FERMILAB-SLIDES-20-013-A[C

Fermilab | U.S. DEPARTMENT OF ENERGY | Office of Science

E-Field/Pitch corrections for Run-1 of the Muon *g*-2 Experiment at Fermilab

David A. Tarazona

APS April Meeting 2020

April 20, 2020

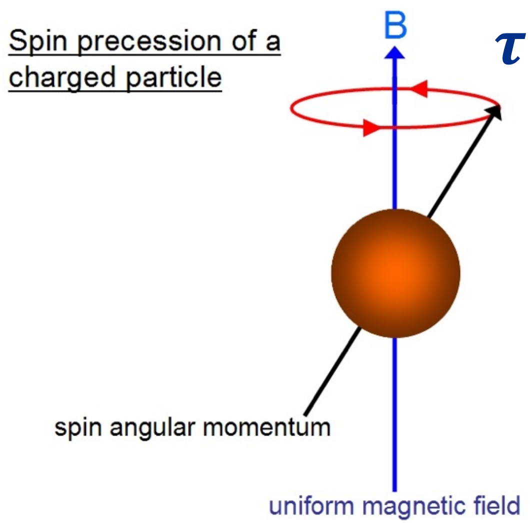
MICHIGAN STATE UNIVERSITY

This manuscript has been authored by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the U.S. Department of Energy, Office of Science, Office of High Energy Physics.

Muon g-2 Overview

Muon g-2 Overview: a_μ

$$\boldsymbol{\mu} = g\frac{e}{2m_\mu}\boldsymbol{S}$$



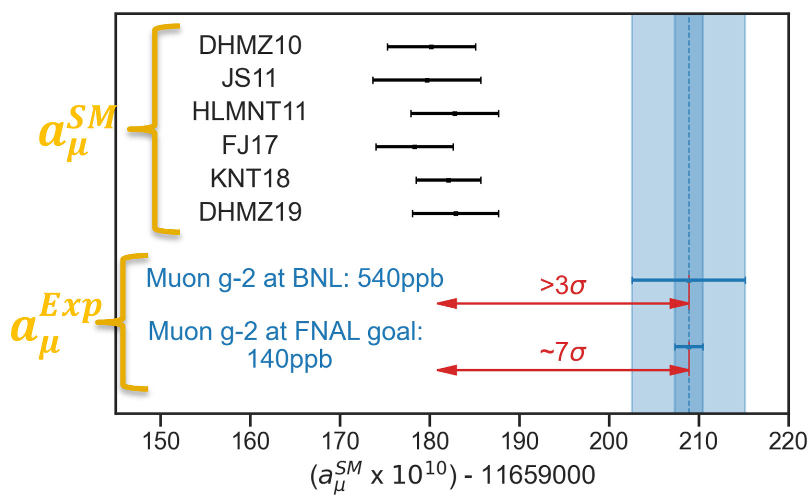
$$\boldsymbol{\tau} = \boldsymbol{\mu}\times\boldsymbol{B}$$

- Dirac equation (relativistic QM) predicts

$$g = 2$$

- Experiments and Standard Model indicate:

$$g \neq 2$$
$$\Downarrow$$
$$g \equiv 2(1 + a_\mu)$$



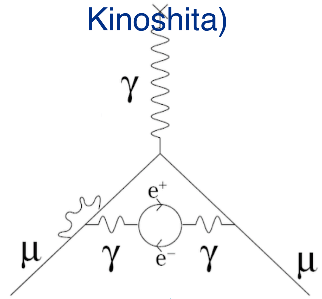
Motivation

$a_\mu^{SM} \neq a_\mu^{Exp}$

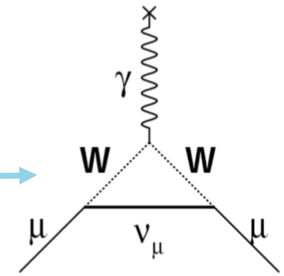
Muon g-2 Overview: a_μ from Standard Model

Standard Model

12672 QED diagrams (up to 10th-order, Kinoshita)



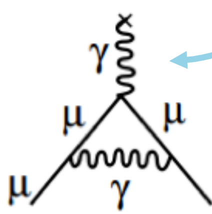
Dirac equation



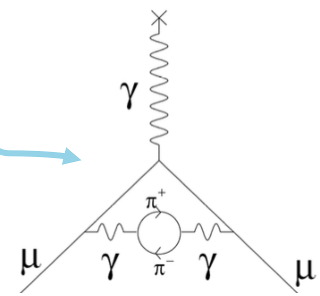
Electroweak contributions

$$g_\mu = 2.00233183622(756)\cdots$$

$\rightarrow a_\mu^{SM}$



1st-order QED (Schwinger)

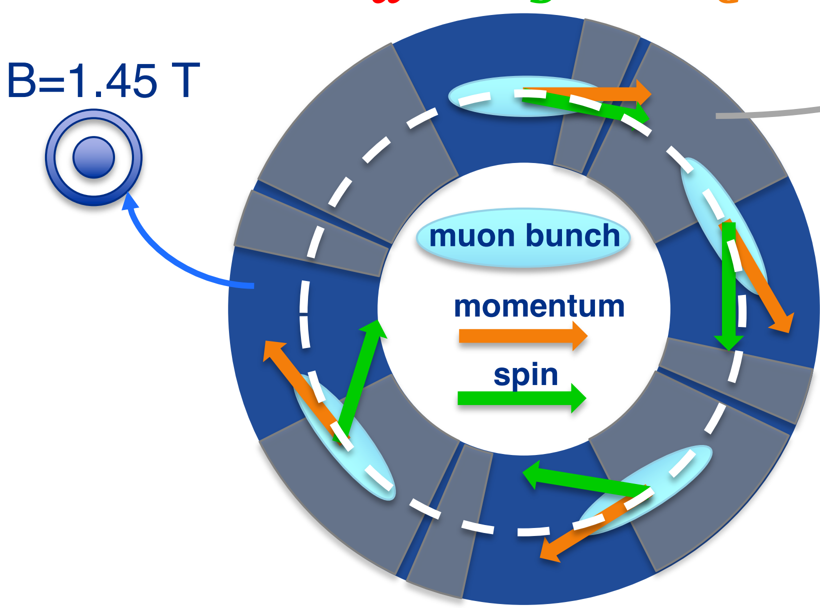


Hadronic contributions

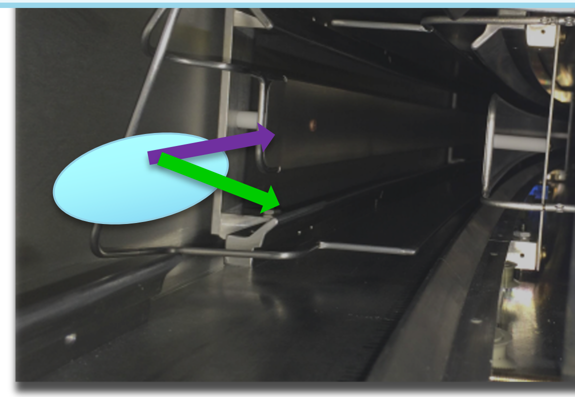
*KNT *Phys.Rev.D* 101 (2020) 014029

Muon g-2 Overview: a_μ from Fermilab

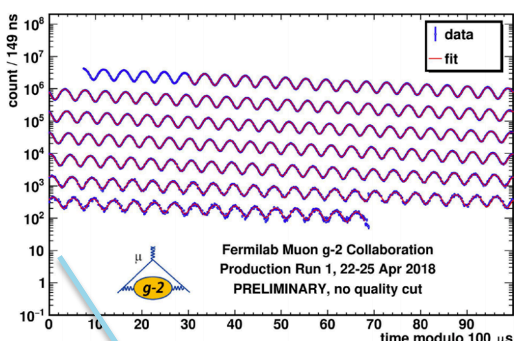
$$\omega_a = \omega_S - \omega_C$$



Electrostatic Quadrupole System (EQS)



$$\omega_a = -\frac{e}{m} a_\mu \langle B \rangle$$



ω_a: Spin precession frequency relative to the momentum direction of muons <u>in the horizontal midplane</u> of the storage ring

$$N(t, E_{th}) = N_0(E_{th}) \exp^{-t/\gamma\tau_\mu}[1 + A(E_{th}) \cos(\omega_a t + \varphi_a(E_{th}))]$$

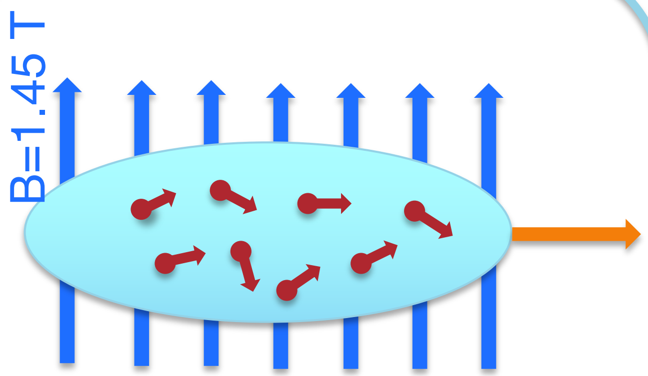
Run-1 E-field and Pitch Corrections

Run-1 E-field and Pitch Corrections

For the general case in lab frame ($p_0 = mc/\sqrt{a_\mu}$=3.094GeV/c):

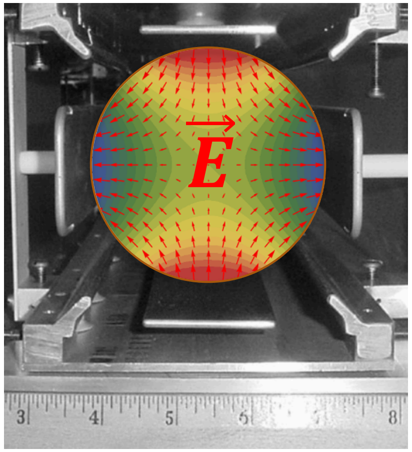
$$\omega_a = \langle (\vec{\omega}_s - \vec{\omega}_C)_y \rangle = -\frac{e}{m} a_\mu \langle B \rangle + \frac{e}{m} a_\mu \left\langle \left(\left(\frac{\gamma}{\gamma+1}\right)(\vec{\beta}\cdot\vec{B})\vec{\beta} + \left(1 - \frac{1}{(1+\delta)^2}\right)\frac{\vec{\beta}\times\vec{E}}{c} \right)_y \right\rangle$$

Pitch Correction "C_P"



- **Muon's** vertical motion aligns with B-field

E-field Correction "C_E"



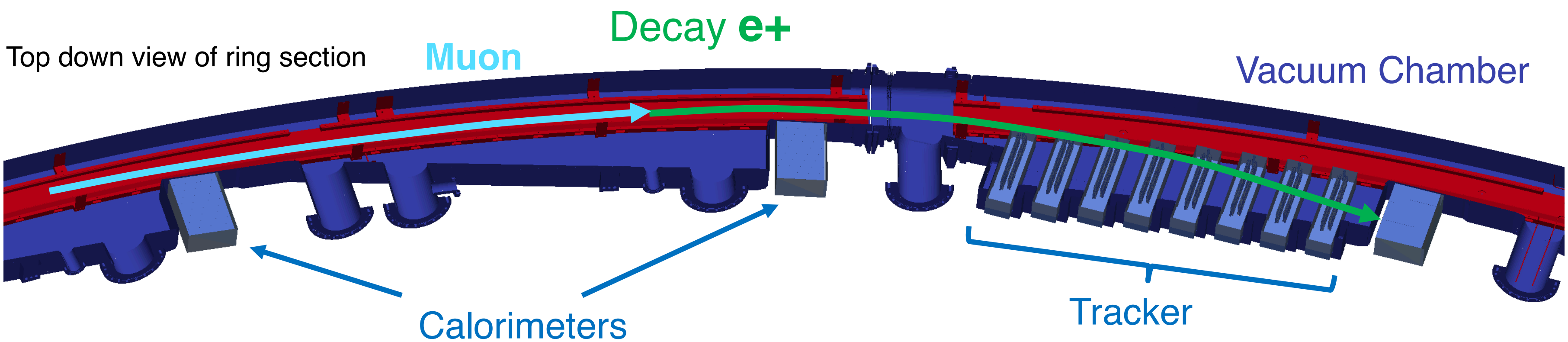
Injected muon bunch's Momentum Acceptance:

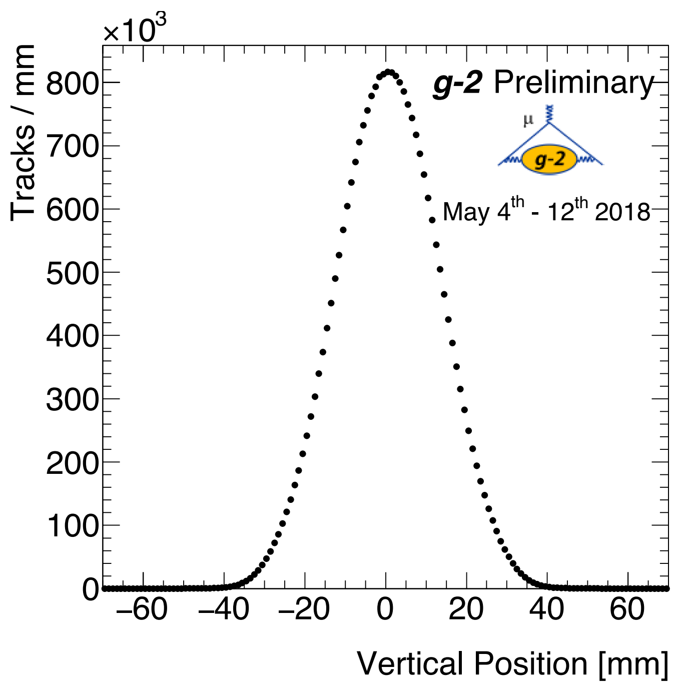
$$\delta_{max} = \frac{dp}{p_0}$$

$$\Downarrow$$

$$\pm 0.5\%$$

Run-1 E-field and Pitch Corrections

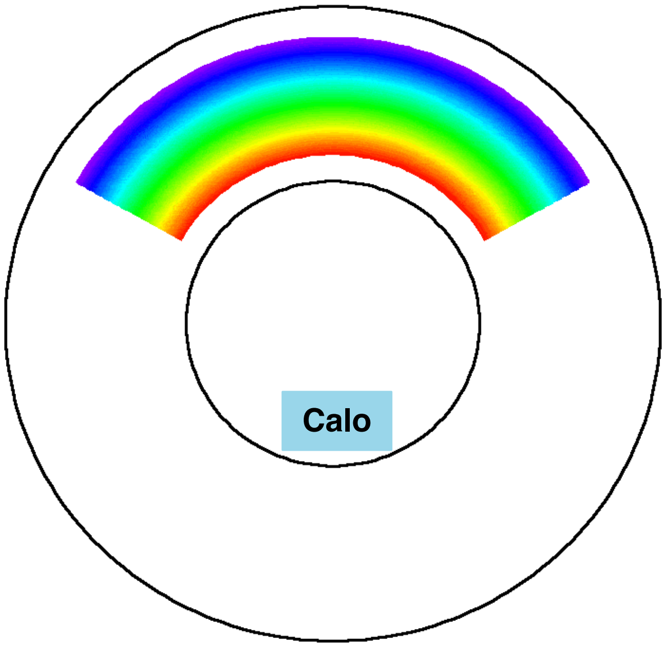




- Muon g-2 straw tracking detectors measure beam's vertical width

$$C_P = -\frac{n_0}{2\rho_0^2}\langle y^2 \rangle \approx -170 \text{ ppb}$$

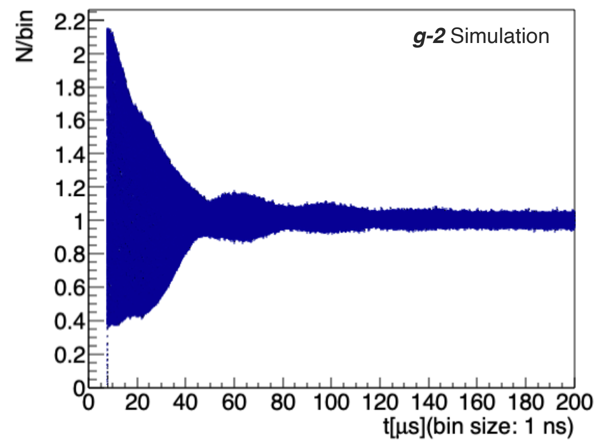
Run-1 E-field and Pitch Corrections



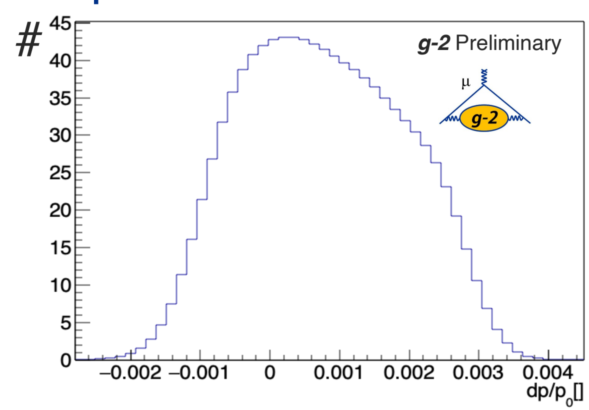
Higher Mom (Lower Freq)

Lower Mom (High Freq)

- Fast signal of muons population seen by Muon g-2 calorimeter system builds from cyclotron frequencies distribution



- Beam's momentum spread is measured from cyclotron frequencies distribution



$$C_E = -\frac{n_0 \beta_0^2}{1 - n_0} 2\langle \delta^2 \rangle \approx -460 \text{ ppb}$$

Fermilab

Nonlinear effects
on
E-field and Pitch Corrections

Nonlinear effects on E-field and Pitch Corrections

- Known corrections to ω_a determination:

$$\omega_a = \omega_{a0}(1 + \langle \Delta\omega_a^E \rangle + \langle \Delta\omega_a^B \rangle) \approx \omega_{a0}(1 + \boldsymbol{C_E} + \boldsymbol{C_P})$$

$$C_E = -\frac{n_0 \beta_0^2}{1-n_0} 2\langle \delta^2 \rangle \quad \text{and} \quad C_P = -\frac{n_0}{2\rho_0^2}\langle y^2 \rangle$$

- Nonlinearities can alter these corrections
- Trying to determine the magnitude of nonlinear effects

- In COSY-based simulations modeling EQS nonlinearities:

$$\left\langle \frac{\Delta\omega_a}{\omega_{a0}} \right\rangle_{sim} = \frac{1}{N_{turns} N_{muons}} \sum_{j=1}^{N_{turns}} \sum_{i=1}^{N_{muons}} \left(\frac{\Delta\omega_a(t'_j)}{\omega_{a0}} \right)_i$$

where $\omega_a(t'_j) = \frac{d\varphi_a}{dt} \approx \frac{\Delta\varphi_a}{\Delta t} = \frac{\varphi_a(t_{j+1}) - \varphi_a(t_j)}{t_{j+1} - t_j}$.

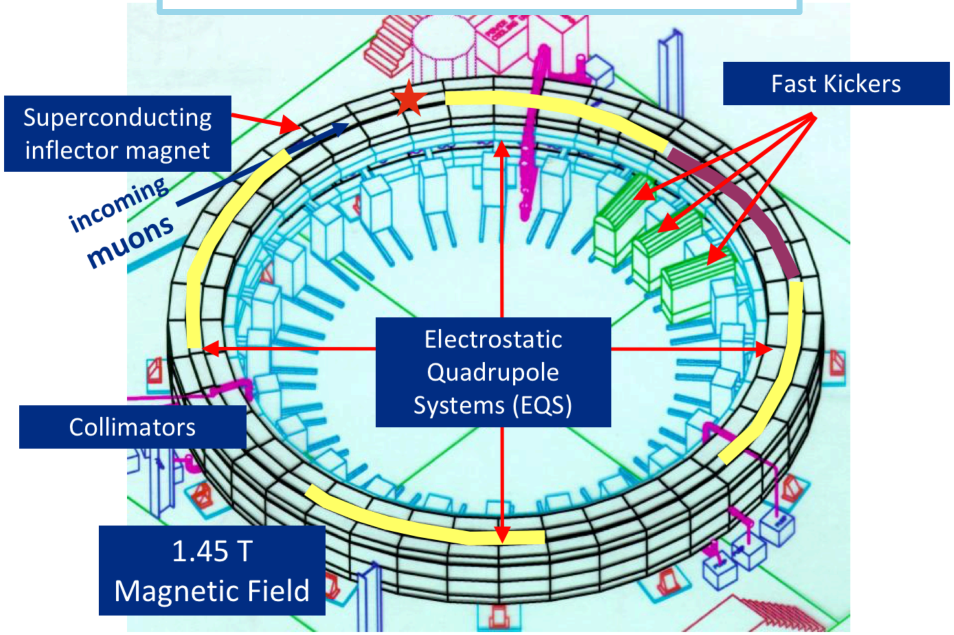
COSY-based Muon g-2 Storage Ring Model

- Preparation of high-order transfer map with COSY INFINITY from Differential algebra methods for symplectic tracking

$$\mathcal{M}(\vec{z}_0) = \vec{z}_f$$

- $\vec{z}$: array made of (x, a, y, b, l, δ) ray vectors
- $\mathcal{M}$: Map containing $(x|x^{l_{x1}}a^{l_{x2}}y^{l_{x3}}b^{l_{x4}}l^{l_{x5}}\delta^{l_{x6}})$, $(a|x^{l_{a1}}a^{l_{a2}}y^{l_{a3}}b^{l_{a4}}l^{l_{a5}}\delta^{l_{a6}})$, …

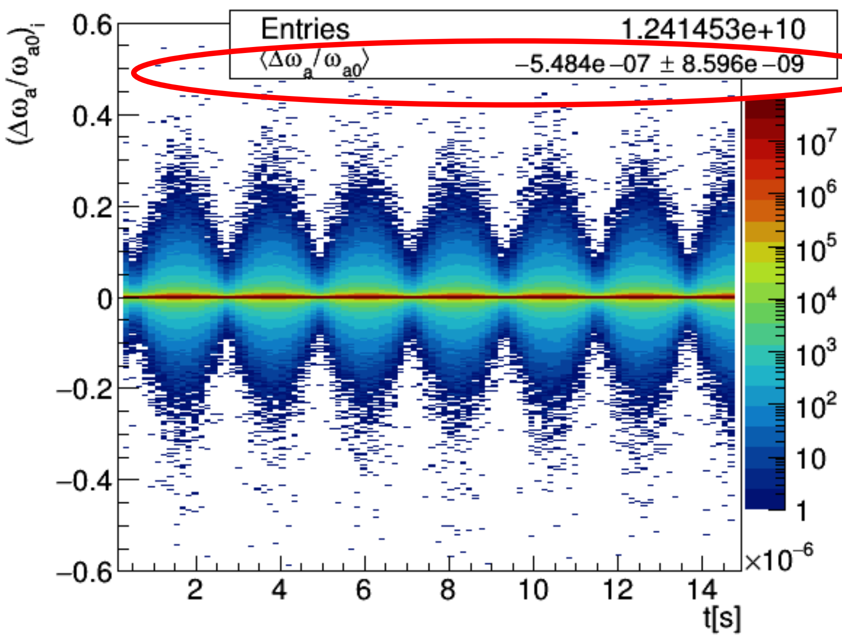
Storage ring configuration

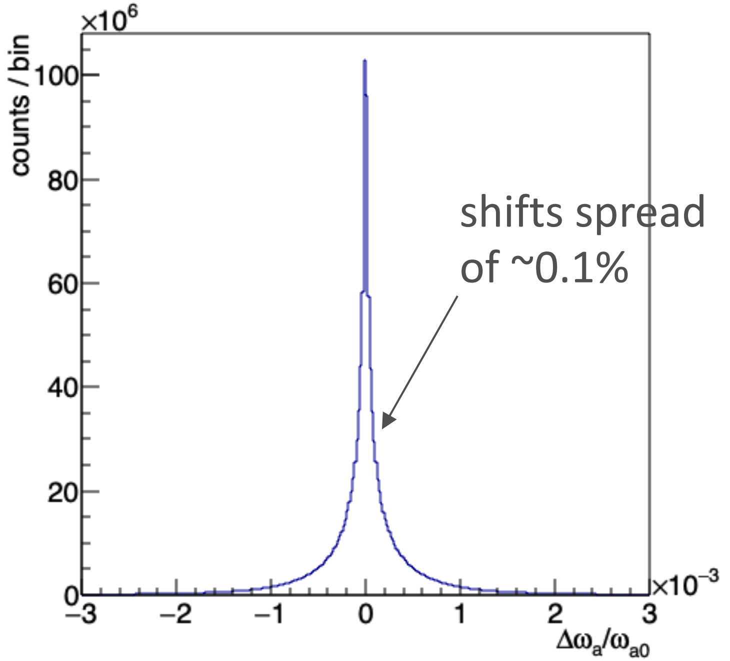


Model accounts for:

- Electric guide fields discrete configuration in Storage Ring
- Fringe fields at edges of electric field regions
- Nonlinearities from electric fields

Nonlinear effects on E-field and Pitch Corrections

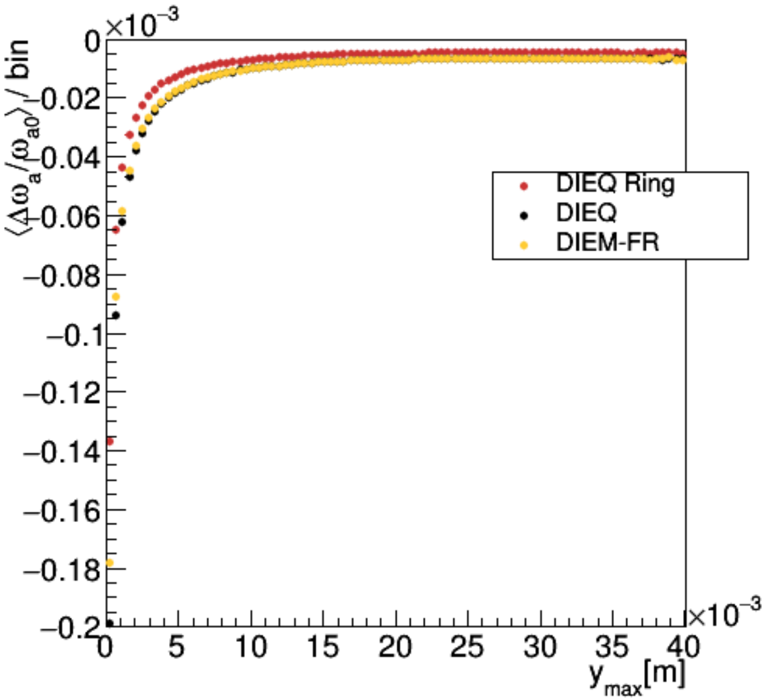


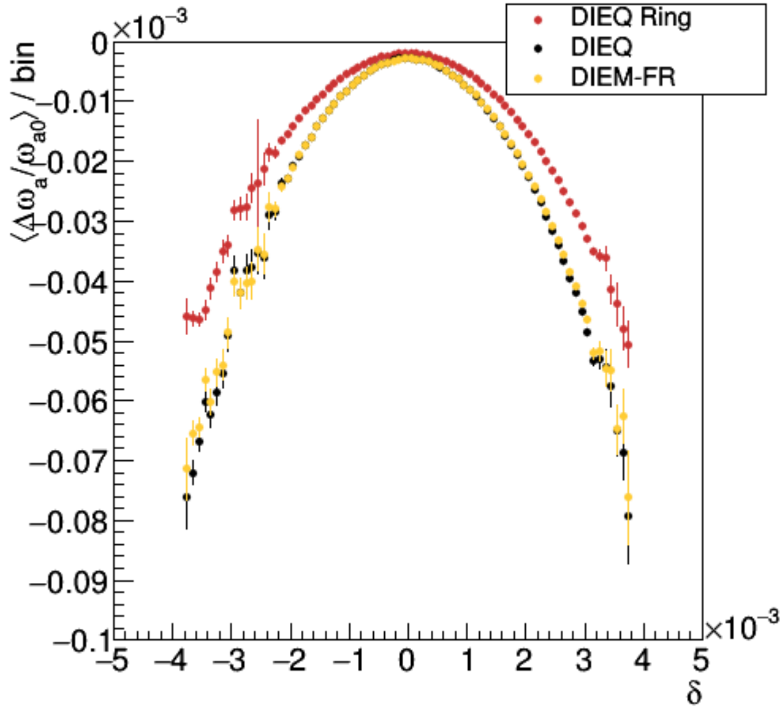


- Pitch correction linear approximations + momentum spread asymmetry + EQS continuous plates approximation + **EQS up to 20th high-order multipole** + EQS fringe fields add <10 ppb shift to $C_E + C_P$.

Fermilab

Nonlinear effects on E-field and Pitch Corrections





Effect			$C_P + C_E - \left\langle\frac{\Delta\omega_a}{\omega_{a0}}\right\rangle_{sim}$ [ppb]
EQS Plates discretization	**EQS high-order multipoles**	**EQS Fringe fields**	
			-6.4
x			-8.7
x	x	x	-10.0

*Sim. statistical uncertainty $\sim \pm$ 8.5 ppb

Summary

- E-Field/Pitch corrections for Run-1 of the Muon g-2 Experiment at Fermilab are well understood.

- Accounting for approximations to get C_E and C_P, tracking simulations agree with standard corrections to ppb level.

- Nonlinearities from electrostatic quadrupoles add ~10 ppb to known corrections.

- Beam physics plays important role in the analysis of the Muon g-2 Experiment.

Acknowledgements

- We acknowledge support from the Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the U.S. Department of Energy, Office of Science, Office of High Energy Physics.

- The author is supported by the U.S. Department of Energy under Contract No. DE-FG02-08ER41546 and Contract No. DE-SC0018636.

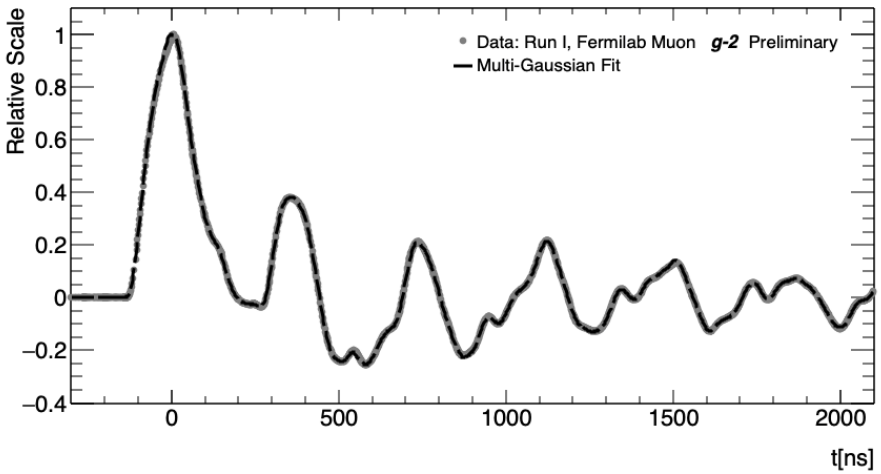
- We are thankful to the PhD Accelerator Program at Fermilab and for the Strategic Partnership Grant program from the MSU Foundation.

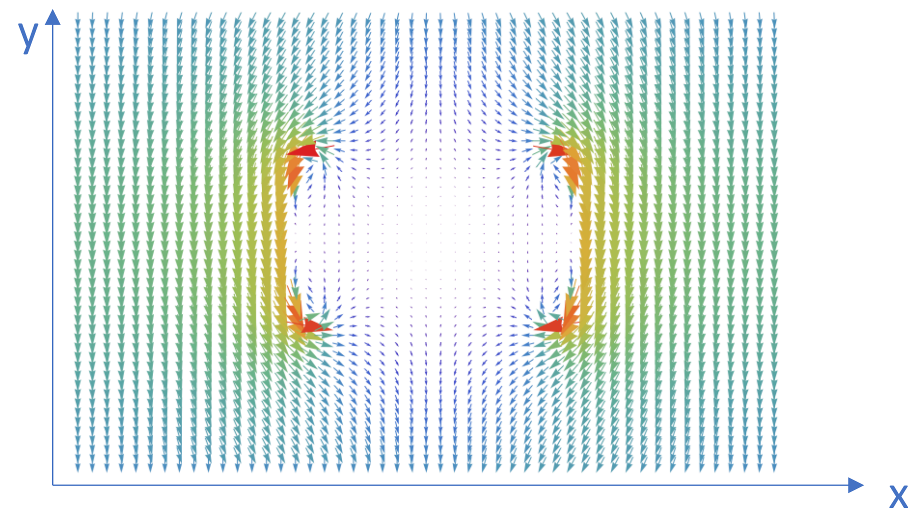
- This research used resources of the National Energy Research Scientific Computing Center (NERSC), a U.S. Department of Energy Office of Science User Facility operated under Contract No. DE-AC02-05CH11231.

BACKUP

COSY-based Muon g-2 Storage Ring Model

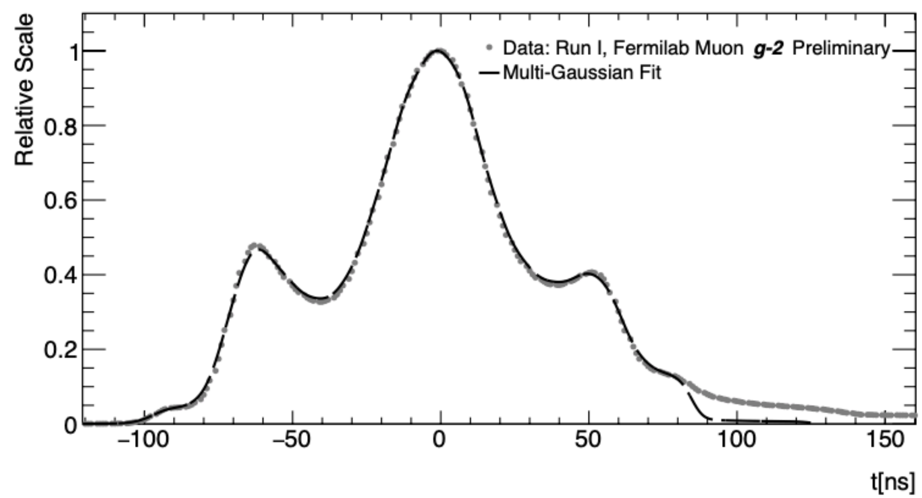
- Non-ideal injection kicker determine stored muon beam





- Pulse shapes interpolated from scintillators data at ring entrance

- Beam parameters downstream inflector from Muon Campus numerical studies



[4]

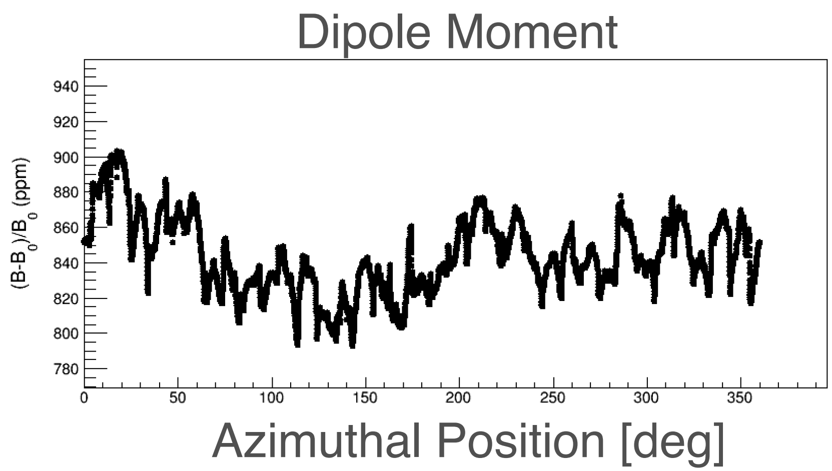
COSY-based Muon g-2 Storage Ring Model

- Midplane symmetry allows full 3D representation of EQS field from $a_{k,0}$'s alone

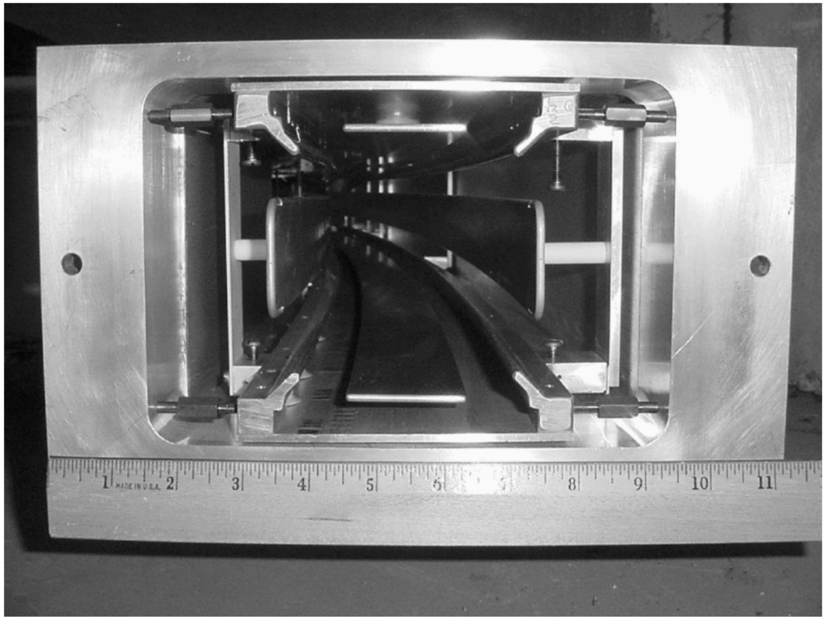
$$V = V(x,y,s) = \sum_{k=0}^{\infty}\sum_{l=0}^{\infty} a_{k,l}(s)\,\frac{x^k y^l}{k!l!}$$

$$\begin{aligned} a_{k,l+2} = &- a''_{k,l} - kha''_{k-1,l} + kh'a'_{k-1,l} - a_{k+2,l} - (3k+1)\,ha_{k+1,l} \\ &- 3kha_{k-1,l+2} - k(3k-1)\,h^2 a_{k,l} - 3k(k-1)\,h^2 a_{k-2,l+2} \\ &- k(k-1)^2 h^3 a_{k-1,l} - k(k-1)(k-2)\,h^3 a_{k-3,l+2}. \end{aligned}$$

Typical Field Map



Electrostatic Quadrupole System



- High-order magnetic multipoles from 2D fits to Field Team's NMR data