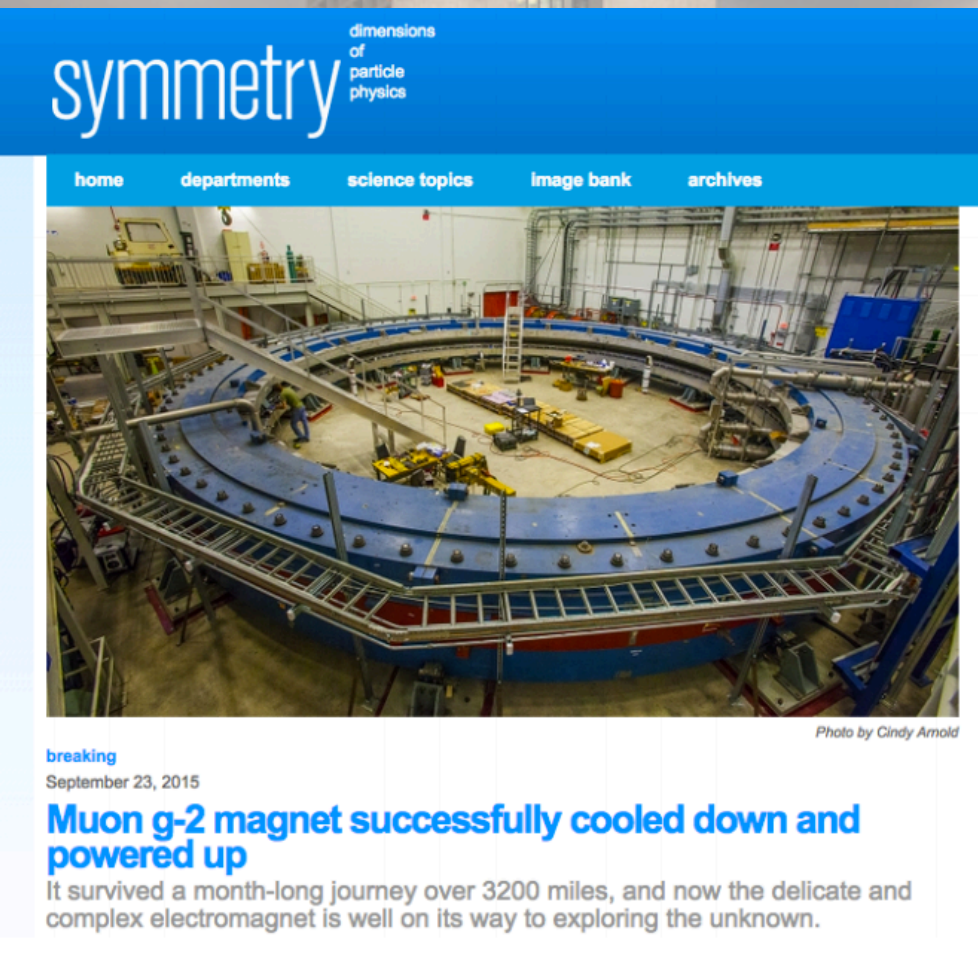
Fermilab

Managed by Fermi Research Alliance, LLC for the U.S. Department of Energy Office of Science


symmetry
dimensions of particle physics

home departments science topics image bank archives

Photo by Cindy Arnold

breaking

September 23, 2015

Muon g-2 magnet successfully cooled down and powered up

It survived a month-long journey over 3200 miles, and now the delicate and complex electromagnet is well on its way to exploring the unknown.

Muon g-2 Experimental Update

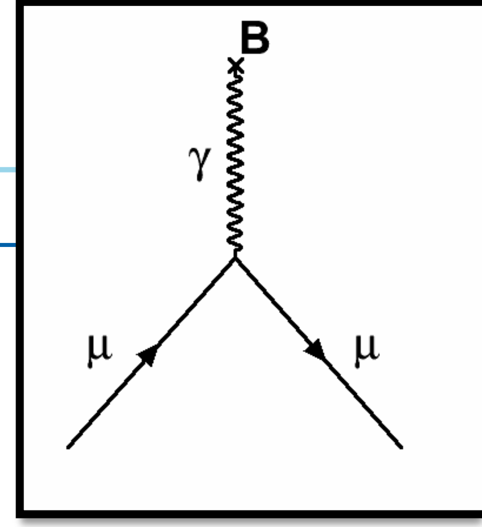
Brendan Kiburg

Fermilab

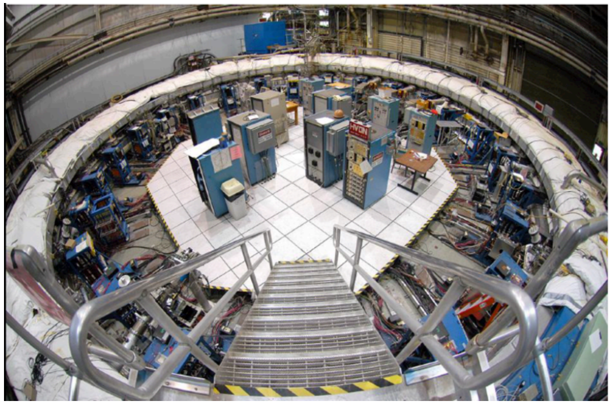
INT Workshop, Seattle WA

Sep 28 – Oct 2 2015

Overview

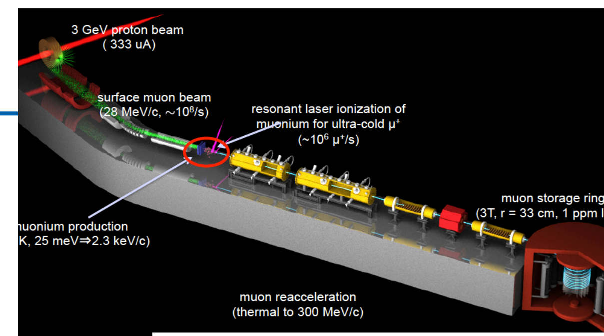


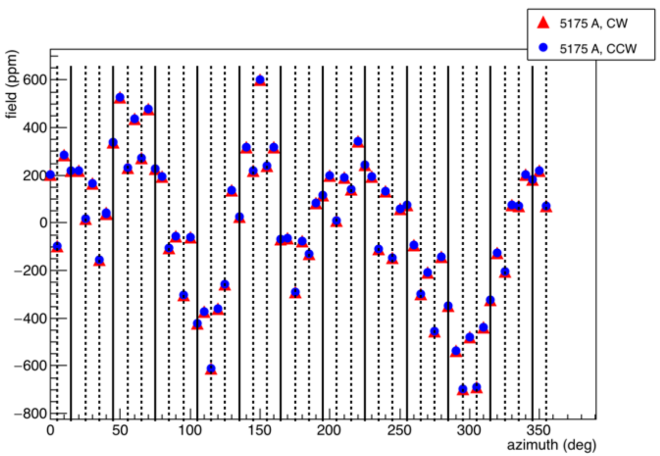
Background



Storage Ring Technique

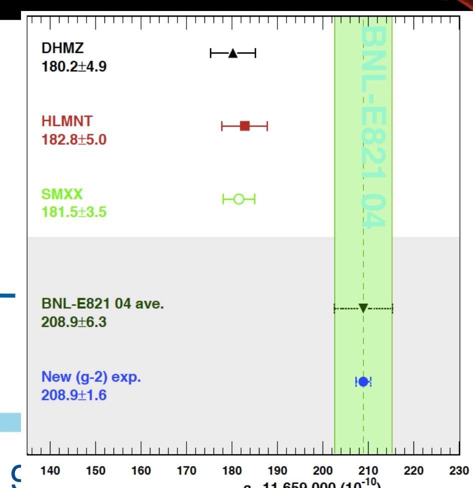
Experimental Details





Recent Fermilab News

Outlook



Muon g-2 : Motivation

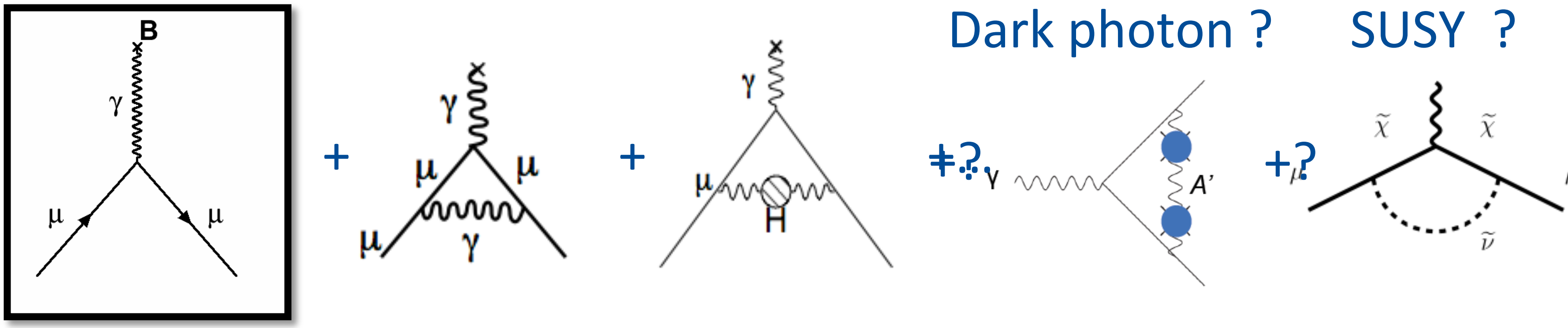
$$\vec{\mu} = g \frac{q}{2m} \vec{S}$$

11h45: Arkady Vainshtein
EDM and MDM Overview

14h30: Liping Gan
BSM searches via pi, eta, eta'
decays

Dark photon ? SUSY ?

g =



$g = 2 + \alpha/2\pi + 6\times10^{-8} + \ldots +? +?$

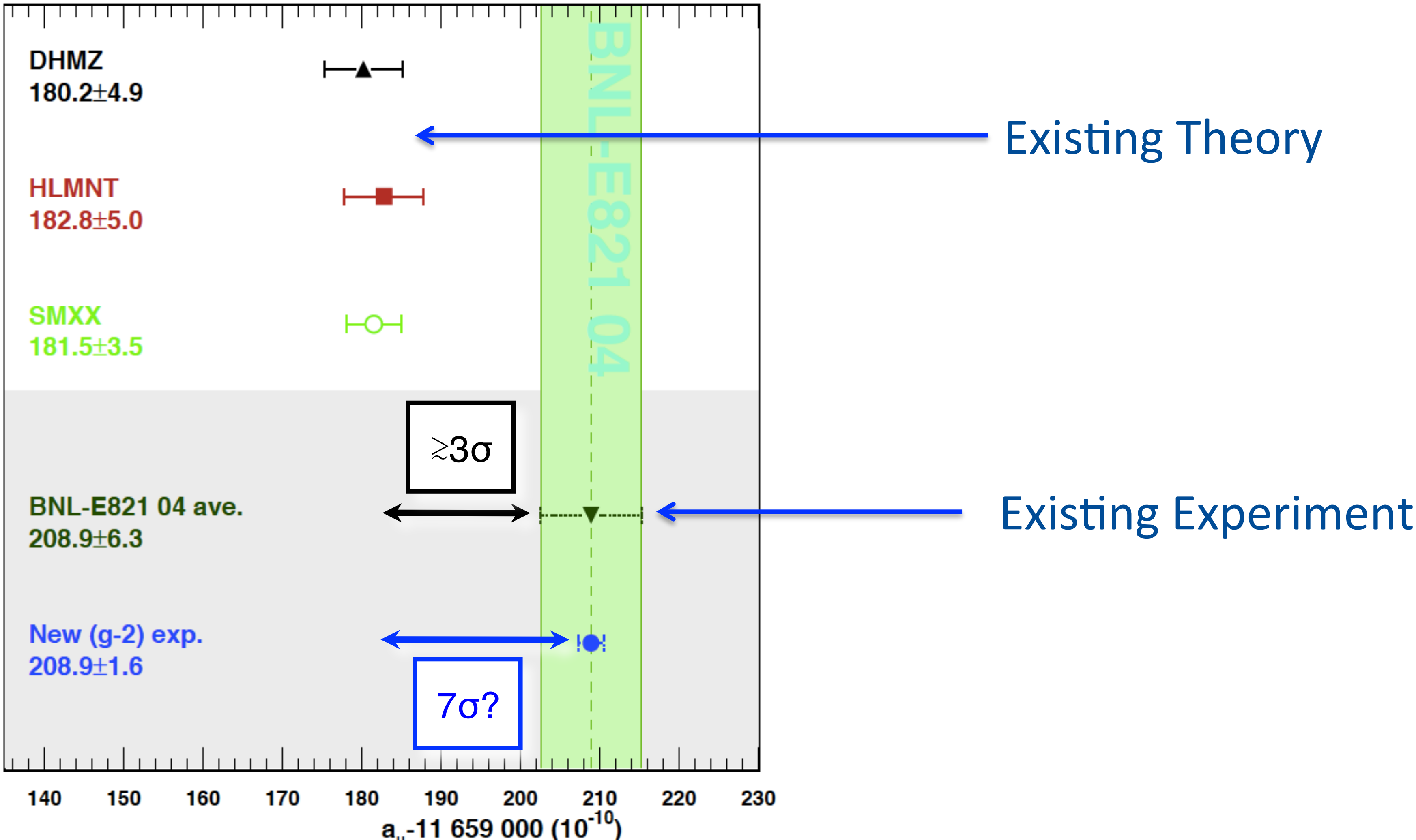
$a_\mu^{SM} = (g_\mu^{SM}-2)/2 = a_\mu^{QED} + a_\mu^{EW} + a_\mu^{QCD}$

9h: William Marciano
Overview of new physics with muons
($g-2$, $\mu-e$, ...)

$a_\mu^{Expt.} = a_\mu^{SM} + a_\mu^{New\ Physics}$

New Physics Opportunities

The Existing Discrepancy



[Blum et al.,arXiv:1311.2198]

Current Uncertainties

Leading contribution to a_μ : QED

	VALUE ($\times 10^{-11}$) UNITS
QED ($\gamma + \ell$)	$116\,584\,718.853 \pm 0.022 \pm 0.029_\alpha$
HVP(lo)*	$6\,923 \pm 42$
HVP(ho)**	-98.4 ± 0.7
H-LBL†	105 ± 26
EW	153.6 ± 1.0
Total SM	$116\,591\,802 \pm 42_{\text{H-LO}} \pm 26_{\text{H-HO}} \pm 2_{\text{other}}\ (\pm 49_{\text{tot}})$

Leading contribution to δa_μ : Hadronic loops

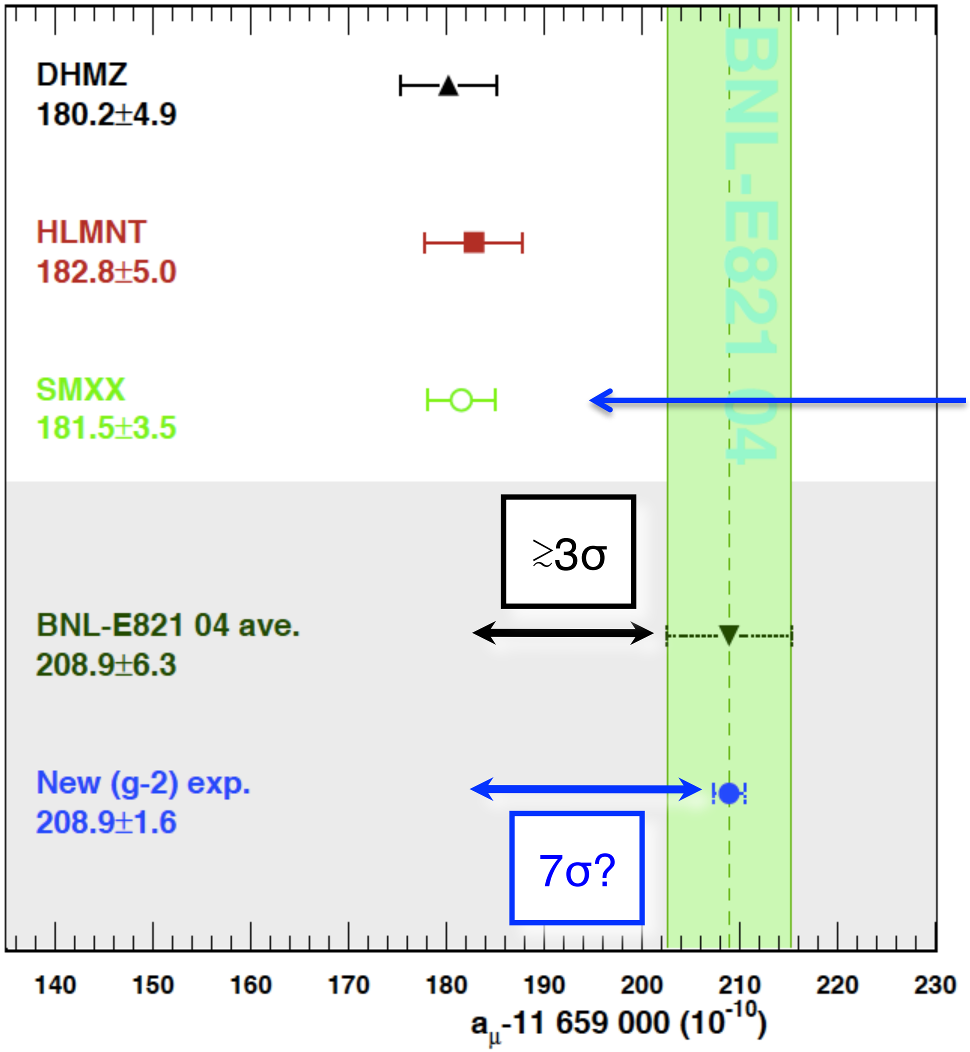
11h: Christine Davies
g–2 on the lattice and HVP

11h45: Tom Blum:
g–2 on the lattice, HLbL

12h15: Martin Hoferichter
Hadronic light–by–light for muon *g*–2

Novel approaches

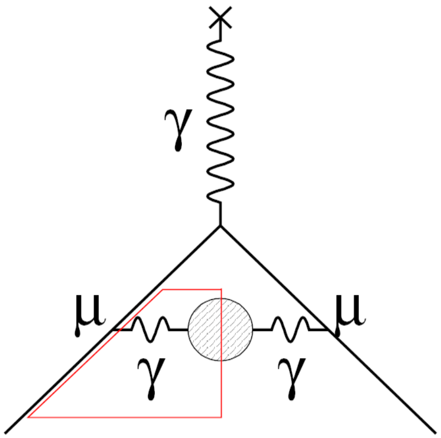
The Existing Discrepancy

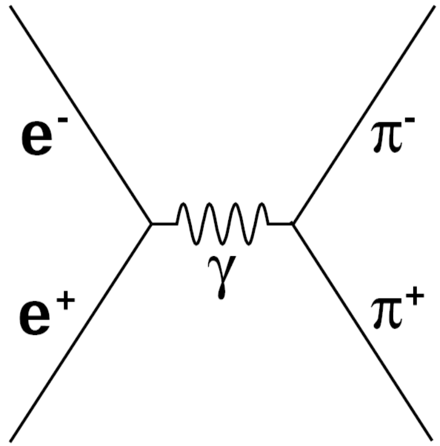


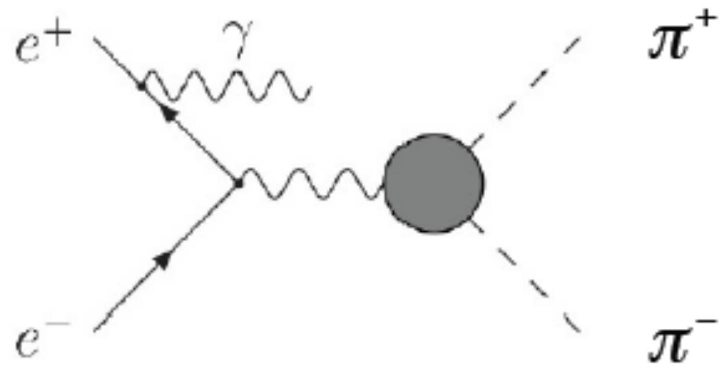
Projection with reduced uncertainty anticipating contributions from e^+e^-

[Blum et al.,arXiv:1311.2198]

Critical inputs to HVP







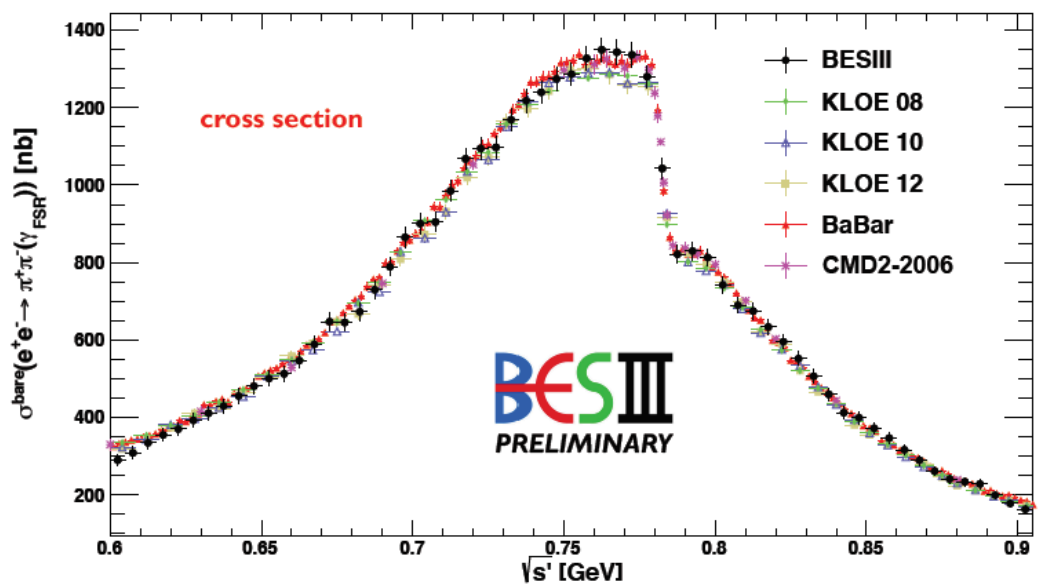
hadronic vacuum polarization:

$$a_\mu^{hadr,VP} = (692.2 \pm 4.2)\cdot 10^{-10}$$ Davier et al.

Dispersion reslation

$$a_\mu^{hadr,VP} \cong \frac{1}{4\pi^3}\int_{4m_\pi^2}^{\infty} K(s)\sigma(e^+e^- \to hadr)ds$$

Kernel function $K(s) \propto \frac{1}{s}$



Critical inputs to HVP ($a_\mu^{2\pi,LO}$)

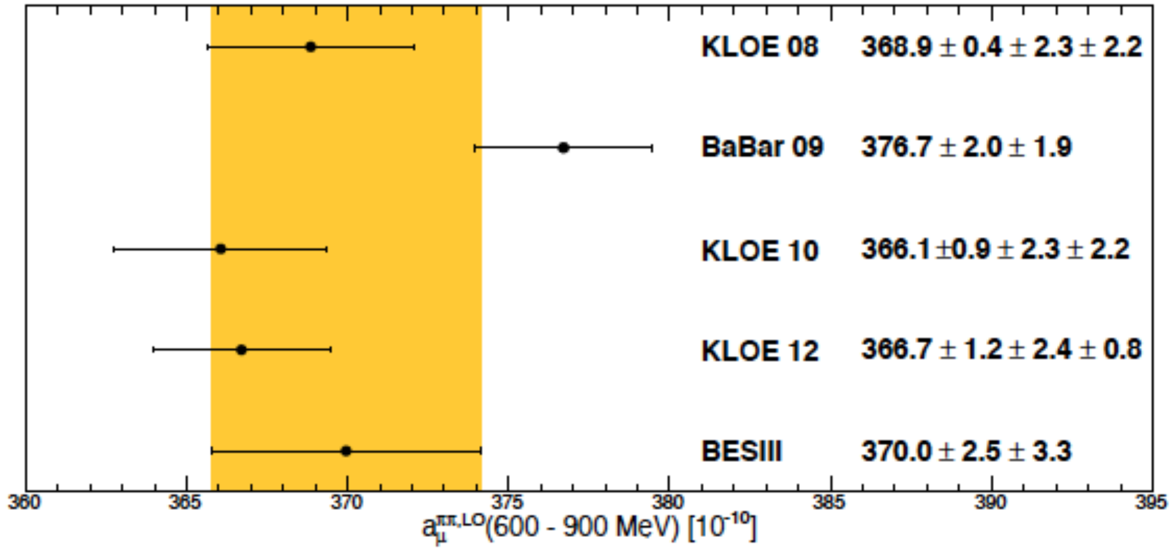


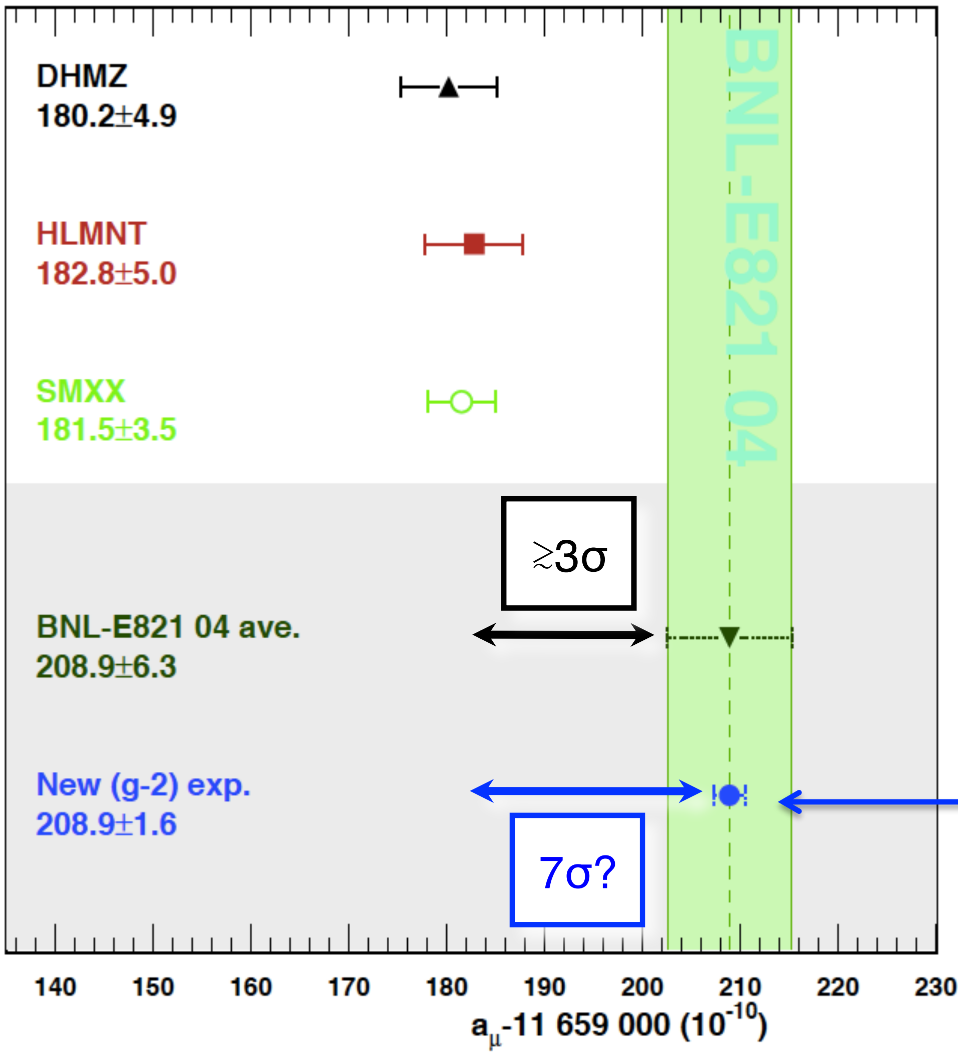
Figure 7: Our calculation of the leading-order (LO) hadronic vacuum polarization 2π contributions to $(g-2)_\mu$ in the energy range 600 - 900 MeV from BESIII and based on the data from KLOE 08 [6], 10 [7], 12 [8], and BaBar [10], with the statistical and systematic errors. The statistical and systematic errors are added quadratically. The band shows the 1σ range of the BESIII result.

http://arxiv.org/pdf/1507.08188.pdf

BES-III : 3x more data available, luminosity measurement improvements

VEPP-2000 : New results this year at ~0.6% on $\pi\pi$, 0.3% by 2017

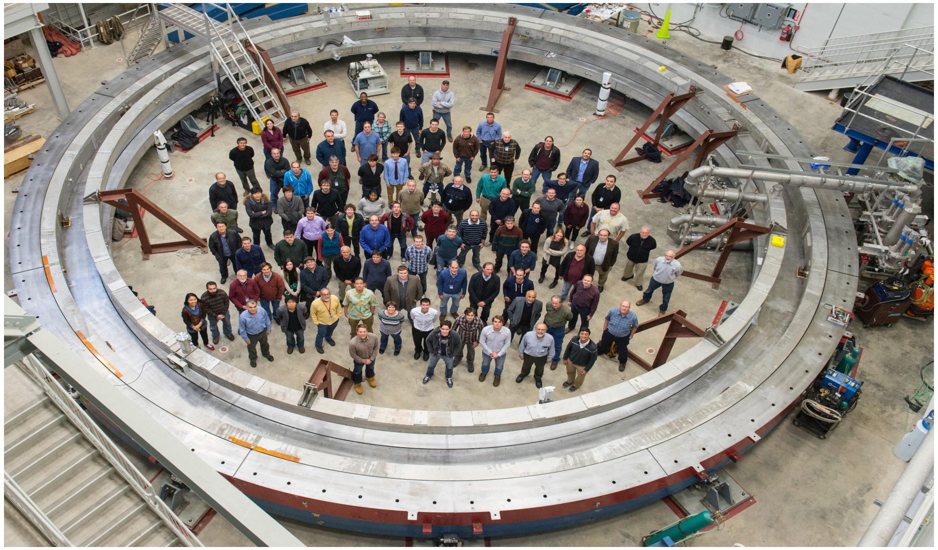
The Existing Discrepancy → Experimental Effort Motivated

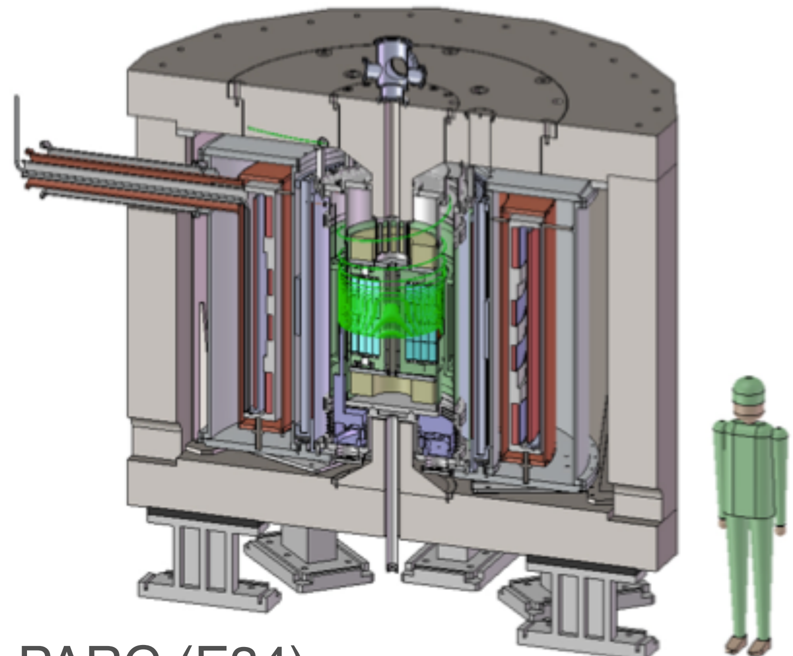


Two new efforts

[Blum et al.,arXiv:1311.2198]

Next-Generation Experiments





Fermilab (E989)

- 7-meter-radius storage ring
- 1.45 Tesla,
- High-rate 3.09 GeV/c muon beam
- Polarization ~ 97%
- Data taking 2017-2018
- 100 ppb by end of 2019

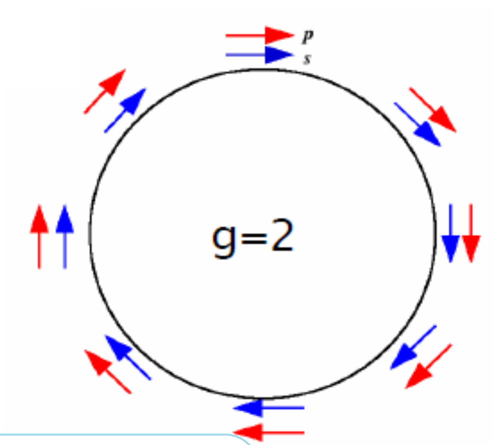
J-PARC (E34)

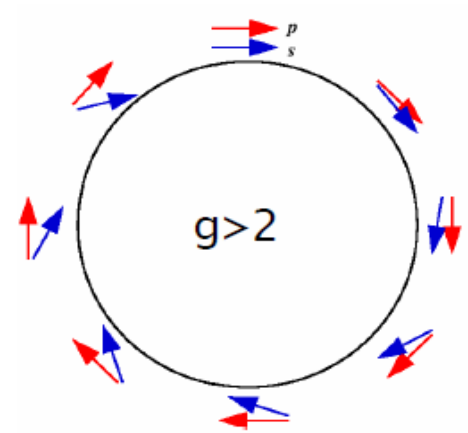
- 0.33-meter-radius storage ring
- 3 Tesla
- Surface muon beam → muonium → 0.3 GeV/c muon beam
- Polarization ~ 50%
- Data taking 2019-2021
- 400 ppb by end of 2023

STORAGE RING TECHNIQUE

Experiment Basics: Muons in a storage ring

1. Start with polarized muon beam (from pion decay)
2. Cyclotron frequency : $\omega_c = \frac{e}{m\gamma} B$
3. Spin precession frequency : $\omega_S = \frac{e}{m\gamma} B \left(1 + \gamma a_\mu\right)$ Larmor + Thomas precession



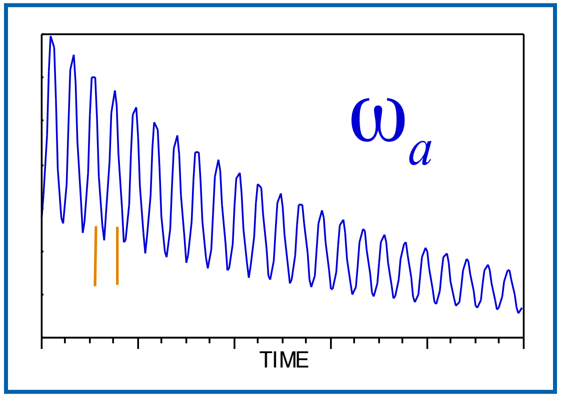


→ momentum

→ spin

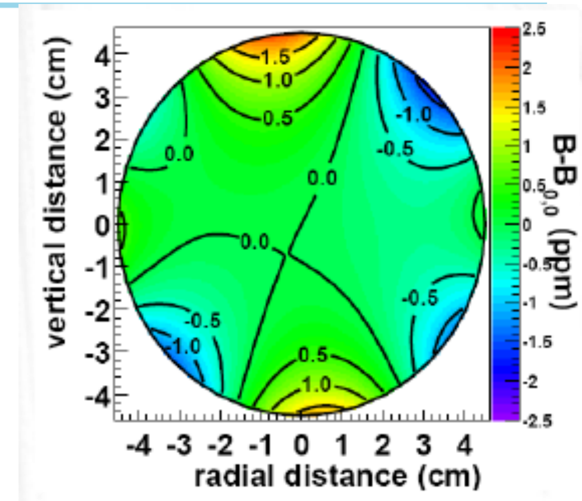
$$\omega_a = \omega_S - \omega_c = \frac{eB}{m} a_\mu$$

Muon g-2 Measurements



$$\omega_a = \frac{eB}{m} a_\mu$$

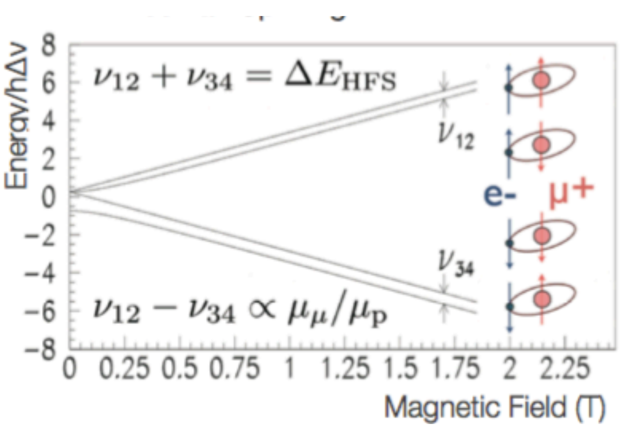
NMR for B field
Recast with proton precession frequency, ω_p



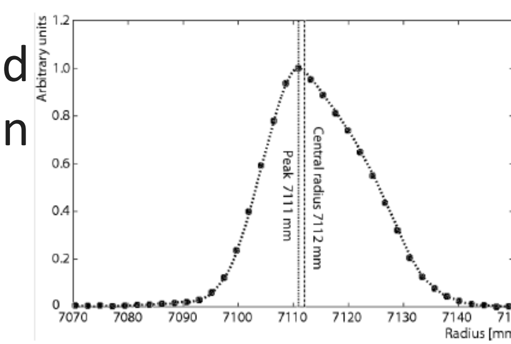
ω_a via electrons

ω_p via NMR

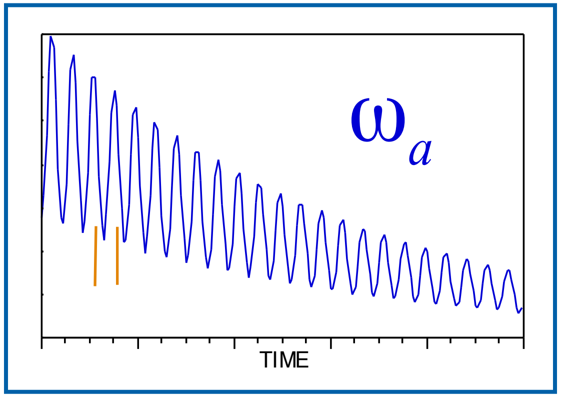
$$a_\mu = \frac{\omega_a/\omega_p}{\mu_\mu/\mu_p - \omega_a/\omega_p}$$



Understand distribution



Muon g-2 Measurements



ω_a via electrons

$$\omega_a = \frac{eB}{m} a_\mu$$

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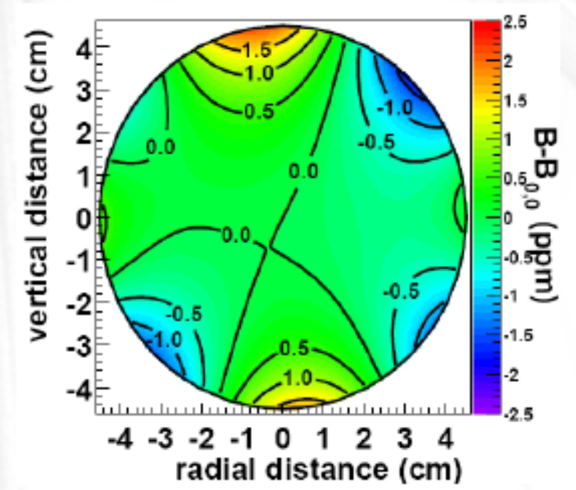
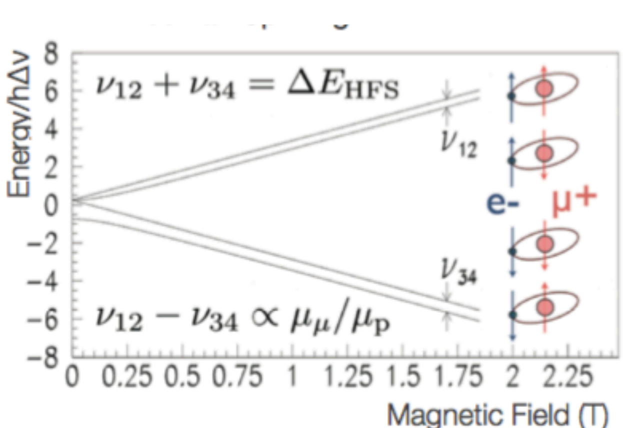


ω_p via NMR

$$a_\mu = \frac{\omega_a/\omega_p}{\mu_\mu/\mu_p - \omega_a/\omega_p}$$



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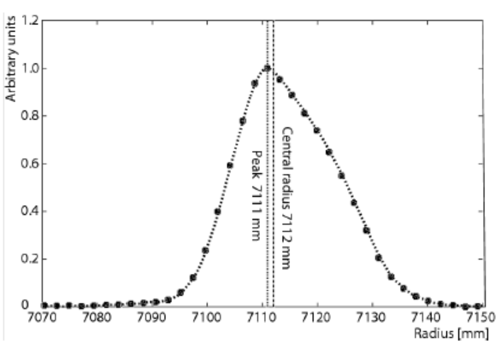


Fermilab

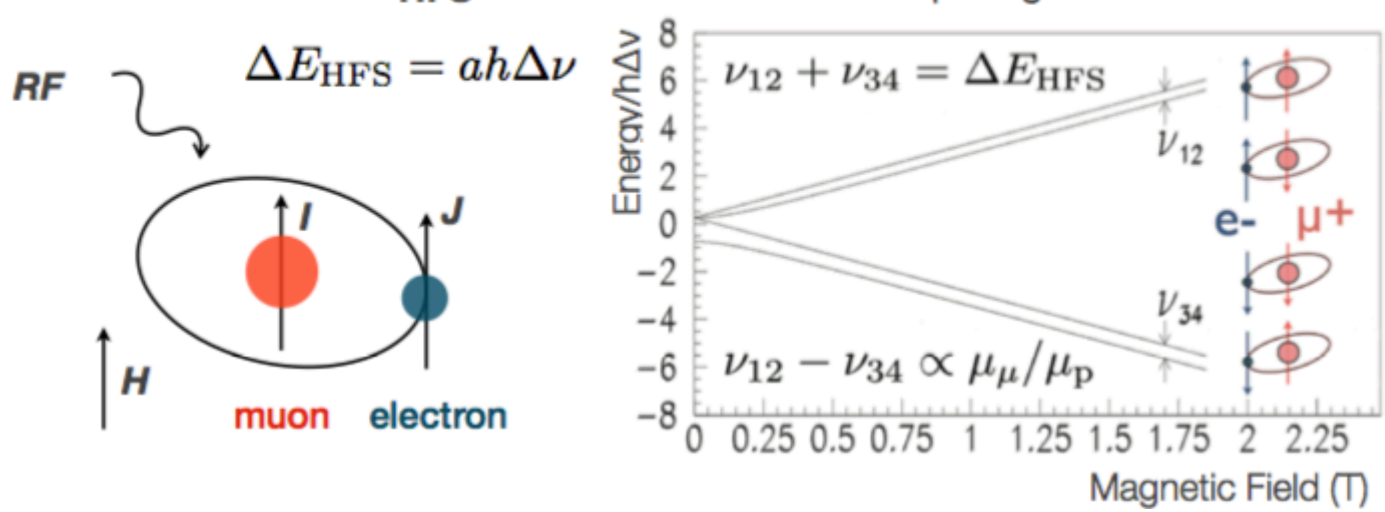
Magnetic Moment Ratio

$$a_\mu = \frac{\omega_a/\omega_p}{\mu_\mu/\mu_p - \omega_a/\omega_p}$$

MUSEUM @ JPARC

Hamiltonian of Muonium $\mathcal{H} = a\vec{I}\cdot\vec{J} + \mu_B^e g_J \vec{J}\cdot\vec{H} - \mu_B^\mu g_\mu' \vec{I}\cdot\vec{H}$ + RF term

HFS — Zeeman Splitting



Extracts
m_μ/m_e
μ_μ/μ_p

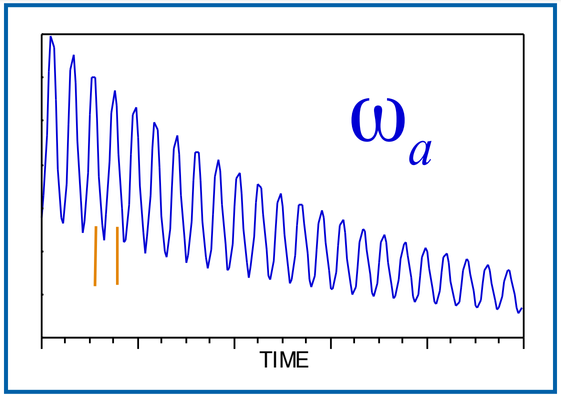
Muon g-2 uncertainty contribution: 25 ppb

Common Probes for determining the magnetic field

- Previous generation of muonium hyperfine, muon g-2
- This generation

Fermilab

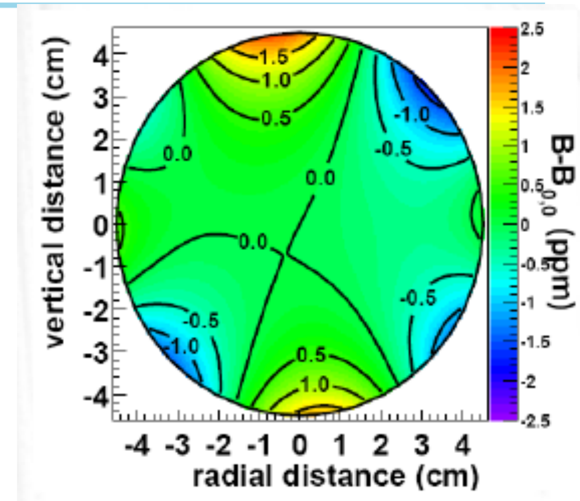
Muon g-2 Measurements



ω_a via electrons

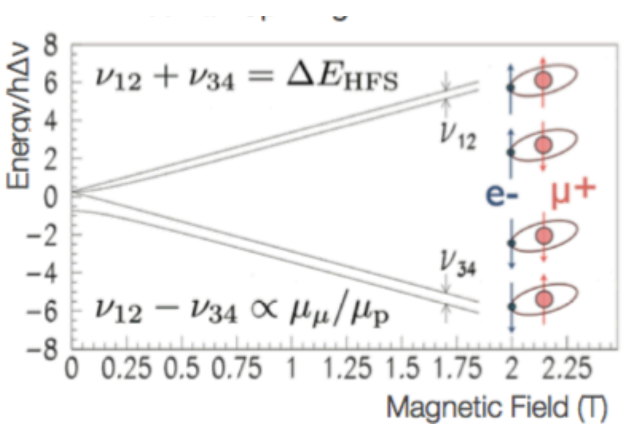
$$\omega_a = \frac{eB}{m} a_\mu$$

NMR for B field
Recast with proton precession frequency, ω_p



ω_p via NMR

$$a_\mu = \frac{\omega_a / \omega_p}{\mu_\mu / \mu_p - \omega_a / \omega_p}$$



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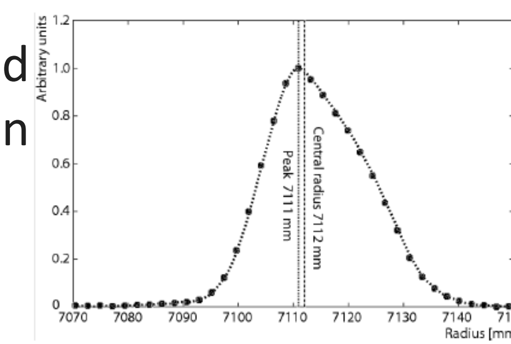
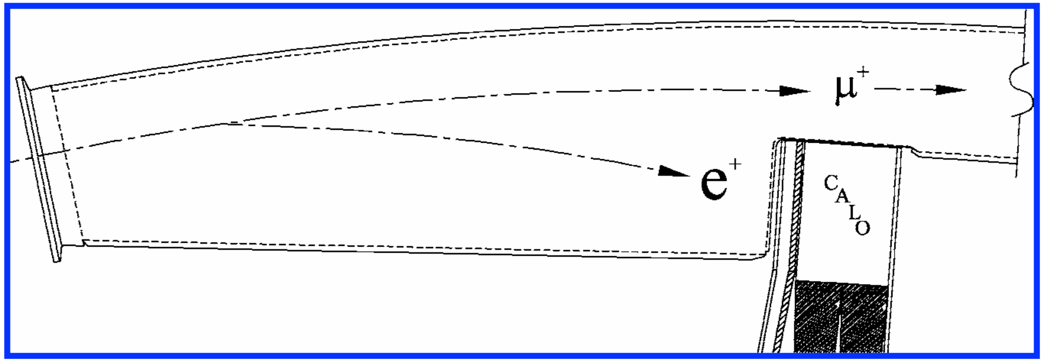


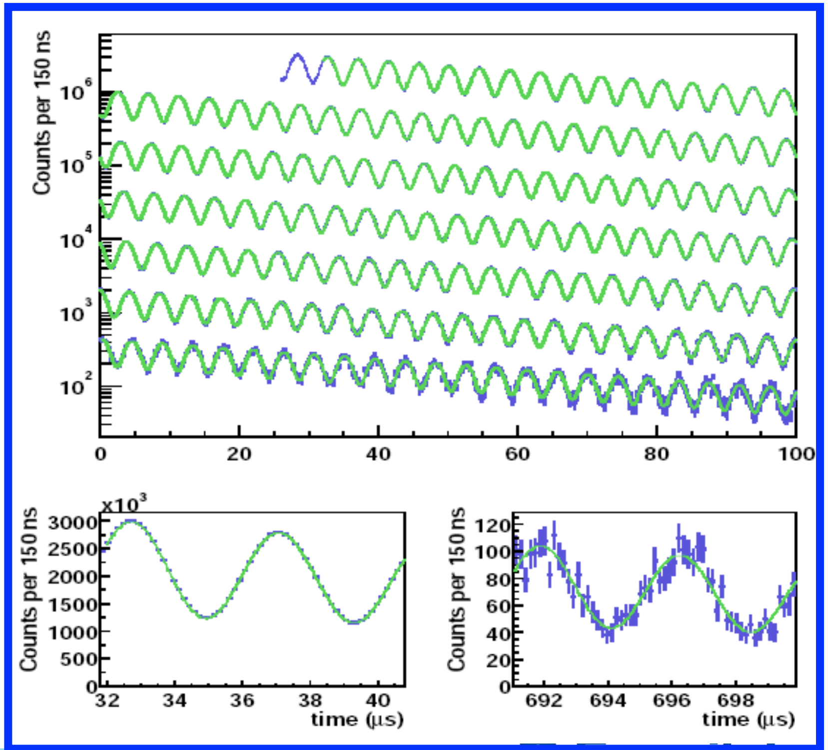
Fermilab

Muon spin precession frequency

$$a_\mu = \frac{\omega_a / \omega_p}{\mu_\mu / \mu_p - \omega_a / \omega_p}$$



E821 selecting positrons with E > 1.8 GeV

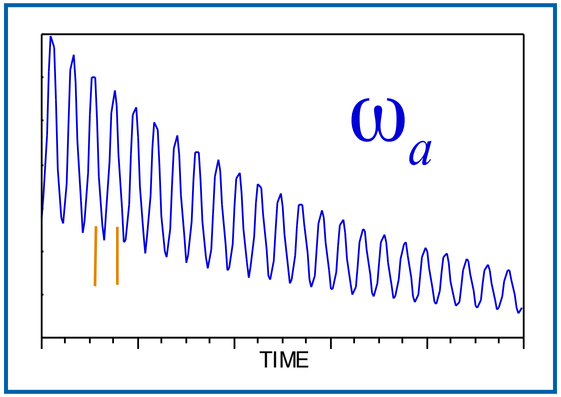


- Muon decay self-analyzing: Higher energy positrons emitted preferentially in direction of muon spin

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

- Spectrum distortions from
  - Pileup, gain stability
  - Beam Effects, Losses

Muon g-2 Measurements



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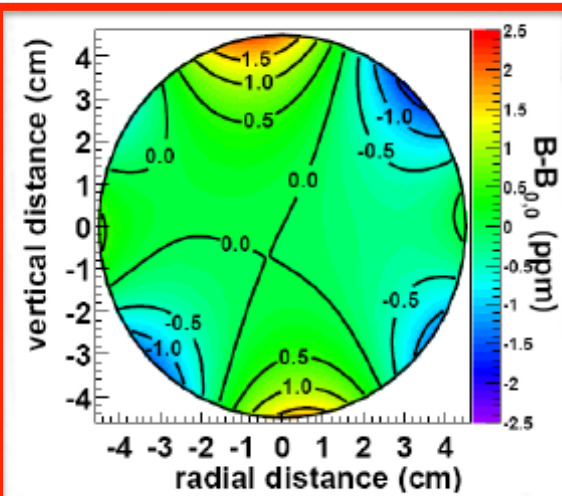
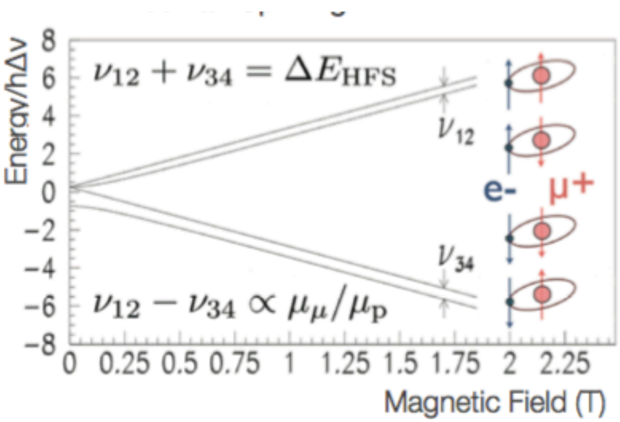


ω_p via NMR

$$a_\mu = \frac{\omega_a / \omega_p}{\mu_\mu / \mu_p - \omega_a / \omega_p}$$



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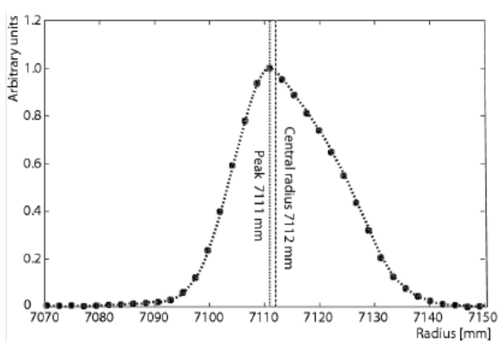

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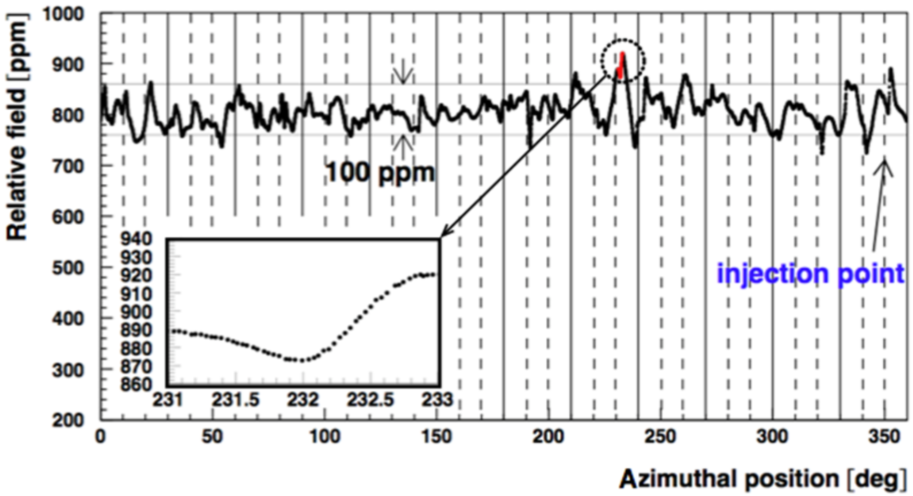
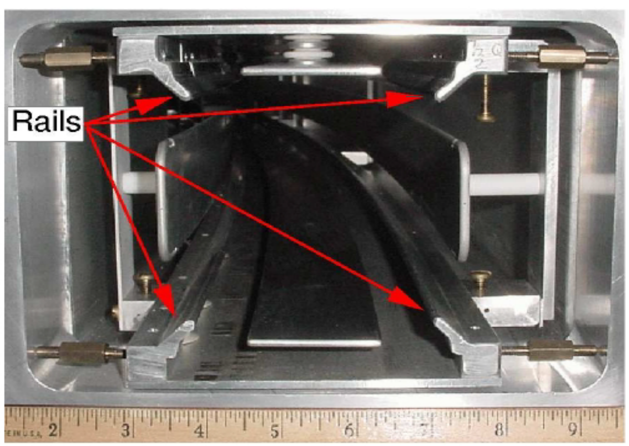
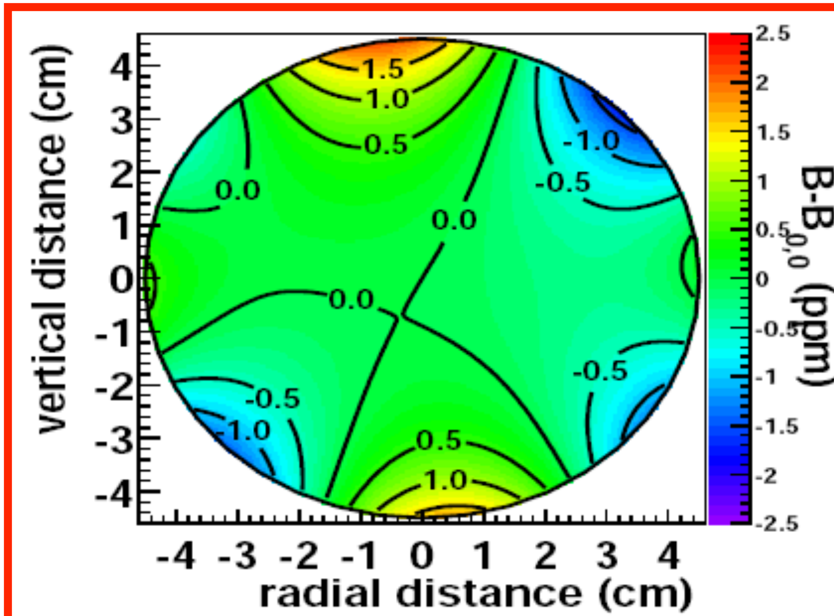
Proton Spin Precession Frequency

$$a_\mu = \frac{\omega_a/\omega_p}{\mu_\mu/\mu_p - \omega_a/\omega_p}$$



- Measure B-Field around the Ring (Azimuth)
- Determine average profile (r,vertical)

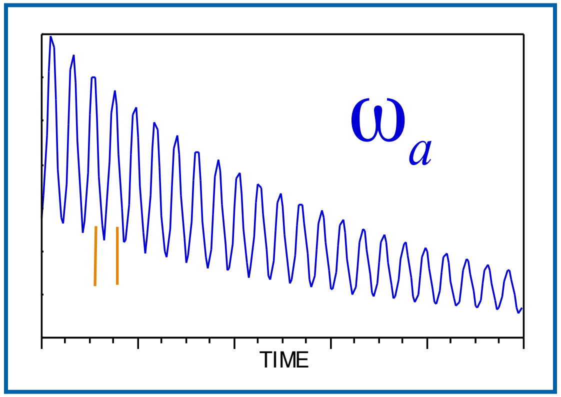




17 NMR probes on trolley to map 6000 azimuthal locations

Fermilab

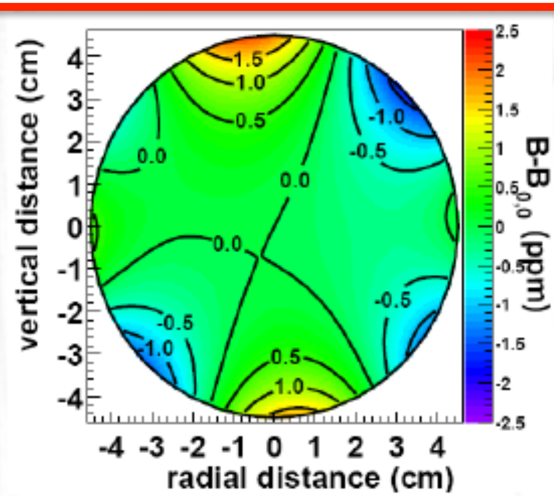
Muon g-2 Measurements



ω_a via electrons

$$\omega_a = \frac{eB}{m} a_\mu$$

NMR for B field
Recast with proton precession frequency, ω_p



ω_p via NMR

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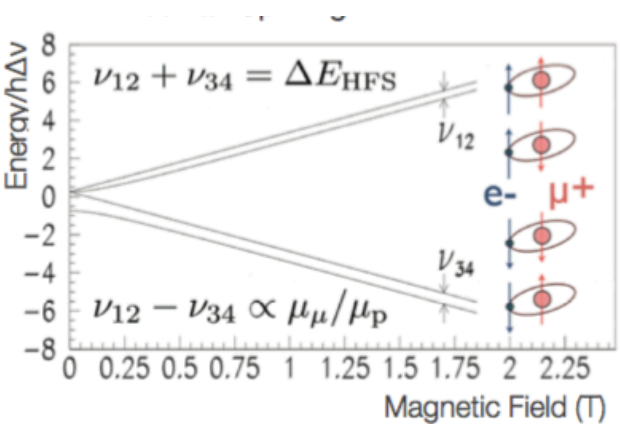
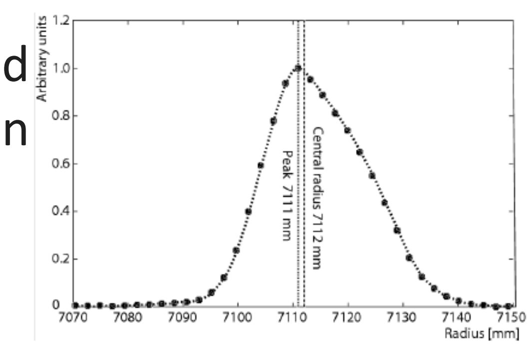


Understand distribution

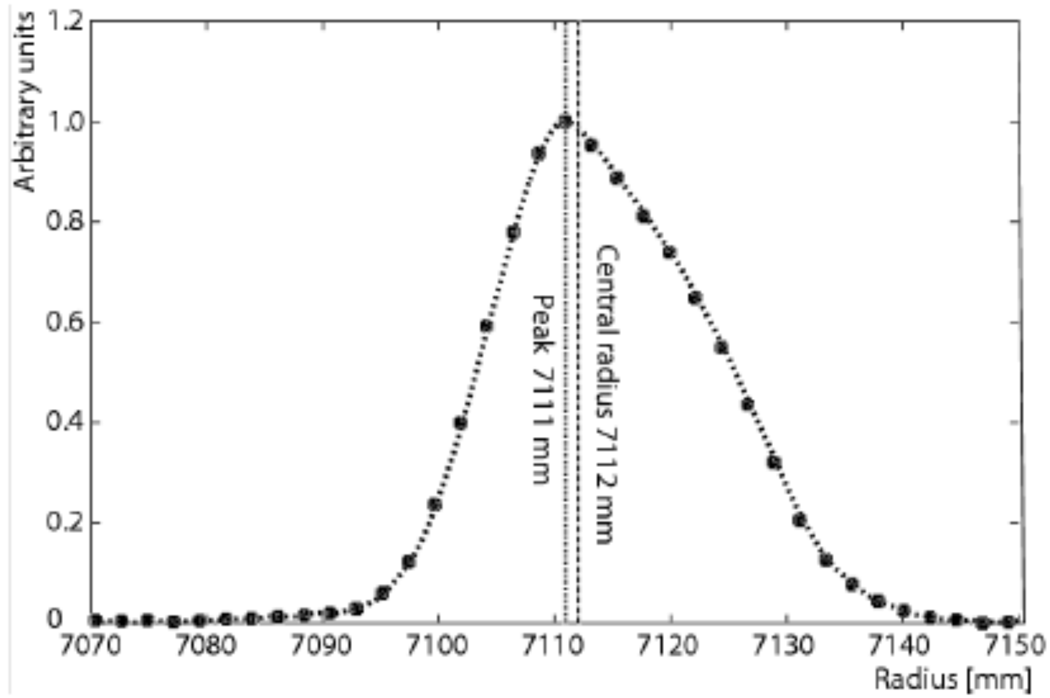


Distribution Convolution

$$a_\mu = \frac{\omega_a / \omega_p}{\mu_\mu/\mu_p - \omega_a / \omega_p}$$

Understand Spatial Muon Distribution over the course of the experiment

Weight the B-Field accordingly



EXPERIMENTAL DETAILS

Experimental Details

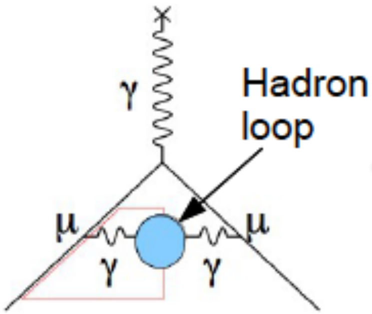
- Statistics
  - Muon Beam Preparation (Accelerator)
  - Kicking onto orbit (Kicker)
  - Containment (Quad)
- Muon Precession
  - Electron Detection (Calorimeter)
  - Electron Tracking (Tracker)
- Proton Precession
  - Field Measurements

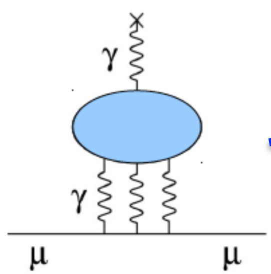
I will focus on Fermilab details and then identify some differences for JPARC

Muon g-2: The path forward

Muon precession → ω_a

Proton precession → ω_p





Uncertainty Source	Status 2015 [ppb]	Projected after E989 [ppb] **
ω_a	180	70
ω_p	170	70
Statistical	460	100
Total Exp.	540	140
Had. Vac. Pol.	360	215 *
Had LBL	225	225
Total Theory	420	310

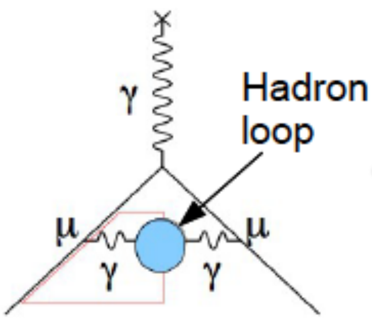
* Projected error anticipating input from e+/e- BES III, VEPP2000, etc.

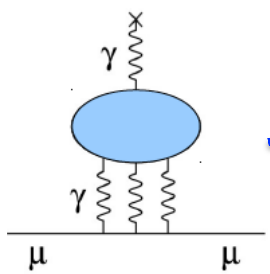
** Ongoing lattice efforts will have a big impact on these projections

Muon g-2: The path forward

Muon precession → ω_a

Proton precession → ω_p





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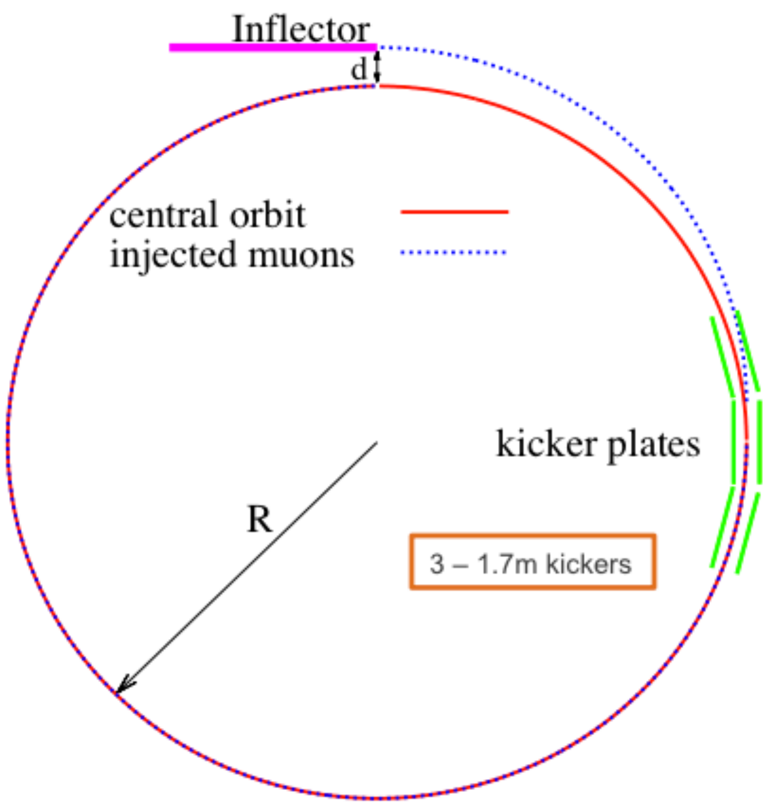
Total Theory	420	310

Muon Beam Preparation for 21x BNL statistics

- Efficiency
  - Improved pion collection
  - Improved capture of muons from pion decay
  - Long decay channel
- Delivery Ring to get rid of protons
  - Eliminate background early
  - Start fits earlier
- Fermilab structure
  - 12 Hz rep rate
- ~10,000 muons per pulse successfully injected
- Run Time: 18-24 months

Preparing Existing Tunnels, Building new ones,

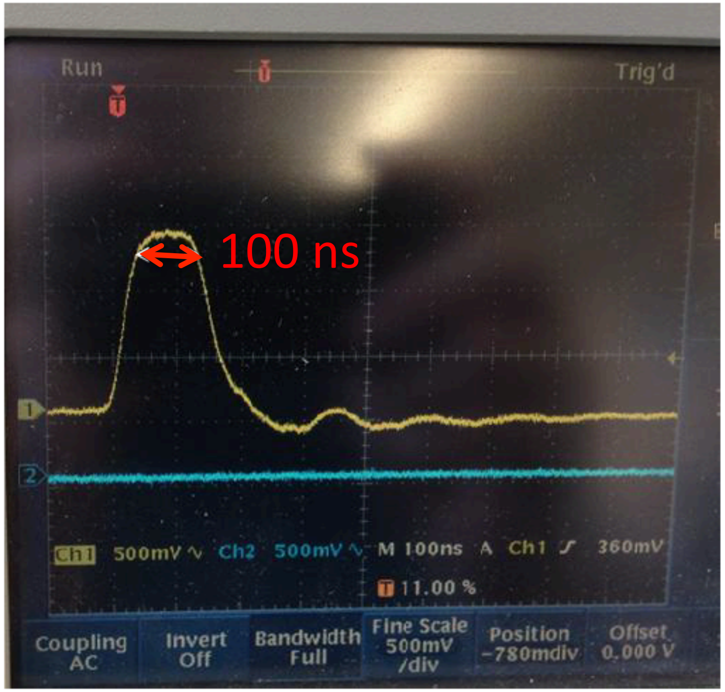
Blumlein kicker knocks muons onto storage orbit



τ_{rev} = 149 ns

d = 77 mm, R=7112 mm
kick angle θ = d/R = 10.8 mrad
From D. Rubin

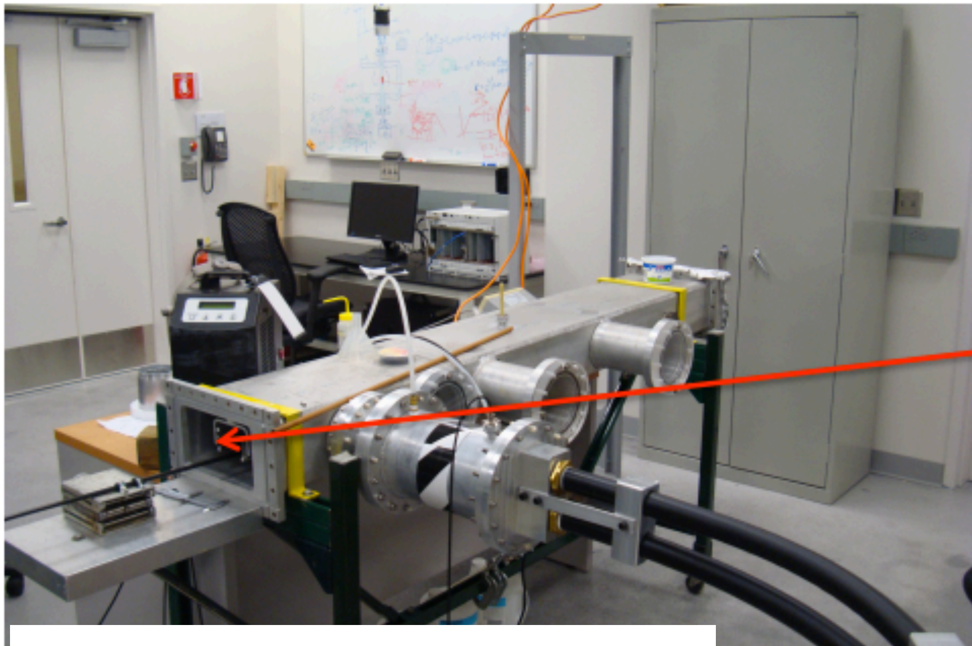
- Pulse is commensurate with 1 muon orbit (149ns)
- Turn off before muons 2nd orbit

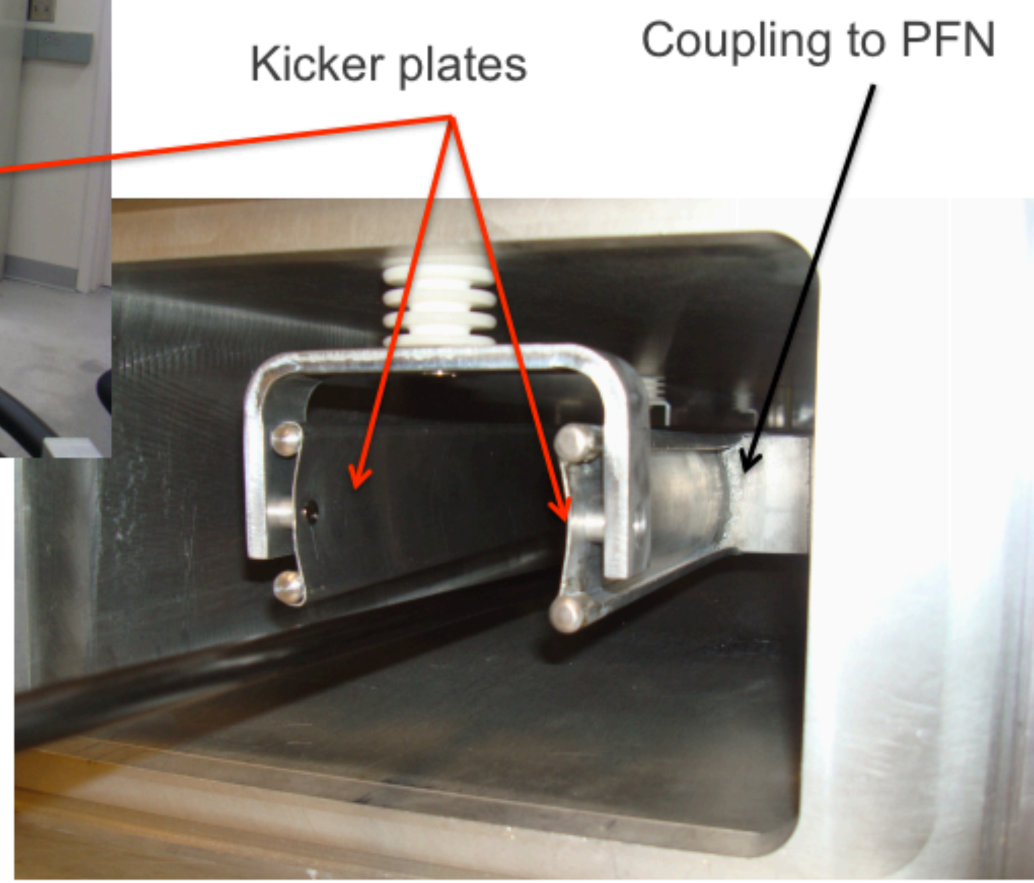


- Tri-axial line filled with Castor oil
- 9-meter long line

Fermilab

Blumlein kicker knocks muons onto storage orbit

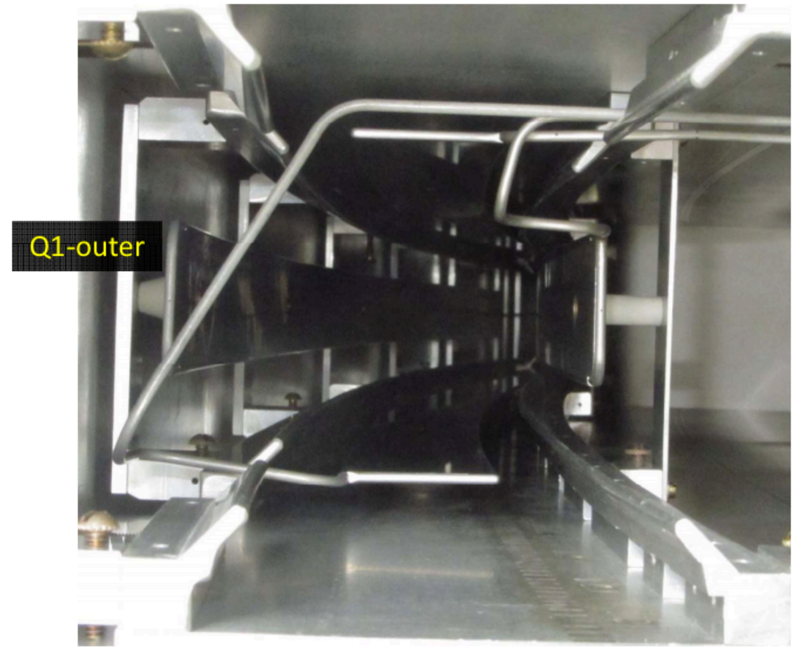




Assembling have been finished in December 2014; first test run in January 8 2015

Electrostatic Quadrupoles for vertical containment

- Muons with $p_{vertical}$ will spiral out
- Quadrupoles for vertical focusing
- New design to improve muon injection



- Caveat: Introducing E-field → affects ω_a

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

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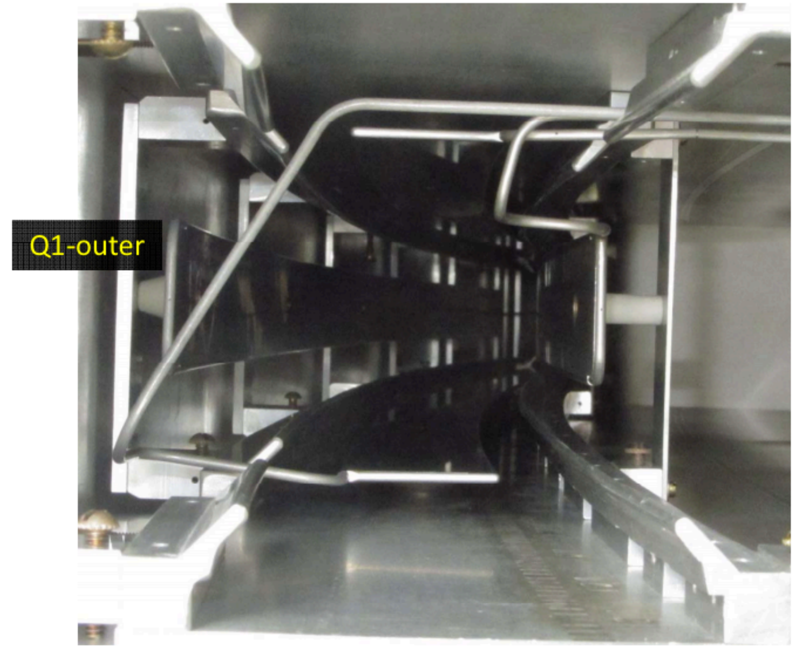

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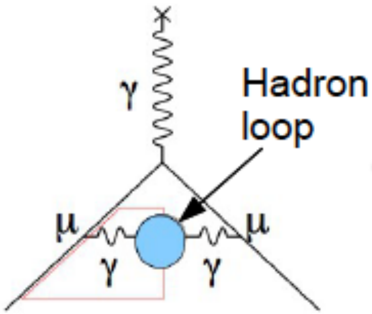
$$\vec{\omega}_a = -\frac{e}{m}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right]$$

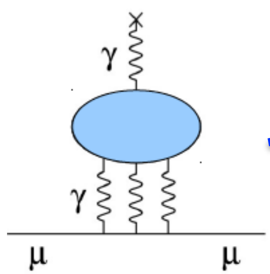
choose $\gamma = 29.3$ ($P_\mu = 3.094$ GeV/c)

Muon g-2: The path forward

Muon precession

Proton precession





Uncertainty Source	Status 2015 [ppb]	Projected after E989 [ppb]
ω_a	180	70
ω_p	170	70
Statistical	460	100
Total Exp.	540	140
Had. Vac. Pol.	360	215 *
Had LBL	225	225
Total Theory	420	310

ω_a Systematics

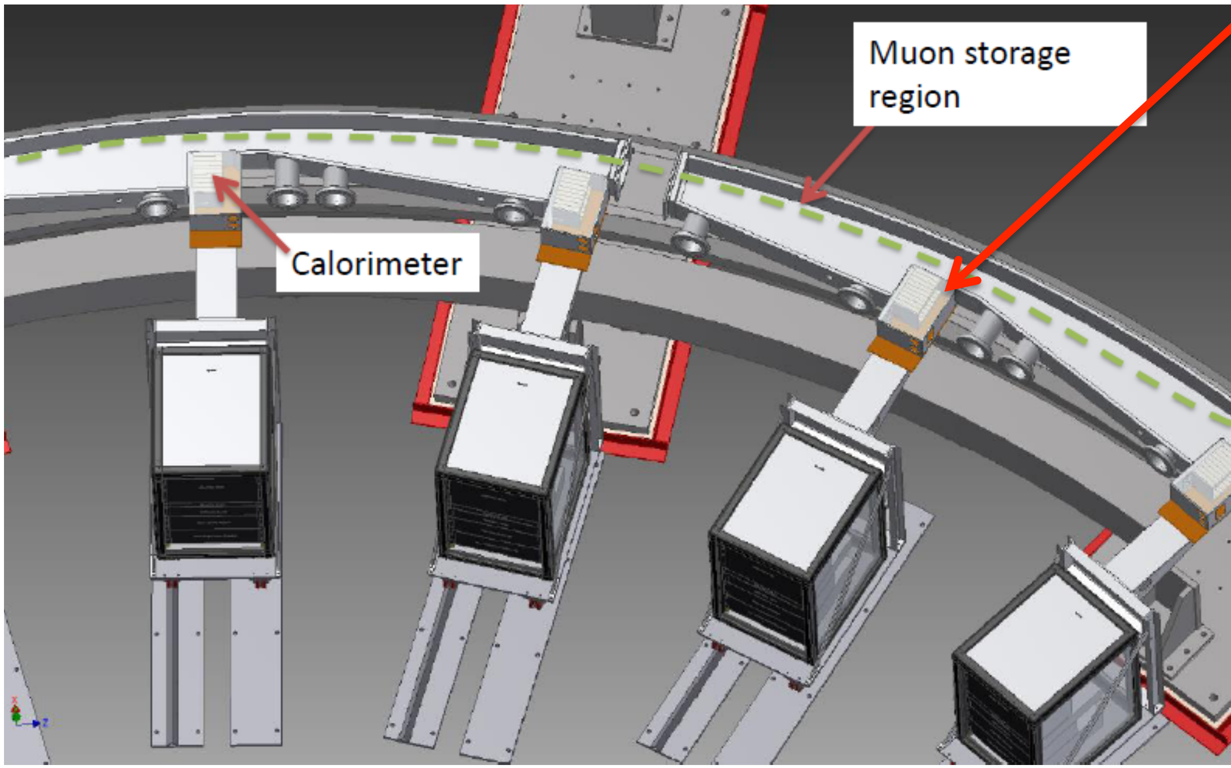
Category	E821 [ppb]	E989 Improvement Plans	Goal [ppb]
Gain changes	120	Better laser calibration	
		low-energy threshold	20
Pileup	80	Low-energy samples recorded	
		calorimeter segmentation	40
Lost muons	90	Better collimation in ring	20
CBO	70	Higher n value (frequency)	
		Better match of beamline to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

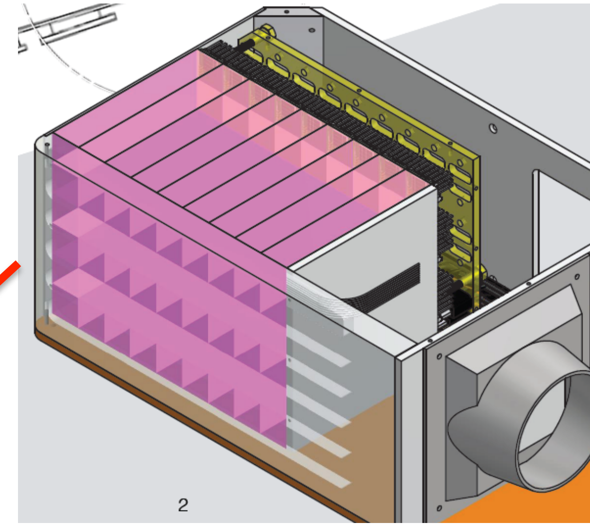
Calorimeters

24 Stations

Segmented: Arrays of 6x9 PbF_2 crystals

Energy resolution 2.8% at 3.5 GeV





Fast

- Cherenkov
- temporal separation

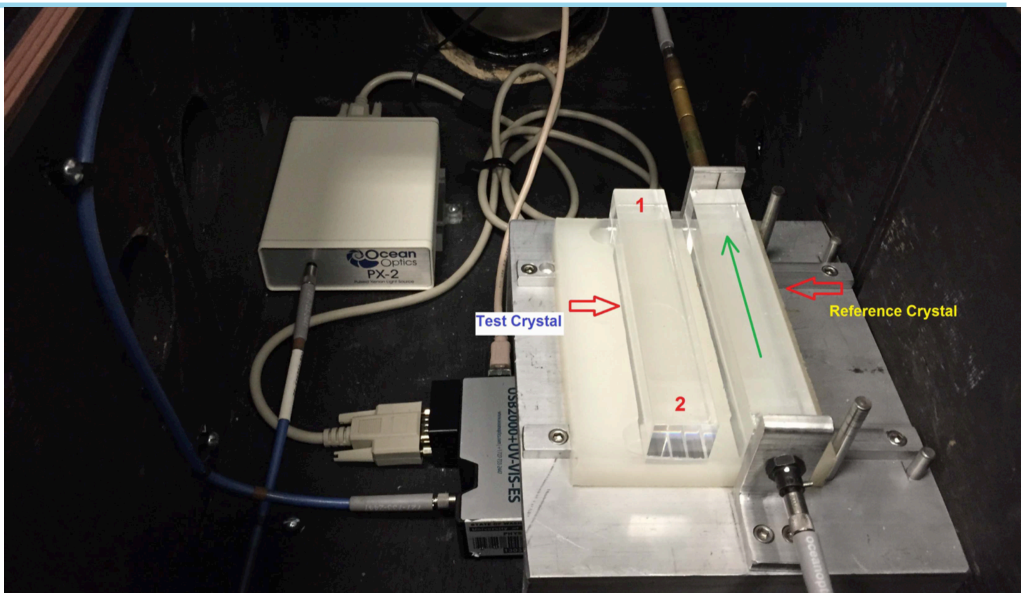
Compact

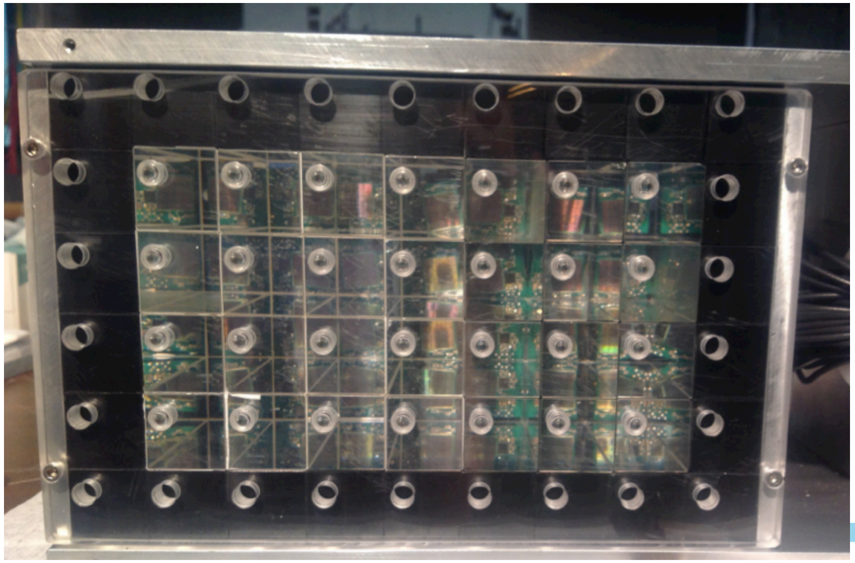
- X_0=0.93 cm
- R_M=1.8cm

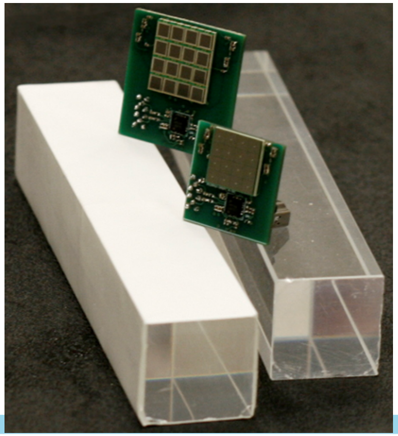
2.5 x cm x 2.5 cm x 14 cm

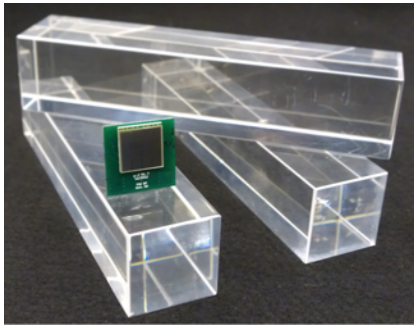
- spatial separation

Calorimeter Production Program

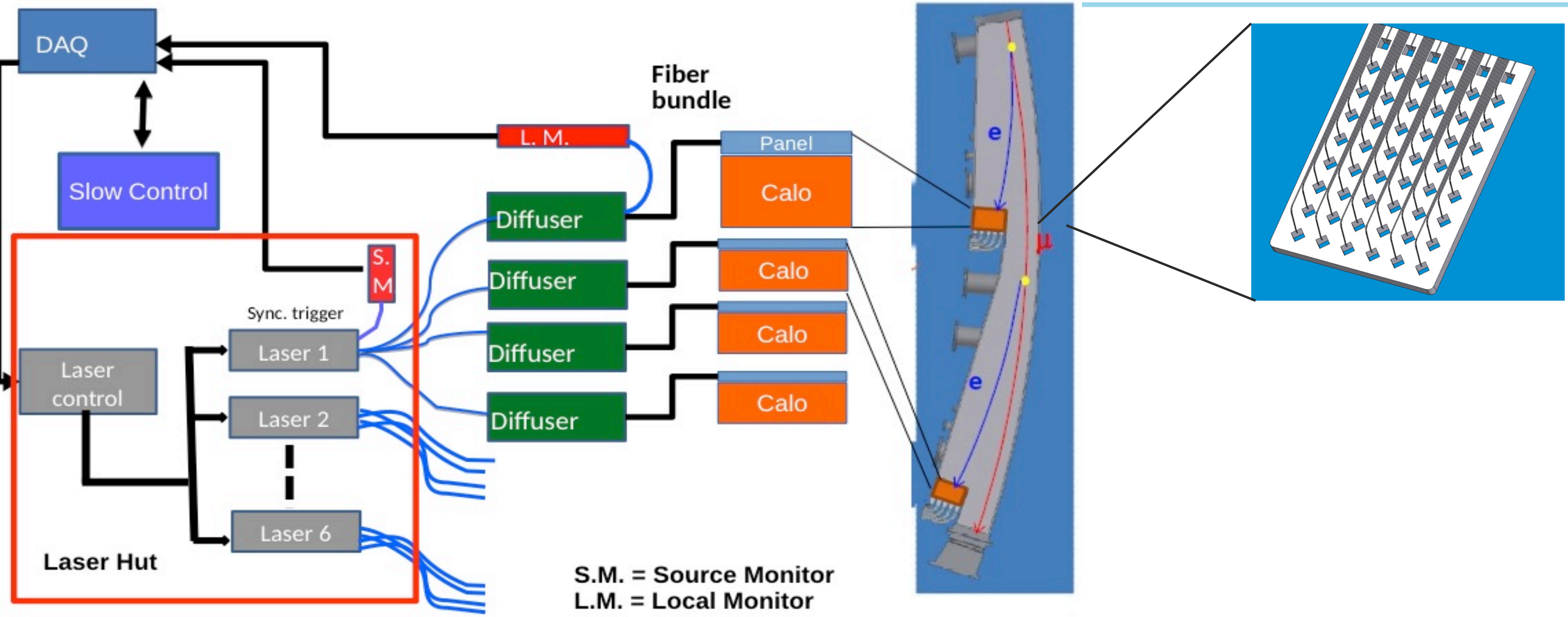








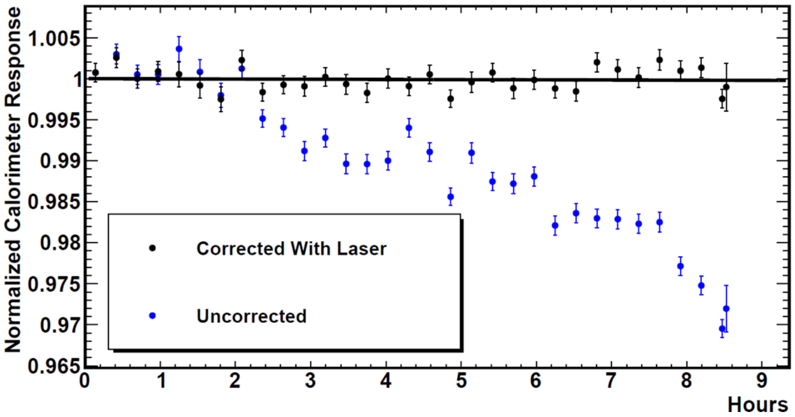
Laser System Will Monitor Gain Stability



Pulsed distributed laser to calo cells

Gain monitoring

- Over long periods of time
- Over 1 fill (~700 μs)



Fermilab

ω_a Systematics

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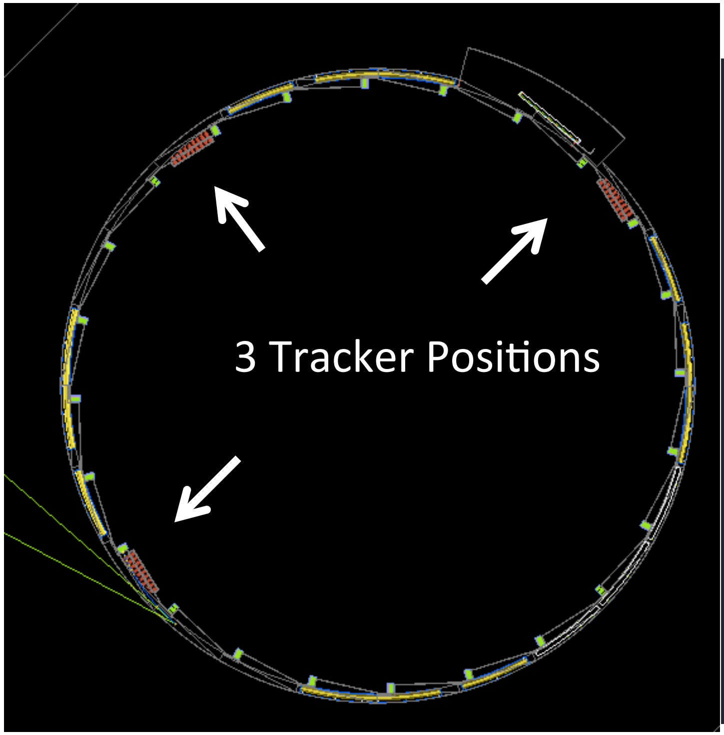
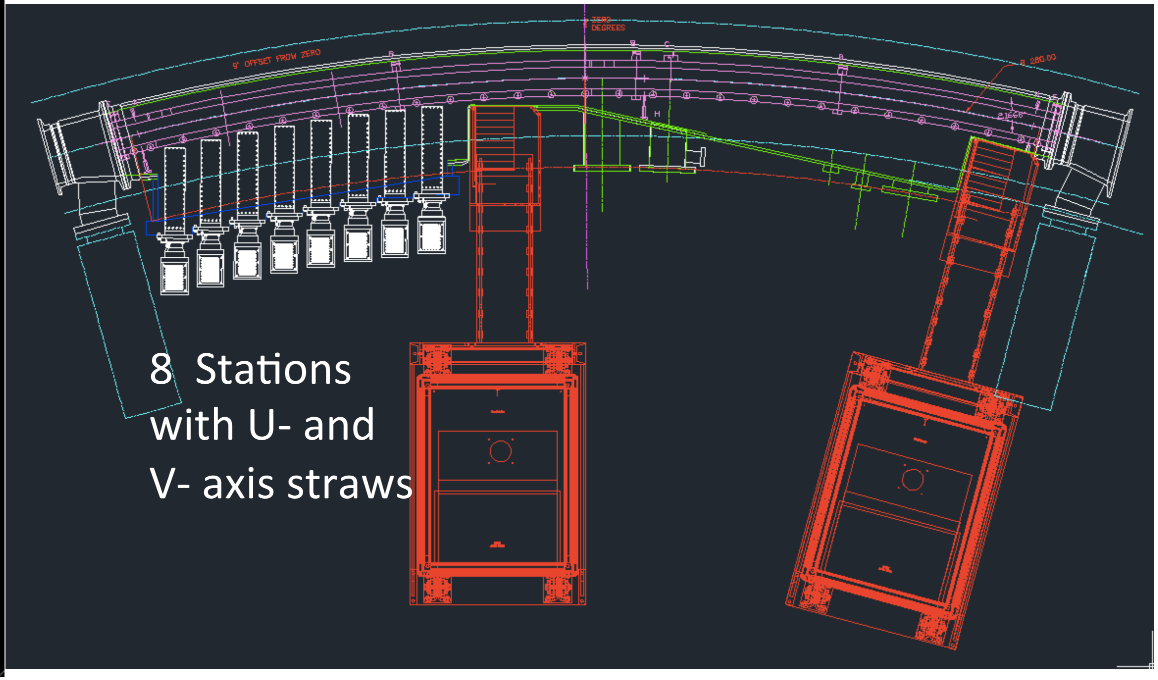
E and pitch	50	Improved tracker	
		Precise storage ring simulations	30
Total	180	Quadrature sum	70

In-vacuum Straw Trackers to measure beam profile

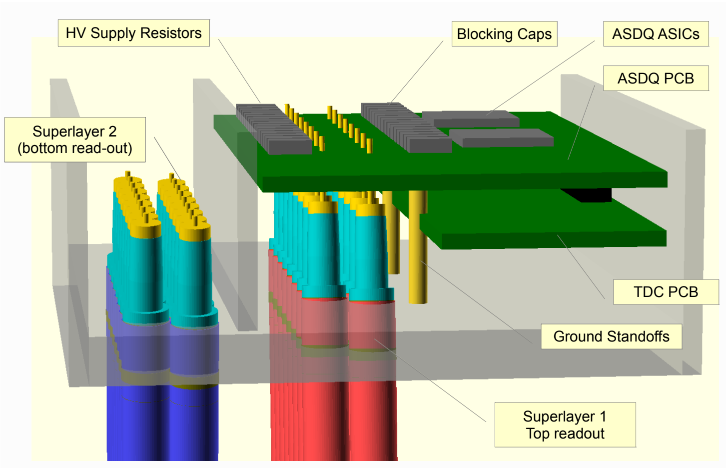
Requirements

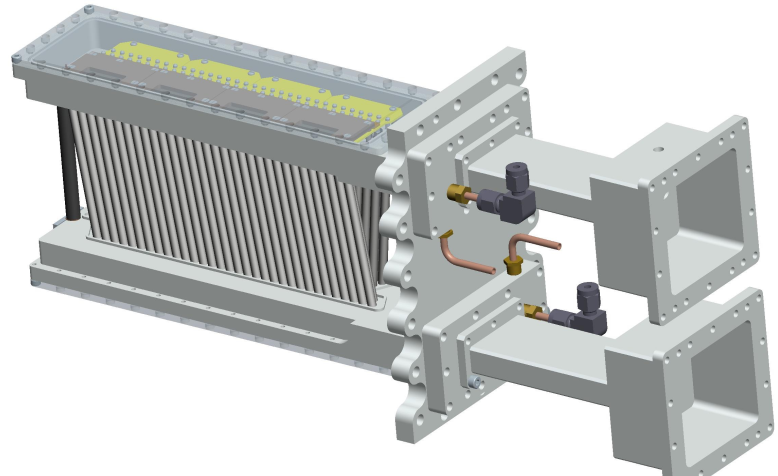
- mm-level measurement of beam profile
- 300 micron precision on individual hits
- Minimize materials in front of calorimeters (showers/scatters)

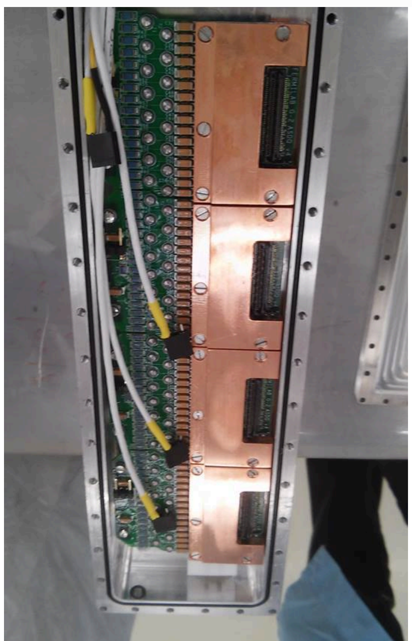


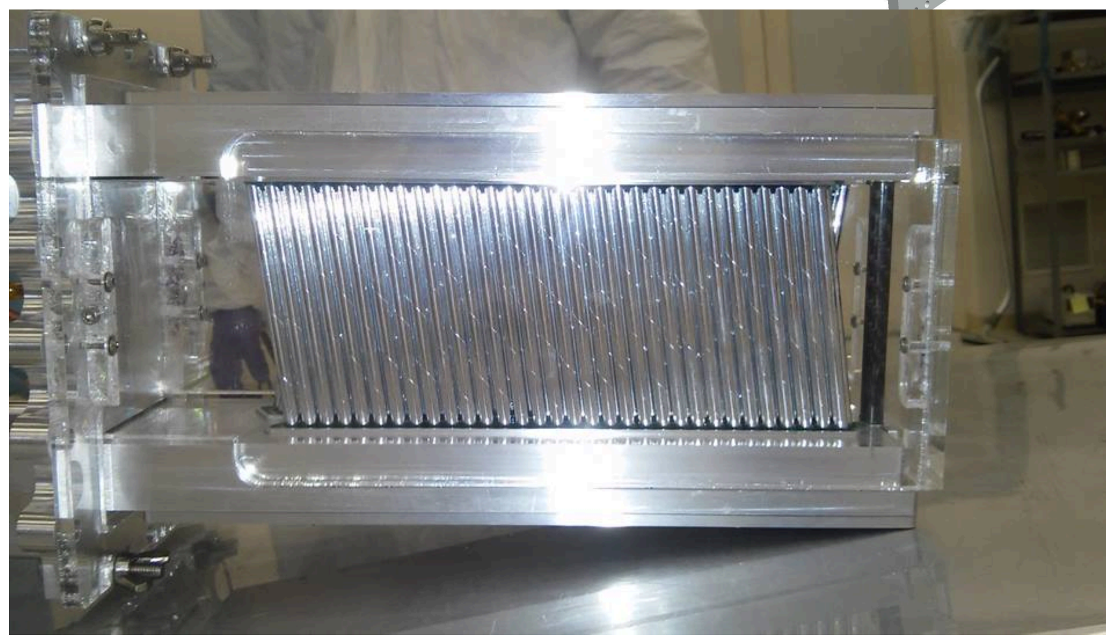


In-vacuum Straw Trackers to measure beam profile







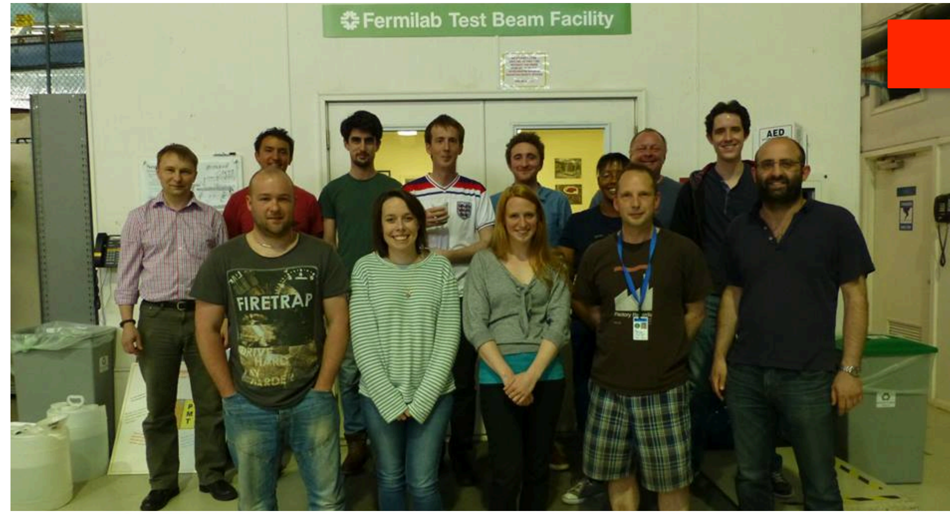


Test Beam Programs

Calo Tracker

New g-2 Test Beam Runs

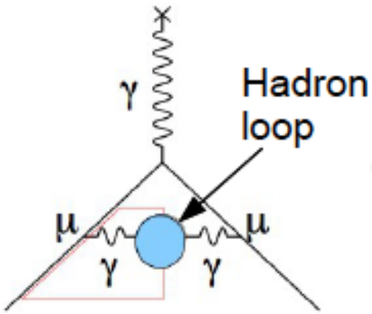
2010-05-18 FNAL MTest Beam Studies for g-2	106
2012-04-11 FNAL 2nd run at MTest - 2x3x2 PbF2 array	148
2012-11-05 Frascati Single PbF2 Crystal with PMT; e- @ 500 MeV	32
2013-11-21 SLAC 1st run at ESA - 3x3 PbF2 Calorimeter; e- @ 2-4 GeV	113
2014-01-22 FNAL Straw Tracker Test	95
2014-07-17 SLAC 2nd run at ESA - 4x7 PbF2 Calorimeter	150
2014-04-23 FNAL Straw Tracker Test II	69
2015-06-02 Straw Tracker Test III Straw Tracker Test II	75

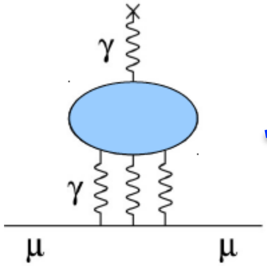


Muon g-2: The path forward

Muon precession

Proton precession





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ω_a	180	70
ω_p	170	70
Statistical	460	100
Total Exp.	540	140
Had. Vac. Pol.	360	215 *
Had LBL	225	225
Total Theory	420	310

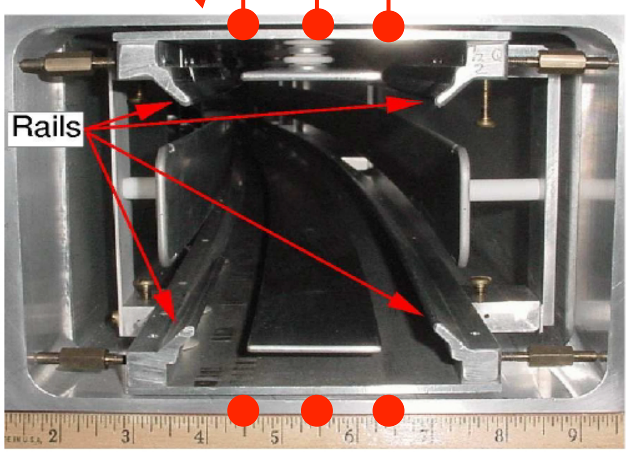
Proton Spin Precession Frequency, wp

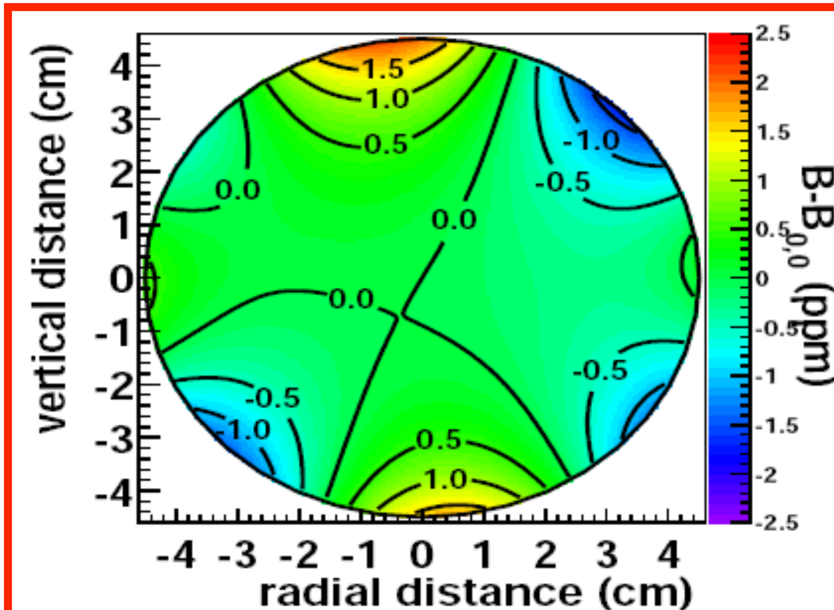
Measure field without muon beam

Monitor field with fixed probes during muon beam periods

Extract field experienced by muons

360 fixed NMR probes





17 NMR probes on trolley to map 6000 azimuthal locations

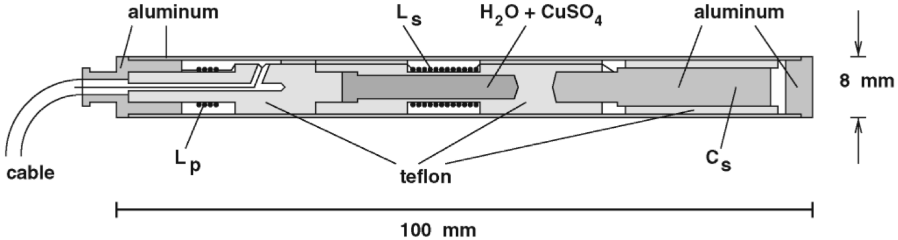
ω_p Systematics

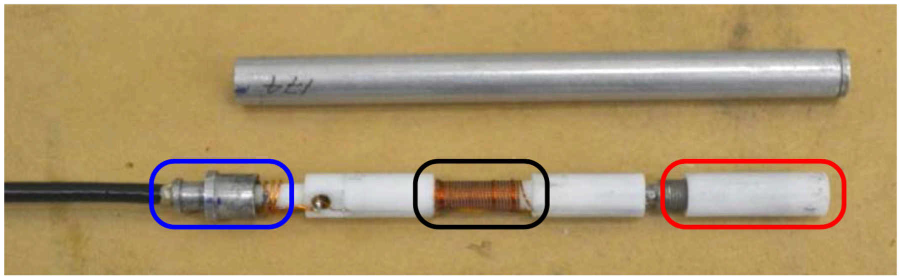
Category	E821 [ppb]	Main E989 Improvement Plans	Goal [ppb]
Absolute field calibration	50	Improved T stability and monitoring, precision tests in MRI solenoid with thermal enclosure, new improved calibration probes	35
Trolley probe calibrations	90	3-axis motion of plunging probe, higher accuracy position determination by physical stops/optical methods, more frequent calibration, smaller field gradients, smaller abs cal probe to calibrate all trolley probes	30
Trolley measurements of B_0	50	Reduced/measured rail irregularities; reduced position uncertainty by factor of 2; stabilized magnet field during measurements; smaller field gradients	30
Fixed probe interpolation	70	Better temp. stability of the magnet, more frequent trolley runs, more fixed probes	30
Muon distribution	30	Improved field uniformity, improved muon tracking	10
External fields	–	Measure external fields; active feedback	5
Others †	100	Improved trolley power supply; calibrate and reduce temperature effects on trolley; measure kicker field transients, measure/reduce O_2 and image effects	30
Total syst. unc. on ω_p	170		70

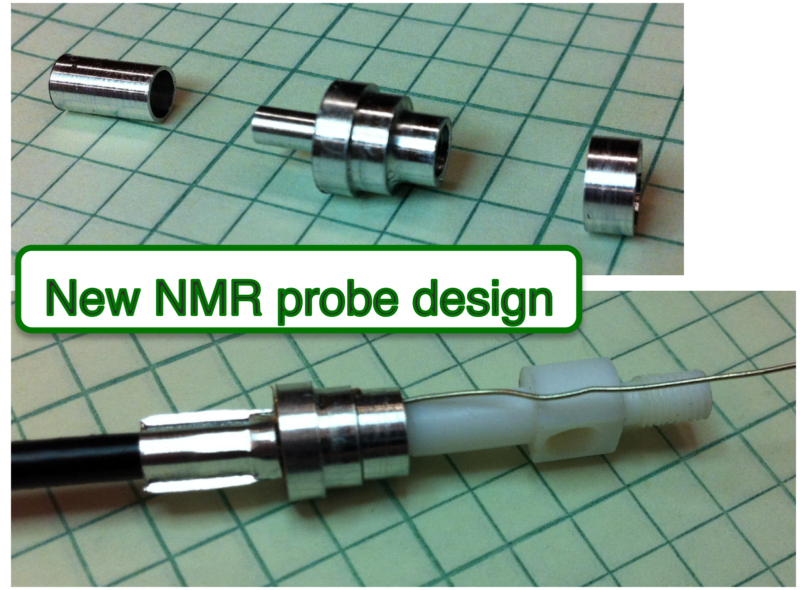
- Better Temperature Stability
- Reduce field gradients
- Improve positioning reproducibility

} Interconnected

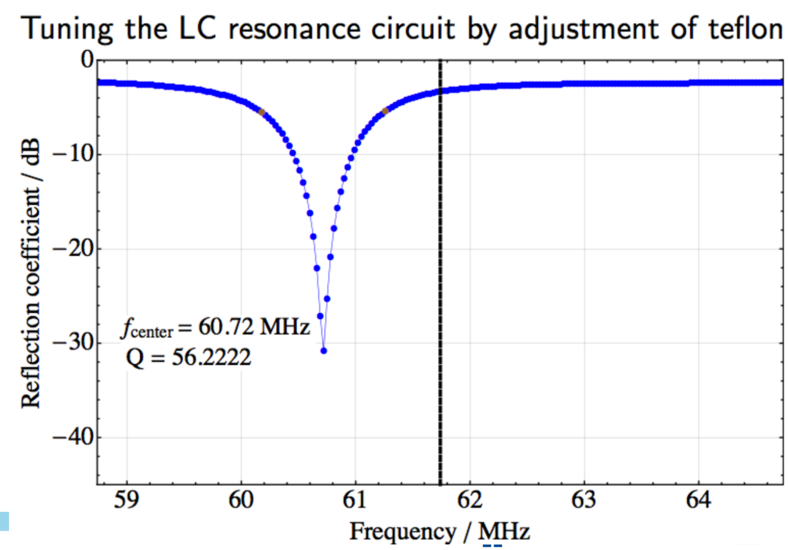
New NMR Probes designed



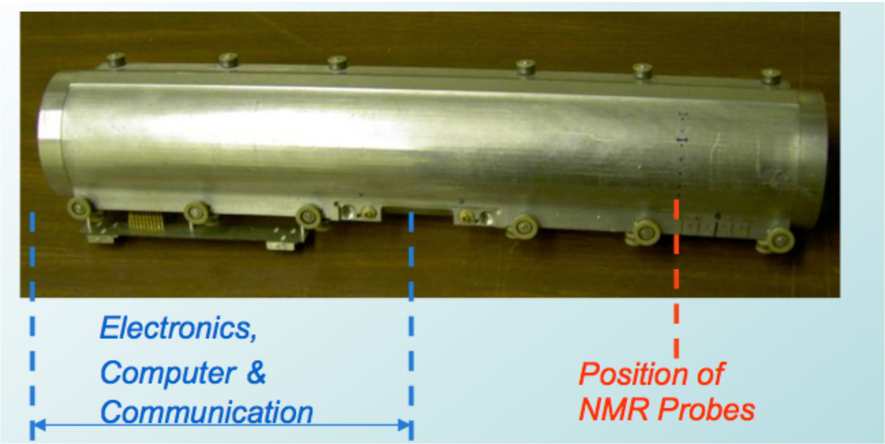


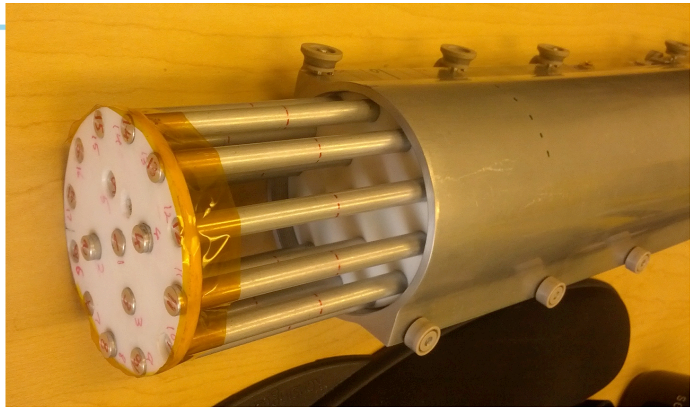


- 400 completely new fixed probes already in production
- Improved design: crimp connection of ground braid, easy probe tuning
- Testing at 1.45T field shows excellent performance



Upgraded Trolley

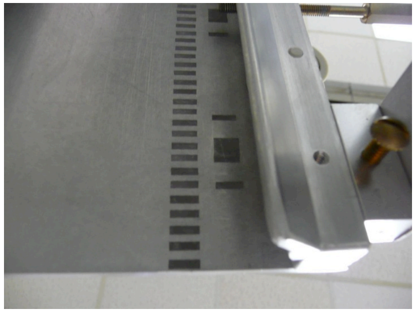


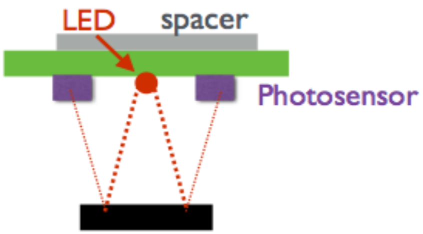


- Onboard processing of NMR signals

- New NMR probes on trolley to measured the field in the muon storage region

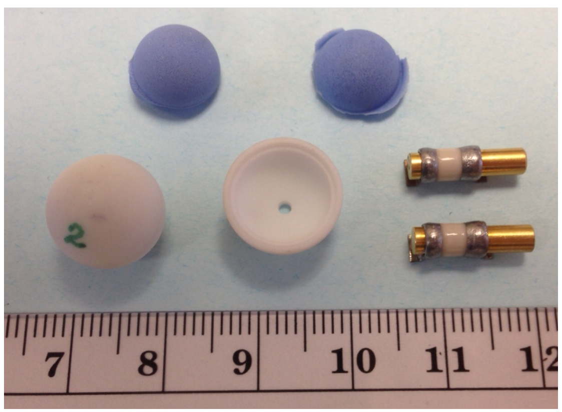
- Better position information via new onboard barcode reader
→ mitigate effects of gradients

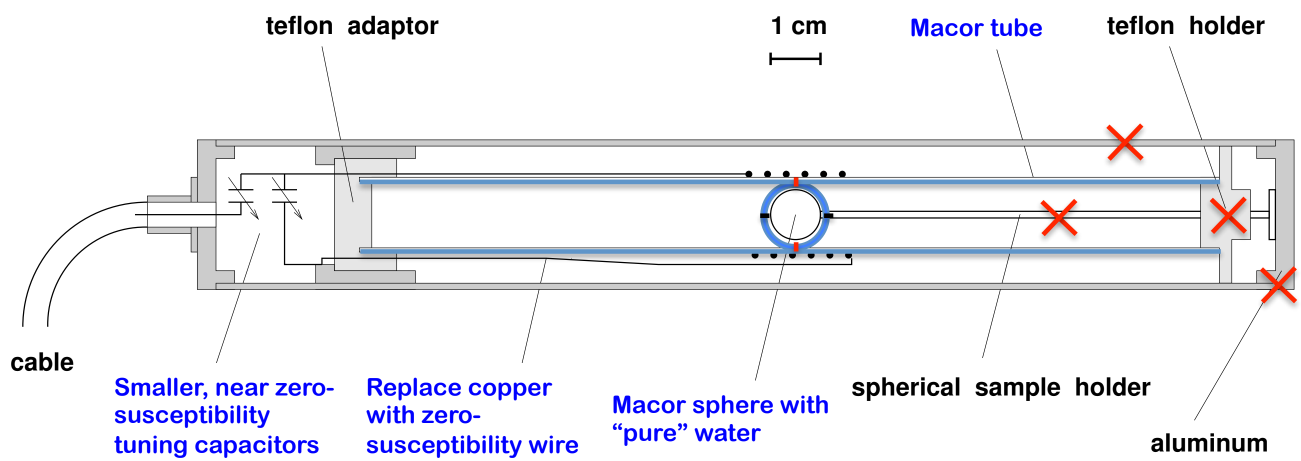




Absolute Calibration Probes

- Absolute calibration to relate NMR probe frequencies to free proton precession frequency
- Absolute Calibration probes: E821 Water Probe, New Water Probe, New He 3 Probe



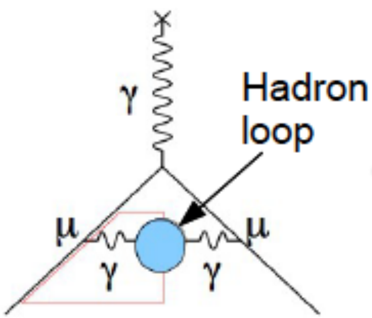


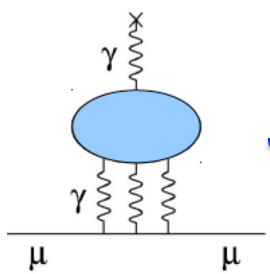
- Currently under construction using spherical water sample from precision machined Macor

Muon g-2: The path forward

Muon precession

Proton precession





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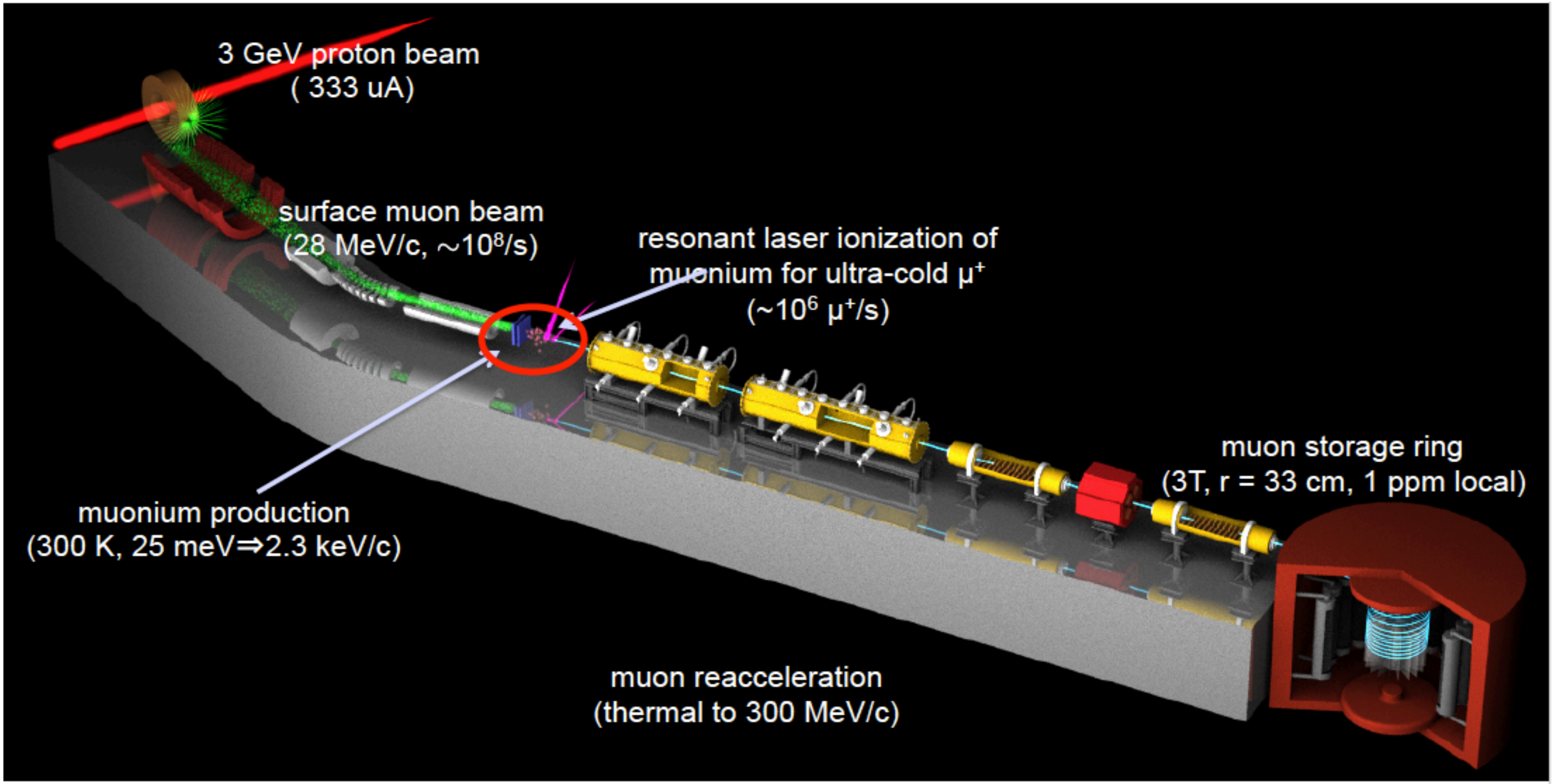
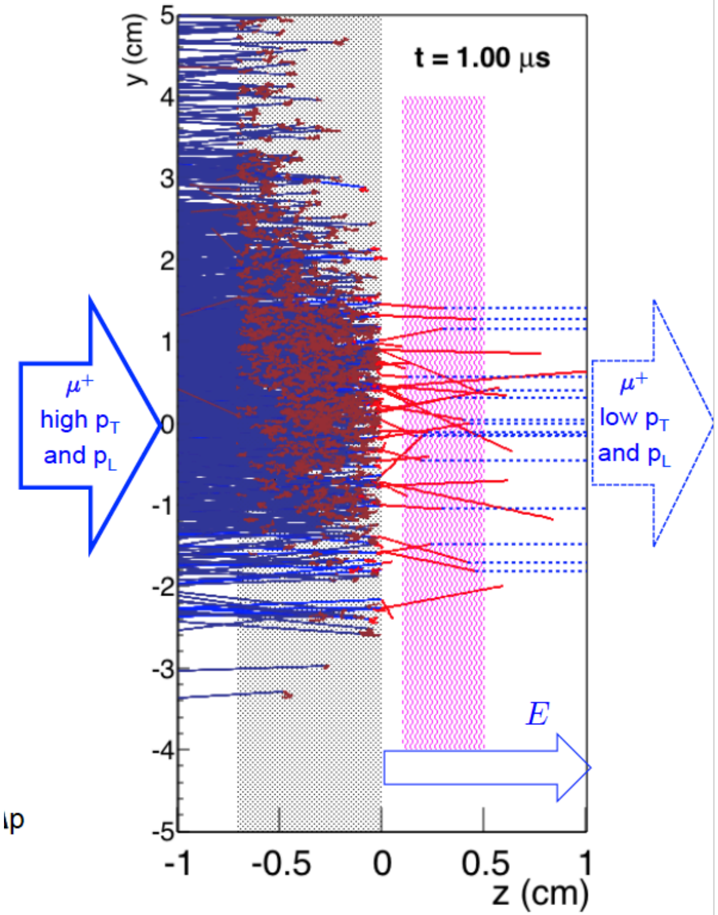
ω_p	170	70
Statistical	460	100
Total Exp.	540	140
Had. Vac. Pol.	360	215 *
Had LBL	225	225
Total Theory	420	310

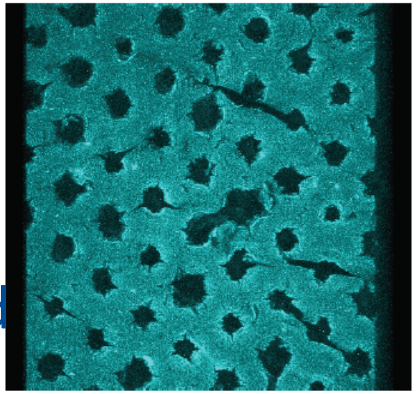
J-PARC g-2 schematic

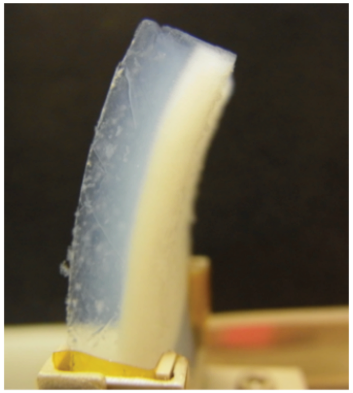


Aerogel Target, Muon beam Production



- Surface muons
- Stop in target, form muonium
- Thermalize → ultra-cold source
- Diffusion into vacuum region
- Ionized
- Accelerated to 300 MeV/c
- Very low spread in p_T → contain muons without E-field → can choose different γ , choice of smaller radius

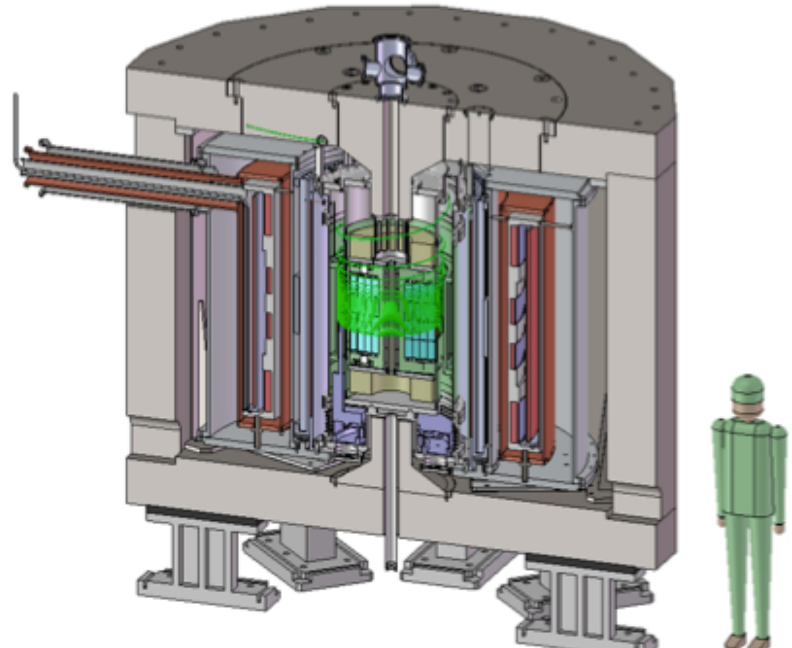




- Recent tests runs with Laser-ablated aerogel target → microchannels

J-PARC storage ring & detectors

- Vertical kicker to inject into solenoid
- Silicon Trackers for positron detection



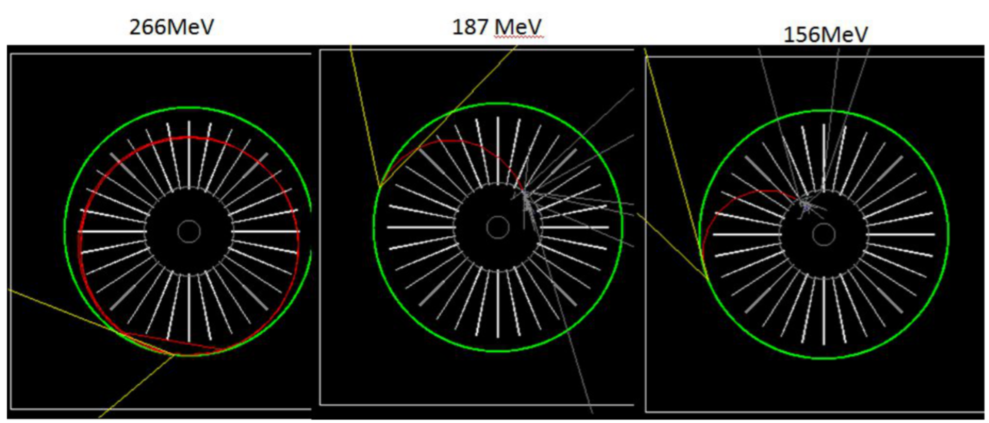
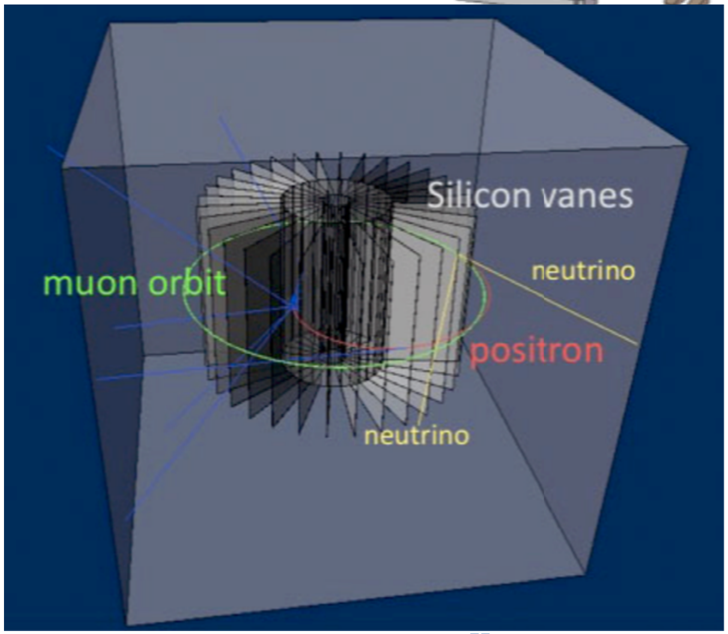
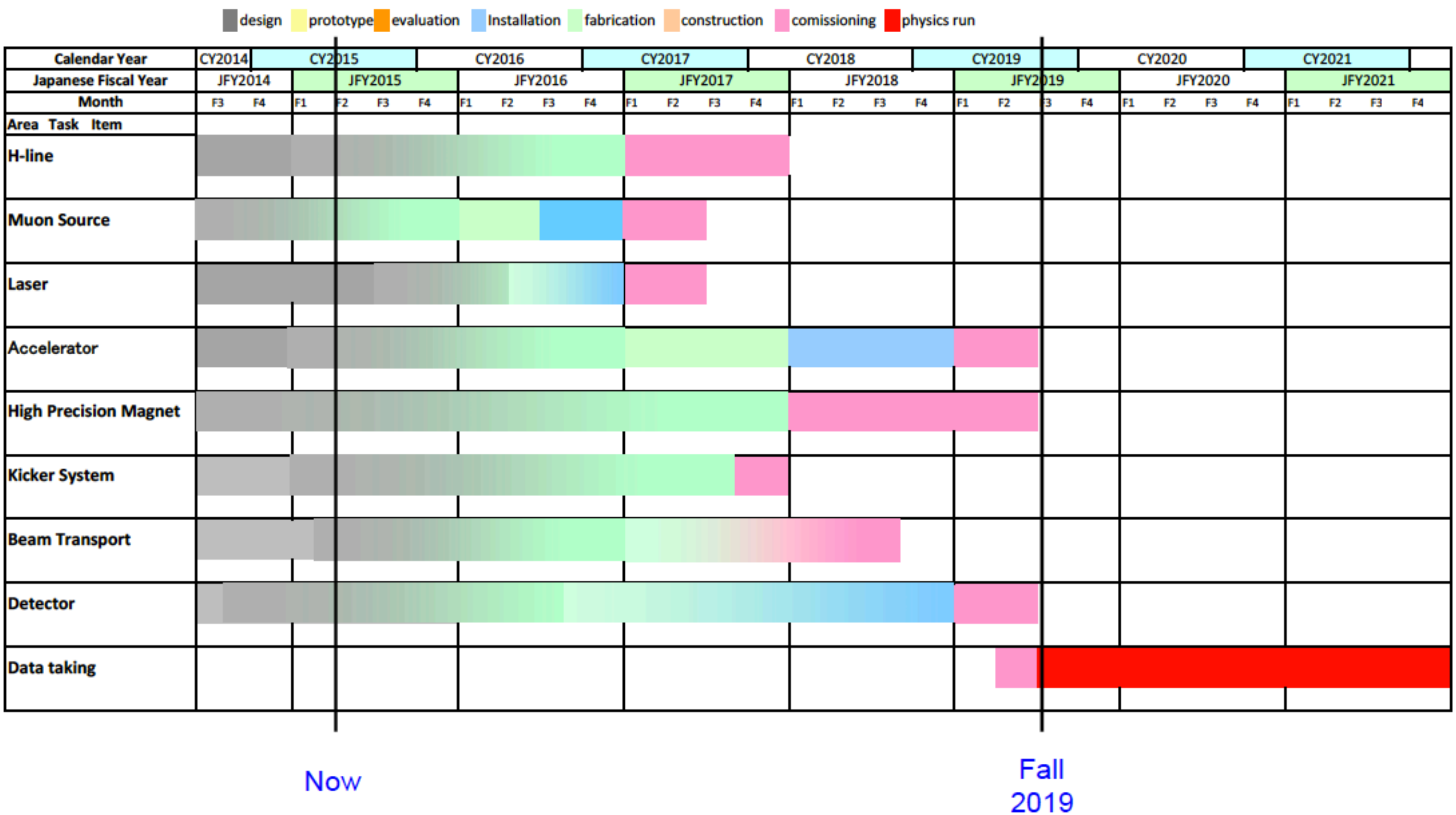


Figure 6: Example positron trajectories in the detector system at three different energies of positrons. The green circle is the muon beam orbit. The red trajectory is the trace of the positron track. The white tracks are photons.



Proposed timeline



From G. Marshall

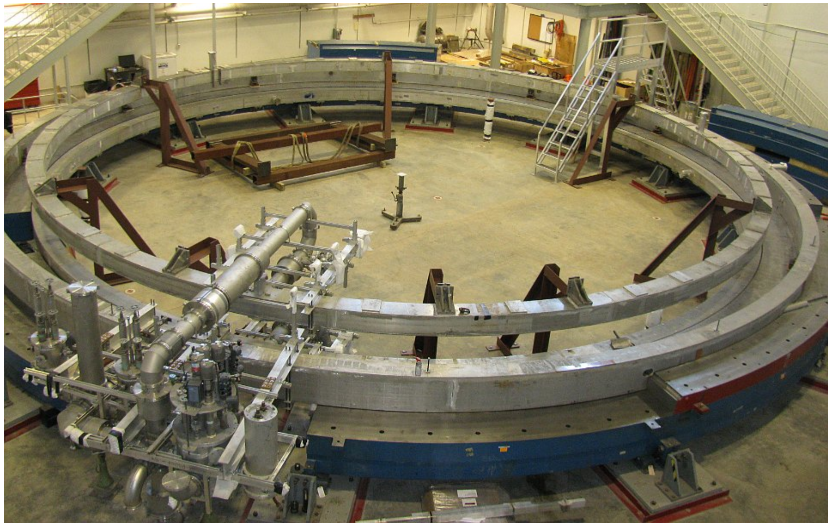
Fermilab

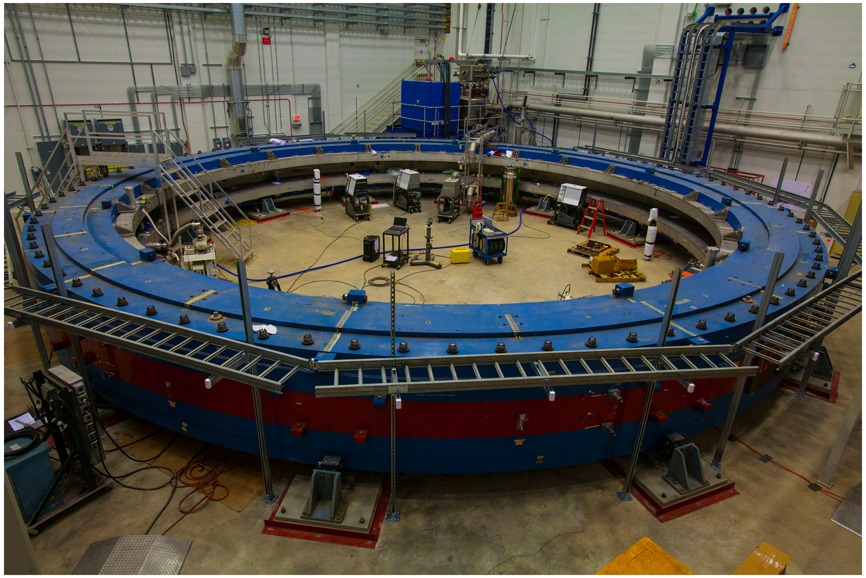
Recent Fermilab News

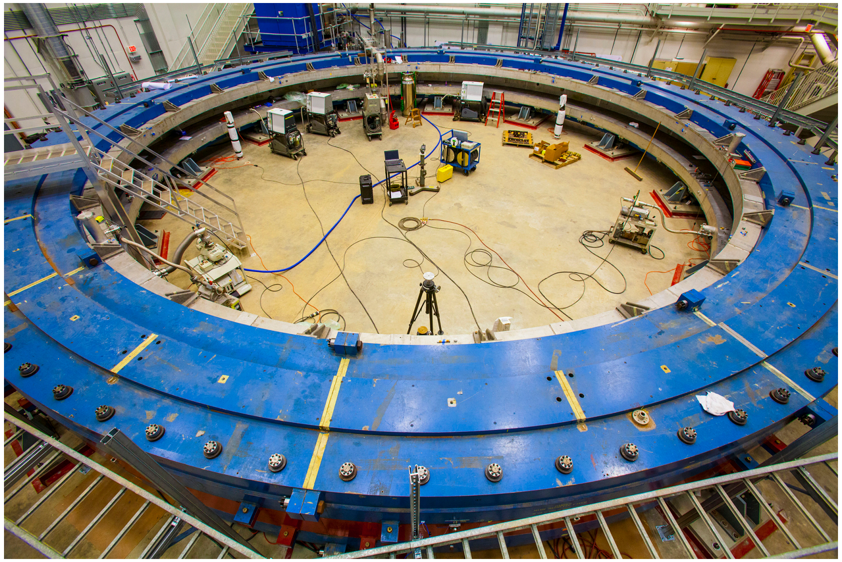
BNL → FNAL June-July 2013, Building installation July 2014



Recent Highlights: Ring Reassembly (July 2014-June 2015)

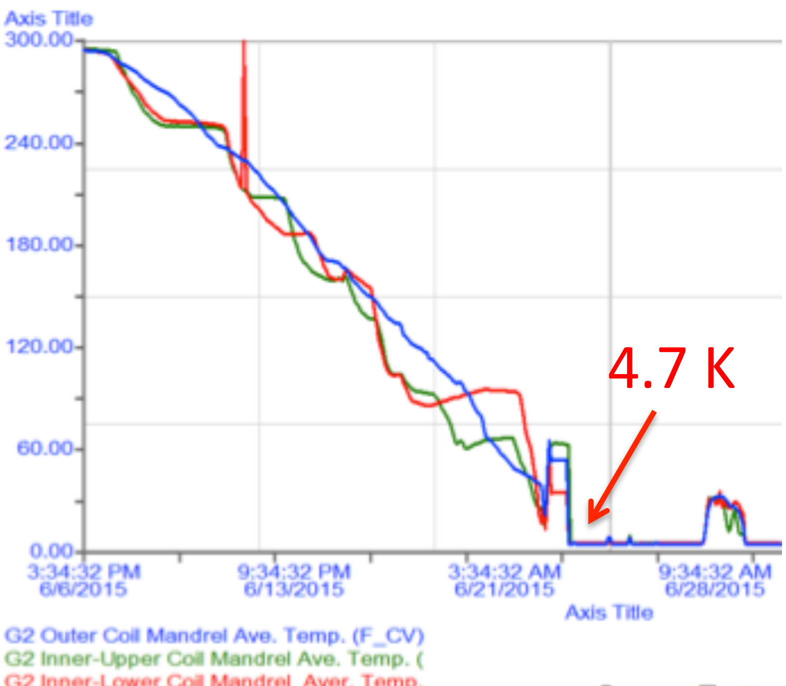






Cooled Down, Powered up

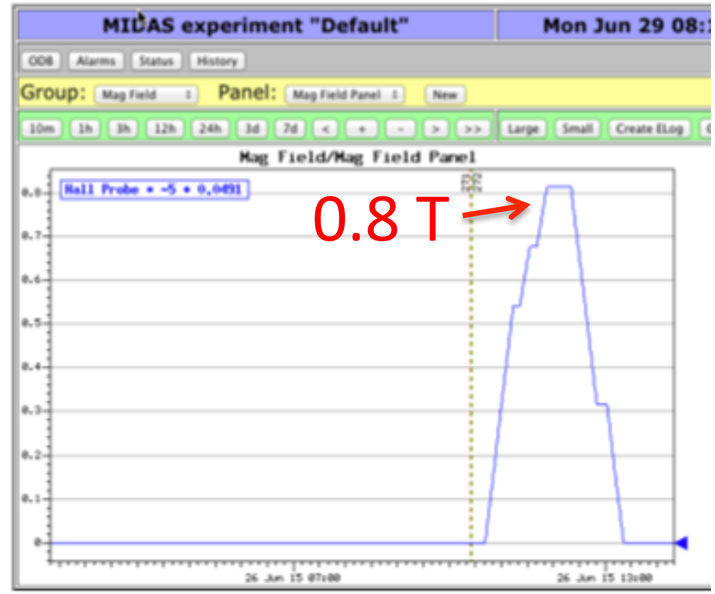
Coil Temperature



Power Test

2.5 Week Cool Down

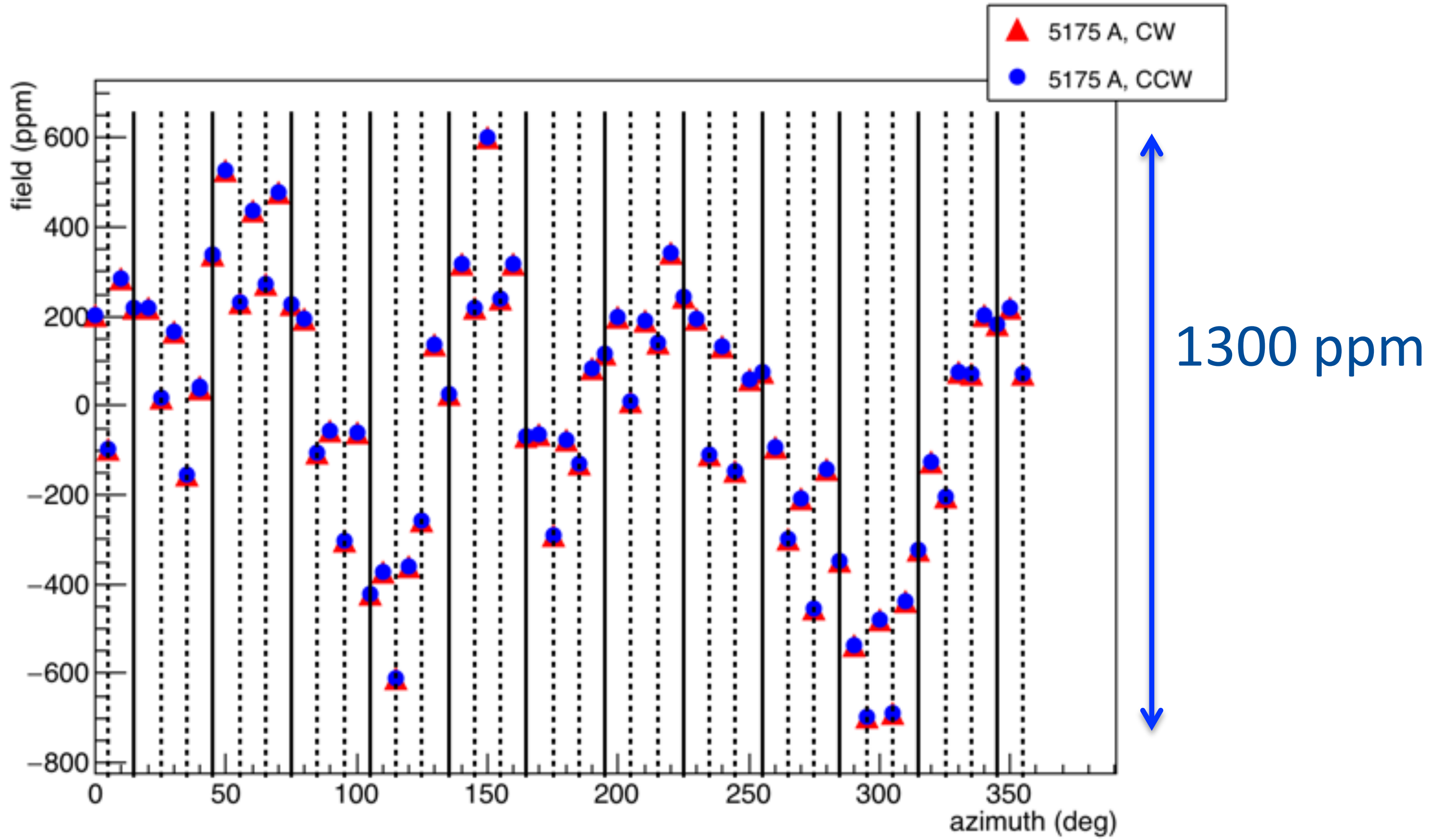
B-Field in Gap, MIDAS DAQ, ½ ramp



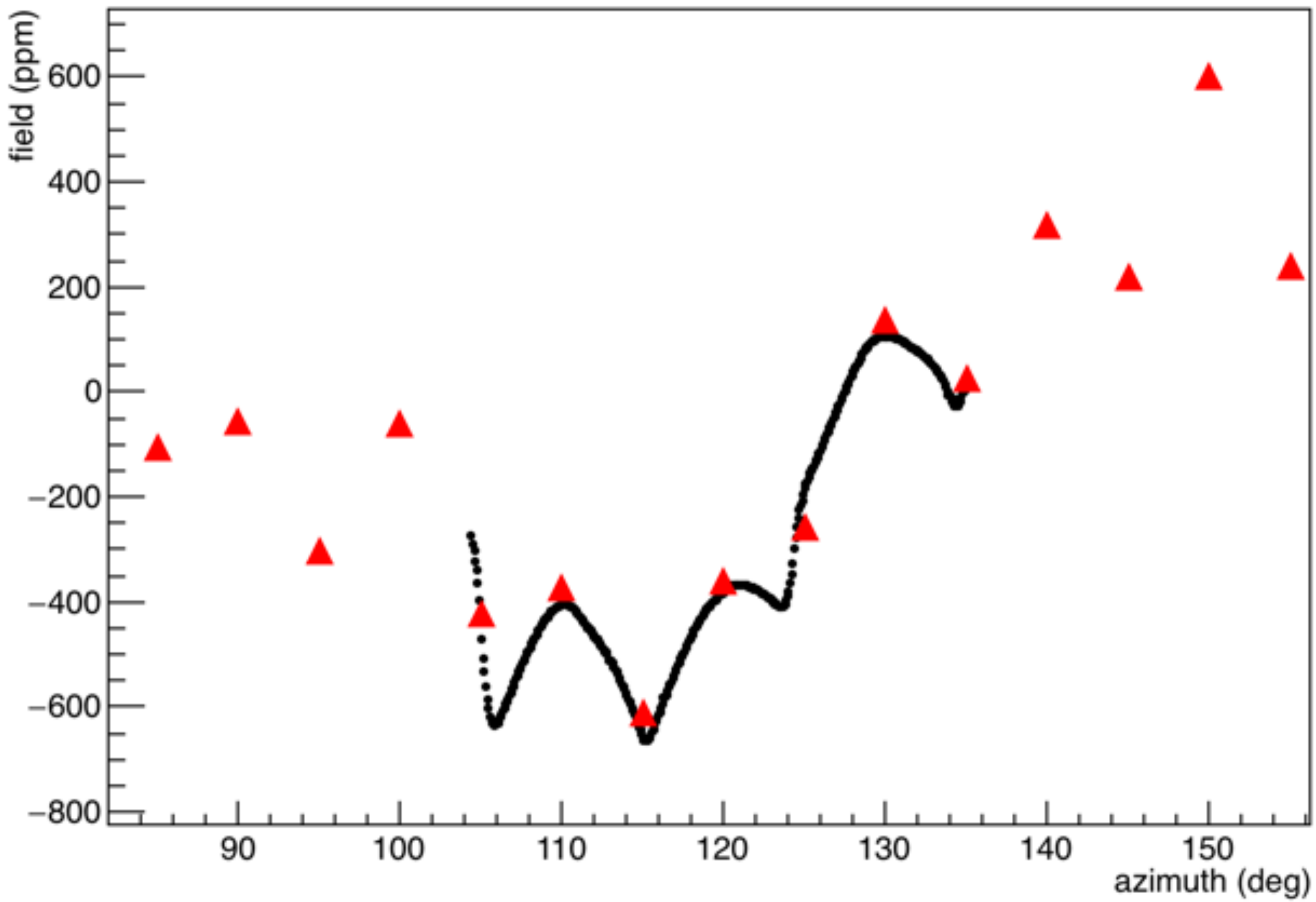
Full power, full field on Sep 21, 2015

First Full Azimuthal Field Scan, Sep 23 2015

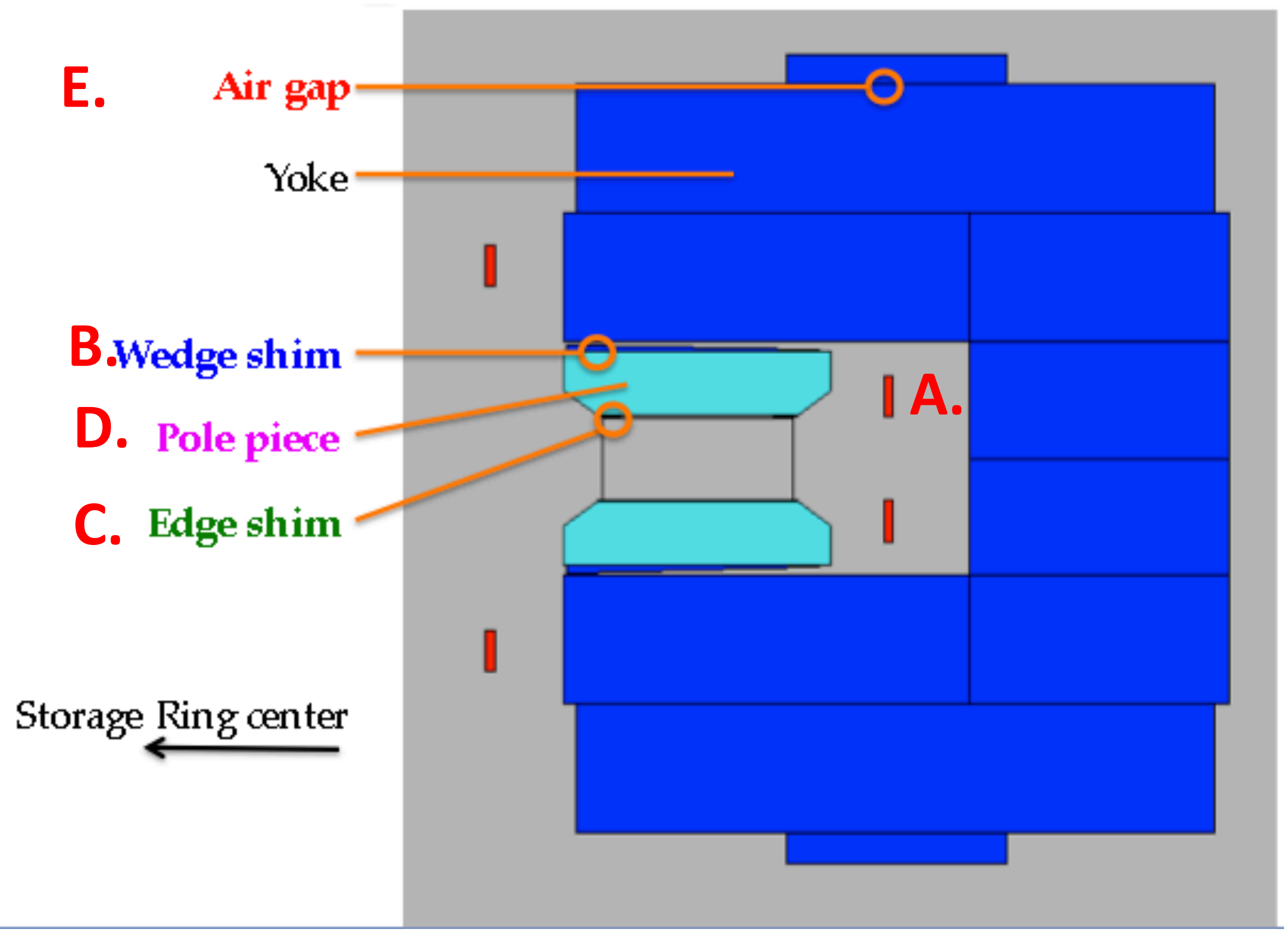
Reproducibility.
Aiming for factor 25 reduction of variation azimuthally



Fine Field Scan of 3 pole pieces (30 degrees total)



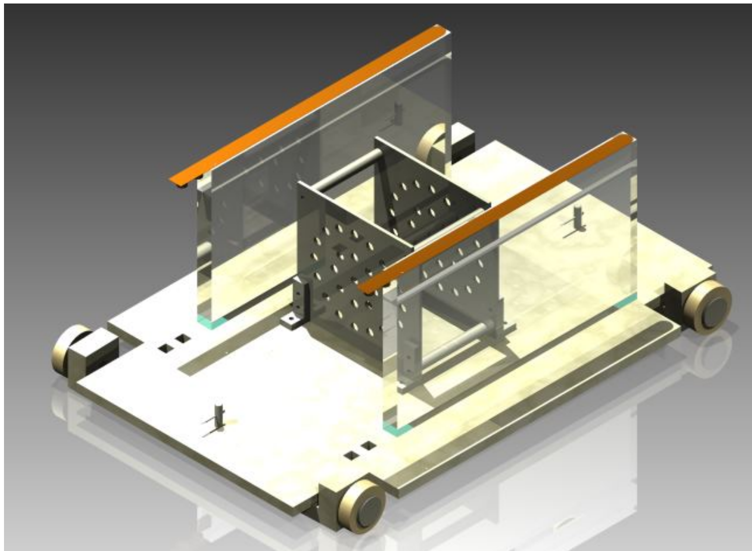
Passive Shimming Knobs

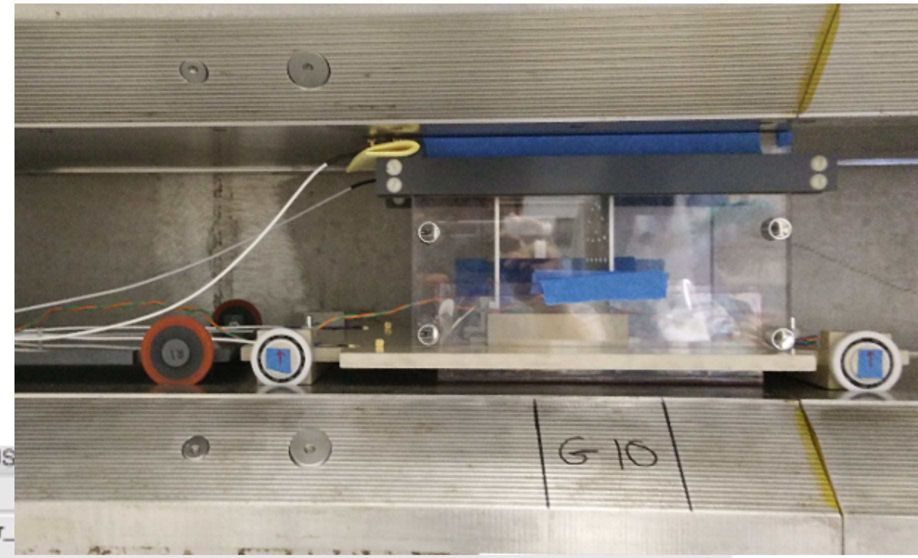


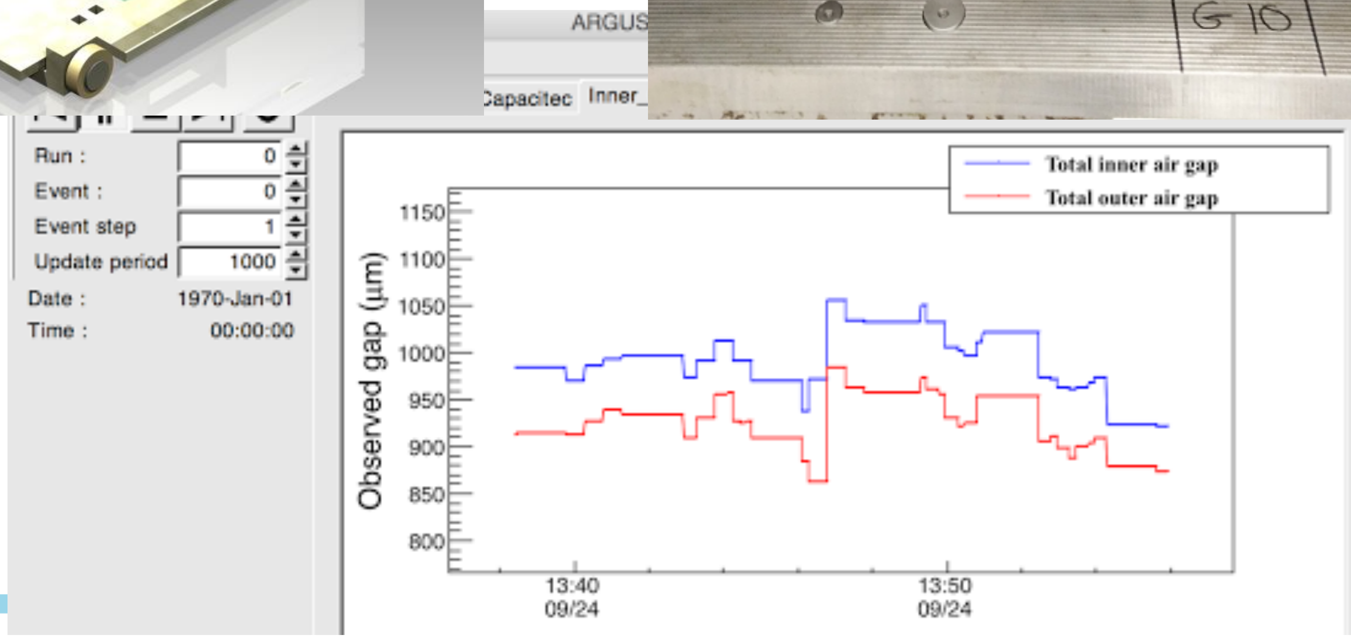
A. Main Coil Current
B. Radial Wedge Position
C. Edge Shim Thickness
D. Pole Tilts
E. Top Hat Adjustment

Shimming Is Underway

- Measuring gaps between the pole pieces, B-Field

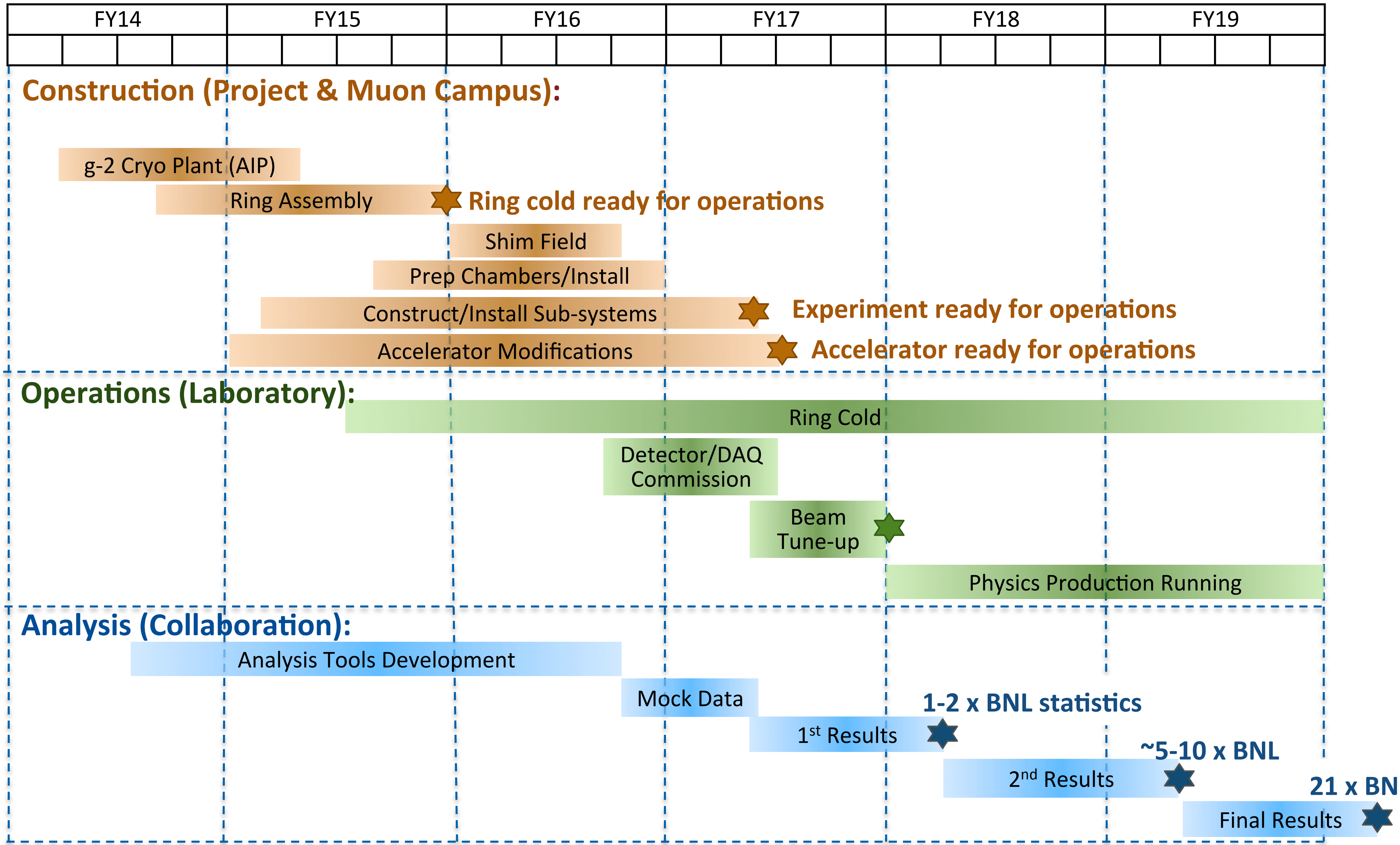






Fermilab

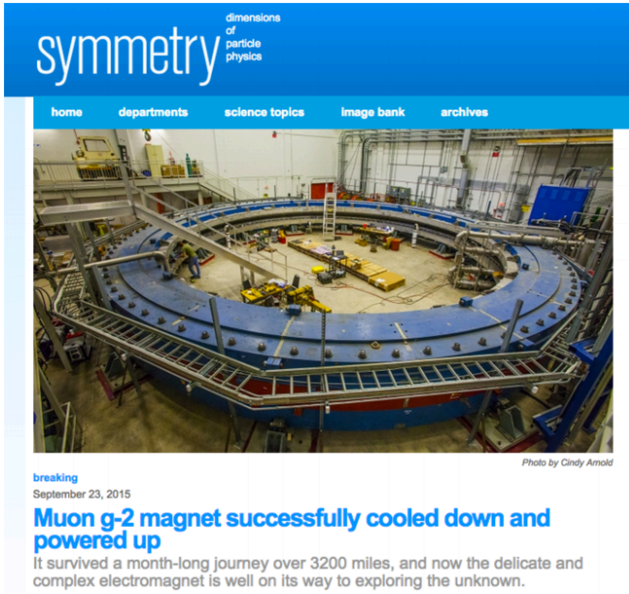
Timeline going forward



Summary

- Compelling experimental suite is happening now
  - Ongoing $e^+e^- \rightarrow$ hadrons inputs to theory
  - Muonium hyperfine at JPARC
  - Innovative new approach to g-2 at JPARC, data starting 2019
  - Fermilab experiment is cold and powered
    - Measurements starting now!
    - Muons in 2017

- These are exciting times!



E989 Collaboration: 34 Institutes; 155 Members

Domestic Universities
- Boston
- Cornell
- Illinois
- James Madison
- Kentucky
- Massachusetts
- Michigan
- Michigan State
- Mississippi
- Northern Illinois University
- Northwestern
- Regis
- Virginia
- Washington
- York College

National Labs
- Argonne
- Brookhaven
- Fermilab

Italy
- Frascati,
- Roma 2,
- Udine
- Pisa
- Naples
- Trieste

China:
- Shanghai

The Netherlands:
- Groningen

Germany:
- Dresden

Russia:
- Dubna
- Novosibirsk

England
University College London

Liverpool

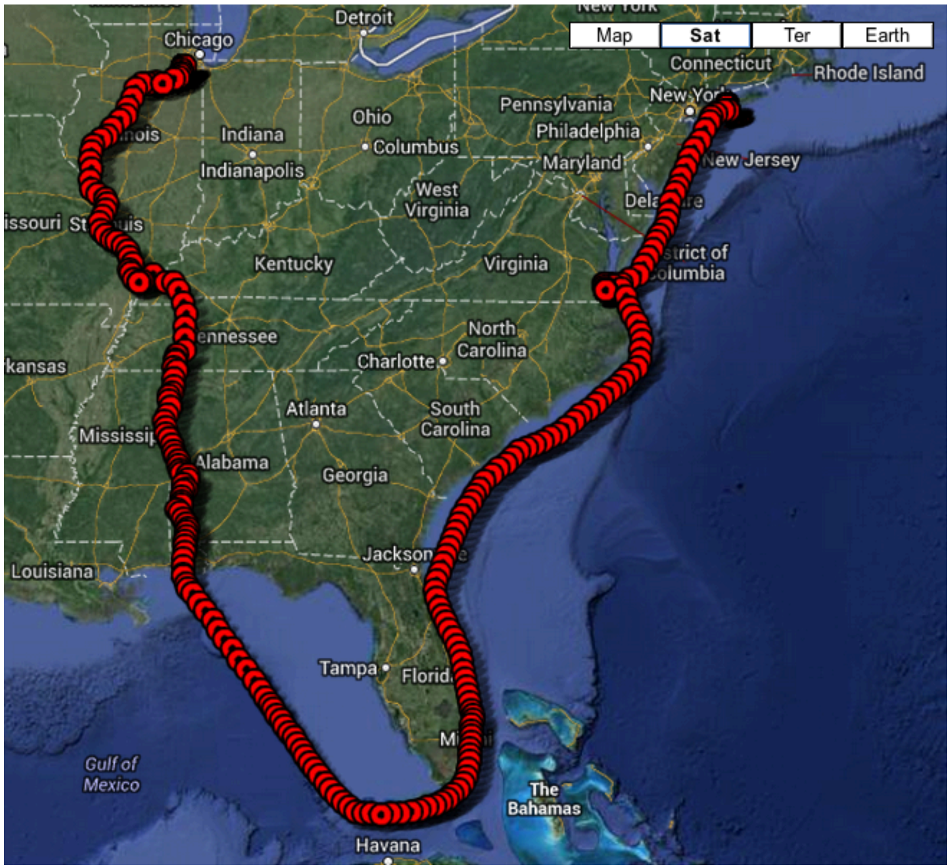
Oxford

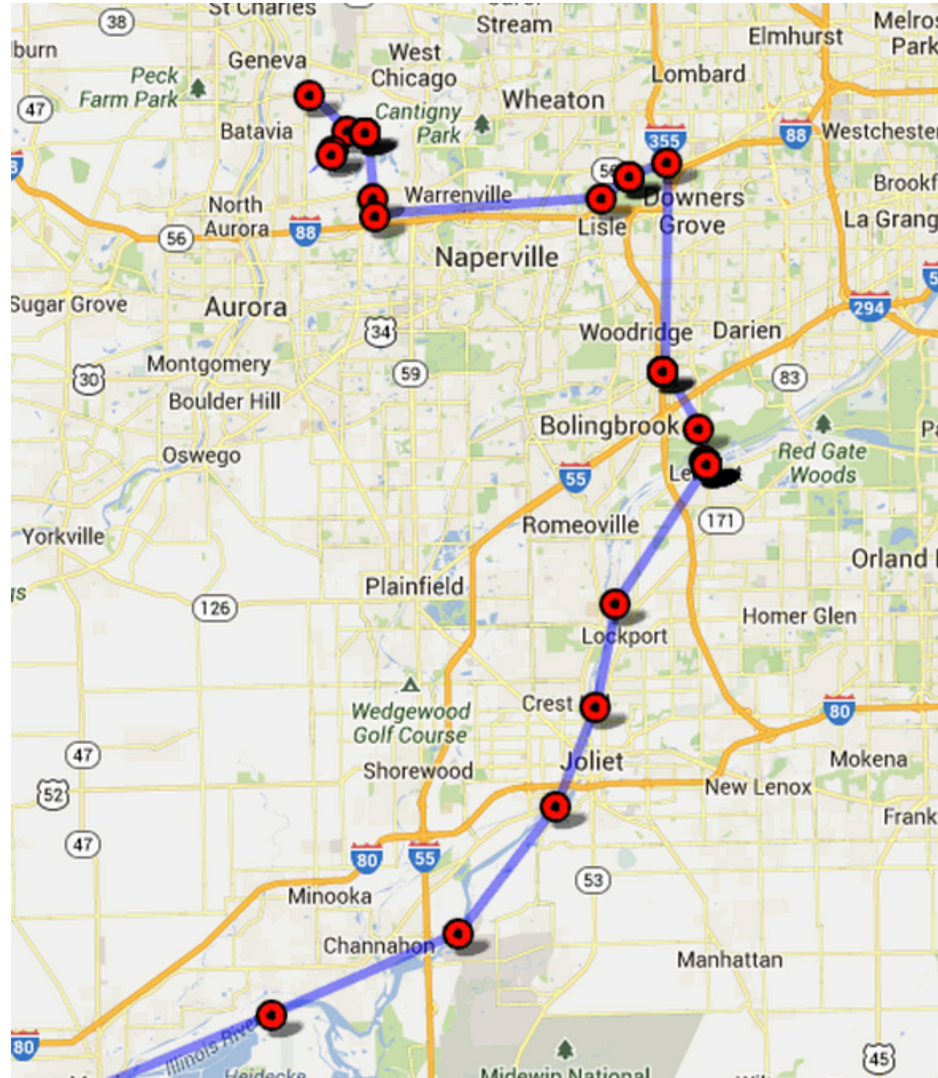
Korea
KAIST

QUESTIONS?

BACKUPS

The journey June – July 2013



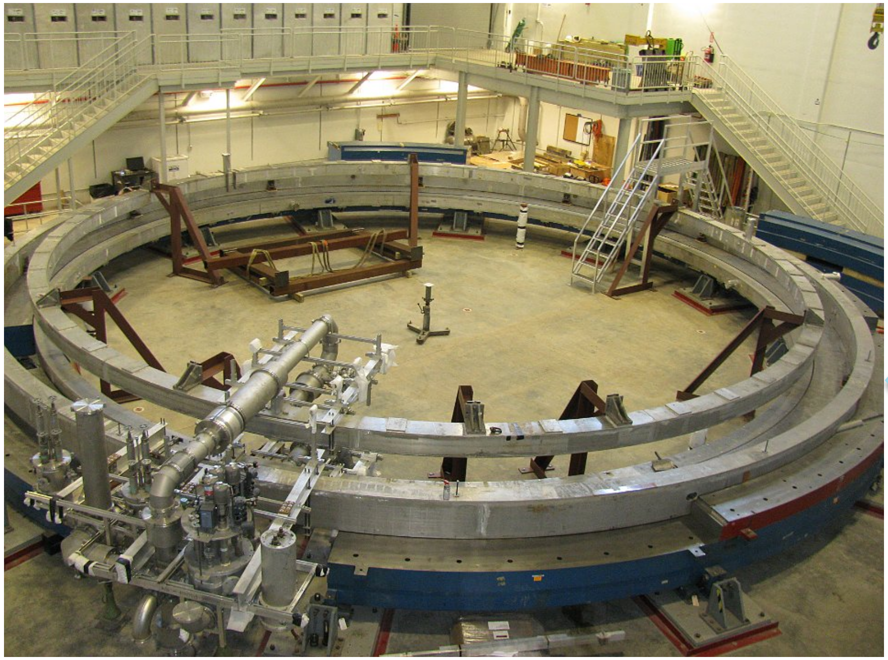


Recent Highlight: The Big Move from BNL to FNAL

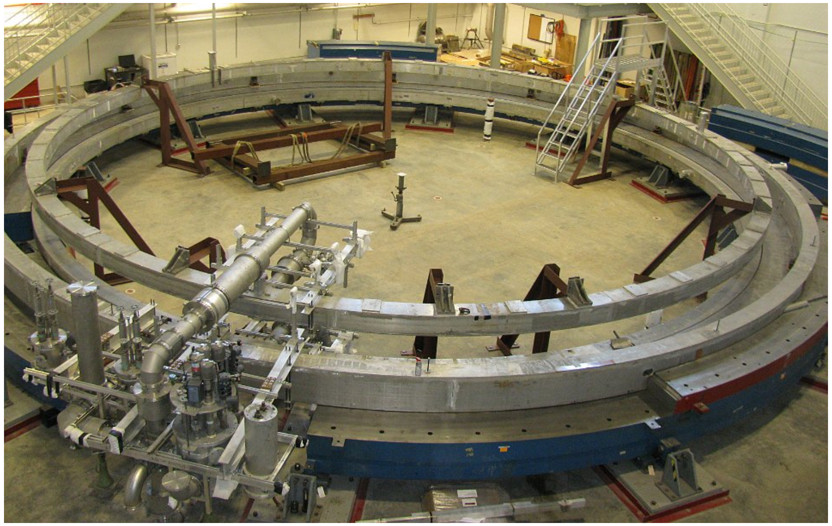
Recent Highlights: Muon Campus 1 Construction

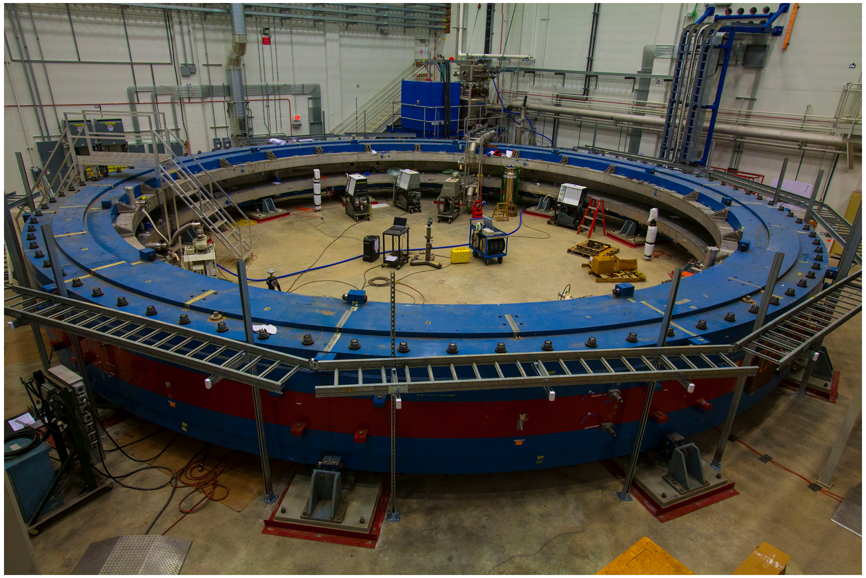

Muon g-2
EMMERT

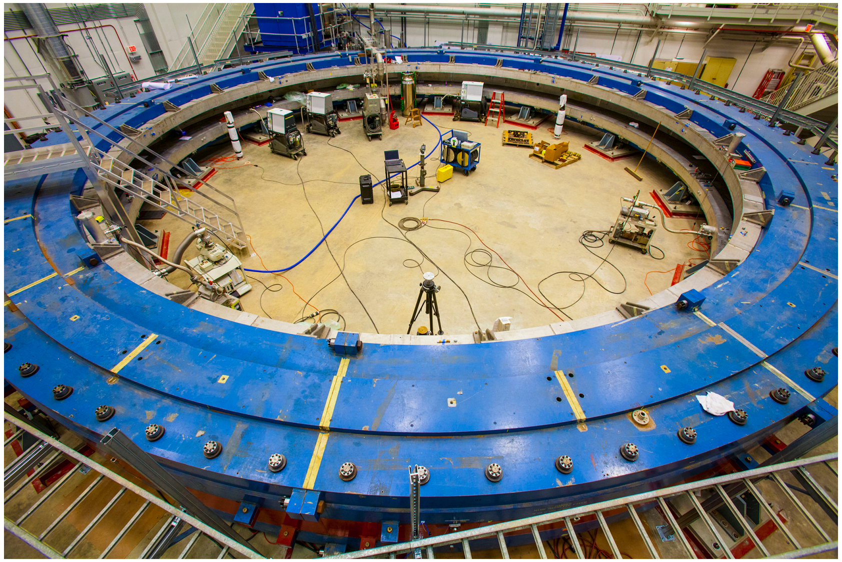
Recent Highlights : The Little Move Across Site to MC-1



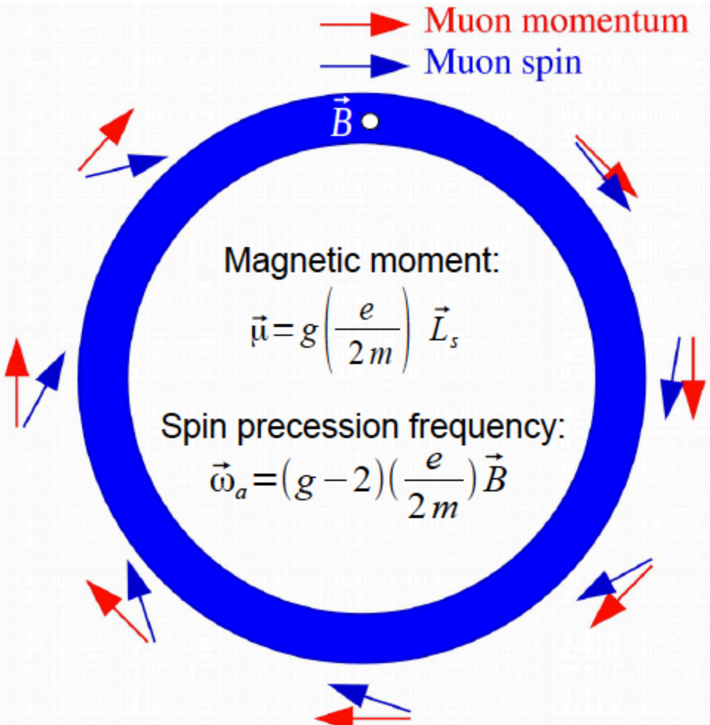
Recent Highlights: Ring Reassembly

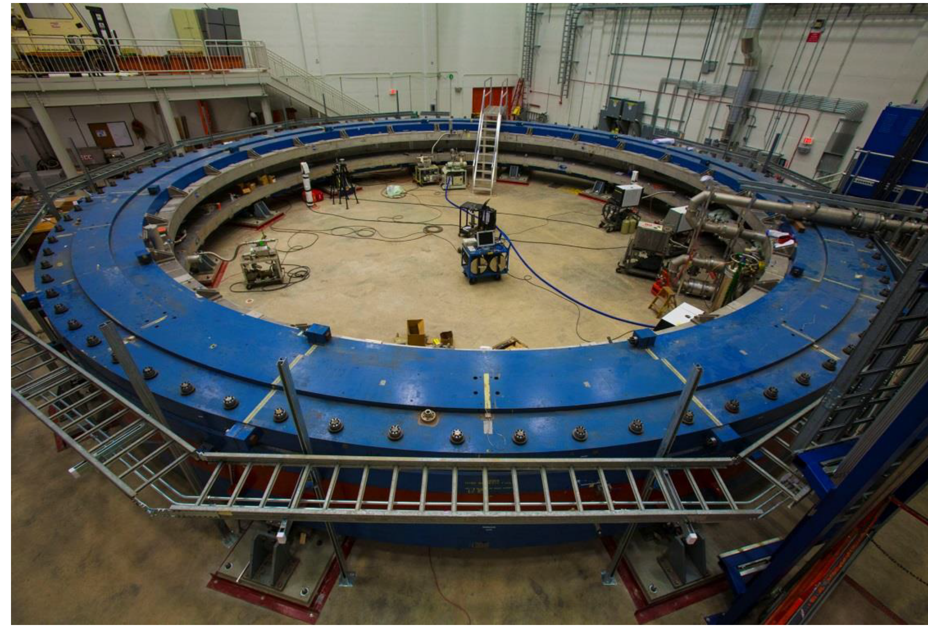




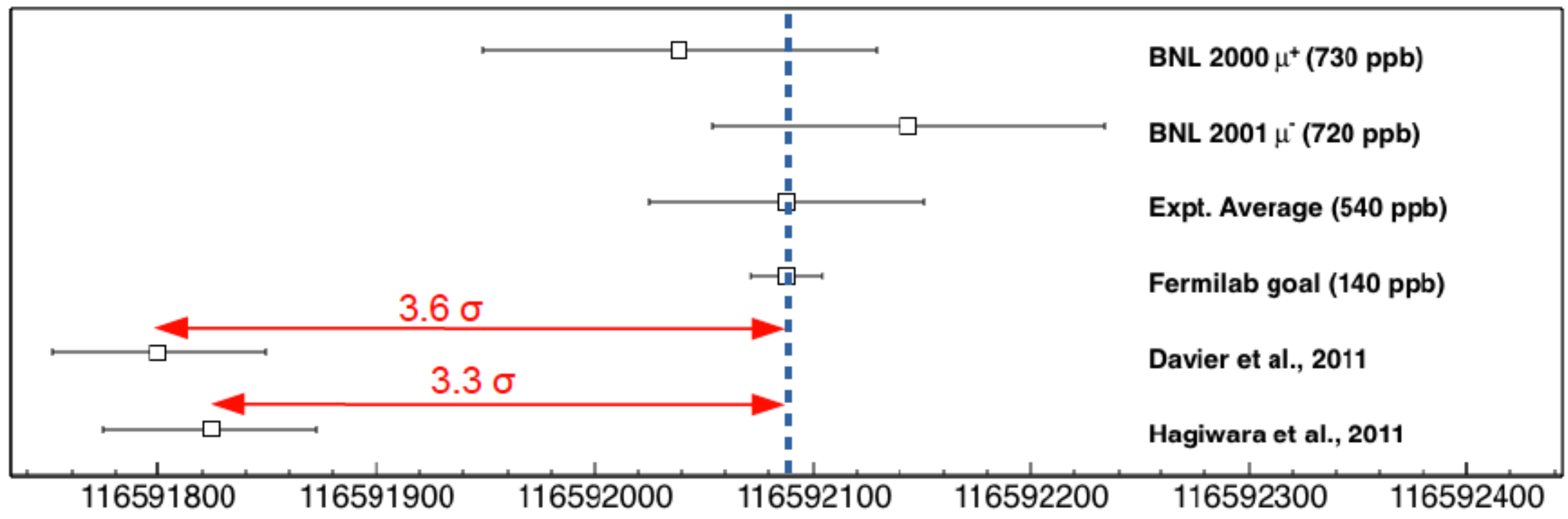


g-2 Storage Ring



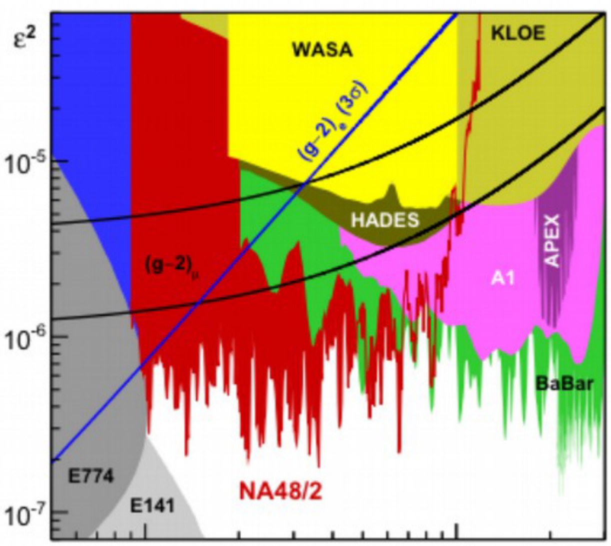


Muon g-2



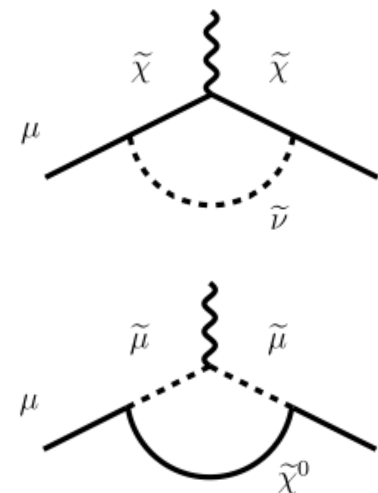
a

μ

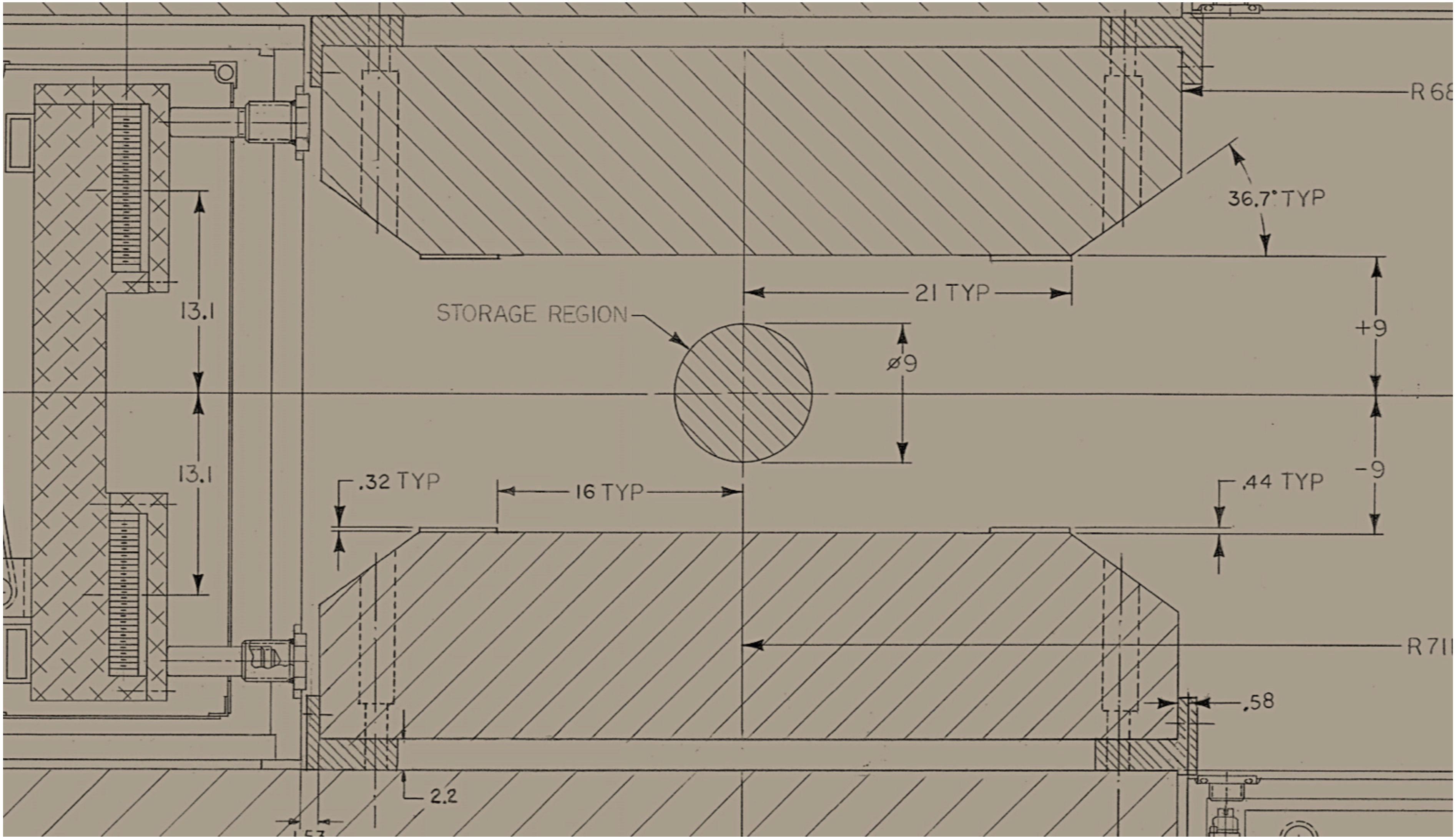


Dark Photons: minimal models mostly excluded (DM summary)

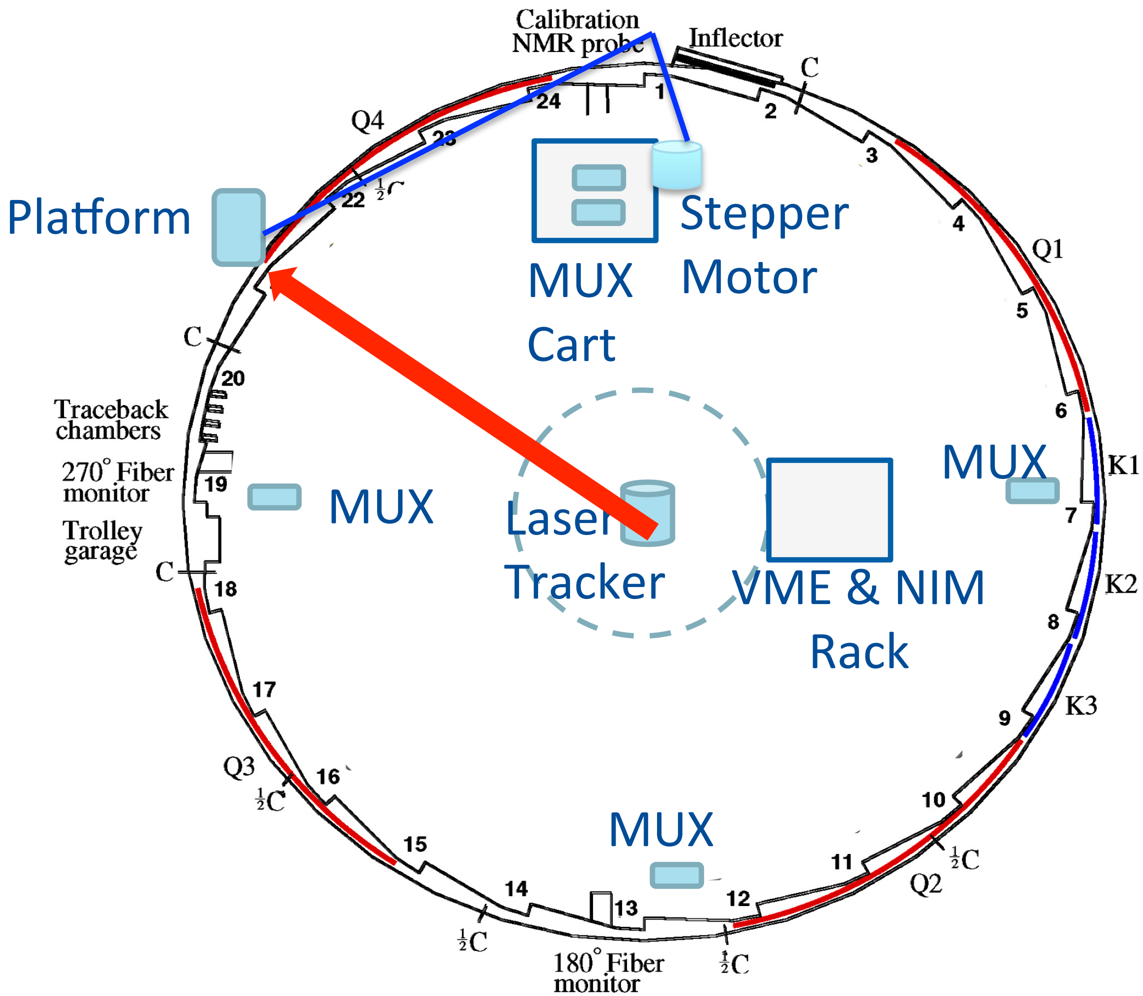
SUSY w/ large tan β



b


R 68
36.7° TYP
21 TYP
STORAGE REGION
ø9
+9
-9
13.1
13.1
.32 TYP
16 TYP
.44 TYP
R 71
.58
2.2
.53

Shimming Hardware Layout



- Non-mag 80/20 cart
- Non-mag pulley that presses between poles

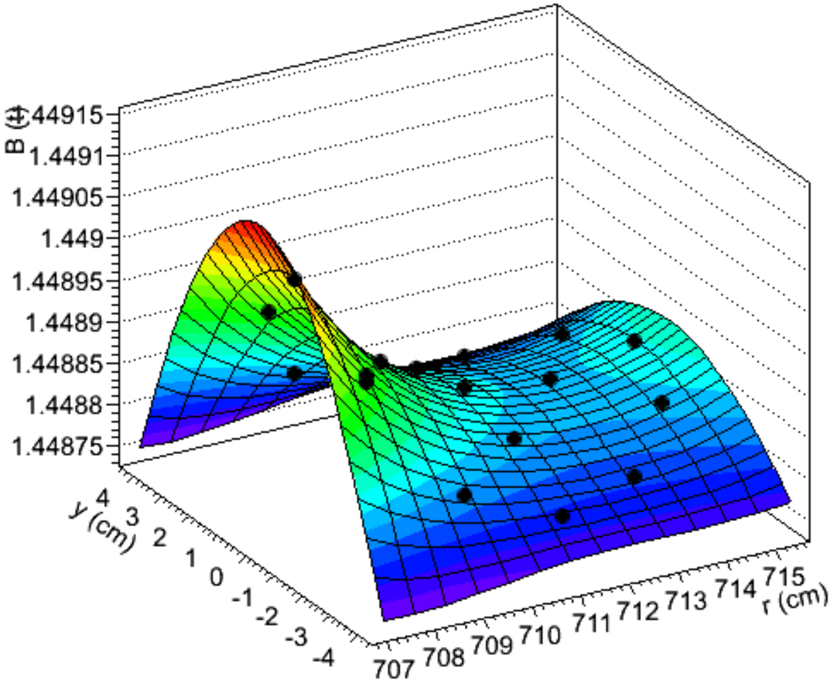
- Will commence this assembly 4th + 5th week of July

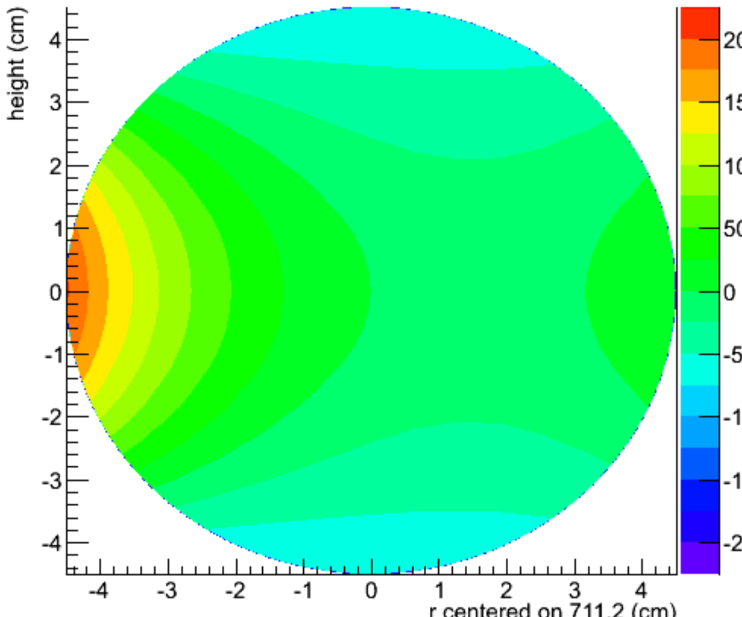
I. Multipole Analysis

$$B(x,y) = B(r,\theta) = B_0 + \sum_{i=1}^{n} \left(\frac{r}{r_0}\right)^i \left[a_i \cos(i\theta) + b_i \sin(i\theta)\right]$$

- Colored Curve = Best Fit
- Points = "Data"

- Reconstruct Storage Region
- Quantify Multipole Component at r=4.5 cm





Slide from Dave Hertzog

a_μ(Expt) is extracted from several measurements

CODATA #s

In E821 ≡ $\mathcal{R}_\mu(\mathrm{E821}) = 0.003\,707\,206\,4(2\,0)$ [0.54 ppm]*

- $a_\mu(\mathrm{Expt}) = \frac{g_e}{2}\frac{\omega_a}{\tilde{\omega}_p}\frac{m_\mu}{m_e}\frac{\mu_p}{\mu_e}$

-2.002 319 304 361 53(53) [0.26 ppt]
Electron g-2 + QED

-.001519270384(12) [8 ppb]

206.768 2843(52) [25 ppb]

Muonium HFS experiment(s)

$$\Delta\nu_{\mathrm{Mu}}(\mathrm{Th}) = \frac{16}{3}cR_\infty\alpha^2\frac{m_e}{m_\mu}\left(1+\frac{m_e}{m_\mu}\right)^{-3}$$

Need to measure $\Delta\nu_{\mathrm{Mu}}$

*0.46 ppm statistical, 0.28 ppm systematics

From ν_{12} and ν_{34} to $\Delta\nu$ and μ_μ/μ_p

- Use the Larmor relation to express the magnetic field, H, in terms of the proton NMR frequency, ν_p :

$$h\nu_p = 2\mu_p H$$

- Then the transition frequencies are given by :

$$\nu_{12} = -\nu_p \frac{g'_\mu}{g_\mu}\frac{\mu_\mu}{\mu_p} + \frac{\Delta\nu}{2}\left[(1+x) - \sqrt{1+x^2}\right]$$
$$\nu_{34} = +\nu_p \frac{g'_\mu}{g_\mu}\frac{\mu_\mu}{\mu_p} + \frac{\Delta\nu}{2}\left[(1-x) + \sqrt{1+x^2}\right]$$

- If we measure ν_{12} and ν_{34} in the same magnetic field :

$$\nu_{12} + \nu_{34} = \Delta\nu$$
$$\nu_{34} - \nu_{12} = 2\nu_p \frac{g'_\mu}{g_\mu}\frac{\mu_\mu}{\mu_p} + \Delta\nu\left[\sqrt{1+x^2} - x\right]$$

- Knowing ν_{12}, ν_{34}, and ν_p yields $\Delta\nu$ and μ_μ/μ_p.

Beam --- Slide from Dave Hertzog

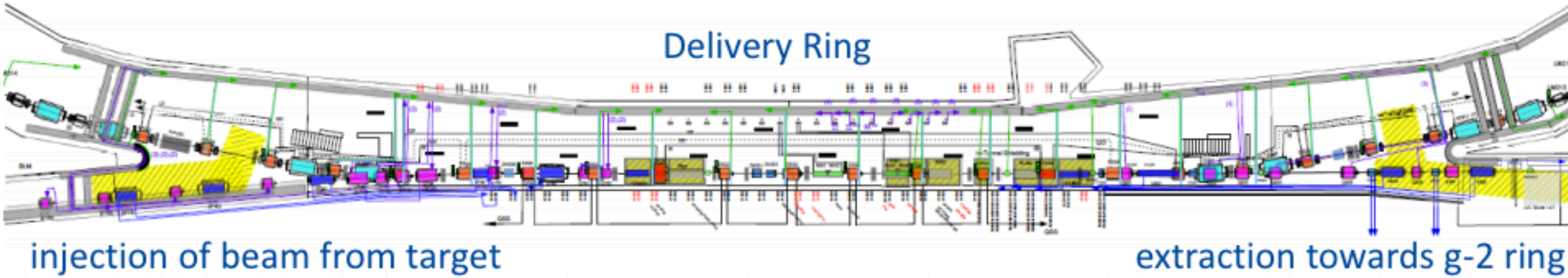
Acquiring x21 statistics at FNAL vs. BNL

: ~ 4000 μ+ / fill *using* 4 TP of 24 GeV p / fill

- FNAL E989: > 10,000 μ+ / fill *using* 1 TP of 8 GeV p / fill
  - Many design factors recover lower σ and proton intensity / fill
    - e.g: target focus, FODO lattice; forward decays; beamline length
  - Additionally: 12 Hz fill rate at FNAL vs 4.4 Hz at BNL (factor x 2.7)
    - *This is a critical advantage*

- NET: Physics / hour 7 times greater at FNAL compared to BNL.

D30 Straight Section



- ✔ Remove existing magnets
- Reconfigure cables, cooling water, electrical bus, lighting (in progress)
- Install injection and extraction lines
- Reinstall Delivery Ring magnets

Beamline Enclosure

Uncertainty Source	Status 2015 [ppb]	Projected after E989 [ppb]	lattice QCD to match exp.[ppb]
	180	70	
	170	70	
Statistical	460	100	
Total Exp.	540	140	
Had. Vac. Pol.	360	215 *	100**
Had LBL	225	225	100
Total Theory	420	310	140

FNAL vs J-PARC

FNAL E989 and J-PARC E34: the numbers

Table 4: Comparison of various parameters for the Fermilab and J-PARC $(g-2)$ Experiments

Parameter	Fermilab E989	J-PARC E24
Statistical goal	100 ppb	400 ppb
Magnetic field	1.45 T	3.0 T
Radius	711 cm	33.3 cm
Cyclotron period	149.1 ns	7.4 ns
Precession frequency, ω_a	1.43 MHz	2.96 MHz
Lifetime, $\gamma\tau_\mu$	64.4 μs	6.6 μs
Typical asymmetry, A	0.4	0.4
Beam polarization	0.97	0.50
Events in final fit	1.5×10^{11}	8.1×10^{11}

Gorringe and Hertzog, Progress in Nuclear and Particle Physics, *Volume 84 (2015) September 2015*