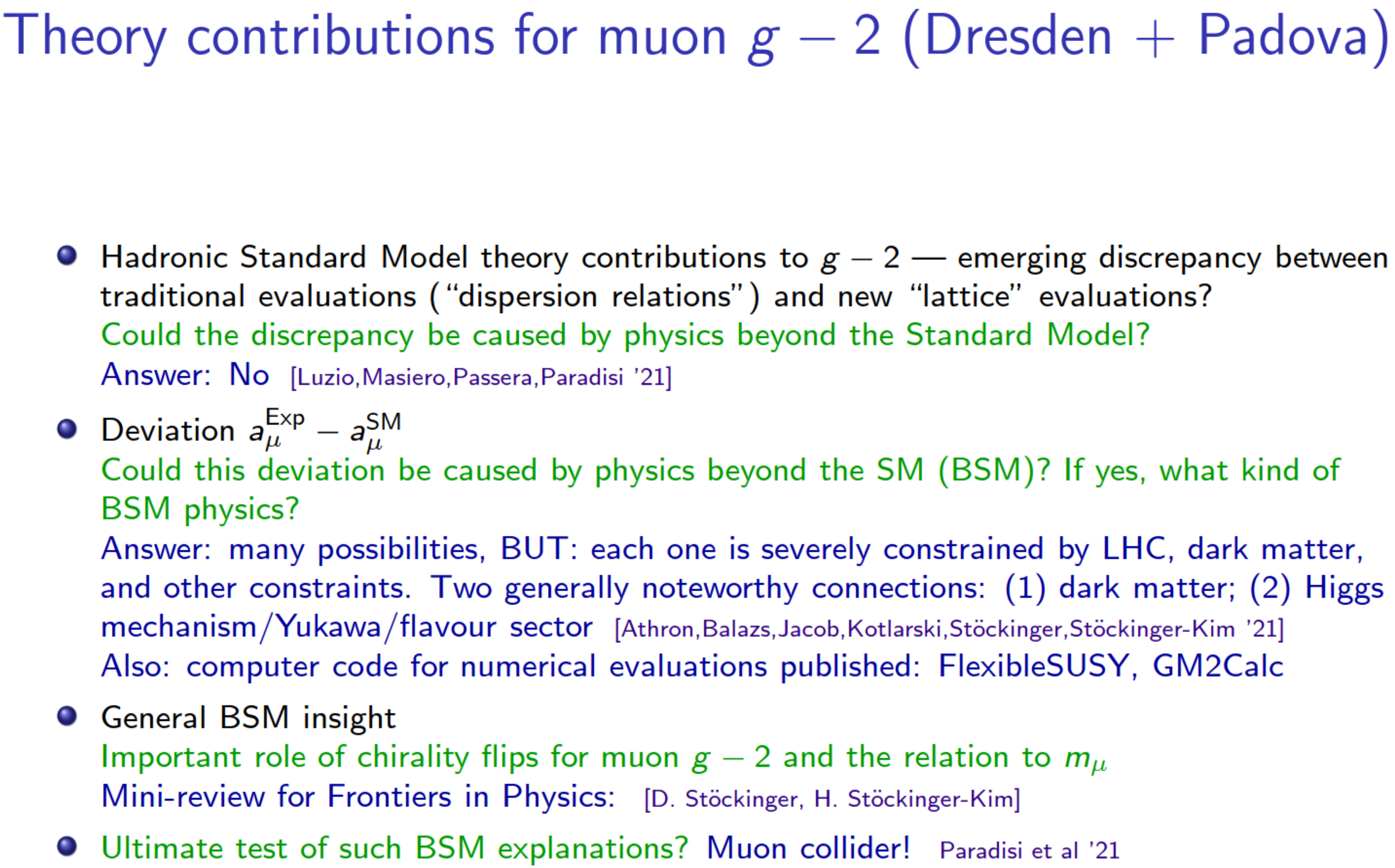


Questions:

- Correlations? Which models predict observable cLFV rates?
- Constraints on explanations of a_μ?
- Relations to neutrino mass mechanisms?

D1.5: Report on theory interpretations on muon g-2 results and on mu2e conversion, M44

Slide from Dominik S.



Theory contributions for muon $g-2$ (Dresden + Padova)

- Hadronic Standard Model theory contributions to $g-2$ — emerging discrepancy between traditional evaluations ("dispersion relations") and new "lattice" evaluations?
  Could the discrepancy be caused by physics beyond the Standard Model?
  Answer: No [Luzio,Masiero,Passera,Paradisi '21]
- Deviation $a_\mu^{\text{Exp}} - a_\mu^{\text{SM}}$
  Could this deviation be caused by physics beyond the SM (BSM)? If yes, what kind of BSM physics?
  Answer: many possibilities, BUT: each one is severely constrained by LHC, dark matter, and other constraints. Two generally noteworthy connections: (1) dark matter; (2) Higgs mechanism/Yukawa/flavour sector [Athron,Balazs,Jacob,Kotlarski,Stöckinger,Stöckinger-Kim '21]
  Also: computer code for numerical evaluations published: FlexibleSUSY, GM2Calc
- General BSM insight
  Important role of chirality flips for muon $g-2$ and the relation to m_μ
  Mini-review for Frontiers in Physics: [D. Stöckinger, H. Stöckinger-Kim]
- Ultimate test of such BSM explanations? Muon collider! Paradisi et al '21

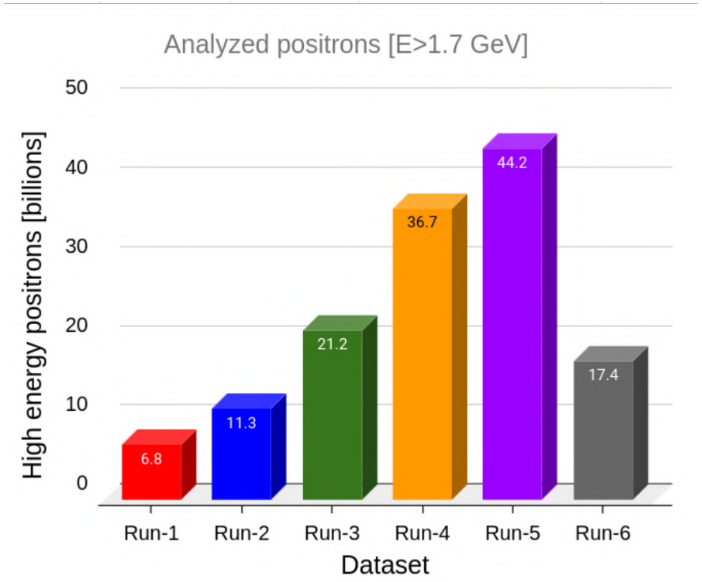
Slide from Dominik S.

Theory contributions for muon $g-2$ (Dresden + Padova)

- MUonE: novel proposal to measure hadronic vacuum polarization contributions to the muon g-2 in the space-like region.
  Theory calculations for MUonE?
  simple exact analytic expressions for the fourth-order space-like kernel that allow to extend the computation of the HVP contribution to the muon g-2 in the space-like region from LO to NLO. [Balzani,Laporta,Passera 2112.05704]
- Development of computer code: add-on to FlexibleSUSY, can compute CLFV processes in arbitrary models (→ see also WP4) [Khasianevich 2022, Khasianevich et al 2024]
- CLFV applications to specific neutrino mass model with new Yukawa couplings:
  If these couplings explain neutrino masses they inevitably also generate CLFV — what is the impact of CLFV limits on the Higgs sector?
  $\mu \to e\gamma$ gives strongest limits on masses and quartic Higgs couplings [Khasianevich et al '22 (JHEP+PRD)]
- CLFV versus g-2 in leptoquark models:
  If leptoquarks explain the muon $g-2$ deviation — how are they then restricted by the non-observation of CLFV effects?
  Strong constraint on the flavour structure of leptoquark couplings, both from $\mu \to e\gamma$, $\tau \to \mu\gamma$ and from $\mu \to e$ conversion [Khasianevich, Stöckinger, Stöckinger-Kim, Wünsche '23]
- Current project:
  Review: BSM physics and muon g-2
  Will provide an overview of the field and facilitate future interpretations

Conclusions

- Fermilab Muon g-2 Experiment published Run-23 measurement at 203 ppb in 2023
- New detailed paper on analysis published Aug 2024: https://doi.org/10.1103/PhysRevD.110.032009
- Systematic uncertainty goal reached and exceeded with Run-23 (70 ppb)
- Statistic uncertainty goal reached with Run-456 (~100 ppb total)
- Still, many improvements on Run-456 hardware and analysis, and key contributions from aMUSE members
- Run-456 analysis will be completed by early 2025
- Theory Initiative Workshop at KEK past week – possibly a new White Paper early 2025
- New data-driven theory calculations to come from BaBar, KLOE, SND, BesIII, Belle II in the next years

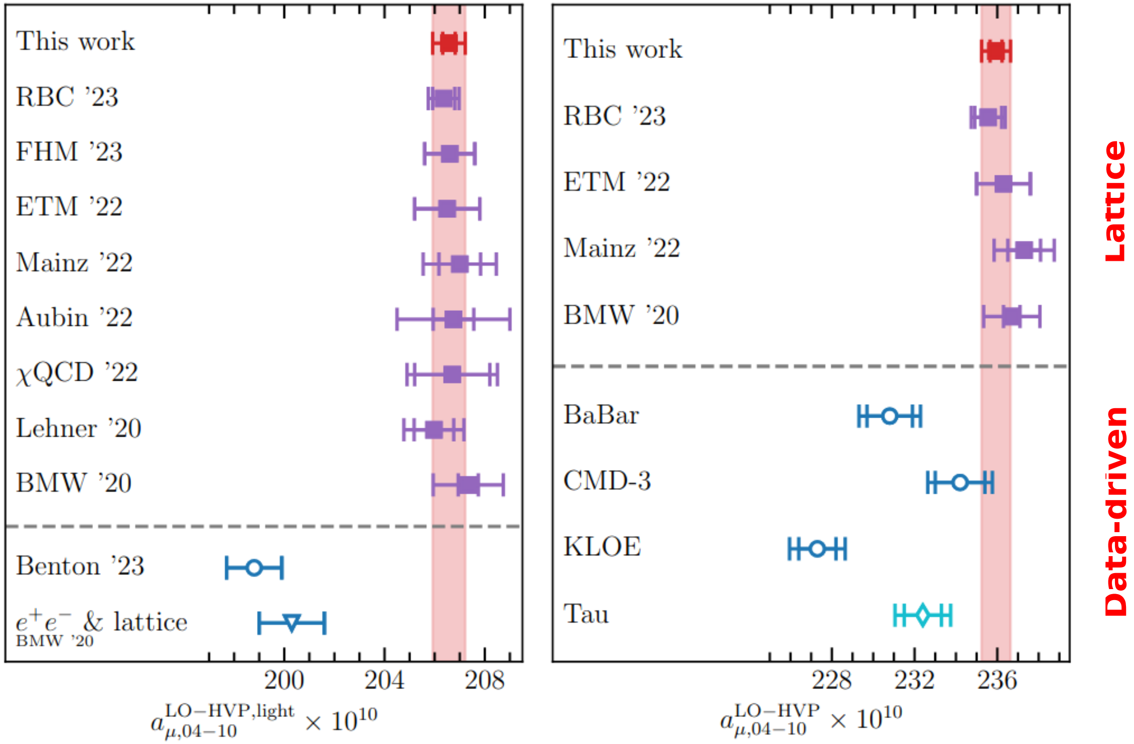


g-2 physics week Ann Arbor July 2024

Backup

Lattice QCD

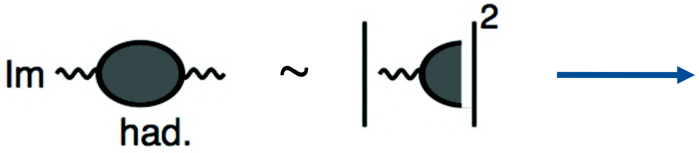
- Precise lattice QCD calculations are close to or compatible with the experimental value
- Many independent lattice calculations agree between each other by selecting energy windows – more complete calculations to come soon



BMW/DMZ24 Jul 2024
arXiv: 2407.10913

HVP Calculation: Dispersive (e^+e^-) Method

- Calculated from data for σ($e^+e^-\rightarrow$ hadrons)

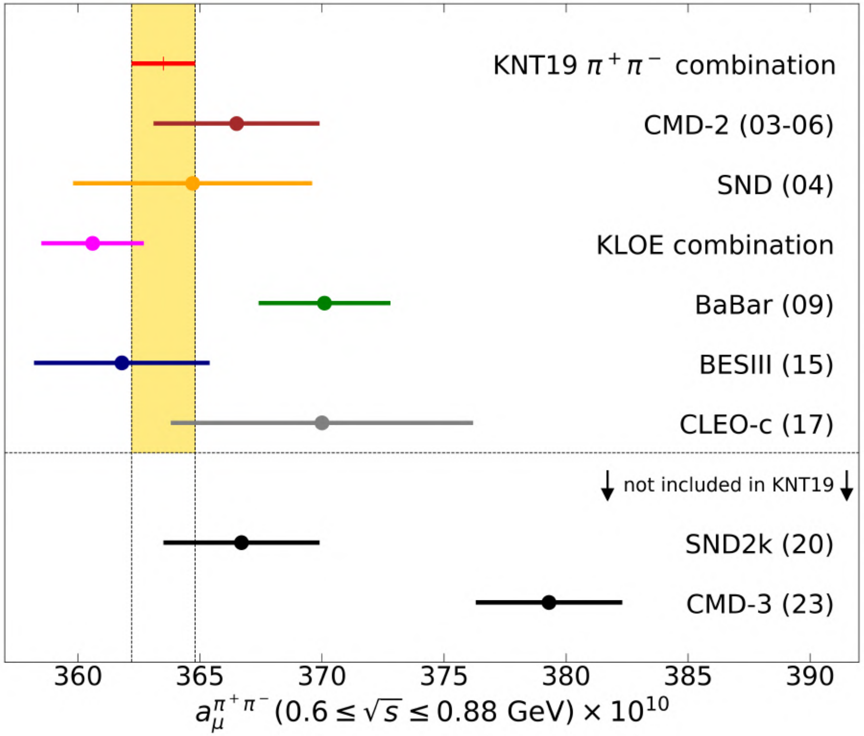


Analyticity & Unitarity

$$a_\mu^{\mathrm{HVP,LO}} = \frac{\alpha^2}{3\pi^2}\int_{s_{th}}^{\infty}\frac{K(s)}{s}\boxed{R(s)}ds$$

Hadronic R-ratio
(Data Driven)

- Uses **data** from different experiments from **20+ years**
- 1/s weights low energy strongly: 73% from **$\pi^+\pi^-$ channel**



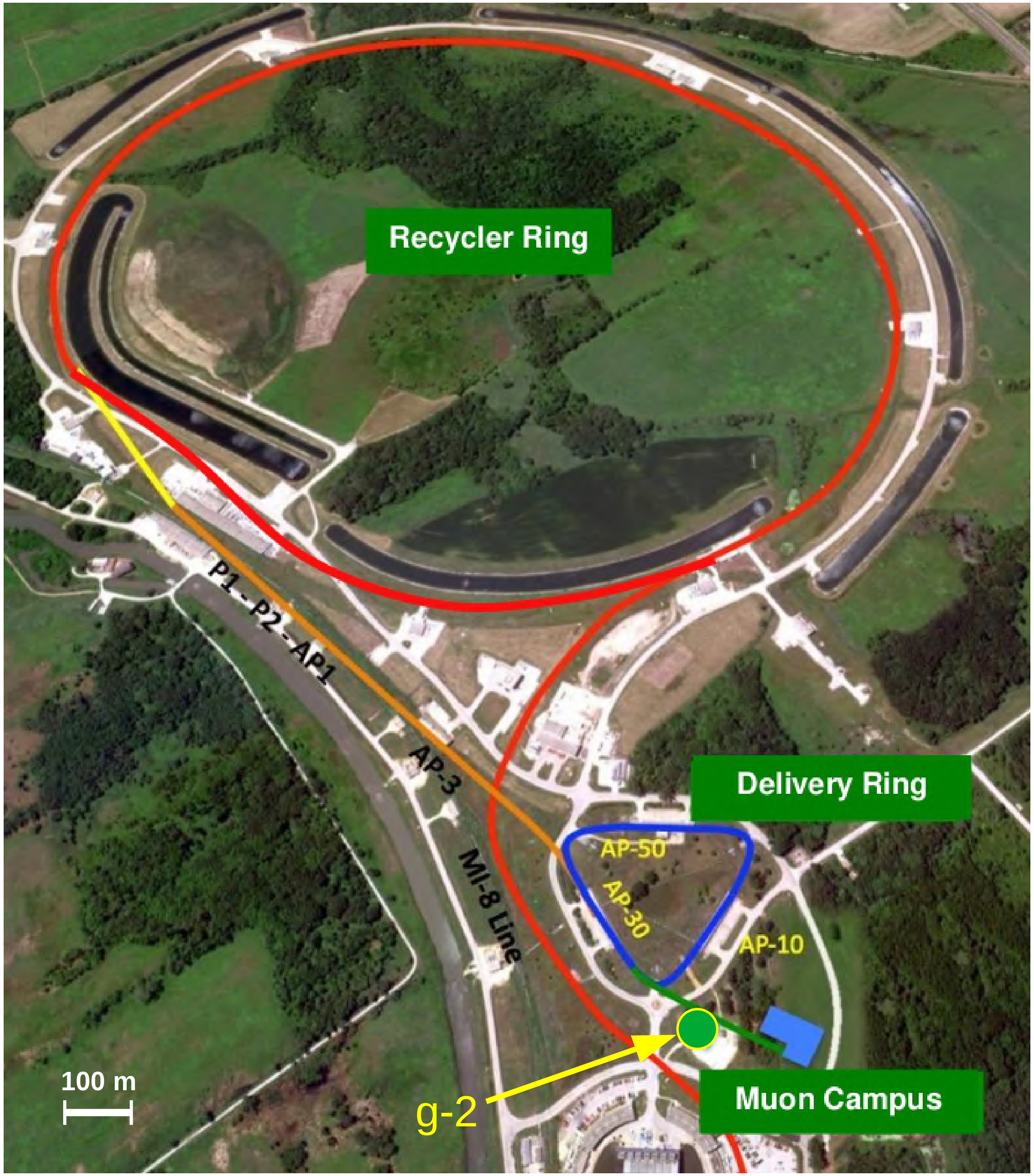
- New results from **SND2k** and **CMD-3** since White Paper
- **CMD-3 is discrepant**
- More results from BaBar, KLOE, SND, BESIII, Belle II expected

Slide from J.Mott, Run23 release 10 Aug 2023

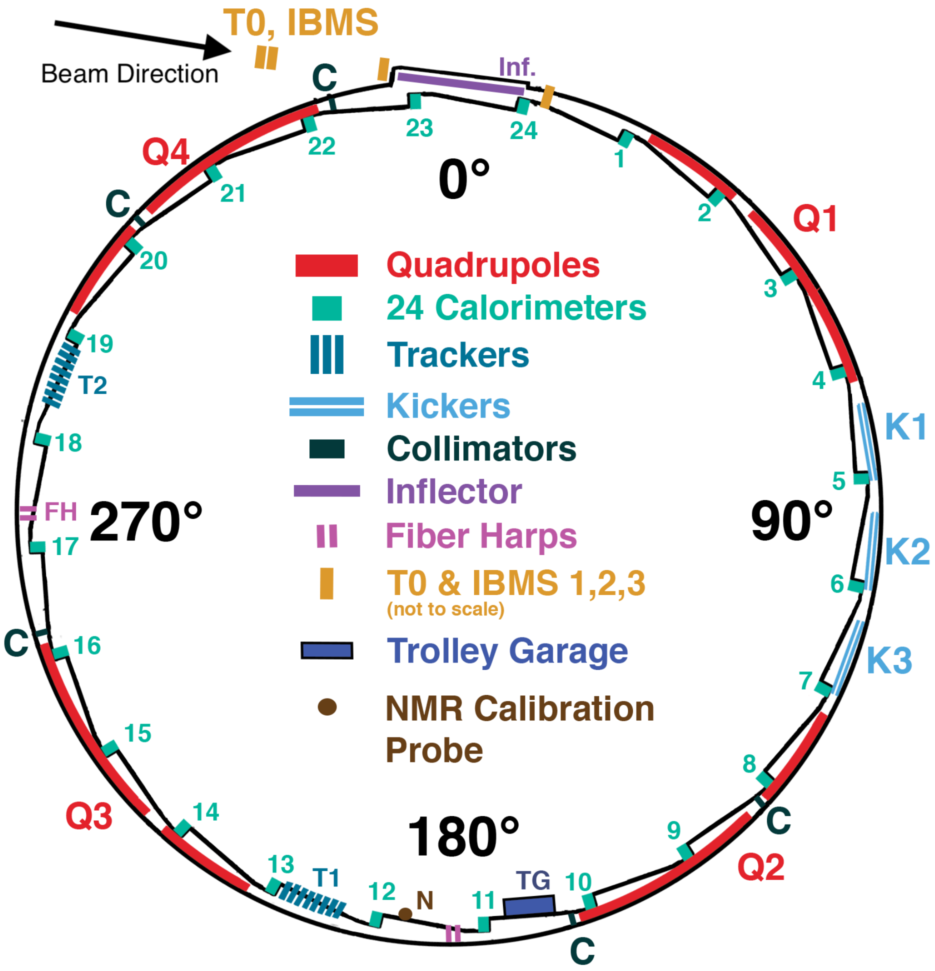
Muon source

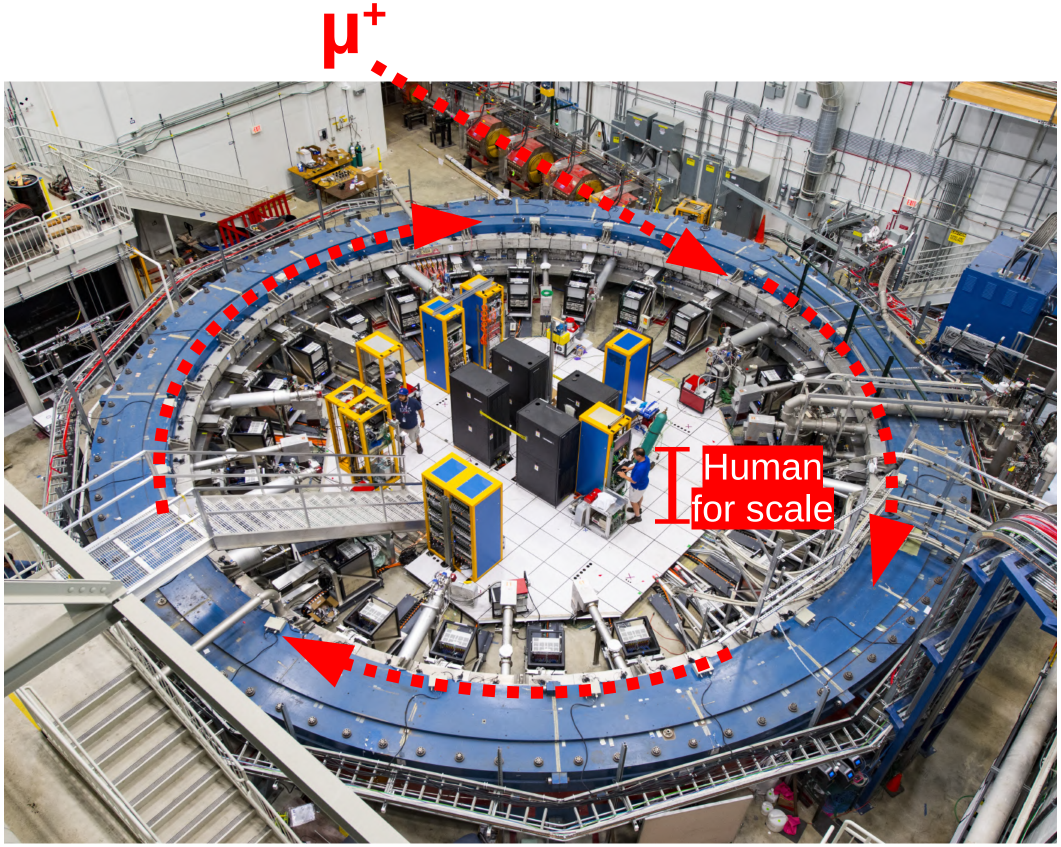
$P \rightarrow \pi^+ \rightarrow \mu^+ \rightarrow e^+$

- 16 bunches of 10^{12} protons @8 GeV get boosted and delivered via the recycler ring every 1.4 seconds
- Each bunch hits a fixed Inconel® (NiCrFe) target
- Positive pions from shower extracted and decay in delivery ring
- Pure and polarized muon beam enters g-2 ring



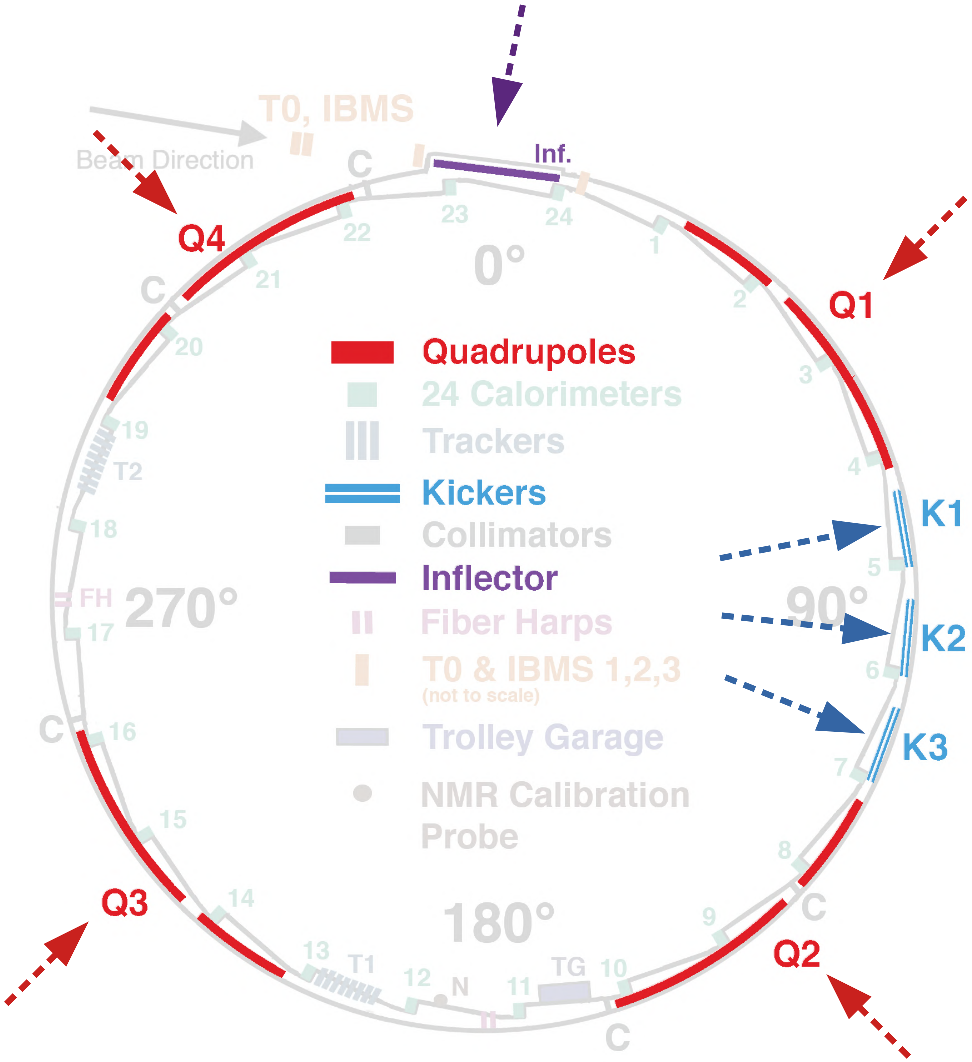
The experiment





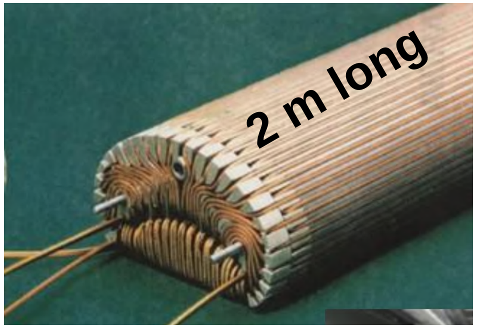
MC-1 building @Fermilab

Beam injection

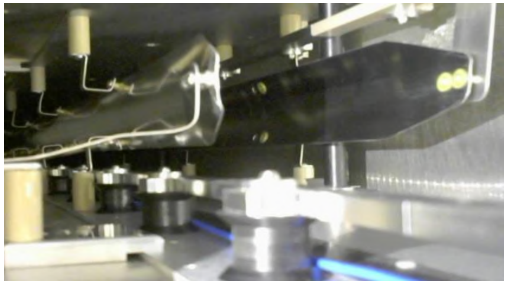


- Superconducting **inflector** ~8 cm offset from nominal orbit
- 3 fast magnetic **kickers** operated at ~4 kA current for ~200 ns
- 8 aluminum electrostatic **quadrupoles** at 13.8 kV to provide weak vertical focus

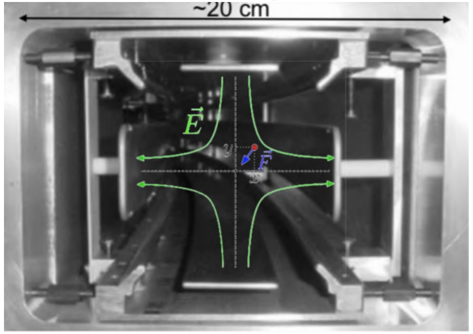
Inflector



Kicker plates

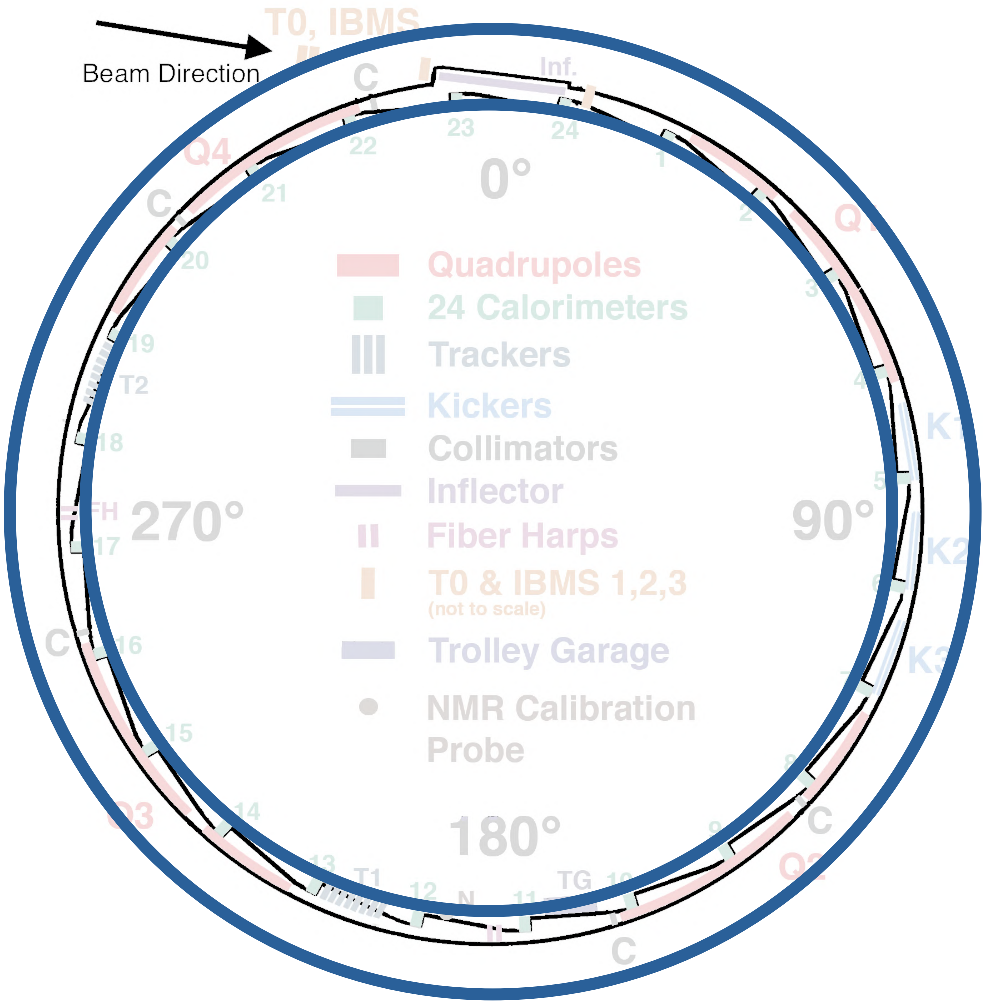


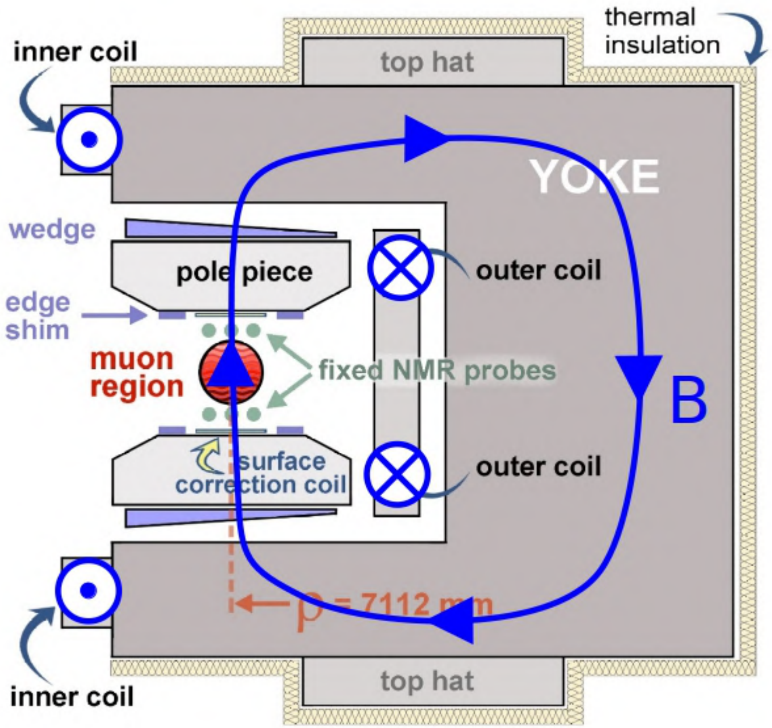
Quadrupoles



Magnet

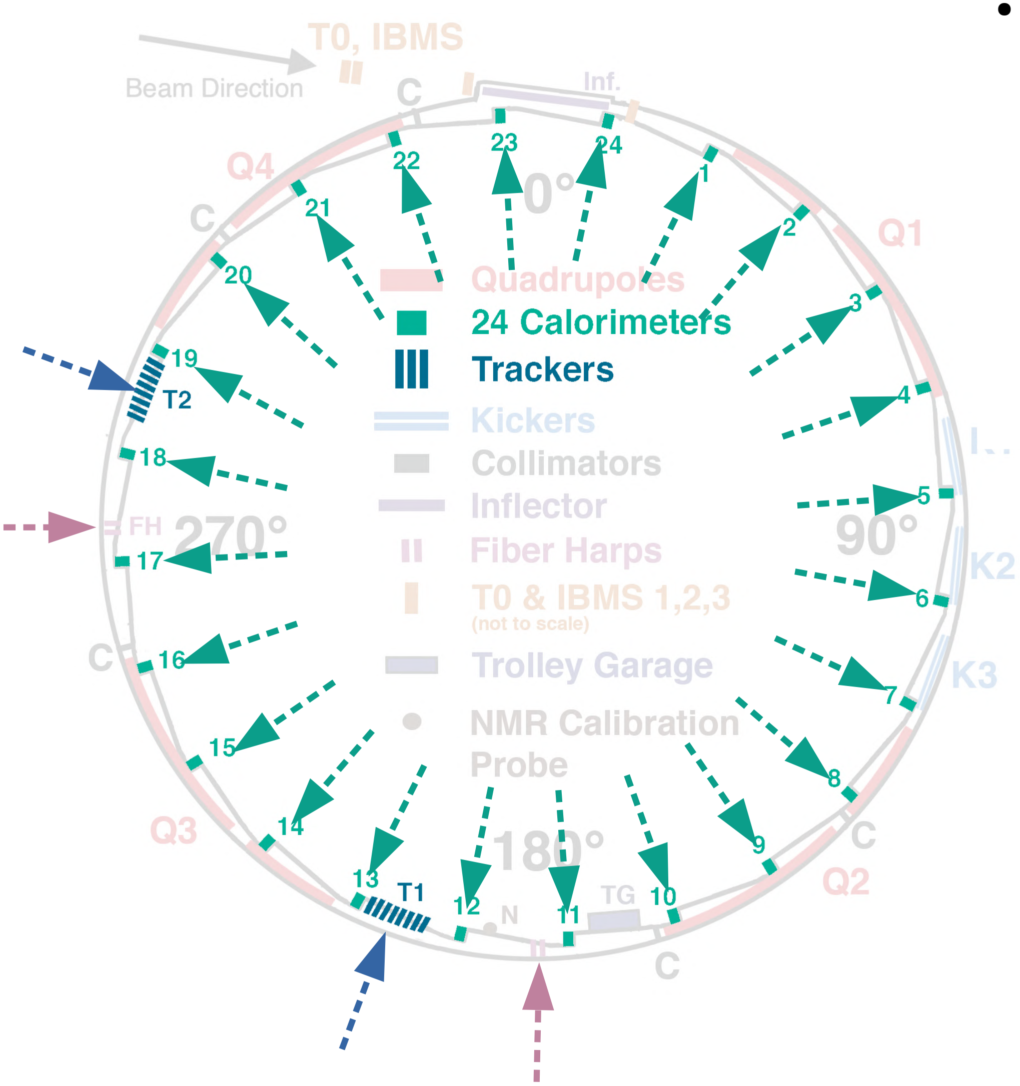
- Superconductive **magnet** cooled at ~5 K with LHe
- 7.112 m radius, highly **uniform 1.45 T** vertical magnetic field
- Shimmed passively and actively stabilized. Better than 14 ppm RMS field homogeneity across the full azimuth



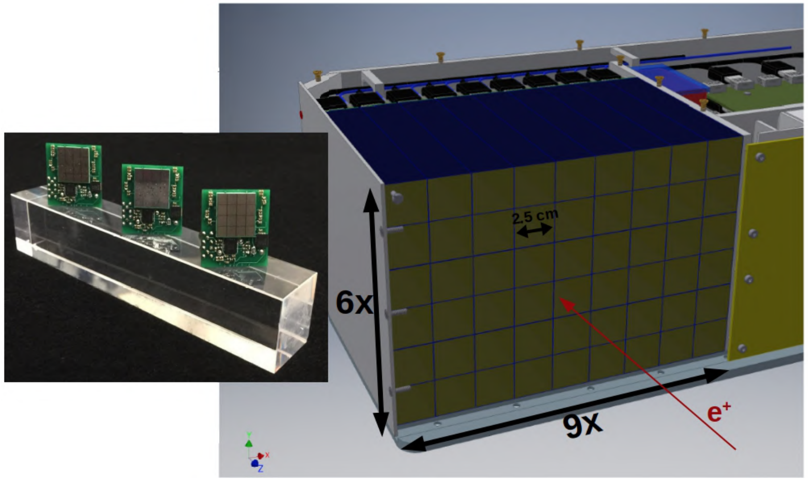


Detectors

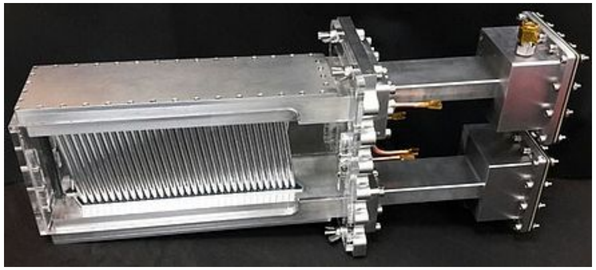
- 24 electromagnetic **calorimeters** for positron energy and time measurement
- 2 **tracker** stations to extrapolate decay vertex location and measure beam distribution



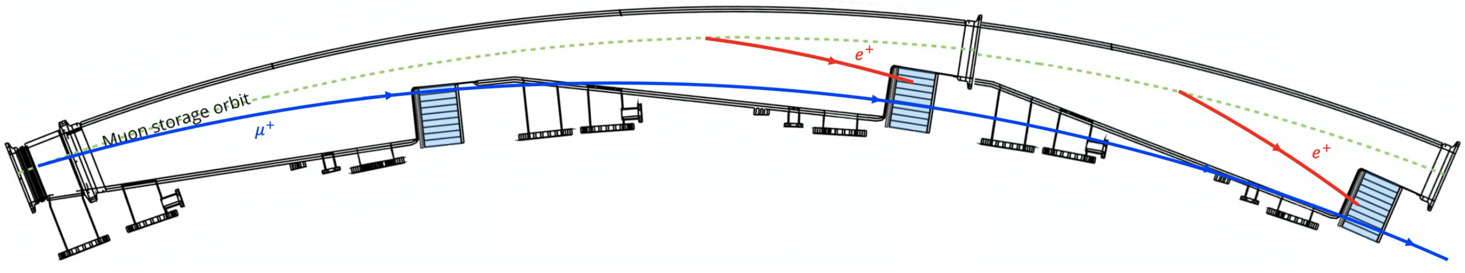
Calorimeter

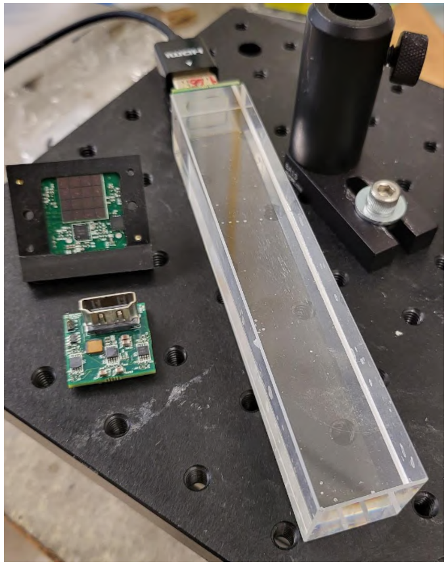


Tracker module

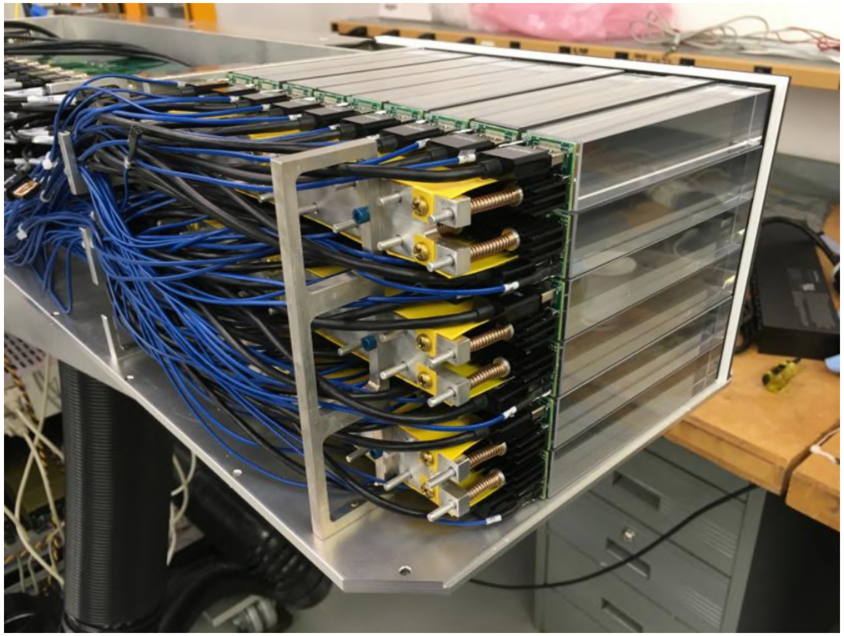


Calorimeters



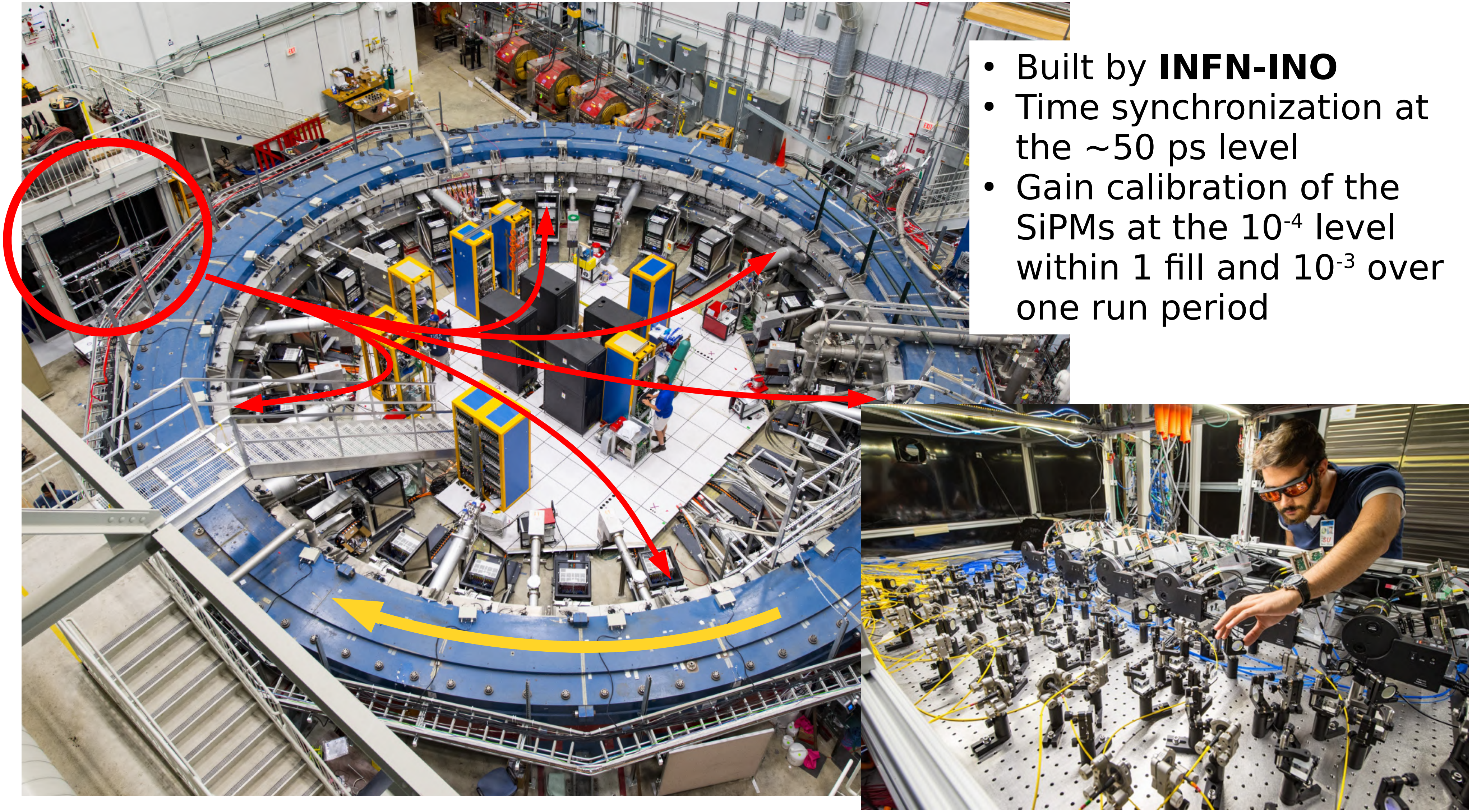


- 24 Electromagnetic calorimeters
- Matrix of 9x6 PbF_2 crystals (25x25x140 mm^3, $15X_0$ length)
- Each coupled with Hamamatsu SiPM of 1.2 mm^2 active size (57344 pixels)
- Positrons generate EM shower
- SiPMs collect Čerenkov light, ~1 pe/MeV
- Waveform sampled at 800 Msps
- Online GPU-based trigger



Laser Calibration System

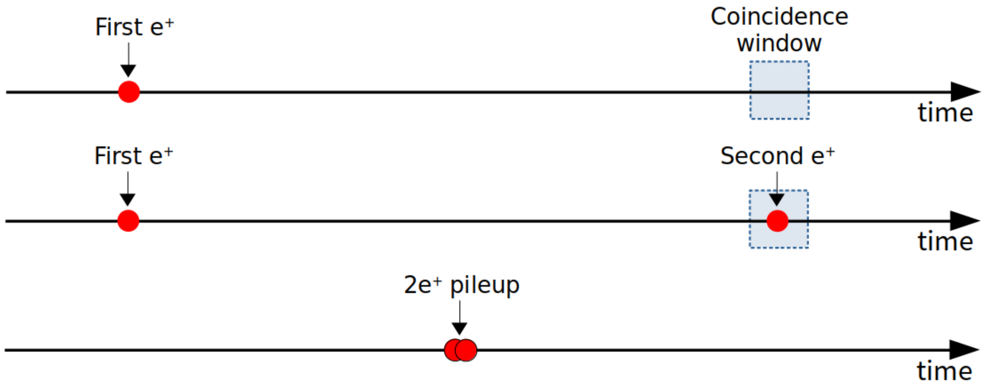
https://doi.org/10.1088/1748-0221/14/11/P11025

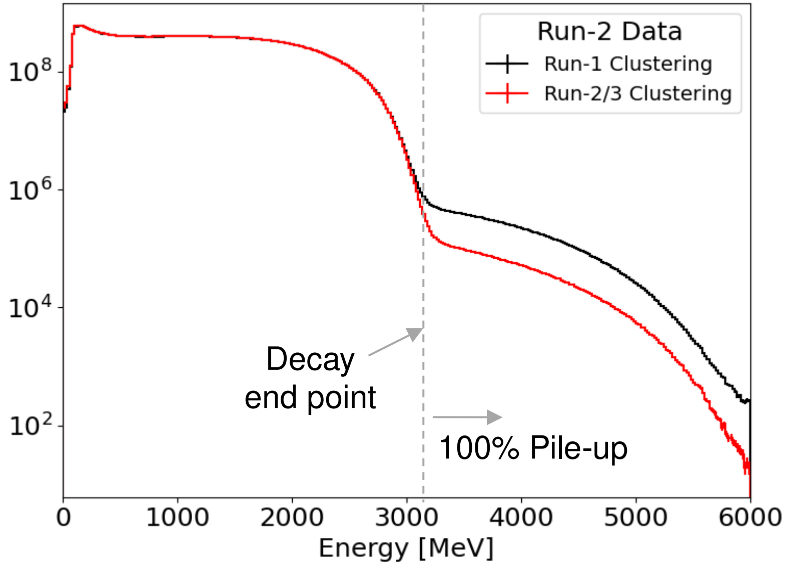


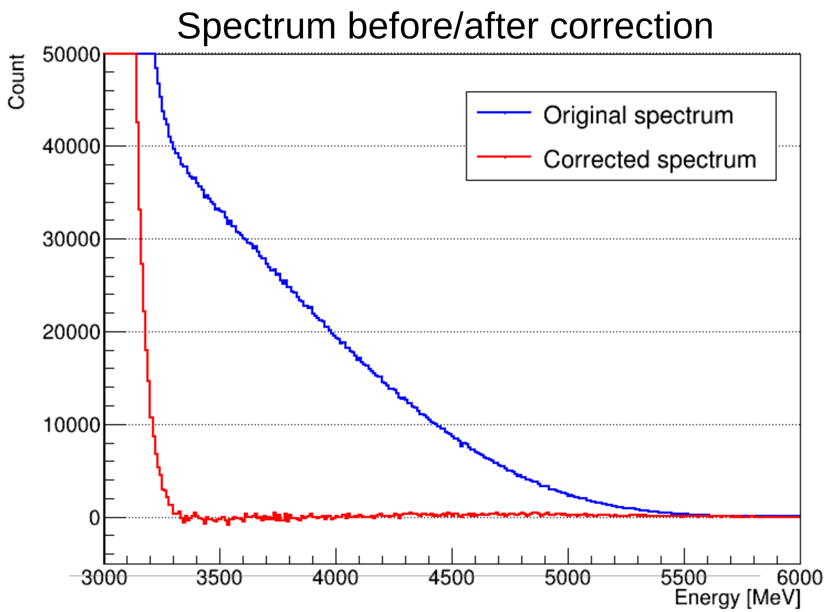
- Built by **INFN-INO**
- Time synchronization at the ~50 ps level
- Gain calibration of the SiPMs at the 10^{-4} level within 1 fill and 10^{-3} over one run period

Pileup

- Pileup = two or more positrons reconstructed as one. Contamination subtracted statistically
- Clustering algorithm already reduced pileup by ~3x
- Improved pileup removal techniques
- <u>Systematic uncertainty reduced from 35 ppb to 7 ppb</u>

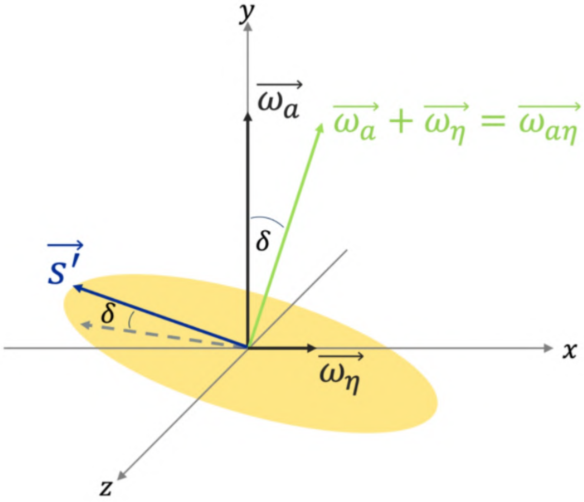




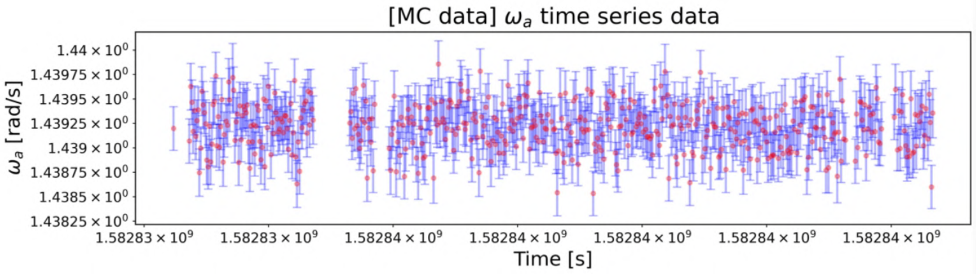


Not only a_μ

- **Electric Dipole Moment (EDM)**
  - If the muon has EDM, the spin precession plane will be tilted
  - Analysis conducted with trackers
  - Run-1 is being reviewed, Run-23 in progress
  - Current limit (BNL): $1.8\text{x}10^{-19}$ e*cm
  - Projected limit: $<3\text{x}10^{-20}$ e*cm



- **CPT and Lorentz Invariance violation**
  - Sidereal modulation of ω_a frequency
  - Run-2/3 in review
  - Current limit (BNL): $1.4\text{x}10^{-24}$ GeV
  - Projected limit: $O(10^{-25})$ GeV



- **Ultralight Muonic Dark Matter (scalar)**
  - ω_a modulated at the DM compton frequency
  - Run-2/3 in progress