Flavour in the era of LHC
CERN, 7 November 2005

Muon g-2 and EDM Experiments of the Muon, Deuteron, and Neutron.

Yannis K. Semertzidis

Brookhaven National Lab

- **Muon g-2 experiment**
- **EDMs: What do they probe?**
- **Physics of Hadronic EDMs**
- **Experimental Techniques**

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

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.

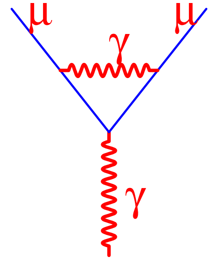
$$\frac{d\vec{s}}{dt} = \vec{\mu} \times \vec{B} + \vec{d} \times \vec{E}$$

g-factors:

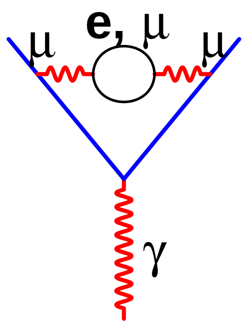
- Proton (g_p=+5.586) and the neutron (g_n=-3.826) are composite particles.
- The ratio g_p/g_n=-1.46 close to the predicted –3/2 was the first success of the constituent quark model.
- The experimental sensitivity of g_e-2 (electron) due to quantum field fluctuations involving only QED.
- The g_μ-2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

g - 2 for the muon

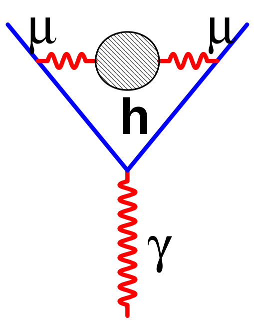
Largest contribution : $a_\mu = \frac{\alpha}{2\pi} \approx \frac{1}{800}$



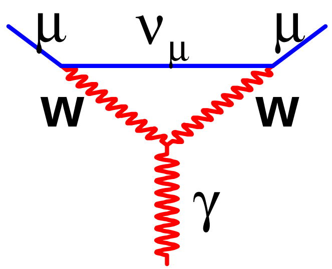
Other standard model contributions :

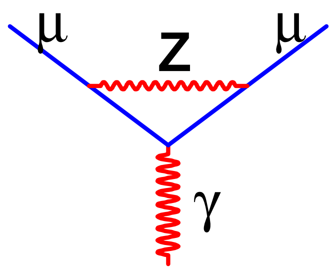


QED



hadronic





weak

Theory of a_μ

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

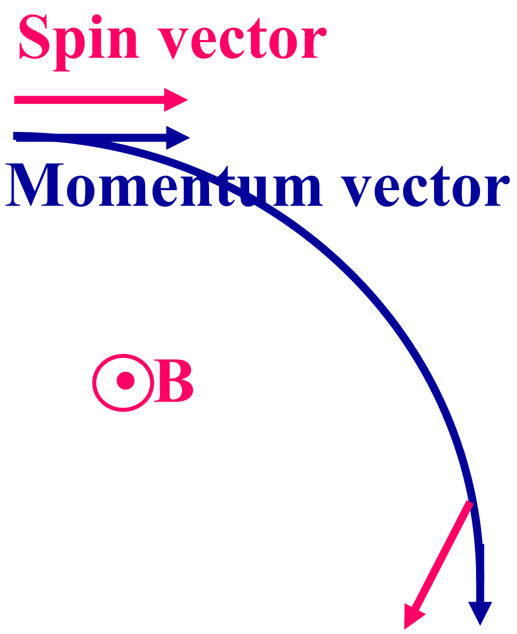
- $a_\mu(\text{QED}) = 11\ 658\ 470.6\ \ (0.3) \times 10^{-10}$
- $a_\mu(\text{had}) = 694.9\ \ (8.)\ \times 10^{-10}$ (based on e^+e^-)
- $a_\mu(\text{had}) = 709.6\ \ (7.)\ \times 10^{-10}$ (based on τ)
- $a_\mu(\text{weak}) = 15.4\ \ (0.3) \times 10^{-10}$

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

Experimental Principle:

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

The Principle of g-2



Non-relativistic case

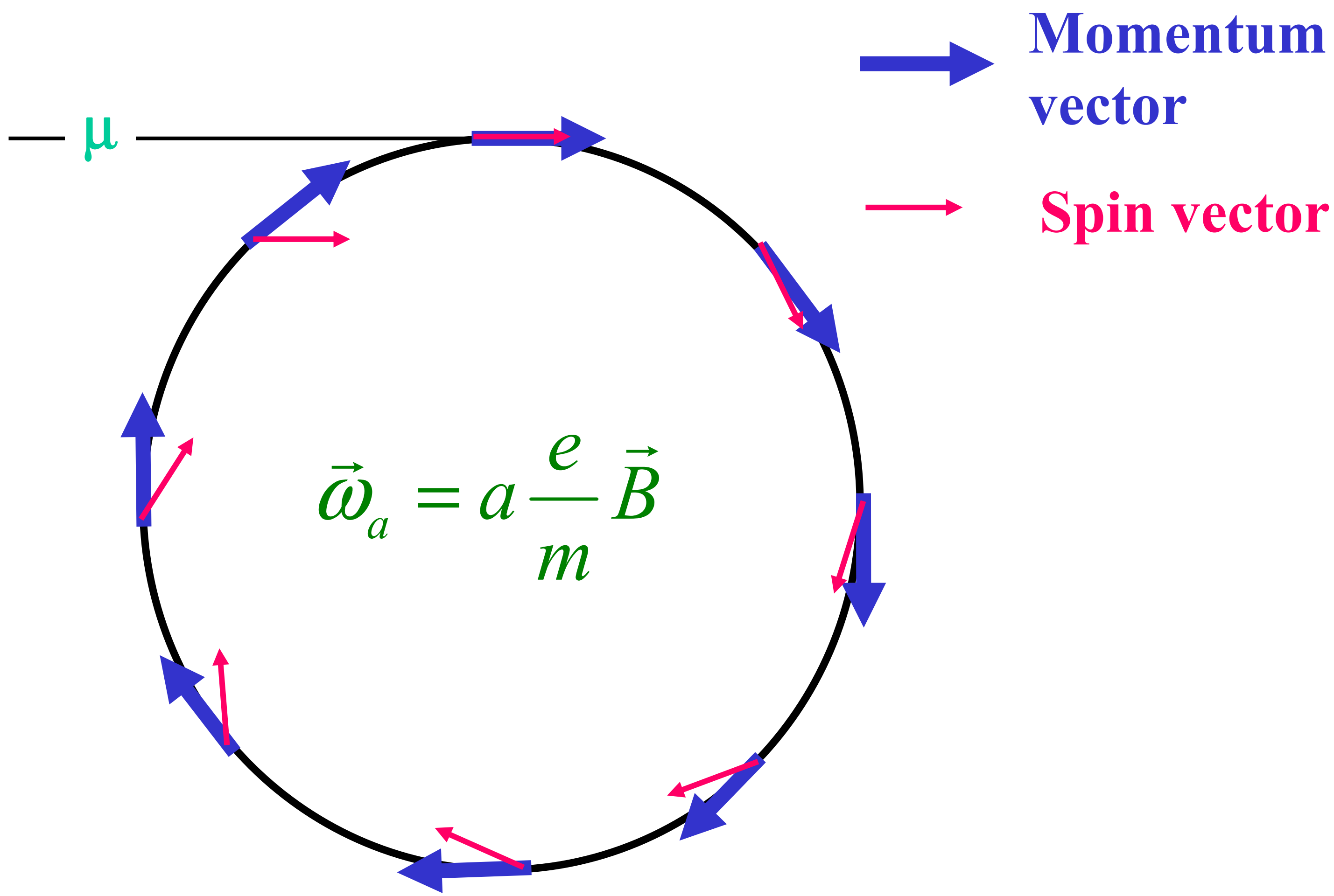
$$\omega_c = \frac{eB}{m}$$

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

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

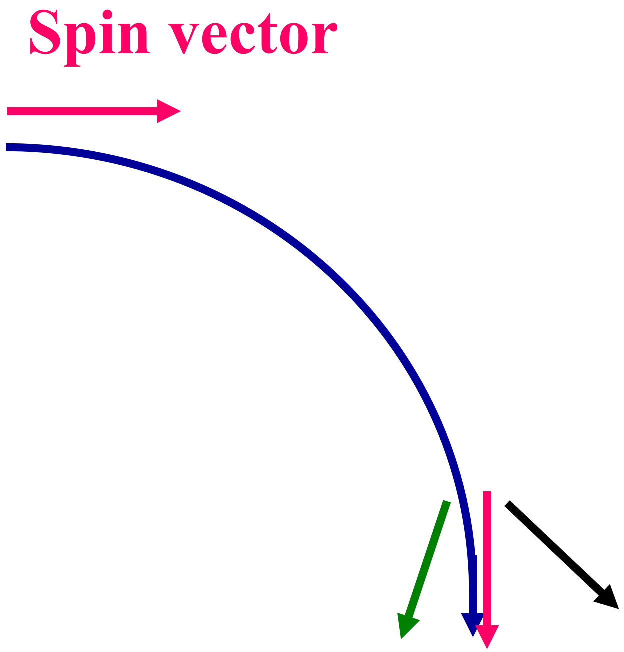
$$\frac{d\vec{s}}{dt} = \vec{\mu} \times \vec{B} + \vec{d} \times \vec{E}$$

Spin Precession in g-2 Ring
(Top View)



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

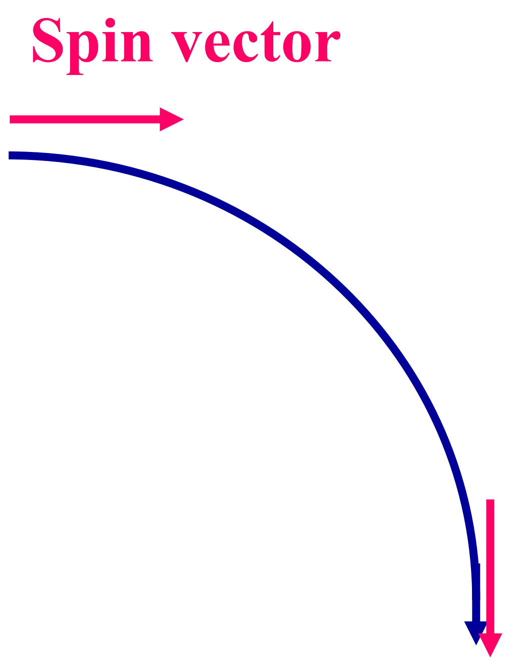
Effect of Radial Electric Field



- 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



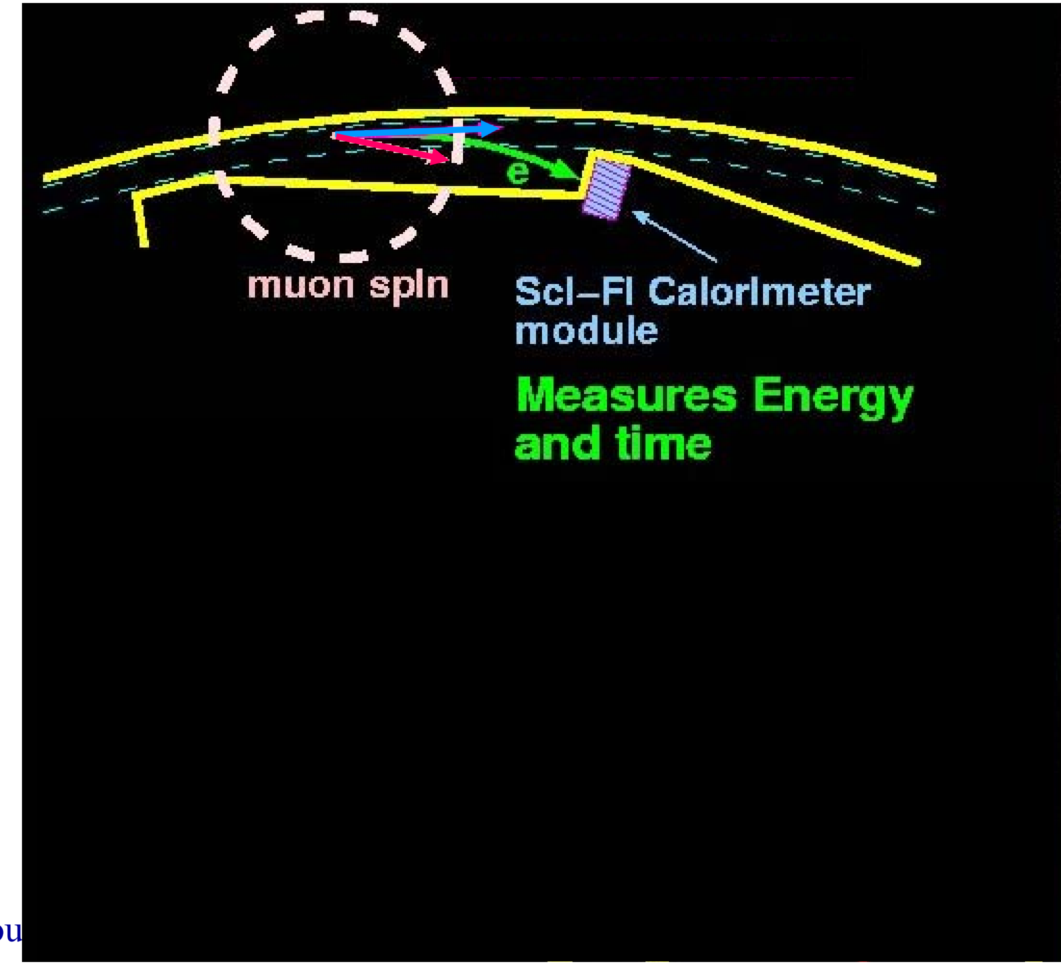
- …just right, γ≈29.3 for muons (~3GeV/c)

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

- The Muon Storage Ring:
  $B \approx 1.45T, P_\mu \approx 3$ GeV/c

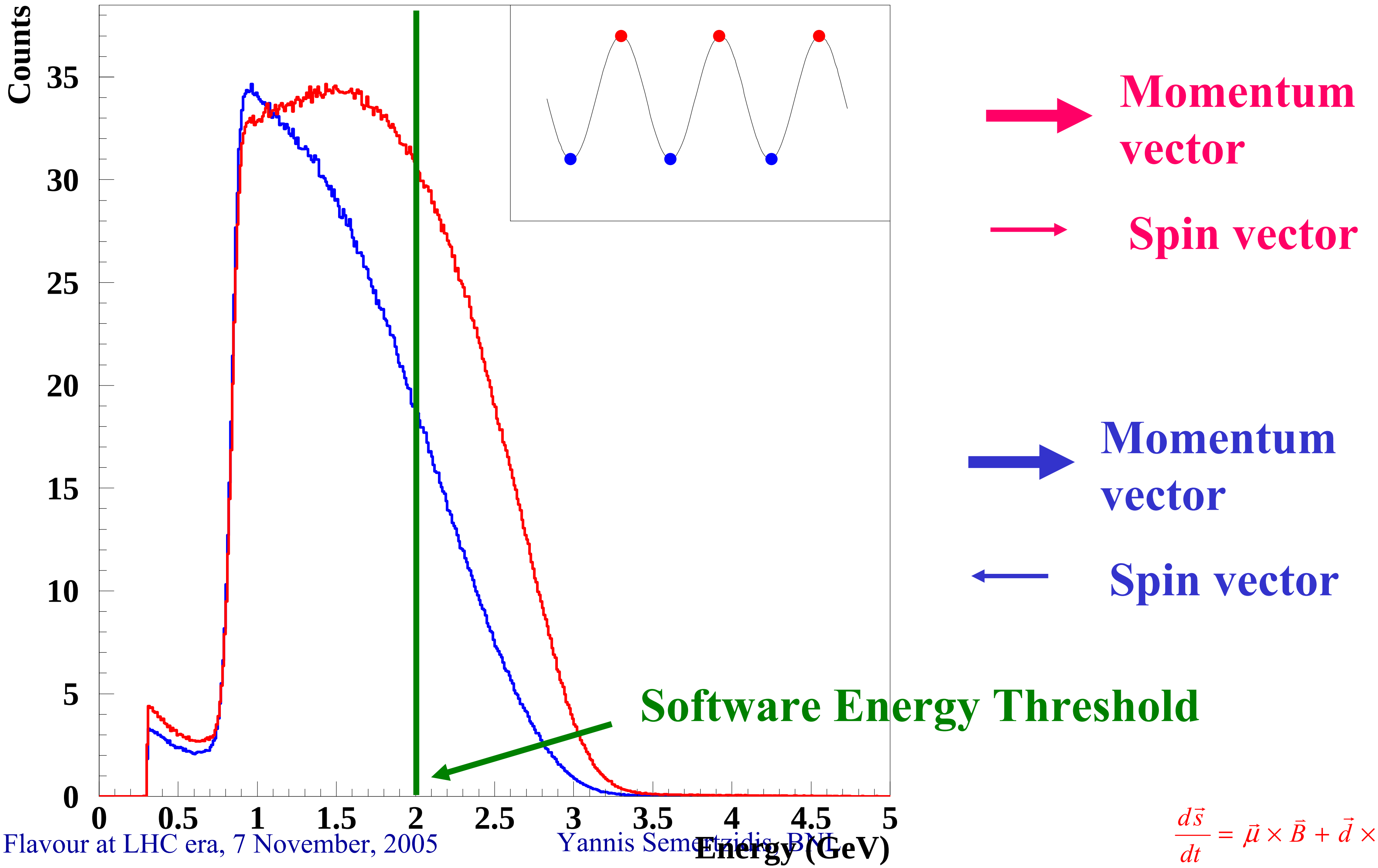
- High Proton Intensity from AGS

Detectors and vacuum chamber



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

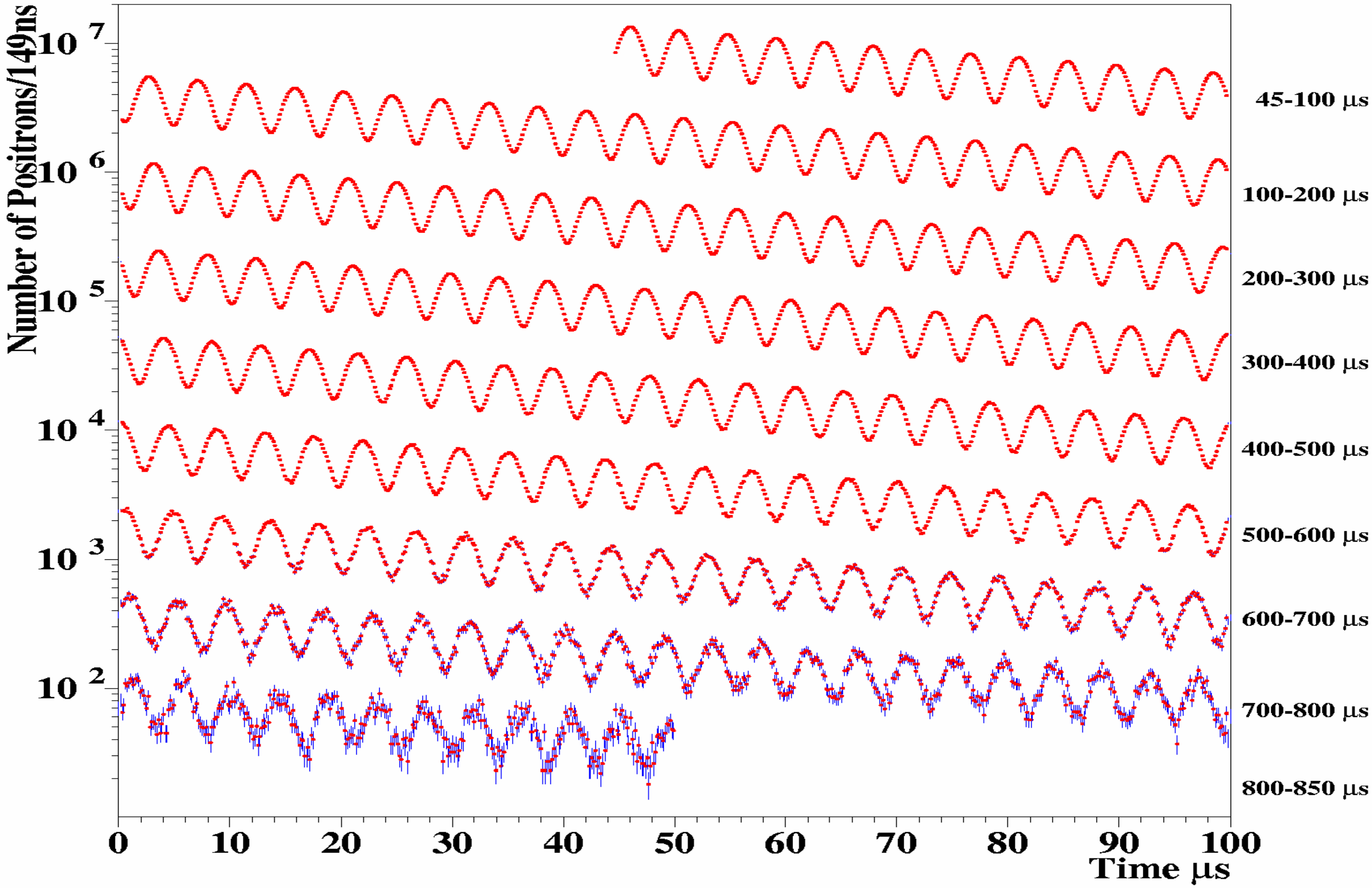
Energy Spectrum of Detected Positrons



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

4 Billion e^+ with E>2GeV

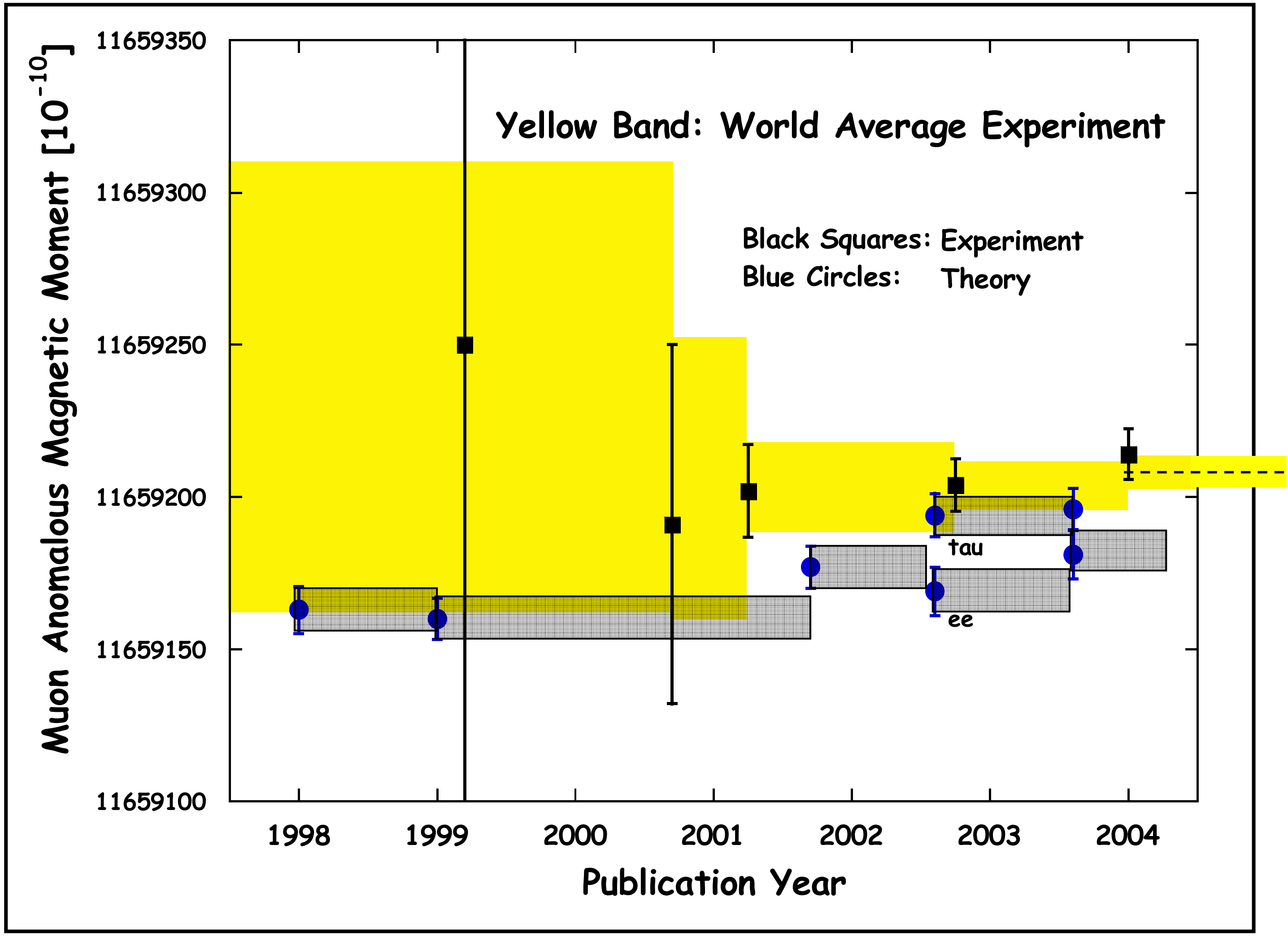
$$dN/dt = N_0 e^{-\frac{t}{\tau}}[1 + A\cos(\omega_a t + \phi_a)]$$



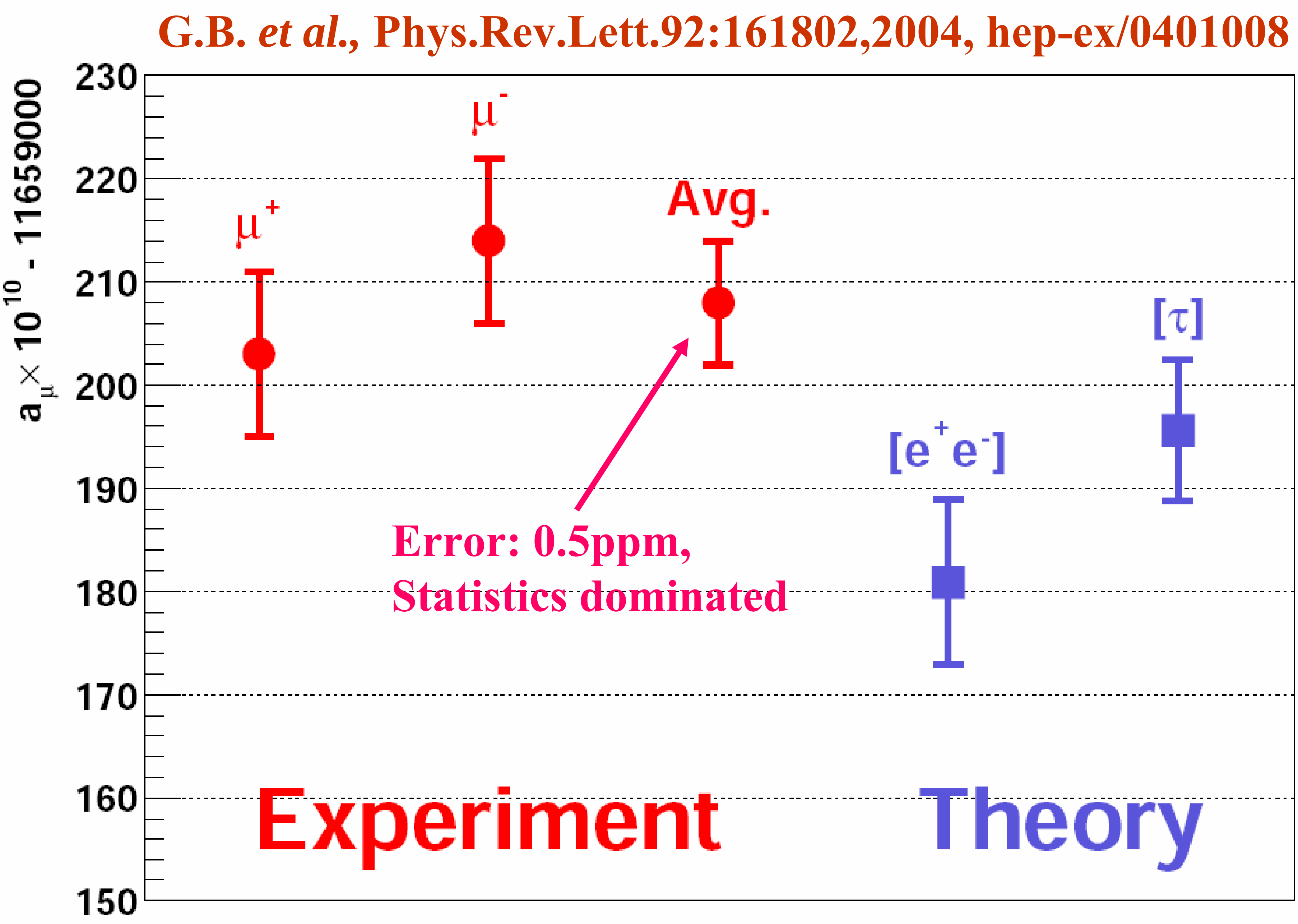
Fla

$\vec{l} \times \vec{E}$

Theory and Experiment vs. Year

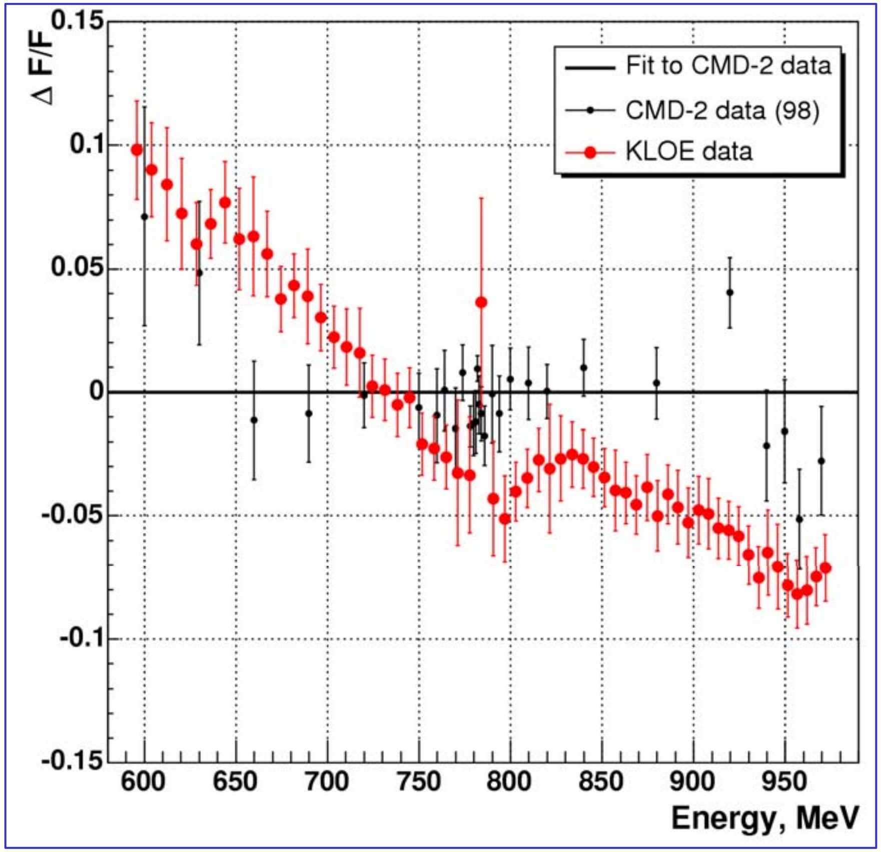


$$\frac{d\vec{s}}{dt} = \vec{\mu} \times \vec{B} + \vec{d} \times \vec{E}$$


G.B. *et al.*, Phys.Rev.Lett.92:161802,2004, hep-ex/0401008
$a_\mu \times 10^{10}$ - 11659000
230
220
210
200
190
180
170
160
150
μ^+
μ^-
Avg.
Error: 0.5ppm,
Statistics dominated
[e^+e^-]
[τ]
Experiment
Theory

Fl

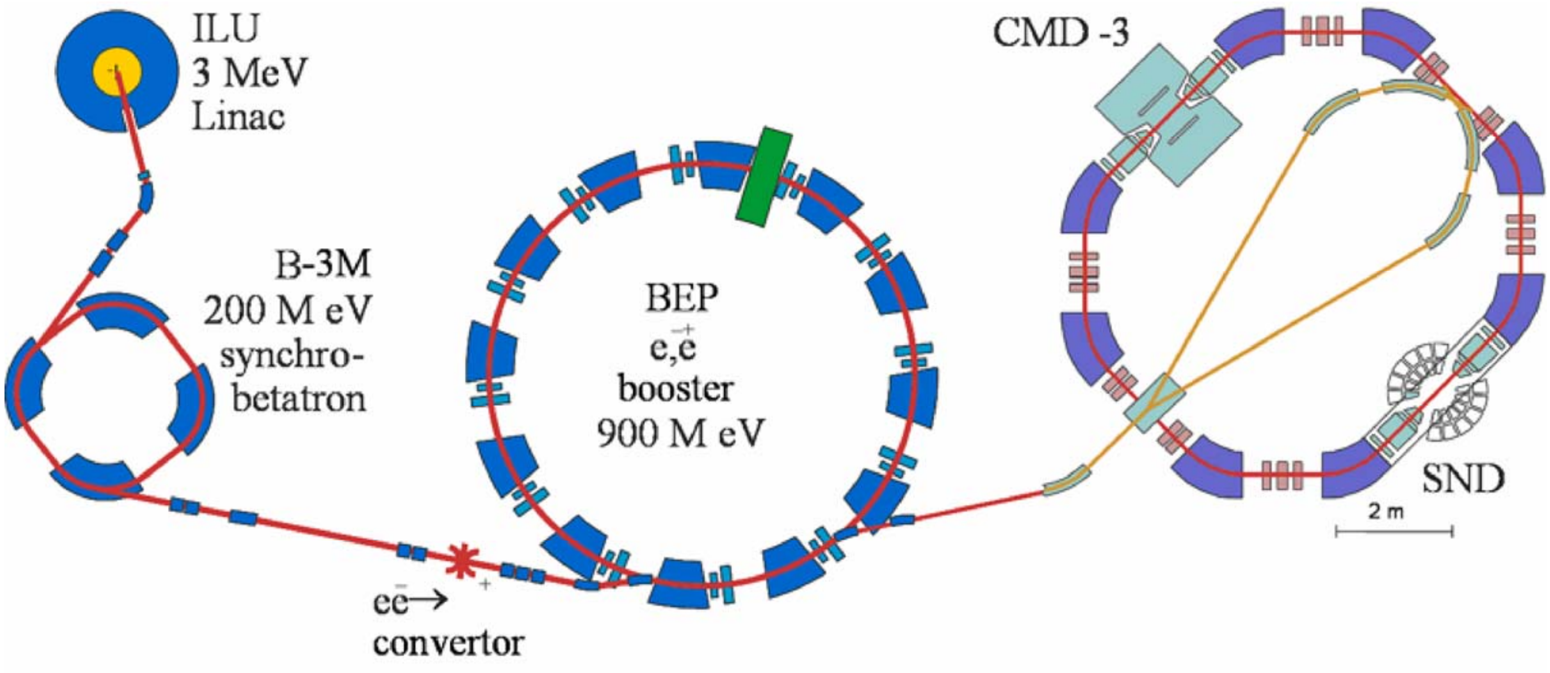
Comparison of CMD2 data with KLOE



Plotted is $\frac{\Delta F}{F} = \frac{|F_\pi|^2 \text{ (exp)}}{|F_\pi|^2 \text{ (CMD-2 fit)}} - 1$

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

Future measurements at VEPP-2000



- Factor >10 in luminosity
- Up to 2 GeV c.m. energy
- CMD-3: major upgrade of CMD-2 (new drift chamber, LXe calorimeter)
- measure 2π mode to 0.2-0.3%
- measure 4π mode to 1-2%
- overall improvement in R precision by factor 2-3

Under construction. Data taking is expected to start is 2007-2008.

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

Prospects and Summary

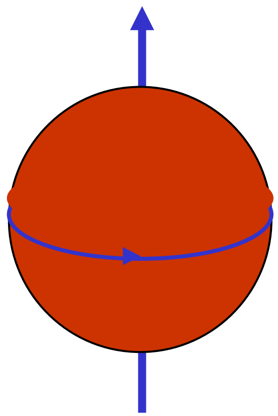
See talk by G. Onderwater on Wednesday, WG3

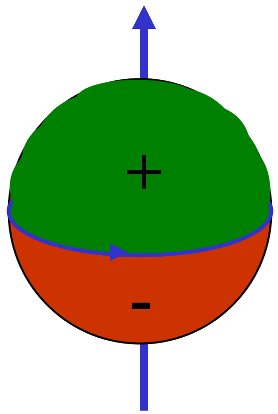
- Total experimental error (statistics dominated): 0.5ppm; probing physics beyond the S.M.

- More data (×10) from the theory front are beeing 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) in 2004 and in Spring 2006 it is going to P5 (a US national committee); funding approval is pending from DOE.

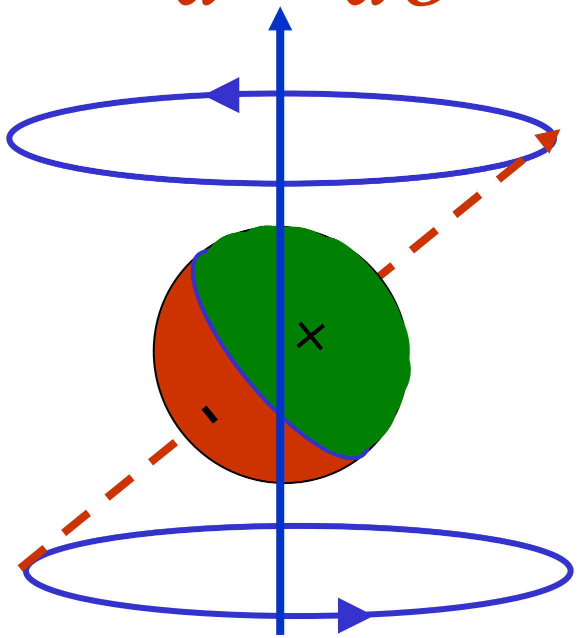
EDM: Particles with Spin…





$$\vec{d} = 0$$

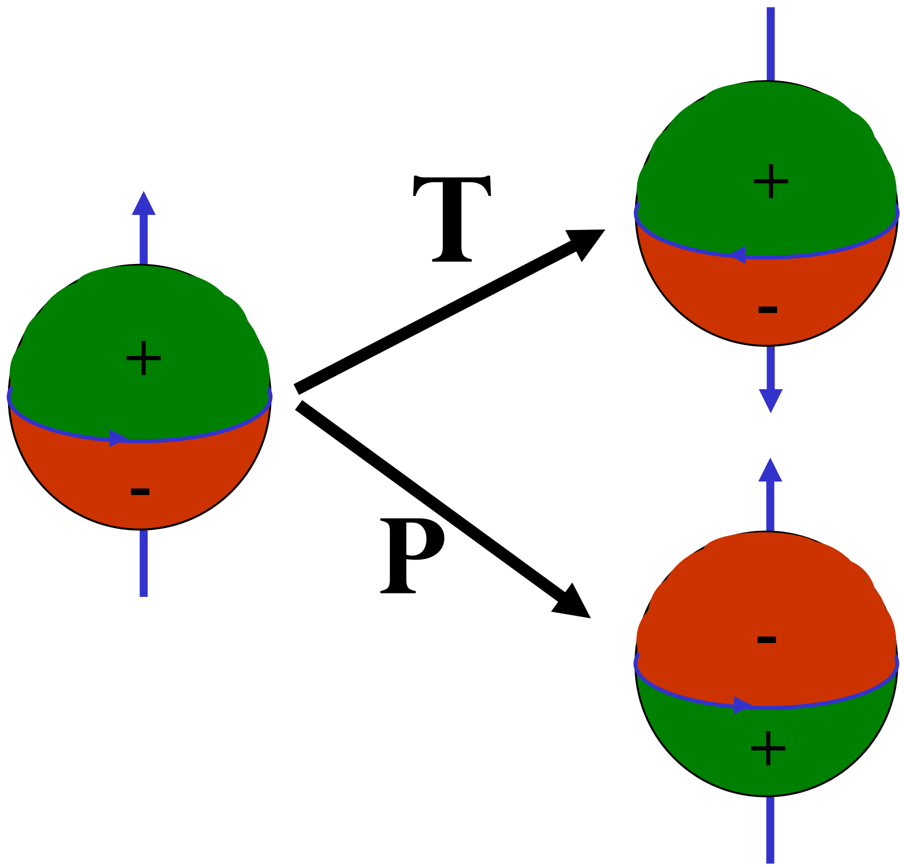
$$\vec{d} \propto d\hat{\sigma}$$



For a particle with a spin, only the EDM component along the spin survives.

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

A Permanent EDM Violates both T & P Symmetries:



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

A Permanent EDM Violates both T & P Symmetries:

$$H = -d\vec{\sigma}\cdot\vec{E} \xrightarrow{\mathbf{T}} H = -d\left(-\vec{\sigma}\right)\cdot\vec{E} = d\vec{\sigma}\cdot\vec{E}$$

$$H = -d\vec{\sigma}\cdot\vec{E} \xrightarrow{\mathbf{P}} H = -d\vec{\sigma}\cdot\left(-\vec{E}\right) = d\vec{\sigma}\cdot\vec{E}$$

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

How about Induced EDMs?

$$\vec{d} \propto d\vec{E}$$

$$H = -d\vec{E}\cdot\vec{E} \quad \xrightarrow{\textbf{T}} \quad \textbf{OK}$$

$$H = -d\vec{E}\cdot\vec{E} \quad \xrightarrow{\textbf{P}} \quad \textbf{OK}$$

$$H = -d\vec{\sigma}\cdot\vec{E}$$

1st order Stark effect. T, P Violation!

$$H = -d\vec{E}\cdot\vec{E}$$

2nd order Stark effect. Allowed!

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

MDMs are Allowed…

$$H = -\mu\vec{\sigma}\cdot\vec{B} \xrightarrow{\quad\mathbf{T}\quad} H = -\mu\left(-\vec{\sigma}\right)\cdot\left(-\vec{B}\right) = -\mu\vec{\sigma}\cdot\vec{B}$$

$$H = -\mu\vec{\sigma}\cdot\vec{B} \xrightarrow{\quad\mathbf{P}\quad} H = -\mu\left(\vec{\sigma}\right)\cdot\left(\vec{B}\right) = -\mu\vec{\sigma}\cdot\vec{B}$$

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

CPT

T-Violation → **CP-Violation**

<u>Andrei Sakharov 1967:</u>

$$n_B / n_\gamma \approx 10^{-9}$$

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….

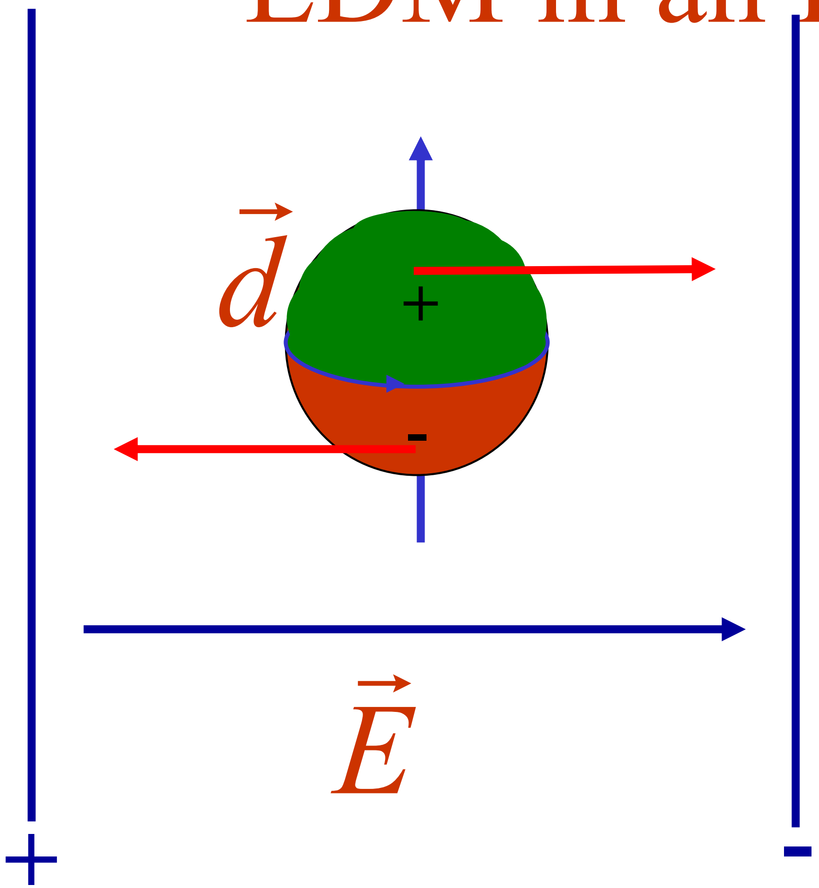
$$\frac{d\vec{s}}{dt} = \vec{\mu} \times \vec{B} + \vec{d} \times \vec{E}$$

EDM Searches are Excellent Probes of Physics Beyond the SM:

Most models beyond the SM predict values within the sensitivity of current or planned experiments:

- SUSY
- Multi-Higgs
- Left-Right Symmetric …

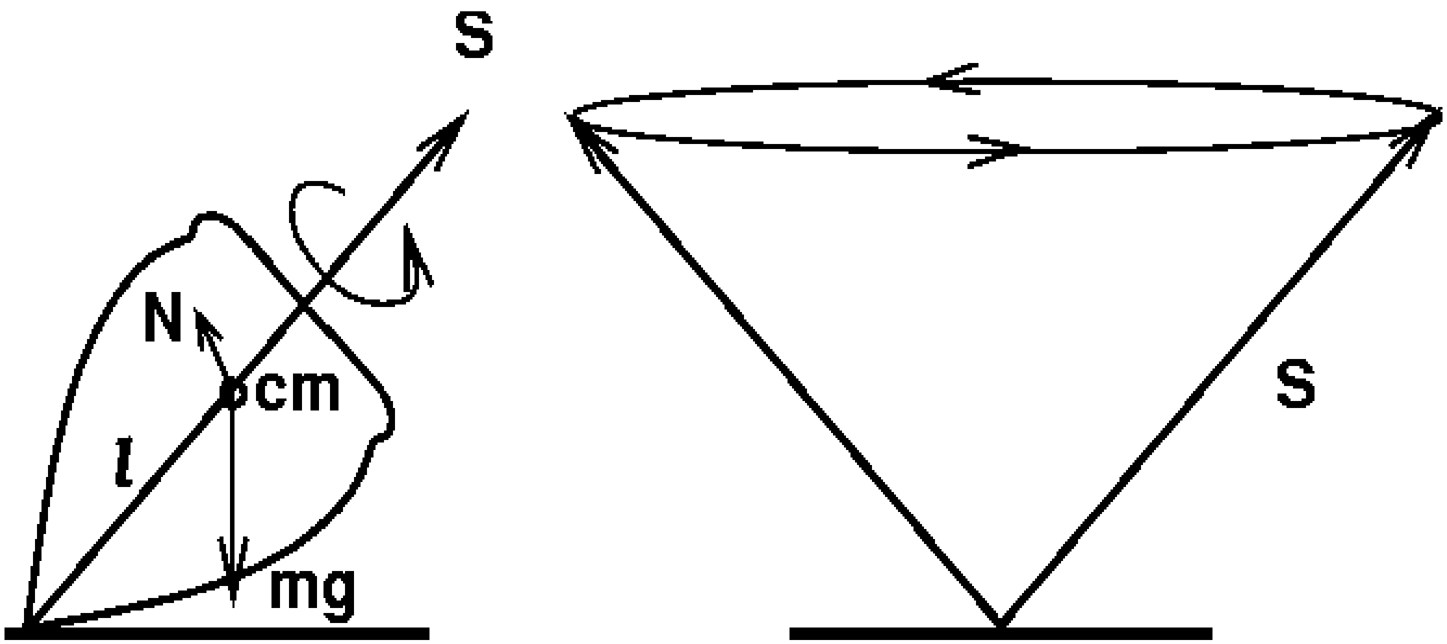
EDM in an Electric Field…



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

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

Precession of a Top in a Gravitational Field



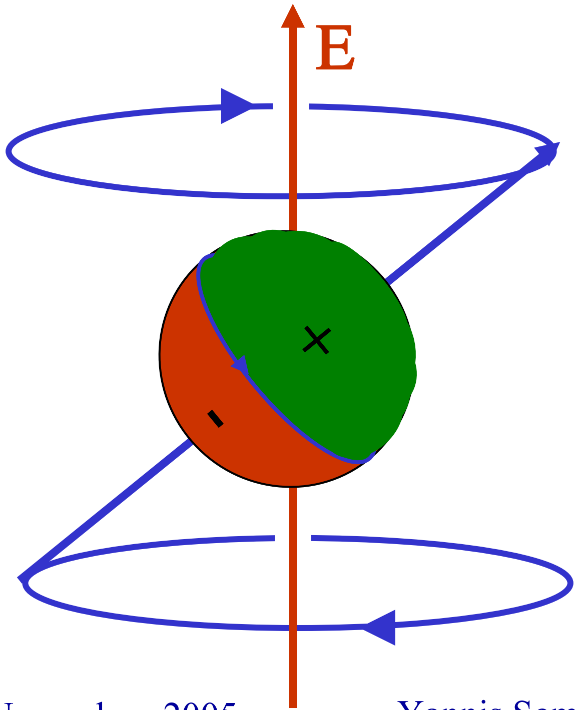
$$\omega = \frac{mgl}{L}, \quad \vec{L} = I\,\vec{S}$$

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

Usual Experimental Method

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

Small Signal

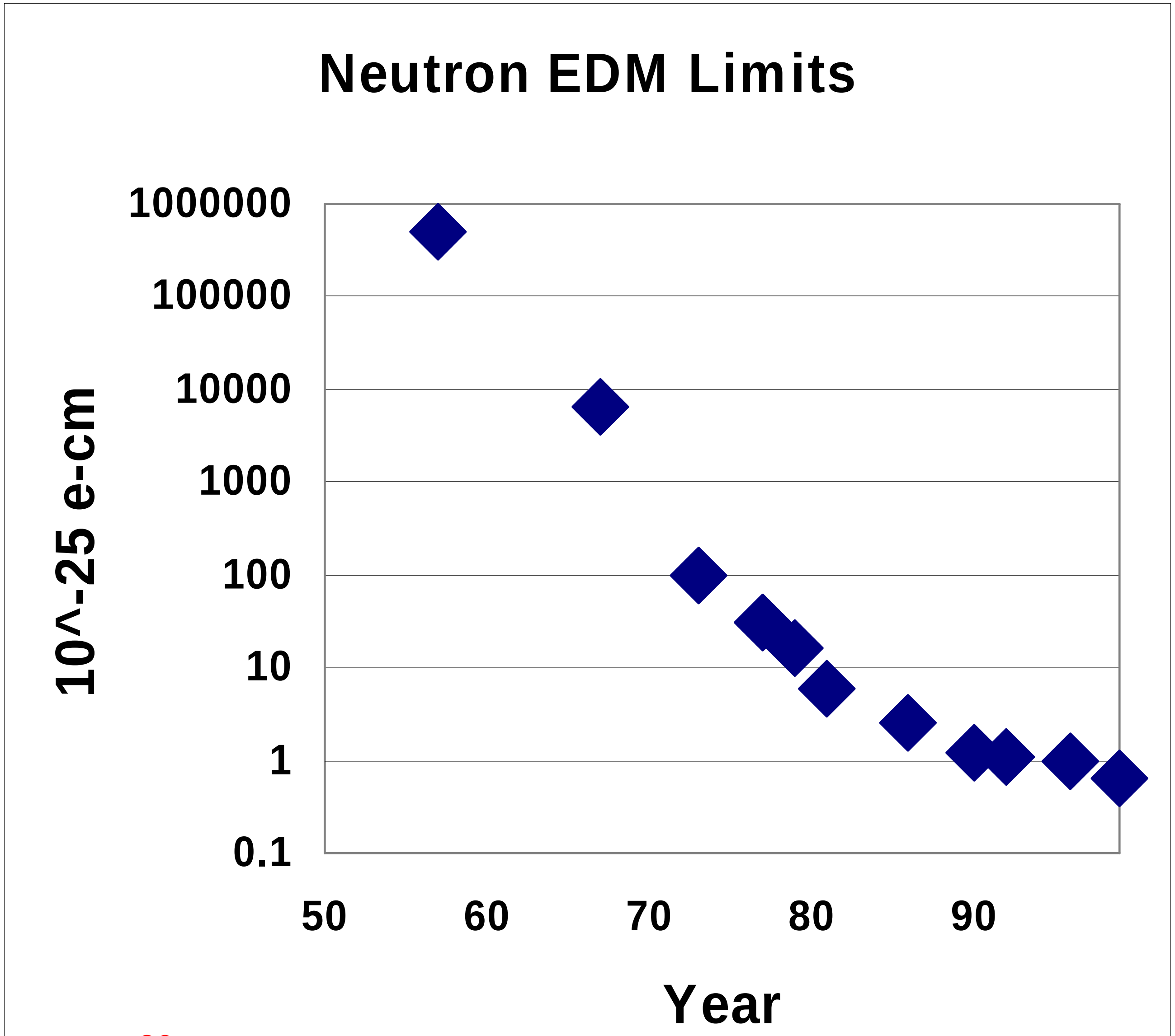


Compare the Zeeman Frequencies When E-field is Flipped:

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

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

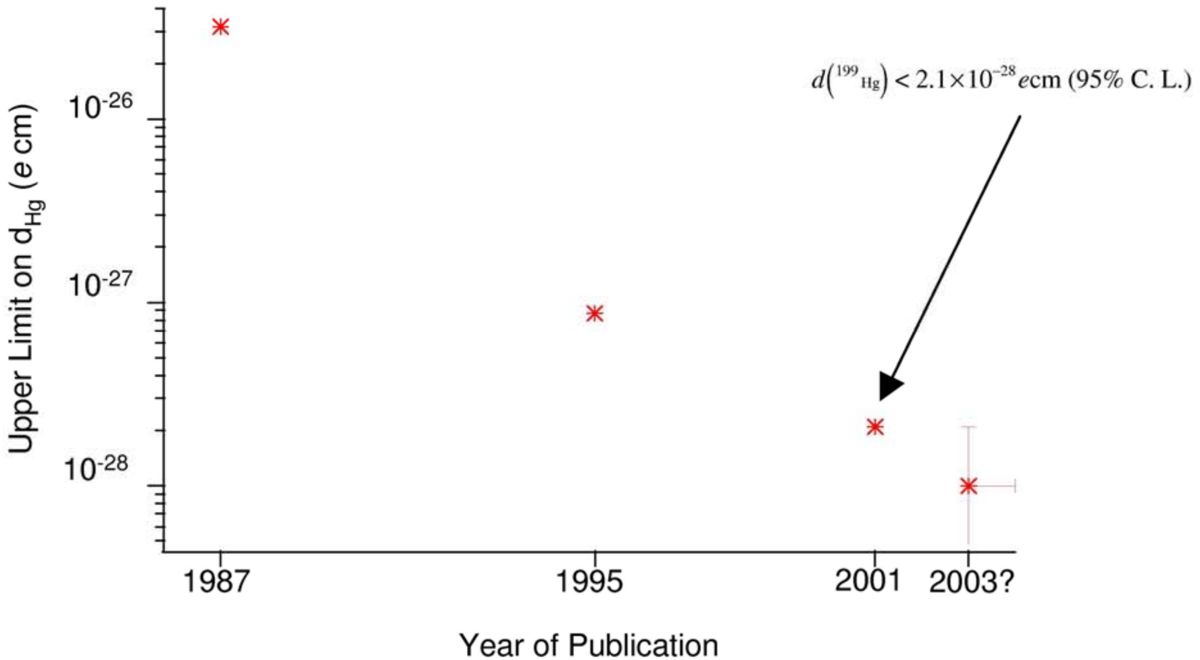
Neutron EDM Vs Year



"…at 6 x 10^{-26} e cm, it is analogous to the Earth's surface being smooth and symmetric to less than 1 μm" (John Ellis).

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

UW ^{199}Hg EDM Limit —Historical Perspective



1987: S.K. Lamoreaux, J.P. Jacobs, B.R. Heckel, F.J. Raab, and E.N. Fortson, Phys. Rev. Lett. **59**, 2275 (1987).

1995: J.P. Jacobs, W.M. Klipstein, S.K. Lamoreaux, B.R. Heckel, and E.N. Fortson, Phys. Rev. A **52**, 3521 (1995)

2001: M.V. Romalis, W.C. Griffith, J.P. Jacobs, and E.N. Fortson, Phys. Rev. Lett. **86**, 2505 (2001).

EDM Status

Particle	System	Limit [e·cm]
Electron	^{205}Tl (~10^{-24} e·cm)	1.5×10^{-27}
Mercury	^{199}Hg atom	2×10^{-28}
Neutron	Ultra-Cold n	5×10^{-26}
Proton	^{199}Hg atom	5×10^{-24}

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

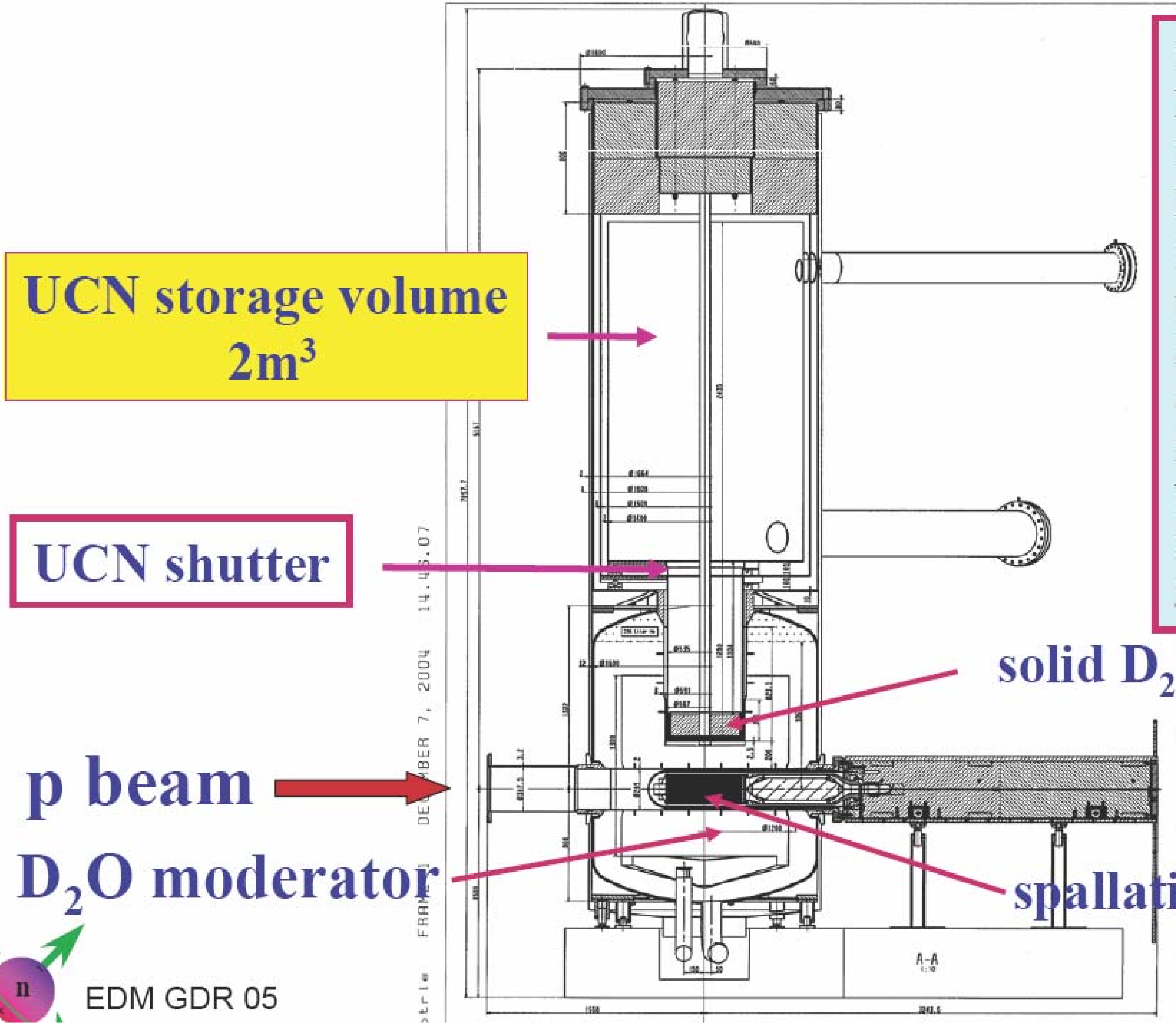
Prospects of neutron EDM:

- UCN at PSI: Ramsey's method of separated oscillatory fields. First goal 1×10^{-27} e·cm, begin data taking ~2007. See talk by Klaus Kirch on Tuesday, WG3.
- UCN at ILL (Sussex, RAL,…): Ramsey's method of separated oscillatory fields. Goal 2×10^{-28} e·cm/year, begin data taking 2009. Plamen Iaydjiev, Tuesday, WG3.
- Ultra-Cold Neutrons (UCN), at SNS (LANL,…): Polarized ^{3}He stored together in a superfluid ^{4}He. Goal 1×10^{-28} e·cm, begin data taking ~2011.

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

UCN tank system (5 m high)

Ultra Cold Neutron Source

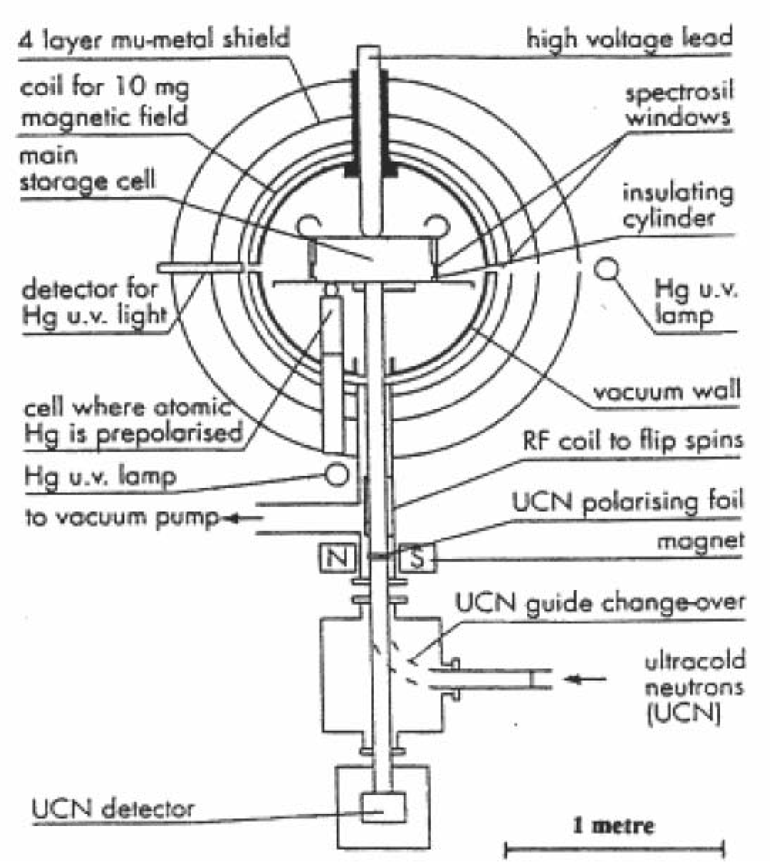


T_p = 600MeV
I_p = 2mA
10n/p
Per pulse:
$10^{17}p \rightarrow 10^{18}n$
thermal flux:
$2 \cdot 10^{14}\ s^{-1}\ cm^{-2}$
cold flux:
$2 \cdot 10^{13}\ s^{-1}\ cm^{-2}$
UCN:
$2 \cdot 10^{5}\ s^{-1}\ cm^{-3}$
$3 \cdot 10^{3}\ cm^{-3}$ stored

UCN experiment at ILL:

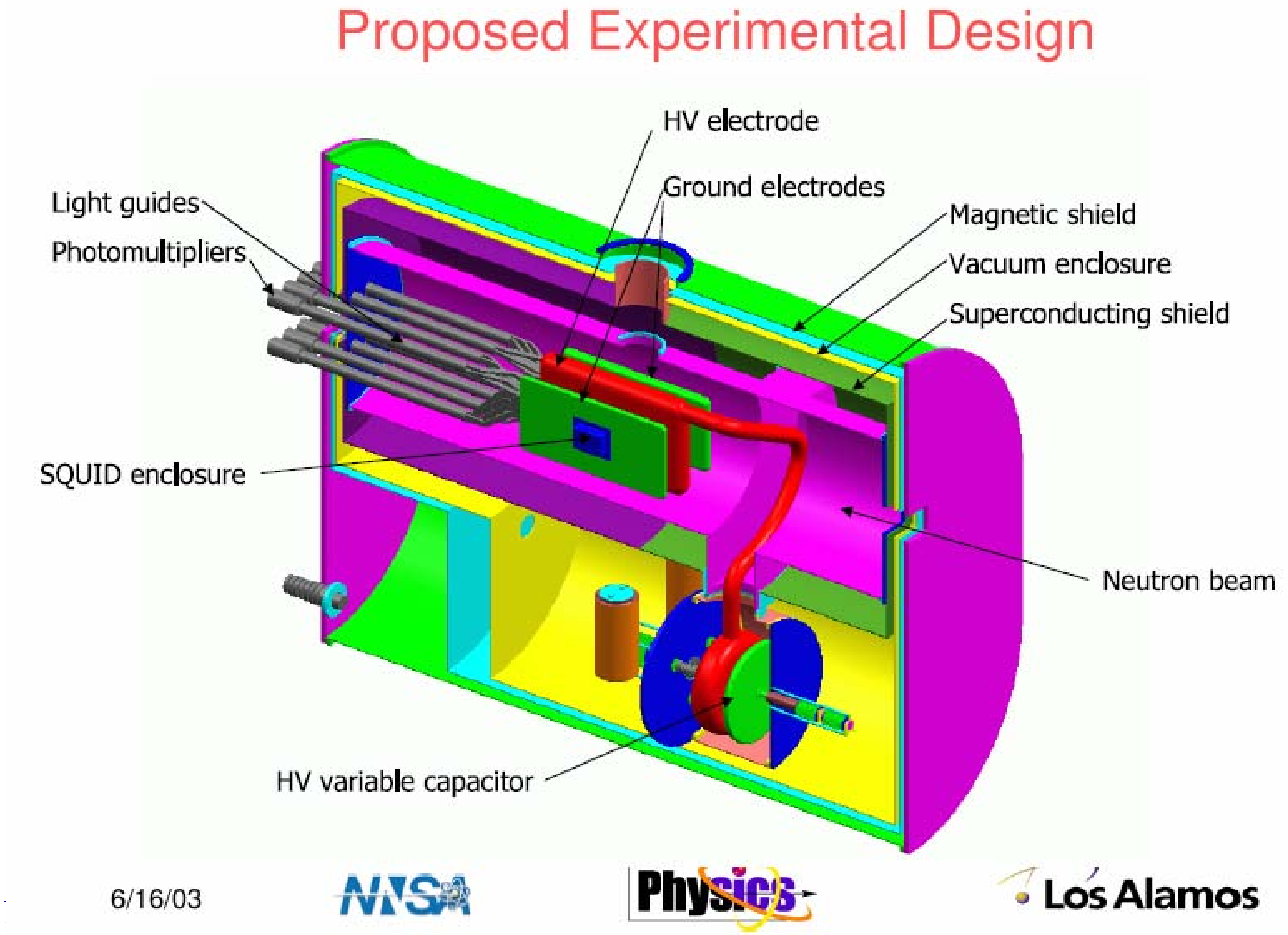
Expect a factor of ~100 improvement in sensitivity due to

- Neutrons in 0.5 K He bath
- ~50× more neutrons
- E-field: 4-6× at cryo temp.
- Longer coherence times



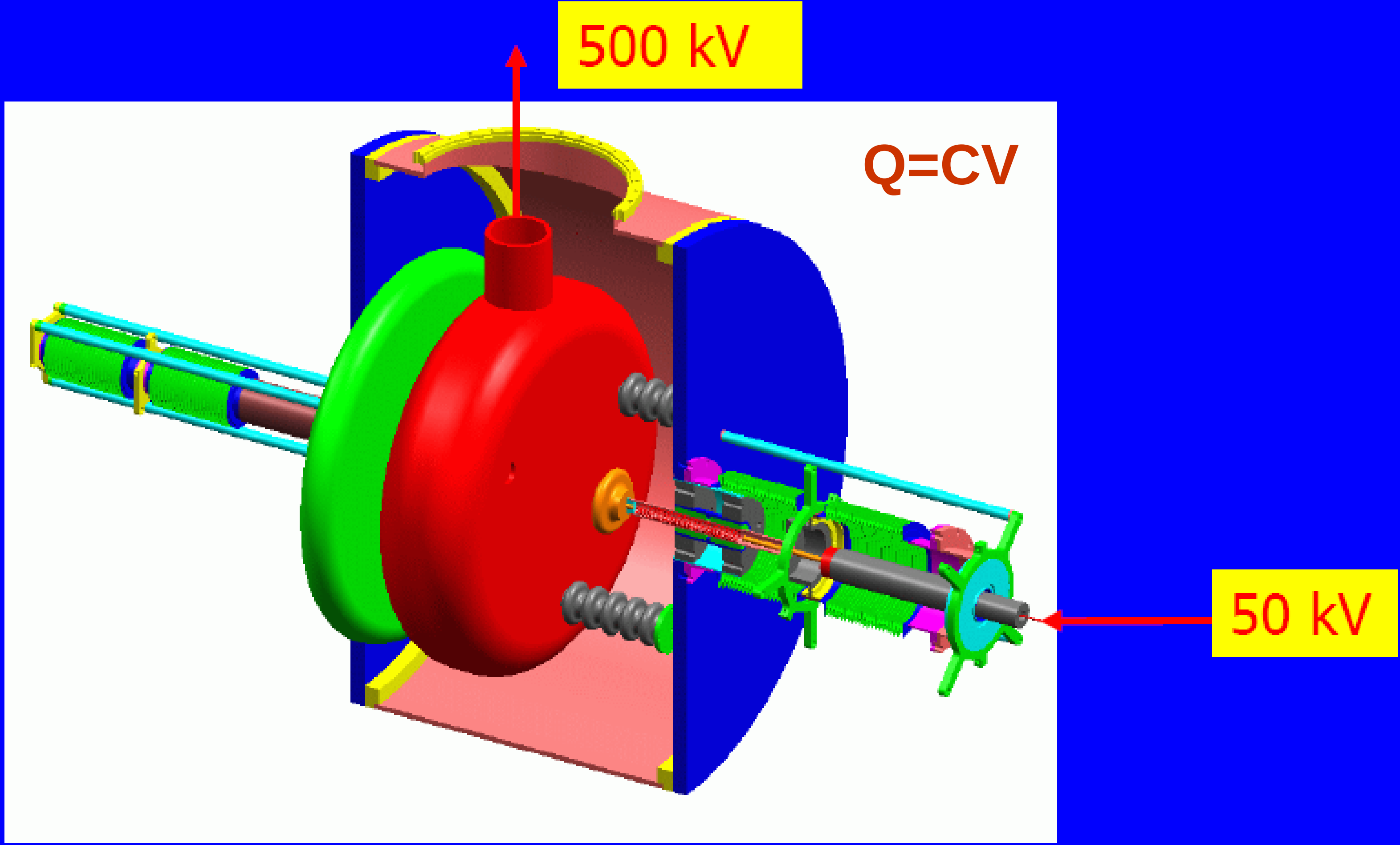
$$\frac{d\vec{s}}{dt} = \vec{\mu} \times \vec{B} + \vec{d} \times \vec{E}$$

Neutron EDM at SNS. Aiming at 1×10^{-28}e·cm, begin construction 2007, begin data taking 2011



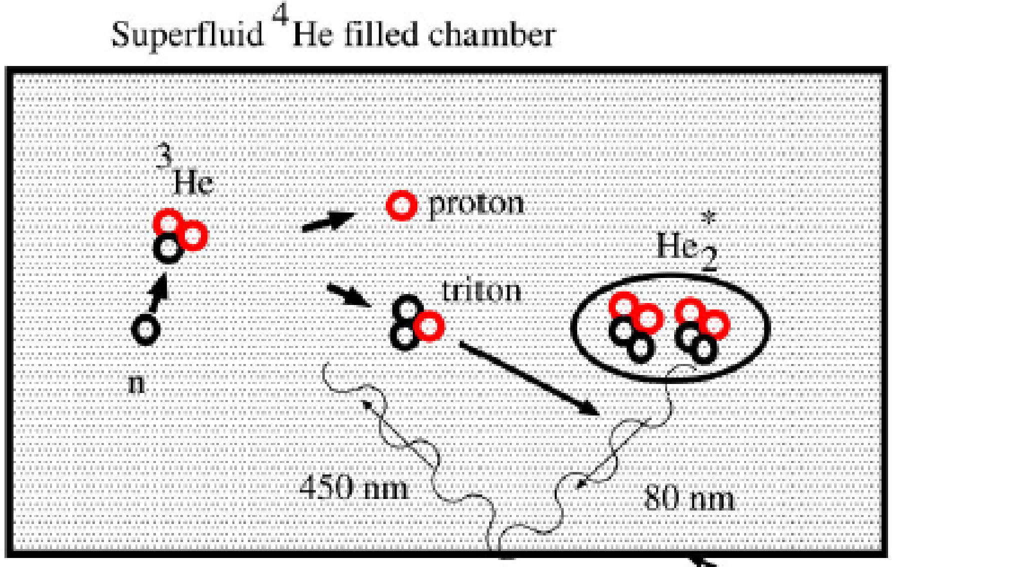
$= \vec{\mu} \times \vec{B} + \vec{d} \times \vec{E}$

Concept for HV generator



Variable capacitor in LHe volume

SUPERFLUID HELIUM AS A DETECTOR



$n + {}^3He \rightarrow p + t + 764$ kV

The energetic charged particles produced excited state helium molecules, He_2^*

The excited state decays in a few nsec (triplet) and produces 80 nm light for which the superfluid helium is transparent.

The 80 nm light is converted to 450 nm (visible) that can be detected by a photomultiplier tube. Approximately 1 photon/keV deposited is produced.

^{3}He-DOPANT AS AN ANALYZER

$^3\vec{He} + \vec{n} \rightarrow t + p$ σ(parallel) $< 10^2$ b

σ(opposite) $\sim 10^4$ b

UCN loss rate ~

$1-\vec{p}_3 \bullet \vec{p}_n = 1-p_3 p_n \cos[(\gamma_n-\gamma_3)B_0 + 2dE]t$

Hadronic EDMs

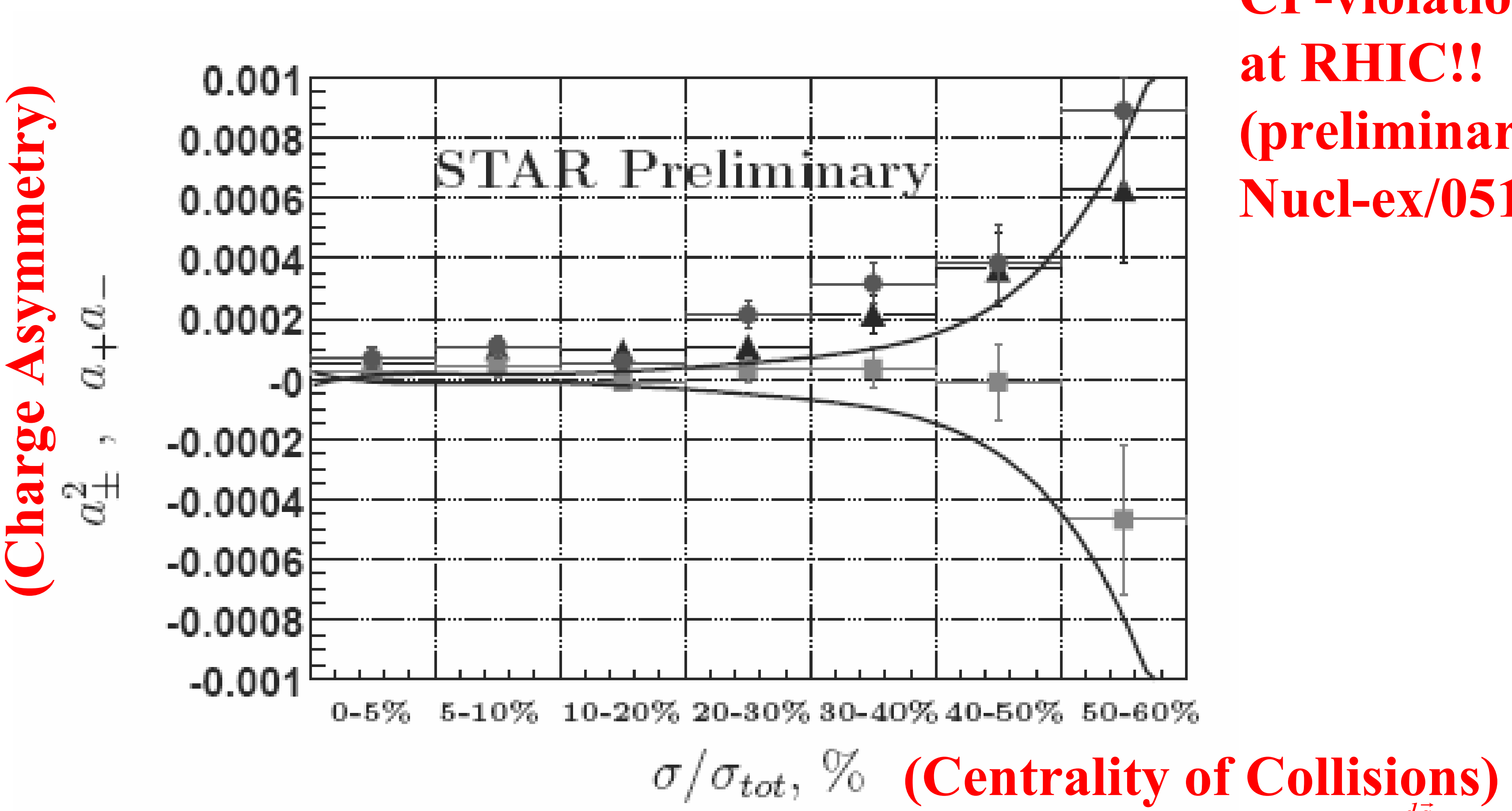
$$L_{\not{CP}} = \bar{\vartheta}\frac{\alpha_s}{8\pi}GG$$

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

Why so small? Axions? Cern Axion Solar Telescope…

…In the vicinity of the deconfinement phase transition θ_{QCD} might not be small: P & CP violating bubbles are possible at H.I. collisions. **D. Karzeev, R. Pisarski, M. Tytgat, PRL81, (1998) 512;**
D. K., R. P., PRD 61 (2000) 111901;
D. K., hep-ph/0406125.

CP-violation at RHIC!! (preliminary) Nucl-ex/0510069

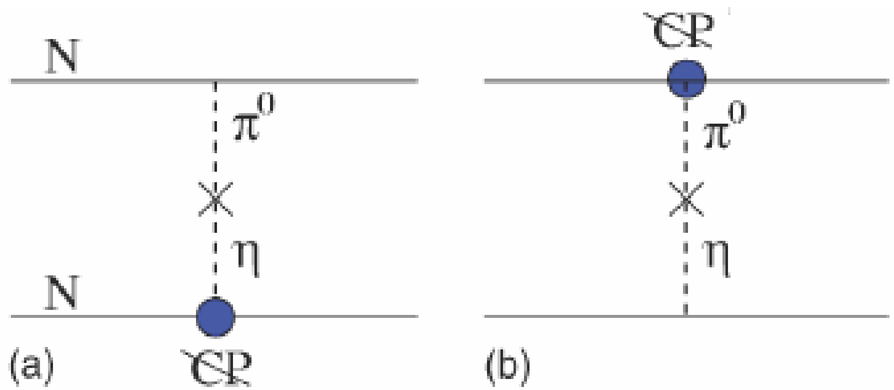


Deuteron EDM

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

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

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



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

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

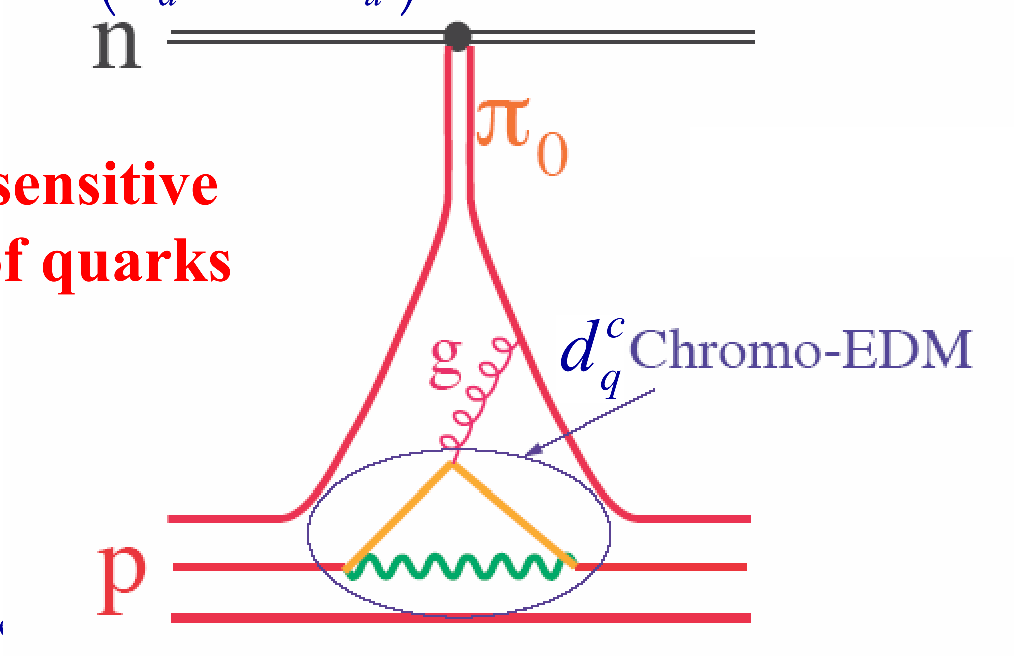
Quark EM and Color EDMs

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

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

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

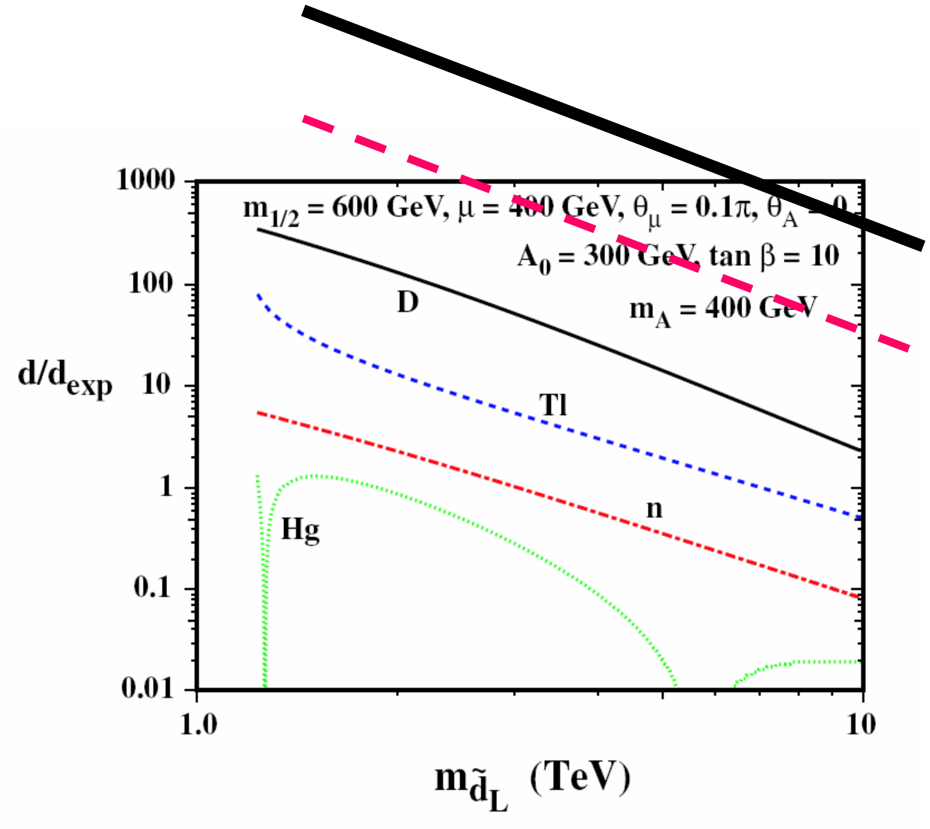
i.e. Deuterons and neutrons are sensitive to different linear combination of quarks and chromo-EDMs…



Sensitivity to SUSY models

d EDM at $\sim 10^{-29} e \cdot cm$

n EDM at $\sim 10^{-28} e \cdot cm$



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)

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

Sensitivity to *right-handed* ν_τ mass

Available online at www.sciencedirect.com

SCIENCE DIRECT

PHYSICS LETTERS B

ELSEVIER

Physics Letters B 604 (2004) 216–224

www.elsevier.com/locate/physletb

Hadronic EDMs in SUSY SU(5) GUTs with right-handed neutrinos

Junji Hisano [a], Mitsuru Kakizaki [a], Minoru Nagai [a], Yasuhiro Shimizu [b]

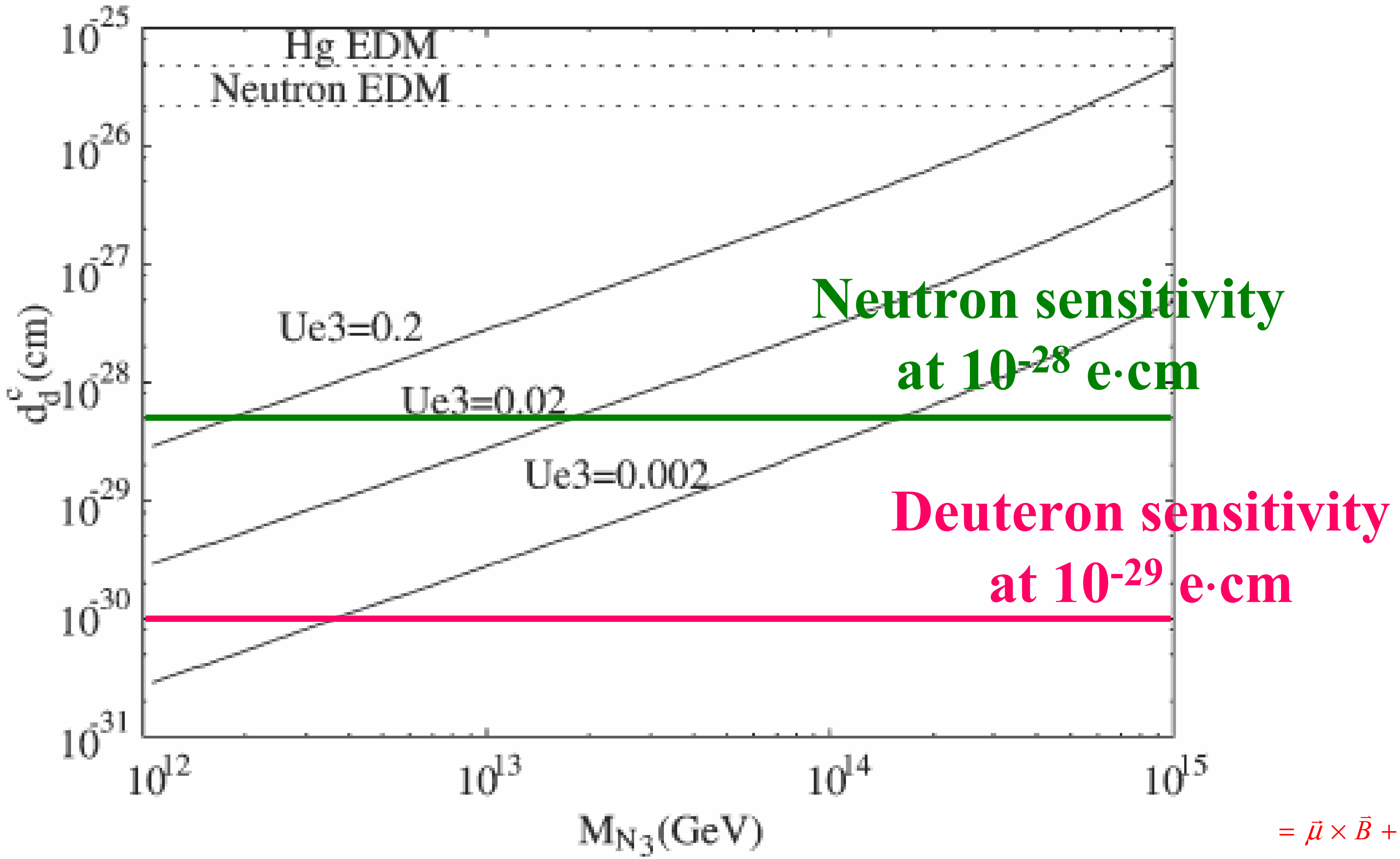
[a] *ICRR, University of Tokyo, Kashiwa 277-8582, Japan*

[b] *Department of Physics, Tohoku University, Sendai 980-8578, Japan*

"… The supersymmetric grand unified models (SUSY GUTs) are ones of the well-motivated models after discovery of the gauge coupling unification at the LEP experiment. Non-vanishing light neutrino masses shown in the neutrino oscillation experiments might also suggest existence of the SUSY GUTs since the right-handed neutrino masses expected from the measurements are near the GUT scale in the seesaw mechanism [1]. Nowadays many efforts are devoted to search for the next signature from both theoretical and experimental sides. …"

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

CEDMs for the down quark vs M_{N3}



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

Experimental Methods of Storage Ring Electric Dipole Moments

- **Parasitic to g-2**

- **Frozen spin**

- **Resonance**

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

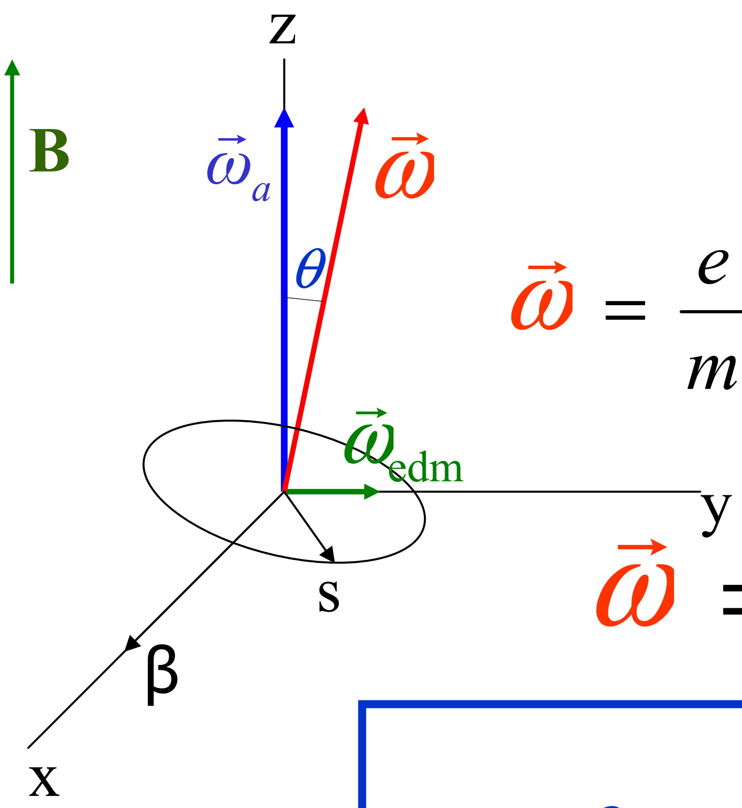
Electric Dipole Moments in Storage Rings

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

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

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

Indirect Muon EDM limit from the g-2 Experiment



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

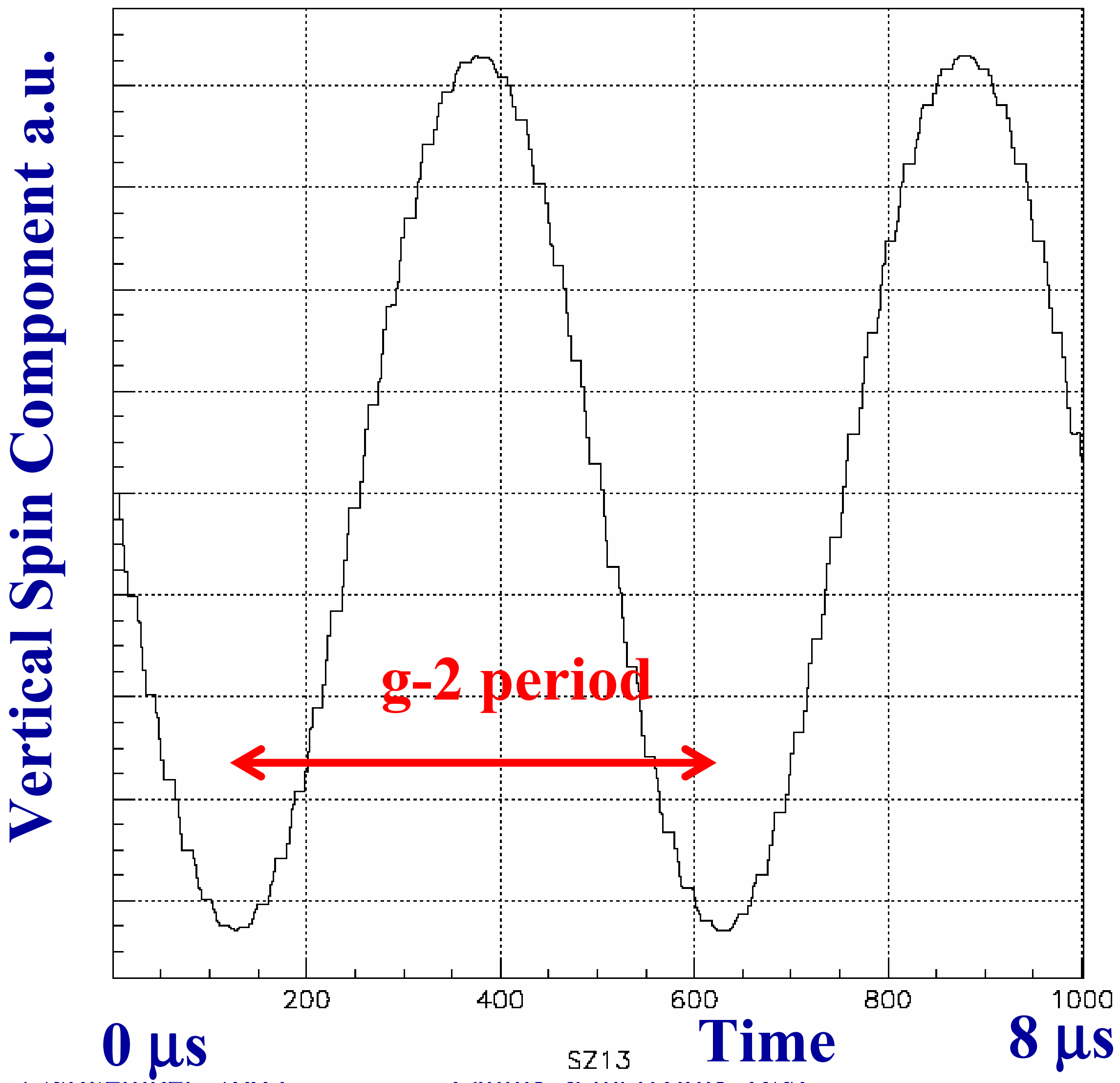
$$\vec{\omega} = \vec{\omega}_a + \vec{\omega}_{\text{edm}}$$

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

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

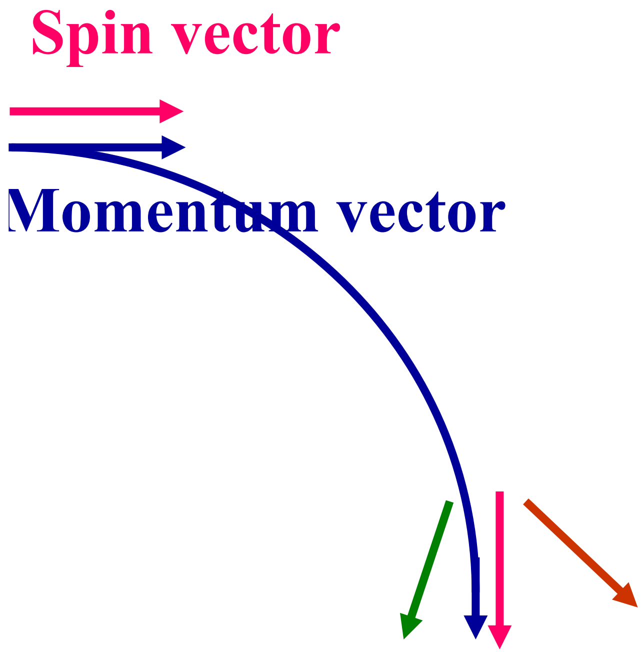
$$\frac{d\vec{s}}{dt} = \vec{\mu}\times\vec{B} + \vec{d}\times\vec{E}$$

The Vertical Spin Component Oscillates due to EDM



$\vec{E}$

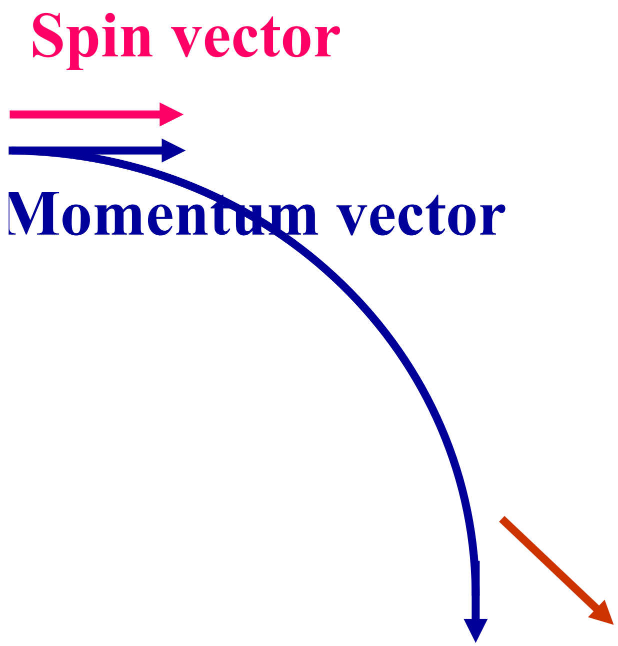
Effect of Radial Electric Field



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

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

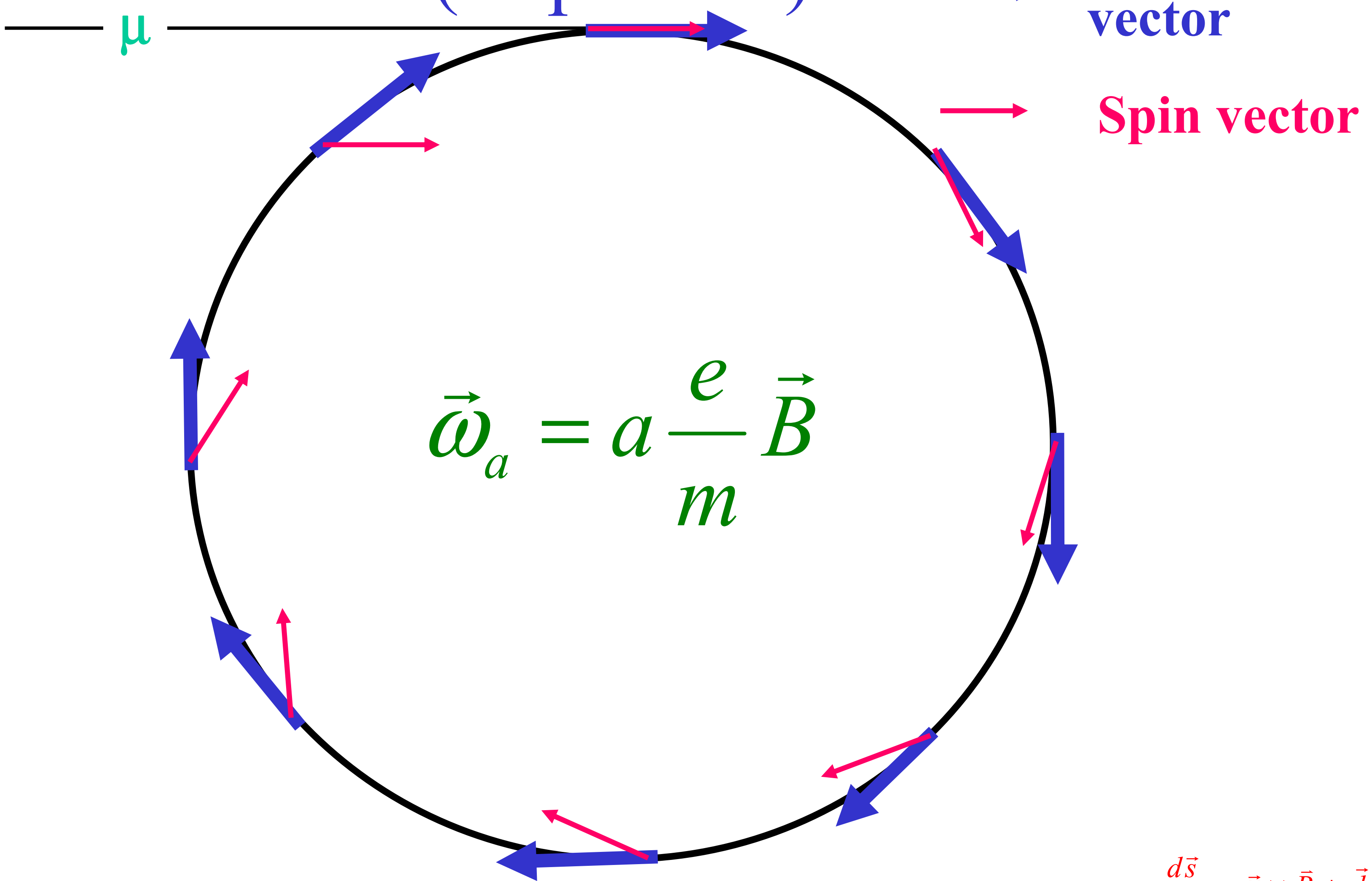
Use a Radial Electric Field and a



- Low energy particle

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

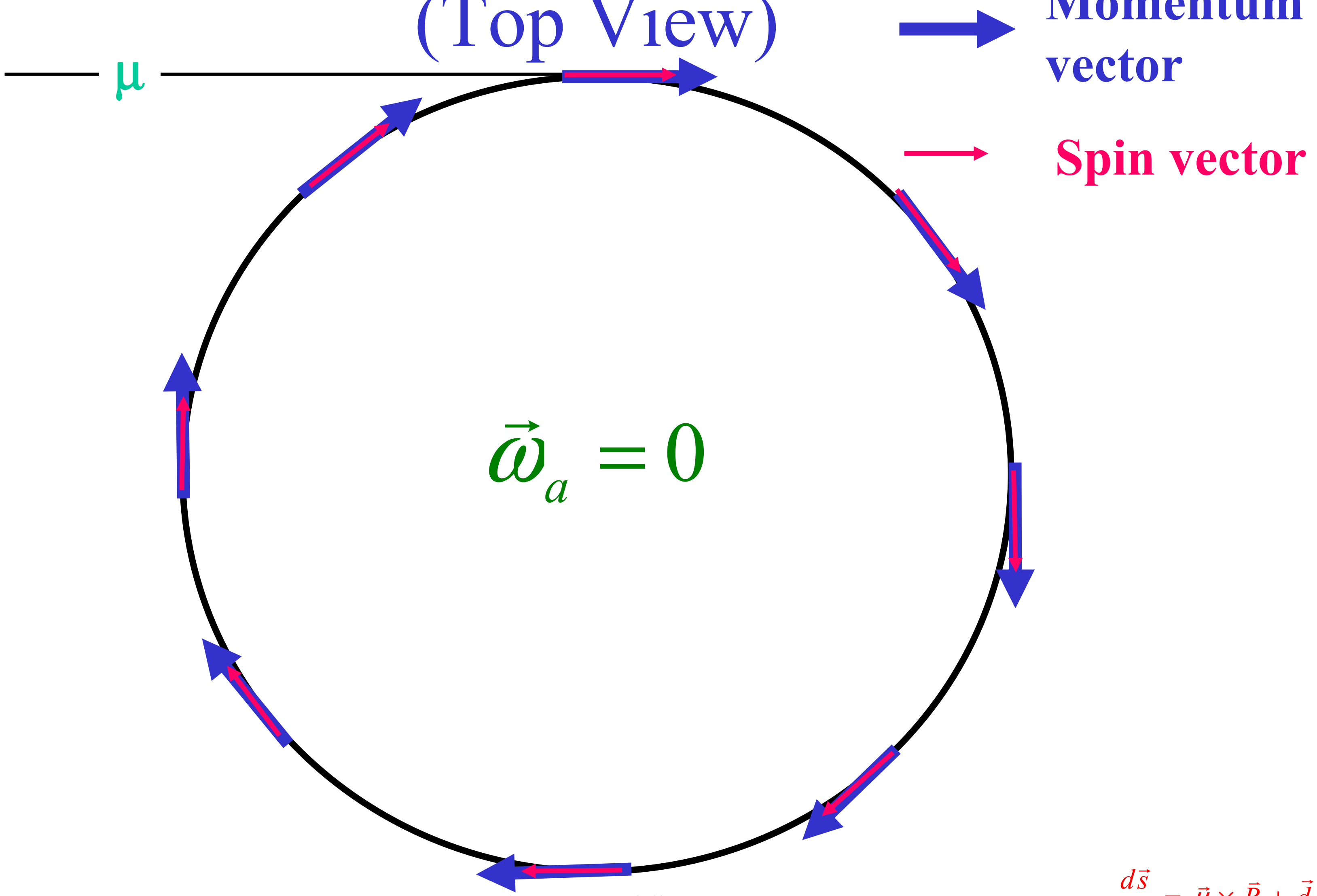
Spin Precession in g-2 Ring (Top View)



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

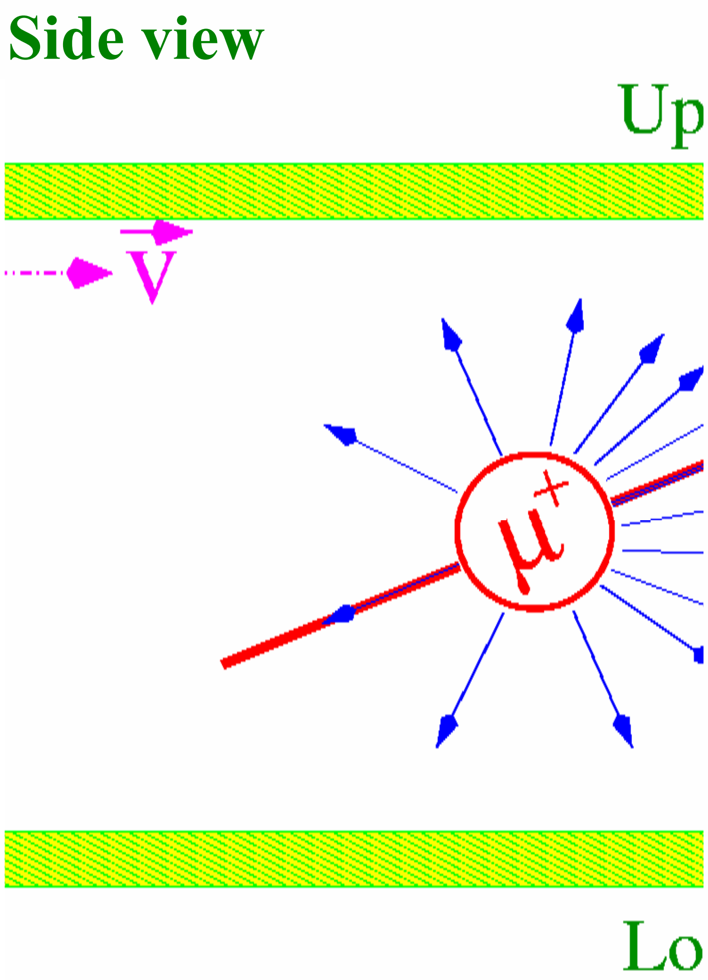
$$\frac{d\vec{s}}{dt} = \vec{\mu} \times \vec{B} + \vec{d} \times \vec{E}$$

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



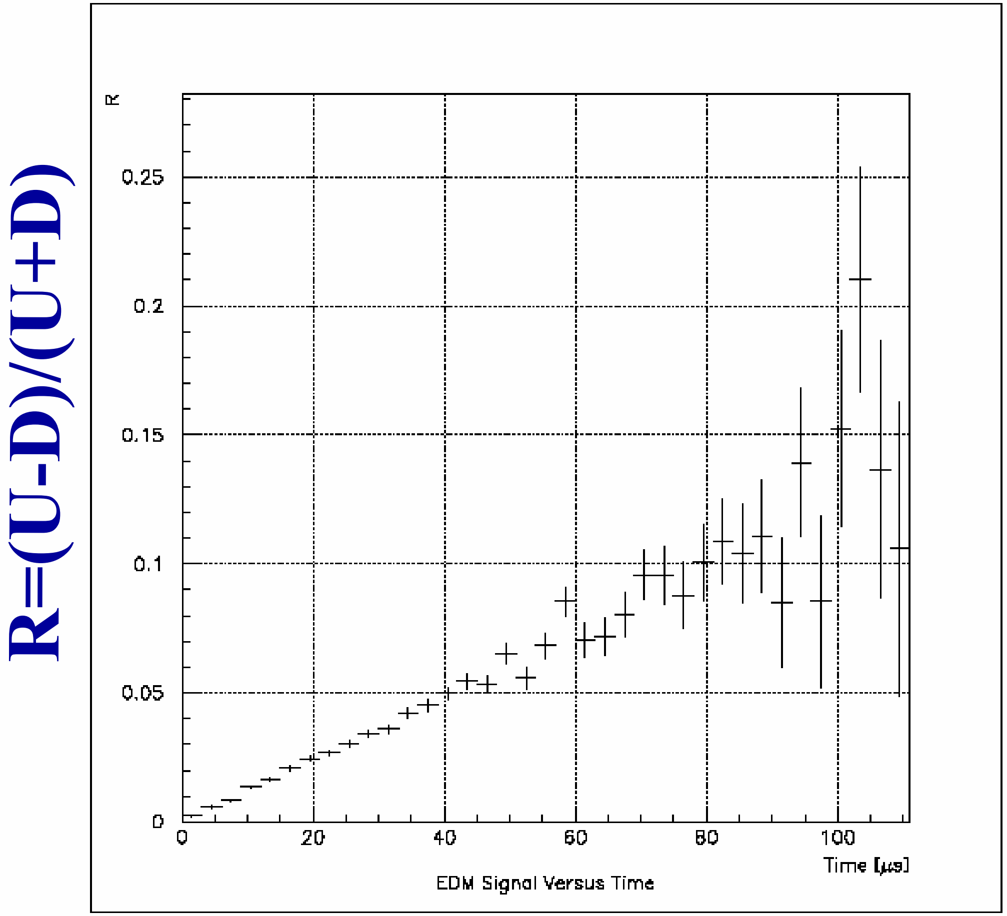


Figure 3: MC simulation of the muon EDM signal, $R = \frac{N_{up}-N_{down}}{N_{up}+N_{down}}$, versus time.

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

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**

January 9, 2003

† Spokesperson

\# Resident Spokesperson

F

$\vec{E}$

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

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

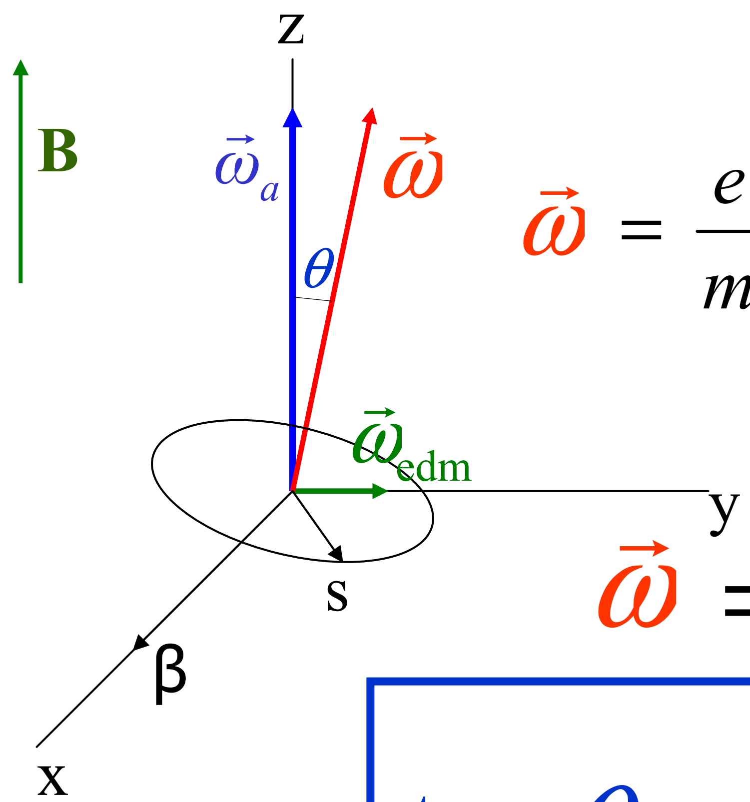
$$d_\mu = \Im D,$$

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

Probe this phase to 1%

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

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



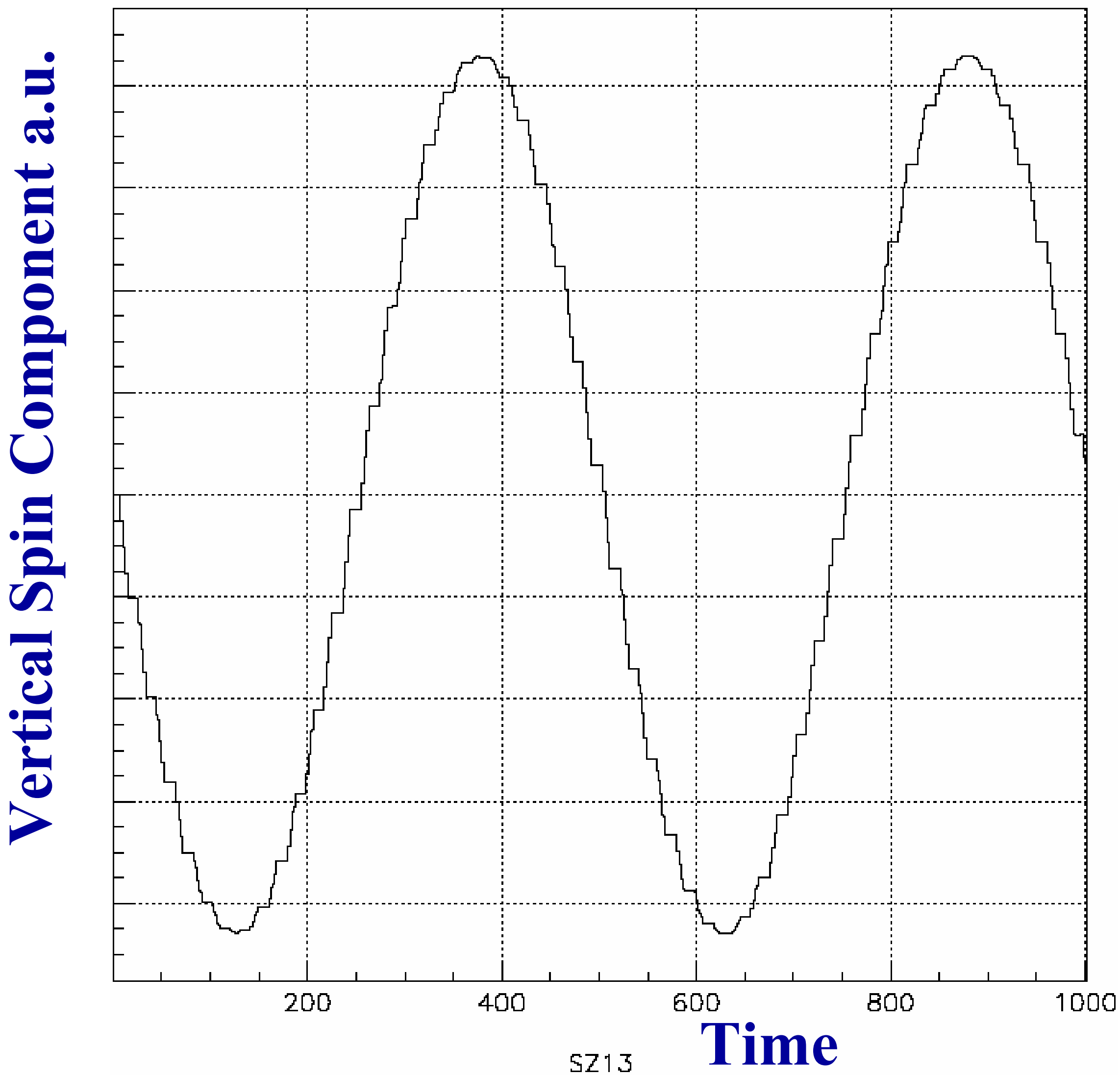
$$\vec{\omega} = \frac{e}{m}\left\{a\vec{B} + \frac{\eta}{2c}\left(\vec{u}\times\vec{B}\right)\right\}$$

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

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

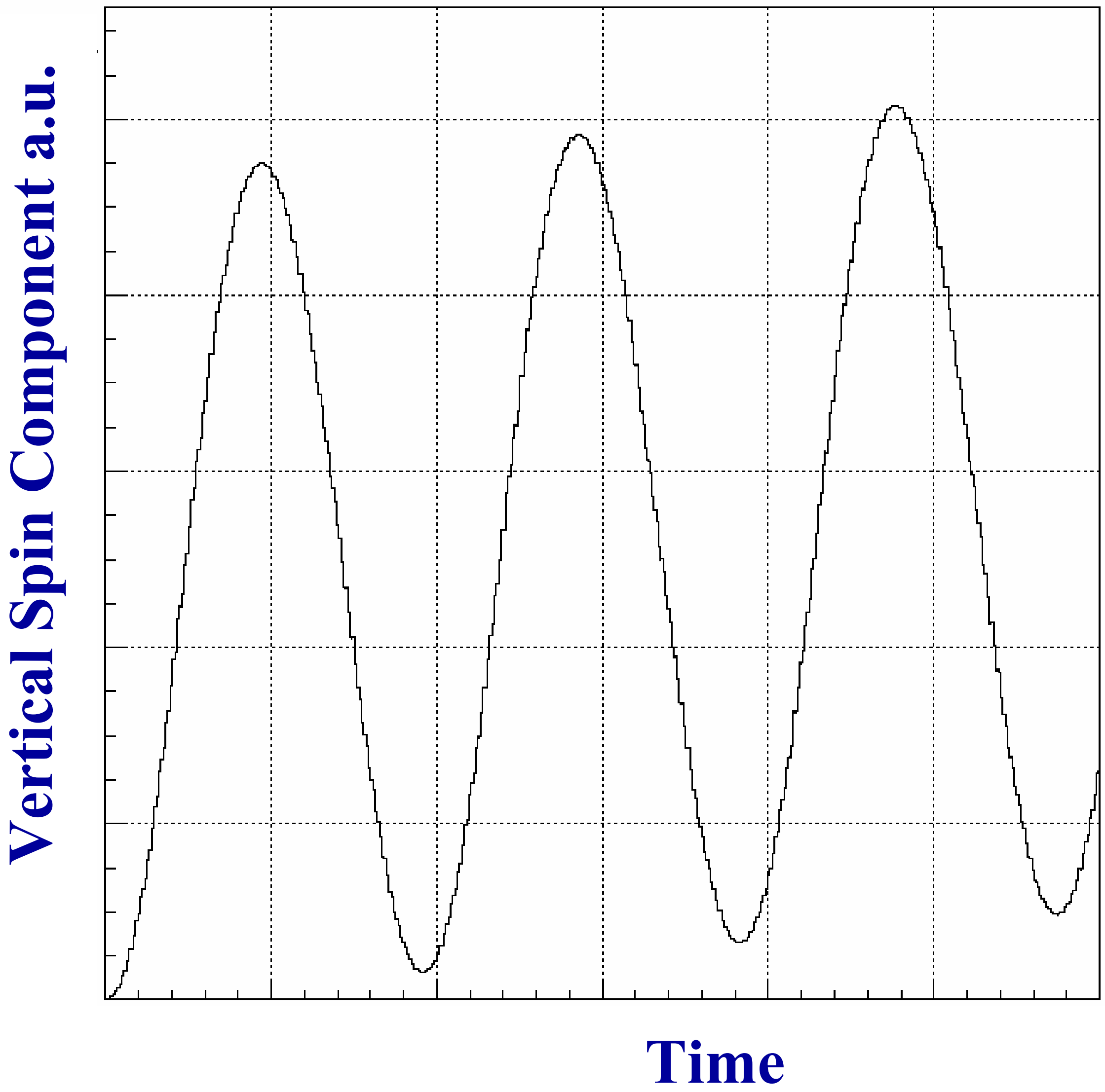
$$\frac{d\vec{s}}{dt} = \vec{\mu}\times\vec{B} + \vec{d}\times\vec{E}$$

Vertical Spin Component <u>without</u> Velocity Modulation (deuterons)



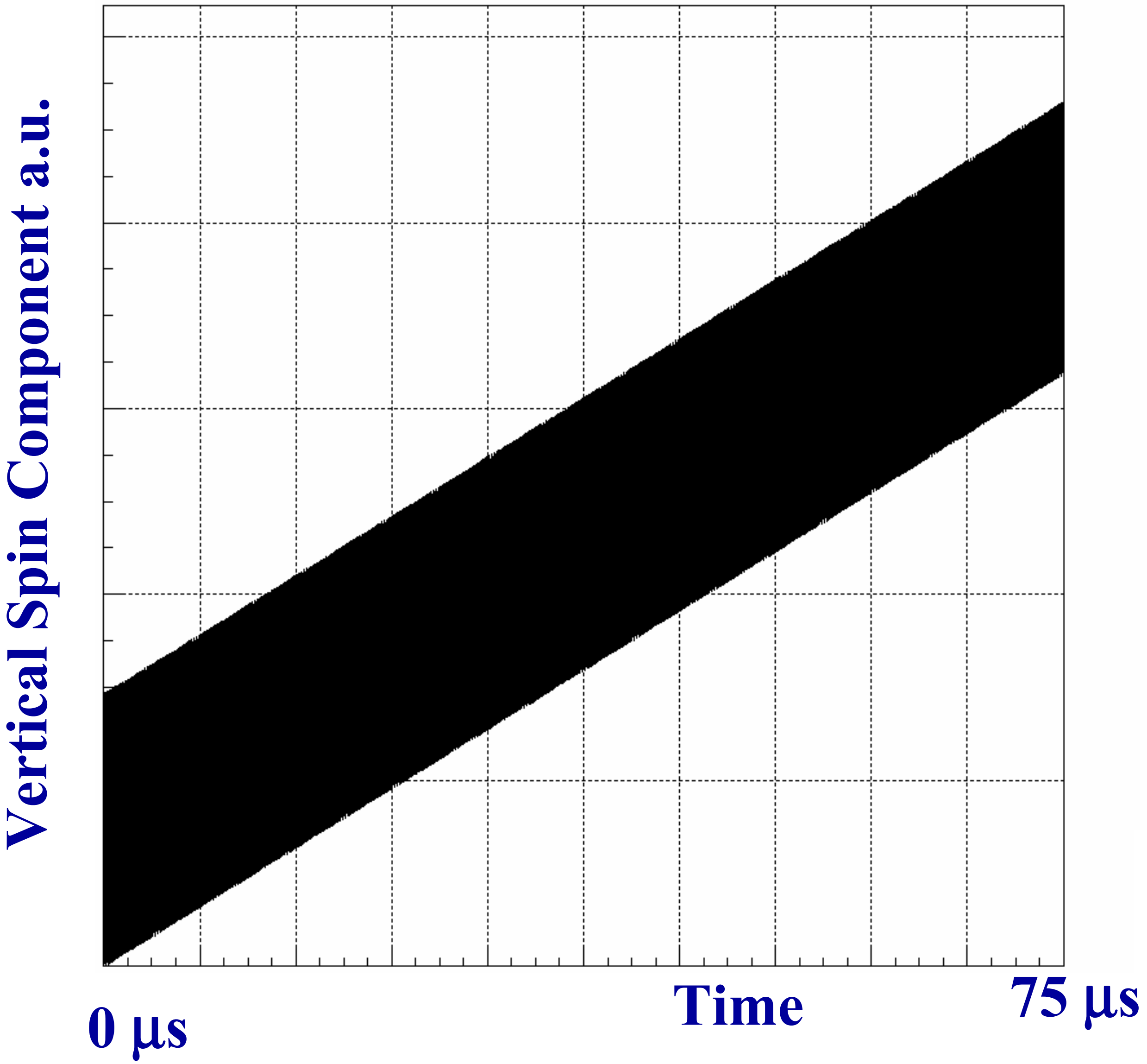
$\vec{E}$

Vertical Spin Component <u>with</u> Velocity Modulation at ω_a



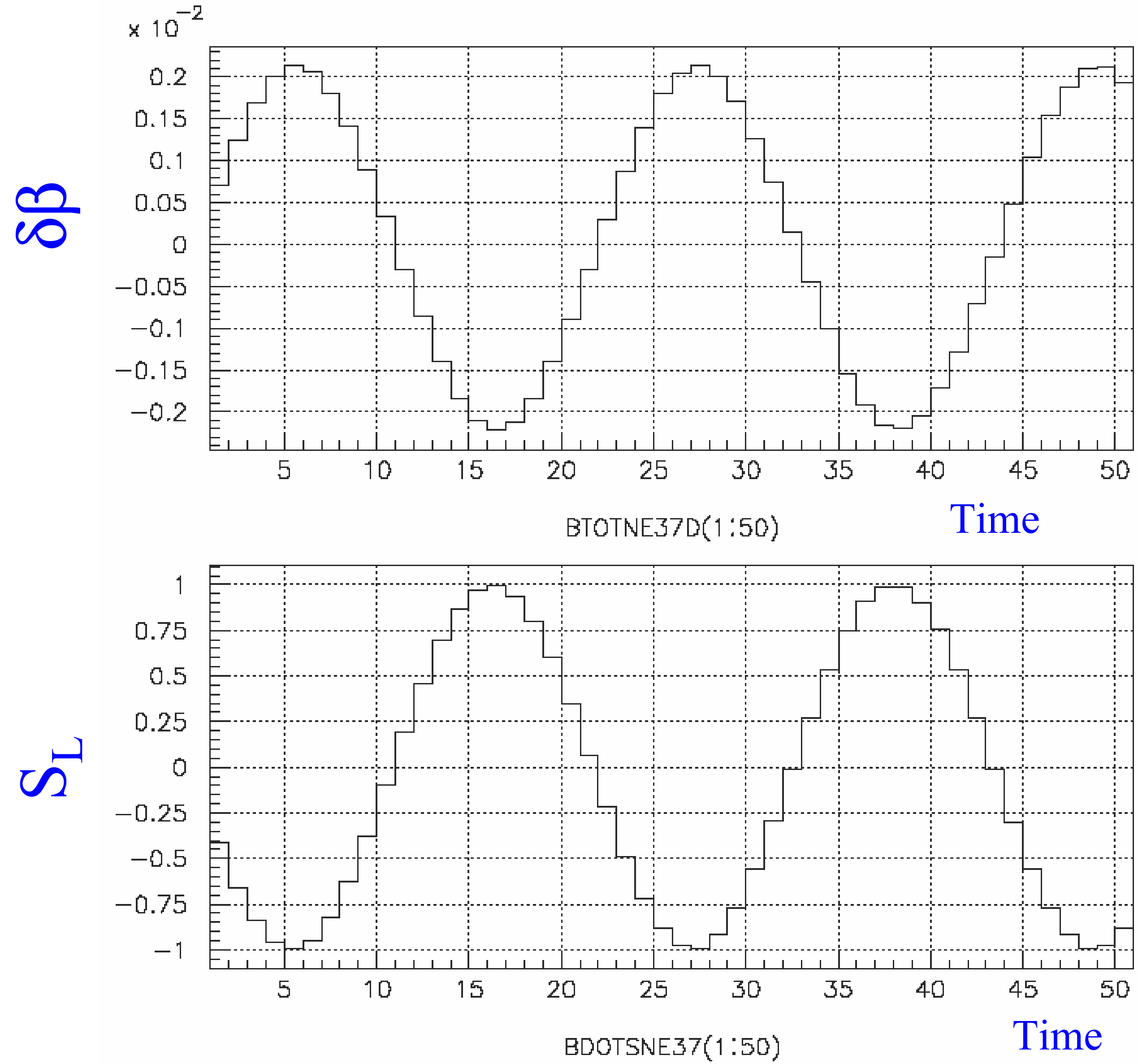
$\vec{E}$

Vertical Spin Component with Velocity Modulation (longer Time)



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

Velocity (top) and g-2 oscillations



A new idea by Yuri Orlov!

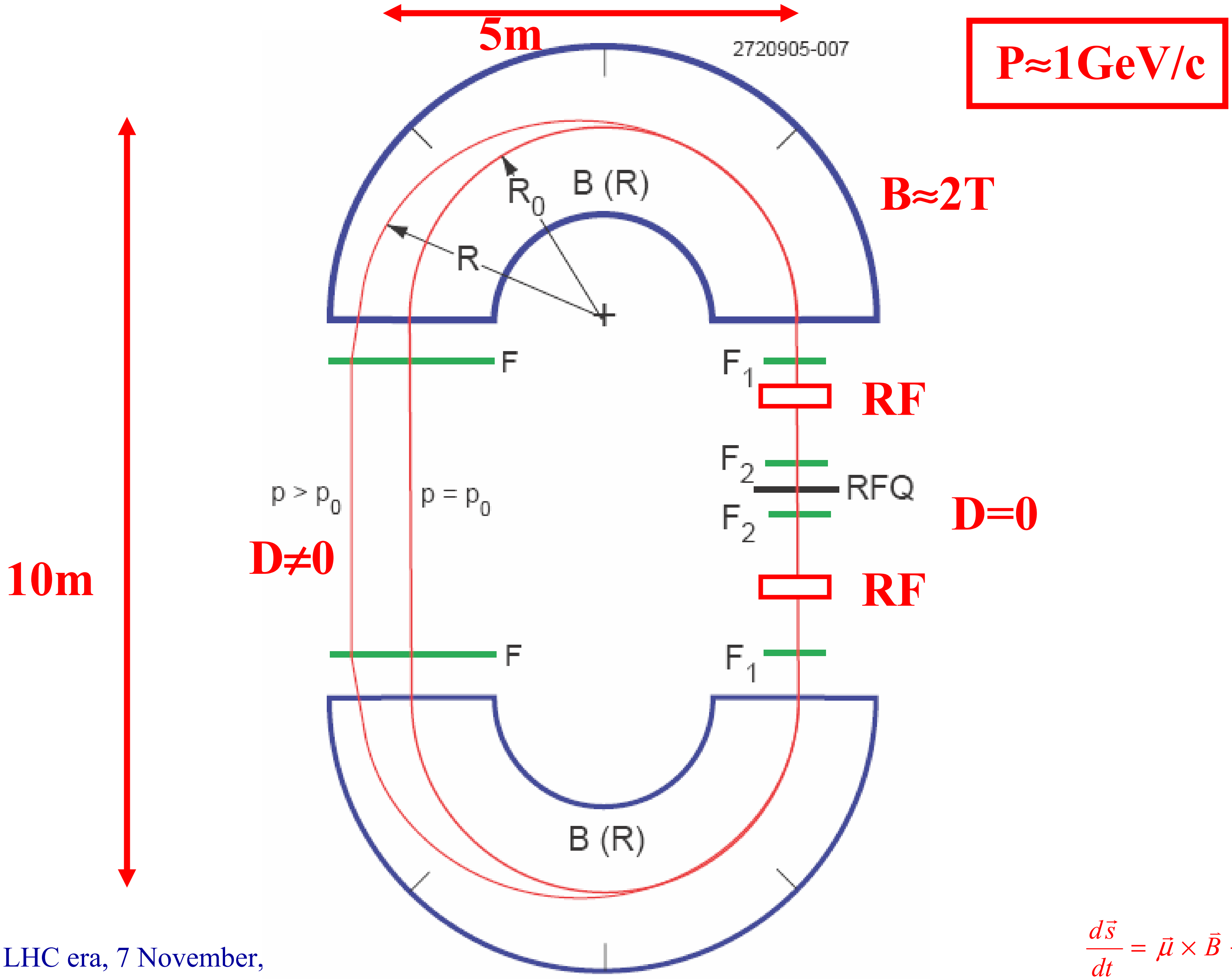
Particle velocity oscillations

Particle S_L oscillations

(i.e. g-2 oscillations)

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

Yuri Orlov’s new lattice



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

Systematic errors due to AC forces

- AC forces, due to modulating v at ω_a.

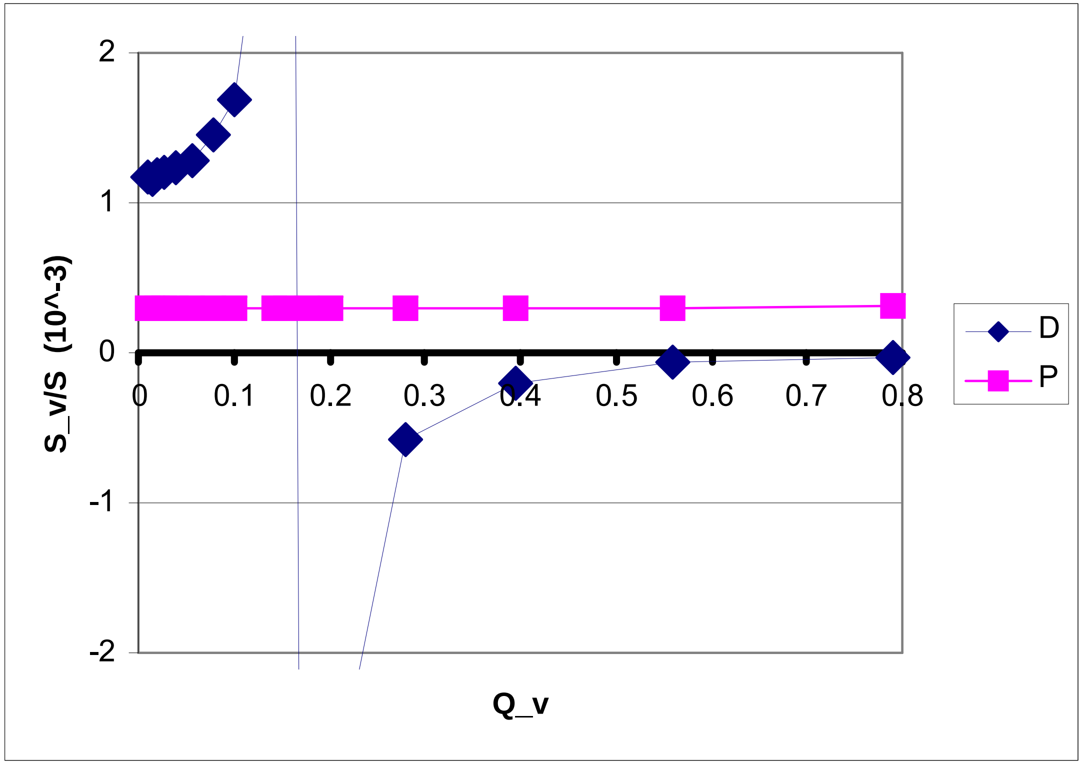
Examples: 1) Radial B-field or skew quadrupole where $D \neq 0$,
2) RF-cavity (vertical offset or misalignment), …

- Remedy: They depend on the vertical tune… They all do!

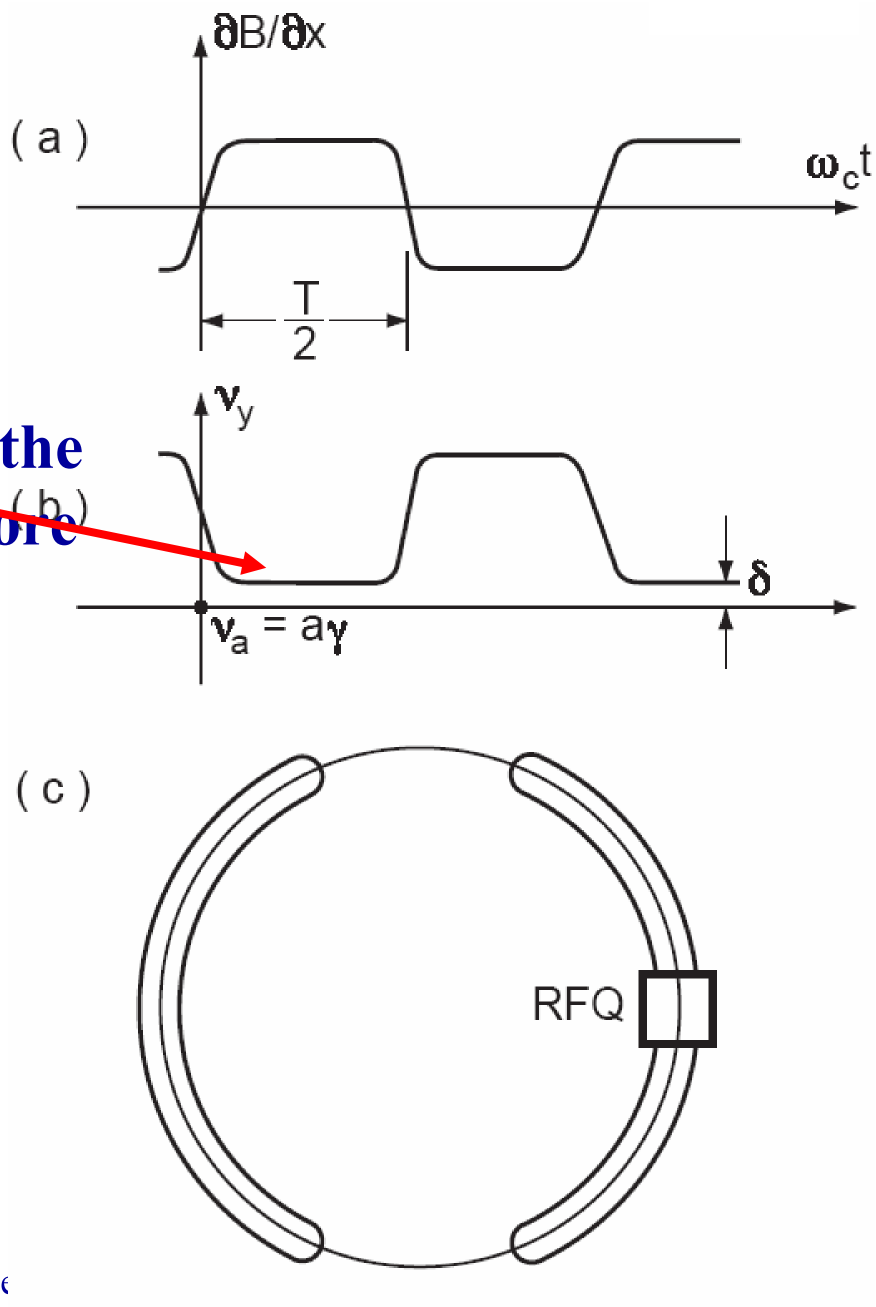
$$\frac{d\vec{s}}{dt} = \vec{\mu} \times \vec{B} + \vec{d} \times \vec{E}$$

AC Backgrounds are vertical tune dependent; EDM signal is not!

$$\frac{ds_v}{dt} \propto \frac{1}{Q_v^2 - Q_s^2}$$



Two half beam technique



This tune makes the Deuteron spin more Sensitive to background

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

Storage Ring Electric Dipole Moments

- D @ 10^{-29}e·cm would be the best EDM sensitivity over *present* or *planned* experiments for θ_{QCD}, quark, and quark-chromo (T-odd Nuclear Forces) EDMs.
- P, D, ^{3}He, etc., i.e. a facility to pin down the CP-violation source.

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

Deuteron EDM Timeline

- ~end of this year/January 2006 Letter of Intent
- We need to develop the final ring lattice and tolerances on parameters
- Goal for a proposal by the end of next year

Neutron/deuteron EDM Timeline

	Exp begin sens. data taking	Exp goal
2005		
2007	UCN-PSI	10^{-27}e·cm
2009	UCN-ILL	2×10^{-28}e·cm/yr
2010	Deuteron in Storage Ring	10^{-29}e·cm
2011	UCN-LANL/SNS	1×10^{-28}e·cm

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

Summary

- Neutron, and deuteron EDM experiments are sensitive probes of physics beyond the SM and of CP-violation in particular.

Unique sensitivity to

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

Both n and deuteron EDM exp: pinpoint EDM source

Promising a very exciting decade…!

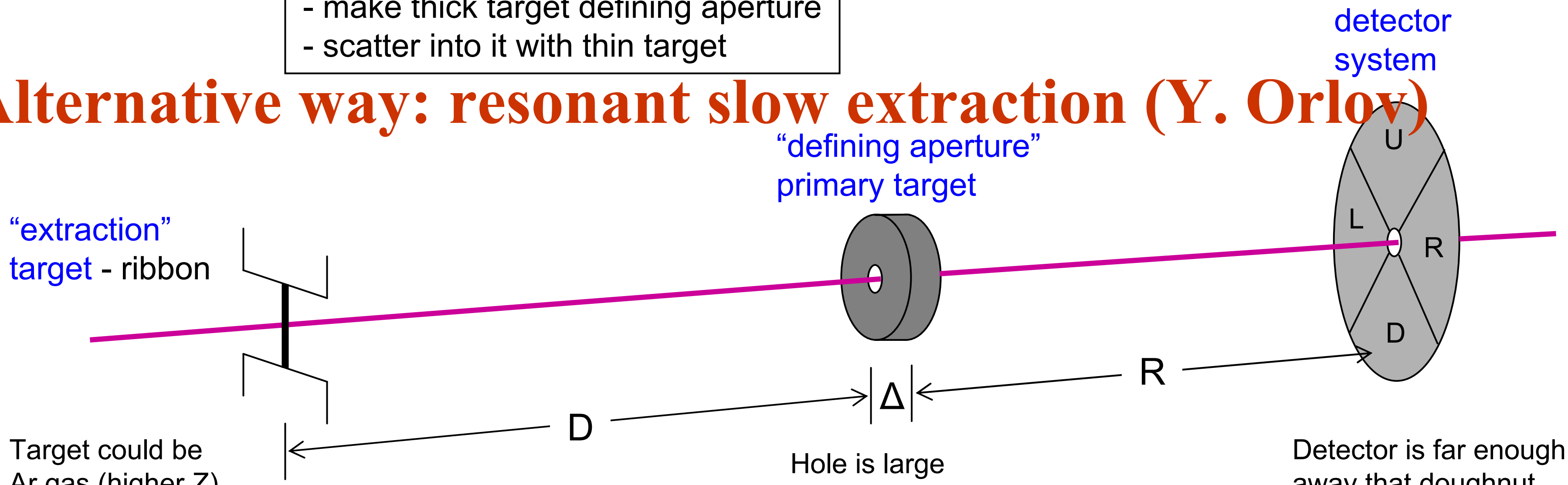
Extra Slides

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.

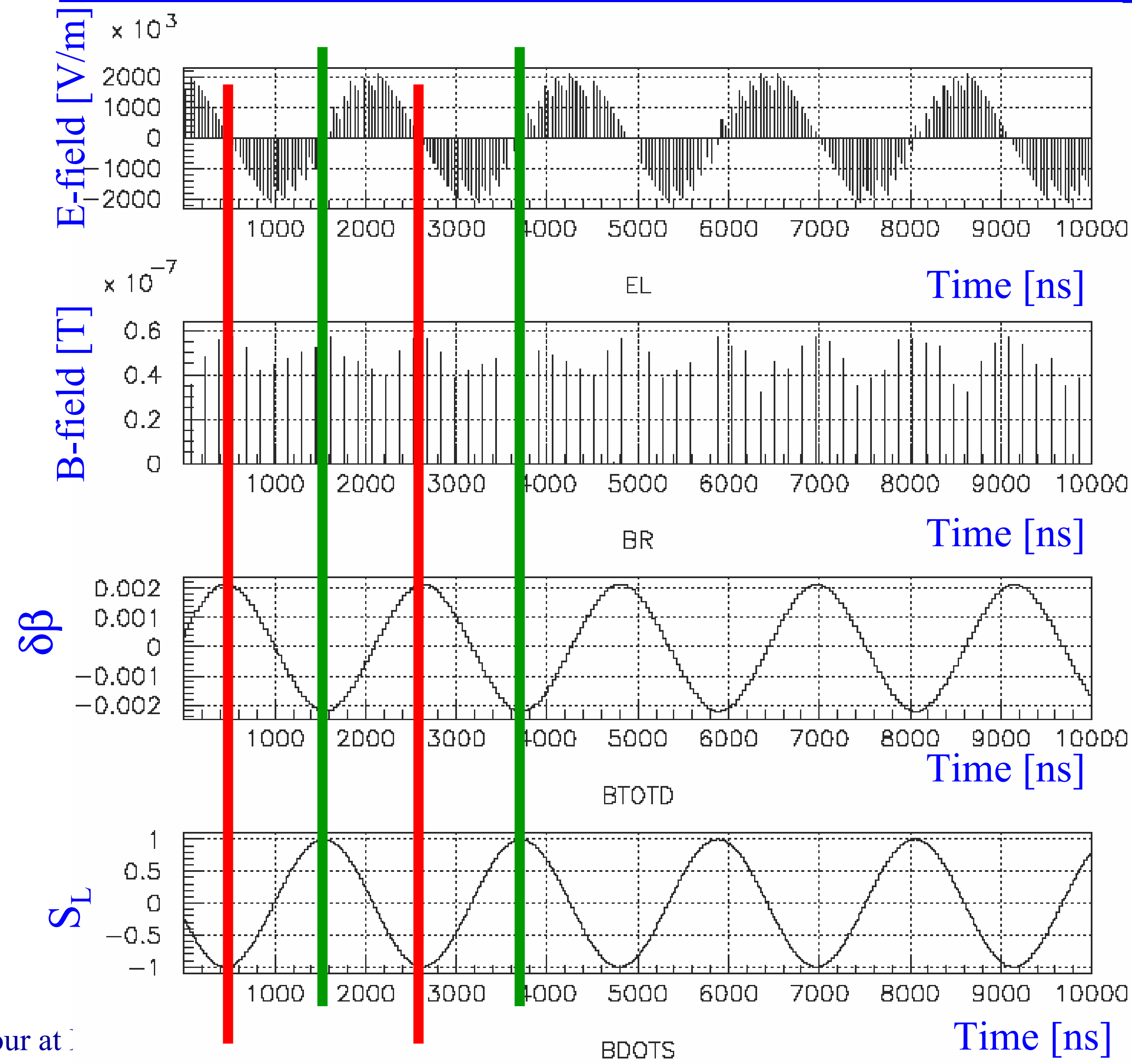
Hole is large compared to beam. Every-thing that goes through hole stays in the ring.

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

List of things to do…

1. Compaction factor: $\alpha_p=1$ or $\alpha_p\neq1$ Graziano Venanzoni, and Yuri Orlov
2. Low beta (=0.6) Super-Conducting Cavities with one mode having $\omega=3\omega_{RF}$ Alberto Facco, …
3. Space Charge, Impedance, etc. Mikhail Zobov
4. RFQ
5. Polarimetry M.C. Anna Ferrari, Ed Stephenson
6. Slow Extraction together with polarimetry
7. Spin Coherence Time Yuri Orlov
8. Sextupoles, Decapoles, how many needed? Y.O.

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)

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

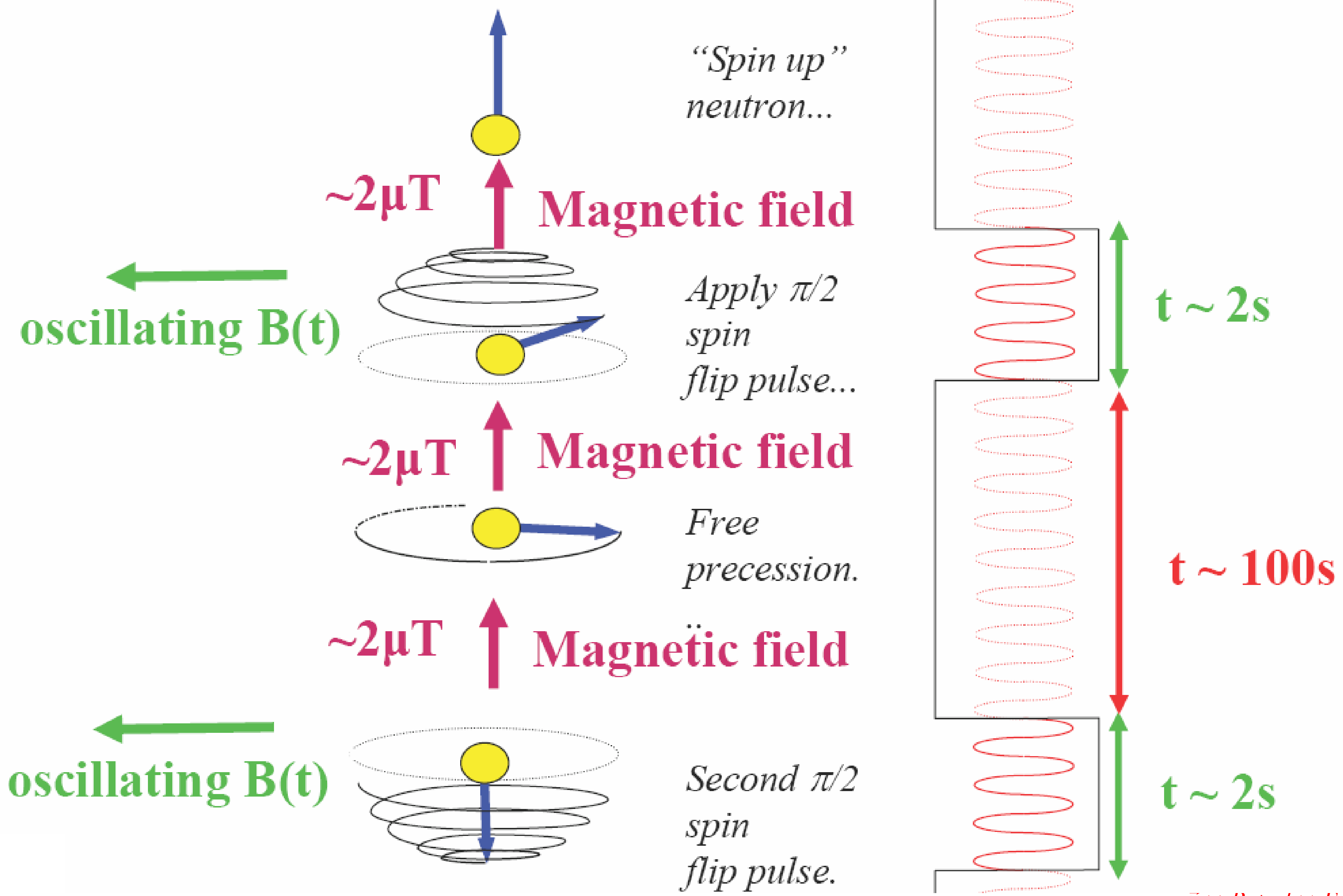
Other Issues

- Spin coherence time. I.B. Vasserman *et al.,* Phys. Lett. **B198**, 302 (1987); A.P. Lysenko, A.A. Polunin, and Yu.M. Shatunov, Particle Accelerators **18**, 215 (1986).

- RF-system: frequency, shape, strength, normal/SC. Is partial linearization needed? C. Ohmori, *et al.,* 14^{th} Symposium on Accelerator Science and Technology, Tsukuba, Japan, Nov. 2003; M. Yamamoto *et al.,* PAC99.

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

Ramsey's method



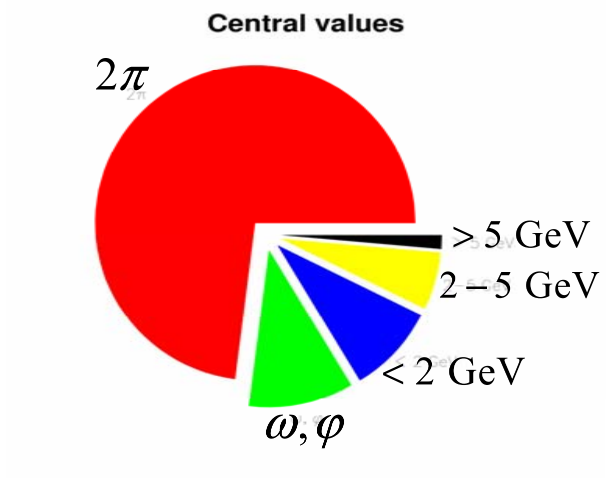
$\frac{\ }{dt} = \bar{\mu} \times B + d \times E$

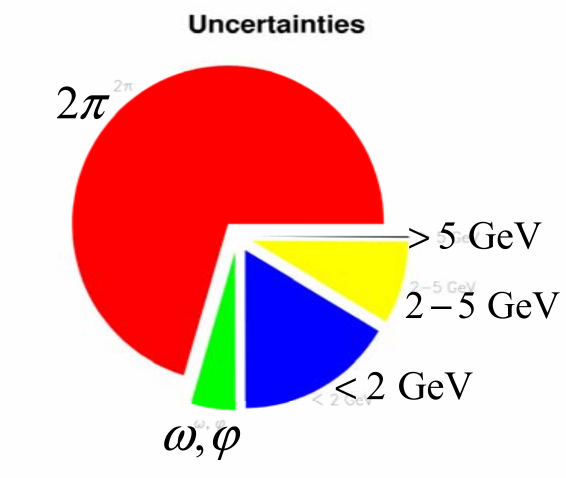
Hadronic contribution to muon (g-2)

Hadronic contribution to the muon (g-2) is calculated via dispersion integral:

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

Contribution to the integral from different modes e+e-→hadrons:

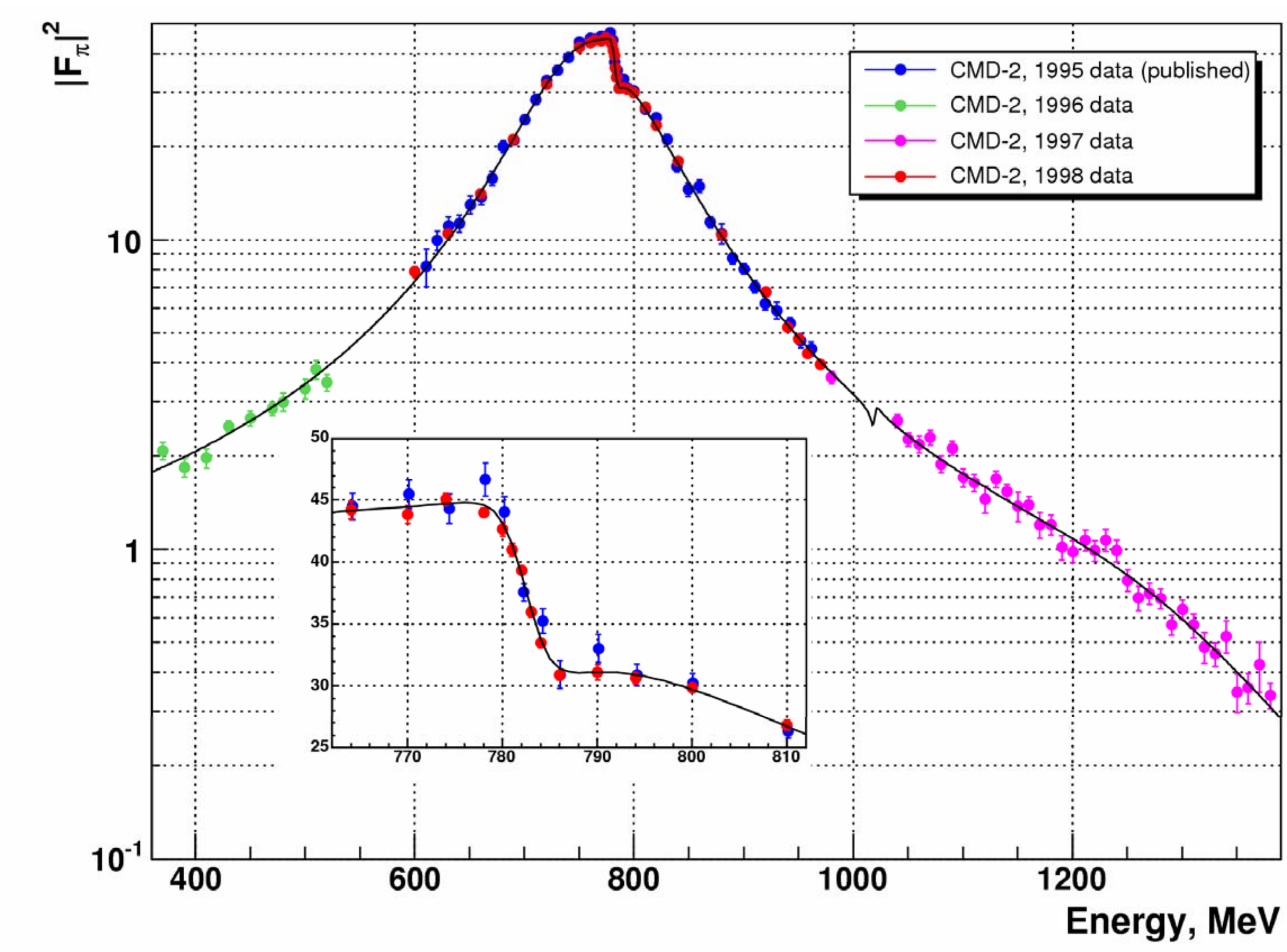




$e^+e^- \to 2\pi$ gives dominant contribution both to the value and to the uncertainty of the hadronic contribution

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

CMD-2 Result

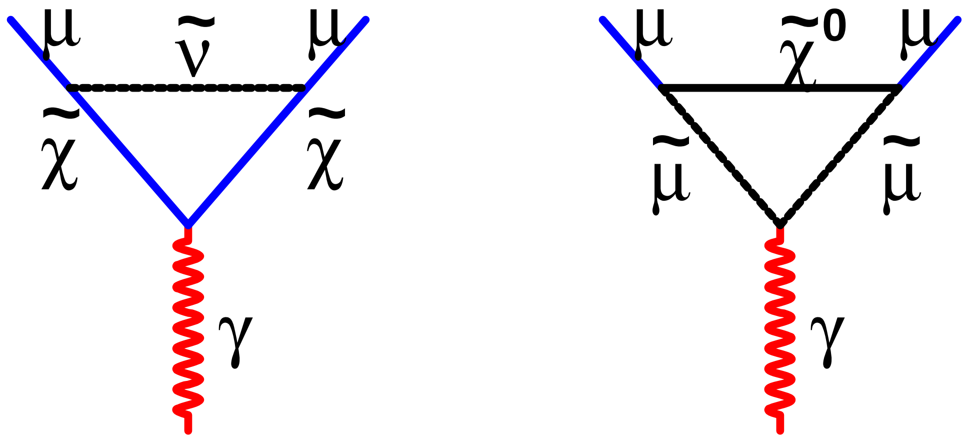


Systematic error

0.7% 0.6 / 0.8% 1.2-4.2%

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

Beyond standard model, e.g. SUSY

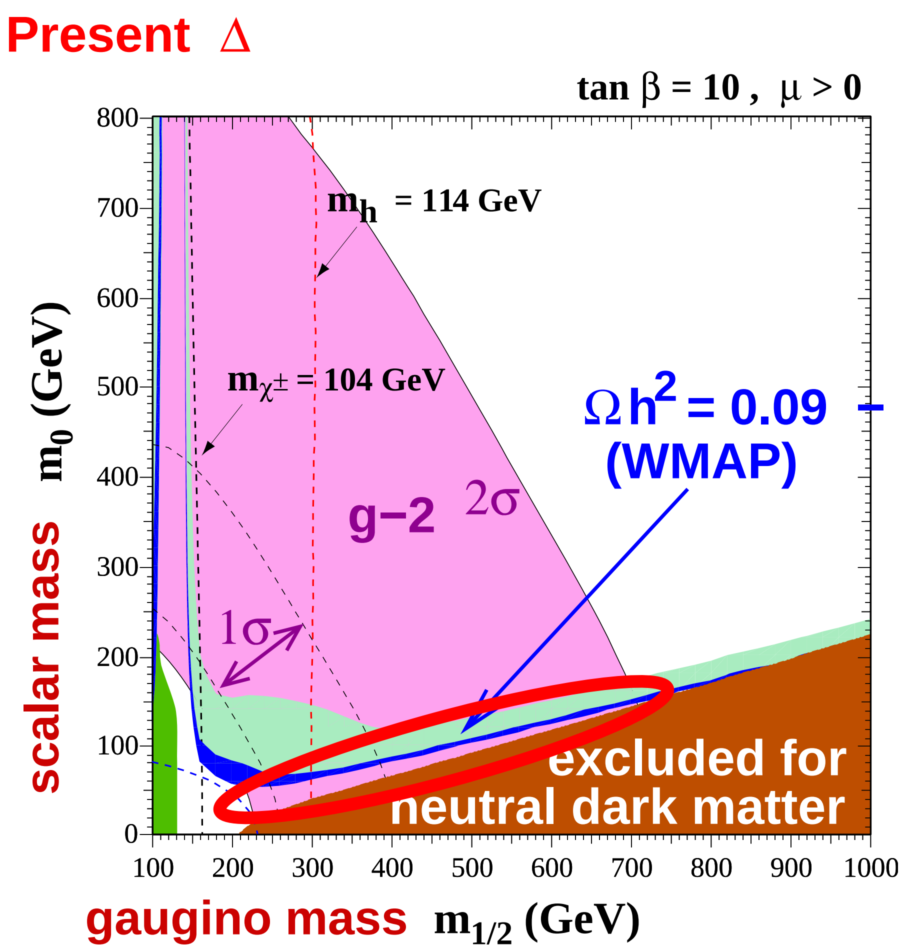


$$a_\mu^{\text{susy}} \cong \text{sgn}(\mu)\times 13\times 10^{-10}\left(\frac{100\text{GeV}}{m_{\text{susy}}}\right)^2 \tan\beta$$

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

SUSY, dark matter, (g-2) Δ_{E821}

$$\Delta a_\mu(\mathrm{E821} - \mathrm{SM}) = (23.9 \pm 9.9) \times 10^{-10}$$



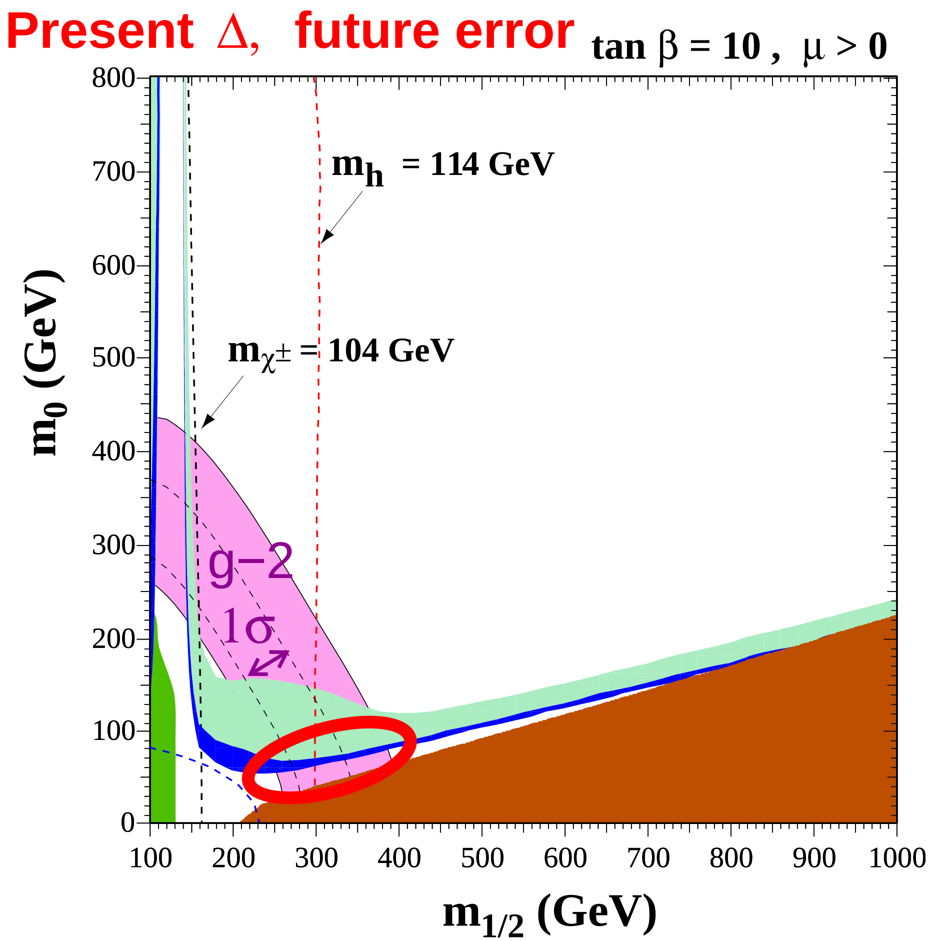
following Ellis, Olive, Santoso Spanos

(Provided by K. Olive)

CMSSM (constrained minimal supersymmetric model)

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

Future Comparison: $\Delta_{E969} = \Delta_{now}$



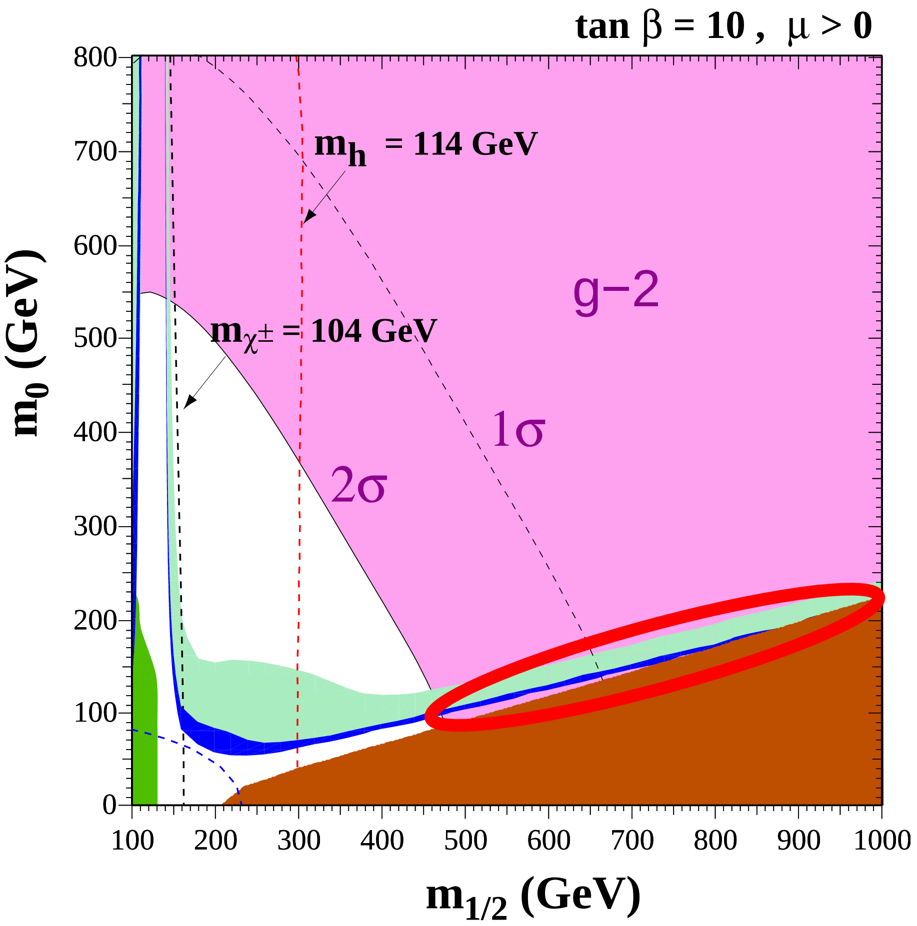
following Ellis Olive, Santoso Spanos

(Provided by K. Olive)

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

Future Comparison: $\Delta_{E969} = 0$

$\Delta=0$ **Future error**



following Ellis Olive, Santoso, Spanos

(Provided by K. Olive)

Historically (g-2) has played an important role in restricting models of new physics.