Wick Haxton, UC Berkeley and LBL

Symmetry in Subatomic Physics: In Memory of Ernest Henley

September 10-11, 2018 INT

Ernest Henley and Time Reversal Invariance

- *Working with Ernest*
- *A bit on hadronic PNC*
- *Time reversal: atomic and nuclear edms*

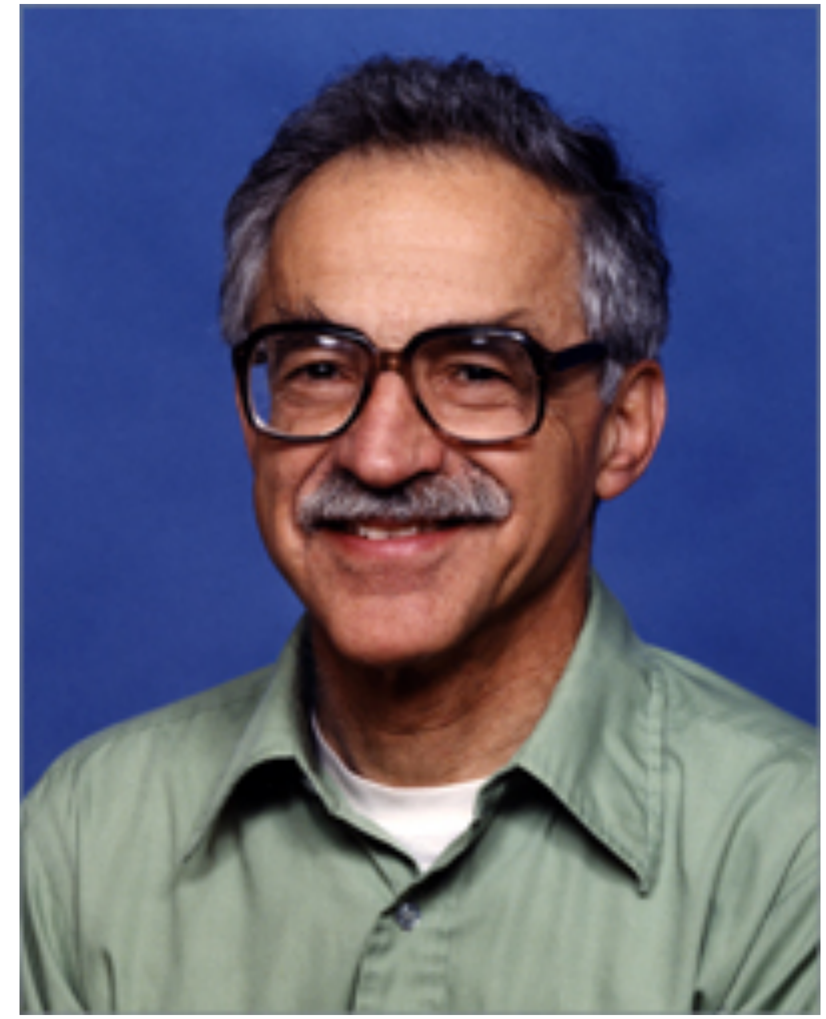
- Ernest was a frequent visitor to Los Alamos, serving on T-Division and other advisory committees

- I joined the lab as a postdoc, in 1977: that is where I met Ernest

- My first paper on hadronic parity violation was written with Ernest and Ben Gibson in 1980: dealt with a topic still of interest

- In 1984 we collaborated on an early paper on atomic electric dipole moments: also remains of interest, in part because of FRIB — main subject today

- It may have been a good paper: the UW hired me soon after



Parity Violation: Analyzing Experiments in Light Nuclei

- Several heroic experiments on hadronic PNC were done in the late 1970s, early 1980s — including ones at the UW

- Experimentalists turned to certain nuclei because (in contrast to the NN system) the experiments were doable and because nuclei offer advantages

They can filter interactions:

- *the quantum labels of nuclear states allow one to isolate parts of interactions of particular interest*

They can enhance the PNC signal:

- *Through nuclear energy degeneracies: mixing of nearby states*

- *By competing symmetry-allowed but suppressed transitions (e.g., E1s in a self-conjugate nucleus) against a symmetry-forbidden strong one (M1)* hadronic weak interactions: as the weak neutral current is suppressed in $\Delta S \neq 0$ weak processes, neutral current can only be studied in $\Delta S = 0$ reaction

NN and nuclear reactions the only feasible possibilities, isospin is the filter

$$L^{\text{eff}} = \frac{G}{2}\left[J_W^\dagger J_W + J_Z^\dagger J_z\right] + h.c.$$

$$J_W = \cos\theta_C J_W^{\Delta \mathrm{S}=0} + \sin\theta_C J_W^{\Delta S=-1}$$

↕ ↕

ΔI=1 ΔI=1/2

$$L^{eff}_{\Delta S=0} = \frac{G}{\sqrt{2}}\left[\cos^2\theta_C J_W^{0\dagger} J_W^0 + \sin^2\theta_c J_W^{1\dagger} J_W^1 + J_Z^\dagger J_Z\right]$$

↕ ↕

symmetric ⇒ ΔI=0,2 ΔI=1 but Cabibbo suppressed motivation for our study: as the weak neutral current is suppressed in $\Delta S \neq 0$ weak processes, neutral current can only be studied in $\Delta S = 0$ reaction

NN and nuclear reactions the only feasible possibilities

$$L^{\text{eff}} = \frac{G}{2}\left[J_W^\dagger J_W + J_Z^\dagger J_z\right] + h.c.$$

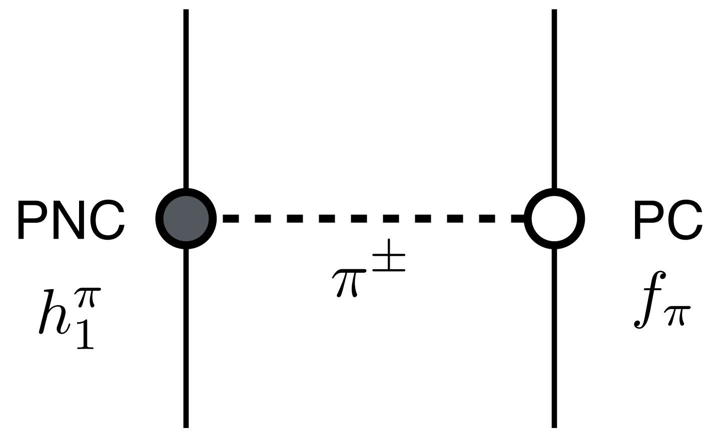
$$J_W = \cos\theta_C J_W^{\Delta\text{S}=0} + \sin\theta_C J_W^{\Delta S=-1}$$

$\updownarrow$ ΔI=1 $\qquad$ $\updownarrow$ ΔI=1/2

$$L_{\Delta S=0}^{eff} = \frac{G}{\sqrt{2}}\left[\cos^2\theta_C J_W^{0\dagger} J_W^0 + \sin^2\theta_c J_W^{1\dagger} J_W^1 + J_Z^\dagger J_Z\right]$$

$\updownarrow$ symmetric ⇒ ΔI=0,2 $\qquad$ $\updownarrow$ ΔI=1 but Cabibbo suppressed

leads to the expectation that the weak hadronic neutral current will dominate nuclear experiments sensitive to isovector PNC — this is the only SM current not yet isolated meson-exchange view of HPNC



Pion exchange is isovector, assumed for many years to dominate the $\Delta I = 1$ channel due to the propagator enhancement $(m_\rho/m_\pi)^2$

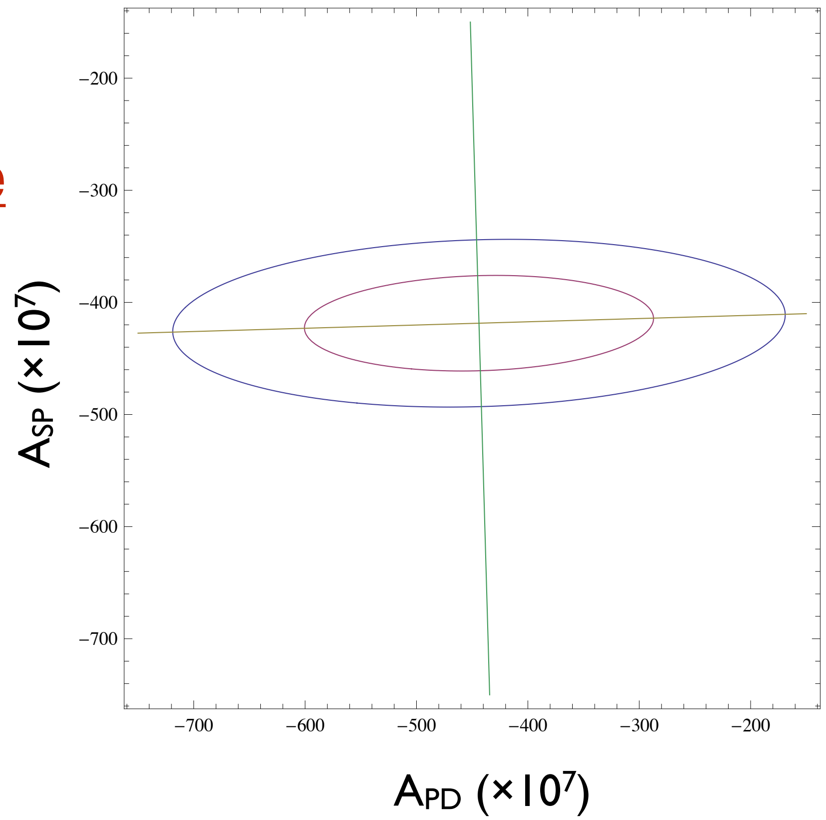
Would like to know its effective weak coupling to the composite nucleon, for comparison with the underlying SM quark couplings

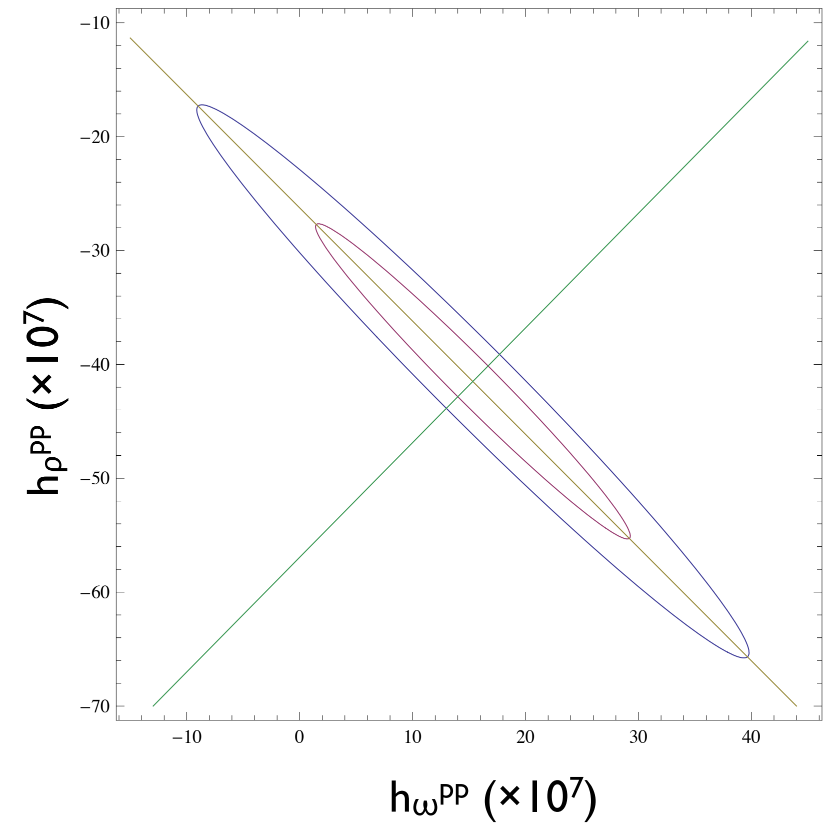
<u>Constraints in isospin space</u>

$\vec{p}+p$ asymmetry:

at 13.6, 45, 221 MeV

$\Delta I = 0,\ 2$





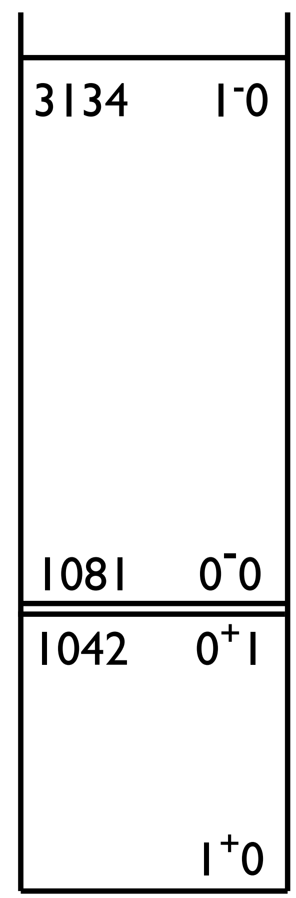
circular polarization of the 1.081 0^-0 MeV gamma ray from ^{18}F $\quad \Delta I = 1$

enhanced by M1/E1 ~ 100

enhance by small splitting of the mixed states ~ 100

$P_\gamma \sim 10^{-3}$

but only an upper bound found $(1.2 \pm 3.9) \times 10^{-4}$



|M1/E1|= 112 — Enhancement #1

39 keV — Enhancement #2

Isospin filter

^{18}F — Little NP uncertainty

Essentially equivalent DDH (meson exchange), Danilov (5 s-p amplitudes analysis), and pionless EFT treatments

Pionless EFT treatments
- S. L. Zhu et al., Nucl. Phys. A748 (2005) 435
- L. Girlanda, Phys. Rev. C77 (2008) 067001
- D. R. Phillips, M. R. Schindler, and R. P. Springer, Nucl. Phys. A822 (2009) 1

Early Danilov amplitude or contact interaction expansions
- B. Desplanques and J. Missimer, Nucl. Phys. A300 (1978) 286
- G. S. Danilov, Phys. Lett. 18 (1965) 40 and B35 (1971) 579

Coeff	DDH	Girlanda	Zhu
$\Lambda_{0\ DDH}^{1S_0-^3P_0}$	$-g_\rho h_\rho^0(2+\chi_V) - g_\omega h_\omega^0(2+\chi_S)$	$2(\mathcal{G}_1+\tilde{\mathcal{G}}_1)$	$2(\mathcal{C}_1+\tilde{\mathcal{C}}_1+\mathcal{C}_3+\tilde{\mathcal{C}}_3)$
$\Lambda_{0\ DDH}^{3S_1-^1P_1}$	$g_\omega h_\omega^0\chi_S - 3g_\rho h_\rho^0\chi_V$	$2(\mathcal{G}_1$-$\tilde{\mathcal{G}}_1)$	$2(\mathcal{C}_1$-$\tilde{\mathcal{C}}_1$-$3\mathcal{C}_3+3\tilde{\mathcal{C}}_3)$
$\Lambda_{1\ DDH}^{1S_0-^3P_0}$	$-g_\rho h_\rho^1(2+\chi_V) - g_\omega h_\omega^1(2+\chi_S)$	$\mathcal{G}_2$	$(\mathcal{C}_2+\tilde{\mathcal{C}}_2+\mathcal{C}_4+\tilde{\mathcal{C}}_4)$
$\Lambda_{1\ DDH}^{3S_1-^3P_1}$	$\frac{1}{\sqrt{2}}g_{\pi NN}h_\pi^1\left(\frac{m_\rho}{m_\pi}\right)^2+g_\rho(h_\rho^1$-$h_\rho^{1\prime}) - g_\omega h_\omega^1$	$2\mathcal{G}_6$	$(2\tilde{\mathcal{C}}_6+\mathcal{C}_2$-$\mathcal{C}_4))$
$\Lambda_{2\ DDH}^{1S_0-^3P_0}$	$-g_\rho h_\rho^2(2+\chi_V)$	$-2\sqrt{6}\mathcal{G}_5$	$2\sqrt{6}(\mathcal{C}_5+\tilde{\mathcal{C}}_5)$

Not enough accurate data

The introduction of 1/N$_c$ arguments to build a hierarchy among the 5 s-p LECs

- D. Phillips, D. Samart, and C. Schat, PRL 114 (2015) 062301
- M. R. Schindler, R. P. Springer, and J. Vanasse, PRC 93 (2016) 025502

DDH-informed analysis

	I=0	I=1		
I=0	$\Lambda_0^{{}^3S_1-{}^1P_1}$			
I=1		$\Lambda_0^{{}^1S_0-{}^3P_0}$		

phenomenology indicated only one linear combination of these important

	I=0	I=1
I=0		$\Lambda_1^{{}^3S_1-{}^3P_1}$
I=1	$\Lambda_1^{{}^3P_1-{}^3S_1}$	$\Lambda_1^{{}^1S_0-{}^3P_0}$

pion involved in both:

$V_\pi/V_\rho \sim m_\rho^2/m_\pi^2 \sim 30$

so only one parameter, h_1^π

	I=1
I=1	$\Lambda_2^{{}^1S_0-{}^3P_0}$

sub-dominate

consequently two leading parameters, one isoscalar and h_π^1

Large Nc Classification

	Coeff	DDH	Girlanda	Large N_c
LO	$\Lambda_0^+ \equiv \frac{3}{4}\Lambda_0^{^3S_1-^1P_1} + \frac{1}{4}\Lambda_0^{^1S_0-^3P_0}$	$-g_\rho h_\rho^0(\frac{1}{2}+\frac{5}{2}\chi_\rho) - g_\omega h_\omega^0(\frac{1}{2}-\frac{1}{2}\chi_\omega)$	$2\mathcal{G}_1 + \tilde{\mathcal{G}}_1$	$\sim N_c$
NNLO	$\Lambda_0^- \equiv \frac{1}{4}\Lambda_0^{^3S_1-^1P_1} - \frac{3}{4}\Lambda_0^{^1S_0-^3P_0}$	$g_\omega h_\omega^0(\frac{3}{2}+\chi_\omega) + \frac{3}{2}g_\rho h_\rho^0$	$-\mathcal{G}_1 - 2\tilde{\mathcal{G}}_1$	$\sim 1/N_c$
NNLO	$\Lambda_1^{^1S_0-^3P_0}$	$-g_\rho h_\rho^1(2+\chi_\rho) - g_\omega h_\omega^1(2+\chi_\omega)$	$\mathcal{G}_2$	$\sim \sin^2\theta_w$
NNLO	$\Lambda_1^{^3S_1-^3P_1}$	$\frac{1}{\sqrt{2}}g_{\pi NN}h_\pi^1\left(\frac{m_\rho}{m_\pi}\right)^2 + g_\rho(h_\rho^1 - h_\rho^{1\prime}) - g_\omega h_\omega^1$	$2\mathcal{G}_6$	$\sim \sin^2\theta_w$
NLO	$\Lambda_2^{^1S_0-^3P_0}$	$-g_\rho h_\rho^2(2+\chi_\rho)$	$-2\sqrt{6}\mathcal{G}_5$	$\sim N_c\sin^2\theta_w$

$$\frac{2}{5}\Lambda_0^+ + \frac{1}{\sqrt{6}}\Lambda_2^{^1S_0-^3P_0} + \left[-\frac{6}{5}\Lambda_0^- + \Lambda_1^{^1S_0-^3P_0}\right] = 419 \pm 43 \qquad A_L(\vec{\mathrm{p}}\mathrm{p})$$

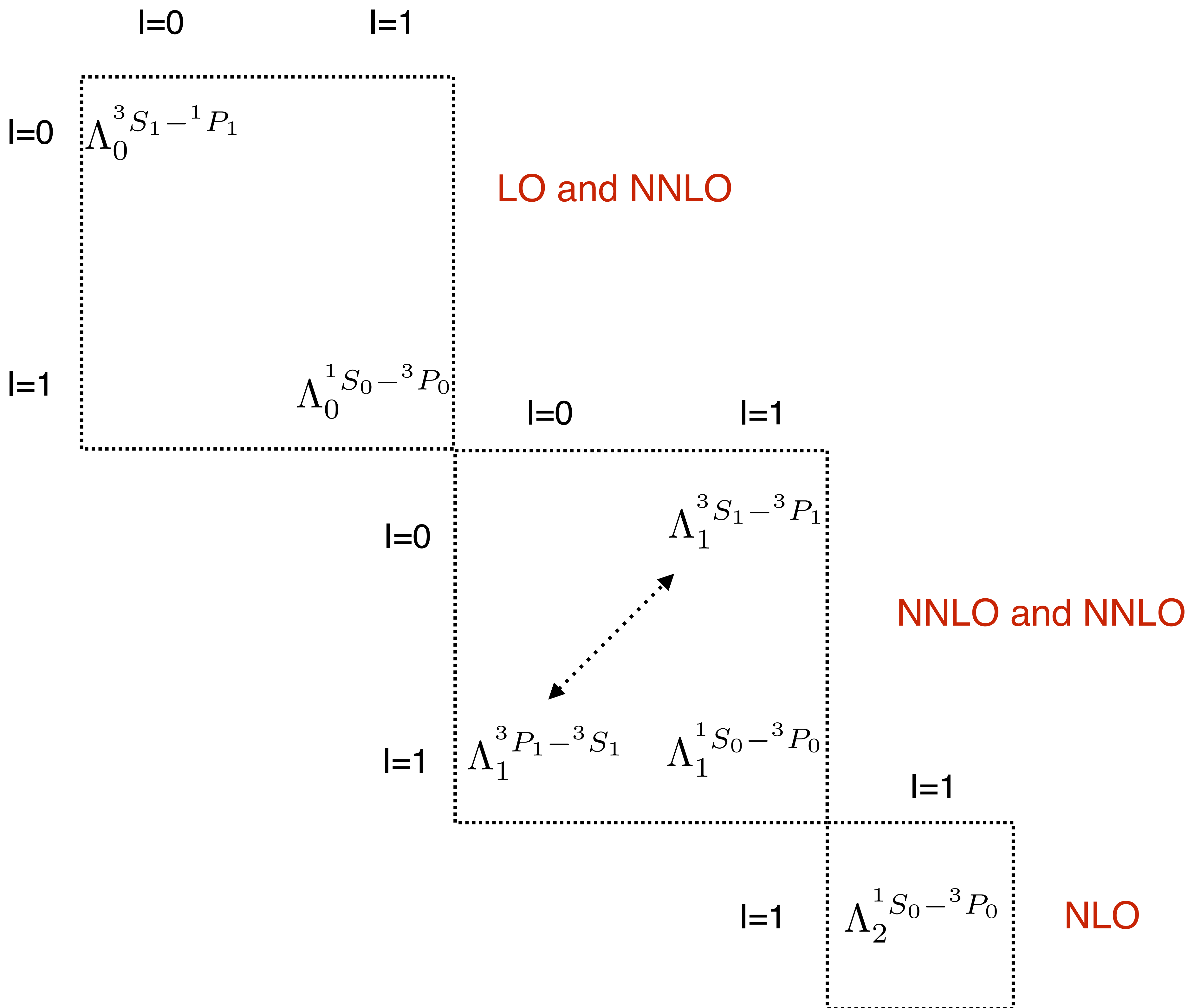
$$1.3\Lambda_0^+ + \left[-0.9\Lambda_0^- + 0.89\Lambda_1^{^1S_0-^3P_0} + 0.32\Lambda_1^{^3S_1-^3P_1}\right] = 930 \pm 253 \qquad A_L(\vec{\mathrm{p}}\alpha)$$

$$\left[\left|2.42\Lambda_1^{^1S_0-^3P_0} + \Lambda_1^{^3S_1-^3P_1}\right|\right] < 340 \qquad P_\gamma(^{18}\mathrm{F})$$

PREVIOUSLY A PUZZLE

$$0.92\Lambda_0^+ + \left[-1.03\Lambda_0^- + 0.67\Lambda_1^{^1S_0-^3P_0} + 0.29\Lambda_1^{^3S_1-^3P_1}\right] = 661 \pm 169 \qquad A_\gamma(^{19}\mathrm{F})$$

<u>Large-Nc analysis</u>



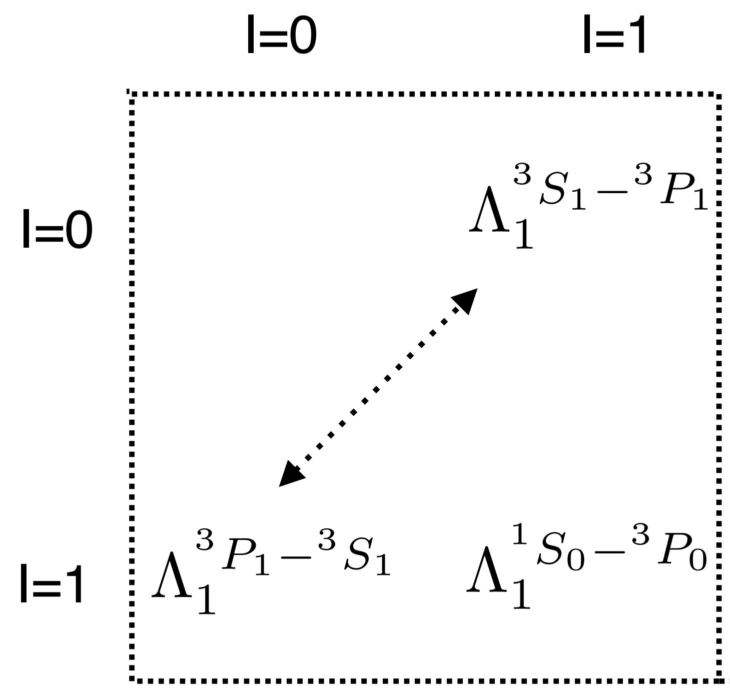
Large-Nc analysis

This has had an impact on the experimental program and its interpretation

10 years of effort has gone into $A_\gamma(\vec{n} + p \to d + \gamma)$ at the SNS

Previously had been considered a second avenue to h_π^1

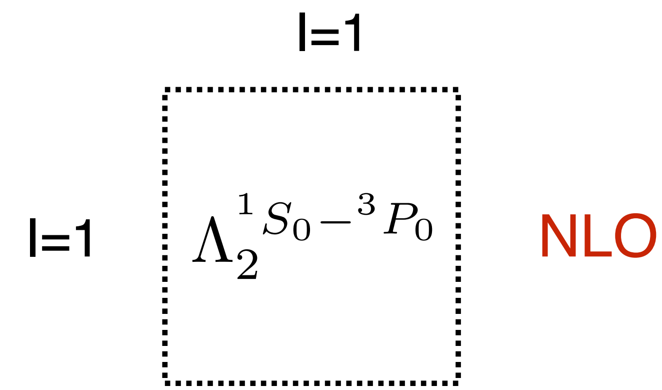
Now 18F and NPDGamma are viewed as nearly orthogonal constraints on this 2D diagonal space

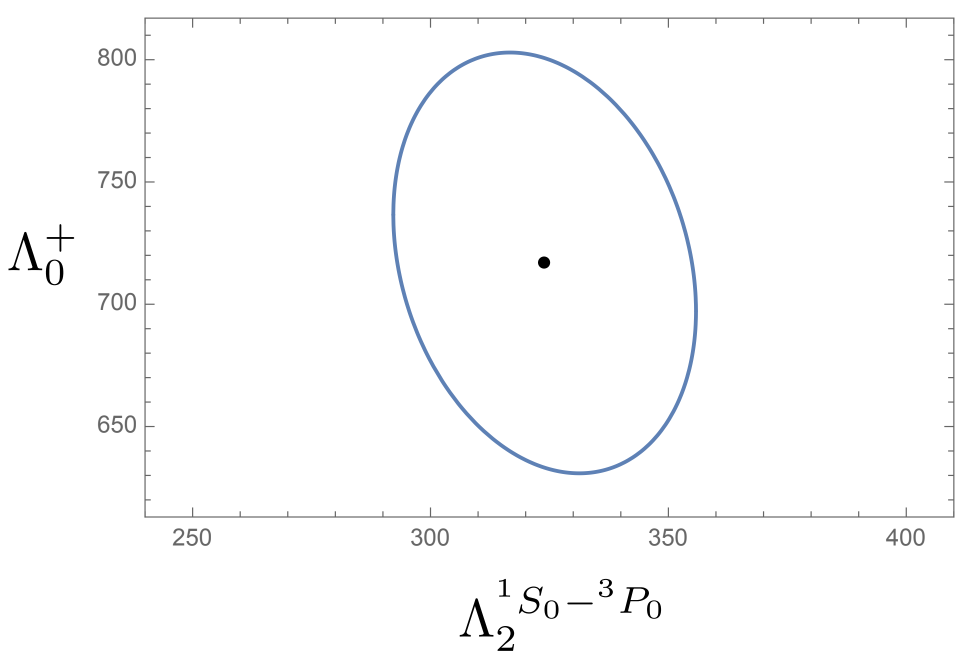


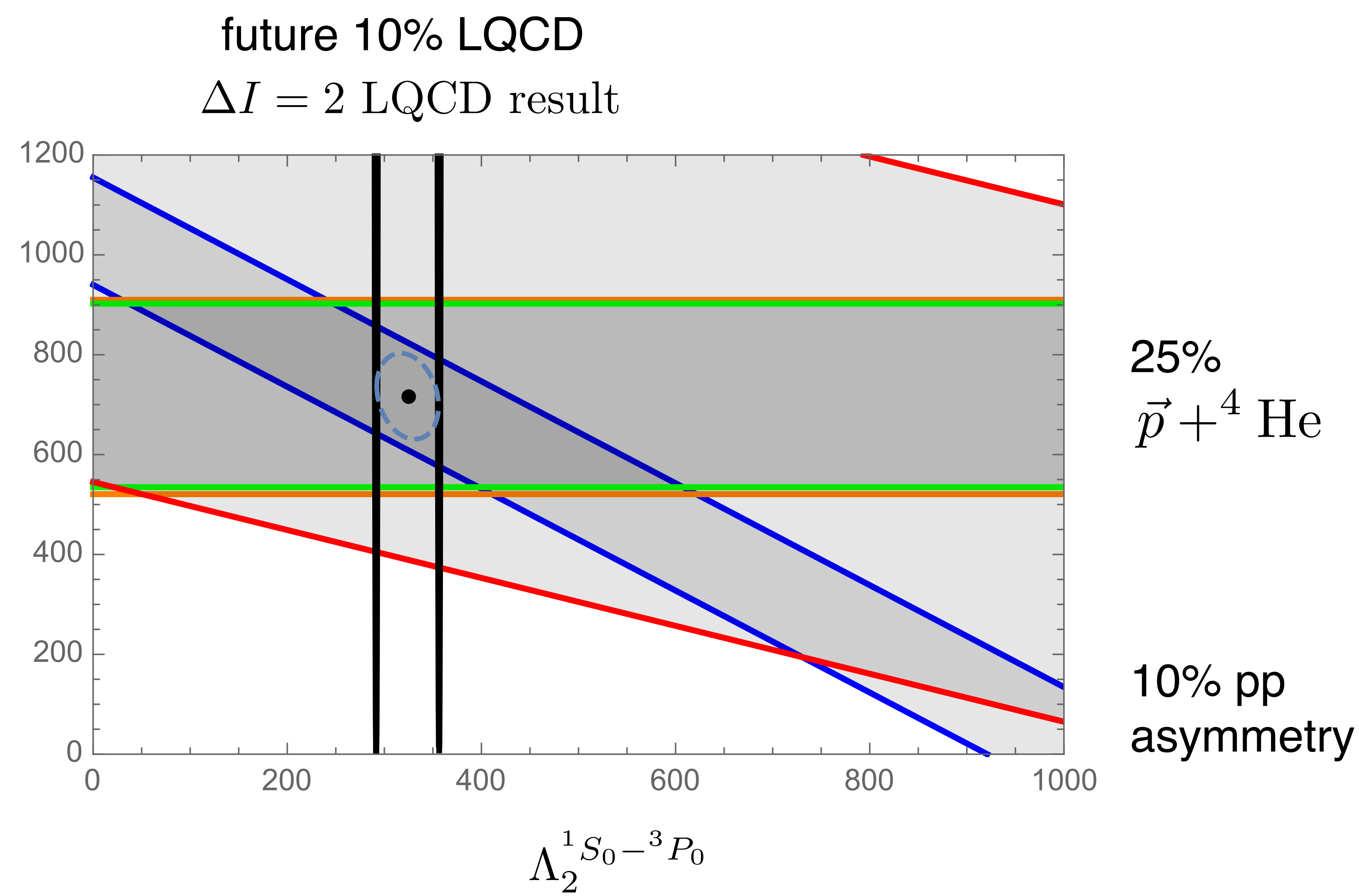
NNLO and NNLO

And a test of the large-Nc LEC hierarchy (if one has two good measurements)
Has renewed interest in modern improvements of the analysis of ^{18}F

<u>also interest in improving our understanding of the LO/NLO isoscalar/isotensor space</u>

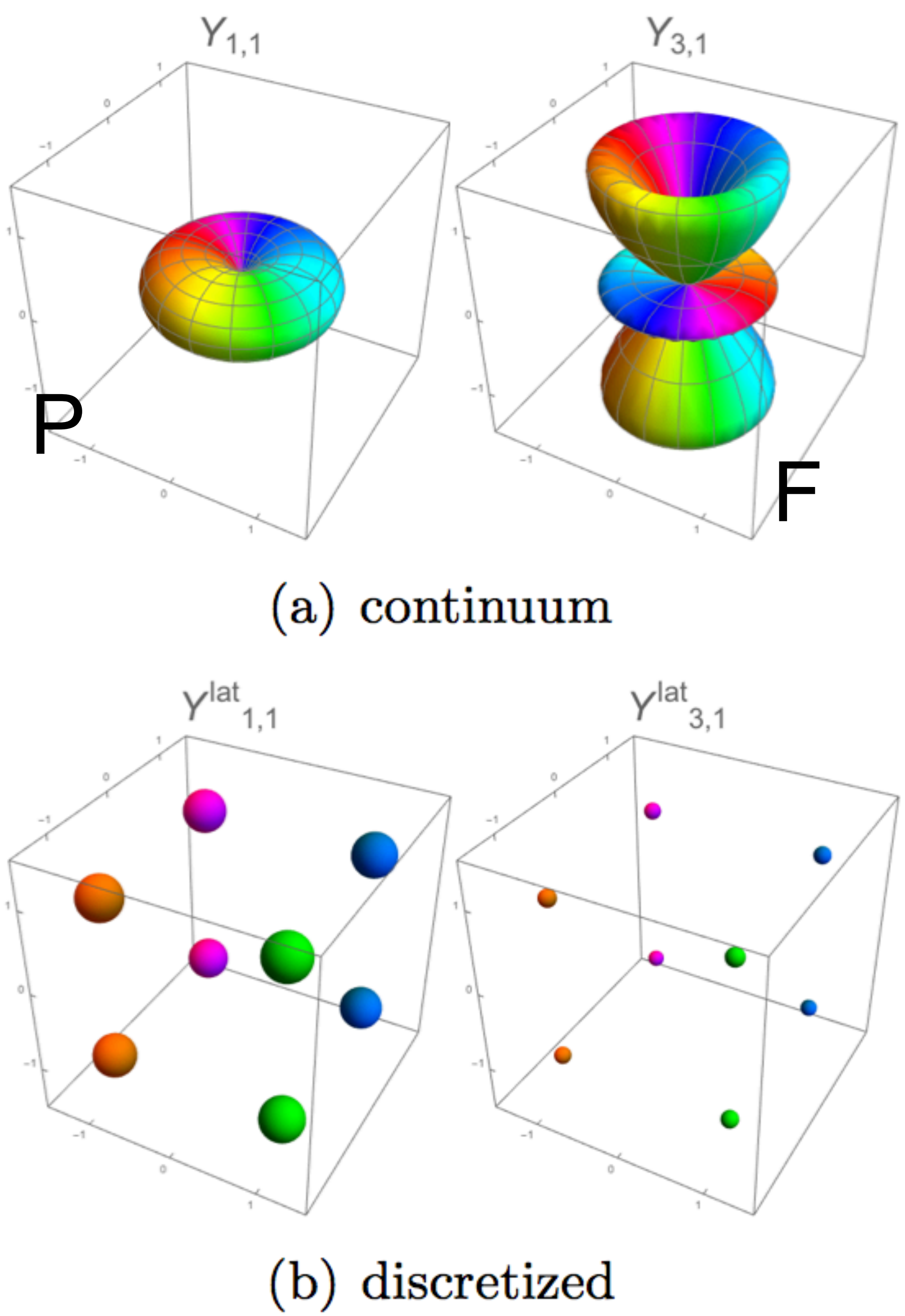




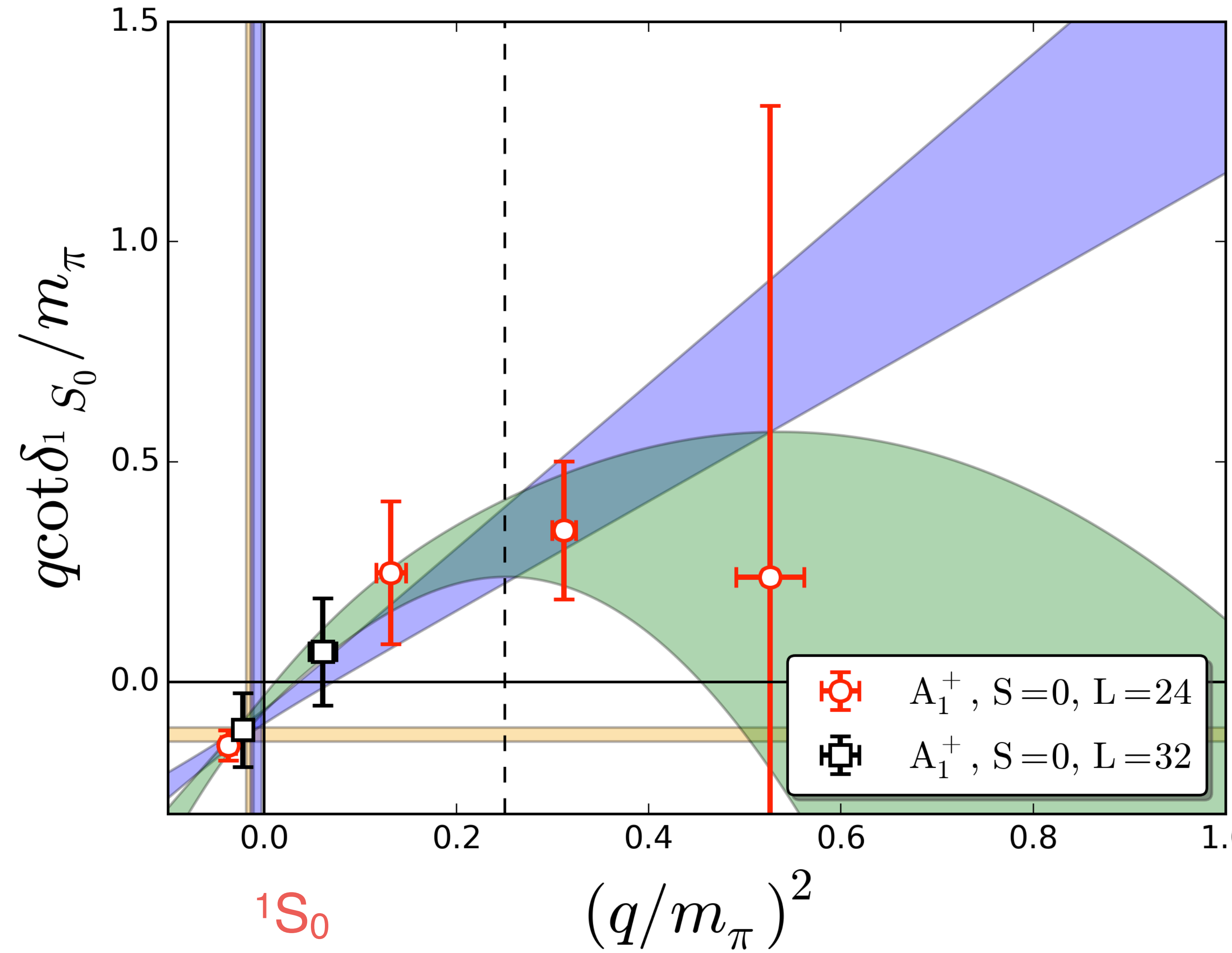


Impact of a 10% LQCD calculation of the I=2 amplitude

<u>LQCD work</u> on HPNC builds on recent efforts to build the technology to use extended nuclear sources required for calculating NN partial waves beyond s-wave



Cubic to rotational symmetry

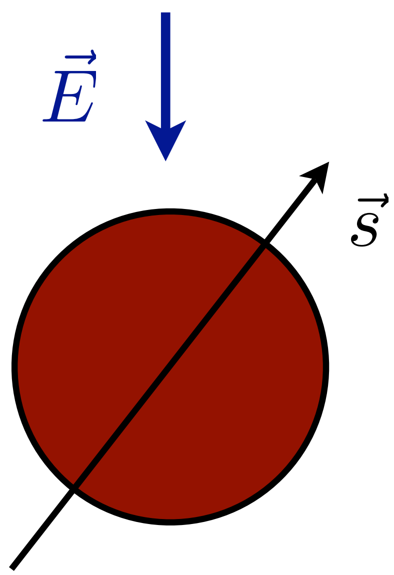


$^1S_0$

Higher partial waves with extended sources:
E. Berkowitz et al. (CalLat Collab.) arXiv:1508.00886
K. Murano et al. (HAL QCD Collab.) arXiv:1305.2293

<u>Electric Dipole Moments and CP Violation</u>

Permanent electric dipole moments of an elementary particle or a composite s requires requires both P and T violation



$$H_{edm} = d\ \vec{E} \cdot \vec{s}$$

$$\vec{E}(t \to -t) \to \vec{E}$$
$$\vec{s}(t \to -t) \to -\vec{s}$$
$$\Rightarrow H_{edm} \to -H_{edm}$$

Two important motivations for edm searches

CP phases show up generically in the Standard Model and its extensions

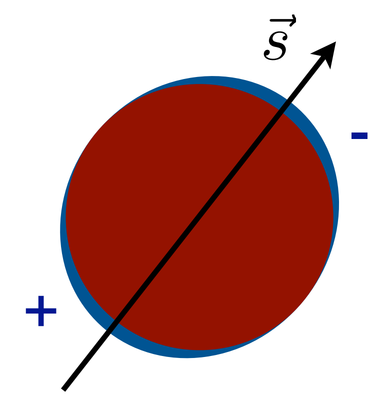
The need for additional sources of CP violation to account for baryogengesis

Experimental sensitivity: The dipole moment of a classical distribution

$$\vec{d} = \int d^3x \; \vec{x} \; \rho(\vec{x})$$

Limit* $d(^{199}\mathrm{Hg}) < 7.5 \times 10^{-30}$ e cm (95% c.l.) corresponds to a strain over atom of 10^{-19} — comparable to what LIGO achieves over a 4 km interferometer arm

E.g., expand the atom to the size of the earth: equivalent to a shell of excess charge (difference between + and - charge at the poles) of thickness ~ 10^{-4} angstroms



The limit on the precession in the applied field (10^{-5} V/m) corresponds to a sensitivity to a difference in the energies of atom levels of ~ 10^{-26} eV

* B Graner et al. (Seattle group), PRL 116 (2016) 161601

General classification of electromagnetic moments:

Multipole	P-even, T-even	P-odd, T-odd	P-odd, T-even	P-even, T-odd
$\langle C_J{}^M \rangle$	even J≥0	odd J≥1	x	x
$\langle M_J{}^M \rangle$	odd J≥1	even J≥2	x	x
$\langle E_J{}^M \rangle$	x	x	odd J≥1	even J≥2

edm is the C1 moment; other P- and T-odd moments include M2, C3, …, and are present for J ≥ 1

General current for a spin-1/2 fermion:

$$\langle p|J_\mu^{\rm em}|p\rangle = \bar{N}(p')\left(F_1\gamma_\mu + F_2\sigma_{\mu\nu}q^\nu + \frac{a(q^2)}{M^2}(\not{q}q_\mu - q^2\gamma_\mu)\gamma_5 + d(q^2)\sigma_{\mu\nu}q^\nu\gamma_5 \right) N(p)$$

Charge Magnetic Anapole Electric Dipole

Experiments:

e/p/n edm experiments break into three general categories

- —neutron or electron beam/trap/fountain edm experiments
- —paramagnetic (unpaired electrons) atoms or molecules with sensitivity to the electron edm
- —diamagnetic atoms (electrons paired, nonzero nuclear spin) with sensitivity to p and n edm and to CPNC nuclear interactions

Key limits, from neutral systems, in units of e cm

Particle	edm limit	system	SM prediction*
e	8.7×10^{-29}	atomic TlO	10^{-38}
p	2.0×10^{-25}	Hg vapor cell	10^{-31}
n	2.9×10^{-26}	ultracold n	10^{-31}
^{199}Hg	7.5×10^{-30}	Hg vapor cell	10^{-33}

*CKM phase

n: Baker et al, PRL 97 (2006) 131801; Pendlebury et al., PRD 92 (2015) 9092003
e: J. Baron et al., Science 343 (2014) 269
Hg: B. Graner et al., PRL 116 (2016) 161601

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Key limits, from neutral systems, in units of e cm

Particle	edm limit	Potential window for discovery	SM prediction*
e	8.7×10^{-29}	↔	10^{-38}
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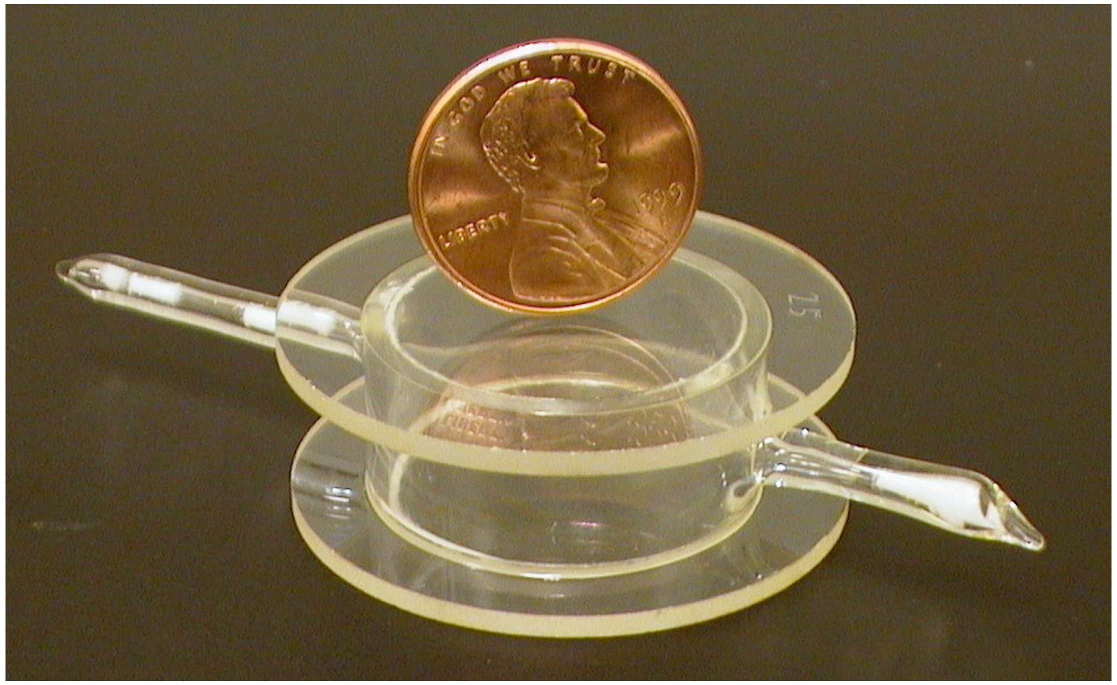
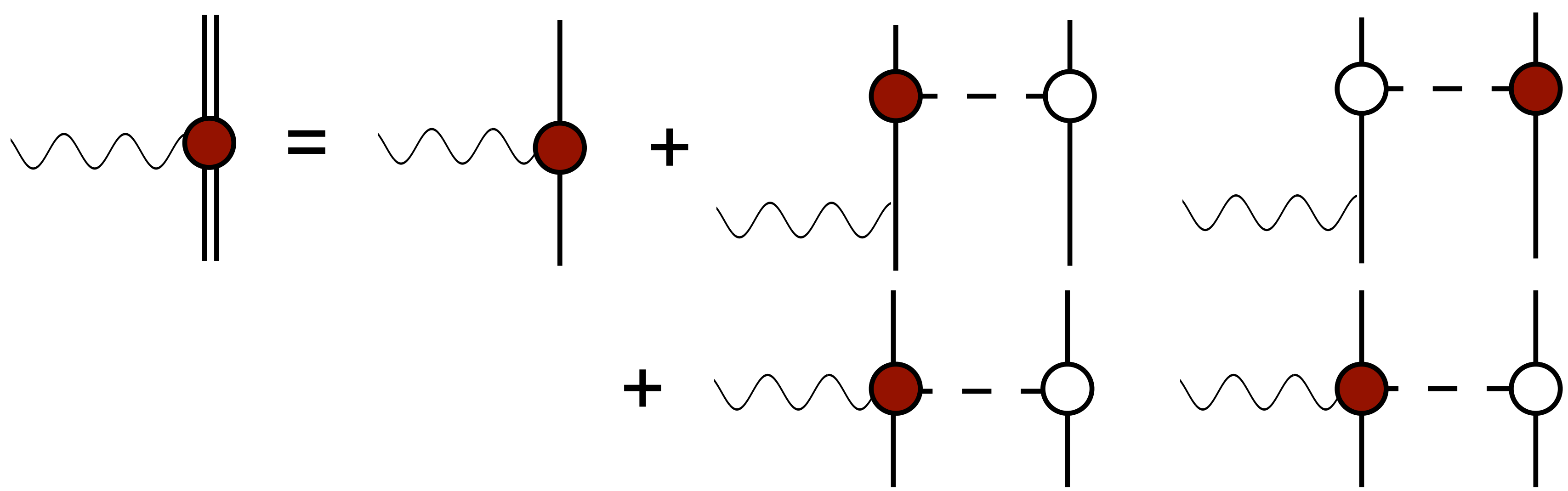
^{199}Hg vapor cells:



- Number of ^{199}Hg atoms: 10^{14}
- Leakage currents at 10 kV: 0.5 – 1 pA
- N_2 + CO buffer gas (500 Torr)
- Paraffin wall coating
- Spin relaxation time: 100 – 200 sec

(Heckel's workshop presentation)

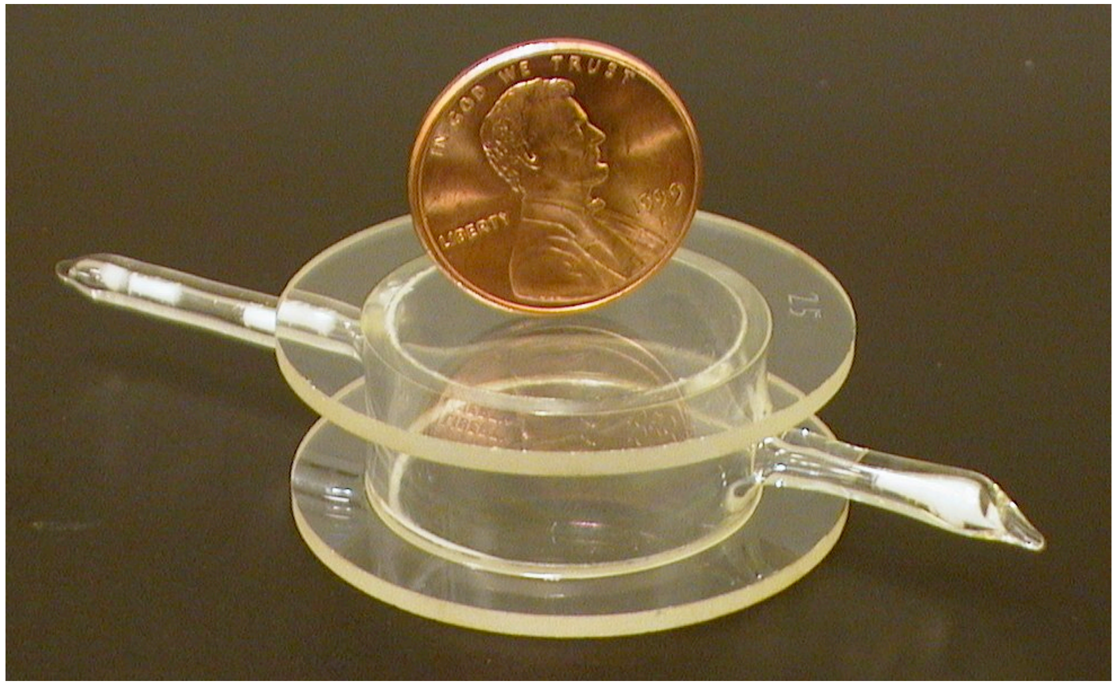
Nuclear edm:



nuclear edm = 1-body + polarization + exchange current

This division and the evaluation of the various terms was in the paper with Ernest

^{199}Hg vapor cells:



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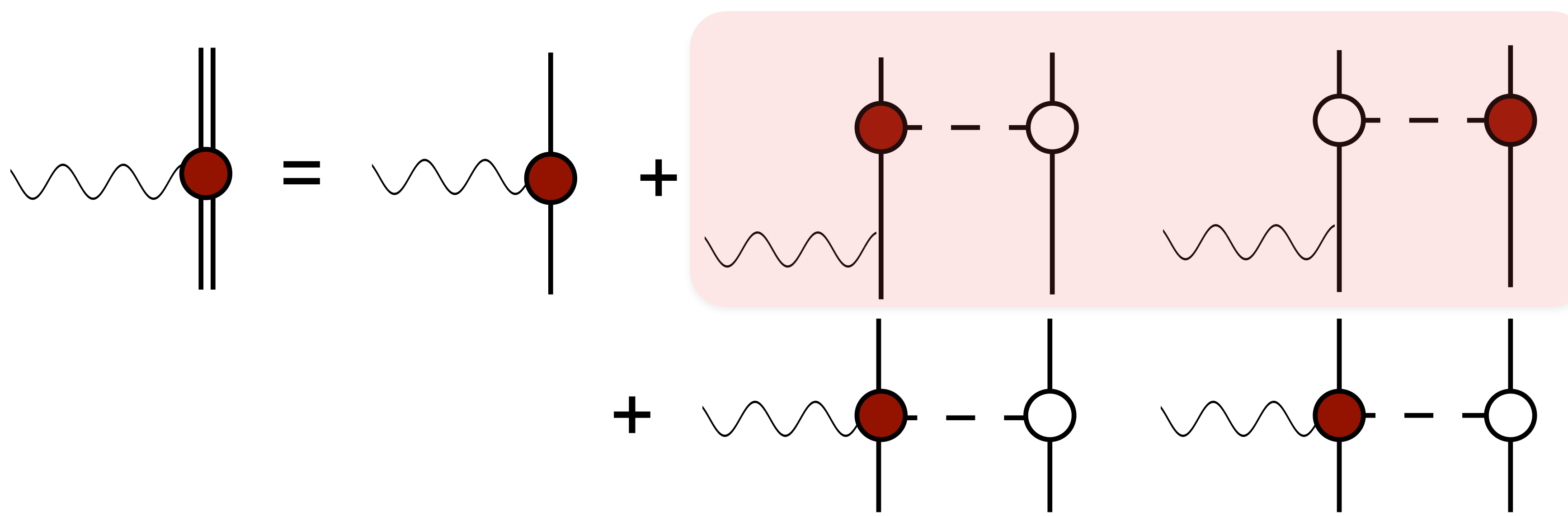
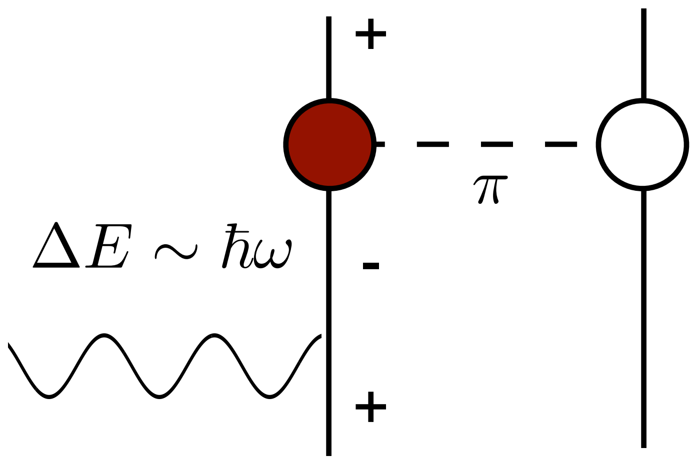


nuclear edm = 1-body + polarization + exchange current

That paper was the first to study nuclear enhancements in any systematic way

Dimensional estimate of generic nuclear edm:

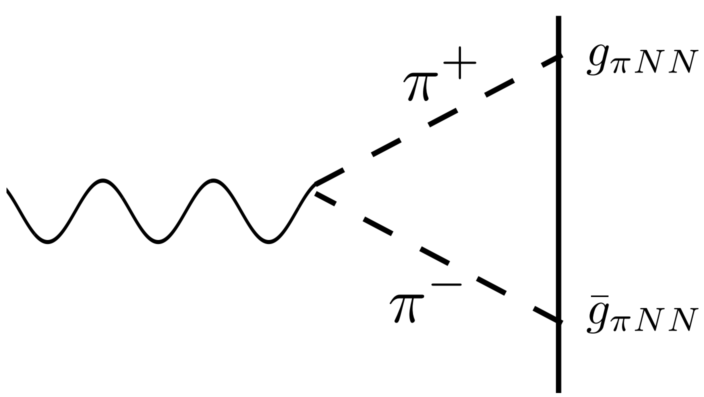


nuclear edms dominated by the polarization term

charge separation governed by nuclear size: polarized valence orbits

$$V_{12}^{\theta} = -0.9\ d_n\ m_\pi^2\ \vec{\tau}\cdot\vec{\tau}\ \ (\vec{\sigma}(1)-\vec{\sigma}(2))\cdot\hat{r}\ \frac{e^{-m_\pi r}}{m_\pi r}\left[1+\frac{1}{m_\pi r}\right]$$

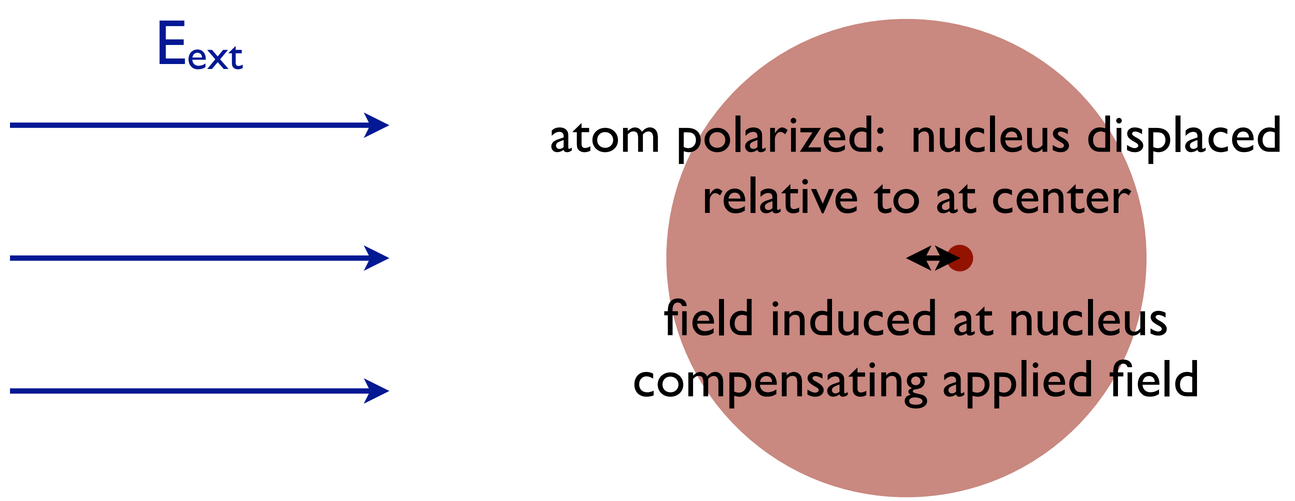
Nucleon edm: charge separation determined by pion mass



$$d_{nuclear} \sim d_n \frac{m_\pi}{\hbar\omega} \sim 10 d_n$$

$$d_n \sim \frac{g_{\pi NN}\bar{g}_{\pi NN}}{4\pi^2 M}\log\frac{M}{m_\pi}$$

But the embedding in a neutral atom less to very significant shielding



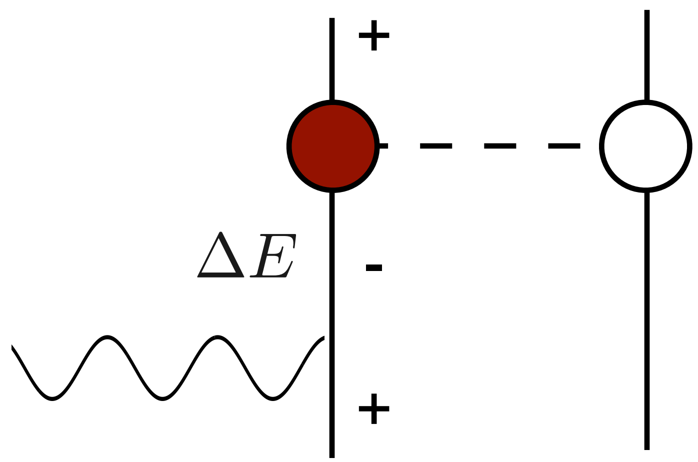
Schiff screening: Interaction energy of a non relativistic point nucleus with a nonzero edm, inside a neutral atom, is zero

Residual effect depends on the incomplete shielding due to the nuclear finite size and associated electron penetration

reduction in edm sensitivity $\sim (R_N/R_A)^2 \sim 10^{-3}$ in heavy atoms

(The M2 moment is unshielded)

The paper also made the first search for degeneracy enhancements:



$$d_{\text{Nuclear}} \sim 10 d_n \frac{\hbar\omega}{\Delta E}$$

a small ΔE can greatly enhance d_{Nuclear}

TABLE I. Nuclear electric dipole and magnetic quadrupole moments.

Nucleus	$[Nn_Z\Lambda, K^\pi]_{\text{g.s.}}$ [a]	$[Nn_Z\Lambda, K^\pi]_{\text{e.s.}}$ [a]	ΔE (keV)	$\langle 1 \vert V \vert 0 \rangle / \bar{g}$ (keV) [b]	$\langle 0 \Vert \text{GT} \Vert 0 \rangle$ [b]	$\langle 0 \Vert E1 \Vert 1 \rangle$ [c]	D_N/d_n	$M2/m2$
^{153}Sm	[651, $\frac{3}{2}^+$]	[521, $\frac{3}{2}^-$]	35.8	−170	−0.65	>3.74	>86.1	>10.1
^{161}Dy	[642, $\frac{5}{2}^+$]	[523, $\frac{5}{2}^-$]	25.7	−237	−1.21	0.39	10.3	−541
^{165}Er	[523, $\frac{5}{2}^-$]	[642, $\frac{5}{2}^+$]	47.2	213	1.03	0.64	9.6	664
^{225}Ac	[532, $\frac{3}{2}^-$]	[651, $\frac{3}{2}^+$]	40.0	180	−0.56	<−0.74	>19.3	<−610
^{227}Ac	[532, $\frac{3}{2}^-$]	[651, $\frac{3}{2}^+$]	27.4	187	−0.56	−0.21	8.7	−926
^{229}Pa	[642, $\frac{5}{2}^+$]	[523, $\frac{5}{2}^-$]	0.22	39	1.05	−4.58	2390	12400

FRIB and the strange case of ^{229}Pa

There was a spectacular case of enhancement identified in that study, the 160 eV parity doublet in ^{229}Pa $(5/2^+ \leftrightarrow 5/2^-)$ — a factor > 10^3 - 10^4 for C1/M2

Half life of 1.5d, decays by electron capture

Strong E1 between doublet states, governs IC lifetime

At that time, no source of ^{229}Pa that could satisfy the needs of a practical experiment

FRIB includes an isotopes harvesting program, focused on medical isotopes

In a parasitic mode, the production of ^{229}Pa is anticipated to be high, 10^{10} atoms/sec

Harvesting over several hours would thus yield in excess of 10^{14} atoms/day

Nuclear Enhancements:

From collective motion: In rotational nuclei, intrinsic state breaks spherical symmetry, deformed into a football, restored by the "Goldstone mode" of rotations

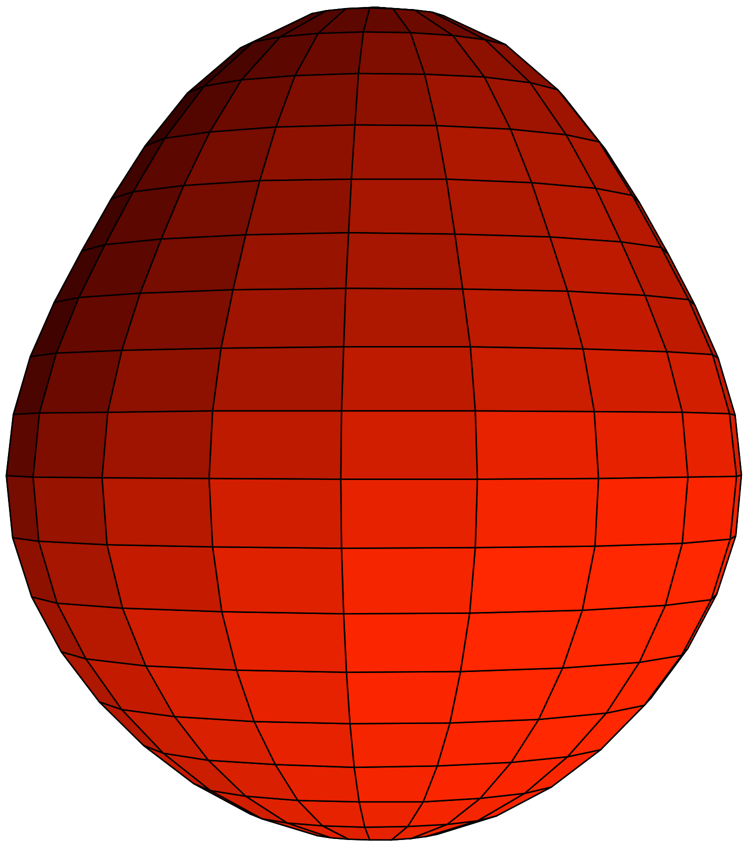
Octupole deformation: deformed intrinsic state and its parity reflection can be combined

$$|\text{even}\rangle = |+\rangle + |-\rangle$$
$$|\text{odd}\ \rangle = |+\rangle - |-\rangle$$

Deformation violates P and T, symmetry restored by collective motion, yielding parity doublets that strongly mix through P-odd operators

⇒ CPNC polarization enhancement

*WH and Henley, PRL 51 (1983) 1937
Sushkov, Flambaum, Khriplovich, JETP 60 (1984) 873



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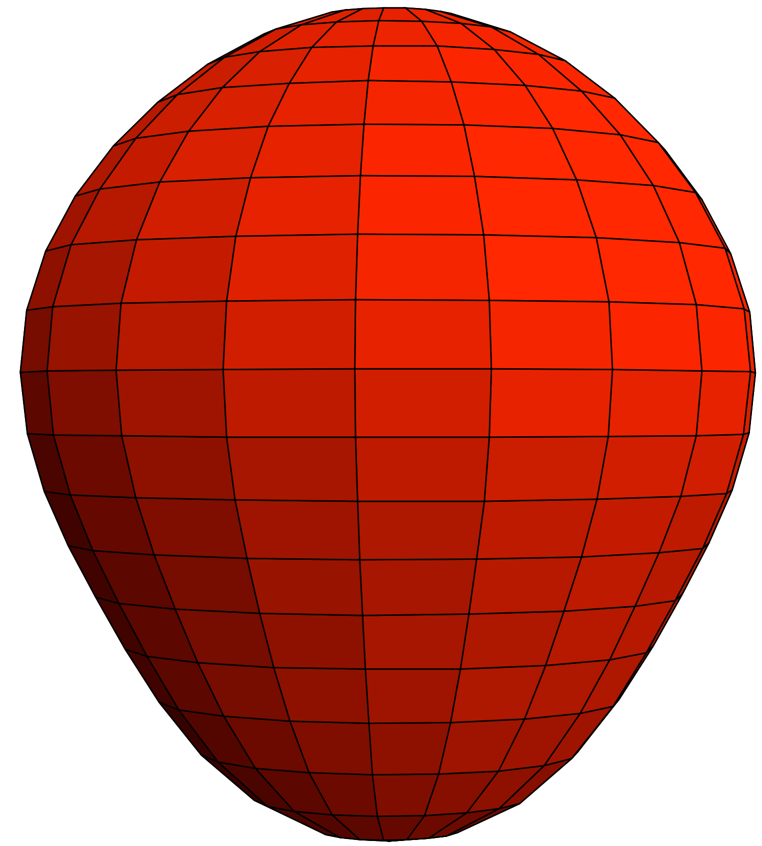


Likely explanation of the doublet degeneracy, large E1 in ^{229}Pa

Experimental challenge of using radioactive nuclei in edm experiments recently put to the test

^{225}Ra: first edm study with a radioactive nucleus

M. Bishof et al., arXiv:1606.0493

theory: Dzuba et al, PRA 66 (2002) 012111
Auerbach et al., PRL 76 (1996) 4316
Dobaczewski, Engel PRL 94 (2005) 232502

Argonne experiment used a radioactive isotope (14.9 d) produced off-site (ORNL)
Utilized a magneto optical trap: 10^{14} atoms used over the experiment's lifetime

Achieved a bound of $< 1.4 \times 10^{-23}$ e cm

Projected statistical sensitivity of the experiment is $\sim 10^{-28}$ e cm

^{225}Ra provides a factor 100 advantage over ^{199}Hg: 55 keV degeneracy

^{229}Pa provides a factor of 250 advantage over ^{225}Ra: 160 eV degeneracy

An experiment could be attempted on-site at FRIB, using the daily harvest

The strange case of ^{229}Pa: The IC rate is a puzzle

The doublet parity mixing means there is a contribution to the edm proportional to

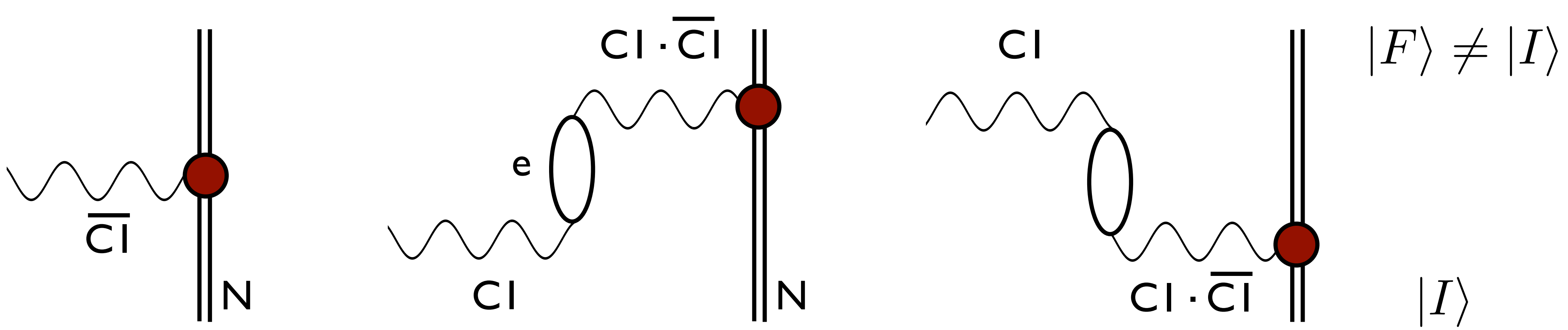
$$\sim \epsilon_{CP} \, \langle 5/2^- | C1 | 5/2^+ \rangle$$

and the C1 matrix element can be taken from the lifetime of the $5/2^-$ state

This state decays by internal conversion 100% due to its low energy:
standard tables of IC coefficients (atomic HF) needed matrix element

It is large (additional enhancement): 14 times the naive Nilsson model estimate

But the Schiff theorem has a generalization for dynamic transitions (Leon and Seki)



if the wavelength of the photon is long on the atomic scale: yes in this crazy case

Does this photo absorption argument also work for IC? $1 - \frac{Z'}{Z}$

Applied an atomic RPA code: the RPA corrections change the HF result by a factor of 50, suppressing the decay

But the lifetime is measured, so to keep this fixed, the C1 amplitude must be further enhanced by $\sqrt{50}$

Becomes 80 times the s.p. Nilsson model estimate

It seems extreme … large enhancement both because of the degeneracy, and because of the crazy C1 strength

It would be great if true (one is “getting back” part of the Schiff shielding)

Enhanced C3 and C1 strengths accompany octupole deformation: perhaps the extreme degeneracy and the extreme C1 strengths are reflections of the same physics… *but there are other possibilities too*

It would be very nice if FRIB enabled this rather special/exotic edm experiment — one that Ernest helped identify