EDM Search on the Deuteron

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Outline

Theoretical Perspective

what is so special about the deuteron?

sensitivities to SM and beyond

relative to other EDM searches

in relation to HEP

an experimentalists rendition of a theorical effort

Experimental Perspective

how to get sensitive to the deuteron EDM?

concept

implementation

reach

a theoretical rendition of an experimental effort

Summary

CP/T

Cosmology *(WMAP)*

Cosmological matter-antimatter asymmetry explainable with *e.g.* Sakharov-conditions*

- *baryon number violation*
- *C & CP violation*
- *thermal non-equilibrium*

$\neq$

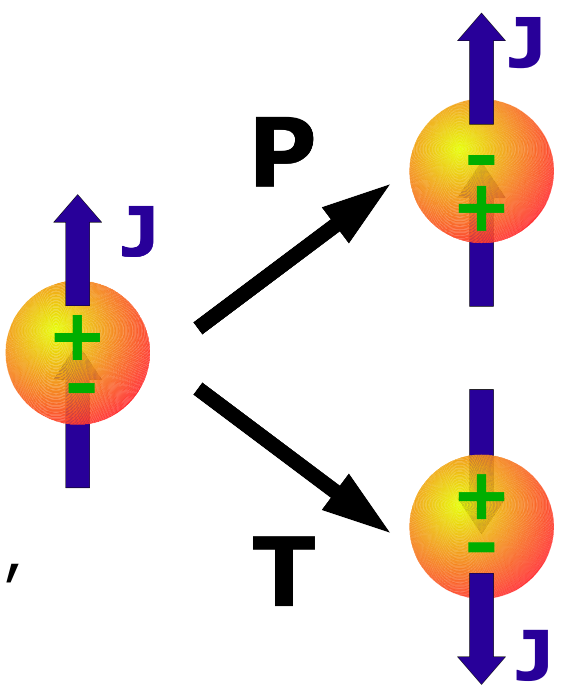
δ_{CKM} *from K- and B-physics*

Direct measurements

K, B, D

Precision searches

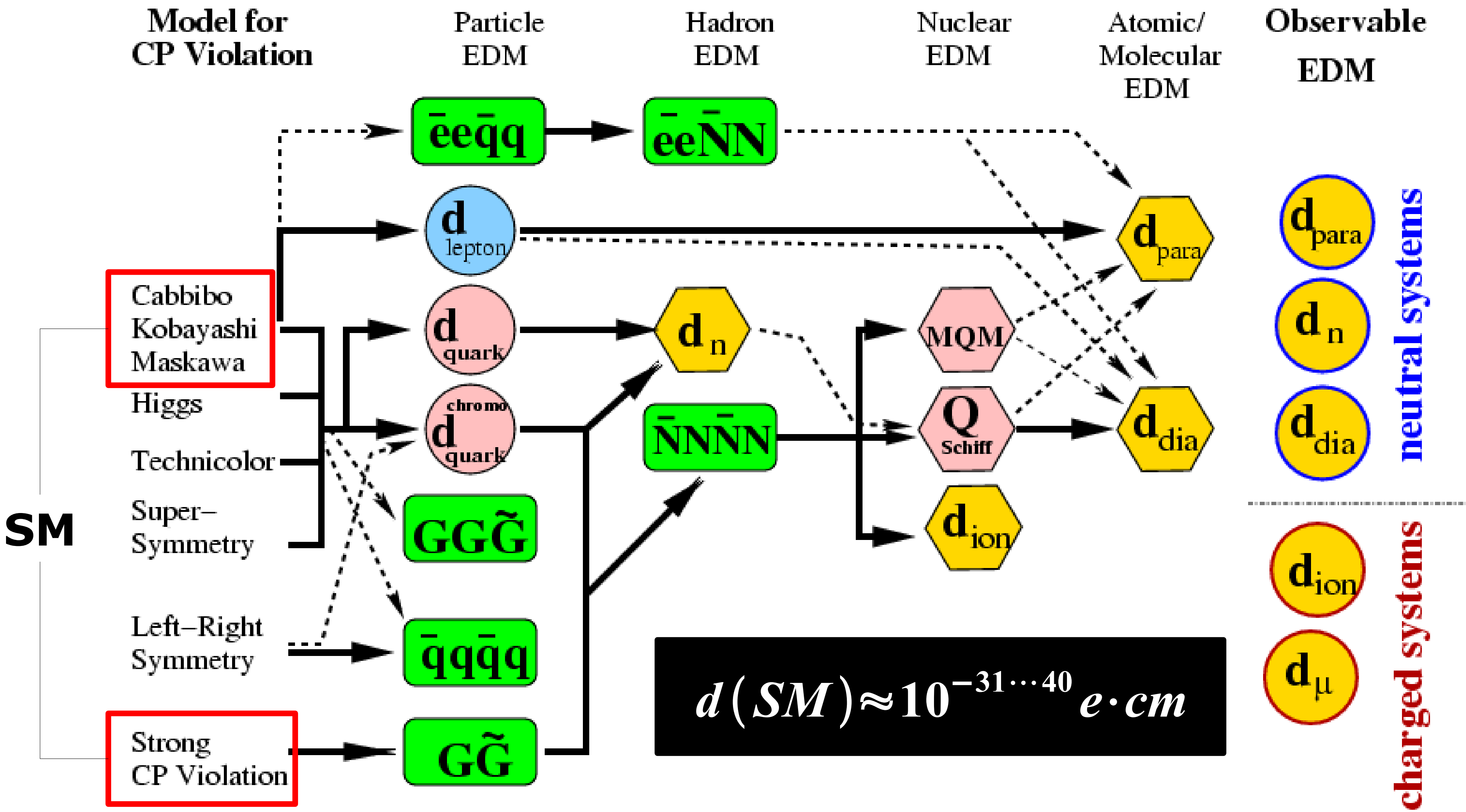
- *Permanent electric dipole moments*
- *Correlations in (super-allowed) β-decay*



SM values are beyond experimental reach, so **sensitive probe for new physics!**

**Alternative routes*:PMNS, CPT-V, ...

EDM genealogy



First nonzero EDM will be a *major discovery*. Ultimately, we need the whole picture to address the *origin* of CP

Nuclear EDMs

Nuclear EDMs from constituents and from $\not{CP}$ NN interaction

$$d_{nucl} = d_n \oplus d_p \oplus d_{\pi NN}$$

n, p, ^{2}H ,^{3}H, ^{3}He, … , ^{255}Ra

Different nuclei have different sensitivities, *e.g.* chromo-EDM or $\bar{\theta}$

$$\begin{aligned} d_D &= -4.67\,\tilde{d}_d + 5.22\,\tilde{d}_u \\ d_n &= -0.01\,\tilde{d}_d + 0.49\,\tilde{d}_u \end{aligned}$$

$$d_p(\bar{\theta}) : d_D(\bar{\theta}) : d_{3\mathrm{He}}(\bar{\theta}) \approx 3 : 1 : -3$$

Structure of light nuclei is well understood → firm prediction

Search for EDMs on light nuclei!

W. Marciano

dEDM in EDM Landscape

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

Deuteron Competitive - Better !

W. Marciano

dEDM Connection to HEP

Generic Loop Prediction: $d \sim \frac{eg^2}{16\pi^2} \frac{m_q}{M^2} \sin\delta$

$d \sim 10^{-24}$ e-cm $\times \sin\delta \times \left(\frac{1\,\text{TeV}}{M}\right)^2$

SUSY → $d_n \sim 10^{-25} - 10^{-28}$ e-cm $\sim d_D$ (Observable)

δ very small or $M > 1$ TeV (SUSY CP Crisis)?

If LHC discovers SUSY < 1 TeV

$d_n, d_D \ldots d_p, d_{He^3}$ Sort Phase Structure.. (Complementary)

If LHC Fails To Find SUSY

d_D probes up to $M \sim 1000$ TeV! (Spectacular!)

Experimental Techniques

Generic EDM Experiment

1. **Prepare spin polarized ensemble**

2. **Interaction with electric field**

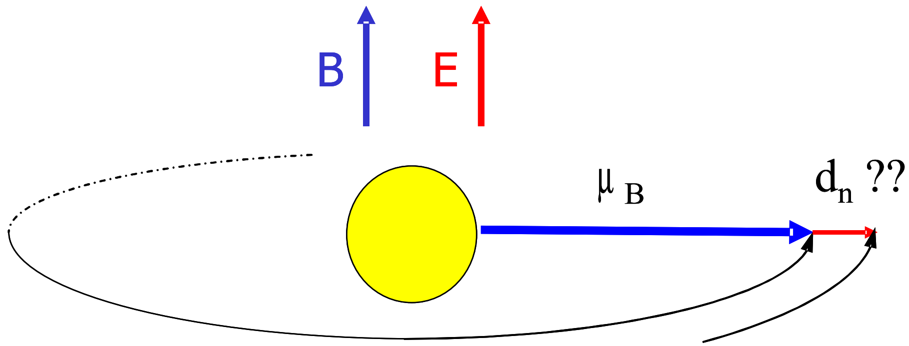
3. **Measure spin evolution**

$$\frac{d\langle \vec{S} \rangle}{dt} = \left(\mu \vec{B} + d \vec{E}\right) \times \langle \hat{S} \rangle$$

N: number of particles in full experiment
P: initial polarization of sample
A: analyzing power of polarimeter
E: electric field strength in particle rest frame
T: characteristic time of a single measurement

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

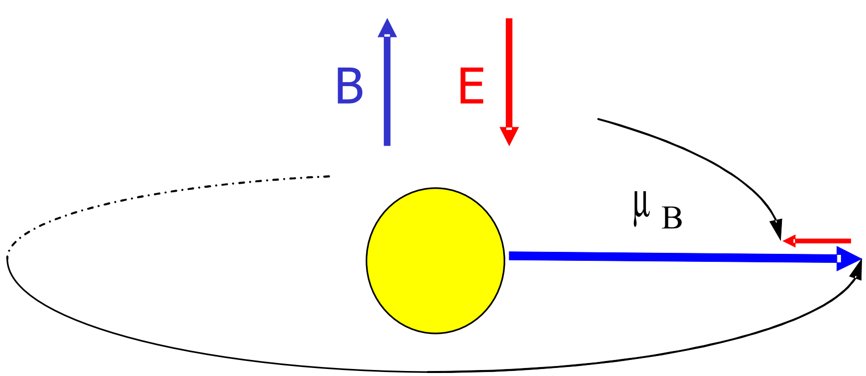
Most EDM Experiments



$$\nu_{\uparrow\uparrow} = \Delta E_{\uparrow\uparrow}/h = \left[-2B\mu_n - 2Ed_n\right]/h$$

EDM SIGNAL IN THE FREQUENCY

$$h\left(\nu_{\uparrow\uparrow} - \nu_{\uparrow\downarrow}\right) = 4Ed_n$$



$$\nu_{\uparrow\downarrow} = \Delta E_{\uparrow\downarrow}/h = \left[-2B\mu_n + 2Ed_n\right]/h$$

Problems w/ Charged Particles

*Electric field causes charged particle to accelerate and escape (**Lorentz**)*

$$T = \sqrt{\frac{2\mathrm{mL}}{qE}} \sim ns$$

*Charged constituents of neutral systems rearrange themselves to balance forces (**Schiff**-screening)*

$$d_{Deuterium} \sim 10^{-7} d_{Deuteron}$$

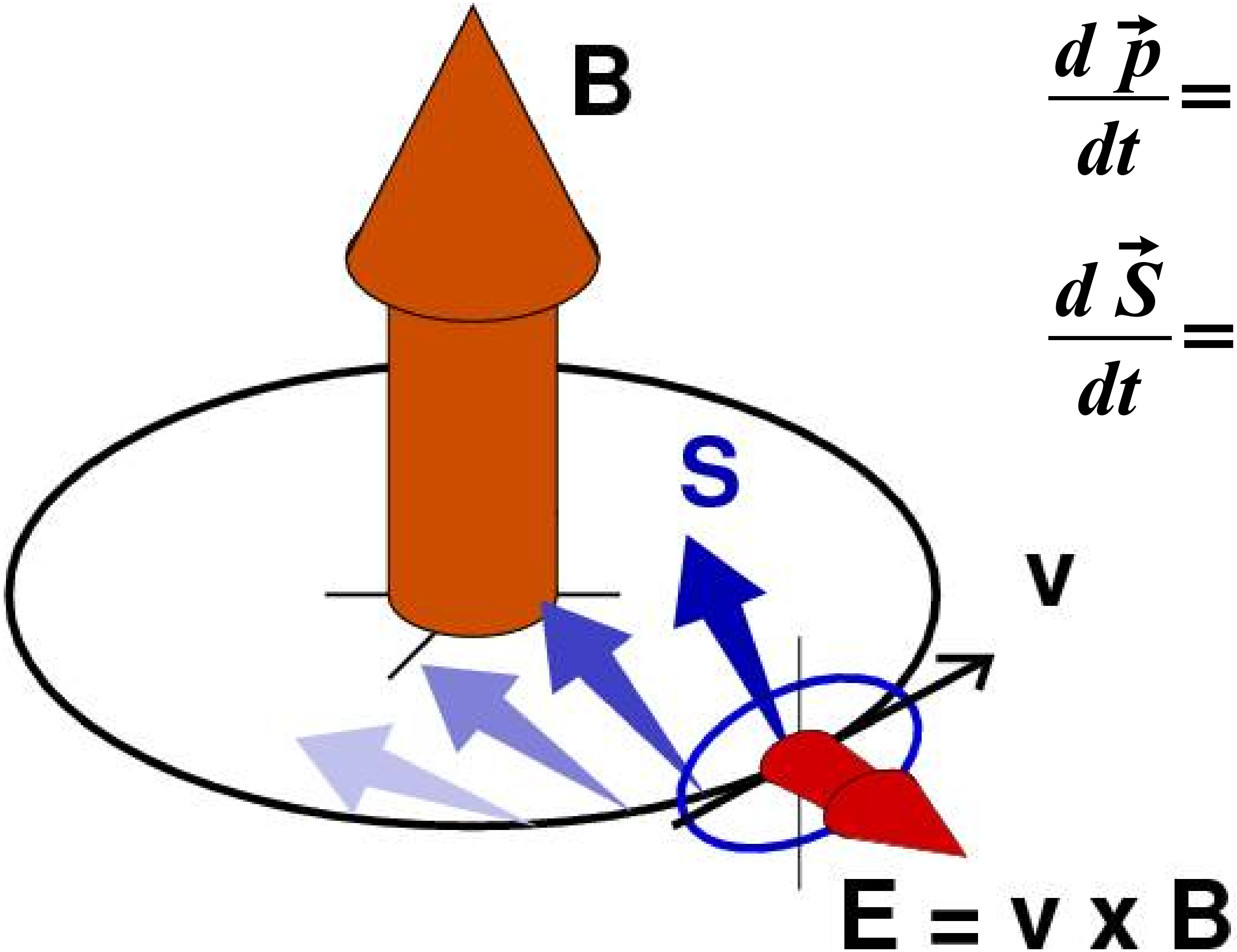
Established techniques inadequate

Solution

Store relativisitic particle in magnetic field

EDM interacts with motional electric field

The Basic Idea



$$\frac{d\vec{p}}{dt} = q\,\vec{v}\times\vec{B}$$

$$\frac{d\vec{S}}{dt} = d\,\hat{S}\times\left[\vec{v}\times\vec{B}\right]$$

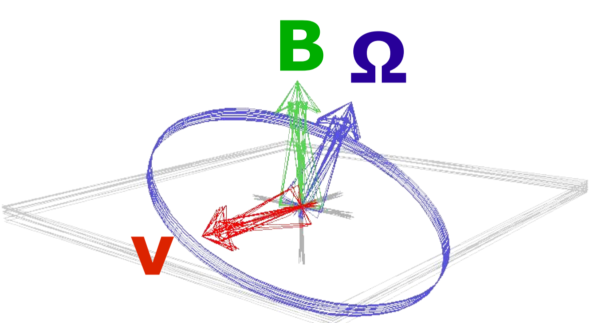
$\vec{E}^{cm} = \vec{v}\times\vec{B}$ **can be very large (GV/m)**

For relativistic particles

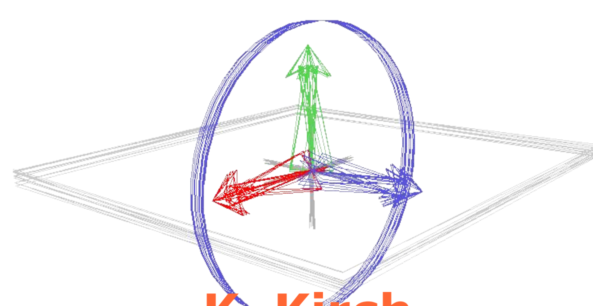
$$\vec{\Omega} = \frac{e}{m}\left[a\vec{B} + \left(a - \frac{1}{\gamma^2 - 1} \right) \vec{v} \times \vec{E} + \frac{\eta}{2}\left(\vec{E} + \vec{v} \times \vec{B} \right) \right]$$

magnetic moment anomaly **EDM**

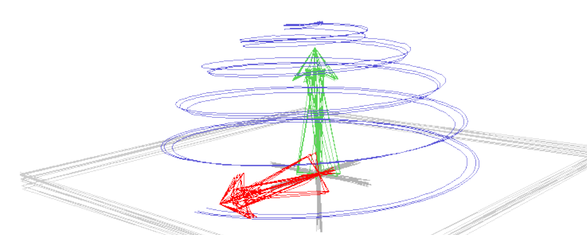
Parasitic	Frozen spin	Resonance
For $E=0$, $B=B_z$	**For $E_r \approx aBc\beta\gamma^2$**	**For $E_z \approx E\cos(\Omega t)$**
(1) $\Omega = \sqrt{a^2 + (\eta\beta)^2/4}\, B$	**(1)** $\Omega = \eta\beta B/2$	**(1)** $\langle \Omega_\eta \rangle = \eta\Delta\beta B/4$
(2) $\hat{\Omega} \times \hat{B} = \eta\beta/2a$	**(2)** $\hat{\Omega} \times \hat{B} = 1$	**(2)** $\langle \hat{\Omega}_\eta \times \hat{B} \rangle = 1$



E.g. a_μ (F. Farley, J. Miller)



K. Kirch



this talk

$\hat{z}\|\vec{B}, \hat{x}\|\vec{v}$

A closer look at spin dynamics

EOM for in-plane spin component (MDM)

$$\frac{d\vec{S}_\perp}{dt} \propto a\left[\vec{S}_\perp \times \vec{B}\right] \qquad S_x = S_0 \cos\omega t$$

... and for the out-of-plane one (EDM)

$$\vec{S}(t=0)\|\vec{v}$$

$$\frac{d\vec{S}_\parallel}{dt} \propto \frac{\eta}{2}\left[\vec{S}_\perp \times \left(\vec{v} \times \vec{B}\right)\right] = \frac{\eta}{2} S_x v_x B_z \hat{z}$$

Continuous growth of S_z if $\eta \langle S_x v_x \rangle \neq 0$

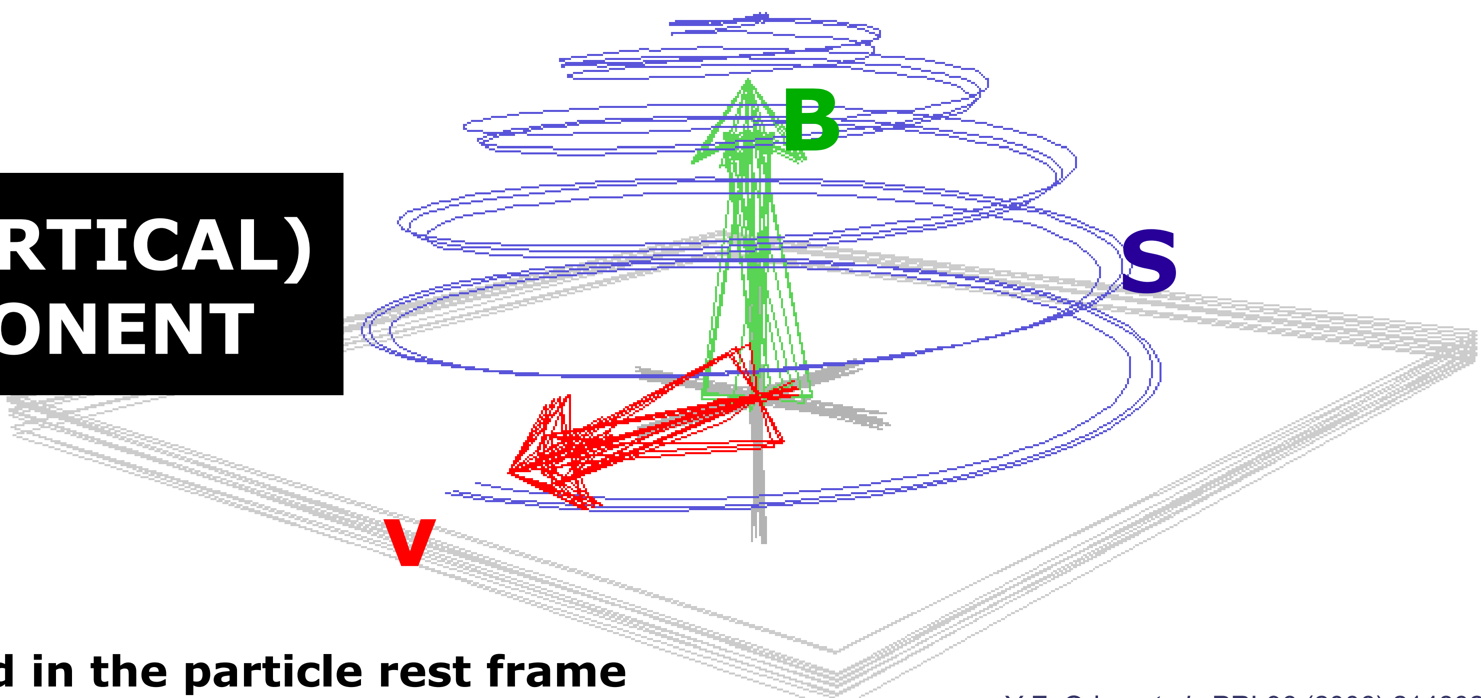
Resonance

With velocity modulation

$$= S_0 \cos\omega t \times \left(v_0 + dv(t)\right)$$

Need strong (Fourier) component at ω

$$\frac{dS_z}{dt} \propto S_x v_x \propto \frac{1}{4}\eta\, B\, S_0\, dv \cos\phi$$ ← S_z growth = EDM

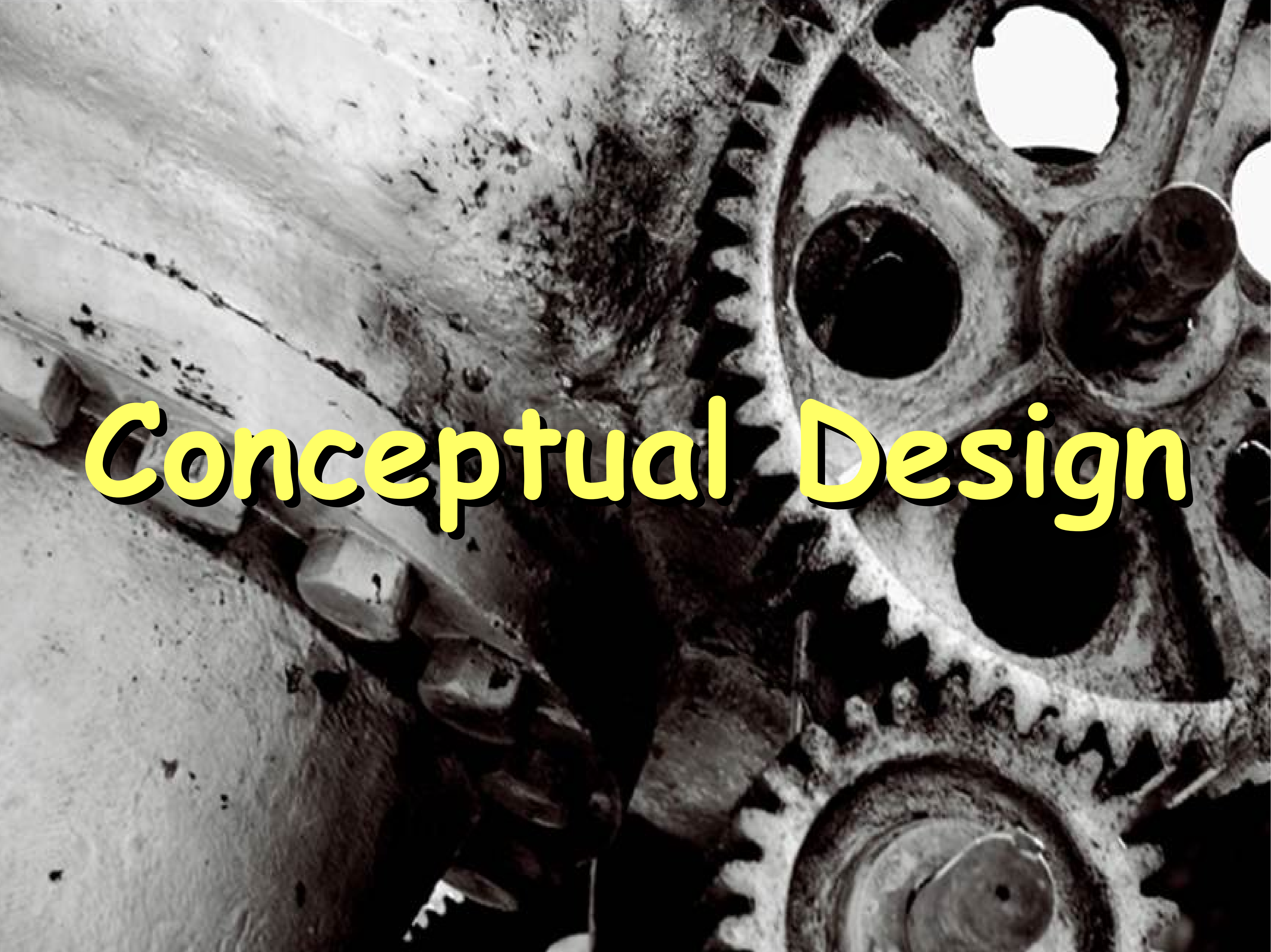


EDM IN (VERTICAL) SPIN COMPONENT

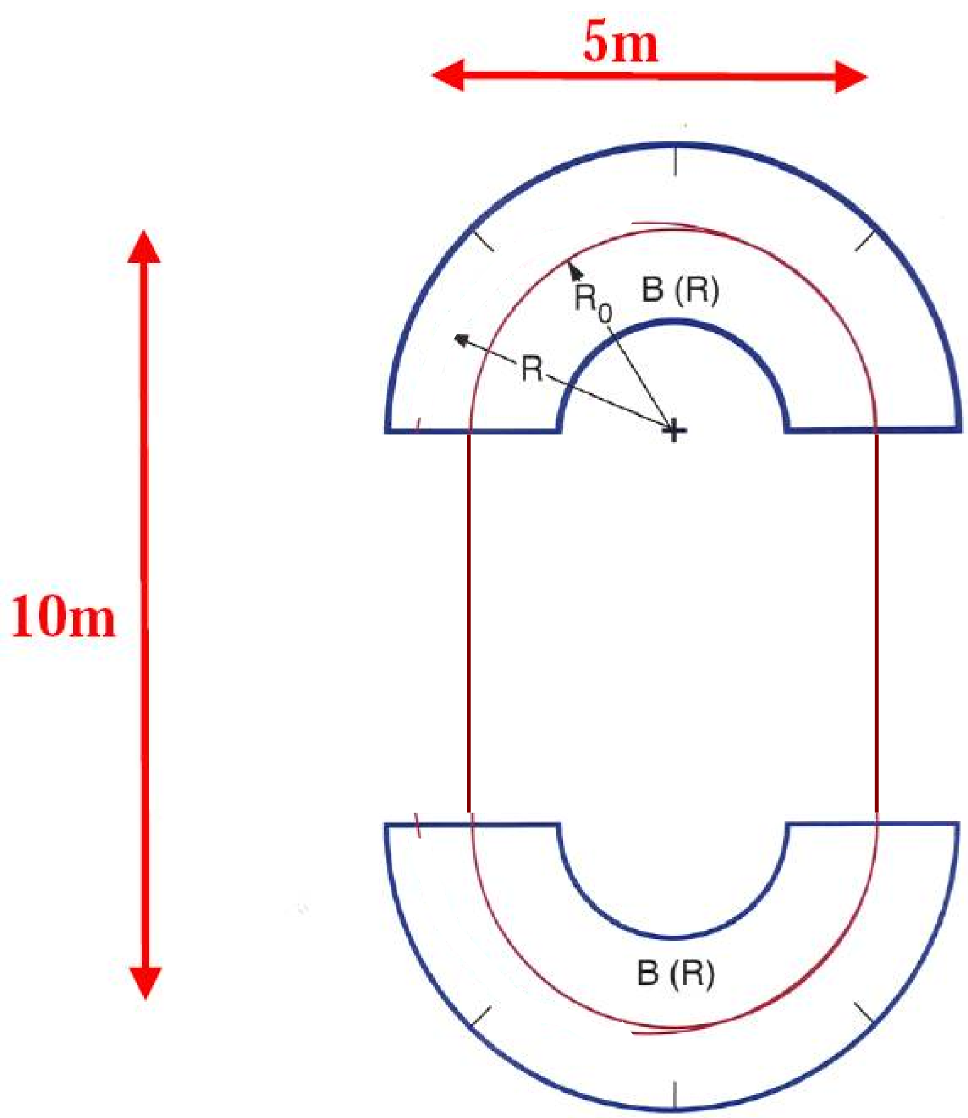
c.f. **Rabi oscillatory field in the particle rest frame**

Y.F. Orlov *et al.*, PRL96 (2006) 214802

Conceptual Design



Basic Configuration



Parameters

B = 2T

p = 1.5GeV/*c*

$\beta = 0.62, \gamma = 1.27$

$\rho = 2.5$m

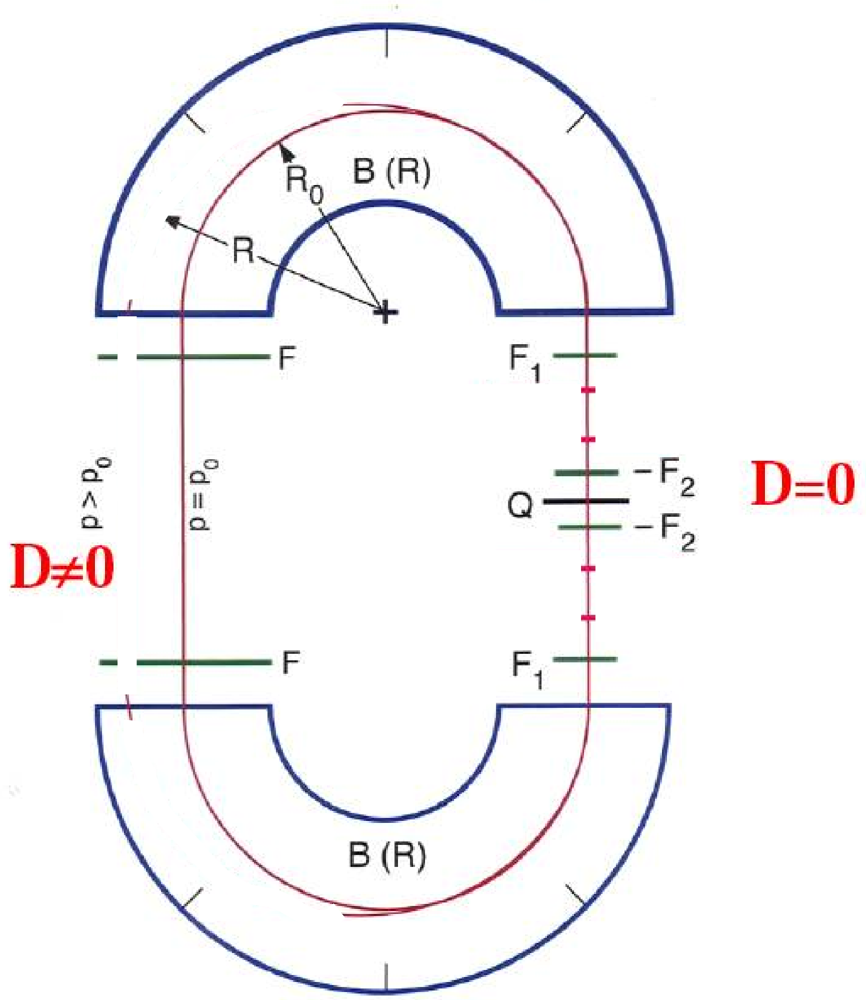
L ~ 25m

$f_C \sim 8$ Mhz

a_D = -0.143

$f_S \sim 1.4$ MHz

Beam Optics



Parameters

Dipole magnets

$B(R) = B_0 R_0 / R$

Quadrupoles

no resonances

D=0 & D≠0

$\alpha_p = 1$

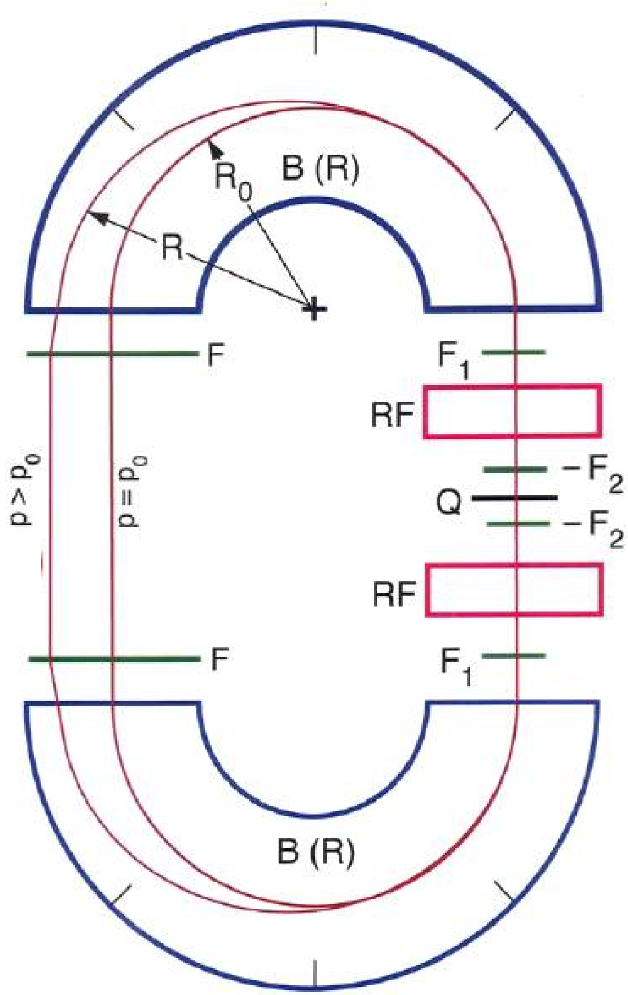
RFQ to flip tunes

Higher multipoles

spin coherence

More details in A. Luccio's talk

Velocity Modulation



Parameters

Support RF-Cavity

h_0 = 20-40

V_0 = 10-20MV

free f_L *close to* f_S

Driving RF-Cavity

$h_1 = h_0 + a\gamma$

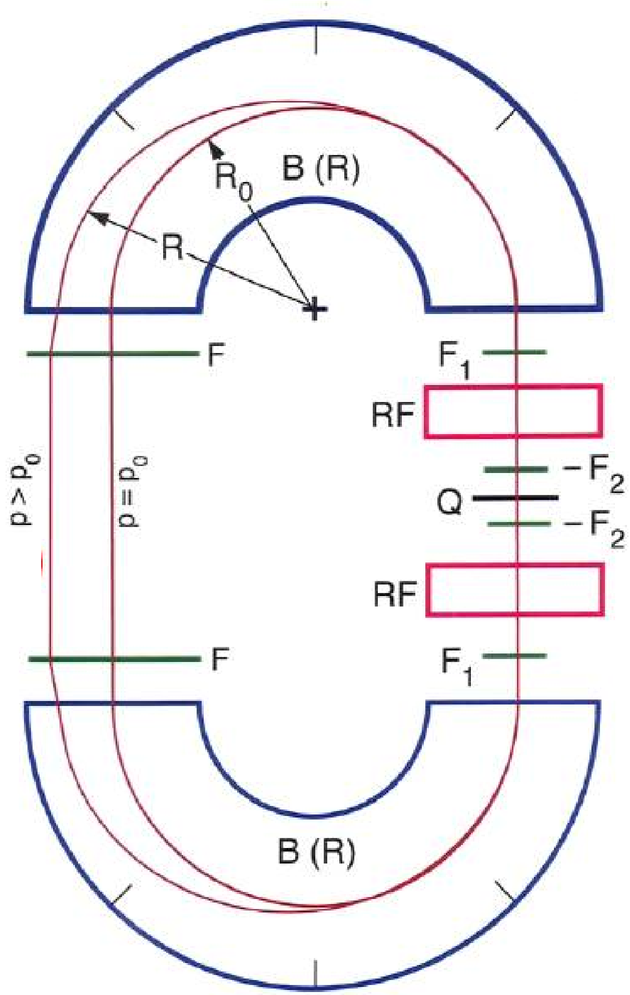
$V_1 \ll V_0$

force $f_L = f_S$

Need ν_L = 0.18

For Δv/v ~ 1%, ΔE = 0.01<vxB> = 10kV/cm

Spin Coherence



Aiming for 10-1000s

Coherence time of 10^7 spin turns @ VEPP-2M

More details in Y. Orlov's talk

Polarimetry

Efficiently resolve *time dependence* of spin

- fast oscillating <u>horizontal</u> spin component (few MHz)
  use to phase-lock velocity modulation to spin
- slow growing <u>vertical</u> spin component (≤nHz)
  EDM signal

Possible via *spin-dependent* nuclear scattering

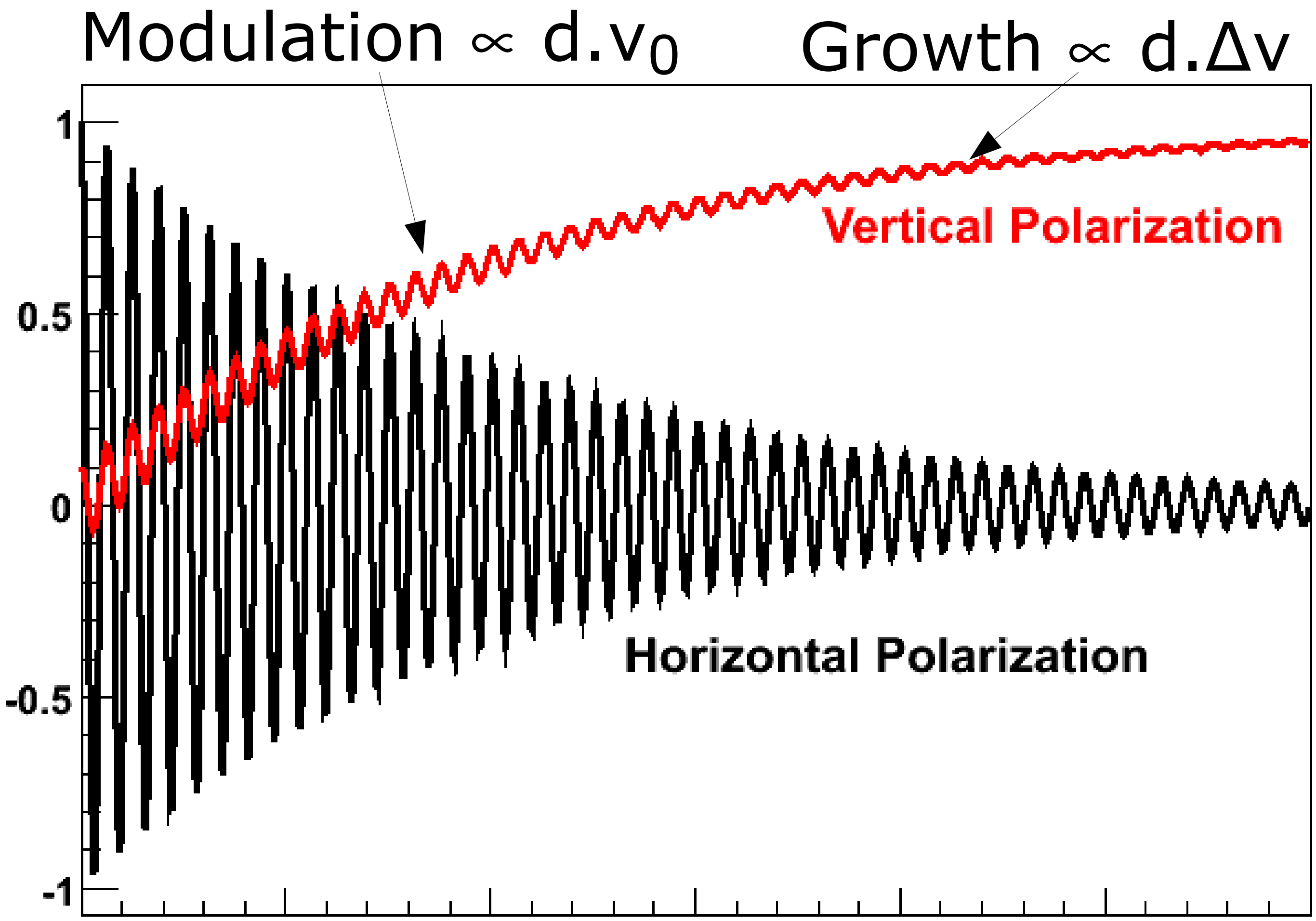
slowly extract beam to scatter from analyzer

$$\sigma(\theta,\phi)=\sigma_{unp}(\theta)\left(1+pA(\theta)\cos(\phi)\right)$$

at 1.5GeV/*c*, **ε~2%** and **A~0.4** seem doable

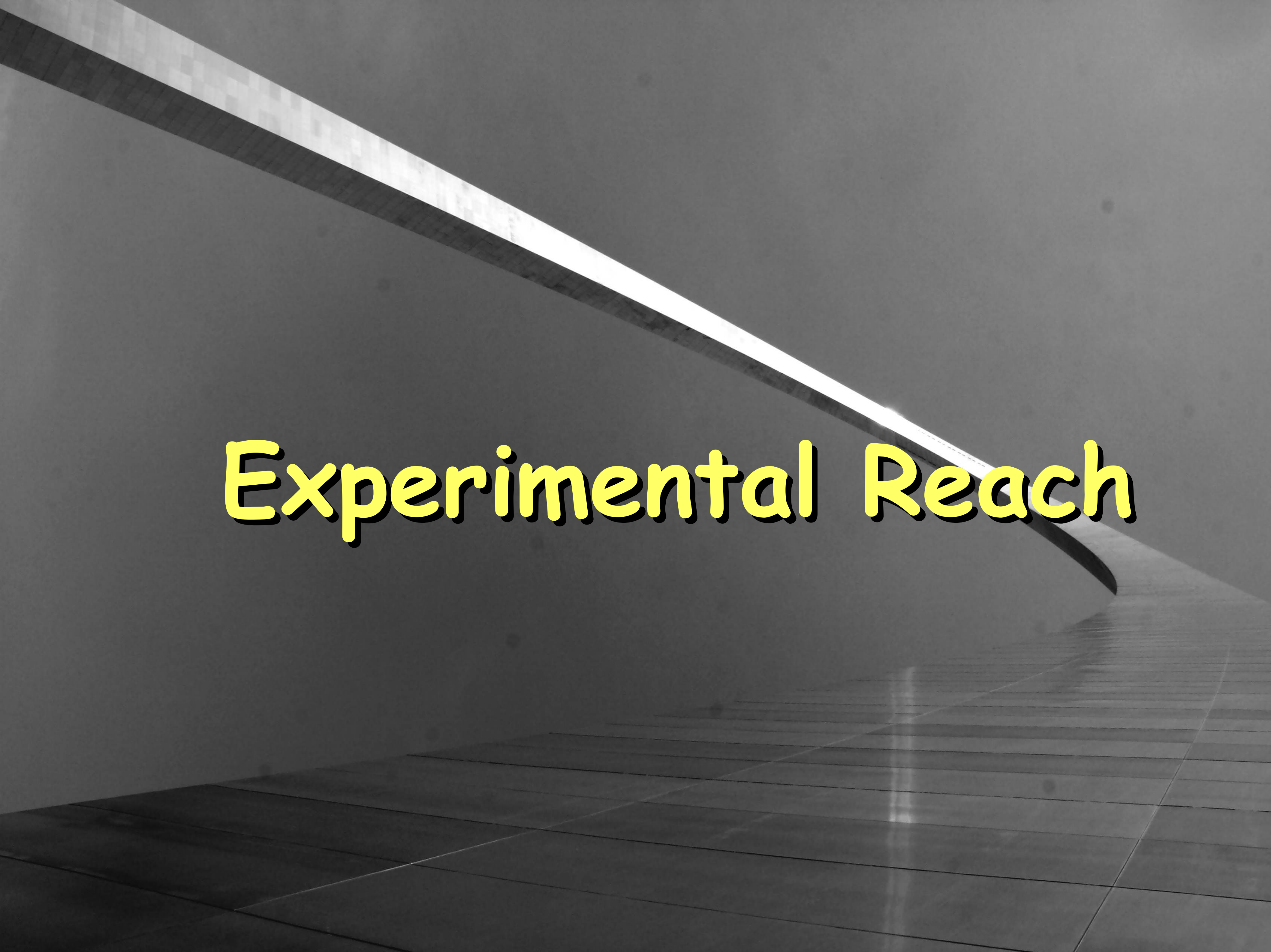
More details in G. Venanzoni's talk

Signal



Modulation ∝ d.v0
Growth ∝ d.Δv
1
0.5
0
-0.5
-1
Vertical Polarization
Horizontal Polarization

Experimental Reach



Statistical Sensitivity

P: Polarization

P_z = 90-95% available

E: Effective Electric Field

E = <v x B> = 112MV/m

dE = 1% . E = 11kV/cm

N: Source Intensity

10^{12} injected

2% detected

T: Time Scale

coherence 10-1000s feasible

beam lifetime ~ spin lifetime

A: Analyzing Power

A~0.4 typical

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

$d_D \sim 10^{-29}$ e·cm

↔

$\omega_{EDM} \sim$ 1 nrad/s

↔

$\Delta P_z \sim 10^{-6}$

Doable in ~1 year of beamtime!

Two Classes of Systematics

Beam and Polarimeter Related

collective effects,
beam/polarimeter displacement/orientation,
polarimeter rate effects, ...

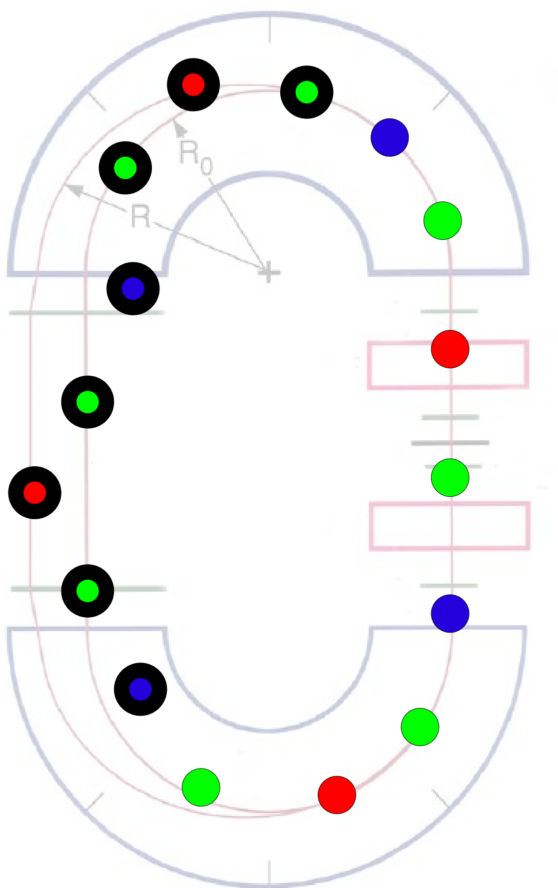
Spin Dynamics Related

second order spin resonances,
$<B_r.p> \neq 0$,
geometric phase from B_V and B_L, ...

Remedies

Temporal & spatial dependence
(Simultaneously) run “experiments” under different conditions
vertical tune $\rightarrow$ all background depend on it, EDM does not
spin-synchrotron phase $\rightarrow$ EDM affected, not backgrounds
extraction rate, source polarization, injection direction, ...

Simultaneous Experiments



$$\left\langle \frac{dS_z}{dt} \right\rangle \propto \frac{1}{4} \eta\, B\, S_0\, dv \cos\phi$$

- (red) Cosφ = -1 $S_z \propto$ +EDM
- (green) Cosφ = 0 $S_z \propto$ no EDM
- (blue) Cosφ = +1 $S_z \propto$ -EDM

- (open circle) true EDM bunch ($\nu_{y} \neq \nu_{S}$)
- (black ring) fake EDM bunch ($\nu_{y} \sim \nu_{S}$)

highly sensitive to field perturbations

Magnetometer, field-flip & *imperfection probe*

More details in Y. Orlov's talk

Towards Realization

Simulations

beam dynamics $\rightarrow$ acceptance, coherence, systematics
detector acceptance $\rightarrow$ efficiency & robustness
suitability for other particles (p, ^{3}He, ...)*
...

Technical Feasibility

RF system
polarimeter
injection, ejection
...

Funding

LOI @ Brookhaven $\rightarrow$ expert support
VIDI @ KVI $\rightarrow$ polarimeter development
Full proposal planned for FY07
...

***More details in W. Morse's talk**

Collaboration

2006 BNL LOI

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

Summary

W. Marciano

Theoretical Perspective

EDMs Violate P+T Symmetries (N. Ramsey d_n)

Standard Model: $|d_n| \sim 10^{-31}-10^{-32}$ e-cm $|d_e| \sim 10^{-40}$ e-cm

Currently unobservable

Window to "New Physics" (eg Supersymmetry $d_n \sim 10^{-25}-10^{-28}$ e-cm)

BNL L.O.I. Goal: $d_D \to 10^{-29}$ e-cm! Spectacular!

Competitive (Better) - Other EDM Exps.

Clean (Theory) - Simple pn bound state (No Schiff shielding)

Complementary - LHC + Other EDMs ...

Compelling - $M_{CP} \sim$ 1-1000 TeV (SUSY, LR, Higgs...)

Baryogenesis!

Experimental Perspective

Resonance method a new sensitive tool to search for EDMs

All major concept are in place

Established accelerator-physics techniques can be used to assure intrinsic sensitivity

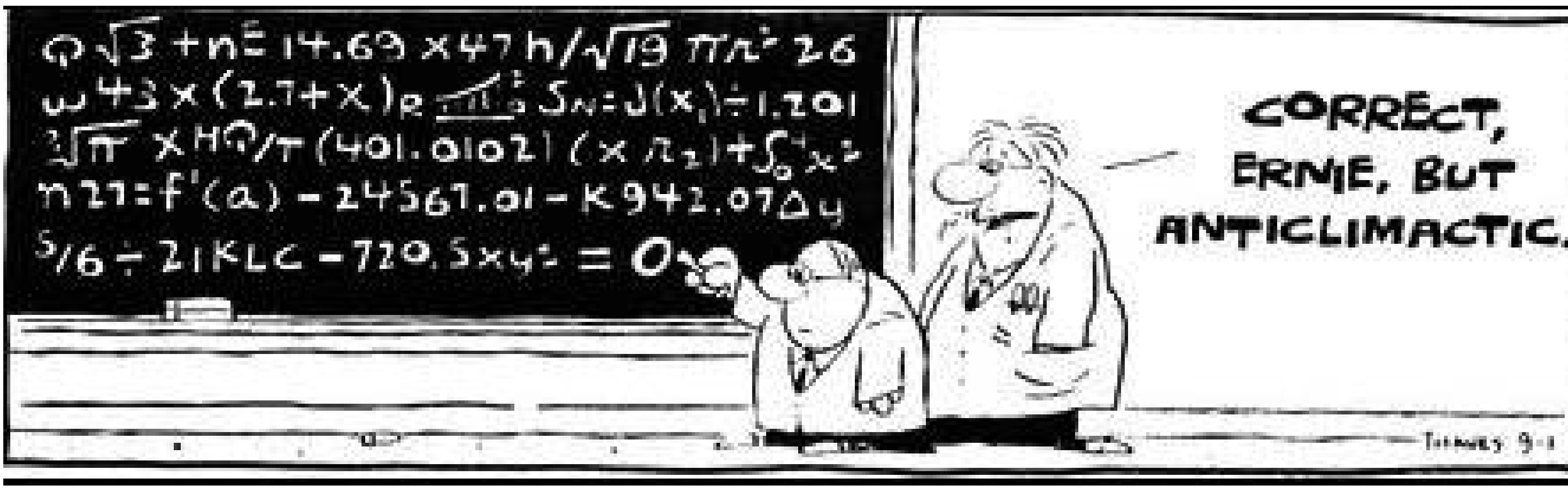
Existing polarized deuteron sources provide high intensity, highly polarized beams

Polarimetry based on nuclear scattering provides high sensitivity at reasonable efficiency

Sensitivity of d_D ~ 10-29 e·cm reachable

Work going on to confirm statistic and systematic (in)sensitivity

Totally different systematic issues wrt. other EDM searches


CORRECT, ERNIE, BUT ANTICLIMACTIC.