A New Initiative to Measure the Muon Anomalous Magnetic Moment at Fermilab

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Fermilab
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Representing the E989 Collaboration

Boston, BNL, Budker, Cornell, Fermilab, Illinois, James Madison, KEK, Kentucky, KVI Netherlands, Frascati, Massachusetts, Michigan, Muons Inc., Northwestern, Osaka, Petersburg, Regis, TU Dresden, Virginia, Washington

University of Minnesota
HEP Seminar

Spokesmen:
D. Hertzog (Washington)
L. Roberts (Boston)

Project Manager:
C. Polly (Fermilab)

Outline

The Physics

The (beautiful) experimental technique of BNL E821

E989: The New Initiative at Fermilab

Probing High Energy Scales with Quantum Corrections

Few Robust Probes

Neutral Kaon Mixing
Neutral B Meson Mixing
Rare K, B, and Pion Decays
Trapped electrons

Muon Anomalous Magnetic Moment (G_μ-2)

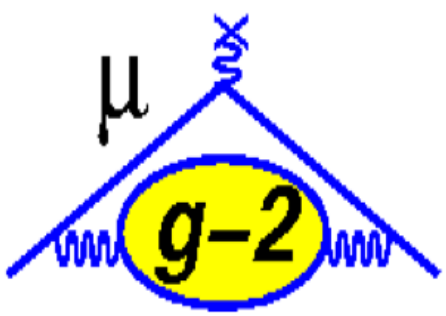
Among these, G_μ-2 is *Special*

Theoretically Robust QED and EW Corrections

No Strong interactions at first order.

QCD Corrections are Small and in good control

Lucky Combination of lifetime, mass, and charge



Could probe the muon using several techniques:
atomic nucleus, laser, electric field, ...

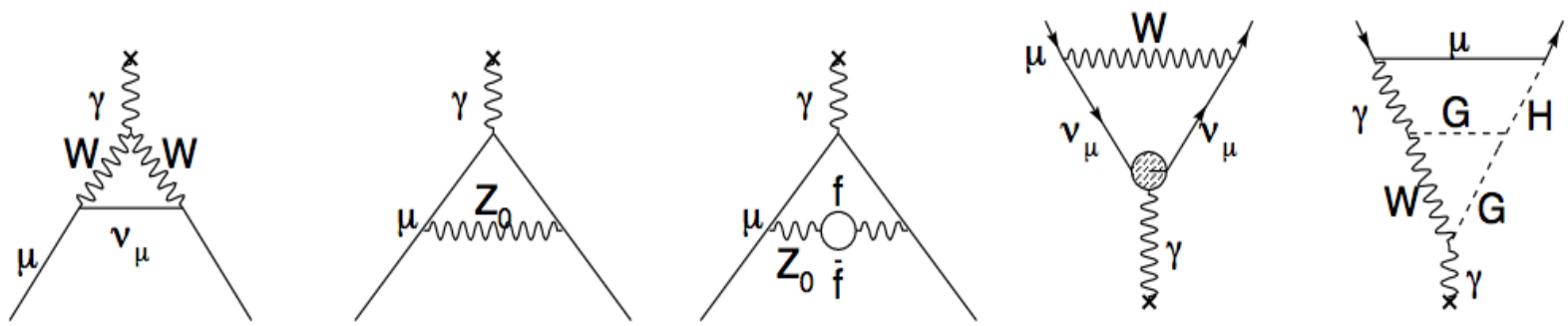
But can use a precision magnetic field to continuously probe the muon at least 10 lifetimes.

Experimentally can see the EW corrections

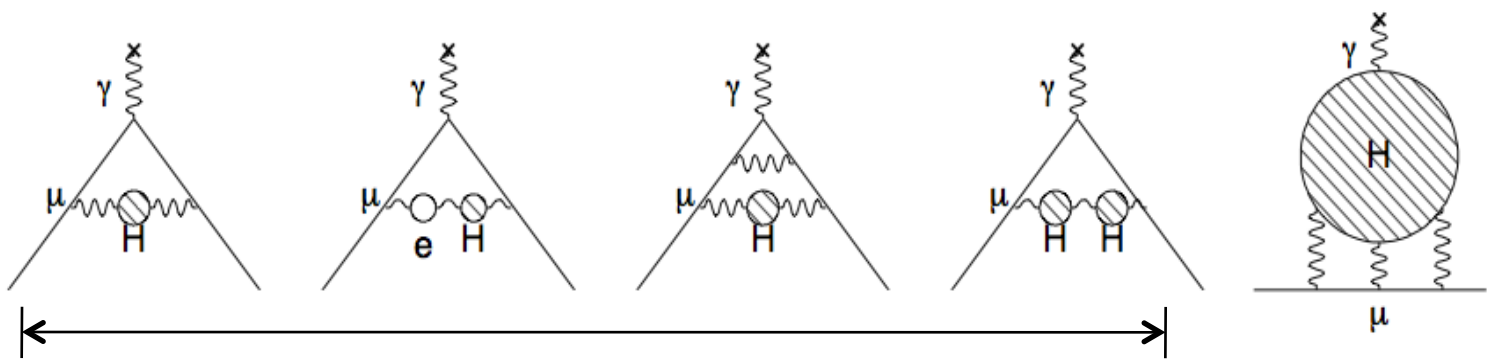
Quantum Corrections to G_μ

QED (known to 5 loops)

EW



QCD



Hadronic Vacuum Polarization

Hadronic Light-by-Light

$G_\mu - 2$ Theoretical Estimates

Contribution	Result ($\times 10^{-11}$) units
QED (leptons)	$116\,584\,718.09 \pm 0.14 \pm 0.04_\alpha$
HVP(lo)	$6\,914 \pm 42_{\text{exp}} \pm 14_{\text{rad}} \pm 7_{\text{pQCD}}$
HVP(ho)	$-98 \pm 1_{\text{exp}} \pm 0.3_{\text{rad}}$
HLxL	105 ± 26
EW	$152 \pm 2 \pm 1$
Total SM	$116\,591\,793 \pm 51$

A. Höcker Tau 2010, U. Manchester September 2010

Predictions of HVP and HLxL are continually being scrutinized

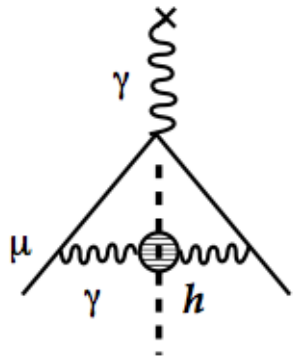
Central Values are stable

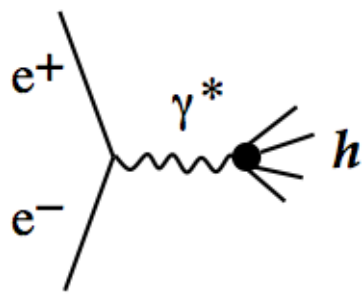
Errors are gradually getting smaller

Recent HLxL estimate by Prades, deRafael, Vainshtein (and others)

HLxL estimate from Lattice QCD.

Estimates of the HVP

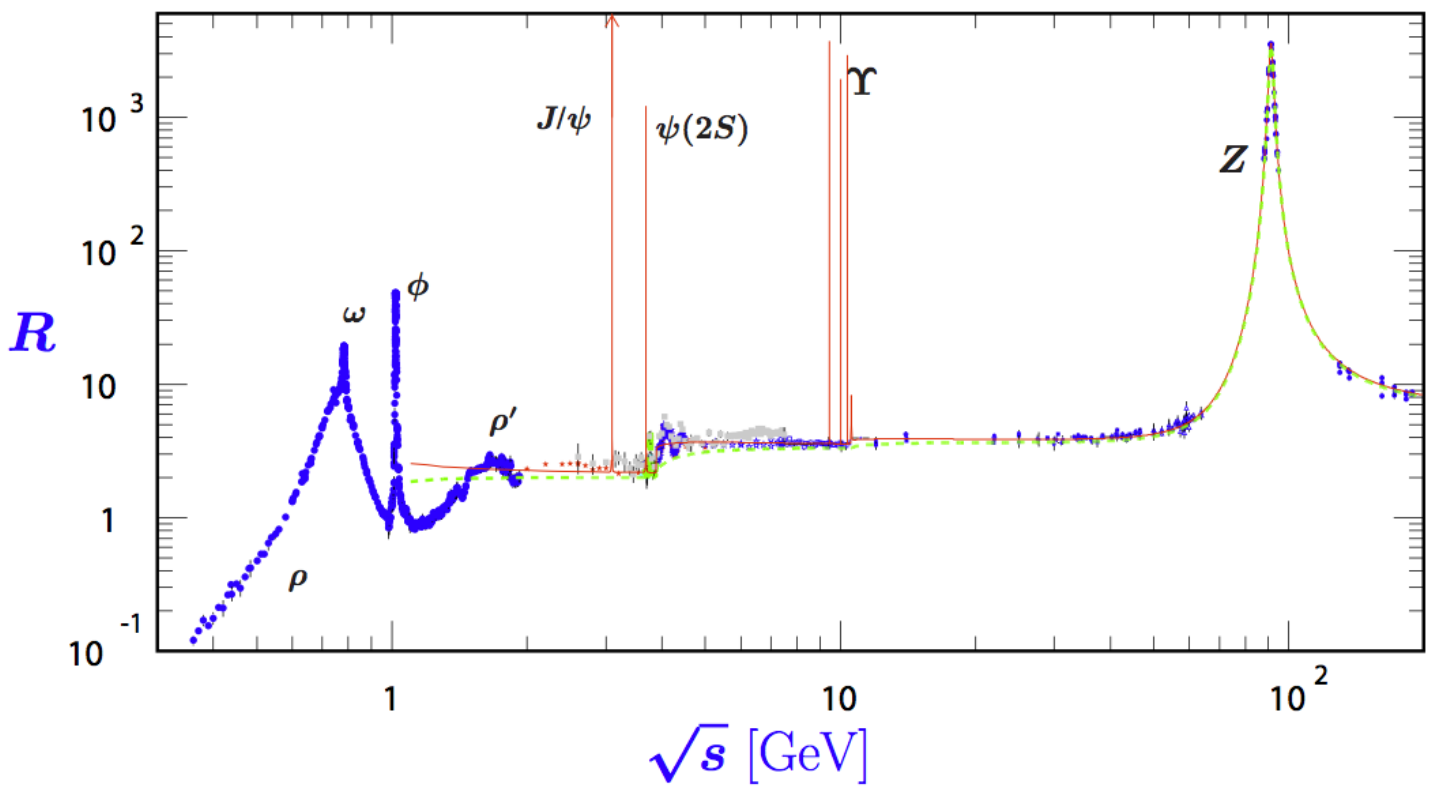




Related to $R \equiv \frac{\sigma_{\rm tot}(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)}$

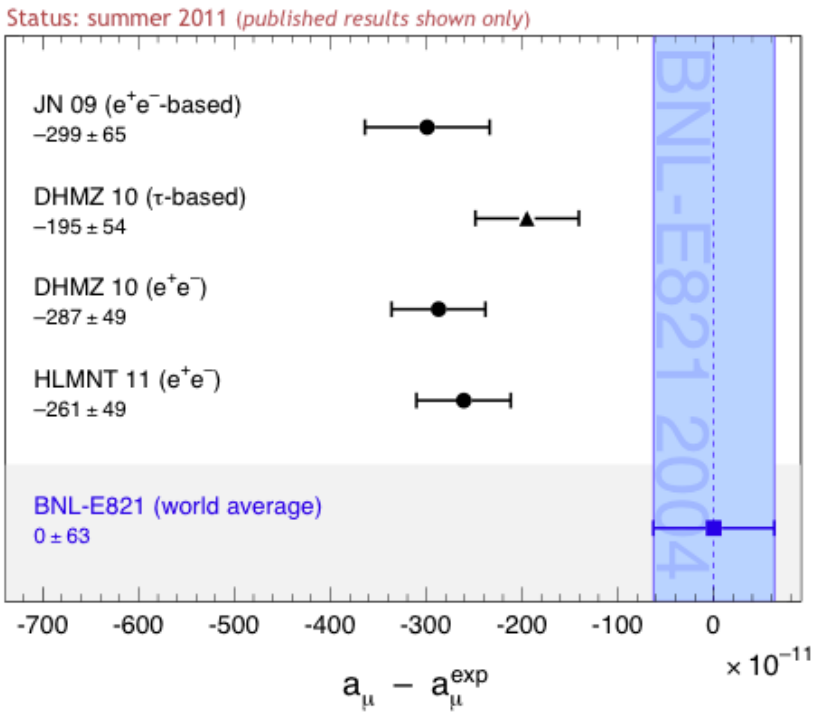
R comes primarily from low energy e^+e^- collider data: CMD2, SND, KLOE, Babar.

New upgrades: CMD3, SND2000, VEPP2000



PDG2011

A > 3σ Disagreement Between Theory and Experiment



$$a_\mu^{\rm QED} = 0.00\,116\,584\,718\,09(15)$$
$$a_\mu^{\rm had} = 0.00\,000\,006\,930(49)$$
$$a_\mu^{\rm EW} = 0.00\,000\,000\,154(2)$$

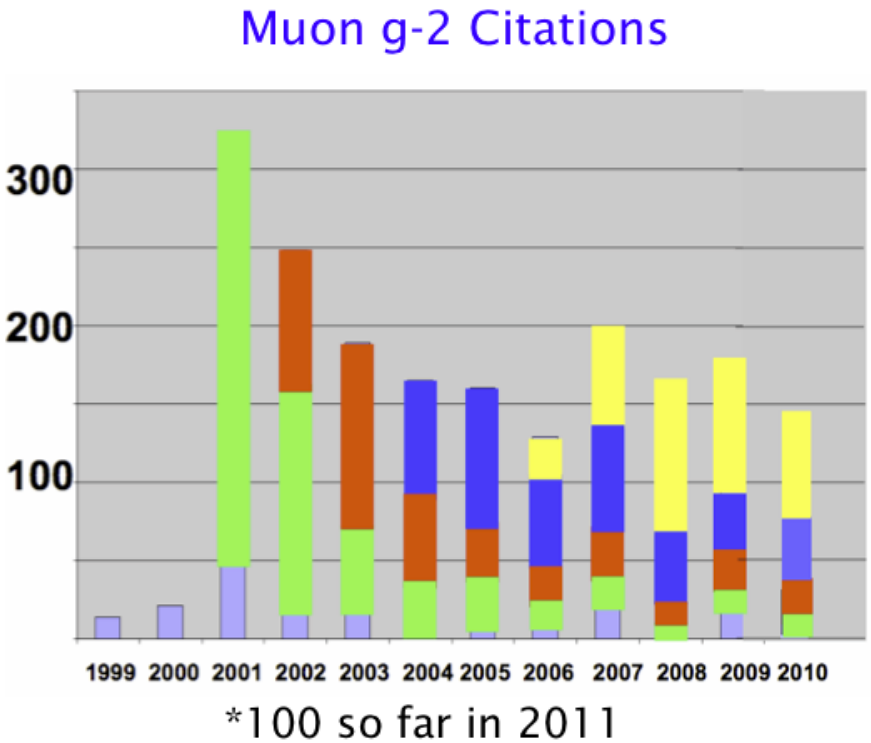
$$a_\mu^{\rm SM} = 0.00\,116\,591\,802(49)$$
$$a_\mu^{\rm exp} = 0.00\,116\,592\,089(63)$$

M. Davier ICFA 2011

$$\mathbf{a}_\mu^{\rm exp} - \mathbf{a}_\mu^{\rm SM} = \mathbf{287(80)} \times \mathbf{10^{-11}}$$

Dominant Theoretical Uncertainty: Experimental input into HVP calculations, followed by HLxL calculations

Significant Interest in this Discrepancy as a Sign of New Physics

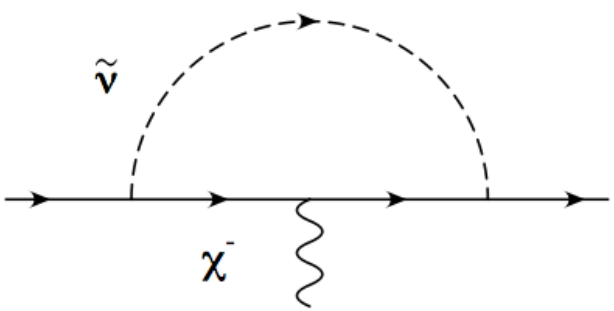


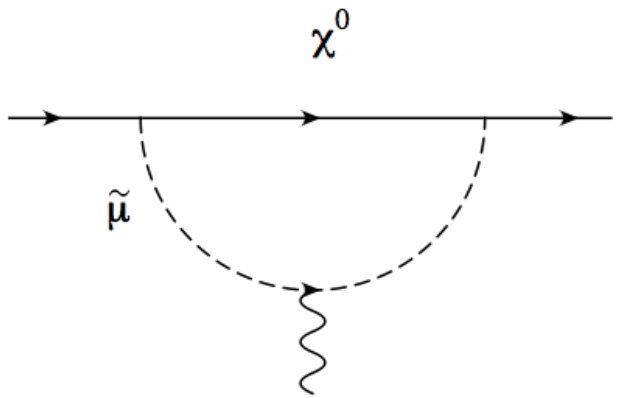
Universal Extra Dimensions
Extra Gauge Bosons
Radiative Muon Mass Generation
Extended Technicolor
Dark Matter Models
Dark Photons (to explain positron excess seen at Galactic center)

Generic SUSY
Constrained Minimal SUSY

From Marciano, Munich 2011

- Most likely (popular?)
- $a_\mu(\mathrm{SUSY}) = \mathrm{sgn}(\mu)\, 130 \times 10^{-11} \left(\frac{100\mathrm{GeV}}{m_{\mathrm{SUSY}}}\right)^2 \tan\beta$
- $\mathrm{sgn}(\mu) = +$, $\tan\beta = 3 - 40$, $m_{\mathrm{SUSY}} = 100 - 500$ GeV





If SUSY: $\mathrm{sgn}(\mu)+$, dark matter easier, SUSY at LHC likely, EDMS,

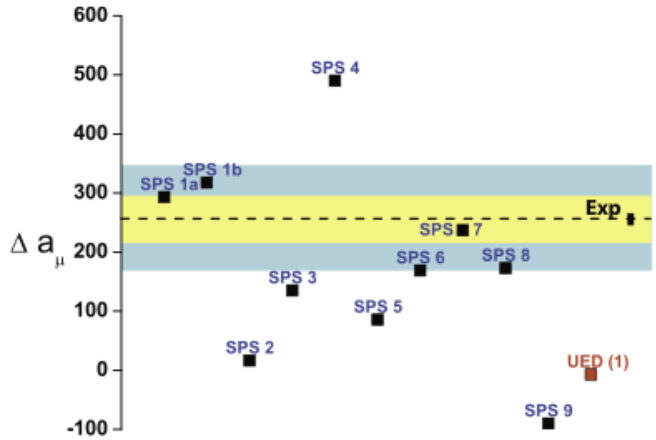
Motivation for a New G_μ-2 Measurement

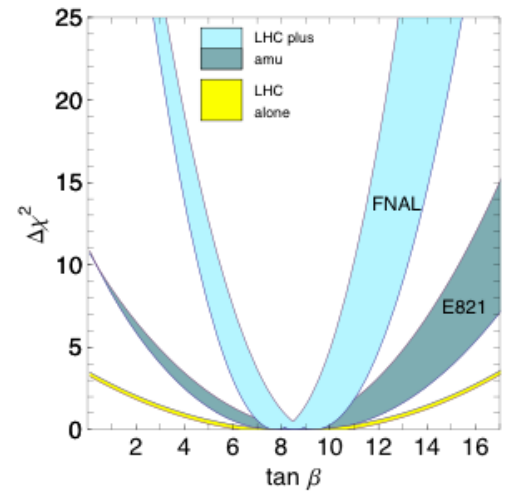
From 2011 HLBL Seattle Workshop

- Can HLbL error be reduced to 10% level in $\sim$ 5 years?
- Conclusion: Yes, with concerted effort by modelers, lattice theorists, new experiments.
- current $a_\mu(\mathrm{Expt})$-$a_\mu(\mathrm{SM}) = 287(63)(51)$ ($\times 10^{-11}$), or $\sim 3.6\sigma$
- If both central values stayed the same,
  - E989 (3$\times$ smaller error) $\rightarrow\sim 5\sigma$
  - E989+new HLBL theory $\rightarrow\sim 6\sigma$
  - E989+new HLBL +new HVP (50% reduction) $\rightarrow\sim 8\sigma$
- Big discrepancy! (New Physics $\sim$ 2$\times$ EW)

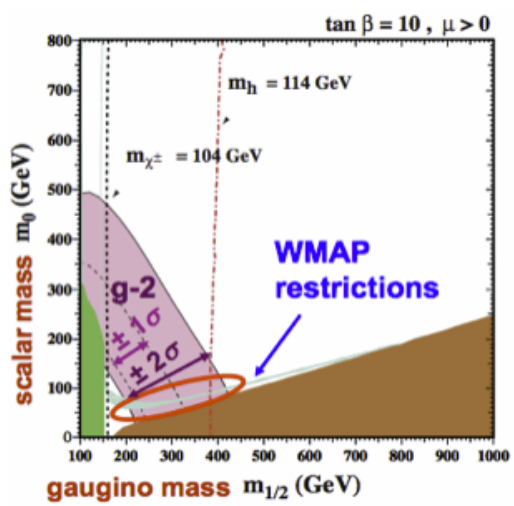
Special Role of G_μ-2 in the LHC Era

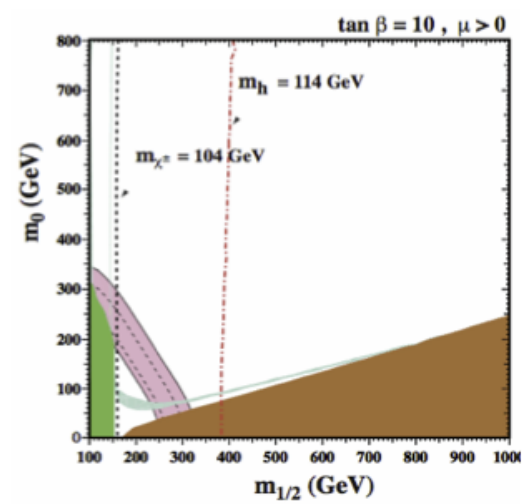
If See New Physics (NP) at the LHC, then G_μ will resolve ambiguities NP Models





If unlucky, and see no NP, then precision measurements such as G_μ are the only way to probe high energy scales

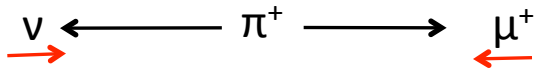




Measuring G_μ

Making Polarized Muons and Spin Determination

Muons from $\pi^+ \longrightarrow \mu^+\nu$ **decay are polarized**

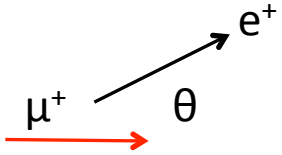


Idea: Select a narrow band in the decay phase space

Determine Muon Spin Direction from $\mu^+ \longrightarrow e^+\nu\nu$ **Decay:**

In muon CM frame, positron direction tends to *align with* the muon spin direction.

Decay Rate in muon CM goes as:



$1 + A_\mu (\cos\theta) / 3$ all positrons

$1 + A_\mu (\cos\theta)$ maximum energy positrons

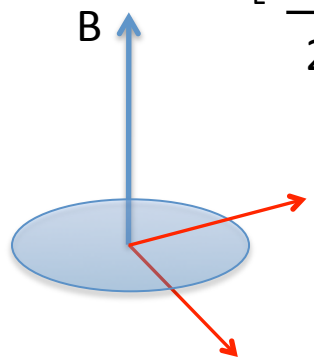
A_μ = muon polarization fraction

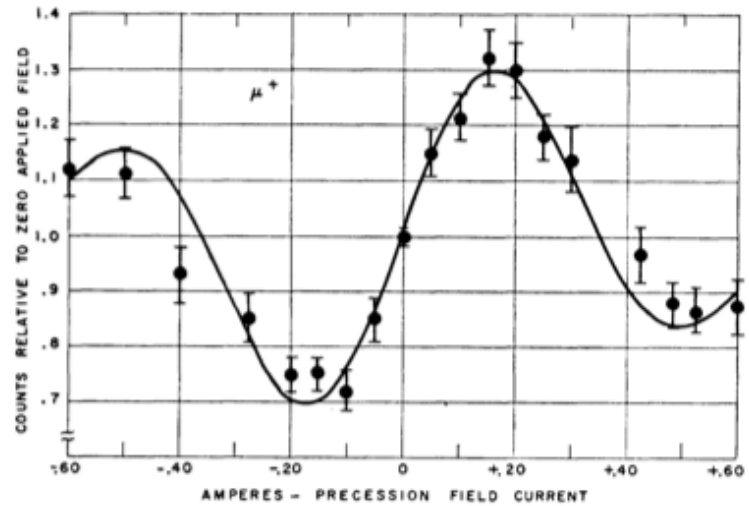
The Basic Concept: Measure the Larmor Precession of Muons in a B-field

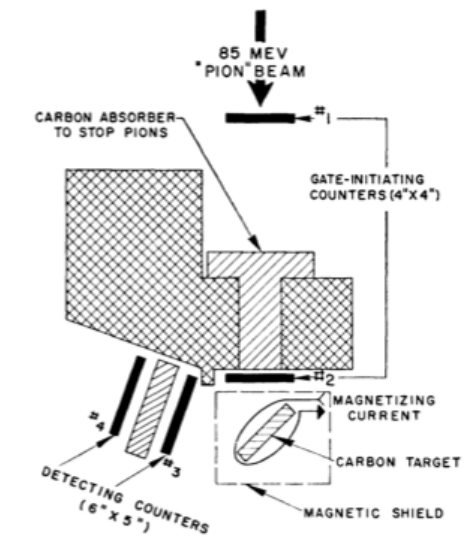
Directly Measure g_μ. Similar to NMR Technique.

B-field transverse to muon spin

$$\omega_L = \frac{g_\mu e B}{2 m_\mu c}$$







1957: Garwin, Lederman, Weinrich (stopped muon technique)

$g_\mu = 2.00 \pm 0.10$ (5% error)

Incredible Ingenuity Needed to Achieve 0.6 ppm Precision

$\mu_\mu/(e\hbar/2m_\mu)-1 = (g_\mu-2)/2$

VALUE (units 10^{-10})	DOCUMENT ID		TECN	CHG	COMMENT
11659203± 7 OUR AVERAGE					
11659204± 7±5	BENNETT	02	MUG2	+	Storage ring
11659202± 14±6	BROWN	01	MUG2	+	Storage ring
11659191± 59	BROWN	00	MUG2	+	
• • • We do not use the following data for averages, fits, limits, etc. • • •					
11659100± 110	[7] BAILEY	79	CNTR	+	Storage ring
11659360± 120	[7] BAILEY	79	CNTR	−	Storage ring
11659230± 85	[7] BAILEY	79	CNTR	±	Storage ring
11620000±5000	CHARPAK	62	CNTR	+	

[7] BAILEY 79 values recalculated by HUGHES 99 using the COHEN 87 μ/p magnetic moment. The improved MOHR 99 value does not change the result.

4 decades
of hard work

Measurement of the Negative Muon Anomalous Magnetic Moment to 0.7 ppm

G.W. Bennett[2], B. Bousquet[9], H.N. Brown[2], G. Bunce[2], R.M. Carey[1], P. Cushman[9], G.T. Danby[2], P.T. Debevec[7], M. Deile[11], H. Deng[11], S.K. Dhawan[11], V.P. Druzhinin[3], L. Duong[9], F.J.M. Farley[11], G.V. Fedotovich[3], F.E. Gray[7], D. Grigoriev[3], M. Grosse-Perdekamp[11], A. Grossmann[6], M.F. Hare[1], D.W. Hertzog[7], X. Huang[1], V.W. Hughes[11†], M. Iwasaki[10], K. Jungmann[5], D. Kawall[11], B.I. Khazin[3], F. Krienen[1], I. Kronkvist[9], A. Lam[1], R. Larsen[2], Y.Y. Lee[2], I. Logashenko[1,3], R. McNabb[9], W. Meng[2], J.P. Miller[1], W.M. Morse[2], D. Nikas[2], C.J.G. Onderwater[7], Y. Orlov[4], C.S. Özben[2,7], J.M. Paley[1], Q. Peng[1], C.C. Polly[7], J. Pretz[11], R. Prigl[2], G. zu Putlitz[6], T. Qian[9], S.I. Redin[3,11], O. Rind[1], B.L. Roberts[1], N. Ryskulov[3], Y.K. Semertzidis[2], P. Shagin[9], Yu.M. Shatunov[3], E.P. Sichtermann[11], E. Solodov[3], M. Sossong[7], L.R. Sulak[1], A. Trofimov[1], P. von Walter[6], and A. Yamamoto[8].

(Muon $(g-2)$ Collaboration)

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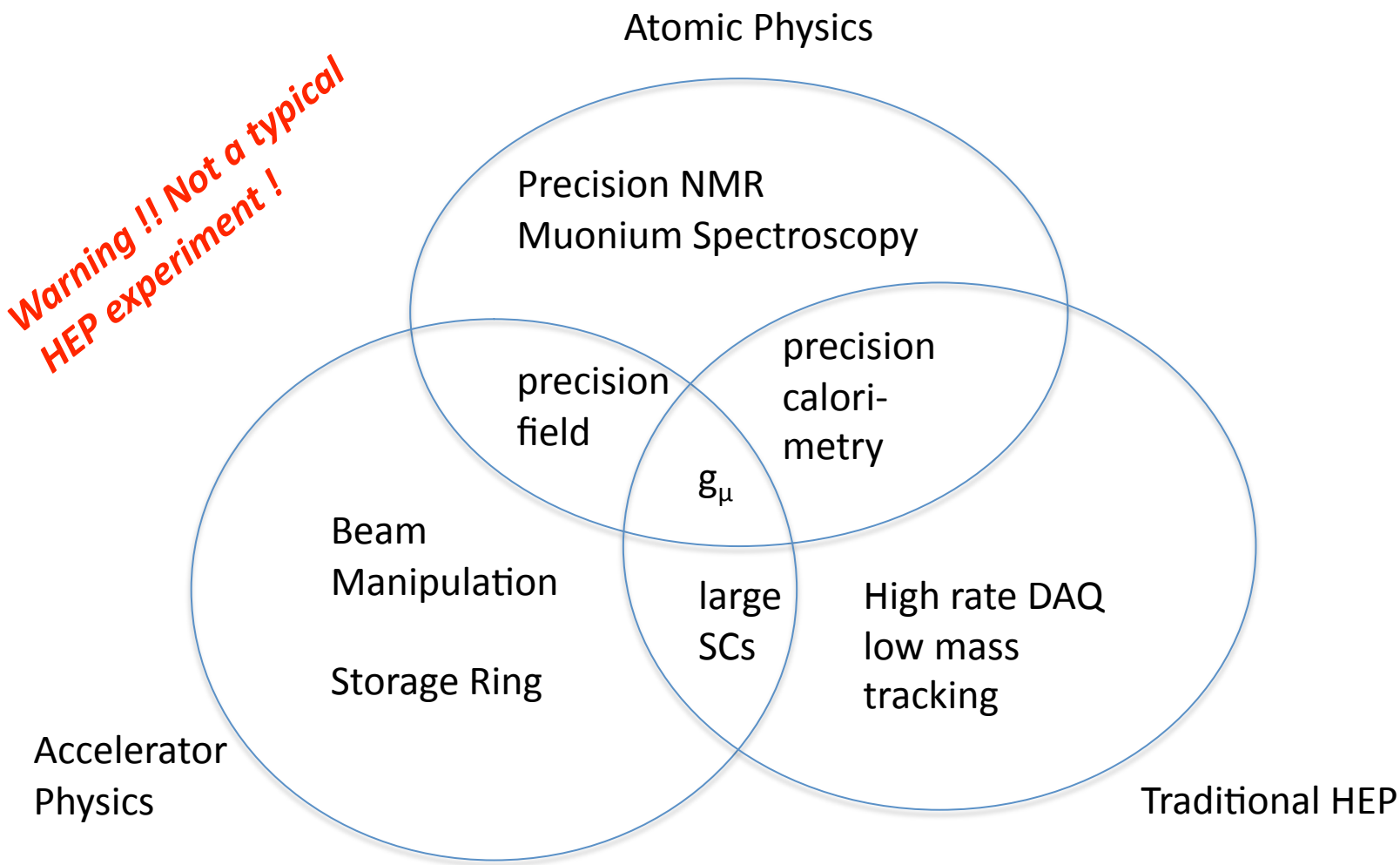
[2] *Brookhaven National Laboratory, Upton, New York 11973*
[3] *Budker Institute of Nuclear Physics, Novosibirsk, Russia*
[4] *Newman Laboratory, Cornell University, Ithaca, New York 14853*
[5] *Kernfysisch Versneller Instituut, Rijksuniversiteit Groningen, NL 9747 AA Groningen, The Netherlands*
[6] *Physikalisches Institut der Universität Heidelberg, 69120 Heidelberg, Germany*
[7] *Department of Physics, University of Illinois at Urbana-Champaign, Illinois 61801*
[8] *KEK, High Energy Accelerator Research Organization, Tsukuba, Ibaraki 305-0801, Japan*
[9] *Department of Physics, University of Minnesota, Minneapolis, Minnesota 55455*
[10] *Tokyo Institute of Technology, Tokyo, Japan*
[11] *Department of Physics, Yale University, New Haven, Connecticut 06520*

A Minnesota Connection !

Breakthroughs Needed to Measure g_μ to 0.6 ppm



Muon Storage Ring Technique allows DIRECT determination of g_μ - 2

Muon Spin precession rate

$$\omega_S = g_\mu eB/(2m_\mu c) + (1-\gamma)eB/(m_\mu c\gamma)$$

↑ Larmor precession Term

↑ Thomas precession term (kinematic effect of SR in a rotating frame)

Muon Momentum Precession Rate

$$\omega_C = eB/m_\mu c\gamma$$

(a.k.a. cyclotron frequency)

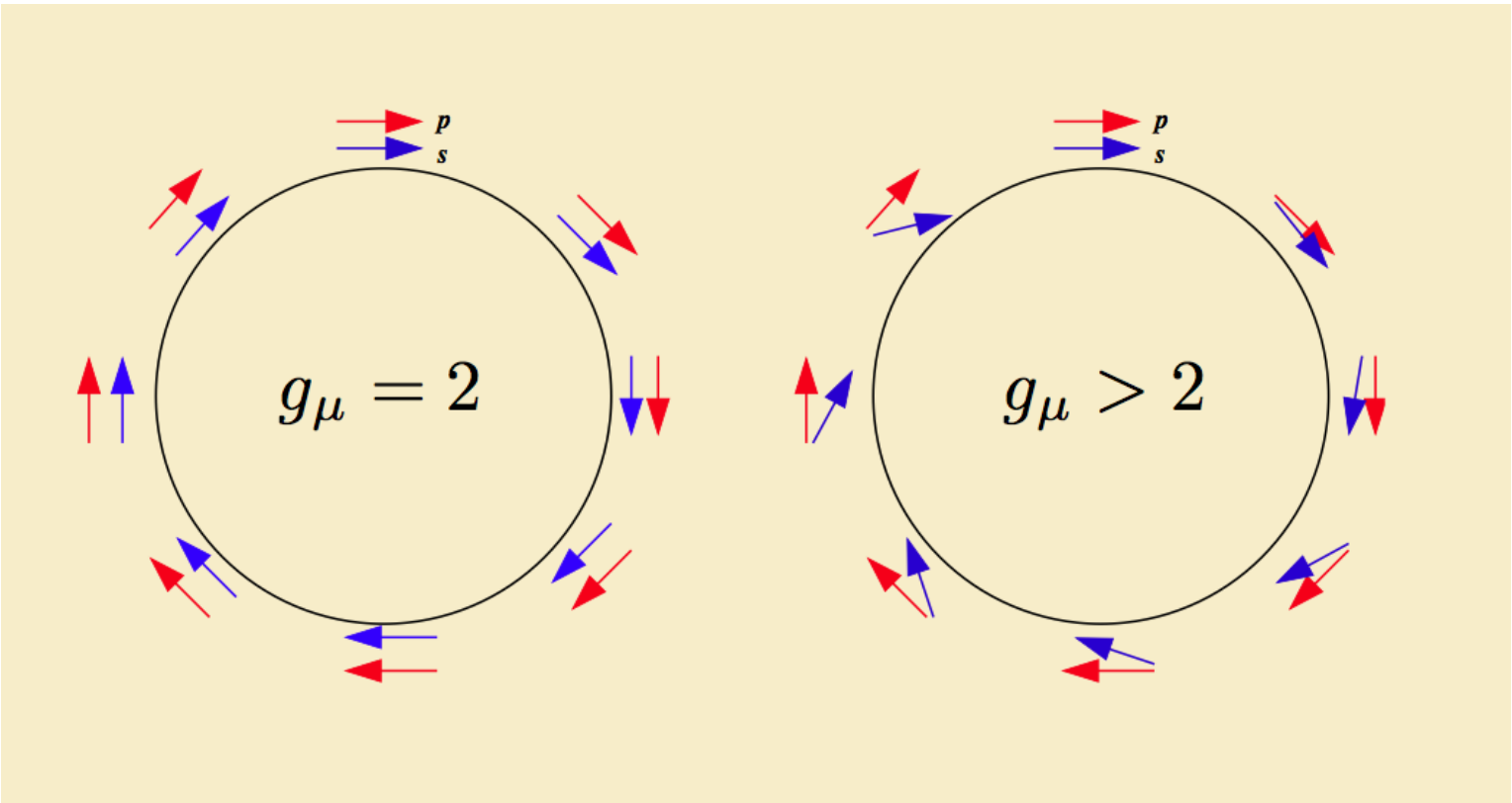
Difference measures g_μ -2 directly

$$\omega_S - \omega_C = \tfrac{1}{2}(g_\mu - 2)\, eB/m_\mu c$$

$\omega_a = \omega_S - \omega_C = \frac{1}{2}(g_\mu - 2)\, eB/(m_\mu c)$

$= a_\mu\, eB/(m_\mu c)$

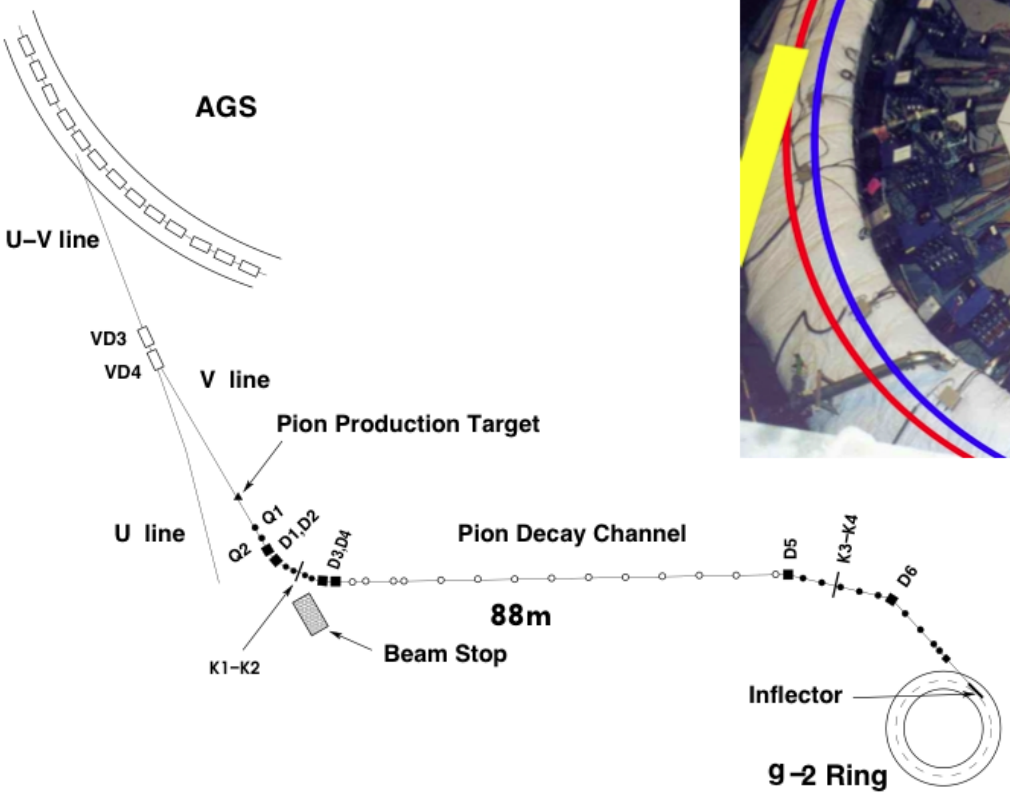
Allows ~ 1000x improvement over measuring g_μ

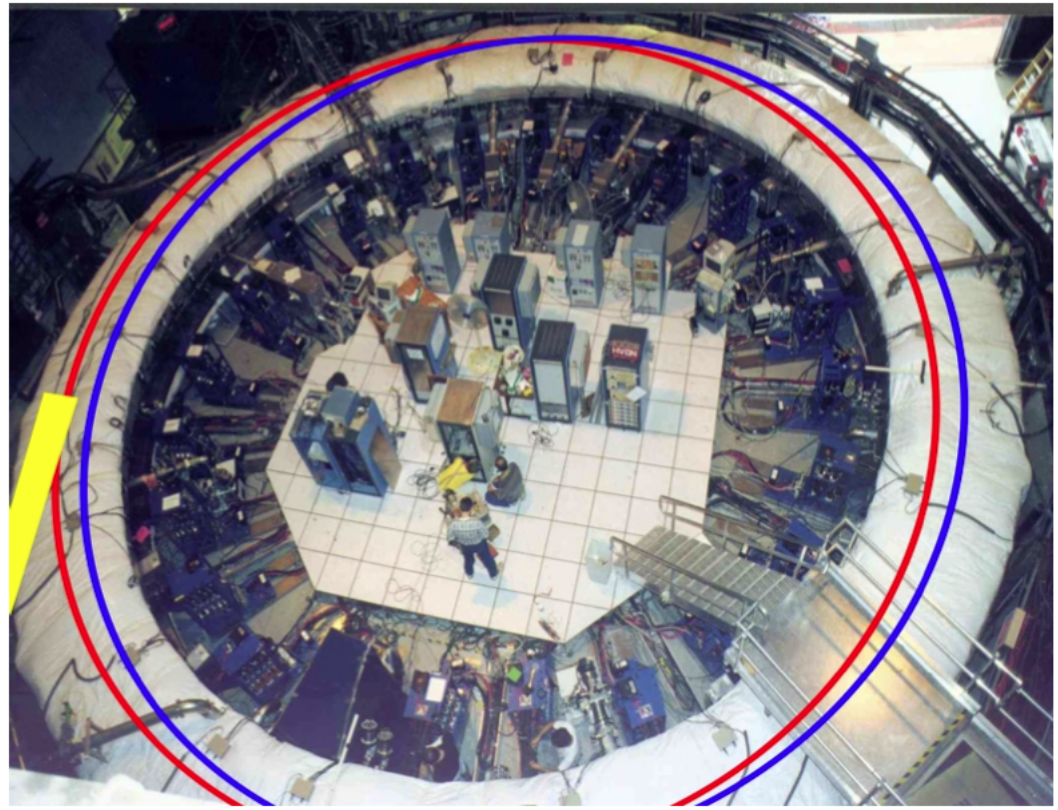


True for any momentum, ie. Any Ring Size

Injection of Muons into Storage Ring

By selecting a narrow pion and muon momentum range, muons will have a high (~100%) initial net polarization.



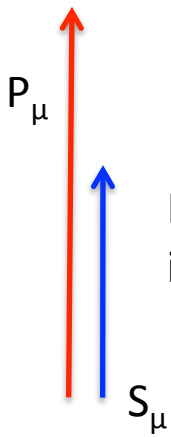


Beautiful and Subtle Beam Manipulation Techniques !

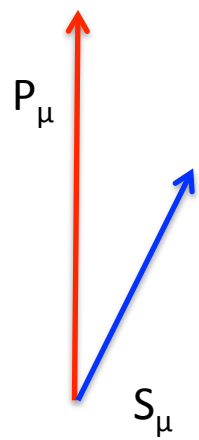
Inflector
Kicker

Measuring the Frequency Difference in a Storage Ring

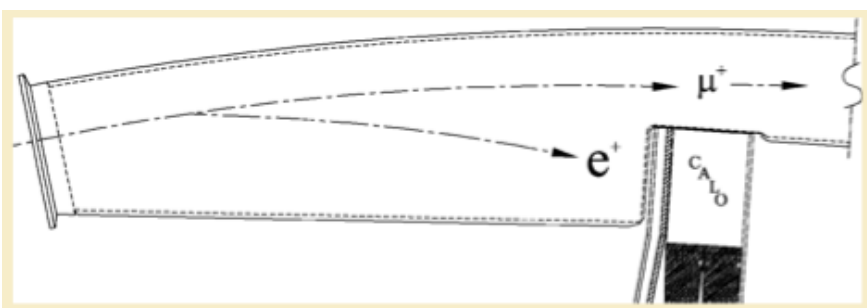
In muon CM, positron direction tends to align with muon spin: $1 + A_\mu (\cos\theta) / 3$



Positrons gets additional boost if P_μ and S_μ are aligned



Positrons get less boost if P_μ and S_μ are not aligned



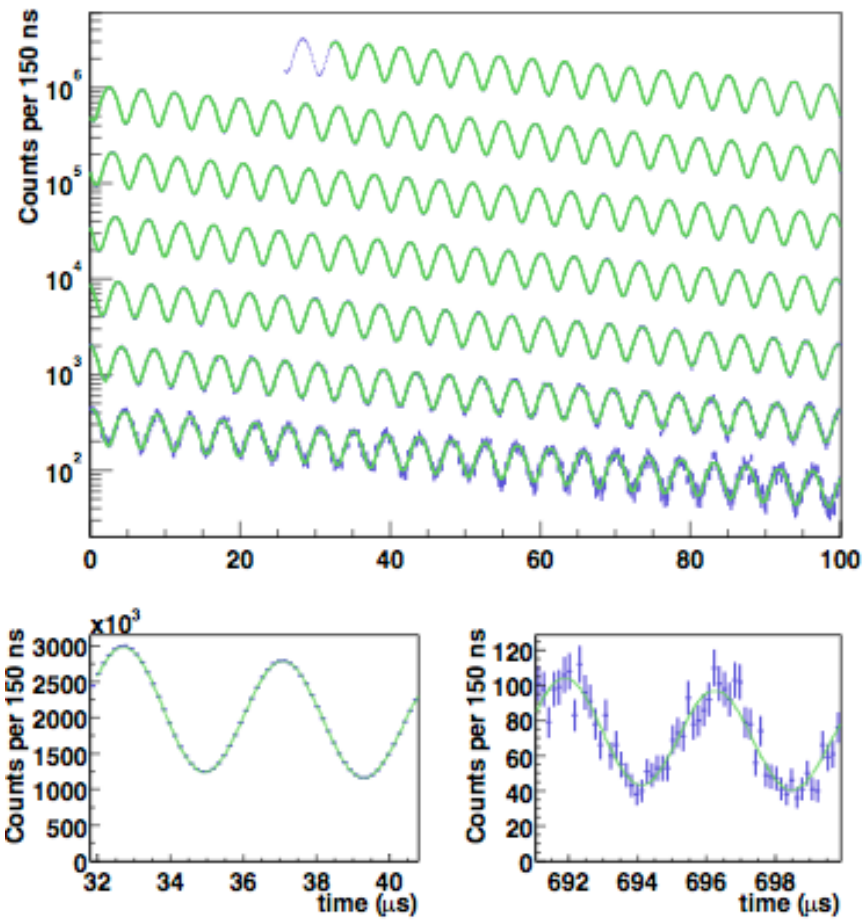
Calorimeter would see a Time-varying Positron Energy Distribution with frequency $\omega_a = \omega_S - \omega_C$.

Stronger time variation if select only high energy positrons

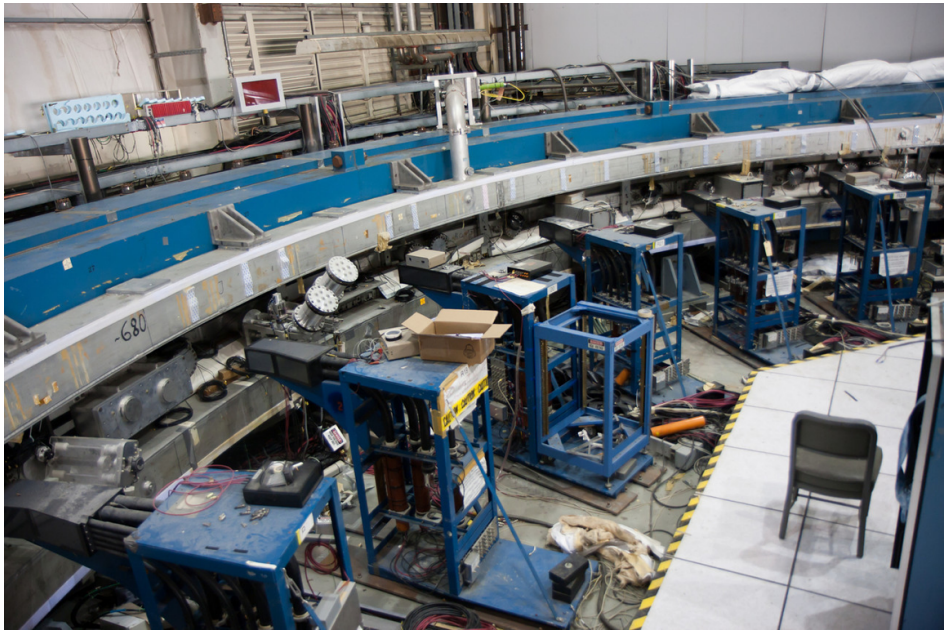
$$N(t) = N_0 e^{-t/\tau}\left[1 + A\cos(\omega_a t + \phi)\right]$$

Analyzing power:

$$\frac{\delta\omega_a}{\omega_a} = \frac{\sqrt{2}}{\omega_a A \tau \sqrt{N}}$$

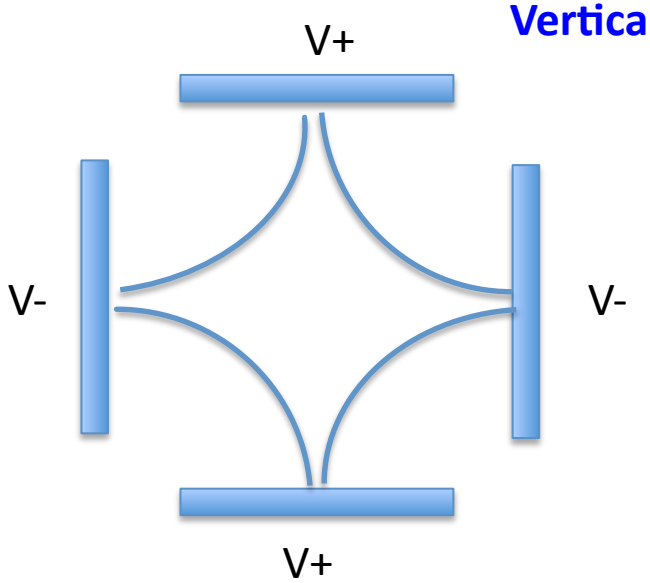


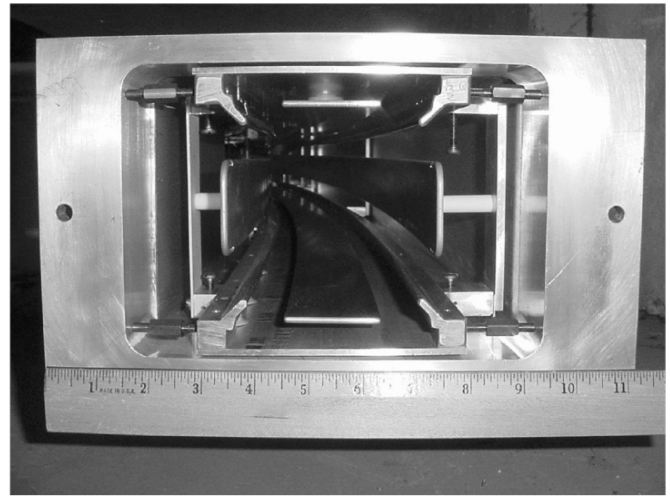
A depends on Initial Muon Polarization and Energy Threshold Cut



From E821 2000 Result: 4 billion decays, 5 parameter fit, 10 muon lifetimes

Vertical Confinement in A Storage Ring with Electric Quadrupoles





BNL E821 Electric Quadrupole

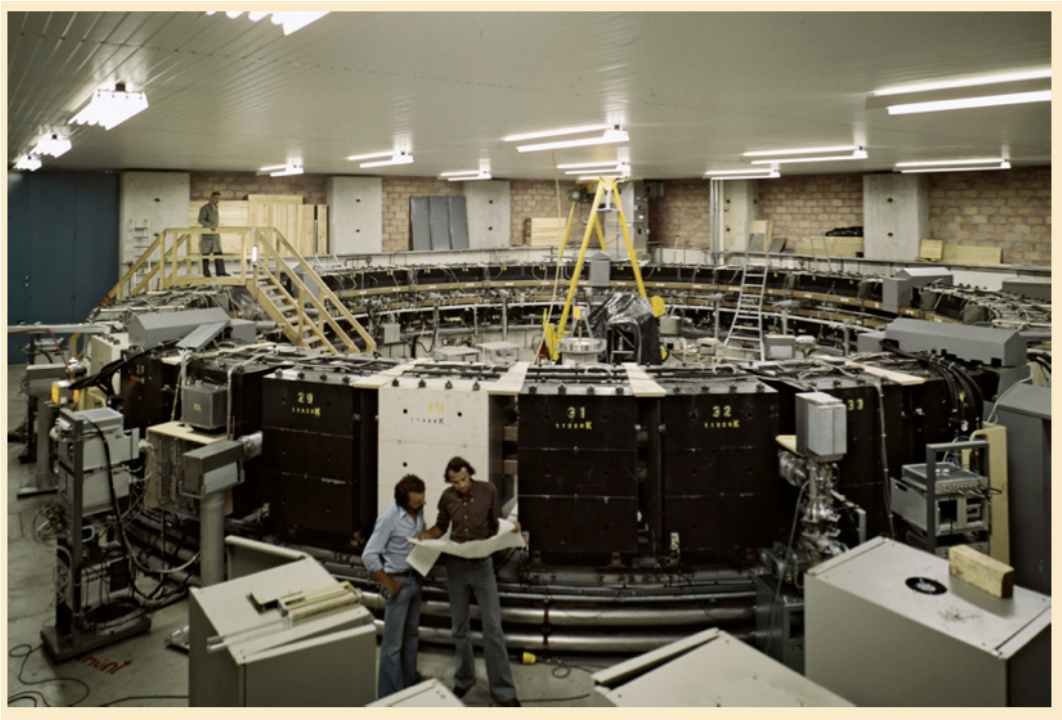
Electric Quads add an extra Spin Precession Term:

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

But Extra Precession term is CANCELLED using if γ=29.3, P_μ = 3.09 GeV/c.

Note: Can Use Magnetic Quadrupoles, but hard to monitor and measure well.

CERN 1968: Magnetic Quadrupole Vertical Confinement. P_μ = 1.27 GeV/c B=1.7 Tesla



CERN 1979. , P_μ = 3.09 GeV/c.
B=1.45 Tesla Warm Magnet.

Electric Focusing Quads.

Penalty:

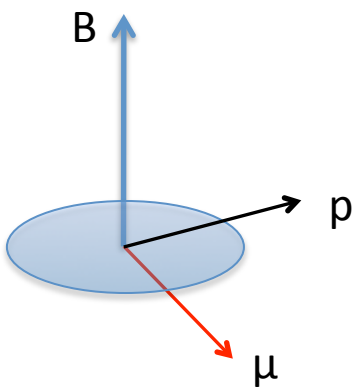
Large (7 meter) Radius Ring.
No longer a table top experiment.

NMR Measurement of the B-field CANCELS the dependence on B, m_μ, e, and c

$\omega_a = a_\mu eB/(m_\mu c)$

Larmor precession of proton in a B-field

$\omega_p = g_p eB/(2m_p c)$



Can show that :

$\mathbf{a_\mu = R / (\lambda - R)}$

$R = \omega_a/\omega_p$

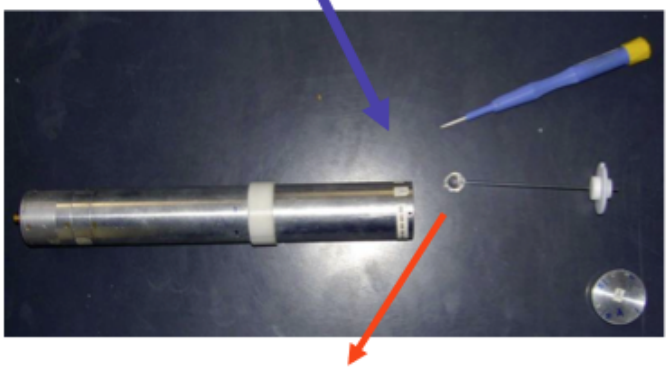
$\lambda = g_\mu m_p/(g_p m_\mu)$ taken from muonium hyperfine splitting

$\lambda = 3.183345137 \pm 0.000000085$
(26 ppb)

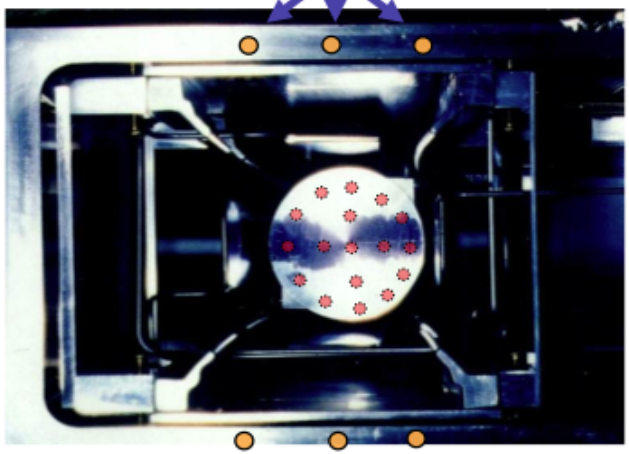
λ known well enough not to affect a_μ

Measuring the Proton Larmor Precession Frequency

Absolute Calibration Probe:
a Spherical Water Sample

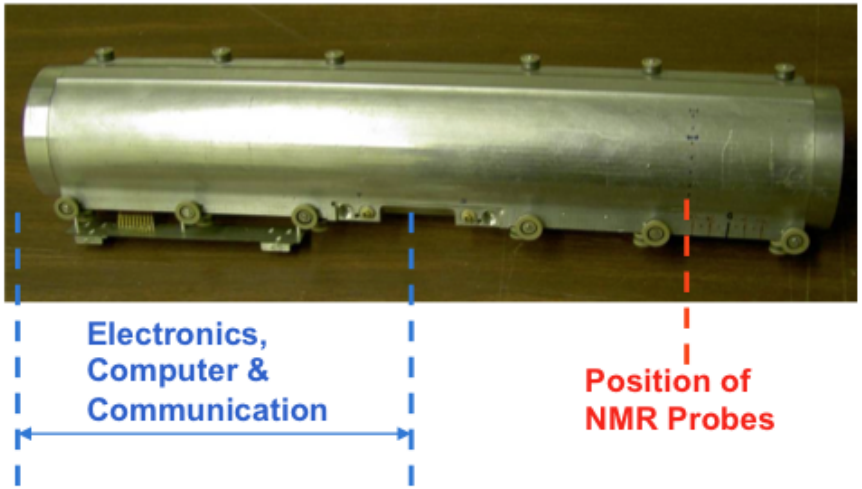


Fixed Probes in the
walls of the vacuum tank

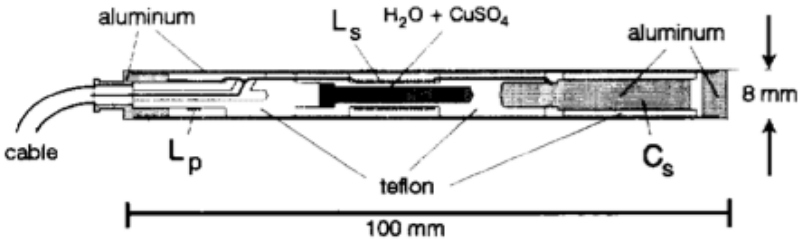


360 Fixed Probes

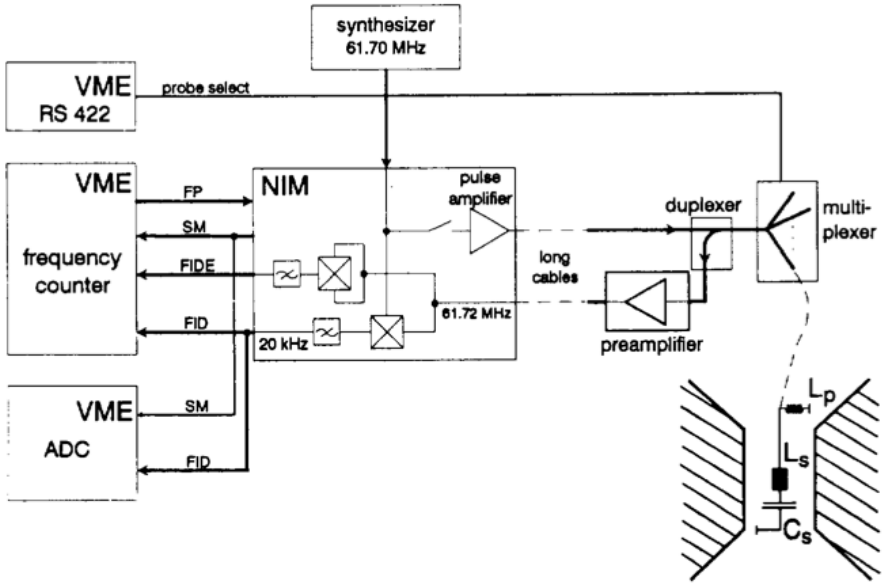
Trolley with matrix of 17 NMR Probes



Measuring the Proton Larmor Frequency at 1.45 Tesla

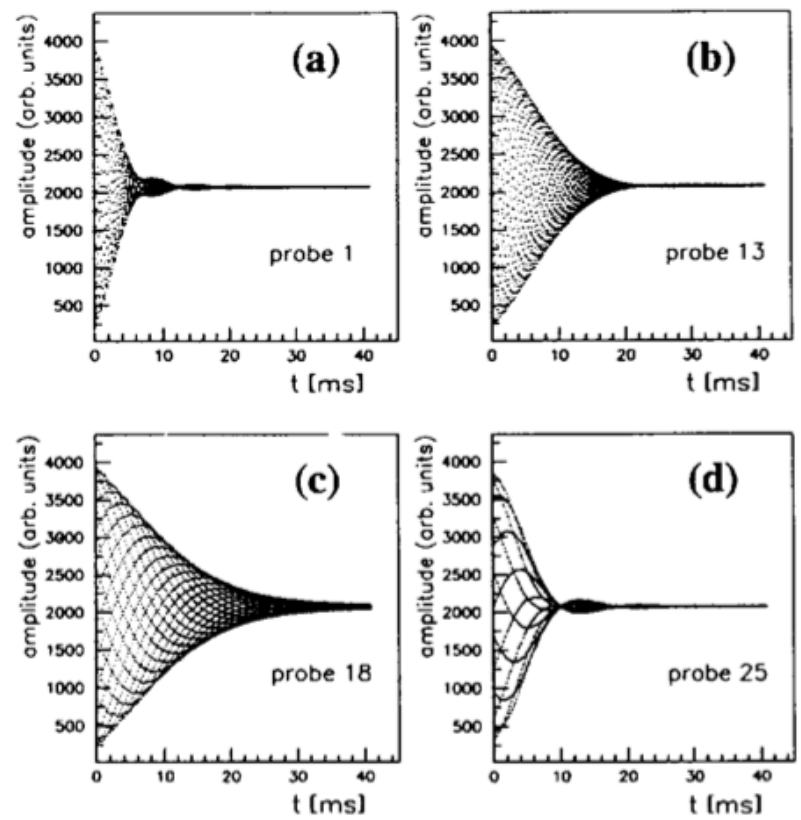


R. Prigl et al. / Nucl. Instr. and Meth. in Phys. Res. A 374 (1996) 118–126



Pulsed NMR Technique and
Multiplexing and Frequency Mixing System

Results from 4 NMR Trolley Probes

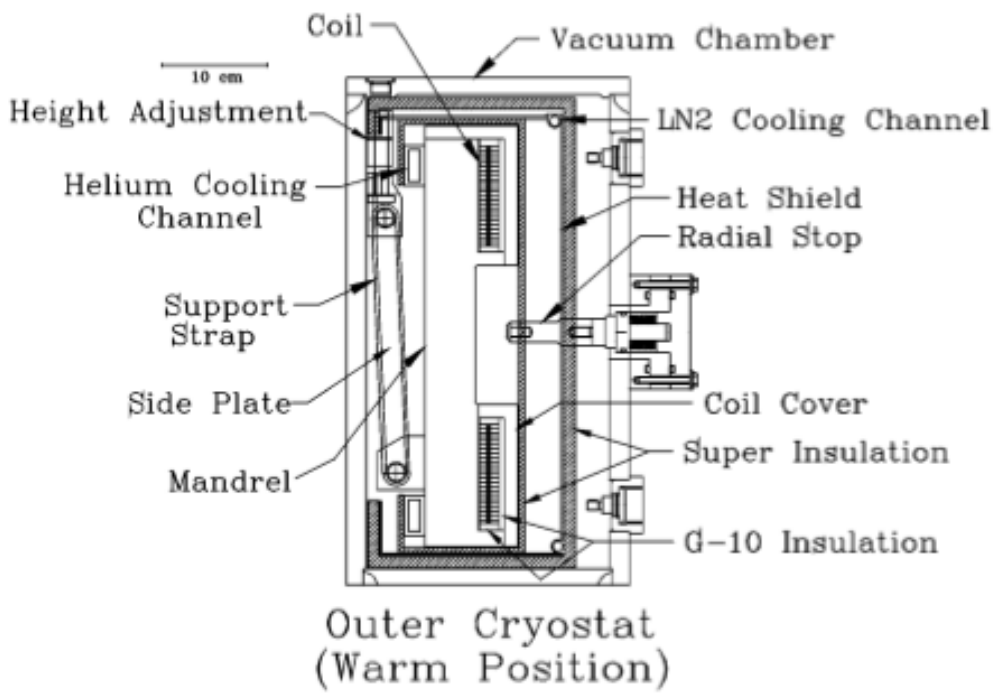


Proton Larmor Frequency ~ 62 MHz

Frequency Mix Down to ~ 30 KHz
(easier to handle)

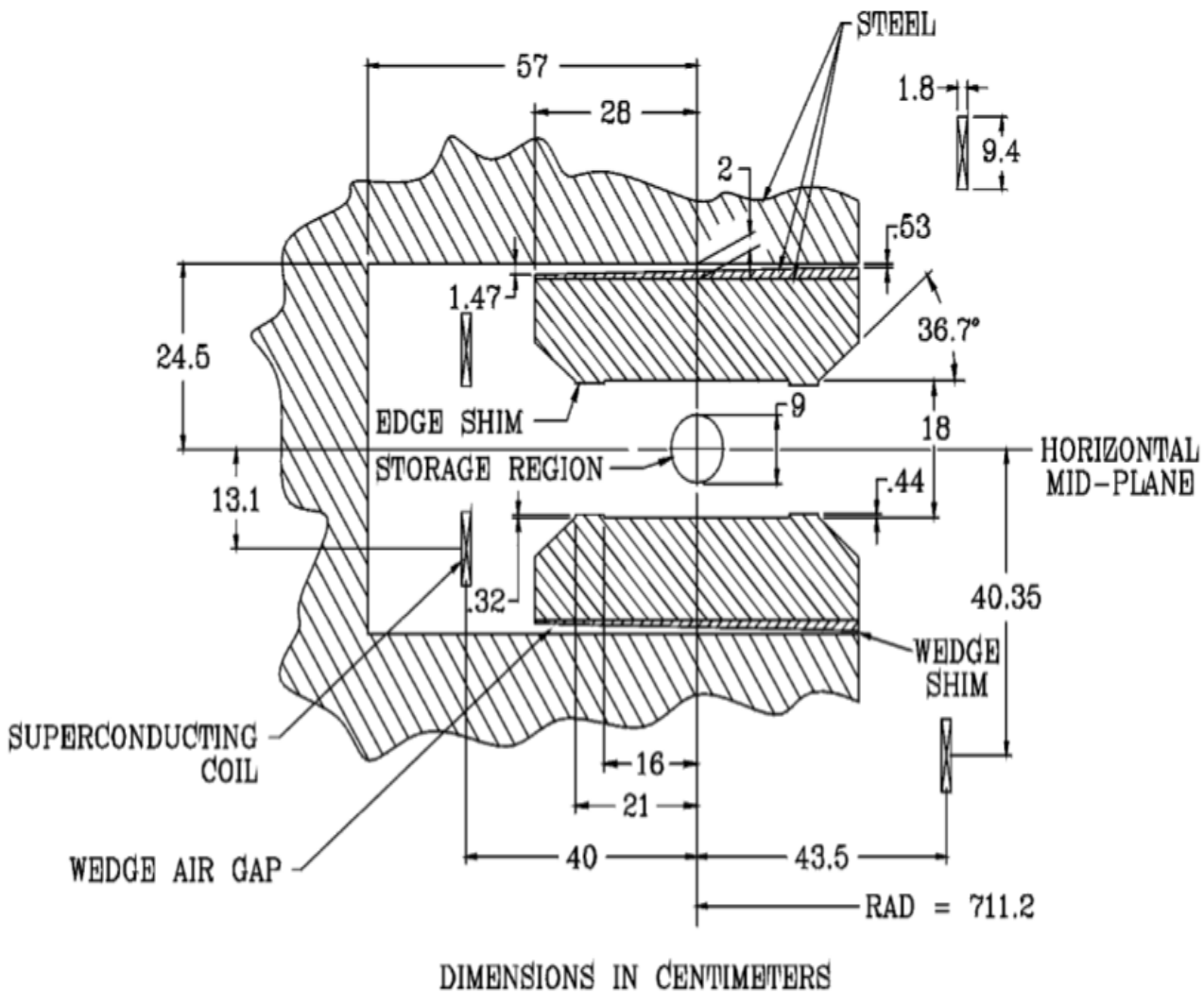
The BNL E821 1.45 Tesla Super Conducting Magnet

Built in 1993. Was the world's largest SC magnet. Has been surpassed by ATLAS and ITER.
SC technology was chosen for overall stability, low heat load, use of low voltage supplies.



3 50' diameter SC coils
Total of 5200 Amps x 96 turns

Achieving a Pure Vertical Dipole Field



Wedge Shims set the overall Dipole Center and Skew.

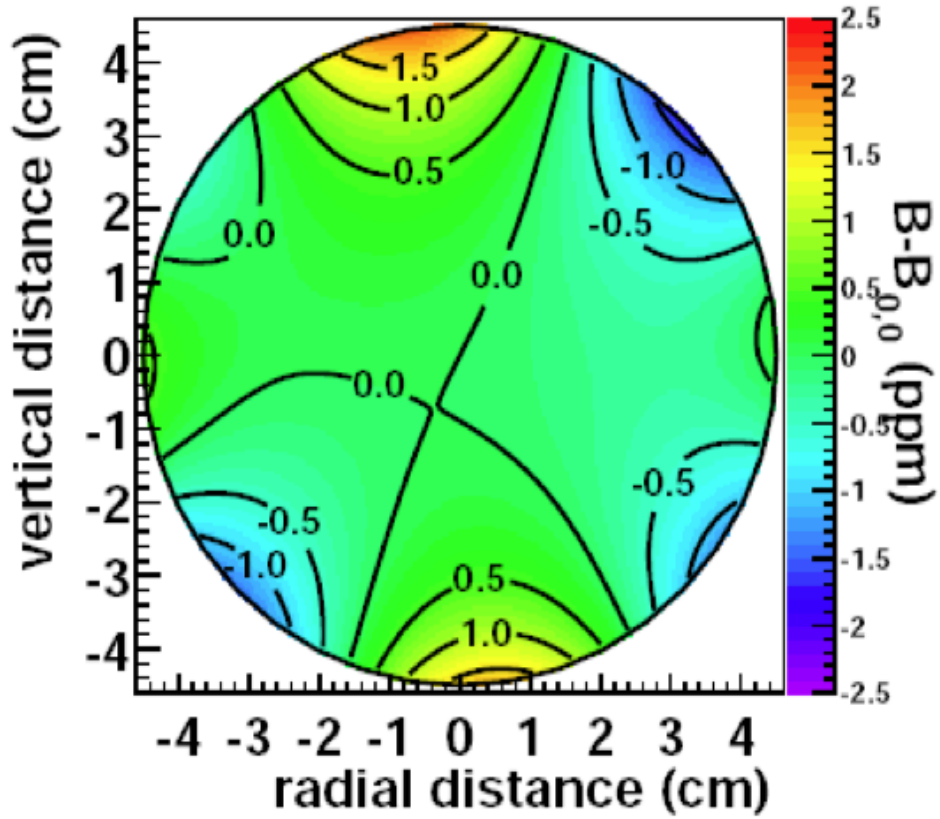
Edge Shims remove the unwanted Quadrupole and Sextupole components

Field Uniformity confirmed by Proton Larmor Frequency Measurements

0.5 ppm contours of ω_p (or B) averaged over azimuth

Multipoles [ppm]

	Normal	Skew
Quad	-0.28	0.11
Sext	-0.72	-0.45
Octu	0.09	0.01
Decu	1.04	0.38



Correction needed to account for presence of paramagnetic material, and atomic/nuclear effects.

Systematic Errors

σ_{syst} ω_p	1999 (ppm)	2000 (ppm)	2001 (ppm)	σ_{syst} ω_a	1999 (ppm)	2000 (ppm)	2001 (ppm)
Inflector fringe field	0.20	-	-	Pile-Up	0.13	0.13	0.08
Calib. of trolley probes	0.20	0.15	0.09	AGS background	0.10	0.01	‡
Tracking B with time	0.15	0.10	0.07	Lost muons	0.10	0.10	0.09
Measurement of B_0	0.10	0.10	0.05	Timing shifts	0.10	0.02	‡
μ-distribution	0.12	0.03	0.03	E-field/pitch	0.08	0.03	‡
Absolute calibration	0.05	0.05	0.05	Fitting/binning	0.07	0.06	‡
Others†	0.15	0.10	0.07	CBO	0.05	0.21	0.07
				Beam debunching	0.04	0.04	‡
				Gain changes	0.02	0.13	0.12
Total for ω_p	0.4	0.24	0.17	Total for ω_a	0.3	0.31	0.21

Total Systematic Error = 0.28 ppm Statistical Error = 0.46 ppm

E989: The New g-2 Initiative at Fermilab

Goal: Measure a_μ to 0.17 ppm

BNL E821 Event Sample
(used in final fit): 8.55×10^9 $e^\pm$

Increase Final Event Sample by 21x (1.8 x 10^{11} e^+)

AND DO IT AT A REASONABLE COST !!

How ?

Accelerator Upgrades and New Beam Line

Synergy with Other Fermilab Projects

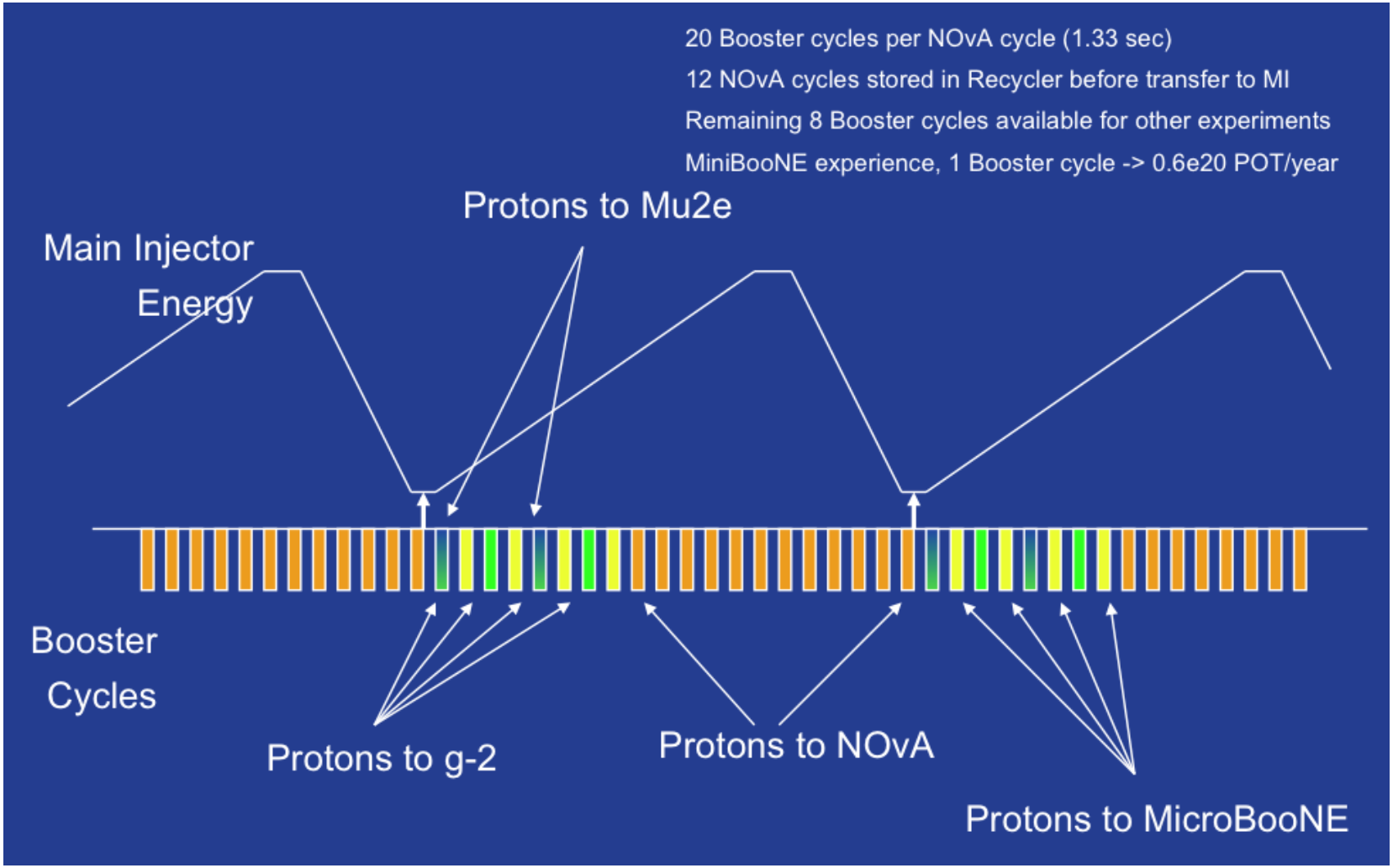
Improve the Storage Ring Beam Steering Components

New Detectors and DAQ

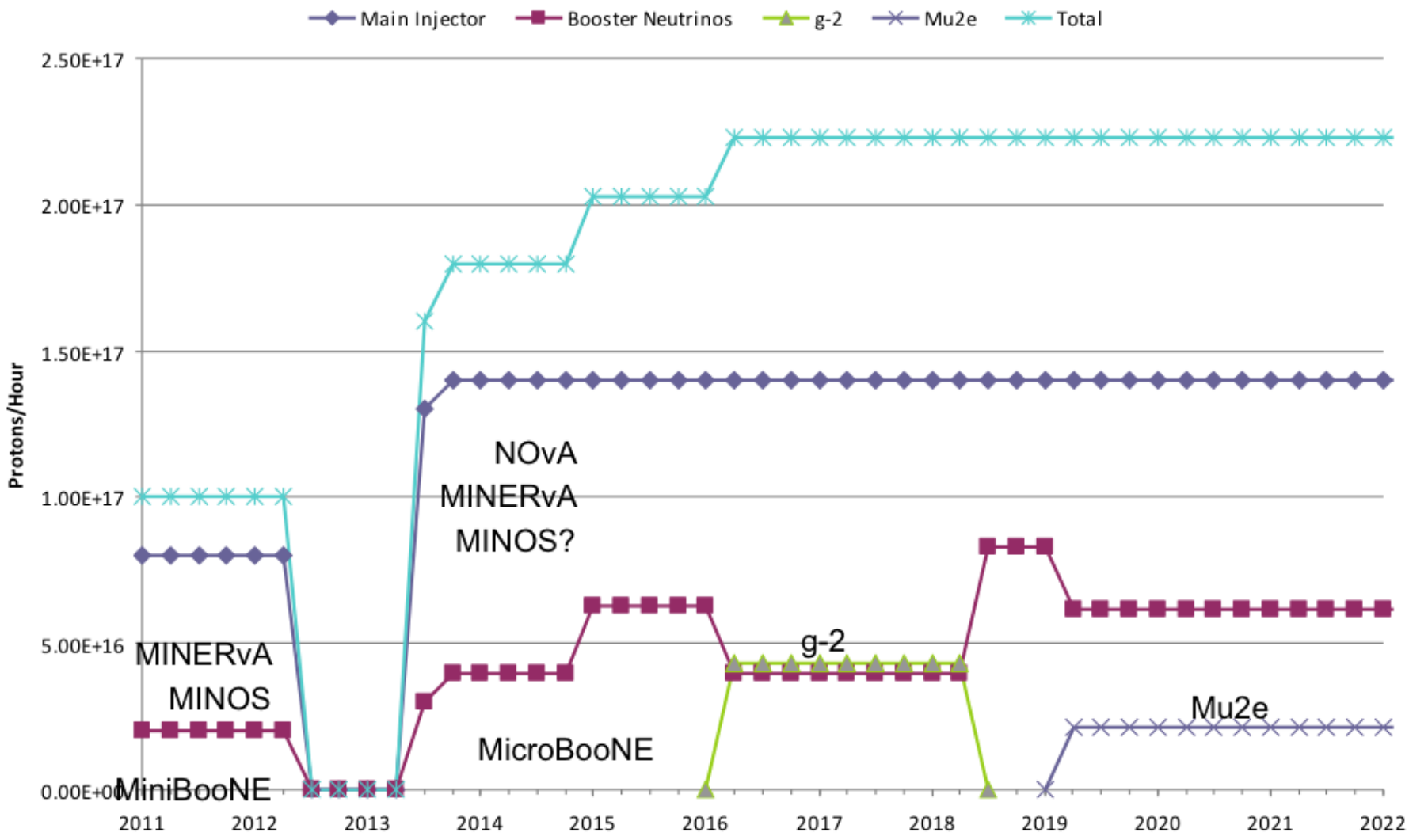
Reuse E821 Storage Ring and Tevatron Infrastructure

The Fermilab Proton Improvement Plan:

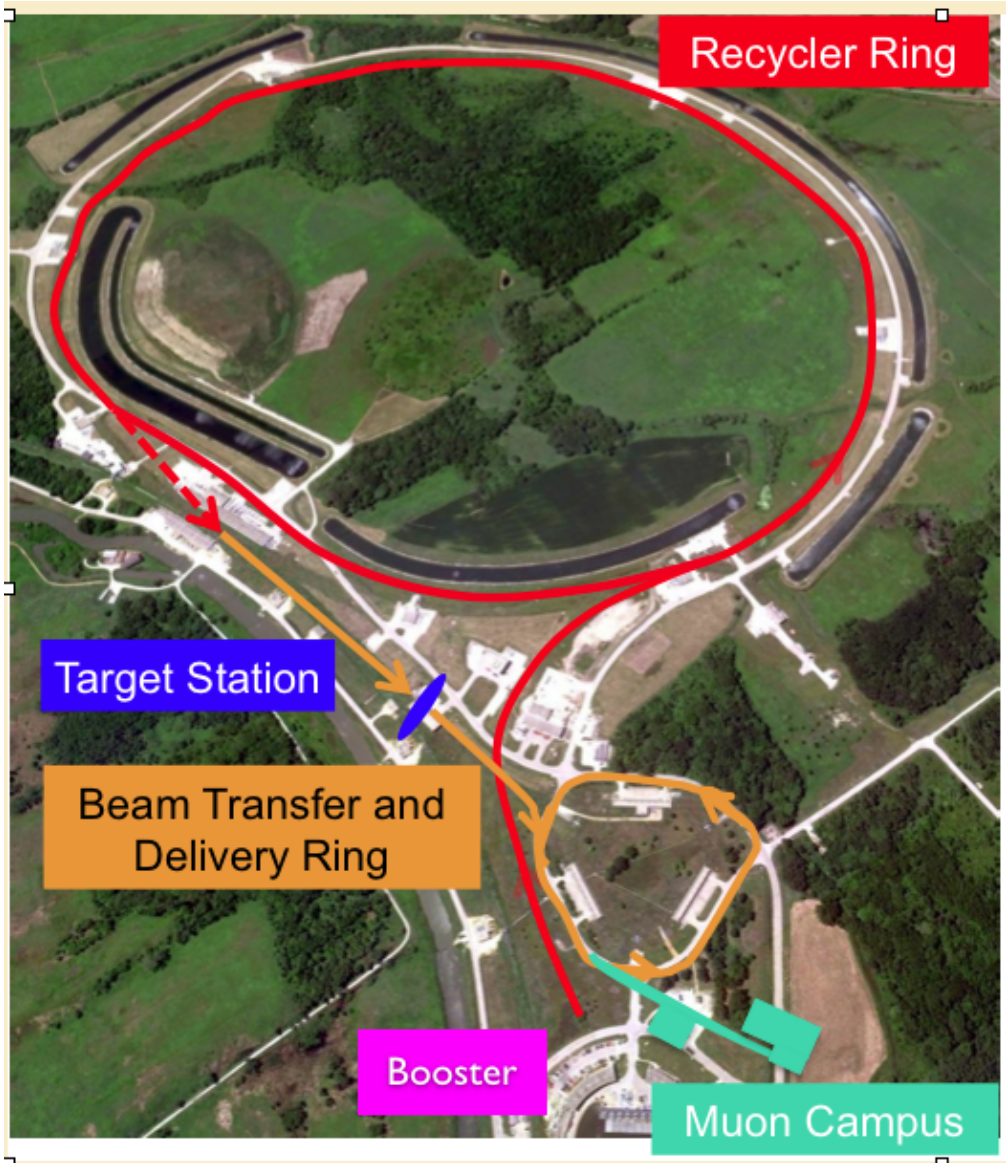
Increase Booster Rate to 15 Hz
Decrease Main Injector Cycle to Time to 1.33 sec



Sharing the Protons



Proton Delivery to G-2 Reduces the Instantaneous Rate and backgrounds



Recycler

Splits each Booster Batch into 4 smaller batches 8-12 msec apart, each 100 nsec wide. (reduces instantaneous rate)

Target Station

Reuse "Lithium Lens" that was used to make antiprotons

Longer pion decay channel

Old Antiproton Accumulator and Debuncher

Additional decay line
Time-of-flight separation of background protons.

Estimate of Required Protons-on-Target

Item	**Factor**	**Net**	**Note**
Booster cycle - 15 Hz operation	1.33 s/cycle	0.75 Hz	1
Batches to $(g-2)$	6	4.51 Hz	2
Protons on target	4×10^{12} p/batch	1.80×10^{13} p/s	3
Bunches (each bunch provides 1 fill of the ring)	4 /batch	18 fills/s	4
BNL stored muons per proton	1×10^{-9} μ/p	1000 μ/Tp	5
Minimum stored μ/p improvement FNAL *vs.* BNL	6.0	6000 μ/Tp	6
Positrons with $t > 30$ μs and $E > 1.8$ GeV	10 %	603 e^+/fill	7
DAQ / Expt. production and uptime	66 %		8
Time to collect 1.8×10^{11} events (2×10^7s/y)		1.25 years	9
Commissioning time		0.1 years	10
FNAL running years		1.35 years	11
Total Protons on Target		4×10^{20} **POT**	12

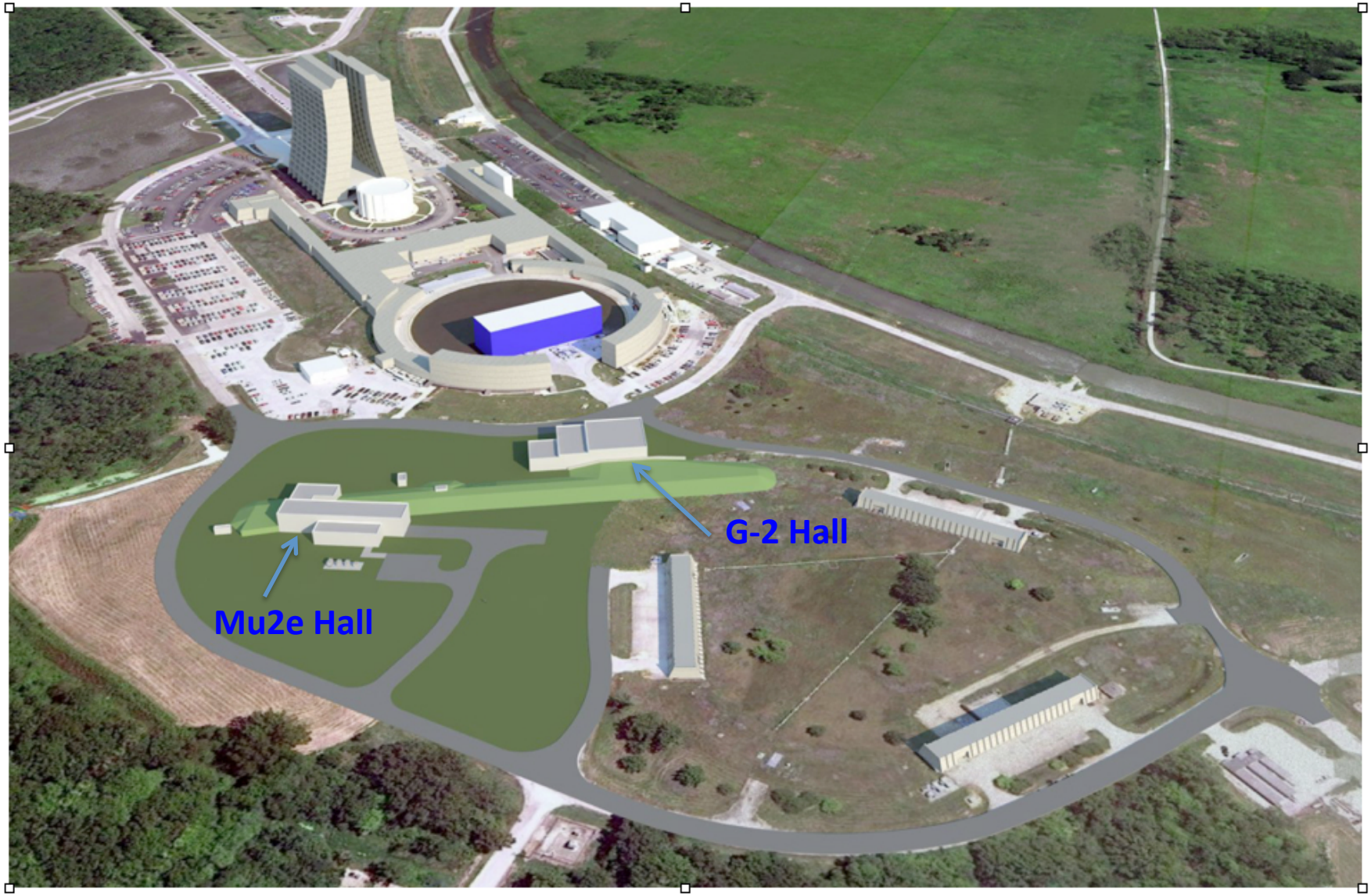
Improve Muon Yield Per Proton

Factor 11.5 expected.

Need factor 6.

parameter	BNL	FNAL	gain factor FNAL/BNL
Y_π pion/p into channel acceptance	$\approx$ 2.7E-5	$\approx$ 1.1E-5	0.4
L decay channel length	88 m	900 m	2
decay angle in lab system	3.8 $\pm$ 0.5 mr	forward	3
$\delta p_\pi / p_\pi$ pion momentum band	$\pm$0.5%	$\pm$2%	1.33
FODO lattice spacing	6.2 m	3.25 m	1.8
inflector	closed end	open end	2
total			11.5

The New Fermilab Muon Campus

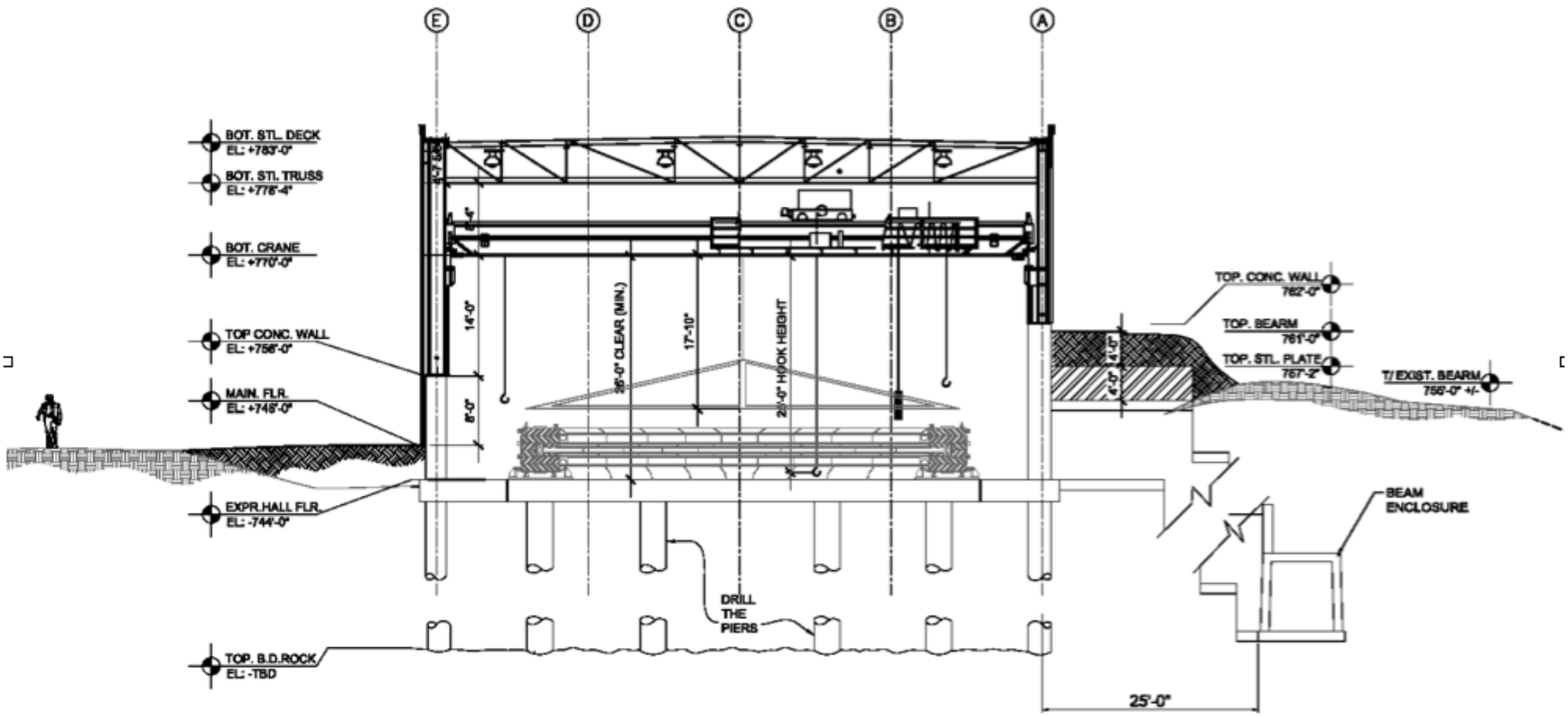


The New G-2 Building (MC 1)

Improvement over BNL:

HVAC Temperature Control
80’ x 80’ High Bay

May need magnetic shielding from Booster (time-varying field)
Evaluation underway



Improving ω_a

E821 Error	Size [ppm]	Plan for the New $g-2$ Experiment	Goal [ppm]
Gain changes	0.12	Better laser calibration and low-energy threshold	0.02
Lost muons	0.09	Long beamline eliminates non-standard muons	0.02
Pileup	0.08	Low-energy samples recorded; calorimeter segmentation	0.04
CBO	0.07	New scraping scheme; damping scheme implemented	0.04
E and pitch	0.05	Improved measurement with traceback	0.03
Total	0.18	Quadrature sum	0.07

+ No hadronic flash, better laser calibration

+ New hodoscopes, tracking, open inflector, scraping

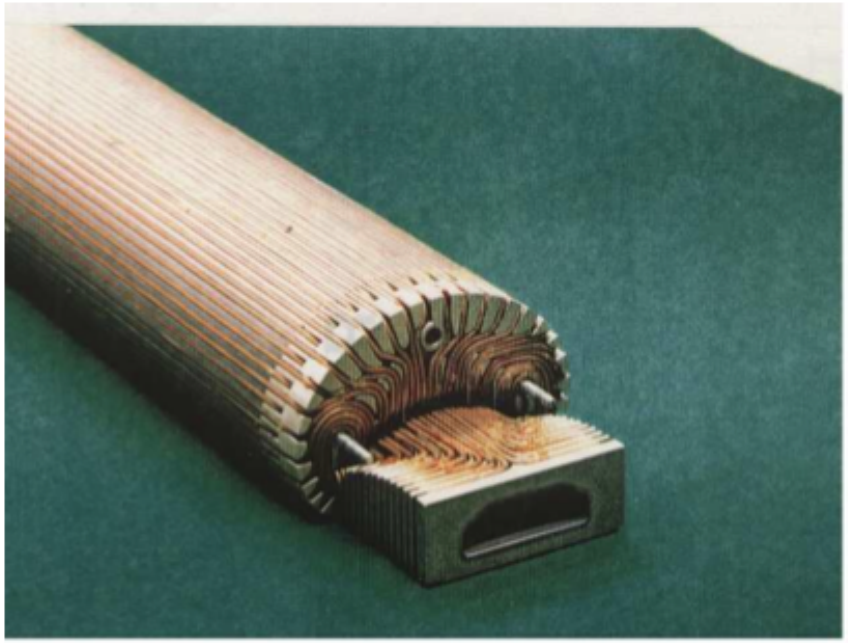
+ Segmented calorimeters

+ Improved kickers

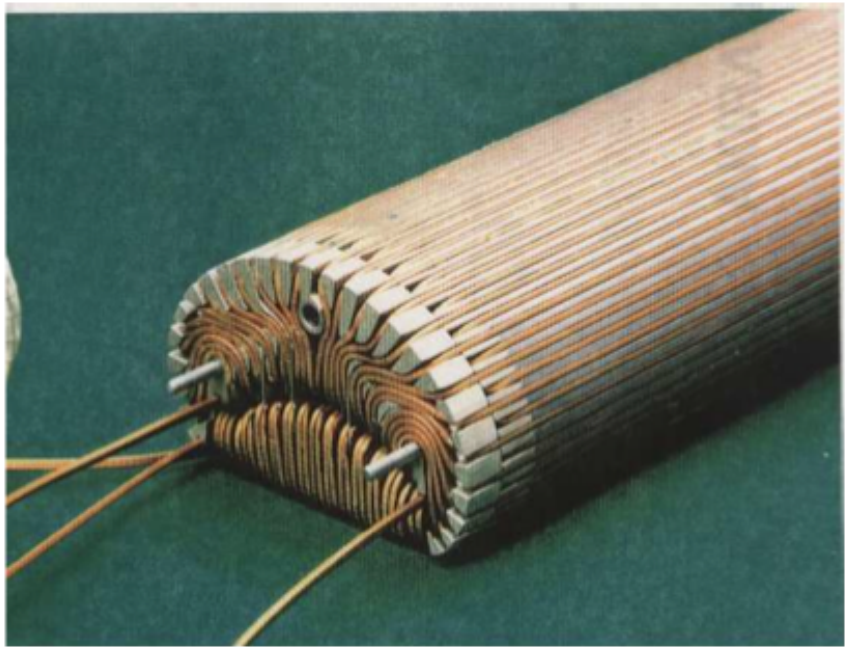
New Open Ended Inflector

Inflector: Used to cancel Main Storage Ring Field at the Muon Injection Location

Open Ended Inflector



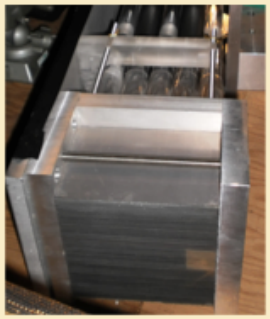
Close Ended Inflector



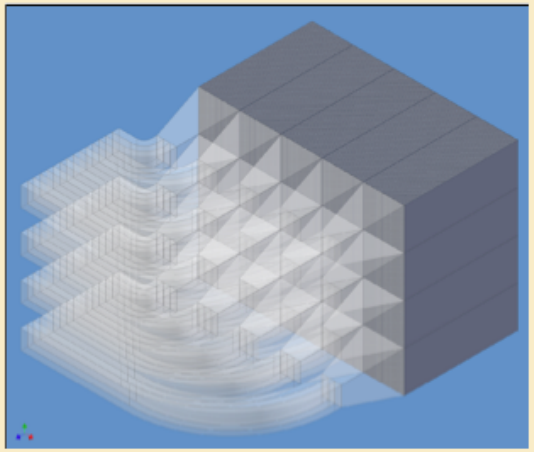
Beautiful and Subtle SC coil winding technology from KEK

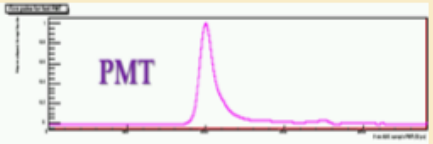
Segmented calorimeters

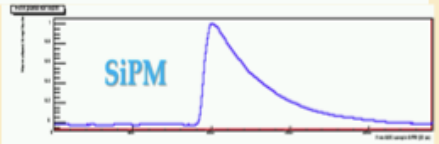
For reduced pileup



W/SciFi or PbF_2 Cherenkov?

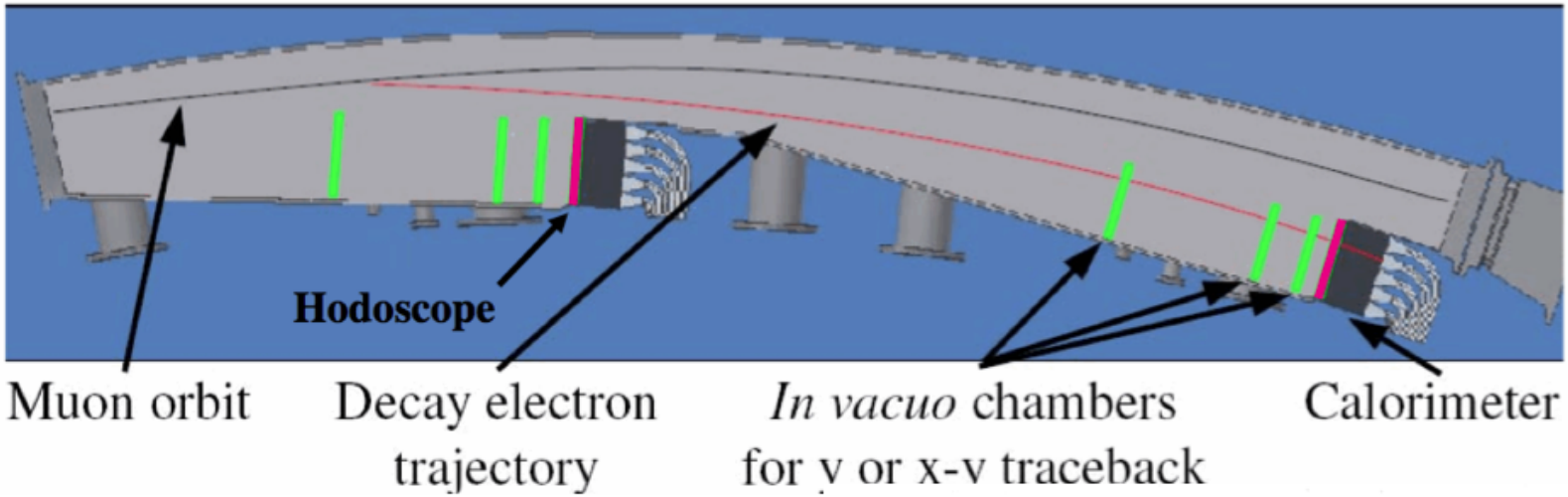


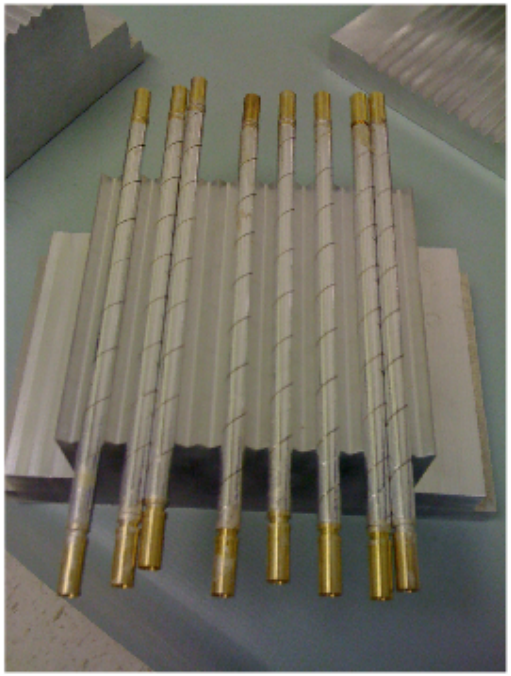




Ultra-fast PMTs or SiPM's?

Trace-Back Chambers to Measure Muon Trajectory





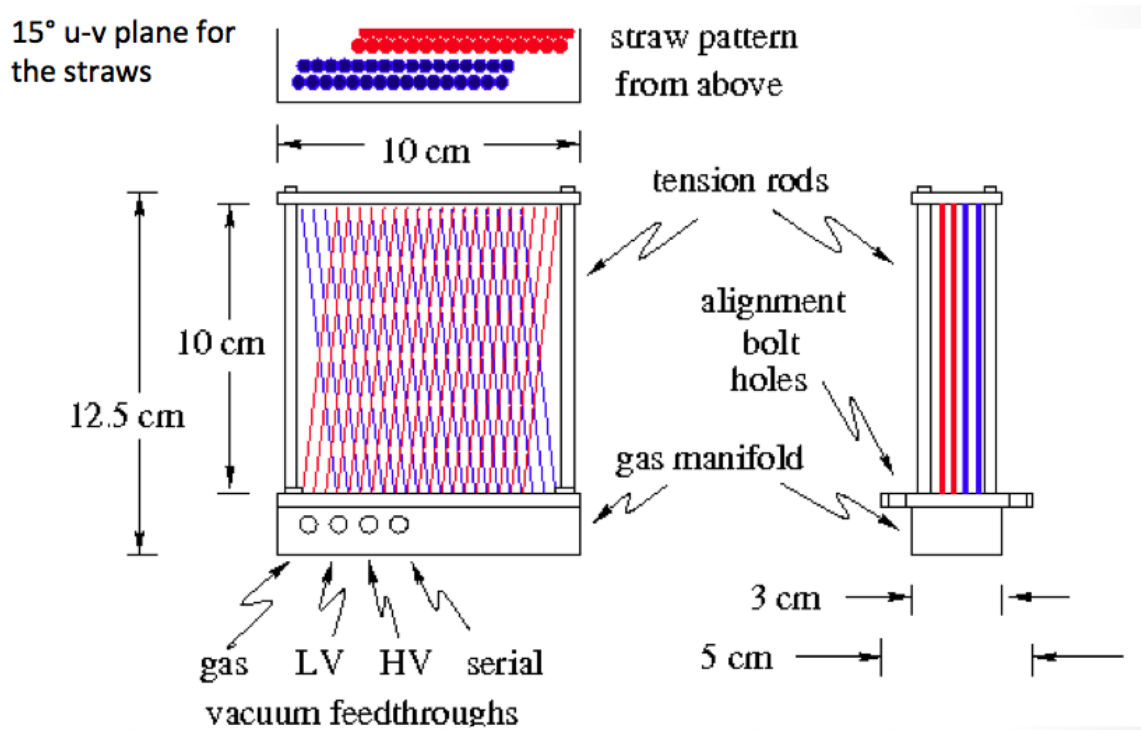
Straws Drift Chambers in Vacuum

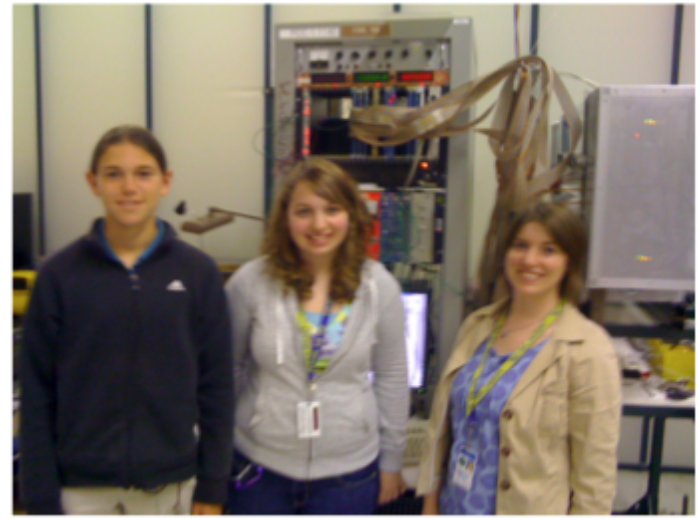
Optimize Multiple Scattering and and High Rate Performance

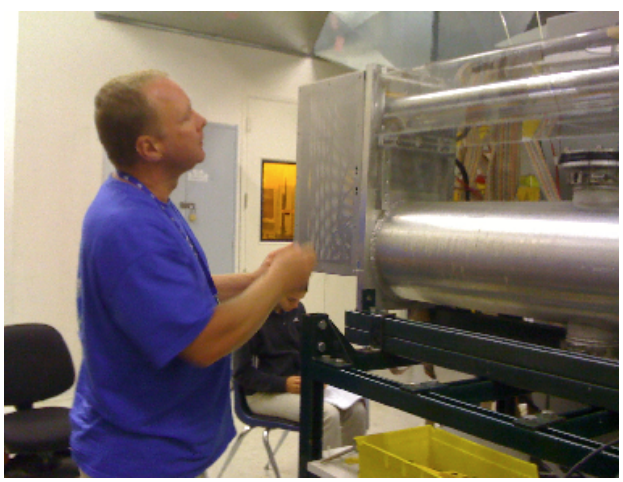
15 µm straw wall (kapton or mylar)

Also Adopted by:

NA62 (New CERN K^+ experiment)
Mu2e







2d Tracking allows sensitivity to S_μ precessing *out-of-plane of orbit*

Sensitive to Muon Electric Dipole down to $d_\mu < 10^{-20}$ e-cm

Improving ω_p

Source of errors	Size [ppm]				
	1998	1999	2000	2001	future
Absolute calibration of standard probe	0.05	0.05	0.05	0.05	0.05
Calibration of trolley probe	0.3	0.20	0.15	0.09	0.06
Trolley measurements of B_0	0.1	0.10	0.10	0.05	0.02
Interpolation with fixed probes	0.3	0.15	0.10	0.07	0.06
Inflector fringe field	0.2	0.20	-	-	-
Uncertainty from muon distribution	0.1	0.12	0.03	0.03	0.02
Others		0.15	0.10	0.10	0.05
Total systematic error on ω_p	0.5	0.4	0.24	0.17	0.11

To get to 0.07 ppm, more probes, mapping, shimming, temp control

The Ultimate Recycling Project

Make excellent use of existing Tevatron infrastructure

Beam line from BNL

- g-2 ring
- g-2 beamline
- Debuncher Ring
- Magnets, pumps, stands and other Accumulator Ring components
- AP transfer lines
- AP-0 Target Station
- AP-2 beamline magnets
- Main Injector RF ferrites
- Tevatron satellite refrigerators
- Tevatron N_2 and He storage tanks
- Tevatron cryo line
- Tevatron High Temperature Superconducting leads
- Tevatron vacuum equipment
- Tevatron loss monitors
- Tevatron BPM electronics
- Tevatron electronics crates
- Tevatron control cards
- Tevatron damper system
- Misc. Tevatron Instrumentation
- Shielding steel
- Transformers

Reuse the E821 Storage Ring

> $20M investment

Major Difficulty

3 Large 50’ Diameter Coils inside cryostats

Can Separate 3 coils from one another

But cannot disassemble each coil into shorter sections (would spoil the field uniformity) !

SC Ring Cryostat Transport

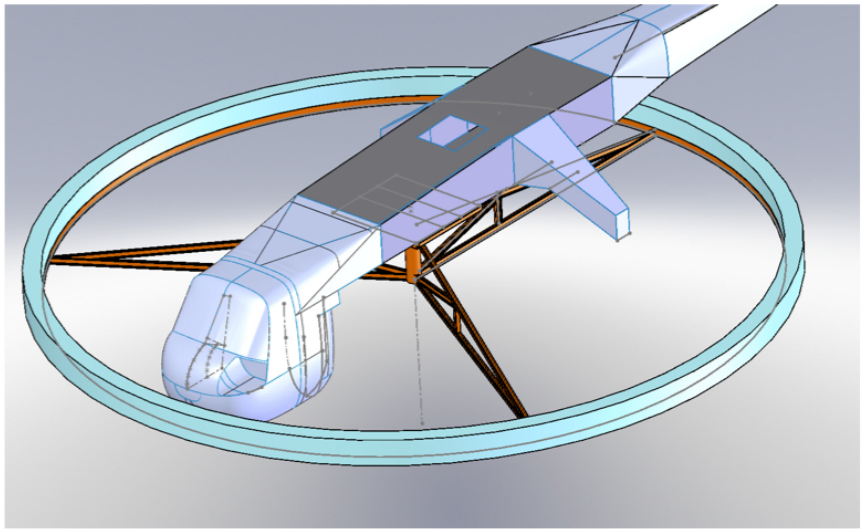
Most of the transportation will be done via barge. Must be ready to move by Summer 2013.

Transport from BNL to shipping port, from shipping port to Fermilab: either air or ground

Issued Request for Vendor Bids to Perform Technical Feasibility Study and Cost Estimate

Expect at least 3 vendors to bid

Courtesy of Erickson Skycrane



Main Helicopter Difficulty:

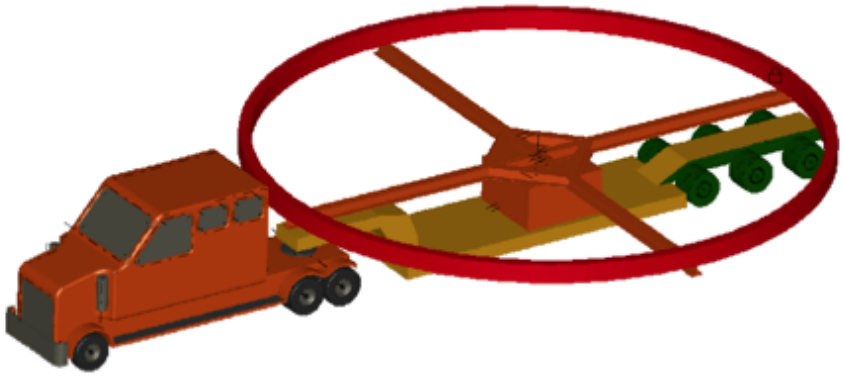
Heaviest Ring weighs 17K lbs.
Helicopter Load Limit is 25K lbs.
FAA restrictions

Main Truck Difficulty:

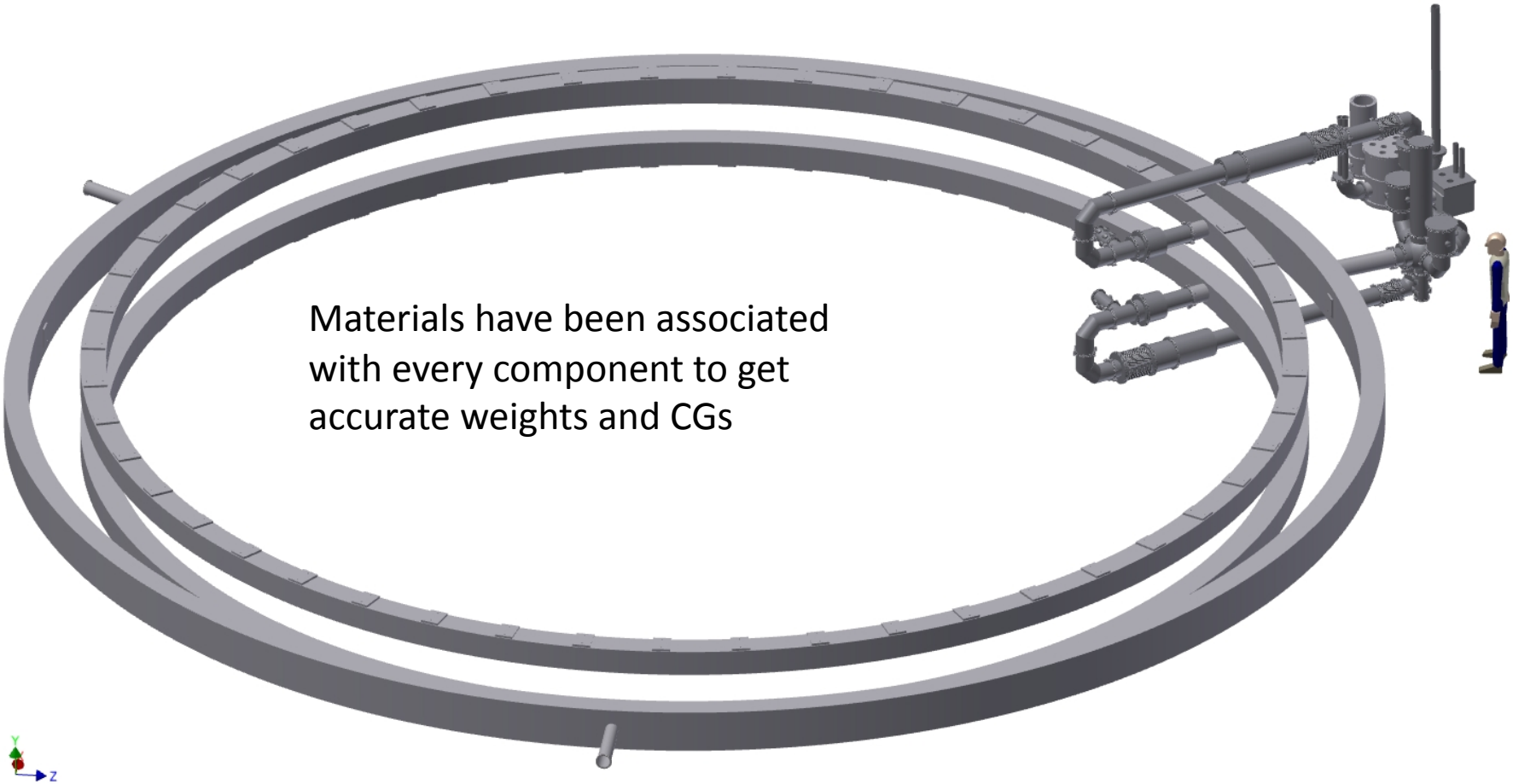
Need 4 lane roads or any road without side obstructions.

Can remove or crane over obstructions, but will cost.

Vendor Selection in Early May !

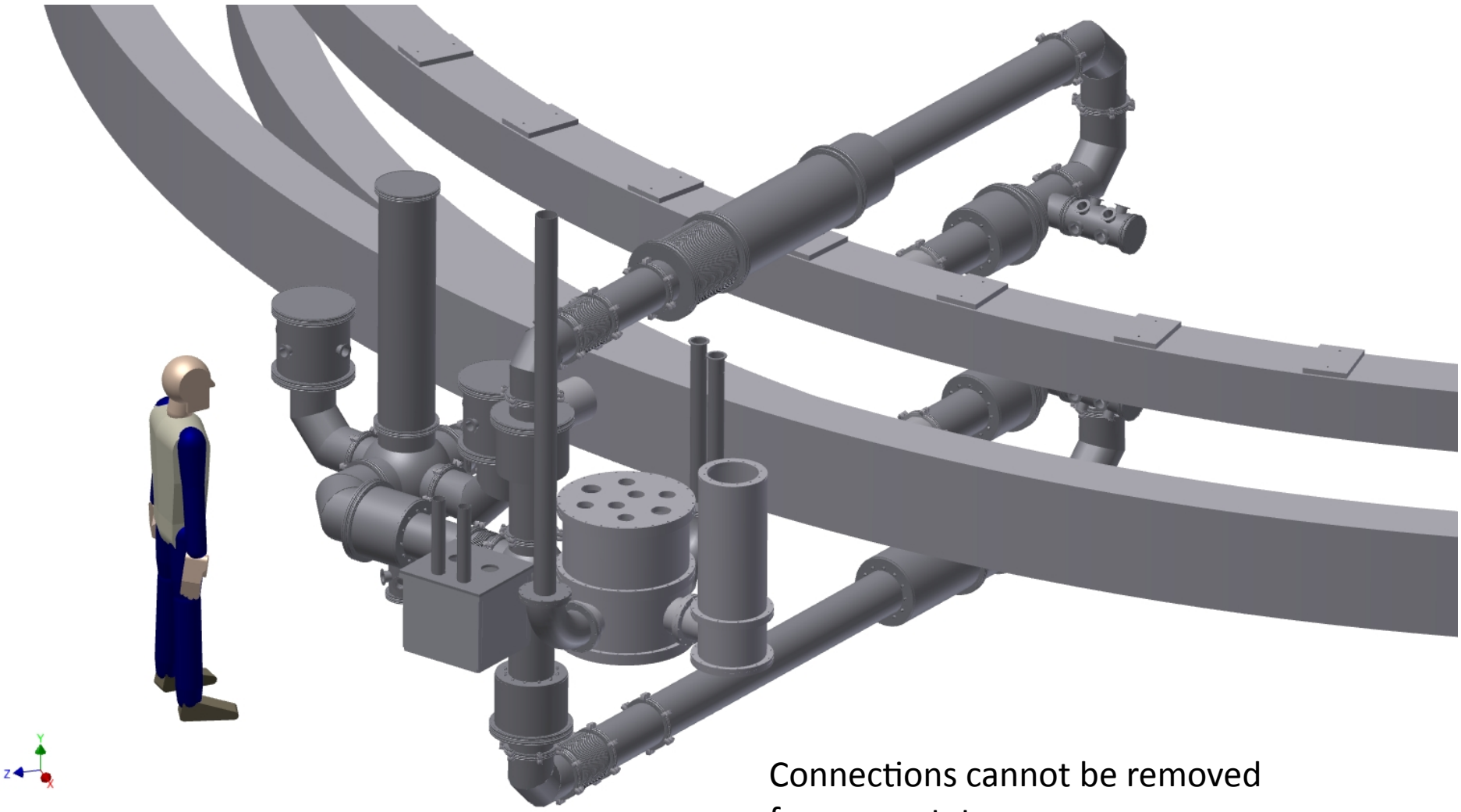


Ring 3D Modeling from Bartosek Engineering



Transportation Vendors will use 3D Model to design shipping fixture

Cryogenics and LV Power Connections to the 3 coils



Connections cannot be removed from cryostats.

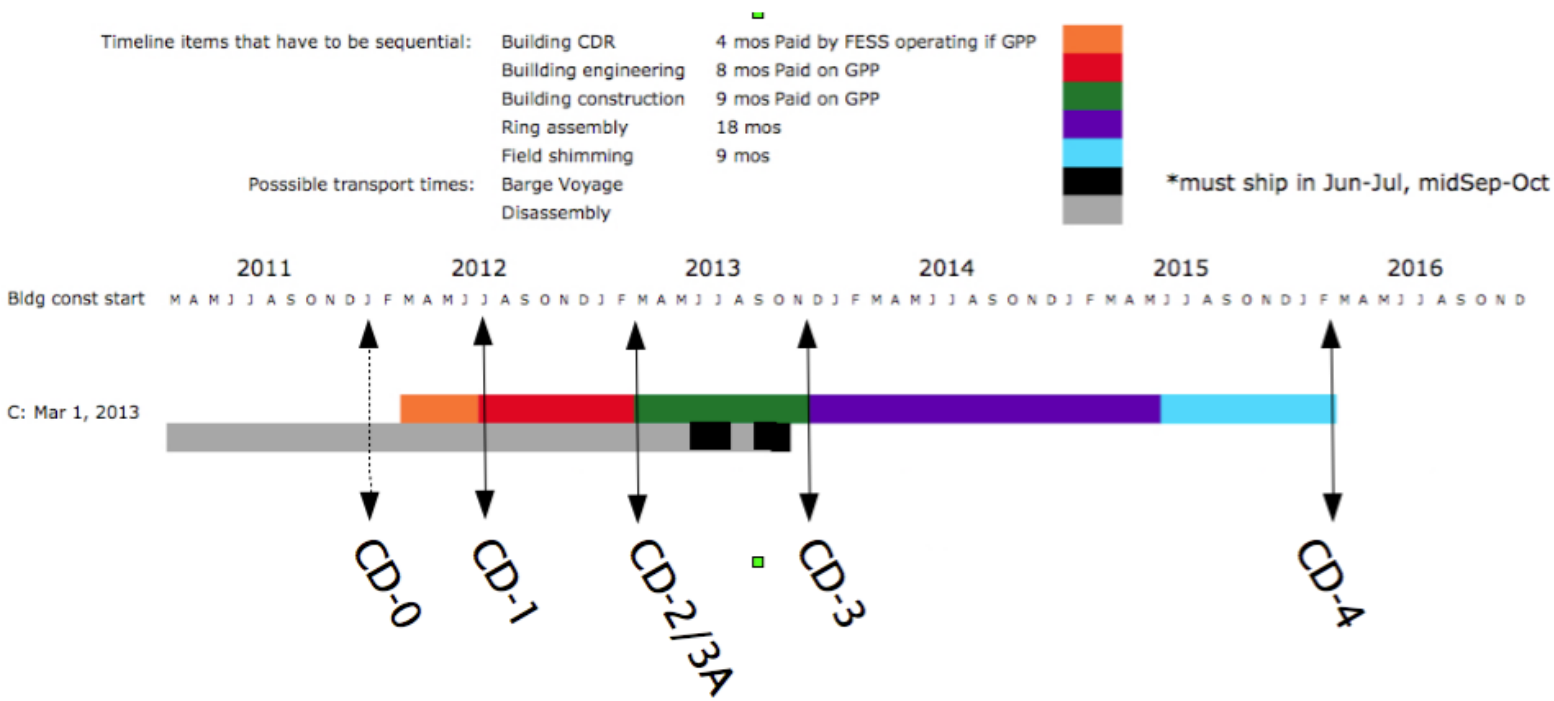
BNL E821 Equipment Move Has Started !

Summer 2011

Early April 2012

Next trip in Mid May: Remove the Magnet Iron !

Summary

- A very exciting time for E989

- Muon Physics ... A New era at Fermilab !