Measurement of the Muon Anomalous Magnetic Moment to 0.7 ppm at BNL

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on behalf of the g-2 Collaboration

Results from the Data of 2000

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Outline

- Motivation of BNL g-2 Experiment
- Method
- Experiment
- 2000 Data Analysis
- Results and Summary

Motivation of BNL g-2 Experiment

- Precision Test of the Standard Model

  ElectroWeak Contributions
  Muon Substructure,
  W Compositeness and Anomalous
  Couplings, etc...

- Probe Physics Beyond the Standard Model

  Supersymmetry, etc..

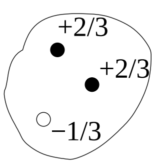
g-factor

A particle with spin has a magnetic moment :

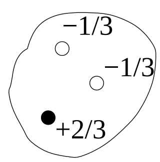
$$\vec{\mu} \;=\; \mathbf{g}\frac{e\hbar}{2mc}\;\vec{\mathbf{S}}$$

1930's : For Point particles with spin $\frac{1}{2}$, **g=2** (Dirac)

Hadrons:



$g_p \approx$ 5.586



$g_n \approx$ -3.826

Leptons: g=2 ?

1940's : $g_e \approx$2.002 (Lamb shift), later on $g_\mu \approx$2.002

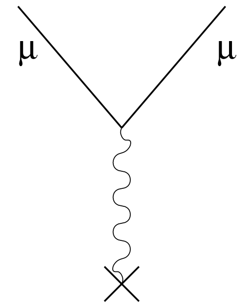
Anomalous magnetic moment : $a = \frac{g-2}{2}$

$g \neq$2 (QED) $\qquad a = \frac{\alpha}{2\pi} + ...$

Forces

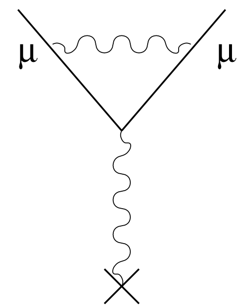
Dirac Particles

$g = 2$



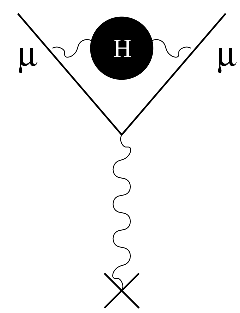
Electromagnetic (QED)

$\Delta g = 0.00233169411(6)$



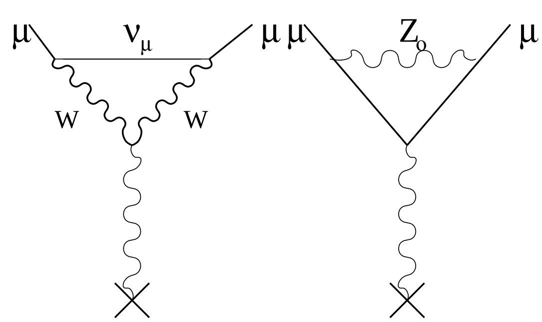
Strong Force (Hadronic)

$\Delta g = 0.00000013818(70)$

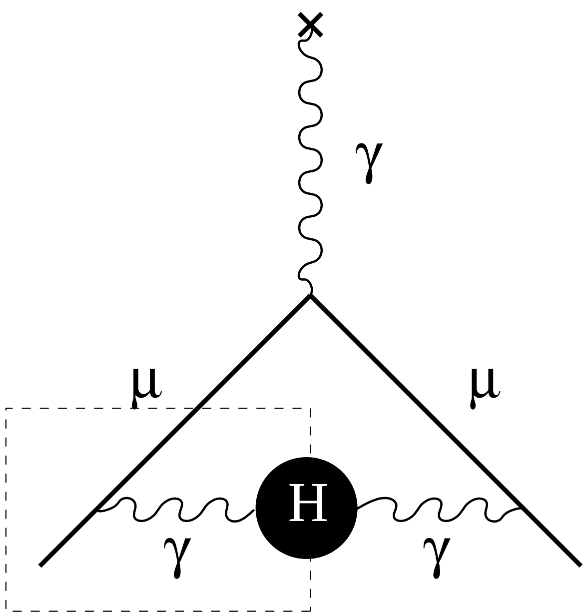


Weak Force

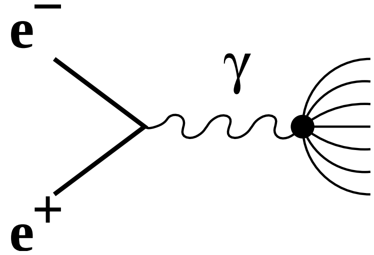
$\Delta g = 0.00000000302(8)$



Hadronic Vacuum Polarization



HADRONIC CONTENT of the PHOTON



Hadronic Contribution

Dispersion Relation :

$$a_\mu^{had} = \frac{\alpha^2(0)}{3\pi^2} \int_{4m_\pi^2}^{\infty} ds \frac{K(s)}{s^2} R(s)$$

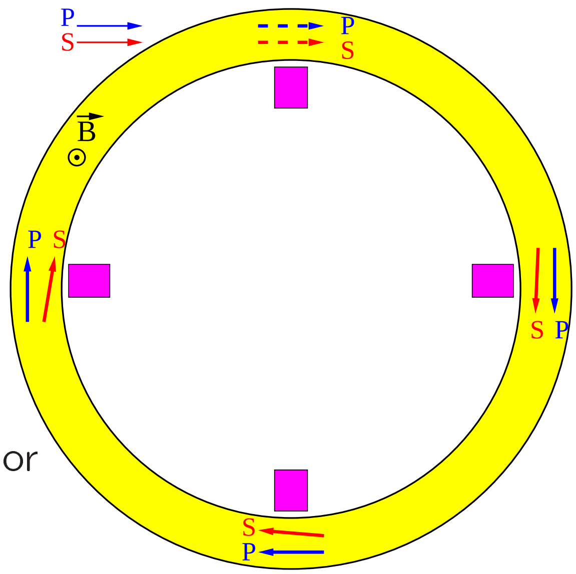
s : square of center of mass energy
K(s) : smooth weight function (0.63-1)
strong weight to low energy
$\sqrt{s} < 1.8$ GeV, 92% of the a_μ)

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

Method

In the presence of the vertical field, **B**
for g=2

$\omega_c = \frac{eB}{m_\mu c\gamma} = \frac{2\mu_B B}{\hbar\gamma}$ $\quad \omega_c = \omega_s$



Due to anomaly on the magnetic moment,
Spin precess faster than the momentum

$$\omega_s = \frac{eB}{m_\mu c\gamma}(1 + a_\mu\gamma)$$

Spin precession relative to momentum vector

$$\omega_a = \omega_s - \omega_c = \frac{e}{m_\mu c} a_\mu B$$

Plus weak focusing electric field $\vec{E}$:

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

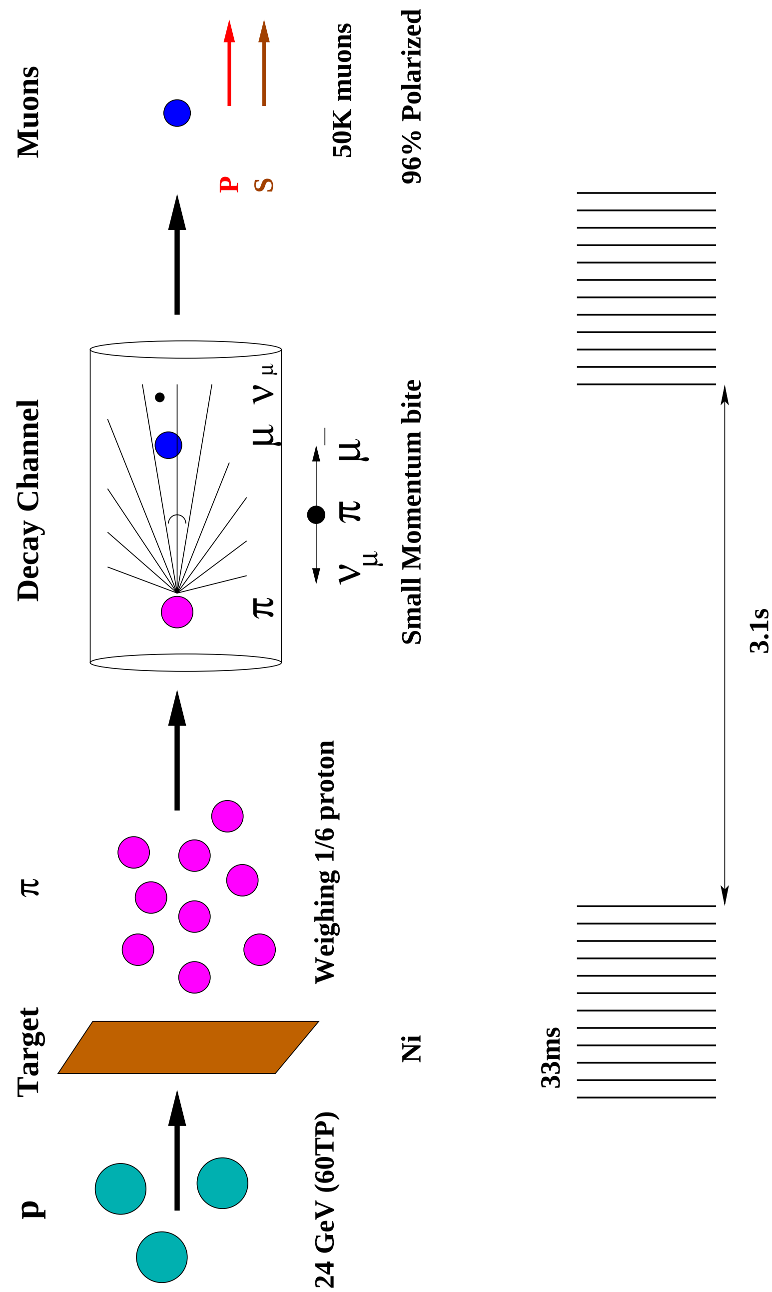
Choose $\gamma = 29.3$, so the contribution of $\vec{\beta} \times \vec{E}$ is removed.
$\Rightarrow P_\mu = 3.1\text{GeV}$

$\Rightarrow$ Measure $|\vec{B}|$ and ω_a and calculate a_μ !

Why This Experiment was Possible

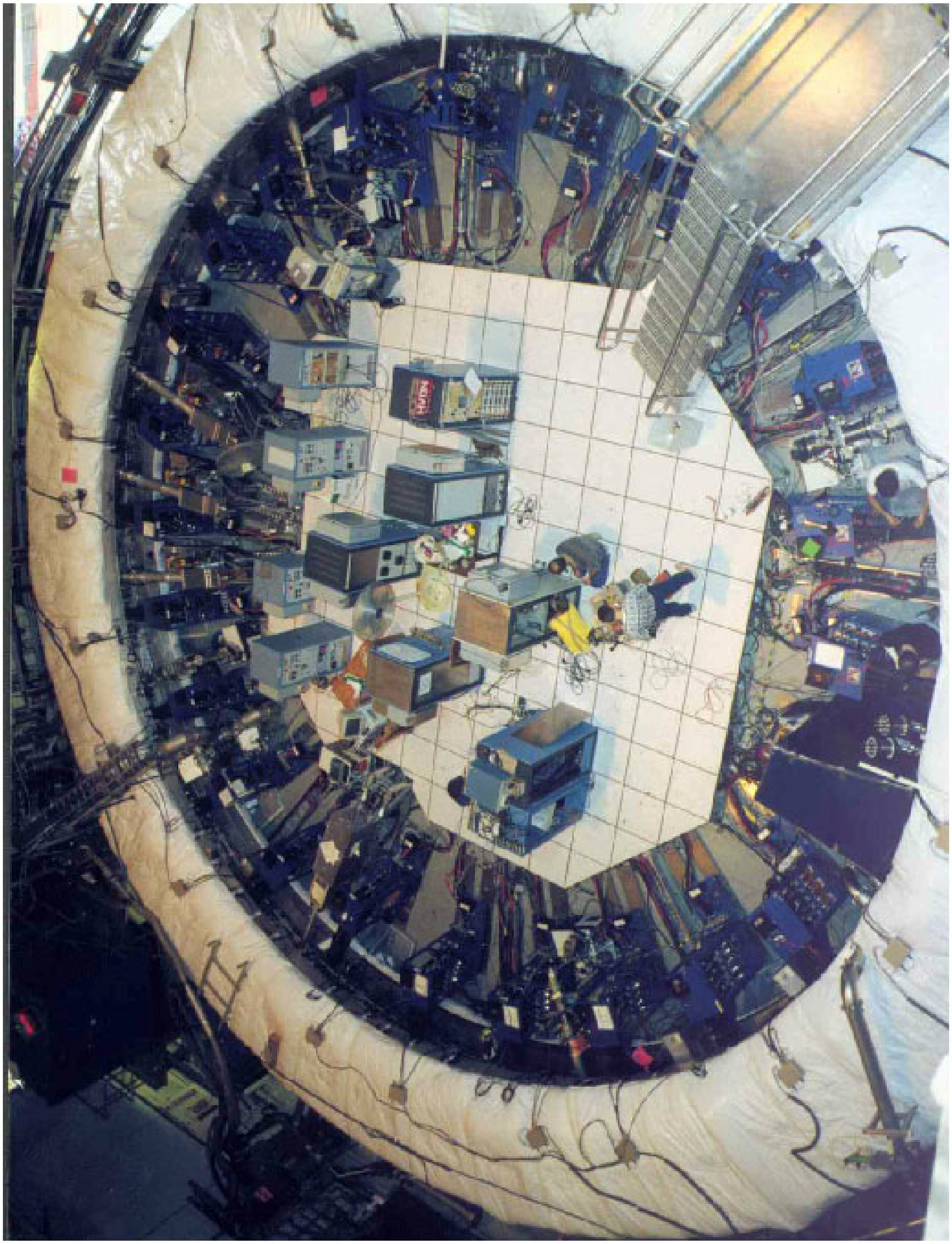
- AGS, the Highest Intensity Proton Source,
- Store Directly Polarized Muons,
- The Largest Single-Coiled Superconducting Magnet (r=7.11m), Provides 1.45T Uniform Magnetic Field.

The Beam



p
Target
π
Decay Channel
Muons
24 GeV (60TP)
Ni
Weighing 1/6 proton
Small Momentum bite
50K muons
96% Polarized
P
S
33ms
3.1s

The g-2 Ring

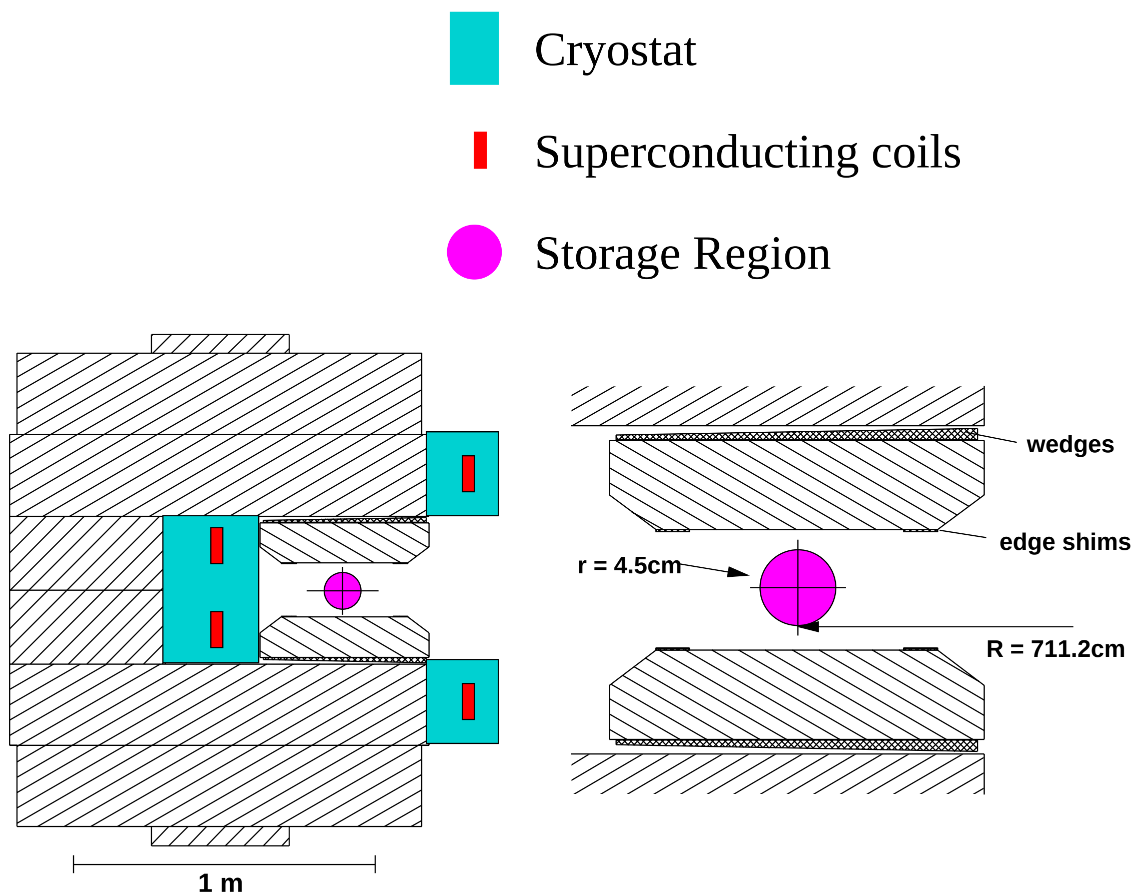


Magnet

1.45 Tesla uniform field

7.112m radius

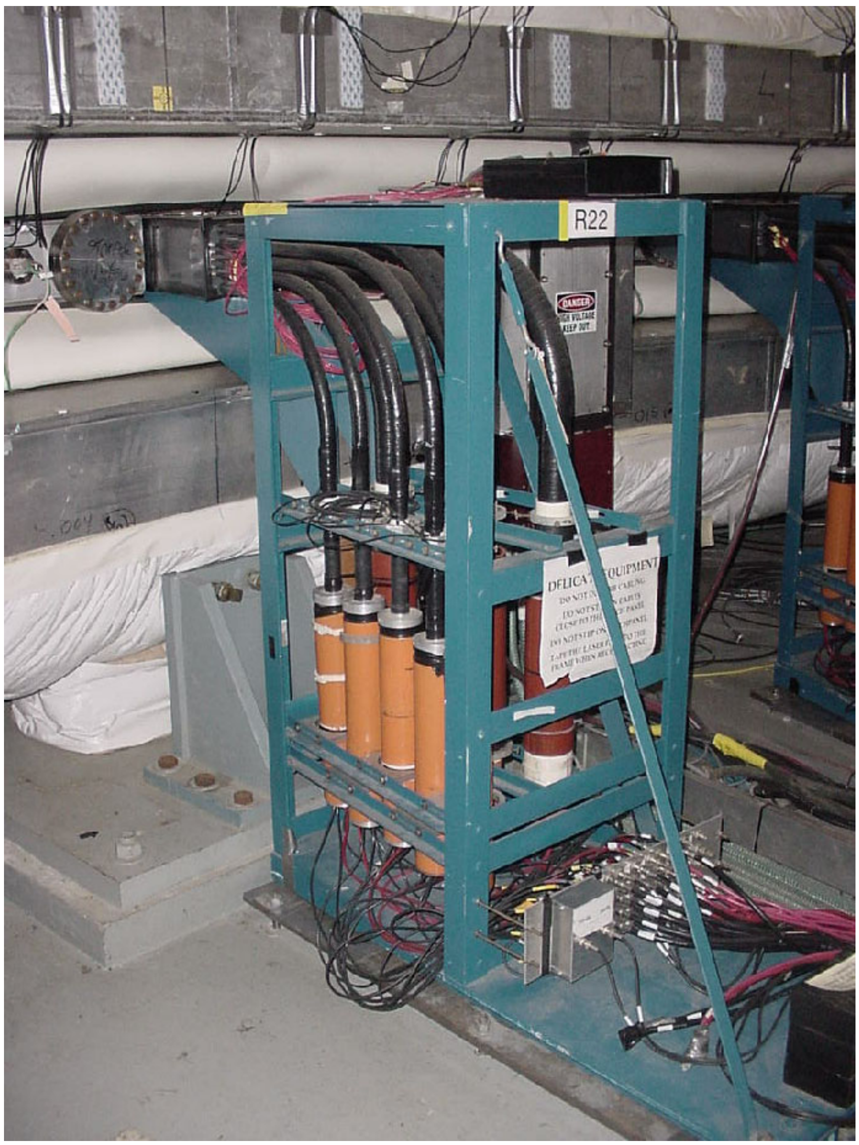
700 Ton



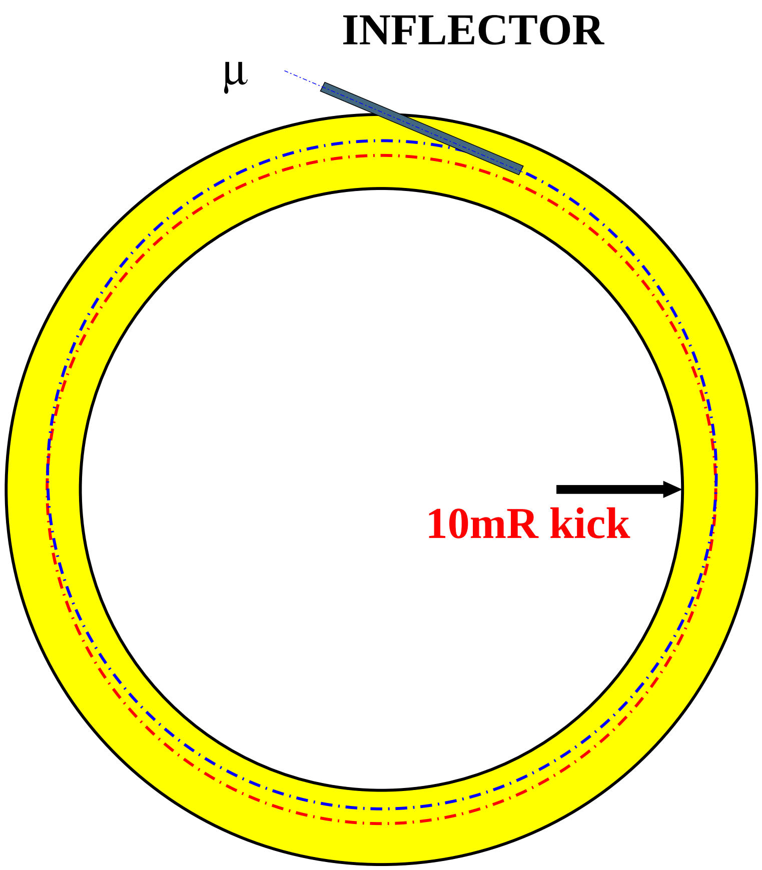
Detectors

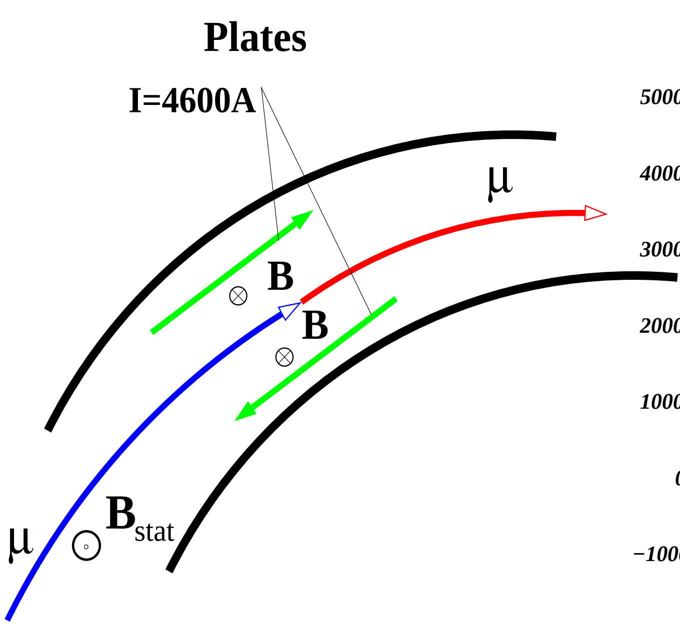
24 Pb/Scintillating fiber electromagnetic calorimeters

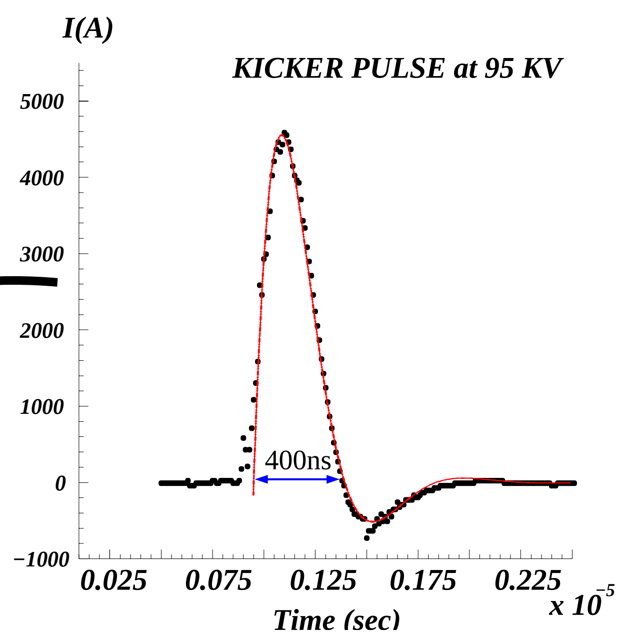
Energy resolution of $\sigma \approx 10\%\sqrt{E(GeV)}$



Inflector and Muon Kicker

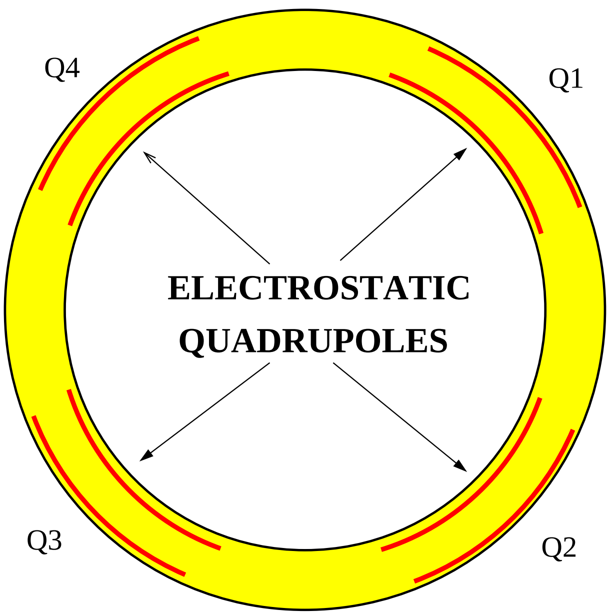




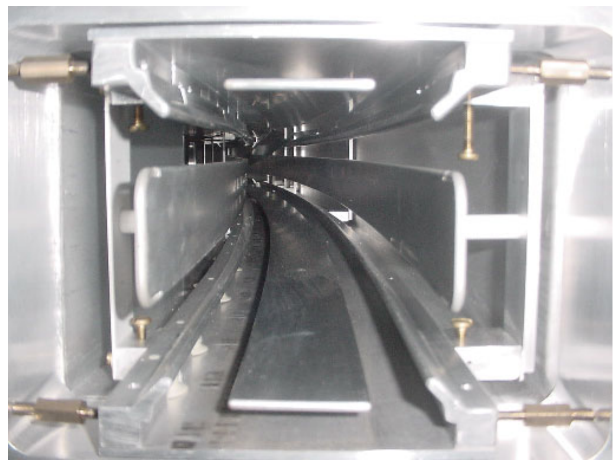


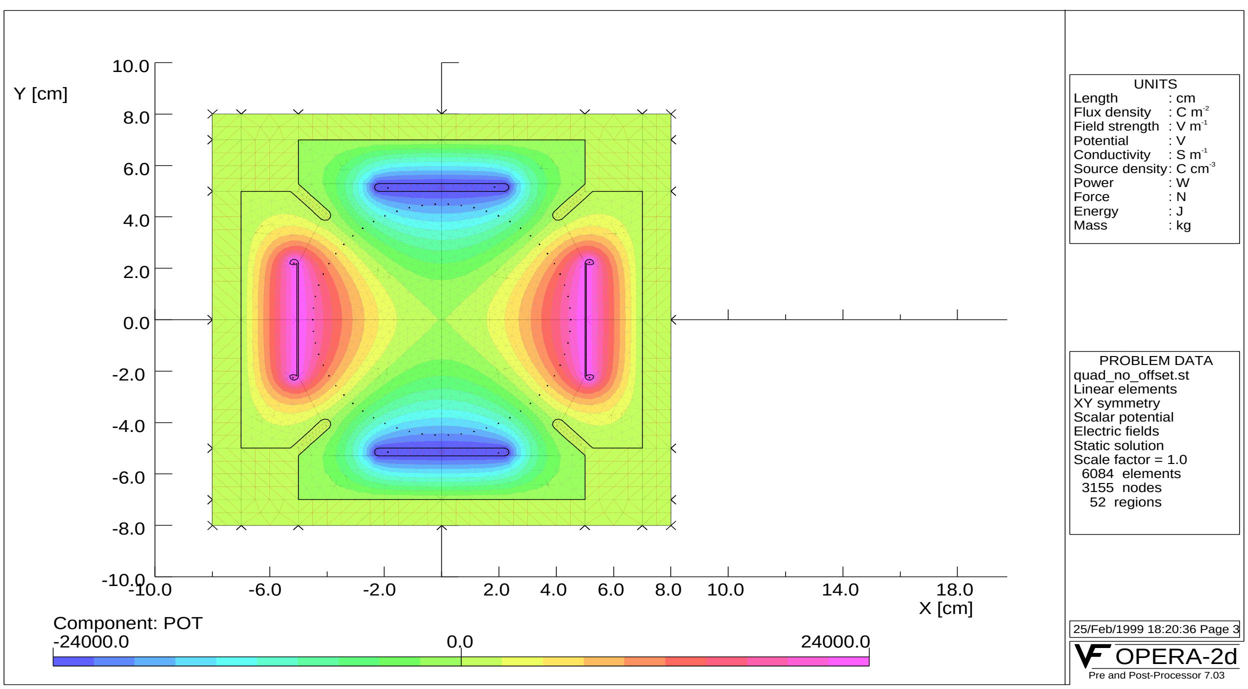
Electrostatic Quadrupoles

The Weak Focusing Provided by



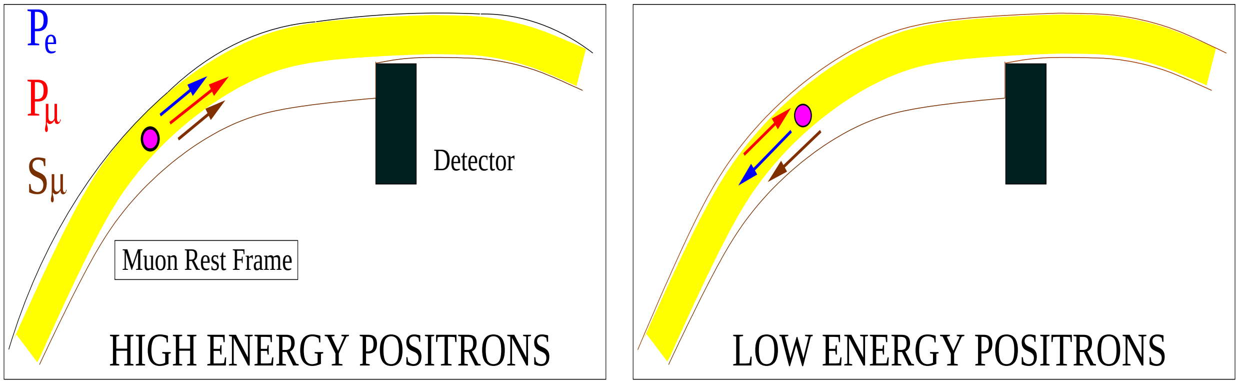
43% of circuference of the Ring





Measurement of ω_a

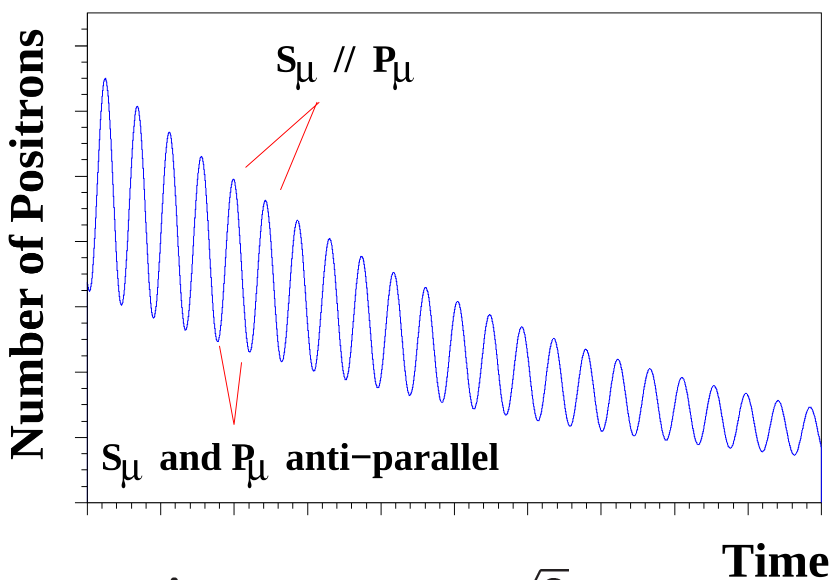
Parity violating 3 body decay : $\mu^+ \to e^+ \ \nu_e \ \bar{\nu}_\mu$



S_μ is precessing in the field $\to$ e^+ counting rate is modulated with the μ spin precession

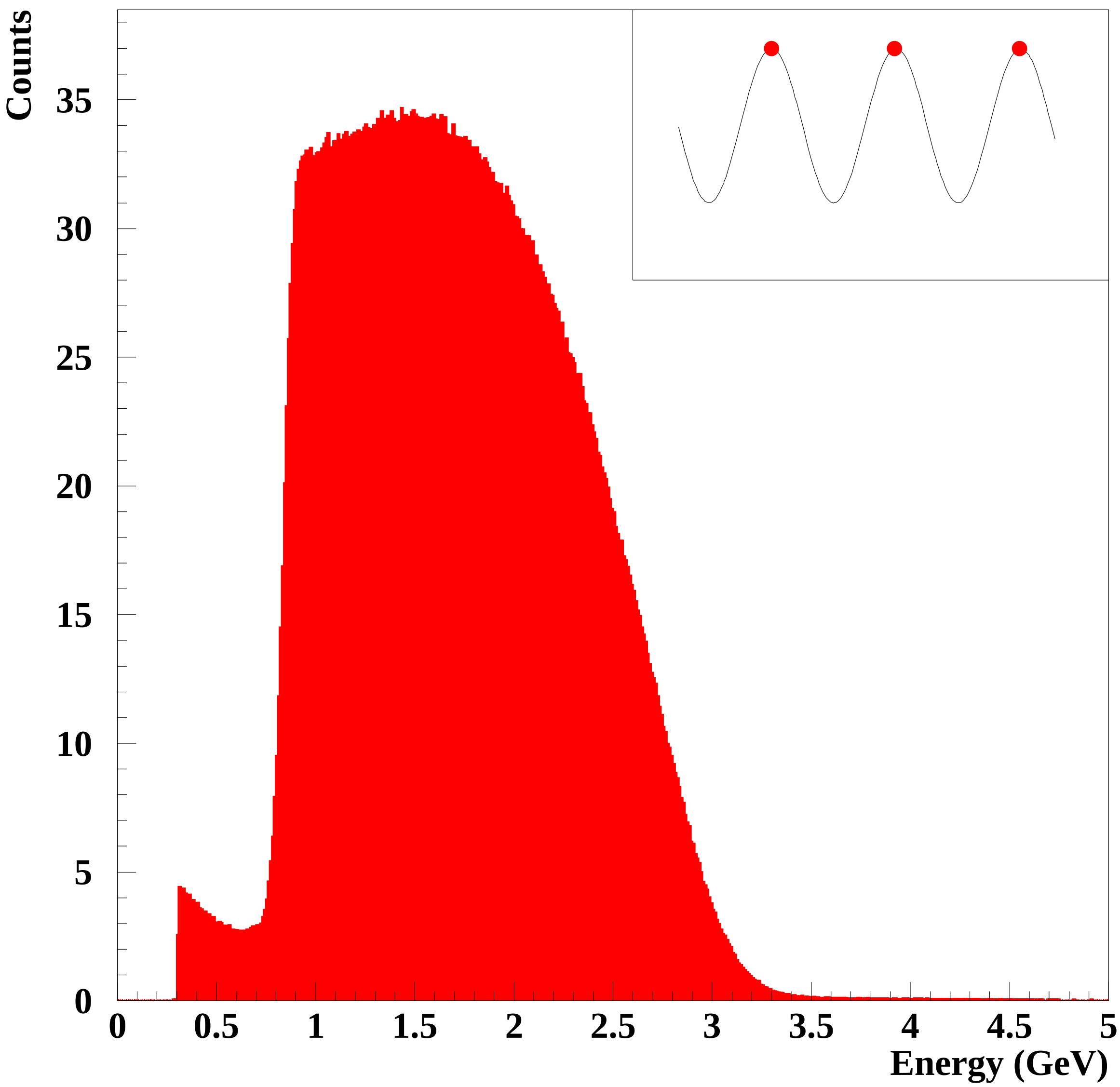
Decay Positron Spectrum :

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

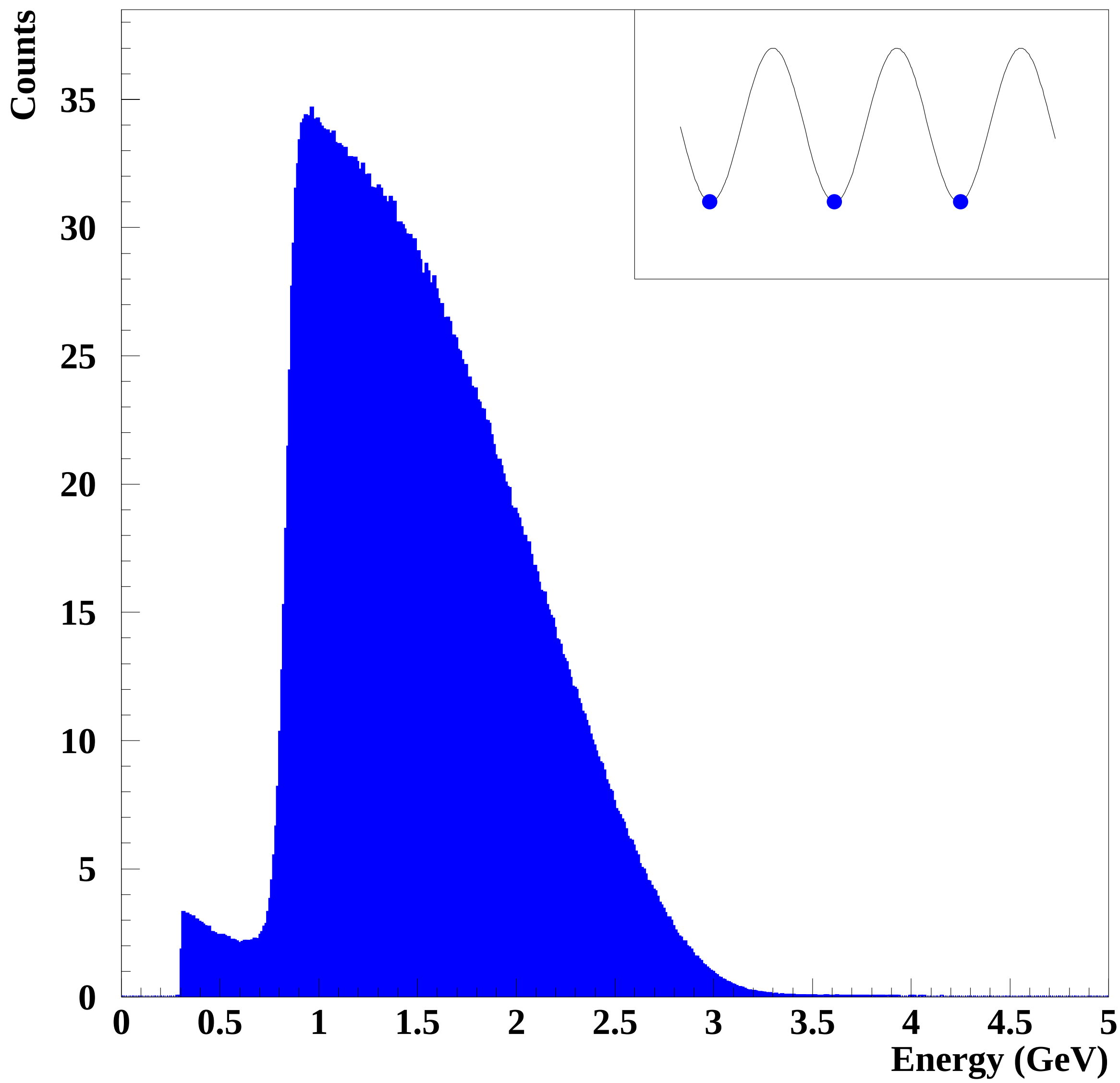


$$\frac{\Delta\omega_a}{\omega_a} = \frac{\sqrt{2}}{A\omega_a\gamma\tau\sqrt{N(E)}}$$

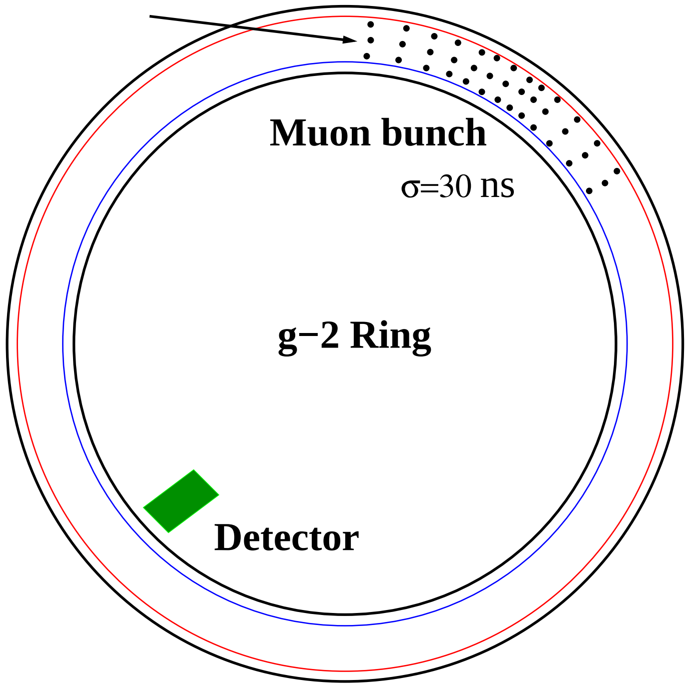
Energy Spectrum

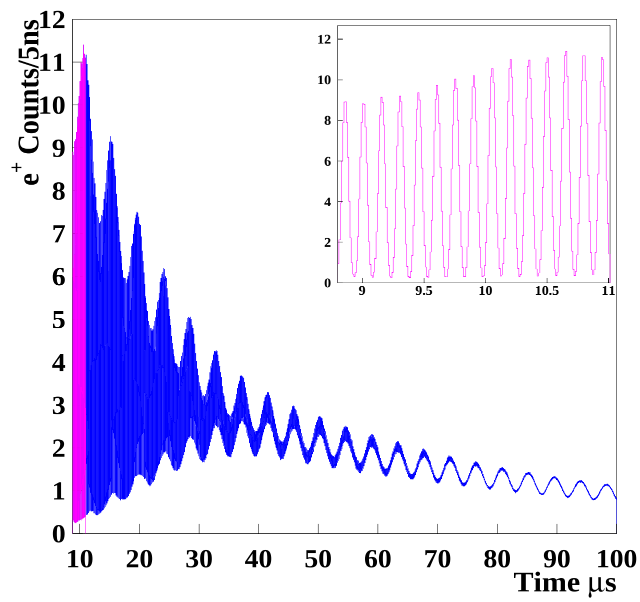


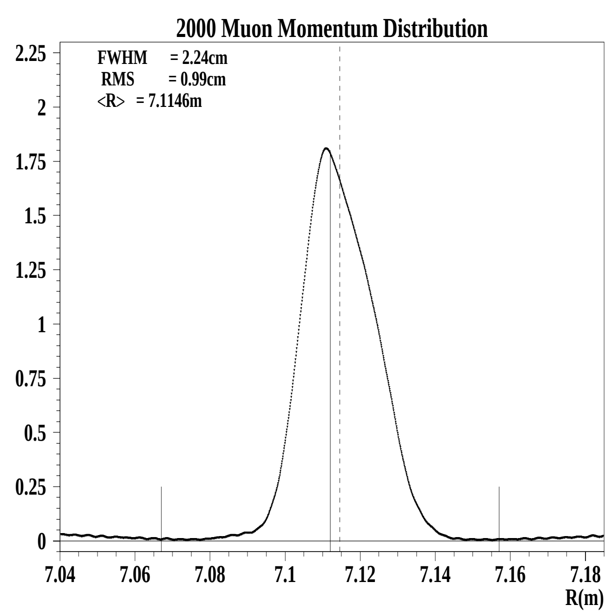
Energy Spectrum



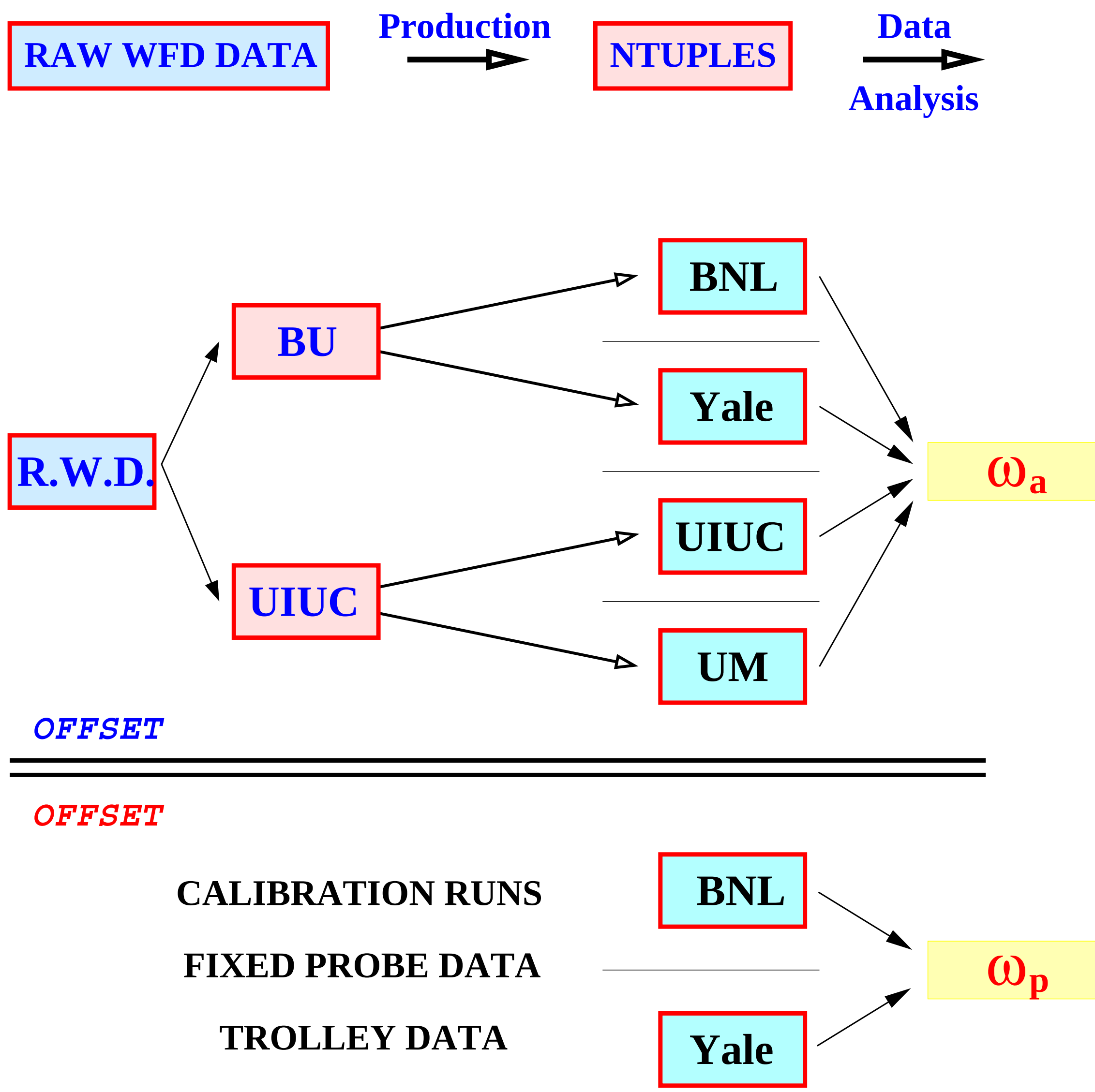
Fast Rotation







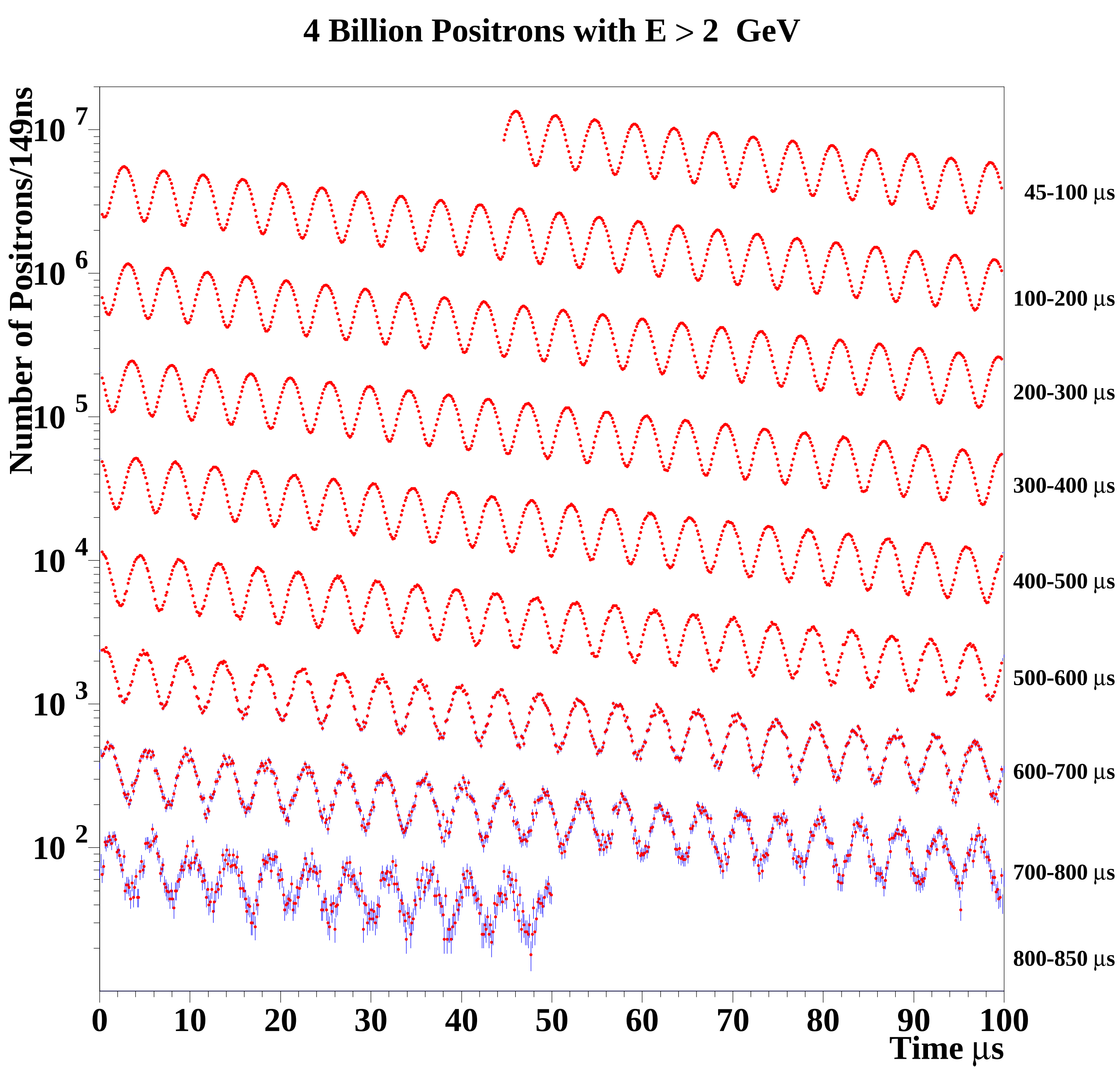
Analysis of the 2000 Data



$$a_\mu = \frac{\frac{\omega_a}{\omega_p}}{\lambda - \frac{\omega_a}{\omega_p}} \qquad \lambda = \frac{\mu_\mu}{\mu_p} = 3.183\,345\,39(10)^*$$

* W. Liu et al. Phys. Rev. Lett. **82**, 711 (1999);
D. E. Groom et al. Eur. Phys. J. **C15**, 1 (2000).

2000 Data


4 Billion Positrons with E > 2 GeV
Number of Positrons/149ns
10 7
10 6
10 5
10 4
10 3
10 2
0
10
20
30
40
50
60
70
80
90
100
Time μs
45-100 μs
100-200 μs
200-300 μs
300-400 μs
400-500 μs
500-600 μs
600-700 μs
700-800 μs
800-850 μs

Fitting Function

Ideal Fitting Function :
$dN/dt = N_0\ e^{-t/\tau}\ (1\ +\ A\ cos[\omega_a t\ +\ \phi_a])$

10M e^+/bin requires to include small effects!!
CBO Related Effects :

- $N_0 \to N_0(t)$
- $A \to A(t)$
- $\phi_a \to \phi(t)$

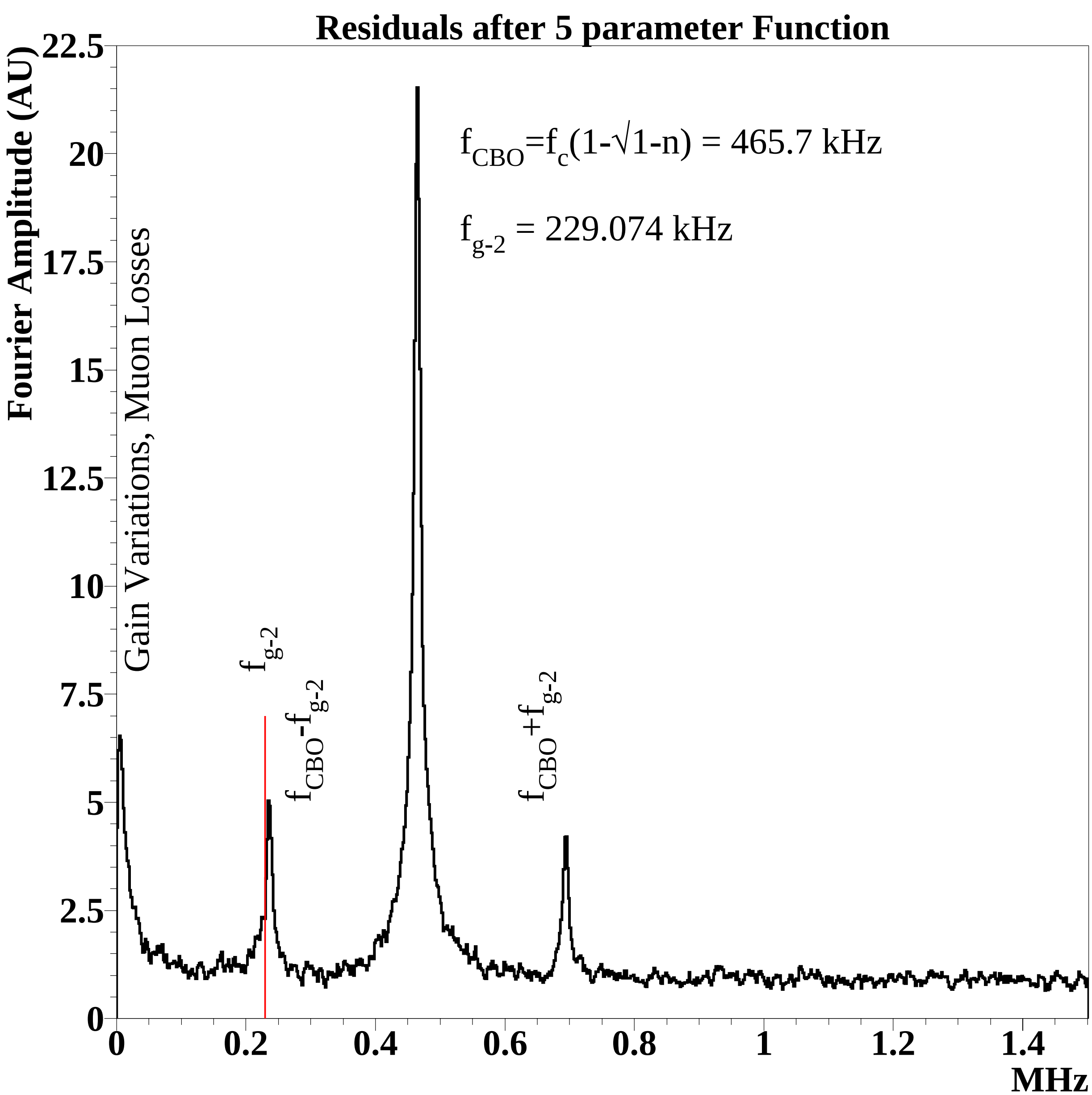
$$N_0(t) \ = \ N_0\{1 + A_N e^{-t/\tau_{cbo}} \ \cos(2\pi f_{cbo} t + \phi_N)\}$$

$$A(t) \ = \ A\{1 + A_A e^{-t/\tau_{cbo}} \ \cos(2\pi f_{cbo} t + \phi_A)\}$$

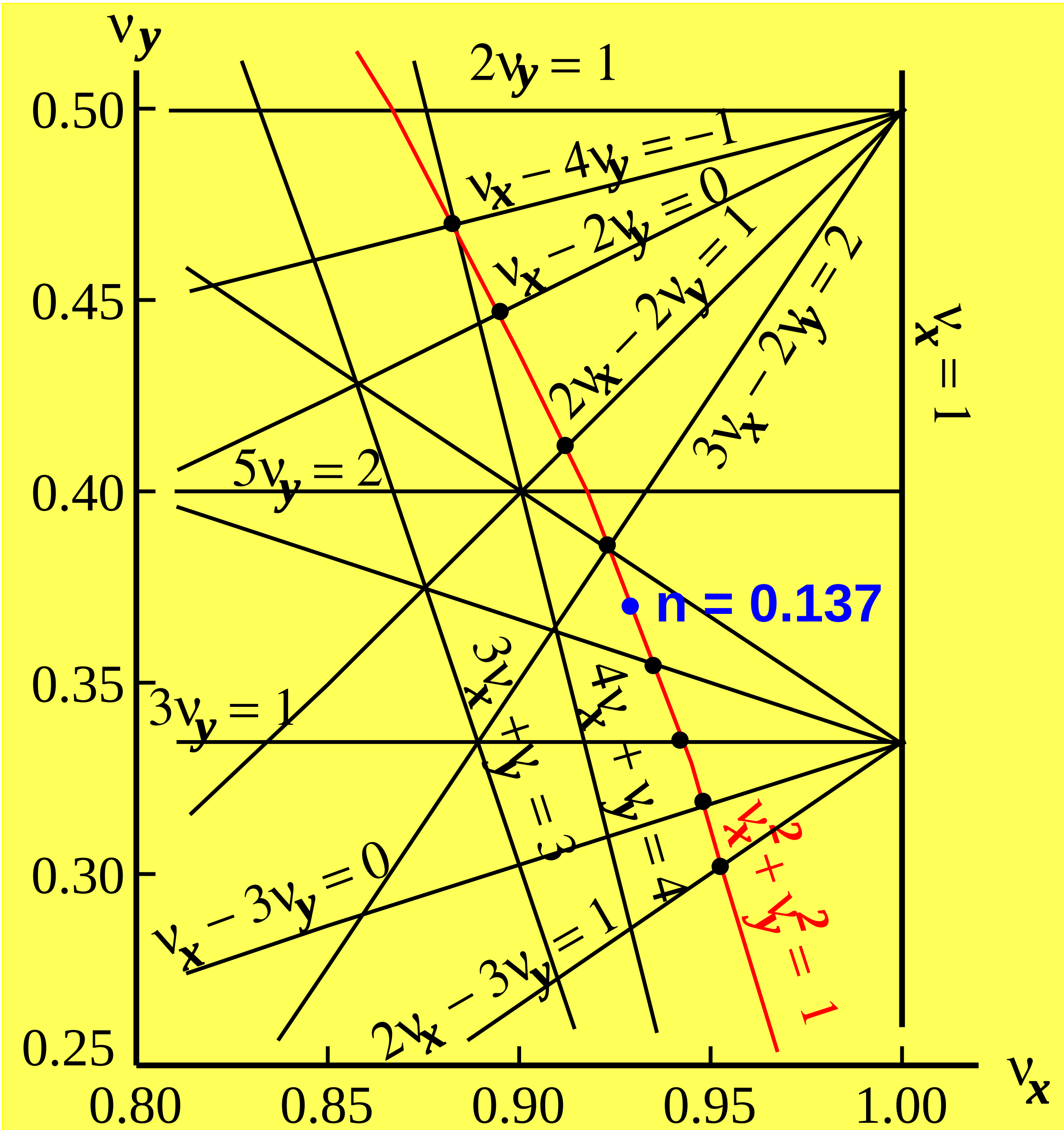
$$\phi_a(t) \ = \ \phi + A_\phi e^{-t/\tau_{cbo}} \ \cos(2\pi f_{cbo} t + \phi_\phi)$$

A_N, A_A and A_ϕ amplitudes are consistent with MC results. ($A_N = 1\%, A_A \approx 0.1\%, A_\phi \approx$ 1mR)

Fourier Analysis

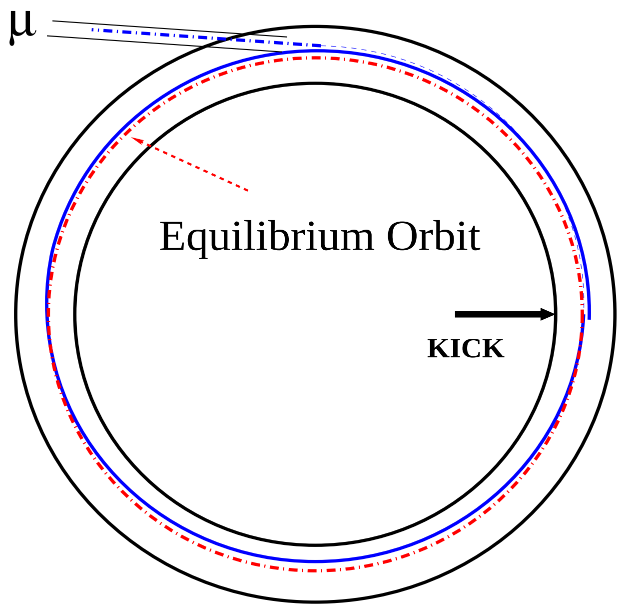


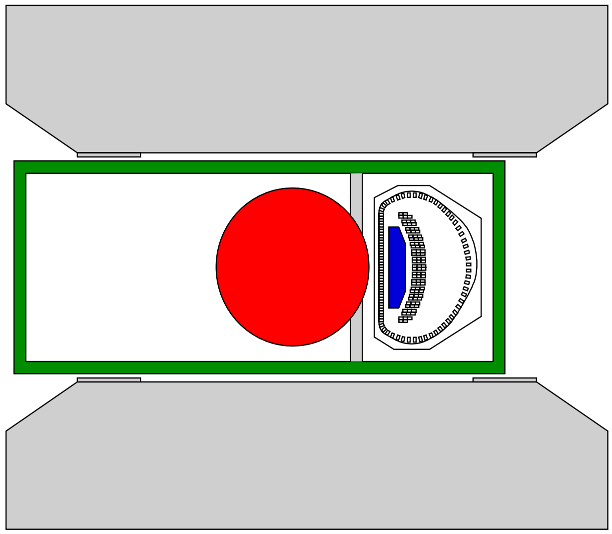
Beam Tune



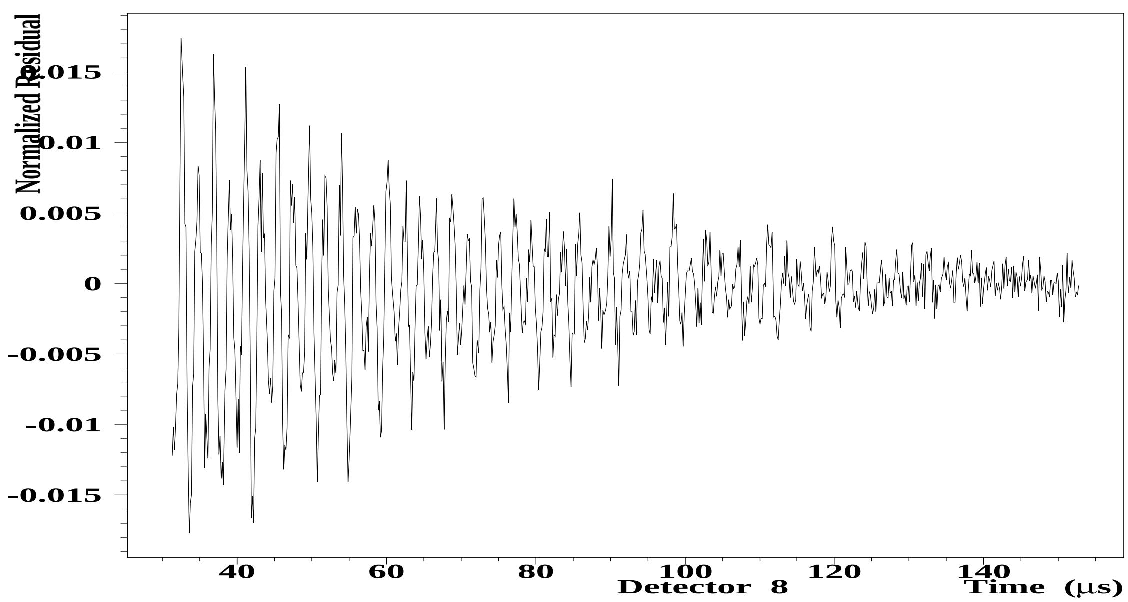
ν_y
$2\nu_y = 1$
$\nu_x - 4\nu_y = -1$
$\nu_x - 2\nu_y = 0$
$2\nu_x - 2\nu_y = 1$
$3\nu_x - 2\nu_y = 2$
$\nu_x = 1$
$5\nu_y = 2$
n = 0.137
$3\nu_y = 1$
$3\nu_x + \nu_y = 3$
$4\nu_x + \nu_y = 4$
$\nu_x^2 + \nu_y^2 = 1$
$\nu_x - 3\nu_y = 0$
$2\nu_x - 3\nu_y = 1$
0.50
0.45
0.40
0.35
0.30
0.25
0.80
0.85
0.90
0.95
1.00
ν_x

CBO(Coherent Betatron Oscillations)

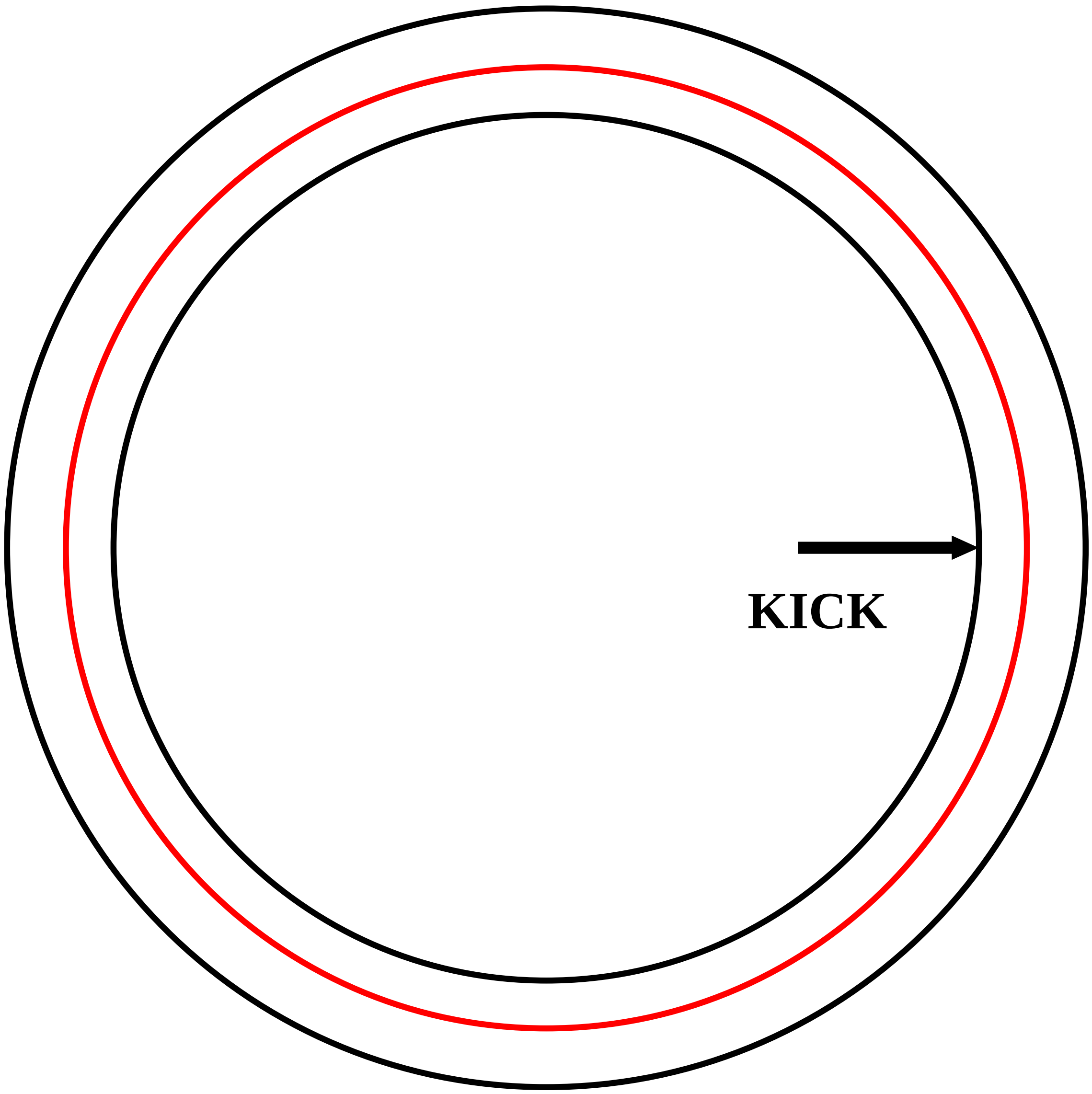


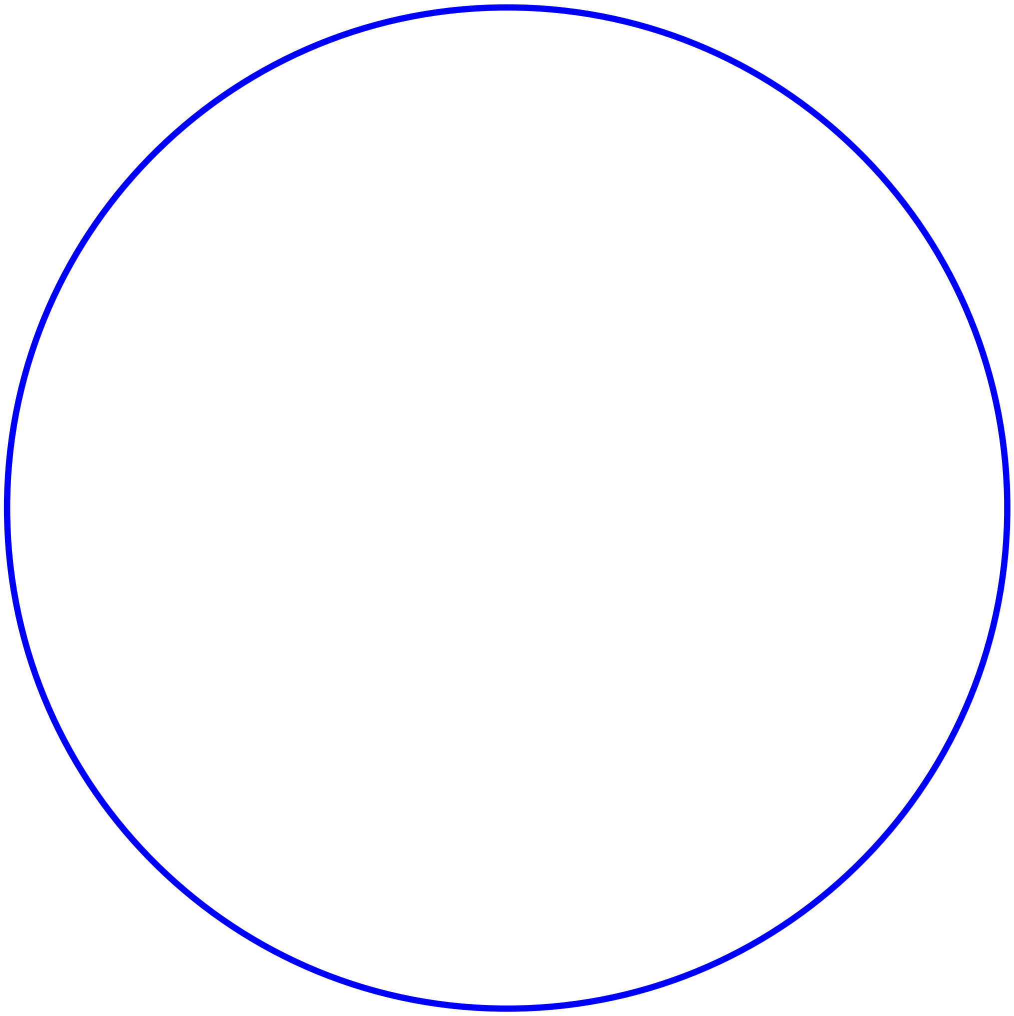


Look at the residuals (DATA - 5 Parameter Fit)
Fourier Analysis of this residual → CBO



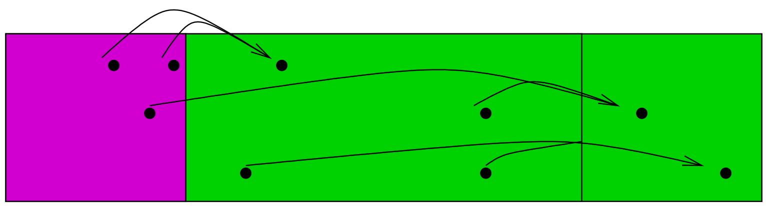
Coherent Betatron Oscillations (CBO)





Pileup

Pileup e^+ carry wrong energy and phase information for g-2



An early to late effect caused by the change on muon intensity (due to decay) and enhanced by the Fast Rotation Factor

It can be accounted for by adding the related terms to the fitting function

$$N_0\ e^{-t/\tau}(1\ +\ A\ \cos(w_a + \phi))\times$$
$$[n_p\ e^{-t/\tau}(1\ +\ A_p\ \cos(w_a + \phi + \phi_{pu}))]$$

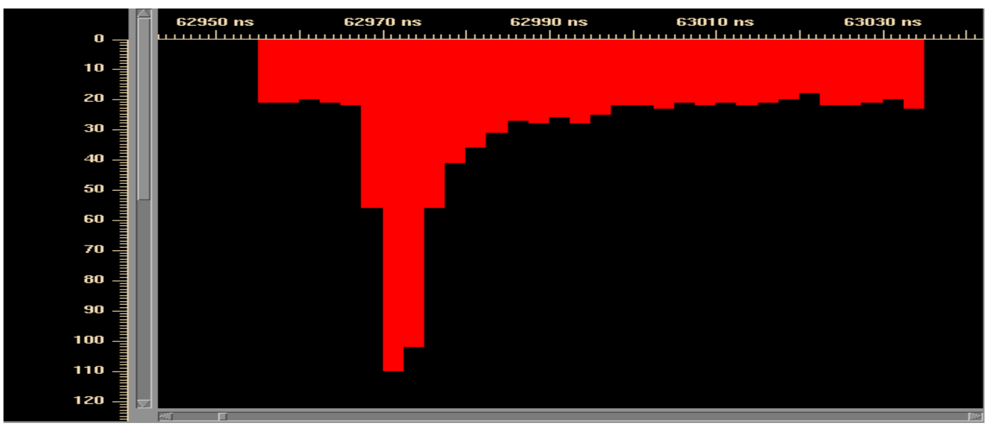
Factor two loss in the statistical error of w_a !

Therefore a different solution to the problem is neccessary

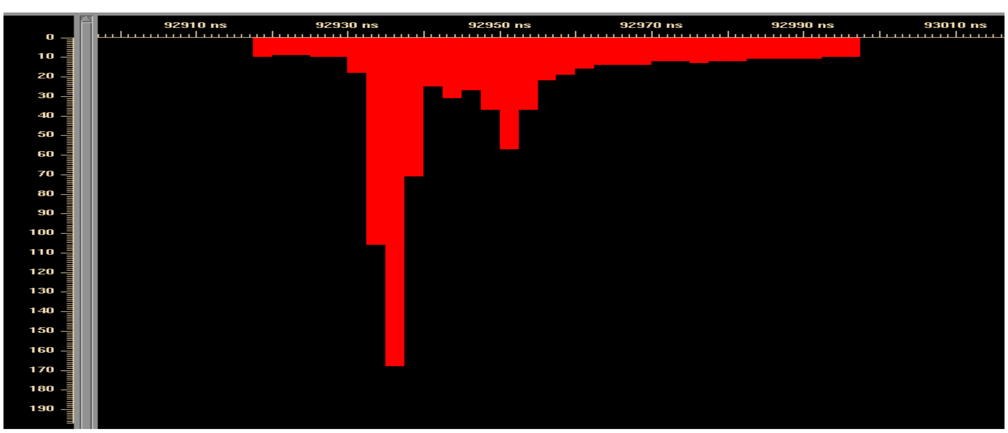
Pileup

Each positron pulse above 1GeV is digitized with a 400MHz WFD

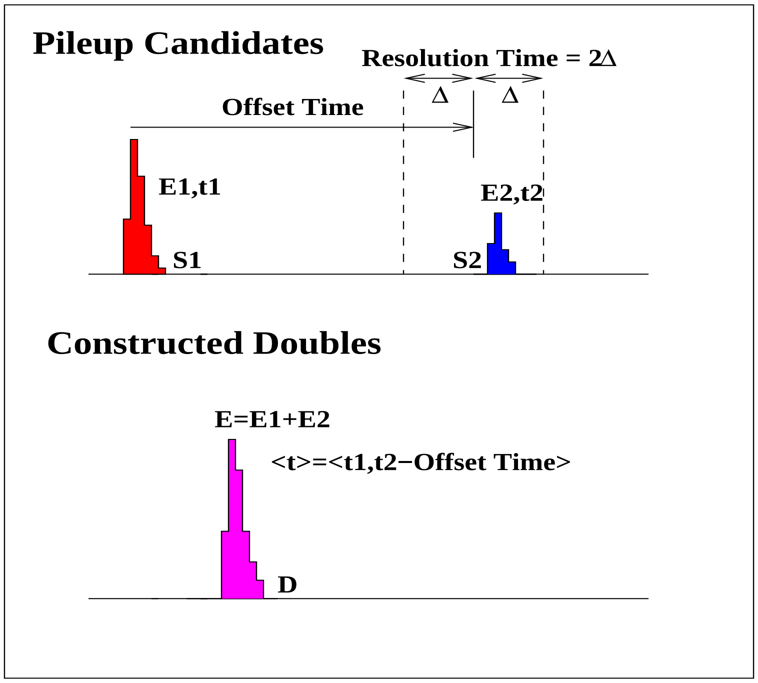
If the pulse height is above the threshold, start digitizing ("WFD Island" ≈ 80ns)



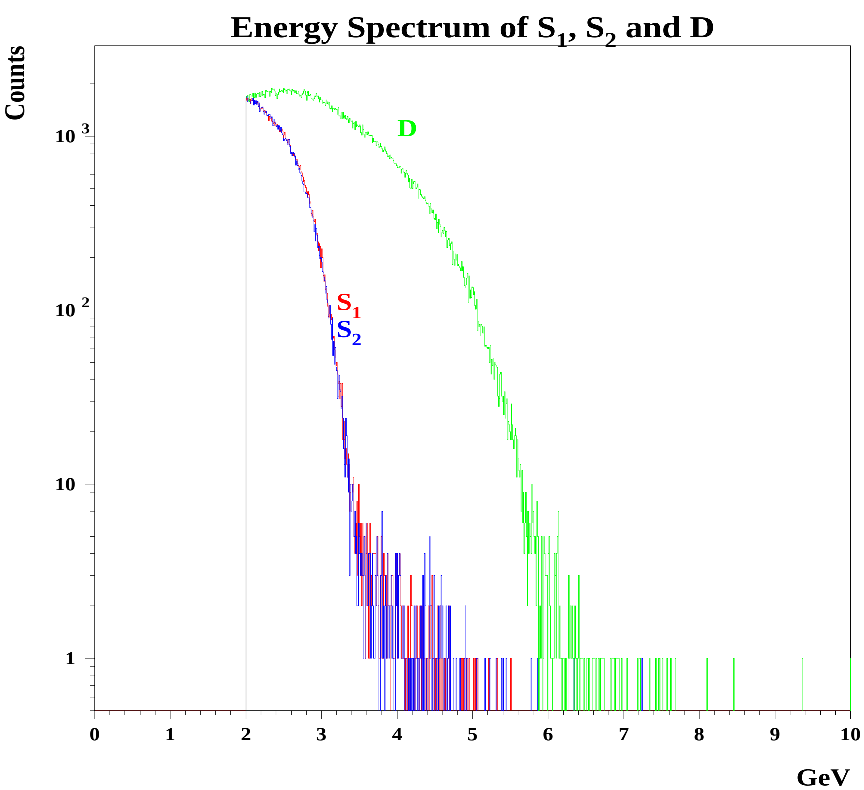
If there are pulses after the main triggering pulse on the same island (shadow pulses).



Pileup



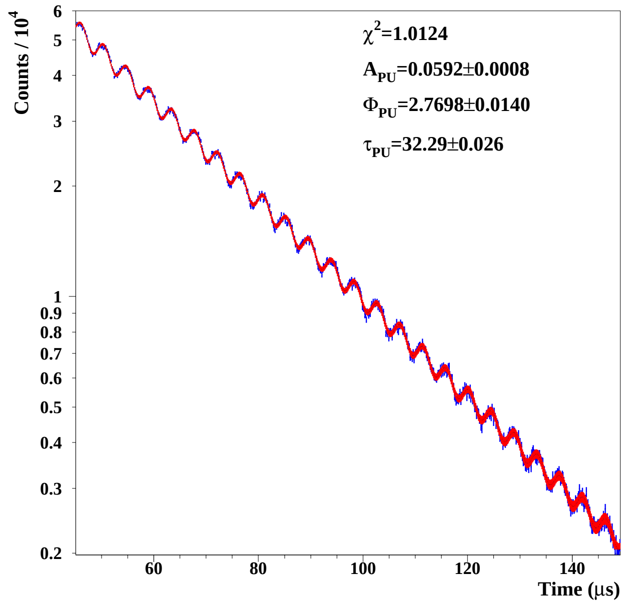
Pileup Candidates
Resolution Time = 2Δ
Δ
Δ
Offset Time
E1,t1
E2,t2
S1
S2
Constructed Doubles
E=E1+E2
<t>=<t1,t2−Offset Time>
D

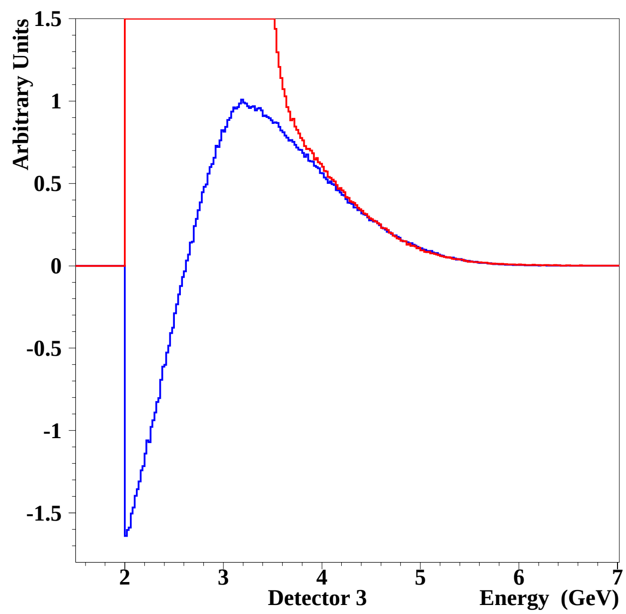


Energy Spectrum of S1, S2 and D
Counts
D
S1
S2
10 3
10 2
10
1
0
1
2
3
4
5
6
7
8
9
10
GeV

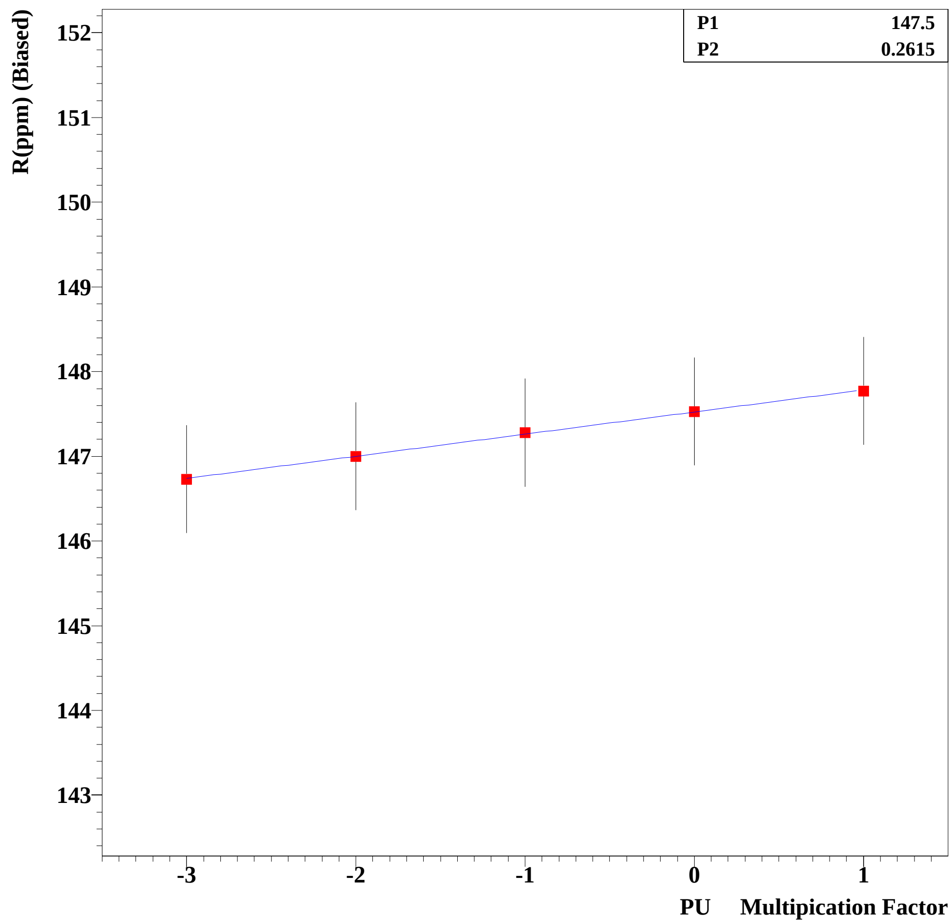
Pileup

Fit to Constructed Pileup $(D - S_1 - S_2)$





Pileup Systematic



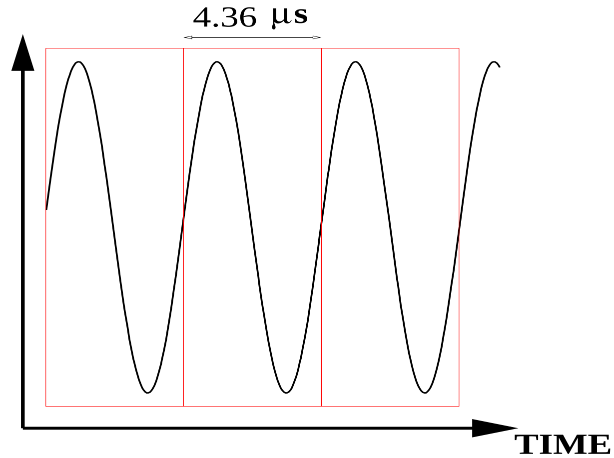
$$Data \times (1 + \lambda \times PU)$$

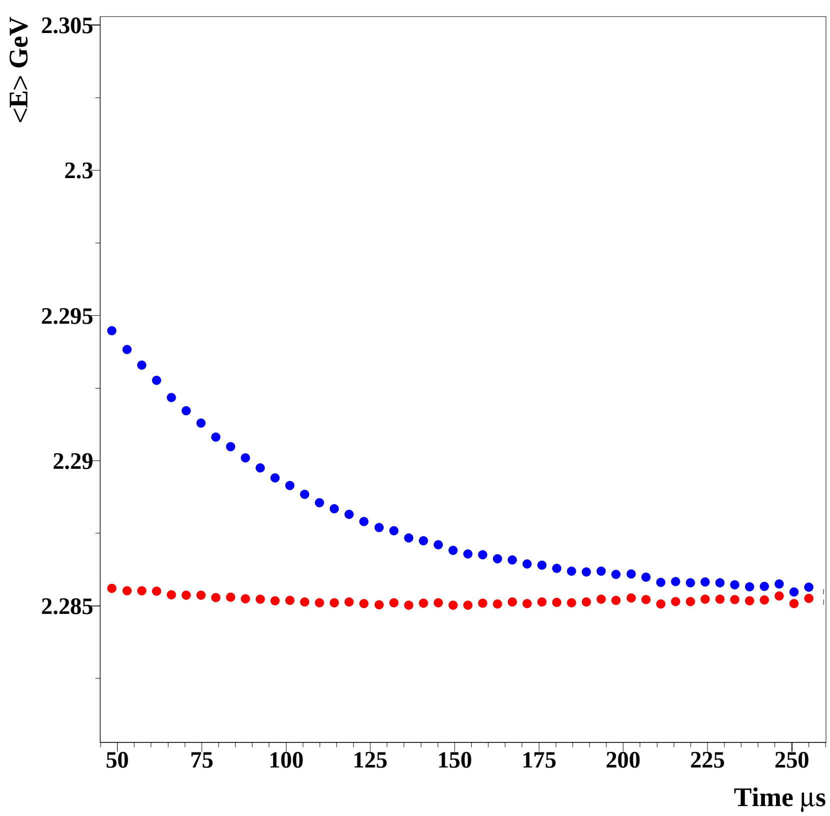
No pileup subtraction $\rightarrow$0.26ppm

Gain Variations

Average Energy

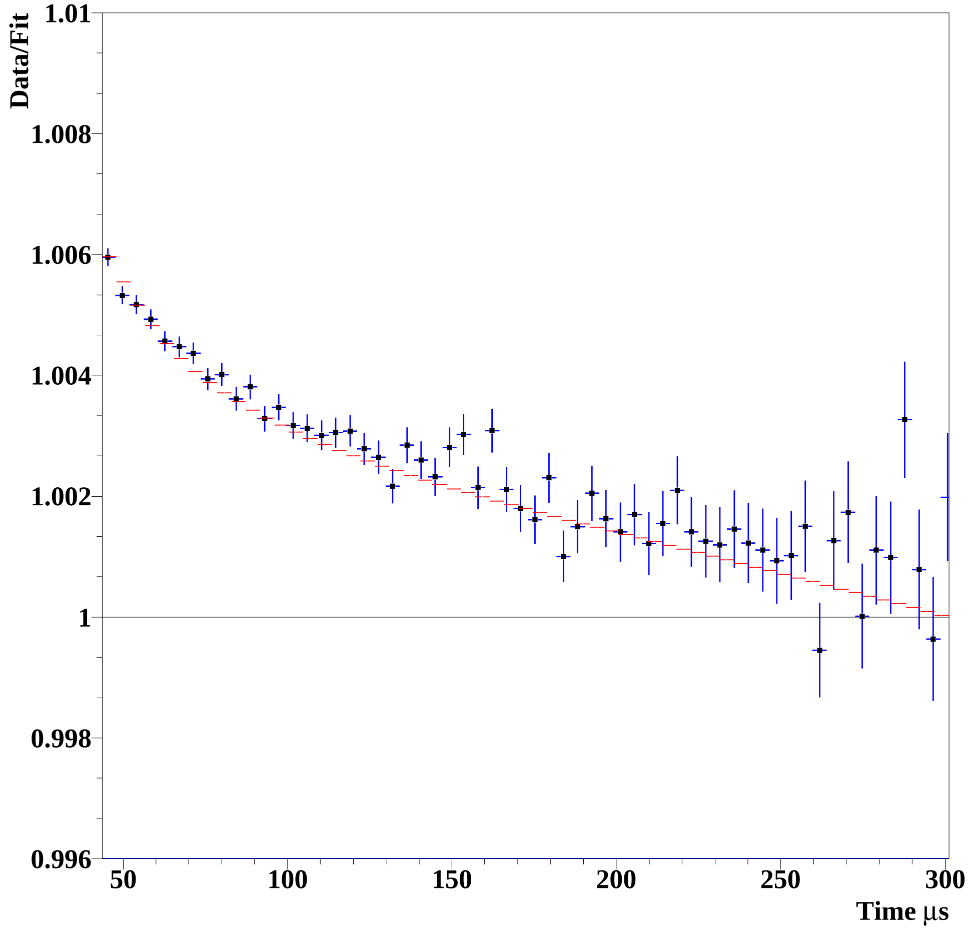
$$\overline{\mathbf{E}} = \frac{\sum_i \mathbf{E_i}\ \mathbf{n_i}}{\sum_i \mathbf{n_i}}$$

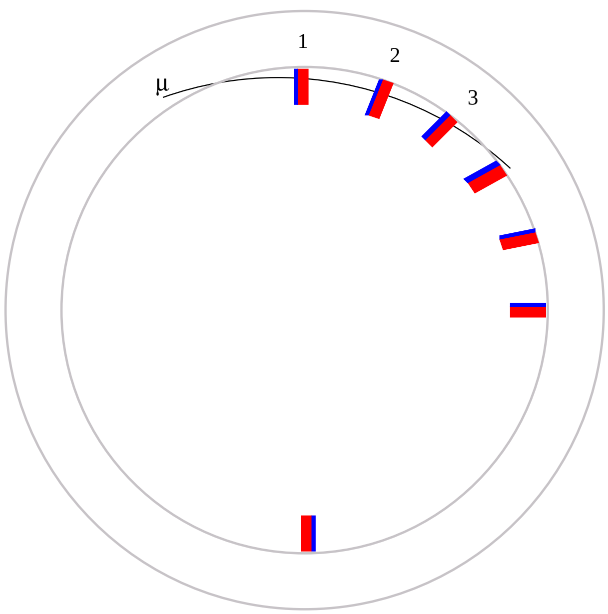




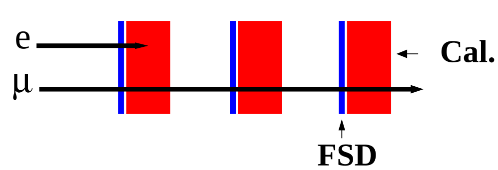
Muon Losses

After Pileup Subtraction and including the CBO

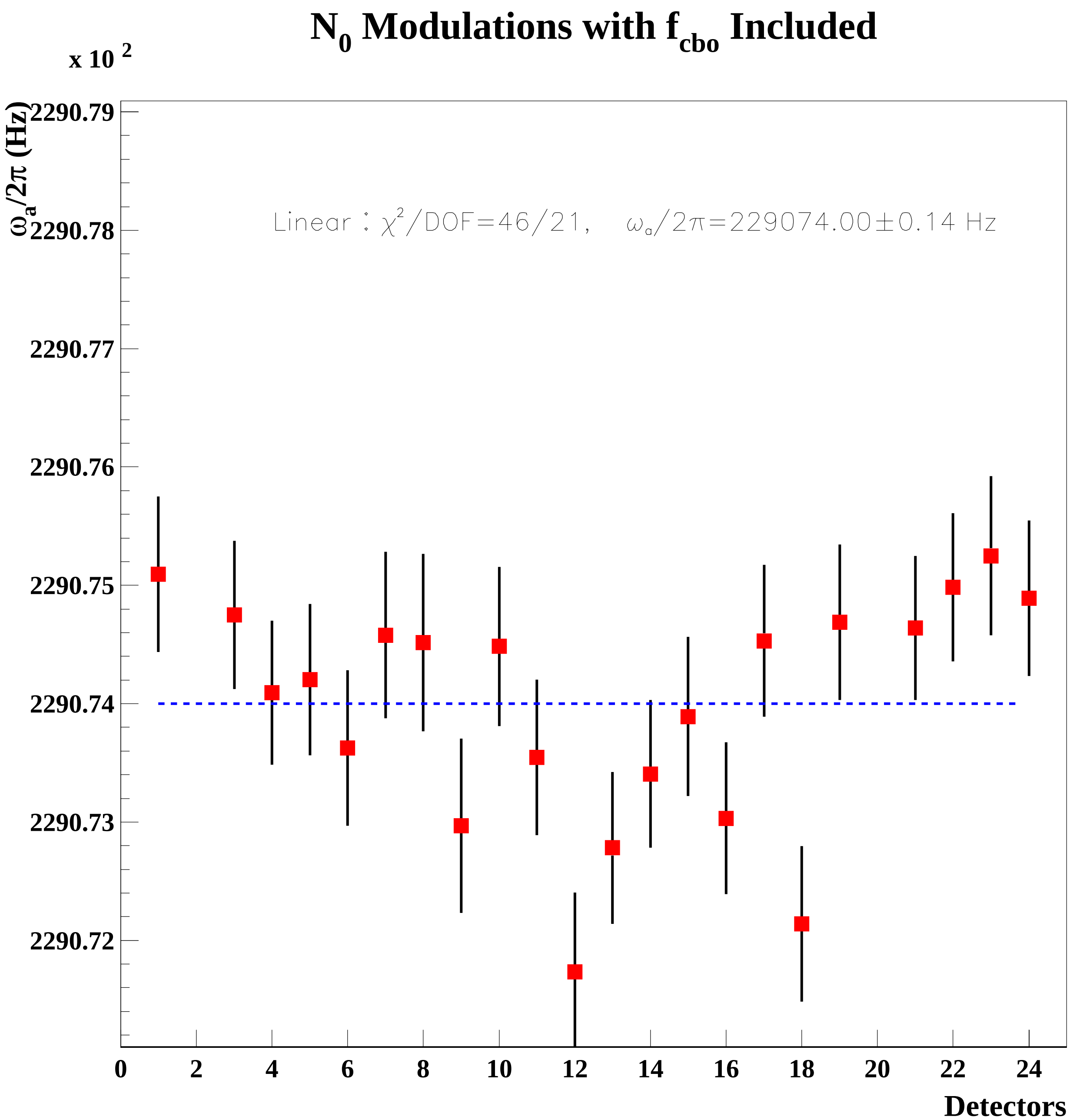




Calorimeters : allmost no energy deposition
FSD’s : Hits to any finger

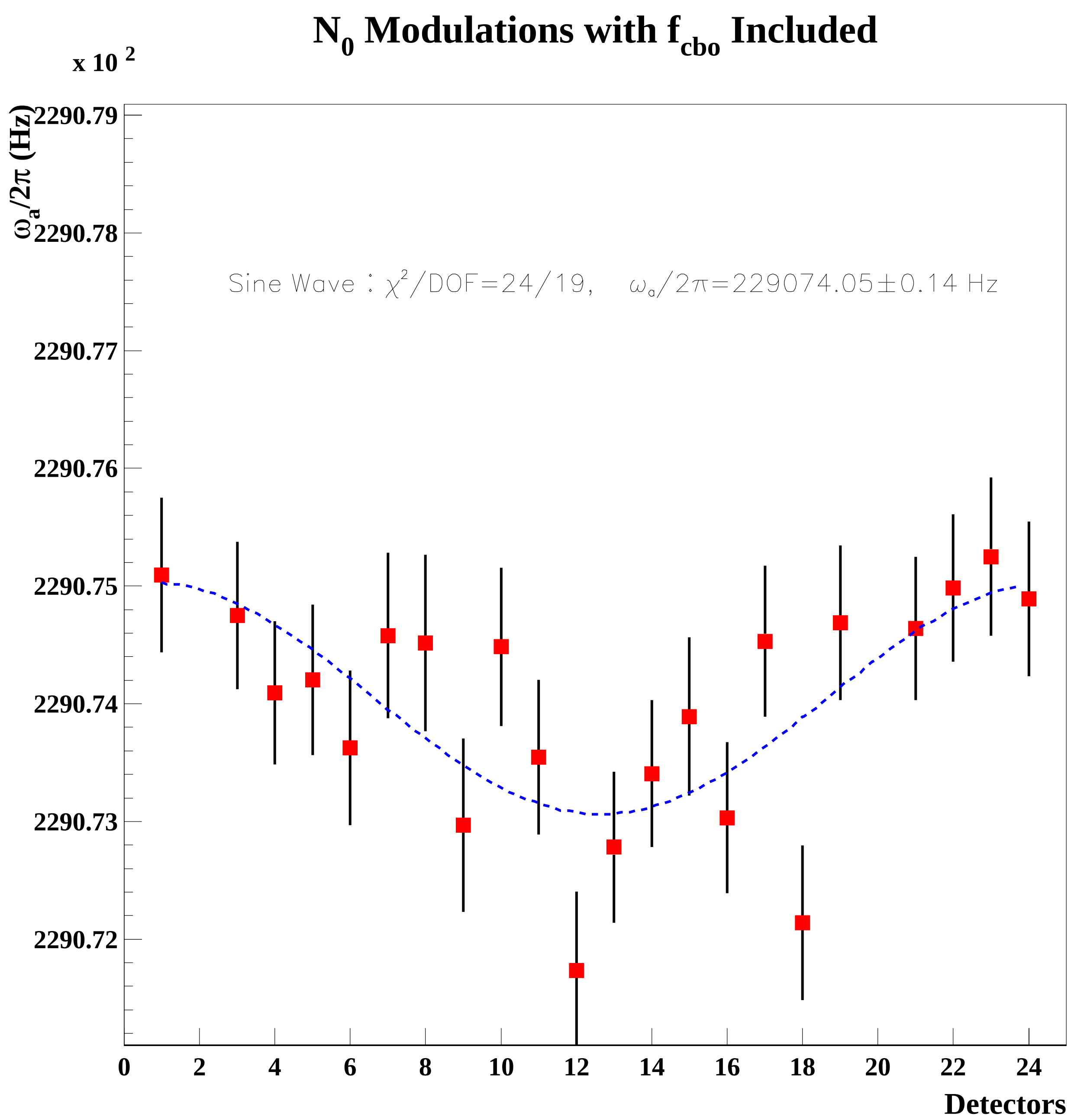


2000 Data



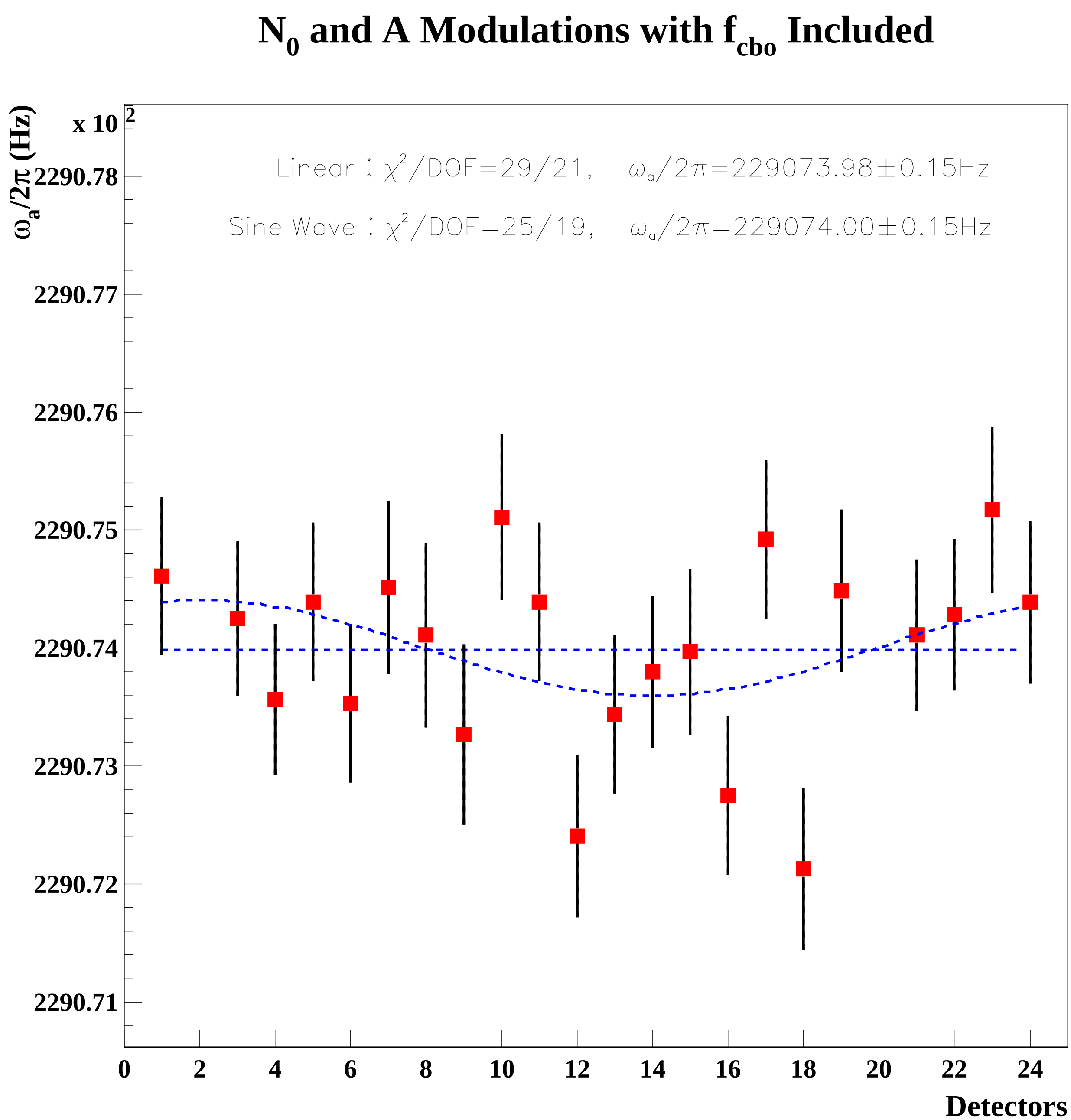
N0 Modulations with fcbo Included
x 10 2
ωa/2π (Hz)
2290.79
2290.78
2290.77
2290.76
2290.75
2290.74
2290.73
2290.72
Linear : χ2/DOF=46/21, ωa/2π=229074.00±0.14 Hz
0
2
4
6
8
10
12
14
16
18
20
22
24
Detectors

2000 Data



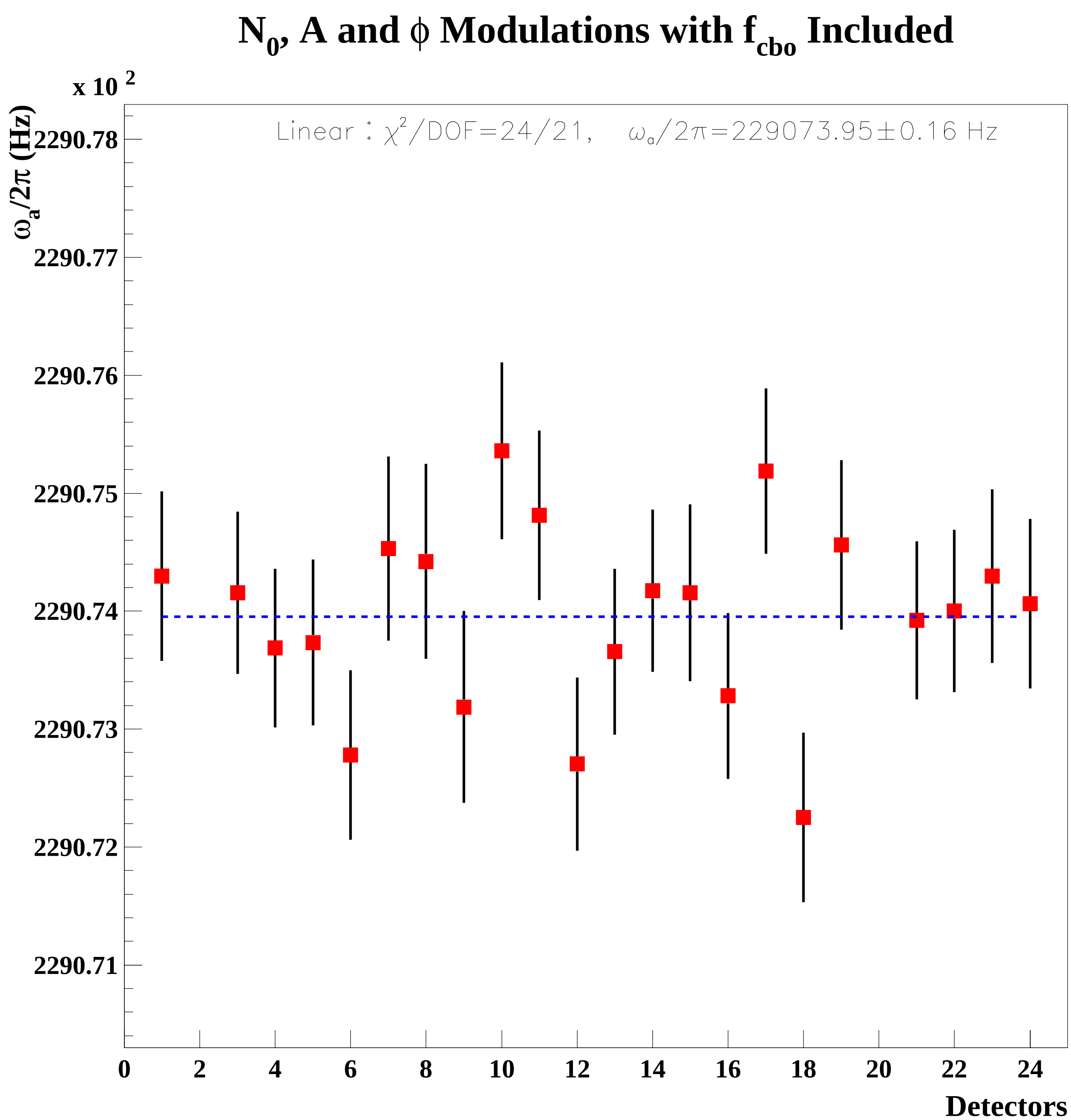
N0 Modulations with fcbo Included
x 10 2
ωa/2π (Hz)
2290.79
2290.78
2290.77
2290.76
2290.75
2290.74
2290.73
2290.72
Sine Wave : χ2/DOF=24/19, ωa/2π=229074.05±0.14 Hz
0
2
4
6
8
10
12
14
16
18
20
22
24
Detectors

2000 Data



N0 and A Modulations with fcbo Included
x 10 2
ωa/2π (Hz)
Linear : χ2/DOF=29/21, ωa/2π=229073.98±0.15Hz
Sine Wave : χ2/DOF=25/19, ωa/2π=229074.00±0.15Hz
2290.78
2290.77
2290.76
2290.75
2290.74
2290.73
2290.72
2290.71
0
2
4
6
8
10
12
14
16
18
20
22
24
Detectors

2000 Data



N0, A and ϕ Modulations with fcbo Included
x 10 2
Linear : χ2/DOF=24/21, ωa/2π=229073.95±0.16 Hz
ωa/2π (Hz)
2290.78
2290.77
2290.76
2290.75
2290.74
2290.73
2290.72
2290.71
0
2
4
6
8
10
12
14
16
18
20
22
24
Detectors

4 Independent Analysis of ω_a

- Function Modulating N_0, A, ϕ_a with f_{cbo}.
- Function Modulating N_0, A with f_{cbo}.
- Strobing the data @ f_{cbo} so ω_a becomes independent of f_{cbo}.
- Ratio Method; ω_a becomes independent of slow effects, e.g. muon losses.

Systematic Uncertainities on ω_a

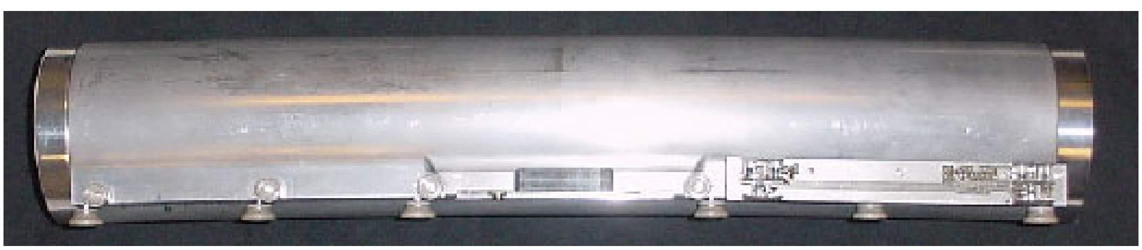
Source of Errors	Size (ppm)
CBO	0.21
Pileup	0.13
Gain Changes	0.13
Lost Muons	0.10
Binning and Fitting Procedure	0.06
Others	0.06
Total	**0.31**

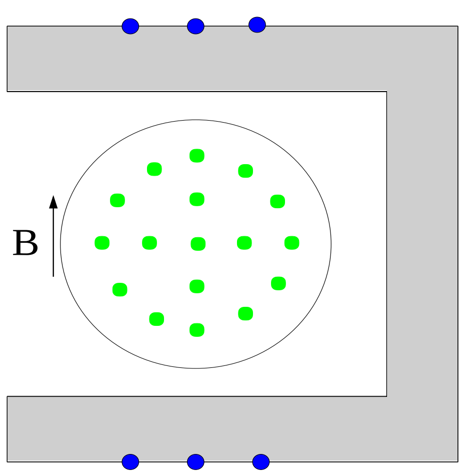
B Field Measurements

Two complementary methods for the field measurement

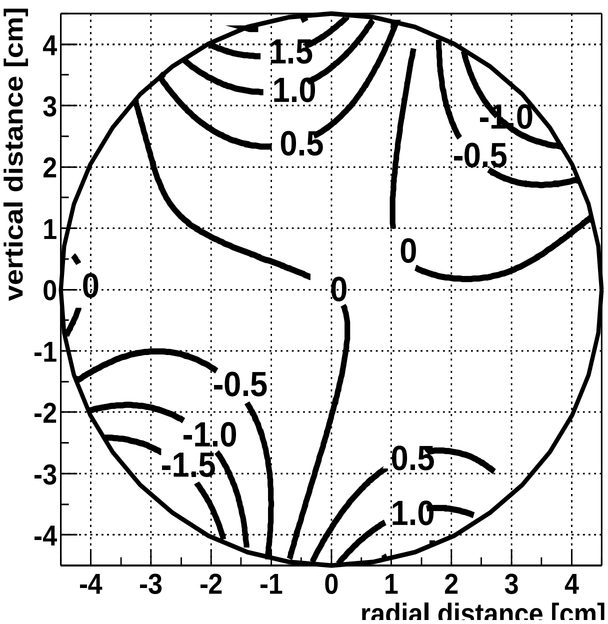
- Fixed NMR probes
  366 Fixed NMR probes
  Distrubuted around the ring
  Continuous measurement

- Beam Tube Trolley
  17 NMR probes
  Field measurements in the vacuum
  2-3 times a week



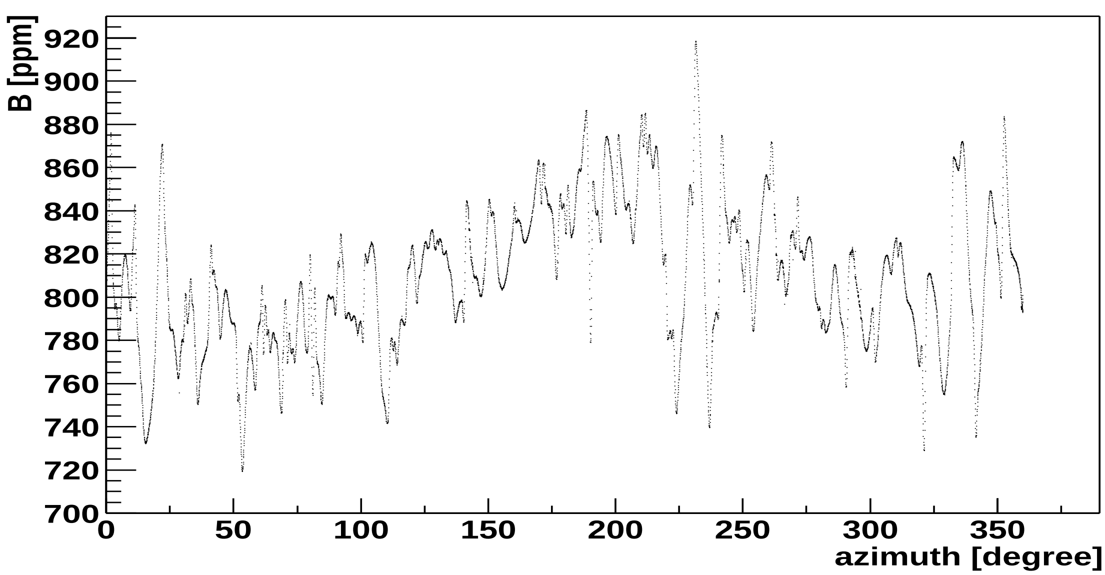


B Field Measurements



Multipoles (ppm)

	normal	skew
Quad	0.24	0.29
Sext	-0.53	-1.06
Octu	-0.10	-0.15
Decu	0.82	0.54



Total 0.24 ppm systematic uncertainity for the ω_p.

Computation of a_μ :

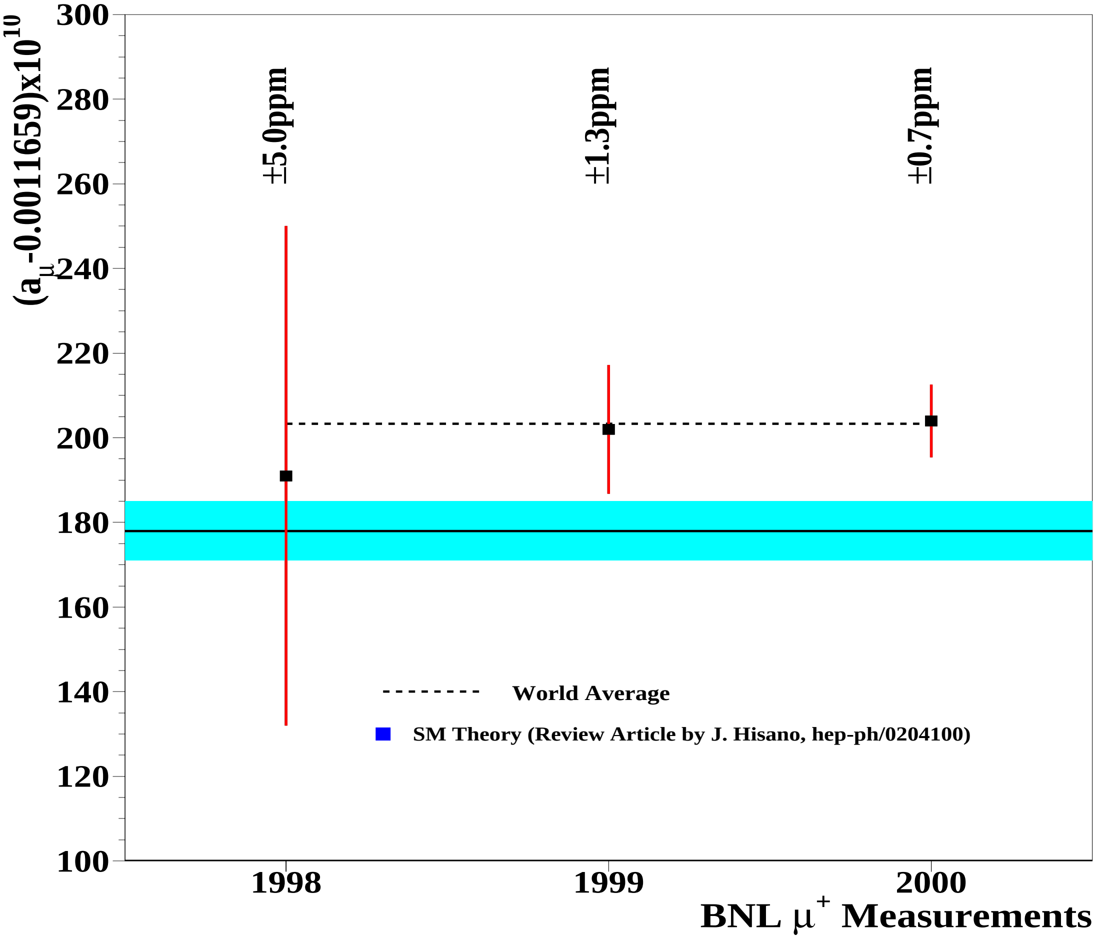
Independent/blind analysis of ω_a and ω_p provides a_μ :

$$a_\mu = \frac{\omega_a}{\frac{e}{m_\mu} < B >} = \frac{\omega_a / \omega_p}{\mu_\mu / \mu_p - \omega_a / \omega_p}$$

Results

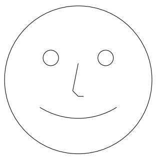
$a_\mu(SM) = 11659178(7) \times 10^{-10}(0.6ppm)^*$
More a_μ(SM) available !

BNL Data of 2000 :
$a_\mu(exp) = 11659204(7)(5) \times 10^{-10}$ (0.7 ppm)
Exp. World Average :
$a_\mu(exp) = 11659203(8) \times 10^{-10}$ (0.7 ppm)



2001 at a Glance

Excellent Run



$\approx$ 3.5B e^- collected ($E > 2$ GeV, $t > 30\mu$s)

Production, parallel with the data taking

Purpose : To monitor as many parameters as possible during the data taking

Beam quality,
Muon losses,
Detector thresholds,
Gate-on times continuously monitored

Energy thresholds ; All detectors $1GeV \leq E_{th}$
Gate on Times ; All detectors $t \leq 20\mu s$
Two different focusing index ; n=0.122 n=0.142 will provide a better understanding of the CBO