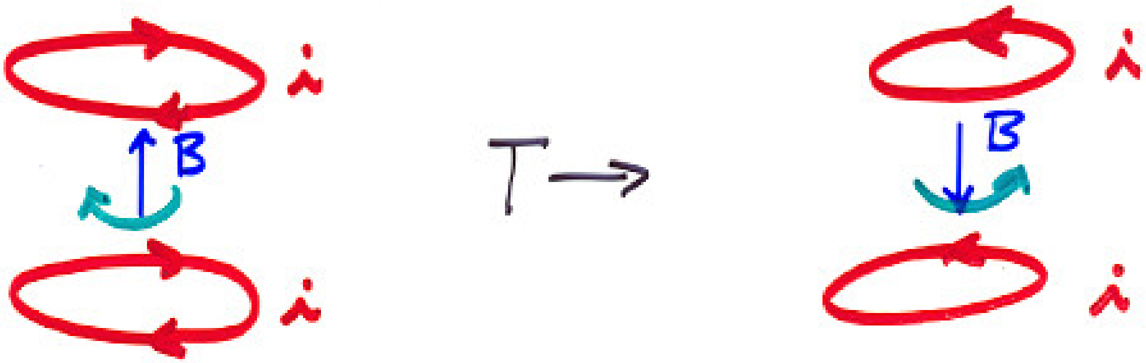
Measuring the Electric Dipole Moment of the Muon and Deuteron in Storage Rings?

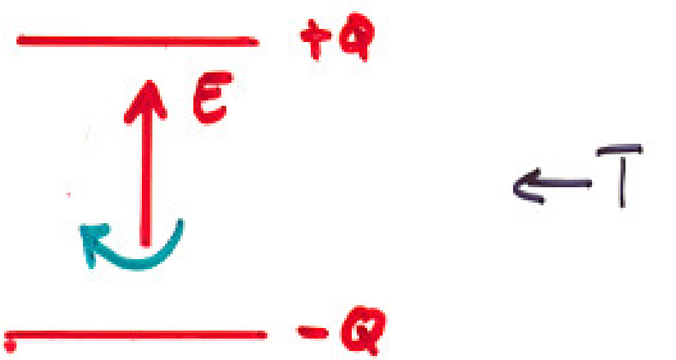
William Morse - BNL

EDM violates time reversal invariance:

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



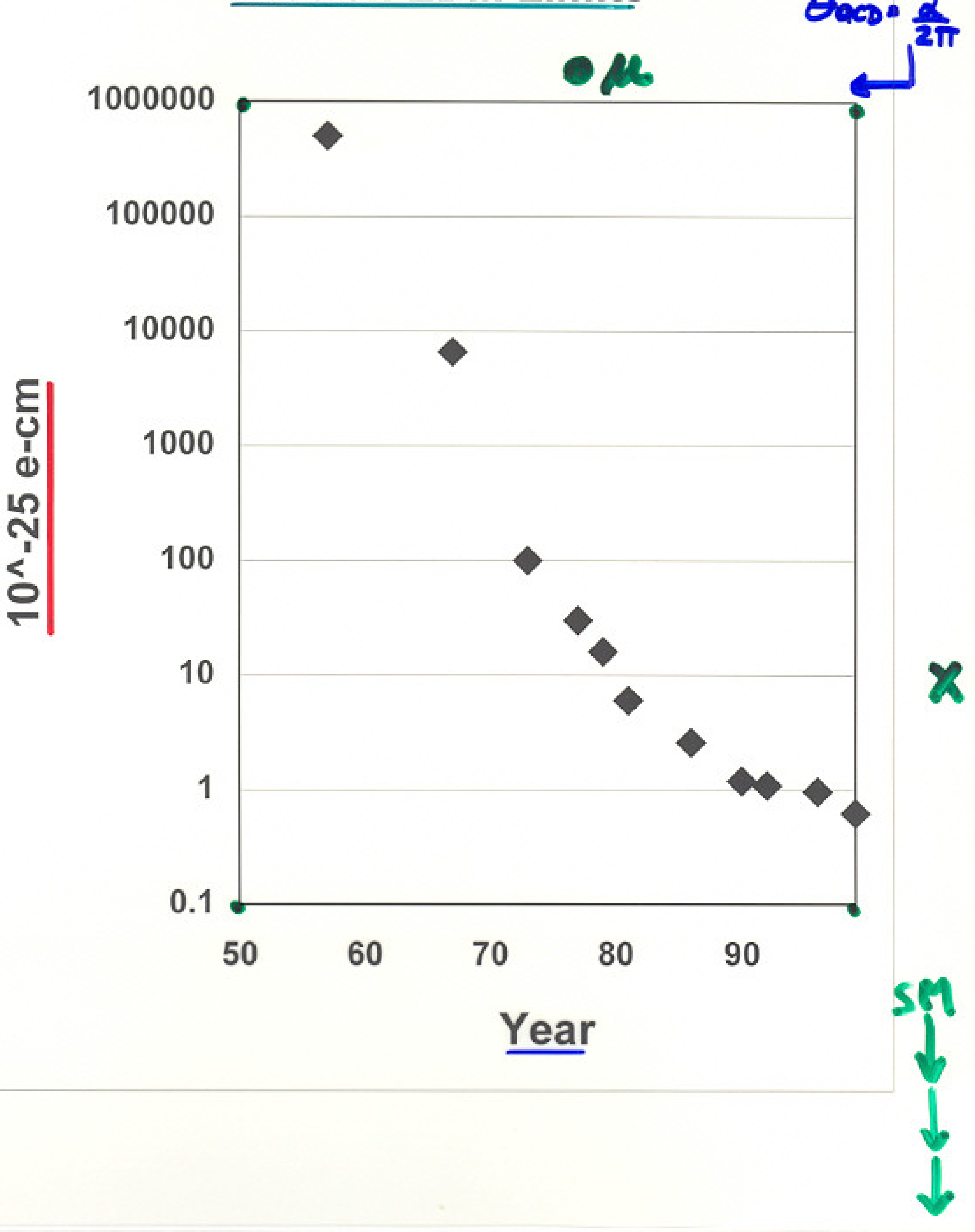
$$d\vec{S}/dt = \vec{d}\times\vec{E}$$



$$\mathcal{E} = \vec{d}\cdot\vec{E}$$

P violated
PT conserved
CPT conserved (μ^+ and μ^-)

Neutron EDM Limits



Enhanced Electric Dipole Moment of the Muon in the Presence of Large Neutrino Mixing

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The electric dipole moment (edm) of the muon (d_μ^e) is evaluated in supersymmetric models with nonzero neutrino masses and large neutrino mixing arising from the seesaw mechanism. It is found that if the seesaw mechanism is embedded in the framework of a left-right symmetric gauge structure, the interactions responsible for the right-handed neutrino Majorana masses lead to an enhancement in d_μ^e to values as large as $5 \times 10^{-23} e$ cm, with a correlated value of $(g-2)_\mu \simeq 13 \times 10^{-10}$. This should provide a strong motivation for improving the edm of the muon to the level of $10^{-24} e$ cm as has recently been proposed.

$d_e^e \simeq 10^{-28} e$ cm.

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It has long been recognized that electric dipole moments (edm) of fermions can provide a unique window to probe into the nature of the forces that are responsible for CP violation [1]. Experimental limits on the edm of neutron have reached the impressive level of $6 \times 10^{-26} e$ cm [2] and have already helped constrain and sometimes exclude theoretical models of CP violation. Electric dipole moment of the electron has severely been constrained by atomic measurements in Cs ($d_e^e \leq 10^{-26}$) and Tl ($d_e^e \leq 4.3 \times 10^{-27} e$ cm) [3]. The limits on the muon edm, on the other hand, are much weaker, the present limit derived from the CERN $(g-2)$ experiment [4] is $d_\mu^e \leq 1.1 \times 10^{-18} e$ cm. There has been a recent proposal to improve this limit on d_μ^e to the level of $10^{-24} e$ cm [5]. In this paper we will argue that there is a strong motivation for this proposed improvement, related to the observation of neutrino masses and oscillations.

In a large class of models, a generic scaling law holds for leptonic edm given by $d_\mu^e / d_e^e \simeq m_\mu / m_e$. The present limit on d_e^e would then imply that $d_\mu^e \leq 10^{-24} e$ cm. Examples where such a scaling law holds are (i) multi-Higgs models where the dominant contribution to the leptonic edm arises from a two-loop diagram involving γ-V-Higgs vertex, with $V = Z, W$ [6], and (ii) the minimal supersymmetric standard model (MSSM) with the usual assumption of universality of scalar masses and proportionality of trilinear A terms [7]. In both cases, $e - \mu$ universality in edm is broken only by the lepton masses, and hence the scaling law. (Recently an extended Higgs model [8] has been analyzed, where it has been shown that for large values of the parameter $\tan\beta$, the one-loop Higgs exchange diagram can compete with the two-loop diagram [6], leading to order one violation of the scaling law.)

In the light of Super-Kamiokande [9], MSSM must be extended to incorporate small neutrino masses. A natural place is left-right (LR) symmetric gauge theories [10] with the seesaw mechanism. We have recently advocated a simple supersymmetric realization of left-right symmetry (SUSYLR) [11], where we simply embed the MSSM into a LR gauge structure at a high scale $v_R \sim 10^{11}$–10^{15} GeV. The effective theory that emerges from this model at scales below v_R is a constrained MSSM with far fewer number of phases. In particular, it has a built-in solution to the SUSY CP problem [11,12]. In this paper we study d_μ^e in this class of models and show that the interactions responsible for the Majorana masses of the ν_R will lead to an enhancement of d_μ^e. Our main effect arises through the renormalization group extrapolation from the Planck scale to v_R [13]. In this interval the Majorana Yukawa couplings of the ν_R fields, as well as the associated trilinear A terms, will affect the soft supersymmetry breaking parameters of the effective MSSM, leading to the enhancement of d_μ^e. Since the Majorana Yukawa couplings do not obey $e - \mu$ universality, the scaling law $d_\mu^e / d_e^e = m_\mu / m_e$ is not obeyed by these new diagrams.

The model.—The electroweak gauge group of the model is $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ with the standard assignment of quarks and leptons—left-handed quarks and leptons (Q, L) transform as doublets of $SU(2)_L$, while the right-handed ones (Q^c, L^c) are doublets of $SU(2)_R$. The Dirac masses of fermions arise through their Yukawa couplings to a Higgs bidoublet $\Phi(2,2,0)$. We will confine to the minimal version with only one such $\Phi(2,2,0)$ field. The $SU(2)_R \times U(1)_{B-L}$ symmetry is broken to $U(1)_Y$ by $B - L = 2$ triplet scalar fields, the left triplet Δ and right triplet Δ^c (accompanied by $\bar{\Delta}$ and $\bar{\Delta}^c$ fields, their conjugates to cancel anomalies). These fields also couple to the leptons and are responsible for inducing large Majorana masses for the ν_R. The gauge invariant matter part of the superpotential involving these fields is

$$W = \mathbf{Y}_q Q^T \tau_2 \Phi \tau_2 Q^c + \mathbf{Y}_l L^T \tau_2 \Phi \tau_2 L^c + (\mathbf{f} L^T i\tau_2 \Delta L + \mathbf{f}_c L^{cT} i\tau_2 \Delta^c L^c). \qquad (1)$$

Under left-right parity, $Q \leftrightarrow Q^{c*}$, $L \leftrightarrow L^{c*}$, $\Phi \leftrightarrow \Phi^\dagger$, $\Delta \leftrightarrow \Delta^{c*}$, along with $W_{SU(2)_L} \leftrightarrow W^*_{SU(2)_R}$, $W_{B-L} \leftrightarrow W^*_{B-L}$, and $\theta \leftrightarrow \bar{\theta}$. Here the transformations apply to the respective superfields. As a consequence, $\mathbf{Y}_q = \mathbf{Y}_q^\dagger$,

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Lepton Dipole Moments and Rare Decays in the CP-violating MSSM with Nonuniversal Soft-Supersymmetry Breaking

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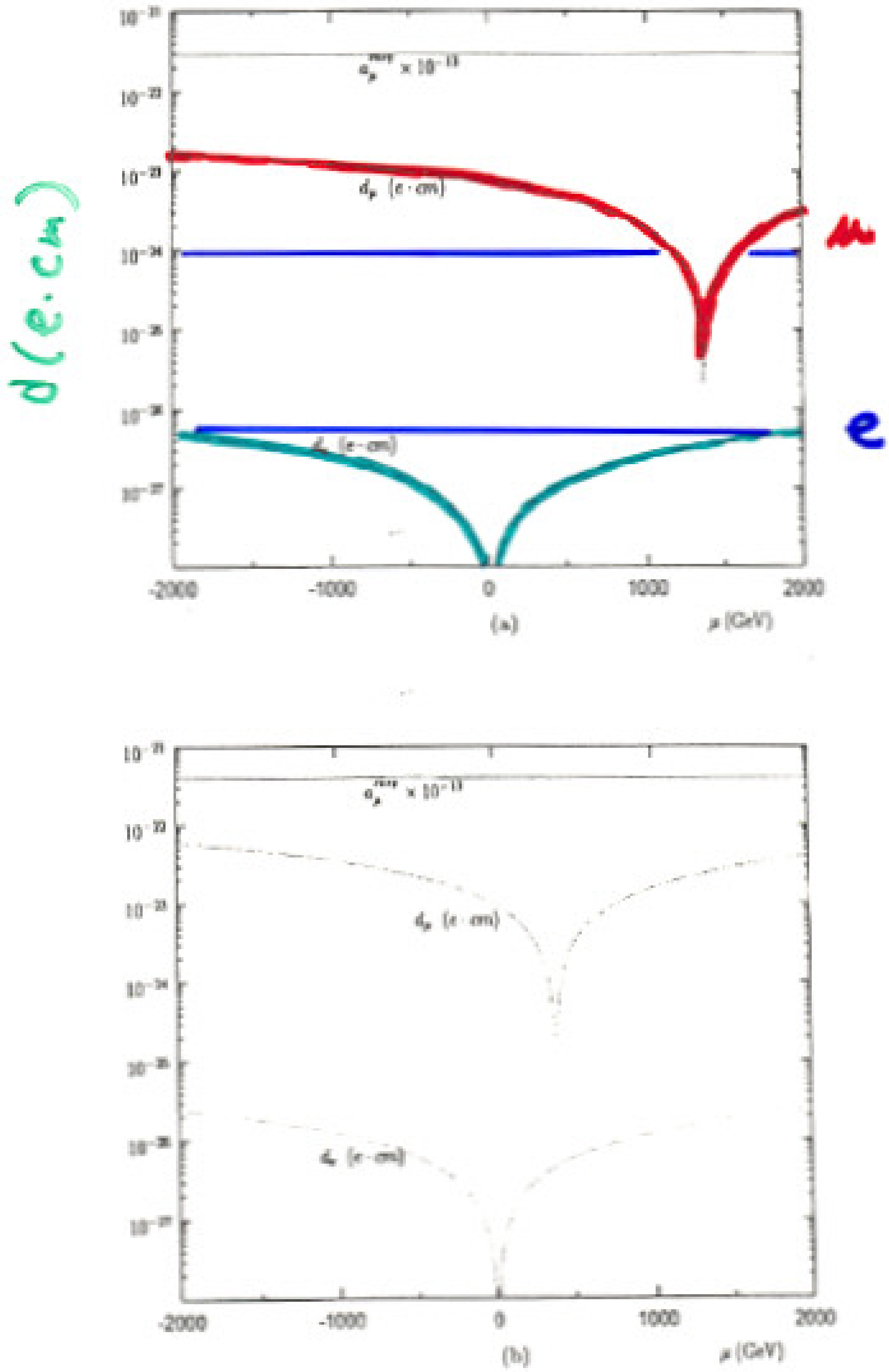
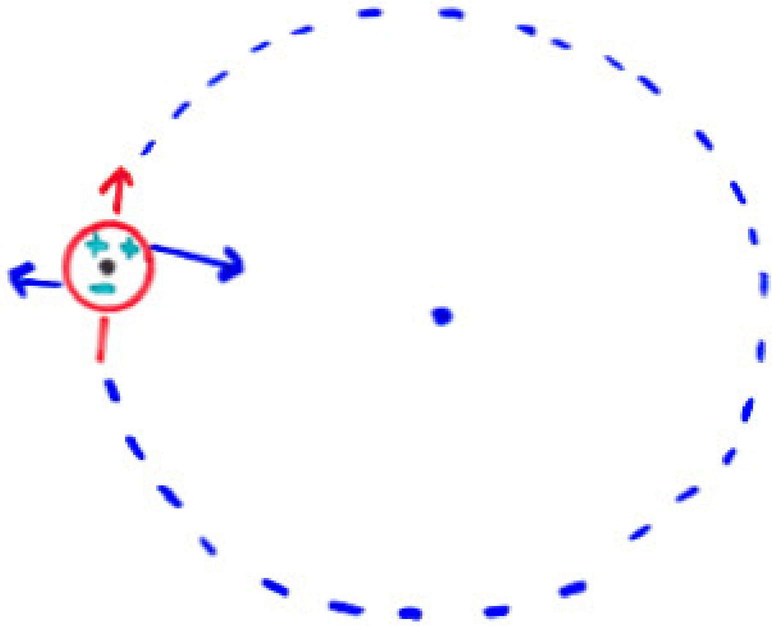


Figure 6: The muon's MDM and EDM, the electron's EDM verus the parameter μ in MSSM with (a)$\tan\beta = 5$, (b)$\tan\beta = 50$; the other parameters are the same as in the text.



$g = 2$

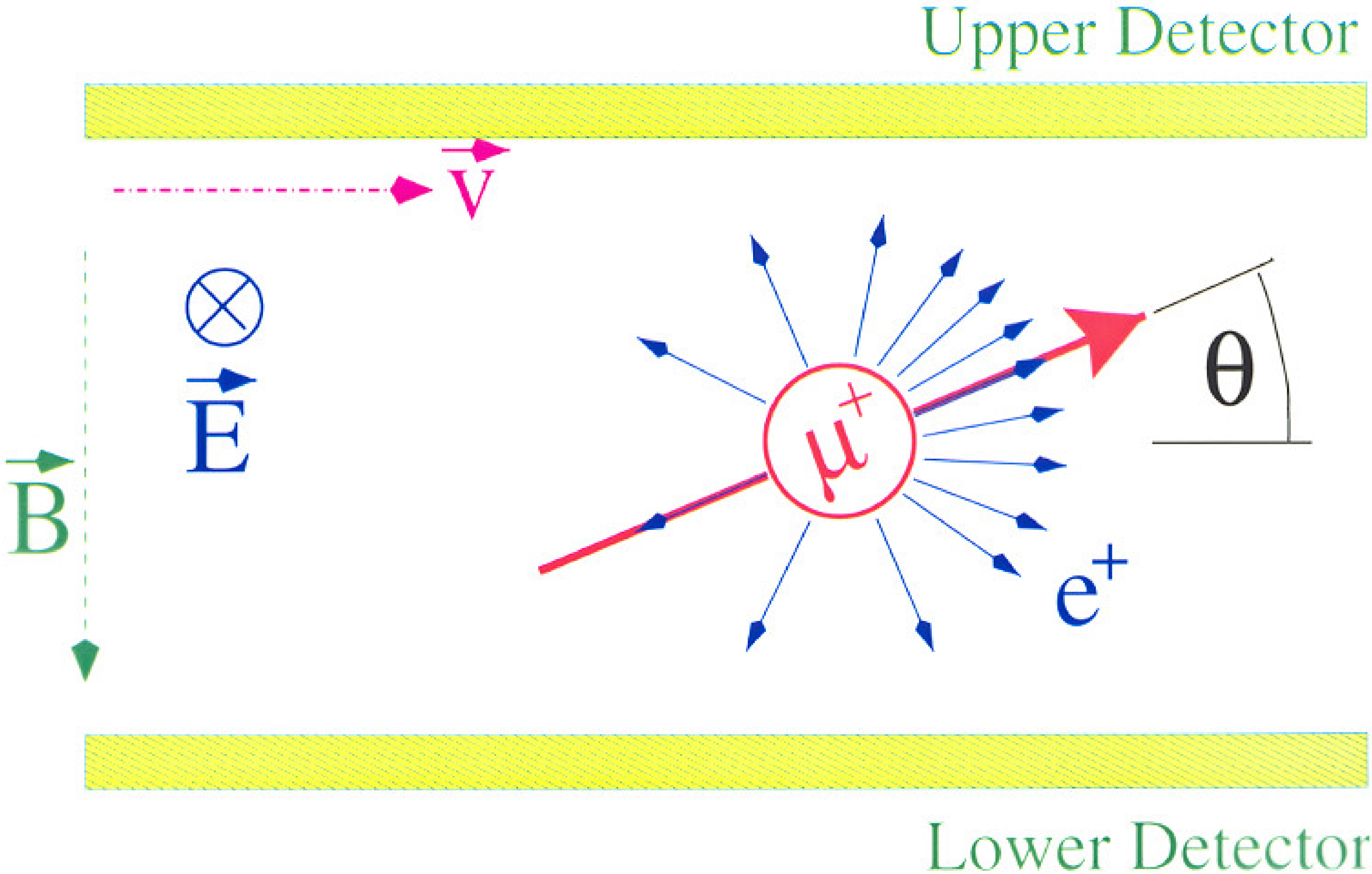
$$\vec{F} = ec\,\vec{\beta} \times \vec{B}$$

$$\frac{d\vec{S}}{dt} = \vec{d} \times (c\vec{\beta} \times \vec{B})$$

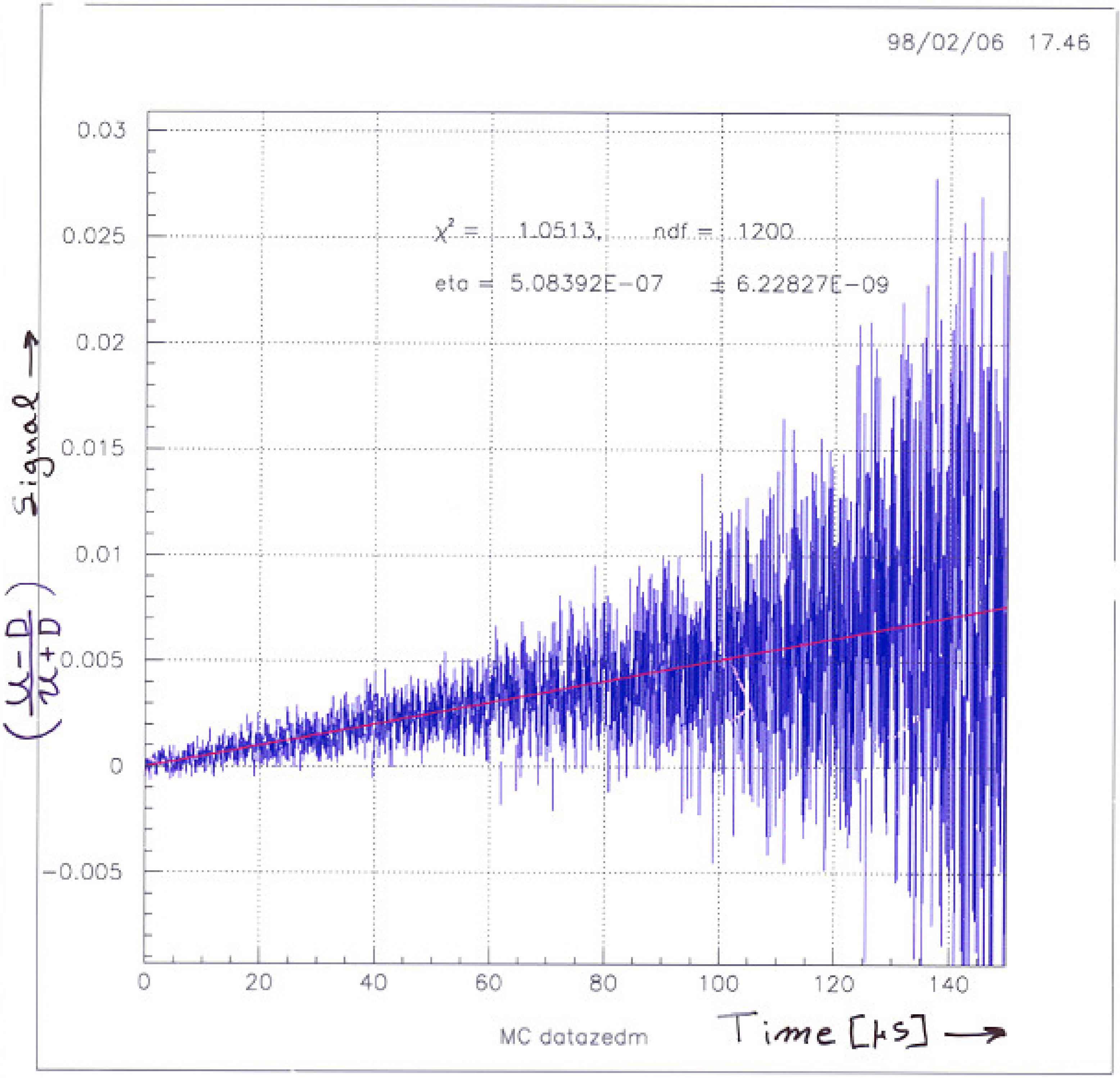
$$\vec{\omega}_a = -\frac{e}{mc}\left[a\vec{B} + \left(\frac{1}{\gamma^2 - 1} - a\right)\vec{\beta} \times \vec{E}\right]$$

Apply $E \simeq aBc\beta\gamma^2$ to cancel $g-2$

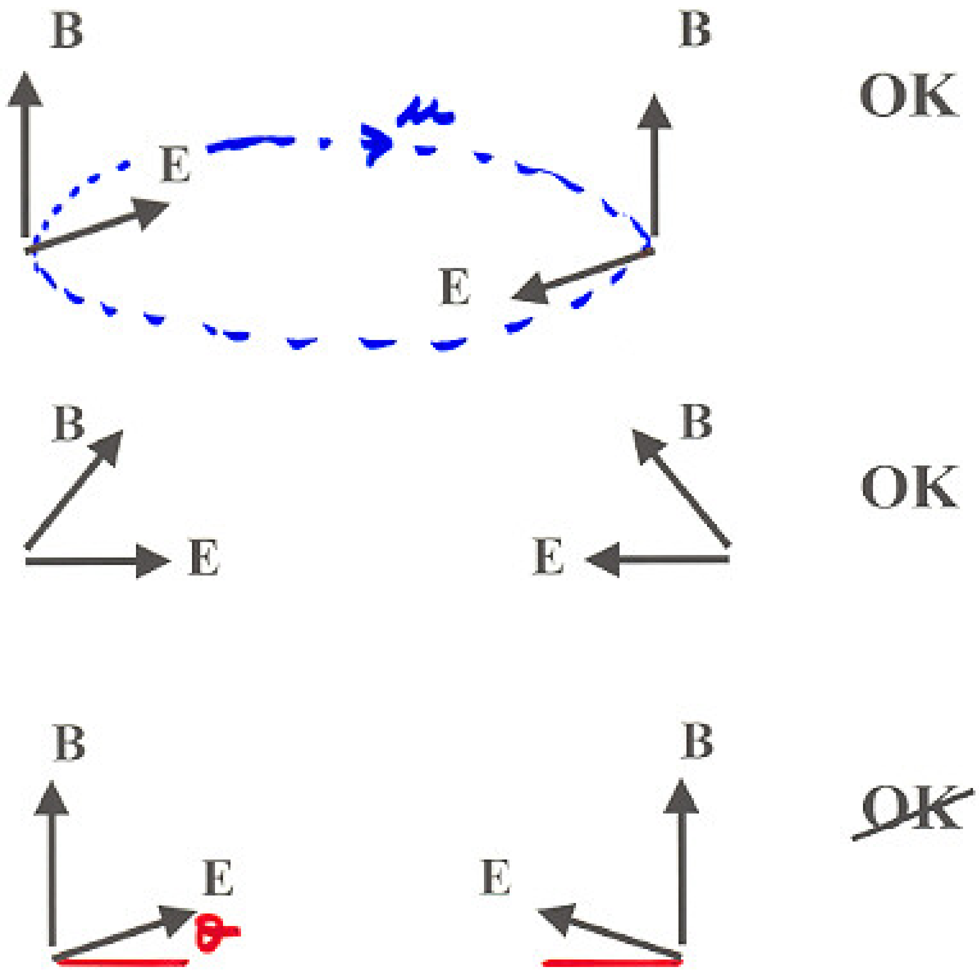
$$a = \frac{(g-2)}{2}$$



(b)


98/02/06 17.46
χ² = 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
(U-D / U+D) Signal →
MC datazedm
Time [μs] →

Beam/Spin Dynamics Systematic Errors



For muon edm ≈ 10^{-24} e-cm, $\theta \approx 0.01\mu$rad.

To cancel g-2 $E \simeq aBc\beta\gamma^2$ $a = (g-2)/2$

$$f = \frac{a\sqrt{1+p^2/m^2}}{m}$$

Table 4: The factor f for different particles. $p \approx 0.5$ GeV/c

Particle	S	a	$(1+p^2/m^2)^{1/2}$	m (MeV/c^2)	f
μ	1/2	0.001166	≈ 5	105	0.054
p	1/2	1.793	≈ 1	938	1.912
d	1	-0.143	≈ 1	1876	-0.076

Table 5: Relative sign of B, E and the spin observable due to the EDM and from non-planar fields for muons and deuterons when injecting CW and CC. Both longitudinal (L) and radial (R) polarizations are possible with the deuteron.

Mode	B-field direction	E-field direction	EDM	E_{NP}, etc.
μ^+ CW	up	in	$+d_\mu$	$+E_{NP}$
μ^+ CC	down	in	$-d_\mu$	$+E_{NP}$
μ^- CW	down	out	$+d_\mu$	$+E_{NP}$
μ^- CC	up	out	$-d_\mu$	$+E_{NP}$
D_L CW	up	out	$+d_d/5$	+~~12~~ 6 E_{NP}
D_L CC	down	out	$-d_d/5$	+~~12~~ E_{NP}
D_R CW	up	out	0	0
D_R CC	down	out	0	0

Clockwise (CW)
Counter clockwise (CC)

www.bnl.gov/edm

J-PARC Letter of Intent: Search for a Permanent Muon Electric Dipole Moment at the 10^{-24} e · cm Level.

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Table 2: Main parameters of PRISM-II FFAG.

Parameters	normal conducting	super-conducting
number of sector	32	16
k value	50	15
transition gamma	7.1	4
orbit excursion	0.50 m	0.77 m
average radius	21 m	10 m
B@F/D	1.8 T	2.8 T
F/2 angle	0.026 rad	0.052 rad
D angle	0.018 rad	0.036 rad
F/2 bend angle	17 degree	26 degree
packing f	0.45	0.46
phase advance(H/V)	120/61 deg.	131/103 deg.
drift length	2.060 m	2.120 m
BF length	1.104 m	1.065 m
BD length	0.382 m	0.367 m

Table 3: The expected muon yield and NP^2 for the PRISM-II

Muon Momentum	500 MeV/c	350 MeV/c
Momentum Acceptance of the FFAG ring	±30%	±30%
Horizontal and Vertical Acceptance of the muon EDM ring	800 π mm·mrad	800π mm·mrad
Yield of Unpolarized Muon per proton (50 GeV/c)	0.040%	0.025%
Yield of Polarized Muon per proton (50 GeV/c)	0.016%	0.009%
Muon Polarization (Longitudinal)	60%	64%
Expected NP^2 per 10^7 seconds at J-PARC	5×10^{16}	3×10^{16}

need $NP^2 = 10^{16}$ for 10^{-24} e·cm

Y. Orlov

$P_m = 0.5$ GeV/c
N = 16
⟨R⟩ = 11m

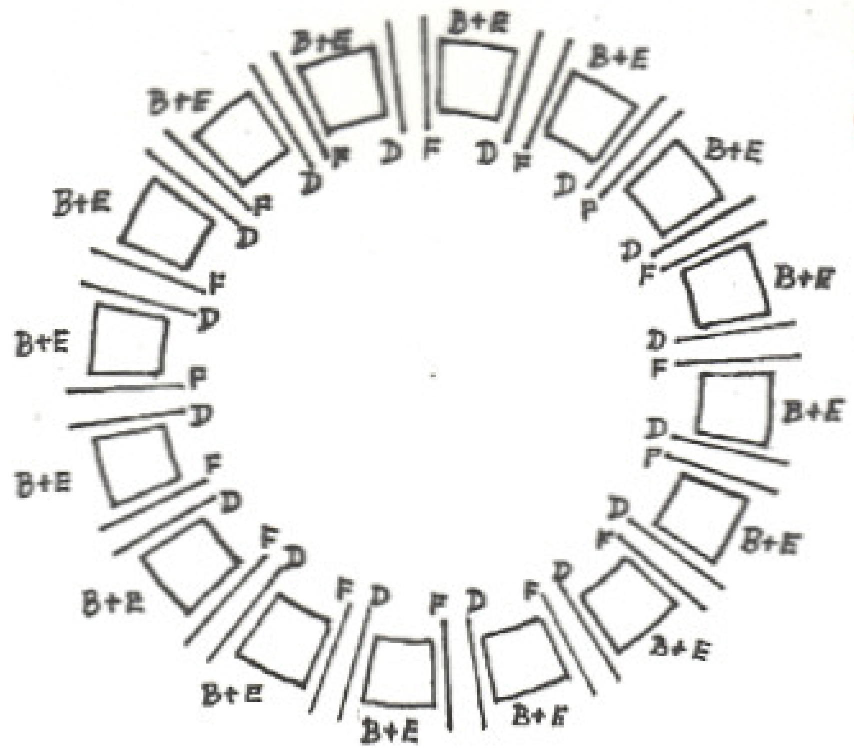


Figure 3: A setup of the EDM ring for the 500 MeV/c case.

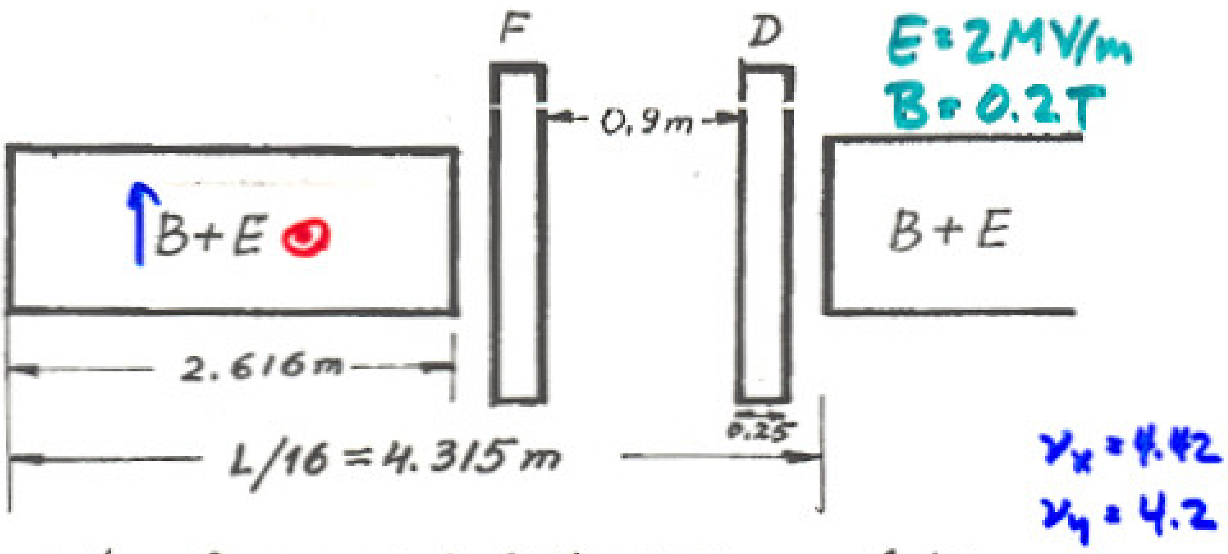
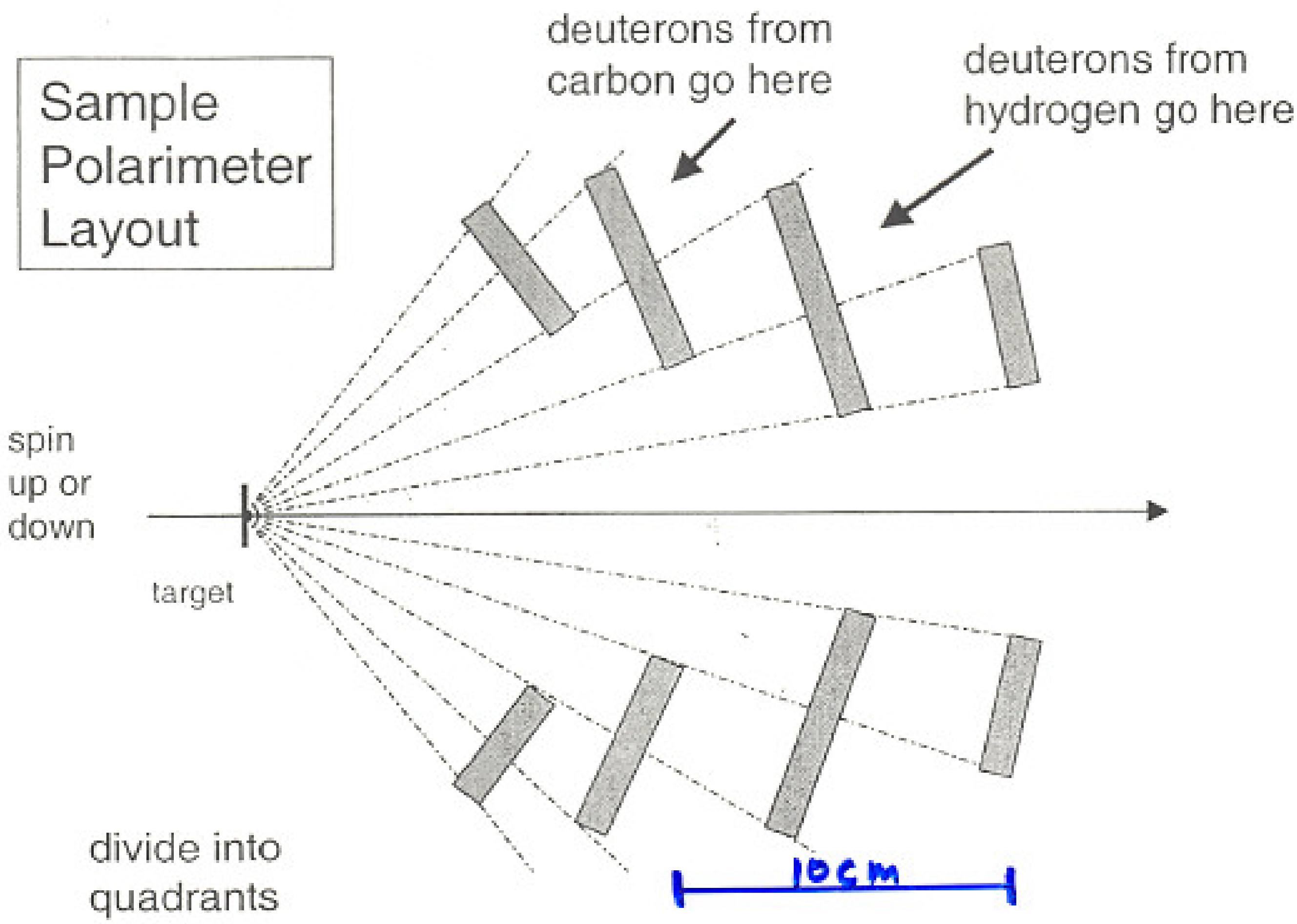
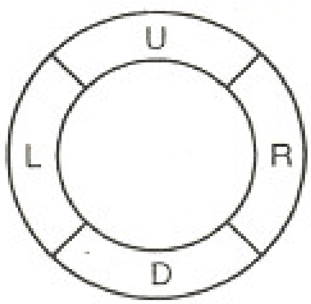


Figure 4: One period of the EDM ring lattice.
The ring contains 16 such periods.

Ed Stephenson I.U.



divide into quadrants



	cross section	$3A_y/2$	
H	17 mb	- 0.38	dp→dp
C	7 mb	- 0.43	dC→dC

With losses at ~2 kb, useful fraction is 1.8×10^{-5}.

Conclusions

- Standard Model prediction unambiguous: $d_\mu \approx 10^{-35}$ e-cm.

- An observation implies T violation from new physics.

- New idea makes sensitive search to 10^{-24} e-cm possible at JPARC ($NP^2 \approx 10^{16}$).

- Systematic errors $< 10^{-24}$ e-cm.

- Then move to NuFact: $NP^2 \approx$??