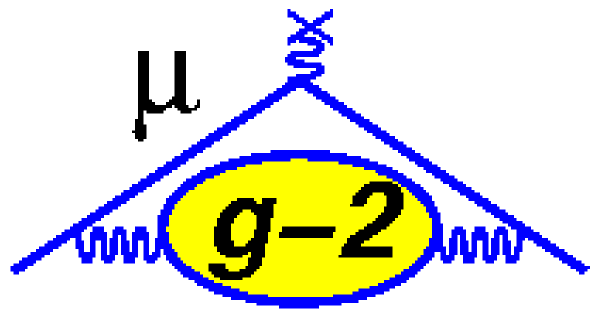
The New Muon g-2 Experiment at Fermilab

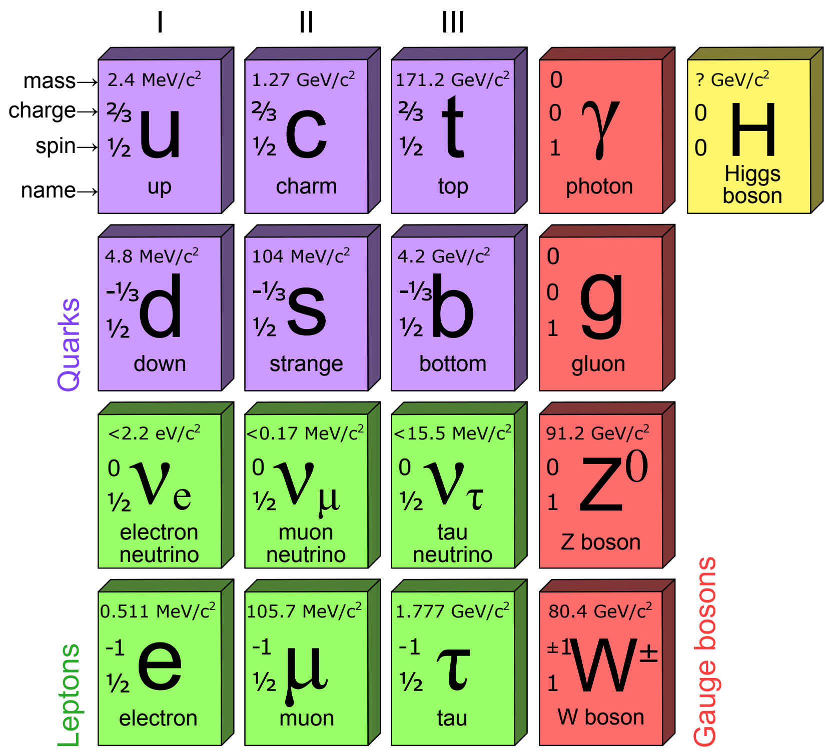
Dave Kawall, University of Massachusetts Amherst



Goal : Measure the muon anomalous magnetic moment, a_μ, to 0.14 ppm, a fourfold improvement over the 0.54 ppm precision of Brookhaven E821

The Standard Model of Particle Physics : 2013

- What is the world made of? Standard Model includes $\approx$ 200 particles
- These particles all formed from elementary building blocks

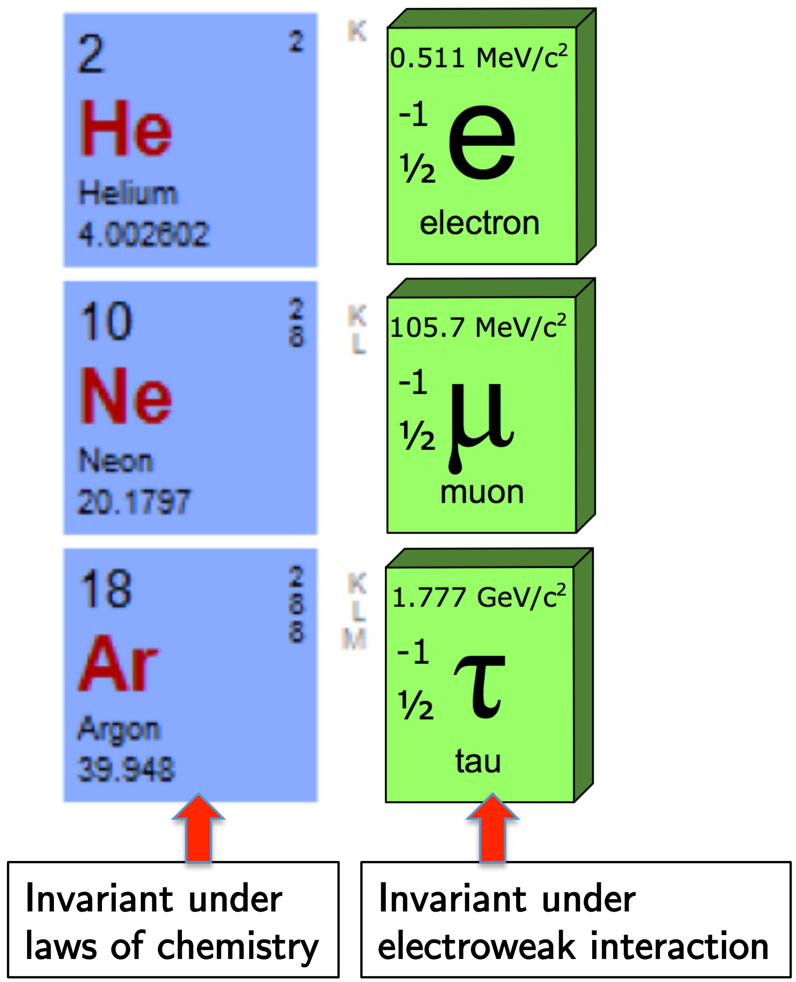


Wikipedia

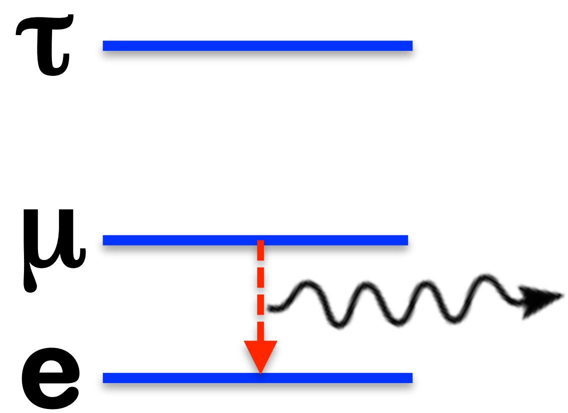
- Three generations of spin $^1\!/_2$ fermions, four spin 1 gauge bosons

- Higgs boson discovered, completes Standard Model : spin 0^+, March 2013
- All visible matter is made up of the first generation of matter particles
- No idea why there are three generations
- Anti-matter equivalents too
- Periodic table spans range of $\approx$ 240 in mass
- Elementary particle masses span sub-eV to 171 GeV, range of 10^{11}
- Particle masses not understood

- Behavior of generations is similar despite large differences in mass
- Explained by symmetries deep in the structure of Standard Model



- Symmetries explain similarity - but not why there are 3 generations

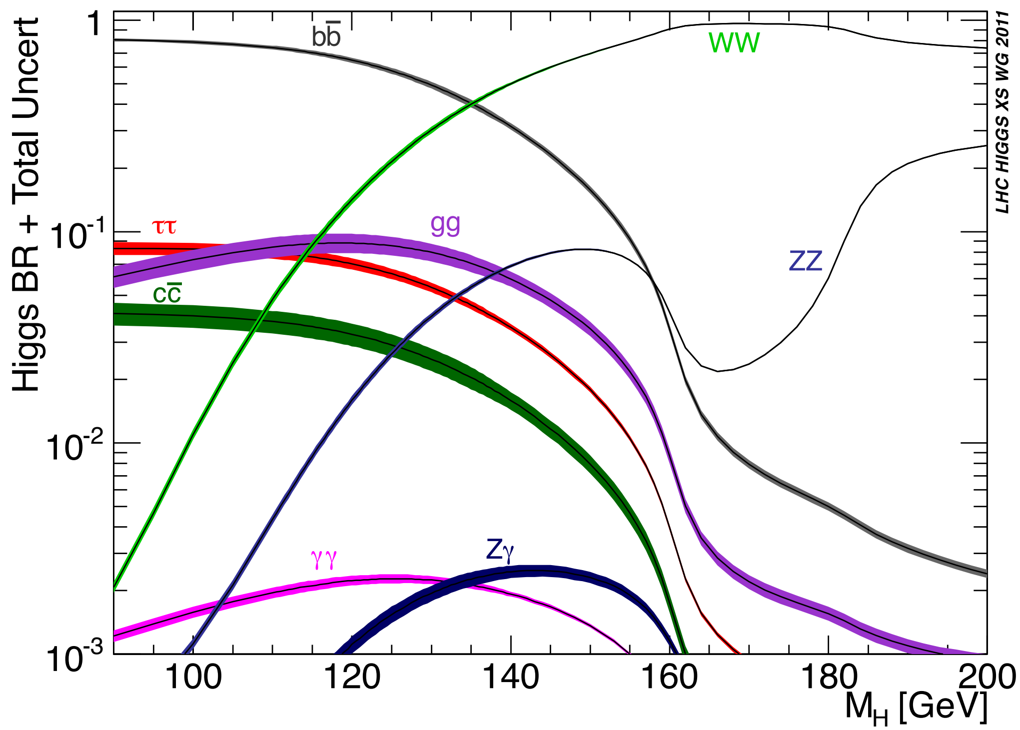


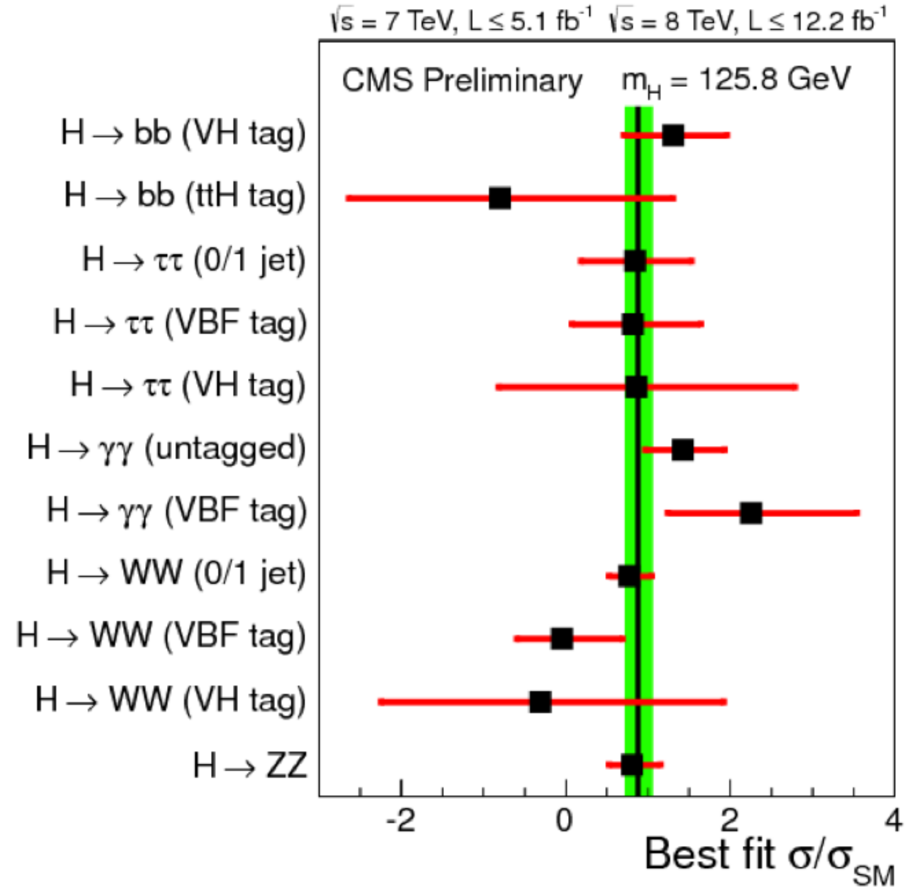
- Perhaps 2nd, 3rd generations are excited states of 1st?
- Branching ratio from MEG : $\mu \rightarrow e + \gamma \ < \ 5.7 \times 10^{-13}$ (90% CL)

The Standard Model of Particle Physics : 2013

- Standard Model : theory of EM, weak, and strong interactions of fundamental particles
- Makes precise predictions, describes experimental results : **incredibly successful**

- SM predictions of Higgs decay channels

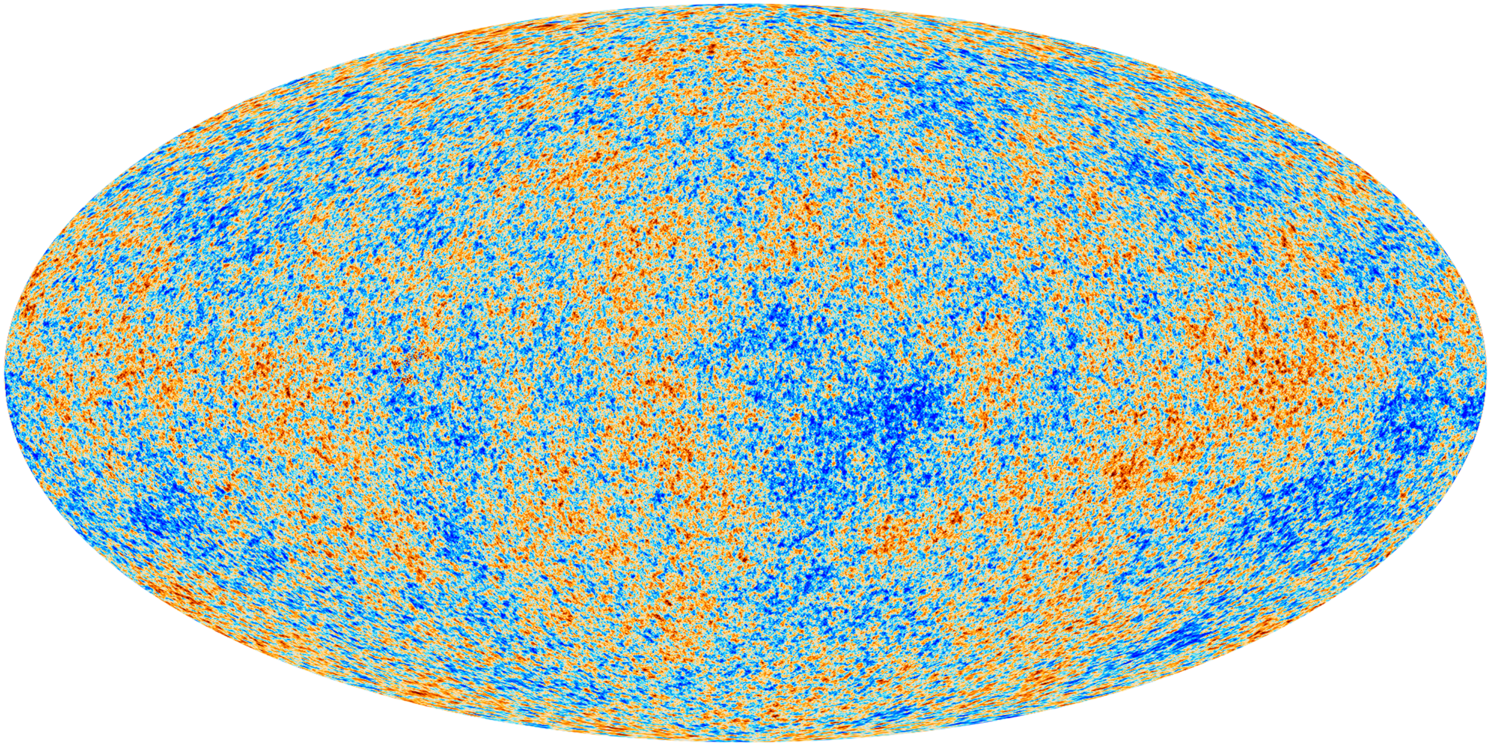




$\boldsymbol{\sigma/\sigma_{SM} = 0.88 \pm 0.21}$

(A. Whitbeck, QCD Moriond, Mar 14, 2013)

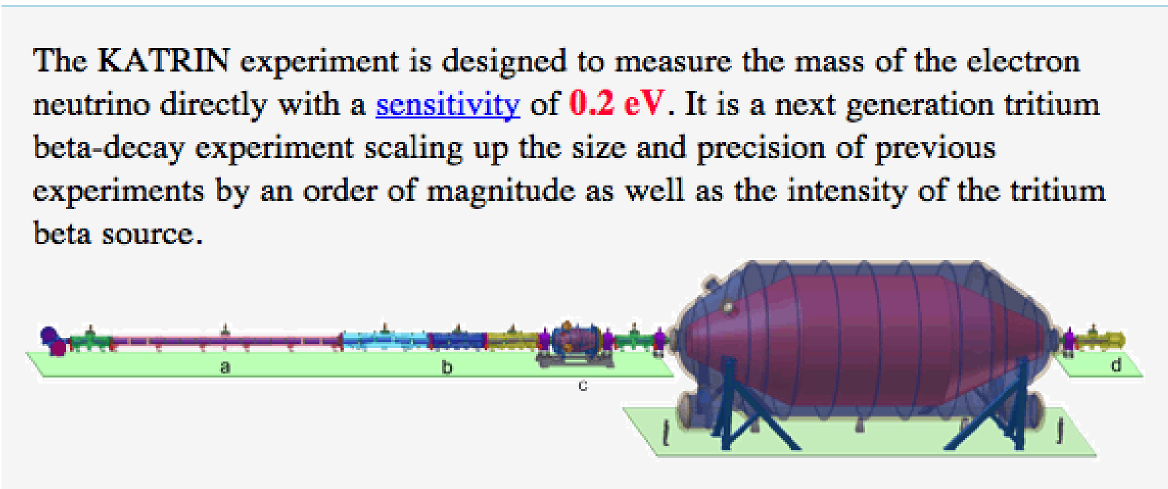
The Standard Model of Particle Physics : Not done yet



- Standard Model does not describe gravity
- Why 3 generations of fermions? Why more matter than antimatter?
- Hierarchy problems :
  - Why is weak force 10^{30+} times stronger than gravity?
  - Why Higgs so light; 126 GeV vs 10^{16}-10^{19} GeV ?
- Planck CMB : 4.9% Ordinary matter, 26.8% Dark Matter, 68.3% Dark Energy
  - What is Dark Matter? What is Dark Energy? We're only 5% done.

How do we solve these mysteries?

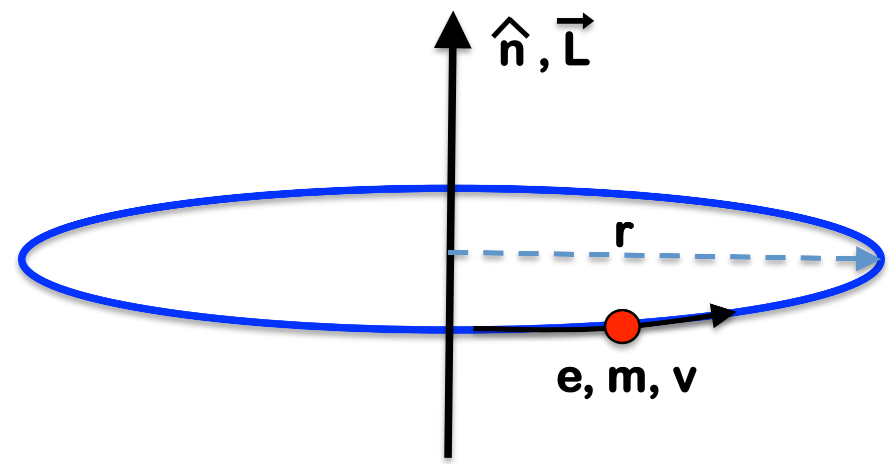
- Energy Frontier : Colliders SLC, LEP, Tevatron, DESY, LHC : directly produce particles of Standard Model - but can't provide all the answers
- Low energy tests important : neutrino oscillations, dark matter ...



- To fill in the gaps we need :
  - Intensity Frontier : look for new phenomena or ultra-rare processes that shouldn't happen in SM ($\mu N \rightarrow eN$, proton decay))
  - Fundamental Symmetries : look for violations of symmetries incompatible with Standard Model : EDMs, Local Lorentz Invariance, new sources CP-violation, ...
  - Precision Frontier : look for variation of constants, deviations from Standard Model predictions, ...

- Classically, magnetic dipole moment of current loop given by :

$$
\begin{aligned}
\vec{\boldsymbol{m}} &= \frac{IA}{c}\,\hat{\boldsymbol{n}} \\
&= \frac{1}{c}\,\frac{ev}{2\pi r}\,\pi r^2\,\hat{\boldsymbol{n}} \\
&= \frac{e}{2mc}\,mvr\,\hat{\boldsymbol{n}} \\
\vec{\boldsymbol{m}} &= \frac{e}{2mc}\,\vec{\boldsymbol{L}}, \quad \vec{\boldsymbol{m}} = g\frac{e}{2mc}\,\vec{\boldsymbol{S}},
\end{aligned}
$$



- Bohr Magneton : magnetic moment of an electron with 1 $\hbar$ of angular momentum :

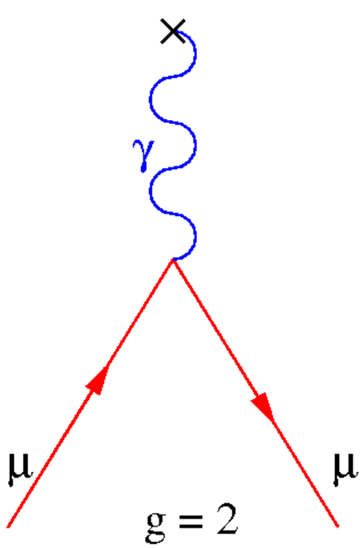
$$\mu_B = \frac{e\hbar}{2m_e c}, \quad g = 1$$

- But : spectroscopy indicated anomalous Zeeman transitions (involving electron spin in a magnetic field) $\Rightarrow$ required g=2 !
- Explained by relativistic treatment of quantum mechanics by Dirac in 1928 :
  $\Rightarrow$ predicted g=2 for fundamental spin 1/2 particle, huge success!
- 1933 Otto Stern measured proton μ_p : required g=5.6 !
- Later recognized as first indication of proton substructure. g factors have been important

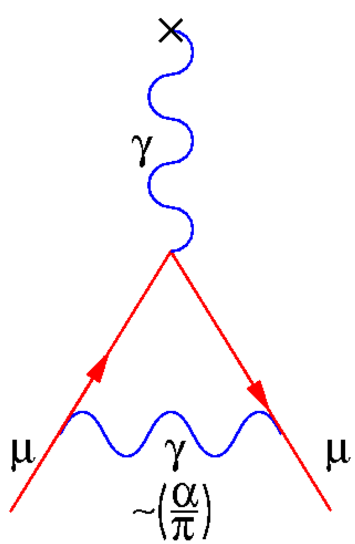
- Recall magnetic moment interaction $H_{\text{Zeeman}} = -\boldsymbol{\mu}\cdot\boldsymbol{B}$

$$\boldsymbol{\mu} = -\, g\, \frac{e}{2mc}\,\boldsymbol{S}, \qquad \boldsymbol{S} = \frac{\hbar}{2}\,\boldsymbol{\sigma} \text{ from quantum mechanics}$$

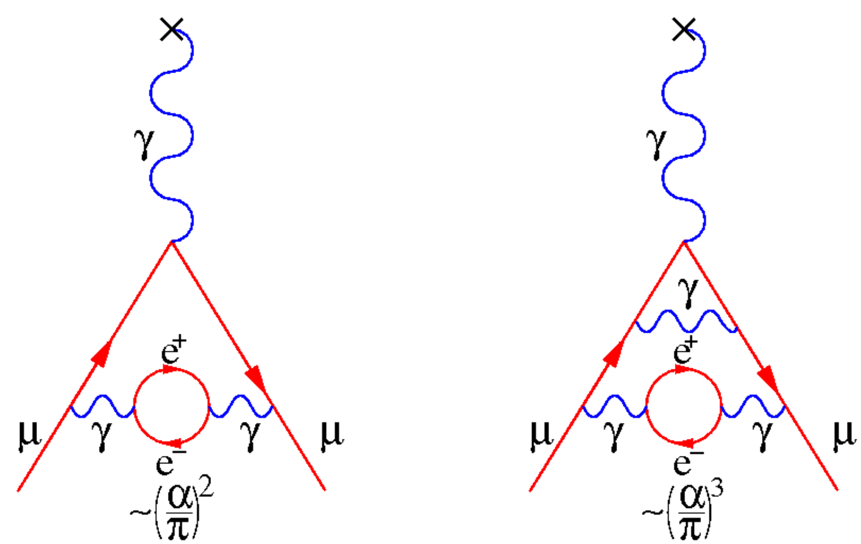
- Dimensionless g-factor can be predicted from theory
- 1947 : 0.1% discrepancies in spectroscopy. G. Breit suggests $g_e = 2+\epsilon$
- 1948 : Measurements of Kusch and Foley found g_e deviates from 2
- 1948 : Schwinger QED calculation of *anomalous* part of g_e factor, a_e where $g_e \equiv 2(1+a_e)$



Dirac



Schwinger



Kinoshita and others

- $a_e = \alpha/2\pi \approx 0.00116$ due to *radiative corrections* from virtual particles in loops
- 1 part in 850 effect, huge success for QED !

The Anomalous Magnetic Moment of the Electron

PRL **100,** 120801 (2008) PHYSICAL REVIEW LETTERS week ending 28 MARCH 2008

New Measurement of the Electron Magnetic Moment and the Fine Structure Constant

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(Received 4 January 2008; published 26 March 2008)

A measurement using a one-electron quantum cyclotron gives the electron magnetic moment in Bohr magnetons, $g/2 = 1.001\,159\,652\,180\,73\,(28)$ [0.28 ppt], with an uncertainty 2.7 and 15 times smaller than for previous measurements in 2006 and 1987. The electron is used as a magnetometer to allow line shape statistics to accumulate, and its spontaneous emission rate determines the correction for its interaction with a cylindrical trap cavity. The new measurement and QED theory determine the fine structure constant, with $\alpha^{-1} = 137.035\,999\,084\,(51)$ [0.37 ppb], and an uncertainty 20 times smaller than for any independent determination of α.

- g_e most precisely known quantity in physics, to 0.28 ppt

PRL **100,** 120801 (2008) PHYSICAL RE

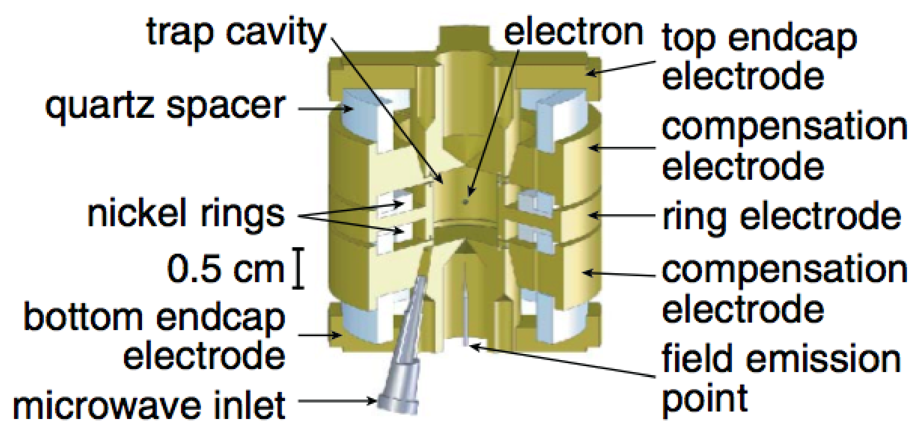


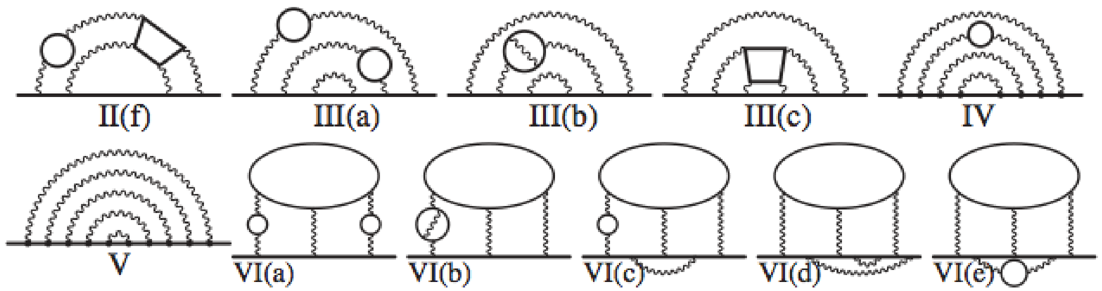
FIG. 2 (color). Cylindrical Penning trap cavity used to confine a single electron and inhibit spontaneous emission.

- Penning trap for single electron
- Magnetic confinement in radial
- Electrodes for vertical confinement
- Trapped for months
- $a_e = (g_e - 2)/2$ determined to 0.24 ppb

Theory of the Anomalous Magnetic Moment of the Electron

$$\frac{g_e}{2} = 1 + C_2\left(\frac{\alpha}{\pi}\right) + C_4\left(\frac{\alpha}{\pi}\right)^2 + ... + C_{10}\left(\frac{\alpha}{\pi}\right)^5 + ... + a_{\mu,\tau} + a_{\text{hadonic}} + a_{\text{weak}}$$

- T. Kinoshita 9 years for QED calculation of 12672 Feynman diagrams for $C_{10}(\alpha/\pi)^5$, T. Aoyama *et al.*, Phys. Rev. Lett. **109**, 111807 (2012).



- Extract α, compare with other measurements, confirms QED at ppt level

$\Rightarrow$ $a_e = (g_e - 2)/2$ determined to 0.24 ppb

- Muons live 2.2 μseconds - why bother measuring a_μ ?
- Sensitivity to new physics : $\Delta a_{e,\mu}(\text{New Physics}) \approx C\left(\frac{m_{e,\mu}}{\Lambda}\right)^2$

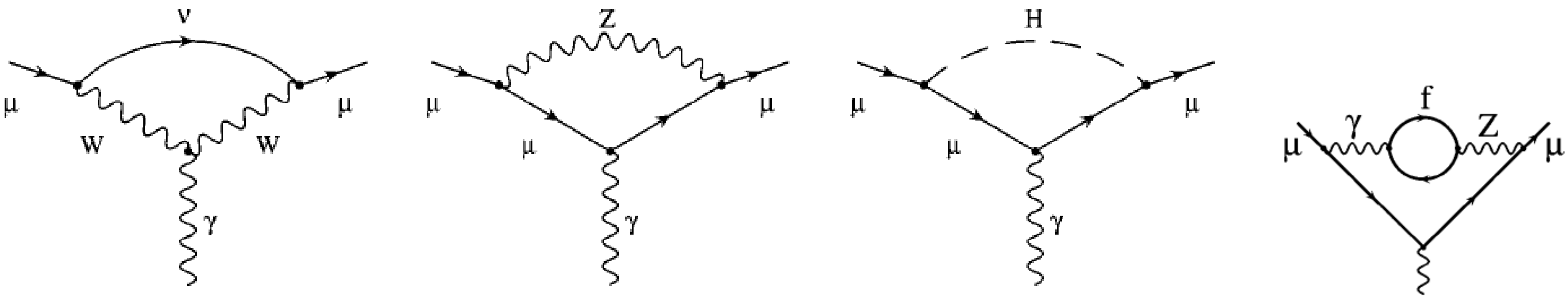
$\Rightarrow$ Muon mass 206 times electron mass, so new physics contribution 40,000 times larger

$\Rightarrow$ New physics contribution of 0.24 ppb on a_e corresponds roughly to 9 ppm on a_μ

- a_μ known from Brookhaven E821 to 0.54 ppm, hope to push at Fermilab to 0.14 ppm

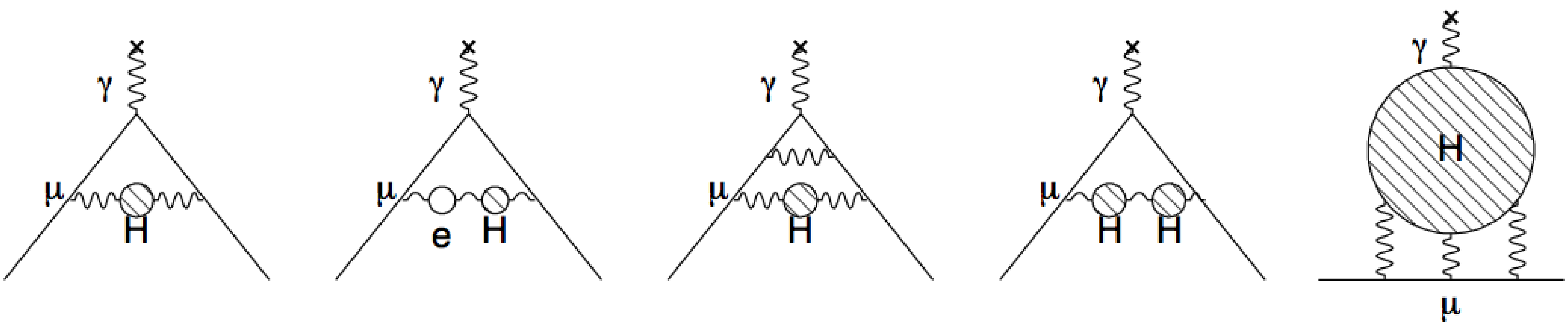
Contributions to the Anomalous Magnetic Moment of the Muon

$$a_\mu(\text{Standard Model}) = a_\mu(\text{QED}) + a_\mu(\text{Weak}) + a_\mu(\text{Hadronic})$$



EW 1 Loop

EW 2 Loop



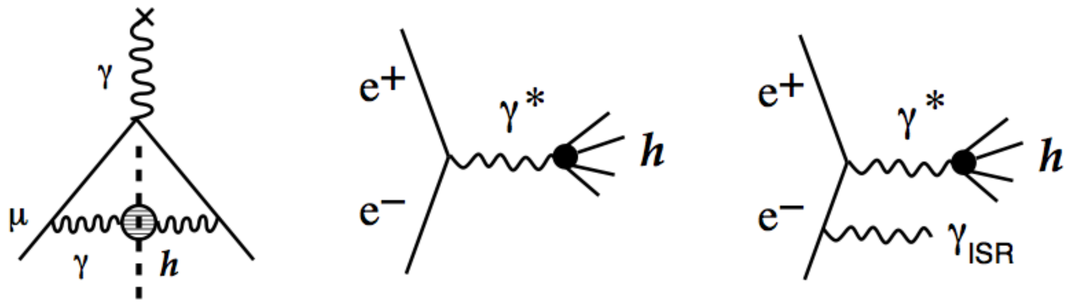
Hadronic Leading Order

Higher Order

Light-by-Light

⇒ a_μ gets contributions from *all* physics - including the unknown

$a_\mu^{\mathrm{had;LO}}$ can be extracted from measurements by SND, CMD2, BaBar, KLOE, Belle



$$a_\mu^{\mathrm{had;LO}} = \left(\frac{\alpha m_\mu}{3\pi}\right)^2 \int_{4m_\pi^2}^{\infty} \frac{ds}{s^2} K(s) R(s), \quad \text{where} \quad R \equiv \frac{\sigma_{\mathrm{tot}}(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)}$$

- CMD3 will measure up to 2.0 GeV, using energy scan and ISR, good cross-check
- KLOE will measure $\gamma^*\gamma^* \to \pi^0$, might reduce uncertainty on a_μ(Had;LBL)

Standard Model prediction, in units of 10^{-11} : (M. Davier *et al.* Eur. Phys. J. C **71**, 1515 (2011))

a_μ(QED)	=	116 584 718.951	$\pm$ 0.080(α^5)
a_μ(HadVP; LO)	=	6 923.	$\pm$ 42(Exp)
a_μ(HadVP; LO)	=	6 949.	$\pm$ 43(Exp)
a_μ(HadVP; HO)	=	-98.4	$\pm$ 0.6(Exp) $\pm$ 0.4(Rad)
a_μ(Had; LBL)	=	105.	$\pm$ 26
a_μ(Weak; 1 loop)	=	194.8	
a_μ(Weak; 2 loop)	=	-41.2	$\pm$ 1(Had) $\pm$ 2$\to$ 0(Higgs)
$\Rightarrow$ a_μ(SM)	=	116 591 802.	$\pm$ 49 $\times 10^{-11}$ (0.42 ppm)
$\Rightarrow$ a_μ(SM)	=	116 591 828.	$\pm$ 50 $\times 10^{-11}$ (0.43 ppm)

Brookhaven E821 $g_\mu - 2$ Results (G.W. Bennett *et al.* Phys. Rev. D **73**, 072003 (2006))

In units of 10^{-11} :

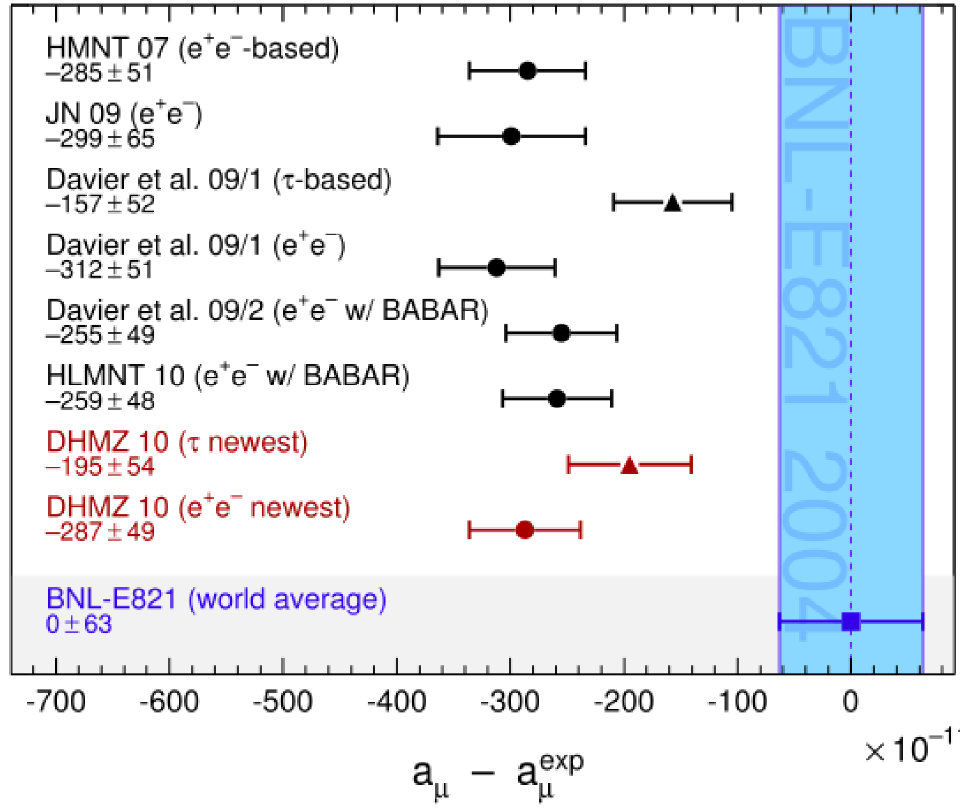
a_μ(Expt) $=$ $116\,592\,089 \pm 54 \pm 33$ (0.54 ppm

a_μ(SM) $=$ $116\,591\,802 \pm 49$ (0.42 ppm

a_μ(SM) $=$ $116\,591\,828 \pm 50$ (0.43 ppm

a_μ(Expt) $-$ a_μ(SM) $=$ 287$\pm$ 80 (3.6σ)

a_μ(Expt) $-$ a_μ(SM) $=$ 261$\pm$ 80 (3.3σ)



⇒ Theory (HVP from e^+e^-, no τ) from M. Davier *et al.*, Eur. Phys. J. C **71**, 1515 (2011).

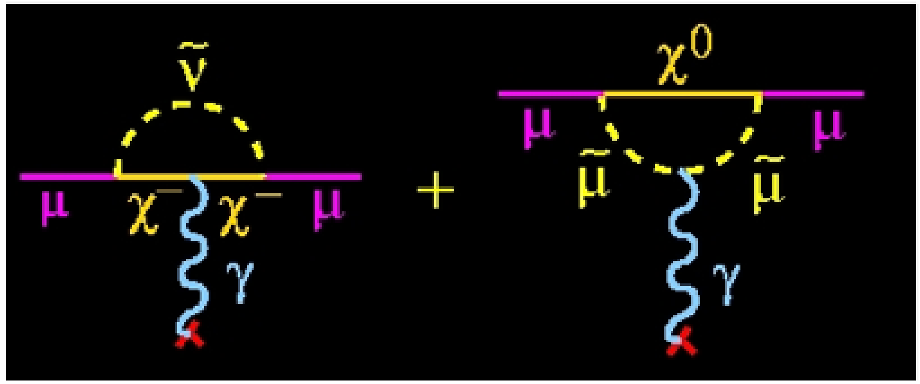
⇒ Deviation is large compared to weak contribution and uncertainty on hadronic terms

⇒ Signature of new physics?

⇒ Deviation doesn't reach 5σ threshold for discovery - need to reduce uncertainties

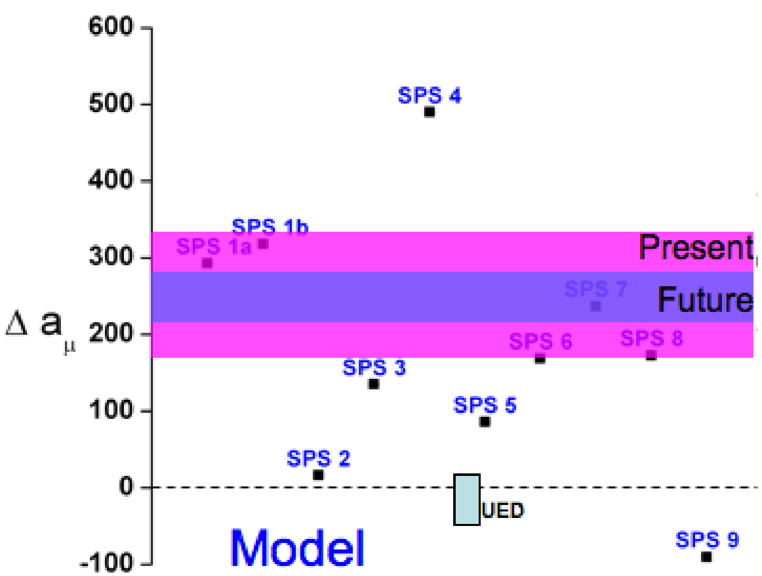
⇒ Need to do a better experiment! Need to reduce theoretical uncertainties

- a_μ is sensitive to variety of new physics; including many SUSY models



$$\Delta a_\mu(\mathrm{SUSY}) \simeq (\mathrm{sgn}\mu) \times \left(130 \times 10^{-11}\right) \times \tan\beta \times \left(\frac{100\ \mathrm{GeV}}{\tilde{m}}\right)^2$$

$\Rightarrow$ μ and $\tan\beta$ are difficult to measure at LHC, $g_\mu - 2$ can provide tighter constraints



- Snowmass Points and Slopes take benchmark points in SUSY parameter space and predict observables
- Muon g-2 is a powerful discriminator amongst models of physics
- *Regardless of the final value*, it strongly constrains *all* the possibilities

Low Energy Precision Tests : Motivation for reducing uncertainty on a_μ

- Many well motivated theories predict large Δa_μ - new g-2 can constrain parameters
- Many well motivated theories predict tiny Δa_μ - if large Δa_μ found by new g-2, these are excluded
- Some models predict similar signatures at LHC but distinguishable by Δa_μ (MSSM and UED (1D), Littlest Higgs)
- New g-2 sensitive to parameters difficult to measure at LHC [tan(β), sgn(μ)]
- Provides constraints on new physics that are independent and complementary to LHC, CLFV ($\mu \rightarrow e$), EDMs, ...

$\Rightarrow$ Even agreement with the Standard Model would be very interesting

$\Rightarrow$ Sensitivity to new particles with TeV scale mass

$\Rightarrow$ Many reasons to pursue a new measurement of a_μ at Fermilab, reduce δa_μ from 0.54 ppm $\rightarrow$ 0.14 ppm

The Future : E989 at Fermilab

- E989 will measure the Muon Anomalous Magnetic Moment to ± 0.14 ppm precision
- Factor of 4 improvement possible due to advantages at Fermilab

Overview of the the Experimental Method

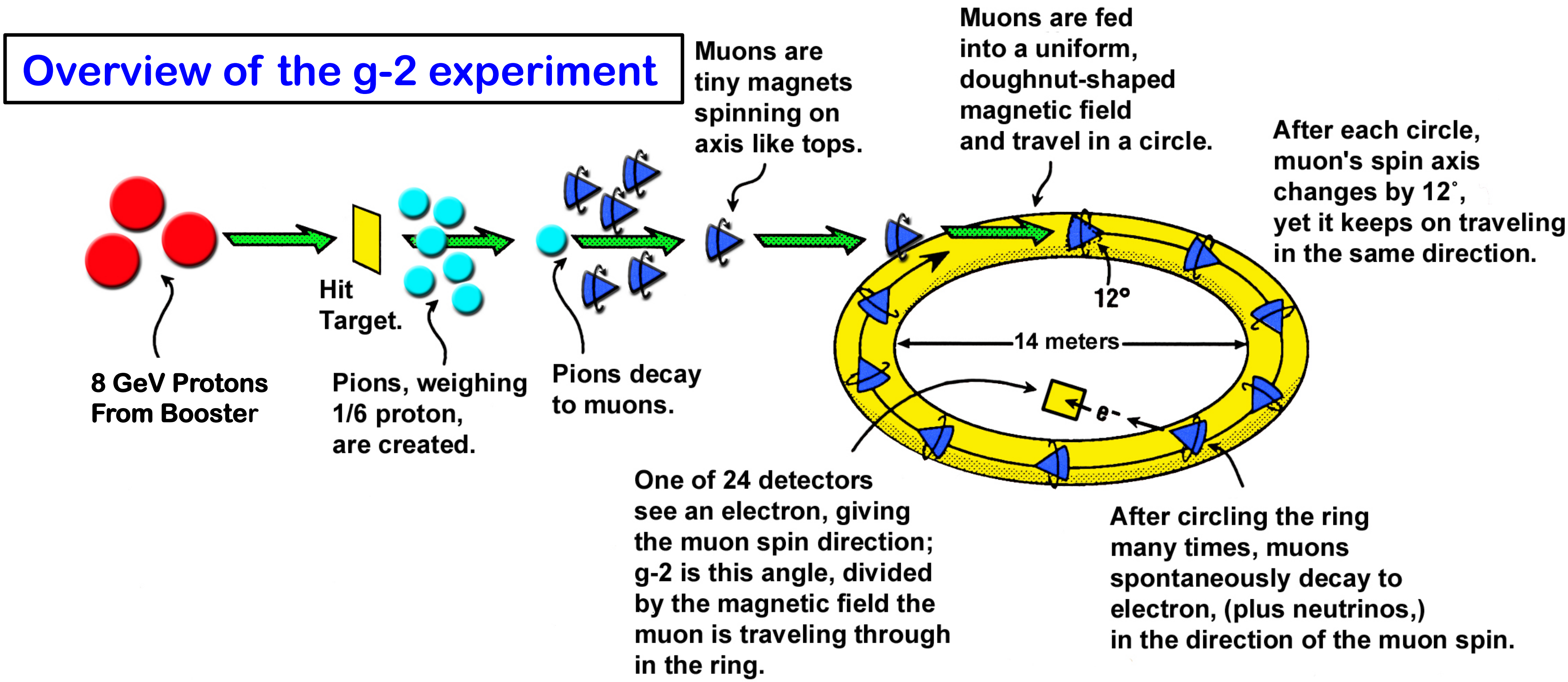
- Produce an 8 GeV pulsed proton beam, direct it onto a production target
- Capture pions from production target
- Capture muons ¿90% polarized from "forward" pion decay $\pi^+ \rightarrow \mu^+ \nu_\mu$
- Transport muon beam, inject it into g-2 storage ring
- Kick the muon beam onto a stored orbit
- Measure arrival time and energy of positron from muon decay in ring $\mu^+ \rightarrow e^+ \bar{\nu}_\mu \nu_e$

- Determine $a_\mu = (g_\mu - 2)/2$ from the spin equation :

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

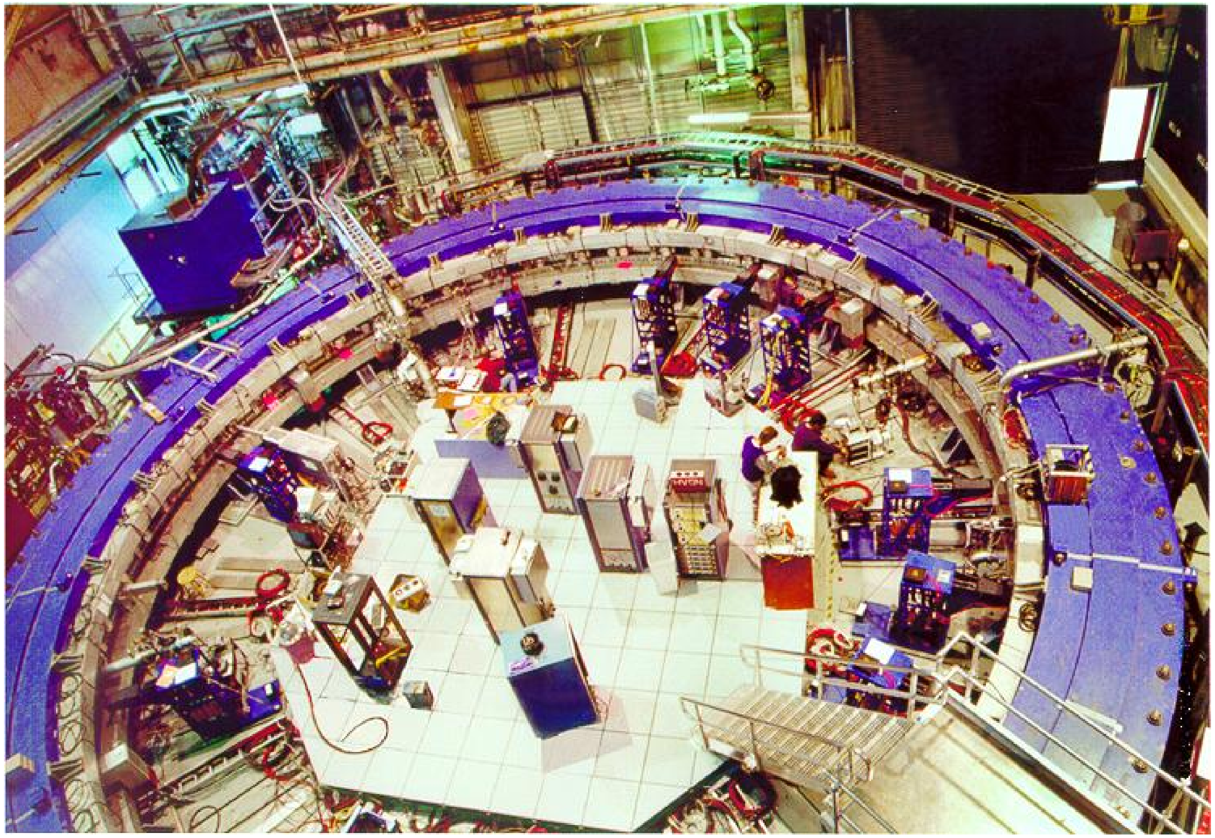
- Spin vector precesses differently from momentum vector precessing at cyclotron frequency
- Difference directly sensitive to $a_\mu \approx \alpha/2\pi \approx 0.00116...$, not $g_\mu \approx 2.00232...$
- Cancel term from electrostatic vertical focusing at $p_{\text{magic}} = m_\mu c/\sqrt{a_\mu} \approx$ 3.094 GeV$/c$

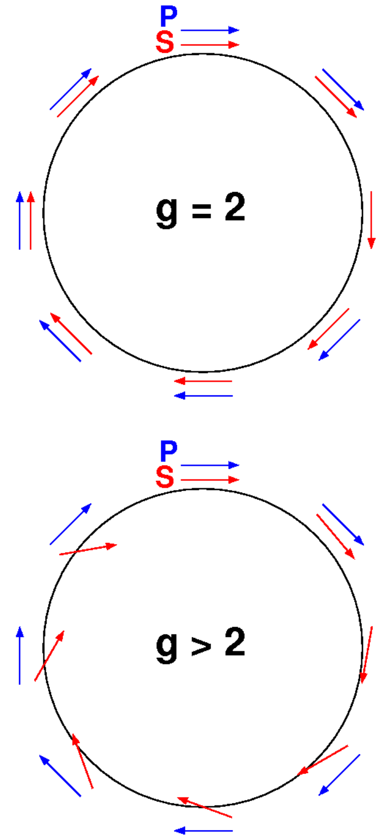
$\Rightarrow$ Need to measure muon spin frequency ω_a and magnetic field $\vec{B}$ averaged over muon distribution in ring



- Just like a_e use a Penning trap, except 7.112 meter radius, 650 tons
- Muons enter storage ring through a SC inflector that cancels storage ring $\boldsymbol{B}$ field
- Muons kicked onto orbit by pulsed magnetic field
- Muons confined vertically by electric quadrupoles

Experimental Procedure : Based on BNL E821 Muon $g_\mu - 2$ Experiment





- Inject polarized muons at 3.094 GeV/c into superferric storage ring, radius = 711.2 cm
- Muon spin precesses in homogeneous 1.45 T field, time dilated lifetime of 64.4 μs, measure for 700 μs

$$\vec{\omega}_a = \vec{\omega}_s - \vec{\omega}_c \quad : \quad \text{difference between spin and cyclotron frequencies}$$

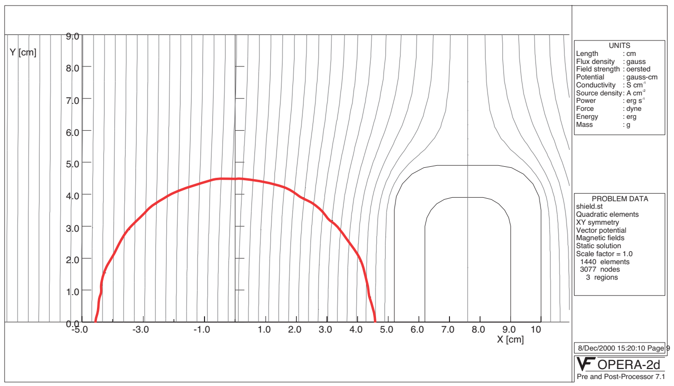
$$\vec{\omega}_a = -\frac{q}{mc}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\vec{\beta} \times \vec{E}\right] \quad \Rightarrow \text{at } \gamma = 29.3 \quad \Rightarrow \quad \vec{\omega}_a = -\frac{q}{mc}\left[a_\mu \vec{B}\right]$$

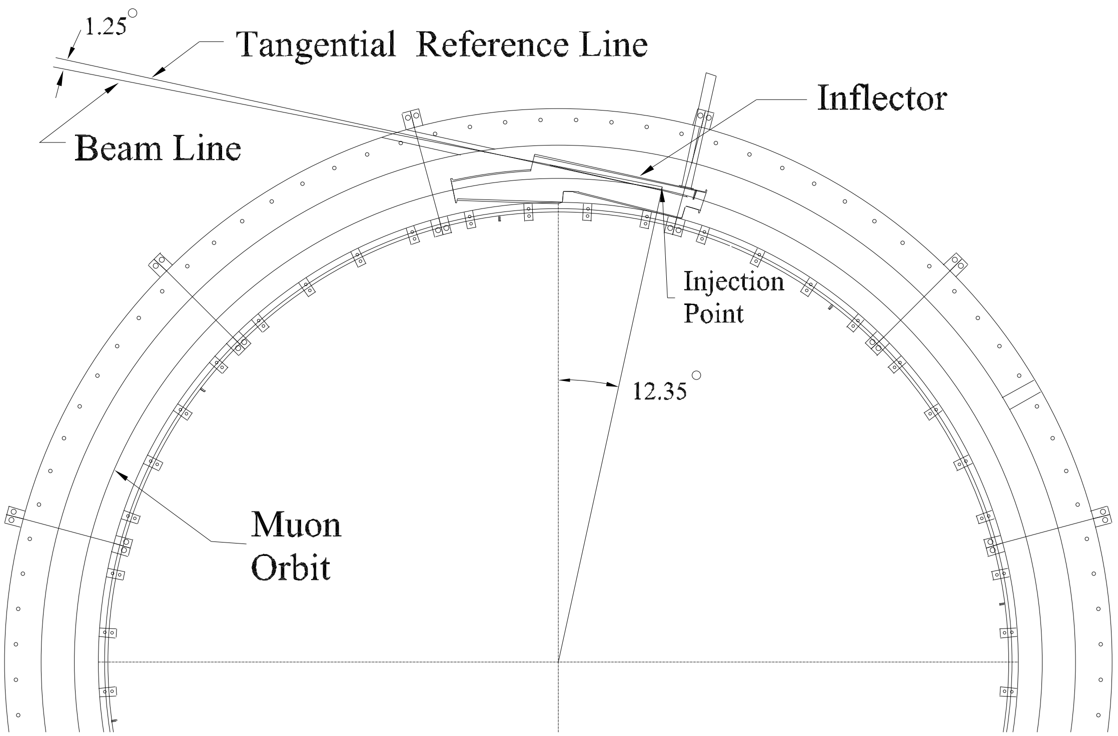
$\Rightarrow$ To determine a_μ, need to measure ω_a and B (weighted by muon distribution)

- Sub-ppm corrections applied due to vertical betatron motion (pitch correction) and muons not at magic γ

Superconducting Inflector

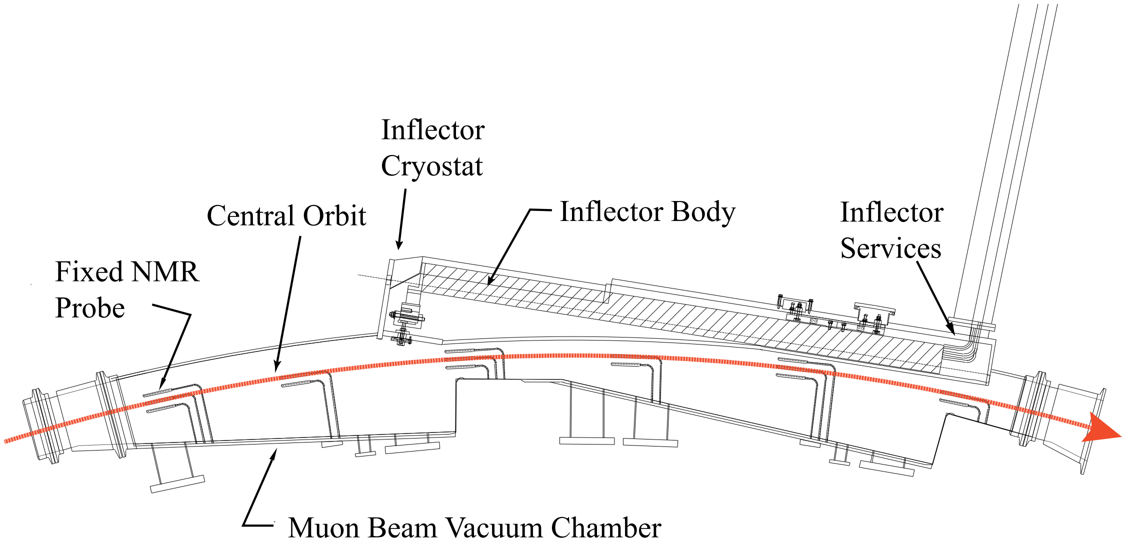
- Have to get the muon beam into the storage ring - from low/fringe field area outside to 1.45 T inside - beam strongly deflected unless we cancel this field
- Use a superconducting flux-exclusion tube? Perturbations in storage region too large

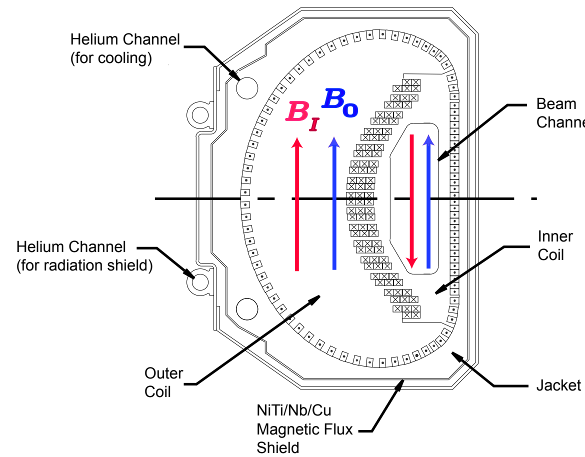




Superconducting Inflector

- Base plan: use double-$\cos\theta$ design from BNL E821, $\int \vec{B} \cdot d\vec{L} = 2.55$ T·m

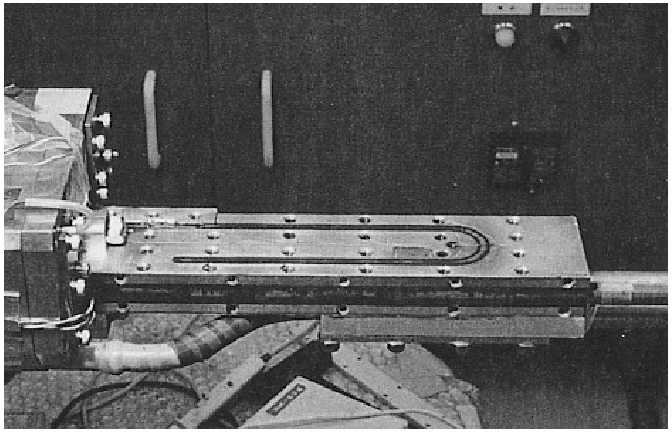
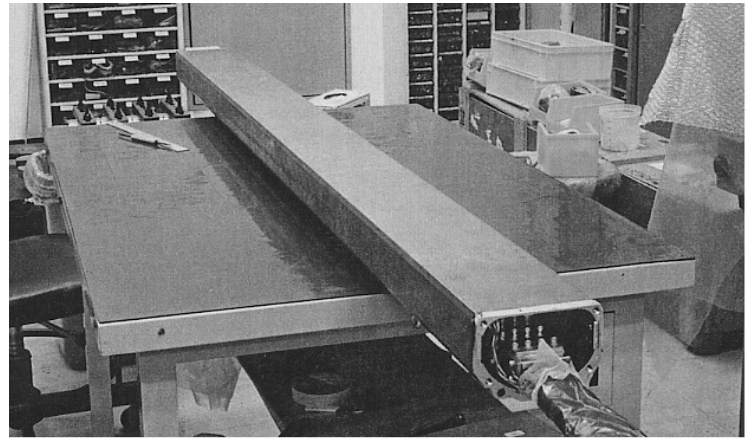
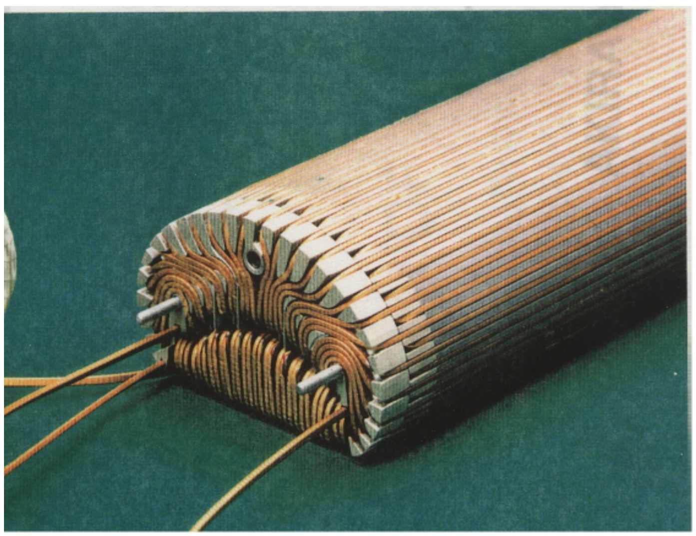
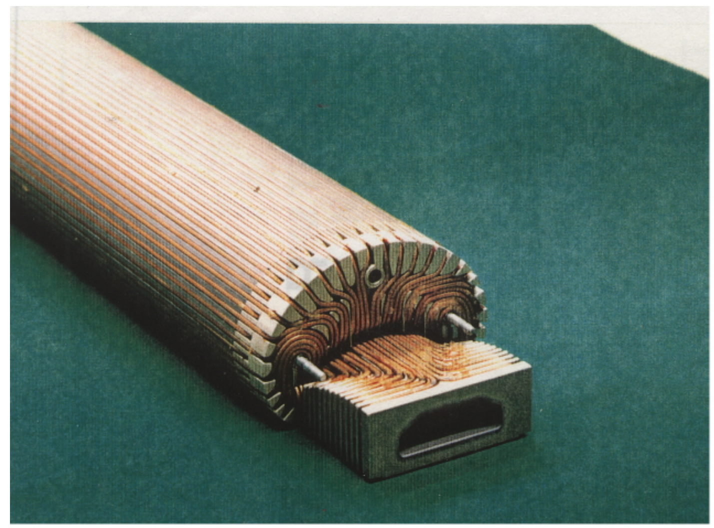




- Procedure :
  - Warm inflector+Type II SC shield, turn on main magnet, flux penetrates inflector and SC shield
  - Cool inflector and shield, since $H > H_{C1}$ field fully penetrates shield
  - Energize coils - cancels field in beam channel, eddy currents in passive shield prevents flux leaking out
  - Cancels B field in beam channel, no perturbation to field outside SC shield

Superconducting Inflector

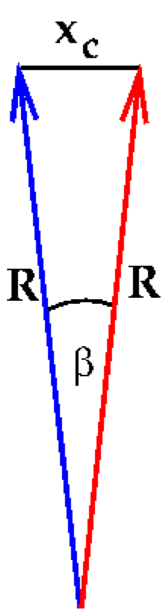
- Versions of superconducting inflector with closed and open ends

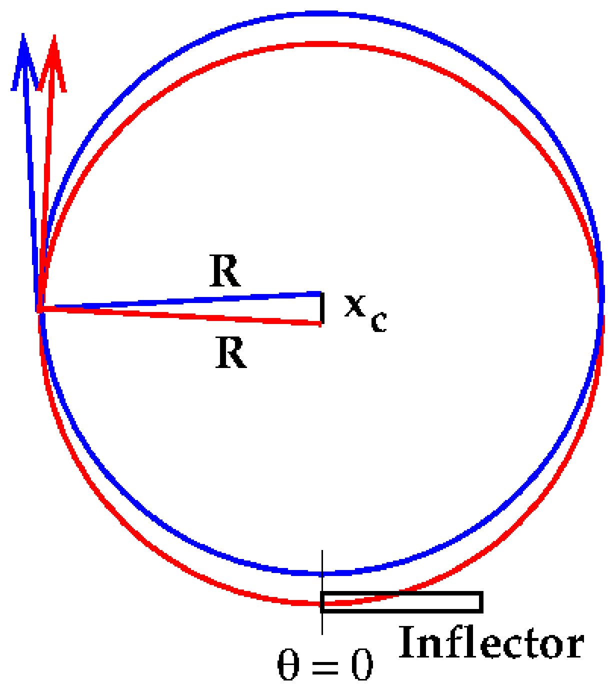





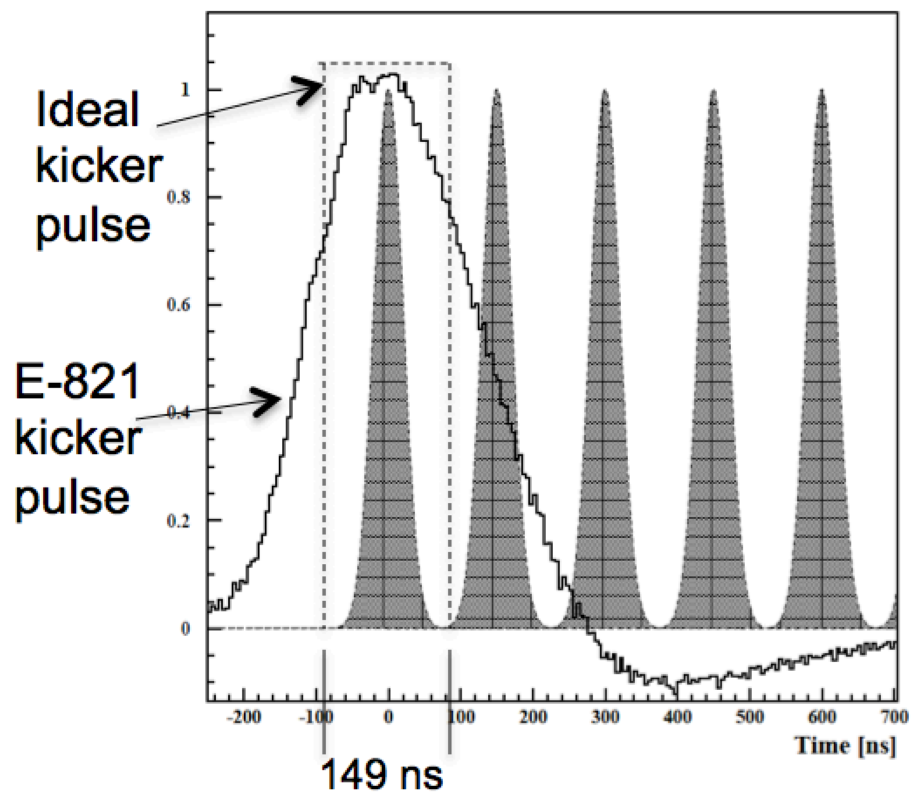
- BNL E821 inflector closed ends, significant multiple scattering, aperture 18×56 mm^2, injection efficiency $\approx 2\%$
- New inflector : open ends, 40×56 mm^2 (storage aperture ± 45mm) $\rightarrow$ $4\times$ more stored muons, could do μ^- and μ^+

The Fast Muon Kicker

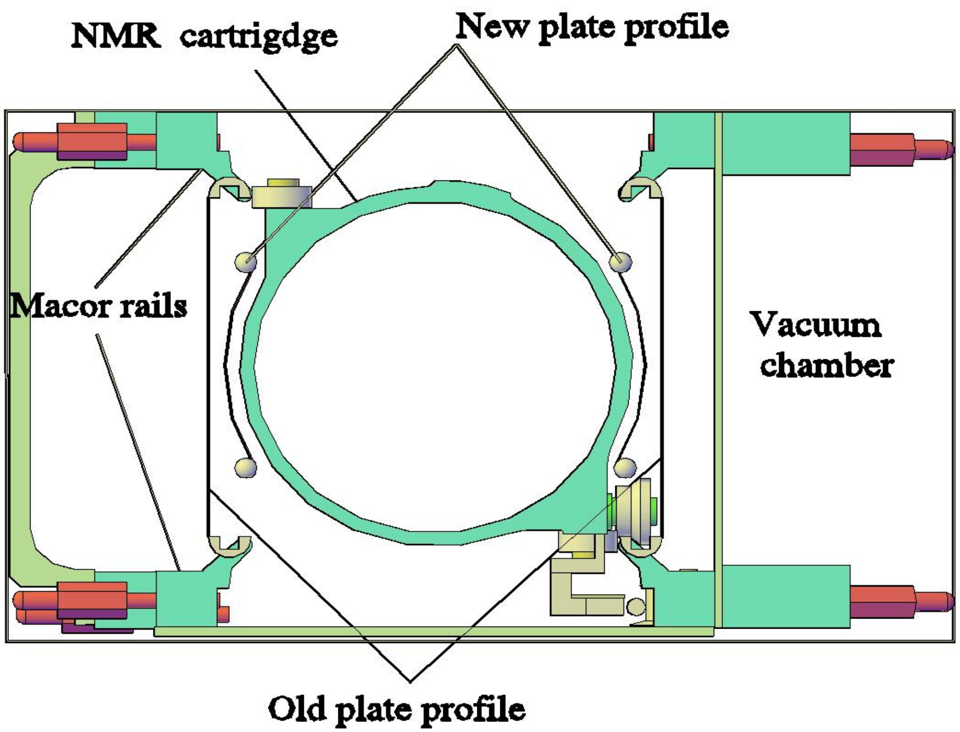
- Muons exit the inflector, enter storage region at radius 77 mm outside ideal closed orbit
- Muons cross ideal orbit $\approx\ 90^\circ$ later in azimuth, angle off by 10.8 mrad
- Including momentum spread, multiple scattering in inflector, need 14 mrad kick
- Temporarily reduce $\mathbf{B}$ by 280 Gauss, $\int \vec{B} \cdot d\vec{L}$=1.4 kG·m for 14 mrad kick
- Pulse width 80 ns $< \tau <$149 ns, 100 Hz, 10% homogeneity

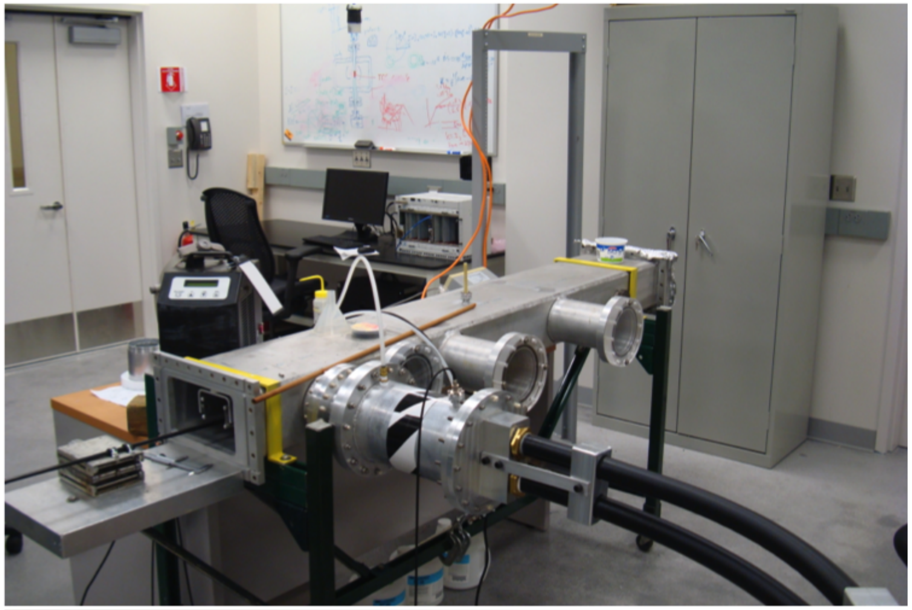


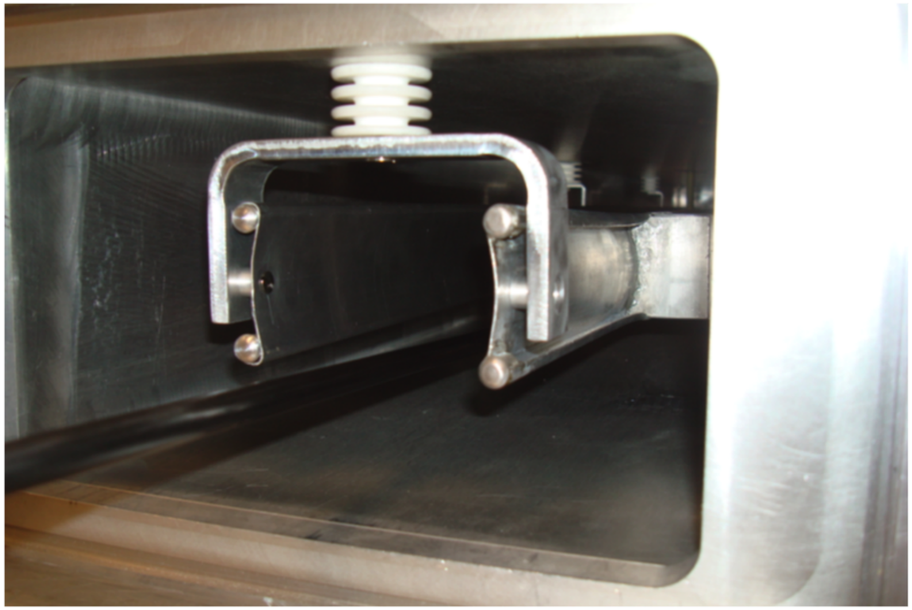




The Fast Muon Kicker

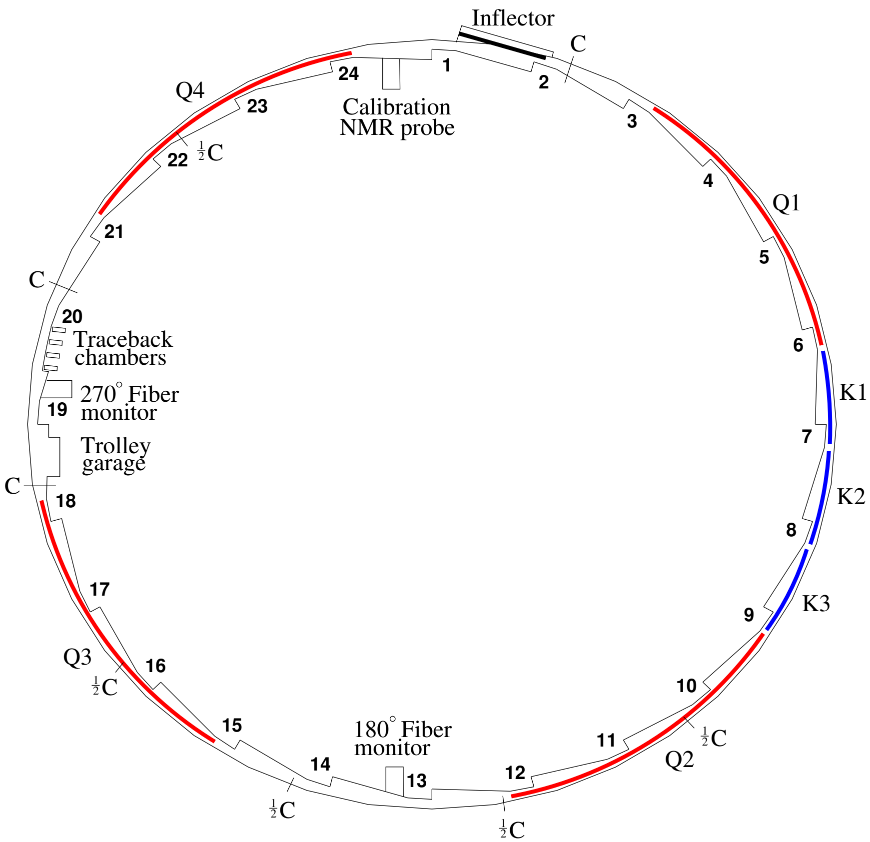


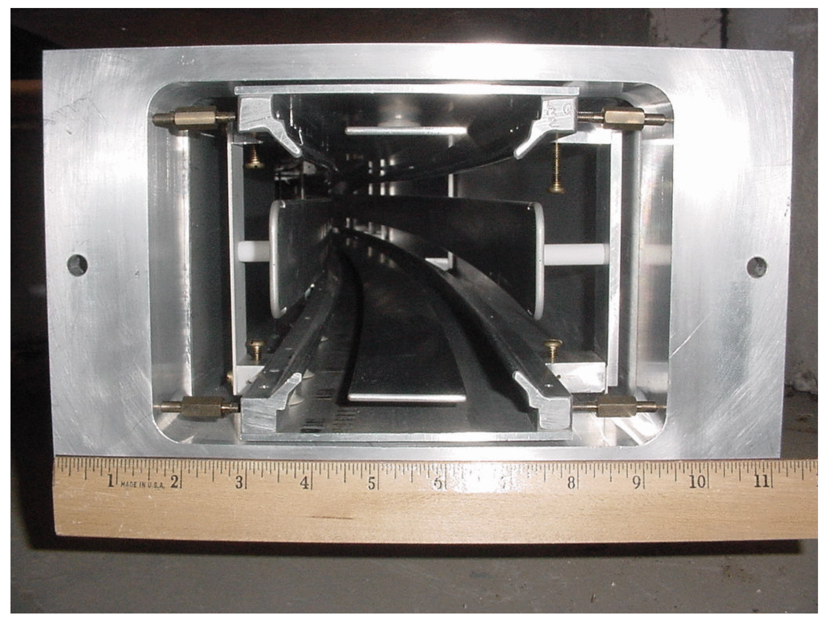




- New geometry yields 33%-50% higher field/current than BNL E821
- 3×1.7 m stripline kickers, Blumlein PFN
- Tracking studies determine optimal shape
- Dave Rubin and collaborators at Cornell

- Storage ring is a weak-focusing betatron using electric quadrupoles for linear restoring force in vertical, $\kappa = dE_y/dy$, Field Index $n = \kappa R_0/\beta B_0 \approx 0.137$
- Uniform quadrupole field leads to simple harmonic motion - radial x and vertical y betatron oscillations of beam





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

Stored Beam Dynamics and Related Systematic Uncertainties

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

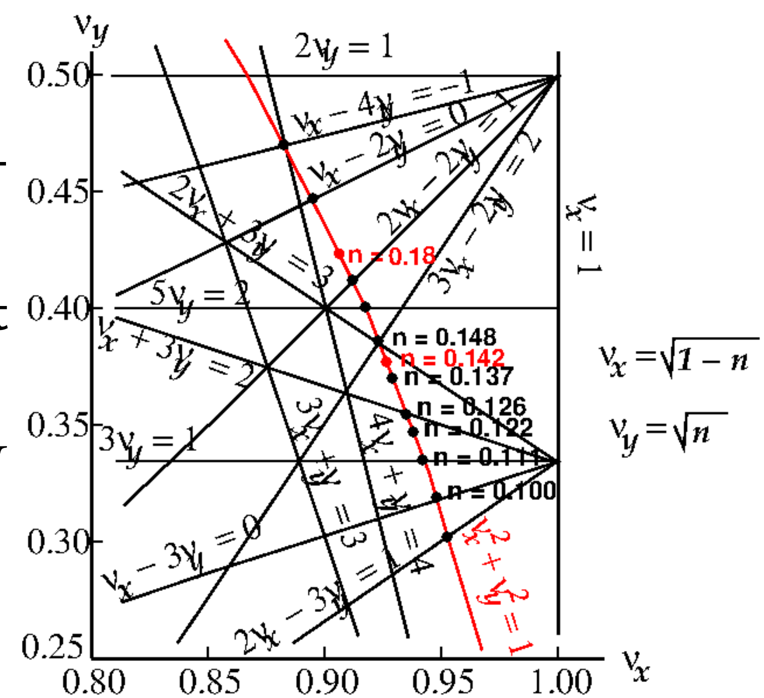
$$\nu_x = \sqrt{1-n}, \;\; \nu_y = \sqrt{n}, \;\; n \approx 0.137, \;\; f_x = f_C\sqrt{(1-n)} \approx 0.929 f_C, \;\; f_y = f_C\sqrt{n} \approx 0.37 f_C$$

Quantity	Expression	Frequency [MHz]	Period [μs]
f_a	$\frac{e}{2\pi mc} a_\mu B$	0.228	4.37
f_C	$\frac{v}{\pi R_0}$	6.7	0.149
f_x	$\sqrt{1-n} f_c$	6.23	0.160
f_y	$\sqrt{n} f_c$	2.48	0.402
f_{CBO}	$f_c - f_x$	0.477	2.10
f_{VW}	$f_c - 2f_y$	1.74	0.574

- Perturbations of stored muon beam from ideal circular orbit affect ω_a

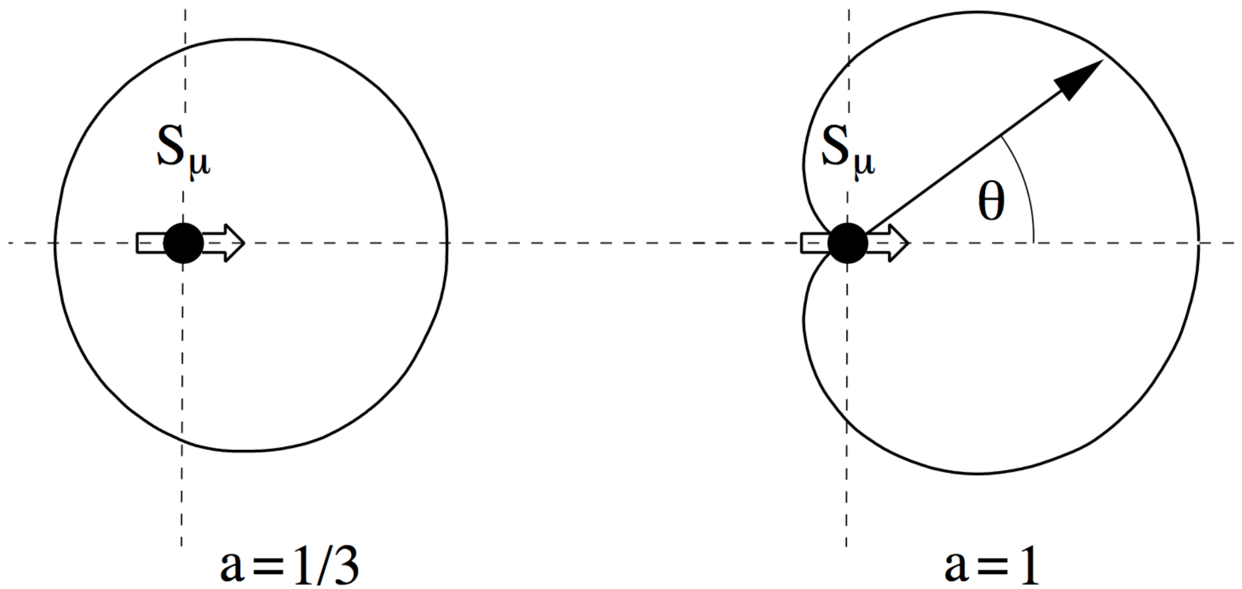
$\Rightarrow$ Resonances in ring cause muon beam losses, distort time spectrum

- Resonances occur if $L\nu_x + M\nu_y = N$ where L, M, N integers. Operating points have $\nu_x^2 + \nu_y^2 = 1$



How will we measure ω_a ?

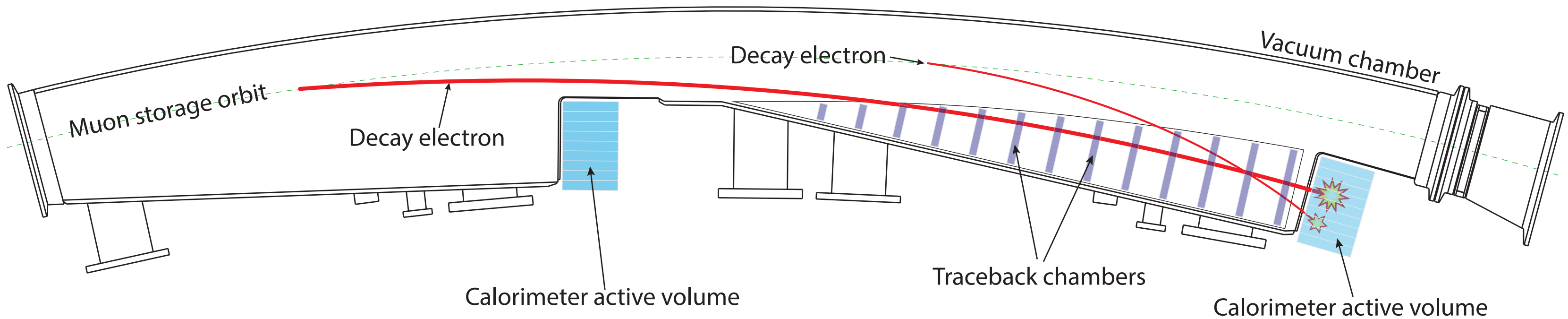
- To measure ω_a, need to know muon spin direction when it decayed
- Nature is kind here : muon decay $\mu^+ \to e^+\nu_e\bar{\nu}_\mu$ is self-analyzing due to PV
- Muon spin direction correlated with decay positron direction



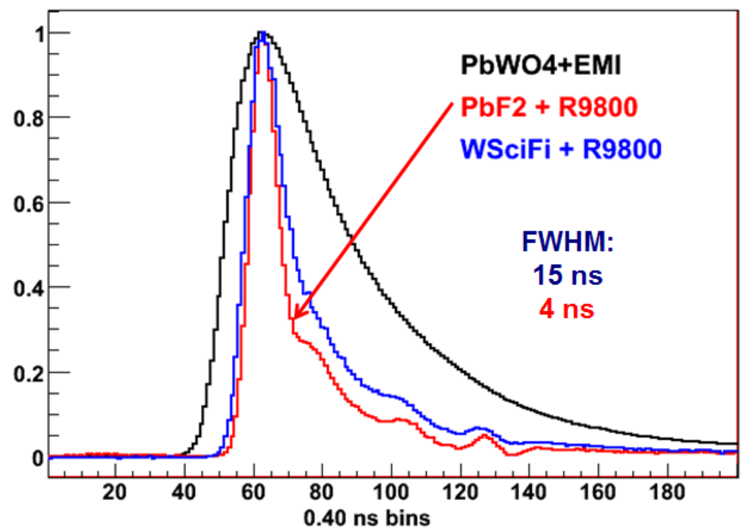
- Averaged over all positron energies, forward-backward asymmetry wrt muon spin is a=1/3
- For highest energy positrons (3.1 GeV), asymmetry a=1
- $E_{\text{lab}} \approx \gamma E^* \left(1 + \cos\theta^*\right)$
- Detect decay e^+ above 1.8 GeV $\Leftrightarrow$ cut on θ^*, reconstruct muon spin direction versus time

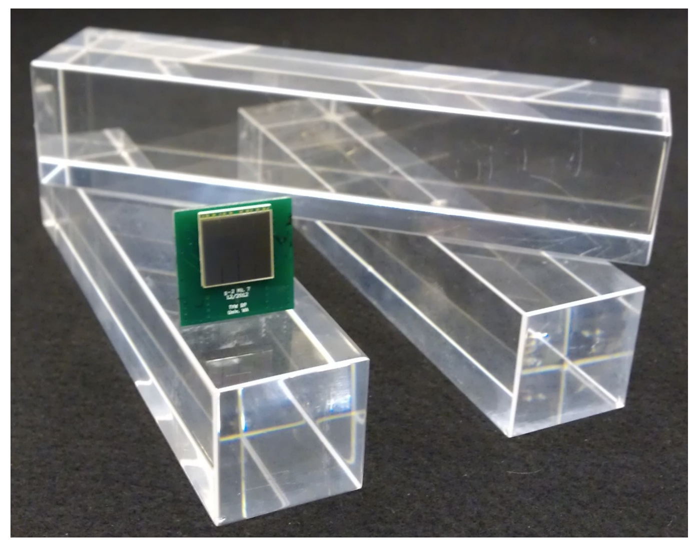
Figures from thesis of Alex Grossmann

Detecting the e^+ from Muon Decay : Dave Herzog UW + Collaborators

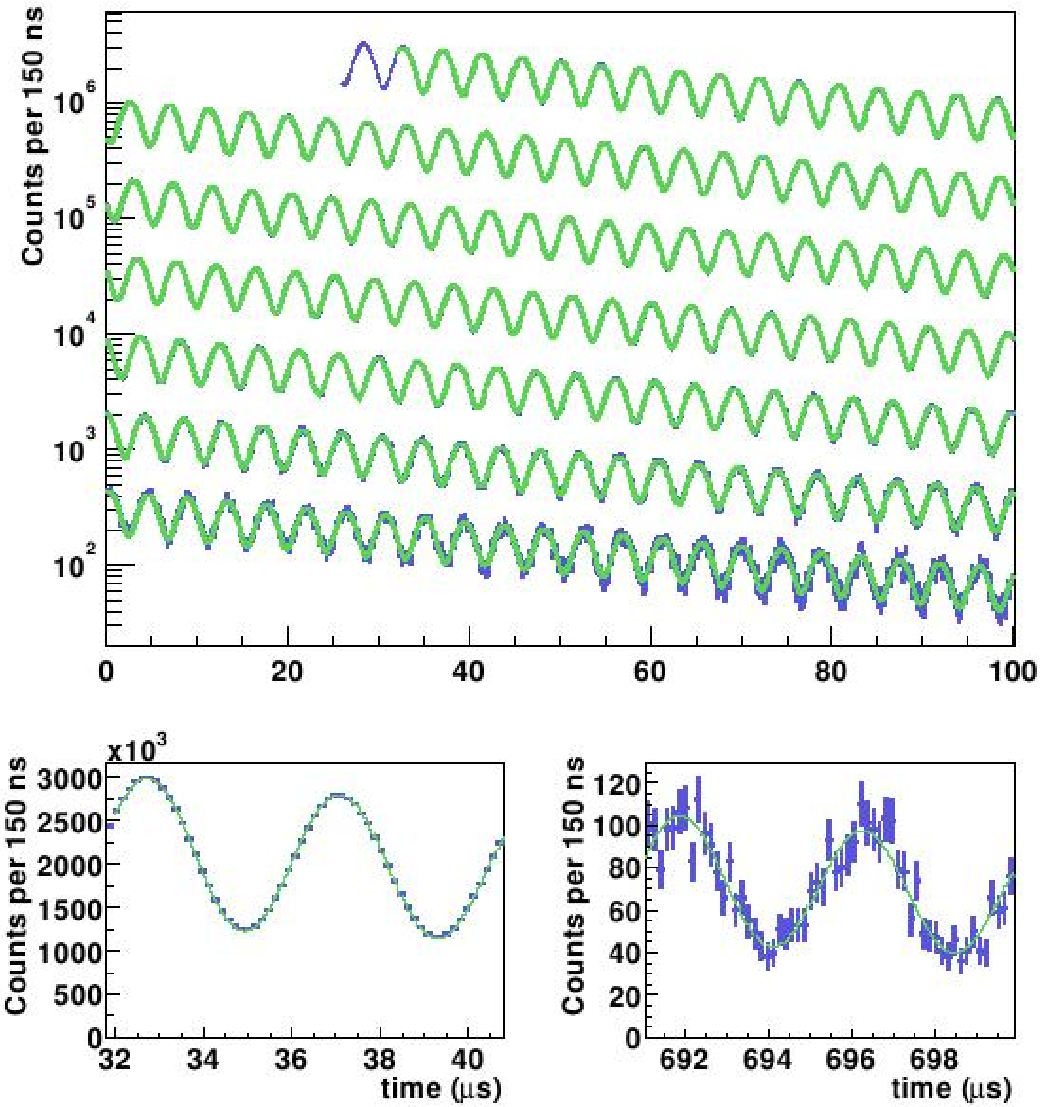


- Need fast calorimeter to detect e^+ from muon decay - made from PbF_2 crystals
- Each calorimeter segmented into 9×6 individual crystals to handle pileup
- Čerenkov light detection with silicon photomultipliers (SiPMs)
- Smaller Moliere radius, greater segmentation, greater immunity to pileup then BNL E821
- Signals digitized with 500 MHz waveform digitizers for 700+μs, extract e^+ signals offline





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

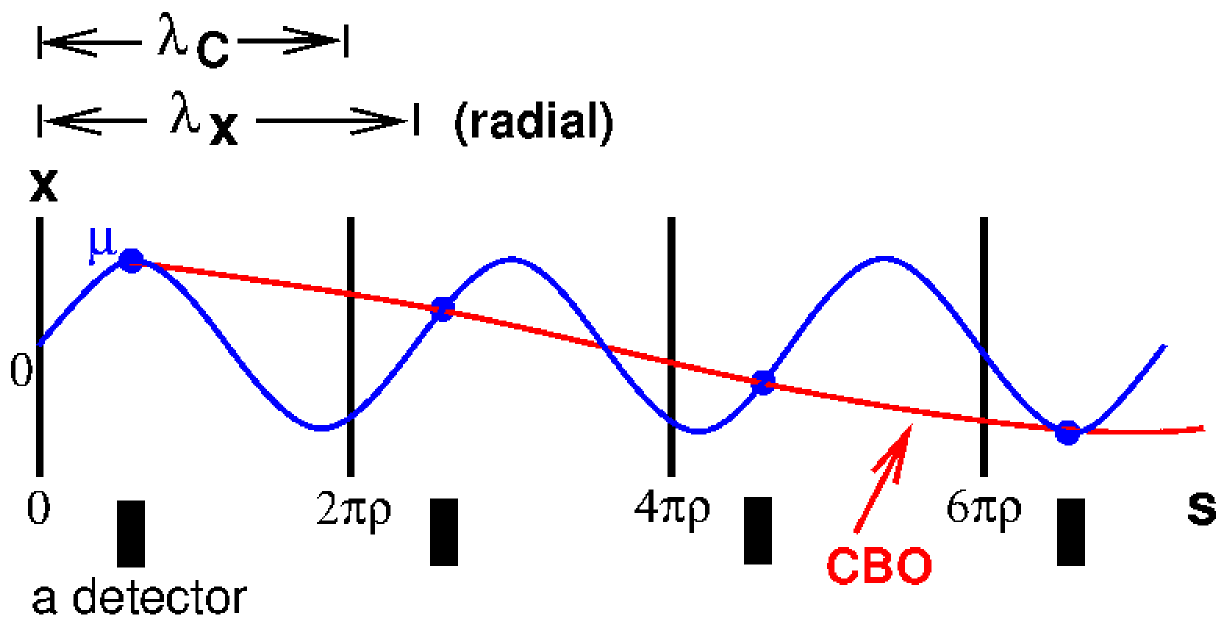


$$\frac{\delta\omega_a}{\omega_a} = \frac{\sqrt{2}}{\omega_a \tau_\mu A \sqrt{N}}$$

- $3.6 \times 10^9\ e^+$, corrections for muon losses, pileup, coherent betatron oscillations

Coherent Betatron Oscillations (CBO)

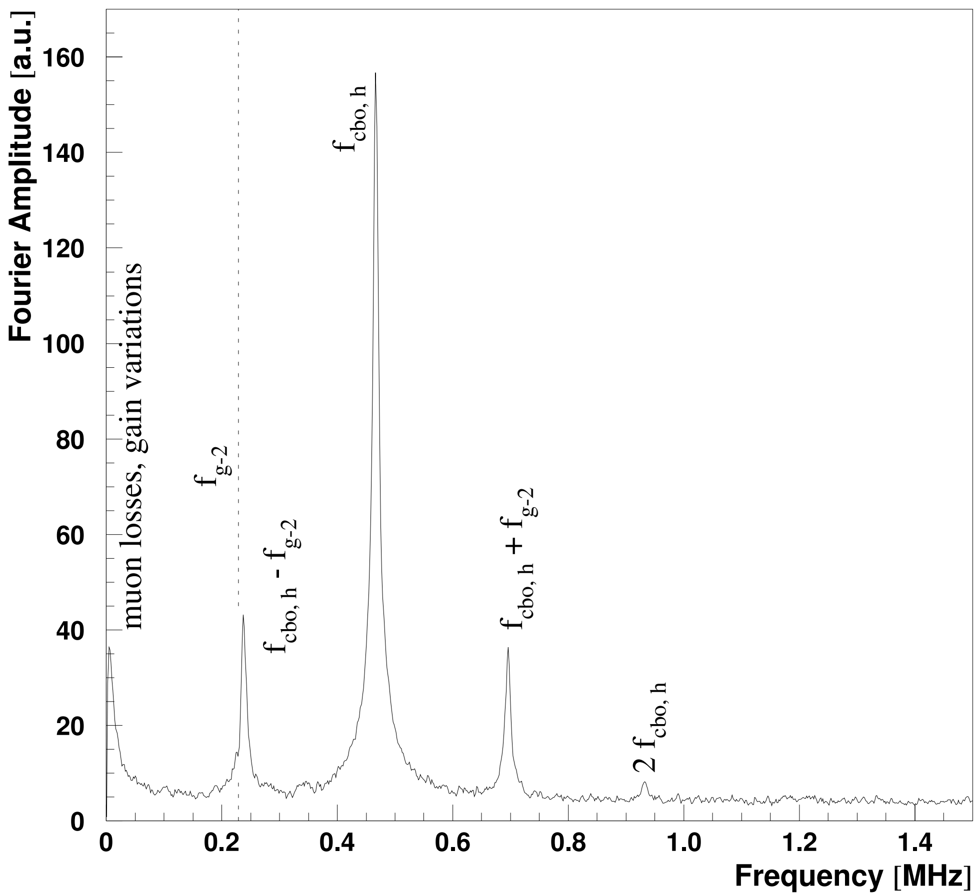
- Detector acceptance depends on muon radius at decay - coherent radial motion modulates electron time spectrum
- Radial betatron wavelength (blue line) is longer than circumference (cyclotron wavelength), $f_x < f_{\rm C}$
- At fixed detector location, each pass of bunched beam appears at different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

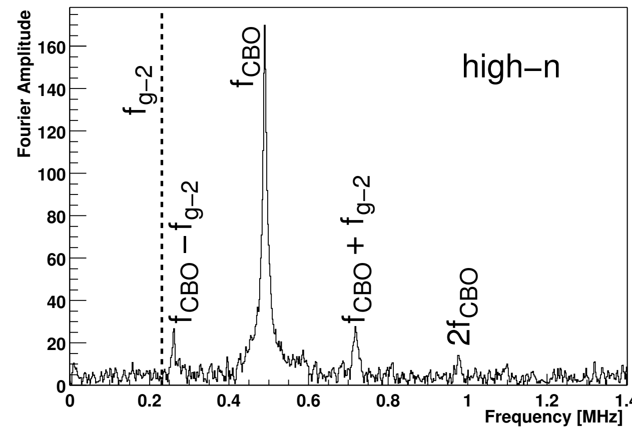


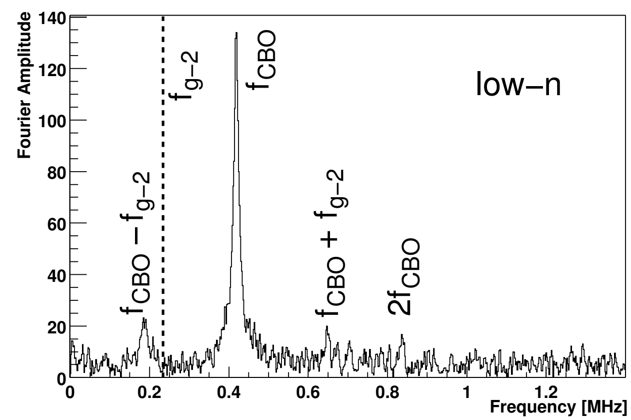
- Cyclotron wavelength marked by black lines, single detector by black block, betatron oscillations in blue
- Red line : apparent radial breathing in and out of beam at $f_{\rm CBO}$
- Effect nearly cancels when all detectors added together

Coherent Betatron Oscillations (CBO)

- In BNL E821 2000 data taken 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







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

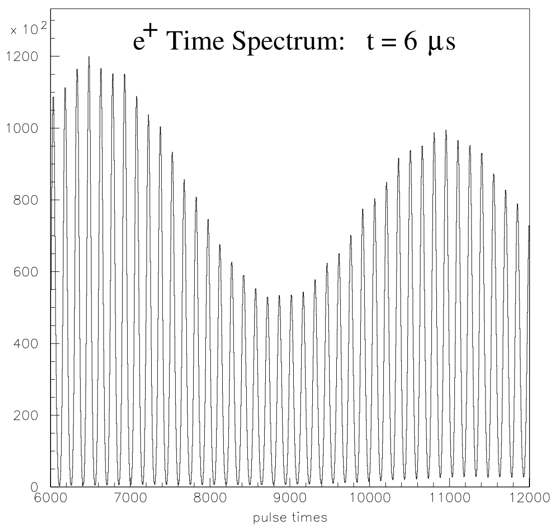
- Not all muons at magic momentum, $p = p_m + \Delta p$,
- Storage ring momentum acceptance $\Delta p \approx \pm 0.5\%\; p_m,\; p_m \approx 3.094$ GeV/c

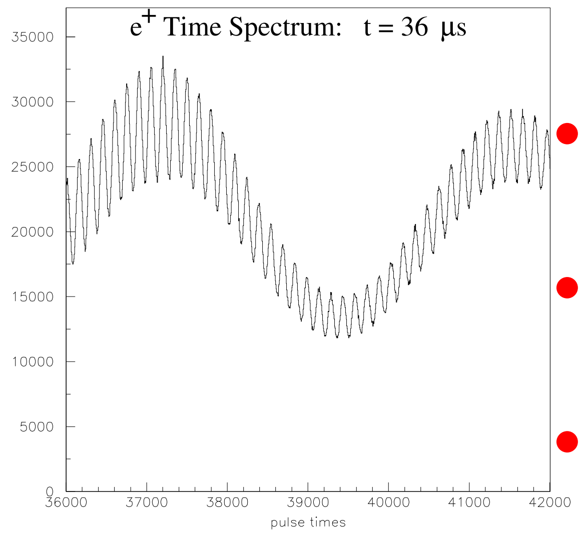
$$\frac{p - p_m}{p_m} = (1-n)\left[\frac{R - R_0}{R_0}\right] = (1-n)\frac{x_e}{R_0}$$

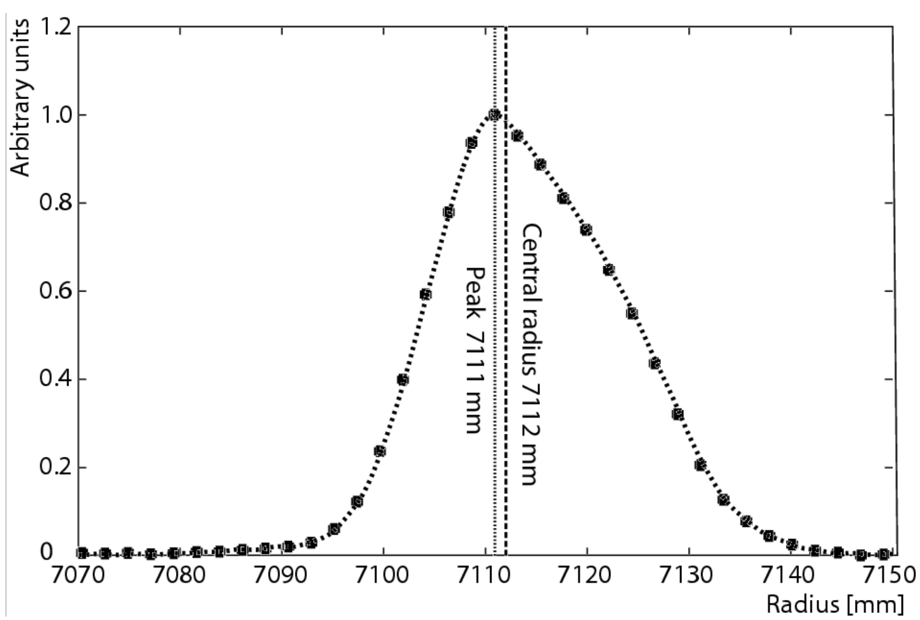
$$\frac{\omega_a' - \omega_a}{\omega_a} = \frac{\Delta\omega_a}{\omega_a} = -2\frac{\beta E_r}{cB_y}\left(\frac{\Delta p}{p_m}\right) = -2n(1-n)\beta^2\frac{\langle x_e^2\rangle}{R_0^2}$$

- Momentum distribution from fast-rotation (de-bunching) analysis, decay e^+ tracking chambers, muon beam fiber monitors

- Momentum distribution from fast-rotation (de-bunching) analysis, decay e^+ tracking chambers, muon beam fiber monitors







- Bunch structure visible at early times, $\tau_{\text{cyclotron}} \approx$ 149 ns
- Bunch structure erased by 60μs due to momentum spread Δp
- BNL E821 injected beam width $\approx$ 23 ns
- BNL E821 $\sqrt{\langle x_e^2 \rangle} \approx 10$ mm $\Rightarrow$ electric field correction $+0.47 \pm 0.05$ ppm
- FNAL E989 beam width $\gg$ 23 ns
- FNAL E989 uncertainty on correction ± 0.03 ppm using improved traceback system

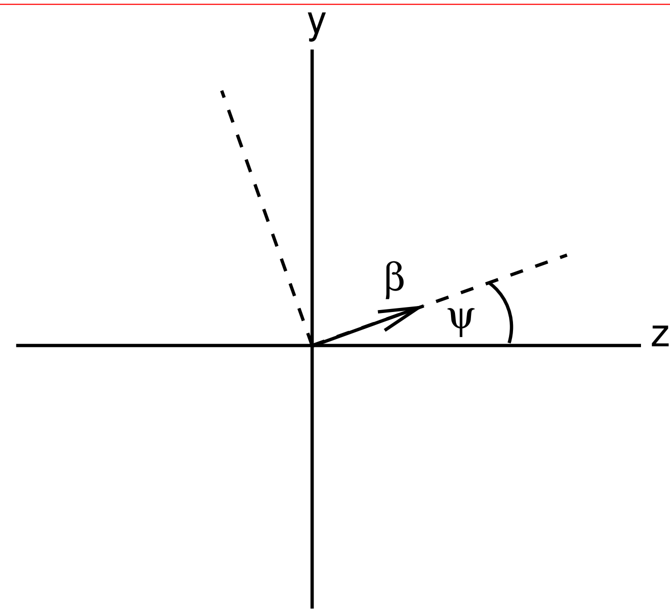
Corrections to ω_a: Pitch Correction

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

- Vertical betatron motion
  $\rightarrow$ $\vec{\beta}$ not perpendicular to $\vec{\mathbf{B}}$

$$\omega_a' \approx \omega_a \left(1 - \frac{\psi^2}{2}\right),$$

$$C_p = -\frac{<\psi^2>}{2} = -\frac{n}{2}\frac{<y^2>}{R_0^2}$$



- Electric field and pitch corrections reduce observed frequency
- BNL E821 pitch correction $+0.27 \pm 0.036$ ppm
- Electric field and pitch are the only corrections made to the ω_a data
- Improved E989 muon tracking reduces uncertainties ± 0.05 ppm $\Rightarrow 0.03$ ppm level

Projected Systematic Uncertainties on ω_a and Comparison with E821

- The largest systematics uncertainties on ω_a from the final E821 run, and projected future uncertainties are outlined :

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

Introduction to $\boldsymbol{B}$ Field Measurement and ω_p Systematics

- E989 relies on precision measurement of two quantities, ω_a and $\tilde{\omega}_p$:

$$a_\mu = \frac{\omega_a/\tilde{\omega}_p}{\mu_\mu/\mu_p - \omega_a/\tilde{\omega}_p}$$

- $\tilde{\omega}_p$: free proton precession frequency weighted by muon distribution $\approx 2\pi \times 61.79$ MHz

⇒ Goal is to determine $\tilde{\omega}_p$ with uncertainty 0.070 ppm ($\delta\tilde{\omega}_p \ \leq \ 2\pi \times 4.3$)

- E989 largely based on principles and hardware developed by Heidelberg and Yale for E821
- E821 fractional uncertainty on field was 0.17 ppm : E989 needs to do 2.4 times better
- Changes to hardware and techniques to get from 0.17 to 0.070 ppm on ω_p outlined below

Four Field Measurement Tasks :

(1) Monitor magnetic field with fixed probes on vacuum chambers while muons stored in ring;

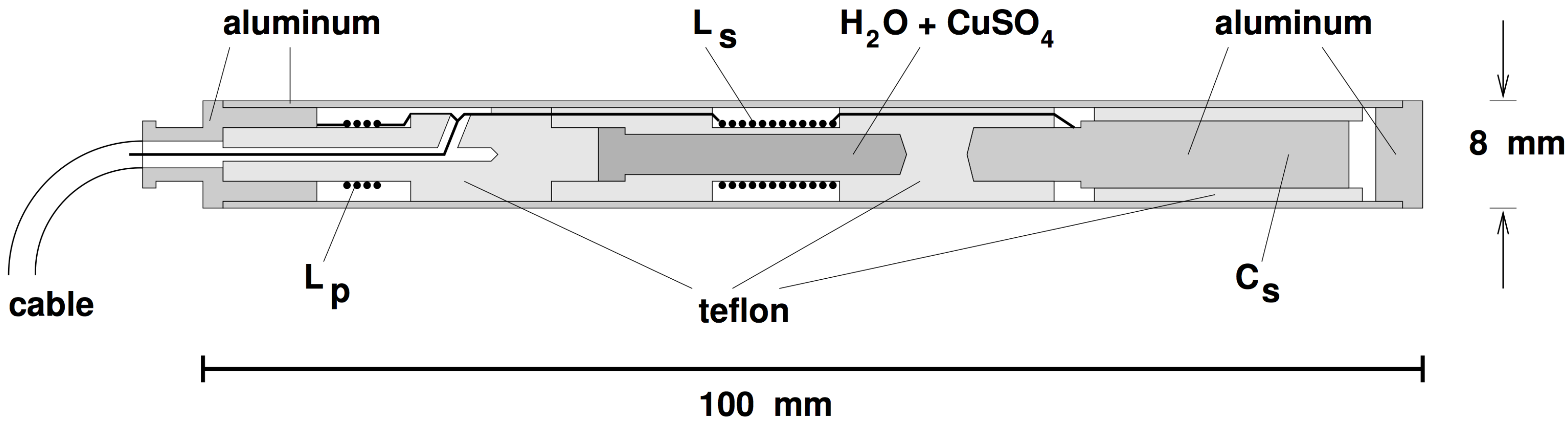
(2) Map the magnetic field in muon storage volume with NMR trolley when the beam is off;

(3) Provide an absolute calibration relating NMR trolley field measurements inside storage volume to the precession frequency of a free proton;

(4) Provide feedback to the power supply to stabilize field when muon data are collected.

Field Measurement with Pulsed NMR

- Measure field using pulsed NMR to induce and detect free induction decay (FID) of protons in a water sample[1]
- Typical NMR probe shown below (field direction vertical, perpendicular to L_s coil axis) :

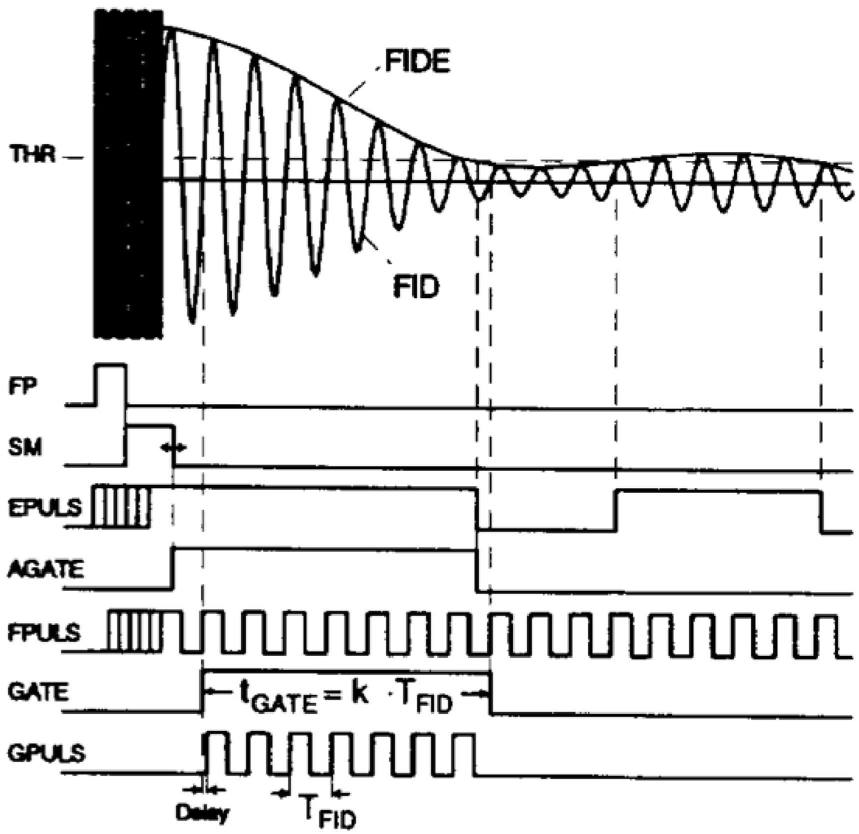


- RF pulse at $f_{\rm ref}$=61.74 MHz produces RF magnetic field in coil L_s around sample
- Rotates magnetization of protons in sample perpendicular to main field
- After pulse, proton spins process freely, coherently at $f_{\rm NMR} \approx 61.79$ MHz, $\omega \approx \gamma_{p'} B$
- Rotating magnetization induces V in coil L_s, signal decays exponentially, $\tau \approx 1$ ms

[1] May use petroleum jelly (CAS 8009-03-08) : long $T_2 \approx 40$ ms, doesn't evaporate, low temp. coefficient

Field Measurement with Pulsed NMR

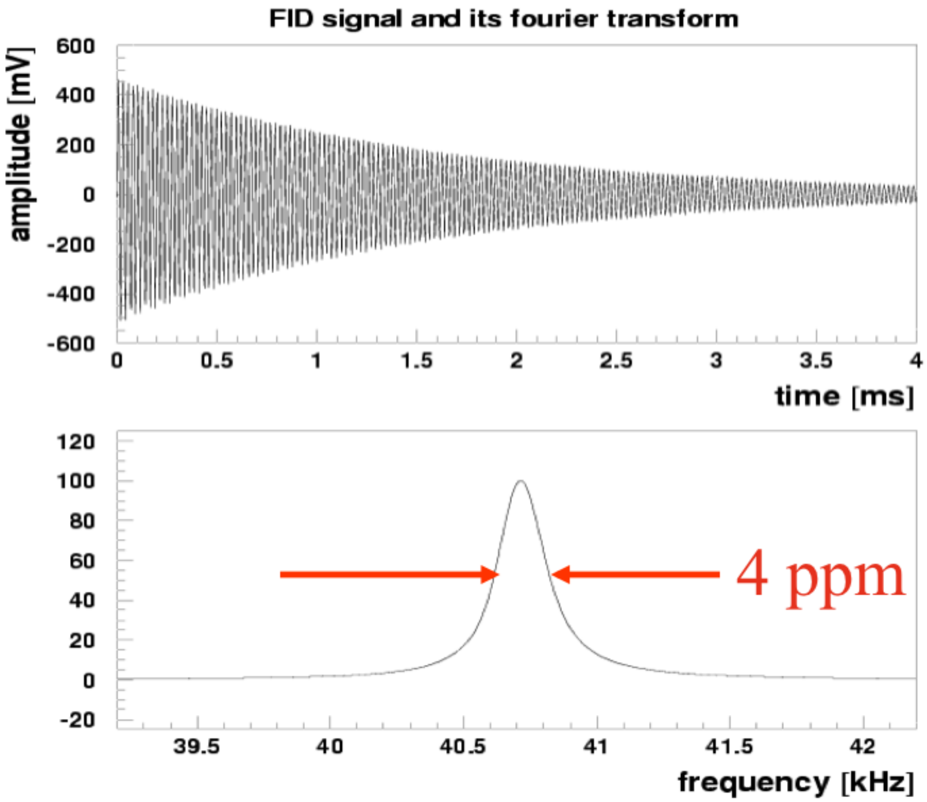
- NMR signal at $f_{\rm NMR}$ goes to low noise amplifier, mixed with $f_{\rm ref} = 61.74$ MHz from synthesizer
- Difference frequency $f_{\rm NMR} - f_{\rm ref} \equiv f_{\rm FID}$ ranges from 45-55 kHz, dependent on local field
- Difference of 62 Hz in $f_{\rm FID}$ corresponds to 1 ppm difference in field
- Count zero crossings of this free induction decay (FID) and ticks of clock running at 20 MHz till signal decays to roughly $1/e$ of peak, ≈ 1 ms



$\Rightarrow$ Local field characterized by Larmor frequency, $f_{\rm NMR} = f_{\rm ref} + f_{\rm FID}$

- Single shot resolution on $f_{\rm NMR}$ ≈ 0.020 ppm
- Depends on signal duration, S/N
- See R. Prigl *et al.*, Nucl. Inst. Meth. A **374**, 118 (1996).

Field Measurement with Pulsed NMR



$\Leftarrow$ FID from E821 and Fourier transform

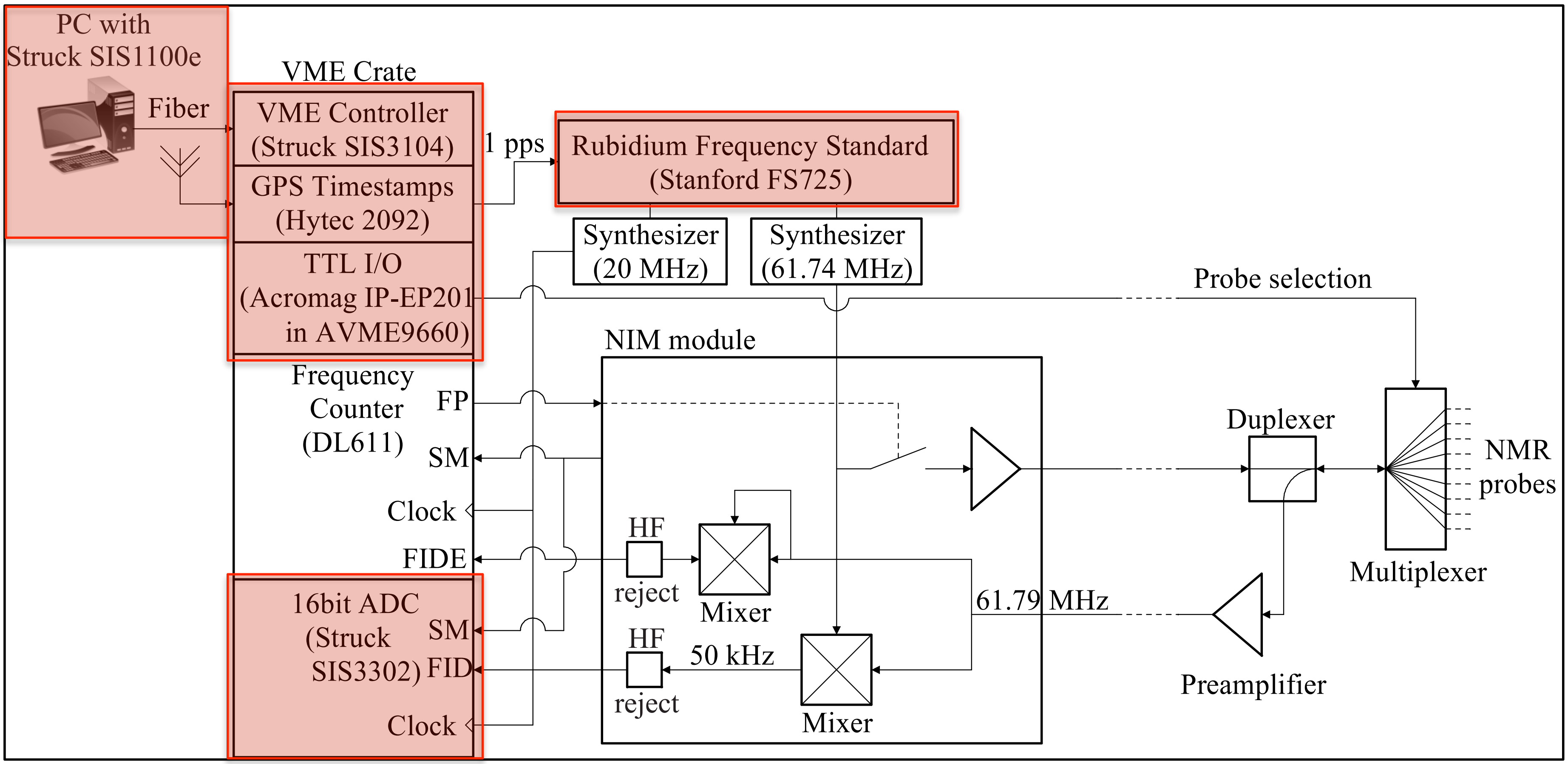
- Signals typically last 1 ms
- Signal : noise $\geq$ 100 : 1
- Frequency resolution $\approx$ linewidth$/[S/N]$ $\approx$ 130 Hz / 100 = 1.3 Hz
- Resolution on f_{NMR} of δf_{NMR}=1.3 Hz $\Leftrightarrow$ $\delta f_{\mathrm{NMR}}/f_{\mathrm{NMR}}$ = 1.3 Hz/61.79 MHz $\Leftrightarrow$ 0.020 ppm resolution on field

- Corrections necessary to get from f_{NMR} of protons in H_2O to ω_p of free proton

$\Rightarrow$ Need absolute calibration of probes in terms of free proton precession frequency; demonstrated at level of 0.034 ppm (see X. Fei *et al.*, Nucl. Inst. Meth. A **394**, 349 (1997))

$\Rightarrow$ Main challenge of field measurement : effectively transfer high accuracy absolute calibration to many probes providing high resolution monitoring field over long periods in which muons are stored

- Block diagram of the proposed NMR electronics shown.



- Multiplexer connects to 20 NMR probes, and contains a duplexer and preamplifier
- DL611 frequency counter, NIM modules, multiplexers, NMR probes from E821 will be refurbished for E989; parts shaded red are new

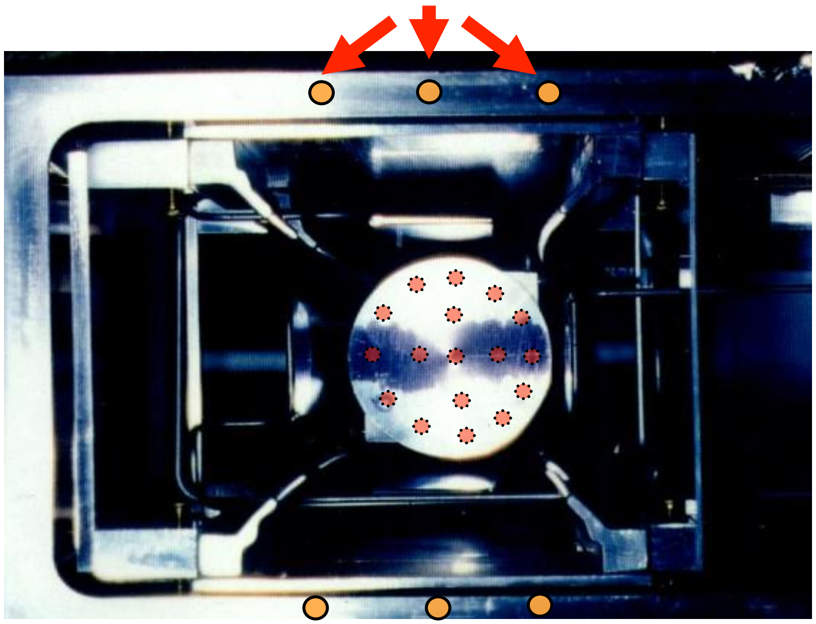
⇒ Need Larmor frequency of free protons in storage volume while muons are stored

(1) Fixed probes measure field at same time as muons stored, but outside storage volume

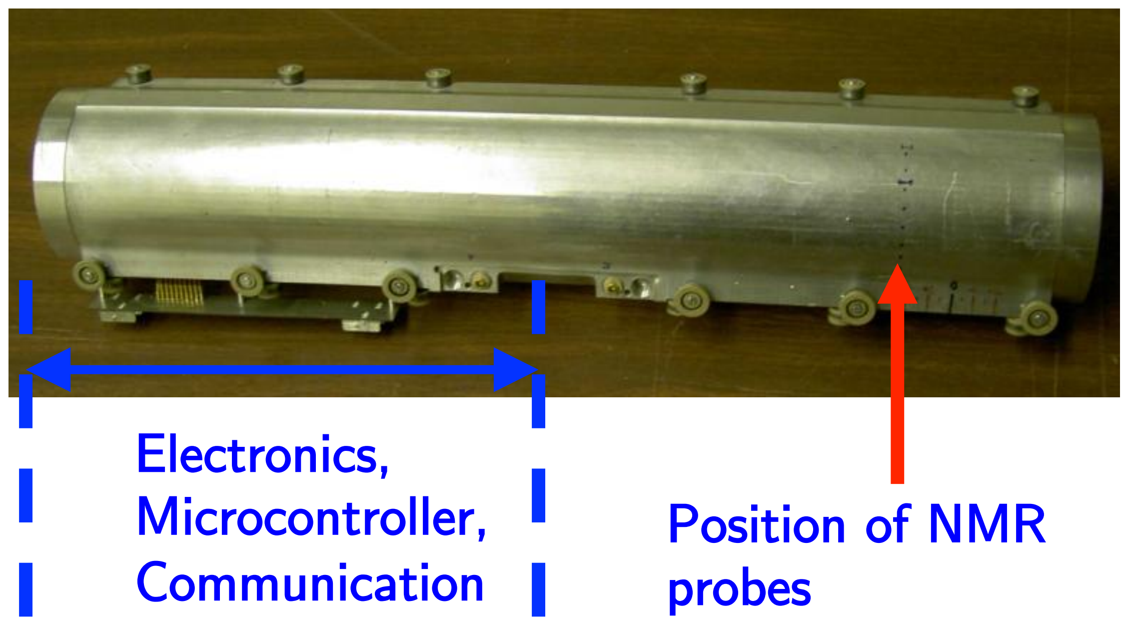
(2) Field inside storage volume measured by NMR trolley, but not when muons stored

- Fixed probes are cross-calibrated when trolley goes by; can infer field inside storage volume when muons stored from fixed probes

Fixed probes on vacuum chambers



Trolley with matrix of 17 NMR probes



(3) Trolley probes calibrated in terms of free proton frequency by an absolute calibration probe

- Construct absolute calibration probe with spherical water sample at known temperature

⇒ Larmor frequency of proton in spherical water sample related to that of free proton by :

$$\omega_p(\mathrm{sph}-\mathrm{H_2O},T) = [1-\sigma(\mathrm{H_2O},T)]\,\omega_p(\mathrm{free}),$$

- $\sigma(\mathrm{H_2O},T) \approx 26$ ppm, is the temperature-dependent diamagnetic shielding of the proton in a water molecule
- E821 absolute calibration probe properties known well enough to determine fields in terms of free protons to accuracy of 0.034 ppm

- E821 used this probe with accuracy of 0.050 ppm (limited in part by temp. uncertainties)
- E989 will repeat and improve study of probe properties, *improve temperature stability and monitoring* to reduce temperature related uncertainties, calibration goal is 0.035 ppm

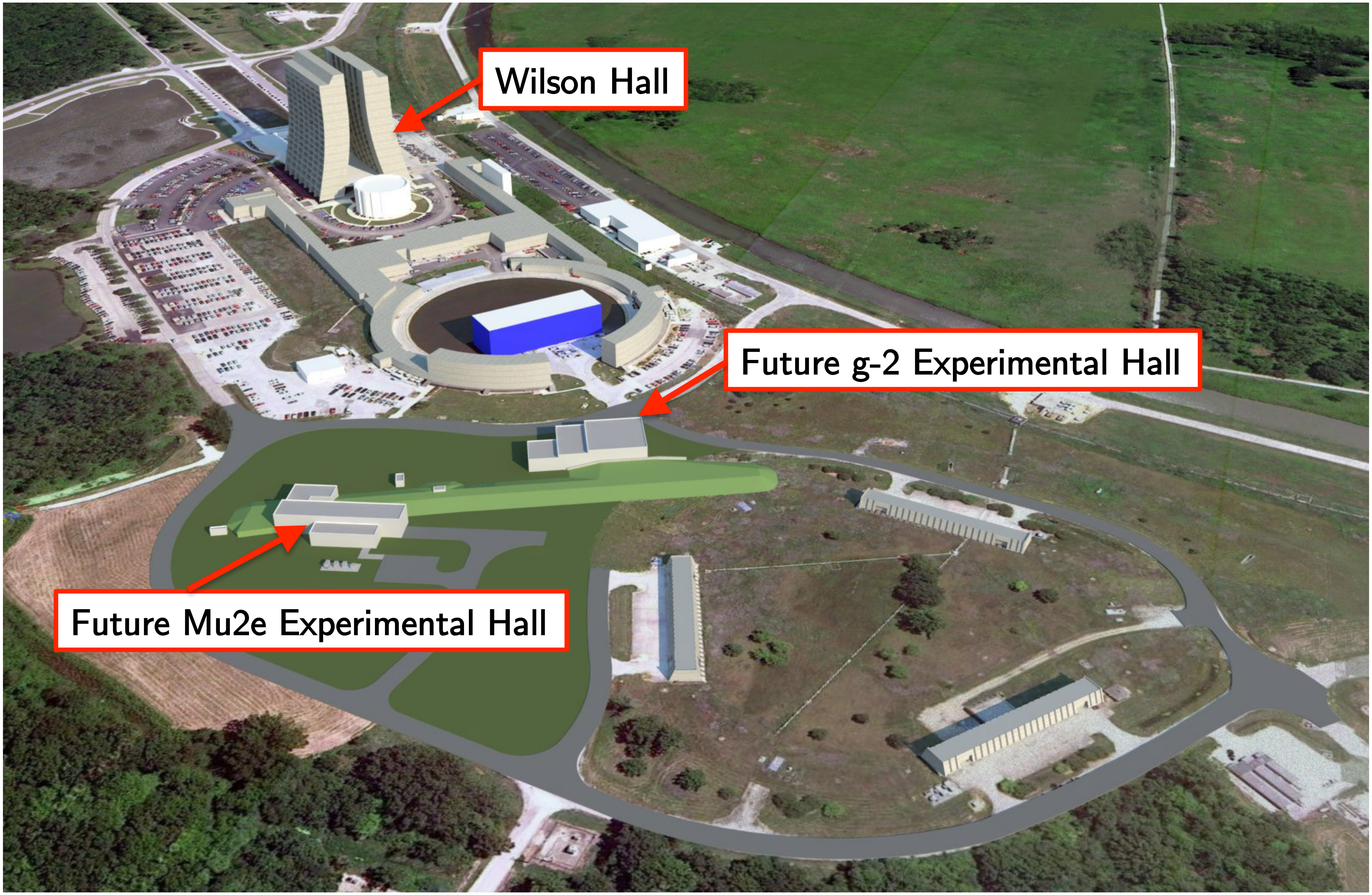
Error budget for the ω_p measurement

- Systematic errors on E821 field measurements from 1999, 2000, 2001 listed below
- The final column lists the uncertainties anticipated for E989

Source of uncertainty	R99 [ppm]	R00 [ppm]	R01 [ppm]	E989 [ppm]
Absolute calibration of standard probe	0.05	0.05	0.05	0.035
Calibration of trolley probes	0.20	0.15	0.09	0.03
Trolley measurements of B_0	0.10	0.10	0.05	0.03
Interpolation with fixed probes	0.15	0.10	0.07	0.03
Uncertainty from muon distribution	0.12	0.03	0.03	0.01
Inflector fringe field uncertainty	0.20	–	–	–
Time dependent external B fields	–	–	–	0.005
Others †	0.15	0.10	0.10	0.03
Total systematic error on ω_p	0.4	0.24	0.17	0.070
Muon-averaged field [Hz]: $\tilde{\omega}_p/2\pi$	61 791 256	61 791 595	61 791 400	–

- †Higher multipoles, trolley temperature (≤ 0.05 ppm/$^\circ$C) and power supply voltage response (0.4 ppm/V, ΔV=50 mV), and eddy currents from the kicker.
- Note the steady reduction in uncertainties achieved in E821

The Future : E989 at the new Muon Campus at Fermilab



Recycler

- Rebunches 8 GeV protons from booster

Target Station

- Target + focusing lens

Decay Line

- Target to M2 to M3 to delivery ring

$\Rightarrow$ 900 m long decay channel for $\pi \Rightarrow \mu$
reduced π and p in ring,
factor 20 reduction in hadronic flash

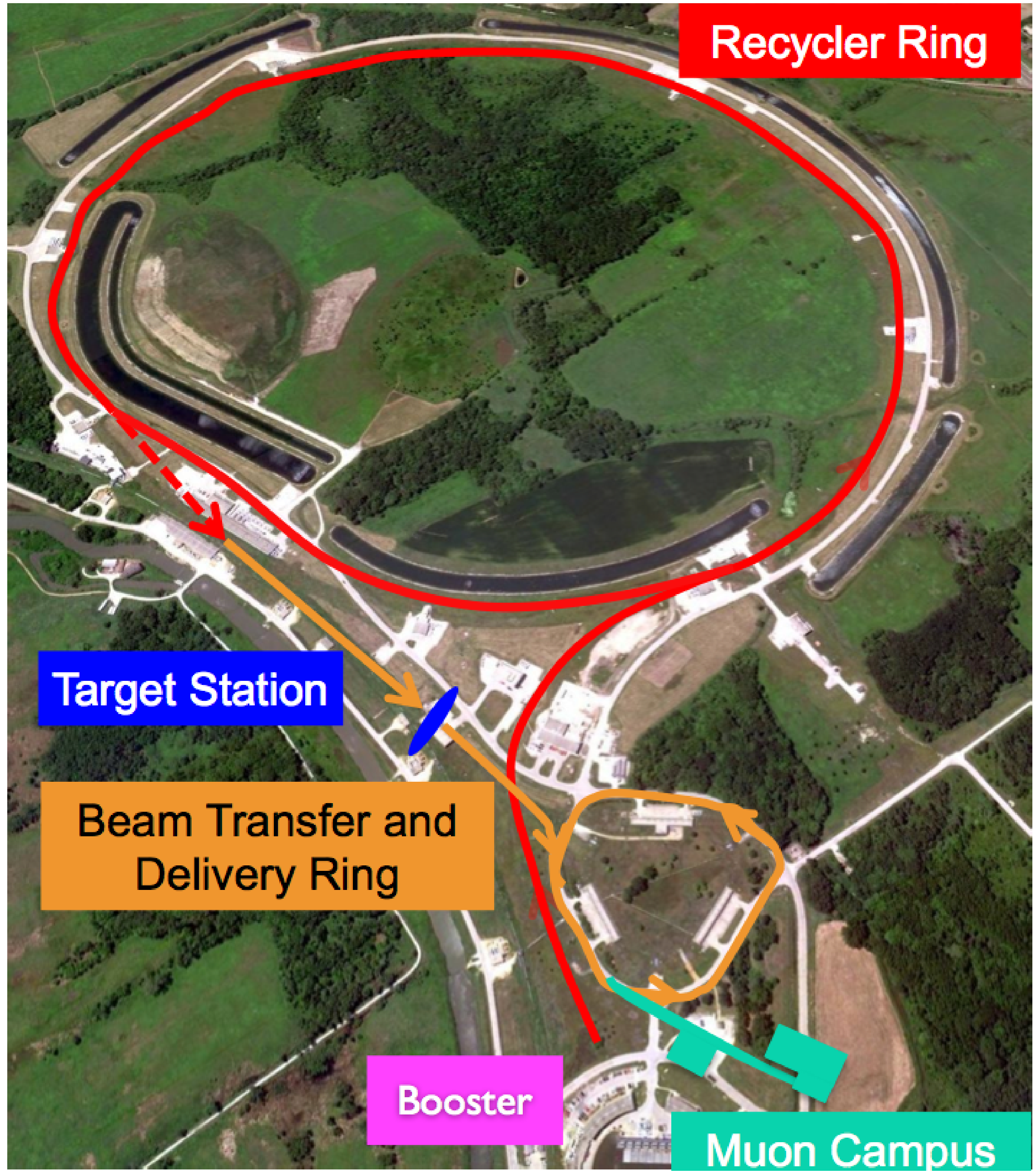
$\Rightarrow$ 4$\times$ higher fill frequency than E821

$\Rightarrow$ Muons per fill about the same

$\Rightarrow$ 21 times more detected e^+, 2×10^{11}

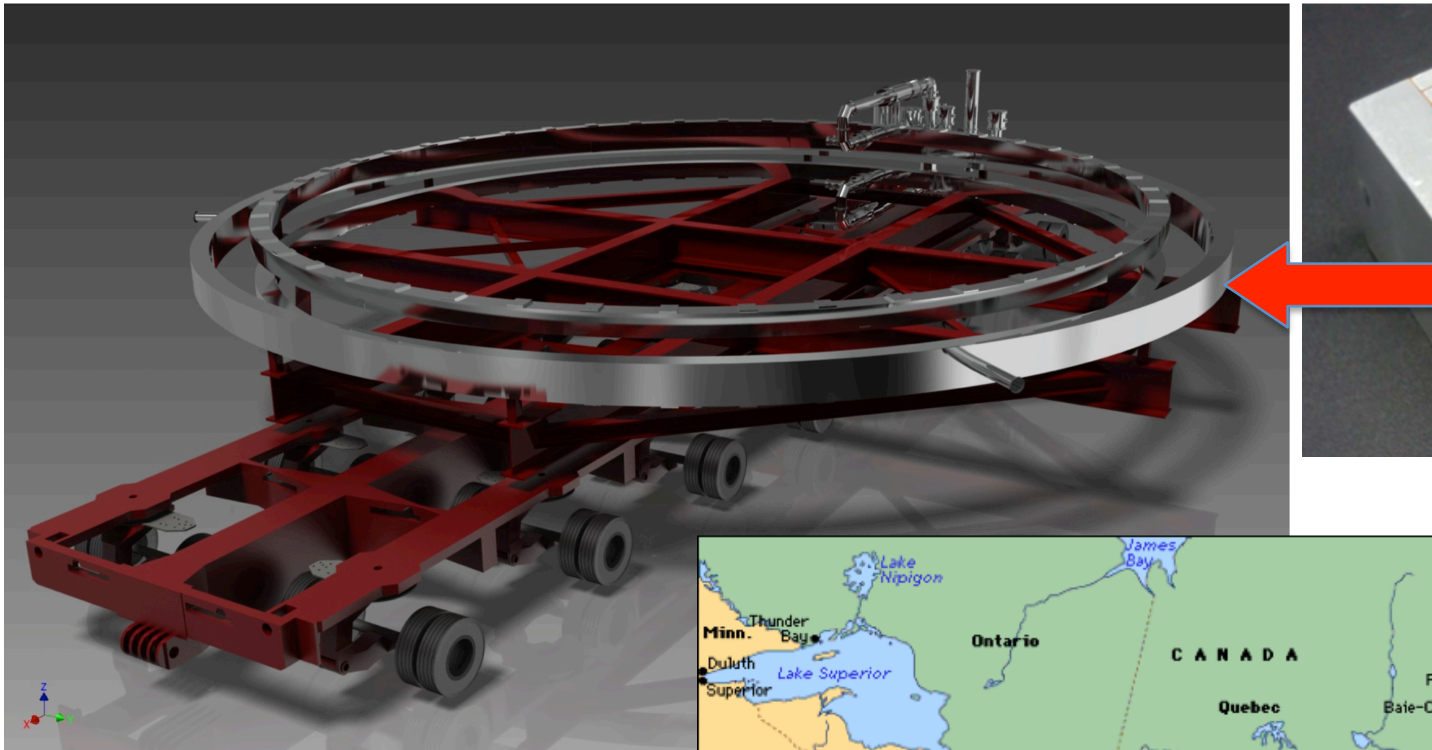
$\Rightarrow$ Better temperature control in experimental hall

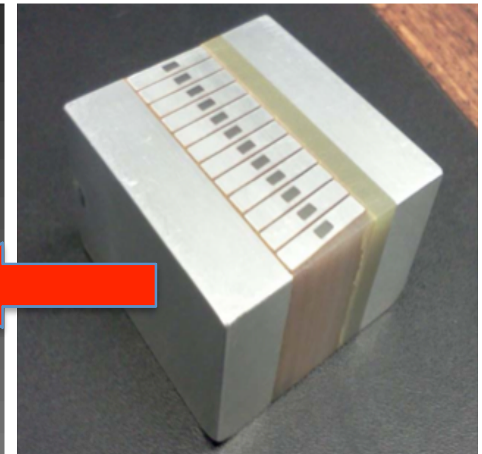
$\Rightarrow$ Reduction in systematics by factor of 3 without major modifications



The Future : E989 at Fermilab

- 650 ton magnet iron yoke and pole pieces are being disassembled, transported by barge
- 8 ton, 15 m diameter superconducting coils must be transported in one piece





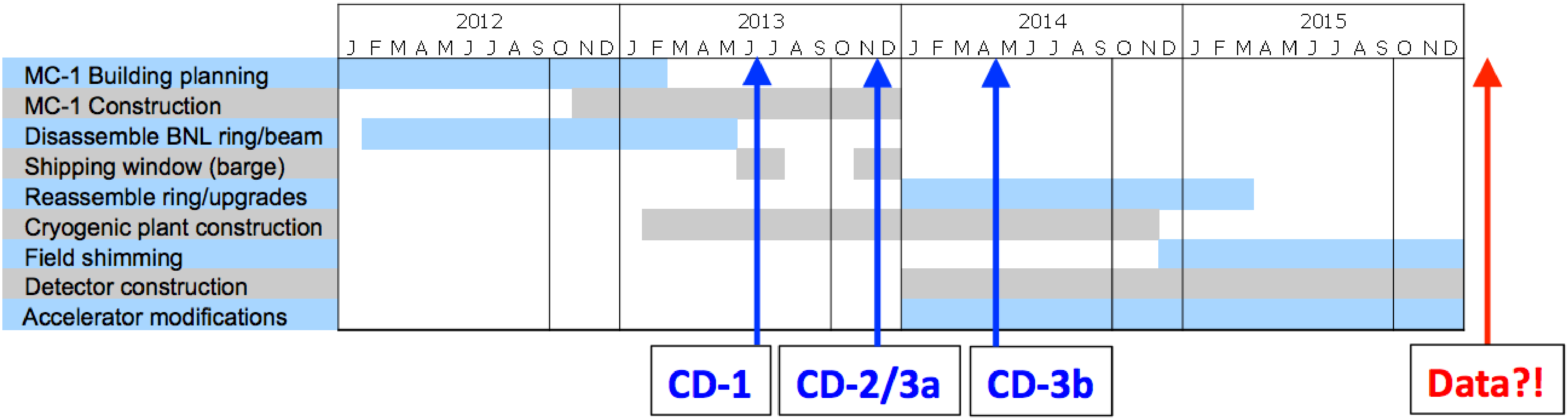
Transporting the coils to FNAL : ~~E-ZP~~ass

- Trailer with coils passes toll arches with 6" clearance on each side
- "Nature is hard and unyielding" - Martin Perl, *Reflections on Experimental Science*
- We were lucky this time

Fermilab E989

- 28 Institutions
- 106 Collaborators

Preliminary Schedule



- Extensive review process. Total project cost is $\approx$ \$40 million : nearly 1/2 is for upgrade of accelerator and new multipurpose facilities at FNAL
- First data in 2016? Run for 2 or more years
- Precision measurements take a lot of patience - but they're worth it

Summary

- Experiment under development to measure a_μ to 0.14 ppm, fourfold improvement over BNL E821
- Reduction in statistical uncertainty by factor 4; reduce ω_a, ω_p systematics by factor 3

- Hope to motivate improvements in theory and more exp. work :
  - Currently δa_μ(HadVP,LO) $=$ 0.36 ppm, and δa_μ(Had,LBL) $=$ 0.23 ppm
- Before E821 (1983), expt. known to 7 ppm, theory to 9 ppm : now 0.54 and 0.42 ppm

- Regardless of where final result for a_μ lands :
  - Precision test Standard Model
  - Determine parameters (tan(β)) or viability of many new physics models predicting $\Delta a_\mu \neq 0$ (SUSY models)
  - UED (1D) predict tiny effects incompatible with $\Delta a_\mu << 300 \times 10^{-11}$
  - Constraint on all future models
  - Provide complementary information to direct searches at LHC, CLFV, EDMs