Muon g-2 Experiment at Fermilab

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SIST/GEM Summer Lectures

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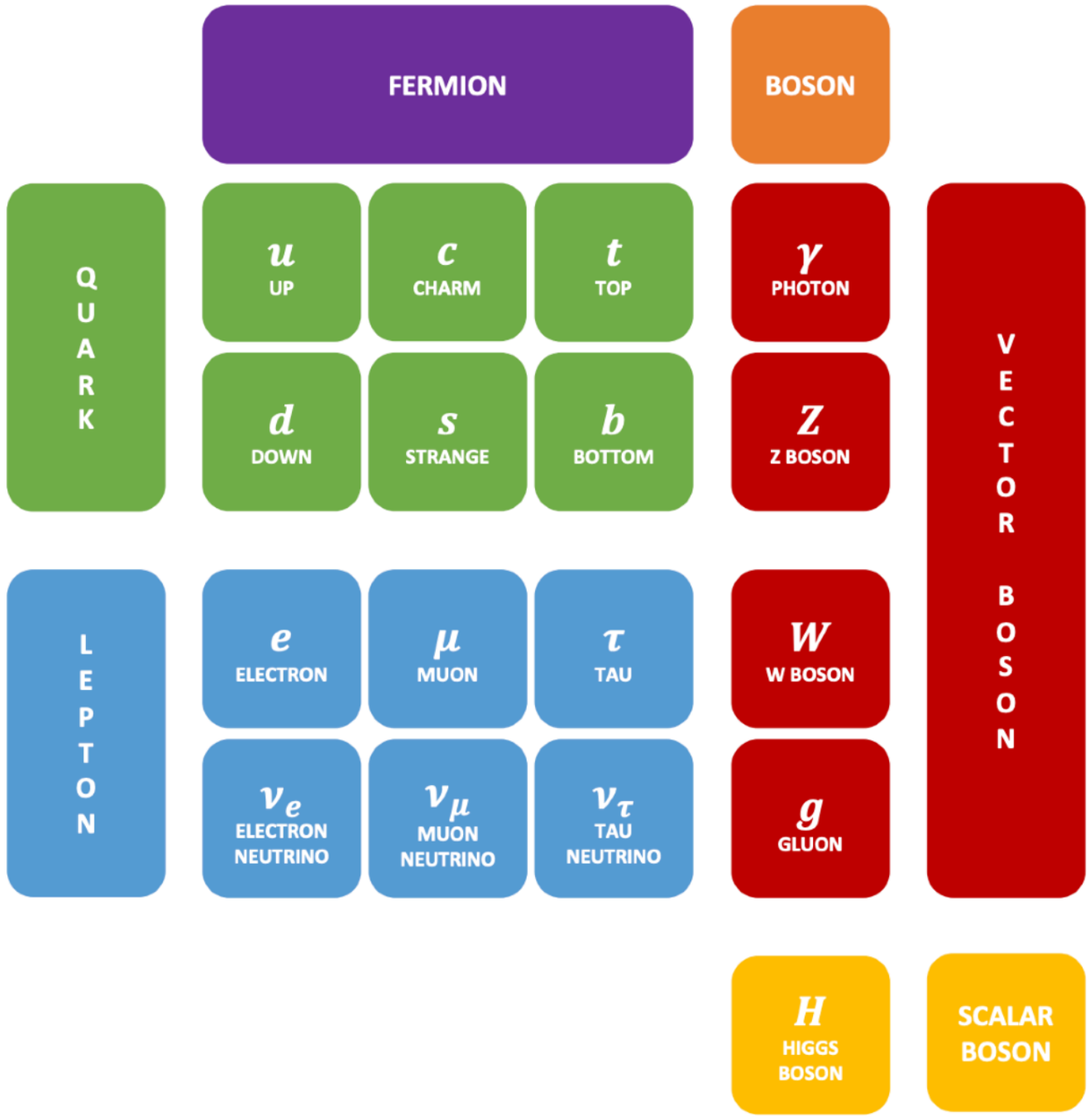
ILLINOIS
UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

What leads us to searching for new physics

- We have SM to explain
  - Three out of four fundamental forces
  - Classify all elementary particles
  - Successful on providing experimental prediction

- But it is not complete on describing fundamental interactions



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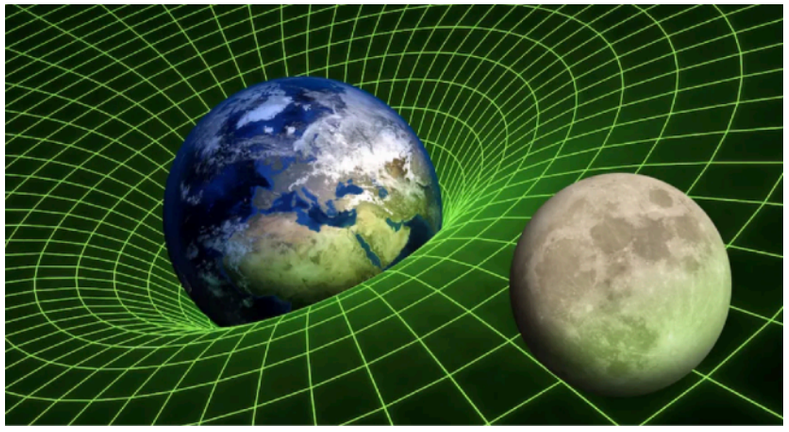
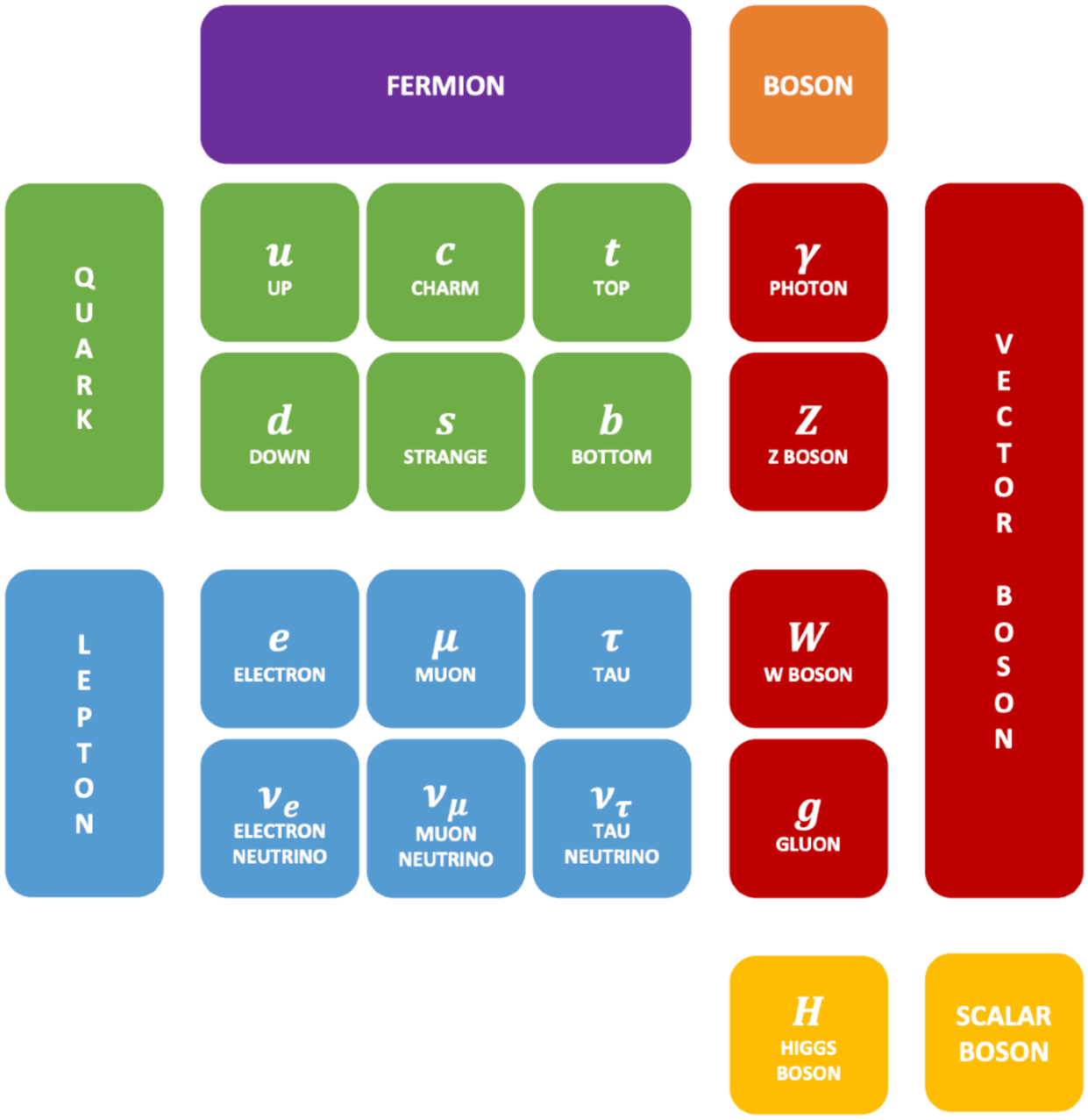
❖Theory of gravitation





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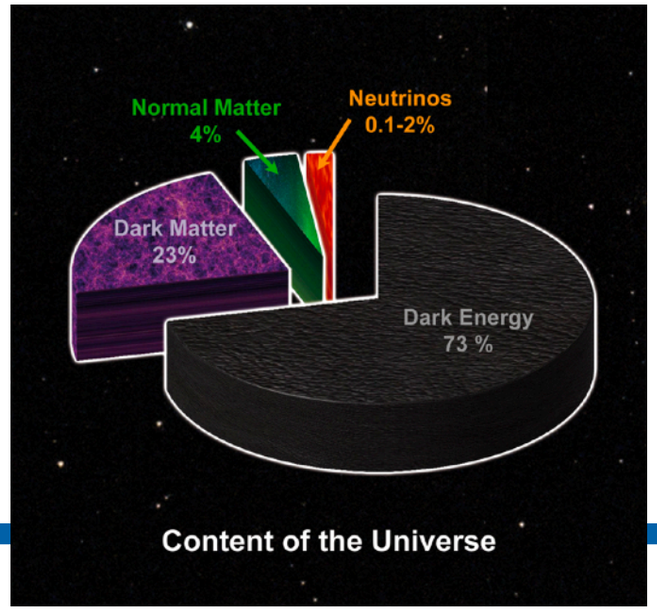
❖Dark Energy



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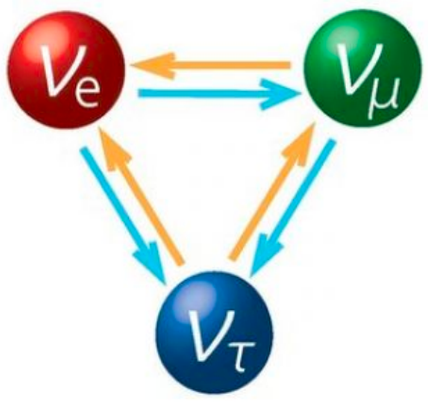
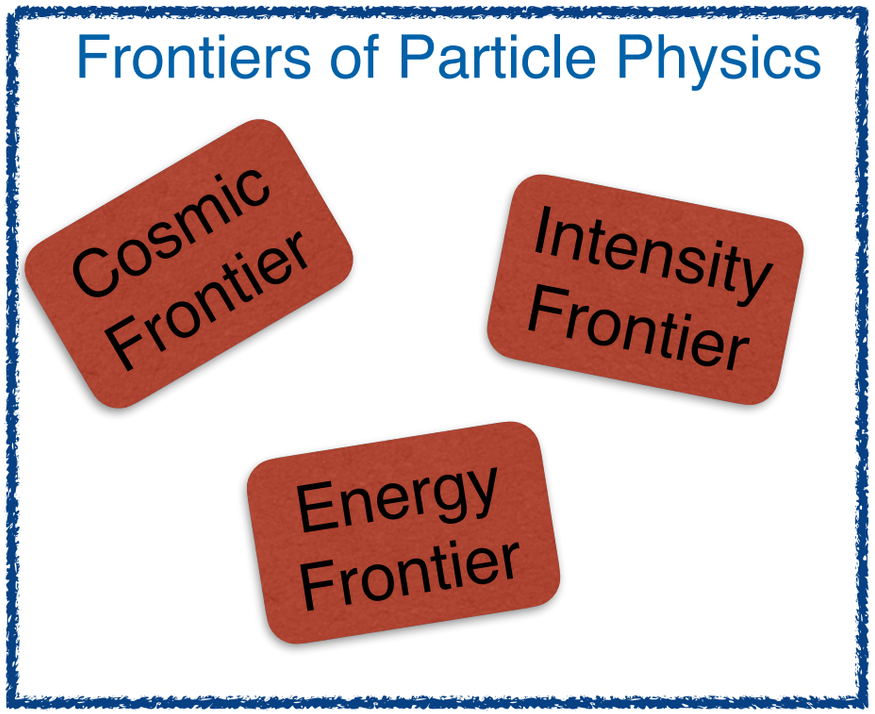
❖Neutrino oscillations

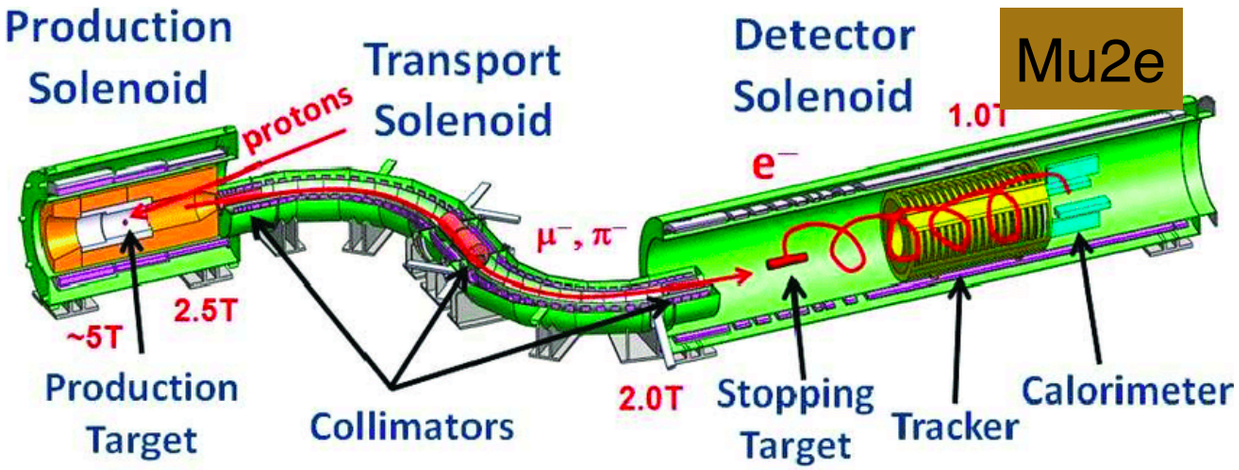


Searching for new physics

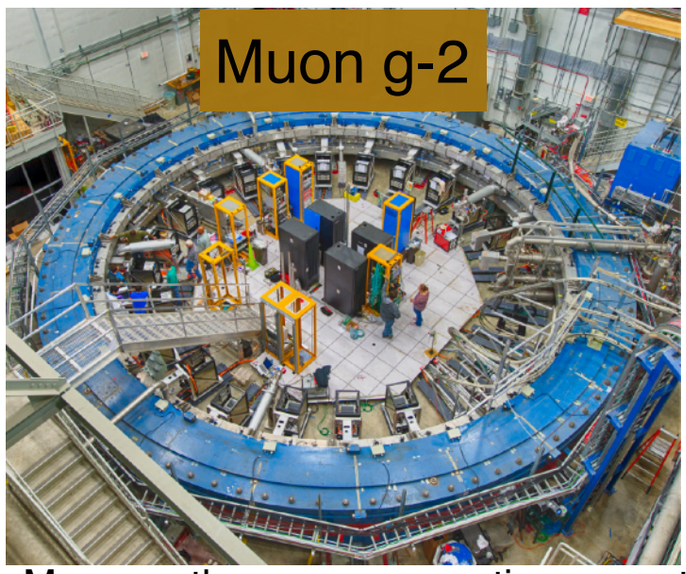


High Intensity:

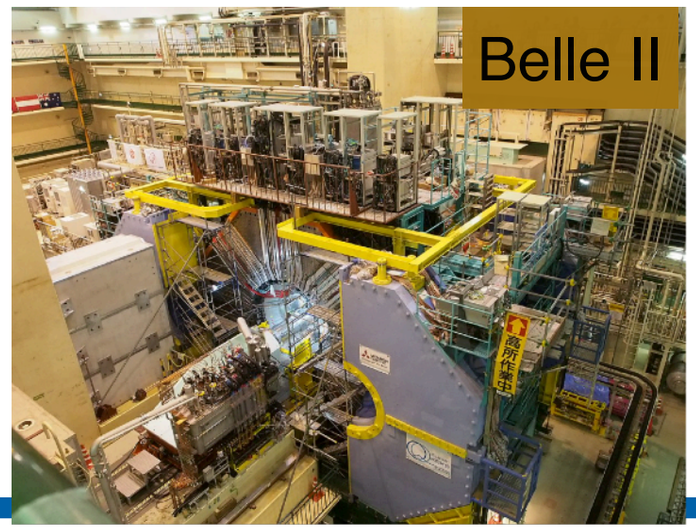
- Accurate and sensitive measurement to test SM
  - Lower energy
  - See new particles or forces
  - Even forbidden processes…



Searching for muon to electron event



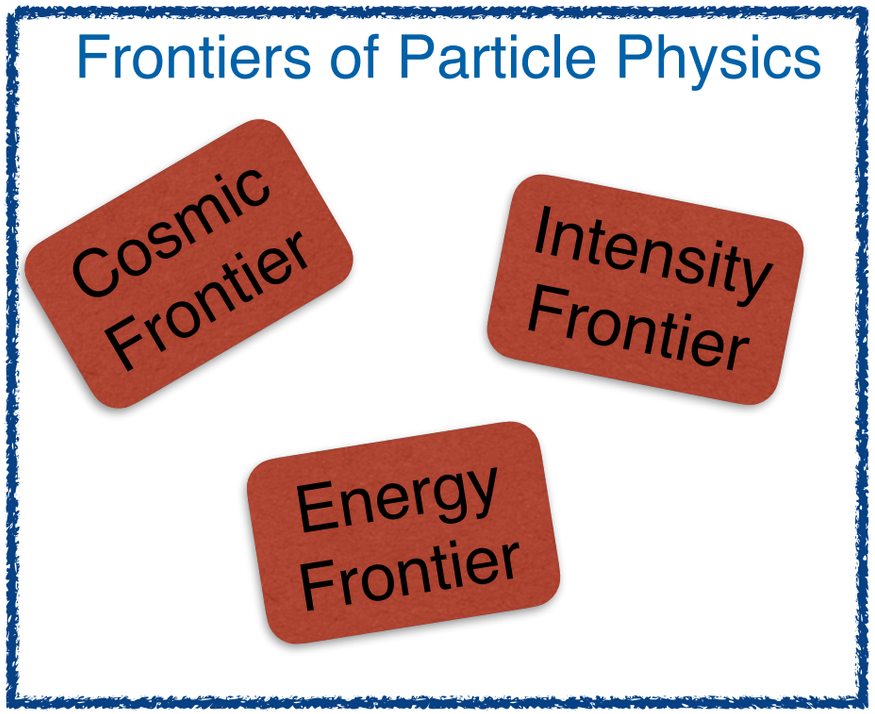
Measure the muon magnetic moment Anomaly



Study the properties of B mesons

-Exploring with precision measurements-

Searching for new physics



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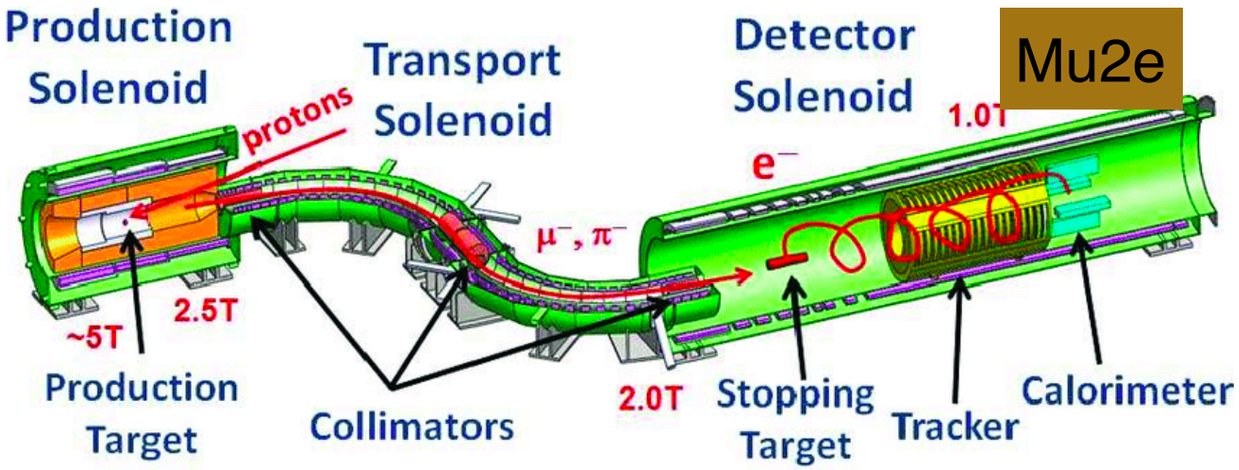

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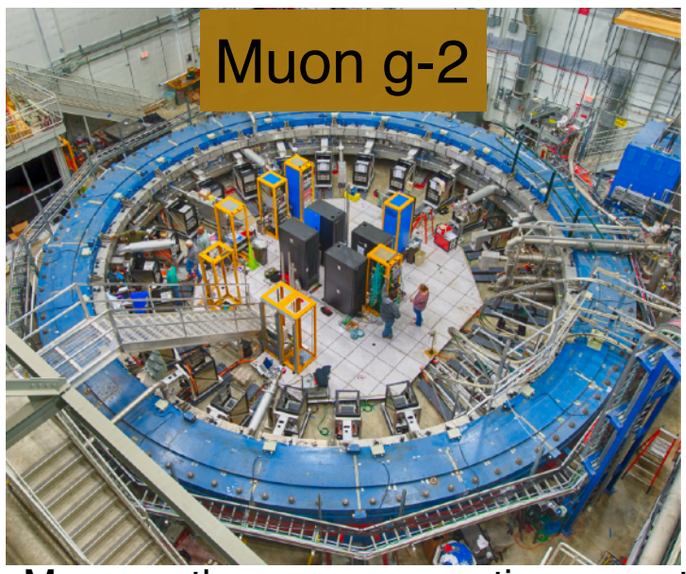

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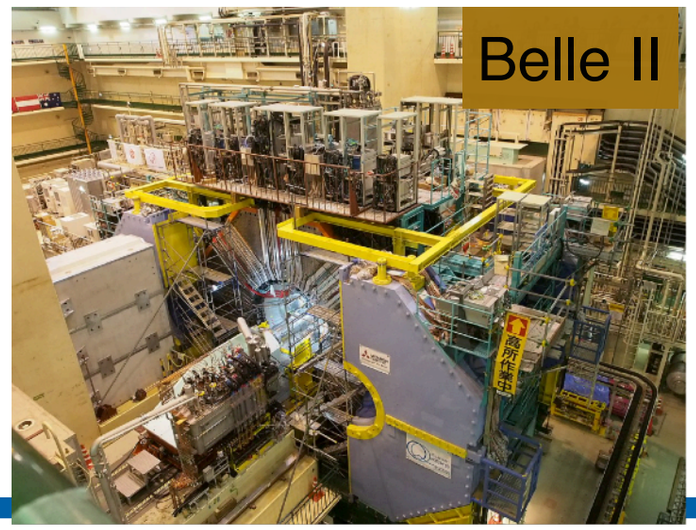

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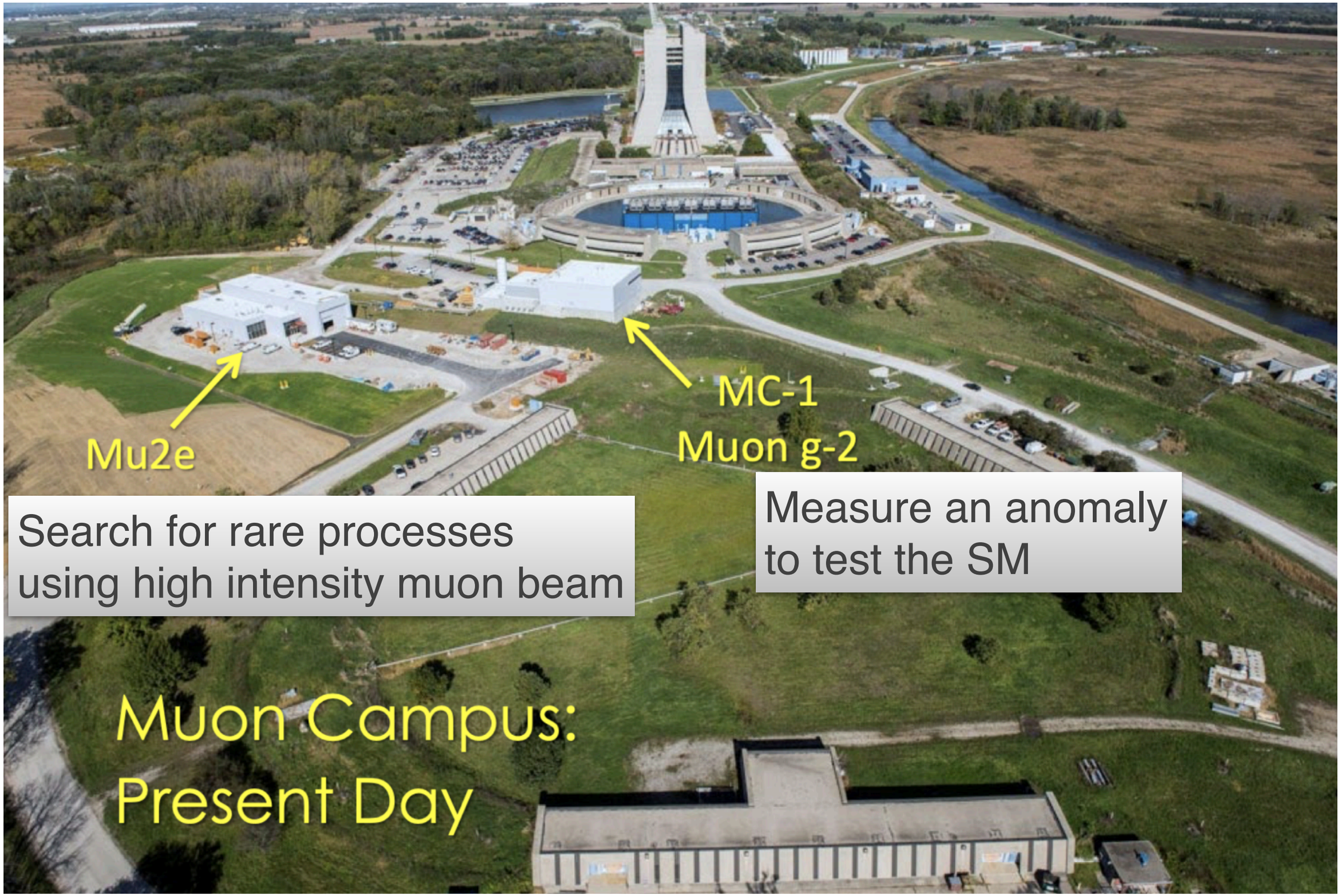
Muon Physics at Fermilab



Why the Muons?

Muons are useful!

- $(m_\mu/m_e)^2 = 40000$ -> More sensitive to new physics.
- Easy to produce, muon beams from pion decays(99.9%).
- Relatively long lifetime (2.2 μs) -> In the lab frame 64.4μs

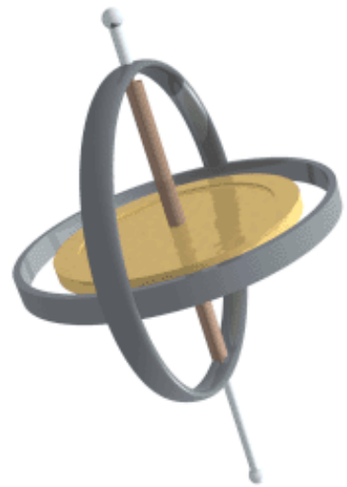
Why measure the muon anomaly

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

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 (shows strength of the 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!

Measuring this anomaly could tell us if there are new particles or even forces that contribute to a_μ

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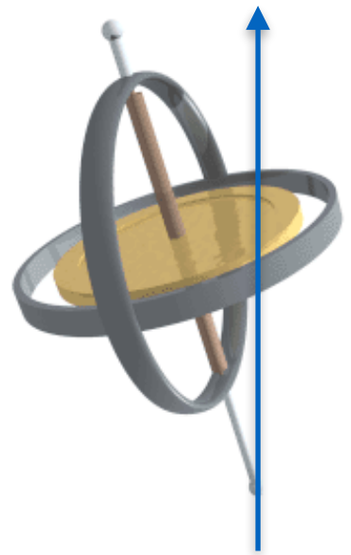

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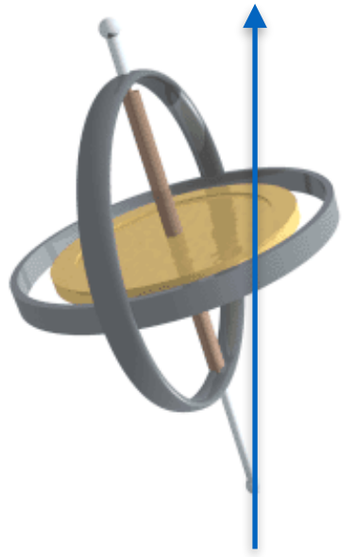

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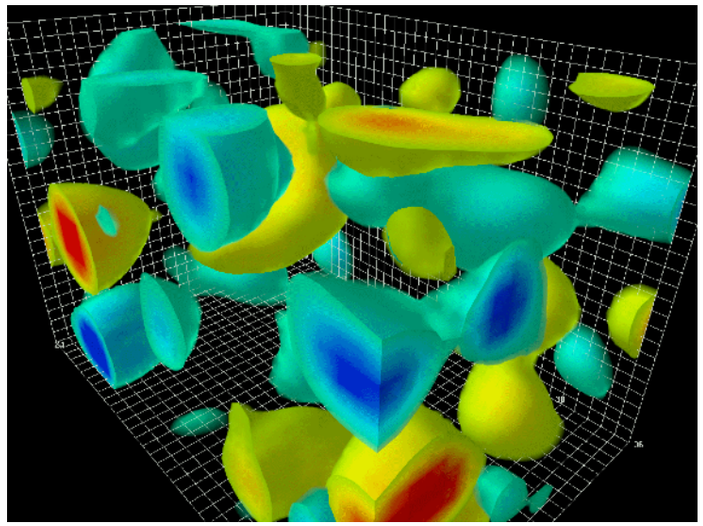
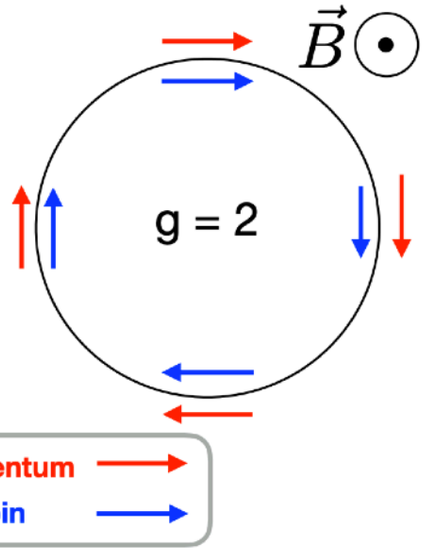


- Particles don't exist by themselves
- They are surrounded by a quantum vacuum where virtual particles exists for a short time
- That could explain muon's interaction with the magnetic field

Muon Magnetic Moment and Measuring the Anomaly

polarized muons in a magnetic field

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



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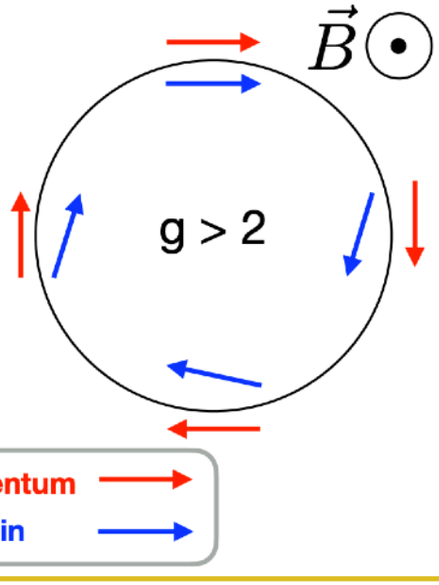

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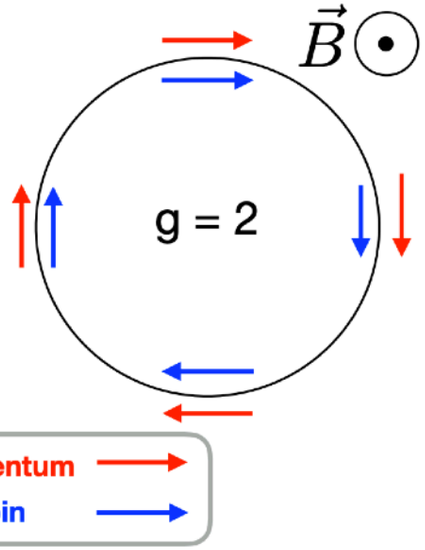

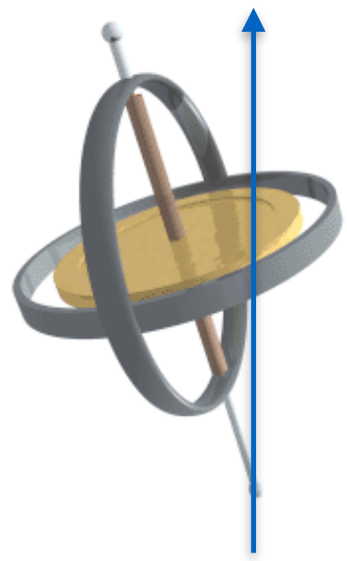

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$\vec{\omega}_c = -\frac{e}{\gamma m}\vec{B}$, cyclotron frequency (freq. of charged particle under magnetic field)

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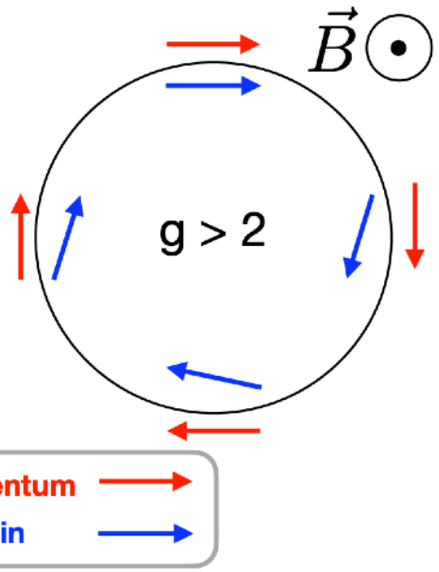

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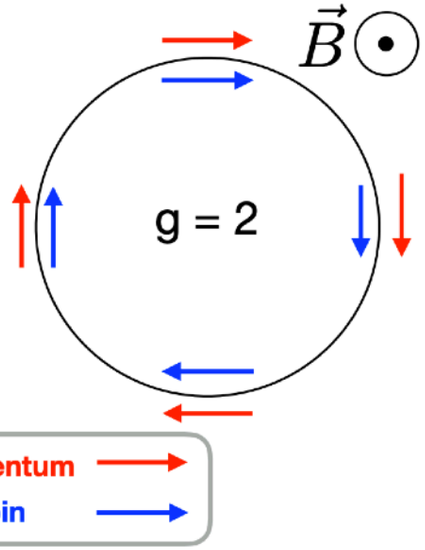

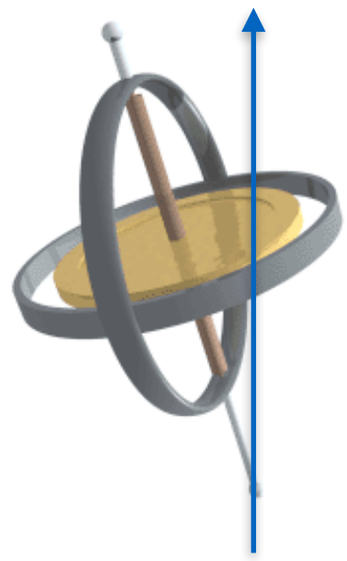

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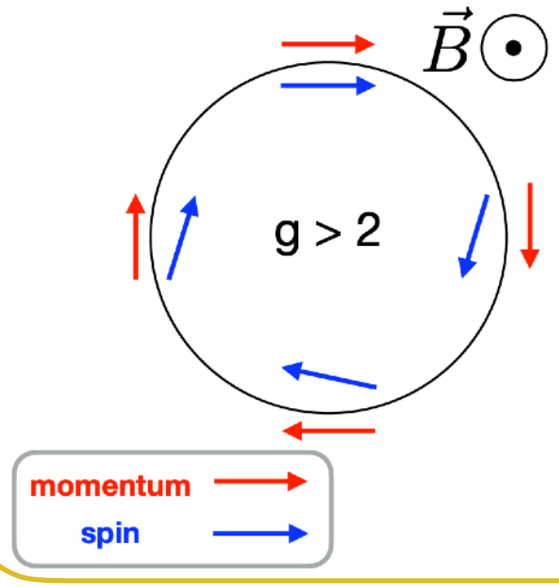

$\vec{\omega}_s = -\frac{e}{\gamma m}\vec{B}(1 + \gamma a_\mu)$, Larmor precession frequency(total spin precession freq.)

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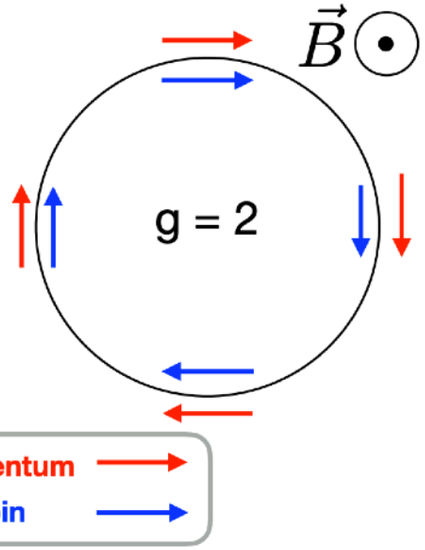

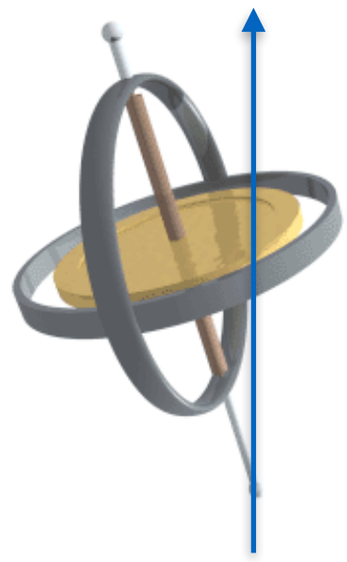

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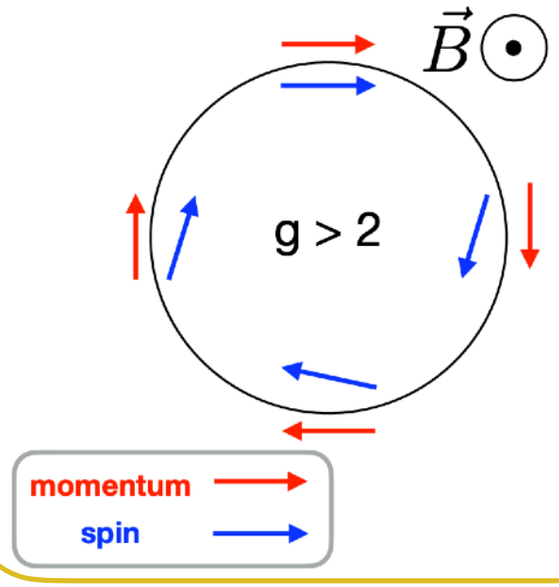

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$\vec{\omega}_a \cong \vec{\omega}_s - \vec{\omega}_c$, anomalous precession frequency

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

Measure them to extract anomaly

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polarized muons in a magnetic field

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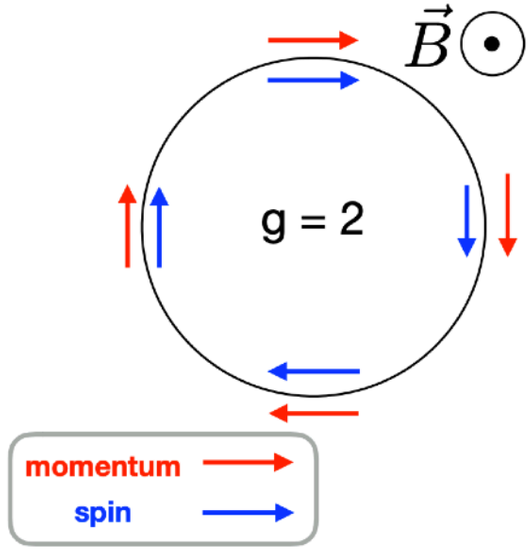

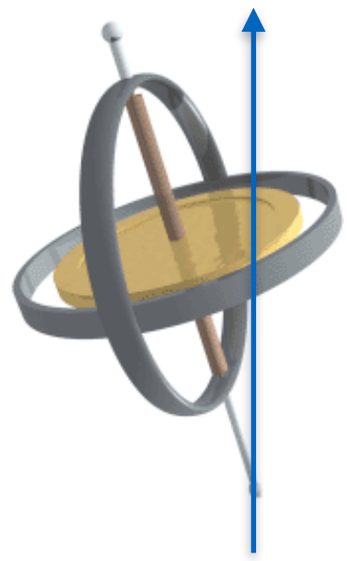

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$\vec{\omega}_a \cong \vec{\omega}_s - \vec{\omega}_c$, anomalous precession frequency

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

Measure them to extract anomaly

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

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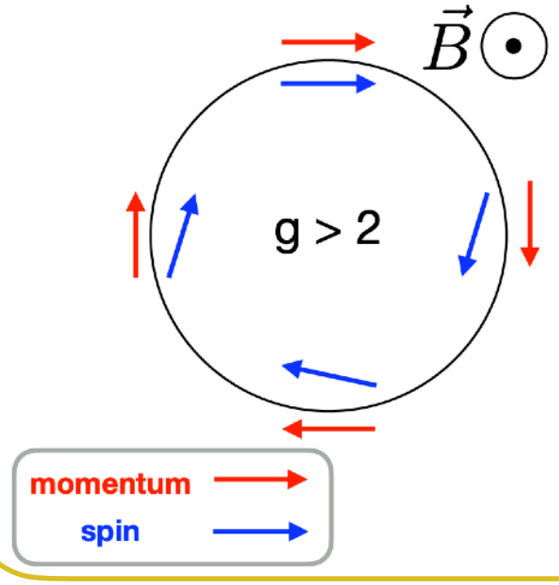
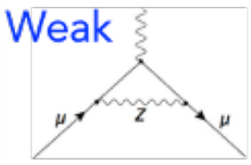
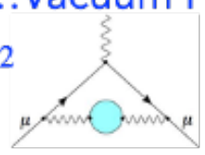
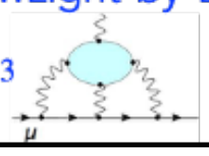


Muon Magnetic Moment and Standard Model

- g-factor was expected to be 1 around 1900
- Dirac predicted g-factor as 2 for spin 1/2 particles
- But then Kusch & Foley measured electron spin factor as 2.00238
- Julian Schwinder calculated this deviation in QED (1948)

$$a = (g-2)/2 = \alpha/2\pi$$=0.0016, where $\alpha = 1/137$

More loops of calculations are added today

QED  +…	$116\,584\,718.9\,(1) \times 10^{-11}$	0.001 ppm
Weak  +…	$153.6\,(1.0) \times 10^{-11}$	0.01 ppm
Hadronic…		
…Vacuum Polarization (HVP) α^2  +…	$6845\,(40) \times 10^{-11}$	0.37 ppm
…Light-by-Light (HLbL) α^3  +…	$92\,(18) \times 10^{-11}$	0.15 ppm

Well-known

Non-perturbative
(Data-driven & lattice QCD)

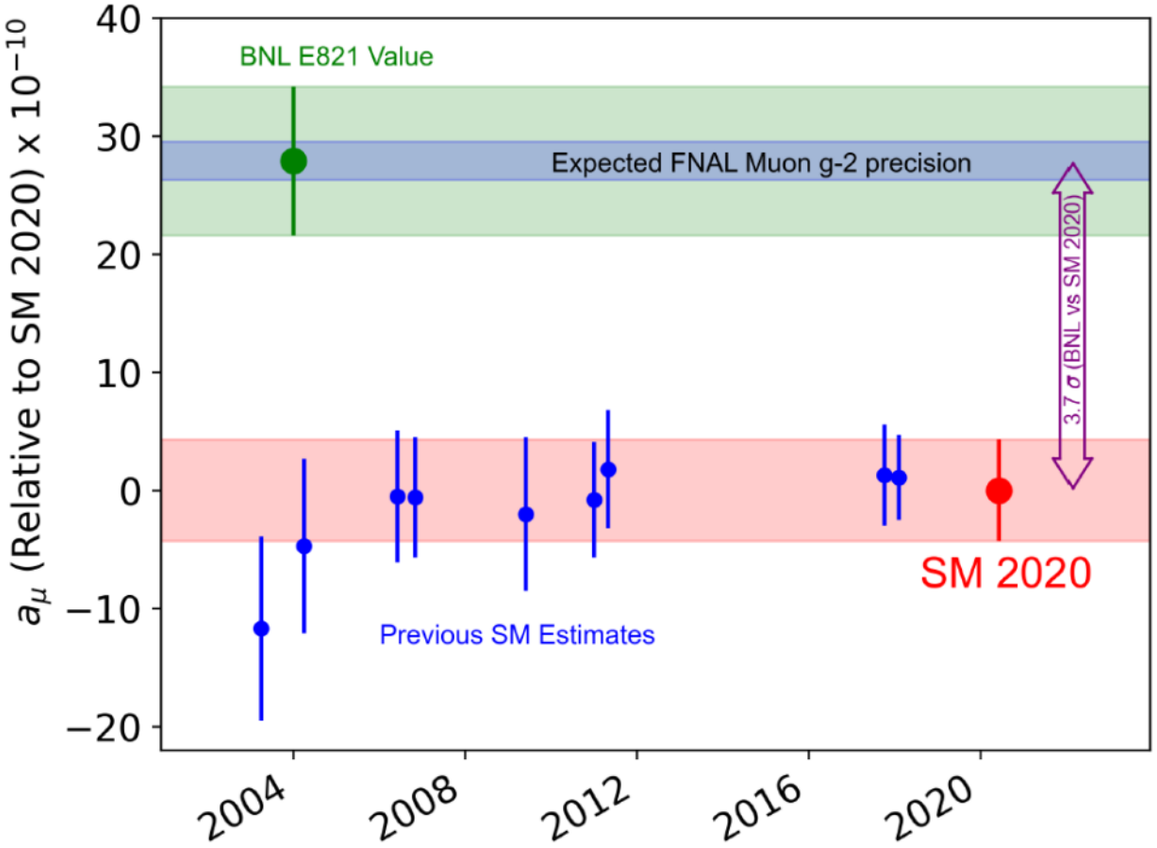
Hadronic Contribution:
FPCP talk from Maarten Golterman

Muon g-2 Theory Initiative to combine all theoretical inputs

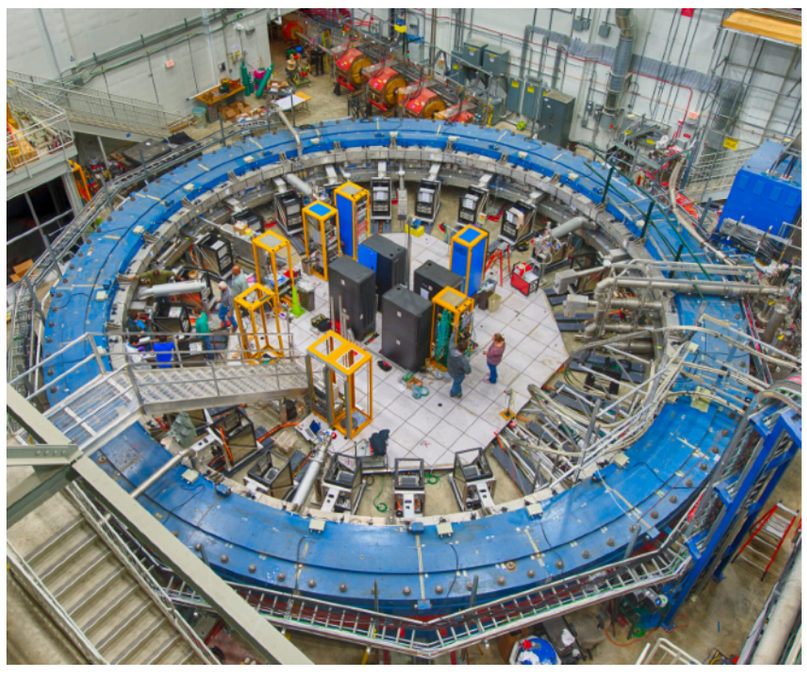
A bit of History: CERN and BNL g-2 Experiments

- Muon g-2 experiments were launched at CERN to measure a_μ
  - Launched a measurement(with a long dipole magnet) with precision of 2% and finally **0.4%** (1961,1962)
  - Second measurement with a storage ring-> x25 more precise- **270ppm**-> Revealed a quantitative discrepancy with the theory (1966)
  - Third measurement with a storage ring + electrostatic quadrupole field-> **7.3 ppm** precision (1969-1979)
- BNL took over the effort on measuring the anomaly more precisely (1997-2001)
  - Storage ring magnet + electrostatic quadrupole field + Fast Kickers +24 calorimeters
  - μ^+ and μ^- running
  - A factor of 14 improvement on precision after latest CERN measurement - **0.54ppm**

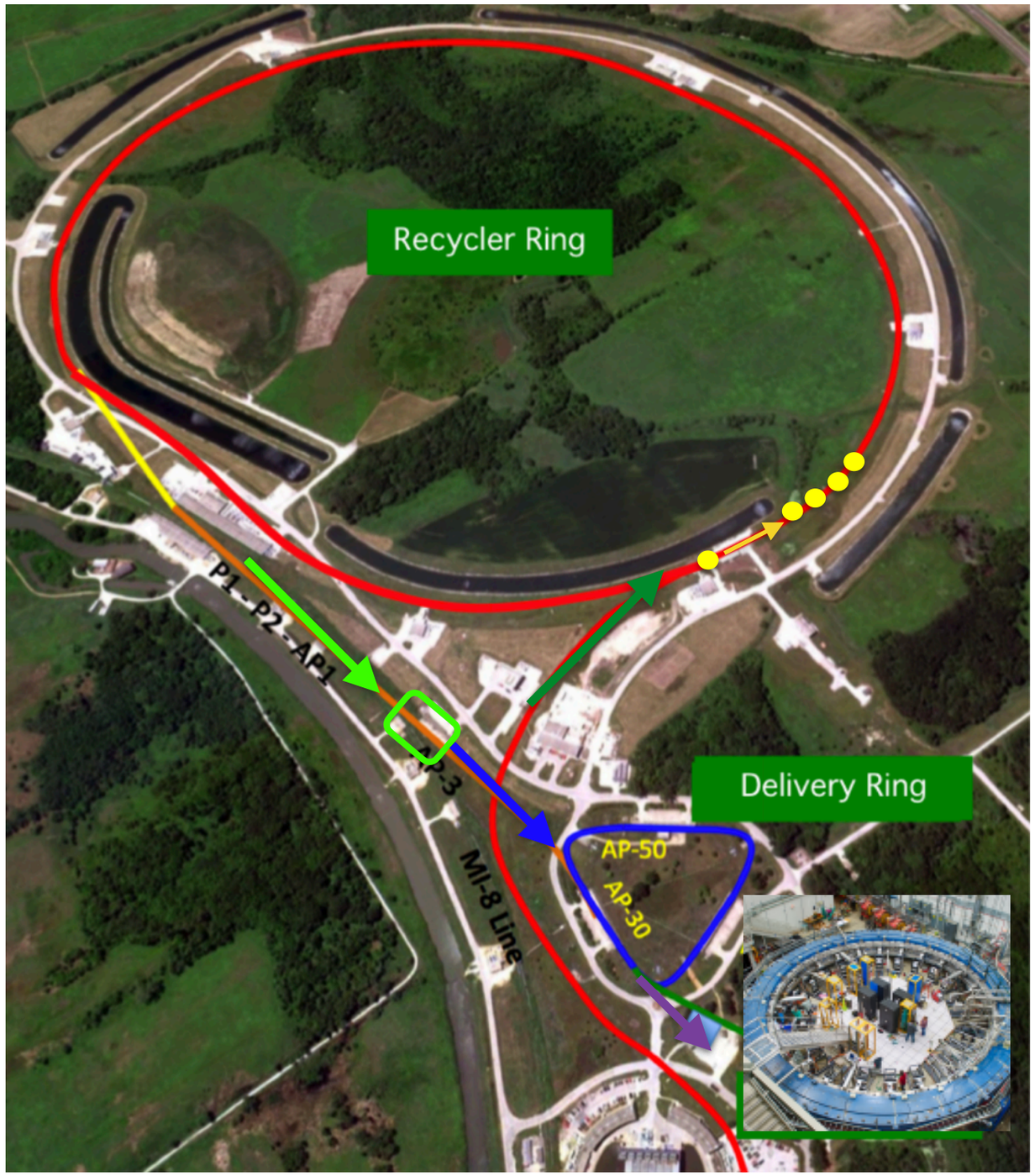
Fermilab Muon g-2 Experiment



BNL measured the anomaly with 2.7 σ discrepancy and later it increased to 3.7σ with new theory results



Muon Delivery to g-2 Experiment



- 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.

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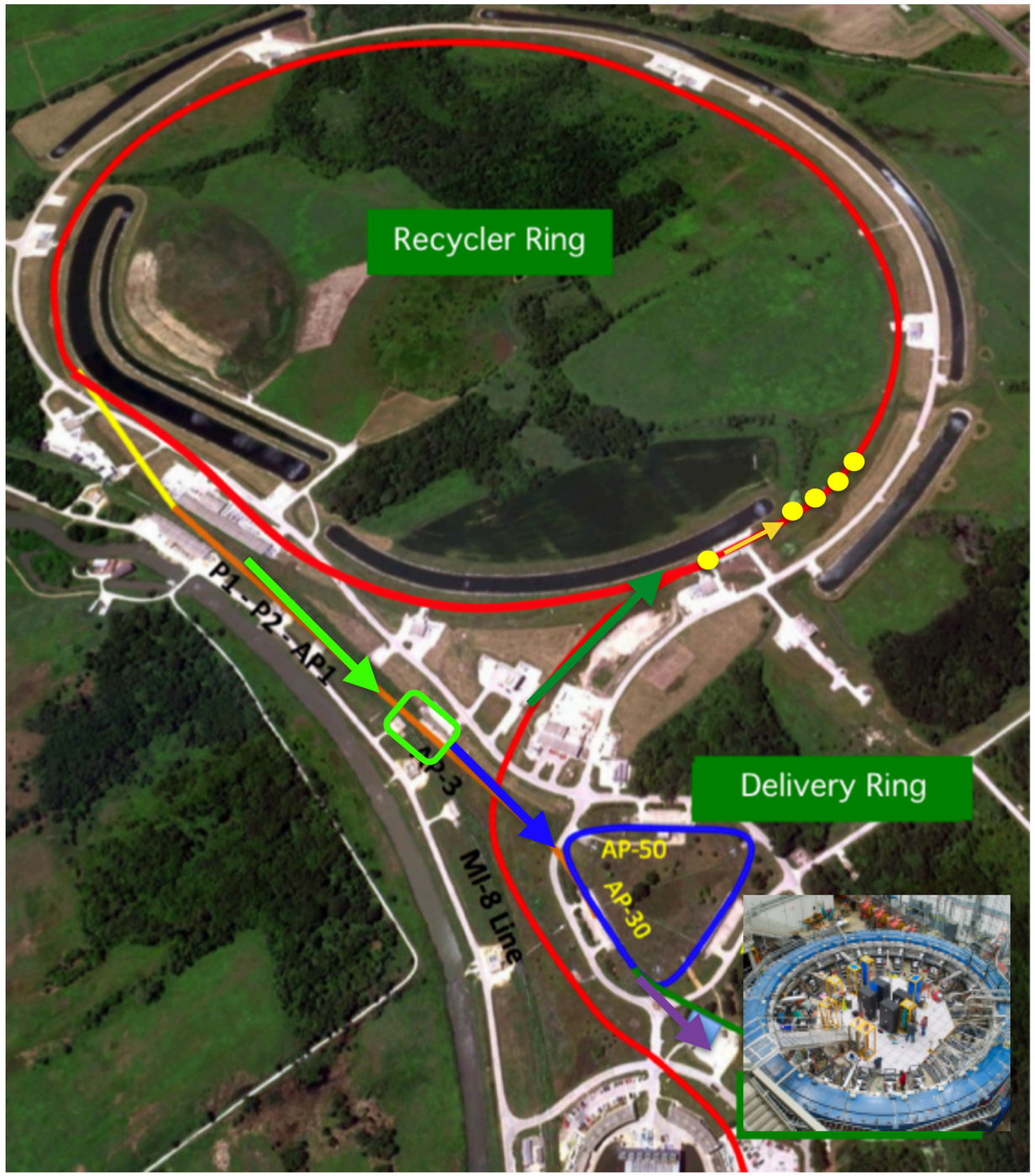

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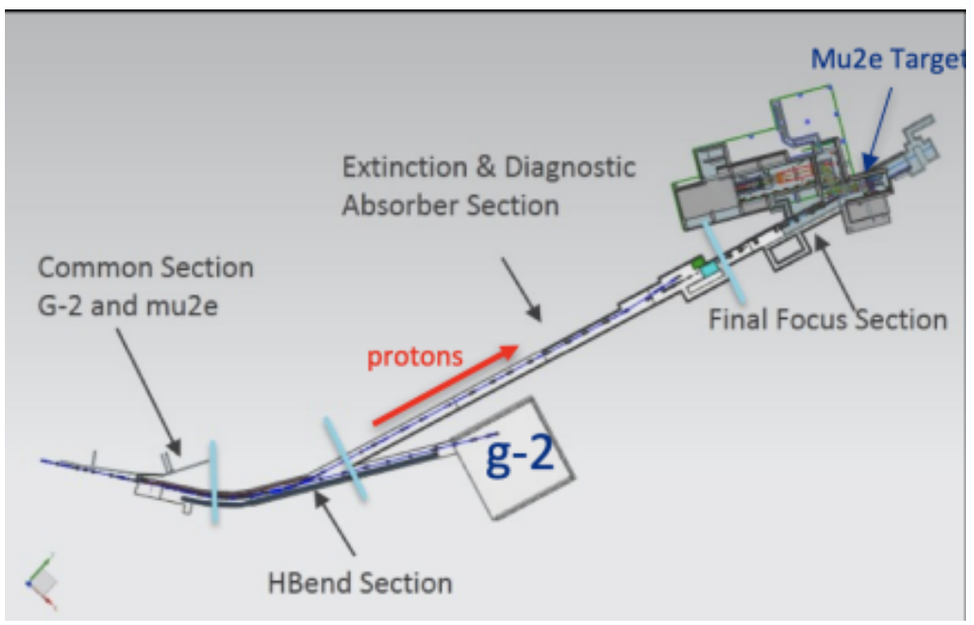
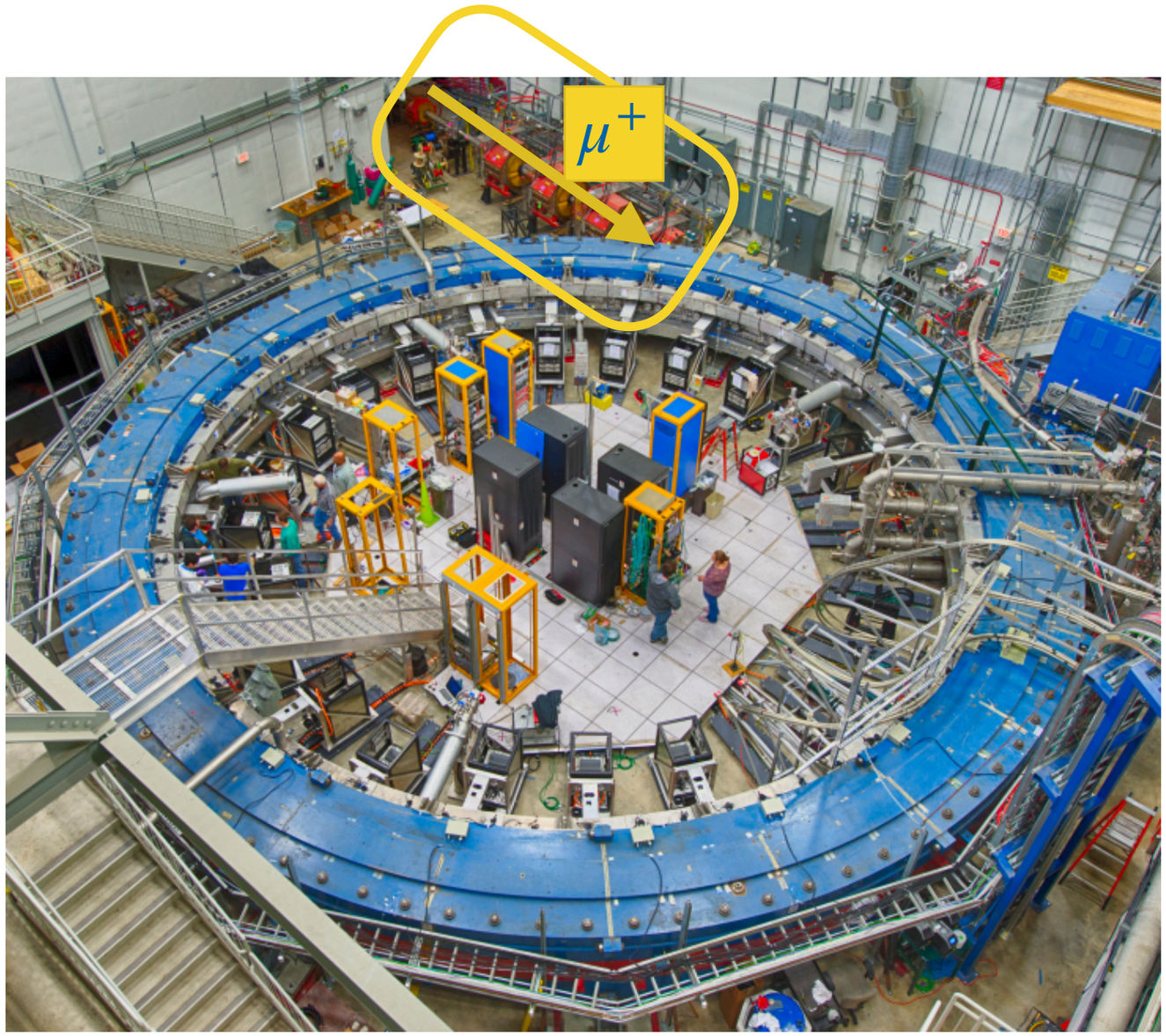
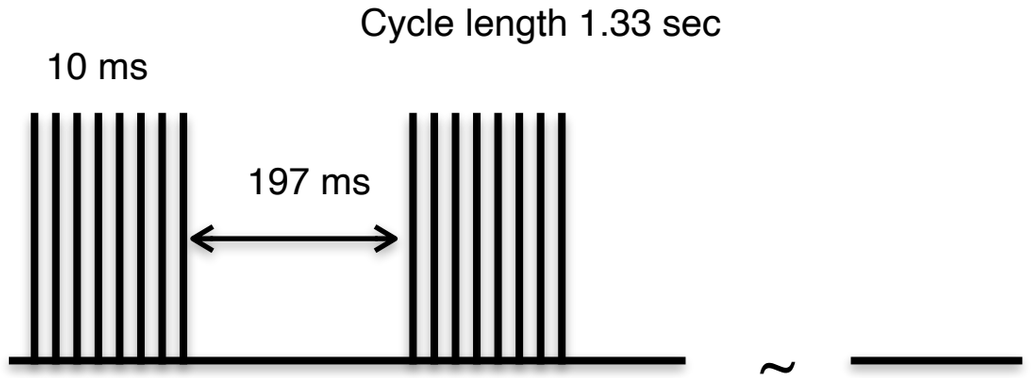


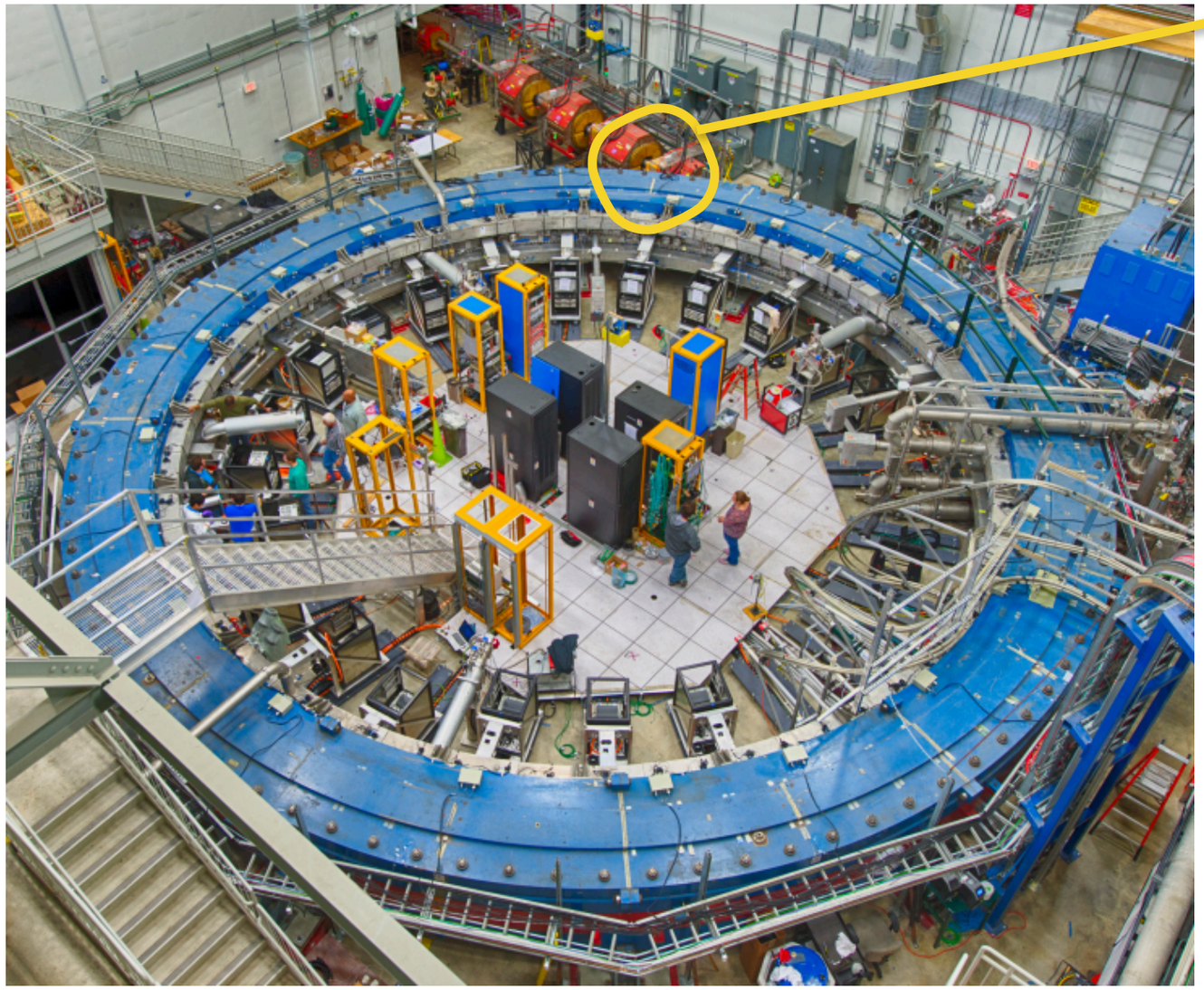
Muons at the Experimental Hall !



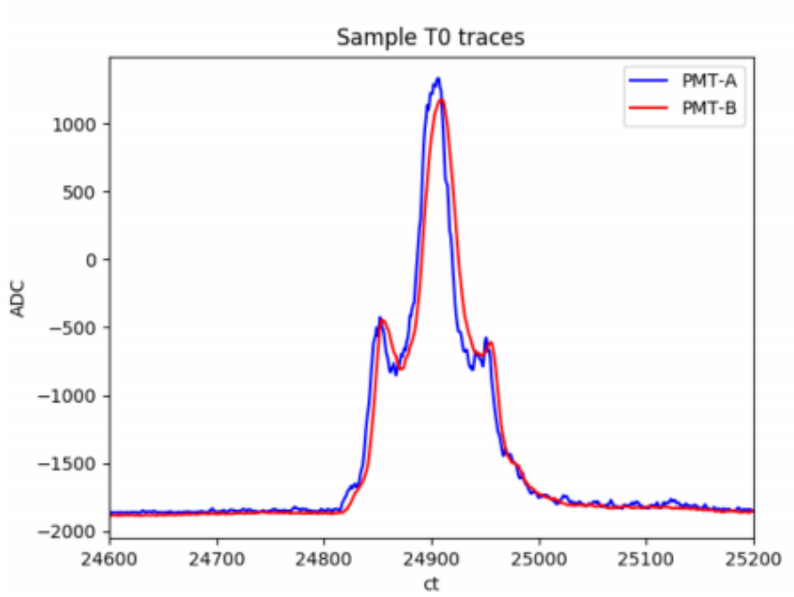
- Polarized muons at 3.1 GeV



Monitoring the Injected Beam: T0 counter

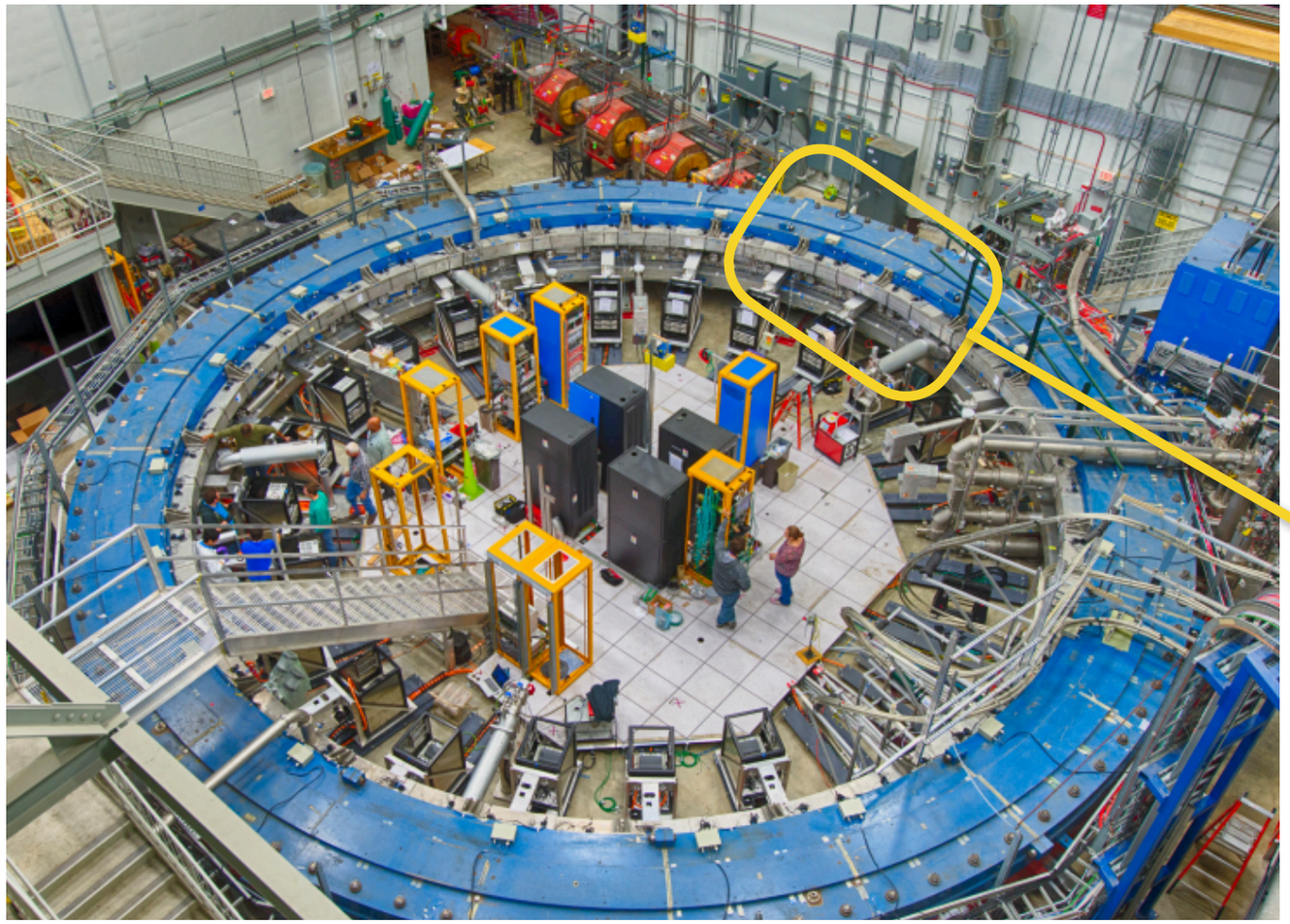


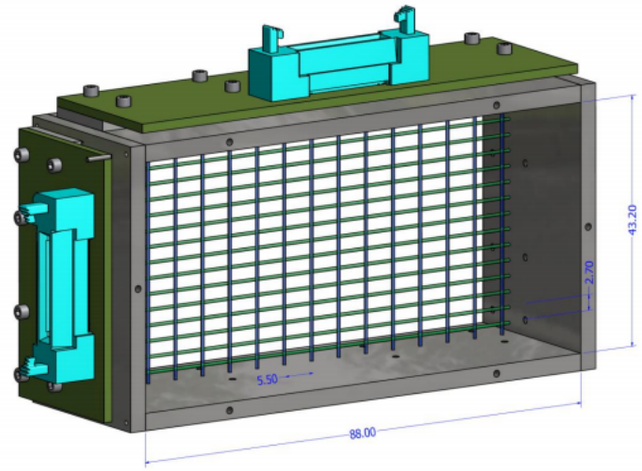
- **T0 Counter**
  - Thin scintillator with 2 PMT readouts
  - Provides beam time profile before beam enters the storage ring

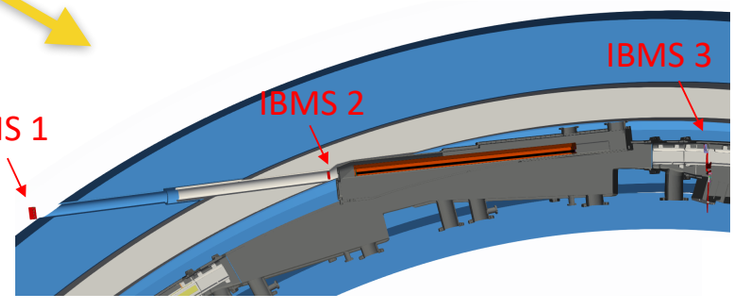


Monitoring the Injected Beam: IBMS detectors

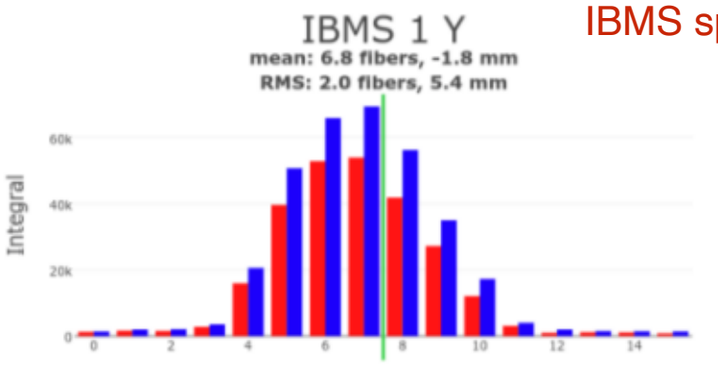
- **IBMS (Inflector beam monitoring systems)**
  - Check beam injection characteristics
  - 2 planes of scintillation fibers

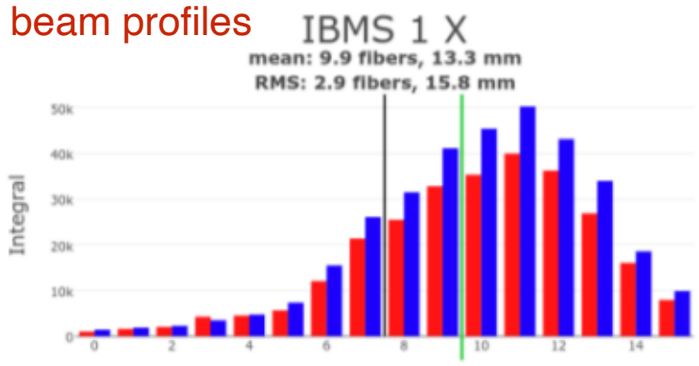




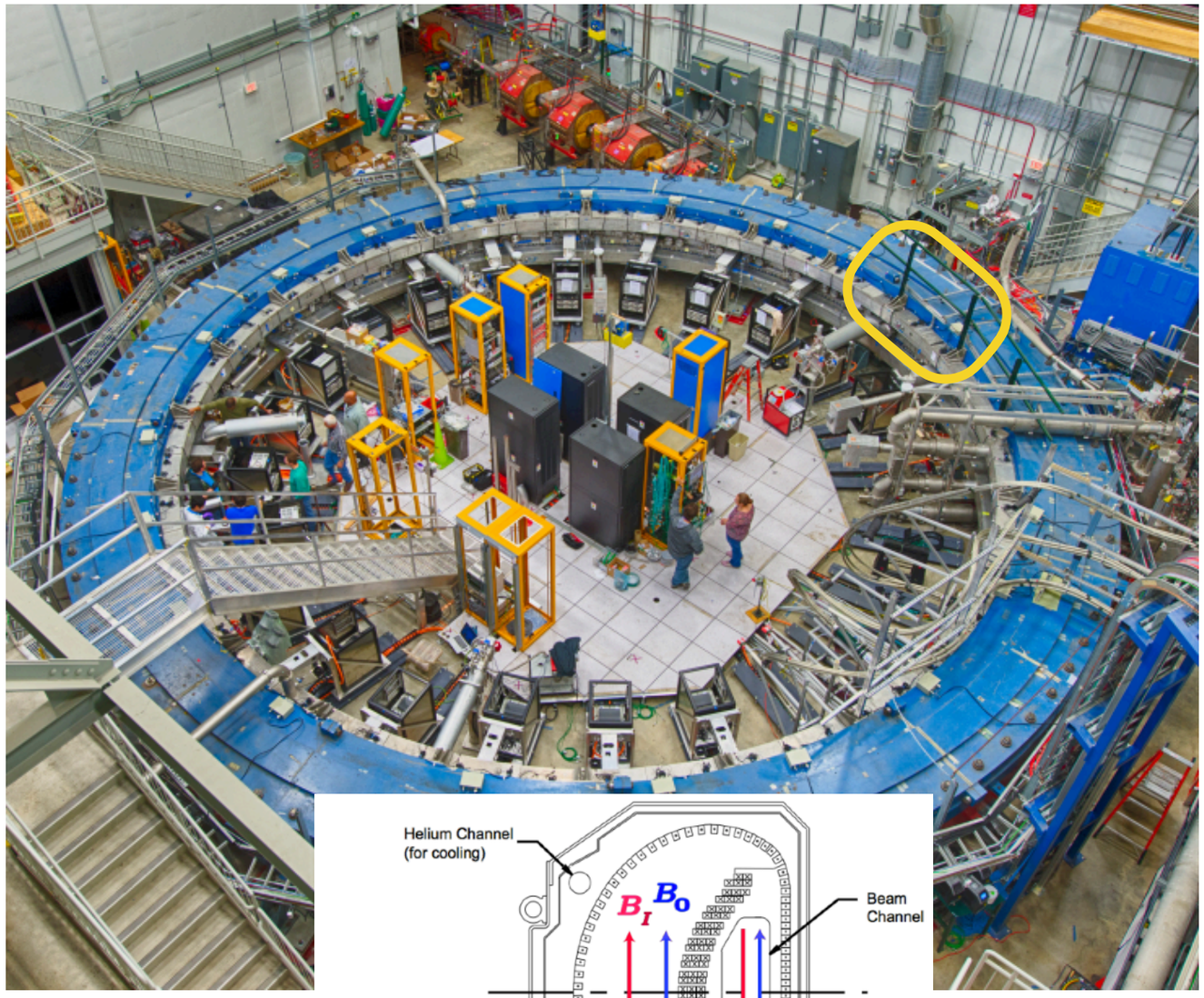


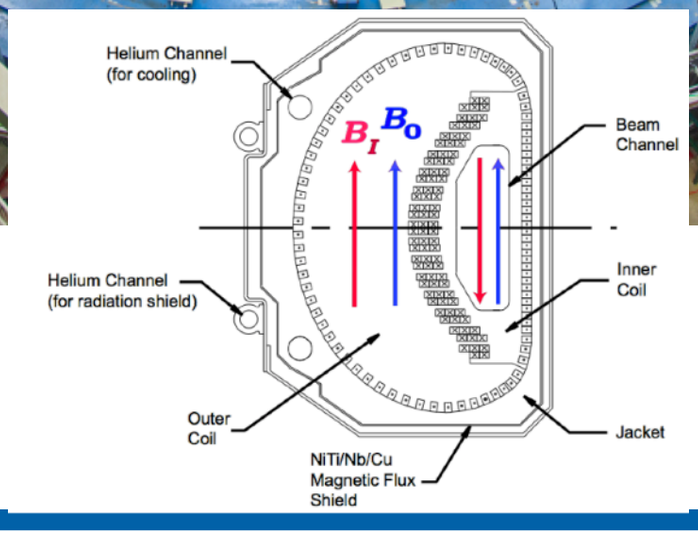
IBMS spatial beam profiles



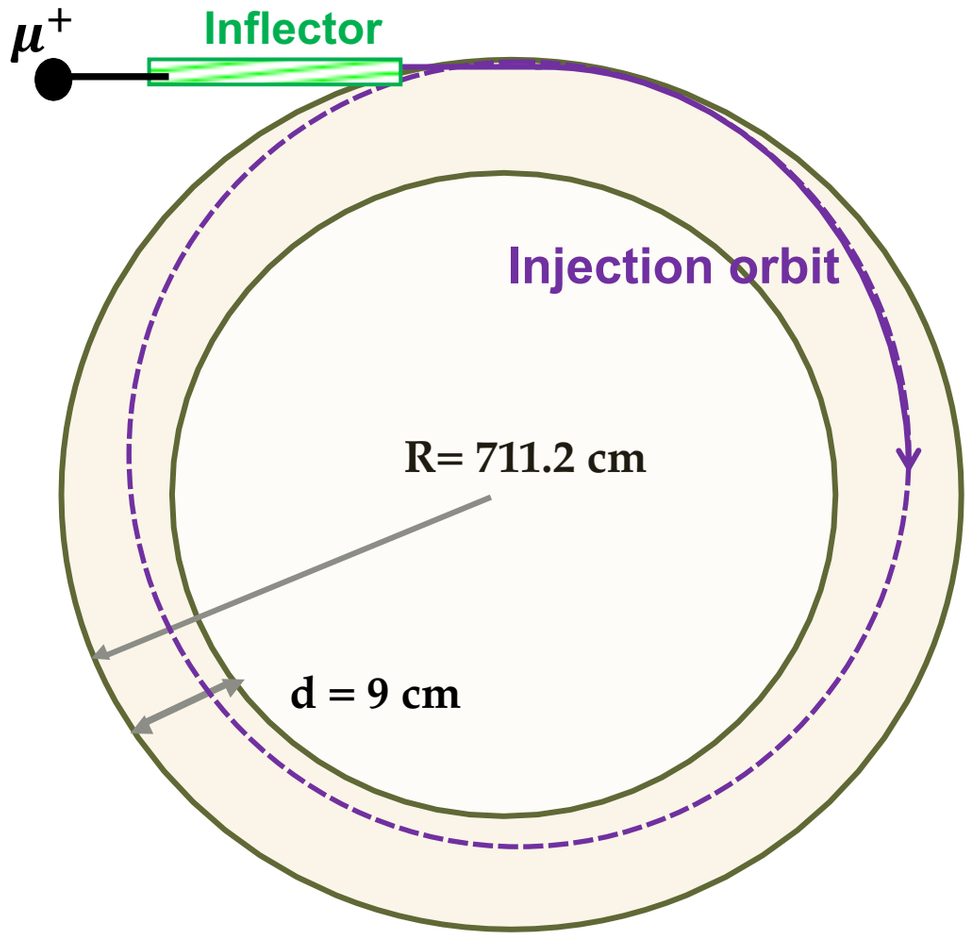


Storing the Muons : Inflector and Kickers





- **Inflector**
  - Super conducting magnet
  - Cancels B field(1.45T) in the magnet gap and let the beam enter the storage ring without being deflected.
  - They are at r=77mm outside central closed orbit



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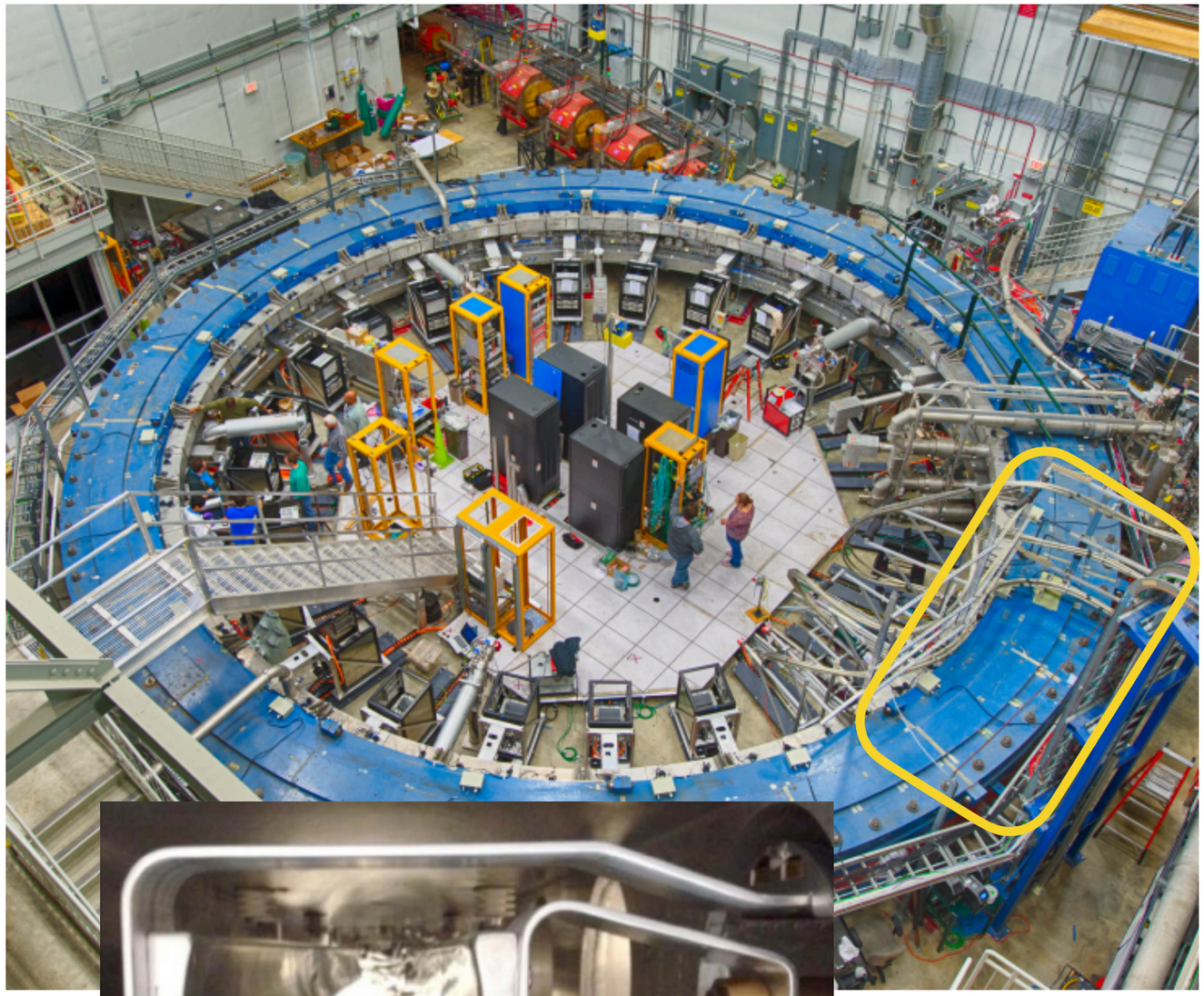
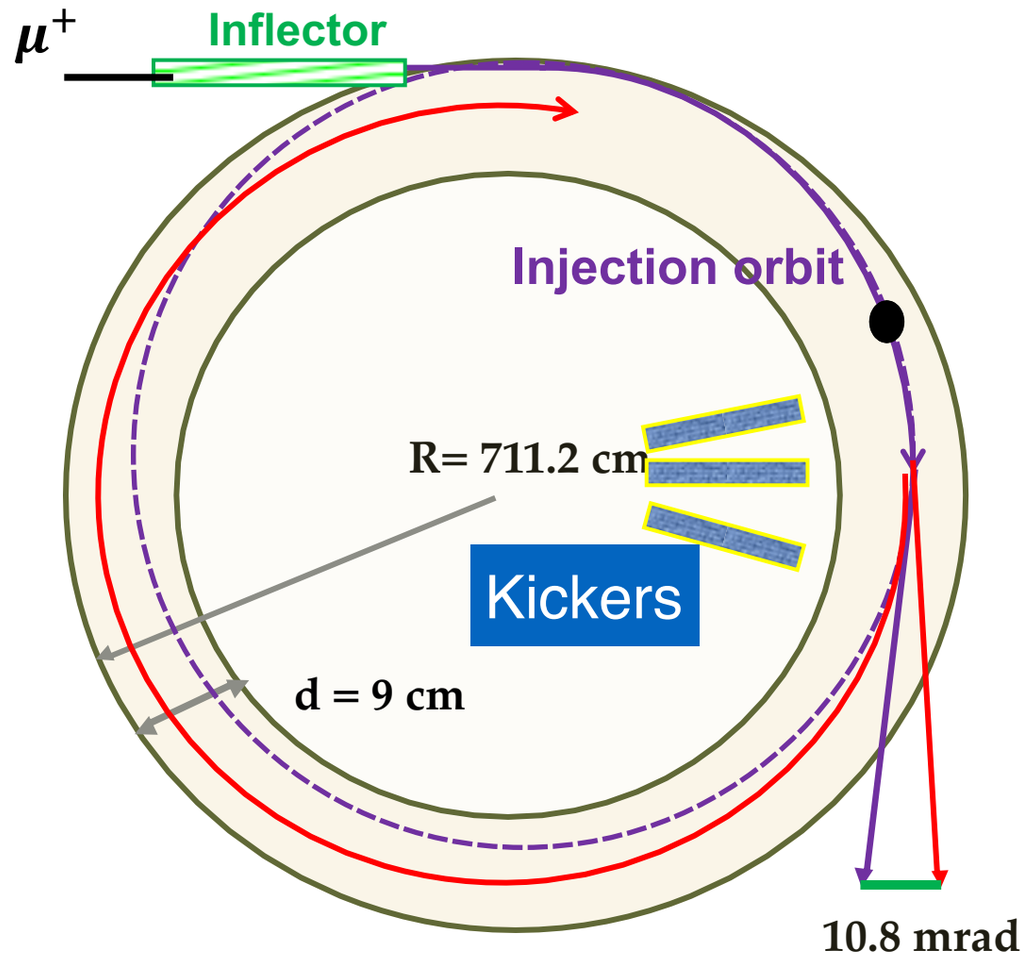
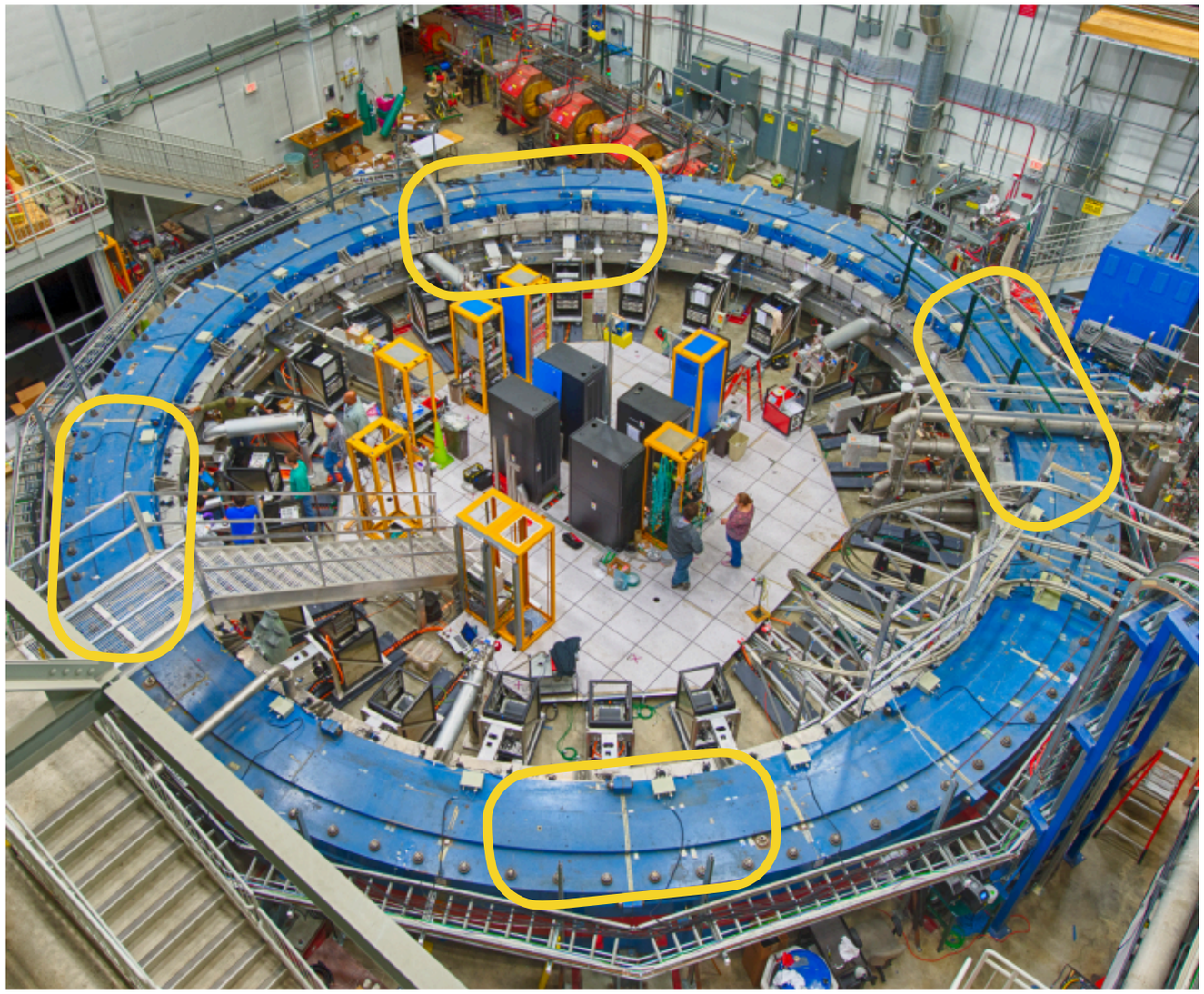


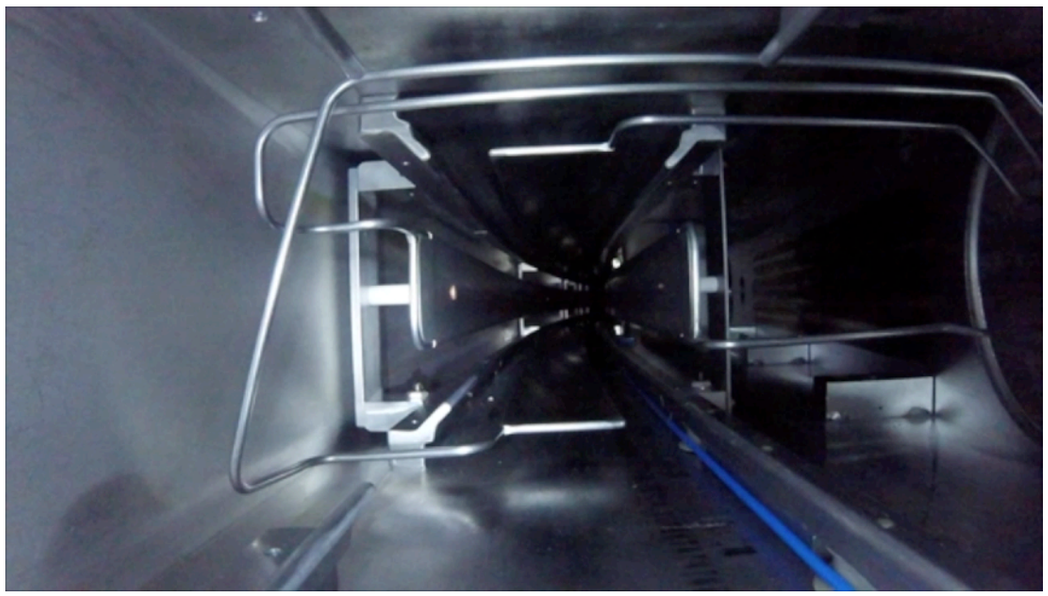
- **Magnetic Kickers**
  - Kick some more to direct the muons into ideal orbit.
  - Use 10.8 mrad pulsed kicks (<149 ns)



Storing the Muons: Electrostatic Quadrupoles



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



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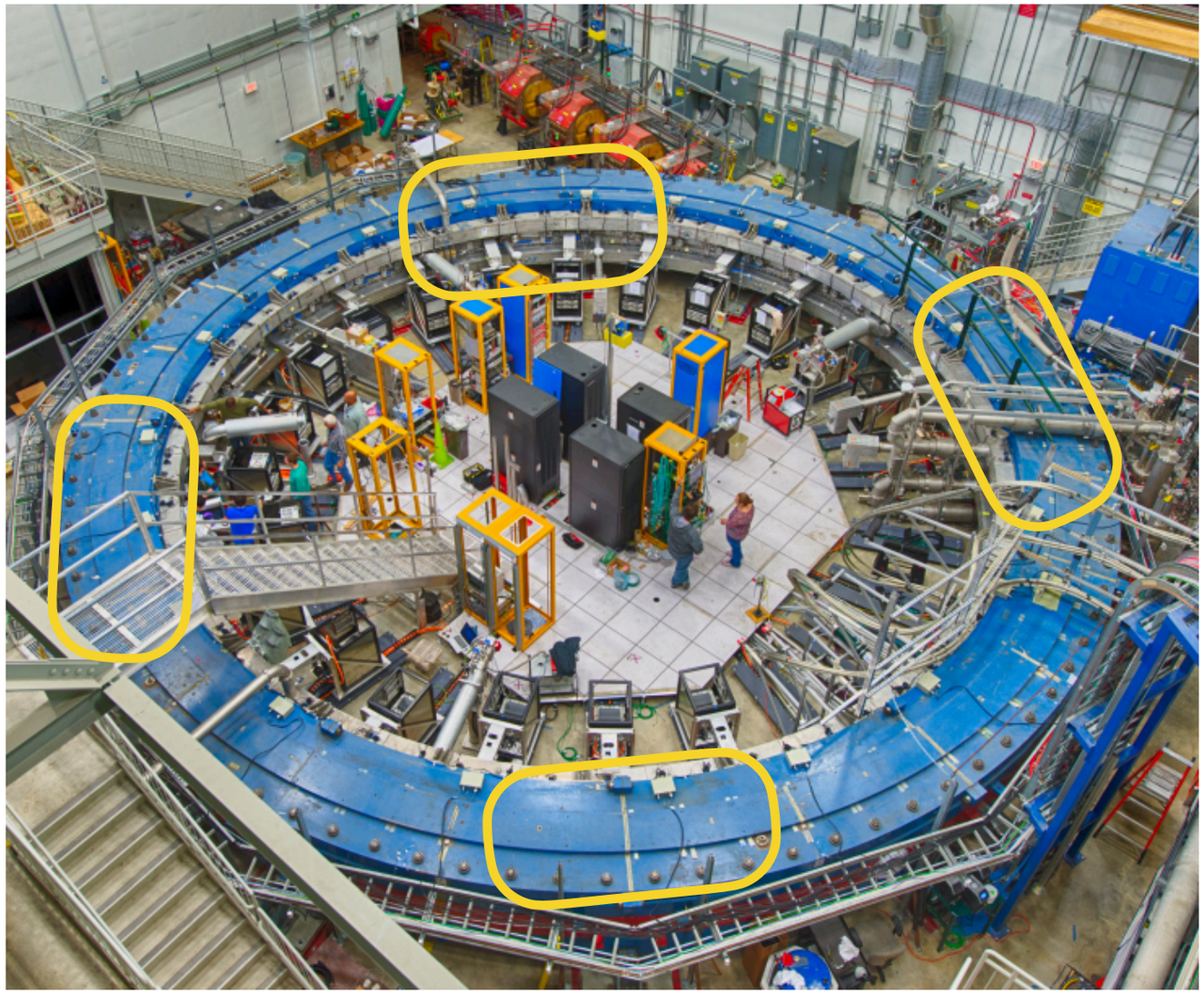

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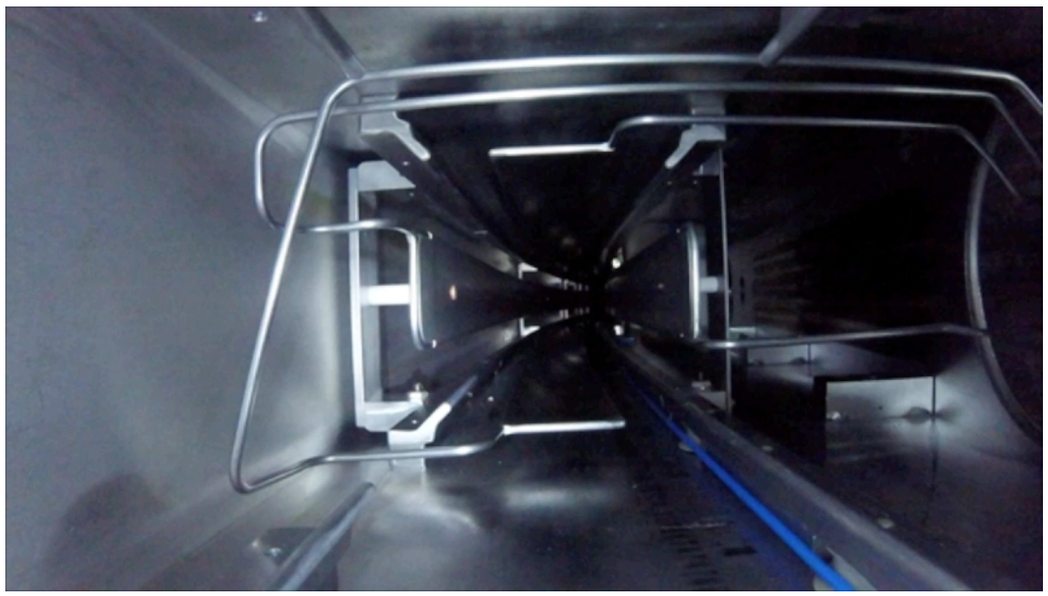

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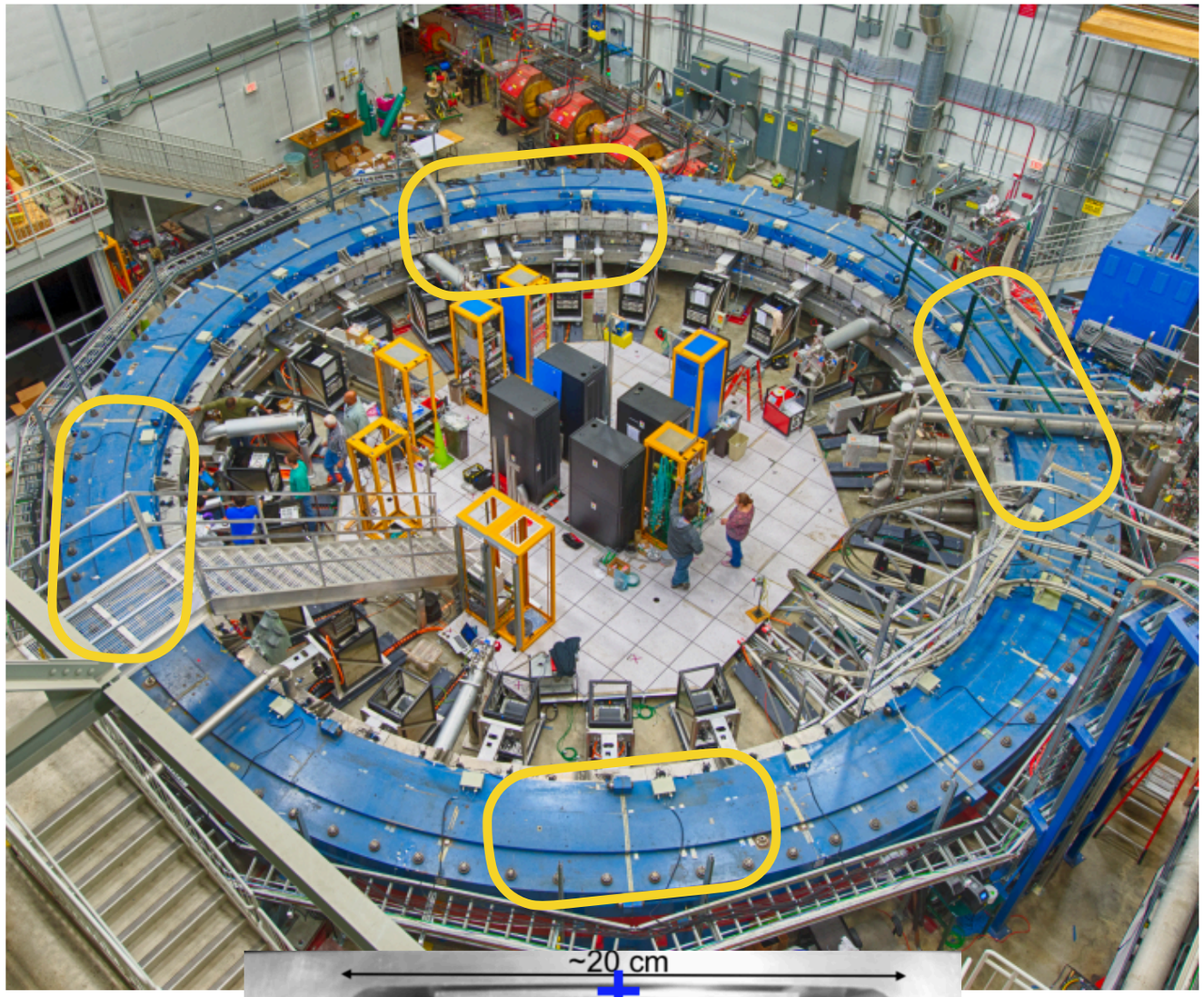

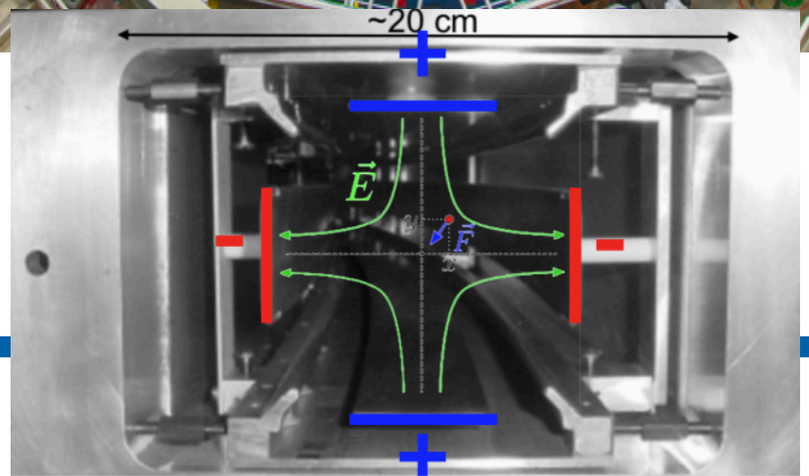

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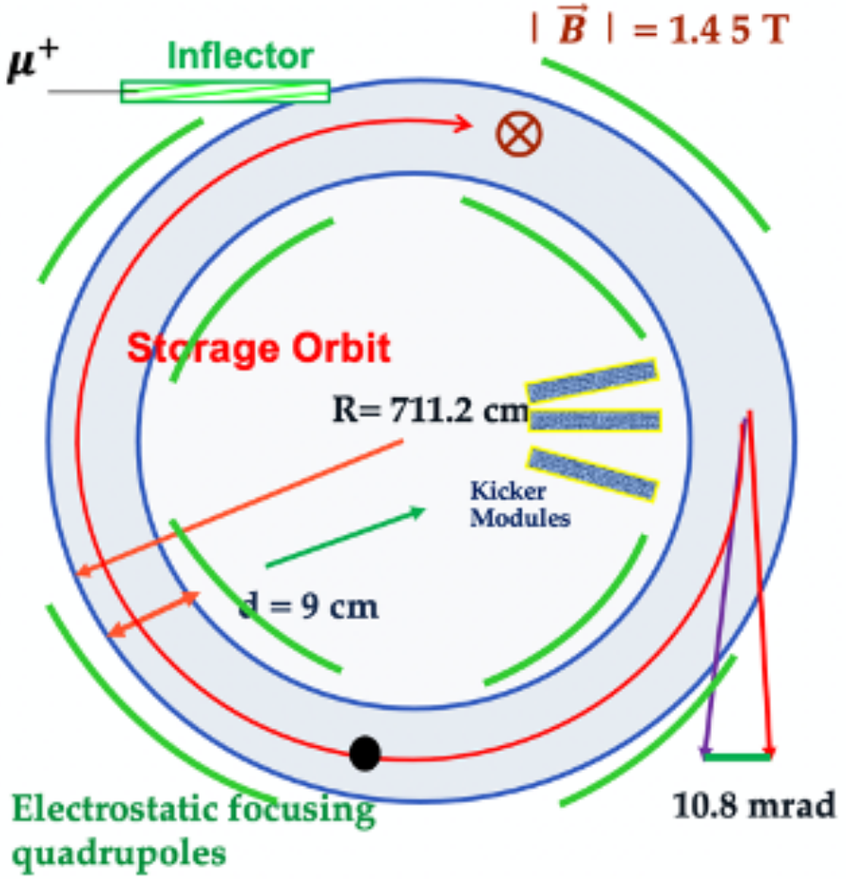

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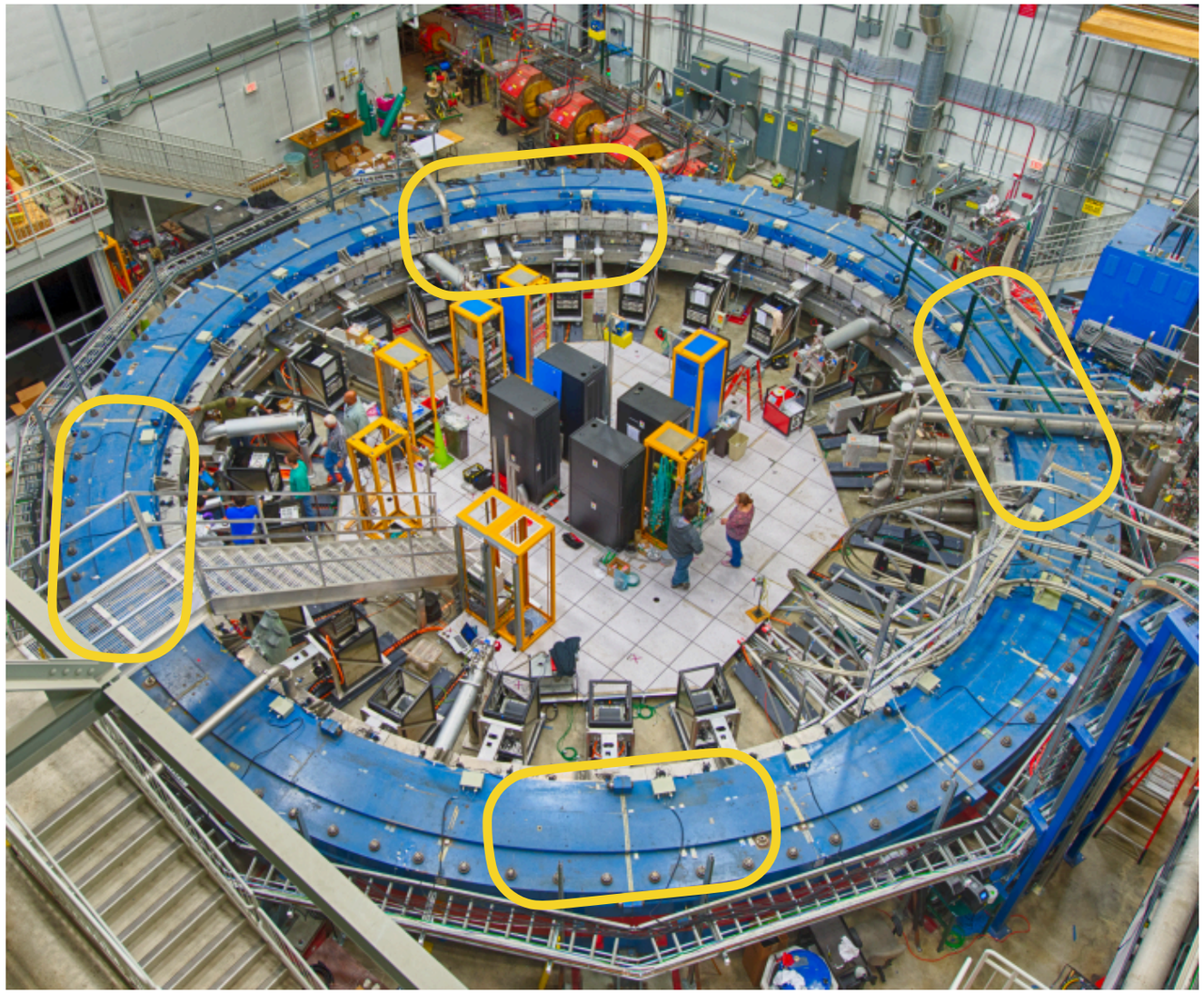

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$$\vec{\omega}_a = \frac{e}{m}\left[a_\mu \vec{B} - a_\mu \frac{\gamma}{\gamma+1}\left(\vec{\beta}\cdot\vec{B}\right)\vec{\beta} - \left(a_\mu - \frac{1}{\gamma^2-1}\right)\vec{\beta}\times\vec{E}\right]$$

0 if in plane

Term cancels at the magic momentum

Cheat-Sheet for Electrostatic Quadrupoles

- **Electrostatic Quadrupoles**
  - 4 Pulsers : 2 Positive, 2 Negative Polarities
    - Each has one step and two steps voltage configurations

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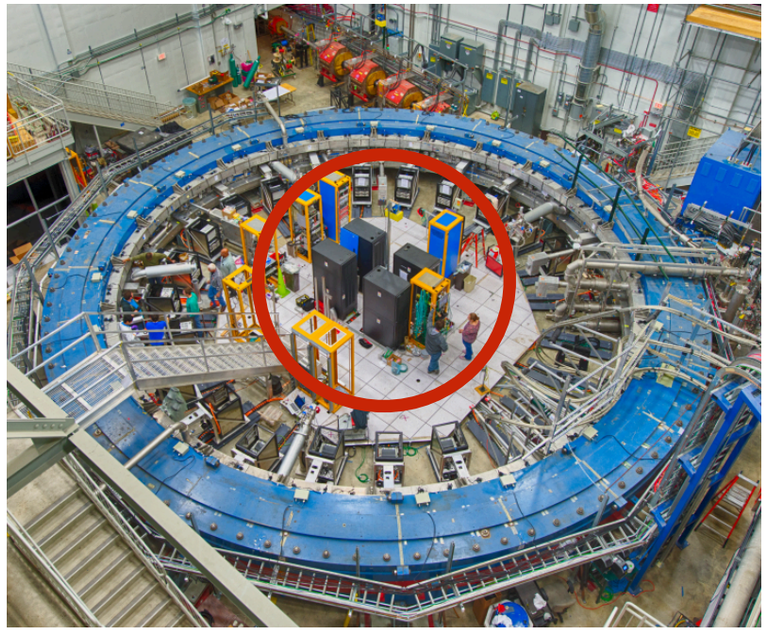

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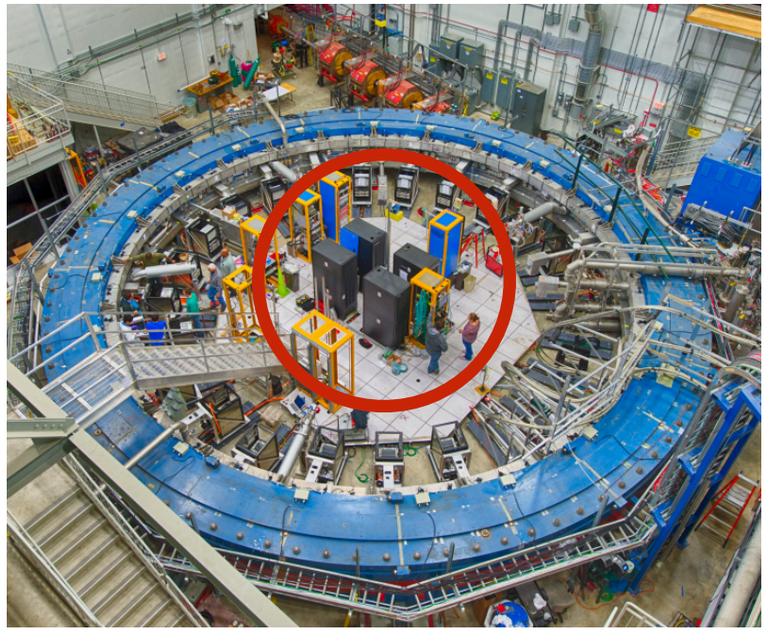
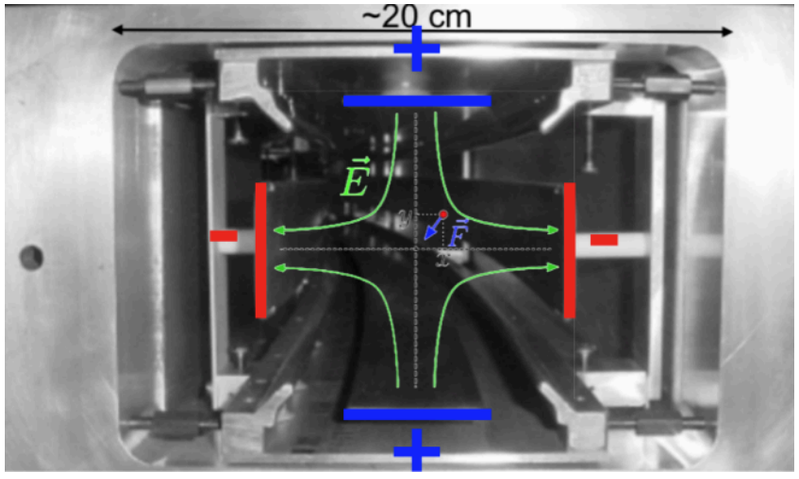


Quads

Vertical Focusing



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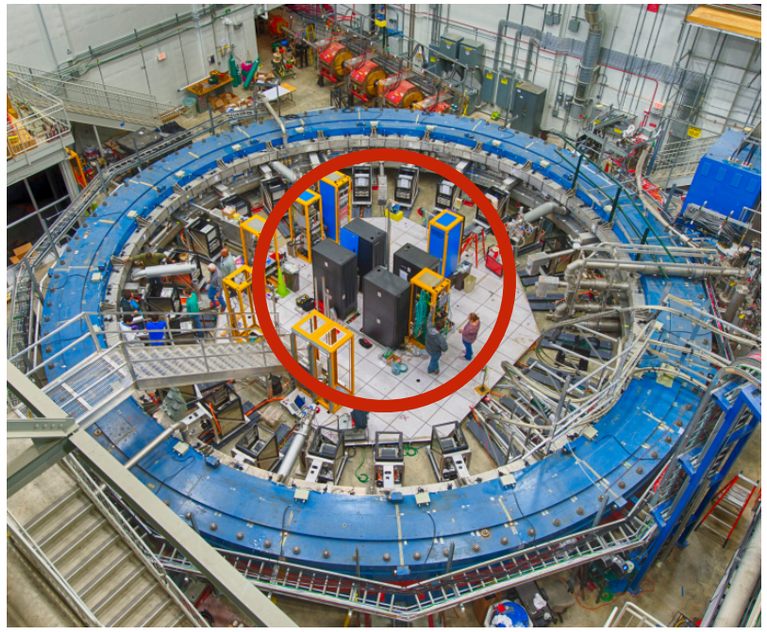

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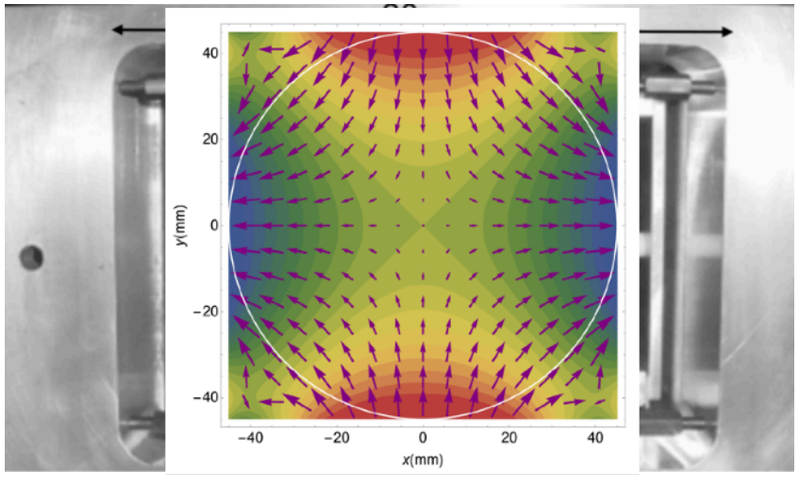

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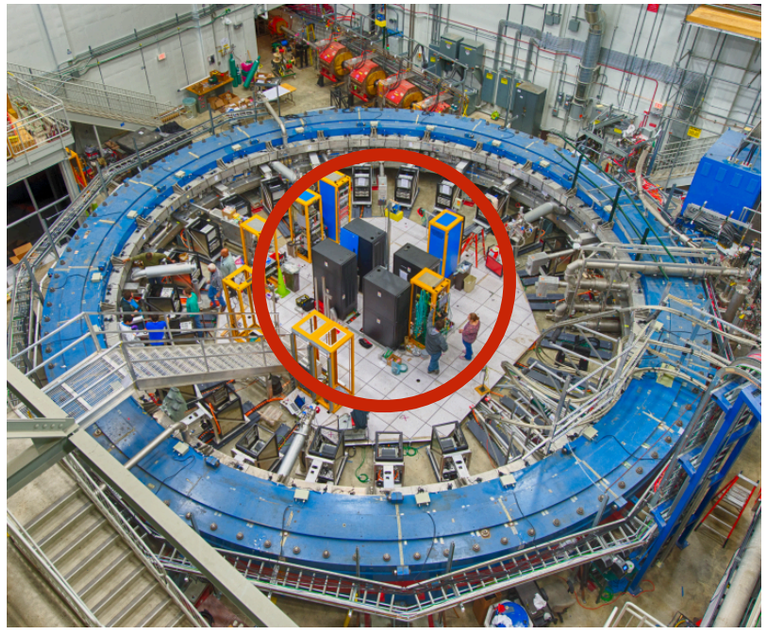

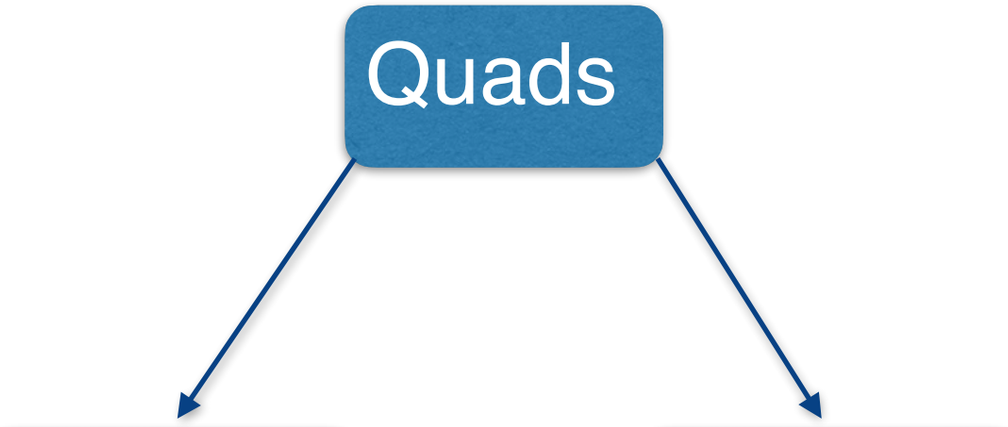

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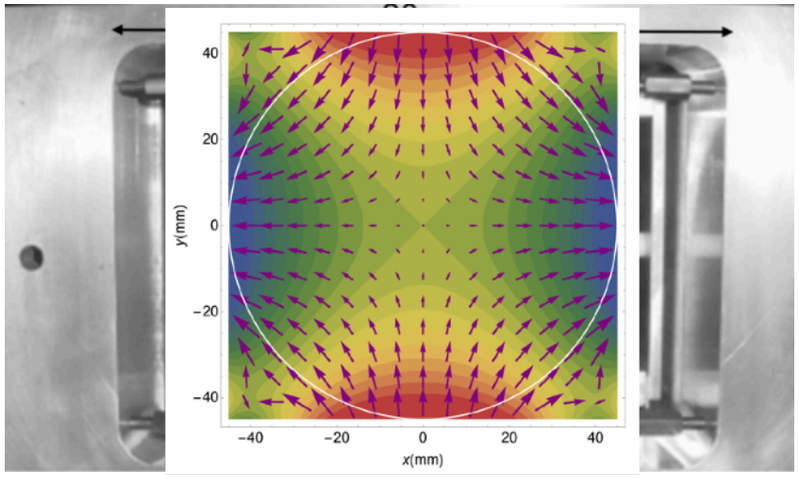

Scraping

- **Power quad plates asymmetrically**
- **Displace closed orbit from the center by 2.6mm**
- **Scrape off the muons outside the reduced aperture**
- **Restore the quad symmetry after 30μs**

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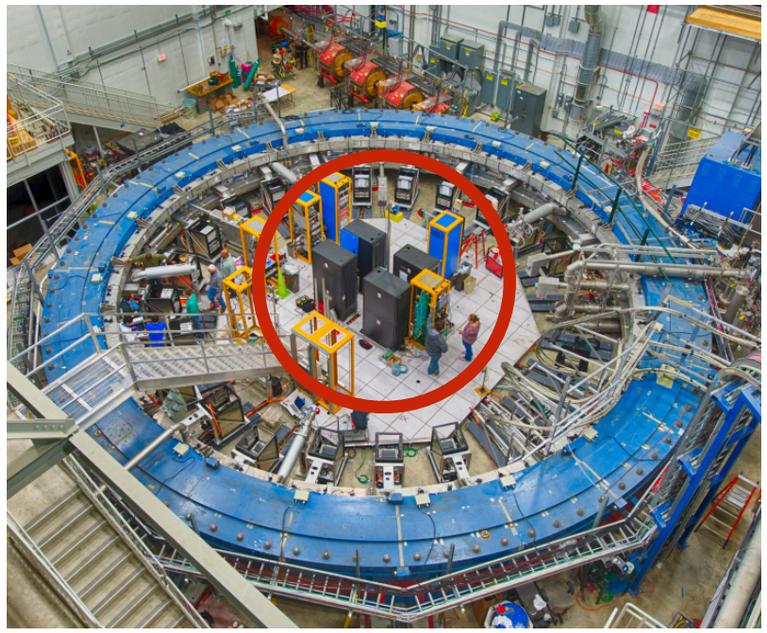

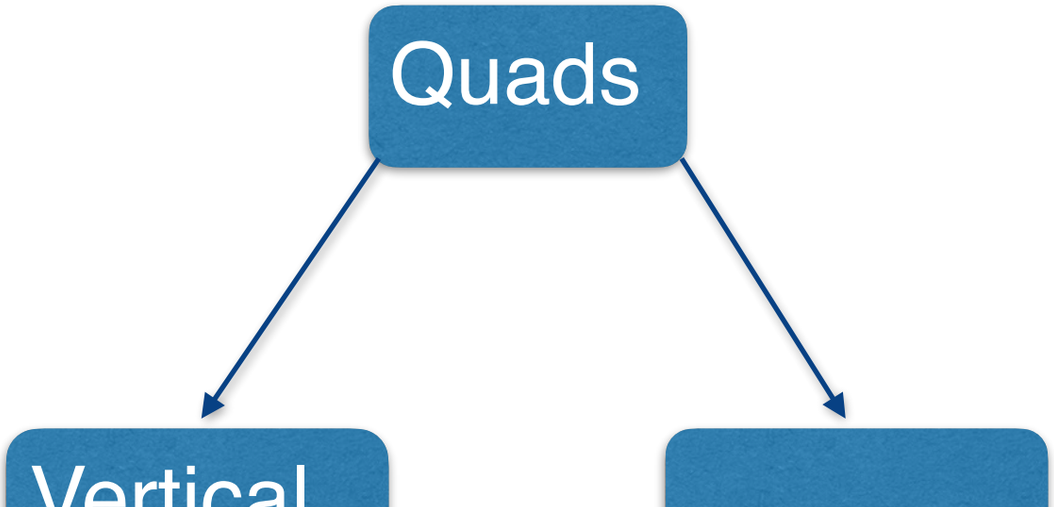

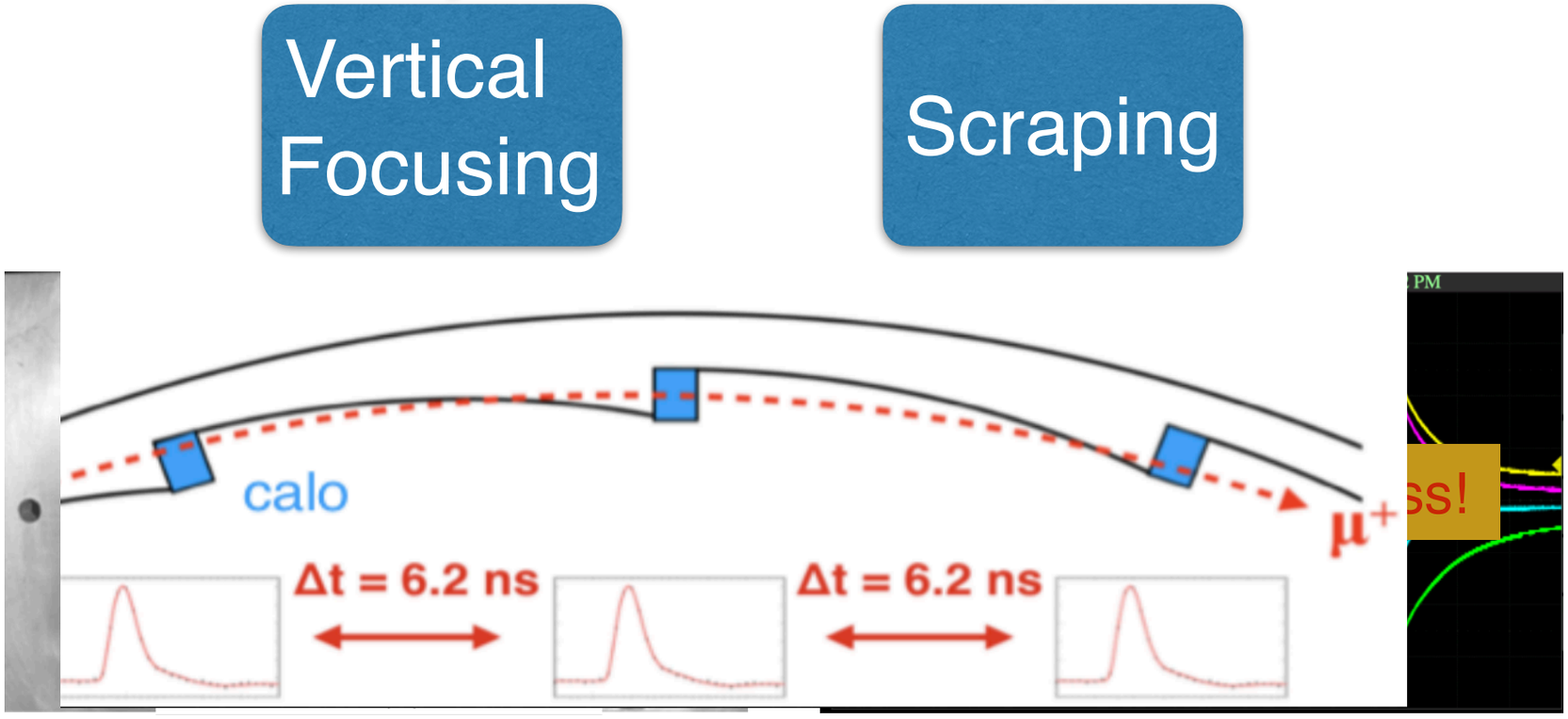

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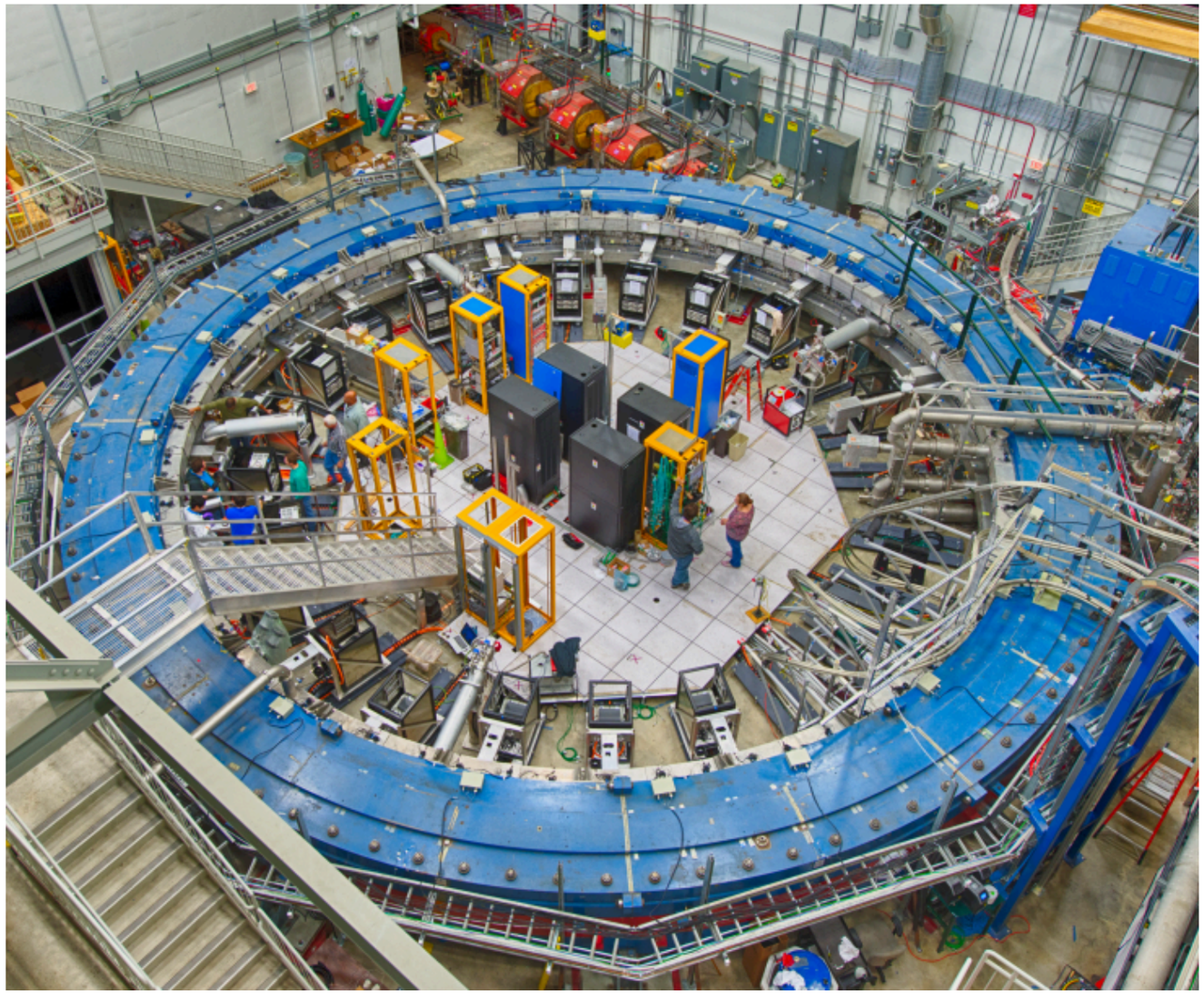
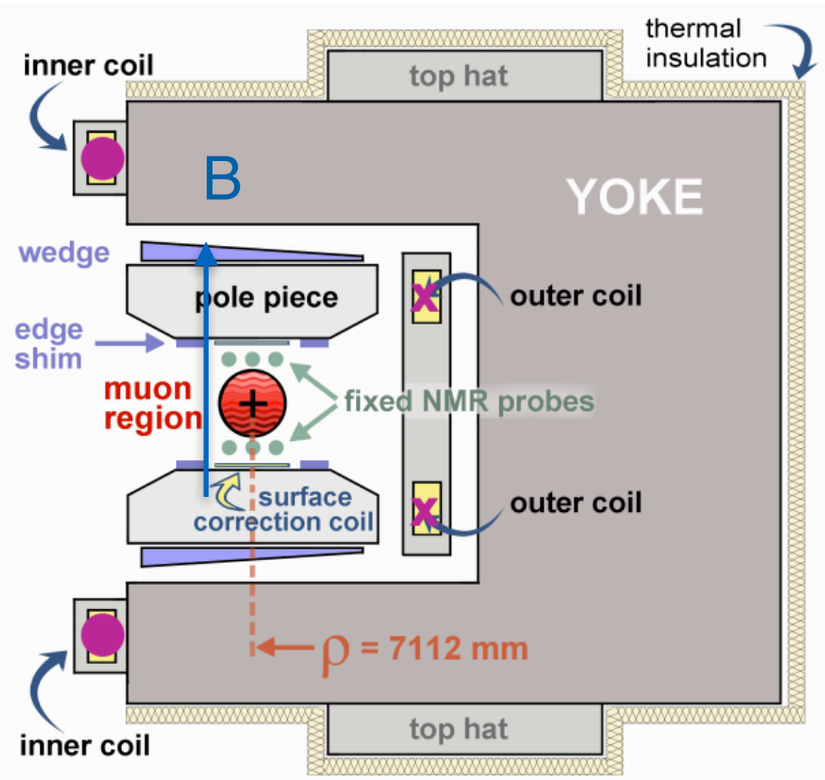
Several mechanisms contributes to Muon Loss Rate: Muons that were scattered from different materials before decaying and then punch through multiple calorimeters. They have different phase than stored muons so they modulate ω_a, producing a systematic error. We need to identify them in the data!

Storing the Muons: Magnet



Achieved 25 ppm on field uniformity



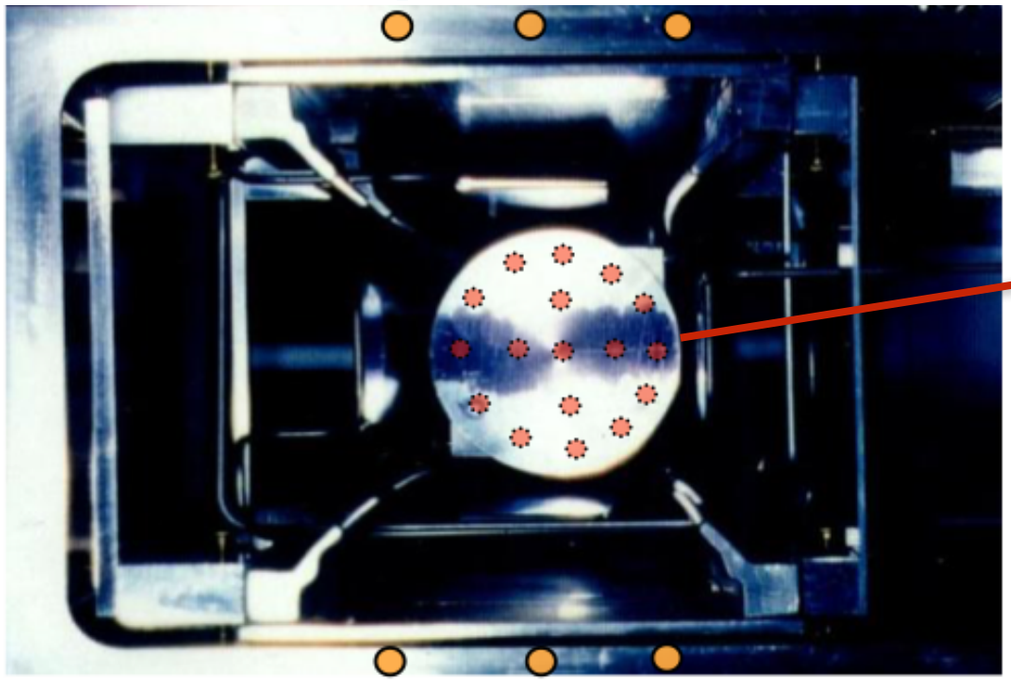
g-2 Magnet in Cross Section

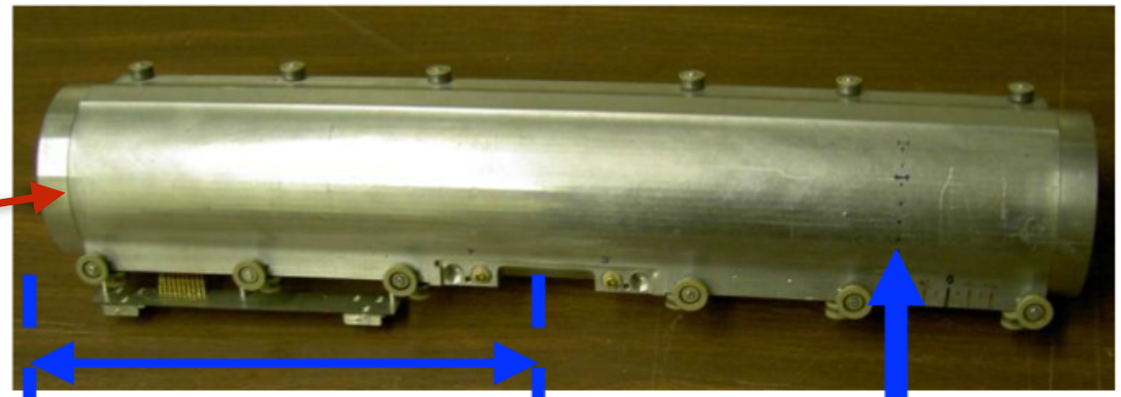
Superconducting C shaped magnet

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 ω_p: Monitoring and Measuring the Magnetic Field

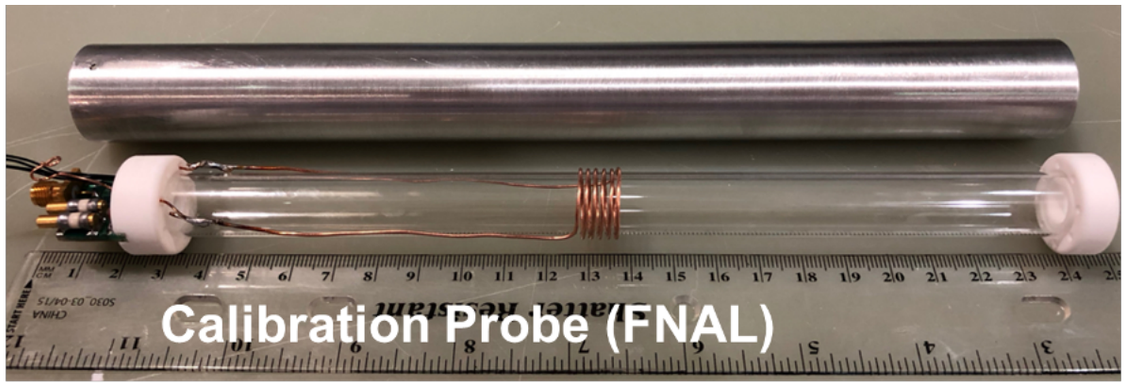


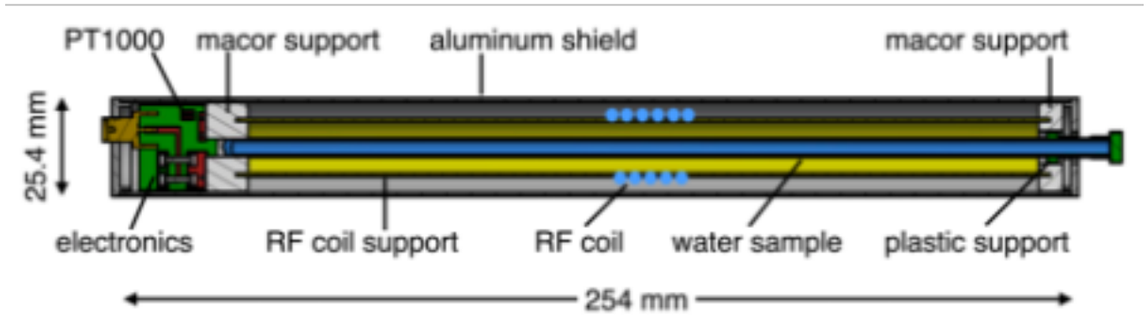


- **Fixed probes:**
  - 378 probes located on vacuum chamber
  - Measure the magnetic field while muons are inside the storage ring

- **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

NMR Probes
Calibration Uncertainty





ω_p: free proton precession frequency

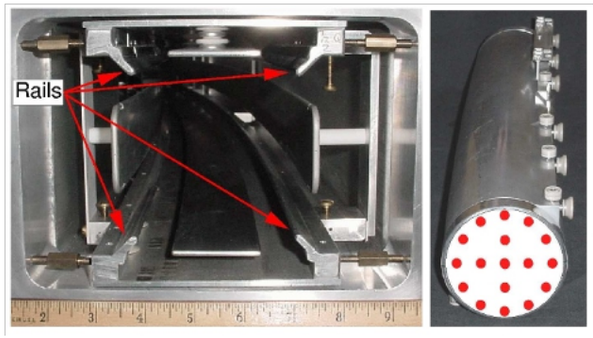
Using proton NMR

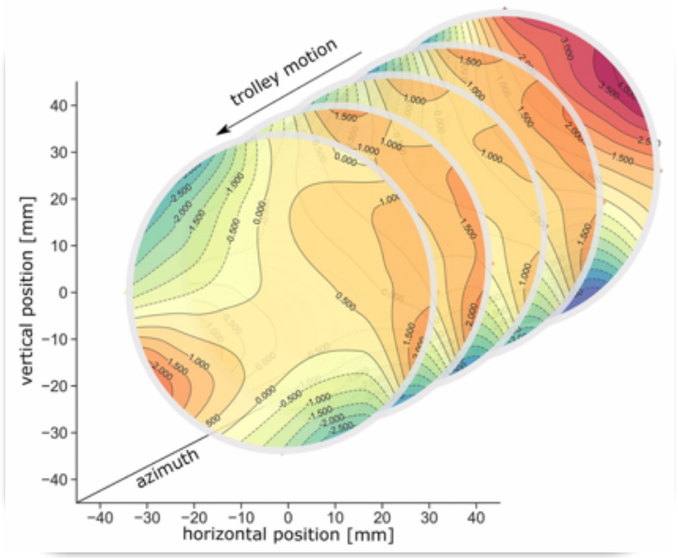
$\hbar\omega_p = 2\mu_p B$

Absolute field calibration:

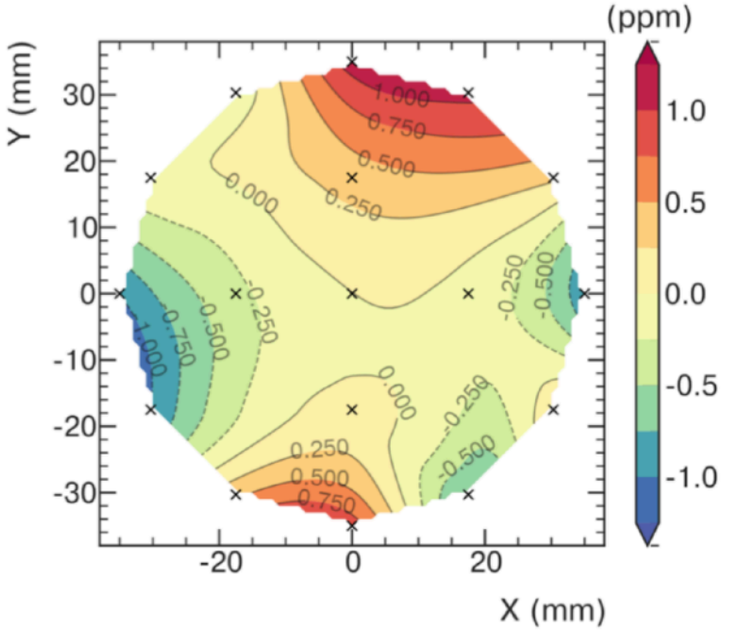
- Absolute probes were used to calibrate NMR probes
- Proton NMR, calibrated in terms of $\omega_p(T_r)$ of a proton shielded in a spherical sample of water at an exact temperature.

Measuring ω_p: Monitoring and Measuring the Magnetic Field





azimuthally averaged field



To determine ω_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

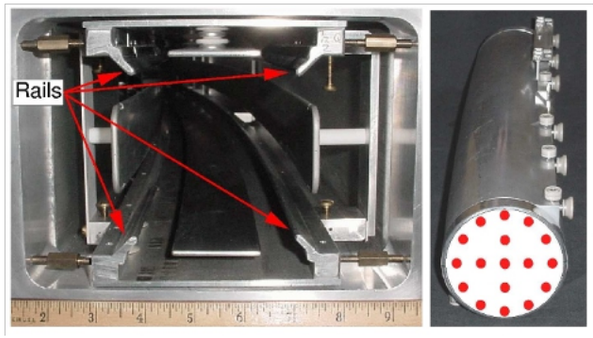
$$a_\mu = \left(\frac{g_e}{2}\right)\left(\frac{\omega_a}{\langle\omega_p\rangle}\right)\left(\frac{\mu_p}{\mu_e}\right)\left(\frac{m_\mu}{m_e}\right)$$

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

ω_p: free proton precession frequency

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

Measuring ω_p: Monitoring and Measuring the Magnetic Field



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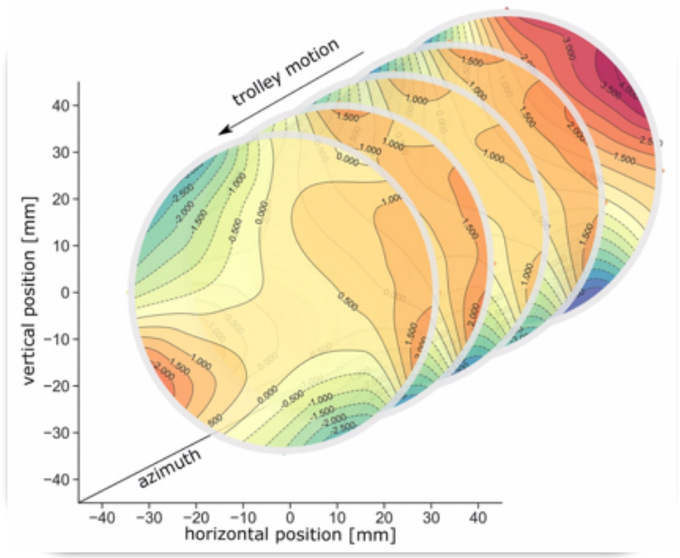

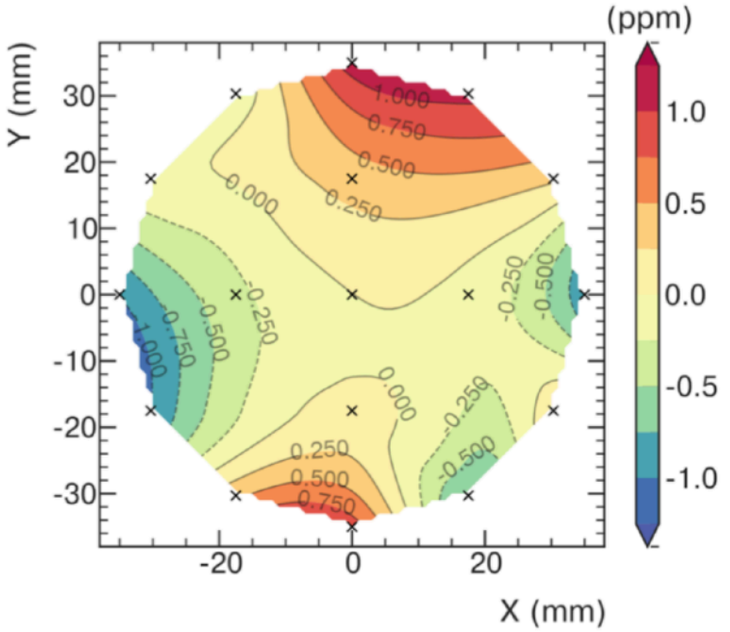

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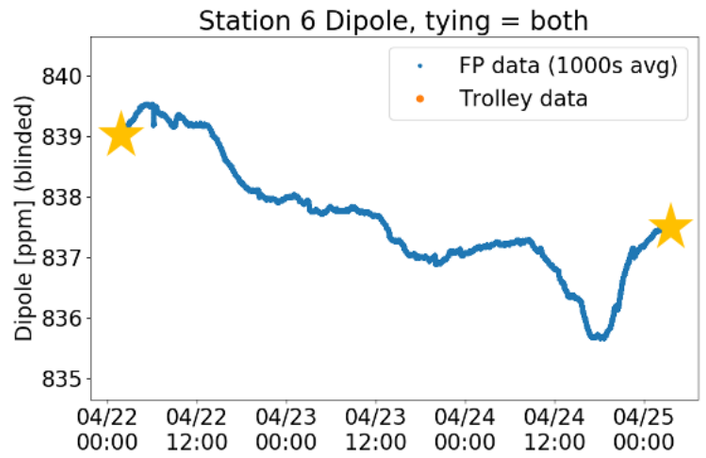
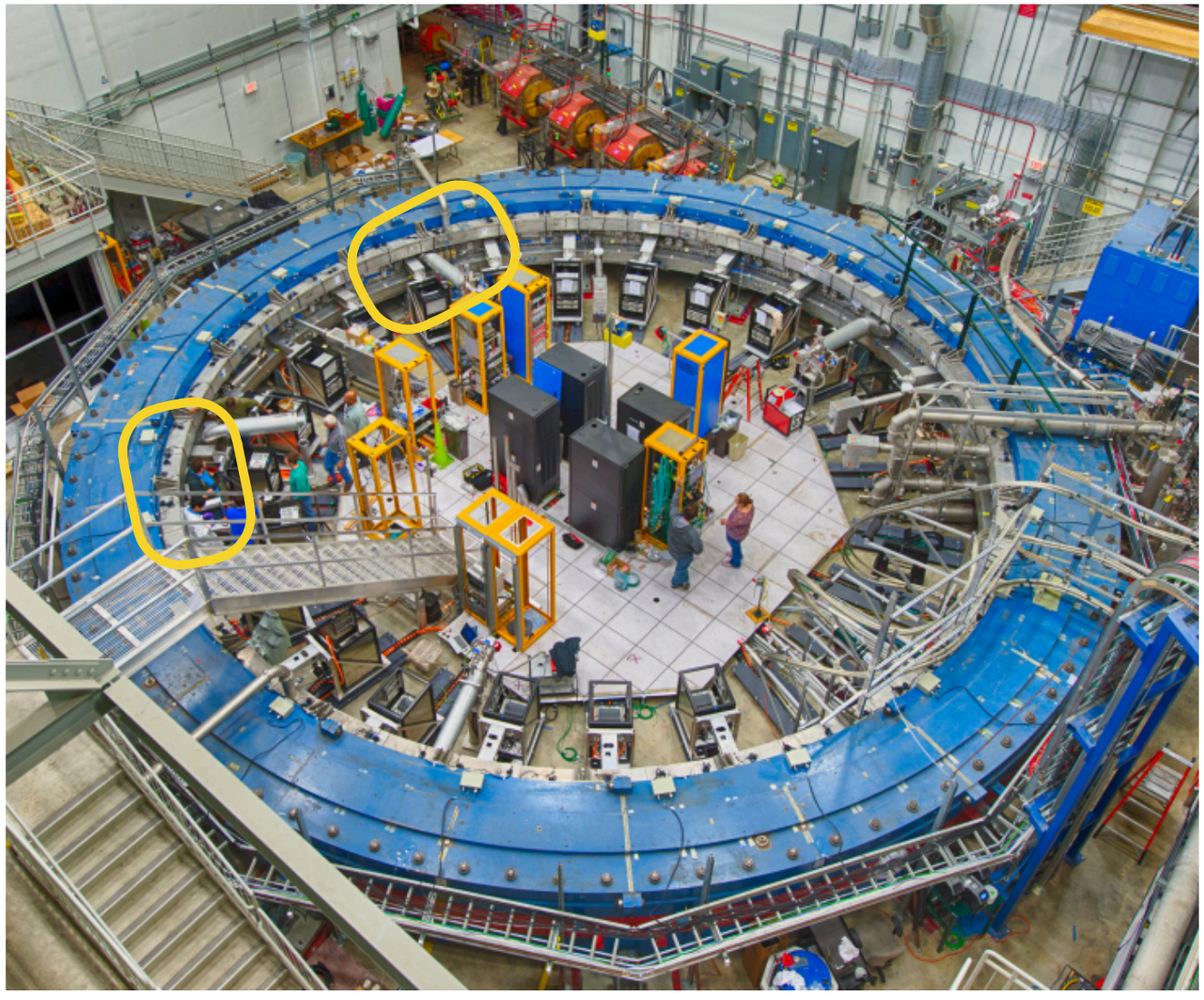
$$a_\mu = \left(\frac{g_e}{2}\right)\left(\frac{\omega_a}{\langle\omega_p\rangle}\right)\left(\frac{\mu_p}{\mu_e}\right)\left(\frac{m_\mu}{m_e}\right)$$

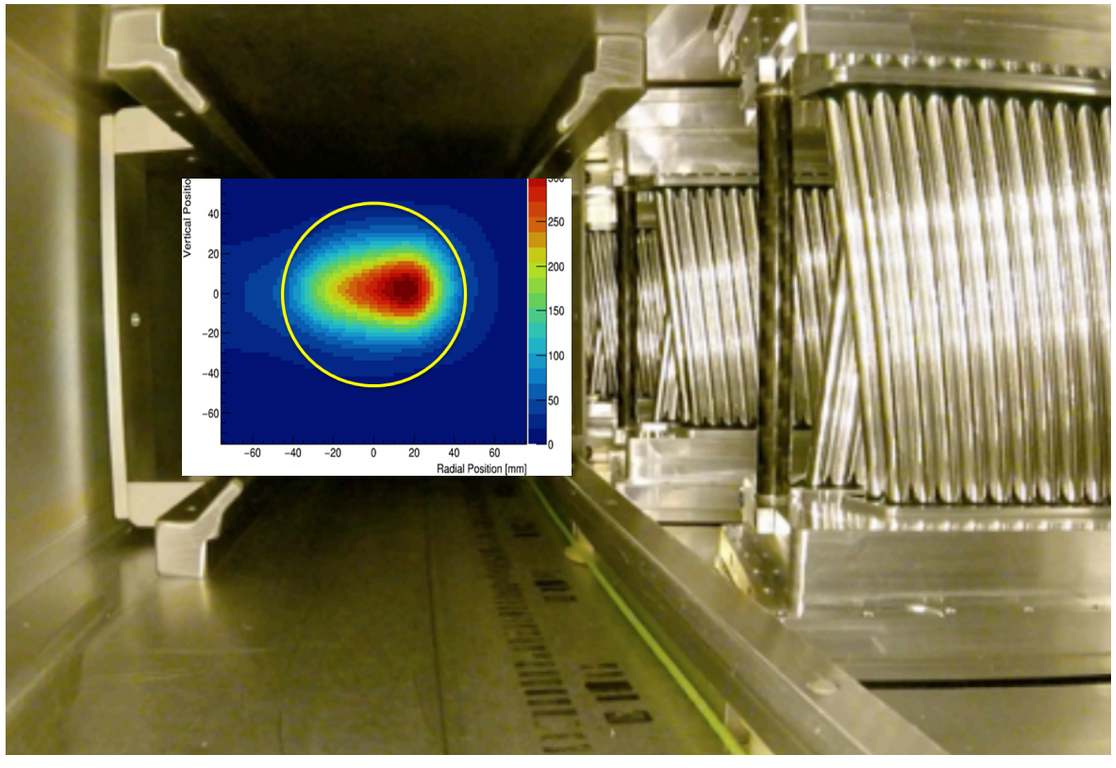
$$\langle\omega_p\rangle \approx \omega_p \otimes \rho(r)$$



Detectors: Trackers for Reconstructing the Beam Profile

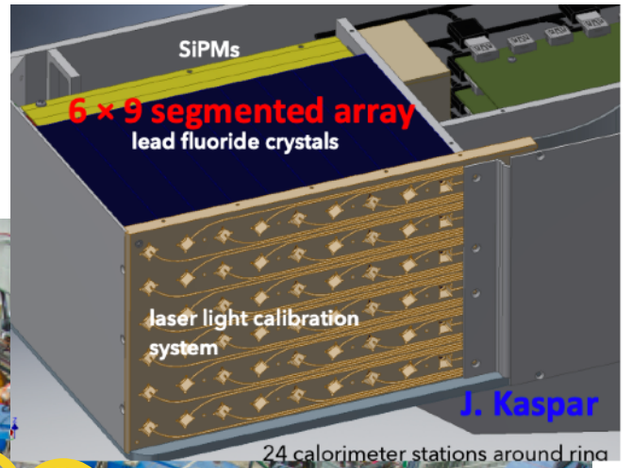


- **Trackers**
  - 2 straw-tracker stations
  - 8 modules per station each with 128 straws
  - Reconstruct muon beam profile from positron trajectories

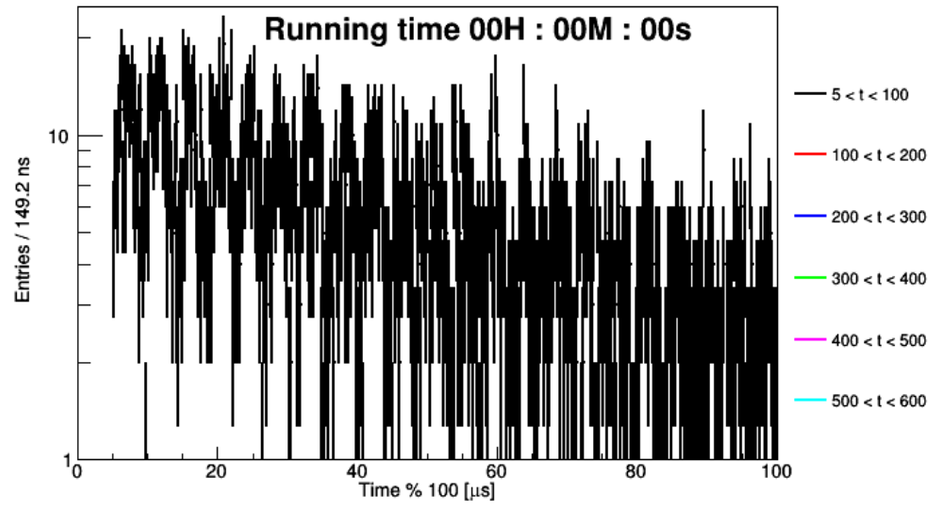


$$a_\mu = \left(\frac{g_e}{2}\right)\left(\frac{\omega_a}{\langle\omega_p\rangle}\right)\left(\frac{\mu_p}{\mu_e}\right)\left(\frac{m_\mu}{m_e}\right) \qquad \langle\omega_p\rangle \approx \omega_p \otimes \rho(r)$$

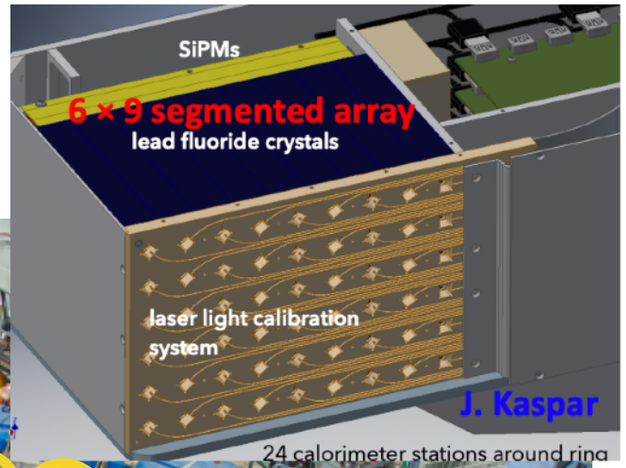
Detectors : Calorimeters



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



Detectors : Calorimeters



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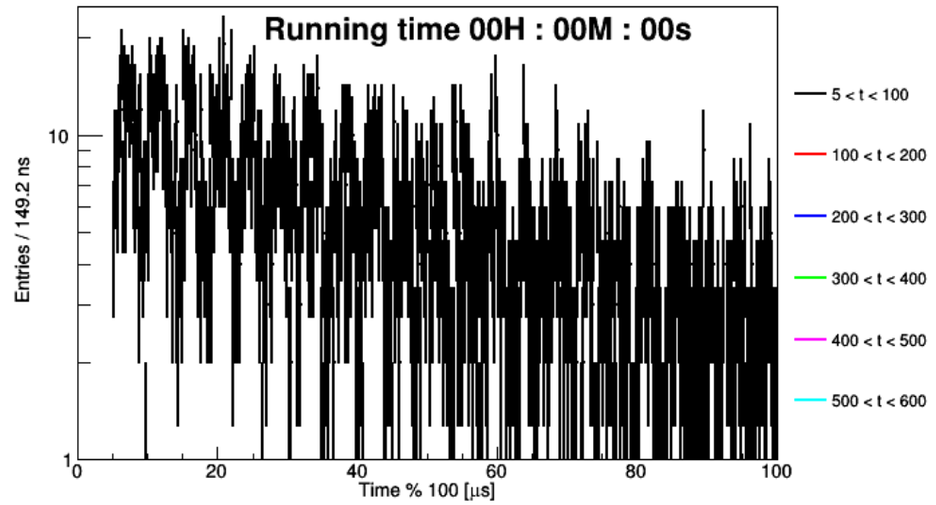

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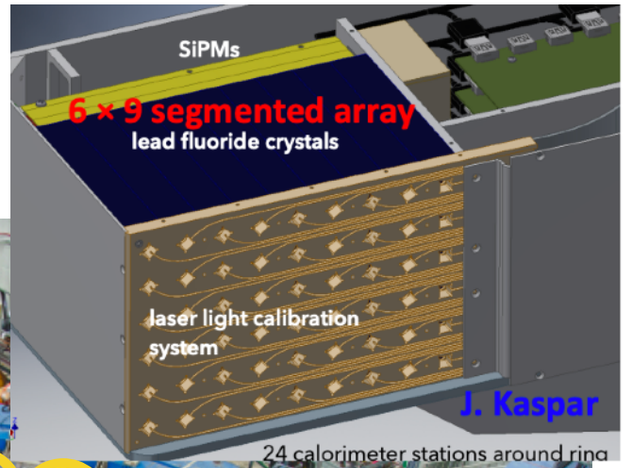

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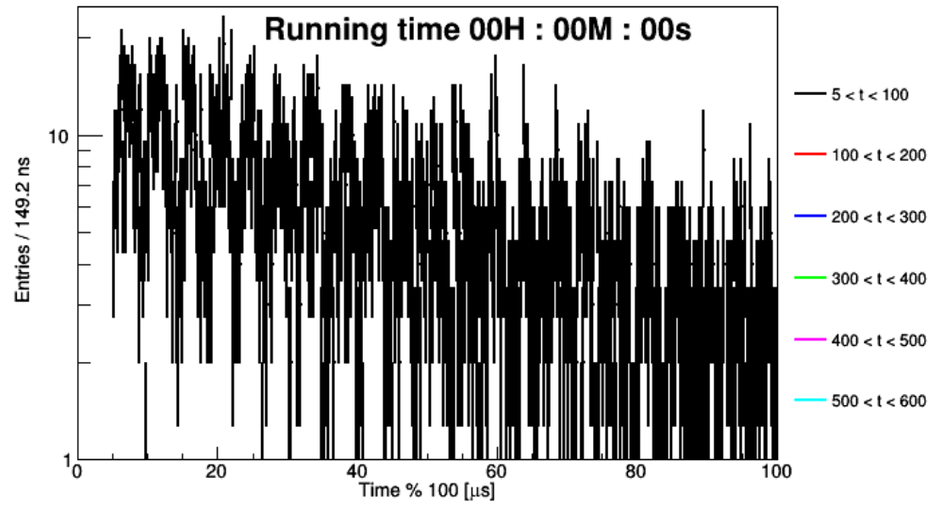

$$N(t) = N_0 e^{-t/\tau}[1 + A\cos(\omega_a t + \phi)]$$

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

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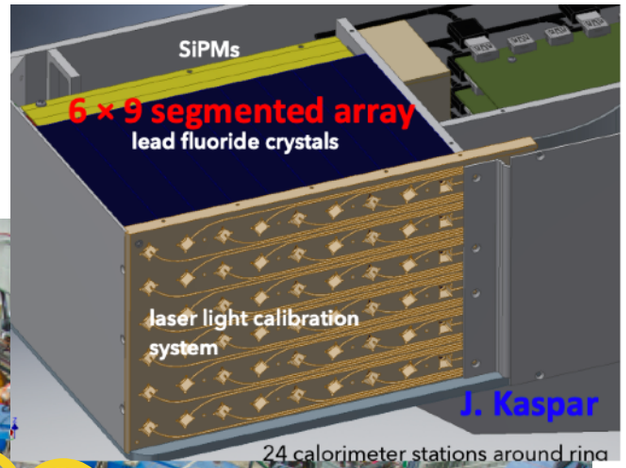

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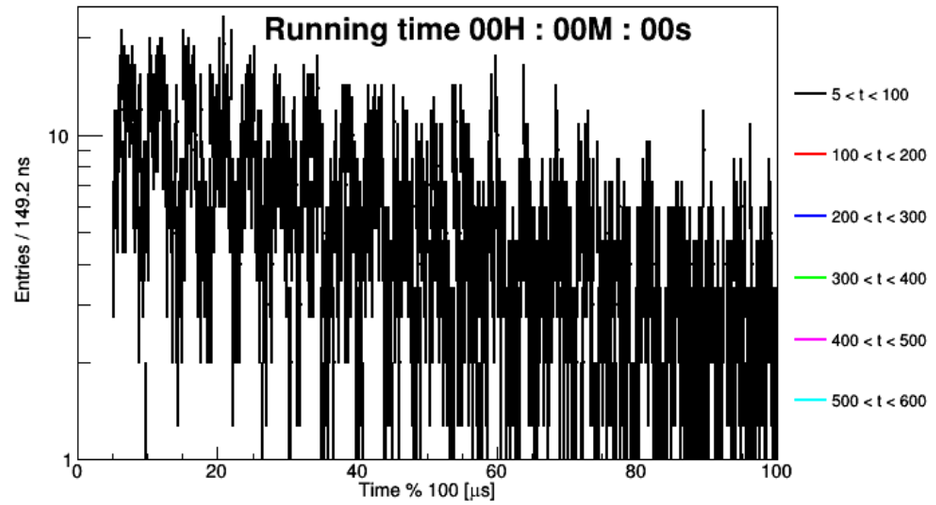

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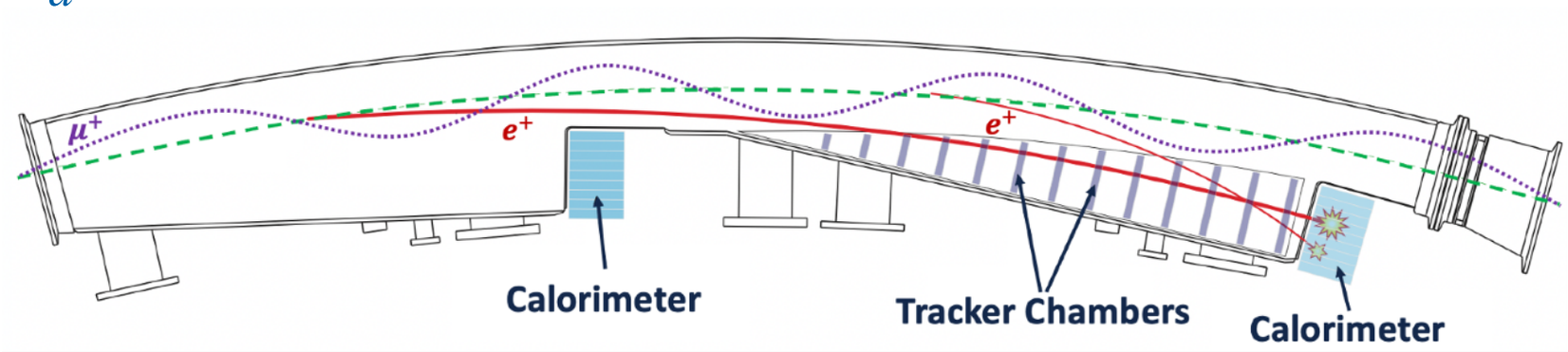
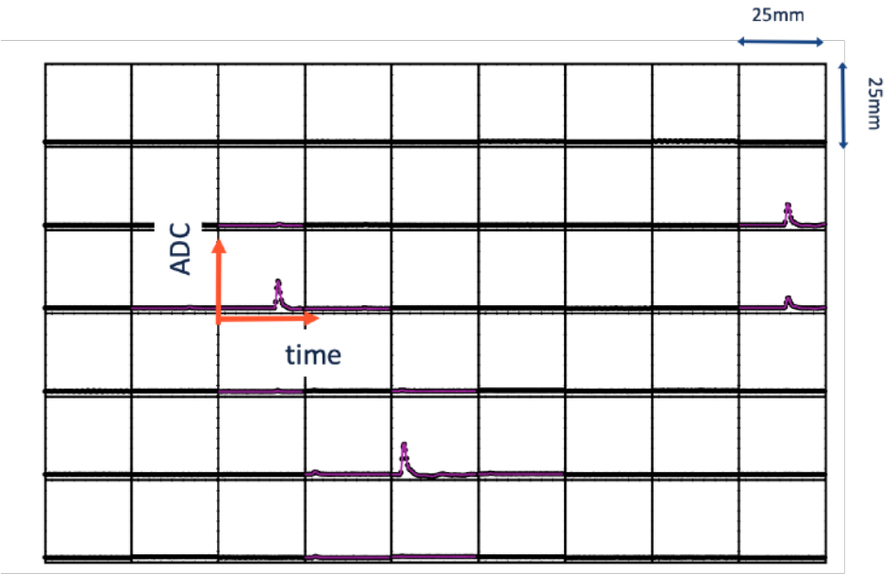
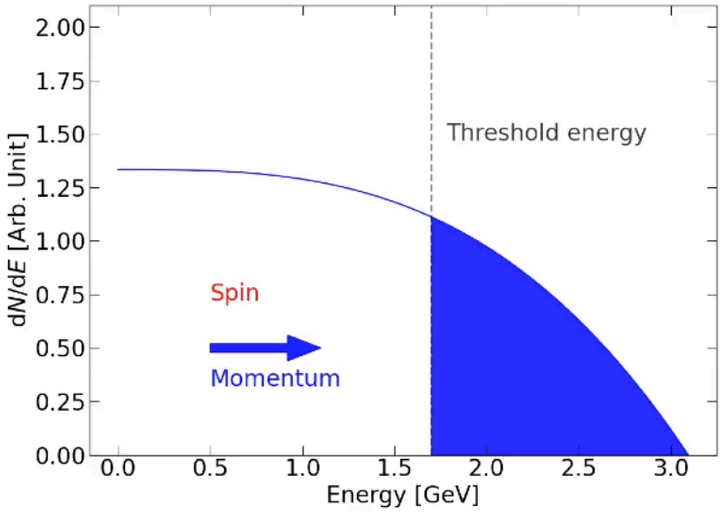
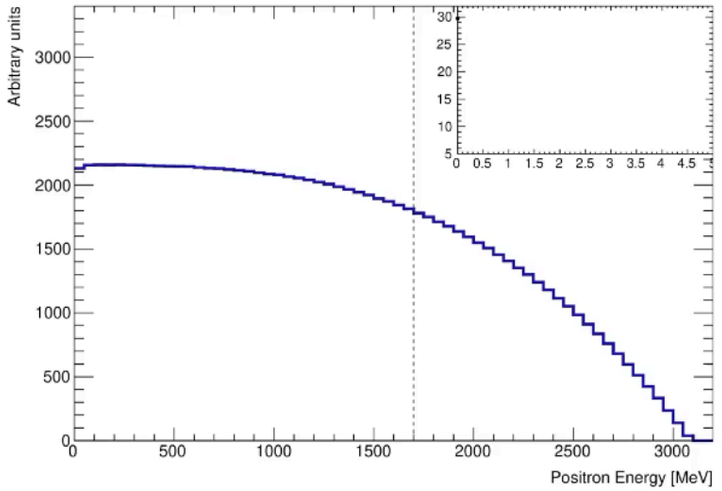
Calculating ω_a:



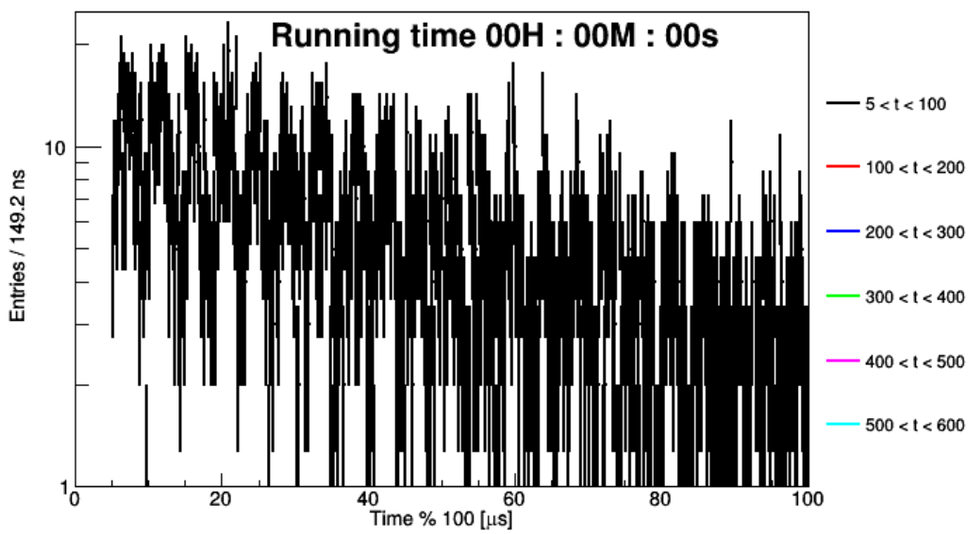
Energy distribution recorded in the calorimeter.





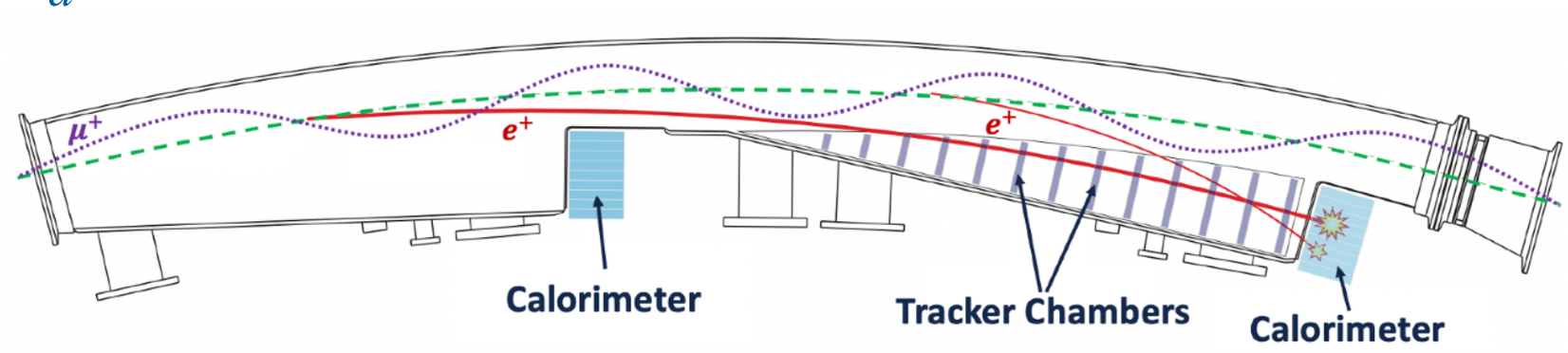


ω_a blinded by both hardware and software

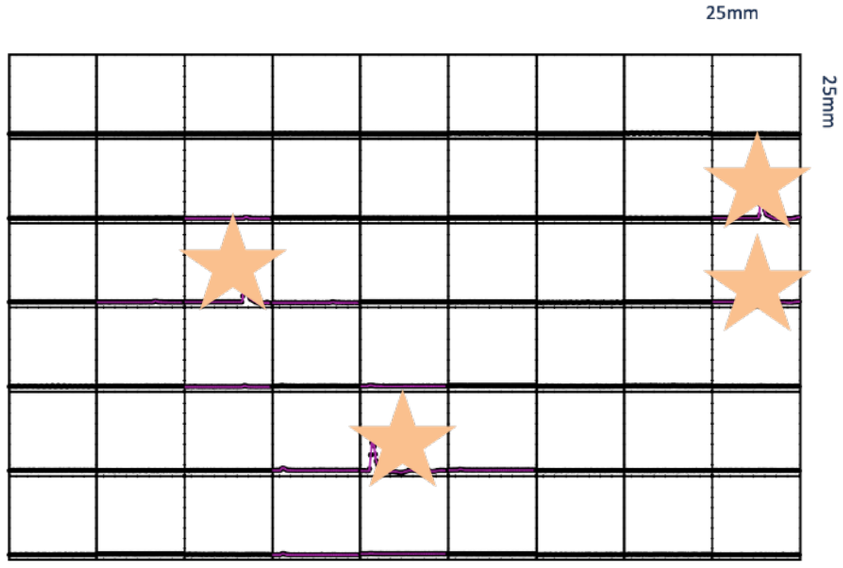


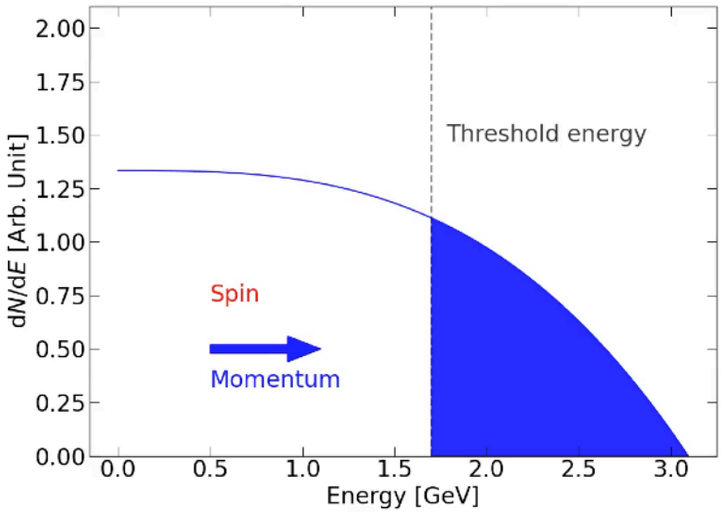
Wiggle plot

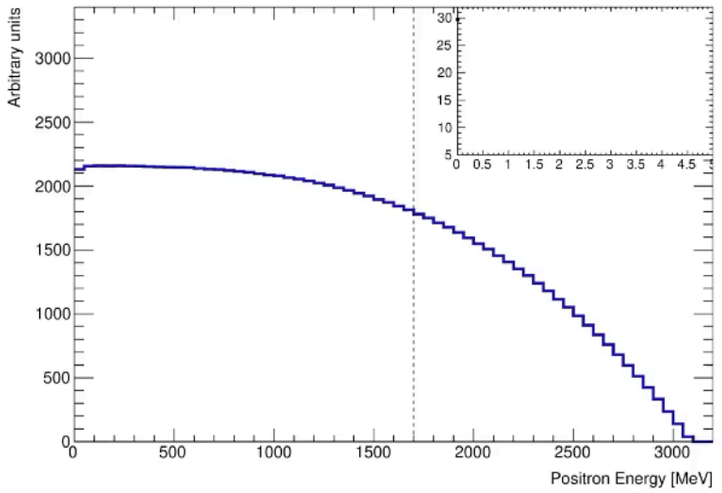
Calculating ω_a:



Energy distribution recorded in the calorimeter.







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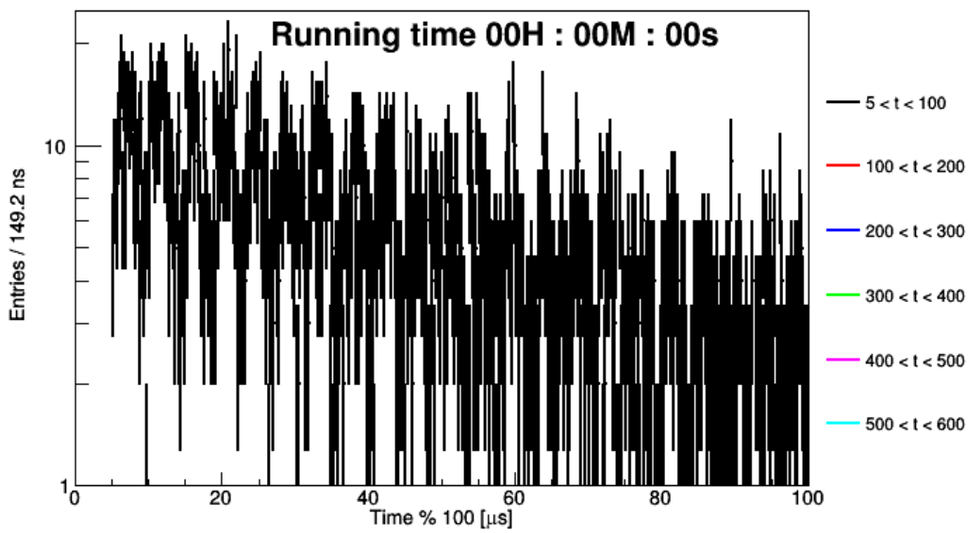
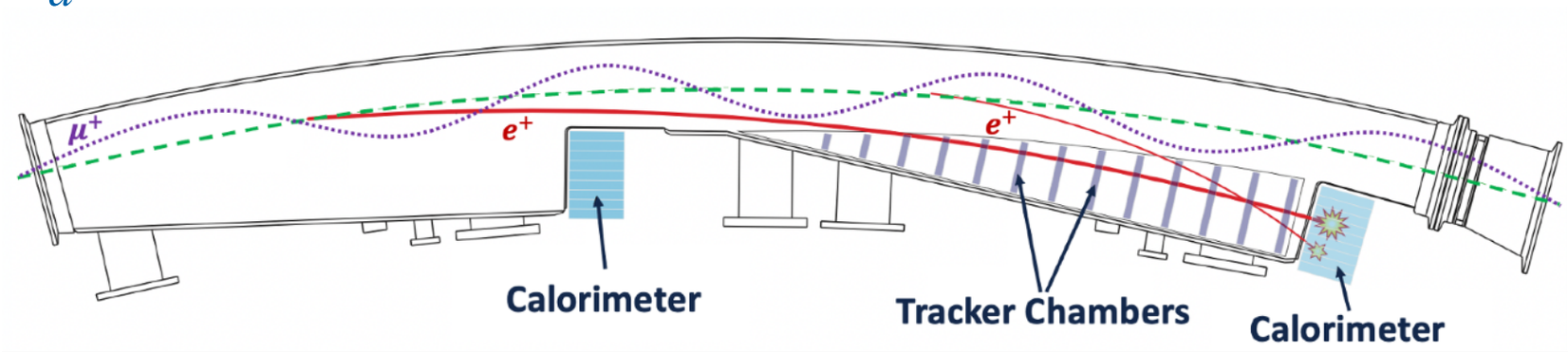
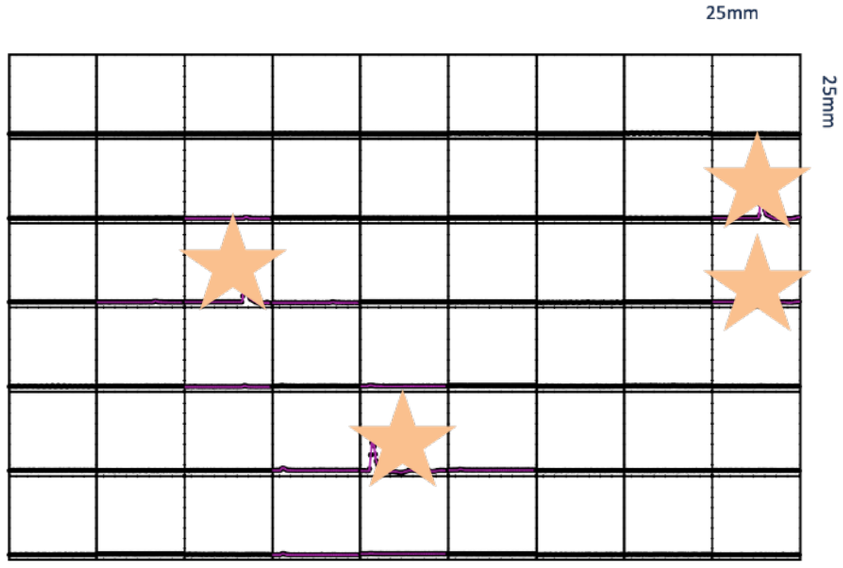


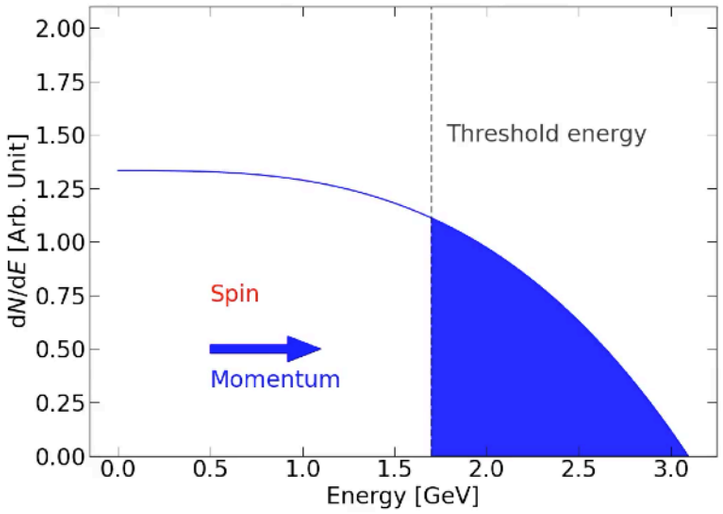
Wiggle plot

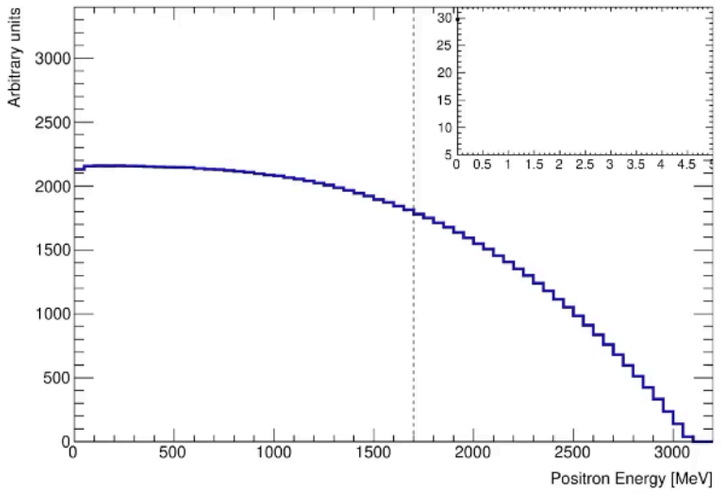
Calculating ω_a:



Energy distribution recorded in the calorimeter.







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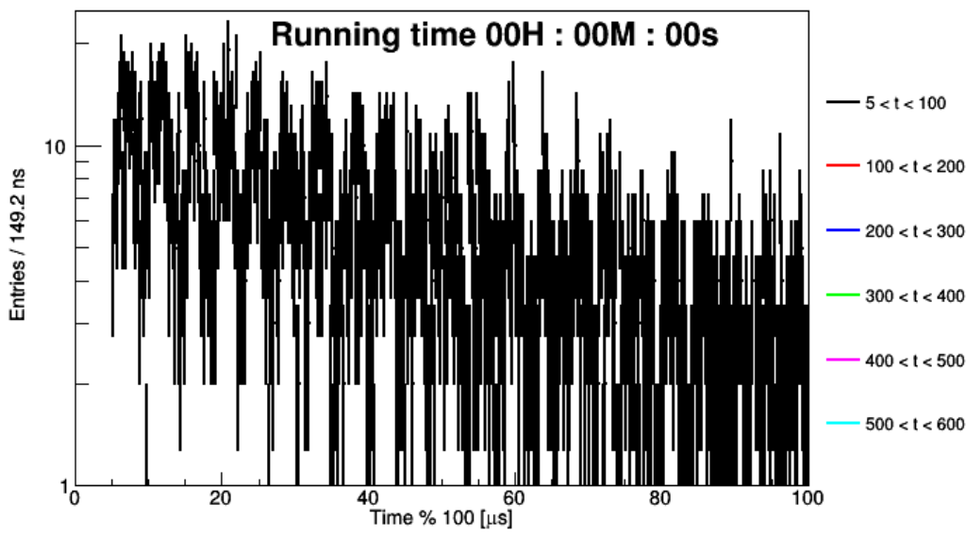

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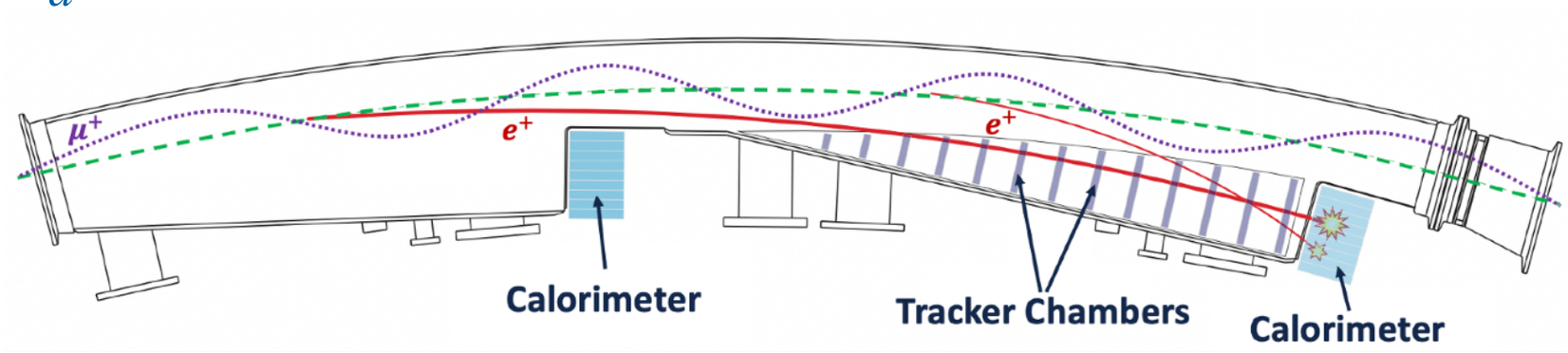

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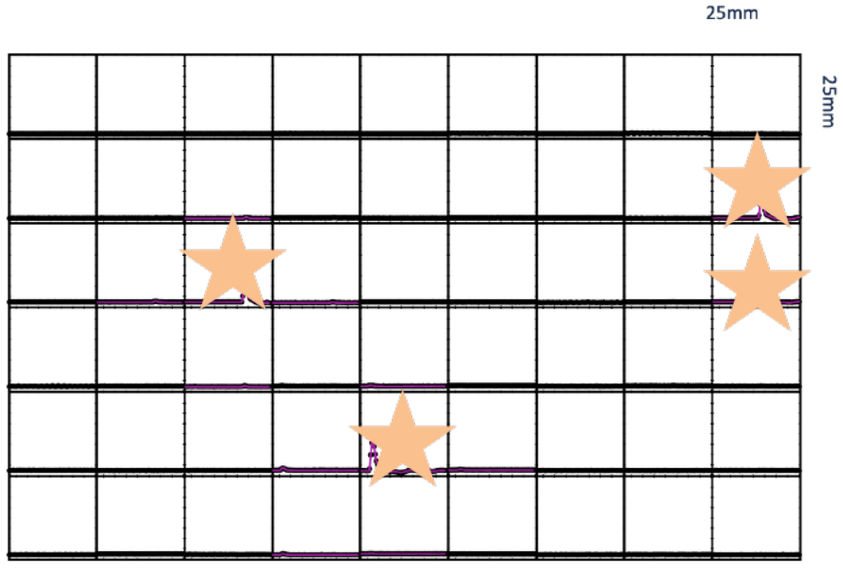

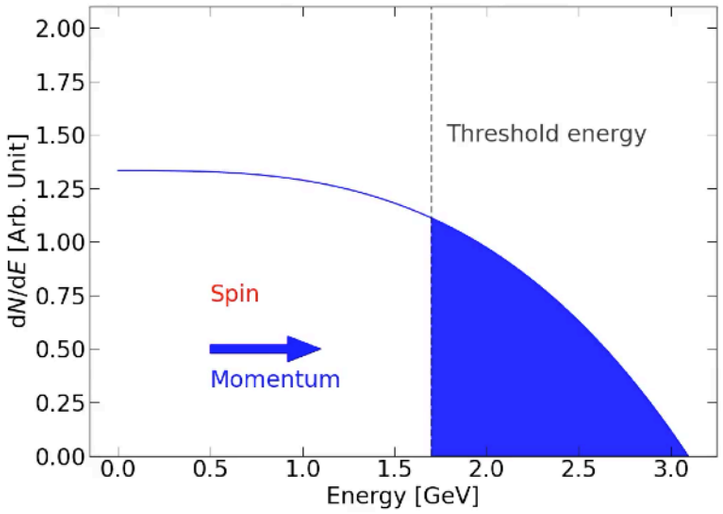

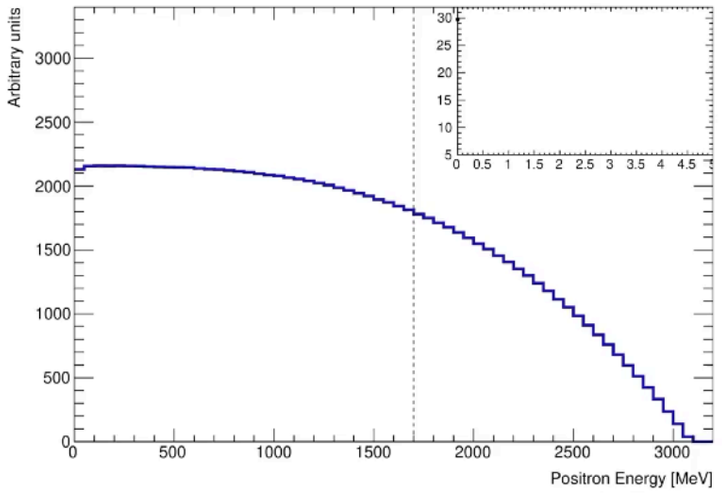

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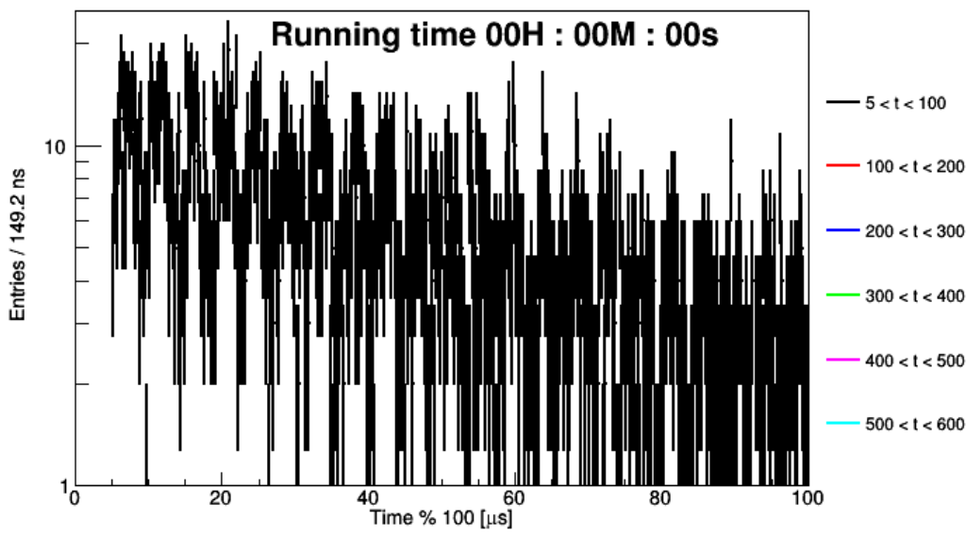
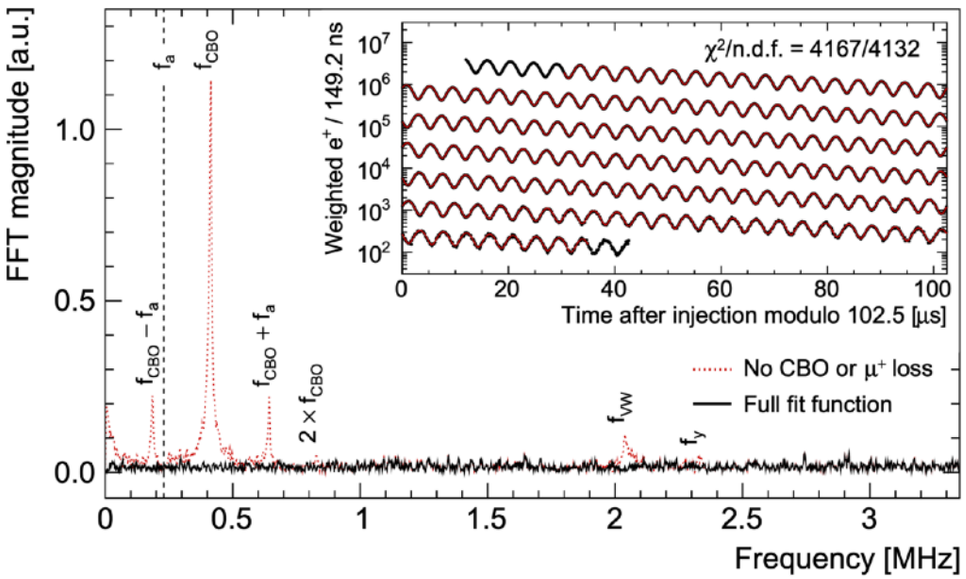


Wiggle plot

Calculating ω_a: Hidden information in the wiggle plot

FFT analysis of fit residuals



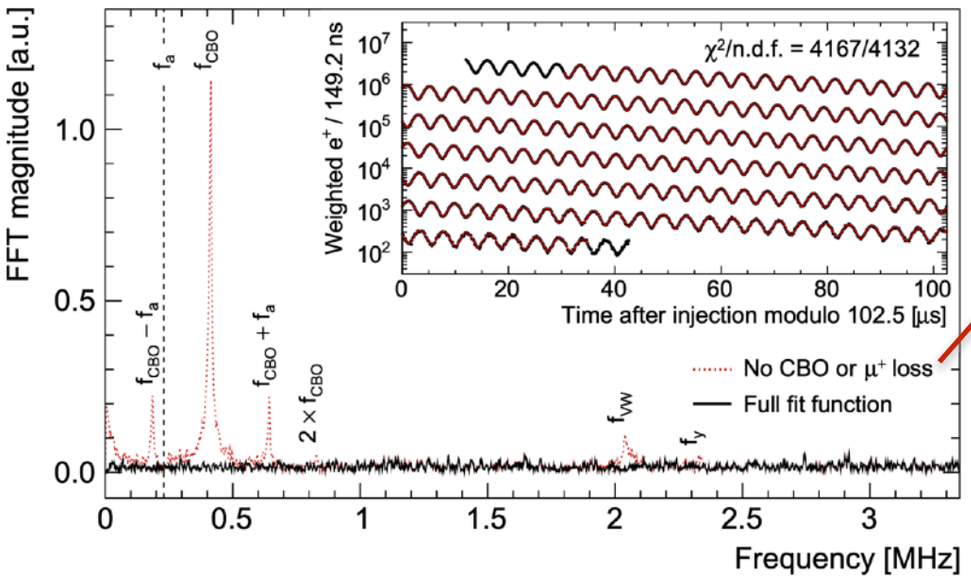
Calculating ω_a: Hidden information in the wiggle plot

Underling Physics

5 parameter fit function

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

FFT analysis of fit residuals



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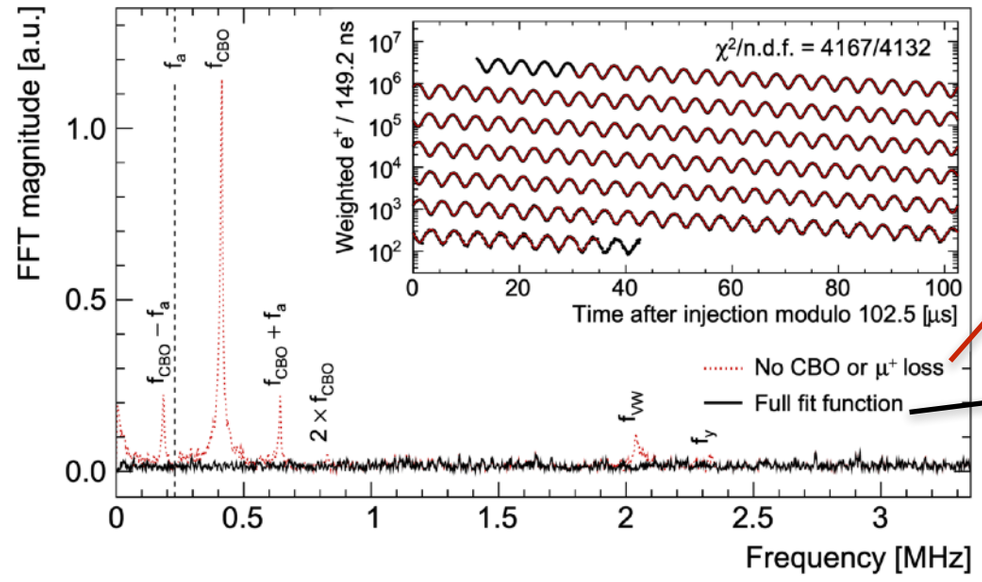

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Systematic Effects

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

$$N_0\, e^{-\frac{t}{\gamma\tau}}\,(1 + A \cdot A_{BO}(t)\cos(\omega_a t + \phi \cdot \phi_{BO}(t)\,)) \cdot N_{\mathrm{CBO}}(t) \cdot N_{\mathrm{VW}}(t) \cdot N_y(t) \cdot N_{2\mathrm{CBO}}(t) \cdot J(t)$$

$$A_{\mathrm{BO}}(t) = 1 + A_A \cos(\omega_{\mathrm{CBO}}(t) + \phi_A) e^{-\frac{t}{\tau_{\mathrm{CBO}}}}$$

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

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

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

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

$$N_y(t) = 1 + A_y \cos(\omega_y(t)t + \phi_y) e^{-\frac{t}{\tau_y}}$$

$$J(t) = 1 - k_{LM} \int_{t_0}^{t} \Lambda(t) dt$$

$$\omega_{\mathrm{CBO}}(t) = \omega_0 t + A e^{-\frac{t}{\tau_A}} + B e^{-\frac{t}{\tau_B}}$$

$$\omega_y(t) = F\omega_{\mathrm{CBO}(t)} \sqrt{2\omega_c / F\omega_{\mathrm{CBO}}(t) - 1}$$

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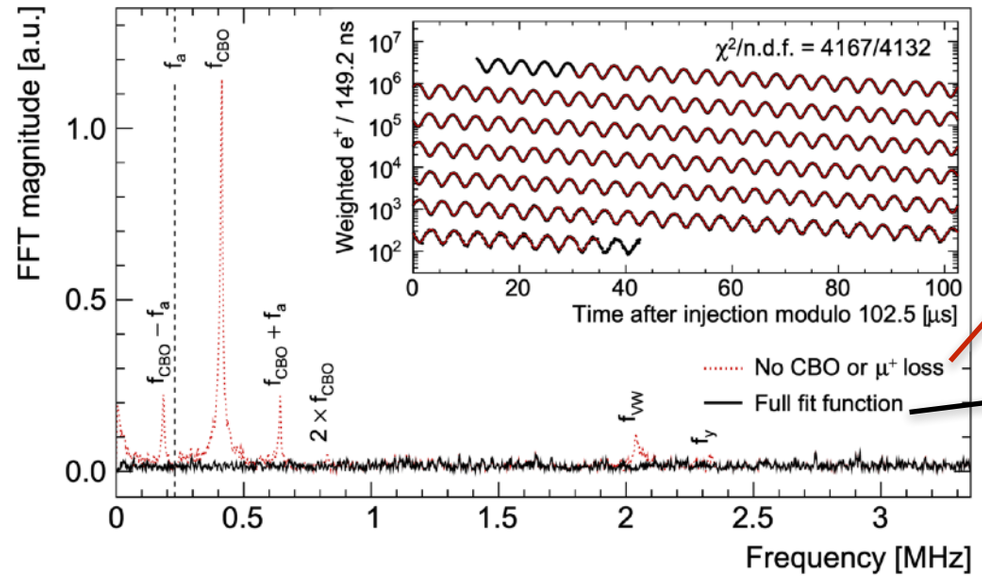
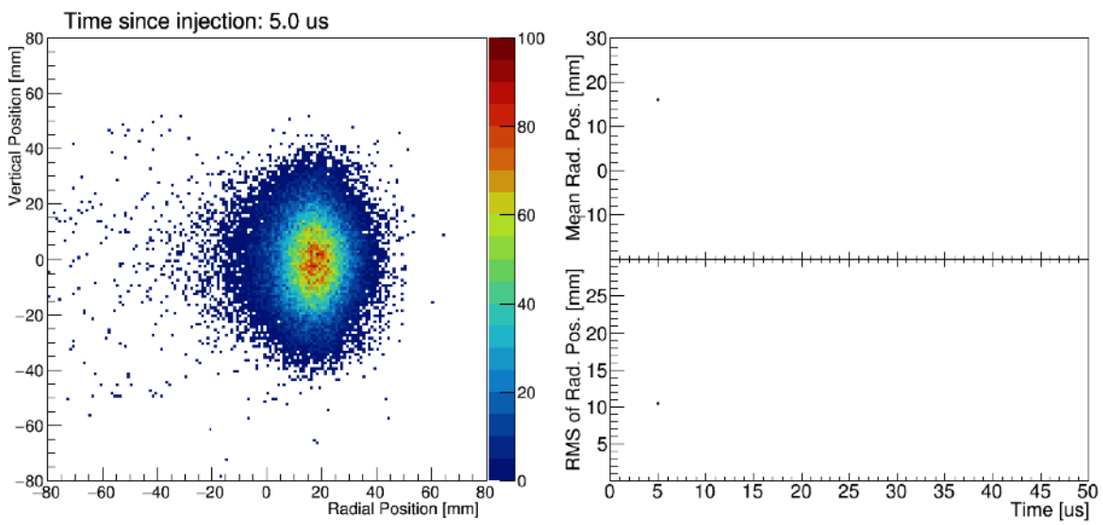
Calculating ω_a: Hidden information in the wiggle plot

FFT analysis of fit residuals





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Systematic Effects

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

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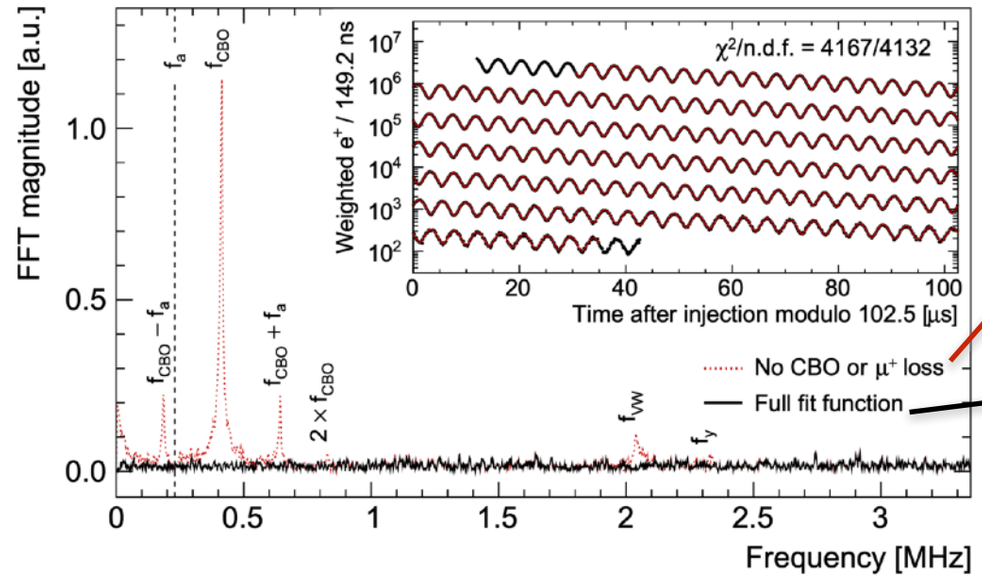
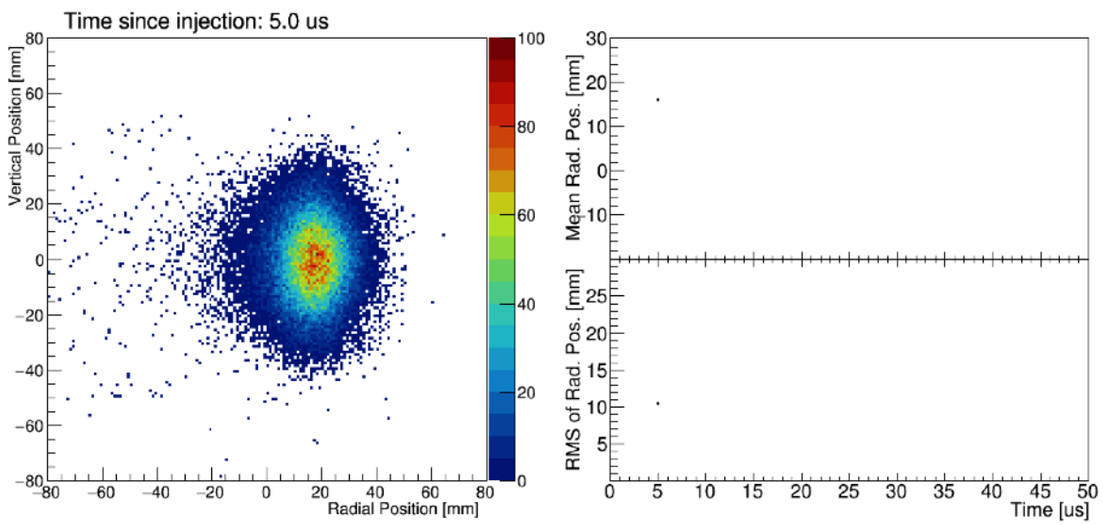
Calculating ω_a: Hidden information in the wiggle plot

FFT analysis of fit residuals





Underling Physics

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Systematic Effects

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

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

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$$N_y(t) = 1 + A_y \cos(\omega_y(t)t + \phi_y) e^{-\frac{t}{\tau_y}}$$

$$J(t) = 1 - k_{LM} \int_{t_0}^{t} \Lambda(t) dt$$

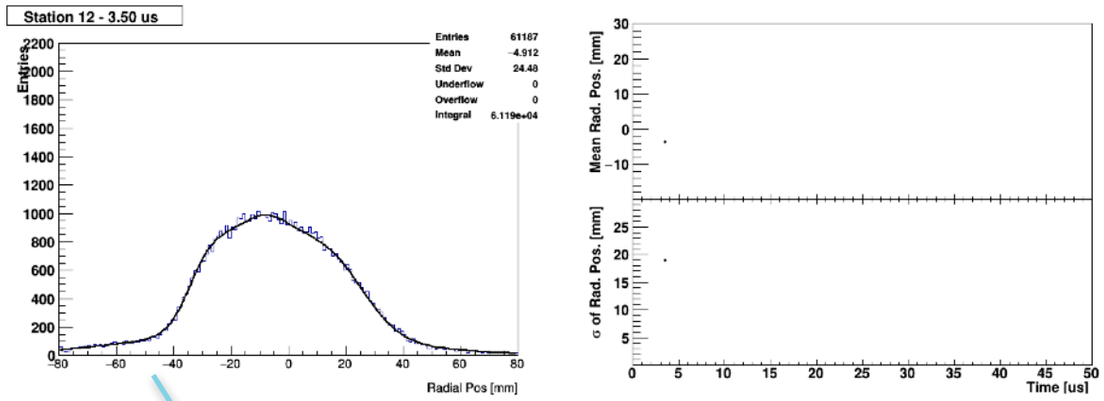
$$\omega_{\mathrm{CBO}}(t) = \omega_0 t + A e^{-\frac{t}{\tau_A}} + B e^{-\frac{t}{\tau_B}}$$

$$\omega_y(t) = F\omega_{\mathrm{CBO}(t)} \sqrt{2\omega_c / F\omega_{\mathrm{CBO}}(t) - 1}$$

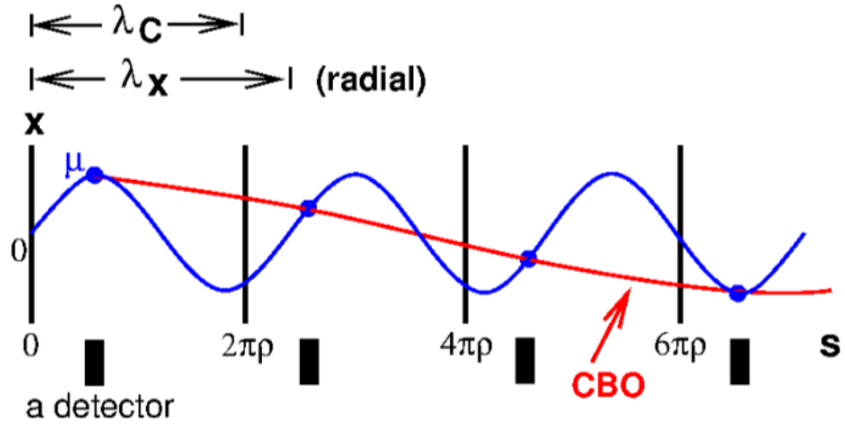
$$\omega_{\mathrm{VW}}(t) = \omega_c - 2\omega_y(t)$$

What is the beam doing after all these pulses and kicks

- CBO - Coherent Betatron Oscillation



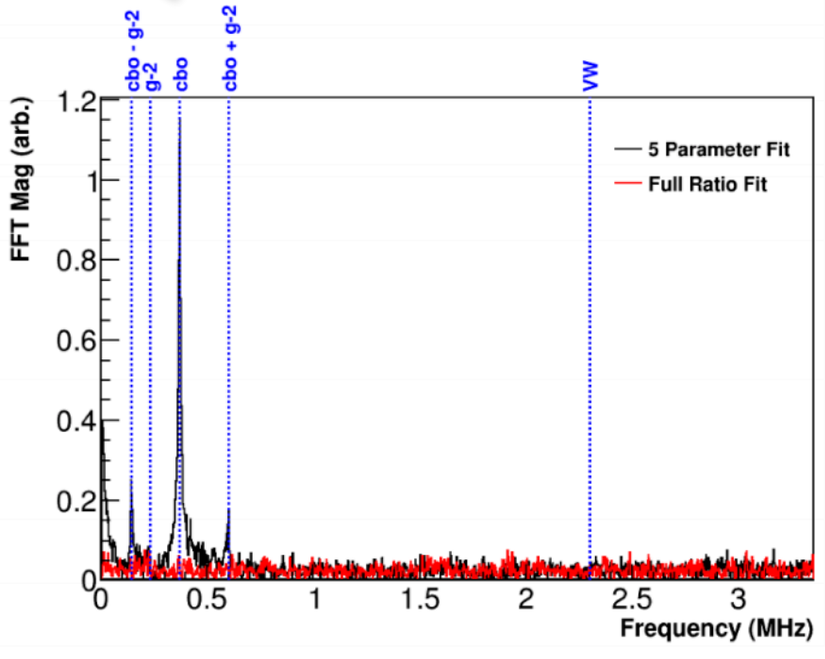
Radial CBO movement



λ_x - radial wavelength

λ_C - cyclotron wavelength

Frequency from detector point of view = $f_c - f_x$



$$x = x_e + A_x cos(f_x t + \delta_x) \quad y = A_y cos(f_y t + \delta_y)$$

Simple Harmonic Motion

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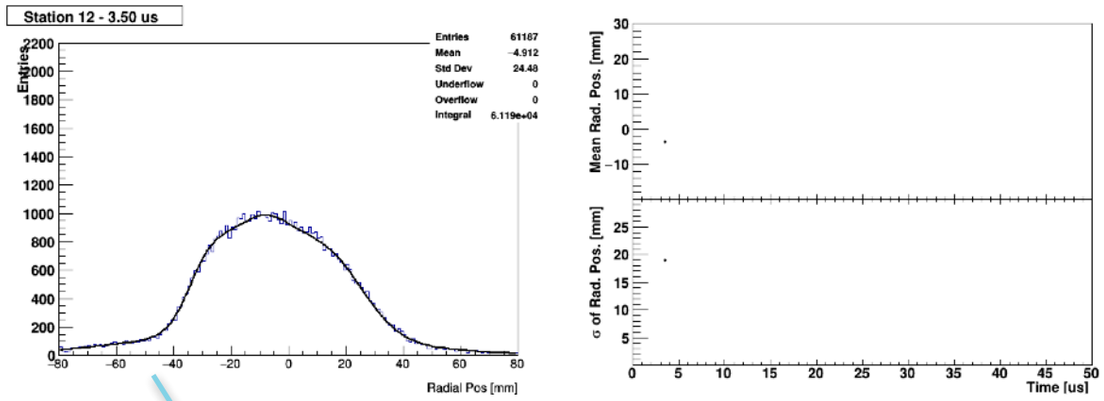

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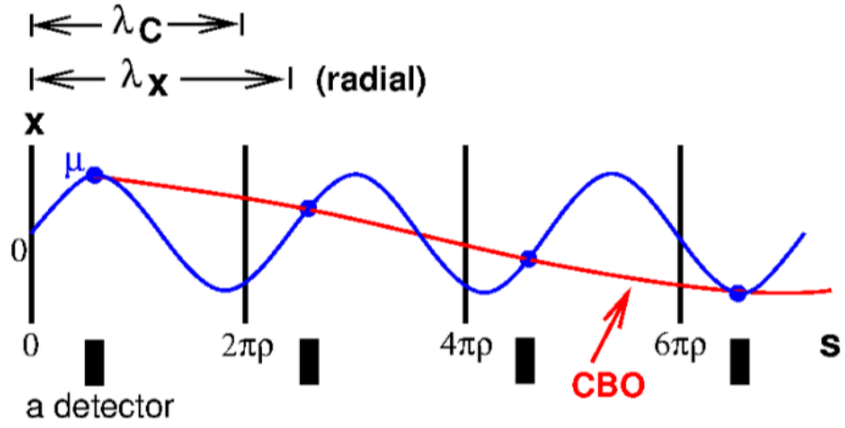

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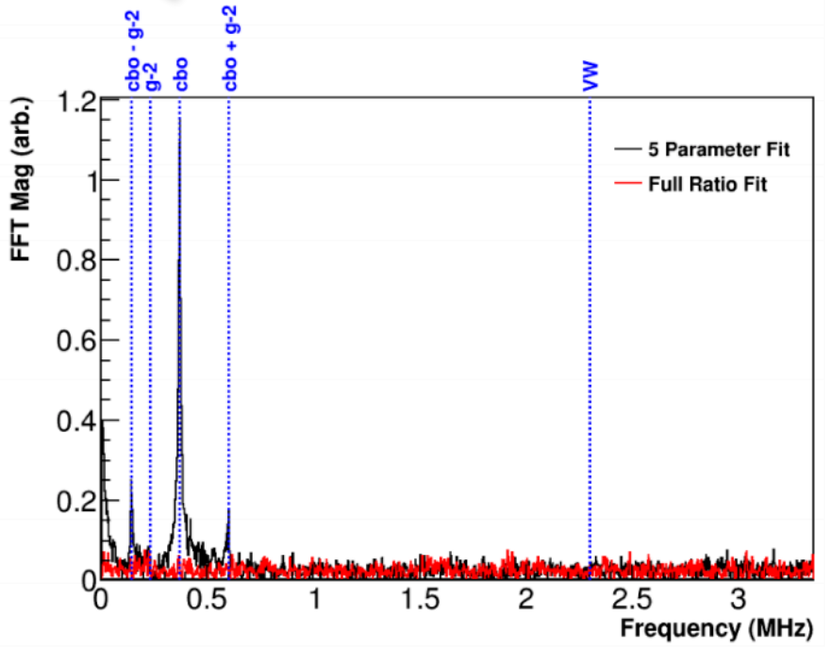

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Simple Harmonic Motion

Gathered all the numbers!

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

0.26 ppt — 3 ppb — 22 ppb ⇨ 2017 CODATA

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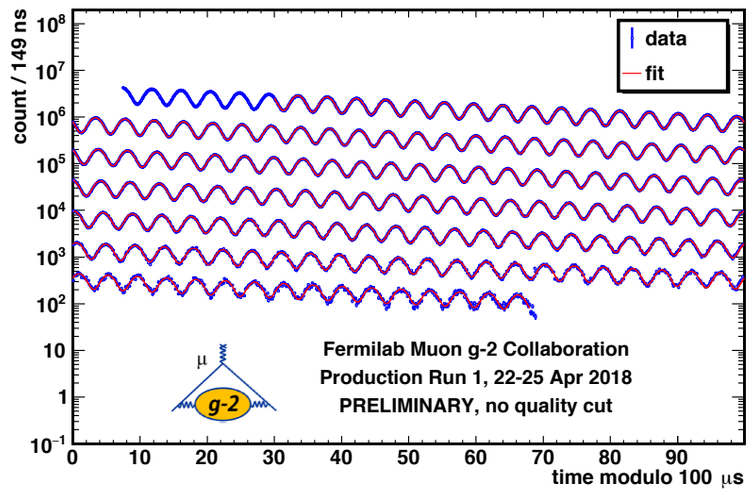

ω_a

Extract from decay positron time spectra

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

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

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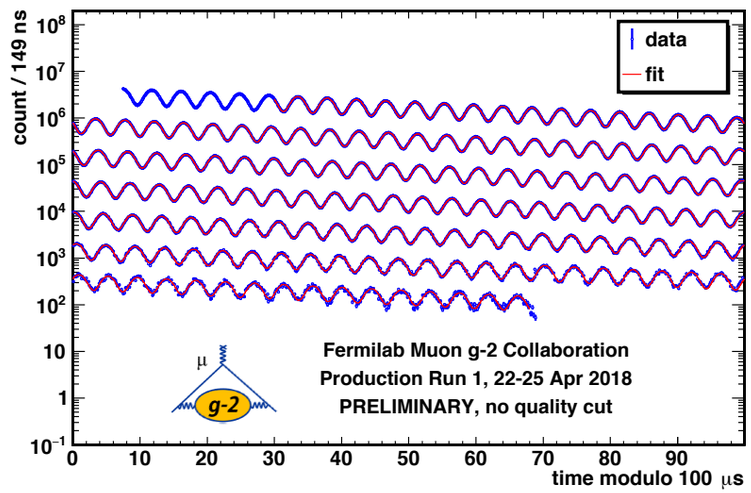

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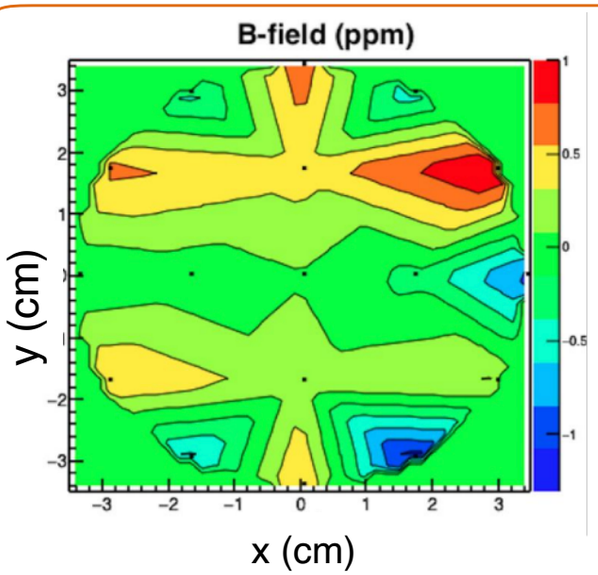
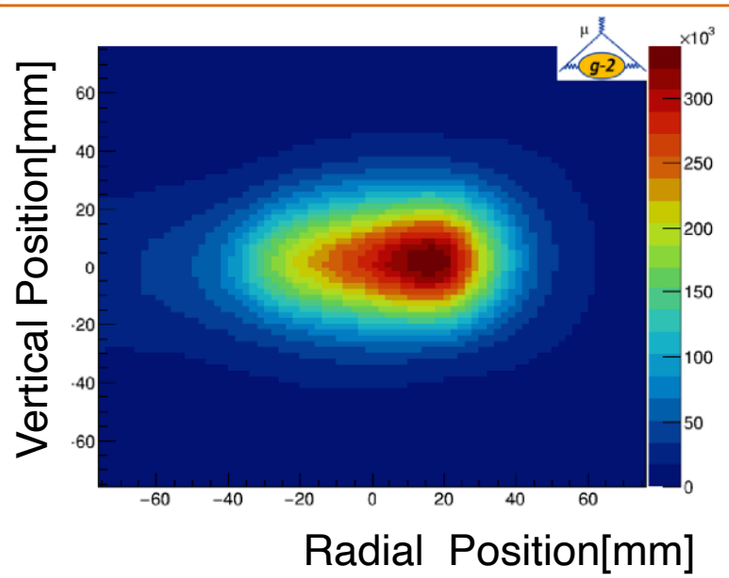


Map the magnetic field



Obtain muon distribution In the storage ring

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

Average magnetic field weighted by muon distribution

ω_p: free proton precession frequency

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

Systematics

$$a_\mu \propto \frac{f_{\rm clock}\ \ \omega_a^m\,(1 + C_e + C_p + C_{ml} + C_{pa})}{f_{\rm calib}\,\langle \omega_p'(x,y,\phi) \times M(x,y,\phi)\rangle\,(1 + B_k + B_q)}$$

$f_{\rm clock}$ •Blinded clock

ω_a^m •Measured precession frequency

C_e •Electric field correction

C_p •Pitch correction

C_{ml} •Muon loss correction

C_{pa} •Phase-acceptance correction

$f_{\rm calib}$ •Absolute magnetic field calibration

$\omega_p'(x,y,\phi)$ •Field tracking multipole distribution

$M(x,y,\phi)$ •Muon weighted multipole distributed

B_k •Transient field from the eddy current in kicker

Bq •Transient field from the quad charging

Phase Acceptance

$$a_\mu \propto \frac{f_{\rm clock}\ \ \omega_a^m\,(1 + C_e + C_p + C_{ml} + C_{pa})}{f_{\rm calib}\,\langle \omega_p'(x,y,\phi) \times M(x,y,\phi)\rangle\,(1 + B_k + B_q)}$$

When there is a time dependent phase,

It shifts the ω_a !

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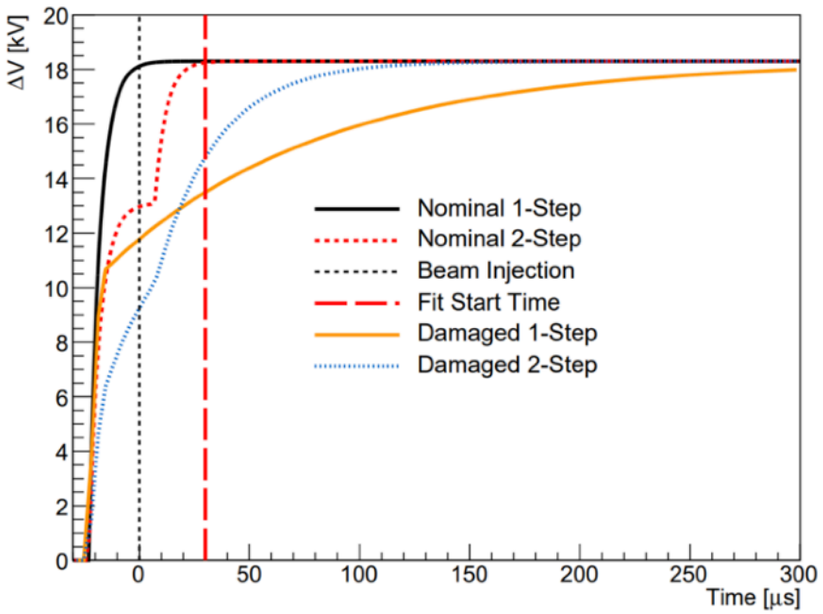

Due to damaged HV resistors; stored beam distribution was unstable.

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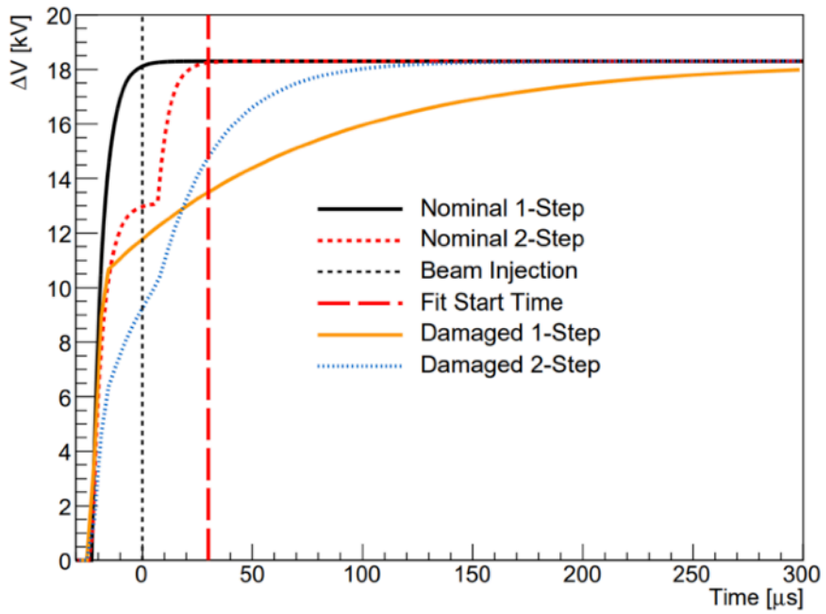
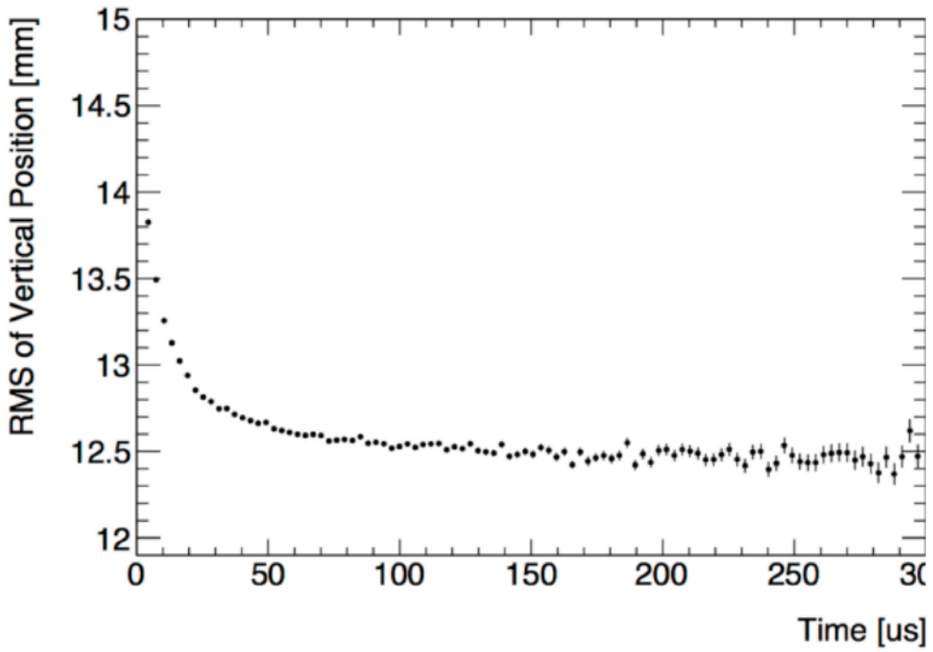
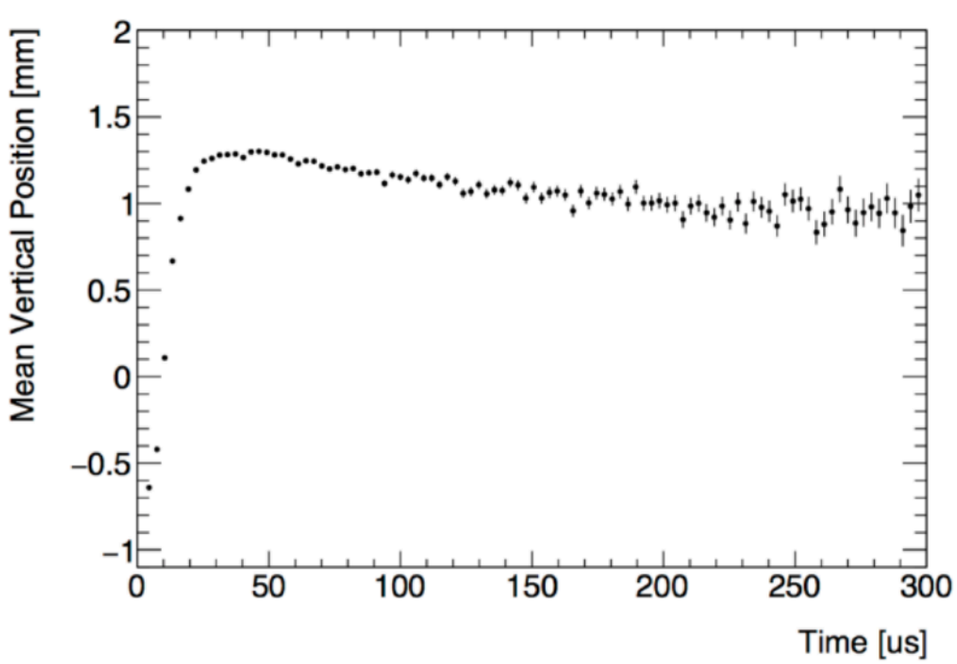


Due to damaged HV resistors; stored beam distribution was unstable.

It caused a time dependent phase

Beam vertical mean and width changed





ESQ Transients

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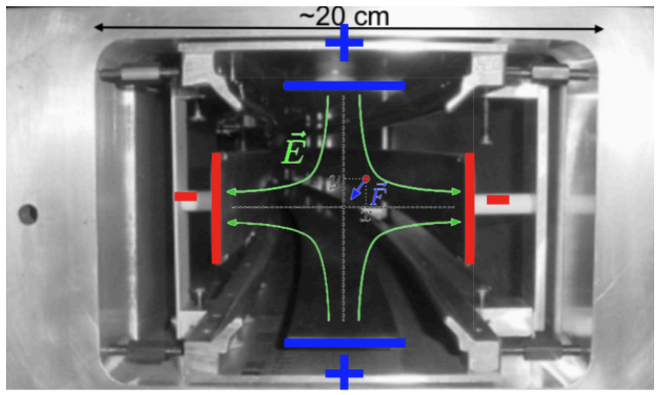
Quads charging and discharging cause mechanical vibration



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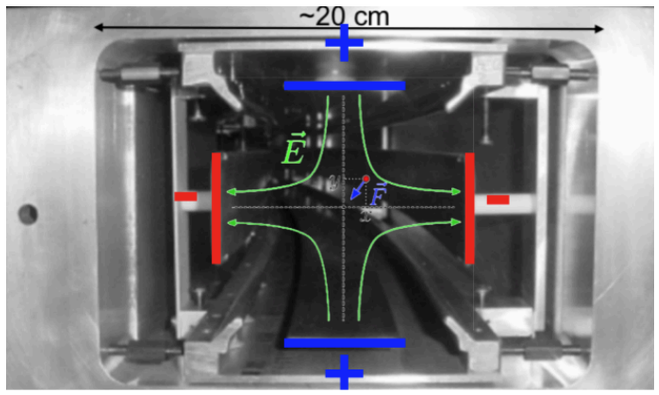

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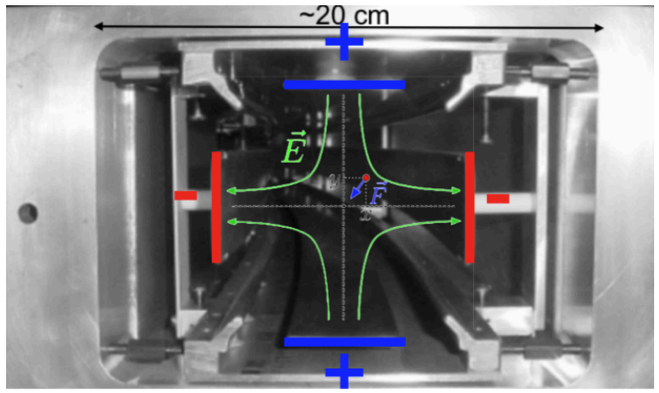
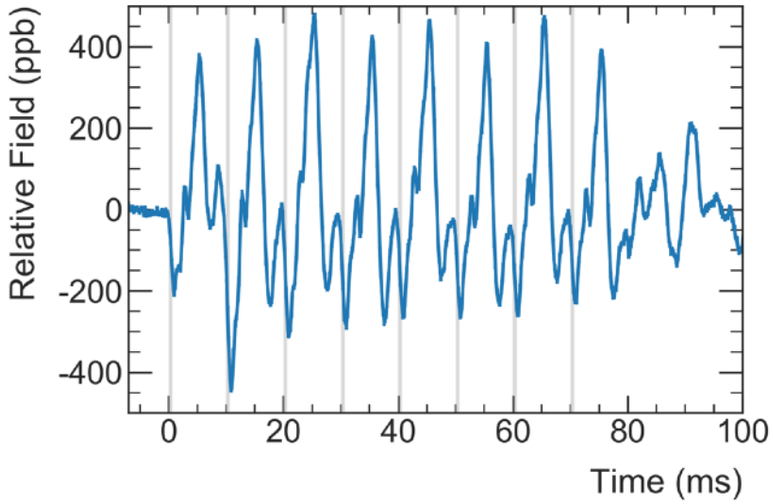


Field Perturbation



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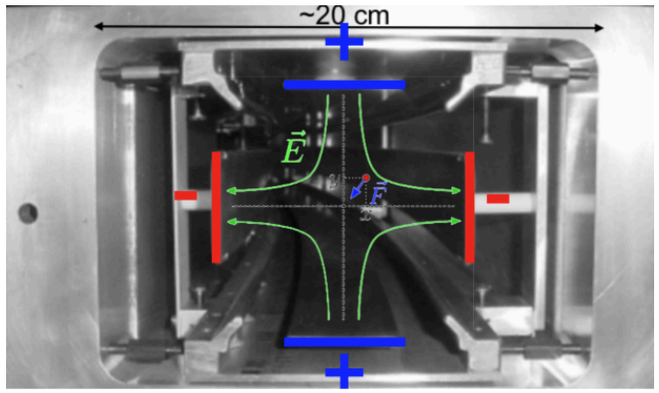

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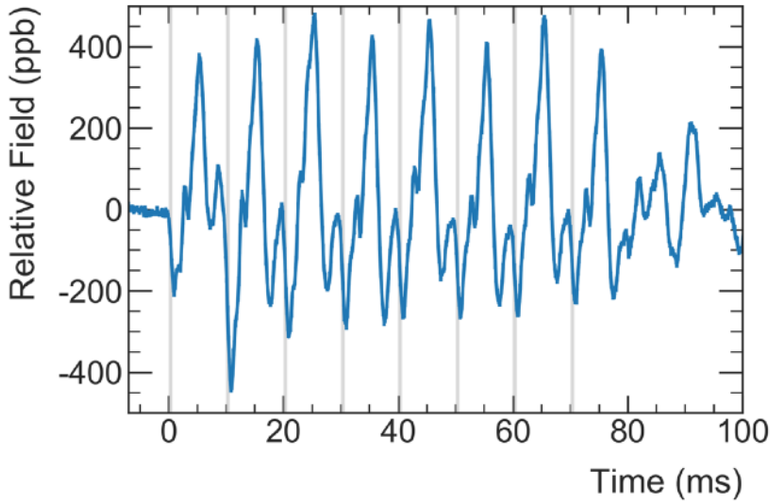

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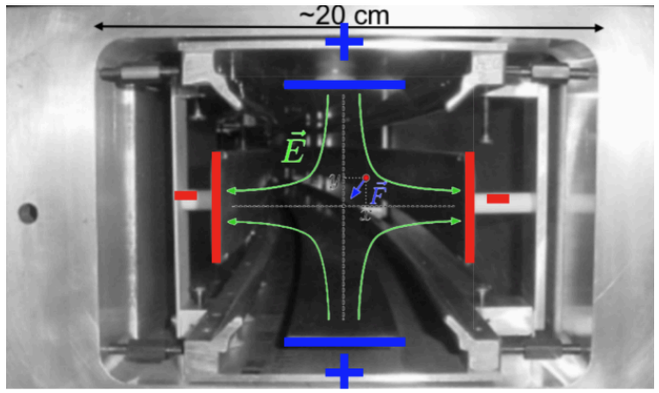

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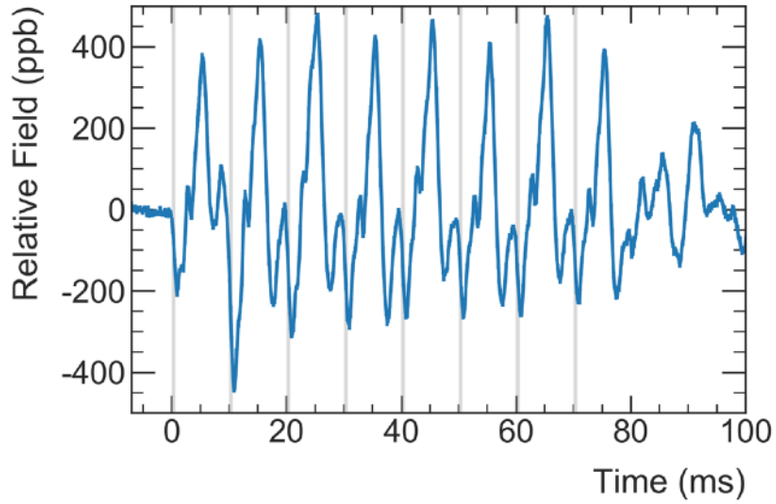
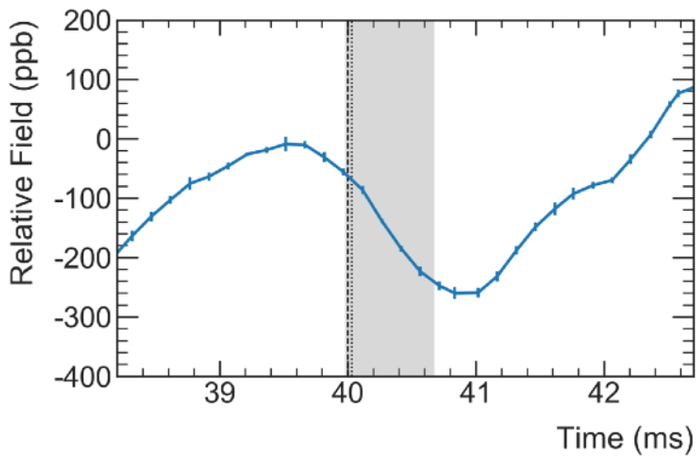


Measure the field with special NMR probes and map the effect!



E-field and Pitch Correction

$$a_\mu \propto \frac{f_{\rm clock}\ \ \omega_a^m\,(1 + C_e + C_p + C_{ml} + C_{pa})}{f_{\rm calib}\ \langle \omega_p'(x,y,\phi) \times M(x,y,\phi)\rangle\ (1 + B_k + B_q)}$$

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

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There is a 0.5% momentum acceptance

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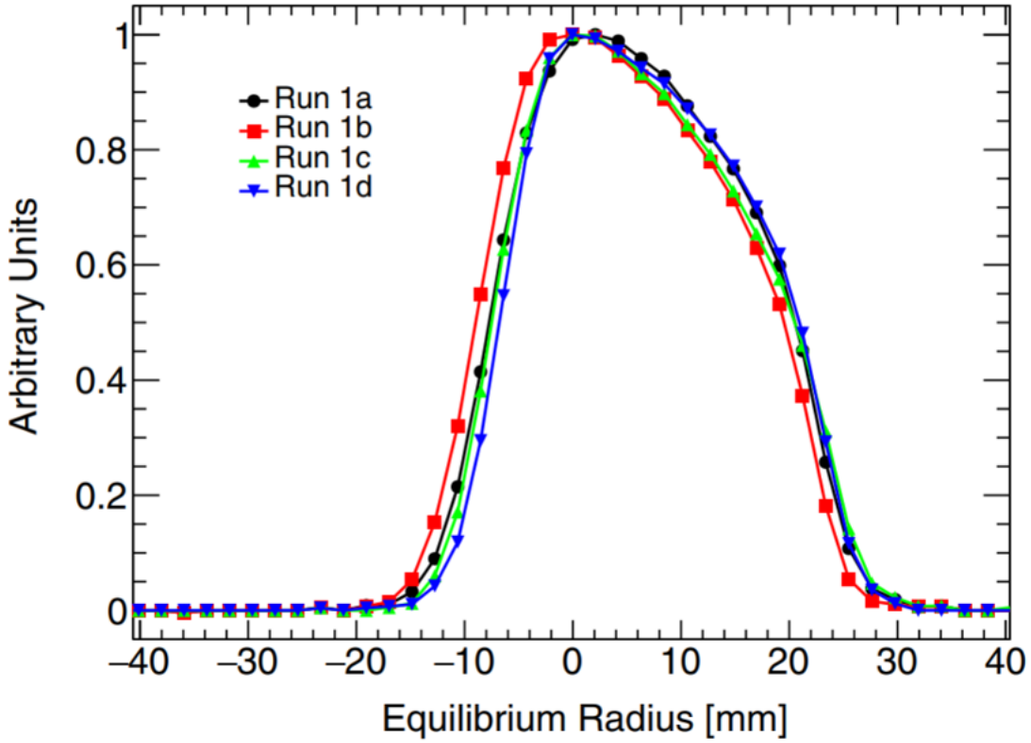

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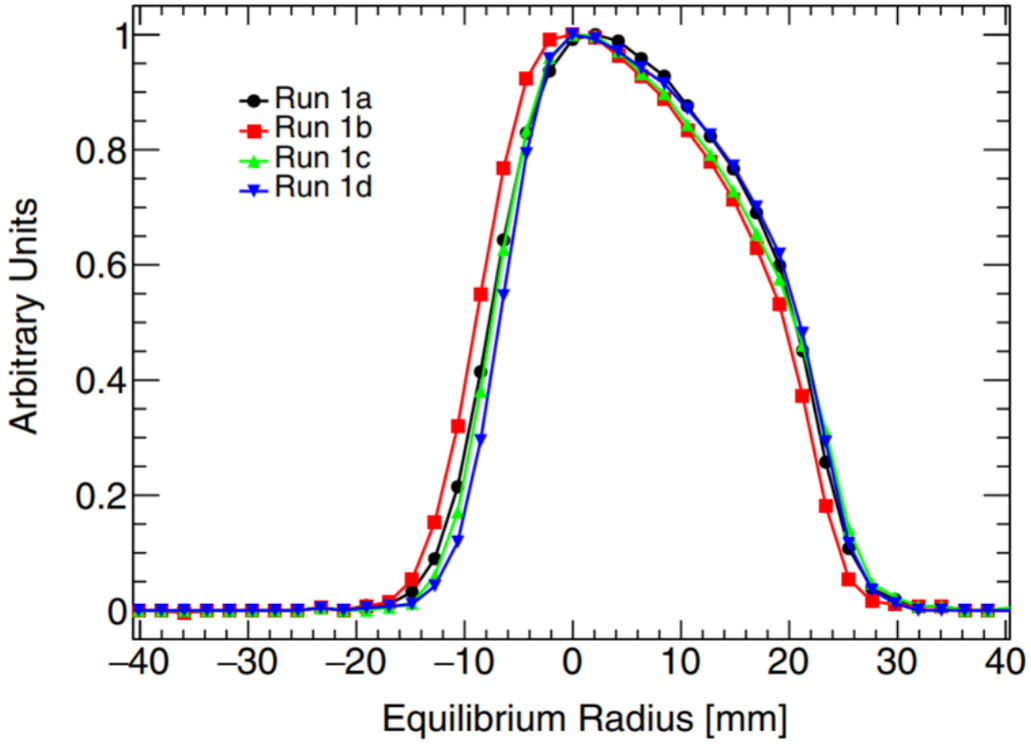

Vertical betatron oscillations cause non-zero average value for $\vec{\beta}\,.\,\vec{B}$

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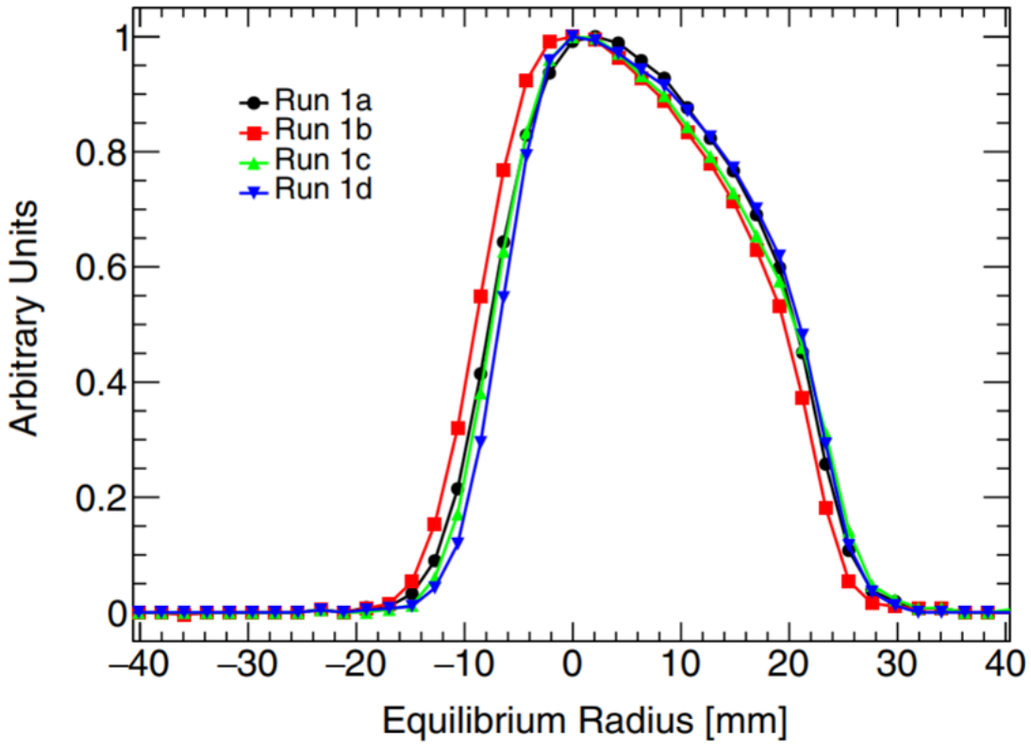

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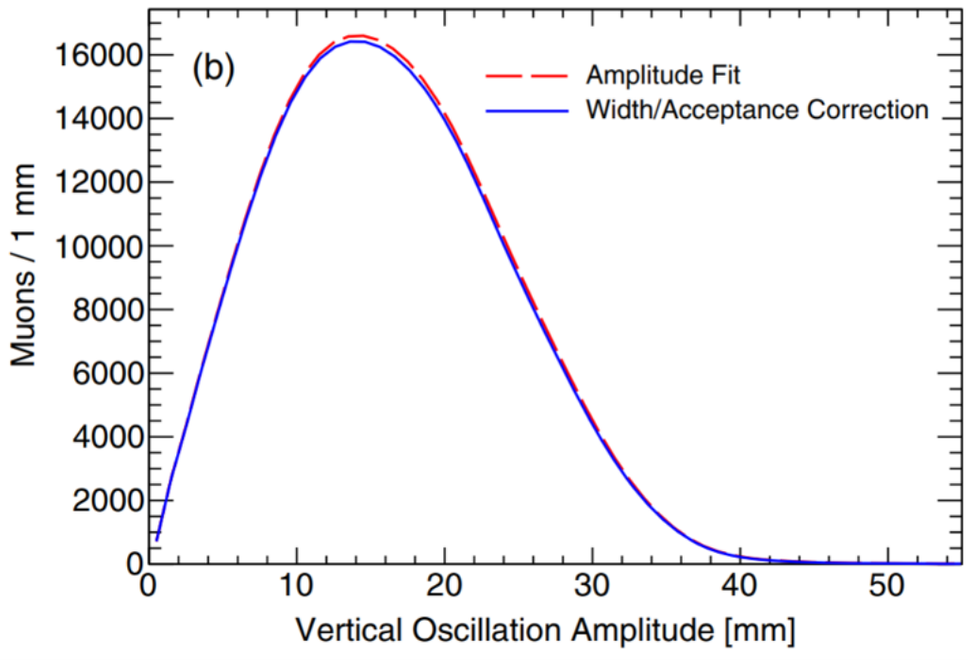
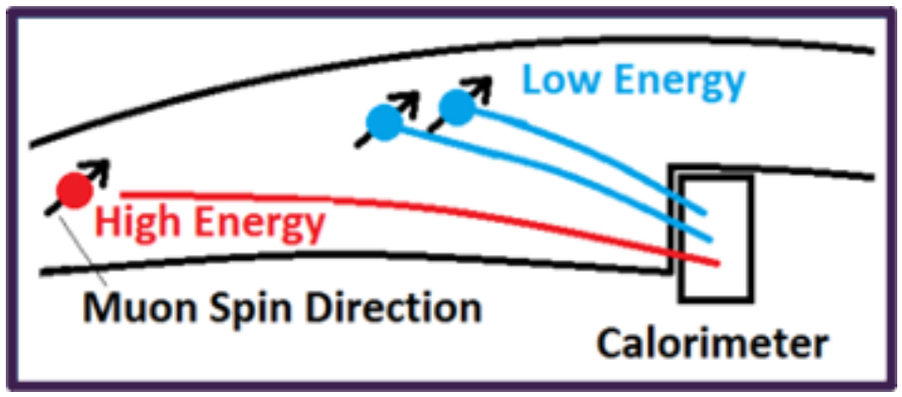
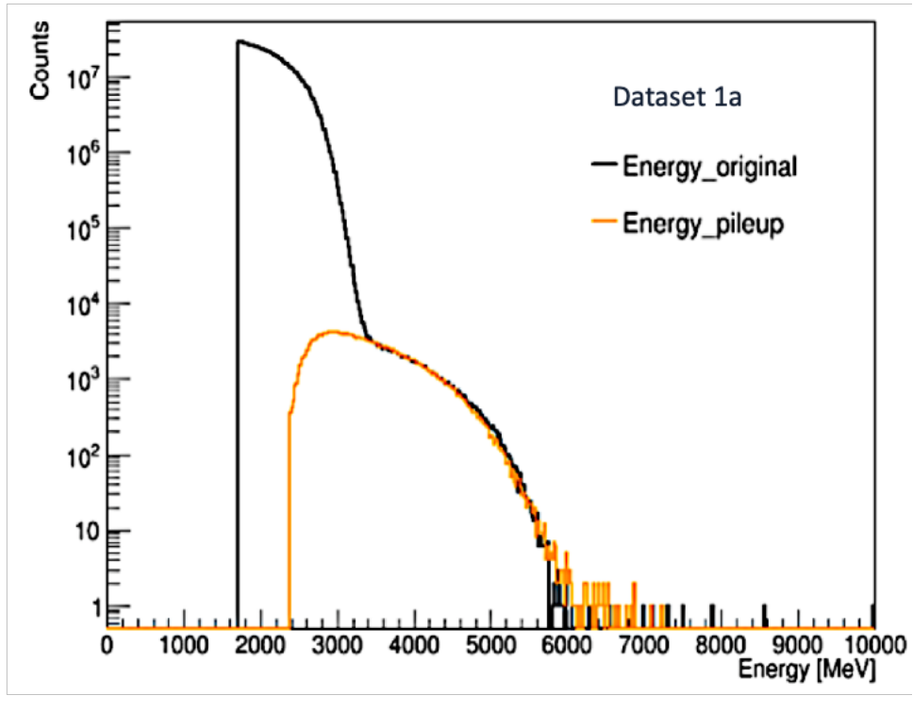


Pileup

$$a_\mu \propto \frac{f_{\text{clock}}\ \omega_a^m\ (1 + C_e + C_p + C_{ml} + C_{pa})}{f_{\text{calib}}\ \langle \omega_p'(x, y, \phi) \times M(x, y, \phi) \rangle\ (1 + B_k + B_q)}$$

- Pileup is one of the systematics that modulated precession frequency.
- When more than two positrons hit the detector at the same time and place, they could be treated as a single pulse.
- That distorts the time and energy spectrum!





Muon Loss

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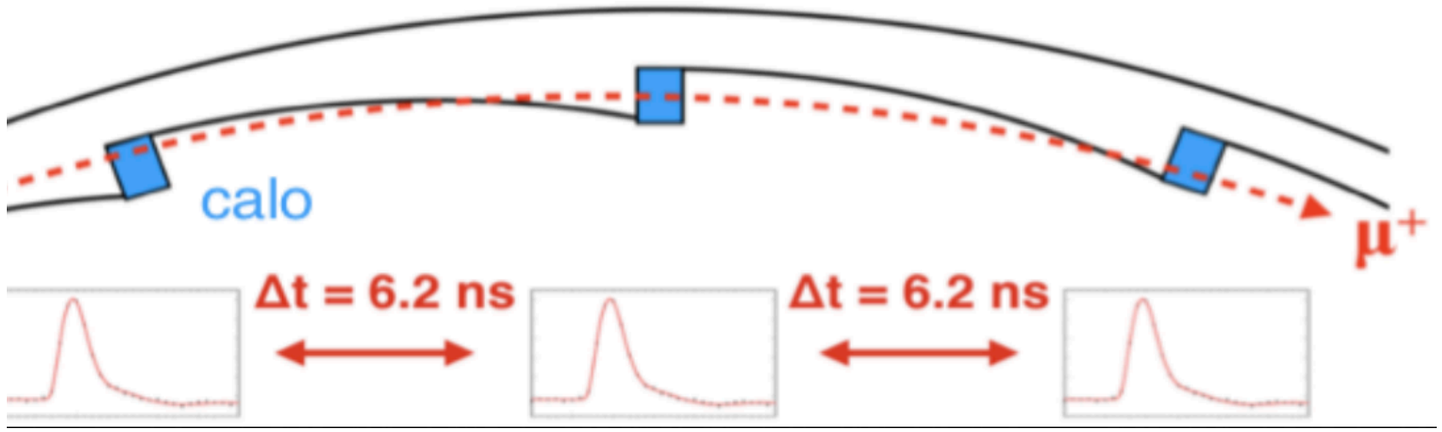

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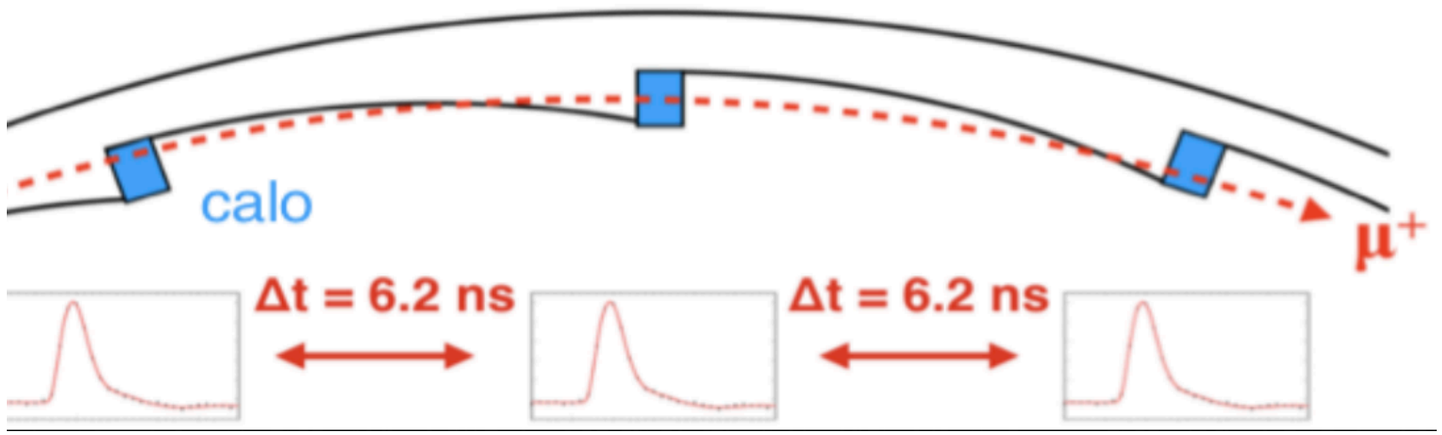

- Muons that were scattered from different materials before decaying and then punch through multiple calorimeters.
- They have different phase than stored muons so they modulate ω_a, producing a systematic error.
- We need to identify them in the data!

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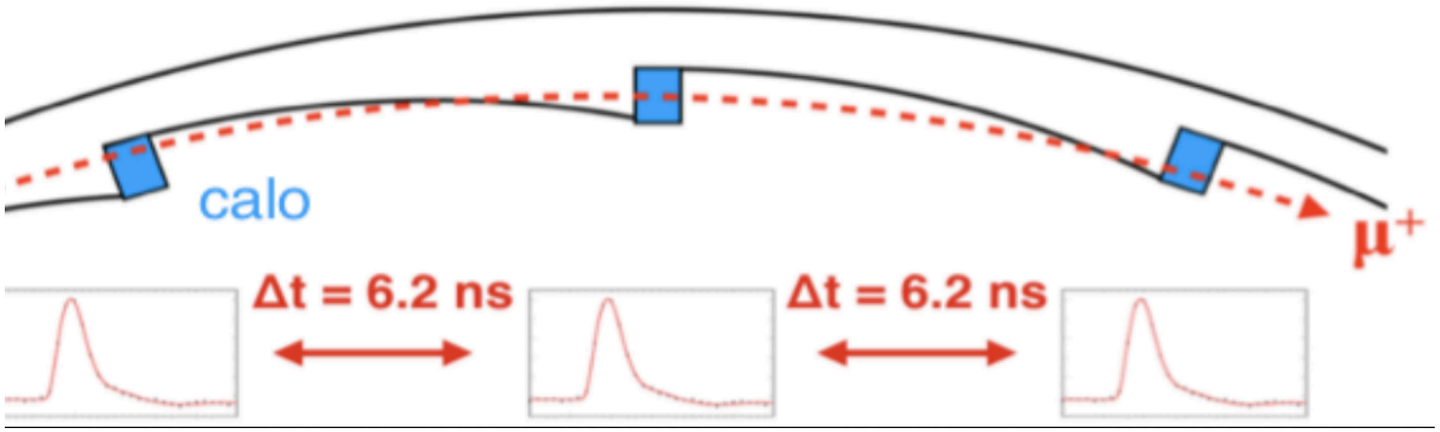

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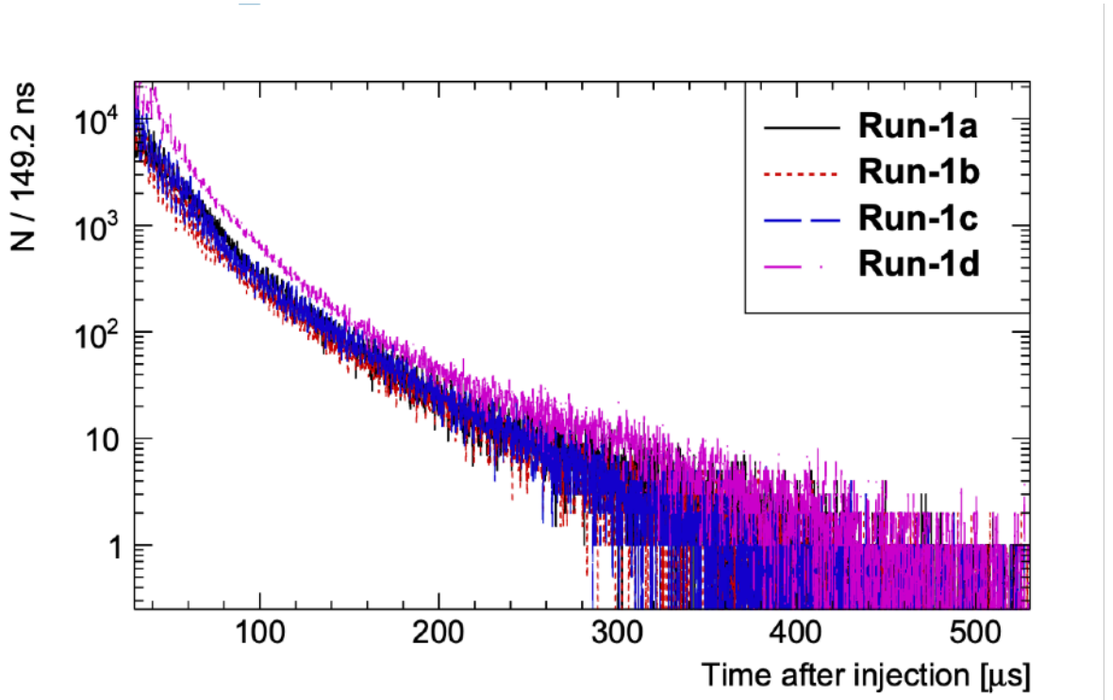

Crunching the numbers…

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

Dominated by statistical uncertainty

Crunching the numbers…

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Systematics dominated by PA and Field Transients

*Nearly half of BNL

*Will be even better for Run-2 and beyond

Crunching the numbers…

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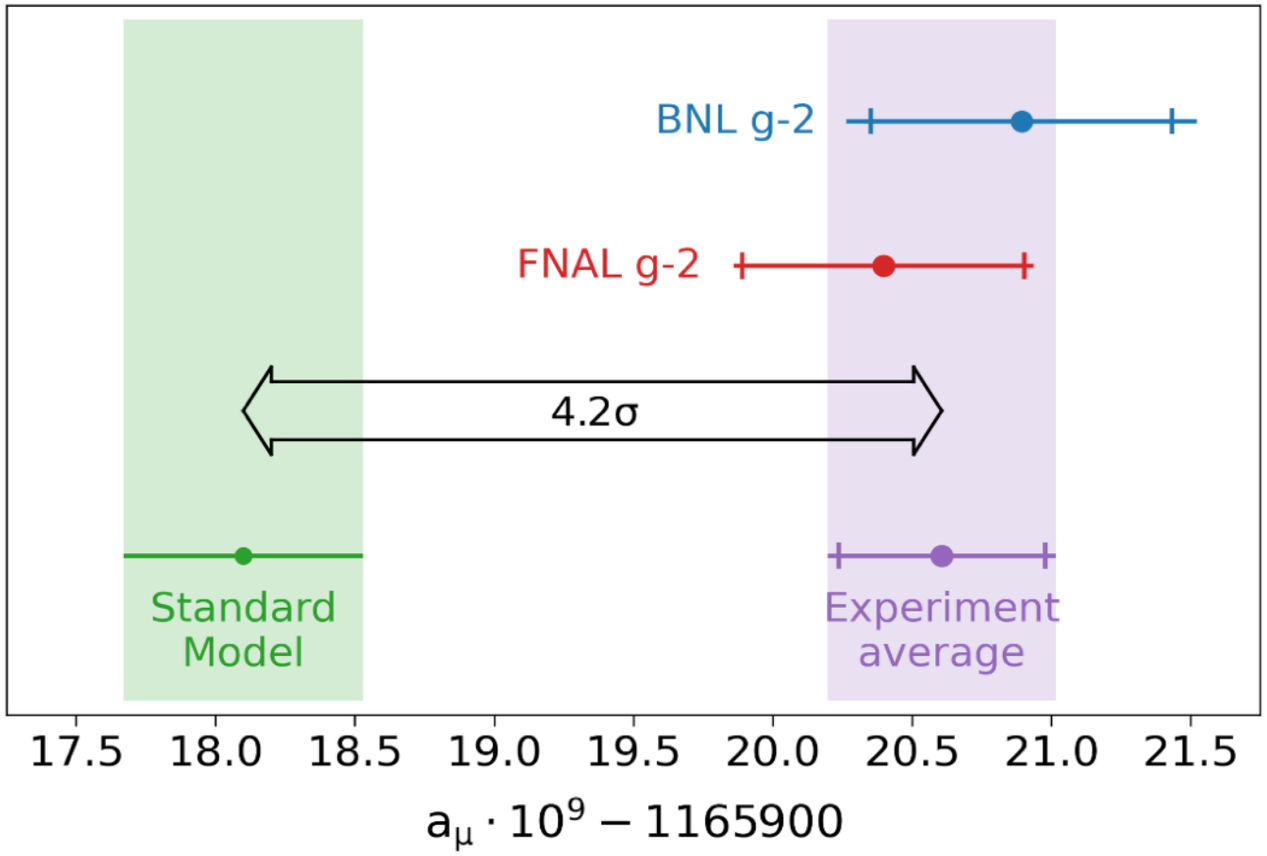
Enormous effort to evaluate every number !

Experimental Result and the Comparison



- ✓FNAL determined anomaly with 460 ppb precision
- ✓Nothing was found that indicated contradiction with BNL results
- ✓15% smaller error
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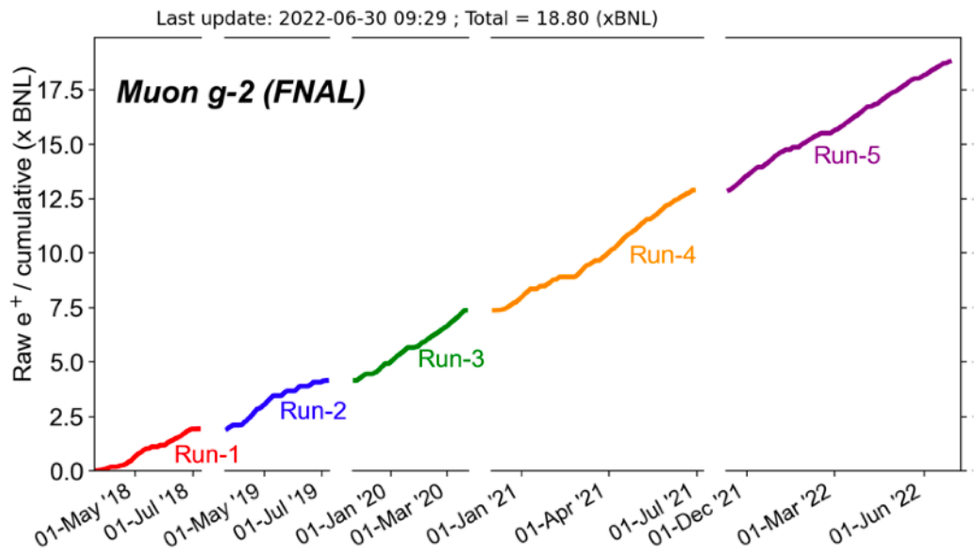

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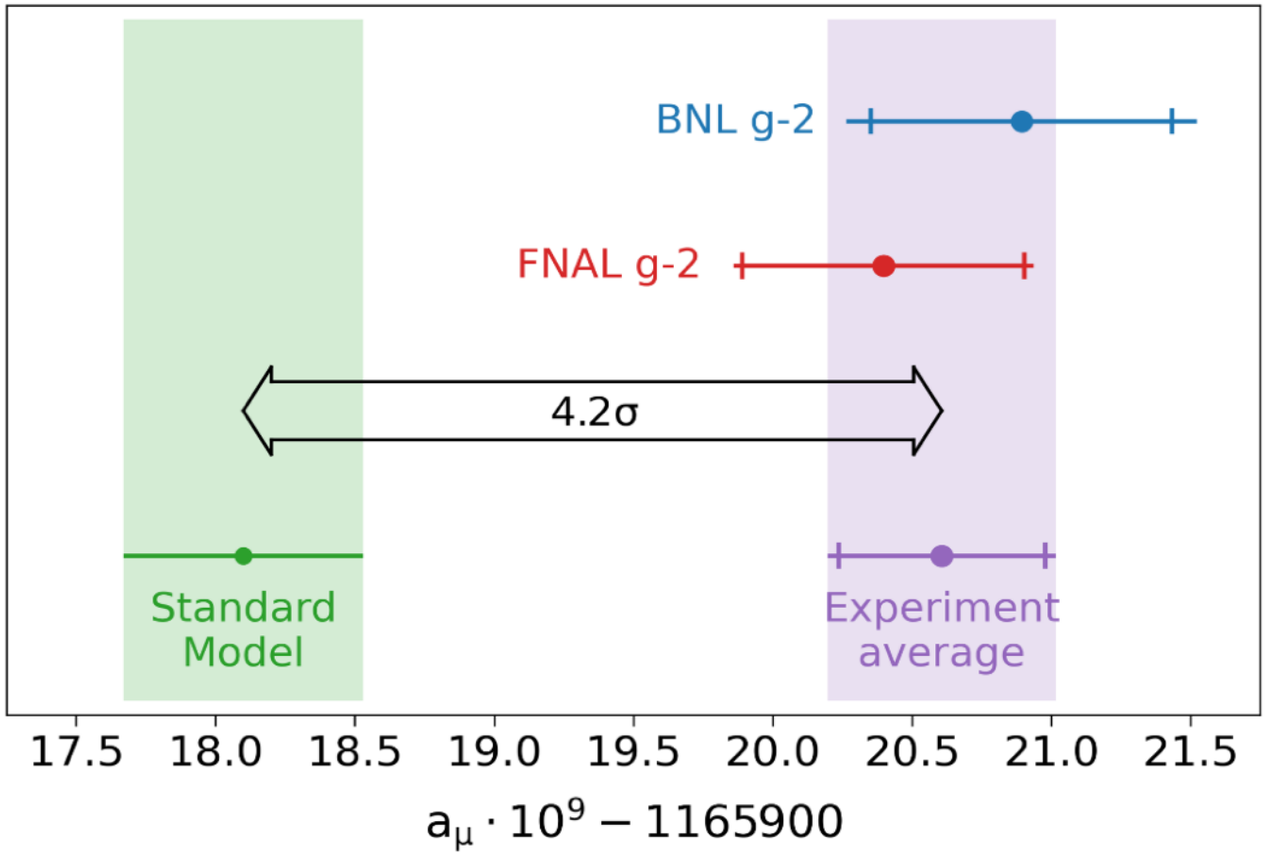

a_μ (BNL)=116 592 089(63)×10^{-11} (540 ppb)

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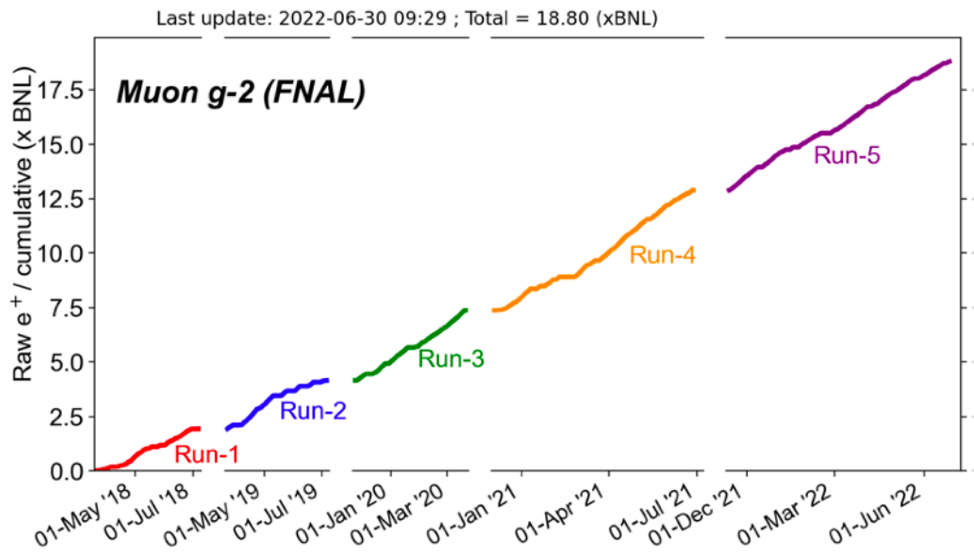

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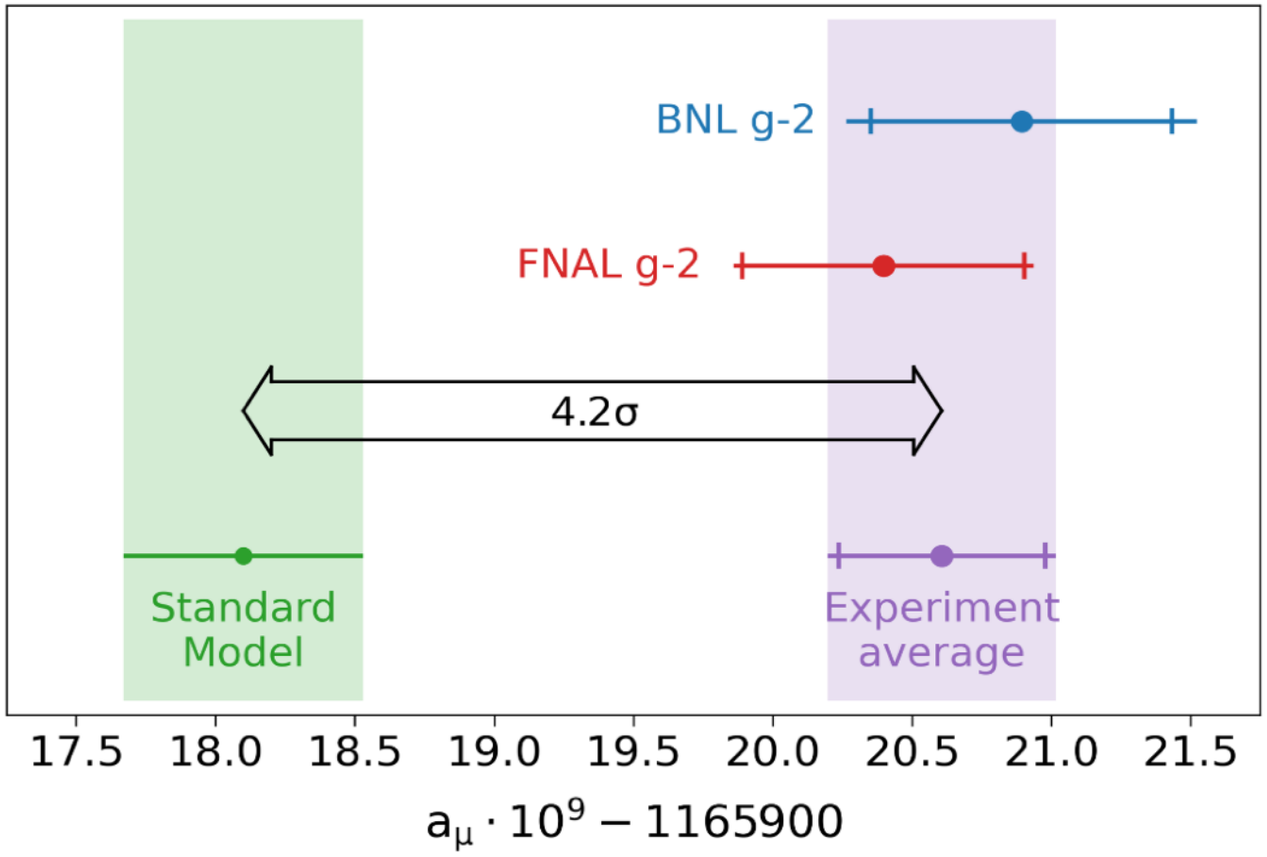

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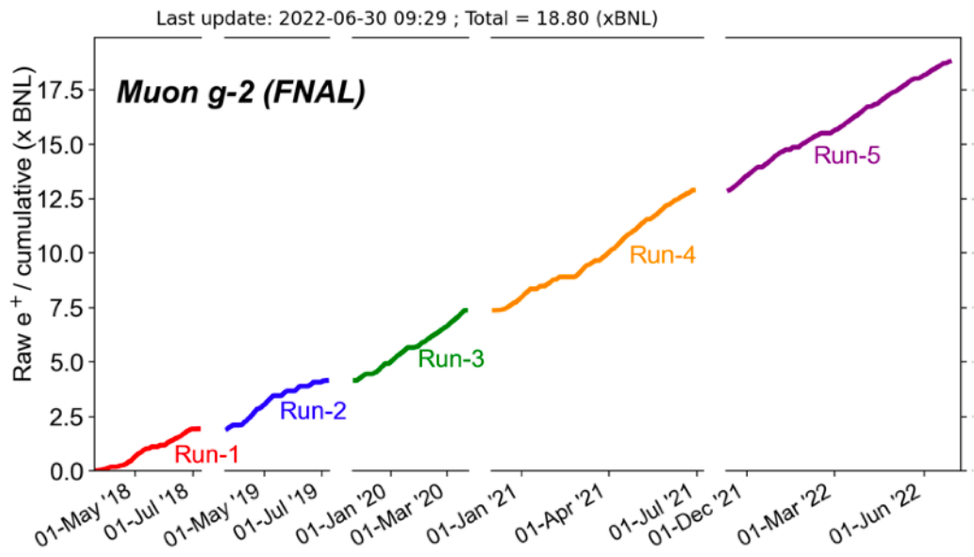

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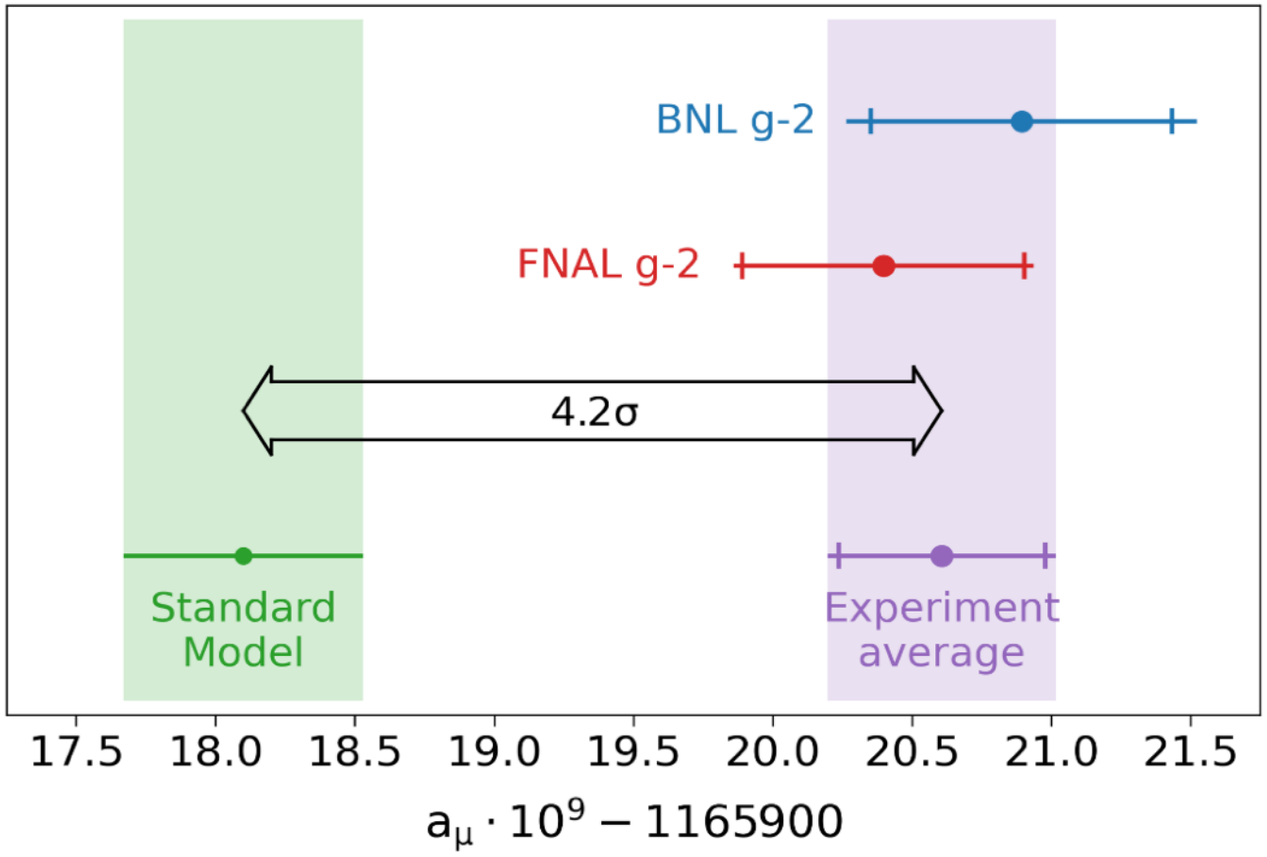

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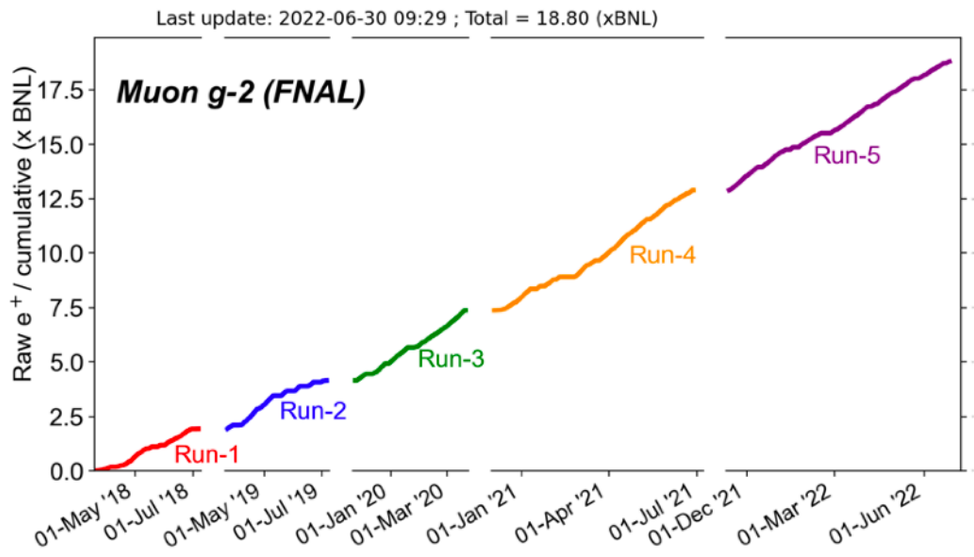

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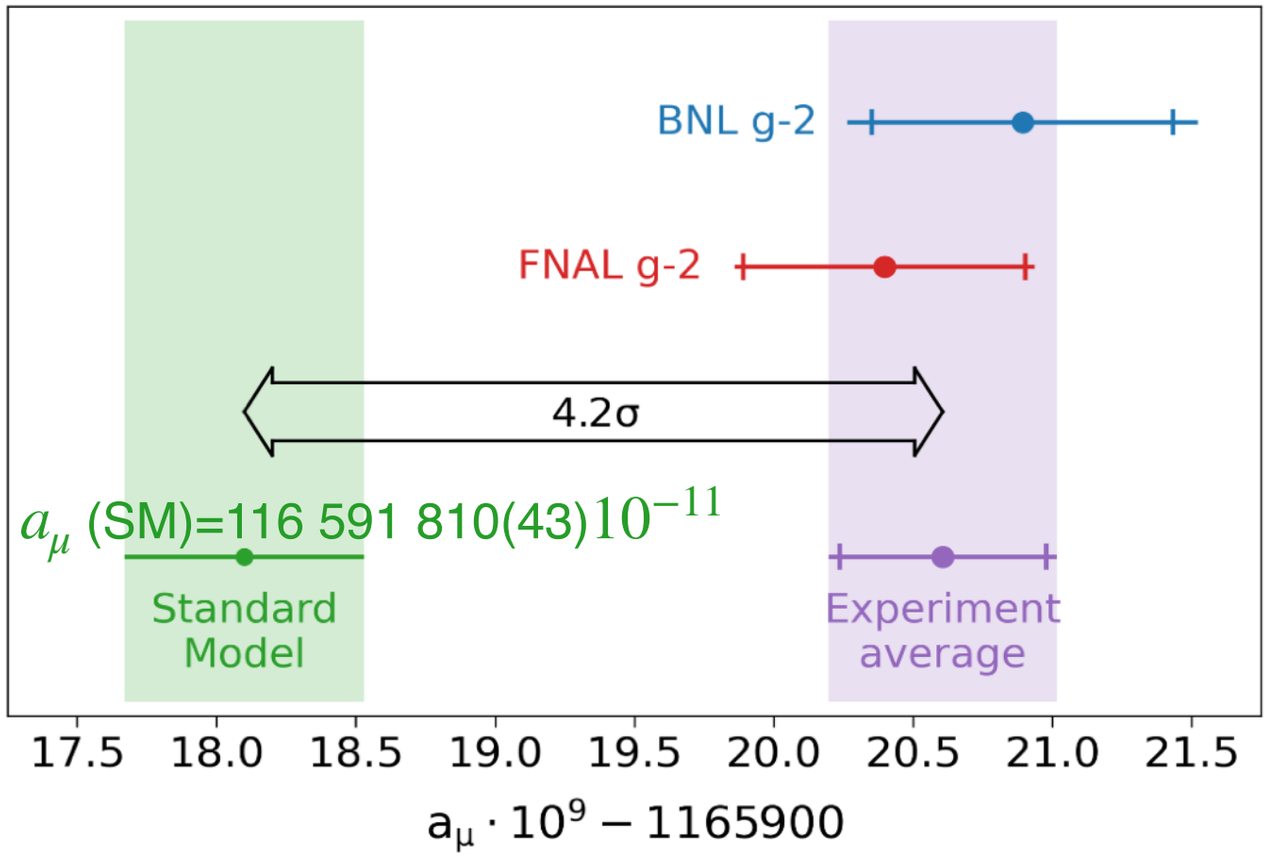

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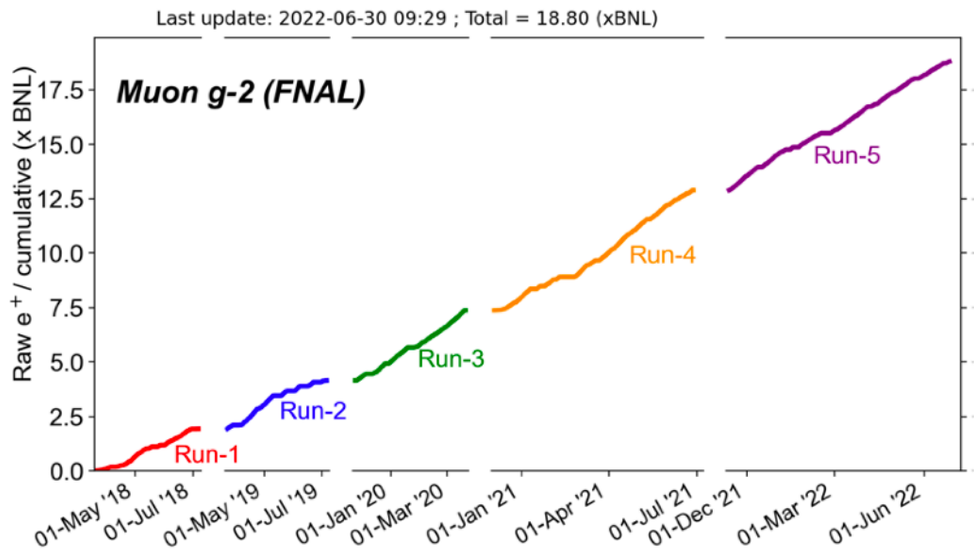

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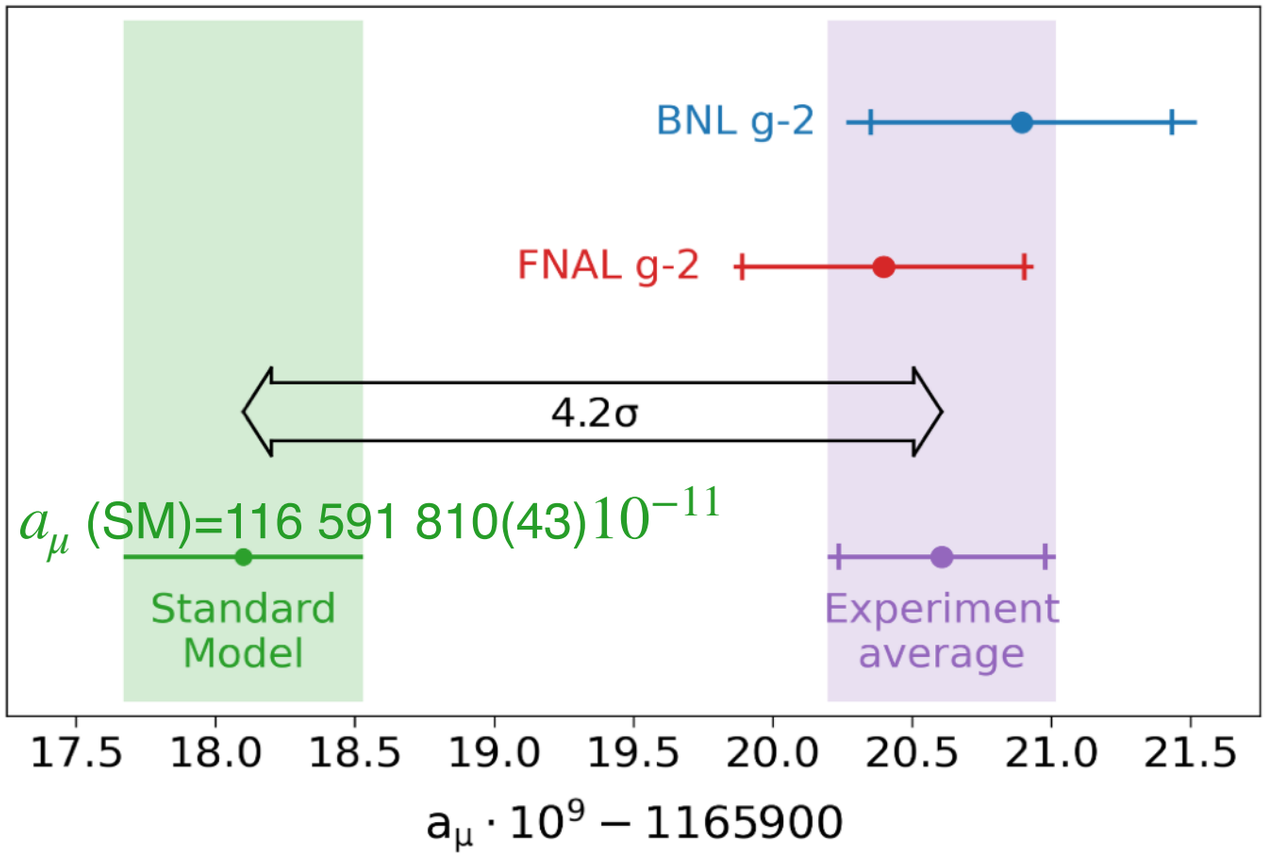

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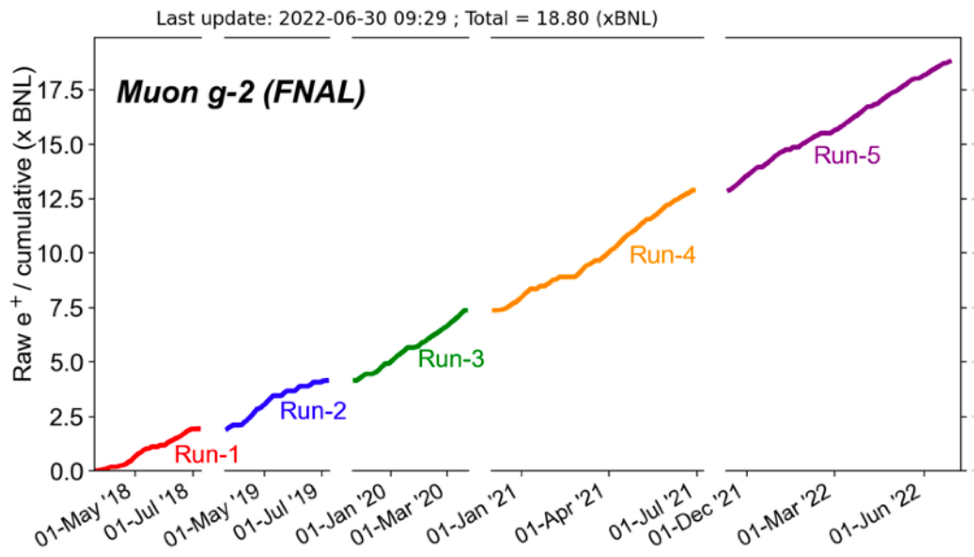

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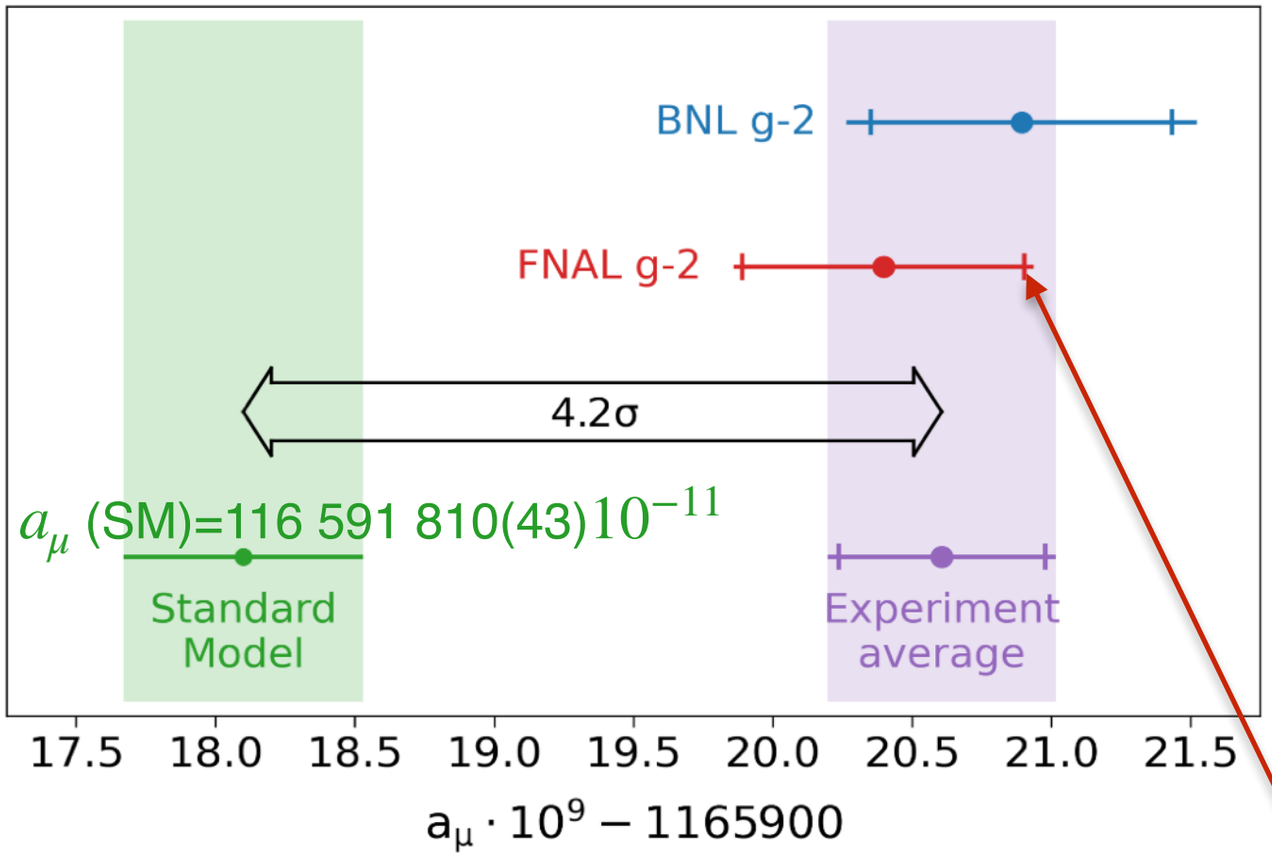

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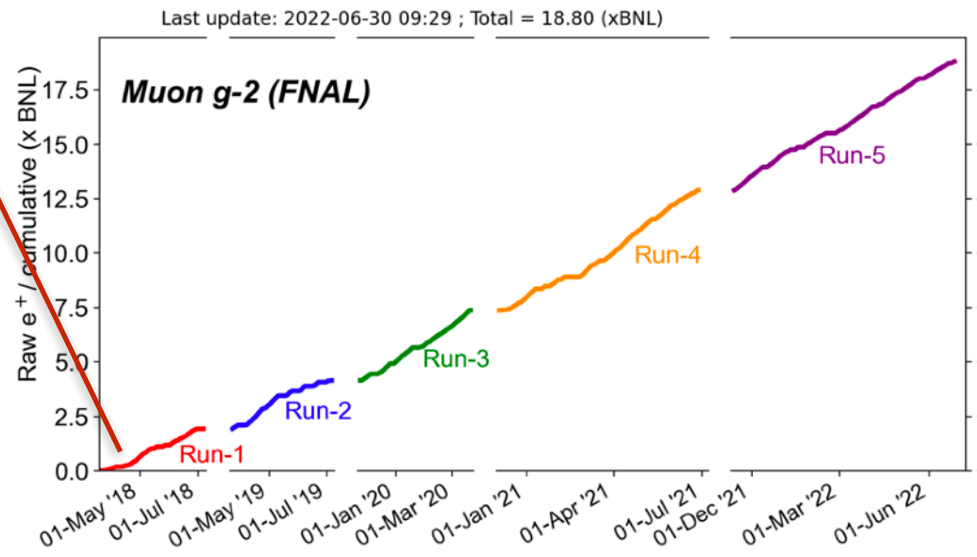


Big Splash at the Media

Beam dynamics corrections: PRAB (TBD) arXiv:2104.03240

$\tilde{\omega}_p$ analysis: Phys. Rev. A **103**, 042208

ω_a analysis: Phys. Rev. D **103**, 072002

Phys. Rev. Lett. **126**, 141801

Beam dynamics corrections to the Run-1 measurement of the muon anomalous magnetic moment at Fermilab

Magnetic Field Measurement and Analysis for the Muon $g-2$ Experiment at Fermilab

Measurement of the anomalous precession frequency of the muon in the Fermilab Muon $g-2$ experiment

Measurement of the Positive Muon Anomalous Magnetic Moment to 0.46 ppm

4/7/2021 9:55:55 AM Fermilab and Illinois Physics

UIUC scientists play leading role in paradigm-shifting experiment

The first results from the Muon g-2 experiment hosted at Fermi National Accelerator Laboratory show fundamental particles called muons behaving in a way not predicted by the standard model of particle physics. These results confirm an earlier experiment of the same name performed at Brookhaven National Laboratory. Combined, the two results show strong evidence that our best theoretical model of the subatomic world is incomplete. One potential explanation would be the existence of undiscovered particles or forces.

The Muon g-2 ring sits in its detector hall amidst electronics racks, the muon beamline, and other equipment. This impressive experiment operates at negative 450 degrees Fahrenheit and studies the precession (or wobble) of muons as they travel through the magnetic field. Photo by Reidar Hahn/Fermilab

The long-awaited first results from the Muon g-2 experiment at the U.S. Department of Energy's Fermi National Accelerator Laboratory show fundamental particles called muons behaving in a way that is not predicted by scientists' best theory, the Standard model of particle physics. This landmark result, made with unprecedented precision, confirms a discrepancy that has been gnawing at researchers for decades.

Physicists at the University of Illinois Urbana-Champaign played a major role in producing the new result, which confirms the result from two decades ago: muons behave in a way that is not predicted by scientists' best theory, the Standard model of particle physics.

"It was extremely exciting to produce such a tantalizing result," said Paul Debevec, UIUC emeritus physics professor and member of the Brookhaven experiment. "We knew that we were going to have to do the experiment again—and do it better. What we didn't know at the time was that it would take us 20 years to get to a new result."

"All the News That's Fit to Print"

The New York Times

Late Edition

VOL. CLXX .... No. 59,022 NEW YORK, THURSDAY, APRIL 8, 2021 $3.00

Biden Tax Plan Aims to Curtail

Contagious Variant Is Fueling Surge in Infections Across the U.S.

Some states where new cases of the coronavirus are rising have been hit hard by the B.1.1.7 variant. Page A6.

PAIR OF SETBACKS FOR ASTRAZENECA

A Particle's Tiny Wobble Could Upend the Known Laws of Physics

By DENNIS OVERBYE

A ring at the Fermi National Accelerator Laboratory in Illinois is used to study the wobble of muons.

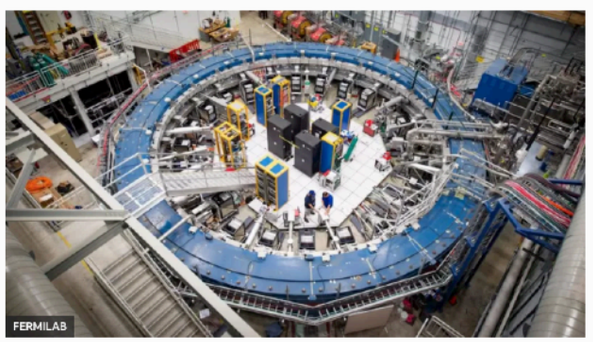
Adventurers Fleeing Pandemic Strain the West's Rescue Teams

By ALI WATKINS

A trail in the Wind River Range in western Wyoming.

Fizikçilere göre, doğadaki 5. temel kuvvete ilişkin 'güçlü kanıtlar ortaya çıktı'

8 Nisan 2021



ABD'de bilim insanları, yapılan bir deneyde küçük bir atom altı parçacığın bilinen fizik yasalarına uymadığını açıkladı. Fizikçiler bu durumun doğadaki beşinci temel kuvvetin kanıtı olduğunu söylüyor.

SM Theory Calculations

Lattice

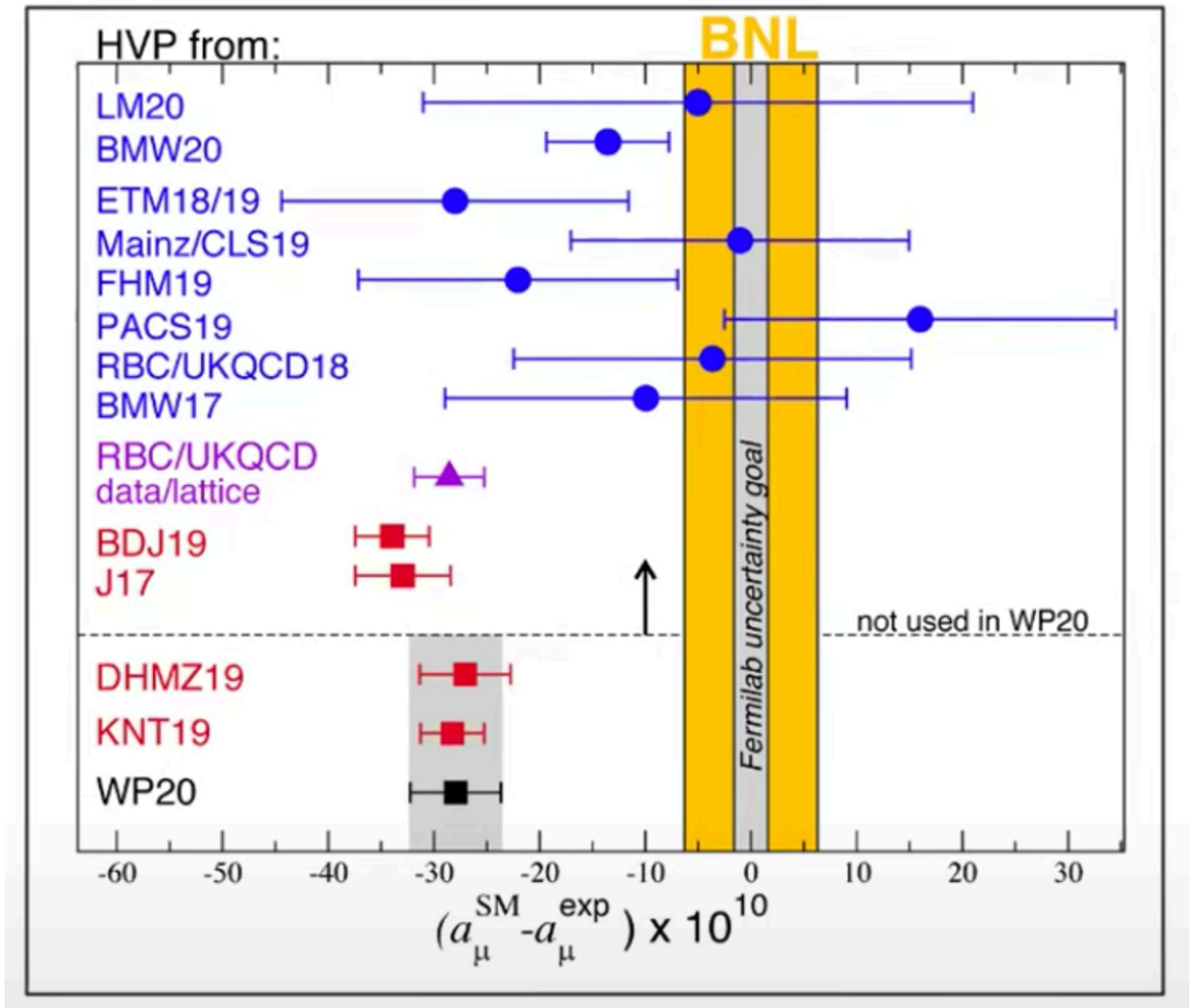
Data-based Dispersive

Lattice and Data

Official WP20

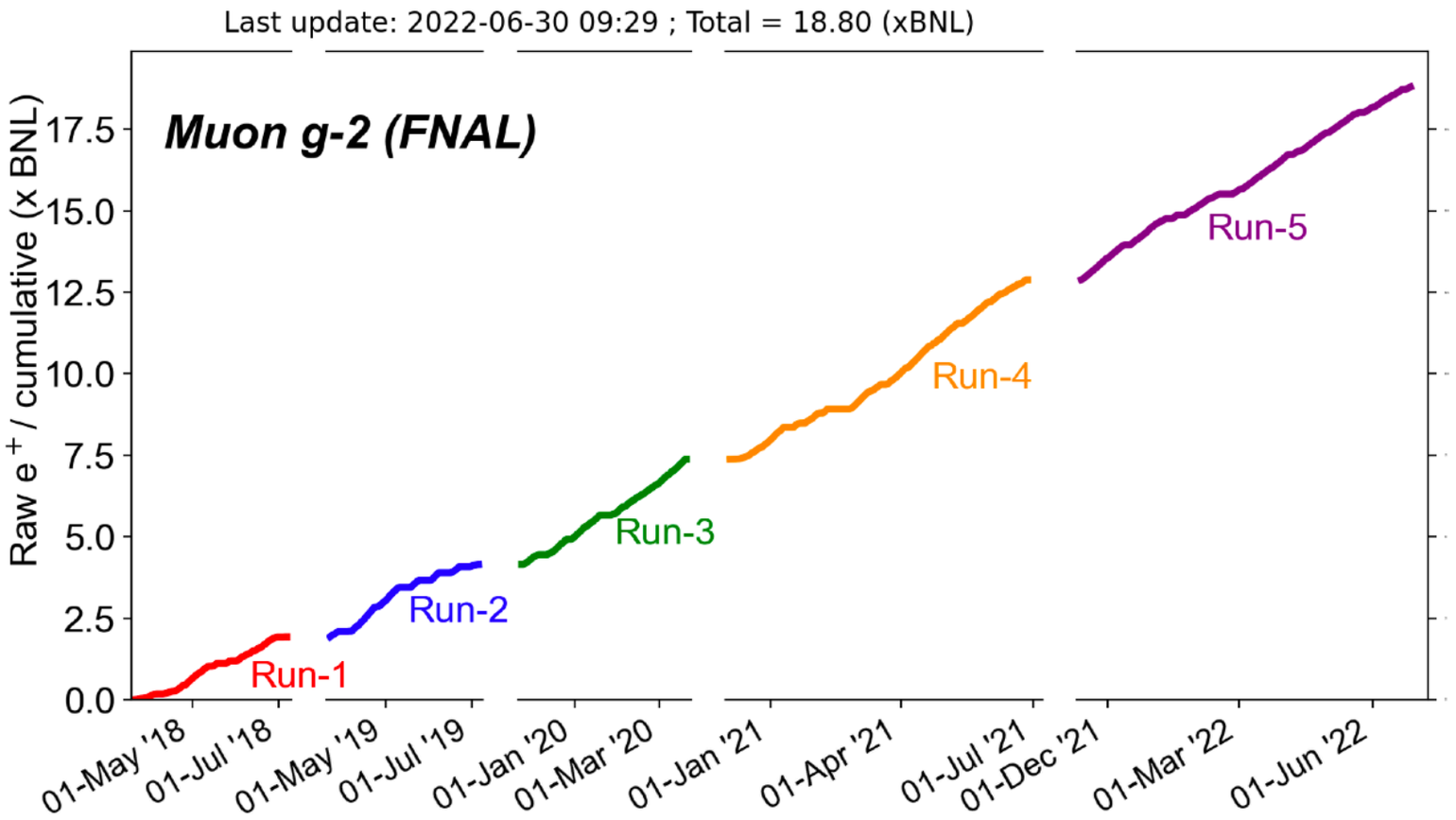
The anomalous magnetic moment of the muon in the Standard Model

T. Aoyama[1,2,3], N. Asmussen[4], M. Benayoun[5], J. Bijnens[6], T. Blum[7,8], M. Bruno[9], I. Caprini[10], C. M. Carloni Calame[11], M. Cè[9,12,13], G. Colangelo[†14], F. Curciarello[15,16], H. Czyż[17], I. Danilkin[12], M. Davier[†18], C. T. H. Davies[19], M. Della Morte[20], S. I. Eidelman[†21,22], A. X. El-Khadra[†23,24], A. Gérardin[25], D. Giusti[26,27], M. Golterman[28], Steven Gottlieb[29], V. Gülpers[30], F. Hagelstein[14], M. Hayakawa[31,2], G. Herdoíza[32], D. W. Hertzog[33], A. Hoecker[34], M. Hoferichter[†14,35], B.-L. Hoid[36], R. J. Hudspith[12,13], F. Ignatov[21], T. Izubuchi[37,8], F. Jegerlehner[38], L. Jin[7,8], A. Keshavarzi[39], T. Kinoshita[40,41], B. Kubis[36], A. Kupich[21], A. Kupść[42,43], L. Laub[14], C. Lehner[†26,37], L. Lellouch[25], I. Logashenko[21], B. Malaescu[5], K. Maltman[44,45], M. K. Marinković[46,47], P. Masjuan[48,49], A. S. Meyer[37], H. B. Meyer[12,13], T. Mibe[†1], K. Miura[12,13,3], S. E. Müller[50], M. Nio[2,51], D. Nomura[52,53], A. Nyffeler[†12], V. Pascalutsa[12], M. Passera[54], E. Perez del Rio[55], S. Peris[48,49], A. Portelli[30], M. Procura[56], C. F. Redmer[12], B. L. Roberts[†57], P. Sánchez-Puertas[49], S. Serednyakov[21], B. Shwartz[21], S. Simula[27], D. Stöckinger[58], H. Stöckinger-Kim[58], P. Stoffer[59], T. Teubner[†60], R. Van de Water[24], M. Vanderhaeghen[12,13], G. Venanzoni[61], G. von Hippel[12], H. Wittig[12,13], Z. Zhang[18], M. N. Achasov[21], A. Bashir[62], N. Cardoso[47], B. Chakraborty[63], E.-H. Chao[12], J. Charles[25], A. Crivellin[64,65], O. Deineka[12], A. Denig[12,13], C. DeTar[66], C. A. Dominguez[67], A. E. Dorokhov[68], V. P. Druzhinin[21], G. Eichmann[69,47], M. Fael[70], C. S. Fischer[71], E. Gámiz[72], Z. Gelzer[23], J. R. Green[9], S. Guellati-Khelifa[73], D. Hatton[19], N. Hermansson-Truedsson[14], S. Holz[36], B. Hörz[74], M. Knecht[25], J. Koponen[1], A. S. Kronfeld[24], J. Laiho[75], S. Leupold[42], P. B. Mackenzie[24], W. J. Marciano[37], C. McNeile[76], D. Mohler[12,13], J. Monnard[14], E. T. Neil[77], A. V. Nesterenko[68], K. Ottnad[12], V. Pauk[12], A. E. Radzhabov[78], E. de Rafael[25], K. Raya[79], A. Risch[12], A. Rodríguez-Sánchez[6], P. Roig[80], T. San José[12,13], E. P. Solodov[21], R. Sugar[81], K. Yu. Todyshev[21], A. Vainshtein[82], A. Vaquero Avilés-Casco[66], E. Weil[71], J. Wilhelm[12], R. Williams[71], A. S. Zhevlakov[78]



- BMW20 is also in tension with data-based dispersive result.
- Will be interested to see how it evolves in future but lattice QCD calculations requires a huge amount of computing resource. All groups are working on defining intermediate results (simpler way to compare things)
- By 2025, both hadronic calculations (HVP and HLbL) will give both data-driven and lattice results which will match the experiment precision

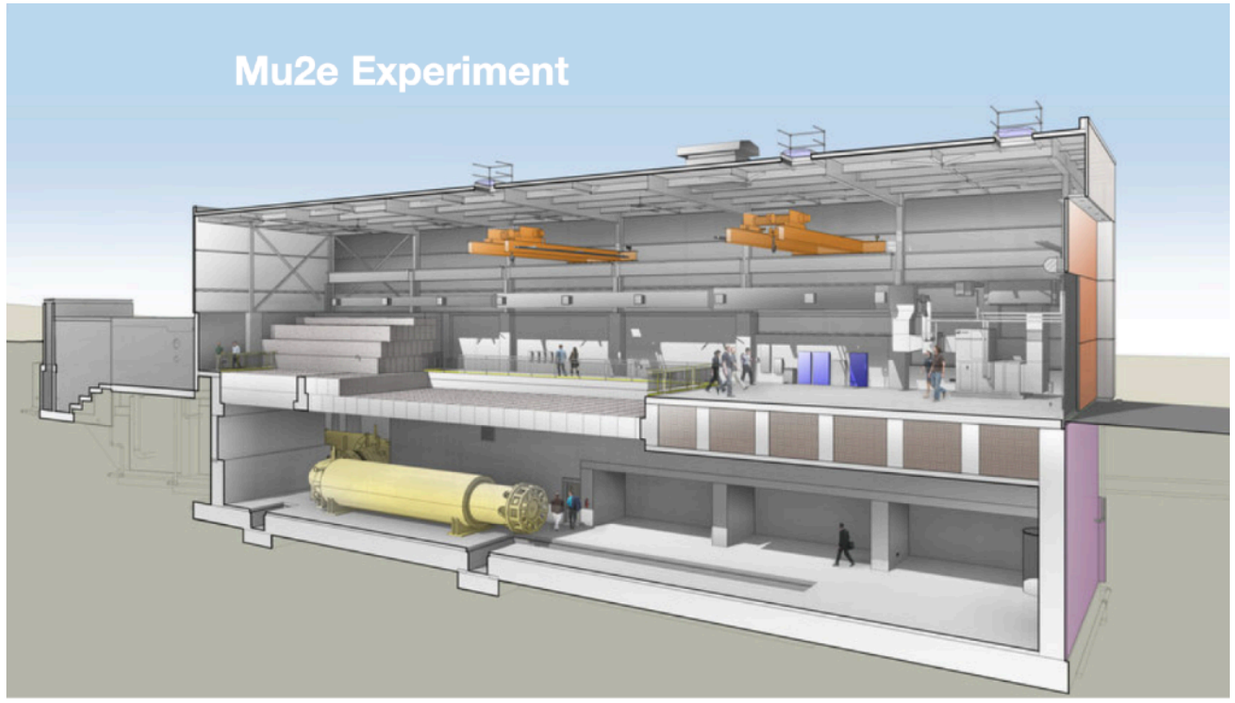
Experiment Status

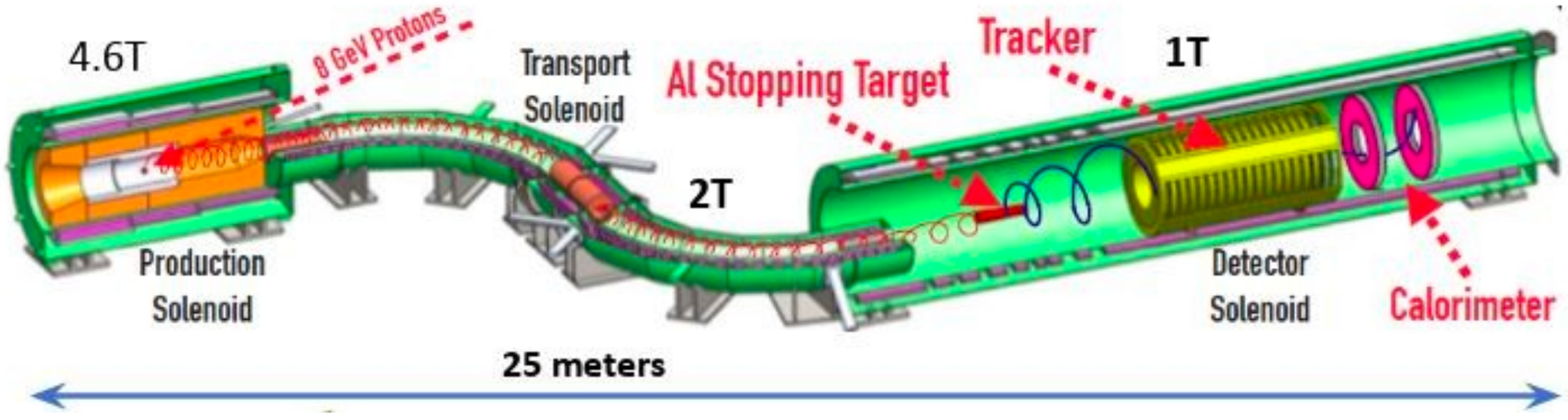


- Run-2 and Run-3 analysis are ongoing -> reduce combined exp. error by 2 times
- Run-5 will end in July-> Run-4 and beyond will reduce the statistical uncertainties down to **100 ppb** in total.
- Run-6 will be the last year to collect data

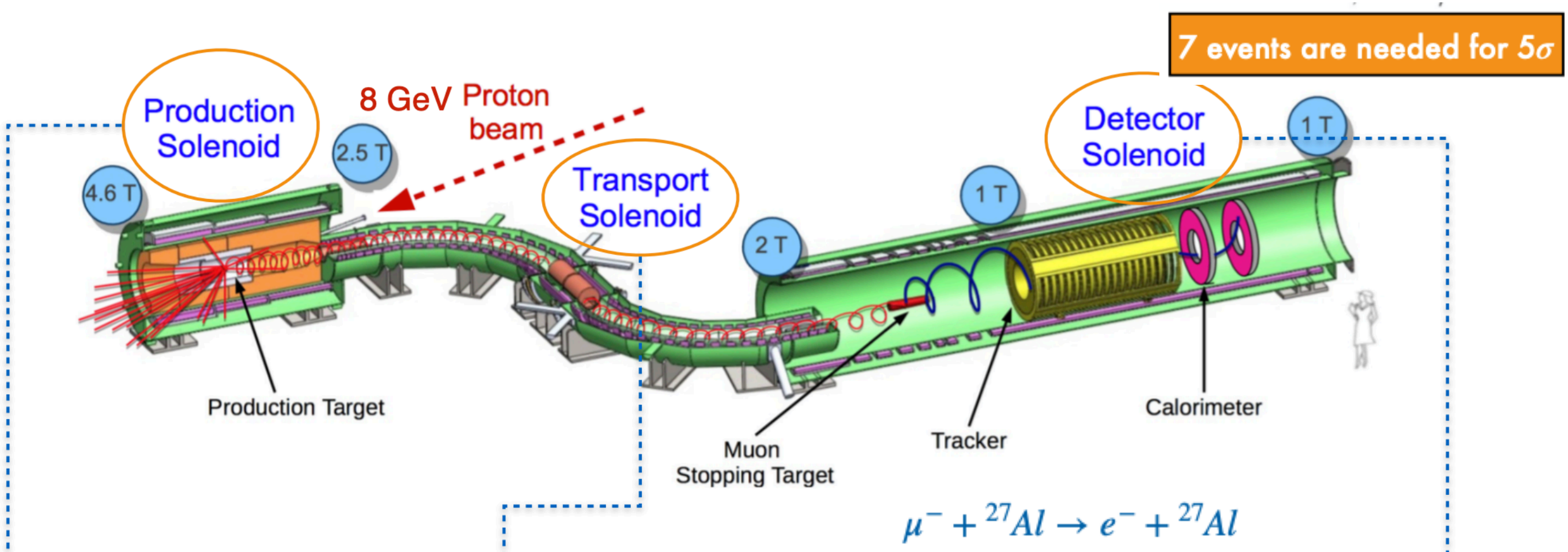
Next muon project at Fermilab: Mu2e Experiment

- Mu2e will start right after muon g-2 stops taking data
- Potential Experiments after PIP-II
  - Mu2e-II and Potential Storage ring experiments are being discussed





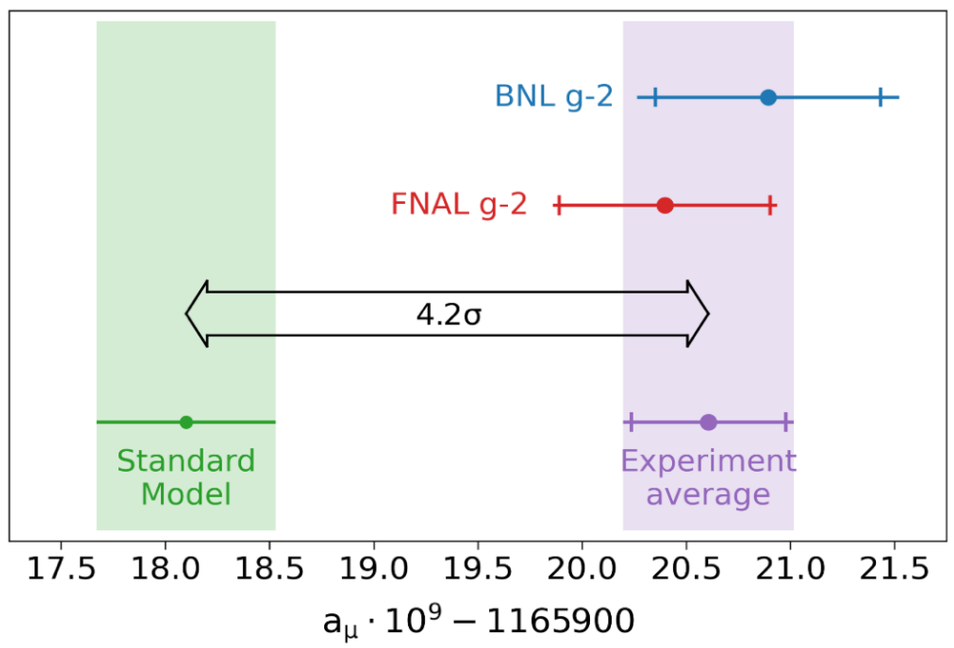
Mu2e Basics



- Direct low momentum pions/muons to transport solenoid.
- S-shaped geometry with collimators select low momentum and negatively charged particles.
- Houses muon stopping target, tracker & calorimeter.

Summary and Outlook

- Fermilab g-2 experiment published first result with 460 ppb precision
- Experiment combination increased the tension with theory to 4.2 σ level
- Rest of the data will take the statistical uncertainty to 100 ppb
- Systematic uncertainty will hit the 100 ppb goal
- Next result will be published in the beginning of 2023
- Mu2e experiment will begin after g-2 to focus on neutrino-less conversion of the muon in the presence of Al nucleus
- Mu2e is expected to start commissioning in 2023 and start taking data in 2026 until Fermilab accelerator shutdown, will continue later to collect more data



Thanks!

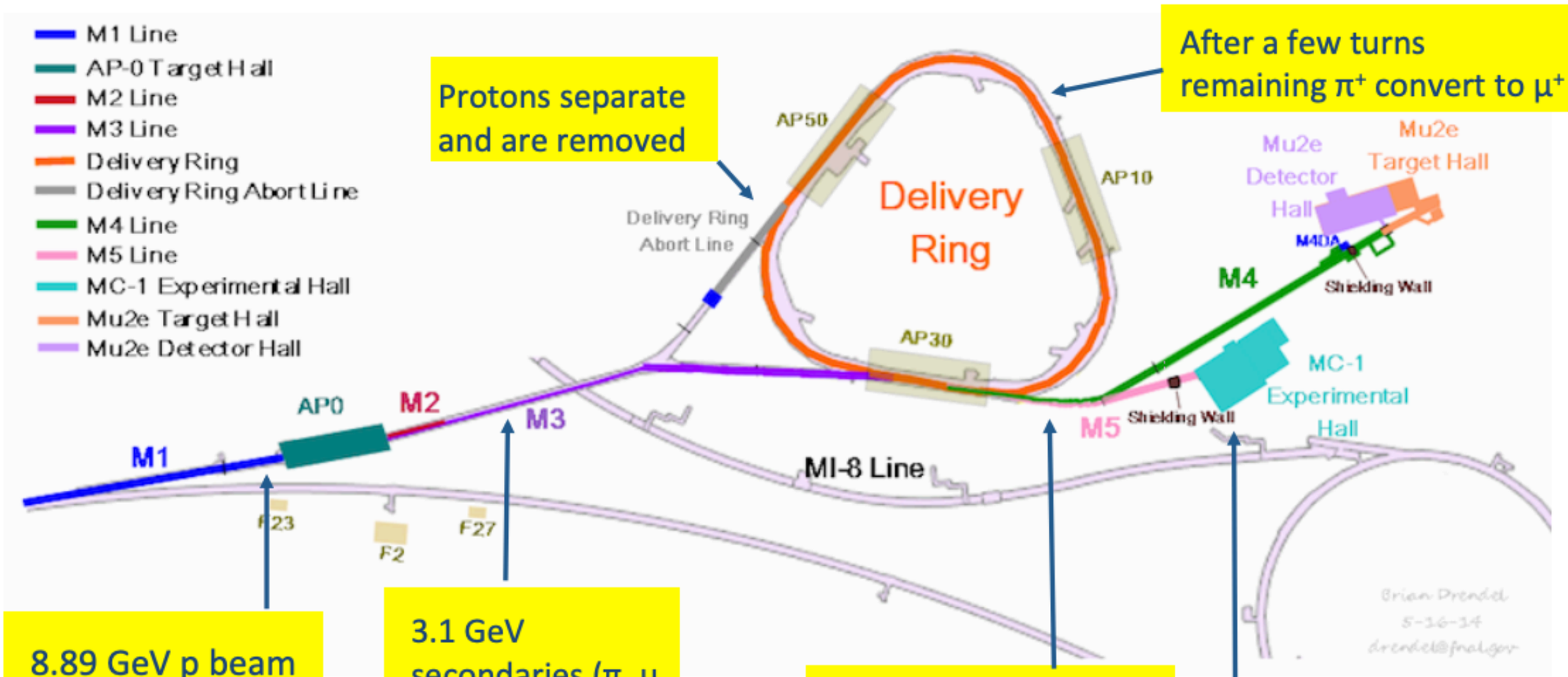
Back-up

Most promising models to explain the discrepancy

- Muon g-2 can indicate if there is a CP-conserving, lepton-flour conserving or BSM chirality-flipping interaction but can’t tell which one is the most promising.
- Possible explanations:
  - SUSY models (while evading LHC limits)
  - Leptoquark models (if leptoquark masses are above all LHC limits)
  - 2-Higgs doublet models

Establishing a g-2 discrepancy from SM would place a strict limit on BSM scenarios

Muon Beamline at Fermilab

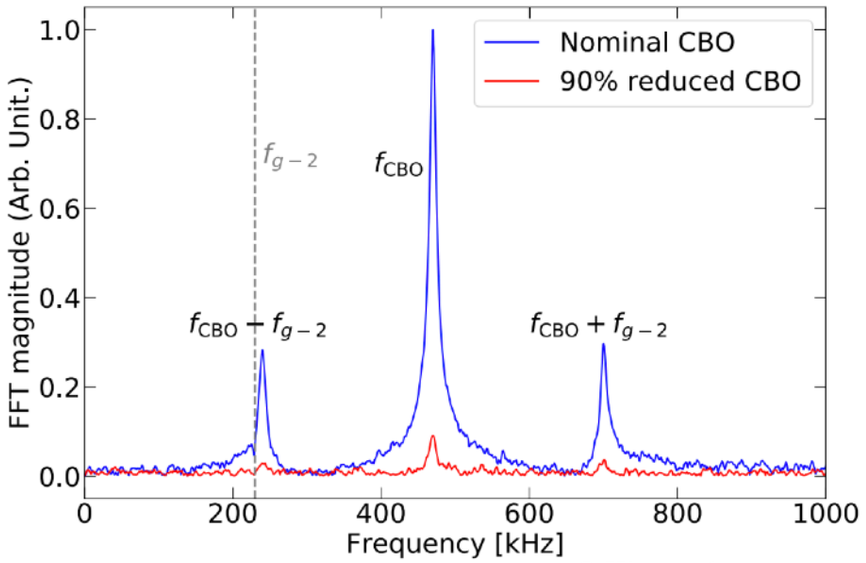


D. Stratakis

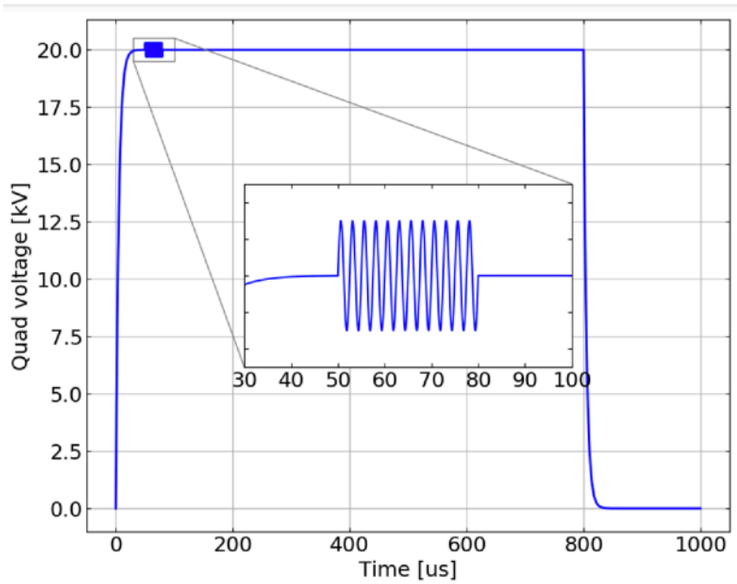
Improvements since Run-1: Quad-RF System

Original idea from Yuri F. Orlov and Yannis Semertzidis (Muon g-2 Note #431). By applying RF dipole or quadrupole electric field; (by kicking the beam out of phase with CBO)

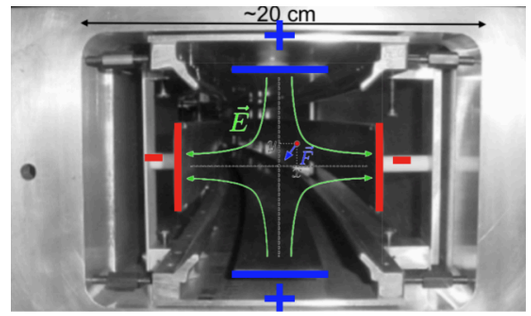
- Reduce CBO Amplitude (Due to an imperfect kicker system, the beam executes CBO oscillations with a large amplitude)
- Reduce muon loss by scraping the beam



O Kim et al
New J. Phys. 22 (2020) 063002



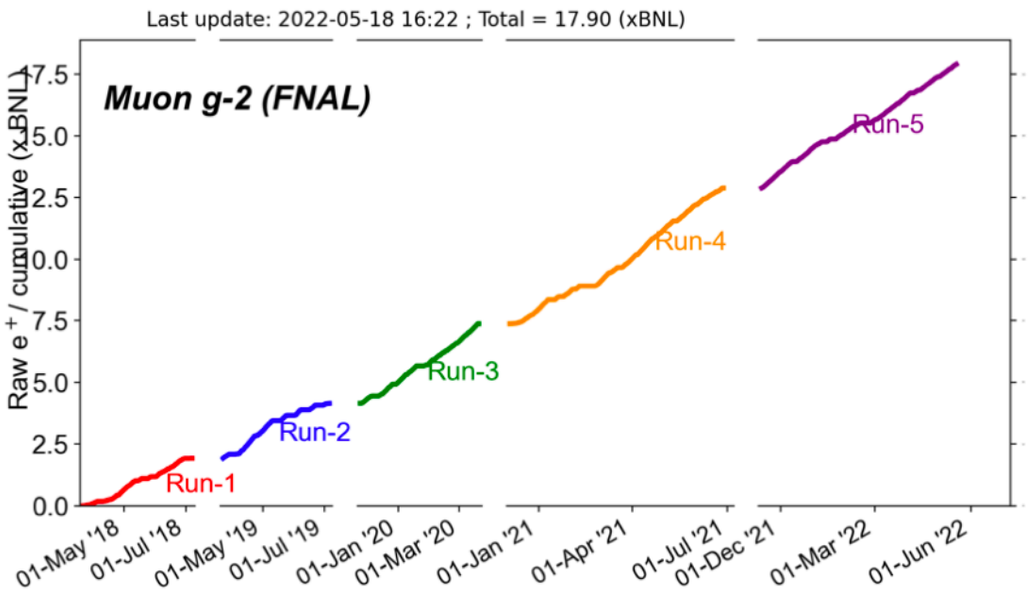
RF can be applied through the quad plates



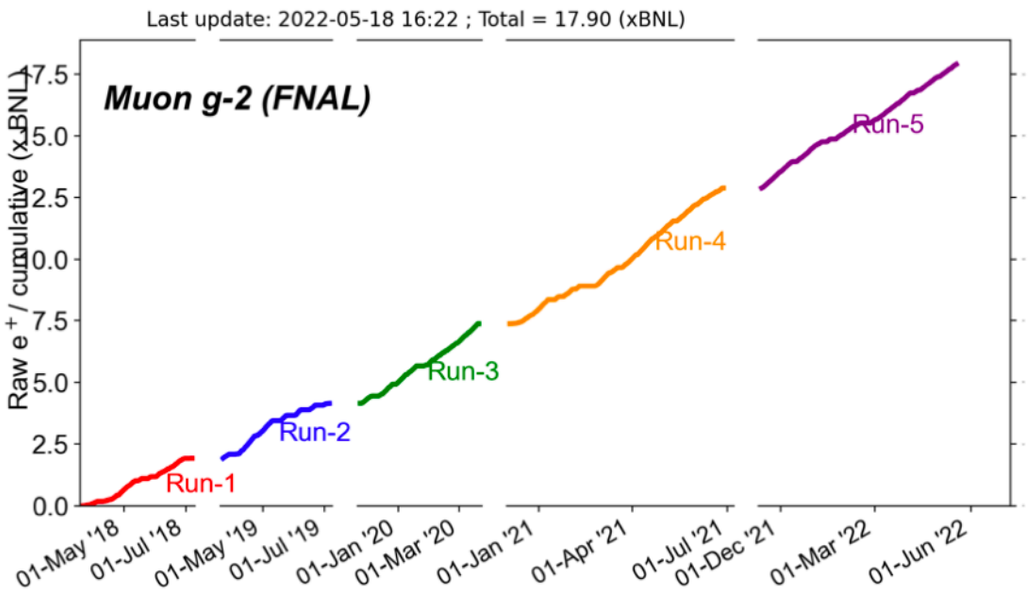
CBO Amplitude: 5-6mm->0.5-1mm

Muon Loss : factor of 4 reduction

Improvements on the g-2 uncertainty

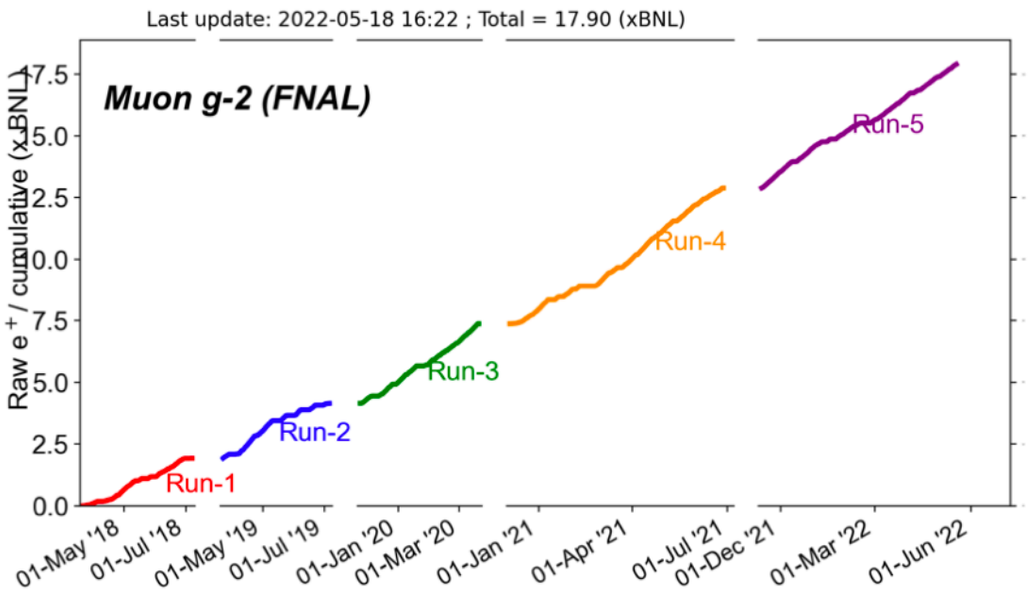


Improvements on the g-2 uncertainty

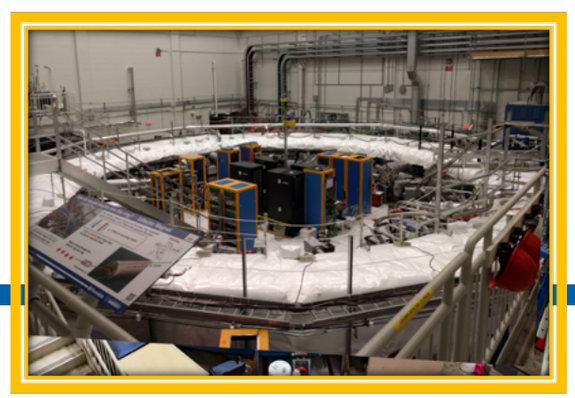


- Run-5 started in November 2021
  - Improved kick: Most recent part of Run-3 had a perfectly centered beam owing to improved kicker system.

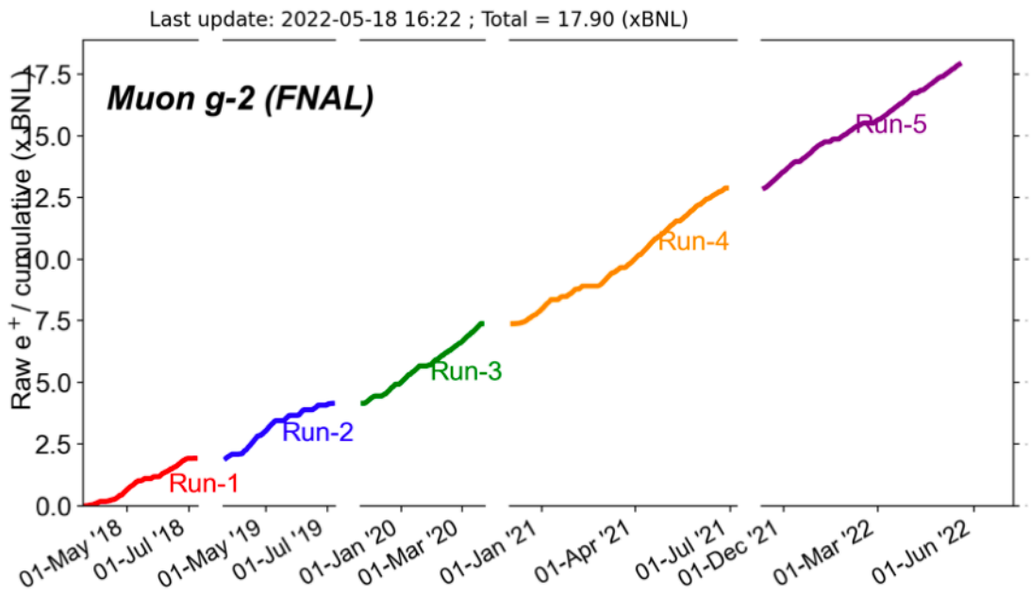
Improvements on the g-2 uncertainty



- Run-5 started in November 2021
  - Improved kick: Most recent part of Run-3 had a perfectly centered beam owing to improved kicker system.
  - Improved field stability:More stable temperature and better magnet insulation.



Improvements on the g-2 uncertainty



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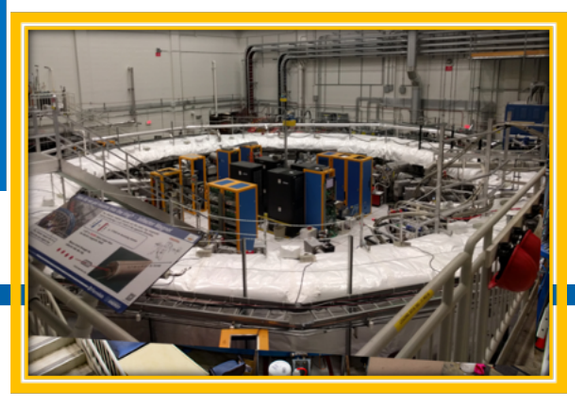
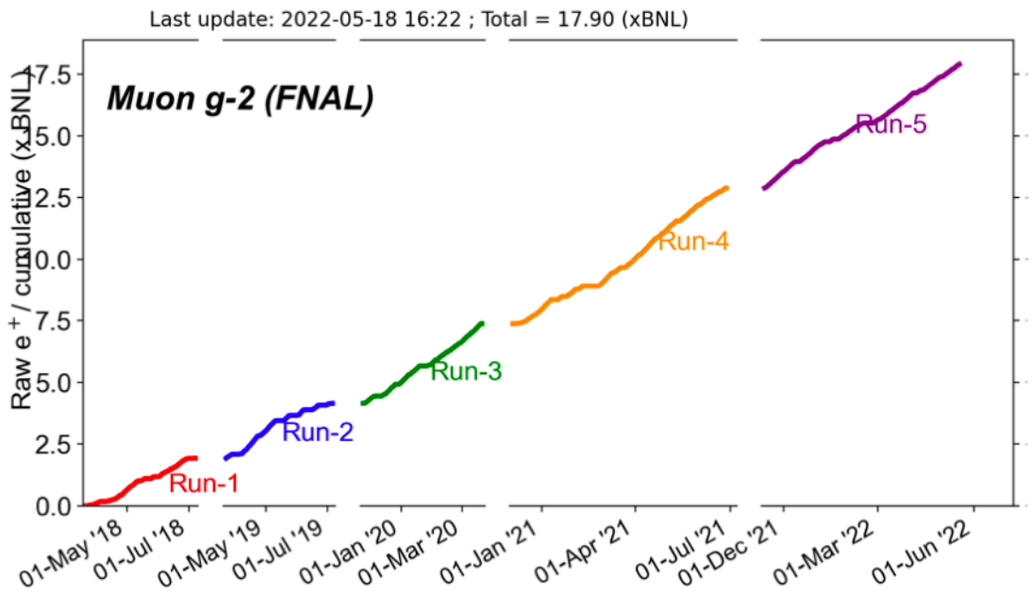


Improvements on the g-2 uncertainty



- Run-5 started in November 2021
  - Improved kick: Most recent part of Run-3 had a perfectly centered beam owing to improved kicker system.
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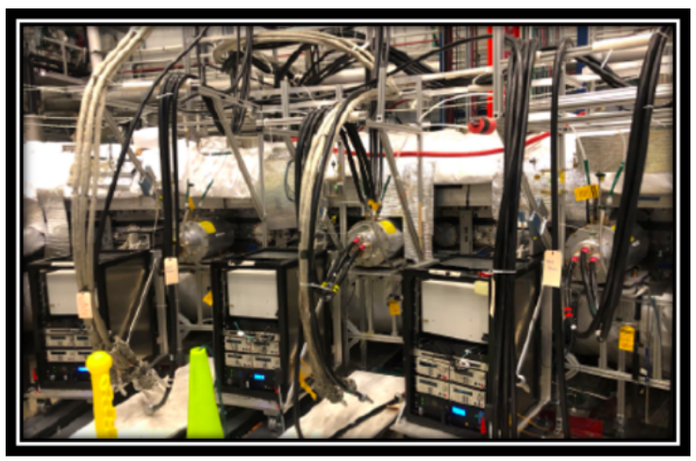
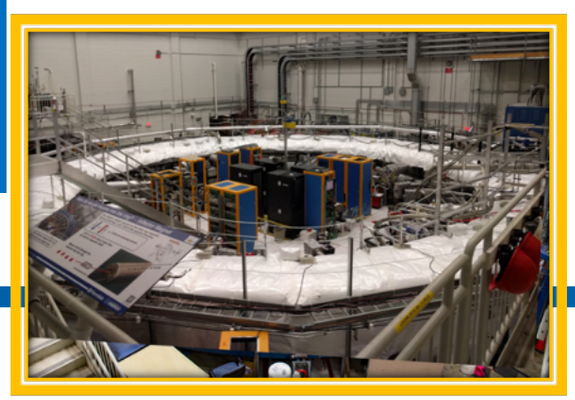
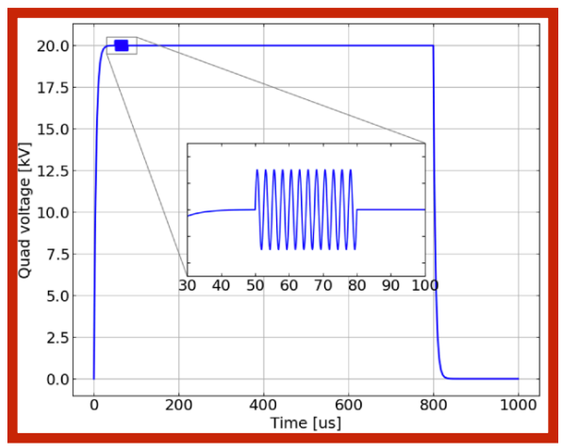
  - Damaged HV resistors were replaced after Run-1
  - RF System is fully integrated in Run-5

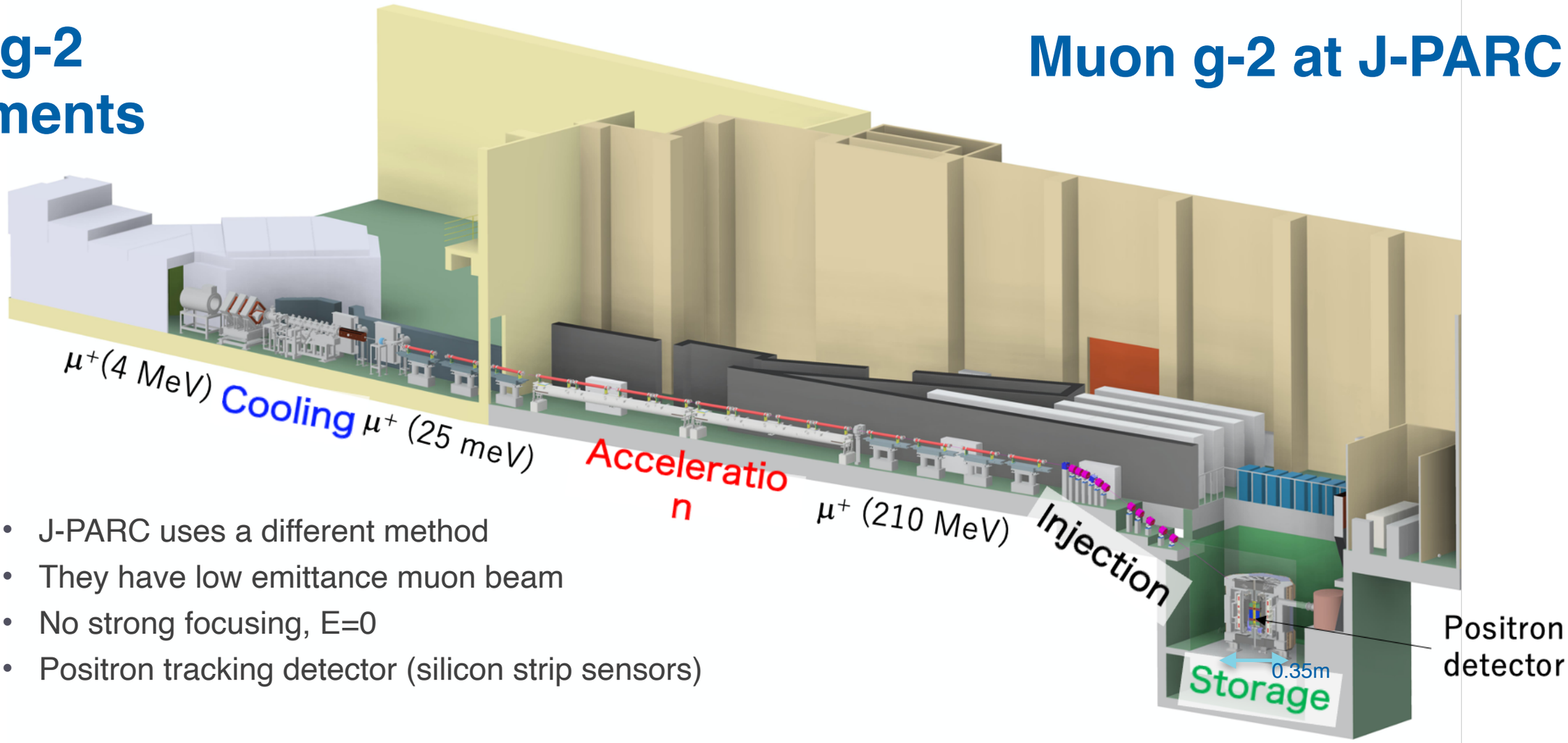






Future g-2 Experiments

Muon g-2 at J-PARC



- J-PARC uses a different method
- They have low emittance muon beam
- No strong focusing, E=0
- Positron tracking detector (silicon strip sensors)

- Electric field will be eliminated by using reaccelerated thermal muon beam
- Lower momentum muon beam + compact storage region with highly uniform magnetic field
- Tracking detector for decay positrons —> reduced pile-up + able to measure the momentum direction of positrons.
- Final Goal is to reach **0.46ppm—> 0.1ppm** on a_μ
- Beam line construction has started and commissioning is expected to start in 2027

*Takashi Yamanaka Muon g-2 BAM talk