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A Precision Measurement of the Anomalous Magnetic Moment of the Muon.

($\pm$0.35 ppm)

Spin Precession in Constant B Field
in Storage Ring

Cyclotron frequency: $\vec{\omega}_c = e\vec{\mathbf{B}}/(mc\gamma)$ $\gamma = E/m$

p = 0.3 B R in GeV/c, T, and m

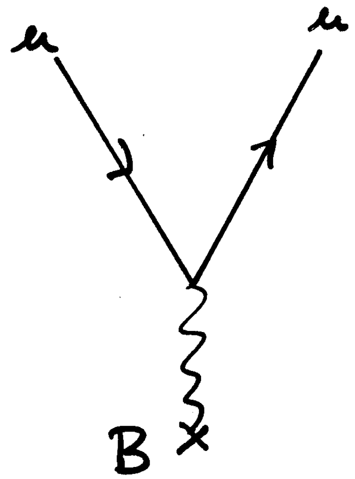
Thomas precession: $\vec{\omega}_T = (\gamma - 1)\,\vec{\omega}_c$

$d\vec{\mathbf{S}}/dt = \vec{\mu}\times\vec{\mathbf{B}}$

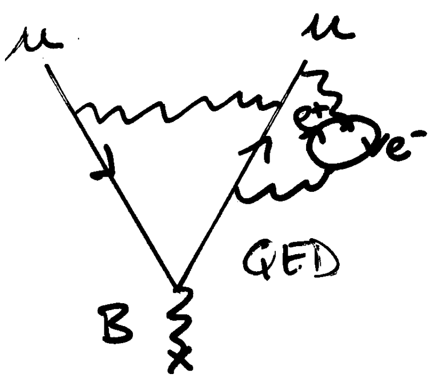
$\vec{\omega}_s = ge/(2mc)\,\vec{\mathbf{B}}$

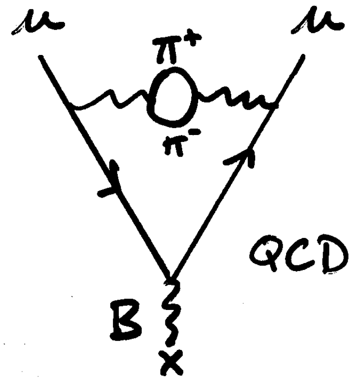
$\vec{\omega}_a = \vec{\omega}_s - \vec{\omega}_c - \vec{\omega}_T = (g-2)e\vec{\mathbf{B}}/(2mc)$

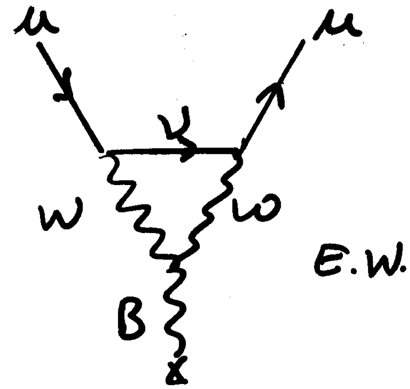
Define $a = (g-2)/2$: $\vec{\omega}_a = a\,(e\vec{\mathbf{B}}/mc)$



$g=2$ Dirac Equation
point particle

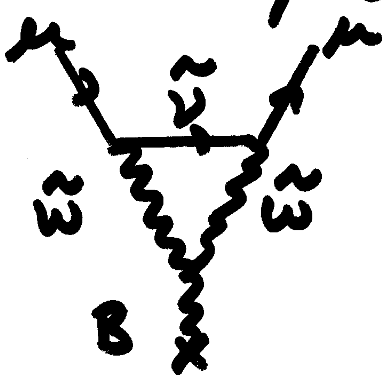




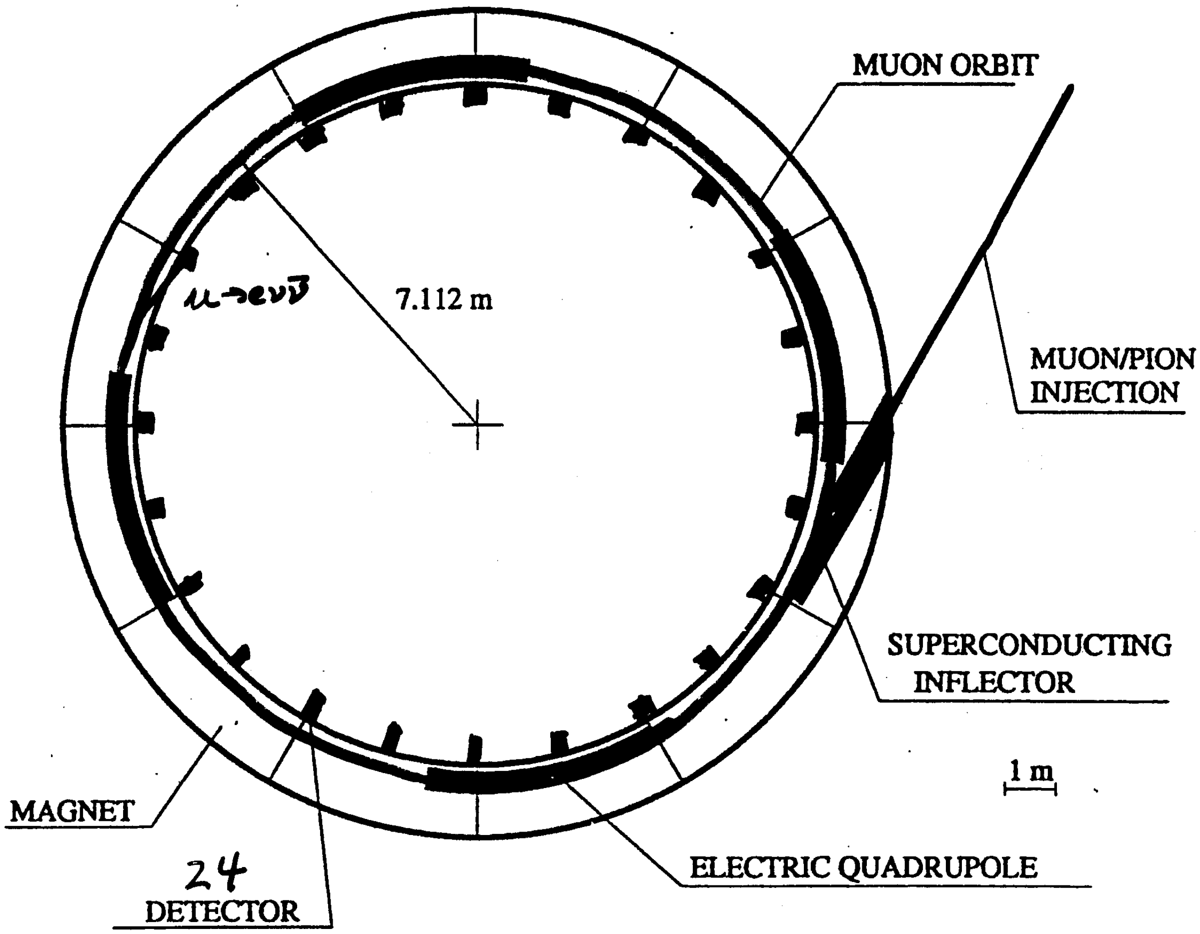


S.M. $g = 2.002331833\,(35)$

New Physics ?



BNL MUON G–2 EXPERIMENT



$$\omega_c = \frac{eB}{mc\gamma}$$

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

$$\omega_s = \frac{eB}{mc\gamma} + \frac{e}{mc}aB$$

$$\omega_a = \omega_s - \omega_c = \frac{e}{mc}aB$$

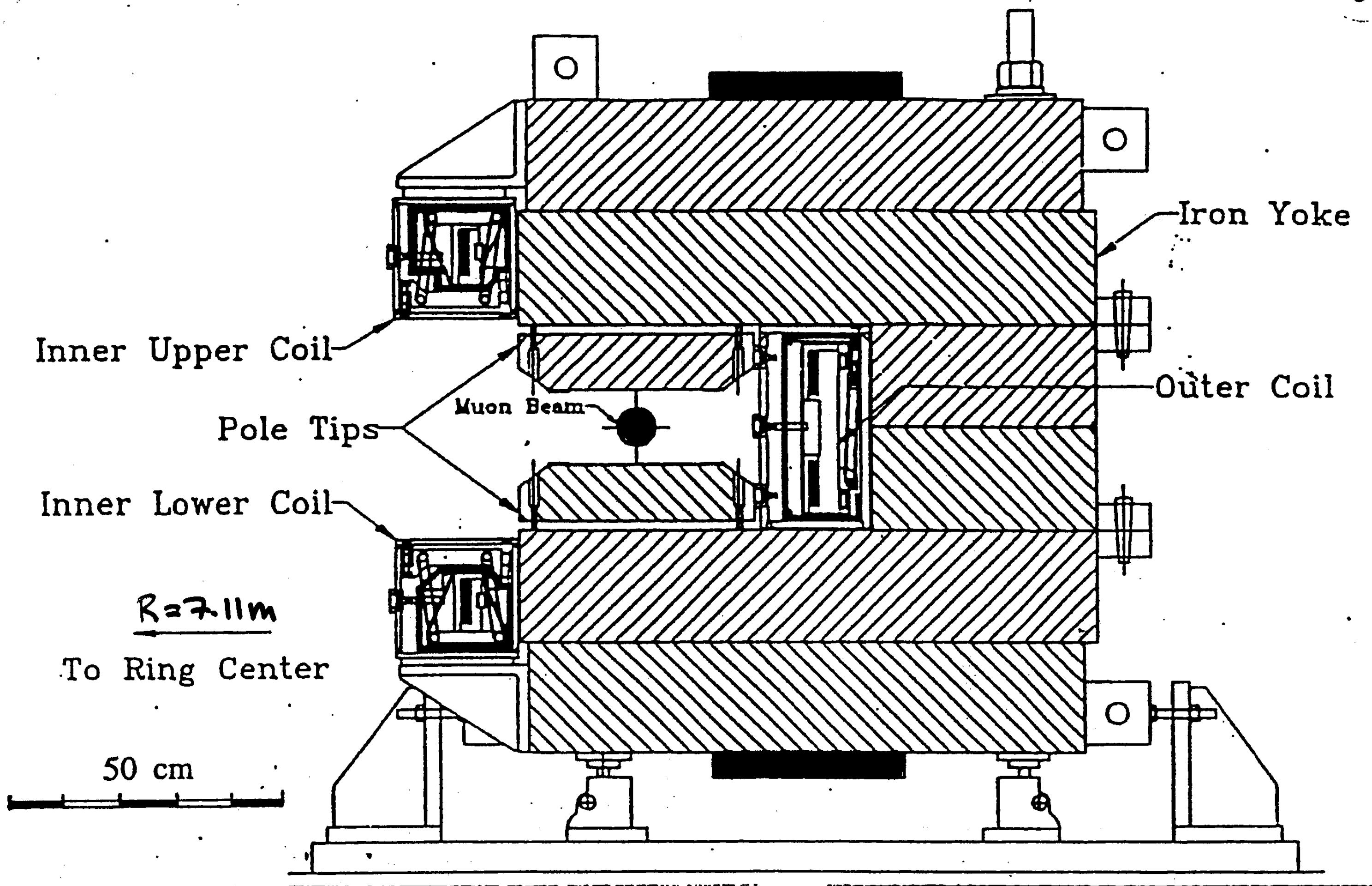
$$\omega_a = \frac{e}{mc}\left[aB - (a - \frac{1}{\gamma^2 - 1})(\vec{\beta} \times \vec{E})\right]$$

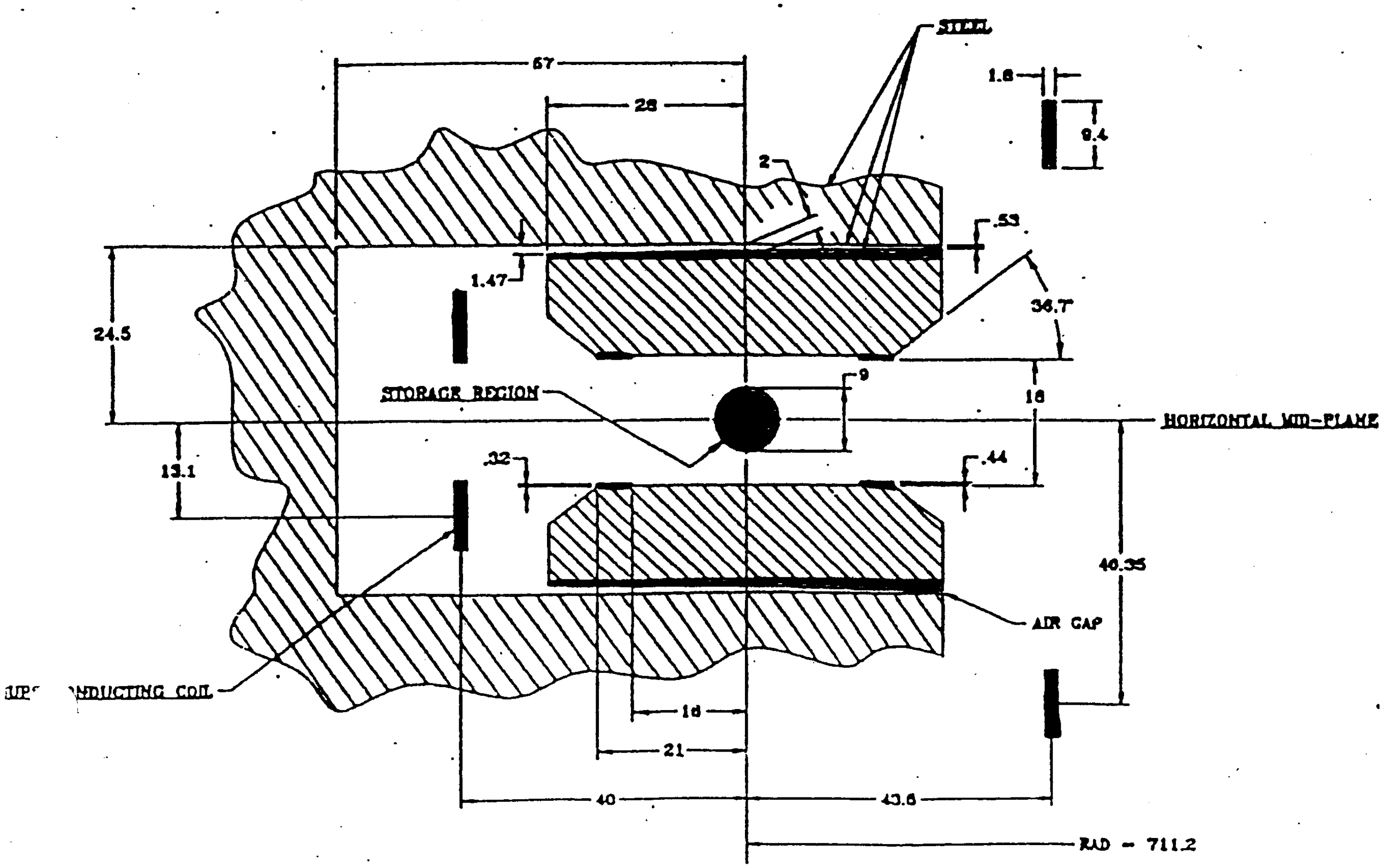
at $\gamma = 29.3, p = 3.09\,\frac{GeV}{c}, \omega_a$ is independent of E

PRINCIPAL PARAMETERS OF BNL EXPERIMENT

MAGNET	
Orbit radius	7.11 m
Central magnetic field	1.45 T
STORAGE SYSTEM	
Storage region, circle with diameter	9 cm
Vertical focusing by electric quadrupole field (pulsed 1 ms)	24 kV
Field index n (average)	0.138
PARTICLE INJECTION	
Superconducting inflector	
Pion injection, π-μ decay	
Muon injection, fast kicker	
ELECTRON DETECTORS	
Lead-scintillating fiber calorimeter (24)	
Position sensitive detector	
Electron traceback chambers	
KINEMATICS	
Muon Momentum	3.09 GeV/c
Gamma, γ	29.3
Lifetime, τ	64.4 us
Revolution frequency, f_a	6.70 MHz
Period	149 ns
(g-2) frequency, f_a	0.229 MHz
Period	4.37 μs
AGS WITH BOOSTER	4×10^{13} protons/cycle
Ejected pulse width	50 ns (FWHM)
Number of pulses	12 ~~8~~ per cycle / 33 msec.
Cycle period	2.6 sec

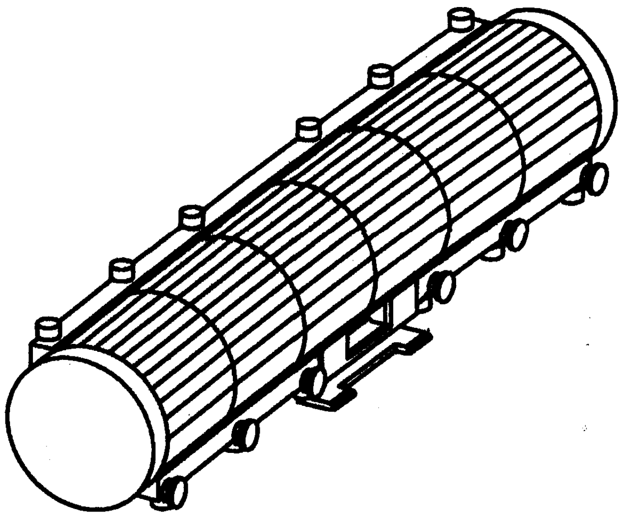
STORAGE RING CROSS SECTION

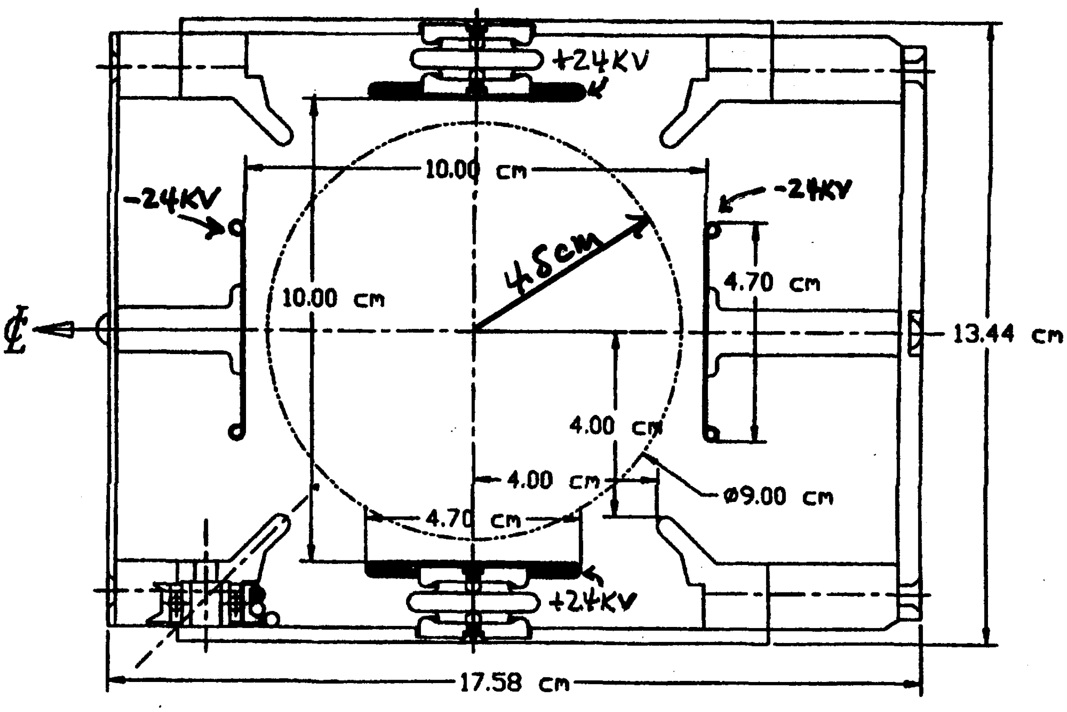




NMR

Beam Tube Trolley





$$n = \frac{R}{cB_0} \frac{\partial E}{\partial r} = 0.139$$

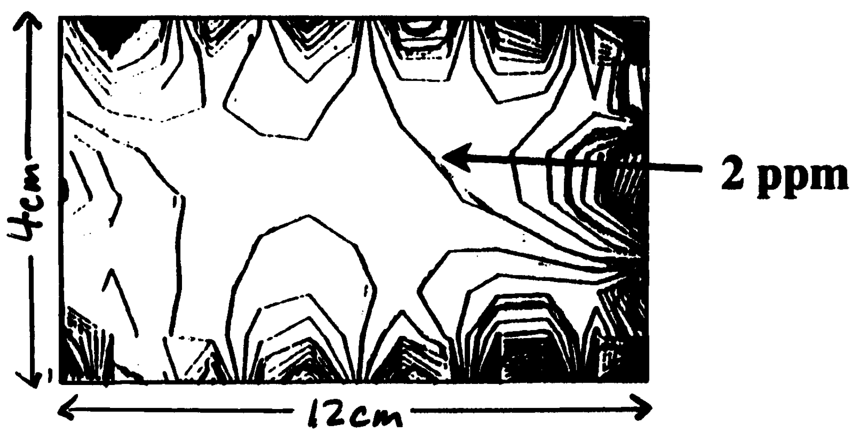
$\theta_V^{max} = 2.3\,mr$

$\theta_R^{max} = 5.6\,mr$

$\frac{dp}{p} = \pm 0.5\%$

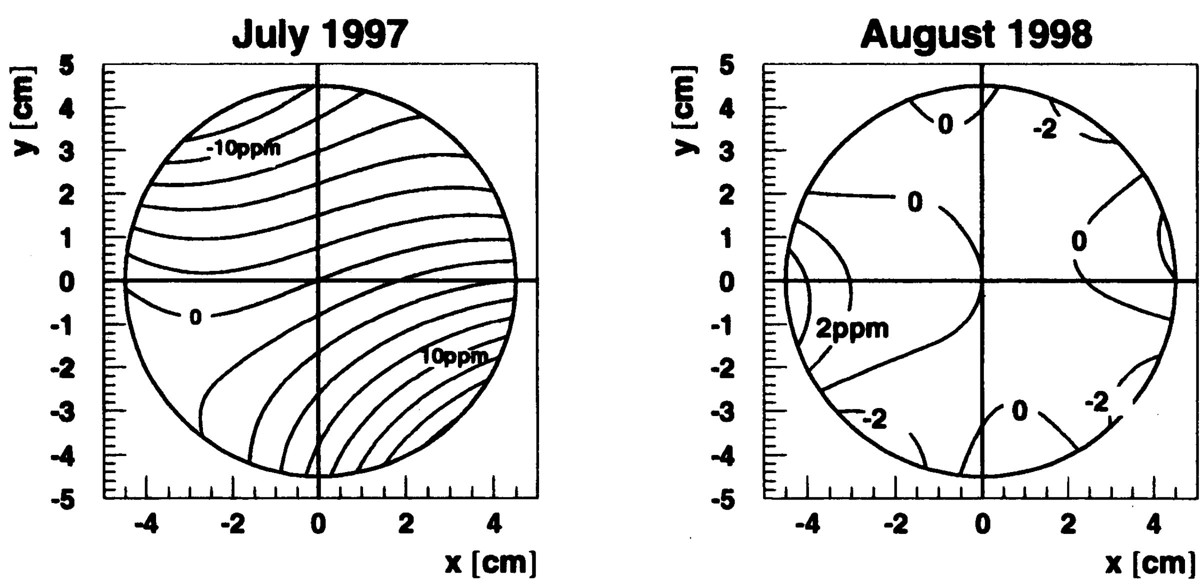
B-field precision

- **CERN: "final" B - field distribution:**



- **BNL: circular aperture:**

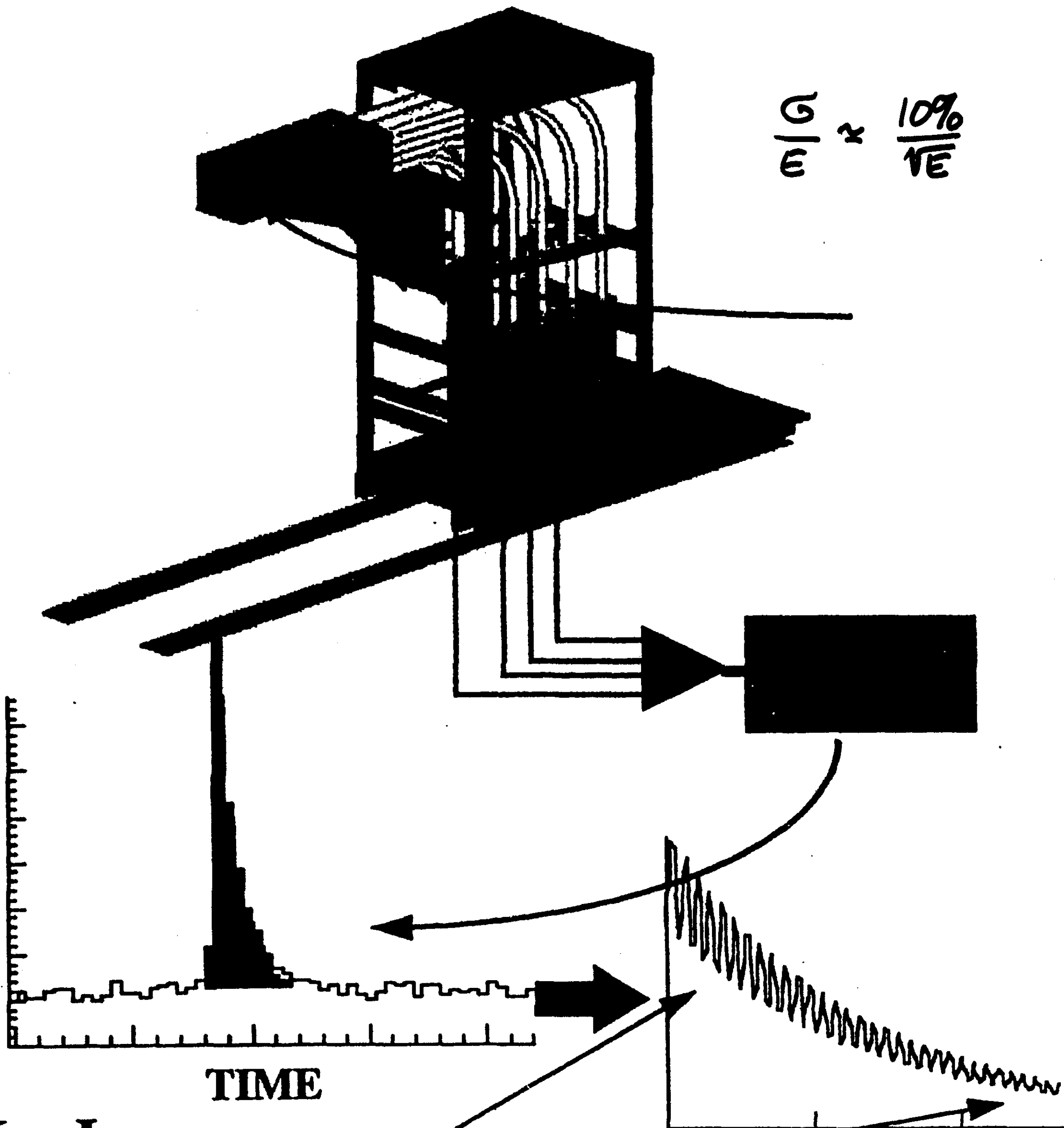
integrated field contour plots



$\mu \to e\nu\bar{\nu}$

Electromagnetic Calorimeters Pb/SciFi + Very Fast & Stable Tubes

$\frac{\sigma}{E} \approx \frac{10\%}{\sqrt{E}}$



- **Key Issue:**
  - Timing Shifts Early-to-Late < 20 ps
  - Gain Shifts Early-to-Late < 0.2%

✓ In "Proof" Stage Still

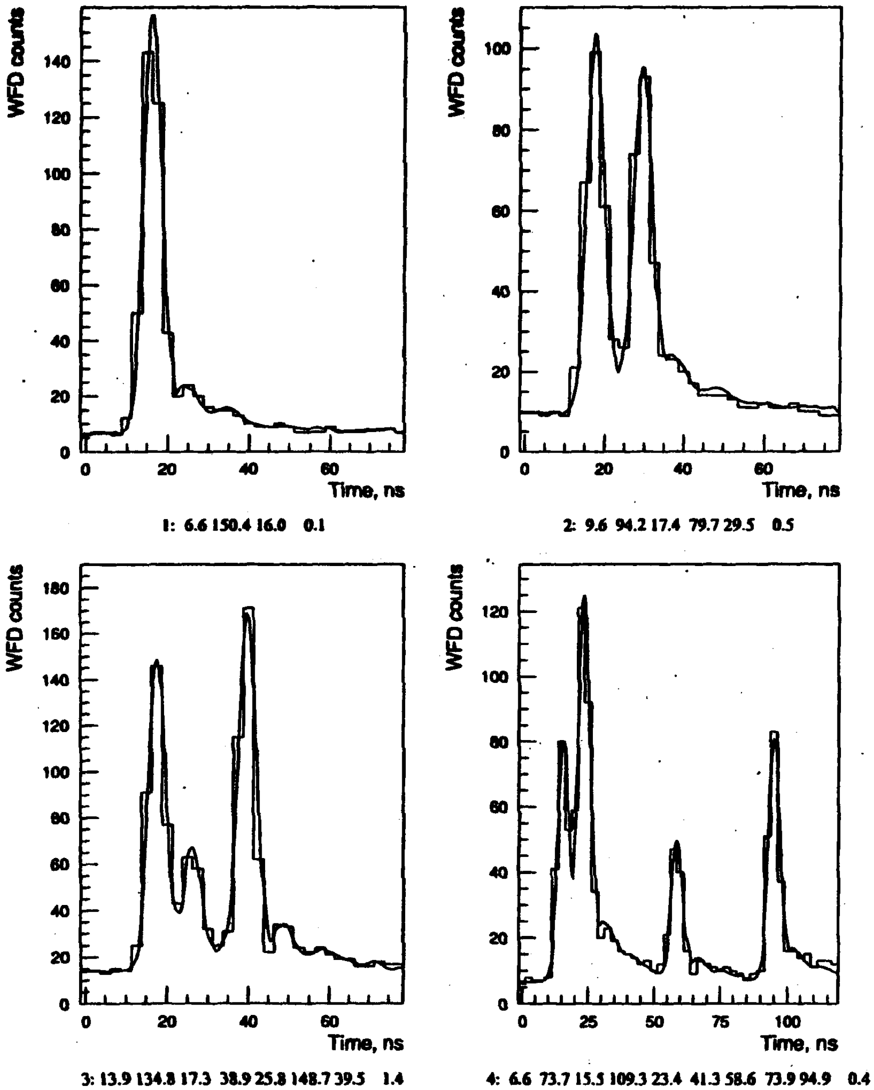


Figure 9: Examples of groups of samples with different number of pulses for the case, when the number of pulses is the same as the number of prepulses. Histogram title reflect the fit results: `NP: PED A1 T1 ... AN TN CHI2`, where `NP` is the number of pulses, `PED` is the pedestal value, `Ai` and `Ti` are the amplitude and the time for i-th pulse and `CHI2` is χ^2 of the fit.

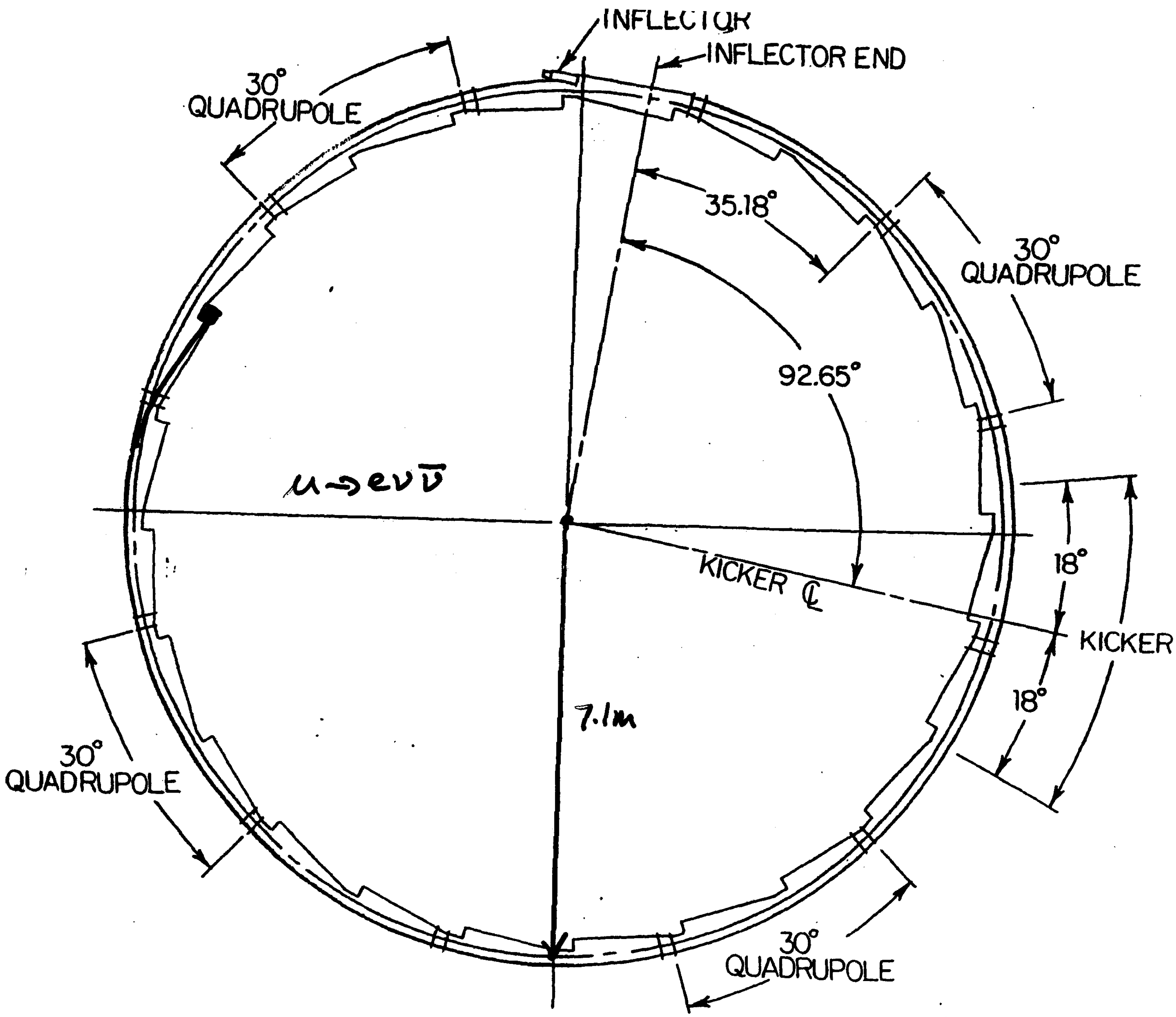
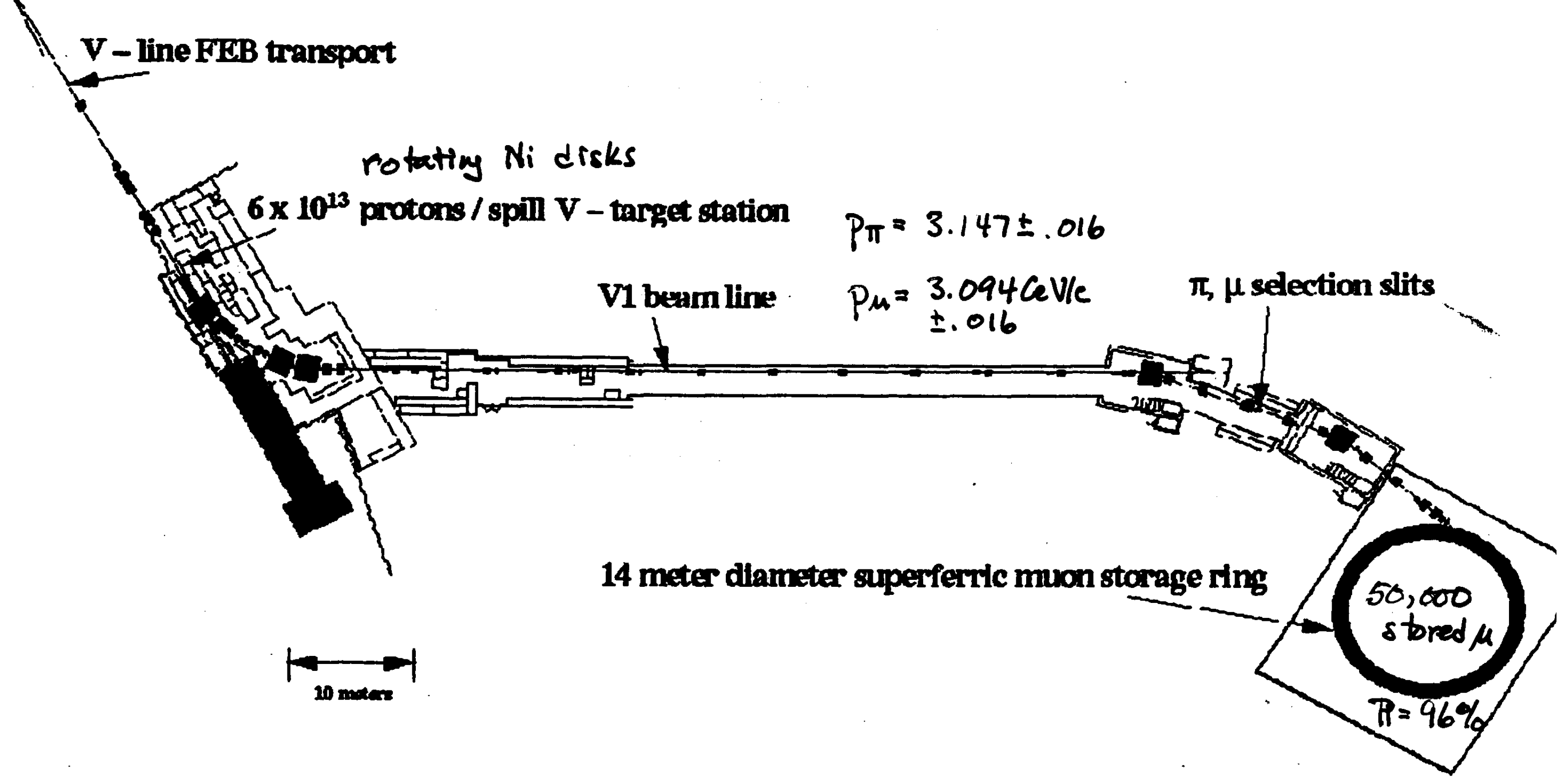
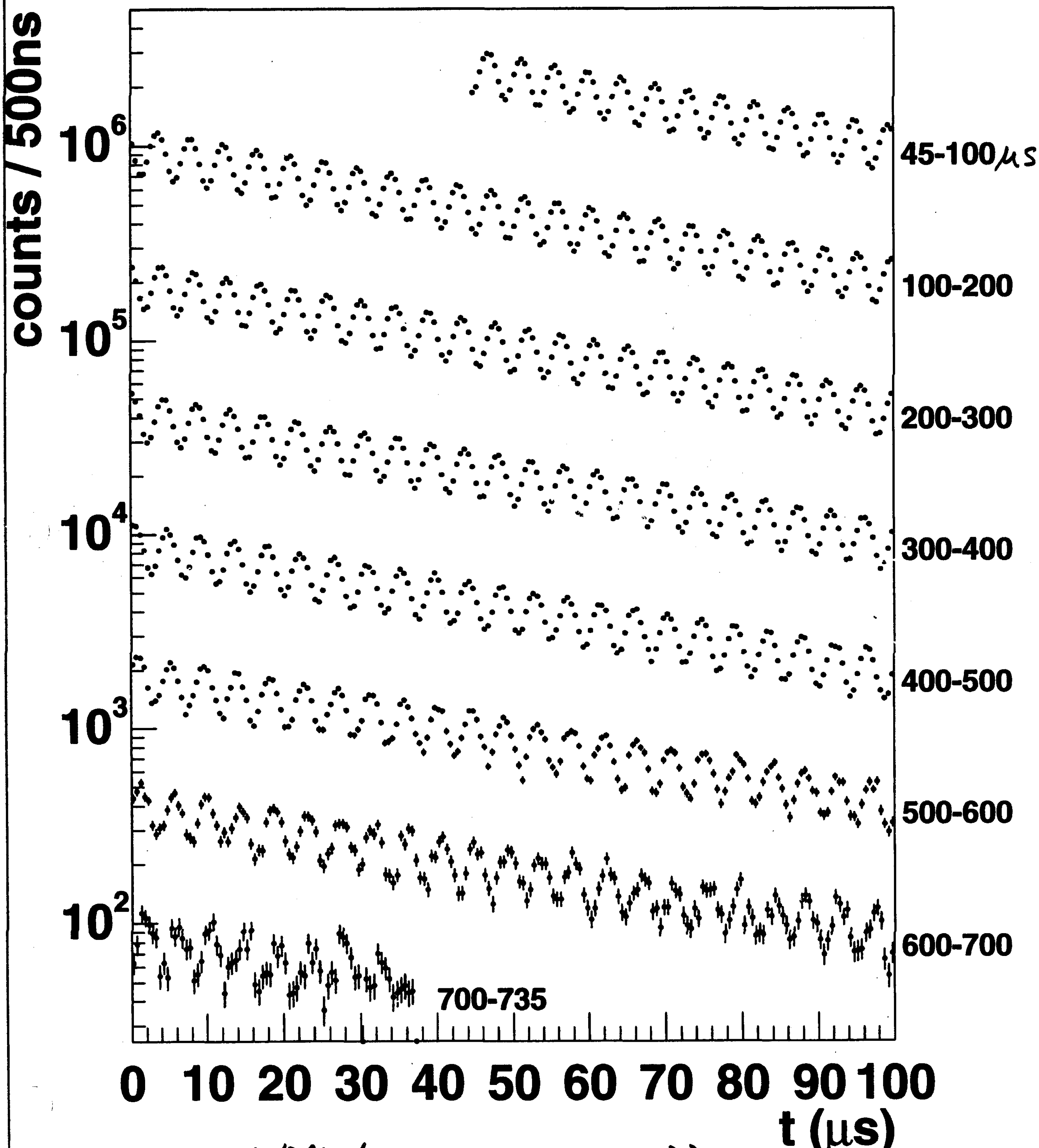


Fig. *VIII*.2 Storage Ring Vacuum Chamber (config. for 30° quadrupole)

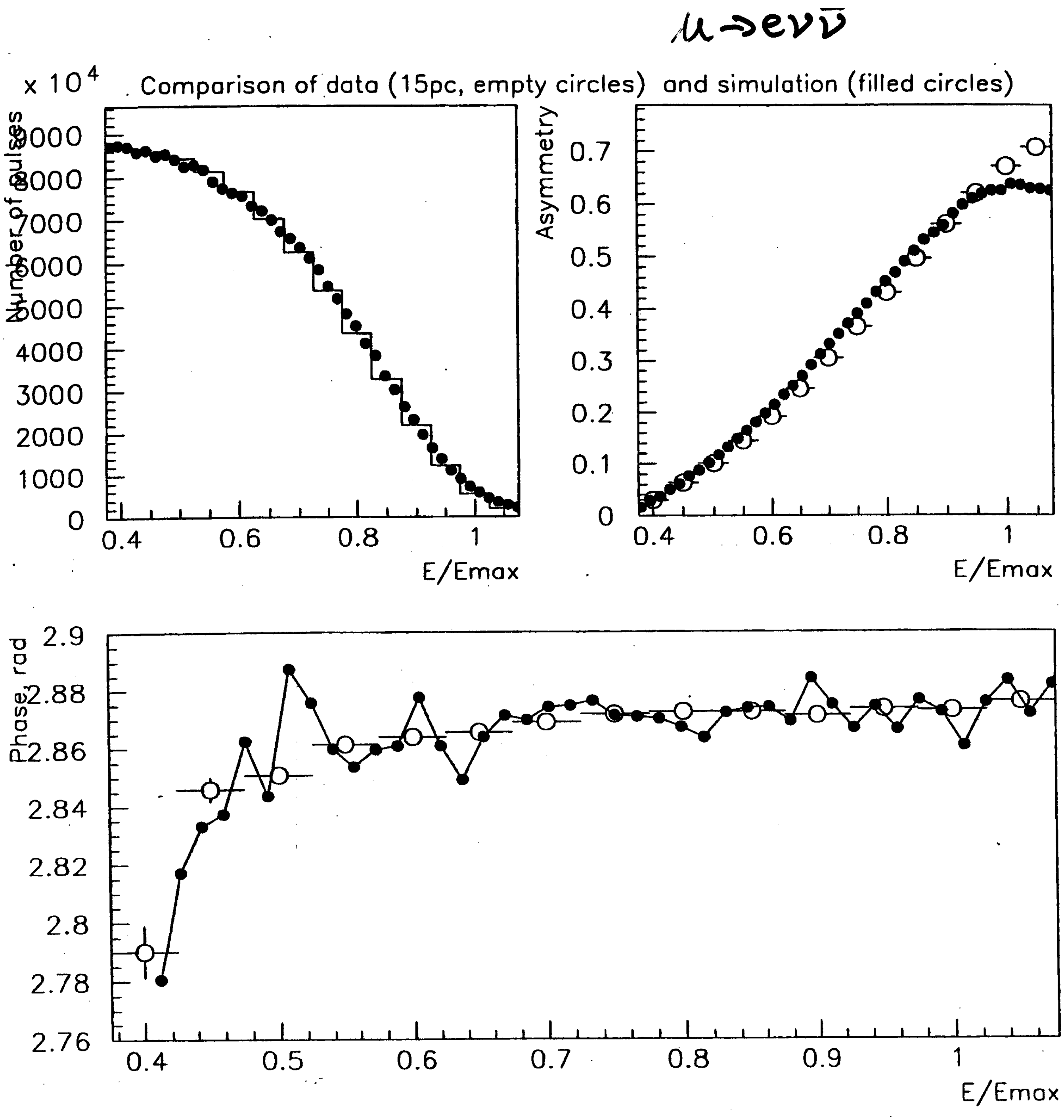
E821 beam line and muon storage ring



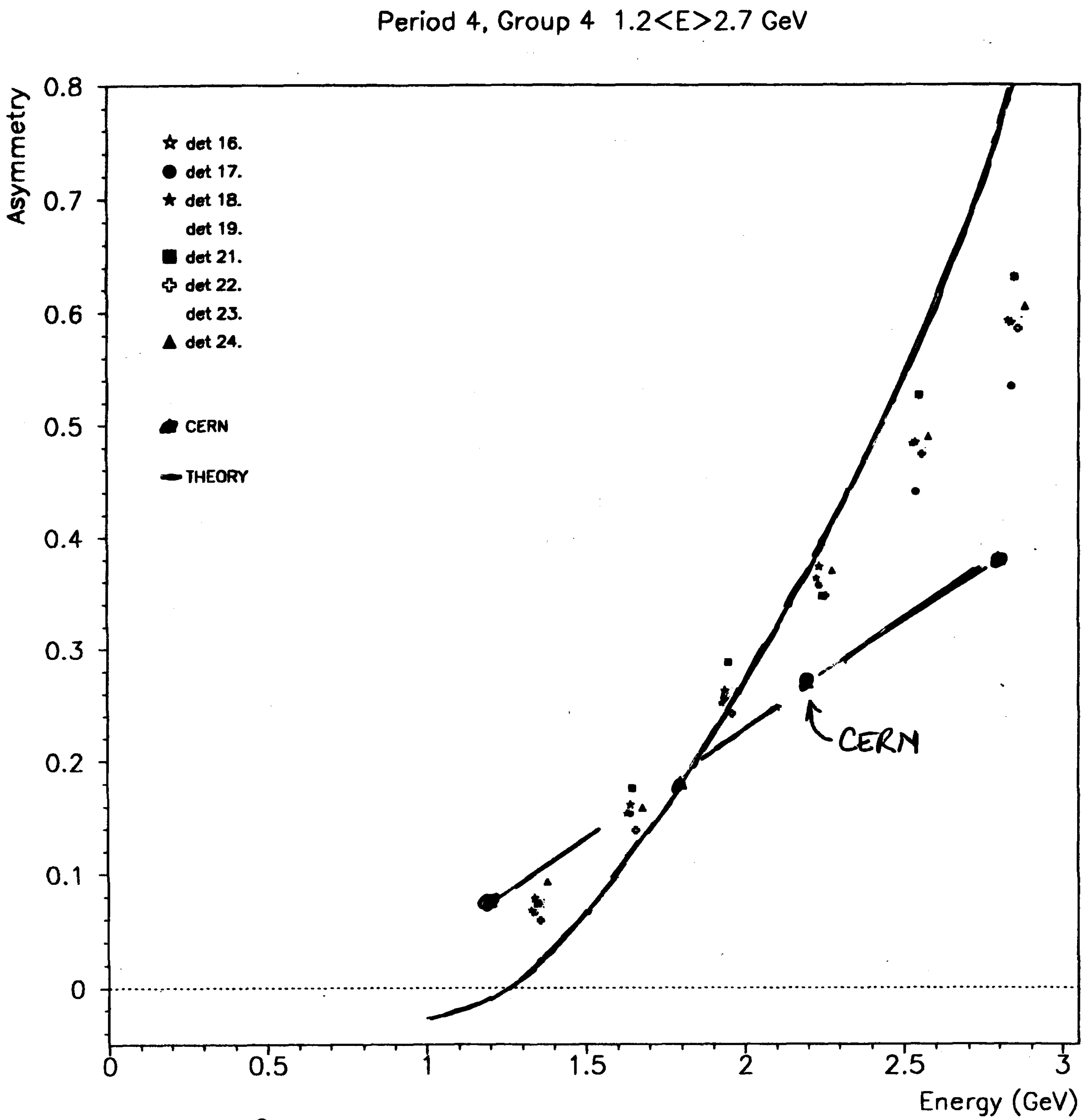
$$\vec{\omega}_a = \frac{e}{m}\left(a\vec{B} + \left(\frac{1}{\gamma^2-1} - a\right)\frac{\vec{\beta}\times\vec{E}}{c}\right)$$



$$\frac{dN}{dt} = N_0 e^{-t/\gamma\tau}\left(1 + A\cos(\omega_a t + \phi)\right)$$

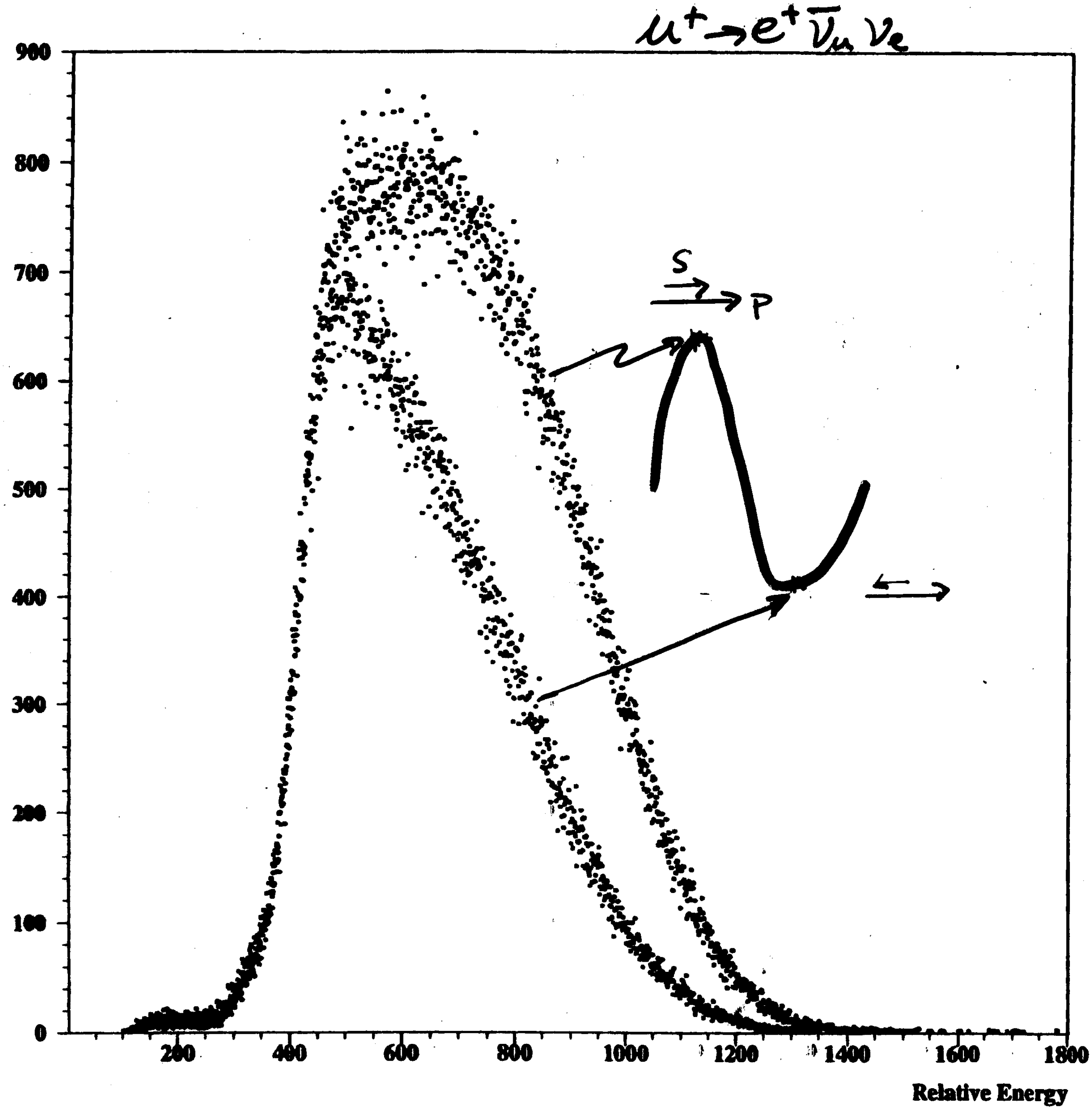


μ→eνν̄
Comparison of data (15pc, empty circles) and simulation (filled circles)
x 10^4
Number of pulses
Asymmetry
E/Emax
Phase, rad



$$A = \frac{-8y^2 + y + 1}{4y^2 - 5y - 5} \qquad y = E_e/E_\mu \qquad \gamma_\mu >> 1$$

$$\frac{dN}{dE_e} = \frac{(y-1)(4y^2 - 5y - 5)}{5}$$



μ+ → e+ ν̄μ νe
900
800
700
600
500
400
300
200
100
0
200
400
600
800
1000
1200
1400
1600
1800
Relative Energy
S
P

IIT-HEP-98/4
September 1998

SEARCHING FOR *CP* VIOLATION IN PION DECAY[a]

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Abstract

Surprisingly, until recently CP violation in pion decay was not ruled out experimentally even at the percent level. I have derived the first experimental limit, $-0.01 < A_{CP} < 0.02$, from old data on the anomalous magnetic moment $g-2$ of the muon. New data from the Brookhaven $g-2$ experiment might extend the search by a few orders of magnitude, but probably will not probe the theoretically-interesting sub-10^{-7} regime.

1 Introduction

While the main topic of this Workshop is CP violation in heavy-quark systems (s, c, b, and even t have been discussed), it is perhaps surprising to realize that we don't even know whether *pion* decay conserves CP! If we consider this question, we are likely to assume that the answer is yes, but an experimental test would be desirable.

2 A Possible CP-Violation Signature

A conceptually-straightforward test is to measure the angular distribution of the electrons from the $\pi \to \mu \to e$ decay chain. This distribution is nonuniform due to parity violation in the weak interaction. CP symmetry implies that the nonuniformity will be the same for electrons from π^- as for positrons from π^+.[1] This approach has the added benefit of being sensitive to CP violation whether it occurs in pion decay or in muon decay.

The original observation[2] of parity violation in this decay chain was carried out using positive pions stopping in carbon. A complementary experiment using π^- would in principle allow a CP test but is not feasible due to the bias introduced by negative-pion and muon capture in matter. It follows that pions decaying in flight in vacuum are required for such a CP test.

[a]Presented at the *Workshop on CP Violation*, 3–8 July 1998, Adelaide, Australia.

$\mu \to e \nu \bar{\nu}$

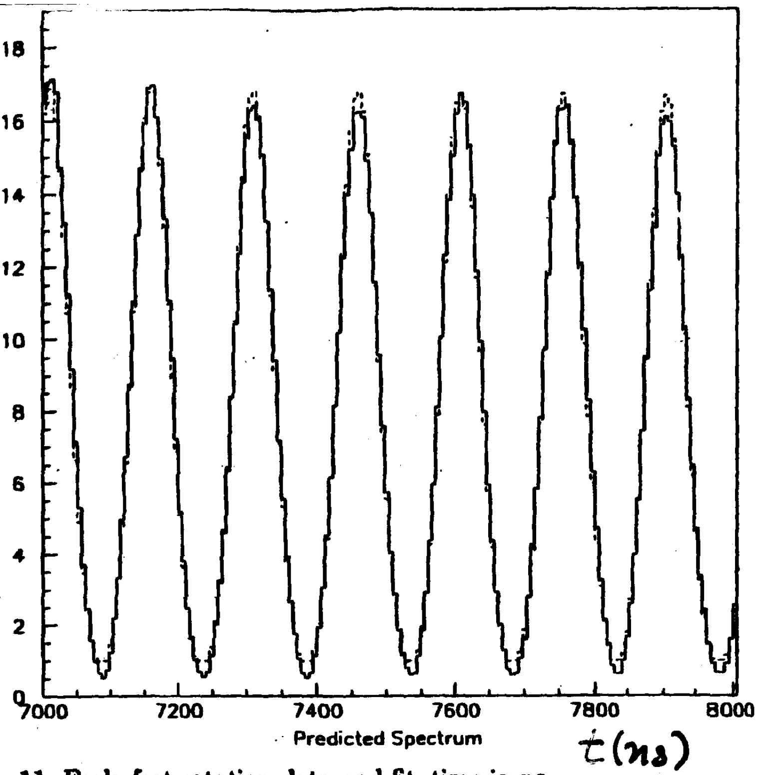


Figure 11: Early fast rotation data and fit, time in ns

1999/08/30 10.30

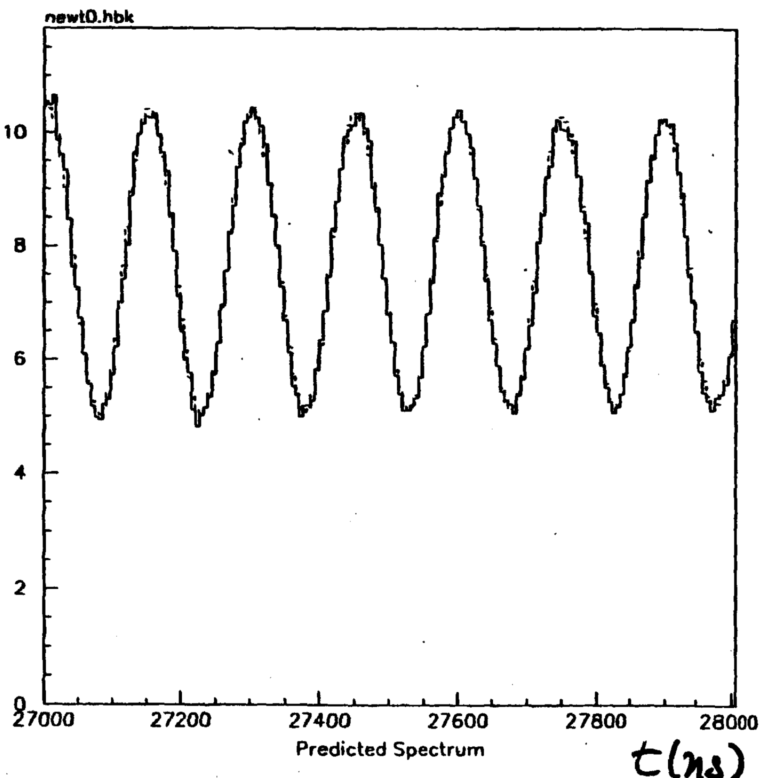
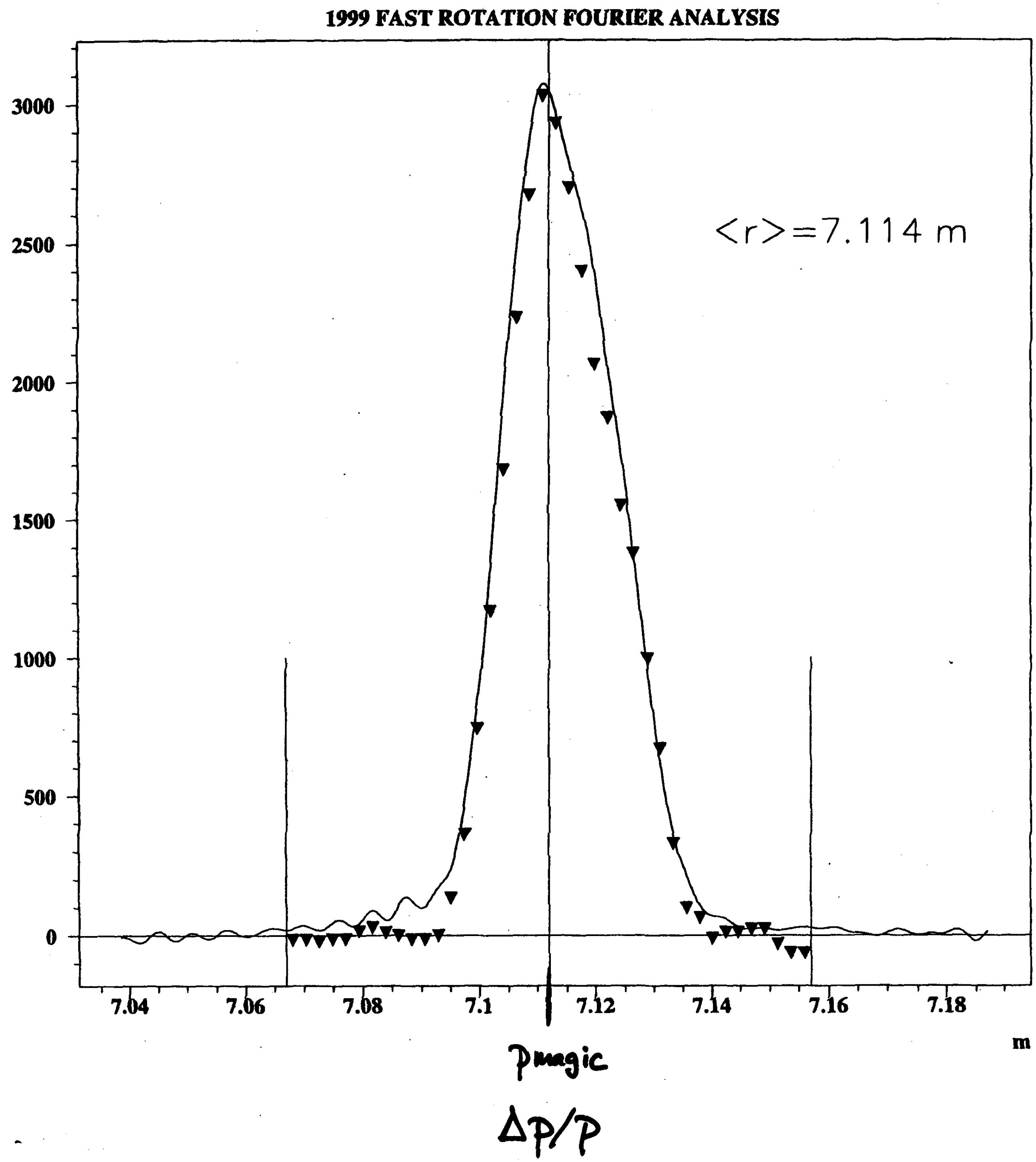


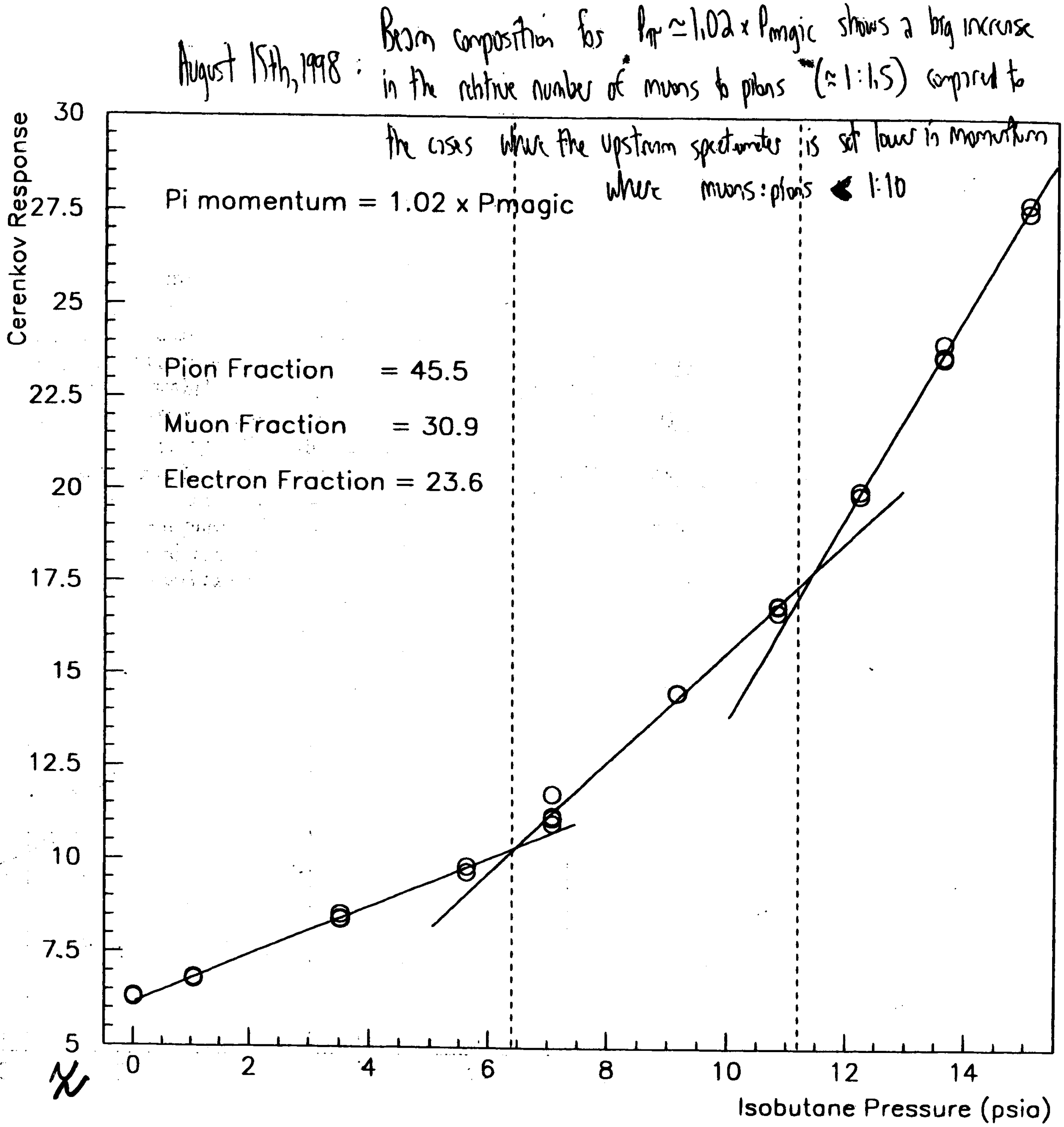
Figure 12: Middle times fast rotation data and fit,time in ns



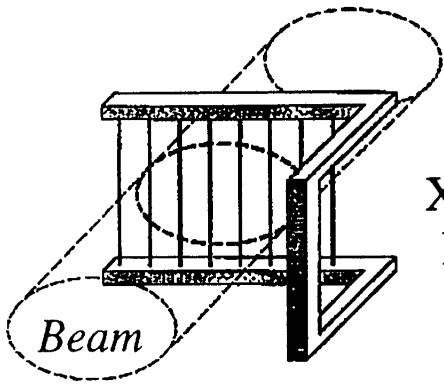
1999 FAST ROTATION FOURIER ANALYSIS
3000
2500
2000
1500
1000
500
0
<r>=7.114 m
7.04
7.06
7.08
7.1
7.12
7.14
7.16
7.18
m
pmagic
ΔP/P

Fast Beam Čerenkov Counter

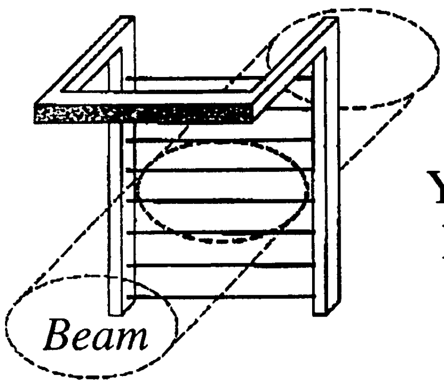
David Kawall (Yale Univ.).



Scintillating Fiber Beam Monitor



X–profile Monitor



Y–profile Monitor

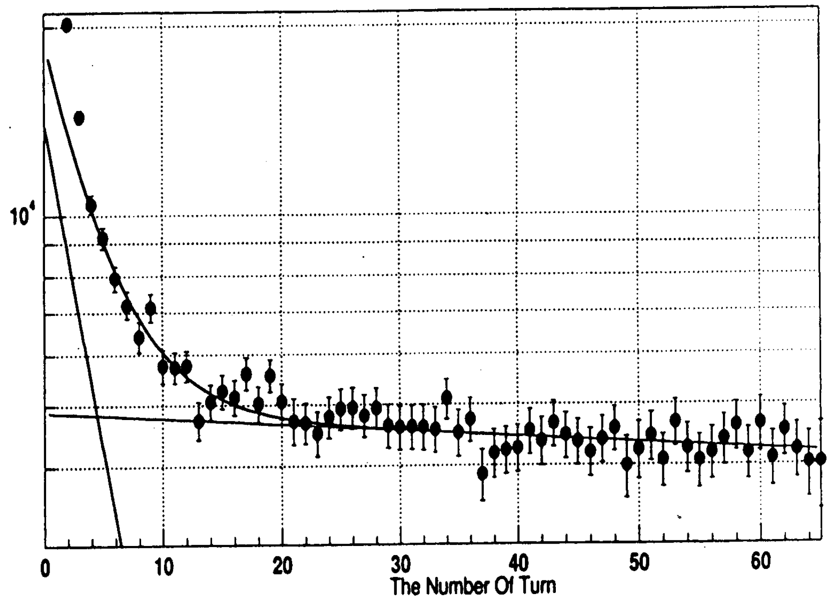
- Measure radial and vertical profiles of muon beam on a turn–by–turn basis
- Two locations in the storage ring: 180° and 270° from injection point
- 7 fibers, 0.5 mm thick, 13 mm spacing
- Destructive measurement ⇒ remotely controlled pneumatic operation for insertion into beam

Life Time

$$N_{0\mu} \exp\left(-\frac{2\pi R_0}{c\tau_\mu}\frac{m_\mu I}{p_0}\right) + N_{0\pi} \exp\left(-\frac{2\pi R_0}{c\tau_\pi}\frac{m_\pi I}{p_0}\right)$$

$$\tau_\mu = 2.15 \pm 0.32 \times 10^{-6} s$$

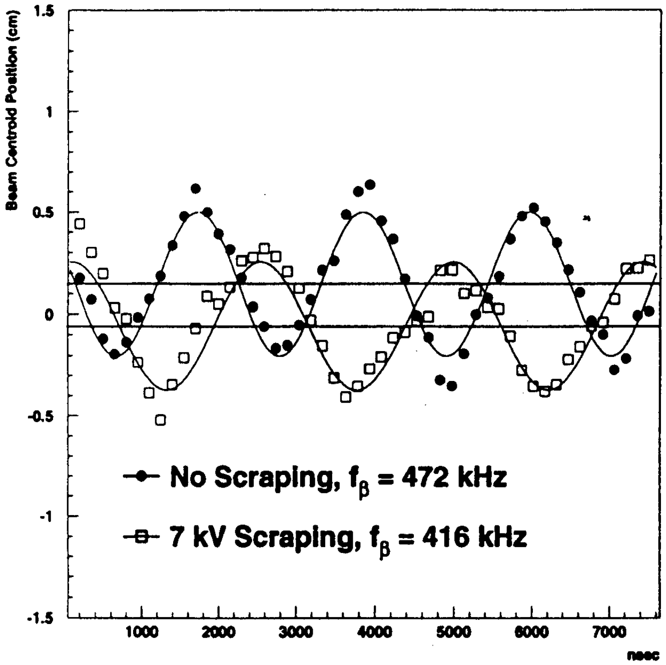
$$\tau_\pi = 2.78 \pm 0.24 \times 10^{-8} s$$



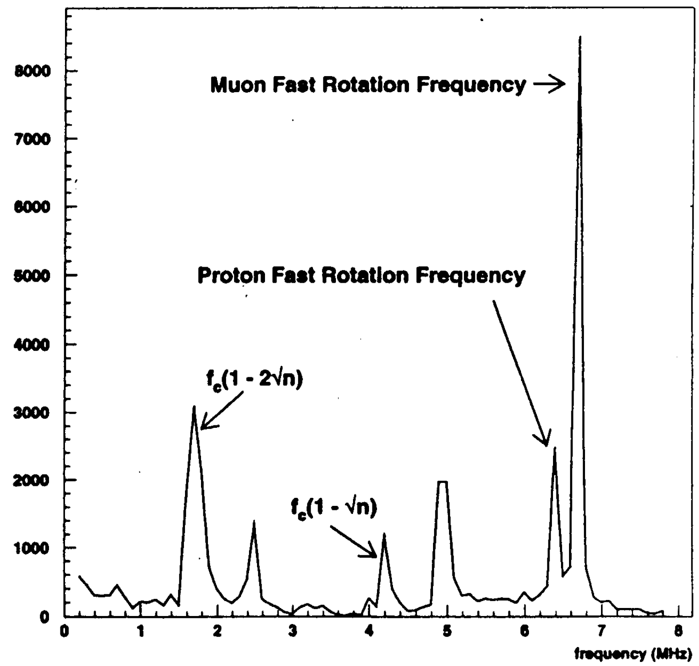
- These values are consistent with muon and pion mean life.

Measurement of Beam Dynamics and Composition

Turn–by–turn Evolution
of Radial Beam Centroid



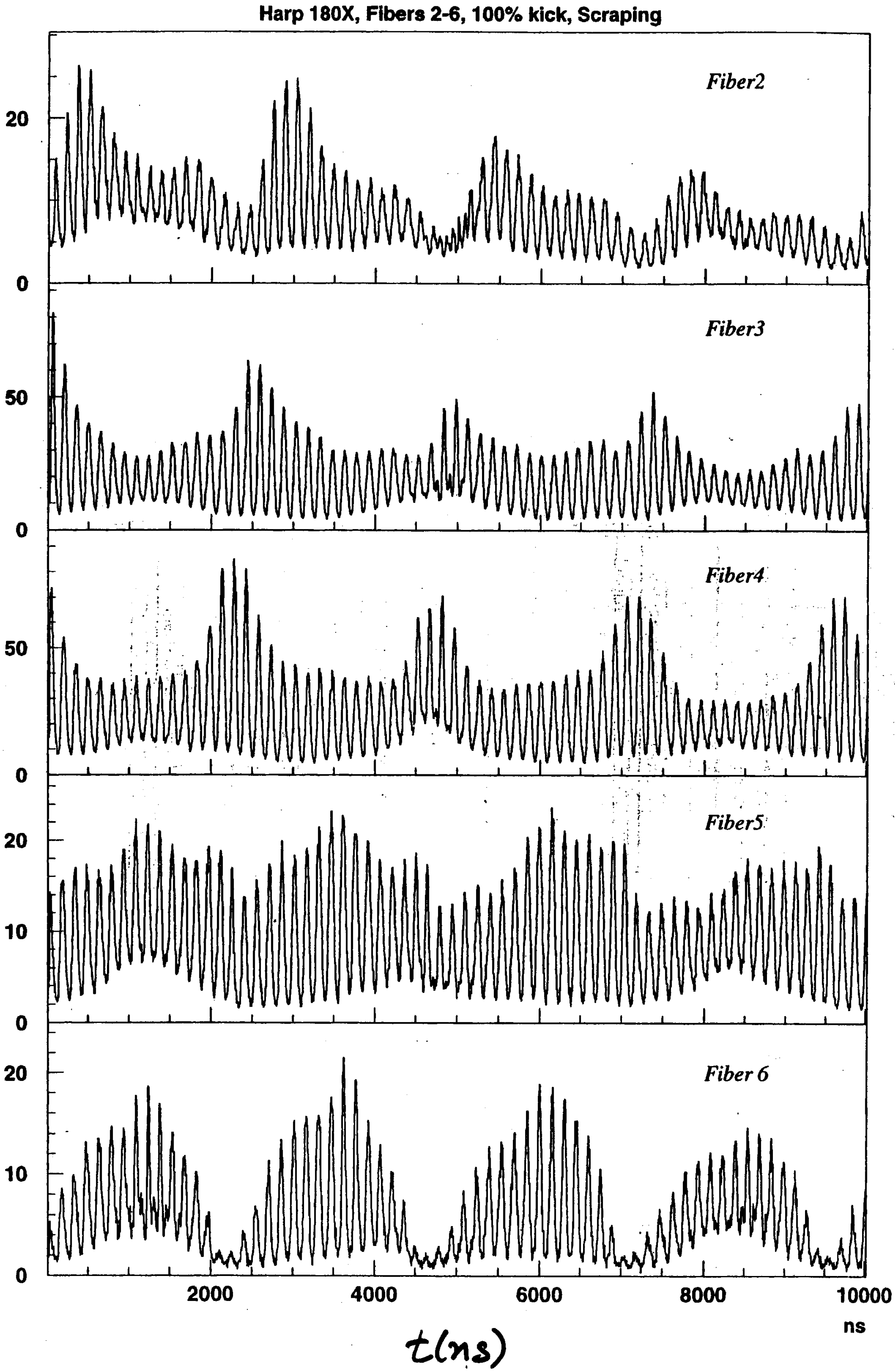
Fast Fourier Transform of
Single Fiber Trace



n–value of storage ring changes from 0.136 to 0.120 during 7 kV quadrupole scraping

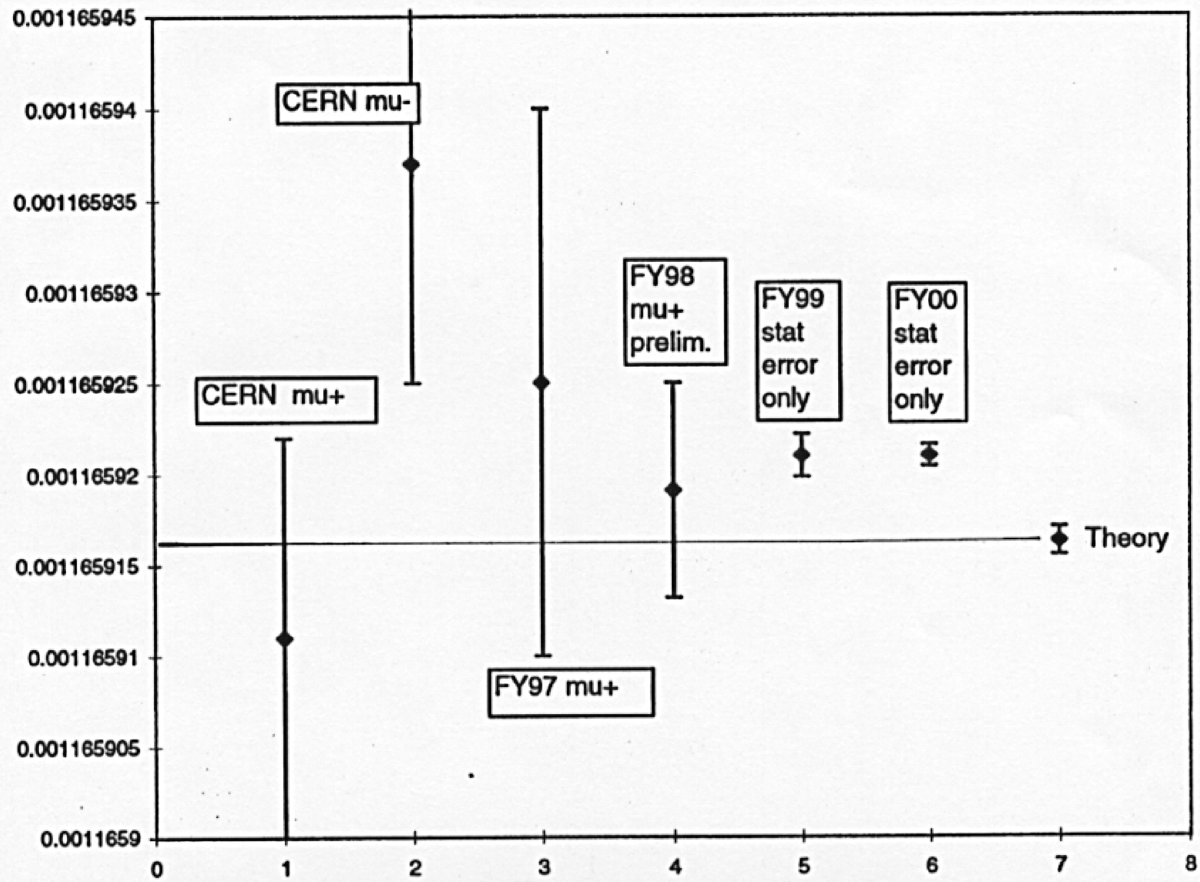
Measurement of fast rotation frequency, betatron frequency, and evidence of stored protons

2000 nm



Harp 180X, Fibers 2-6, 100% kick, Scraping
Fiber2
Fiber3
Fiber4
Fiber5
Fiber 6
20
0
50
10
2000
4000
6000
8000
10000
ns
t(ns)

Muon Anomaly CERN and BNL



	a	da	Comments
CERN mu+ (1978)	0.001165911	1.10E-08	
CERN mu- (1978)	0.001165937	1.20E-08	
FY97 mu+	0.001165925	1.50E-08	
FY98 mu+ (preliminary)	0.001165919	5.90E-09	
FY99 mu+ stat error only	0.001165921	1.17E-09	a = world average
FY00 mu+ stat error only	0.001165921	5.90E-10	a = world average
Theory	0.001165916	7.70E-10	

World average $a_\mu = 0.001165921 \pm 4.5$

16 ± 0.8 Theory