Axion Academic Training
CERN, 1 December 2005

Magnetic & Electric Dipole Moments.

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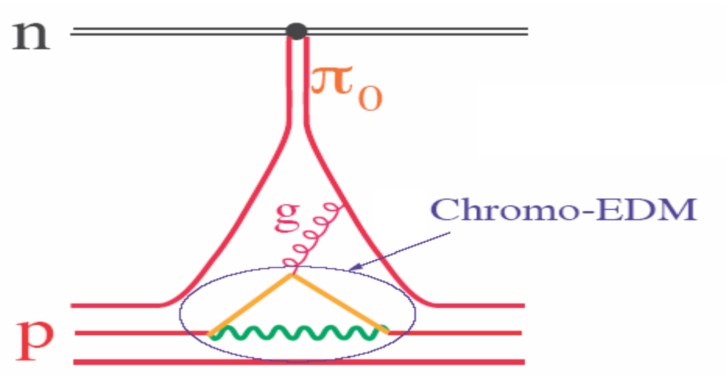
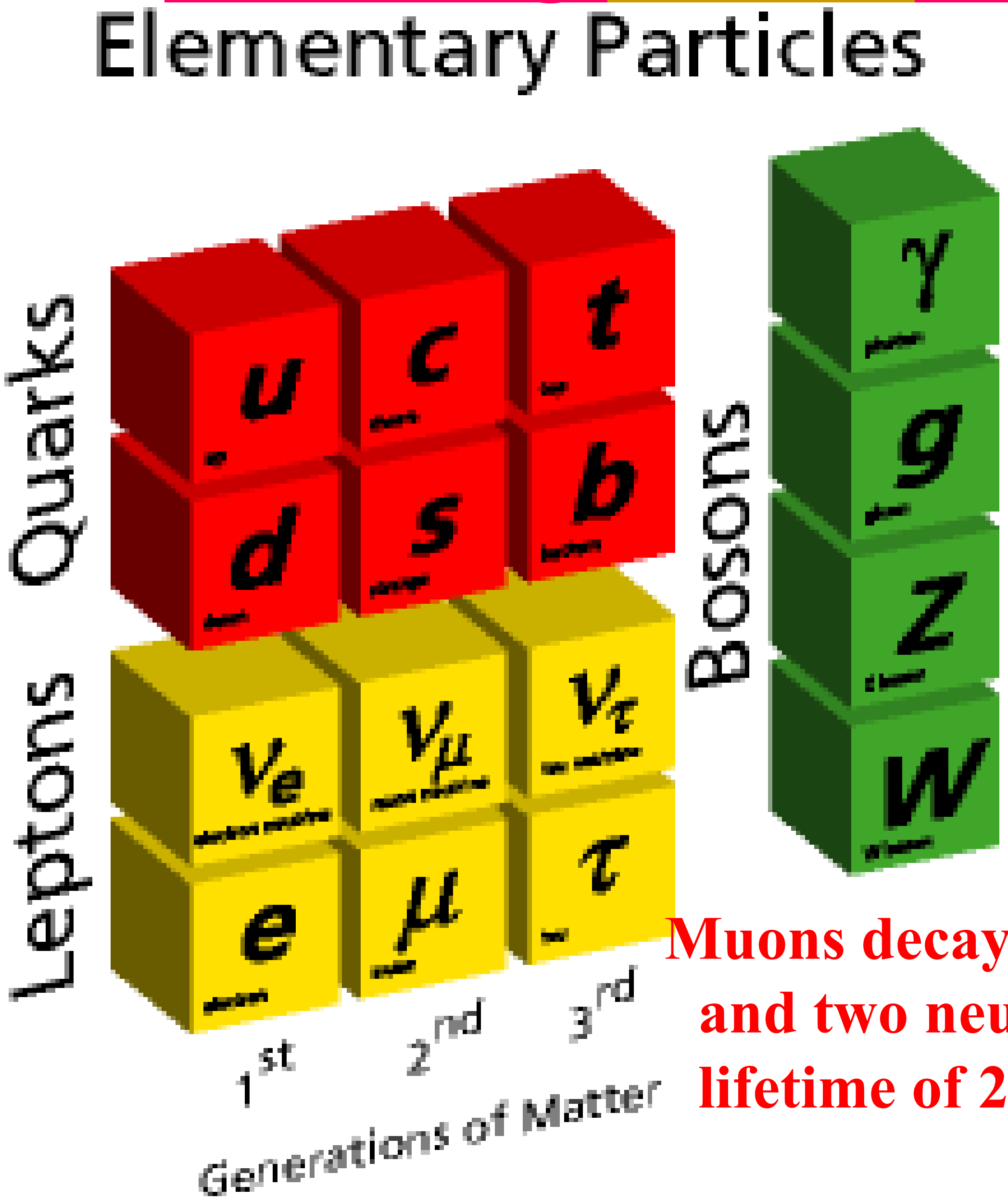


- Muon g-2 experiment
- EDMs: What do they probe?
- Physics of Hadronic EDMs
- Probing θ_{QCD} directly (RHIC), & indirectly (Hadronic EDM)
- Experimental Techniques

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

Building blocks of matter



Force carriers

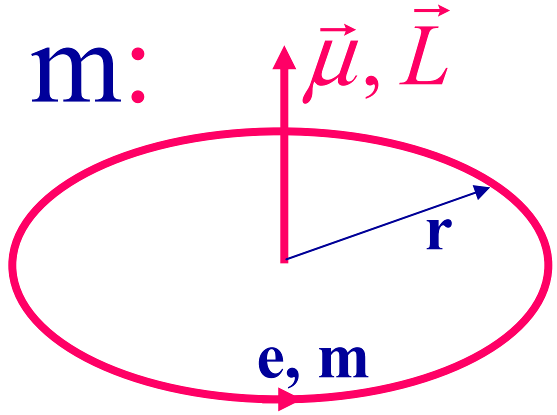
Muons decay to an electron and two neutrinos with a lifetime of 2.2μs (at rest).

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

Quantum Mechanical Fluctuations

- The electron particle is surrounded by a cloud of virtual particles, a …soup of particles…
- The muon, which is ~200 times heavier than the electron, is surrounded by a heavier soup of particles…

A circulating particle with charge e and mass m:



- Angular momentum

$$L = mvr$$

- Magnetic dipole moment

$$\mu = IA$$

$$\vec{\mu} = \frac{e}{2m}\vec{L}$$

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

For particles with intrinsic angular momentum (spin S):

$$\vec{\mu} = g \frac{e}{2m} \vec{S}$$

The anomalous magnetic moment *a*:

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

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

In a magnetic field (B), there is a torque:

$$\vec{\tau} = \vec{\mu} \times \vec{B}$$

Which causes the spin to precess in the horizontal plane:

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

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

Definition of g-Factor

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

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

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

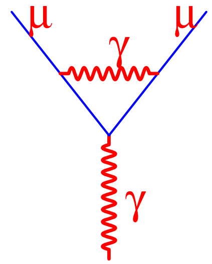
$$\frac{d\vec{s}}{dt} = \vec{\mu} \times \vec{B} + \vec{d} \times \vec{E}$$

g-factors:

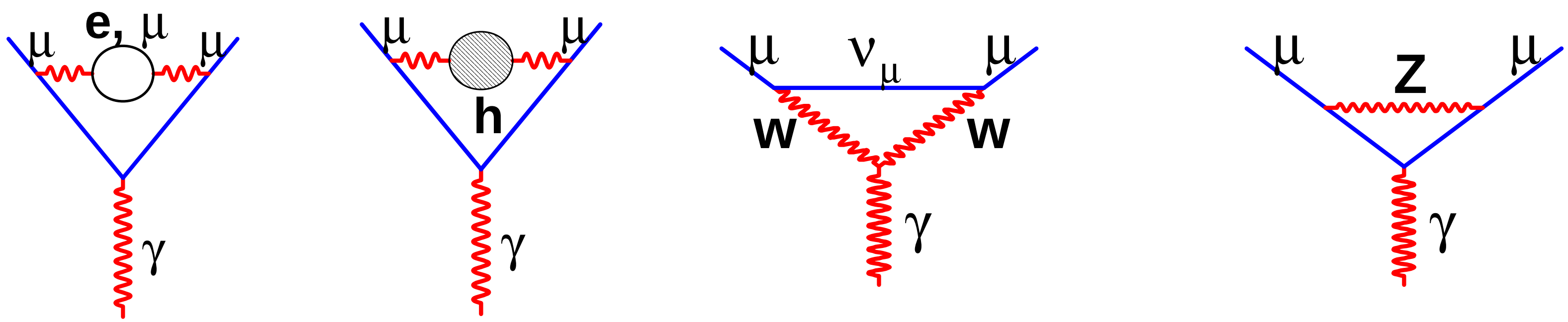
- Proton (g_p=+5.586) and the neutron (g_n=-3.826) are composite particles.
- The ratio g_p/g_n=-1.46 close to the predicted –3/2 was the first success of the constituent quark model.
- The experimental sensitivity of g_e-2 sensitive to quantum field fluctuations involving only QED.
- The g_μ-2 is sensitive to heavier particles more 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)

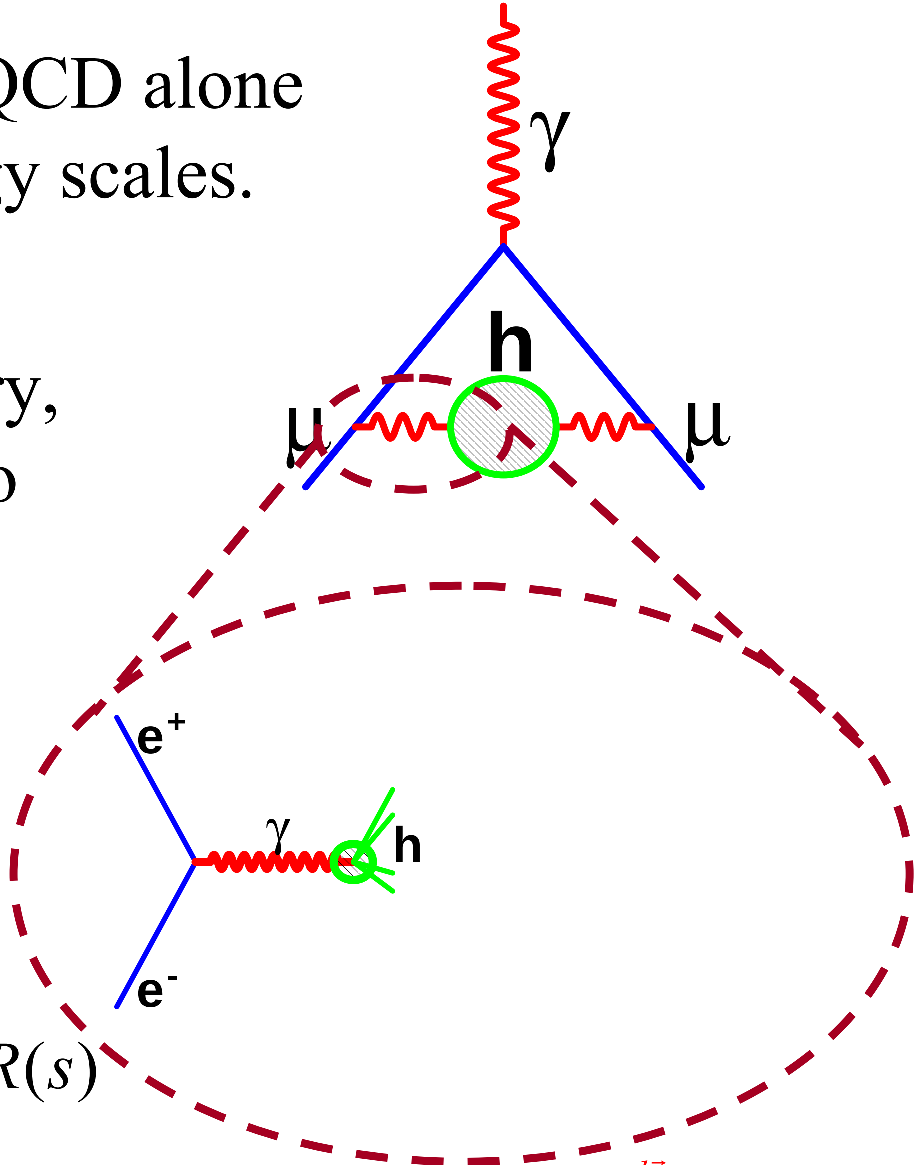
Hadronic contribution (had1)

Cannot be calculated from pQCD alone because it involves low energy scales.

However, by dispersion theory, this a_μ(had1) can be related to

$$R = \frac{\sigma(e^+e^- \to hadrons)}{\sigma(e^+e^- \to \mu^+\mu^-)}$$

measured in e^+e^- collisions.



$$a_\mu(had,1) = \left(\frac{\alpha m_\mu}{3\pi}\right)^2 \int_{4m_\pi^2}^{\infty} \frac{ds}{s^2} K(s) R(s)$$

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

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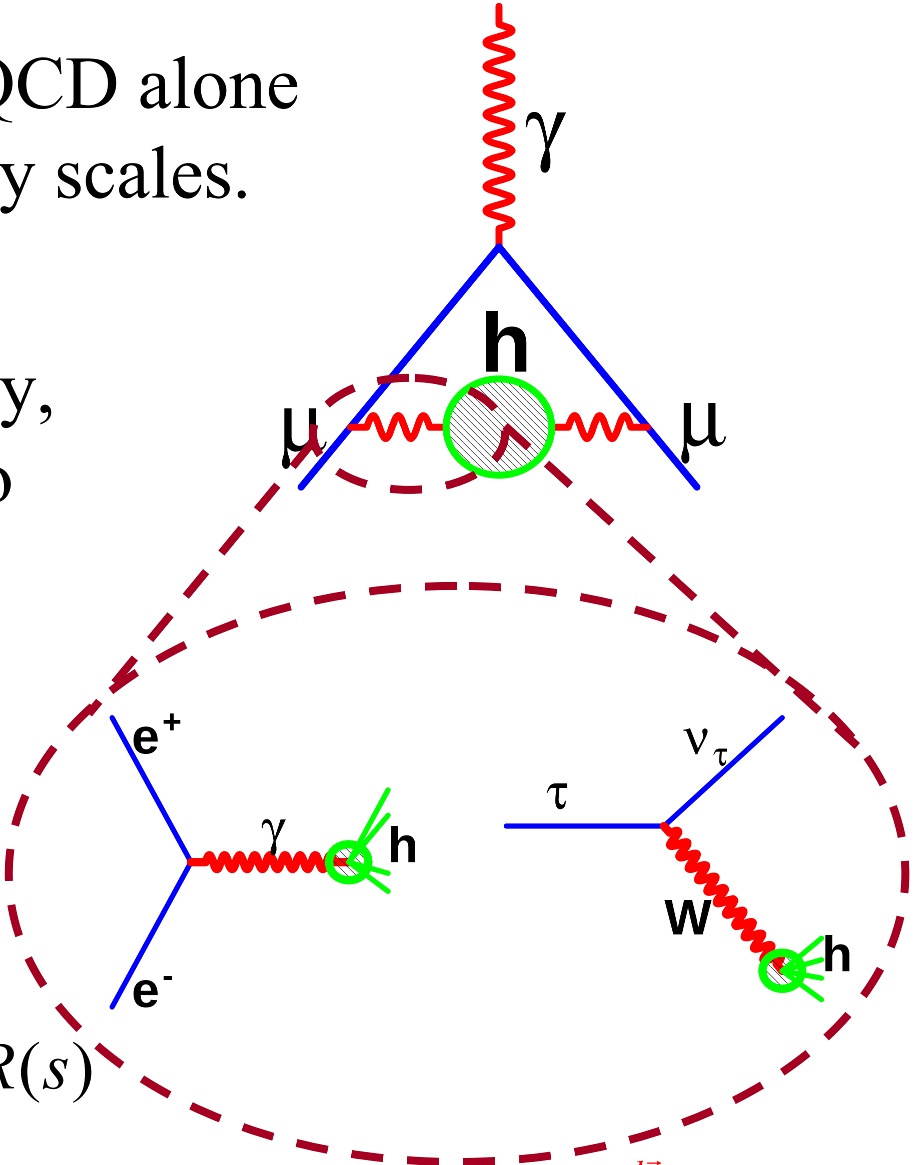
Cannot be calculated from pQCD alone because it involves low energy scales.



However, by dispersion theory, this a_μ(had1) can be related to

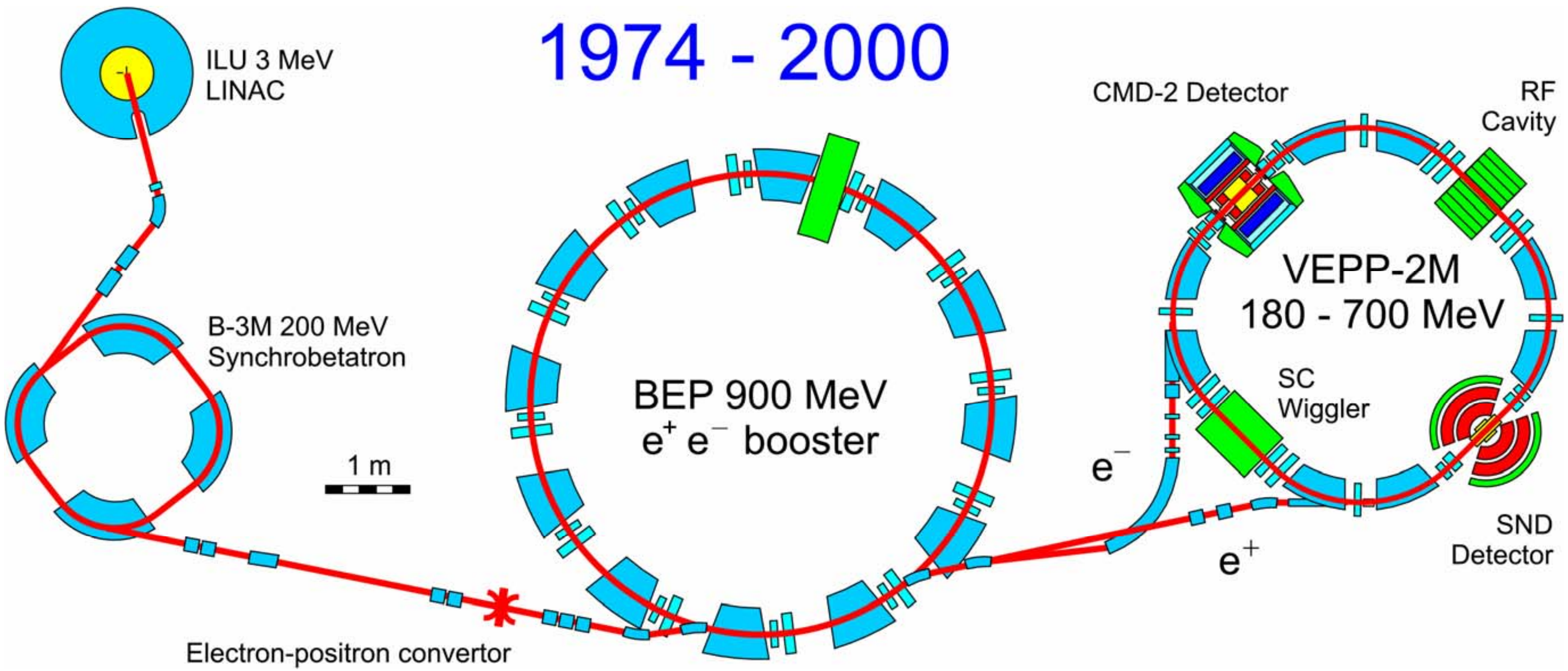
$$R = \frac{\sigma(e^+e^- \to hadrons)}{\sigma(e^+e^- \to \mu^+\mu^-)}$$

measured in e^+e^- collisions or τ decay (assuming CVC).

$$a_\mu(had,1) = \left(\frac{\alpha m_\mu}{3\pi}\right)^2 \int_{4m_\pi^2}^{\infty} \frac{ds}{s^2} K(s) R(s)$$

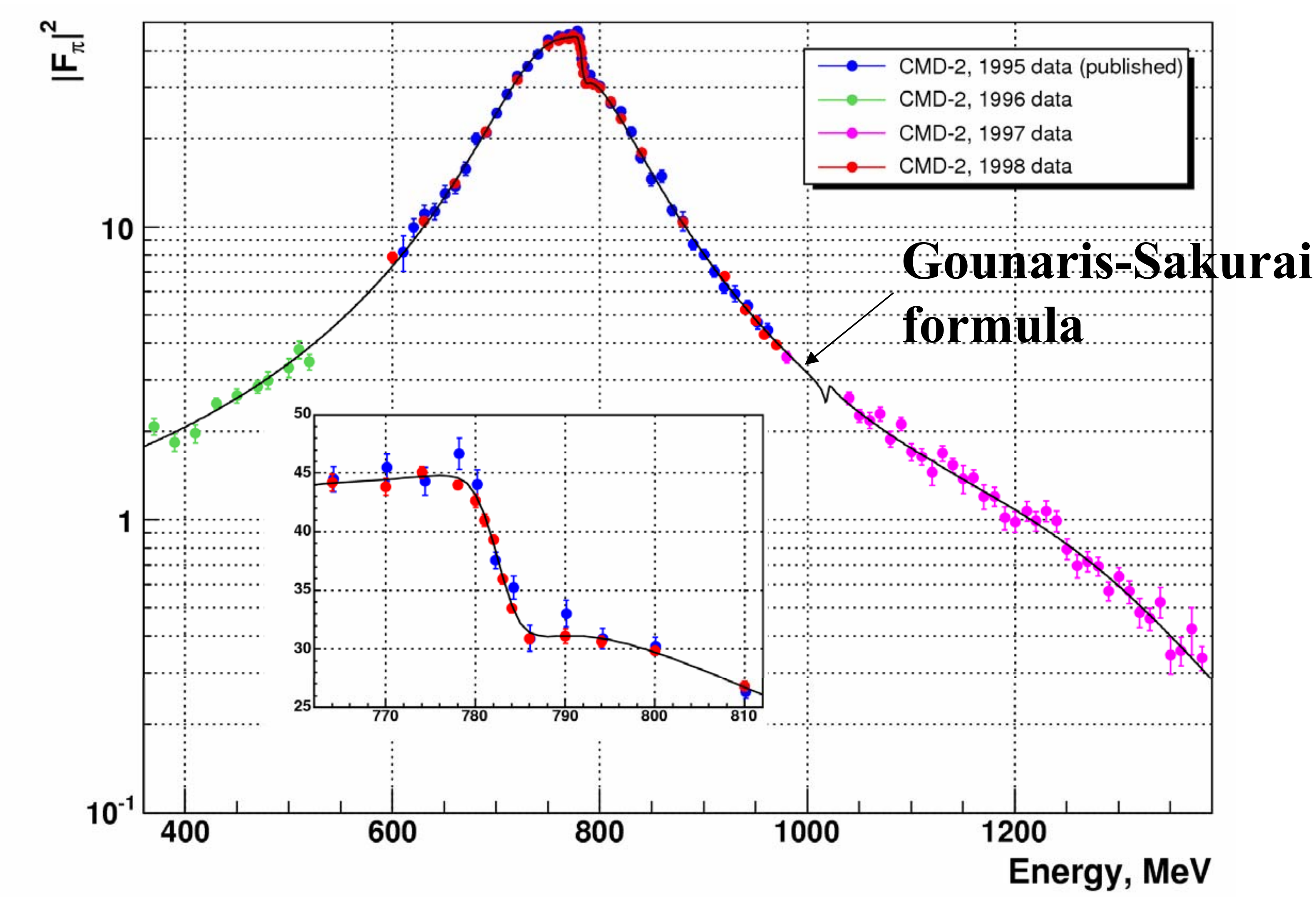
$$\frac{d\vec{s}}{dt} = \vec{\mu} \times \vec{B} + \vec{d} \times \vec{E}$$

VEPP-2M collider



- VEPP-2M collider: 0.36-1.4 GeV in c.m., L≈10^{30} 1/cm^{2}s at 1 GeV
- Detectors CMD-2 and SND: 50 pb^{-1} collected in 1993-2000

CMD-2 Result

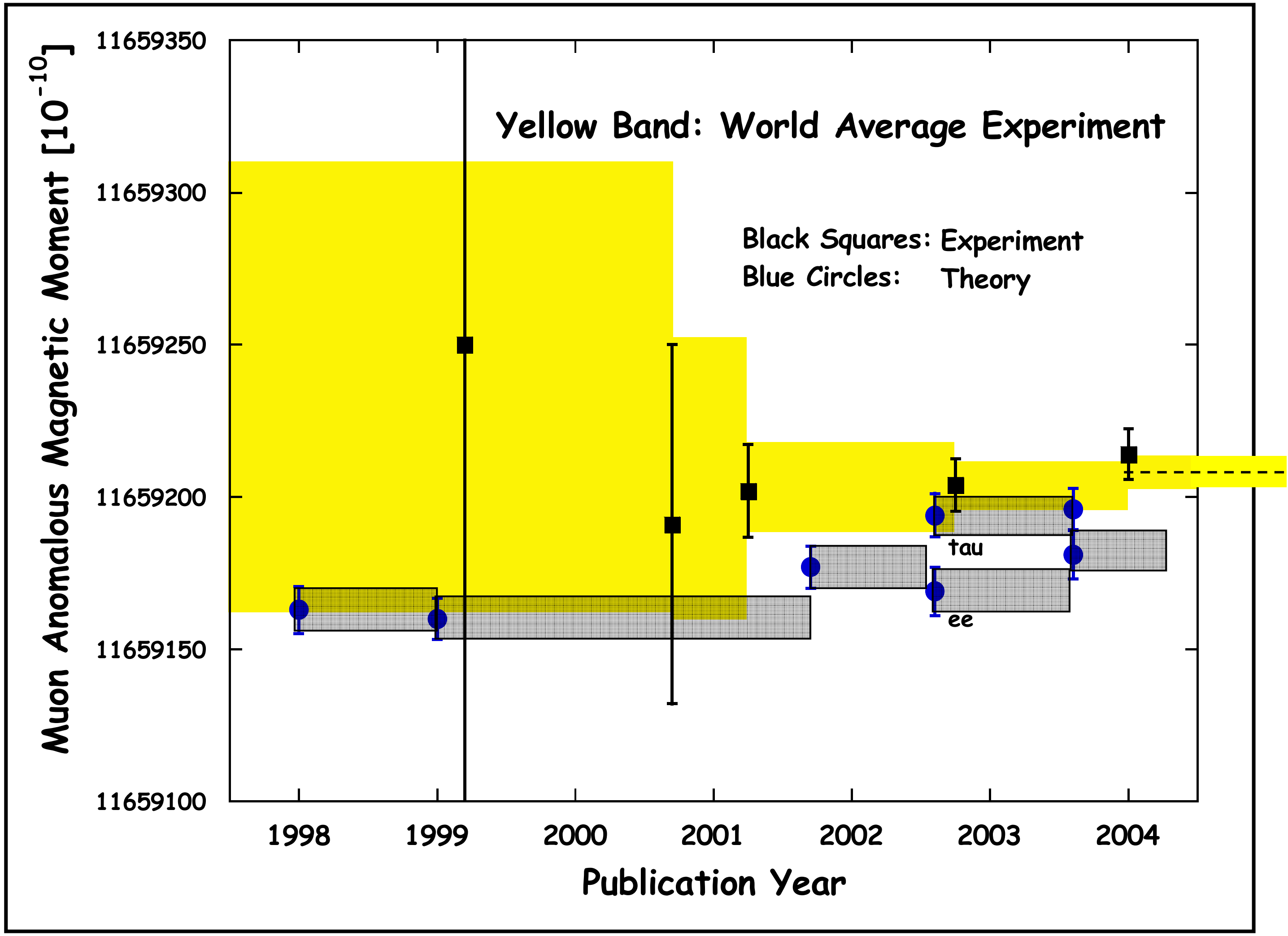


Systematic error

0.7% 0.6 / 0.8% 1.2-4.2%

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

Theory and Experiment vs. Year



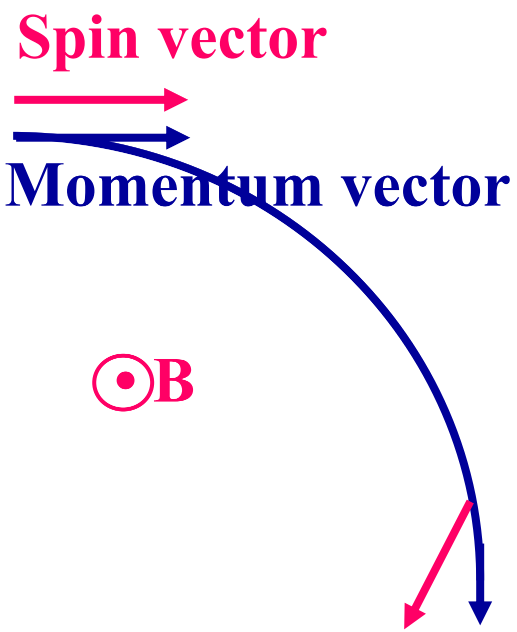
$$\frac{d\vec{s}}{dt} = \vec{\mu} \times \vec{B} + \vec{d} \times \vec{E}$$

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

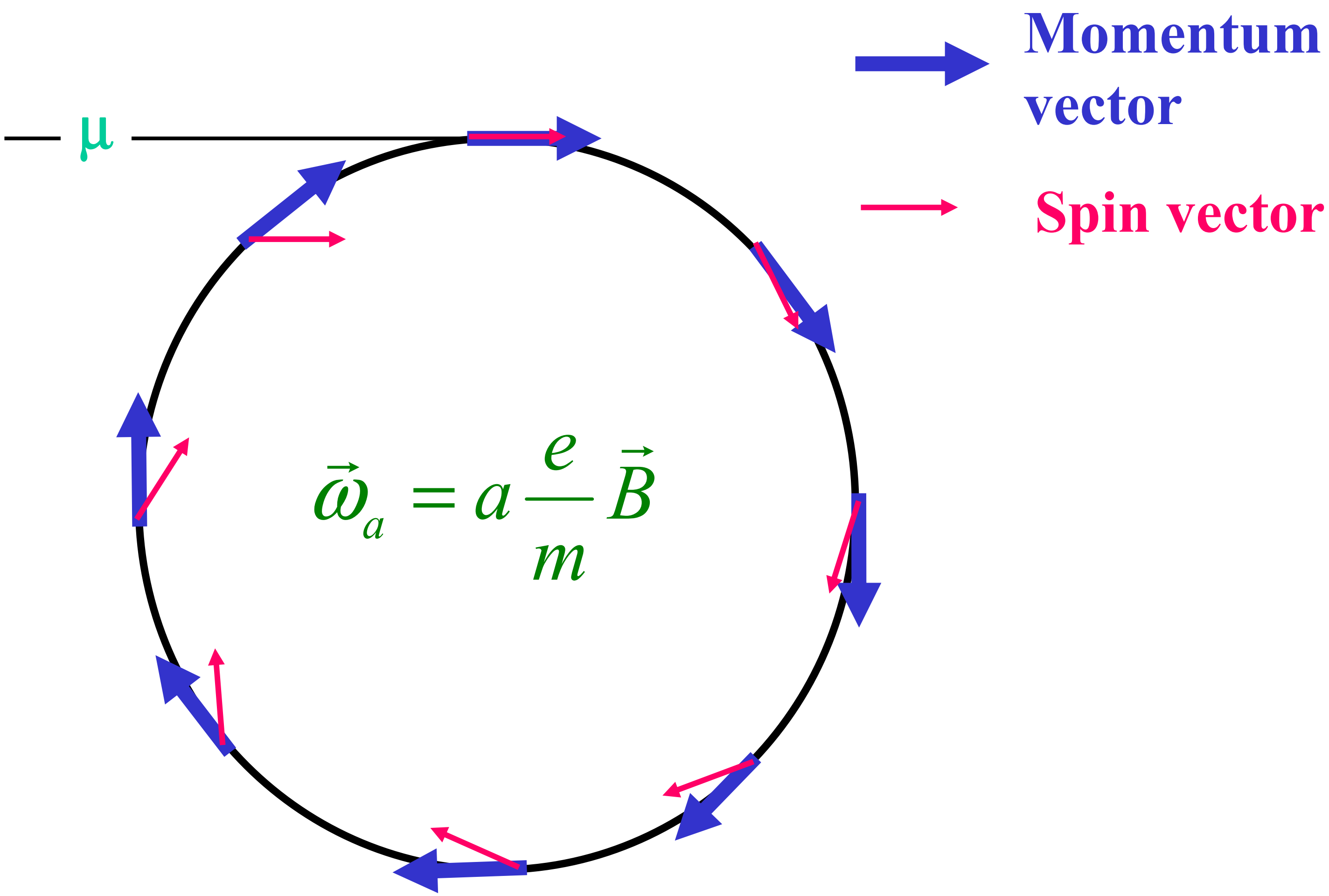
$$\omega_c = \frac{eB}{m}$$

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

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

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

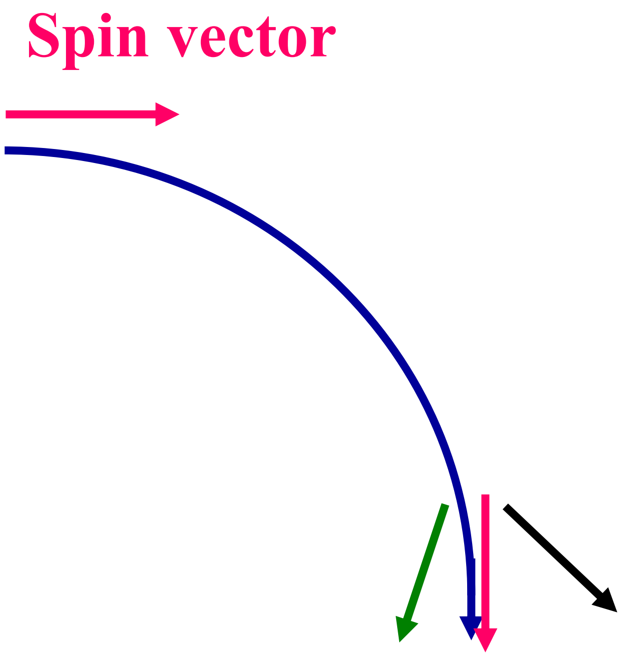
Spin Precession in g-2 Ring
(Top View)



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

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

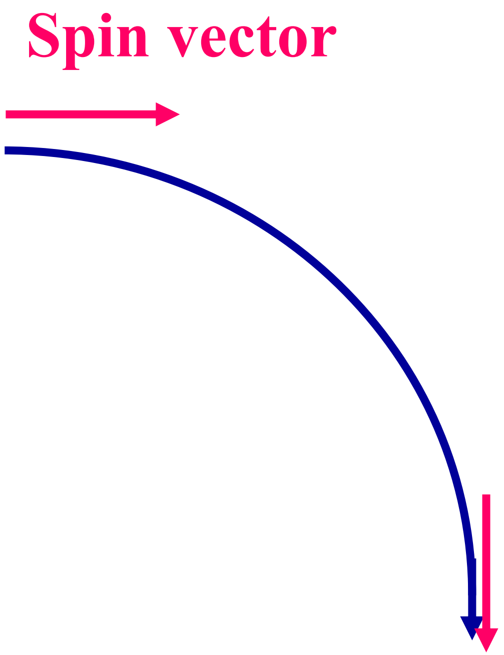
Effect of Radial Electric Field



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

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

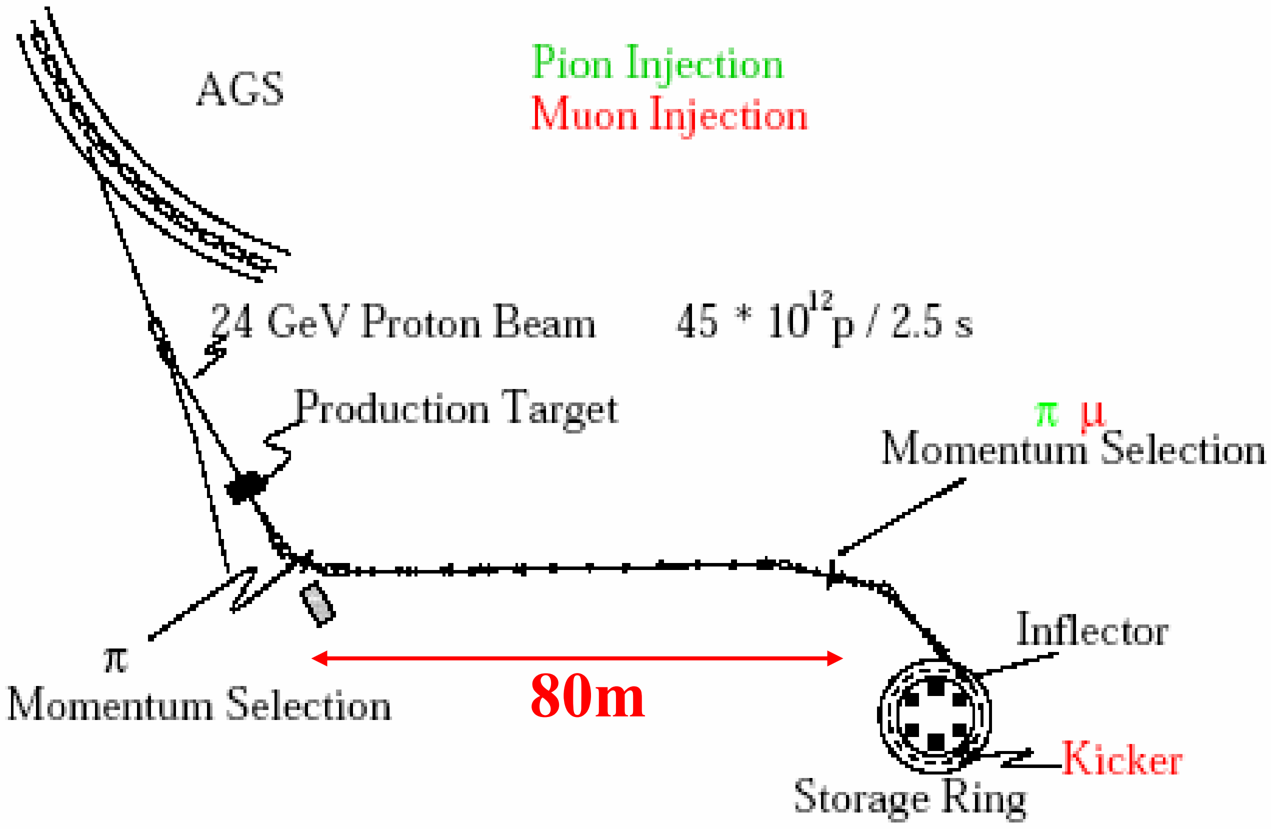
Effect of Radial Electric Field



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

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

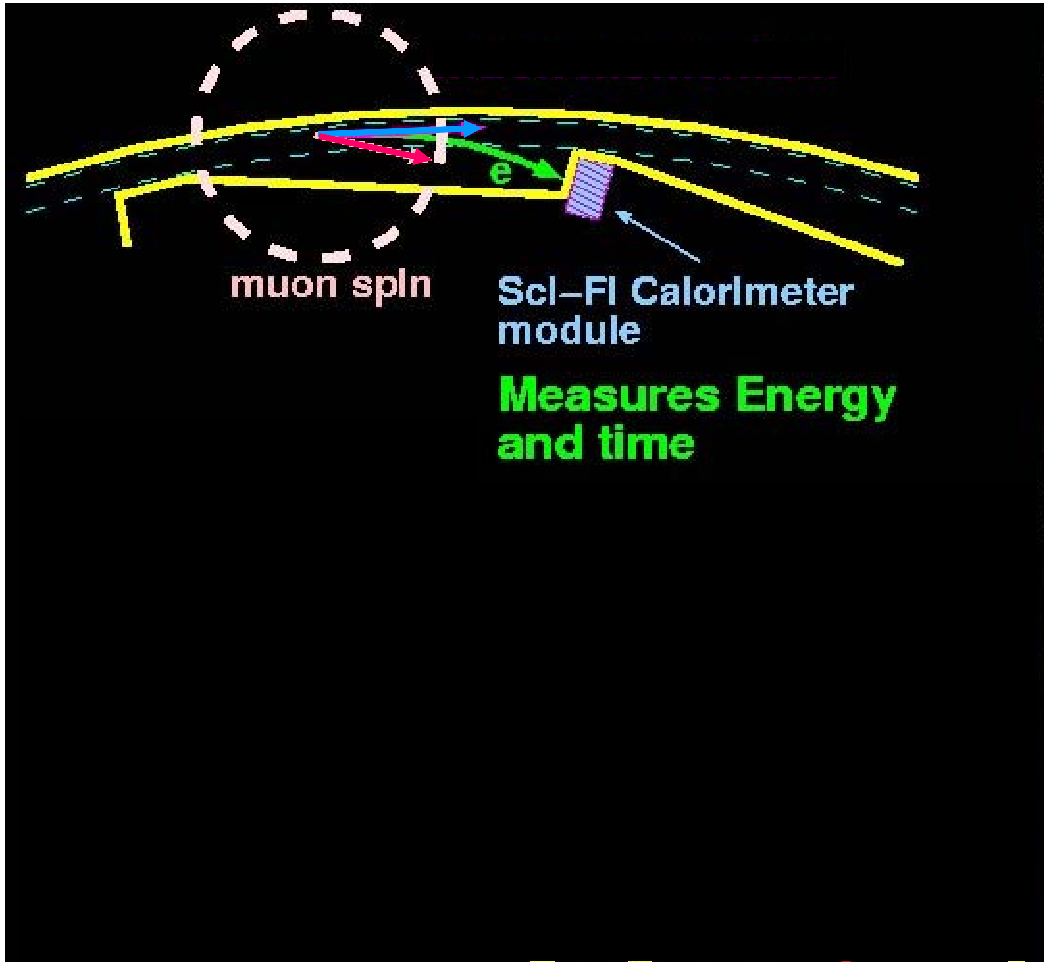
Beamline:
Polarized Muon Beam Production



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


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

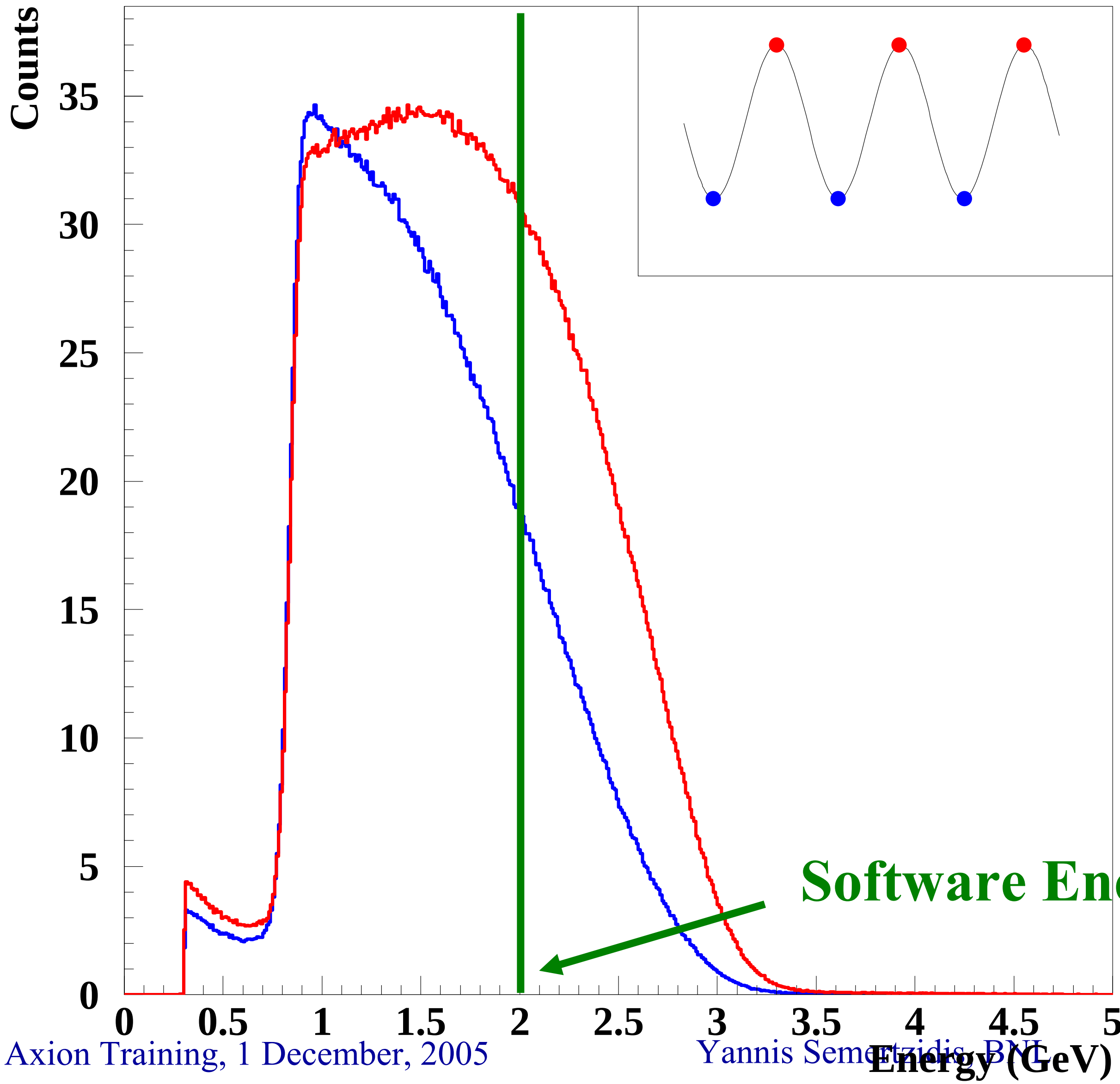
Detectors and vacuum chamber

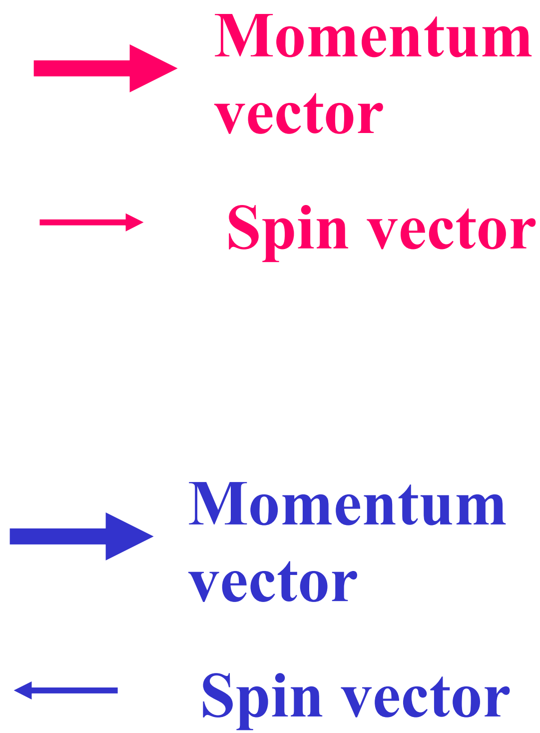


Axion

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

Energy Spectrum of Detected Positrons

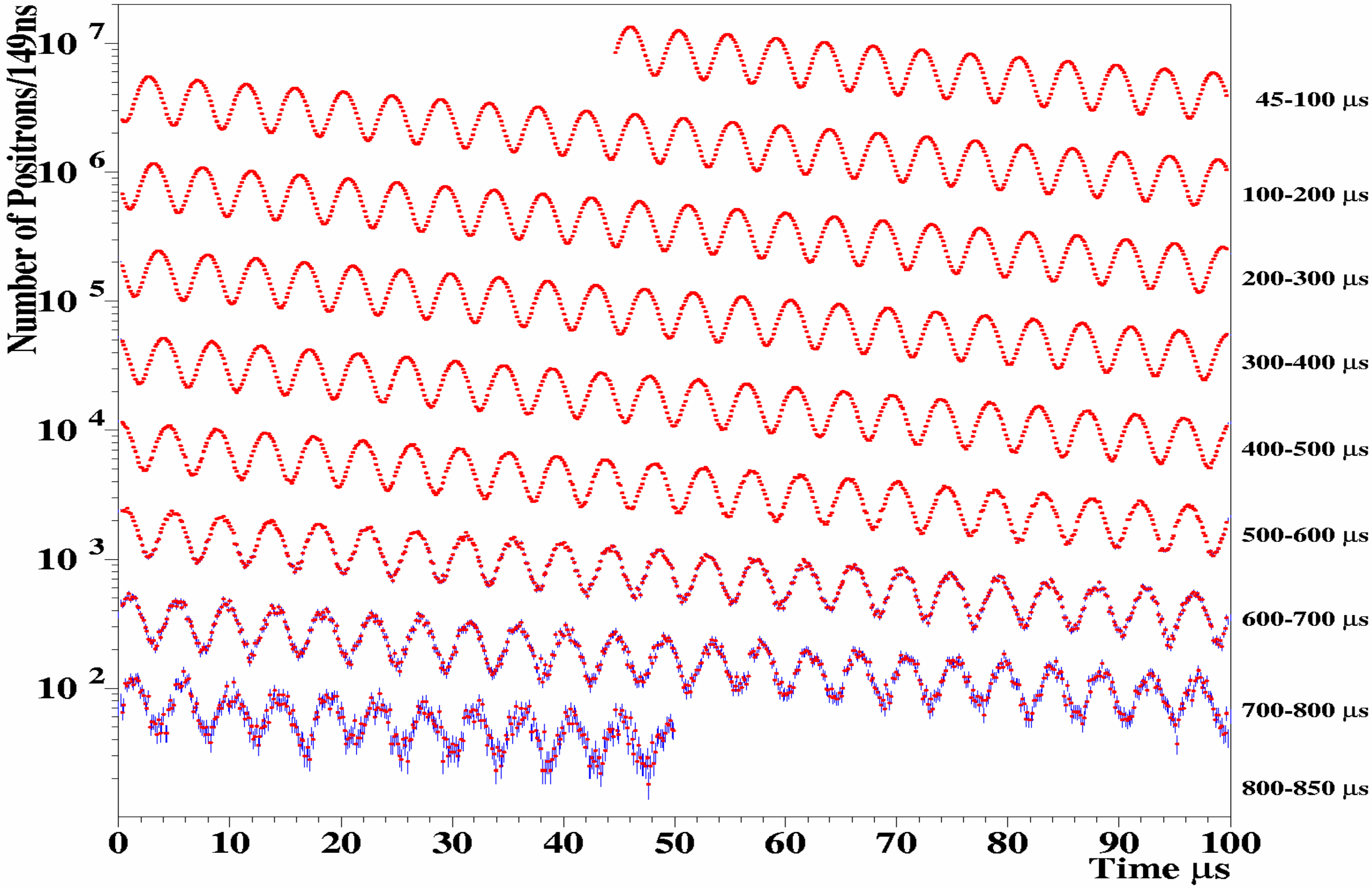




$$\frac{d\vec{s}}{dt} = \vec{\mu} \times \vec{B} + \vec{d} \times \vec{E}$$

4 Billion e^+ with E>2GeV

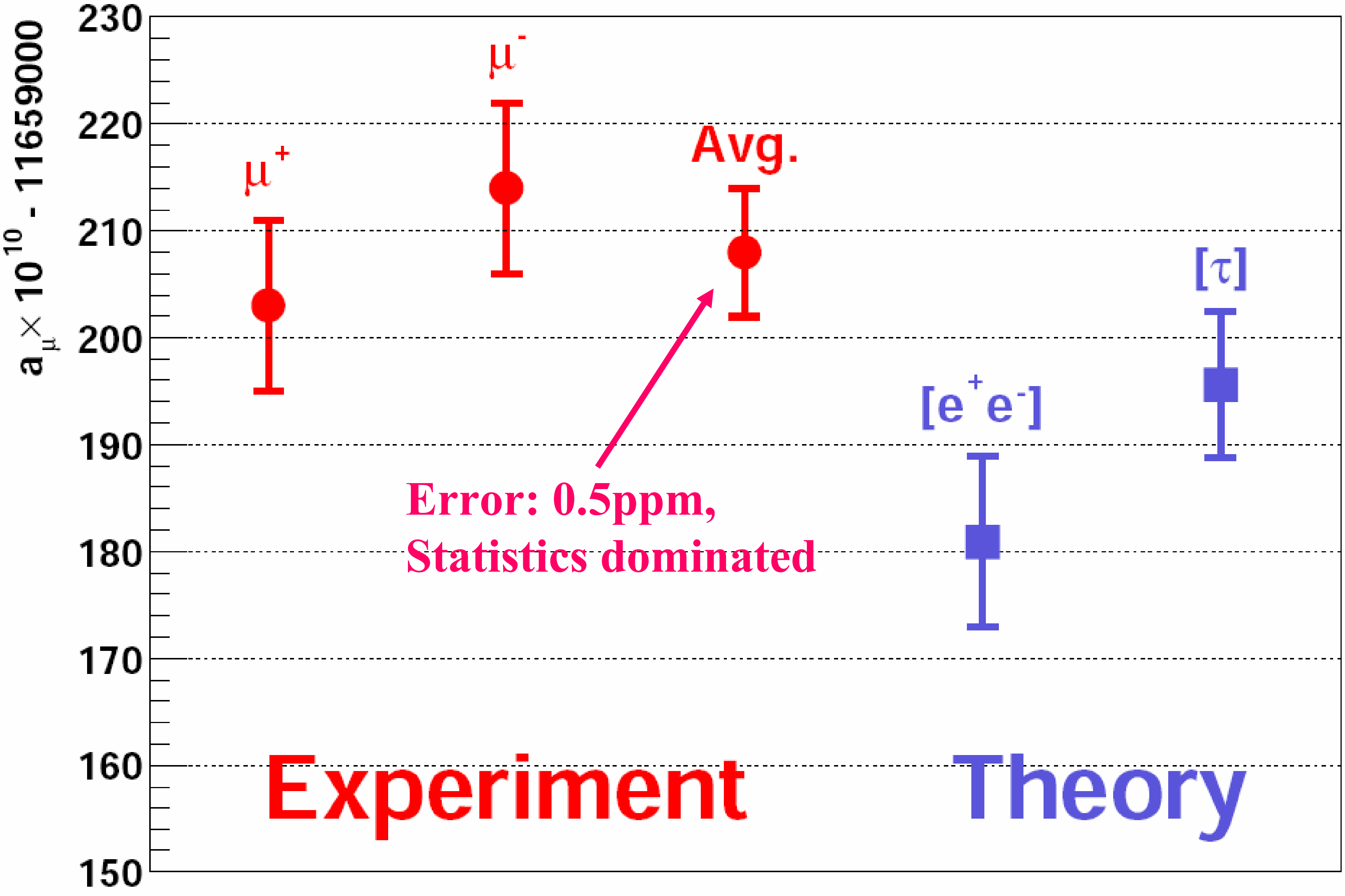
$$dN/dt = N_0 e^{-\frac{t}{\tau}}[1 + A\cos(\omega_a t + \phi_a)]$$



Ax

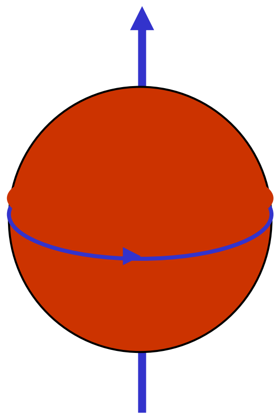
$\vec{l} \times \vec{E}$

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

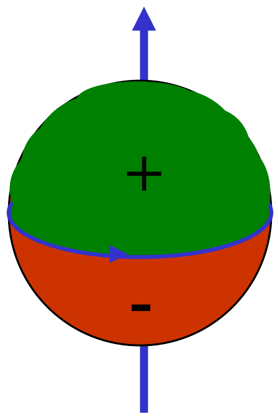


A:

EDM: Particles with Spin…



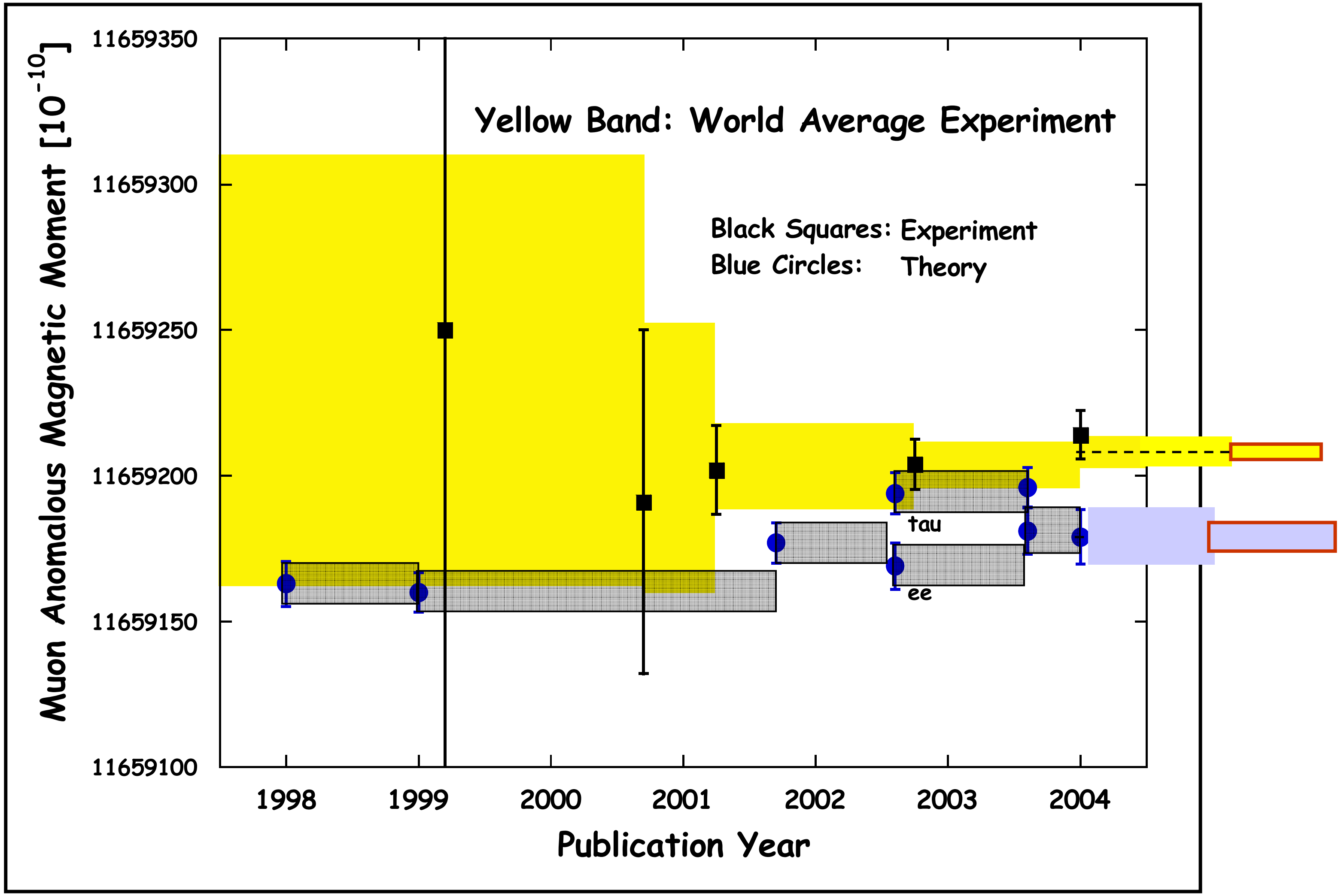
$\vec{d} = 0$



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

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

Current Status and Future Prospects

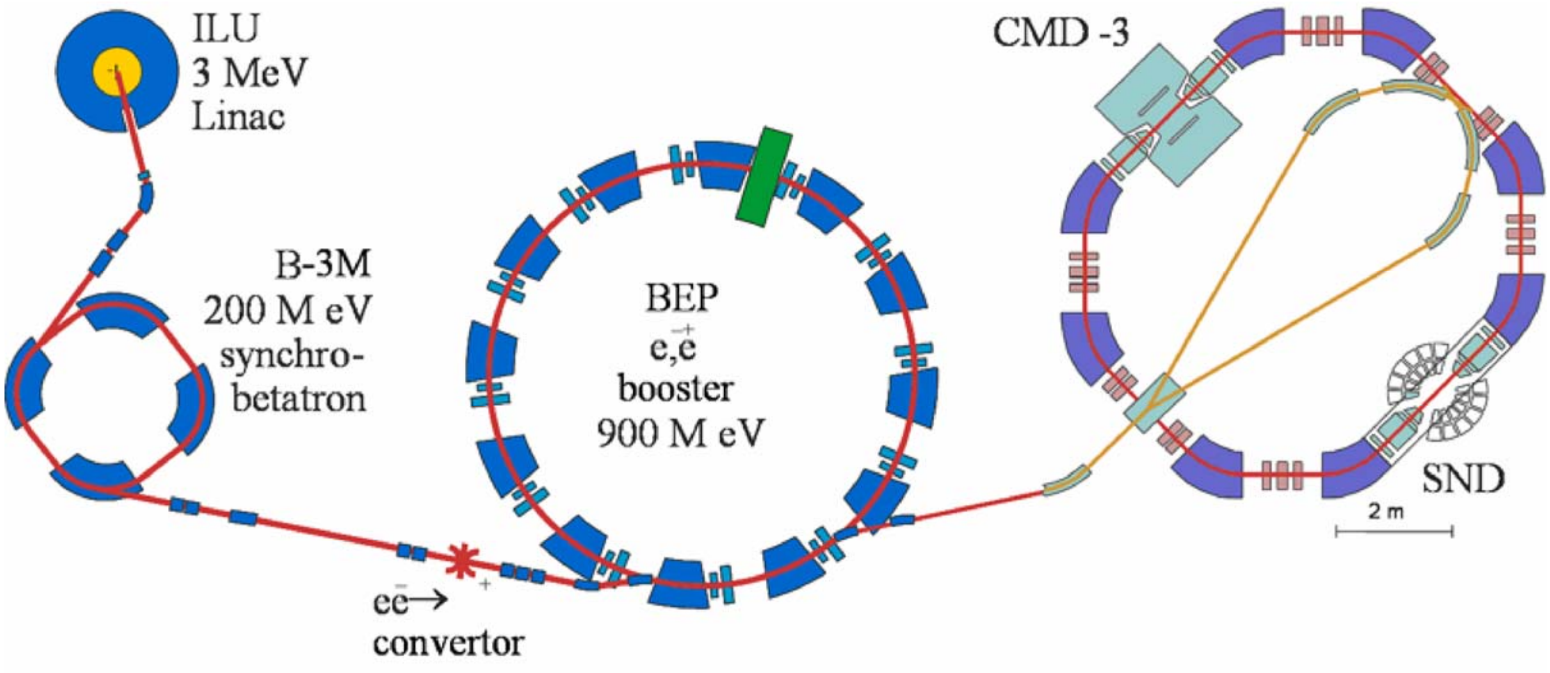


$$\frac{d\vec{s}}{dt} = \vec{\mu} \times \vec{B} + \vec{d} \times \vec{E}$$

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

Future measurements at VEPP-2000

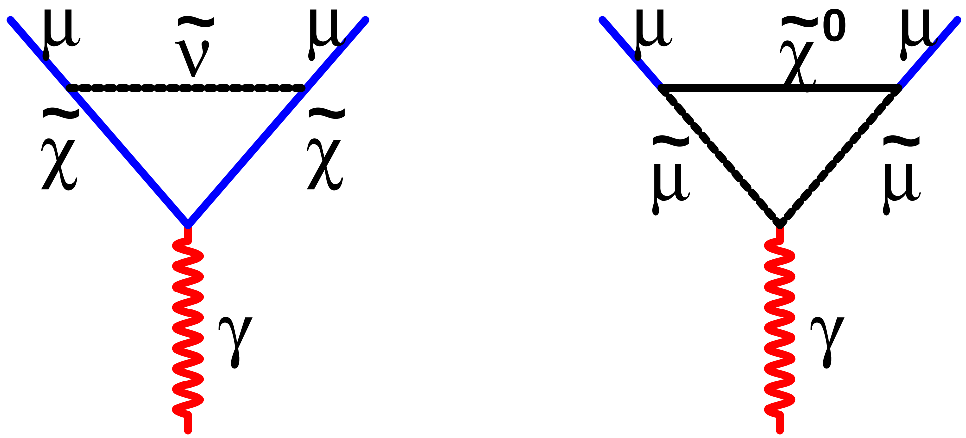


- Factor >10 in luminosity
- Up to 2 GeV c.m. energy
- CMD-3: major upgrade of CMD-2 (new drift chamber, LXe calorimeter)
- measure 2π mode to 0.2-0.3%
- measure 4π mode to 1-2%
- overall improvement in R precision by factor 2-3

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

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

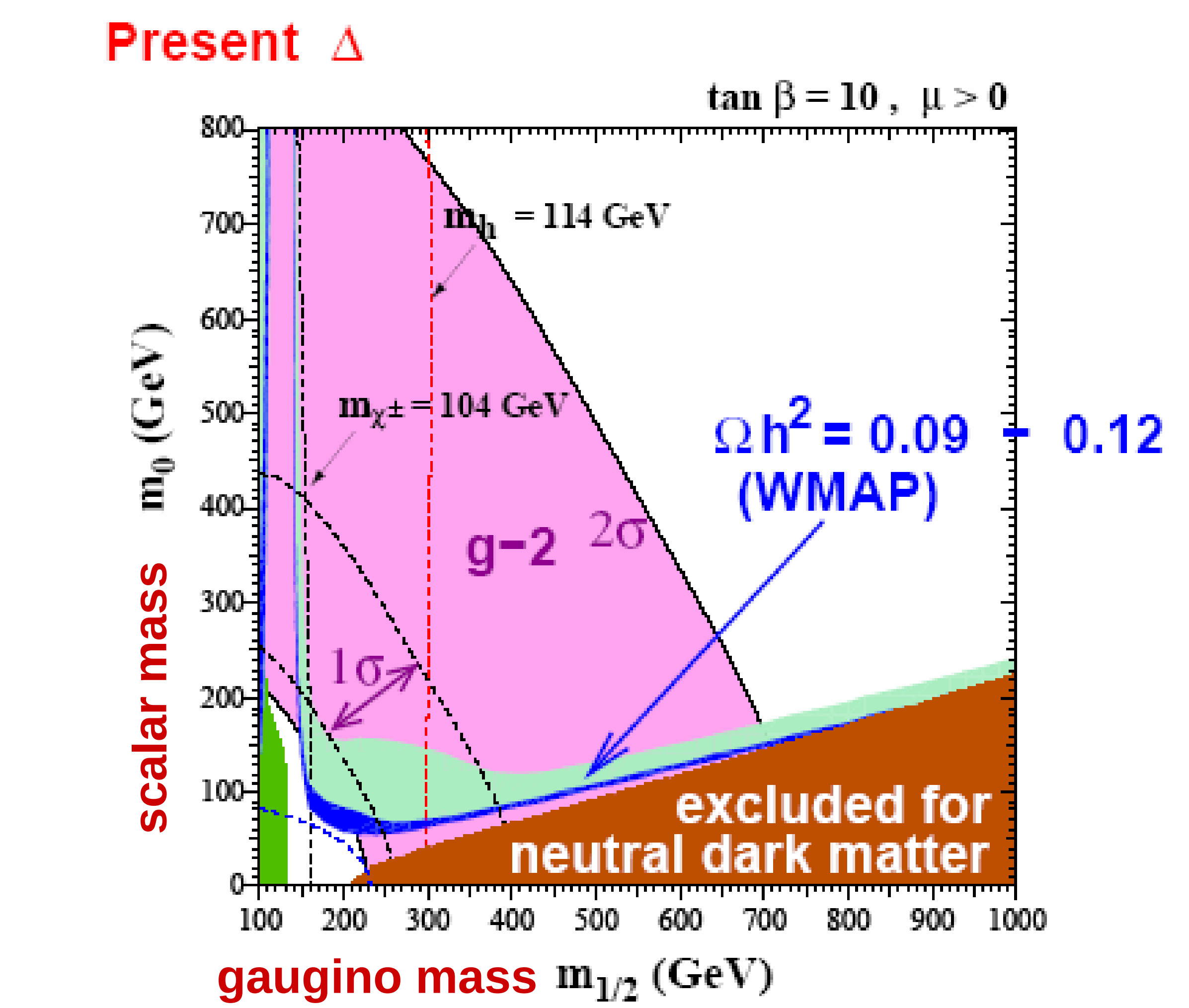
Beyond standard model, e.g. SUSY



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

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

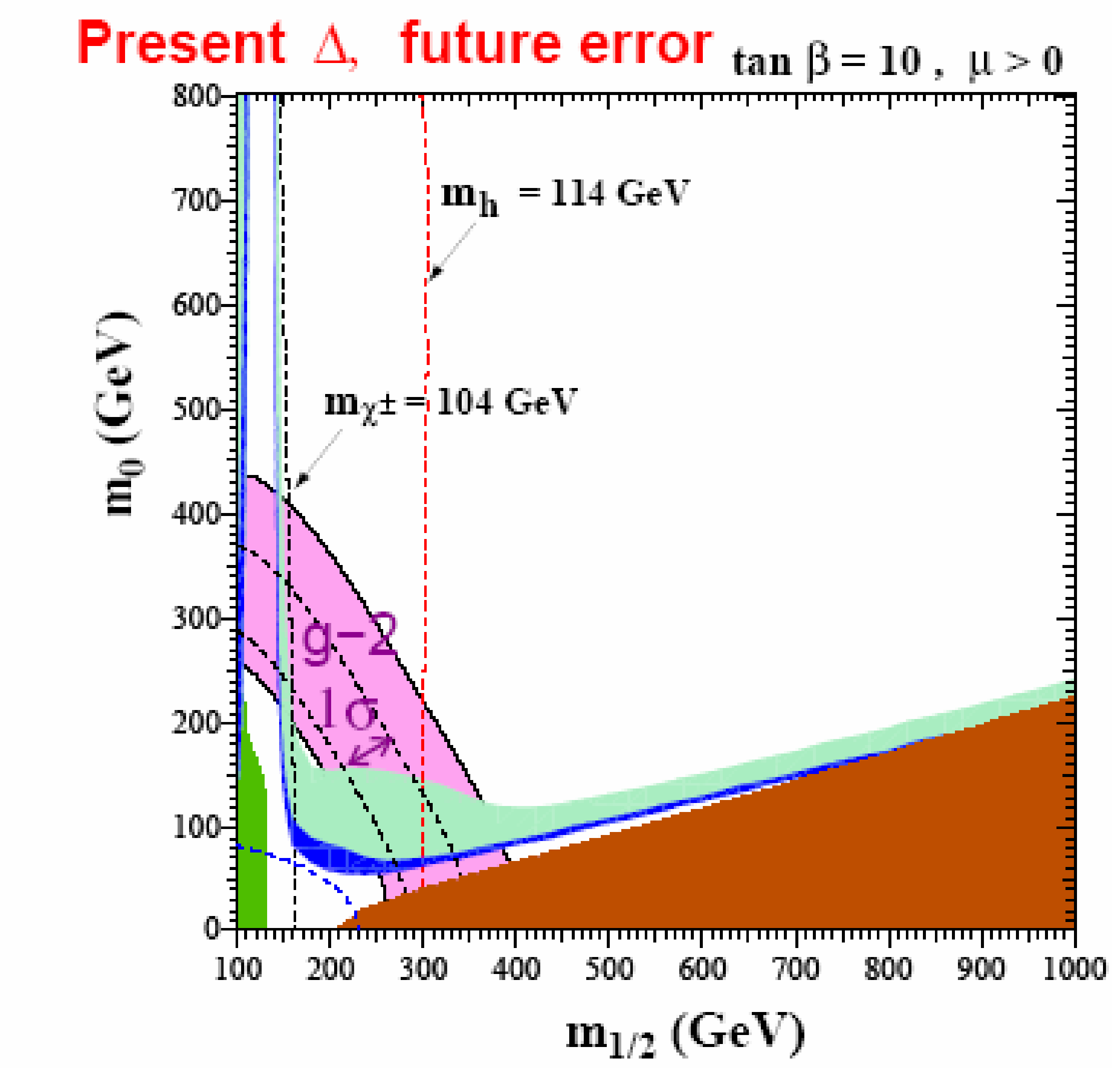
SUSY Dark Matter



Following Ellis, Olive, Santoso, Spanos.
Plot by K. Olive

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

SUSY Dark Matter



Following Ellis, Olive, Santoso, Spanos.
Plot by K. Olive

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

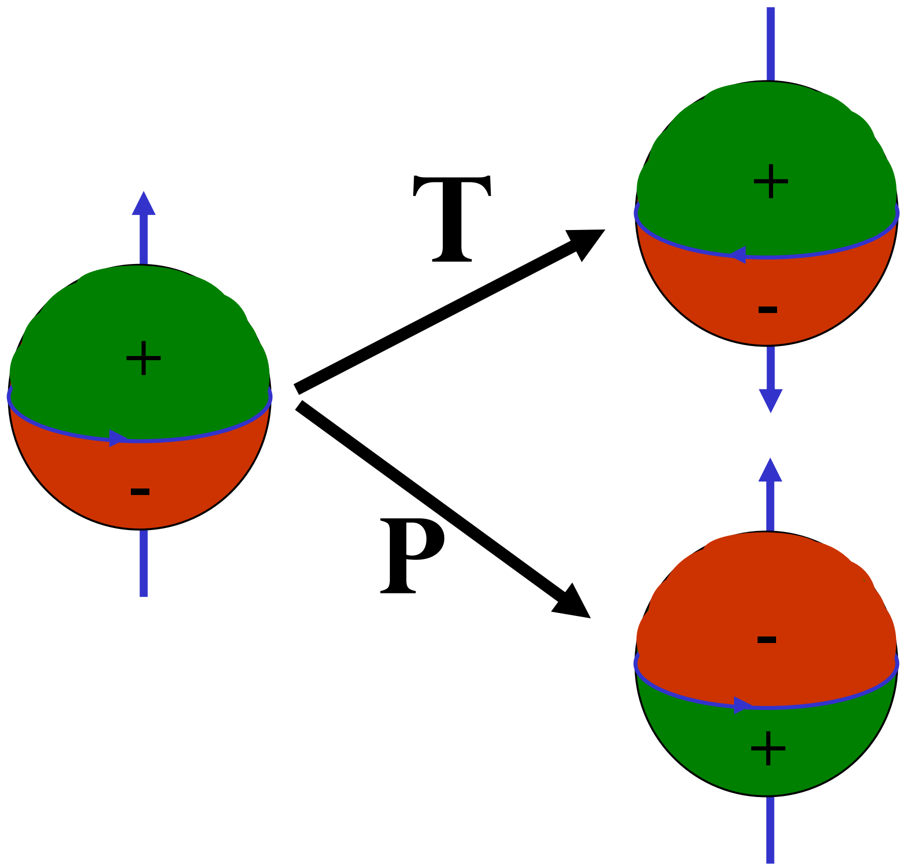
Prospects and Summary for g-2

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

- More data ($\times 10$) from the theory front are being 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.

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?

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

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

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

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

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

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

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

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

Andrei Sakharov 1967:

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

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....

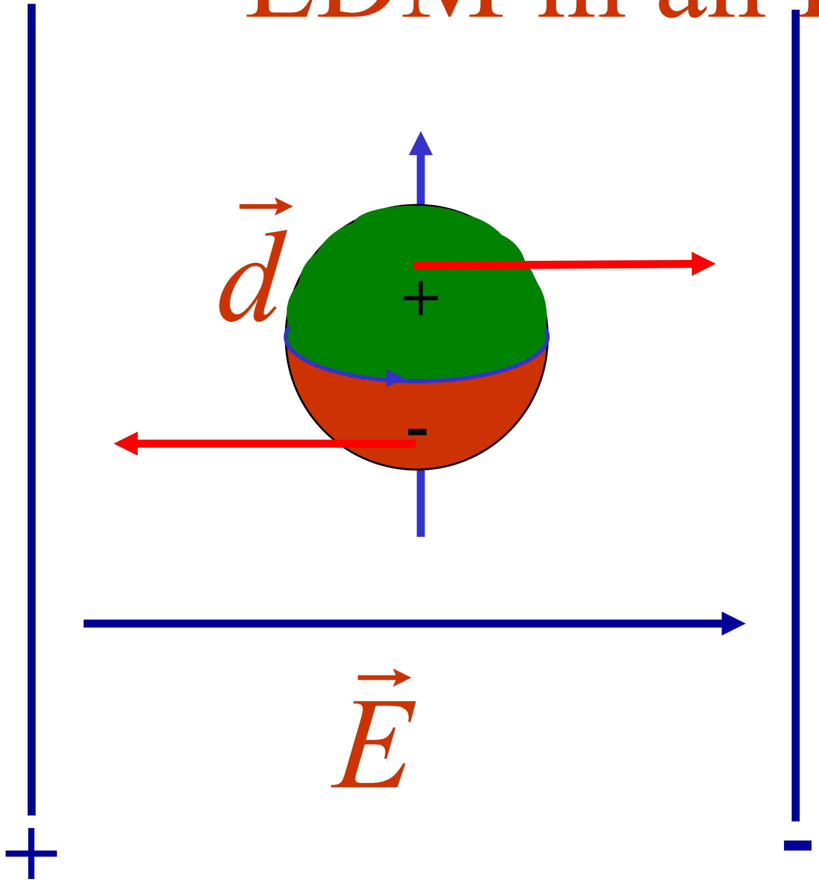
$$\frac{d\vec{s}}{dt} = \vec{\mu} \times \vec{B} + \vec{d} \times \vec{E}$$

EDM Searches are Excellent Probes of Physics Beyond the SM:

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

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

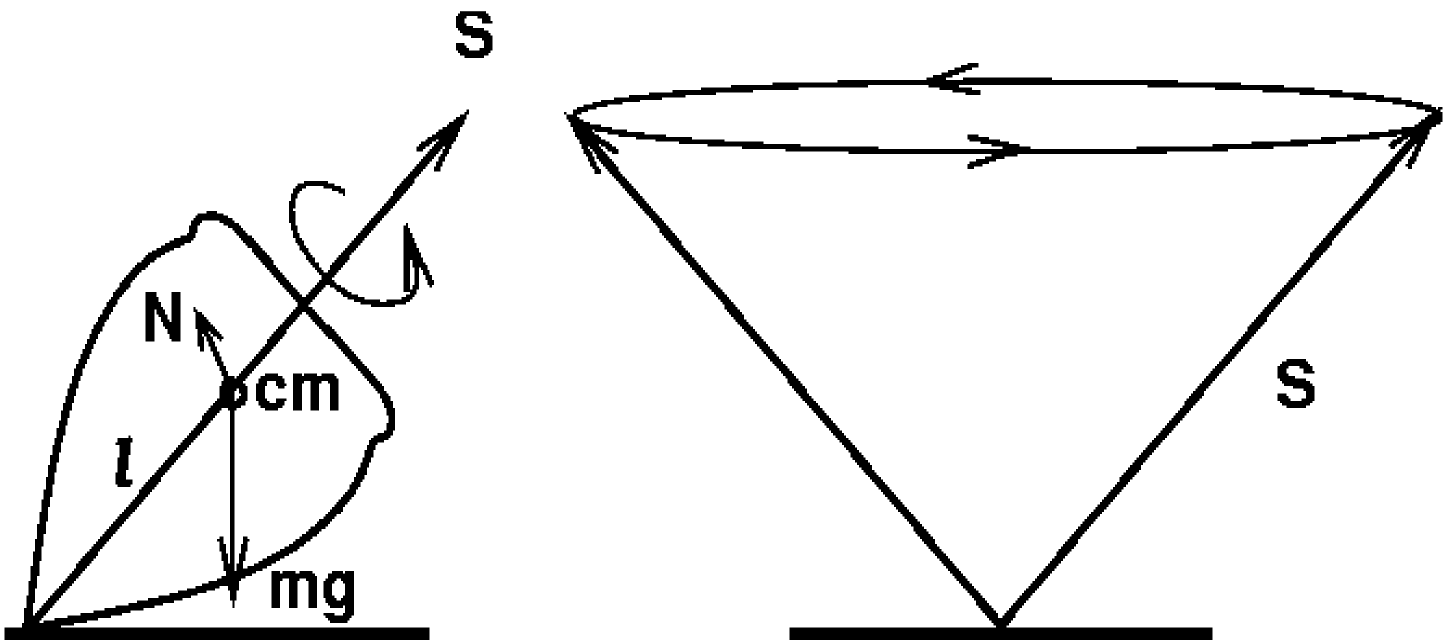
EDM in an Electric Field…



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

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

Precession of a Top in a Gravitational Field



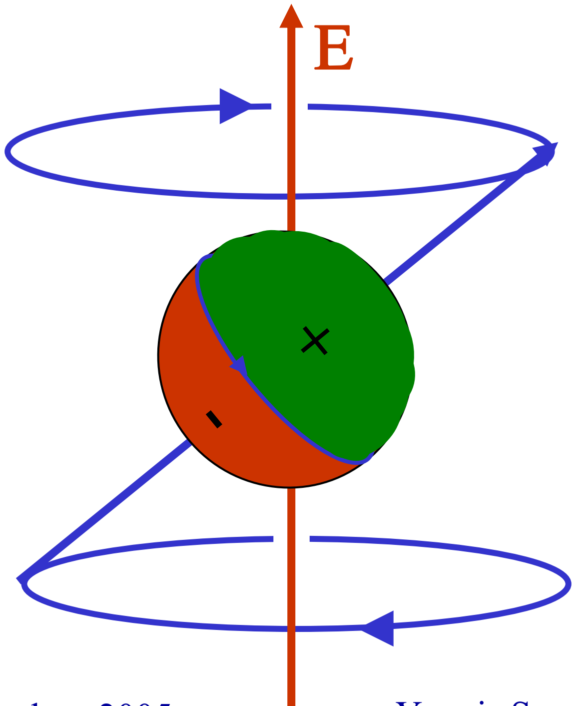
$$\omega = \frac{mgl}{L}, \quad \vec{L} = I\,\vec{S}$$

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

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:

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

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

Schiff Theorem:

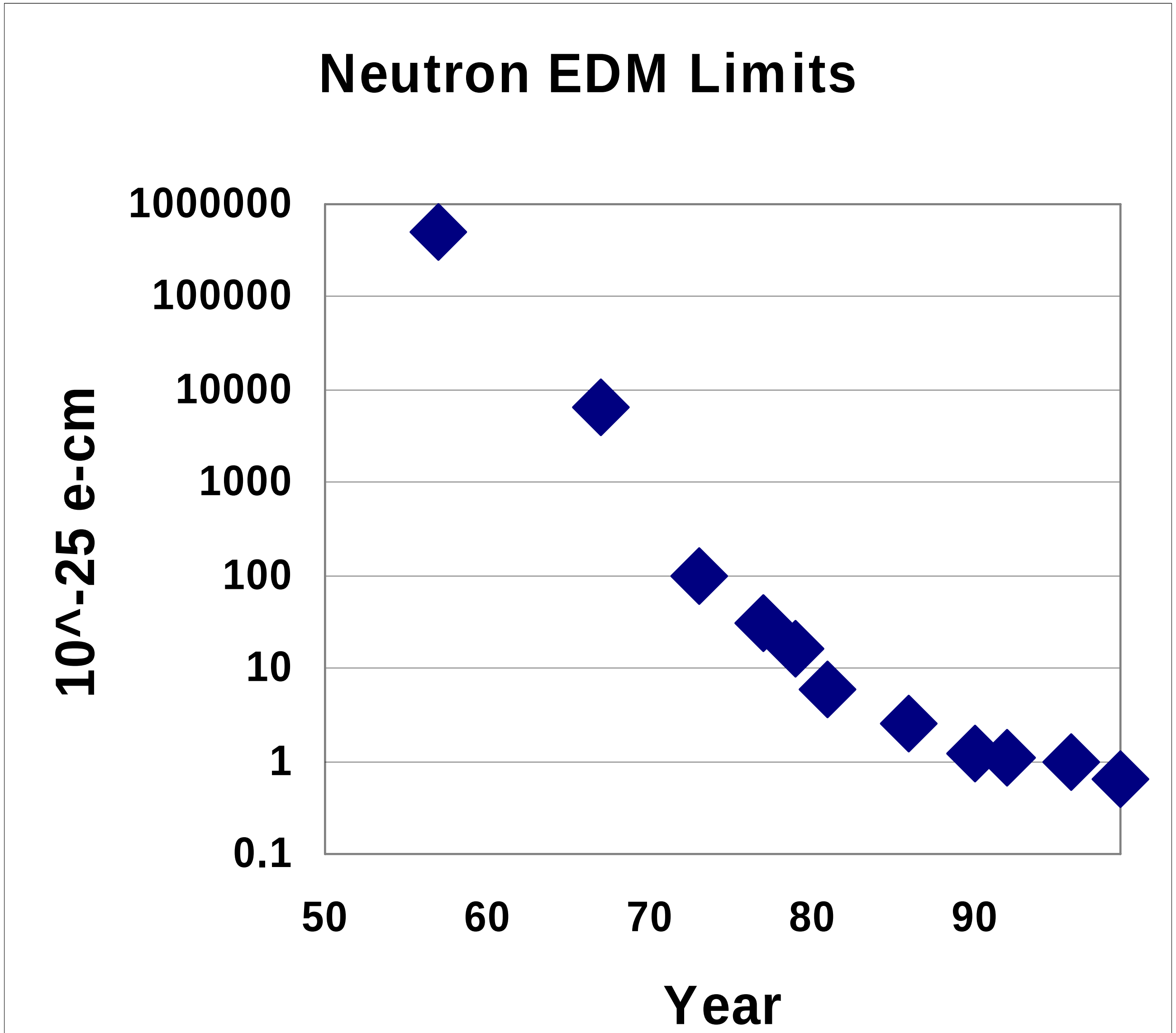
A Charged Particle at Equilibrium Feels no Force…

…An Electron in a Neutral Atom Feels no Force Either:

$$\left\langle \vec{E}_{Tot} \right\rangle = \left\langle \vec{E}_{ext} + \vec{E}_{\mathrm{int}} \right\rangle = 0$$

…Otherwise it Would be Accelerated…

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).

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

Schiff Theorem:

A Charged Particle at Equilibrium Feels no Force… …An Electron in a Neutral Atom Feels no Force Either. However:

$$\left\langle \vec{F}_{Tot} \right\rangle = \left\langle q\vec{E}_{ext} + q\vec{E}_{\text{int}} + Other\ Forces \right\rangle = 0$$

…the net E-field is not zero!

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

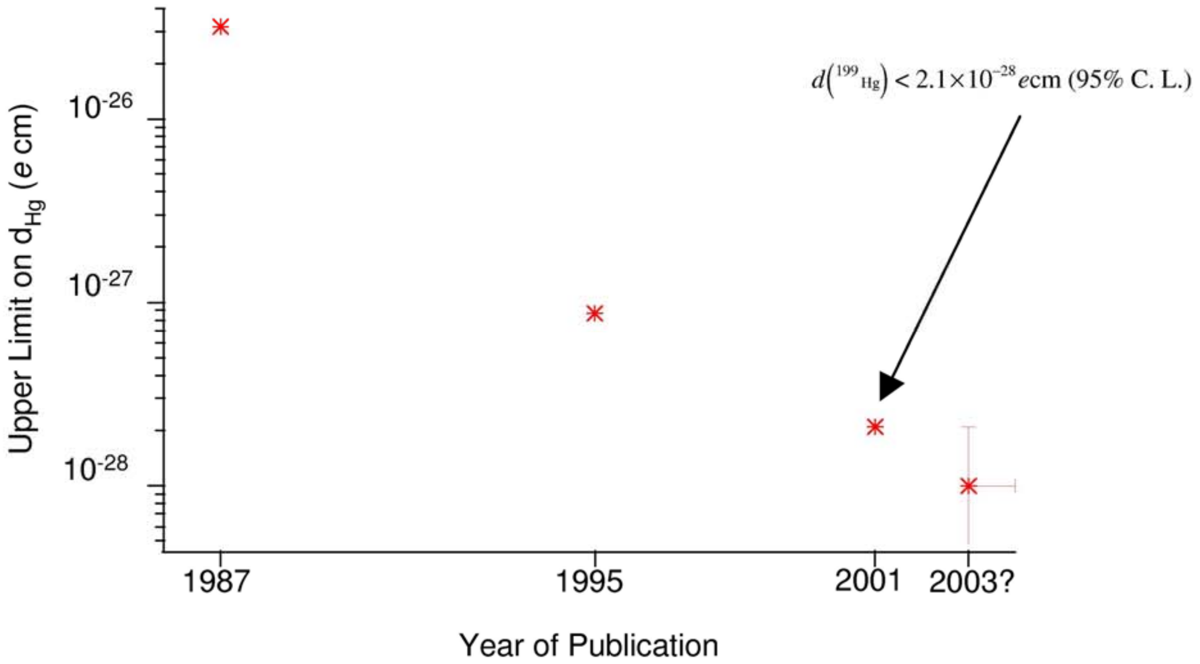
Current Atomic EDM Limits

- **Paramagnetic Atoms, ^{205}Tl: electron**
  $|d_e| < 1.6\times10^{-27}$ e·cm (90%CL)
  PRL 88, 071805 (2002)

- **Diamagnetic Atoms, ^{199}Hg Nucleus:**
  $|d(^{199}Hg)| < 2.1\times10^{-28}$ e·cm (95%CL)
  PRL 86, 2505 (2001)

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

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}

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

Future Prospects on electron EDM:

- Electron: YbF Ultra-cold molecules. Goal ~1000, B.E. Sauer *et al.*

- Electron: PbO^*, goal ~1000, D. DeMille *et al.*

Prospects of neutron EDM:

- UCN at PSI: Ramsey's method of separated oscillatory fields. First goal 1×10^{-27} e·cm, begin data taking ~2008.

- UCN at ILL (Sussex, RAL,…): Ramsey's method of separated oscillatory fields. Goal 2×10^{-28} e·cm/year, begin data taking 2009.

- 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.

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

Hadronic EDMs

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

Order of magnitude estimation of the neutron EDM:

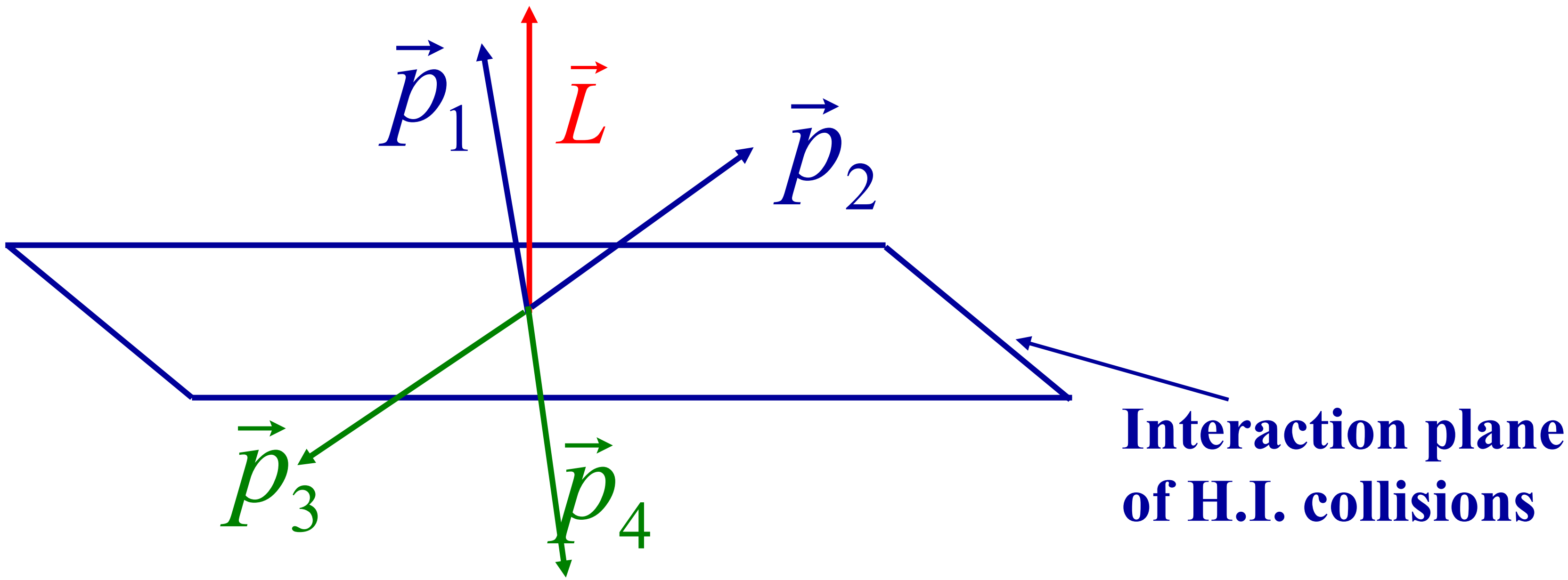
$$d_n\left(\bar{\theta}\right) \sim \bar{\theta}\,\frac{e}{m_n}\frac{m_*}{m_n} \sim \bar{\theta}\cdot\left(6\times10^{-17}\right)\mathrm{e}\cdot\mathrm{cm}, \quad m_* = \frac{m_u m_d}{m_u + m_d}$$

M. Pospelov,
A. Ritz, Ann. Phys.
318 (2005) 119.

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

Why so small? Axions? CAST, ADMX,…

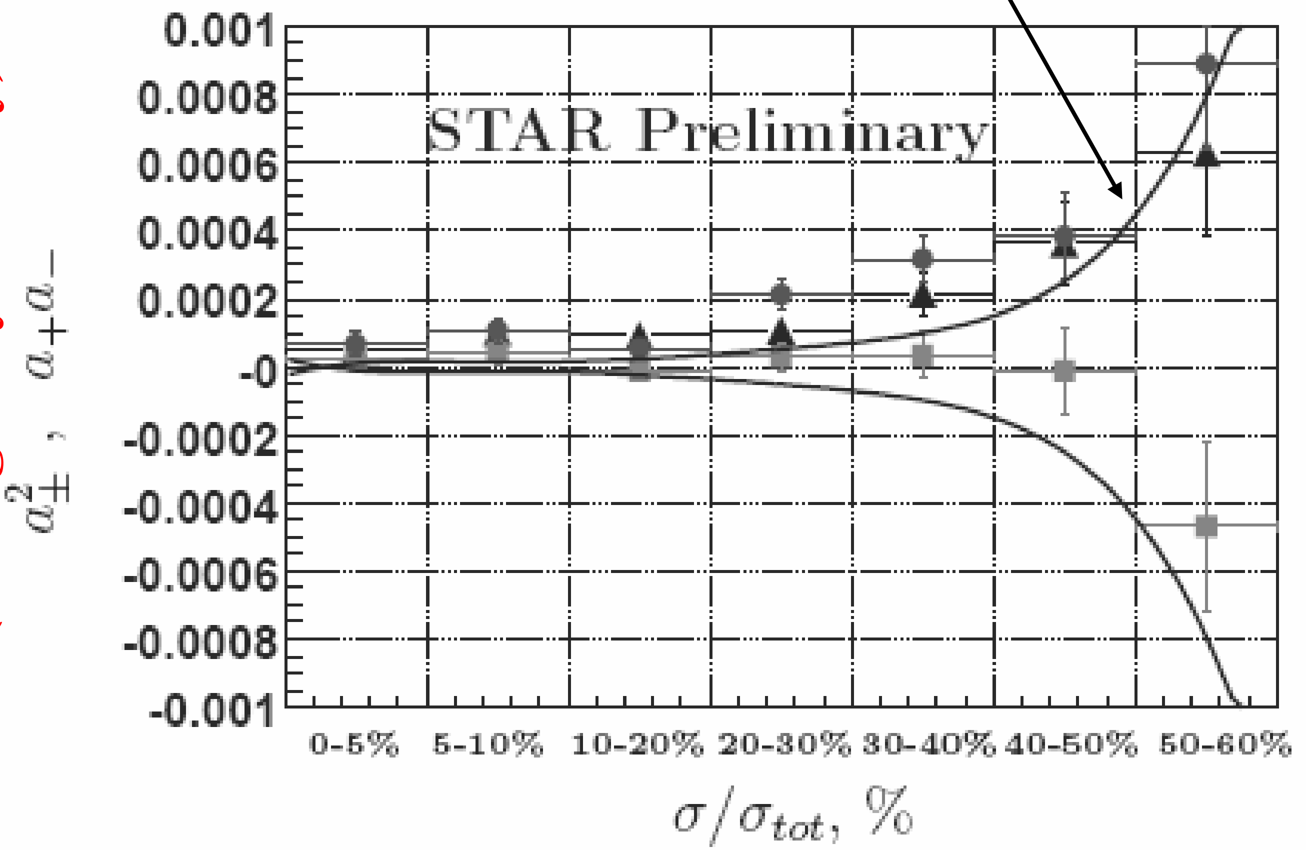
…In the vicinity of the deconfinement phase transition θ_{QCD} might not be small: P & T-violating bubbles are possible at H.I. collisions. **D. Kharzeev, R. Pisarski, M. Tytgat, PRL81, (1998) 512;**
D. K., R. P., PRD 61 (2000) 111901;
D. K., hep-ph/0406125.



Where p_1 and p_2 are the momenta of the positive pions and p_3 and p_4 those of the negative pions.

prediction

(Charge Asymmetry)



(Centrality of Collisions)

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

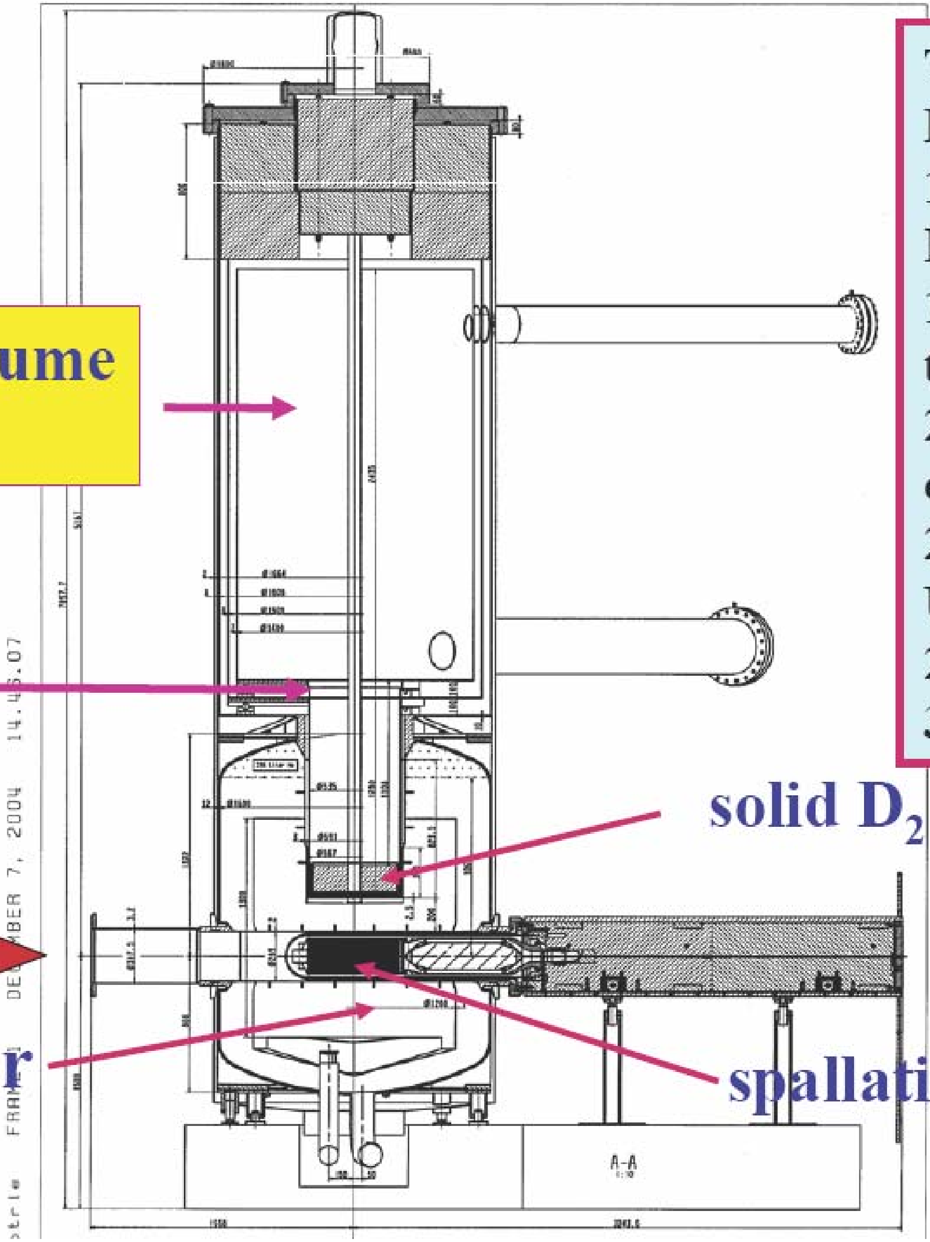
Comments

- If it survives the systematics checks it will be a phenomenal discovery
- The bubbles can evaporate by emitting axions…!

UCN tank system (5 m high)

PAUL SCHERRER INSTITUT PSI

Ultra Cold Neutron Source

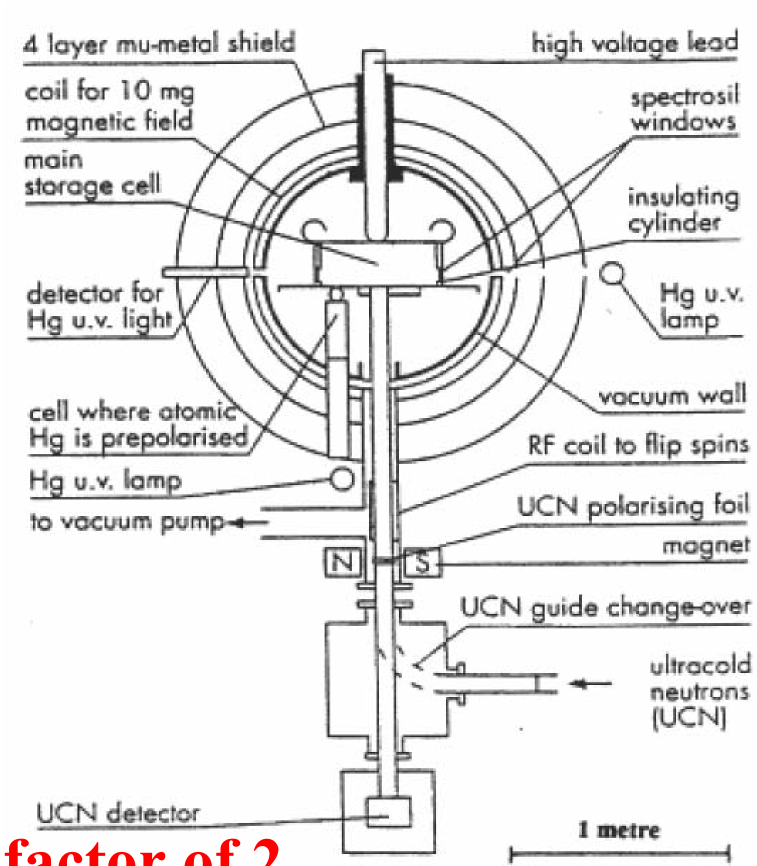


$T_p = 600MeV$
$I_p = 2mA$
10n/p
Per pulse:
$10^{17}p \rightarrow 10^{18}n$
thermal flux:
$2 \cdot 10^{14}\ s^{-1}\ cm^{-2}$
cold flux:
$2 \cdot 10^{13}\ s^{-1}\ cm^{-2}$
UCN:
$2 \cdot 10^{5}\ s^{-1}\ cm^{-3}$
$3 \cdot 10^{3}\ cm^{-3}$ stored

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

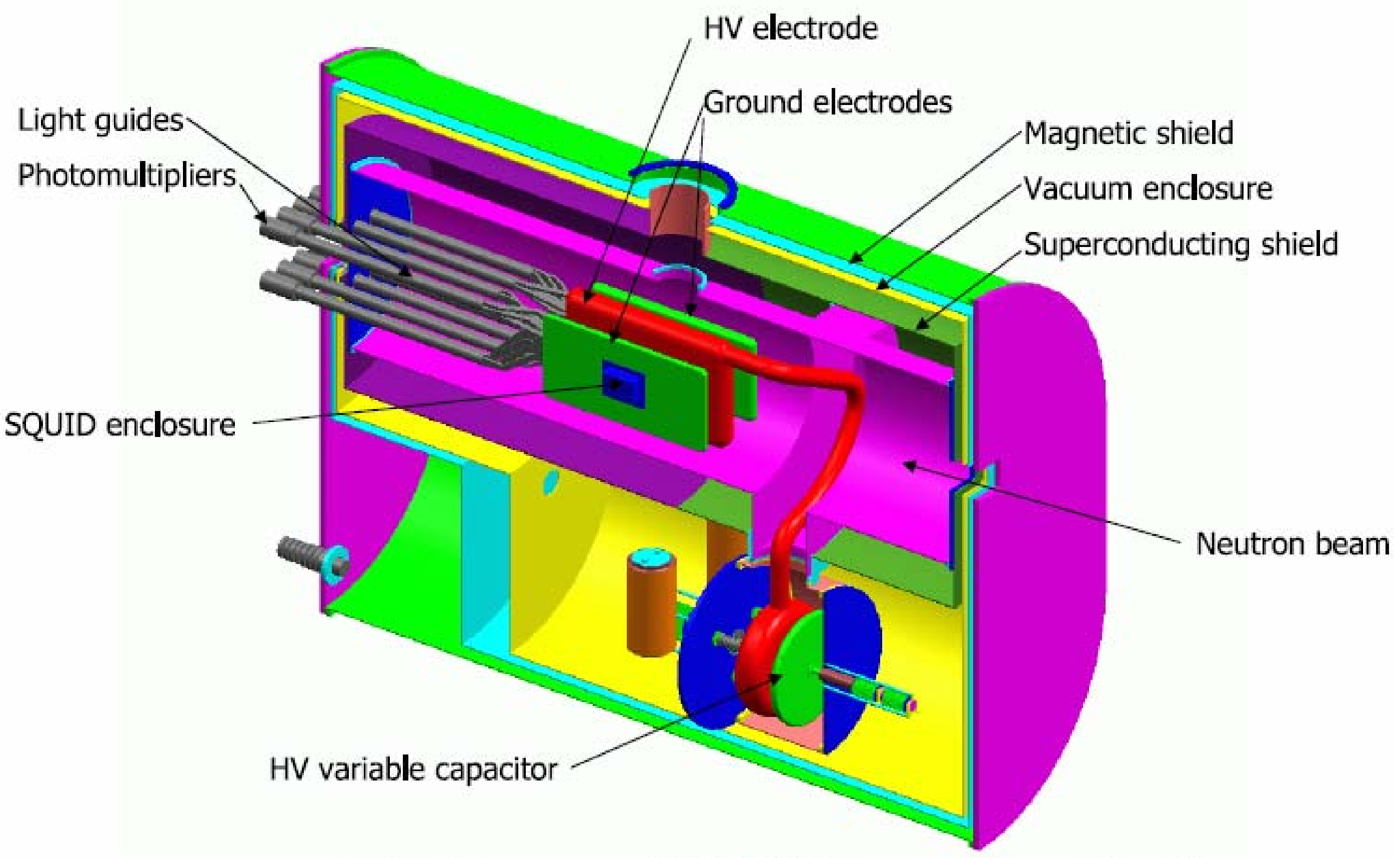


They are expecting to announce a factor of 2 improvement in the neutron EDM limit, shortly

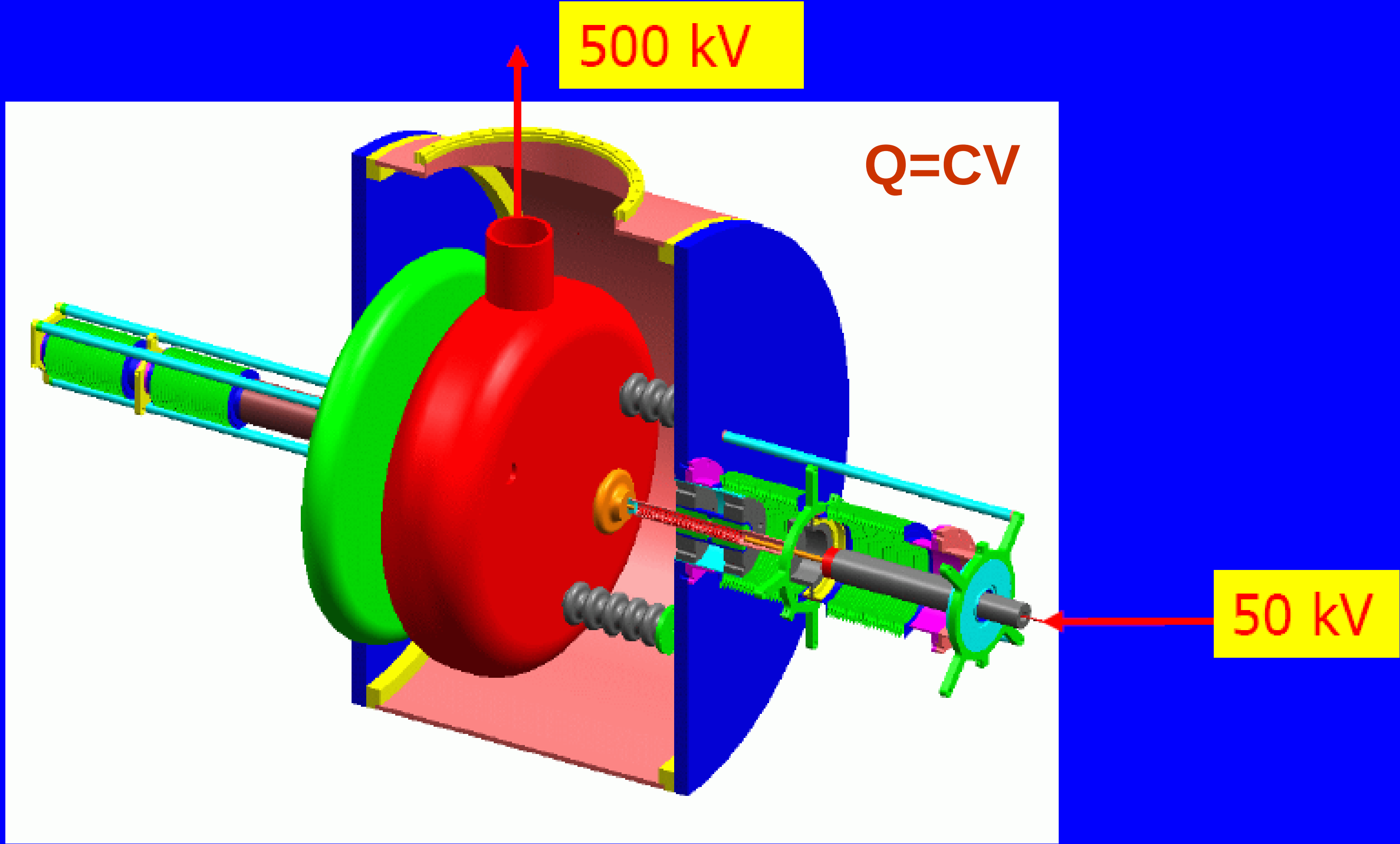
$$\frac{d\vec{s}}{dt} = \vec{\mu} \times \vec{B} + \vec{d} \times \vec{E}$$

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

Proposed Experimental Design

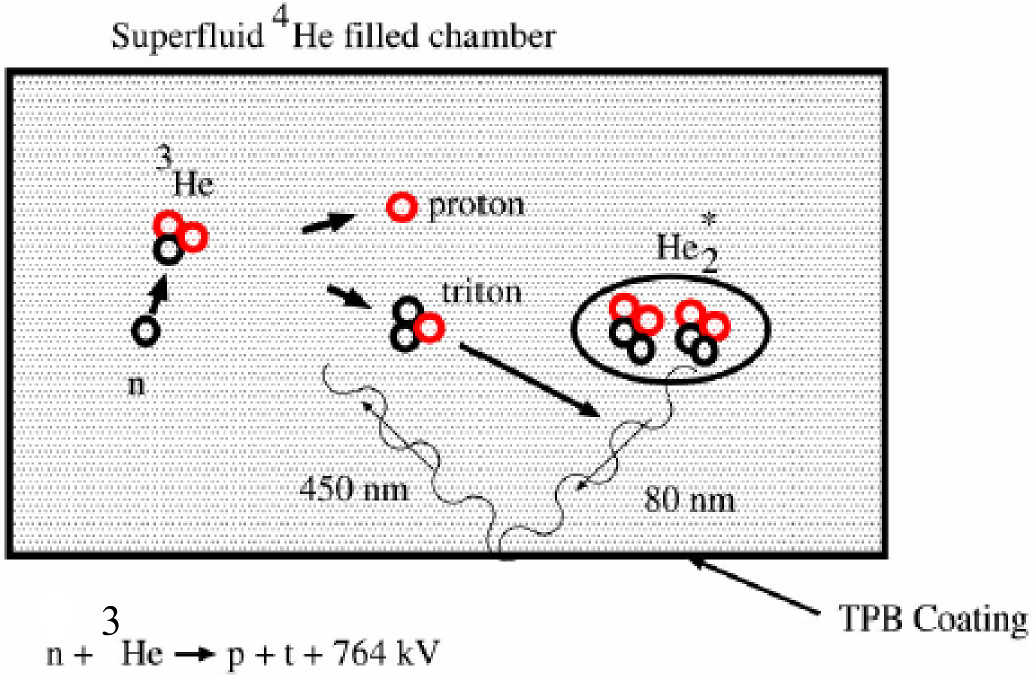


Concept for HV generator



Variable capacitor in LHe volume

SUPERFLUID HELIUM AS A DETECTOR



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 ~

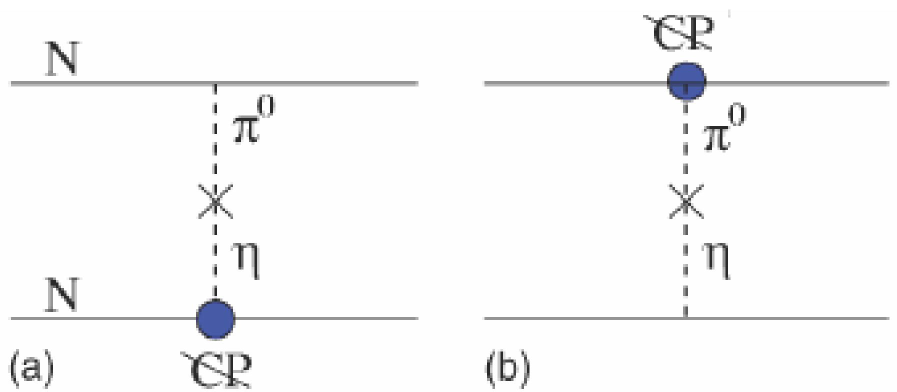
$$1 - \vec{p}_3 \bullet \vec{p}_n = 1 - p_3 p_n \cos[(\gamma_n - \gamma_3)B_0 + 2dE]t$$

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 θ_{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

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

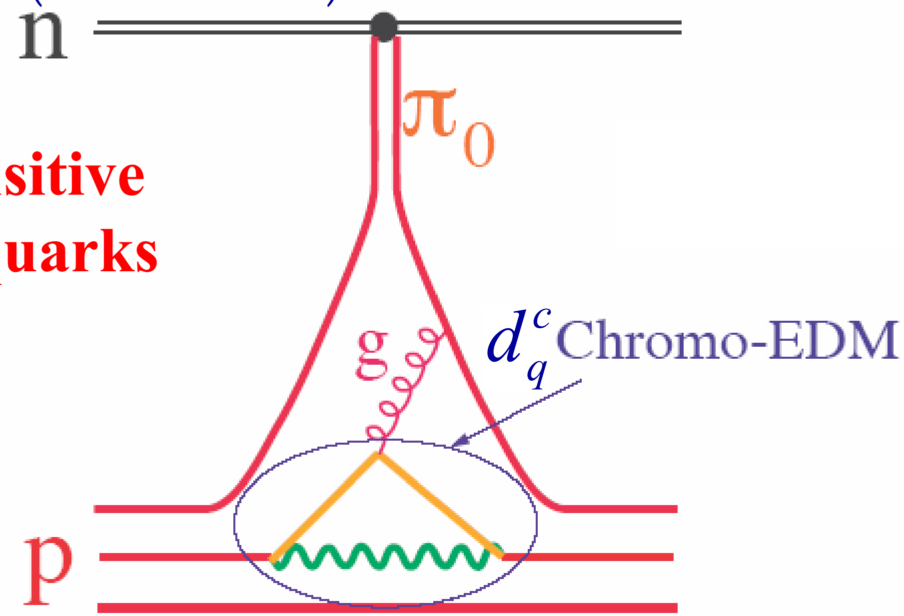
Quark EM and Color EDMs

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

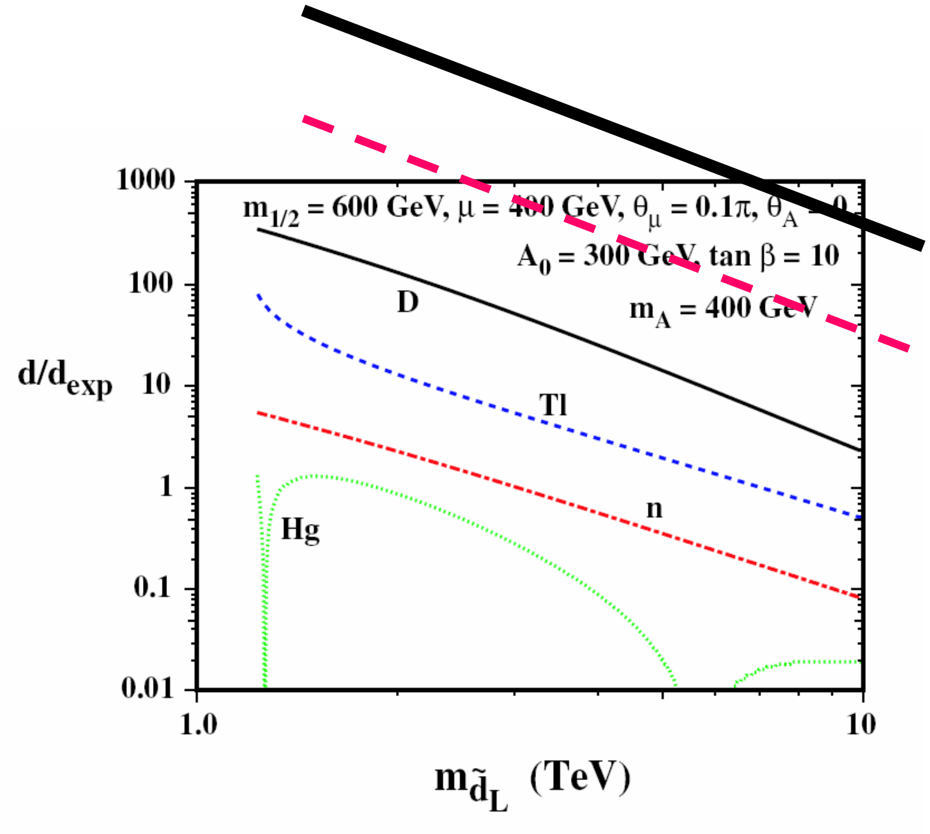
$$d_D\left(d_q, d_q^c\right) \approx 0.5\left(d_u + d_d\right) - 5.6e\left(d_u^c - d_d^c\right) - 0.2e\left(d_u^c + d_d^c\right)$$

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

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·cm

n EDM at $\sim 10^{-28}$ e·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)

Sensitivity to *right-handed* ν_τ mass

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Physics Letters B 604 (2004) 216–224

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

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

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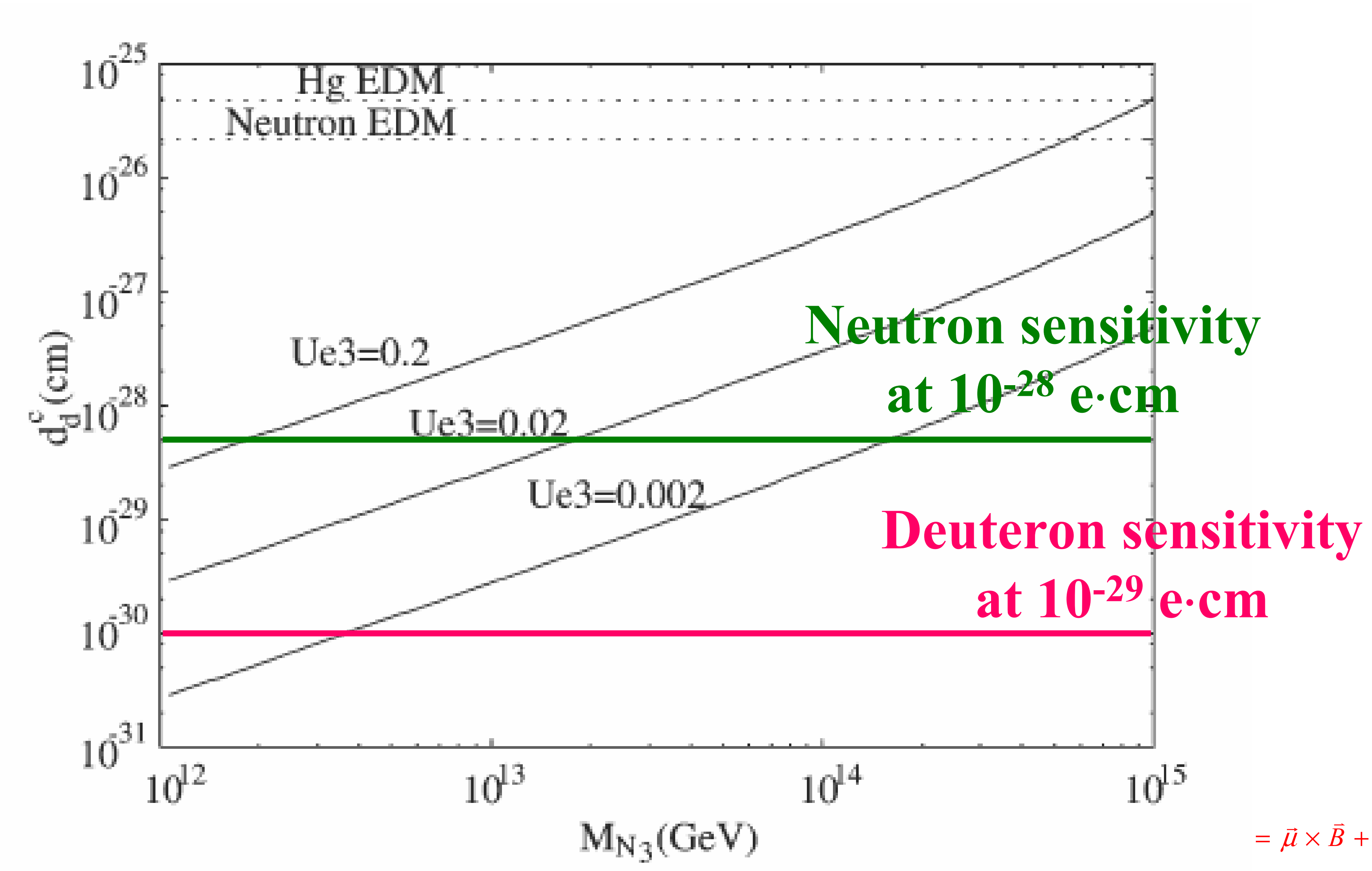
"… The supersymmetric grand unified models (SUSY GUTs) are ones of the well-motivated models after discovery of the gauge coupling unification at the LEP experiment. Non-vanishing light neutrino masses shown in the neutrino oscillation experiments might also suggest existence of the SUSY GUTs since the 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}



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

Deuteron vs. neutron sensitivity …it depends on the source

Color EDM: $d_D\left(d_q^c\right) \approx 10 \times d_n\left(d_q^c\right)$

$\bar{\theta}_{QCD}$: $d_D\left(\bar{\theta}\right) \approx \frac{1}{3} \times d_n\left(\bar{\theta}\right)$

Experimental Principle of EDM

- Polarize (e.g. deuteron polarized source, ~100%)
- Interact in an E-field
- Analyze as a function of time (e.g. deuteron polarimeter, analyzing power up to 100%)

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

Experimental Methods of Storage Ring Electric Dipole Moments

- Parasitic to g-2
- Frozen spin
- Resonance

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

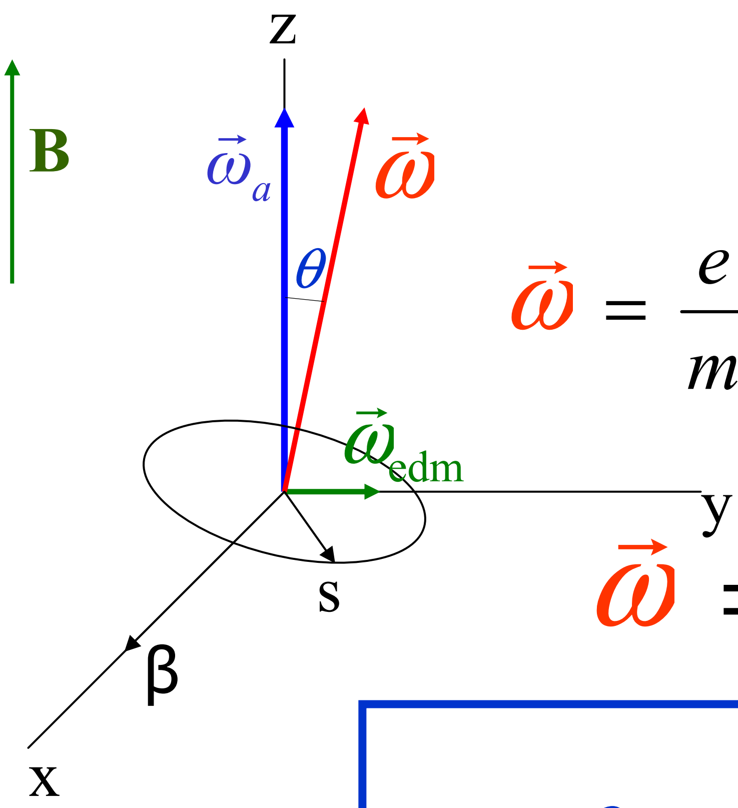
Electric Dipole Moments in Storage Rings

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

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



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

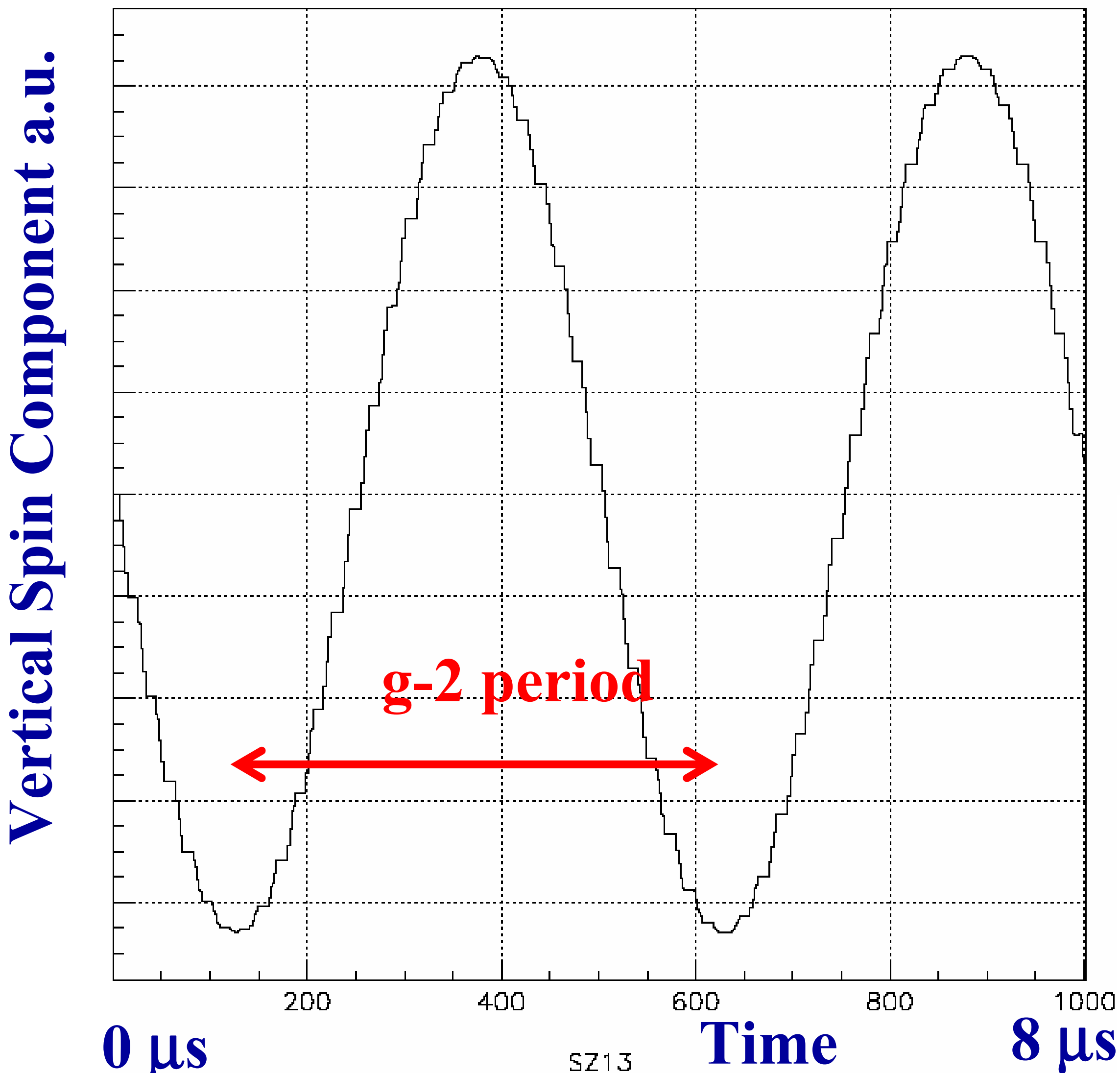
$$\vec{\omega} = \vec{\omega}_a + \vec{\omega}_{edm}$$

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

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

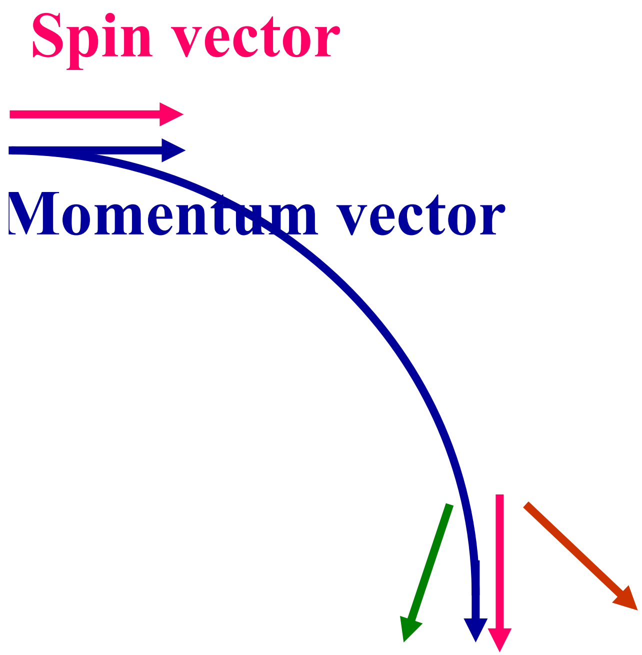
$$\frac{d\vec{s}}{dt} = \vec{\mu} \times \vec{B} + \vec{d} \times \vec{E}$$

The Vertical Spin Component Oscillates due to EDM



$\vec{E}$

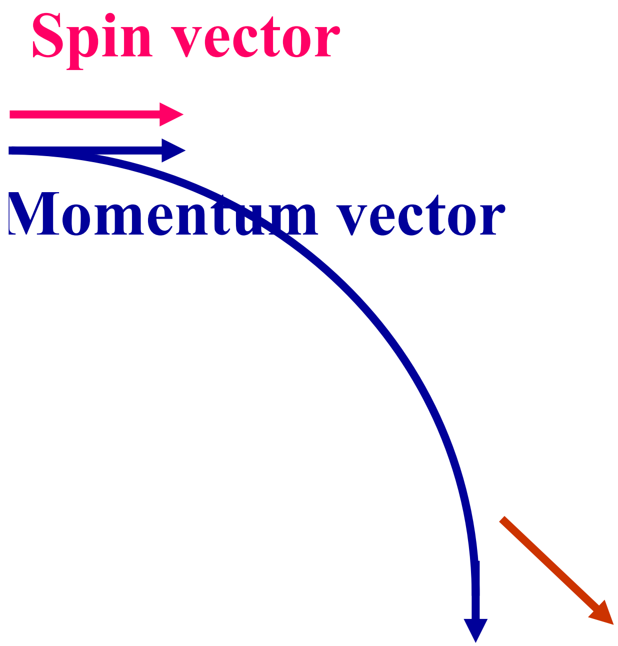
Effect of Radial Electric Field



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

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

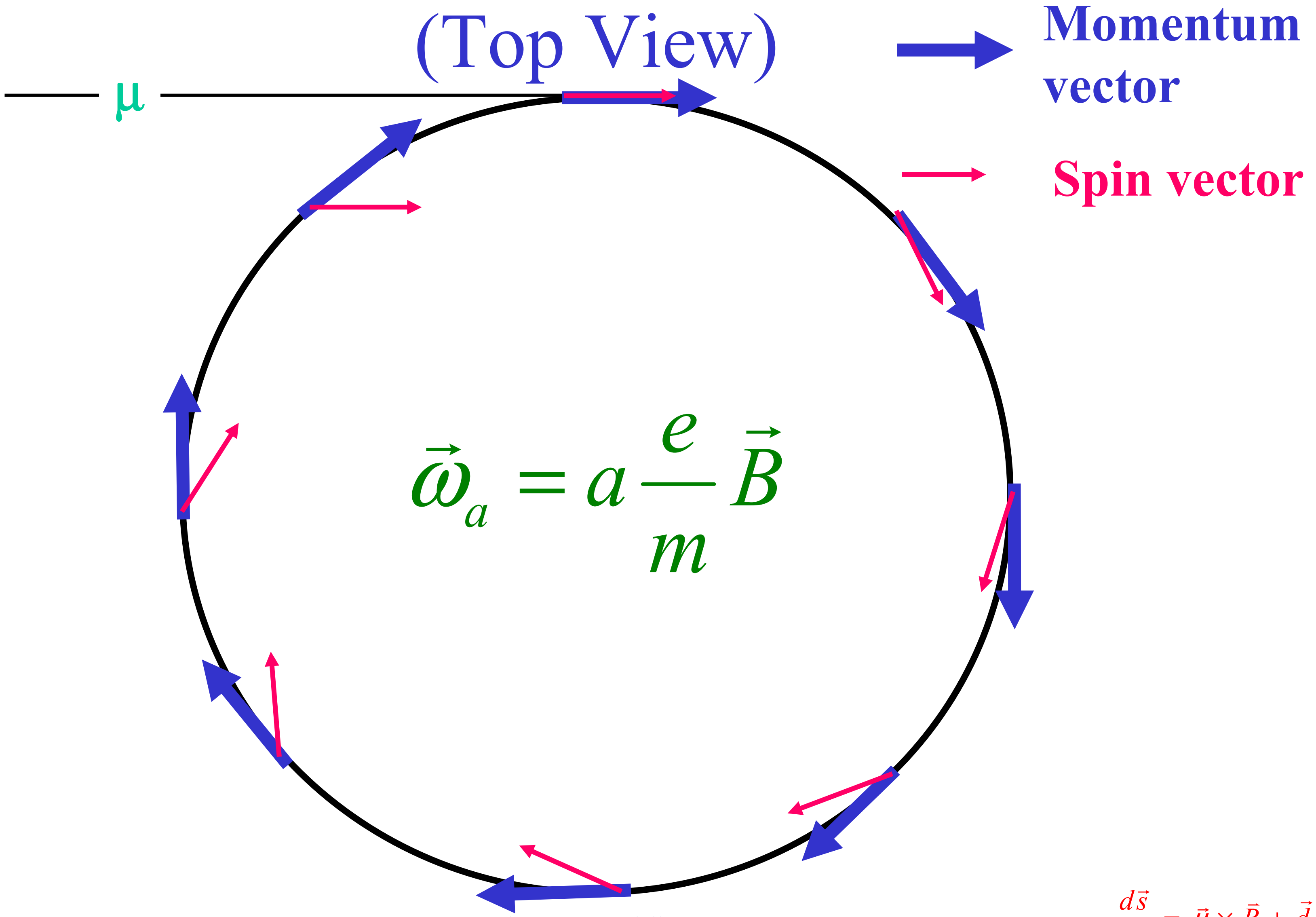
Use a Radial Electric Field and a



- Low energy particle

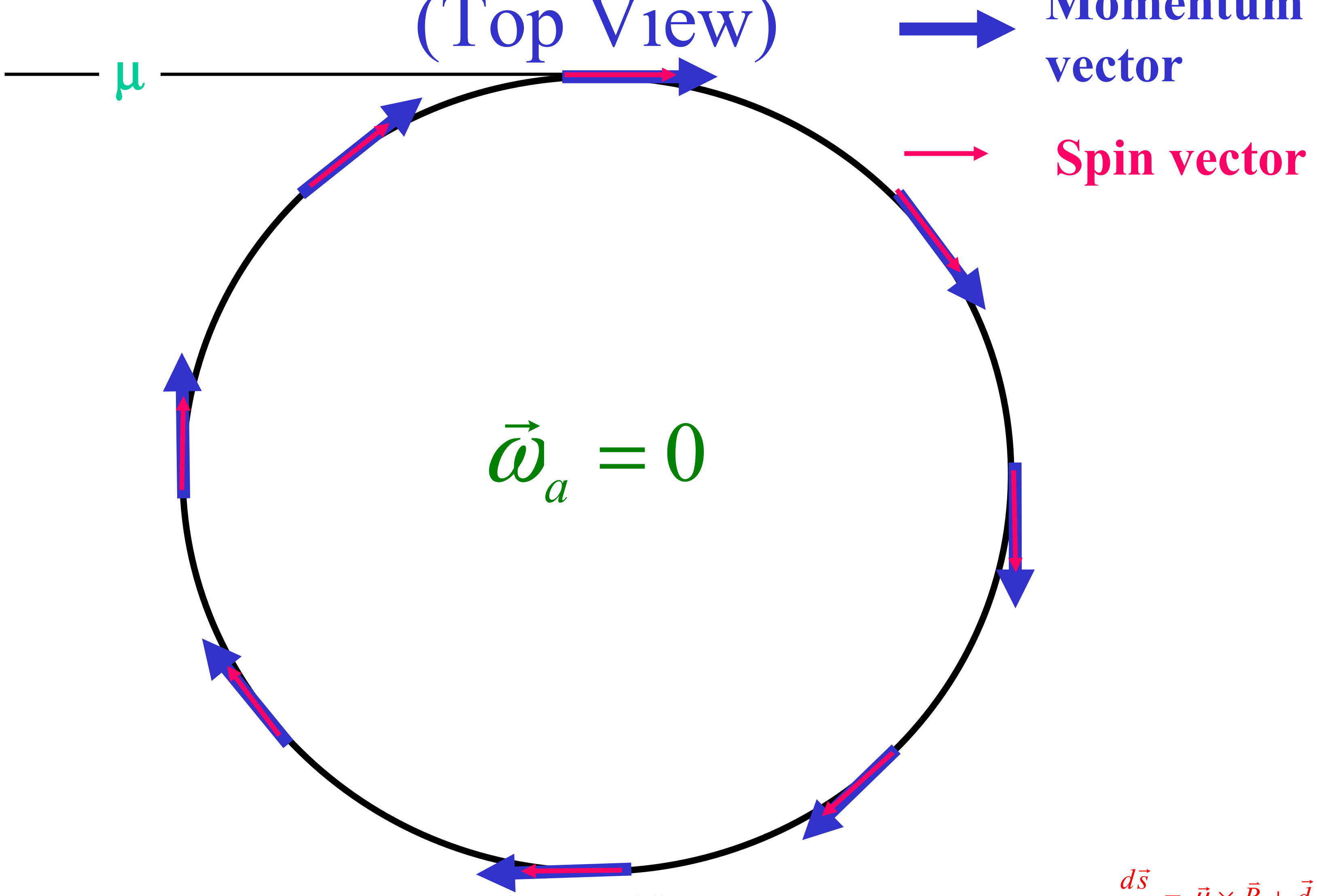
$$\frac{d\vec{s}}{dt} = \vec{\mu} \times \vec{B} + \vec{d} \times \vec{E}$$

Spin Precession in g-2 Ring (Top View)



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

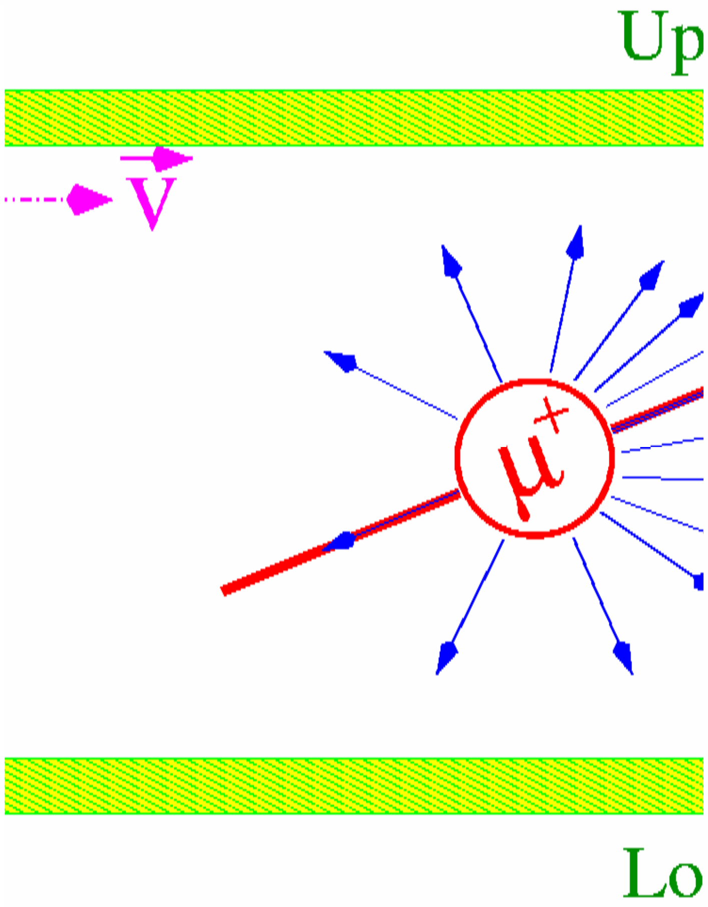
Spin Precession in EDM Ring (Top View)



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

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

Side view



R=(U-D)/(U+D)

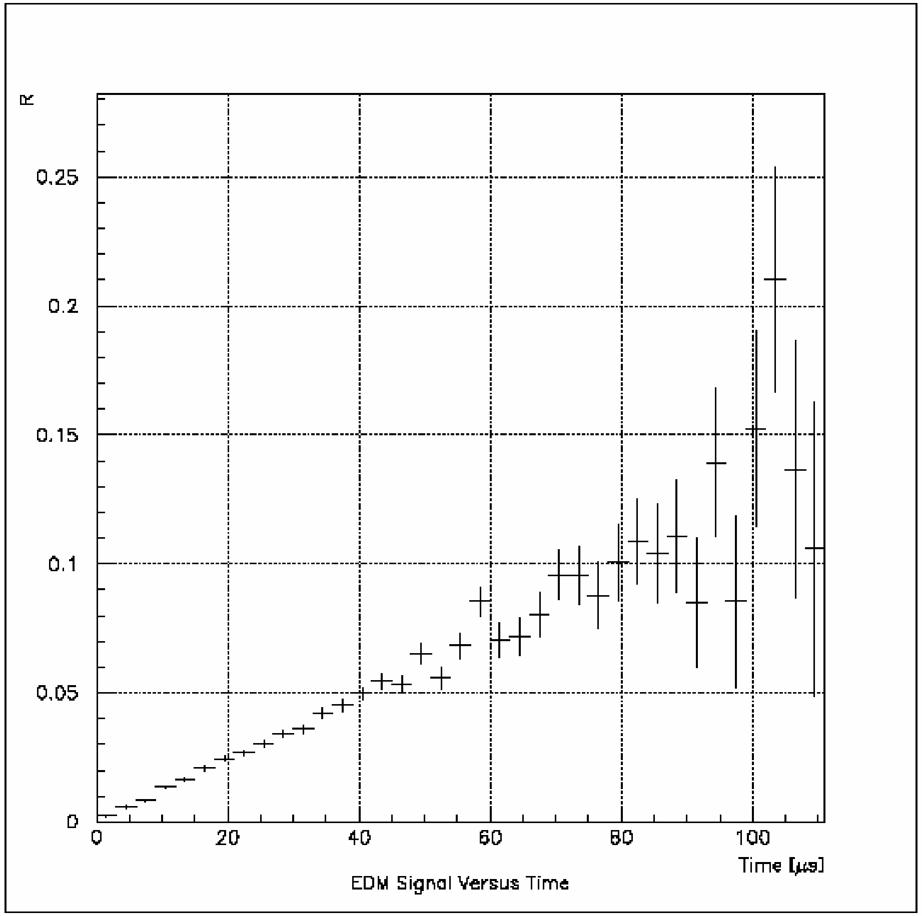


Figure 3: MC simulation of the muon EDM signal, $R = \frac{N_{up} - N_{down}}{N_{up} + N_{down}}$, versus time.

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

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 · 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

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BINP, Novosibirsk

Y. Orlov, **Cornell University**

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

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University of Illinois

E. Stephenson, **Indiana University**

M. Auzinsh, **University of Latvia**

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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**

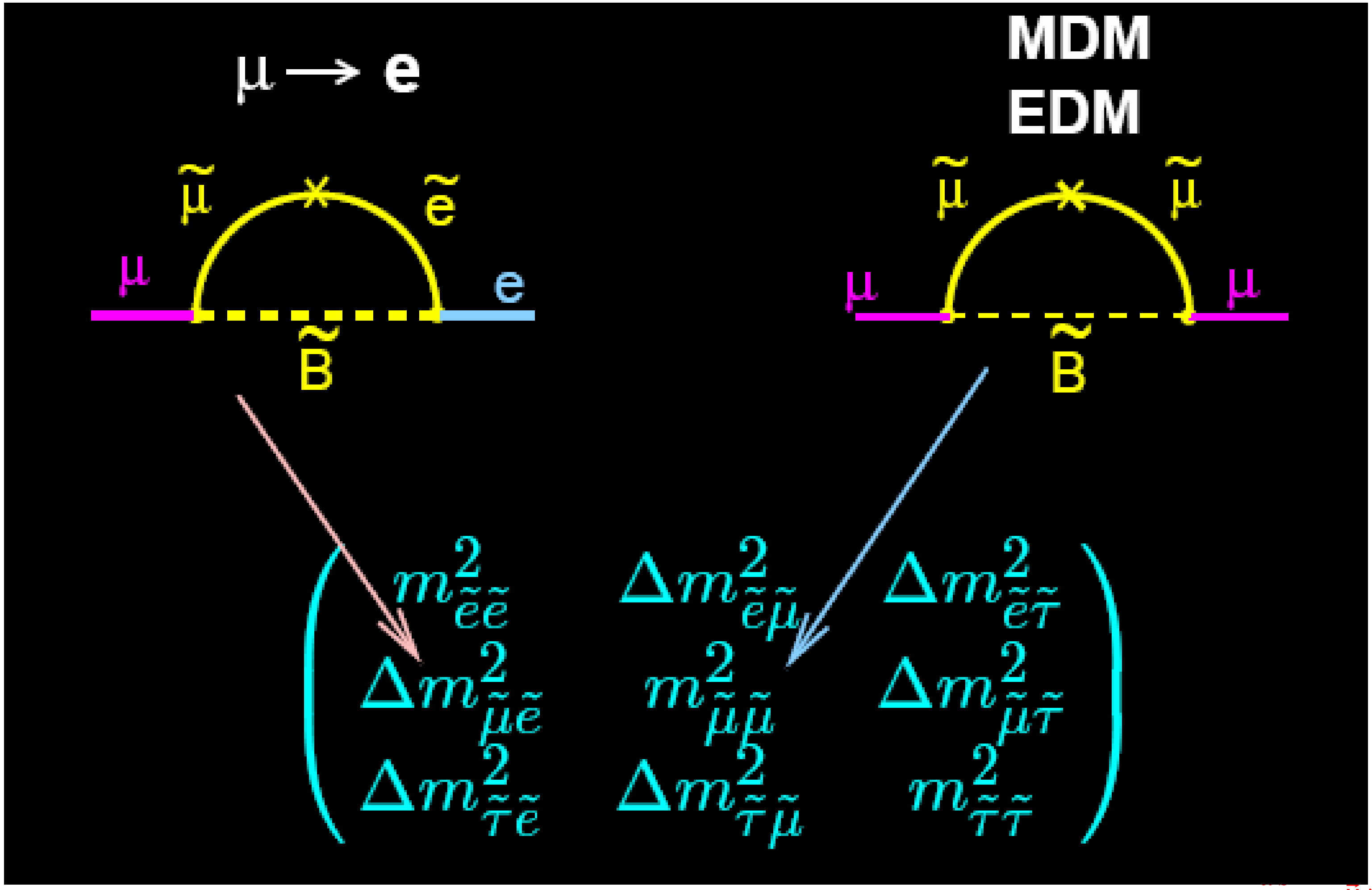
† Spokesperson

Resident Spokesperson

January 9, 2003

$\vec{E}$

SUSY: EDM, MDM and Transition Moments are in Same Matrix



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

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

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

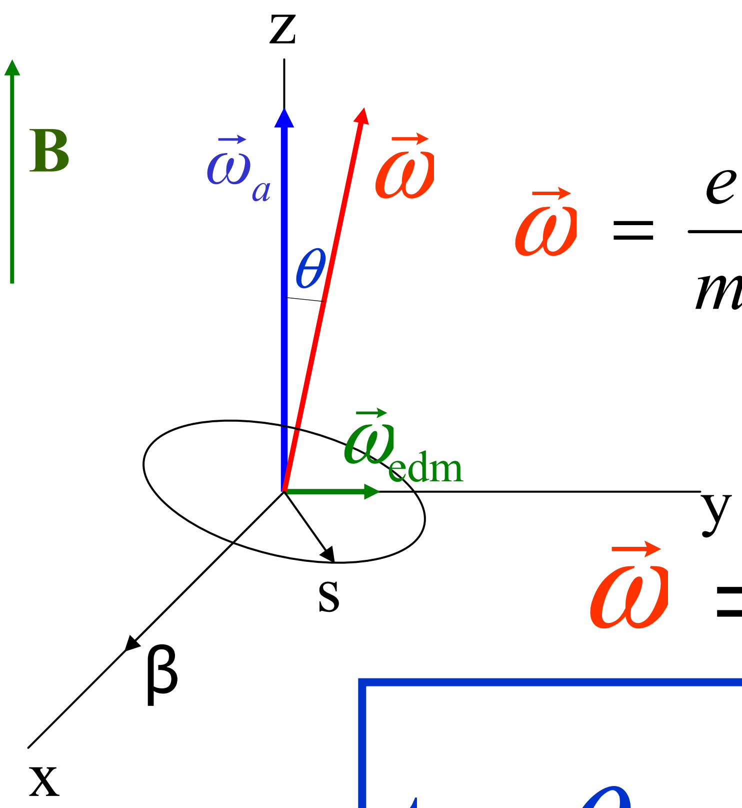
$$d_\mu = \Im D,$$

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

Probe this phase to 1%

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

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



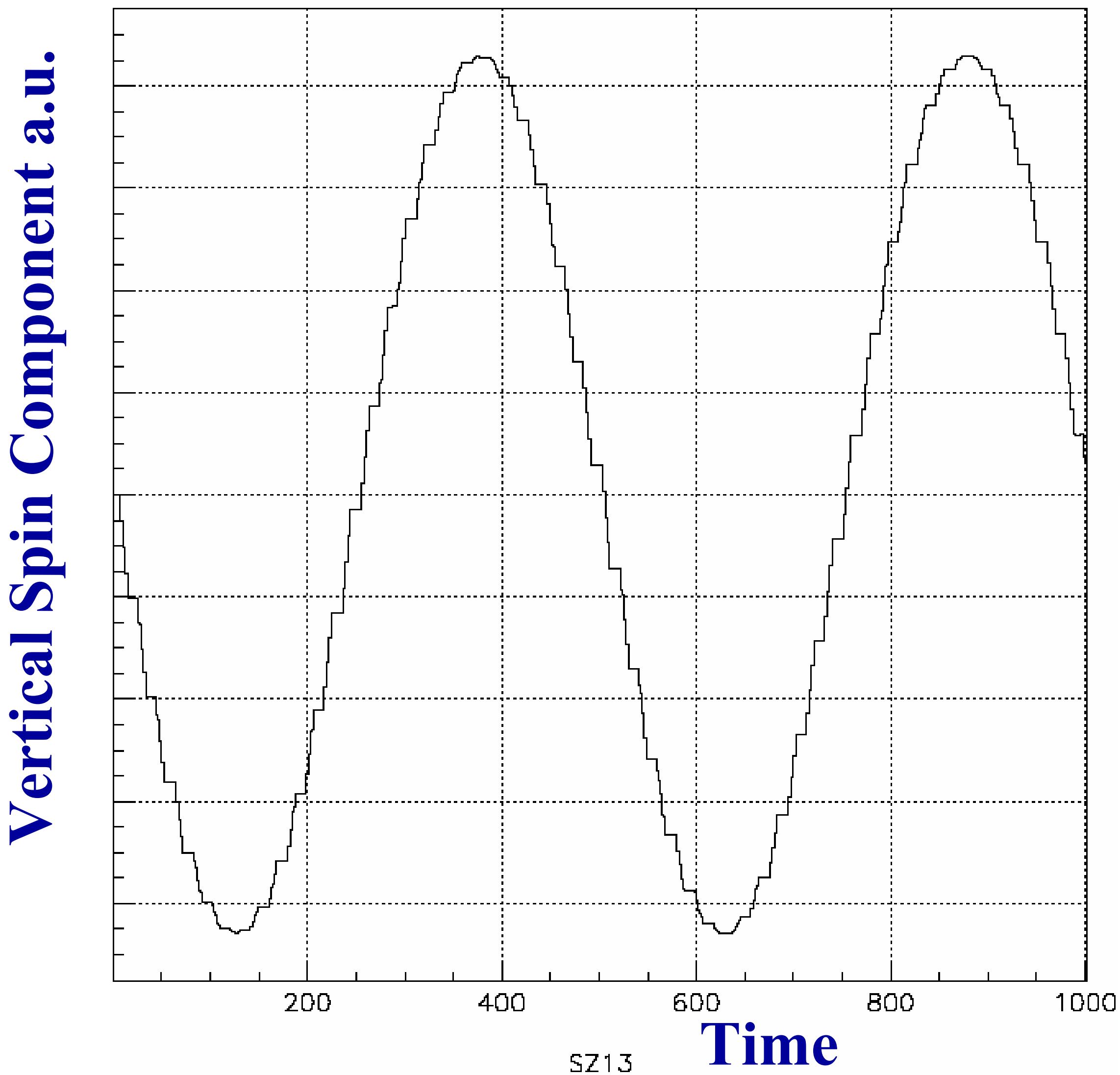
$$\vec{\omega} = \frac{e}{m}\left\{a\vec{B} + \frac{\eta}{2c}\left(\vec{u}\times\vec{B}\right)\right\}$$

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

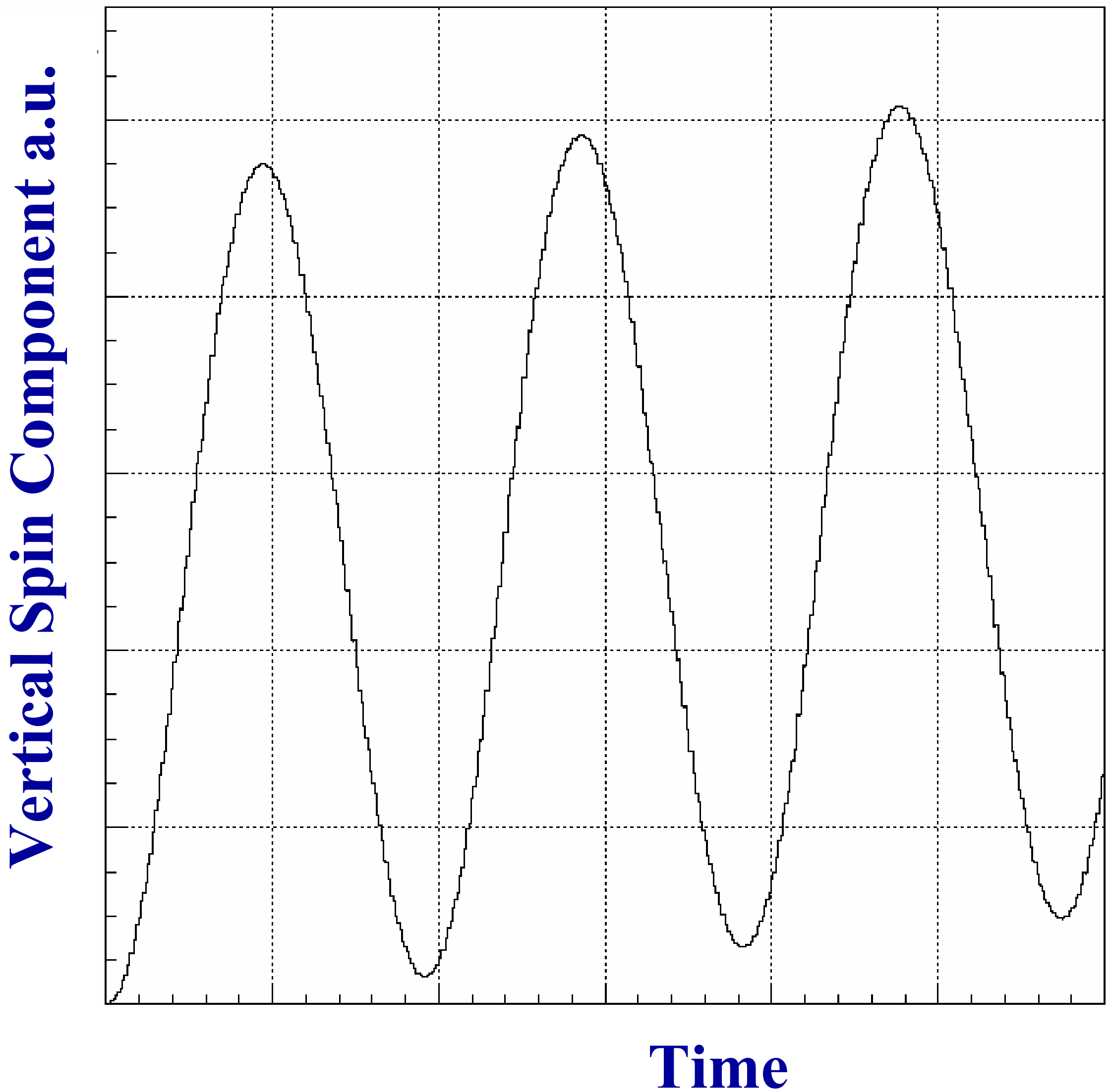
$$\tan\theta = \frac{\omega_{edm}}{\omega_a}$$

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

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

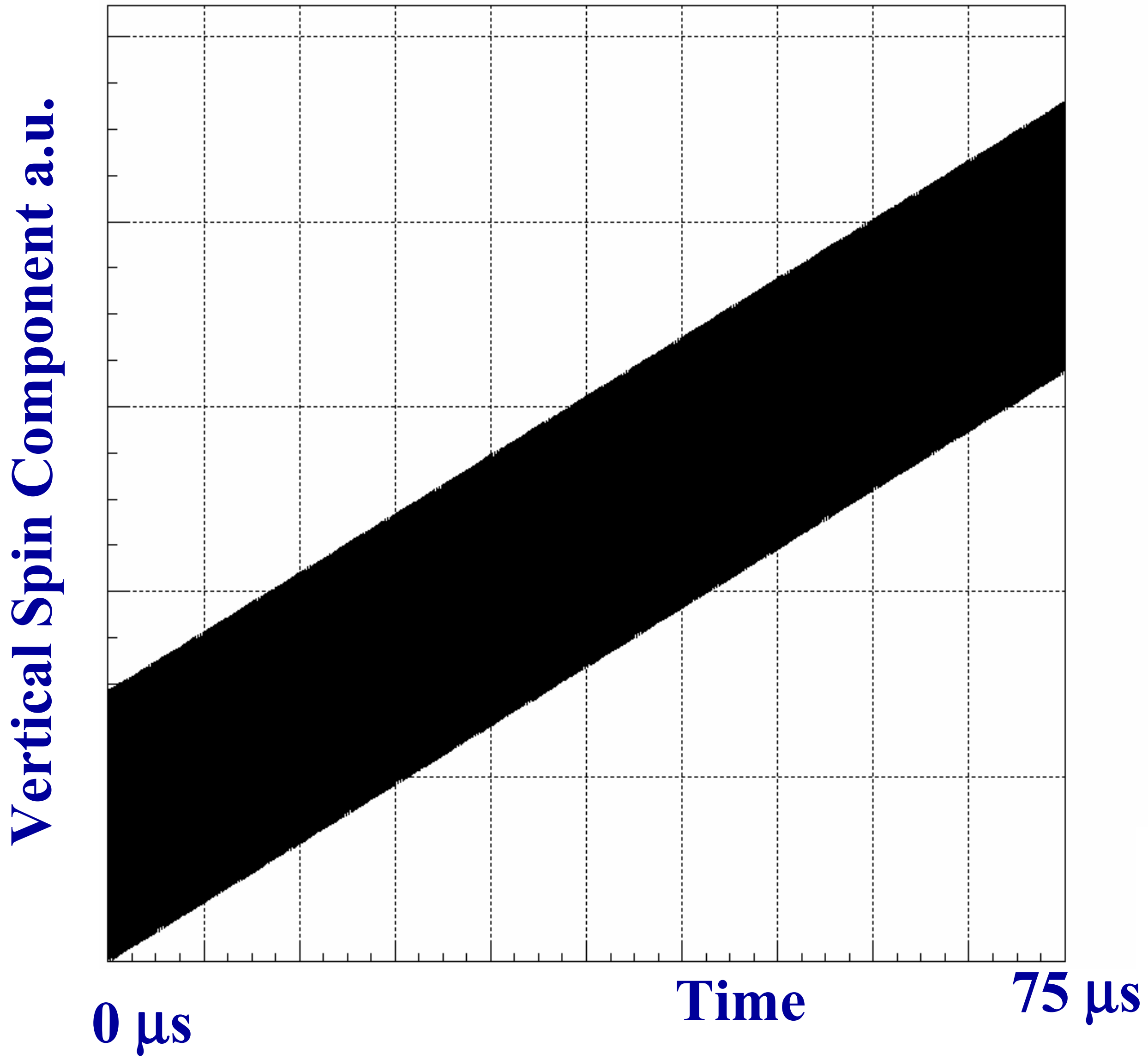


Vertical Spin Component with Velocity Modulation at ω_a



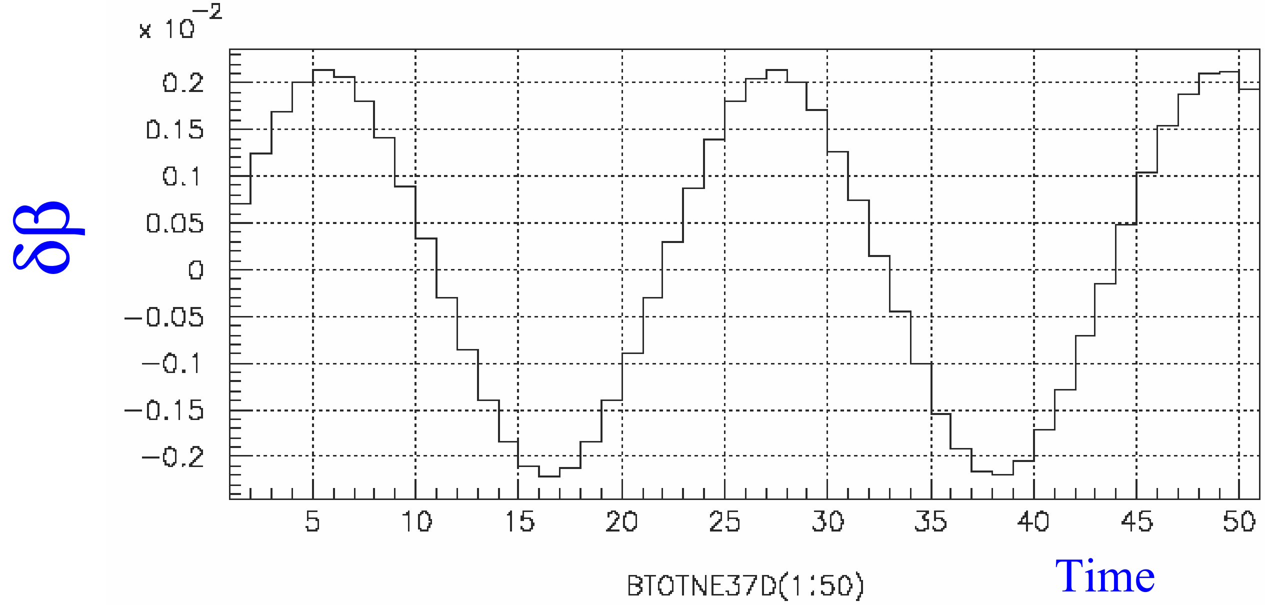
$\vec{E}$

Vertical Spin Component with Velocity Modulation (longer Time)



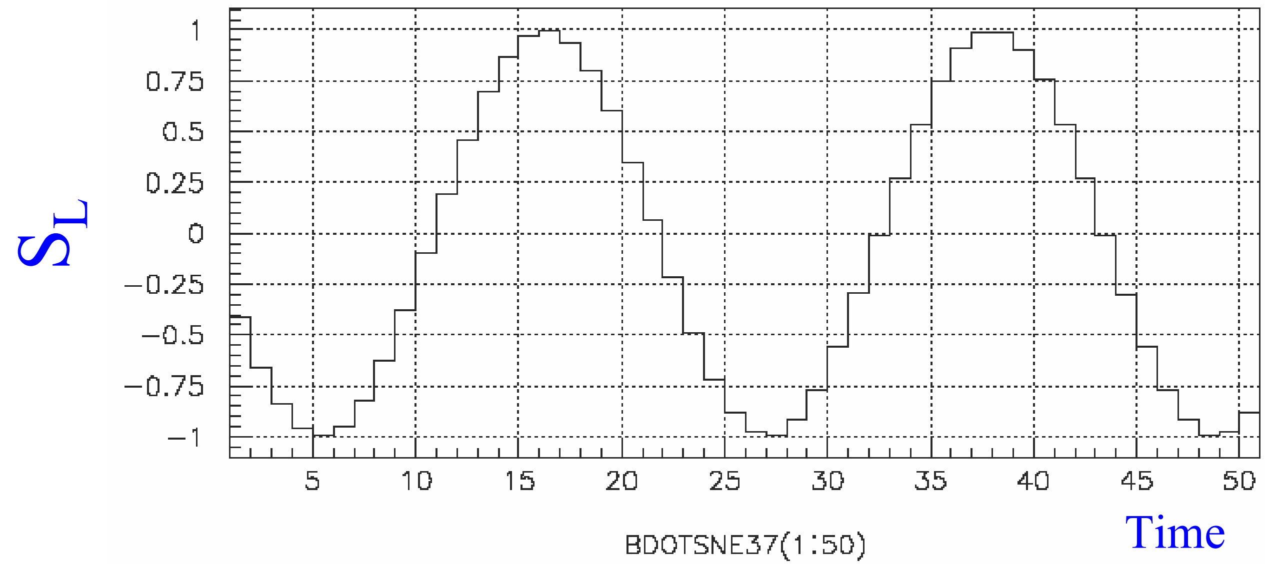
$+ \vec{d} \times \vec{E}$

Velocity (top) and g-2 oscillations



A new idea by Yuri Orlov!

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

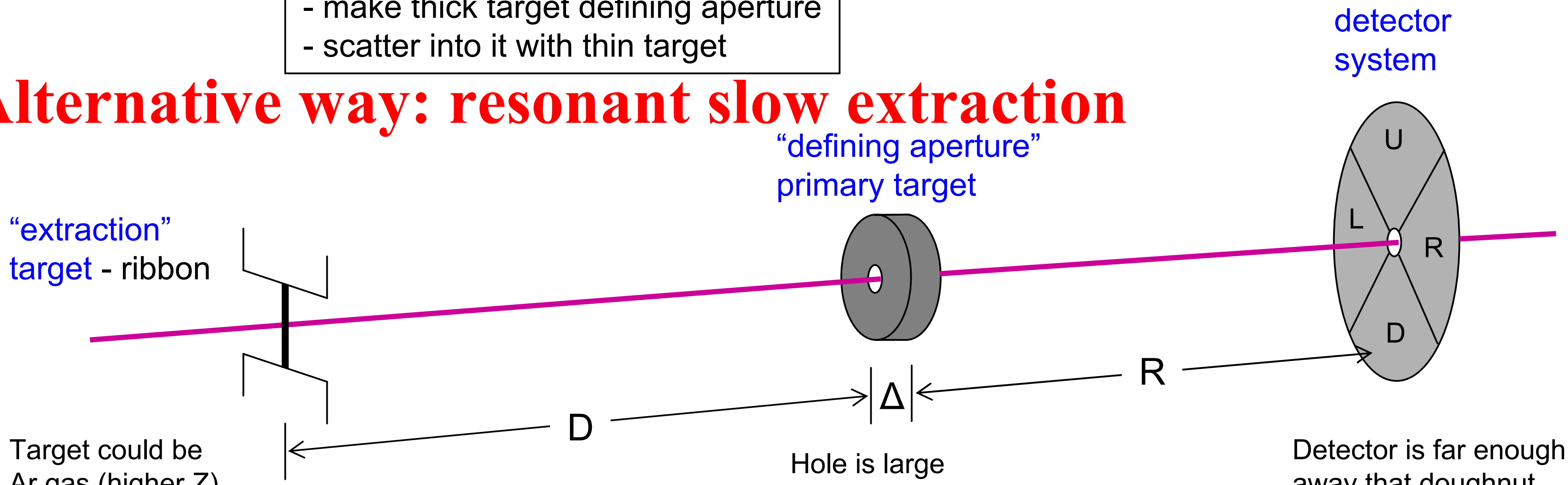
$$\frac{d\vec{s}}{dt} = \vec{\mu} \times \vec{B} + \vec{d} \times \vec{E}$$

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



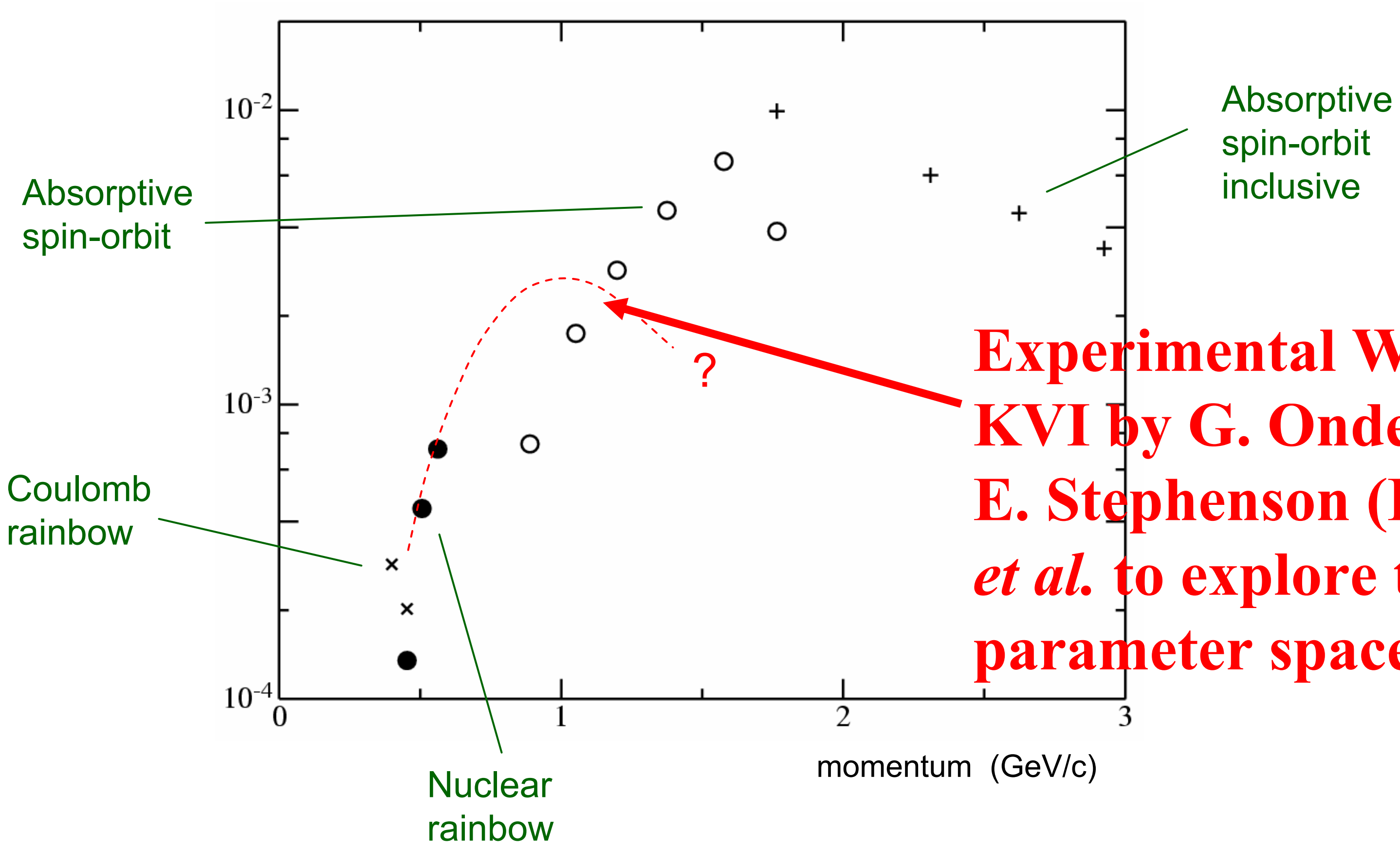
Target could be Ar gas (higher Z).

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: $\Delta < R$.

Figure of merit = effiency $\times \langle iT_{11} \rangle^2$



Experimental Work at KVI by G. Onderwater, E. Stephenson (IUCF), *et al.* to explore this parameter space.

Extrapolation of nuclear rainbow effect is not known.

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

Deuteron Coherence Time

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

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).

Deuteron Statistical Error:

$$\sigma_d \approx \frac{16\hbar}{\delta\beta_0 c \langle B \rangle AP\sqrt{N_c f \tau_p T_{Tot}}}$$

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

A : 0.6 **The left/right asymmetry observed by the polarimeter**

P : 0.95 **The beam polarization**

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

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

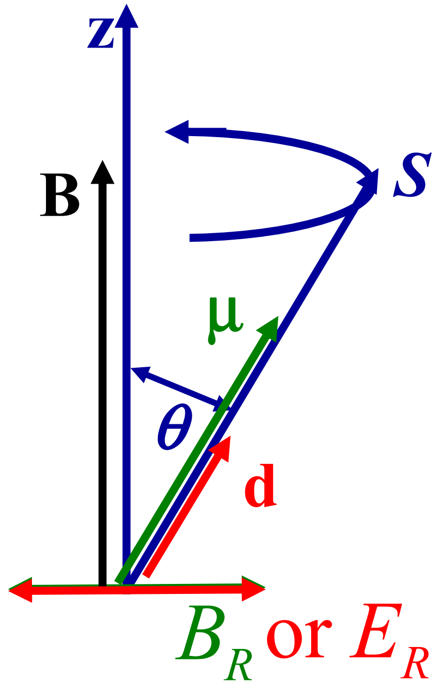
f : 0.05 **Useful event rate fraction**

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

$<B>$: 1T **The average magnetic field around the ring**

$$\sigma_d \approx 3\times10^{-29}\,\mathrm{e\cdot cm\,/\,year}$$

Resonance spin-flip



$$\cos\theta = \frac{s_z}{\sqrt{s(s+1)}}$$

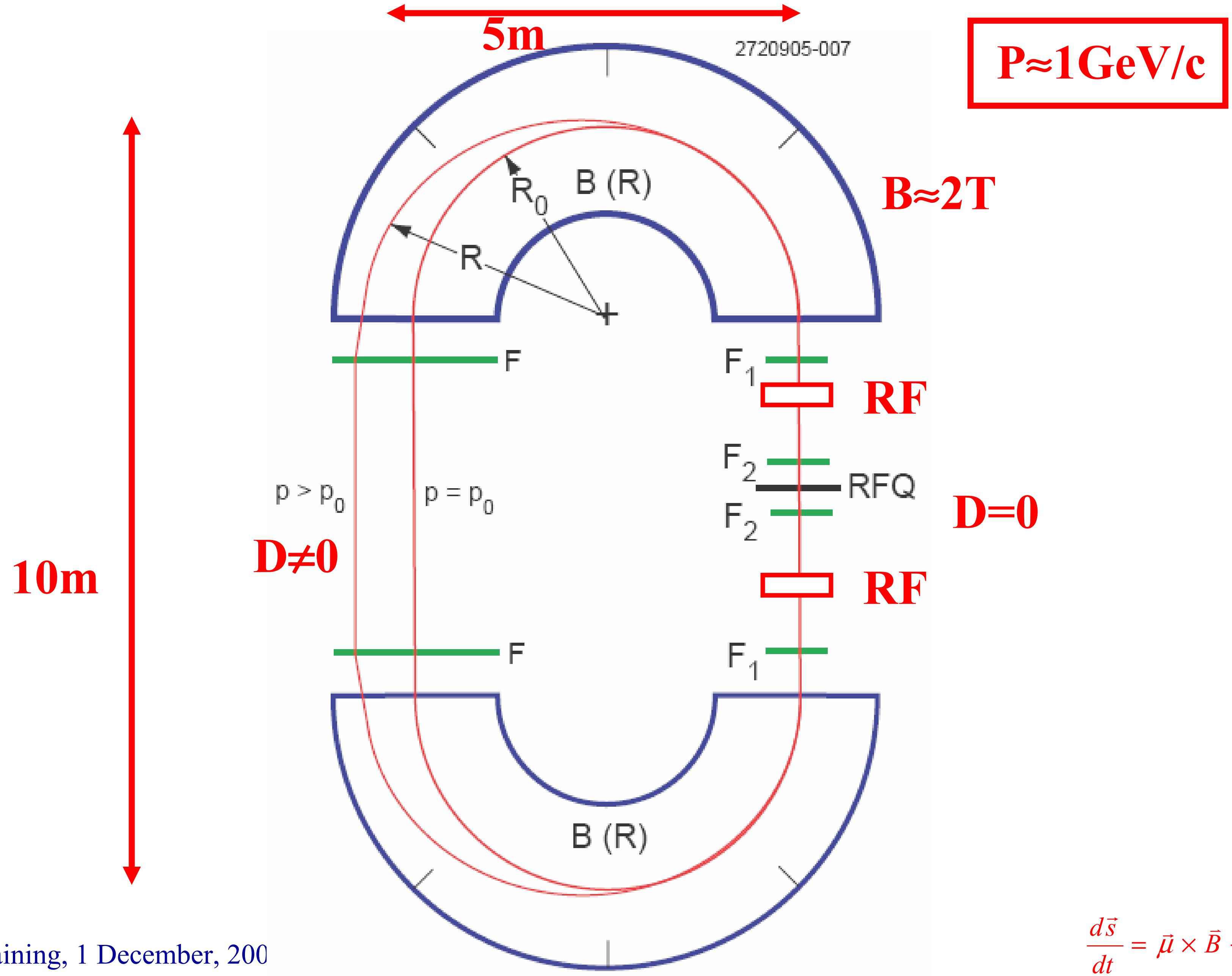
$$B_R = B_0 \sin(\omega_a t)$$

$$\vec{E}_R = \gamma(\vec{v}\times\vec{B}) = \gamma v B = \gamma B v_0 \sin(\omega_a t), \quad \omega_a = a\gamma\omega_c$$

- E_R works on the EDM (signal)
- B_R works on the magnetic moment (background)

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

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.

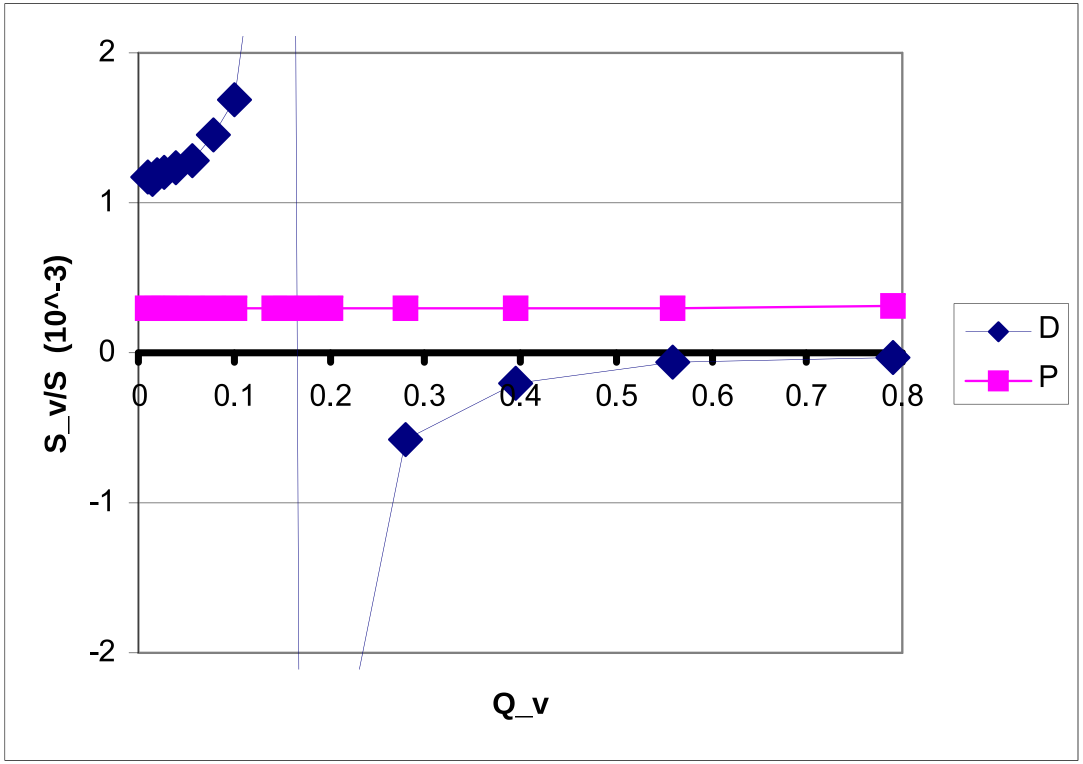
Examples: 1) Radial B-field or skew quadrupole where $D \neq 0$,
2) RF-cavity (vertical offset or misalignment), …

- 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!

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



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

Year	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

with the deuteron at 10^{-29}e·cm holding the best EDM sensitivity over *present* or *planned* experiments.

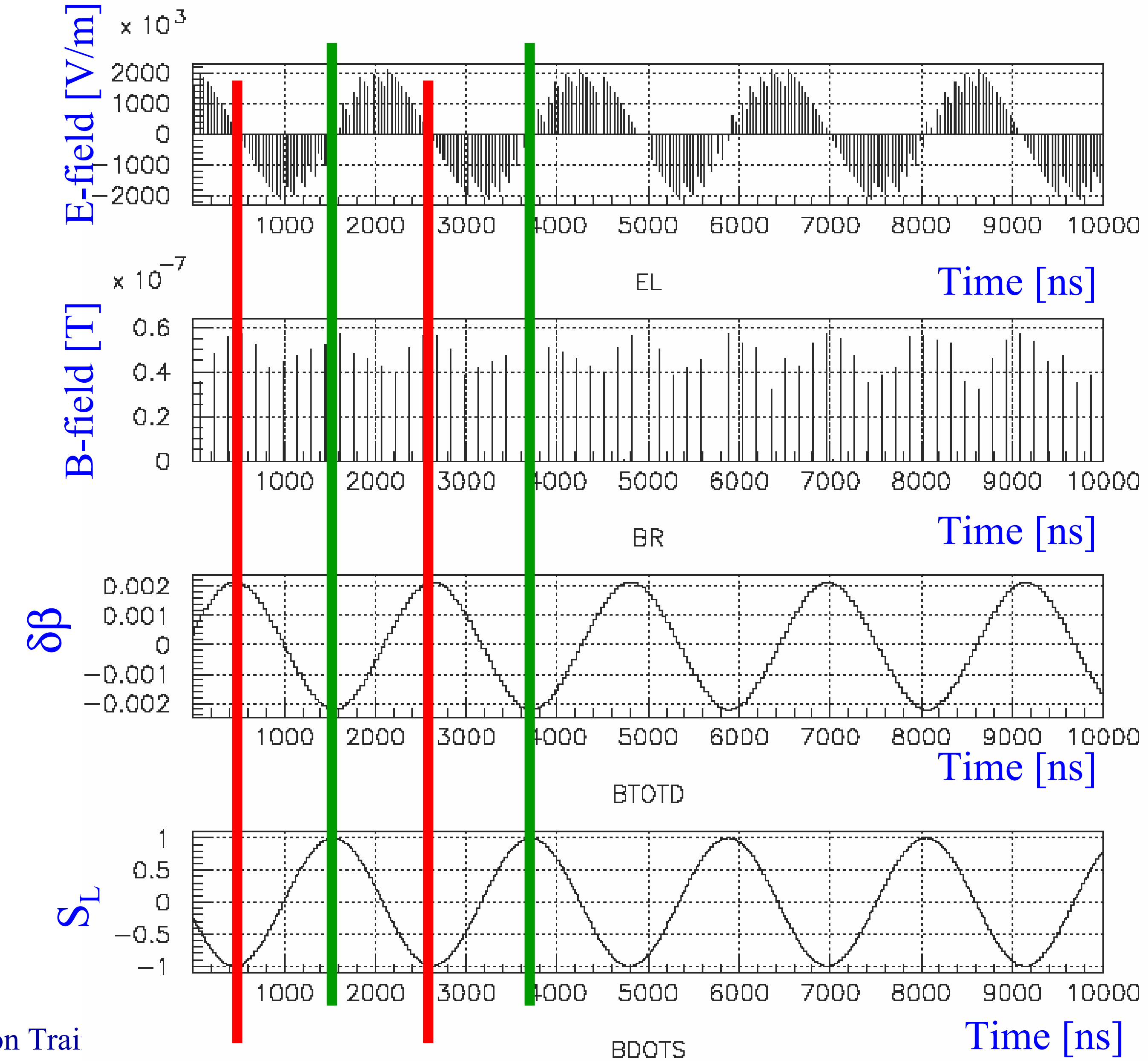
Together n (p) and deuteron EDM exp: pinpoint EDM source, promising a very exciting decade…!

Extra Slides

List of things to do…

1. Compaction factor: $\alpha_p=1$ or $\alpha_p\neq 1$ 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

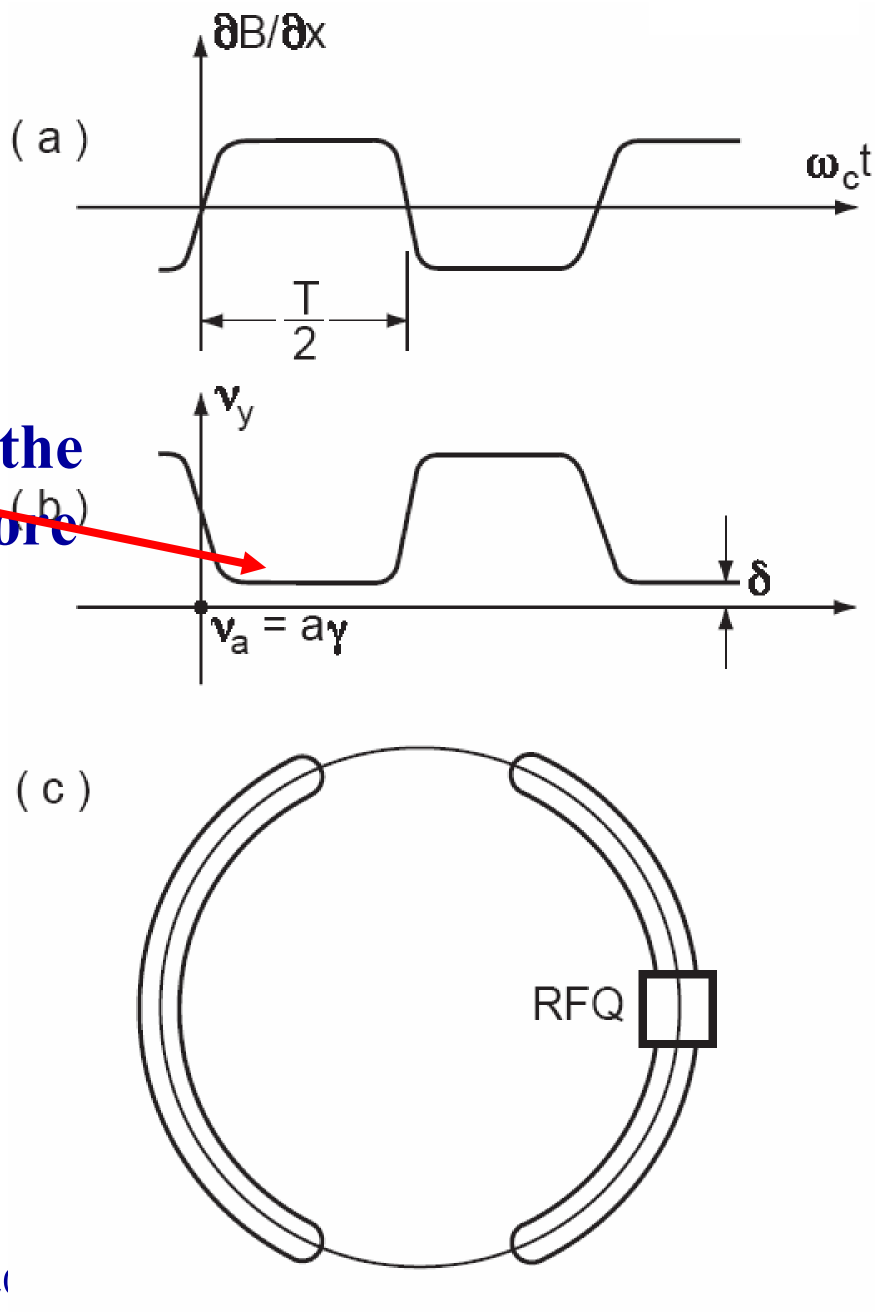


$$\frac{d\vec{s}}{dt} = \vec{\mu} \times \vec{B} + \vec{d} \times \vec{E}$$

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.

Two half beam technique



This tune makes the Deuteron spin more Sensitive to background

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

Resonance EDM Systematic Errors

- Two classes of systematic errors: DC, or frequency dependent (AC)
- Vertically offset RF-cavity
- Misaligned in angle RF-cavity

S. Lamoreaux at "Lepton Moments"

HV Effects on SQUIDs

1. Sparks will likely destroy a SQUID; however, a sudden change in electric field will likely destroy the experiment due to expansion associated with the electrostriction effect for superfluid ^4He
2. ^3He signal: 0.2 pG, 1 nA leakage in a 10 cm loop: 60 pG (at least 100 X expected field)
3. Dressed spin technique is an alternative method and a profitable goal

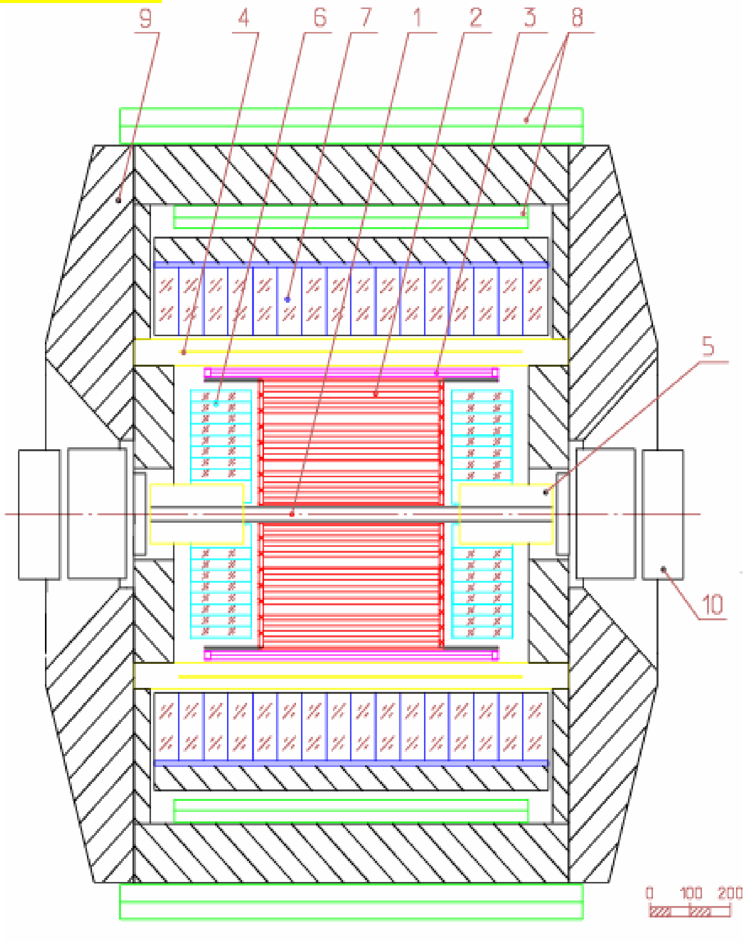
E=5MV/m, T=10^8s

R&D

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

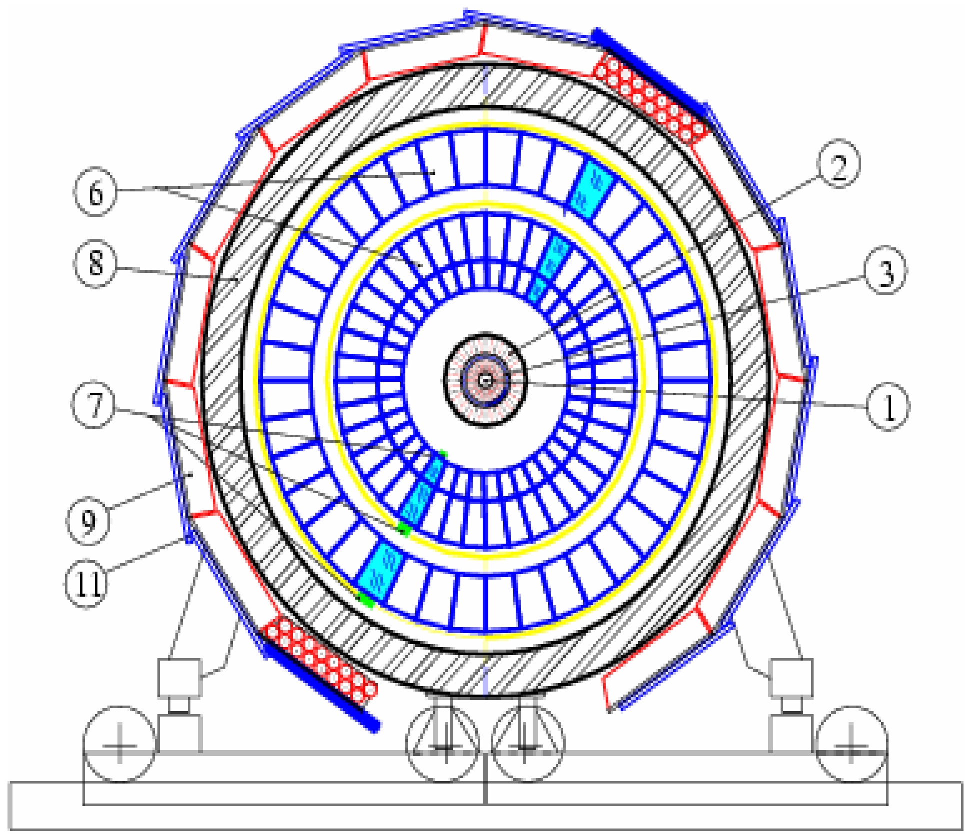
Last generation of detectors at VEPP-2M

CMD-2



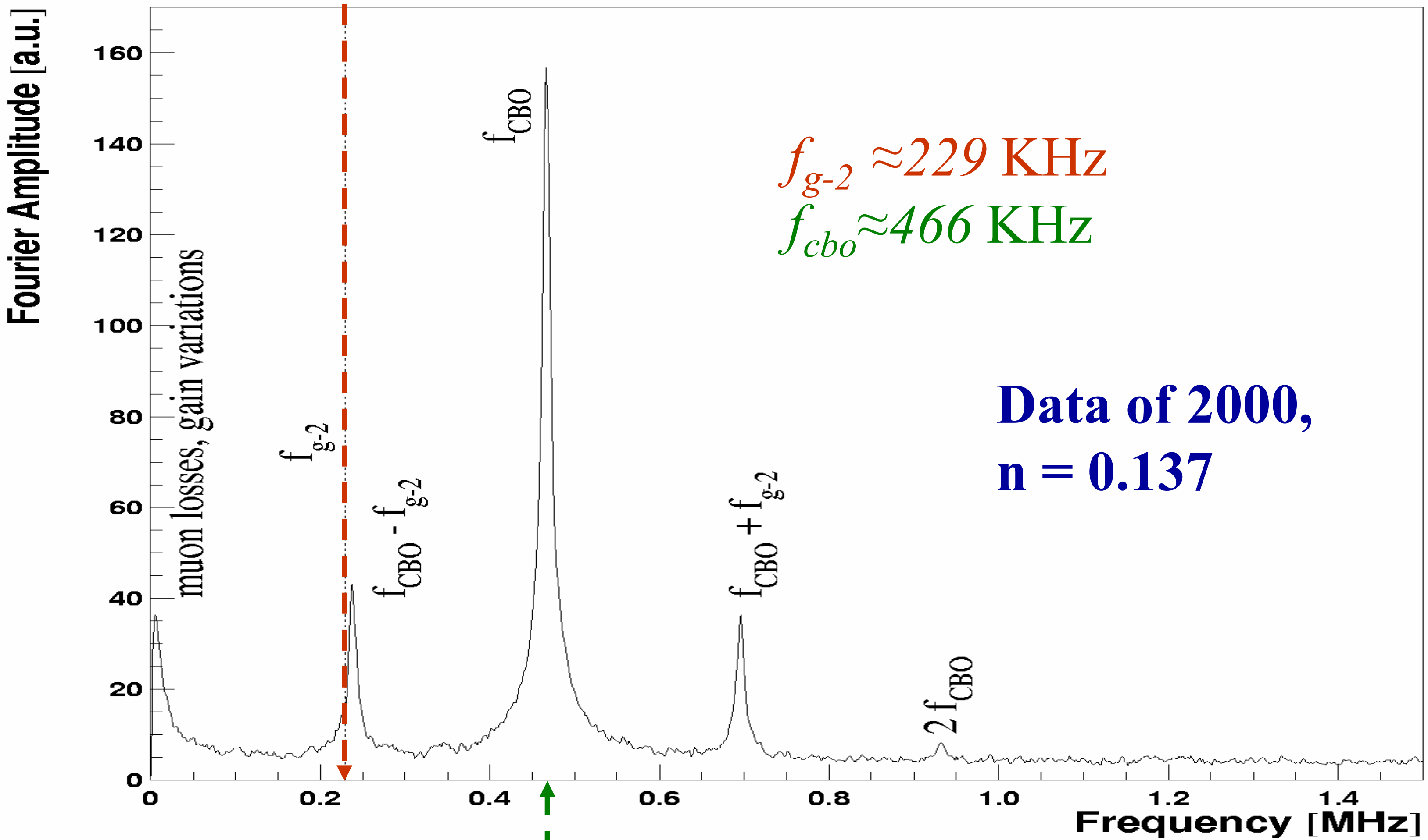
1-vacuum chamber; 2- drift chamber;
3 – Z-chamber; 4-main solenoid;
5-compensating solenoid;
6-BGO calorimeter; 7-CsI calorimeter;
8-muon range system; 9-yoke;
10-quadrupoles

SND



1-vacuum chamber; 2 – drift chambers; 3 – internal scintillating counter; 6-NaI crystals; 7-vacuum phototriodes; 8-absorber; 9-strimer tubes; 11- scintillator plates;

5-parameter Function Not Quite Adequate. Fourier Spectrum of the Residuals:



$f_{g-2} \approx 229$ KHz

$f_{cbo} \approx 466$ KHz

Data of 2000,
n = 0.137

$$f_{cbo} \approx f_C\left(1-\sqrt{1-n}\right)$$

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

Modulation of N_0, A, ϕ_a with f_{cbo}:

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

$$N_0(t) = N_0\left[1 + A_N e^{-\frac{t}{\tau_{cbo}}}\cos(2\pi f_{cbo}t + \phi_N)\right]$$

$$A(t) = A\left[1 + A_A e^{-\frac{t}{\tau_{cbo}}}\cos(2\pi f_{cbo}t + \phi_A)\right]$$

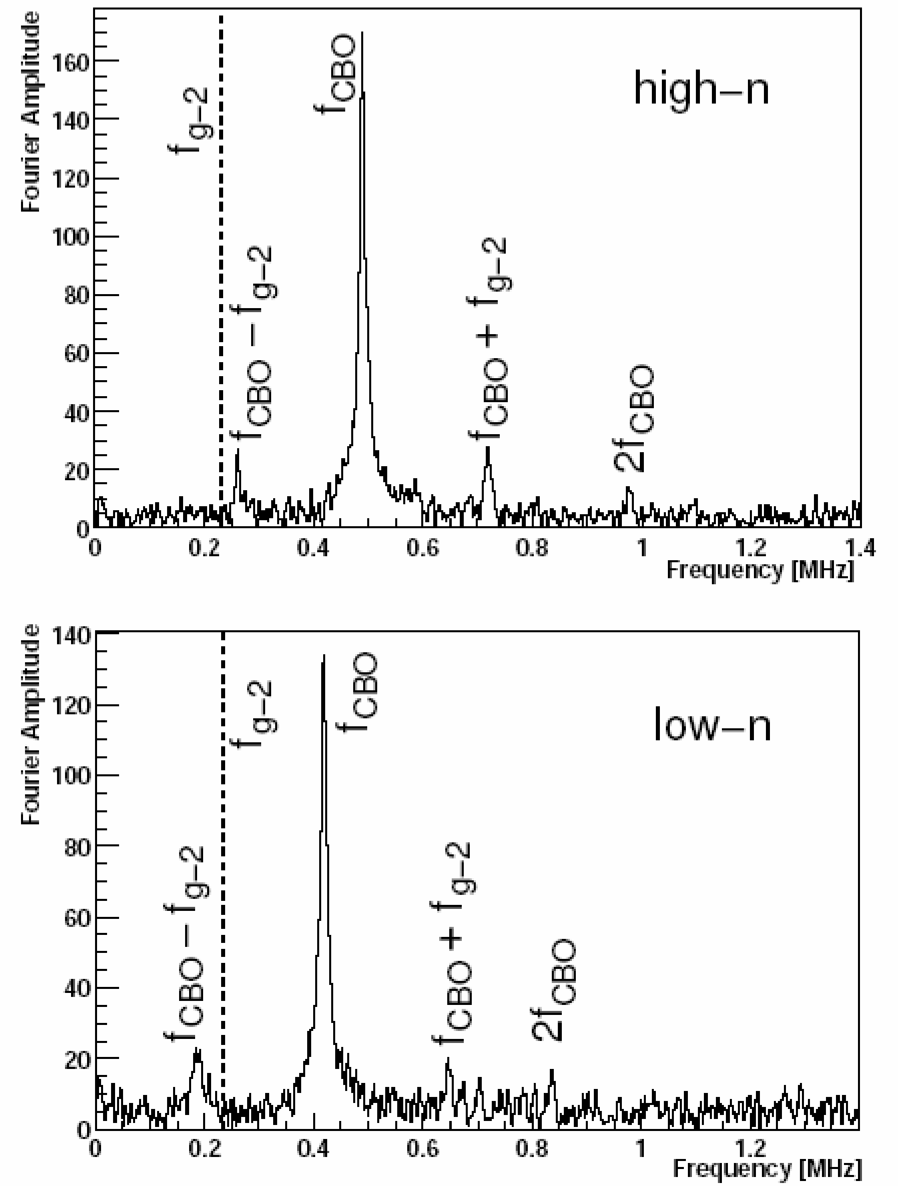
$$\phi_a(t) = \phi_a + A_\phi e^{-\frac{t}{\tau_{cbo}}}\cos(2\pi f_{cbo}t + \phi_\phi)$$

Amplitudes of A_N, A_A, A_ϕ, Consistent with Values from MC Simulations (10^{-2}, 10^{-3}, 10^{-3} respectively)

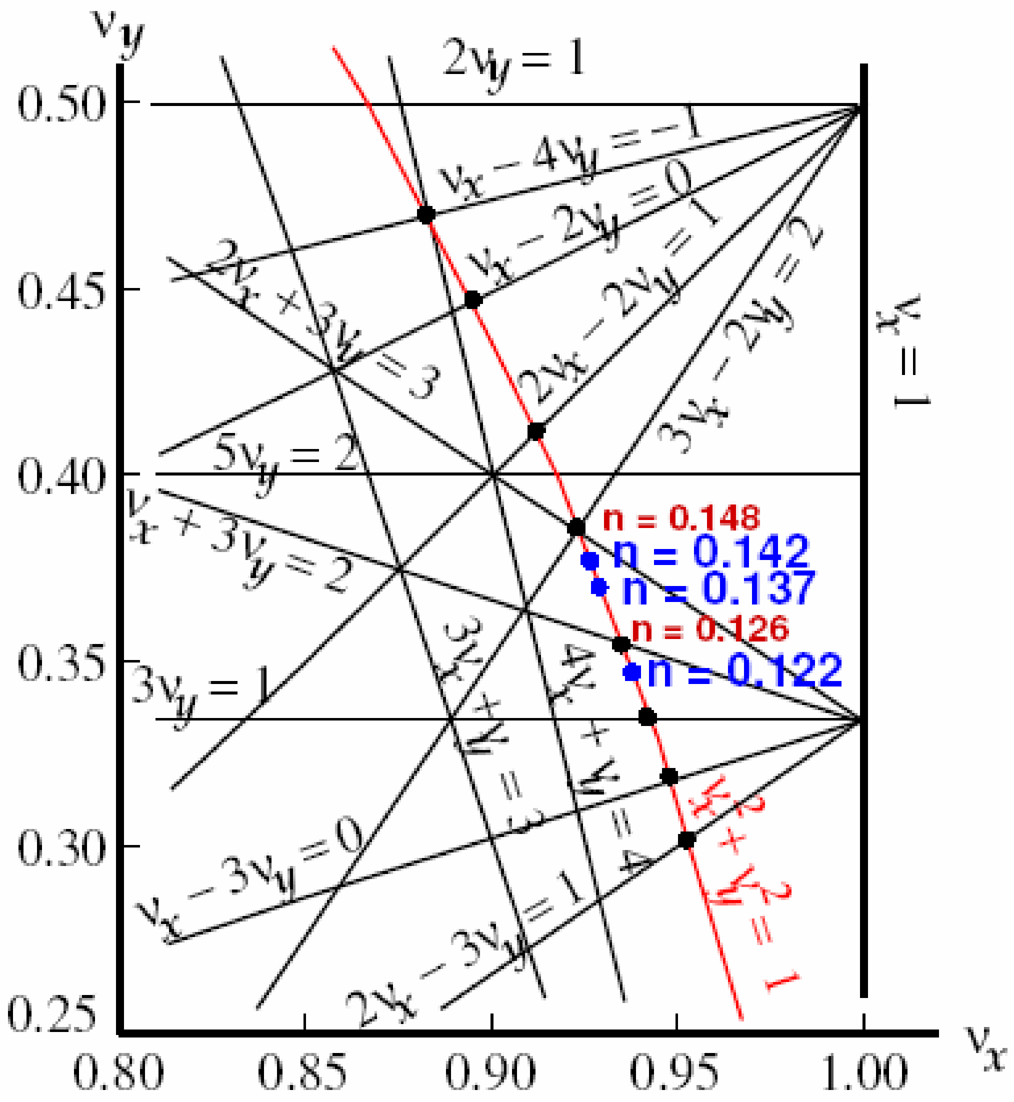
$$\frac{d\vec{s}}{dt} = \vec{\mu}\times\vec{B} + \vec{d}\times\vec{E}$$

2001 Run with Negative Muons

- In 2001 we have collected 3.7 Billion electrons with E>1.8GeV from a run with negative muons (μ^-). Run at n=0.122 and n=0.142.



Vertical vs. Horizontal Tune



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

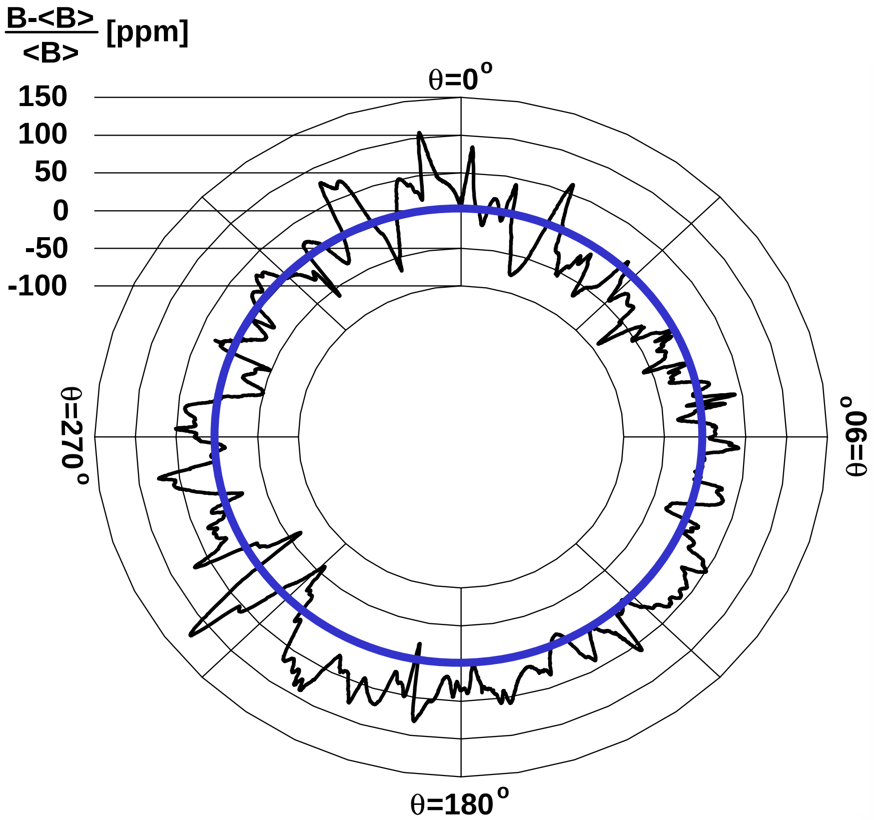
Systematic/Statistical Uncertainties for the ω_a Analysis.

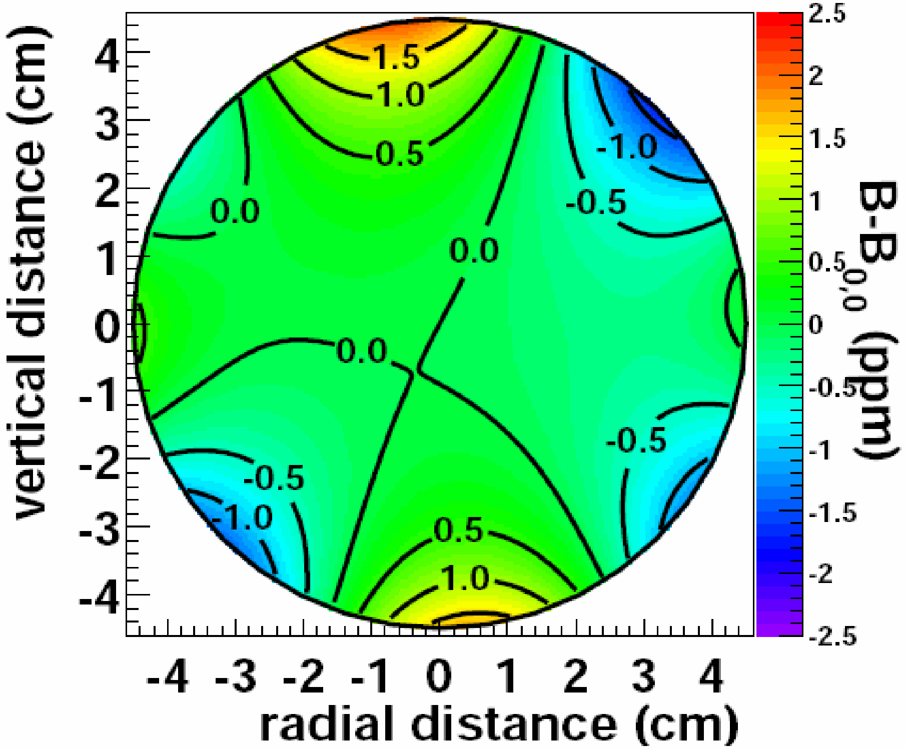
	Size [ppm]	
Systematic Uncertainties	**2001**	**2000**
Coherent Betatron Oscillations (CBO)	0.07	0.21
Pileup (Overlapping Signals)	0.08	0.13
Gain Changes	0.12	0.12
Lost Muons	0.09	0.10
Others	0.11	0.08
Total Systematics	0.21	0.31
Statistical Uncertainty	0.66	0.62

Total Uncertainty:	**0.7**	**0.7**

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

Magnetic Field measurement





The *B* field azimuthal variation at the center of the storage region. <B>≈1.45 T

The *B* field averaged over azimuth.

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

Magnetic Field Measurement

Systematic Uncertainties for the ω_p Analysis.

Source of Errors	Size [ppm] 2001	2000
Absolute Calibration of Standard Probe	0.05	0.05
Calibration of Trolley Probe	0.09	0.15
Trolley Measurements of B-field	0.05	0.10
Interpolation with Fixed Probes	0.07	0.10
Uncertainty from Muon Distribution	0.03	0.03
Others	0.10	0.10
Total	0.17	0.24

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

Computation of a_μ:

$$a_\mu = \frac{\omega_a}{\frac{e}{m_\mu}\langle B\rangle} = \frac{\omega_a / \omega_p}{\mu_\mu / \mu_p - \omega_a / \omega_p}$$

- *Analyses of ω_a and ω_p are Separate and Independent ("**Blind Analysis**"). When Ready, only then, Offsets are Removed and a_μ is Computed.*

Computation of a_μ:

$$a_{\mu^-} = \frac{\omega_a}{\frac{e}{m_{\mu^-}}\langle B\rangle} = \frac{\omega_a/\omega_p}{\mu_{\mu^-}/\mu_p - \omega_a/\omega_p} = \frac{R_{\mu^-}}{\lambda - R_{\mu^-}}$$

$$R_{\mu^-} \equiv \omega_a/\omega_p = 0.003\,707\,208\,3\,(26)$$

$$\lambda = \mu_\mu/\mu_p = 3.183\,345\,39\,(10)$$

W.L. *et al.*, PRL **82**, 711 (1999)

Data of 2001:

a_μ(exp)=11 659 214(8)(3)×10^{-10} **(0.7 ppm)**

Average of a_μ:

CPT? $\Delta R = R_{\mu^-} - R_{\mu^+} = (3.5 \pm 3.4) \times 10^{-9}$

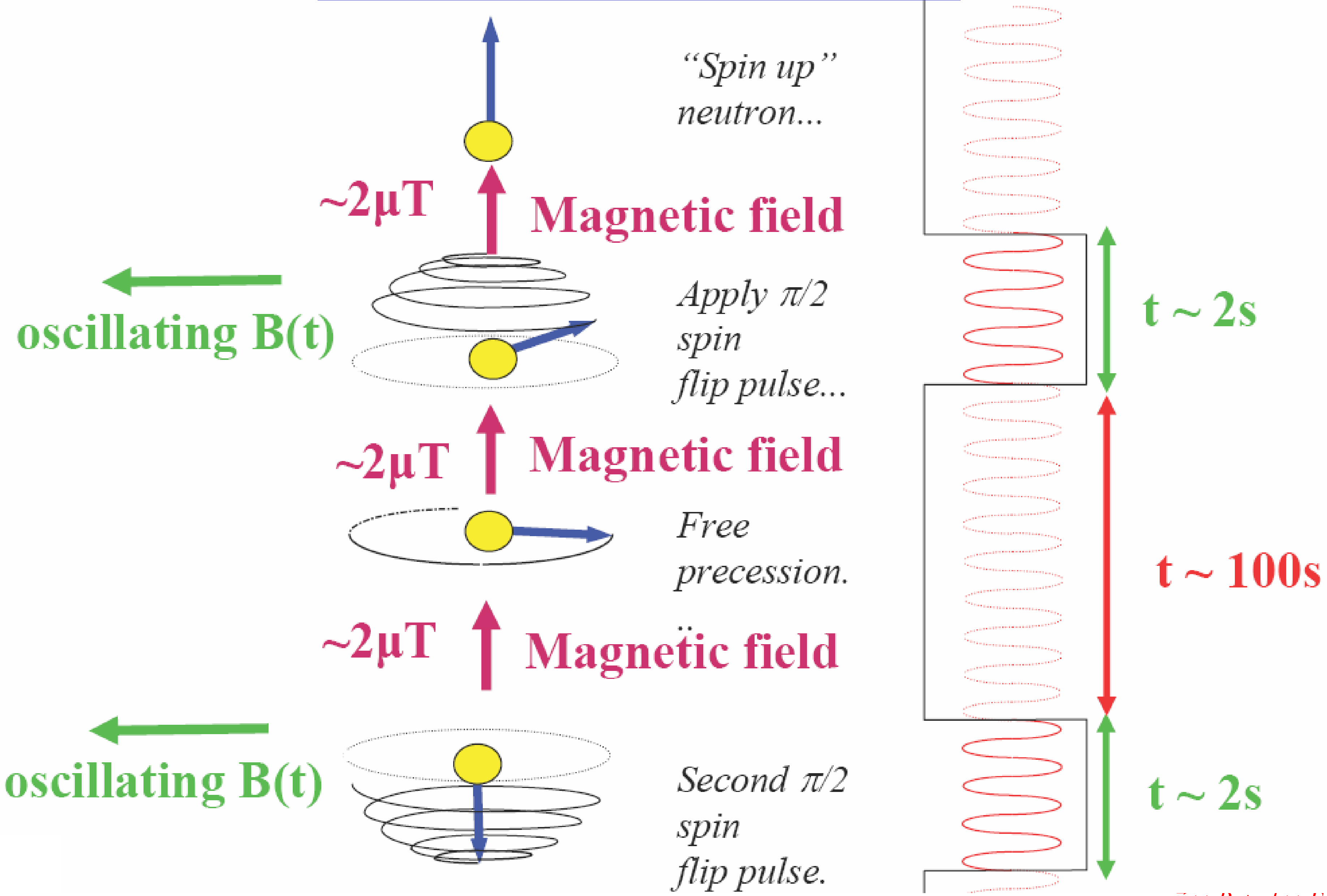
Exp. World Average:

a_μ(exp)=11 659 208(6)×10^{-10} **(0.5 ppm)**

a_μ(exp)- a_μ(SM) = 27 (10)×10^{-10}, 2.7σ, based on e^+e^- data

a_μ(exp)- a_μ(SM) = 12 (9) ×10^{-10}, 1.4σ, based on τ-data

Ramsey's method



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

Systematic errors due to ~0Hz forces

- DC, or almost DC forces (other than magnetic)

$$\vec{F}_{\mathrm{v}} = 0 \Rightarrow \vec{F}_{\mathrm{ext}}(\mathrm{DC}) + q\left\langle \vec{\mathrm{v}} \times \vec{B}_R \right\rangle = 0$$

i.e. modulating v at ω_a modulates B_R at the same frequency.

- Examples: 1) Gravity,

  2) Charging up the beam pipe…

Remedy

- Clock-Wise (CW) injection and Counter-Clock-Wise (CCW) injection (Imitates $T \to -T$):

$$B \to -B$$

$$v \to -v$$

$$v \times B \to v \times B$$

Developments in Theory

- a_μ(had, LBL) = +8.6(3.5)×10^{-10} Large N QCD+Chiral
  +13.6(2.5)×10^{-10} Melnikov + Vainshtein
  +11.1(1.7)×10^{-10} Dubnicka *et al*
  +9.2(3.0)×10^{-10} T+Ynd.
  +11.0(2.0)×10^{-10} W. Marciano, prelim.

- Use +12.0(3.5)×10^{-10} WM

- a_μ(QED) = 11 658 472.07(0.04)(0.1)×10^{-10} Recent Kinoshita Update

Developments in had1

- a_μ(had,1) = 696.3(6.2)(3.6)$\times 10^{-10}$ DEHZ

  696.2(5.7)(2.4)$\times 10^{-10}$ HMNT

  694.8 (8.6) $\times 10^{-10}$ GJ

  692.4(5.9)(2.4)$\times 10^{-10}$ HMNT inclusive

  693.5(5.0)(1.0)$\times 10^{-10}$ TY

- Use = 694.4 (6.2)(3.6)$\times 10^{-10}$ WM

- 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)$\times 10^{-10}$

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

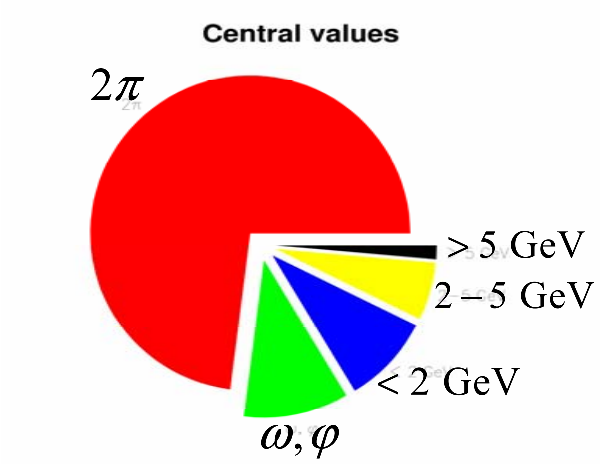
$$\frac{d\vec{s}}{dt} = \vec{\mu} \times \vec{B} + \vec{d} \times \vec{E}$$

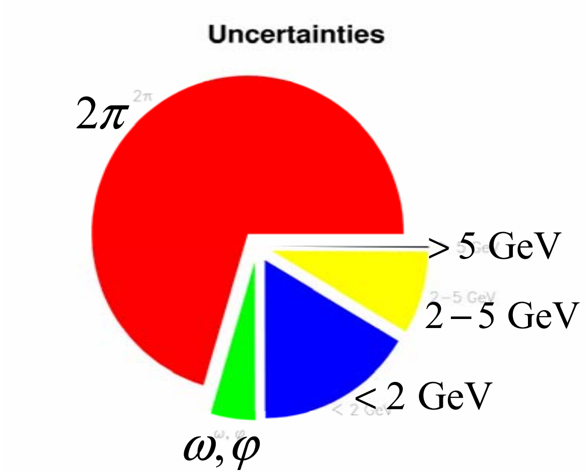
Hadronic contribution to muon (g-2)

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:

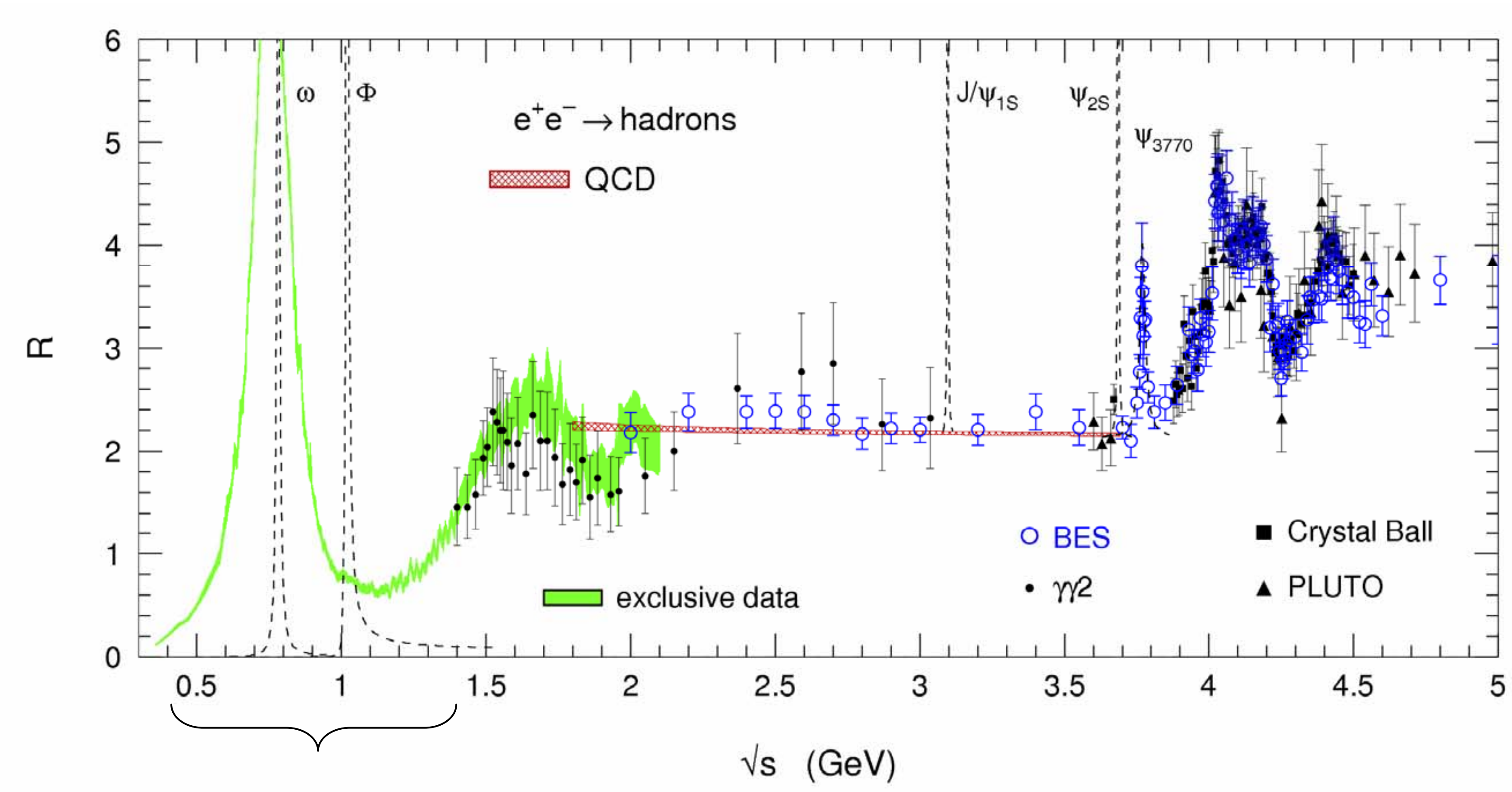




$e^+e^- \rightarrow 2\pi$ gives dominant contribution both to the value and to the uncertainty of the hadronic contribution

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

R, the current status



VEPP-2M energy region

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

Implication to a_μ (very unofficial)

Michel Davier, Bill Marciano-2004:

$\Delta a_\mu = (23.9 \pm 7.2_{had,LO} \pm 3.5_{other} \pm 5.8_{exp}) \cdot 10^{-10}$

- $0.6 < \sqrt{s} < 1.0$ GeV

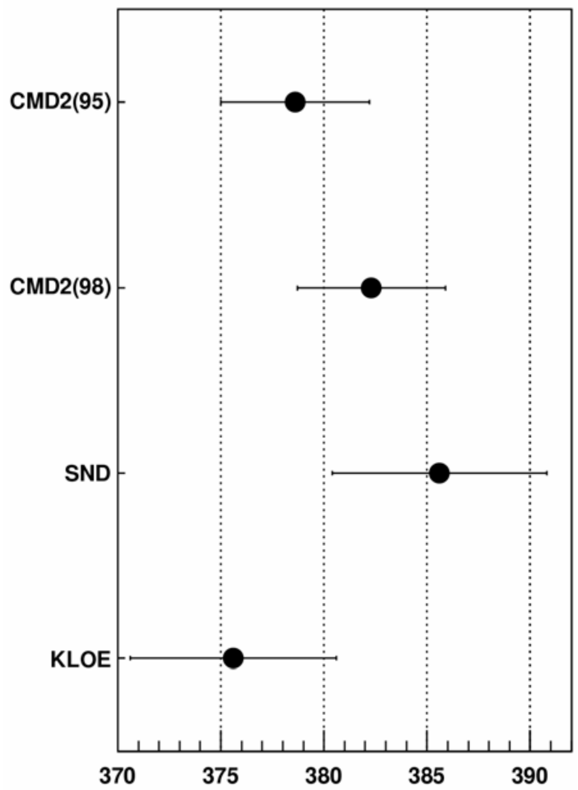
CMD-2 (95):	378.6 ± 2.7 ± 2.3 (3.6)
CMD-2 (98):	382.3 ± 1.9 ± 3.1 (3.6)
SND:	385.6 ± 5.2
KLOE:	375.6(?) ± 0.8 ± 4.9 (5.0)

- $0.4 < \sqrt{s} < 1.0$ GeV

CMD-2 (95,96,98):	482.1 ± 3.1 ± 3.2 (4.4)
SND:	488.7 ± 2.6 ± 6.6 (7.1)

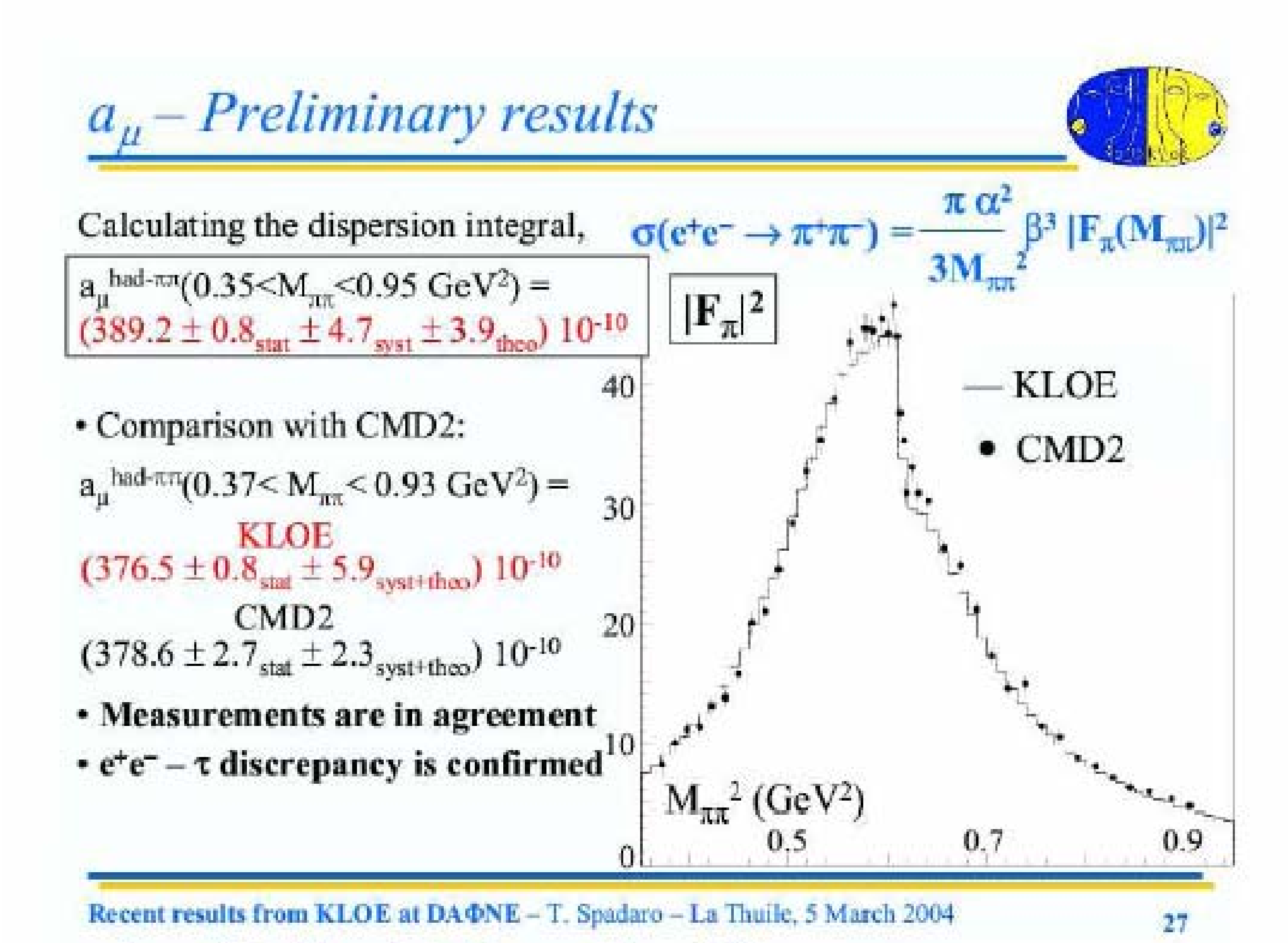
- $0.4 < \sqrt{s} < 1.4$ GeV

CMD-2 (all): 495.23 ± 3.07 ± 3.38 (4.57)



$a_\mu(had; 0.6 < \sqrt{s} < 1.0 \text{ GeV})$

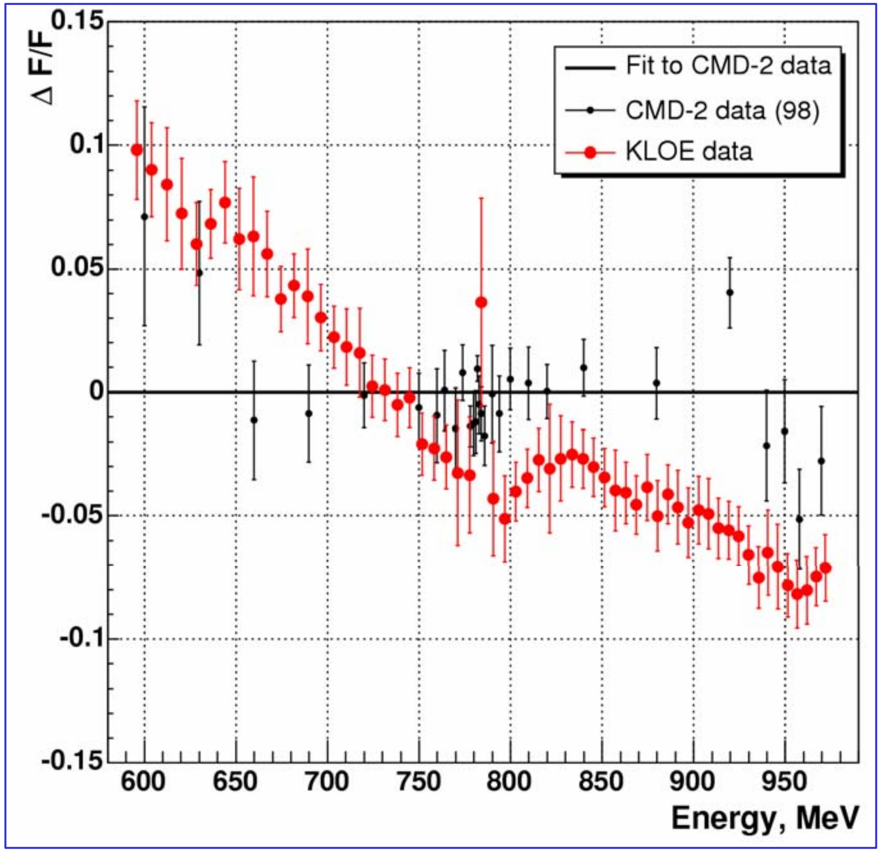
Recent KLOE Results



(provided by Juliet Lee-Franzini)

$dt \quad \times \vec{B} + \vec{d} \times \vec{E}$

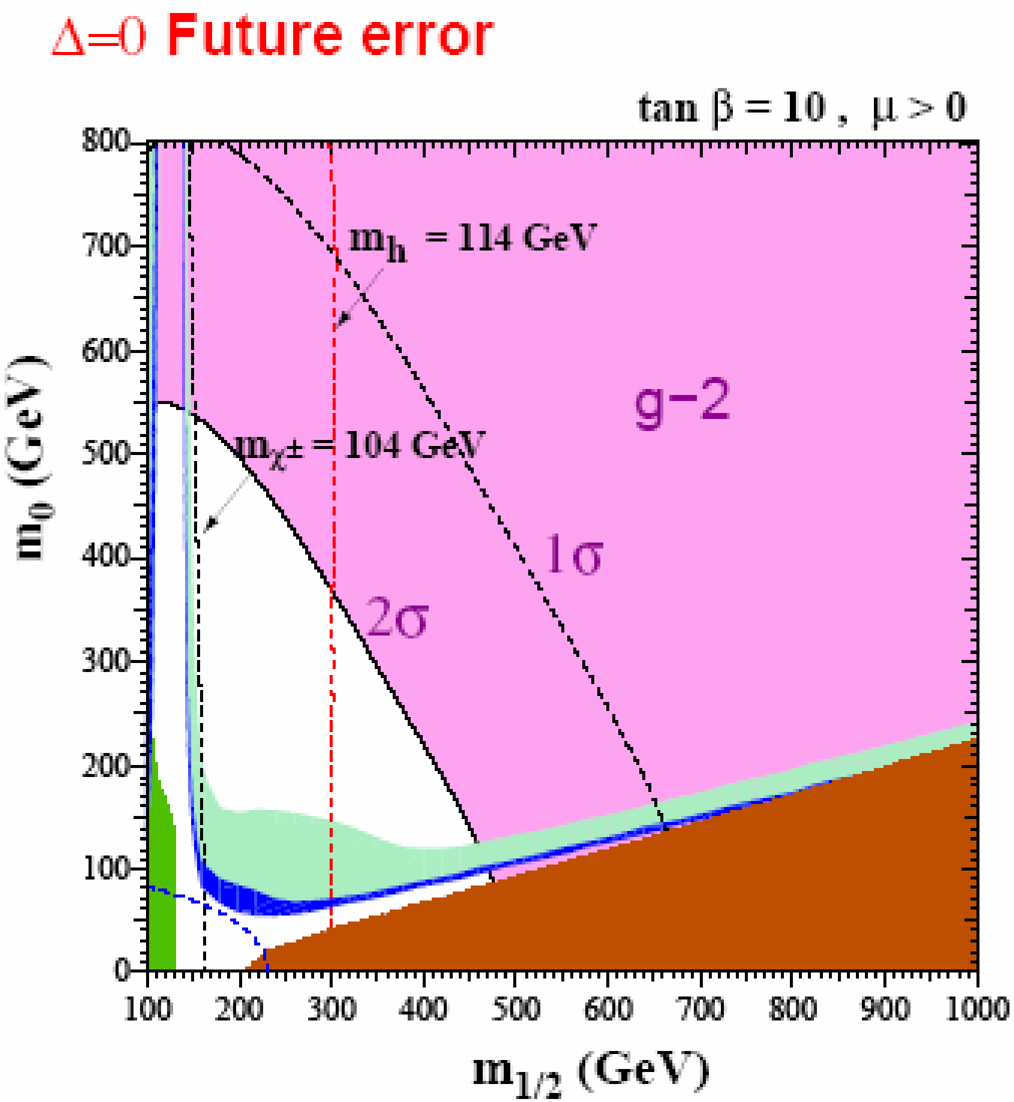
Comparison of CMD2 data with KLOE



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

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

SUSY Dark Matter



Following Ellis, Olive, Santoso, Spanos.
Plot by K. Olive

Upper Limits on SUSY Mass Scales are set by Muon g-2