The Muon g-2 Experiment at Fermilab

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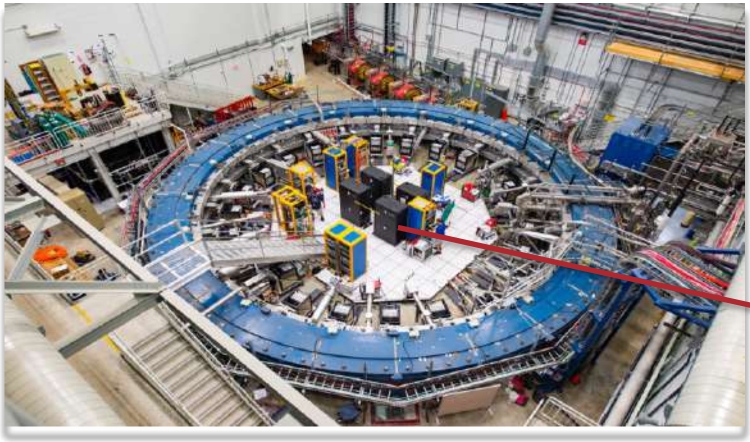
PhiPsi 2019, Novosibirsk, Russia

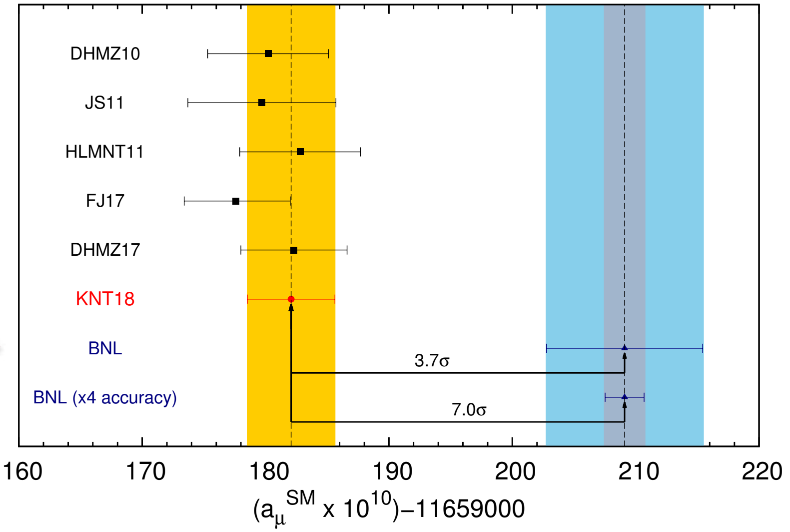
28th February 2019

THE UNIVERSITY of MISSISSIPPI

Motivation for a new Muon g-2 experiment

Fermilab experiment is set to improve the uncertainty on a_μ by 4x compared to BNL





Keshavarzi, Nomura & Teubner (KNT18), Phys. Rev. D. **97** 114025 (2018).

- BNL experiment achieved 540ppb precision.
- Fermilab experiment targeted to reach 140ppb precision.
- Requires taking 20x statistics compared to BNL.
- If mean value is unchanged, this would result in a 7σ discrepancy between theory and experiment.
- And theory estimates are further improving as we have seen…

How do we measure a_μ?

Inject polarised muons in a magnetic storage ring (dipole B-field → 1.45T).

➢ Measure the difference between the muon cyclotron and spin frequencies:

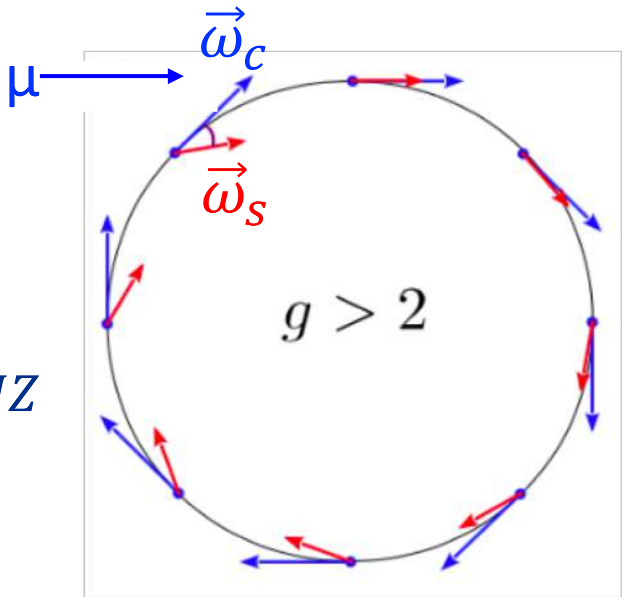
Spin frequency: $\vec{\omega}_s = \frac{ge\vec{B}}{2mc} + (1-\gamma)\frac{e\vec{B}}{\gamma mc}$

Cyclotron frequency: $\vec{\omega}_c = \frac{e\vec{B}}{\gamma m}$

Anomalous precession frequency:

$$\vec{\omega}_a = \vec{\omega}_s - \vec{\omega}_c = \left(\frac{g-2}{2}\right)\frac{e\vec{B}}{mc} = \boldsymbol{a_\mu}\frac{e\vec{B}}{mc} \approx 229kHZ$$

(Note that if $a_\mu = 0$, then $g = 2$ and $\vec{\omega}_s = \vec{\omega}_c$.)



Therefore, the Fermilab Muon g-2 experiment will measure two quantities:

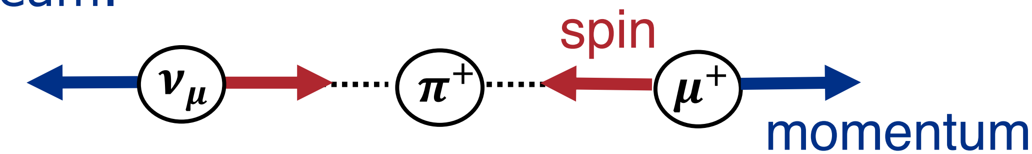
1. The anomalous precession frequency, $\vec{\omega}_a$ to ± 100 ppb (stat) ± 70 ppb (syst).
2. Magnetic field $\vec{B}$ in terms of proton NMR frequency to ± 70 ppb (syst).

How do we measure a_μ?

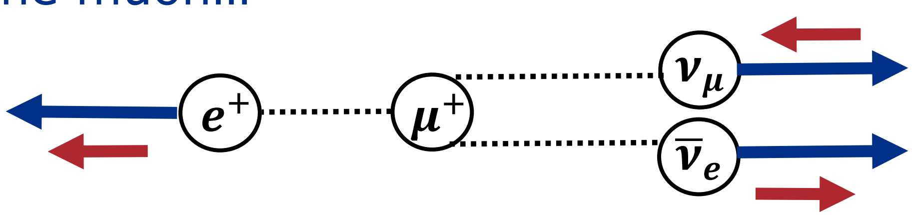
→ We need to know the spin of the muon…

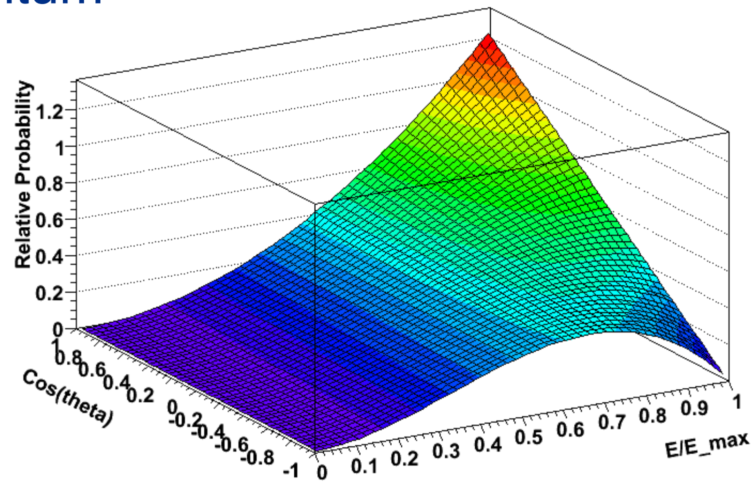
In the weak decay of a pion, the neutrino spin must be opposite of momenta.

- The same must be true for the muon, resulting in a polarised muon beam.



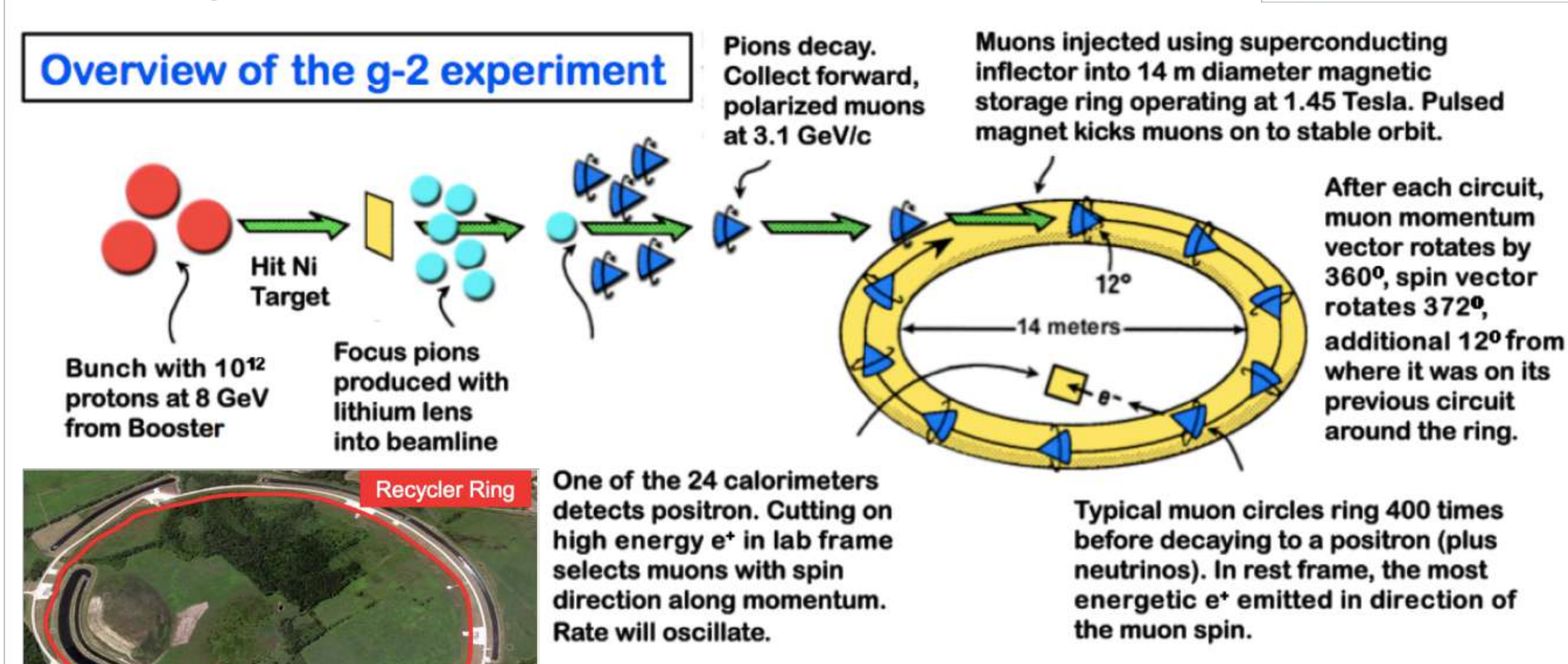
Then, the highest energy positrons are emitted along the direction of the spin of the muon…





So, by detecting positrons above a certain energy threshold using calorimeters, we know the spin of the parent muon.

Producing the muons



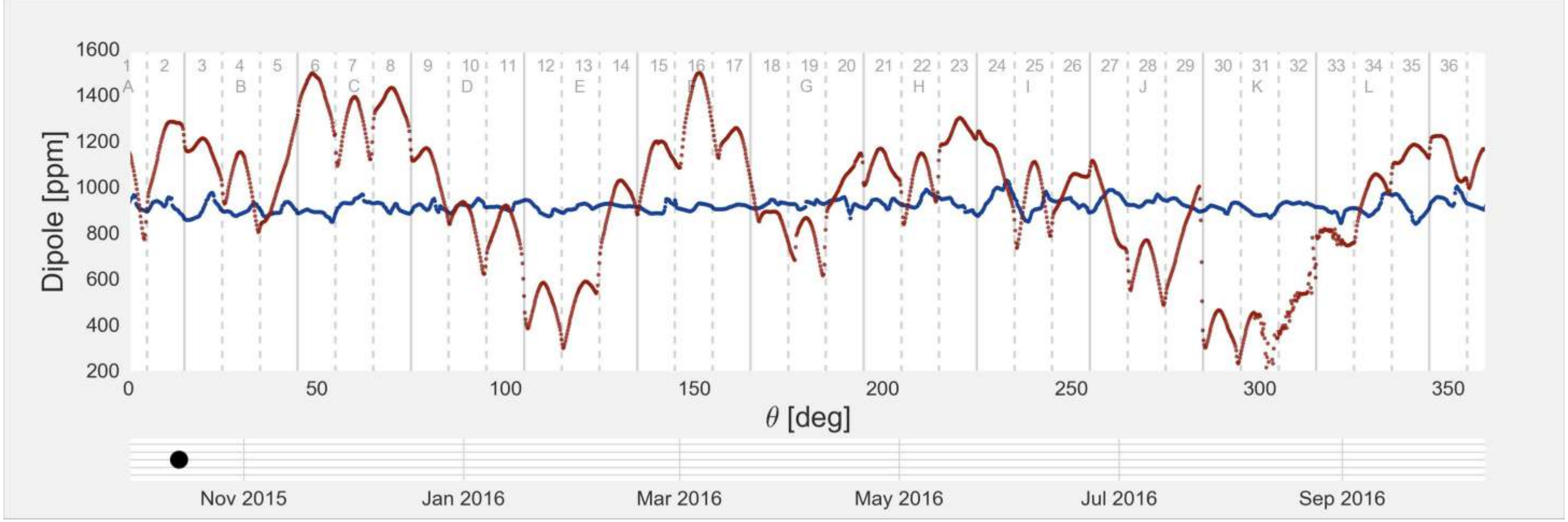
<u>Fermilab statistics advantages</u>

- Long decay channel for $\pi \rightarrow \mu$
- Reduced p and π in ring
- Factor 20 reduction in hadronic flash
- 4x higher fill frequency than BNL

→ 21 times more positrons detected than at BNL

Shimming the magnet

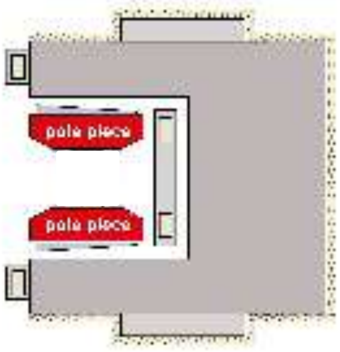
→ Progress towards a uniform magnetic field from Oct 2015 to Sep 2016:



Red = Initial dipole field starting point at Fermilab
Blue = typical BNL final field *after* shimming

→ Final Fermilab Result is better than BNL by a factor of ~3 (p-p & RMS)

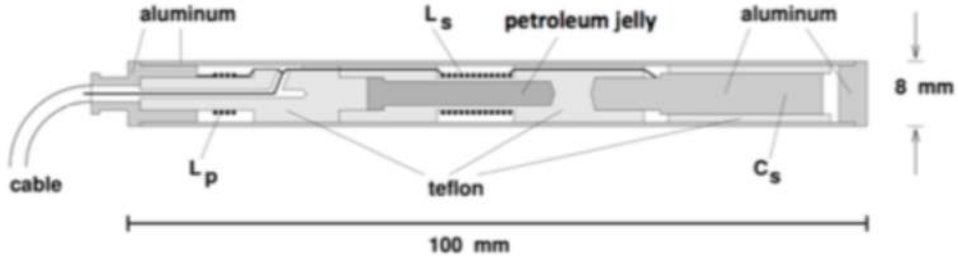
→ Shimming checked between runs to ensure uniformity.



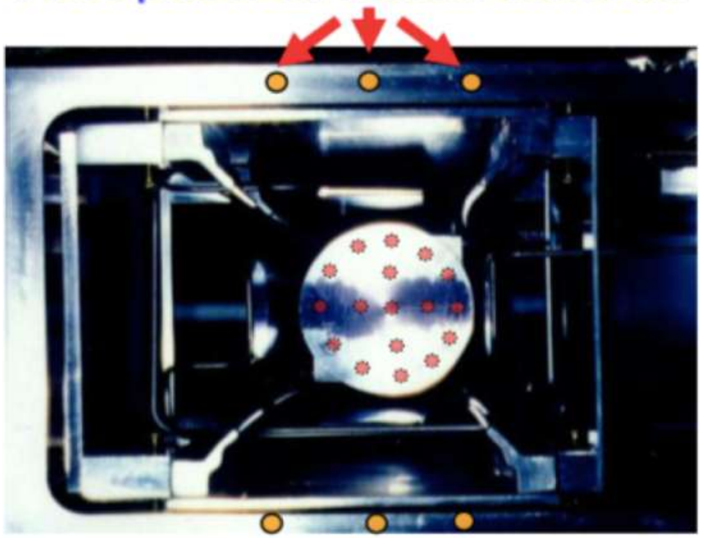
James Mott, SSP 2018, Aachen, 12th June 2018

Measuring the B-Field to 70 ppb using Pulsed Proton NMR

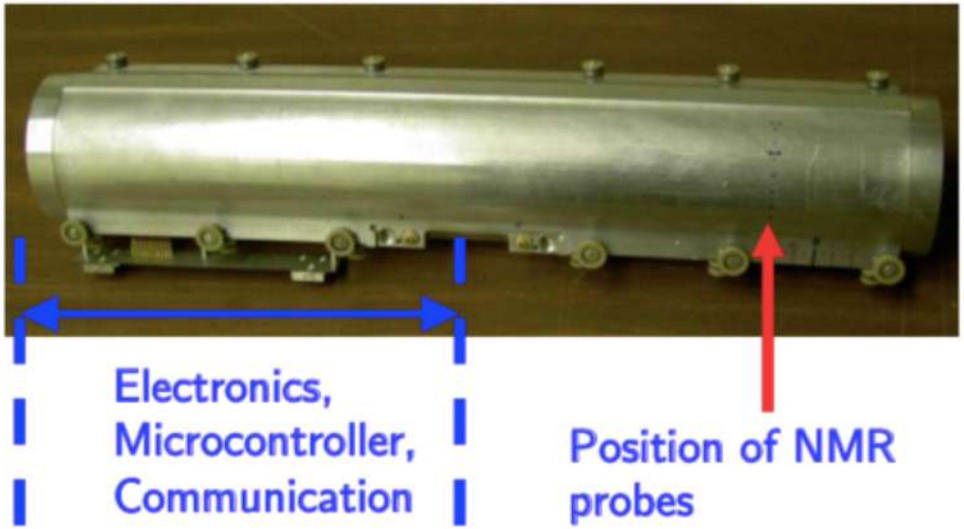
- 387 Fixed NMR probes outside storage volume measure field while muons stored
- Field inside storage volume measured by NMR trolley periodically
- Fixed probes calibrated when trolley passes; can infer field inside storage volume



Fixed probes on vacuum chambers



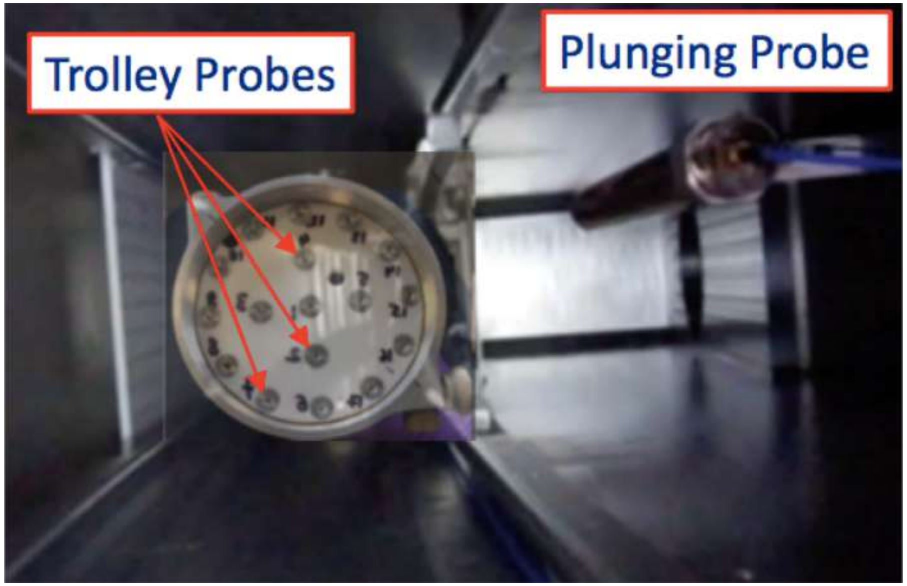
Trolley with matrix of 17 NMR probes

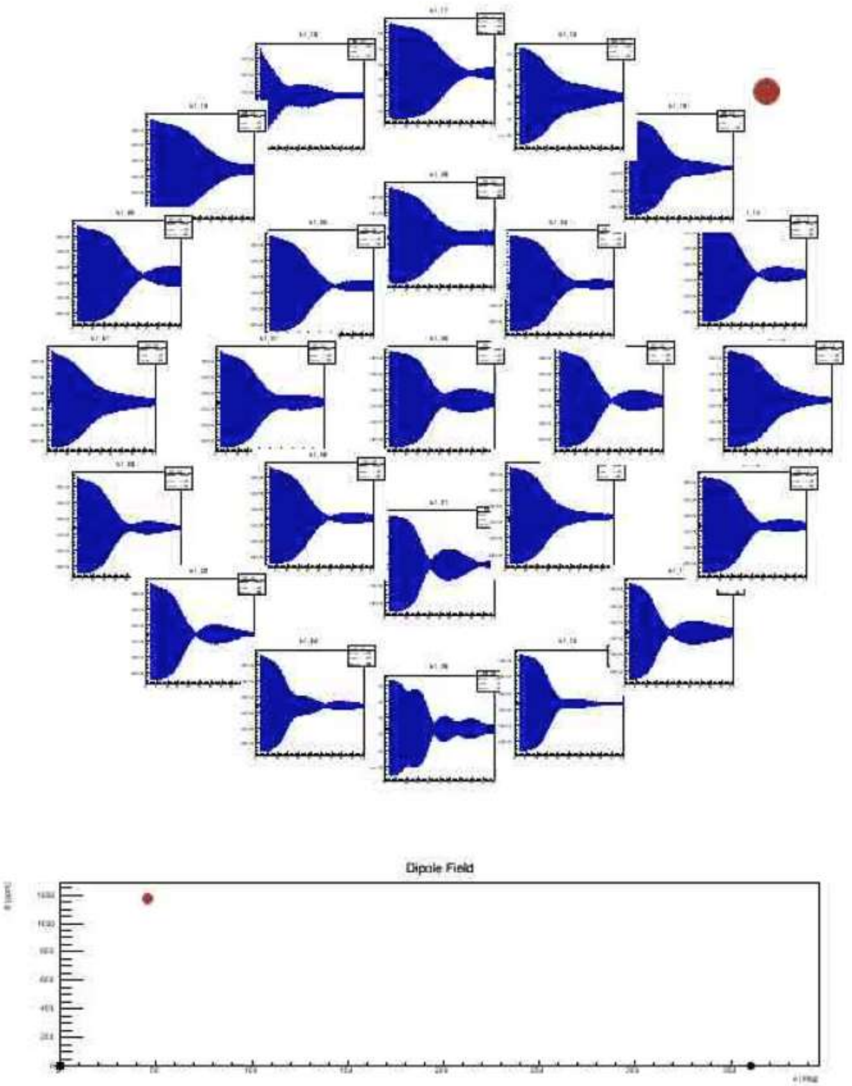


Dave Kawall, Fermilab Measurement of Muon g-2, g-2 Theory Initiative Workshop in Mainz, June 18-22, 2018

Mapping the field seen by the muons…

→ The NMR trolley maps the B-field inside the storage region:

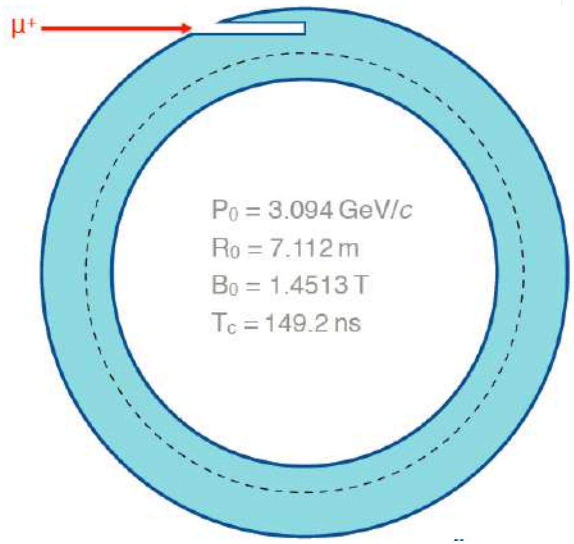


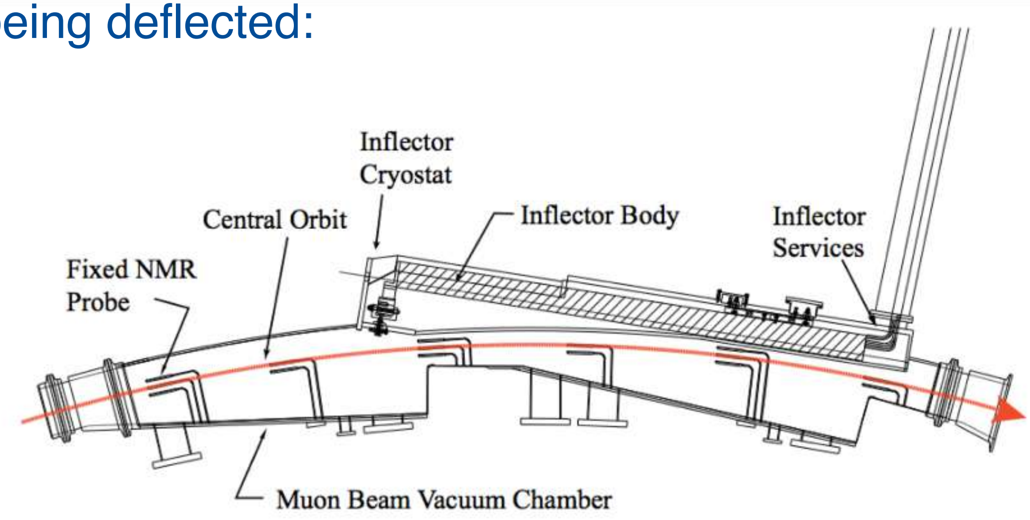


Mark Lancaster, UCL Schuster Colloquim, 5th December 2018

Storing the beam: the inflector

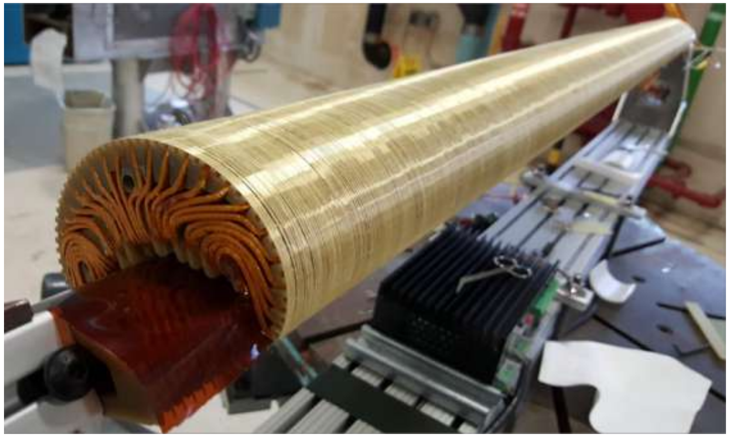
A superconducting inflector magnet at injection cancels the 1.45 T storage field to allow the muon to enter without being deflected:





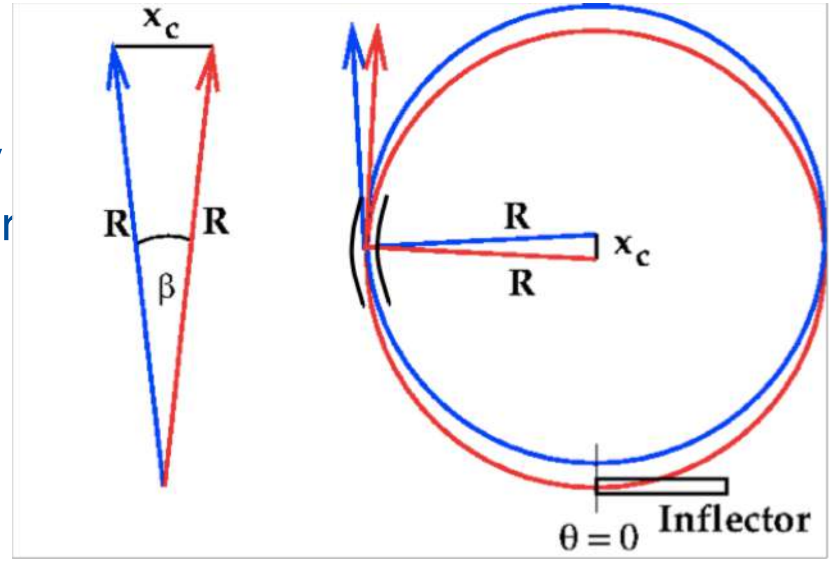
Note: new open-ended inflector upgrade being installed in summer of this year.

→ Projected 40% gain in statistics.



Storing the beam: the kicker

- Beam enters the ring displaced by 11mrads from ideal orbit.
- Kicker magnets inside ring require 65kv pulse to produce 300 Gauss $\vec{B}$ field over 4 metres for 100 ns at 100 Hz.
  → "Kick" muons onto correct orbit.



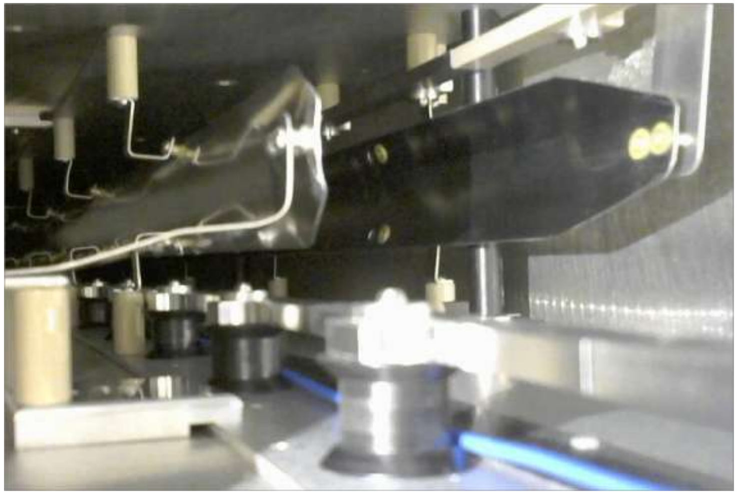
<u>Run-2 upgrades</u>

Run-1 kicker performance problems:

- 30% less kick strength than necessary.
- Kick reflection due to impedance mismatching.

This has lead to a **full kicker system upgrade,** which has just been completed ready for Run-2 data taking.

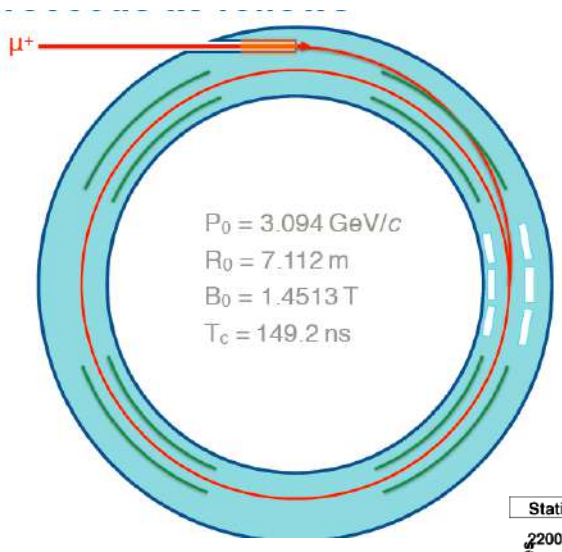
➢ Projected to give us up to 30% better storage efficiency.

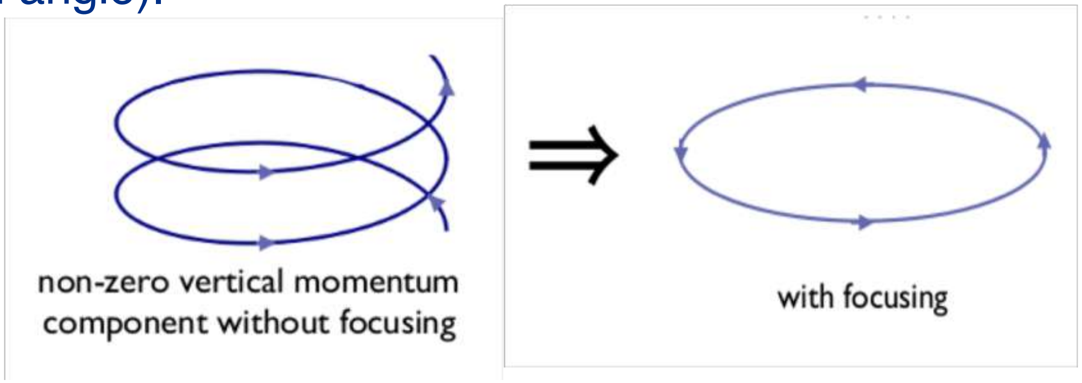


Storing the beam: electrostatic quadrupoles

→ Storage ring B-field **only provides radial focusing.**

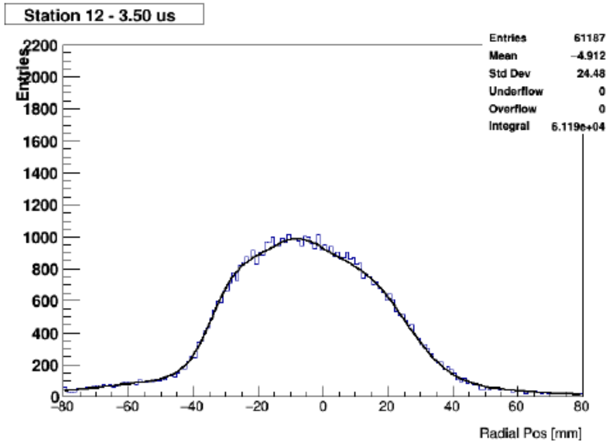
→ Use electric field (electrostatic quadrupoles) to provide vertical focusing (to counteract vertical pitch angle).

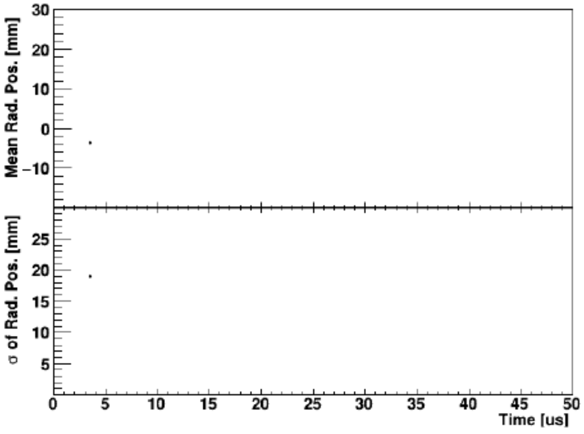




However, combination of E and B field leads to 2D SHM about closed orbit (in the form of betatron oscillations)

The amplitude, frequency and damping time of these beam oscillations are critical to the measurement





Dealing with a less than ideal world…

In addition, our expression for $\vec{\omega}_a$ now includes two more terms:

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

→ Choosing the "magic momentum" $\gamma = 29.3$ ($p = 3.094$ GeV) cancels the electric field term to first order.

→ This leaves two effects that we have to correct for:

Electric-field correction

- Not all muons are at the magic momentum.
- Have to correct $\vec{\omega}_a$ for those muons.
- This E-field correction, C_E, can be determined via the **'Fast Rotation' analysis**.
- This results in a systematic uncertainty.

Pitch correction

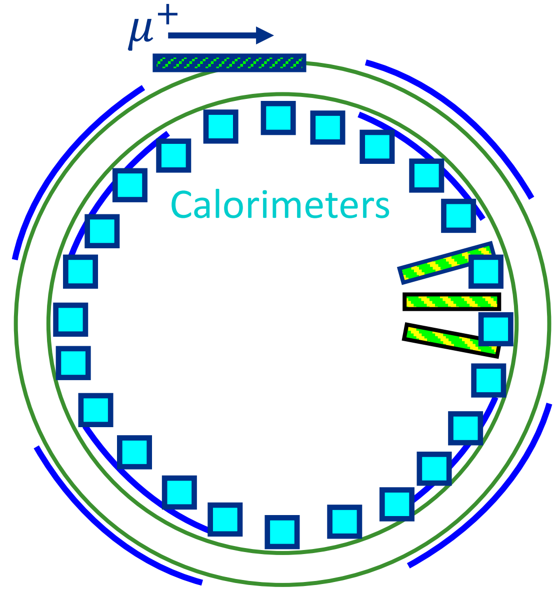
- Some muons still have a small amount of vertical pitching.
- Have to correct $\vec{\omega}_a$ for those muons.
- This Pitch correction, C_P, can be determined from **straw tracker data**.
- This results in a systematic uncertainty.

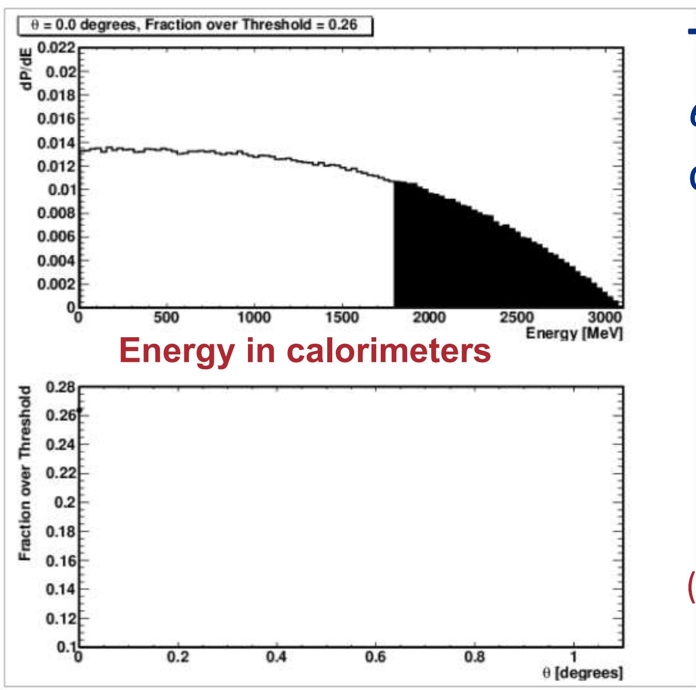
Measuring the decay positrons

24 calorimeters located equidistantly around the storage ring measuring arrival time and energy of decay positrons:

➔ Each calorimeter has 54 Cherenkov PbF_2 crystals with very fast SiPMs.

The muons pass the calorimeters at cyclotron frequency, so the oscillation occurs at the difference frequency ω_a:





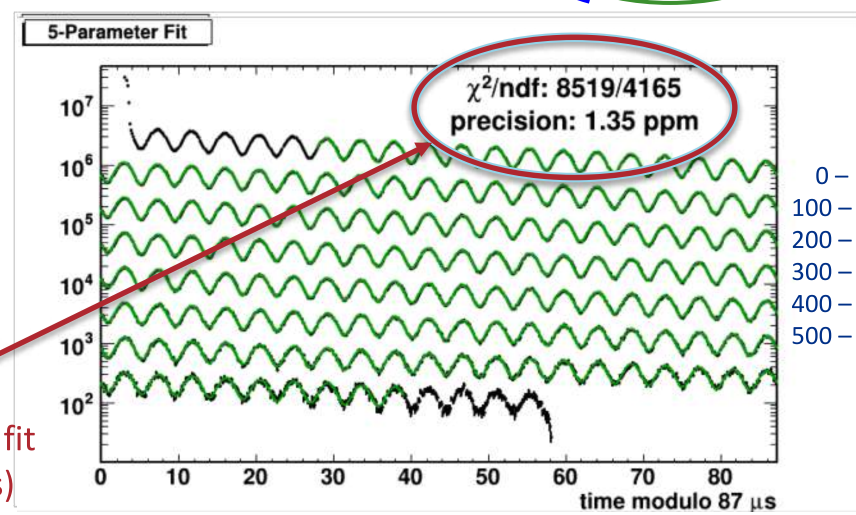
Energy in calorimeters

Direction/phase of muon spin

The wiggle plot: no. of e^+ (>1.8GeV) as a function of time.

Run-1 '60 hour' data set

Not good (not enough fit parameters)



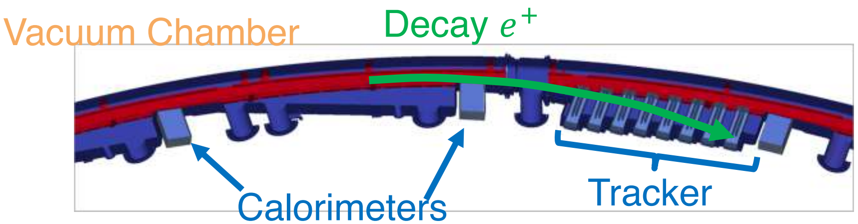
0 – 100 μs
100 – 200 μs
200 – 300 μs
300 – 400 μs
400 – 500 μs
500 – 600 μs

$$N_e(t) \simeq N_0 e^{-\frac{t}{\gamma\tau}}[1 - A\cos(\omega_a t + \phi_a)]$$

Trackers and fiber harps

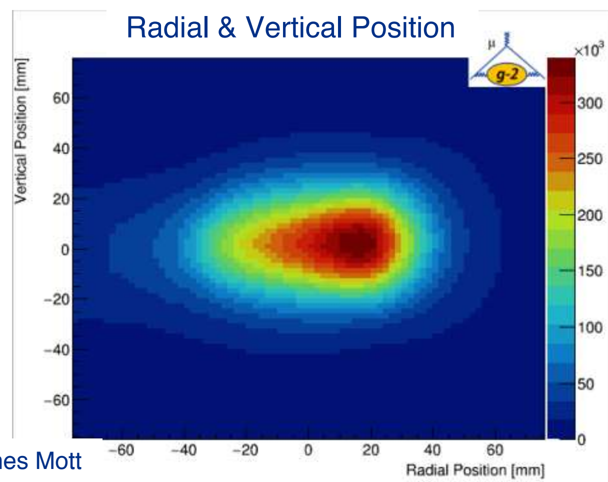
We have two other detectors that we use to monitor the beam dynamics:

Straw trackers (non-destructive)



Provides essential information for:

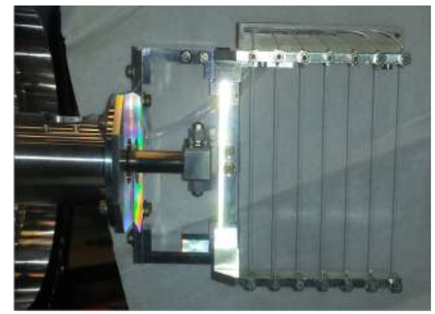
- Weighting magnetic field data by muon distribution.
- Acceptance corrections for calorimeter due to beam oscillations.
- Pitch correction C_p to ω_a.



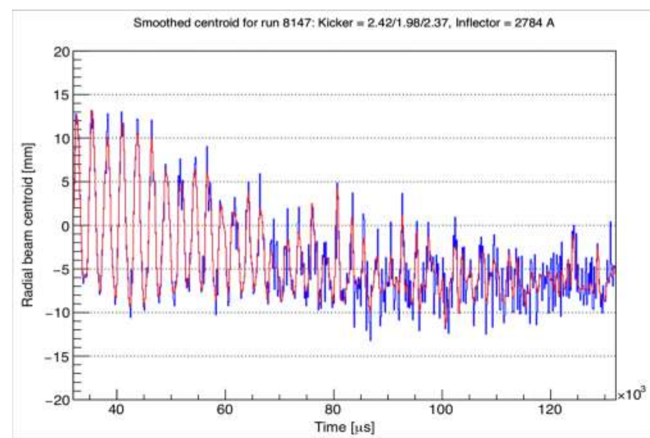
James Mott

Fiber harps (destructive)

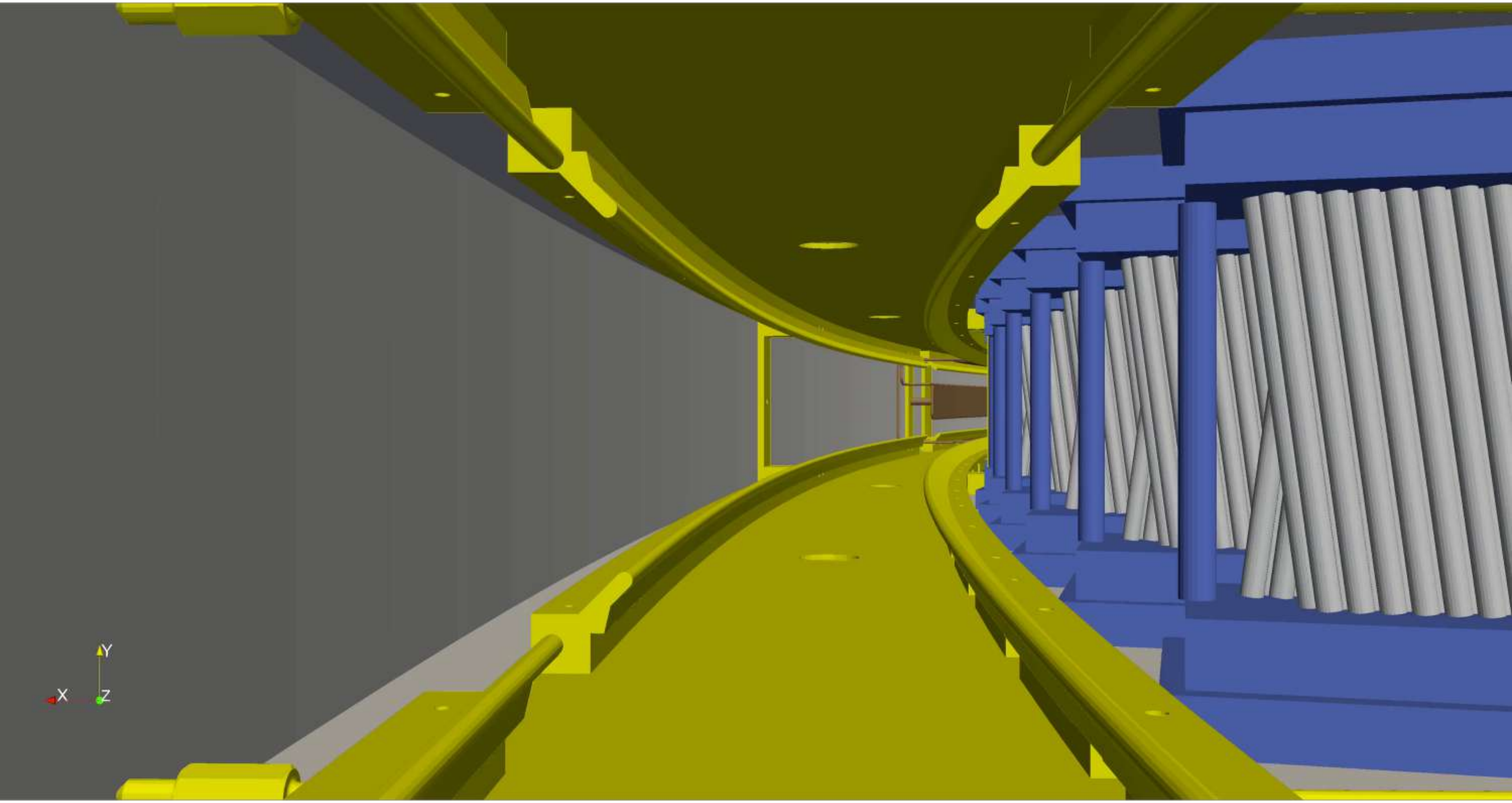
Fiber profile beam monitor measure vertical position of beam at 180° and 270° around ring:



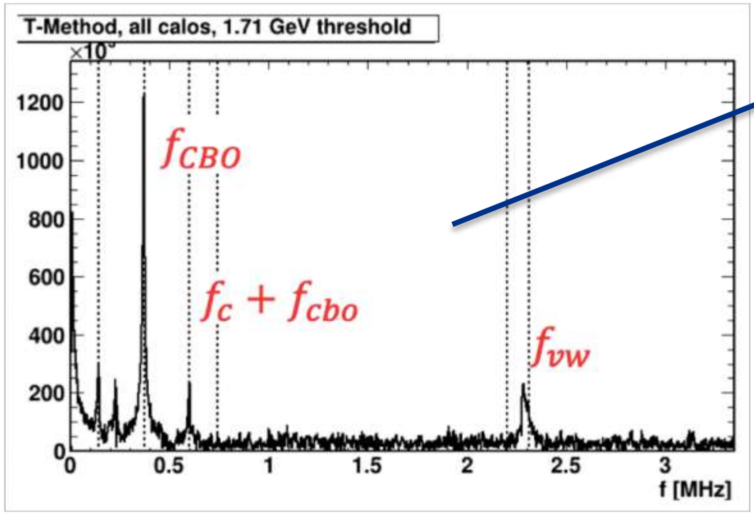
…and provides information on Coherent Betatron Motion amplitude:



The muon's view



Fitting all the relevant beam dynamics



FFT of frequency spectrum shows other systematic effects

Physical frequency	Variable	Frequency (MHz)	Period (μs)
Anomalous precession	f_a	0.23 MHz	4.37
Cyclotron	f_c	6.70 MHz	0.149
Horizontal Betatron	f_x	6.34 MHz	0.158
Vertical Betatron	f_y	2.2 MHz	0.455
CBO	f_{CBO}	0.37 MHz	2.7
Vertical Waist	f_{VW}	2.3 MHz	0.435

→ Fit function must account for all these effects: CBO, vertical waist, pileup, muon losses, in-fill gain changes...

And so, five-parameter function:

$$N_e(t) \simeq N_0 e^{-\frac{t}{\gamma\tau}} [1 - A\cos(\omega_a t + \phi_a)]$$

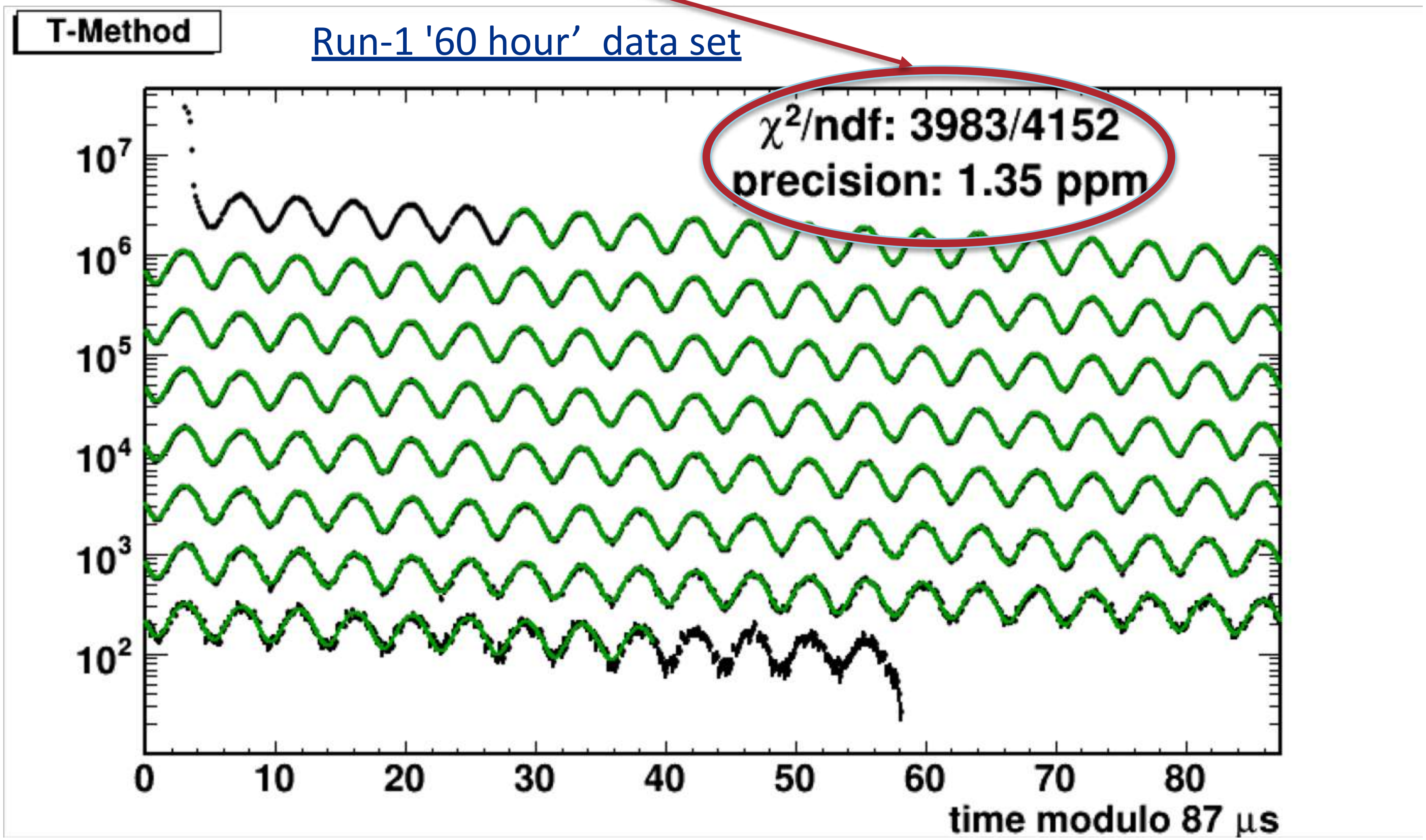
… becomes 17-parameter function:

$$N(t) = N_0 N_{CBO}(t) N_{2CBO}(t) N_{VW}(t) L(t) \exp(-t/\tau) \left[1 + A_0 A_{CBO}(t) \cos\left(\omega_a(R)t + \phi(t)\right)\right]$$

... that fully describes the beam dynamics.

Fitting all the relevant beam dynamics

And the fit is complete…

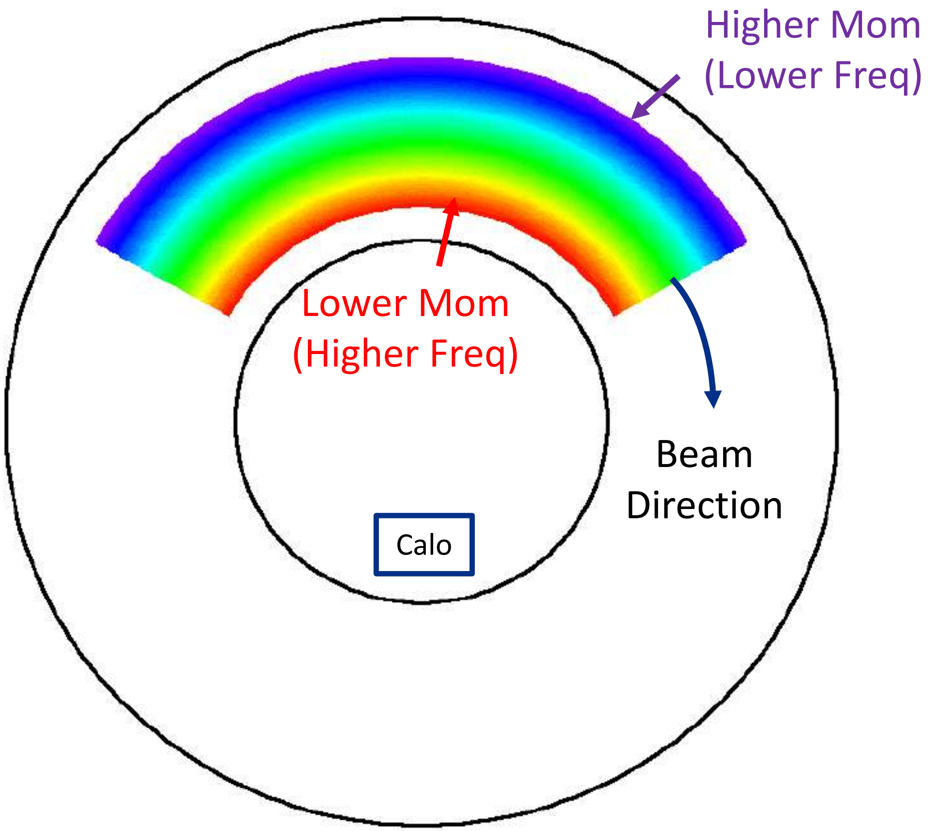


Determining the E-field correction

An Electric-field correction accounts for those muons **not at the magic radius**

→ This is achieved via a 'Fast Rotation' analysis of the stored beam de-bunching.

→ Over time, lower momentum will catch up with higher momentum…



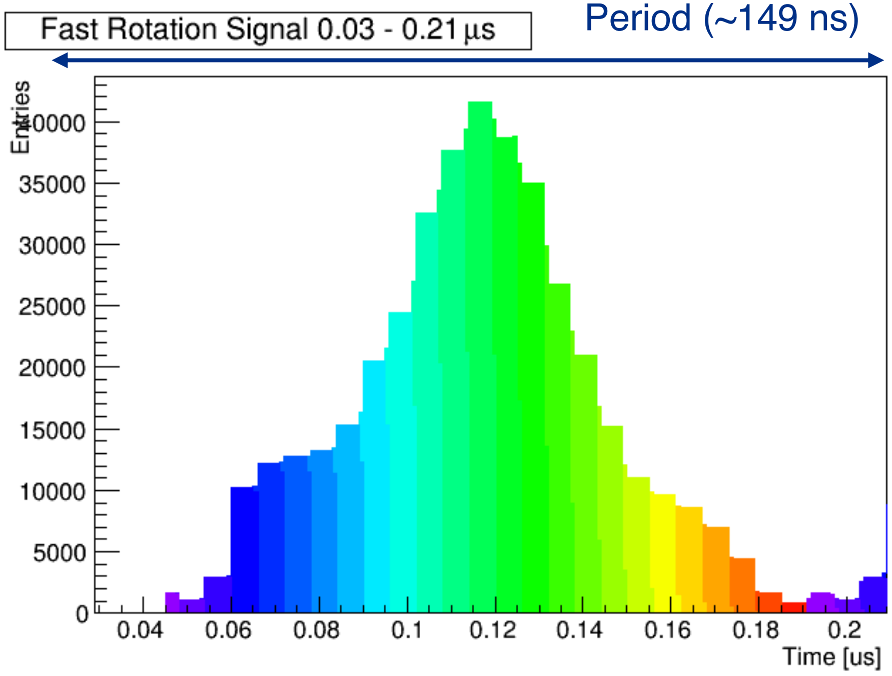
The way that the gaps between bunches are filled is related to the momentum distribution of the stored beam.

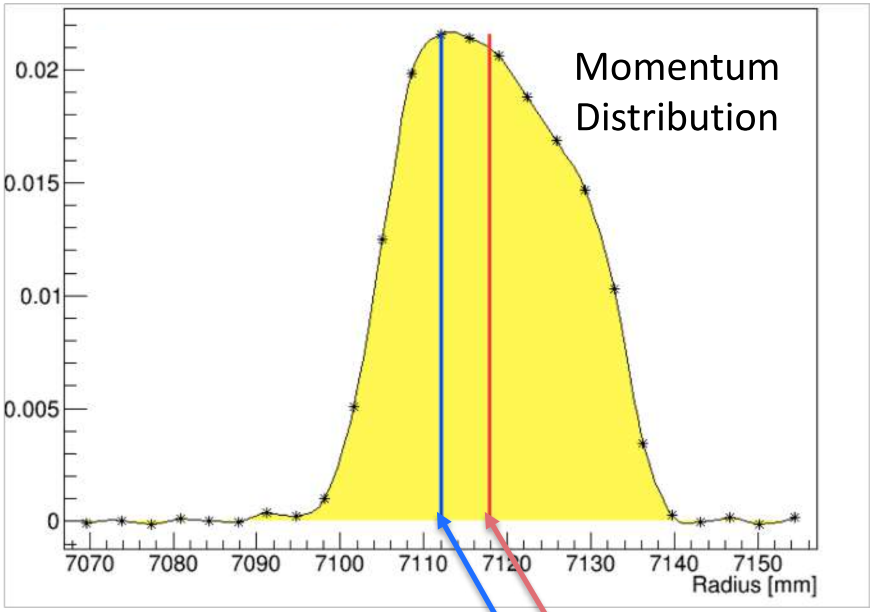
Determining the E-field correction

The E-field correction accounts for those muons **not at the magic radius**

Use either an iterative χ^2 minimization or Fourier analysis to determine stored beam's time profile and momentum distribution

One Cyclotron Period (~149 ns)





E-field correction: $$C_E = -2\langle n\rangle(1-\langle n\rangle)\beta^2 \frac{\langle x_e^2\rangle}{R_0^2}$$

Now, a disclaimer…

There are two things in this world that currently remain a total mystery:

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1.

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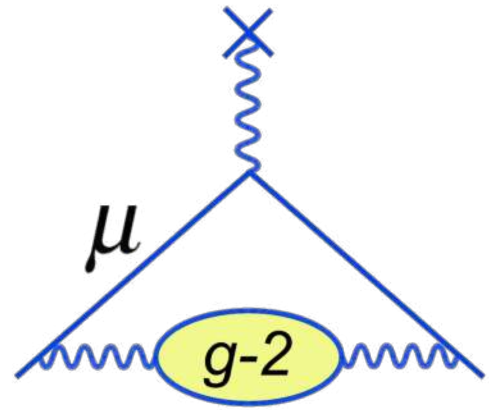
1.

2.



The Muon g-2 experiment is currently **fully blinded!**

Blinding

The experiment is both hardware and software blinded:

Software blinding

- Analysis package applies two frequency offsets to ω_a and ω_p:

$$\omega_a = 2\pi \cdot 0.2291 \text{ MHz} \cdot [1 - (R - \Delta R) \times 10^{-6}]$$

→ Each analyser has an individual, unknown personal offset ΔR.

→ We are currently **fitting for R** and are very close to a relative unblinding of the first data set.

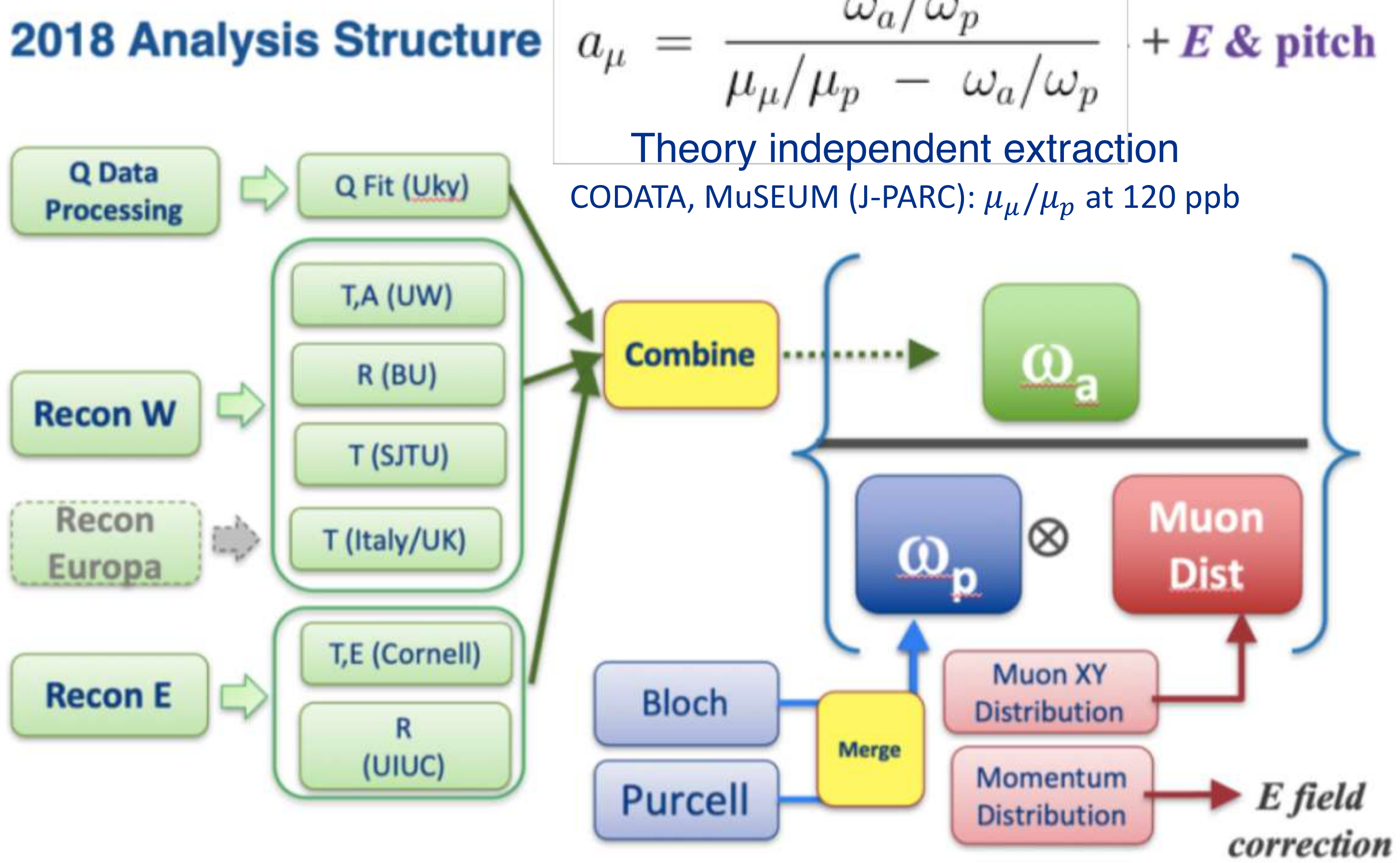
Hardware blinding

- A 40MHz clock drives the calorimeter digitizers, straw tracker and NMR digitisers.
- This has been shifted by a small amount in the range +/- 25ppm.
- The offset is known only to two people (not part of the experiment).

Take-home message:

We can't say anything about the final result (yet), despite recent rumours…

The full picture (after unblinding)



$$a_\mu = \frac{\omega_a/\omega_p}{\mu_\mu/\mu_p - \omega_a/\omega_p} + E \,\&\, \text{pitch}$$

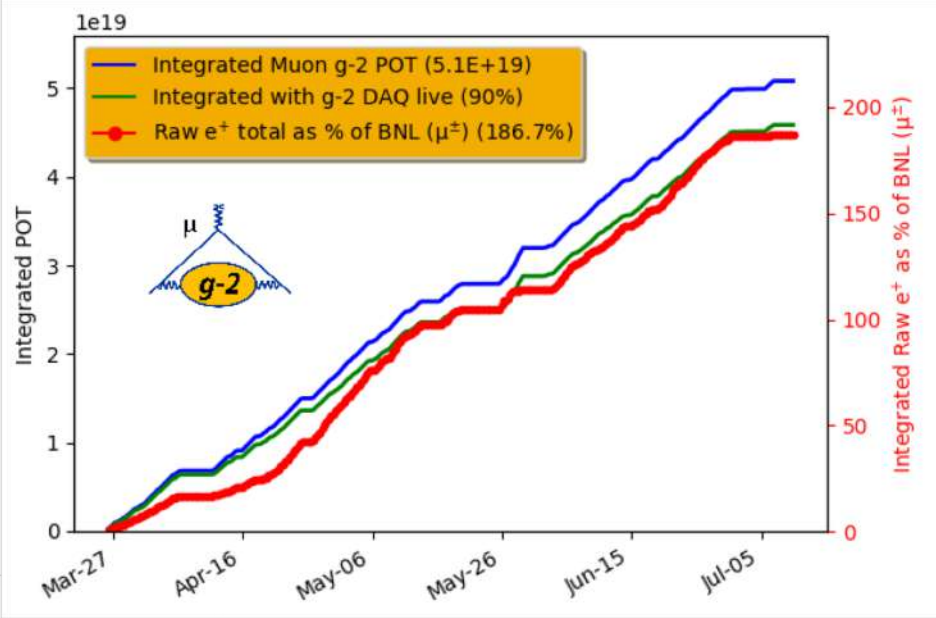
Theory independent extraction

CODATA, MuSEUM (J-PARC): μ_μ/μ_p at 120 ppb

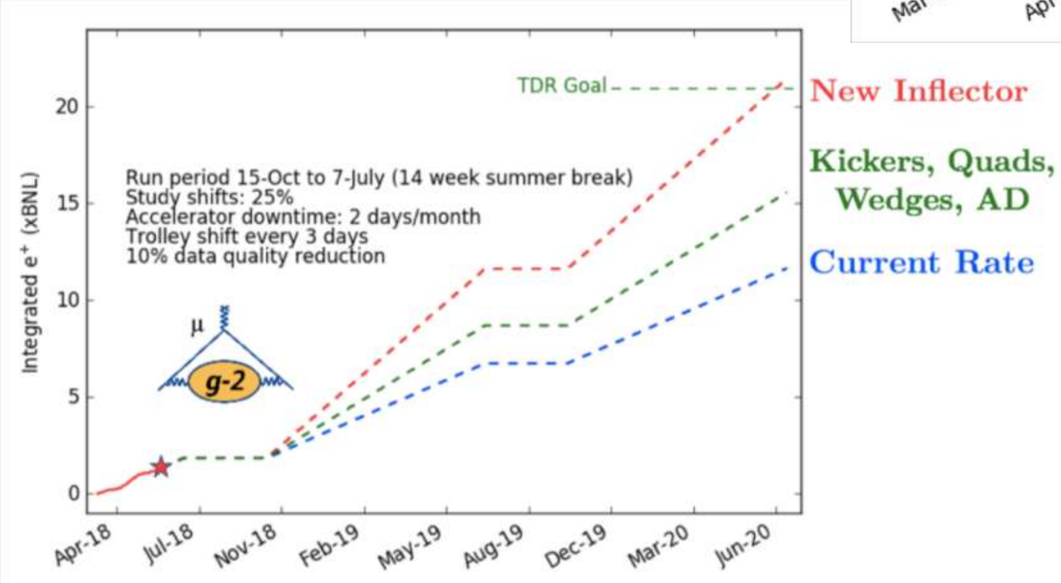
Result from 1st physics run with BNL level statistics planned for mid-late 2019.

Reaching 100ppb statistics…

In Run-1, we recorded 17.5B e^+ (x2 Brookhaven dataset), enough to establish 5σ discrepancy if the mean value stays the same.



→ In next 2 years we will increase dataset by factor of 10.



A large amount of upgrade work has taken place (and is ongoing) to ensure that we will reach the 100ppb statistics goal

Systematic uncertainty budget

ω_a

- New calorimeters, trackers, techniques to reduce uncertainties factor 2.6
- Upgrades will drastically reduce systematics issues in Run-1.

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

Source of uncertainty	1999	2000	2001	E989
Systematics of calibration probes	50	50	50	→ 35
Calibration of trolley probes	200	150	90	→ 30
Trolley measurements of B_0	100	100	50	→ 30
Interpolation with fixed probes	150	100	70	→ 30
Uncertainty from muon distribution	120	30	30	→ 10
Inflector fringe field uncertainty	200	–	–	–
Time dependent external B fields	–	–	–	→ 5
Others †	150	100	100	→ 30
Total systematic error on ω_p	400	240	170	→ 70
Muon-averaged field [Hz]: $\omega_p/2\pi$	61 791 256	61 791 595	61 791 400	–

ω_p

- New electronics, new probes, new techniques reduce uncertainties factor 2.5
- Temperature issues in Run-1 now alleviated via magnet insulation.

Conclusions

- Fermilab Muon g-2 experiment on track to ascertain whether current discrepancy with SM is well established.
- The experiment will measure two frequencies, ω_a and ω_p, to an unpresented precision.
- Major upgrade work has taken place over the shutdown to ensure that the experiment reaches its statistics and systematics goals (with more planned for summer 2019).
- Run-1 (2018) data is currently being analysed, but **is currently fully blinded.**
- The blinding is applied for both hardware and software, for both ω_a and ω_p.
- First result from Run-1 with BNL level statistics is planned for mid-late 2019.
- Run-2 and Run-3 will ensure we reach the 20x BNL statistics goal, and systematics are currently very well under control.

Thank you.

Backup slides

Motivation for a new Muon g-2 experiment

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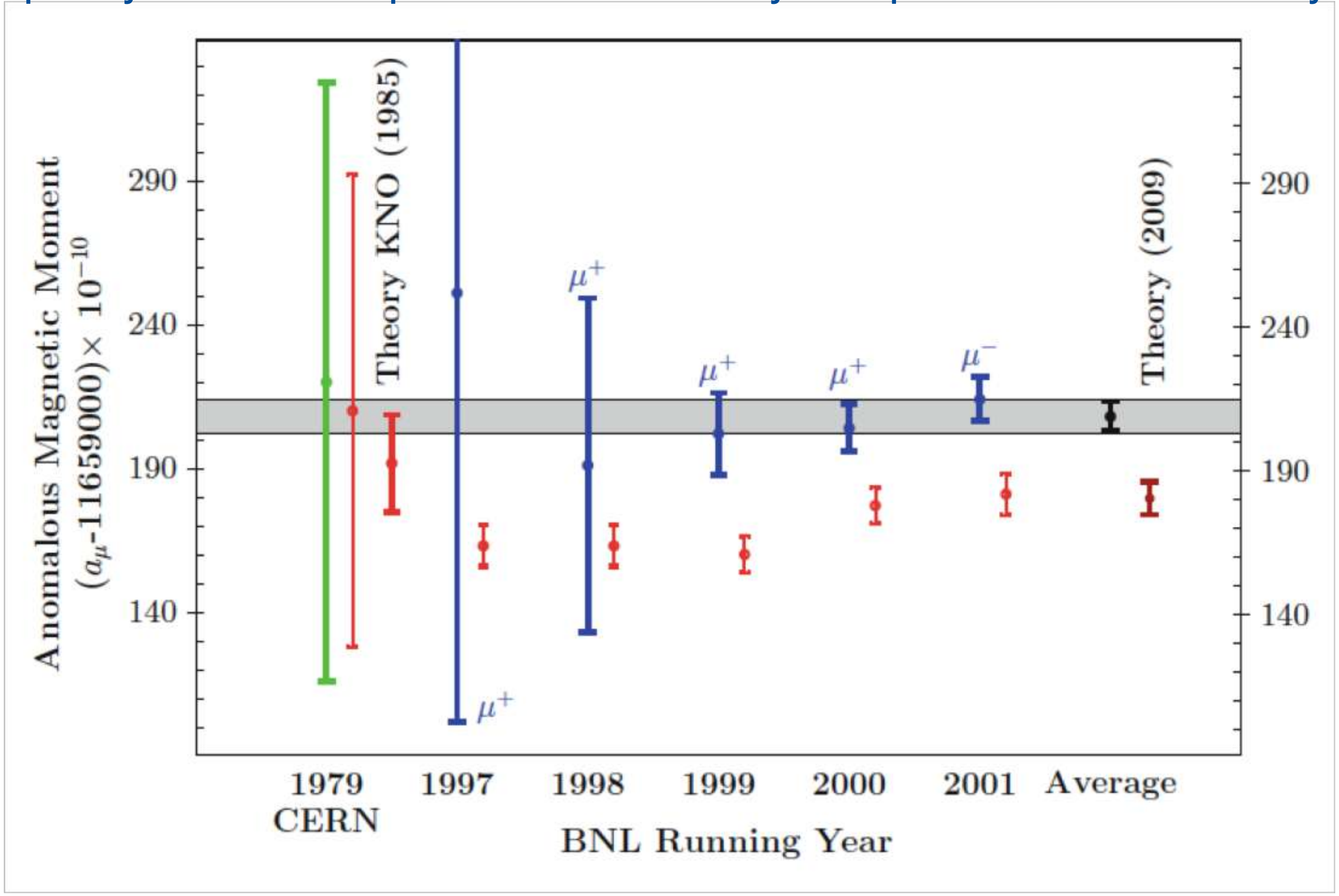
Discrepancy between experiment and theory has potential for discovery…

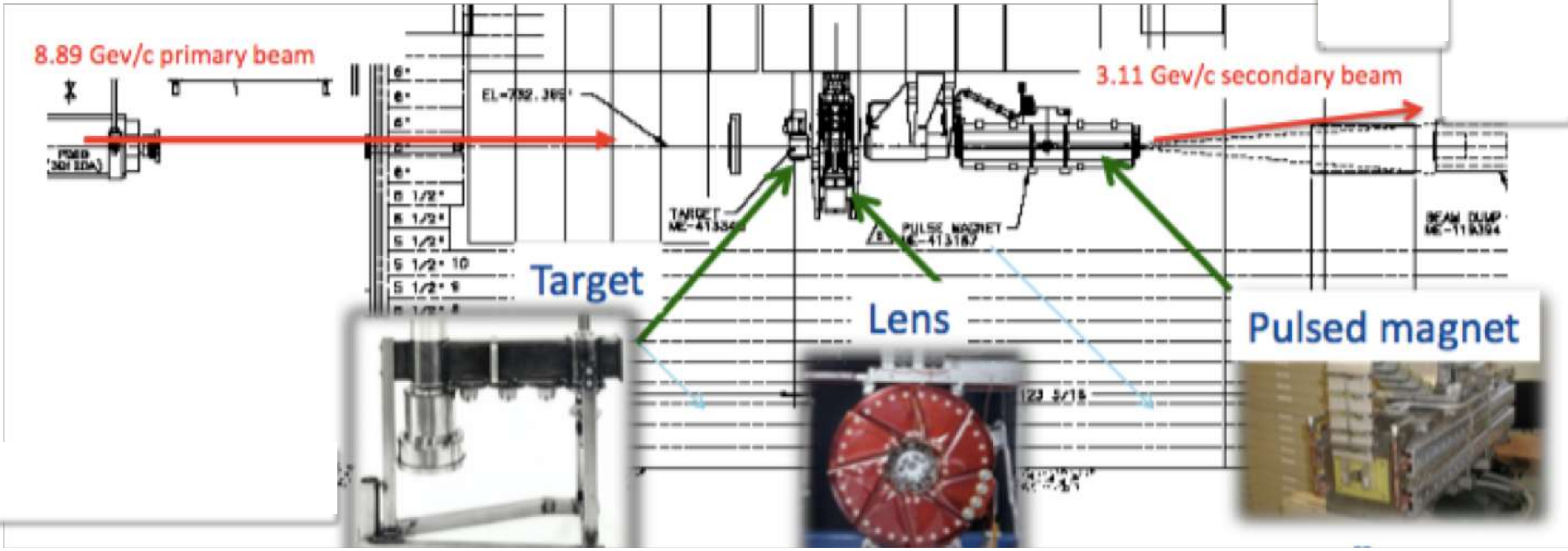


Fermilab experiment is set to improve the uncertainty on a_μ by 4x compared to BNL

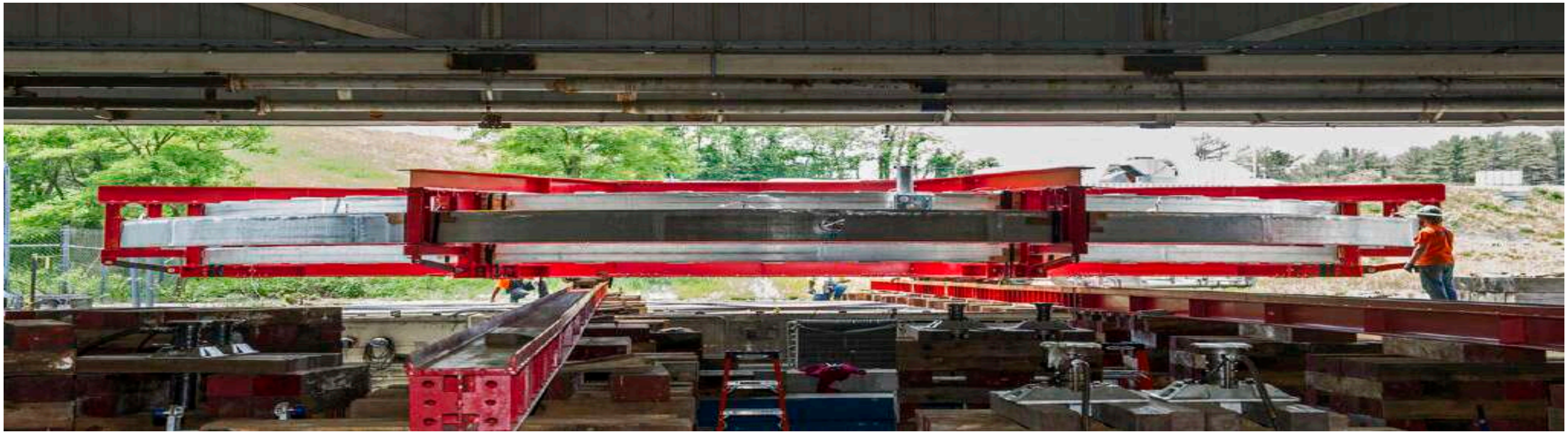

MAIN INJECTOR/RECYCLER RINGS
TEVATRON (RIP)
DR
BOOSTER
LINAC

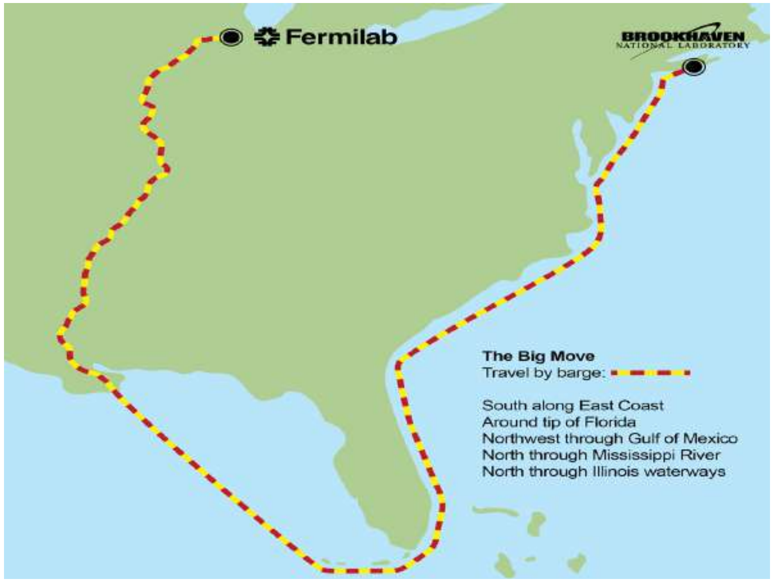

CHICAGO
BOOSTER
Mu2e
g-2
MUON TARGET & DELIVERY RING

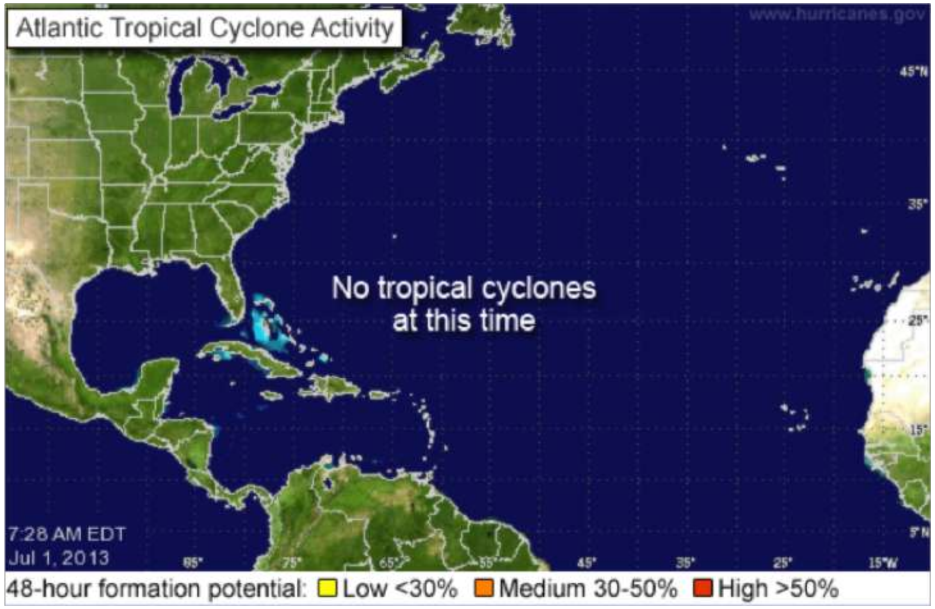
900m of instrumented beamline



From BNL to FNAL

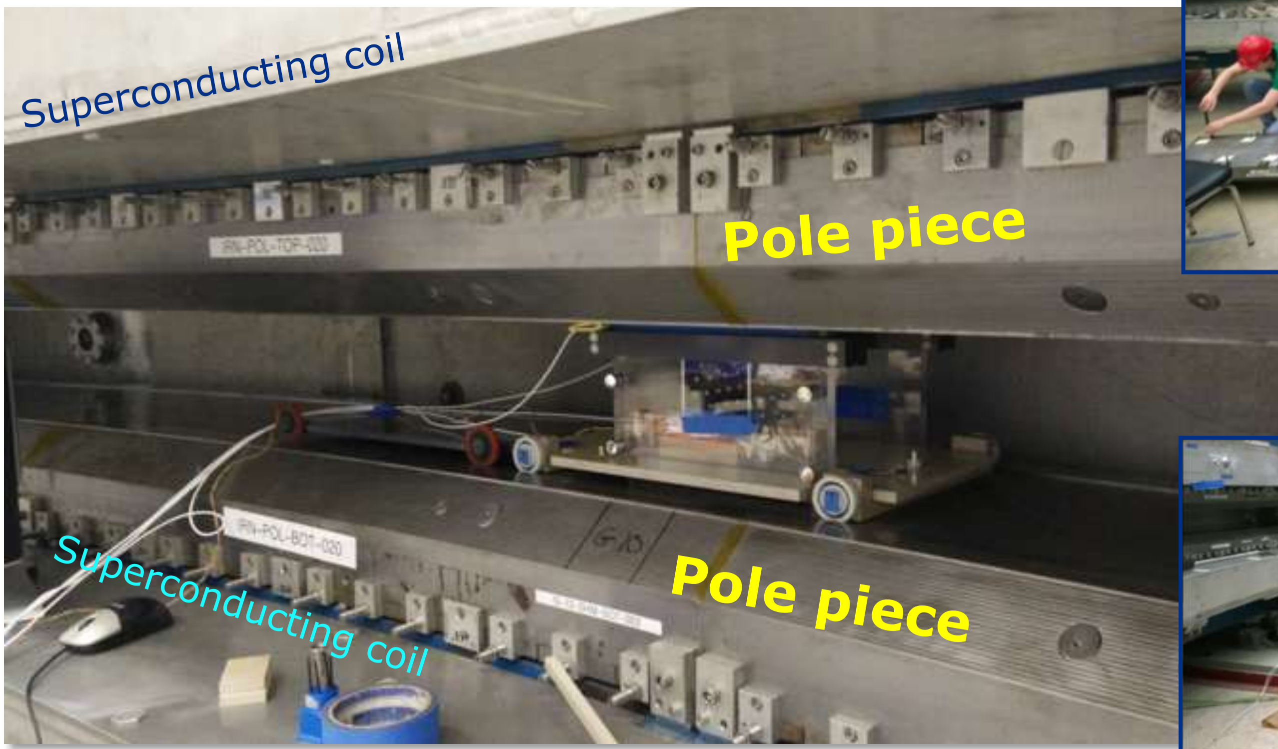






2.5 years to get magnet field uniformity

It took 2.5 years to shim the magnetic field to achieve the ppm uniformity required …

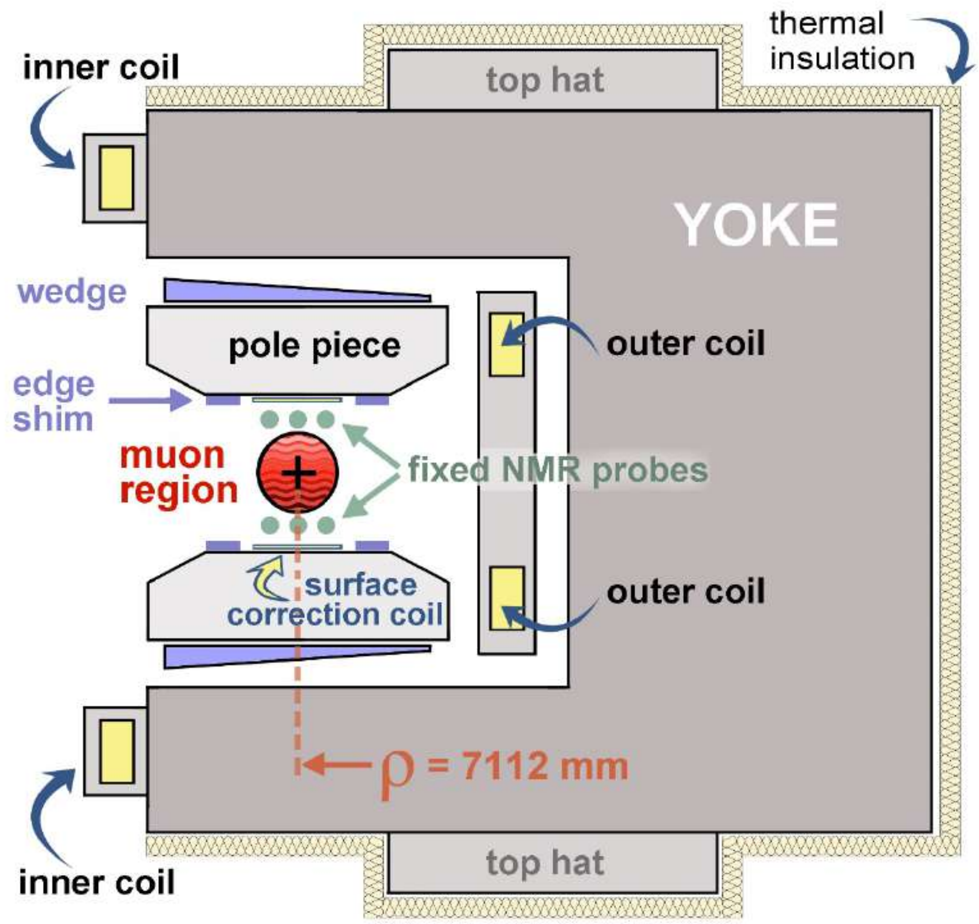


Anatomy of the magnet

Not simply a coil & 72 pole pieces but:

864 wedges
48 iron "top hats"
144 edge shims
8000 surface iron foils
100 active surface coils

requiring precision alignment & "shimming"



Yoke : 26 tons to 125 microns….

The kicker magnet

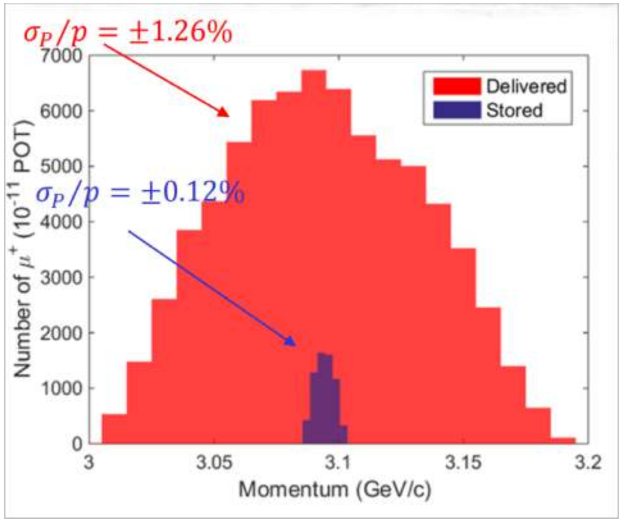
Shutdown performance issues

- Shutdown 2018 had a few key improvements to improve the number of muons we store:

System	Improvement	Gain
Accelerator	Beam Wedge	20%
	Power Supplies & Vacuum Window	11%
Kicker	Rework to provide higher strength	10%
Quads	More reliable operation at higher voltage	10%
Total		60%

- Total expected improvement is 1.6x run 1 storage rate
- Next year, will likely install new inflector (+40%)

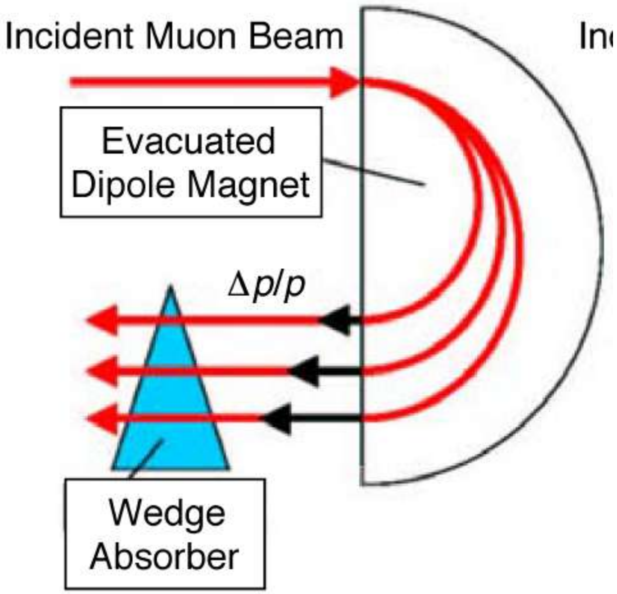
Beamline wedges

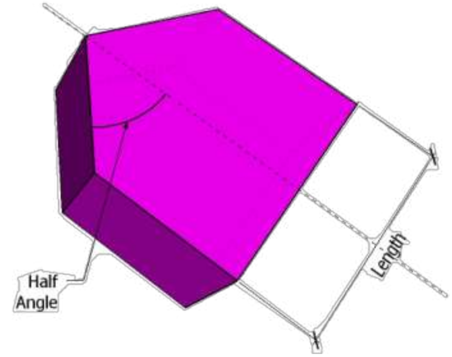


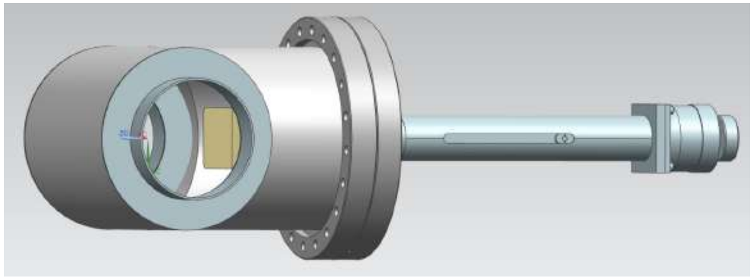
Only store a small fraction of delivered muons

Upstream wedges placed in region with dispersion to compactify momentum (during 2018 shutdown)

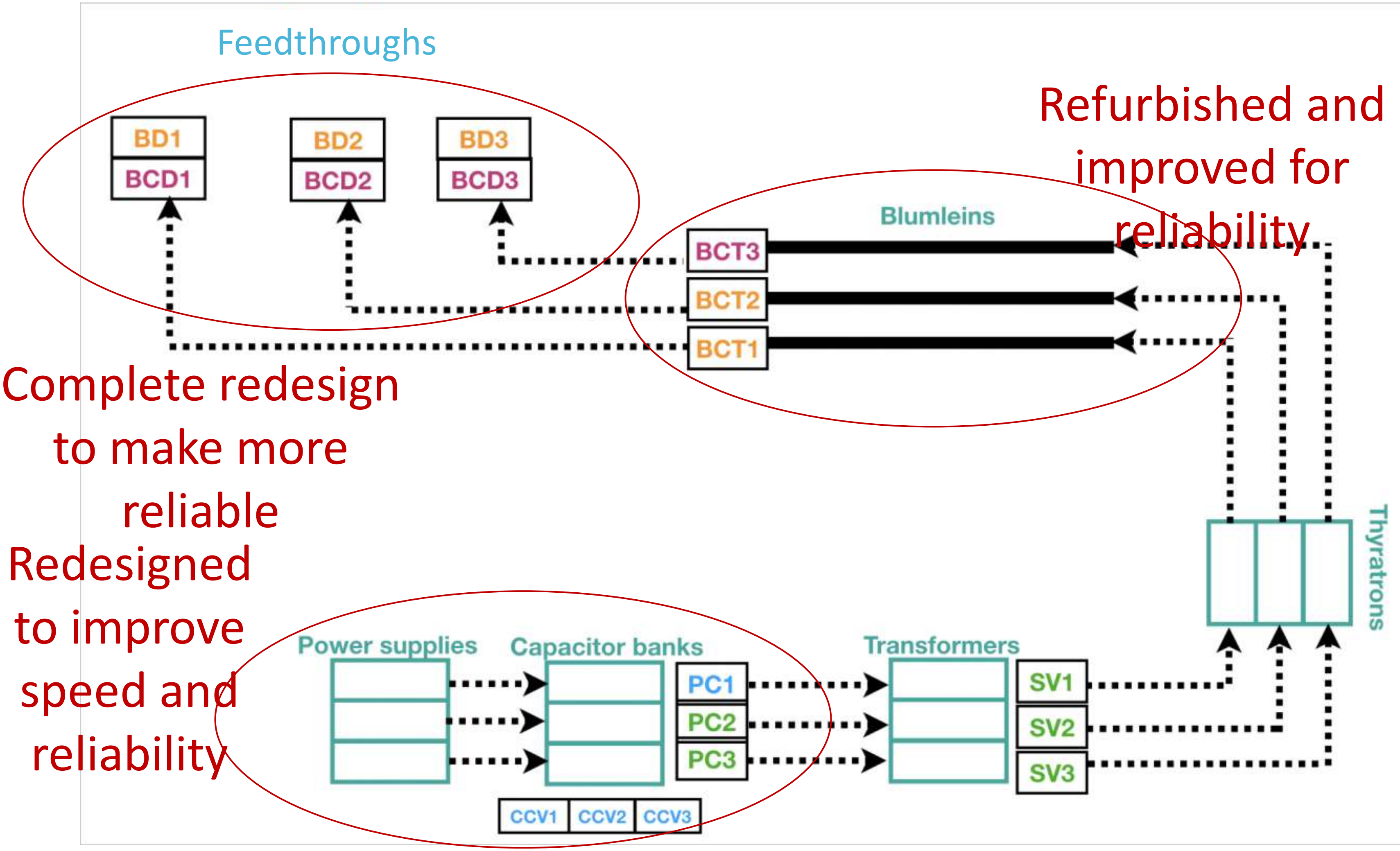
Simulations indicate gain of ~20%







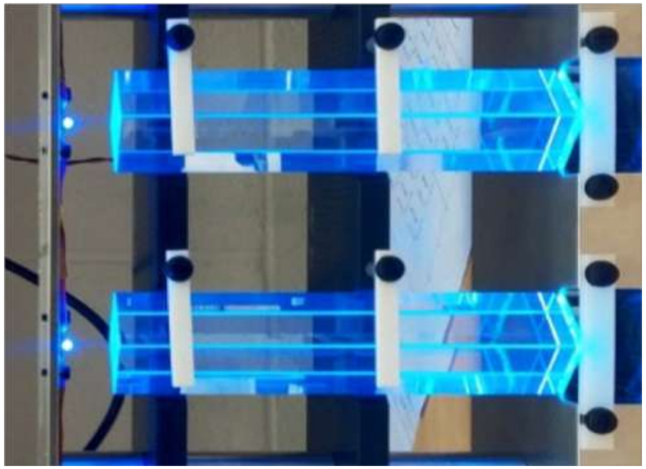
Kicker upgrade

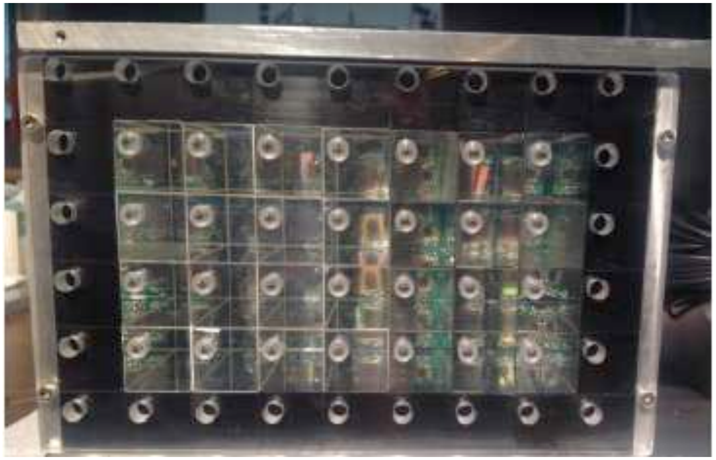


Expect +15% from more stored muons and better reliability

PbF_2 calorimeter

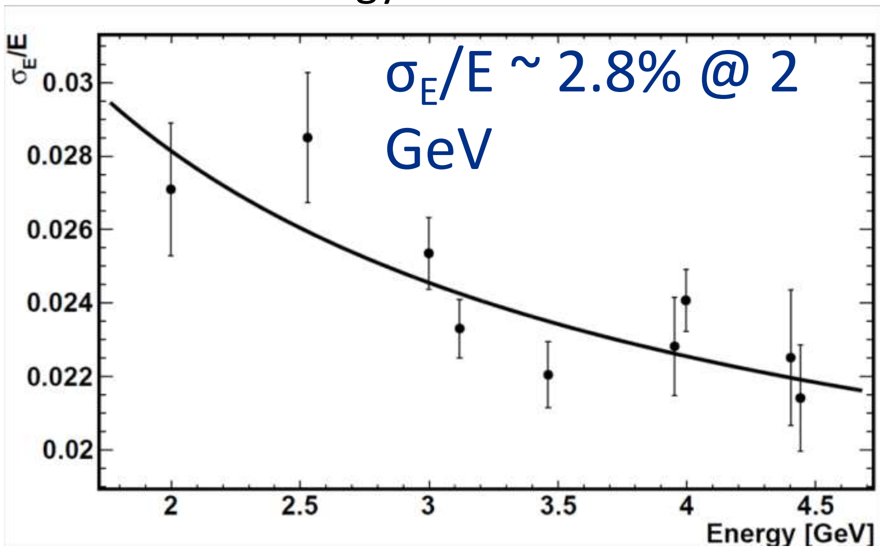
- Each calorimeter is array of 54 PbF_2 crystals - 2.5 x 2.5 cm^2 x 14 cm ($15X_0$)
- Readout by SiPMs to 800 MHz WFDs (1296 channels)



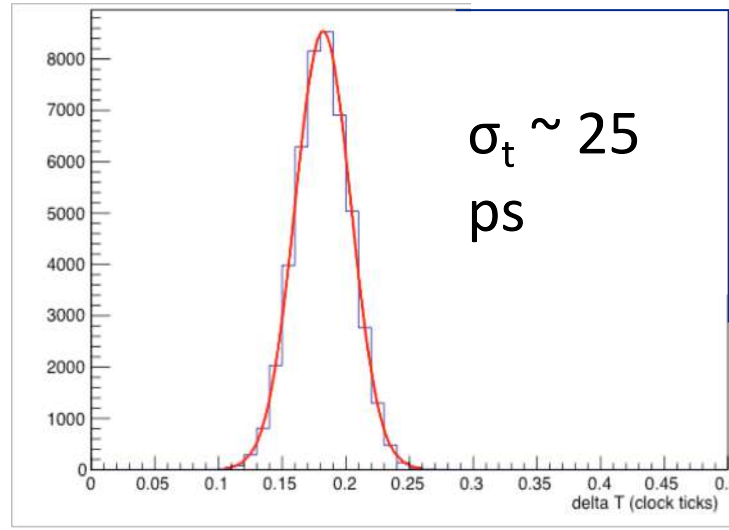


Calorimeter performance

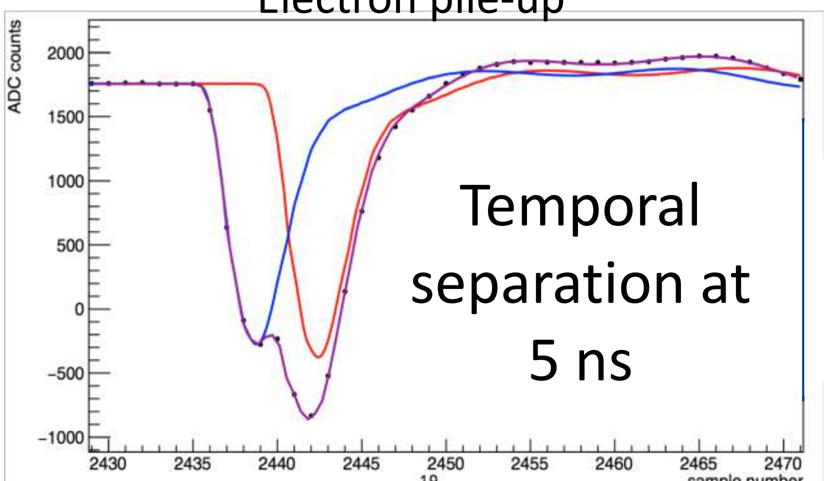
Energy Resolution



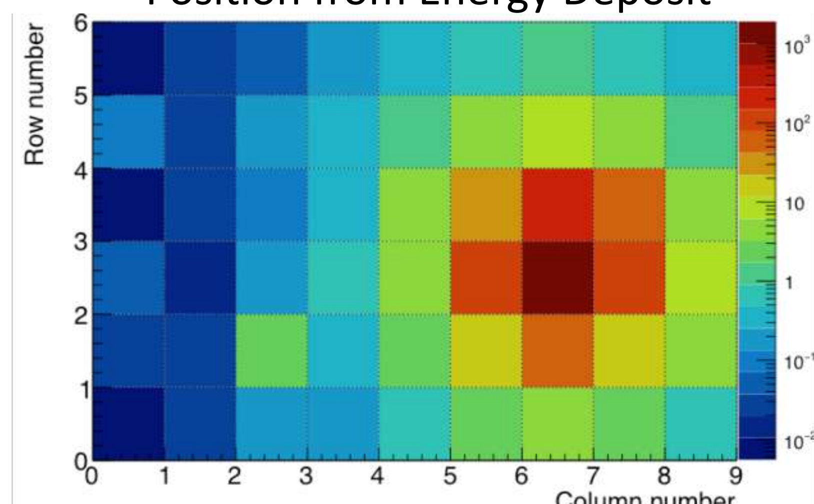
Timing Resolution



Electron pile-up



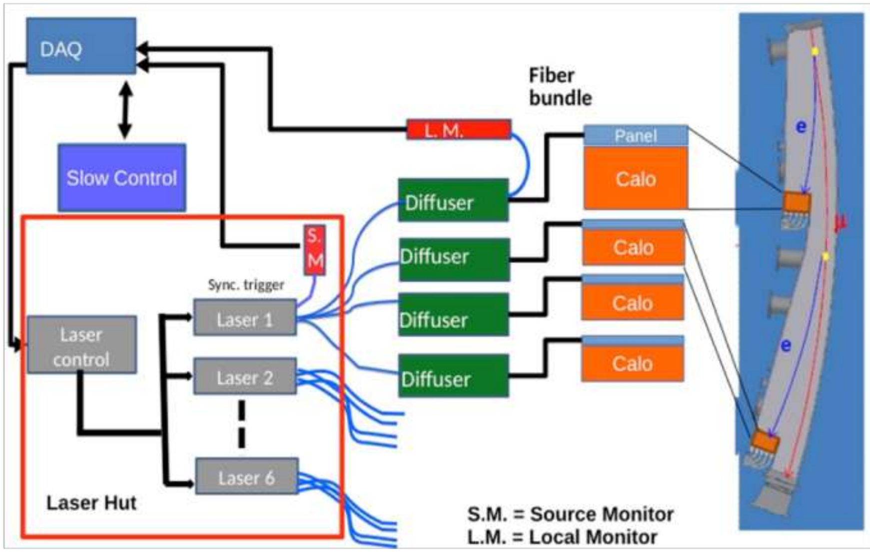
Position from Energy Deposit

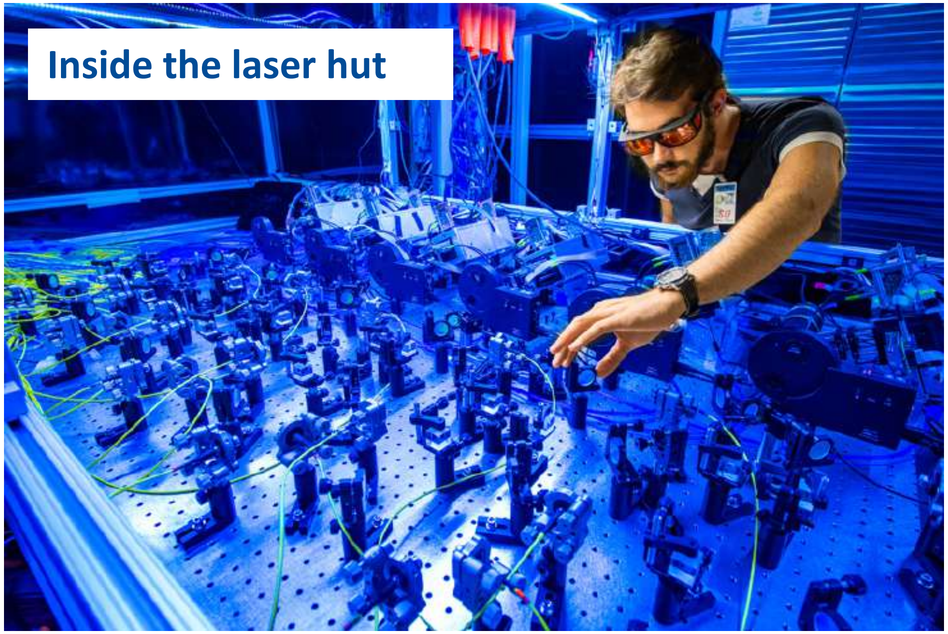


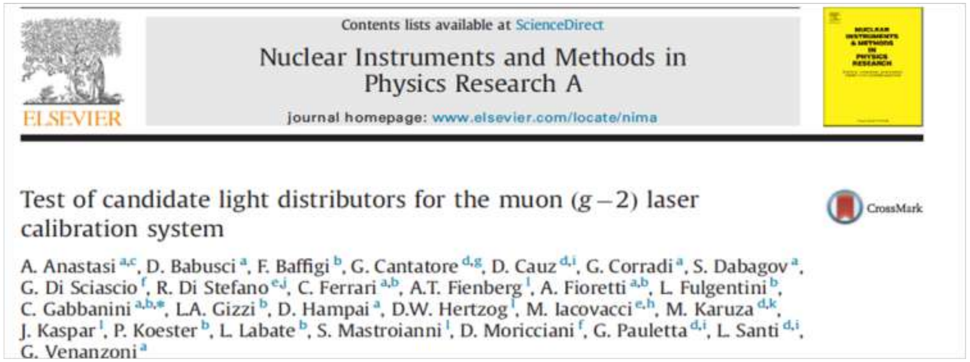
See NIM A 783 (2015), pp 12–21 for details

Gain stability

State-of-the-art Laser-based calibration system also allows for pseudo data runs for DAQ



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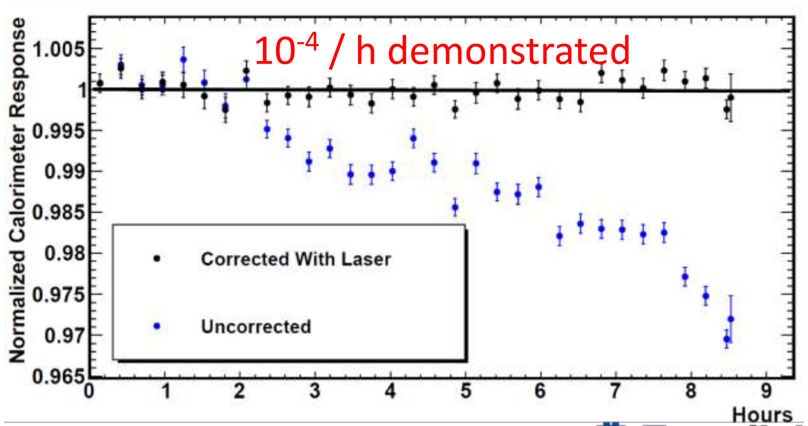
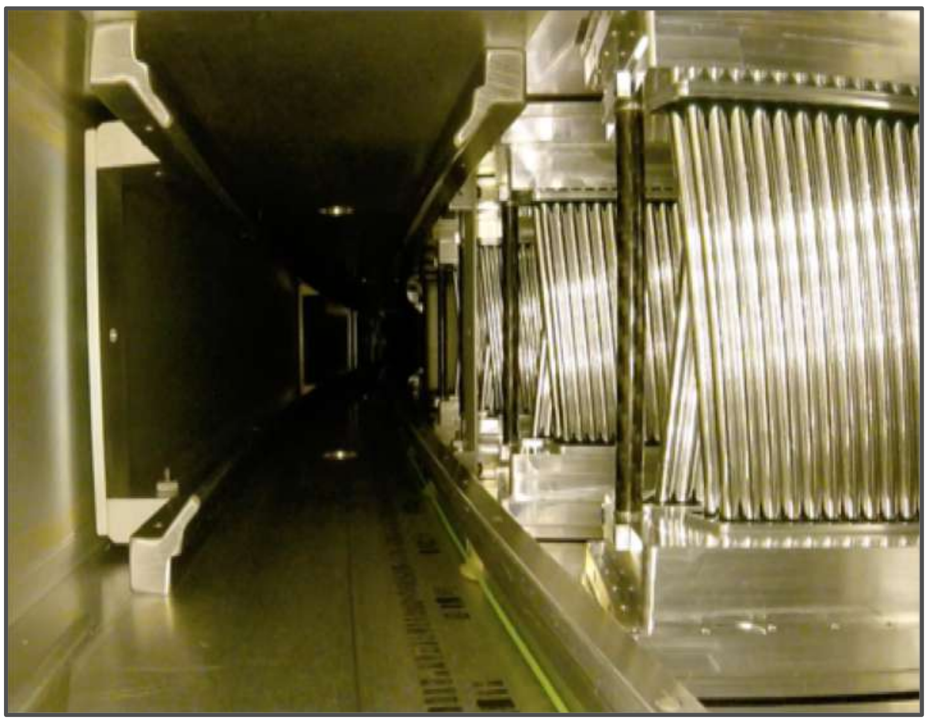
Test of candidate light distributors for the muon (g − 2) laser calibration system

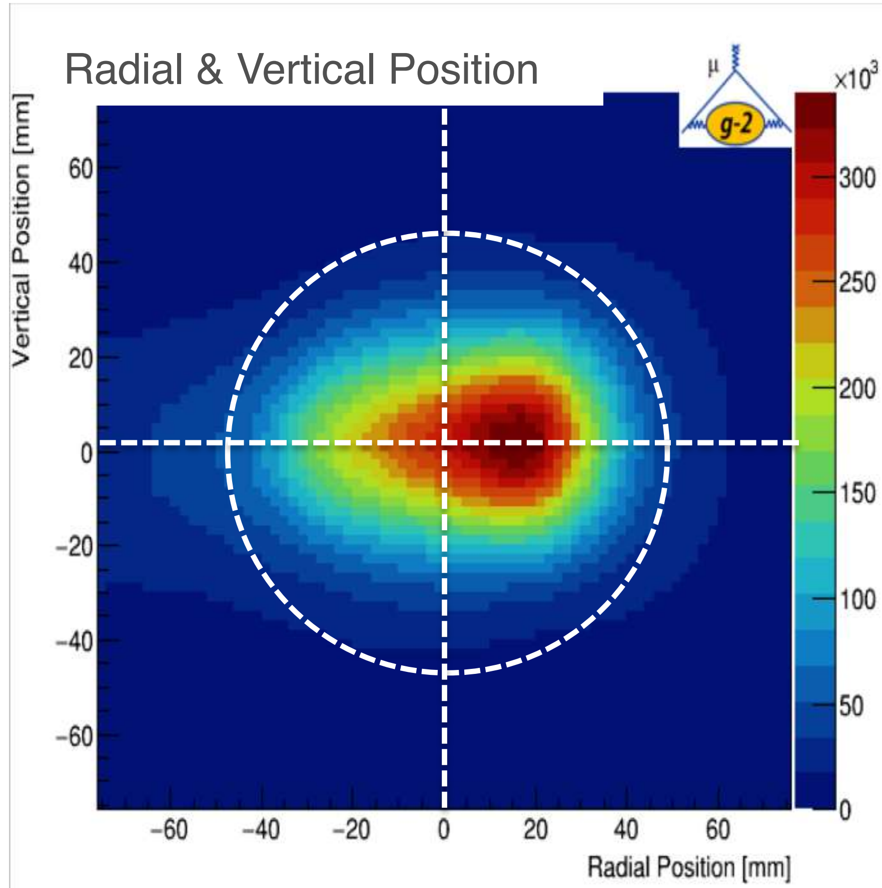
A. Anastasi[a,c], D. Babusci[a], F. Baffigi[b], G. Cantatore[d,g], D. Cauz[d,i], G. Corradi[a], S. Dabagov[a], G. Di Sciascio[f], R. Di Stefano[e,j], C. Ferrari[a,b], A.T. Fienberg[l], A. Fioretti[a,b], L. Fulgentini[b], C. Gabbanini[a,b,*], L.A. Gizzi[b], D. Hampai[a], D.W. Hertzog[l], M. Iacovacci[e,h], M. Karuza[d,k], J. Kaspar[l], P. Koester[b], L. Labate[b], S. Mastroianni[l], D. Moricciani[f], G. Pauletta[d,i], L. Santi[d,i], G. Venanzoni[a]



Trackers mapping the muon beam motion

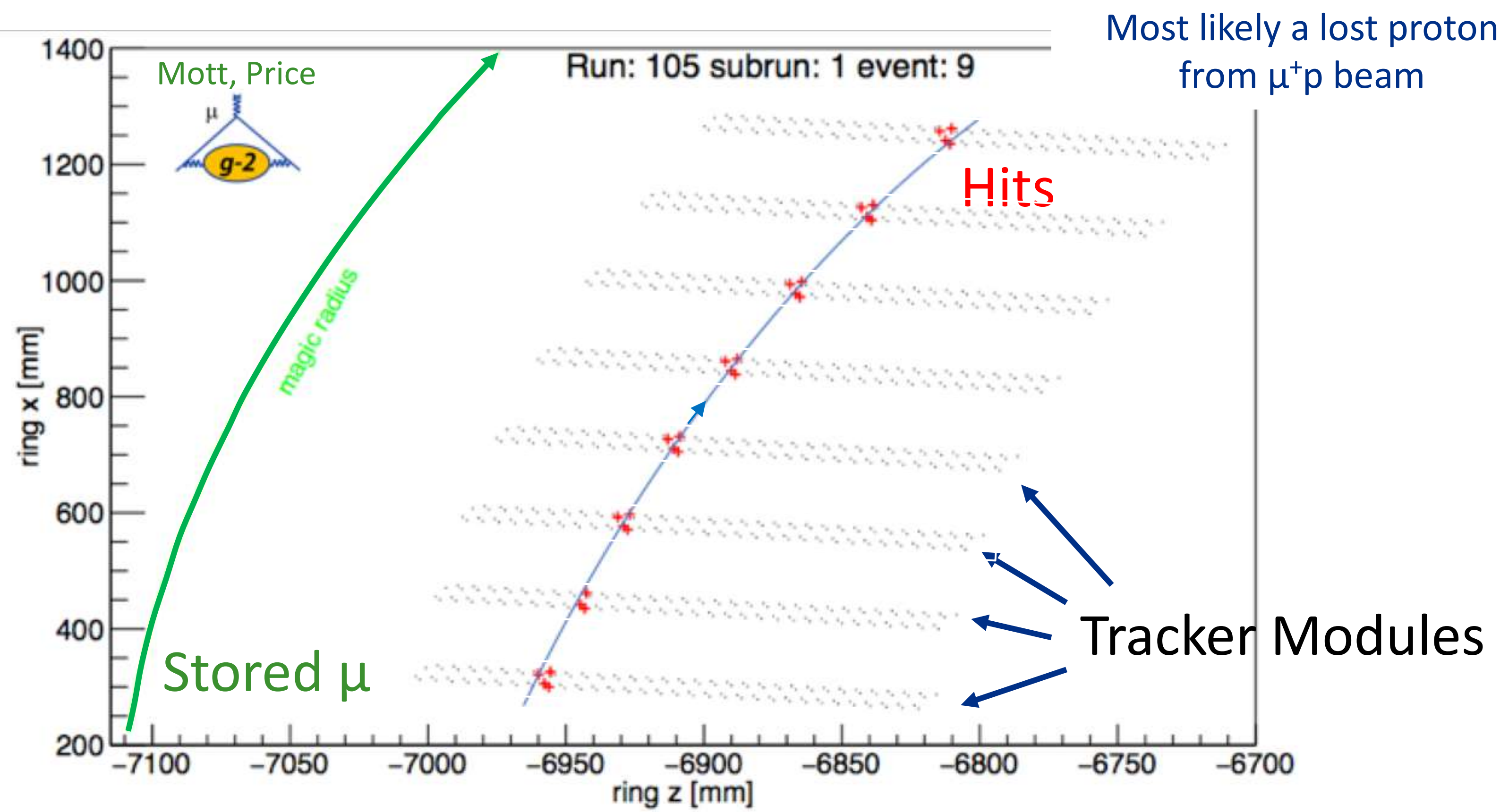
Cannot have detectors directly in the beam but instead we measure trajectory of decay e^+ and do an extrapolation back…





What does a track look like?

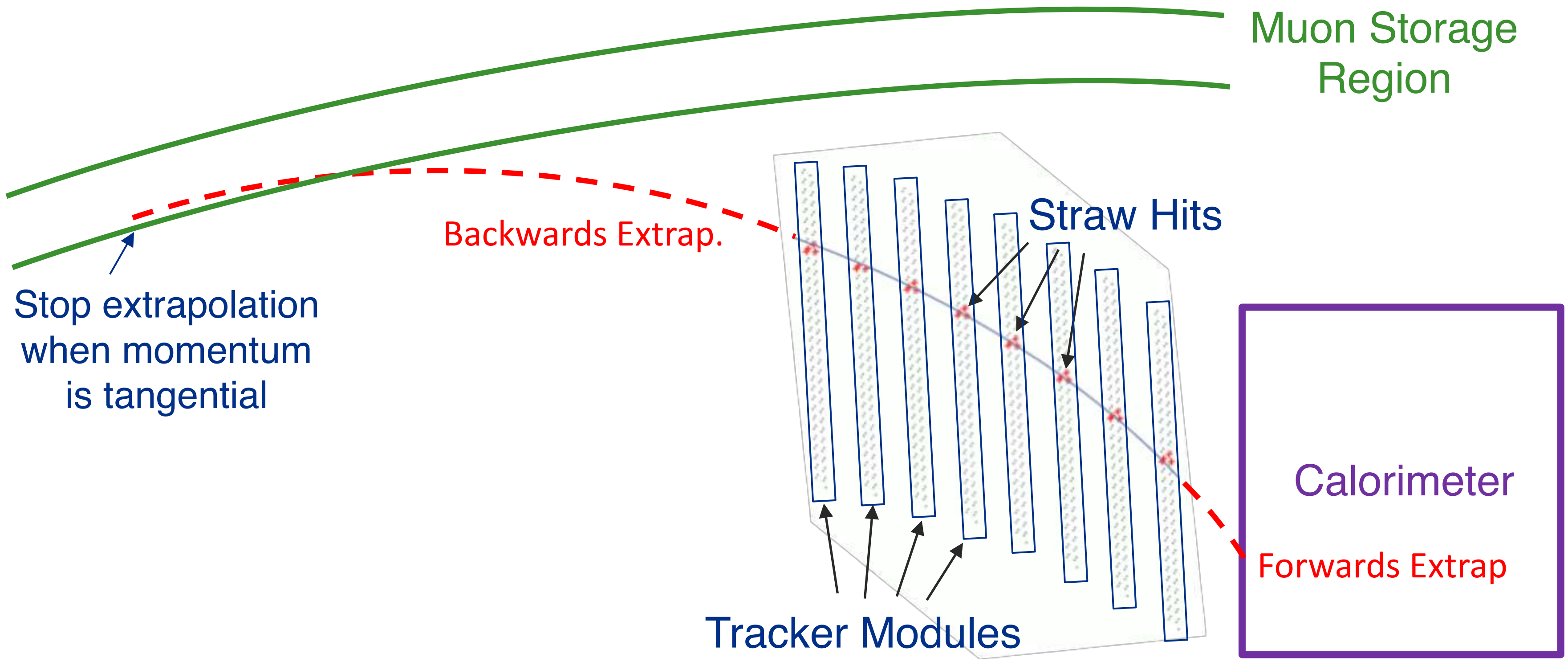
- First track seen at start of engineering run (June 2017)



- Track-fitting algorithm is a global χ^2 minimisation using Geant4 for particle propagation

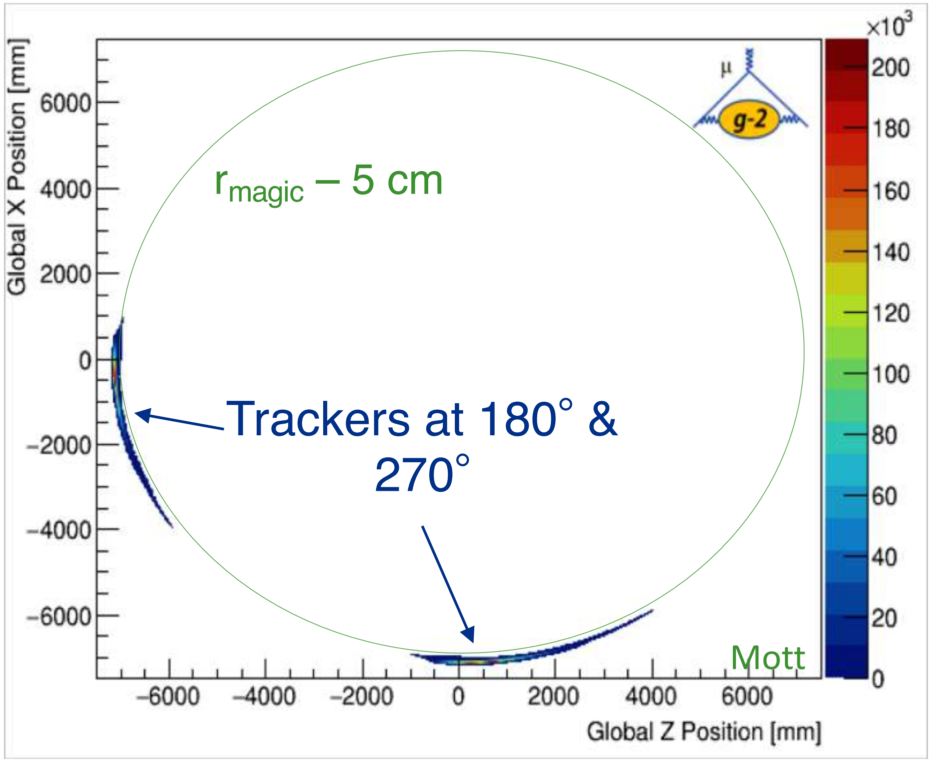
Track extrapolation

- We extrapolate tracks backwards to decay point and forwards to calorimeter:

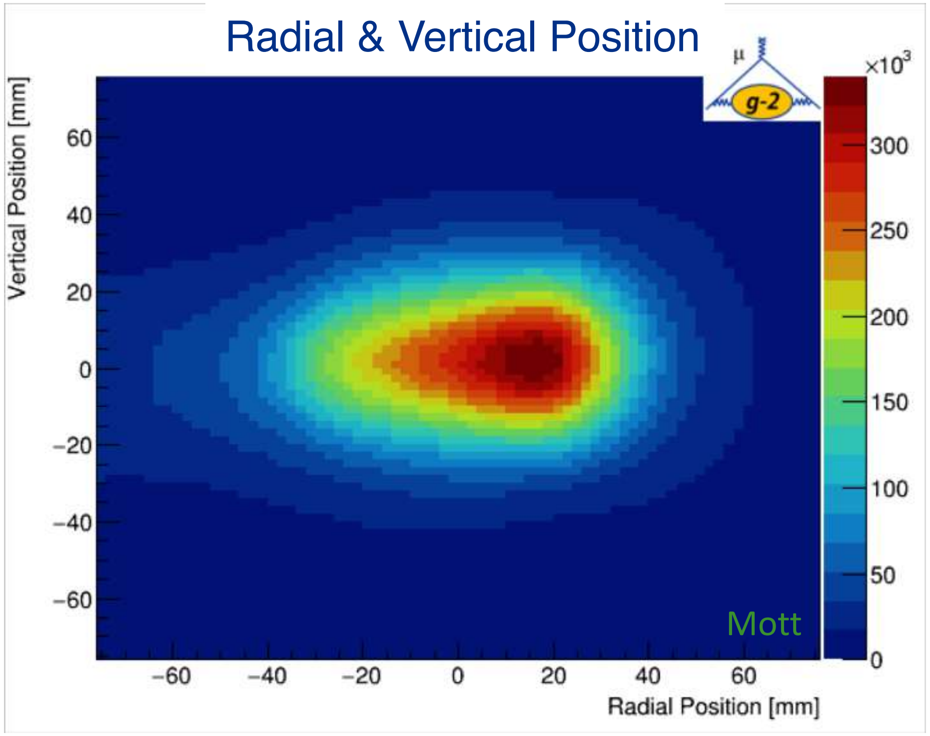


Beam distribution

- Extrapolate tracks to where they are tangential to magic radius:



Top-down view of decay vertices

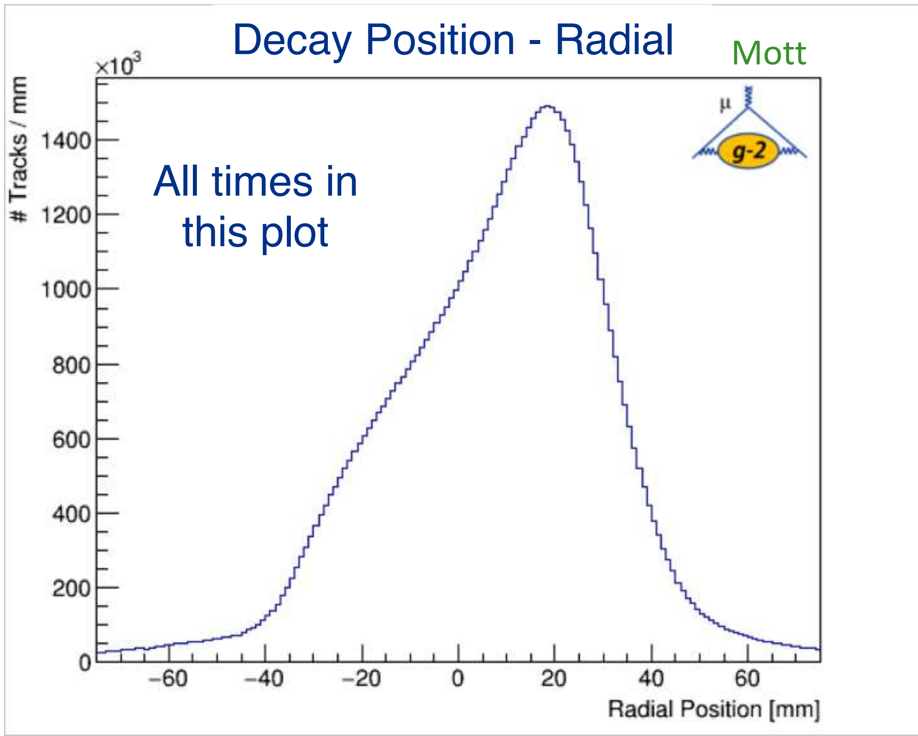


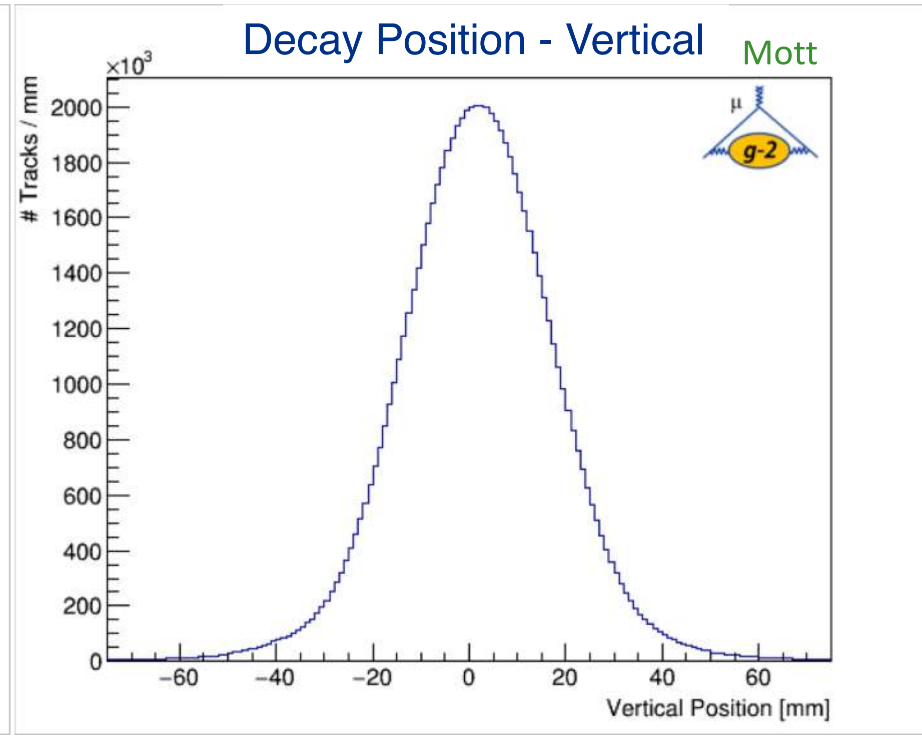
Projection of beam onto radial slice

- Use these distributions to get the effective field seen by the muons $B \circledast M_{\mu}$

Beam distribution

- Projections of 2D beam spot from previous slide onto radial and vertical directions:

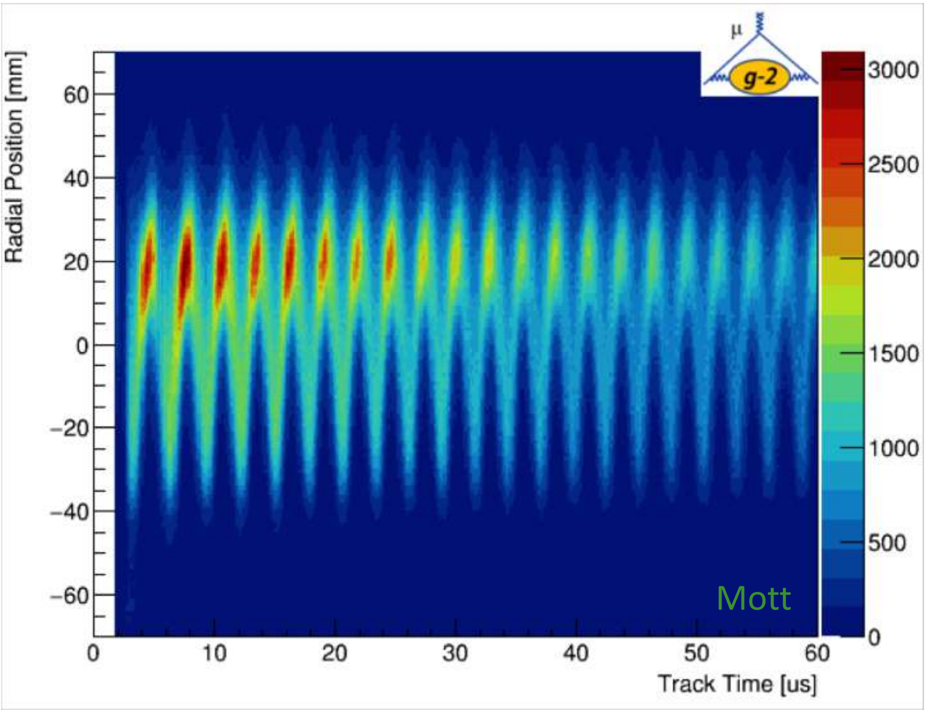




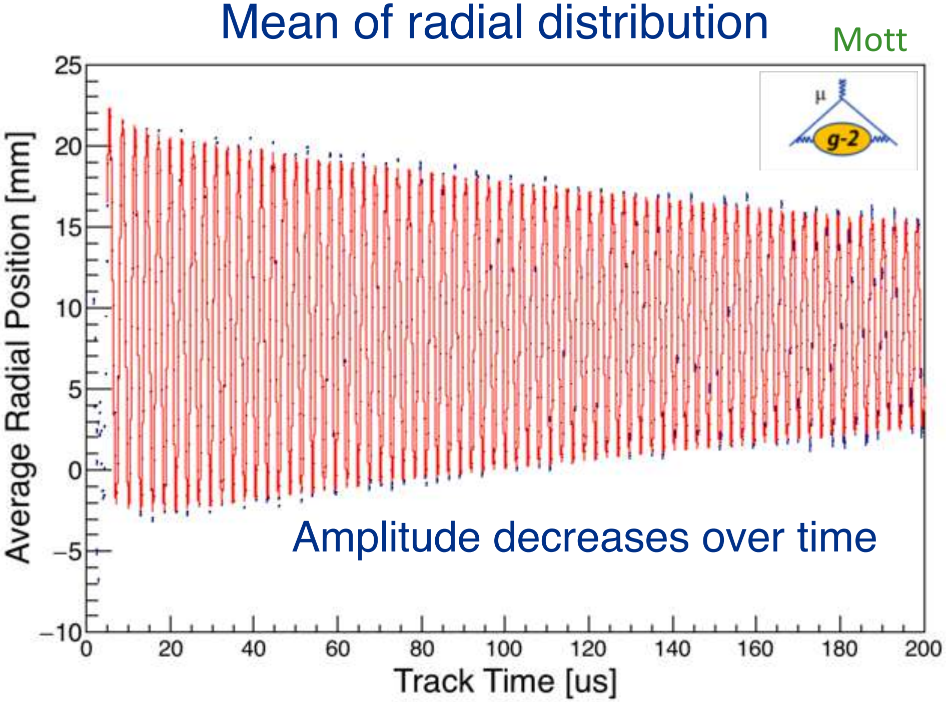
- Distributions are wider because the beam is oscillating
- We can also look at them in individual time slices…

Beam radial oscillation: amplitude

- Amplitude of radial oscillation decreases as beam spreads out:



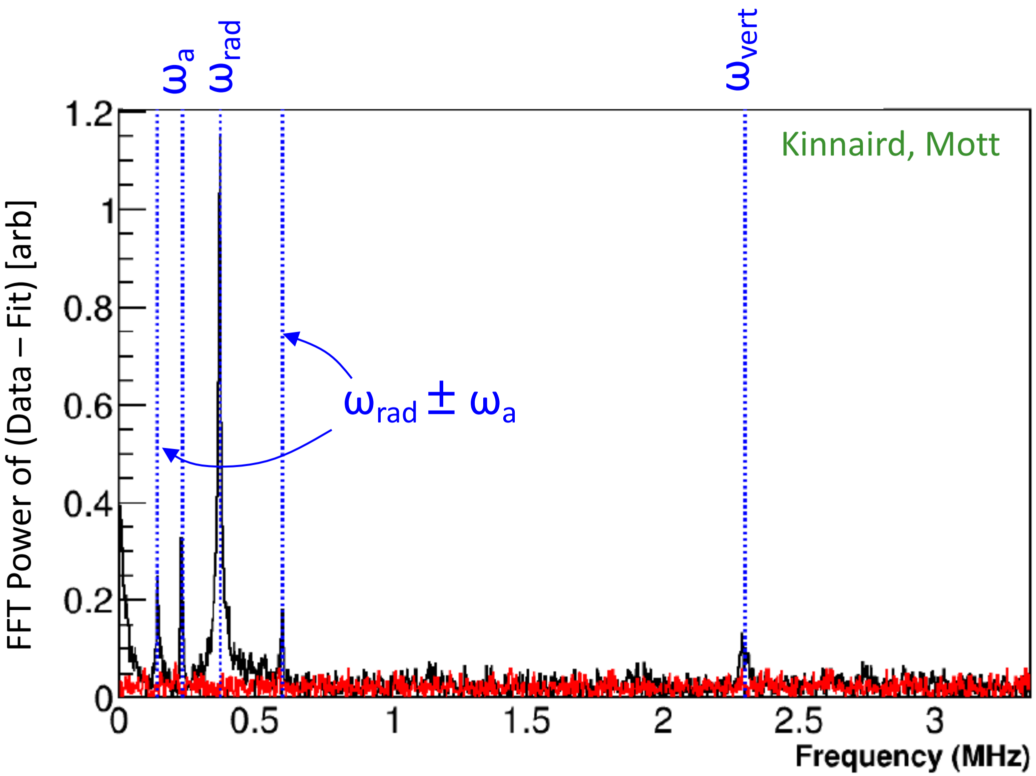
Mean of radial distribution

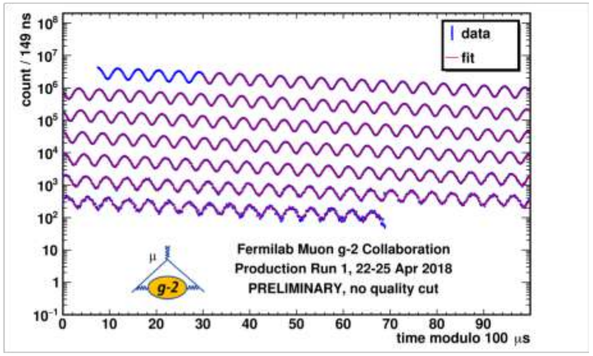


- Tracker measurements essential for calorimeter ω_a analysis:
  – Amplitude shape and lifetime
  – Oscillation frequency change

Beam radial oscillations and ω_a

- Beam oscillations couple to acceptance – change number of e^+ detected with time
- Oscillation frequencies in fit residuals which are removed by modifying fit function:





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

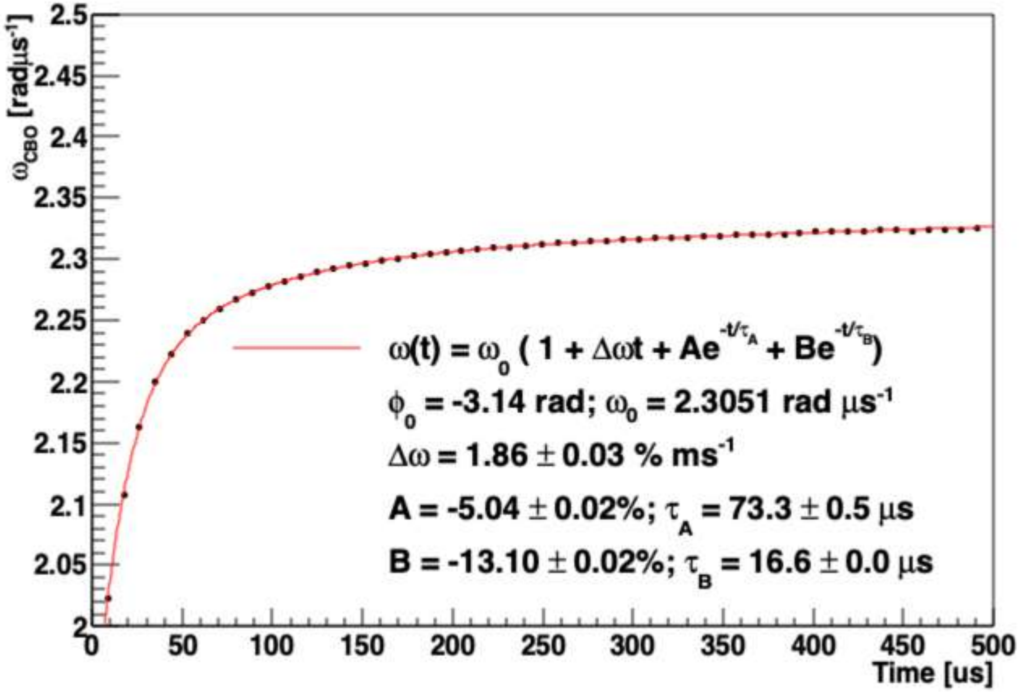
χ^2 / ndf = 7006 / 3148

Fit* including beam oscillations

χ^2 / ndf = 3052 / 3145

Beam radial oscillations: frequency

- We expected the oscillation frequency to be constant but I found that it was changing over time:

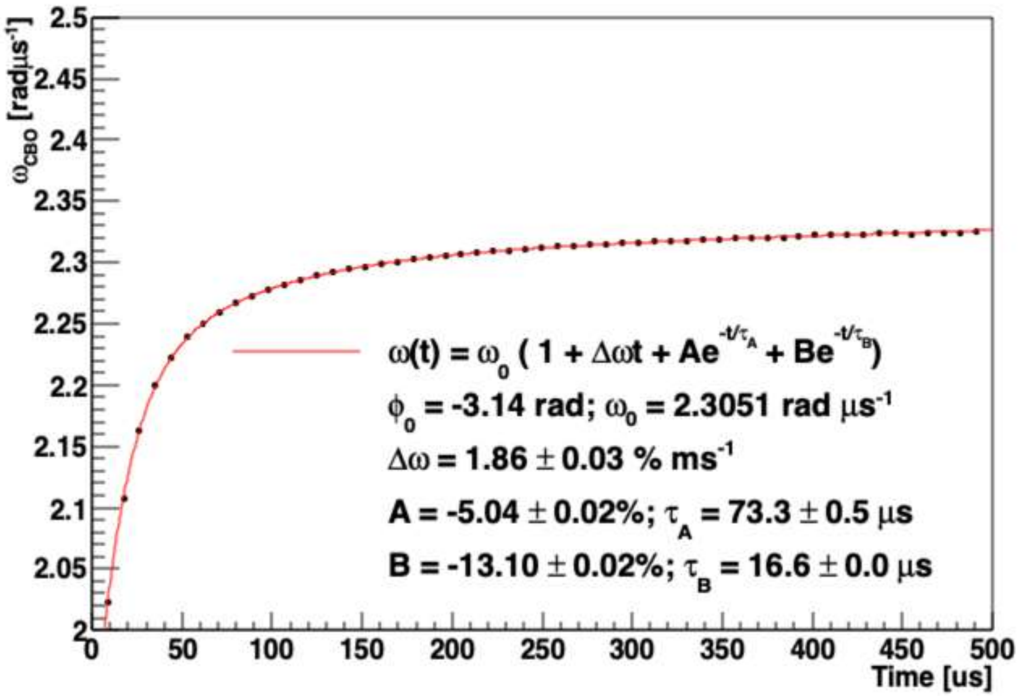


- Helped us to eventually locate the problem as faulty resistors in the electrostatic quadrupole system.

*Raio fit

Beam radial oscillations: frequency

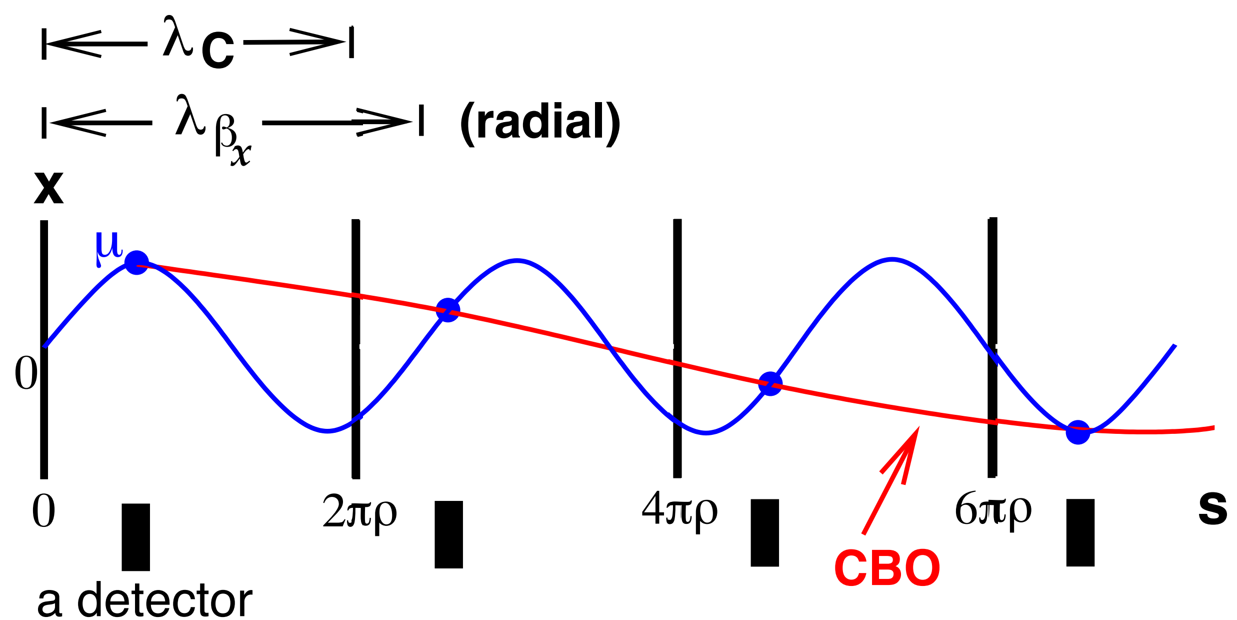
- We expected the oscillation frequency to be constant but I found that it was changing over time:



- Helped us to eventually locate the problem as faulty resistors in the electrostatic quadrupole system.

*Raio fit

Coherent betatron oscillations



$$f_{\rm CBO} = f_C - f_x = (1 - \sqrt{1-n}) f_c$$

$$\lambda_{\rm CBO} \simeq \ 14 \ \rm turns$$

- Detector acceptance depends on the radial coordinate x.
- The CBO amplitude modulates the signal in the detectors

Weak focusing betatron

$$\text{Field index}: n = \frac{R_0}{\beta B_0}\frac{dE_r}{dr} \simeq 0.135$$

$$\text{radial}: f_x = f_C\sqrt{1-n} \simeq 0.929 f_c$$

$$\text{vertical}: f_y = f_C\sqrt{n} \simeq 0.37 f_C$$

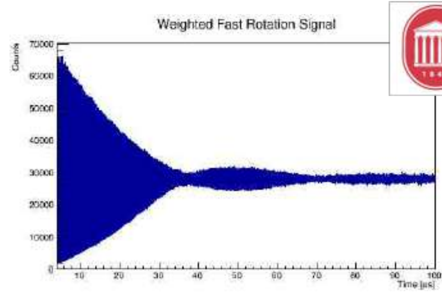
- The beam moves coherently radially relative to a detector with the “Coherent Betatron Frequency (CBO)

$$f_{\text{CBO}} = f_C - f_x = (1-\sqrt{1-n})f_C$$

The fast rotation analysis (FRA)

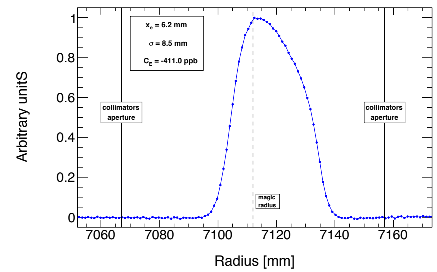
What's so important about the fast rotation?

Fast rotation analysis ⟷



↓

Radial Distribution ⟷



↓

Muon equilibrium radius ⟷ x_e

↓

Electric (E) field correction ⟷ $C_E = -2\langle n\rangle(1-\langle n\rangle)\beta^2 \frac{\langle x_e^2\rangle}{R_0^2}$

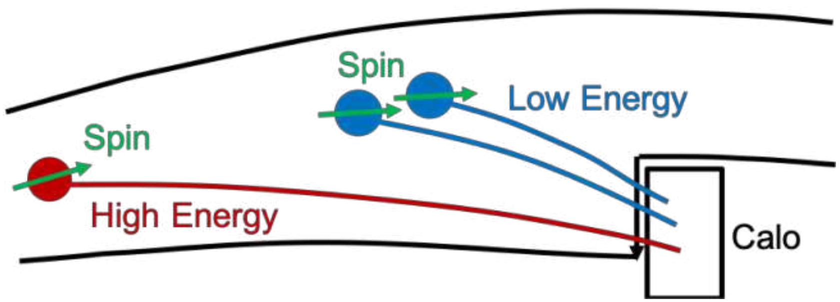
There are two approaches to the FRA:

1. The Fourier transform method
2. The CERN III method

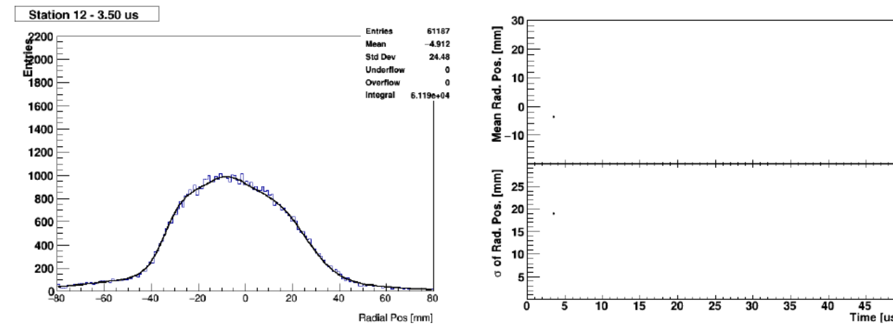
Should be in agreement to achieve E989 E and pitch correction goal of < 30ppb

Main systematic issues

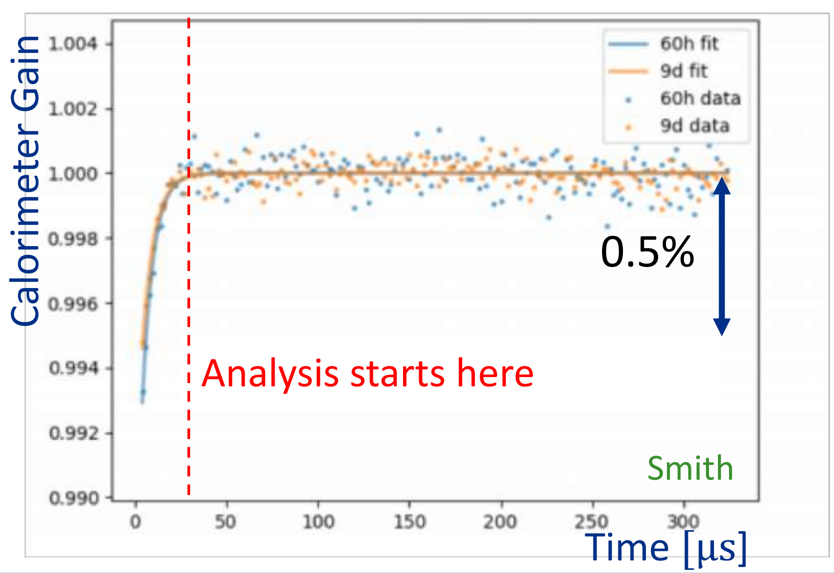
Pile Up



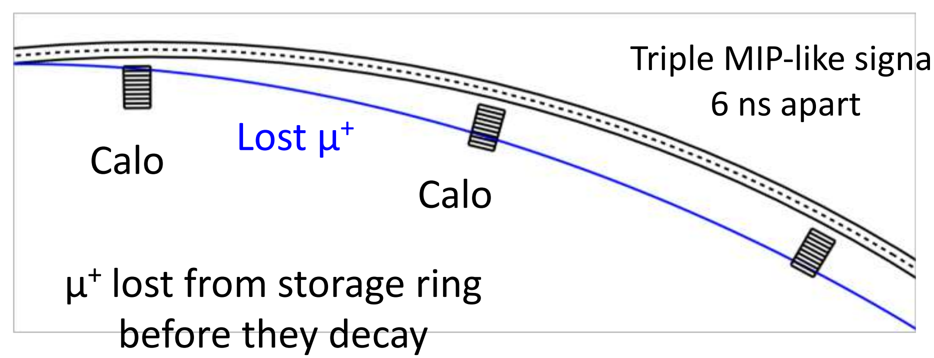
Beam Oscillations



Gain Change

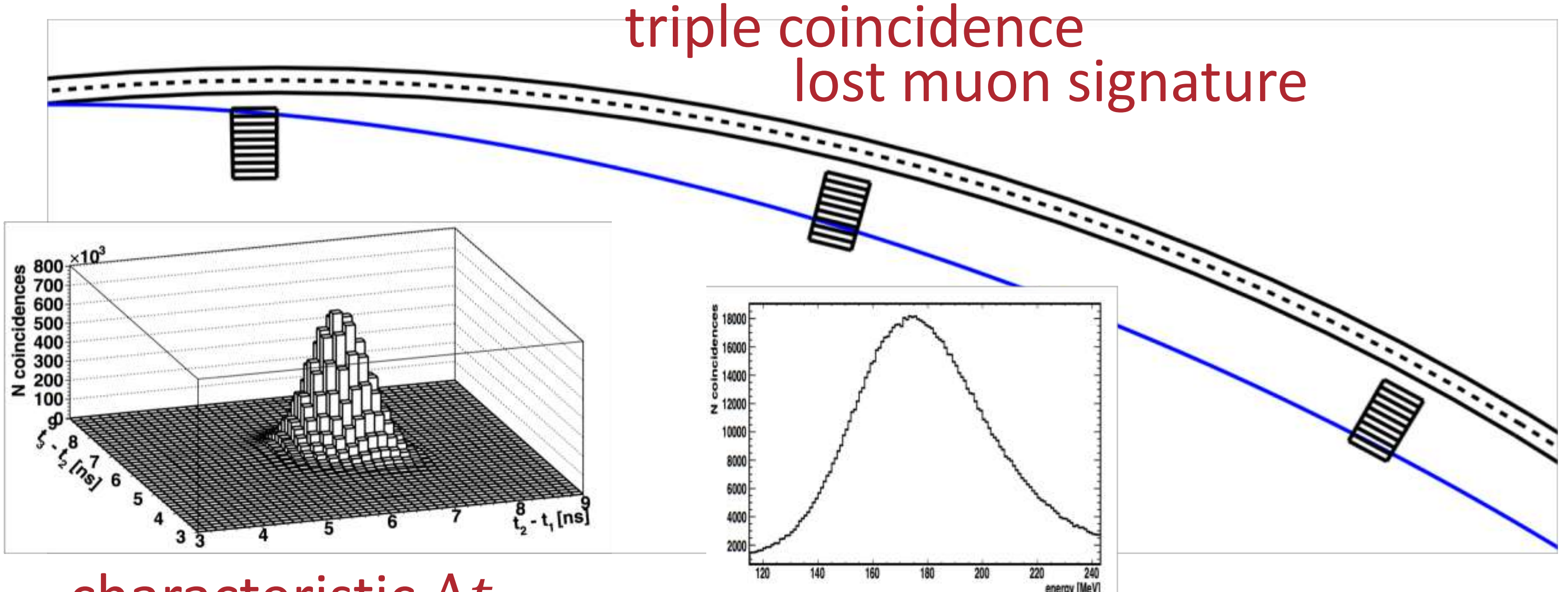


Lost Muons

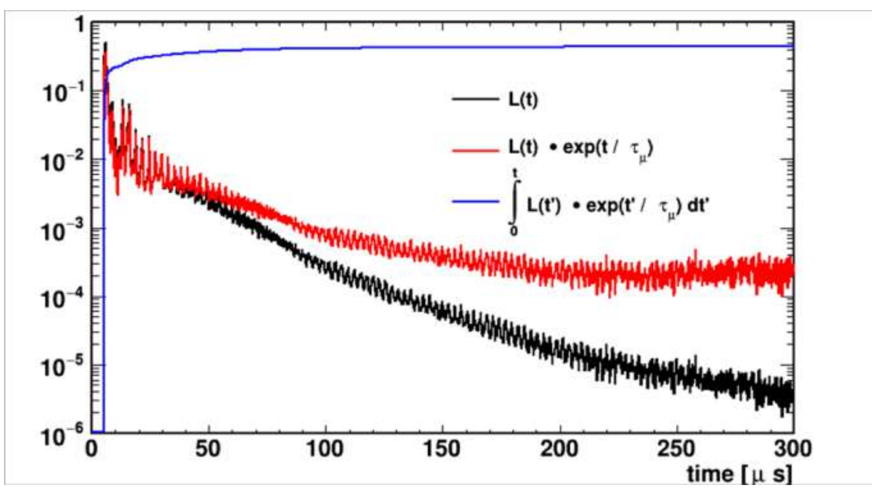


Lost muons

triple coincidence
lost muon signature



characteristic Δt



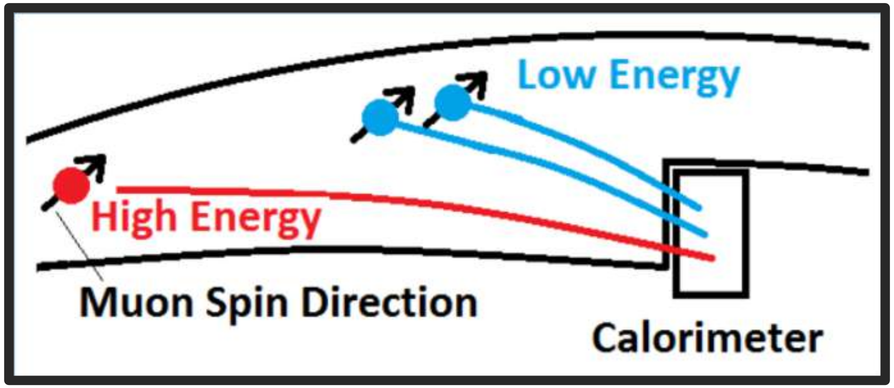
MIP-like energy deposition

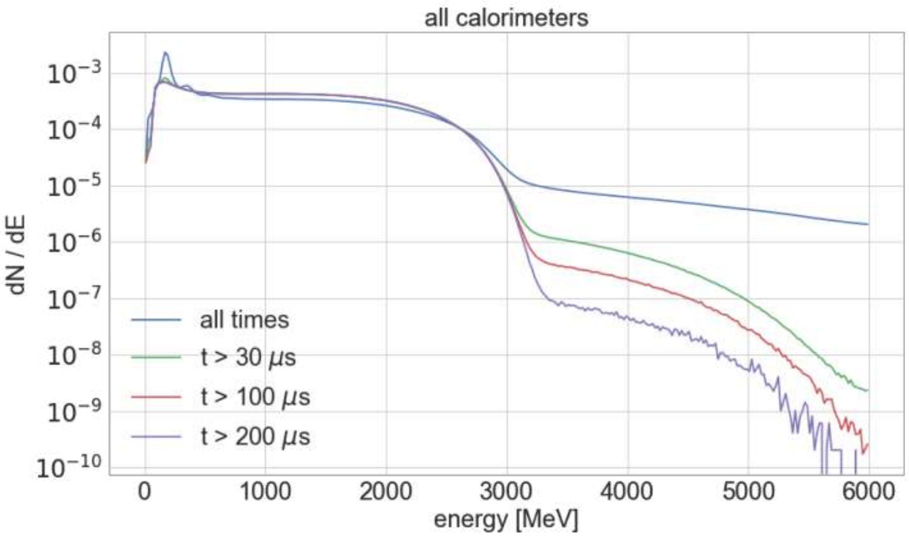
Describes the rate of muons escaping the ring; not decaying

Pileup and energy calibration

Direction of muon spin depends on energy of e^+

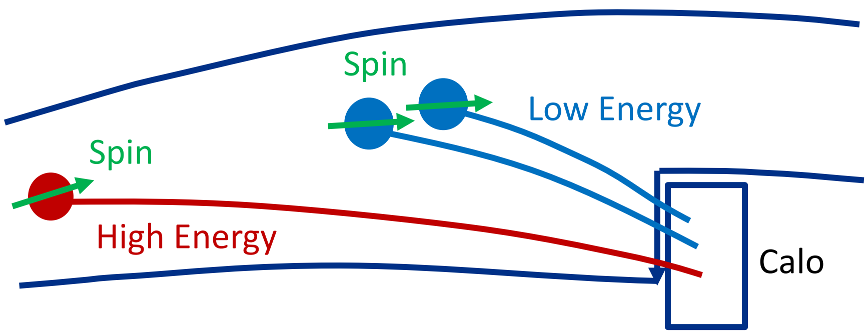
- need to track variations in energy calibration (laser system)
- correct for when two low energy e^+ fake one high energy (pileup)



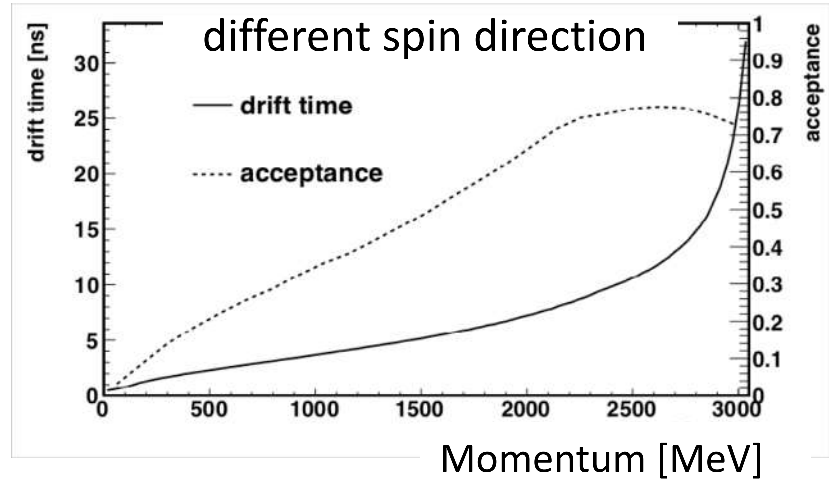


Pileup

Two low E e⁺ can look like one high energy e⁺



Different travel time means different spin direction



- Pile up happens less often as the muons decay so phase changes with time and we get ω_a wrong

- Derive a pile up correction from data and check validity above 3.1 GeV