掲示

KEK Physics Seminar

(Language:English)

March 23(Tue) 16:00 ~ 17:00

Room345, 4th Building

The New Muon g-2 Result

Gerry Bunce

(BNL for the Muon g-2 collaboration)

abstract: A new measurement of the anomalous magnetic moment of the negative muon has just been completed, hep-ex/0401008. The result is a(μ-)= 11 659 214(8)(3) x 10^{-10} (0.7 ppm). The result is consistent with our previous μ+ results, and the combined precision is 0.5 ppm. I will present the measurement, and comparisons with the Standard Model.

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Organizers: T.Komatsubara & I.Adachi

2004.02.03

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23 March 2004
KEK

The New Muon g-2 Result

Gerry Bunce for the Muon g-2 Collaboration

A new measurement of the anomalous magnetic moment of the negative muon has just been completed, hep-ex/0401008. The result is

$a(\mu^-)$= 11 659 214(8)(3) x 10^{-10} (0.7 ppm).

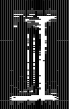
The result is consistent with our previous mu^+ results, and the combined precision is 0.5 ppm. I will present the measurement, and comparisons with the Standard Model.

Collaboration

Most recent paper: 70 authors, 11 institutions, 5 countries

Boston University	Boston, Massachusetts, USA
Brookhaven National Laboratory	Upton, New York, USA
Budker Institute of Nuclear Physics	Novosibirsk, Russia
Cornell University	Ithaca, New York, USA
Universität Heidelberg	Heidelberg, Germany
University of Illinois	Urbana, Illinois, USA
KEK	Tsukaba, Japan
Kernfysisch Versneller Instituut	Groningen, The Netherlands
University of Minnesota	Minneapolis, Minnesota, USA
Tokyo Institute of Technology	Tokyo, Japan
Yale University	New Haven, Connecticut, USA

Funding: Department of Energy, National Science Foundation, National Computational Science Alliance, German Bundesminister für Bildung und Forschung, Russian Ministry of Science, and U.S.-Japan Agreement in High-Energy Physics.



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scan for file

Important Contributions from Japan:*

Design of 14m diameter coils: (KEK)
H. Hirabayashi, A. Yamamoto

Topaz-type superconductor (~4 km): KEK

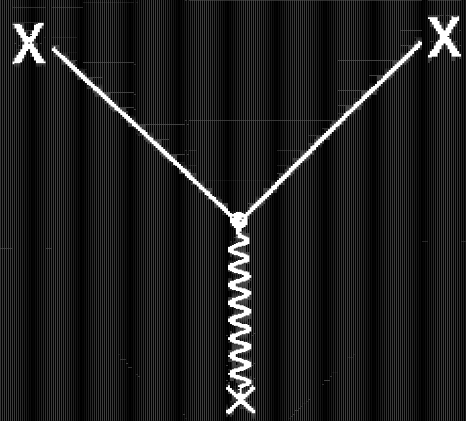
Iron yoke specifications; ultra-low carbon pole steel: (KEK)
K. Endo

Scintillating fiber monitors inside storage ring
Y. Mizumachi (KEK)
M. Iwasaki, M. Kawamura (Tokyo I Tech)

Superconducting inflector:
A. Yamamoto (KEK)
Tokin, Nippon Steel Co.
[M. Tanaka] [Dr. I. Itoh]

* under U.S.-Japan agreement in HEP

The Anomalous Magnetic Moment



$$\vec{\mu} = g\frac{e\hbar}{2mc}\vec{s}$$

Dirac: $g = 2$ for a point-like spin-$\frac{1}{2}$ particle

g_e	$\approx$	2.002
g_μ	$\approx$	2.002
g_p	$\approx$	5.586
g_n	$\approx$	-3.826

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

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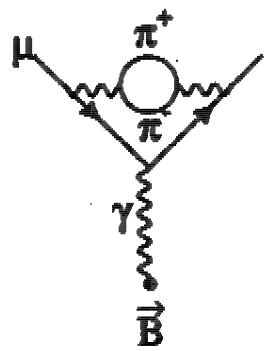
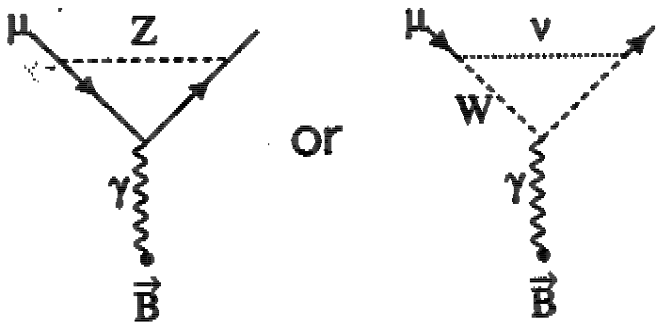
μ
μ
γ
μ
μ
μ

Standard Model Contributions

- electromagnetic (previous slide)
- hadronic, i.e.



- weak, i.e.



$$a^{SM} = a^{em} + a^{had} + a^{weak}$$

A.Steinmetz DNP99/5

(1) $(g-2)_\mu$ is a sum rule for the Standard Model

(2) measure $g-2$ directly, not g

(3) ingredients:

a) polarized muons $\not{p}\ \pi \to \vec{\mu}$

b) store μs in B know B to 10^{-7}

c) polarimeter to measure spin advance with time $\not{p}\ \vec{\mu} \to e$

$$a_\mu = \frac{g-2}{2} = \frac{m_\mu e}{c}\ \frac{\omega_a}{B}$$

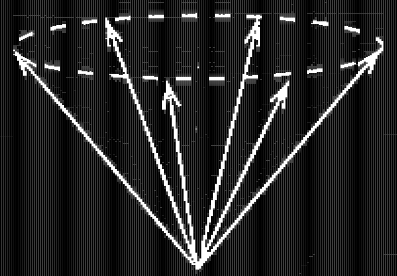
(4) trick: to store μs, need focusing at 3 GeV: E field effect on spin is zero to 1st order

(5) precision B field: use iron to shape
$\Rightarrow$ 1.5 T field max $\Rightarrow$ 7 m radius

(6) analyze ω_a and B separately
$\to$ blindfolded analysis

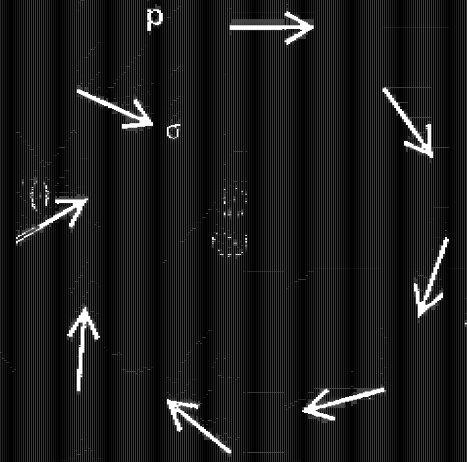
For muons at rest:

$$= g\frac{eB}{2m_\mu c}$$



For muons in flight:

$$= \left[1 + \gamma\left(\frac{g-2}{2}\right)\right]\underbrace{\frac{eB}{m_\mu c\gamma}}$$



$$\omega_a \equiv \quad - \quad = a_\mu \frac{e}{m_\mu c} B$$

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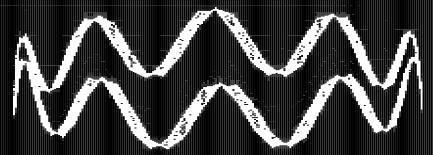
Orbiting particles will escape on the top or the bottom ....

Need vertical confinement!



$\Rightarrow$ Electric Quadrupole

But: muons "see" the electric field as a magnetic one because of the relativistic boost:

$$\vec{\omega}_a = \frac{e}{mc}\left[a_\mu \vec{B} - \underbrace{\left(a_\mu - \frac{1}{\gamma^2 - 1}\right)}_{0 \text{ for } \gamma=29.3} \vec{\beta} \times \vec{E}\right]$$

$\gamma = 29.3 \Rightarrow p = 3.094$ GeV/c; $\tau = 64$ μs

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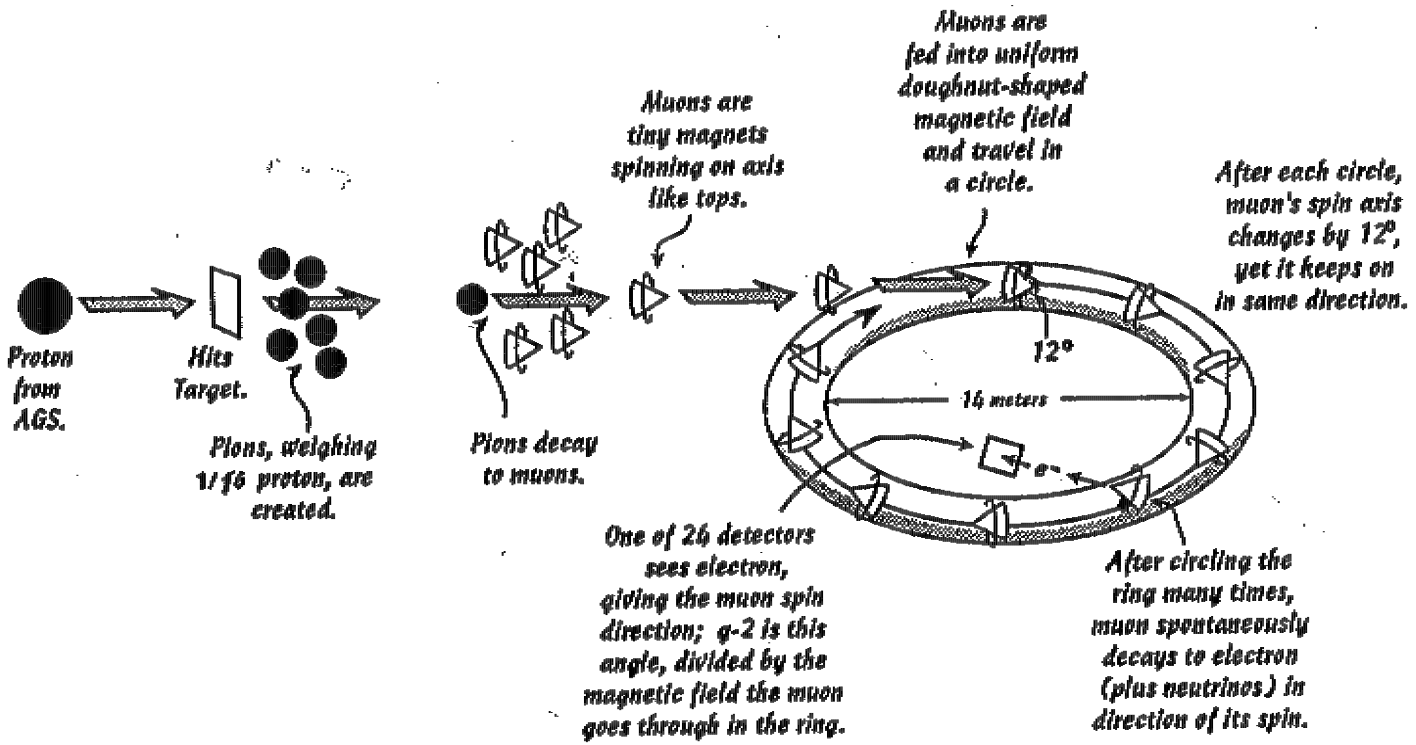
Life of a Muon : The g-2 Experiment



Construction started in 1989.

Beam in 1996.

SEUBERT 1a 9/91 IR

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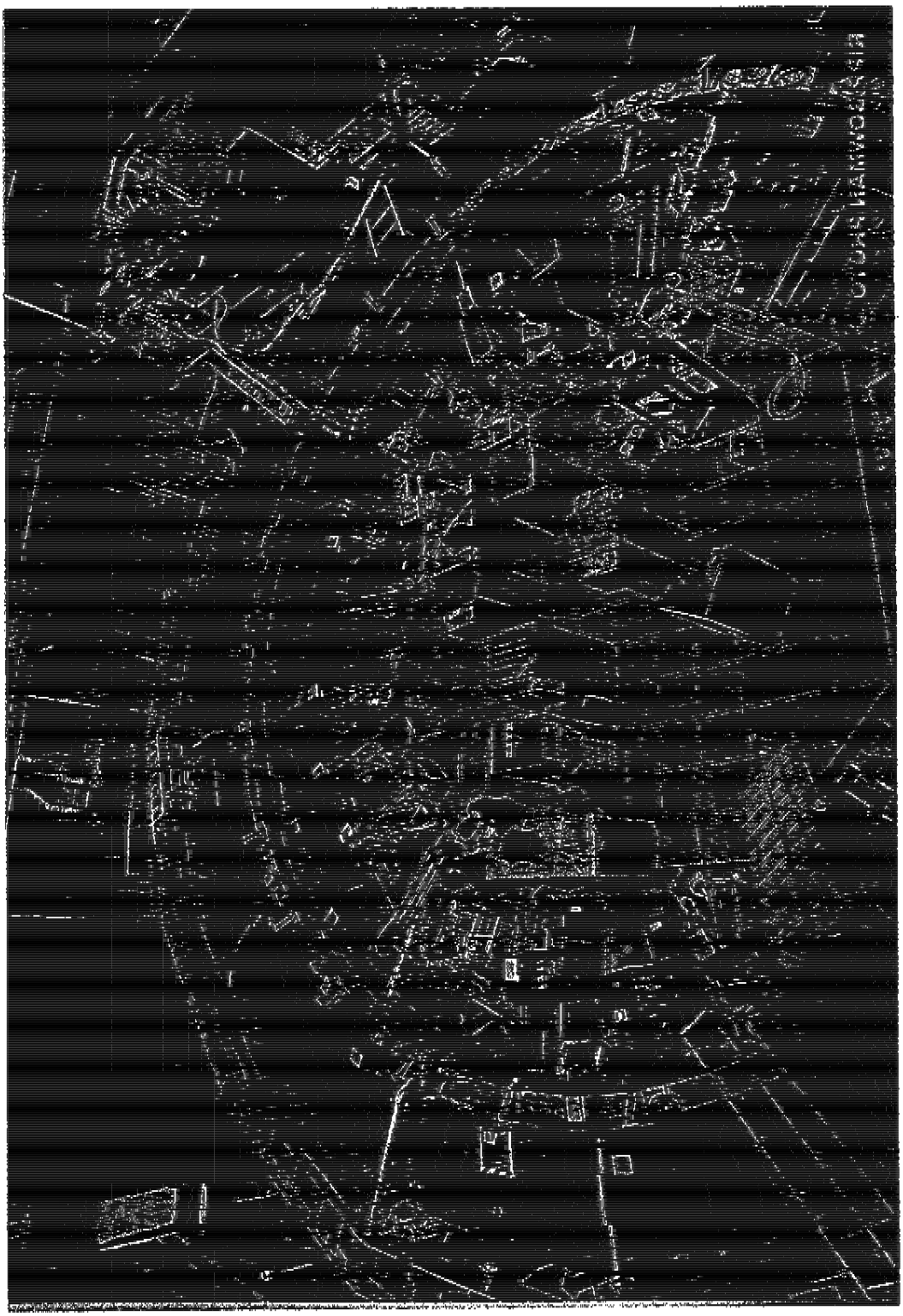
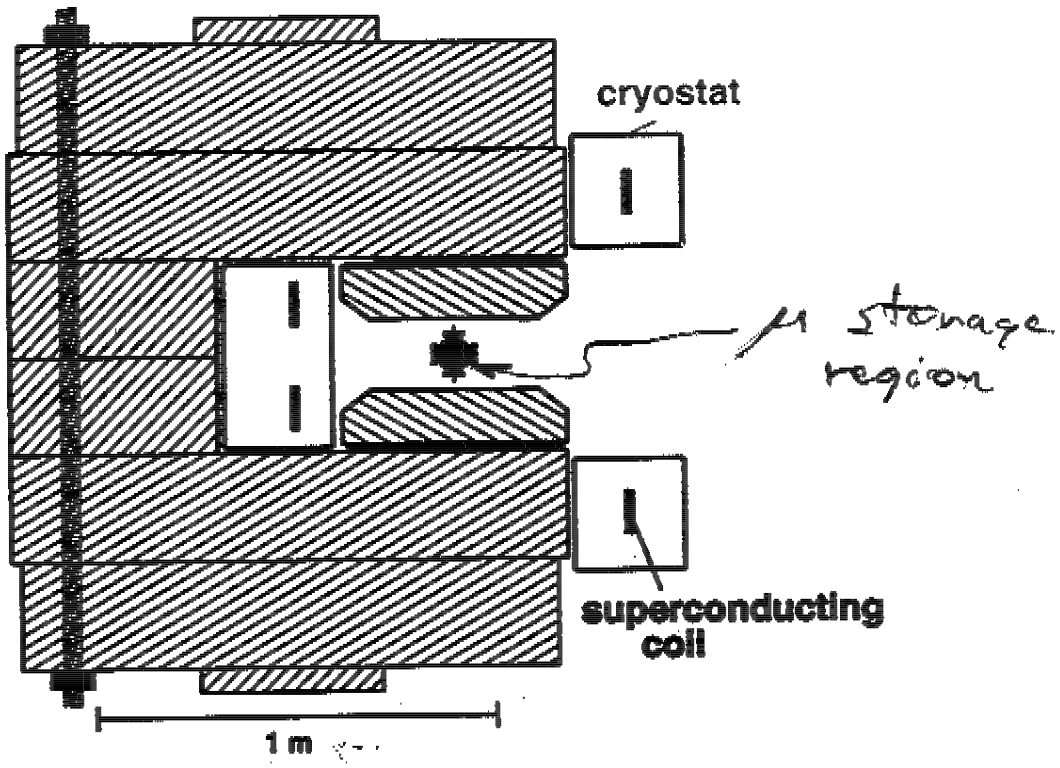
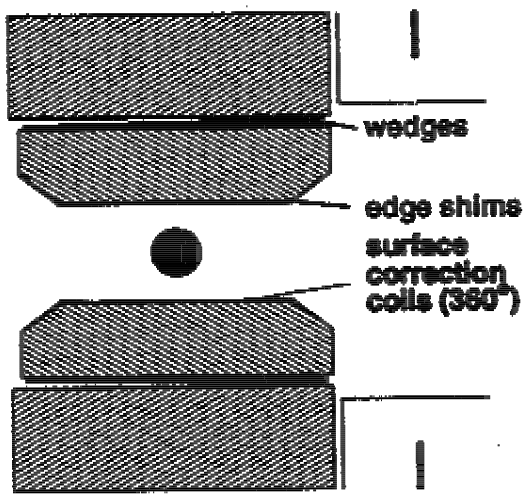


The E821 Ring Magnet



shimming tools:



A.Steinmetz DNP99/17

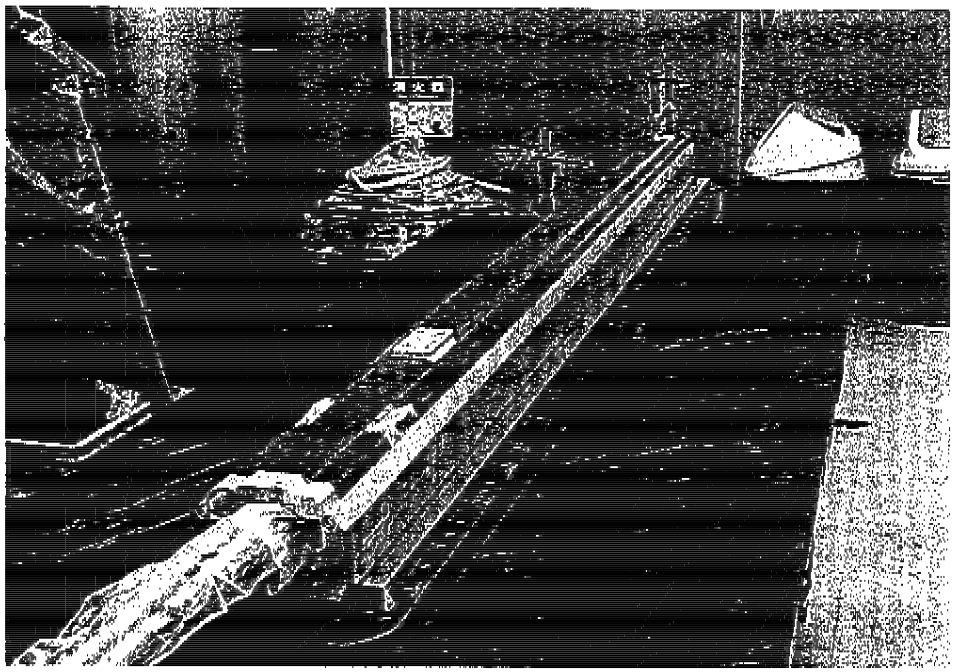
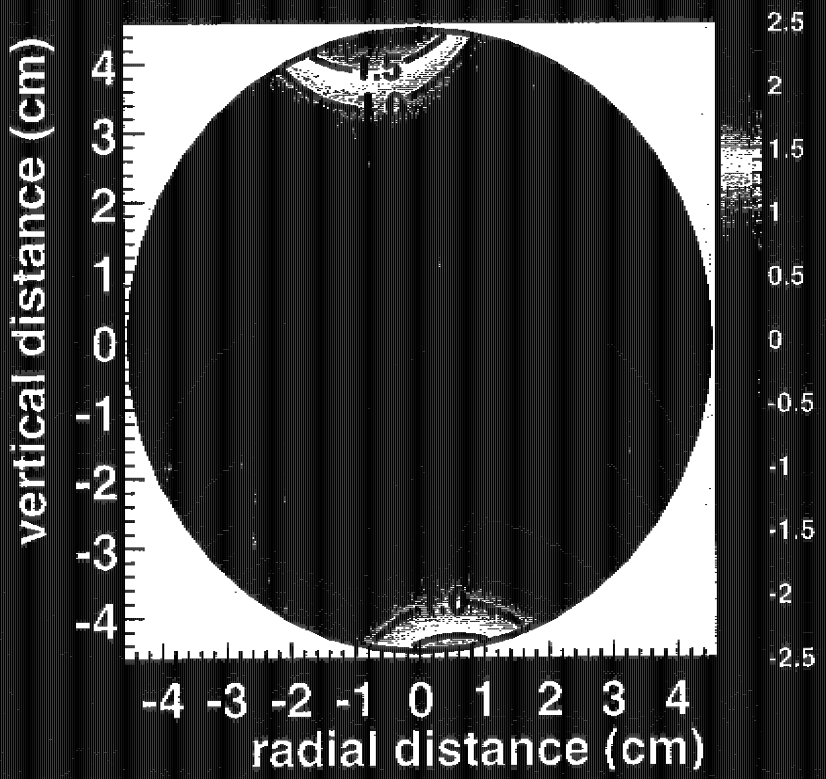
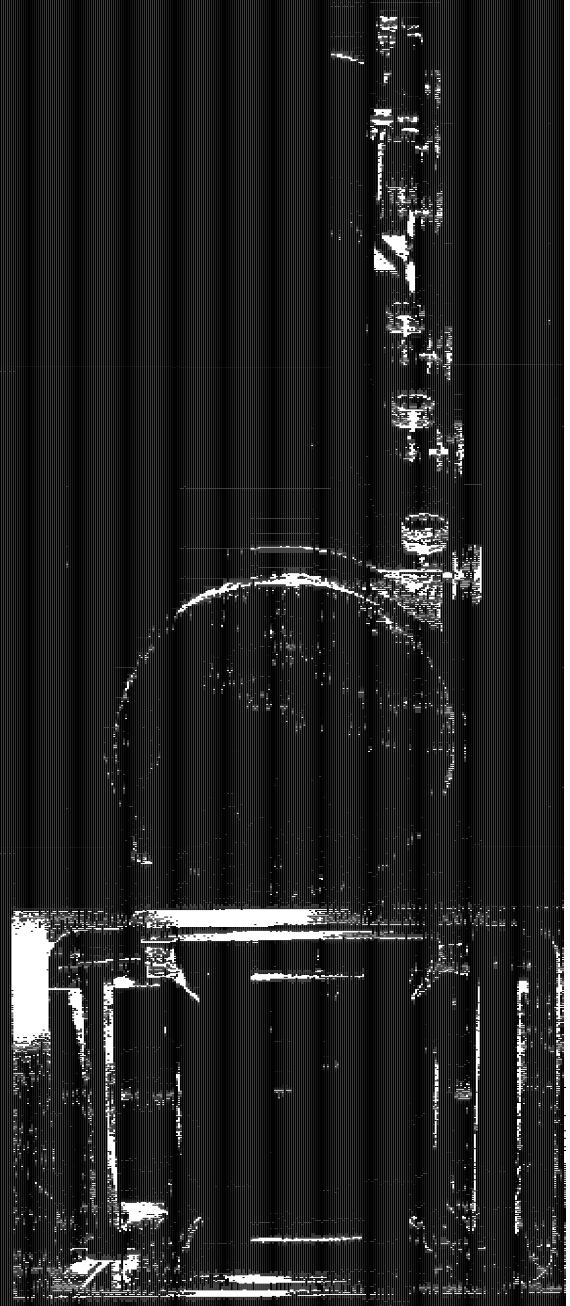


Photo 15. Attaching SC shield cover by using green-epoxy

Photo 16. Attaching SC shield body by using green-epoxy

Measured in terms of the proton NMR frequency (ω_p) inside the vacuum chamber every couple of days using 17 calibrated probes in a "trolley"





Absolute calibration from spherical water probe

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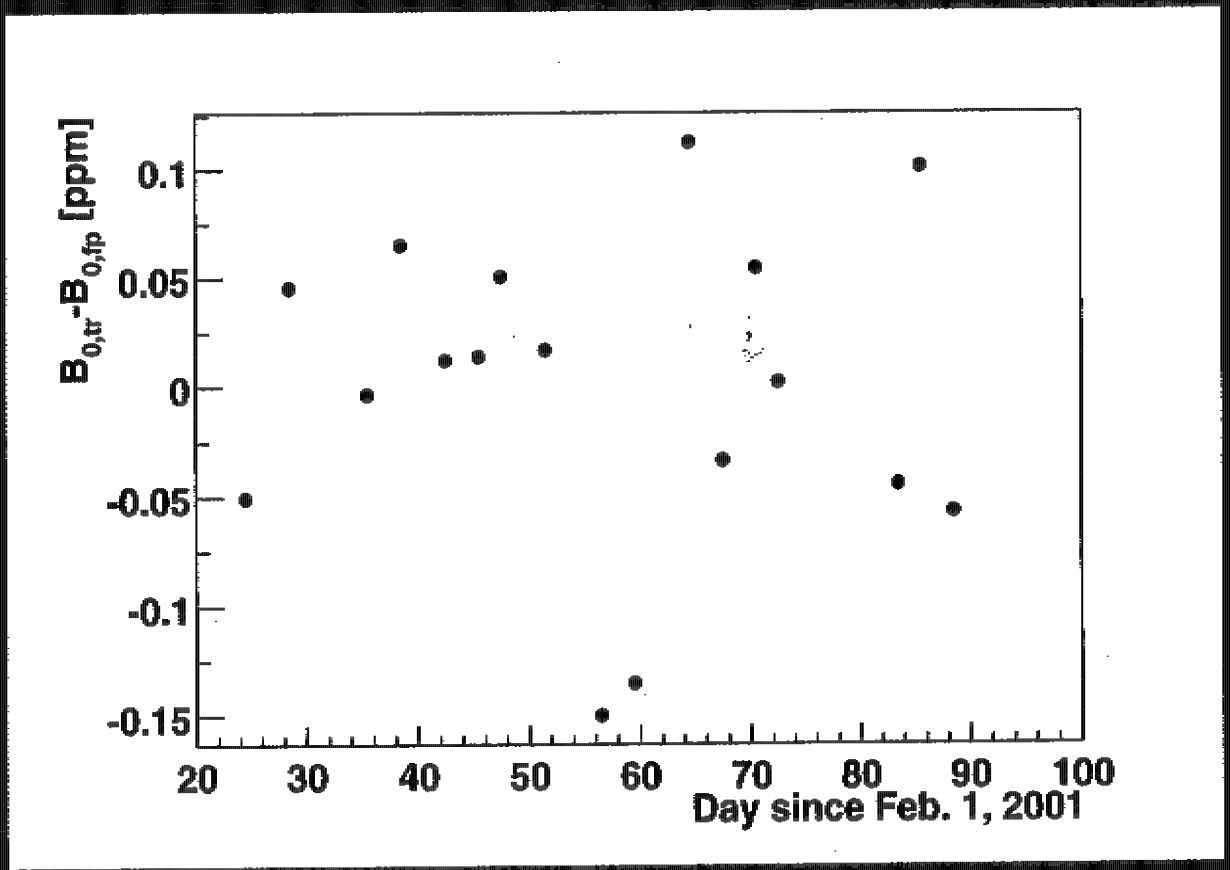
Between trolley measurements, ~150 fixed probes monitor the field



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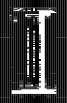
scan for file

Effect	2001 [ppm]	2000 [ppm]
Absolute calibration of standard probe	0.05	0.05
Calibration of trolley probes	0.09	0.15
Trolley measurements of B_0	0.05	0.10
Interpolation with fixed probes	0.07	0.10
Uncertainty from muon distribution	0.03	0.03
Others	0.10	0.10
Total	0.17	0.24



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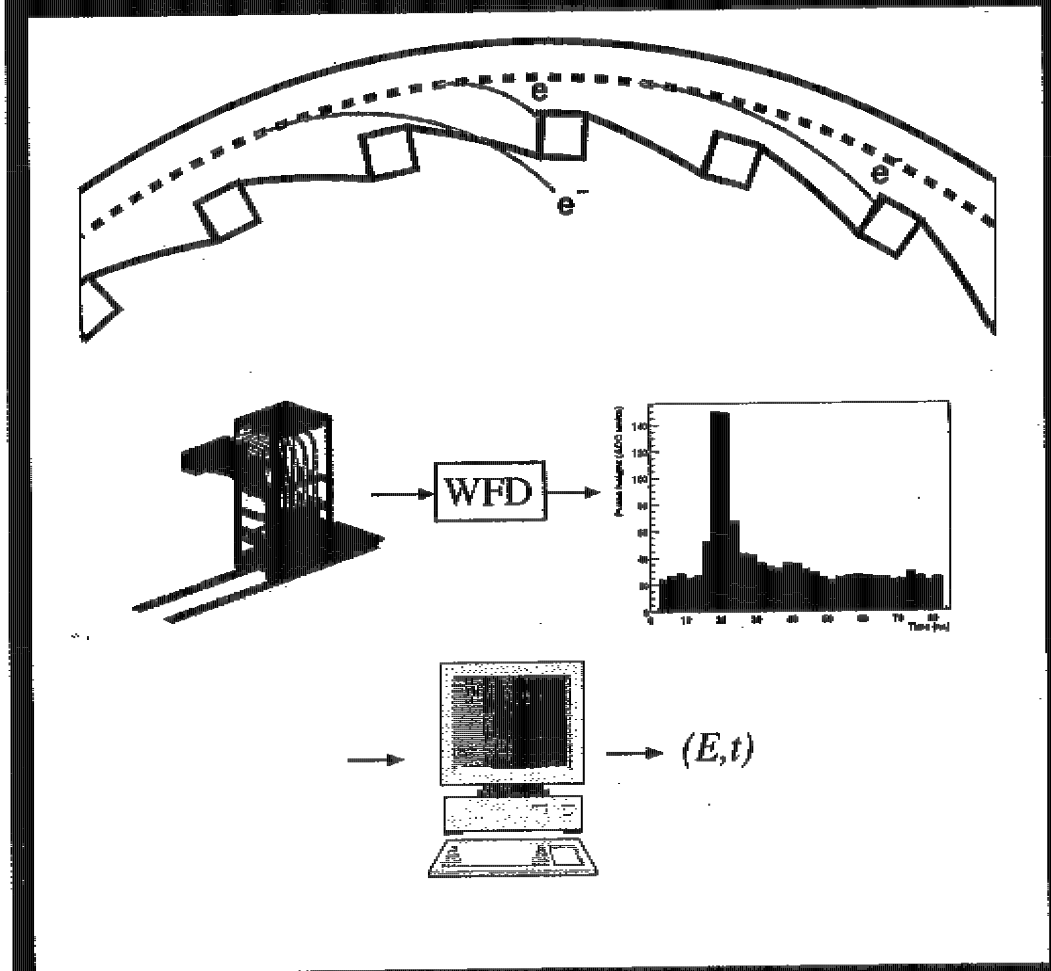

e
e⁻
e
WFD
(E,t)

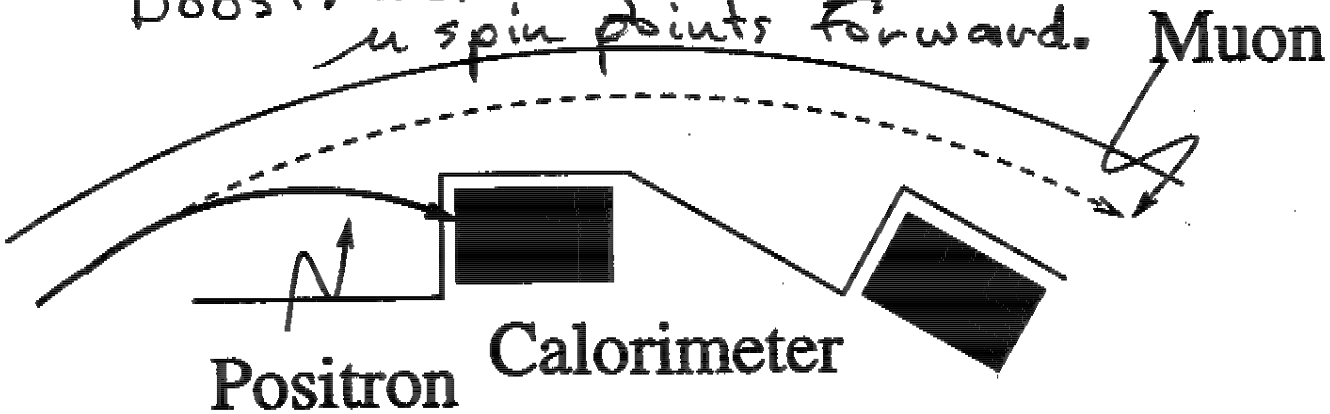
Polarimeter

high energy positrons from muon decay

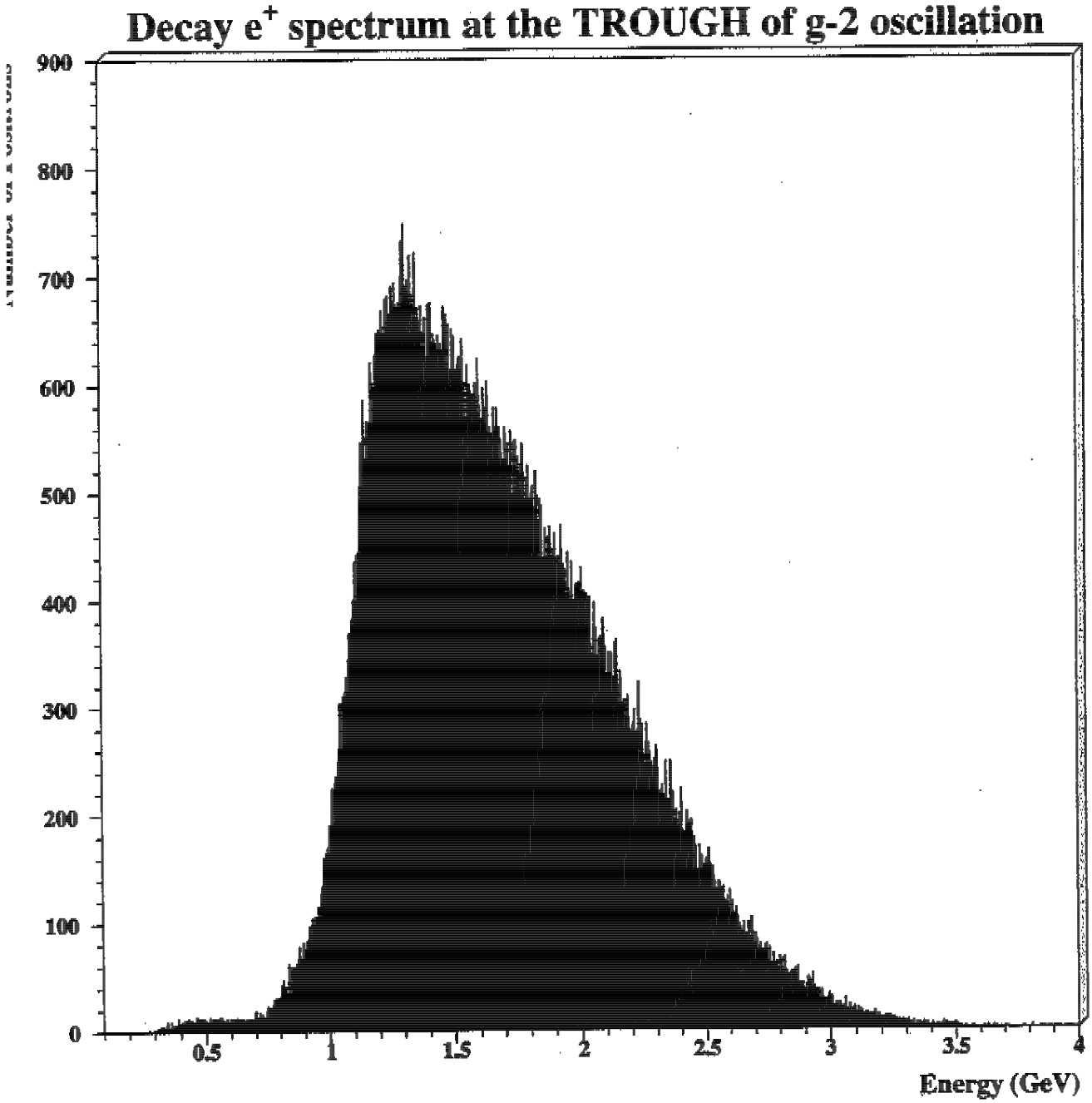
$$\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$$

Parity violation: more e^+ in direction of muon spin.

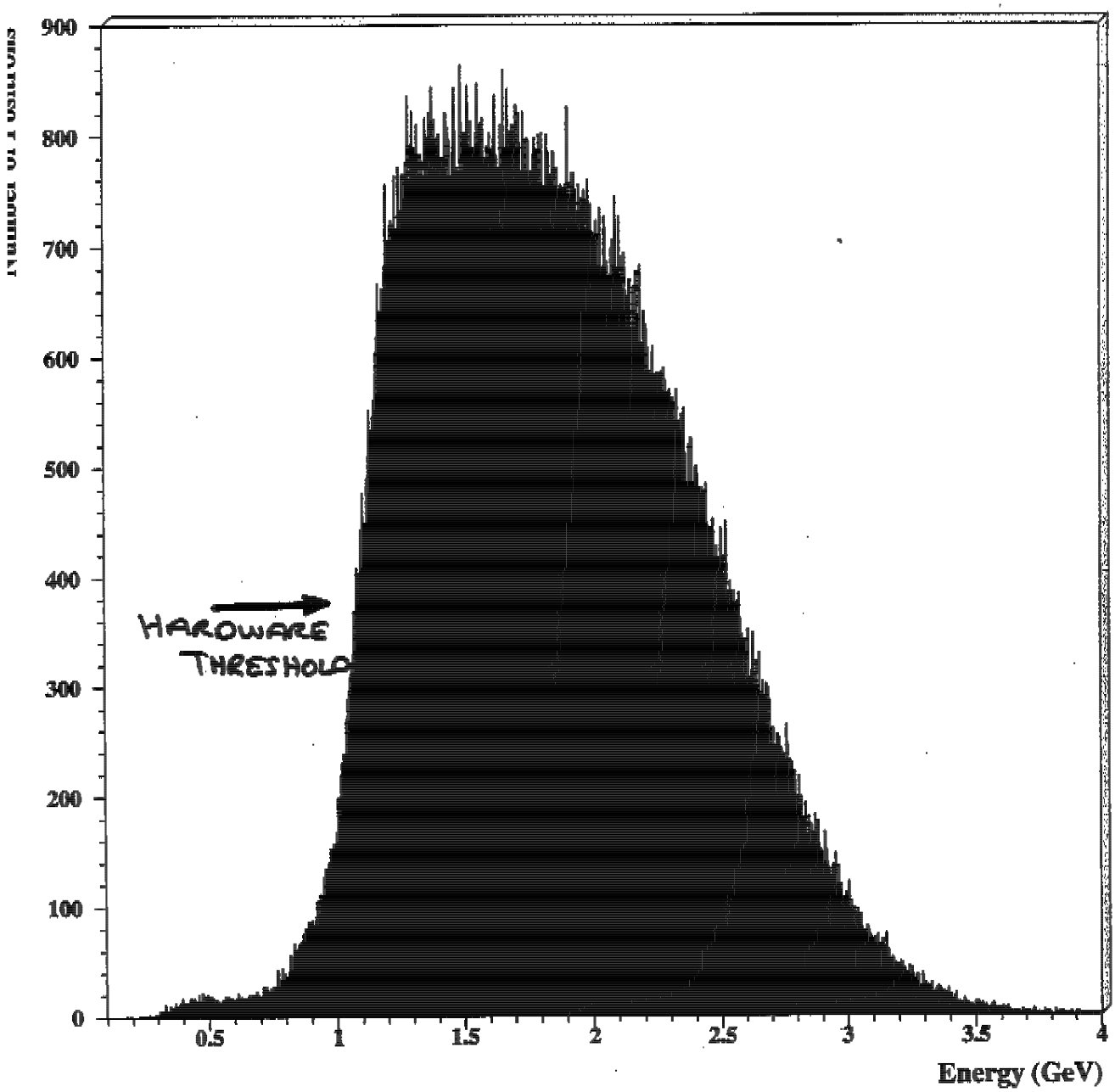
Boost: more high energy e^+ when μ spin points forward.



A.Steinmetz DNP99/10


Decay e+ spectrum at the TROUGH of g-2 oscillation
900
800
700
600
500
400
300
200
100
0
0.5
1
1.5
2
2.5
3
3.5
4
Energy (GeV)

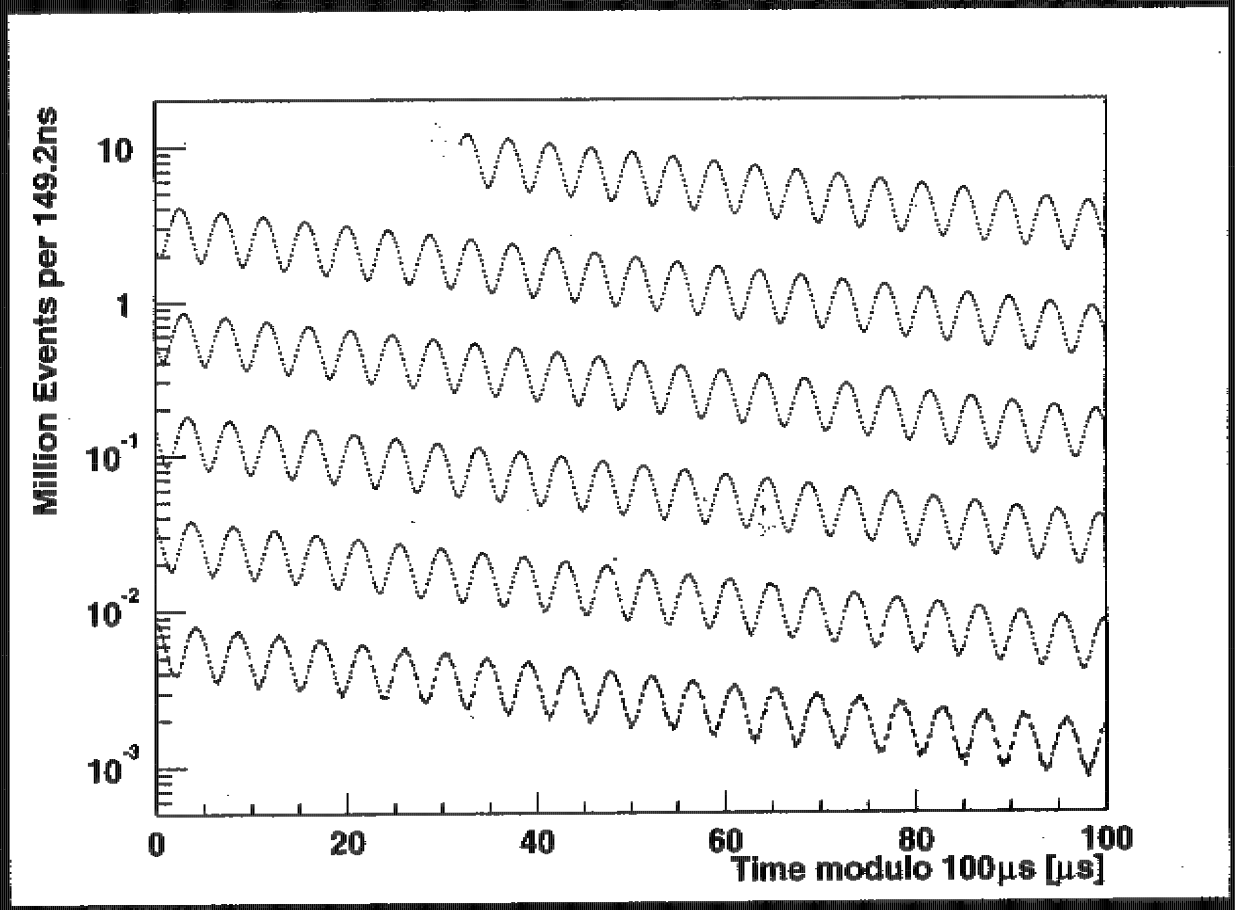
Decay e^+ spectrum at the PEAK of g-2 oscillation



$\mu^+ \rightarrow e^+ \nu \bar{\nu}$

The Wiggle Plot

4×10^9 events with $t > 32\mu$s, $E > 1.8$ GeV



$$N(t) = Ne^{-t/\gamma\tau}\ [1 + A\cos(\omega_a t + \phi)]$$

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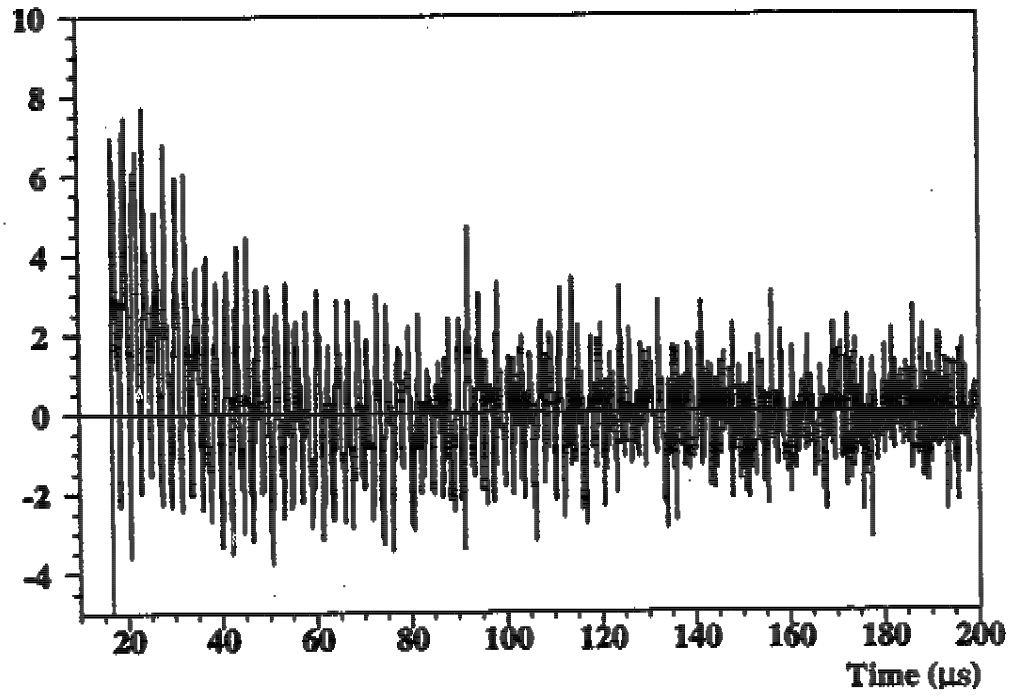
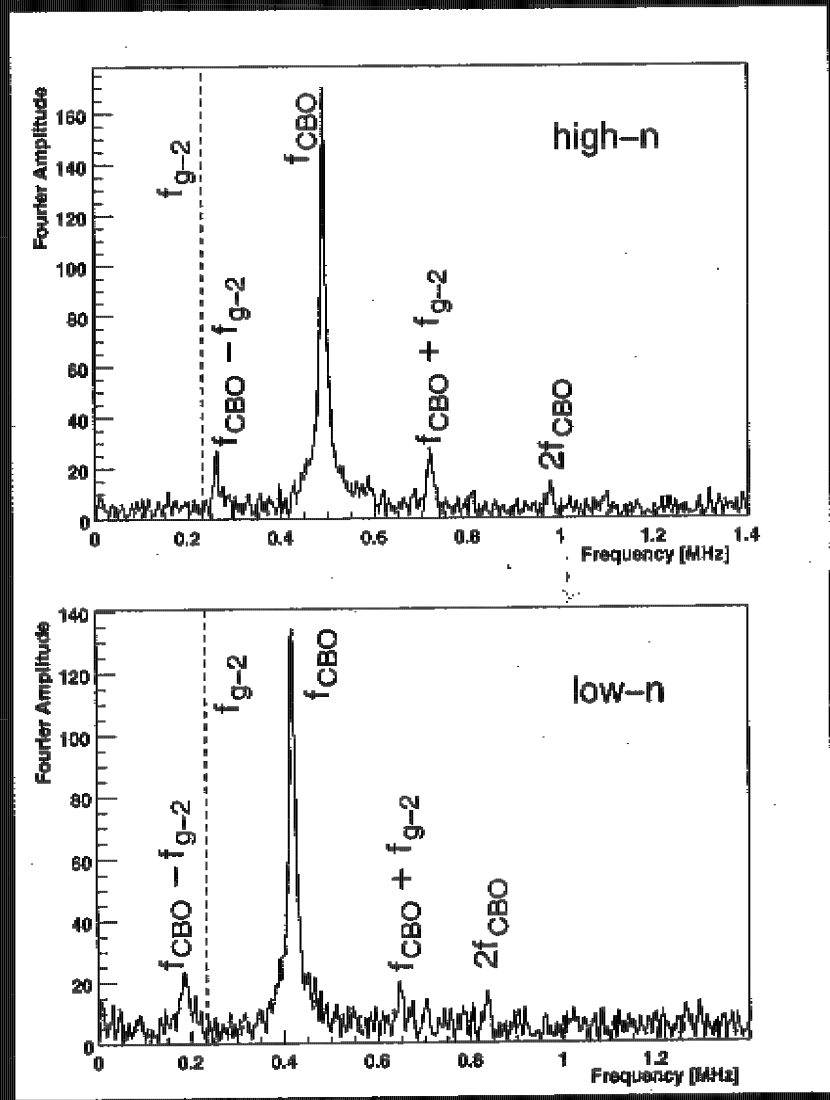
Residuals from 5 parameter fit to "wiggle" plot:



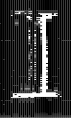
CBO Explosion



Coherent Betatron Oscillations

The detector acceptance depends on the muon decay position and the energy of the electron

- Phase space not filled
- Beam as a whole "swims" and "breathes"
- Beating with cyclotron frequency results in $\omega_{CBO} = (1 - \sqrt{1-n})\omega_a$
- Must avoid beam and spin resonances, and $\omega_{CBO} \simeq 2\omega_a$
- Use $n = 0.122$ and $n = 0.142$
- ϕ varies by 2π going around the ring
  $\Rightarrow$ Adding detectors reduces effect



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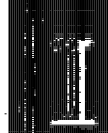
Goal: Describe the spectrum of (weighted) counts adequately using a function with as few parameters as possible

Effects to deal with:

- gain: effective energy threshold changes
  can be reconstructed from $\langle E \rangle$

- pileup/overlapping signals: affects N, A and ϕ
  can be reconstructed from data itself

- muon loss: affects N; couples weakly to ω_a
  can be reconstructed from scintillator detectors



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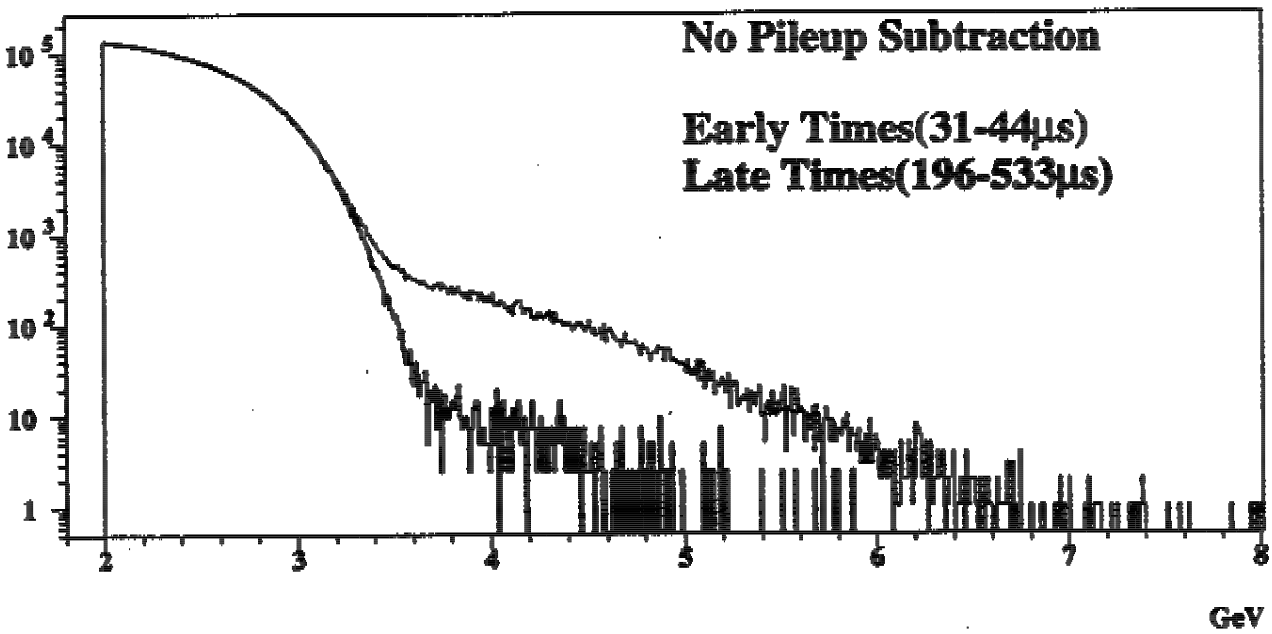
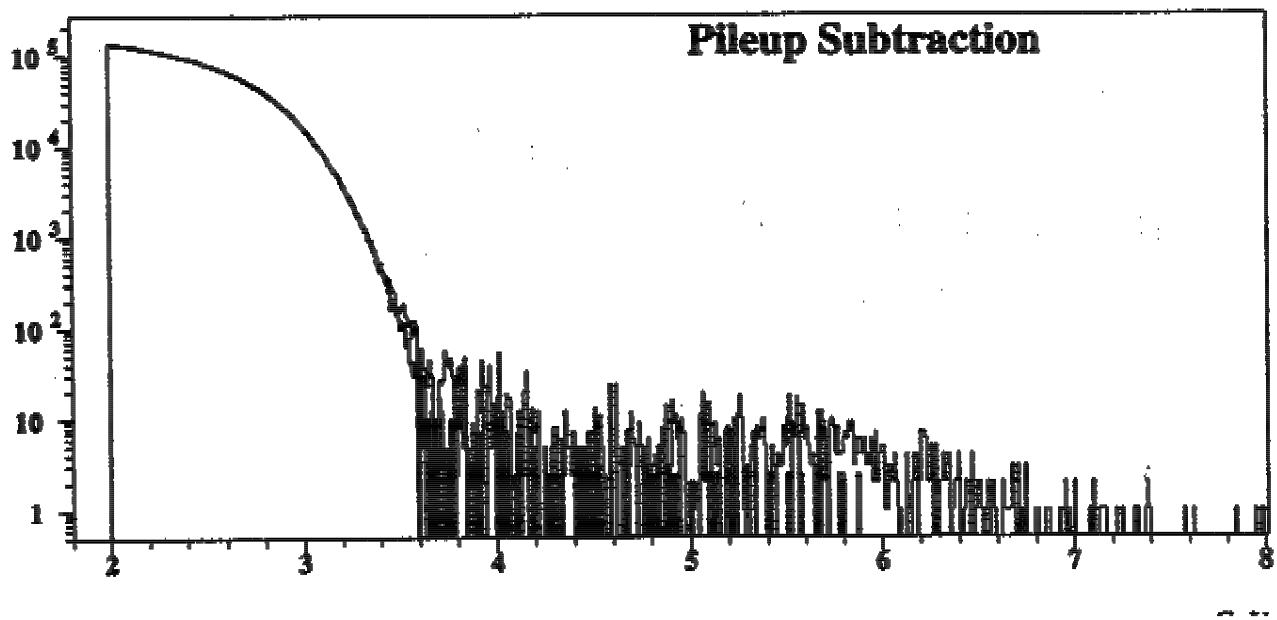
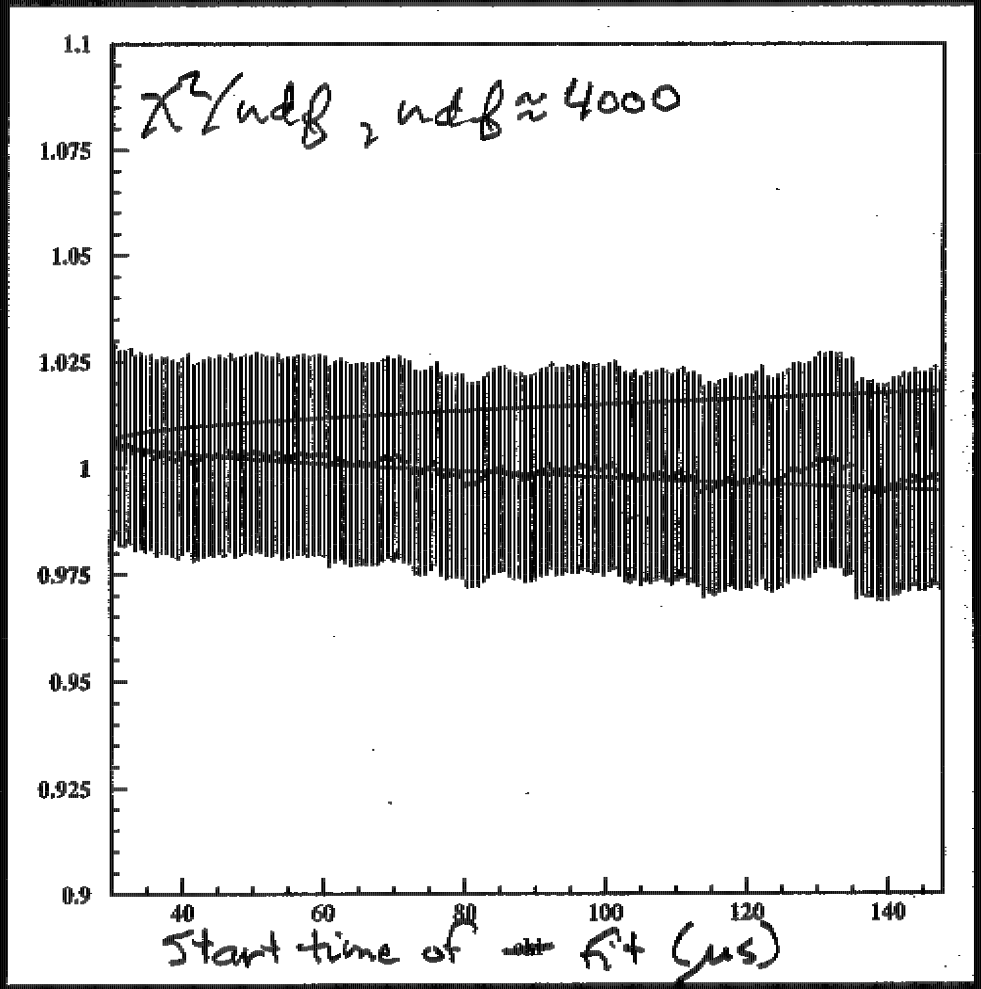
Energy Spectra







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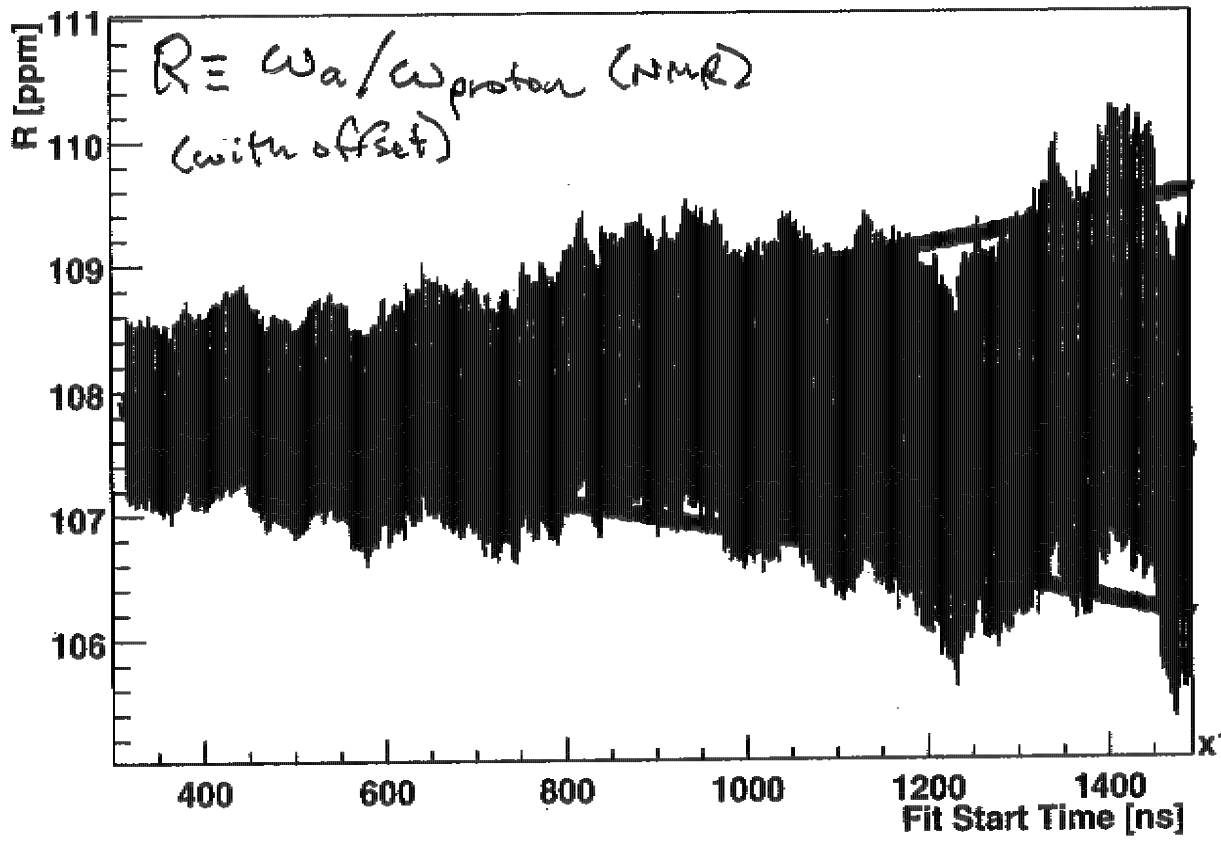

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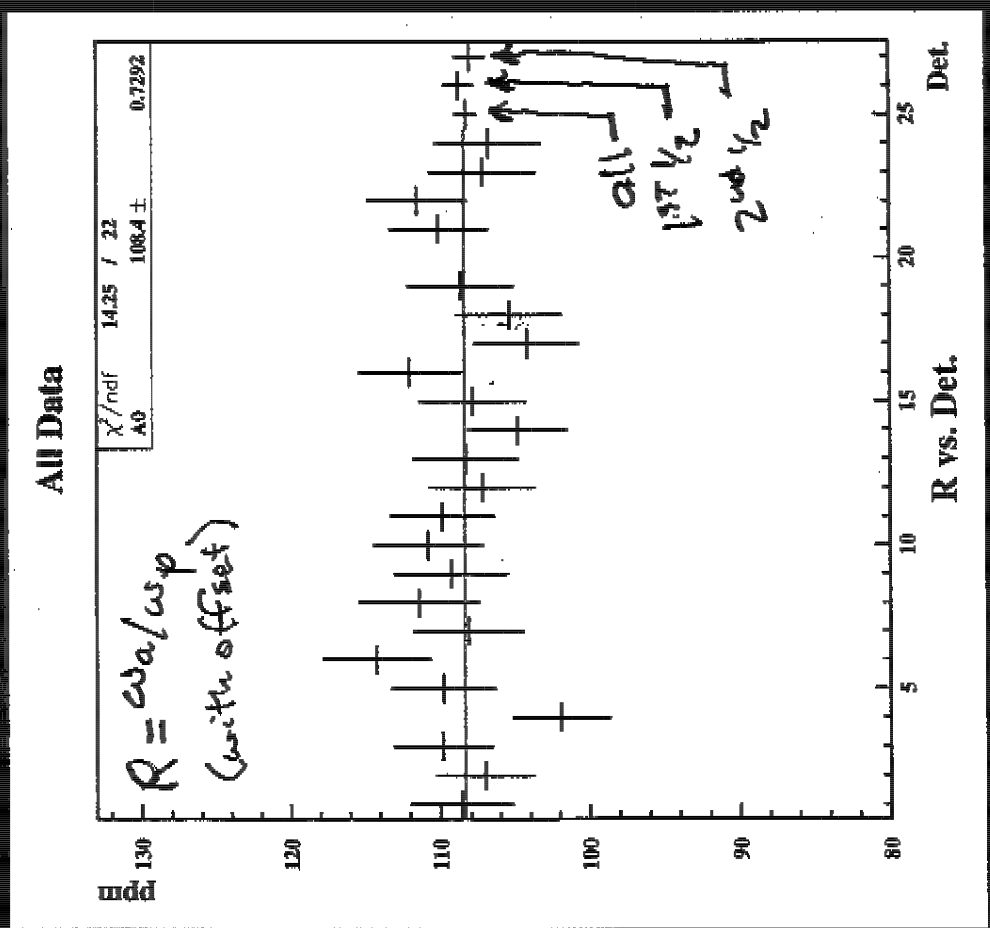
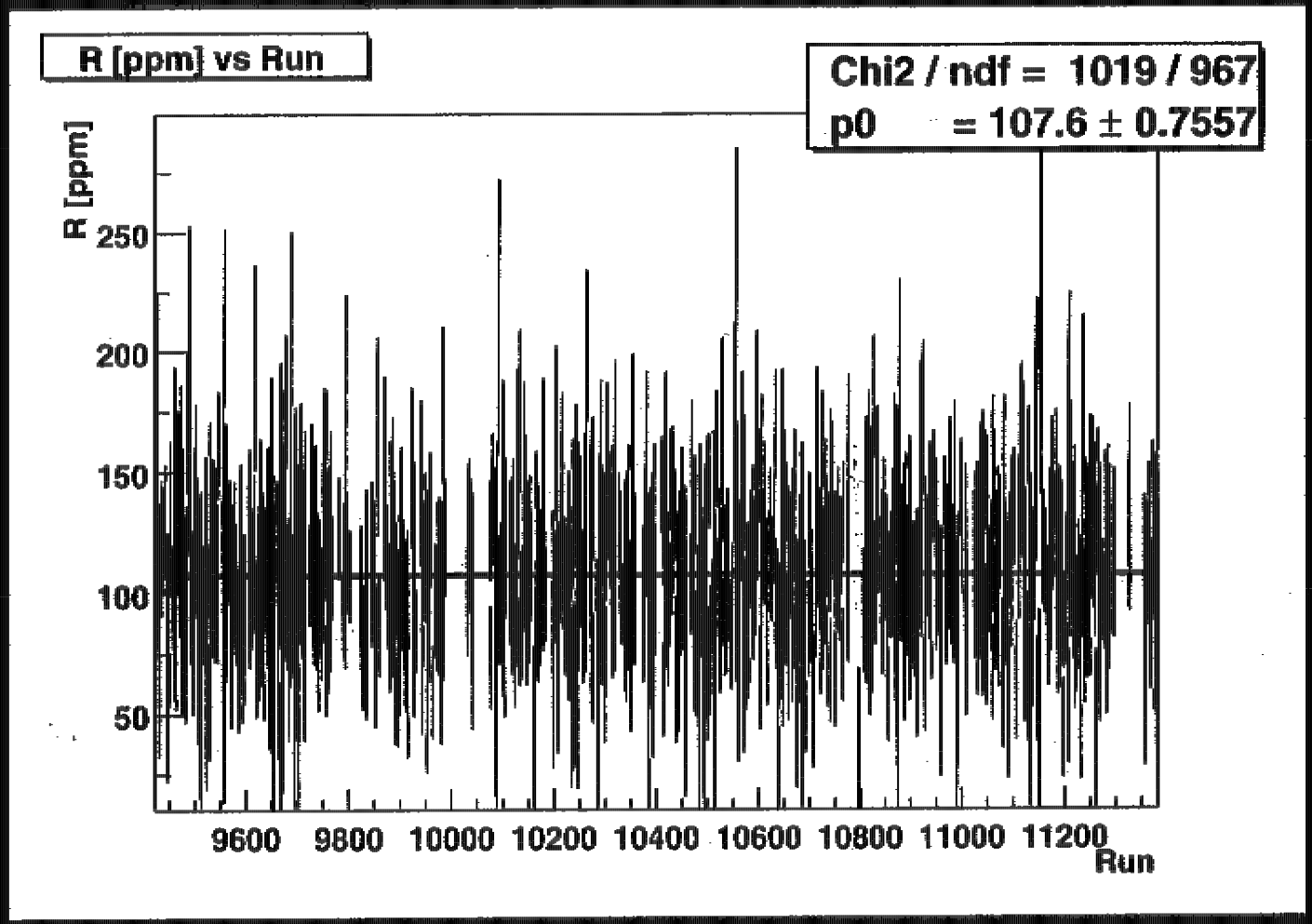

All Data
χ²/ndf 1425 / 22
A0 108.4 ± 0.7292
R = ωa/ωp
(with offset)
all
1st ½
2nd ½
R vs. Det.
Det.
ppm
130
120
110
100
90
80
5
10
15
20
25



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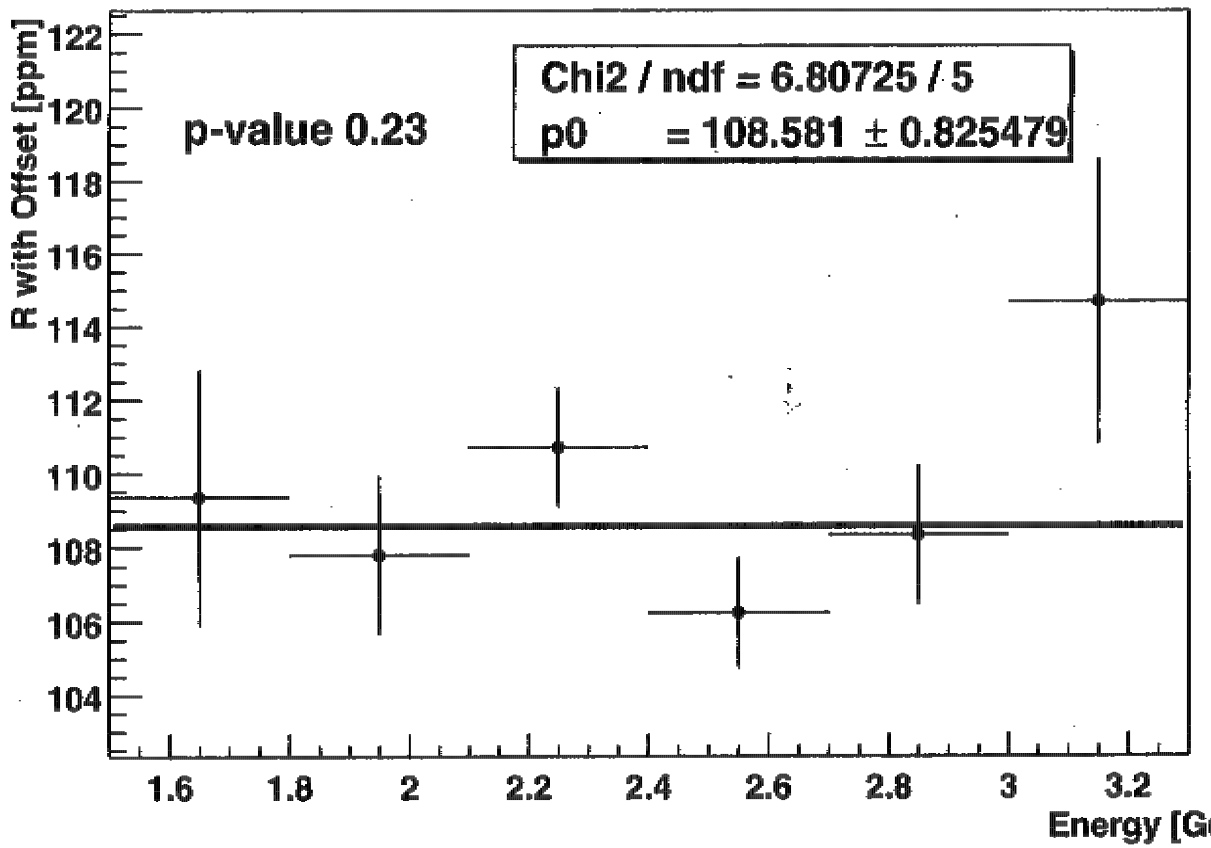

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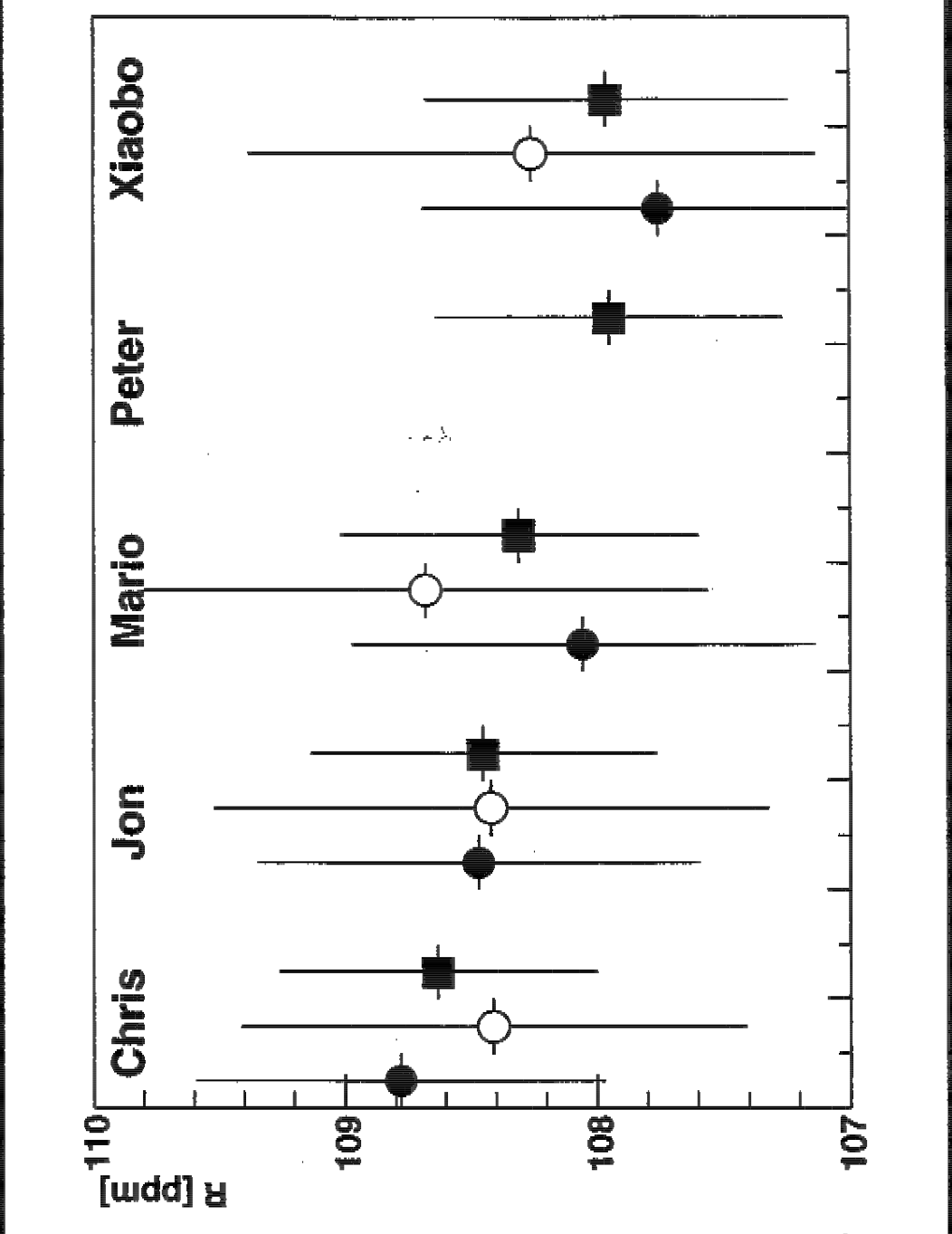
Chris
Jon
Mario
Peter
Xiaobo
110
109
108
107
π [ppm]

Item	Xiaobo	Jon	Peter	Mario	Chris
Gain					
Slow term	0.04/0.02	0.01/0.02	0.09	0.05/0.03	0.07/0.03
G-2 term			0.1		
CBO					
Frequency	0.02/0.07	0.01/0.02	--	--	---
Quads droop		0.02	--	0.01	
Lifetime env.	0.02/0.01	0.02/0.07	--	0	0.06/0.03
Rob/Jan env.	0.02	0.01/0.06	0.05	0.01/0.03	0.06
Rob/Jan func.		0.04	--		
Cancellation	--	--	0.17	--	--
DCBO	0.02/0.01	0.03	--	0.01/0.004	0.03
V2O	0.01/0.02	0.01/0.02	--		
VW	0.01/0.02	0.03/0.04	--		0.03
Pileup					
Efficiency	0.01/0.02	0.03/0.01	0.07	0.04	0.02/0.05
Phase	0.02/0.04	0.04		0.07/0.08	0.04/0.05
Unseen	0.03	0.02	0.02	0.03	0.03
Losses and RSE					
Fit-related	0.01	0.01	--	0.05/0.03	0.04
Spin direction	0.05/0.09	0.11/0.06	0.11/0.08	0.08/0.06	0.06/0.09
Acceptance effect	0.04	0.05	0.05	0.04	0.04
Other					
FlashPots	0.01/0.02	0.01	0.02	0.01	0.02
Bin width	0.05	0.05	0.05	0.06	0.06
Randomization	0.04	0.01/0.05	0.05	0.03	0.03
Timing shifts			0.02		
Fit procedure		0.04	0.01	---	0.03
Beam relaxation					0.05
Fairey effect in $\langle y \rangle$			0.03		
Fairey effect in σ_y			0.02		
Differential decay			0.03		
E-field uncert.			0.05		
Pitch uncert.			0.04		
Total					
Syst., low-n/high-n	0.193/0.207	0.217/0.228		0.234/0.225	0.246/0.248
Syst., total	0.199	0.216	0.281	0.229	0.244

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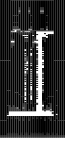
Effect	Uncertainty [ppm]	
	2001	2000
Statistics	0.66	0.62
Overlapping pulses (pileup)	0.08	0.13
Gain changes	0.12	0.12
Lost muons	0.09	0.10
CBO	0.07	0.21
Other	0.11	0.08
Total systematics	0.21	0.31
Total uncertainty	0.72	0.69

Unfortunately still limited by statistics ....



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Determining a_μ

a_μ is finally determined by taking a ratio of two frequencies:

$$a_\mu = \frac{R}{\lambda - R}$$

Where, $R = \dfrac{\omega_a}{\omega_p}$ Measured by E821

$\lambda = \dfrac{\mu_\mu}{\mu_p}$ From muonium hyperfine structure

$= 3.183\ 345\ 39(10)$ D.E. Groom, et. al., Review of Particle Physics, *Eur. Phys. J.* **C15**, p. 1, (2000)

BNL E821 *1999 Result*

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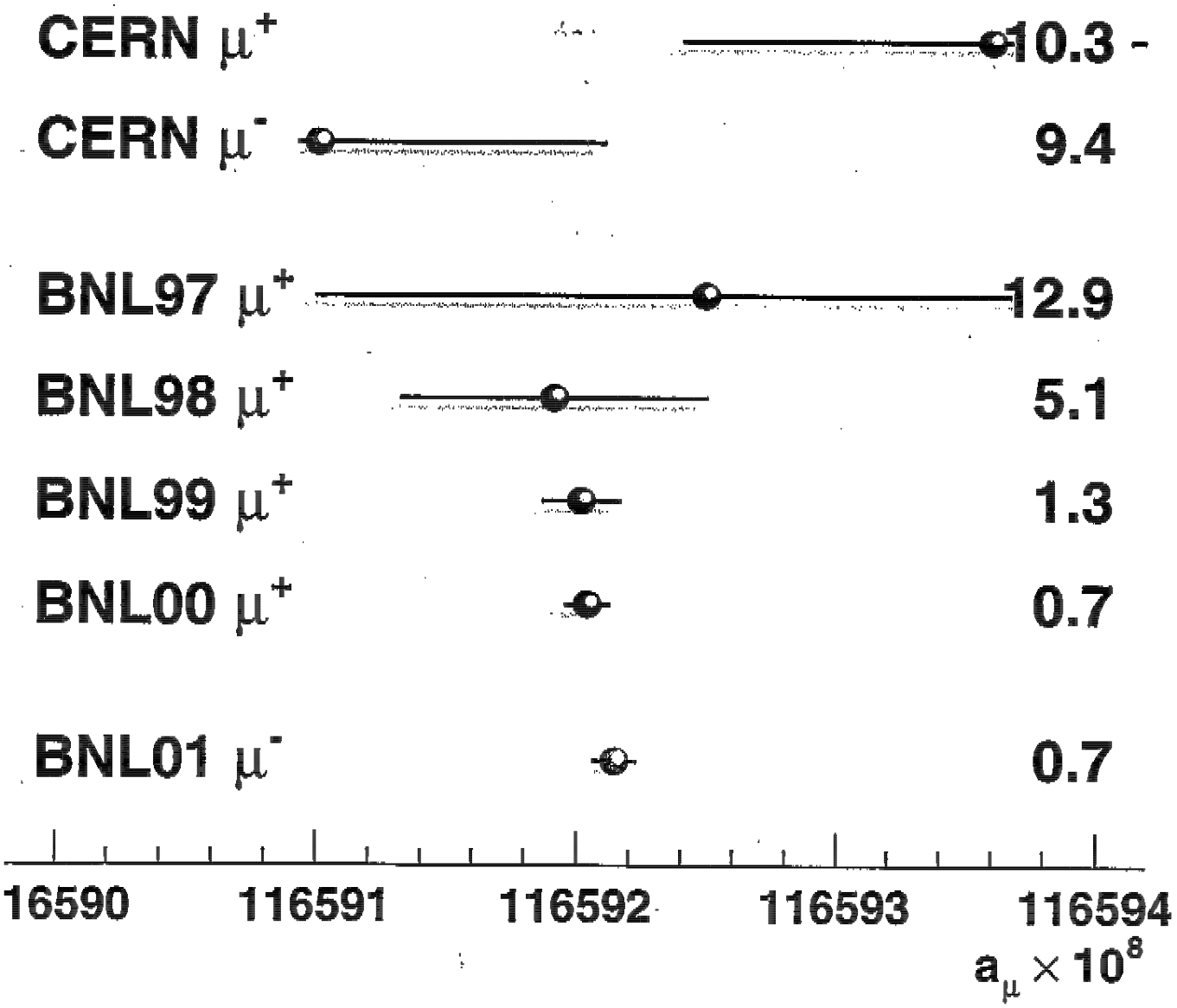
CERN μ+
10.3
CERN μ-
9.4
BNL97 μ+
12.9
BNL98 μ+
5.1
BNL99 μ+
1.3
BNL00 μ+
0.7
BNL01 μ-
0.7
16590
116591
116592
116593
116594
a_μ × 10^8

Compare $R = \dfrac{\omega_a}{\omega_p}$

$R_{\mu^+} = 0.0037072048(25)$ $\qquad$ $R_{\mu^-} = 0.0037072083(26)$

$$\epsilon = \frac{R_{\mu^+} - R_{\mu^-}}{\frac{1}{2}\left(R_{\mu^+} + R_{\mu^-}\right)} = (-9.4 \pm 9.7) \times 10^{-7}$$

$$a_\mu = 11\,659\,208(6) \times 10^{-10}\ [0.5\ \text{ppm}]$$

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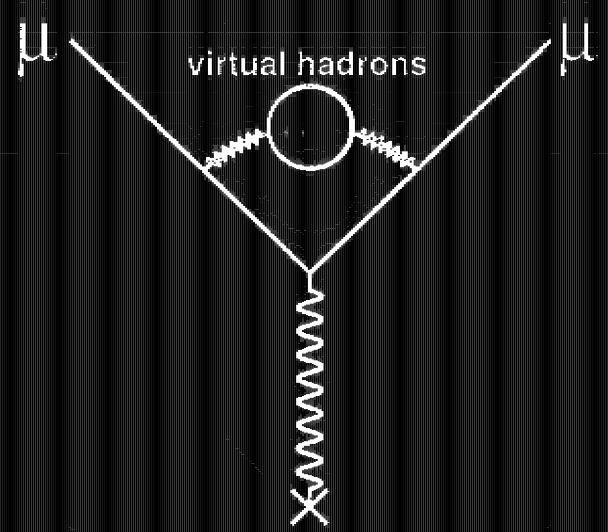
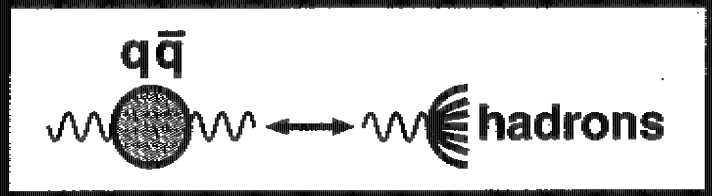


$$a_\mu = a_\mu^{qed} + \qquad +$$

δa : $0.03\,ppm$: :

Low-energy QCD is nonperturbative, so this contribution cannot be calculated reliably from first principles $\Rightarrow$ fortunately data can help ...

electron-positron annihilation



$$R(s) = \frac{\sigma(e^+e^- \to hadrons)}{\sigma(e^+e^- \to \mu^+\mu^-)}$$

$$a_\mu^{had,1} \propto \int_{(2m_\pi)^2}^{\infty} ds \; \frac{K(s)}{s} R(s)$$

$$a_\mu^{had,1} = 696 \; (7.0) \times 10^{-10} (59.7 \pm 0.6\text{ppm})$$

M. Davier, S. Eidelman, A. Höcker and Z. Zhang, Eur. Phys. J. **C31, 503 (2003)**

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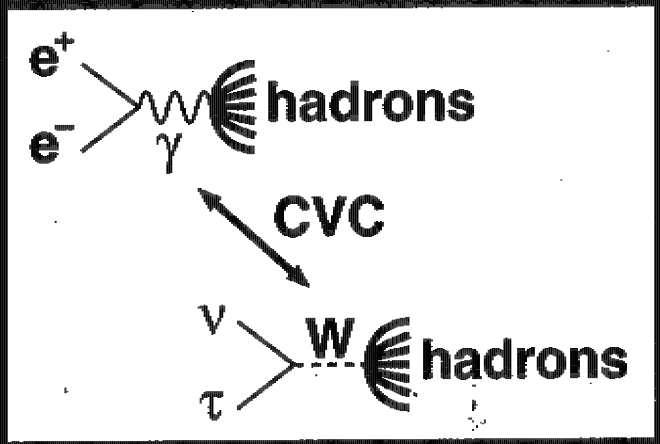
Assume exact isospin symmetry; from CVC:



$$a_\mu^{had,1} = \begin{cases} (696.3 \pm 6.2_{\text{exp}} \pm 3.6_{\text{rad}}) \times 10^{-10} & [e^+e^-] \\ (711.0 \pm 5.0_{\text{exp}} \pm 0.8_{\text{rad}} \pm 2.8_{\text{SU(2)}}) \times 10^{-10} & [\tau] \end{cases}$$

M. Davier, S. Eidelman, A. Höcker and Z. Zhang, Eur. Phys. J. **C31, 503**
S. Ghozzi and F. Jegerlehner, hep-ph/0310181

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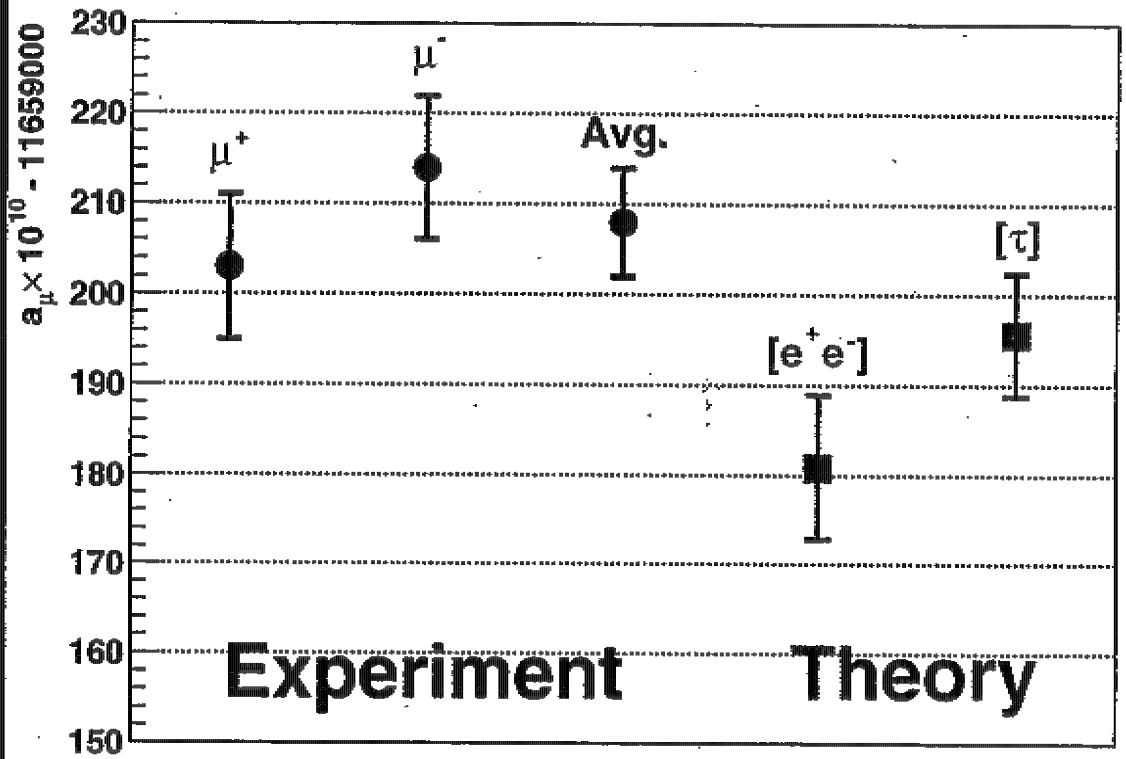
Comparison to theory



$$a_\mu^{exp} = 11\,659\,208(6) \times 10^{-10}$$
$$a_\mu^{th;ee} = 11\,659\,181(8) \times 10^{-10} \quad \Delta a = 2.7\sigma$$
$$a_\mu^{th;\tau} = 11\,659\,196(7) \times 10^{-10} \quad \Delta a = 1.4\sigma$$

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Conclusions and Outlook

New measurement of $a_\mu^- = 11\,659\,214\,(8)(3) \times 10^{-10}$ (0.7 ppm)

Results for a_{μ^-} and a_{μ^+} are statistically compatible

Average anomaly $a_\mu = (11659208 \pm 6) \times 10^{-10}$ (0.5ppm)

$a_\mu^{EXP} - a_\mu^{SM}$ either 1.4σ (τ) or 2.7σ (e^+e^-)

There is (a lot) more e^+e^- data coming

There are attempts to get a_μ^{had} from lattice QCD.

Experiment still statistics limited ....

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