Fermilab Measurement of Muon g-2

Dave Kawall, University of Massachusetts Amherst, on behalf of the Muon g-2 Collaboration

Goal: Measure the muon anomalous magnetic moment a_μ to 140 ppb, a fourfold improvement over the 540 ppb precision of Brookhaven

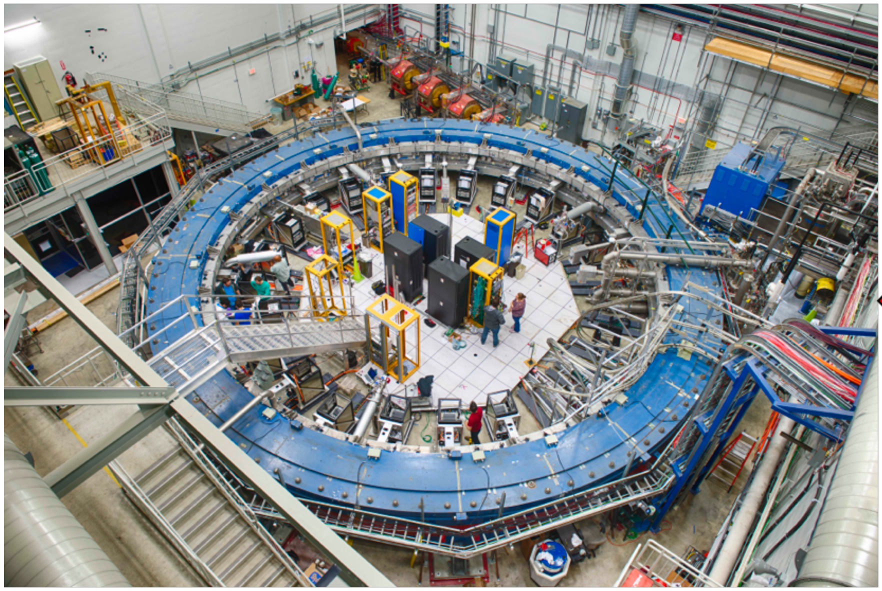
Muon g-2 experiment collaboration

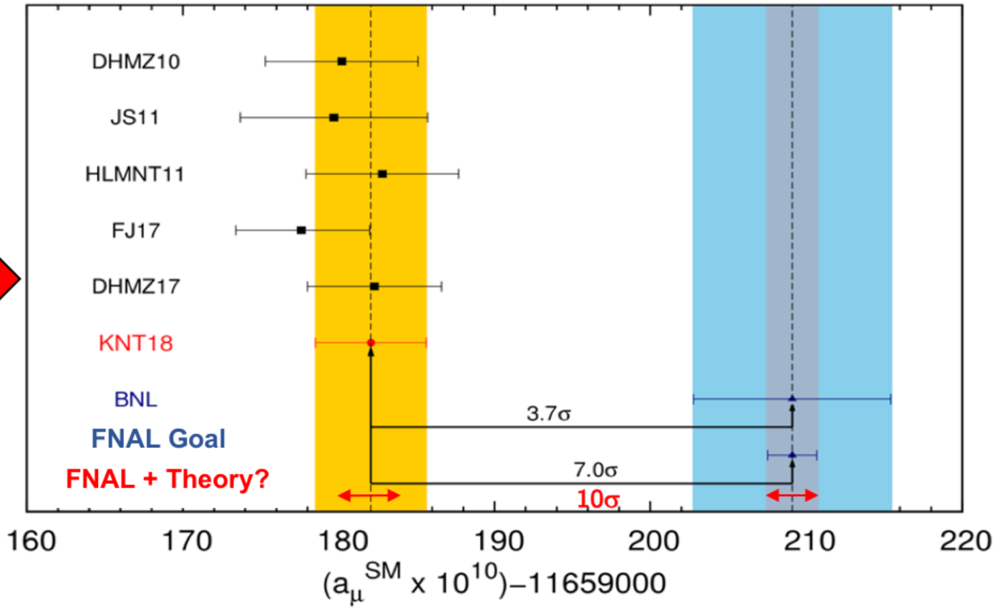
Muon g-2 Collaboration

7 Countries, 34 Institutions, 185 Collaborators

Argonne National Laboratory
Boston University
Brookhaven National Laboratory
Budker Institute of Nuclear Physics
CAPP/IBS Korea
Cornell University
Fermi National Accelerator Lab
INFN, Sezione di Napoli
INFN, Sezione di Pisa
INFN, Sezione di Roma Tor Vergata
James Madison University
JINR Dubna
KAIST
Laboratory Nazionali di Frascati
Lancaster University
Michigan State University
North Central College
Northern Illinois University
Regis University
Shanghai Jiao Tong University
Technische Universitat Dresden
Universita di Molise
Universita di Udine
University College London
University of Illinois at Urbana-Champaign
University of Kentucky
University of Massachusetts Amherst
University of Michigan
University of Mississippi
University of Texas at Austin
University of Virginia
University of Washington

Thanks to Everyone for your Effort!





arXiv:1802.02995 [hep-ph]

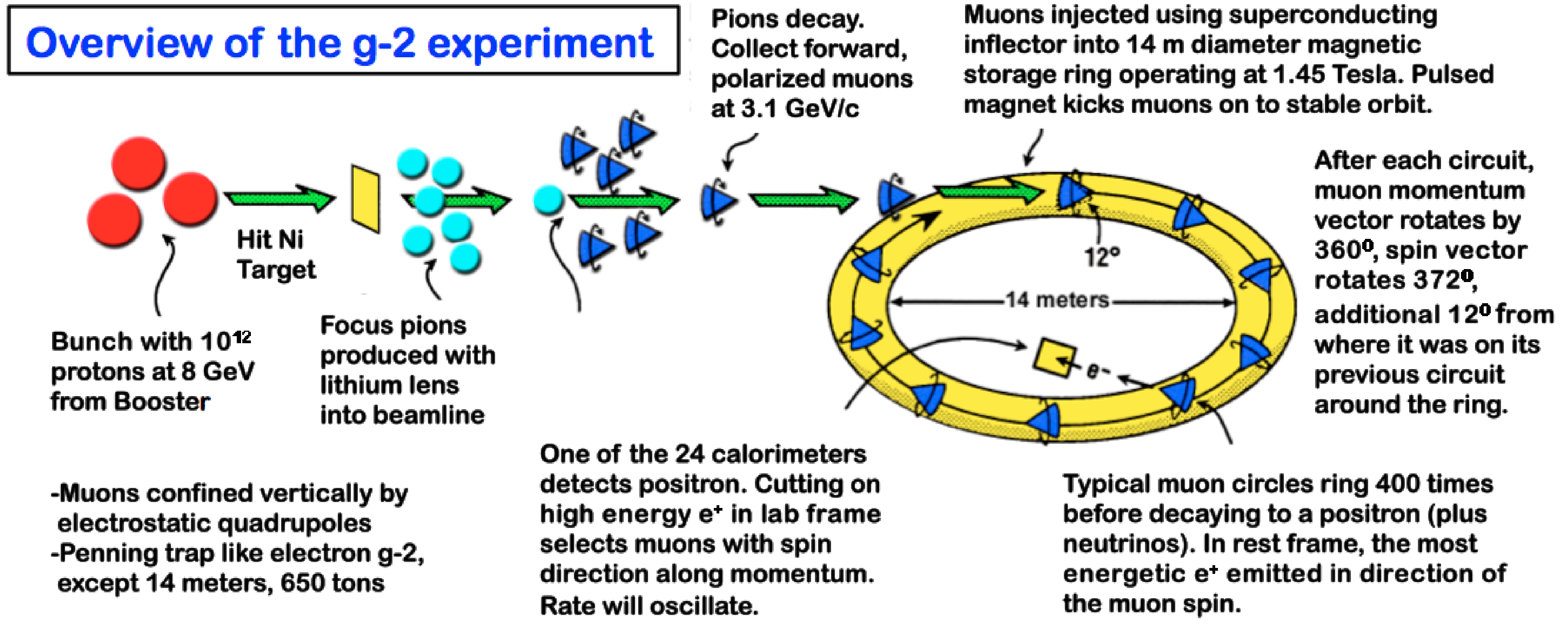
- All here to improve SM Prediction and Measurement of a_μ
- Wouldn't be here except for rare combination of circumstances:

(1) We can measure a_μ really well
(2) You can predict a_μ really well
(3) The comparison can change future direction of physics

- 3.5 σ discrepancy on a_μ large compared to EW contribution: 27×10^{-10} vs 15.36×10^{-10}

- Great challenge for physics! Thanks for your efforts!

Overview of the Measurement Technique



Overview of the g-2 experiment

Bunch with 10^{12} protons at 8 GeV from Booster

Focus pions produced with lithium lens into beamline

Pions decay. Collect forward, polarized muons at 3.1 GeV/c

Muons injected using superconducting inflector into 14 m diameter magnetic storage ring operating at 1.45 Tesla. Pulsed magnet kicks muons on to stable orbit.

After each circuit, muon momentum vector rotates by 360°, spin vector rotates 372°, additional 12° from where it was on its previous circuit around the ring.

-Muons confined vertically by electrostatic quadrupoles
-Penning trap like electron g-2, except 14 meters, 650 tons

One of the 24 calorimeters detects positron. Cutting on high energy e^+ in lab frame selects muons with spin direction along momentum. Rate will oscillate.

Typical muon circles ring 400 times before decaying to a positron (plus neutrinos). In rest frame, the most energetic e^+ emitted in direction of the muon spin.

- 14 meter radius, 650 tons Penning trap for 3.1 GeV muons
- Radial confinement: 1.45 T B field; vertical confinement: electric quadrupoles
- Superconducting inflector to inject muons in ring
- Pulsed magnetic kickers put muons on stored orbit

Overview of the *Idealized* Measurement Technique

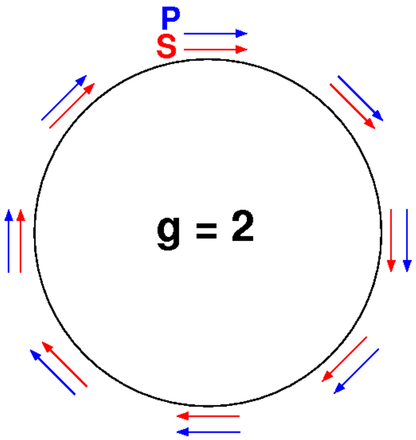
- Inject polarized muons into **magnetic** storage ring 1.45 T

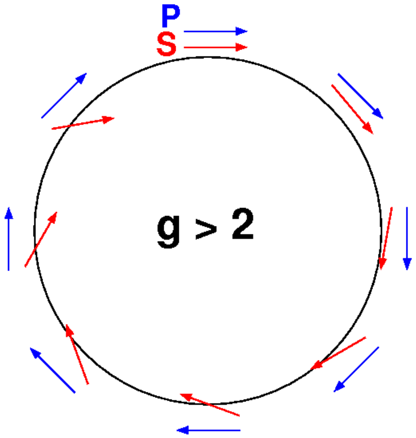
$$\vec{\omega}_{\text{cyclotron}} = \frac{e}{\gamma m}\vec{B} \approx 2\pi \times 6.7\,\text{MHz}$$

$$\vec{\omega}_{\text{spin}} = g\frac{e}{2m}\vec{B} - (1-\gamma)\frac{e}{\gamma m}\vec{B} \approx 2\pi \times 6.9\,\text{MHz}$$

$$\vec{\omega}_a \equiv \vec{\omega}_s - \vec{\omega}_c = \left(\frac{g-2}{2}\right)\left[\frac{e}{m}\vec{B}\right]$$

$$\Rightarrow \quad \vec{\omega}_a = a_\mu \left[\frac{e}{m}\vec{B}\right] \approx 229\,\text{kHz}$$





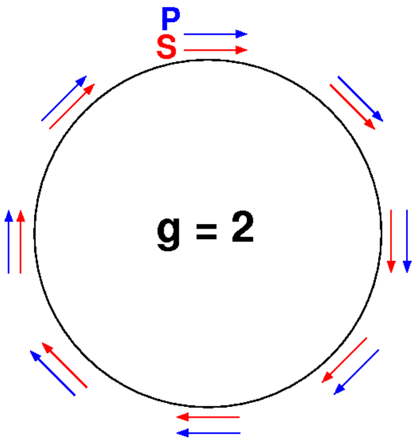
- Difference between spin and cyclotron frequencies: $\underline{\omega_a \text{ proportional to } a_\mu}$
- Difference sensitive to $a_\mu \approx 0.00116...$, not $g_\mu \approx 2.00232...$

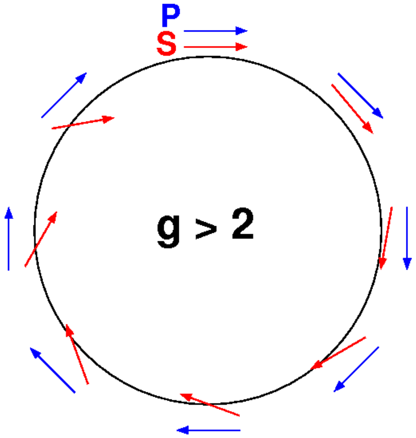
$\Rightarrow$ Experiment measures two quantities:

(1) Muon anomalous precession frequency ω_a to ± 100 ppb (stat) ± 70 ppb (syst)

(2) Magnetic field $\vec{B}$ in terms of proton NMR frequency ω_p to ± 70 ppb (syst)

Overview of the *Less-Idealized* Measurement Technique





- Inject polarized muons into magnetic storage ring with **electric vertical focusing**

- Muon cyclotron frequency $\omega_c \approx 2\pi \times 6.7\,\mathrm{MHz}$
- Muon spin vector precession $\omega_s \approx 2\pi \times 6.9\,\mathrm{MHz}$

$$\vec{\omega}_a = \vec{\omega}_S - \vec{\omega}_C$$

$$\vec{\omega}_a \approx \frac{e}{mc}\left[a_\mu \vec{B} - \left(a_\mu - \left[\frac{mc}{p}\right]^2\right)\vec{\beta}\times\vec{E}\right]$$

$$\vec{\omega}_a \approx 229\,\mathrm{kHz}$$

⇒ Cancel term from electrostatic vertical focusing at $p_{\mathrm{magic}} = \frac{mc}{\sqrt{a_\mu}} \approx 3.094\ \mathrm{GeV}/c$

⇒ Experiment measures two quantities:

(1) Muon anomalous precession frequency ω_a to ± 100 ppb (stat) ± 70 ppb (syst)

(2) Magnetic field $\vec{B}$ in terms of proton NMR frequency ω_p to ± 70 ppb (syst)

Why Fermilab? Statistics!

⇒ Brookhaven statistics limited:
$a_\mu^{\mathrm{BNL}} = 0.001\,165\,920\,89\,(54)_{\mathrm{stat}}\,(33)_{\mathrm{sys}}$

- BNL ± 540 ppb uncertainty on a_μ, 9×10^9 events

⇒ Fermilab goal 2×10^{11}, factor 21

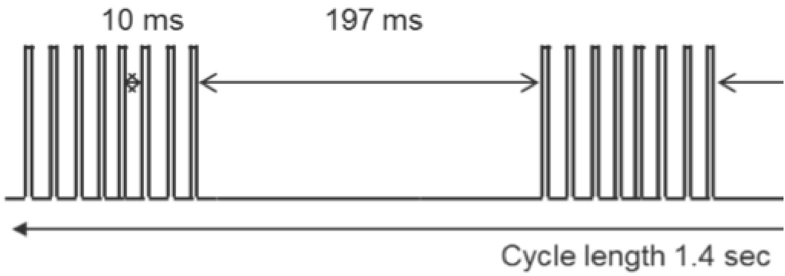
Fermilab Advantages:

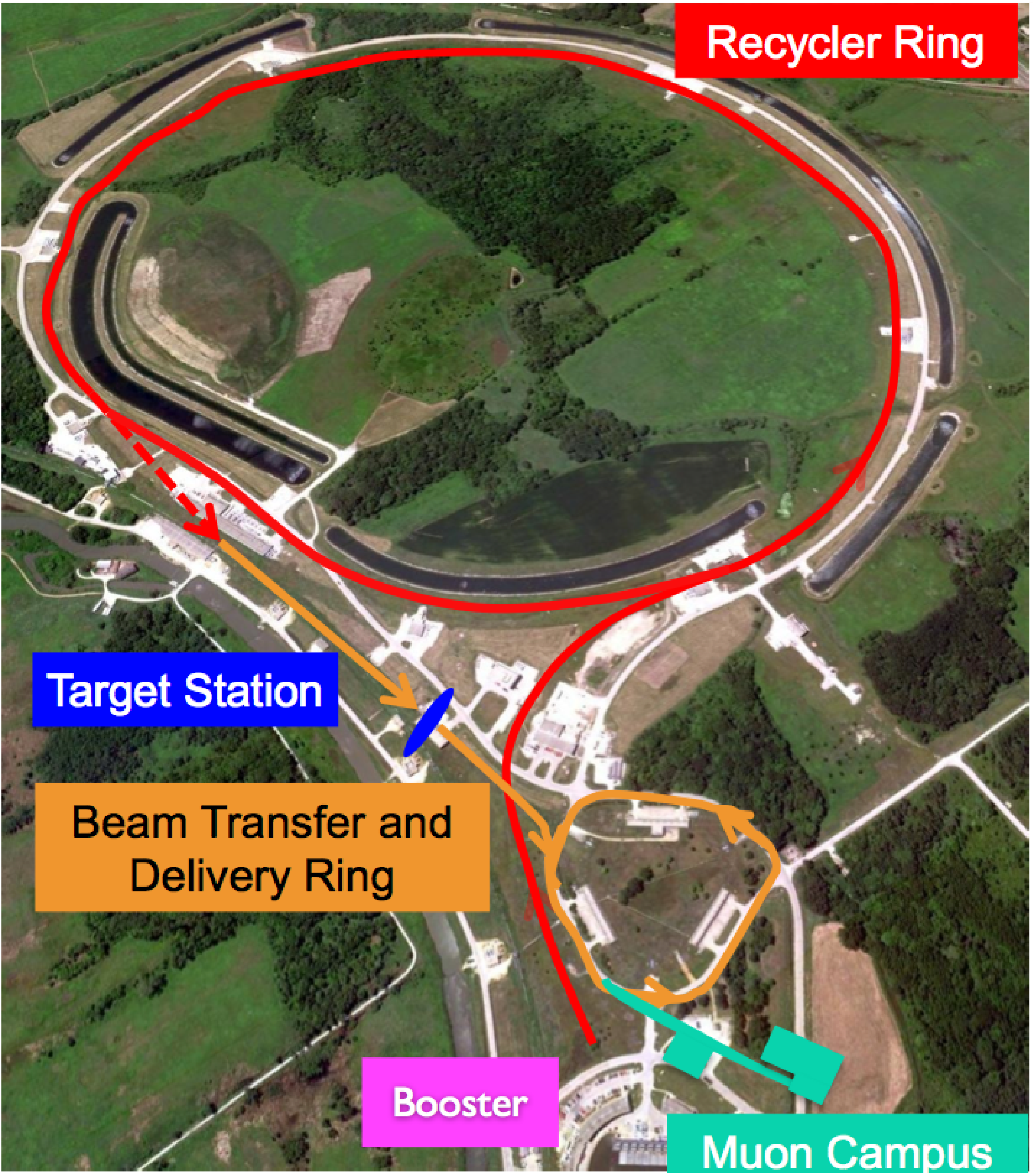
- Long decay channel for $\pi \Rightarrow \mu$
- Reduced π and p in ring
- Factor 20 reduction in hadronic flash

⇒ 4× higher fill frequency than BNL

- Muons per fill about the same

⇒ 21 times more detected e^+, 2×10^{11}





From Brookhaven to Fermilab

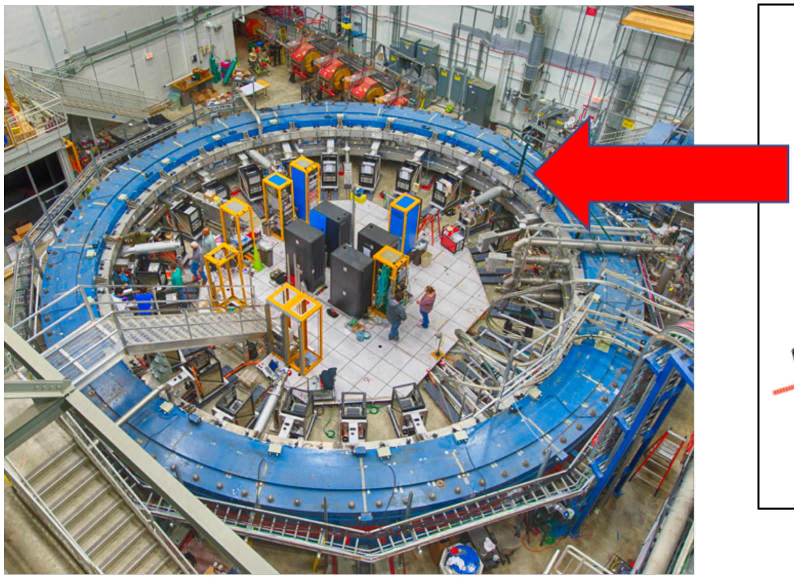
- 650 ton magnet disassembled, put on trucks to Fermilab, coils went by barge down Atlantic coast, up Mississippi in 2013

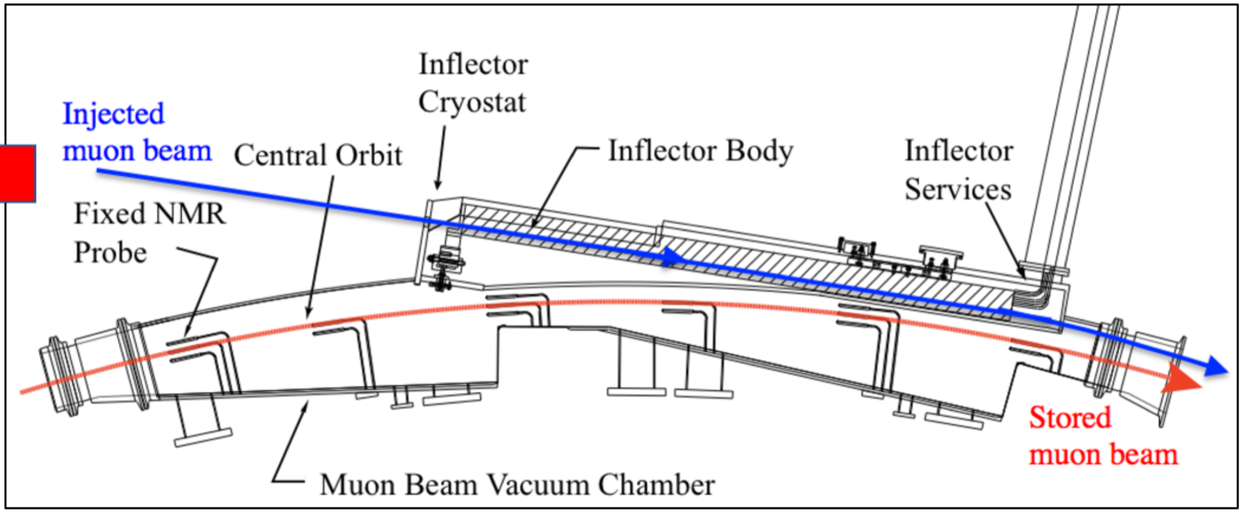
From Brookhaven to Fermilab

- Closed two interstates near Chicago to transport coils to Fermilab
- Coils pass toll arches with 6” clearance on each side

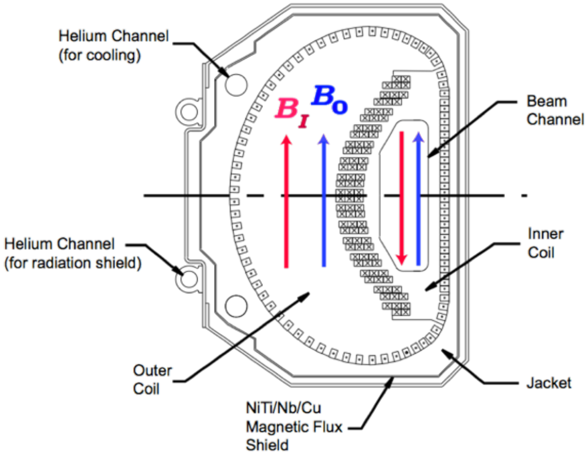
Magnet Reassembly at Fermilab June 2014 - June 2015

How do we get muons into the ring? Superconducting Inflector

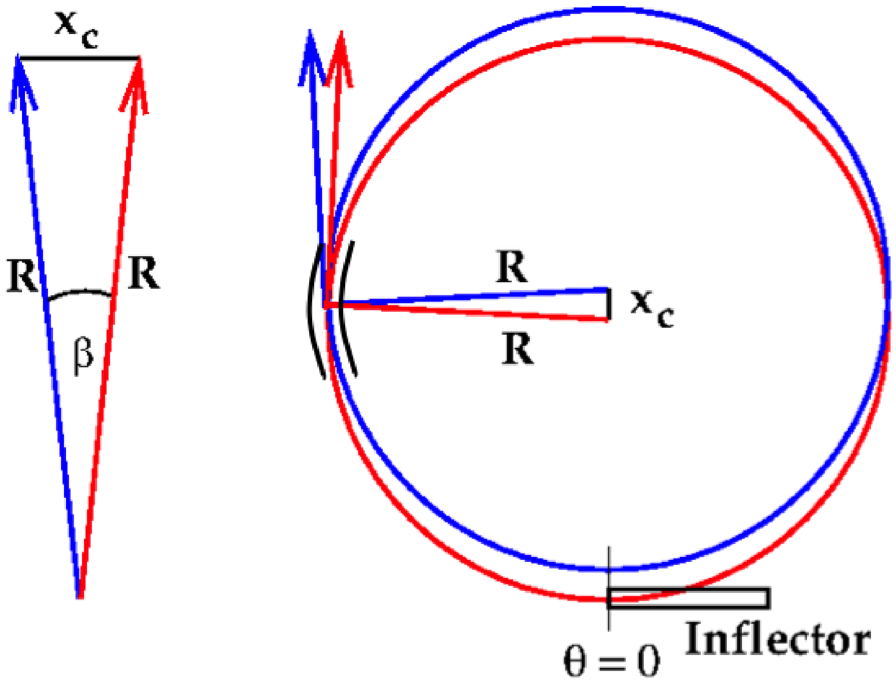


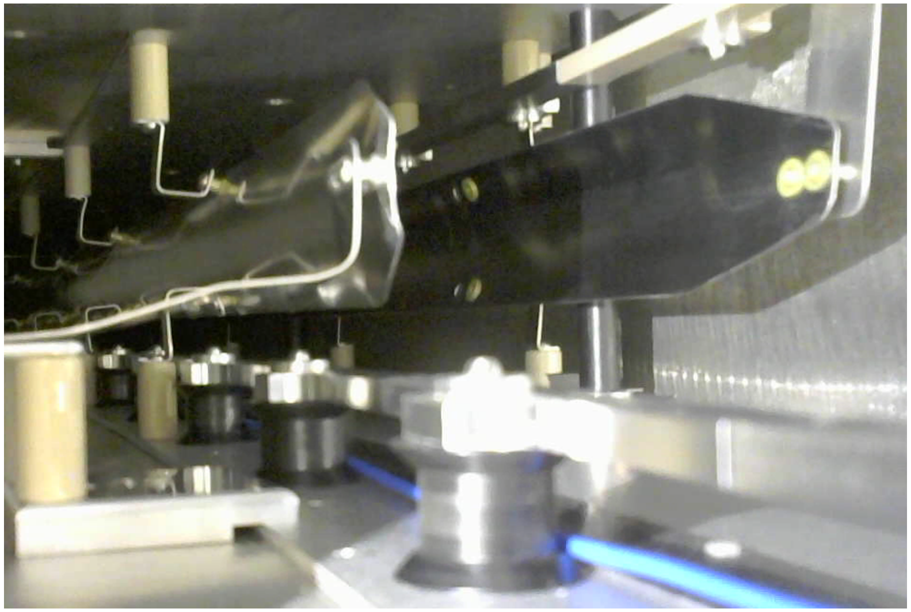


- Cancel 1.45 T field inside channel
- Prevents strong deflection of beam
- Minimal perturbation of field in muon storage volume



Storing the Muon Beam: The Fast Muon Kicker





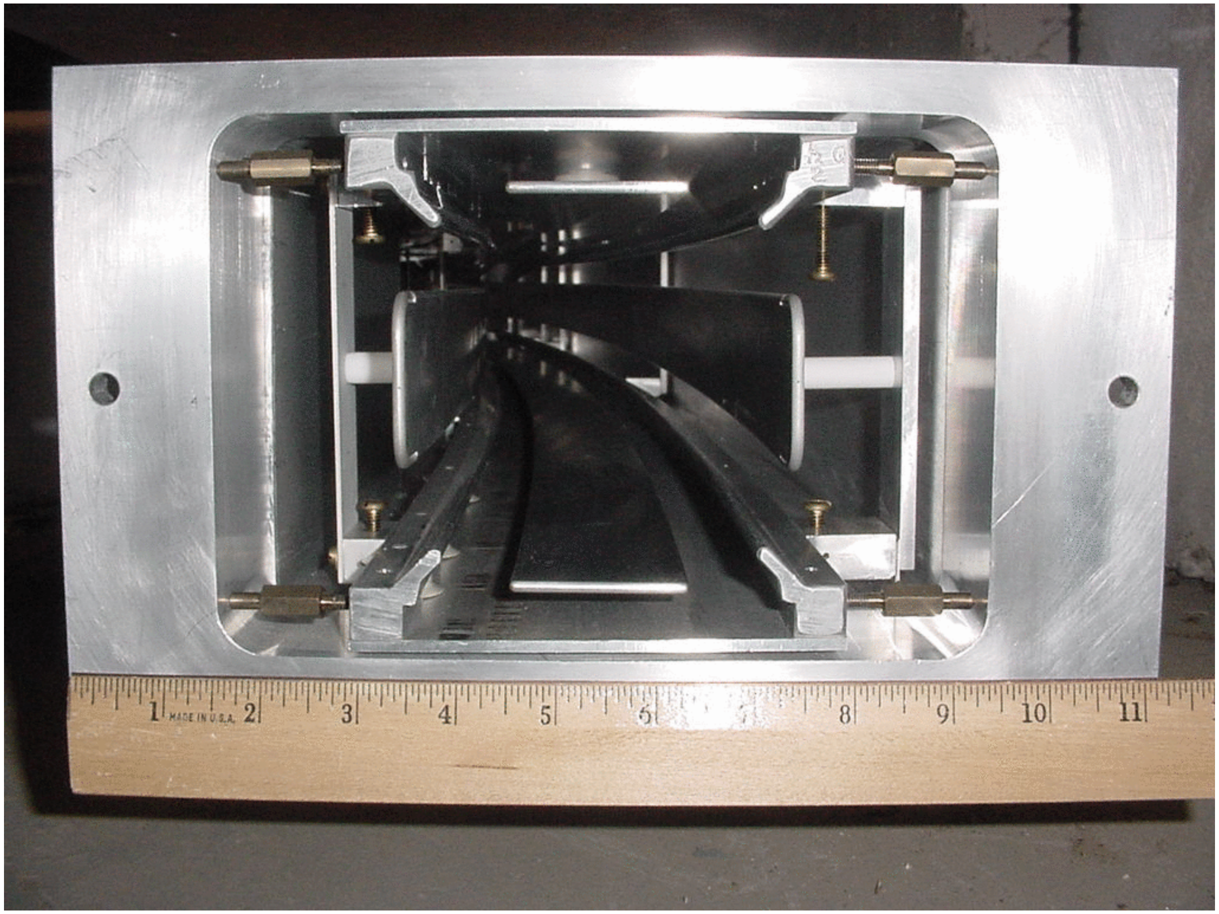
- Muons enter 77 mm outside ideal closed orbit with radius 7112 mm
- Muons cross ideal orbit at 90°, angle off by 77 mm/7112 mm $\approx$ 11 mrads

⇒ Reduce $\mathbf{B}$ by $\approx$ 300 Gauss over 4 metres for 149 ns at 100 Hz, 10% homogeneity

- Kicker steers muons onto stored orbit with $\approx$ 50 kV, 5000 Amp pulse

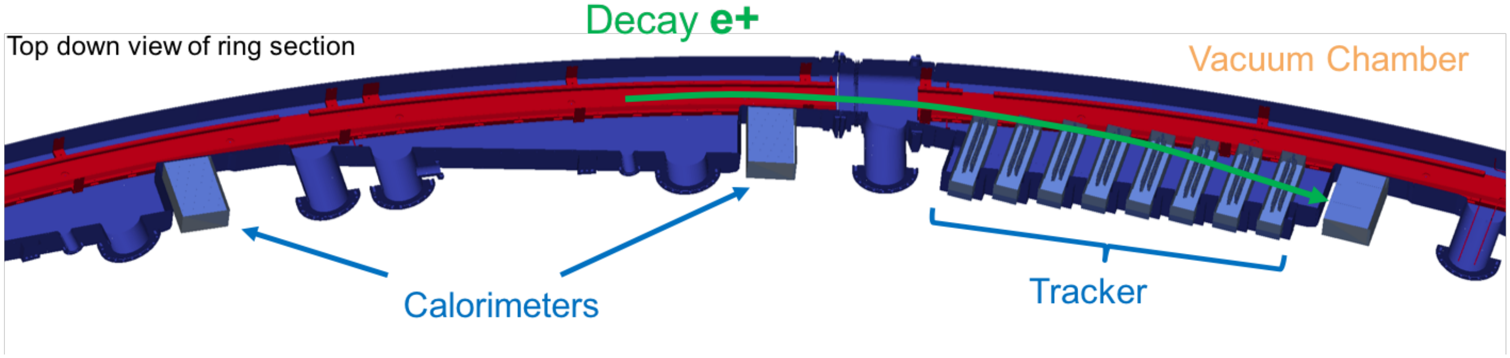
Storing the Muon Beam: Vertical Focusing Electric Quadrupoles

- Use electric quadrupoles for linear restoring force in vertical
- Uniform quadrupole field leads to simple harmonic motion about closed orbit



$$x = x_e + A_x \cos\left(\nu_x \frac{s}{R_0} + \delta_x\right), \quad y = A_y \cos\left(\nu_y \frac{s}{R_0} + \delta_y\right)$$

Measuring ω_a: Detecting the e^+ from muon decay with calorimeters

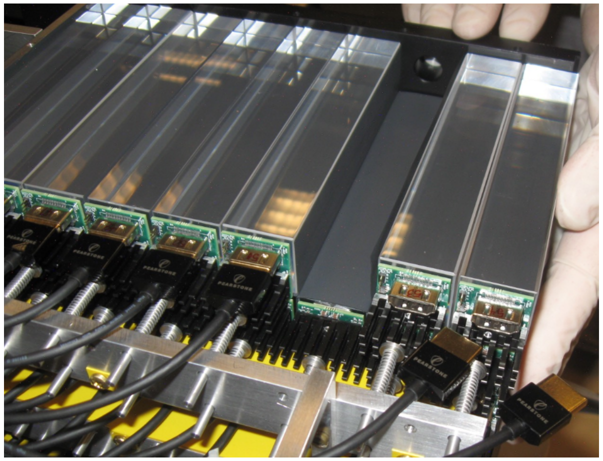


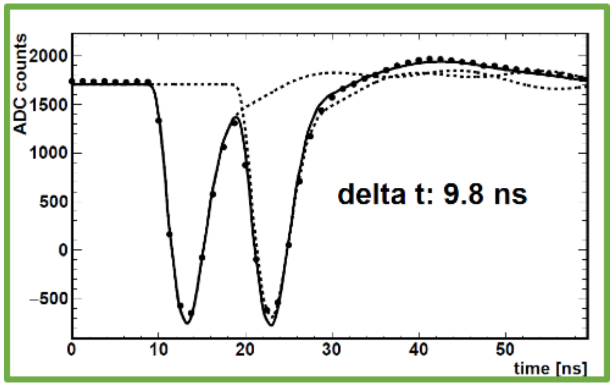
⇒ Muon Rest Frame: highest energy decay e^+ emitted in muon spin direction, rotates around

⇒ Lab Frame Positron Energy: $E_{\text{lab}} \approx \gamma E^* \left[1 + \cos\left(\omega_a t\right)\right]$

⇒ Positron detection rate above threshold $\propto \cos\left(\omega_a t\right)$

- 24 calorimeters of 9×6 PbF$_2$ crystals + SiPMs detect e^+ from μ decay,
- Digitize at 800 MSPS 12 bits for 700 μs, timing resolution 25 ps, gain stability 10^{-4}
- Reconstruct e^+ energy and time ⇔ extrapolate for phase of μ^+ spin at decay





Overview of Storage Ring Magnetic Field and its Measurement: ω_p

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$$\omega_a \approx a_\mu \left[\frac{eB}{m_\mu}\right]$$

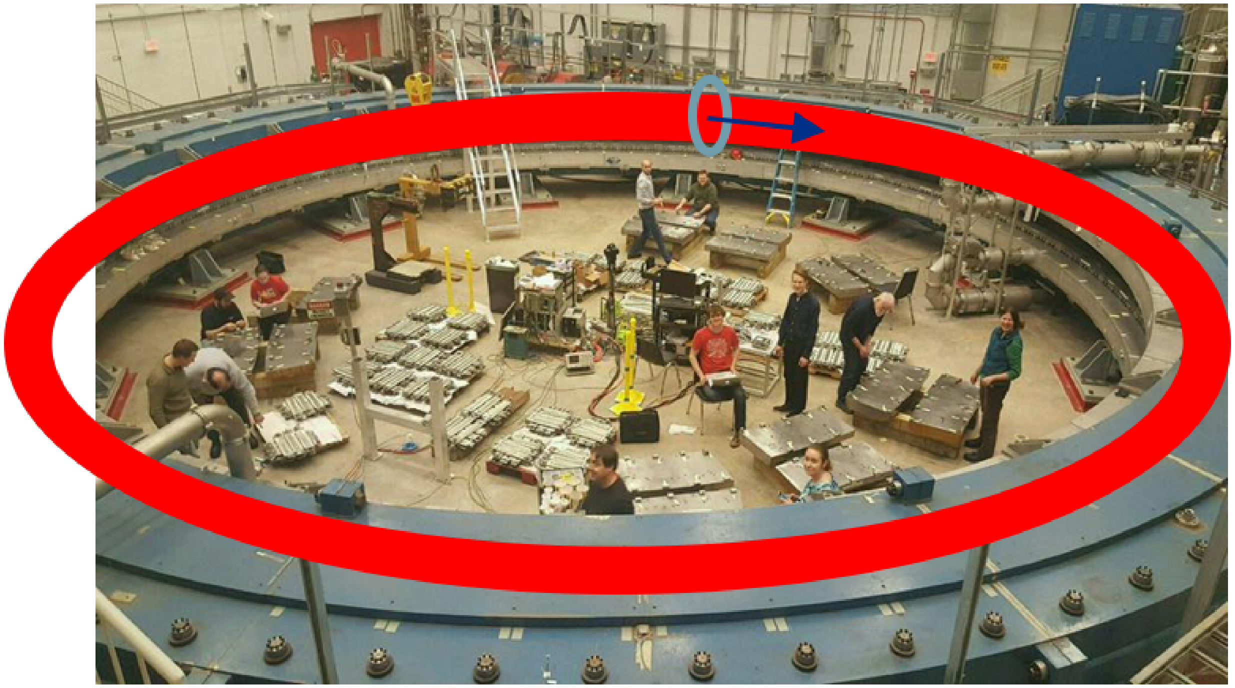
- Want $a_\mu \Rightarrow$ need to measure ω_a and eB/m_μ
- Measure B in terms of *equivalent free proton precession frequency* ω_p using proton NMR: $\hbar\omega_p = 2\mu_p|\vec{B}|$

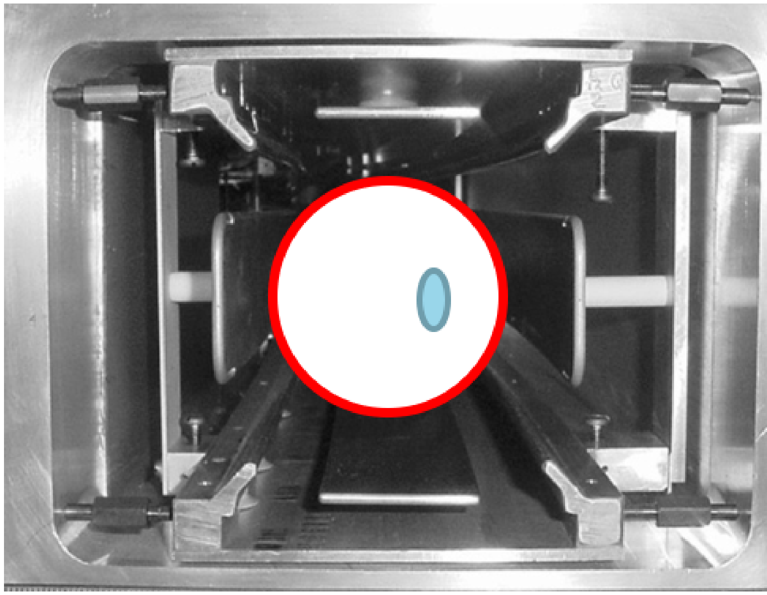
$$a_\mu = \frac{\omega_a}{\omega_p}\frac{2\mu_p}{\hbar}\frac{m_\mu}{e} = \frac{\omega_a}{\omega_p}\frac{\mu_p}{\mu_e}\frac{m_\mu}{m_e}\frac{g_e}{2}$$

$\Rightarrow$ Experiment must measure ratio of two frequencies: ω_a/ω_p

- Other ratios known to 22 ppb precision or better (but some subtleties involved!)
- $\omega_p \approx 2\pi \times 61.79$ MHz when B = 1.45 T
- Magnetic field team measures ω_p to 70 ppb

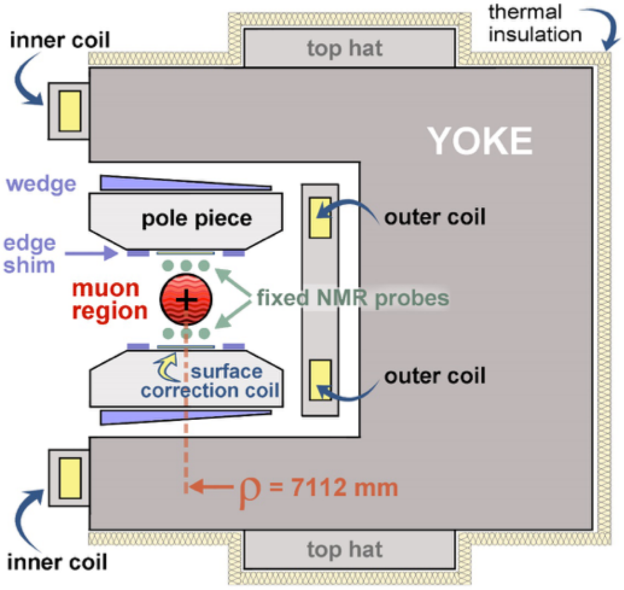
Storage Ring Magnetic Field Homogeneity





- Muons occupy volume determined by vertical and radial $\boldsymbol{B}$ fields, betatron oscillations
- Muon spin precesses according to $\boldsymbol{B}$ in small volume
- Need $\boldsymbol{B}$ field weighted by stored muon distribution $\Rightarrow$ $\tilde{\omega}_p$
- Reasons for homogeneous field:
  - Stable beam dynamics, adiabaticity
  - Smaller uncertainty on $\tilde{\omega}_p$ from convolution of muon distribution with field
  - Easier to measure

Storage Ring Magnet: Centerpiece of the Experiment



g-2 Magnet in Cross Section

- 682 tons, 4 coils×24 windings×5200 Amps/winding, 72 poles, B=1.4513 T
- B×gap ≈ $\mu_0 I$ ⇒ 1.45 T× 0.2 m ≈ $4\pi \times 10^{-7} \times 48 \times 5200$ Amps, $\dfrac{\Delta B}{B} \approx -\dfrac{\Delta \mathrm{gap}}{\mathrm{gap}}$
- Oct 2015-Aug 2016: adjustments of pole gaps, tilts, 8000+ fine iron laminations
- B uniformity at ± 15 ppm level (RMS) ⇔ gap uniform at 2.7 micron level over 45 m!

Fermilab Goal: Measurement of B-Field to 70 ppb using Pulsed Proton NMR

⇒ Want precession frequency of free protons ω_p in storage volume while muons stored

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⇒ Want precession frequency of free protons ω_p in storage volume while muons stored

- Can't have NMR magnetometer probes in storage volume at same time/place as muons!

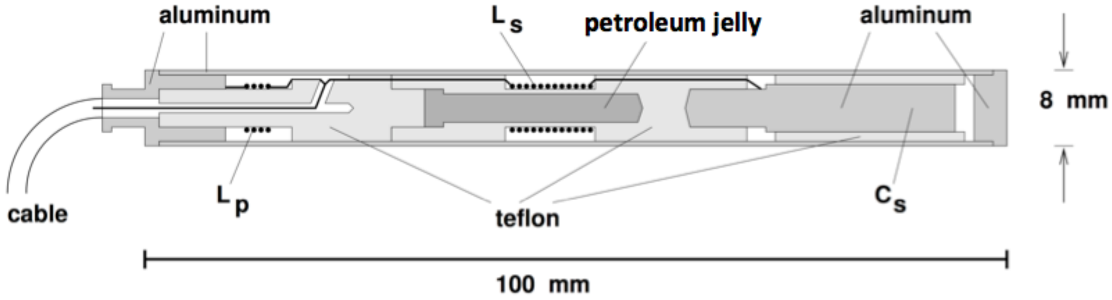
Fermilab Goal: Measurement of B-Field to 70 ppb using Pulsed Proton NMR

$\Rightarrow$ Want precession frequency of free protons ω_p in storage volume while muons stored

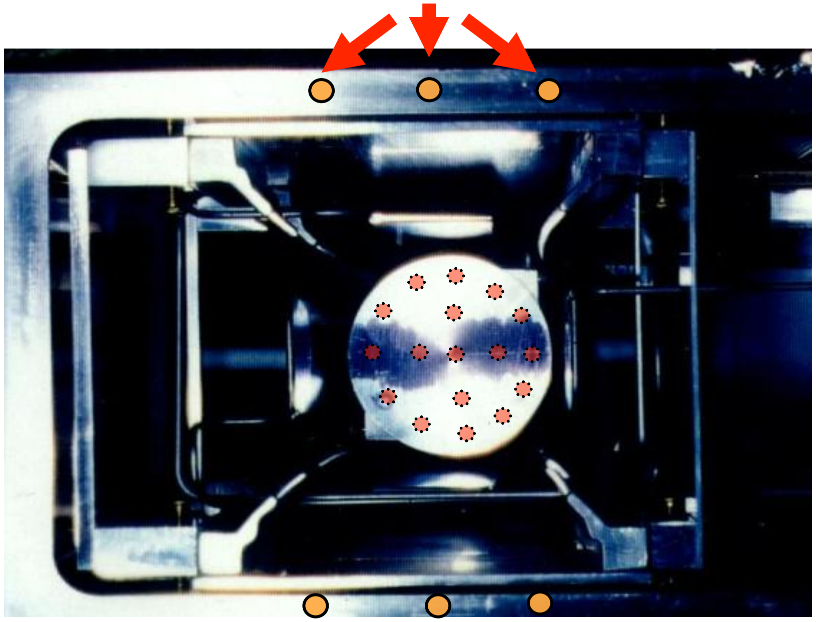
- Can't have NMR probes in storage volume at same time/place as muons!
- Whatever we use to measure B-field perturbs the local field!
  $\Rightarrow$ measured B-field different than what muons see!
- Calibration/corrections necessary to go from magnetometer measurements to free proton ω_p

Fermilab Goal: Measurement of B-Field to 70 ppb using Pulsed Proton NMR

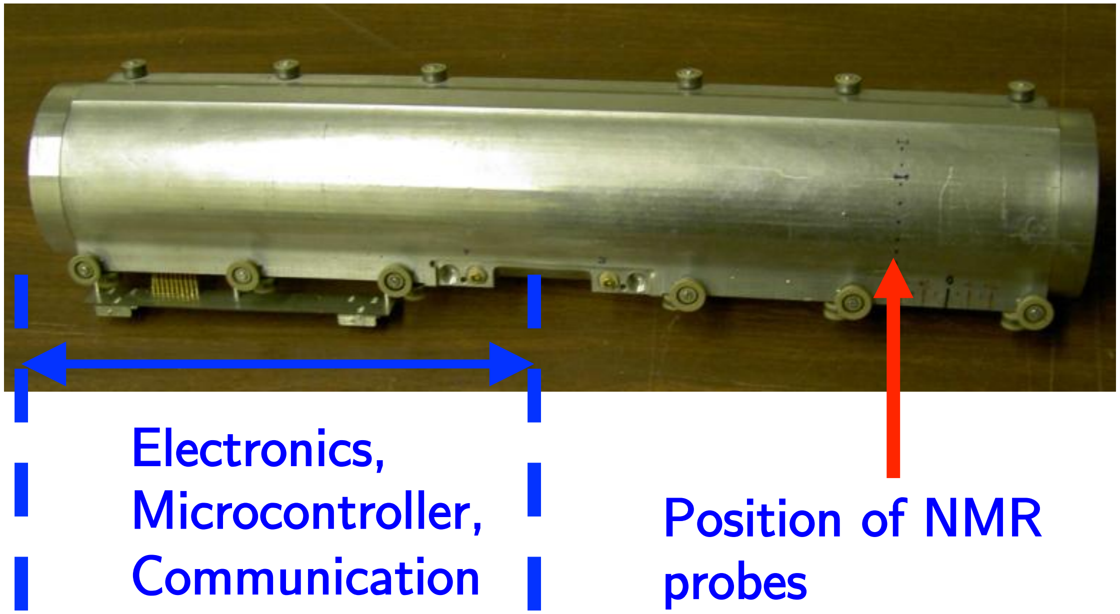
- 387 Fixed NMR probes outside storage volume measure field while muons stored
- Field inside storage volume measured by NMR trolley periodically
- Fixed probes calibrated when trolley passes; can infer field inside storage volume



Fixed probes on vacuum chambers



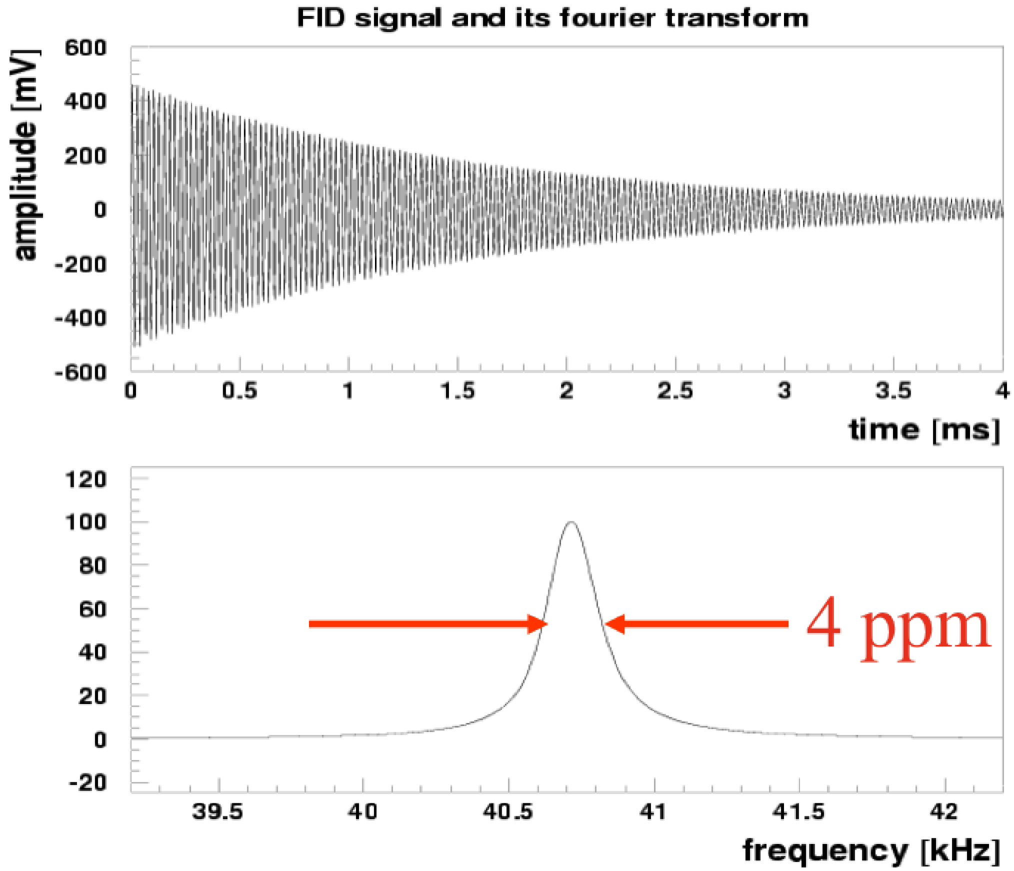
Trolley with matrix of 17 NMR probes



Electronics,
Microcontroller,
Communication

Position of NMR probes

Field Measurement with Pulsed NMR



$\Leftarrow$ Free induction decay (FID) and Fourier transform

- Signal : noise $\geq$ 200 : 1
- Frequency resolution $\approx$ linewidth / $[S/N]$ $\approx$ 120 Hz / 200 = 0.6 Hz

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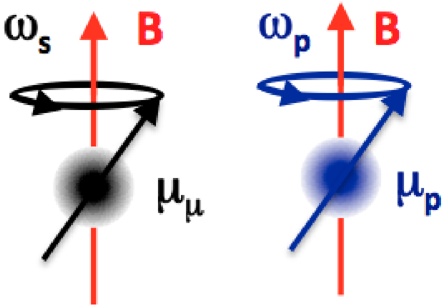
- Resolution of field measurement in single NMR pulse:

$$\frac{\delta B}{B} \approx \frac{\delta f_{\rm NMR}}{f_{\rm NMR}} \approx \frac{0.6\,{\rm Hz}}{61.79\,{\rm MHz}} \approx 10\ {\rm ppb}$$

- All $\approx$ 400 probe read out every 1.7 seconds
- Corrections necessary to get from $f_{\rm NMR}$ of NMR magnetometers to ω_p of free proton

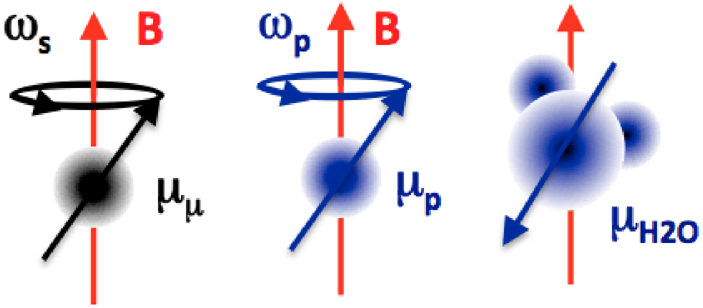
How do we go from NMR probe precession frequencies to ω_p



$$\omega_p^{\text{probe}} = \left[1 \qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\right] \omega_p^{\text{free}}$$

⇒ Determine B seen by muons from measurement of ω_p of free protons

How do we go from NMR probe precession frequencies to ω_p

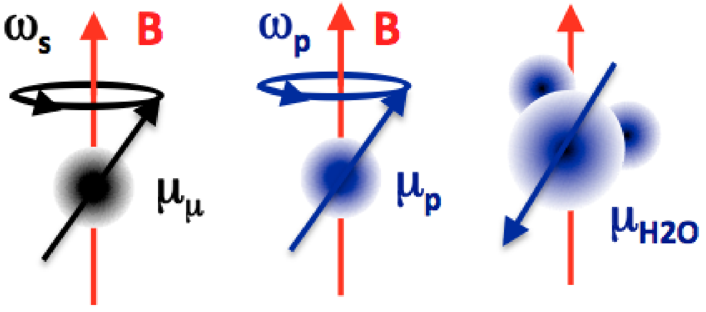


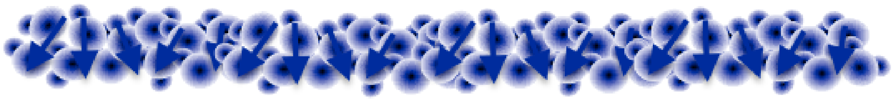
$$\omega_p^{\text{probe}} = \left[1 - \sigma(\mathrm{H_2O}, T) \qquad\qquad\qquad\qquad\qquad\qquad \right] \omega_p^{\text{free}}$$

⇒ Determine B seen by muons from measurement of ω_p of free protons

- Complication: protons in $\mathrm{H_2O}$ molecules, diamagnetism of electrons screens protons, *changes local B*
- $\sigma(\mathrm{H_2O}, T) = 25\,680(\pm 2.5) \times 10^{-9}$ at 25.0°C (Y. Neronov and N. Seregin, Metrologia **51**, 54 (2014))

How do we go from NMR probe precession frequencies to ω_p





$$\omega_p^{\text{probe}} = \left[1 - \sigma(\mathrm{H_2O}, T) - \left(\epsilon - \frac{4\pi}{3}\right)\chi_{\mathrm{H_20}}(T)\right]\omega_p^{\text{free}}$$

⇒ Determine B seen by muons from measurement of ω_p of free protons

- Complication: protons in H_2O molecules, diamagnetism of electrons screens protons, *changes local B*
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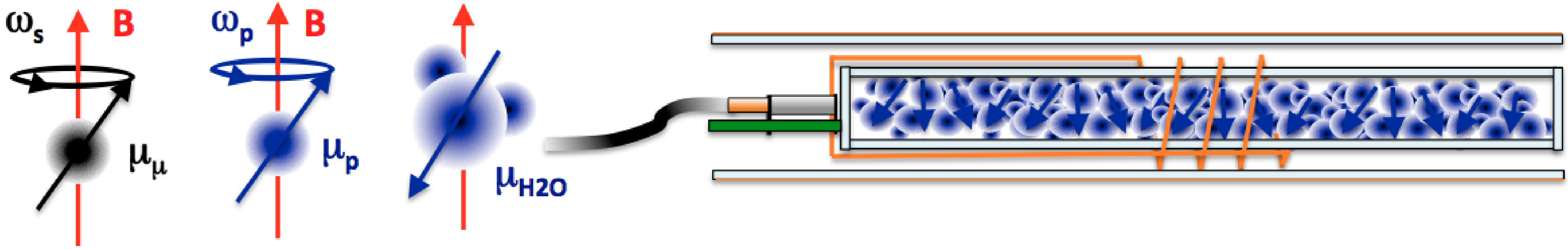
- Complication: Magnetization of water sample gives shape-dependent field perturbation: $\epsilon = 4\pi/3$ for a sphere, $\epsilon = 2\pi$ for cylinder $\perp \vec{B}$

How do we go from NMR probe precession frequencies to ω_p



$$\omega_p^{\text{probe}} = \left[1 - \sigma(\mathrm{H_2O}, T) - \left(\epsilon - \frac{4\pi}{3}\right)\chi_{\mathrm{H_2 0}}(T) - \delta_{\text{probe}}\right]\omega_p^{\text{free}}$$

⇒ Determine B seen by muons from measurement of ω_p of free protons

- Complication: protons in H_2O molecules, diamagnetism of electrons screens protons, *changes local B*
- $\sigma(\mathrm{H_2O}, T) = 25\,680(\pm 2.5) \times 10^{-9}$ at 25.0°C (Y. Neronov and N. Seregin, Metrologia **51**, 54 (2014))
- Complication: Magnetization of water sample gives shape-dependent field perturbation: $\epsilon = 4\pi/3$ for a sphere, $\epsilon = 2\pi$ for cylinder $\perp \vec{B}$
- Complication: Magnetization of probe materials perturbs field at protons

⇒ Need special NMR electronics and probes to determine corrections to 35 ppb accuracy

Corrections to ω_a: Pitch and Electric Field Correction

- Corrections to ω_a determined by calorimeter required because:

(1) Not all muons at magic momentum ⇒ not on center orbit ⇒ see net electric field

(2) Vertical betatron motion: muons pitching up/down out of horizontal plane

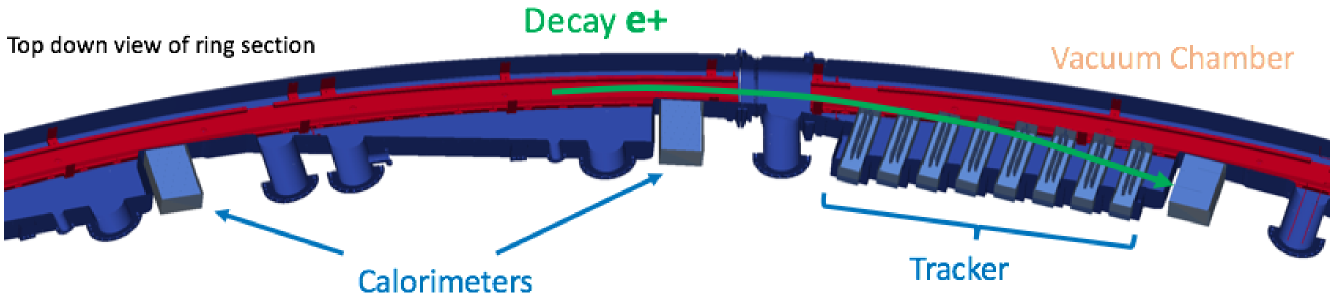
$$\vec{\omega}_a \approx \vec{\omega}_S - \vec{\omega}_C = \underbrace{-\frac{e}{m}\left[a_\mu \vec{B}\right.}_{\text{What we want}} \underbrace{- a_\mu \left(\frac{\gamma}{\gamma+1}\right)\left(\vec{\beta}\cdot\vec{B}\right)\vec{\beta}}_{\text{Pitch Correction}} \underbrace{- \left.\left(a_\mu - \frac{1}{\gamma^2-1}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right]}_{\text{E-Field Correction}}$$

- E-field correction needs momentum distribution: from fast-rotation (de-bunching) analysis, straw tracking chambers, muon beam fiber monitors
- For BNL: electric field correction ≈ $+0.47 \pm 0.05$ ppm

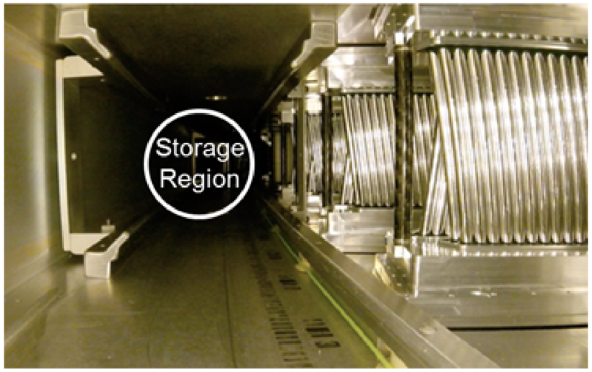
- Pitch correction: needs muon distribution: from straw tracking chambers
- For BNL: pitch correction ≈ $+0.27 \pm 0.04$ ppm

Corrections verified from detailed spin tracking analysis using complete relativistic equations, actual discontinuous quad geometry, actual magnetic field distributions, ...

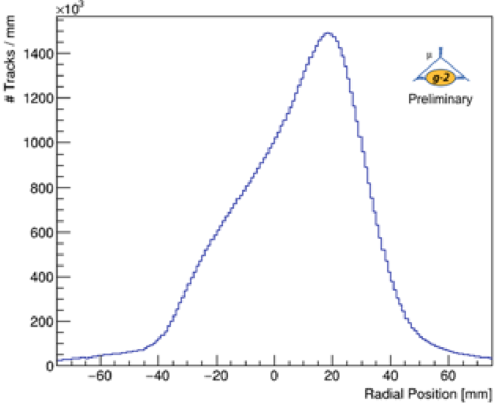
Measuring Stored Muon Distribution with Straw Tracker Chambers



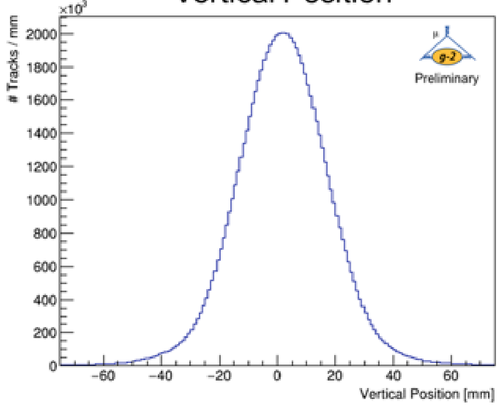
Muon's-eye view inside vacuum chamber



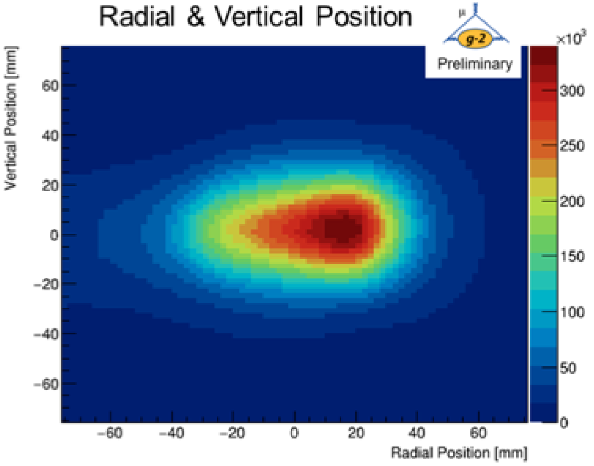
Radial Position



Vertical Position

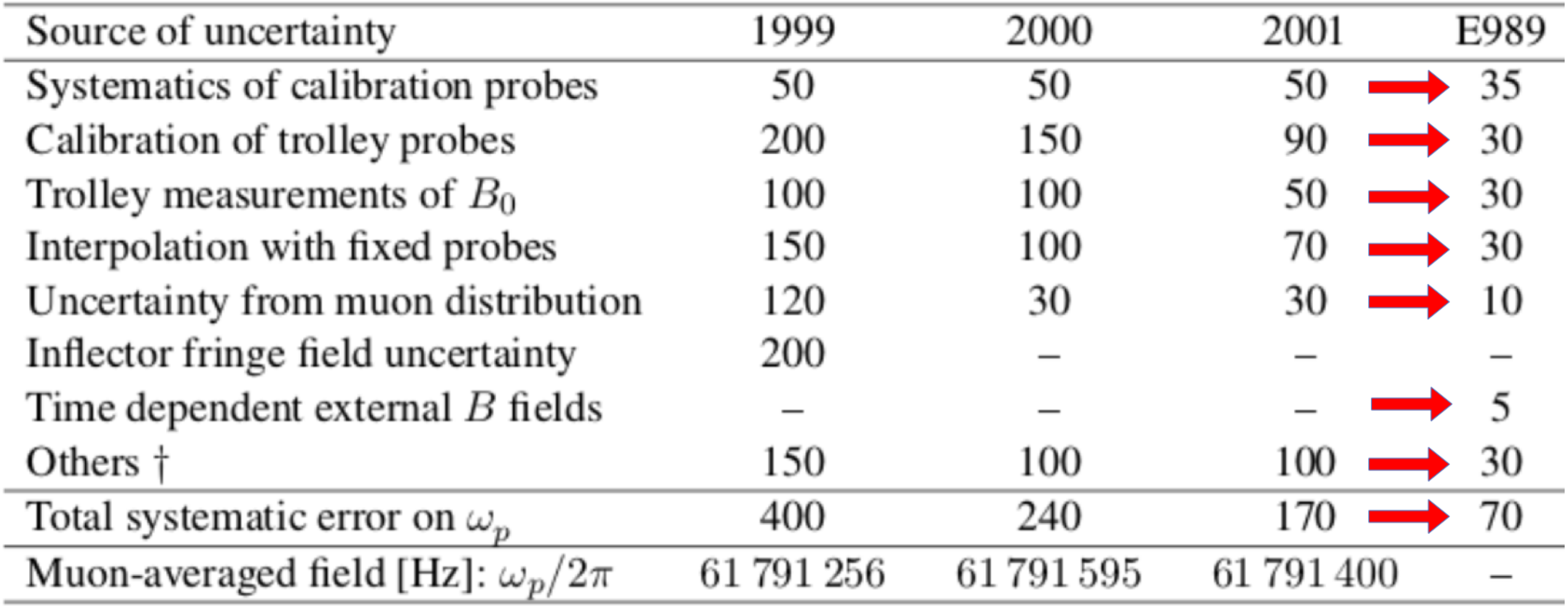


Radial & Vertical Position



- Two sets of straw trackers: exquisite measurement of stored muon distribution
- Important for optimizing injection parameters
- Required for electric field and pitch corrections, convolution with magnetic field
- Center of mass of muon distribution currently above ideal value

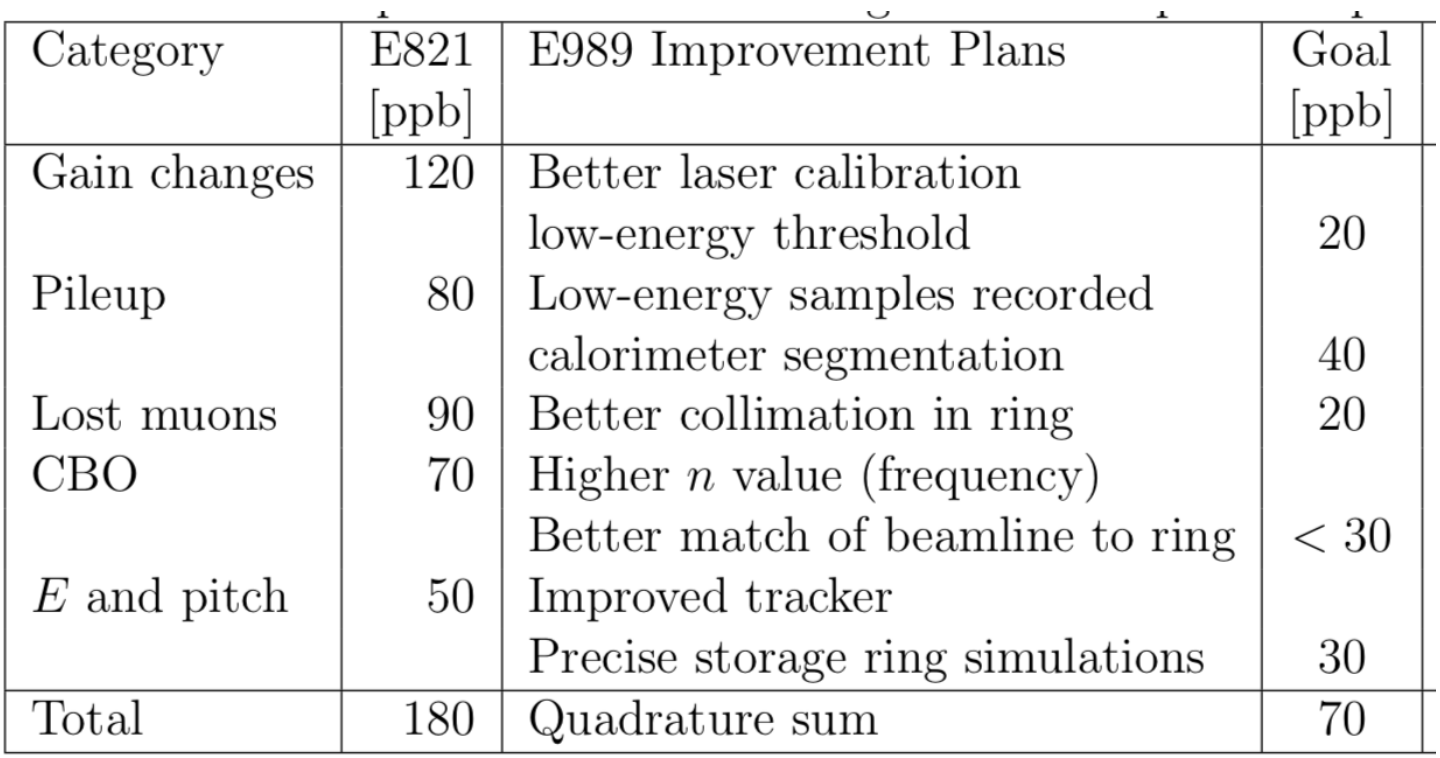
Systematic Uncertainty Goals on B Field Measurement ω_p



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		–

- Implemented new electronics, new probes, new techniques reduce uncertainties factor 2.5
- Main issue: magnet not currently insulated, field not as stable as we'd like (1°C change $\Rightarrow$ 35 ppm !)

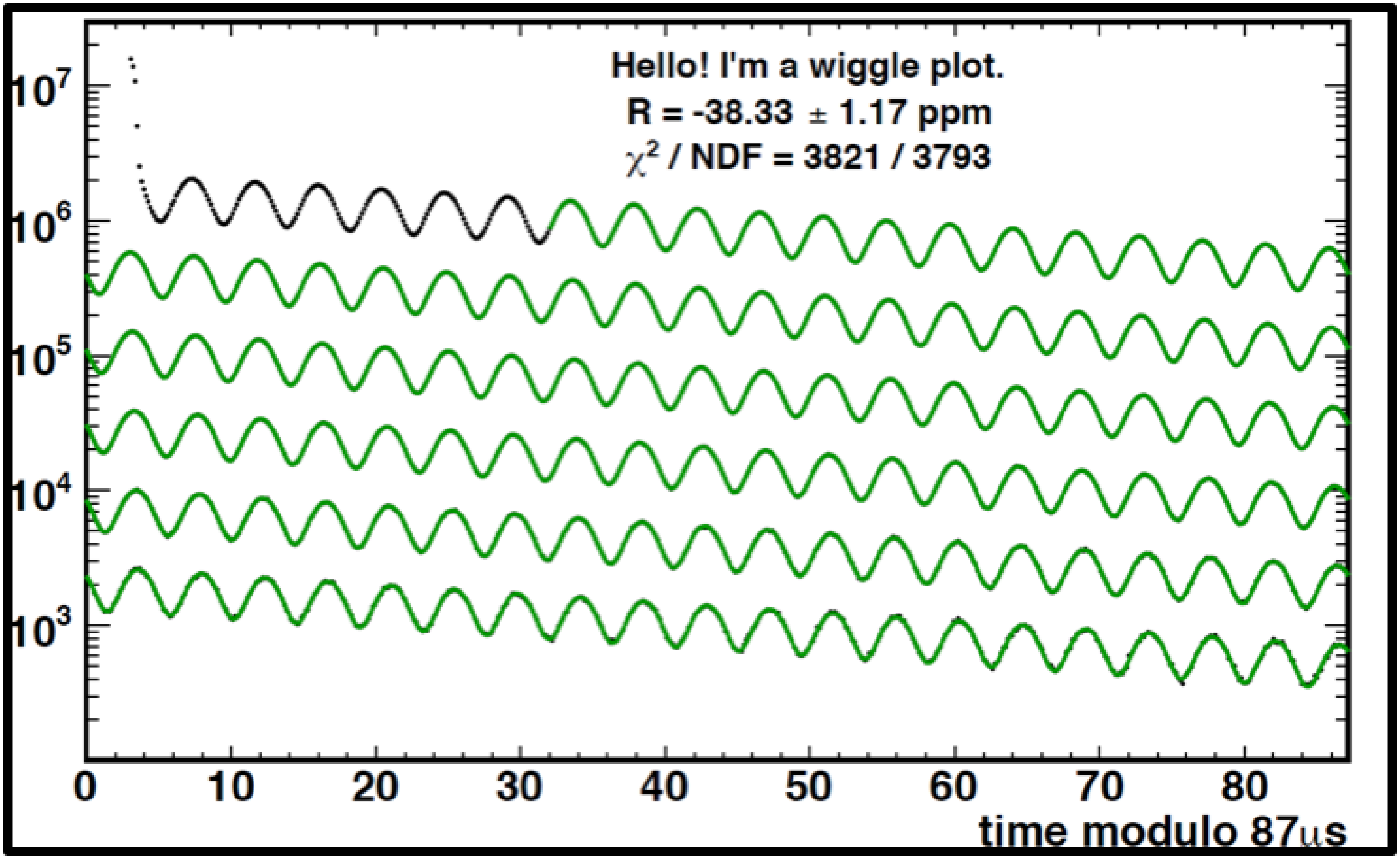
Systematic Uncertainty Goals on Muon Precession Measurement ω_a



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

- Implemented new calorimeters, trackers, new techniques to reduce uncertainties factor 2.6
- Main issues: muons underkicked, momentum of stored muon above p_{magic}, fixes planned
- Stored muon flux below design value, fixed planned

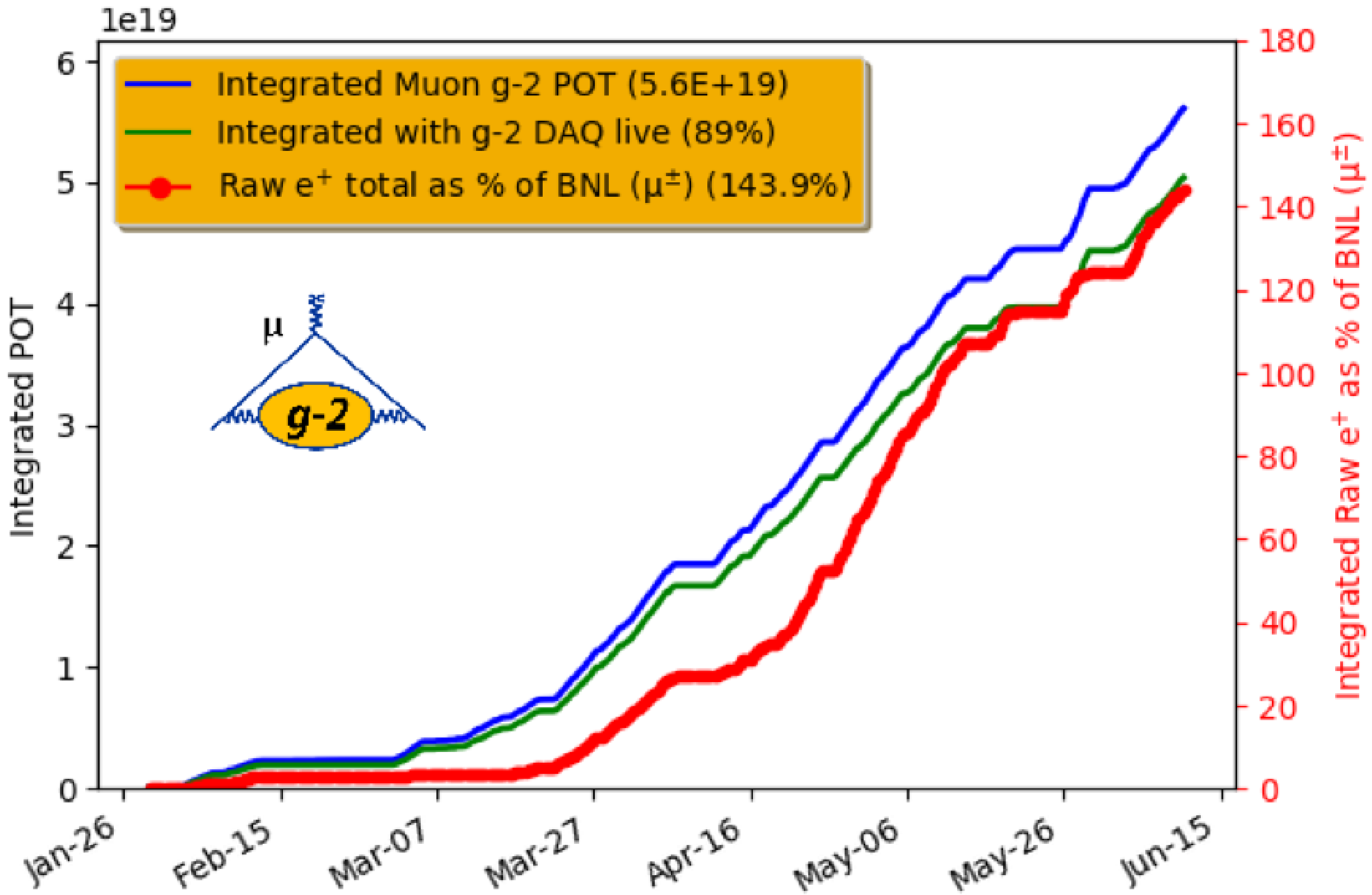
Progress in 2018: The Wiggle Plot



e^+ Signal from Muon Decay: $N_{\text{ideal}}(t) = N_0 \exp\left(-t/\gamma\tau_\mu\right)\left[1 - A\cos\left(\omega_a t + \phi\right)\right]$

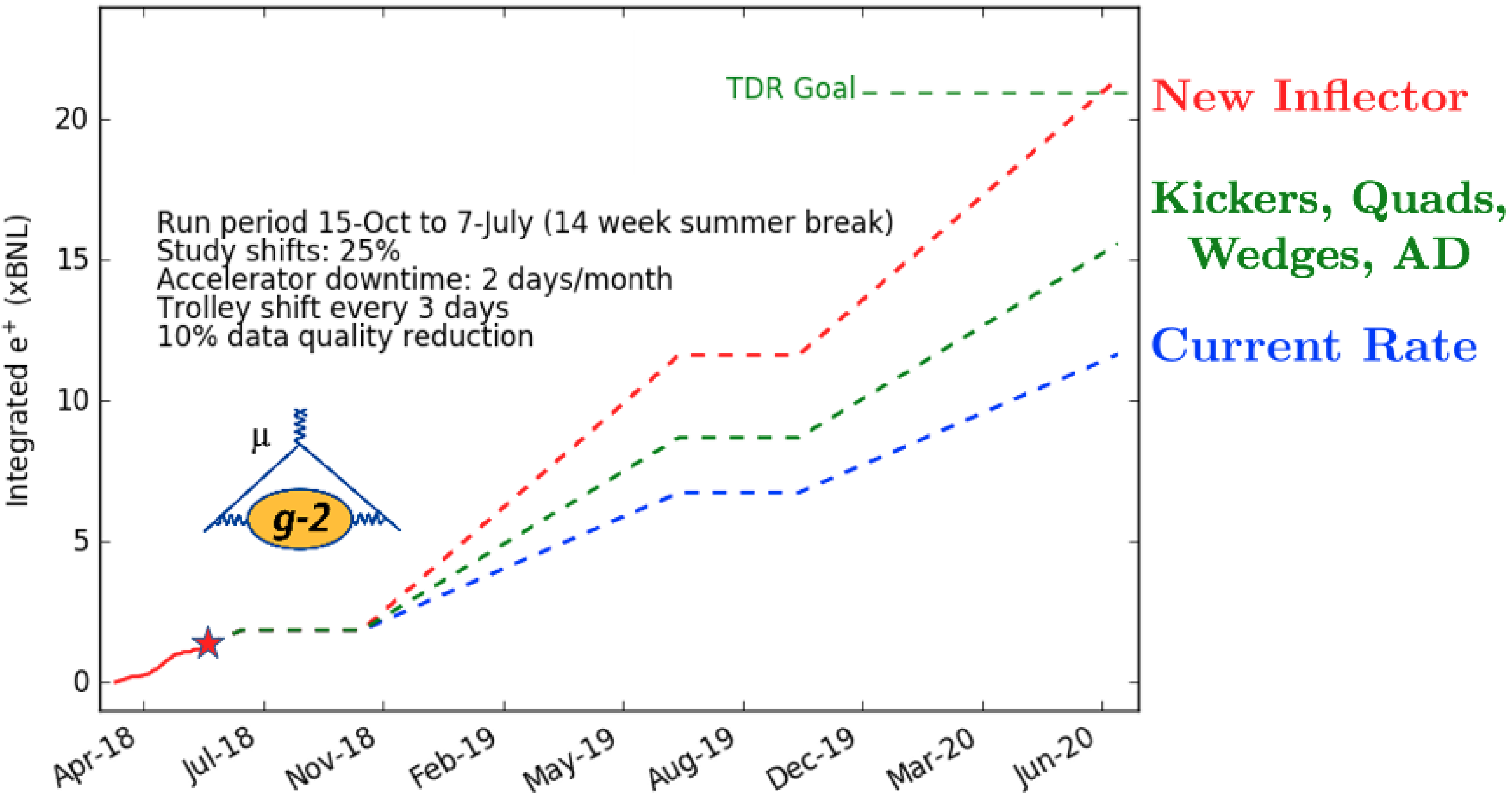
- Data from 60 hour period, ω_p offline analysis very advanced
- Corrections for pileup, muon losses, CBO effects, long-term gain changes

Progress in 2018: Accumulating Statistics



- Have data set comparable to BNL statistics !
- Cuts on data quality (still to come) will reduce analyzable data set

The Path to Statistical Uncertainty Goals of 100 ppb



Summary and Thanks to Everyone Here

- Muon g-2 persists as interesting result: highly cited, community paying attention

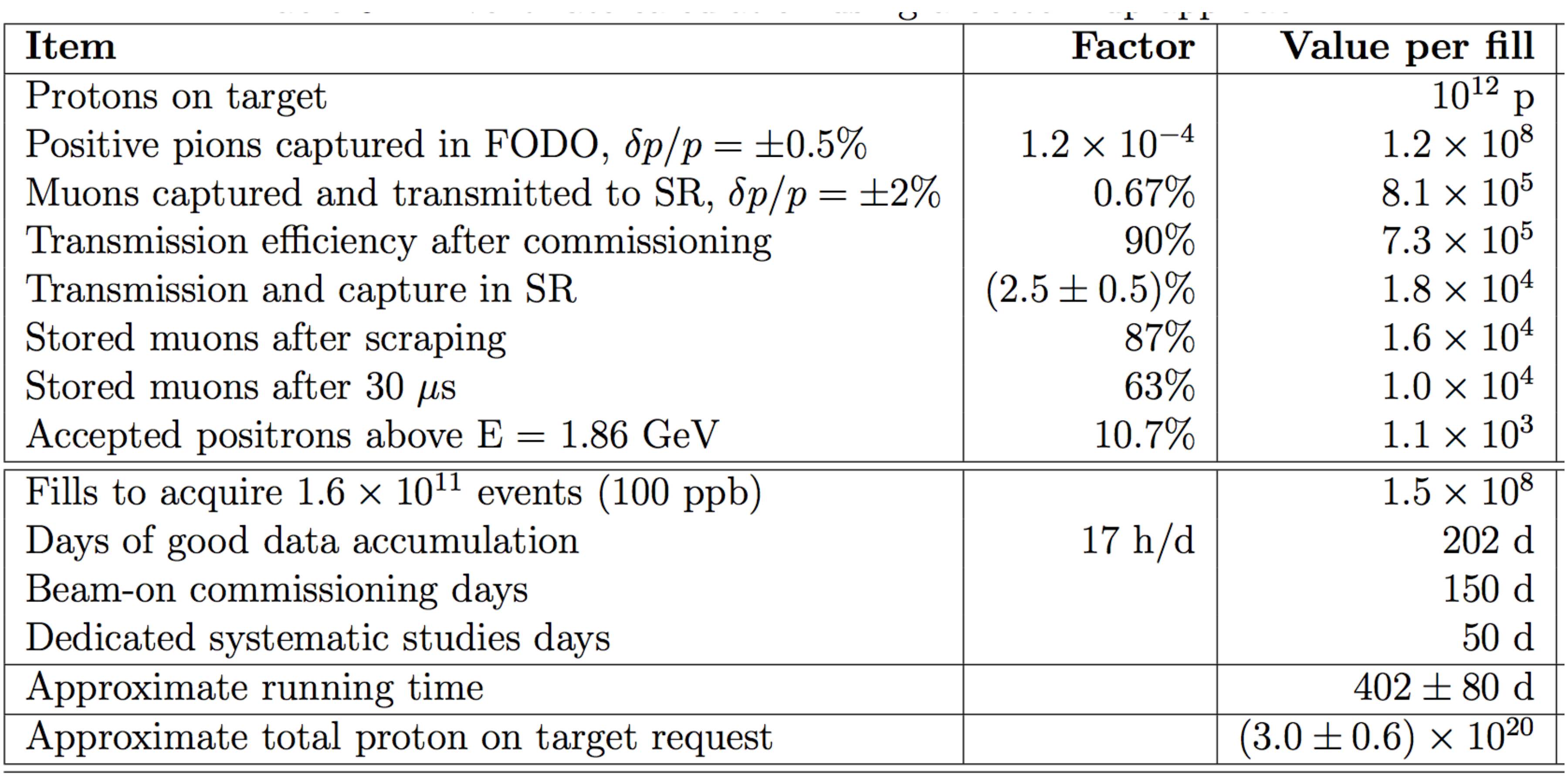
- Significant progress by experiment:
  - ⇒ First muons stored in June 2017
  - ⇒ Result from 1st physics run with BNL level statistics by late 2018/early 2019?
  - ⇒ Full statistics on $\mu^+ \approx$ 2020, four-fold reduction in uncertainty to 140 ppb

- Theory community has made remarkable progress!
  - ⇒ Uncertainties projected in 2013 for final result already achieved!
  - ⇒ Remarkable progress on hadronic uncertainties, lattice

Your effort and improvements are what makes all of this interesting. Thank You!

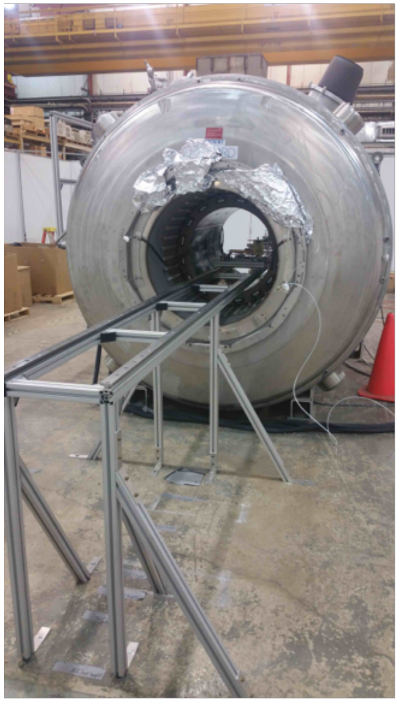
Work supported by U.S. Department of Energy Office of Science

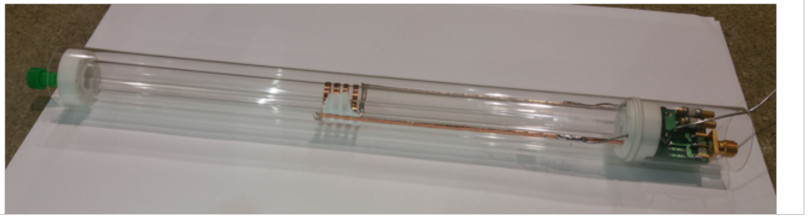
Event rate estimates at Fermilab

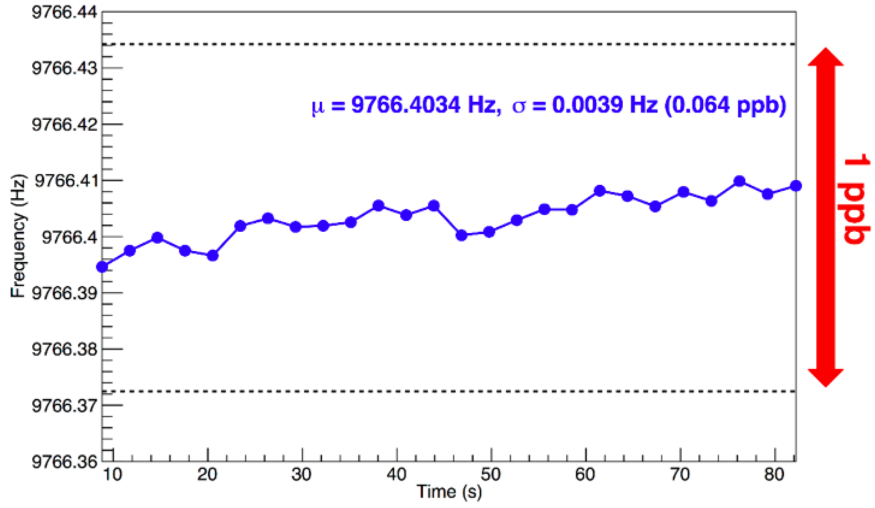


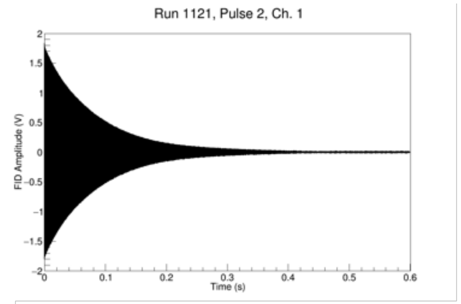
Item	**Factor**	**Value per fill**
Protons on target		10^{12} p
Positive pions captured in FODO, $\delta p/p = \pm 0.5\%$	1.2×10^{-4}	1.2×10^{8}
Muons captured and transmitted to SR, $\delta p/p = \pm 2\%$	0.67%	8.1×10^{5}
Transmission efficiency after commissioning	90%	7.3×10^{5}
Transmission and capture in SR	$(2.5 \pm 0.5)\%$	1.8×10^{4}
Stored muons after scraping	87%	1.6×10^{4}
Stored muons after 30 μs	63%	1.0×10^{4}
Accepted positrons above E = 1.86 GeV	10.7%	1.1×10^{3}
Fills to acquire 1.6×10^{11} events (100 ppb)		1.5×10^{8}
Days of good data accumulation	17 h/d	202 d
Beam-on commissioning days		150 d
Dedicated systematic studies days		50 d
Approximate running time		402 ± 80 d
Approximate total proton on target request		$(3.0 \pm 0.6) \times 10^{20}$

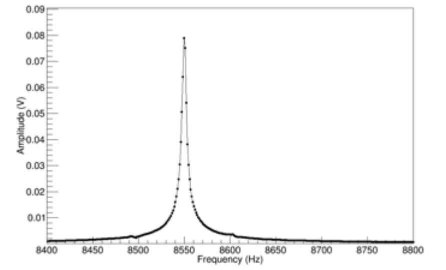
Calibration NMR Probe Testing at MRI Solenoid at Argonne

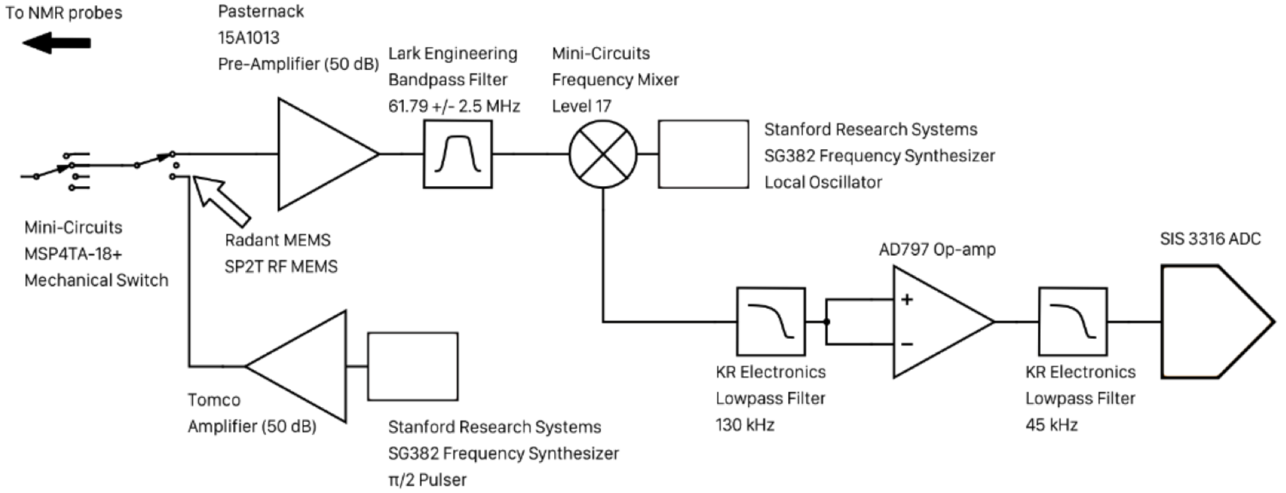












To NMR probes

Pasternack
15A1013
Pre-Amplifier (50 dB)

Lark Engineering
Bandpass Filter
61.79 +/- 2.5 MHz

Mini-Circuits
Frequency Mixer
Level 17

Stanford Research Systems
SG382 Frequency Synthesizer
Local Oscillator

Mini-Circuits
MSP4TA-18+
Mechanical Switch

Radant MEMS
SP2T RF MEMS

AD797 Op-amp

SIS 3316 ADC

KR Electronics
Lowpass Filter
130 kHz

KR Electronics
Lowpass Filter
45 kHz

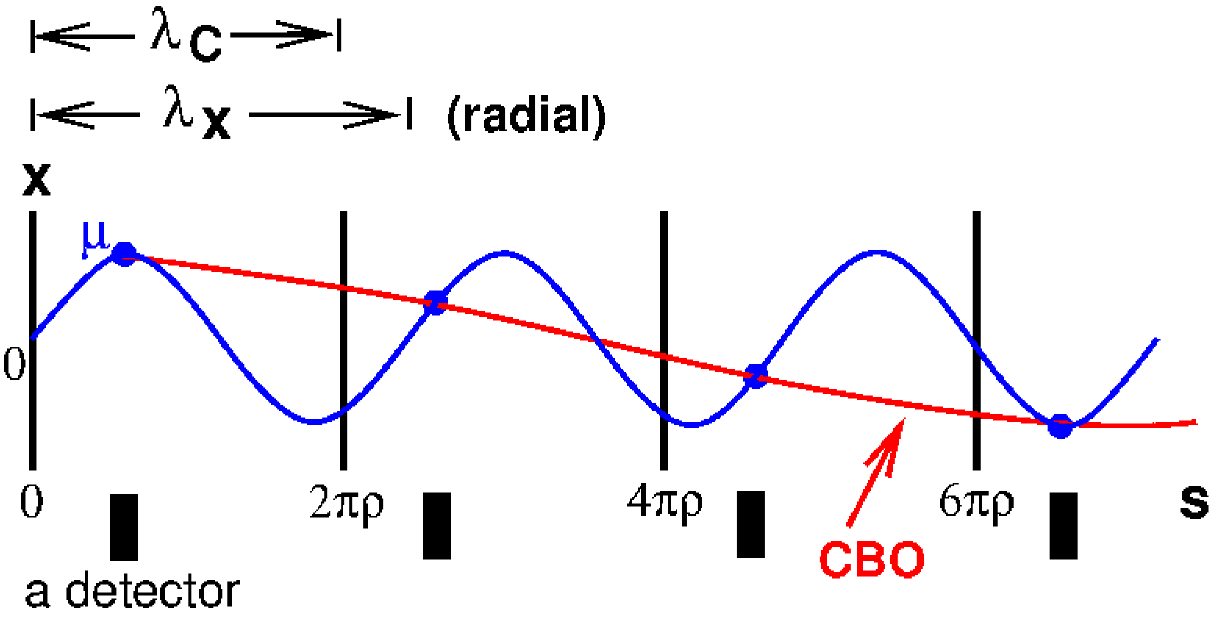
Tomco
Amplifier (50 dB)

Stanford Research Systems
SG382 Frequency Synthesizer
π/2 Pulser

- Signal/Noise > 1500
- Linewidths of few Hz
- Frequency resolution <100 ppt
- Easily see effects at ppb level

Coherent Betatron Oscillations (CBO)

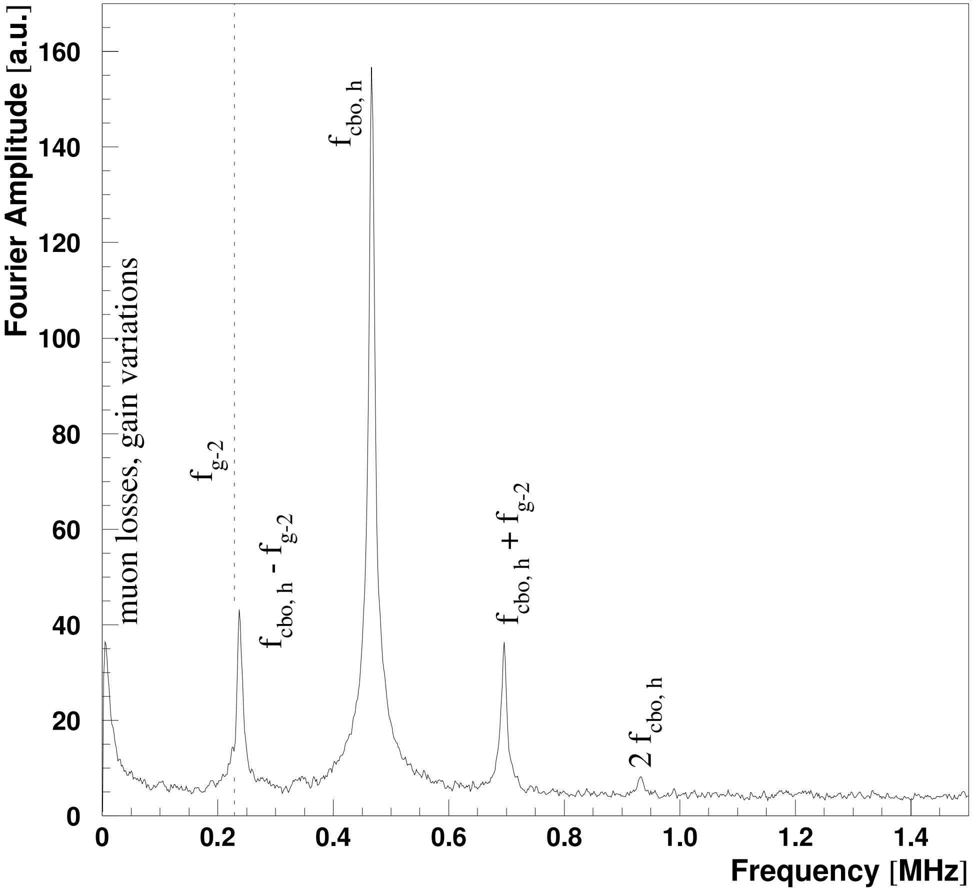
- Detector acceptance depends on muon radius at decay - coherent radial motion modulates electron time spectrum
- Radial betatron wavelength (blue line) is longer than circumference (cyclotron wavelength), $f_x < f_\mathrm{C}$
- At fixed detector location, each pass of bunched beam appears at different radius - moving at f_CBO
- CBO frequency $f_\mathrm{CBO} = f_\mathrm{C} - f_x$ must be kept far from f_a

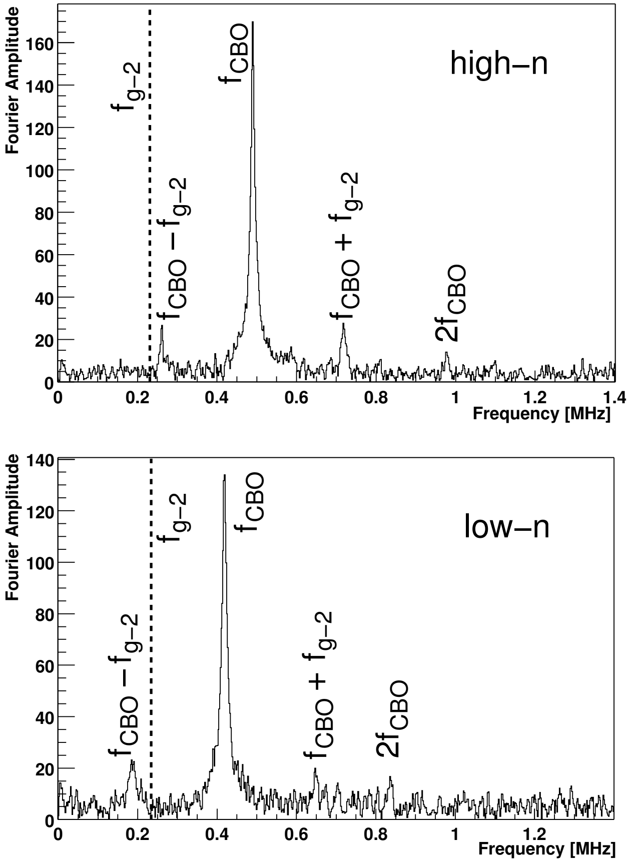


- Cyclotron wavelength marked by black lines, single detector by black block, betatron oscillations in blue
- Red line: apparent radial breathing in and out of beam at f_CBO
- Effect nearly cancels when all detectors added together

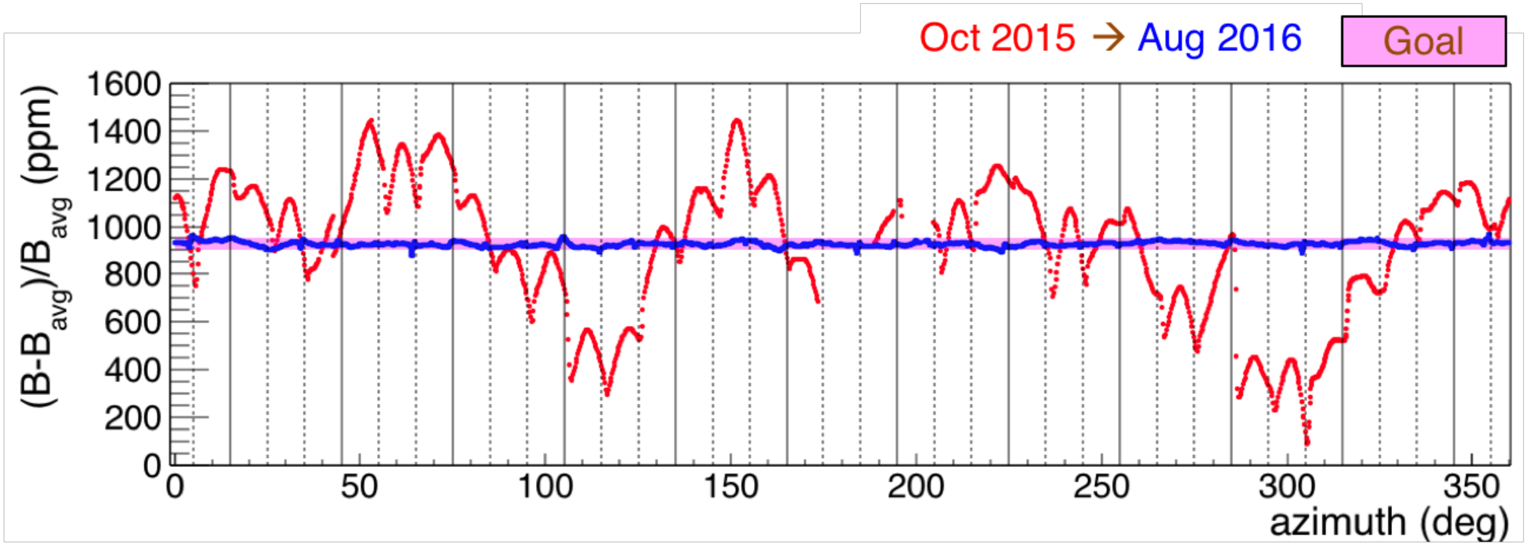
Coherent Betatron Oscillations (CBO)

- BNL data taken in 2000 when CBO frequency close to f_a - can be seen in residual to 5 parameter fit
- In 2001, field index n changed to move f_{CBO} away from f_a

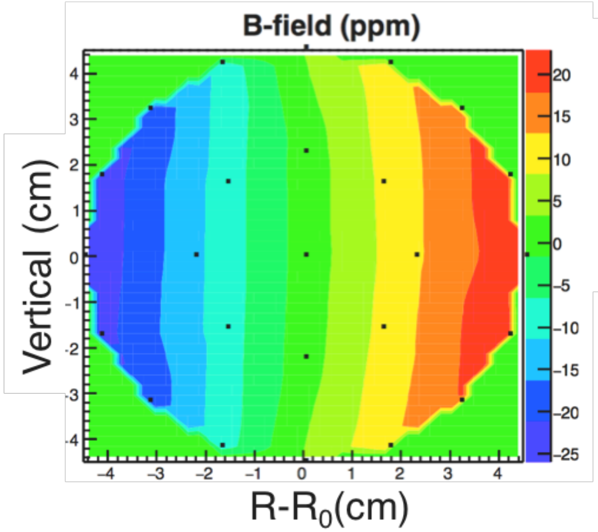




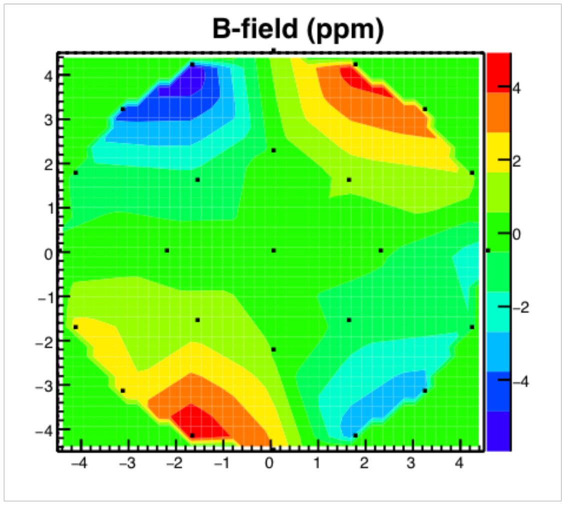
Progress in shimming the storage ring magnet to ±25 ppm



Azimuthally Averaged Field Maps: Oct 2015 → Aug 2016



	Norm	Skew
Quad	25.13	-0.53
Sext	-1.99	-0.11
Octu	-1.16	-0.31
Decu	0.95	-0.07



Norm	Skew
-0.02	-0.57
-0.70	3.84
-0.76	0.56
0.44	-1.61

- Field nearly 3 times more homogeneous than BNL: easier to measure, smaller systematics
- Final shimming with surface coils will reduce remaining inhomogeneity