EDMs and CP-violation
UoW, 19-23 March 2007

deuteron EDM (dEDM) to 10^{-29} e·cm

Yannis K. Semertzidis, BNL
for the Storage Ring EDM Collaboration

- **Storage ring EDM method**
- **Resonance dEDM experiment**
- **Status of dEDM systematic error studies**

$$\frac{d\vec{s}}{dt} = \vec{\mu} \times \vec{B} + \vec{d} \times \vec{E}$$

Experimental Methods of Storage Ring Electric Dipole Moments

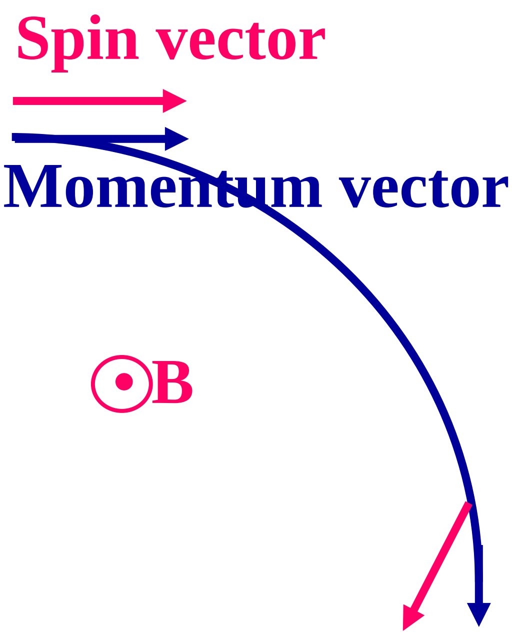
- Parasitic to g-2 (muon)
- Frozen spin (muon)
- Resonance EDM (deuteron, proton, …)

$$\frac{d\vec{s}}{dt} = \vec{\mu} \times \vec{B} + \vec{d} \times \vec{E}$$

Muon g-2 experiment

The Principle of g-2

Non-relativistic case



$$\frac{d\vec{s}}{dt} = \vec{\mu} \times \vec{B}$$

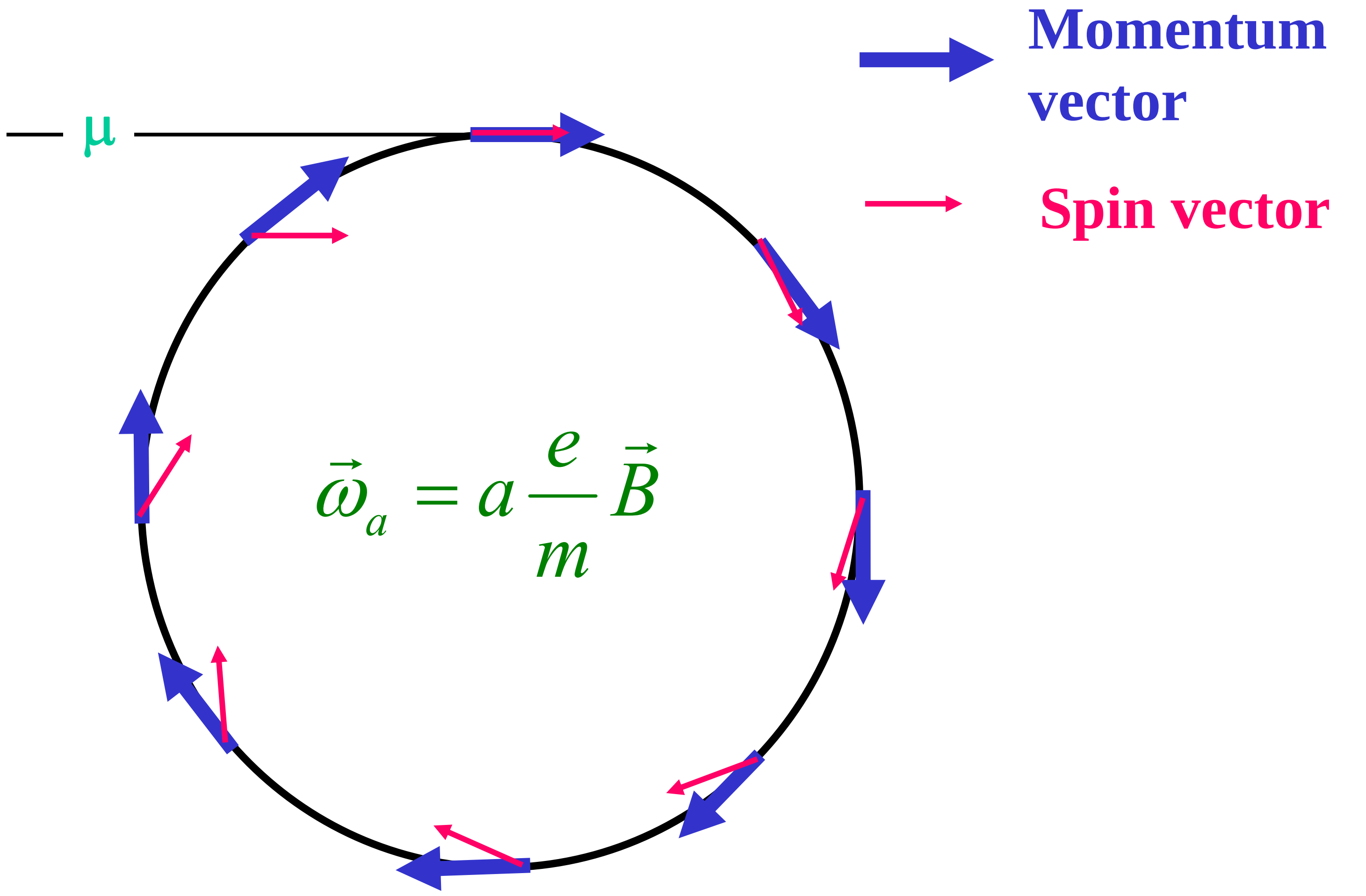
$$\omega_c = \frac{eB}{m}$$

$$\omega_s = \frac{g}{2}\frac{eB}{m}$$

$$\omega_a = \omega_s - \omega_c = \frac{g}{2}\frac{eB}{m} - \frac{eB}{m} = \left(\frac{g-2}{2}\right)\frac{eB}{m} \Rightarrow \boxed{\omega_a = a\frac{eB}{m}}$$

$$\frac{d\vec{s}}{dt} = \vec{\mu} \times \vec{B} + \vec{d} \times \vec{E}$$

Spin Precession in g-2 Ring (Top View)

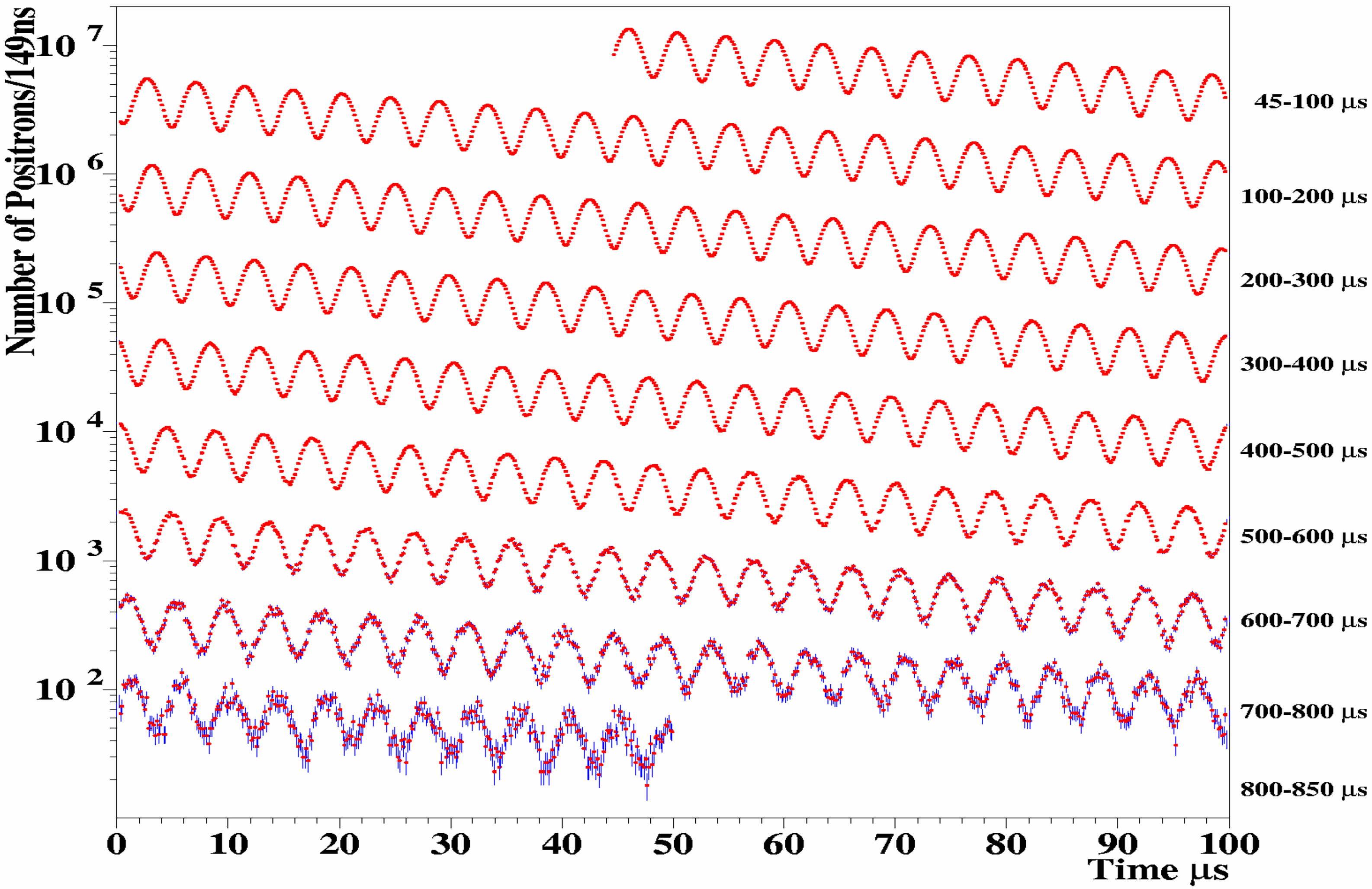


$$\vec{\omega}_a = a\frac{e}{m}\vec{B}$$

$$\frac{d\vec{s}}{dt} = \vec{\mu} \times \vec{B} + \vec{d} \times \vec{E}$$

4 Billion e^+ with E>2GeV

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



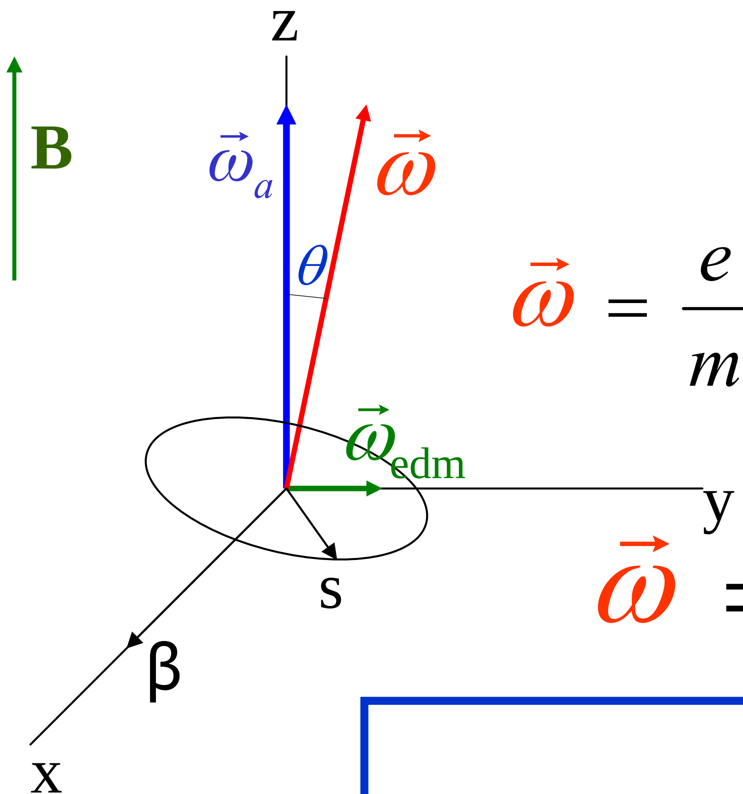
Electric Dipole Moments in Storage Rings

$$\frac{d\vec{s}}{dt} = \vec{d} \times \left(\vec{v} \times \vec{B} \right)$$

e.g. 1T corresponds to 300 MV/m for relativistic particles

$$\frac{d\vec{s}}{dt} = \vec{\mu} \times \vec{B} + \vec{d} \times \vec{E}$$

Indirect Muon EDM limit from the g-2 Experiment



$$\vec{\omega} = \frac{e}{m}\left\{a\vec{B} + \frac{\eta}{2c}\left(\vec{v}\times\vec{B}\right)\right\}$$

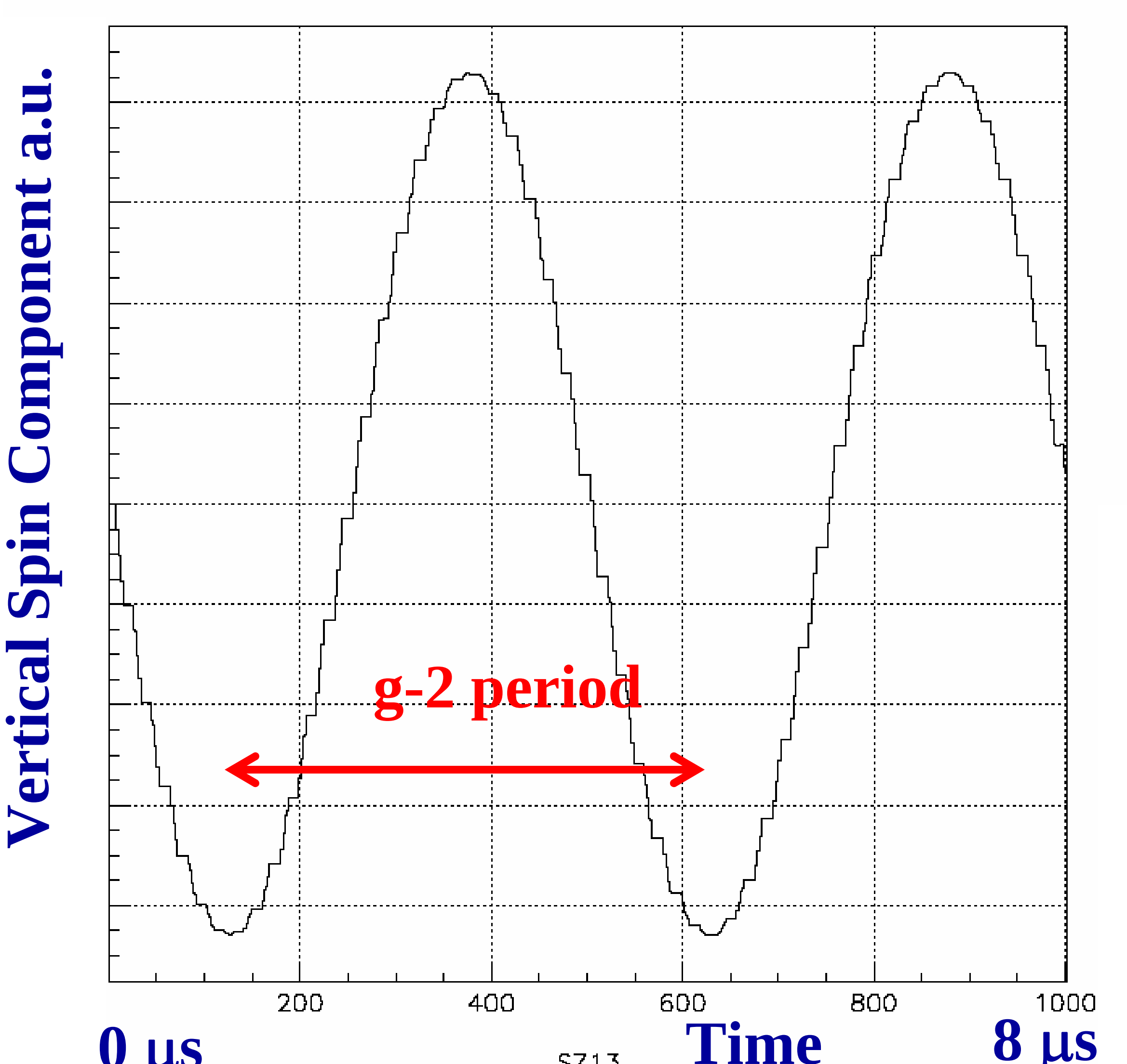
$$\vec{\omega} = \vec{\omega}_a + \vec{\omega}_{\text{edm}}$$

$$\tan\theta = \frac{\omega_{edm}}{\omega_a}$$

Ron McNabb's Thesis 2003: $< 2.7\times 10^{-19}\,\mathrm{e}\cdot\mathrm{cm}$ 95% C.L.

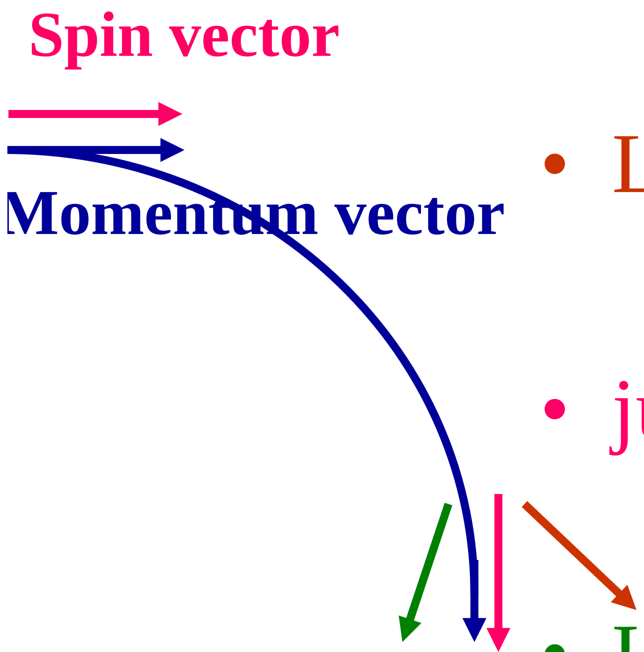
$$\frac{d\vec{s}}{dt} = \vec{\mu}\times\vec{B} + \vec{d}\times\vec{E}$$

The Vertical Spin Component Oscillates due to EDM



$\vec{E}$

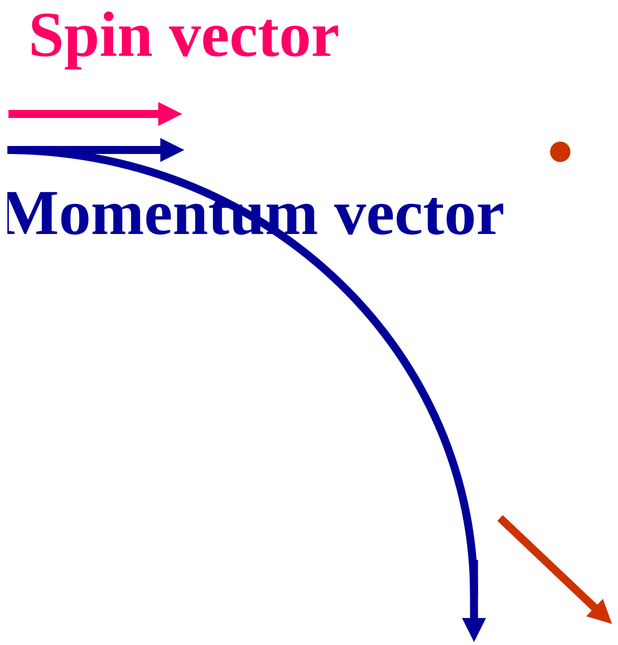
Effect of Radial Electric Field



- Low energy particle
- just right, magic momentum
- High energy particle

$$\frac{d\vec{s}}{dt} = \vec{\mu} \times \vec{B} + \vec{d} \times \vec{E}$$

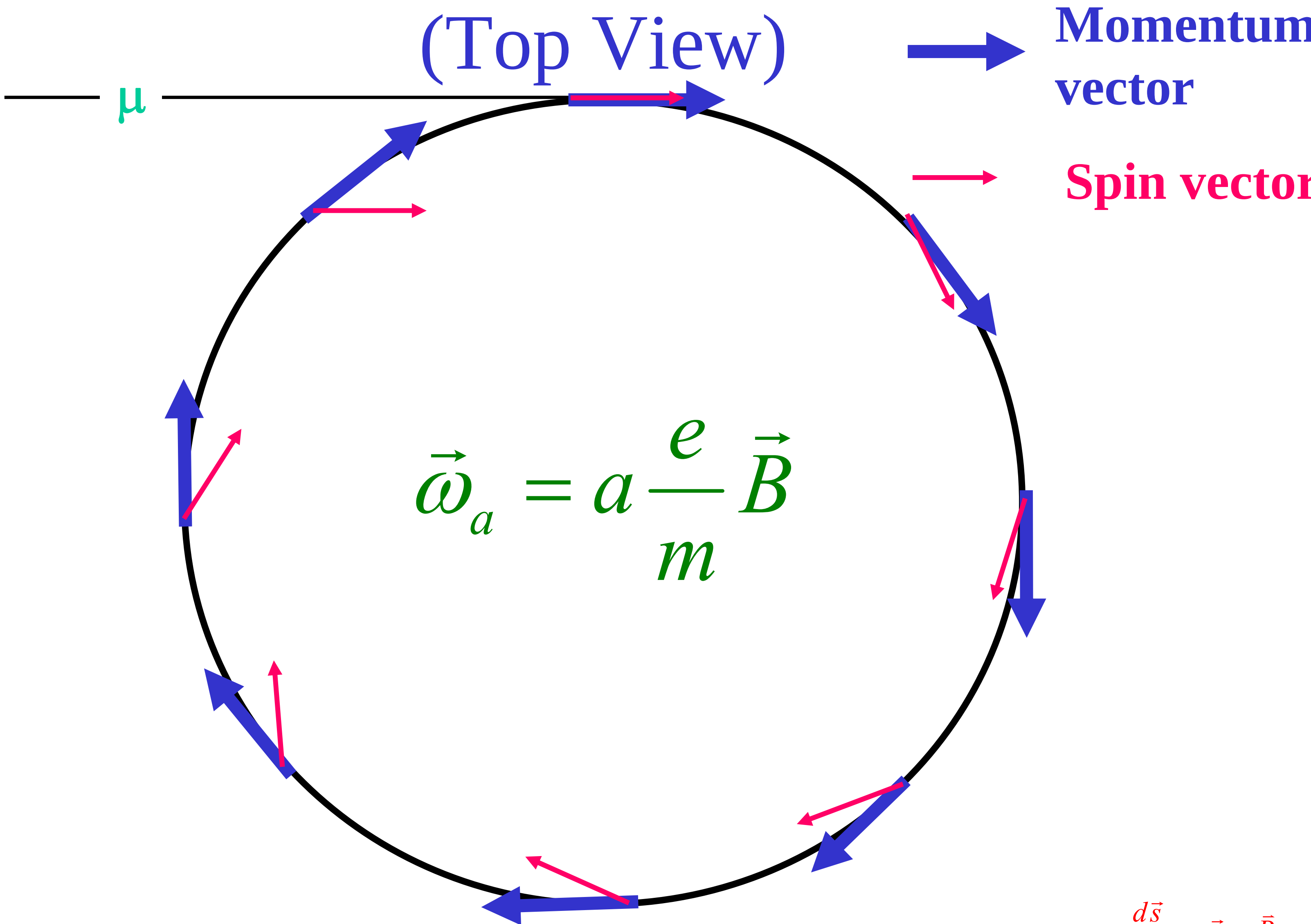
Use a Radial Electric Field and a



- Low energy particle

$$\frac{d\vec{s}}{dt} = \vec{\mu} \times \vec{B} + \vec{d} \times \vec{E}$$

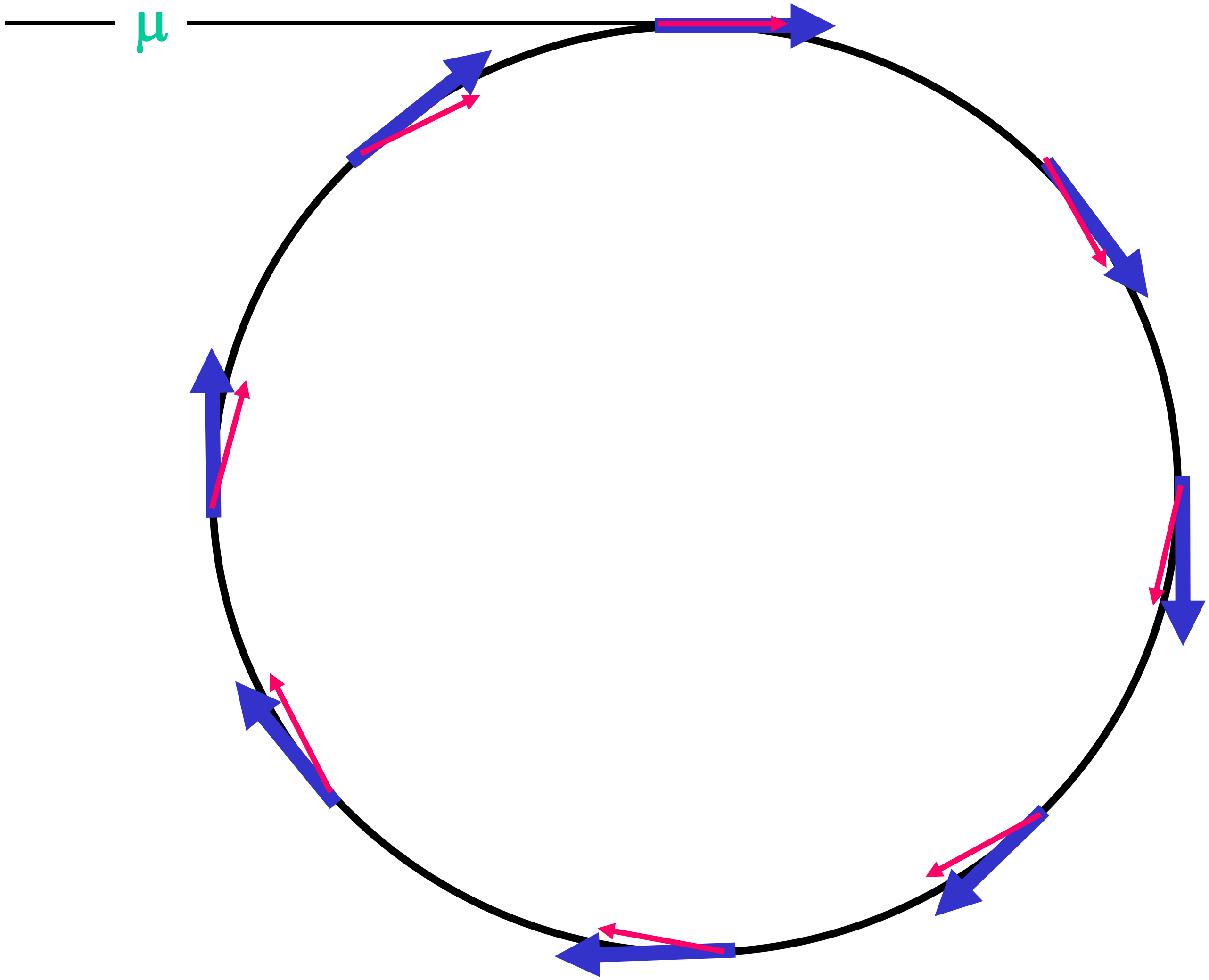
Spin Precession in g-2 Ring (Top View)



$$\vec{\omega}_a = a\frac{e}{m}\vec{B}$$

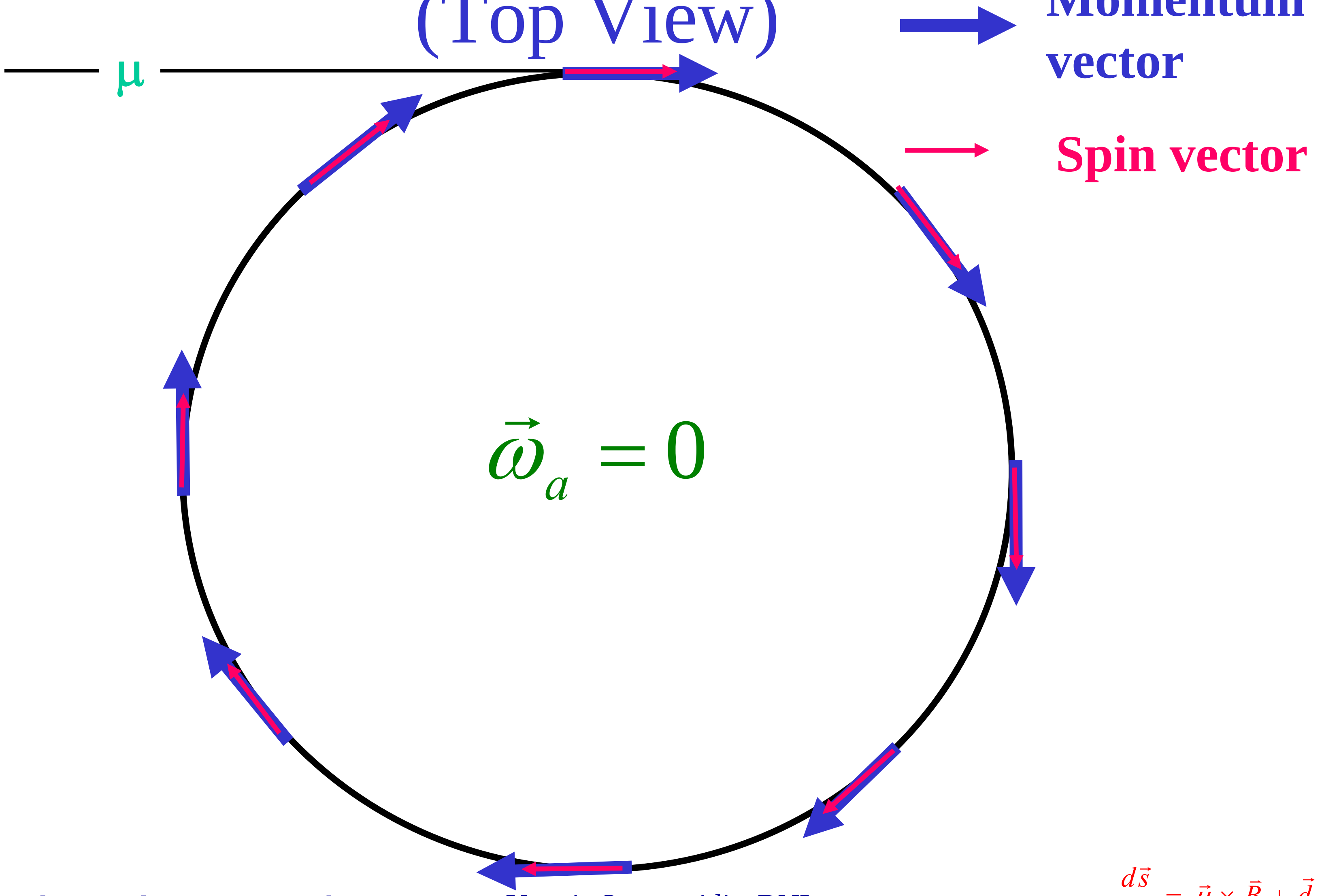
$$\frac{d\vec{s}}{dt} = \vec{\mu}\times\vec{B} + \vec{d}\times\vec{E}$$

Lowering the B-field and applying a radial E-field to keep the muons in the same orbit…



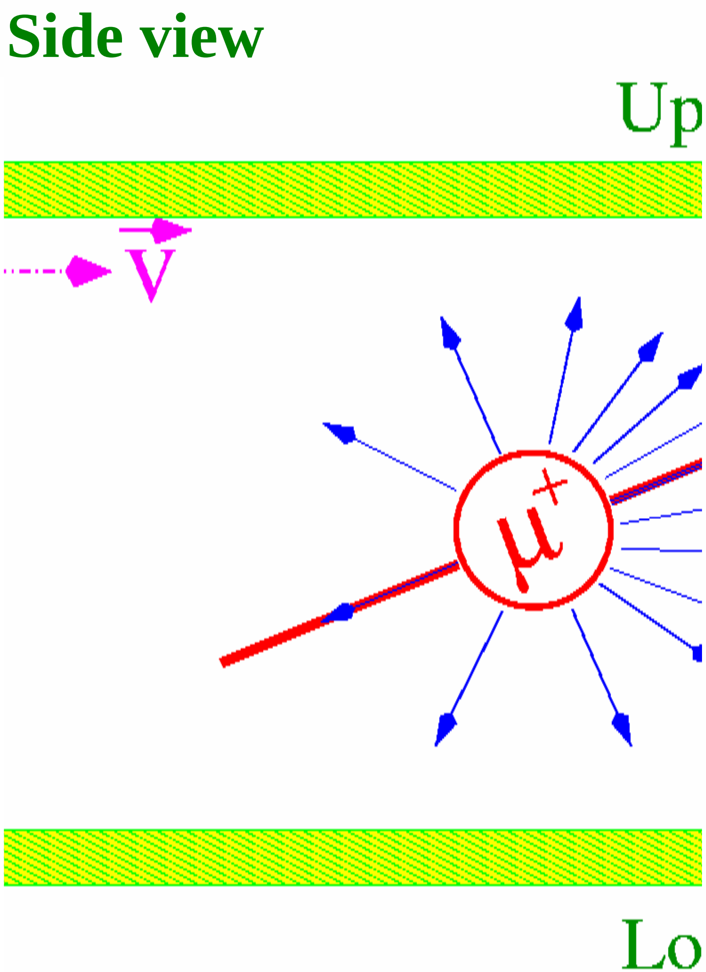
$$\frac{d\vec{s}}{dt} = \vec{\mu} \times \vec{B} + \vec{d} \times \vec{E}$$

Spin Precession in EDM Ring (Top View)



$$\frac{d\vec{s}}{dt} = \vec{\mu} \times \vec{B} + \vec{d} \times \vec{E}$$

(U-D)/(U+D) Signal vs. Time



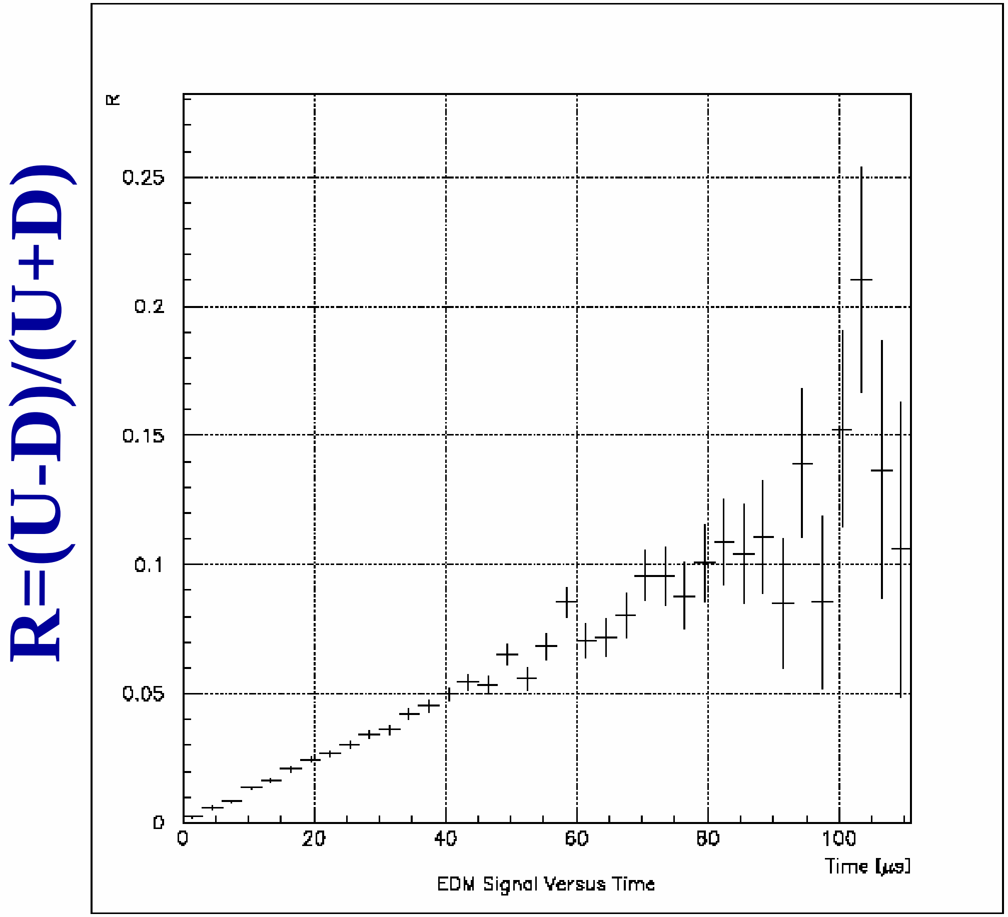


Figure 3: MC simulation of the muon EDM signal, $R = \frac{N_{up} - N_{down}}{N_{up} + N_{down}}$, versus time.

$$\frac{d\vec{s}}{dt} = \vec{\mu} \times \vec{B} + \vec{d} \times \vec{E}$$

Muon EDM Letter of Intent to J-PARC/Japan, 2003

J-PARC Letter of Intent: Search for a Permanent Muon

Electric Dipole Moment at the $10^{-24}\,e \cdot cm$ Level.

A. Silenko, **Belarusian State University, Belarus**

R.M. Carey, V. Logashenko, K.R. Lynch, J.P. Miller†, B.L. Roberts

Boston University

G. Bennett, D.M. Lazarus, L.B. Leipuner, W. Marciano,

W. Meng, W.M. Morse, R. Prigl, Y.K. Semertzidis†

Brookhaven National Lab

V. Balakin, A. Bazhan, A. Dudnikov, B. Khazin, I.B. Khriplovich, G. Sylvestrov

BINP, Novosibirsk

Y. Orlov, **Cornell University**

K. Jungmann, **Kernfysisch Versneller Instituut, Groningen**

P.T. Debevec, D.W. Hertzog, C.J.G. Onderwater, C. Ozben

University of Illinois

E. Stephenson, **Indiana University**

M. Auzinsh, **University of Latvia**

P. Cushman, Ron McNabb, **University of Minnesota**

N. Shafer-Ray, **University of Oklahoma**

K. Yoshimura, **KEK, Japan**

M. Aoki, Y. Kuno#, A. Sato, **Osaka, Japan**

M. Iwasaki, **RIKEN, Japan**

F.J.M. Farley, V.W. Hughes, **Yale University**

†Spokesperson

Resident Spokesperson

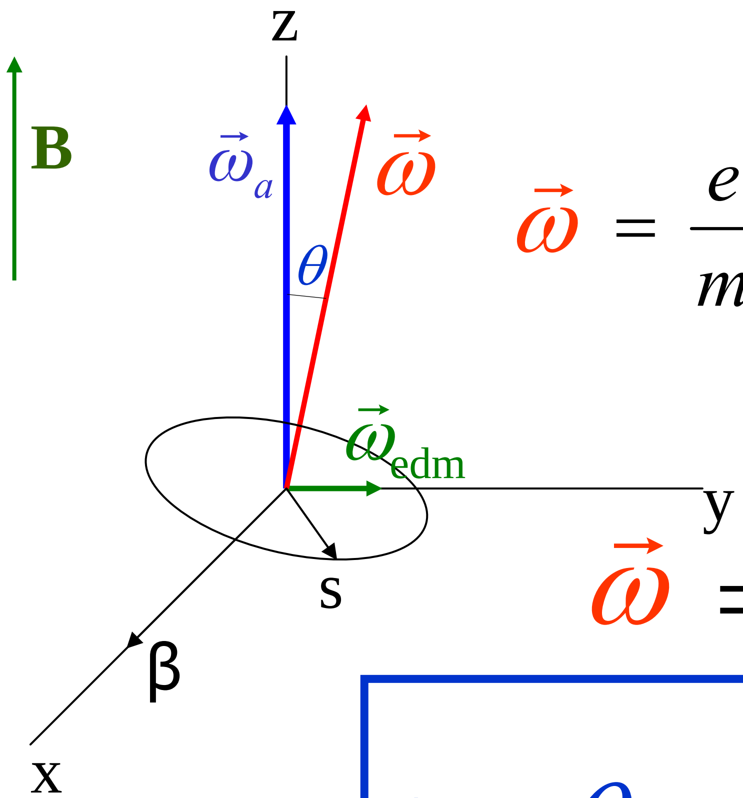
January 9, 2003

$\vec{E}$

Muon EDM exp. at PSI?

See next talk by Klaus Kirch using an ingenious version of the frozen spin method…!

$$\frac{d\vec{s}}{dt} = \vec{\mu} \times \vec{B} + \vec{d} \times \vec{E}$$

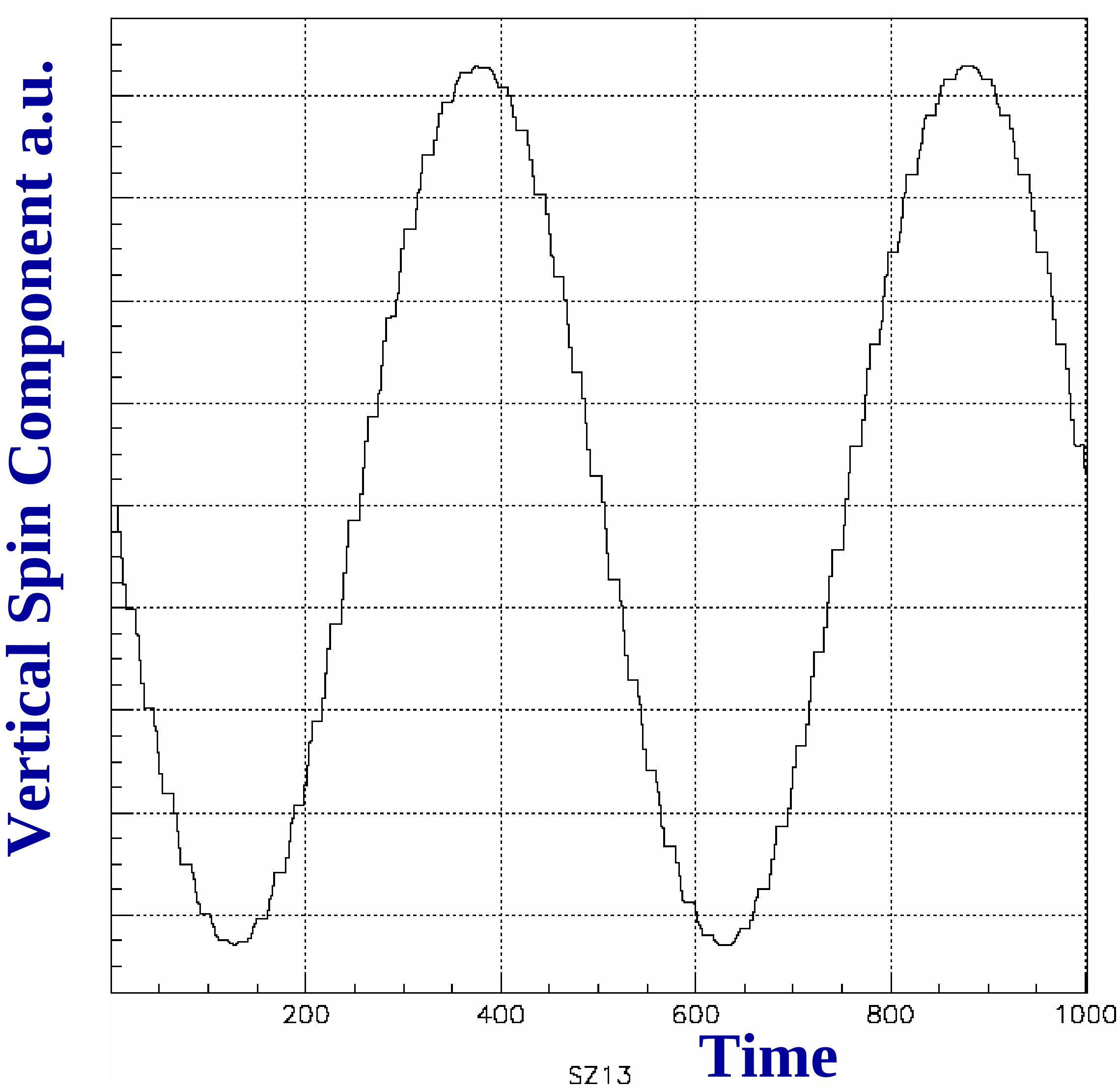


$$\vec{\omega} = \frac{e}{m}\left\{a\vec{B} + \frac{\eta}{2c}\left(\vec{v}\times\vec{B}\right)\right\}$$

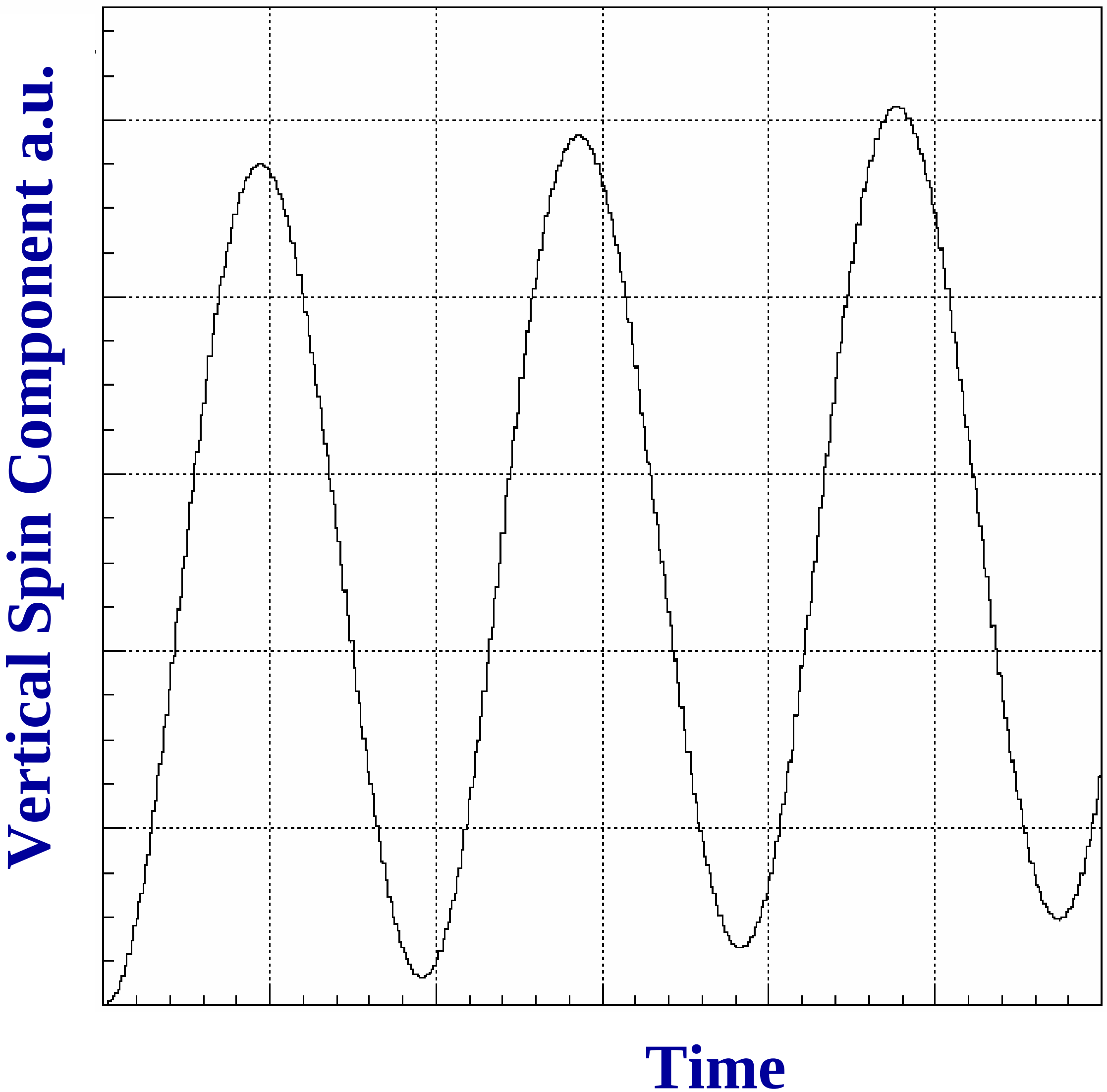
$$\vec{\omega} = \vec{\omega}_a + \vec{\omega}_{\text{edm}}$$

$$\boxed{\tan\theta = \frac{\omega_{edm}}{\omega_a}}$$

Vertical Spin Component without Velocity Modulation (deuterons)

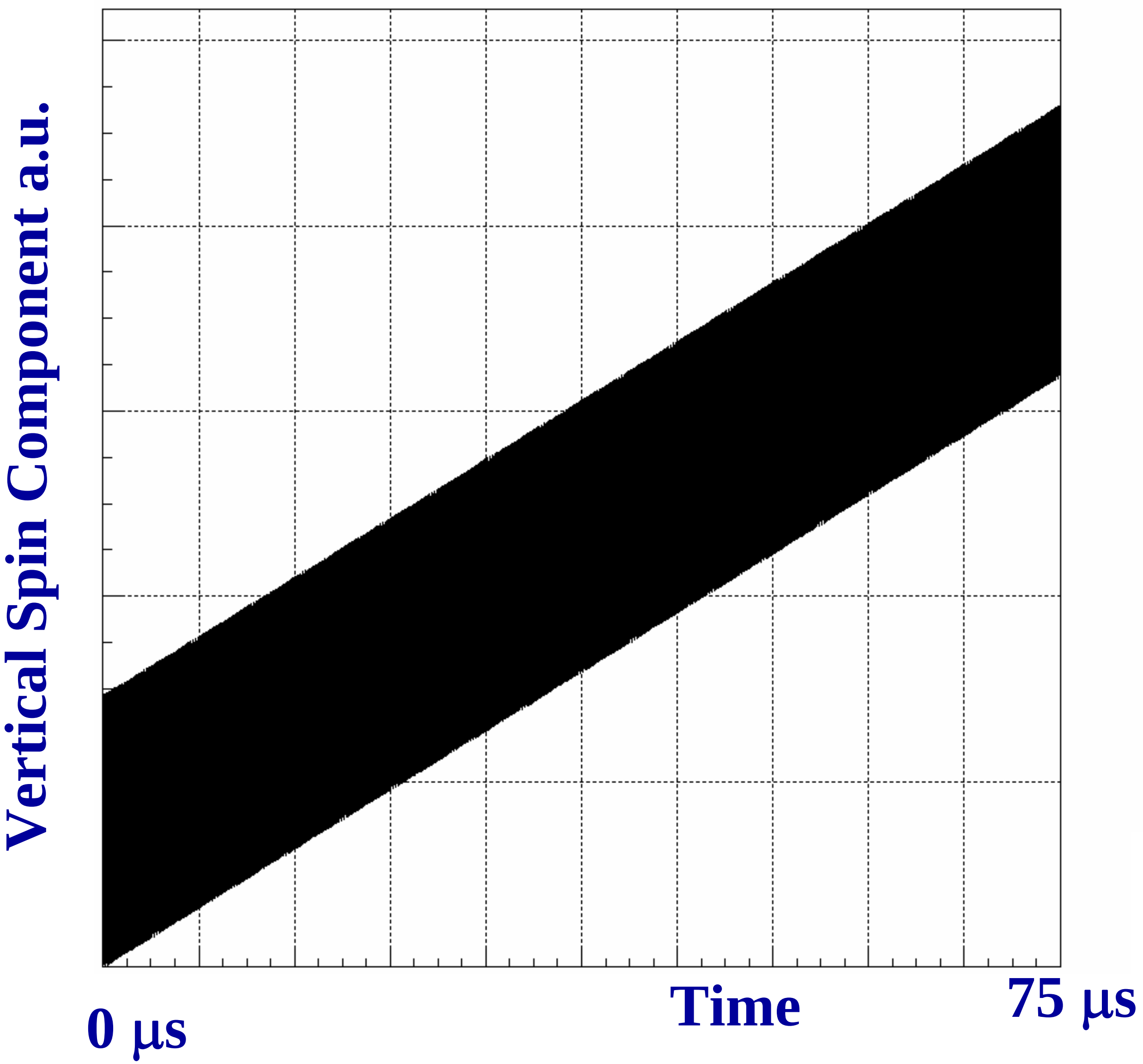


Vertical Spin Component with Velocity Modulation at ω_a



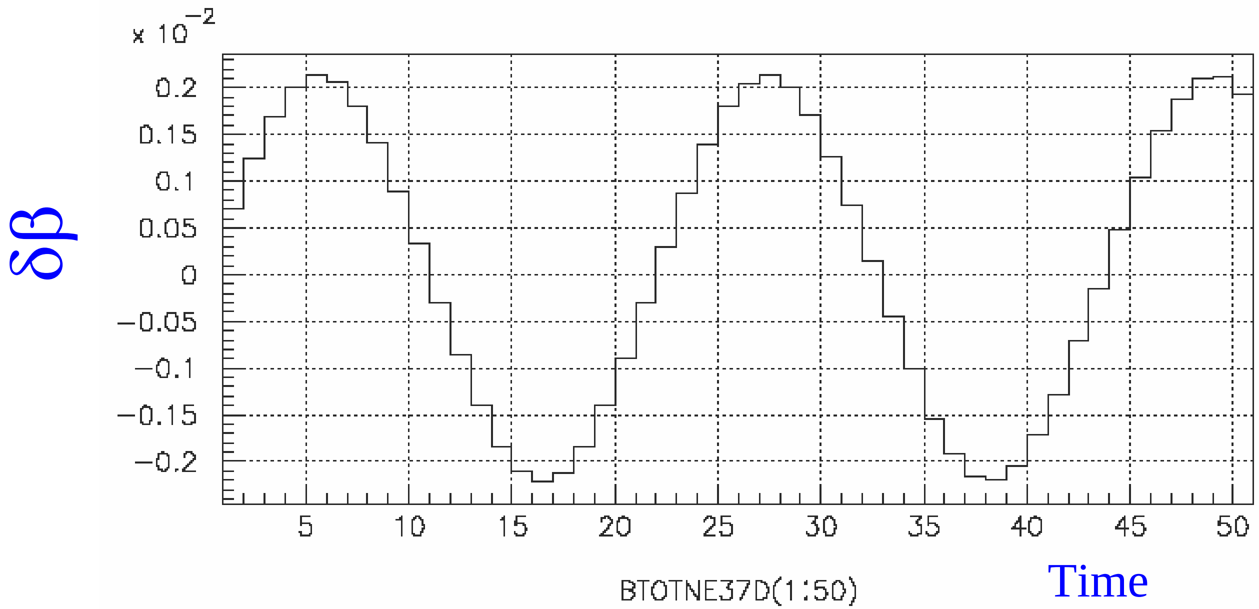
$\vec{E}$

Vertical Spin Component with Velocity Modulation (longer Time)

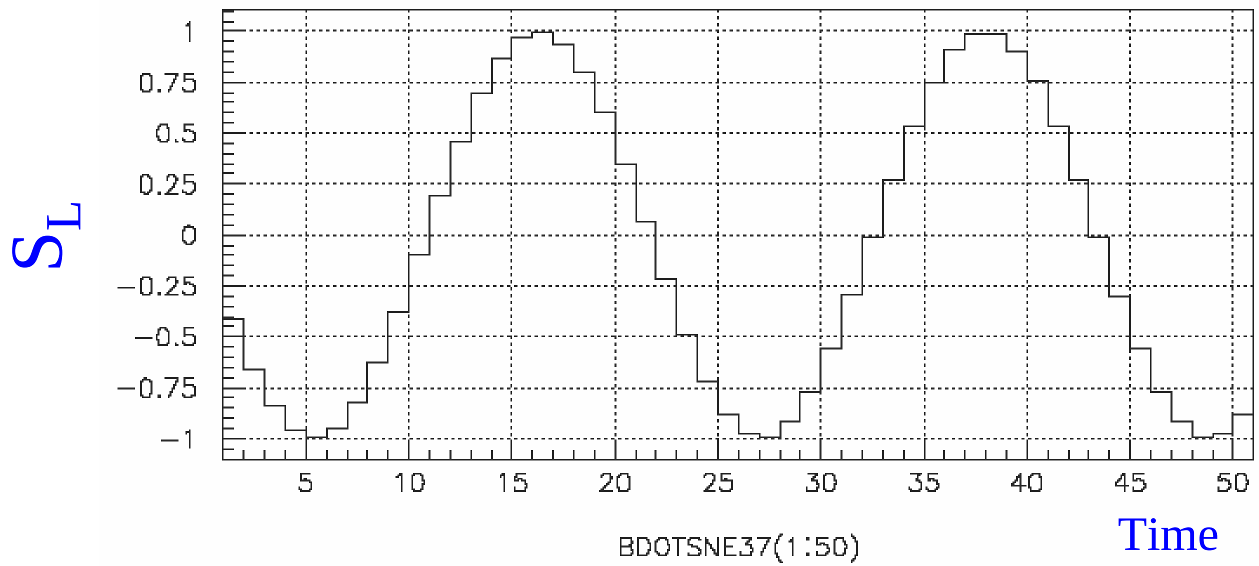


$+ \vec{d} \times \vec{E}$

Velocity (top) and g-2 oscillations



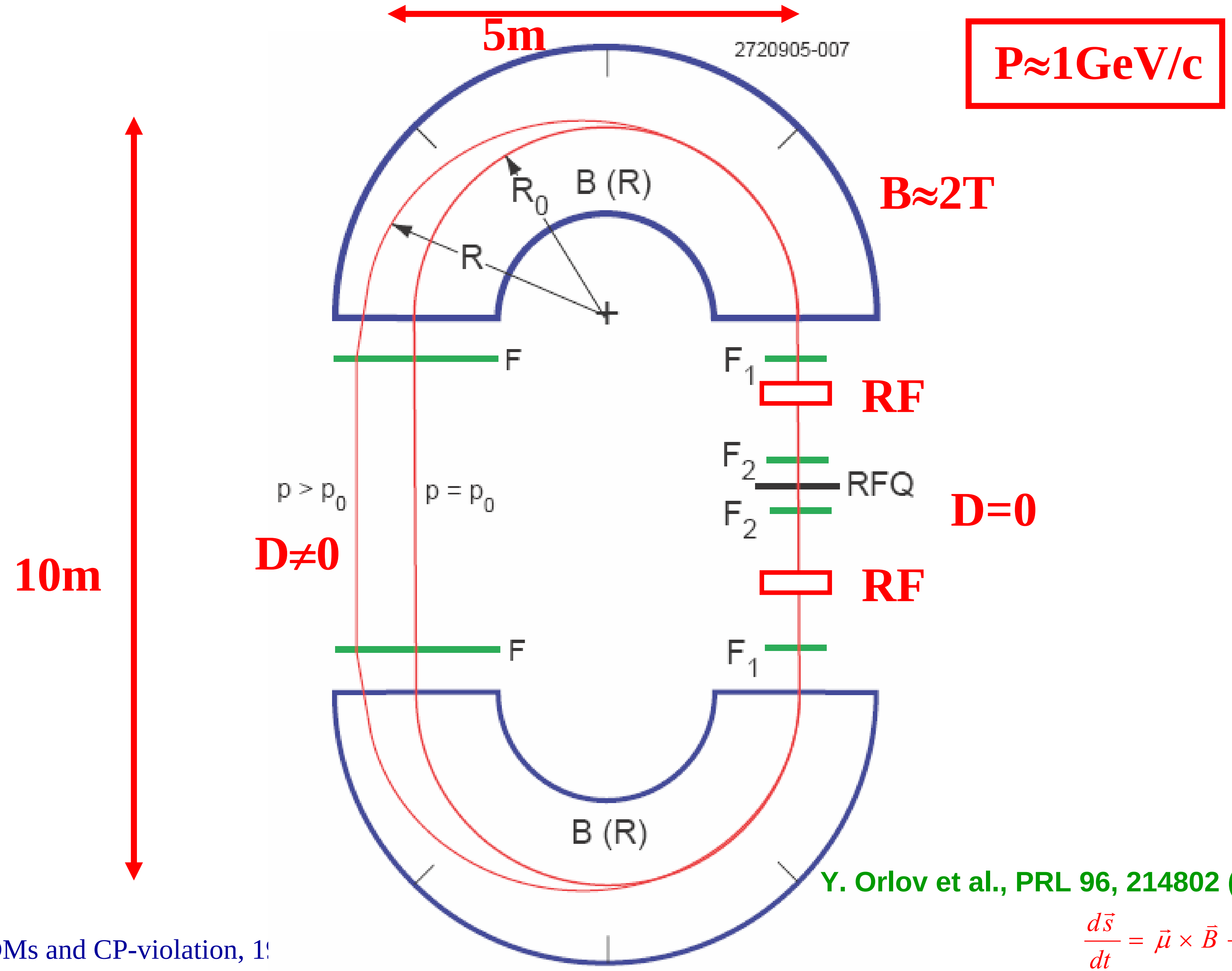
Particle velocity oscillations



Particle S_L oscillations **(i.e. g-2 oscillations)**

The synchrotron oscillation phase (top) compared to g-2 phase (bottom). ~5us total horizontal scale $\frac{d\vec{s}}{dt} = \vec{\mu} \times \vec{B} + \vec{d} \times \vec{E}$

The Orlov lattice



Y. Orlov et al., PRL 96, 214802 (2006)

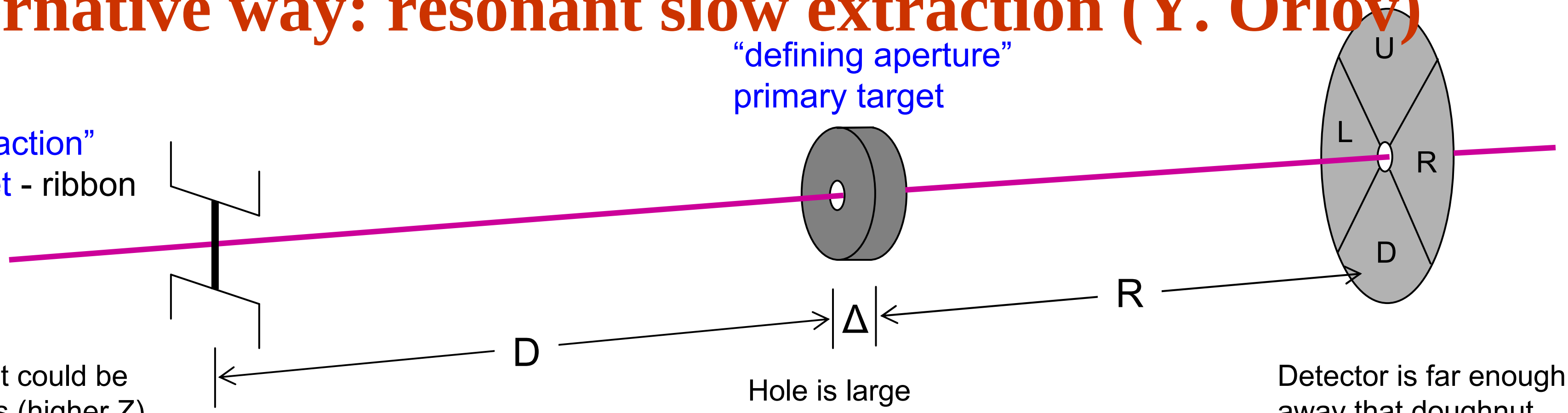
$$\frac{d\vec{s}}{dt} = \vec{\mu} \times \vec{B} + \vec{d} \times \vec{E}$$

Nuclear Scattering as Deuteron EDM polarimeter

Ed Stephenson's

IDEA:
- make thick target defining aperture
- scatter into it with thin target

Alternative way: resonant slow extraction (Y. Orlov)



Target could be Ar gas (higher Z).

Target "extracts" by Coulomb scattering deuterons onto thick main target. There's not enough good events here to warrant detectors.

Hole is large compared to beam. Every-thing that goes through hole stays in the ring.

Detector is far enough away that doughnut illumination is not an acceptance issue: Δ < R.

$$\frac{d\vec{s}}{dt} = \vec{\mu} \times \vec{B} + \vec{d} \times \vec{E}$$

Why resonance EDM?

- **Resonance EDM method using 1.5GeV/c deuterons in a 5m×10m storage ring seems possible**

- **Using well established accelerator techniques**

- **EDM Study of d, P, ^{3}He, … is possible with same method**

$$\frac{d\vec{s}}{dt} = \vec{\mu} \times \vec{B} + \vec{d} \times \vec{E}$$

Why resonance deuteron EDM?

- High intensity (~10^{12}/cycle), highly polarized, low emittance deuteron beams are available
- Interact in a strong E-field (Coherent synchrotron tune equals the g-2 tune → Rabi resonance: Effective rest frame E-field is oscillating at the g-2 frequency)
- deuteron polarimeters are available, with high analyzing power for ~1.5 GeV/c d-momentum

$$\frac{d\vec{s}}{dt} = \vec{\mu} \times \vec{B} + \vec{d} \times \vec{E}$$

Major Concepts in Place:

- Polarized source, spin manipulation, high efficiency injection
- Analyzing method
- Spin Dynamics
- Systematics

$$\frac{d\vec{s}}{dt} = \vec{\mu} \times \vec{B} + \vec{d} \times \vec{E}$$

Deuteron Statistical Error:

$$\sigma_d \approx \frac{13\hbar}{\delta\beta_0 c \langle B \rangle AP\sqrt{N_c f \tau_p T_{Tot}}}$$

τ_p : 1000s **Polarization Lifetime (Coherence Time)**

A : 0.36 **The left/right asymmetry observed by the polarimeter**

P : 0.95 **The beam polarization**

N_c : 10^{12}d/cycle **The total number of stored particles per cycle**

T_{Tot}: 5000h/yr. **Total running time per year**

f : 0.042 **Useful event rate fraction**

$\delta\beta_0/\beta_0$: 0.01 **Velocity modulation**

$<B>$: 1.2T **The average magnetic field around the ring**

$$\sigma_d \approx 2\times 10^{-29}\, \text{e}\cdot\text{cm / year}$$

Why deuteron EDM?

$$d_D \sim 10^{-24}\, e \cdot cm \;\; \sin \delta_{SUSY} \left(\frac{1 TeV}{M} \right)^2$$

At 10^{-29} e·cm, the mass probed is M ~ 300 TeV. If there is new physics at the LHC energy scale, it can probe δ_{SUSY} to 10^{-5} rad. Both are well beyond the LHC design sensitivity.

$$\frac{d\vec{s}}{dt} = \vec{\mu} \times \vec{B} + \vec{d} \times \vec{E}$$

Why deuteron EDM?

Comparison With Other EDM Efforts

	Current Bound	Future Goal	$\sim d_n$ Equivalent
Neutron	$d_n < 3\times10^{-26}$ e-cm	$\sim 10^{-28}$ e-cm	10^{-28} e-cm
^{199}Hg atom	$d_{Hg} < 2\times10^{-28}$ e-cm	$\sim 2\times10^{-29}$ e-cm	$10^{-25} - 10^{-26}$ e-cm
^{129}Xe atom	$d_{Xe} < 6\times10^{-27}$ e-cm	$\sim 10^{-30} - 10^{-33}$ e-cm	$10^{-26} \sim 10^{-29}$ e-cm
Deuteron	–	10^{-29} e-cm	$3\times10^{-29} - 5\times10^{-31}$ e-cm

Deuteron Competitive – Better!

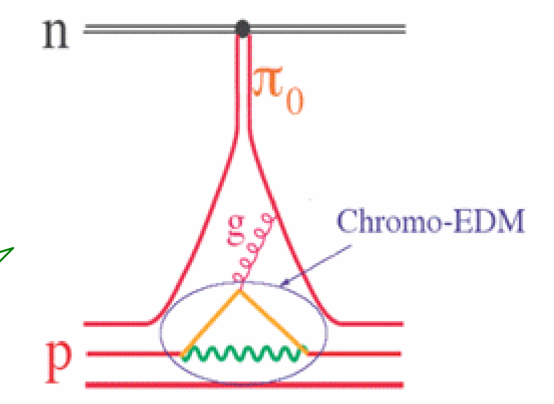
Marciano 9/2006

$$\frac{d\vec{s}}{dt} = \vec{\mu} \times \vec{B} + \vec{d} \times \vec{E}$$

Why the deuteron?

Special sensitivity to chromo-EDMs.

Complementary to neutron



source	$\bar{\theta}_{QCD}$	isoscalar $d_d^c + d_u^c$	isovector $d_d^c - d_u^c$
d_n	3×10^{-16}	0.83	0.27
d_D	-1×10^{-16}	–0.20	6

Distinctive sensitivities allow separation of sources for EDM signal.

Deuteron easily accommodates P-wave, so this gives the deuteron enhanced sensitivity to chromo-EDMs.

$$\frac{d\vec{s}}{dt} = \vec{\mu} \times \vec{B} + \vec{d} \times \vec{E}$$

Storage Ring EDM Collaboration

Presented to the BNL PAC, September 2006.

Letter of Intent:

Development of a Resonance Method to Search for a Deuteron Electric Dipole Moment using a Charged Particle Storage Ring

D. Babusci,[8] M. Bai,[4] G. Bennett,[4] J. Bengtsson,[4] M. Blaskiewicz,[4] G. Cantatore,[17] P.D. Eversheim,[2] M.E. Emirhan,[11] A. Facco,[13] A. Fedotov,[4] A. Ferrari,[8] G. Hoffstaetter,[6] H. Huang,[4] M. Karuza,[17] D. Kawall,[14] B. Khazin,[5] I.B. Khriplovich,[5] I.A. Koop,[5] Y. Kuno,[15] D.M. Lazarus,[4] P. Levi Sandri,[8] A. Luccio,[4] K. Lynch,[3] W.W. MacKay,[4] W. Marciano,[4] A. Masaharu,[15] W.M. Meng,[4] J.P. Miller,[3] D. Moricciani,[16] W.M. Morse,[4] C.J.G. Onderwater,[9] Y.F. Orlov,[6] C.S. Ozben,[11] V. Ptitsyn,[4] S. Redin,[5] G. Ruoso,[13] A. Sato,[15] Y.K. Semertzidis,[4,*] Yu. Shatunov,[5] V. Shemelin,[6] A. Sidorin,[12] A. Silenko,[1] M. da Silva e Silva,[9] E.J. Stephenson,[10] G. Venanzoni,[8] G. Zavattini,[7] A. Zelenski,[4] I. Ben-Zvi[4]

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[6]Cornell University, Ithaca, NY 14853
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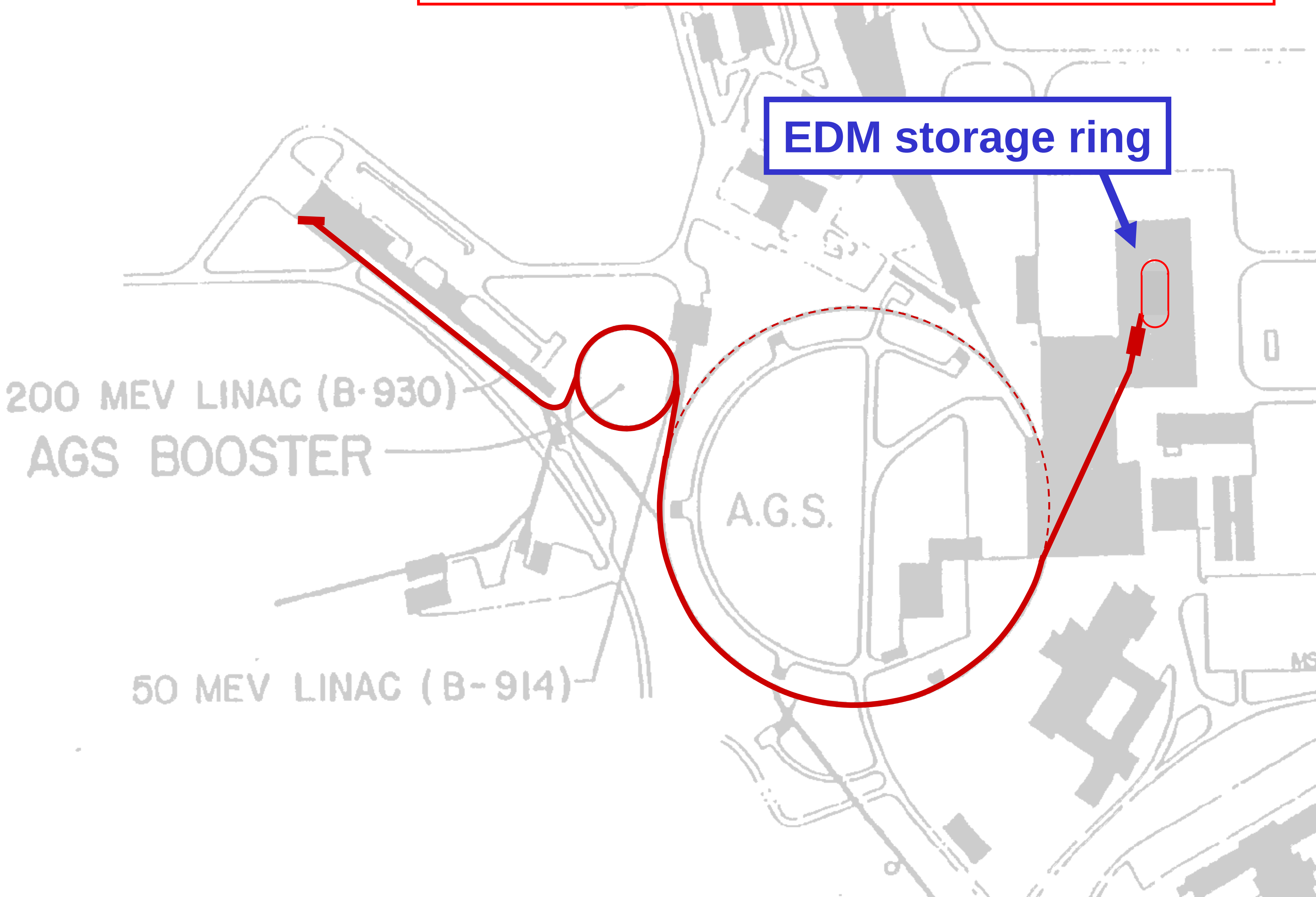
[15]Osaka University, Osaka, Japan
[16]Dipartimento di Fisica, Universita' "Tor Vergata" and Sezione INFN, Rome, Italy
[17]University and INFN Trieste, Italy

dt $\times \vec{E}$

Status

- PAC response: enthusiastic. They requested a plan for studying systematic errors
- We are presenting the Plan to the PAC on March 29, 2007
- Proposal to KVI (The Netherlands) and COSY (Germany) to study a plethora of issues (mostly polarimeter related)

The deuteron EDM search at BNL

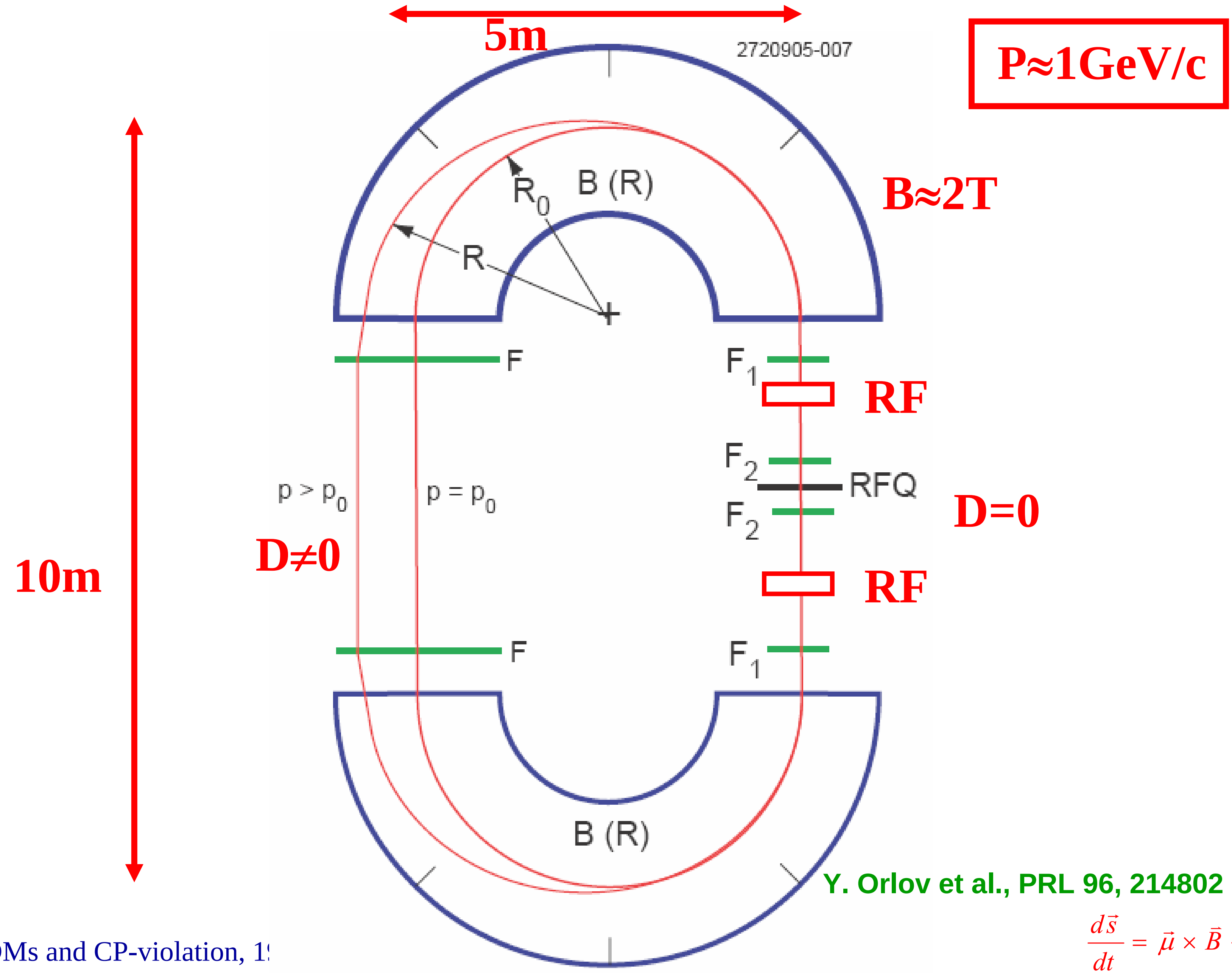


From the Systematic Errors Plan…

The current list of potential spin related systematic errors includes:

1) <u>Radial-vertical coupled oscillations</u>
2) Collective effects
3) Instrumental alignment tolerances
4) Polarimeter instrumental errors

The Orlov lattice



Y. Orlov et al., PRL 96, 214802 (2006)

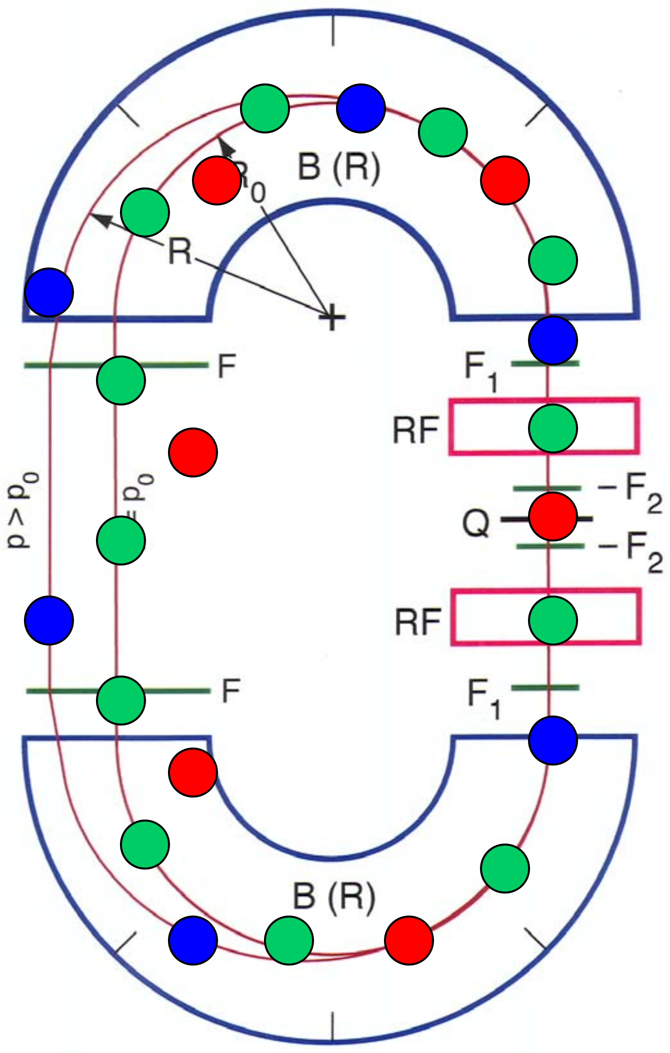
$$\frac{d\vec{s}}{dt} = \vec{\mu} \times \vec{B} + \vec{d} \times \vec{E}$$

From the Systematic Errors Plan…

Our general strategy for studying systematic errors is to identify and exploit the specific symmetries of the method. Those are:

1) Our stored beam will be undergoing synchrotron oscillations in resonance with the g-2 frequency. Consecutive beam bunches will have 180° phase difference in their synchrotron oscillations while the polarization directions remain the same, meaning that their respective EDM signals will also have the opposite sign. A large range of systematic errors will have the same sign and will therefore be eliminated by properly subtracting the signals from consecutive bunches. Most of the polarimetry errors fall in this category.
2) Many systematic errors, including those from spin dynamics, have opposite symmetry to the EDM signal when the direction of the beam in the storage ring goes from clock-wise (CW) to counter-clock-wise (CCW).
3) Changing the ring lattice parameters in specific ways to make the systematic errors time dependent while keeping the EDM effect constant can effect a separation. This will provide a tool to identify many of the spin systematic error sources and eliminate them.
4) Eliminating the source of the main spin related systematic errors by modifying the ring response function with the help of nonlinearities is an important tool.

Simultaneously Controlled Experiments



- EDM: Spin Up
- EDM: Spin Down
- No EDM effect

Proposal to COSY/Germany

Proposal:

Polarimeter Development for a Search for
a Permanent Electric Dipole Moment on the Deuteron

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H.W.E.M. Wilschut,[2] A. Lehrach,[3] B. Lorentz,[3] M. Bai,[4] A. Luccio,[4] W.M. Morse,[4]
Y.K. Semertzidis,[4] J.P. Miller,[5] Yu.F. Orlov,[6] D. Babusci,[7] A. Ferrari,[7]
P. Levi Sandri,[7] G. Venanzoni,[7] R. Messi,[8] D. Moricciani,[8] and G. Zavattini[9]

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[2] *Kernfysisch Versneller Instituut, Groningen, The Netherlands*
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[6] *Cornell University, Ithaka, NY 14853, USA*
[7] *Laboratori Nazionali di Frascati dell' INFN, Frascati, Italy*
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[9] *University and INFN, Ferrara, Italy*

We propose to perform an R&D program in the COSY storage ring at IKP/FZJ aimed at the design of a highly sensitive and efficient deuteron polarimeter. This polarimeter is intended for use on a storage ring set up to measure (or limit) a permanent electric dipole moment of the deuteron at the level of 10^{-29} e · cm. The polarimeter would be designed for

$$\frac{d\vec{s}}{dt} = \vec{\mu} \times \vec{B} + \vec{d} \times \vec{E}$$

Summary

- deuteron EDM experiment is a sensitive probe of physics beyond the SM and of CP-violation in particular.

Unique sensitivity to

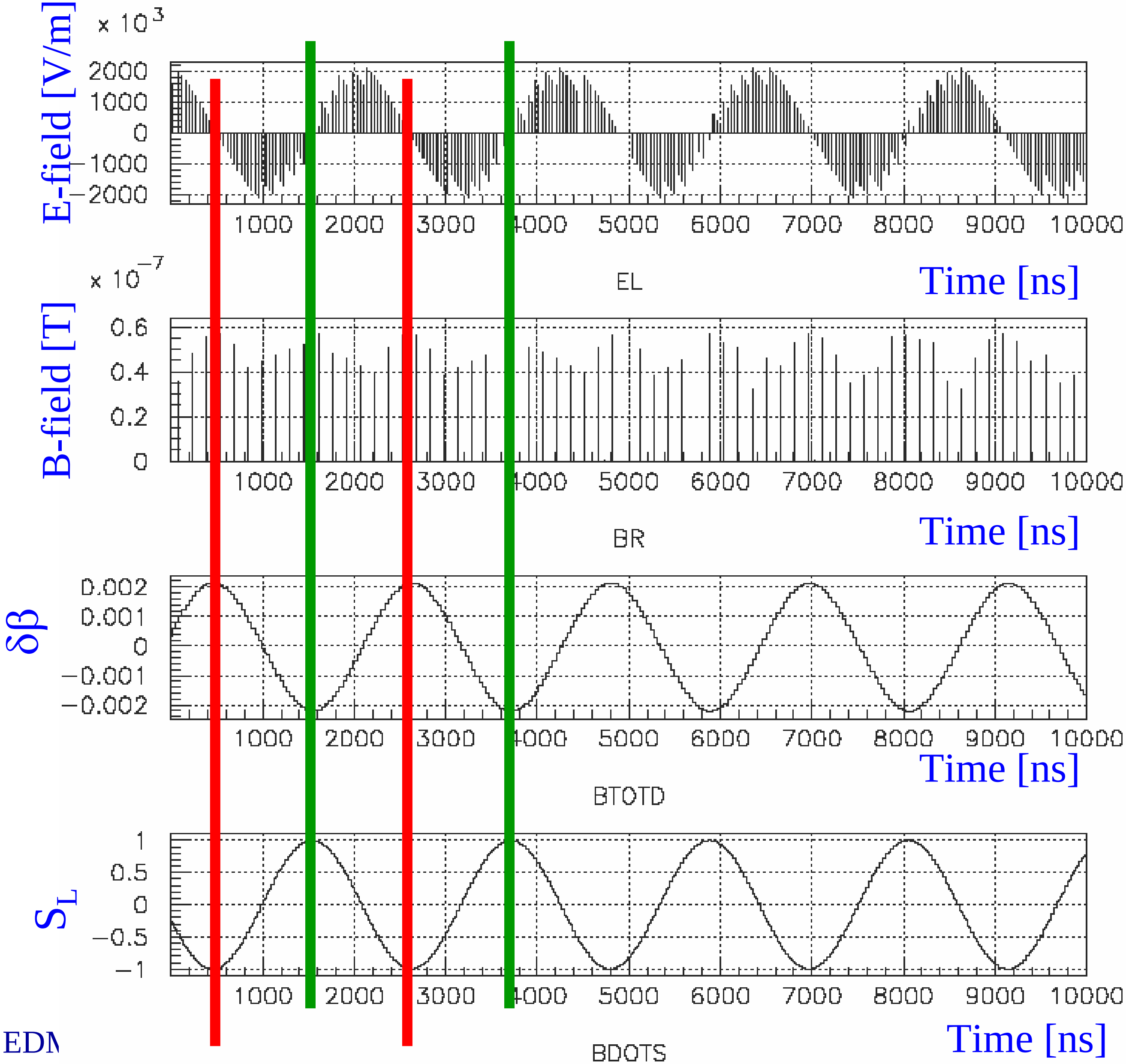
- θ_{QCD}
- Quark EDM
- Quark-color EDM

Systematic error studies plan for spin dynamics and polarimetry are in place

$$\frac{d\vec{s}}{dt} = \vec{\mu} \times \vec{B} + \vec{d} \times \vec{E}$$

Extra Slides

RF-fields and oscillation phases



E-field in RF-cavity

B_R-field in RF-cavity

Particle velocity oscillations

Particle S_L oscillations (g-2)

$$\frac{d\vec{s}}{dt} = \vec{\mu} \times \vec{B} + \vec{d} \times \vec{E}$$

A value of $\theta_{QCD} = 10^{-13}$ would create an EDM of

System	**EDM value**
Proton	$\approx 3\times10^{-29}$ e·cm
Neutron	$\approx -3\times10^{-29}$ e·cm
Deuteron	$\approx 1\times10^{-29}$ e·cm
Tl atom	$\approx 5\times10^{-31}$ e·cm
Hg atom	$\approx 1\times10^{-32}$ e·cm

$$\frac{d\vec{s}}{dt} = \vec{\mu} \times \vec{B} + \vec{d} \times \vec{E}$$

Hadronic EDMs

$$L_{\not{CP}} = \bar{\vartheta}\,\frac{\alpha_s}{8\pi}\,G\tilde{G}$$

$$d_n\left(\bar{\vartheta}\right) \approx -d_p\left(\bar{\vartheta}\right) \approx 3.6\times10^{-16}\,\bar{\vartheta}\ \mathrm{e\cdot cm} \rightarrow \bar{\vartheta} \le 2\times10^{-10}$$

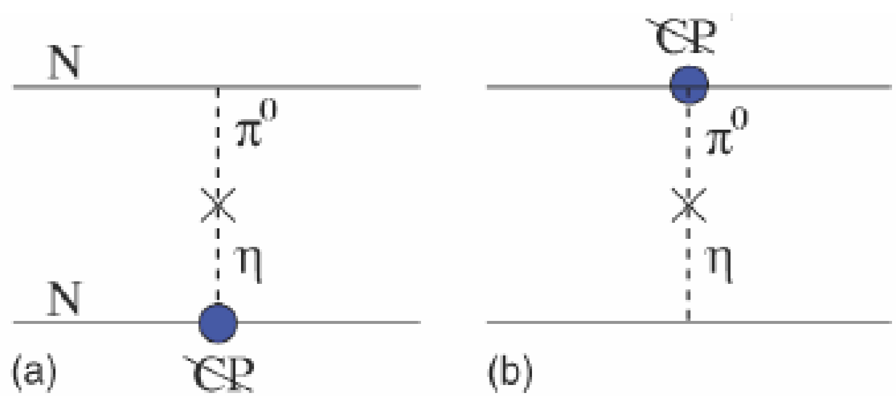
Why so small?

Deuteron EDM

$$d_D = (d_n + d_p) + d_D^{\pi NN}$$

$$d_D(\bar{\vartheta}) \approx -10^{-16}\,\bar{\vartheta}\ \mathrm{e\cdot cm}$$

i.e. @ 10^{-29}e·cm: $\bar{\vartheta} \leq 10^{-13}$

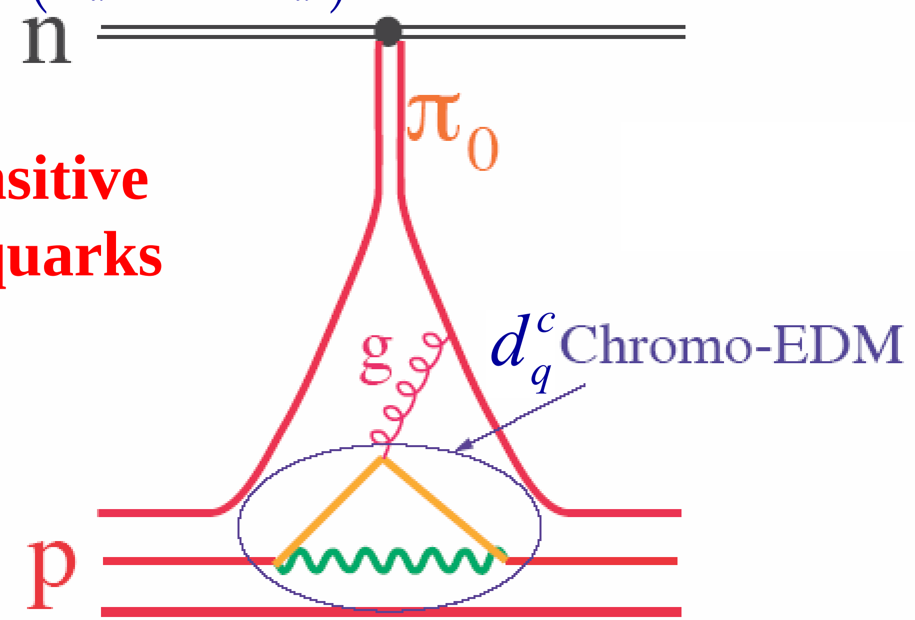


Quark EM and Color EDMs

$$L_{CP} = -\frac{i}{2}\sum_q \overline{q}\left(d_q\sigma_{\mu\nu}F^{\mu\nu} + d_q^c\sigma_{\mu\nu}G^{\mu\nu}\right)\gamma_5 q$$

$$d_D\left(d_q, d_q^c\right) \square\ 0.5\left(d_u + d_d\right) - 5.6e\left(d_u^c - d_d^c\right) - 0.2e\left(d_u^c + d_d^c\right)$$

$$d_n\left(d_q, d_q^c\right) \square\ 0.7\left(d_d - 0.25 d_u\right) + 0.55e\left(d_d^c + 0.5 d_u^c\right)$$



i.e. Deuterons and neutrons are sensitive to different linear combination of quarks and chromo-EDMs…