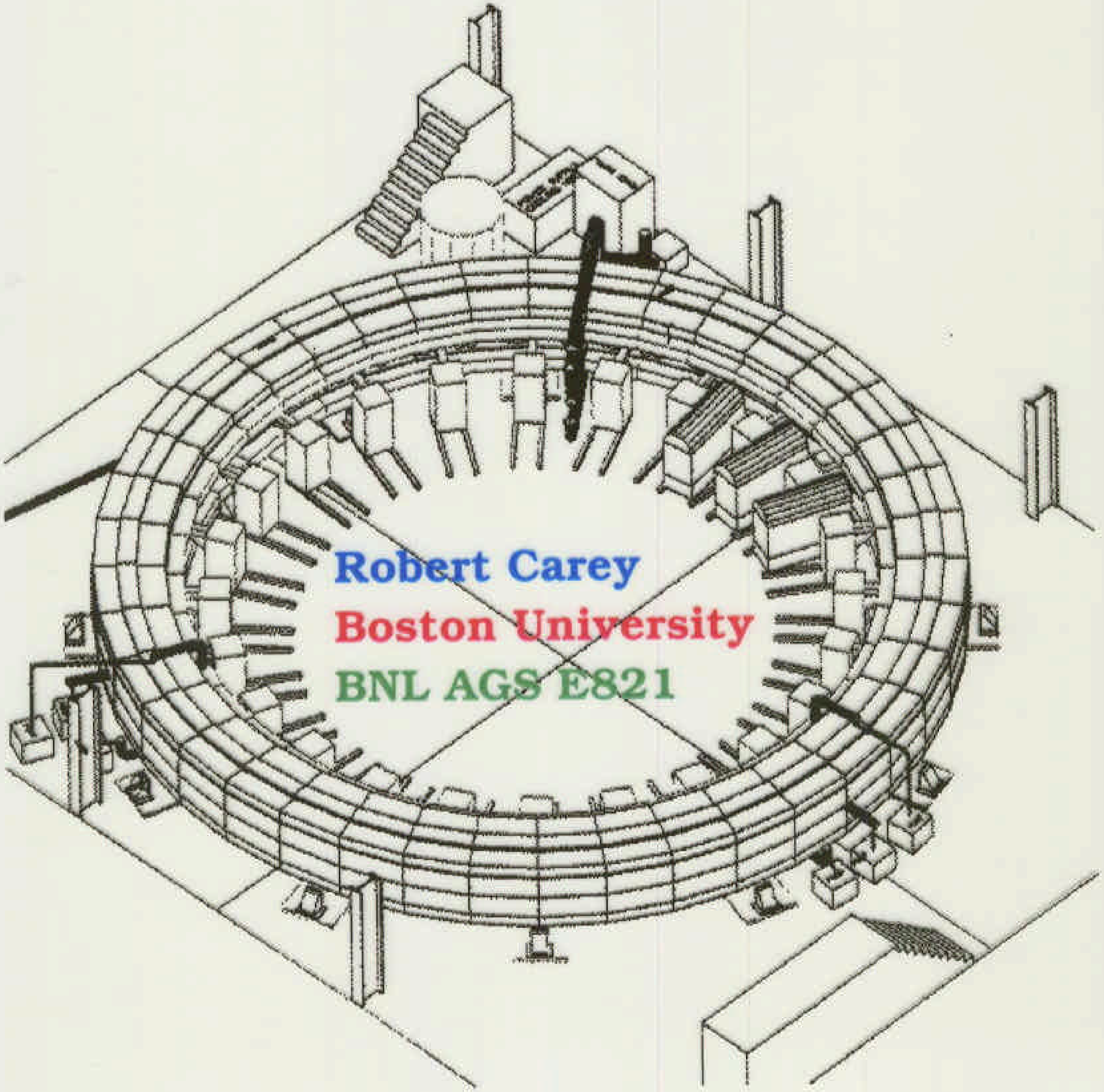
New Results from the Muon g-2 Experiment at BNL



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E821 Collaboration

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g-factors and Magnetic Moments

$$\vec{\mu}_s = g_s \left(\frac{e}{2m} \right) \vec{s}$$

Dirac theory of pointlike, spin 1/2 particles $\rightarrow g_s = 2$

The anomalous magnetic moment a is defined

$$a = \frac{g_s - 2}{2}$$

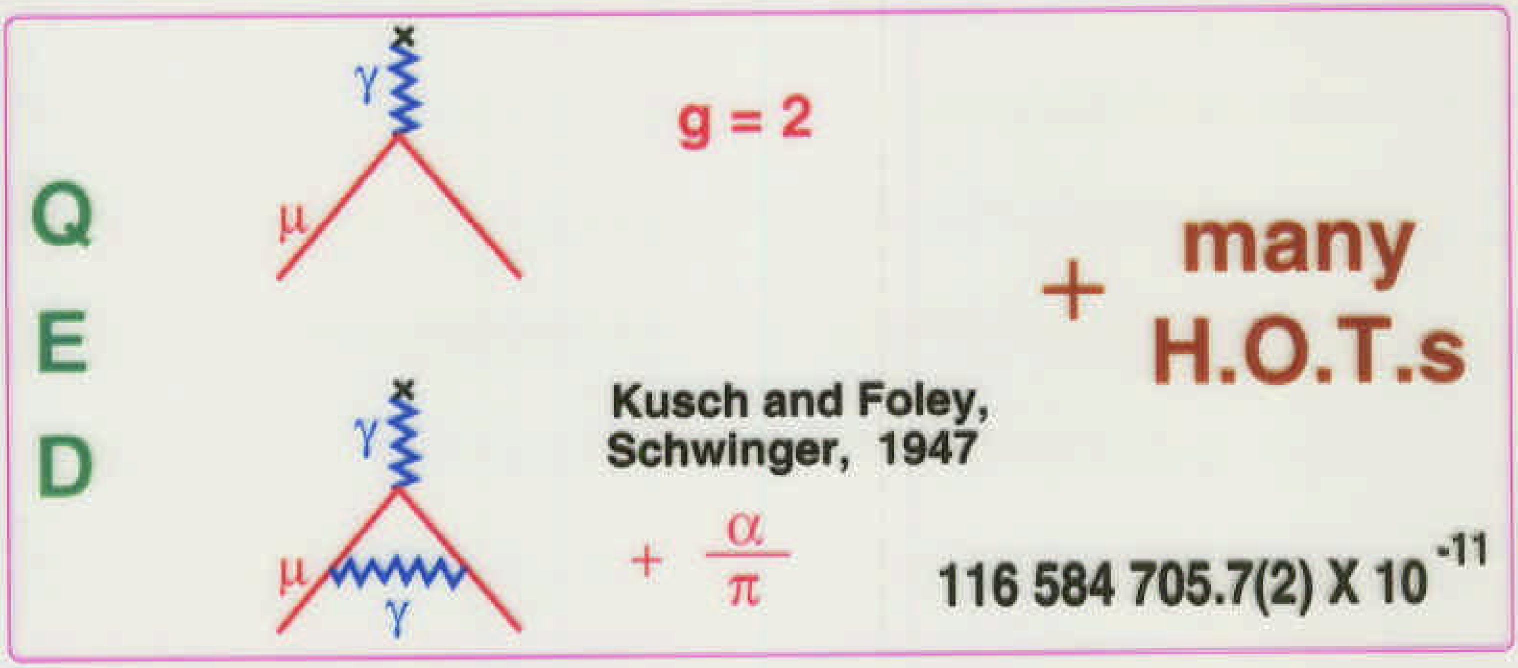
Long history of fundamental physics

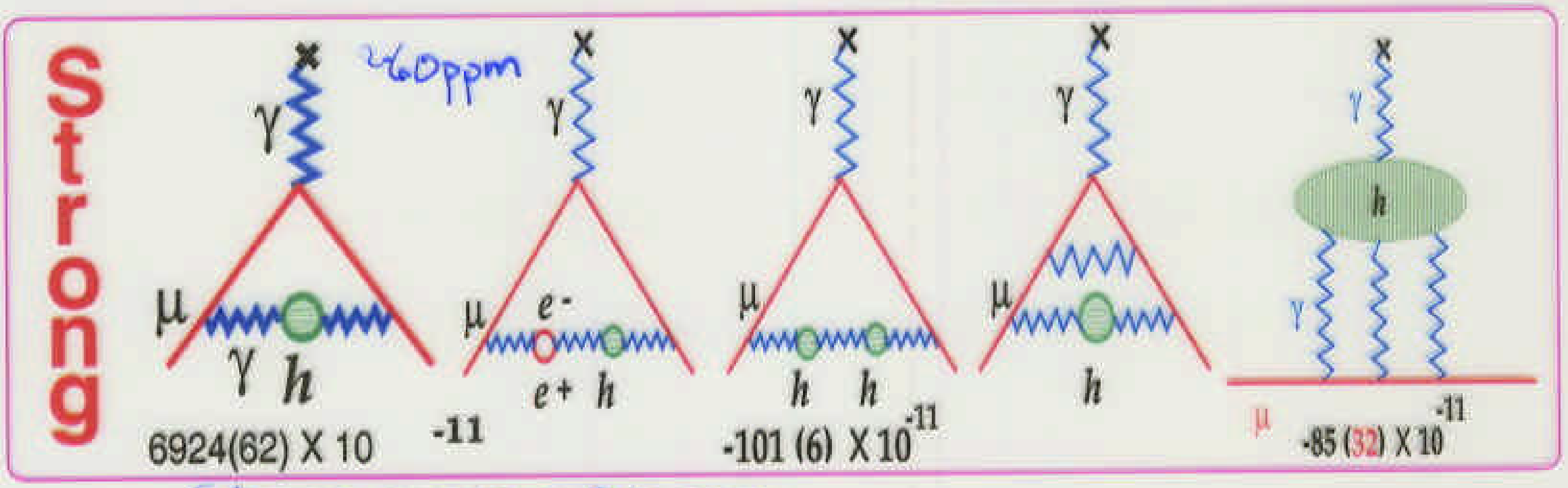
- QED calculations, precision measurements of a_e
- Baryon g-factors very different from 2
- Tests of very short distance scales: a_μ

  CERN III: 7 ppm

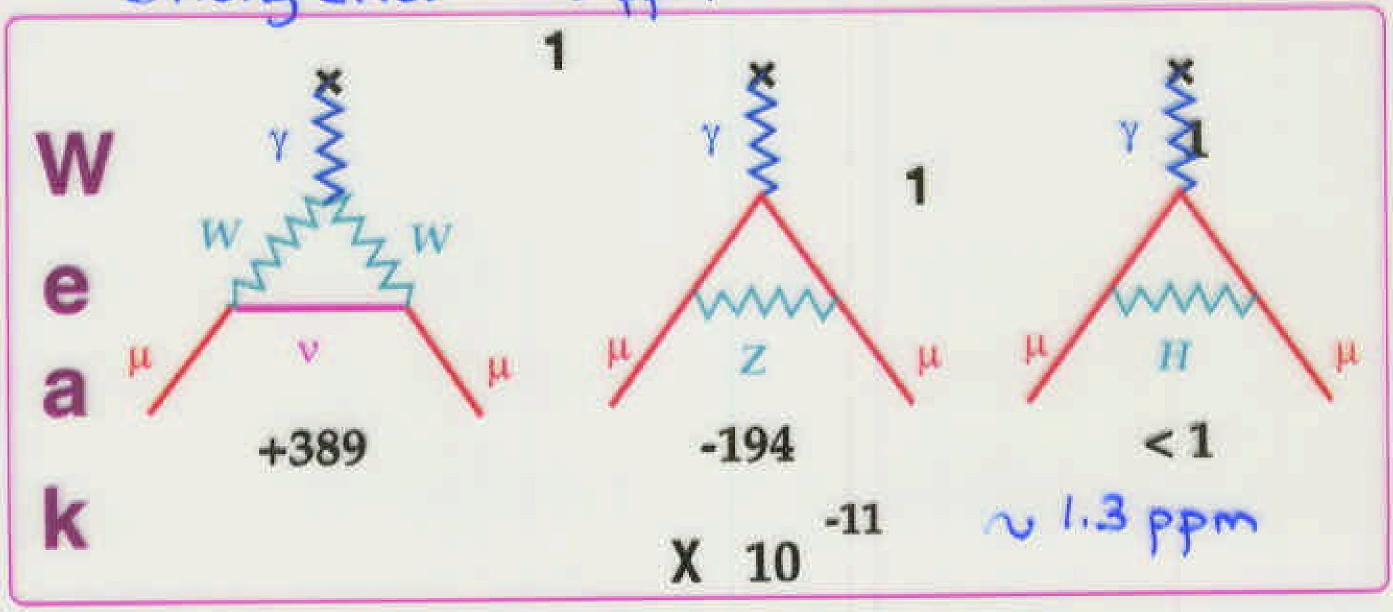
  BNL E821: 0.35 ppm

Theoretical Understanding of g-factors



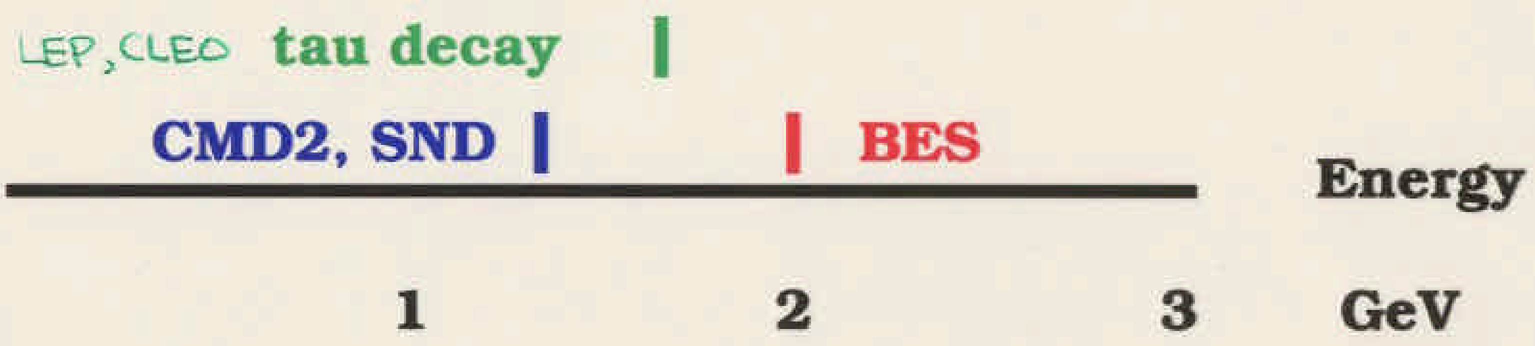


Strong error ~ 0.6 ppm



a_μ (HAD) Scorecard

Where's the error^2?



with $\tau \Rightarrow (0.5)^2$ $(0.2)^2$ $(0.3)^2$ Error^2 (ppm)^2

or

$\overline{\tau} \Rightarrow (0.7)^2$

Tau decay data

1) CVC : relate e+ e- => 2n pion cross sections with tau decay rate to 2n pions
=> major part of total low energy contribution (isovector piece)

2) Status: results more or less consistent but tau decay data is systematically higher than that from e+ e-.

=> deviation largest in latest 4 pion data sets. More modest in 2 pion

=> Preliminary indication: 2 pion discrepancy has not grown

=> Coming soon : new analysis of full LEP tau decay data set (M. Davier)

Hadronic Vacuum Polarization

Experimental measurements of R

$$R(s) = \frac{\sigma_{tot}(e^+e^- \to \textbf{Hadrons})}{\sigma_{tot}(e^+e^- \to \mu^+\mu^-)}$$

are used as input

$$a_\mu(\textbf{Had}; 1) = \left(\frac{\alpha m_\mu}{3\pi}\right)^2 \int_{4m_\pi^2}^{\infty} \frac{ds}{s^2} K(s) R(s)$$

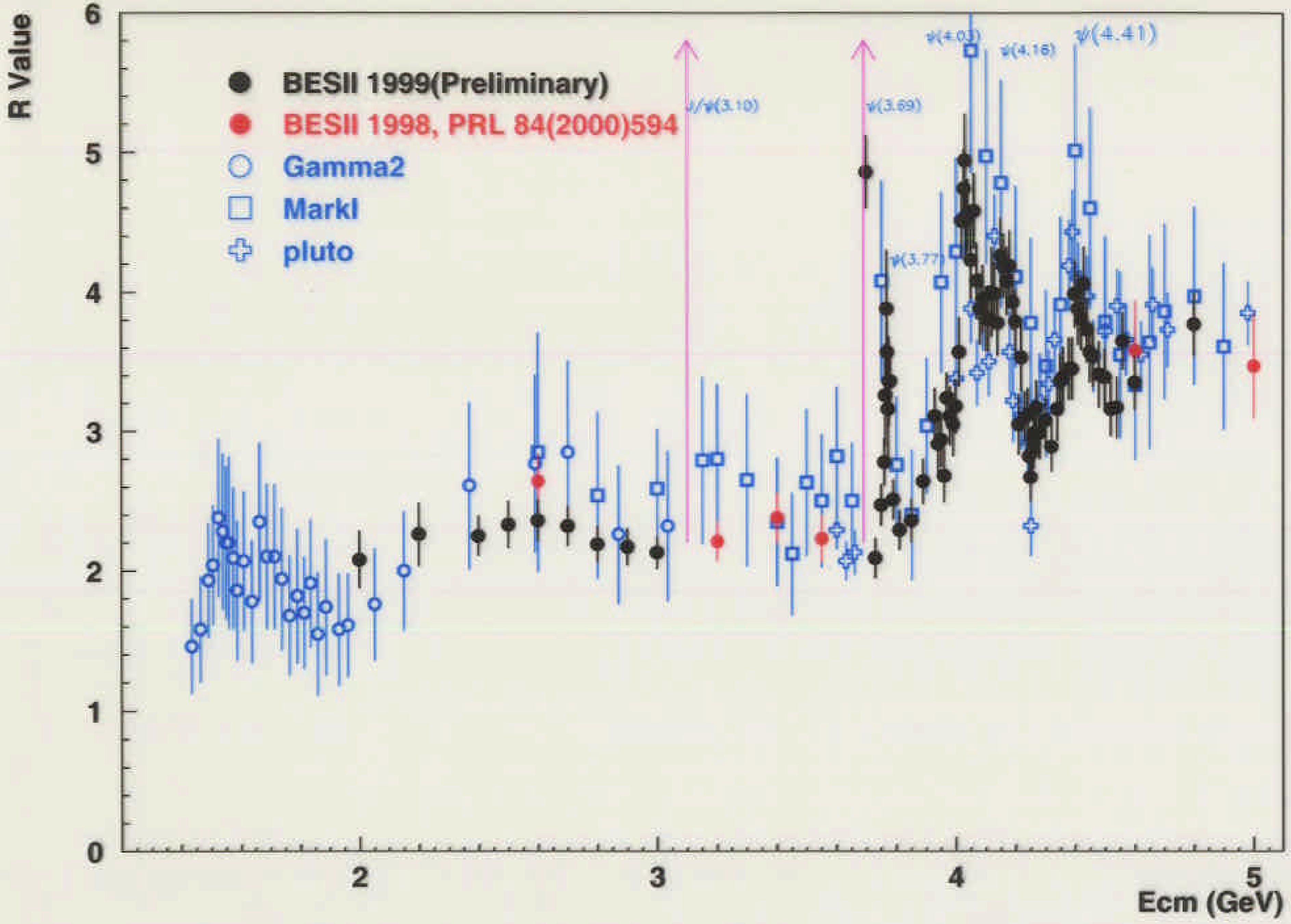
Recent Developments

- **Energy sweep at BES, includes 9 points from 2.0 to 3.1 GeV with 5 to 10 percent errors**

  → impact on a_μ(Had) TBA

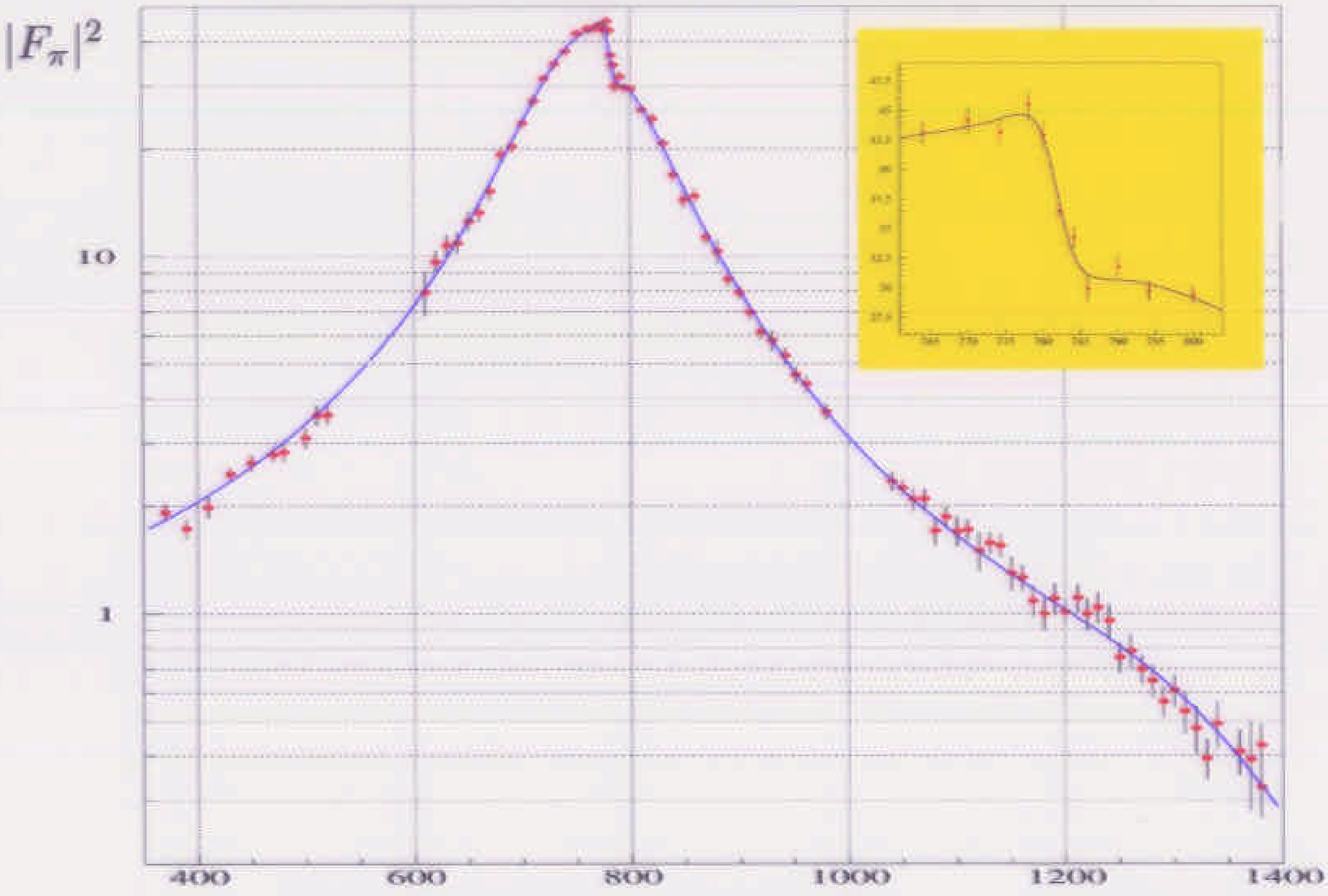
- **Using data from e^+e^- only, new data from CMD2 and SND (E<1.4 GeV) have reduced *overall* error from 14 to 9×10^{-10} (0.8 ppm) (S. Eidelman).**

- **Energy, luminosity and detector upgrades are planned (VEPP2000)**



R Value
BESII 1999(Preliminary)
BESII 1998, PRL 84(2000)594
Gamma2
MarkI
pluto
J/ψ(3.10)
ψ(3.69)
ψ(3.77)
ψ(4.03)
ψ(4.16)
ψ(4.41)
Ecm (GeV)
0
1
2
3
4
5
6

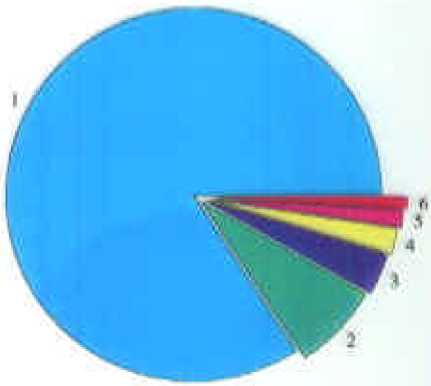
Pion formfactor study at VEPP-2M



Expected systematic errors ≈ 0.6%

$E_{c.m.}$, MeV

Hadronic Contribution to Muon Anomalous Magnetic Moment from VEPP-2M Data



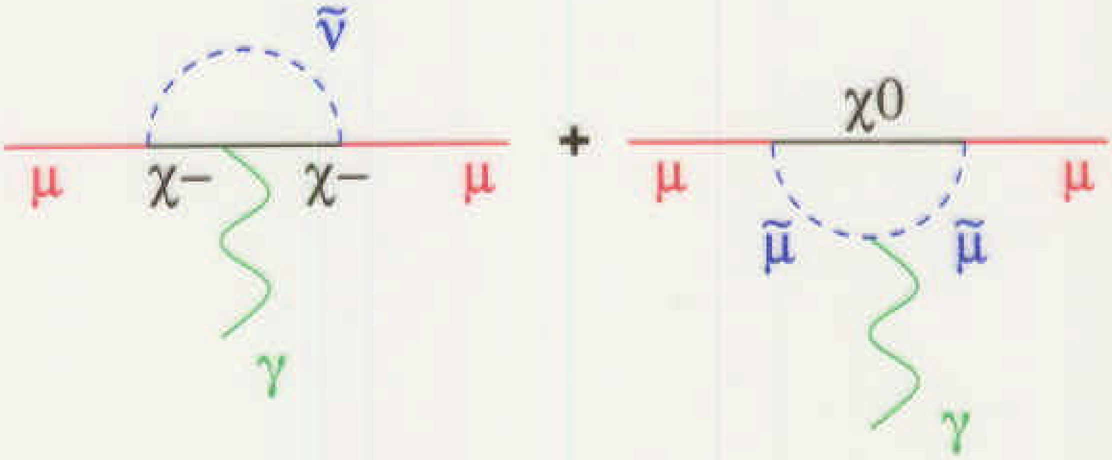
$a_\mu = \frac{g-2}{2}$

$a_\mu^{had}(total) = 70.2 \times 10^{-9}$ (60.21 ppm)

$a_\mu^{had}(VEPP-2M) = 60.18 \times 10^{-9}$ (51.61 ppm)

	Channel	Contr. ppm	Cross section error, %	Error in a_μ, ppm
1	$\pi^+\pi^-$	43.19	0.6	0.26
2	$\pi^+\pi^-\pi^0$	3.88	1.5	0.06
3	K^+K^-	1.81	5.2	0.09
4	$K_L K_S$	1.12	1.9	0.02
5	$\pi^+\pi^-\pi^0\pi^0$	0.77	7	0.05
6	$\pi^+\pi^-\pi^+\pi^-$	0.53	7	0.04
7	$\pi^0\gamma$, $\eta\gamma$	0.31	6	0.02
	Total	51.61		0.29

Supersymmetry



a_μ is a particularly sensitive test for SUSY models with large $\tan\beta$. In such models

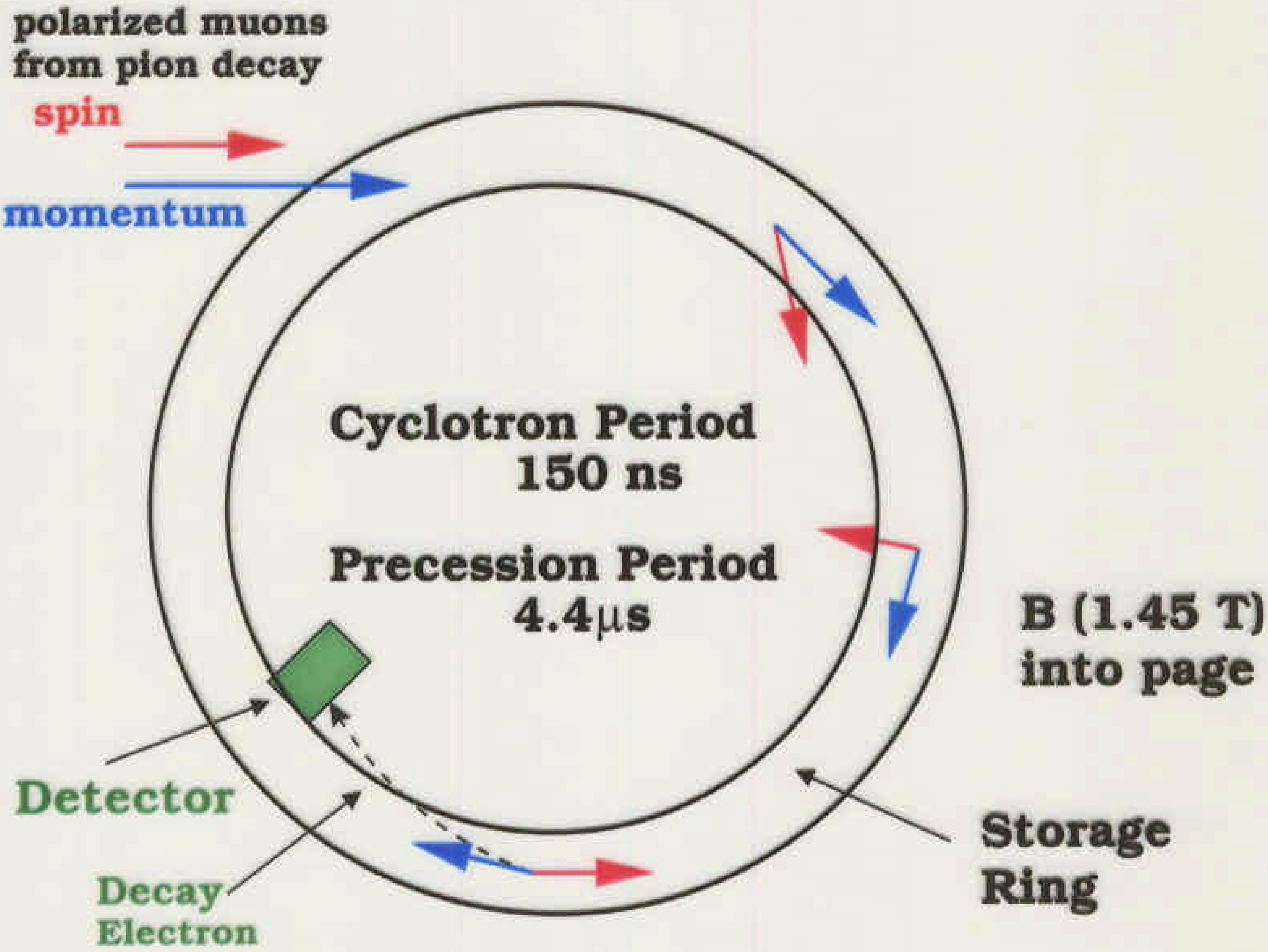
$$a_\mu(\mathbf{SUSY}) \approx \frac{\alpha}{8\pi\sin^2\theta_W}\frac{m_\mu^2}{\tilde{m}^2}\tan\beta$$

$$\approx 140 \times 10^{-11}\left(\frac{100\ \mathbf{GeV}}{\tilde{m}}\right)^2 \tan\beta$$

: nominal electroweak effect scaled by $\tan\beta$ and relative mass squared

Muon Spin Precession in a Circular Orbit

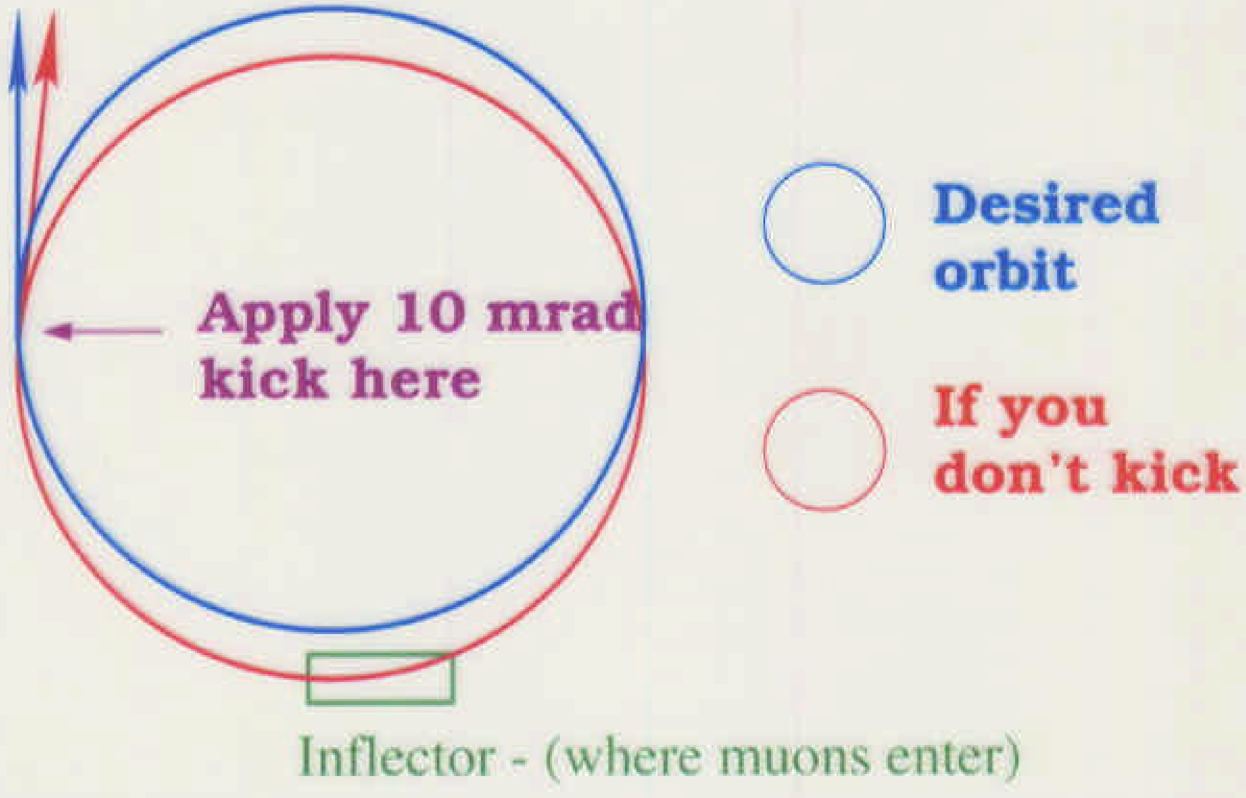
(exaggerated 30x)



ω_a is the time rate of change, in the lab, of the angle between the spin and momentum vectors.

{ Cyclotron motion, Larmor precession, Thomas precession } →

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



1) More stored muons than pion injection
2) Much less injection-related background

The Magic Gamma

With a focusing electric field, the equation for spin rotation becomes

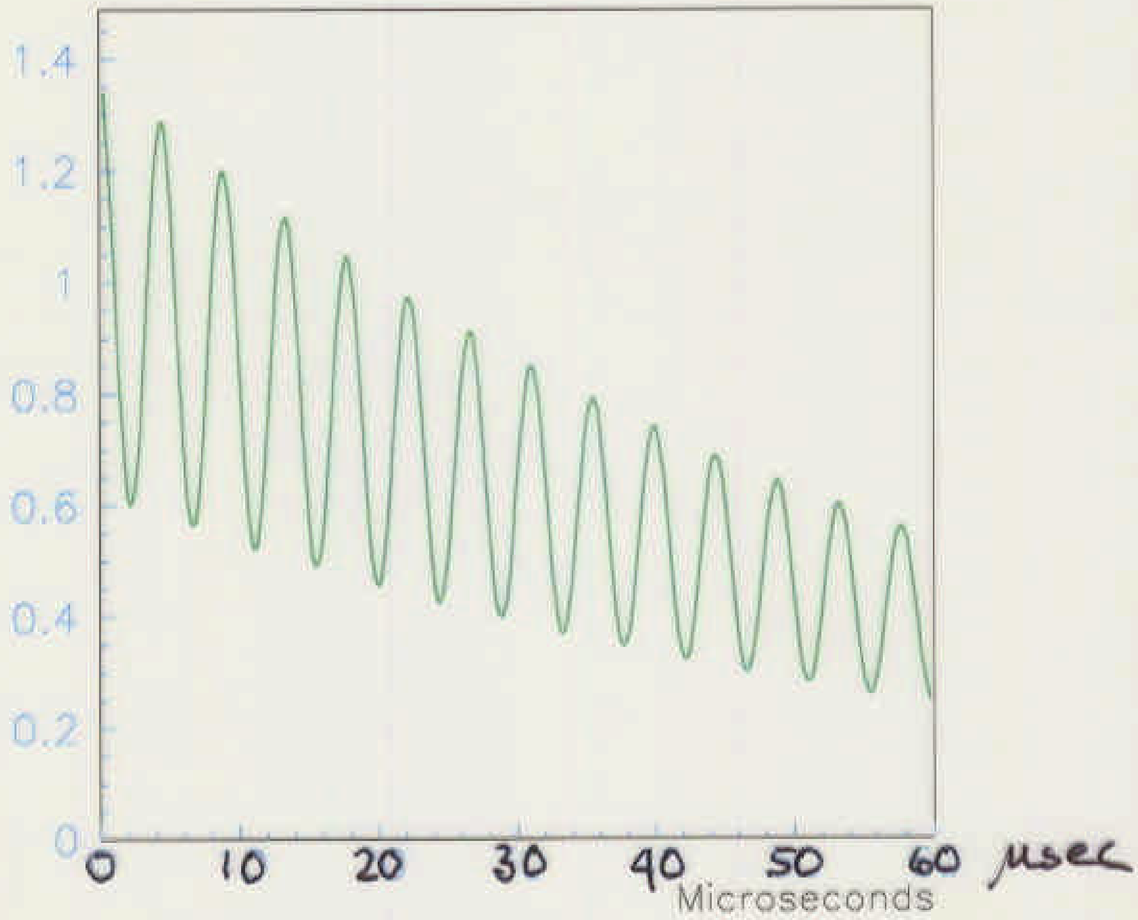
$$\vec{\omega}_a = \frac{e}{mc}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\vec{\beta} \times \vec{E}\right]$$

For the magic γ

$$\gamma^2 = 1 + 1/a_\mu \qquad E \approx 3.1\ \text{GeV}$$

the second term does not affect ω_a.

g-2 time spectrum



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

where

- τ: dilated muon lifetime $\approx$ 64.4 μsec
- ω_a: g-2 precession frequency $\approx$ 1.44 MHz
- A: asymmetry parameter

The statistical significance of the measurement goes as $(N_0 A^2)^{\frac{1}{2}}$

Magnetic Field

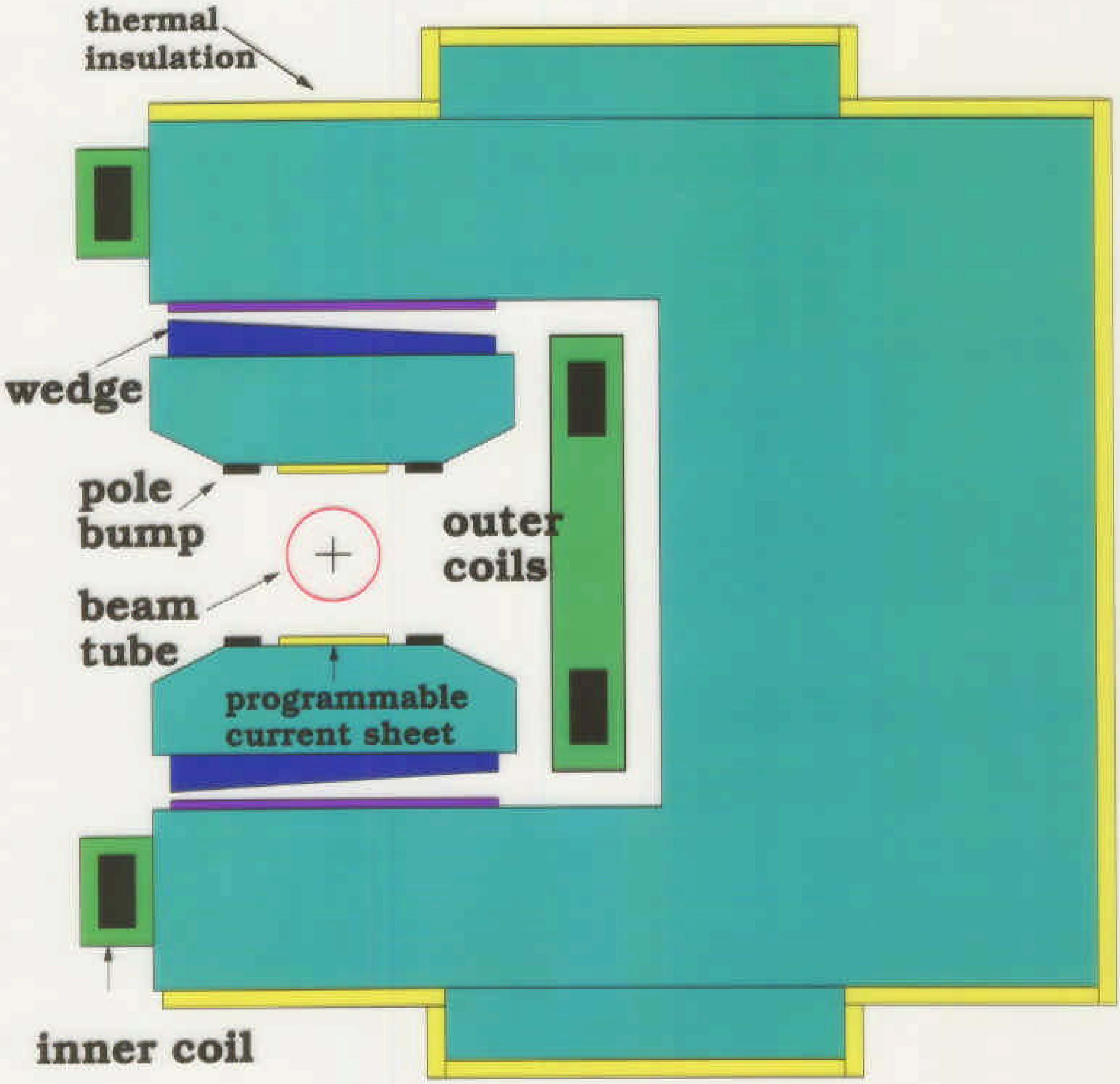
Error goal : 0.1 ppm

- => Map field periodically with NMR probes on trolley
- => Track B with 366 fixed NMR probes
- => Calibrate measurement probes to standard probe
- => Weight B-field by muon distribution

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

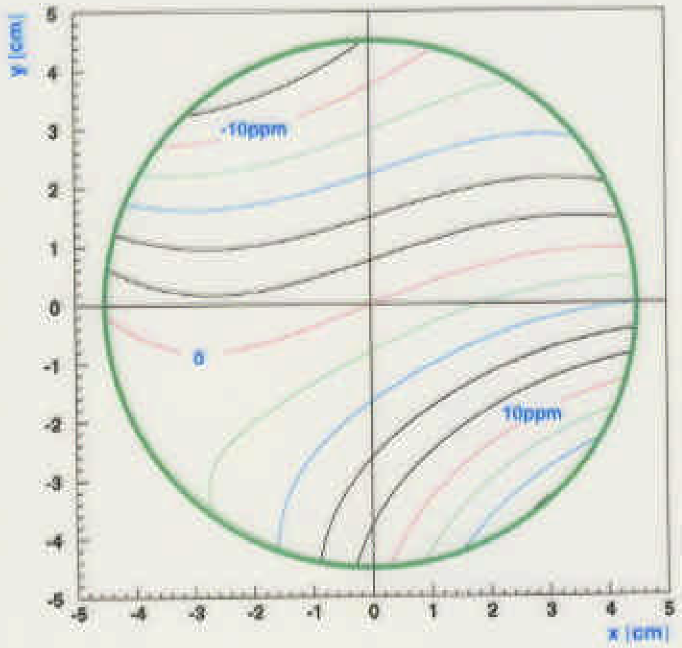
geometric average — averaged over muons

Year	ΔB (ppm)	$\Delta < B >$ (ppm)
1997	25	0.9
1998	4	0.5
1999	4	0.4 (est.)
2000	<2	

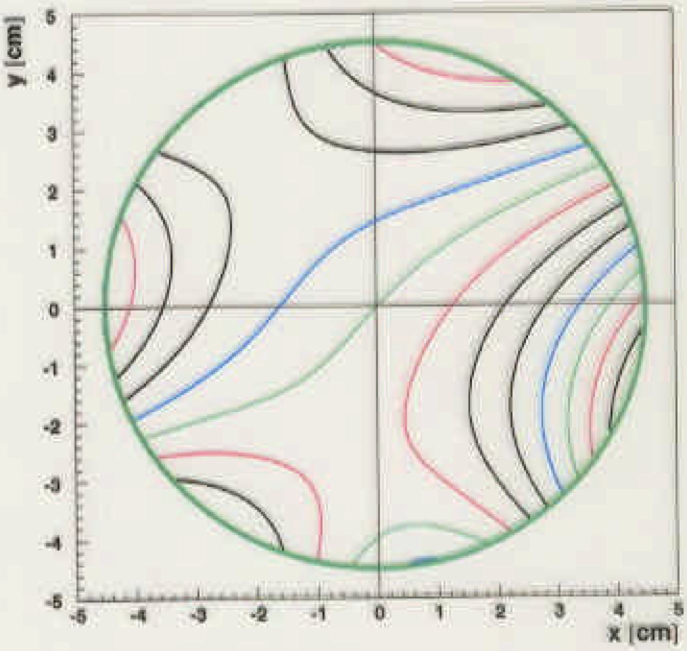


g-2 Magnet in Cross Section

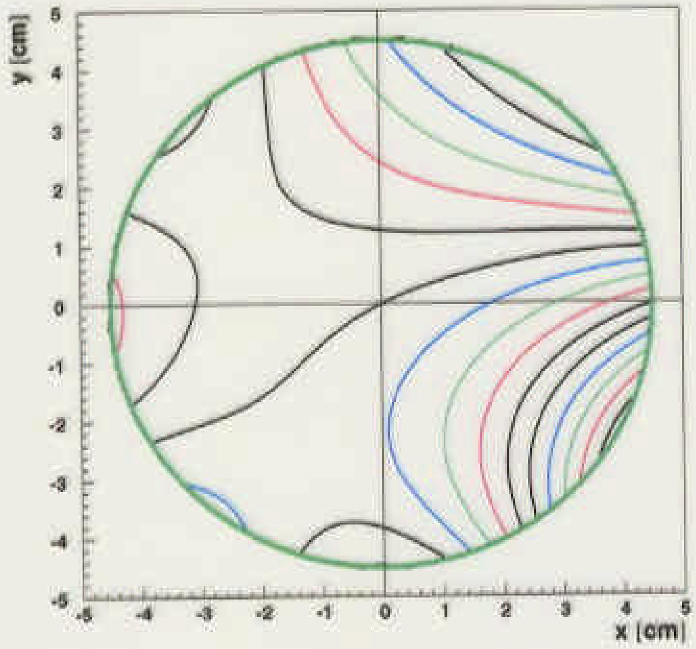
Magnetic Field Uniformity
(Azimuthal Average, 1 ppm contours, except '97)



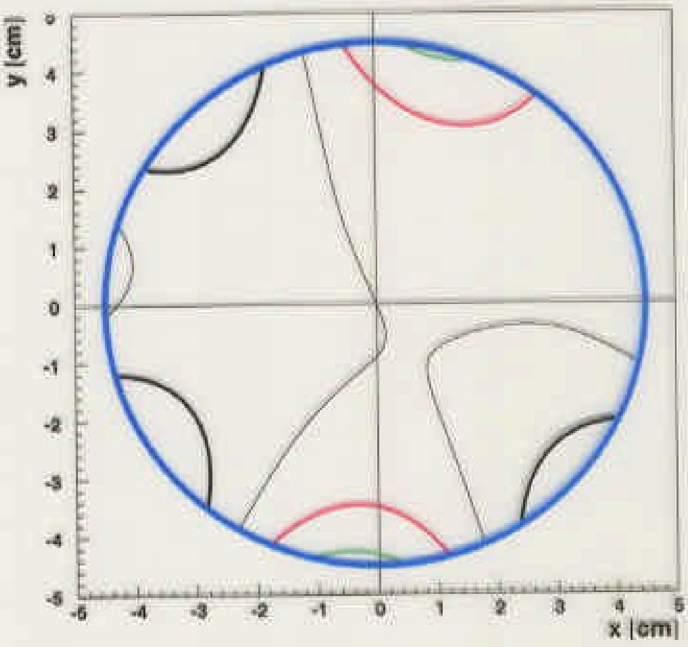
1997 run



1998 run

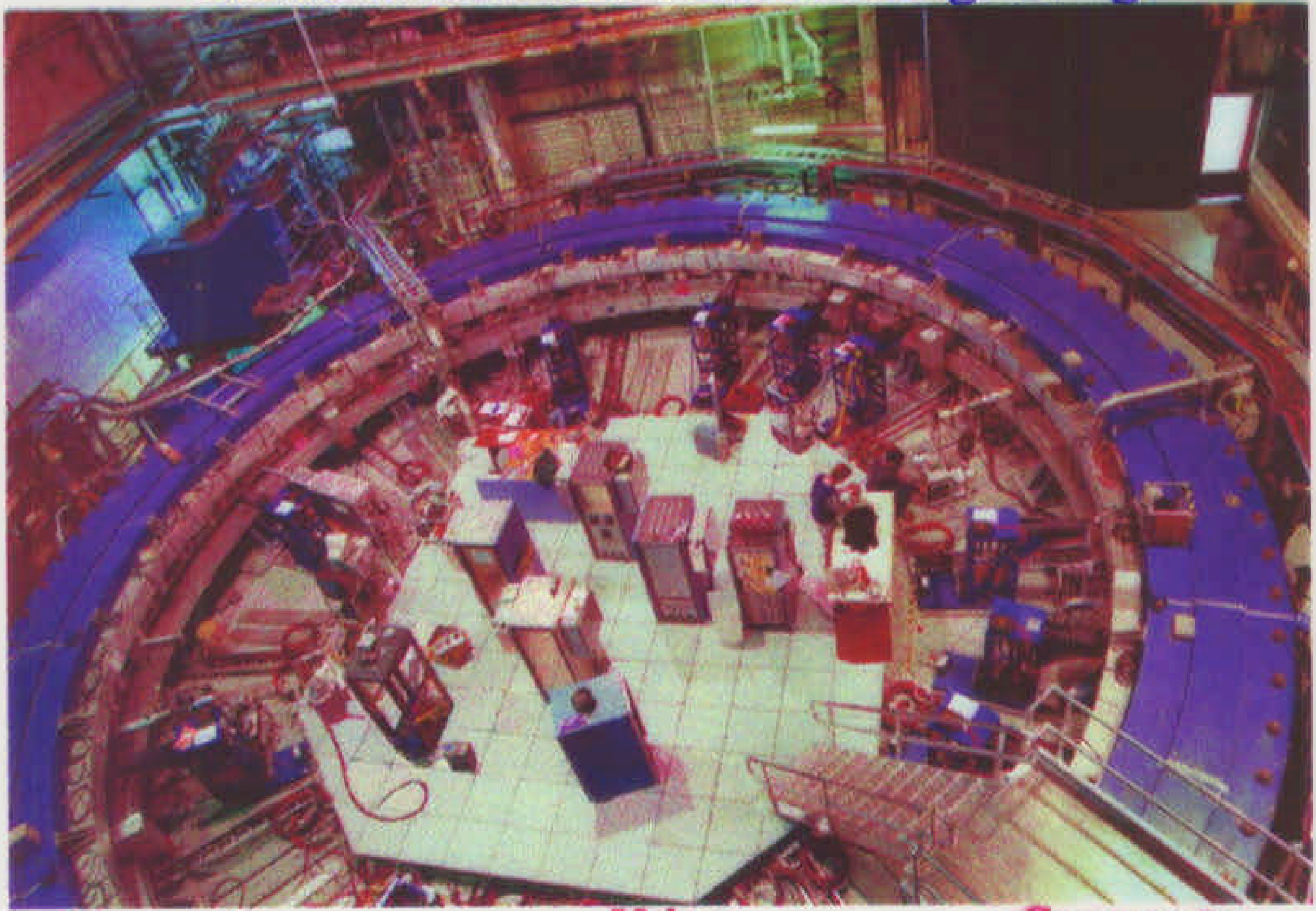


1999 run



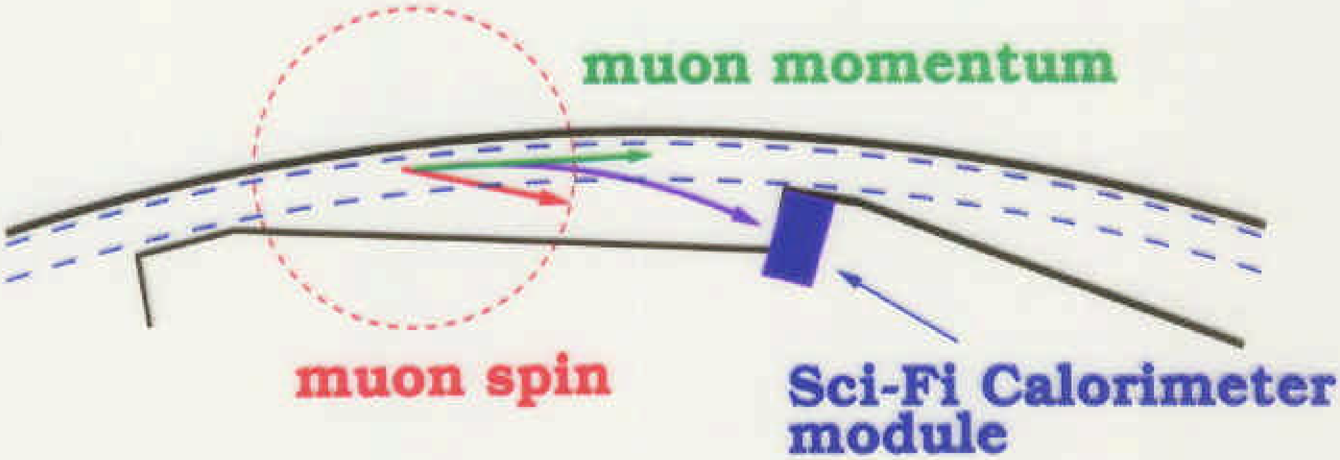
2000 run

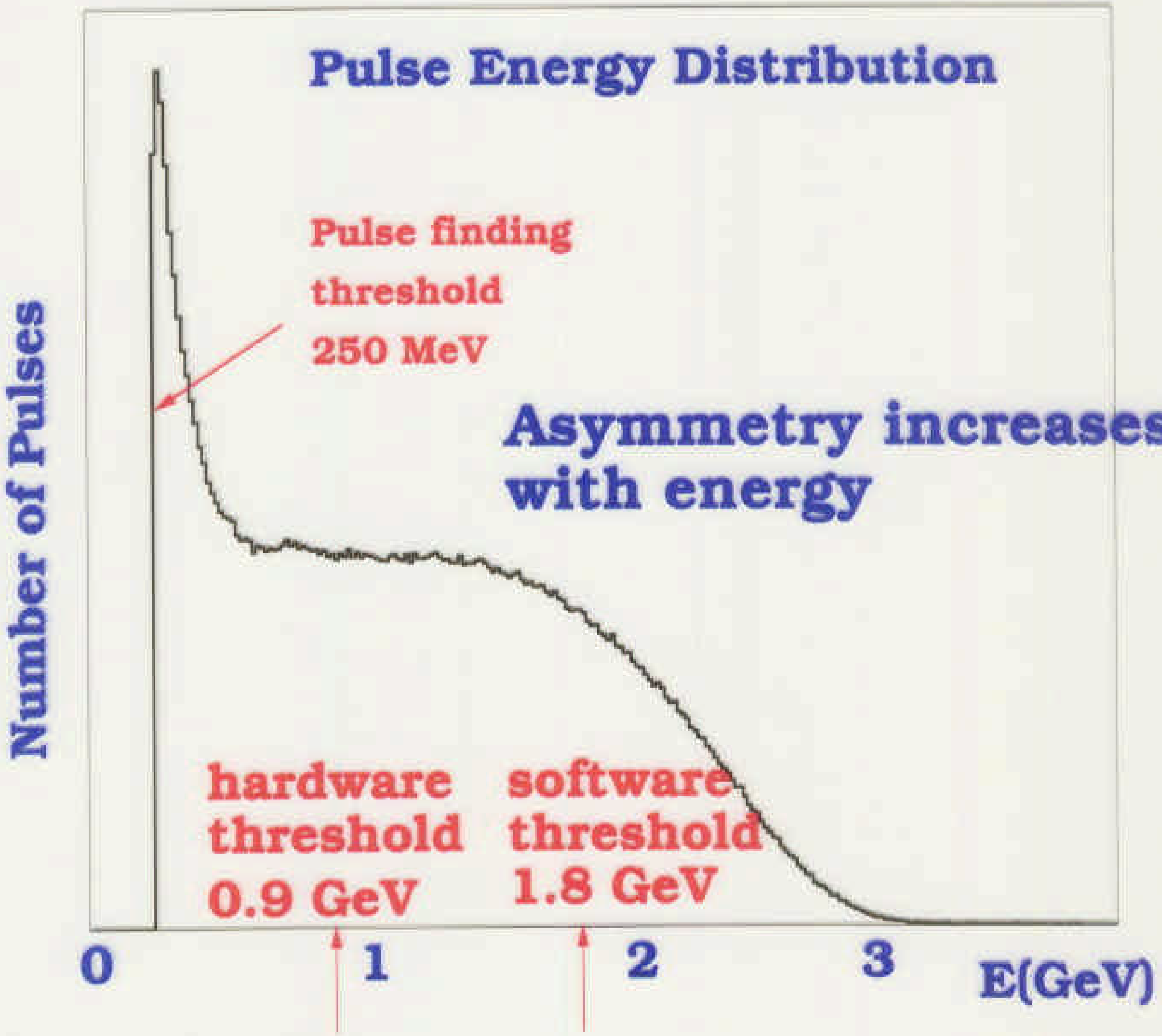
Brookhaven E821 Muon Storage Ring



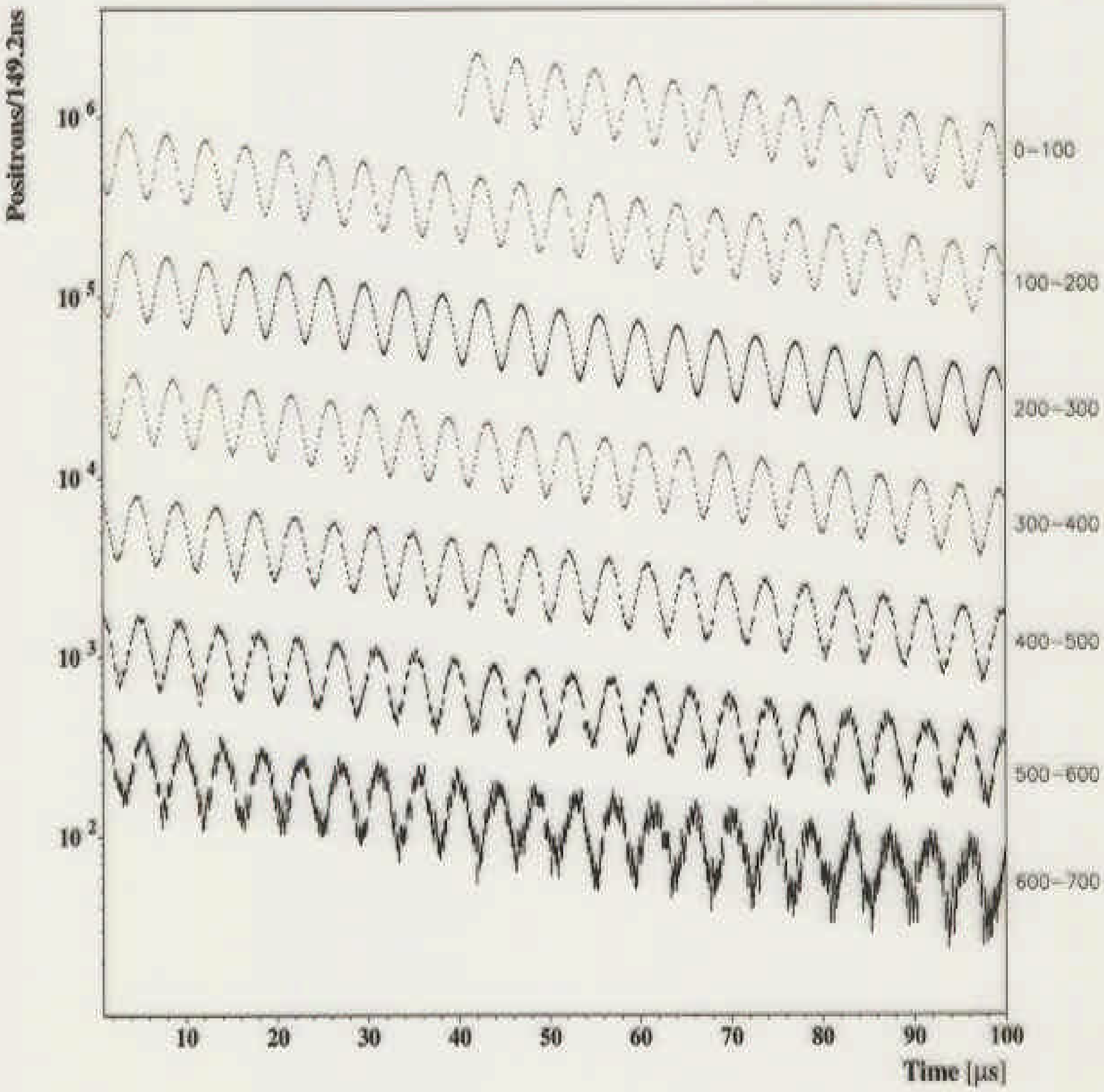
Parameter	Value	Comments
(g-2) Frequency	$f_a \sim 0.23 \times 10^6/\text{s}$	$\omega_a = 2\pi f_a$ $\tau_a = 4.37 \mu\text{s}$
Muon Lifetime	$\gamma\tau = 64.4\ \mu\text{s}$	
Muon kinematics	$p_\mu = 3.094\ \text{GeV/c}$ $\gamma_\mu = 29.3$	
Cyclotron Period	$\tau_{cyc} = 149$ ns	
Central Radius	$\rho = 7112$ mm	$(280'')$
Magnetic Field	$B = 1.451$ T	
Storage Aperture	9.0 cm circle	
In one lifetime:	432 revolutions around ring 14.7 *(g-2)* periods	

The Anomalous Precession





A Sample of 1999 data

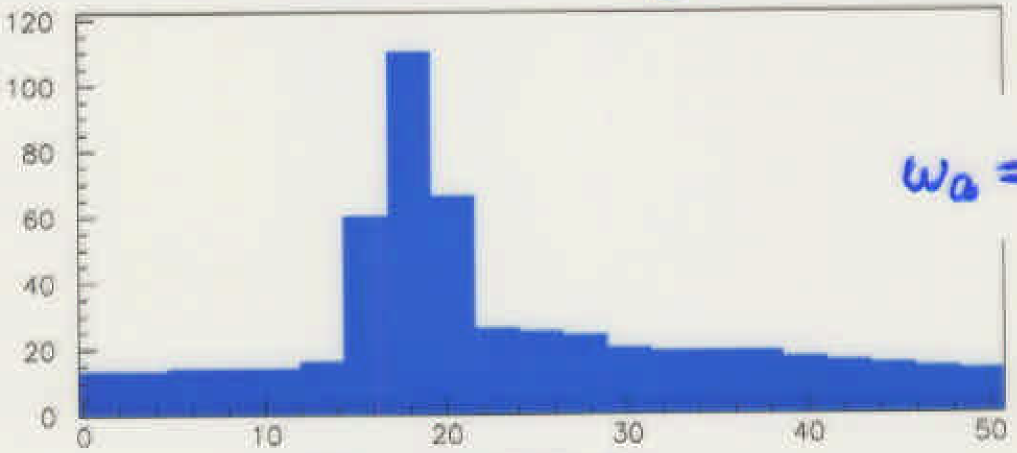


~ 750 Million Positrons

Fit to $N(t) = \underline{N_o} e^{-t/\tau}(1 + \underline{A}\cos(\underline{\omega_a} t + \underline{\phi}))$

ω_a error goal : 0.1 ppm

Detector Systematics

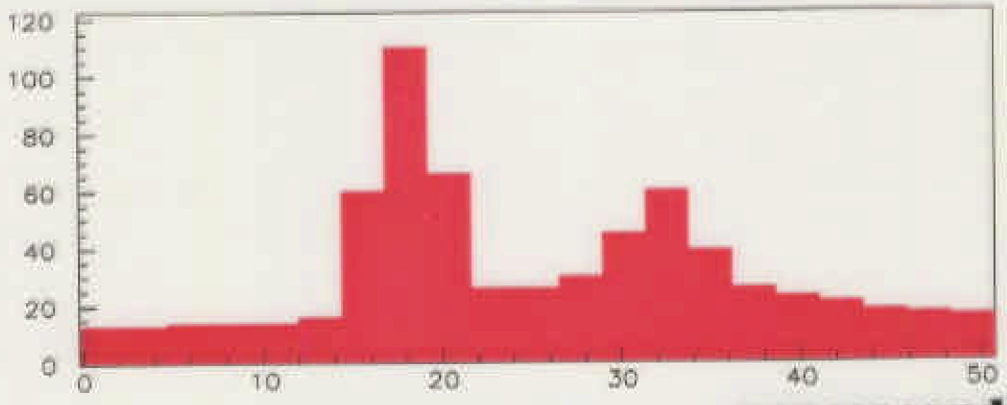


$$\omega_a = a_\mu \frac{eB}{m}$$

Normal Pulse nanoseconds

- **average time pickoff stable to 20 ps**
- **average gain stable to 0.2%**

over the first 200 μseconds of data taking cycle

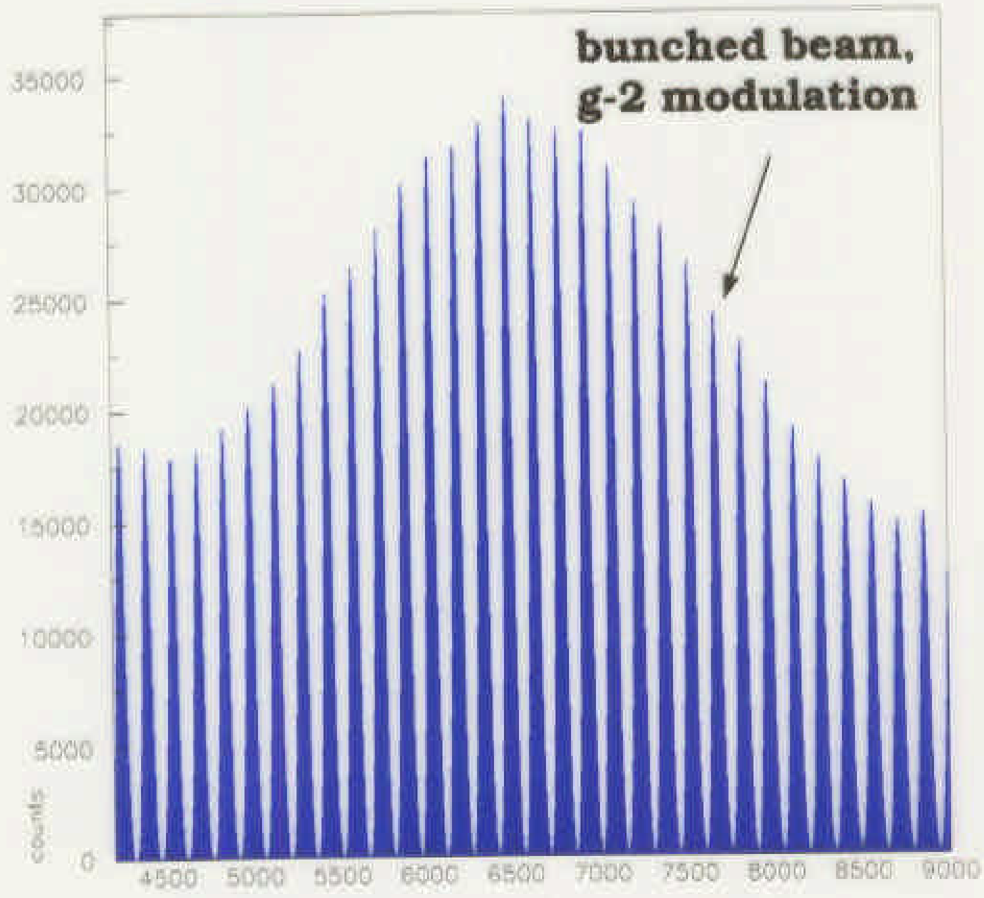


Pileup

- **small pulses disappear behind large ones**
- **two smaller pulses combine to form a larger one**

=> correction required, dominant systematic error in 1998 (0.6 ppm)

Beam Dynamics



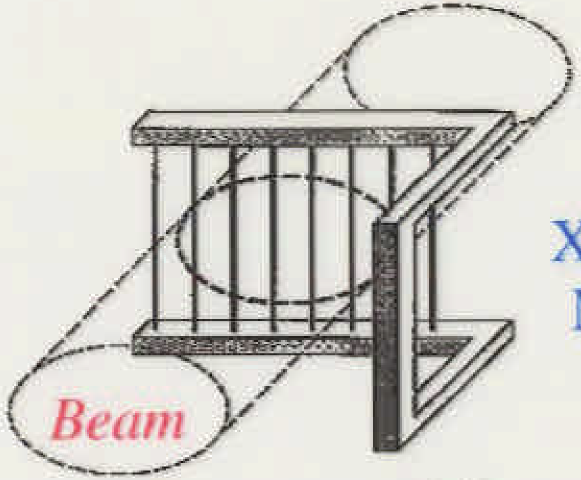
Pulse times in ns

Bunching of beam at early times and debunching

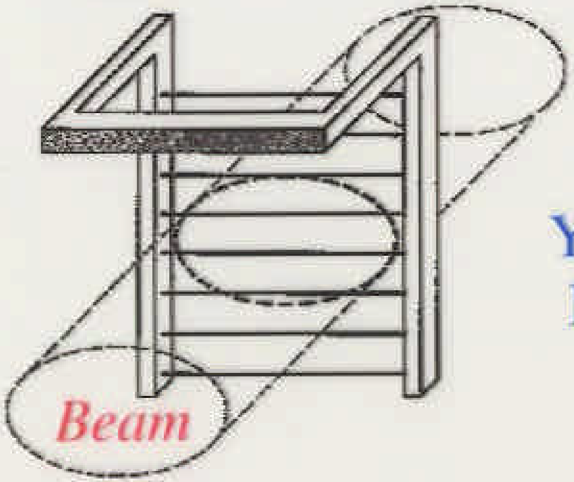
1) are used to determine momentum distribution of stored muons

2) must be accounted for in fitting the anomalous precession frequency

Scintillating Fiber Beam Monitor



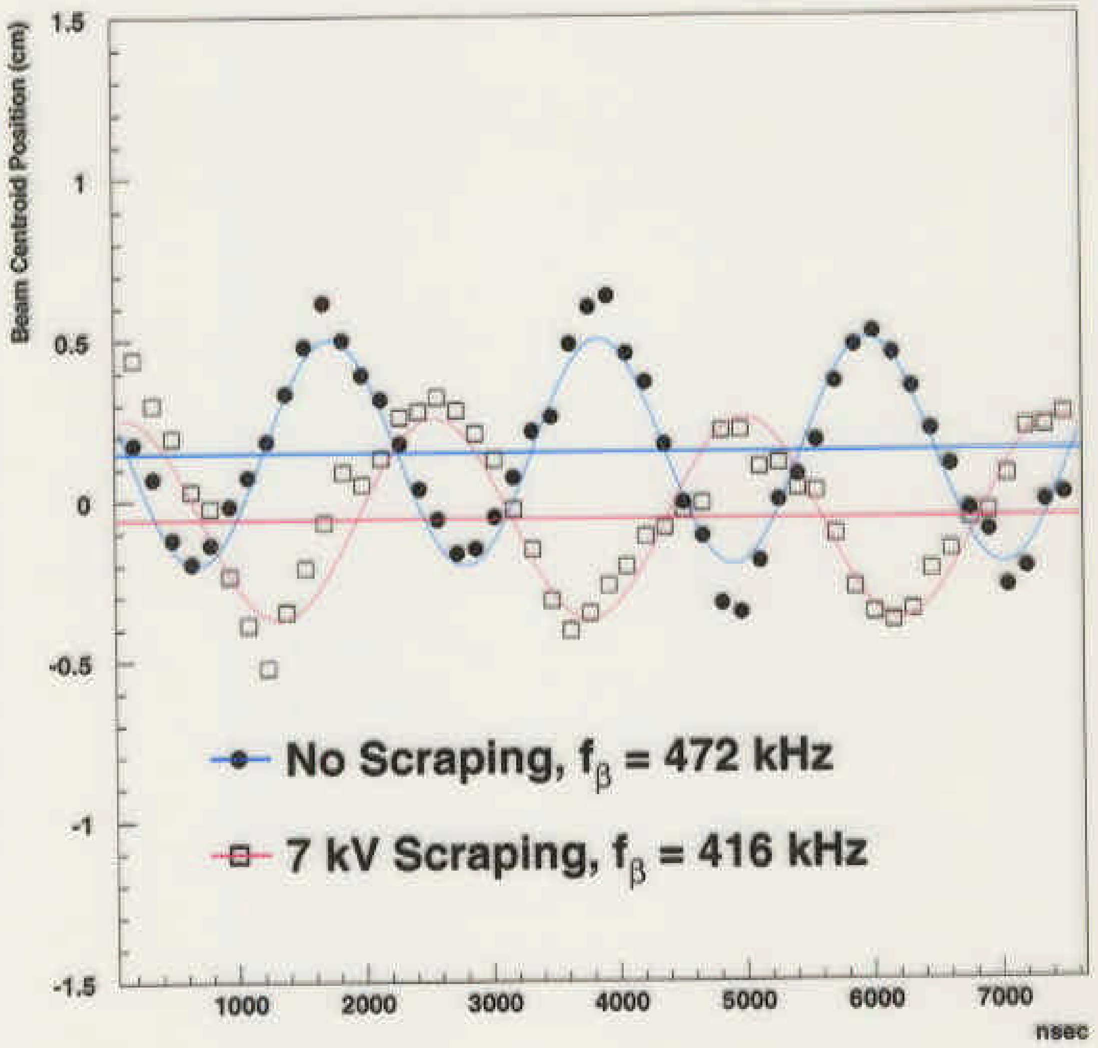
X–profile Monitor



Y–profile Monitor

- Measure radial and vertical profiles of muon beam on a turn–by–turn basis
- Two locations in the storage ring: 180° and 270° from injection point
- 7 fibers, 0.5 mm thick, 13 mm spacing
- Destructive measurement ⇒ remotely controlled pneumatic operation for insertion into beam

Coherent Betatron Oscillations



- **Average radial beam position oscillates with an amplitude of ~ 0.4 [redacted] cm**
- **Oscillation frequency ~ 2 ω_a**
- **Variation in detector acceptance vs. radius => small modulation in count rate**

Result From 1998 Running

$$a_{\mu^+}(\mu_{\rm inj}) = 116\,591\,91\ (59) \times 10^{-10} \quad (\pm 5\text{ppm})$$

errors statistically dominated

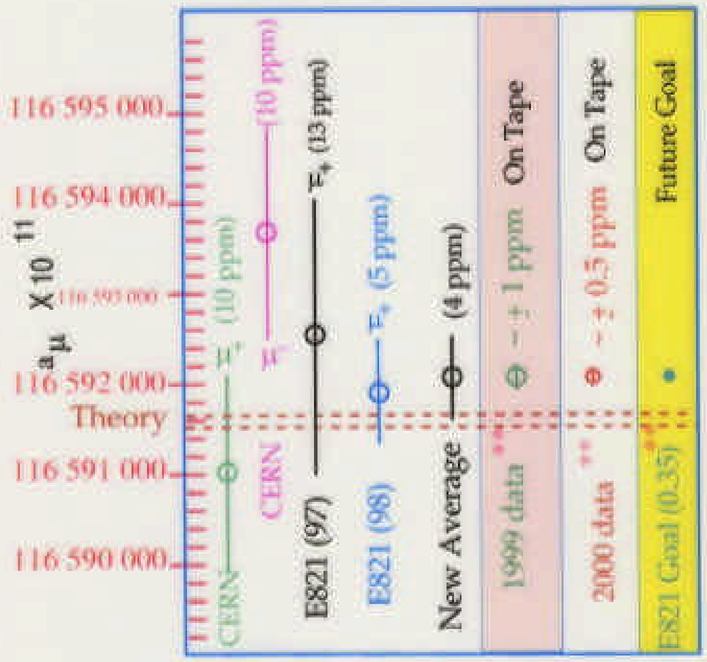
Experiment	$a_\mu \times 10^{10}$
CERN[1] μ^+	116 591 00 (110) (9.4 ppm)
CERN[1] μ^-	116 593 65 (120) (10 ppm)
E821[2] μ^+ $\pi_{\rm inj}$	116 592 51 (152) (13 ppm)
E821 μ^+ $\mu_{\rm inj}$	116 591 91 (59) (5 ppm)
NewAverage $\chi^2/\nu = 2.7/3$	116 592 05 (45) (3.9 ppm)
Theory[3]	116 591 62 (8) (0.66 ppm)

[1] J. Bailey et al.,Nucl. Phys. B150, 1 (1979) and the PDG

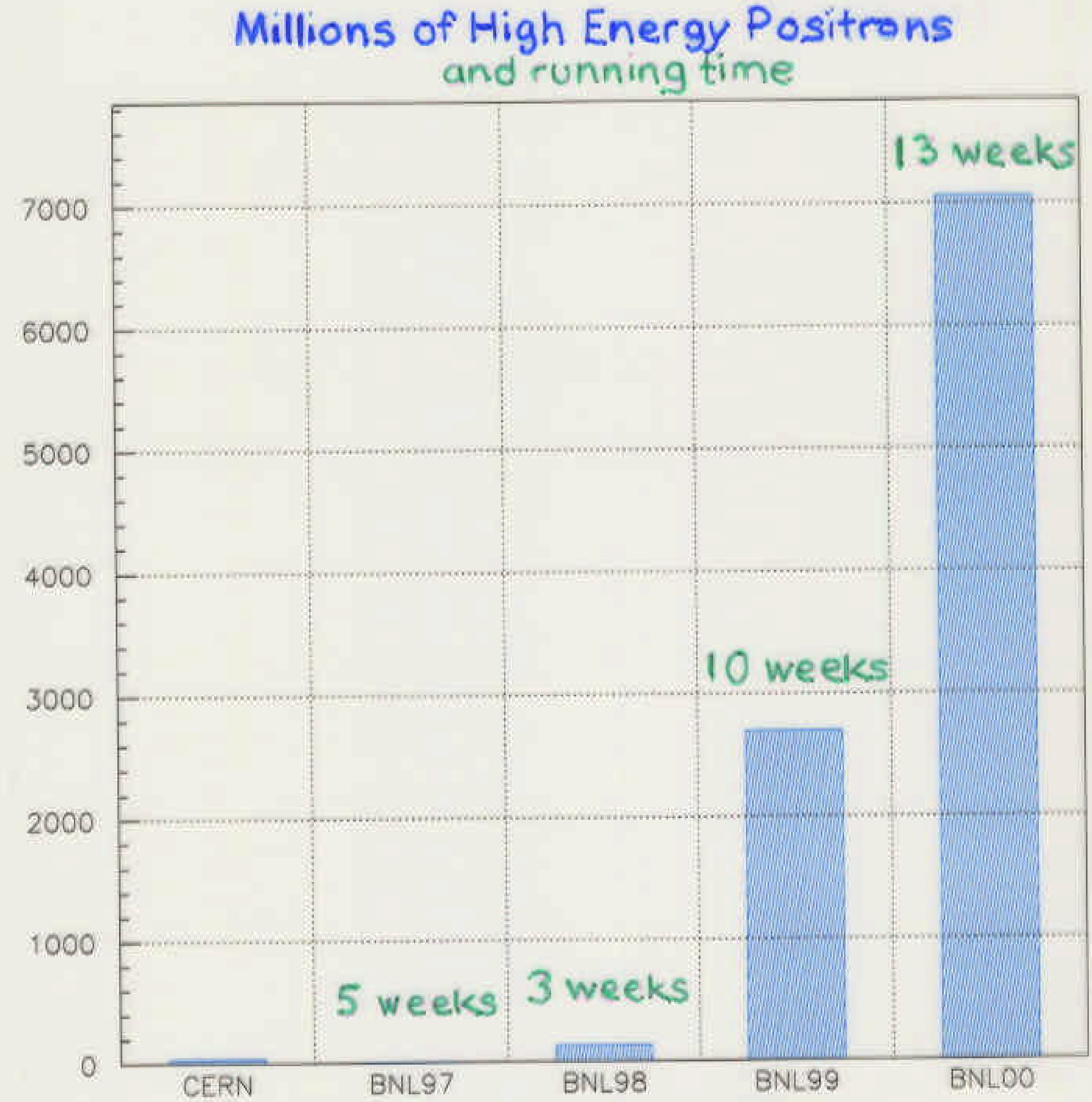
[2] R.M. Carey, et al., Phys. Rev. Lett. 82, 1632 (1999)

[3] V.W. Hughes and T. Kinoshita, Rev. Mod. Phys. 71, S133 (1999).

$$\text{Experiment} - \text{Theory} = (43 \pm 45) \times 10^{-10}$$



**projected errors with current value



Analysis time 50 weeks 40 weeks 25 weeks (so far!)

Also: 3/4 ω_a analyses complete and consistent

(99 RUN) 1/4 due soon

2 3 field analyses - a week away

Conclusions

1) Our newly submitted, 5ppm measurement of the muon anomalous magnetic moment is consistent with previous results and with the standard model.

2) The analysis of our 1999 data will be complete early this fall. A 1.5 ppm error (statistical) is expected. Production of the 2000 data has already begun. Together, the 1999 and 2000 data sets will provide a statistical precision of about 0.6 ppm.

3) Our next run, with negative muons, is scheduled to start in February, 2001.

4) Steady progress on the hadronic correction continues thanks to the efforts at BES, CMD2, SND, ALEPH and CLEO. More work is needed to resolve the differences between tau decay and e+e- data at low energy.