The g-2 Experiment at Fermilab

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μ g-2

Barry King. On behalf of the Muon g-2 Collaboration.

August 3rd 2018.

Magnetic dipole moments lead to spin precession.

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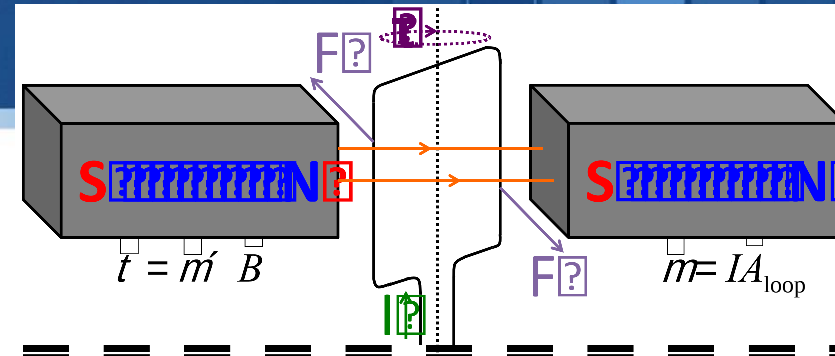
Classical Picture



Quantum Picture

g-factor:

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

Dirac Equation for EM potential:

$$\left[i\gamma^\mu(\partial_\mu + ieA_\mu) - m\right]\psi = 0$$

- Spin-1/2 point particles
- Leads to Pauli Theory
- Predicts g = 2

Larmor Precession (particle rest frame):

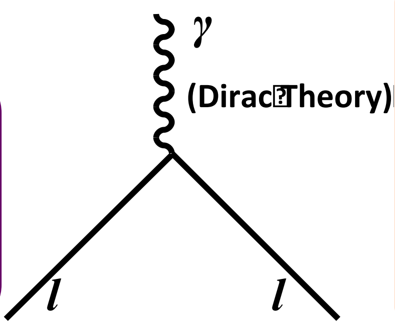
$$\frac{d\vec{s}}{dt} = \vec{\tau} = g\left(\frac{q}{2m}\right)\vec{s}\times\vec{B}$$

Quantum Field Theory Picture

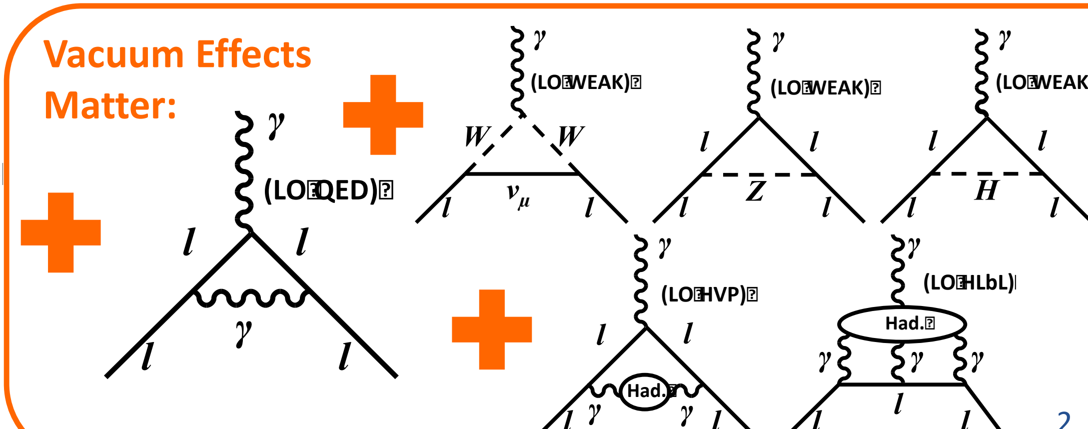
Anomaly:

$$a \equiv \frac{g-2}{2}$$

- Predicts g ≠ 2



Vacuum Effects Matter:



Standard Model Prediction.

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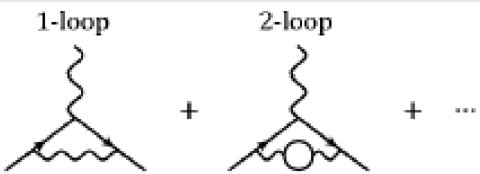
Sensitivity of muons to new physics is ~ $\frac{m_\mu^2}{m_e^2} \sim 40{,}000$ greater than electrons.

The Standard Model determination of a_μ

$$a_\mu^{\text{SM}} = a_\mu^{\text{QED}} + a_\mu^{\text{EW}} + a_\mu^{\text{had, VP}} + a_\mu^{\text{had, LbL}} + a_\mu^{\text{BSM??}}$$

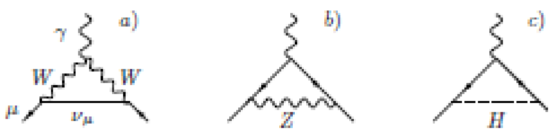
QED



Known to five-loop (12,672 diagrams)

99.99% of a_μ^{SM} ~0.001% of δa_μ^{SM}

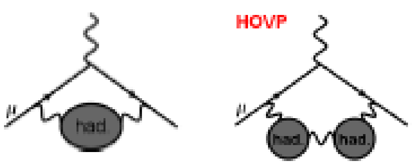
EW



Known to two-loop (with m_H known)

0.0001% of a_μ^{SM} ~0.2% of δa_μ^{SM}

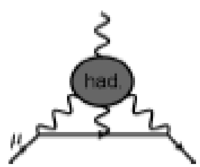
HVP



Non-perturbative (data input + lattice)

0.006% of a_μ^{SM} ~47% of δa_μ^{SM}

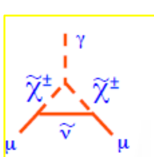
HLbL



Non-perturbative (data input + model/lattice)

0.0001% of a_μ^{SM} ~53% of δa_μ^{SM}

BSM



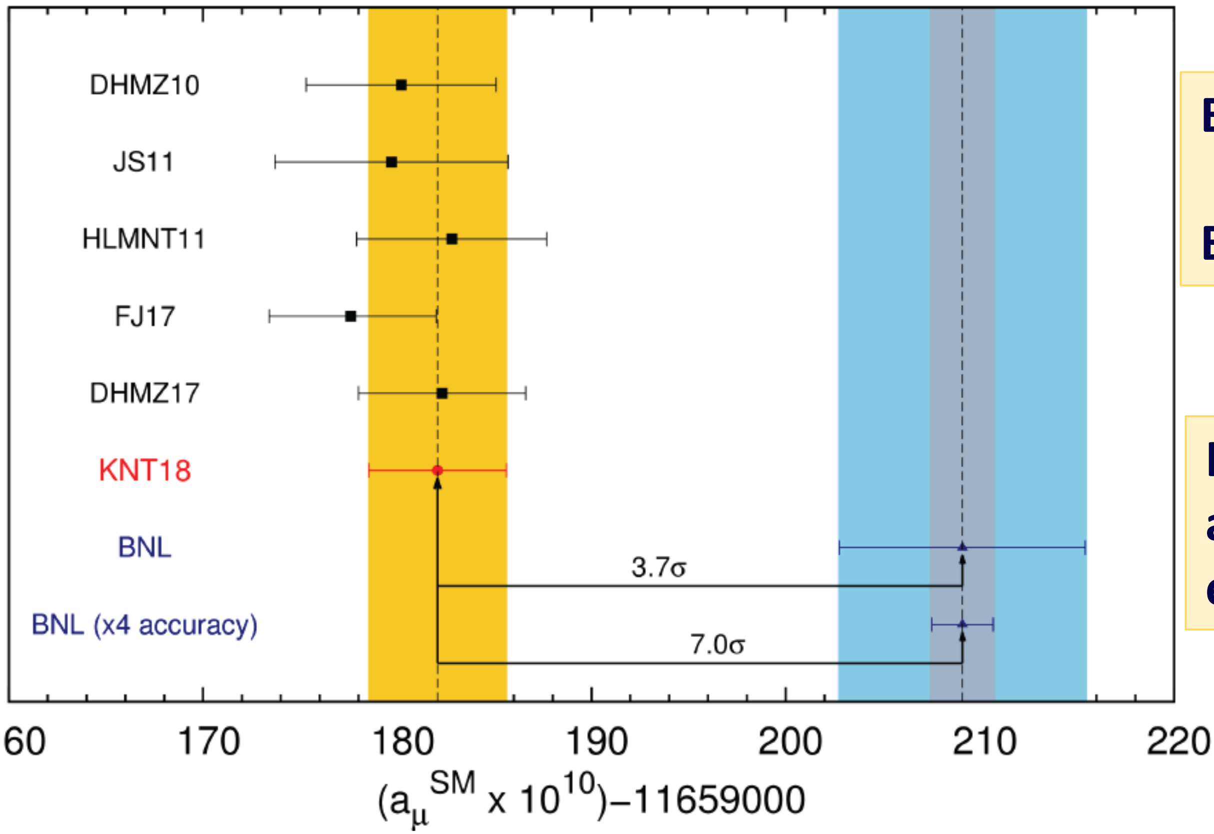
? ? ? ? ? ? ?

$$a_\mu^{SM} = 11\,659\,182.05\,(3.56) \times 10^{-10}$$ (Theory Total)

$$a_\mu^{EX} = 11\,659\,208.9\,(6.3) \times 10^{-10}$$ (World Average)

$$a_\mu^{exp} - a_\mu^{SM} = 26.85\,(7.26) \times 10^{-10} > 3\sigma \text{ discrepancy}$$

The discrepancy between the latest SM prediction and the result from the Brookhaven experiment (E821) is greater than 3 σ



E821 error: 540 ppb.

E989 goal: 140 ppb.

If central value persists, achieving the Fermilab design error will give ~ 7σ difference.

Muon Spin Dynamics in a Storage Ring.

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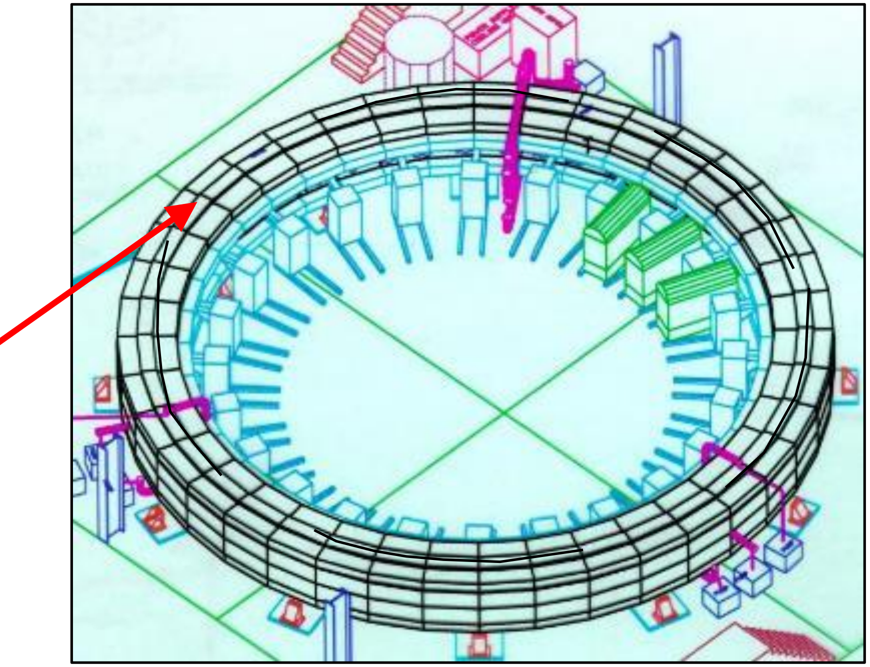
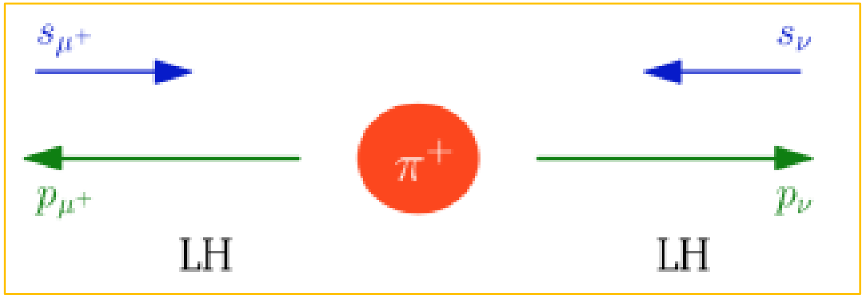
1) Inject polarized muon source

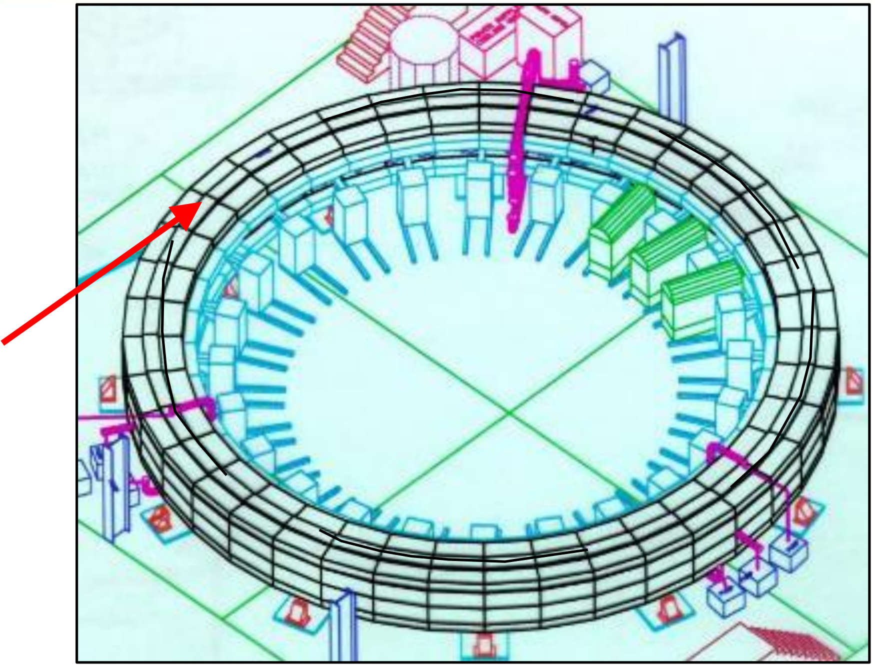


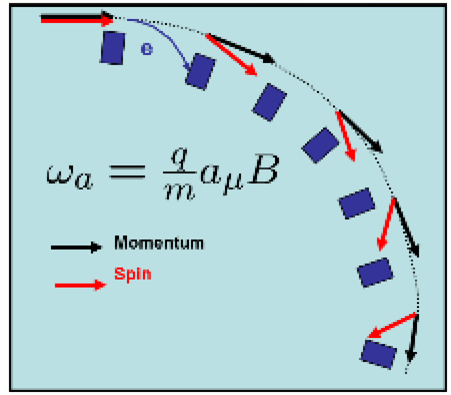


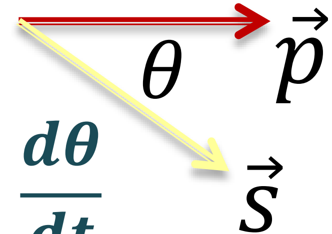
The muons circulate with an angular frequency:

$$\omega_c = \frac{eB}{\gamma m}$$

Muon Spin Dynamics in a Storage Ring.







$$\omega_a = \frac{d\theta}{dt}$$

Muon spin precesses in the vertical external magnetic field of B = 1.45 Tesla (Lamor Precession).

$$\omega_S = \frac{geB}{2m} + (1-\gamma)\frac{eB}{\gamma m}$$

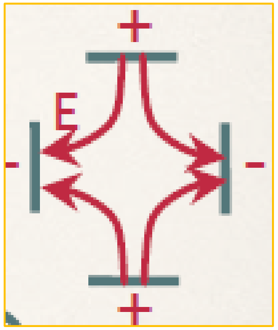
$$\omega_a = \omega_s - \omega_c = \left(\frac{g}{2} - 1\right)\frac{eB}{m} = a_\mu \frac{eB}{m}$$

Measure two quantities in g-2

Muon spin precession relative to momentum in cyclotron is directly proportional to a_μ

Muon Spin Dynamics in a Storage Ring.

We would like to use electrostatic quadrupoles for vertical focussing of the muon beam.



This introduces an extra term into the formula for ω_a

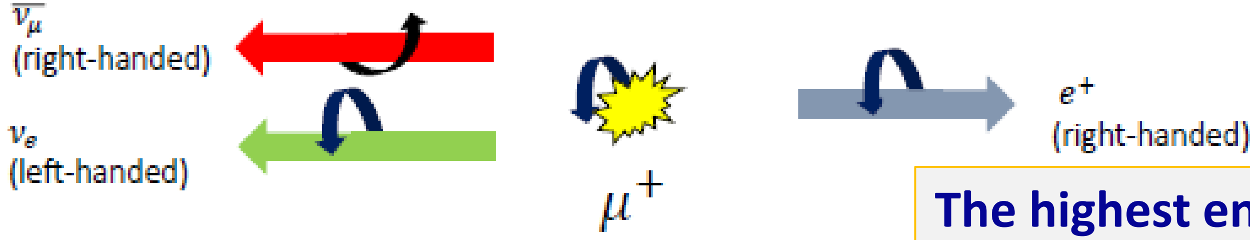
$$\omega_a = \frac{e}{m}\left\{a_\mu B - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\frac{\beta \times E}{c}\right\}$$

~0

Use muons of specific momentum such $\gamma = \gamma_{magic} = \sqrt{1 + \frac{1}{a_\mu}} = 29.3$

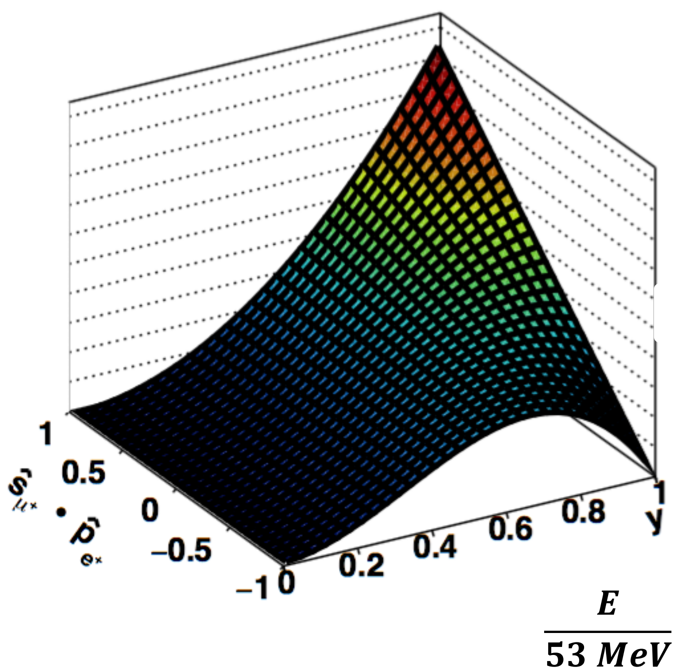
Muon momentum = 3.094 GeV.
Lifetime dilated to ~ 64.4 μsecs.

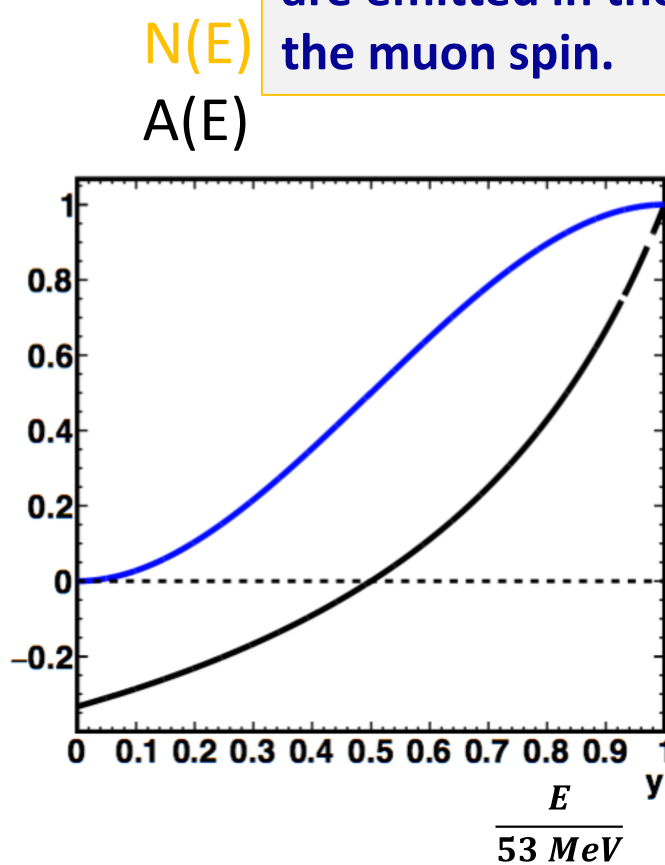
Decay positron distribution in the muon rest frame



The highest energy positrons are emitted in the direction of the muon spin.

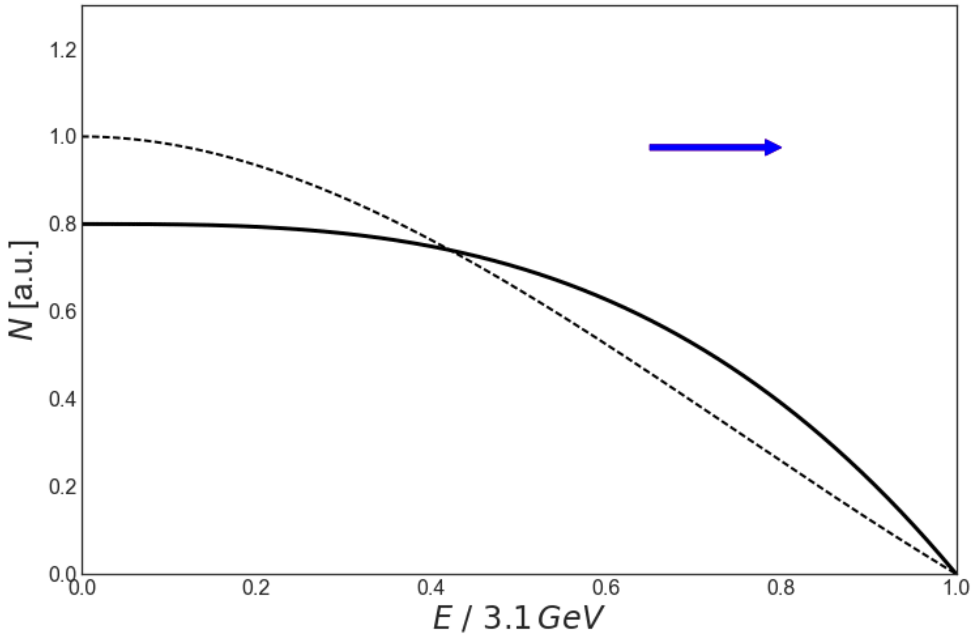
$$\frac{d^2N}{dE\ d\ cos(\theta)} \propto N(E)[1 + A(E)\ cos(\theta)]$$





Decay positron distribution in the lab frame

As the spin vector rotates relative to the momentum vector the decay positron energy distribution alters:

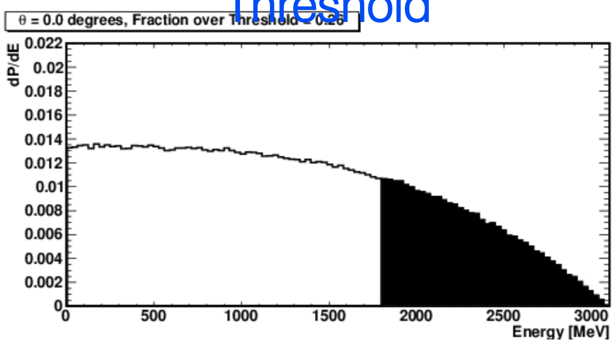


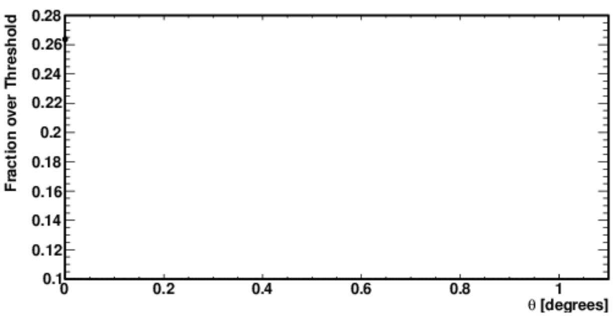
Can use the observed number of decay positrons above some energy threshold to measure ω_a:

Spin Precession in g-2 Ring

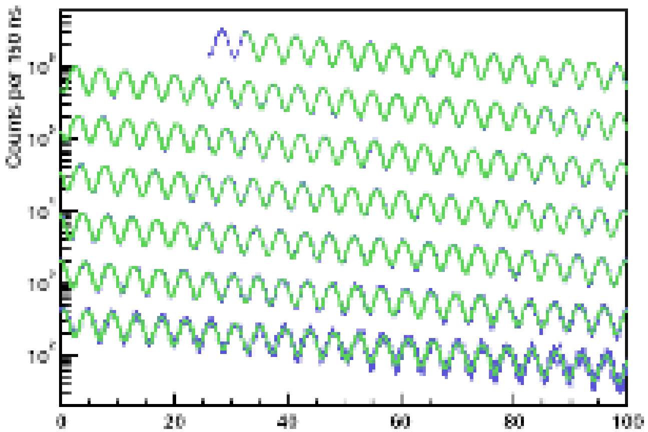
- Higher energy positrons emitted preferentially in direction of muon spin
- Threshold Energy Cut in calorimeters
- Results in sinusoidally oscillating energy deposition

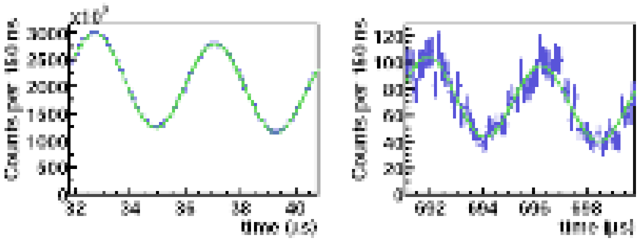
Fraction of e^+ above Threshold





Result from E821 Brookhaven experiment.





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What g-2 actually measures.

It is possible to rearrange $a_\mu = \frac{\omega_a m_\mu}{eB}$ in terms of precisely known ratios:

The g-2 experiment then measures ω_a
and ω_p (measure the magnetic field via precession of free protons)

$$a_m = \frac{\frac{g_e}{2}\,\frac{m_m}{m_e}\,\frac{w_a}{\langle w_p \rangle}}{\frac{m_e}{m_p}}$$

Average magnetic field seen by muons measured with NMR

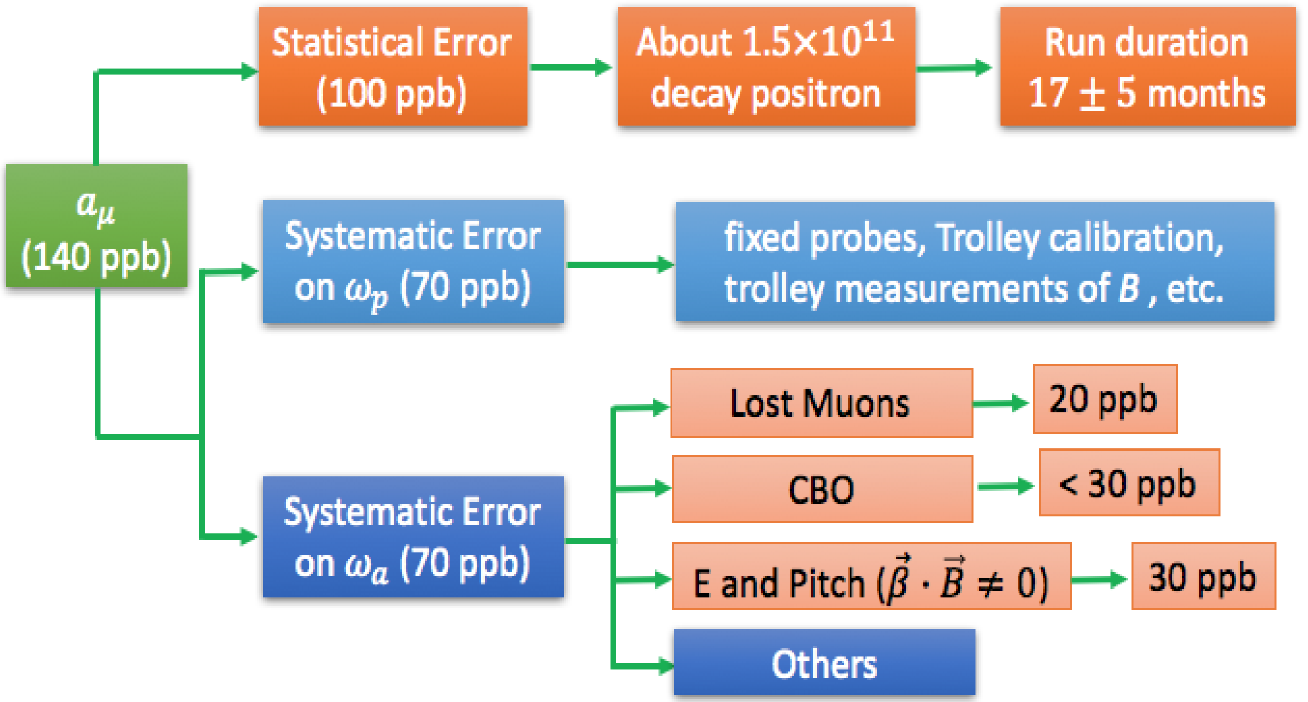
$$\hbar\omega_p = 2\mu_p\left|\vec{B}\right|$$

g_e = -2.002 319 304 361 82(52) (0.00026 ppb)
m_μ/m_e = 206.768 2826(46) (22 ppb)
μ_e/μ_p = -658.210 6866(20) (3.0 ppb)

Fermilab Experiment a_μ total error goal is 140 ppb

How to obtain a more precise measurement.

- **Increase statistics by a factor of > 20 and reduce systematics by a factor of ~3 w.r.t BNL experiment**



More beam !!!

Better Uniform Magnetic Field!!!

Better ω_a measurement !!!

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Systematics on ω_a

The goal of the Fermilab experiment is to reduce the systematic error on ω_a ***180 → 70 ppb***

- Improved Calorimeters
- New Laser control system
- New Tracker to give accurate beam profile and position.

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

Systematics on ω_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 ω_p	170		70

How to obtain a more precise measurement: Summary.

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Systematic Uncertainties: Improvements Over E821

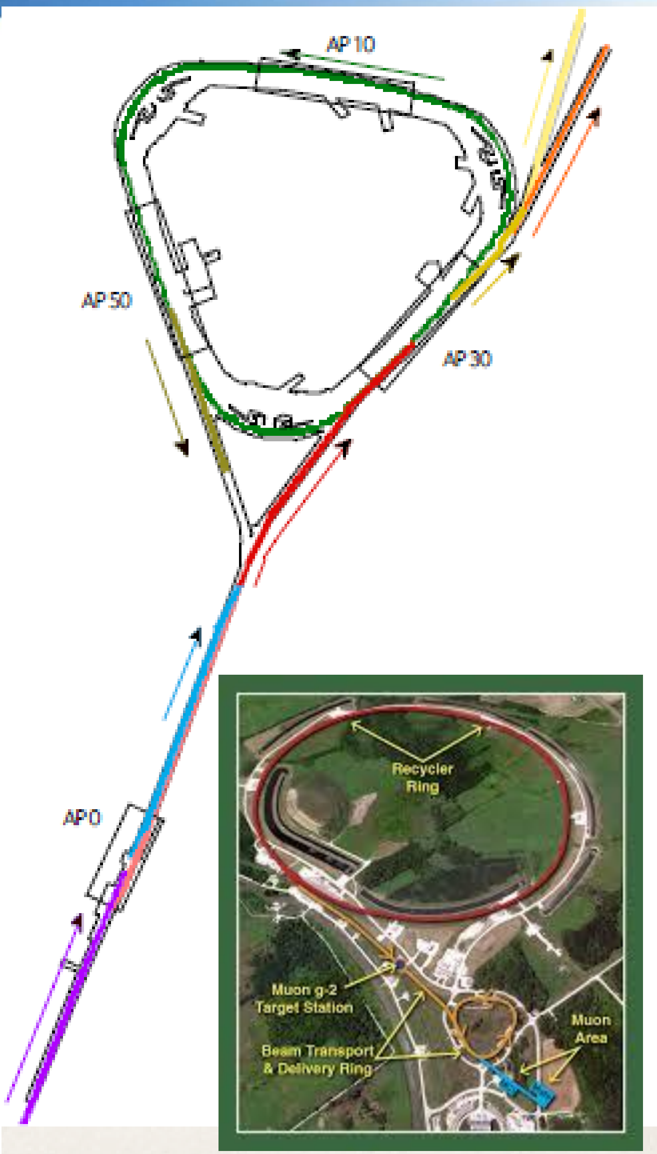
Reduce ω_a systematic uncertainties by a factor of 3

E821 Error	Size (ppb)	E989 Improvements	Goal (ppb)
Gain Changes	120	Better laser calibration; low-energy threshold, temperature stability, no hadronic flash	35
Lost Muons	90	Less scattering due to material at injection; muons reconstructed by calorimeters	30
Pileup	80	Low-E samples recorded; calo segmentation; trackers cross-calibrate pileup efficiencies	30
Coherent Betatron Oscillations	70	Higher n-value, straw trackers to determine parameters	10
E-field/pitch	60	Straw trackers to reconstruct muon distribution, better collimators, better kick	30
Diff. Decay	50	Better kicker, tracking simulation	20
Total	**200**		**70**

Reduce ω_p systematic uncertainties by a factor of 2.5

E821 Error	Size (ppb)	E989 Improvements	Goal (ppb)
Field Calibration	50	Dedicated test solenoid, more probes, better electronics	35
Trolley Measurements	50	Reduced rail irregularities, field gradients	30
Fixed Probe Interpolation	70	More trolley runs, fixed probes; better temperature stability of magnet	30
Muon Convolution	30	Improved field uniformity, muon tracking	10
Time-Dependent Fields	–	Direct measurements of external fields, active feedback	5
Others	100	Improved electronics, reduced temperature dependence, kicker transients	50
Total	**170**		**70**

Why Fermilab?



Fermilab is able to produce many more muons than Brookhaven

- ~ 20 times more statistics in the experiment.

Fermilab produces "better" muons

- much less pion contamination.

Coupled with improvements in the experiment design:

- will measure a_{μ} to 0.14 ppm.

If the discrepancy persists should provide an ~ 7σ disagreement with the Standard Model.

Muon delivery to g-2

Muon Beam: From Protons to Muons

Recycler

- Rebunches 8 GeV protons from booster

Target Station

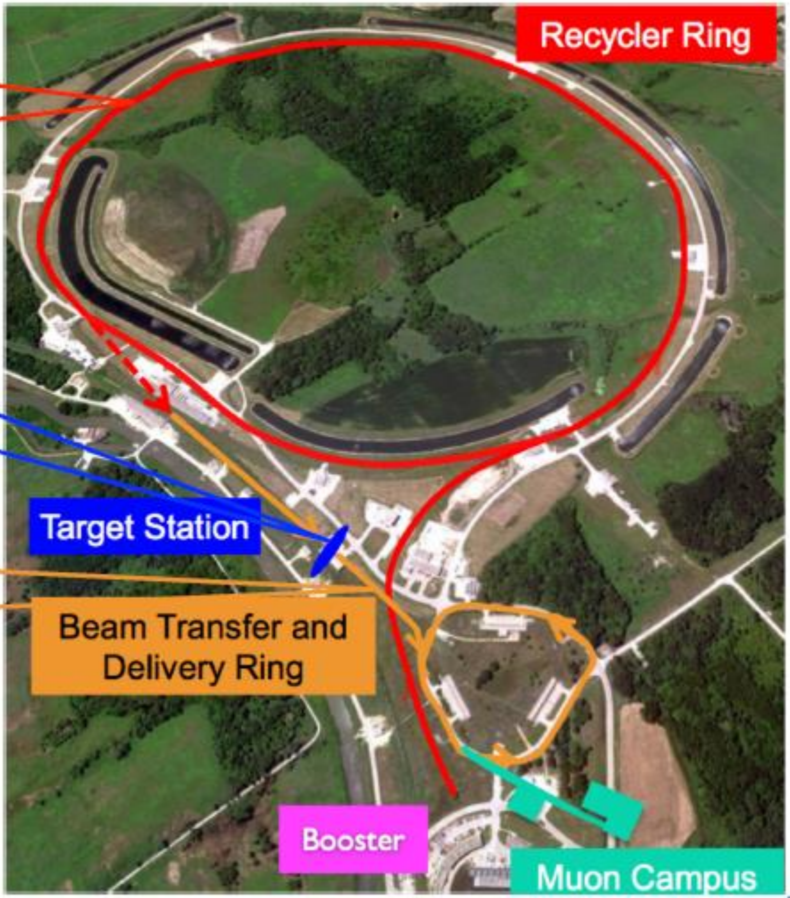
- Protons impinge upon Inconel target
- Focusing lens captures pions

Beam Transfer and Delivery

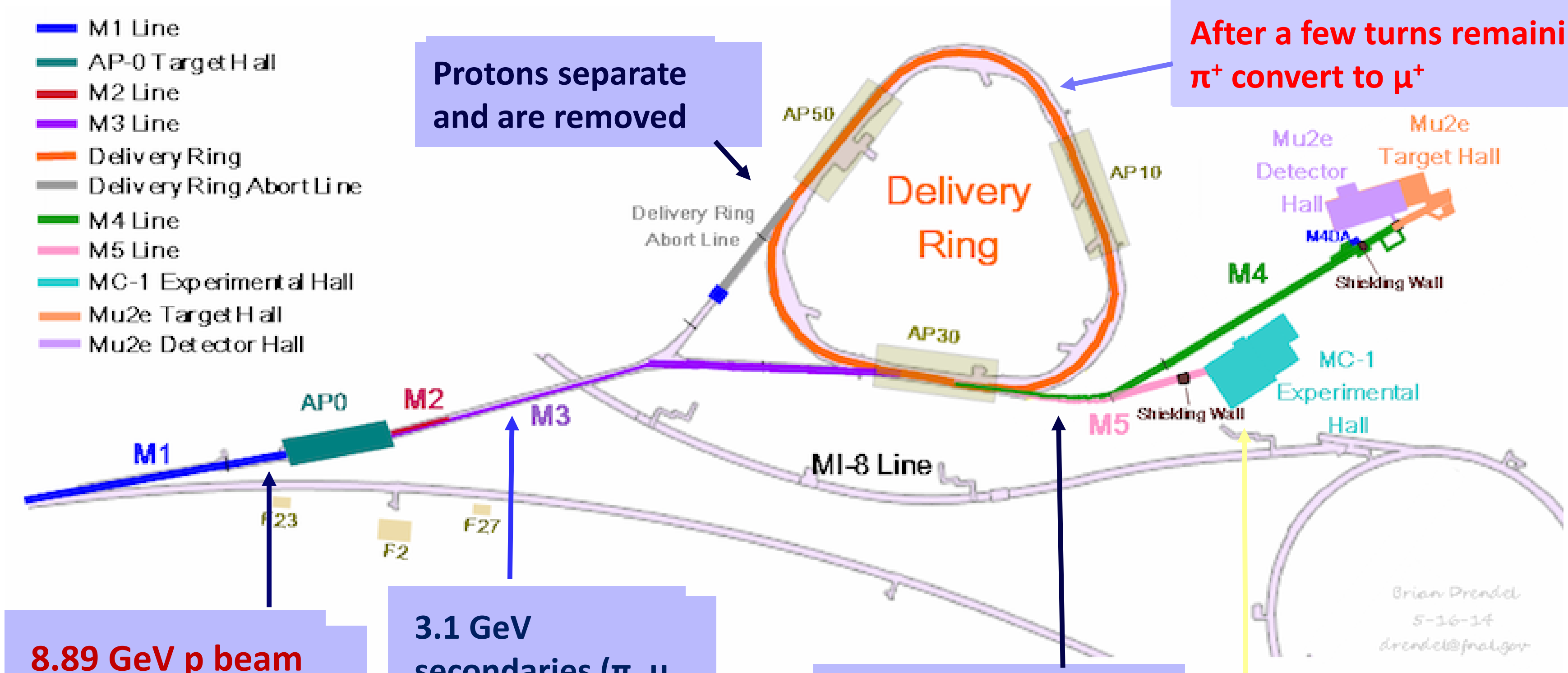
- Straight section: capture muons from forward-decaying pions (polarized)
- Remove protons by time-of-flight
  - Reduce number of pions and protons in ring

Characteristics

- Fill storage ring 16 times/1.4 sec (2x muons/fill compared to BNL)
- Expect 21x more statistics than BNL



Fermilab beamline decays away most of the pions.



Protons separate and are removed

After a few turns remaining π^+ convert to μ^+

8.89 GeV p beam impacts the target

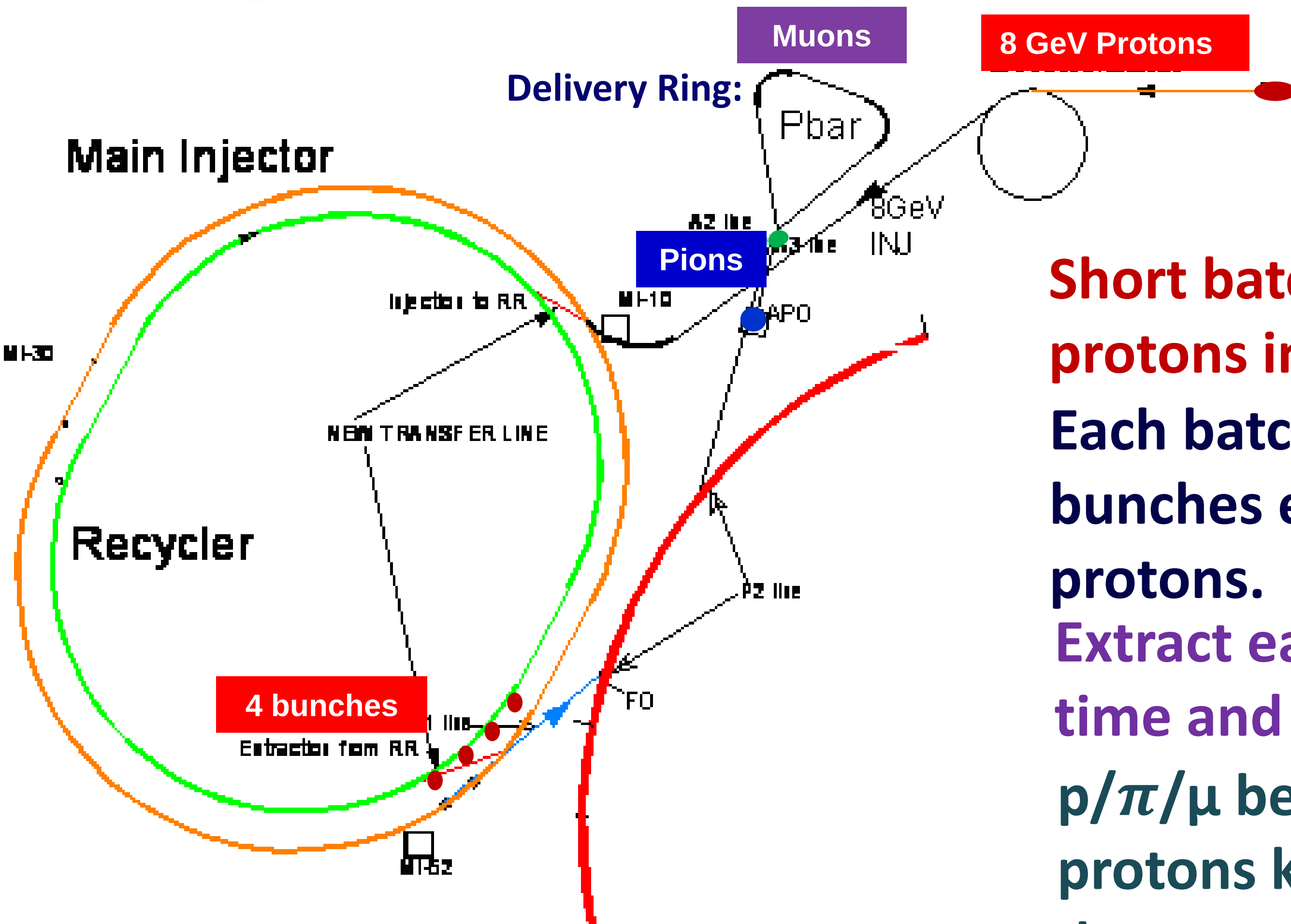
3.1 GeV secondaries (π, μ, p) travel along M2 & M3, where μ^+ are collected from π^+ decays

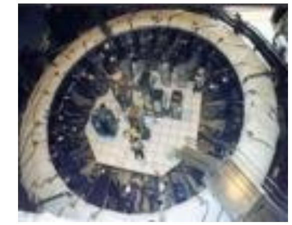
μ^+ are extracted from the ring and transferred into the storage ring via M5

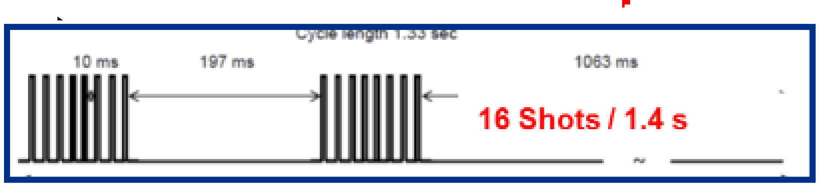
μ^+ enter the g-2 storage ring

D. Stratakis

A pure muon beam of 3.094 GeV







Short batches of 8 GeV protons into Recycler

Each batch divided into 4 bunches each of 10^{12} protons.

Extract each bunch at a time and direct to target

p/π/μ beam enters DR; protons kicked out; pions decay away

μ enter storage ring (220 muons/fill achieved)

Fermilab Muon g-2 Collaboration …

US Universities

- Boston
- Cornell
- Illinois
- James Madison
- Kentucky
- Massachusetts
- Michigan
- Michigan State
- Mississippi
- Northern Illinois
- Regis
- Texas
- Virginia
- Washington

National Labs

- Argonne
- Brookhaven
- Fermilab

Italy

- INFN
  - LNF Frascati,
  - Naples
  - Pisa
  - Roma 2
  - Trieste
  - Lecce
- Udine
- Naples
- Trieste
- Rjeka
- Molise
- SNS Pisa

China

- Shanghai

The Netherlands

- Groningen

Germany

- Dresden (thy)

England

Cockroft Institute
Lancaster
Liverpool
University College London

Korea

KAIST
CAPP

Russia

Dubna
Novosibirsk

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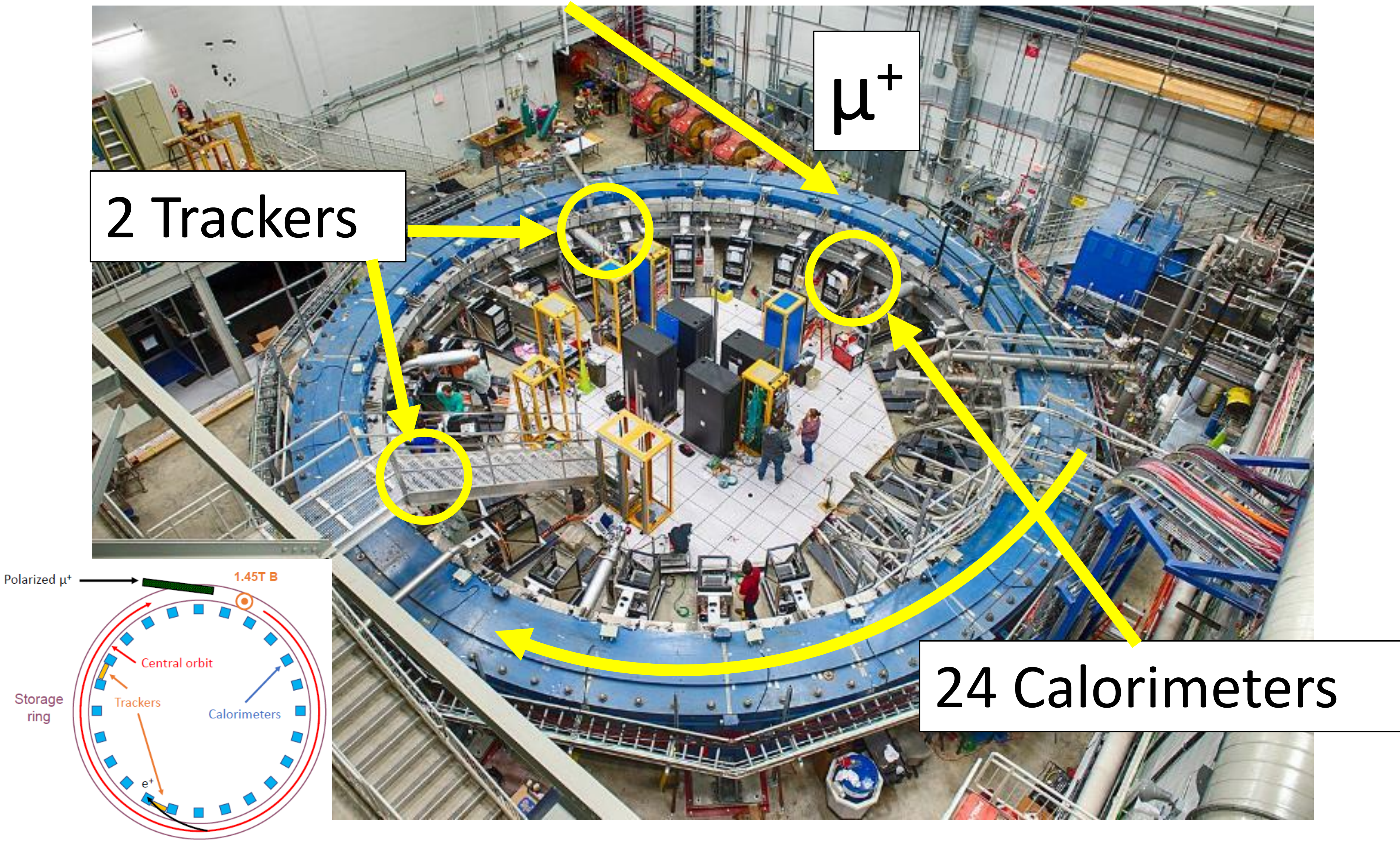
Fermilab

E989: The Fermilab g-2 Experiment.



IBMS: Beam monitors on entry to g-2 ring.

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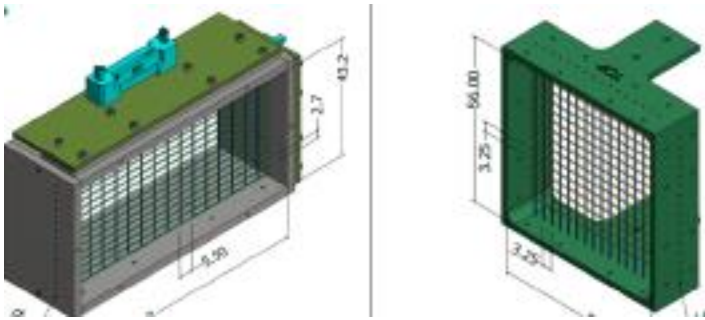
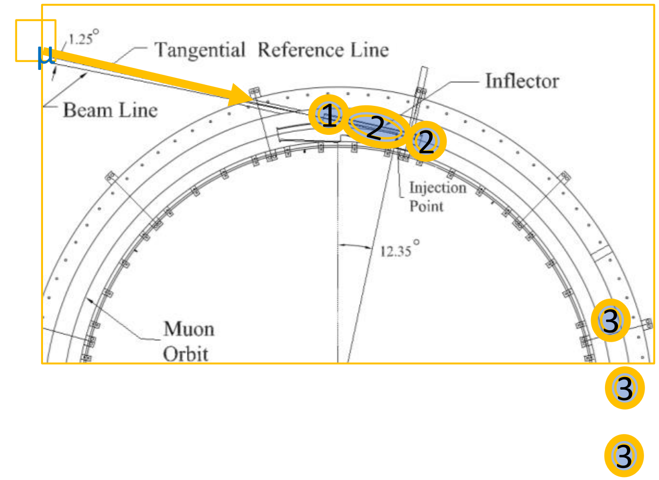
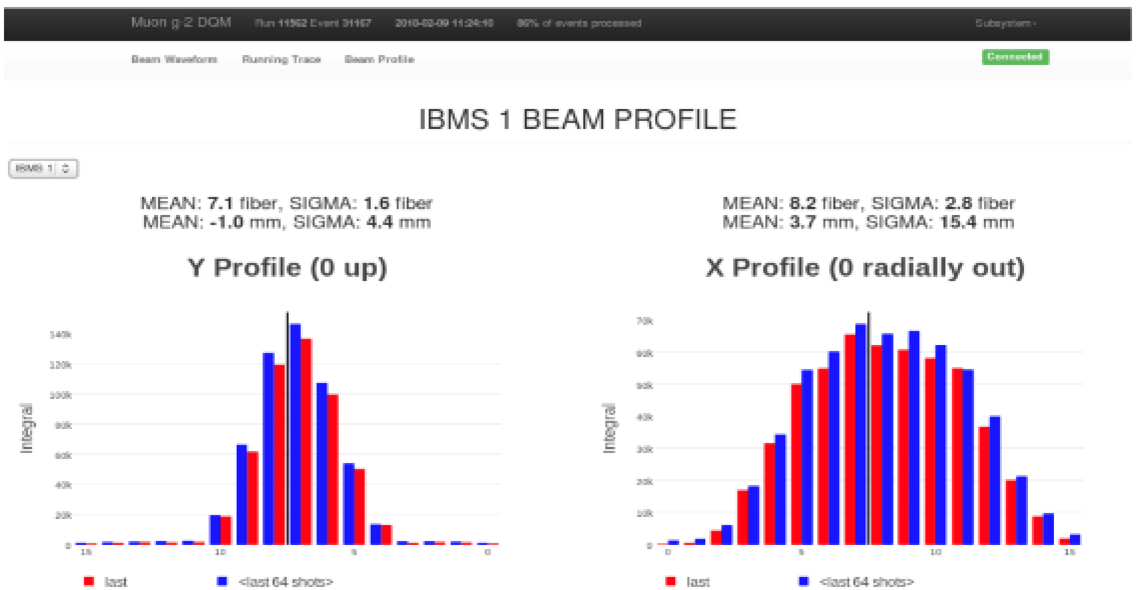
Just upstream of the inflector:







Beam X, Y profiles at Inflector Beam Profile Monitor 1

Scintillators provide map of temporal and transverse beam profile.
Gives guidance on muon beam tuning.

Inflector.

B = 1.45 Tesla

R = 7.112 m

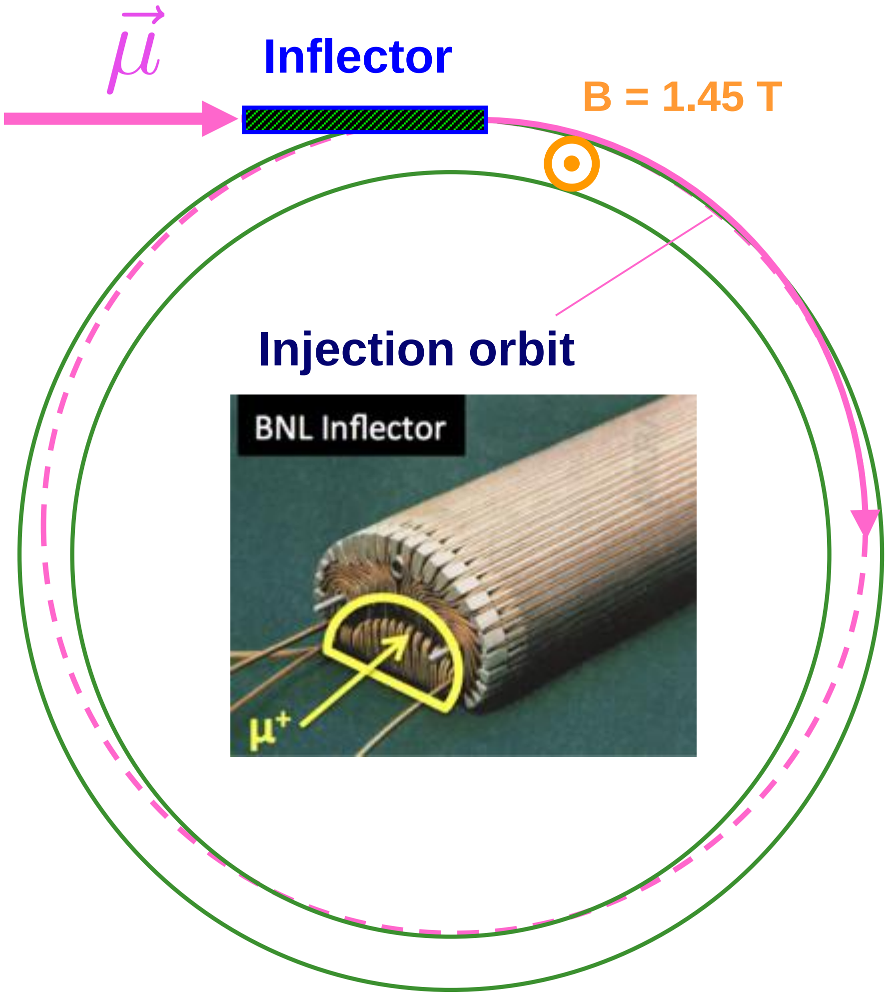
$\tau_c = 149\ ns$

$\gamma\tau = 64.4\ \mu s$

$\tau_a = 4.37\ \mu s$

- M5 magnetic quads do final focusing before injection into ring
- Inflector injects muons into ring while minimizing disturbance to B-field

Provides nearly field free region for muons to enter the ring.
Muons exiting the inflector take a circle 77mm outward than needed for storage.

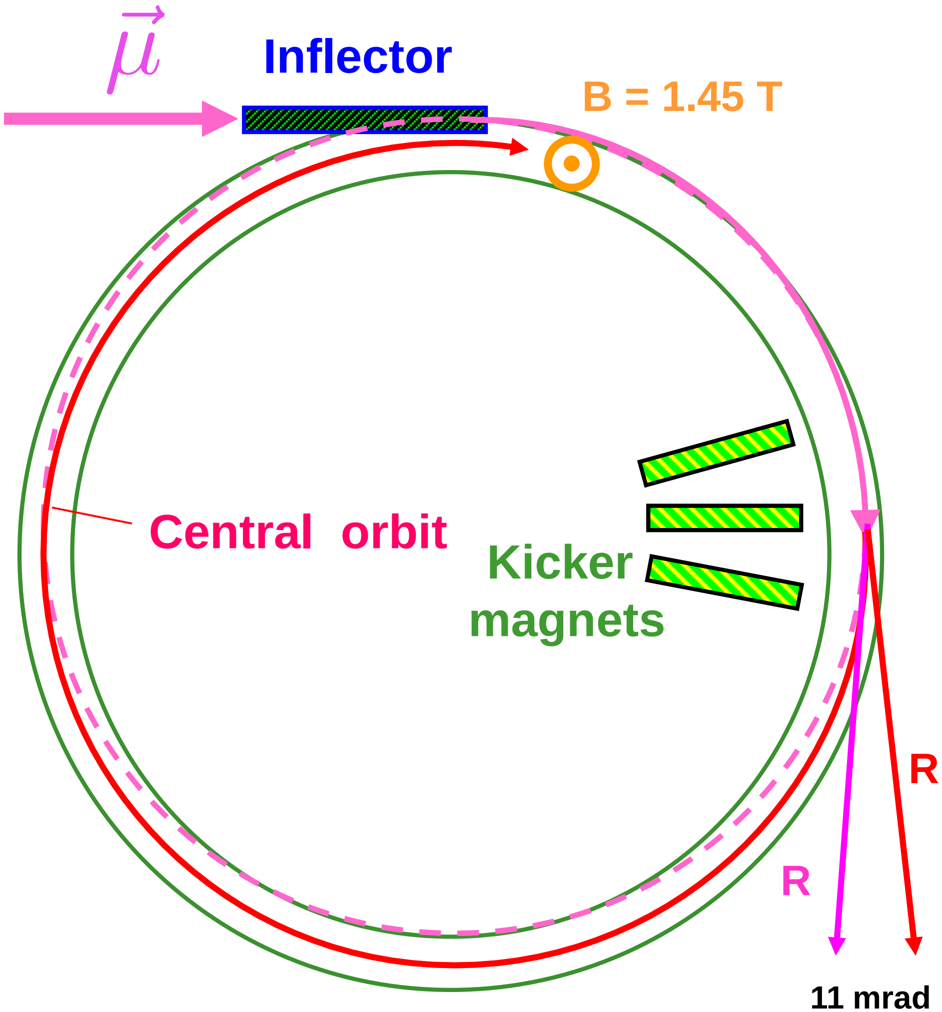


Kickers.

New 1.7m long, 3 kicker magnets are used to kick the muons back into ideal orbit.

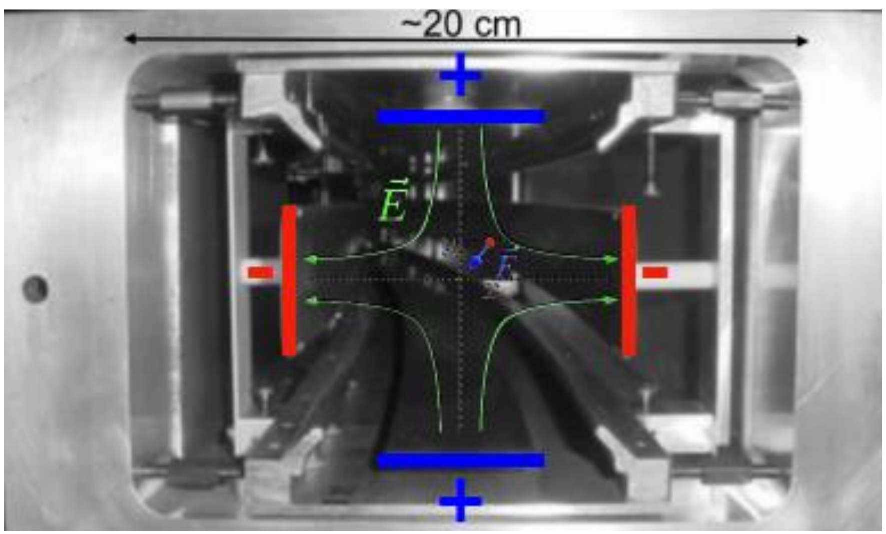
Kickers give a 11 mrad bend to the muon beam

The kicker pulse has to be shorter than the cyclotron frequency, which is ~149ns

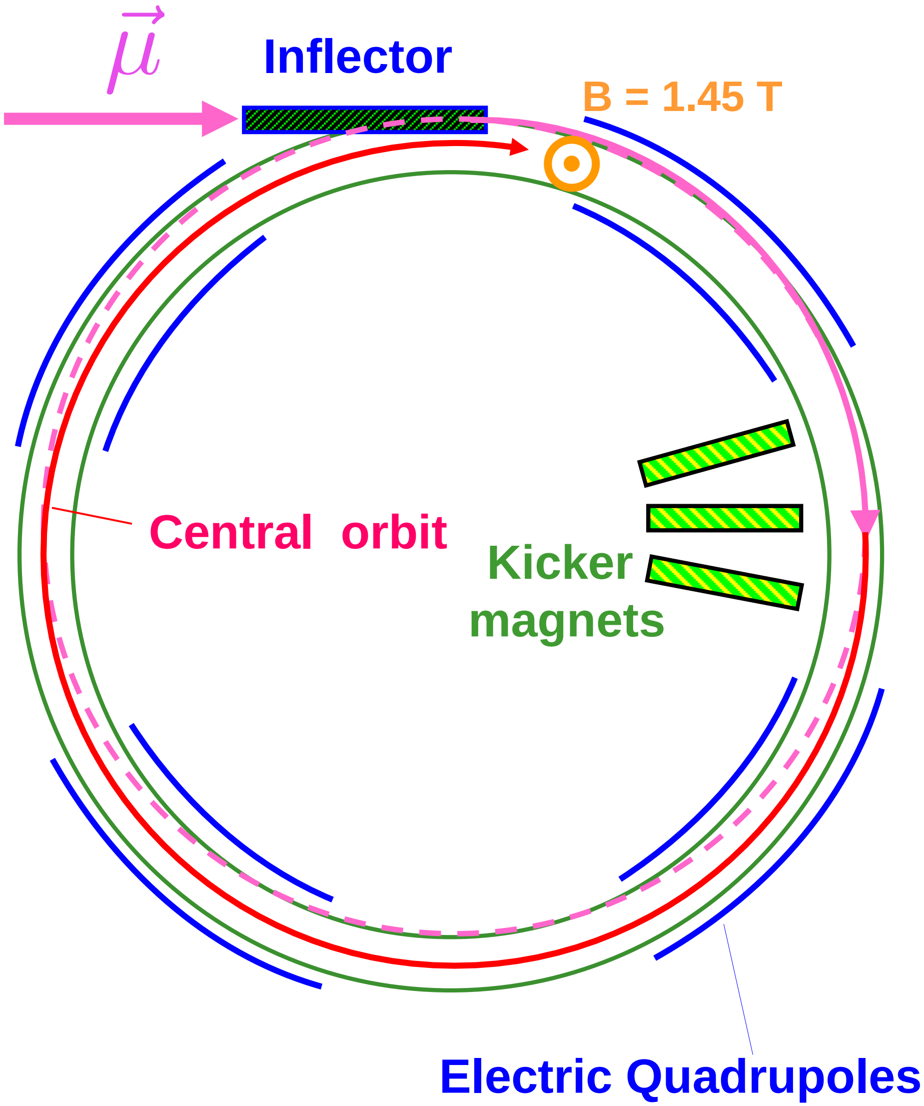


Quadrupoles.

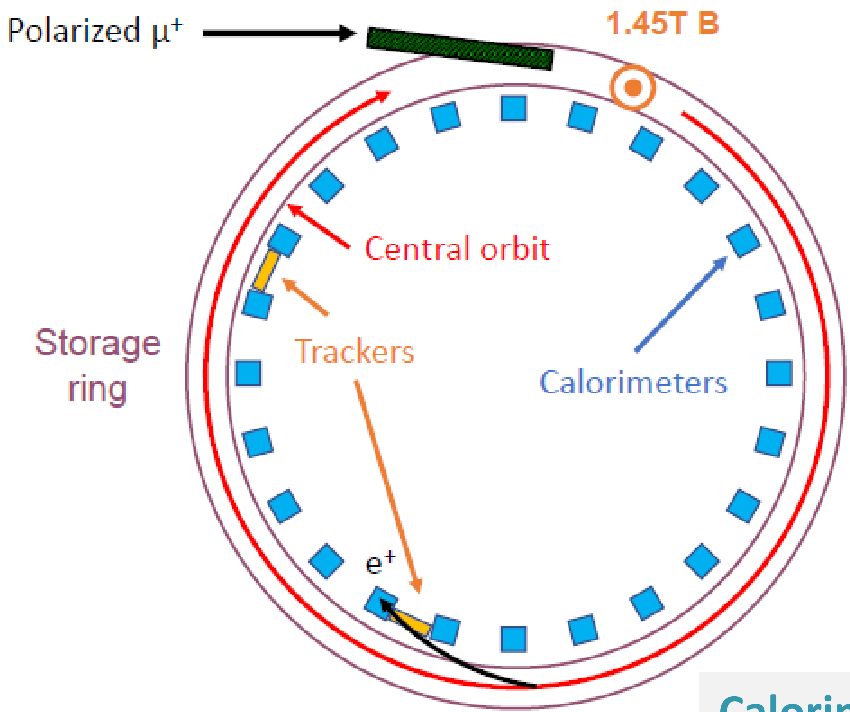
- **Muons focused vertically with electrostatic quadrupoles**



Quad Plates in Vacuum Chamber



Calorimeters.



Calorimeter Improvements:

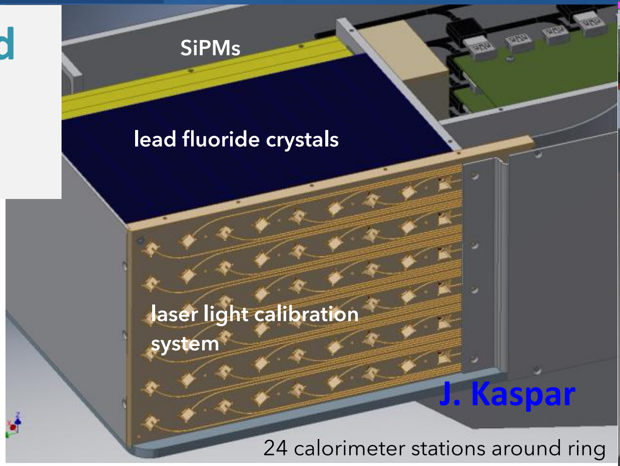
6 × 9 segmented array of PbF_2 crystals (reduces pileup from 2 close low energy positrons).

Laser calibration system to ensure gain stability.

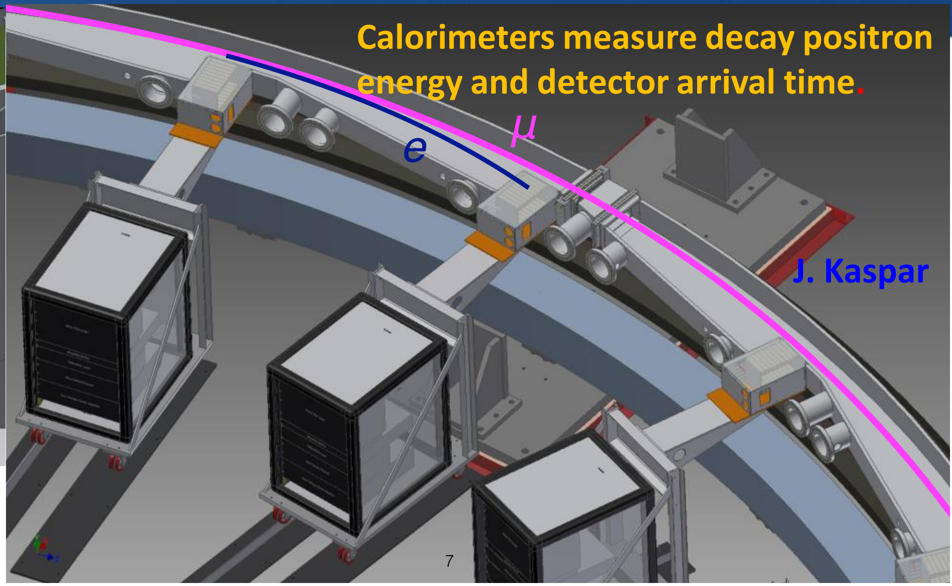
Better time synchronization with beam injection.

Segmented calorimeters provide spatial resolution that can be used to separate positron hits.

6 × 9 segmented array of PbF_2 crystals.

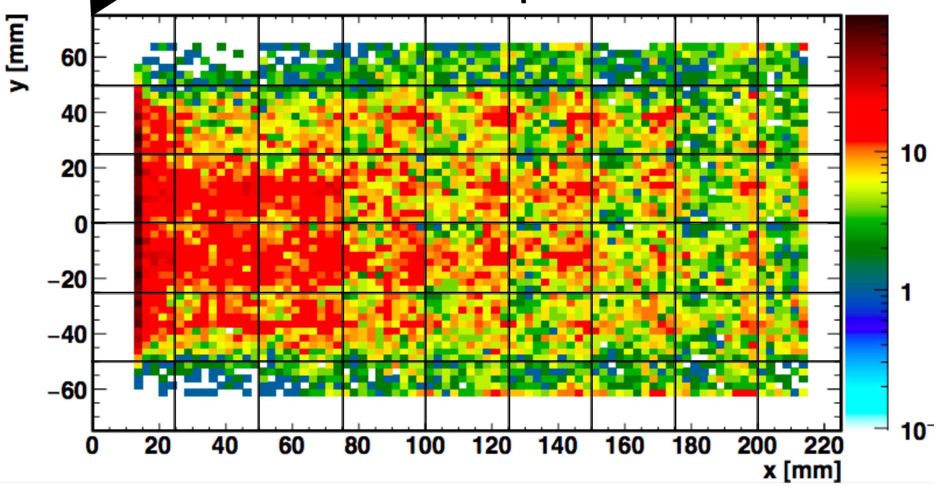


Crystals are 25×25×140 mm

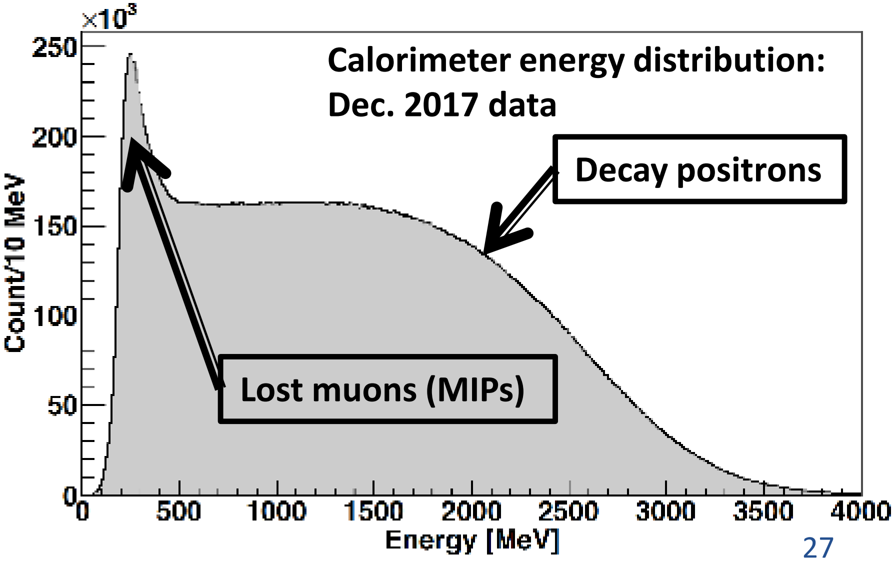


Ring side of calorimeter

Calorimeter cluster spatial distribution



The above June 2017 commissioning data has large proton contamination: 60 p: 4 π: 1 μ



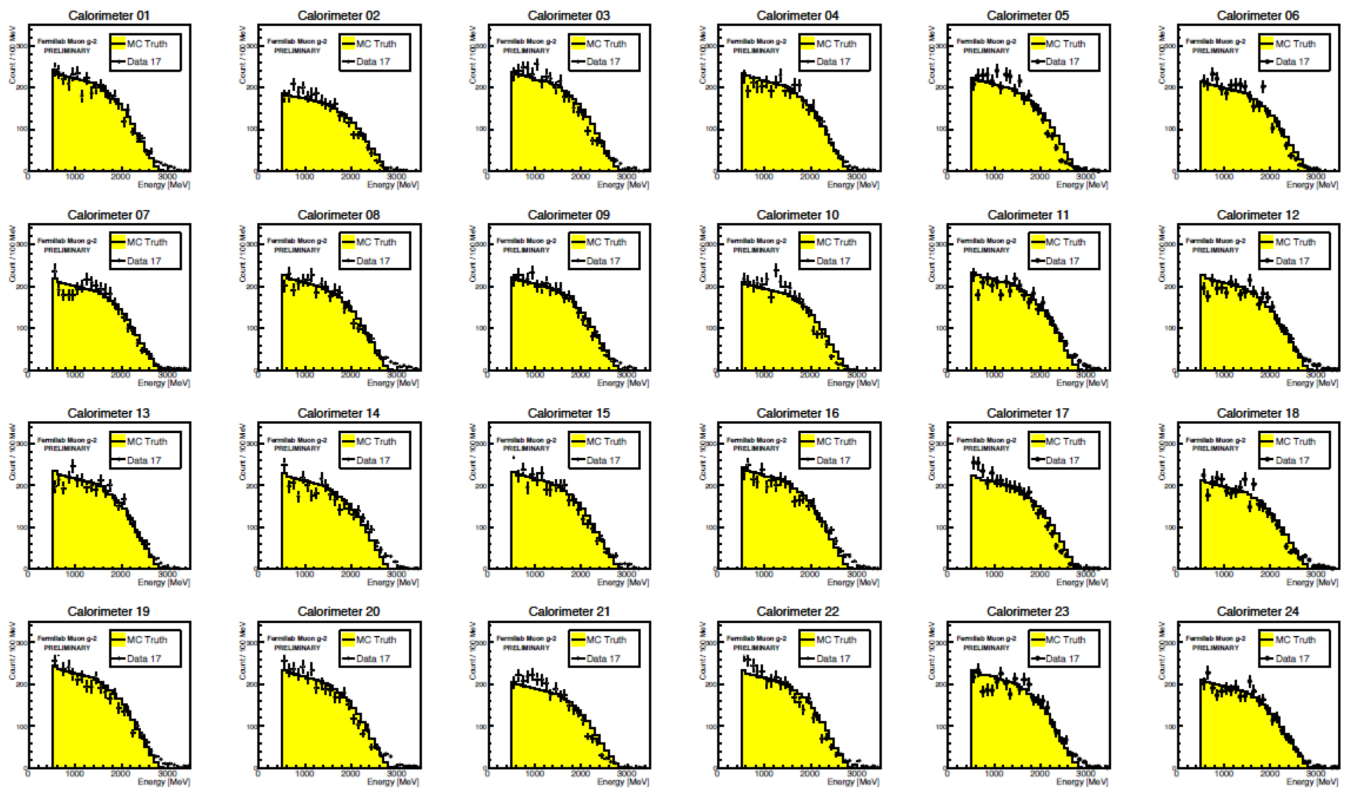
Calorimeter Response.

Calorimeters well understood both in data and simulations.

Used as online monitors of # of stored muons.

Commissioning data provided opportunity to :

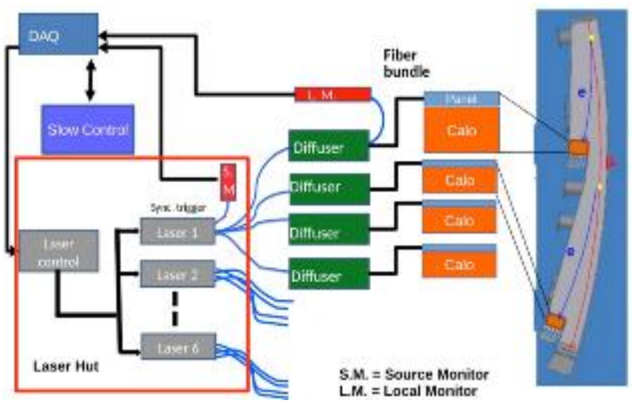
- search for and correct mapping error
- Determine timing offsets between crystals



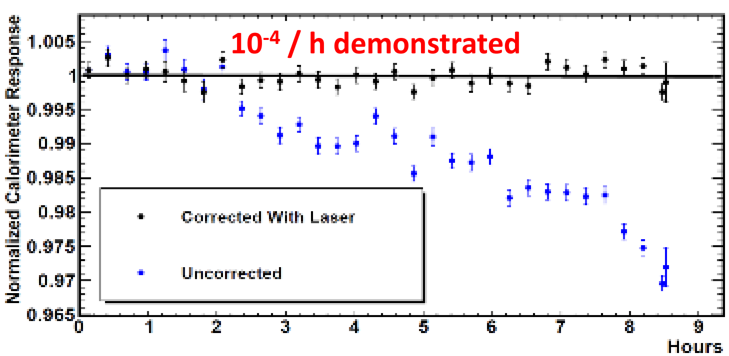
Calorimeter gain stability established to ~ few x 10^{-4}

Vital to ensure stability of the calorimeter response in order to avoid introducing varying acceptance as a function of time.

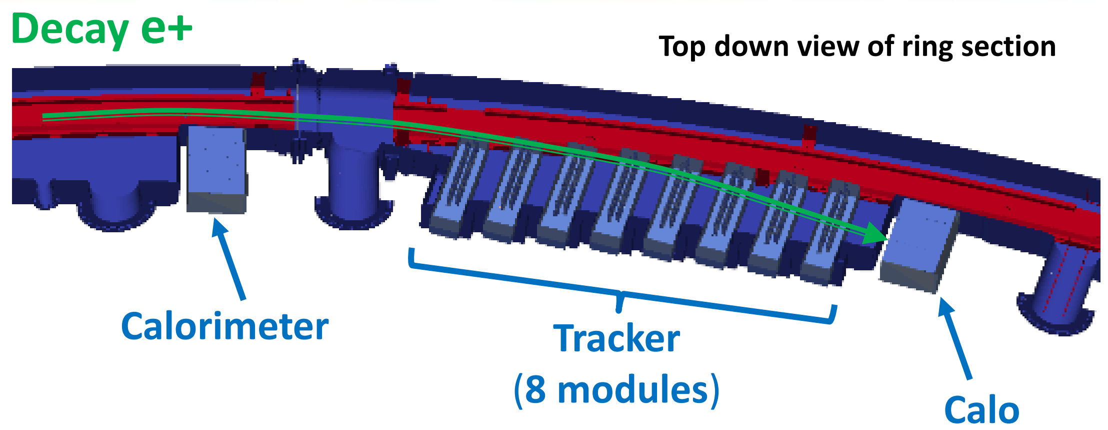
Achieved with a state-of-the-art laser-based calibration system.



Test Beam Data



Straw Trackers.

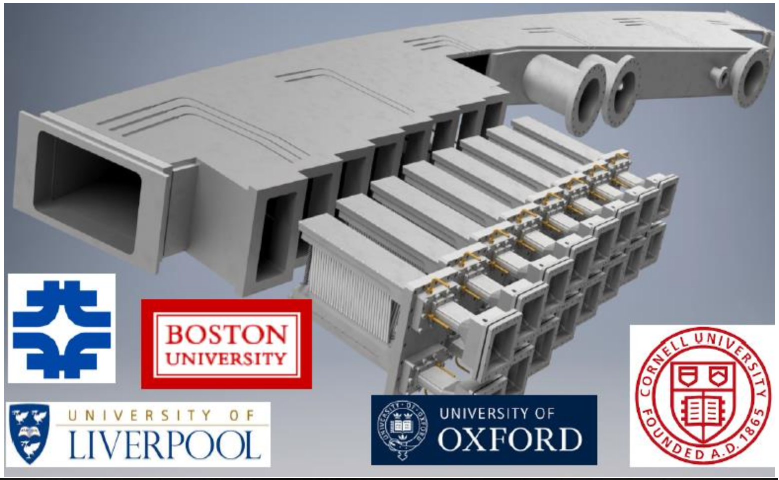


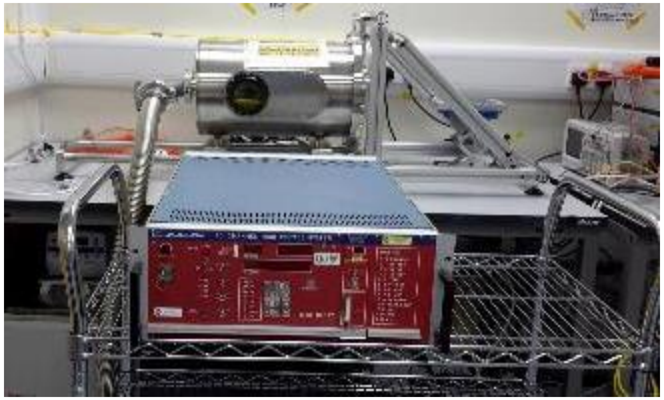
- Main tool for beam position measurements:
  - CBO frequency, envelope, amplitude vs muon momentum
  - Pitch correction
  - B-field convolution

- Provides complementary information to calorimeters:
  - Gain, efficiency, pile-up
  - E-field correction (both fast rotation and directly at late times)
  - Lost muon tagging

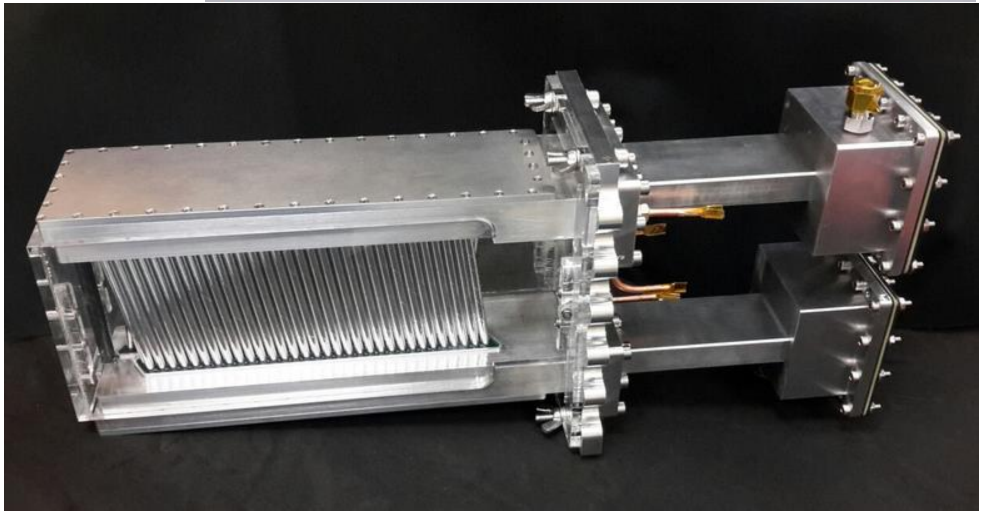
Straw Trackers.

3 Trackers were built in Liverpool for g-2.
Each consists of 8 4-layer Straw Modules.
Reconstruct trajectory and momentum of positrons from muon decays.
Determine the muon decay point to reduce systematic errors on muon g-2 measurement.
Tracker based muon EDM measurement.





Vacuum Tank + HV for Module Testing In Liverpool prior to shipping to FNAL.



4 layers of 32 straws, 7.5° stereo angle

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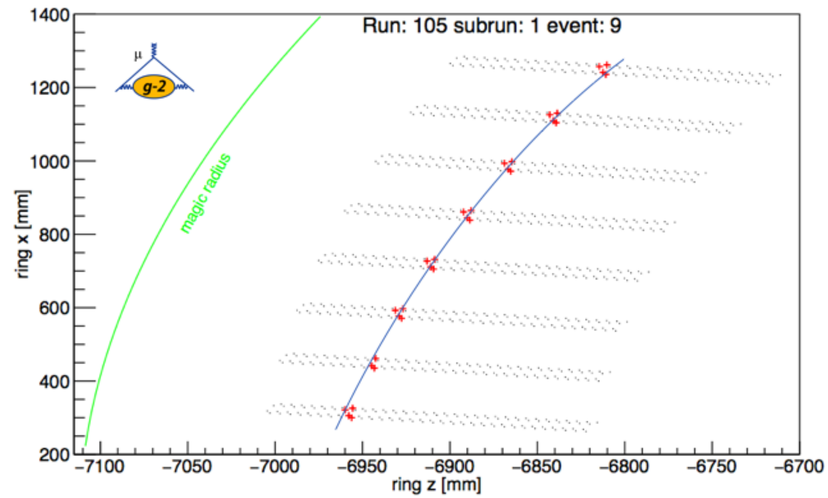
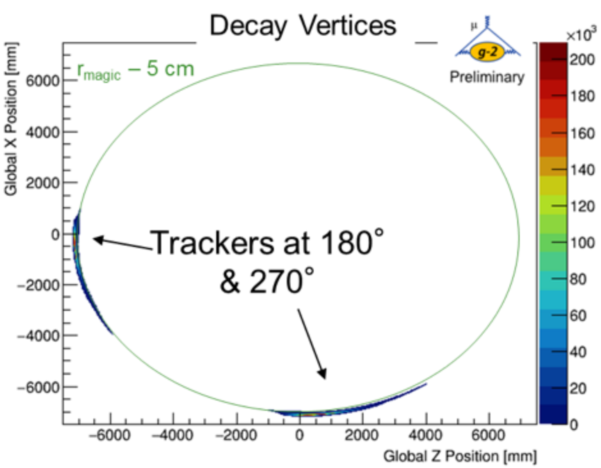
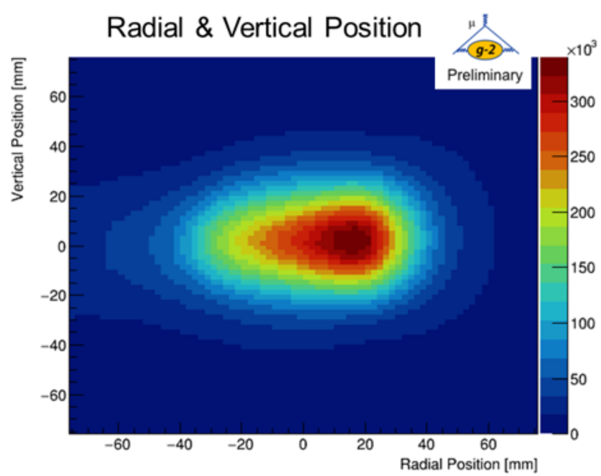
Straw Trackers.

Muon's-eye view inside vacuum chamber





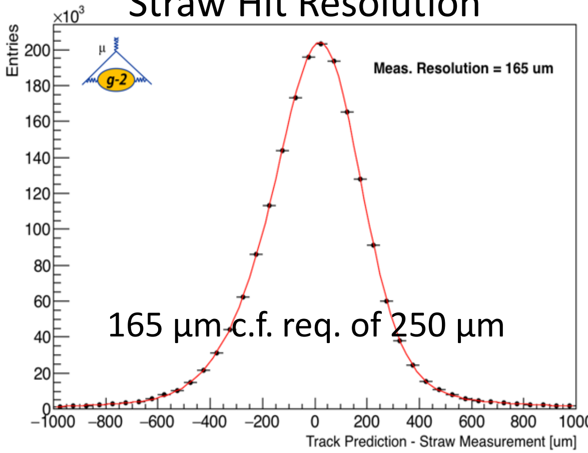


Beam profile is calculated in real time and available during data taking.

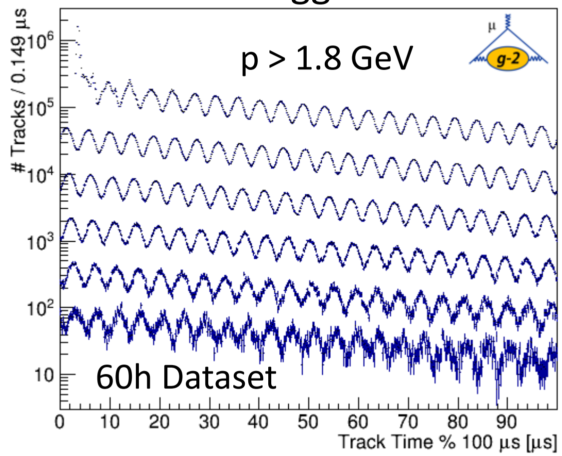
Straw Trackers.

- **Track finding & fitting work well:**

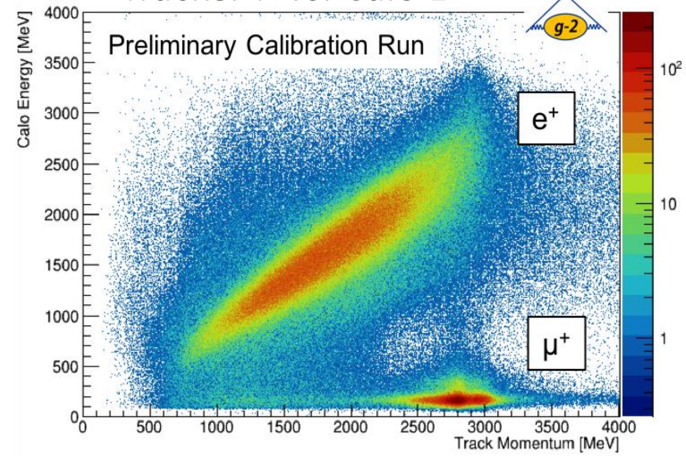
Straw Hit Resolution



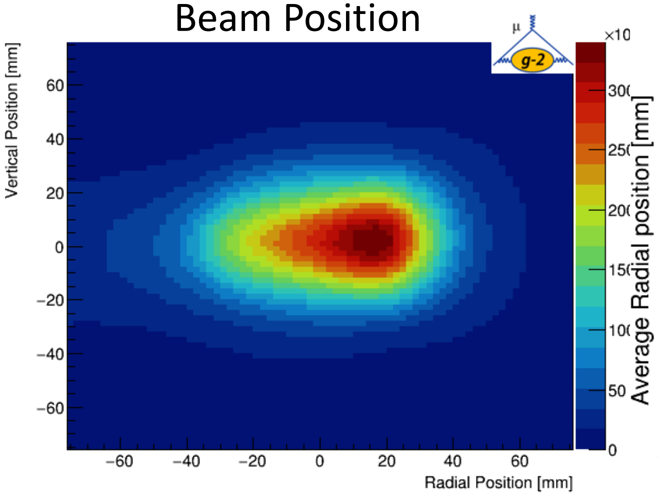
Tracker Wiggle Plot



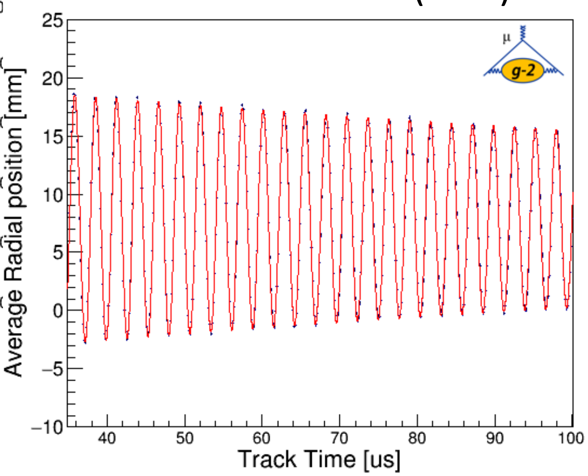
Tracker P vs. Calo E



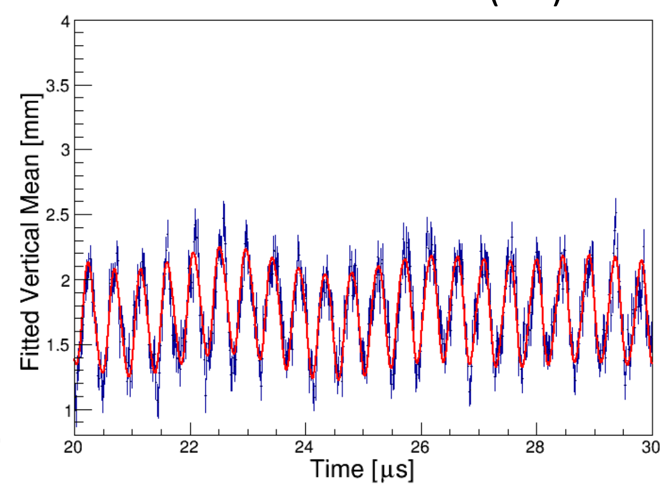
Beam Position



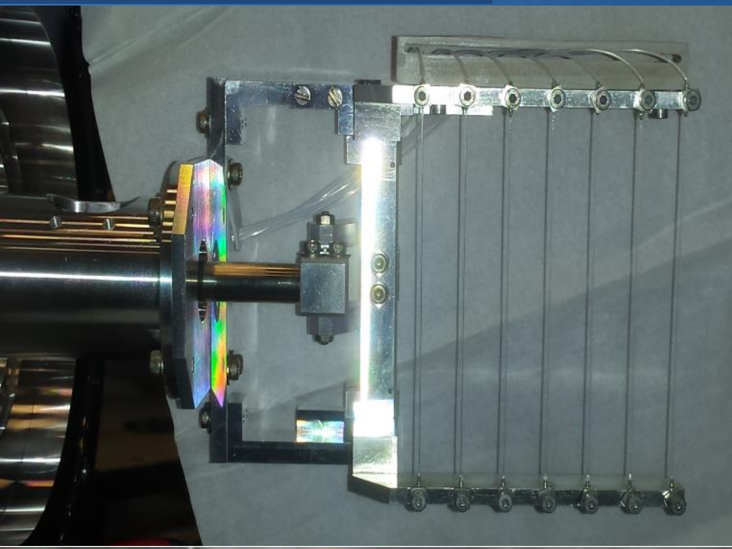
Radial Mean vs Time (CBO)



Vertical Mean vs Time (BO)



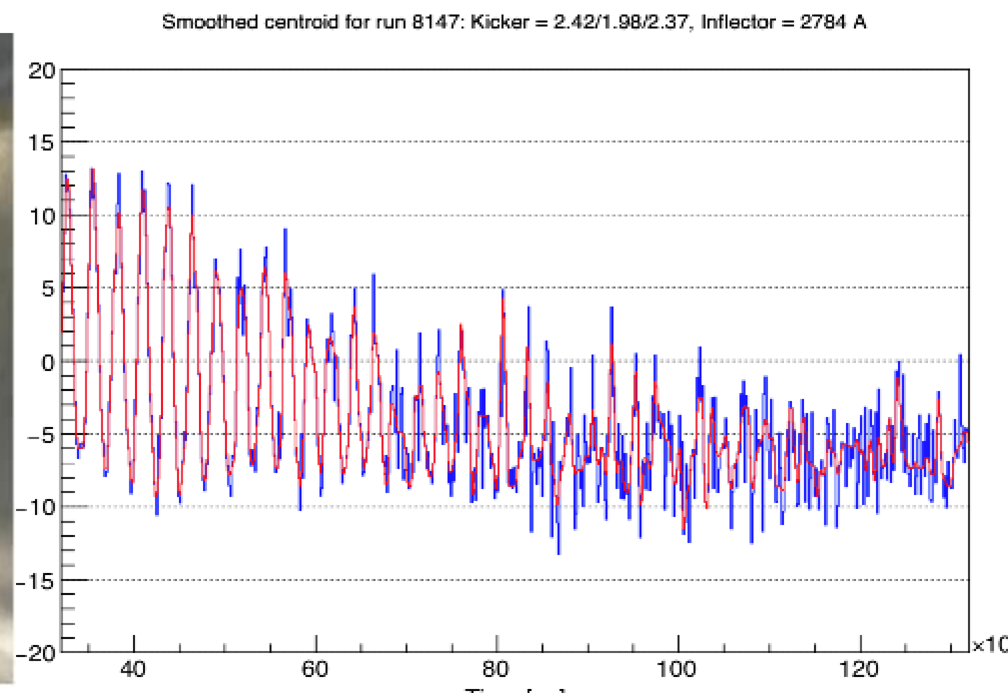
Fibre Harps also measure the beam profile.



Consist of 7 parallel scintillating fibres at 180 and 270 degrees around the ring.

Horizontal and vertical detectors to measure radial and vertical beam profile.

Retractable since they interfere with the muon beam during normal data taking.



Achieving highly uniform magnetic field.

The magnet completed its epic journey from Brookhaven to Fermilab in 2014.
It was then reassembled and on initial turn on had a field non-uniformity of ~1400 ppm.
Then began a period of magnet shimming that culminated in a uniformity of ~25 ppm by Sept 2016.

First stage of shimming: pole surface adjustments

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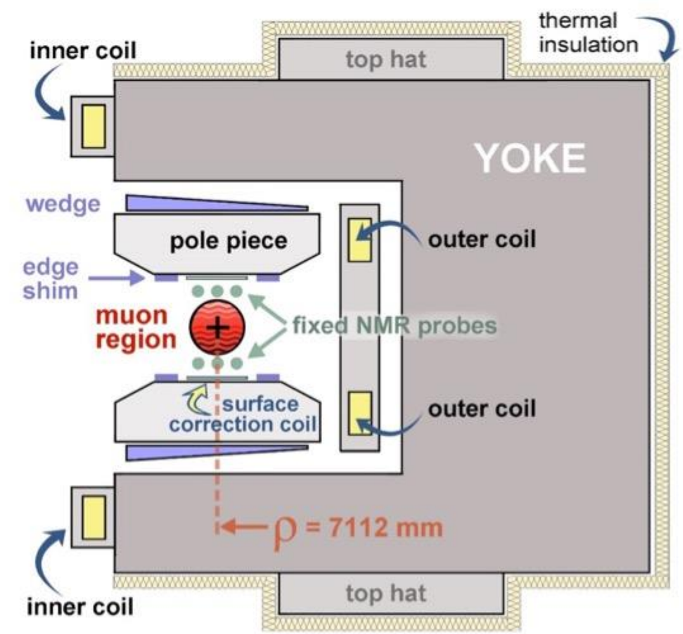
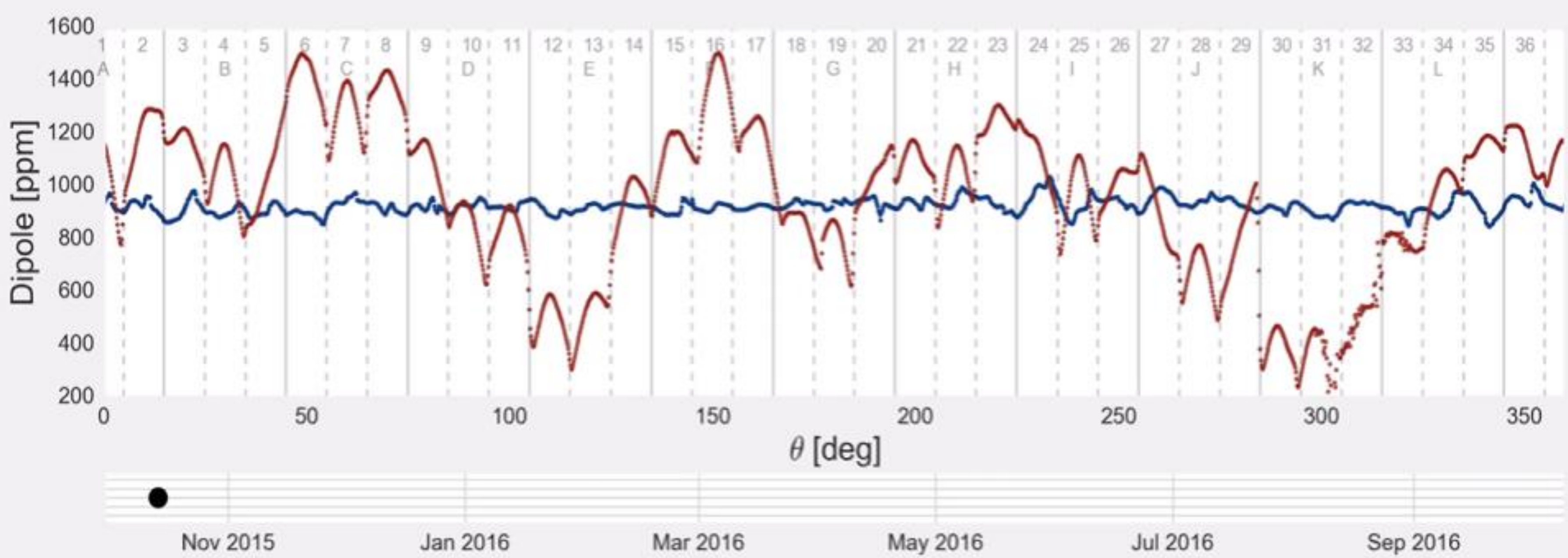
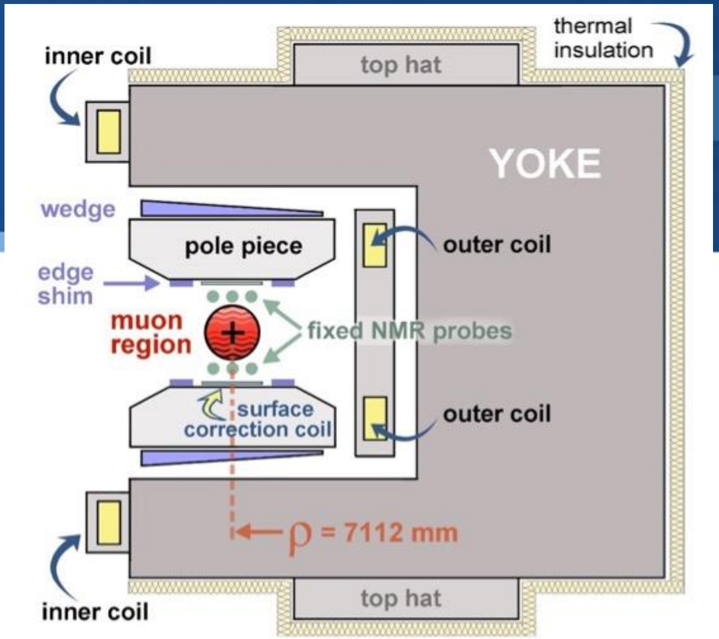
- **Blue was shimmed field at Brookhaven**
- **Red was starting point at Fermilab**



g-2 Magnet in Cross Section

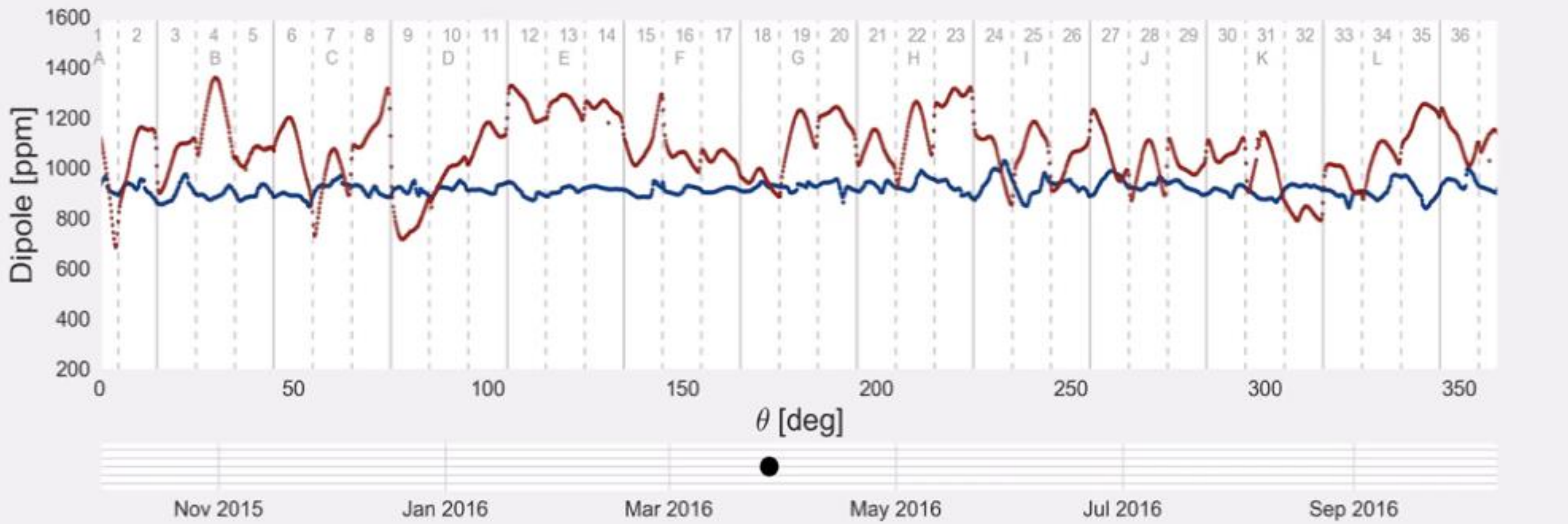


Next: "top hats" and wedge shims



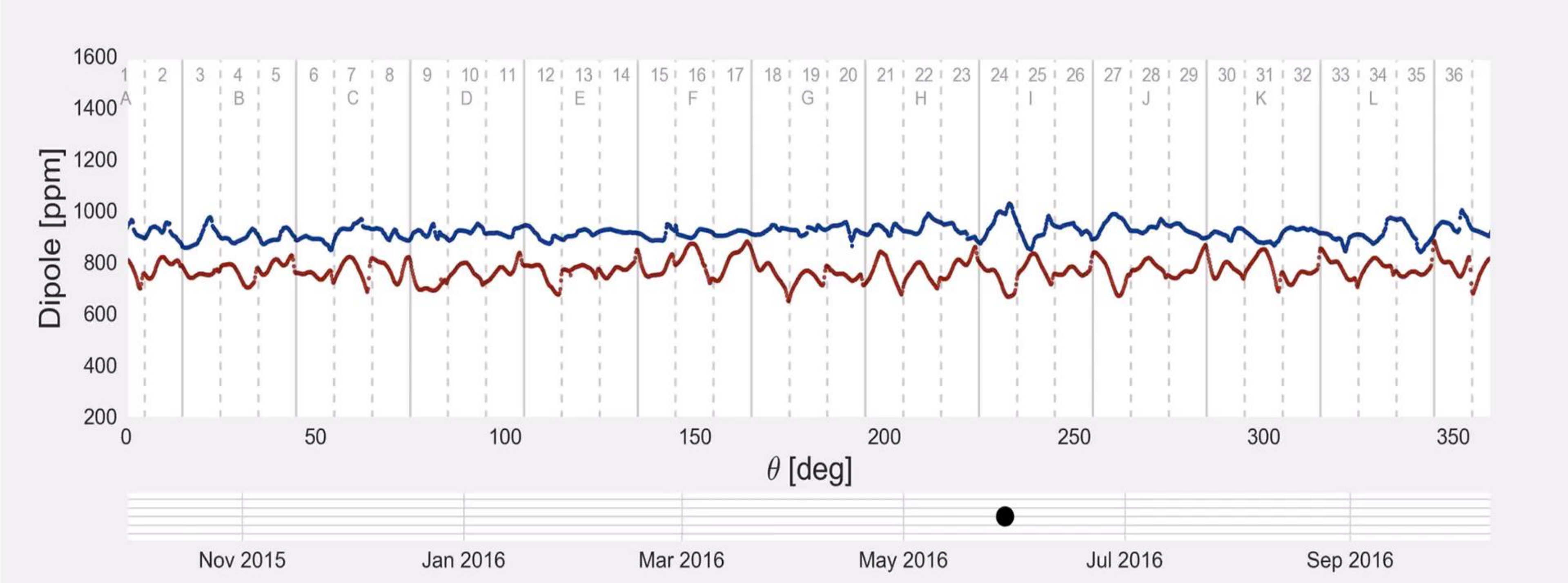
g-2 Magnet in Cross Section

Blue: Brookhaven **Red: Fermilab**



leaving azimuthal uniformity comparable to Brookhaven.

Blue: Brookhaven **Red: Fermilab**



Final step: iron foil laminations

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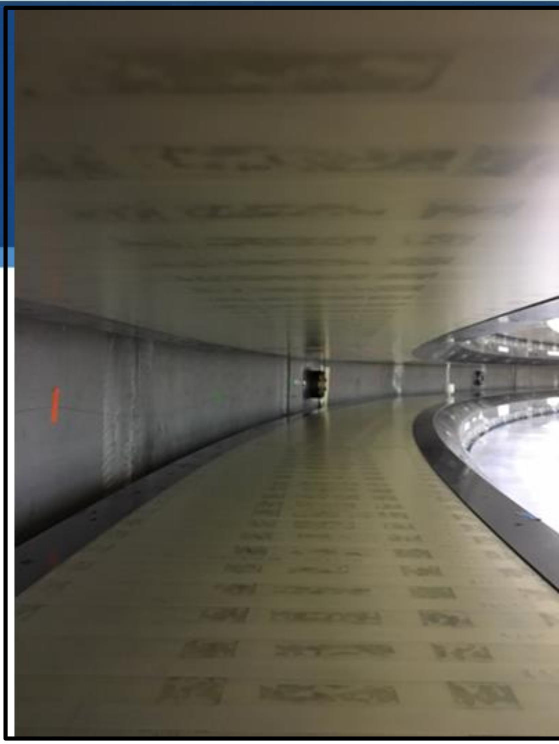
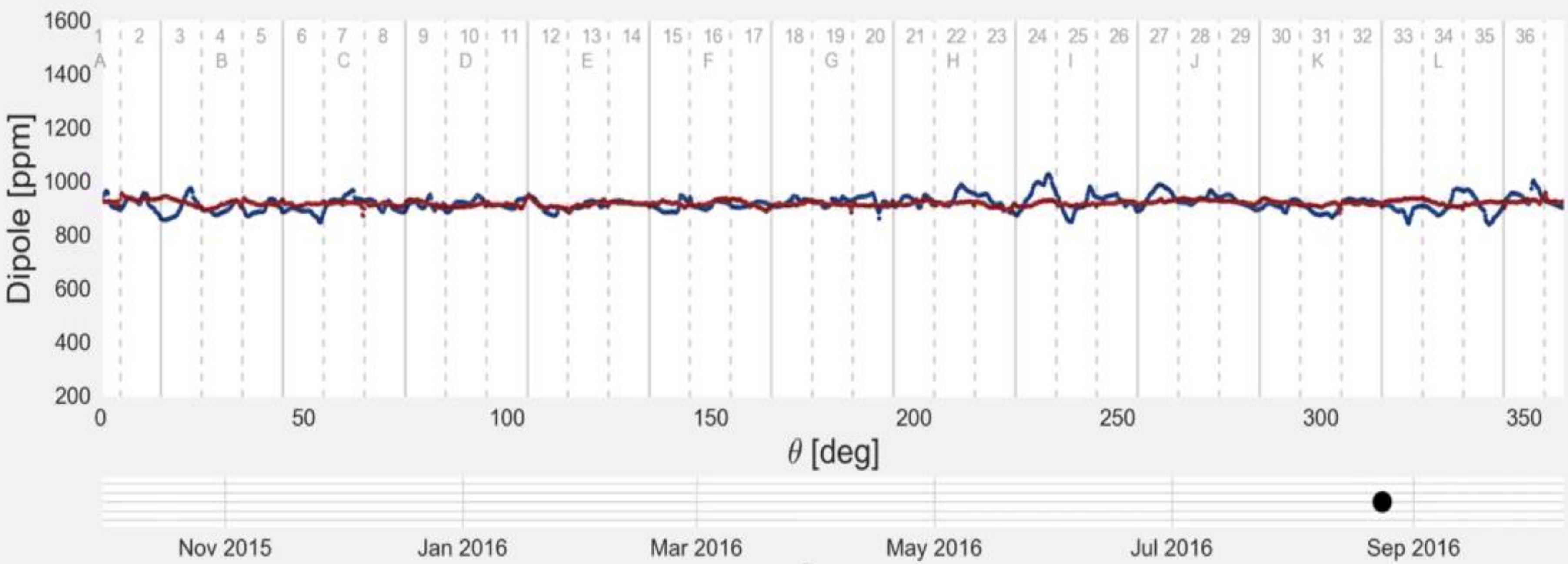


Blue: Brookhaven **Red: Fermilab**



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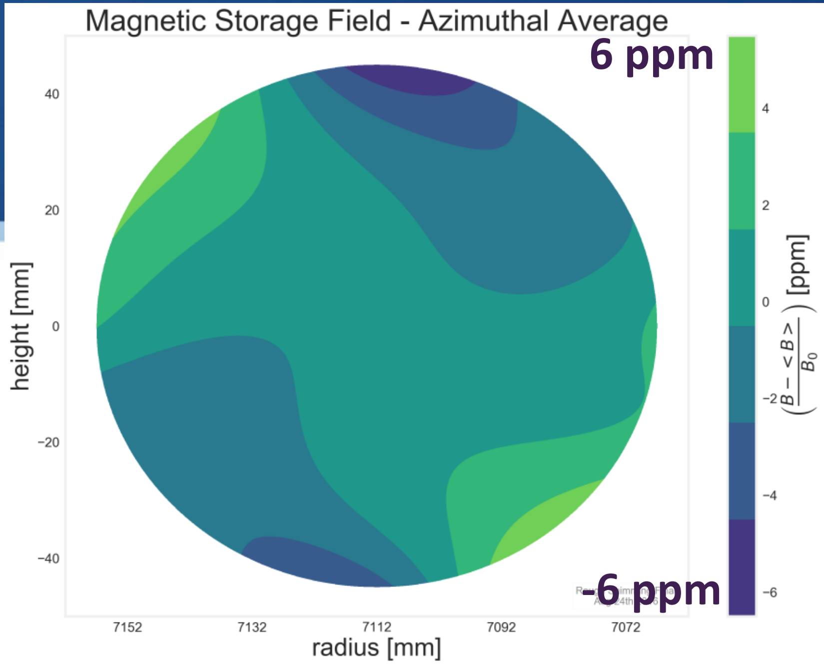
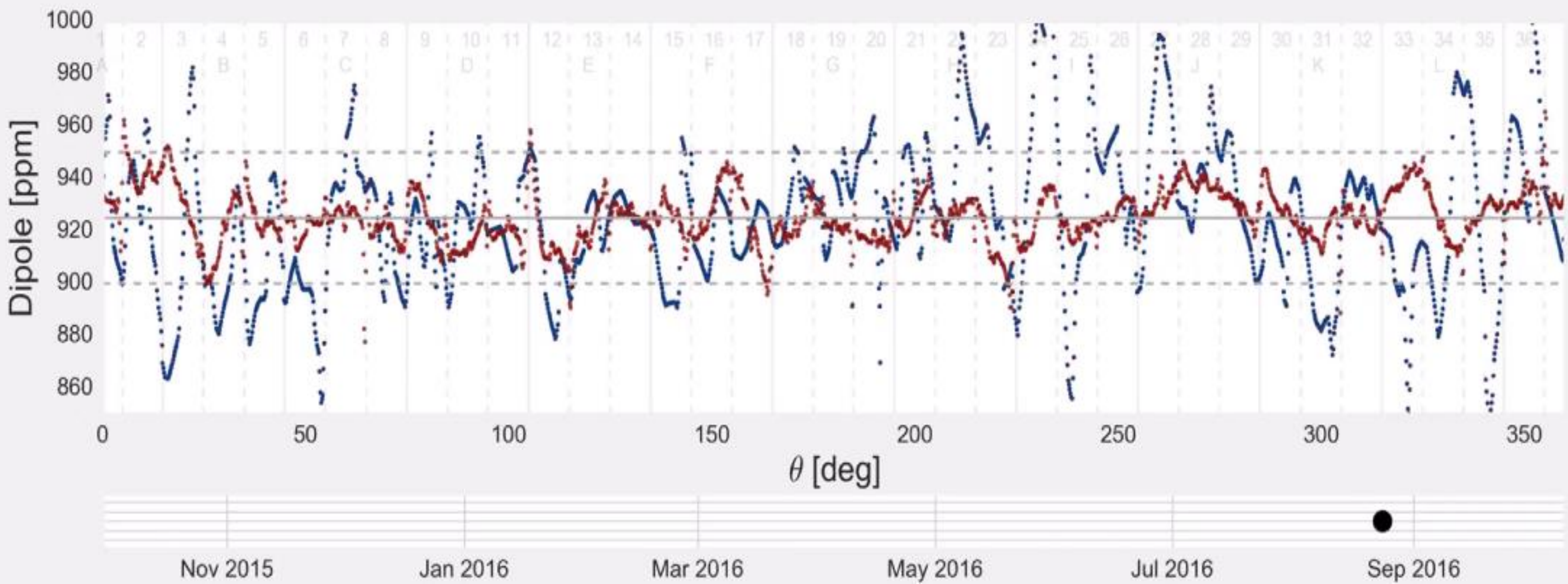


requiring a different scale for the graph.

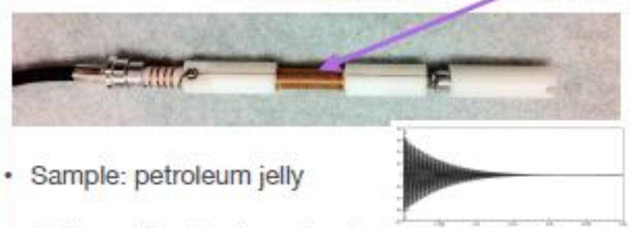
8000 iron shims inserted to achieve a uniformity of +/- 25ppm. (Sept 2016).

Blue: Brookhaven   Red: Fermilab

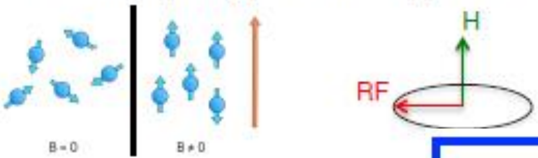


Magnetic Field measured with NMR.

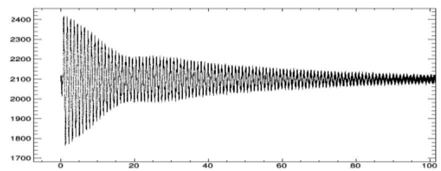
Pulsed NMR



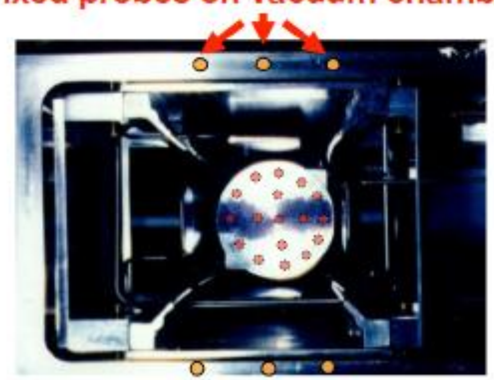
- Sample: petroleum jelly
- Deliver π/2 pulse to probe, induce & record the free-induction decay (FID)
- Extracted frequency precision: 10 ppb/FID



Free-proton spin precession frequency ω_p



Fixed probes on vacuum chambers

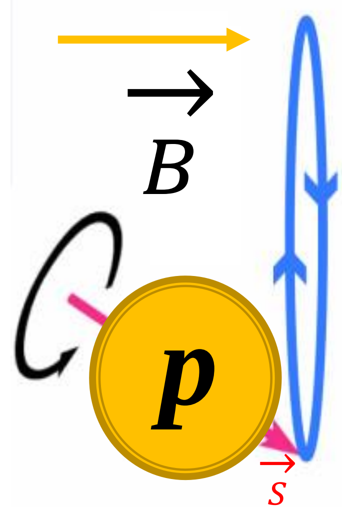


- Measure field while muons are in ring
  — 378 probes **outside** storage region

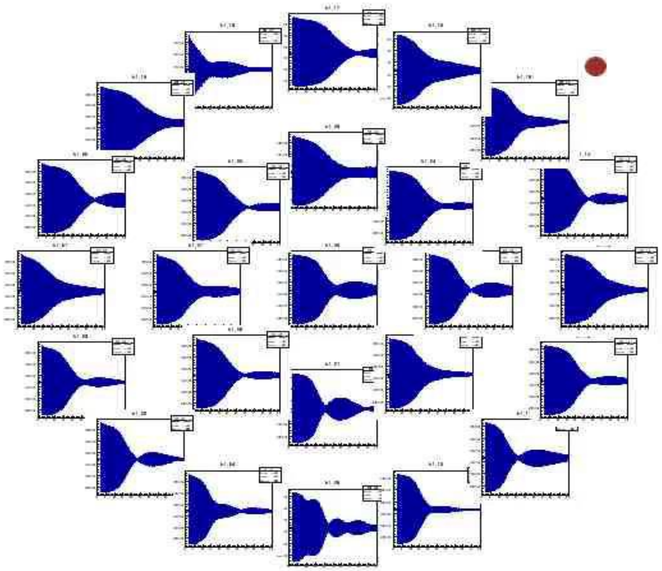
Trolley matrix of 17 NMR probes

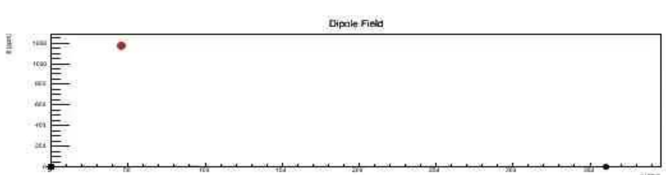
- Measure field in storage region during **specialized runs** when **muons are not being stored**
- Map the field every 3–4 days

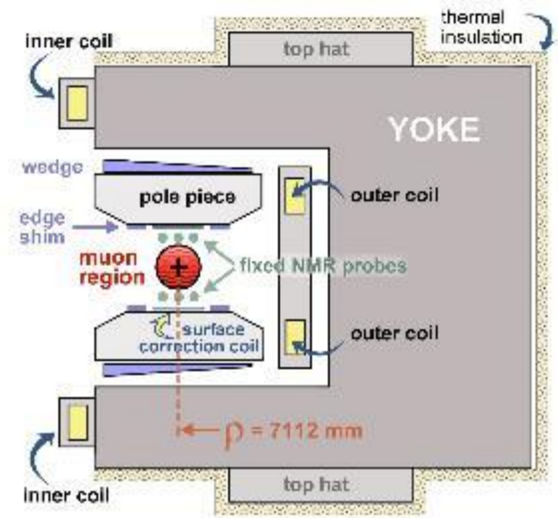
Trolley can be pulled around storage ring when beam is not being delivered.



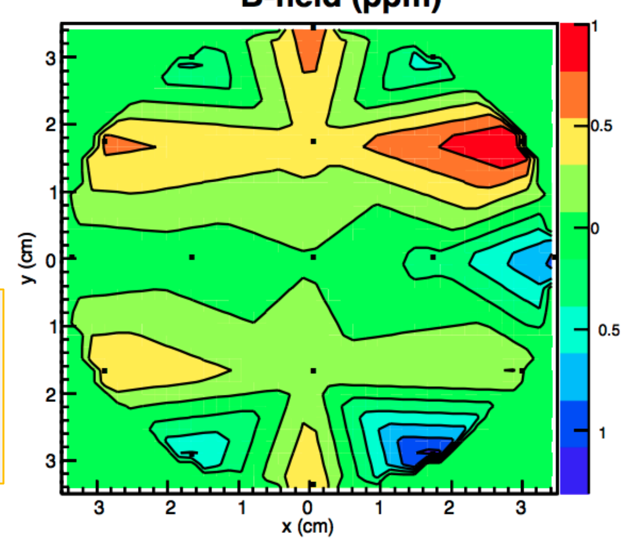
Magnetic Field Determination.







g-2 Magnet in Cross Section



	Norm	Skew
Quad	-0.19	0.28
Sext	0.05	0.27
Octu	-0.07	0.25
Decu	0.23	0.07

Field map from March 2018 (averaged over azimuth)
Good to 1 ppm.

Determination of B field actually seen by the muon beam.

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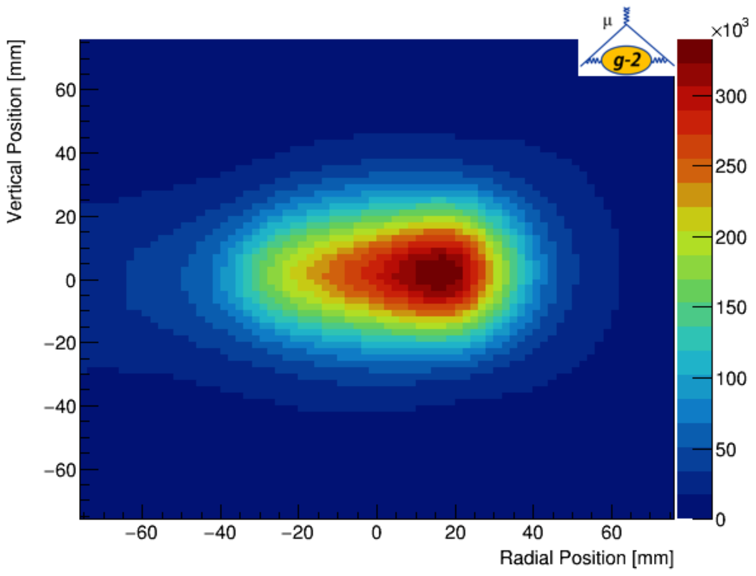
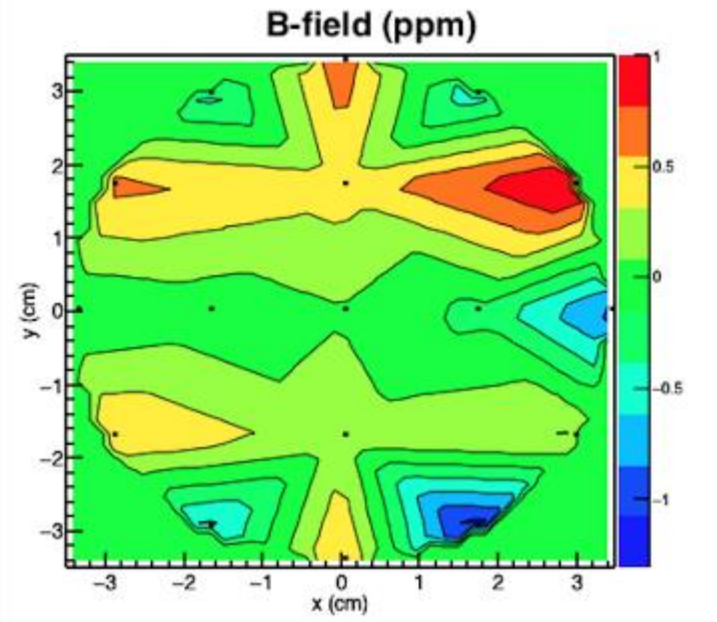
Obtain the muon beam distribution from the Straw Trackers.



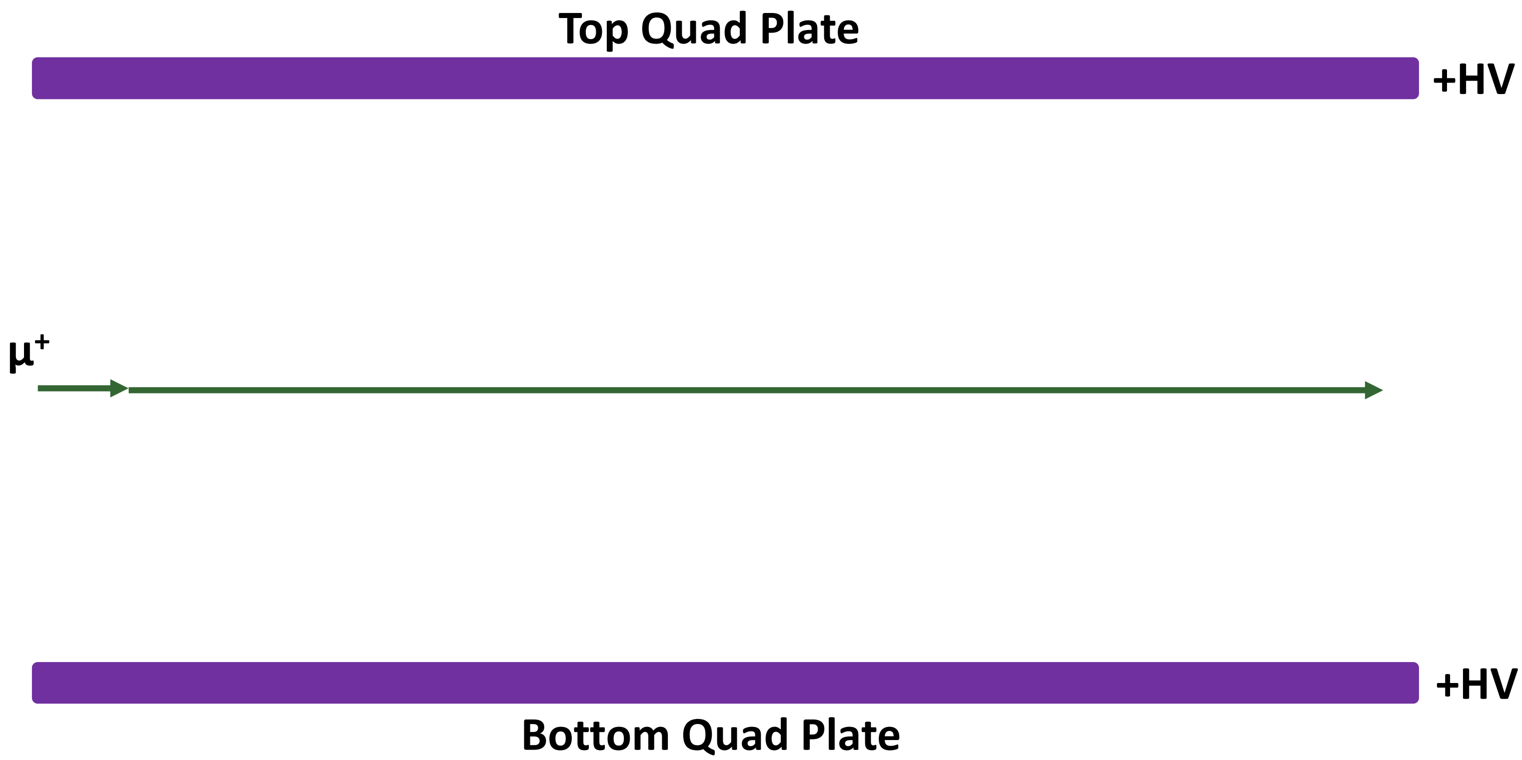
Obtain the B field from NMR measurement probes.



Combine to obtain the actual magnetic field experienced by the muons.

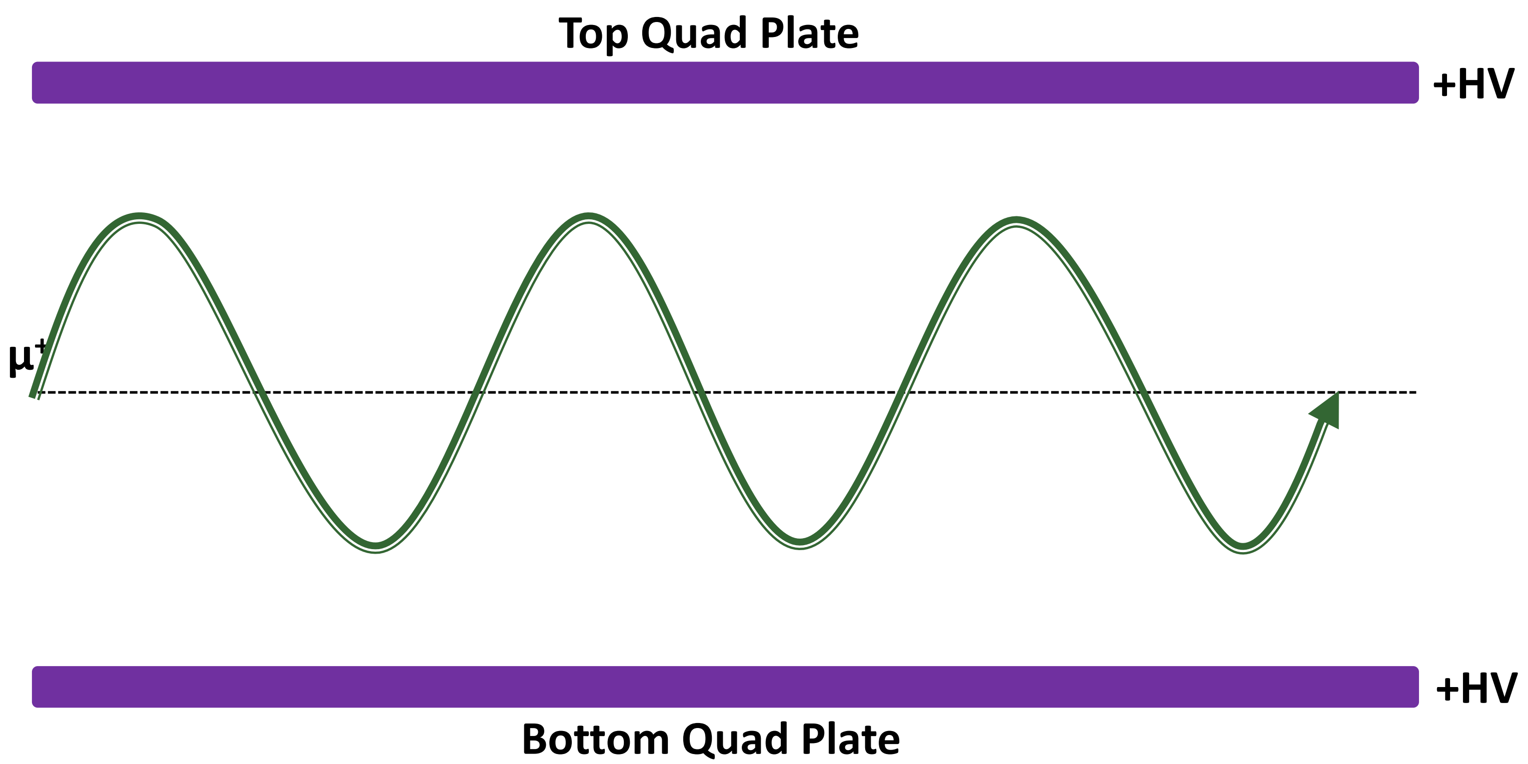
Example of an ω_a systematic: Betatron Oscillations.

- Imagine that we could inject all our muons into the ring at y = 0 with no vertical momentum at all
- The muon stays perfectly horizontal until it decays:



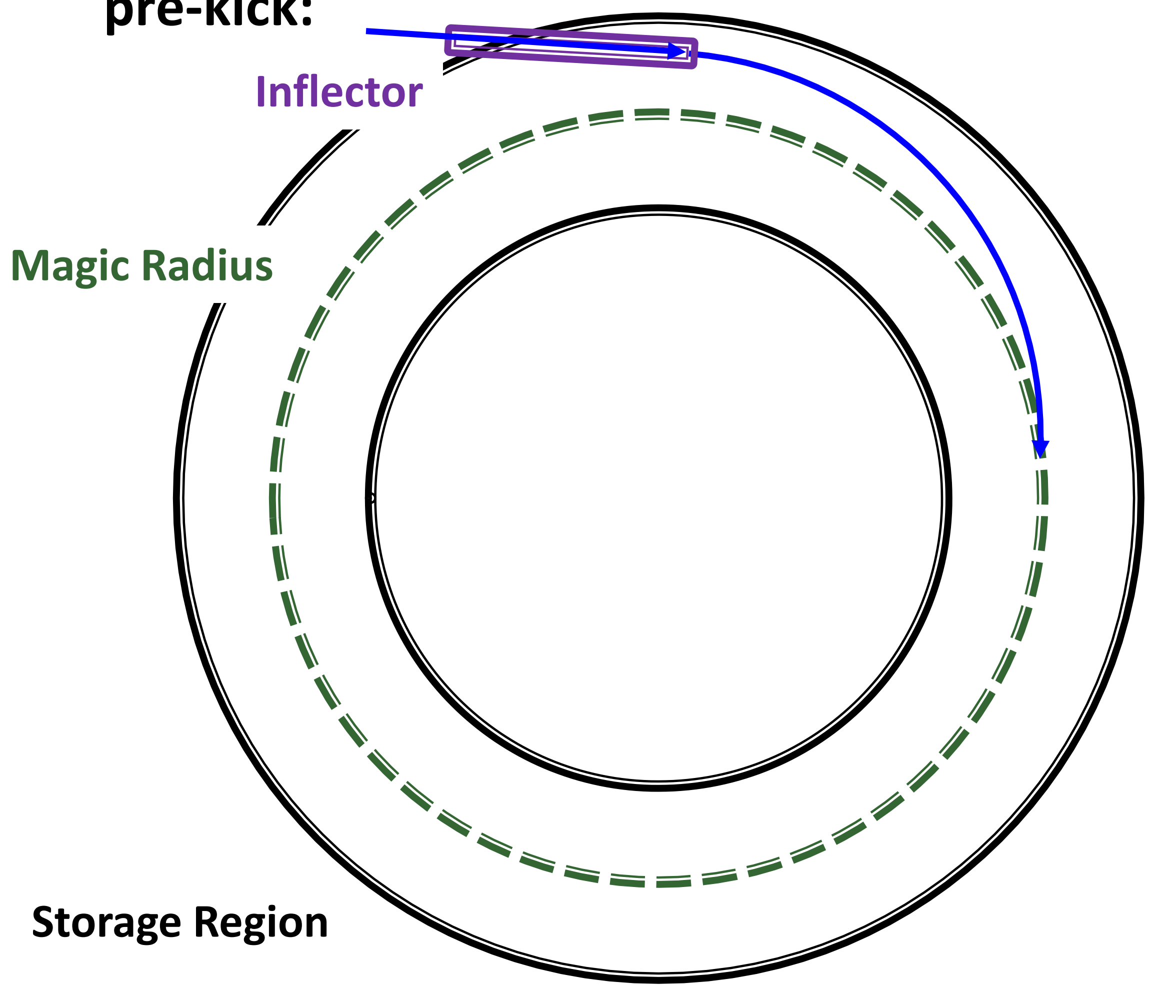
Vertical Betatron Oscillations:

- If we inject with a non-zero vertical momentum, the particle will oscillate due to the restoring force from the quad field
- Amplitude is related to incoming direction (momentum)



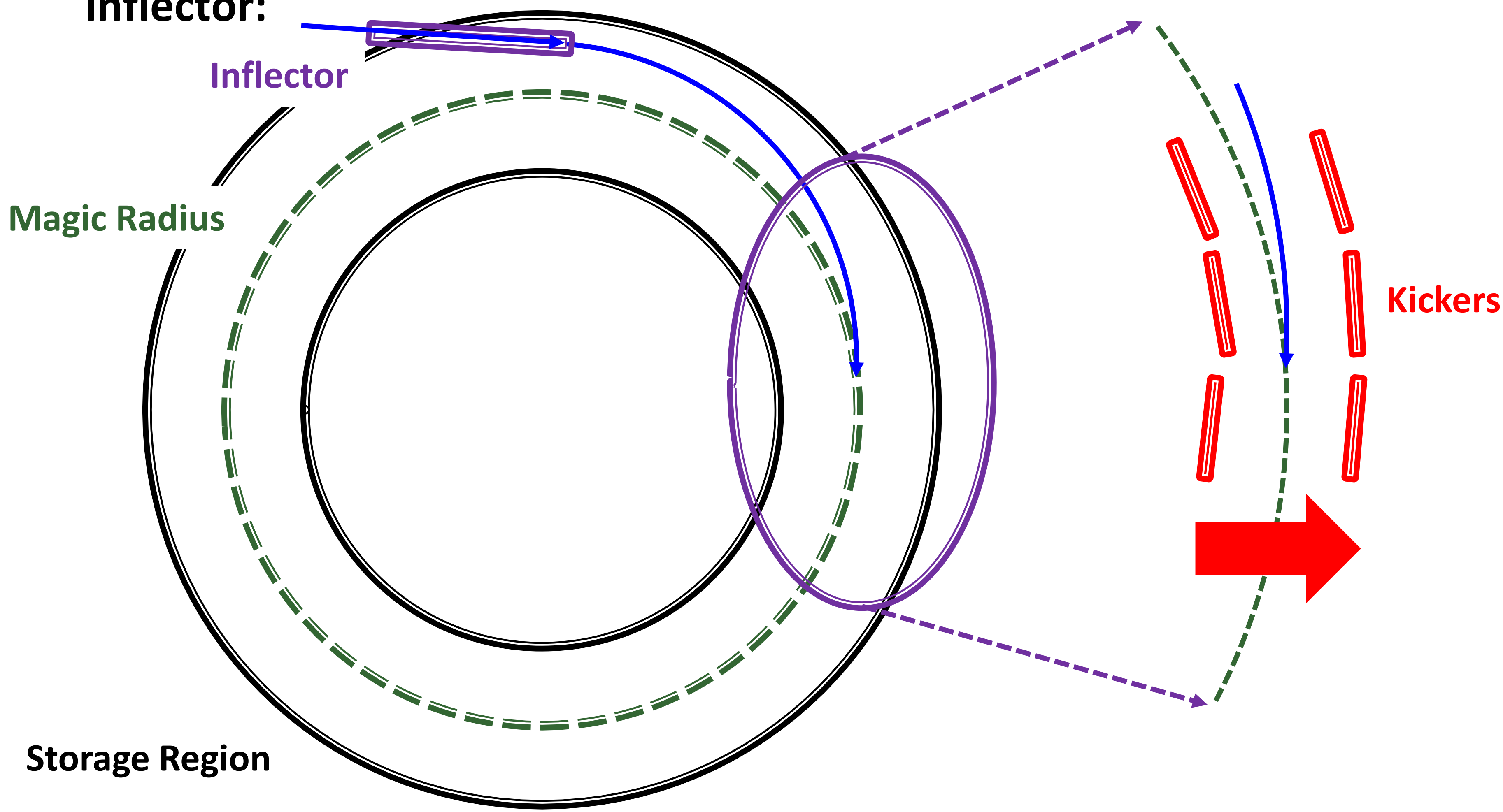
Betatron Oscillations: Radial Case

- Radial case is a bit more complicated. Start with a horizontal muon pre-kick:



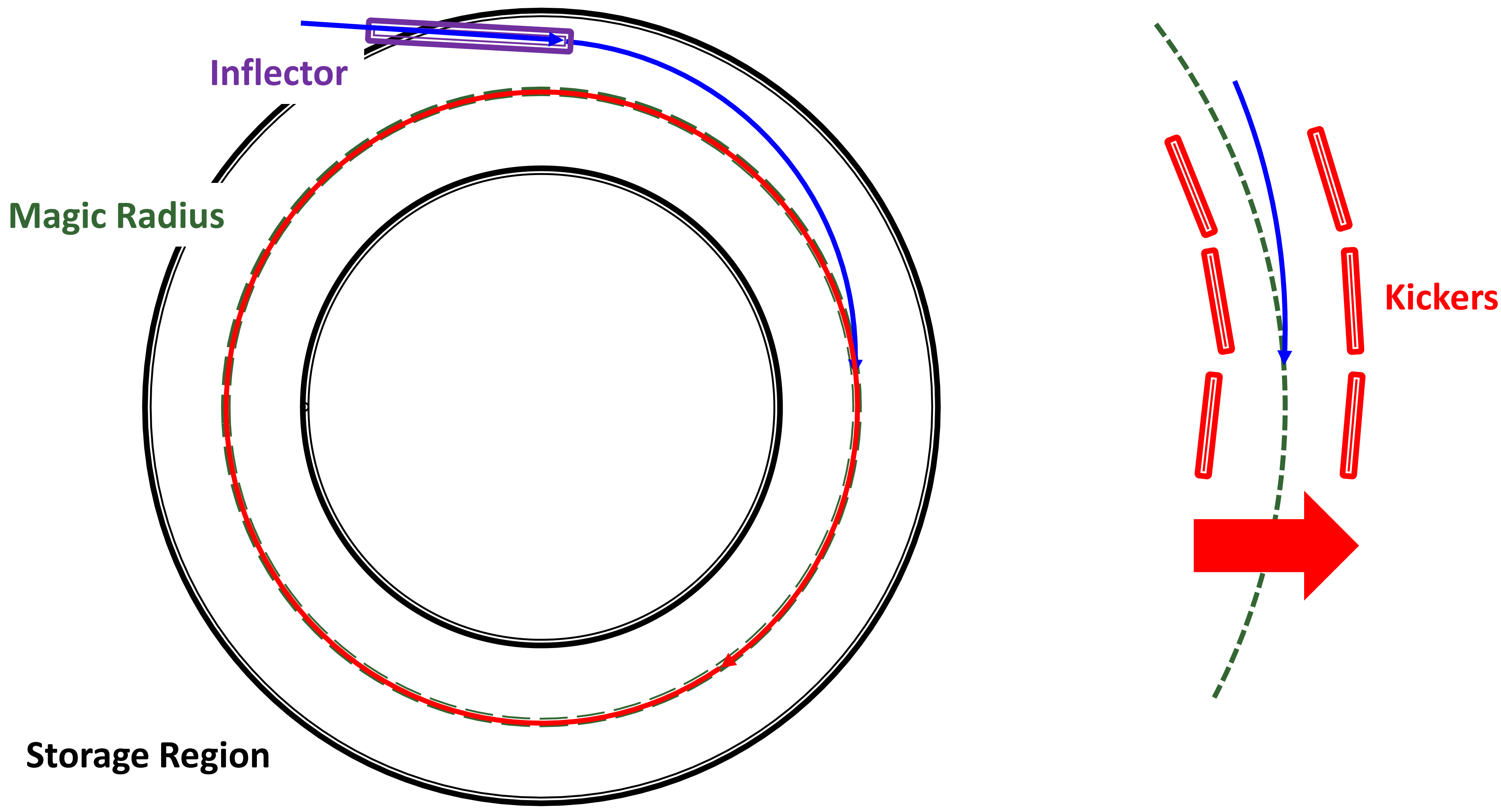
Betatron Oscillations: Radial Case

- We need to kick the particle to stop it coming back round into the inflector:



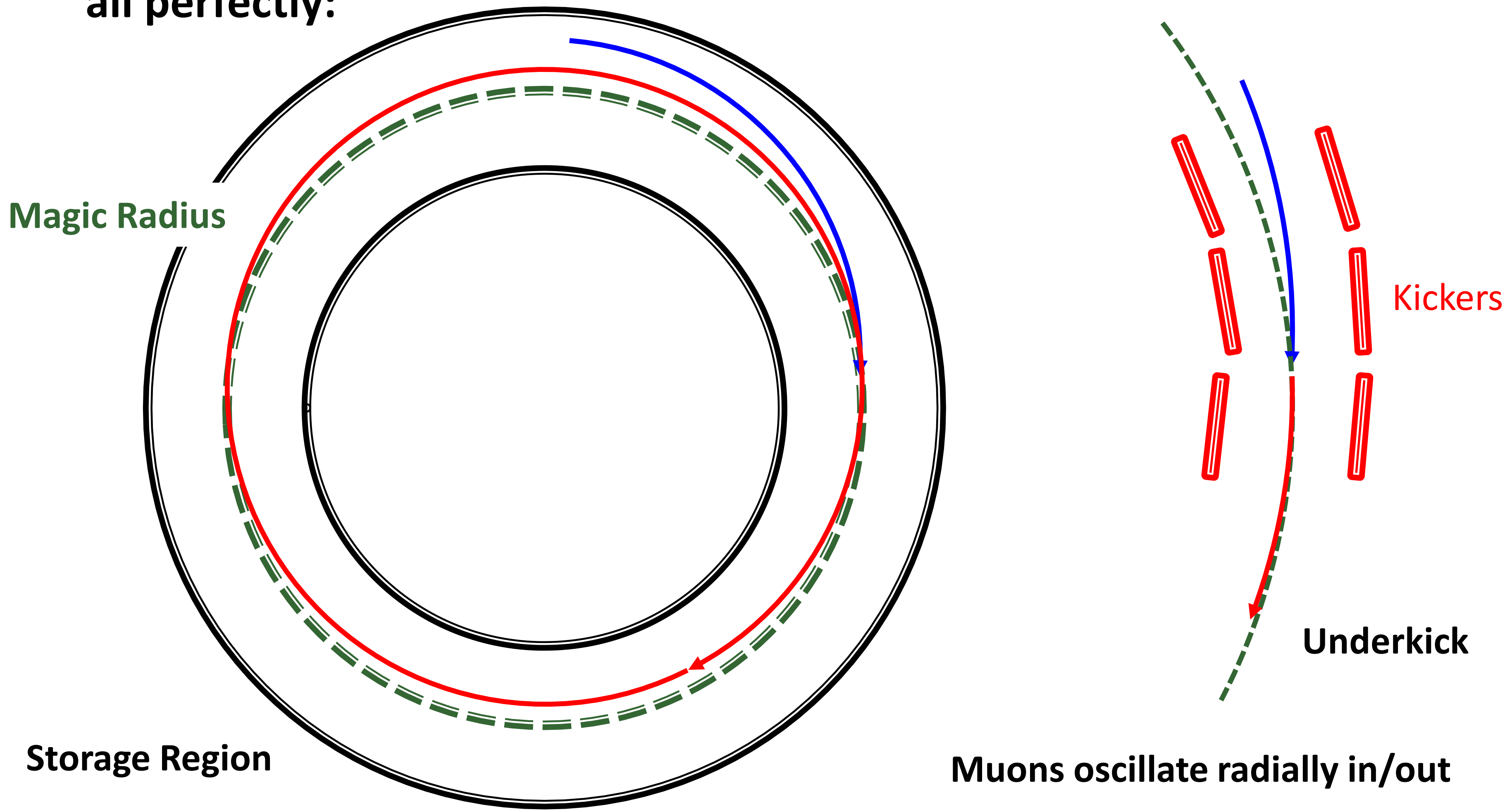
Betatron Oscillations: Radial Case

- If kick is perfect, we end up on the magic orbit with no radial motion:



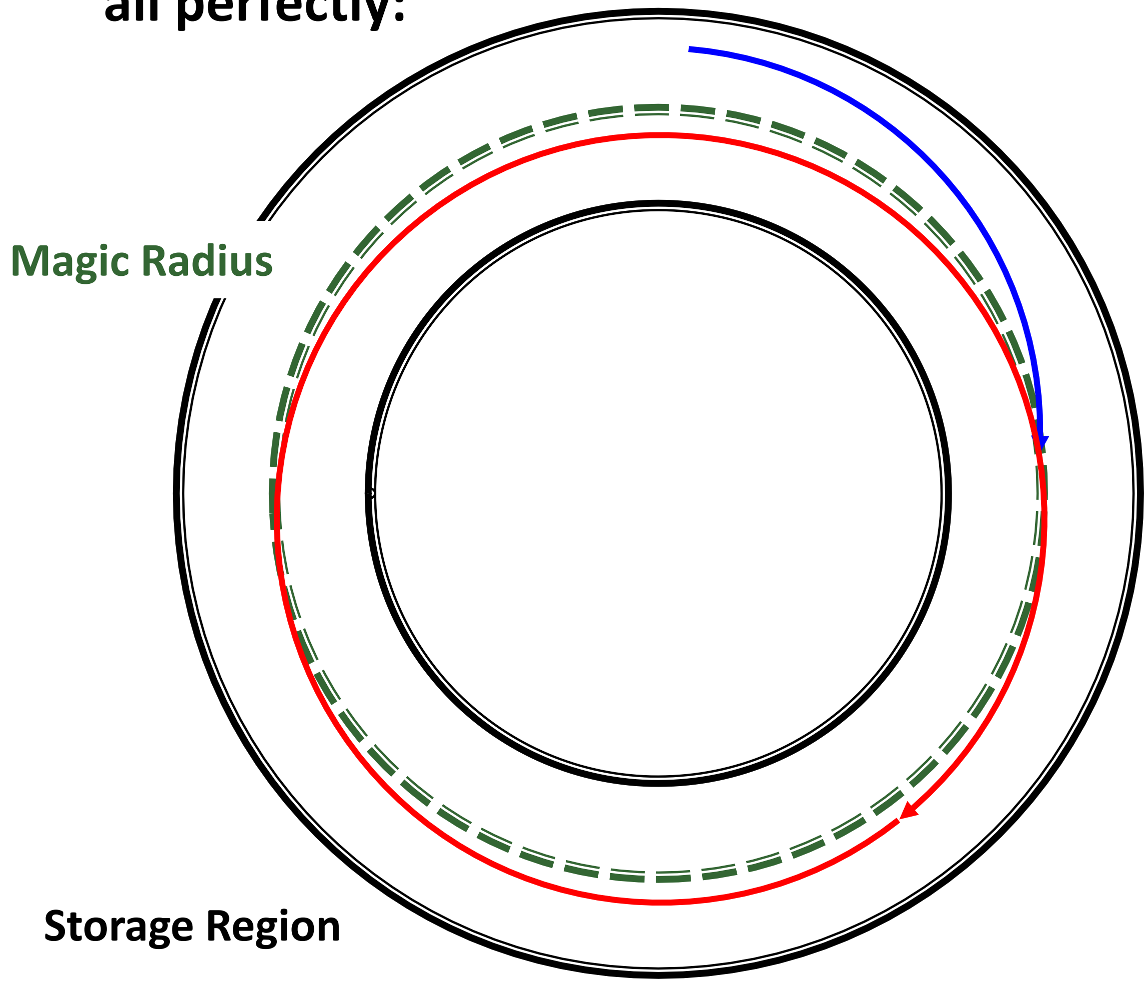
Betatron Oscillations: Radial Case

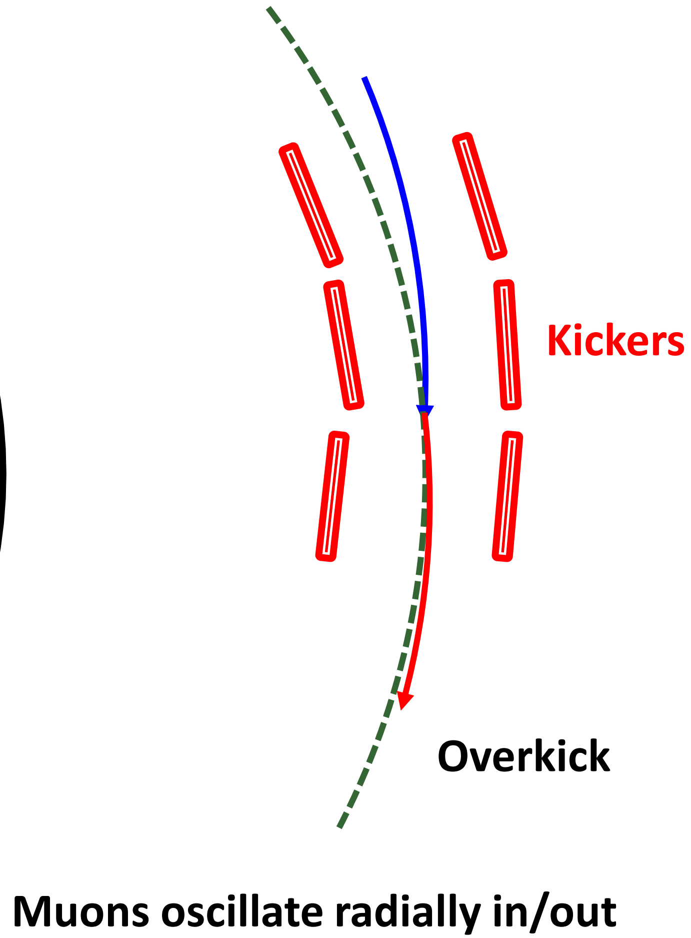
- But we have many muon directions/momenta and we can't kick them all perfectly:



Betatron Oscillations: Radial Case

- But we have many muon directions/momenta and we can't kick them all perfectly:





What is CBO?

- **C**oherent **B**etatron **O**scillation – movement of all muons together
- Muons all started at **similar position** (as they came through inflector)
- They have **same betatron frequency**, so there's a coherent movement back and forth on average
- **Smeared out** by **different kicks** that each particle gets
- This is **washed out** over time due to the different **cyclotron frequencies** of different momenta (as with fast rotation)
- This is caused by both imperfect kick and because we can't fill entire phase-space of ring at injection

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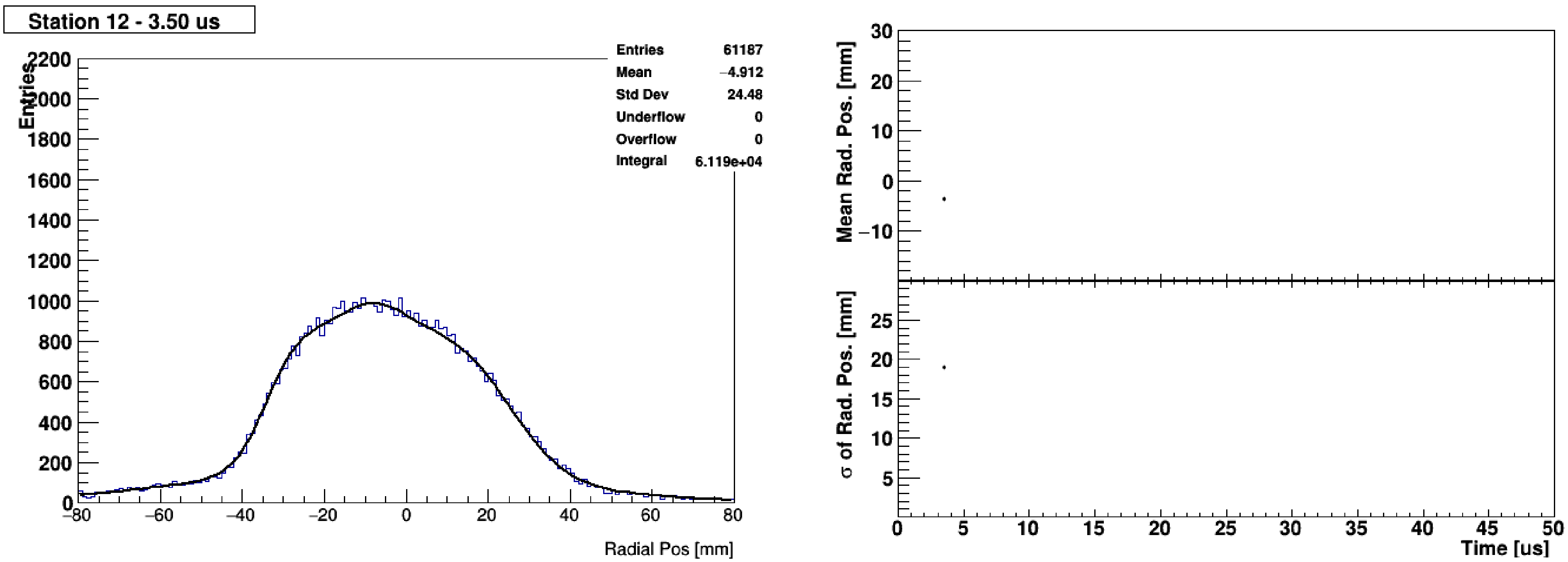
But does this really happen?

- Yes! Here's some data showing the radial CBO in a tracker:



Why do we care? We will see that the wiggle plot is affected.

The data so far.

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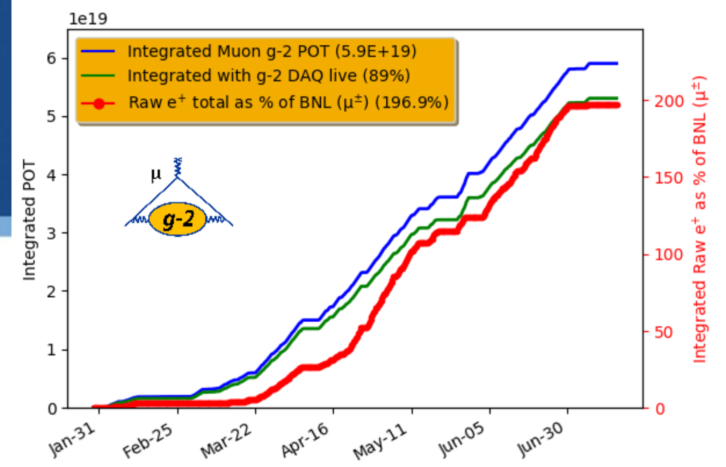
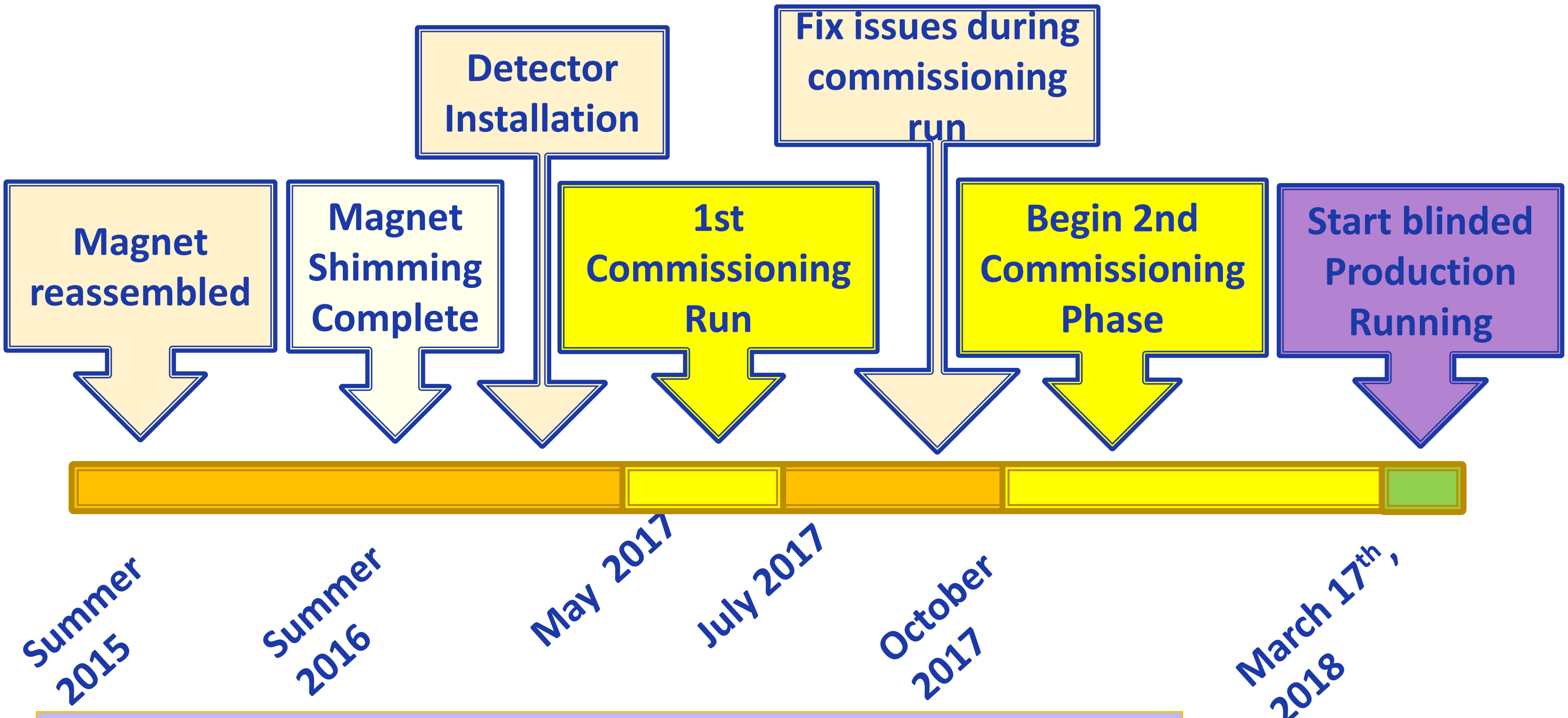


The recent physics run ended on July 7th.

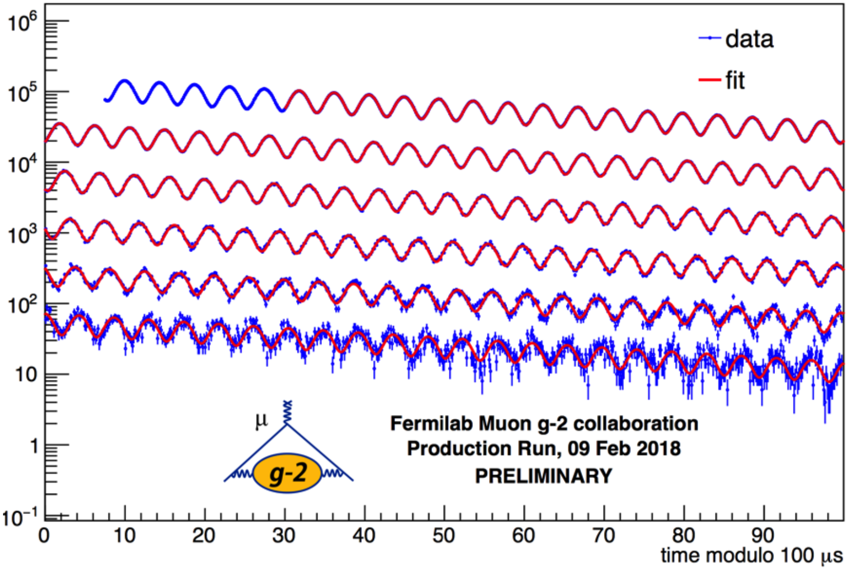


Approximately twice the BNL dataset collected.

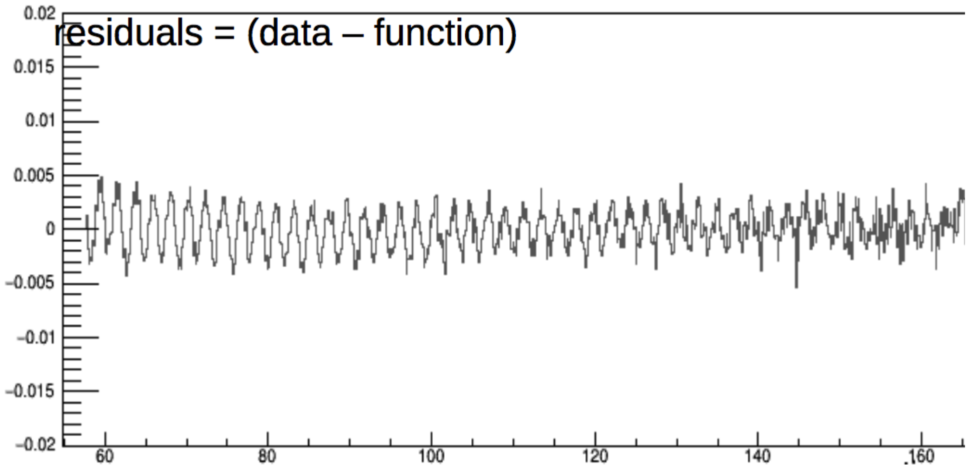
Measurement of ω_a

In principle, we perform a 5 parameter fit to the wiggle plot to extract ω_a. The analysis is blinded – I don't know the result!

$$dN/dt = N_0(t)e^{-\frac{t}{\tau}}\left[1 + A(t)\cos(\omega_a t + \phi_a(t))\right]$$



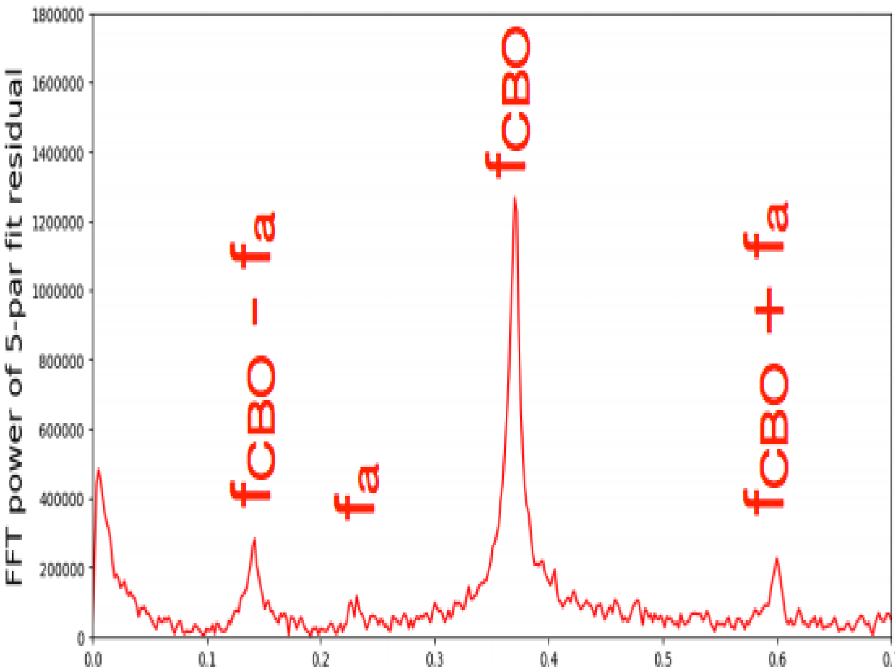
Residuals to the fit highlight the effects of systematics such as the CBO discussed earlier.



Why do we care about CBO and other systematics?

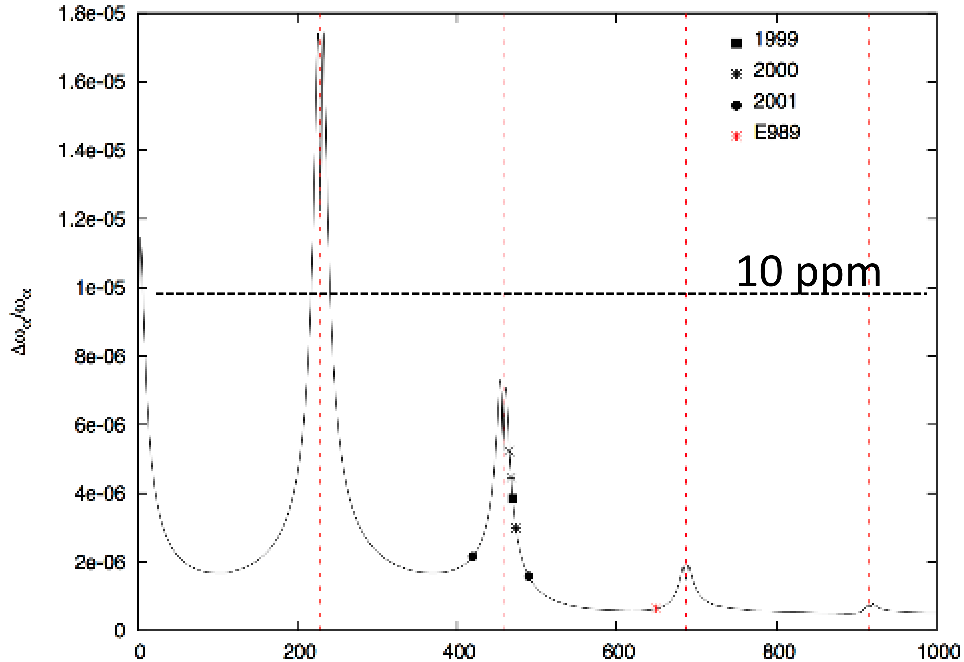
- Fraction of decay e^+ at detectors (acceptance) changes with CBO affecting A(t) term. (Instability in the calorimeter gain would as well.)
- This shows up the wiggle plot and pulls our result for ω_a:

FFT of Residuals to 5-par fit



Frequency (MHz)

$\Delta\omega_a$ if CBO uncorrected



CBO Frequency (kHz)

55

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Why are Early/Late effects important?

Anything leading to early/late variations in $A(t)$ and $\phi(t)$ have to be kept under control as they lead to a pull on ω_a

$$\cos(\omega_a t - \phi) = \cos\left[\omega_a t - \phi_0 - \frac{\mathrm{d}\phi}{\mathrm{d}t} t + \mathcal{O}(\frac{\mathrm{d}^2\phi}{\mathrm{d}t^2})\right]$$

$$= \cos\left[\left(\omega_a - \frac{\mathrm{d}\phi}{\mathrm{d}t}\right) t - \phi_0 + \mathcal{O}(\frac{\mathrm{d}^2\phi}{\mathrm{d}t^2})\right]$$

$$= \cos\left[\omega_a' t - \phi_0 + \mathcal{O}(\frac{\mathrm{d}^2\phi}{\mathrm{d}t^2})\right]$$

Things that might change f(t):

- Gain change.
- Pileup contamination (mixture of e+ having different average phases)
- Muon Loss with different average phases
- CBO (radial and vertical)
- Rate dependent energy and time reconstruction

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Modulation of N_0, A, ϕ with f_{cbo}

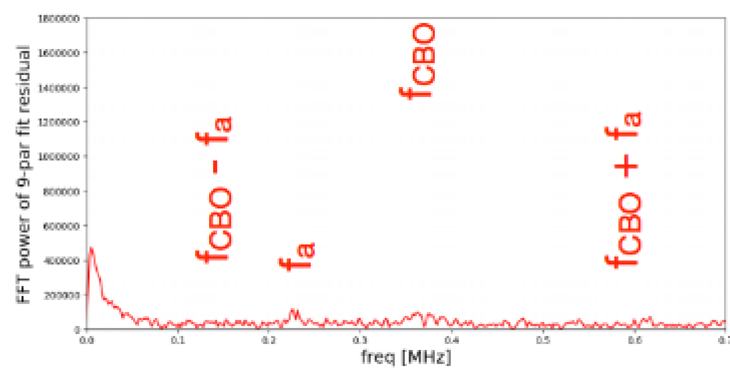
$$dN/dt = N_0(t)e^{-\frac{t}{\tau}}\left[1 + A(t)\cos\left(\omega_a t + \phi_a(t)\right)\right]$$

$$N_0(t) = N_0\left[1 + A_N e^{-\frac{t}{\tau_{cbo}}}\cos\left(2\pi f_{cbo}t + \phi_N\right)\right]$$

$$A(t) = A\left[1 + A_A e^{-\frac{t}{\tau_{cbo}}}\cos\left(2\pi f_{cbo}t + \phi_A\right)\right]$$

$$\phi_a(t) = \phi_a + A_\phi e^{-\frac{t}{\tau_{cbo}}}\cos\left(2\pi f_{cbo}t + \phi_\phi\right)$$

FFT of Fit Residuals including BCO in fit.



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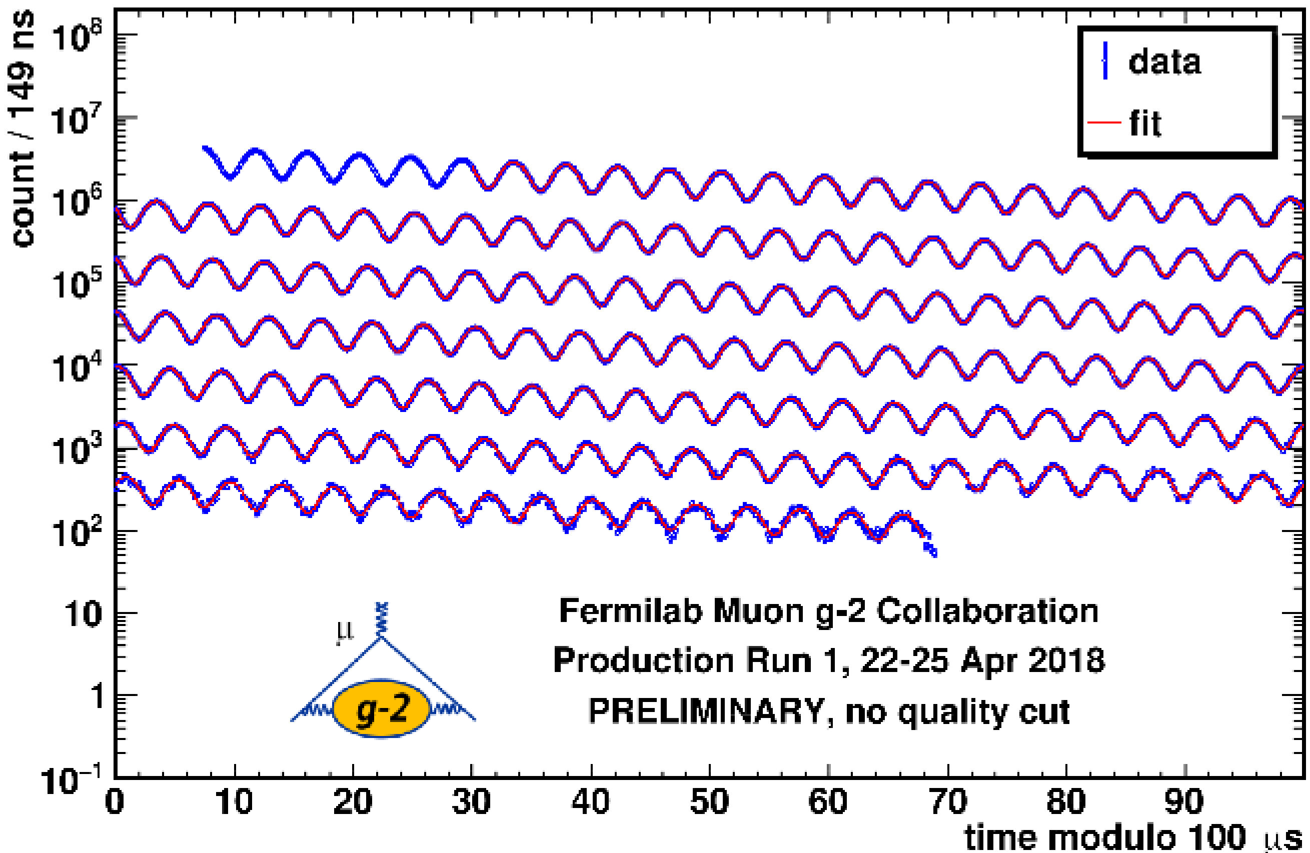
The analysis is in full flow .....

We are busy analysing $\sim 9\ x\ 10^9$ recorded muon decays.



~60 hours of data yielding ~0.95 billion decay positrons

Final E989 goal is $\sim 2\ x\ 10^{11}$ is muon decays.

Pitch Correction for vertical oscillations..

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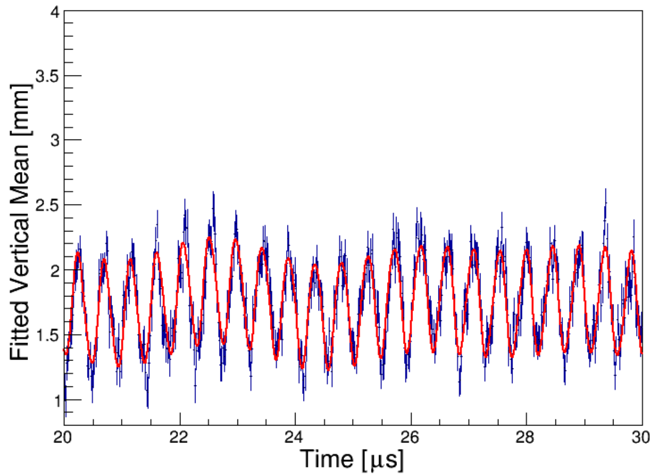

Also important to measure vertical beam oscillations in the straw trackers. They contribute another term to ω_a if the dot product $(\beta . B)$ is not zero :

$$\omega_a = \frac{e}{m}\left\{a_\mu B - a_\mu \left(\frac{\gamma}{\gamma+1}\right)(\beta . B)\beta\right\}$$

We will add a small correction for this to the fitted ω_a

$$\frac{\Delta\omega}{\omega_a} = -\frac{\langle\psi^2\rangle}{2} = -\frac{\langle\psi_0^2\rangle}{4} = -\frac{n\langle y^2\rangle}{2R_0^2}$$

There is a similar small correction for muons that are off the magic momentum and are subject to the electric field from the quadrupoles.
Important to measure the momentum distribution and mean radius of the muon orbits. Again the Trackers are vital for this. Aim to keep uncertainty arising from each of these effects to < 30 ppb.

The Ratio Method for ω_a

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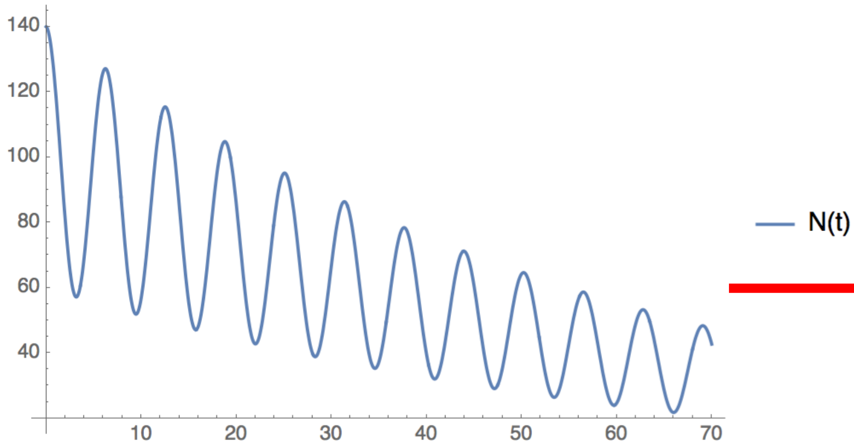
How the ratio method works:

$$N_5(t) = N_0 e^{-t/\tau}(1 + A\cos(\omega_a t + \phi))$$

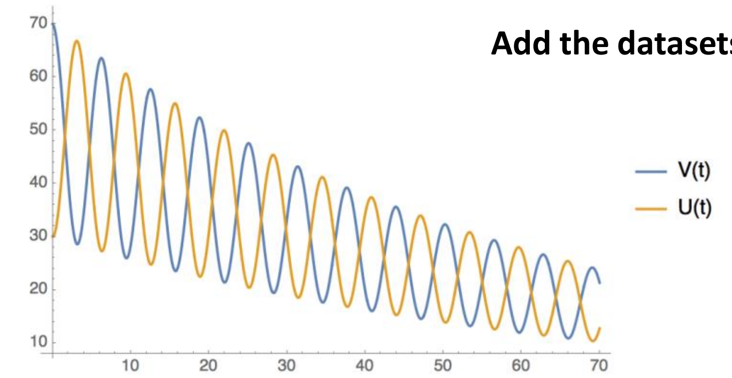


$$u_+(t) = N_5(t + T/2)/4$$
$$u_-(t) = N_5(t - T/2)/4$$
$$v_1(t) = v_2(t) = N_5(t)/4$$

Randomly split positron time spectra into 4 sets, two with time spectra shifted up and down by half a g-2 period, and two unchanged. (Equal weighting corresponding to ¼ factors.)

$$N_5(t \pm T/2) = N_0 e^{-t/\tau} e^{\mp T/2\tau}(1 + A\cos(\omega_a t \pm \omega_a \frac{T}{2} + \phi)) \qquad T \approx \frac{2\pi}{\omega_a}$$

The Ratio Method for ω_a

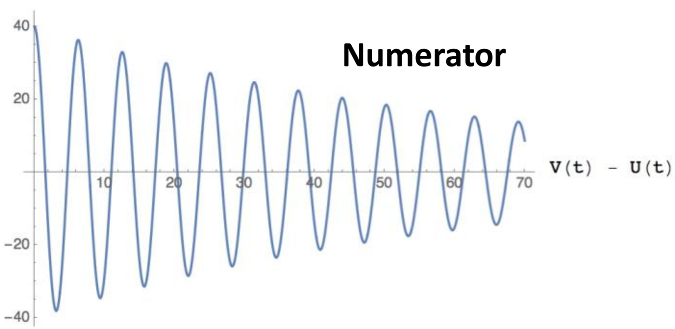


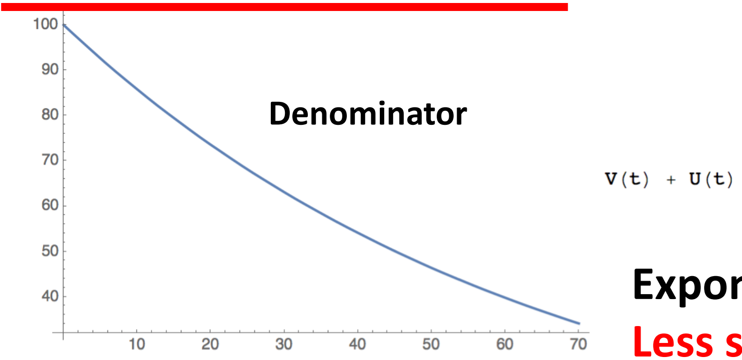
Add the datasets separately:

$$U(t) = u_+(t) + u_-(t)$$

$$V(t) = v_1(t) + v_2(t)$$

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





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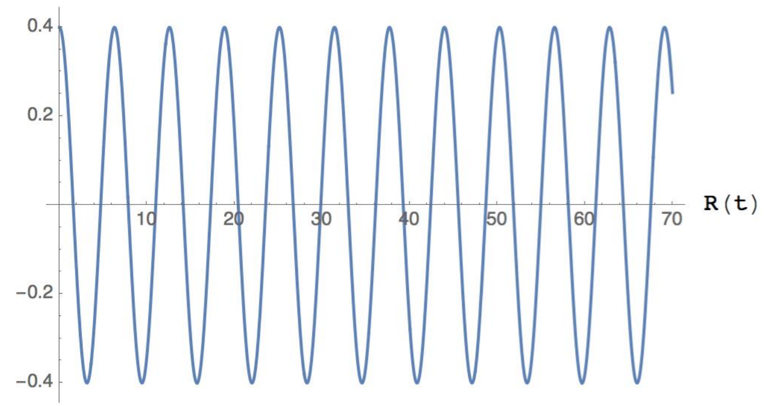


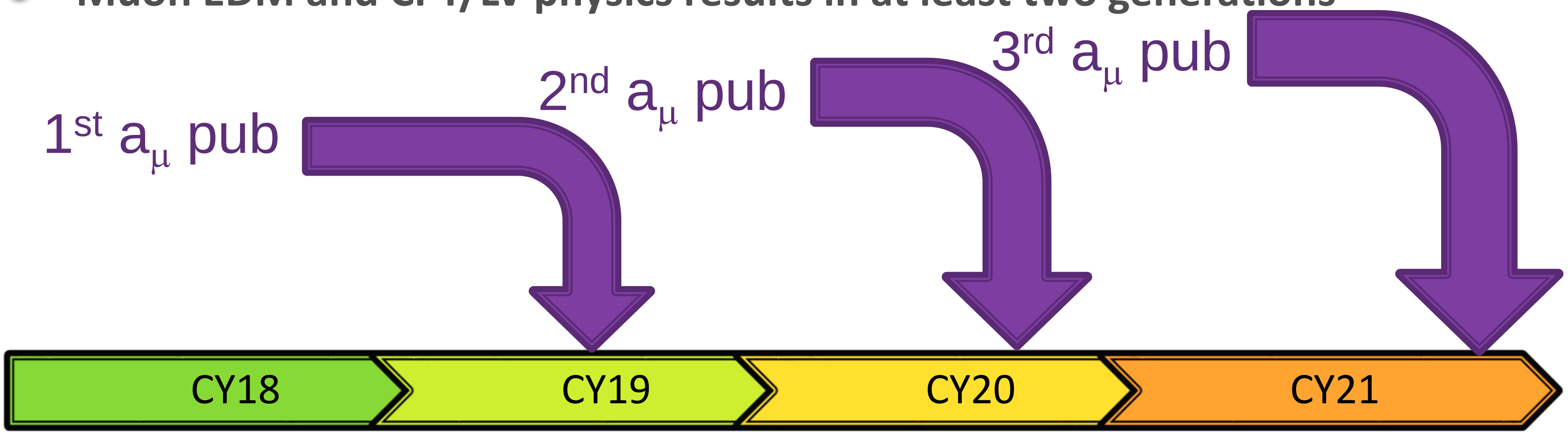
$$R(t) = A\cos(\omega_a t + \phi) - \frac{1}{16}(\frac{T}{\gamma\tau})^2 + (h.o.)$$

Exponential gets divided out – fit is now down to 3 parameters.

Less sensitivity to slow effects which divide out.

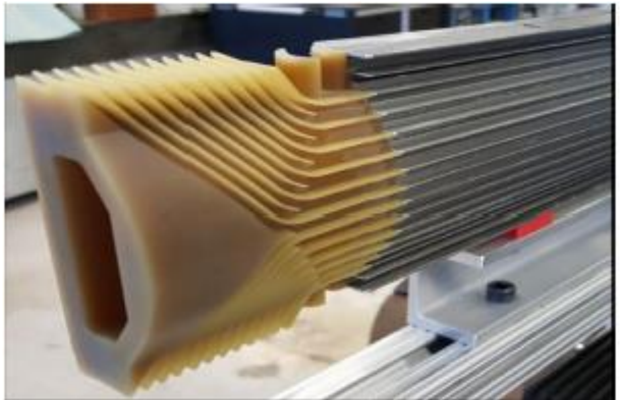
Publication Plan

- Planning on three generations of a_μ publications
  - 1-2 x BNL (~400 ppb) collected in FY18 and aiming for publication by Summer 2019 conferences
  - 5-10 x BNL (~200 ppb) collected over FY18+FY19 with publication by end of 2020…caveat that we now enter unknown regime
  - 20+ x BNL (~140 ppb) collected by end of FY20 with final publication at end of 2021 or early 2022
- Muon EDM and CPT/LV physics results in at least two generations



Summer Upgrades

- **Several improvements foreseen for this summer, each contributing to increase the stored muons by 10-30%**
- **Accelerator upgrades**
  - **faster switching between MuonCampus-BeamTest**
  - **New target**
  - **Add wedges for beam momentum compaction**
- **Ring upgrades**
  - **Kicker : key upgrade for improving quality of stored beam.**
  - **Quads : fix instabilities which cause Quads to run at HV lower than BNL (20kV vs 25kV)**
  - **Inflector : install new inflector.**



Conclusions.

Fermilab experiment finished 1st physics data run July 7th.

Fermilab 1st physics data set is ~2 × BNL data set with a goal of publishing in 2019.

Fermilab experiment has the ultimate goal of measuring muon g-2 ~4 times more precisely than the BNL experiment. Work is ongoing to drive down the systematics exploiting the improved detector.

Detector improvements taking place over the summer ready for next physics run.

Work continues on improving the precision of the SM muon g-2 prediction.