PRECISE MEASUREMENT OF THE ANOMALOUS MAGNETIC MOMENT OF THE MUON

Long Duong
University of Minnesota
BCP4 Workshop, Feb 20, 2001
(for the g-2 Collaboration)

- Experimental setup

- Results from 1999 data run

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~ 70 persons from 12 institutions

{ KEK — Inflector, magnet designs
{ TOKYO — Fiber beam monitors

Definition of (g-2)

- The magnetic moment $\vec{\mu}$ of an elementary particle is related to its intrinsic spin $\vec{S}$ by

$$\vec{\mu} = g \left(\frac{e}{2mc}\right) \vec{S}$$

- Dirac's theory predicts the value $g \equiv 2$.

- However, quantum field fluctuations make g slightly different from 2 and the difference is called the anomalous magnetic moment

$$a \equiv \frac{g-2}{2}$$

$$
\begin{aligned}
a_\mu\,(CERN) &= 0.001\ 165\ 923(8)\ (7\ ppm) \\
a_{\mu^+}\,(E821\ '97) &= 0.001\ 165\ 925(15)\ (13\ ppm) \\
a_{\mu^+}\,(E821\ '98) &= 0.001\ 165\ 919(6)\ (5\ ppm) \\
a_\mu\,(SM)^\dagger &= 0.001\ 165\ 916\ 0(7)\ (0.6\ ppm)
\end{aligned}
$$

$\dagger$ A. Czarnecki and W.J. Marciano, Nucl. Phys. (Proc. Suppl.) **B76**, 245 (1999).

SM Calculation of a_μ

- The theoretical value of a_μ in the SM

$$a_\mu \equiv a_\mu^{QED} + a_\mu^{HAD} + a_\mu^{EW}$$

$$\begin{array}{ccc} 10^6 & 60 & 1.3 \\ (\pm 0.02) & (\pm 0.7) & (\pm 0.03) \end{array} \Big\} \begin{array}{c} \text{in} \\ \text{PPm} \end{array}$$

QED

$$\left(\frac{\alpha}{2\pi}\right) \cong 0.001\ 16!$$

HAD

Hadron states
Dispersion thy $\left\{ \begin{array}{c} e^+e^- \\ \tau\ \text{decay} \end{array} \right\}$

EW

AGS at Brookhaven Lab,
Long Island , New York

E821 beam line and muon storage ring

24 GeV/c P
V – line FEB transport

6 x 10¹³ protons / spill V – target station

V1 beam line 3 GeV/c π

14 meter diameter superferric muon storage ring

π, μ selection slits

$P \approx 96\%$

3 GeV muons

polarized muons from pion decay

π → μ
ν

10 meters

B = 1.45 T ; R = 7.112 m ; I = 5000 A

Iron Yoke

Inner Upper Coil

Pole Tips — Muon Beam

Outer Coil

Inner Lower Coil

R=7.11m

To Ring Center

50 cm
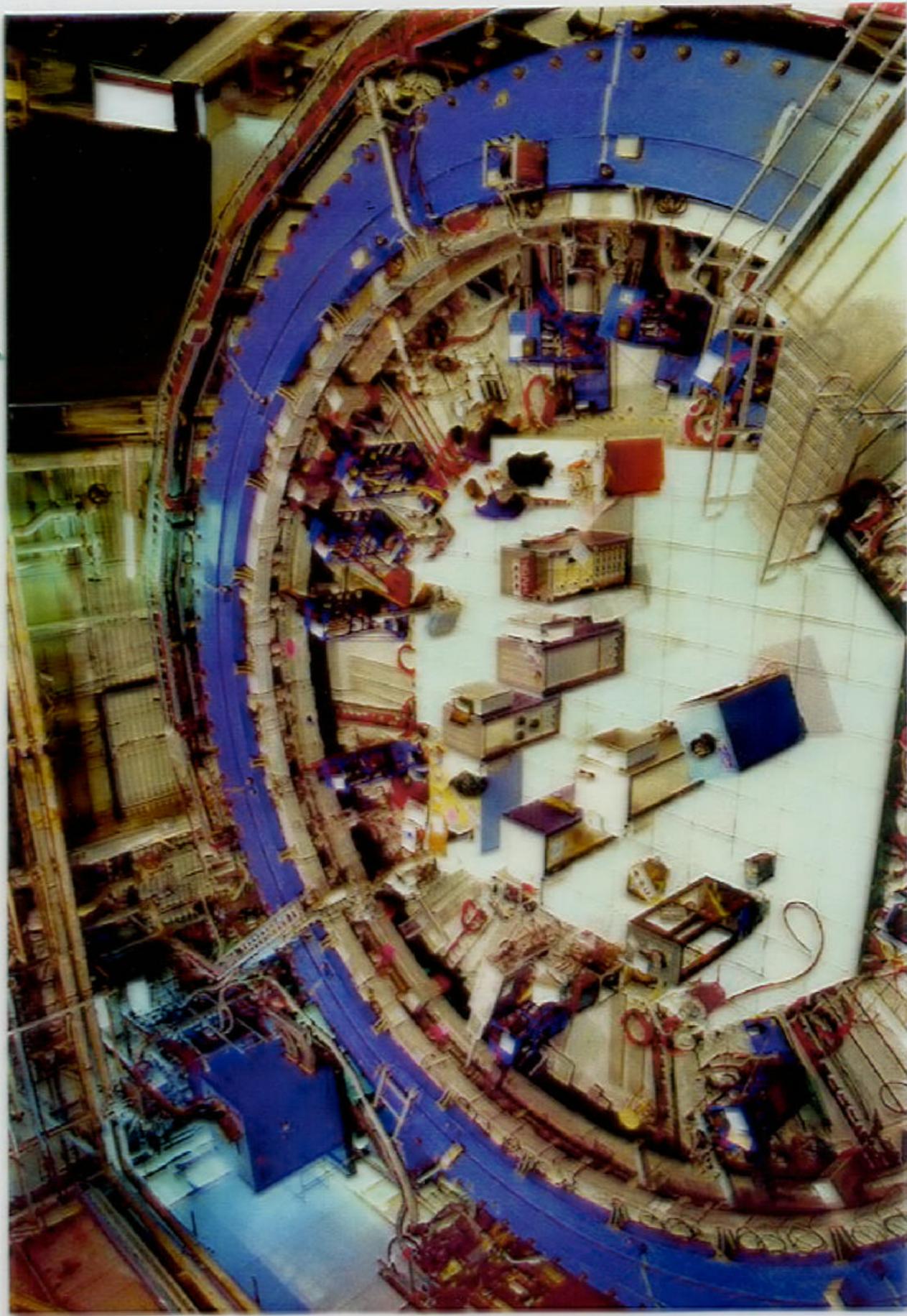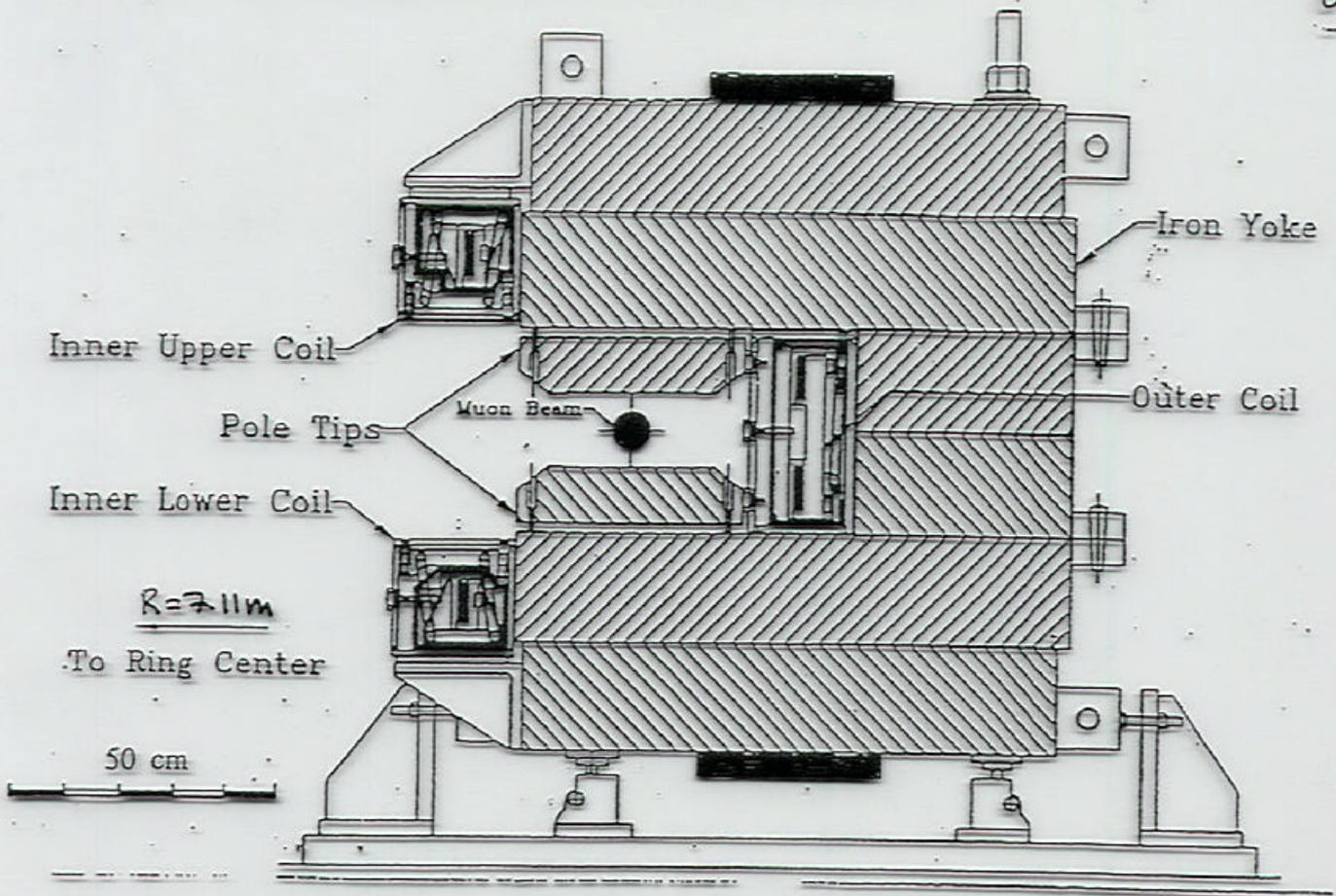
integrated field contour plots

July 1997

-10ppm

0

10ppm

August 1998

0   -2

0

0

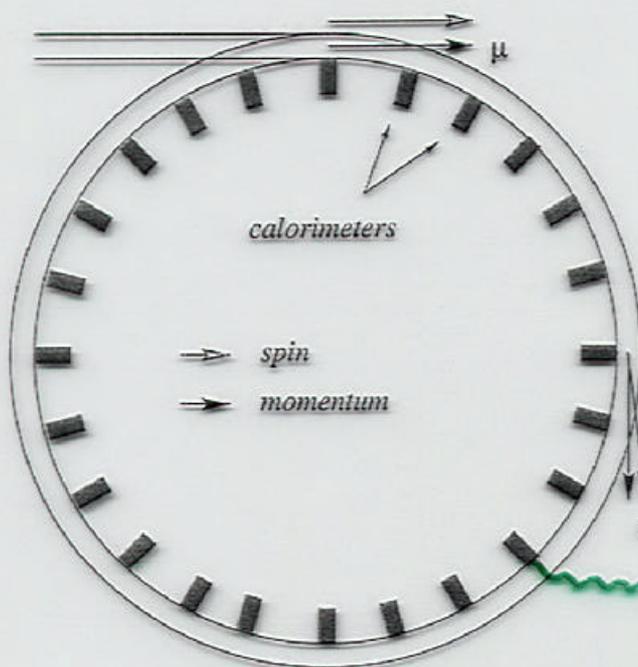2ppm
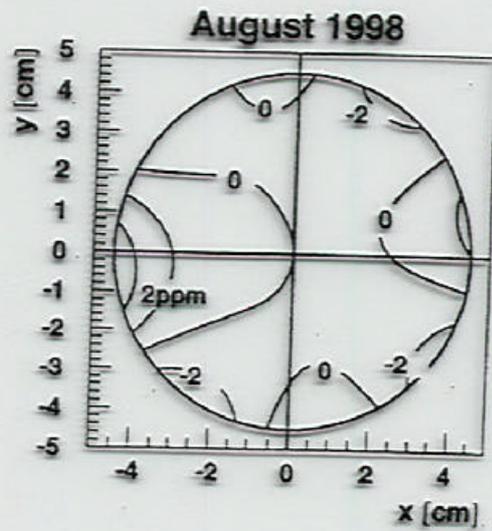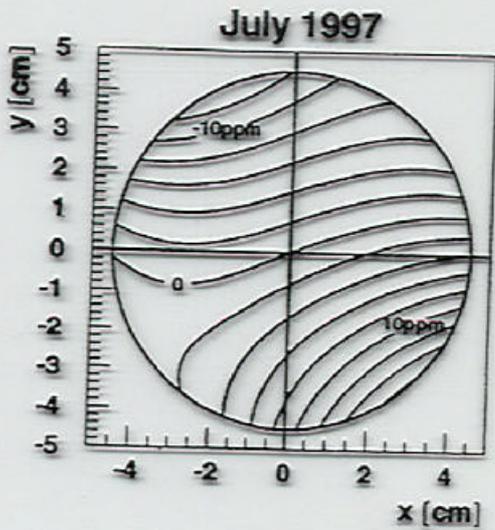
-2   0   -2
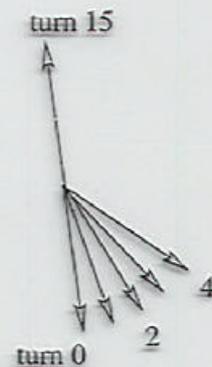
Physics of Muon Precession

- In general $(\vec{E}, \vec{B})$ fields, the spin precesses (ω_s), and the momentum vector rotates (ω_c). The observed difference frequency ω_a in the lab is

$$\vec{\omega}_a^\dagger \equiv \vec{\omega}_s - \vec{\omega}_c = \frac{e}{mc}\left[a\vec{B} - \left(a - \frac{1}{\gamma^2 - 1}\right)\vec{\beta} \times \vec{E}\right]$$

- The muons are at $\gamma = 29.3$ so that the term $\vec{\beta} \times \vec{E}$ vanishes to allow vertical focusing by a weak electric field.

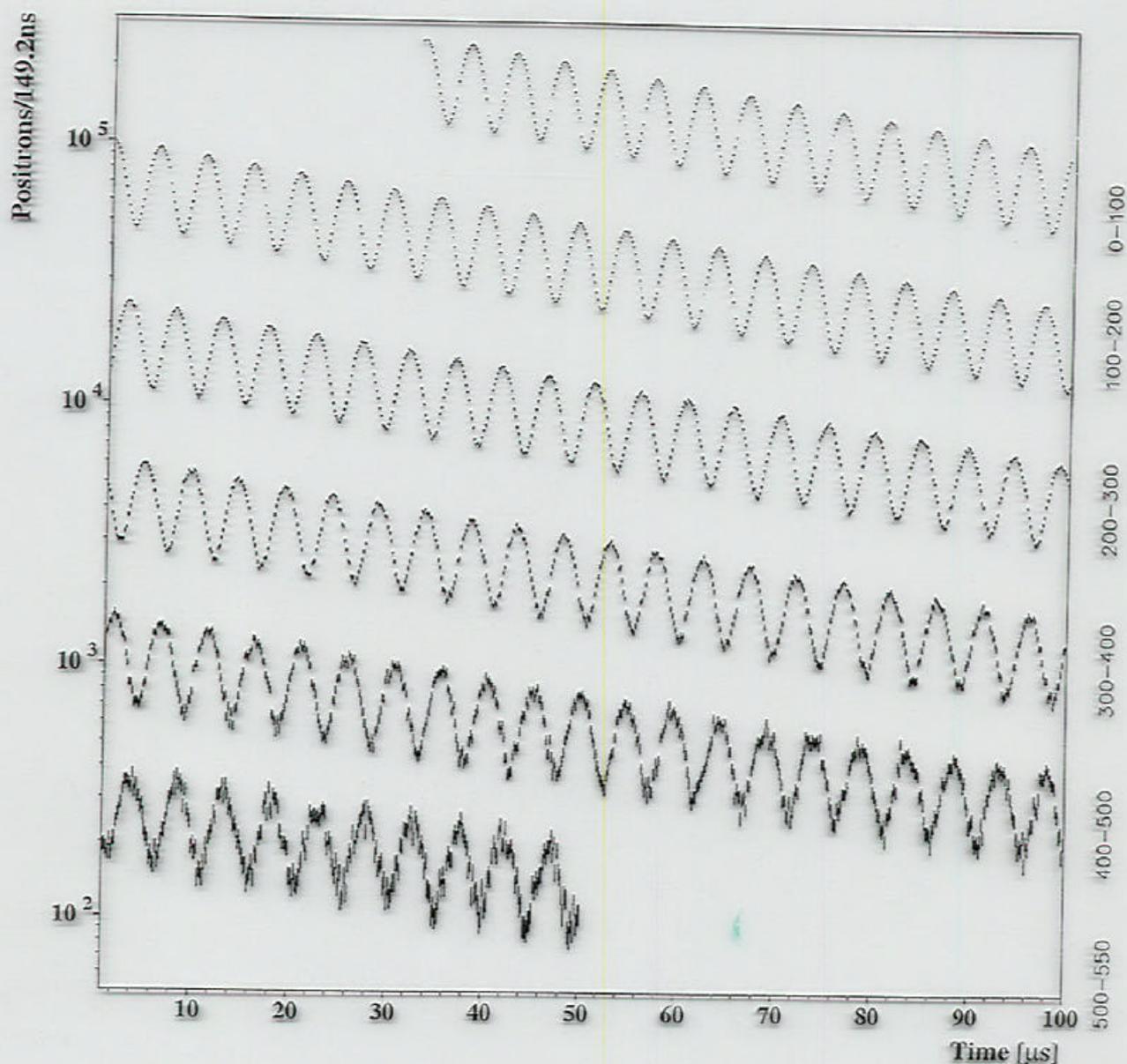$$\left.\begin{array}{l}\tau_c = 149 \text{ ns} \\ \tau_a = 4366 \text{ ns}\end{array}\right\} 29\,X$$

calorimeters

→ spin

→ momentum

turn 15

turn 0

0   2   4

Lead - Scintillating fiber (Res. ~ 10% E)

† V. Bargmann, L Michel and V.L. Telegdi, Phys. Rev. Lett. 2, pg 435 (1959)

$(g-2)_\mu$

Counting high energy positrons from muon decays shows the anomalous precesssion frequency ω_a (We count for $\sim 600-1500\ \mu s$, and the anomalous precession period is 4.366 μs)

Determining a_μ

The principal equations are

$$\omega_a \equiv a\left(\frac{eB}{mc}\right) \ ; \ \omega_L \equiv \frac{g}{2}\left(\frac{eB}{mc}\right) \ ; \ a \equiv \frac{g-2}{2}$$

$$\frac{\omega_a}{\omega_L} \equiv \frac{a}{\left(\frac{g}{2}\right)} \equiv \frac{a}{1+a}$$

$$\equiv \frac{\omega_a}{\omega_L(p) * \frac{\omega_L(\mu)}{\omega_L(p)}} \equiv \frac{\omega_a}{\omega_p * \frac{\mu_\mu}{\mu_p}} \equiv \frac{R}{\lambda}$$

free proton NMR freq. in B

and finally

$$\boxed{a = \frac{R}{\lambda - R}}$$

$$R \equiv \frac{\omega_a}{\omega_p} \ (measured \ by \ (g-2) \ experiment) \ \sim \frac{1}{300}$$

$$\lambda \equiv \frac{\mu_\mu}{\mu_p} \ (from \ muonium \ hyperfine \ structure)$$

$$= 3.183\ 345\ 39\ (10)^\dagger$$

† D.E. Groom et all., Review of Particle Physics, *Eur. Phys. J.* **C15**, pg 1 (2000)

"Blind Analysis" Determination of a_μ

Separate and independent ω_p and ω_a analyses with offsets for the two groups unknown to each other.

- ω_p: two analyses (Yale, BNL)

- ω_a: two groups (four analyses)

  1. g2off: FORTRAN/PAW based (BNL, Boston, MN)

  2. G2Too: C++/ROOT based (Illinois, MN)

After the two (ω_p, ω_a) analyses are final, then remove offsets and combine to get a_μ.

   ↳ for 1999 data
   offsets removed at
    Jan 11-12 Coll. Mtg.

$(g-2)_\mu$

The ω_p Measurement

→ ~ 6000 pts in azimuth
~ 1 cm

- Trolley measurements using 17 NMR probes about $2-3$ times each week

- Between trolley measurements B is tracked using 366 NMR probes fixed to vacumn chamber

- The trolley probes are calibrated before/after data taking periods using an absolute calibration probe (spherical water volumn)

Improvements Since 1997 Run

- Thermal insulation of the magnet (better azimuthal homogeneity)

- Fixed NMR probe readings used in feedback loop to the main magnet power (better stability between trolley measurements)

- Passive/active shimming using iron wedges/surface correction coils (reduction in multipoles)
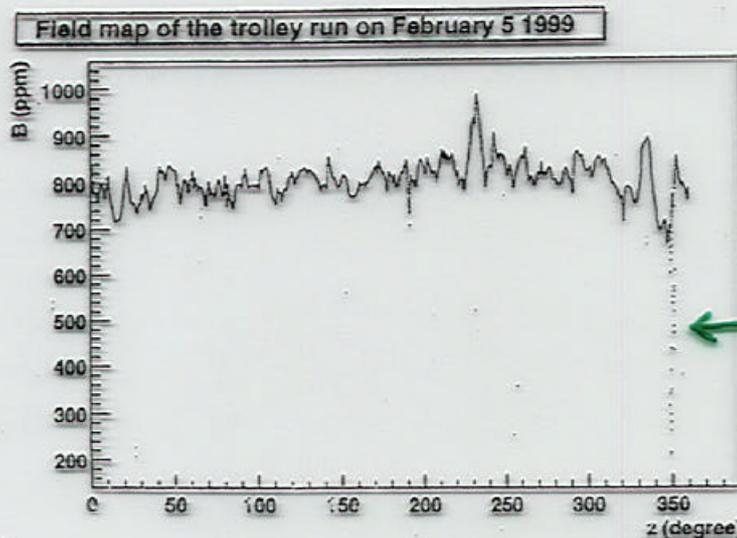
TROLLEY PROBE POSITIONS
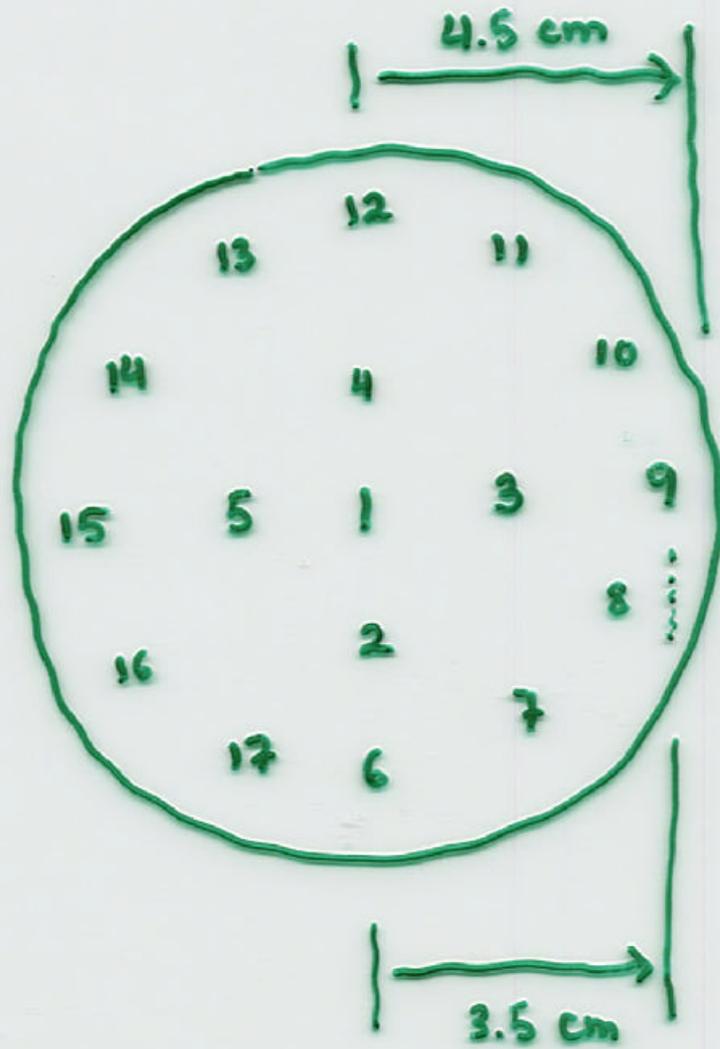
The 2 ω_p analyses agree within 0.03 ppm

TABLE I. Systematic errors for the ω_p analysis

Source of errors	Size [ppm]
Absolute calibration of standard probe	0.05
Calibration of trolley probes	0.20
Trolley measurements of B_0	0.10
Interpolation with fixed probes	0.15
Inflector fringe field	0.20 *
Uncertainty from muon distribution	0.12
Others †	0.15
Total systematic error on ω_p	0.4

† higher multipoles, trolley temperature and its power supply
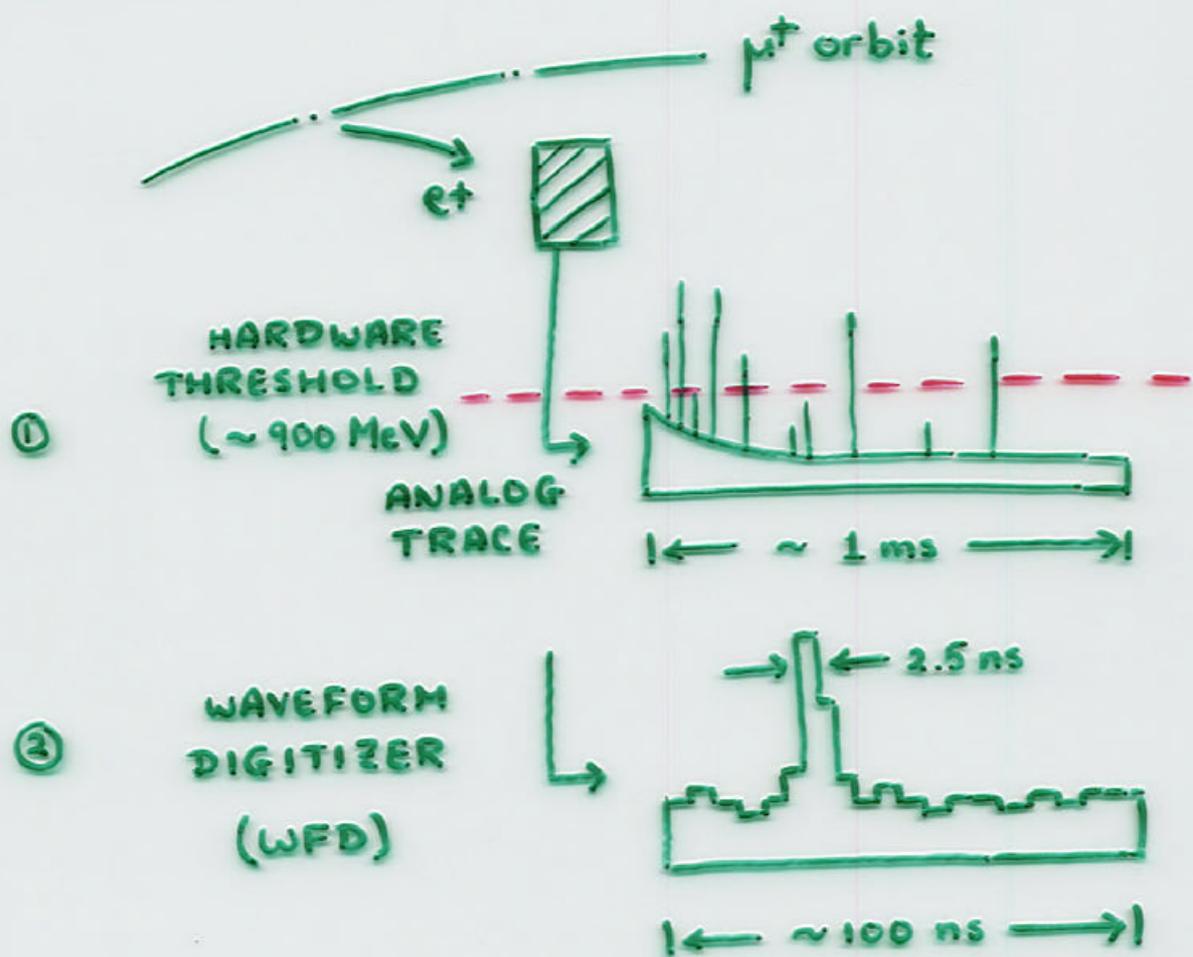voltage response, and eddy currents from the kicker.

Field map of the trolley run on February 5 1999

The magnetic field measured with the trolley center probe vs. azimuth for the measurements taken on February 5 1999. The dip at 350° is due to the inflector fringe field.

much reduced in 2000 (< 0.1 ppm)

$351° - 349°$ ± 0.10 ppm (~359° non-inflector)

$350°$ ± 0.20 ppm (~1° inflector)

EVENT RECONSTRUCTION

μ^+ orbit

e^+

① HARDWARE THRESHOLD (~ 900 MeV)

ANALOG TRACE

$|\leftarrow \sim 1\ ms \rightarrow|$

② WAVEFORM DIGITIZER (WFD)

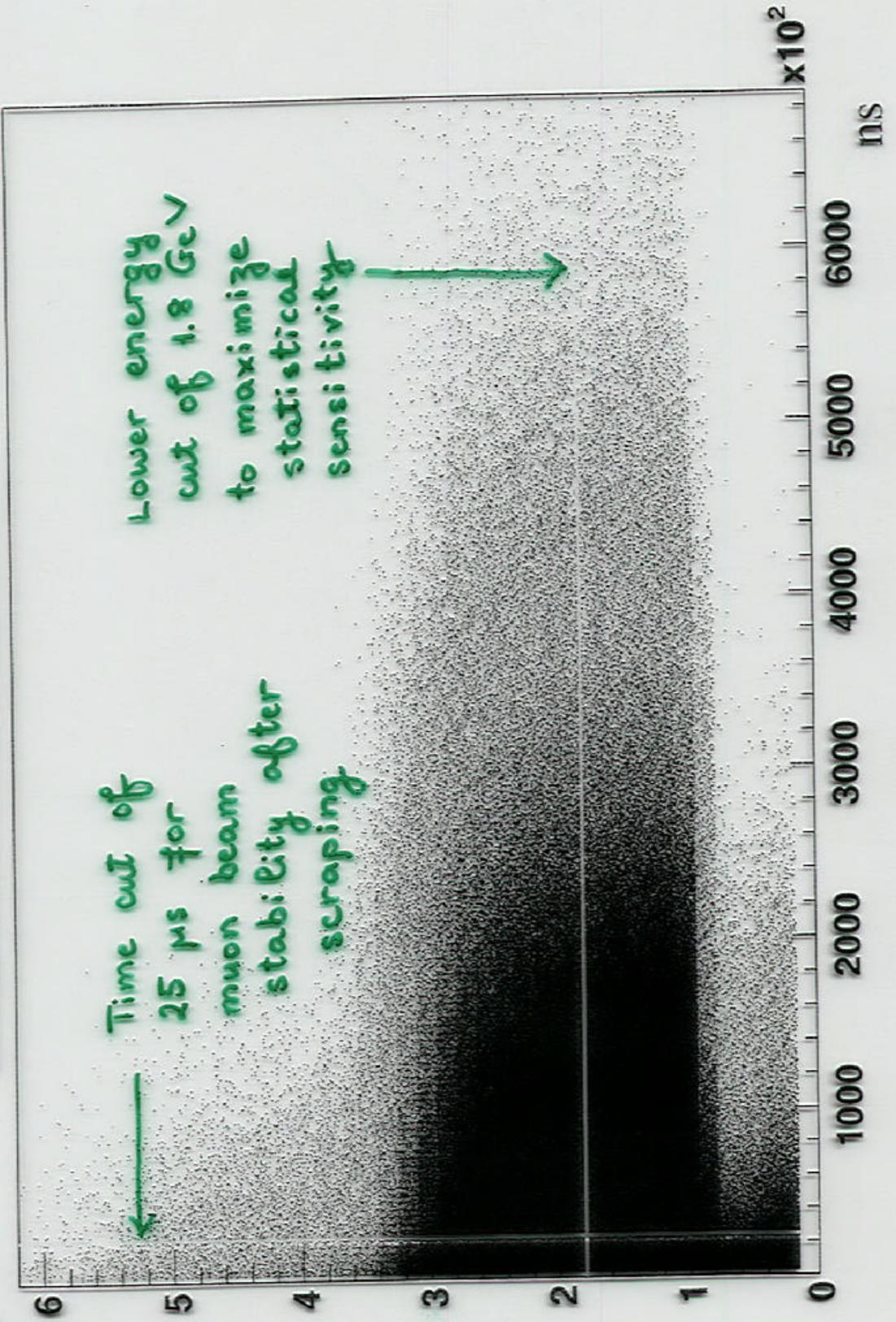$\leftarrow$ 2.5 ns

$|\leftarrow \sim 100\ ns \rightarrow|$

③ Build pulse shape library using pulses at late times

④ Energy (E) and time (t) for all pulses gotten by fitting the WFD samples for each pulse to the average pulse shape

G-2 Data (Det 24)(sub 4)

Time cut of 25 μs for muon beam stability after scraping

Lower energy cut of 1.8 GeV to maximize statistical sensitivity

GeV

ns

×10²

ω_a Measurement

- Fit data to the function $G(t)$ which has the anomalous precession and muon decay

BNL
Boston
&

$$G(t) \equiv N_o e^{\frac{-t}{\tau}}(1 - A(E) * \cos(\omega_a t + \phi(E)))$$

$\left(10^{-5}\right)$ ↑

Illinois

plus additional effects

$\rightarrow$ AGS trickle $\left(\begin{smallmatrix}\text{not}\\\text{fitted}\end{smallmatrix}\right)$

$$n(t) \equiv [G(t) + PU(t) + B(t)] * [1 + CBO(t)] *$$
$$[1 + MU(t)]$$

↑ coherent β oscillation $\left(10^{-4}\right)$

$\sqcup$ muon losses $\left(10^{-2}\right)$

- Fit data to the ratio function $r(t)$ defined by

Minnesota

$$r(t) \equiv \frac{n_1(t + \frac{\tau_a}{2}) + n_2(t - \frac{\tau_a}{2}) - n_3(t) - n_4(t)}{n_1(t + \frac{\tau_a}{2}) + n_2(t - \frac{\tau_a}{2}) + n_3(t) + n_4(t)}$$

$$r(t) \equiv A(E) * \cos(\omega_a t + \phi(E)) \times$$
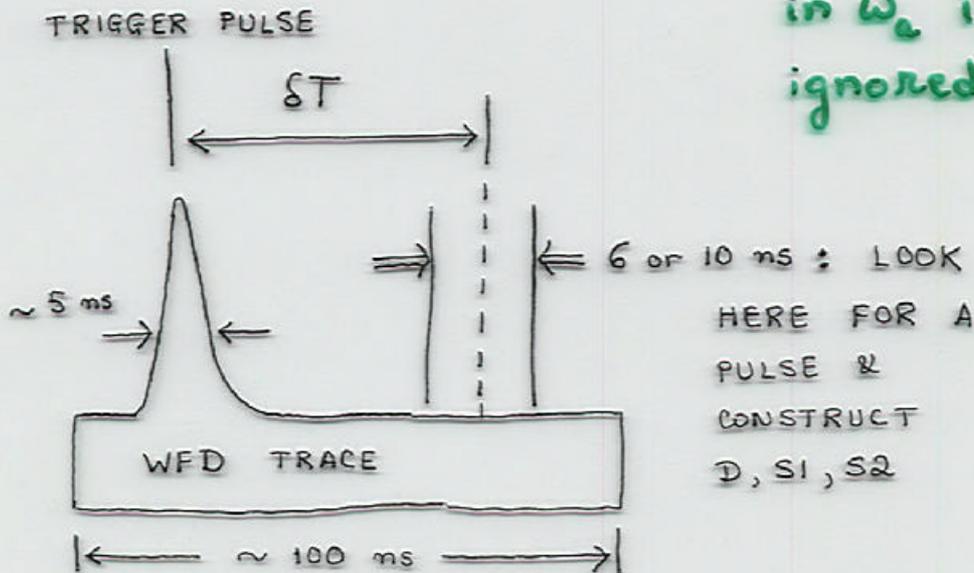$$[1 + PU^*(t) + B^*(t)] + \lambda$$
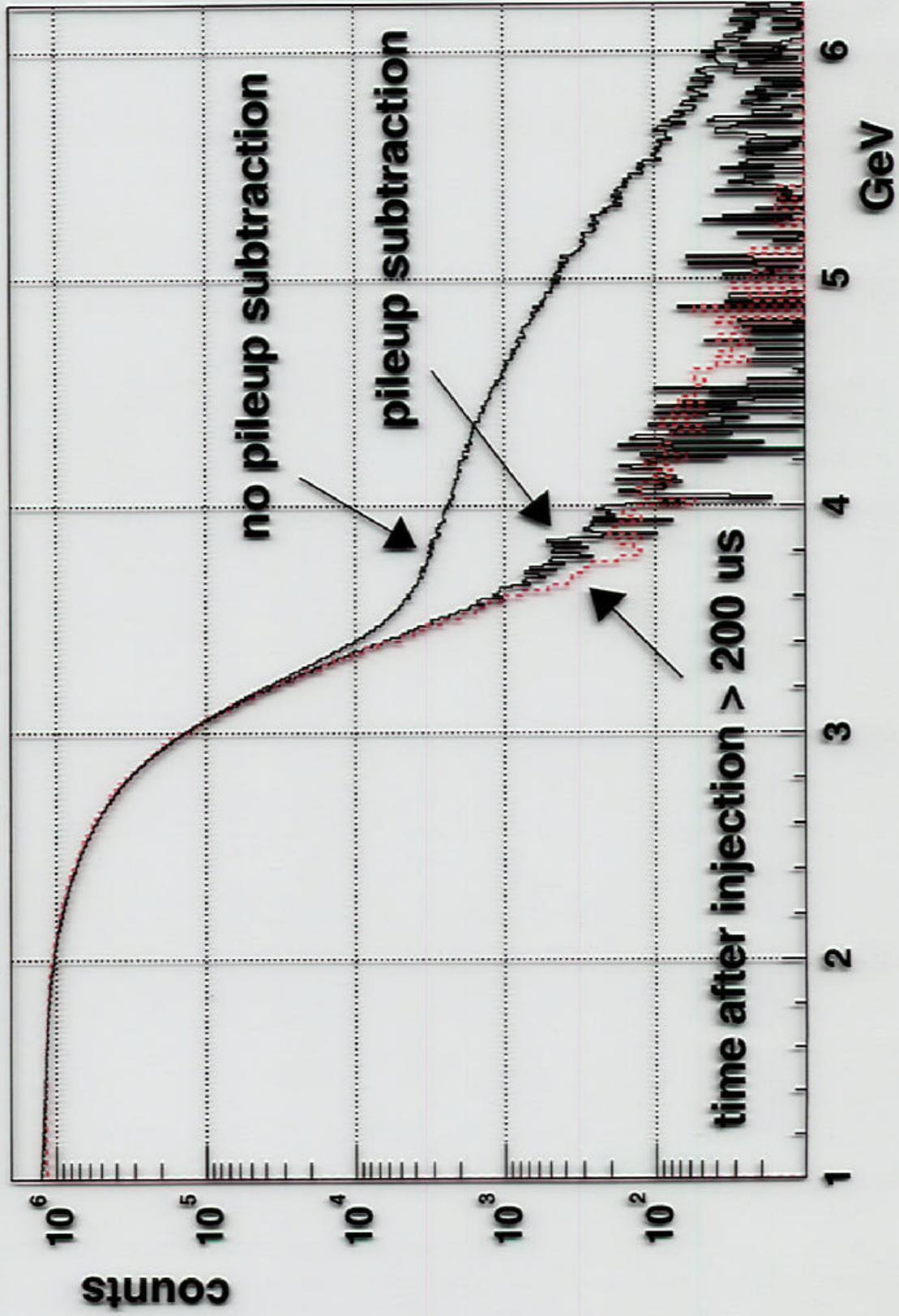
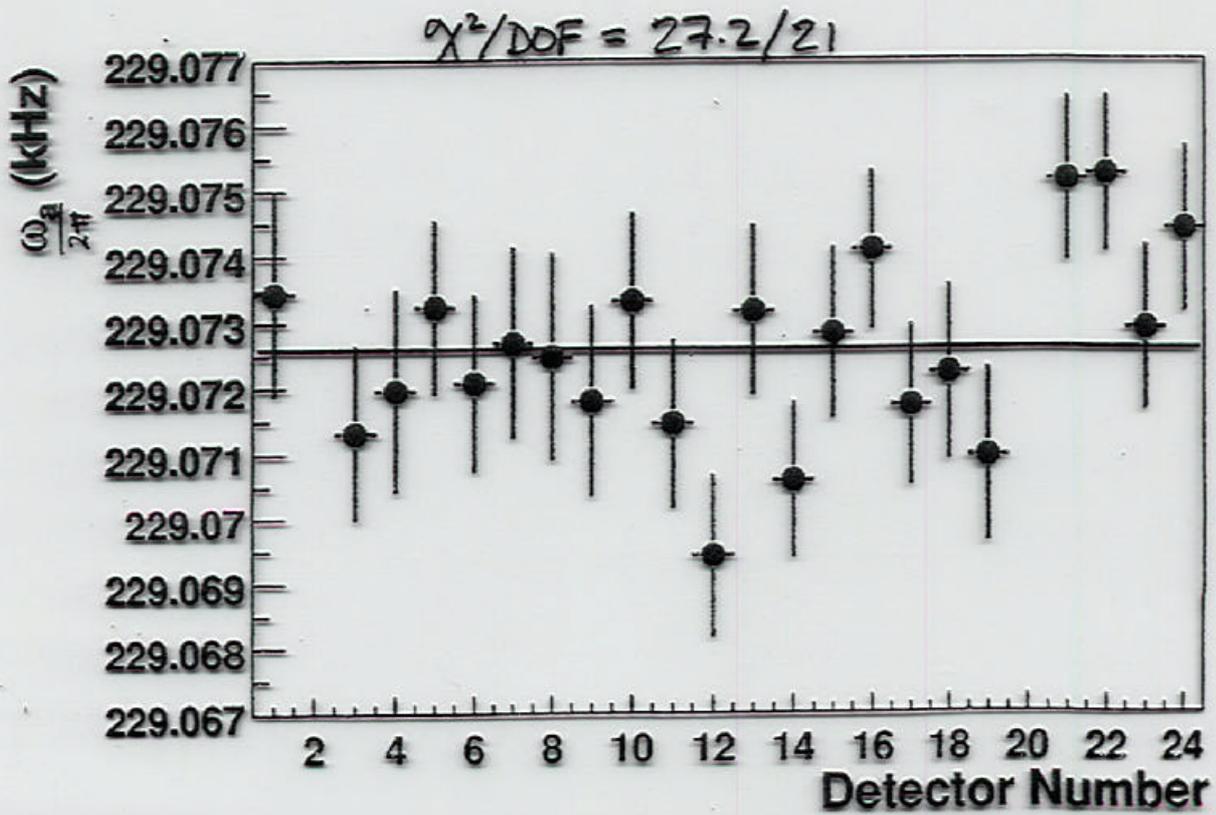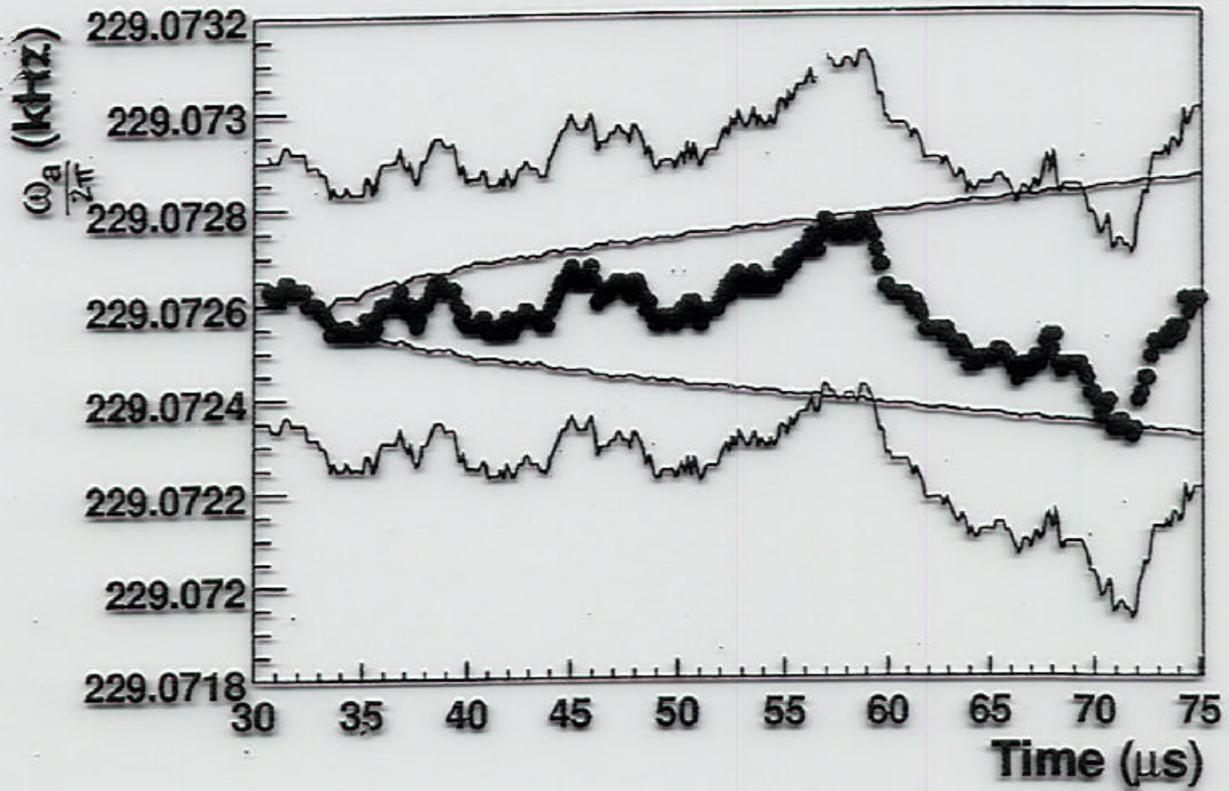with $|B^*| \ll 1$ and $\lambda \ll 1$

Pileup (the term PU(t))

- Pileup has two components: "D-(S1+S2)"

    - Two positrons arriving at the detector at the same time get reconstructed as one event ("D" event)

    - The two positrons which came together to make one "pileup" event get lost from distribution ("S1" and "S2" events)

- Statistical pileup construction and subtraction

$(\sim 0.8$ ppm error in ω_a if ignored $)$

TRIGGER PULSE

δT

~ 5 ms

$\Leftarrow$ 6 or 10 ns : LOOK HERE FOR A PULSE & CONSTRUCT D, S1, S2

WFD TRACE

~ 100 ms

Energy Distribution: Det 15

$\chi^2/DOF = 27.2/21$

Alex Trofimov 1999 Analysis (B.U.)

$$\chi^2/\mathrm{dof} \equiv 12.3/11$$

R vs. 1999 Run Number
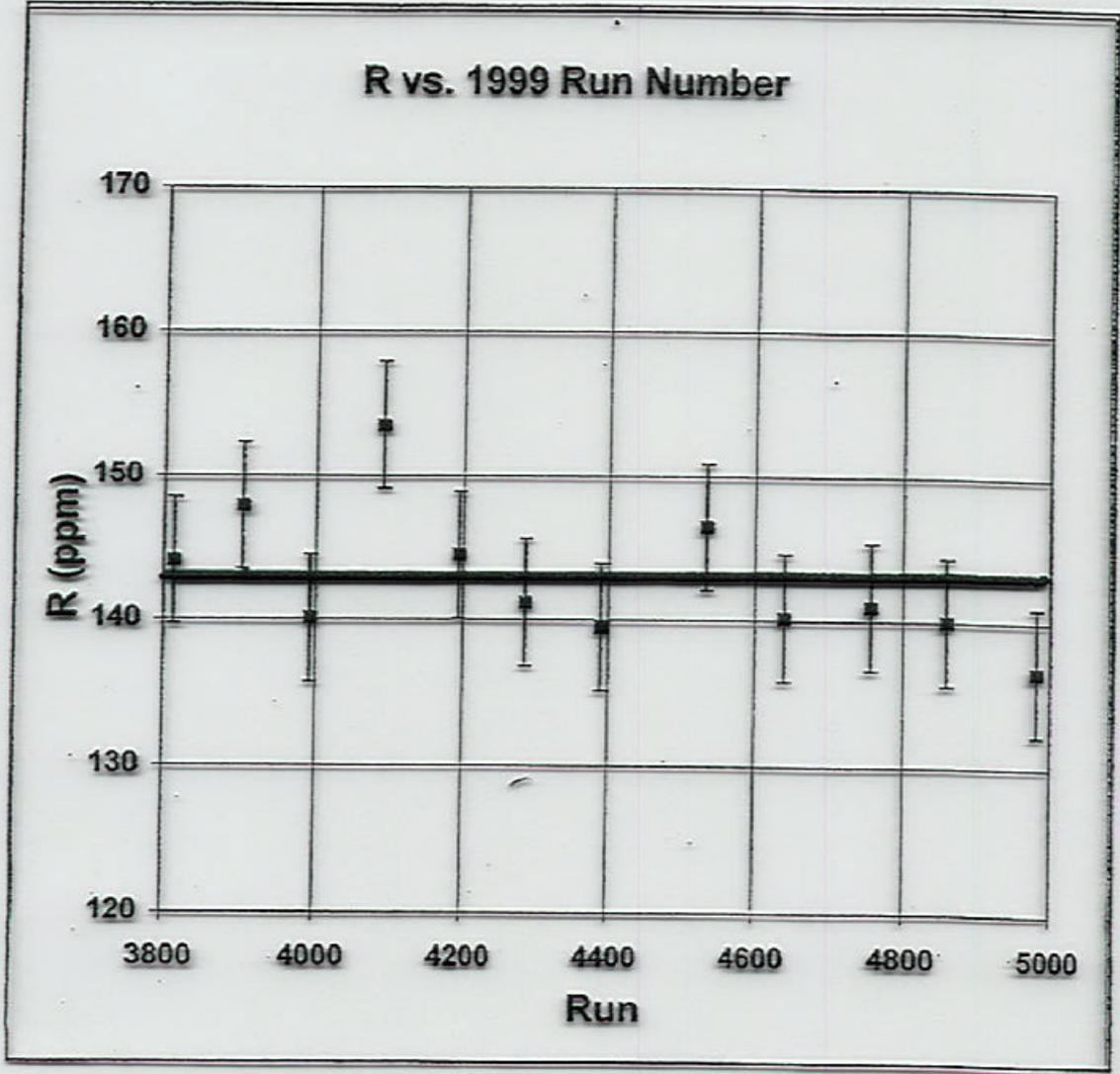
TABLE II. Systematic errors for the ω_a analysis.

Source of errors	Size [ppm]
Pileup	0.13
AGS background	0.10
Lost muons	0.10
Timing shifts	0.10
E field and vertical betatron oscillation	0.08
Binning and fitting procedure	0.07
Coherent betatron oscillation	0.05
Beam debunching/randomization	0.04
Gain changes	0.02
Total systematic error on ω_a	0.3

statistical uncertainty $\longrightarrow$ 1.3

($\sim$ 950 Me$^+$)

4 independent ω_a analyses:

$(\omega_a - \omega_0)$

Institution	Production	Fit Start time	Para. Fit	χ^2/DOF	(R $\pm$ statistical error) ppm
B.U.	I	32µs	13	1.012 ± 0.023	143.25 ± 1.24
BNL-based	I	32µs	10	1.005 ± 0.023	143.08 ± 1.24
Illinois	II	25-56µs	9	1.016 ± 0.005	143.30 ± 1.23
Minn	II	34µs*	3	0.986 ± 0.025	143.37 ± 1.28

* average start time.

I $\leftrightarrow$ II : allowed statistical variation $\sim$ 0.4 ppm

$(g-2)_\mu$

Summary

- 1999 data run gives

0.5 ppm Systematic

$$a_{\mu^+}\,(E821\,'99) \;=\; 0.001\,165\,920\,2(16)\ (1.3\,ppm)$$
$$a_\mu\,(SM) \;=\; 0.001\,165\,916\,0(7)\ (0.6\,ppm)$$
$$diff \;=\; 42 \pm 17 \times 10^{-10}$$
$$(3.6 \pm 1.4\,ppm\ or\ 2.6\sigma)$$

~ 1% probability
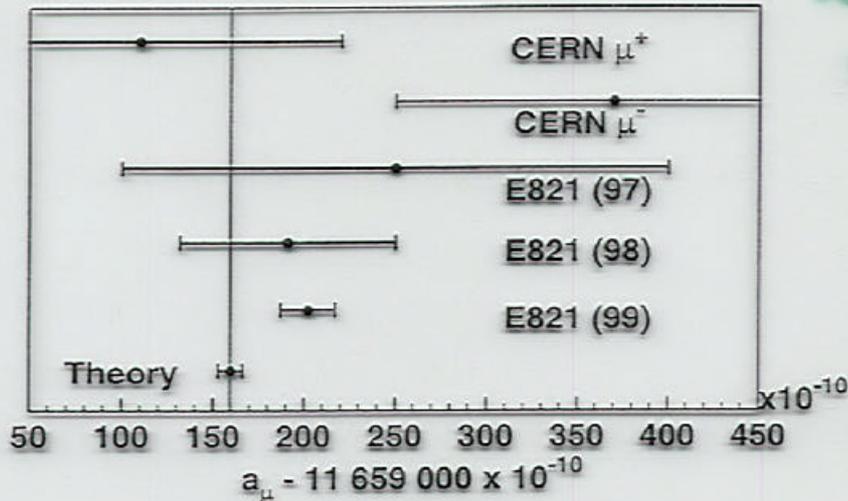
- 2000 data has about 4.5 times number of positrons with projected measurement uncertainty 1/2 of 1999 value

- 2001 run with $\mu^=$ in progress (Feb., Mar., April)