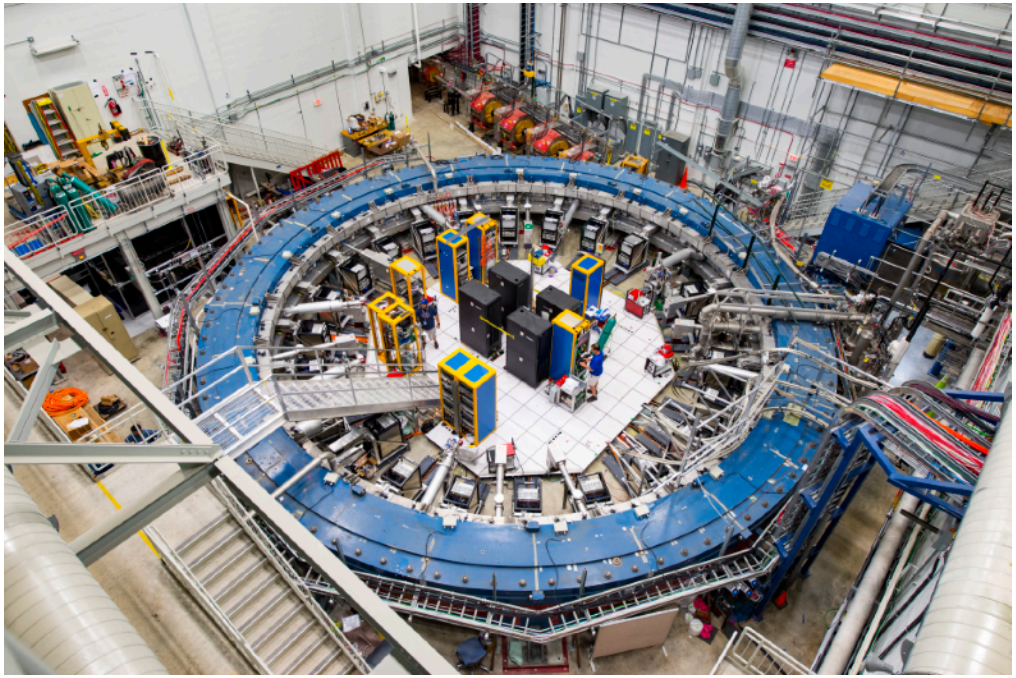
Muon g-2 & EDM at Fermilab



Muon4Future Workshop

Venezia, IT

May 30, 2023

Sean Foster, Boston University

on behalf of the E989 Muon g-2 Collaboration

Muon magnetic moment & g-factor

- Muon's have an intrinsic magnetic moment due to their spin

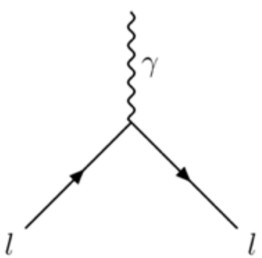
$$\vec{\mu} = g\frac{e}{2m}\vec{s}$$

- "g-factor" quantifies the strength of the magnetic moment
- Measure & predict g to test Standard Model & search for new physics

Anomalous magnetic moment

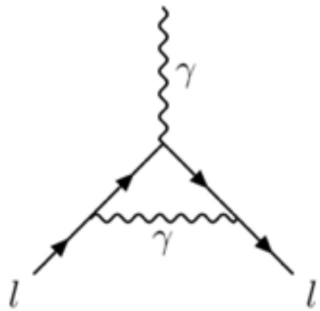
- The Dirac theory predicts $g = 2$
- Loop corrections cause g to deviate from 2
- Define the magnetic anomaly

$$a_\mu = \frac{g-2}{2}$$



Tree level:

$$g = 2$$



First QED term:

$$g = 2 + \frac{\alpha}{\pi}$$ (0.1% correction)

All other physics can contribute here!

$$g = 2 + \frac{\alpha}{\pi} + \ldots$$

- **Measure & predict a_μ to test Standard Model & search for new physics**

Muon electric dipole moment

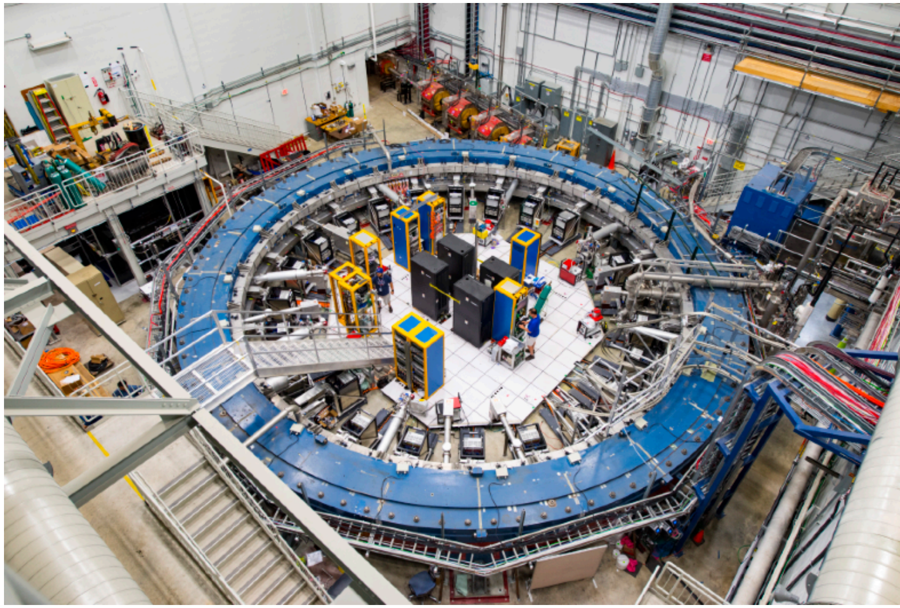
- Electric dipole moment of the muon has not been observed
- Strongest limit set by BNL Muon g-2 experiment

  $< 1.8 \times 10^{-19} e$ cm (95% C.L.)

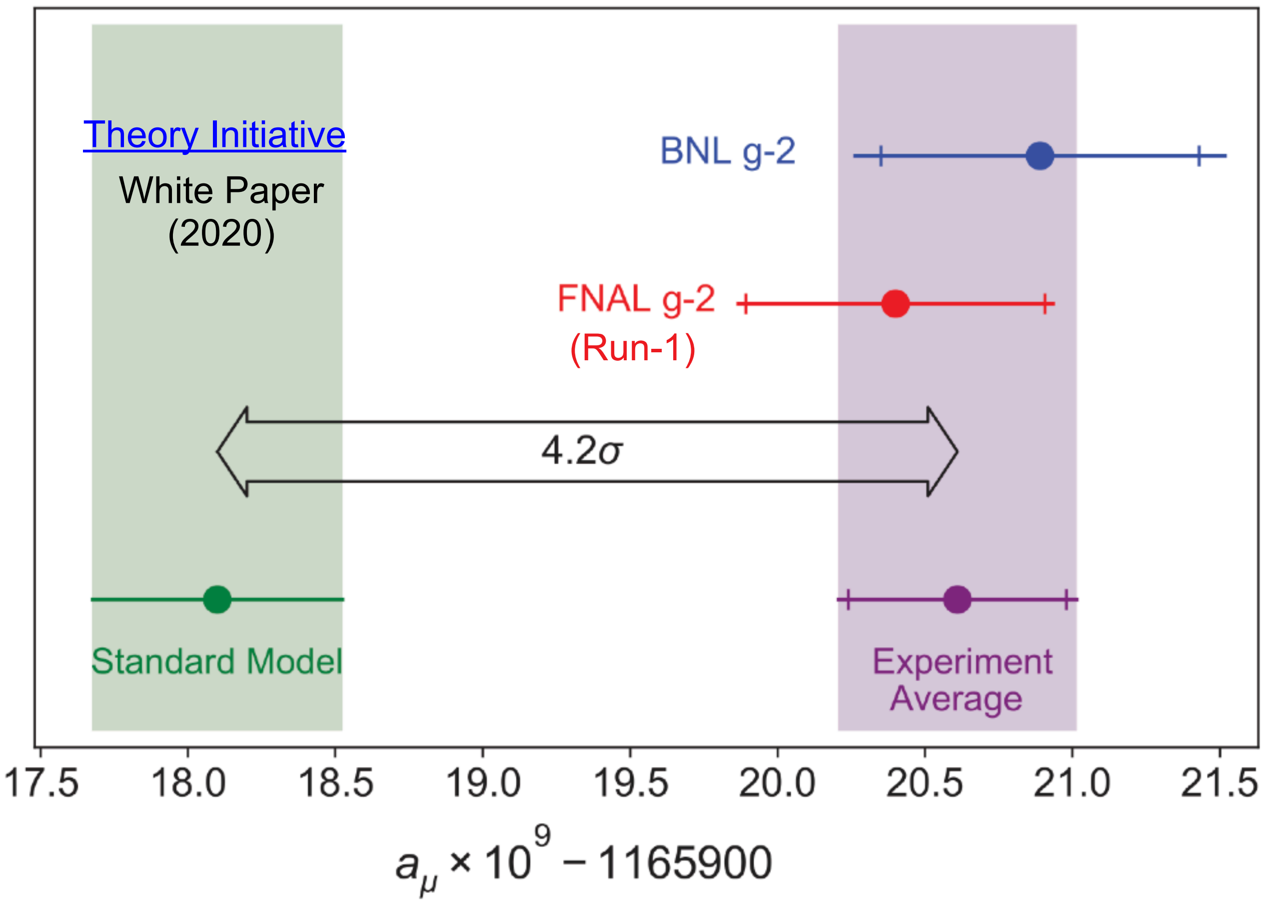
$$\overrightarrow{d} = \eta \frac{q}{2m} \vec{s}$$

- EDM violates parity (P) & time-reversal (T)
  - Assuming CPT invariance, EDM violates CP
- Standard model value *many* orders of magnitude below limit
- **Observation of a nonzero EDM = evidence of new physics**

E989 Muon g-2 Experiment at Fermilab



Fermilab Run-1 g-2 result



Brookhaven National Lab measurement (2005): 540 ppb, 3.7σ tension with SM

Fermilab measurement (2021): 460 ppb, 3.3σ tension with SM

Theory Initiative (2020): 369 ppb

Experiment average : 350 ppb, 4.2σ tension with SM

- Fermilab result consistent with previous measurement at BNL
- Experimental average 4.2σ tension with Standard Model; a hint of new physics?

Standard model prediction of a_μ

$$a_\mu^{\mathrm{SM}} \times 10^{11} = (a_\mu^{\mathrm{QED}} + a_\mu^{\mathrm{EW}} + a_\mu^{\mathrm{Had}}) \times 10^{11}$$

	116584718.931 ± 0.104	**Quantum electrodynamics (QED)** ▸ 99.994% of total, 0.89 ppb uncertainty
+	153.6 ± 1.0	**Electroweak (EW)** ▸ 1317 ppb of total, 9 ppb uncertainty
+	6845 ± 40	**Hadronic vacuum polarization (HVP)** ▸ 58709 ppb of total, 343 ppb uncertainty
+	92 ± 18	**Hadronic light-by-light (HLbL)** ▸ 789 ppb of total, 154 ppb uncertainty
=	116591810 ± 43	**Total Standard Model prediction**
	369 ppb prediction	Theory Initiative (2020)

Theory status

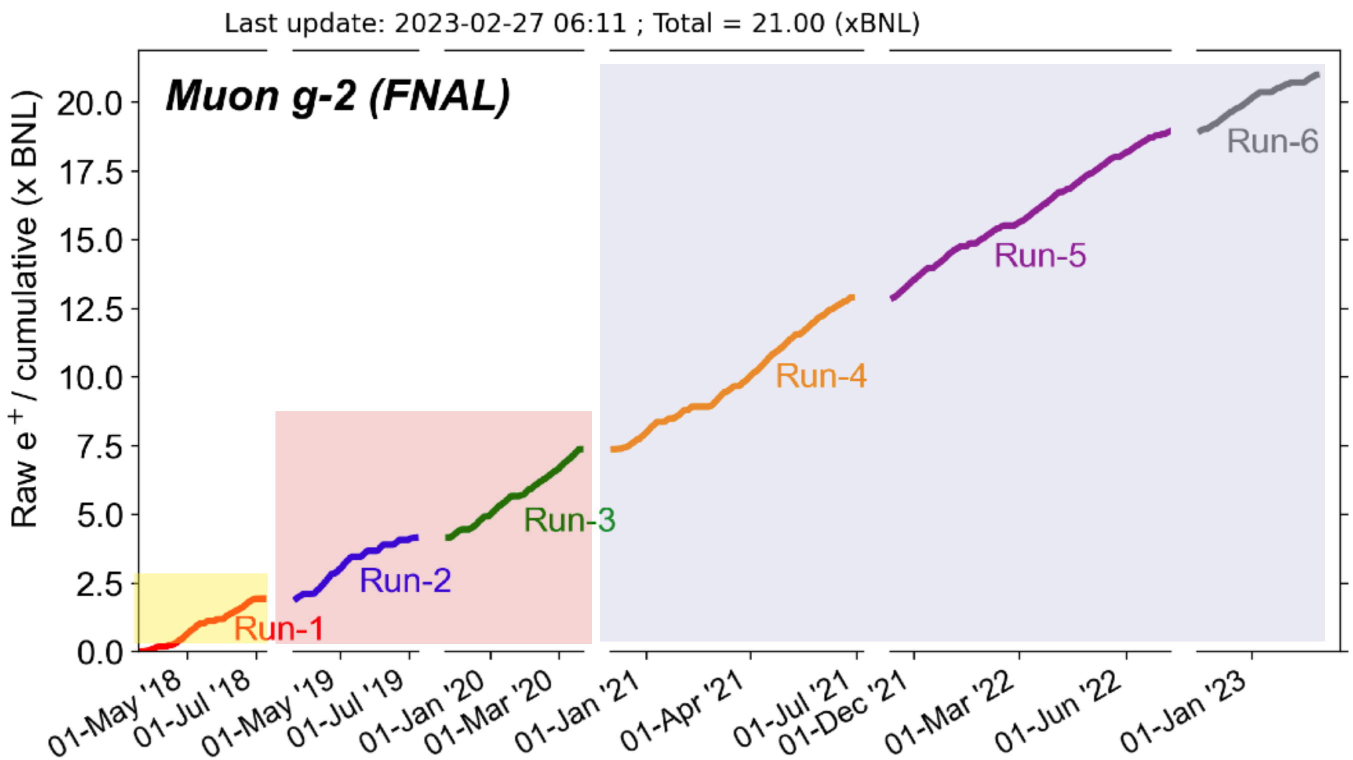
- We just heard an overview

Theory overview of muon g-2 and EDM	*Paride Paradisi*
Palazzo Franchetti, Venezia, Istituto Veneto di Lettere, Scienze ed Arti - Palazzo Franchetti	11:30 - 12:00

- Lots of effort to understand discrepancy in HVP contribution between **R-Ratio** and **Lattice QCD** approaches
  - See afternoon session today!

Hadronic Vacuum Polarization dispersive and data-driven methods	*Gilberto Colangelo*
Palazzo Franchetti, Venezia, Istituto Veneto di Lettere, Scienze ed Arti - Palazzo Franchetti	14:30 - 15:00
Hadronic Vacuum Polarization on lattice	*Zoltan Fodor*
Palazzo Franchetti, Venezia, Istituto Veneto di Lettere, Scienze ed Arti - Palazzo Franchetti	15:00 - 15:30
The MuonE experiment	*Dinko Pocanic*
Palazzo Franchetti, Venezia, Istituto Veneto di Lettere, Scienze ed Arti - Palazzo Franchetti	15:30 - 16:00
R-ratio measurements	*Riccardo Aliberti*
Palazzo Franchetti, Venezia, Istituto Veneto di Lettere, Scienze ed Arti - Palazzo Franchetti	16:00 - 16:30
Discussion	
Palazzo Franchetti, Venezia, Istituto Veneto di Lettere, Scienze ed Arti - Palazzo Franchetti	16:30 - 17:00

Muon g-2 at Fermilab: status



- Run-1: 6% of target statistics (460 ppb) **TDR goal: 140 ppb**
- Runs 2 & 3: x4 statistics compared to Run-1 **Analysis nearly done**
- Runs 4, 5, 6: reached statistics goal **x21 BNL** on Feb. 27, 2023!

Muon g-2 measurement technique

- In a magnetic field,
  - **Momentum** vectors rotates at cyclotron frequency
  - **Spin** vector precess due to Larmor +Thomas precession

Momentum

$$\vec{\omega}_c = -\frac{e\vec{B}}{\gamma m}$$

Spin

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

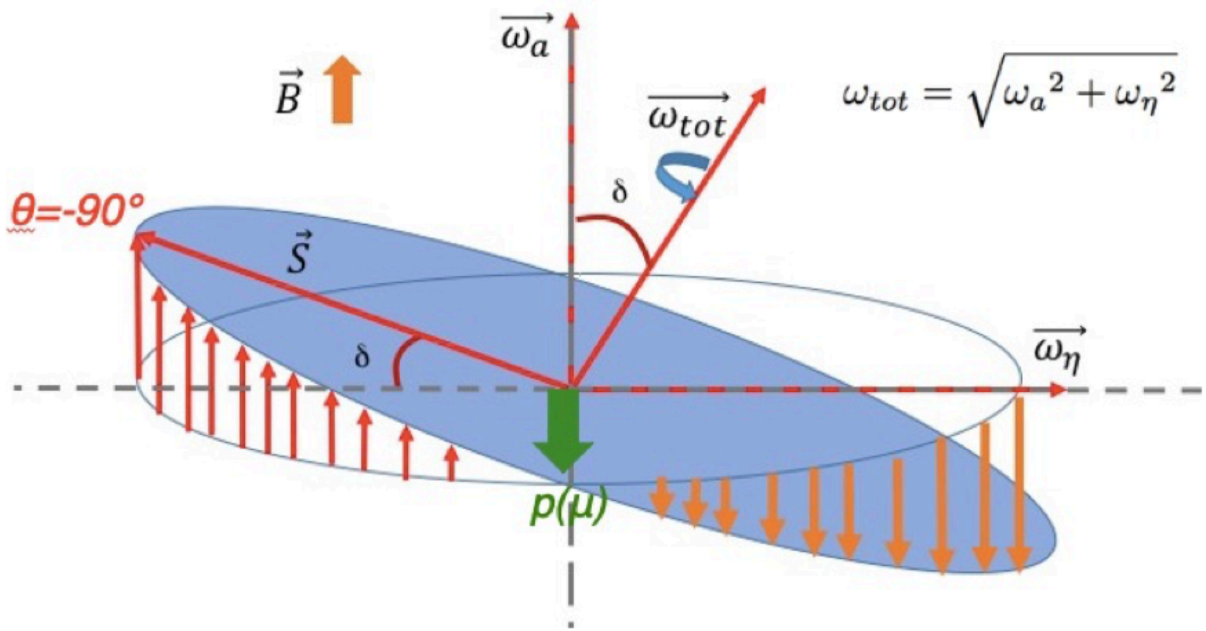
- *Spin difference* frequency is proportional to a_μ:

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

anomalous magnetic anomaly

- **Place muon in a magnetic field and measure anomalous spin precession**

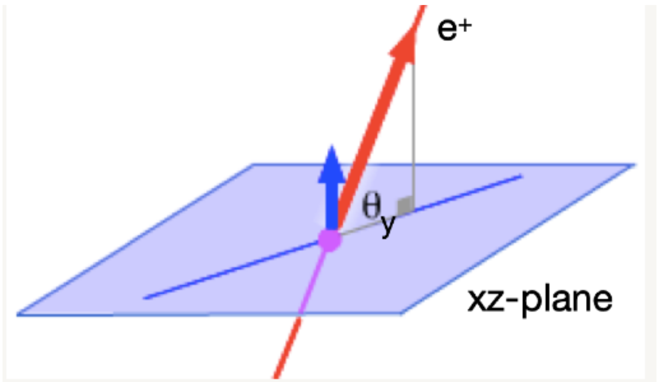
Effect of an EDM & search strategy



- EDM *tilts* muon spin polarization plane
- Maximum tilt occurs at $\phi_a = \pm 90°$
- **Search for EDM by looking for a nonzero average tilt**

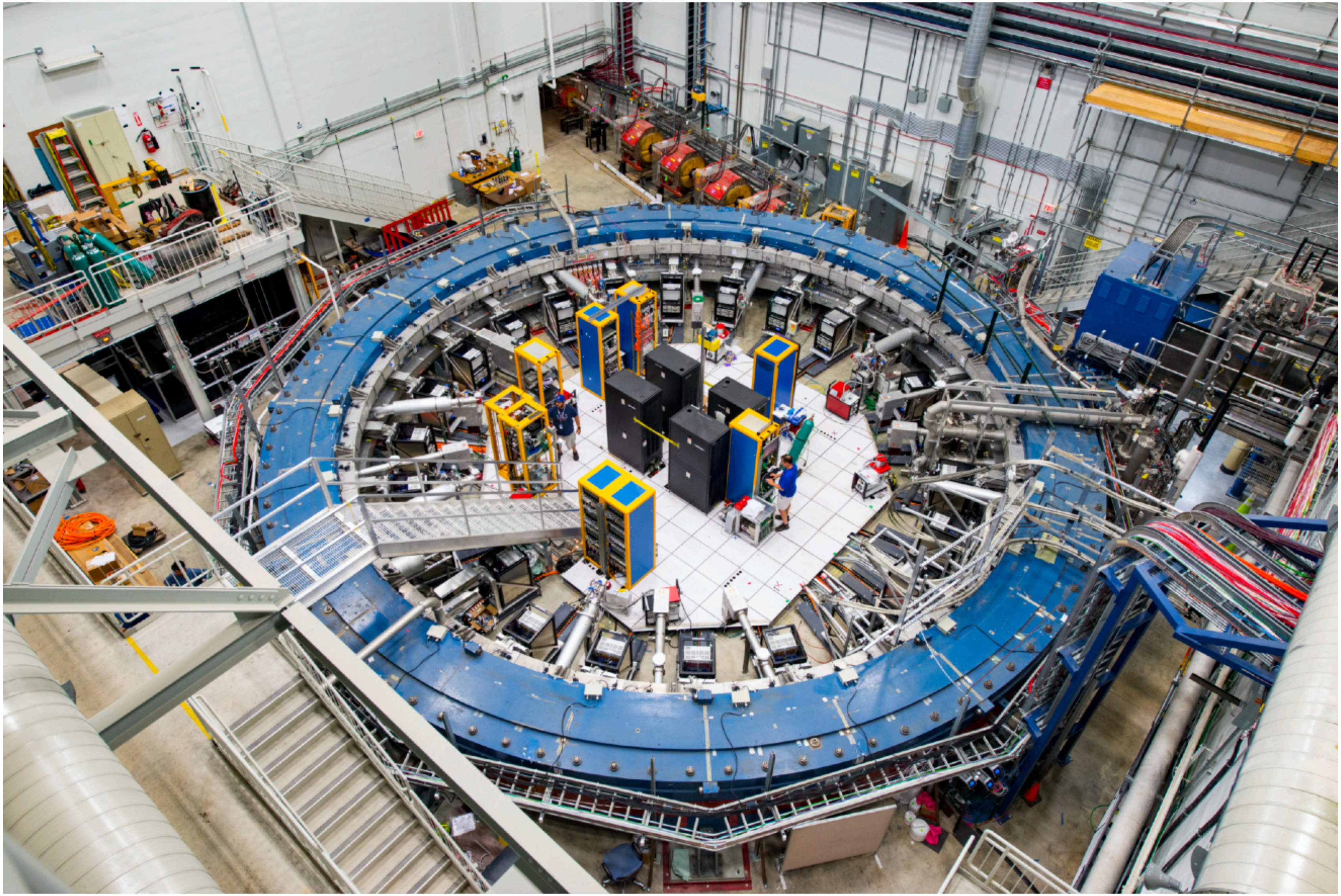
Muon EDM search at Fermilab: status

- Run-1 *tracker-based* analysis nearing completion
  - Directly measure *average vertical decay angle*
  - Limit will be comparable to BNL
  - Analysis is *statistics-limited* (~100M tracks)
- Run 2 & 3 analysis underway
  - 4x more data
  - Improved tracking efficiency (better than x4 scaling

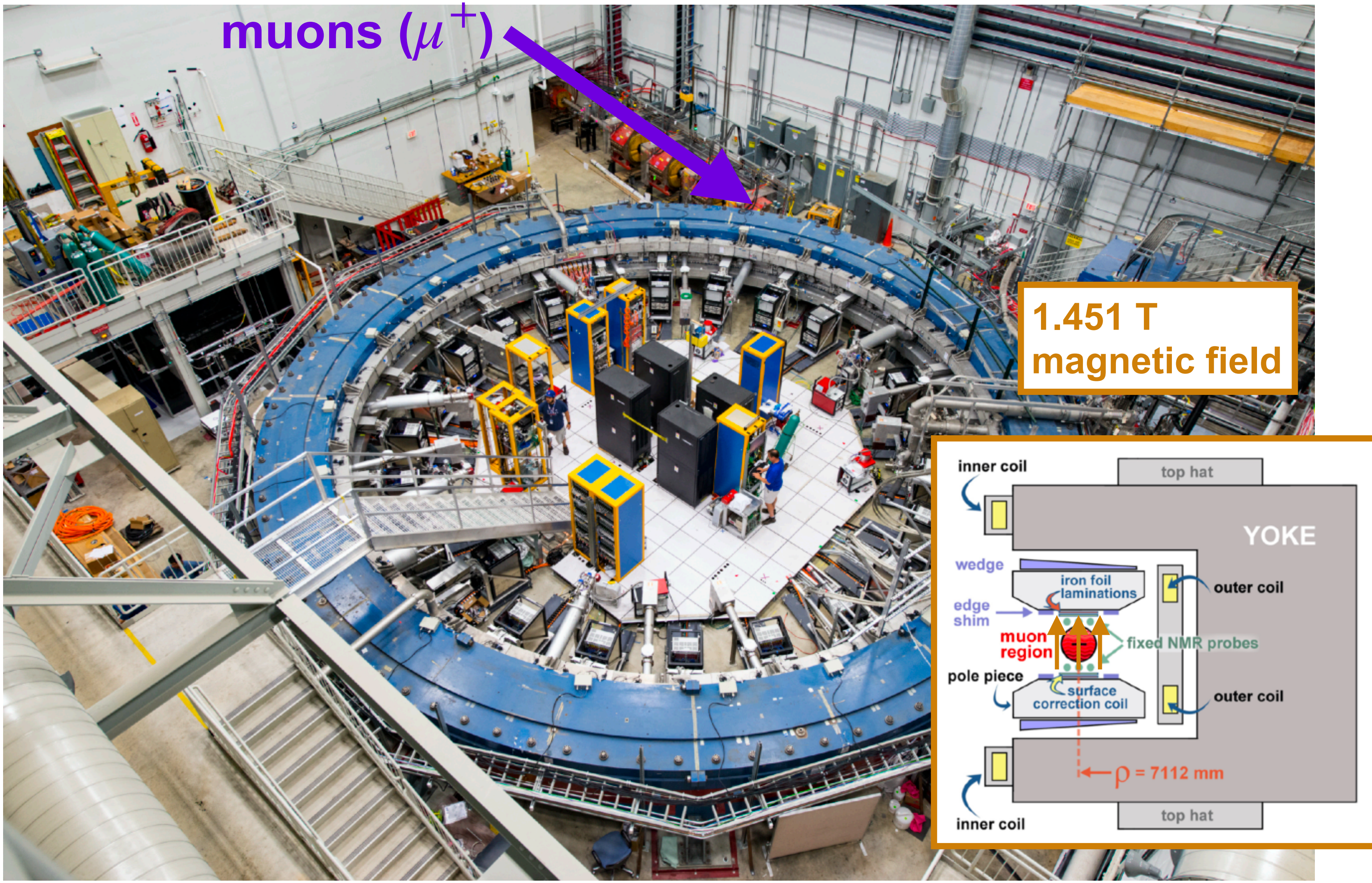


- After runs 4, 5, & 6: sensitive to $d_\mu \sim 1 \times 10^{-20} e \cdot \mathrm{cm}$
- Also a *calorimeter-based* approach (not undertaken in Run-1 due to broken quadruple resistors)

Storage ring at Fermilab



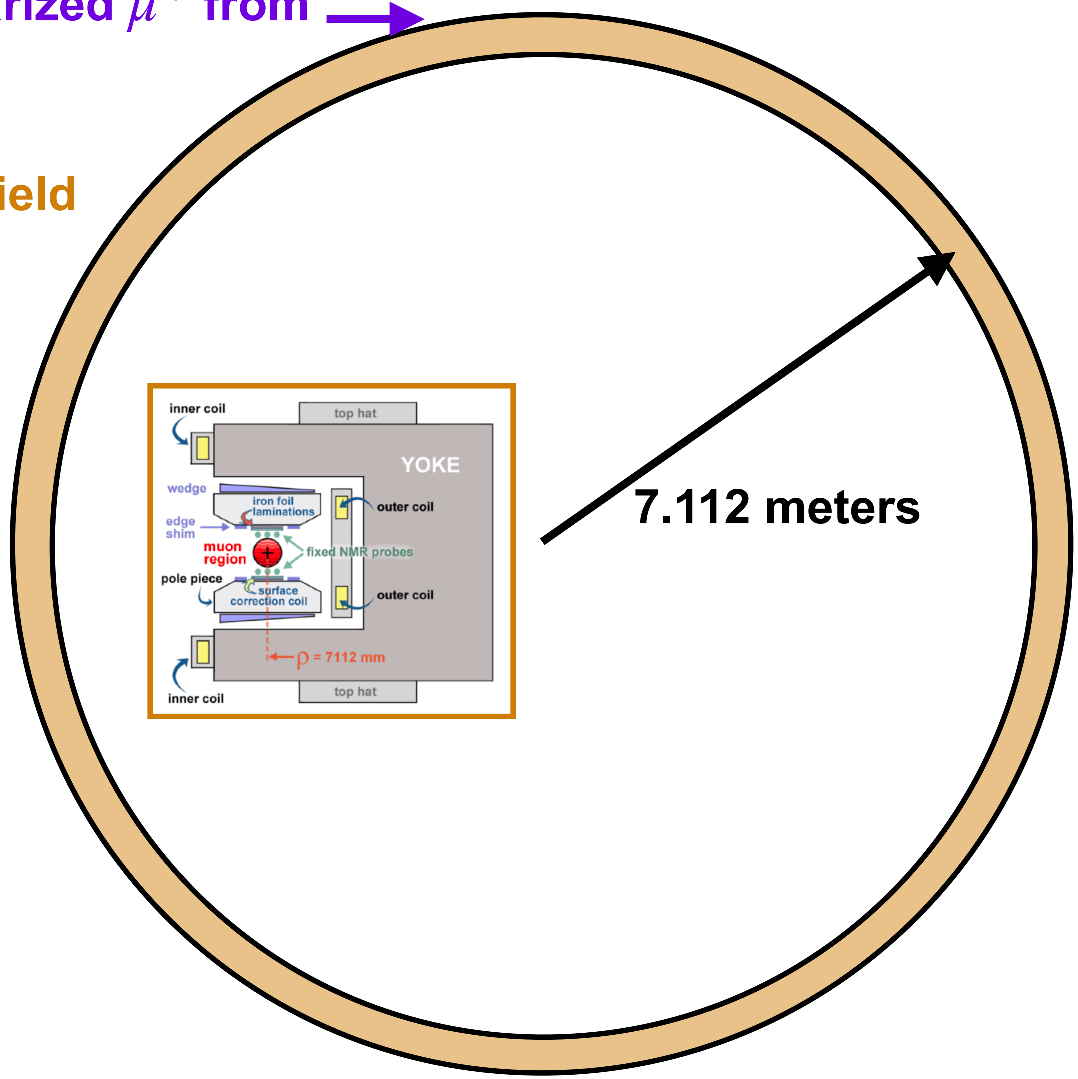
Storage ring



Polarized beam & storage ring magnet

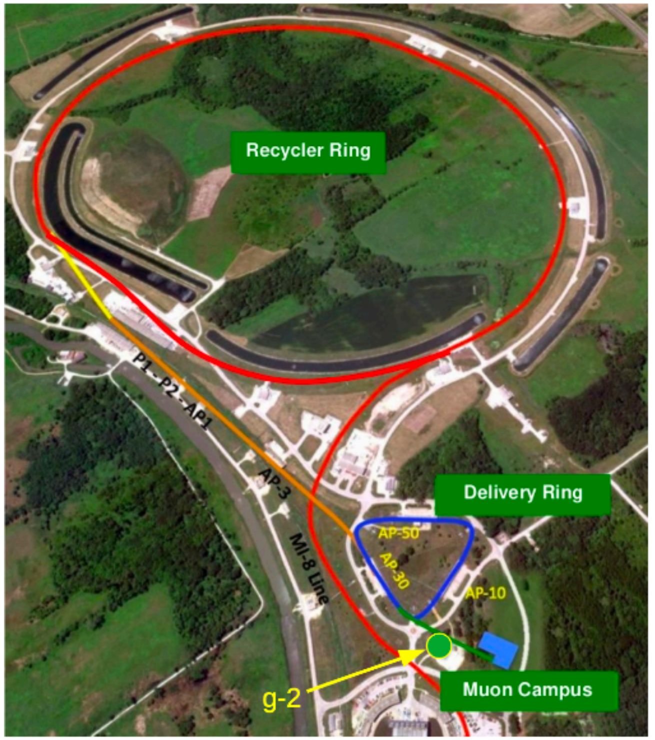
3.094 GeV polarized μ^+ from pion decay

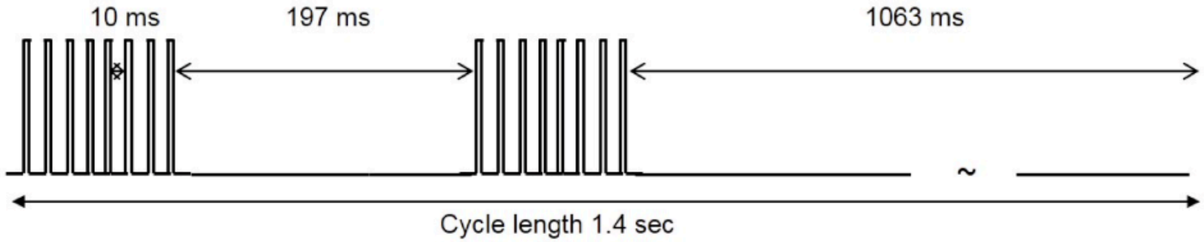
1.451 T magnetic field



Muon production

- Protons accelerated to 8 GeV
- Form 16 proton bunches,120 ns long
- 10^{12} protons per bunch
- Pion production via fixed target
- Pion decay produces polarized μ^+ (~95%)
- ~10,000 stored muons per bunch

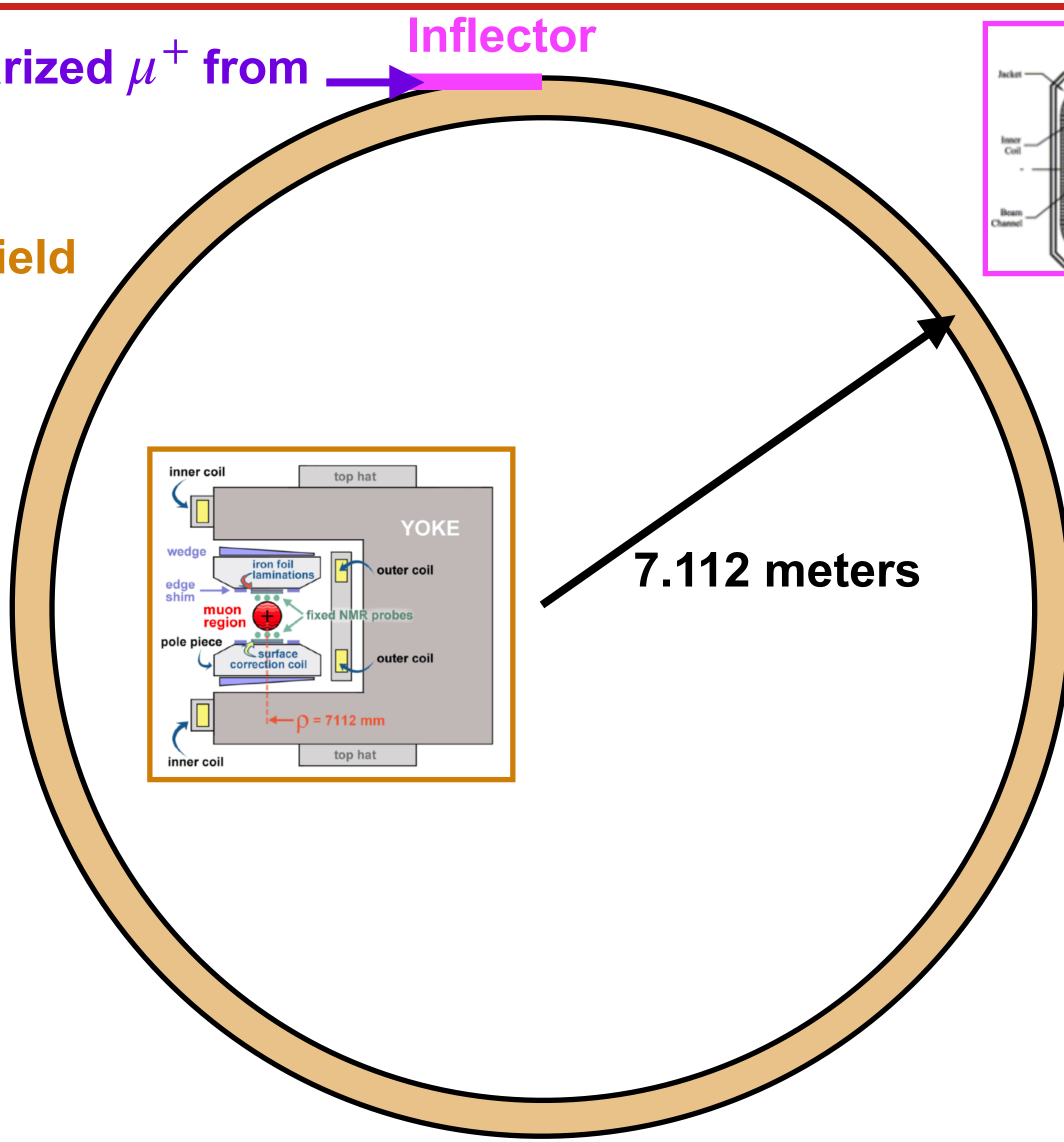


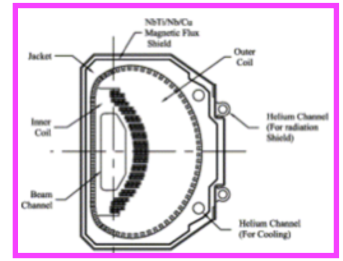


Muon injection: inflector

3.094 GeV polarized μ^+ from pion decay

1.451 T magnetic field

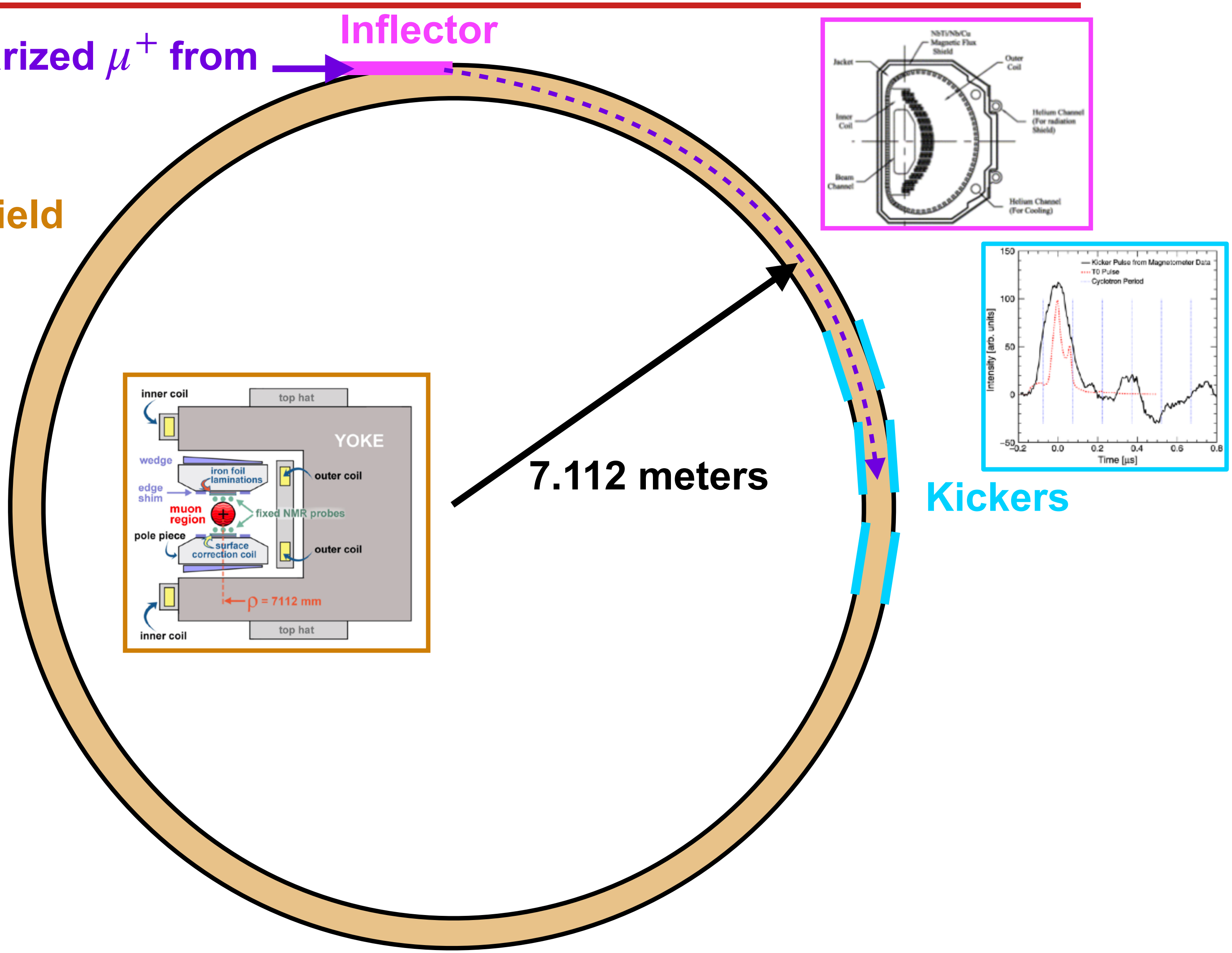




Muon storage: kickers

3.094 GeV polarized μ^+ from pion decay

1.451 T magnetic field



Muon storage: kickers

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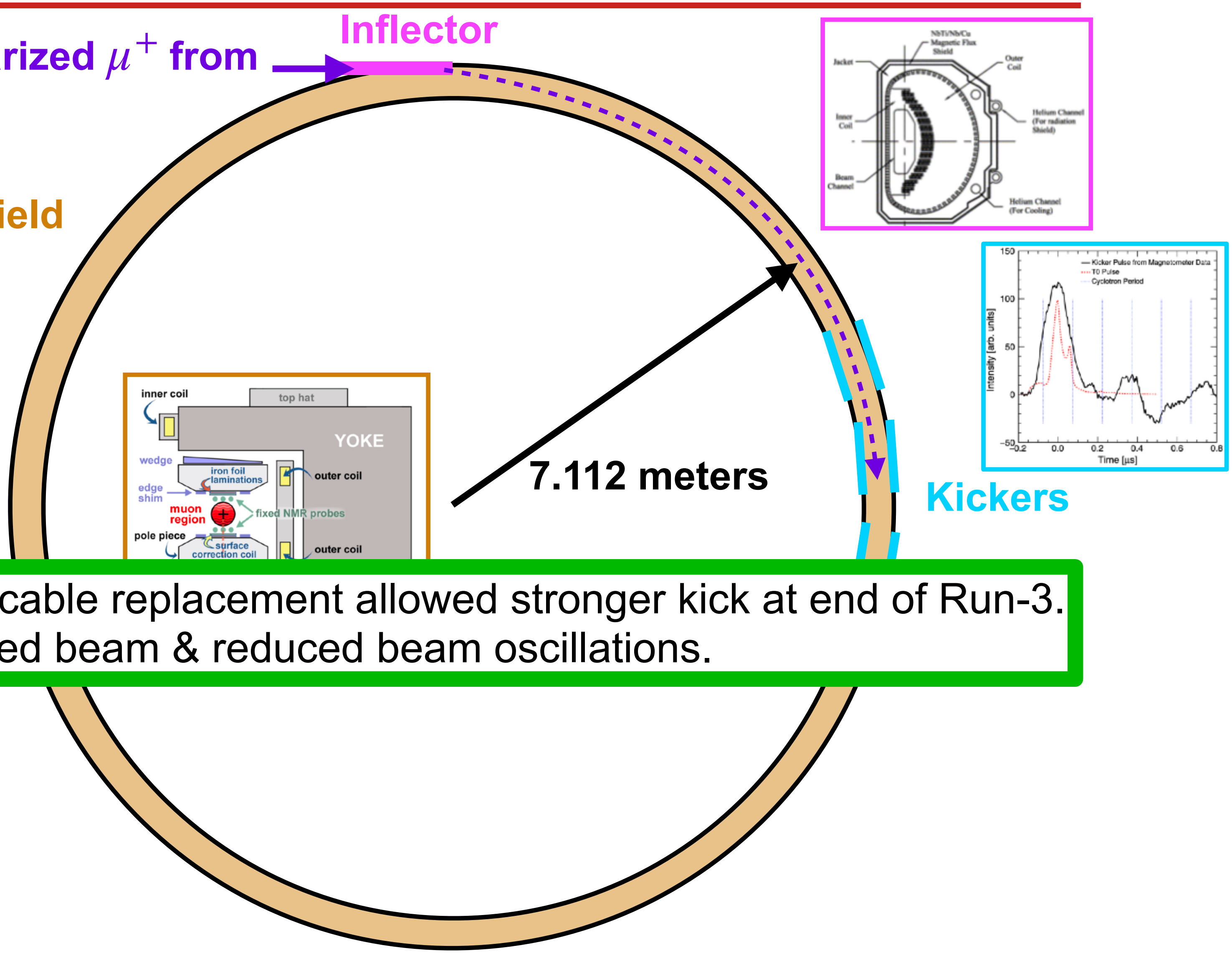
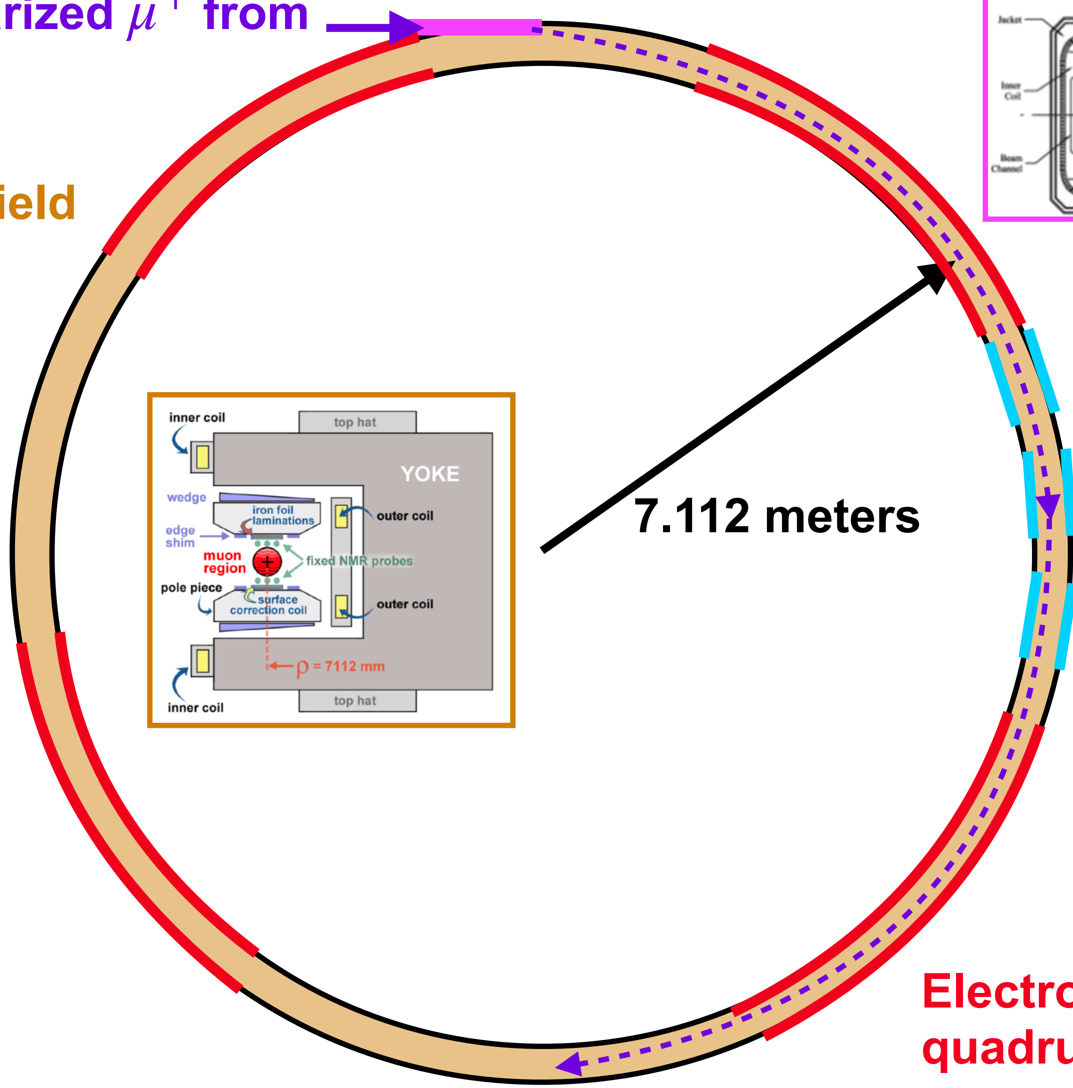


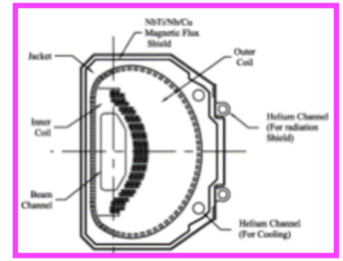
Kicker cable replacement allowed stronger kick at end of Run-3.
Centered beam & reduced beam oscillations.

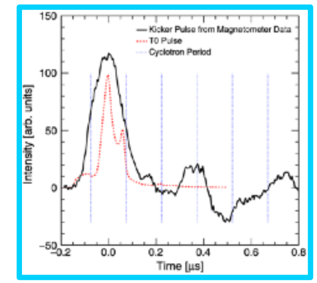
Muon storage: electrostatic quadrupoles

3.094 GeV polarized μ^+ from pion decay

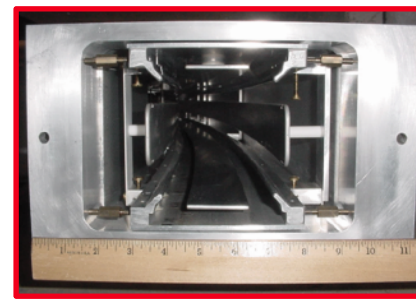
1.451 T magnetic field







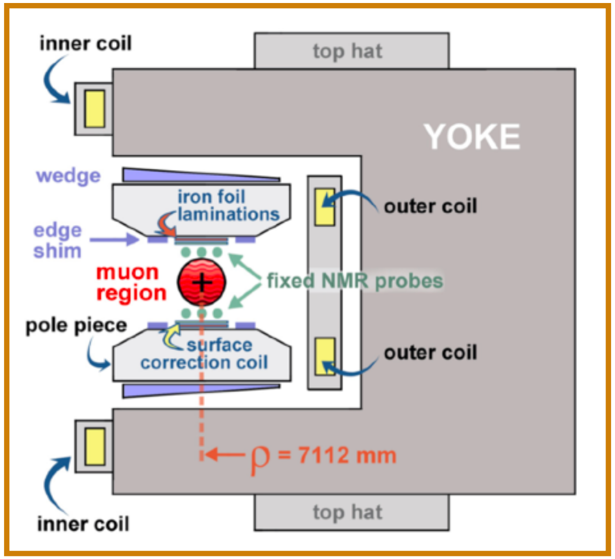
Kickers

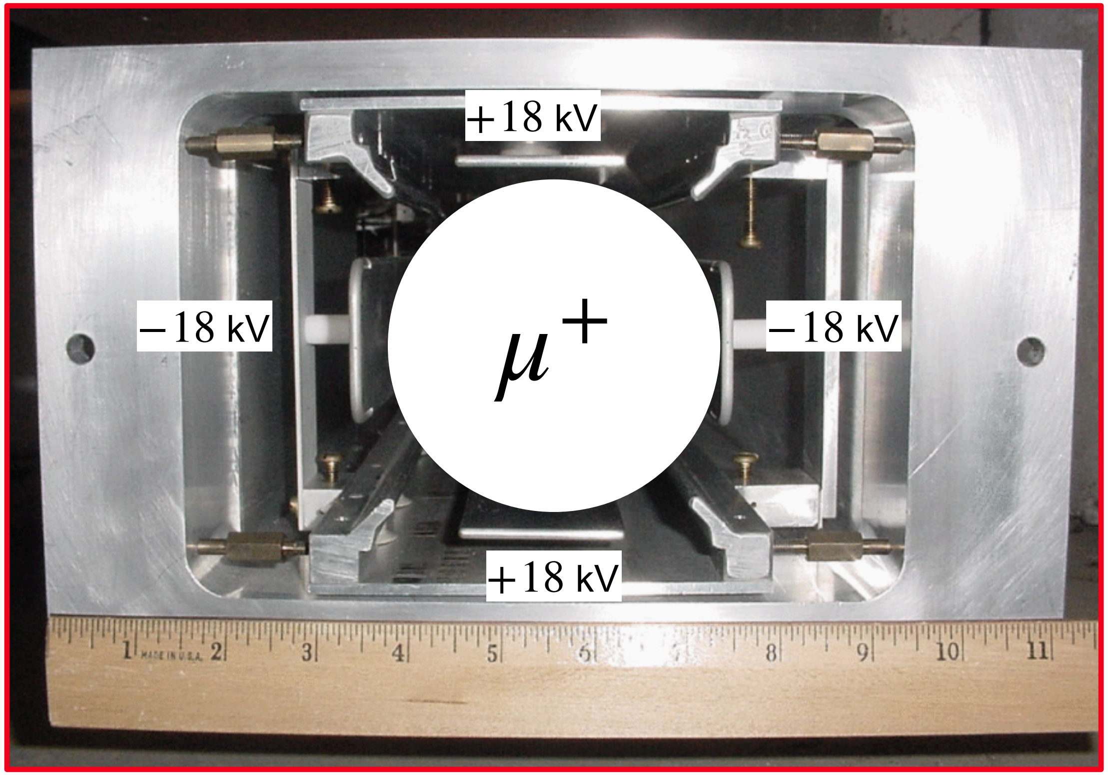


Electrostatic quadrupoles

Beam focusing

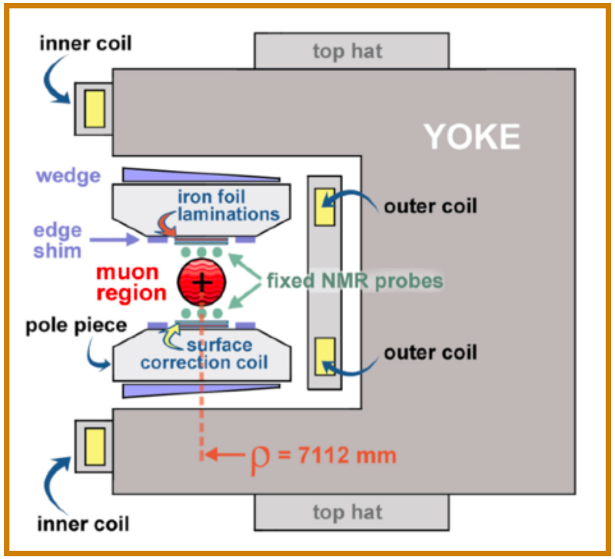
- Radial focusing: main 1.451 T magnetic field
- Vertical focusing: electrostatic quadrupoles

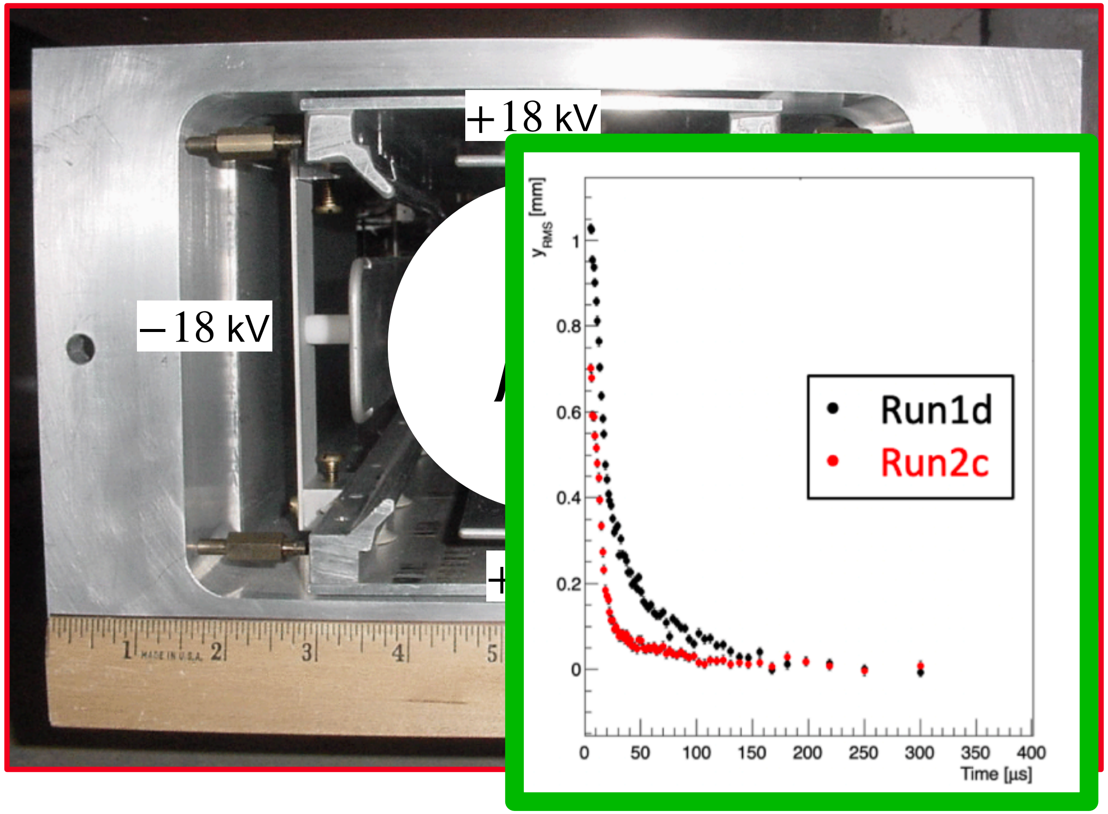




Beam focusing

- Radial focusing: main 1.451 T magnetic field
- Vertical foc Broken resistors in Run-1 fixed; no slow beam drift



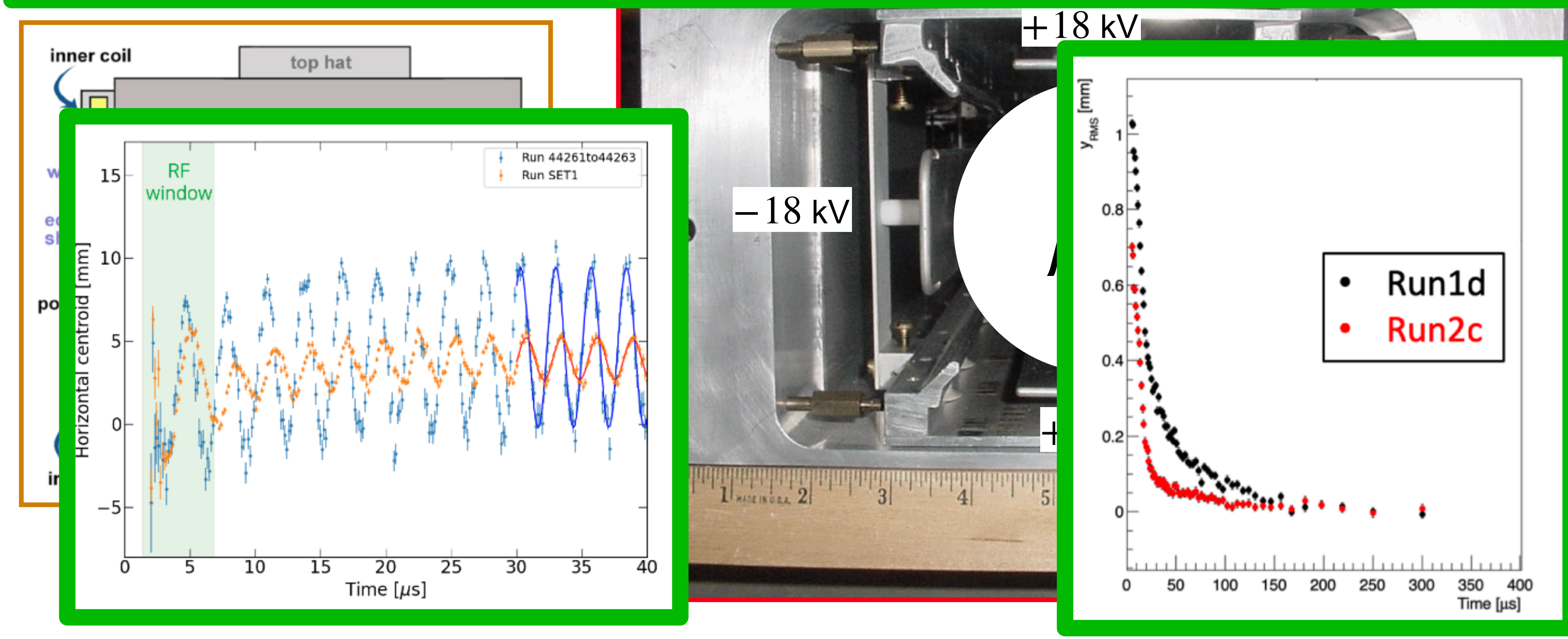


Beam focusing

- Radial focusing: main 1.451 T magnetic field
- Vertical foc

Broken resistors in Run-1 fixed; no slow beam drift

For Run-5, RF pulse applied to quadrupoles to dampen radial beam oscillation



Full spin dynamics with $\vec{E}$ and $\vec{B}$

- Full equation for ω_a with electric & magnetic fields

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

- First term: signal we are trying to measure!
- Second term: contributions from vertical motion: the *pitch correction*
- Third term: contribution due to electrostatic quadrupoles
  - Can be set to 0! $\gamma_0 = \sqrt{\frac{1}{a_\mu}+1} = 29.3 \implies p_0 = 3.094$ GeV/c
  - p_0 is called the "magic" momentum
  - For non-"magic" muons: *electric field correction*

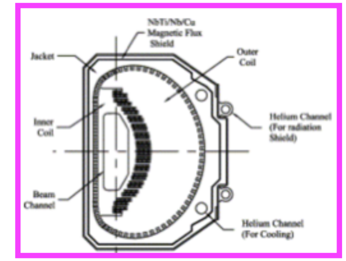
Muon decay produces e^+

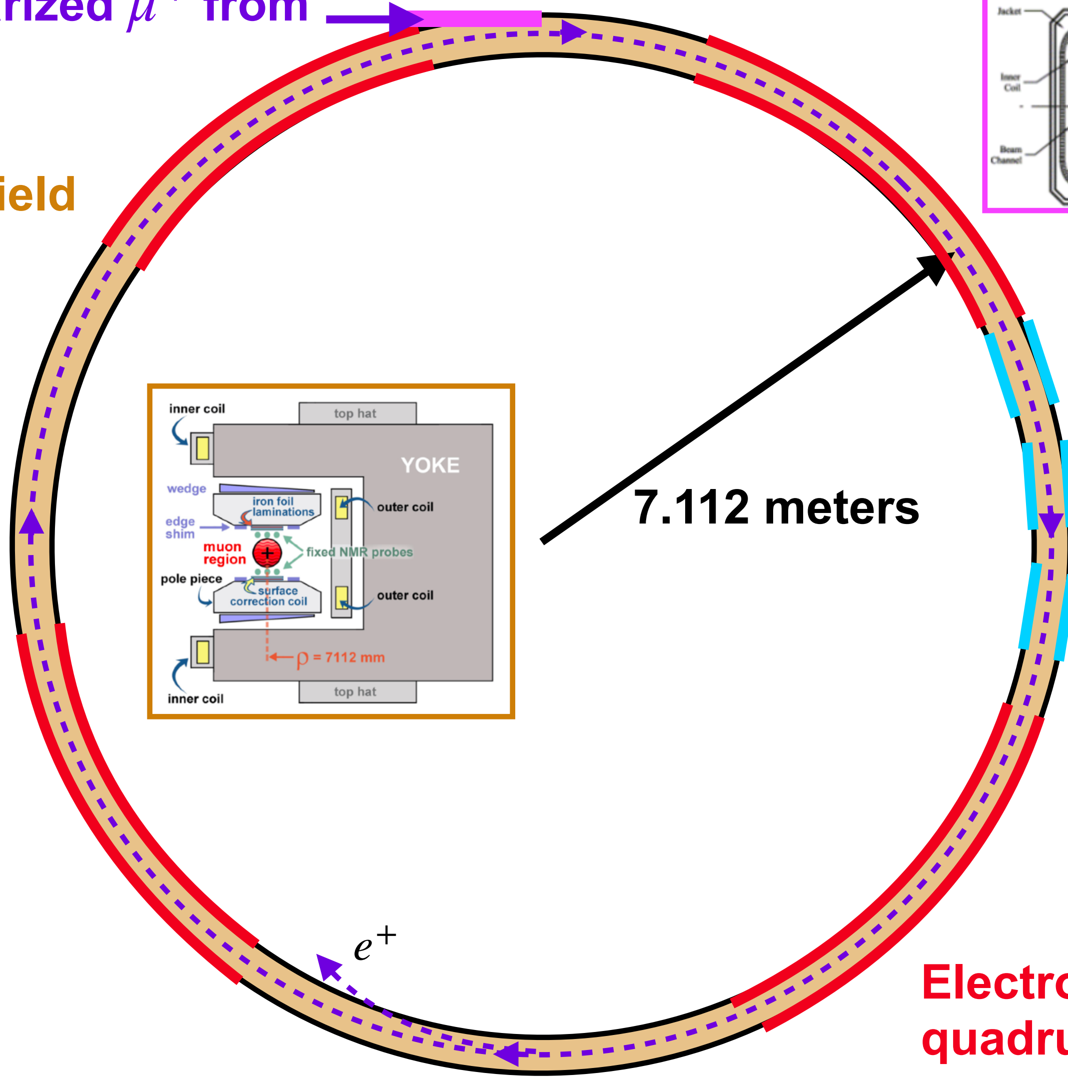
$$\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$$

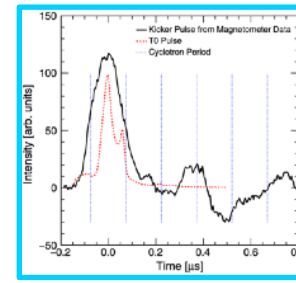
3.094 GeV polarized μ^+ from pion decay

1.451 T magnetic field

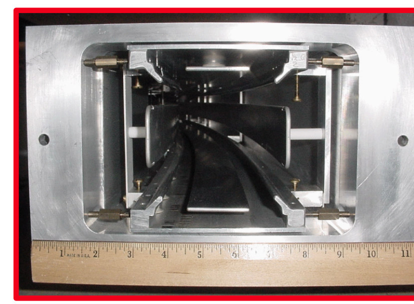
Inflector







Kickers

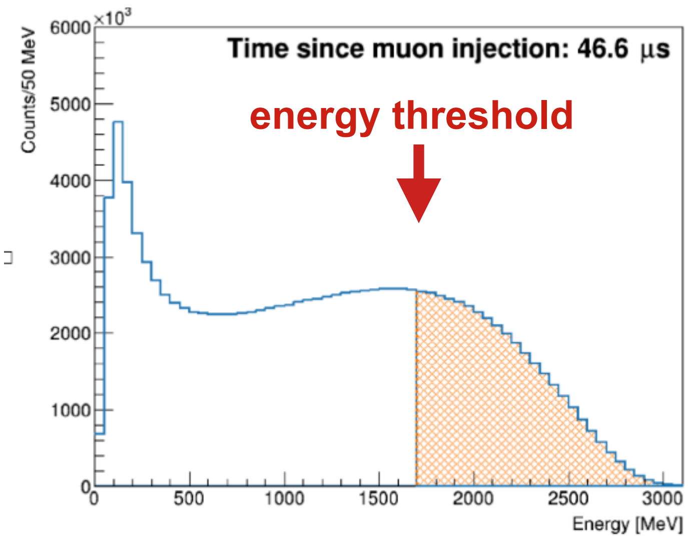


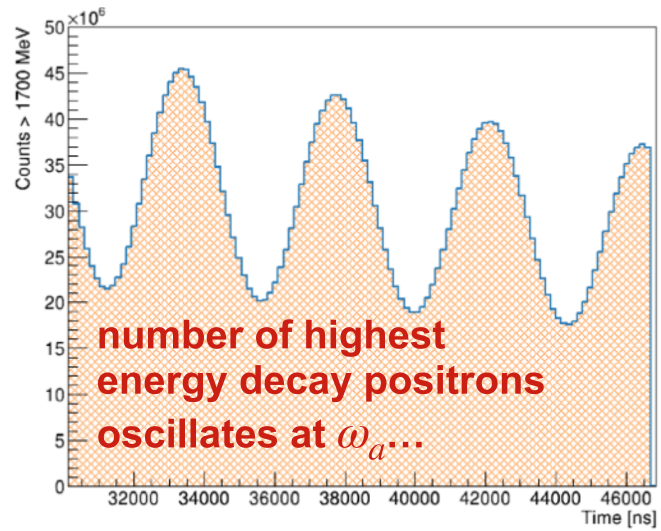
Electrostatic quadrupoles

Muon decay

$$\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$$

- Muon decay violates *parity:* correlates **highest energy decay positron momentum direction** and the **muon spin direction**
- In the lab frame: decay positron energy spectra modulated by ω_a



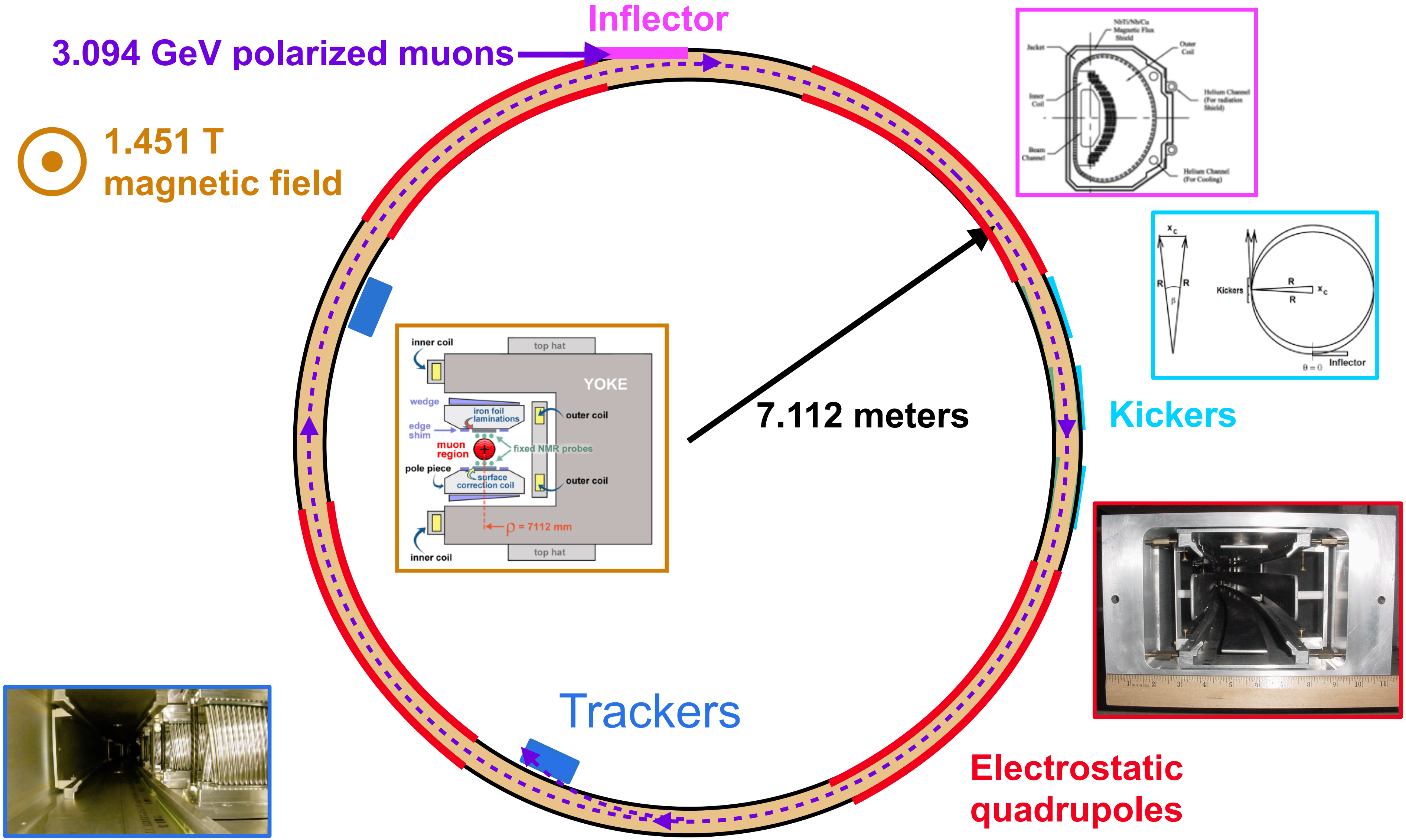


Spin
Momentum

…as muon spin rotates relative to momentum

Data from Run-3a

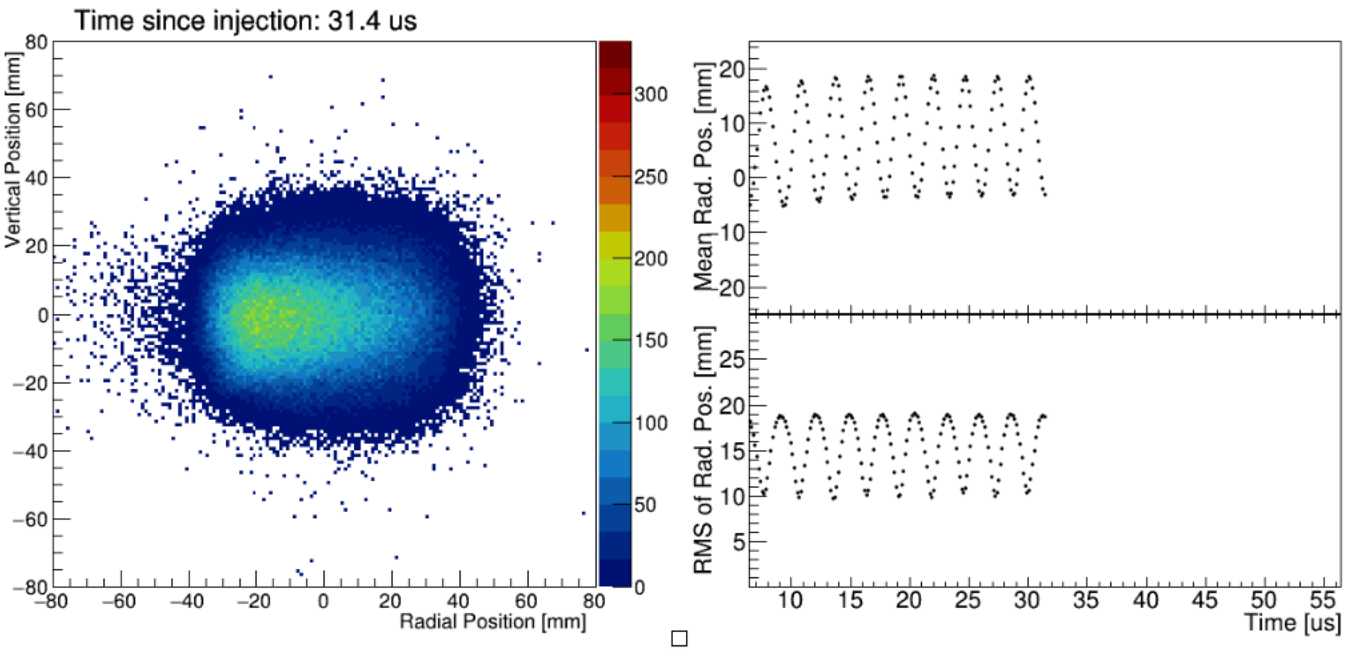
Trackers

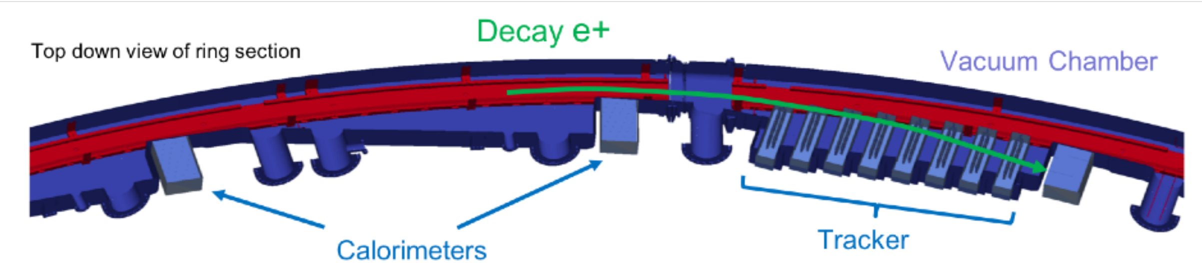


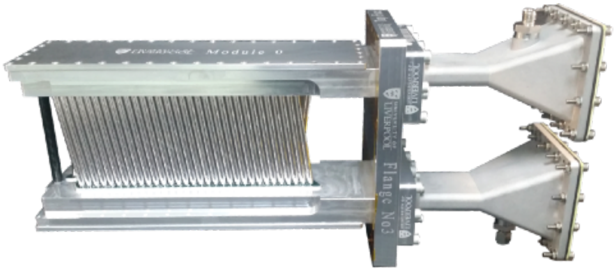
Inflector
3.094 GeV polarized muons
1.451 T
magnetic field
7.112 meters
Kickers
Trackers
Electrostatic
quadrupoles
inner coil
top hat
YOKE
wedge
iron foil
laminations
outer coil
edge
shim
muon
region
fixed NMR probes
pole piece
surface
correction coil
outer coil
ρ = 7112 mm
top hat
inner coil
Kickers
Inflector
θ = 0

Trackers measure beam distribution

- Beam position vs. time determined with 2 straw tracking detectors





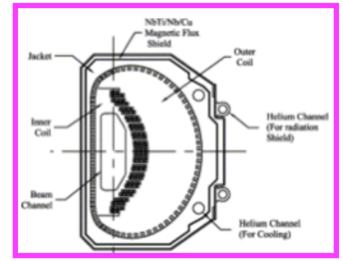


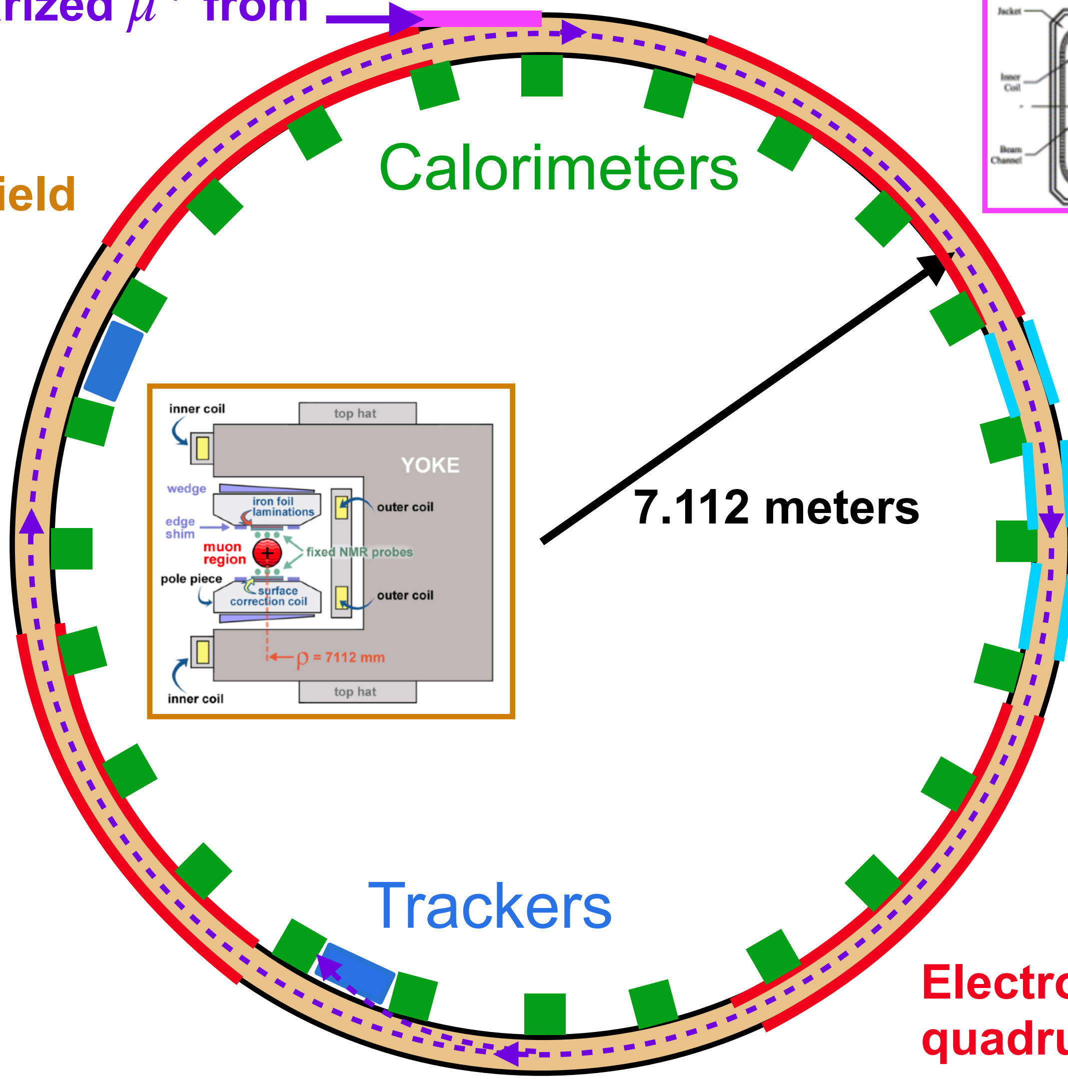
Calorimeters

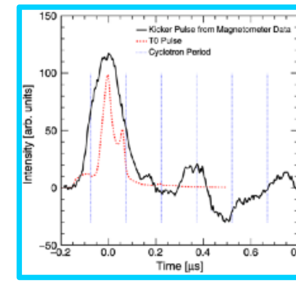
3.094 GeV polarized μ^+ from pion decay

1.451 T magnetic field

Inflector







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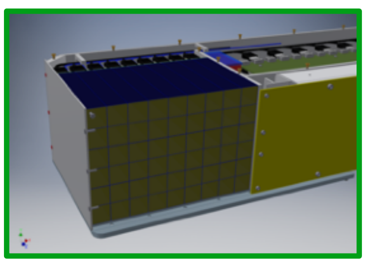
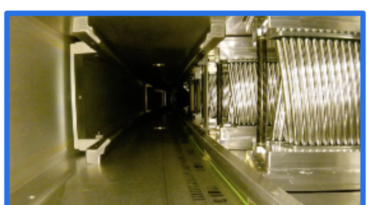
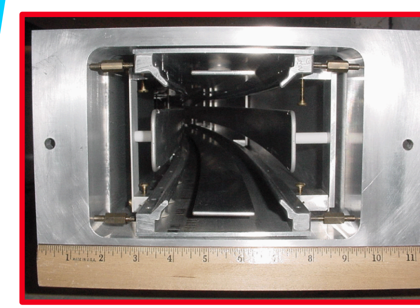


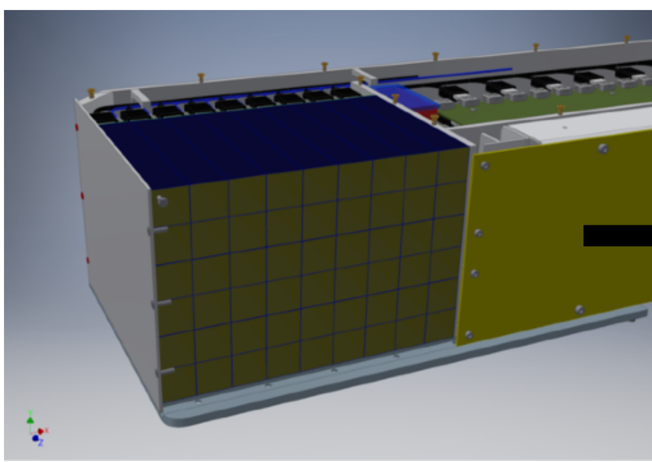


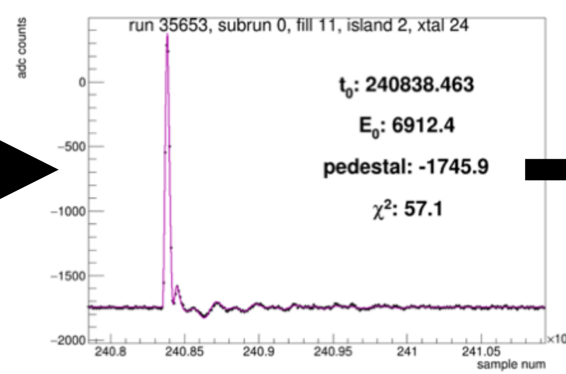


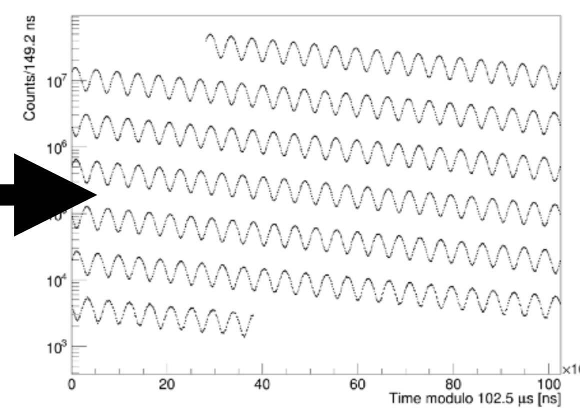
Electrostatic quadrupoles

Calorimeters measure decay positron energies

- 24 electromagnetic calorimeters, each a 6x9 grid of PbF_2 crystals
- Cherenkov light produced by positrons & collected by SiPMs
- Signal is digitized and fit with empirical template functions
- Laser calibration system for gain stability
- Positrons are placed in wiggle plot, from which ω_a is extracted

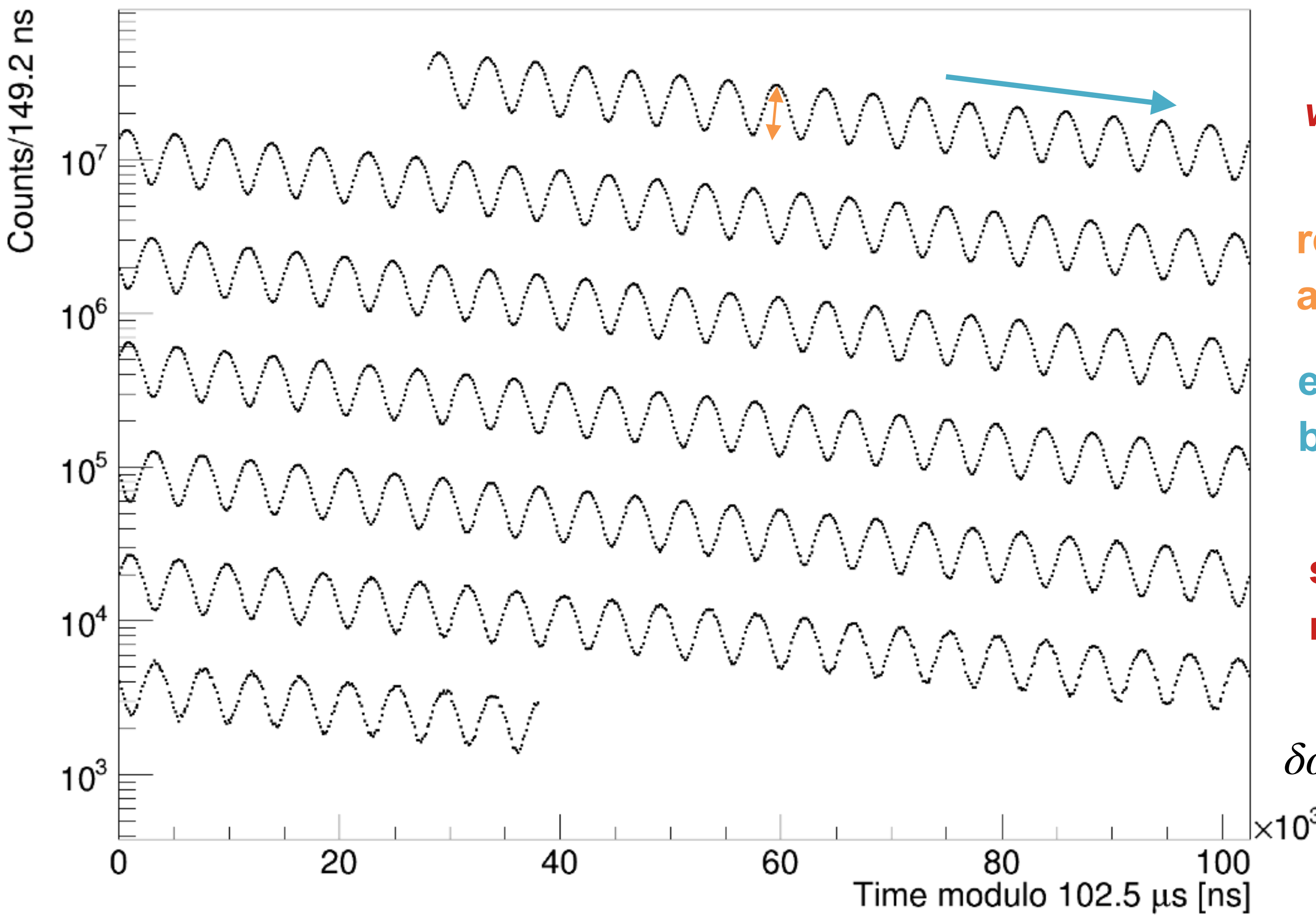






Wiggle plot: Run-3a dataset

Run-3a: $\delta\omega_a$**(stat)** $= 329$ **ppb** 15.3**B positrons**



wiggle **is at** $\omega_a \propto g - 2$

relative size of wiggle:
asymmetry ≈ 0.35

exponential decay:
boosted lifetime $\approx 64.4\ \mu$**s**

statistical figure of merit : NA^2

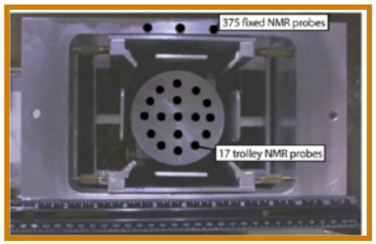
$$\delta\omega_a(\text{stat}) = \frac{\sigma_{\omega_a}}{\omega_a} = \frac{\sqrt{2}}{\sqrt{N}A\gamma\tau\omega_a}$$

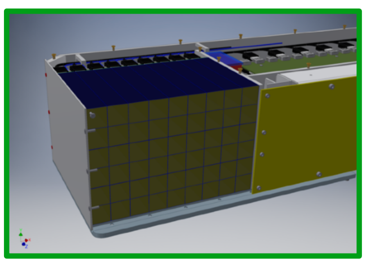
From muon decay: $N(t) = \boldsymbol{N_0} e^{(-t/\boldsymbol{\tau})}\left[1 + \boldsymbol{A}\cos(\boldsymbol{\omega_a} t - \boldsymbol{\phi})\right]$

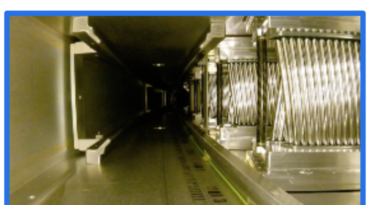
NMR probes

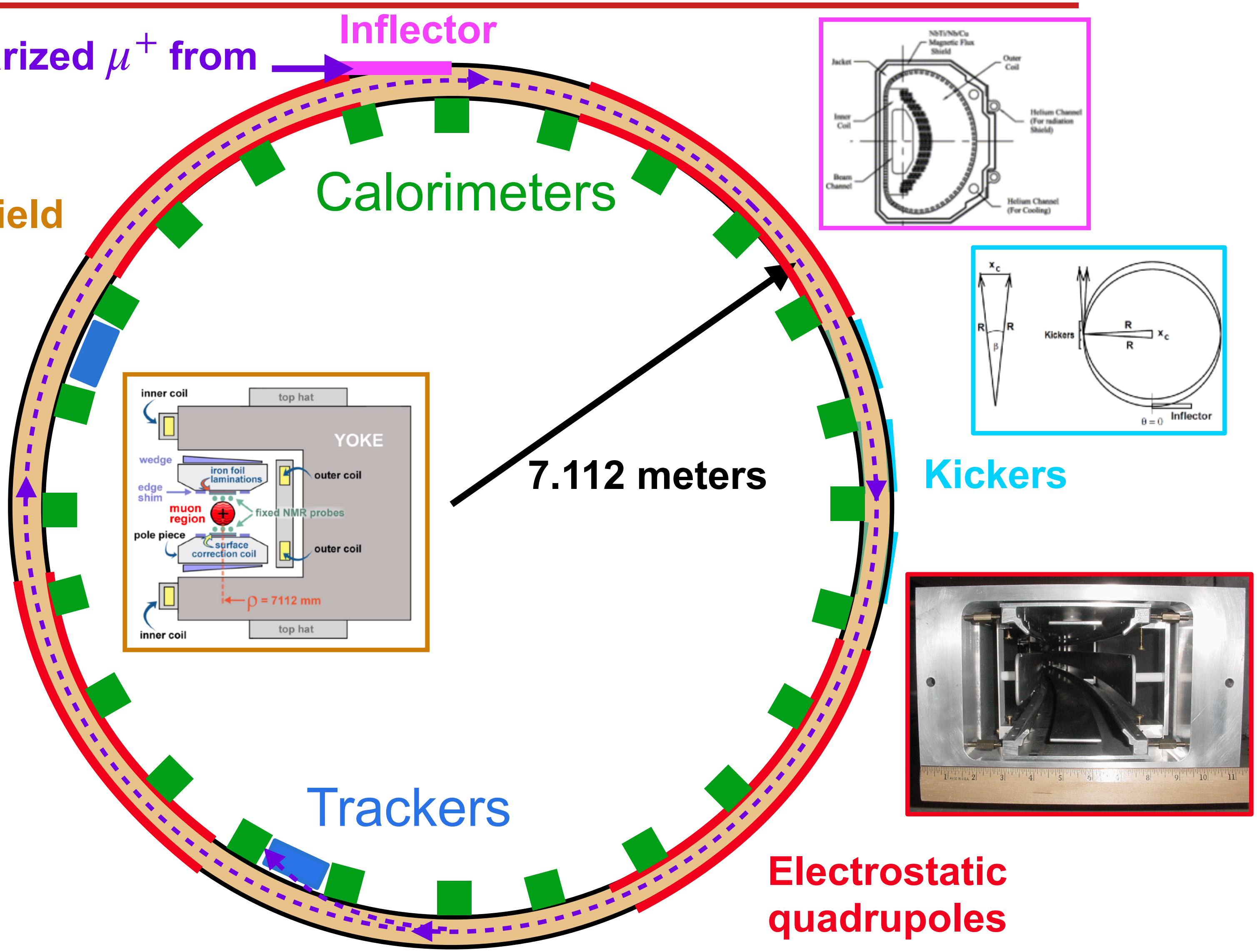
3.094 GeV polarized μ^+ from pion decay

1.451 T magnetic field



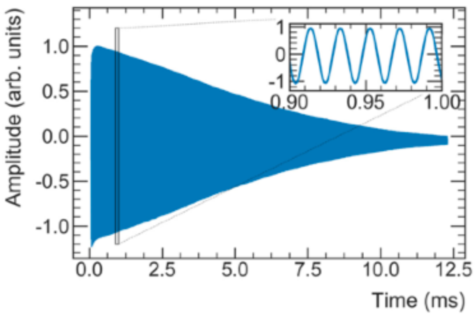


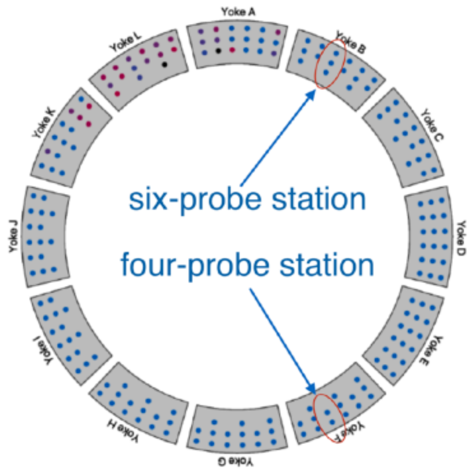


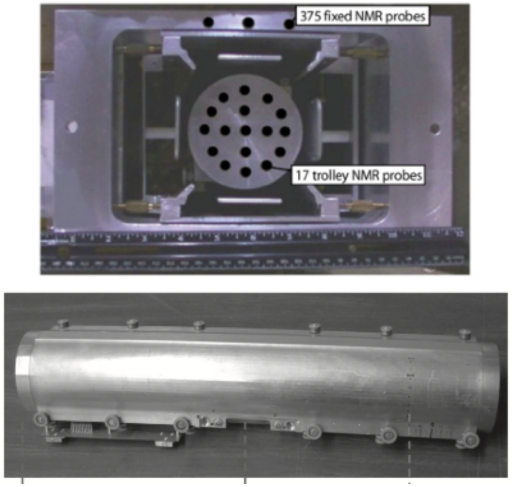


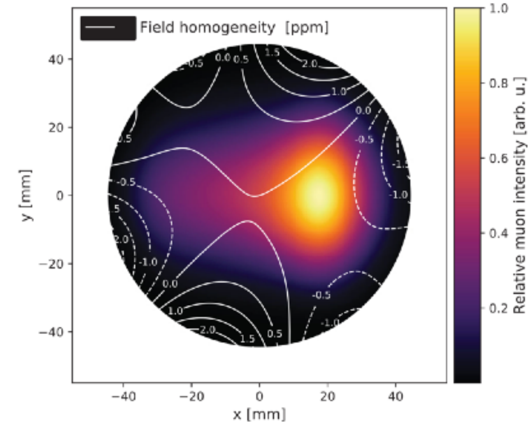
NMR probes to measure magnetic field

- Magnetic field measured with pulsed proton nuclear magnetic resonance (NMR): 378 fixed probes & 17 on a trolley
- Extract *frequency* ω_p from oscillating proton spins
- Create field maps in position and time
- Calibrated to a standard to extract magnetic field









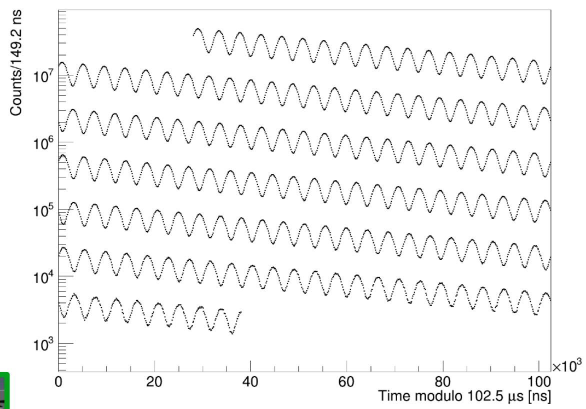
Muon g-2 measurement recipe

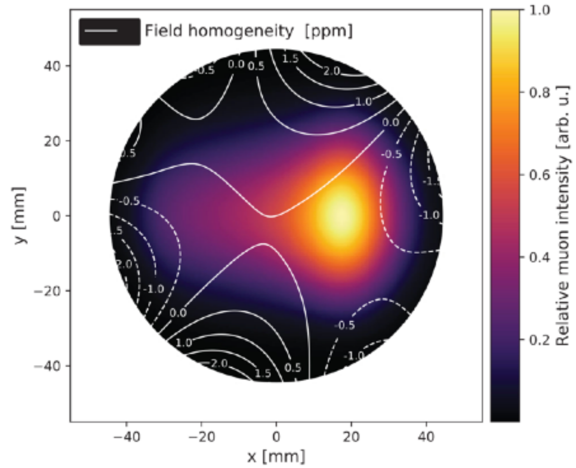
$$\omega_a = -\,a_\mu \frac{e}{m}\langle B \rangle$$

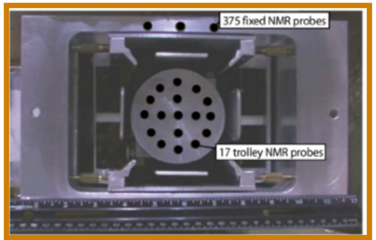
determine this!

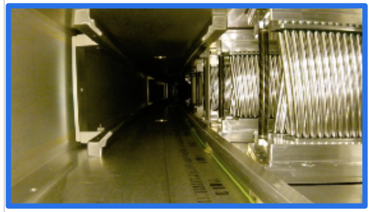
measure this!

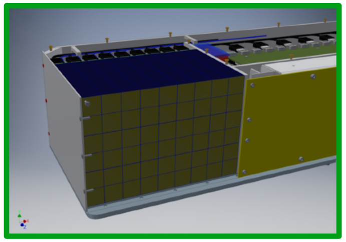
measure this!











Decay positron time spectrum

Magnetic field map

Muon distribution

Determining a_μ

We measure this ratio!

Rev. Mod. Phys. 88, 035009 (2016) Phys. Rev. A 83, 052122 (2011)

exact 0.3 ppt

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

10 ppb 22 ppb

Metrologia 13, 179 (1977) Phys. Rev. Lett. 82, 711 (1999).

$\mathscr{R}'_\mu$(Fermilab Run-1) uncertainty: 460 ppb

External input uncertainties are **small** : 25 ppb

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$\mathcal{R}'_\mu$**(Fermilab Run-1) uncertainty: 460 ppb**

External input uncertainties are **small** : 25 ppb

$$\mathcal{R}'_\mu = \frac{\omega_a}{\tilde{\omega}'_p(T_r)} = \frac{f_{\text{clock}}\, \omega_a^m (1 + C_e + C_p + C_{ml} + C_{pa} + C_{dd})}{f_{\text{calib}} \langle \omega_p(x,y,\phi) \times M(x,y,\phi) \rangle (1 + B_k + B_q)}$$

- Measure muon anomalous precession frequency
- Measure proton Larmor precession & muon beam distribution
- ω_a corrections: electric field, pitch, lost muon, phase acceptance, differential decay
- ω_p corrections: transient fields from quadrupoles & kicker
- Unblinding factor & magnetic field calibration

Uncertainty table

- Run-1 measurement was statistics-limited
- Run 2 & 3 also statistics-limited, numbers being finalized now
- TDR statistics goal: 100 ppb statistical & systematic
- Question: can we go beyond TDR goal with this technique?

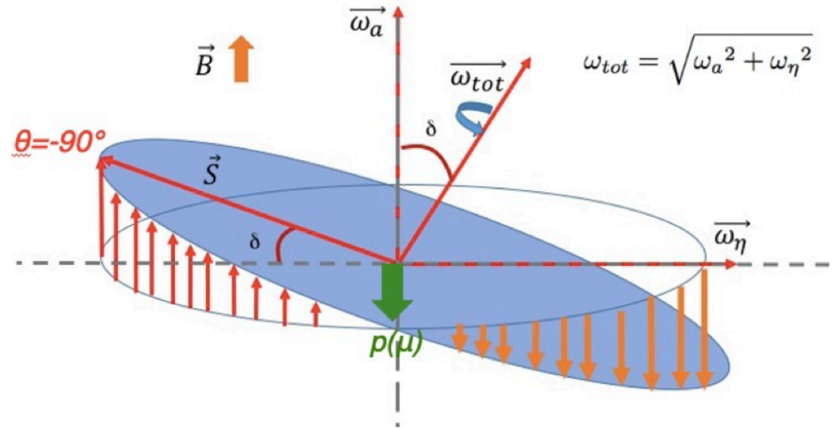
Run-1 table

Quantity	Correction terms (ppb)	Uncertainty (ppb)
ω_a^m (statistical)	$\cdots$	434
ω_a^m (systematic)	$\cdots$	56
C_e	489	53
C_p	180	13
C_{ml}	−11	5
C_{pa}	−158	75
$f_{\text{calib}}\langle\omega_p(x,y,\phi)\times M(x,y,\phi)\rangle$	$\cdots$	56
B_k	−27	37
B_q	−17	92
$\mu_p'(34.7°)/\mu_e$	$\cdots$	10
m_μ/m_e	$\cdots$	22
$g_e/2$	$\cdots$	0
Total systematic	$\cdots$	157
Total fundamental factors	$\cdots$	25
Totals	544	462

Effect of an EDM

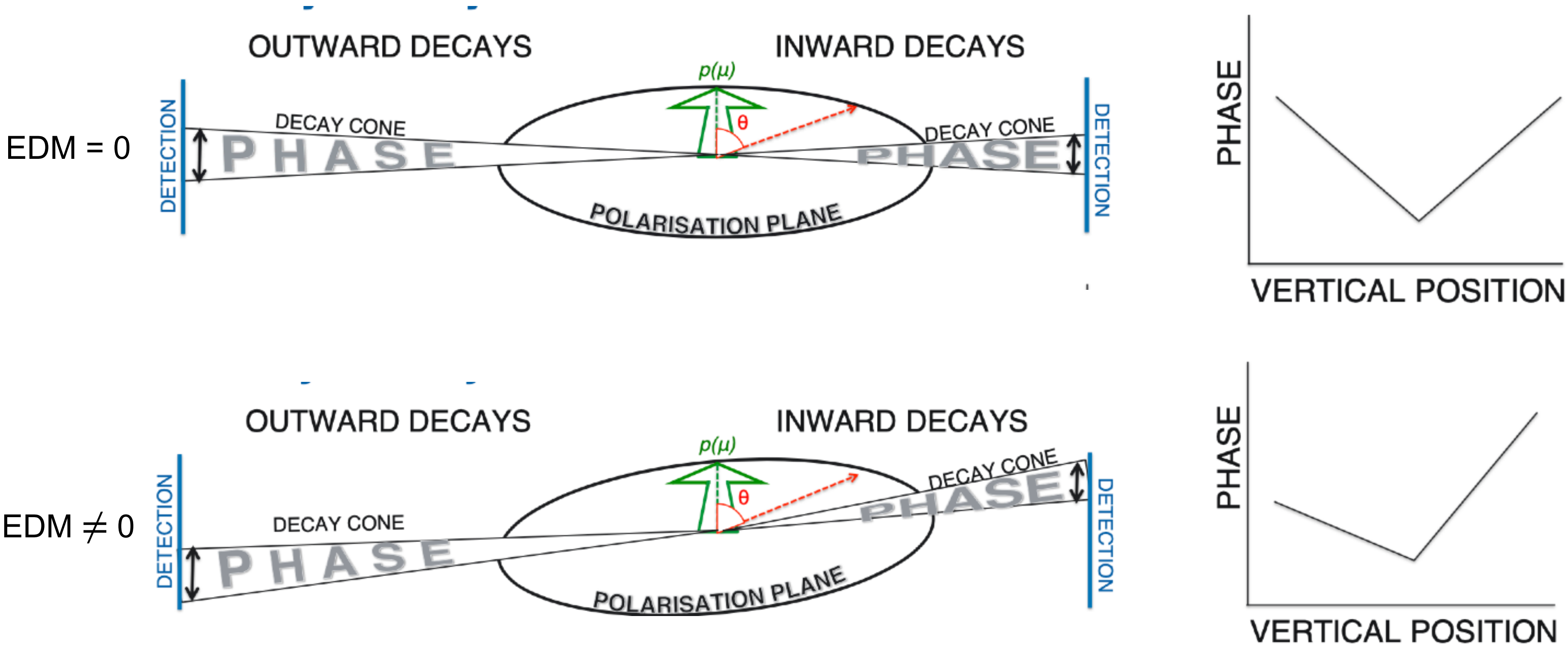
$$\vec{\omega}_a = \frac{e}{m}\left[a_\mu \vec{B} - a_\mu \frac{\gamma}{\gamma+1}(\vec{\beta}\cdot\vec{B})\vec{\beta} - \left(a_\mu - \frac{1}{\gamma^2-1}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right] + \frac{\eta q}{2mc}\left[\vec{E} + c\vec{\beta}\times\vec{B}\right]$$

- An EDM introduces an extra term in spin precession
- Increases precession frequency (but too small to observe)
- Main signature: tilts polarization plane
- Measurement techniques:
  - Calorimeter-based method
  - Tracker-based method



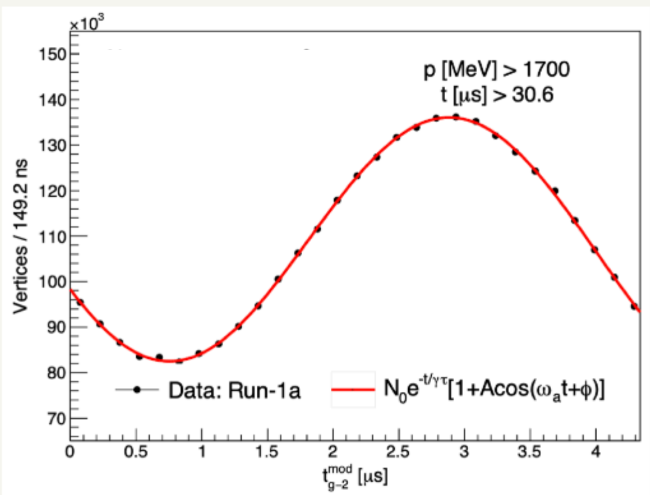
Calorimeter-based approach

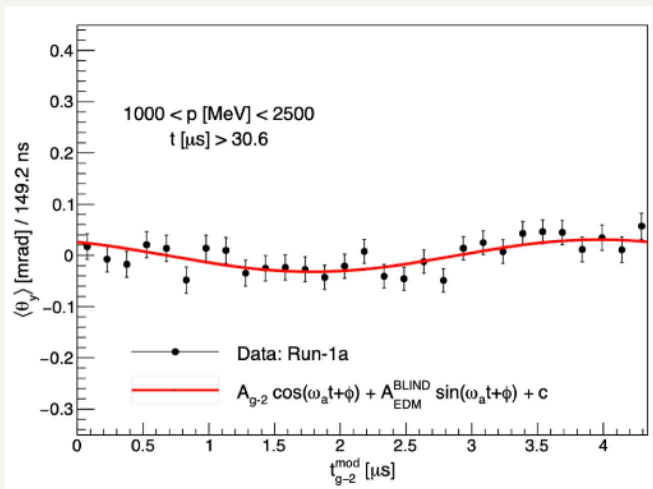
- Look for an asymmetry in the g-2 phase vs. vertical position
- Calorimeter segmentation allows vertical position resolution
- BNL result *systematically limited*; not performed in Fermilab Run-1



Tracker-based method

- Measure vertical decay angle directly & look for an oscillation
  - Oscillation is at the same g-2 frequency ω_a
  - Phase is $\pm 90^{\circ}$ out of phase with ω_a signal
- Extract g-2 phase from number oscillation & fit average vertical angle vs. time with sinusoid
- Can improve measurement by reducing vertical RMS of the beam

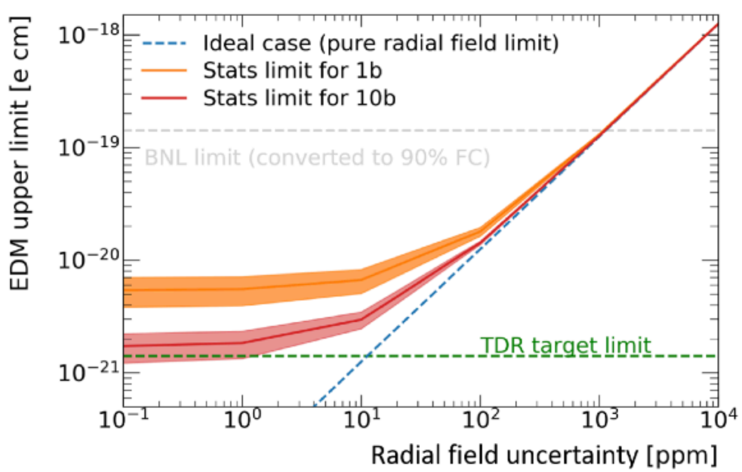


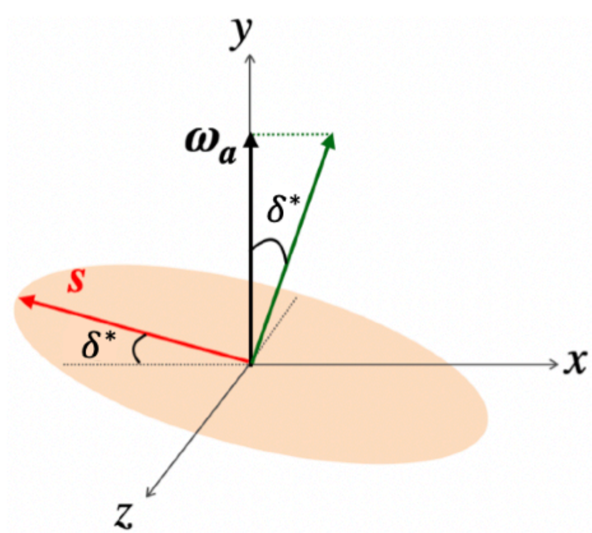


	Sensitivity
Run-1	2 10
Run 2&3	
Run 4/5/6	

Radial field

- A radial magnetic field also tilts the polarization plane & therefore mimics an EDM signal
- Measure radial field by applying a known radial field & scanning quadrupole voltage
- Measured to a precision of <1 ppm





E989 outlook and future

- Reached TDR statistics goal February of this year (x21 BNL)
- Run 2/3 analysis nearing completion (x4 stats compared to Run-1)
- Run 4/5/6 analysis picking up speed
- EDM Run-1 analysis nearing completion (comparable to BNL sensitivity) & Run 2 & 3 analysis underway with improved tracking efficiency
- Can we push storage ring technique further?
- Future use of storage ring? Frozen spin EDM measurement?

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Thanks for listening!