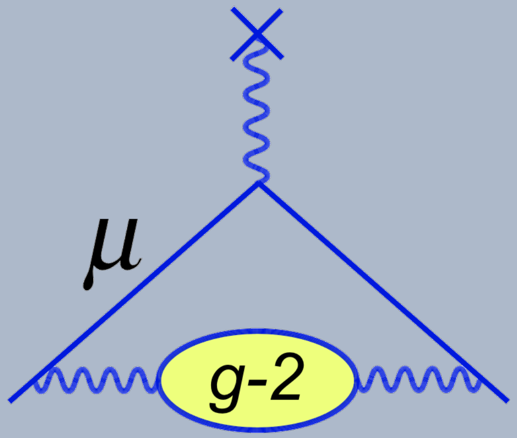

First Results From the Fermilab Muon $g-2$ Experiment

Eremey Valetov

Michigan State University

On behalf of the Muon $g-2$ Collaboration

MICHIGAN STATE UNIVERSITY

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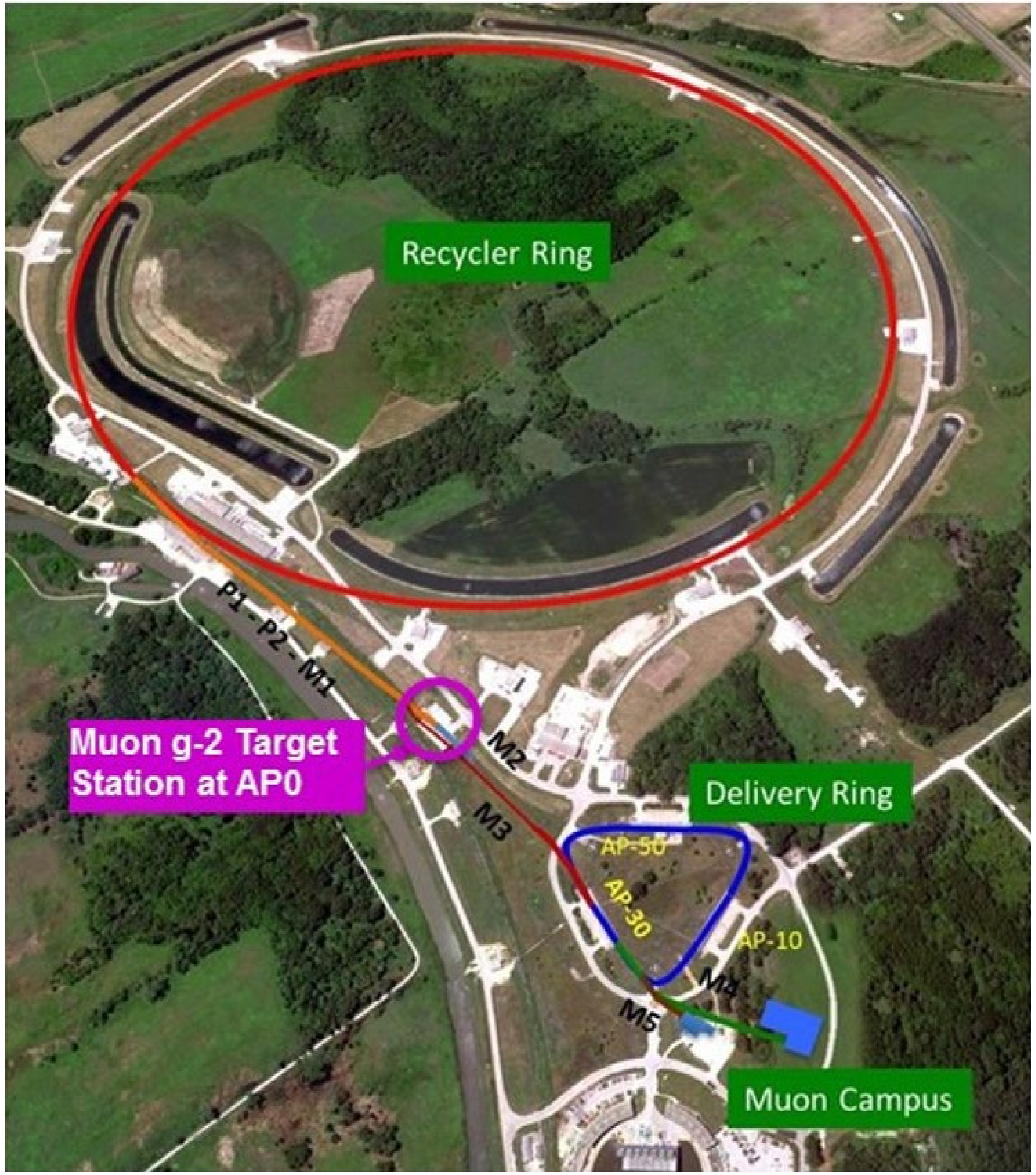
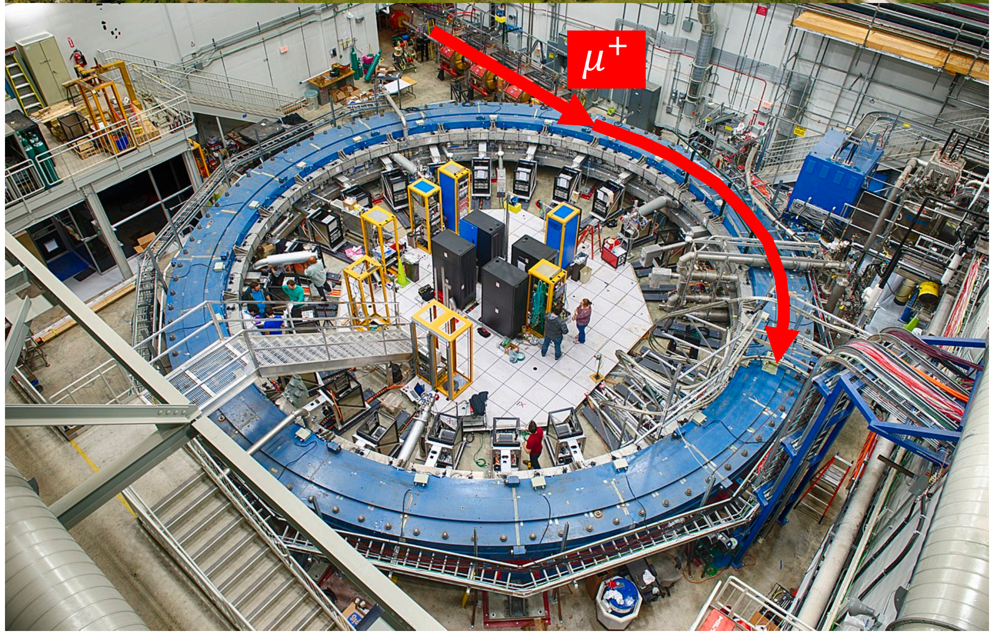
Introduction



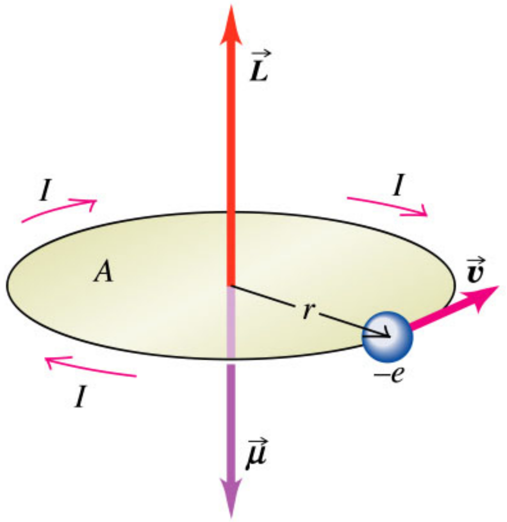


Muon Anomalous Magnetic Dipole Moment (a_μ)

Magnetic moment $\mu = g \frac{e}{2m} s$ ← spin angular momentum

↑ g-factor

Classical: $g = 1$

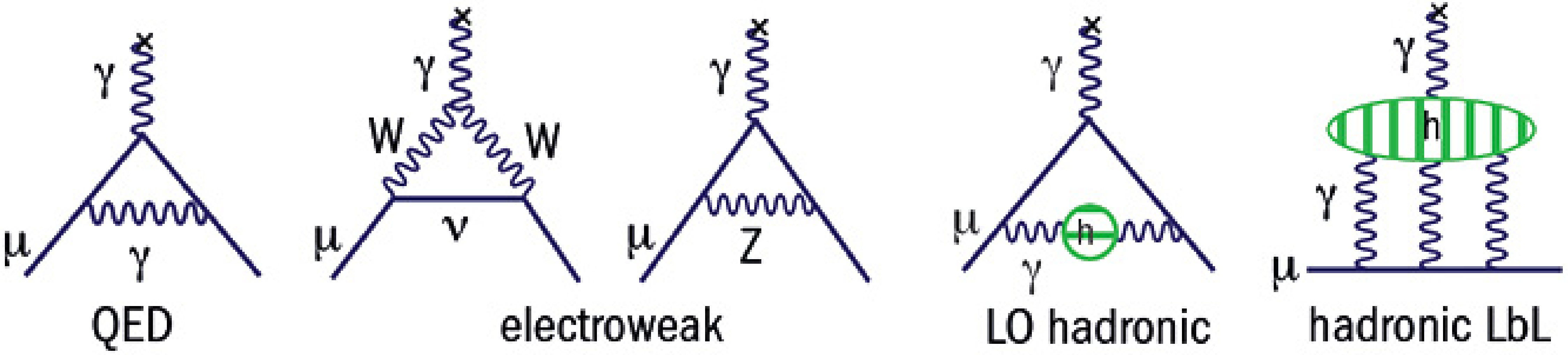


Dirac equation: $g = 2$

$$i\left(\partial_\mu - ieA_\mu(x)\right)\gamma^\mu\psi(x) = m\psi(x)$$

Interactions w/ quantum foam: $g > 2$ $a_\mu = \frac{g-2}{2}$

Contributions to a_μ in the Standard Model



QED incl. 4-loops + 5-loops
$\boldsymbol{a_\mu = 116\,584\,718.86 \times 10^{-11}}$
$\delta a_\mu = 0.03 \times 10^{-11}$

Weak to 2-loops
$a_\mu = 153.6 \times 10^{-11}$
$\delta a_\mu = 1.1 \times 10^{-11}$

Hadronic LO VP
$a_\mu = 6\,894.6 \times 10^{-11}$
$\boldsymbol{\delta a_\mu = 32.5 \times 10^{-11}}$

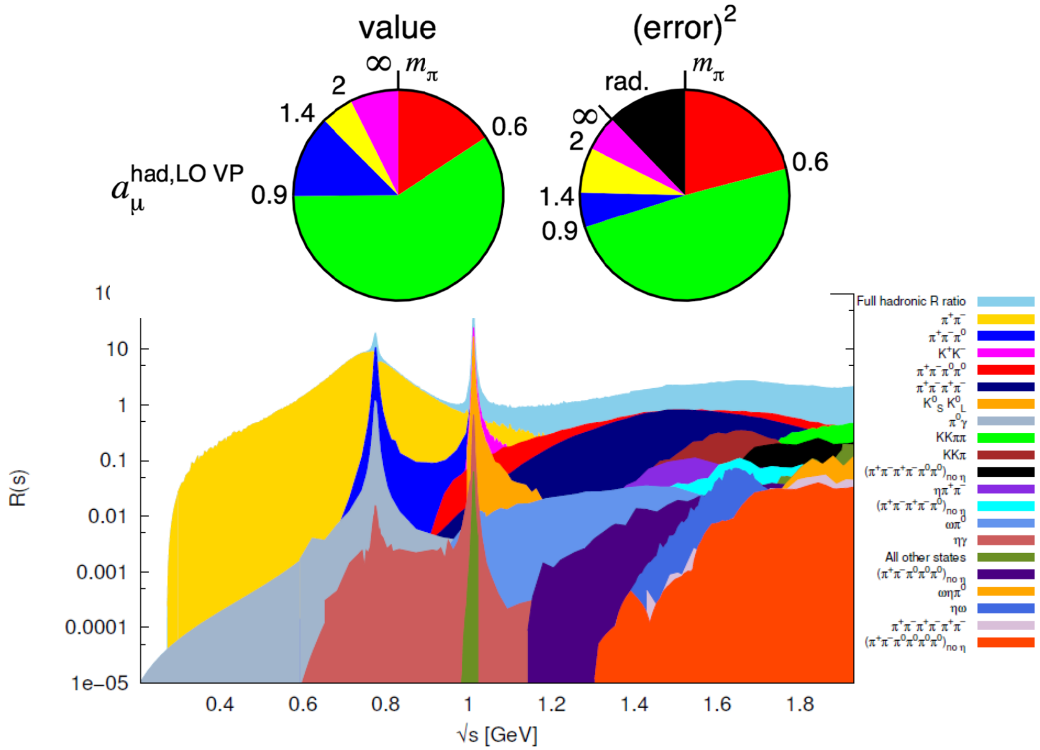
Hadronic LbL
$a_\mu = 103.4 \times 10^{-11}$
$\boldsymbol{\delta a_\mu = 28.8 \times 10^{-11}}$

Theory: $(11\,659\,1783 \pm 43) \times 10^{-11}$
Experiment (2021): $(11\,659\,2061 \pm 41) \times 10^{-11}$

F. Jegerlehner, arXiv:1804.07409 [hep-ph] (2018).

Improvements in $a_\mu^{\text{Had, LO VP}}$ (KNT18)

Direct energy scan: CMD-3, SND, KEDR
Radiative return: BABAR, KLOE/KLOE-2, BESIII

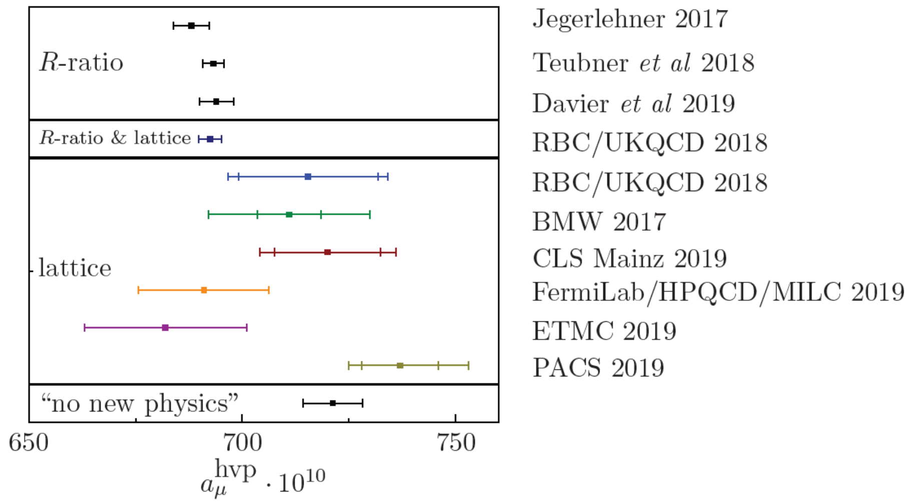


$$a_\mu^{\text{Had,LO VP}} = (693.26 \pm 2.46) \times 10^{-10}$$

A. Keshavarzi, D. Nomura and T. Teubner, Phys. Rev. D **97**, no. 11, 114025 (2018).

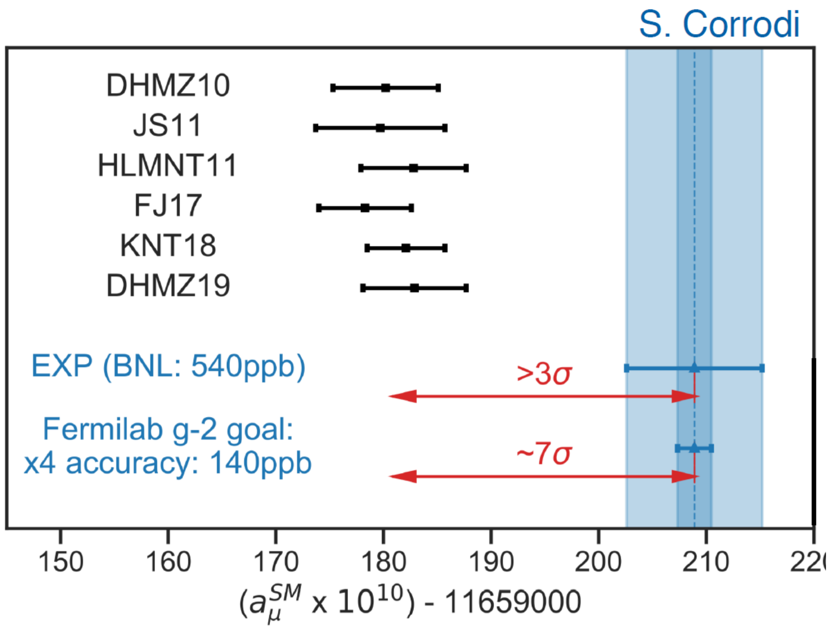
Calculation of $a_\mu^{\text{Had, VP}}$ and $a_\mu^{\text{Had, LbL}}$ using Lattice QCD

- From first principles
- Can be used to improve R-ratio results
- Several collaborations working on this
  - including RBC/UKQCD and Mainz
- Precision needs improvement; calculations ongoing



V. Gülpers, arXiv:2001.11898 [hep-lat] (2020).

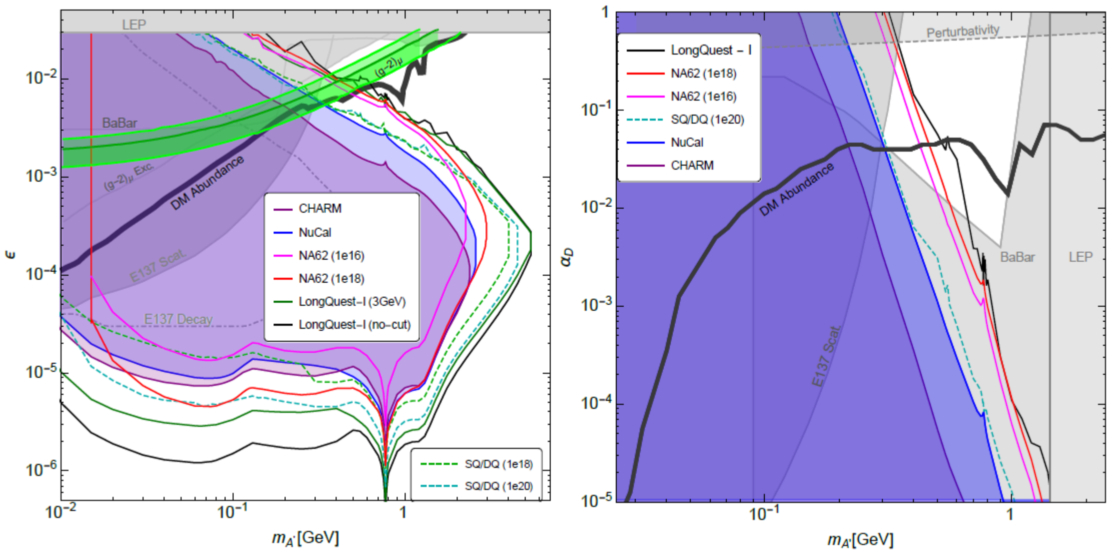
Beyond–Standard Model Possibilities



In case of a Beyond-SM a_μ, some of the possible contributors to the respective discrepancy would be:

- Dark matter
- Supersymmetry (SUSY)
- Extra dimensions
- Additional Higgs Bosons
  [S. Iguro *et al.*, arXiv:1907.09845 [hep-ph]]

Muon g-2 window in the search for inelastic dark matter (iDM) :



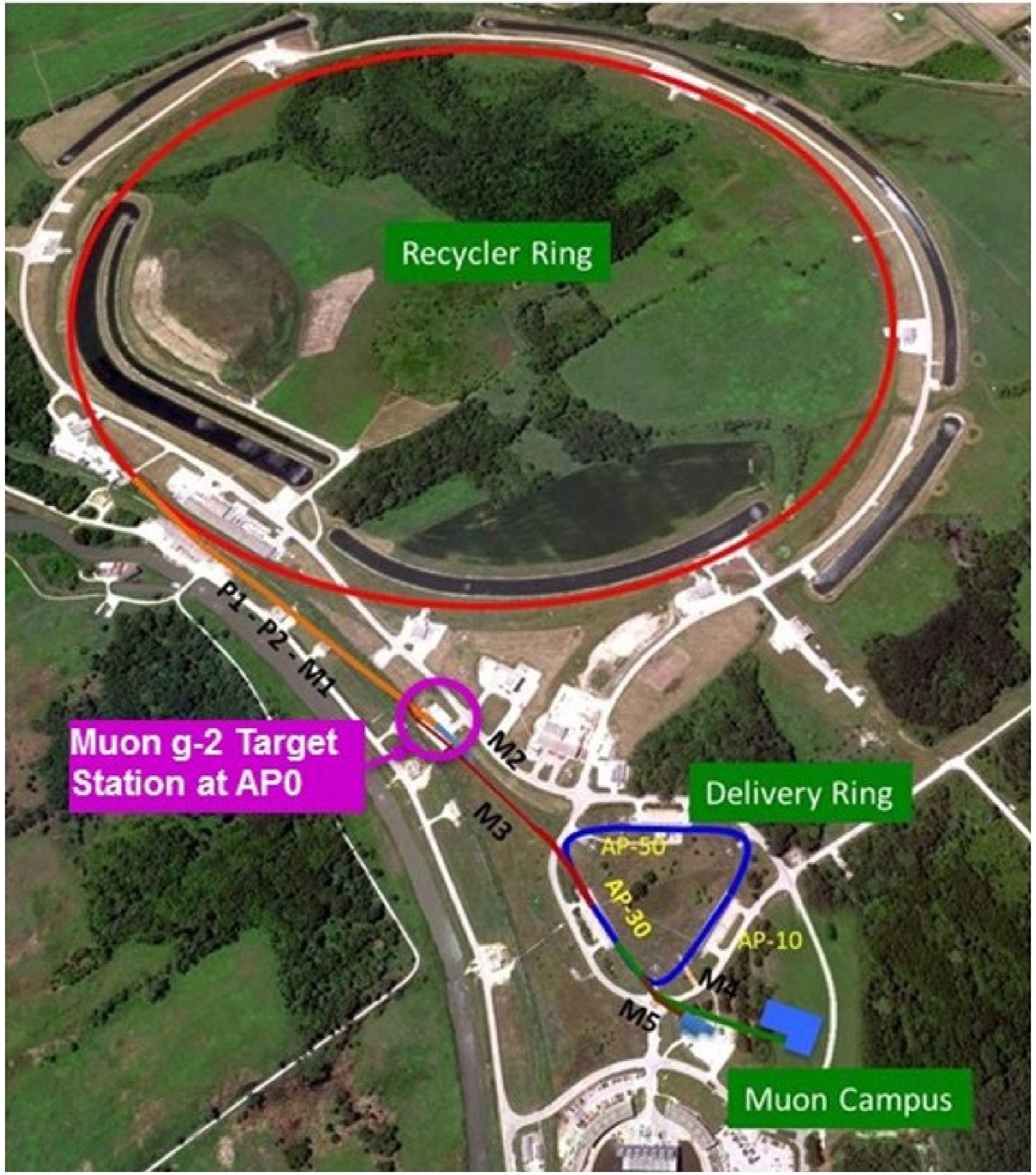
(a) iDM: $\Delta = 0.4$, α_D=0.1. With muon $g-2$ and DM regimes. (b) iDM Muon $g-2$ Target: $\Delta = 0.4$, $\epsilon = \epsilon_{(g-2)_\mu}$.

(α_D: analogue of the fine structure constant for a new $U(1)$ gauge symmetry $U(1)_D$. Δ: mass splitting $\Delta = \frac{(m_2 - m_1)}{m_1}$.)

NA62 Experiment at CERN is ongoing and may yield iDM results.

See Y.-D. Tsai et al., arXiv:1908.07525 [hep-ph] (2019).

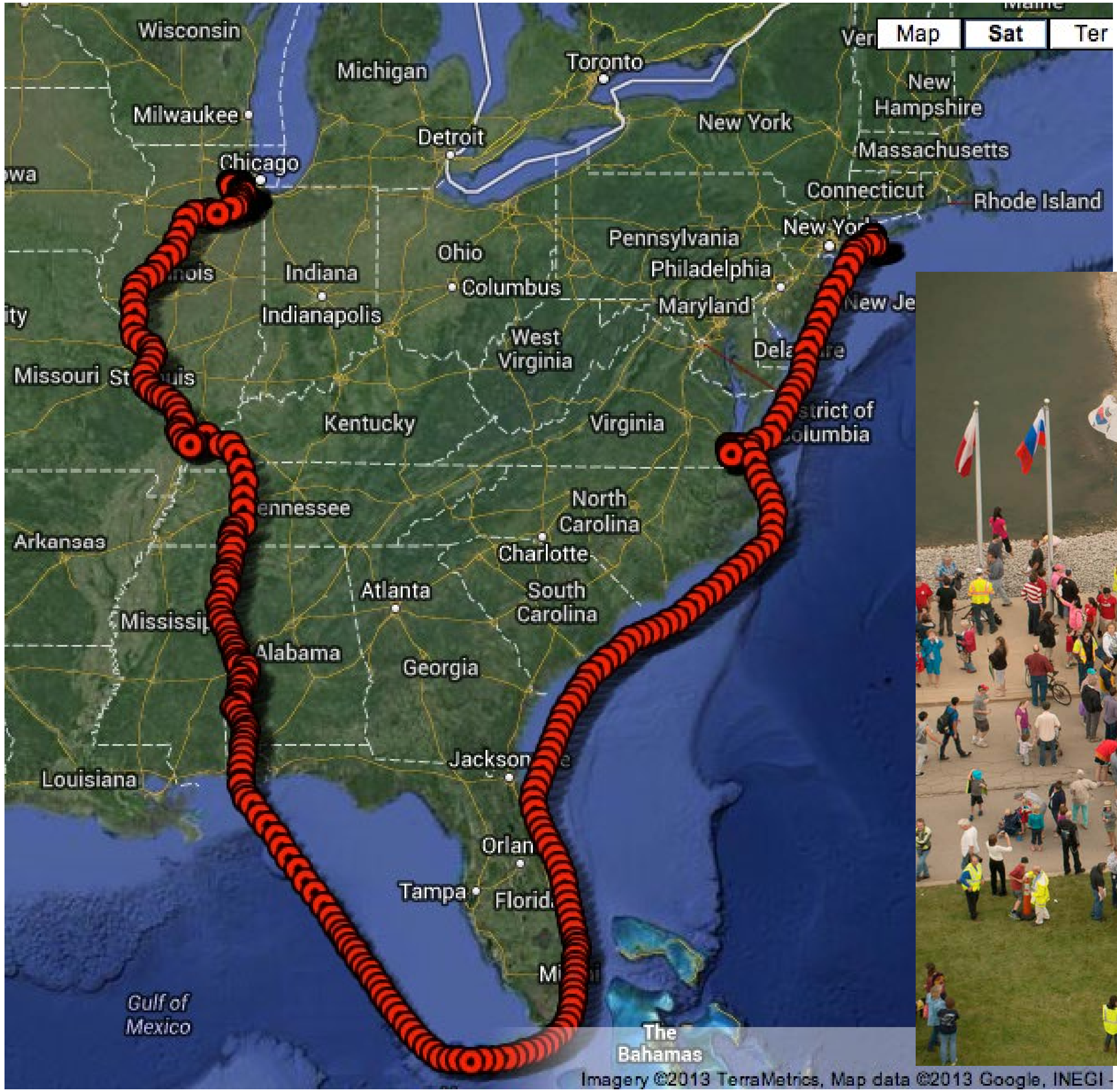
The Muon g-2 Experiment at Fermilab (E989)



Improvements over the Muon g-2 Experiment at BNL (E821):

- ➢ More muons, delivered more often to the storage ring
- ➢ Improved muon storage function
- ➢ Better beam dynamics modeling
- ➢ Higher field uniformity and better field monitoring
- ➢ Reduced spin precession frequency systematics

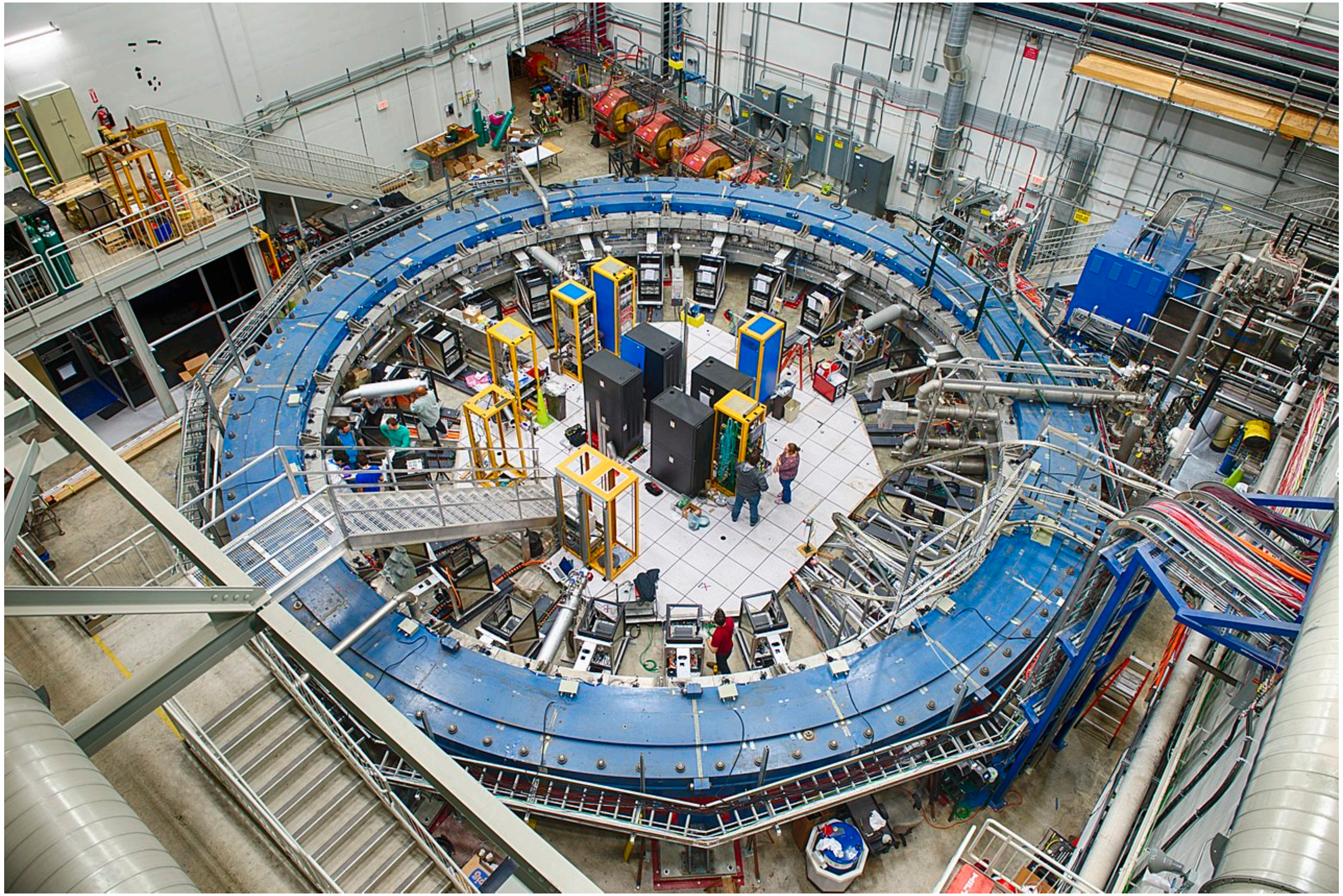
From BNL to FNAL: the Great Move



2013

Tennessee-Tombigbee Waterway / Mississippi, Illinois and Des Plaines rivers

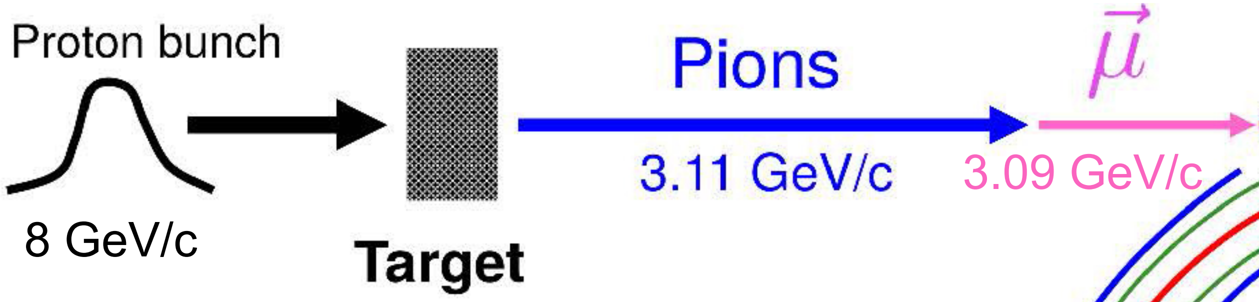
The Muon g-2 Experiment at Fermilab (E989)



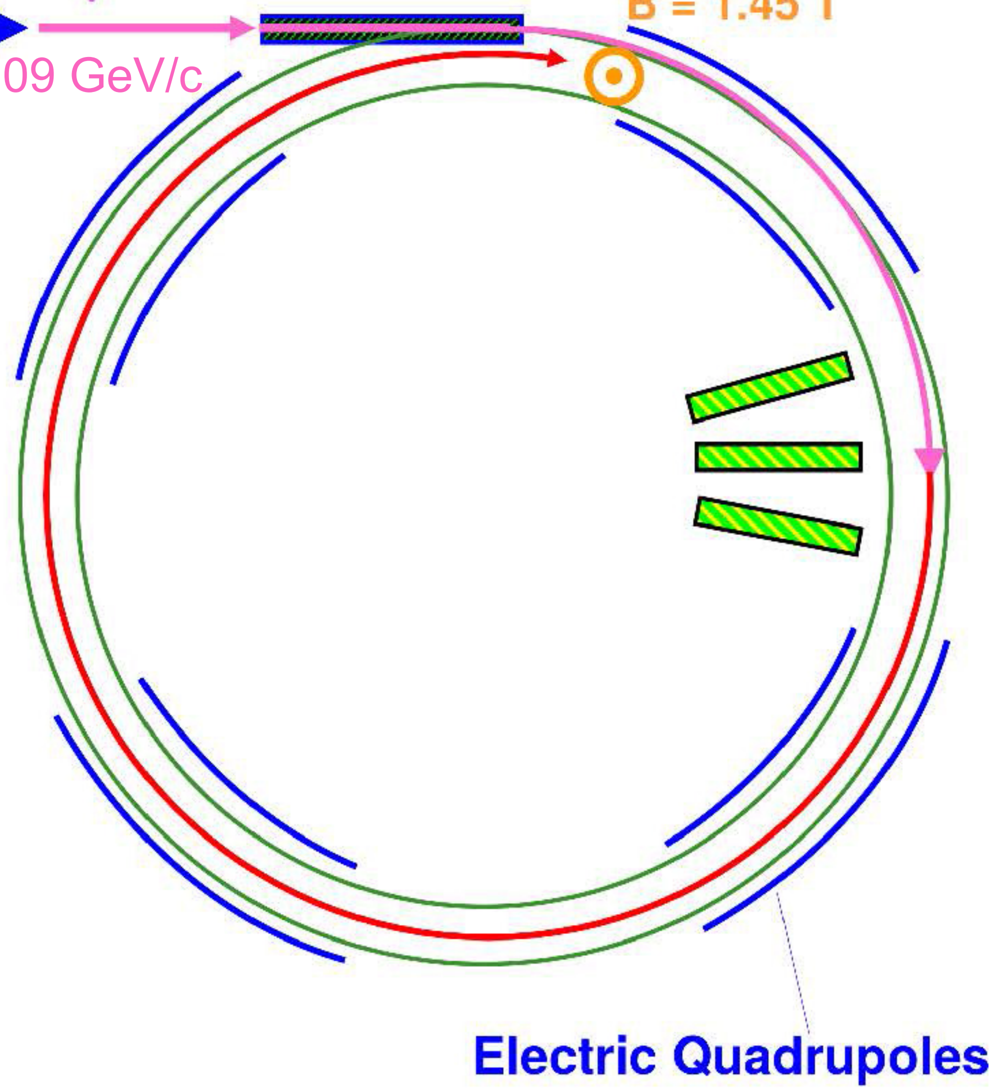
Technical design projection:

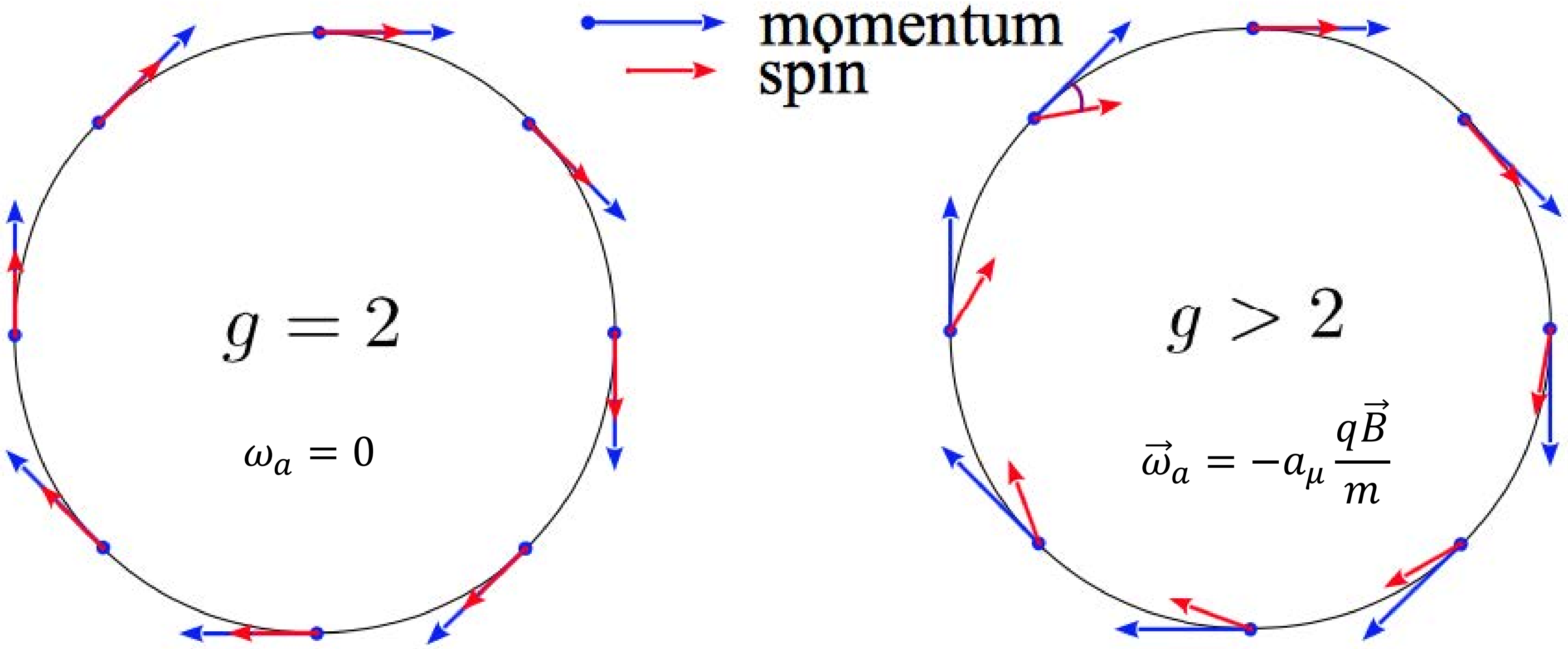
- ~20x more data
- ~3x reduction of systematic errors

The Muon g-2 Storage Ring



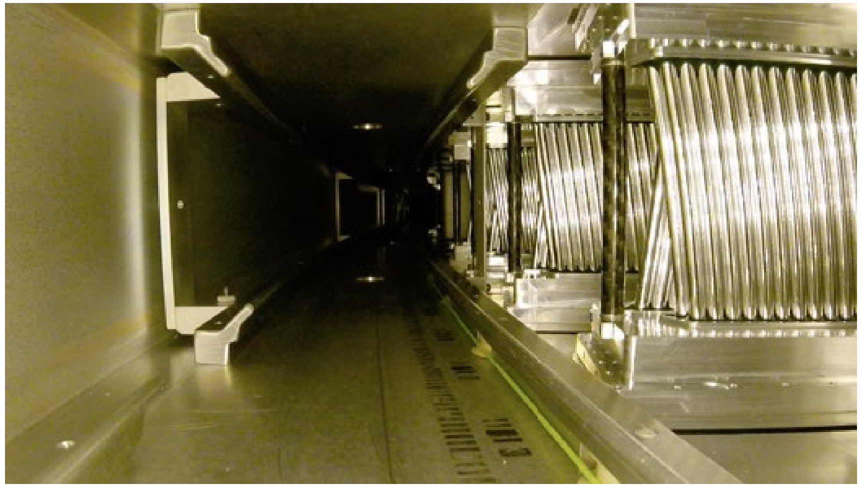
- Storage ring: 7 m radius toroidal C-magnet with 1.45 T magnetic field
- Inflector: cancels the 1.45 T main magnetic field for muons at injection
- Kickers deflect the injected muons onto the centerline orbit
- Electrostatic quadrupoles provide vertical beam focusing

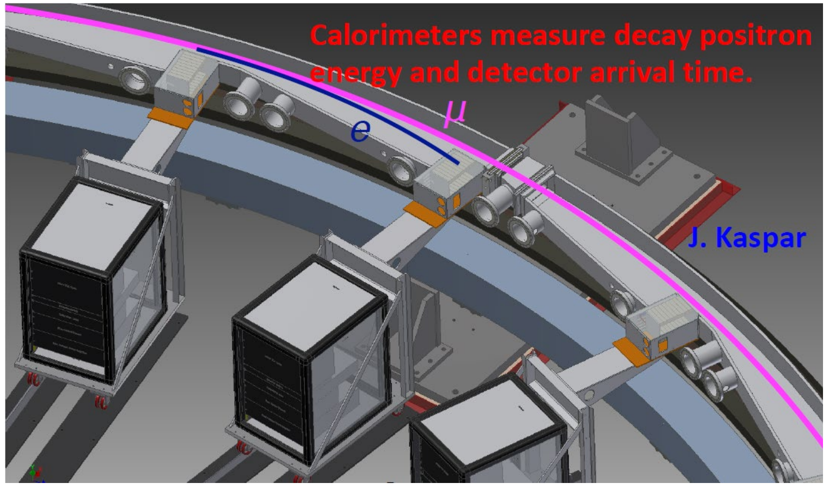


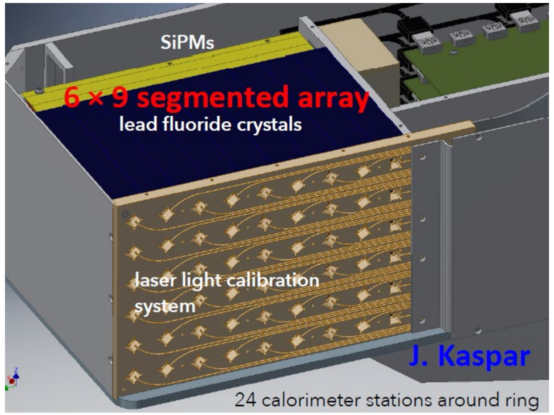


If g=2, the angle between the magnetic moment and the momentum does not change.
If g>2, the angle between the magnetic moment and the momentum changes linearly.

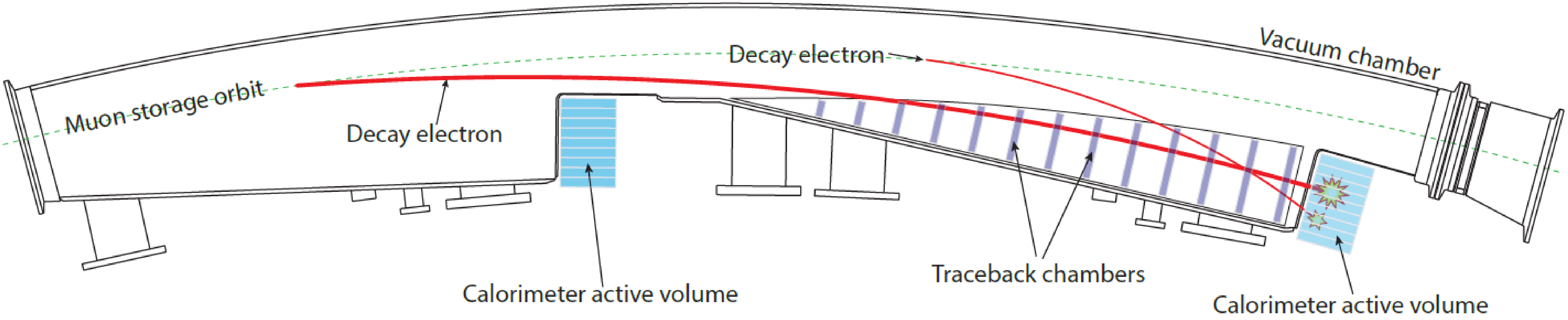
Measurement of Muon Spin Precession







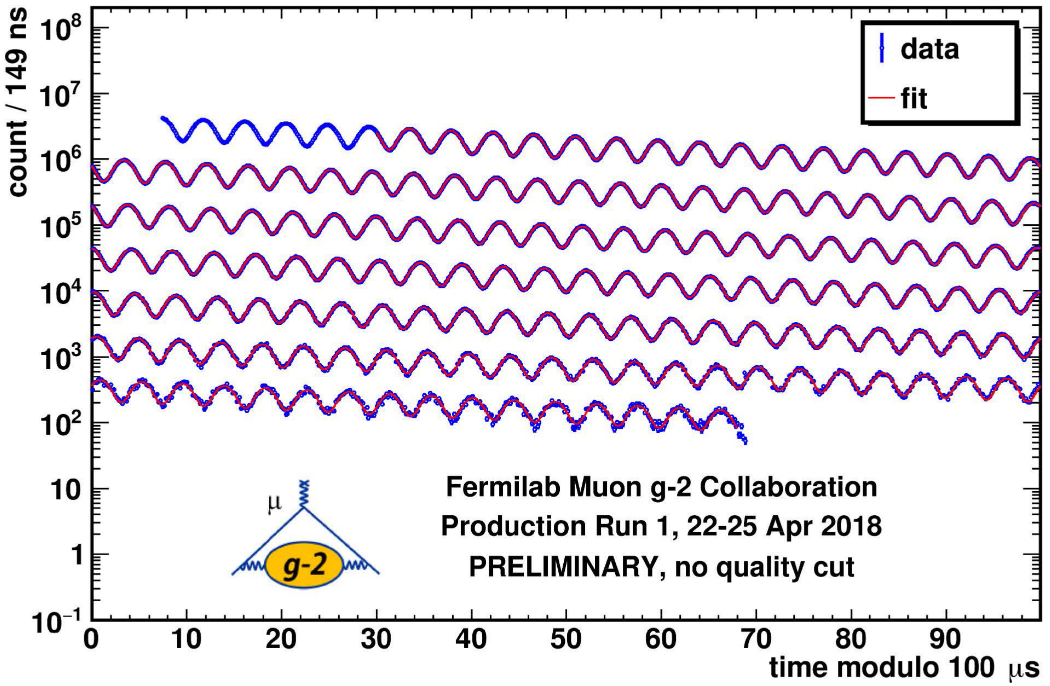
Crystals are 25×25×140 mm

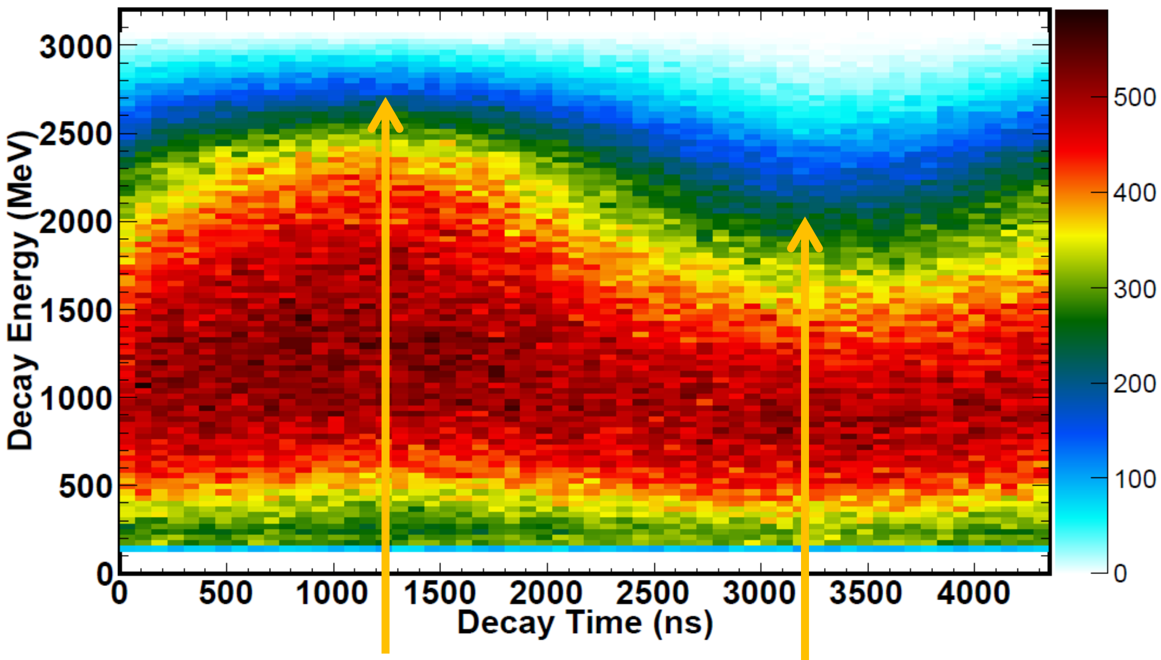


Straw trackers: reconstruct decay e^+ trajectories

Calorimeters: detect decay e^+ energy and arrival times

The Wiggle Plot





Muon spin and momentum are aligned.

Muon spin and momentum are anti-aligned.

$$f(t) = N_0 e^{-\lambda t}[1 + A\cos(\omega_a t + \phi)]$$

λ: exponential decay constant

ω_a: muon anomalous precession frequency

Early-to-late phase change:

If, $\phi = \phi(t) = \phi_0 + \phi_1 t$, then

$\cos(\omega_a t + \phi) = \cos(\omega_a t + \phi_0 + \phi_1 t) =$

$= \cos\left((\omega_a + \phi_1)t + \phi_0\right)$

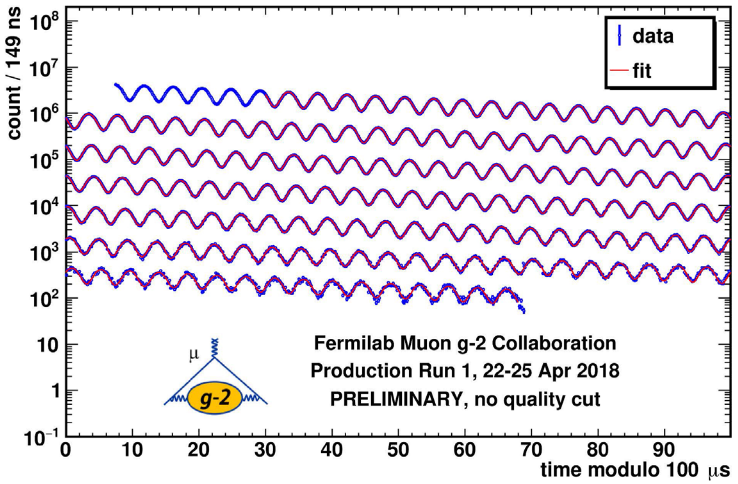
Calculation of a_μ from Muon and Proton Spin Precession

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

(140 ppb)

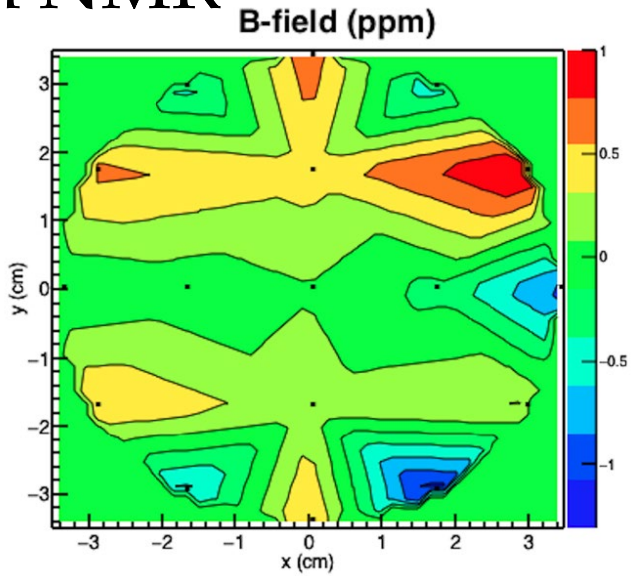
from decay e^+ time spectra

(70 ppb sys. 100 ppb stat.)



from NMR

(70 ppb sys.)



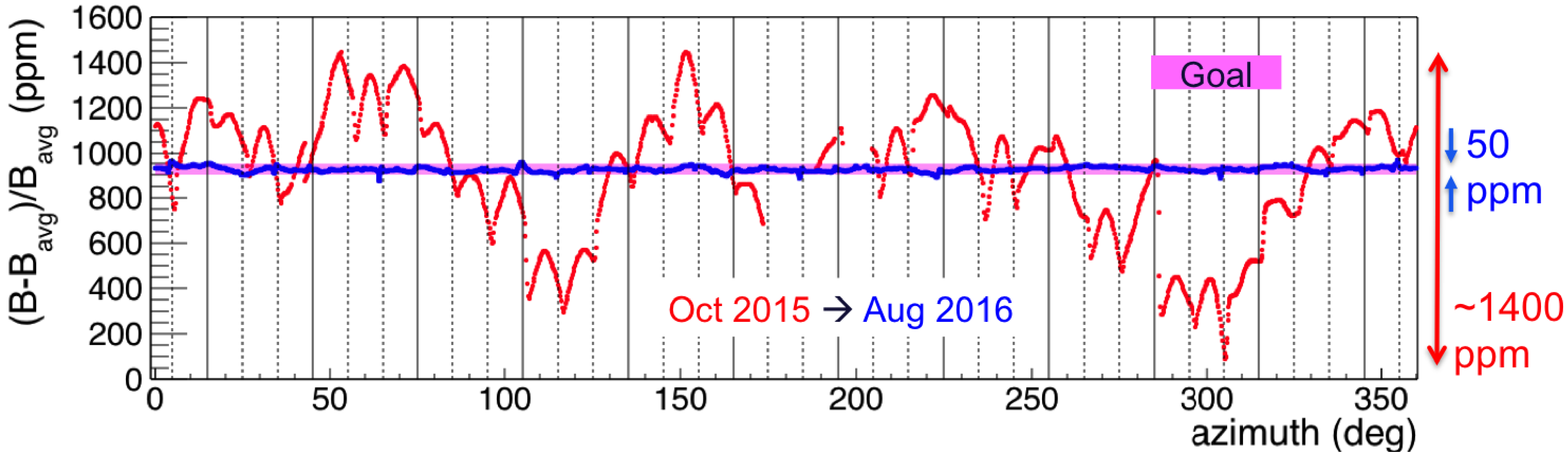
From CODATA [1]:

g_e = -2.002 319 304 361 82(52) (0.00026 ppb)

m_μ/m_e = 206.768 2826(46) (22 ppb)

μ_e/μ_p = -658.210 6866(20) (3.0 ppb)

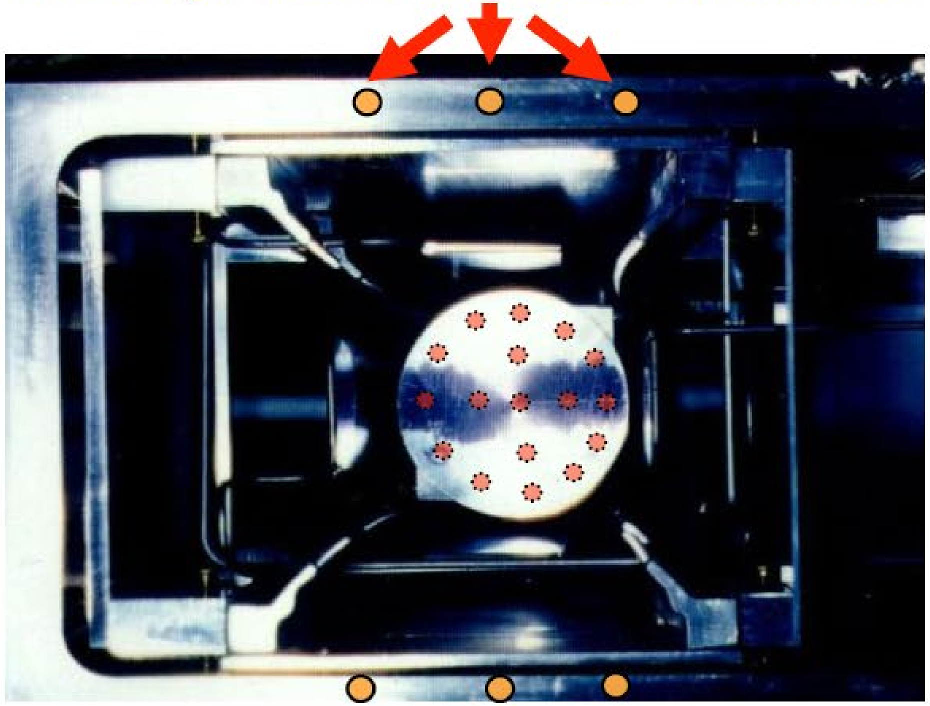
[1] P. J. Mohr, D. B. Newell and B. N. Taylor, Rev. Mod. Phys. 88, no. 3, 035009 (2016).



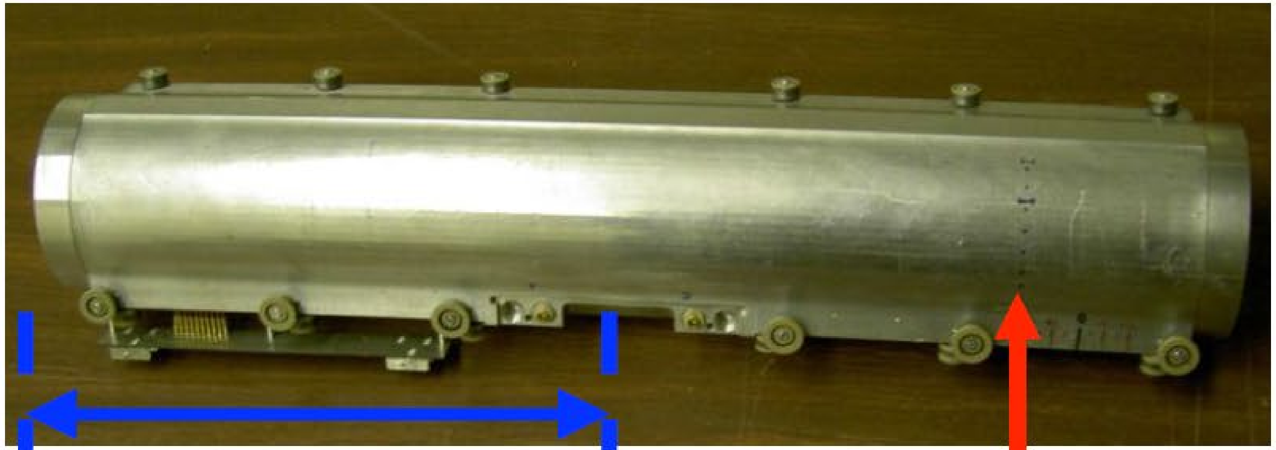
- Passive shimming is performed by inserting tiny metal pieces to increase the field.
- Magnetic field was made 3× more uniform than at BNL.
- Active shimming is also used.

Fixed and Trolley-Mounted NMR Probes

Fixed probes on vacuum chambers



Trolley with matrix of 17 NMR probes



Electronics,
Microcontroller,
Communication

Position of NMR probes

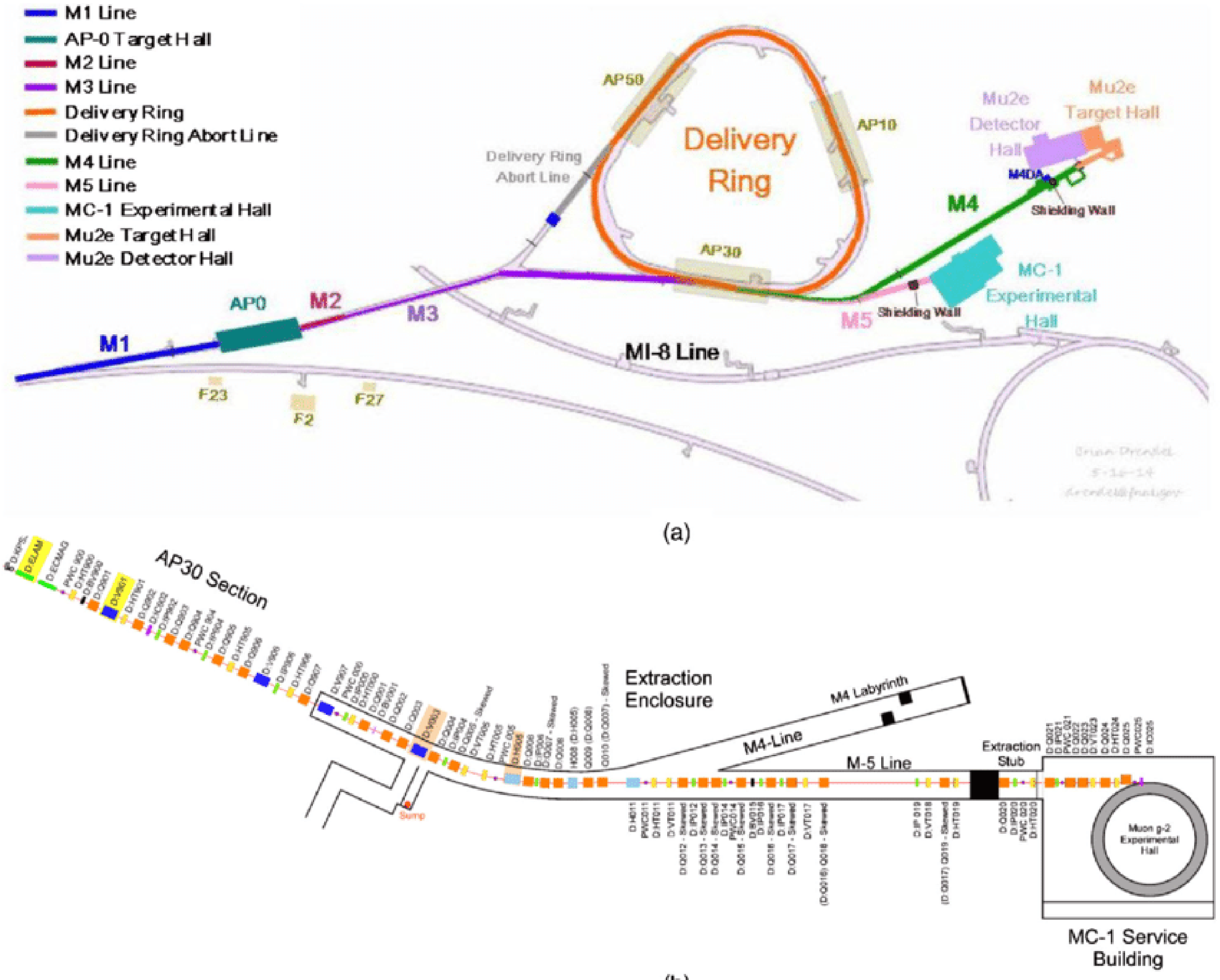
Corrections and Uncertainties Before Unblinding

	Correction	Uncertainty	Design goal
ω_a^m (statistical)	–	434	100
ω_a^m (systematic)	–	56	
base clock	–	2	
C_e	489	53	
C_p	180	13	
C_{ml}	-11	5	
C_{pa}	-158	75	
ω_a beam dynamics corrections $(C_e + C_p + C_{ml} + C_{pa})$	499	93	
ω_a total systematic	499	109	70
$\omega'_p(T)(x, y, \varphi)$	–	54	
$M(x, y, \varphi)$	–	17	
$\langle\omega'_p(T)(x, y, \varphi) \times M(x, y, \varphi)\rangle$	–	56	
B_q	-17	92	
B_k	-27	37	
$\tilde{\omega}'_p(T)$ transient fields corrections $(B_q + B_k)$	-44	99	
$\tilde{\omega}'_p(T)$ total	44	114	70
$\omega_a/\tilde{\omega}'_p(T)$ total systematic	544	157	100
external measurements	–	25	
total [correction is for $\omega_a/\tilde{\omega}'_p(T)$]	544	462	140

In the following eight or nine slides, I will talk about some of my recent personal contributions:

- *end-to-end simulations*
- *application of simulation results to muon loss systematics*

Beamlines of the Muon Campus

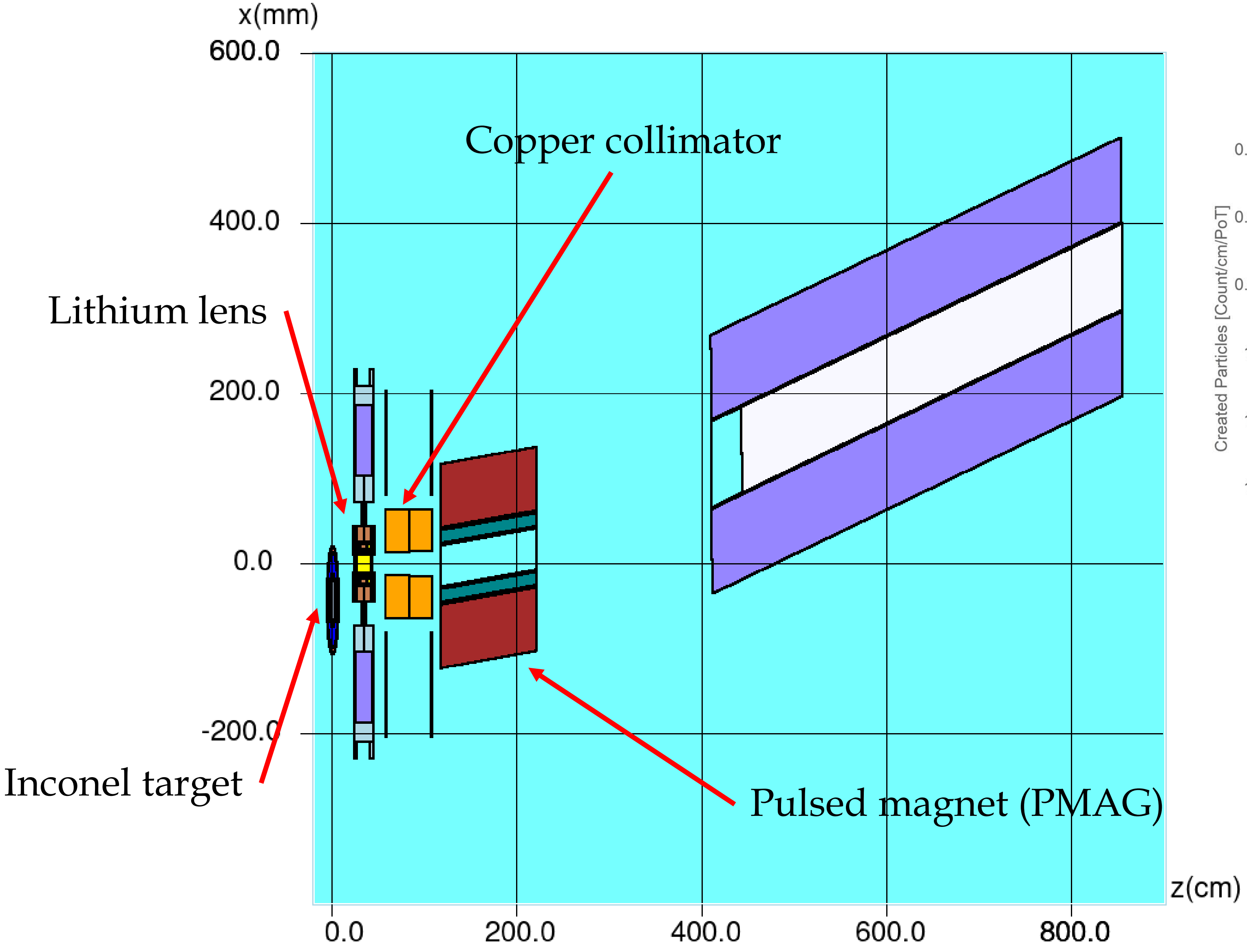


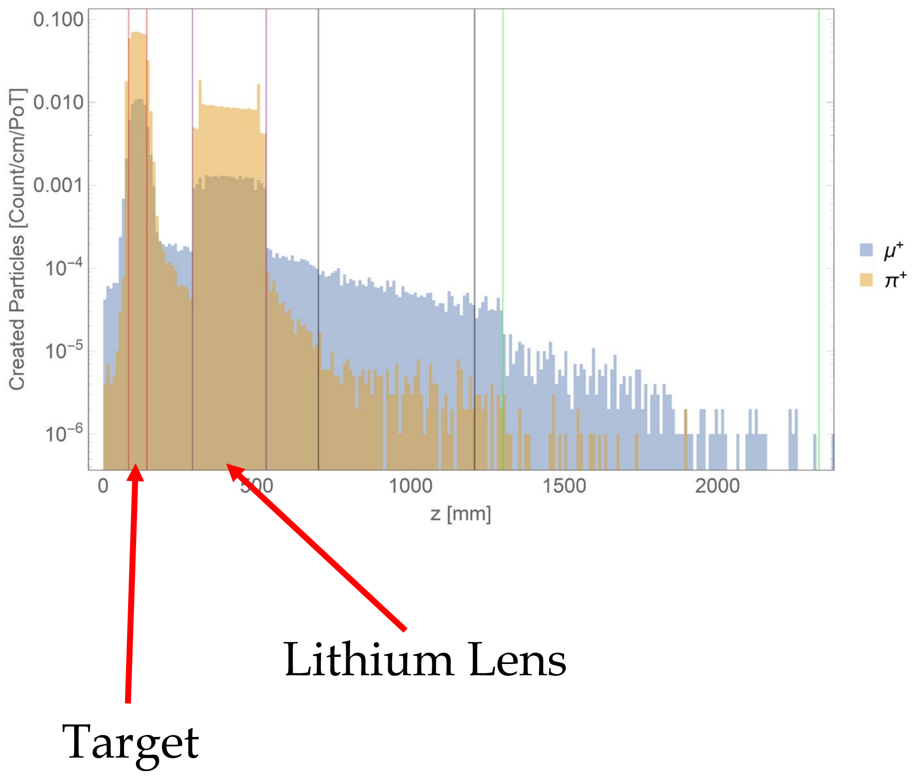
(a)

(b)

Need to understand potential sources of early-to-late beam-related systematics.

Muon g-2 Target Station





Simulations Using High Performance Computing Systems

2×10^{13} protons on target

HPC systems:

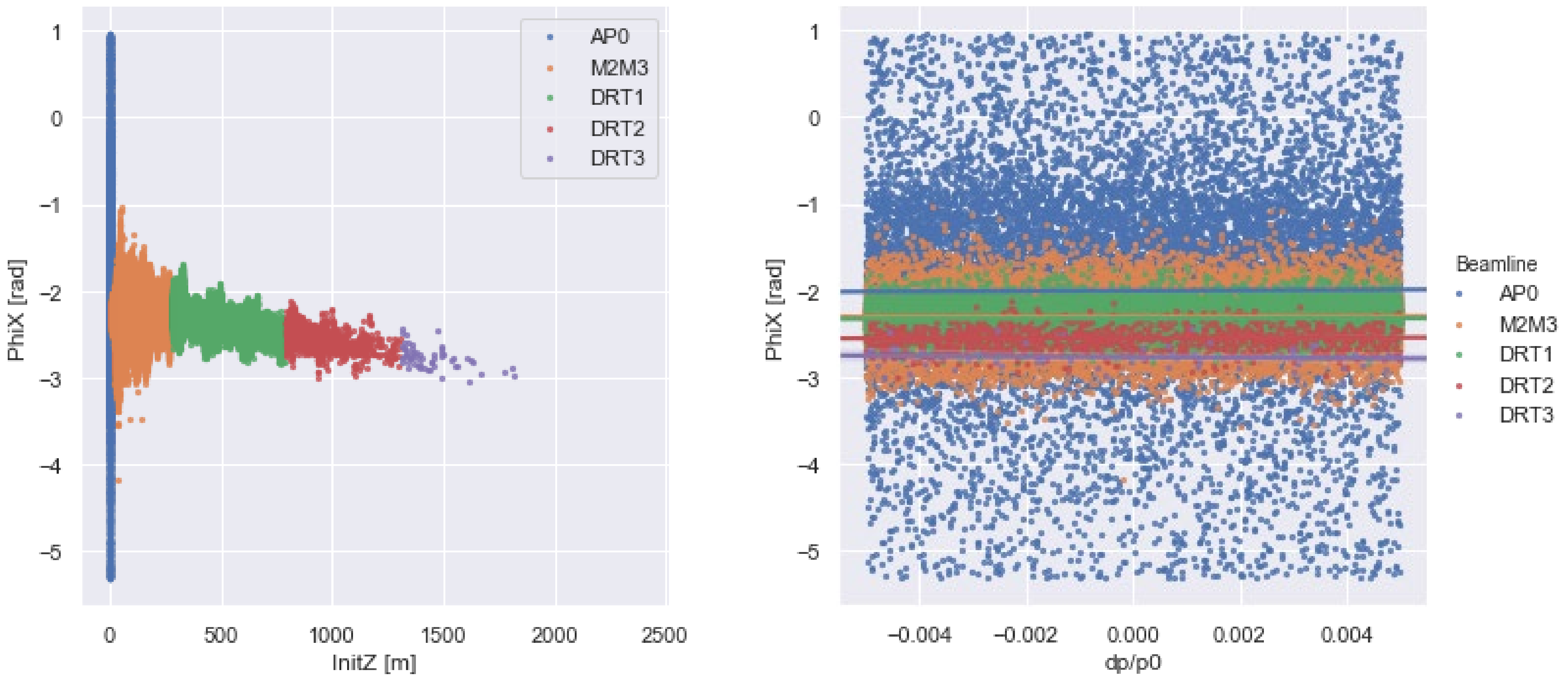
- NERSC
  - Edison (2013–2019): 2.57 PFLOPS
  - Cori (2015–): 30 PFLOPS
- Open Science Grid
  - Up to 10000 cores at a time
- FermiGrid

Simulation tools:

- gm2ringsim (Geant4)
- COSY INFINITY
- BMAD
- MARS
- G4Beamline (Geant4)

Dependence of Initial Phase on Muon Creation Location

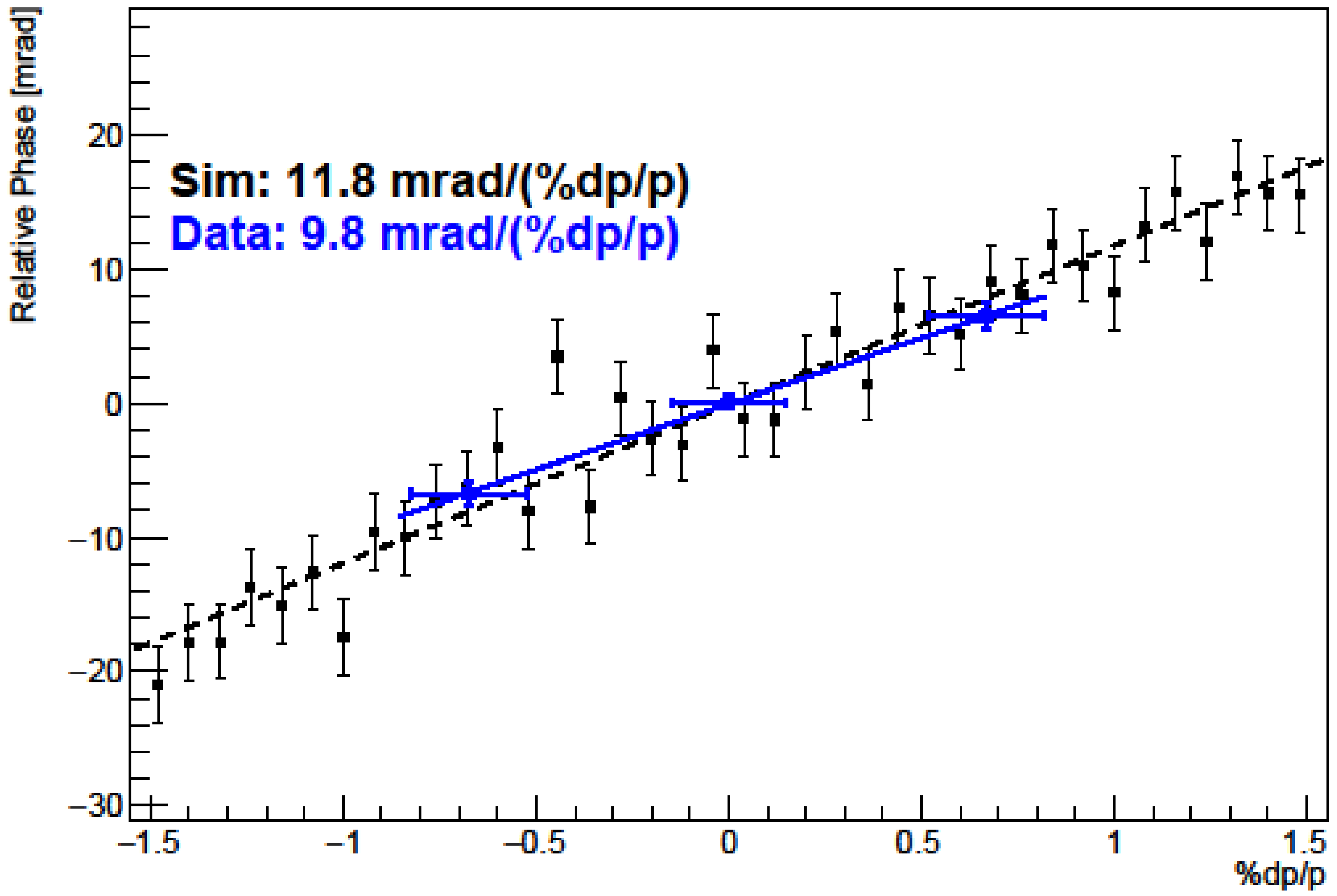
Simulation results, preliminary



InitZ: muon creation location. PhiX: muon spin phase at entrance into the ring. dp/p0: momentum deviation. All data within $\left|\frac{dp}{dp0}\right| < 0.5\%$, i.e. 3σ acceptance of the storage ring.

Dependence of Relative Initial Phase on Momentum

Experimental data: Hannah Binney.

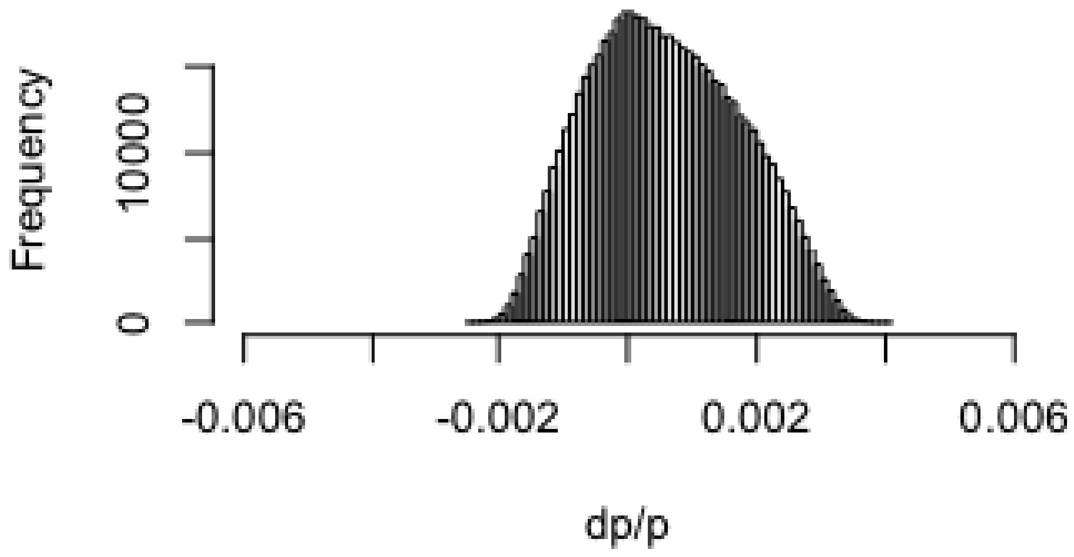


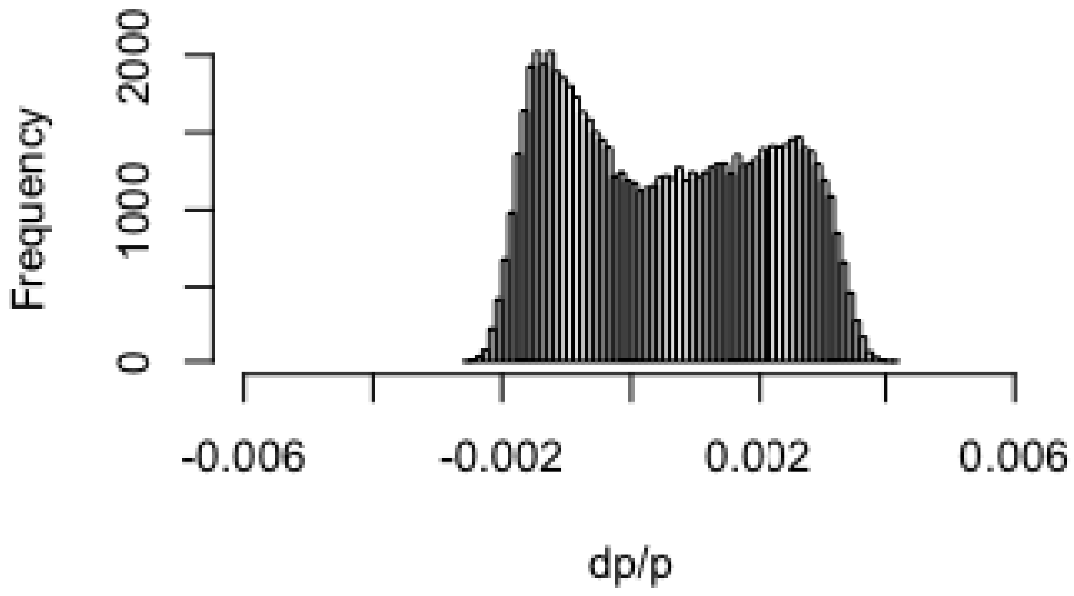
A real momentum dependence of the initial phase develops because of magnetic dipoles in the Delivery Ring.

Experimental data: based on runs with muon storage with higher or lower momenta.

Momentum-Dependent Muon Losses

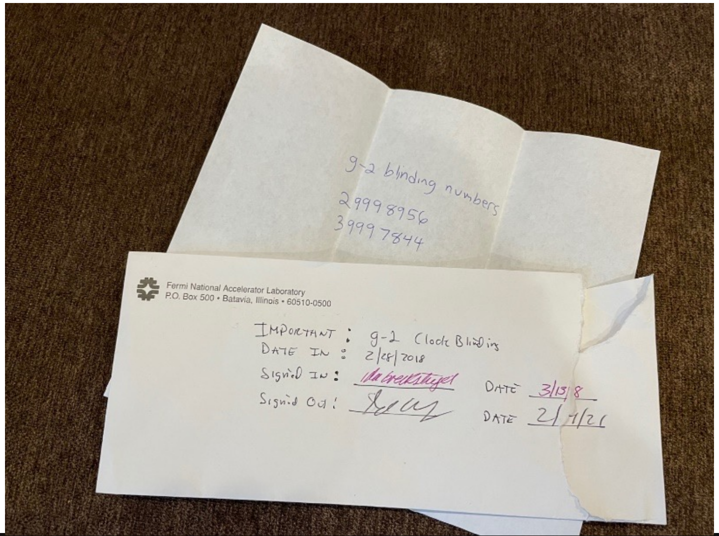
Simulation results (Mike Syphers)

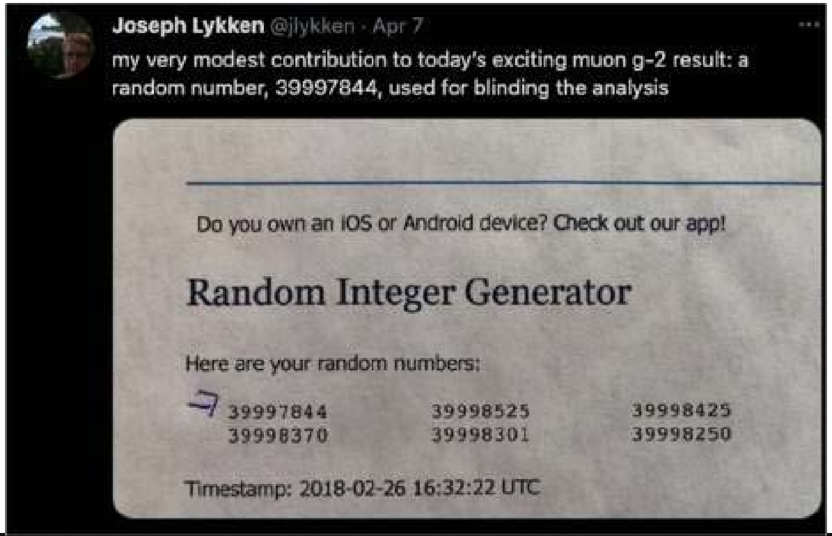




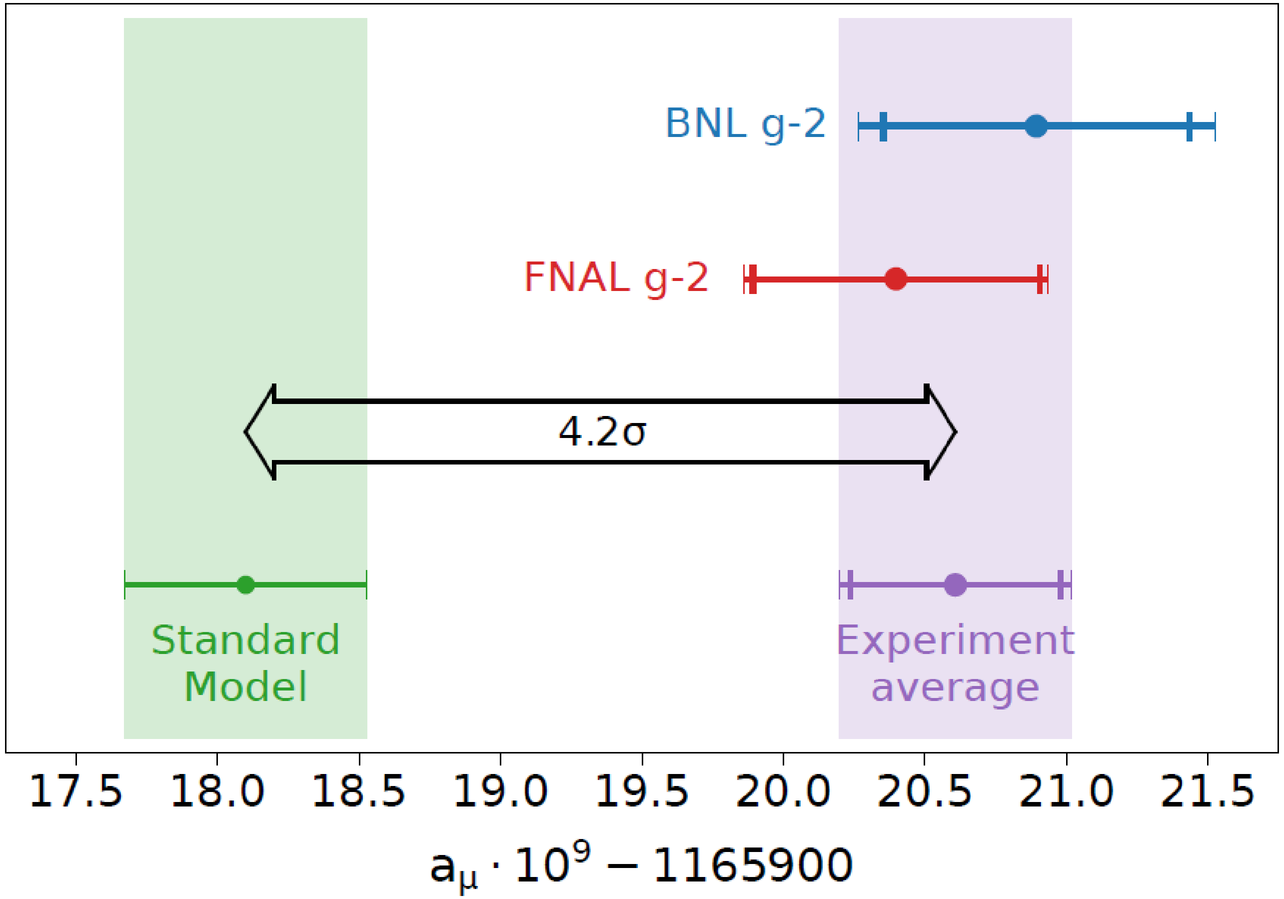
A -11(5) ppb correction due to muon losses.
Far below the overall 70 ppb systematic error on the spin precession.
Meeting the TDR goal of 20 ppb.

The Decision to Unblind: a Remote Meeting of the Collaboration





Run-1 Result of the Muon g-2 Experiment



$+3.66\sigma$, E821

$+3.33\sigma$, E989 Run-1

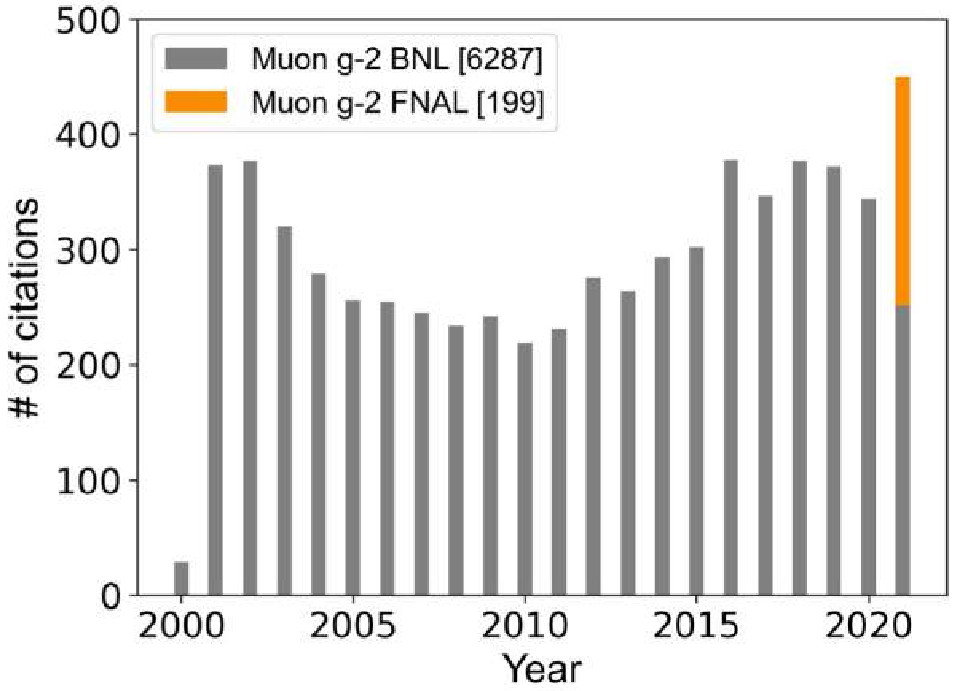
$+4.22\sigma$, E989 Run-1 + E821

The SM value is the Muon g-2 Theory Initiative recommended value.
T. Aoyama *et al.*, Phys. Rep. **887**, 1 (2020).

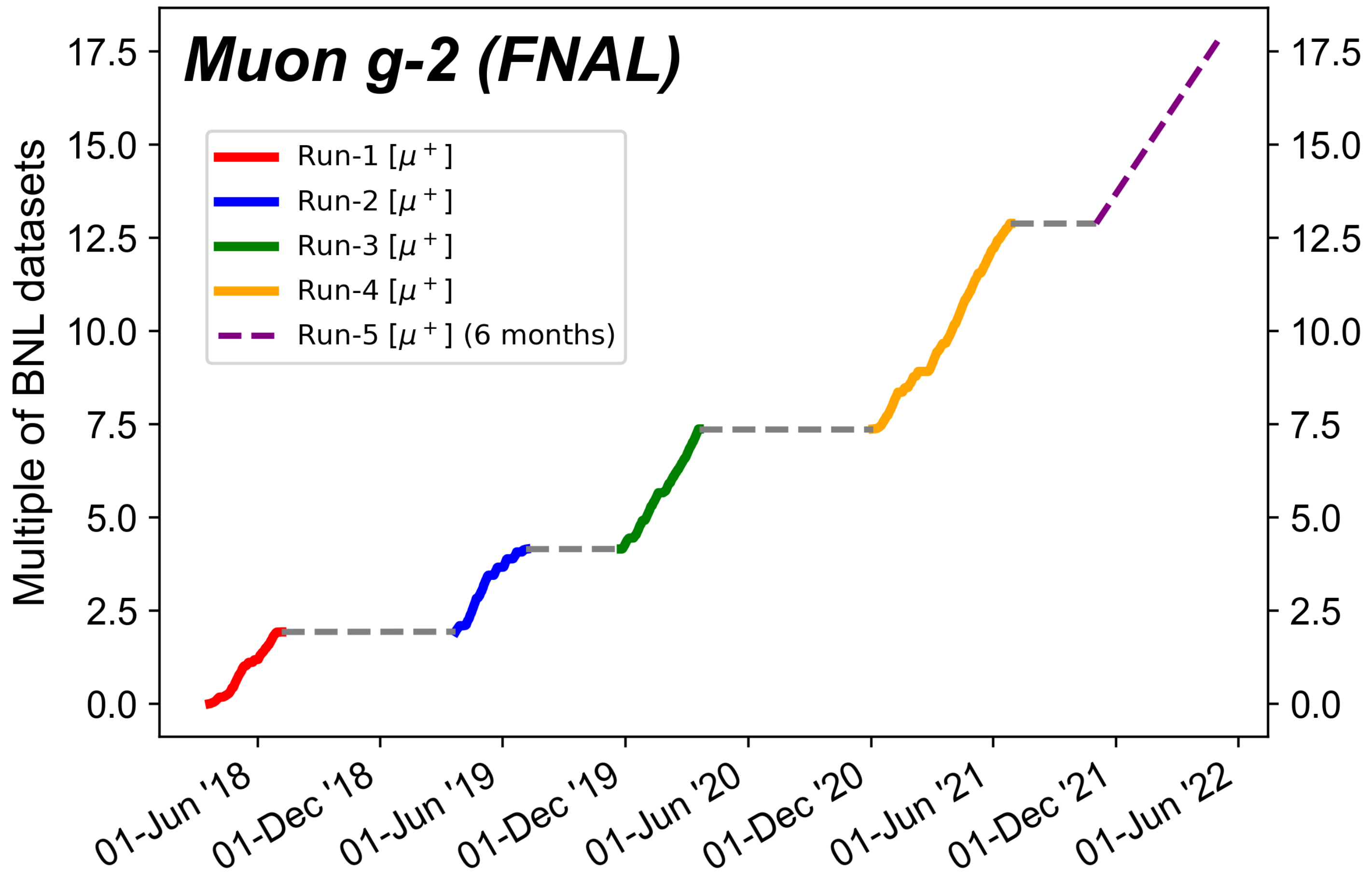
Publications of the Muon g-2 Experiment

Run-1 papers

- Measurement of the Positive Muon Anomalous Magnetic Moment to 0.46 ppm
  https://doi.org/10.1103/PhysRevLett.126.141801
- Measurement of the anomalous precession frequency of the muon in the Fermilab Muon *g*-2 Experiment
  https://doi.org/10.1103/PhysRevD.103.072002
- Magnetic-Field Measurement and Analysis for the Muon *g*-2 Experiment at Fermilab
  https://doi.org/10.1103/PhysRevA.103.042208
- Beam dynamics corrections to the Run-1 measurement of the muon anomalous magnetic moment at Fermilab
  https://doi.org/10.1103/PhysRevAccelBeams.24.044002

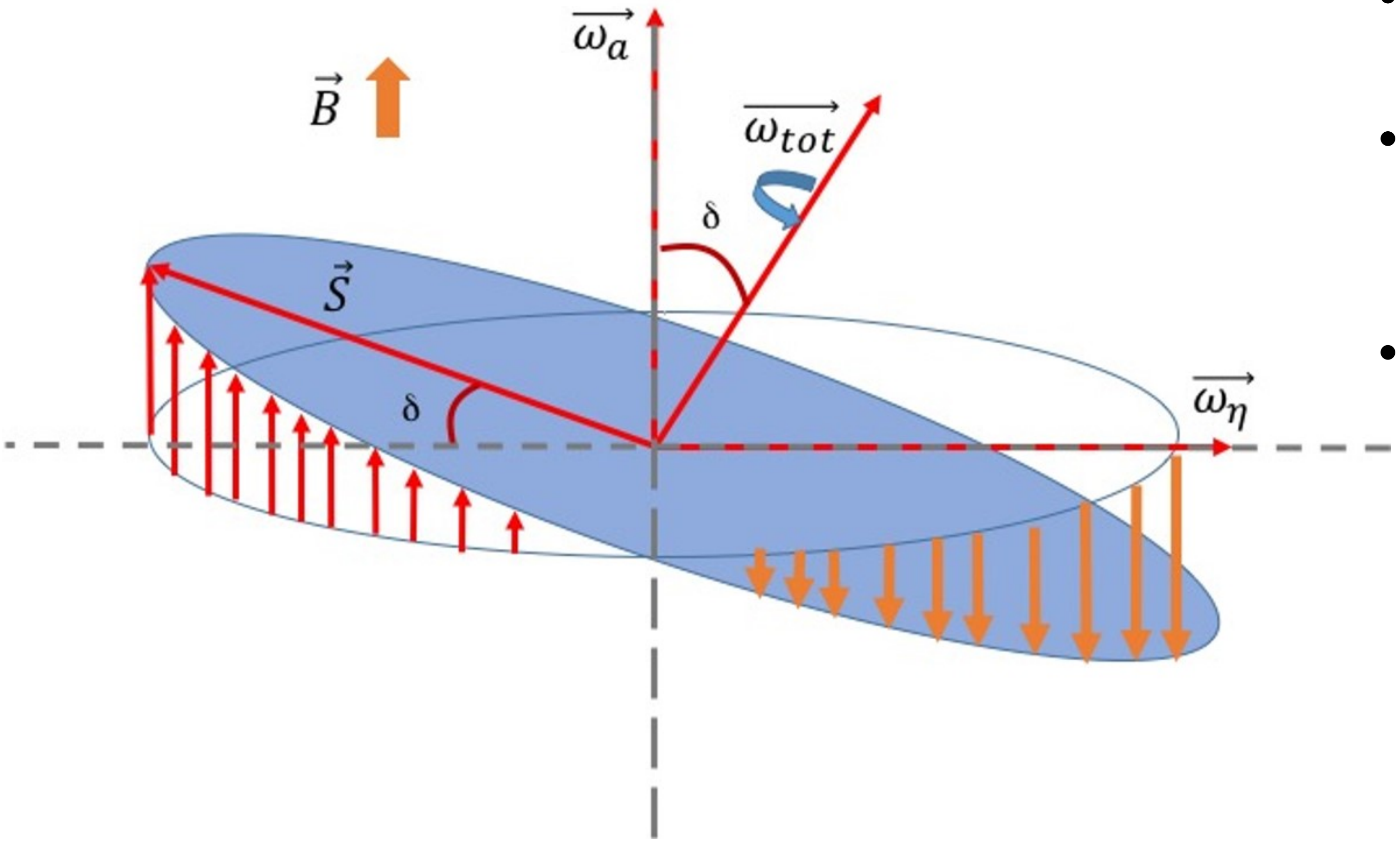


Projection of Data Acquisition as a Multiple of BNL Data



Currently at
$\sim$12.43 $\times$ BNL data

Future EDM or μ^- anomalous MDM Possibilities



- Currently measuring μ^+ anomalous MDM
- Measure μ^+ EDM using vertical phase asymmetry detection in calorimeters
- Measure μ^- by reconfiguring the beamlines and storage ring (switching electric field direction)
  - No other proposed experiment can do μ^- (JPARC μ^+ only)

Conclusion

- The first a_μ result was released (Run-1), with precision 460 ppb
  - The combined FNAL+BNL result has a 4.2σ tension with the SM prediction
- We already have ×10 more data compared to Run-1
- Run-2 and Run-3 results are expected to be ready for release in ~1 year
- The experiment continues physics runs to accumulate statistics for a total uncertainty of 140 ppb
  - Run-4 is complete, and Run-5 will begin soon

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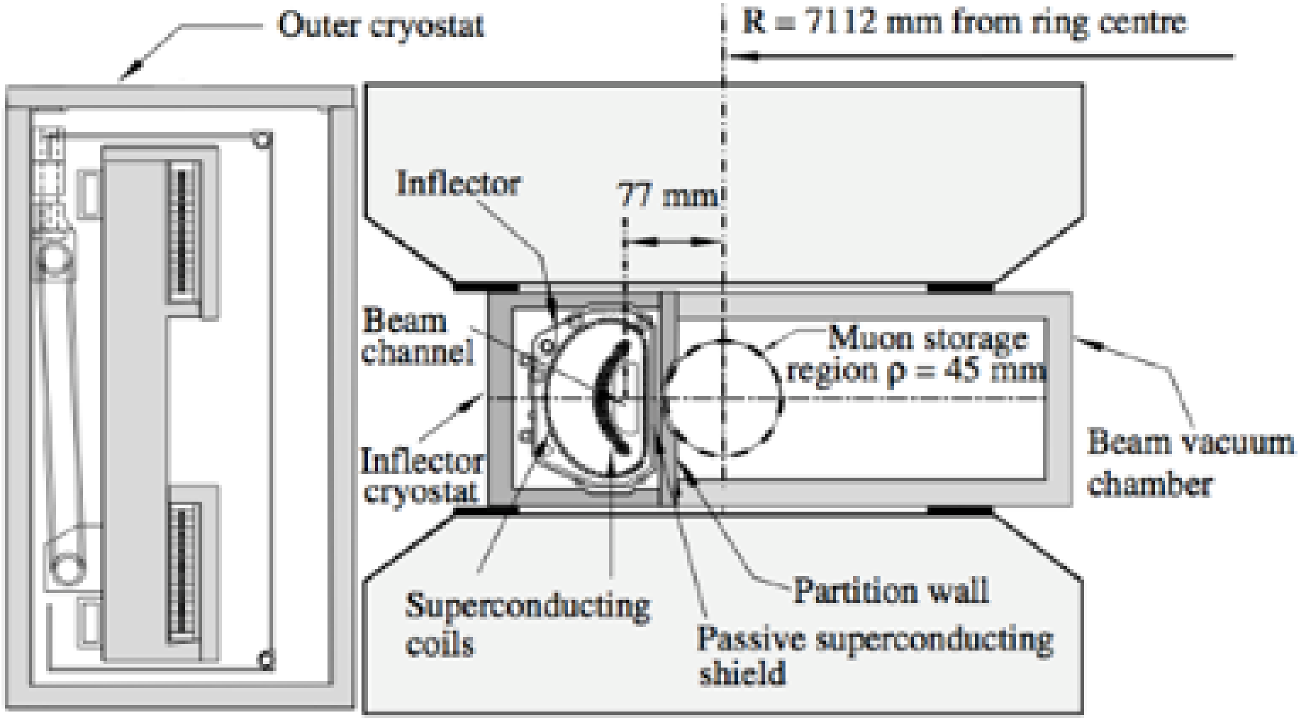
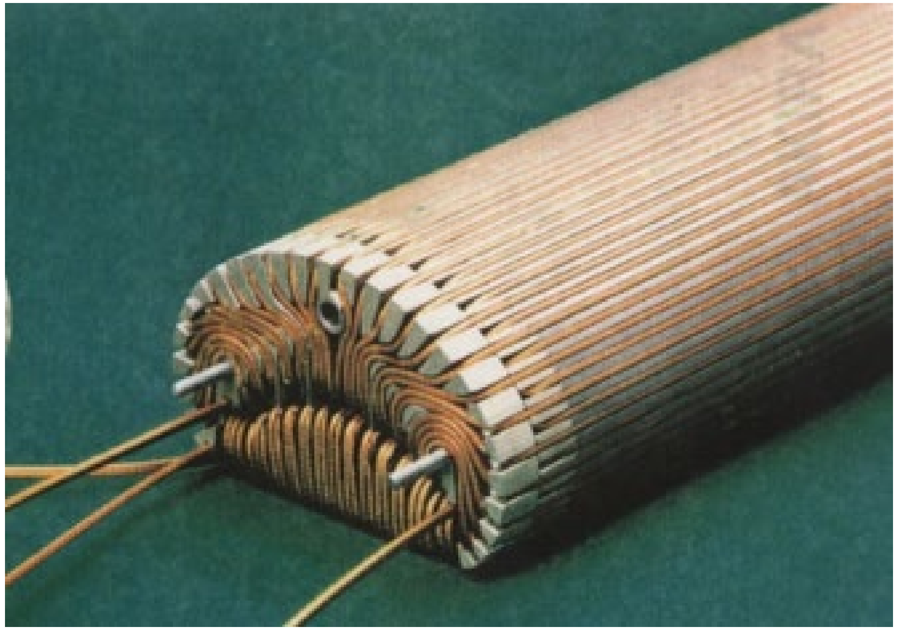
• This document was prepared by the Muon g-2 collaboration using the resources of the Fermi National Accelerator Laboratory (Fermilab), a U.S. Department of Energy, Office of Science, HEP User Facility. Fermilab is managed by Fermi Research Alliance, LLC (FRA), acting under Contract No. DE-AC02-07CH11359.
• This research used resources of the National Energy Research Scientific Computing Center (NERSC), a U.S. Department of Energy Office of Science User Facility operated under Contract No. DE-AC02-05CH11231.
• This research was done using resources provided by the Open Science Grid, which is supported by the National Science Foundation award 1148698, and the U.S. Department of Energy's Office of Science.

Muon g-2 Inflector





- 1.45 T bucking field to cancel main field
- Can’t perturb main field by more than ~1 ppm
- Interface optics of storage ring and the M5 beamline

Fitting Function Example: 20 Point

$$N = N_0 \Lambda N_{cbo} N_{2cbo} N_{vw} e^{-t/\tau} (1 - A A_{cbo} \cos(\omega_a t + \phi \phi_{cbo}))$$

$$N_{cbo} = 1 - A_{1cbo} e^{-\frac{t}{\tau_{cbo}}} \cos(\omega_{cbo} t + \phi_{1cbo})$$

$$N_{2cbo} = 1 - A_{2cbo} e^{-\frac{2t}{\tau_{cbo}}} \cos(2\omega_{cbo} t + \phi_{2cbo})$$

$$N_{vw} = 1 - A_{vw} e^{-\frac{t}{\tau_{vw}}} \cos(\omega_{vw} t + \phi_{vw})$$

$$A_{cbo} = 1 - A_{Acbo} e^{-\frac{t}{\tau_{cbo}}} \cos(\omega_{cbo} t + \phi_{Acbo})$$

$$\phi_{cbo} = 1 - A_{\phi cbo} e^{-\frac{t}{\tau_{cbo}}} \cos(\omega_{cbo} t + \phi_{\phi cbo})$$

$$\omega_{cbo} = \omega_0 (1 + 2.875 e^{-\frac{t}{76}} / \omega_0 t + 5.47 e^{-\frac{t}{8.85}} / \omega_0 t)$$

$$\Lambda = 1 - K_{loss} \int L(t') e^{t'/64.4} dt$$

$$\chi^2 = \sum_{i=1}^{ndf} [\frac{N_{bin} - N_{fit}}{\sigma(N_{bin})}]^2$$

Straw Tracking Detectors