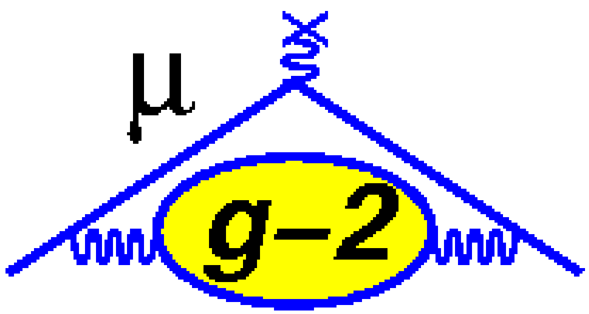
The New Muon g-2 Experiment at Fermilab

Dave Kawall, University of Massachusetts Amherst
on behalf of the E989 Collaboration



Goal : Measure the muon anomalous magnetic moment, a_μ, to 140 ppb, a fourfold improvement over the 540 ppb precision of Brookhaven E821

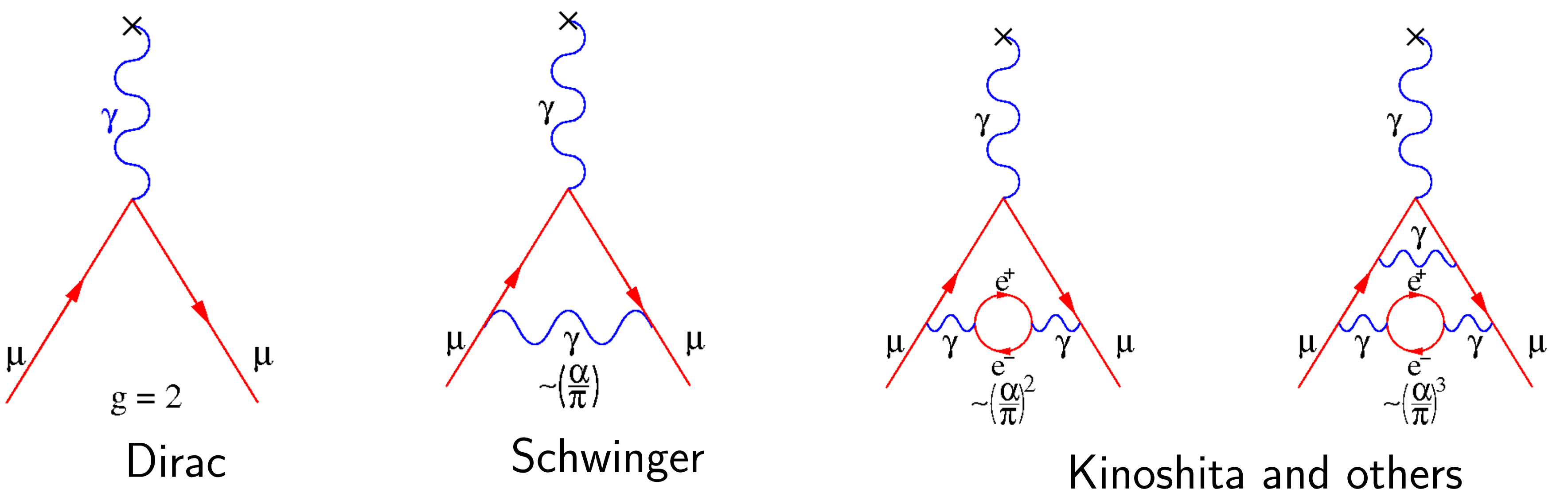
Anomalous part of the Magnetic Moment

- Recall the humble magnetic moment:

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

⇒ Dimensionless g-factor predicted from theory; Dirac $g = 2$ in 1928 for spin 1/2

- 1933 Otto Stern measured proton μ_p: required $g = 5.6$ Spin ⇔ nucleon structure
- 1947 : Rabi 0.3% discrepancies in ground-state HFS of H,D; G. Breit suggests $g_e = 2(1+\epsilon)$
- 1948 : Kusch and Foley measure g_e in Ga, Na; deviates from 2 ⇔ $g_e \equiv 2(1+a_e),\ a_e \neq 0$!
- 1948 : Schwinger QED calculation of *anomalous* part of g_e factor, finds $a_e = \alpha/2\pi$



- $a_e = \alpha/2\pi \approx 0.00116$ 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

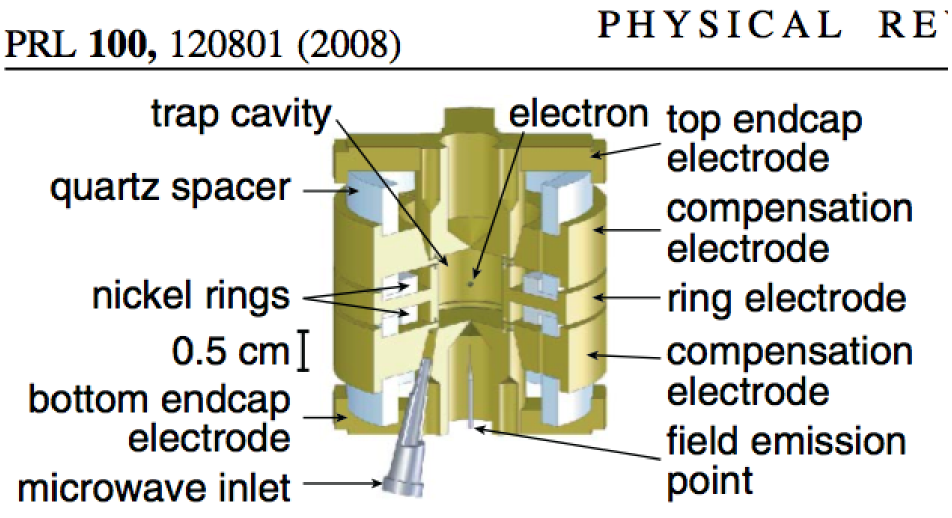


FIG. 2 (color). Cylindrical Penning trap cavity used to confine a single electron and inhibit spontaneous emission.

- D. Hanneke, S. Fogwell, G. Gabrielse, 2008
- Penning trap for single electron
- Magnetic confinement in radial
- Electrodes for vertical confinement
- Trapped for months
- $g_e/2 = 1.001\ 159\ 652\ 180\ 73(28)$ (0.28 ppt), most precise quantity in physics
- $a_e = (g_e - 2)/2$ determined to 0.24 ppb

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

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

---

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

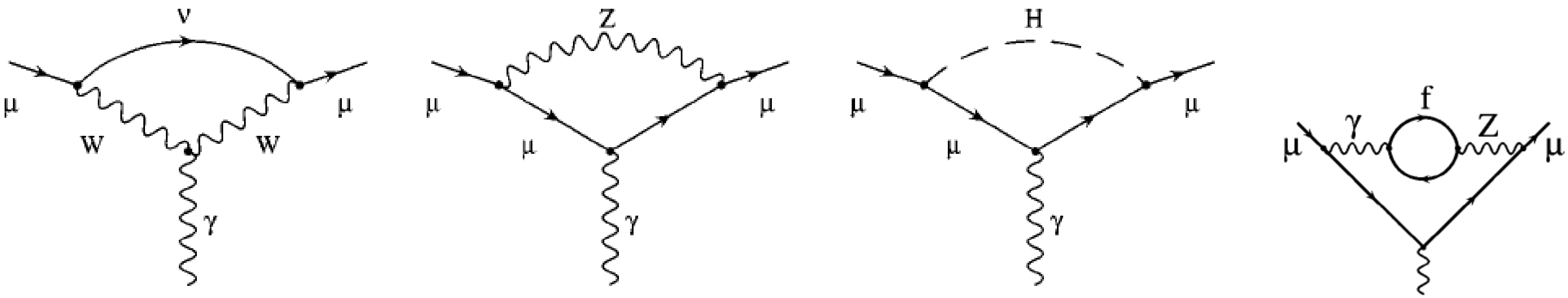
⇒ Muon mass 206 times electron mass, so new physics contribution 43,000 times larger

⇒ 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 540 ppb, hope to push at Fermilab to 140 ppb

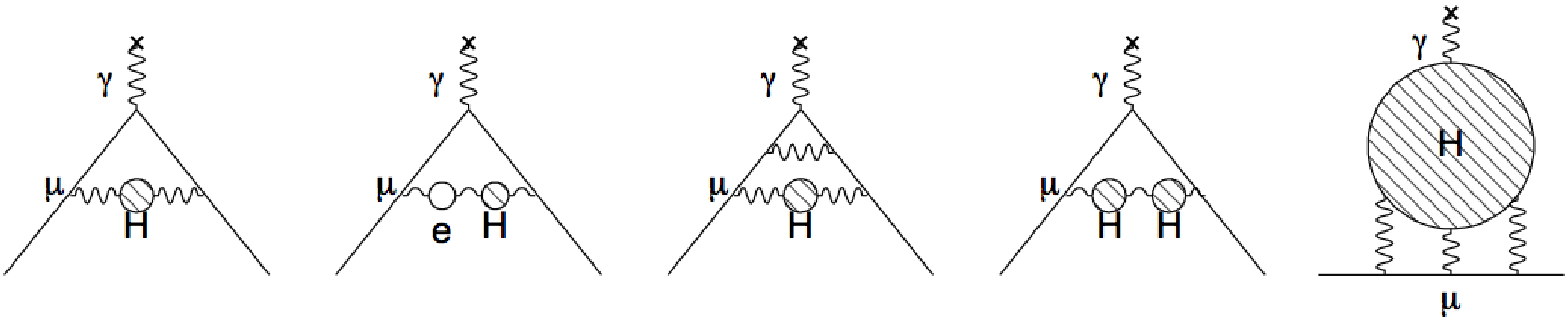
Contributions to the Anomalous Magnetic Moment of the Muon

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



EW 1 Loop

EW 2 Loop



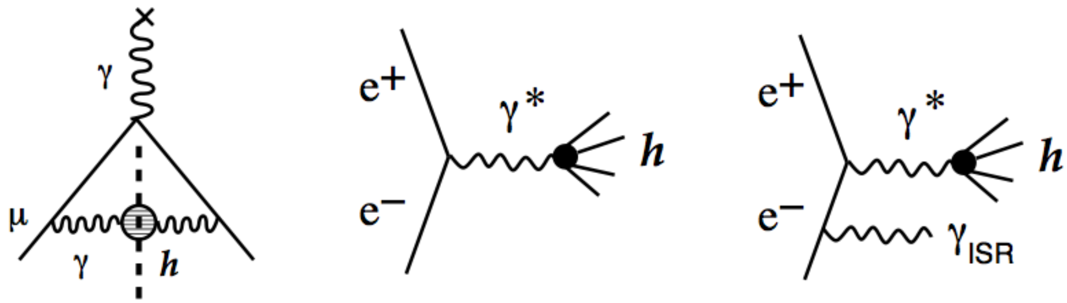
Hadronic Leading Order

Higher Order

Light-by-Light

$\Rightarrow$ a_μ gets contributions from *all* physics - including the unknown

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



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

- 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)

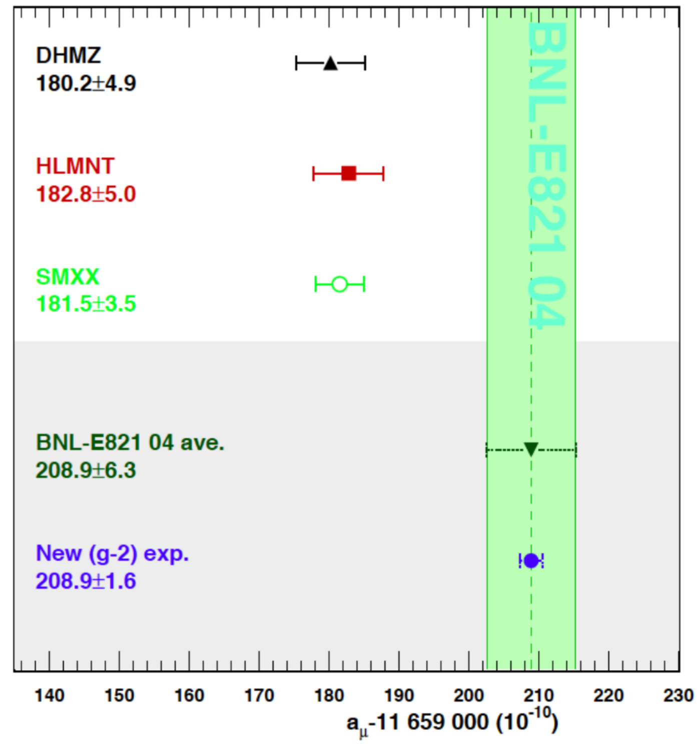
Standard Model prediction, in units of 10^{-11} : (M. Davier *et al.* Eur. Phys. J. C **71**, 1515 (2011))

a_μ(QED)	=	116 584 718.951	$\pm$ 0.080(α^5)	(Kinoshita *et al.* 2012)
a_μ(HadVP; LO)	=	6 923.	$\pm$ 42(Exp)	(Davier *et al.* 2011)
a_μ(HadVP; LO)	=	6 949.	$\pm$ 43(Exp)	(Hagiwara *et al.* 2011)
a_μ(HadVP; HO)	=	-98.4	$\pm$ 0.6(Exp) $\pm$ 0.4(Rad)	(Hagiwara *et al.* 2011)
a_μ(Had; LBL)	=	105.	$\pm$ 26	(Prades *et al.* 2010)
a_μ(Weak; 1 loop)	=	194.8		
a_μ(Weak; 2 loop)	=	-41.2	$\pm$ 1(Had)	(Czarnecki,Marciano,Stöckinger *et al.* 2013)
$\Rightarrow$ 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} :

$$a_\mu(\text{Expt}) = 116\,592\,089 \pm 54 \pm 33 \quad \text{(540 ppb)}$$
$$a_\mu(\text{SM}) = 116\,591\,802 \pm 49 \quad \text{(420 ppb)}$$
$$a_\mu(\text{SM}) = 116\,591\,828 \pm 50 \quad \text{(430 ppb)}$$



$$a_\mu(\text{Expt}) - a_\mu(\text{SM}) = 287 \pm 80\ (3.6\sigma)$$
$$a_\mu(\text{Expt}) - a_\mu(\text{SM}) = 261 \pm 80\ (3.3\sigma)$$

⇒ Theory (HVP from e^+e^-, no τ) from M. Davier *et al.*, Eur. Phys. J. C **71**, 1515 (2011), K. Hagiwara *et al.*, J. Phys. **G38**, 085003 (2011); Plot: T. Blum *et al.*, arXiv:1311.2198

⇒ 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 a better experiment. Need to reduce theoretical uncertainties

Improving the Standard Model Estimate

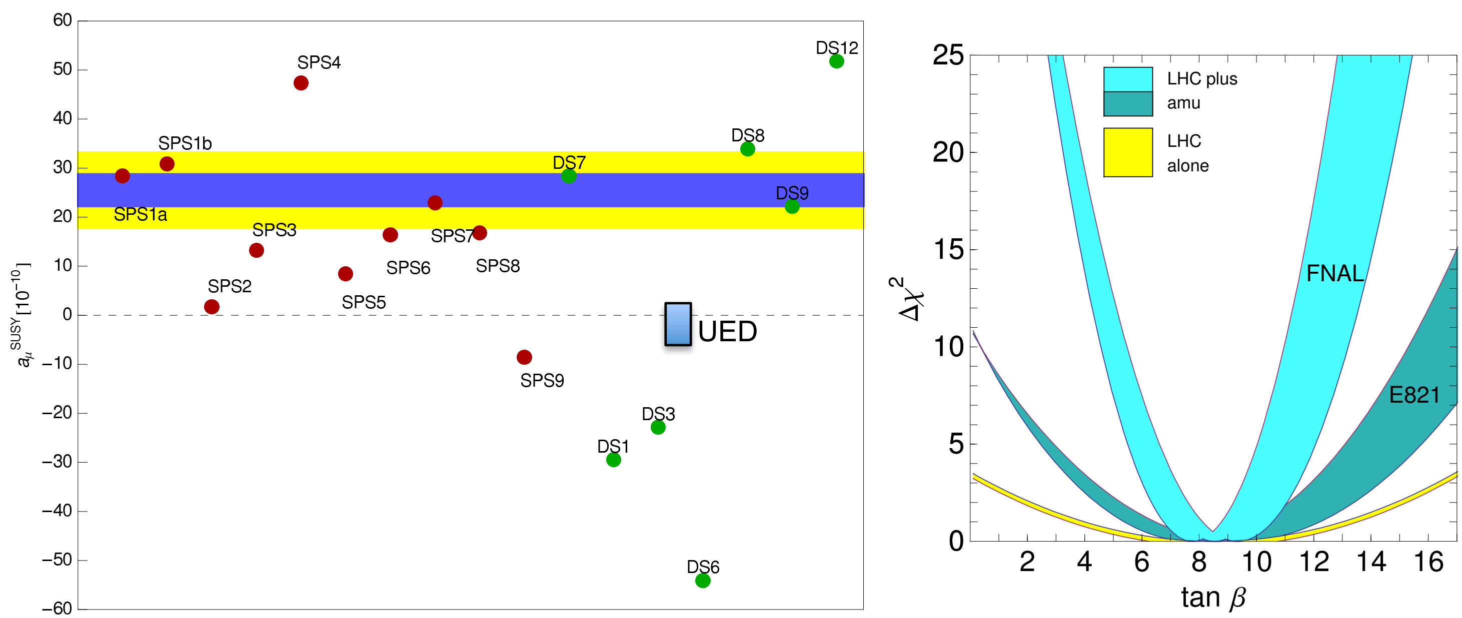
- Substantial e^+e^- cross-section data available soon from VEPP-2000 (SND and CMD3), BESIII - should improve δa_μ(HadLO) significantly
- Lattice estimates at 1% level might by possible

	$\delta(\sigma)/\sigma$ present	δa_μpresent	$\delta(\sigma)/\sigma$ future	δa_μfuture
$\sqrt{s} < 1$ GeV	0.7%	33	0.4%	19
$1 < \sqrt{s} < 2$ GeV	6%	39	2%	13
$\sqrt{s} > 2$ GeV		12		12
total		53		26

- Hadronic light-by-light $(105 \pm 26) \times 10^{-11}$ (1 ppm of a_μ): improve by measurements at BESIII and KLOE-2 of $e^+e^- \rightarrow e^+e^-\gamma^*\gamma^*$ with $\gamma^*\gamma^* \rightarrow \pi^0$
- Lattice estimate of LbL of 30% precision possible 3-5 years

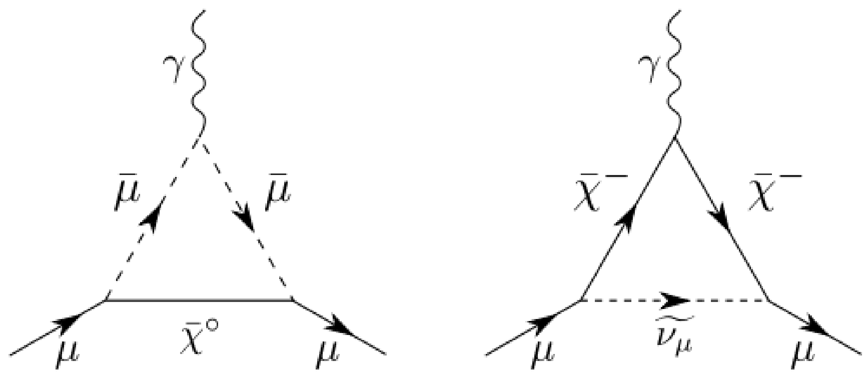
$\Rightarrow$ Reduce theory uncertainty from 50×10^{-10} (0.43 ppm) to 35×10^{-10} (0.30 ppm)

- a_μ sensitive to variety of new physics; including many SUSY models and others
- a_μ sensitive to flavor- and CP-conserving, chirality-flipping, loop-induced contributions
- Most LHC observables chirality conserving; low energy precision observables are CP-violating (EDMs) or flavor-violating (CLFV)



- Snowmass benchmark points in SUSY parameter space show range of contributions to a_μ
- Some models "degenerate" - parameters can't be distinguished by LHC alone, $g_\mu - 2$ helps discriminate, can provide tighter constraints on tanβ
- *Regardless of final value,* a_μ constrains the possibilities, complements other searches

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



- One-loop contributions to anomaly from smuon and neutralino (left) and muon sneutrino and chargino

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

⇒ μ and $\tan\beta$ are difficult to measure at LHC, $g_\mu - 2$ can provide tighter constraints; complementary measurements tanβ important test of universality, underlying structure

- LHC: no evidence of SUSY; TeV-scale limits on squarks, gluinos; looser constraints on smuons, charginos, neutralinos
- If SUSY is origin of deviation in a_μ some SUSY masses less than 700 GeV for tan$\beta < 50$ (smuons, charginos/neutralinos)
- Room for new, well-motivated physics not yet excluded by LHC

Low Energy Precision Tests : Motivation for reducing uncertainty on a_μ

- a_μ sensitive to leptonic couplings; $b-$, or $K-$physics sensitive to hadronic couplings
- CLFV $\mu \to e$ conversion depends on mass and coupling strength of new physics (several unknowns); g_μ help determine nature of new physics
- Dark sector models with additional light neutral gauge bosons mostly hidden from LHC, visible to $g_\mu - 2$

- 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 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 ($\mu \to e$), EDMs, ...

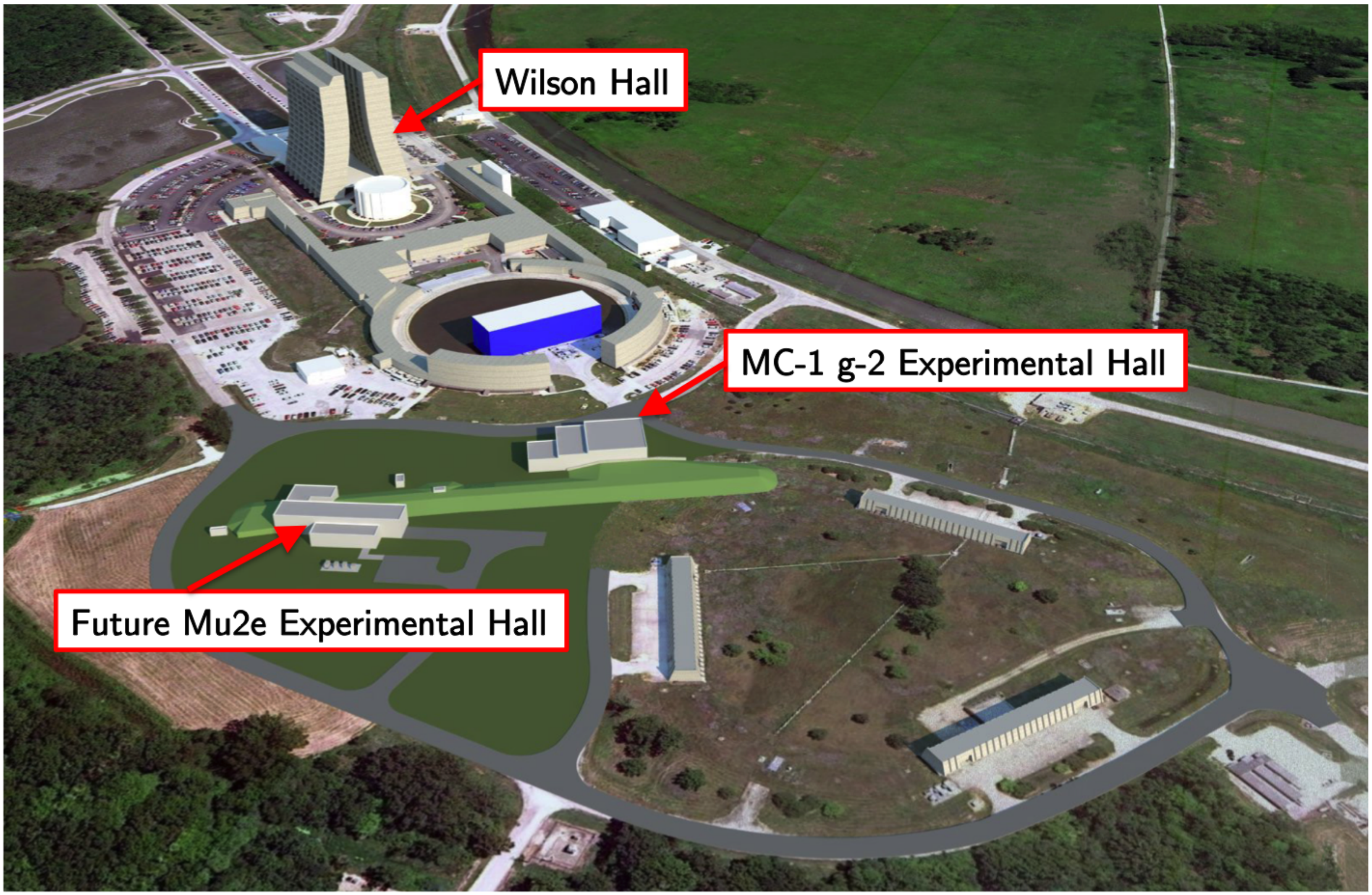
$\Rightarrow$ Sensitivity to new particles close to TeV scale mass

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

$\Rightarrow$ Many reasons to pursue a new measurement of a_μ at Fermilab, reduce δa_μ from 540 ppb $\to$ 140 ppb

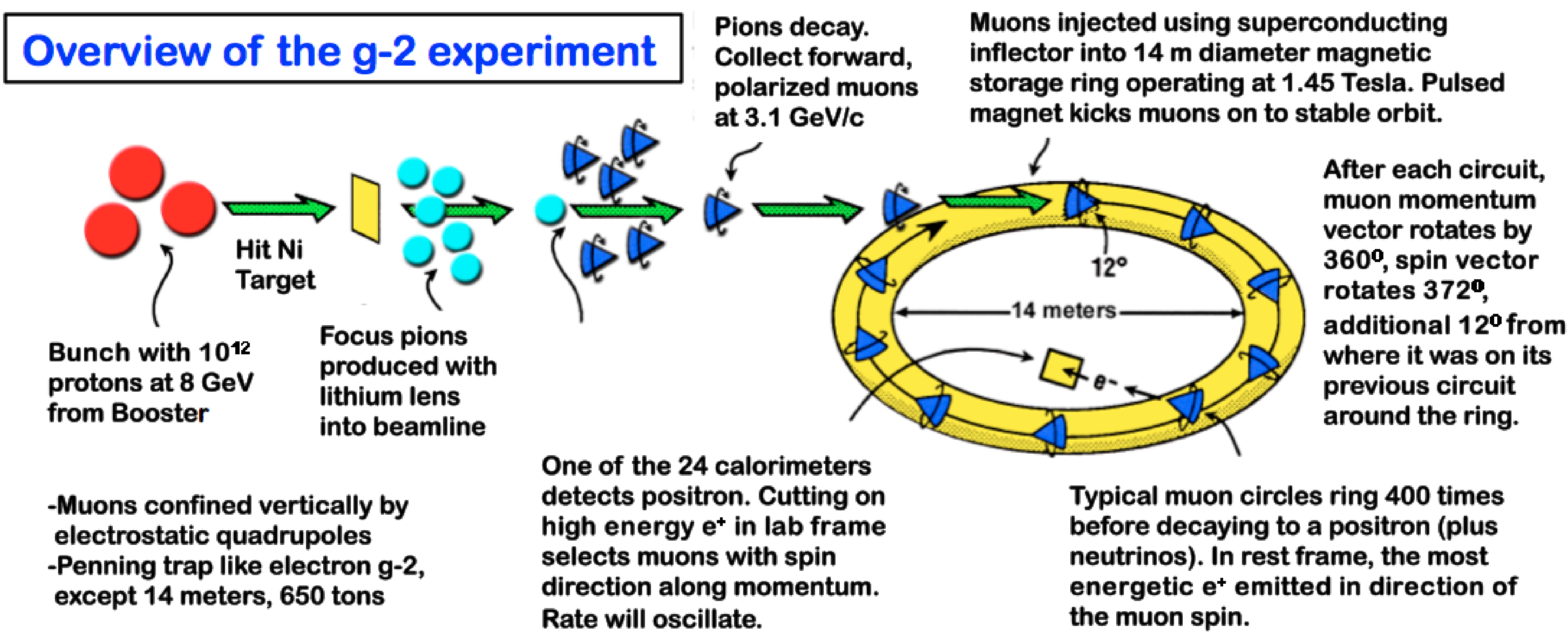
E989 : New Muon g_μ-2 Experiment at Fermilab

- E989 will measure the Muon Anomalous Magnetic Moment to ± 140 ppb precision
- Factor of 4 improvement possible due to advantages at Fermilab



Overview of the the Experimental Method

- Produce an 8 GeV pulsed proton beam 10^{12}/pulse, direct it onto a Ni production target
- Capture pions from production target with lithium lens into long decay beam line
- Capture muons at 3.1 GeV/c, >90% polarized from "forward" pion decay $\pi^+ \to \mu^+ \nu_\mu$
- Polarized muons enter storage ring through SC inflector that cancel storage ring $\boldsymbol{B}$ field
- Kick the 3.094 GeV/c muon beam onto a stored orbit radius=711.2 cm with pulsed magnets
- Measure arrival time and energy of e^+ from muon decay in ring $\mu^+ \to e^+ \bar{\nu}_\mu \nu_e$ for 10+ lifetimes, 700 μs



Overview of the the Experimental Method

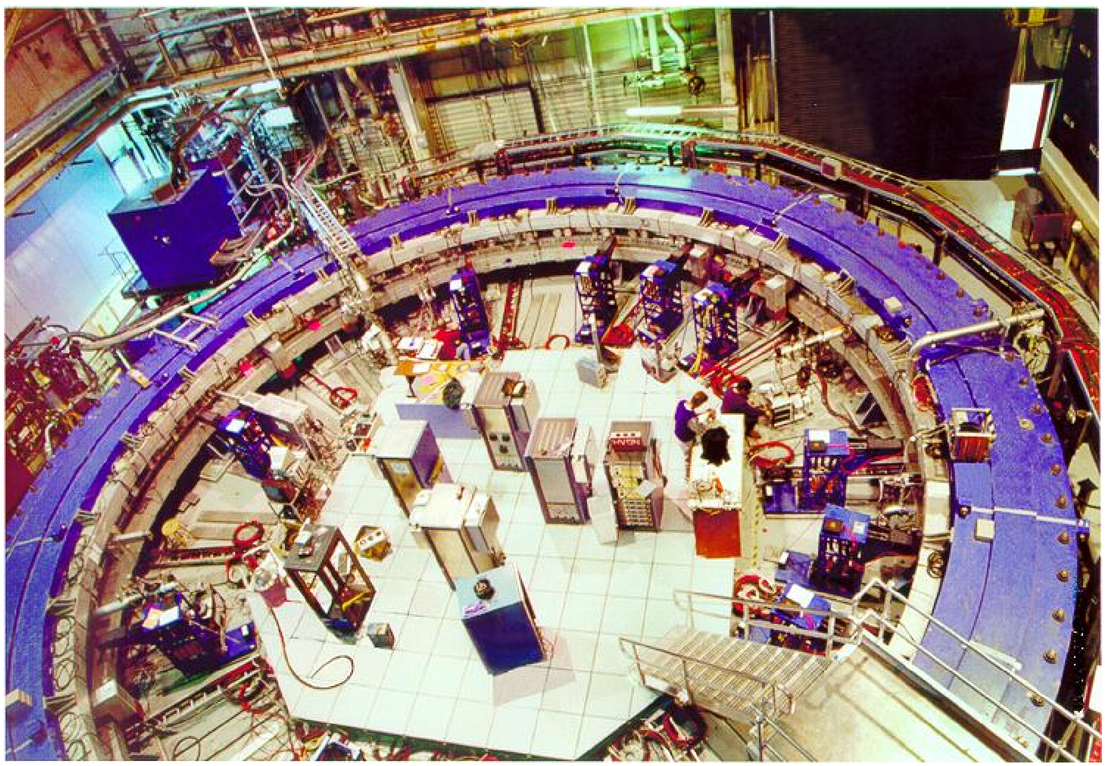
- Thomas-BMT: Spin vector precession ω_s faster than momentum vector cyclotron precession ω_c:

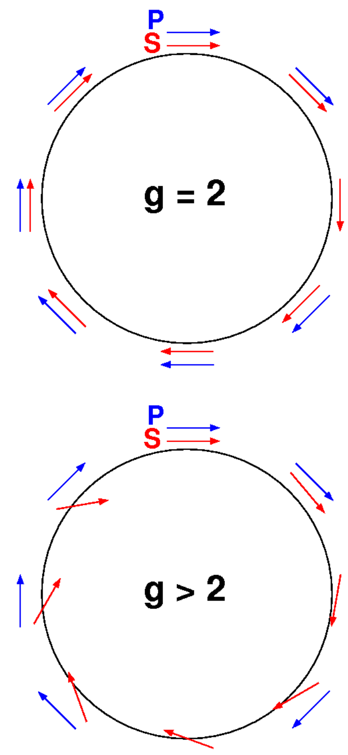
$$\vec{\omega}_a = \vec{\omega}_S - \vec{\omega}_C = -\frac{e}{m}\left[a_\mu \vec{B} - \left(a_\mu - \left(\frac{mc}{p}\right)^2\right)\frac{\vec{\beta}\times\vec{E}}{c}\right]$$

- Cancel term from electrostatic vertical focusing at $p_{\rm magic} = m_\mu c/\sqrt{a_\mu} \approx 3.094$ GeV/c

⇒ Experiment measures two quantities: (1) difference in precession rates - anomalous precession frequency ω_a and (2) magnetic field $\vec{B}$ averaged over muon distribution in ring

- Difference directly sensitive to $a_\mu \approx \alpha/2\pi \approx 0.00116...$, not $g_\mu \approx 2.00232...$

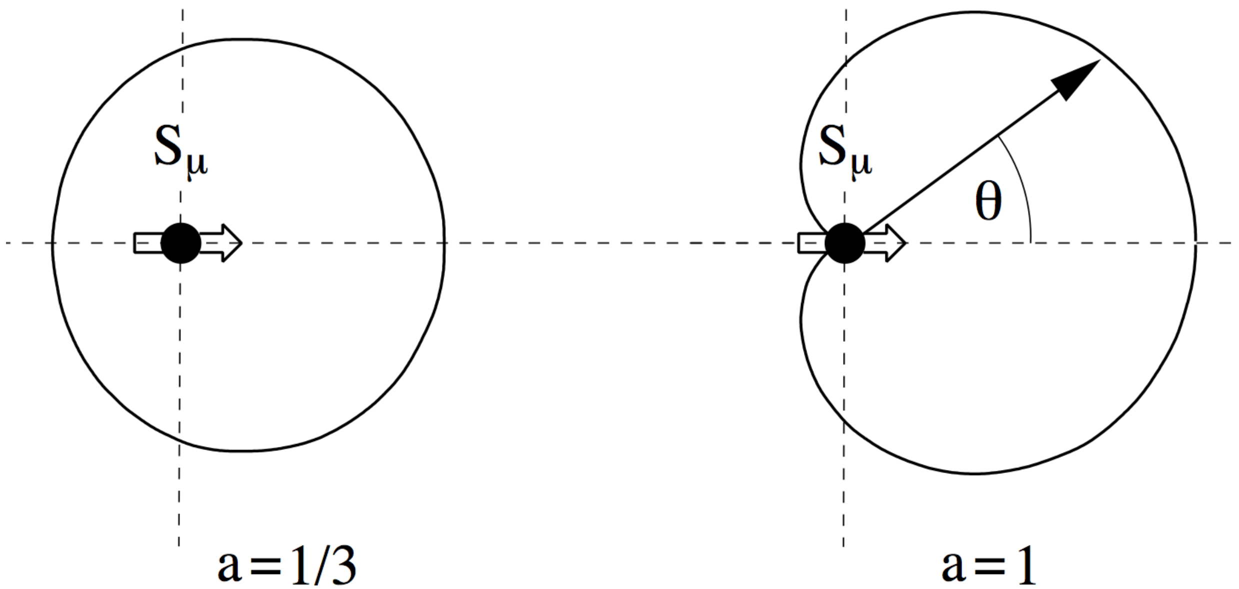




Sub-ppm corrections applied due to vertical betatron motion (pitch correction) and muons not at magic γ

How will we measure ω_a ?

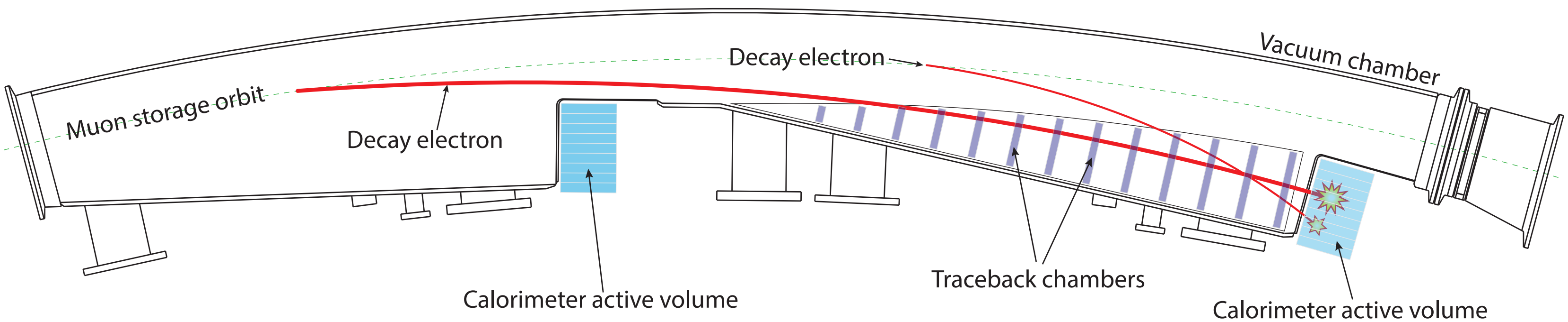
- To measure ω_a, need to know muon spin direction when it decayed
- Nature is kind here : muon decay $\mu^+ \rightarrow e^+\nu_e\bar{\nu}_\mu$ is self-analyzing due to PV
- Rest frame: Muon spin direction correlated with decay positron direction



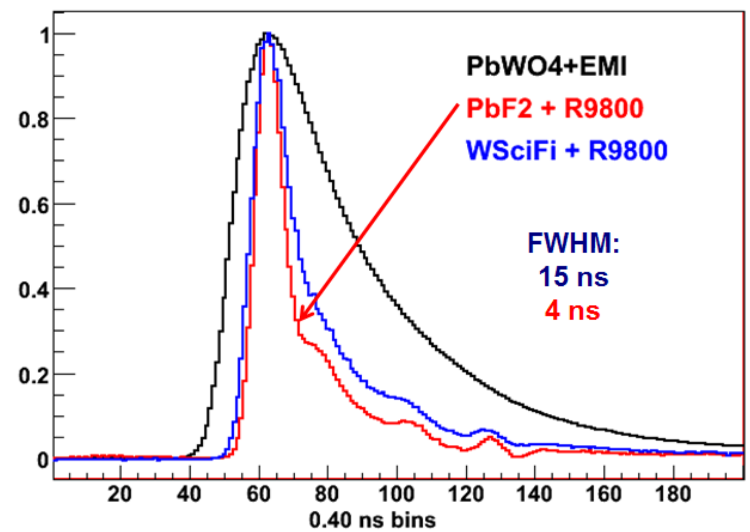
- Averaged over all positron energies, forward-backward asymmetry wrt muon spin is a=1/3
- For highest energy positrons (3.1 GeV), asymmetry a=1
- $E_{\rm lab} \approx \gamma E^* \left(1 + \cos\theta^*\right)$ $\Rightarrow$ positron energy correlated with muon spin
- Detect decay e^+ above 1.8 GeV $\Leftrightarrow$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

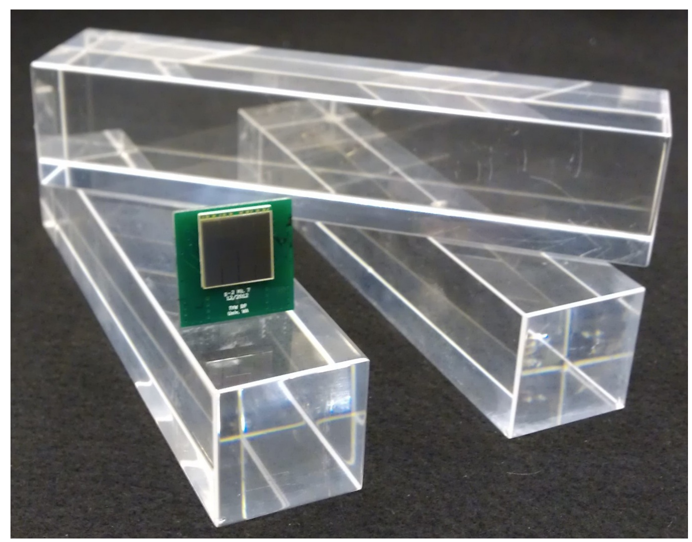
Figures from thesis of Alex Grossmann

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



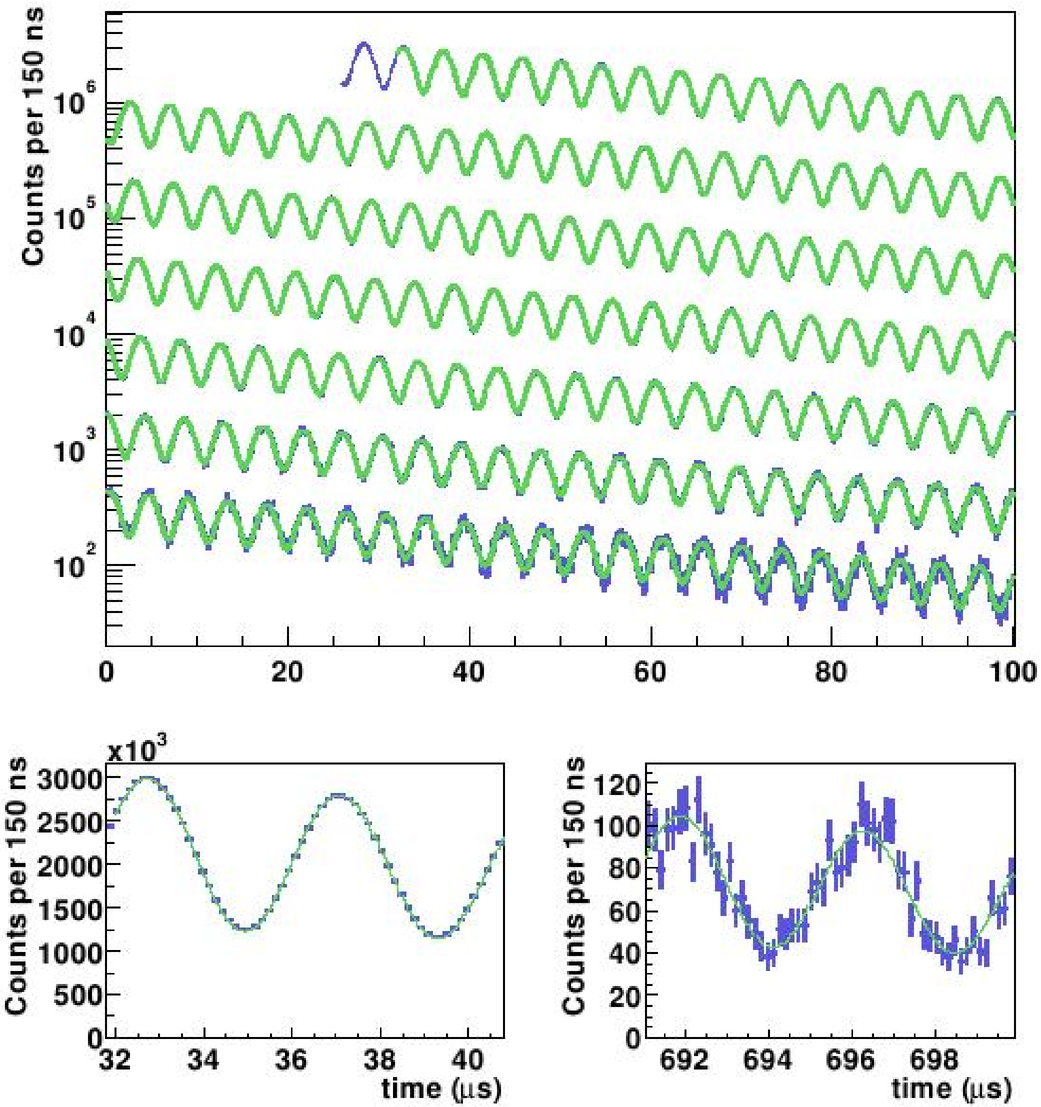
- 24 calorimeter stations detect e^+ from muon decay - made from PbF_2 crystals
- Calorimeter segmented to handle pileup: 9×6 crystals of 2.5×2.5×14 cm^3
- Čerenkov light detection with silicon photomultipliers (SiPMs), E resolution 2.8% at 3.5 GeV
- Smaller Moliere radius (1.8 cm), X_0=0.93cm, greater segmentation, greater immunity to pileup then BNL E821
- Signals digitized with 800 MHz 12-bit waveform digitizers for 700+ μs, extract e^+ signals offline





Measurement of ω_a

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



⇐ Wiggle plot from BNL E821

- $\omega_a \approx \frac{e}{m} a_\mu B = 2\pi \times 229$ kHz
- $3.6 \times 10^9\ e^+$ above 1.8 GeV/c

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

- $\gamma\tau \approx\ 64.4\ \mu$s, $A \approx\ 0.4$, $P \approx 0.95$
- Need $N \approx 1.6 \times 10^{11}$ for 100 ppb
- Corrections for muon losses, pileup, coherent betatron oscillations

Projected Systematic Uncertainties on ω_a and Comparison with BNL E821

- Largest systematics uncertainties on ω_a from BNL E821 and FNAL E989 goals:

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

- Lab-frame energies of e^+ from μ^+ decay depend on angle between μ spin and momentum vectors; highest energy when parallel
- Detector gain changes affect reconstructed e^+ energy, changes phase of detected μ^+

$\Rightarrow$ $\phi_0 \Rightarrow \phi_0 + (d\phi/dt)\delta t \;\Rightarrow\; \cos(\omega_a t + \phi_0) \Rightarrow \cos\left[(\omega_a + d\phi/dt)t + \phi_0\right]$

- Hadronic flash much reduced from BNL E821, detectors remain on during muon injection

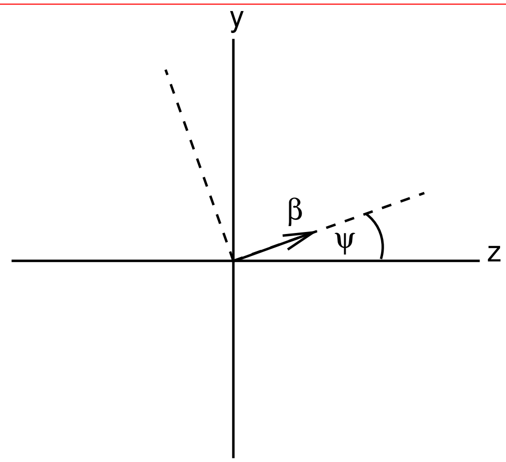
Corrections to ω_a: Electric Field and Pitch Correction

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

- Electric field correction: 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
- Measure momentum distribution from fast-rotation analysis, decay e^+ tracking chambers, muon fiber beam monitors: BNL E821 correction $+470$ ppb

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

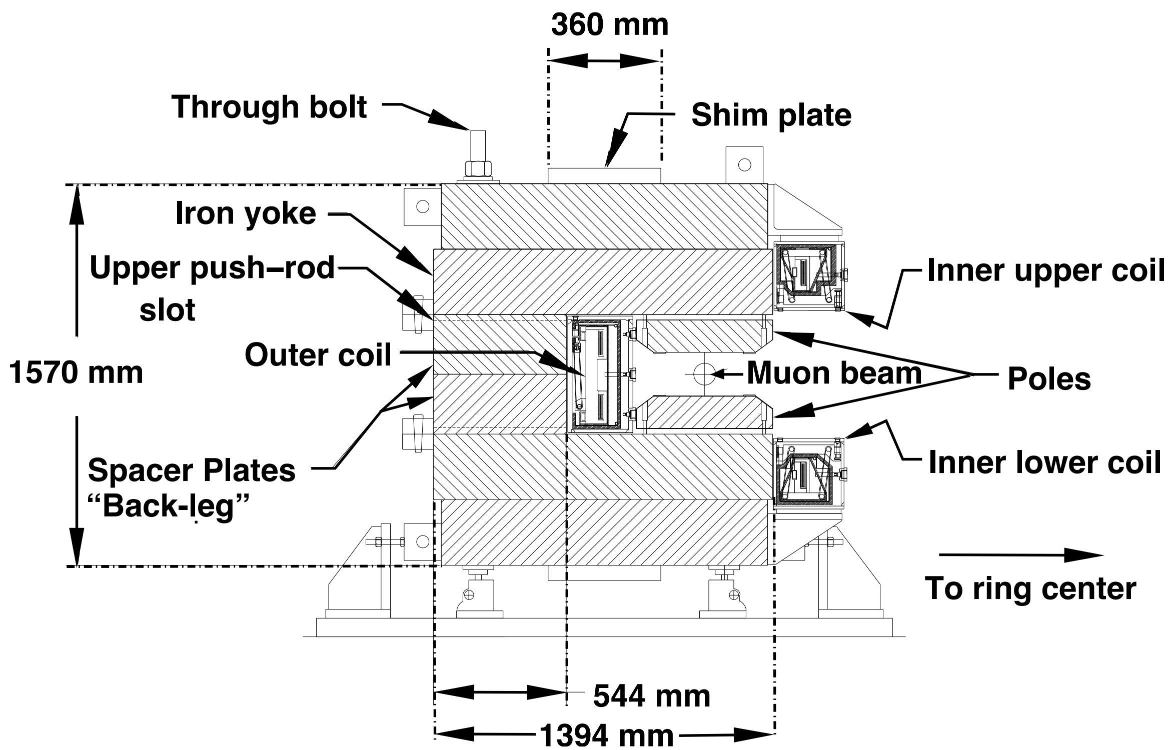
$$\omega_a' \approx \omega_a\left(1 - \frac{\psi^2}{2}\right)$$

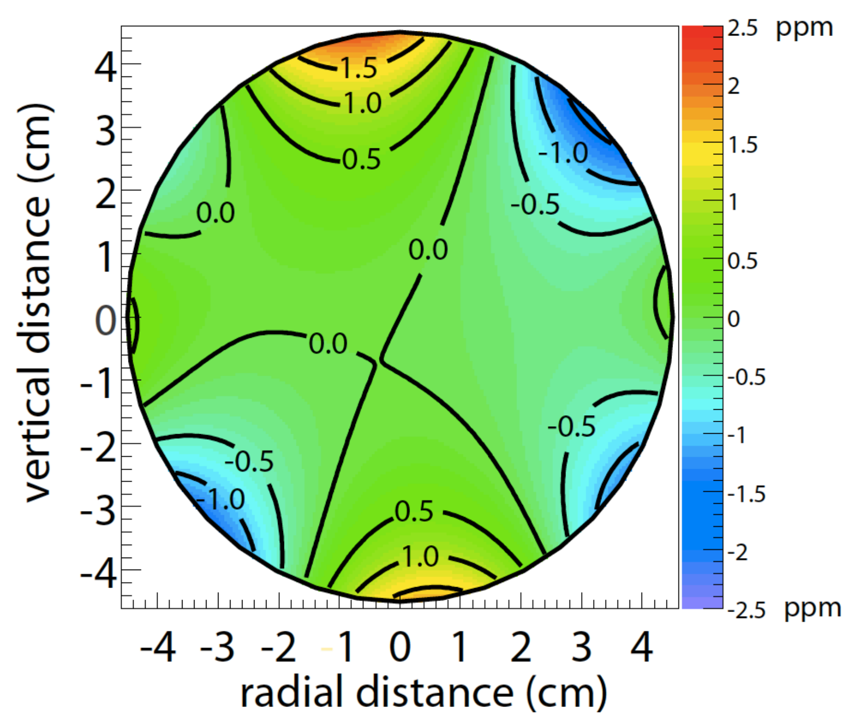


- BNL E821 pitch correction $+270 \pm 36$ ppb
- Electric field and pitch corrections reduce observed frequency, only corrections made
- Improved E989 muon tracking brings E field and pitch uncertainties to 30 ppb level

Measuring ω_p: The Storage Ring Magnet

- Superferric C-magnet, 680 tons of iron, 4 superconducting coils 24 windings each, 5200 A, 7.112 m radius, 9 cm diameter storage volume, 1.4513 T
- Need to know $\boldsymbol{B}$ absolutely at 70 ppb level $\Rightarrow$ high homogeneity and stability required
- Designed as shimmable kit : passive (wedges, edge shims), active (surface coils)





- BNL E821 achieved high homogeneity $\approx \pm 60$ ppm variations over azimuth
- Average over azimuth $\Rightarrow$ at 1 ppm level over muon storage volume

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

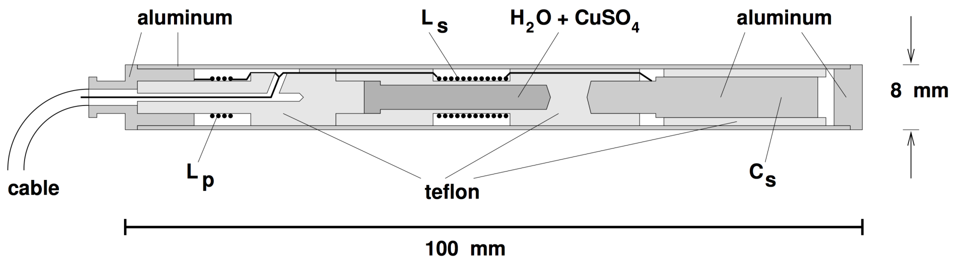
- E989 relies on precision measurement of two quantities, ω_a and magnetic field $B \approx 1.4513$T:
- Measure field with pulsed proton NMR: $\hbar\omega_p = 2\mu_p B$

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

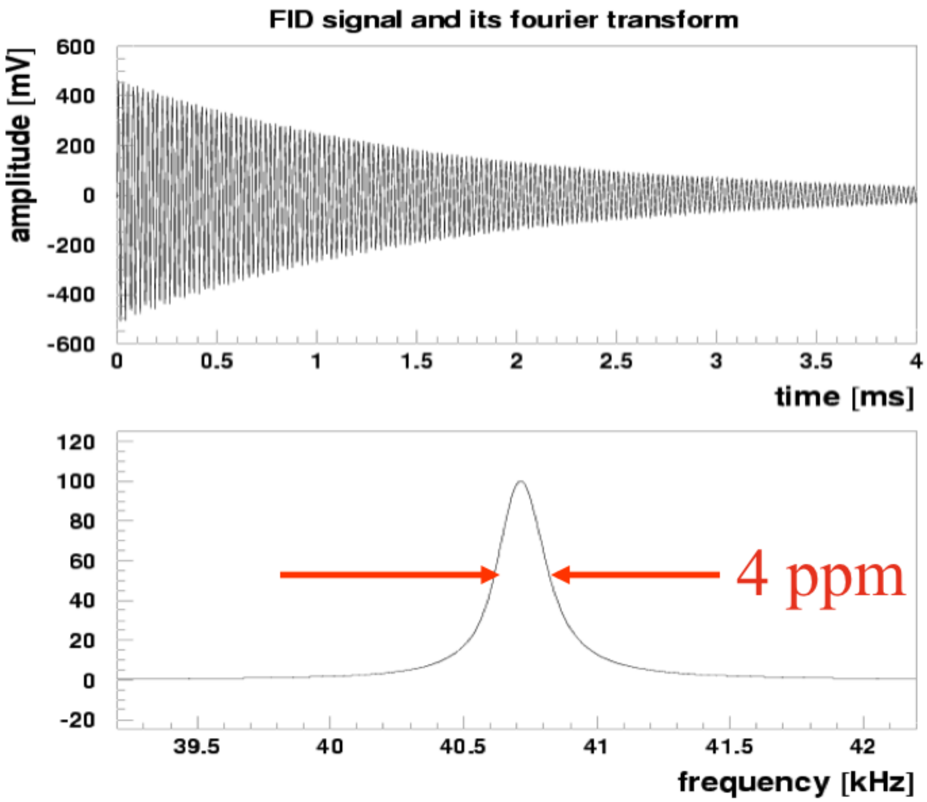
- ω_p : free proton precession frequency weighted by muon distribution $\approx 2\pi \times 61.79$ MHz

$\Rightarrow$ Goal is to determine ω_p, reducing uncertainty from 170 ppb (BNL E821) to 70 ppb (E989)

B Field Measurement with Pulsed NMR



- Field measured with ≈ 400 new NMR probes positioned around 45 meter circumference of ring



⇐ Free induction decay signal 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
- Fractional resolution:
  $\delta f_{\mathrm{NMR}}/f_{\mathrm{NMR}}$ = 1.3 Hz/61.79 MHz $\Leftrightarrow$

  20 ppb resolution on field, single shot

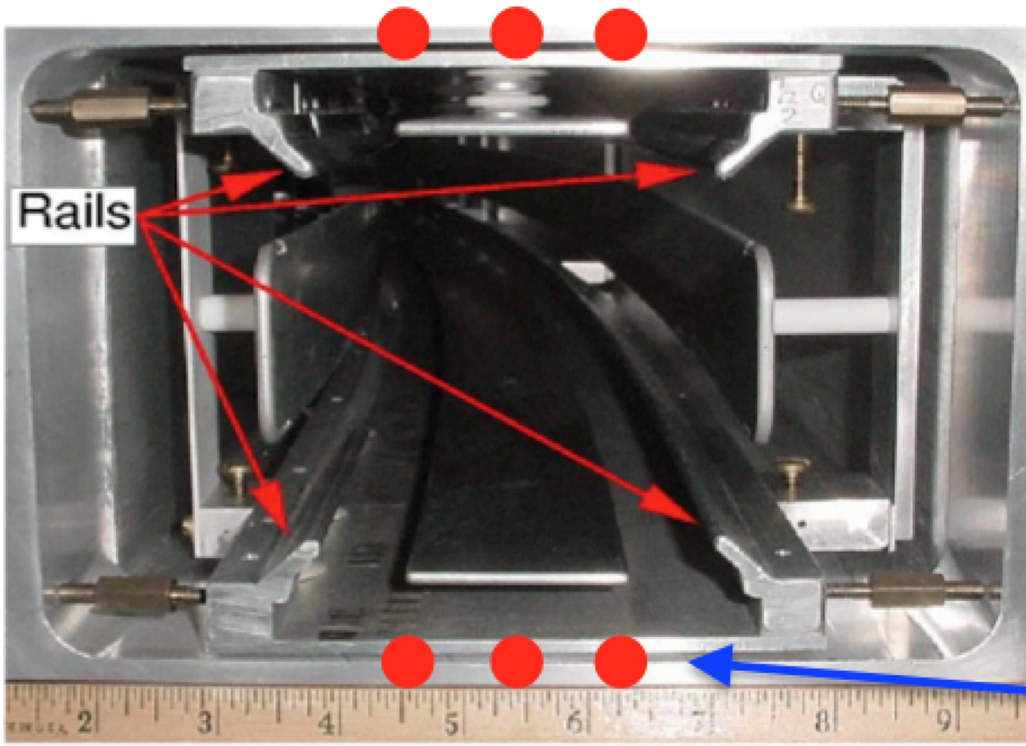
- Fully digitization of FIDs: more robust and higher resolution field determination
- Corrections necessary to get from measurements in NMR probes to ω_p of *free proton*

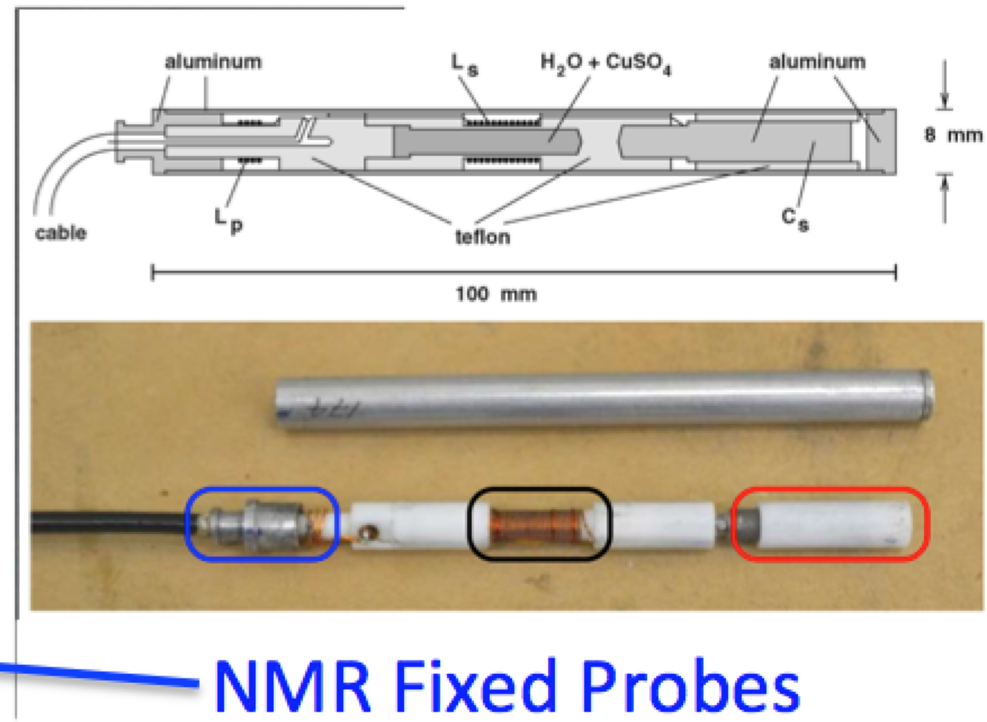
$\Rightarrow$ Need absolute calibration of probes in terms of free proton precession frequency; demonstrated at level of 34 ppb (see X. Fei *et al.*, Nucl. Inst. Meth. A **394**, 349 (1997))

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

(1) Fixed NMR probes measure field at same time as muons stored, but outside storage volume in almost 400 locations

- All probes to be read out every 3 seconds

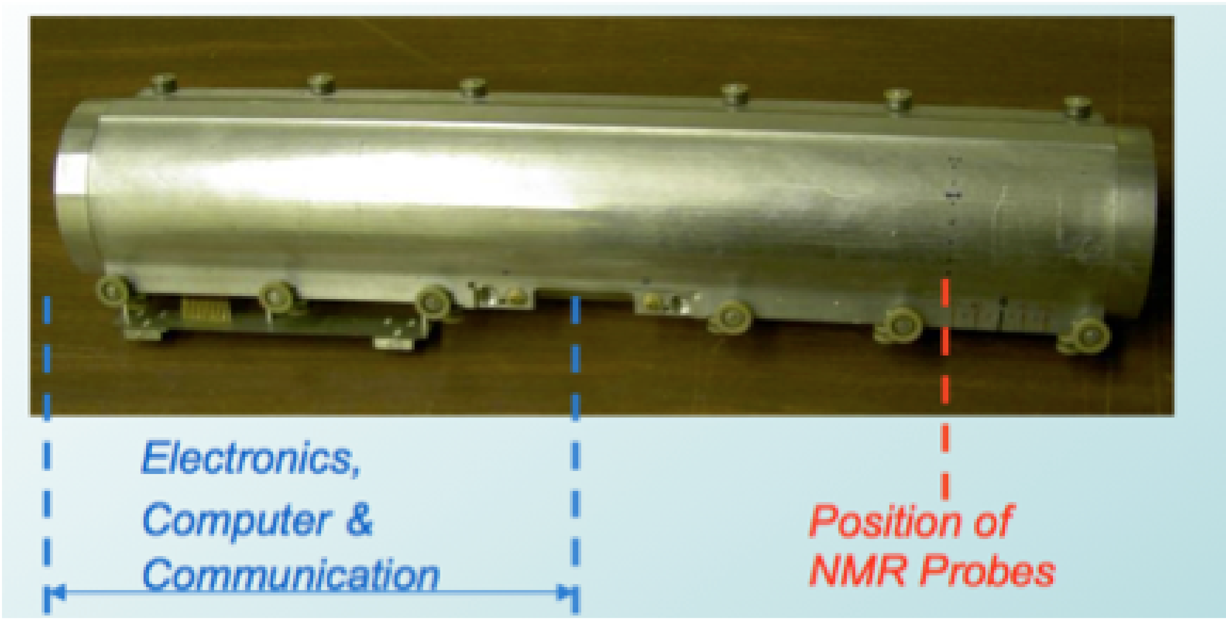


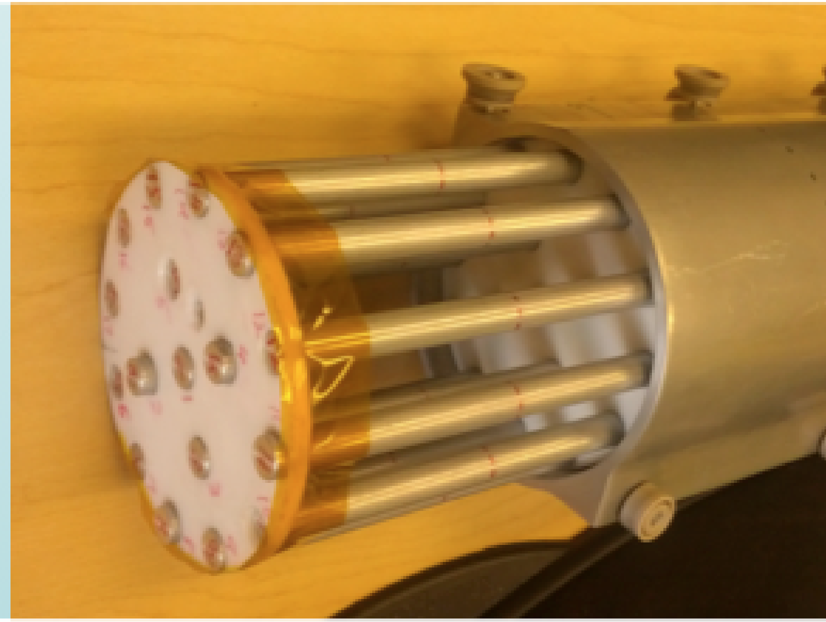


Overview of $\mathbf{B}$ Field Measurement: NMR Trolley

(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





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

Systematics Improvements over BNL E821

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

- Improved temperature and floor stability in new experimental hall will help

E989 : Fermilab offers advantages, factor 4 improvement possible

Recycler

- Rebunches 8 GeV protons from booster

Target Station

- Target + focusing lens

Decay Line

- Target to M2 to M3 to delivery ring

⇒ 1900 m long decay channel for $\pi \Rightarrow \mu$
reduced π and p in ring,
factor 20 reduction in hadronic flash

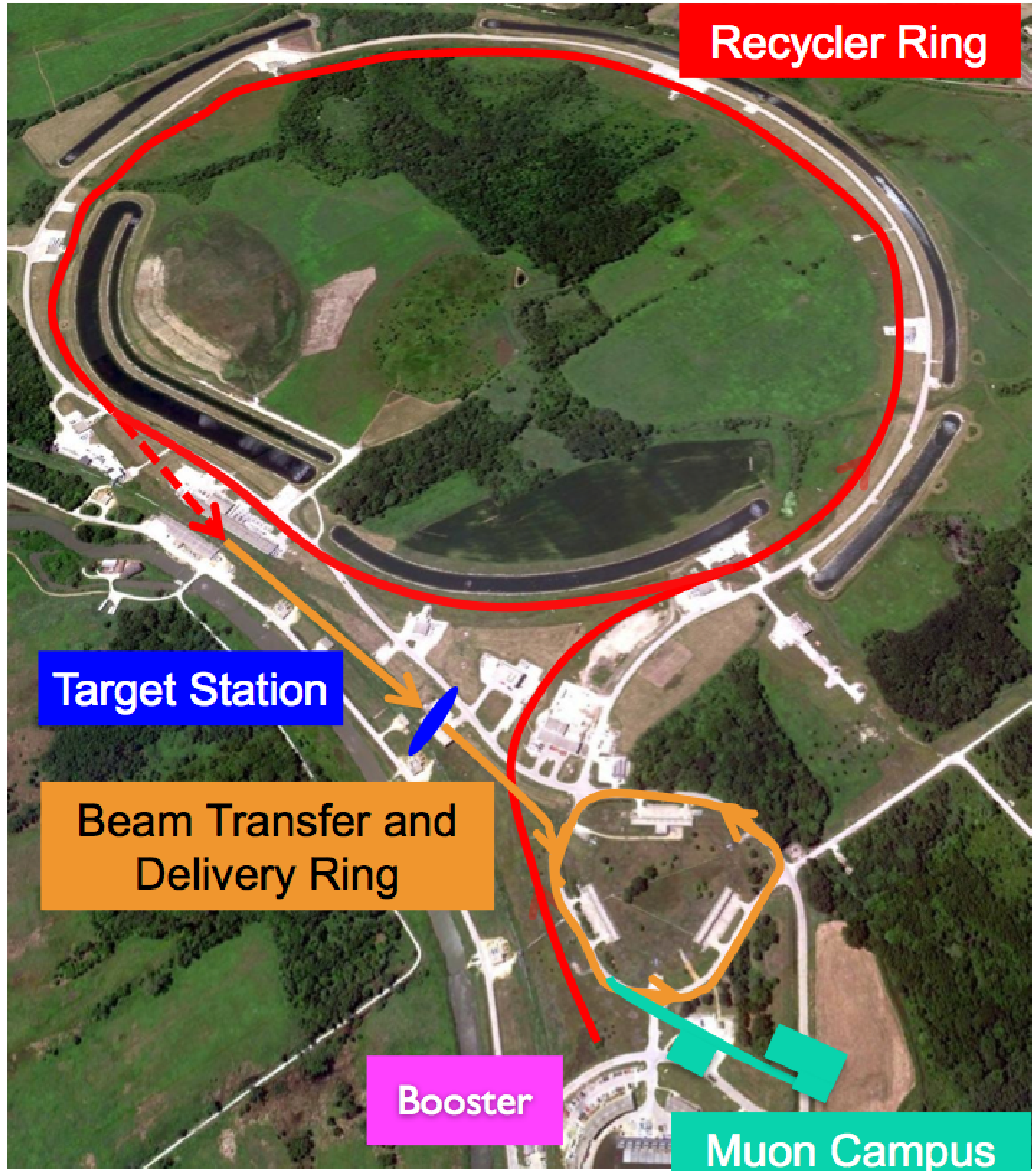
⇒ 4× higher fill frequency than E821

⇒ Muons per fill about the same

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

⇒ Better temperature control in experimental hall

⇒ Reduction in systematics by factor of 3 without major modifications



E989: Rate Estimates

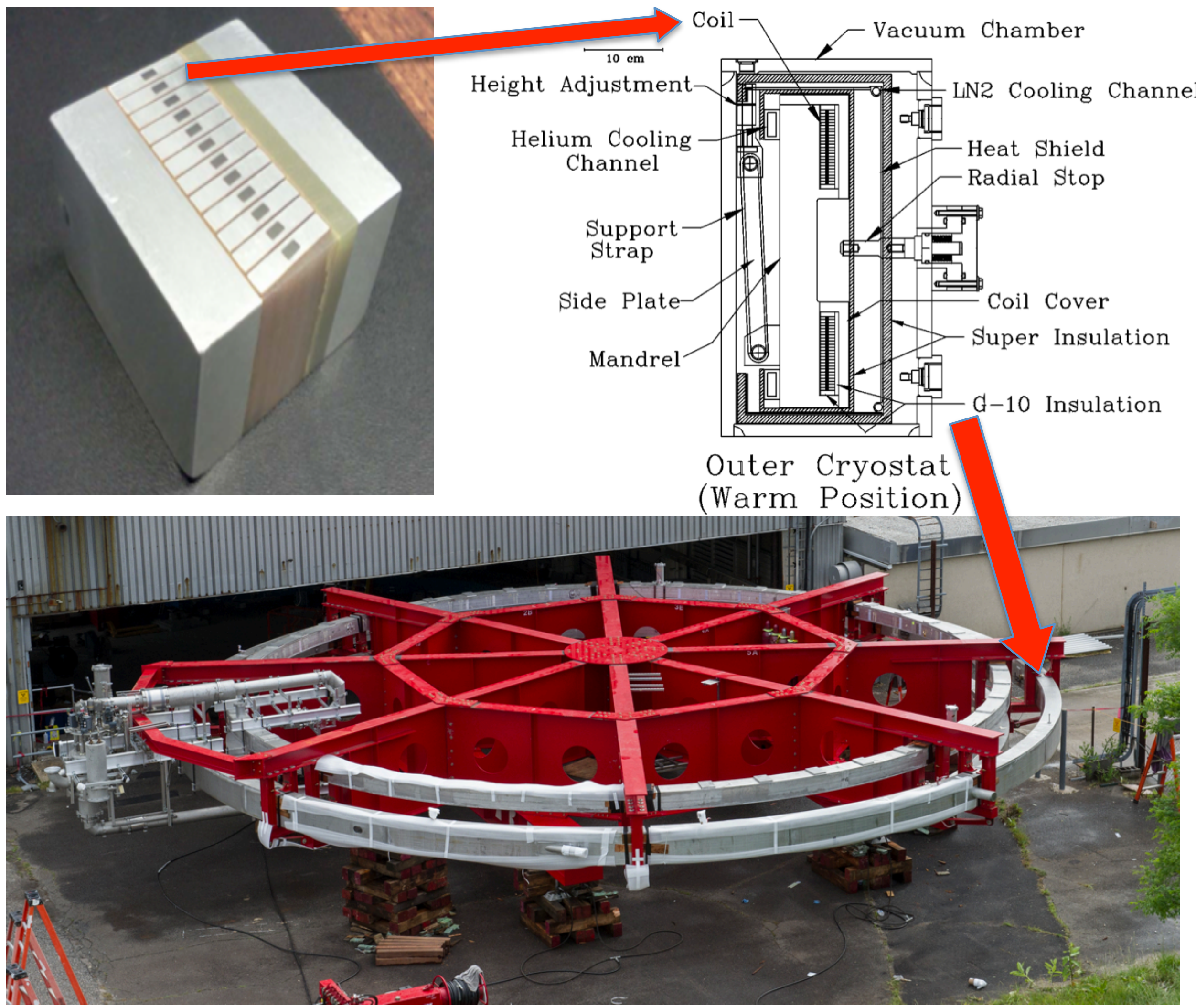
Table 5.1: Event rate calculation using a bottom-up approach.

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

- Estimated rates from Technical Design Report, arXiv:1501.06858
- Will need about 2 years running to reach statistics goals (100 ppb on ω_a)

From BNL E821 to E989 at Fermilab

- 650 ton magnet iron yoke and pole pieces are disassembled, transported by truck to FNAL
- 8 ton, 15 m diameter superconducting coils must be transported in one piece
- Keep accel <1 g, protect delicate superconductor, cooling lines, heat shield, G10 straps,



- Coils moved by barge up Mississippi. Constant monitoring of acceleration, always <12 hrs to safe harbor. Accel <1g, tilt <30°.

Transporting the coils to FNAL : ~~E-Z~~Pass

- 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

Coils arrvived at Fermilab July 2013 and installed July 2014

E989 Collaboration: 35 Institutes; 156 Members

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

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

Current Status

- Magnet cold and powered to full field in Sept 2015 - shimming underway

Summary

- Experiment will measure a_μ to 140 ppb, fourfold improvement over BNL E821
- Reduction in statistical uncertainty by factor 4; reduce ω_a, ω_p systematics by factor 3
- Magnet cold and energized, shim and install detectors by 2016, first data 2017

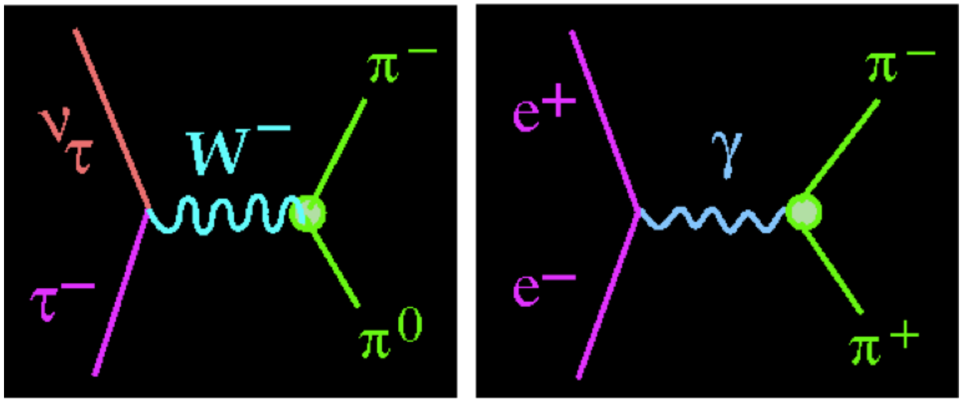
- Hope to motivate improvements in theory and more exp. work :
  - Currently δa_μ(HadVP,LO) $=$ 0.36 ppm, and δa_μ(Had,LBL) $=$ 0.23 ppm
- Before E821 (1983), expt. known to 7 ppm, theory to 9 ppm : now 0.54 and 0.42 ppm

- Regardless of where final result for a_μ lands :
  - Precision test of Standard Model and constraint on all future models
  - Provide complementary information to direct searches at LHC, CLFV, EDMs

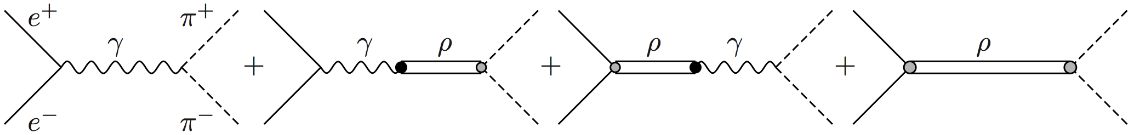
E989 : New Muon g-2 Experiment at Fermilab

What to do with a_μ(HadVP,LO) based on τ data?

- Evaluate a_μ(HadVP,LO) using dispersion integral from threshold to τ mass from hadronic τ decays: relate decay rate $\tau^- \to \pi^-\pi^0\nu_\tau$ to $e^+e^- \to \pi^+\pi^-$:



- Attractive option since lots of precision τ data from LEP, CLEO
- Caveats: need to invoke CVC, and apply isospin corrections
- τ data has only isovector component, insert by hand isoscalar contribution present in e^+e^-
- τ and e^+e^- values for a_μ(HadVP,LO) compatible once $\rho - \gamma$ mixing accounted for (F. Jegerlehner and R. Szafron, Eur. Phys. J **C71**, 1632 (2011))



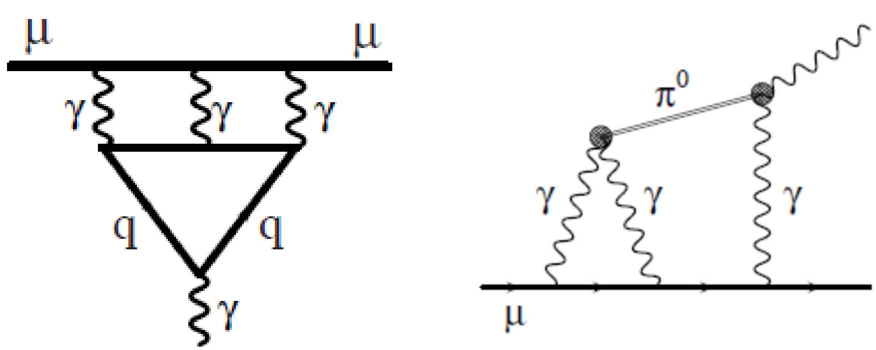
$\Rightarrow$ Lattice QCD experts suggest percent level determination of a_μ(HadVP,LO) possible.

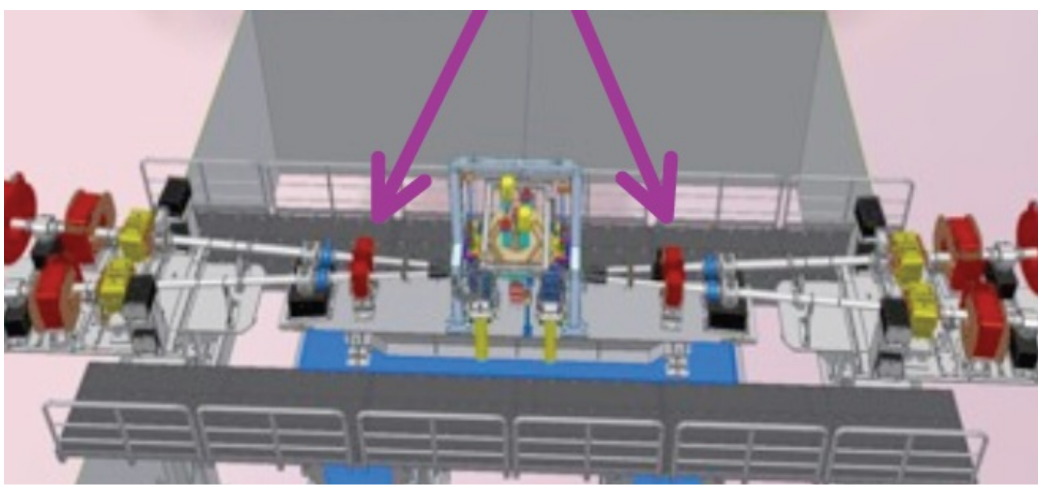
What about a_μ(Had; LBL) $= 105 \pm 26\ (\times 10^{-11})$?

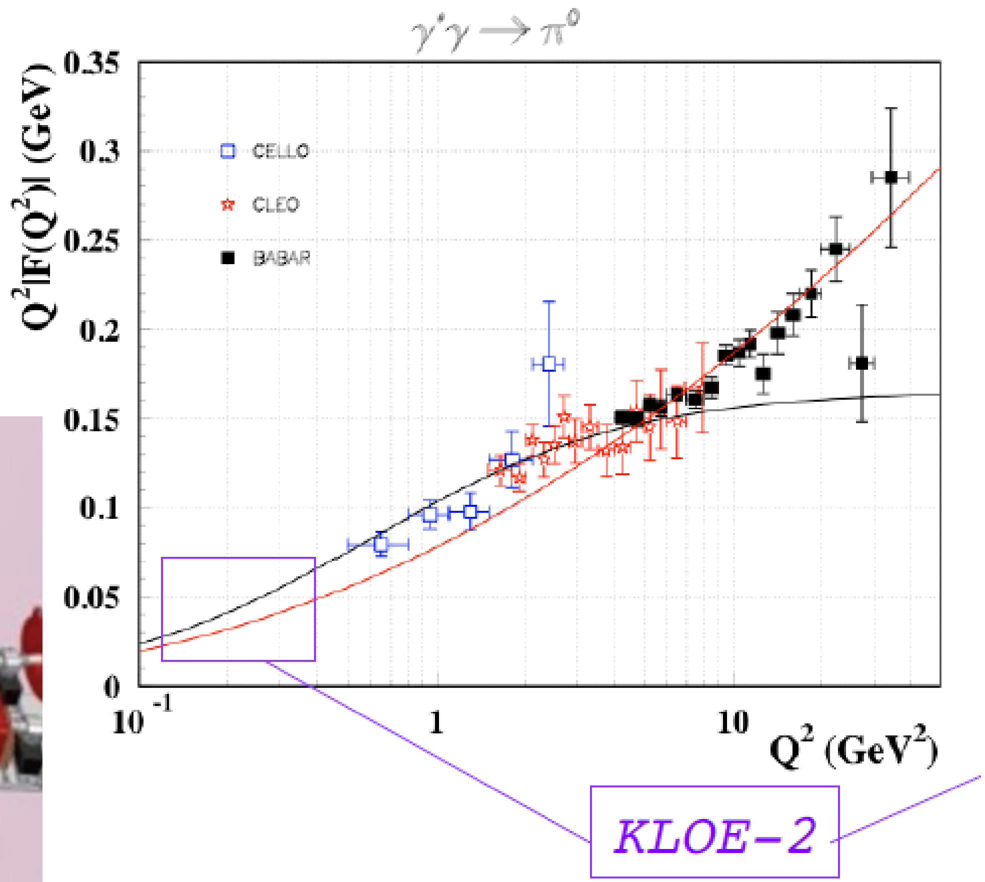
- a_μ(Had; LBL) non-perturbative, high order correction. Value stable since sign error corrected 2002.
- Important - might dominate theoretical uncertainty soon
- KLOE-2 will measure $\gamma^*\gamma \rightarrow \pi^0$ at low Q^2, dominant contribution
- Might reduce leading uncertainty on a_μ(Had; LBL)

⇒ PrimEx effort to reduce uncertainty on π^0 decay width, pion polarizability measurement important

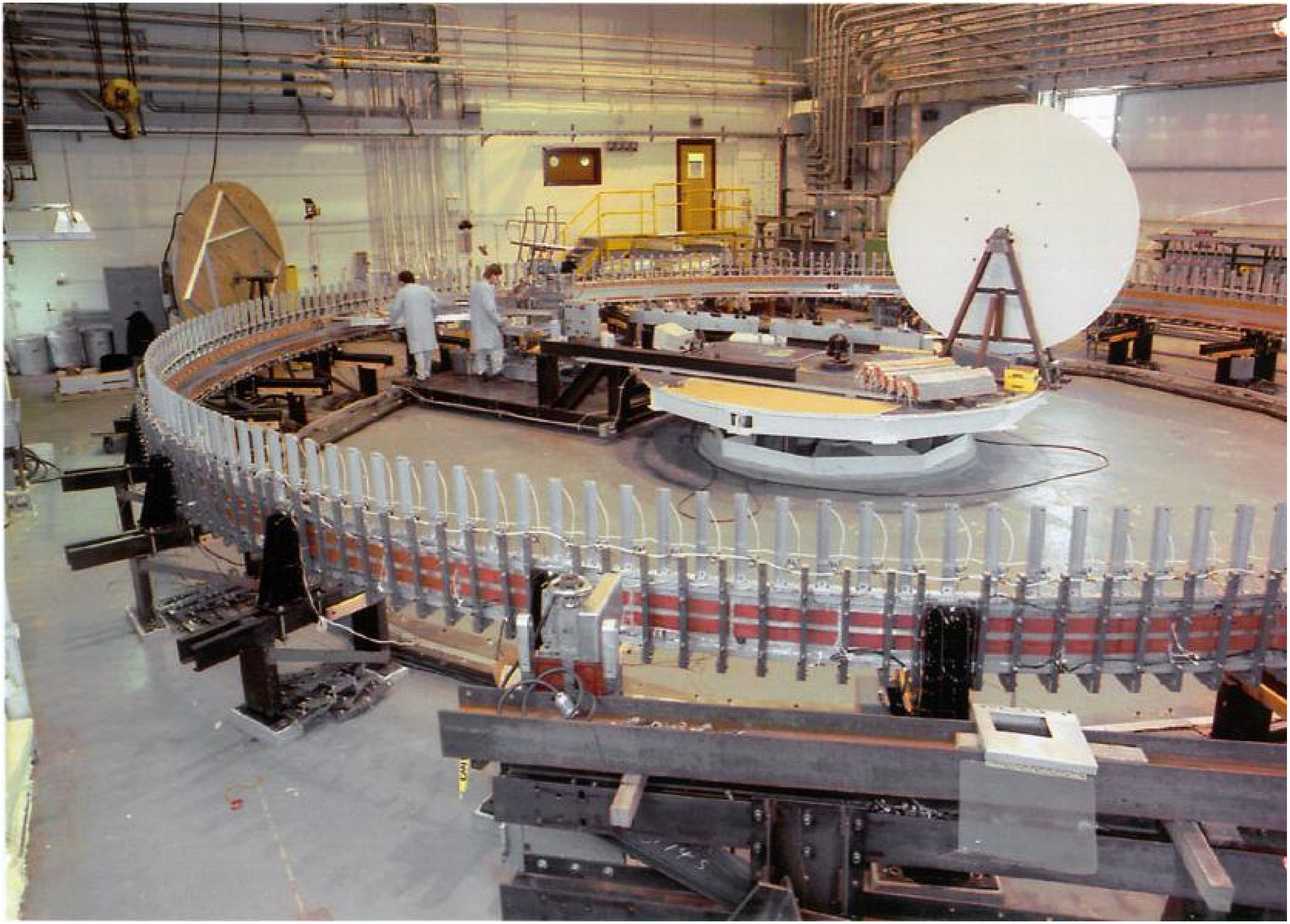
- Lattice QCD effort underway as well (T. Blum and collaborators)



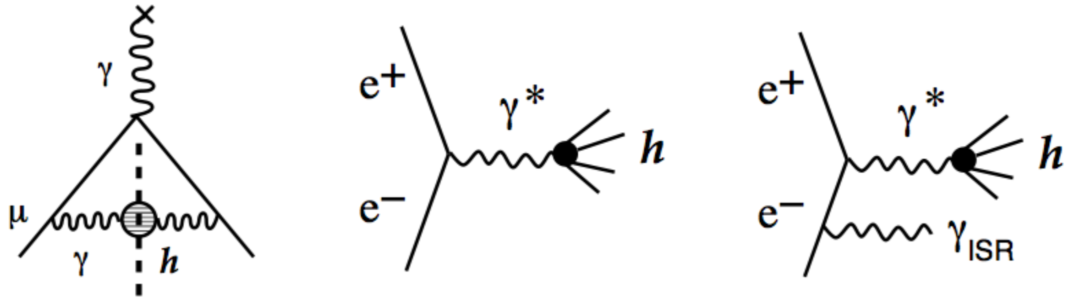




Winding the Coils



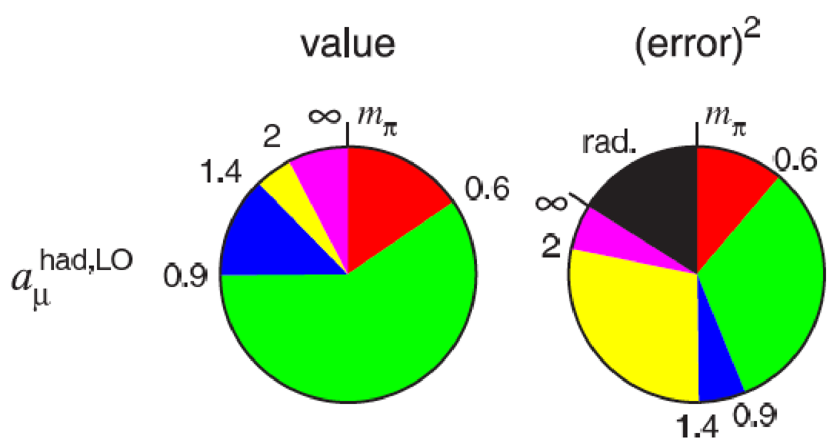
$a_\mu^{\text{had;LO}}$ can be extracted from measurements by SND, CMD2, BaBar, KLOE, Belle



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

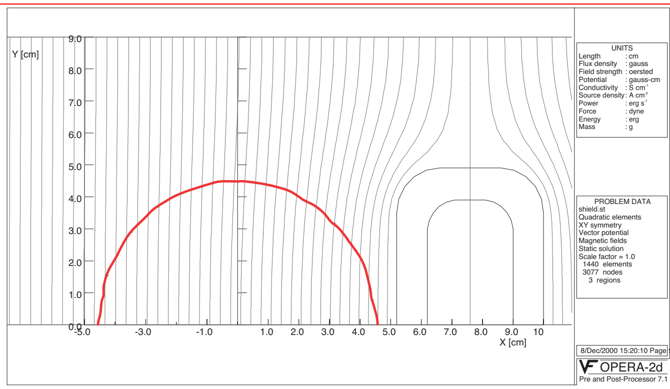
- CMD3 will measure up to 2.0 GeV, using energy scan and ISR, good cross-check
- KLOE will measure $\gamma^*\gamma^* \to \pi^0$, might reduce uncertainty on a_μ(Had;LBL)

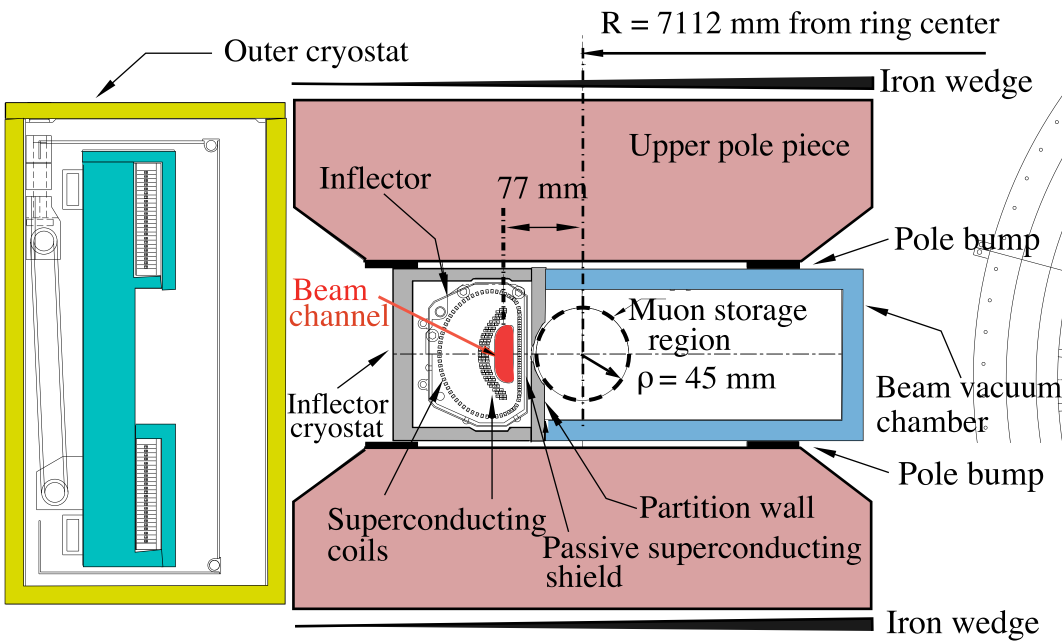
- Dispersion integral weights cross-section ratio $R(s)$ as $1/s^2$, low energy important
- K. Hagiwara *et al.*, J. Phys. G**38**, 085003 (2011) : contribution to $a_\mu^{\text{had,LO}}$ and uncertainty

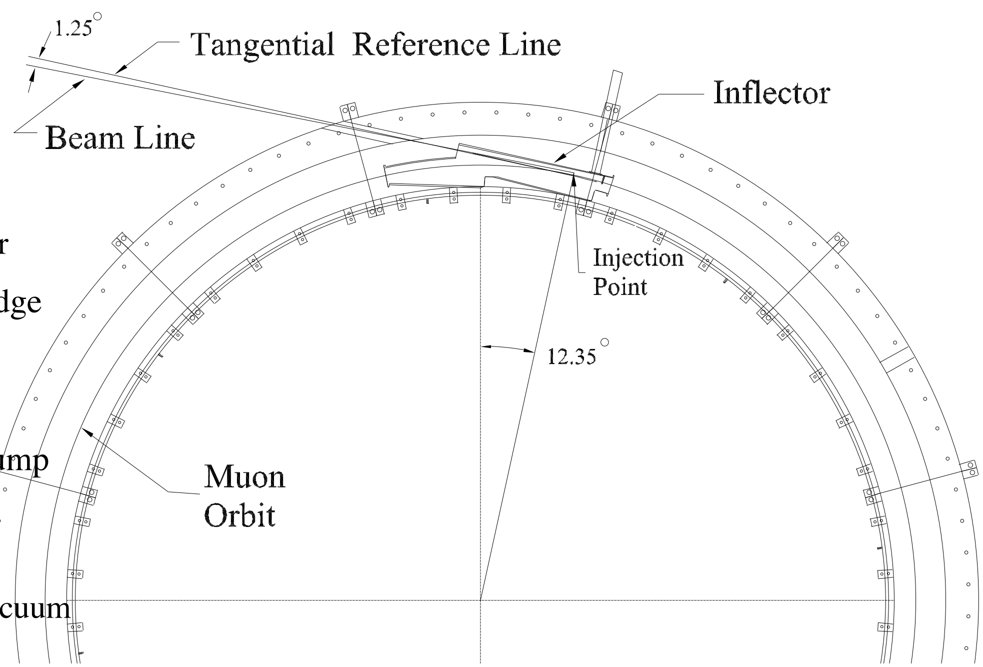


The Superconducting Inflector

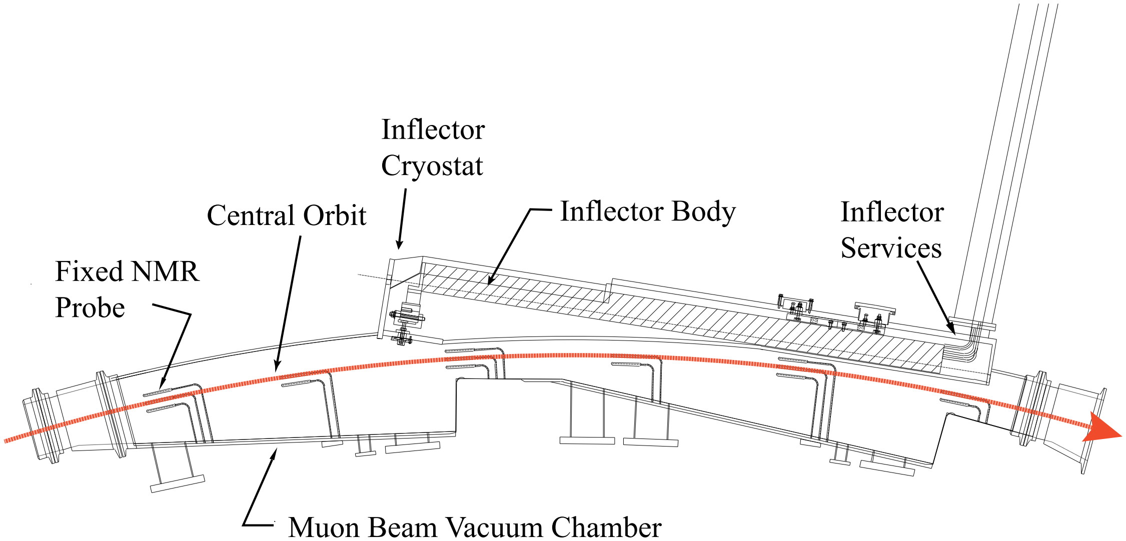
- Have to get the muon beam into the storage ring - from zero field area outside to 1.45 T inside - beam strongly deflected unless we cancel this field
- Use a superconducting flux-exclusion tube? Perturbations in storage region too large

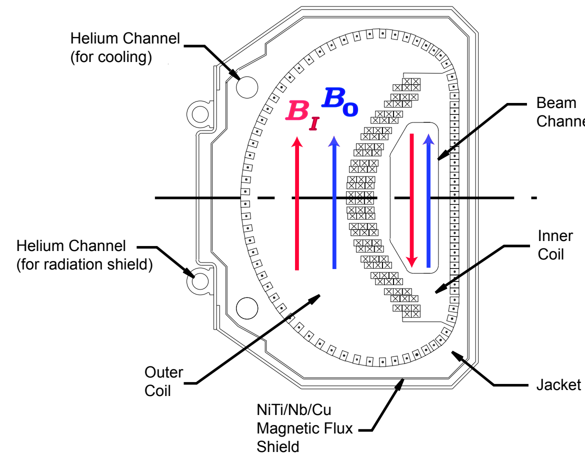






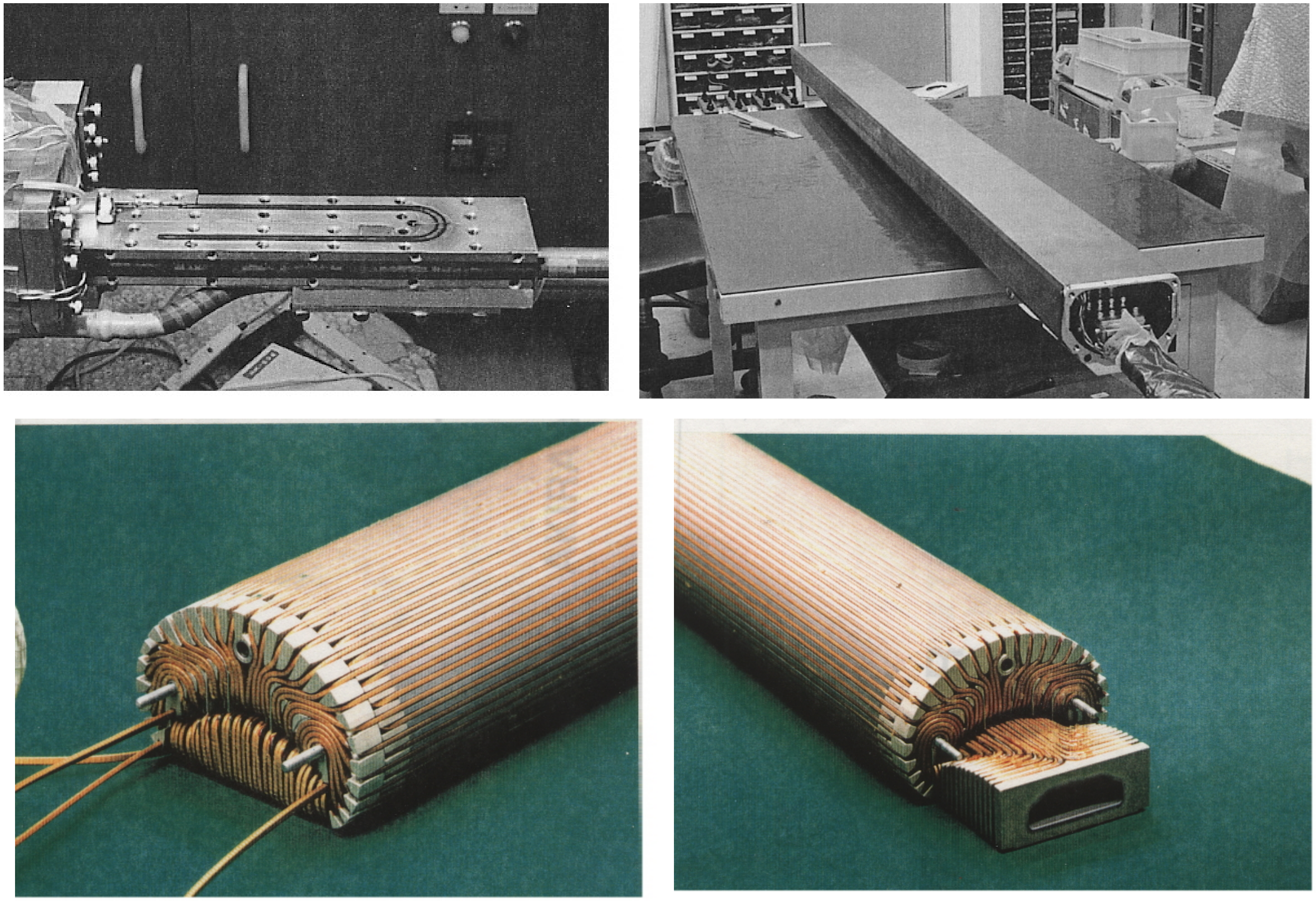
- Base plan: use double-$\cos\theta$ design from BNL E821, $\int \vec{B} \cdot d\vec{L} = 2.55$ T·m





- 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

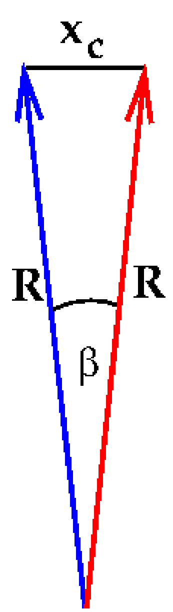
- Versions of superconducting inflector with closed and open ends

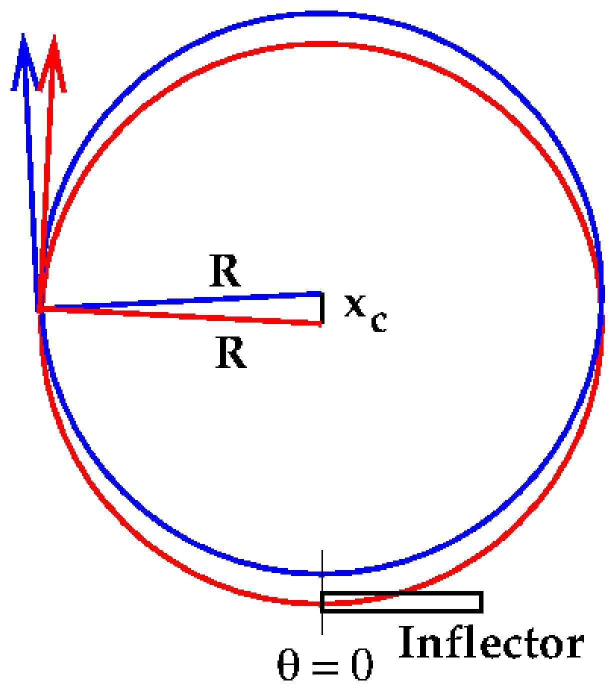


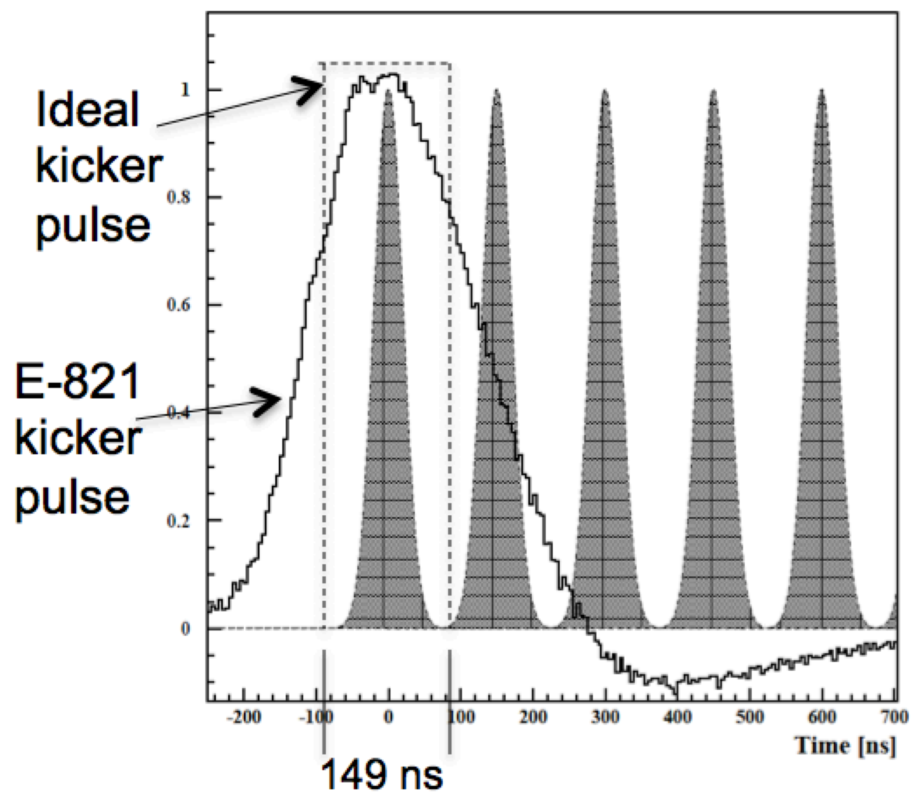
- BNL E821 inflector closed ends, significant multiple scattering, aperture 18×56 mm^2, injection efficiency $\approx 2\%$
- New inflector : open ends, 40×56 mm^2 (storage aperture ± 45mm) $\rightarrow$ $4\times$ more stored muons, could do μ^- and μ^+

The Fast Muon Kicker

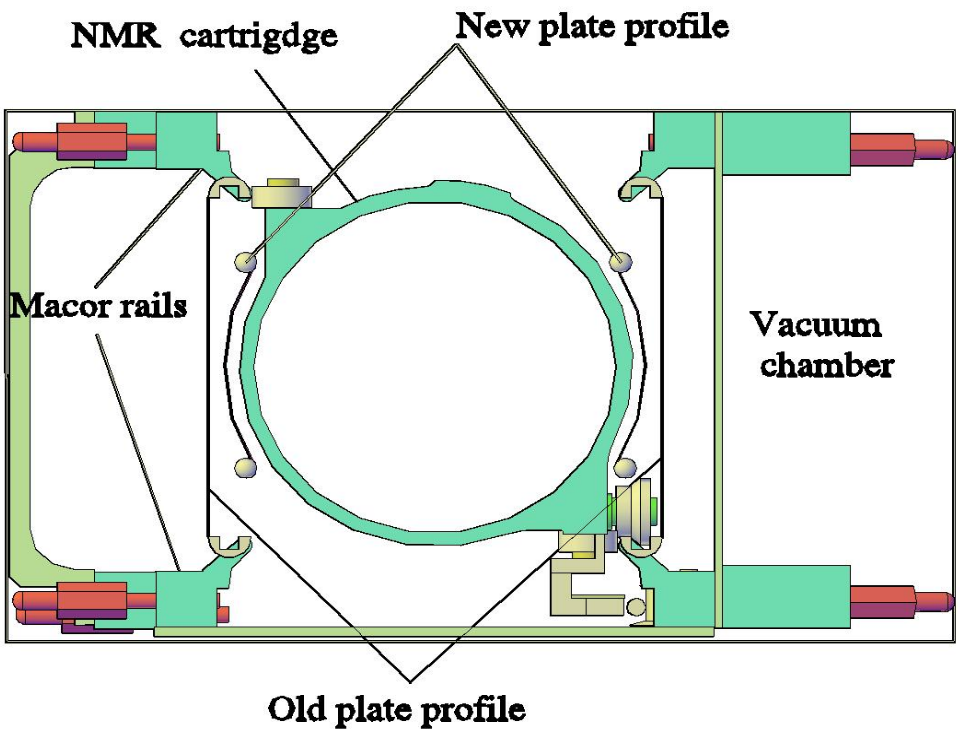
- Muons exit the inflector, enter storage region at radius 77 mm outside ideal closed orbit
- Muons cross ideal orbit $\approx\ 90^\circ$ later in azimuth, angle off by 10.8 mrad
- Including momentum spread, multiple scattering in inflector, need 14 mrad kick
- Temporarily reduce $\mathbf{B}$ by 280 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

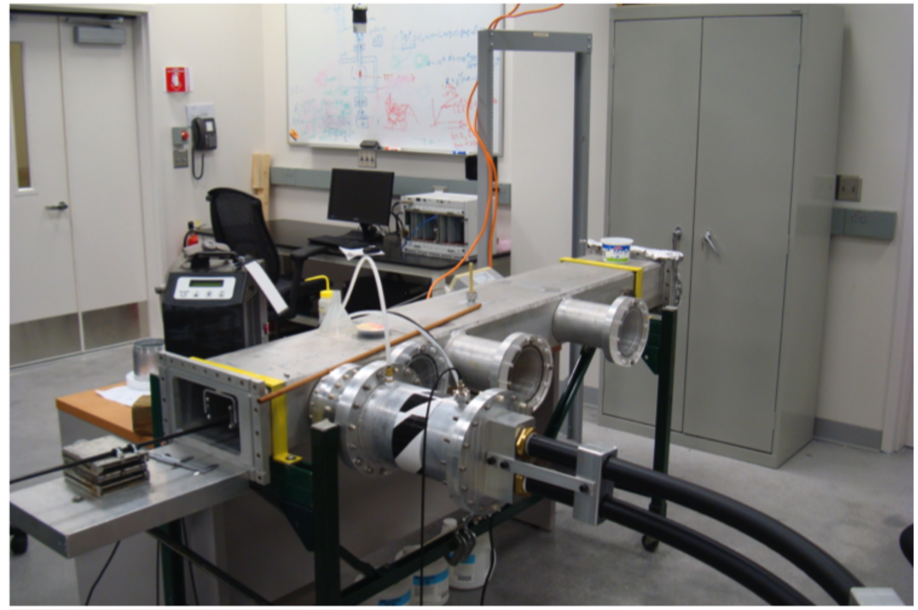


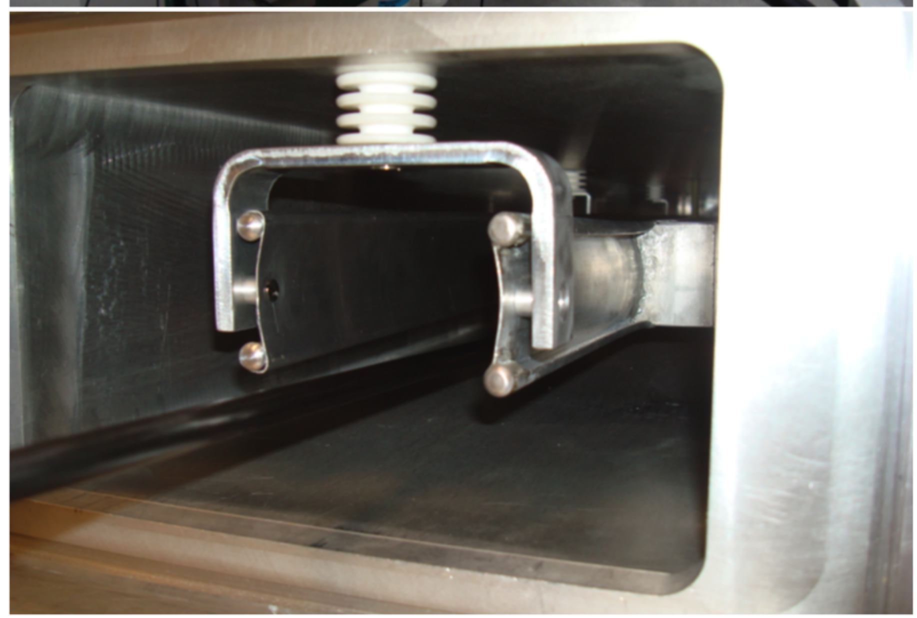




The Fast Muon Kicker



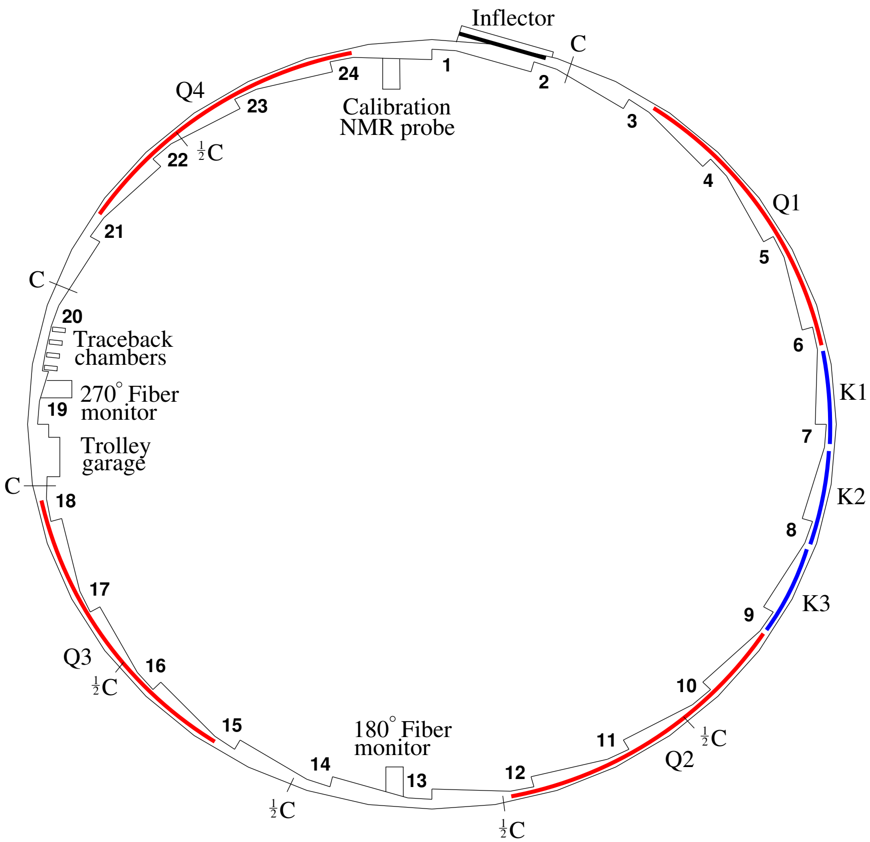


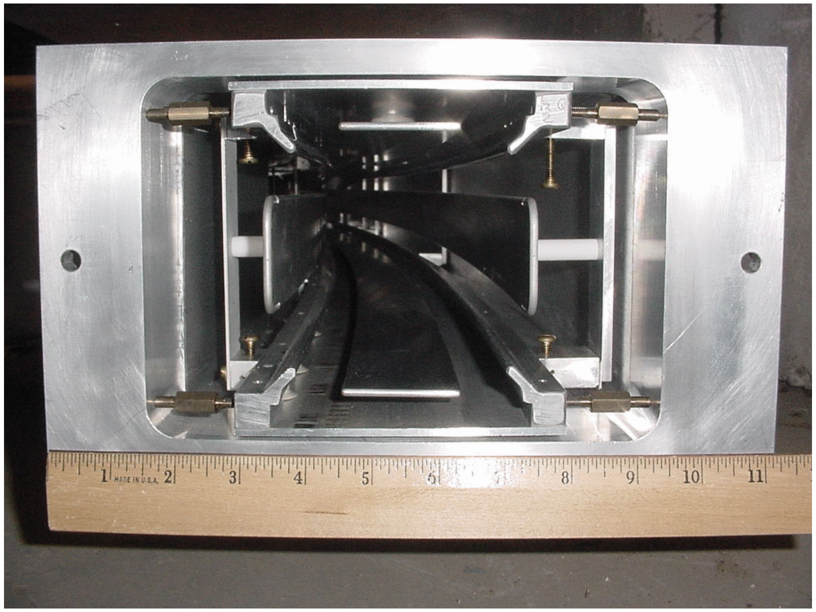


- New geometry yields 33%-50% higher field/current than BNL E821
- 3×1.7 m stripline kickers, Blumlein PFN
- Tracking studies determine optimal shape
- Dave Rubin and collaborators at Cornell

Storing the Muon Beam : Vertical Focusing Electric Quadrupoles

- 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

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

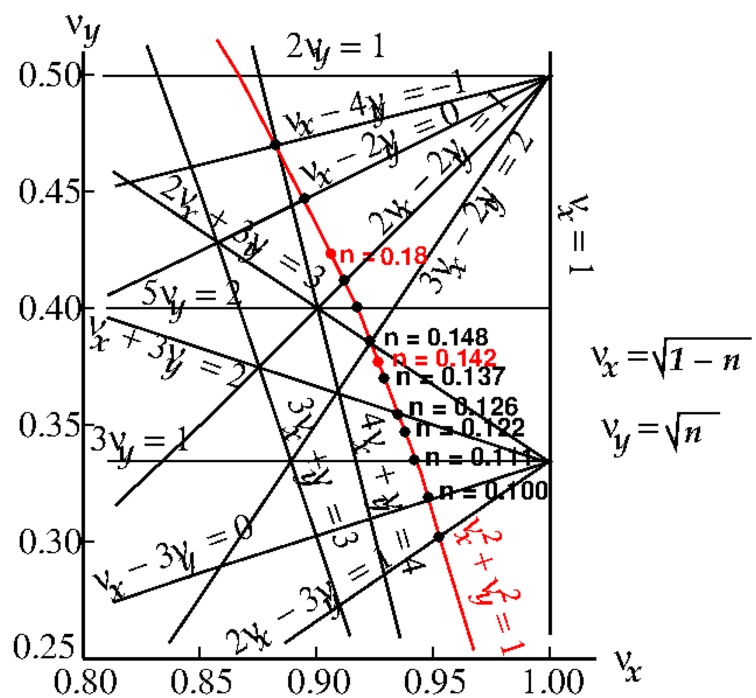
$$\nu_x = \sqrt{1-n},\ \nu_y = \sqrt{n},\ n \approx 0.137,\ f_x = f_C\sqrt{(1-n)} \approx 0.929 f_C,\ f_y = f_C\sqrt{n} \approx 0.37 f_C$$

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

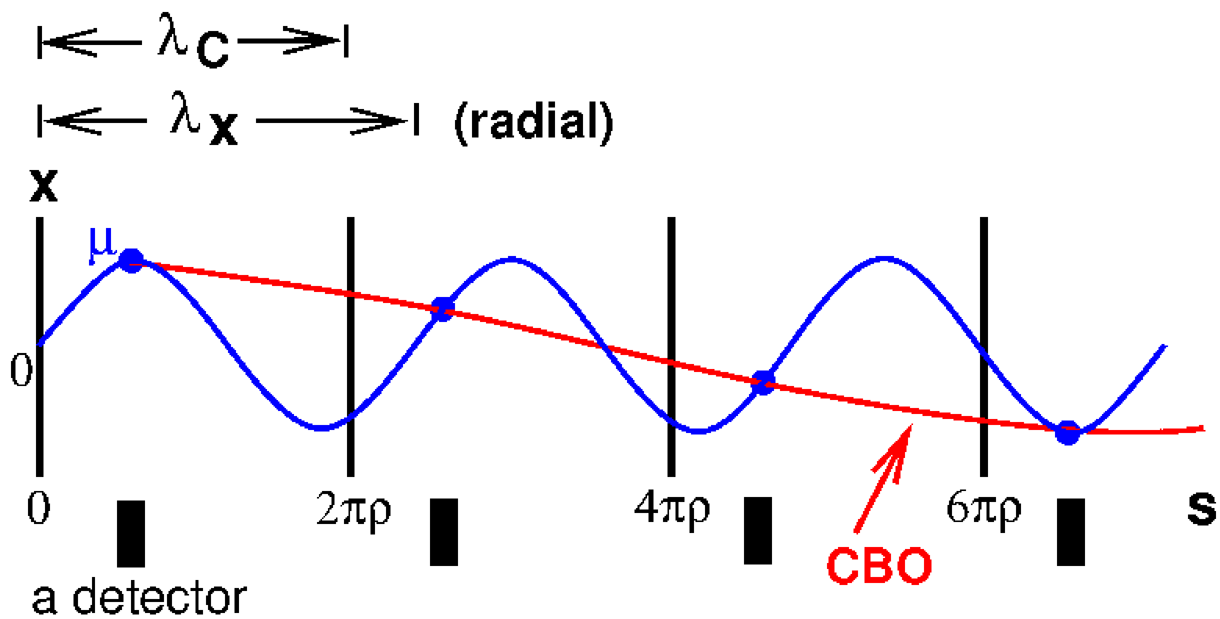
- Perturbations of stored muon beam from ideal circular orbit affect ω_a

$\Rightarrow$ 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 $\nu_x^2 + \nu_y^2 = 1$



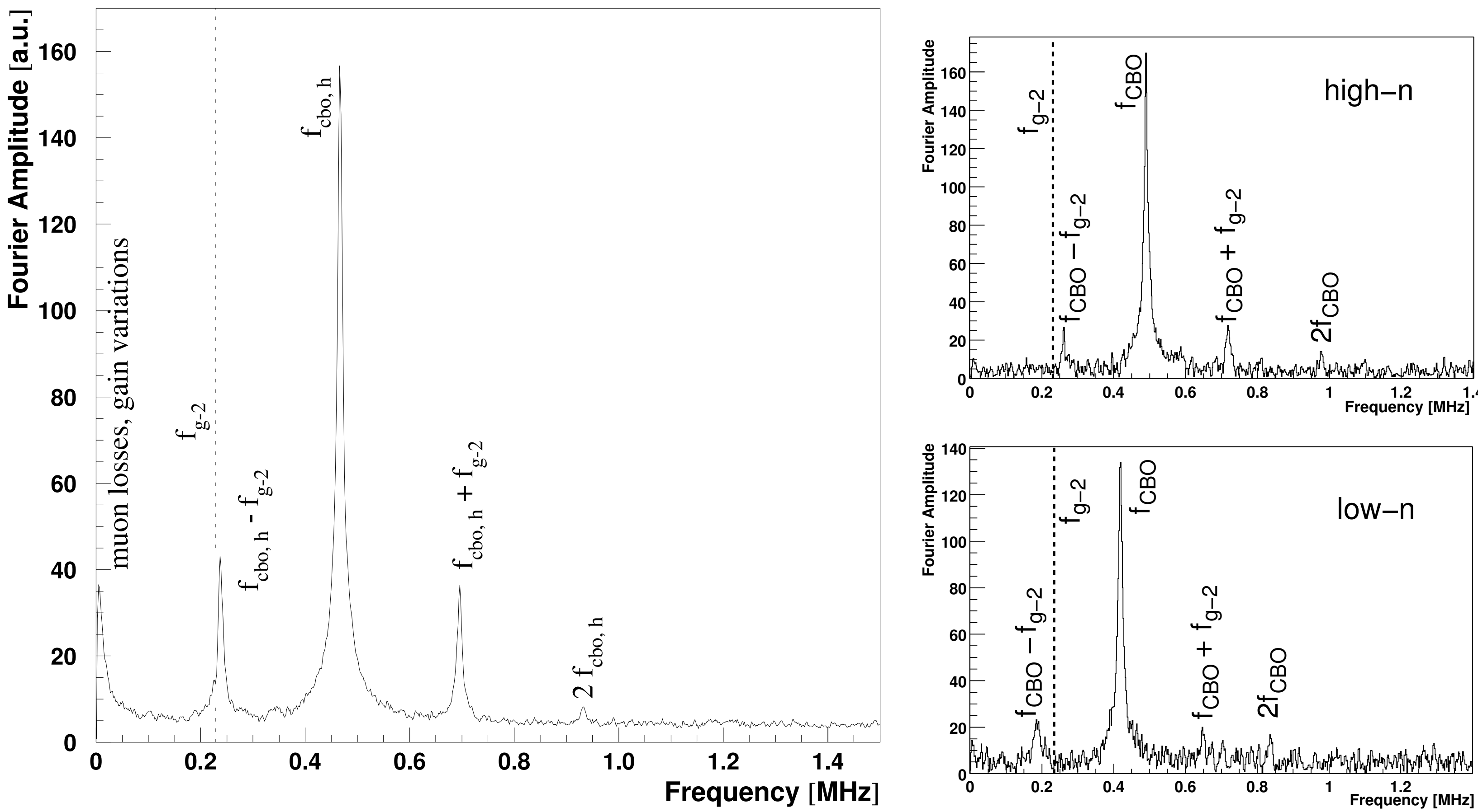
- Detector acceptance depends on muon radius at decay - coherent radial motion modulates electron time spectrum
- Radial betatron wavelength (blue line) is longer than circumference (cyclotron wavelength), $f_x < f_\mathrm{C}$
- At fixed detector location, each pass of bunched beam appears at different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



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

Coherent Betatron Oscillations (CBO)

- 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



Corrections to ω_a: Radial Electric Field Correction

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

- 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

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

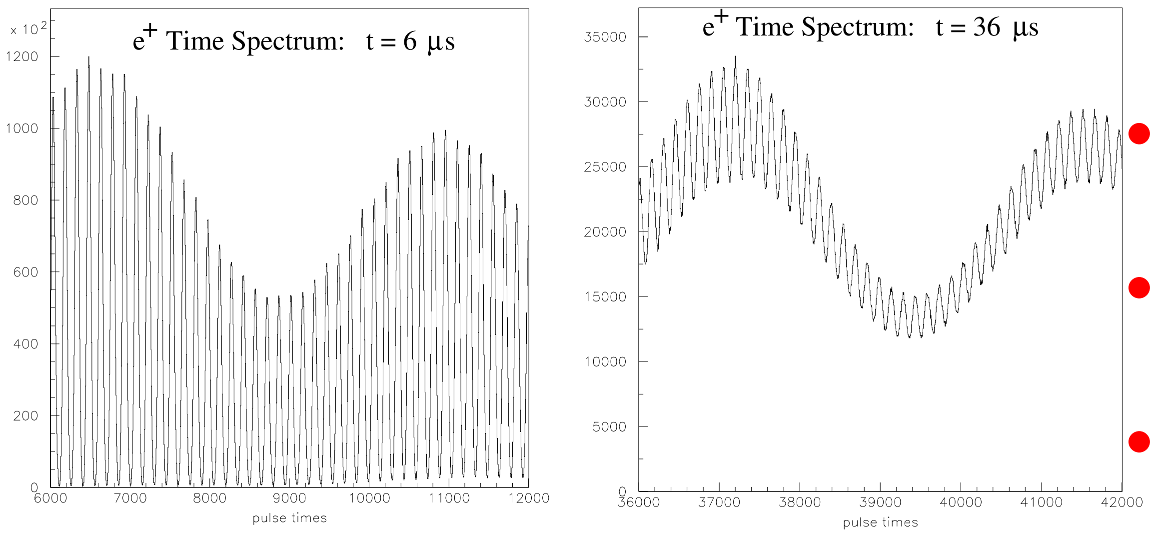
$$\frac{\omega_a' - \omega_a}{\omega_a} = \frac{\Delta\omega_a}{\omega_a} = -2\frac{\beta E_r}{cB_y}\left(\frac{\Delta p}{p_m}\right) = -2n(1-n)\beta^2\frac{\langle x_e^2\rangle}{R_0^2}$$

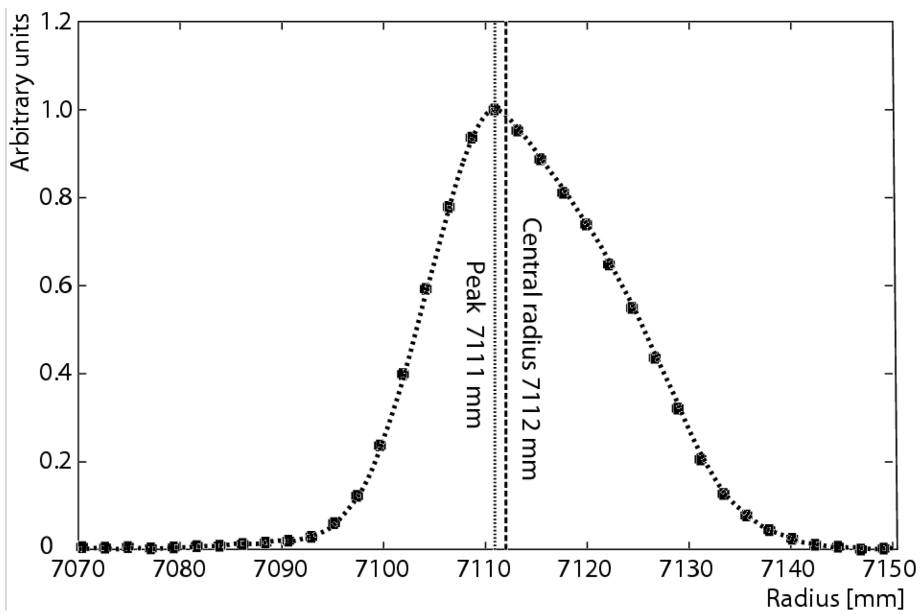
- Momentum distribution from fast-rotation (de-bunching) analysis, decay e^+ tracking chambers, muon beam fiber monitors

$\Rightarrow$ Correction determined from detailed tracking analysis using actual discontinuous quad geometry

Corrections to ω_a: Radial Electric Field Correction

- 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

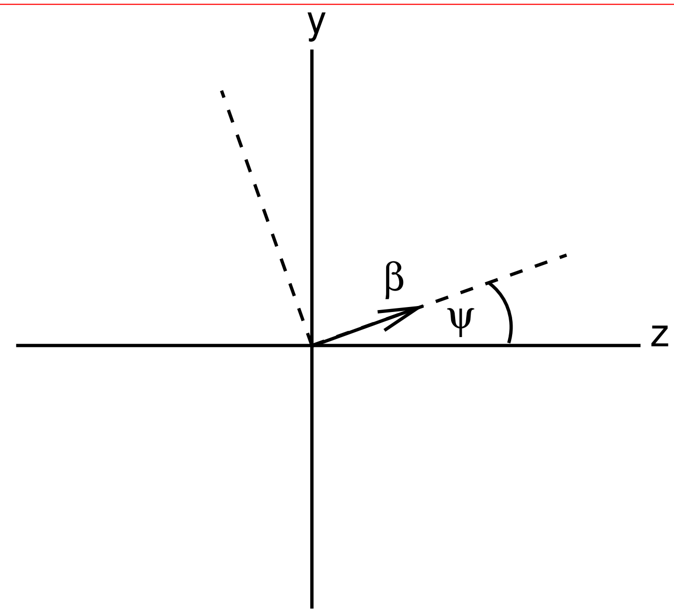
Corrections to ω_a: Pitch Correction

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

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

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

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



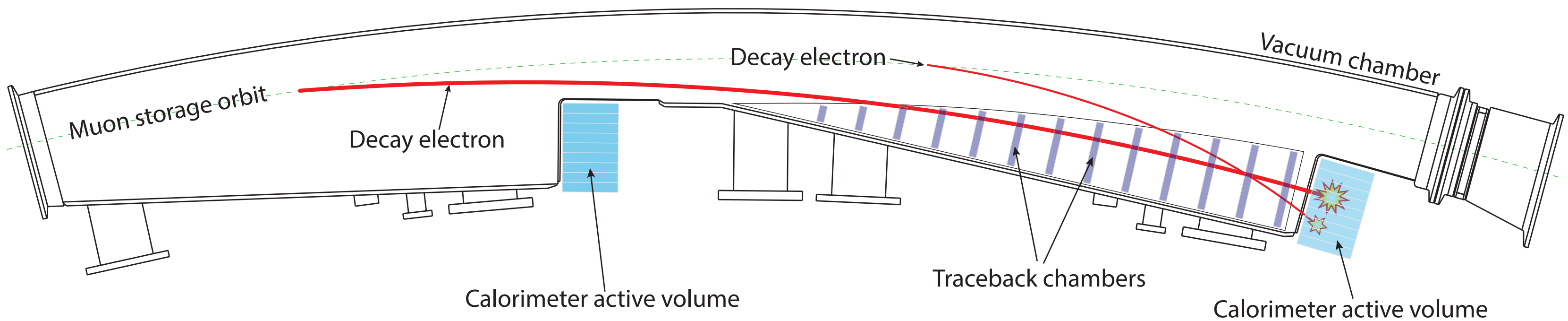
- Electric field and pitch corrections reduce observed frequency
- BNL E821 pitch correction $+0.27 \pm 0.036$ ppm
- Electric field and pitch are the only corrections made to the ω_a data
- Improved E989 muon tracking reduces uncertainties ± 0.05 ppm $\Rightarrow$ 0.03 ppm level

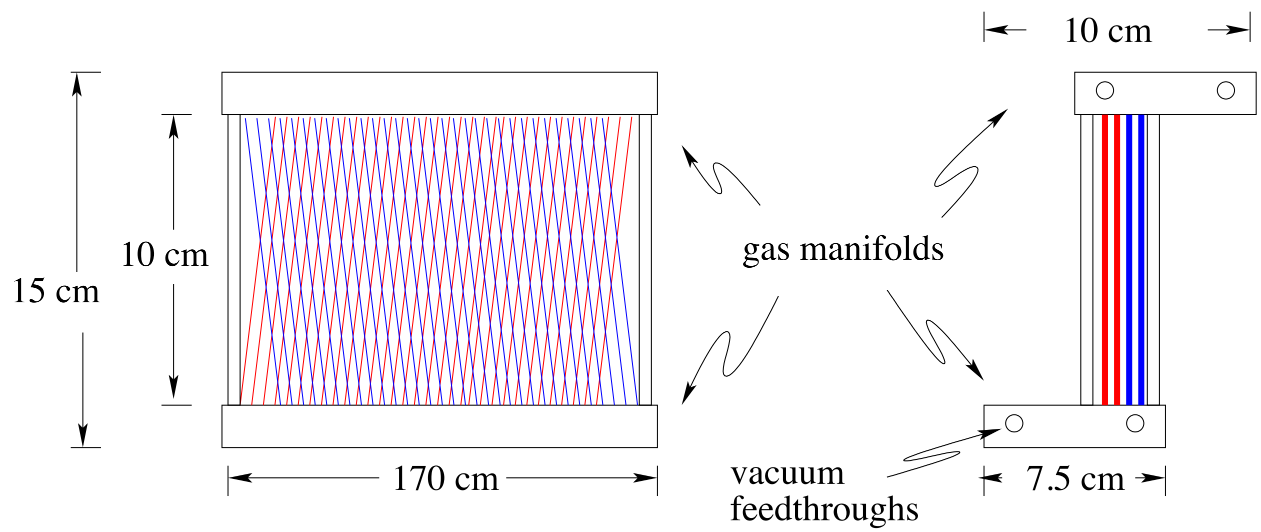
Determining the Stored Muon Distribution

- Need to know muon beam distribution :
  - Finite momentum spread : not all muons at magic momentum, need ppm-level corrections ω_a from E-field
  - Betatron motion : ppm-level correction because muon momentum not always $\perp$ to $\vec{\mathbf{B}}$ (pitch correction)
  - Betatron motion of beam leads to time-dependent acceptance changes in calorimeters, must be corrected
  - Muon distribution convoluted with magnetic field map to determine effective magnetic field seen by muons
- Muon beam distribution determined with straw tube trackers

Determining the Stored Muon Distribution : Straw Tube Trackers

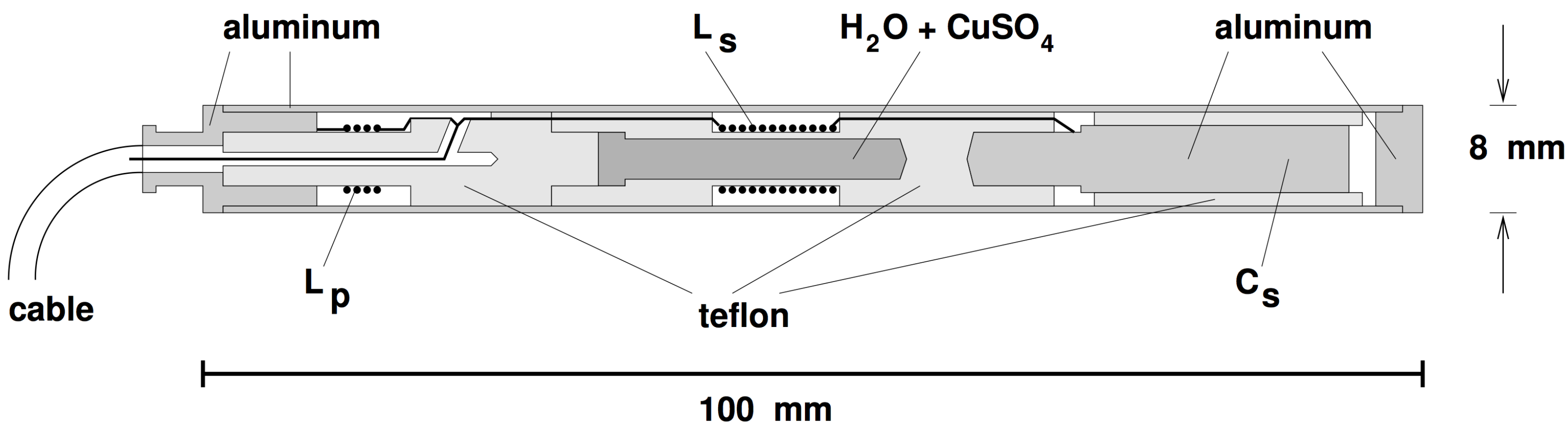
- Two tracker stations planned, reside in vacuum chambers 180° and 270° from injection
- 1216 aluminized mylar straws/station, 12 cm long, 1 atm, 80:20 Argon:CO_2, 1400 V, $\pm 7.5^\circ$ angle from vertical
- Vertical angular resolution < 10 mrad, momentum resolution $< 3.5\%$ at 1 GeV
- Brendan Casey FNAL and collaborators





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) :

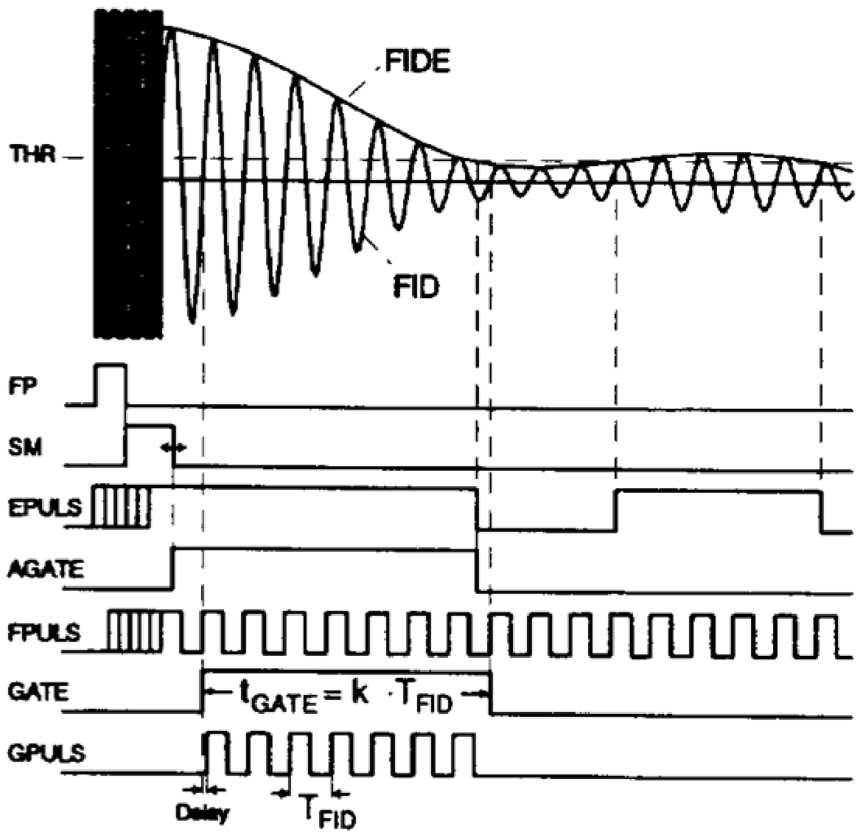


- RF pulse at $f_{\rm ref}$=61.74 MHz produces RF magnetic field in coil L_s around sample
- Rotates magnetization of protons in sample perpendicular to main field
- After pulse, proton spins process freely, coherently at $f_{\rm NMR} \approx 61.79$ MHz, $\omega \approx \gamma_{p'} B$
- Rotating magnetization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

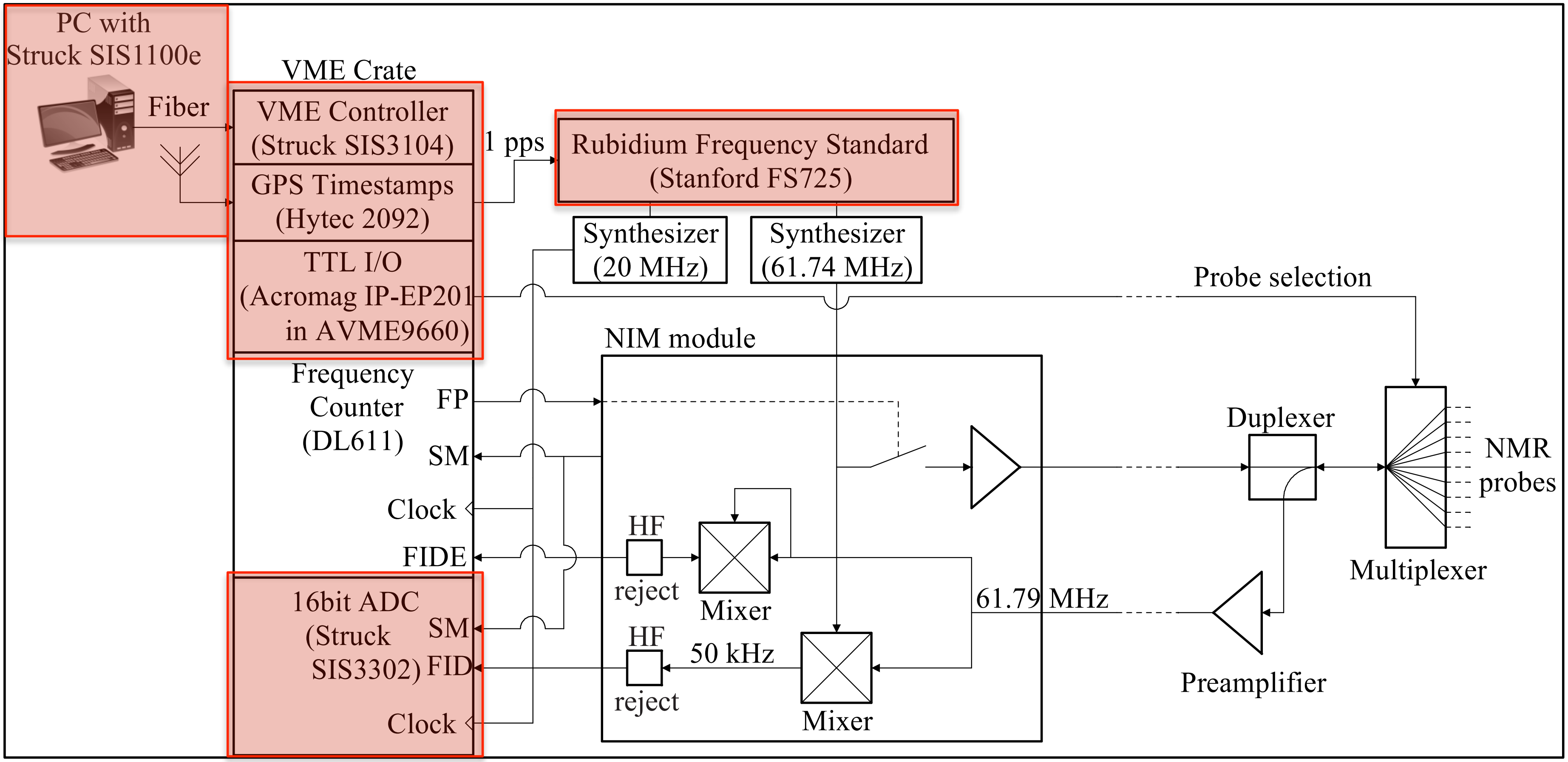
- NMR signal at $f_{\rm NMR}$ goes to low noise amplifier, mixed with $f_{\rm ref} = 61.74$ MHz from synthesizer
- Difference frequency $f_{\rm NMR} - f_{\rm ref} \equiv f_{\rm FID}$ ranges from 45-55 kHz, dependent on local field
- Difference of 62 Hz in $f_{\rm FID}$ corresponds to 1 ppm difference 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 $f_{\rm NMR}$ $\approx$ 0.020 ppm
- Depends on signal duration, S/N
- See R. Prigl *et al.*, Nucl. Inst. Meth. A **374**, 118 (1996).

- 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

Field Measurement Task (3) : Absolute Calibration

- 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