STORI05

Bonn, 23 May 2005

Muon g-2 and Electric Dipole Moments in Storage Rings: Powerful Probes of Physics Beyond the SM

Yannis K. Semertzidis

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"Muon g-2 Collaboration" and

"EDM in Storage Rings Collaboration"

- Muon g-2, Principle, Status, Future
- EDM: a) "Frozen" Spin Method

  b) Resonance Method

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

Muon g-2 Collaboration

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(Muon $(g-2)$ Collaboration)

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

Definition of g-Factor

$$g \equiv \frac{\dfrac{\text{magnetic moment}}{e\hbar / 2mc}}{\dfrac{\text{angular momentum}}{\hbar}}$$

g-2 measures the difference between the charge and mass distribution. g-2=0 when they are the same all the time…

From Dirac equation g-2=0 for point-like, spin ½ particles.

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

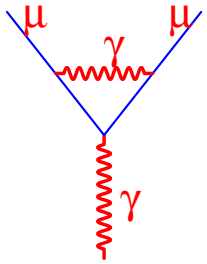
g-factors:

- Proton (g_p=+5.586) and the neutron (g_n=-3.826) are composite particles.
- The ratio g_p/g_n=-1.46 close to the predicted –3/2 was the first success of the constituent quark model.
- The g_e-2 (of the electron) is non-zero mainly due to quantum field fluctuations involving QED.
- The g_μ-2 is more sensitive to a class of particles than the g_e-2 by $(m_\mu/m_e)^2$~40,000.

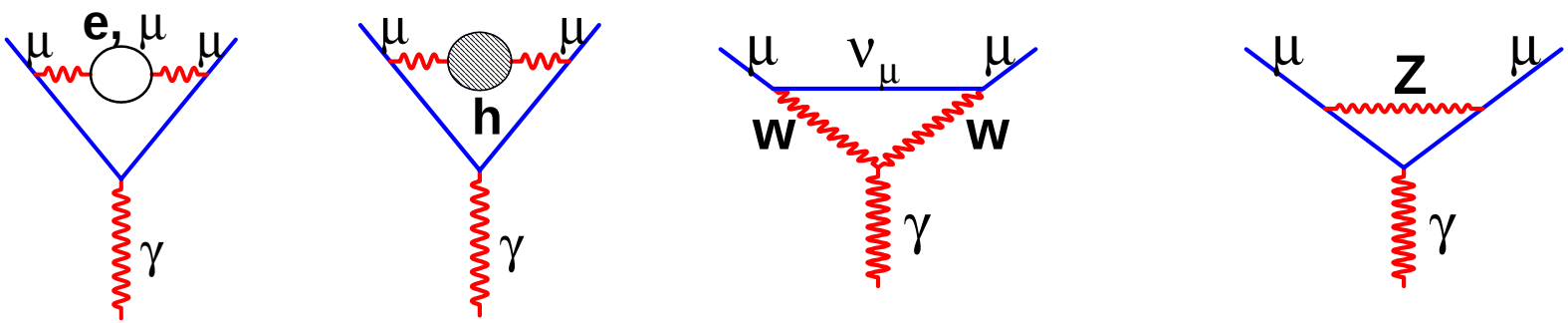
$$\frac{d\vec{s}}{dt} = \vec{\mu} \times \vec{B} + \vec{d} \times \vec{E}$$

$g - 2$ for the muon

Largest contribution : $a_\mu = \frac{\alpha}{2\pi} \approx \frac{1}{800}$



Other standard model contributions :



QED hadronic weak

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

Theory of a_μ

- $a_\mu(\text{theo}) = a_\mu(\text{QED}) + a_\mu(\text{had}) + a_\mu(\text{weak})$
  $+ a_\mu(\text{new physics})$

- $a_\mu(\text{QED}) = 11\ 658\ 470.6\ \ (0.3) \times 10^{-10}$
- $a_\mu(\text{had}) = 694.9\ \ (8.)\ \ \times 10^{-10}$ (based on e^+e^-)
- $a_\mu(\text{had}) = 709.6\ \ (7.)\ \ \times 10^{-10}$ (based on τ)
- $a_\mu(\text{weak}) = 15.4\ \ (0.3) \times 10^{-10}$

- $a_\mu(\text{SM}) = 11\ 659\ 181(8) \times 10^{-10}$ (based on e^+e^-)
- $a_\mu(\text{SM}) = 11\ 659\ 196(7) \times 10^{-10}$ (based on τ)

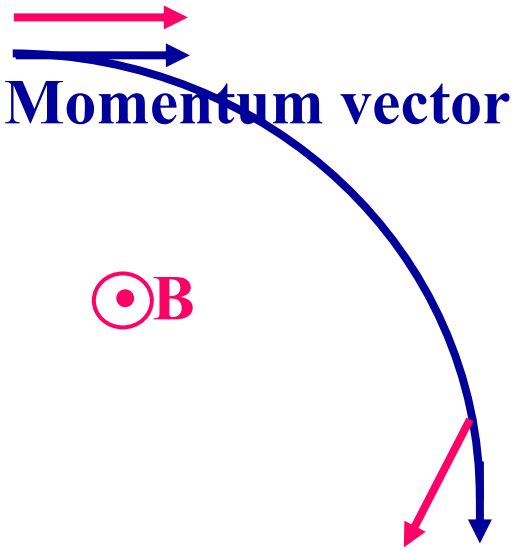
$$\frac{d\vec{s}}{dt} = \vec{\mu} \times \vec{B} + \vec{d} \times \vec{E}$$

Experimental Principle:

- Polarize: Parity Violating Decay $\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$
- Interact: Precess in a Uniform B-Field
- Analyze: Parity Violating Decay $\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$

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

The Principle of g-2



Non-relativistic case

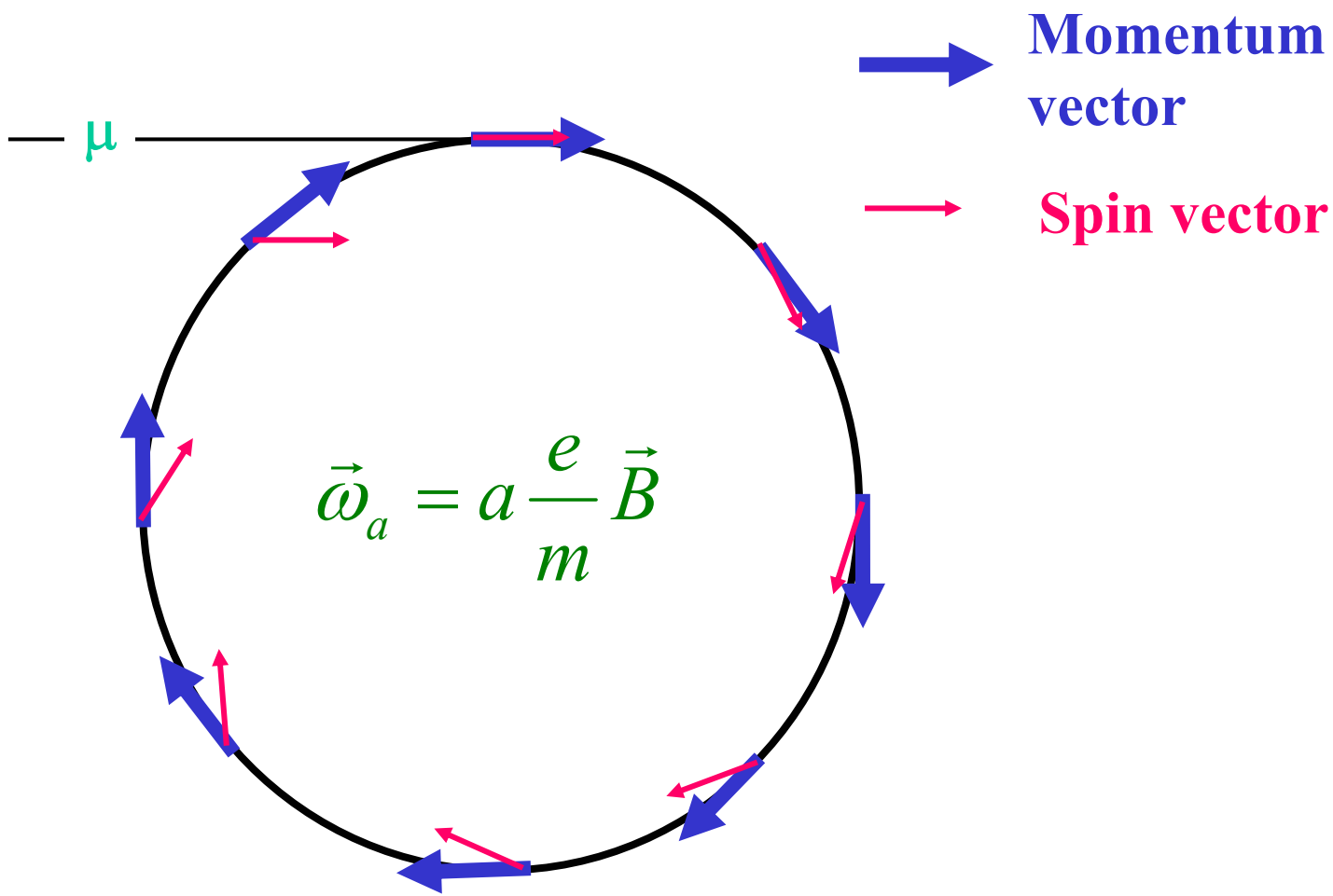
$$\omega_c = \frac{eB}{m}$$

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

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

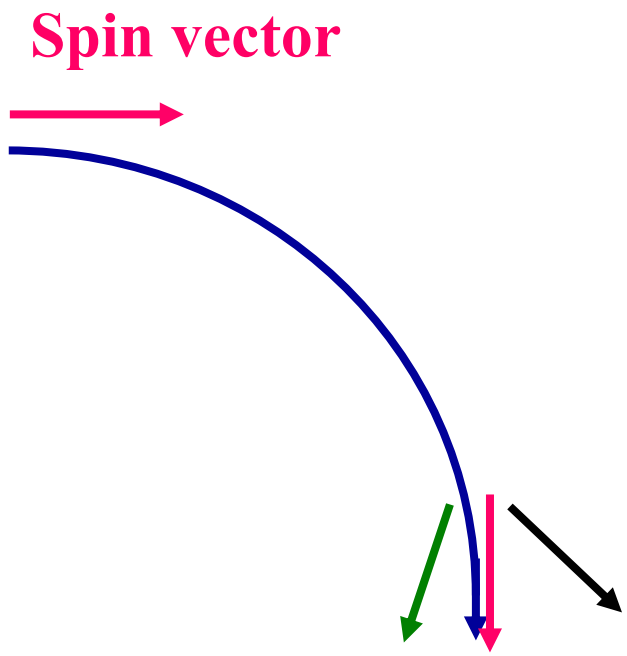
$$\frac{d\vec{s}}{dt} = \vec{\mu}\times\vec{B} + \vec{d}\times\vec{E}$$

Spin Precession in g-2 Ring (Top View)



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

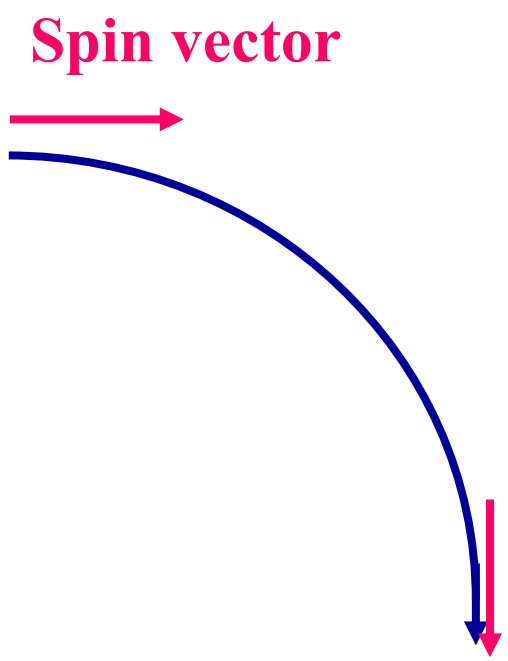
Effect of Radial Electric Field



- Low energy particle
- …just right
- High energy particle

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

Effect of Radial Electric Field

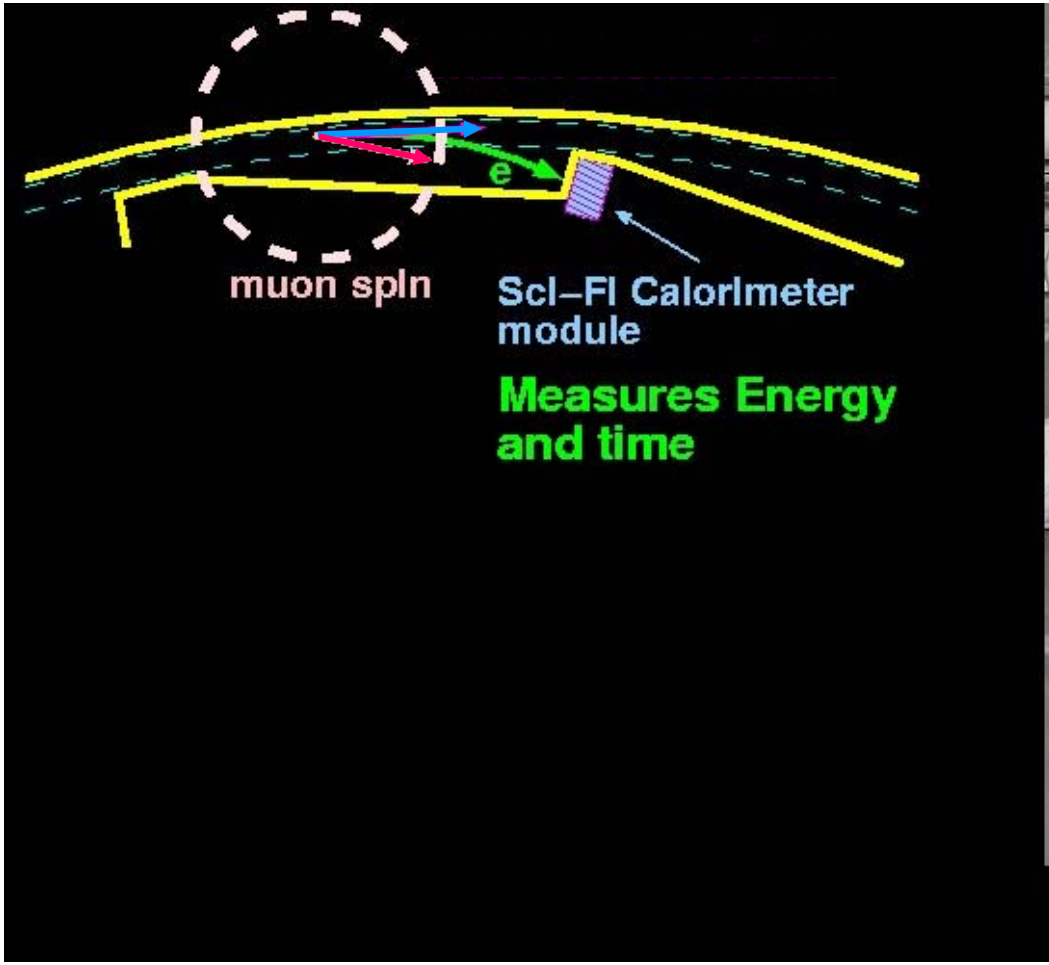


- …just right, $\gamma \approx 29.3$ for muons (~3GeV/c)

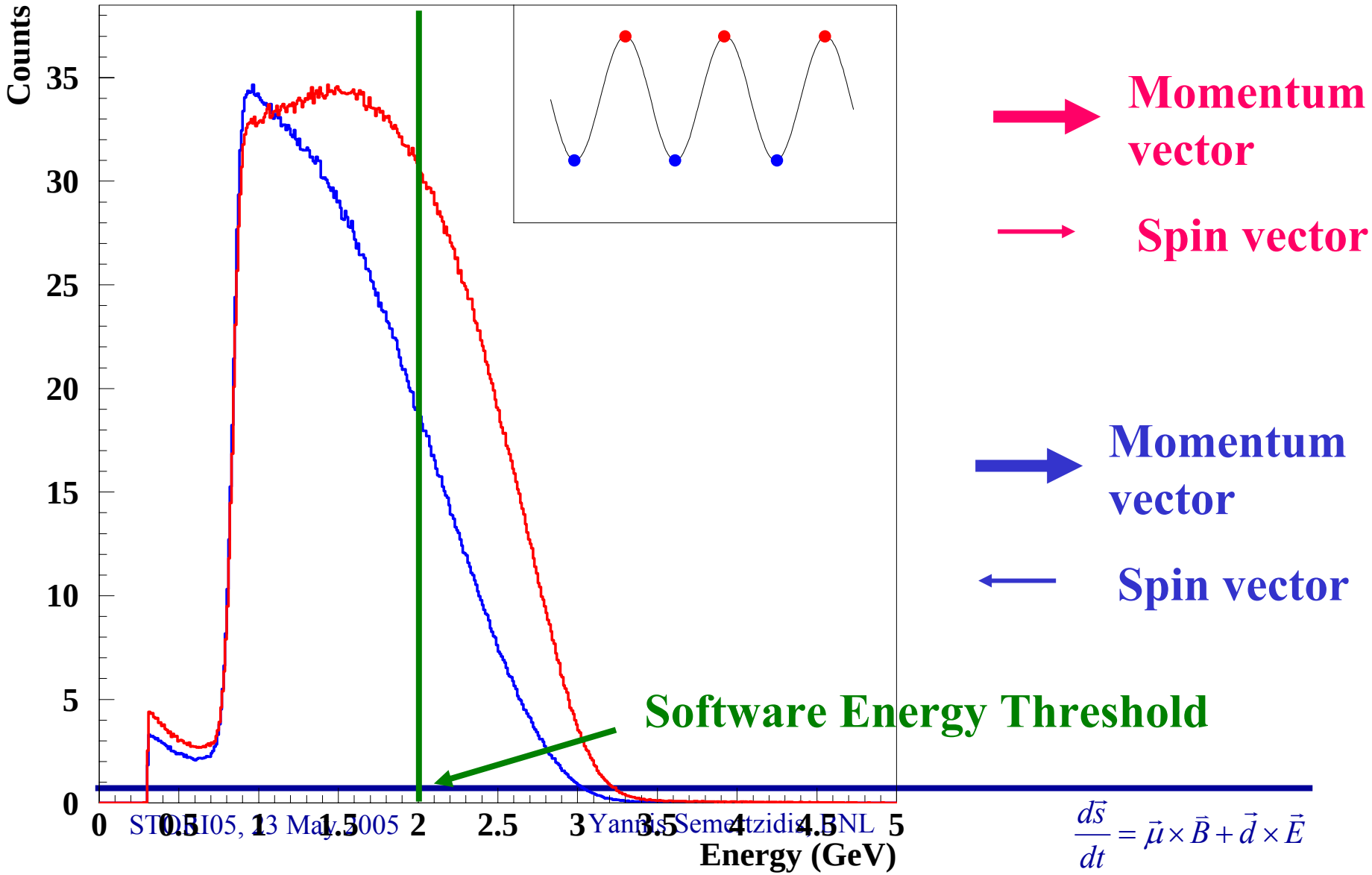
$$\frac{d\vec{s}}{dt} = \vec{\mu} \times \vec{B} + \vec{d} \times \vec{E}$$

• The Muon Storage Ring:
B ≈ 1.45T, P_μ ≈ 3 GeV/c
•High Proton Intensity from AGS
HVON

Detectors and vacuum chamber



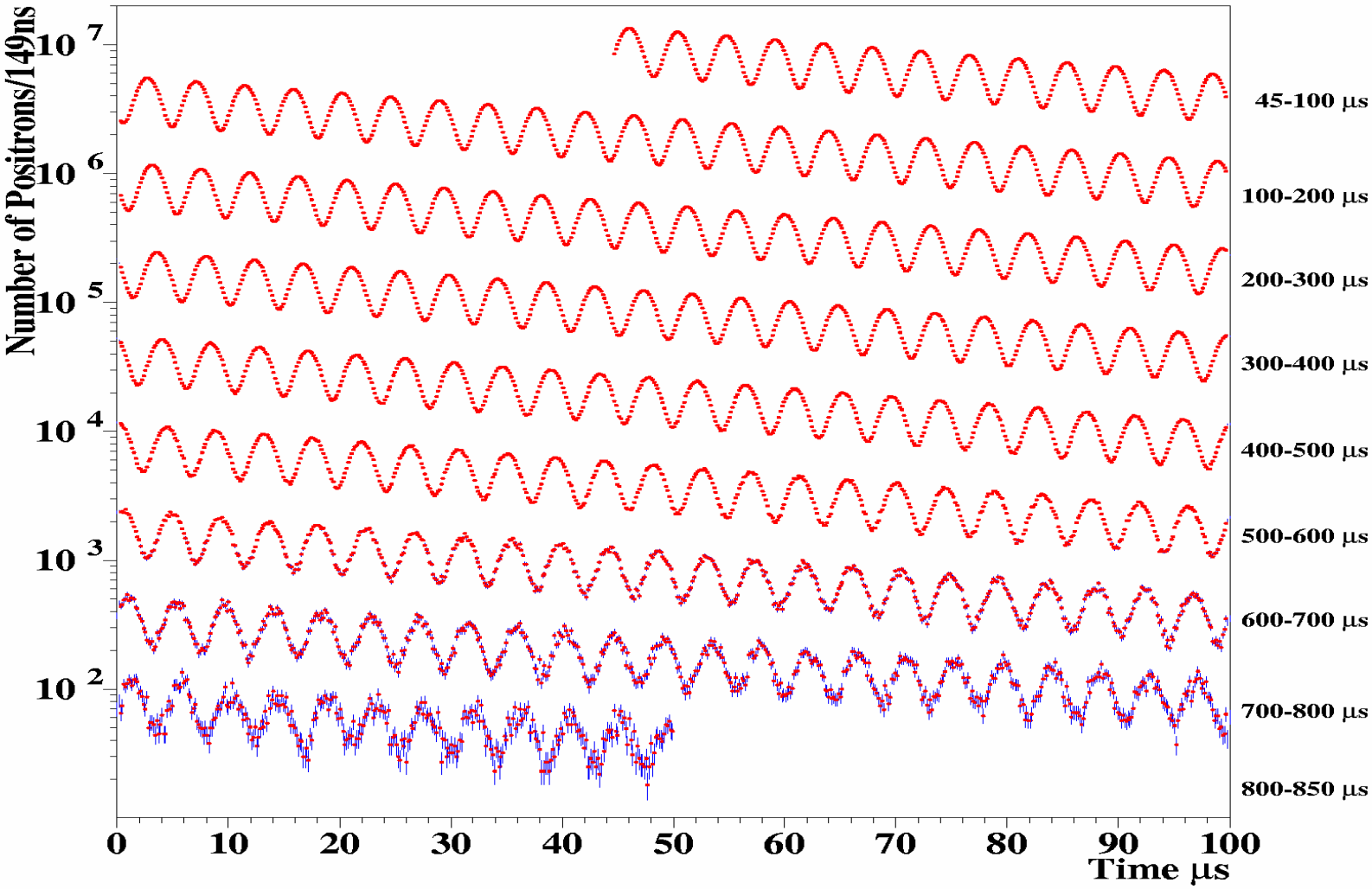
Energy Spectrum of Detected Positrons



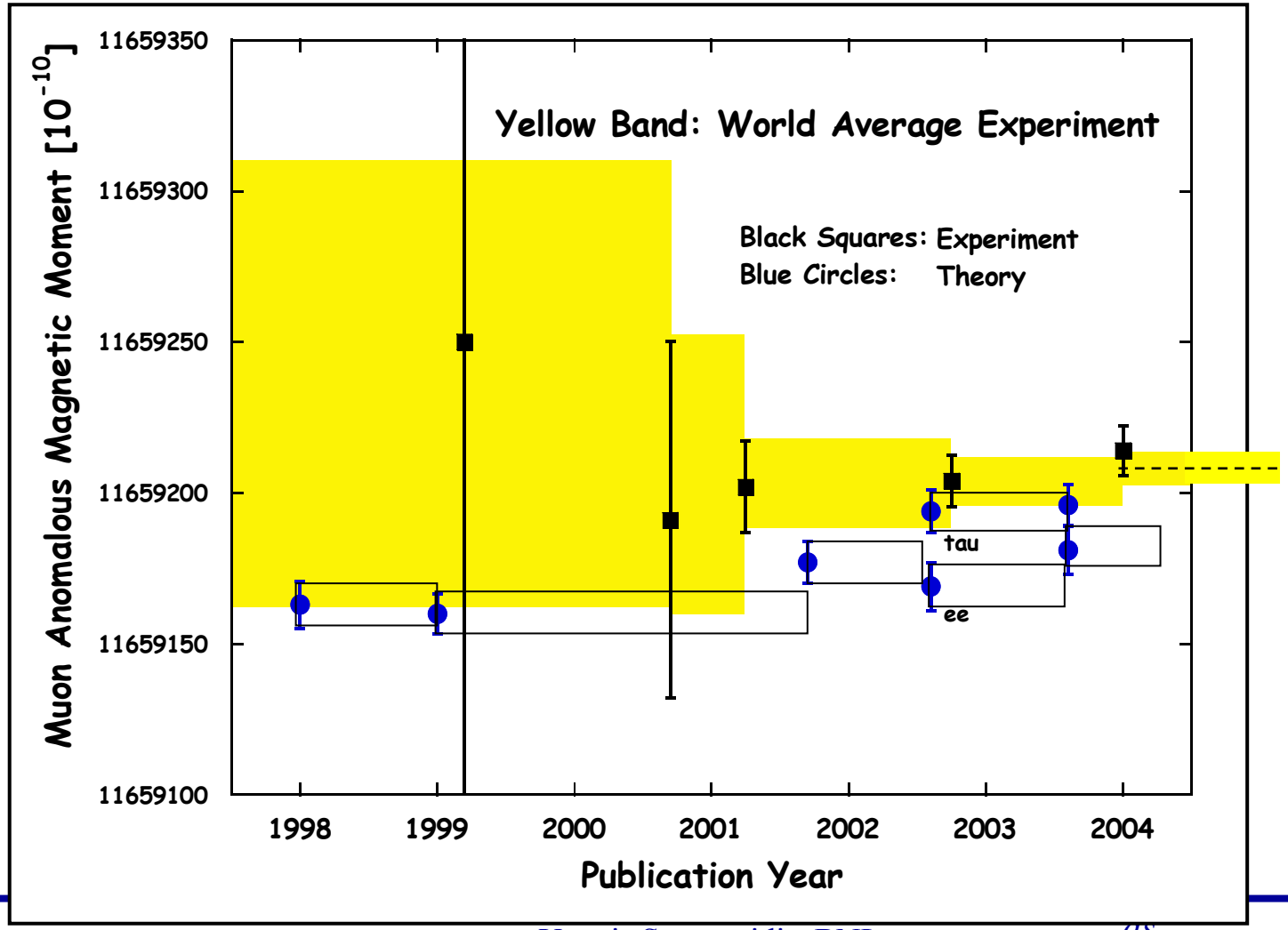
$$\frac{d\vec{s}}{dt} = \vec{\mu} \times \vec{B} + \vec{d} \times \vec{E}$$

4 Billion e^+ with E>2GeV

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

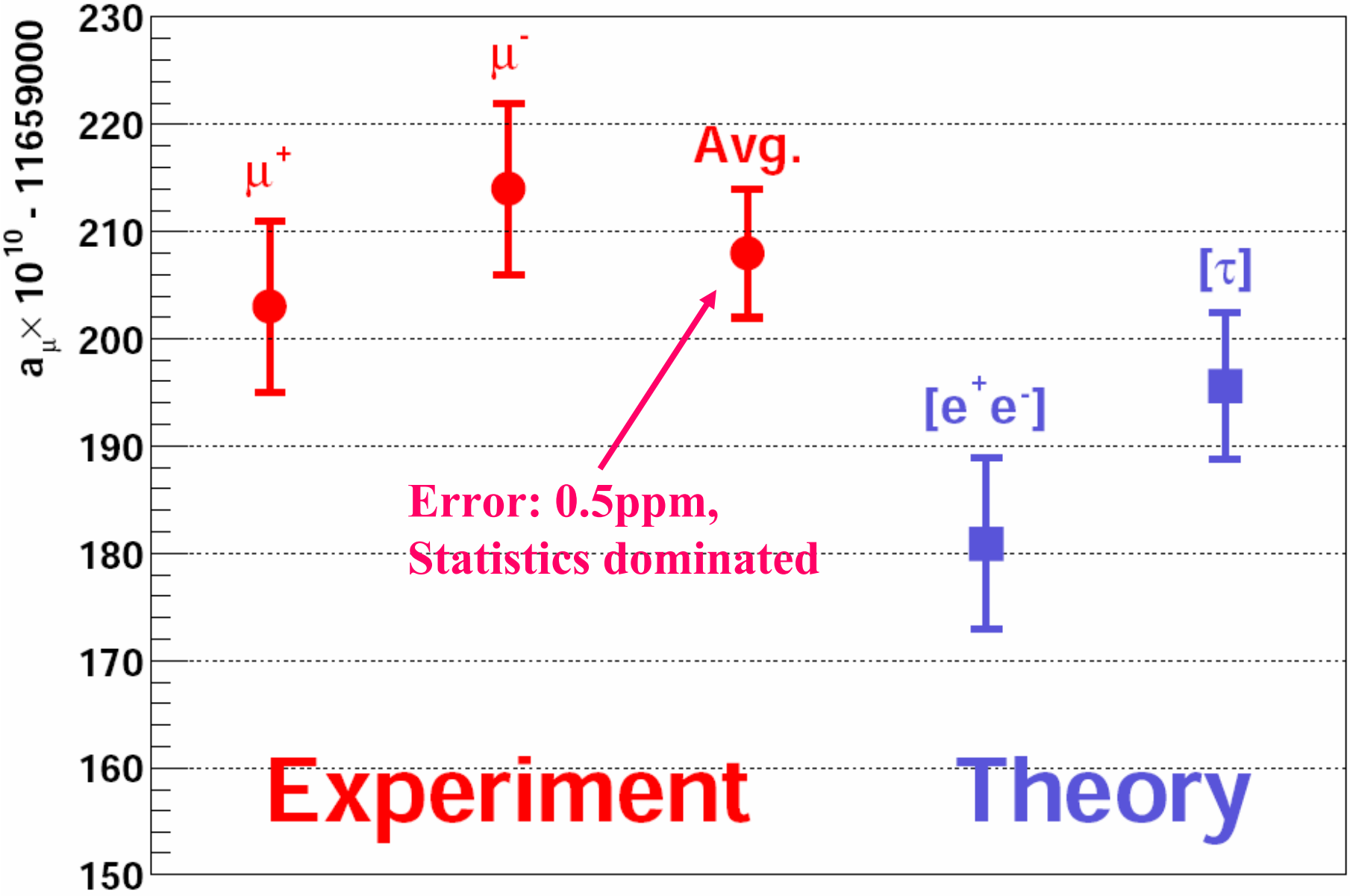


Theory and Experiment vs. Year



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

G.B. *et al.*, Phys.Rev.Lett.92:161802,2004, hep-ex/0401008



Theory Overview by W.Marciano and M. Davier

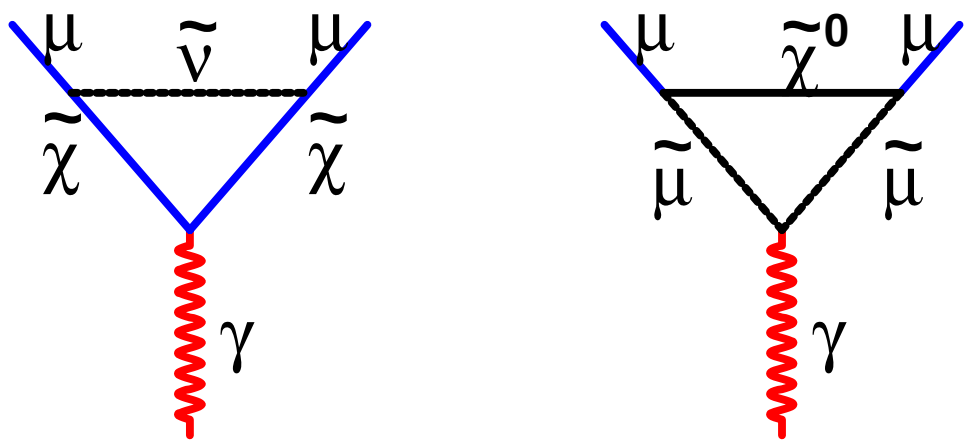
- a_μ(QED) = 11 658 472.07(0.04)(0.1)$\times 10^{-10}$ by Kinoshita
- a_μ(had, LBL)= 12.0(3.5)$\times 10^{-10}$
- a_μ(had,1) = 694.4 (6.2)(3.6)$\times 10^{-10}$

- a_μ(SM) = 11 659 184.1 $(7.2)_{VP}$ $(3.5)_{LBL}$ $(0.3)_{EW,QED}$ $\times 10^{-10}$
- a_μ(Exp) = 11 659 208.0 (5.8)$\times 10^{-10}$

- $\Delta a_\mu = a_\mu(\text{Exp}) - a_\mu(\text{SM}) = 23.9\ (9.9)\times 10^{-10}$ or $2.4\ \sigma$

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

Beyond standard model, e.g. SUSY



$$a_\mu^{\text{susy}} \cong \text{sgn}(\mu) \times 13 \times 10^{-10} \left(\frac{100\text{GeV}}{m_{\text{susy}}} \right)^2 \tan\beta$$

W. Marciano, J. Phys. G29 (2003) 225

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

New g-2 Proposal at BNL

- Increase Beamline acceptance (×4)
- Open up the two Inflector ends (×1.7)
- Use Backward Muons (i.e. π @ 5.3GeV/c, μ @ 3.1GeV/c). Provides great π-Rejection.
- Reduce systematics both in ω_a and in B

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

Prospects and Summary

- Total experimental error: 0.5ppm; probing physics beyond the S.M.

- More data from the theory front are/will be analyzed: Novosibirsk, KLOE, BaBar, Belle.

- The g-2 collaboration is working towards reducing the experimental error to 0.2ppm.
  The proposal at BNL received scientific approval (E969), funding approval is pending from DOE.

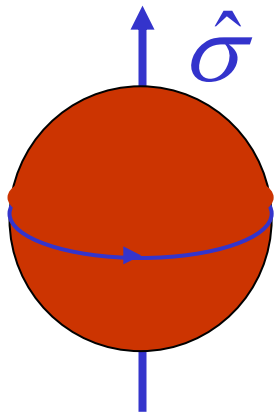
$$\frac{d\vec{s}}{dt} = \vec{\mu} \times \vec{B} + \vec{d} \times \vec{E}$$

Electric Dipole Moments in Storage Rings

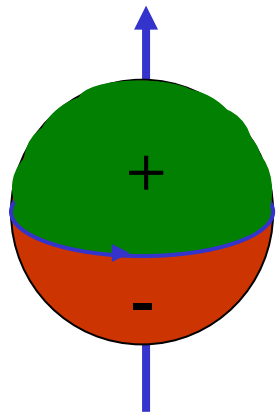
- EDMs: Why are they important?
- EDMs in Storage Rings, new sensitive methods.

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

Spin is the only vector…



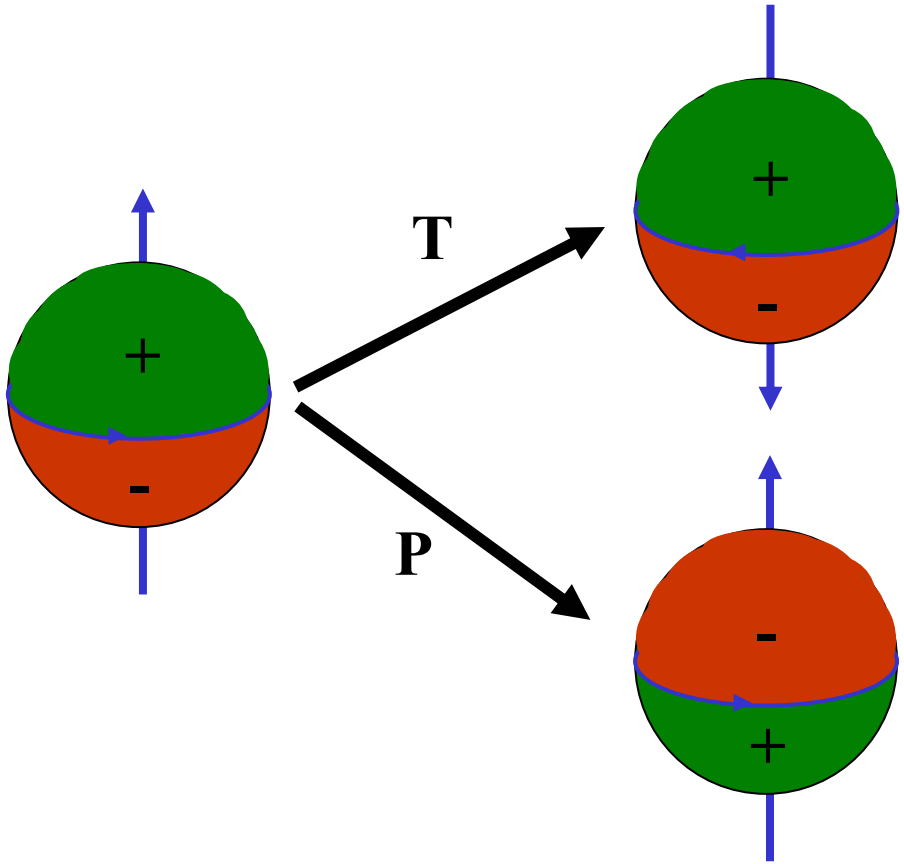
$$\vec{d} = 0$$



$$\vec{d} = d\hat{\sigma}$$

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

A Permanent EDM Violates both T & P Symmetries:



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

T-Violation $\xrightarrow{\text{CPT}}$ **CP-Violation**

<u>Andrei Sakharov 1967:</u>

CP-Violation is one of three conditions to enable a universe containing initially equal amounts of matter and antimatter to evolve into a matter-dominated universe, which we see today….

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

EDM Searches are Excellent Probes of Physics Beyond the SM:

SM: **One CP-Violating Phase (CKM), Needs loops with all quark families for a non-zero result (Third Order Effect).**

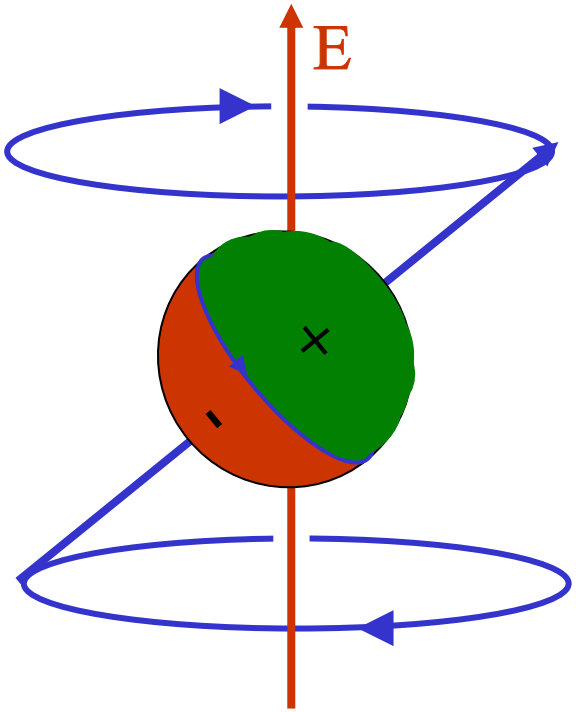
SUSY: **42 CP-Violating Phases, Needs one loop for a non-zero result (First Order Effect).**

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

Usual Experimental Method

Carrier Signal

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



Small Signal

Compare the Zeeman Frequencies When E-field is Flipped:

$$\hbar(\omega_1 - \omega_2) = 4dE$$

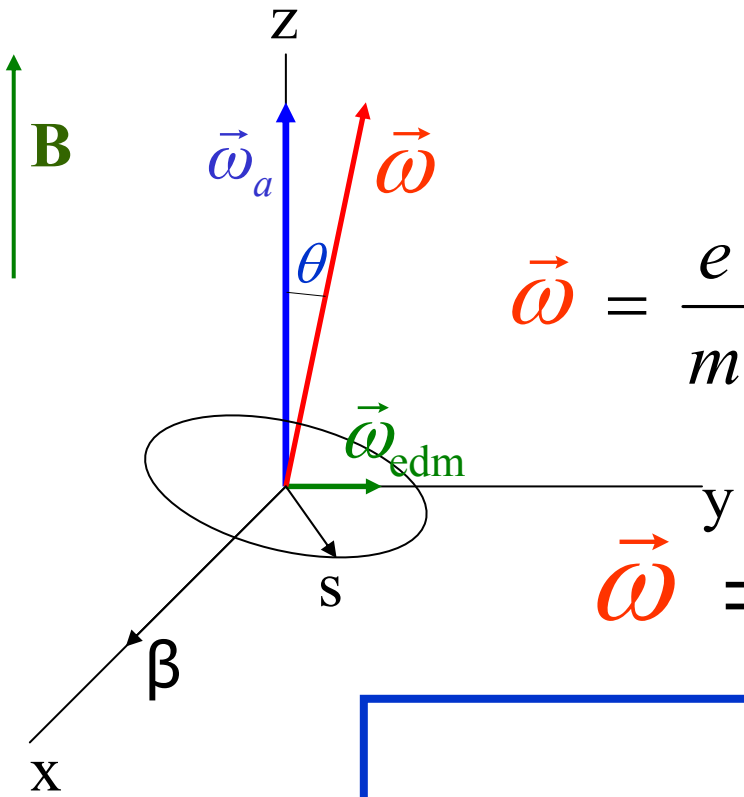
$$\sigma_d \propto \frac{1}{E}\frac{1}{\sqrt{N\tau T}}$$

Electric Dipole Moments in Storage Rings

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

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

Indirect Muon EDM limit from the g-2 Experiment



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

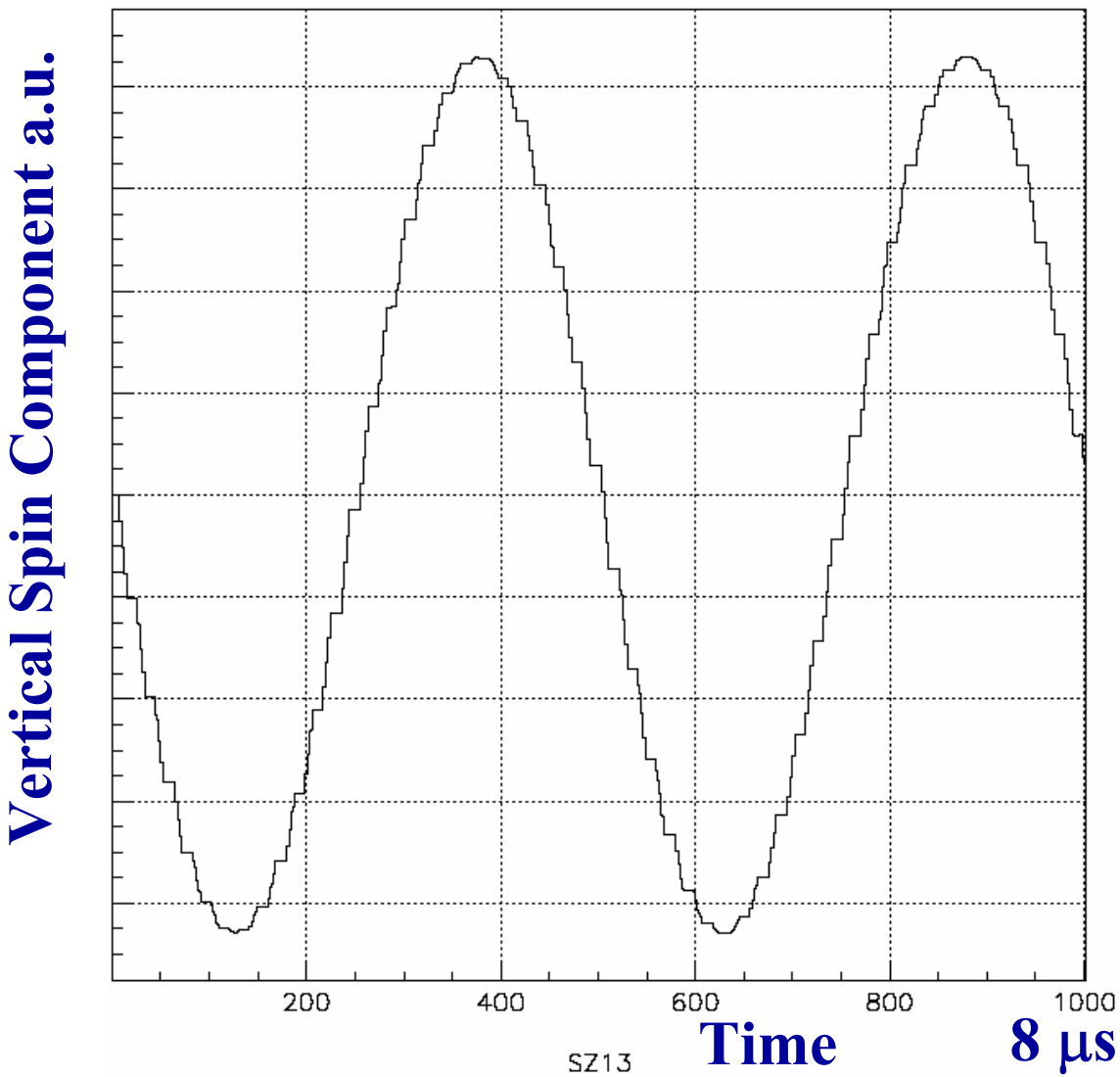
$$\vec{\omega} = \vec{\omega}_a + \vec{\omega}_{edm}$$

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

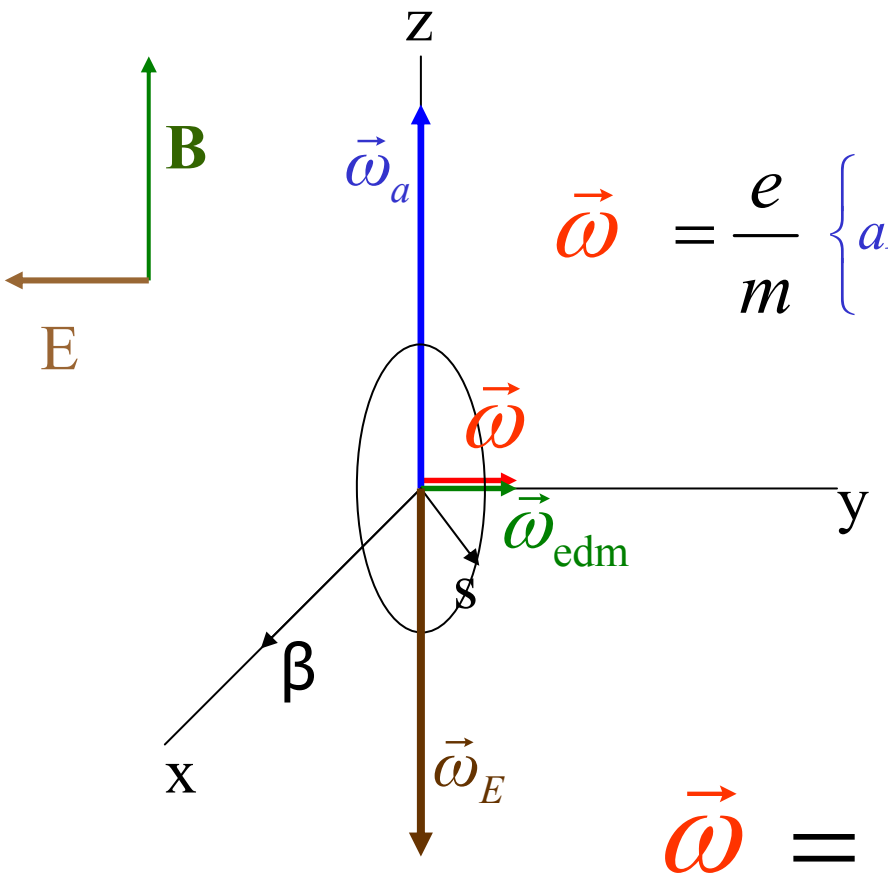
Ron McNabb's Thesis 2003: $< 2.7\times10^{-19}\,\mathrm{e}\cdot\mathrm{cm}$ 95% C.L.

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

The Vertical Spin Component Oscillates



Frozen Spin Method: Canceling g-2 with a Radial E-field

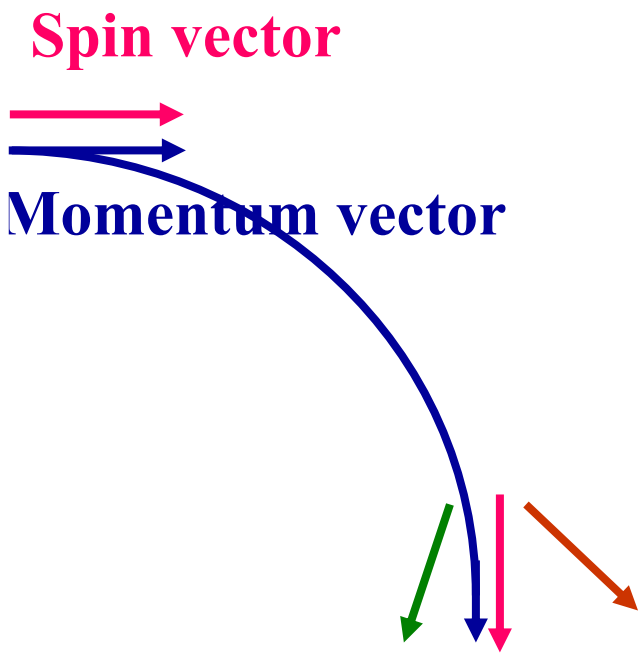


$$\vec{\omega} = \frac{e}{m}\left\{a\vec{B} + \overbrace{\left(\frac{1}{\gamma^2-1} - a\right)\frac{\vec{\beta}\times\vec{E}}{c}}^{\vec{\omega}_E} + \frac{\eta}{2}\left(\frac{\vec{E}}{c} + \vec{\beta}\times\vec{B}\right)\right\}$$

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

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

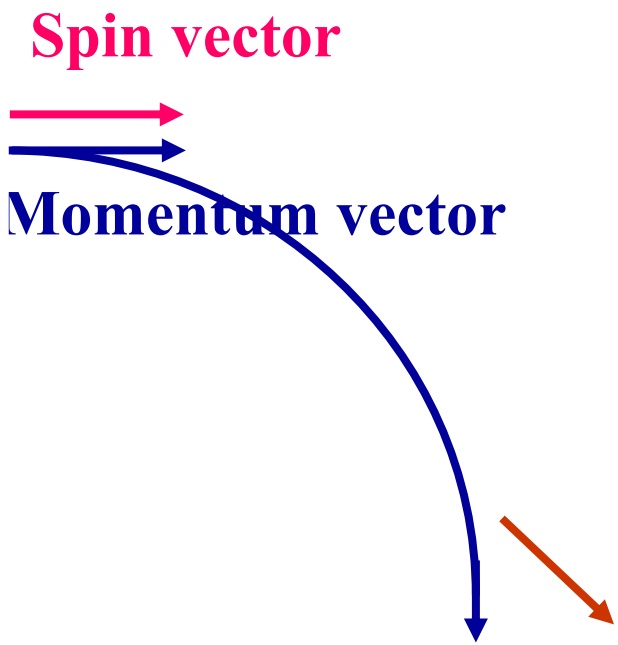
Effect of Radial Electric Field



- Low energy particle
- …just right
- High energy particle

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

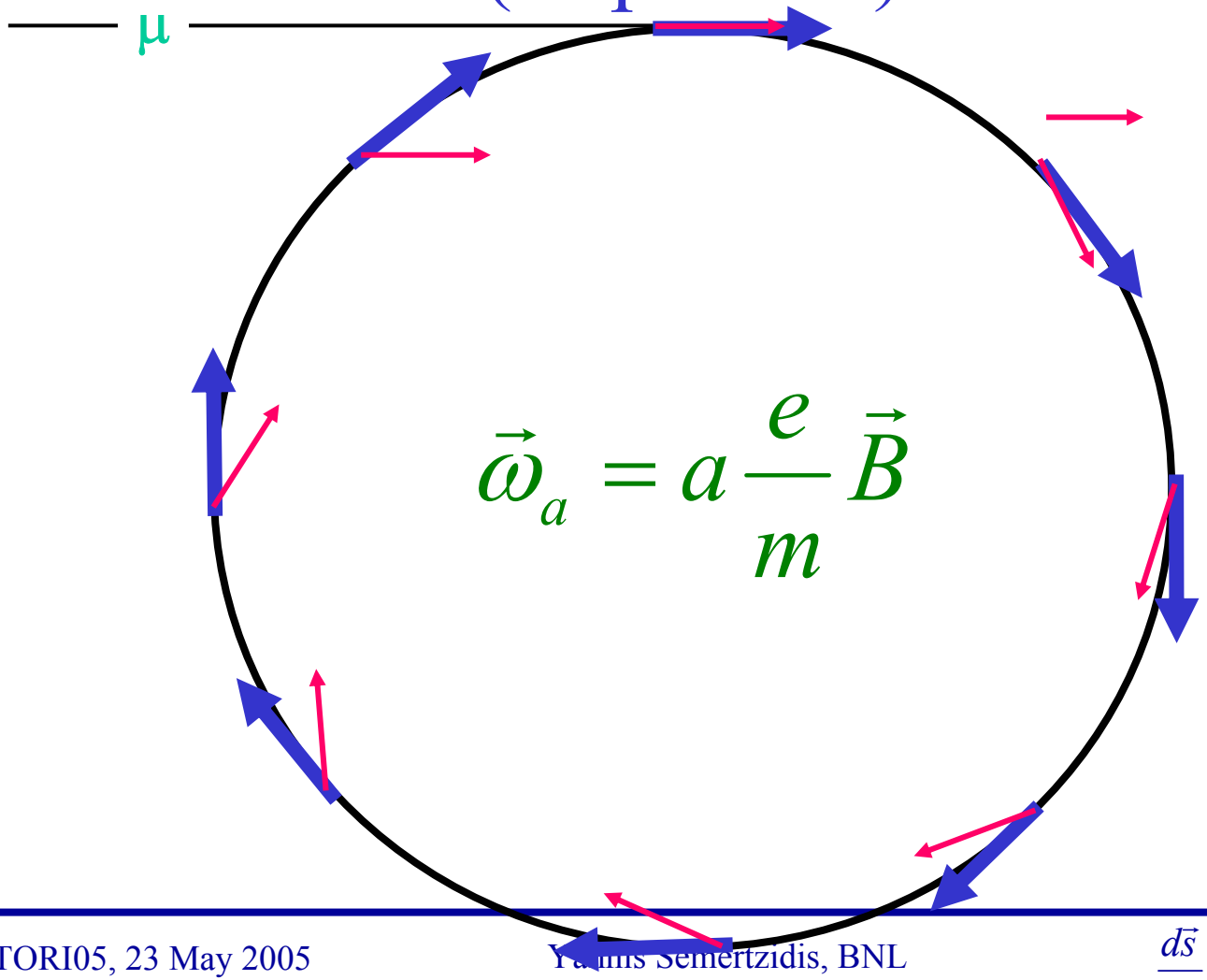
Use a Radial Electric Field and a



- 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)



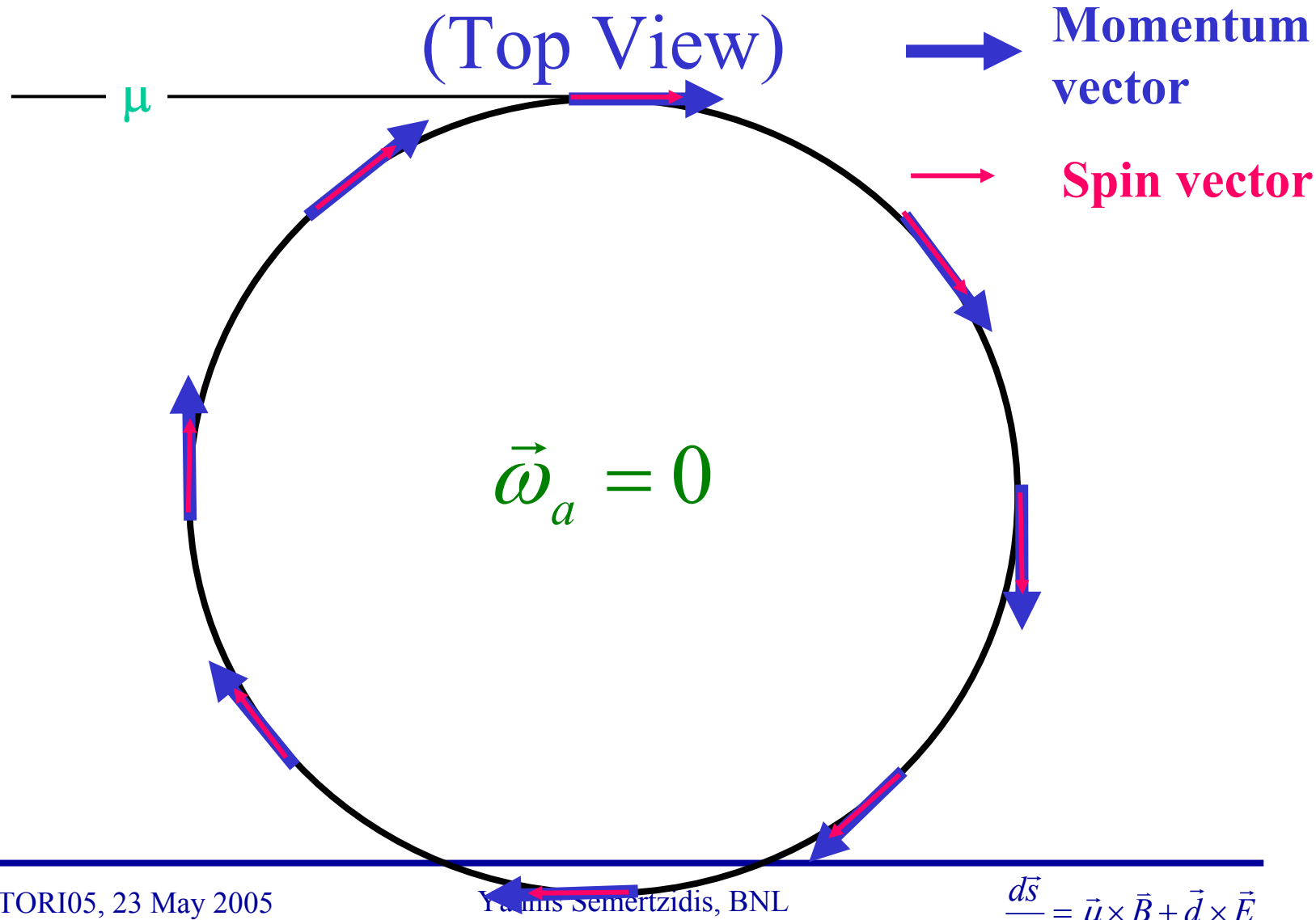
Momentum vector

Spin vector

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

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

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) vs Time

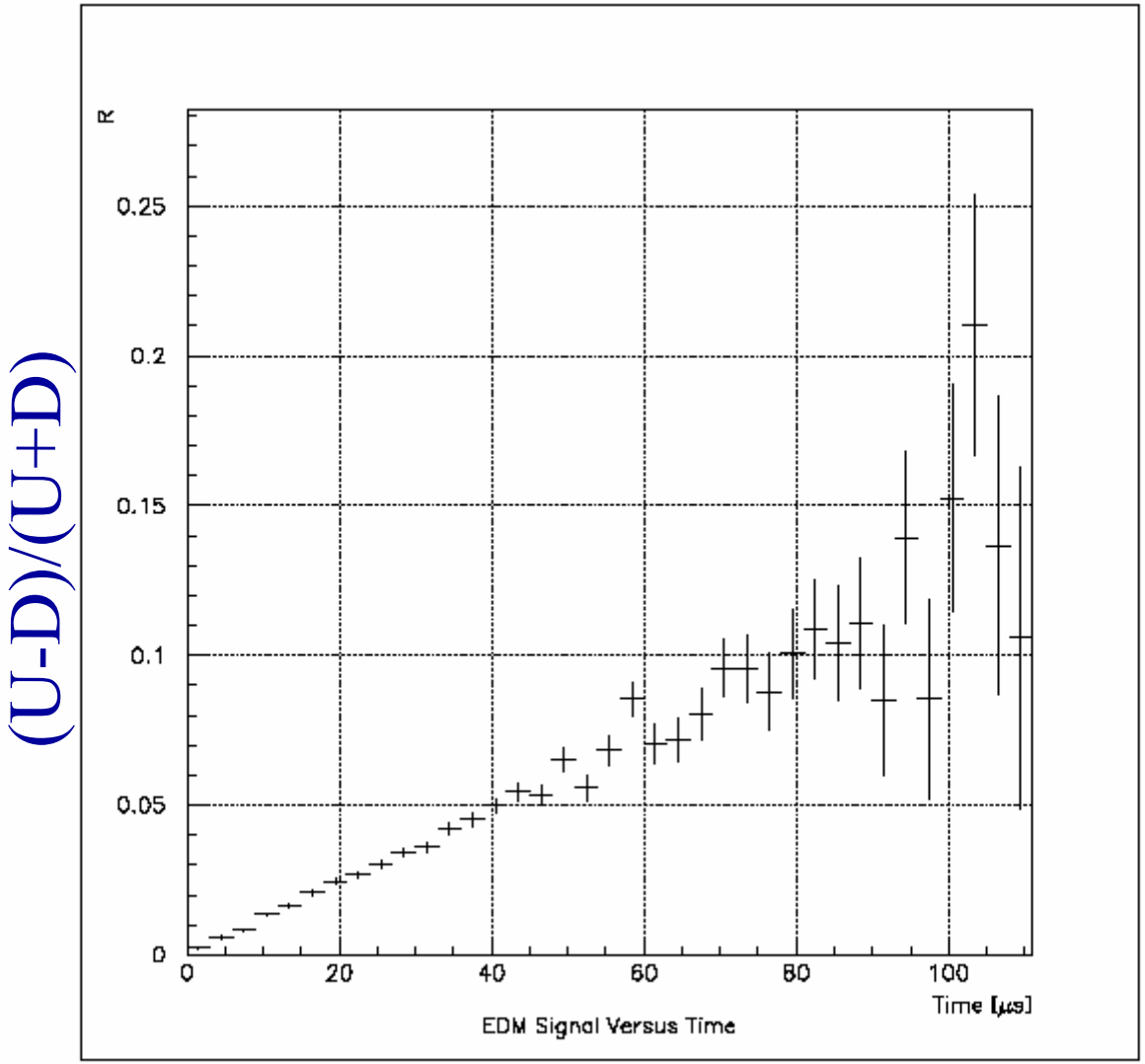


Figure 3: MC simulation of the muon EDM signal, $R = \frac{N_{up}-N_{down}}{N_{up}+N_{down}}$, versus time.

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 · cm Level.

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

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M. Iwasaki, **RIKEN, Japan**

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

January 9, 2003

†Spokesperson

Resident Spokesperson

Expected Muon EDM Value from a_μ

$$L_{DM} = \frac{1}{2}\left[D\bar{\mu}\sigma^{\alpha\beta}\frac{1+\gamma_5}{2} + D^*\bar{\mu}\sigma^{\alpha\beta}\frac{1-\gamma_5}{2}\right]\mu F_{\alpha\beta},$$

where $\sigma^{\alpha\beta} = \frac{1}{2}\left[\gamma^\alpha, \gamma^\beta\right]$ and

$$a_\mu \frac{e}{2m_\mu} = \Re D,$$

$$d_\mu = \Im D,$$

$$D^{SUSY} = \left|D^{SUSY}\right| e^{i\phi_{CP}}$$

Probe this phase to 1%

$$d_\mu = 2\times 10^{-22}\ \mathrm{e}\cdot\mathrm{cm}\ \frac{a_\mu^{\mathrm{SUSY}}}{25\times 10^{-10}}\tan(\phi_{CP})$$

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

Deuteron Coherence Time

- E, B field stability
- Multipoles of E, B fields
- Vertical (Pitch) and Horizontal Oscillations
- Finite Momentum Acceptance $\Delta P/P$

We believe we can do τ_p>10s

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

Deuteron Statistical Error (200MeV):

$$\sigma_d \approx 8 \frac{\hbar a \gamma^2}{\sqrt{\tau_p} E_R (1+a) A P \sqrt{N_c f T_{Tot}}}$$

τ_p : 10s. **Polarization Lifetime (Coherence Time)**

A : 0.5 **The left/right asymmetry observed by the polarimeter**

P : 0.55. **The beam polarization**

N_c : 4×10^{11}d/cycle. **The total number of stored particles per cycle**

T_{Tot}: 10^7s. **Total running time per year**

f : 0.01 **Useful event rate fraction**

E_R : 3.5MV/m. **Radial electric field**

$$\sigma_d \approx 2\times10^{-28}\,\mathrm{e}\cdot\mathrm{cm} \quad \text{per year}$$

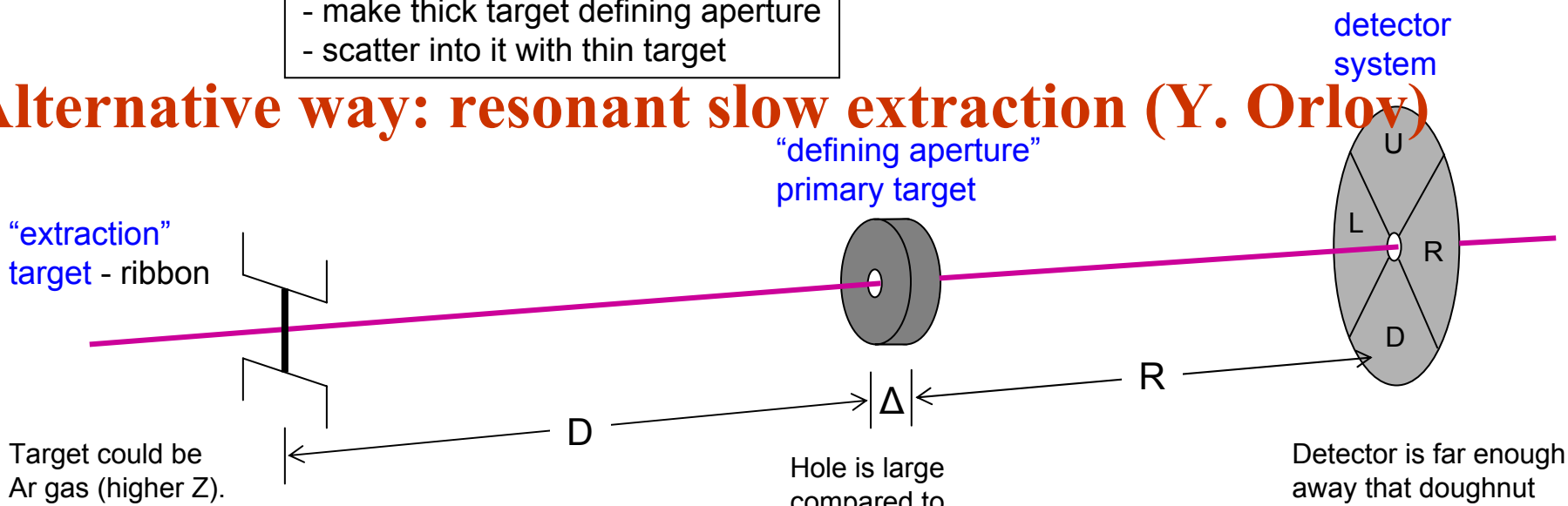
$$\frac{d\vec{s}}{dt} = \vec{\mu}\times\vec{B} + \vec{d}\times\vec{E}$$

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. Everything that goes through hole stays in the ring.

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

See "Polarimeter for Deuteron EDM" talk by Gerco Onderwater on Wednesday

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

Deuteron EDM Signal is Strong:

- Intense Polarized Deuteron Beams $>10^{11}$/cycle
- Long Spin Coherence Time >10s
- Polarimeters: Large Left/Right Asymmetry ~.5

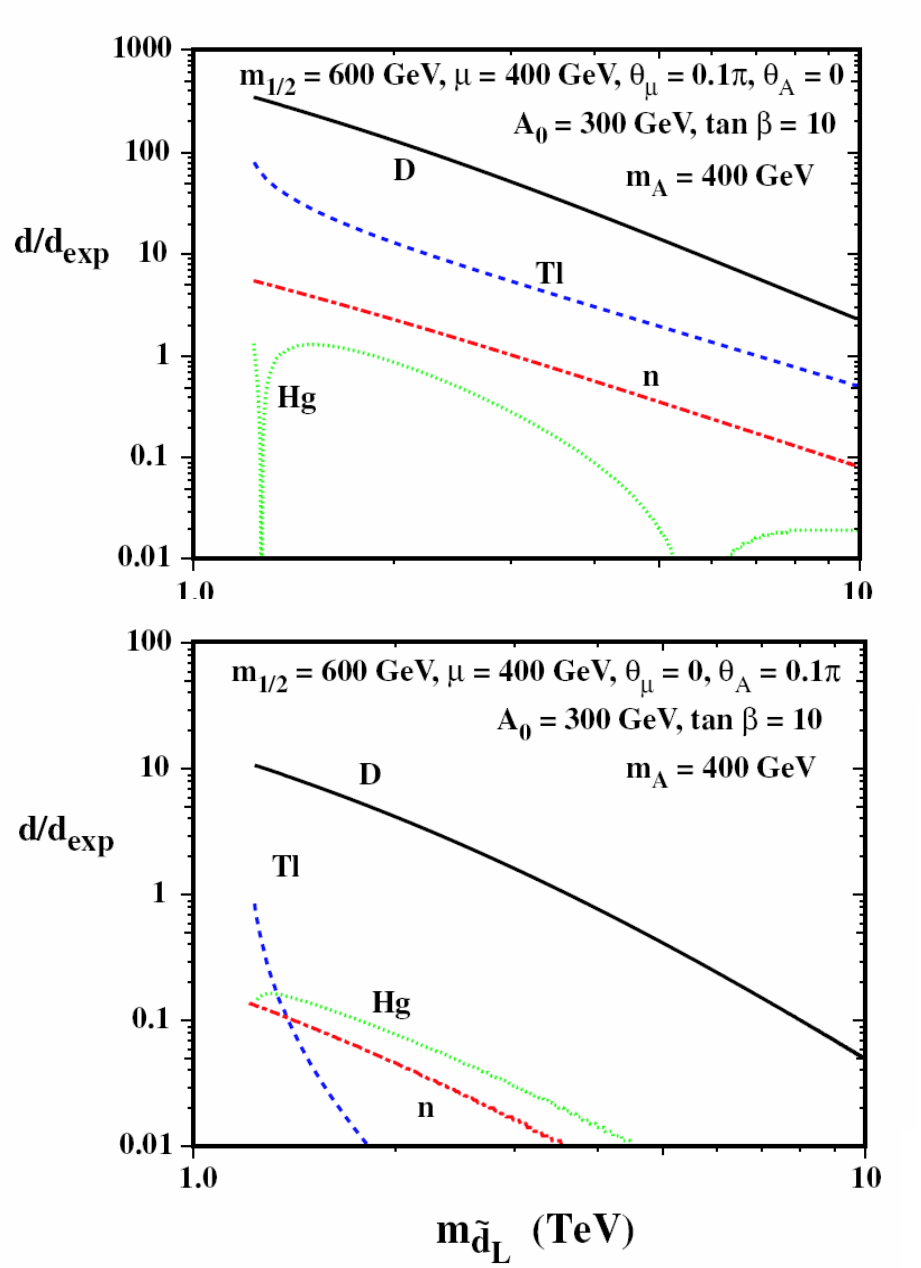
$$\frac{d\vec{s}}{dt} = \vec{\mu} \times \vec{B} + \vec{d} \times \vec{E}$$

Deuteron EDM Systematic Errors at 10^{-27} e·cm:

- Out of Plane Electric Field (E_v)
- Geometrical Phases (2nd Order Effects)
- Tensor Polarization (E.S.: Different Dependence on ω_a …)
- Polarimeter Detector Related Effects

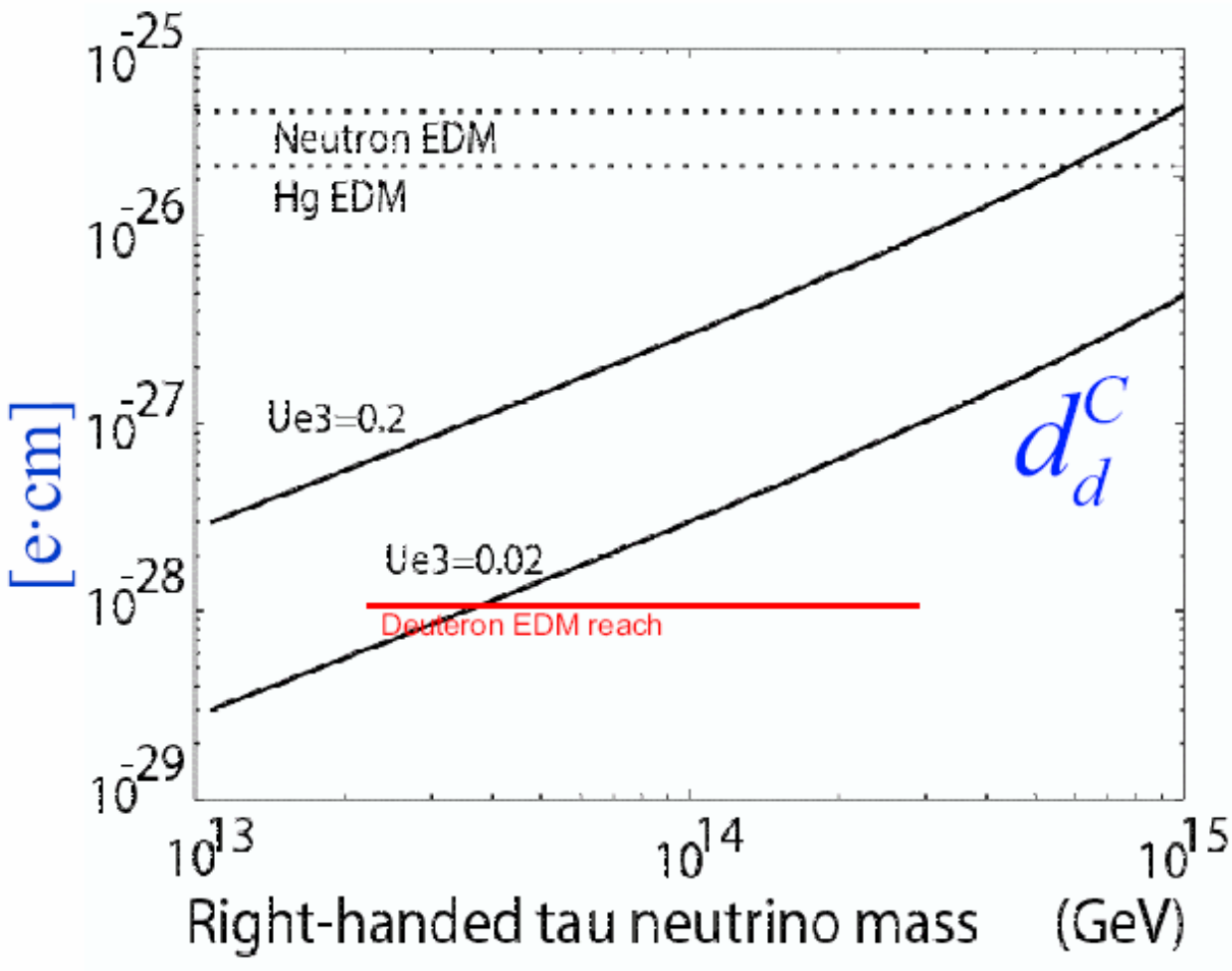
$$\frac{d\vec{s}}{dt} = \vec{\mu} \times \vec{B} + \vec{d} \times \vec{E}$$

Deuteron (D) EDM at 3×10^{-27}e·cm



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

Relative strength of various EDM limits as a function of left handed down squark mass (O. Lebedev, K. Olive, M. Pospelov and A. Ritz, PRD **70**, 016003 (2004) hep-ph/0402023)



J. Hisano et al, Phys. Lett. B604 (2004).

Figure 6. The d-quark color EDM as predicted by the SUSY model (see text). Also shown are the current limits from the neutron and Hg EDMs as well as the sensitivity of the planned deuteron EDM experiment at the 3×10^{-27} e · cm level.

Proposal to BNL by the Storage Ring EDM Collaboration (Fall, 2004)

Deuteron EDM Proposal: Search for a Permanent Deuteron Electric Dipole Moment at the 10^{-27} e·cm Level.

M. Aoki[16], M. Bai[5], G. Bennett[5], A. Bravar[5], H.N. Brown[5], G. Cantatore[17], A. Caracappa[5], R.M. Carey[3], P.T. Debevec[9], H. Denizli[1], P.D. Eversheim[4], F.J.M. Farley[5], C. Guclu[11], R. Hackenburg[5], S. Hoblit[5], H. Huang[5], K.P. Jungmann[8], M. Karuza[17], D. Kawall[13,14], B. Khazin[6], I.B. Khriplovich[6], B. Kirk[5], I.A. Koop[6], Y. Kuno[16], R. Larsen[5], D.M. Lazarus[5], L.B. Leipuner[5], C.P. Liu[8], V. Logashenko[3,6], M. Lowry[5], W.W. MacKay[5], K.R. Lynch[3], W. Marciano[5], W. Meng[5], J.G. Messchendorp[8], L. Miceli[5], J.P. Miller[3,*], W.M. Morse[5], G. Noid[10], C.J.G. Onderwater[8], Y. Orlov[7], C.S. Ozben[11], R. Prigl[5], S. Redin[6], S. Rescia[5], B.L. Roberts[3], G. Ruoso[12], T. Russo[5], A.M. Sandorfi[5], A. Sato[16], N. Shafer-Ray[15], Y. Shatunov[6], Y.K. Semertzidis[5,*], A. Silenko[2], E. Stephenson[10,*], R.G.E. Timmermans[8], C.E. Thorn[5], X. Wei[5], H.W. Wilschut[8], M. Yoshida[16]

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10. **Indiana University, Bloomington, IN 47408, USA**
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12. **Legnaro National Laboratories of INFN, Legnaro, Italy**
13. **University of Massachusetts, Amherst, MA 01003, USA**
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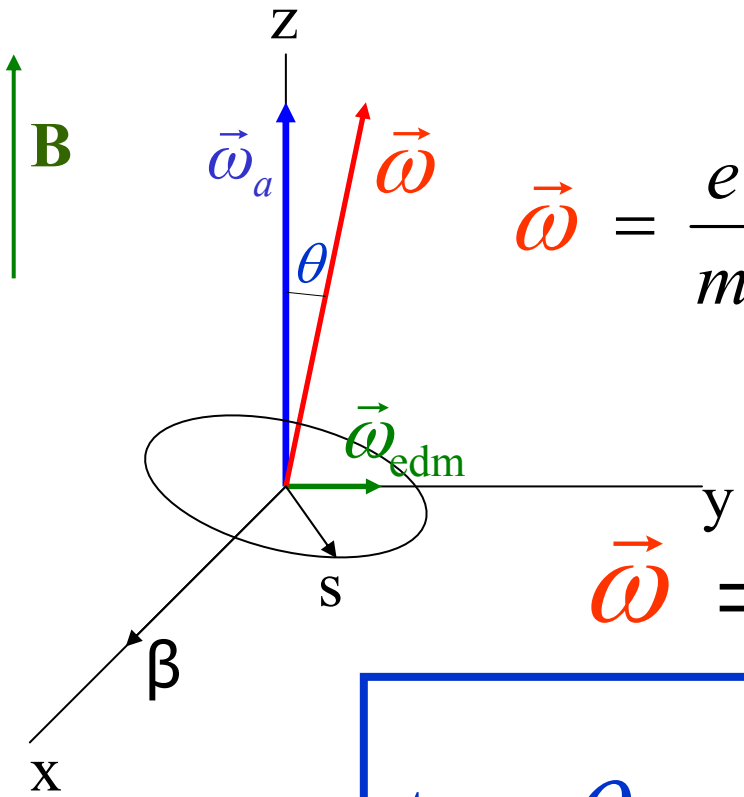
16. **Osaka University, Osaka, Japan**
17. **University and INFN Trieste, Italy**

Resonance EDM Method

- Yuri Orlov's idea: "The resonance Method of EDM Measurements in Storage Rings: Conceptual Design", EDM internal note #69, October 2004.
- It eliminates the main systematic error of the previous method (no need for radial E-field).
- Much smaller size ring (cost).
- It eliminates a whole class of systematic errors associated with "zero" frequency.
- It allows for two bunches stored simultaneously in the ring with different vertical tunes for systematics.

See "EDM search" talk by Y. Orlov on Wednesday

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



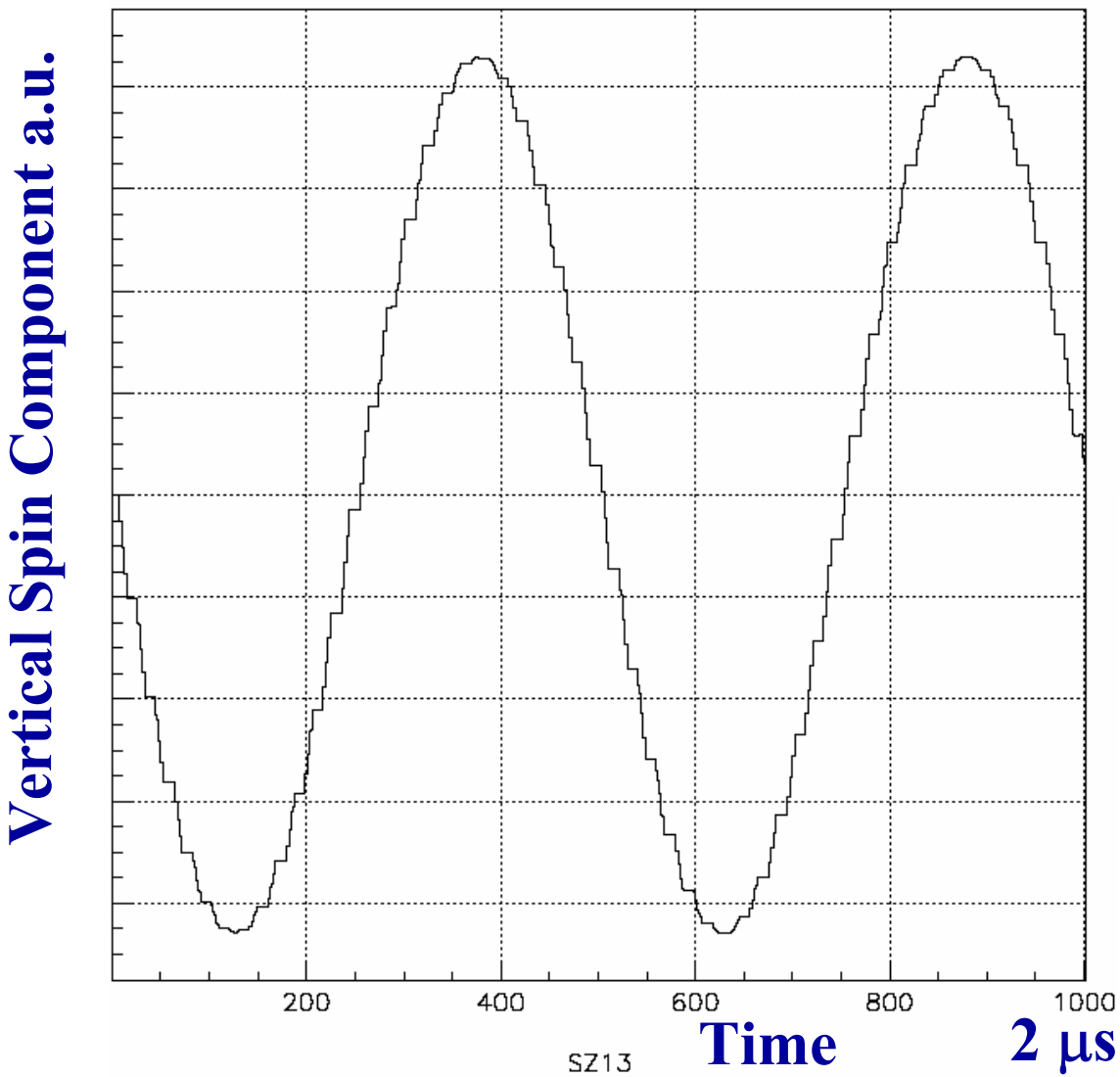
$$\vec{\omega} = \frac{e}{m}\left\{a\vec{B} + \frac{\eta}{2c}\left(\vec{u}\times\vec{B}\right)\right\}$$

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

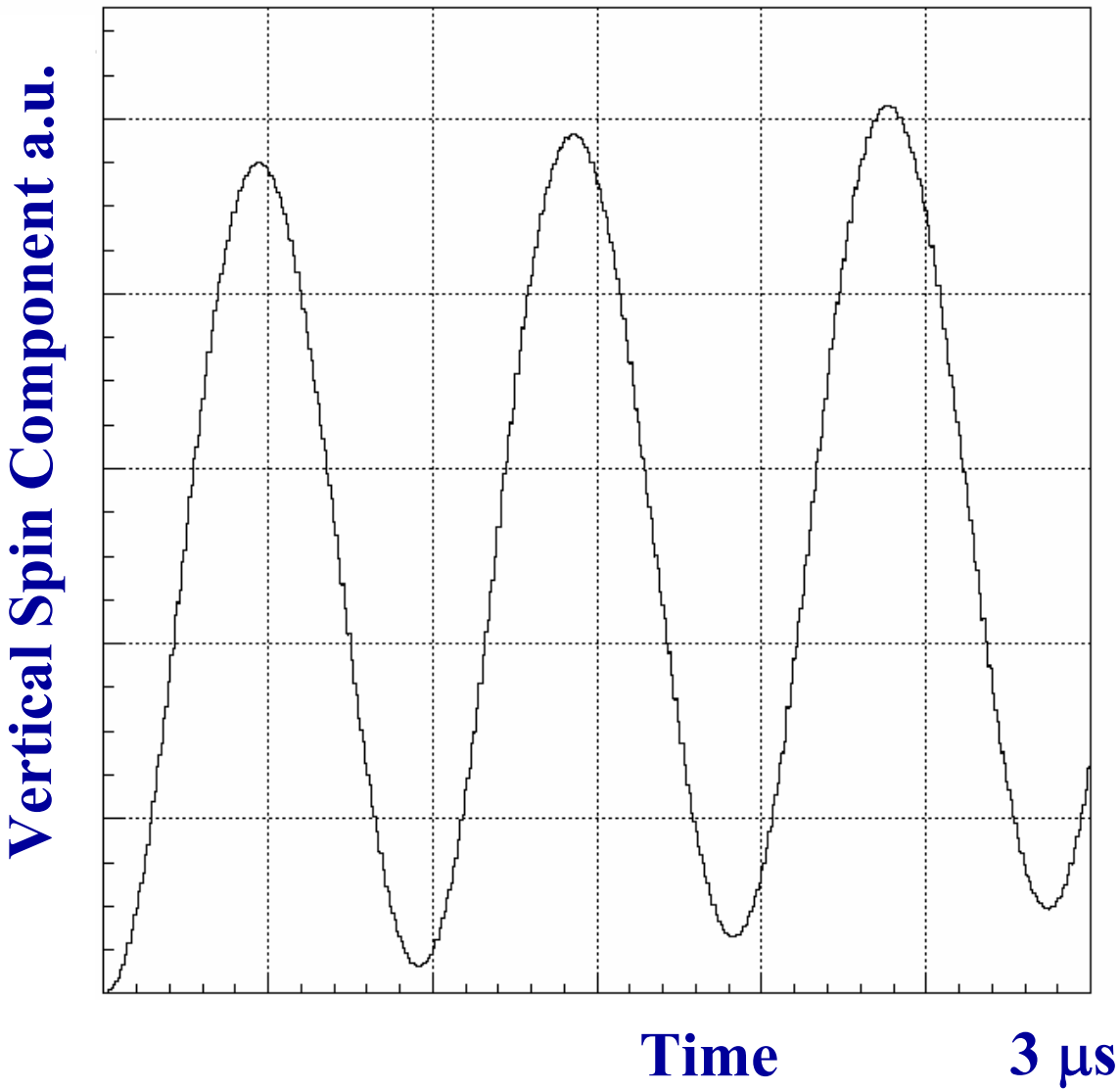
$$\boxed{\tan\theta = \frac{\omega_{edm}}{\omega_a}}$$

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

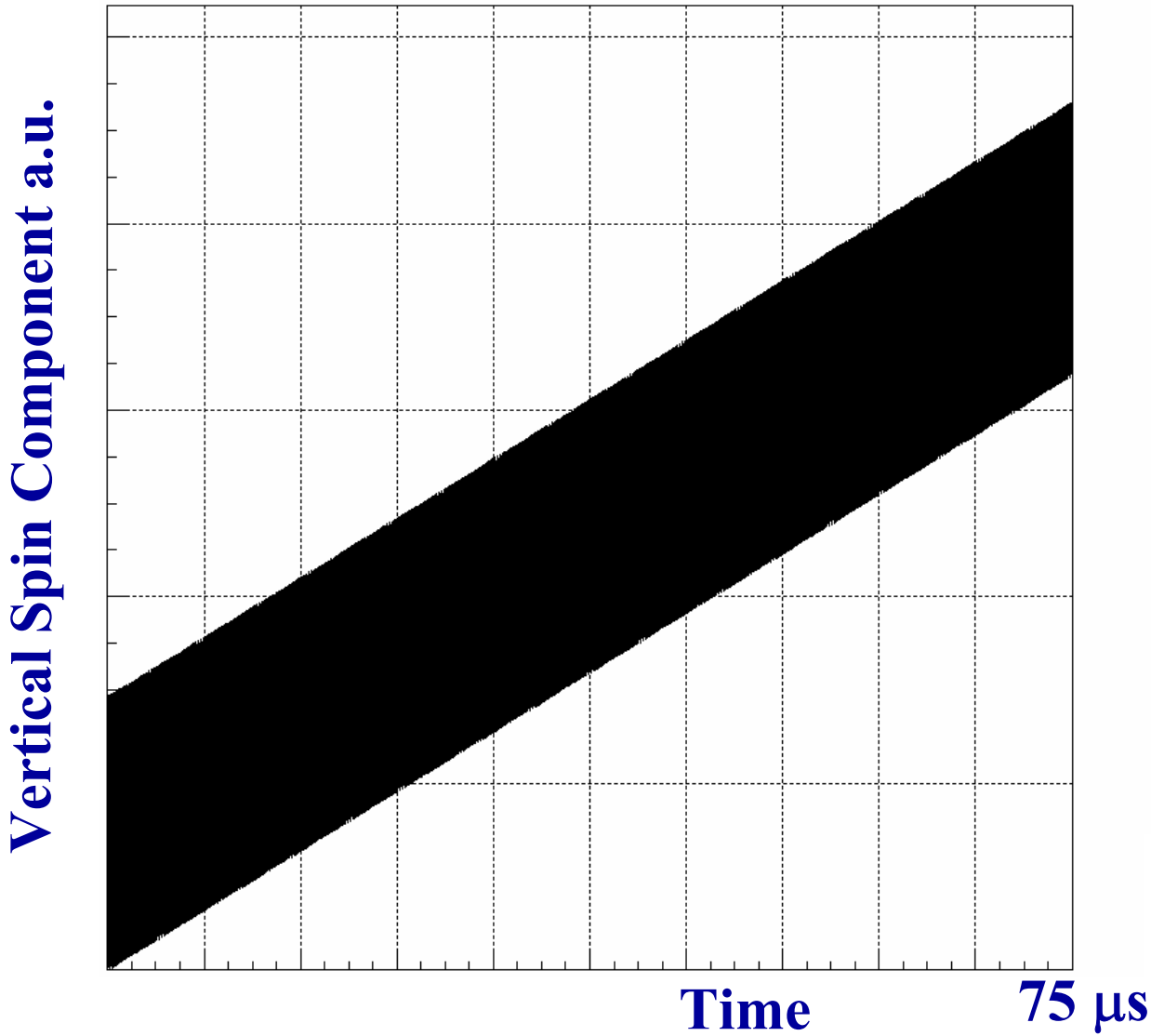
Vertical Spin Component without Velocity Modulation

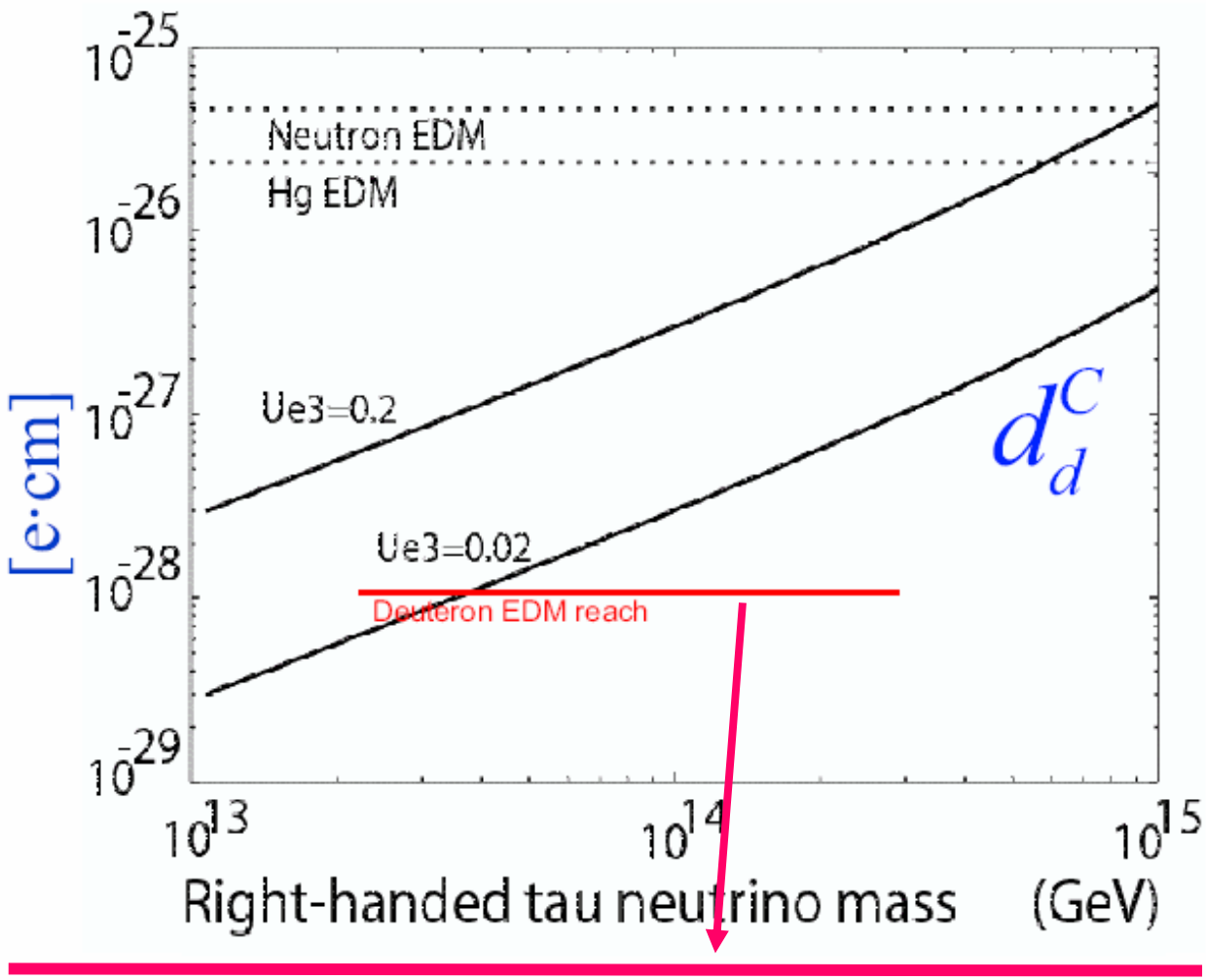


Vertical Spin Component with Velocity Modulation at ω_a



Vertical Spin Component with Velocity Modulation (longer Time)





J. Hisano et al, Phys. Lett. B604 (2004).

With 2 orders of magnitude improvement!

Summary

Electric Dipole Moment Searches:

- Exciting Physics, Forefront of SUSY/Beyond SM Search.
- Revolutionary New Ways of Probing EDMs; Muon and Deuteron Cases-Very Exciting.
- Sensitive EDM Experiments could solve the matter/anti-matter asymmetry mystery.

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

More Information at
http://www.bnl.gov/edm

•Yuri Orlov, “The resonance Method of EDM Measurements in Storage Rings: Conceptual Design”, EDM internal note #69, October 2004.

•F.Farley *et al.,* PRL **93**, 052001 (2004), hep-ex/0307006.

•Y.S. *et al.,* Proceedings High Intensity Muon Sources (HIMUS 99), Tsukuba, Japan, 1-4 Dec 1999, hep-ph/0012087.

•D.F.Nelson *et al.,* Phys. Rev. Lett. **2**, 492-495 (1959).

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