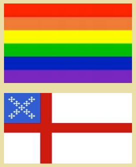
Ernest Henley: Parity-Violation and the Anapole Moment

M.J. Ramsey-Musolf

U Mass Amherst



AMHERST CENTER FOR FUNDAMENTAL INTERACTIONS

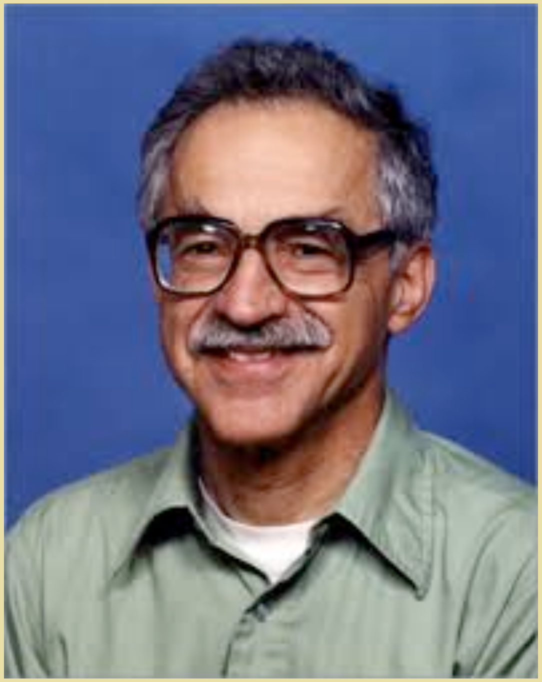
Physics at the interface: Energy, Intensity, and Cosmic frontiers

University of Massachusetts Amherst

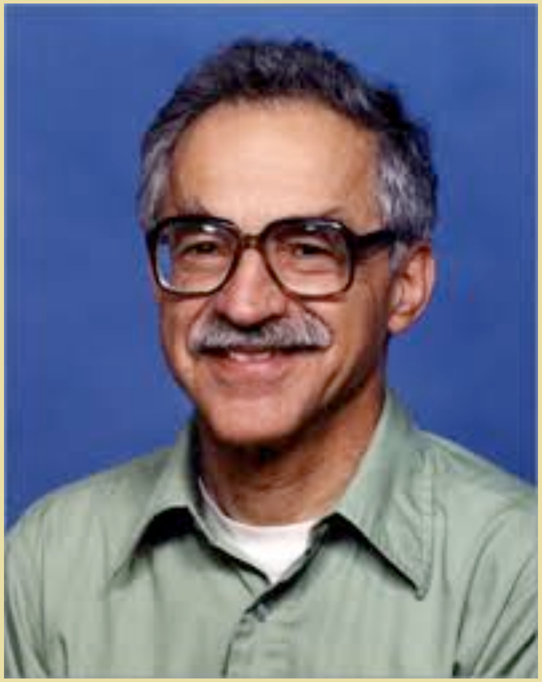
http://www.physics.umass.edu/acfi/

Henley Symposium, INT
9/11/18

Ernest Henley: Role Model & Mentor



Ernest Henley & Pauchy Hwang



1924-2017

1948-2018

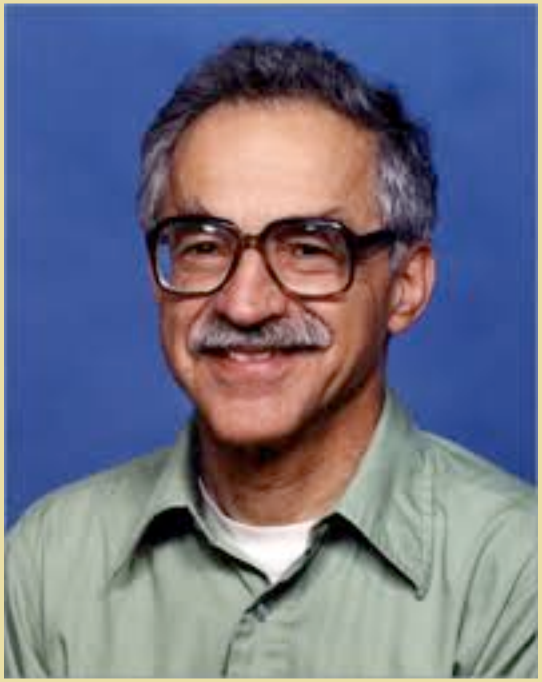
28 Coauthored Papers

Outline

I. *Context*
II. *Hadronic Parity Violation*
III. *Anapole Moment*
IV. *Anapole Moment & PV Electron Scattering*
V. *Summary*

I. Context

Ernest Henley & Parity Violation



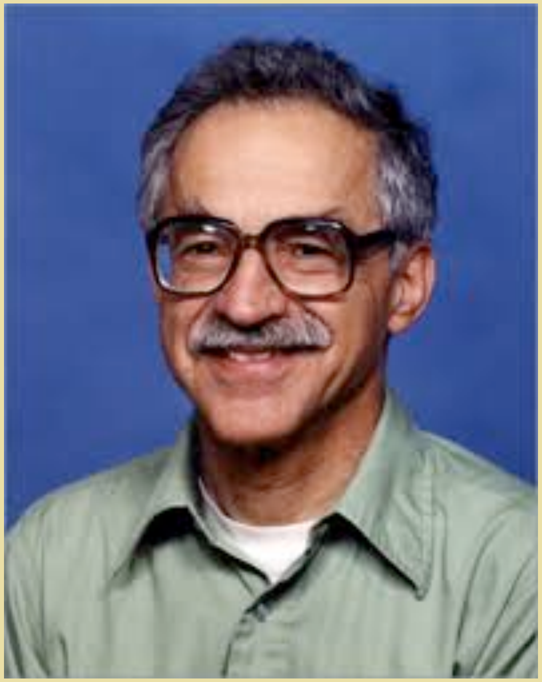
> 40 papers in 30 years !

- *PV π NN coupling*
- *Polarized ep, eD, pp scattering*
- *PV pA, AA scattering*
- *Nuclear PV*
- *Atomic PV*
- *Anapole moment*

- *1968: Nuclear Parity Violation Tests of Nonleptonic Weak Currents Physics Letters B*

- *1996: The Weak Parity Violating Pion-Nucleon Coupling Physics Letters B*

Ernest Henley & Parity Violation



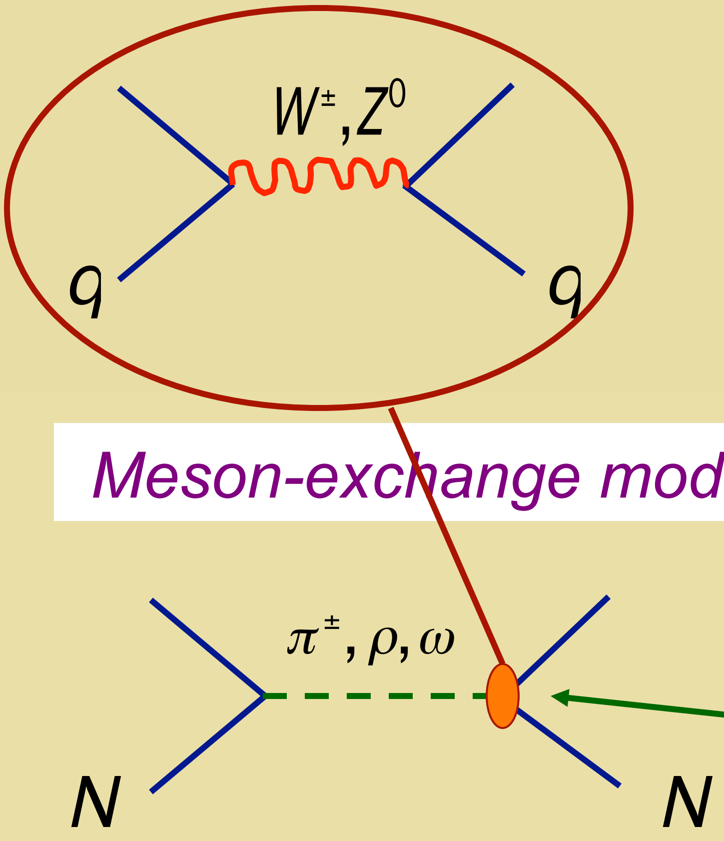
This talk: connecting Ernie's parity violating passions

- *PV π NN coupling*
- *Polarized ep, eD, pp scattering*
- *PV pA, AA scattering*
- *Nuclear PV*
- *Atomic PV*
- *Anapole moment*

- *1968: Nuclear Parity Violation Tests of Nonleptonic Weak Currents Physics Letters B*
- *1996: The Weak Parity Violating Pion-Nucleon Coupling Physics Letters B*

II. Nuclear Parity Violation

$\Delta S = 0$ Hadronic Weak Interaction



Meson-exchange model

Nuclear effects:
$\lambda_{W,Z}$ ~ 0.002 fm << R_{core}

Seven PV meson-nucleon couplings

h_π^1, $h_\rho^{0,1,2}$, $h_\omega^{0,1}$, $h_\rho^{1\prime}$

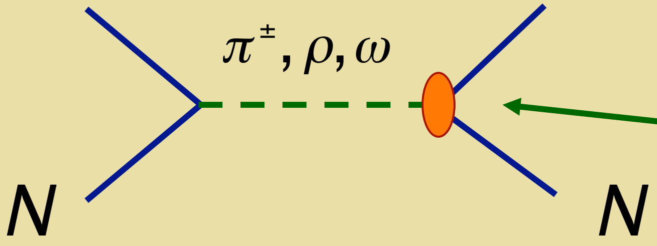
Use parity-violation to filter out EM & strong interactions

Desplanques, Donoghue, & Holstein (DDH)

$\Delta S = 0$ Hadronic Weak Interaction

Meson-exchange model

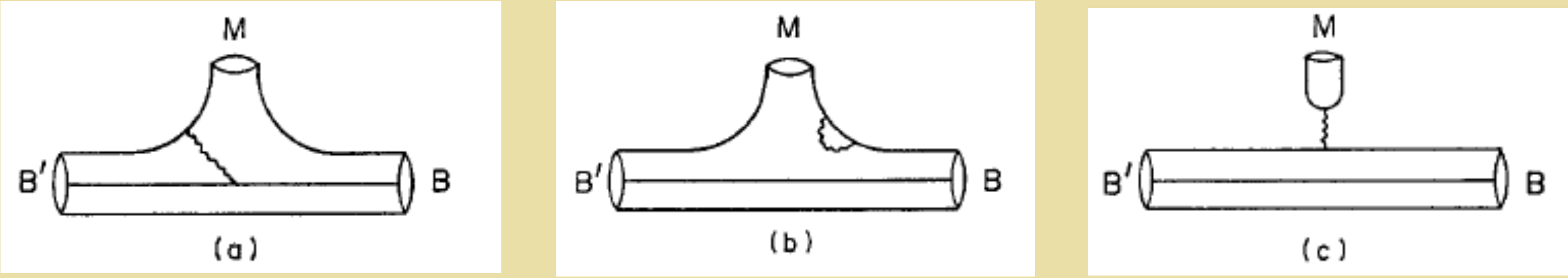
Seven PV meson-nucleon couplings



$$h_{\pi}^{1},\ h_{\rho}^{0,1,2},\ h_{\omega}^{0,1},\ h_{\rho}^{1\,\prime}$$

How to compute couplings from 4q interaction ?

Desplanques, Donoghue, & Holstein (DDH): $SU(6)_w$ + Quark Model



$\Delta S = 0$ Hadronic Weak Interaction

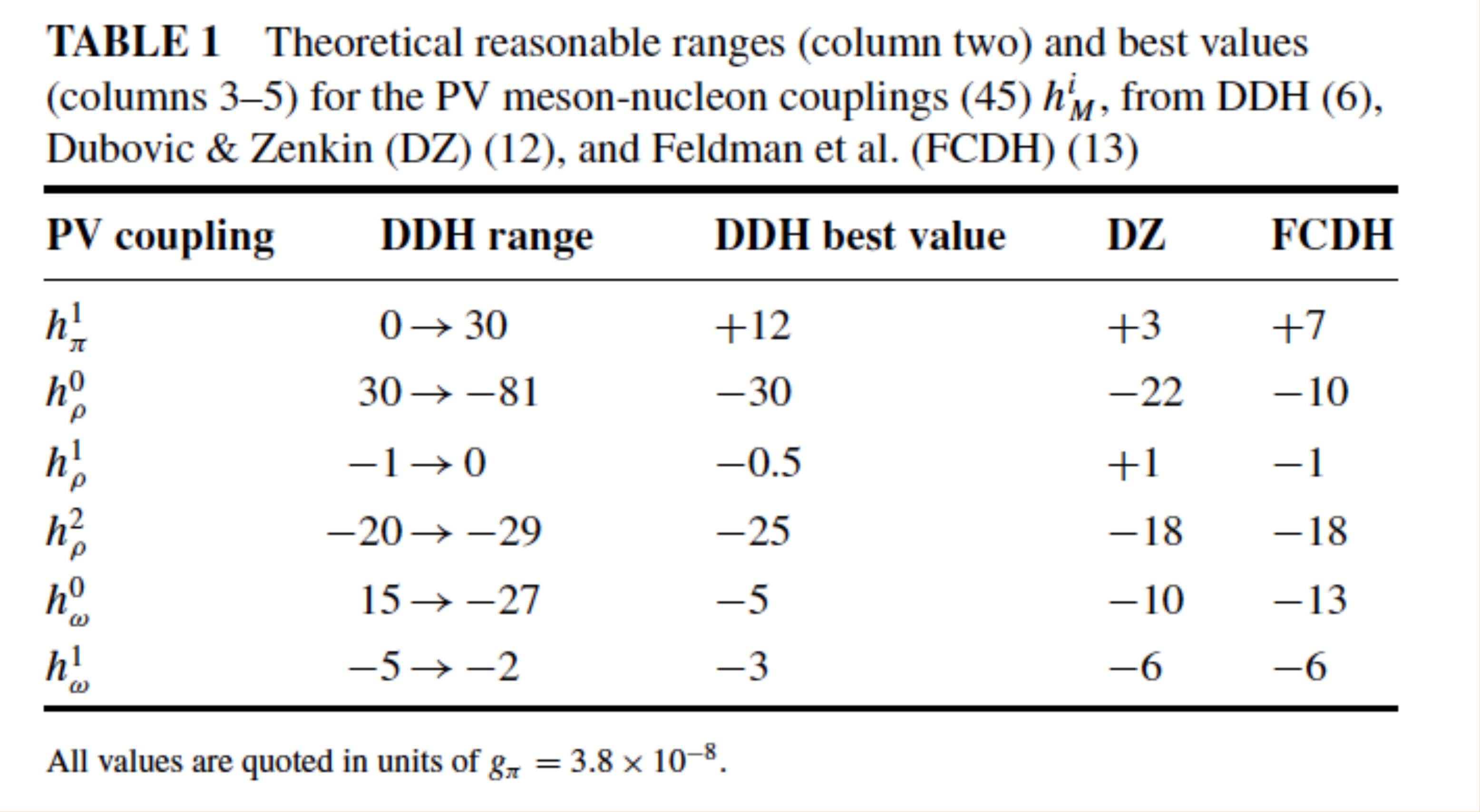


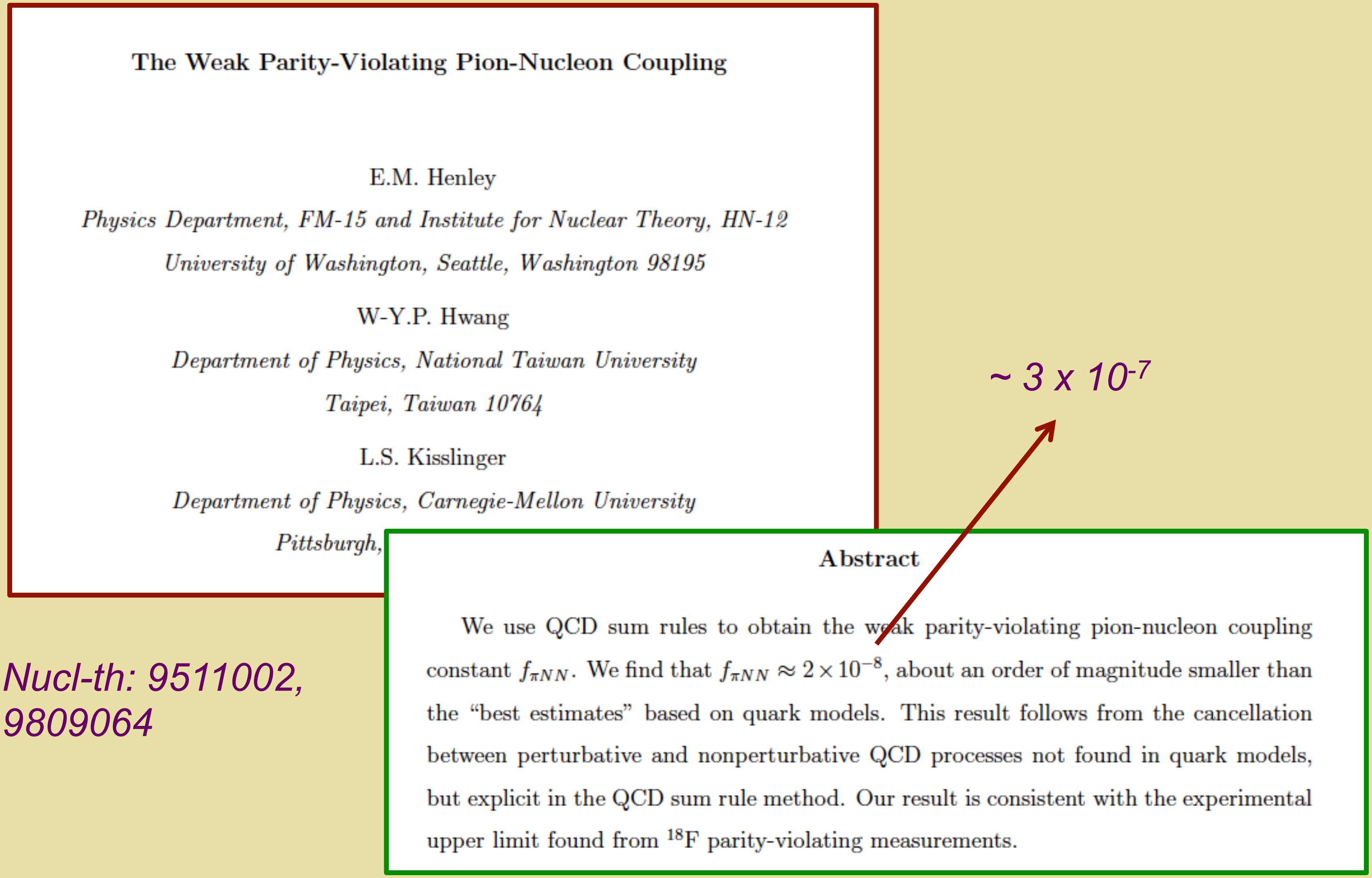
TABLE 1 Theoretical reasonable ranges (column two) and best values (columns 3–5) for the PV meson-nucleon couplings (45) h^i_M, from DDH (6), Dubovic & Zenkin (DZ) (12), and Feldman et al. (FCDH) (13)

PV coupling	**DDH range**	**DDH best value**	**DZ**	**FCDH**
h^1_π	$0 \rightarrow 30$	$+12$	$+3$	$+7$
h^0_ρ	$30 \rightarrow -81$	-30	-22	-10
h^1_ρ	$-1 \rightarrow 0$	-0.5	$+1$	-1
h^2_ρ	$-20 \rightarrow -29$	-25	-18	-18
h^0_ω	$15 \rightarrow -27$	-5	-10	-13
h^1_ω	$-5 \rightarrow -2$	-3	-6	-6

All values are quoted in units of $g_\pi = 3.8 \times 10^{-8}$.

S. Page & MJRM ‘06

$\Delta S = 0$ Hadronic Weak Interaction



The Weak Parity-Violating Pion-Nucleon Coupling

E.M. Henley

Physics Department, FM-15 and Institute for Nuclear Theory, HN-12

University of Washington, Seattle, Washington 98195

W-Y.P. Hwang

Department of Physics, National Taiwan University

Taipei, Taiwan 10764

L.S. Kisslinger

Department of Physics, Carnegie-Mellon University

Pittsburgh,

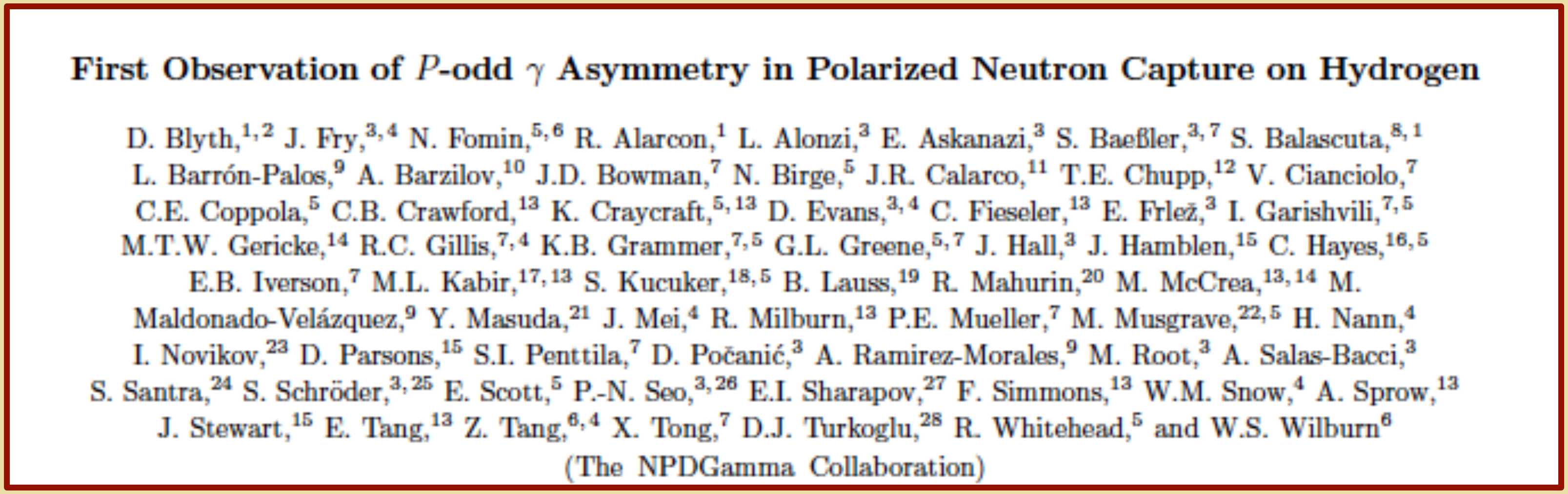
Abstract

We use QCD sum rules to obtain the weak parity-violating pion-nucleon coupling constant $f_{\pi NN}$. We find that $f_{\pi NN} \approx 2 \times 10^{-8}$, about an order of magnitude smaller than the "best estimates" based on quark models. This result follows from the cancellation between perturbative and nonperturbative QCD processes not found in quark models, but explicit in the QCD sum rule method. Our result is consistent with the experimental upper limit found from ^{18}F parity-violating measurements.

$\sim 3 \times 10^{-7}$

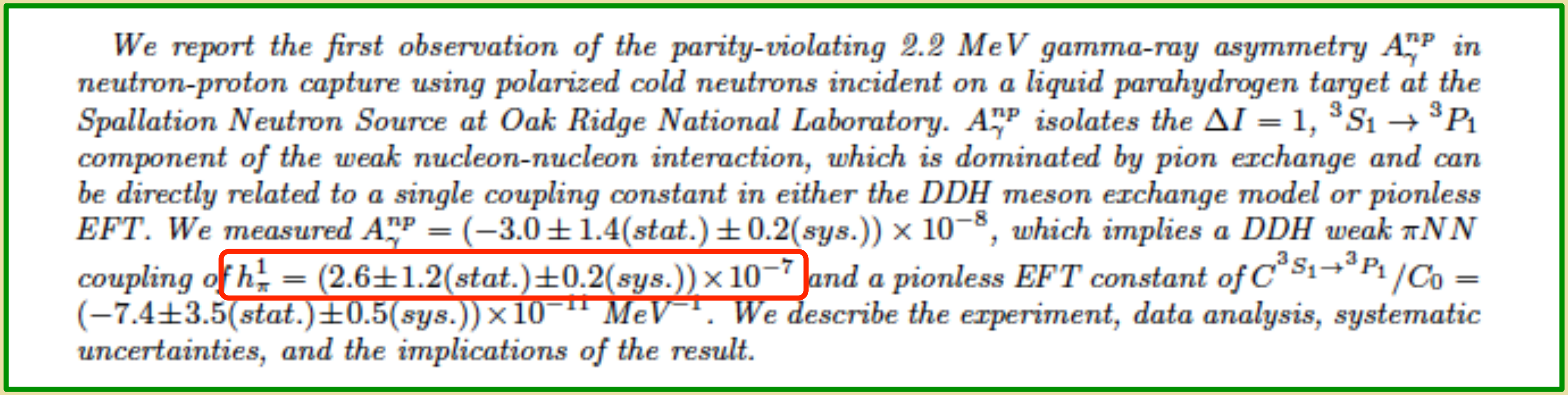
Nucl-th: 9511002, 9809064

$\Delta S = 0$ Hadronic Weak Interaction



First Observation of P-odd γ Asymmetry in Polarized Neutron Capture on Hydrogen

D. Blyth,[1,2] J. Fry,[3,4] N. Fomin,[5,6] R. Alarcon,[1] L. Alonzi,[3] E. Askanazi,[3] S. Baeßler,[3,7] S. Balascuta,[8,1] L. Barrón-Palos,[9] A. Barzilov,[10] J.D. Bowman,[7] N. Birge,[5] J.R. Calarco,[11] T.E. Chupp,[12] V. Cianciolo,[7] C.E. Coppola,[5] C.B. Crawford,[13] K. Craycraft,[5,13] D. Evans,[3,4] C. Fieseler,[13] E. Frlež,[3] I. Garishvili,[7,5] M.T.W. Gericke,[14] R.C. Gillis,[7,4] K.B. Grammer,[7,5] G.L. Greene,[5,7] J. Hall,[3] J. Hamblen,[15] C. Hayes,[16,5] E.B. Iverson,[7] M.L. Kabir,[17,13] S. Kucuker,[18,5] B. Lauss,[19] R. Mahurin,[20] M. McCrea,[13,14] M. Maldonado-Velázquez,[9] Y. Masuda,[21] J. Mei,[4] R. Milburn,[13] P.E. Mueller,[7] M. Musgrave,[22,5] H. Nann,[4] I. Novikov,[23] D. Parsons,[15] S.I. Penttila,[7] D. Počanić,[3] A. Ramirez-Morales,[9] M. Root,[3] A. Salas-Bacci,[3] S. Santra,[24] S. Schröder,[3,25] E. Scott,[5] P.-N. Seo,[3,26] E.I. Sharapov,[27] F. Simmons,[13] W.M. Snow,[4] A. Sprow,[13] J. Stewart,[15] E. Tang,[13] Z. Tang,[6,4] X. Tong,[7] D.J. Turkoglu,[28] R. Whitehead,[5] and W.S. Wilburn[6]
(The NPDGamma Collaboration)



We report the first observation of the parity-violating 2.2 MeV gamma-ray asymmetry A_γ^{np} *in neutron-proton capture using polarized cold neutrons incident on a liquid parahydrogen target at the Spallation Neutron Source at Oak Ridge National Laboratory.* A_γ^{np} *isolates the* $\Delta I = 1$, ${}^3S_1 \rightarrow {}^3P_1$ *component of the weak nucleon-nucleon interaction, which is dominated by pion exchange and can be directly related to a single coupling constant in either the DDH meson exchange model or pionless EFT. We measured* $A_\gamma^{np} = (-3.0 \pm 1.4(stat.) \pm 0.2(sys.)) \times 10^{-8}$, *which implies a DDH weak* πNN *coupling of* $h_\pi^1 = (2.6 \pm 1.2(stat.) \pm 0.2(sys.)) \times 10^{-7}$ *and a pionless EFT constant of* $C^{{}^3S_1 \rightarrow {}^3P_1}/C_0 = (-7.4 \pm 3.5(stat.) \pm 0.5(sys.)) \times 10^{-11}\ MeV^{-1}$. *We describe the experiment, data analysis, systematic uncertainties, and the implications of the result.*

1807.10192 [nucl-ex]

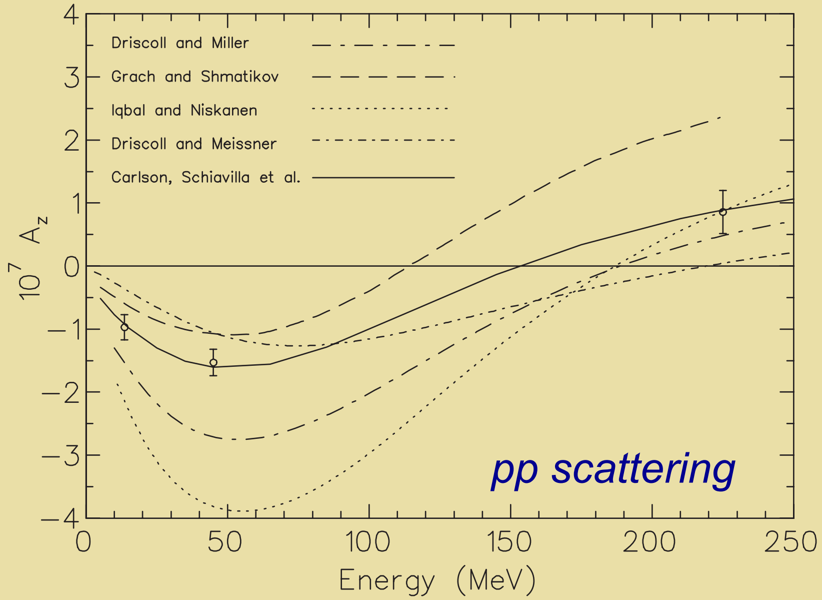
PV NN Interaction

$$
\begin{aligned}
V^{\mathrm{PV}}_{\mathrm{DDH}}(\vec{r}) = {} & i\frac{h^1_\pi g_A m_N}{\sqrt{2}F_\pi}\left(\frac{\tau_1\times\tau_2}{2}\right)_3(\vec{\sigma}_1+\vec{\sigma}_2)\cdot\left[\frac{\vec{p}_1-\vec{p}_2}{2m_N}, w_\pi(r)\right] \\
& - g_\rho\left(h^0_\rho\tau_1\cdot\tau_2 + h^1_\rho\left(\frac{\tau_1+\tau_2}{2}\right)_3 + h^2_\rho\frac{(3\tau_1^3\tau_2^3-\tau_1\cdot\tau_2)}{2\sqrt{6}}\right) \\
& \times\Biggl((\vec{\sigma}_1-\vec{\sigma}_2)\cdot\left\{\frac{\vec{p}_1-\vec{p}_2}{2m_N}, w_\rho(r)\right\} \\
& + i(1+\chi_\rho)\vec{\sigma}_1\times\vec{\sigma}_2\cdot\left[\frac{\vec{p}_1-\vec{p}_2}{2m_N}, w_\rho(r)\right]\Biggr) \\
& - g_\omega\left(h^0_\omega + h^1_\omega\left(\frac{\tau_1+\tau_2}{2}\right)_3\right) \\
& \times\Biggl((\vec{\sigma}_1-\vec{\sigma}_2)\cdot\left\{\frac{\vec{p}_1-\vec{p}_2}{2m_N}, w_\omega(r)\right\} \\
& + i(1+\chi_\omega)\vec{\sigma}_1\times\vec{\sigma}_2\cdot\left[\frac{\vec{p}_1-\vec{p}_2}{2m_N}, w_\omega(r)\right]\Biggr) \\
& -\left(g_\omega h^1_\omega - g_\rho h^1_\rho\right)\left(\frac{\tau_1-\tau_2}{2}\right)_3(\vec{\sigma}_1+\vec{\sigma}_2)\cdot\left\{\frac{\vec{p}_1-\vec{p}_2}{2m_N}, w_\rho(r)\right\} \\
& - g_\rho h'^1_\rho i\left(\frac{\tau_1\times\tau_2}{2}\right)_3(\vec{\sigma}_1+\vec{\sigma}_2)\cdot\left[\frac{\vec{p}_1-\vec{p}_2}{2m_N}, w_\rho(r)\right].
\end{aligned}
$$

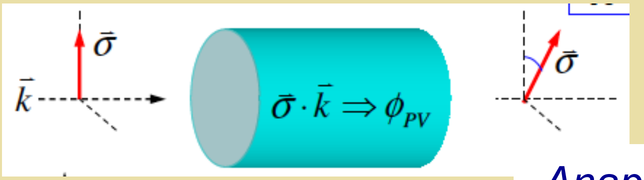
$$w_i(r) = \frac{\exp(-m_i r)}{4\pi r}$$

S. Page & MJRM ‘06

Observables

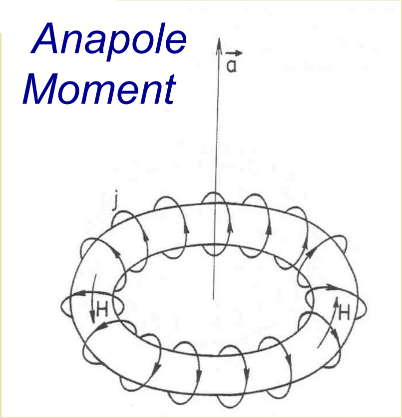


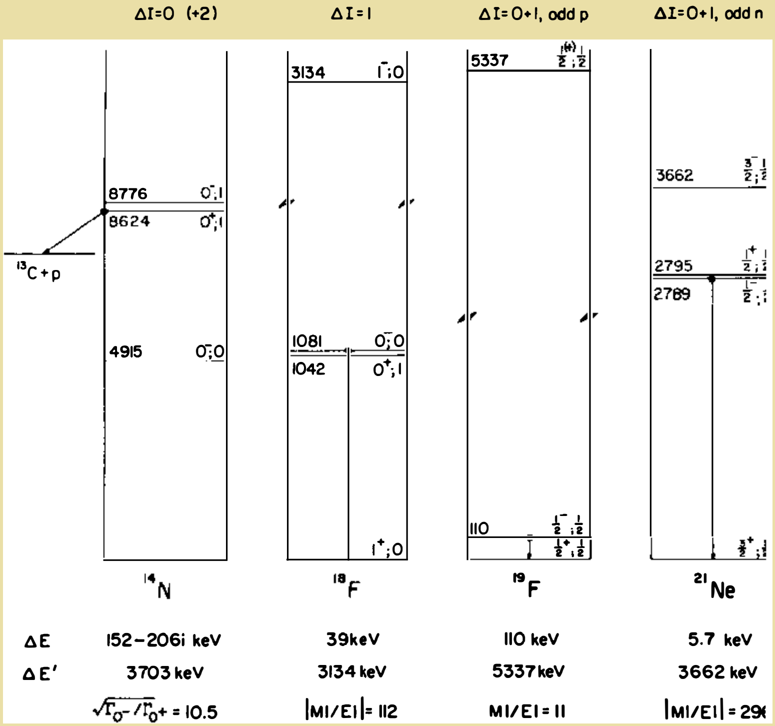
pp scattering



^{4}He spin rotation

Anapole Moment





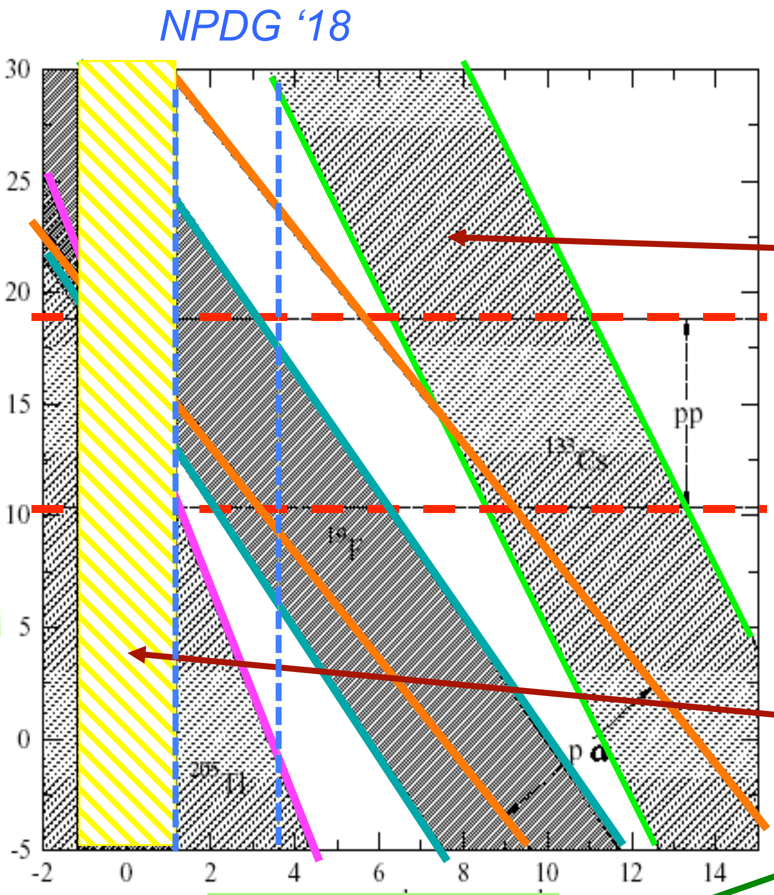
Light nuclei

Parity-doublets: nuclear amplifier

Adelberger & Haxton ‘85

S. Page & MJRM ’06

ΔS = 0 Hadronic Weak Interaction



T=0 force

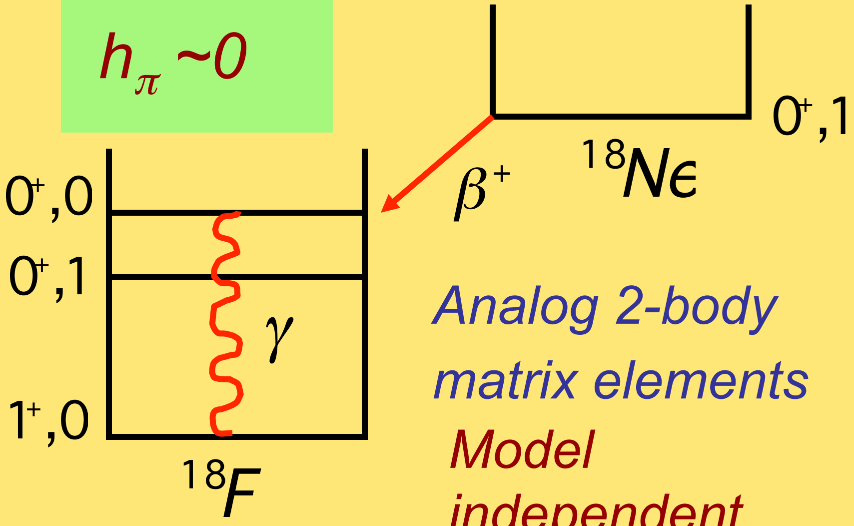
T=1 force

$h_\pi \sim 10\ g_\pi$

^{133}Cs *Anapole moment*

Boulder, atomic PV

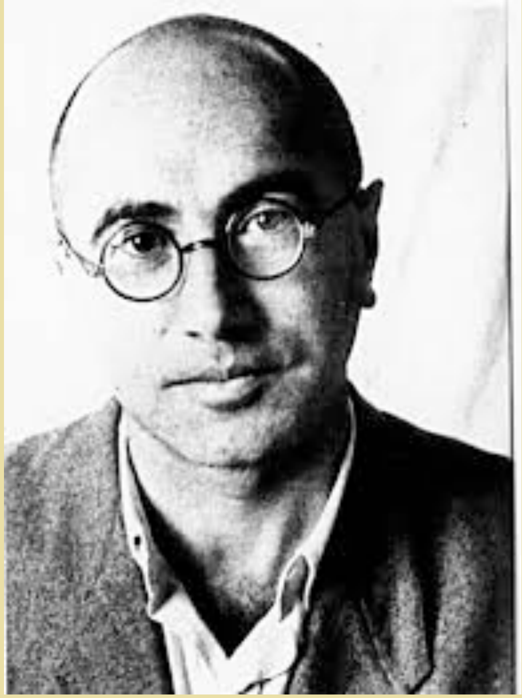
$h_\pi \sim 0$



Analog 2-body matrix elements

Model independent

III. Anapole Moment



1957

What is an Anapole Moment ?

$$\langle p'|\, J_\mu^{\mathrm{EM}}\, |p\rangle = \bar{U}(p')\left[F_1\gamma_\mu + \frac{iF_2}{2M}\sigma_{\mu\nu}q^\nu + \frac{iF_3}{2M}\sigma_{\mu\nu}\gamma_5 q^\nu + \boxed{\frac{F_A}{M^2}(q^2\gamma_\mu - \not{q}\, q_\mu)\gamma_5}\right] U(p)$$

F_1 :	Dirac (charge) form factor	P, T Conserving
F_2 :	Pauli (magnetic) ff	P, T Conserving
F_3 :	Electric Dipole ff	P, T Violating
F_A :	Anapole ff	P Violating

What is an Anapole Moment ?

Nuclear Moments

		PT	$\cancel{P}T$	$P\cancel{T}$	$\cancel{P}\cancel{T}$		
Coulomb	C_J	E	✖	✖	$\boxed{O}$	EDM, Schiff…	
Magnetic	$T^M{}_J$	O	✖	✖	$\boxed{E}$	MQM….	
Transverse electric	$T^E{}_J$	✖	$\boxed{O}$	E	✖	Anapole…	J=1

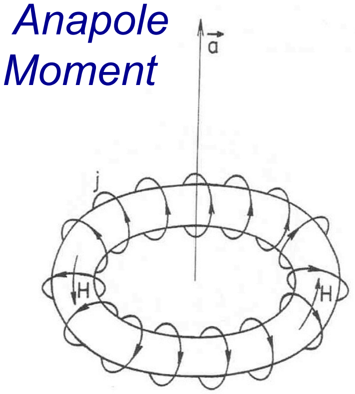
$$\vec{d} = \int d^3x\, \vec{x}\, \rho(\vec{x}) \qquad \vec{\mu} = \frac{1}{2} \int d^3x\, \vec{x} \times \vec{J}(\vec{x}) \qquad \vec{a} = \int d^3x\, x^2\, \vec{J}(\vec{x})$$

What is an Anapole Moment ?

Friar & Fallieros 1984: “Extended Siegert Theorem”

$$T^{\mathrm{el}}_{JM} = -\frac{q^{J-1}[(J+1)/J]^{1/2}}{(2J+1)!!} \times \left[H_0, \int d^3x\, x^J Y_{JM}(\hat{x}) g_J(qx) \rho(\vec{\mathrm{x}})\right] + \frac{2q^{J+1}}{(J+2)(2J+1)!!} \int d^3x\, x^J \vec{\mathrm{Y}}^{M}_{JJ} \cdot \vec{\mu}(\vec{\mathrm{x}}) h_J(qx)$$

Anapole Moment

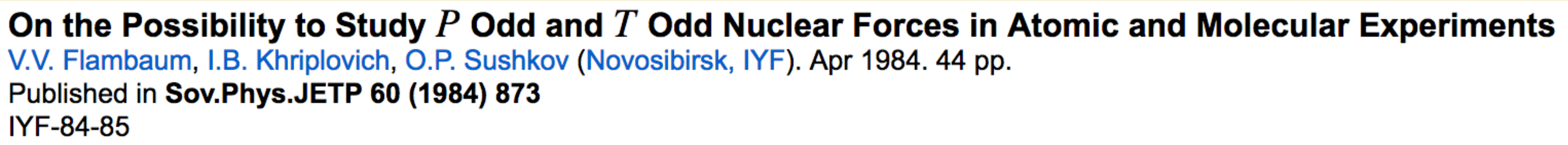


$$\boxed{\langle \mathrm{g.s.} \| E1 \| \mathrm{g.s.} \rangle \underset{\mathbf{q}^2 \to 0}{=}}$$

$$\boxed{-\frac{i\mathbf{q}^2}{9(6\pi)^{1/2}} \int d\mathbf{r}\, r^2 \langle \mathrm{g.s.} \| \mathbf{j}_{\mathrm{em}}(\mathbf{r}) + (2\pi)^{1/2} [Y_2(\Omega_r) \otimes j_{\mathrm{em}}(\mathbf{r})]_1 \| \mathrm{g.s.} \rangle}$$

Haxton, Henley, MJRM 1989

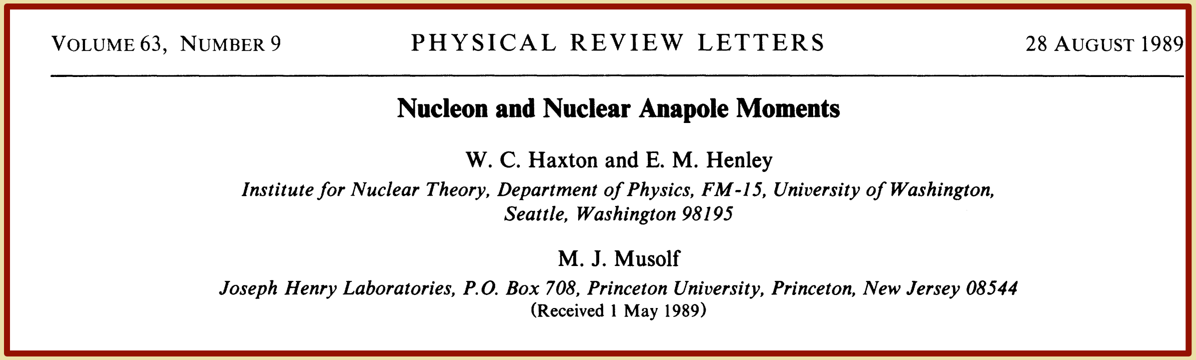
How to Look for the Anapole Moment ?



On the Possibility to Study P Odd and T Odd Nuclear Forces in Atomic and Molecular Experiments
V.V. Flambaum, I.B. Khriplovich, O.P. Sushkov (Novosibirsk, IYF). Apr 1984. 44 pp.
Published in **Sov.Phys.JETP 60 (1984) 873**
IYF-84-85

Nuclear spin-dependent contribution to atomic PV

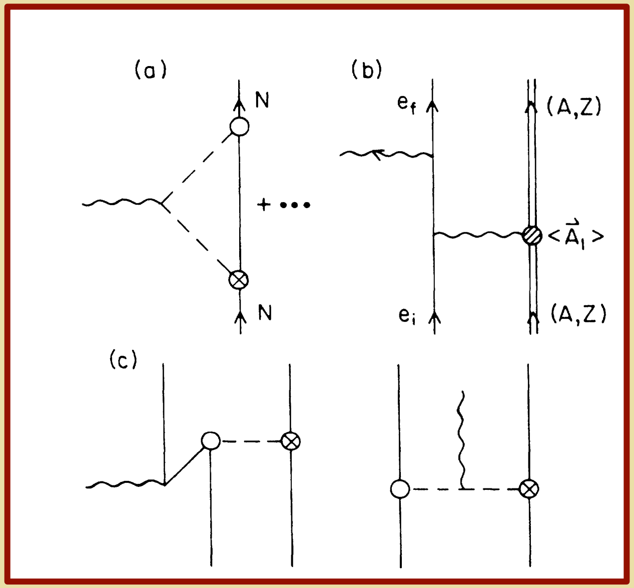
How to Compute the Anapole Moment ?

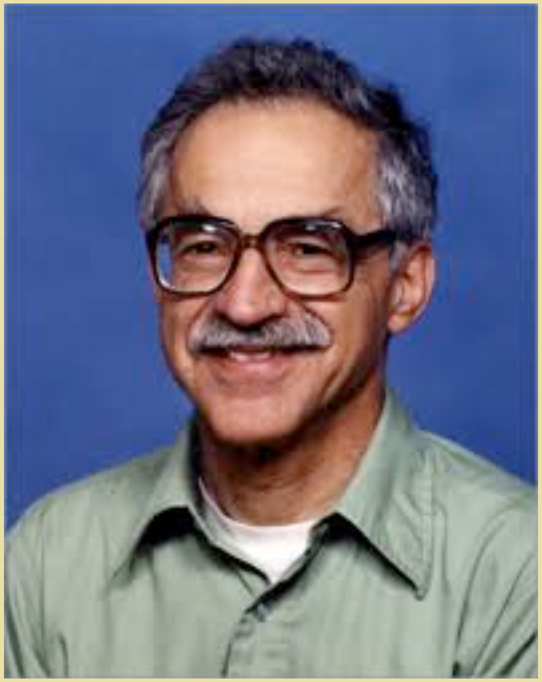

VOLUME 63, NUMBER 9 PHYSICAL REVIEW LETTERS 28 AUGUST 1989

Nucleon and Nuclear Anapole Moments

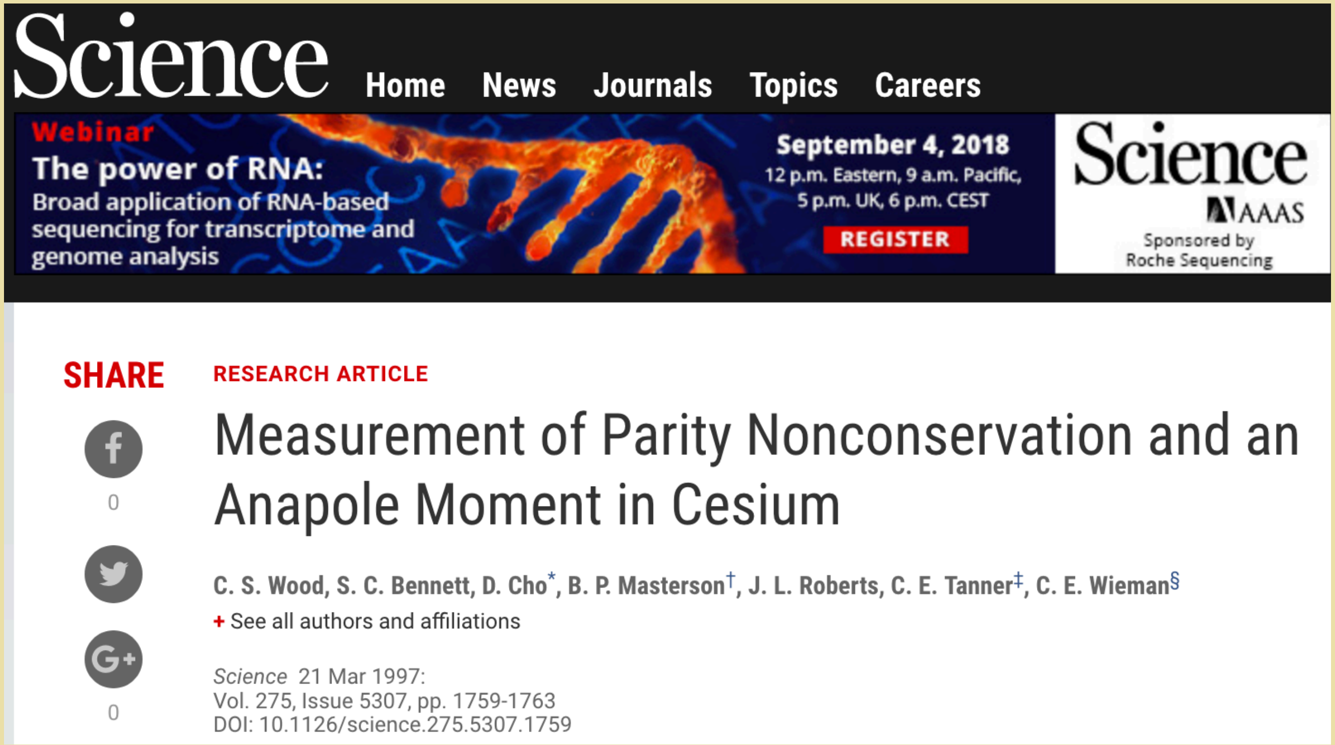
W. C. Haxton and E. M. Henley
Institute for Nuclear Theory, Department of Physics, FM-15, University of Washington,
Seattle, Washington 98195

M. J. Musolf
Joseph Henry Laboratories, P.O. Box 708, Princeton University, Princeton, New Jersey 08544
(Received 1 May 1989)





Evidence for the Anapole Moment



Webinar
The power of RNA:
Broad application of RNA-based sequencing for transcriptome and genome analysis
September 4, 2018
12 p.m. Eastern, 9 a.m. Pacific, 5 p.m. UK, 6 p.m. CEST
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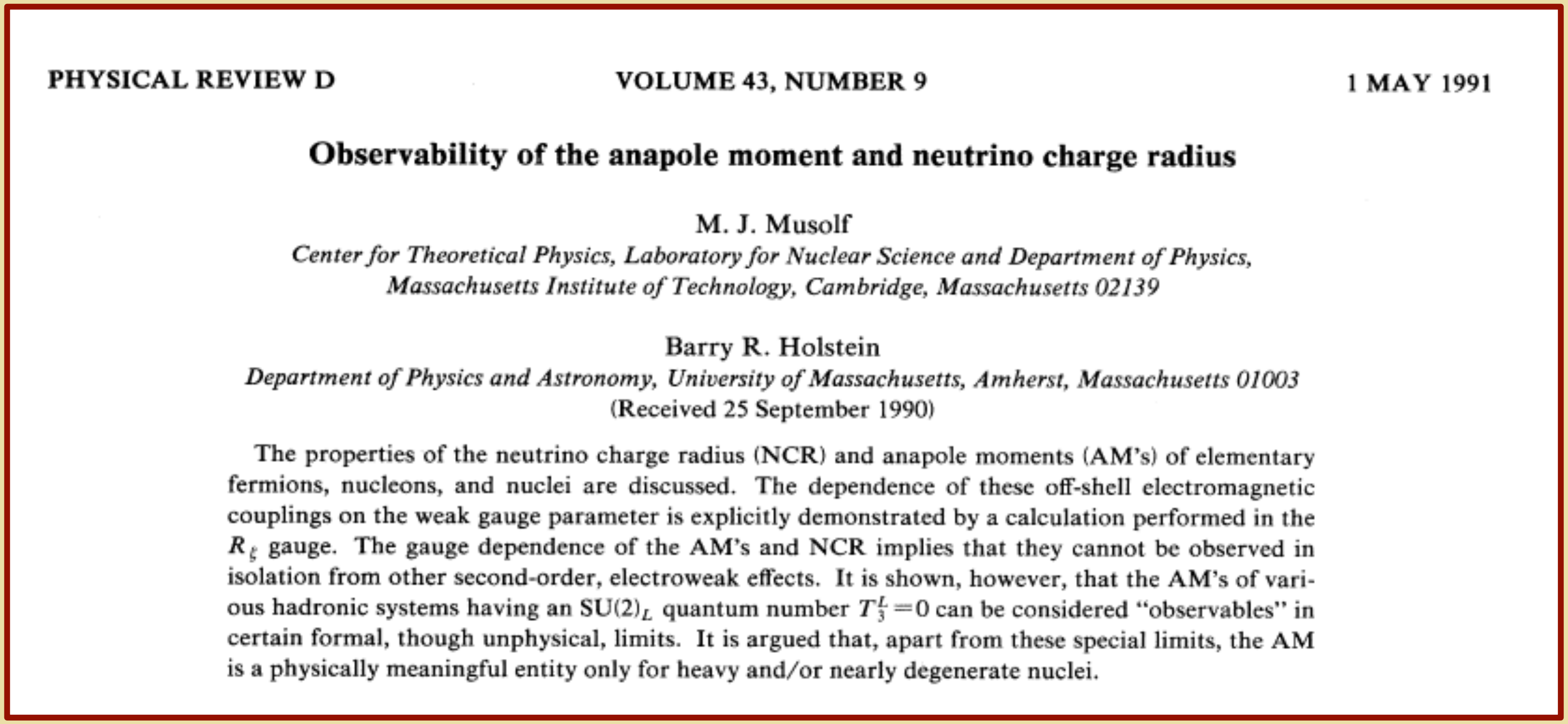
RESEARCH ARTICLE

Measurement of Parity Nonconservation and an Anapole Moment in Cesium

C. S. Wood, S. C. Bennett, D. Cho[*], B. P. Masterson[†], J. L. Roberts, C. E. Tanner[‡], C. E. Wieman[§]
+ See all authors and affiliations

Science 21 Mar 1997:
Vol. 275, Issue 5307, pp. 1759-1763
DOI: 10.1126/science.275.5307.1759

What is an Anapole Moment ?



PHYSICAL REVIEW D VOLUME 43, NUMBER 9 1 MAY 1991

Observability of the anapole moment and neutrino charge radius

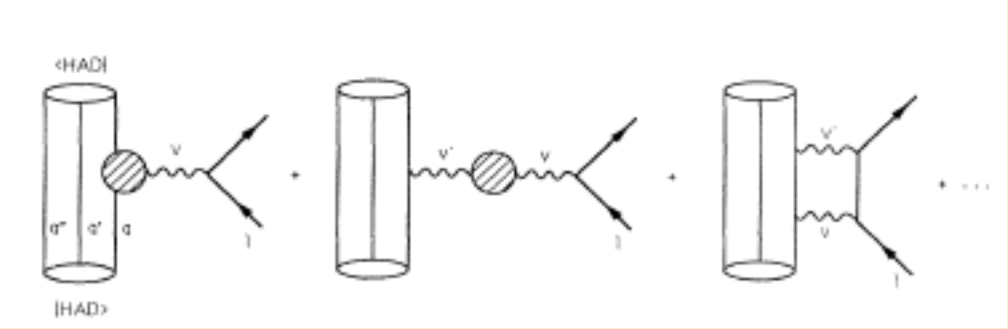
M. J. Musolf
Center for Theoretical Physics, Laboratory for Nuclear Science and Department of Physics,
Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

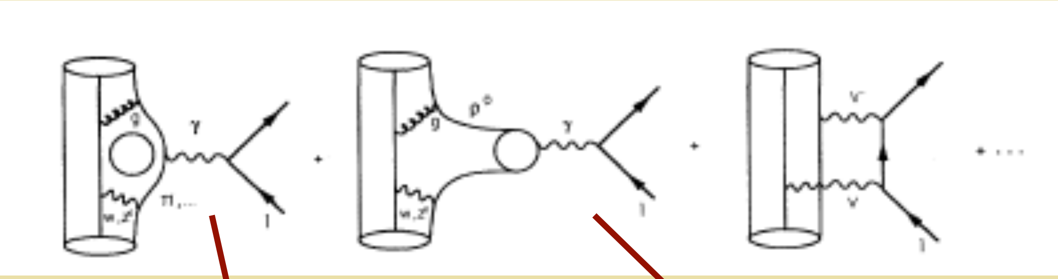
Barry R. Holstein
Department of Physics and Astronomy, University of Massachusetts, Amherst, Massachusetts 01003

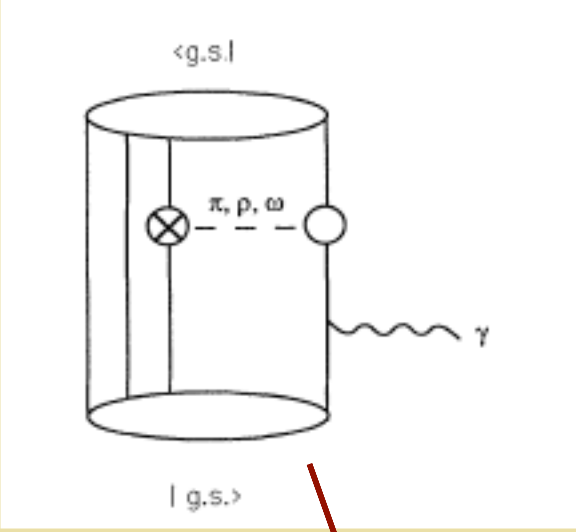
(Received 25 September 1990)

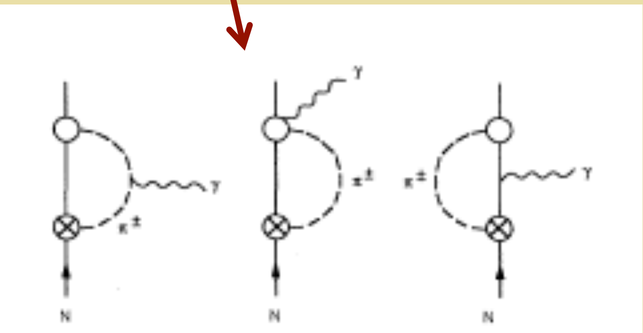
The properties of the neutrino charge radius (NCR) and anapole moments (AM's) of elementary fermions, nucleons, and nuclei are discussed. The dependence of these off-shell electromagnetic couplings on the weak gauge parameter is explicitly demonstrated by a calculation performed in the R_ξ gauge. The gauge dependence of the AM's and NCR implies that they cannot be observed in isolation from other second-order, electroweak effects. It is shown, however, that the AM's of various hadronic systems having an $SU(2)_L$ quantum number $T_3^L=0$ can be considered "observables" in certain formal, though unphysical, limits. It is argued that, apart from these special limits, the AM is a physically meaningful entity only for heavy and/or nearly degenerate nuclei.

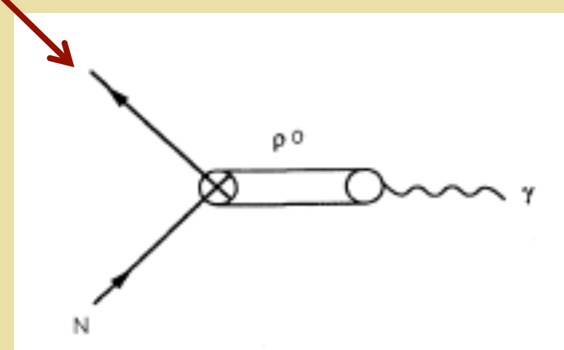
What is an Anapole Moment ?







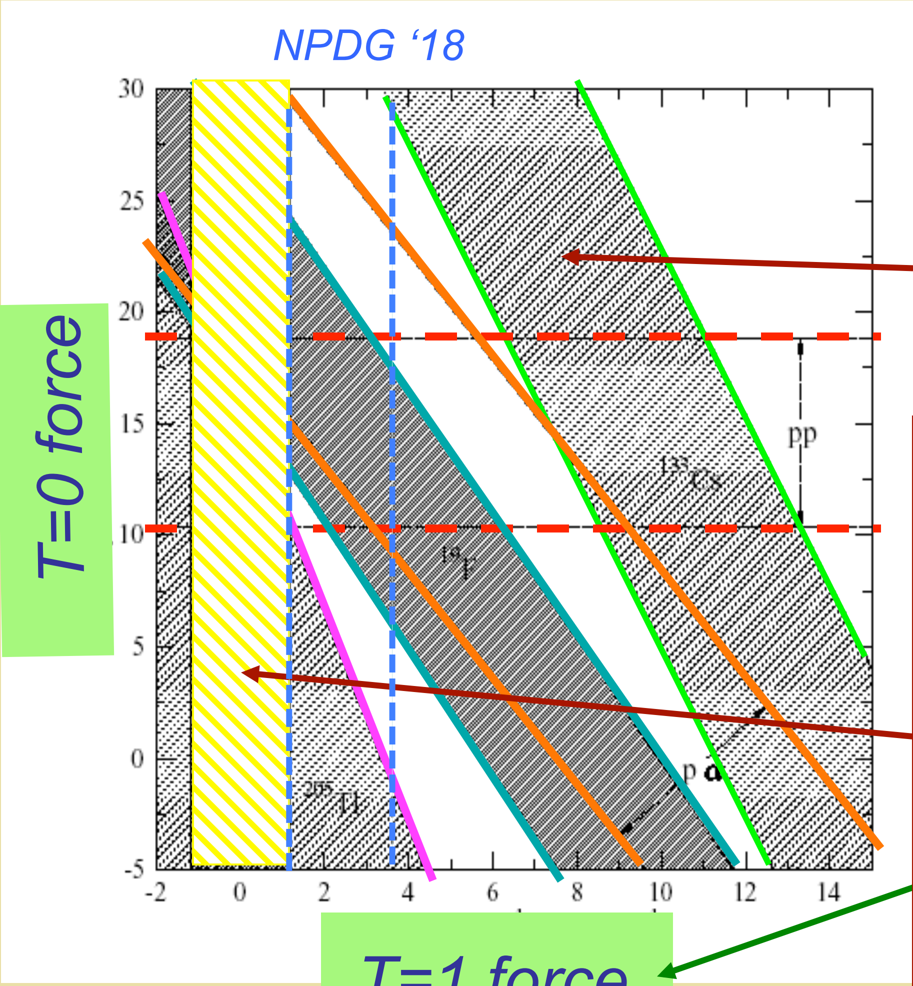




$$|\vec{a}| \sim A^{2/3}$$

Holstein, MRM ‘90

$\Delta S = 0$ Hadronic Weak Interaction



T=0 force

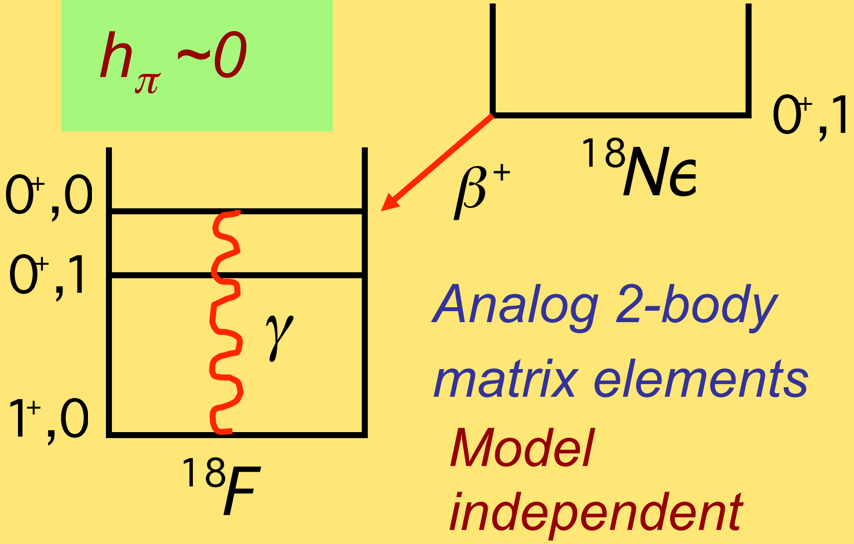
T=1 force

$h_\pi \sim 10\ g_\pi$

^{133}Cs Anapole moment

Boulder, atomic PV

$h_\pi \sim 0$

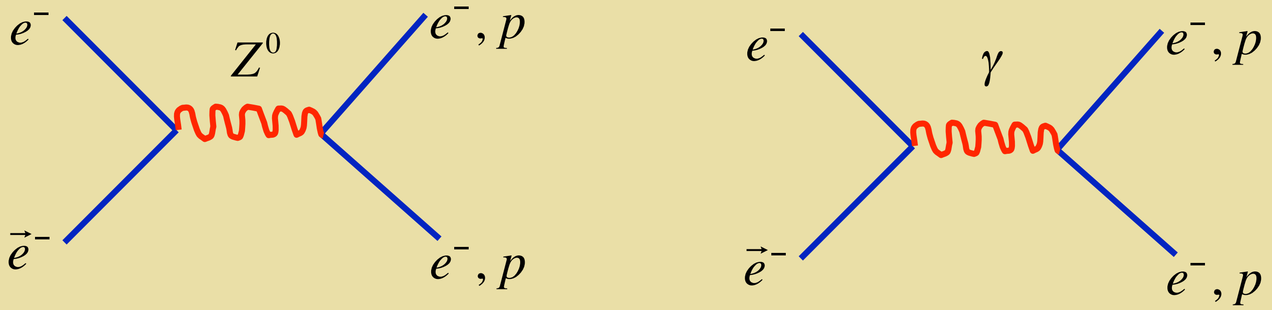


Analog 2-body matrix elements

Model independent

IV. The Anapole Moment & PVES

Parity-Violation & Nucleon Structure



Parity-Violating electron scattering

$$A_{PV} = \frac{N_{\uparrow\uparrow} - N_{\uparrow\downarrow}}{N_{\uparrow\uparrow} + N_{\uparrow\downarrow}} = \frac{G_F Q^2}{4\sqrt{2}\pi\alpha}\left[Q_W + F(Q^2,\theta)\right]$$

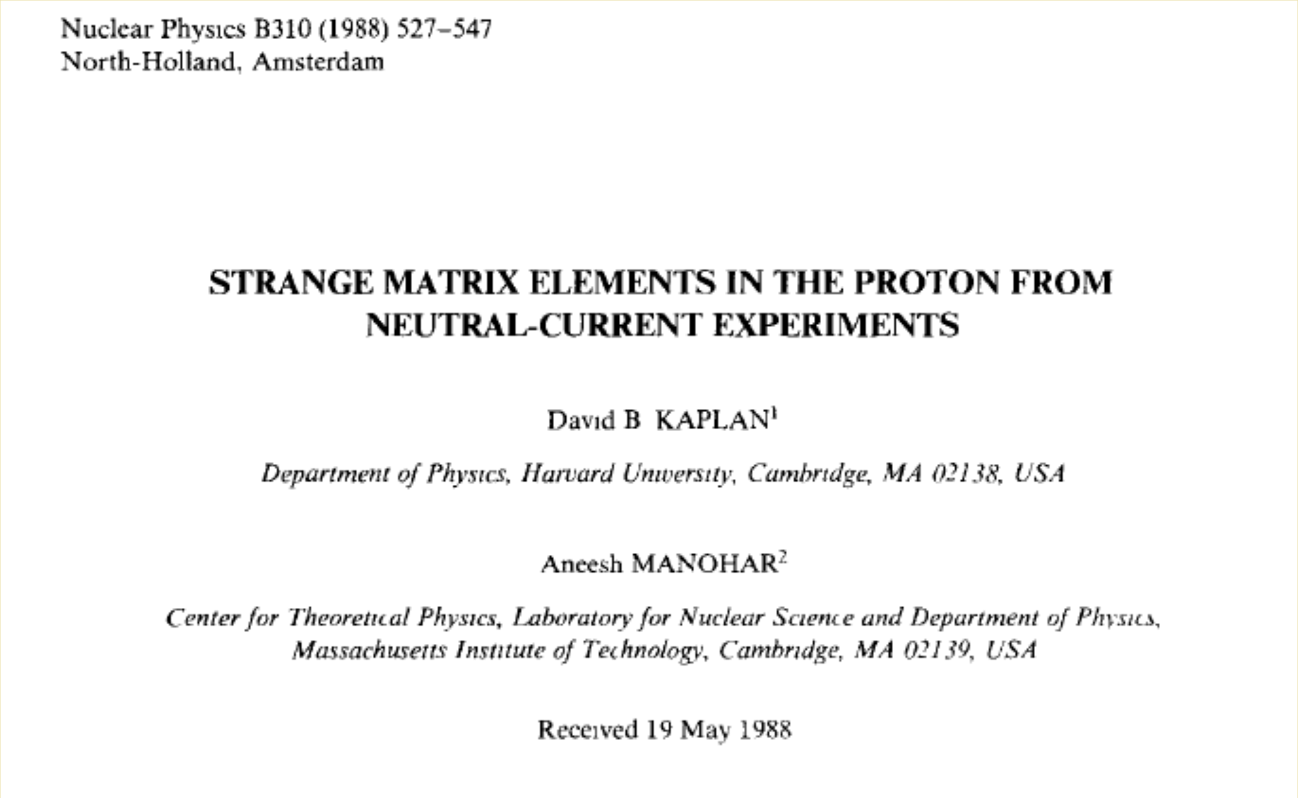
"Weak Charge" ~ 0.1 in SM

Enhanced transparency to new physics

Small QCD uncertainties (Marciano & Sirlin; Erler & R-M)

QCD effects (s-quarks): measured (MIT-Bates, Mainz, JLab)

Strange Quarks: G_M^P & G_E^P



Nuclear Physics B310 (1988) 527–547
North-Holland, Amsterdam

STRANGE MATRIX ELEMENTS IN THE PROTON FROM NEUTRAL-CURRENT EXPERIMENTS

David B KAPLAN[1]

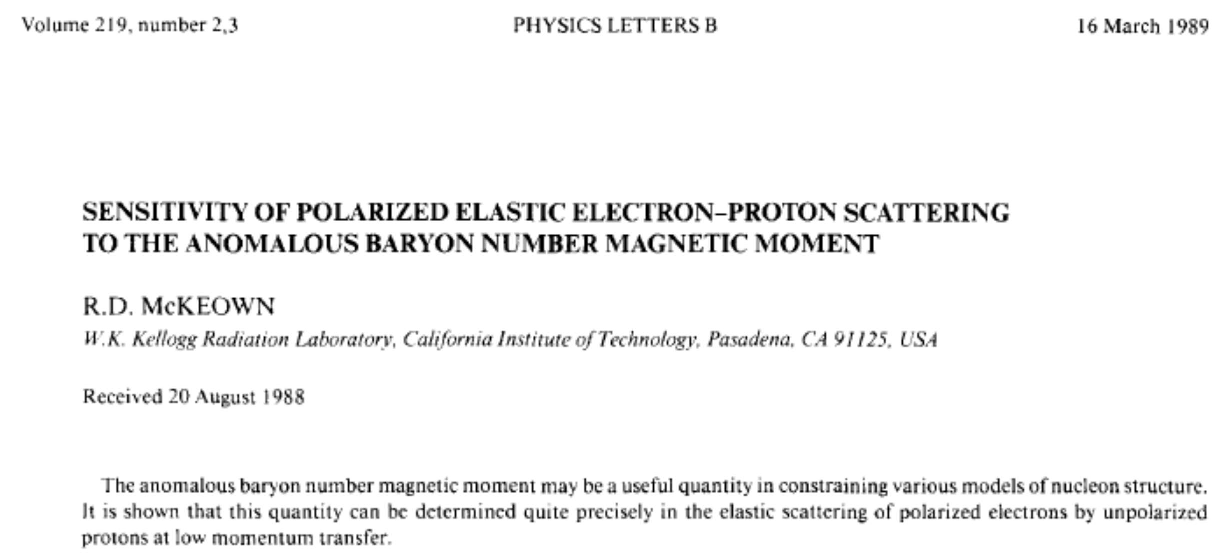
Department of Physics, Harvard University, Cambridge, MA 02138, USA

Aneesh MANOHAR[2]

Center for Theoretical Physics, Laboratory for Nuclear Science and Department of Physics,
Massachusetts Institute of Technology, Cambridge, MA 02139, USA

Received 19 May 1988

Strange Quarks: G_M^P & G_E^P



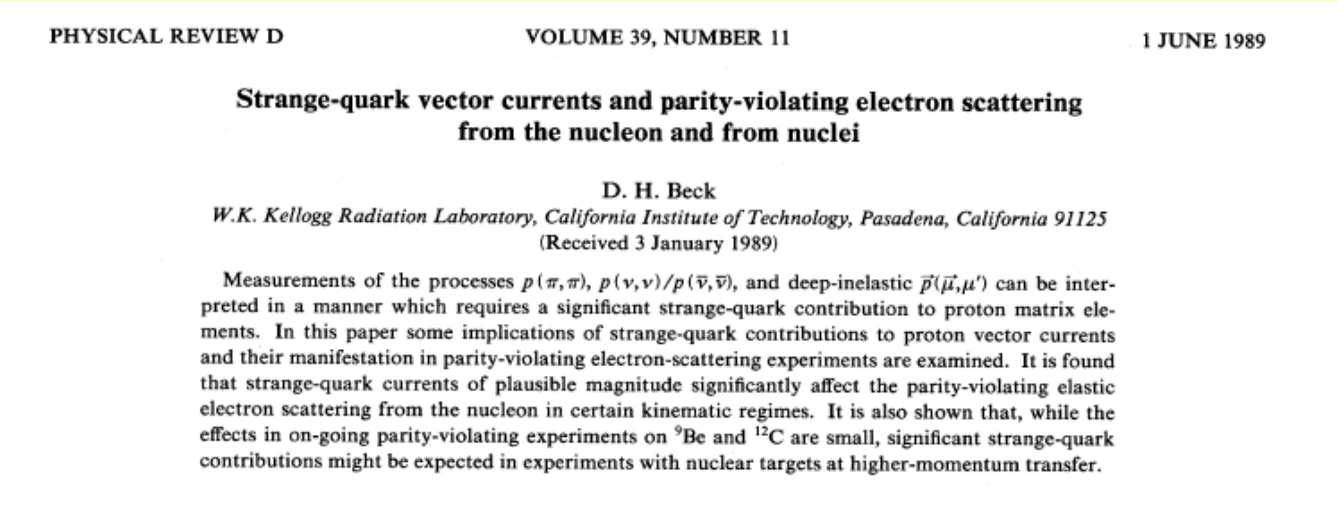
Volume 219, number 2,3 PHYSICS LETTERS B 16 March 1989

SENSITIVITY OF POLARIZED ELASTIC ELECTRON–PROTON SCATTERING TO THE ANOMALOUS BARYON NUMBER MAGNETIC MOMENT

R.D. McKEOWN
W.K. Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, CA 91125, USA

Received 20 August 1988

The anomalous baryon number magnetic moment may be a useful quantity in constraining various models of nucleon structure. It is shown that this quantity can be determined quite precisely in the elastic scattering of polarized electrons by unpolarized protons at low momentum transfer.



PHYSICAL REVIEW D VOLUME 39, NUMBER 11 1 JUNE 1989

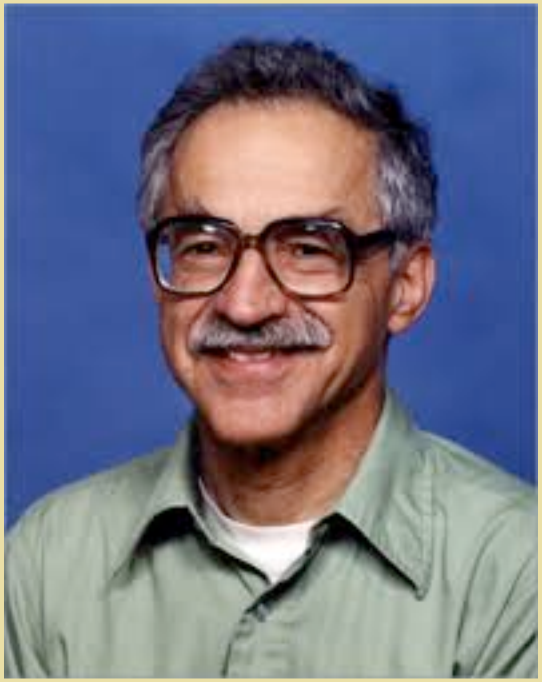
Strange-quark vector currents and parity-violating electron scattering from the nucleon and from nuclei

D. H. Beck
W.K. Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, California 91125

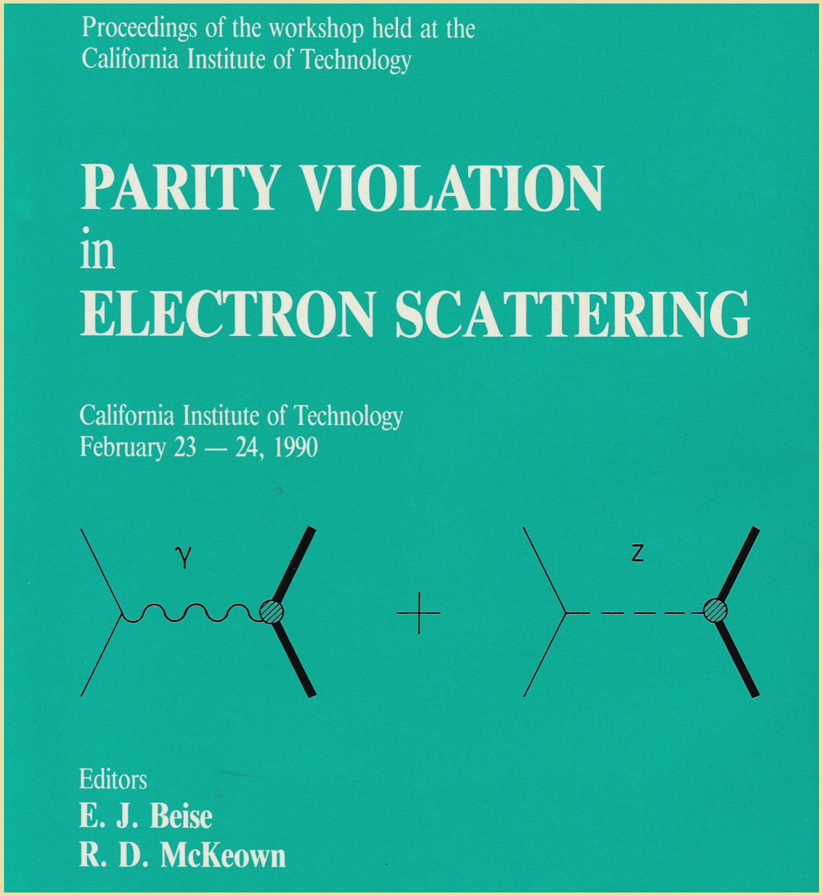
(Received 3 January 1989)

Measurements of the processes $p(\pi,\pi)$, $p(\nu,\nu)/p(\bar{\nu},\bar{\nu})$, and deep-inelastic $\vec{p}(\vec{\mu},\mu')$ can be interpreted in a manner which requires a significant strange-quark contribution to proton matrix elements. In this paper some implications of strange-quark contributions to proton vector currents and their manifestation in parity-violating electron-scattering experiments are examined. It is found that strange-quark currents of plausible magnitude significantly affect the parity-violating elastic electron scattering from the nucleon in certain kinematic regimes. It is also shown that, while the effects in on-going parity-violating experiments on ^{9}Be and ^{12}C are small, significant strange-quark contributions might be expected in experiments with nuclear targets at higher-momentum transfer.

Ernest Henley & Parity Violation



1990 Caltech Workshop



Proceedings of the workshop held at the
California Institute of Technology

PARITY VIOLATION
in
ELECTRON SCATTERING

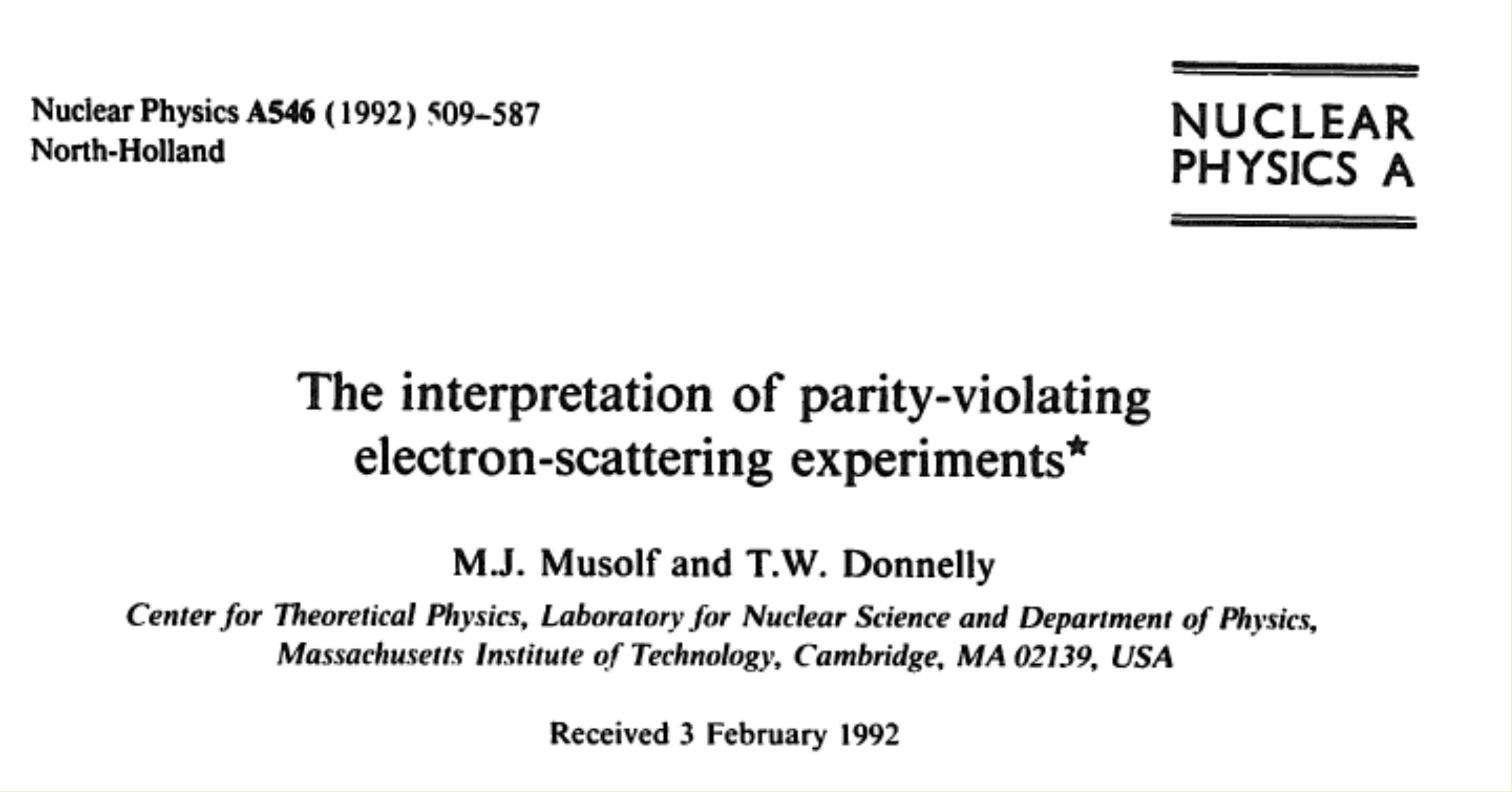
California Institute of Technology
February 23 — 24, 1990

Editors
E. J. Beise
R. D. McKeown

Generating theoretical activity

Strange Quarks: G_M^P & G_E^P

Interpreting the asymmetry



Nuclear Physics A546 (1992) 509–587
North-Holland

NUCLEAR
PHYSICS A

The interpretation of parity-violating electron-scattering experiments*

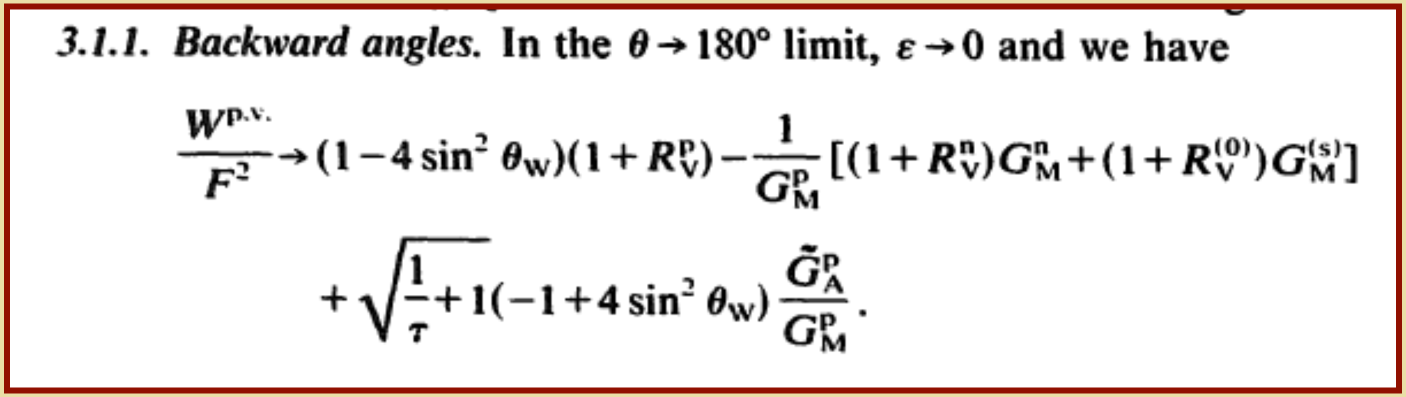
M.J. Musolf and T.W. Donnelly

Center for Theoretical Physics, Laboratory for Nuclear Science and Department of Physics,
Massachusetts Institute of Technology, Cambridge, MA 02139, USA

Received 3 February 1992

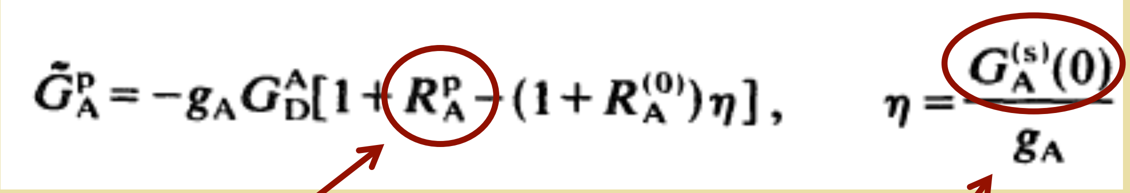
Strange Quarks: G_M^P & G_E^P

Interpreting the asymmetry



3.1.1. Backward angles. In the $\theta \to 180°$ limit, $\varepsilon \to 0$ and we have

$$\frac{W^{\mathrm{p.v.}}}{F^2} \to (1-4\sin^2\theta_W)(1+R_V^p) - \frac{1}{G_M^p}\left[(1+R_V^n)G_M^n + (1+R_V^{(0)})G_M^{(s)}\right] + \sqrt{\frac{1}{\tau}+1}\,(-1+4\sin^2\theta_W)\,\frac{\tilde{G}_A^p}{G_M^p}\,.$$



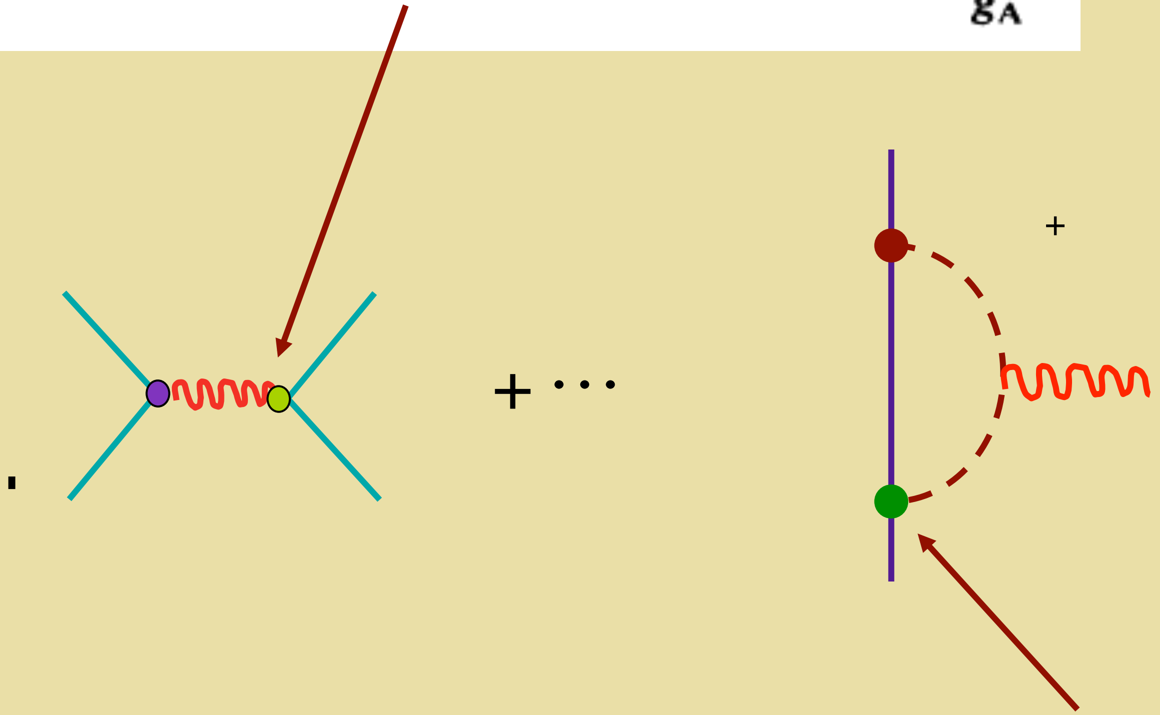
$$\tilde{G}_A^p = -g_A G_D^A\left[1 + \boxed{R_A^p} + (1+R_A^{(0)})\eta\right], \qquad \eta = \frac{\boxed{G_A^{(s)}(0)}}{g_A}$$

Now called " G_A^e "

Strange axial current

Strange Quarks: Radiative Corrections

$$\tilde{G}_A^p = -g_A G_D^A[1+R_A^p-(1+R_A^{(0)})\eta], \qquad \eta = \frac{G_A^{(s)}(0)}{g_A}$$

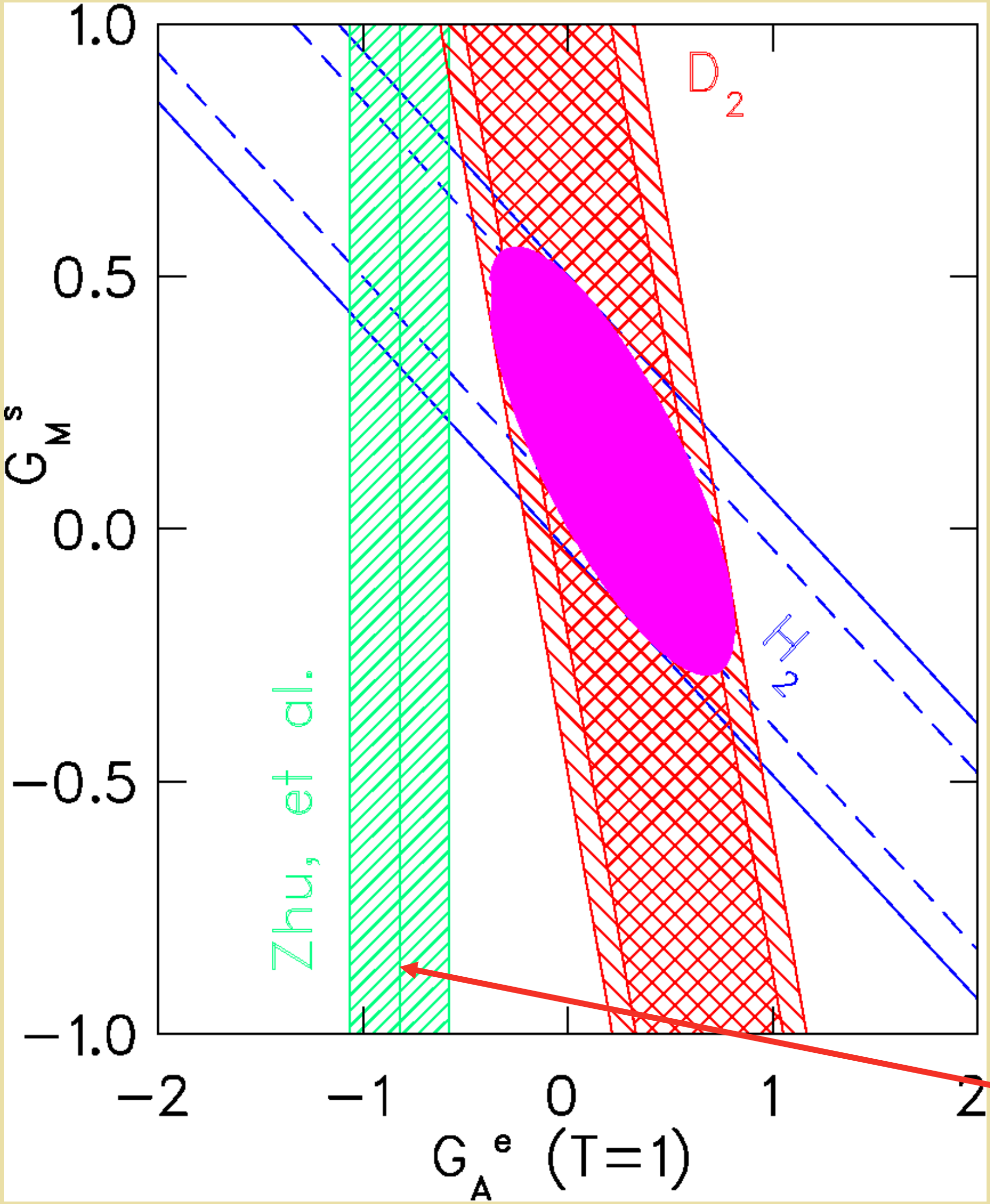


"Anapole"

Hadronic PV

SAMPLE Results

R. Hasty et al., Science 290, 2117 (2000).



at Q^2=0.1 (GeV/c)^2

- s-quarks contribute less than 5% (1σ) to the proton's magnetic moment.

Radiative corrections

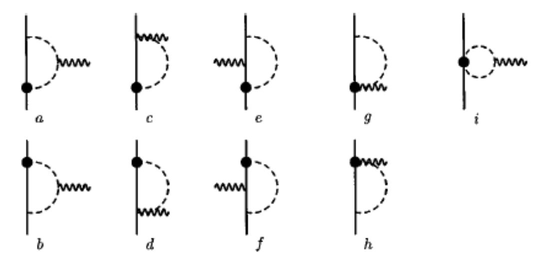
E. Beise, U Maryland

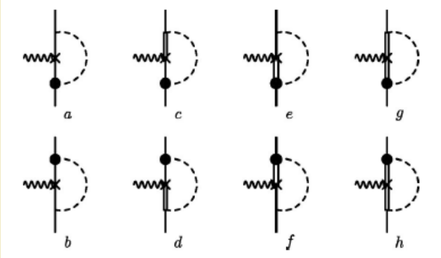
Strange Quarks: Radiative Corrections

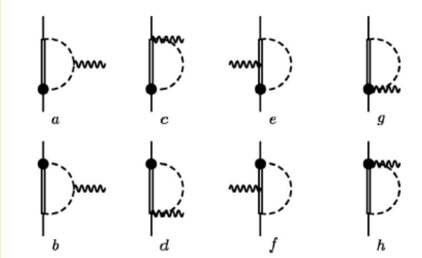
PHYSICAL REVIEW D, VOLUME 62, 033008

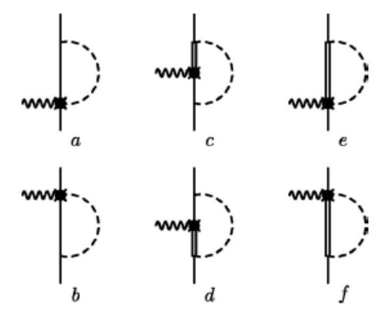
Nucleon anapole moment and parity-violating *ep* scattering

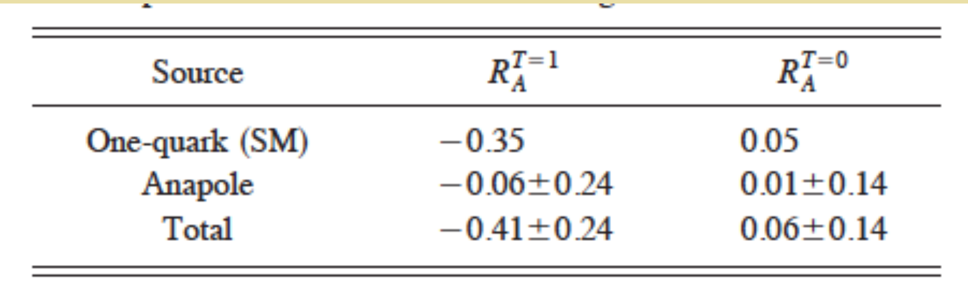
Shi-Lin Zhu,[1] S. J. Puglia,[1] B. R. Holstein,[3] and M. J. Ramsey-Musolf[1,2]
[1]*Department of Physics, University of Connecticut, Storrs, Connecticut 06269*
[2]*Theory Group, Thomas Jefferson National Laboratory, Newport News, Virginia 23606*
[3]*Department of Physics and Astronomy, University of Massachusetts, Amherst, Massachusetts 01003*
(Received 29 February 2000; published 12 July 2000)







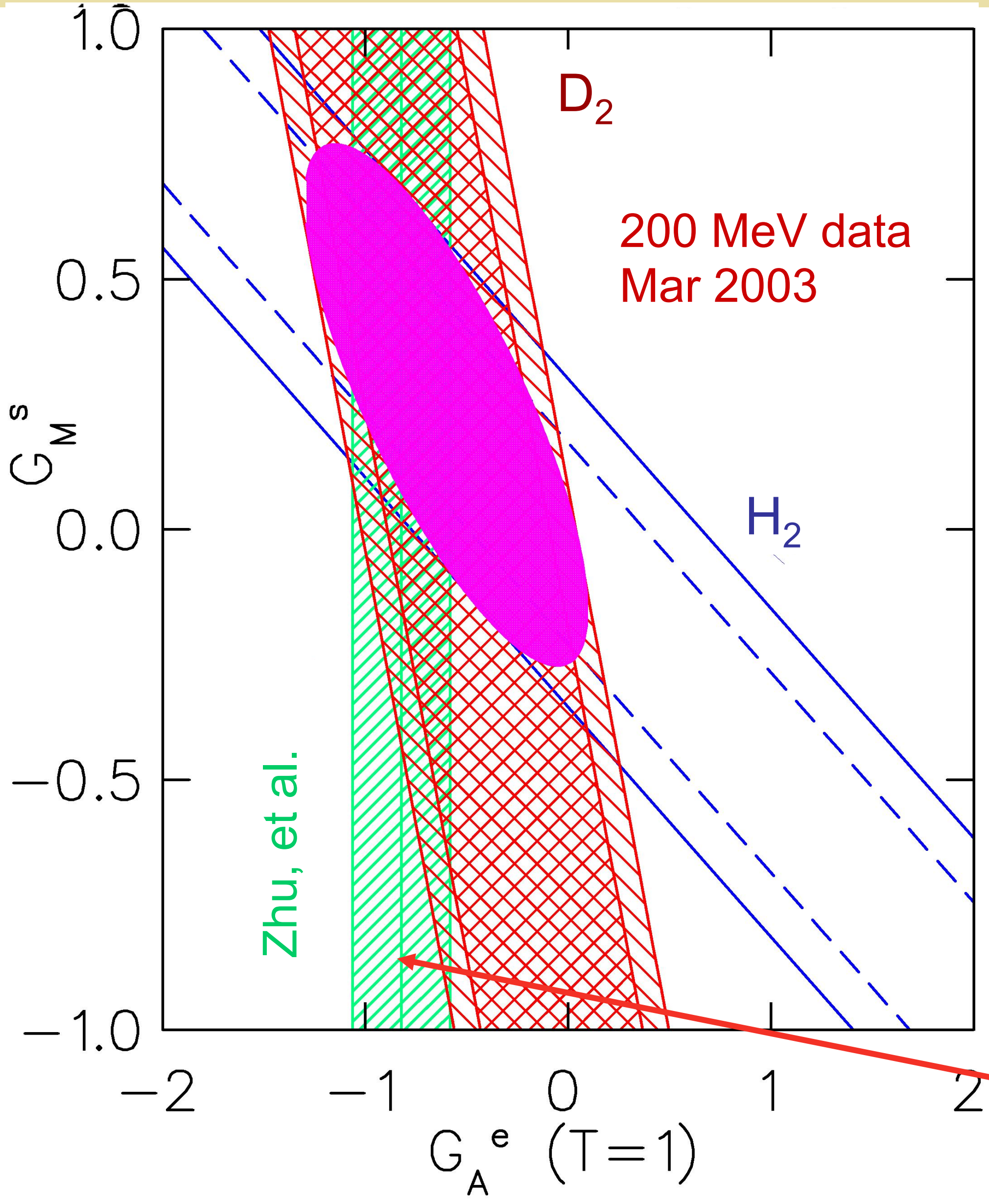




Source	$R_A^{T=1}$	$R_A^{T=0}$
One-quark (SM)	-0.35	0.05
Anapole	-0.06 ± 0.24	0.01 ± 0.14
Total	-0.41 ± 0.24	0.06 ± 0.14

SAMPLE Results

R. Hasty et al., Science 290, 2117 (2000).



at Q^2=0.1 (GeV/c)^2

- s-quarks contribute less than 5% (1σ) to the proton's magnetic moment.

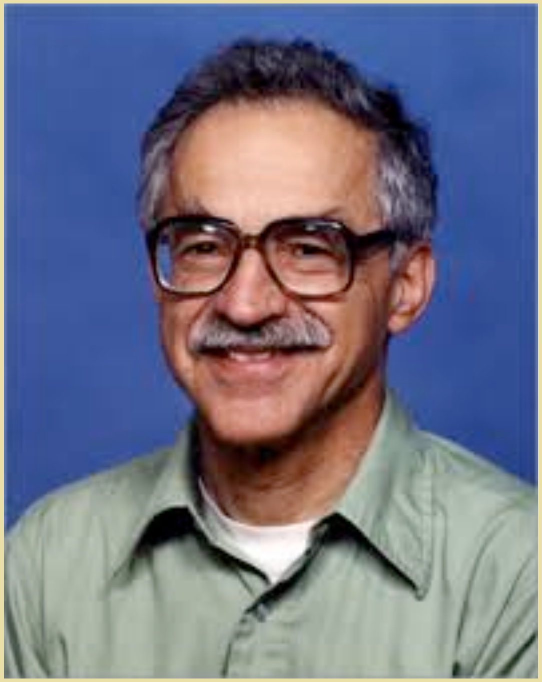
200 MeV update 2003:
Improved EM radiative corr.
Improved acceptance model
Correction for π background

125 MeV:
no π background
similar sensitivity
to G_A^e(T=1)

Radiative corrections

E. Beise, U Maryland

Summary



- *Pioneer in fundamental symmetry tests in general & PV in nuclei in particular*
- *Example of insatiable drive to understand laws of nature*
- *Inspiration to many*