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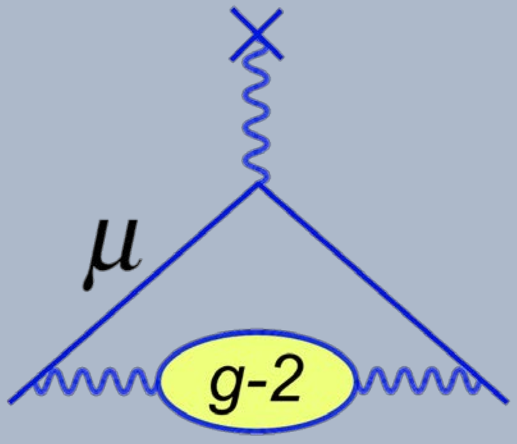

Toward the Frontiers of Particle Physics with the Muon $g-2$ Experiment

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On behalf of the Muon $g-2$ Collaboration

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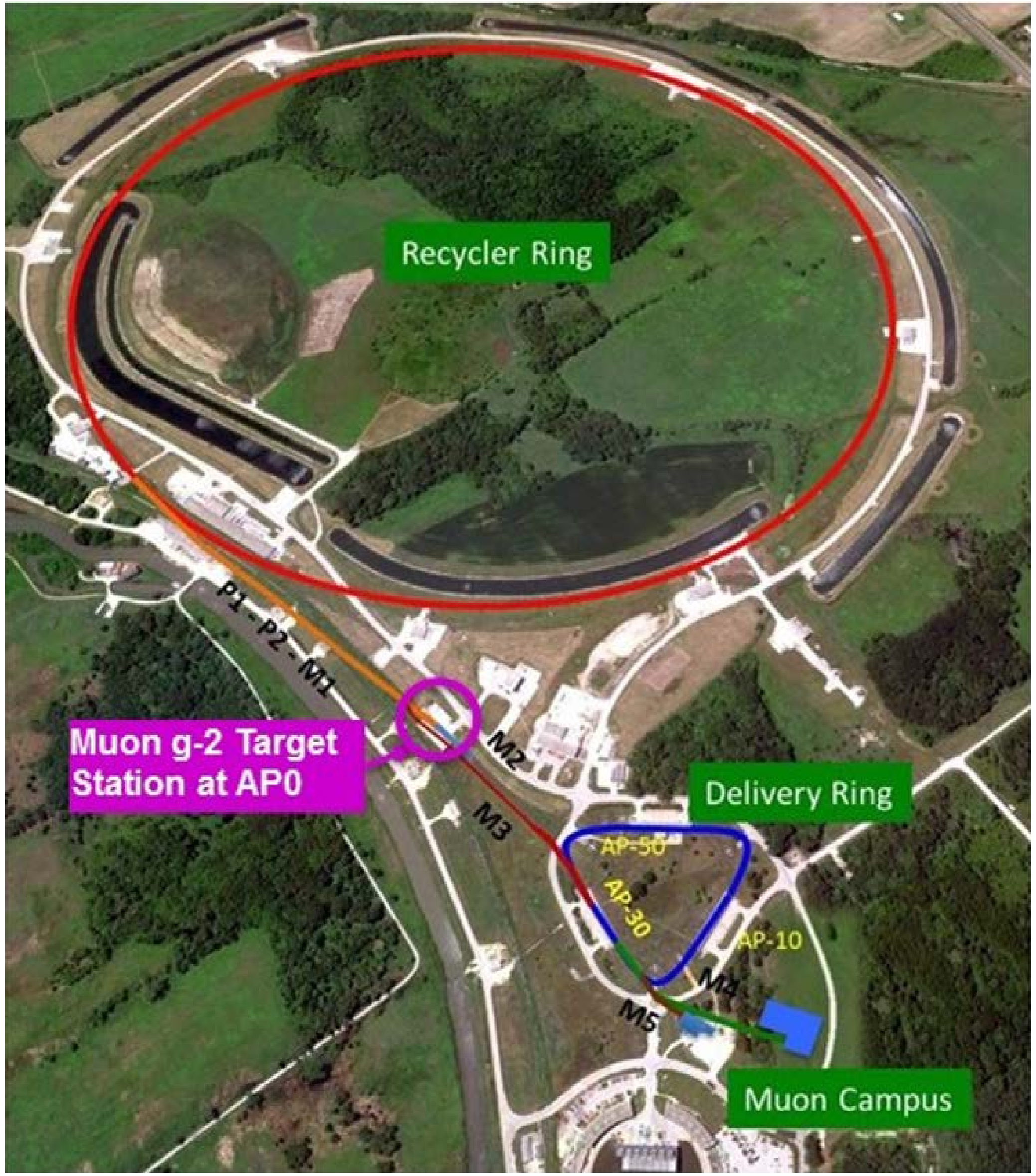
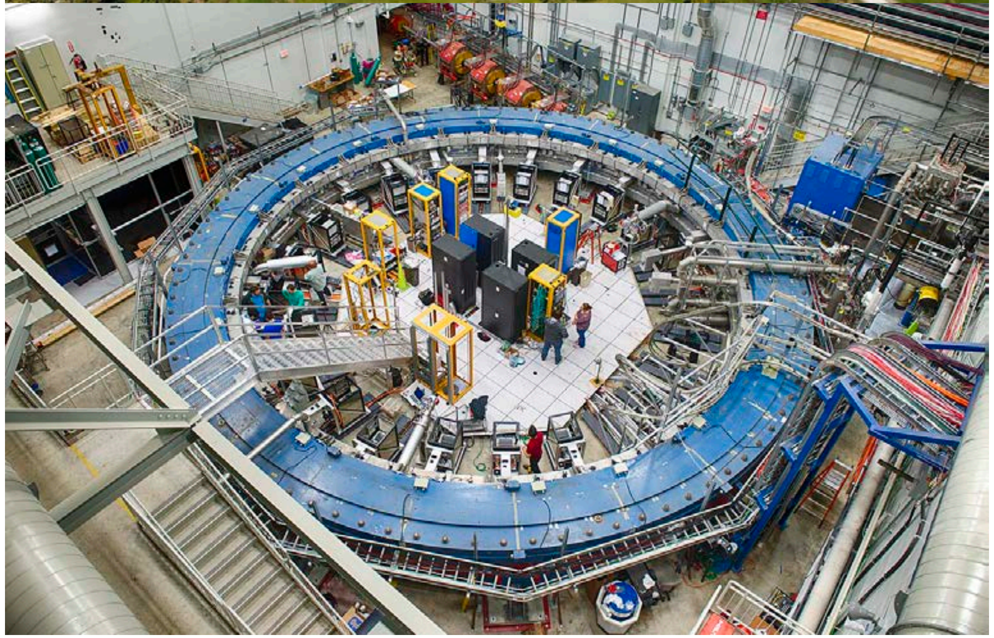
This document was prepared by Muon g-2 collaboration using the resources of the Fermi National Accelerator Laboratory (Fermilab), a U.S. Department of Energy, Office of Science, HEP User Facility. Fermilab is managed by Fermi Research Alliance, LLC (FRA), acting under Contract No. DE-AC02-07CH11359.

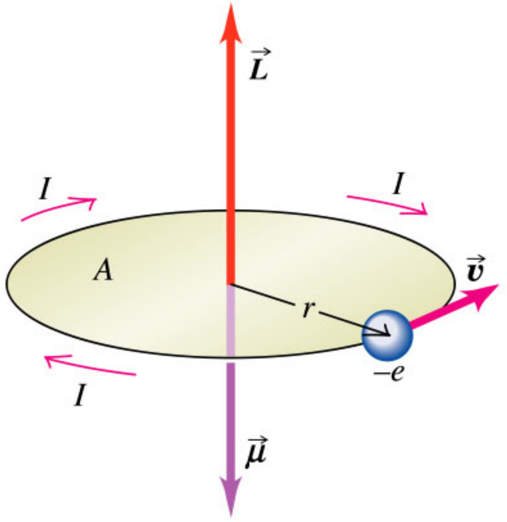
Introduction





Muon Anomalous Magnetic Dipole Moment (a_μ)

$$\mu = g\frac{e}{2m}s$$



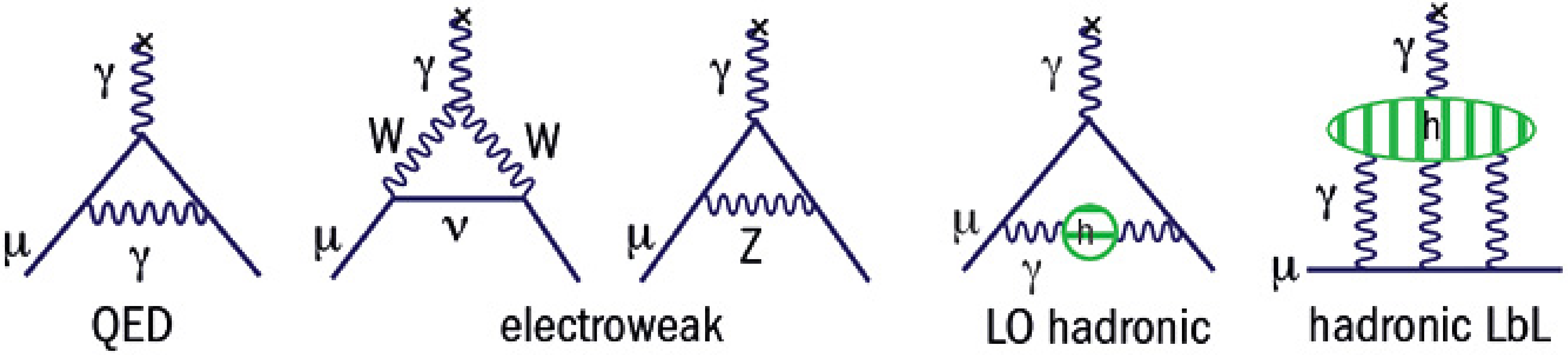
Classical: $g = 1$

Dirac Equation: $g = 2$

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

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

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

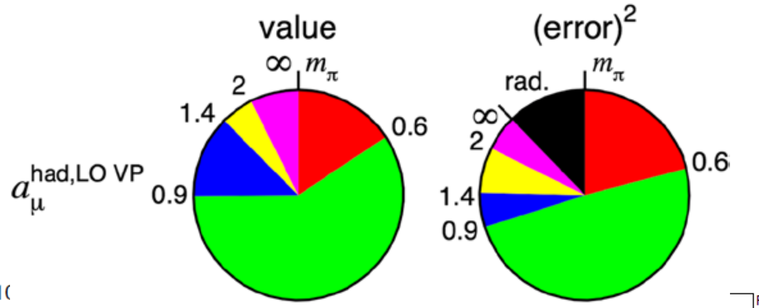
Theory:	$(11\,659\,1783 \pm 43) \times 10^{-11}$
Experiment:	$(11\,659\,2091 \pm 63) \times 10^{-11}$

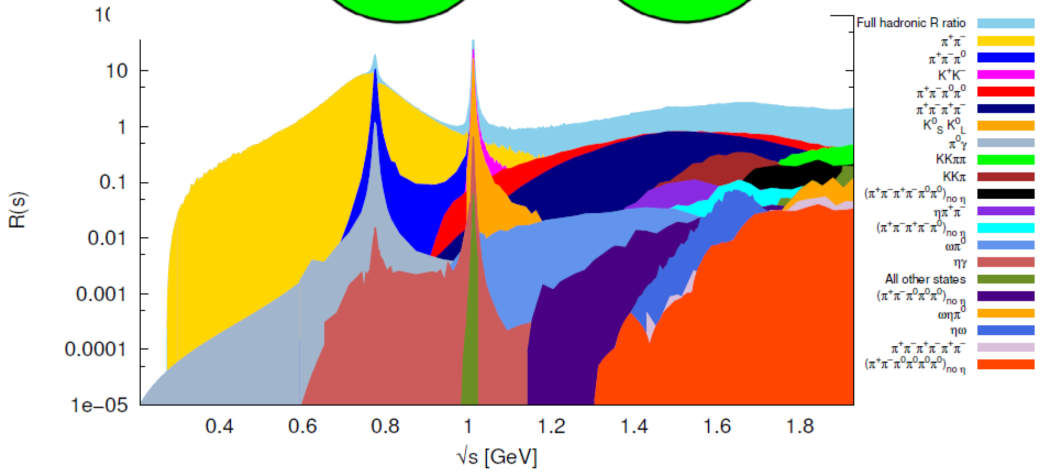
F. Jegerlehner, arXiv:1804.07409 [hep-ph] (2018).

Recent Advances in the Theory

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

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



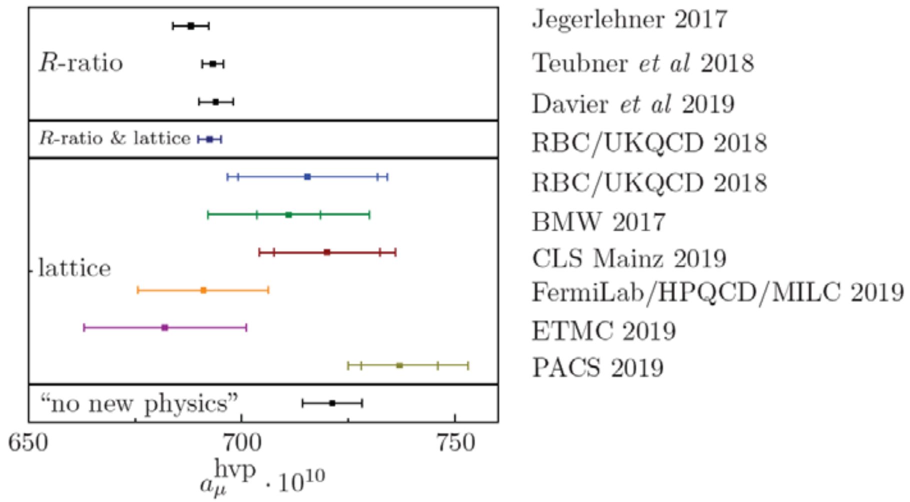


$$a_\mu^{\text{Had,LO VP}} = (693.26 \pm 2.46) \times 10^{-10}$$

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

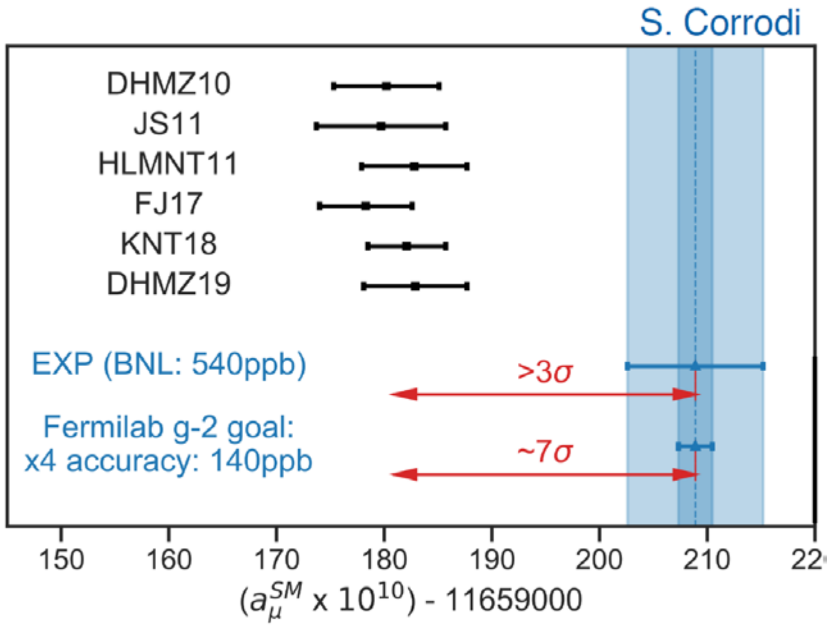
Calculation of $a_\mu^{\text{Had, VP}}$ and $a_\mu^{\text{Had, LbL}}$ using Lattice QCD

- 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).

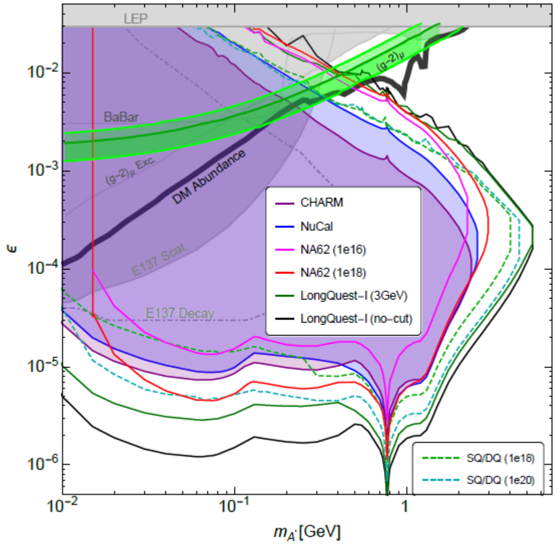
Beyond–Standard Model Possibilities



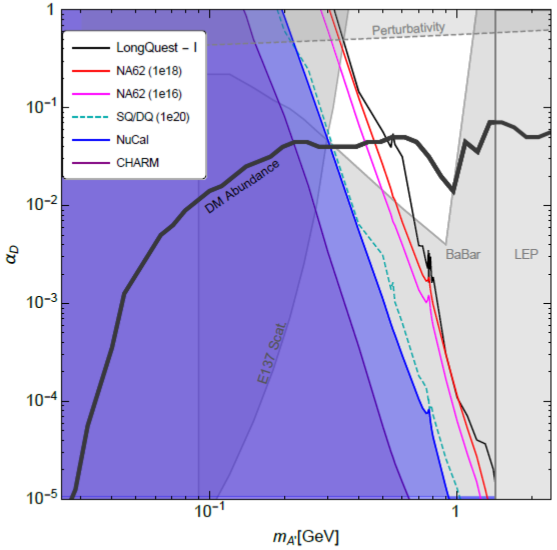
In case of a Beyond-SM a_μ, some of the possible contributors to the respective discrepancy would be:

- 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.



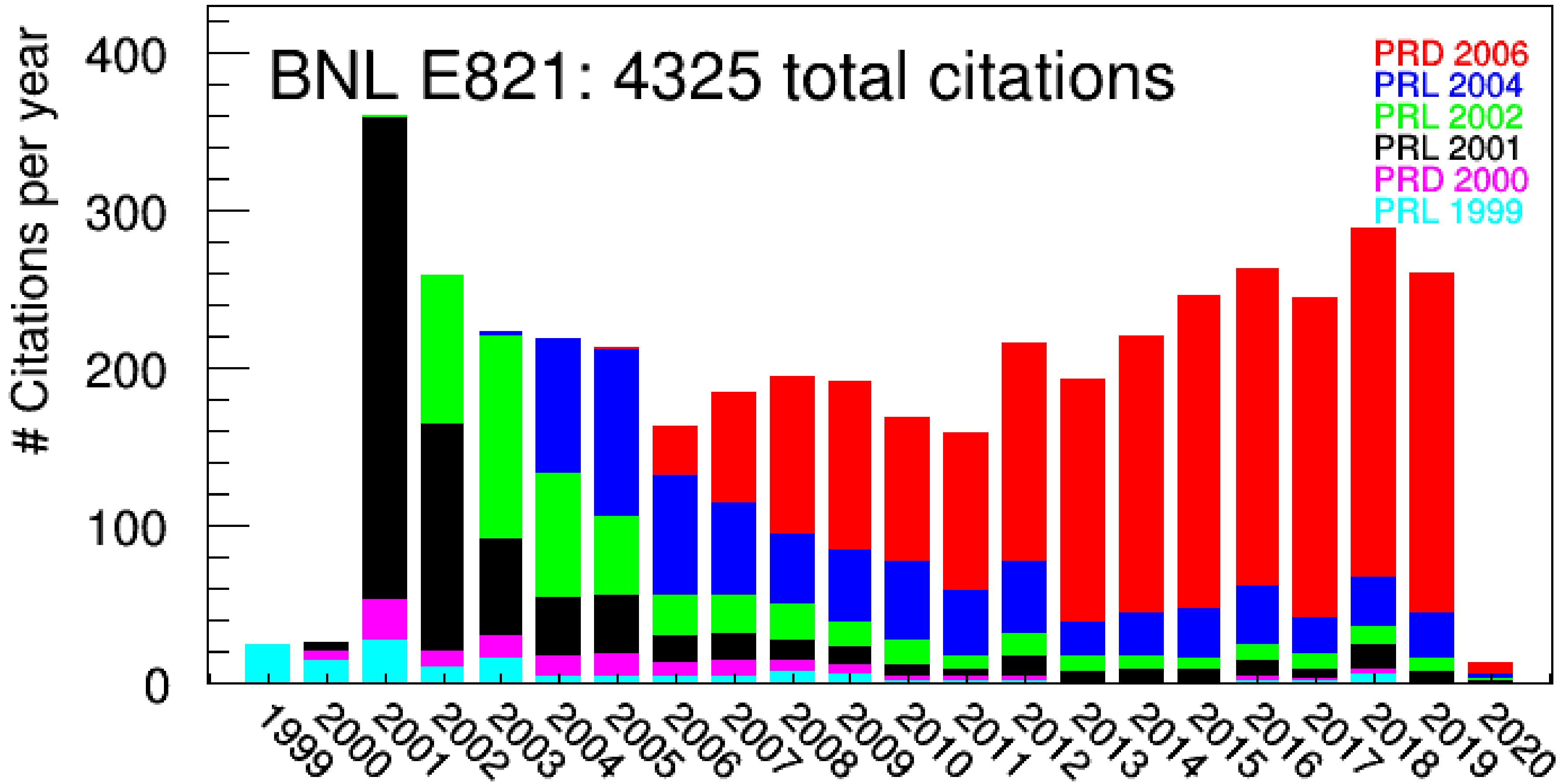
(b) iDM Muon $g-2$ Target: $\Delta = 0.4$, $\epsilon = \epsilon_{(g-2)_\mu}$.

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

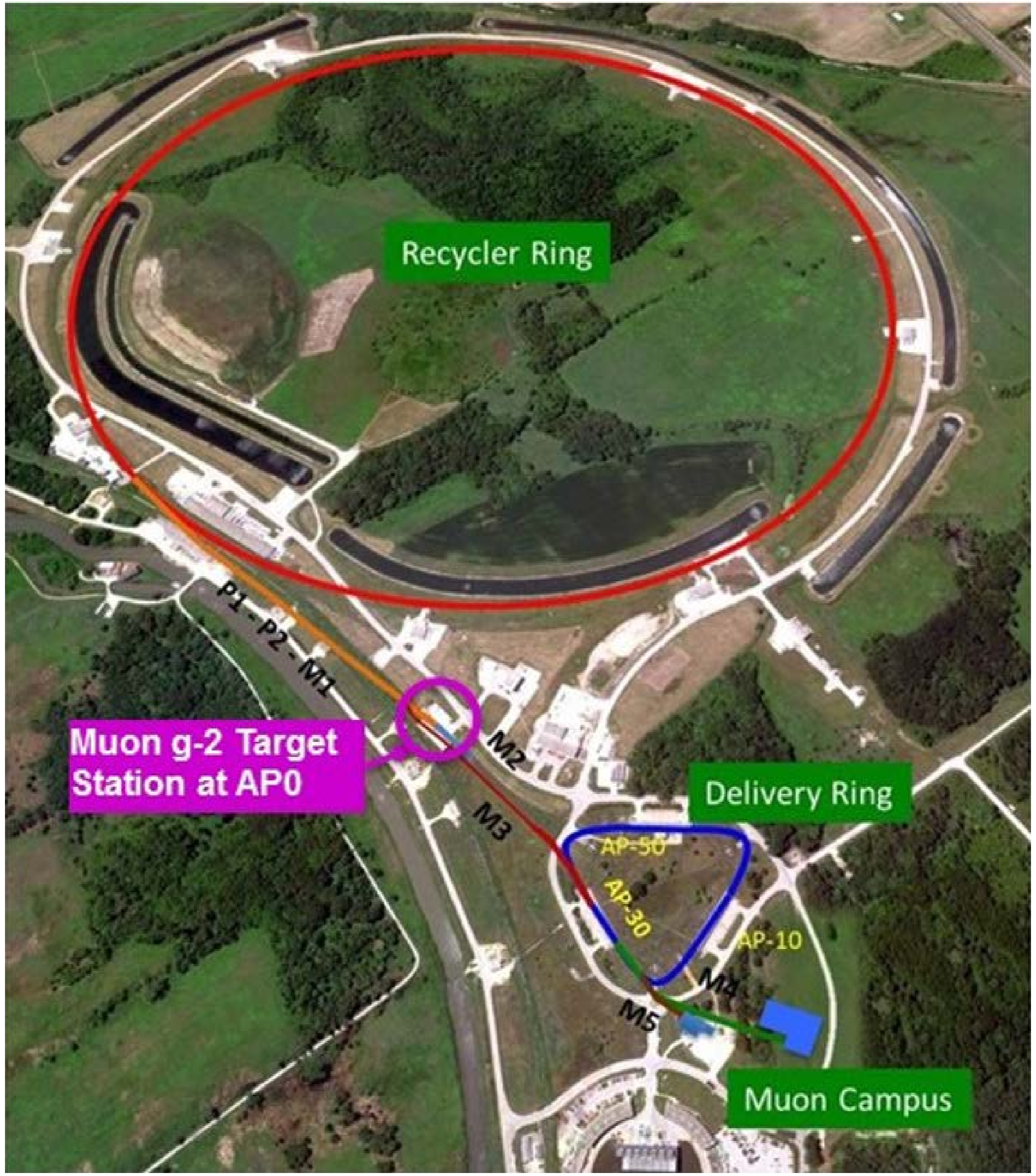
NA62 Experiment at CERN is ongoing and may yield iDM results.

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

Citations of Publications of the Muon g-2 Experiment at BNL



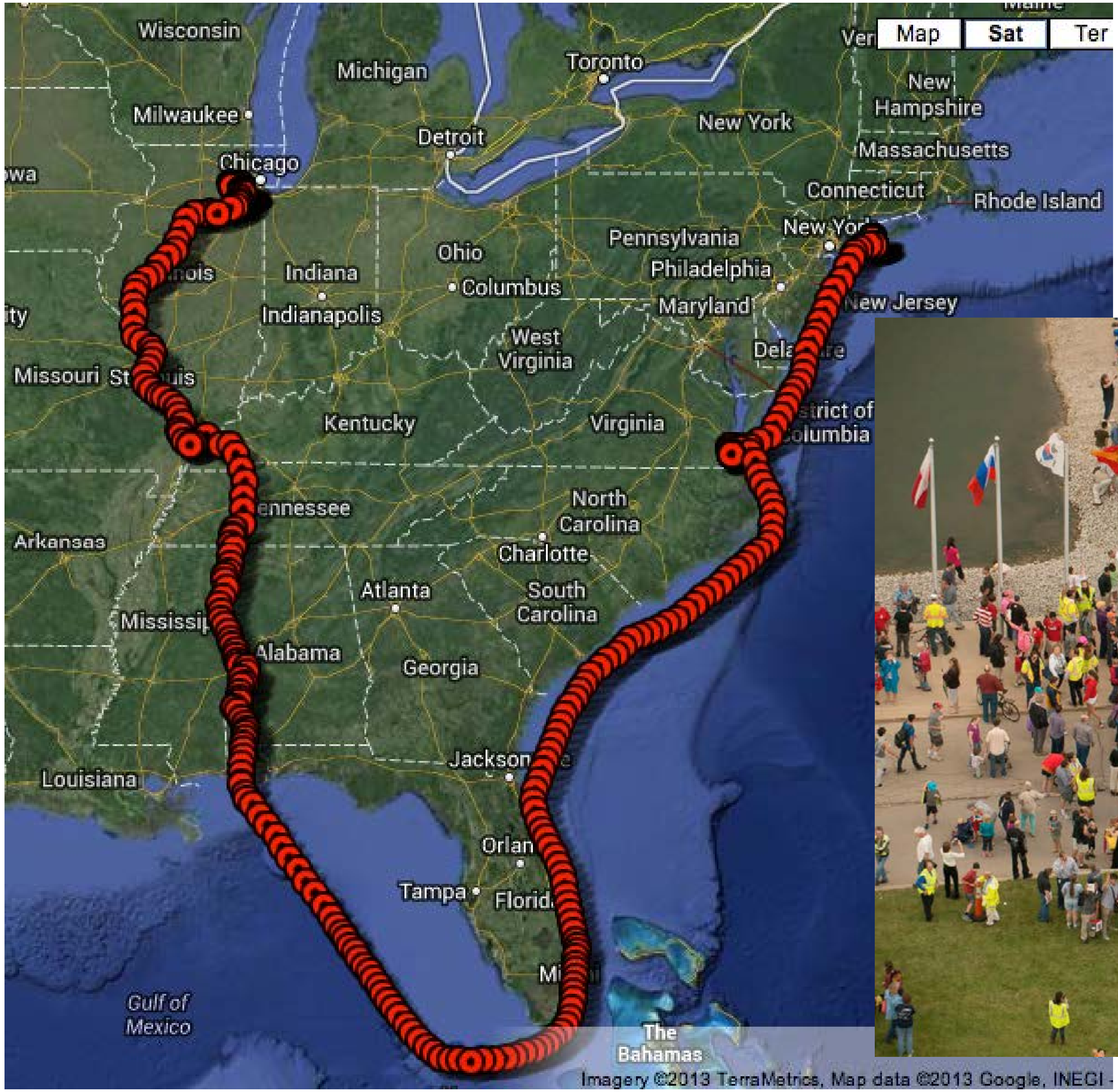
The Muon g-2 Experiment at Fermilab (E989)



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

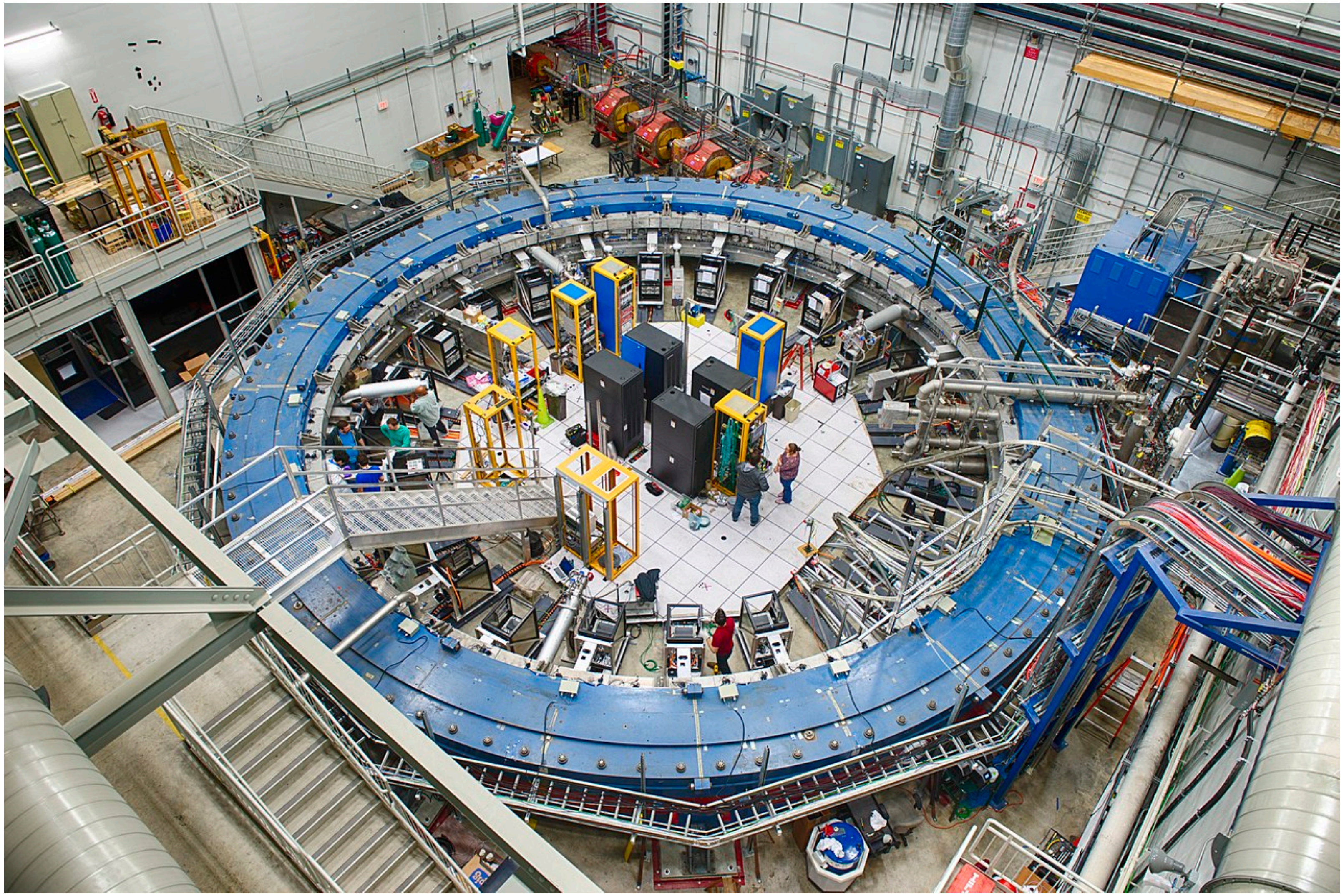
The Great Move



2013

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

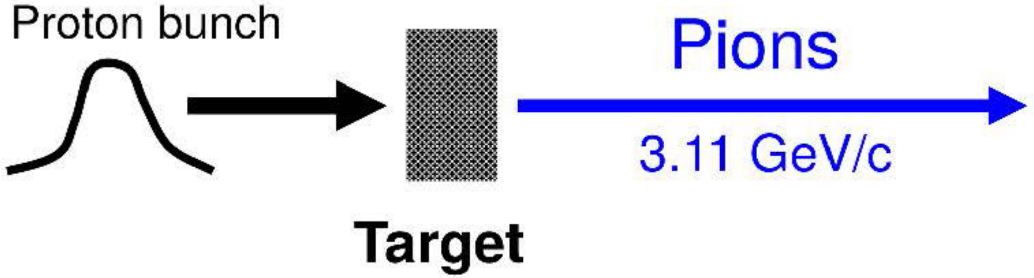
The Muon g-2 Experiment at Fermilab (E989)

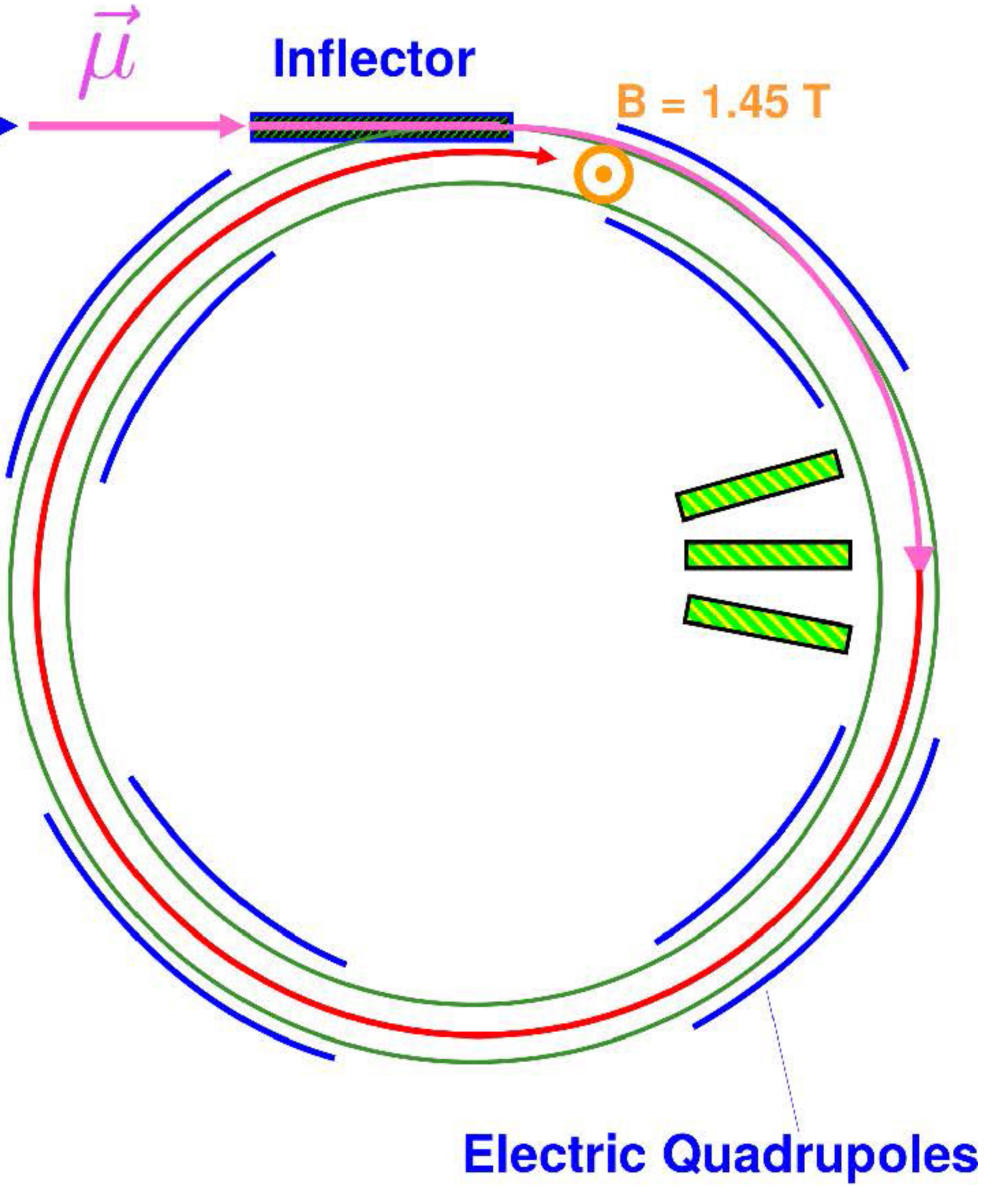


Technical design projection:

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

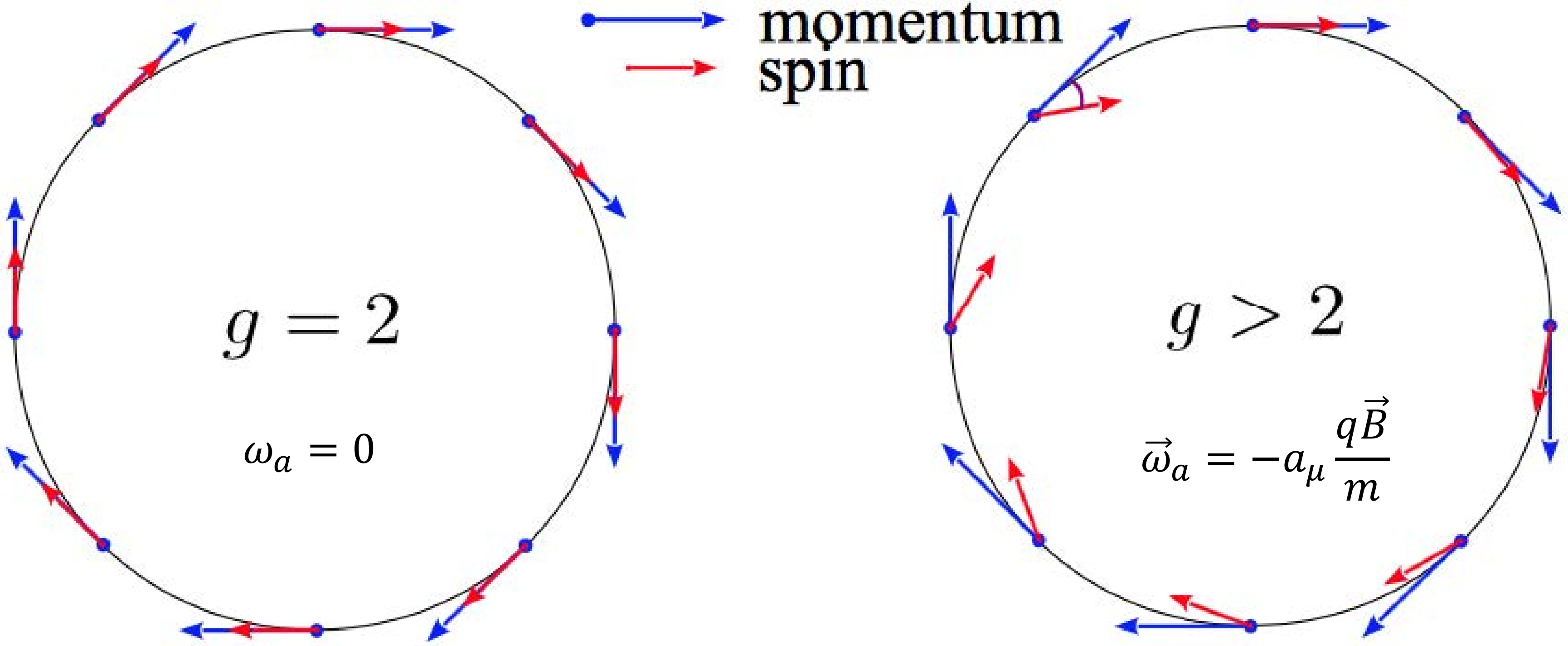
The Muon g-2 Storage Ring





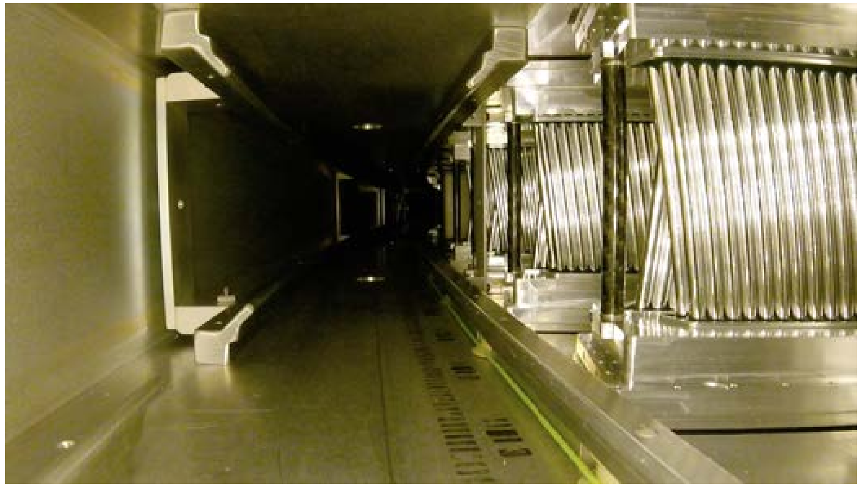
- Storage ring: 7 m radius toroidal C-magnet with 1.45 T magnetic field
- Inflector: cancels the 1.45 T main magnetic field for muons at injection
- Kickers deflect the injected muons onto the centerline orbit
- Electrostatic quadrupoles provide vertical beam focusing

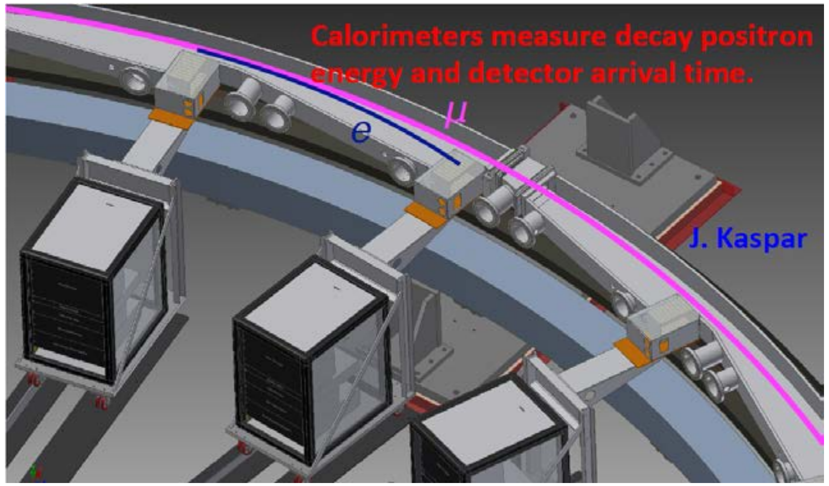
a_μ Measurement Using a Storage Ring

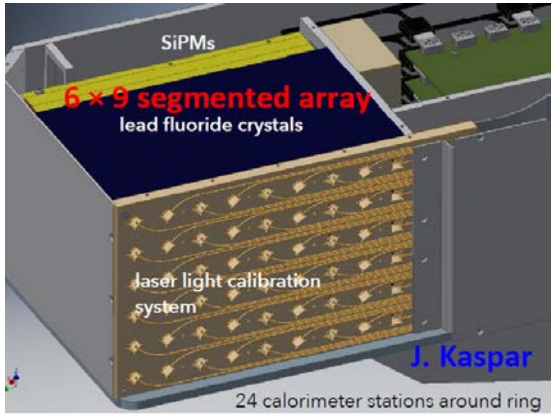


If g=2, the angle between the magnetic moment and the momentum does not change.
If g>2, the angle between the magnetic moment and the momentum changes linearly.

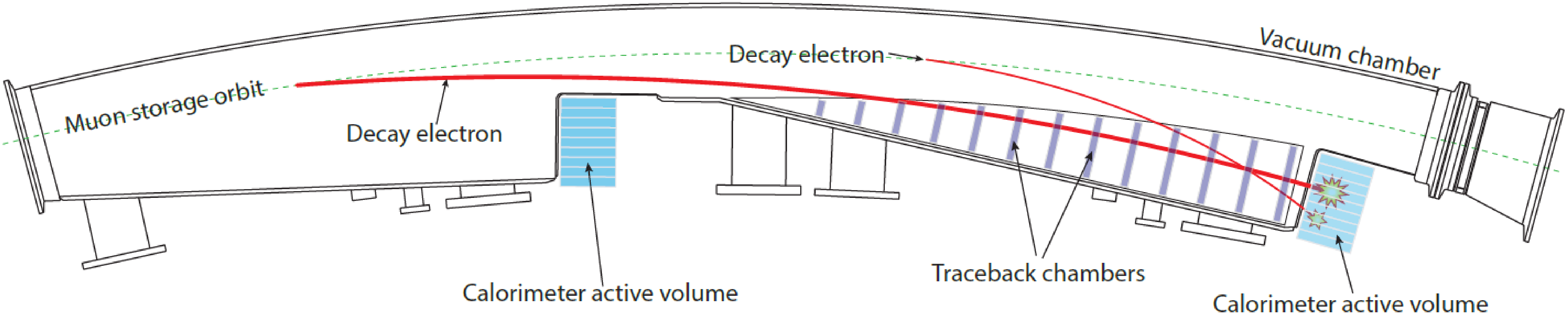
Measurement of Muon Spin Precession







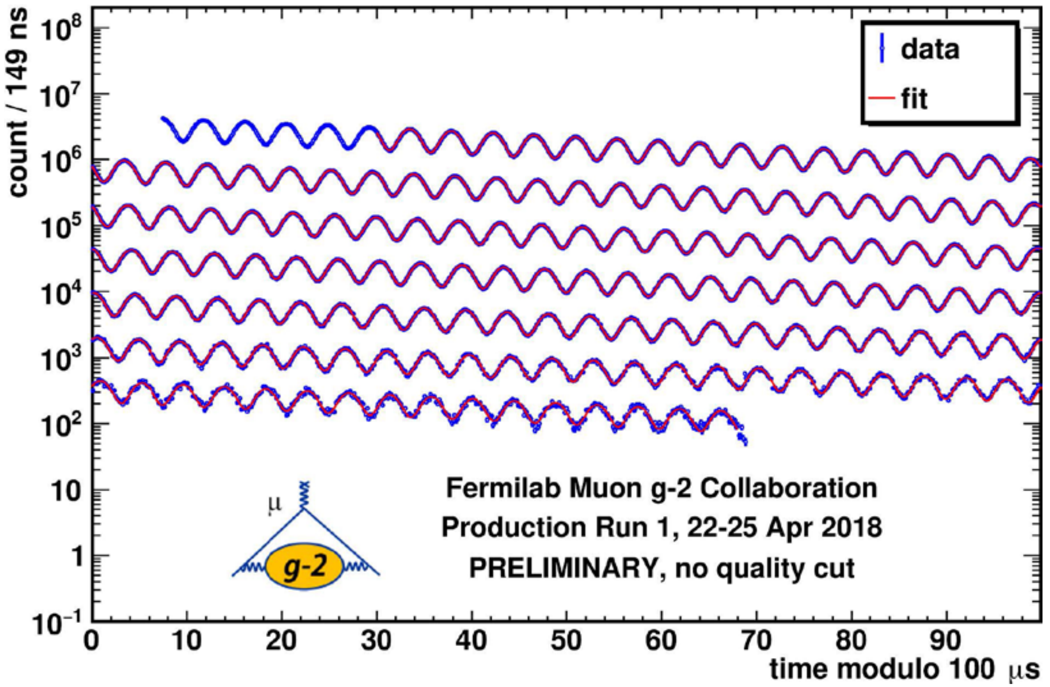
Crystals are 25×25×140 mm

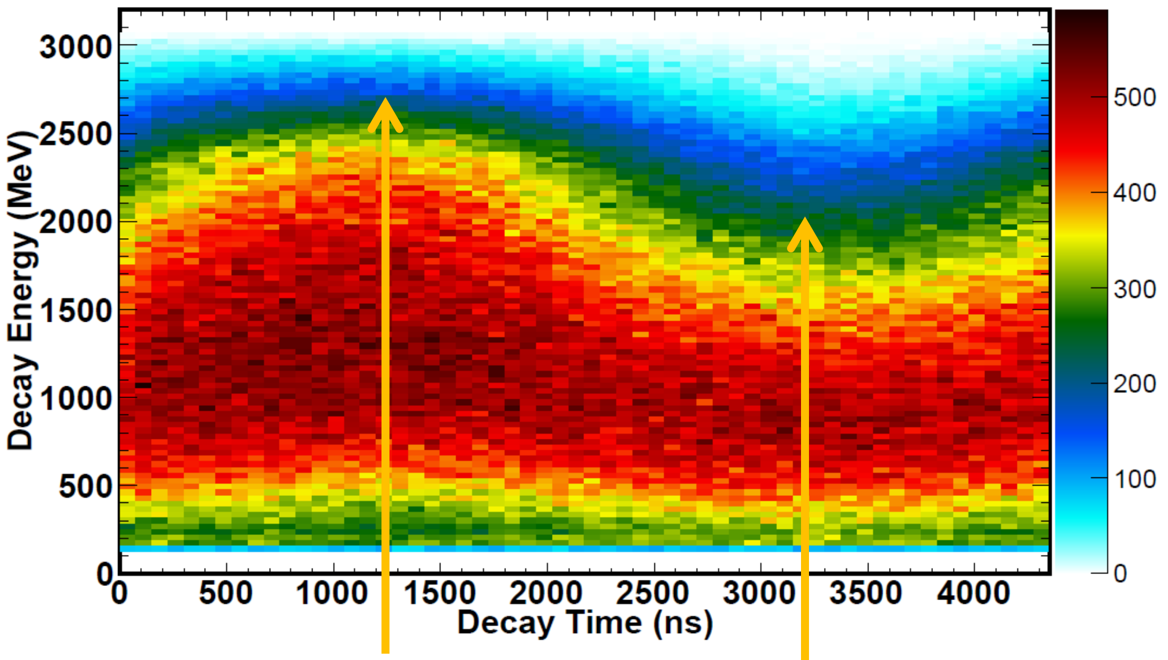


Straw trackers: reconstruct decay e^+ trajectories

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

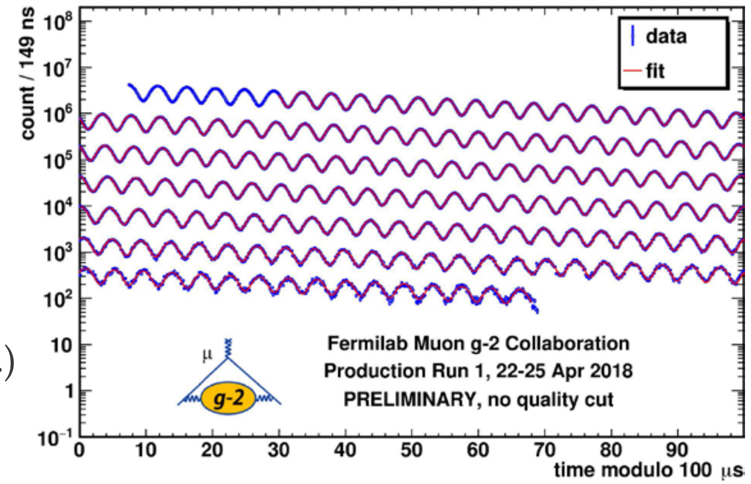
Calculation of a_μ from Muon and Proton Spin Precession

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

(140 ppb)

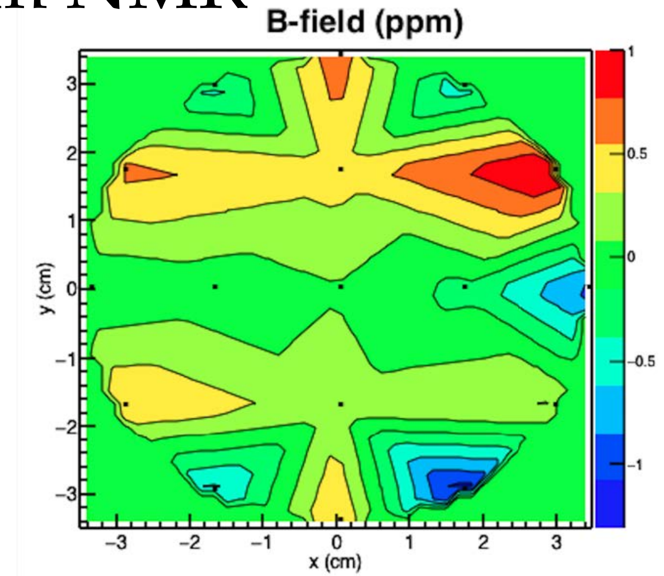
from decay e^+ time spectra

(70 ppb sys.
100 ppb stat.)



from NMR

(70 ppb sys.)



From CODATA [1]:

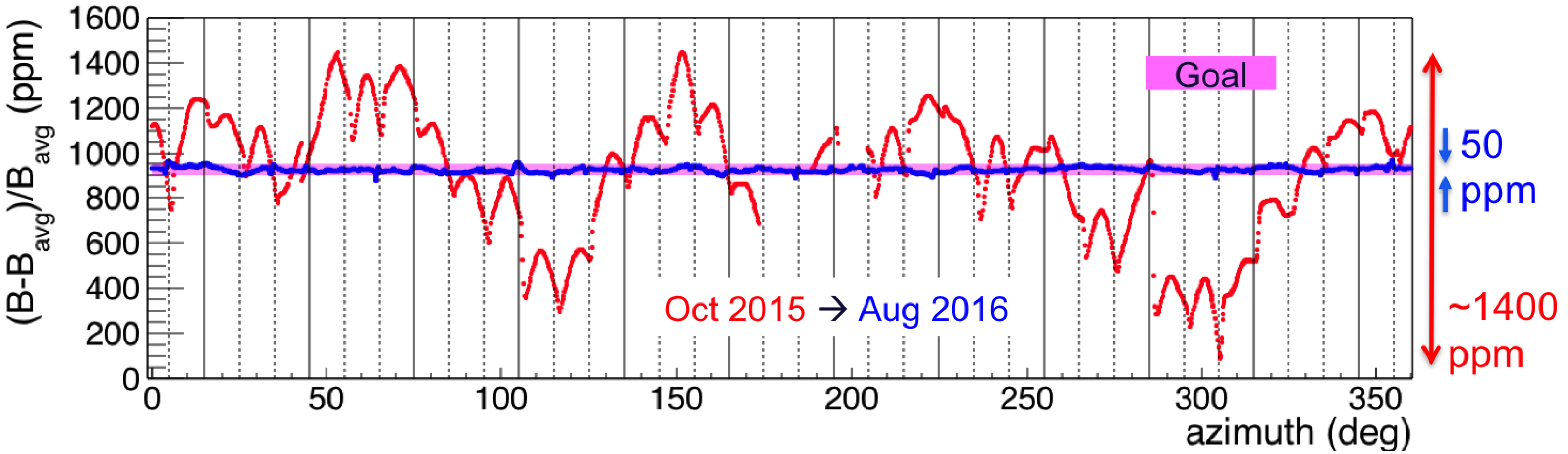
g_e = -2.002 319 304 361 82(52) (0.00026 ppb)

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).

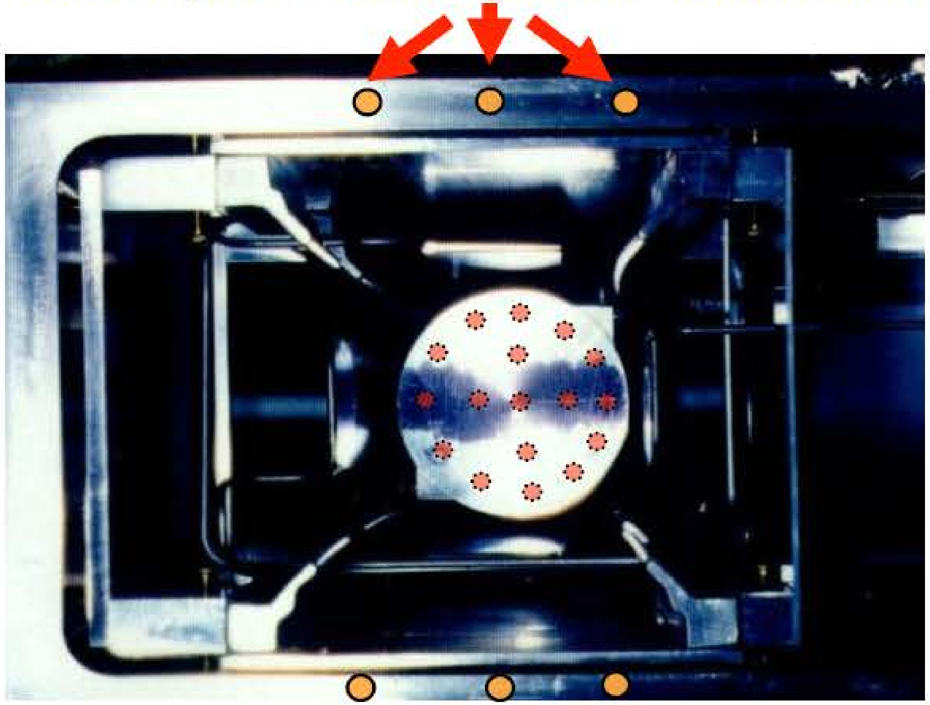
Magnetic Field Shimming



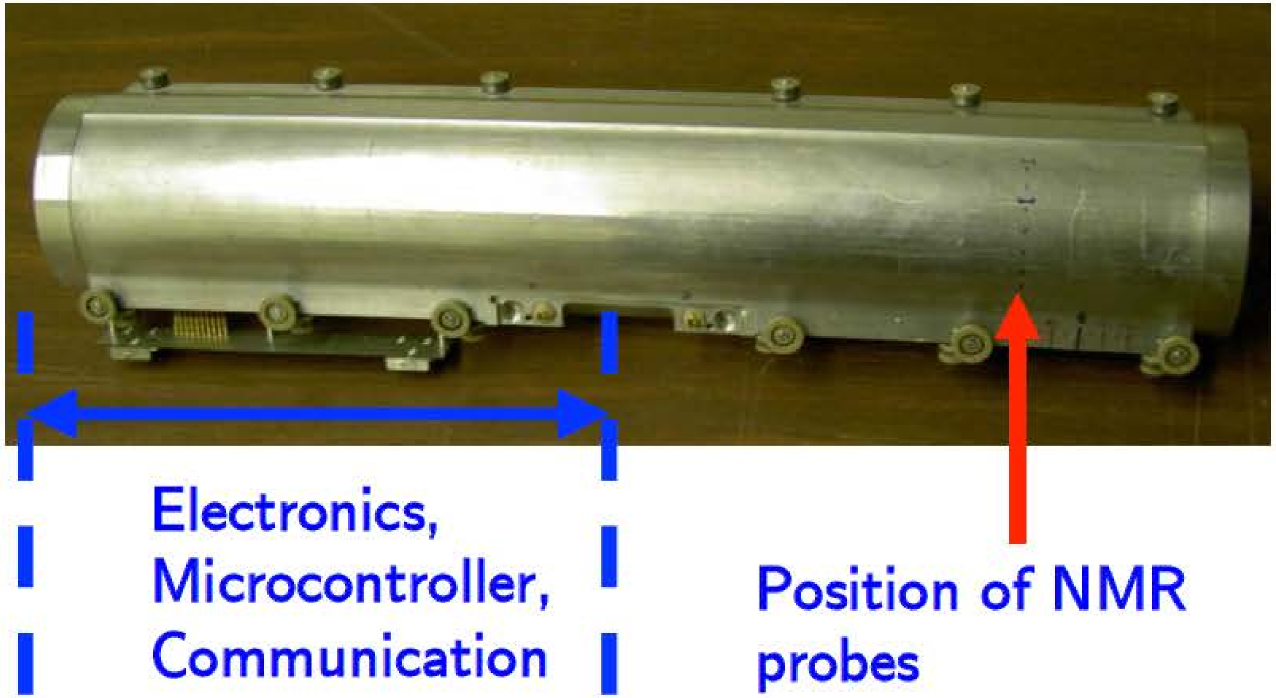
- Passive shimming is performed by inserting tiny metal pieces to increase the field.
- Magnetic field was made 3x more uniform than at BNL.
- Active shimming is also used.

Fixed and Trolley-Mounted NMR Probes

Fixed probes on vacuum chambers



Trolley with matrix of 17 NMR probes



Systematic Overview Tables

ω_a Systematics

Table 5.2: The largest systematic uncertainties for the final E821 ω_a analysis and proposed upgrade actions and projected future uncertainties for data analyzed using the T method. The relevant Chapters and Sections are given where specific topics are discussed in detail.

Category	E821 [ppb]	E989 Improvement Plans	Goal [ppb]	Chapter & Section
Gain changes	120	Better laser calibration		
		low-energy threshold	20	16.3.1
Pileup	80	Low-energy samples recorded		
		calorimeter segmentation	40	16.3.2
Lost muons	90	Better collimation in ring	20	13.10
CBO	70	Higher n value (frequency)		
		Better match of beamline to ring	< 30	13.9
E and pitch	50	Improved tracker		
		Precise storage ring simulations	30	4.4
Total	180	Quadrature sum	70	

We will consider the lost muons systematic error in some detail later in this presentation.

ω_p Systematics

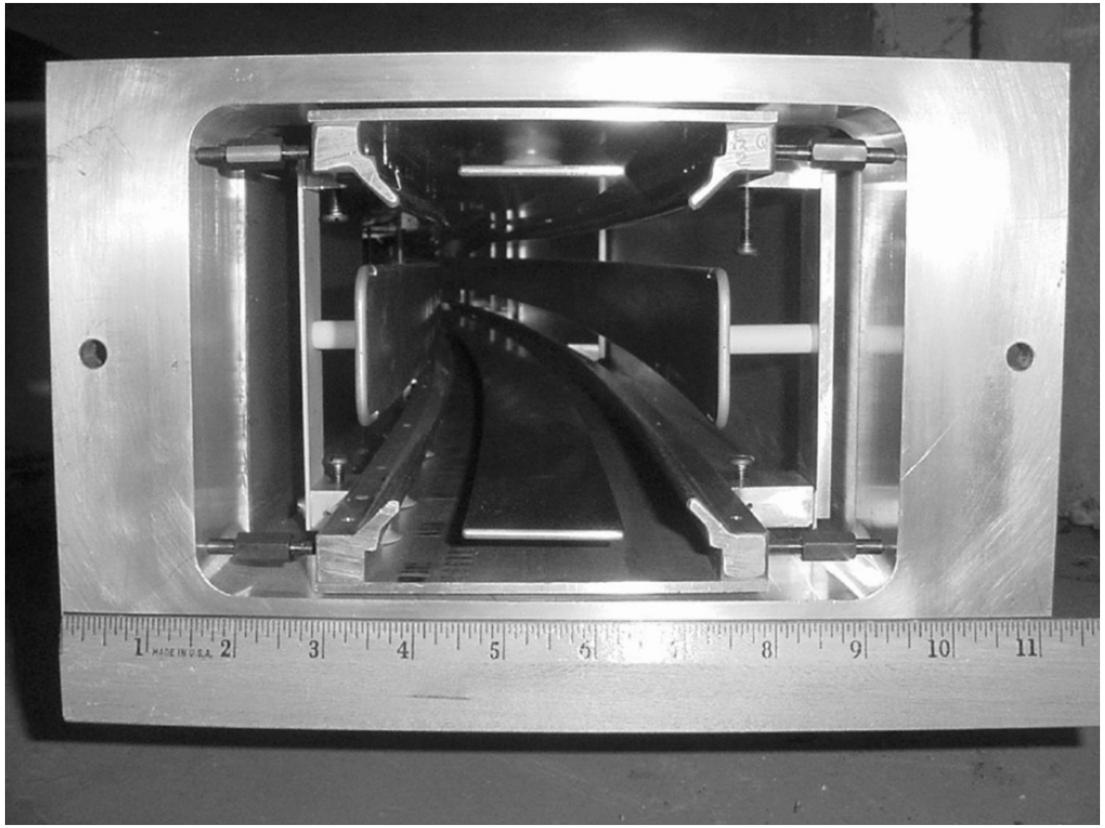
Table 5.3: Systematic uncertainties estimated for the magnetic field, ω_p, measurement. The final E821 values are given for reference, and the proposed upgrade actions are projected. Note, several items involve ongoing R&D, while others have dependencies on the uniformity of the final shimmed field, which cannot be known accurately at this time. The relevant Chapters and Sections are given where specific topics are discussed in detail.

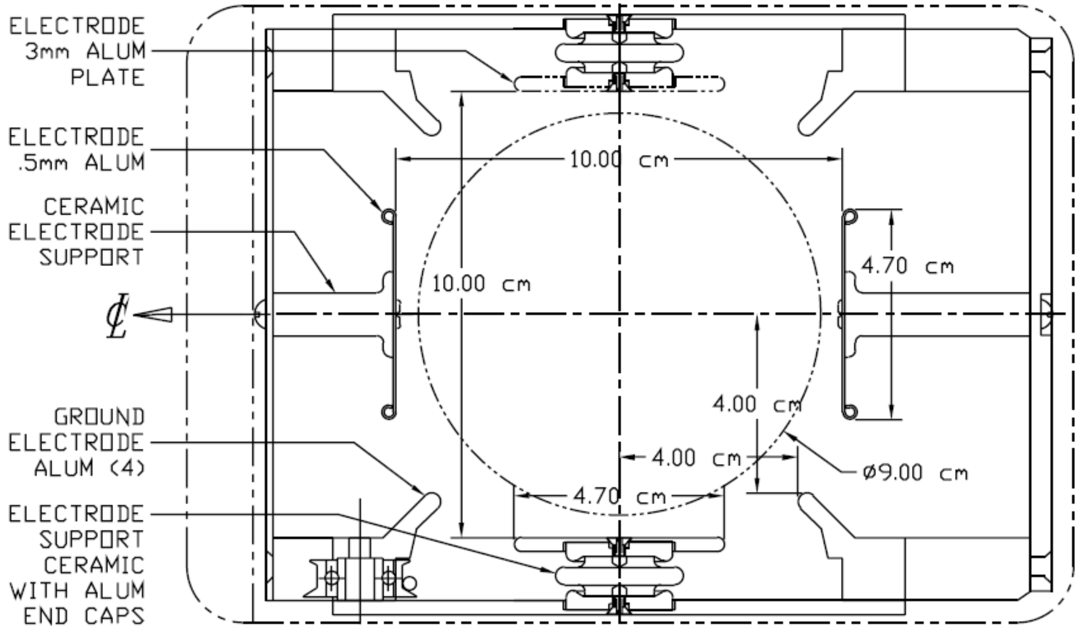
Category	E821 [ppb]	Main E989 Improvement Plans	Goal [ppb]	Chapter
Absolute field calibration	50	Special 1.45 T calibration magnet with thermal enclosure; additional probes; better electronics	35	15.4.1
Trolley probe calibrations	90	Plunging probes that can cross calibrate off-central probes; better position accuracy by physical stops and/or optical survey; more frequent calibrations	30	15.4.1
Trolley measurements of B_0	50	Reduced position uncertainty by factor of 2; improved rail irregularities; stabilized magnet field during measurements*	30	15.3.1
Fixed probe interpolation	70	Better temperature stability of the magnet; more frequent trolley runs	30	15.3
Muon distribution	30	Additional probes at larger radii; improved field uniformity; improved muon tracking	10	15.3
Time-dependent external magnetic fields	–	Direct measurement of external fields; simulations of impact; active feedback	5	15.6
Others †	100	Improved trolley power supply; trolley probes extended to larger radii; reduced temperature effects on trolley; measure kicker field transients	30	15.7
Total systematic error on ω_p	170		70	15

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

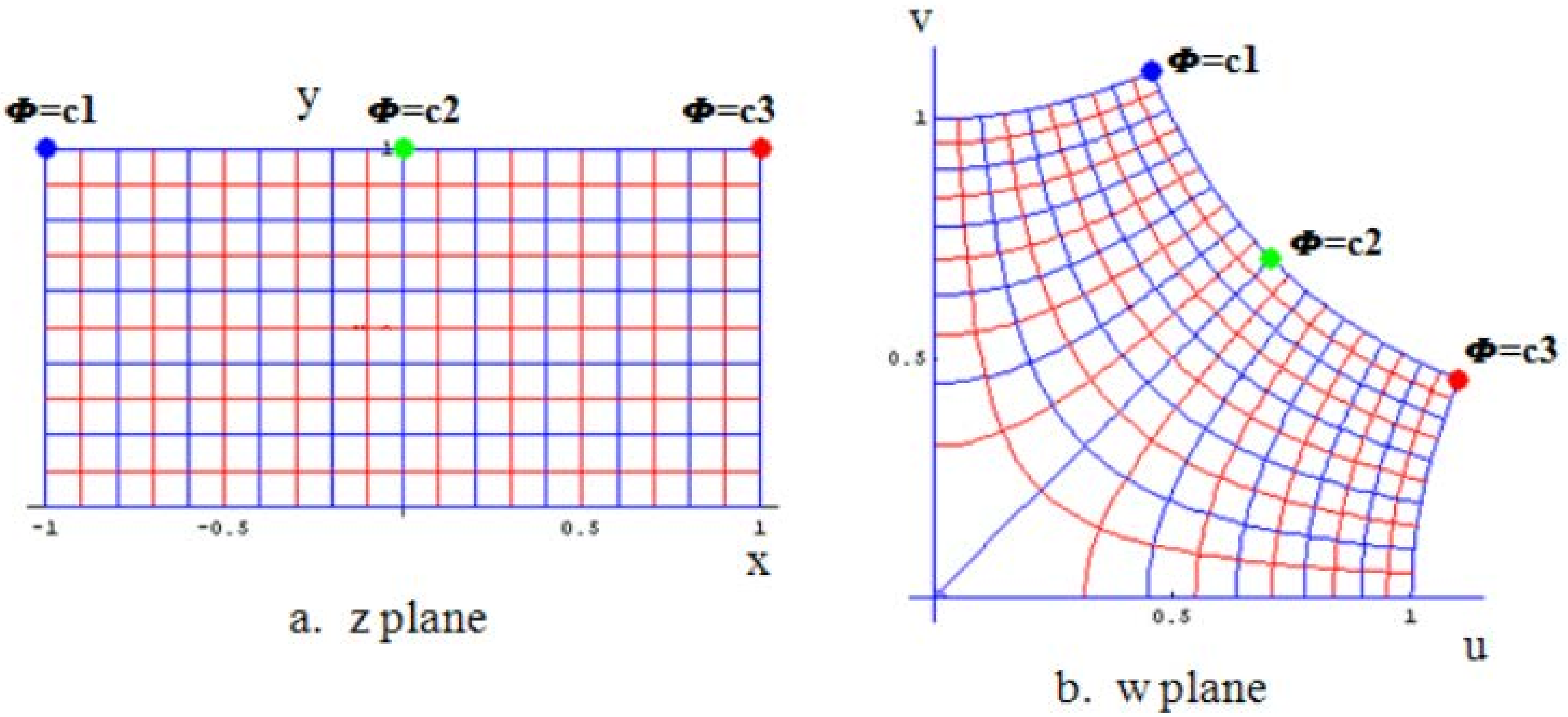
- *field calculation for quads*
- *end-to-end simulations*
- *application of simulation results to muon loss systematics*

Muon g-2 Storage Ring High Voltage Quadrupoles





ELECTRODE AND SUPPORT FRAME - END VIEW



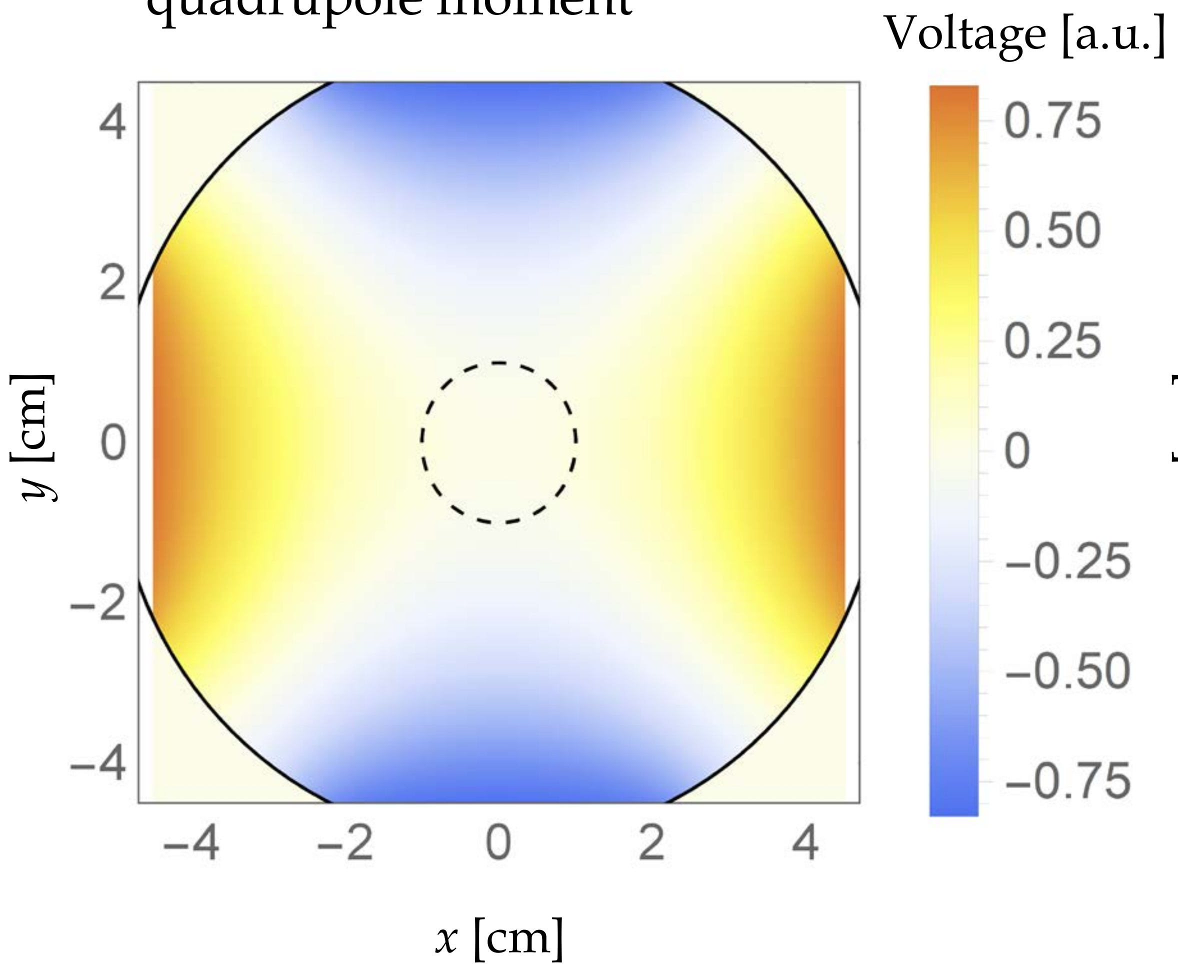
$$f'(z) = c\,\mathrm{cn}(z|m)\,\mathrm{dn}(z|m)\prod_{j=1}^{n}\left(\mathrm{sn}(z|m) - \mathrm{sn}(x_j + iy_j|m)\right)^{\alpha_j - 1}$$

Advantages of conformal mappings for field calculations:

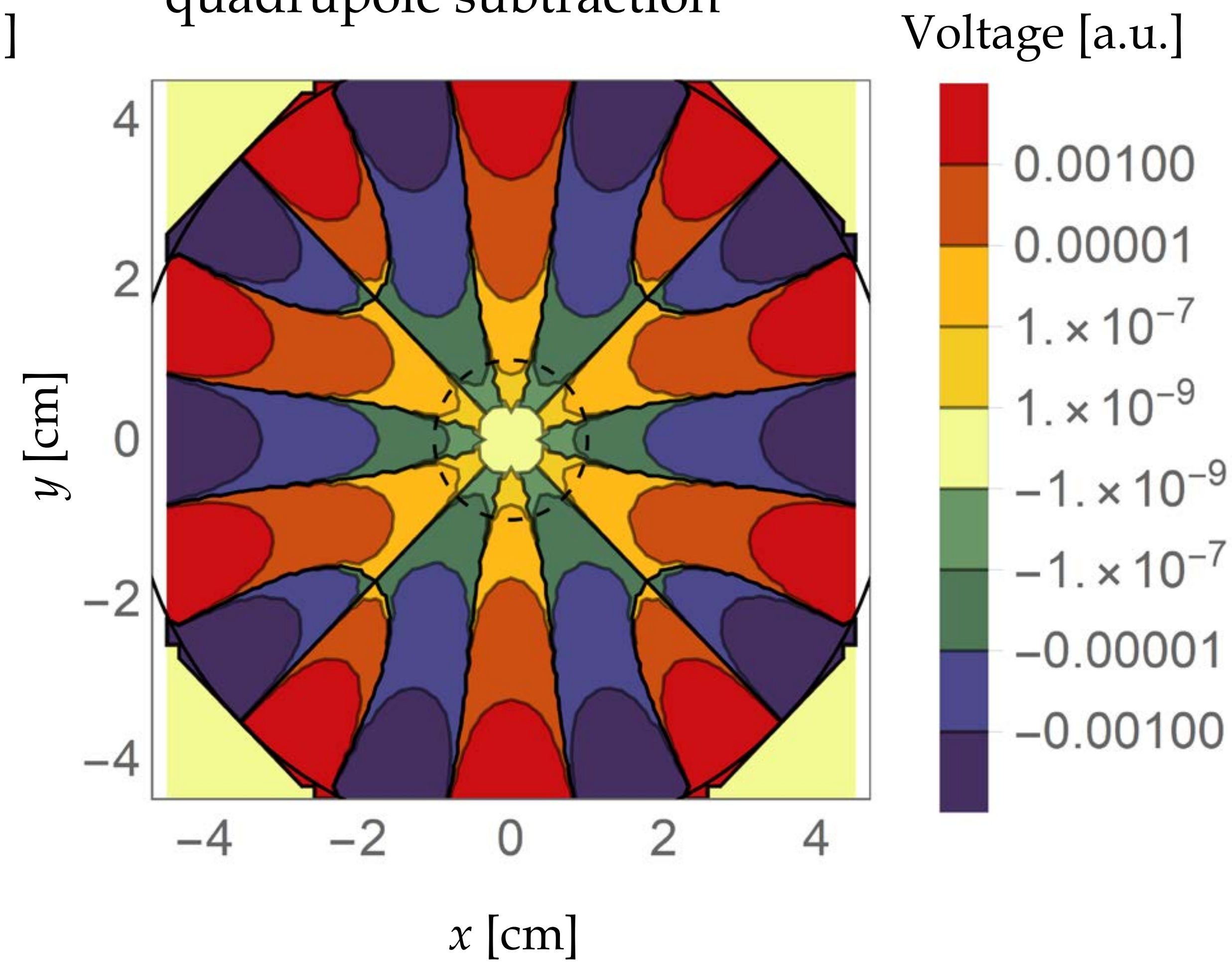
- Fully Maxwellian
- Rapid recalculations with voltage asymmetries (e.g. for RF scraping)

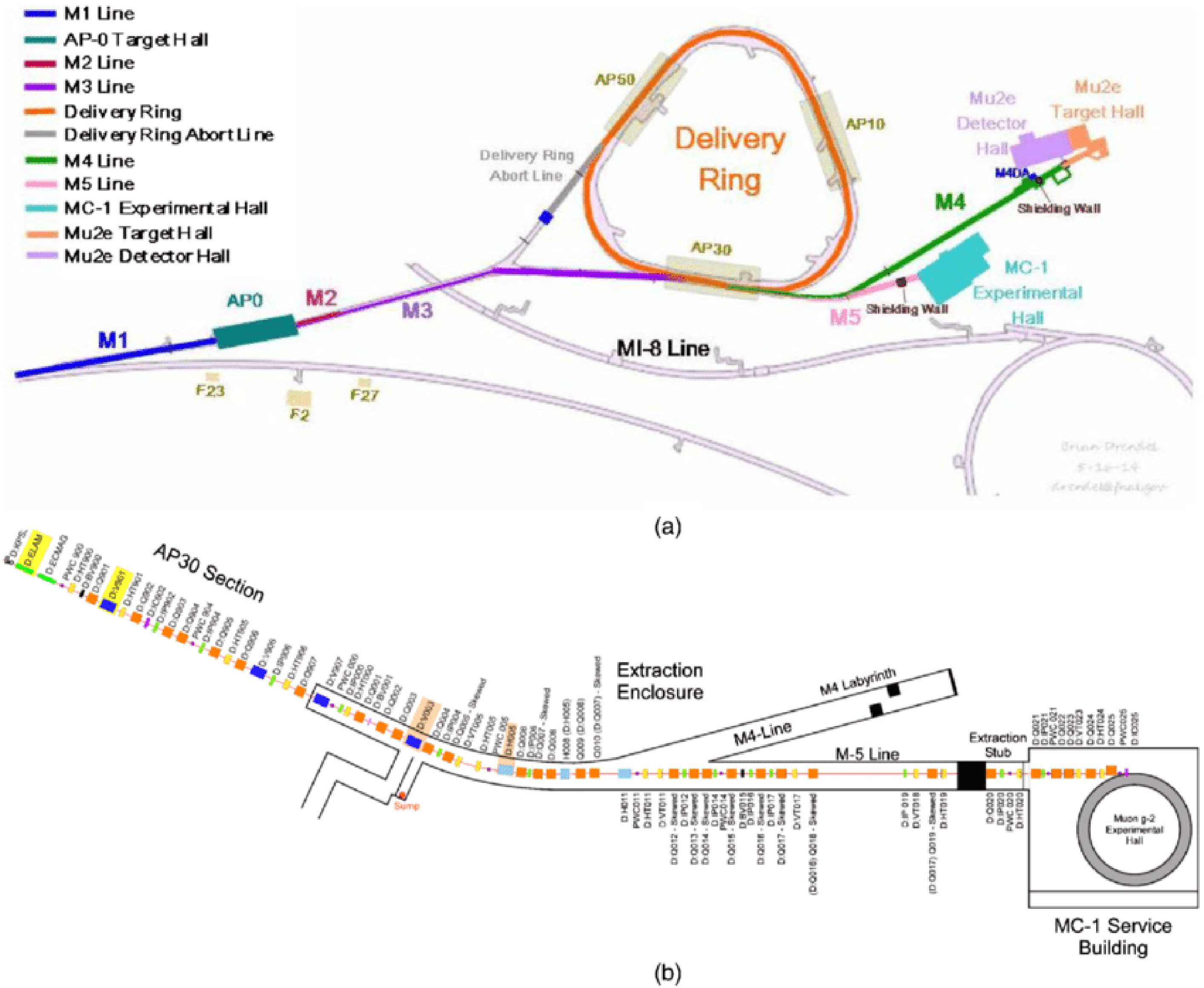
Multipole Expansion of the Quadrupole Potential

Field dominated by quadrupole moment



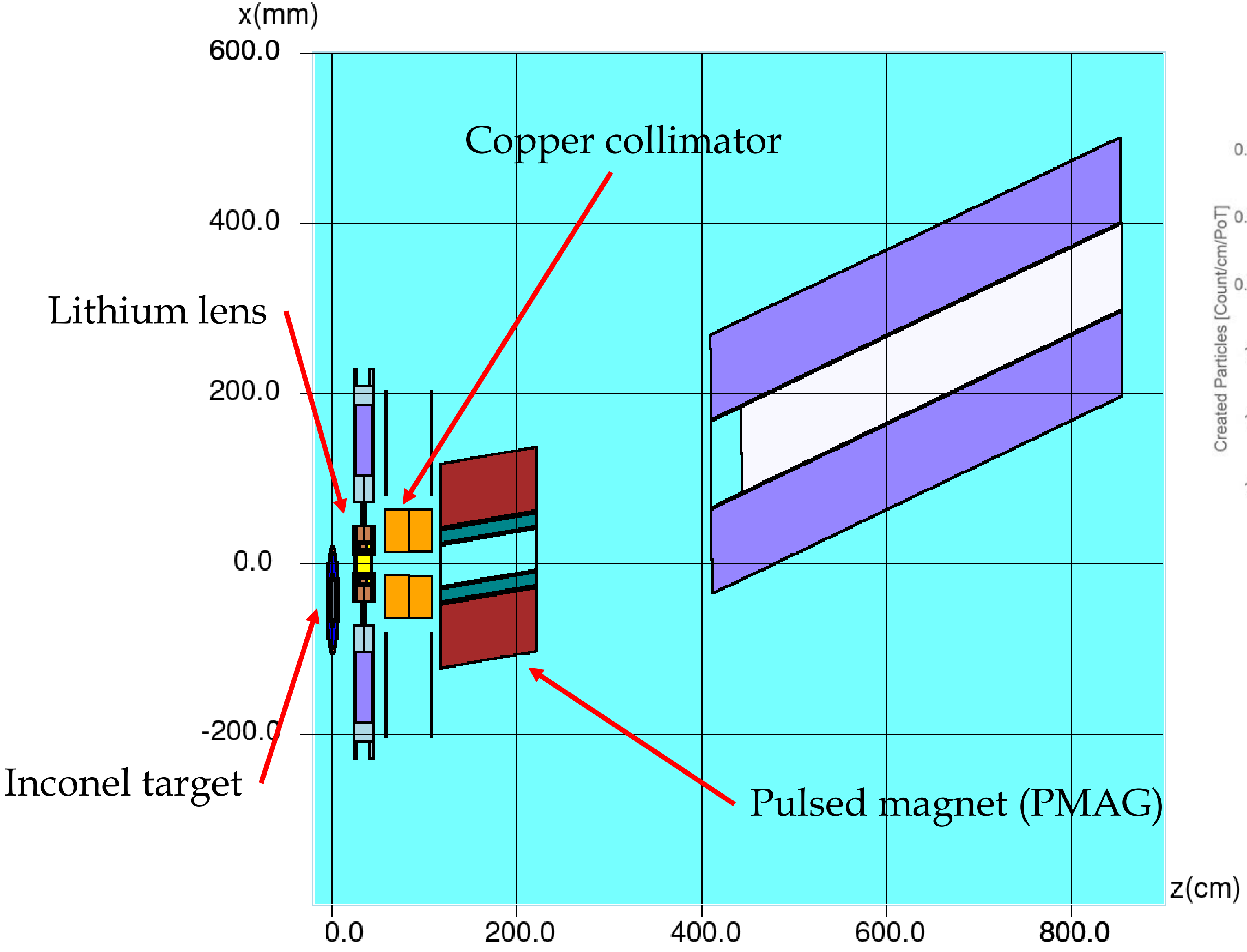
Higher order multipoles after quadrupole subtraction

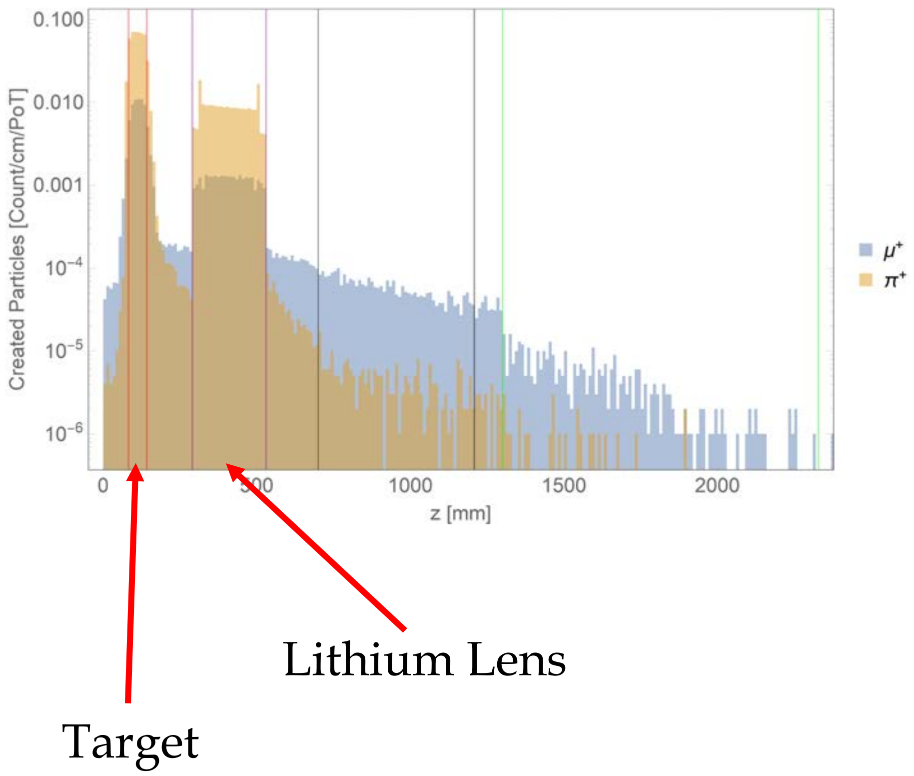




Need to understand potential sources of early-to-late beam-related systematics.

Muon g-2 Target Station





Simulations Using High Performance Computing Systems

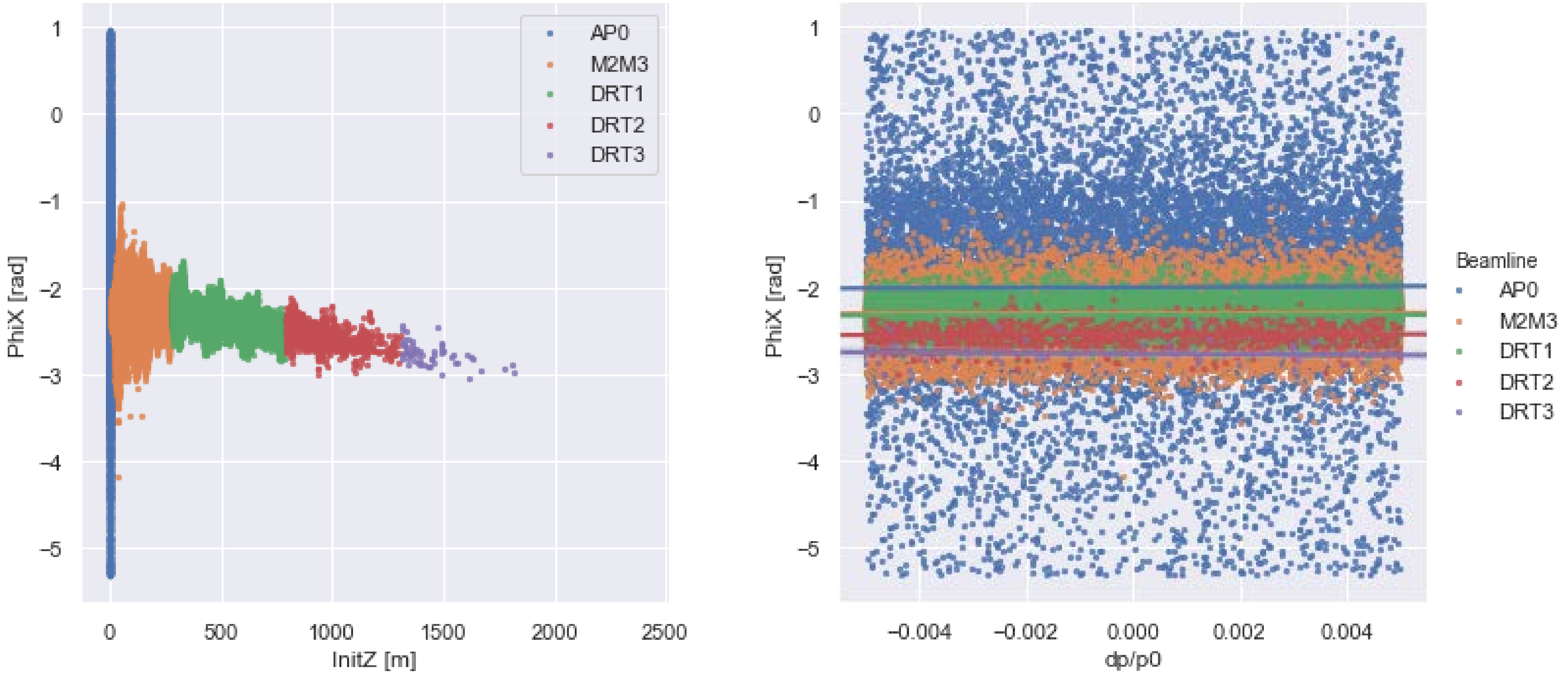
2×10^{13} protons on target

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

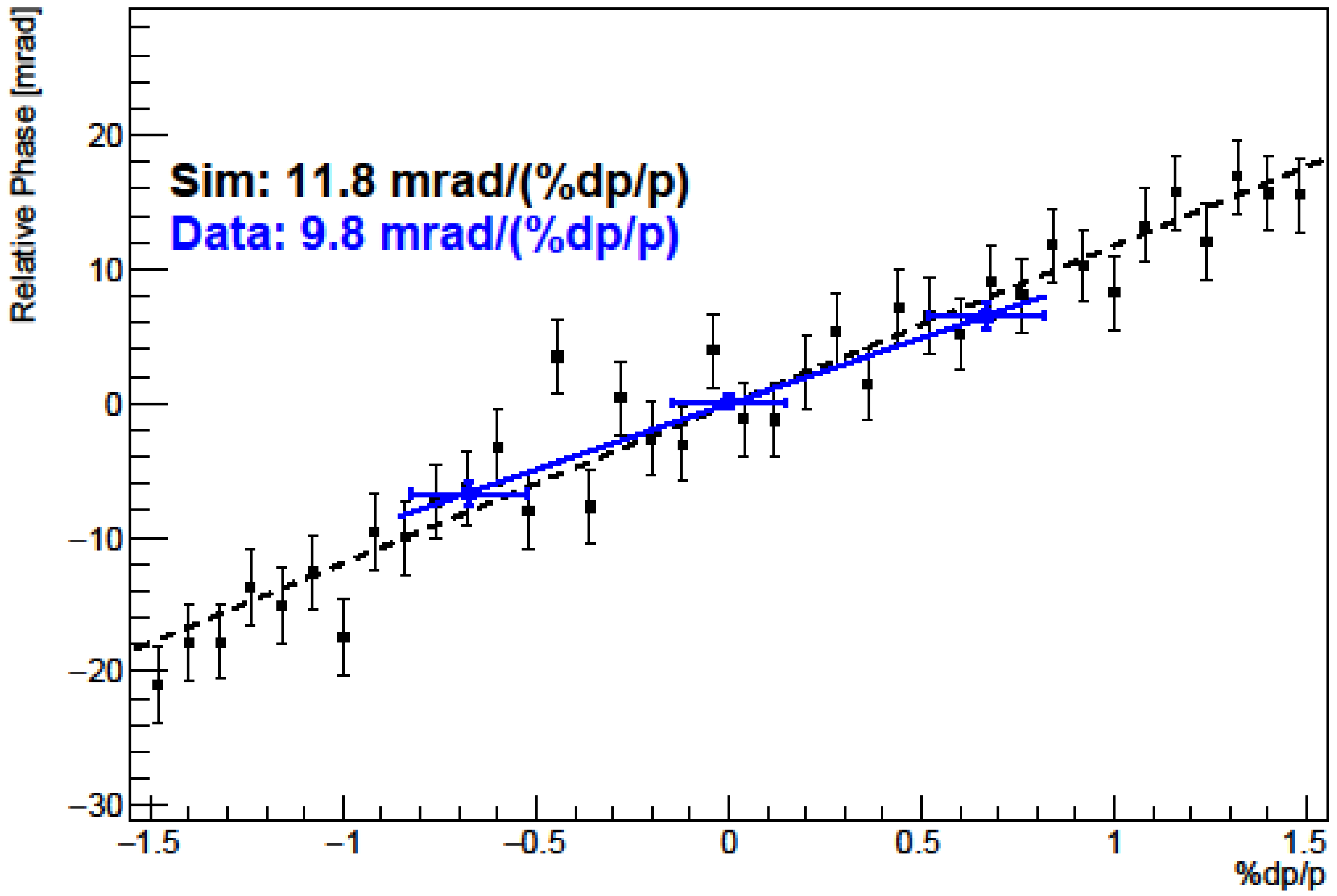
Simulation results, preliminary



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

Preliminary. Experimental data: Hannah Binney.

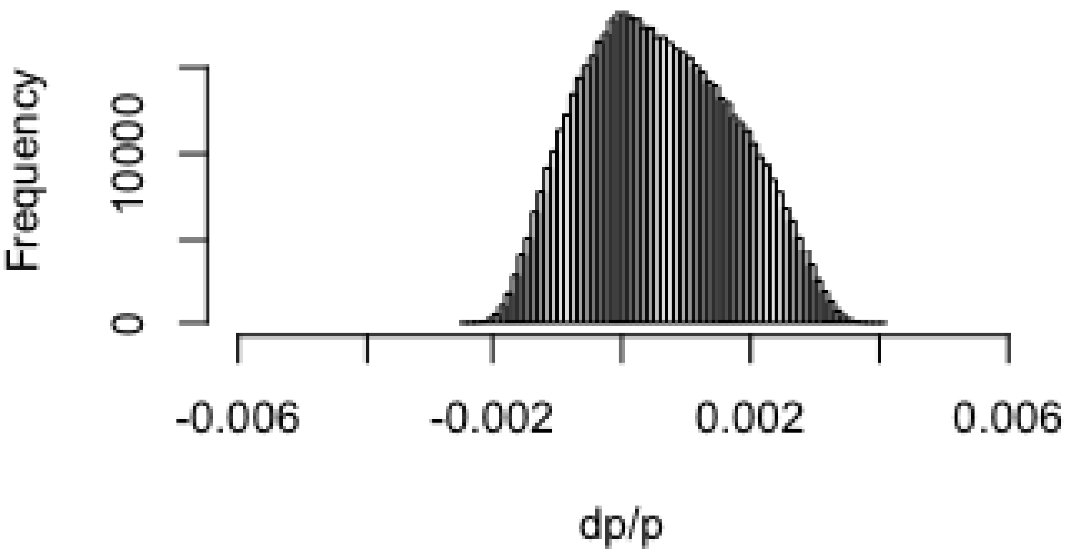


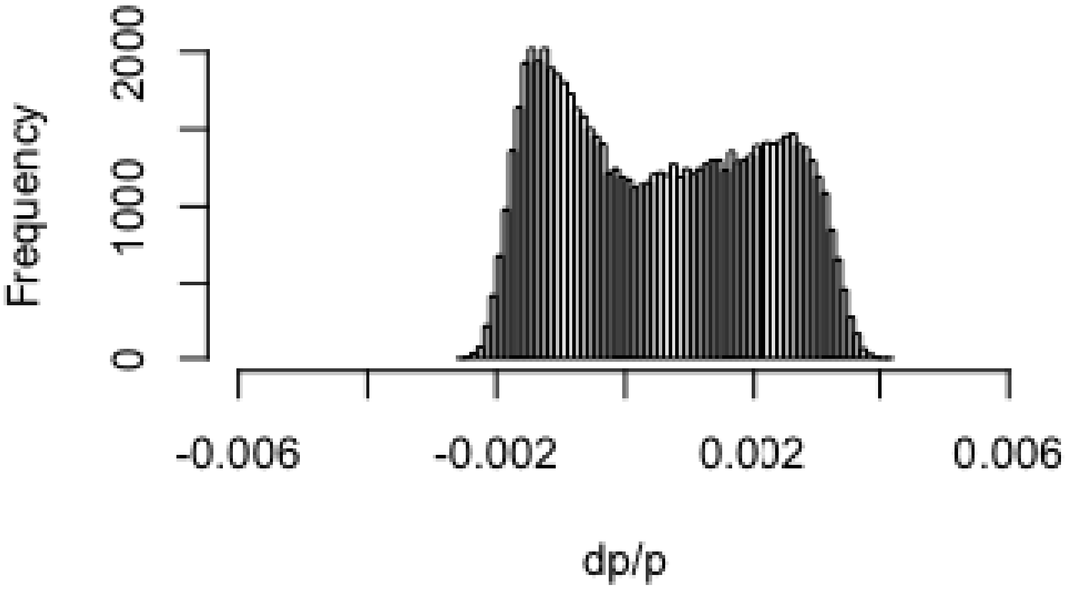
A real momentum dependence of the initial phase develops because of magnetic dipoles in the Delivery Ring.

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

Momentum-Dependent Muon Losses

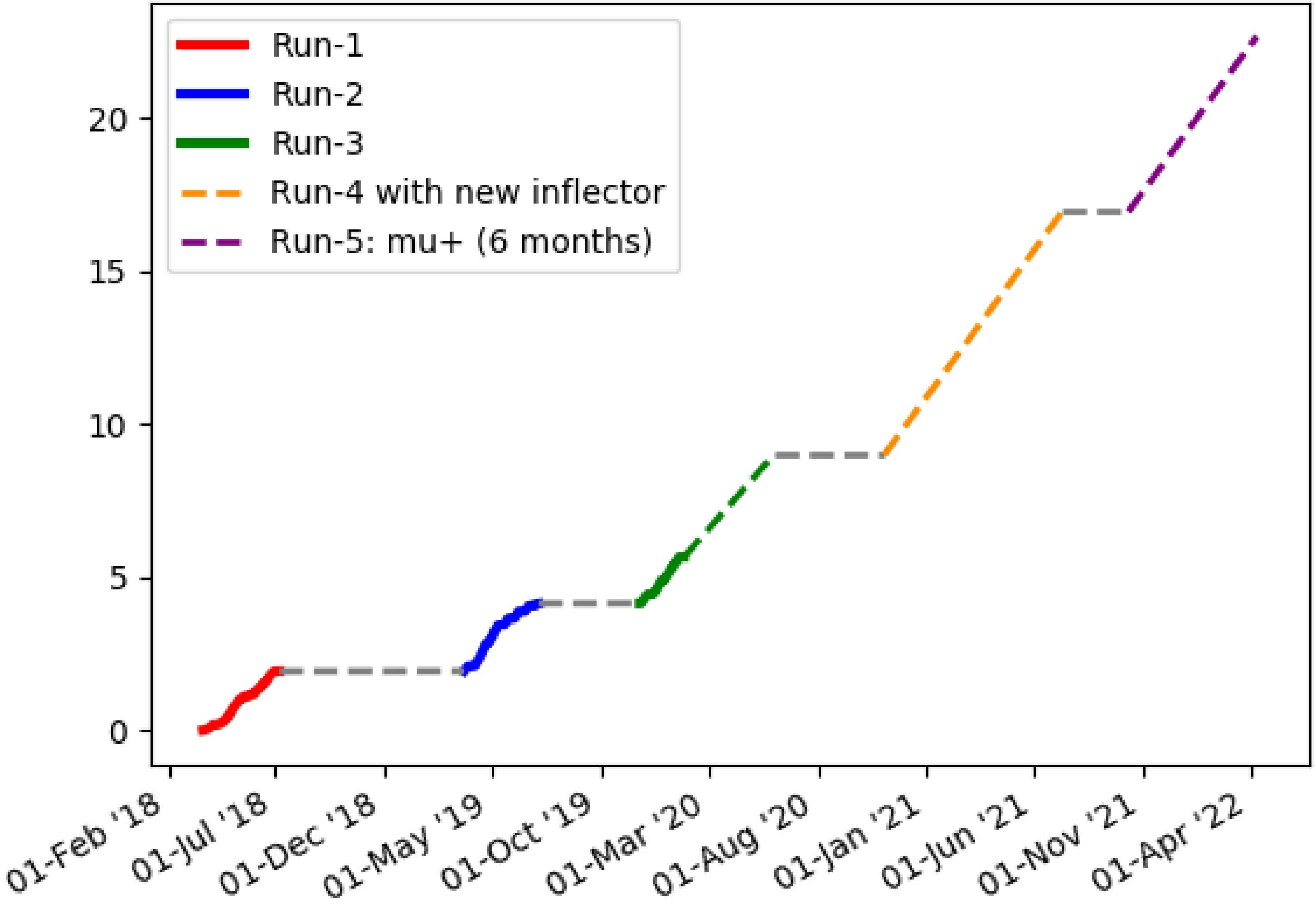
Simulation results, preliminary *(Mike Syphers)*





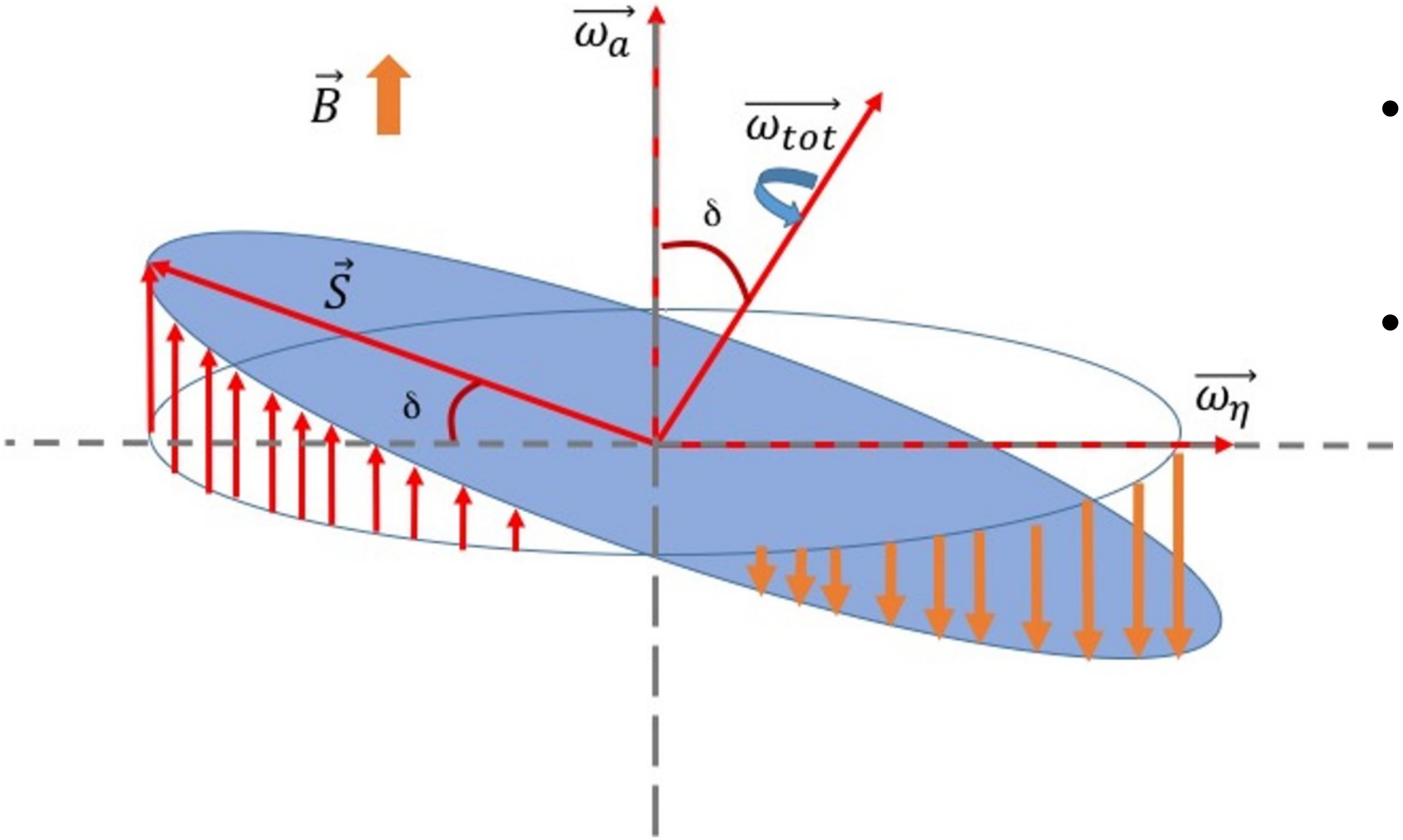
Work is still in progress, but we expect a 10-20 ppb error due to muon losses. Far below the overall 70 ppb systematic error on the spin precession.
Meeting the TDR goal of 20 ppb.

Projection of Data Acquisition as a Multiple of BNL Data



Currently:
~5xBNL physics quality data

Future EDM or μ^- anomalous MDM Possibilities



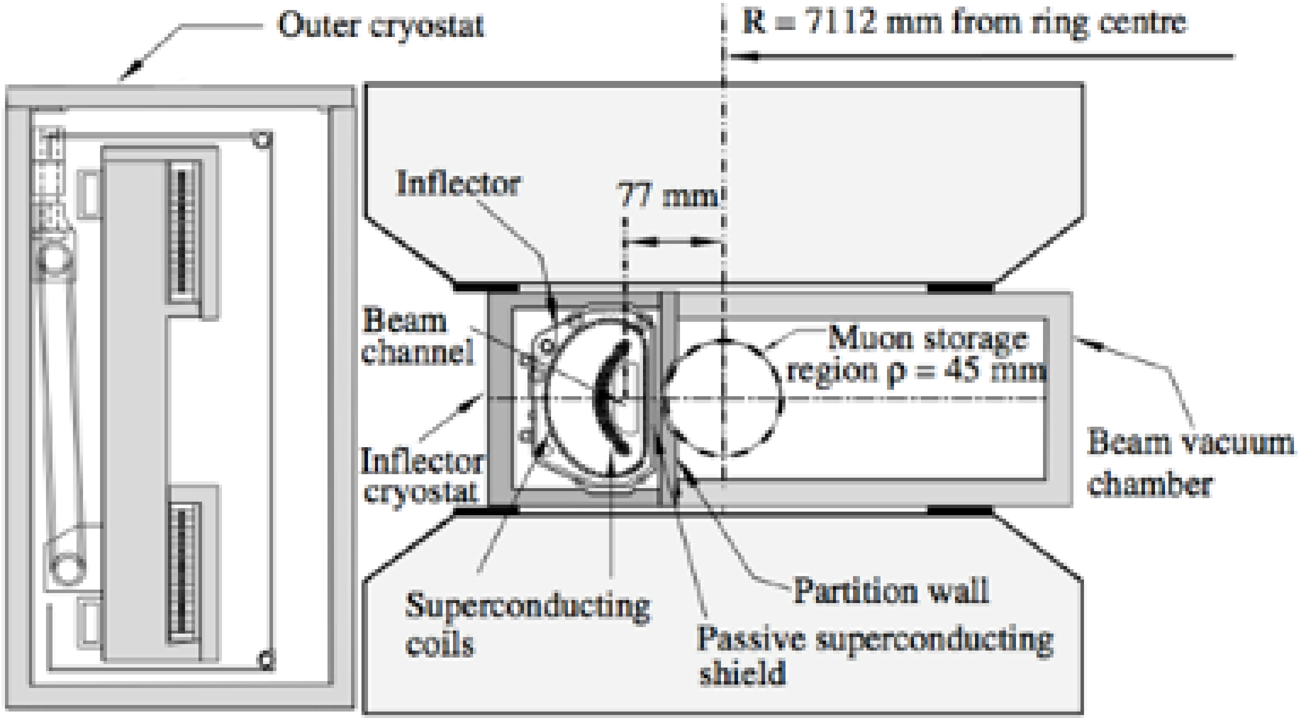
- Currently measuring μ^+ anomalous MDM
- Measure μ^+ EDM using vertical phase asymmetry detection in calorimeters
- Measure μ^- by reconfiguring the beamlines and storage ring (switching electric field direction)
    - No other proposed experiment can do μ^- (JPARC μ^+ only)

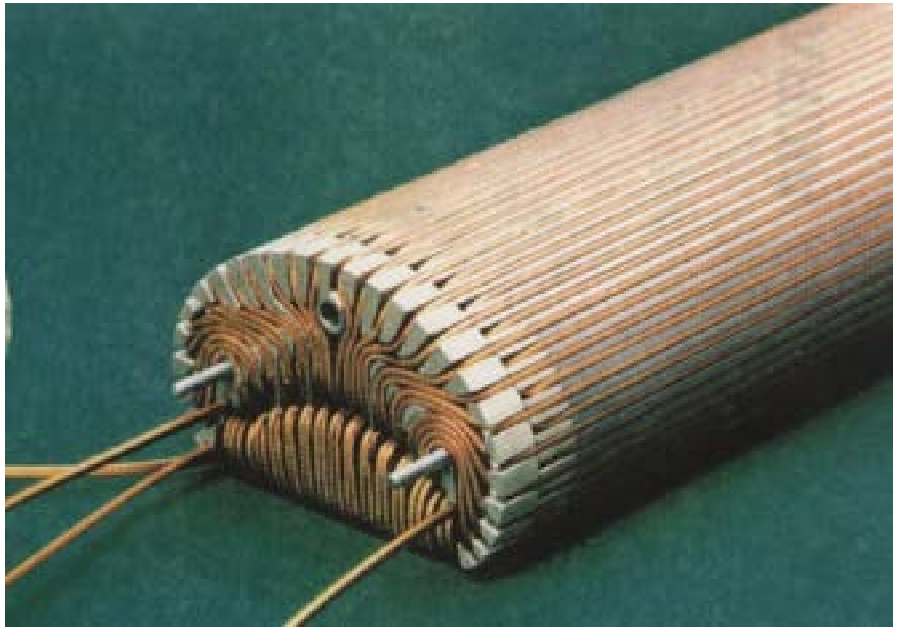
Conclusion

- The experiment is running well and has entered Run-3.
- The analysis is coming along, and we are expecting to publish first results this year.
- We have developed sophisticated modeling tools and data-driven approaches to quantify systematics, e.g. the muon loss phase.

- This material is based upon work supported by the U.S. Department of Energy, Office of Science, under Contract No. DE-FG02-08ER41546 and Contract No. DE-SC0018636.
- 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

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

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

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

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

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

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

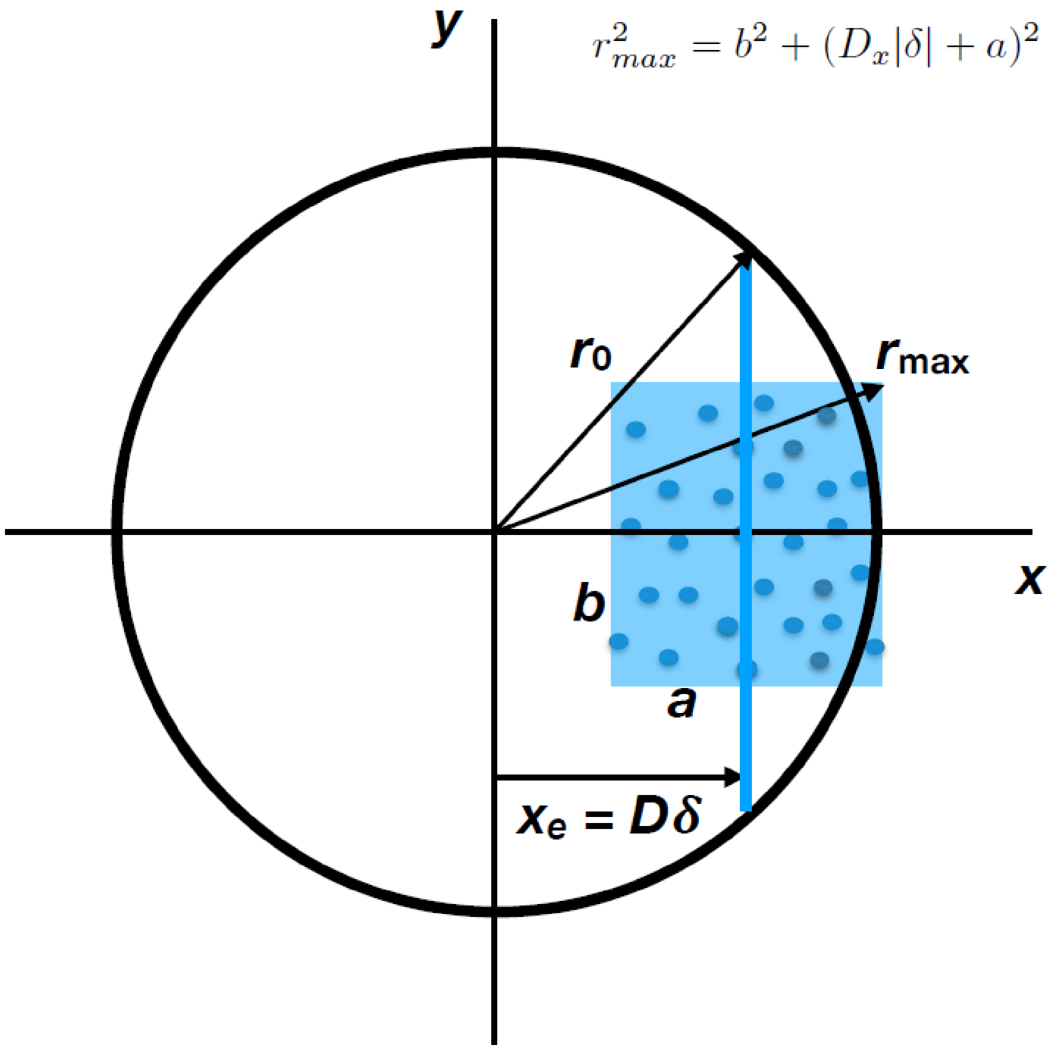
$$\omega_{cbo} = \omega_0 (1 + 2.875 e^{-\frac{t}{76}} / \omega_0 t + 5.47 e^{-\frac{t}{8.85}} / \omega_0 t)$$

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

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

Momentum-Dependent Muon Losses

Mike Syphers



$$\frac{\Delta\omega_a}{\omega_a} = \frac{1}{\omega_a} \frac{d\langle\Phi\rangle}{d\langle dp/p_0\rangle} \frac{d\langle dp/p_0\rangle}{dt}$$

Straw Tracking Detectors