# Current Status of Muon g-2 Experiment at Fermilab

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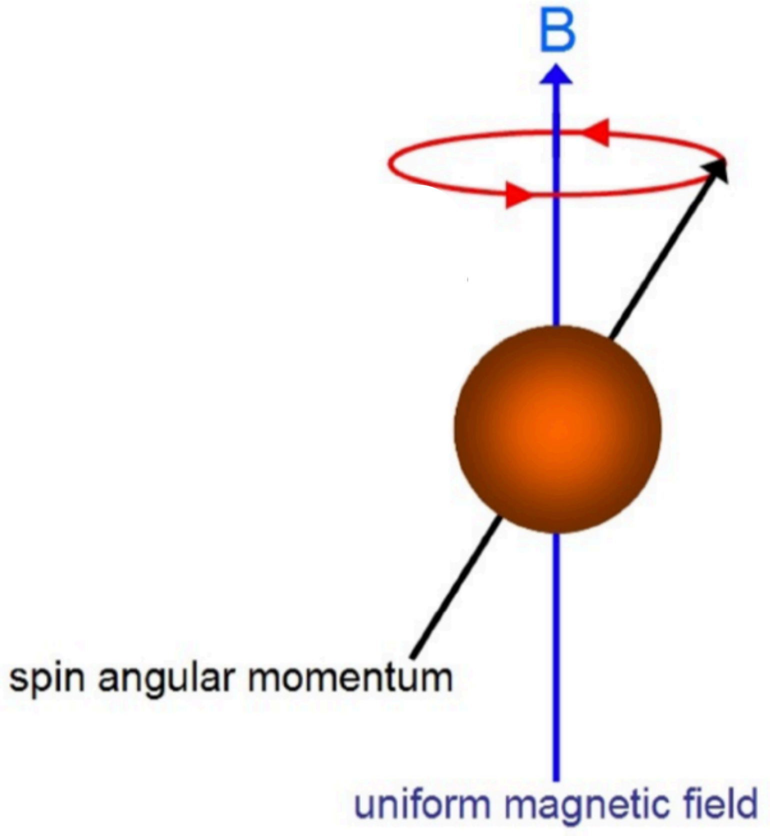
# Outline

- Anomalous Magnetic Moment of Muon
- Muon g-2 Experiment
- Experiment Status
- What's Next?

# Muon Magnetic Moment and Defining the Anomaly




## Magnetic Moment of Muon

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

g: Proportionality constant between spin and magnetic moment

## Anomalous Magnetic Moment of Muon

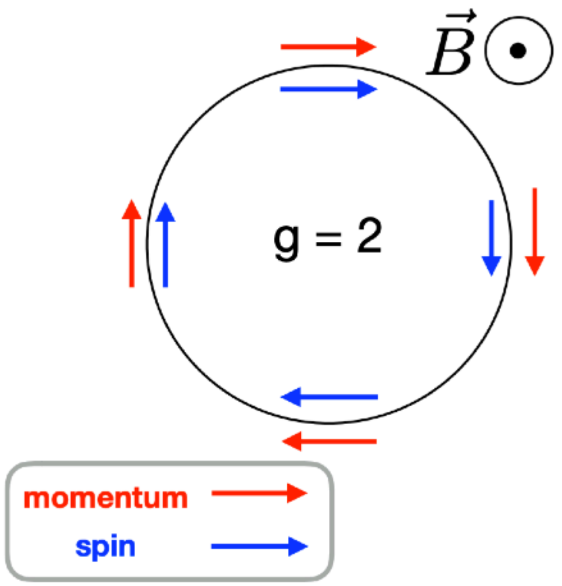
$$a_\mu = \frac{g_\mu - 2}{2}, \qquad \overrightarrow{\mu} = (1 + a_\mu)\frac{e}{m}\vec{s}$$

Shows how much g differs fractionally from 2!

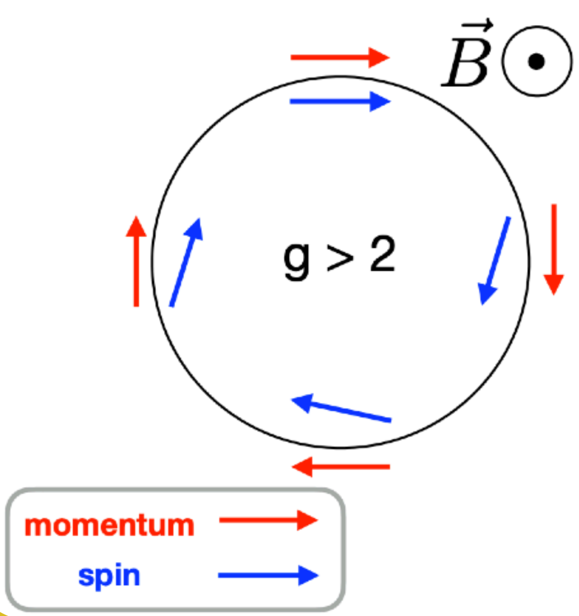
# Muon Magnetic Moment and Measuring the Anomaly

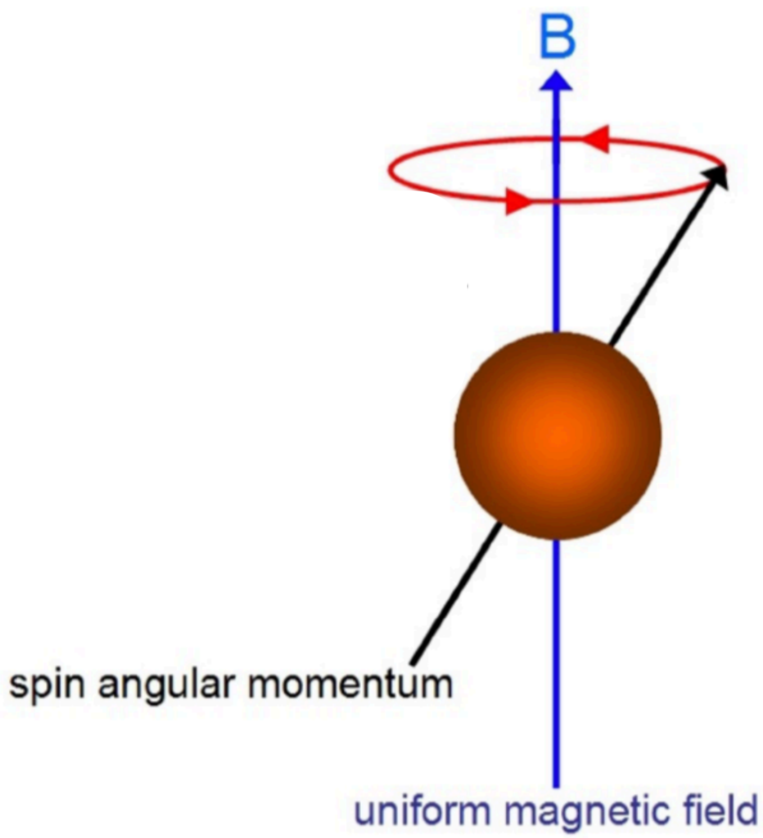
polarized muons in a magnetic field

If $g = 2 \Rightarrow \overrightarrow{\omega}_a = 0$




$g \neq 2 \Rightarrow \overrightarrow{\omega}_a \cong a_\mu \frac{e}{m} \overrightarrow{B}$




$\overrightarrow{\omega}_c = -\frac{e}{\gamma m}\overrightarrow{B}$ , cyclotron frequency

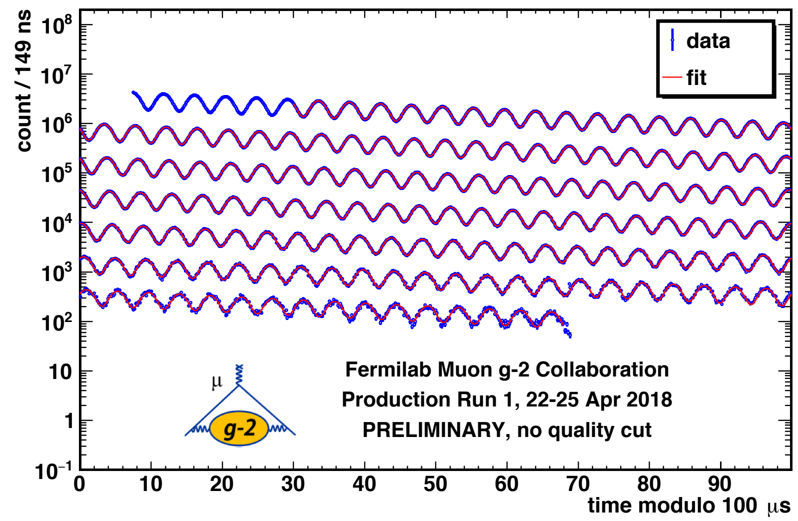
$\overrightarrow{\omega}_s = -\frac{e}{\gamma m}\overrightarrow{B}(1 + \gamma a_\mu)$ , Larmor precession frequency

$\overrightarrow{\omega}_a \cong \overrightarrow{\omega}_s - \overrightarrow{\omega}_c$ , anomalous precession frequency

$\overrightarrow{\omega}_a \cong a_\mu \frac{e}{m} \overrightarrow{B}$

Measure them to extract anomaly

# Measuring the Muon Anomaly



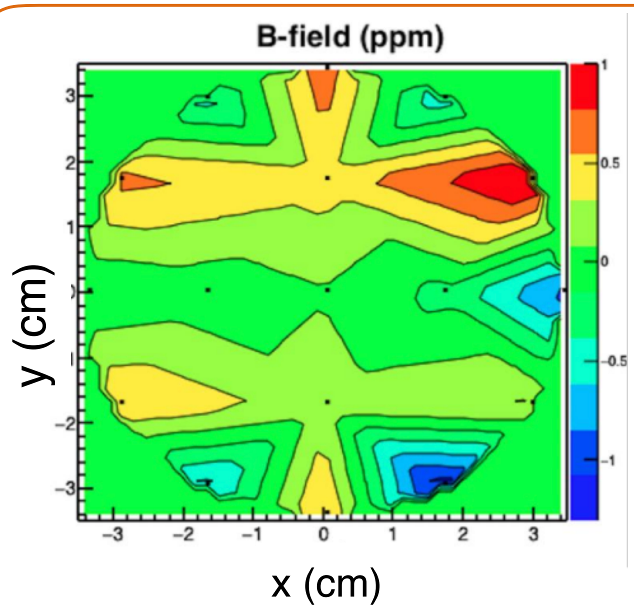

$\omega_a$

Extract from decay positron time spectra

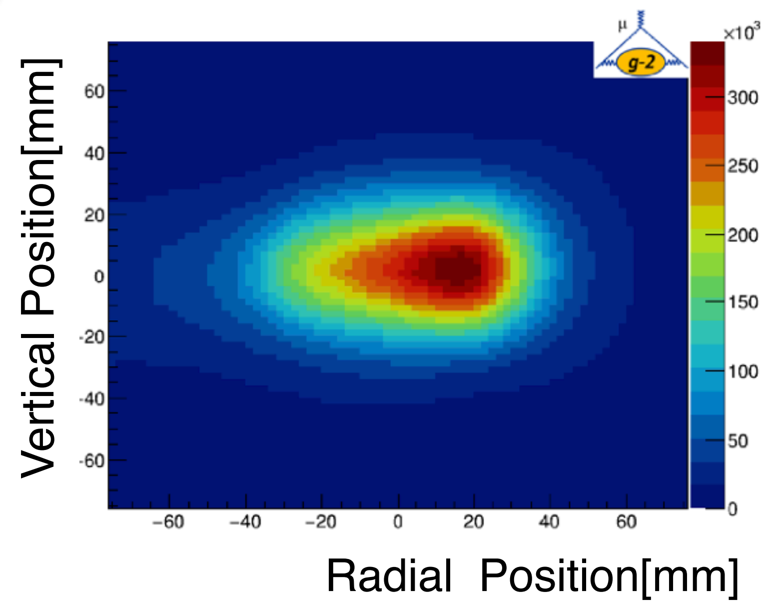
$$N(t) = N_0 e^{-t/\tau_\mu}[1 + A\cos(\omega_a t + \phi)]$$

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

0.26 ppt | 3 ppb | 22 ppb ⇨ 2017 CODATA




Map the magnetic field




Obtain muon distribution In the storage ring

$$\langle\omega_p\rangle \approx \omega_p \otimes \rho(r)$$

Average magnetic field weighted by muon distribution

$\omega_p$: free proton precession frequency

Using proton NMR $\hbar\omega_p = 2\mu_p B$

# Muon g-2 Experiment at Fermilab

**Muons are useful!**

- $(m_\mu/m_e)^2 = 40000$ -> More sensitive to new physics.
- Muon beams from pion decays.
- Relatively long lifetime (2.2 $\mu s$) -> In the lab frame 64.4$\mu s$

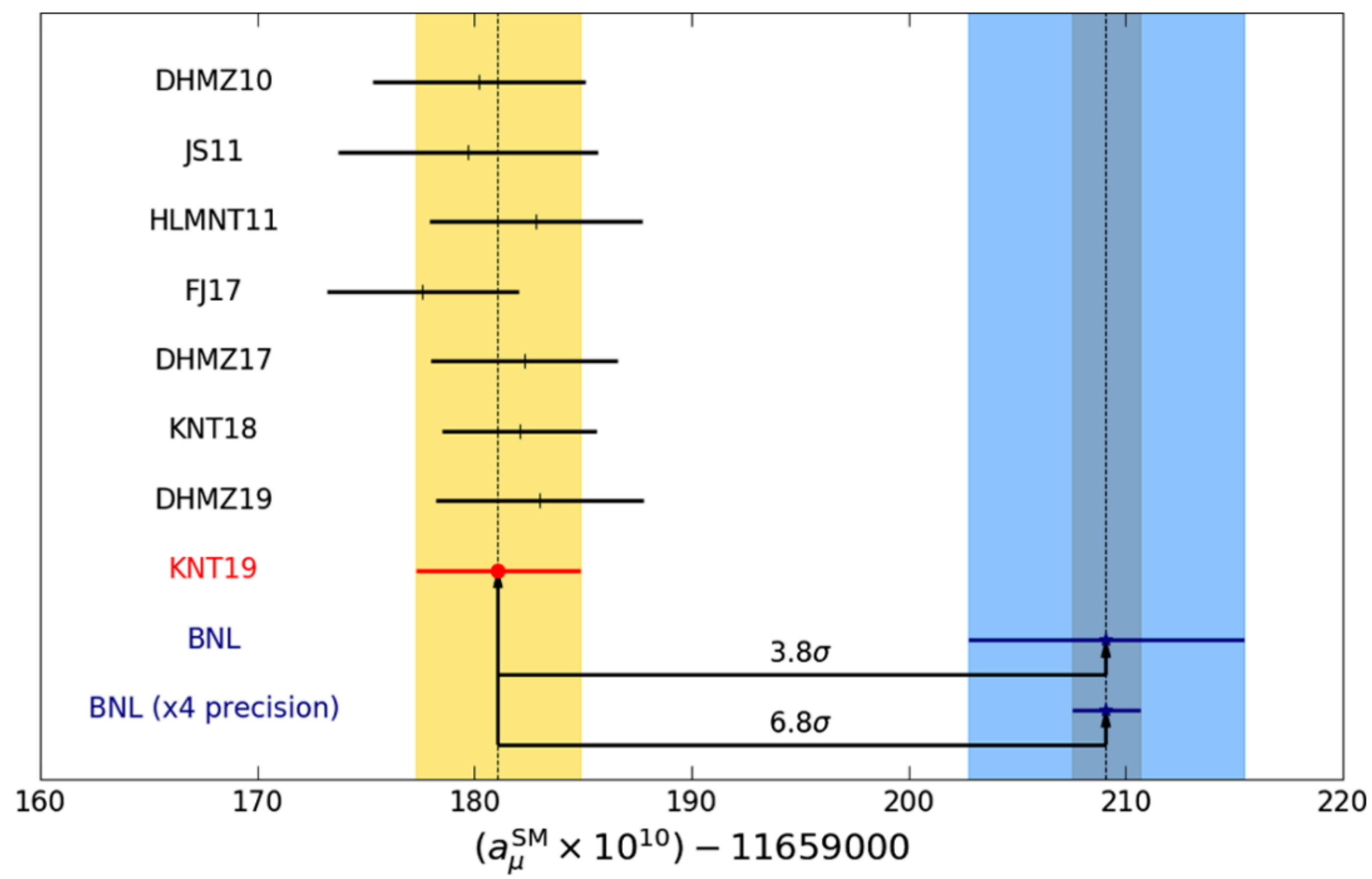
**Why measure the muon anomaly**

- An accurate way to test SM validity
- BNL measurement hints at the possibility of new physics.

**Muon g-2 Experiment Goals:**

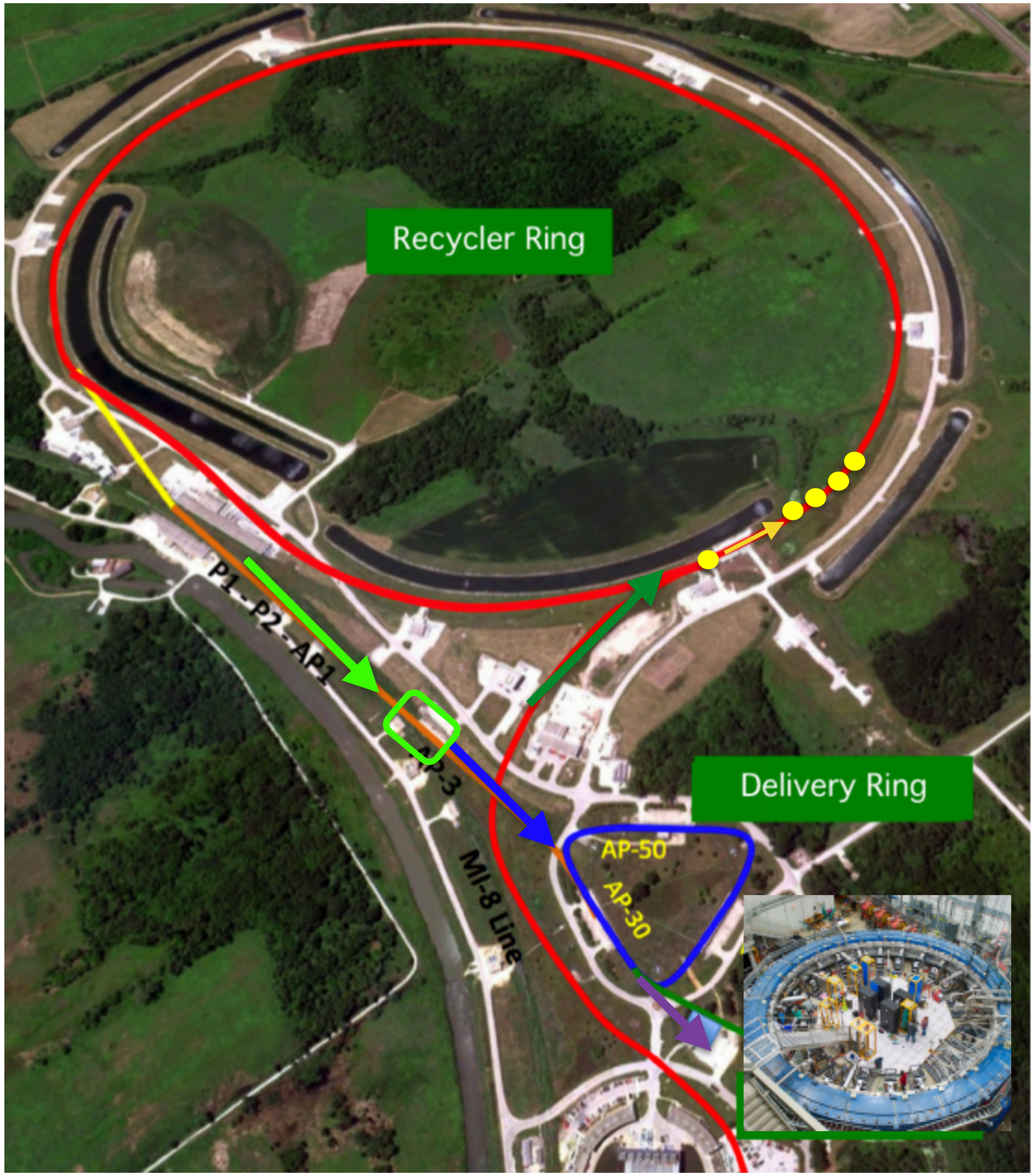
- Measuring $a_\mu$ with 4 times better accuracy requires
  - Recording 21.5 X BNL statistics
  - Reducing the systematics uncertainty

Keshavarzi et al.,2020



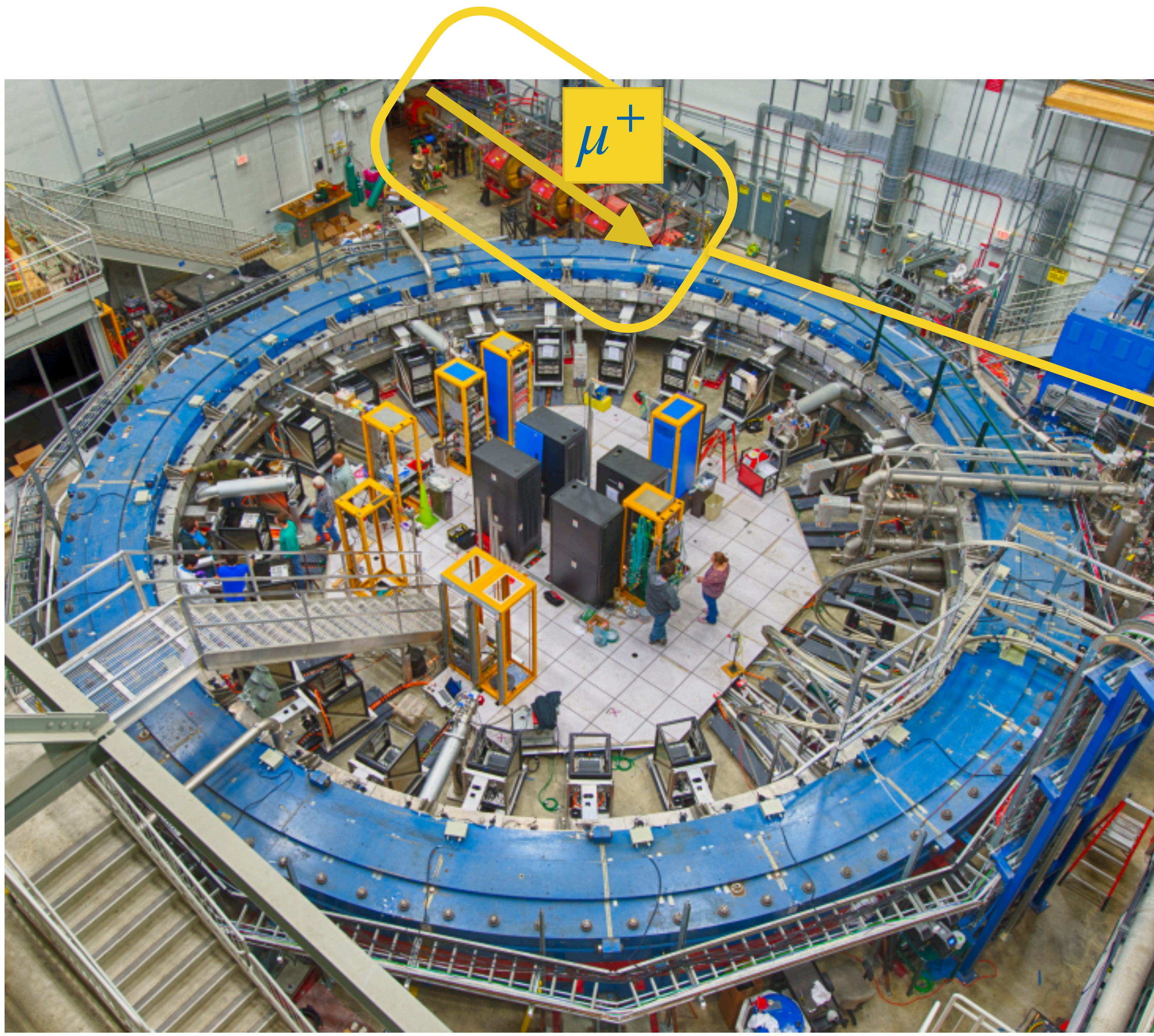

See Dominik Stoeckinger's talk for latest g-2 theory status

# Muon Campus at Fermilab




- 8 GeV protons are delivered to Recycler Ring from Booster
- Split the proton bunch into four bunches with RF system.
- Direct the proton punches to pion production target and obtain pions.
- Muons produced by pion decays circulate in the delivery ring until proton contamination is removed.
- Deliver muons to g-2 storage ring.

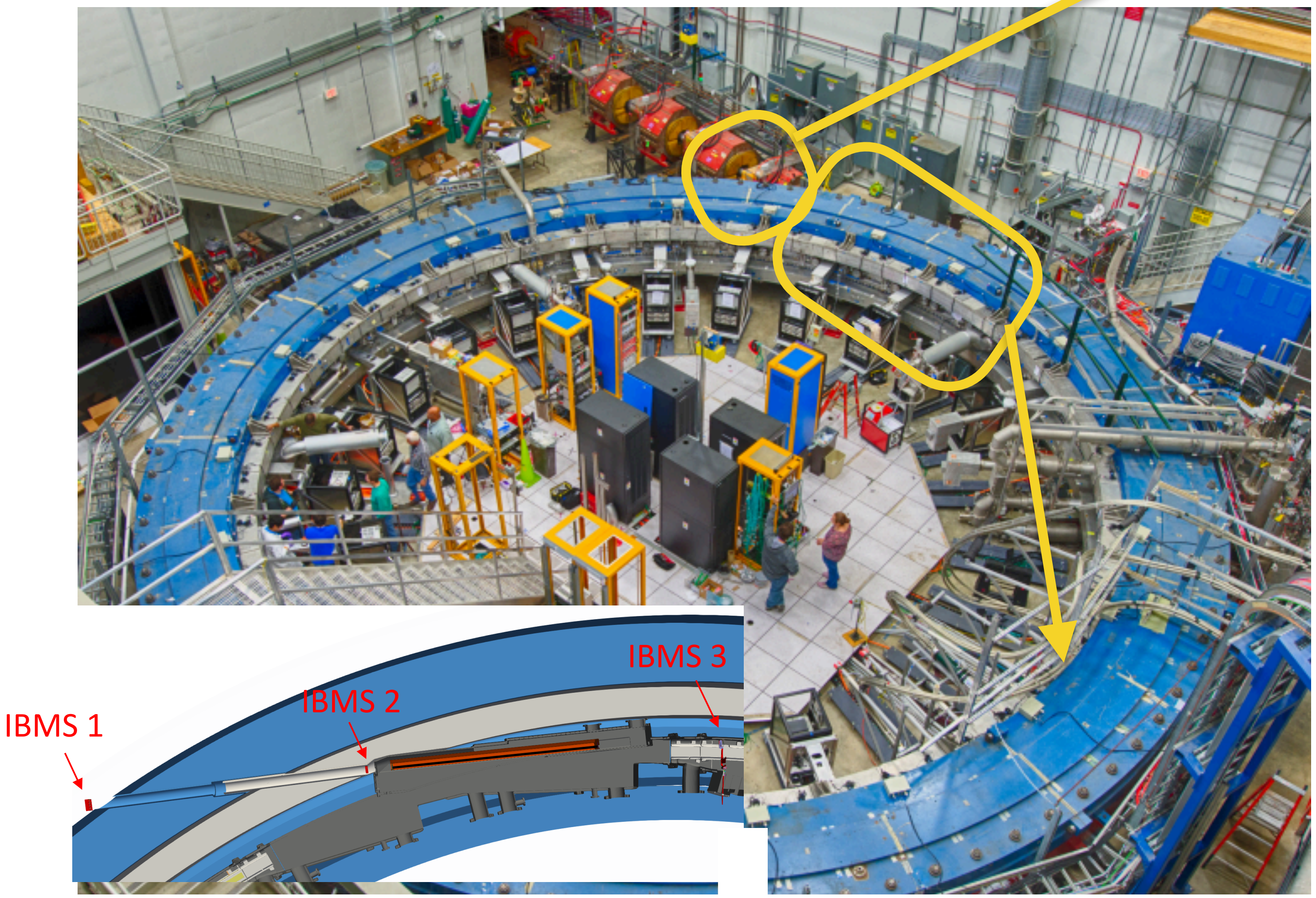
# Muons at the Experimental Hall

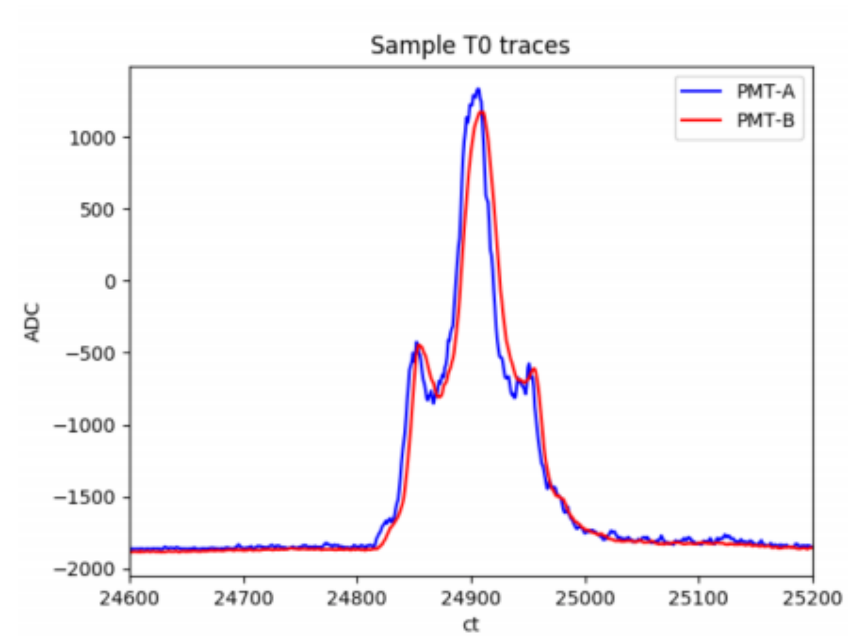



Final focusing by magnetic quads before injecting 3.1 GeV/c muons

# Monitoring the Injected Beam

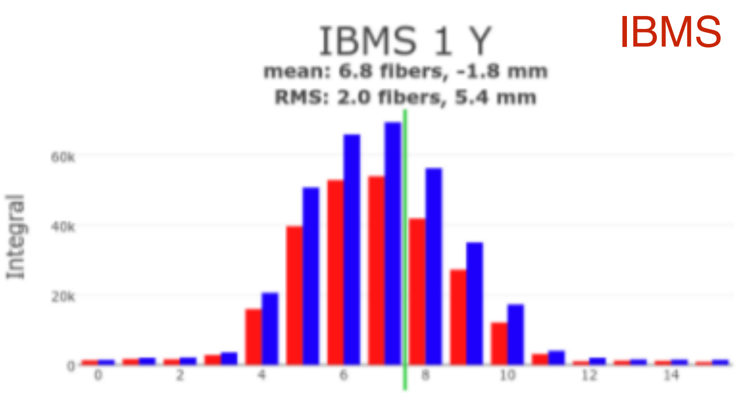
- **T0 Counter**
  - Thin scintillator with 2 PMT readouts
  - Provides beam time profile before beam enters the storage ring

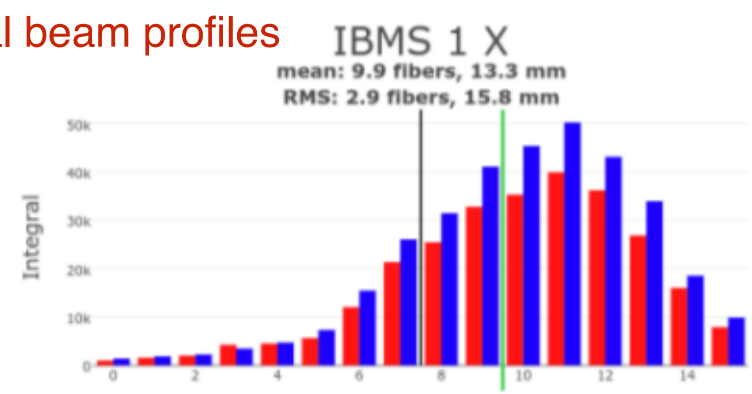


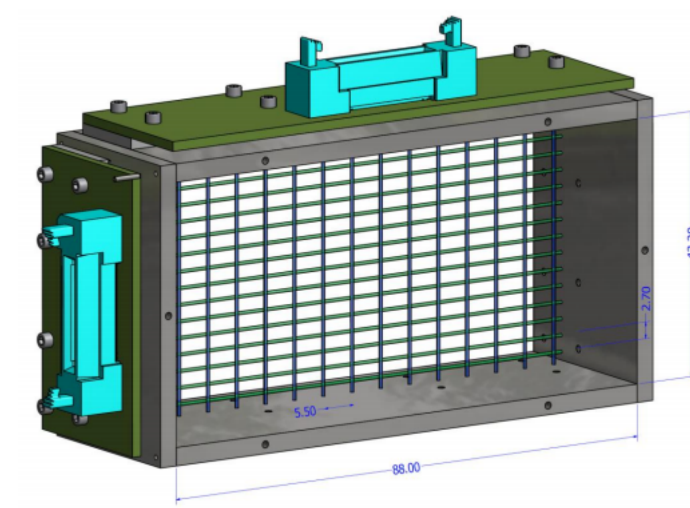




- **IBMS (Inflector beam monitoring systems)**
  - Check beam injection characteristics
  - 2 planes of scintillation fibers

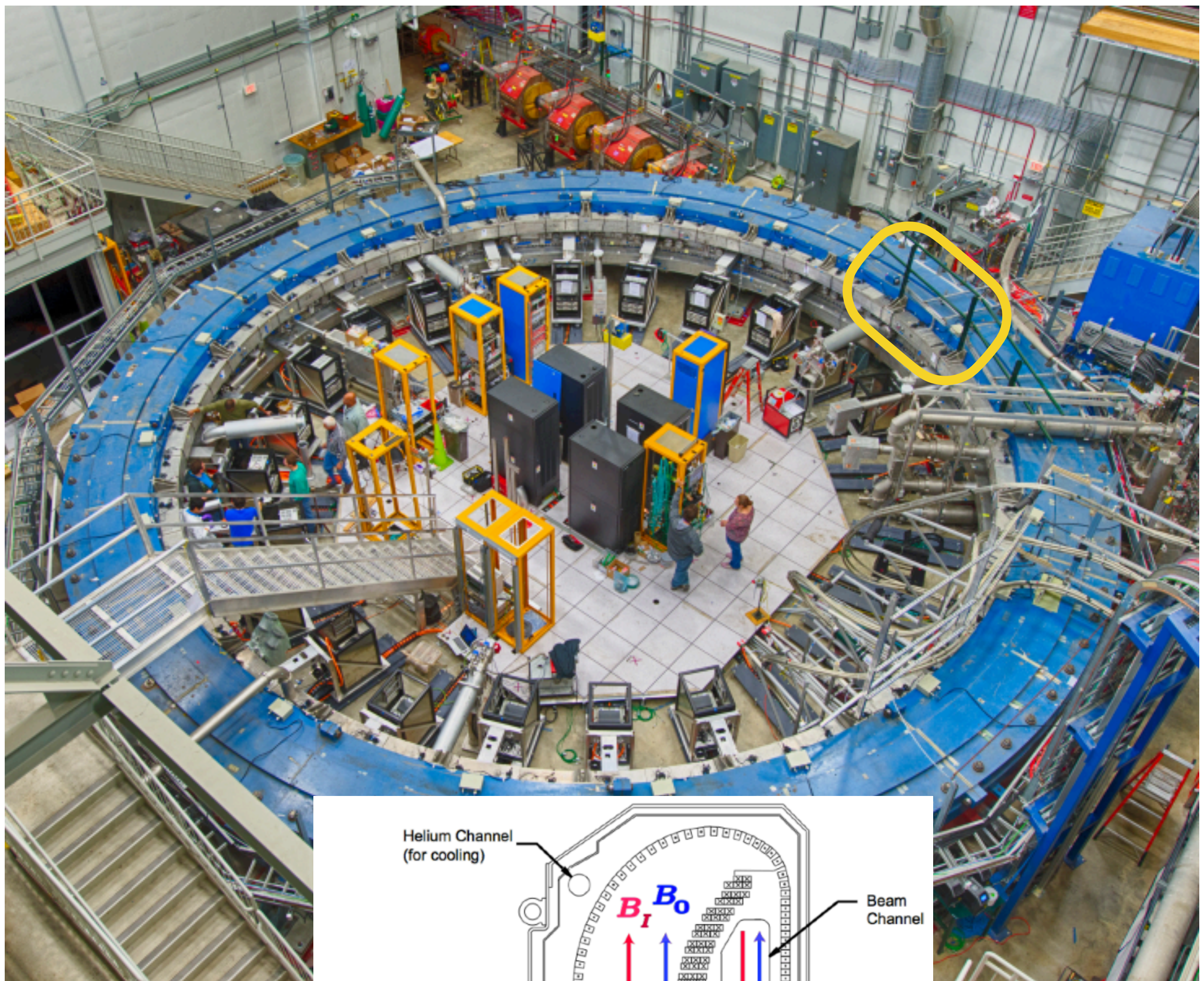
IBMS spatial beam profiles

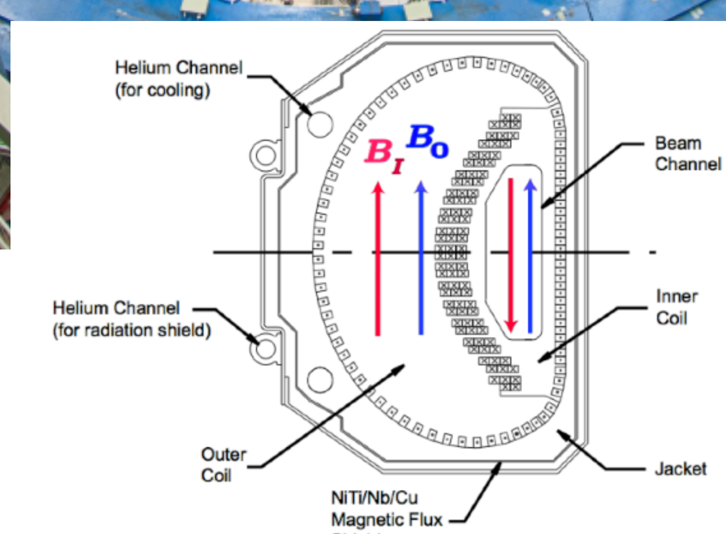


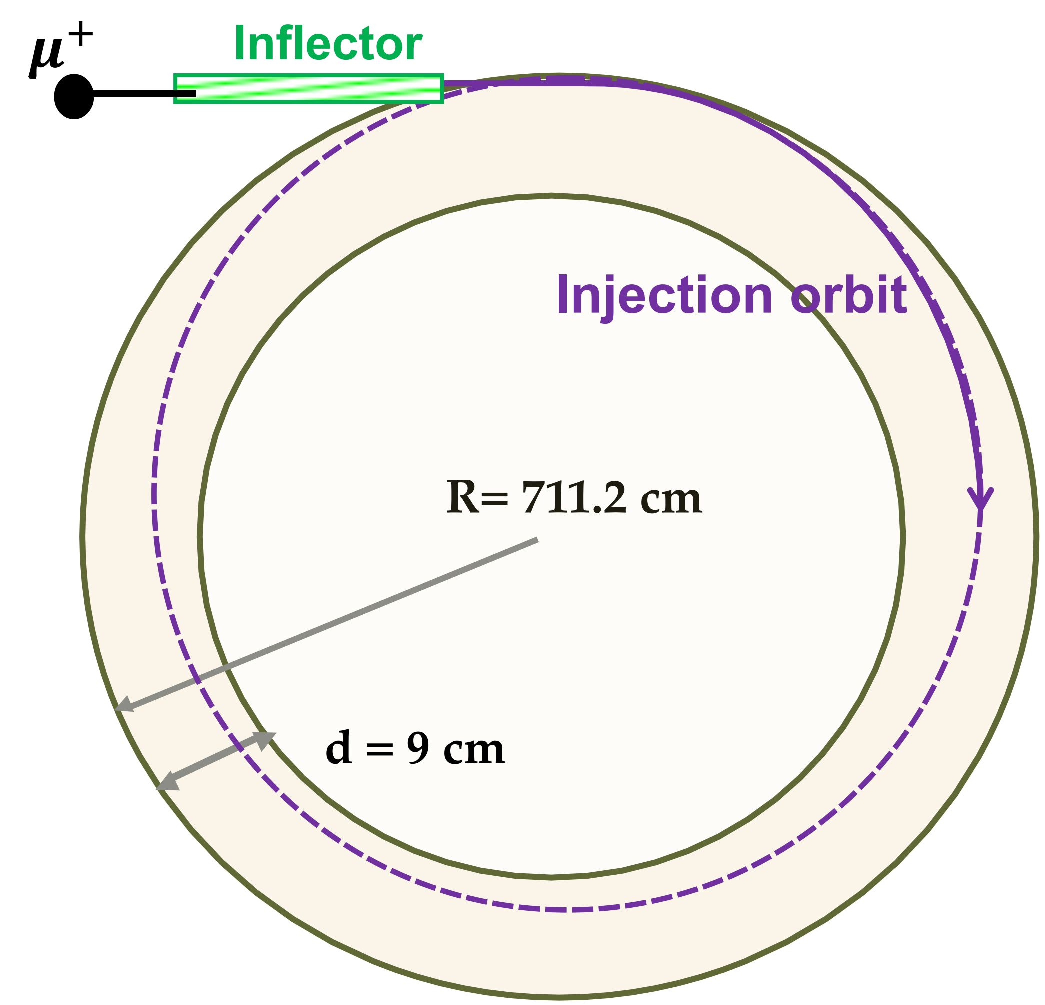



# Storing the Muons : Inflector and Kickers

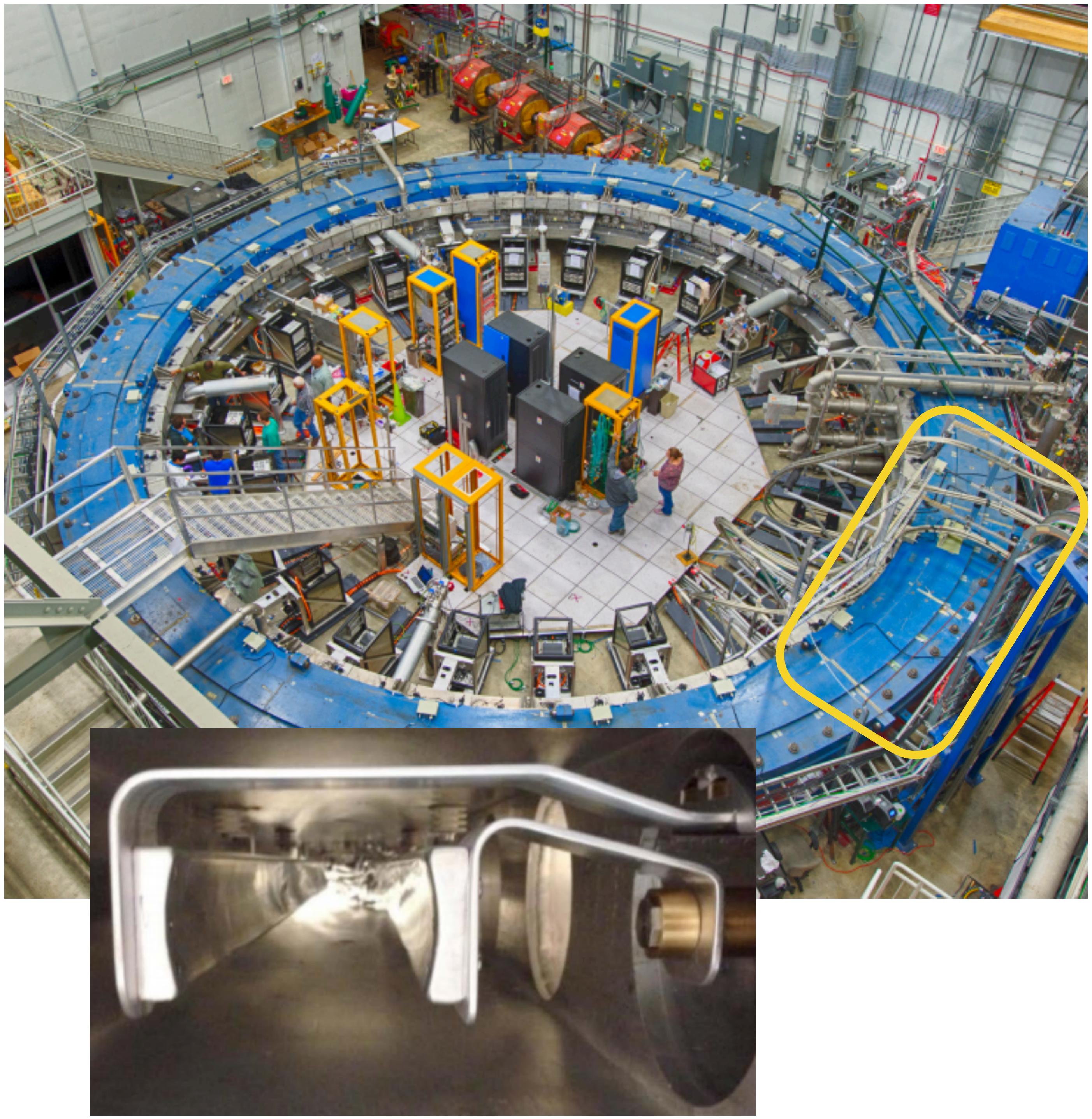




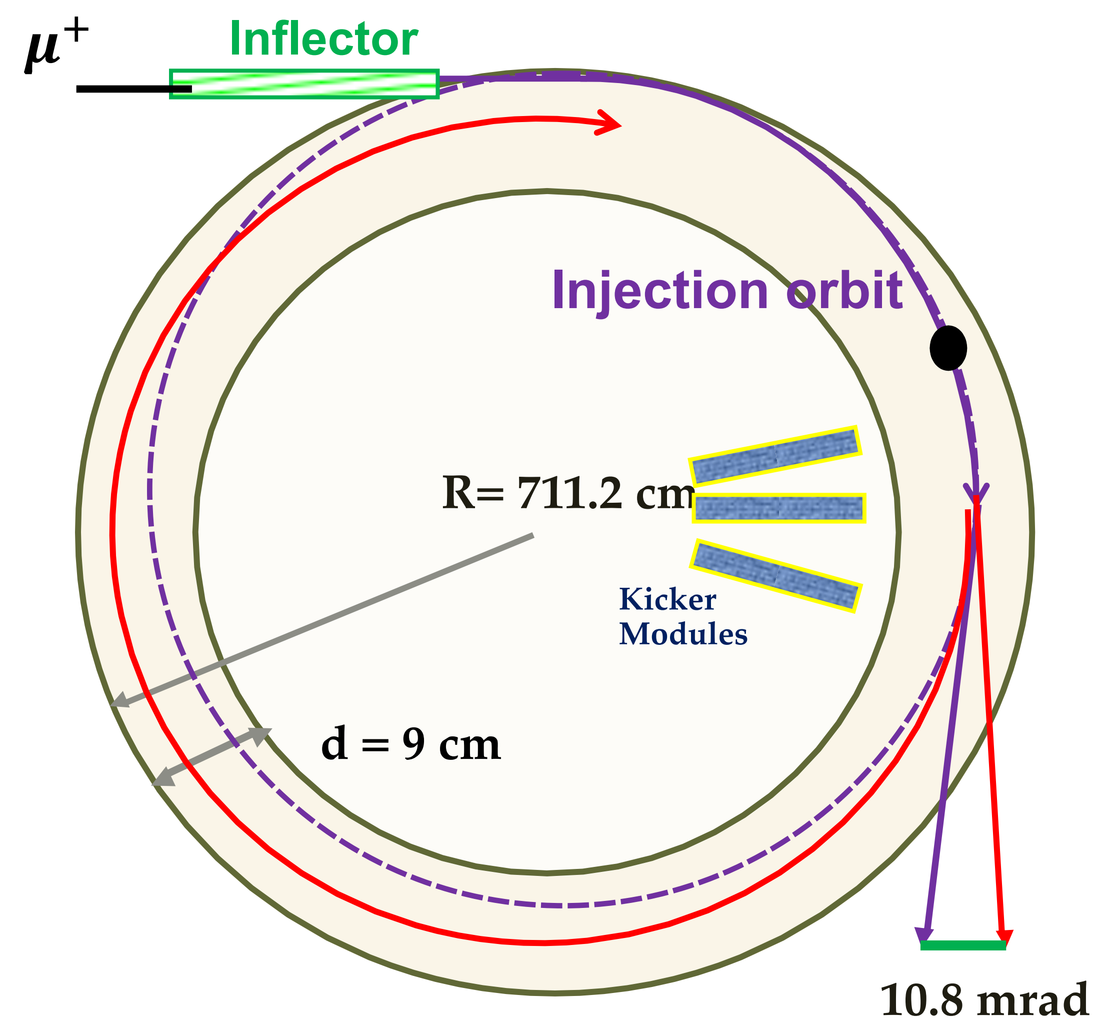

- **Inflector**
  - Cancels B field in the magnet gap and let the beam enter the storage ring without being deflected.
  - They are at r=77mm outside central closed orbit



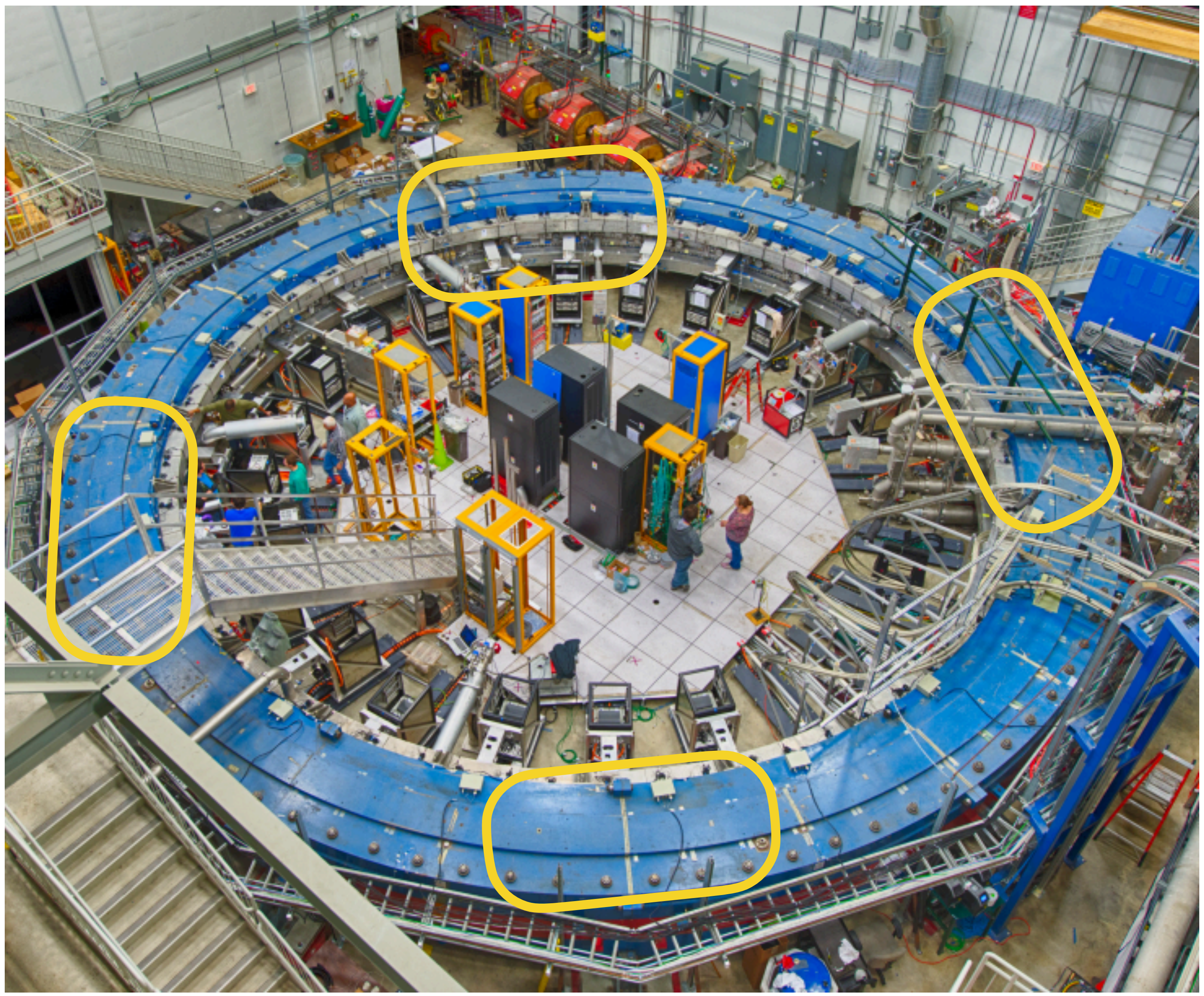
# Storing the Muons : Inflector and Kickers



- **Magnetic Kickers**
  - Kick some more to direct the muons into ideal orbit.
  - Use 10.8 mrad pulsed kicks (<149 ns)

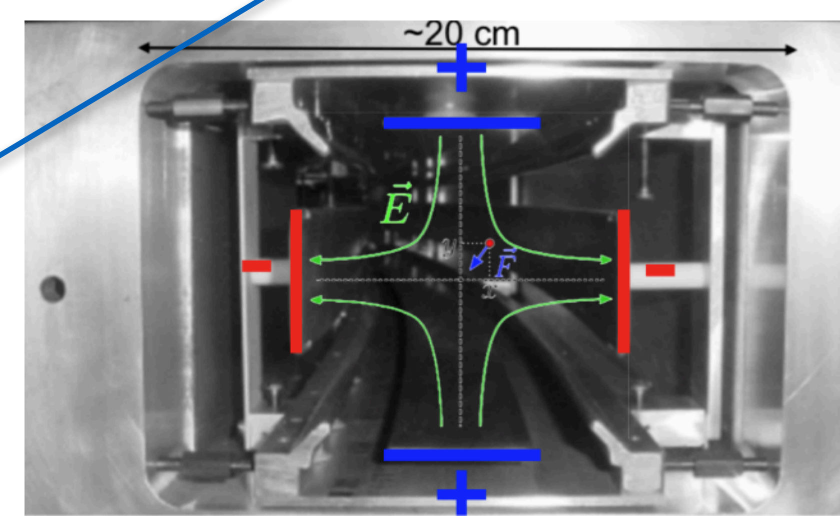


# Storing the Muons: Electrostatic Quadrupoles



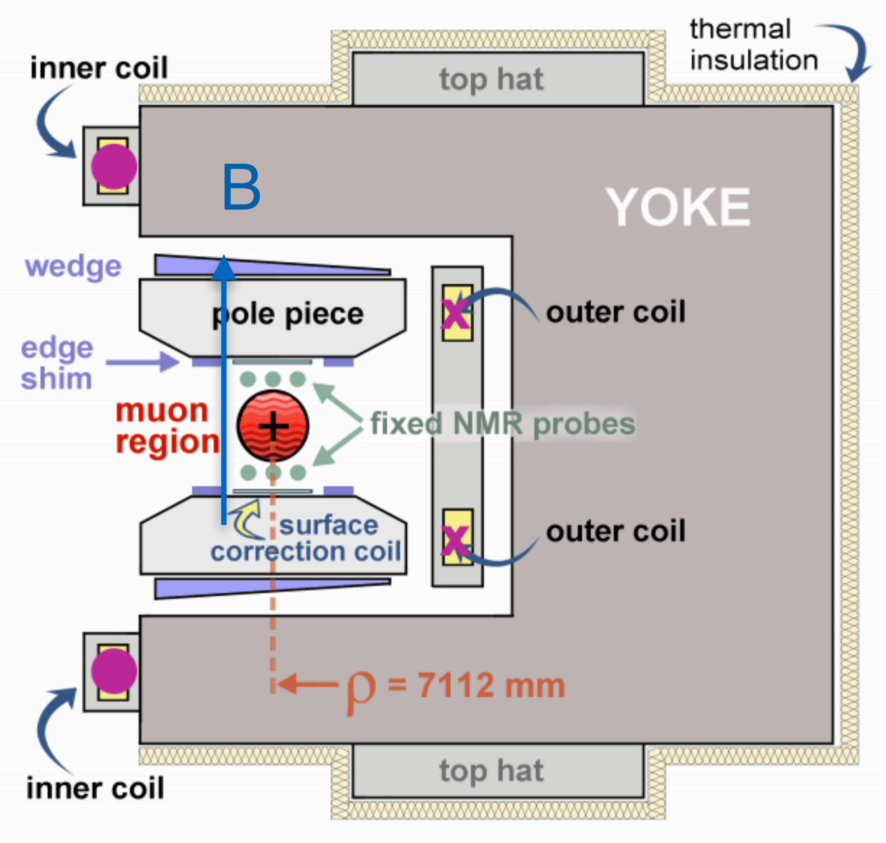
- Electrostatic Quadrupoles
  - 4 sets of quads
  - Storage ring field provides horizontal focusing
  - Electrostatic quadrupoles which cover 43% of the ring are used to focus the beam vertically
  - Cancels out leading order of electric field contribution running at magic momentum p = 3.094 GeV/c

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

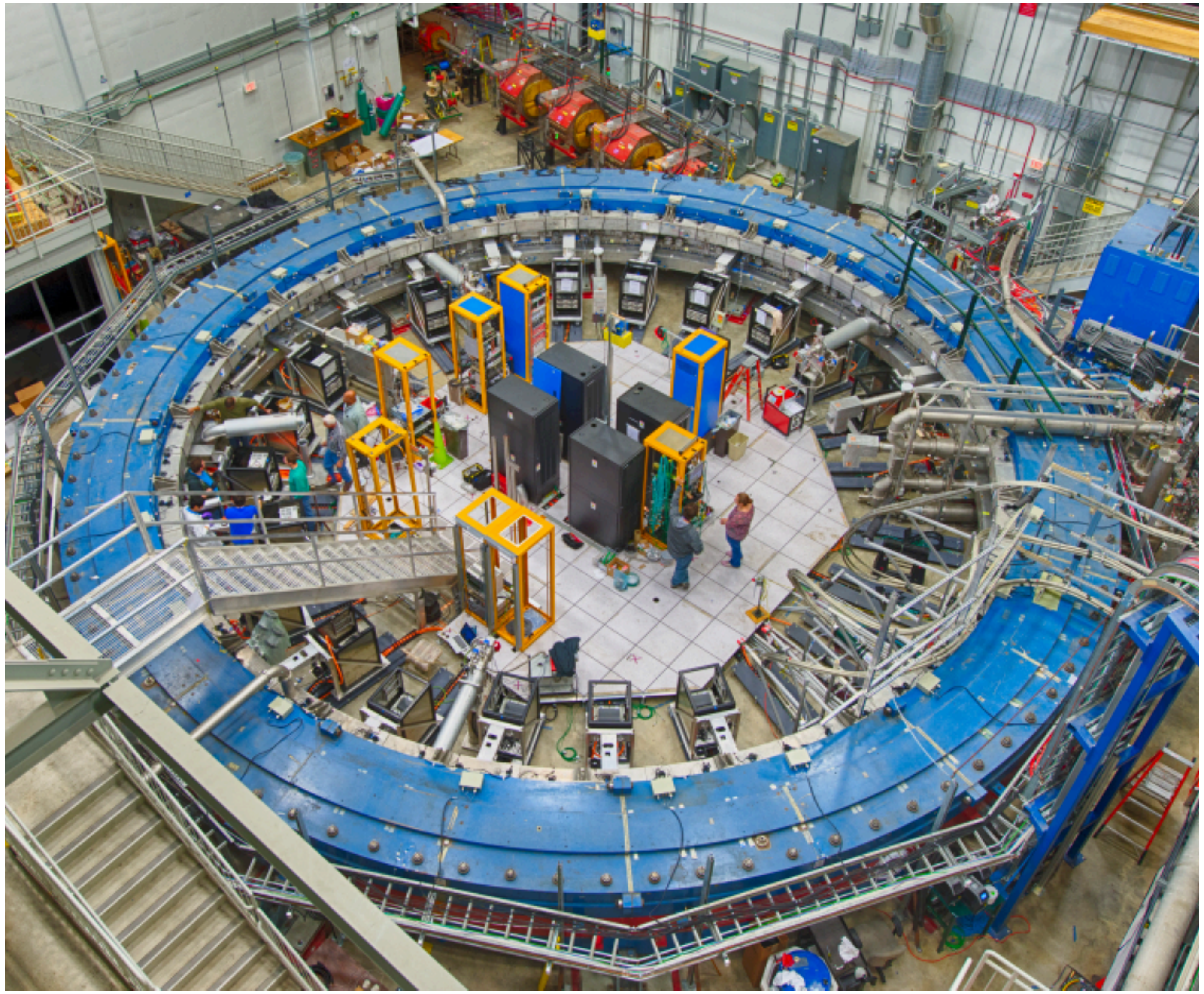



E-field correction is applied due to 0.5% momentum acceptance

# Magnet



g-2 Magnet in Cross Section



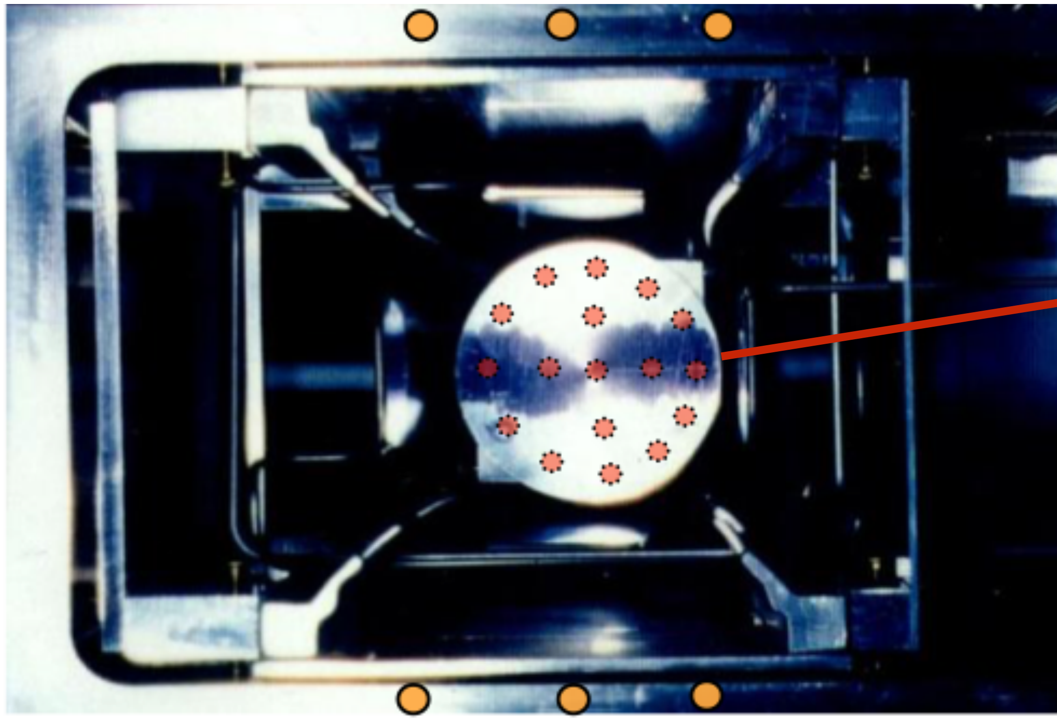
Achieved 25 ppm on field uniformity

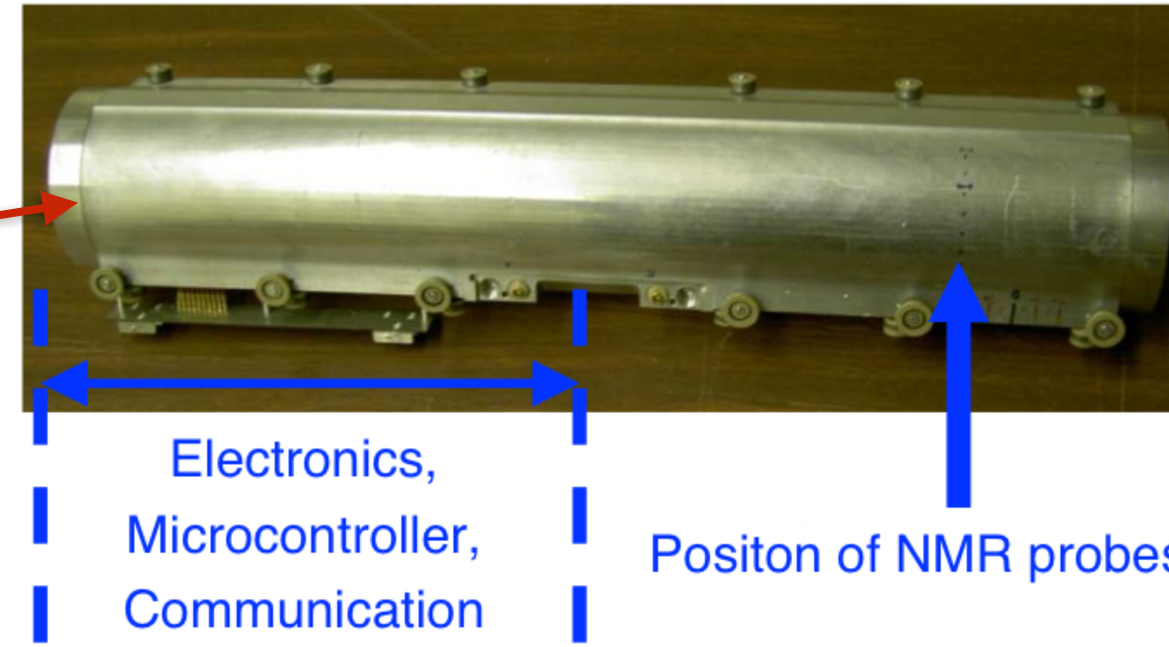
Superconducting C shaped magnet

Provides 1.45T B field(vertical and uniform)

- **12 Yokes**:Open on the inside, allows the decay positrons to reach to the detectors.
- **72 poles:**Low-carbon steel to minimize the impurity
- **144 Edge shims:** Minimize the local sextupole field by changing edge shim thickness
- **864 Steel wedges:** Angle adjustment (compensate quadrupole component), radial adjustment (shim local dipole field).
- **Surface correction coil:** Reduces non-uniformities on higher moment of field.

# Measuring $\omega_p$: Monitoring and Measuring the Magnetic Field

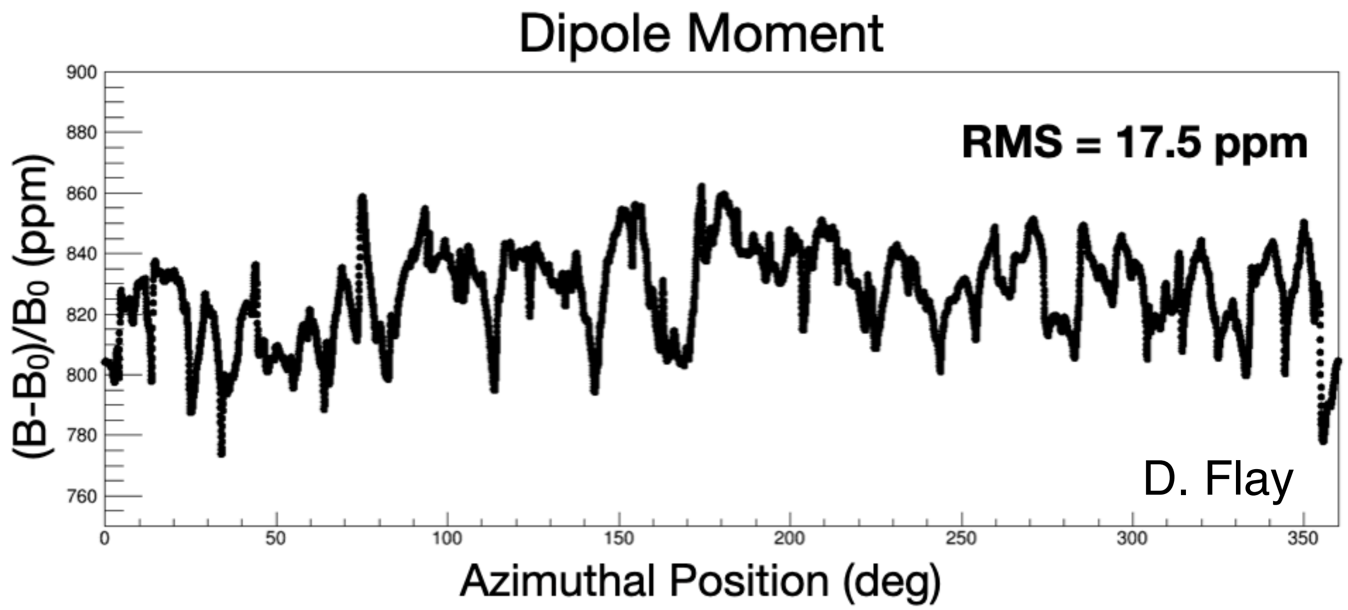


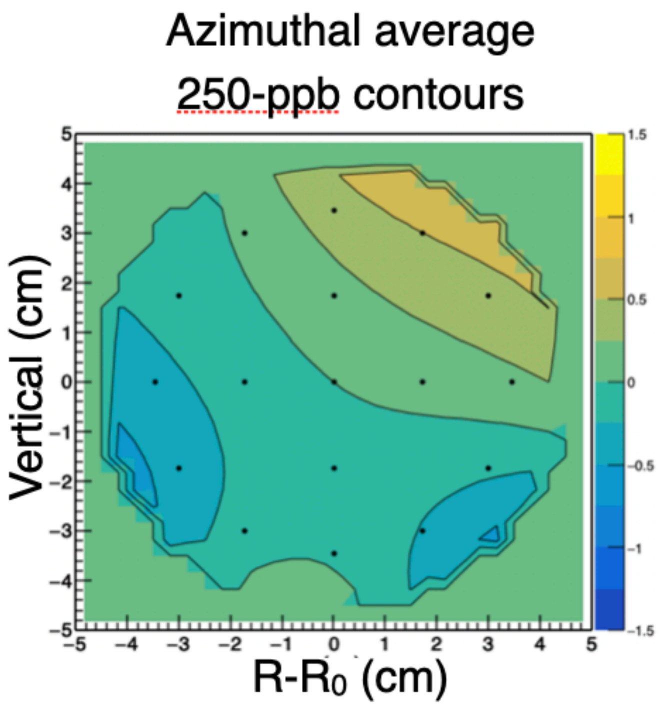



- **Fixed probes:**
  - 378 probes located on vacuum chamber
  - Measure the magnetic field while muons are inside the storage ring

- **Trolley(Motorized cart):**
  - 17 NMR probes
  - Circles around the ring on periodically
  - Measures the magnetic field in the storage region
  - Used to calibrate FP measurements

# Measuring $\omega_p$: Monitoring and Measuring the Magnetic Field




**To determine $\omega_p$ at all times:**

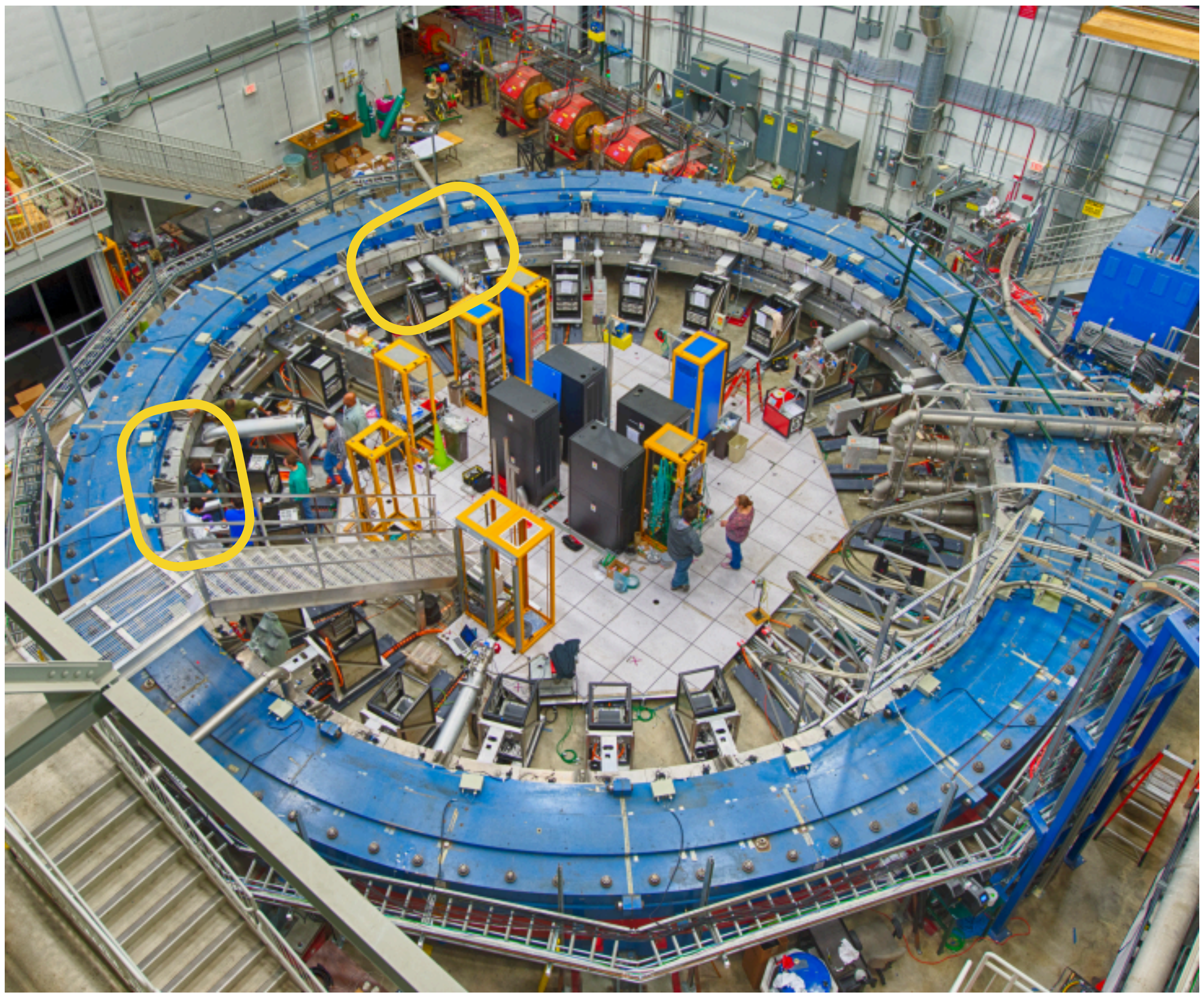
- Map the magnetic field in the storage region with trolley runs every 3 days
- Use fixed probes to interpolate the field between trolley runs

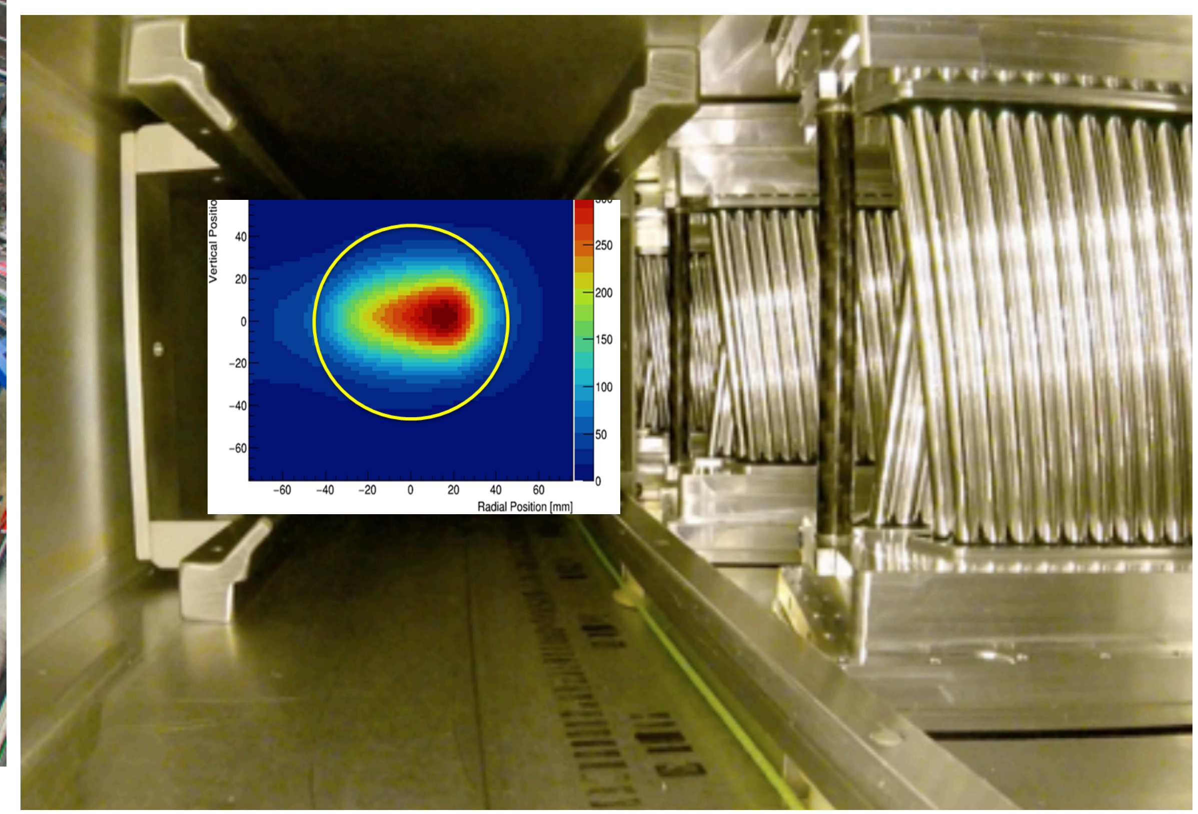
$$a_\mu = \left(\frac{g_e}{2}\right)\left(\frac{\omega_a}{\langle\omega_p\rangle}\right)\left(\frac{\mu_p}{\mu_e}\right)\left(\frac{m_\mu}{m_e}\right)$$

$$\langle\omega_p\rangle \approx \omega_p \otimes \rho(r)$$

# Detectors: Trackers

- Trackers
  - 2 straw-tracker stations
  - 8 modules per station each with 128 straws
  - Reconstruct muon beam profile from positron trajectories

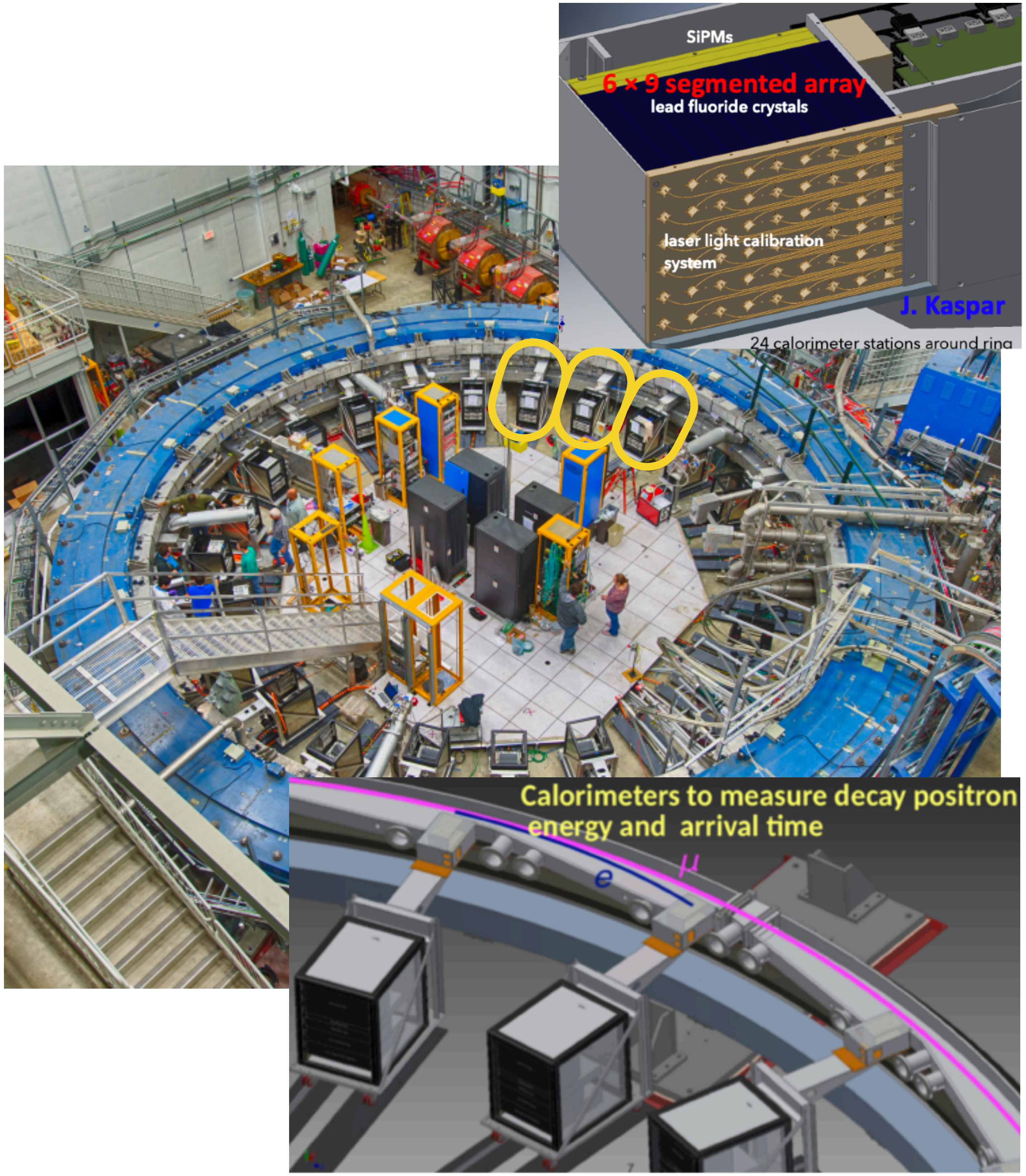




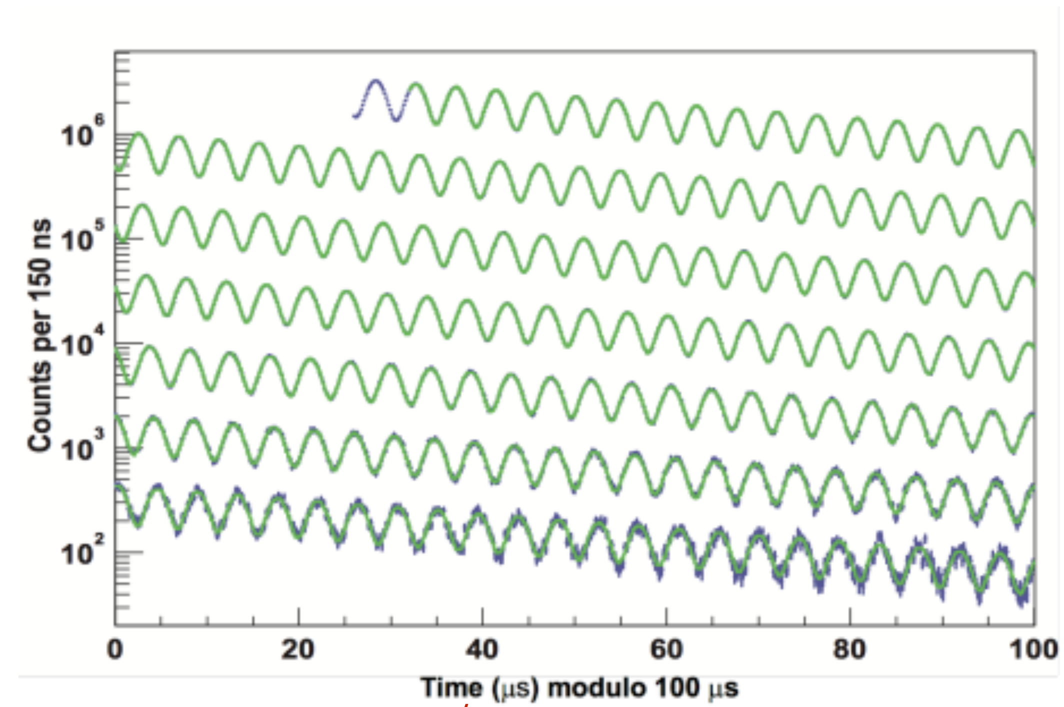

$$a_\mu = \left(\frac{g_e}{2}\right)\left(\frac{\omega_a}{\langle\omega_p\rangle}\right)\left(\frac{\mu_p}{\mu_e}\right)\left(\frac{m_\mu}{m_e}\right)$$

$$\langle\omega_p\rangle \approx \omega_p \otimes \rho(r)$$

# Detectors : Calorimeters




- **Calorimeters**
  - 24 segmented $PbF_2$ crystal calorimeters stationed around the ring
  - Detects energy and arrival time of $e^+$ decayed from muons: $\mu^+ \to e^+ \bar{\nu}_\mu \nu_e$



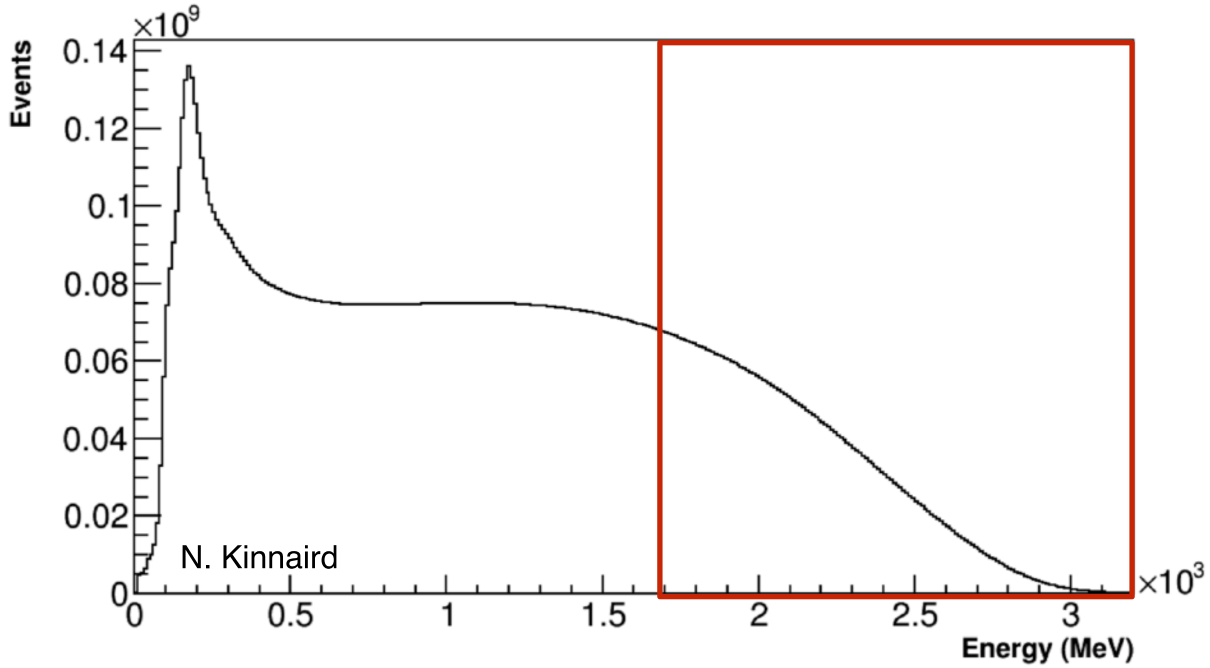

$$N(t) = N_0 e^{-t/\tau_\mu}[1 + A cos(\omega_a t + \phi)]$$

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

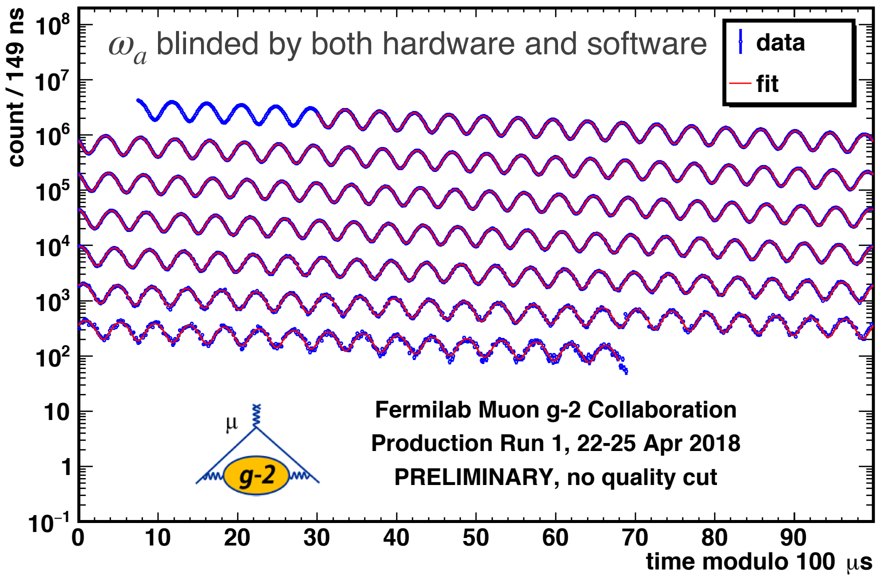
- **Laser System**
  - Calibrates calorimeter gain response
  - Provides time synchronization

# Measuring $\omega_a$: Different analysis techniques to reduce systematic errors

Energy distribution recorded in the calorimeter.




Choosing high energy positrons results in sinusoidal oscillation in positron spectrum




## Fitting Methods

- **T** method:
  - Apply an energy threshold to choose
- **A**symmetry-Weighted Method
  - Apply a smaller energy threshold and weight energy bin by g-2 Asymmetry.
- **R**atio method:
  - Remove the exponential decay of the positron spectrum by sorting the positron time spectra into four equal subsets and then combining them again.

Requires reconstructing the positron time and energy information

- **Q-**method:
  - A unique energy integrated method where you use sum over digitizer traces.

# Measuring $\omega_a$: An example of Fitting Method- Ratio

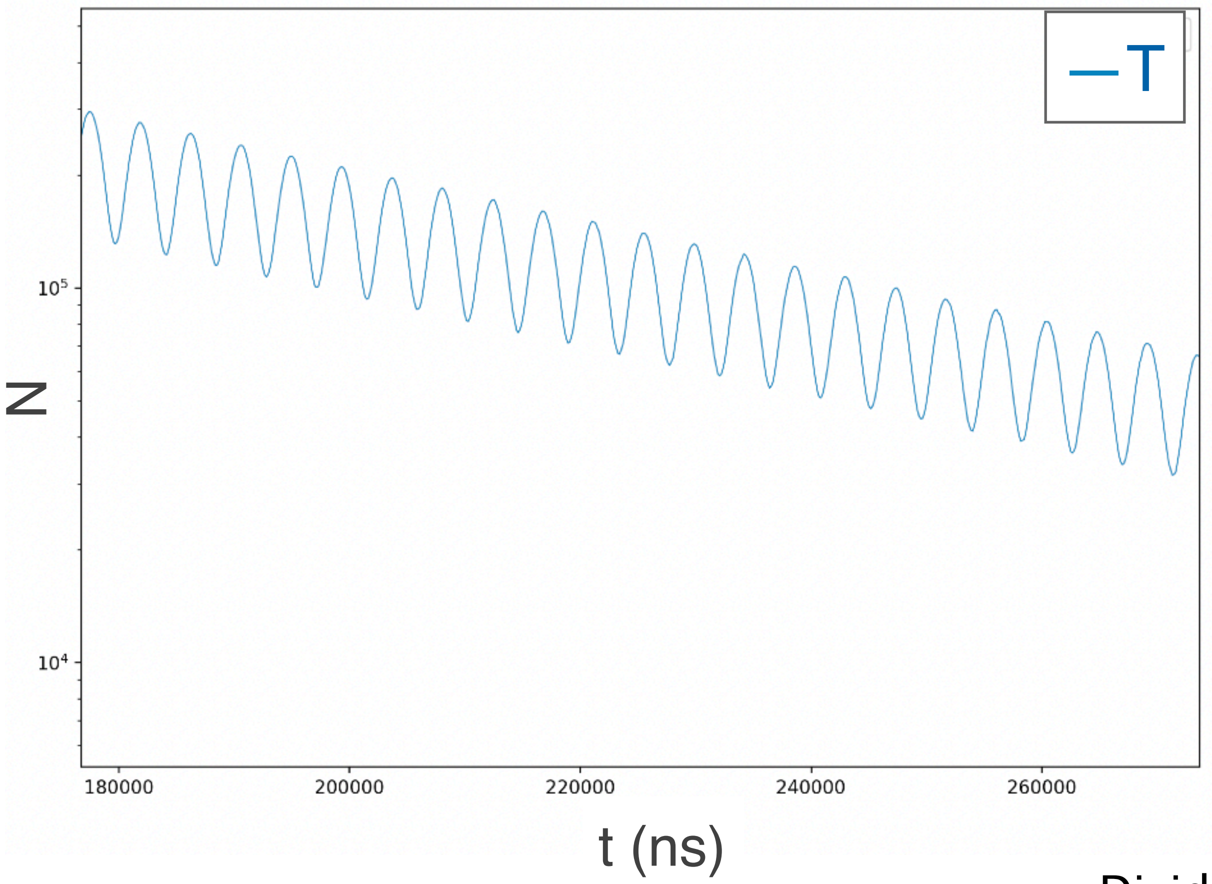
$$N(t) = N_0 e^{-t/\tau_\mu}[1 + A\cos(\omega_a t + \phi)]$$

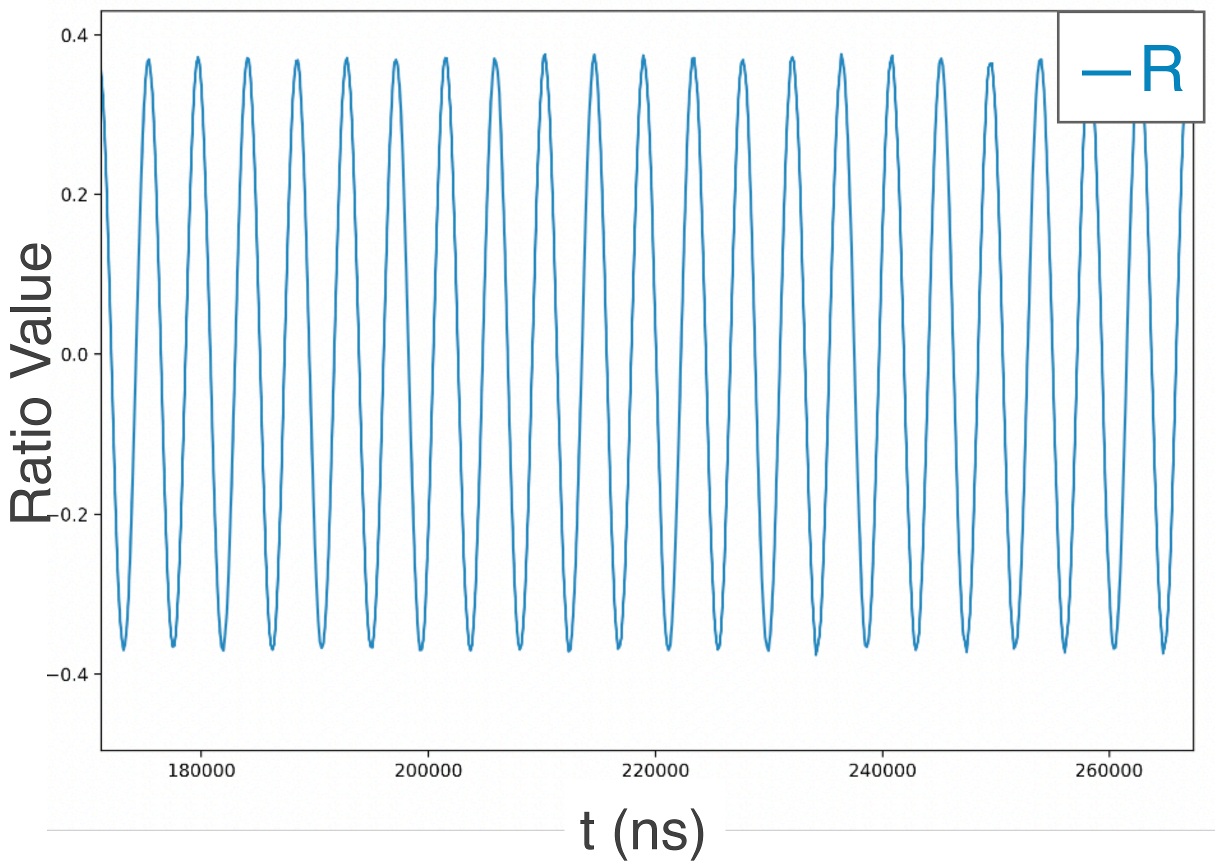
$$u_+(t) = N(t + T/2)/4$$
$$u_-(t) = N(t - T/2)/4$$
$$v_1(t) = v_2(t) = N(t)/4$$

$$U(t) = u_+(t) + u_-(t)$$
$$V(t) = v_1(t) + v_2(t)$$

$$R(t) = \frac{V(t) - U(t)}{V(t) + U(t)}$$

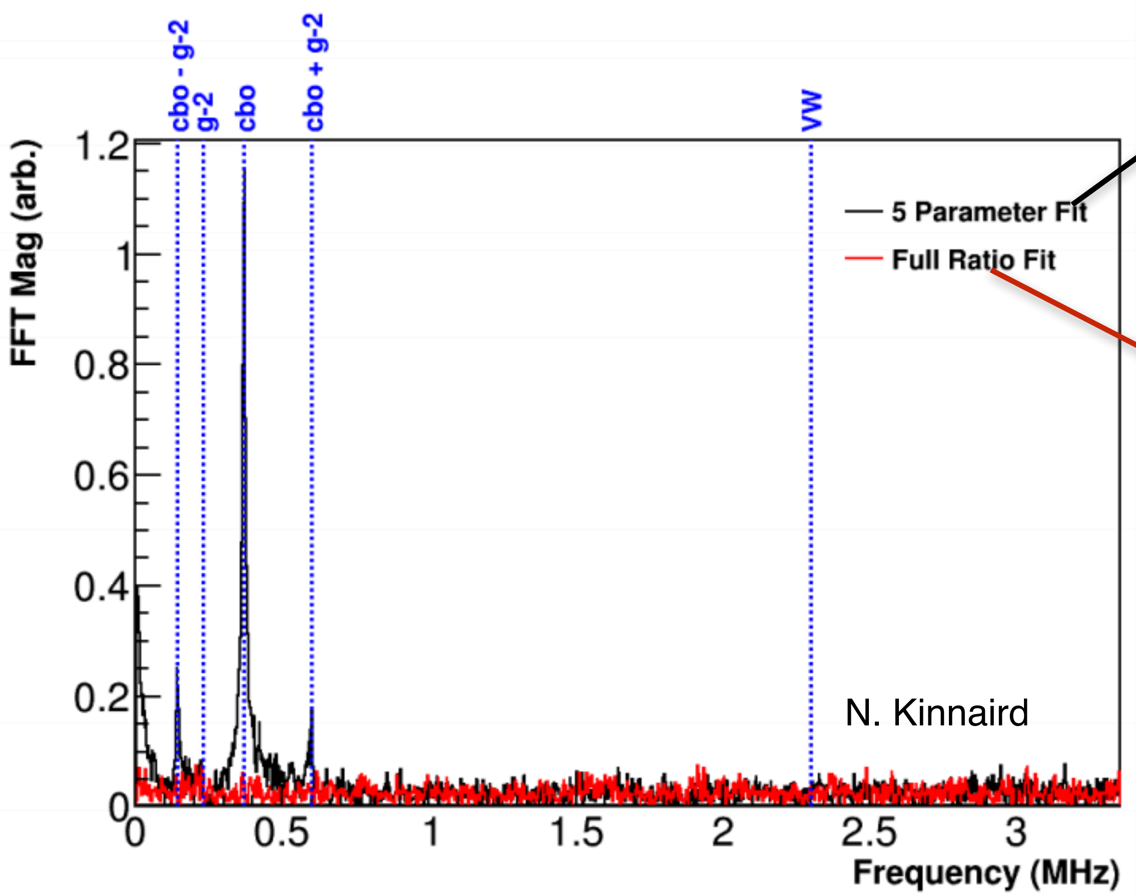
R is calculated differently when N(t) gets more complicated




-Divides out slow effects!

# Measuring $\omega_a$: Example of fitting positron time spectra




FFT analysis of fit residuals

## Underling Physics

5 parameter fit function

$$N(t) = N_0 e^{-t/\tau_\mu}[1 + A cos(\underline{\omega_a} t + \phi)]$$

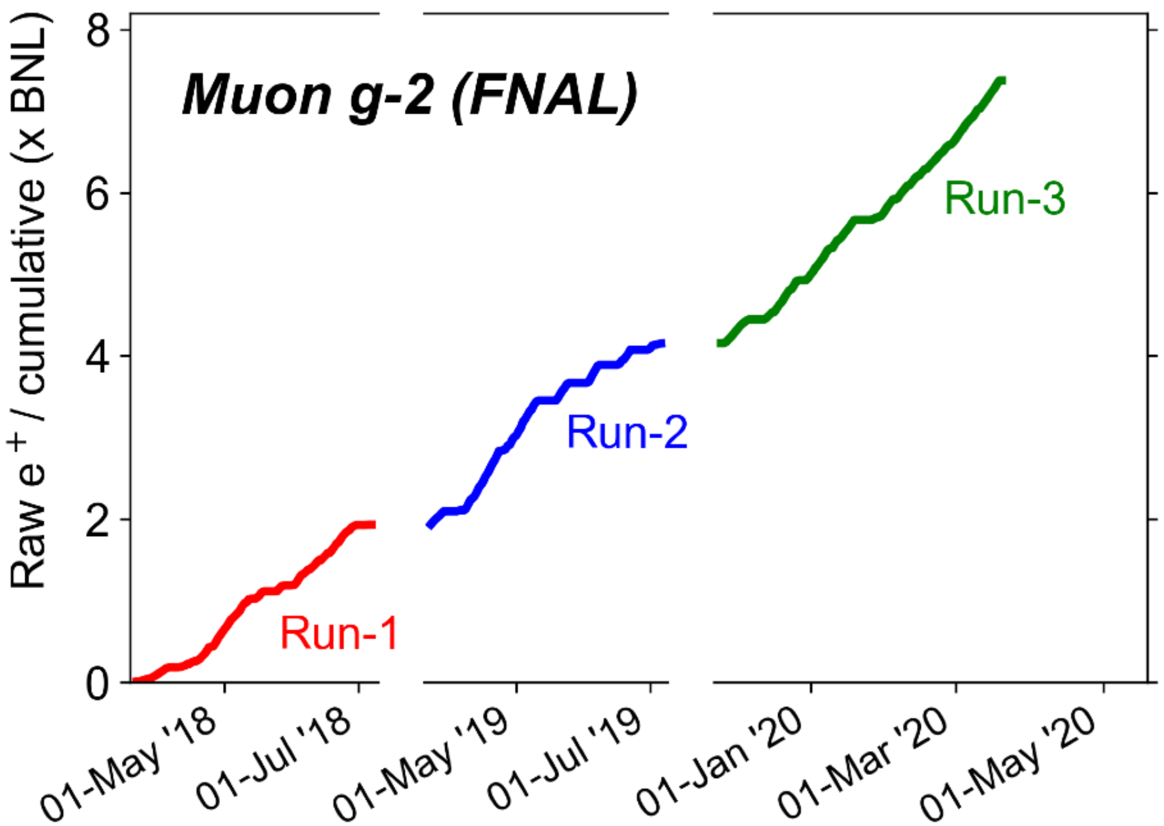
## Systematic Effects

Including CBO, lost muon,
other beam dynamics related parameters
improve the fit results

$$N(t) = N_0 e^{-t/\tau_\mu}[1 + A_{cbo}(t) cos(\underline{\omega_a} t + \phi_{cbo}(t))] \times N_{2cbo}(t)$$
$$\times [1 + A_{cbo} . e^{-t/\tau_{cbo}} . cos(\omega_{cbo} t + \phi_0)]$$
$$\times [1 + A_{vw} . e^{-t/\tau_{vw}} . cos(\omega_{vw}(t) t + \phi_{vw})]$$
$$\times [1 - K_{loss} \int_{t_0}^{t} e^{t/\tau_\mu} L(t) dt]$$

$$A_{cbo}(t) = A(1 + A_{cbo-A} e^{-t/\tau_{cbo}} cos(\omega_{cbo} t + \phi_{cbo-A}))$$
$$\phi_{cbo}(t) = \phi_0 + A_{cbo-\phi} e^{-t/\tau_{cbo}} cos(\omega_{cbo} t + \phi_{cbo-\phi})$$
$$N_{2cbo}(t) = (1 + A_{2cbo-N} e^{-2t/\tau_{cbo}} cos(2\omega_{cbo} t + \phi_{2cbo-N}))$$

# Experiment Data Collection Status

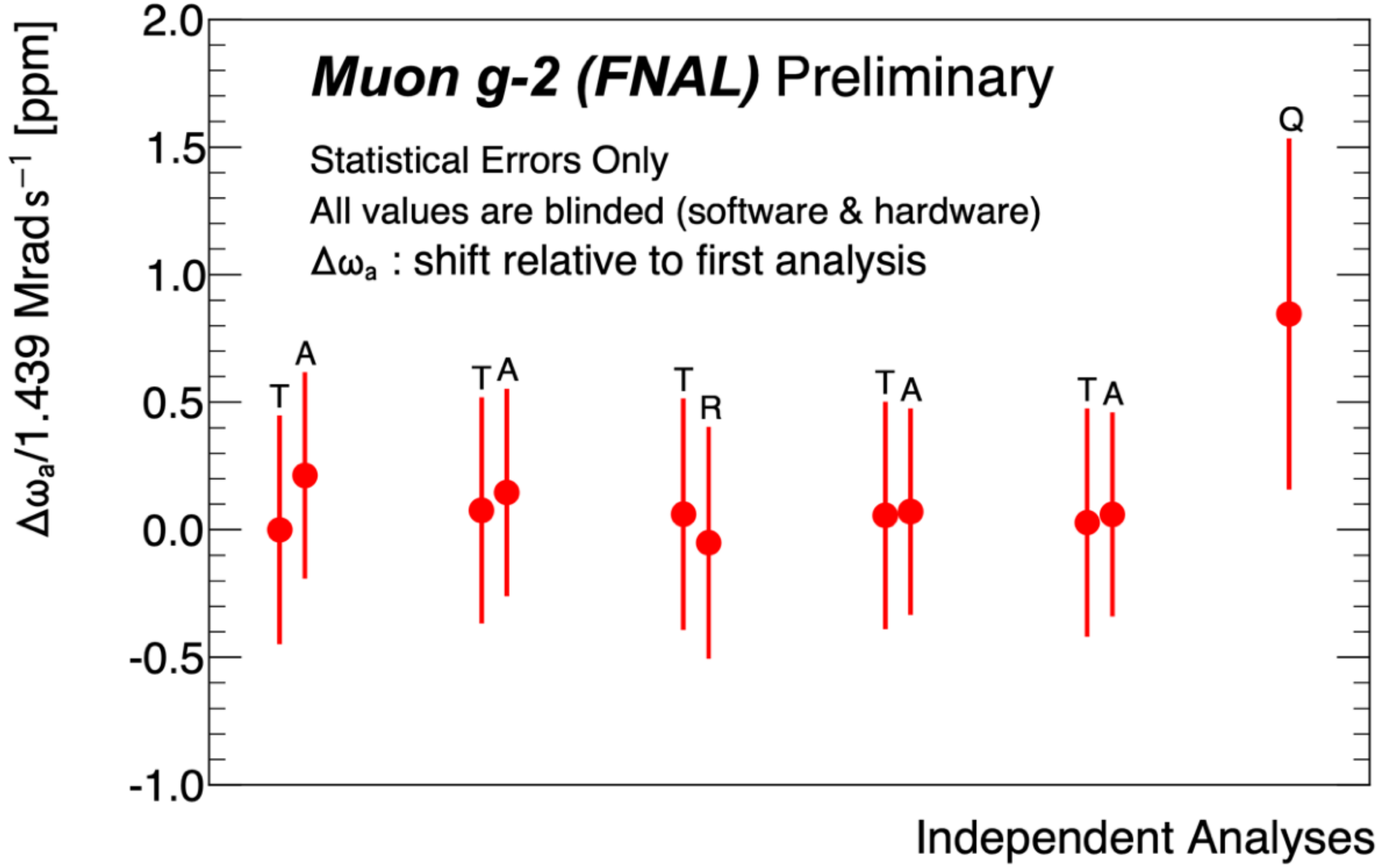



- Total of 6.5 X BNL statistics collected (after the cuts):
  - Run-1 ~ 1 BNL
  - Run-2 ~ 2.2 BNL
  - Run-3 ~ 3.2 BNL
- Run-3 ended in March 2020
  - Improved kick: Most recent part of Run-3 had a perfectly centered beam owing to improved kicker system.
  - Improved field stability:More stable temperature

# Run-1 Analysis Status

- During Run 1:
  - Collected nearly 1xBNL equivalent of data
  - Total statistical error ~ 450 ppb
  - Systematic Error is still being worked through. Major systematics studies are almost completed.

- 6 different $\omega_a$ analysis team look at the precession data and performed a commonly software blinded analysis
  - Still blinded on hardware and software
  - 4 different fitting methods
  - 2 independent reconstruction algorithms
  - All agree with each other
- 2 different $\omega_p$ analysis team is looking at the field data
  - Blinded on software
  - Have just done a relative unblinding
  - Both agree on each other on all relative trends for all Run-1 sub-datasets.



# Systematics (TDR)

## Systematics on $\omega_a$

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

## Systematics on $\omega_p$

| Category | E821 [ppb] | Main E989 Improvement Plans | Goal [ppb] |
|---|---|---|---|
| Absolute field calibration | 50 | Special 1.45 T calibration magnet with thermal enclosure; additional probes; better electronics | 35 |
| 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 |
| Trolley measurements of $B_0$ | 50 | Reduced position uncertainty by factor of 2; improved rail irregularities; stabilized magnet field during measurements* | 30 |
| Fixed probe interpolation | 70 | Better temperature stability of the magnet; more frequent trolley runs | 30 |
| Muon distribution | 30 | Additional probes at larger radii; improved field uniformity; improved muon tracking | 10 |
| Time-dependent external magnetic fields | – | Direct measurement of external fields; simulations of impact; active feedback | 5 |
| Others † | 100 | Improved trolley power supply; trolley probes extended to larger radii; reduced temperature effects on trolley; measure kicker field transients | 30 |
| Total systematic error on $\omega_p$ | 170 | | 70 |

» 100 ppb statistical

» 70 ppb field systematics

» 70 ppb precession systematics

140 ppb uncertainty in total

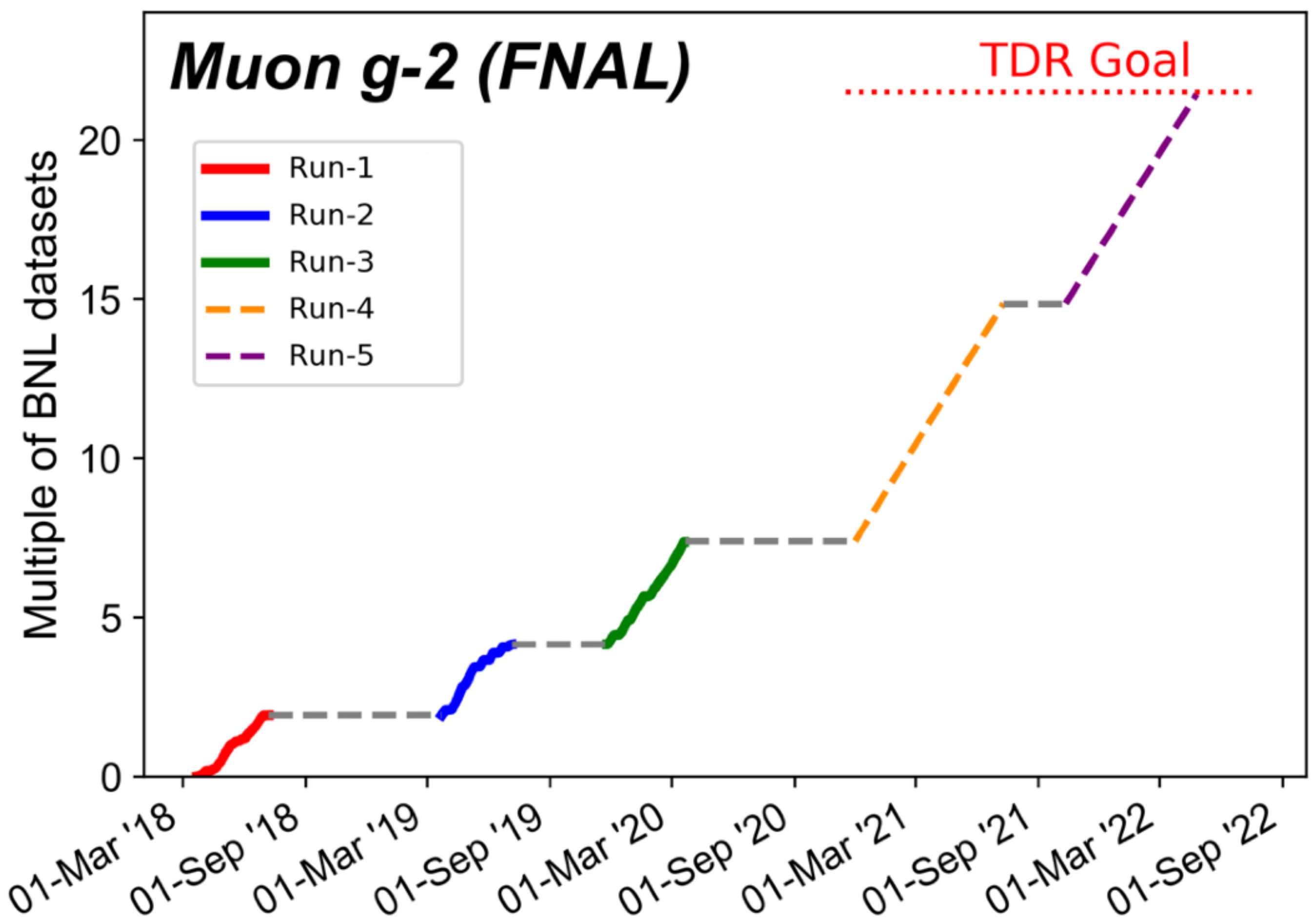
Understanding the systematics with:

- Sophisticated modeling tools
- Hardware based tests backed up with data driven approaches

# What's Next

- Run-1 is close to being published
- Run-2 first phase of analysis has started.
- Calibration program in the summer → Better understanding of systematics
- Run-4 is expected to begin Fall 2020
- Expect to have achieve 21.5 X BNL with Run-4 and Run-5
- Stay Tuned for Run-1 results!

Extrapolated raw positron counts



# Thanks!

# Back-up

## Muon g-2 Collaboration
## 7 Countries, 33 Institutions, 203 Collaborators

### USA
- Boston
- Cornell
- Illinois
- James Madison
- Kentucky
- Massachusetts
- Michigan
- Michigan State
- Mississippi
- North Central
- Northern Illinois
- Regis
- Virginia
- Washington

### USA National Labs
- Argonne
- Brookhaven
- Fermilab

### China
- Shanghai Jiao Tong

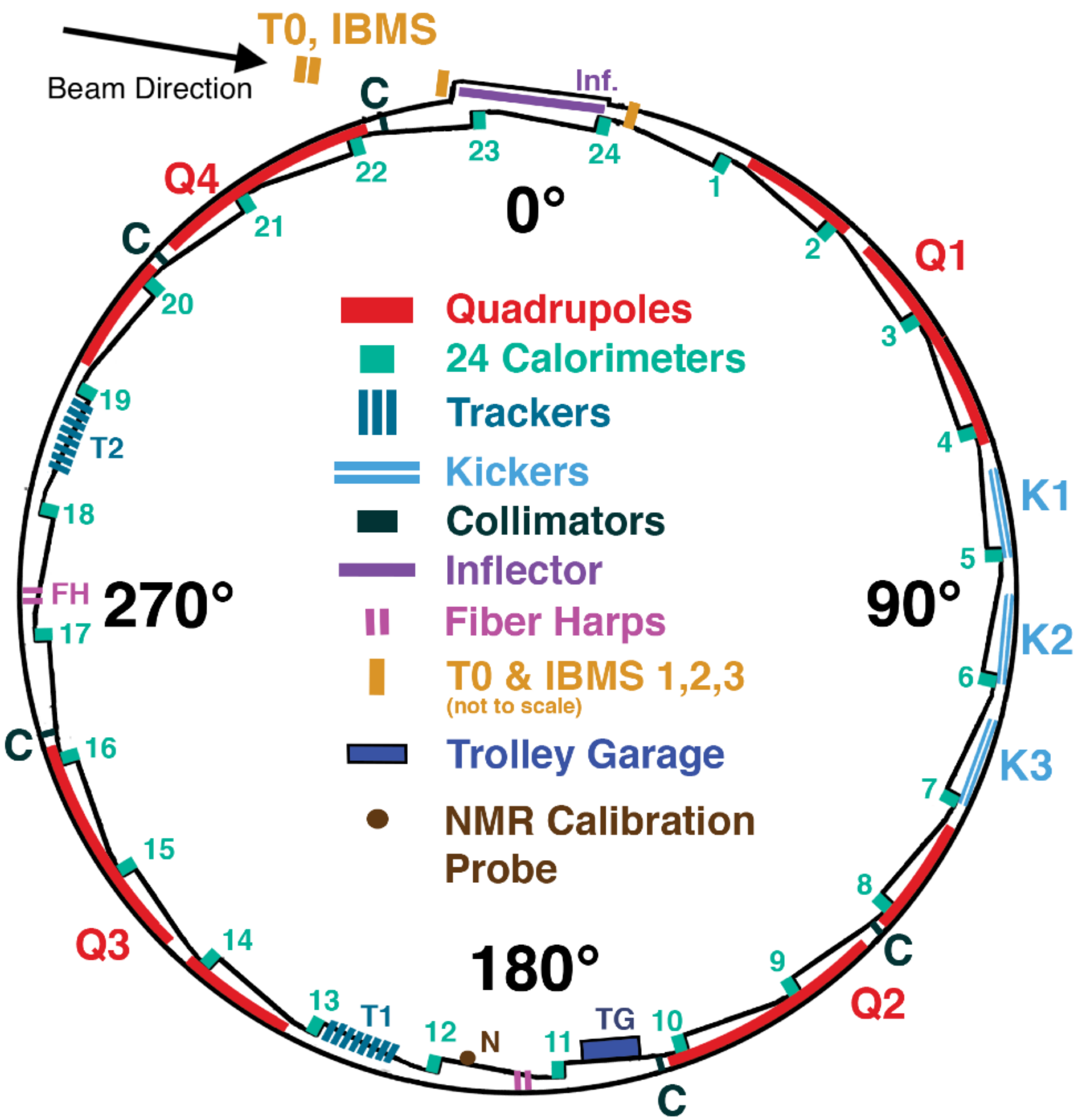
### Germany
- Dresden

### Italy
- Frascati
- Molise
- Naples
- Pisa
- Roma Tor Vergata
- Trieste
- Udine

### Korea
- CAPP/ISB
- KAIST

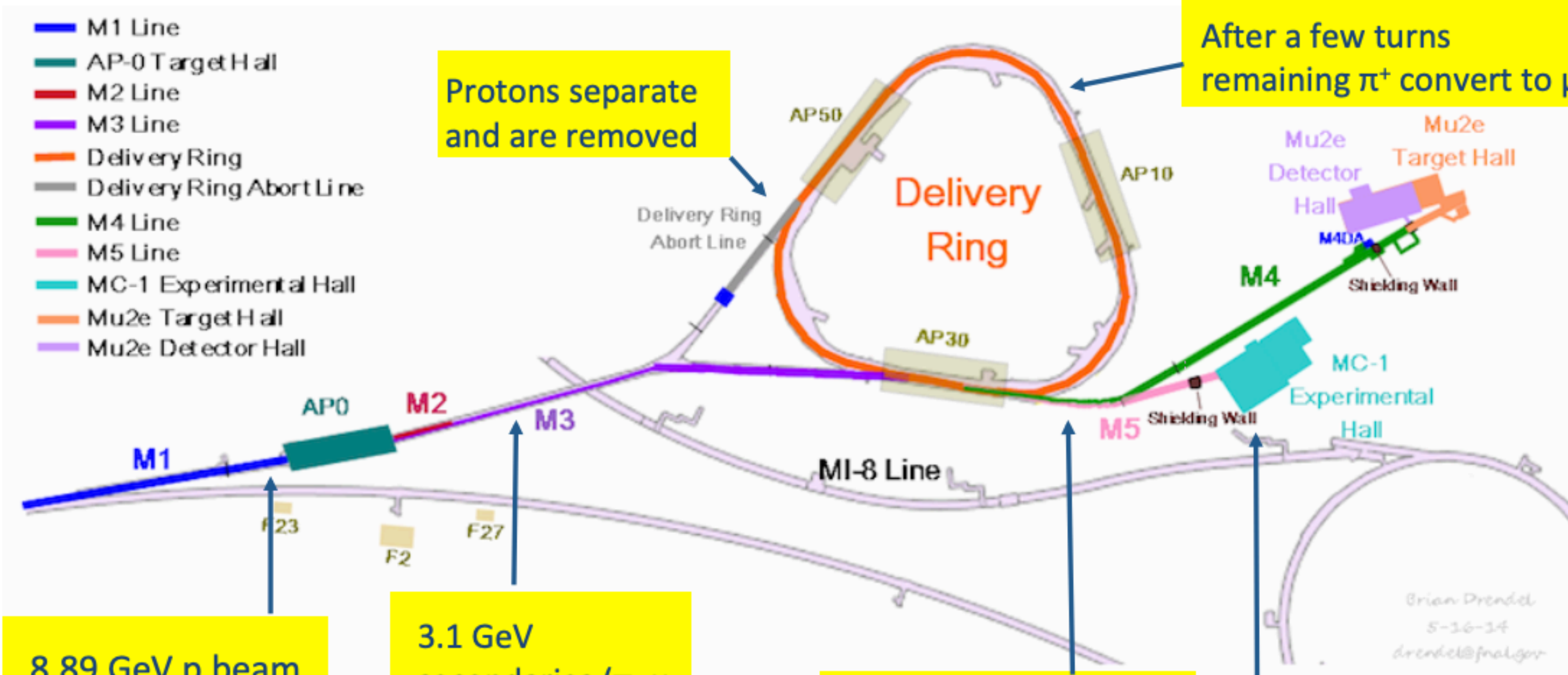
### Russia
- Budker/Novosibirsk
- JINR Dubna

### United Kingdom
- Lancaster/Cockcroft
- Liverpool
- Manchester
- University College London




| | E821 | E989 |
|---|---|---|
| Number of positrons | $9\times10^{9}$ | $2\times10^{11}$ (x 20 BNL ) |
| Statistical Uncertainty | 480 ppb | 100 ppb |
| Systematic Uncertainty | 248 ppb | 100 ppb |
| Total Uncertainty | 540 ppb | 140 ppb |

# Muon Beamline at Fermilab




Protons separate and are removed

After a few turns remaining $\pi^+$ convert to $\mu^+$

8.89 GeV p beam impacts the target

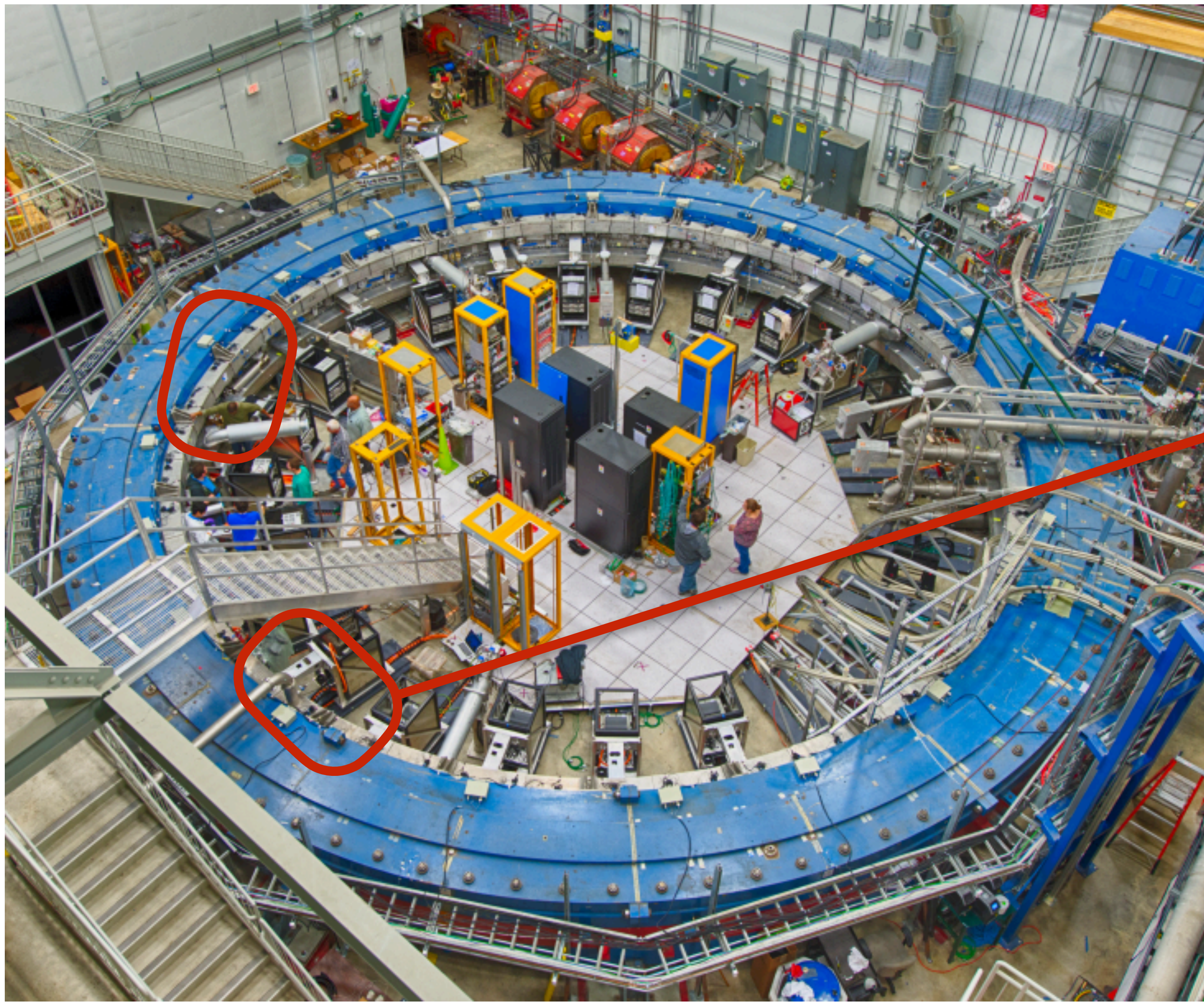
3.1 GeV secondaries ($\pi$, $\mu$, p) travel along M2 & M3, where $\mu^+$ are collected from $\pi^+$ decays

$\mu^+$ are extracted from the ring and transferred into the storage ring via M5

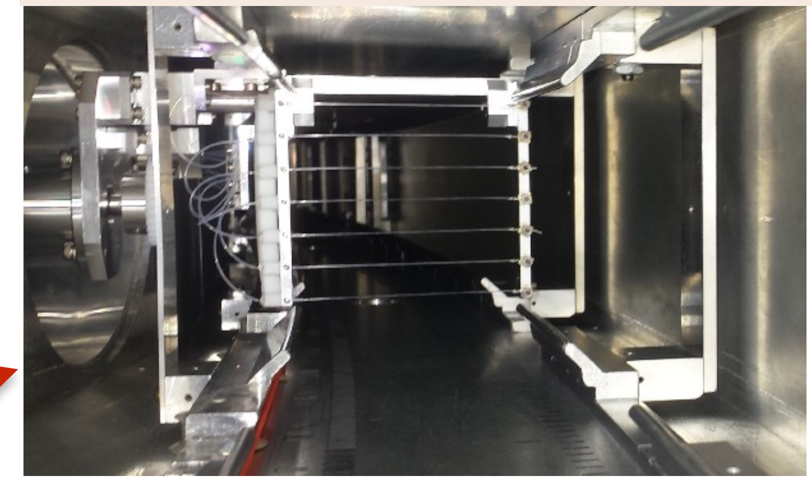
$\mu^+$ enter the g-2 storage ring

D. Stratakis

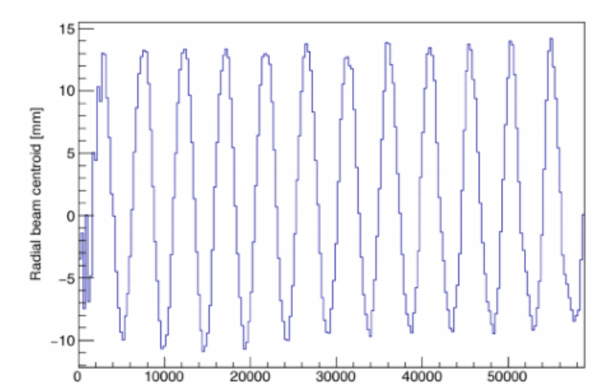
# Monitoring the Injected Beam



Y Profile Monitor at 180 degree position



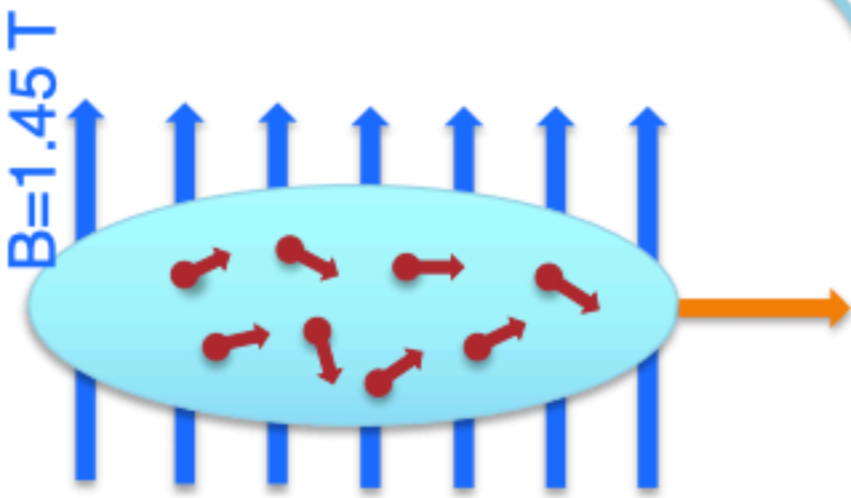
- **Fiber Harps**
  - Scintillating Fibers
  - x and y profile monitoring
  - Tool for beam commissioning



# E-field and Pitch Corrections

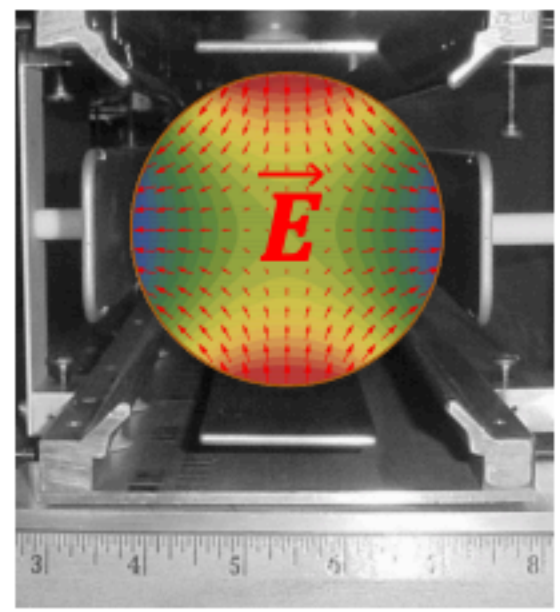
$$\omega_a = \langle (\vec{\omega}_s - \vec{\omega}_C)_y \rangle = -\frac{e}{m} a_\mu \langle B \rangle + \frac{e}{m} a_\mu \left\langle \left( \left(\frac{\gamma}{\gamma+1}\right) (\vec{\beta} \cdot \vec{B})\vec{\beta} + \left(1 - \frac{1}{(1+\delta)^2}\right) \frac{\vec{\beta} \times \vec{E}}{c} \right)_y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

**Pitch Correction "$C_P$"**




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

**E-field Correction "$C_E$"**




Injected muon bunch's Momentum Acceptance:

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

$$\Downarrow$$

$$\pm 0.5\%$$

D. Tarazona