Beam Dynamics Challenges in the Muon g − 2 Experiment

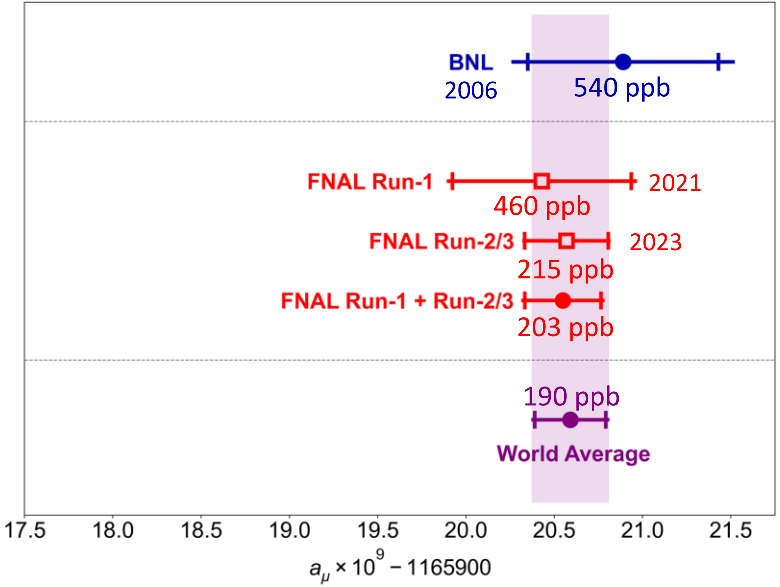
Brynn MacCoy, University of Washington

July 11, 2024

CENPA Center for Experimental Nuclear Physics and Astrophysics

Muon g-2 measurements reached unprecedented precision in 2023

Measured values of the muon anomalous magnetic moment a_μ



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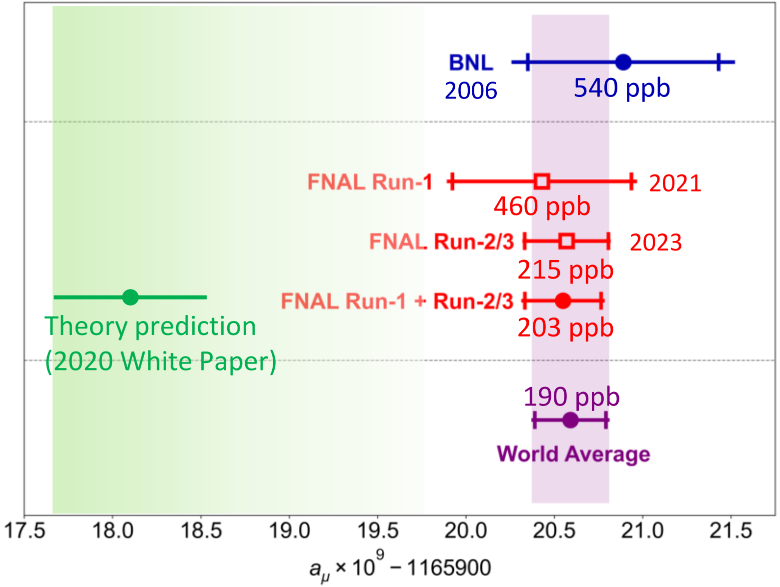

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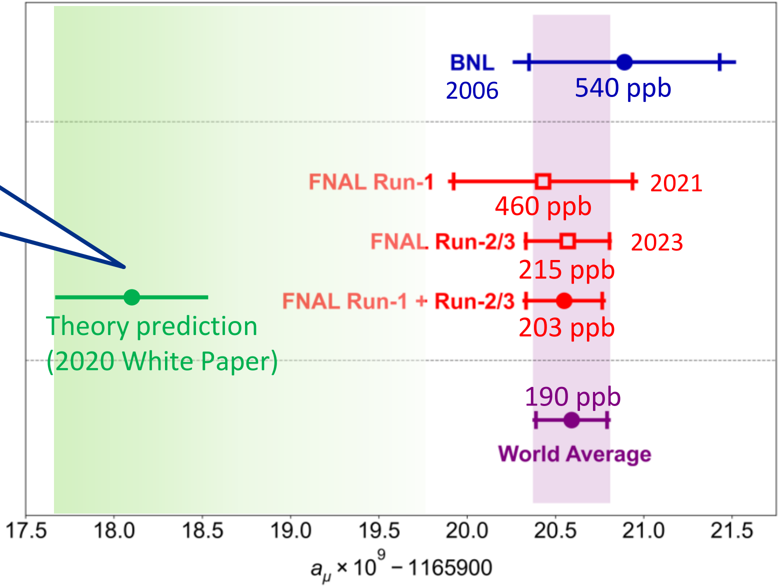

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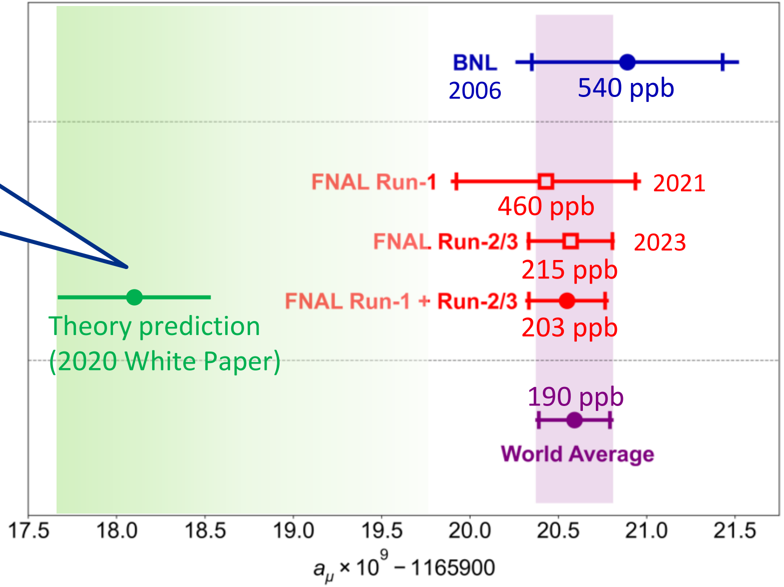

- Latest Fermilab Muon g-2 measurement confirmed previous measurements with highest precision yet
- Strengthened standing discrepancy in experiment vs. Standard Model theory
- More motivation than ever to deliver highest-precision measurement

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Magnetic moment is affected by virtual particles

magnetic moment

spin

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

gyromagnetic ratio

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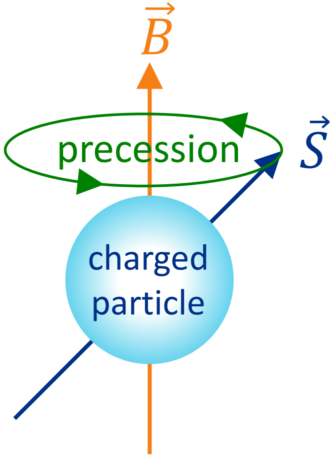
Spins precess in external magnetic field

$$\omega = g \frac{q}{2m} B$$



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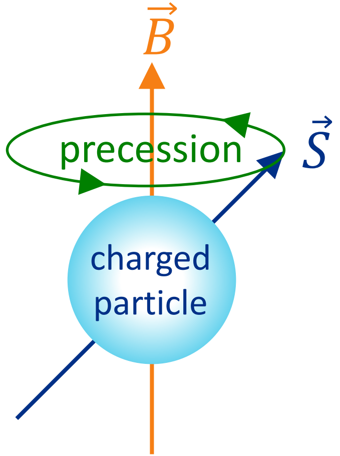
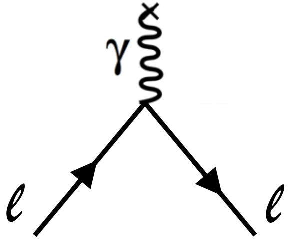


- Dirac equation for spin $\frac{1}{2}$ particles $\mathrm{g} = 2$



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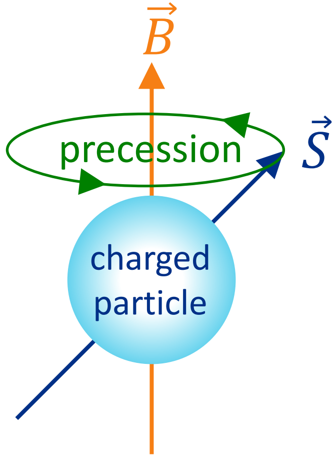
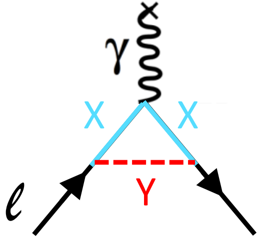


- Dirac equation for spin $\frac{1}{2}$ particles $\quad g = 2$
- Loop corrections → anomalous magnetic moment $\quad g = 2(1 + a)$



Virtual particles X, Y

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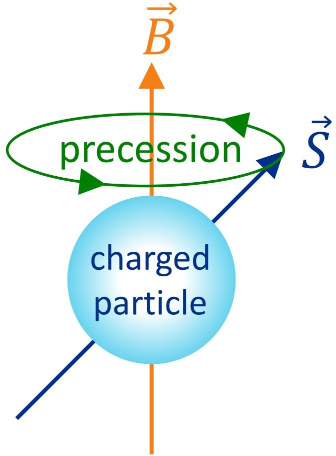

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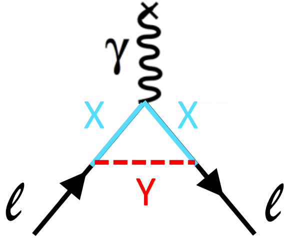

Virtual particles X, Y

- Predict with Standard Model: QED (dominant), EW, QCD contributions

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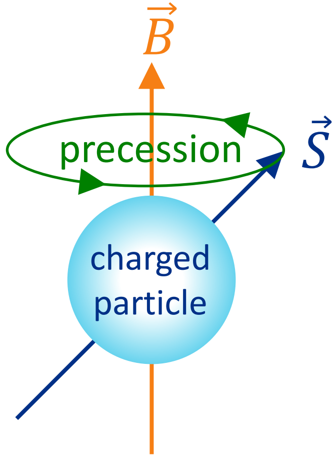

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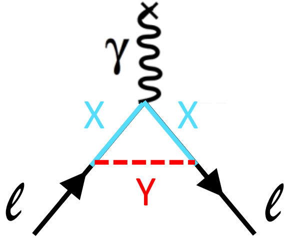
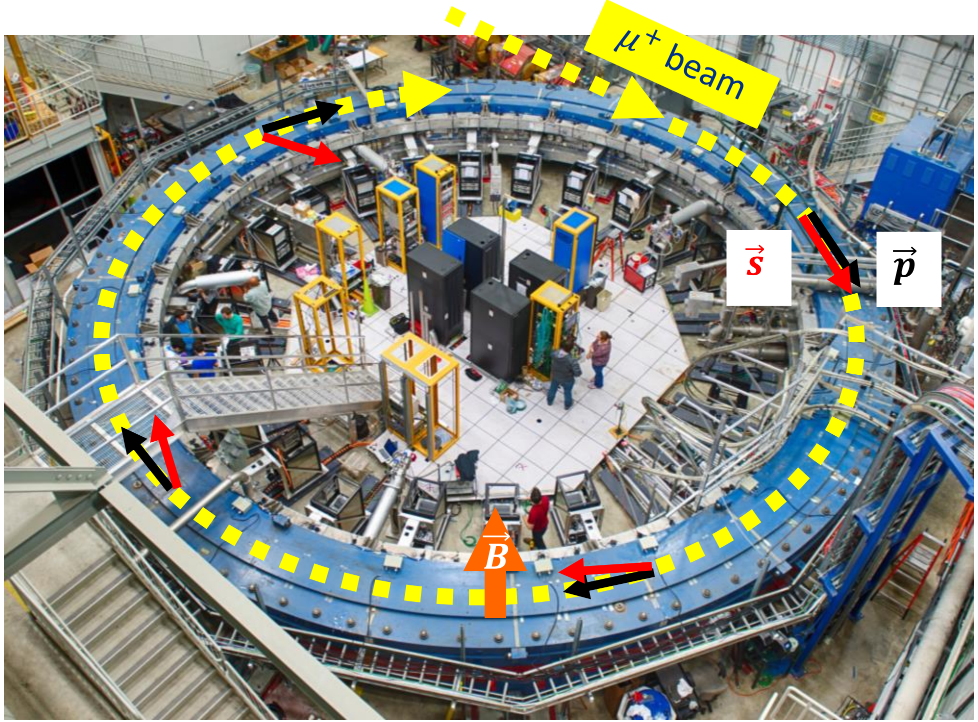


Virtual particles X, Y

- Predict with Standard Model: QED (dominant), EW, QCD contributions
- Discrepancy with experiment suggests new physics

Measuring a_μ at Fermilab Muon g-2

- Goal: Measure a_μ to 140 ppb (4× more precise than BNL, on par with theory precision target)
- Details in On Kim's g-2 report today
- Inject polarized muons (μ^+) into magnetic storage ring



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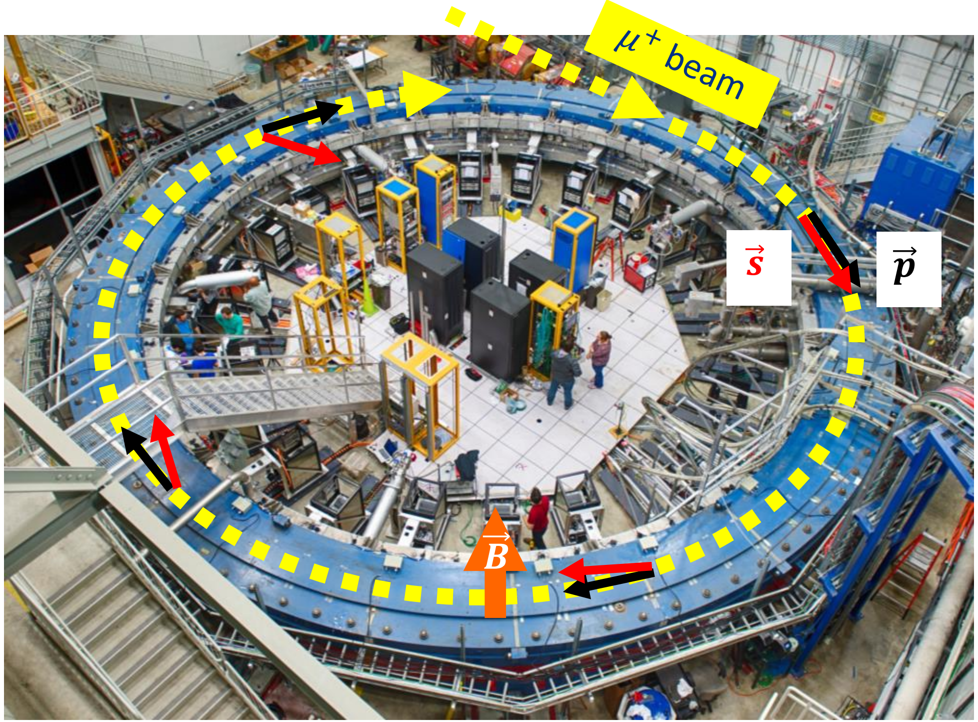

$$\vec{\omega}_a = \vec{\omega}_s - \vec{\omega}_c = -a_\mu \frac{e}{m} \vec{B}$$

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Extract from
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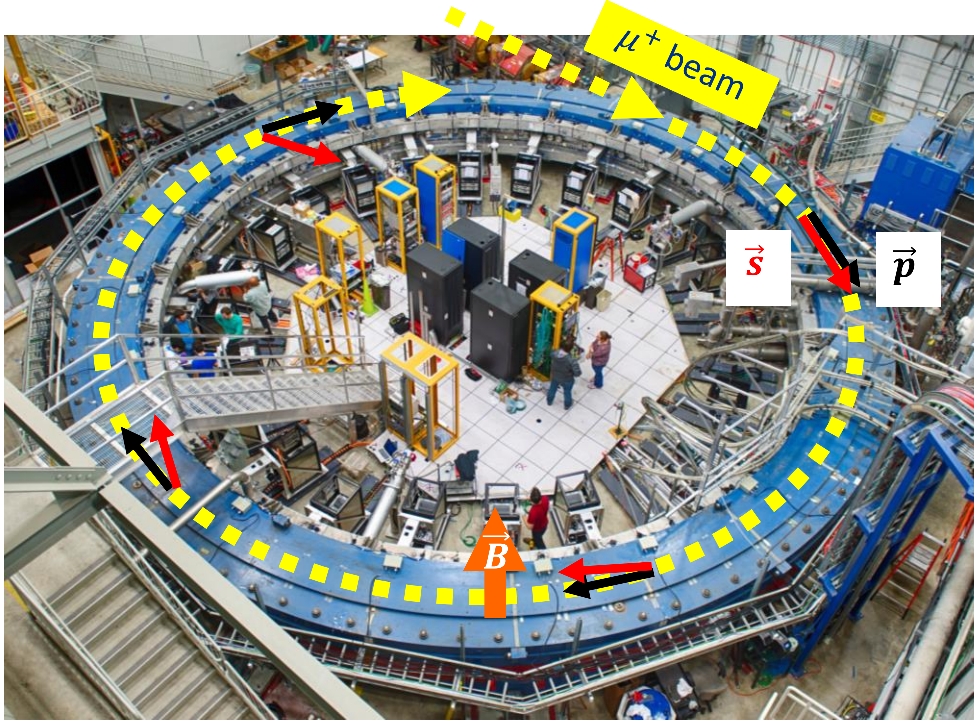

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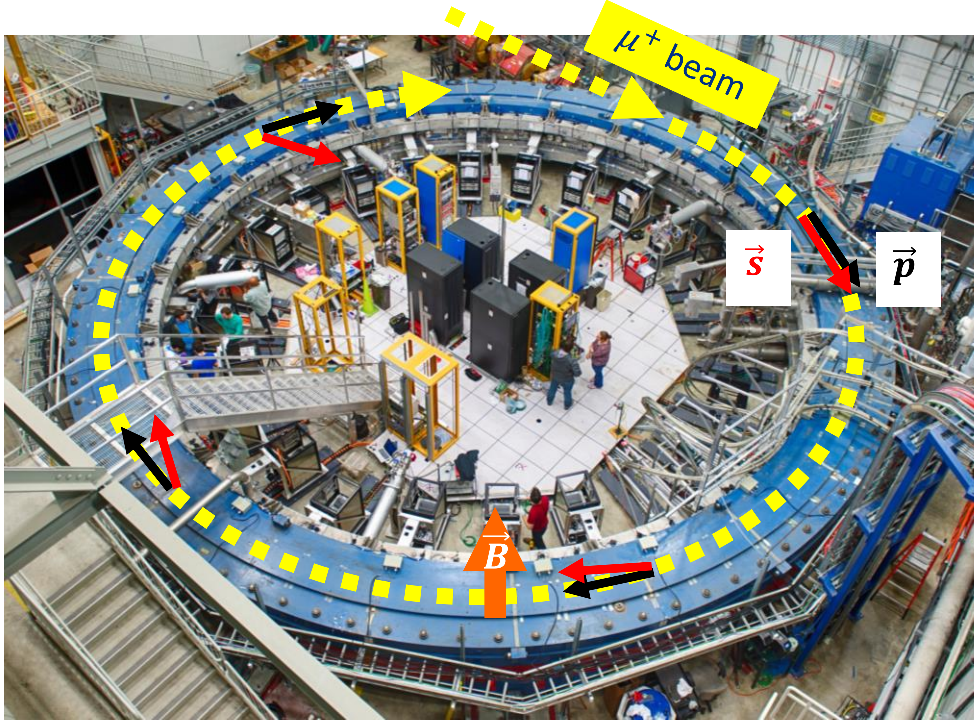
Measure with calorimeters

Measure with proton NMR probes



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Measuring a_μ at Fermilab Muon g-2

- $\mu^+ \rightarrow e^+ \nu_e \overline{\nu_\mu}$
- 24 calorimeters measure e^+ energy and arrival time

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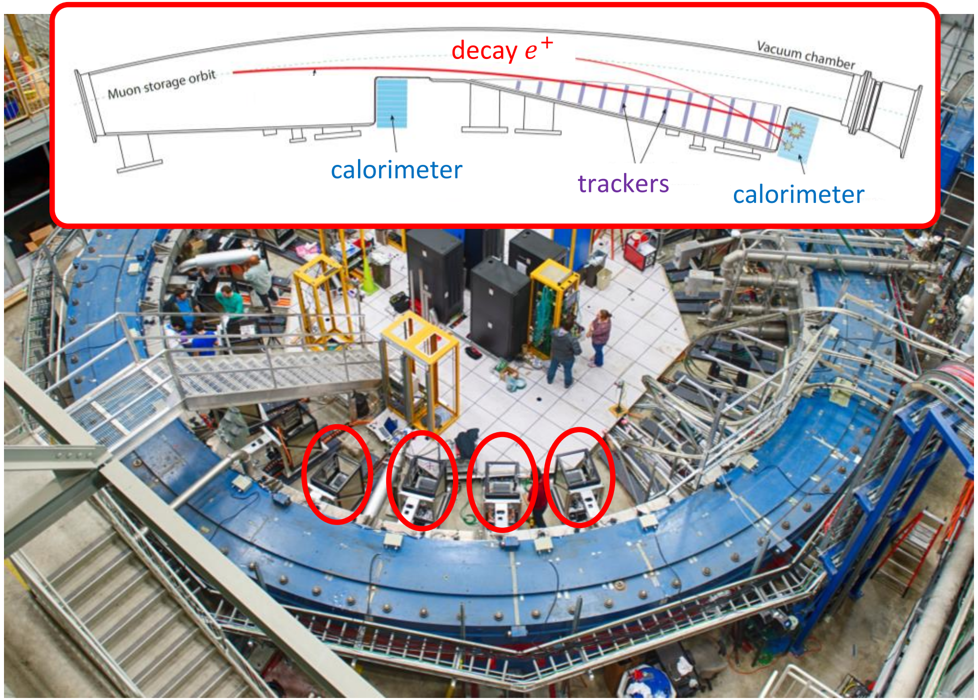

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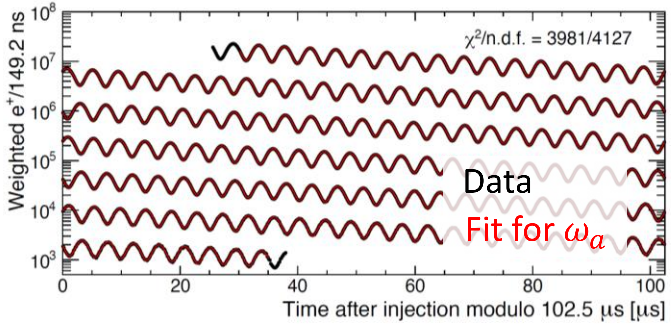
e^+ above E threshold vs time modulated by ω_a



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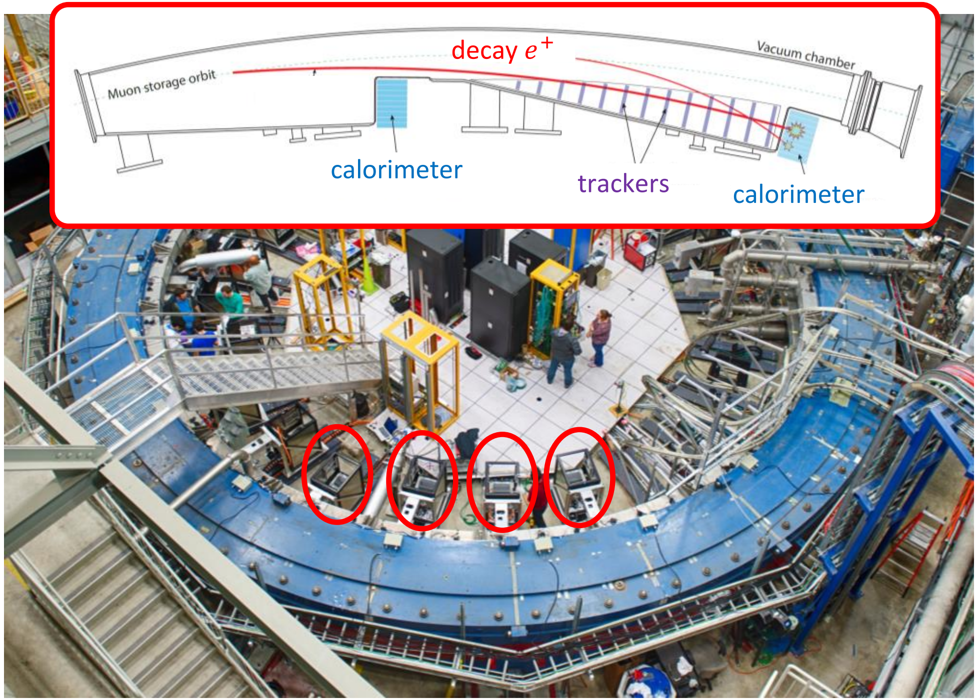

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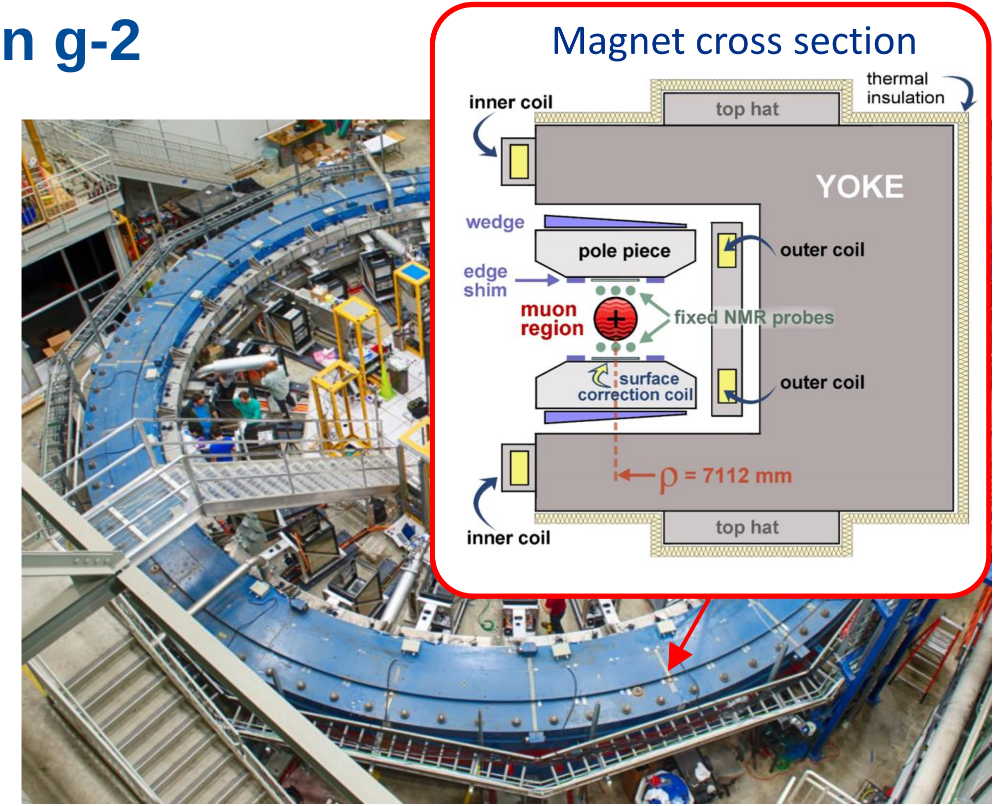

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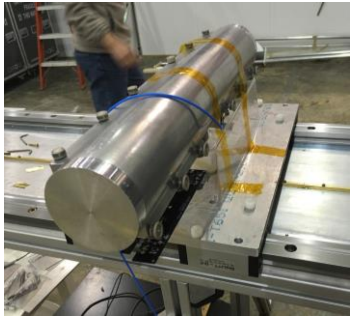
Measuring a_μ at Fermilab Muon g-2

- Trolley maps field every few days



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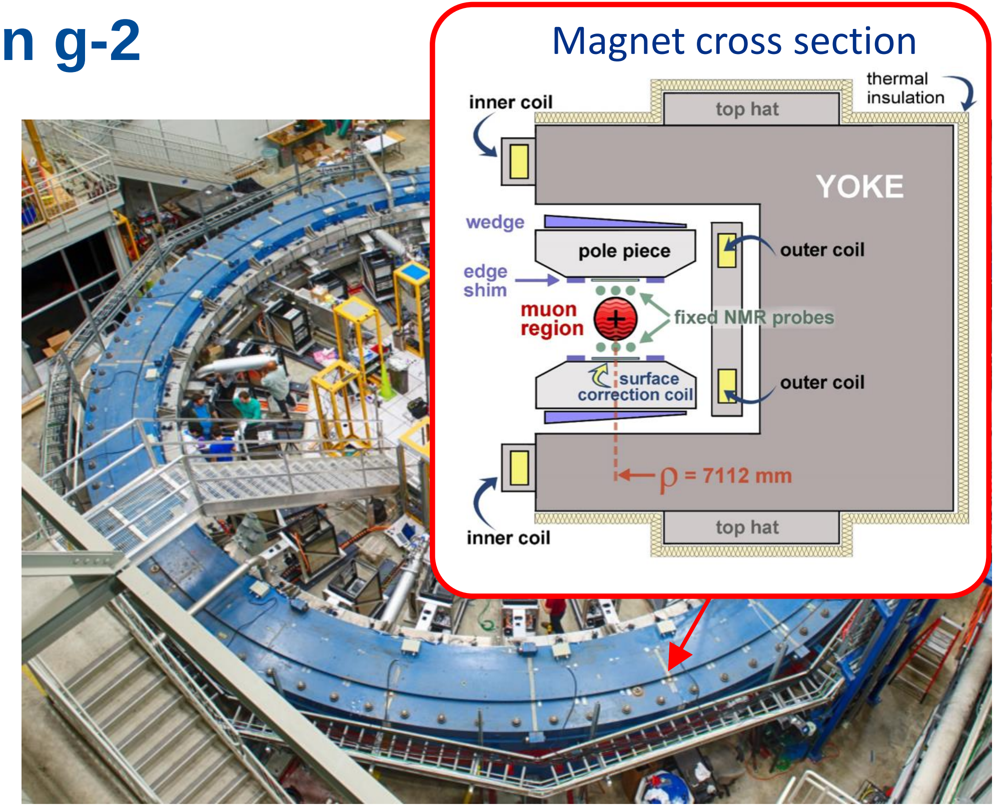

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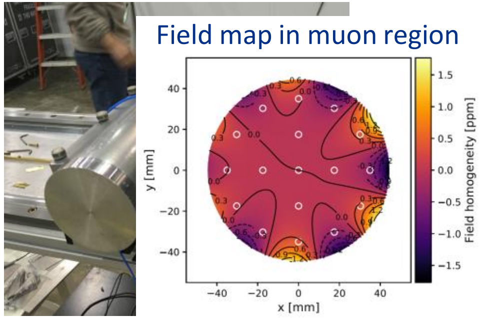

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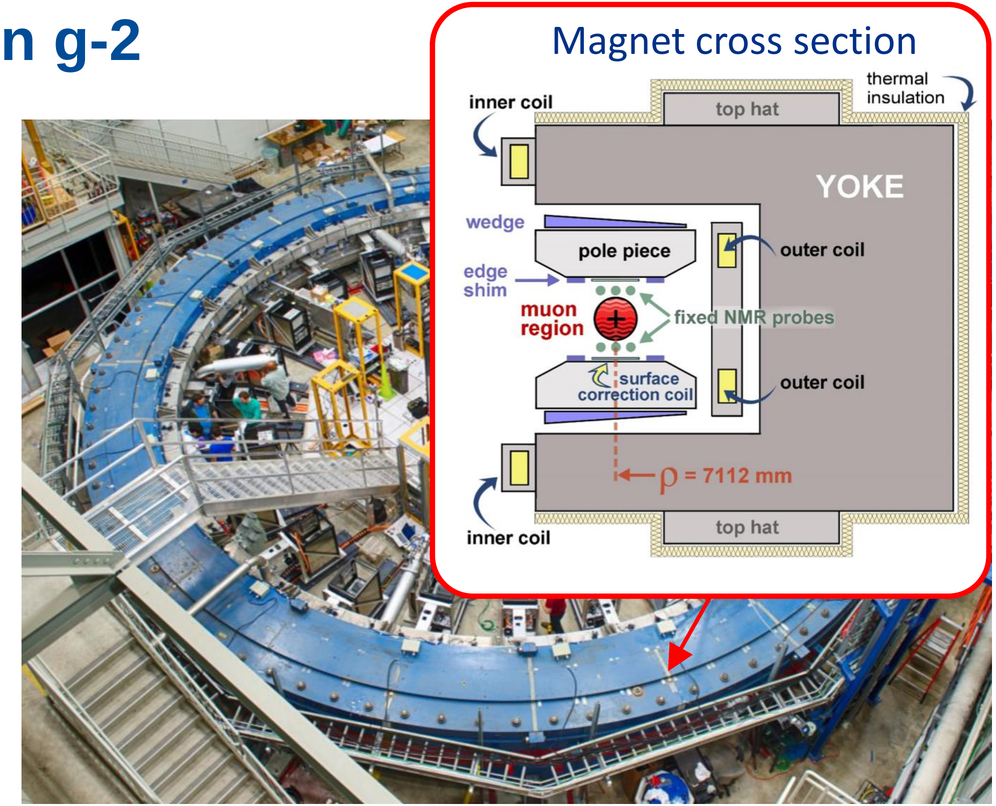

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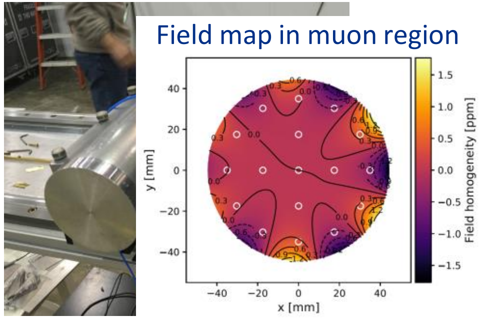
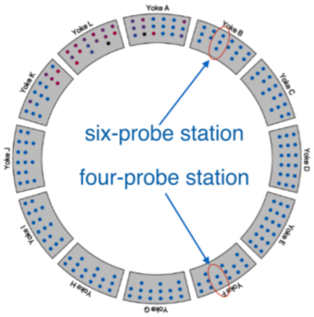


- Fixed probes monitor field drift



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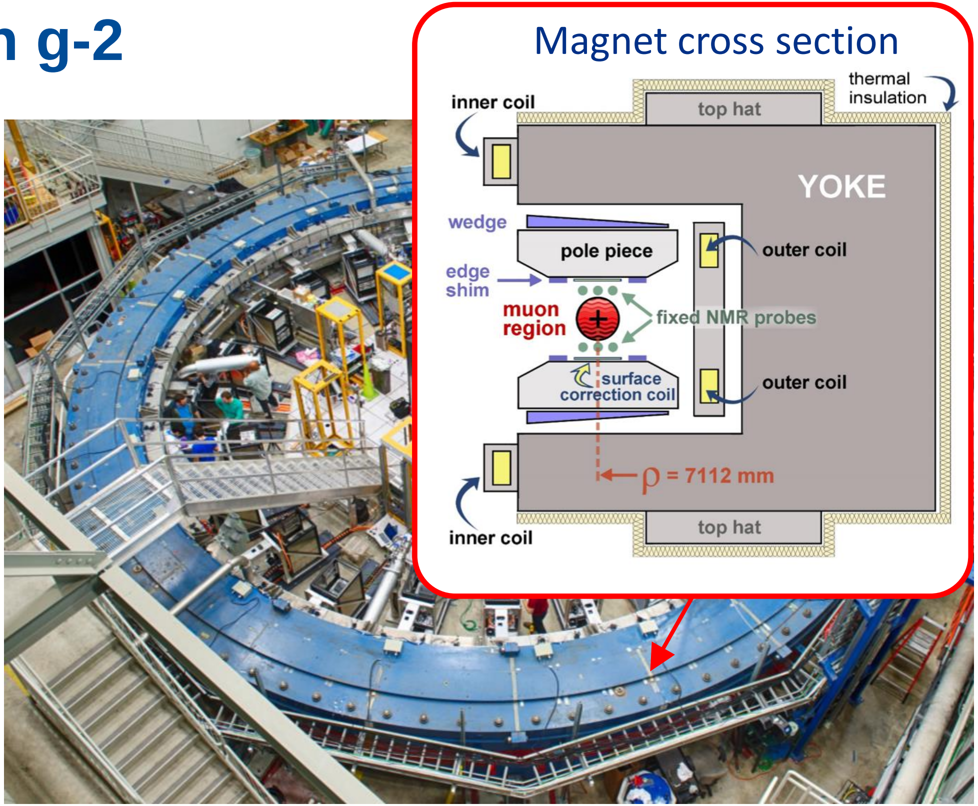

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Measuring a_μ at Fermilab Muon g-2

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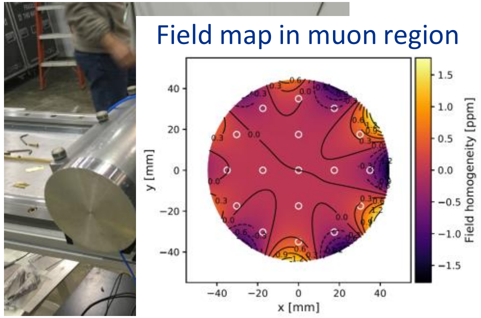

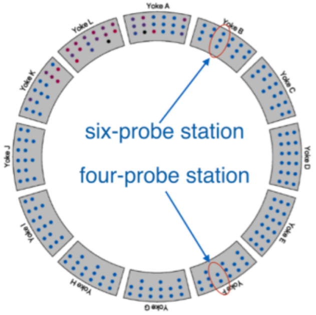

Field in ring during ω_a measurements

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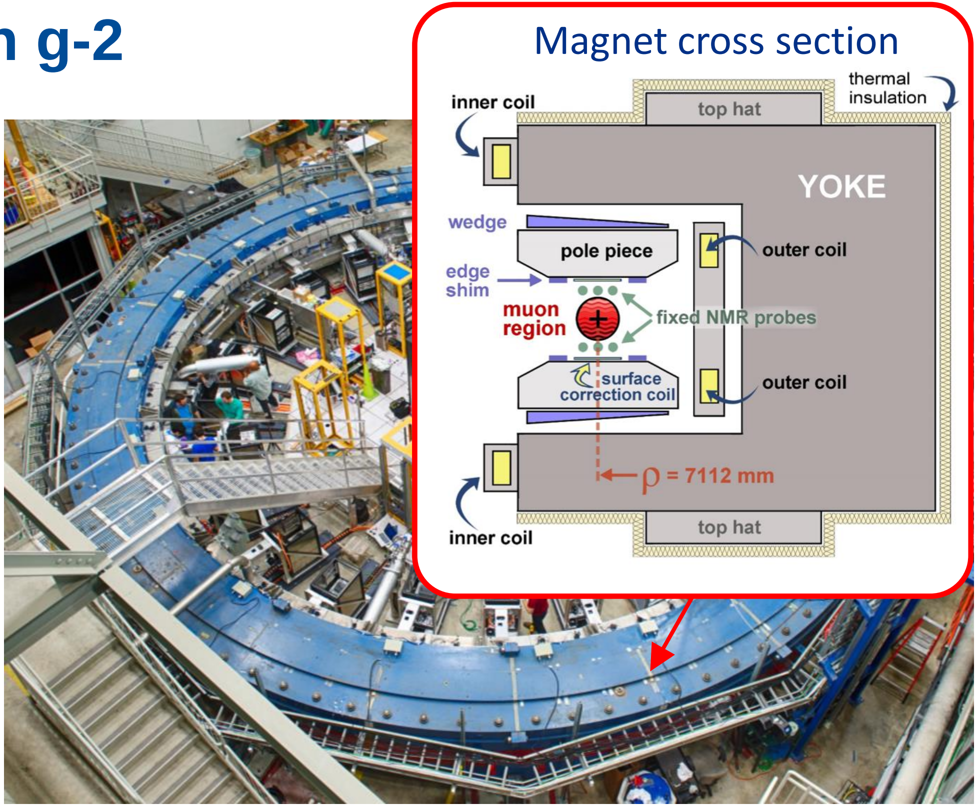
Measure with proton NMR probes



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Measuring a_μ at Fermilab Muon g-2

- Beam dynamics (motion of the muons) affects both observables
- My thesis focused on several beam dynamics effects critical for precision goal

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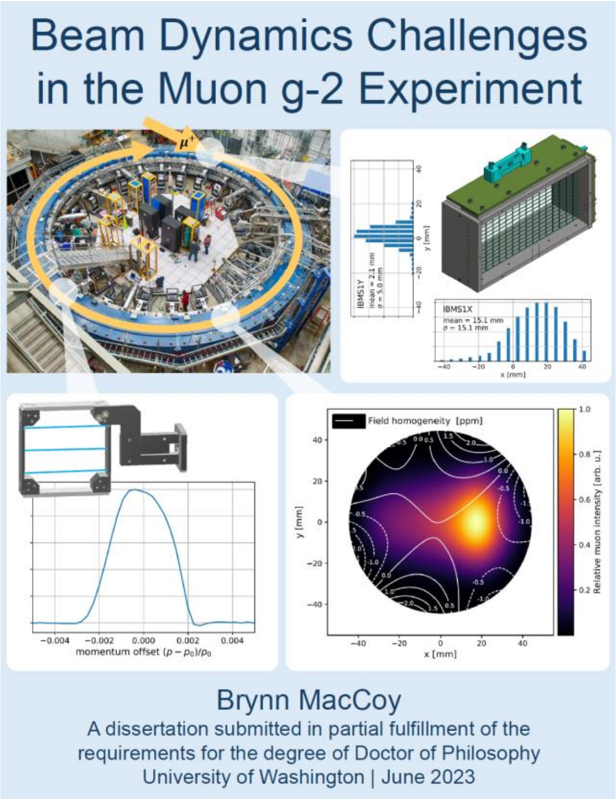
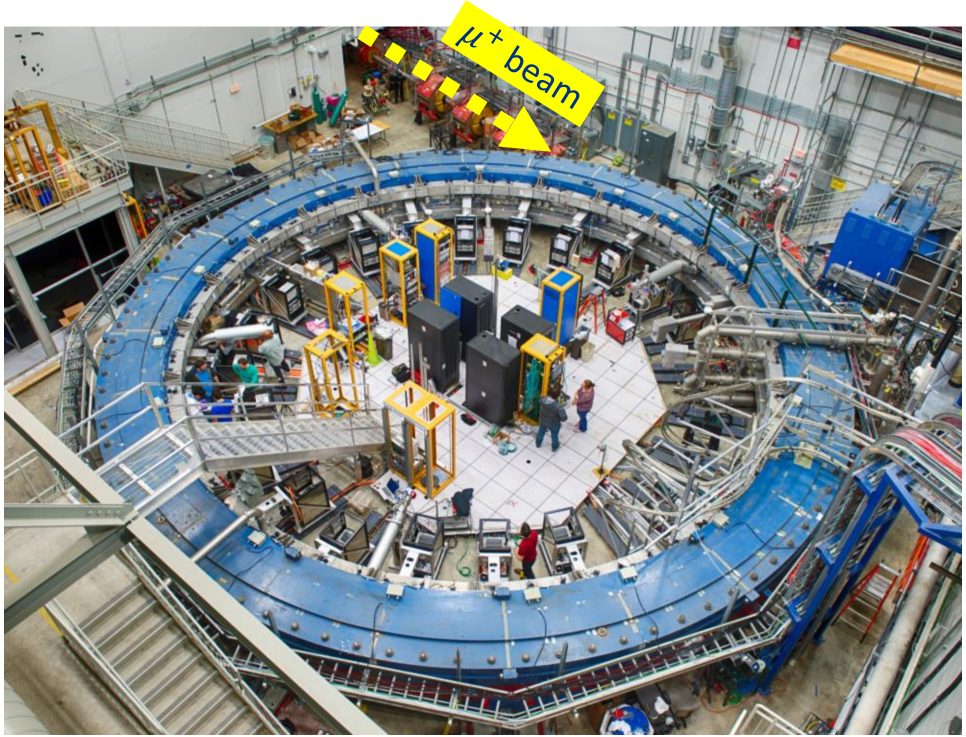


Injecting and storing muons in the ring



Injecting and storing muons in the ring

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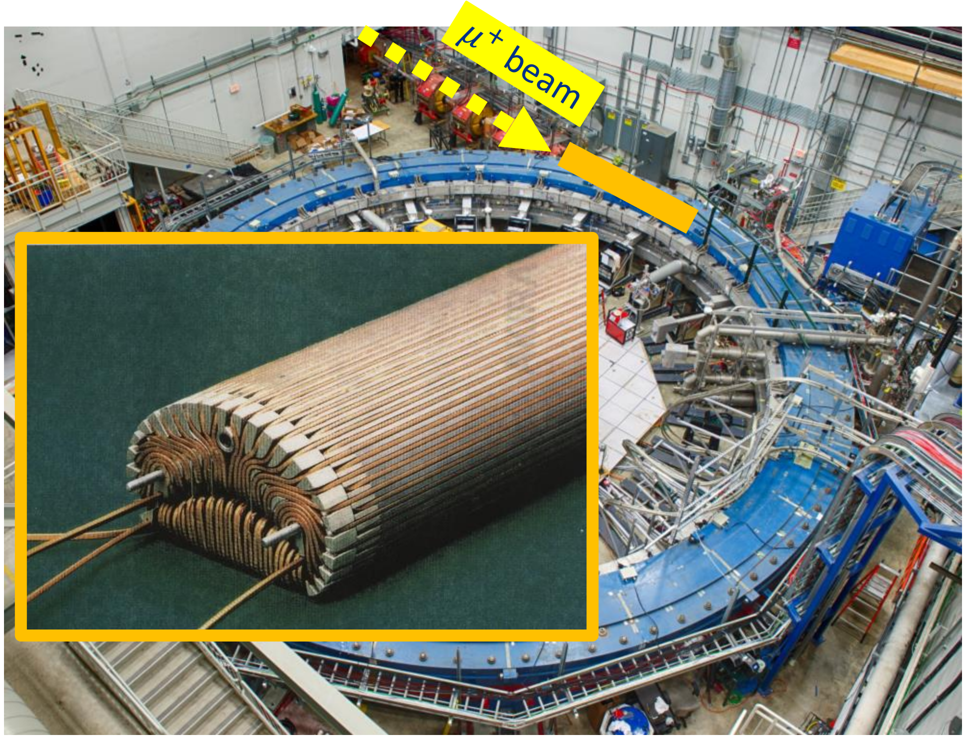

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- Inflector magnet cancels field along injection path
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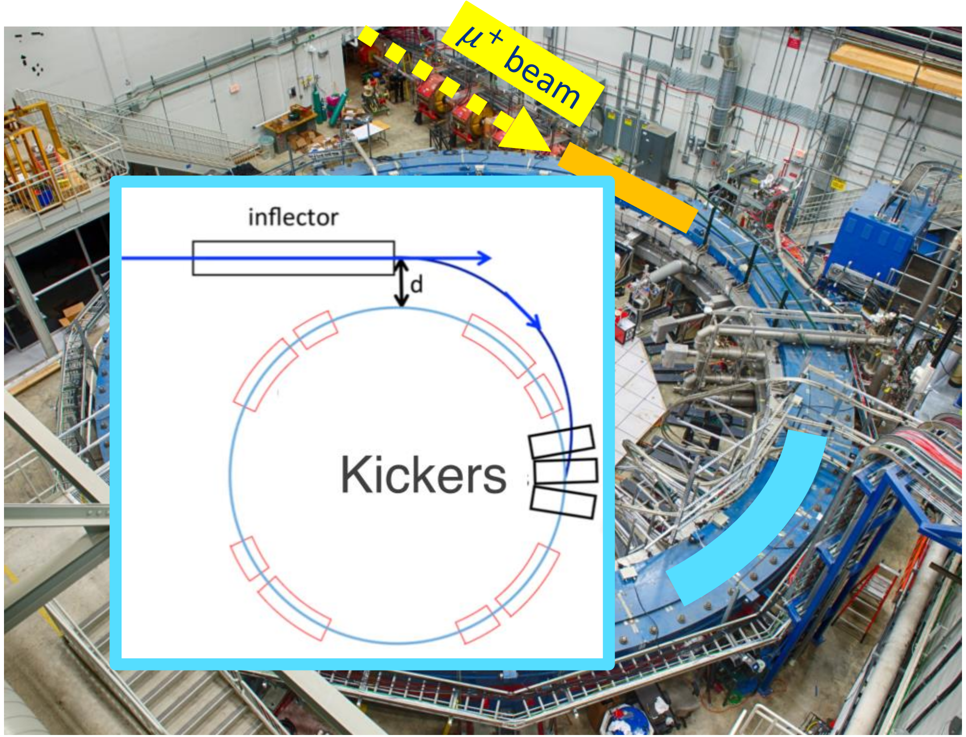

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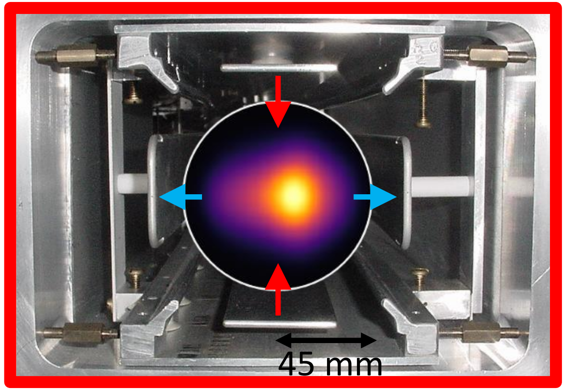
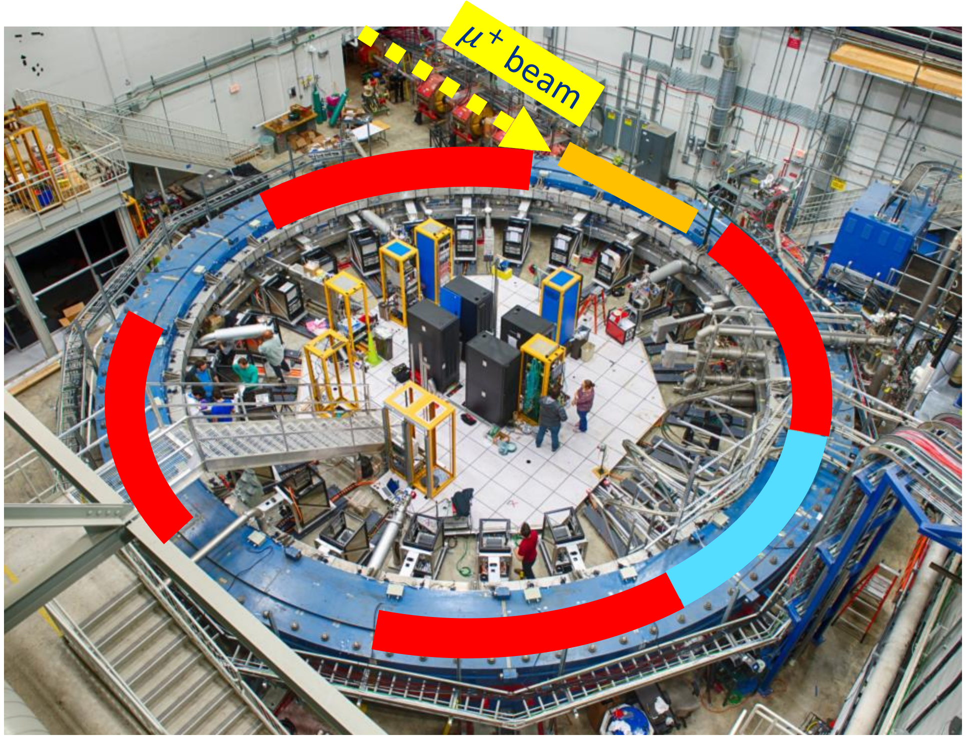
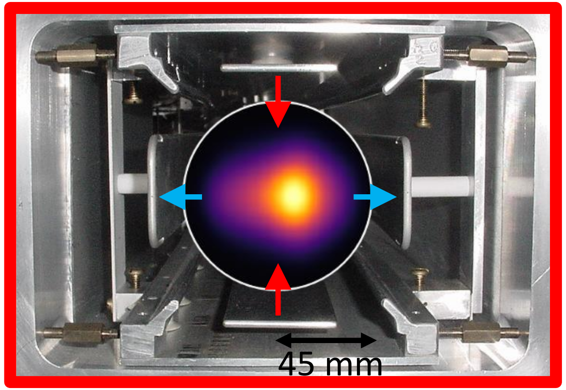
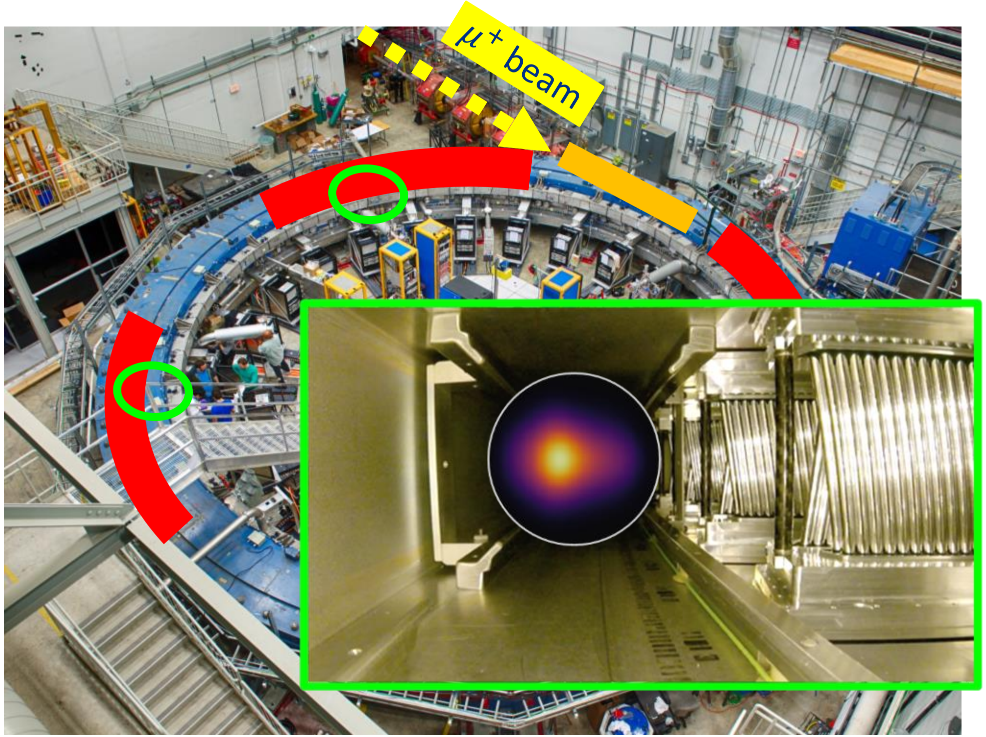




Injecting and storing muons in the ring

- Inflector magnet cancels field along injection path
- Pulsed kicker magnets shift beam to nominal orbit
- Electric quadrupoles contain beam vertically
- Straw trackers reconstruct muon distribution





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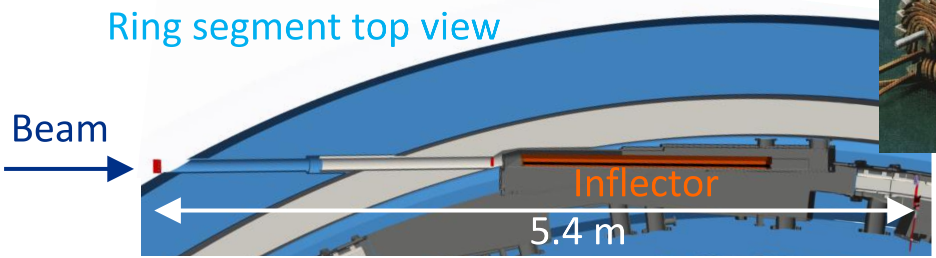
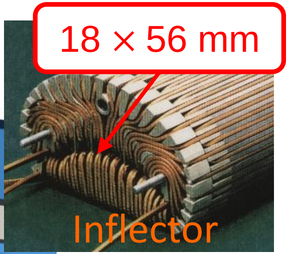
Characterizing beam during challenging injection

- Challenges: fringe fields, no steering elements





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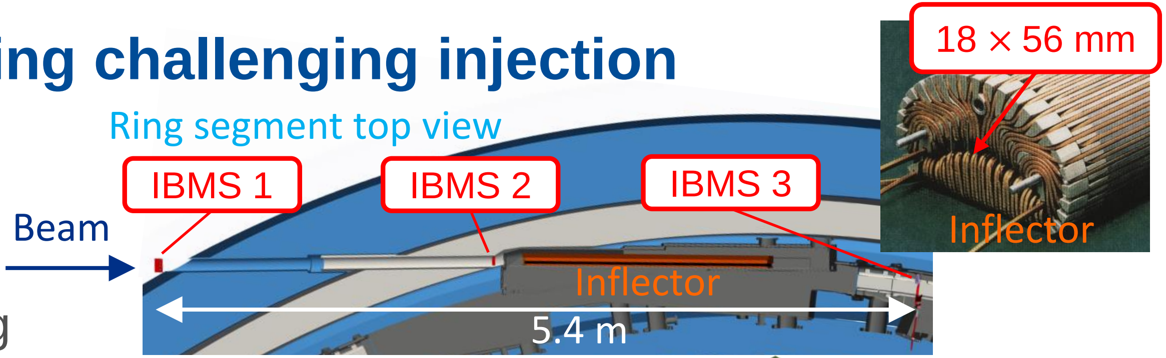
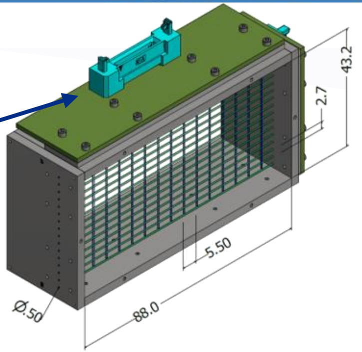
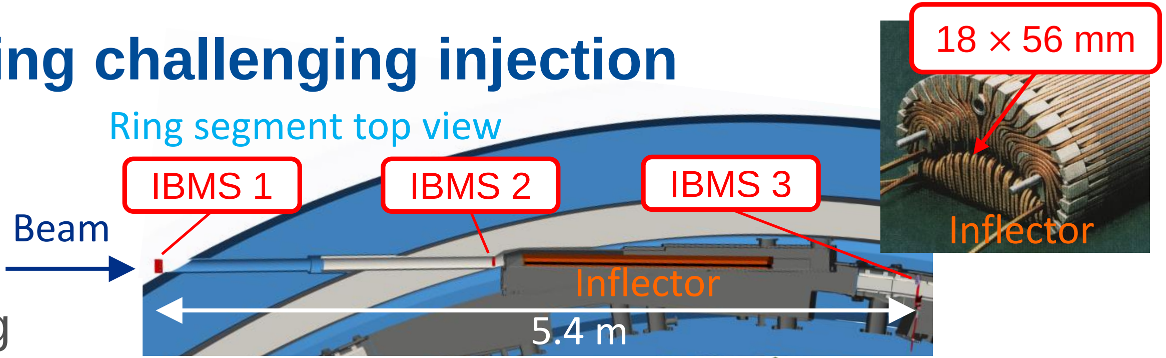
- Built Inflector Beam Monitoring System (IBMS) detectors to monitor injected beam

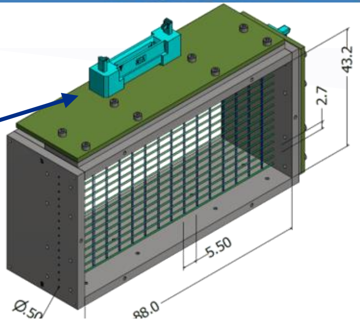




Characterizing beam during challenging injection

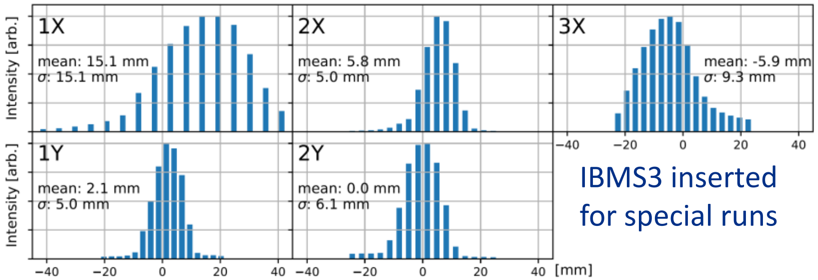
- Challenges: fringe fields, no steering elements
- Built Inflector Beam Monitoring System (IBMS) detectors to monitor injected beam
- IBMS assisted with beam tuning and injection modeling
- Collaboration with AD members
- Critical for muon storage efficiency, systematics





Scintillating fibers coupled to silicon photomultipliers

IBMS beam profiles



IBMS3 inserted for special runs

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Average magnetic field experienced by muons

$$\omega_a = -a_\mu \frac{e}{m} \boxed{\tilde{B}}$$

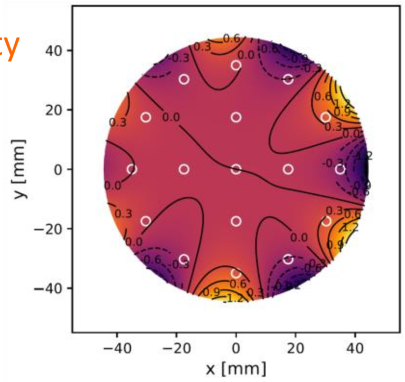
- Inputs: Field maps and beam profiles around the ring
- Weight field in azimuth slices, then average around ring

$$\tilde{B} = \langle B(\vec{r}) \times M(\vec{r}) \rangle$$

Transverse field map

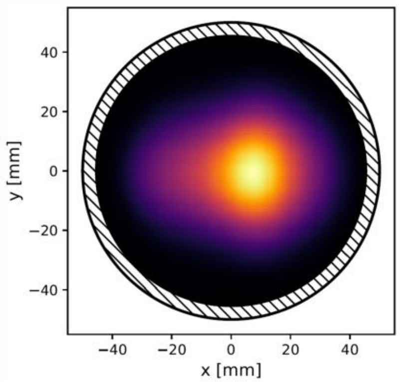
Uniformity <1 ppm

$= \langle$



$\times$

Transverse muon distribution



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Reconstructed from trackers

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Field  Beam dynamics

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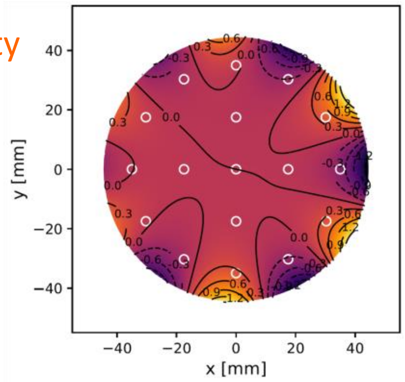
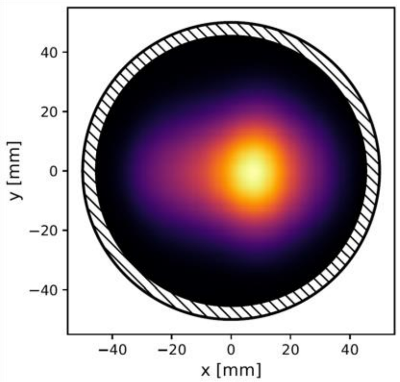


$$\times$$



$$\rangle$$

Reconstructed from trackers

Average magnetic field experienced by muons

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

- Inputs: Field maps and beam profiles around the ring
- Weight field in azimuth slices, then average around ring

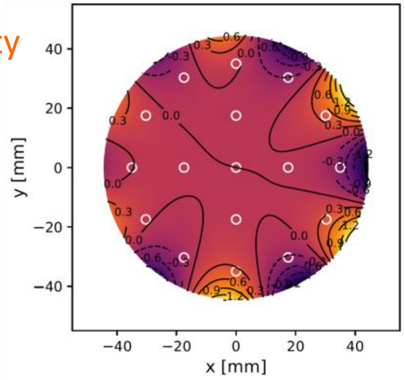
$$\tilde{B} = \langle B(\vec{r}) \times M(\vec{r}) \rangle$$

Field  Beam dynamics

Transverse field map

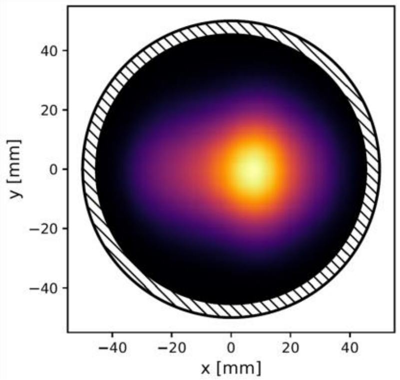
Uniformity <1 ppm

$= \langle$



$\times$

Transverse muon distribution



$\rangle$

Reconstructed from trackers

- Led analysis for 2021 and 2023 results
- Proper muon distribution weighting prevents a bias of up to ~50 ppb with excellent uncertainty ~10 ppb

Correcting for electric field

- Original: Ideal motion in vertical B field

$$\vec{\omega}_a = -a_\mu \frac{e}{m} \vec{B}$$

Correcting for electric field

- Original: Ideal motion in vertical B field
- Electric quadrupole field → motional B field

$$\vec{\omega}_a = -a_\mu \frac{e}{m}\vec{B}$$

$$-\frac{e}{m}\left[-\left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\vec{\beta} \times \vec{E}\right]$$

- Cancel with nominal momentum 3.094 GeV
- Nonzero due to momentum spread (~0.1%) → correction to ω_a

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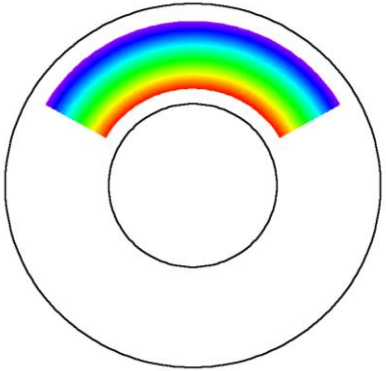
Higher momentum muons orbit at larger radius → lower cyclotron frequency



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Correcting for electric field

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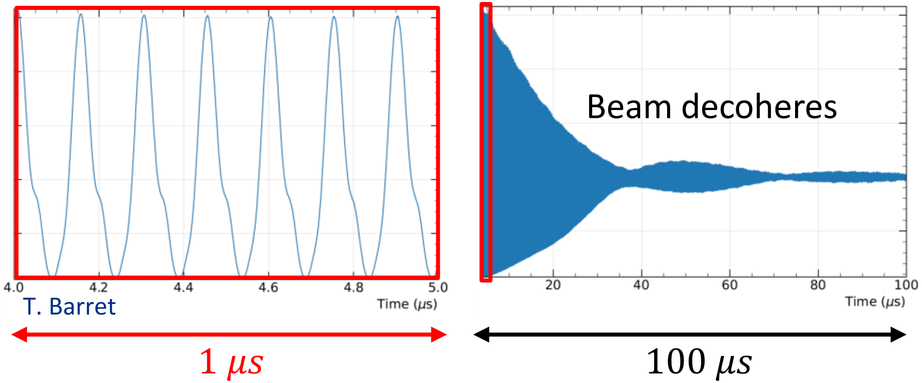
$$\vec{\omega}_a = -a_\mu \frac{e}{m}\vec{B} - \frac{e}{m}\left[-\left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\vec{\beta} \times \vec{E}\right]$$

Circulating beam intensity seen by calos



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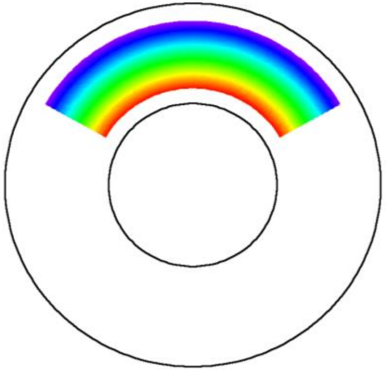

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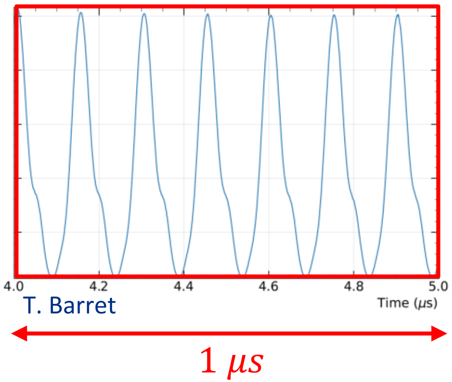
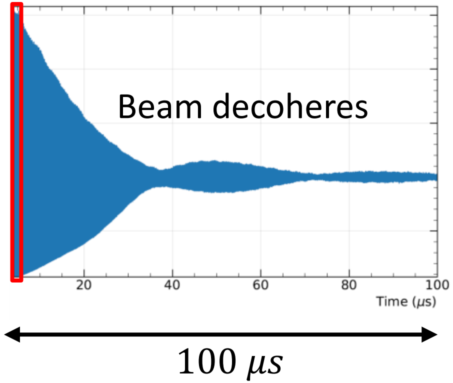
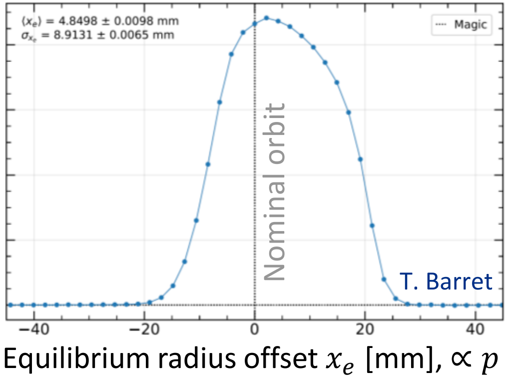




→ Reconstruct momentum from frequency analysis



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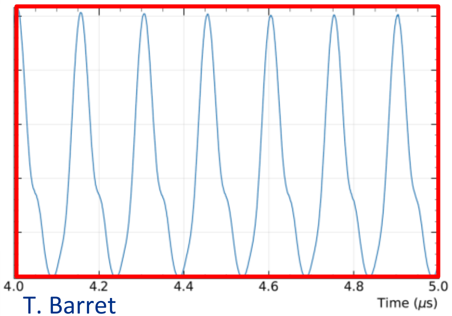
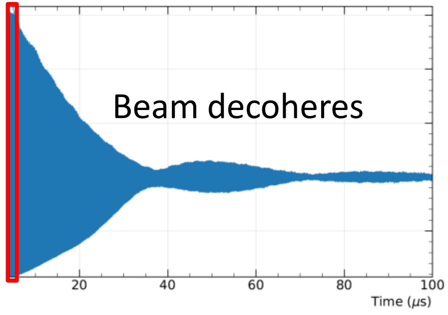
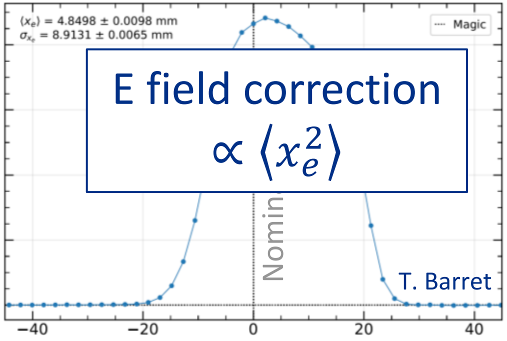
Circulating beam intensity seen by calos → Reconstruct momentum from frequency analysis







E field correction $\propto \langle x_e^2 \rangle$

Equilibrium radius offset x_e [mm], $\propto p$

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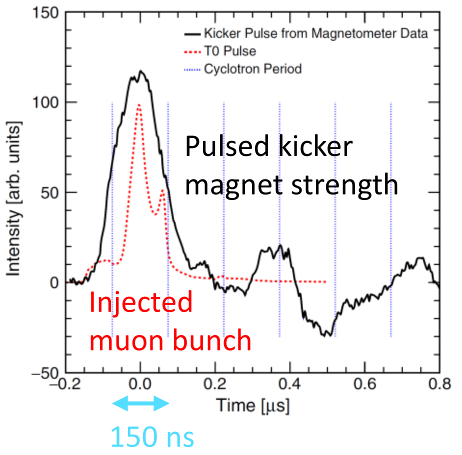
Lingering uncertainty on E field correction

- Injection kicker strength varies over muon injection time → stored momentum is time-dependent; distorts reconstruction



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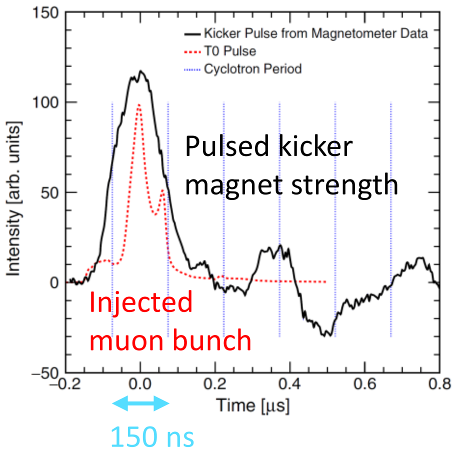
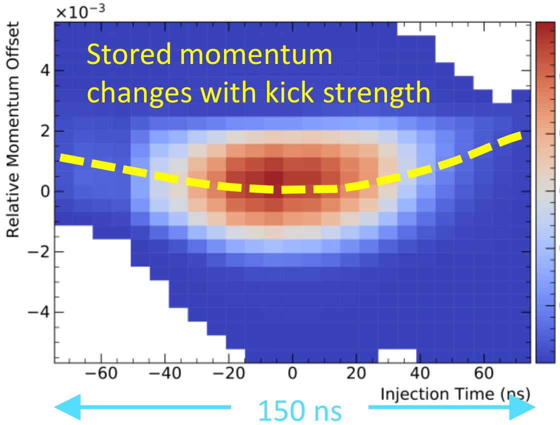
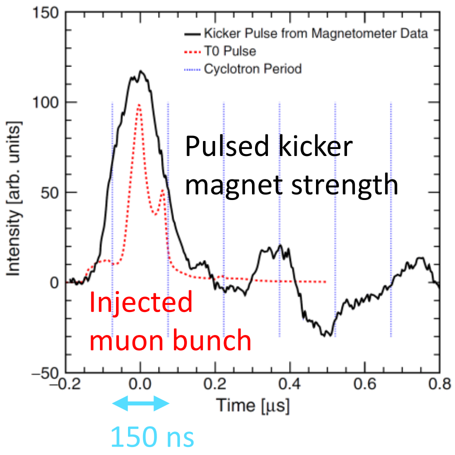


Injection time vs. momentum correlation

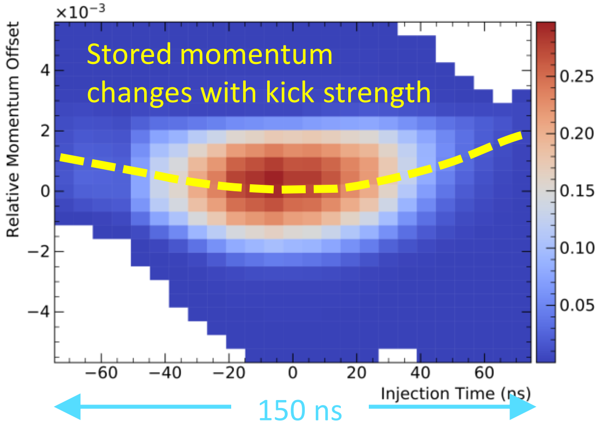


Lingering uncertainty on E field correction

- Injection kicker strength varies over muon injection time → stored momentum is time-dependent; distorts reconstruction
- Still a significant uncertainty in 2023 result (32 ppb out of 70 ppb total systematic)

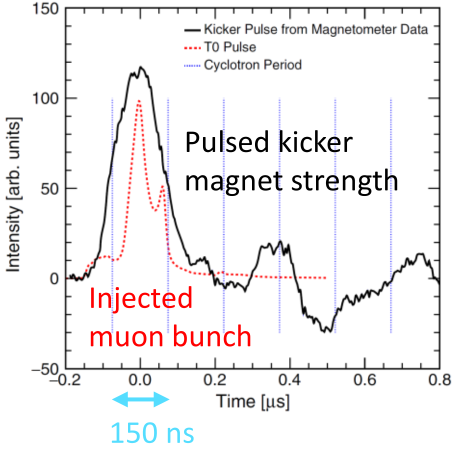


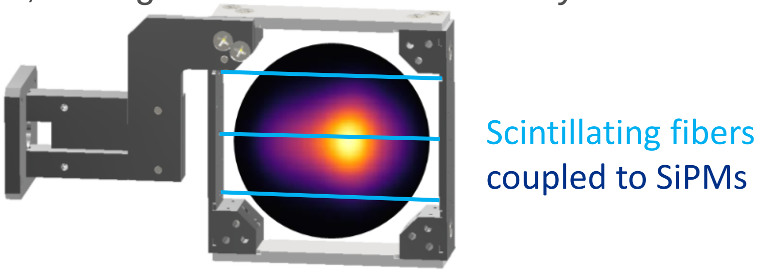
Injection time vs. momentum correlation



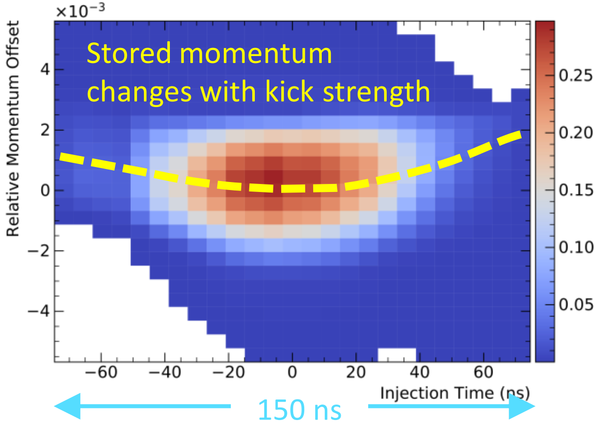
Lingering uncertainty on E field correction

- Injection kicker strength varies over muon injection time → stored momentum is time-dependent; distorts reconstruction
- Still a significant uncertainty in 2023 result (32 ppb out of 70 ppb total systematic)
- Special measurements with new detector in final run to map the correlation
  - Ongoing analysis is helping deepen our understanding of subtle effects, aiming to reduce the uncertainty





Injection time vs. momentum correlation



- Directly sample circulating beam → measure momentum
- Collaborated in development led by C. Claessens

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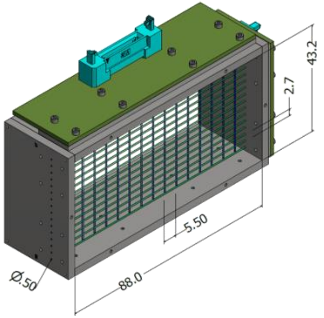
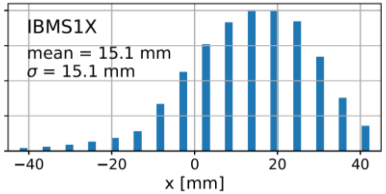
Conclusions

- Characterizing effects from beam dynamics is critical for reaching Muon g-2 precision target of 140 ppb
- My thesis focused on key beam dynamics challenges necessary to achieve this result

Detectors to assist with beam injection





Muon-weighted magnetic field

Field map

Beam profile

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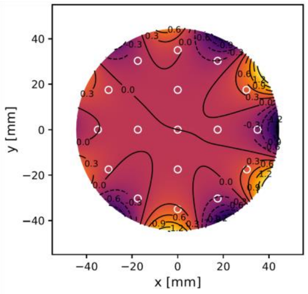

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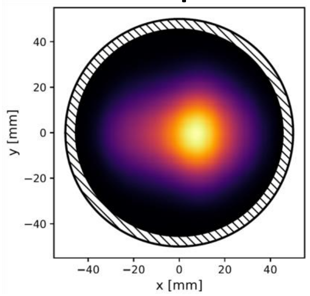

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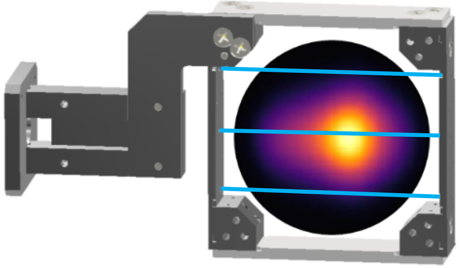
Direct measurement of beam momentum to reduce uncertainty



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Thanks to Muon g-2 members and the URA!