EDM Workshop, BNL
14-15 May, 2001

The Dedicated Muon EDM Experiment

Probing the 2nd generation for CP-Violation

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For the Muon EDM Collaboration

Outline

- Principle of EDM Experiment
- Experimental Design
- Systematics
- Schedule
- Summary

Muon EDM Collaboration

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Electric Dipole Moment

$\vec{d}_{\mu} \propto$ **Spin Vector**

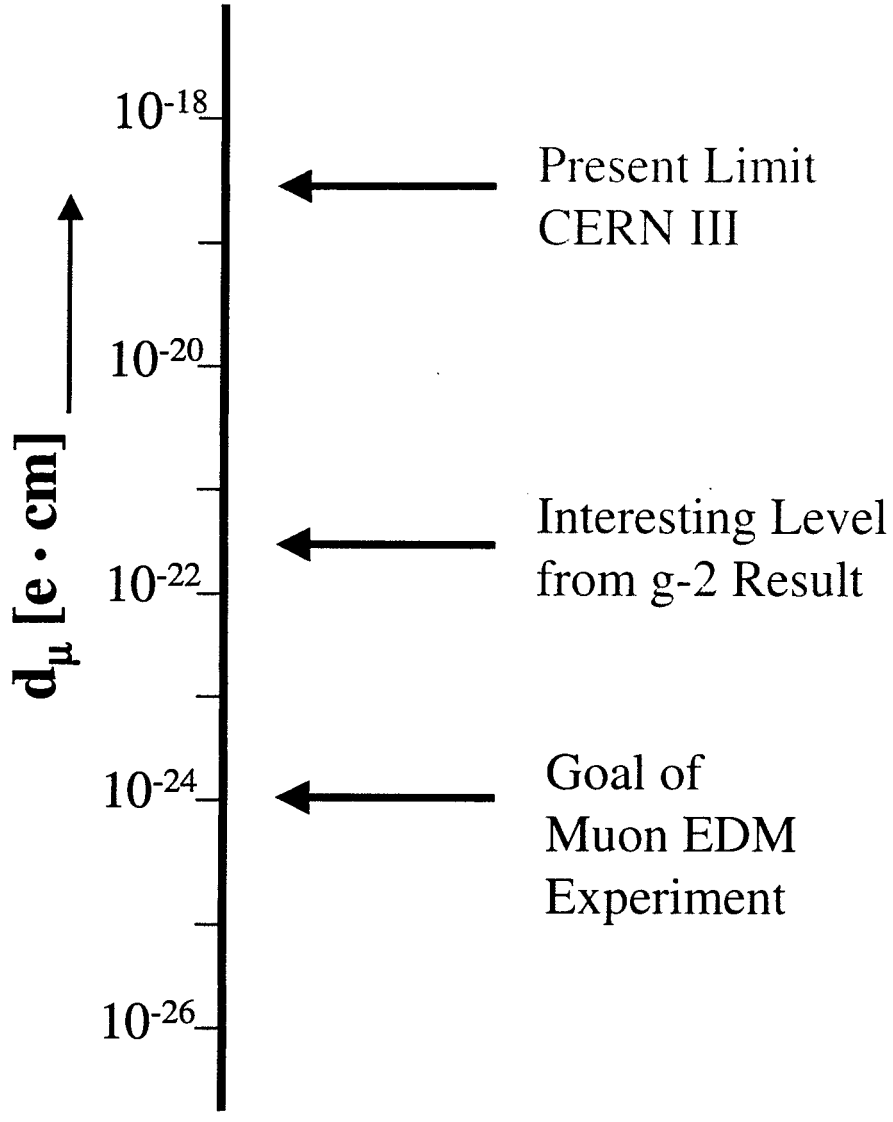
Violates both P & T Symmetries

$\xrightarrow{\text{CPT}}$ $\not{C}\not{P}$

1ppm in g-2: $\frac{\Delta g}{g}\frac{e}{2m} \sim 10^{-22}\,\mathrm{e}\cdot\mathrm{cm}$

Muon: 2nd generation particle

Muon EDM Limits

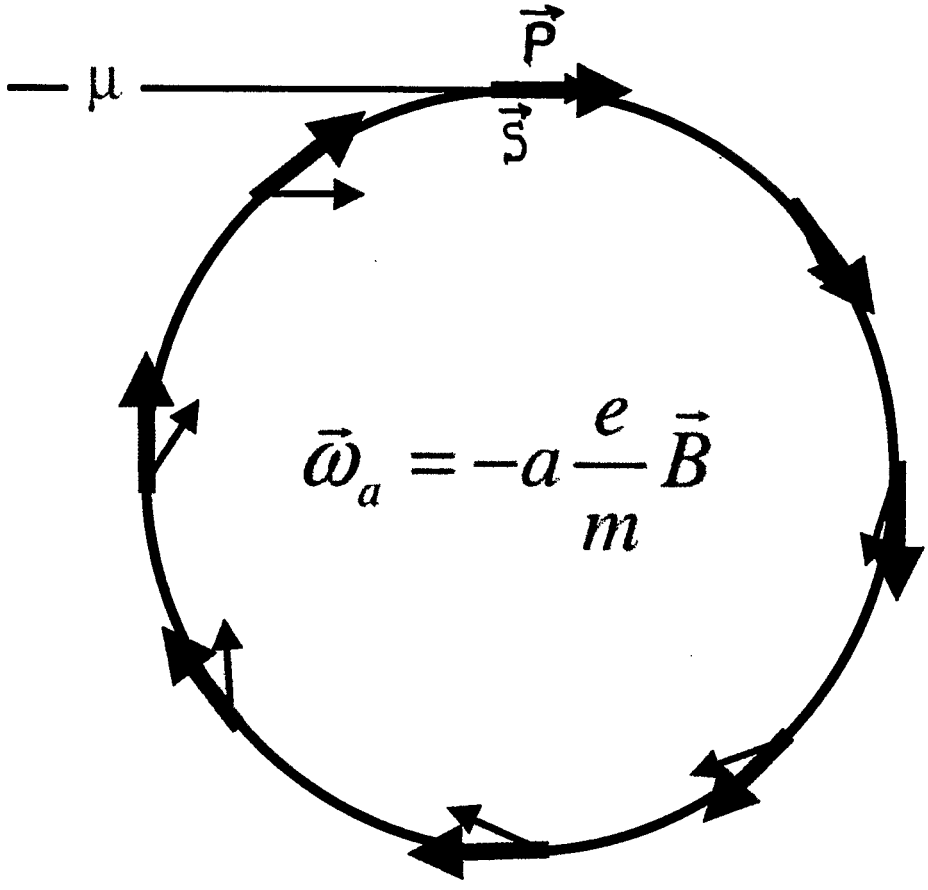


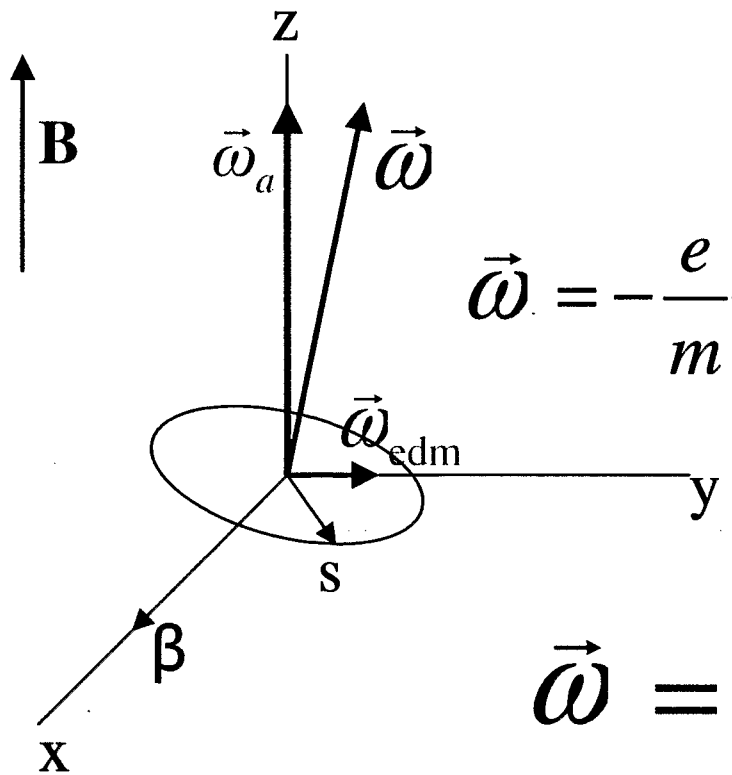
<u>Dedicated</u> EDM Experiment

- Magnetic Field Quality not Crucial $\longrightarrow$ Increase Acceptance, Statistics

- Use a Radial E-field to Control the g-2 Precession $\longrightarrow$ Systematics

Spin Precession in g-2 Ring
(Top View)





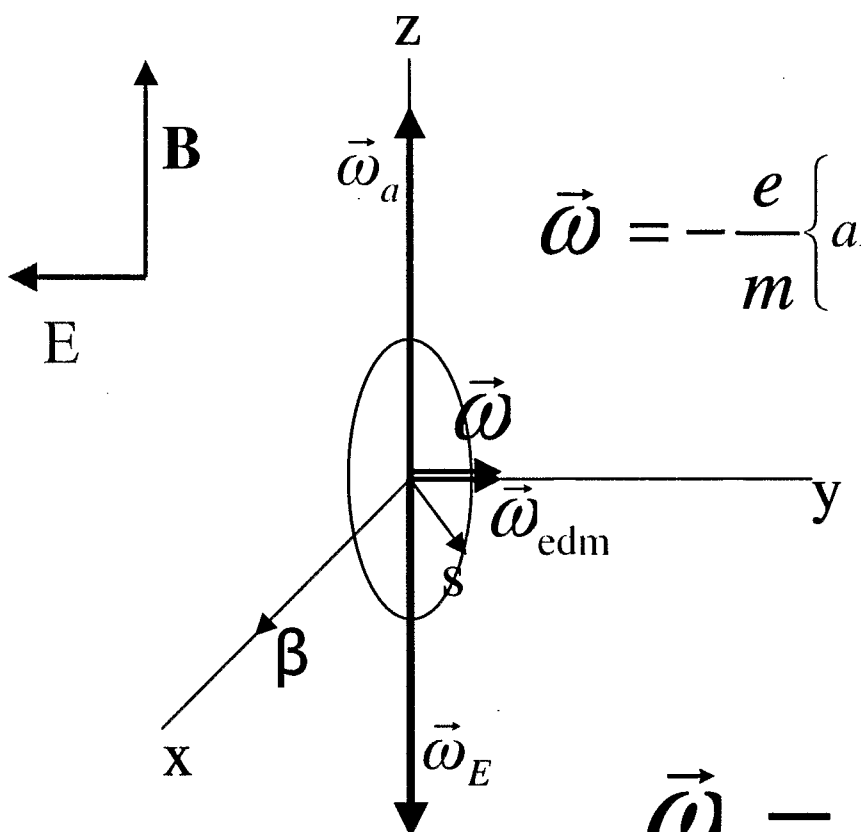
$$\vec{\omega} = -\frac{e}{m}\left\{ a\vec{B} + \overbrace{\left(\frac{1}{\gamma^2-1} - a\right)}^{0 \text{ at Magic Momentum}} \frac{\vec{\beta}\times\vec{E}}{c} + \frac{\eta}{2c}\left(\vec{E} + \vec{u}\times\vec{B}\right) \right\}$$

$$\vec{\omega} = \vec{\omega}_a + \vec{\omega}_{\text{edm}}$$

CERN III Statistical: $\pm 2.7\times10^{-19}\,\text{e}\cdot\text{cm}$

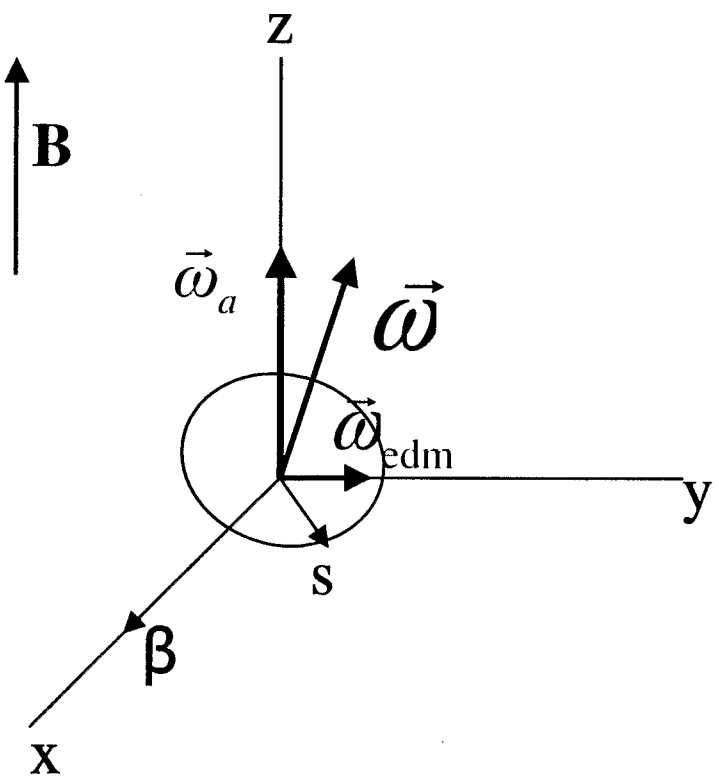
Systematic: $\pm 2\times10^{-19}\,\text{e}\cdot\text{cm}$

Canceling g-2 with a Radial E-field



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

$$\vec{\omega} = \vec{\omega}_{\text{edm}} = \frac{\eta}{2c}\left(\vec{E} + \vec{u}\times\vec{B}\right)$$


z
B
$\vec{\omega}_a$
$\vec{\omega}$
$\vec{\omega}_{edm}$
y
s
β
x

Parameter Values of Muon EDM Experiment

- Radial E-Field: $E = \frac{cBa\beta}{1-(1+a)\beta^2}$

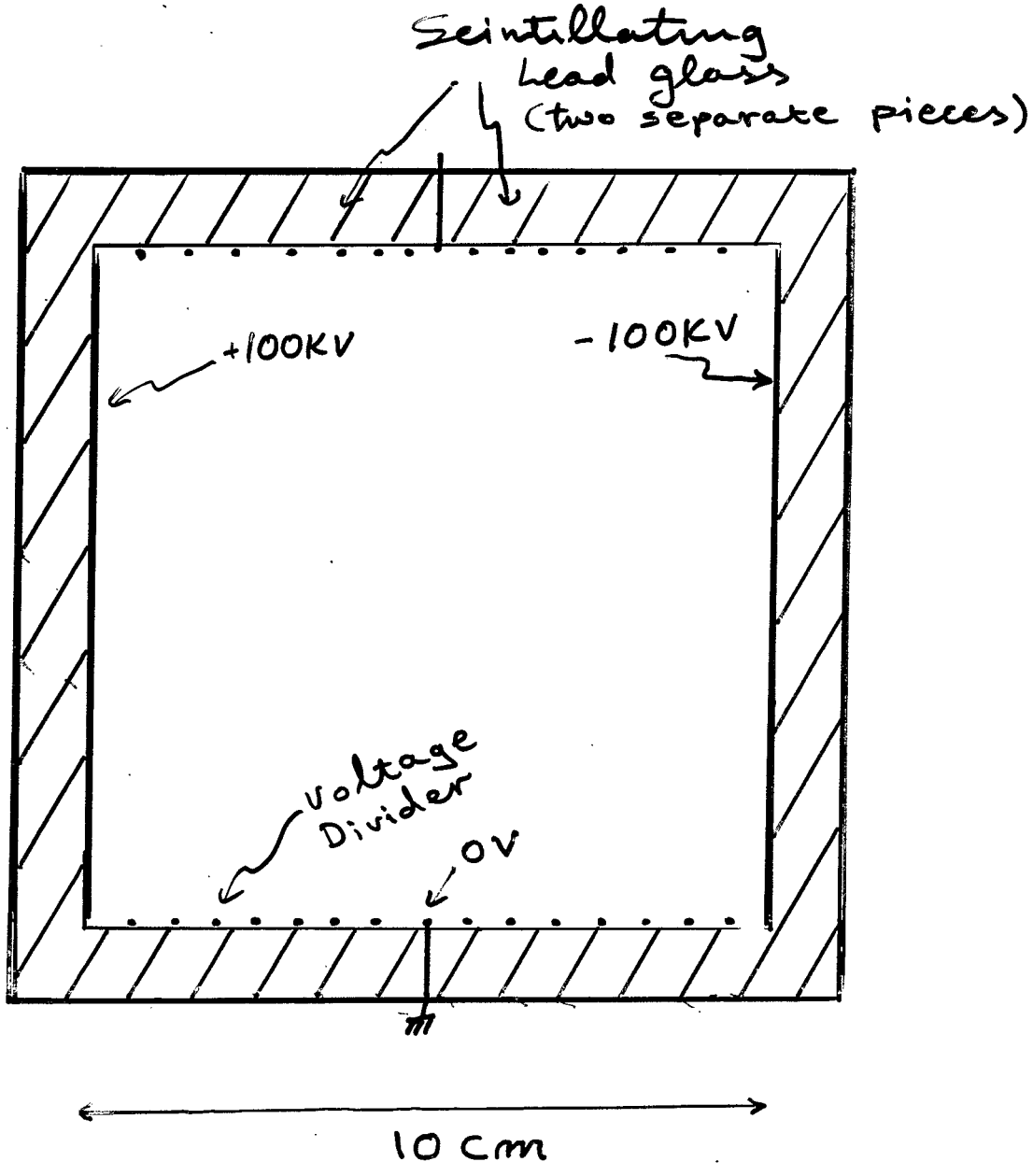
  E=2MV/m

- Dipole B-field: 1/6 of current value

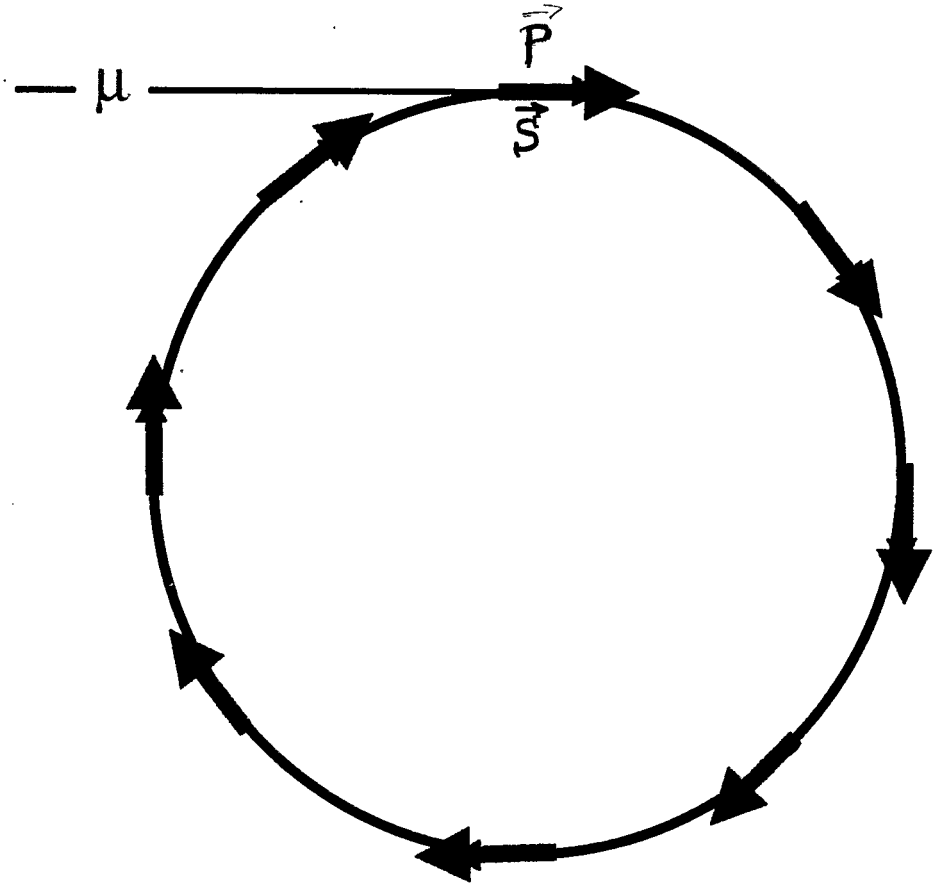
$$B \approx 0.24T$$

- Muon Momentum:

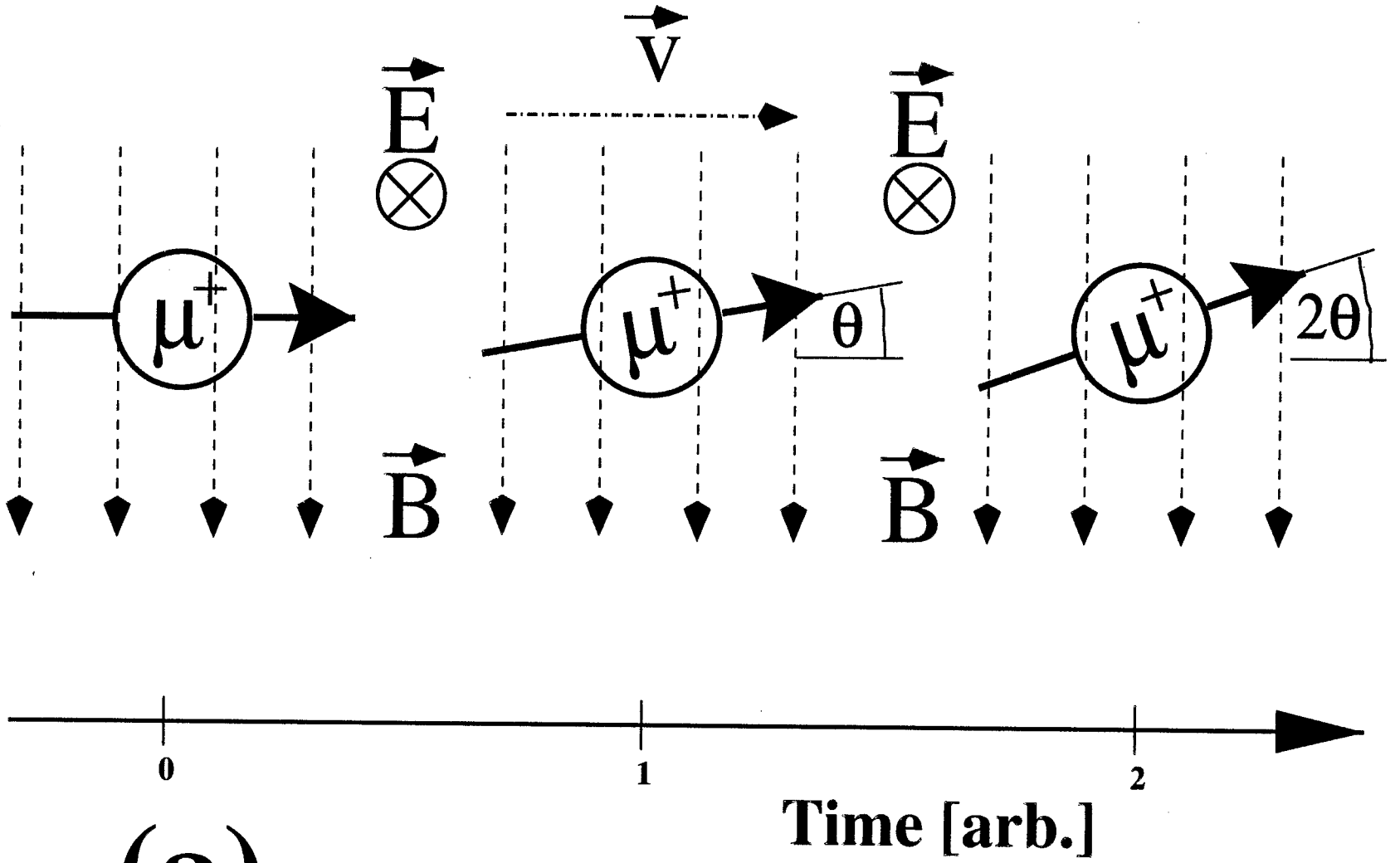
$$P_\mu \approx 500\text{MeV/c}, \gamma \approx 5$$


Scintillating
Lead glass
(two separate pieces)
+100KV
-100KV
voltage
Divider
0V
10 cm

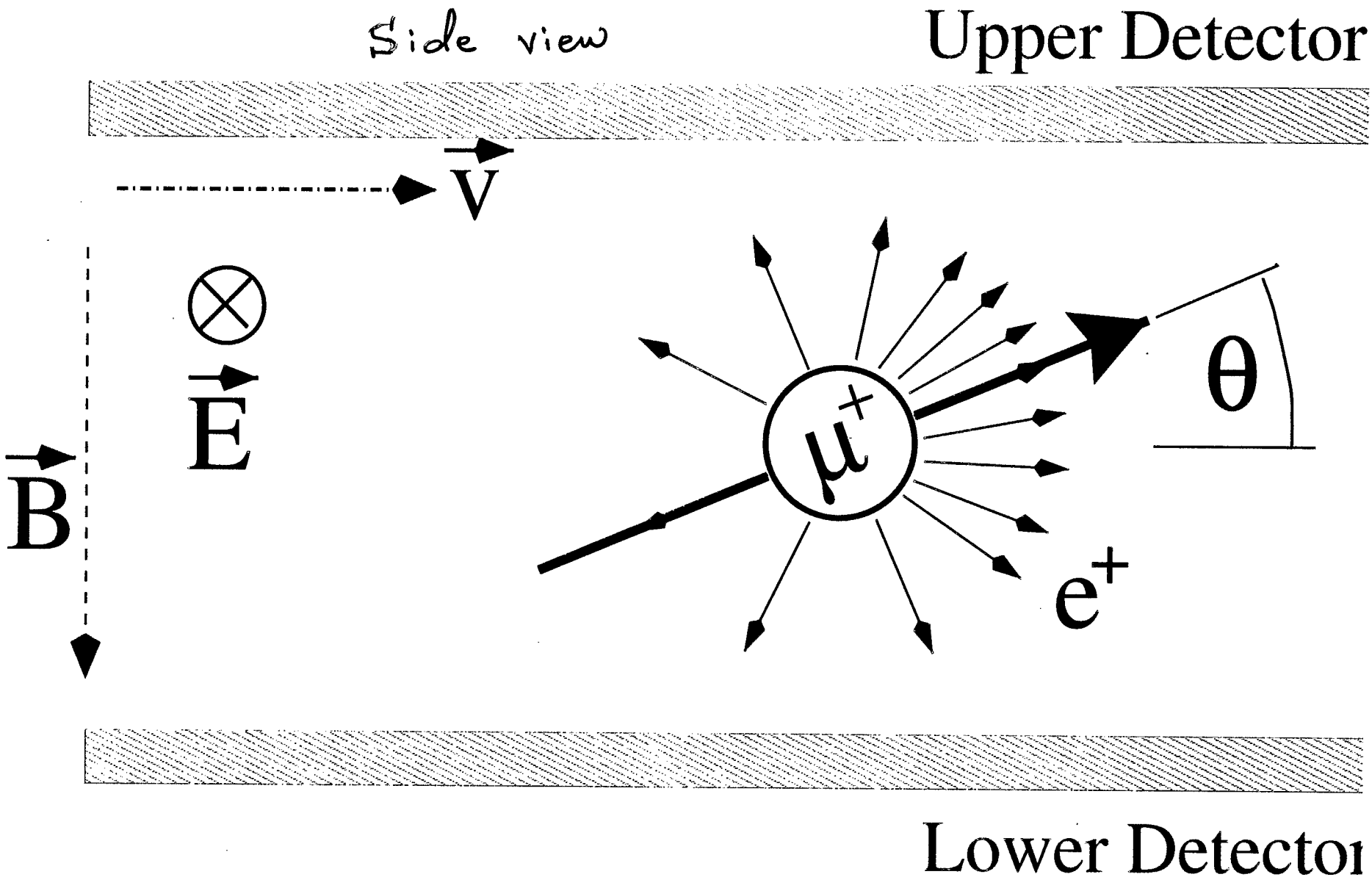
Spin Precession in EDM Ring
(Top View)



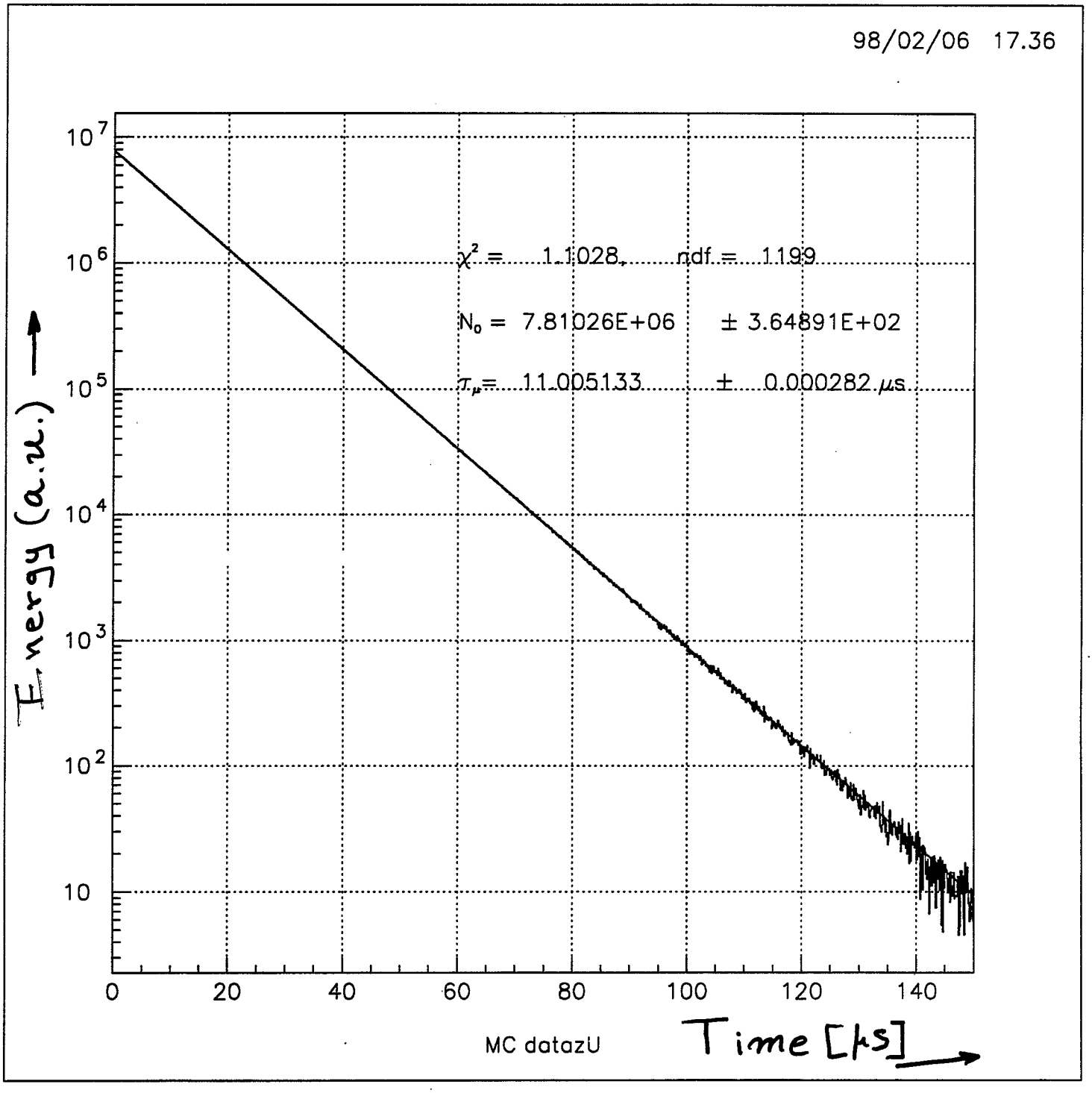
Side view

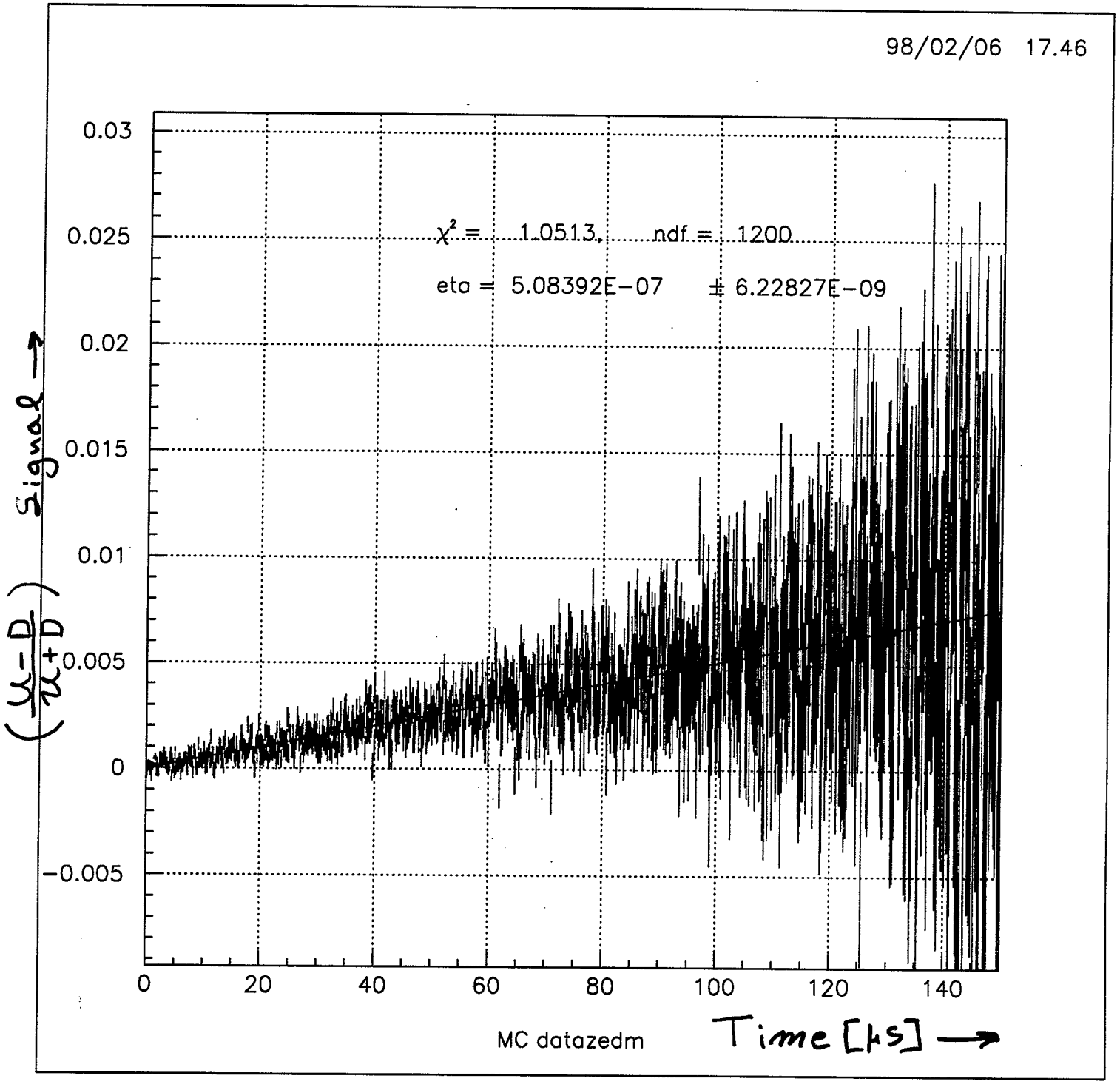


(a)


Side view
Upper Detector
$\vec{V}$
$\vec{E}$
$\vec{B}$
μ^+
θ
e^+
Lower Detector

(b)


98/02/06 17.36
χ^2 = 1.1028, ndf = 1199
N_0 = 7.81026E+06 ± 3.64891E+02
τ_μ = 11.005133 ± 0.000282 μs
10^7
10^6
10^5
10^4
10^3
10^2
10
0
20
40
60
80
100
120
140
MC datazU
Energy (a.u.)
Time [μs]


98/02/06 17.46
χ^2 = 1.0513, ndf = 1200
eta = 5.08392E−07 ± 6.22827E−09
0.03
0.025
0.02
0.015
0.01
0.005
0
−0.005
0
20
40
60
80
100
120
140
MC datazedm
Signal →
$\left(\frac{U-D}{U+D}\right)$
Time [μs] →

Sensitivity:

$$d_\mu = \frac{\eta}{2}\,\frac{e\hbar}{2mc} \simeq \eta \times 4.7 \times 10^{-14}\ e\cdot cm$$

Error in η:

$$\sigma_\eta = \frac{1}{\gamma\tau\, A_1 A \sqrt{2\, N_{tot}}}$$

$\gamma\tau = 11\,\mu s$

A : muon decay asymmetry weighted w/ energy (0.5)

A_1: $\frac{\beta B e}{2m} \simeq 10^8/s$

N_{tot} : Total # of detected decays

$\Downarrow$

$\sigma_\eta \simeq 3.5 \times 10^{-11}$ for 1.5×10^{15} decays

$\Downarrow$

$d_\mu \leq 1.5 \times 10^{-24}\ e\cdot cm$

Modifications:

- Increase Pion/Muon Flux per P.O.T.
  Modify Existing Beamline
- New Inflector (Normal Conducting)
- Use <u>Magnetic</u> (Weak/Strong)
  Focusing in g-2 Ring
- Flat Radial E-field to Cancel
  (Reduce/Control) g-2 Precession
- Deuterons as Inclinometer

Increase Pion/Muon Flux per P.O.T.:

- ***Need to work at Low Muon Momenteum***

  (Off magic Momentum) of 0.5GeV/c With a Required

  DC Radial Electric Field: $E = \{a\, B\, (\gamma^2 - 1) / \beta\} \approx 2$ ***MV/m***

- ***Pion Momentum: 0.9GeV/c (Select Backward Decay Muons)***

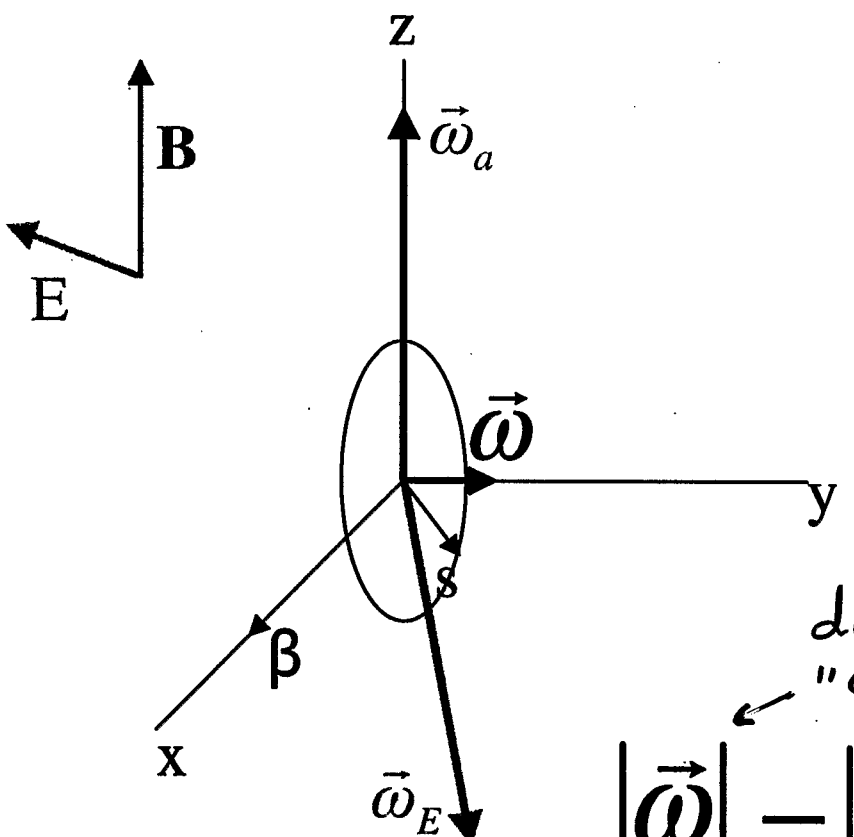
- ***Use Lithium Lens D/S of Target for Pion Focusing***

magnetic Horn

Systematics

- "Vertical" Component of E-field
- Radial B-field and Vertical E-field Stability
- De-phasing due to Radial E-field
- Proton or Pion Contamination of Beam (flash)
- Early to Late Counting Effects (Linearity)
- Muon Losses as a Function of Time
- Stored Positrons at Injection
- Horizontal and Vertical Betatron Oscillations Coupling

Background due to "Vertical" E-field



$$\vec{\omega}_a = -a_\mu \frac{e}{m}\vec{B}$$

$$\vec{\omega}_E = -\frac{e}{m}\left(\frac{1}{\gamma^2 - 1} - a_\mu\right)\frac{\vec{\beta}\times\vec{E}}{c}$$

due to "Out of Plane" E-field Component

$$\left|\vec{\omega}\right| = \left|\vec{\omega}_E\right| Sin\varphi$$

Effect of "Vertical" Component of E

$$F_{\mathrm{v}} = e(E_{\mathrm{v}} + uB_{\mathrm{r}}) = 0$$

$$B_{\mathrm{r}} = -\frac{E_{\mathrm{v}}}{u}$$

$$\vec{\omega}^* = g\frac{e}{2m}\vec{B}_{\mathrm{r}}^*$$

$$\vec{B}^* = \gamma(\vec{B}^* + \vec{\beta}\times\frac{\vec{E}}{c}),\ t^* = \frac{t}{\gamma}$$

$$\boxed{\omega = g\frac{e}{2m}\frac{E_{\mathrm{v}}}{\beta\gamma^2}}$$

$E_v = 10^{-8}E$

μ	2.3mrad/s
d	14mrad/s

Signal and Background

- Signal:

$$\frac{d\vec{s}}{dt} = \vec{d}_{\text{edm}} \times \left[\vec{E} + \vec{u} \times \vec{B}\right]$$

- 2.2mrad/s, assuming $d_{edm}=10^{-24}$e cm
- This gives 10^{-7}rad in 50μs

- Misalignment Error: ϕ~10nrad induces 10^{-7}rad in 50μs

Muon vs Deuteron

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

$$E \cong 2\text{MV/m}, \quad R = 7.11\text{m}$$

μ a=0.0011, P=0.5GeV/c (β=0.98, γ=5)
B=0.24T

d a=-0.143, P=0.4GeV/c (β=0.2, γ=1.02)
B=0.22T

$$\frac{d\vec{s}}{dt} = \vec{d}_{\text{edm}} \times \left[\vec{E} + \vec{u} \times \vec{B}\right]$$

$\frac{\hbar\omega}{2} = d_{\text{edm}} uB$ =2.2mrad/s (for $d_{\text{edm}}=10^{-24}$e·cm)

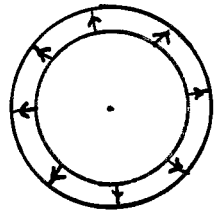
$\hbar\omega = d_{\text{edm}} uB$ =0.2mrad/s (for $d_{\text{edm}}=10^{-24}$e·cm)

	Muon	Deuteron
N	10^8 (10^{14} POT)	5×10^8 ($dp/p=10^{-4}$)
AGS Rep rate	0.4Hz	5Hz
Asymmetry	0.3	0.26
Interaction Time	50μs	5ms
Signal: ωt (10^{-24} e·cm)	10^{-7} rad	10×10^{-7} rad
Background: ωt (10^{-8} E)	10^{-7} rad	700×10^{-7} rad

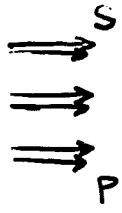
De-phasing of Spin

spin de-phasing

Radial E-field $\sim \frac{1}{r}$



Time $t = 0$:

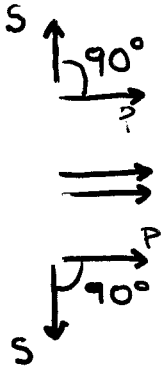


+ 2%

Central momentum

- 2%

μ : $t = 150 \mu s$:



+ 2 %

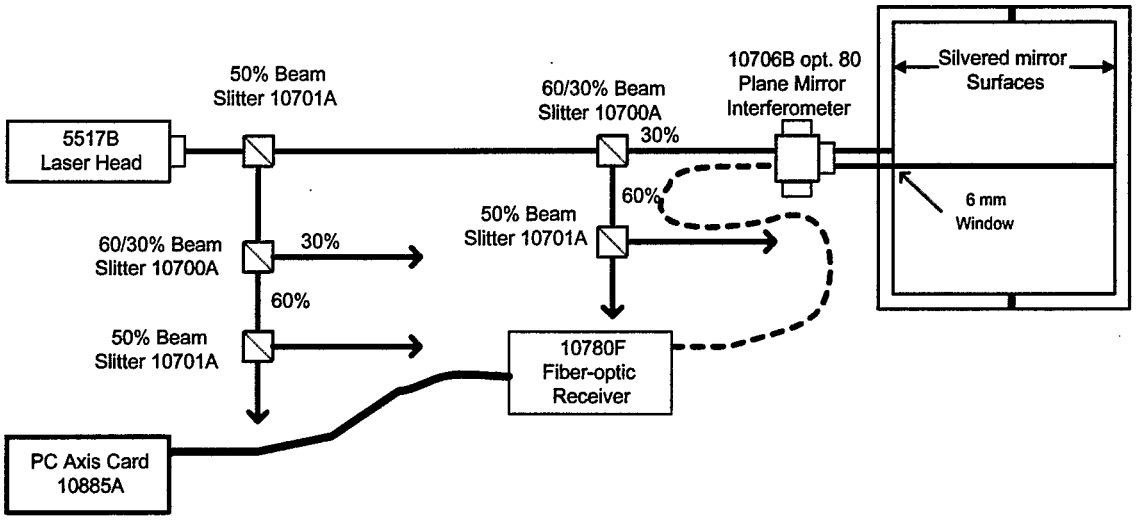
- 2 %

d : 5 ms $\frac{\Delta P}{P} = 10^{-4}$

Probing Vertical E-Field Component

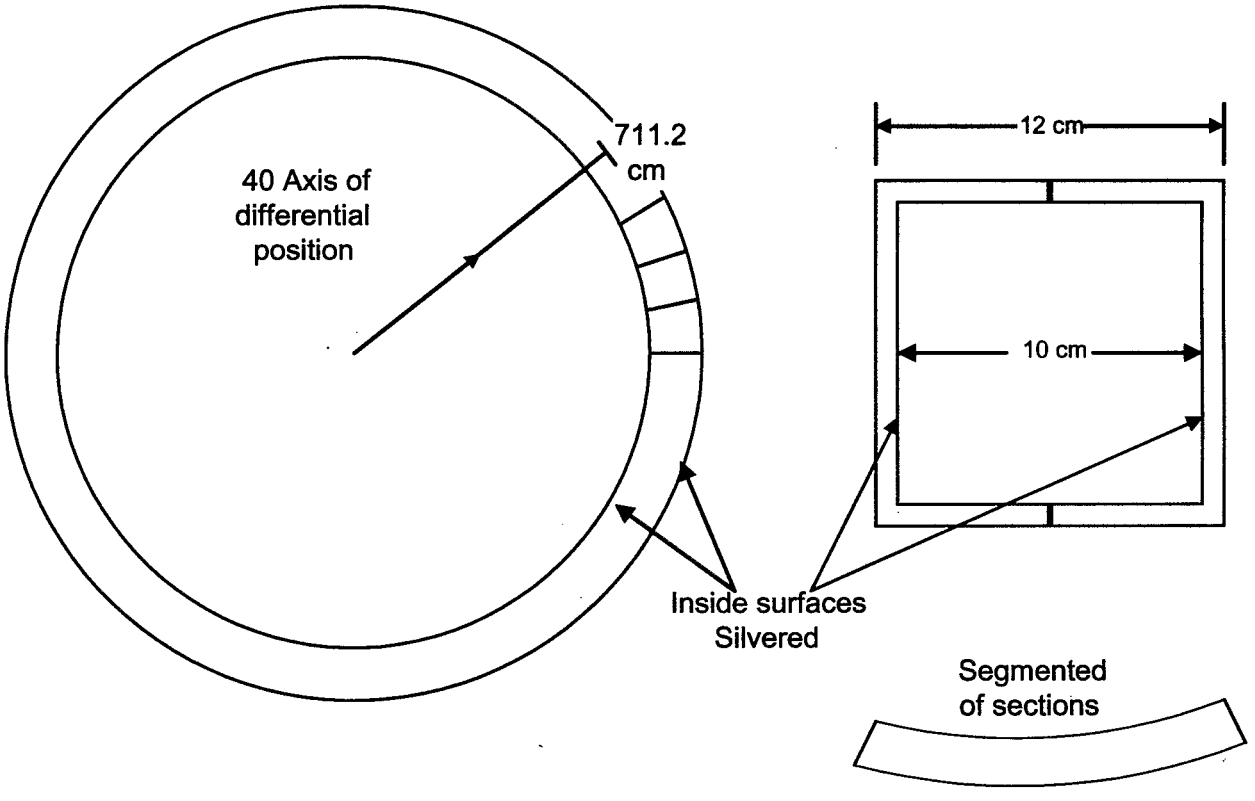
- Inject Deuterons-Inclinometer:
  a) Spin Precession vs Time
  b) Vertical Displacement

- Laser Interferometer to Monitor Stability



6 Axis per Laser Head

The Plane mirror interferometers 10706B will measure the change in spacing of the 2 silvered surfaces. The detailed optical layout for all 40 measurement axis is done by the integrater. Other optical components such as Beam Benders 10707A andAdjustable Mounts,10710A & 10711A, are available to aid in layout and alignment.



Running Plan

- Phase I: Deuteron Run 400h; Weak Magnetic Focusing; 10nrad resolution
- Muon Run 400h; Weak Magnetic Focusing; 10^{-22} Stat., 10^{-24} e·cm Syst. Monitor Stability w/ a Laser System, $N_\mu P^2 = 10^{12}$

- Phase II: Muon Run 4000h; Strong Magnetic Focusing; 10^{-23} Statistical, 10^{-24} e·cm Syst., $N_\mu P^2 = 10^{14}$

- Phase III: Use Better Muon Collection Techniques to Store More Muons; 10^{-24} Stat., 10^{-24} e·cm Syst., $N_\mu P^2 = 10^{16}$

PHASE I

PHASE II

PHASE III

Schedule

- Proposal Fall 2001
- 2002 Work on Beamline, Inflector, Detectors
- 2003 Phase I (weak focusing without changing pole pieces) Deuterons, Muons 10^{-22} e·cm
- 2004 Phase II (Strong Focusing) 10^{-23} e·cm
- 2006 Phase III More Muons 10^{-24} e·cm

Summary

- A New, Sensitive Method of Probing EDM
- Second Generation (Muon)- Very Exciting
- Can Make Use of High Muon Flux