A Brief History of Hadronic Parity Violation

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Parity IQ Question

When was weak interaction PV first seen?

Choices:

i) C.S. Wu et al., Phys. Rev. **105**, 1413 (1957).

ii) J.L. Friedman and V.L. Telegdi, Phys. Rev. **105**, 1681 (1957).

iii) R.T. Cox, C.G. McIlwraith, and B. Korrelmeyer, Proc. Natl. Acad. Sci. **14**, 544 (1928).

Our Problem:

Parity violating effects in strong

and electromagnetic hadronic interactions.

Examples:

First experiment—PV in pp by Tanner (1957)

$$^{180}Hf^*(8^-) \to {}^{180}Hf + \gamma$$

$A_\gamma = -(1.66 \pm 0.18) \times 10^{-2}$ PRC4, 1906 (1971)

$$\vec{n} + {}^{139}La$$

$A_z = (9.55 \pm 0.35) \times 10^{-2}$ PRC44, 2187 (1991)

Theoretical Picture

1964--------

Seminal theoretical paper: "Parity Nonconservation in Nuclei", F. Curtis Michel PR133B, 329 (1964)

Great Progress in Particle/Nuclear Physics:

Standard Model

BUT remain great unsolved problems at low energy:

i) $\Delta I = \frac{1}{2}$ Rule

ii) CP Violation

iii) Hypernuclear Weak Decay

iv) Hadronic Parity Violation

All deal with $J_\mu^{\text{hadron}} \times J^\mu_{\text{hadron}}$

Theoretical Picture

$$\mathcal{H}_w = \frac{G_F}{\sqrt{2}} J_\mu^\dagger J^\mu$$

with

$$J_\mu = J_\mu^{\text{hadron}} + J_\mu^{\text{lepton}}$$

Then

i) $J_\mu^{\text{lepton}} \times J^\mu_{\text{lepton}} \longrightarrow \mu^- \to e^- + \bar{\nu}_e + \nu_\mu$

ii) $J_\mu^{\text{lepton}} \times J^{\mu\dagger}_{\text{hadron}} \longrightarrow n \to p + e^- + \bar{\nu}_e$

iii) $J_\mu^{\text{hadron}} \times J^{\mu\dagger}_{\text{hadron}} \longrightarrow$ hadronic PV

Canonical size: $\mathcal{H}_w/\mathcal{H}_{str} \sim G_F m_\pi^2 \sim 10^{-7}$

Isolate via PV effects in strong and/or EM processes

Standard Model Picture

$$\mathcal{H}_w = \frac{G_F}{\sqrt{2}}(J_c^\dagger \times J_c + \frac{1}{2}J_n^\dagger \times J_n)$$

with

$$J_\mu^c = \bar{u}\gamma_\mu(1+\gamma_5)(\cos\theta_c d + \sin\theta_c s)$$

$$J_\mu^n = \bar{u}\gamma_\mu(1+\gamma_5)u - \bar{d}\gamma_\mu(1+\gamma_5)d - \bar{s}\gamma_\mu(1+\gamma_5)s$$

$$-4\sin^2\theta_w J_\mu^{em}$$

Then

$\mathcal{H}_w(\Delta S = 0)$ carries $\Delta I = 0, 1, 2$

1980: DDH Approach

Historical Aside: At time of writing

i) B. Holstein in Washington, DC

ii) J. Donoghue in Boston, MA

iii) B. Desplanques in France

At no time were two or more authors together!!

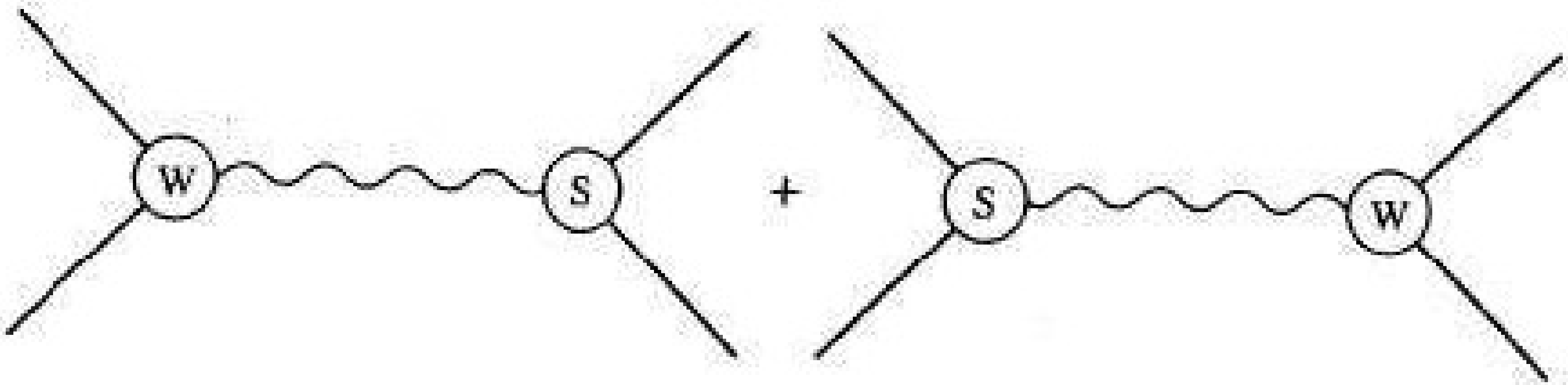
Basic idea:

Meson exchange gives good picture of PC NN interaction, with

$$\mathcal{H}_{\rm st} = i g_{\pi NN} \bar{N} \gamma_5 \tau \cdot \pi N + g_\rho \bar{N} \left(\gamma_\mu + i \frac{\mu_V}{2M} \sigma_{\mu\nu} k^\nu \right) \tau \cdot \rho^\mu N$$

$$+ g_\omega \bar{N} \left(\gamma_\mu + i \frac{\mu_S}{2M} \sigma_{\mu\nu} k^\nu \right) \omega^\mu N$$

so use for PV NN



Then define general PV weak couplings:

$$\mathcal{H}_{\rm wk} = \frac{h_\pi}{\sqrt{2}} \bar{N} (\tau \times \pi)_3 N$$

$$+ \bar{N} \left(h_\rho^0 \tau \cdot \rho^\mu + h_\rho^1 \rho_3^\mu + \frac{h_\rho^2}{2\sqrt{6}} (3\tau_3 \rho_3^\mu - \tau \cdot \rho^\mu) \right) \gamma_\mu \gamma_5 N$$

$$+ \bar{N} (h_\omega^0 \omega^\mu + h_\omega^1 \tau_3 \omega^\mu) \gamma_\mu \gamma_5 N - h_\rho'^1 \bar{N} (\tau \times \rho^\mu)_3 \frac{\sigma_{\mu\nu} k^\nu}{2M} \gamma_5 N$$

Yields two-body PV NN potential

$$V^{\mathrm{PNC}} = i\frac{f_\pi g_{\pi NN}}{\sqrt{2}}\left(\frac{\tau_1 \times \tau_2}{2}\right)_3 (\sigma_1+\sigma_2)\cdot\left[\frac{\mathbf{p}_1 - \mathbf{p}_2}{2M}, f_\pi(r)\right]$$

$$-g_\rho\left(h_\rho^0 \tau_1 \cdot \tau_2 + h_\rho^1\left(\frac{\tau_1 + \tau_2}{2}\right)_3 + h_\rho^2 \frac{(3\tau_1^3\tau_2^3 - \tau_1 \cdot \tau_2)}{2\sqrt{6}}\right)$$

$$\times((\sigma_1 - \sigma_2)\cdot\left\{\frac{\mathbf{p}_1 - \mathbf{p}_2}{2M}, f_\rho(r)\right\}$$

$$+i(1+\chi_V)\sigma_1 \times \sigma_2 \cdot \left[\frac{\mathbf{p}_1 - \mathbf{p}_2}{2M}, f_\rho(r)\right])$$

$$-g_\omega \left(h^0_\omega + h^1_\omega \left(\frac{\tau_1 + \tau_2}{2} \right)_3 \right)$$

$$\times ((\sigma_1 - \sigma_2) \cdot \left\{ \frac{\mathbf{p}_1 - \mathbf{p}_2}{2M}, f_\omega(r) \right\}$$

$$+ i(1 + \chi_S) \sigma_1 \times \sigma_2 \cdot \left[\frac{\mathbf{p}_1 - \mathbf{p}_2}{2M}, f_\omega(r) \right])$$

$$-(g_\omega h^1_\omega - g_\rho h^1_\rho) \left(\frac{\tau_1 - \tau_2}{2} \right)_3 (\sigma_1 + \sigma_2) \cdot \left\{ \frac{\mathbf{p}_1 - \mathbf{p}_2}{2M}, f_\rho(r) \right\}$$

$$-g_\rho h^{1\prime}_\rho i \left(\frac{\tau_1 \times \tau_2}{2} \right)_3 (\sigma_1 + \sigma_2) \cdot \left[\frac{\mathbf{p}_1 - \mathbf{p}_2}{2M}, f_\rho(r) \right]$$

where

$$f_V(r) = \exp(-m_V r)/4\pi r$$

Key problem is to evaluate seven weak couplings

At low energy only *five* independent parameters and can match to model-independent form

$$
\begin{aligned}
V_{LO}^{PNC}(\boldsymbol{r}) &= \Lambda_0^{{}^1S_0-{}^3P_0}\left(\frac{1}{i}\frac{\overleftrightarrow{\boldsymbol{\nabla}}_A}{2m_N}\frac{\delta^3(\boldsymbol{r})}{m_\rho^2}\cdot(\boldsymbol{\sigma}_1-\boldsymbol{\sigma}_2)-\frac{1}{i}\frac{\overleftrightarrow{\boldsymbol{\nabla}}_S}{2m_N}\frac{\delta^3(\boldsymbol{r})}{m_\rho^2}\cdot i(\boldsymbol{\sigma}_1\times\boldsymbol{\sigma}_2)\right)\\
&+ \Lambda_0^{{}^3S_1-{}^1P_1}\left(\frac{1}{i}\frac{\overleftrightarrow{\boldsymbol{\nabla}}_A}{2m_N}\frac{\delta^3(\boldsymbol{r})}{m_\rho^2}\cdot(\boldsymbol{\sigma}_1-\boldsymbol{\sigma}_2)+\frac{1}{i}\frac{\overleftrightarrow{\boldsymbol{\nabla}}_S}{2m_N}\frac{\delta^3(\boldsymbol{r})}{m_\rho^2}\cdot i(\boldsymbol{\sigma}_1\times\boldsymbol{\sigma}_2)\right)\\
&+ \Lambda_1^{{}^1S_0-{}^3P_0}\left(\frac{1}{i}\frac{\overleftrightarrow{\boldsymbol{\nabla}}_A}{2m_N}\frac{\delta^3(\boldsymbol{r})}{m_\rho^2}\cdot(\boldsymbol{\sigma}_1-\boldsymbol{\sigma}_2)(\tau_{1\,z}+\tau_{2\,z})\right)\\
&+ \Lambda_1^{{}^3S_1-{}^3P_1}\left(\frac{1}{i}\frac{\overleftrightarrow{\boldsymbol{\nabla}}_A}{2m_N}\frac{\delta^3(\boldsymbol{r})}{m_\rho^2}\cdot(\boldsymbol{\sigma}_1+\boldsymbol{\sigma}_2)(\tau_{1\,z}-\tau_{2\,z})\right)\\
&+ \Lambda_2^{{}^1S_0-{}^3P_0}\left(\frac{1}{i}\frac{\overleftrightarrow{\boldsymbol{\nabla}}_A}{2m_N}\frac{\delta^3(\boldsymbol{r})}{m_\rho^2}\cdot(\boldsymbol{\sigma}_1-\boldsymbol{\sigma}_2)(\boldsymbol{\tau}_1\otimes\boldsymbol{\tau}_2)_{20}\right),
\end{aligned}
$$

Match to DDH via

$$
\begin{aligned}
\Lambda_0^{{}^1S_0-{}^3P_0} &= -g_\rho(2+\chi_\rho)h_\rho^0 - g_\omega(2+\chi_\omega)h_\omega^0 \\
\Lambda_0^{{}^3S_1-{}^1P_1} &= -3g_\rho\chi_\rho h_\rho^0 + g_\omega\chi_\omega h_\omega^0 \\
\Lambda_1^{{}^1S_0-{}^3P_0} &= -g_\rho(2+\chi_\rho)h_\rho^1 - g_\omega(2+\chi_\omega)h_\omega^1 \\
\Lambda_1^{{}^3S_1-{}^3P_1} &= \sqrt{\tfrac{1}{2}}\, g_{\pi NN}\left(\frac{m_\rho}{m_\pi}\right)^2 h_\pi^1 + g_\rho(h_\rho^1 - h_\rho^{1\prime}) - g_\omega h_\omega^1 \\
\Lambda_2^{{}^1S_0-{}^3P_0} &= -g_\rho(2+\chi_\rho)h_\rho^2
\end{aligned}
$$

Historical Approaches

Theoretical

1964: Michel—Factorization

$$< \rho^+ n|\mathcal{H}_{\rm wk}^c|p >= \frac{G}{\sqrt{2}}\cos^2\theta_c < \rho^+ n|V_+^\mu A_\mu^-|p >$$

$$\approx \frac{G}{\sqrt{2}}\cos^2\theta_c < \rho^+|V_+^\mu|0 >< n|A_\mu^-|p >$$

1968: Tadic, Fischbach, McKeller—SU(3) Sum Rule

$$< \pi^+ n|\mathcal{H}_{\rm wk}^c|p >= -\sqrt{\frac{2}{3}}\tan\theta_c(2 < \pi^- p|\mathcal{H}_{\rm wk}|\Lambda^0 >$$

$$- < \pi^-\Lambda^0|\mathcal{H}_{\rm wk}|\Xi^- >)$$

1980: DDH—Quark Model plus Symmetry

Represent states by

$$|N>\sim b^\dagger_{qs}b^\dagger_{q's'}b^\dagger_{q``s"}|0>$$

$$|M>\sim b^\dagger_{qs}d^\dagger_{q's'}|0>$$

and

$$\mathcal{H}_{\rm wk}\sim\frac{G}{\sqrt{2}}\bar{\psi}\mathcal{O}\psi\bar{\psi}\mathcal{O}'\psi$$

Then structure of weak matrix element is

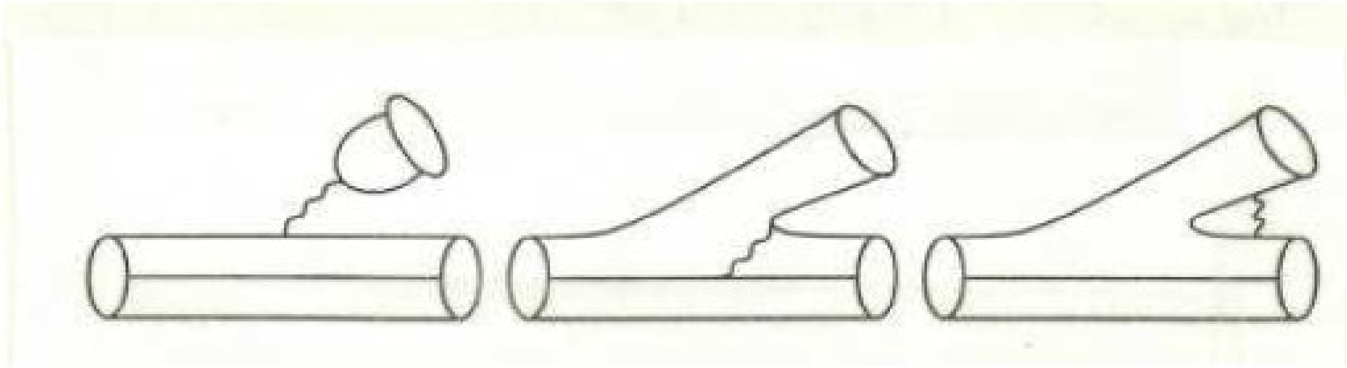
$$< MN|\mathcal{H}_{\rm wk}|N >= \frac{G}{\sqrt{2}} < 0|(b_{qs}b_{q's'}b_{q``s"})(b_{qs}d_{q's'})$$

$$\times\bar{\psi}\mathcal{O}\psi\bar{\psi}\mathcal{O}'\psi(b^\dagger_{qs}b^\dagger_{q's'}b^\dagger_{q``s"})|0 > \times R$$

with R a complicated radial integral—*i.e.*, a "Wigner-Eckart" theorem

$$< MN|\mathcal{H}_{\rm wk}|N >\sim \text{known ``geometrical'' factor} \times R$$

Find three basic structures



Here first is factorization, but two additional diagrams

Represent in terms of "Reasonable Range" and "Best Value"

Coupling	DDH [10] Reasonable Range	DDH [10] "Best" Value	DZ [36]	FCDH [37]
h_π^1	$0 \to 11$	$+4.6$	$+1.1$	$+2.7$
h_ρ^0	$11 \to -31$	-11	-8.4	-3.8
h_ρ^1	$-0.4 \to 0$	-0.2	$+0.4$	-0.4
h_ρ^2	$-7.6 \to -11$	-9.5	-6.8	-6.8
h_ω^0	$5.7 \to -10.3$	-1.9	-3.8	-5.0
h_ω^1	$-1.9 \to -0.8$	-1.2	-2.3	-2.3

Experimental Picture

1957---

How to detect PV?

a) circular polarization in a radiative transition

b) longitudinal analyzing power in a scattering reaction

c) photon asymmetry in radiative decay of a polarized parent

d) photon asymmetry in photodisintegration involving polarized beam

e) decay width of a forbidden transition

f) neutron spin rotation

Lots of Data

Process	Observable	Measurement*
$^{181}\text{Ta}(\frac{5}{2}^+ \to \frac{7}{2}^+)$	P_γ	-52 ± 5
$^{175}\text{Lu}(\frac{9}{2}^- \to \frac{7}{2}^+)$	P_γ	550 ± 50
$^{41}\text{K}(\frac{7}{2}^- \to \frac{3}{2}^+)$	P_γ	200 ± 40
$^{19}\text{F}(\frac{1}{2}^- \to \frac{1}{2}^+)$	A_γ	-850 ± 260
	A_γ	-680 ± 180
$^{18}\text{F}0^- \to 1^+)$	P_γ	-7000 ± 20000
	P_γ	-10000 ± 18000
	P_γ	3000 ± 6000
	P_γ	2000 ± 6000

$^{21}\text{Ne}(\frac{1}{2}^{-} \to \frac{3}{2}^{+})$	P_γ	-8000 ± 14000
$^{16}\text{O}(2^-) \to \alpha +^{12} C$	$\sqrt{\Gamma}_\alpha(\text{eV}^{-\frac{1}{2}})$	100 ± 10
$pp \to pp$	$A_L(13.6\,\text{MeV})$	-0.96 ± 0.20
	$A_L(15\,\text{MeV})$	-1.7 ± 0.8
	$A_L(45\,\text{MeV})$	-1.57 ± 0.23
	$A_L(221\,\text{MeV})$	0.84 ± 0.34
$p\alpha \to p\alpha$	$A_L(46\,\text{MeV})$	-3.3 ± 0.9
$n\alpha \to n\alpha$	$\frac{d\phi}{dz}$	$1.7 \pm 9.1 \pm 1.4$
$np \to d\gamma$	P_γ	1.8 ± 1.8
	A_γ	0.6 ± 2.1
$nd \to t\gamma$	A_γ	42 ± 38

* **all** $\times 10^{-7}$

Experimental

Can use nucleus as amplifier—first order perturbation theory

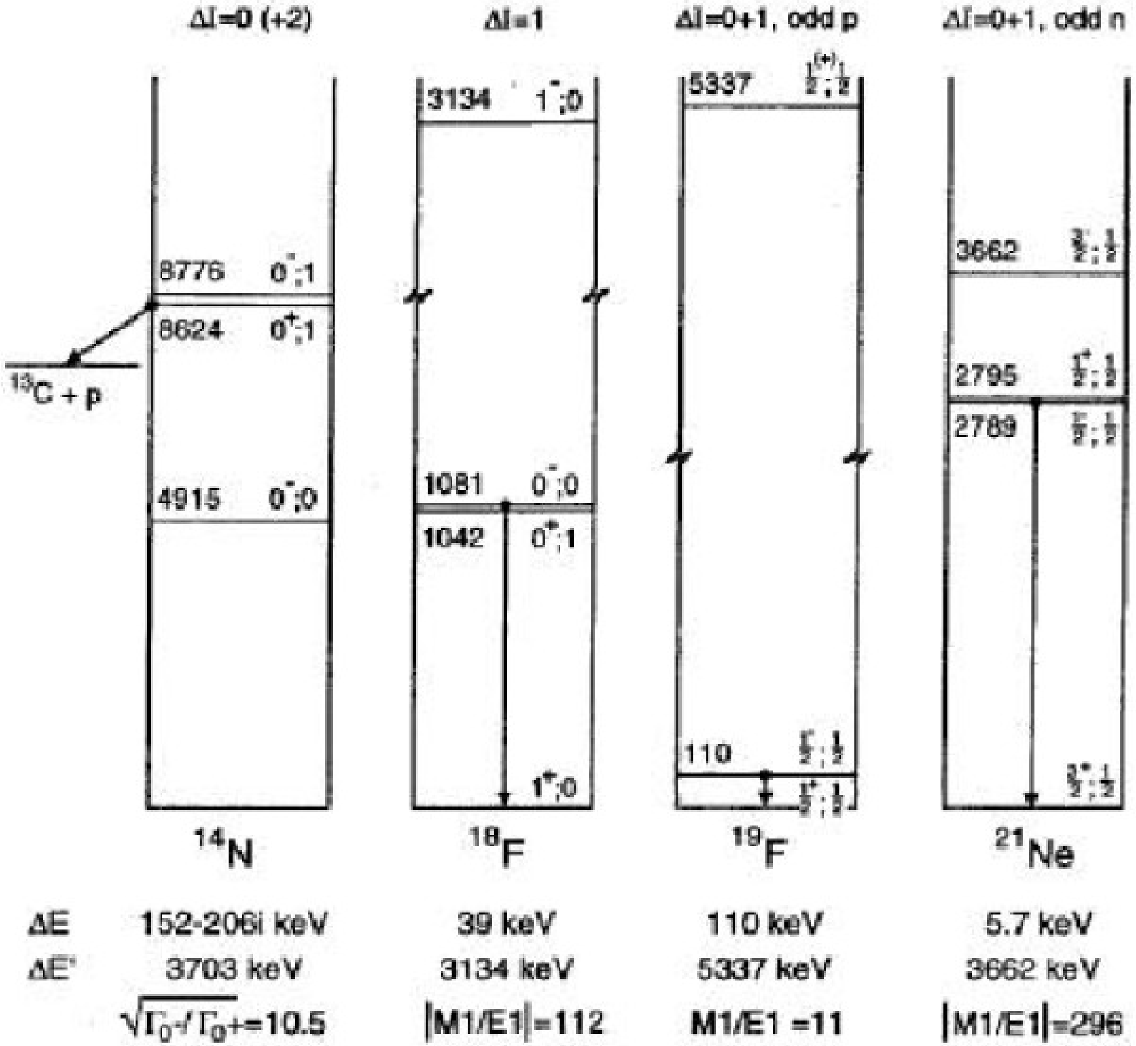
$$|\psi_{J^+}> \simeq |\phi_{J^+}> + \frac{|\phi_{J^-}><\phi_{J^-}|\mathcal{H}_{\rm wk}|\phi_{J^+}>}{E_+ - E_-}$$

$$= |\phi_{J^+}> + \epsilon|\phi_{J^-}>$$

$$|\psi_{J^-}> \simeq |\phi_{J^-}> + \frac{|\phi_{J^+}><\phi_{J^+}|\mathcal{H}_{\rm wk}|\phi_{J^-}>}{E_- - E_+}$$

$$= |\phi_{J^-}> - \epsilon|\phi_{J^+}>$$

Then enhancement if ΔE << typical spacing. Examples are



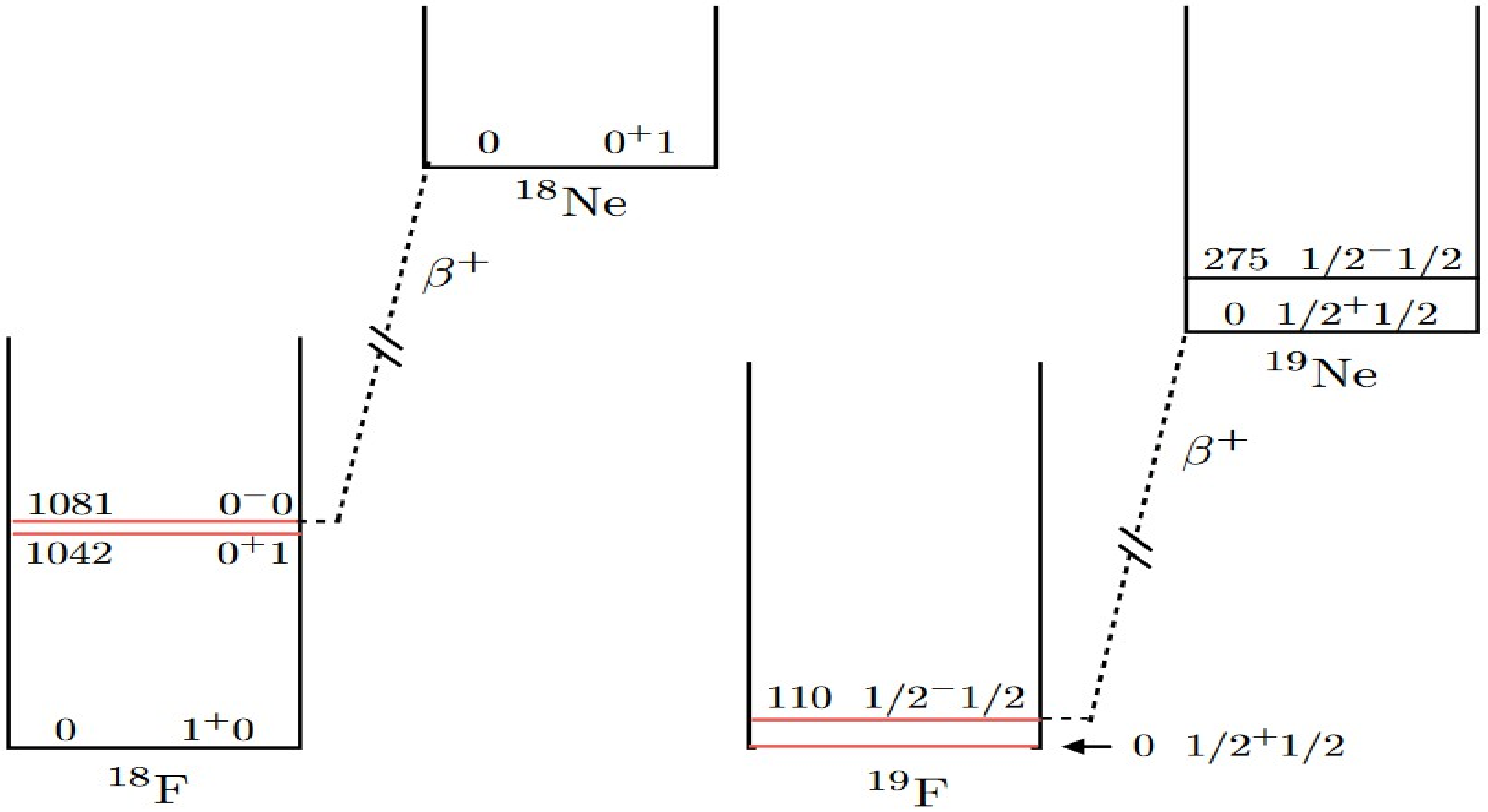
Typical results: Circular polarization in ^{18}F E1 decay of 0^- 1.081 MeV excited state

$$|P_\gamma(1081)| = \left\{ \begin{array}{cc} (-7 \pm 20) \times 10^{-4} & \text{Caltech/Seattle} \\ (3 \pm 6) \times 10^{-4} & \text{Florence} \\ (-10 \pm 18) \times 10^{-4} & \text{Mainz} \\ (2 \pm 6) \times 10^{-4} & \text{Queens} \\ (-4 \pm 30) \times 10^{-4} & \text{Florence} \end{array} \right.$$

Asymmetry in decay of polarized $\frac{1}{2}^-$ 110 KeV excited state of ^{19}F

$$A_\gamma = \left\{ \begin{array}{cc} (-8.5 \pm 2.6) \times 10^{-5} & \text{Seattle} \\ (-6.8 \pm 1.8) \times 10^{-5} & \text{Mainz} \end{array} \right.$$

Note that analysis of F experiments aided by



Circular Polarization in ^{21}Ne E1 decay of $\frac{1}{2}^-$ 2.789 Mev excited state

$$P_\gamma = \begin{cases} (24 \pm 24) \times 10^{-4} & \text{Seattle/Chalk River} \\ (3 \pm 16) \times 10^{-4} & \text{Chalk River/Seattle} \end{cases}$$

Also results on NN systems which are not enhanced:

pp: PSI $A_z^{tot}(45.0\, MeV) = -(1.57 \pm 0.23) \times 10^{-7}$

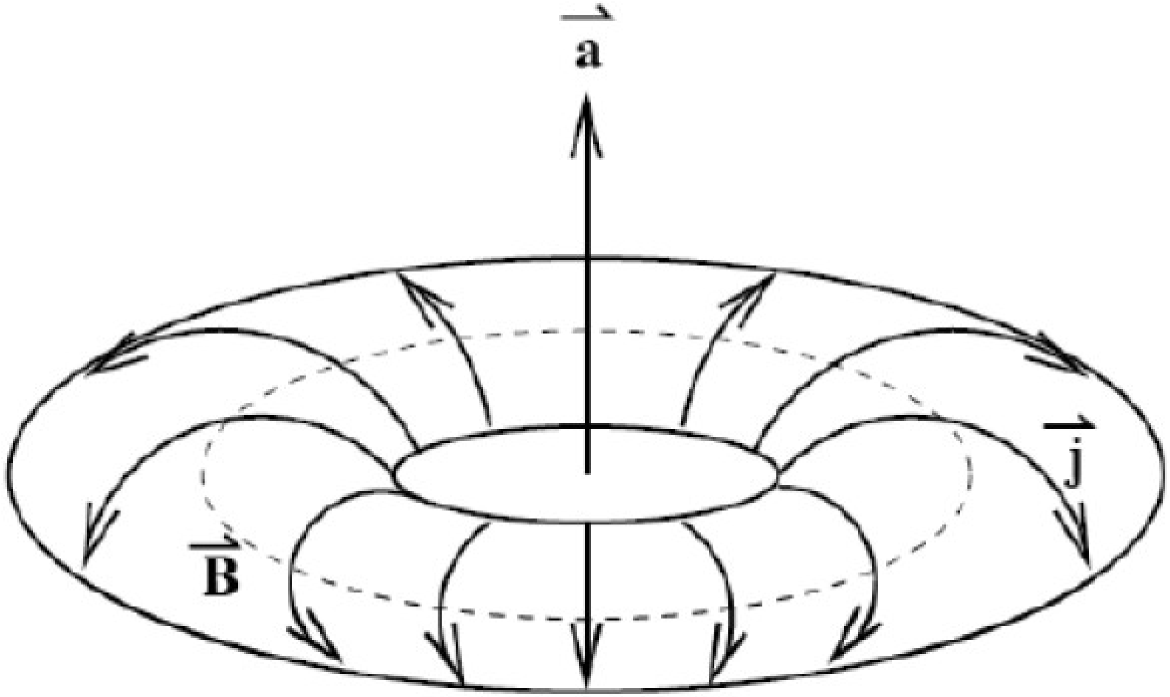
pp: Bonn $A_z(13.6\, MeV) = -(0.93 \pm 0.20 \pm 0.05) \times 10^{-7}$

pα: PSI $A_z(46.0\, MeV) = -(3.3 \pm 0.9) \times 10^{-7}$

A: Anapole Moment

Background—usual analysis of magnetic field away from currents involves multipole expansion—dipole, quadrupole, octupole, etc.

If parity violated a new possibility: toroidal current



Leads to *local* field! Another view: Consider matrix element of V_μ^{em} with parity violation:

$$< f|V_\mu^{em}|i >= \bar{u}(p_f)[F_1(q^2)\gamma_\mu - F_2(q^2)\frac{i\sigma_{\mu\nu}q^\nu}{2M}$$

$$+F_3(q^3)\frac{1}{4M^2}(\gamma_\mu\gamma_5 q^2 - q_\mu \not{q}\gamma_5) + F_4(q^2)\frac{i\sigma_{\mu\nu}q^\nu\gamma_5}{2M}]u(p_i)$$

Here $F_1(q^2)$, $F_2(q^2)$ usual charge, magnetic form factors.

$F_4(q^2)$ violates both P,T and is electric dipole moment.

$F_3(q^2)$ violates only T and is anapole moment—note q^2 dependence—local!

Since involves axial current—spin dependent—find via spin-dependent PV effect. Performed by Wieman et al. in 6S-7S ^{133}Cs transitions.

Effective interaction is

$$\mathcal{H}_w^{eff} = \frac{G_F}{\sqrt{2}}(\kappa_Z + \kappa_a)\vec{\alpha}_e \cdot \vec{J}_{nuc}\rho(r)$$

Here $\kappa_Z = 0.013$ is direct Z-exchange term and

$$\kappa_a = 0.112 \pm 0.016$$

is anapole moment

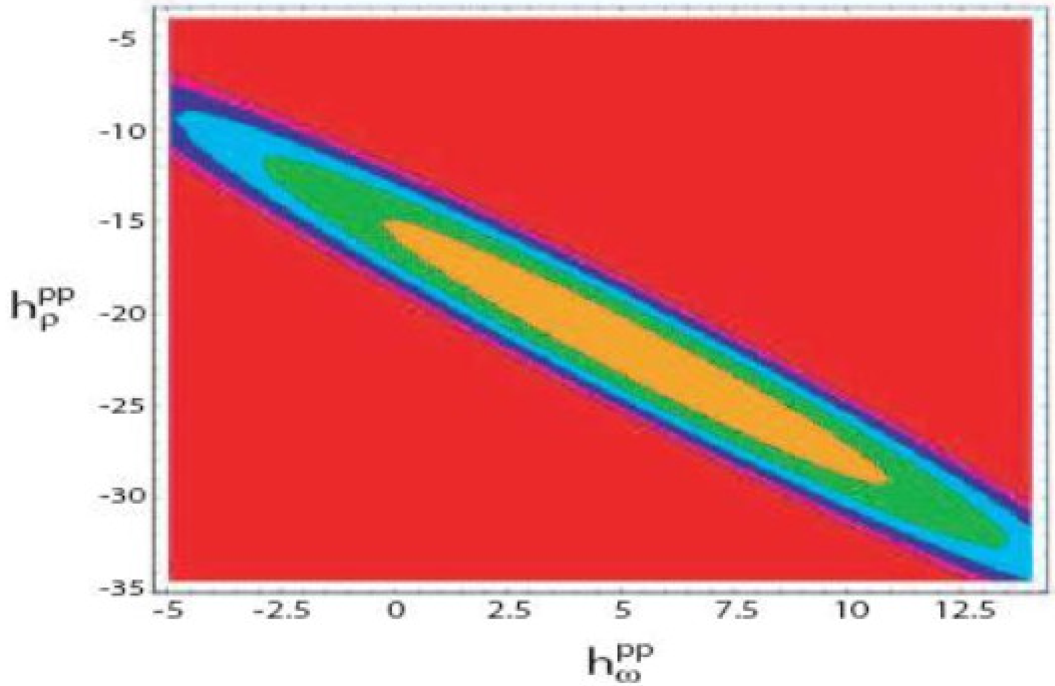
In terms of DDH

$$h_\pi - 0.21(h_\rho^0 + 0.6h_\omega^0) = (0.99 \pm 0.16) \times 10^{-6}$$

TRIUMF E497

$\vec{p}p$ scattering at 221 MeV–special energy S-P vanishes–sensitive to P-D mixing

$$A_L = (0.84 \pm 0.29 \pm 0.27) \times 10^{-7}$$

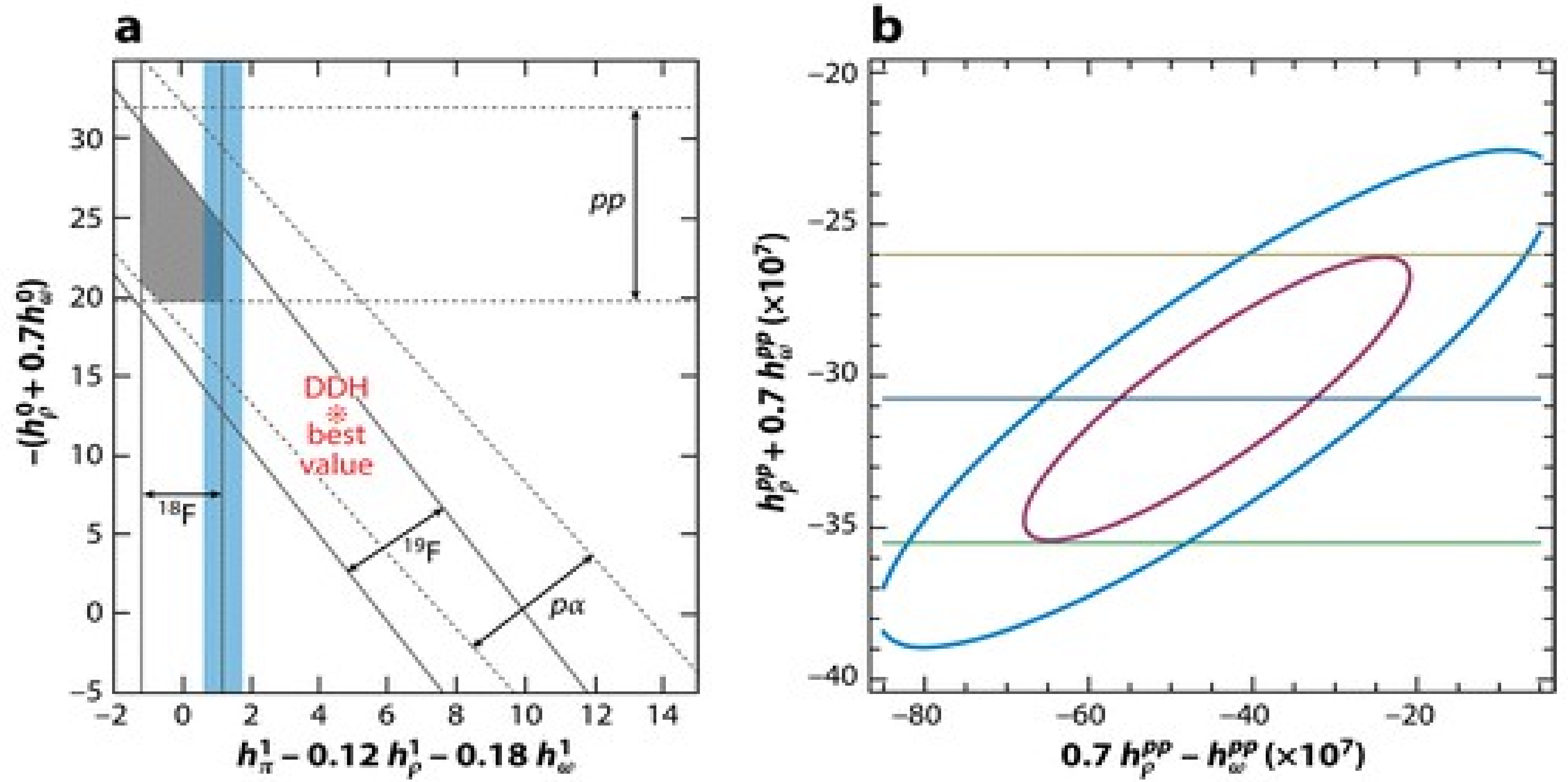


Problem is how to interpret data in terms of fundamental couplings. At low energy only five independent couplings—in DDH language these can be chosen as

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

but better to use model-independent EFT framework.

What is the pattern here? Traditionally, use Adelberger-Haxton plot, emphasizing $h_\pi^{(1)}$ and $h_\rho^{(0)} + 0.7h_\omega^{(0)}$



$$\Lambda_0^+ \equiv \frac{3}{4}\Lambda_0^{{}^3S_1-{}^1P_1} + \frac{1}{4}\Lambda_0^{{}^1S_0-{}^3P_0} \sim N_c$$

$$\Lambda_2^{{}^1S_0-{}^3P_0} \sim N_c,$$

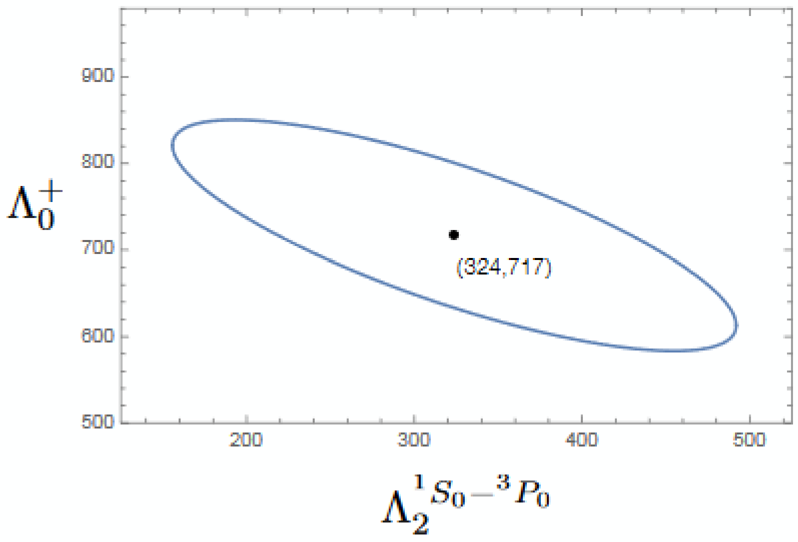
$$\Lambda_0^- \equiv \frac{1}{4}\Lambda_0^{{}^3S_1-{}^1P_1} - \frac{3}{4}\Lambda_0^{{}^1S_0-{}^3P_0} \sim 1/N_c$$

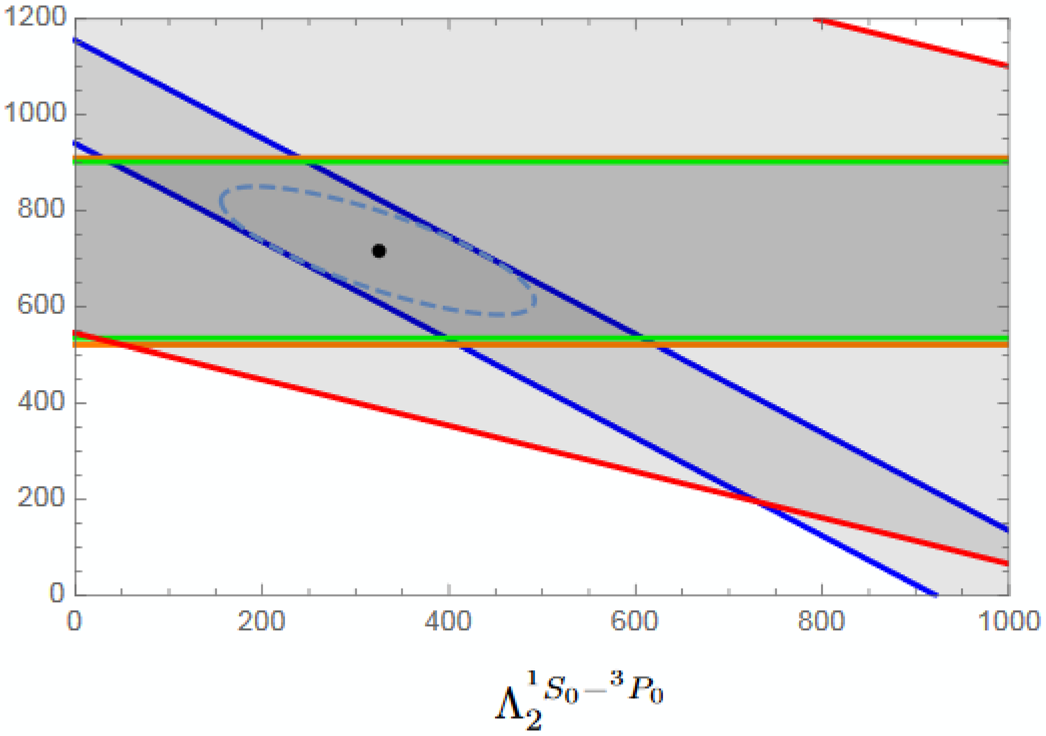
$$\Lambda_1^{{}^1S_0-{}^3P_0} \sim \sin^2\theta_w$$

$$\Lambda_1^{{}^3S_1-{}^3P_1} \sim \sin^2\theta_w.$$

$$
\begin{aligned}
\frac{2}{5}\Lambda_0^{+} + \frac{1}{\sqrt{6}}\Lambda_2^{^1S_0-^3P_0} + \left[-\frac{6}{5}\Lambda_0^{-} + \Lambda_1^{^1S_0-^3P_0}\right] &= 419 \pm 43 & & A_L(\vec{\mathrm{p}}\mathrm{p}) \\
1.3\Lambda_0^{+} + \left[-0.9\Lambda_0^{-} + 0.89\Lambda_1^{^1S_0-^3P_0} + 0.32\Lambda_1^{^3S_1-^3P_1}\right] &= 930 \pm 253 & & A_L(\vec{\mathrm{p}}\alpha) \\
\left[|2.42\Lambda_1^{^1S_0-^3P_0} + \Lambda_1^{^3S_1-^3P_1}|\right] &< 340 & & P_\gamma(^{18}\mathrm{F}) \\
0.92\Lambda_0^{+} + \left[-1.03\Lambda_0^{-} + 0.67\Lambda_1^{^1S_0-^3P_0} + 0.29\Lambda_1^{^3S_1-^3P_1}\right] &= 661 \pm 169 & & A_\gamma(^{19}\mathrm{F})
\end{aligned}
$$

New and "improved" plot:



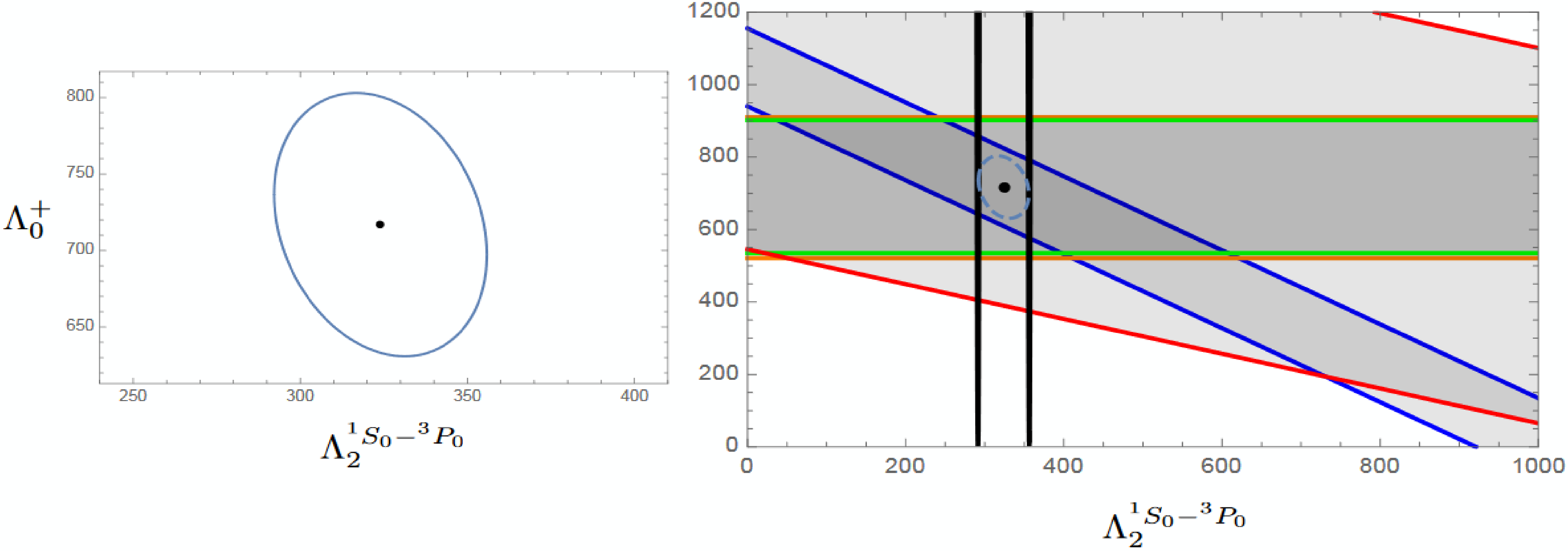


"Rosetta Stone" Table

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

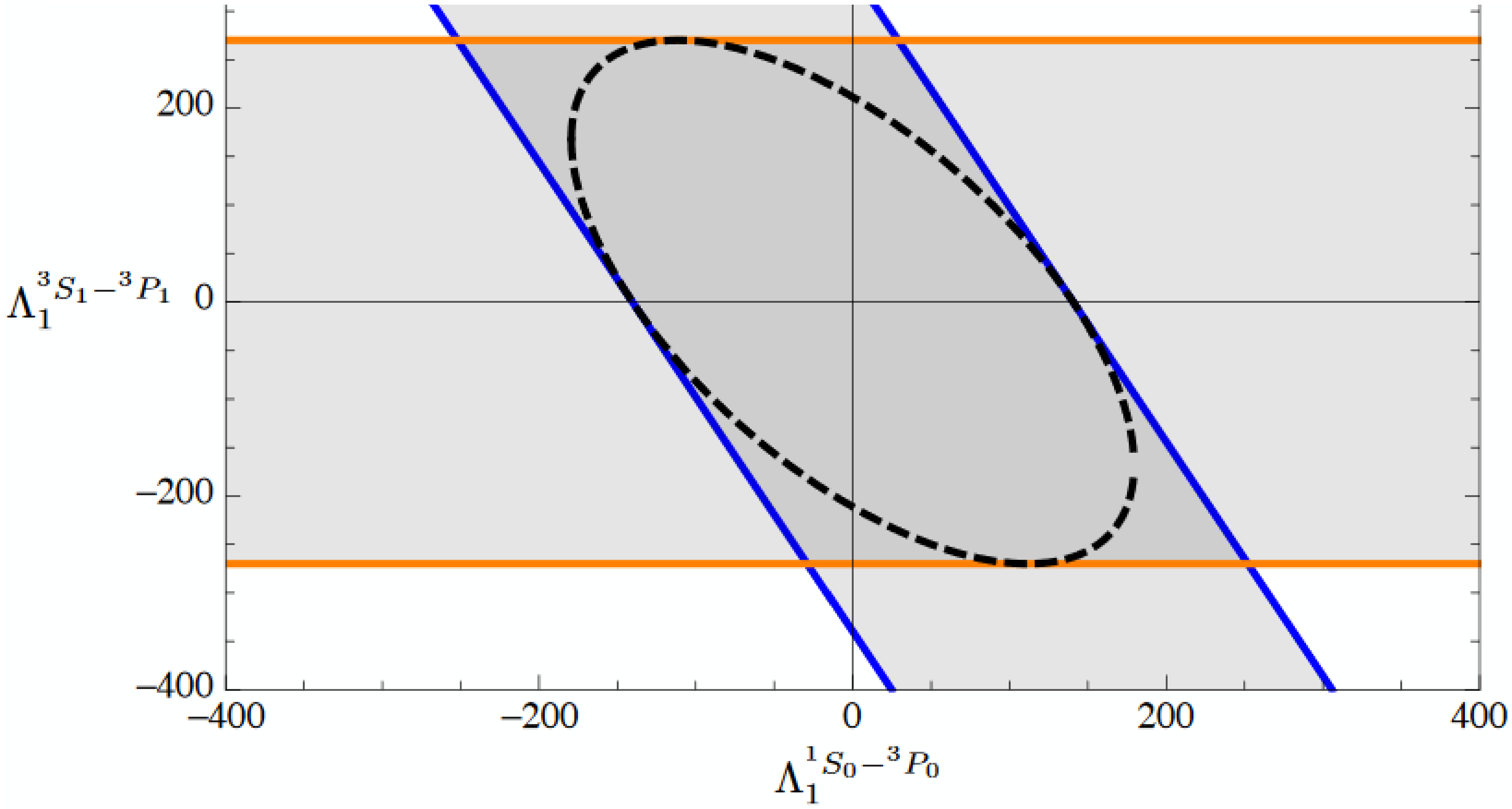
The Future

Lattice Calculation of Λ_2



I=1 Sector: Preliminary Result from $\vec{n}p \to d\gamma$ is

$$A_\gamma = (3.5 \pm 1.5) \times 10^{-8}$$



New Experiments

$$a) \quad \vec{n} + {}^3\mathrm{He} \rightarrow {}^3\mathrm{H} + p$$

$$\frac{364}{10^{-8}} A_{\mathrm{p}} = -\Lambda_0^+ + 0.227\Lambda_2^{^1S_0-^3P_0} - \left[3.82\Lambda_0^- + 8.18\Lambda_1^{^1S_0-^3P_0} + 2.27\Lambda_1^{^3S_1-^3P_1}\right]$$

$$A_p \sim -1.8 \times 10^{-8}$$

$$b) \quad \vec{n} + d \rightarrow t + \gamma$$

$$\frac{118}{10^{-7}} A_\gamma = \Lambda_0^+ + 0.44\Lambda_2^{^1S_0-^3P_0} - \left[1.86\Lambda_0^- + 0.65\Lambda_1^{^1S_0-^3P_0} + 0.42\Lambda_1^{^3S_1-^3P_1}\right]$$

$$A_\gamma \sim 7.3 \times \times 10^{-7}$$

$c) \quad n + p \to d + \vec{\gamma}$

$$\frac{825}{10^{-7}} P_\gamma = \Lambda_0^+ + 1.27\Lambda_2^{{}^1S_0 - {}^3P_0} + [0.47\Lambda_0^-] \, ,$$

$$P_\gamma \sim 1.4 \times \times 10^{-7}$$

Note that alternative is $\vec{\gamma} + d \to n + p$

$d) \quad \vec{n} +^4 He$ Spin Rotation

$$\frac{105}{10^{-7}} \frac{d\phi^{\mathrm{n}}}{dz}\bigg|_{^4\mathrm{He}} = \left(\Lambda_0^+ - \left[1.61\Lambda_0^- + 0.92\Lambda_1^{^1S_0-^3P_0} + 0.35\Lambda_1^{^3S_1-^3P_1}\right]\right) \ \mathrm{rad/m}$$

$$\frac{d\phi_n}{dz} \sim 6.8 \times \times 10^{-7}\,\mathrm{rad/m}$$

NIST result is $(1.7 \pm 9.1 \pm 1.4) \times 10^{-7}$

$e)$ $\vec{n} + p$ Spin Rotation

$$\frac{180}{10^{-7}}\frac{d\phi^{\mathrm{n}}}{dz}\Big|_{\mathrm{parahydrogen}} \quad \frac{d\phi_n}{dz} \sim 9.1 \times \times 10^{-7}\,\mathrm{rad/m} \quad + 1.94\Lambda_1^{{}^3S_1 - {}^3P_1}\big]\big) \ \mathrm{rad/m},$$

$$\frac{d\phi_n}{dz} \sim 9.1 \times \times 10^{-7}\,\mathrm{rad/m}$$

$$f) \quad \vec{p} + d \rightarrow p + d$$

$$\frac{156}{10^{-8}} A_L = -\Lambda_0^+ + \left[1.75\Lambda_0^- - 1.09\Lambda_1^{^1S_0 - ^3P_0} - 1.25\Lambda_1^{^3S_1 - ^3P_1}\right]$$

$$A_L \sim -4.6 \times 10^{-8}$$

Could

i) ^{18}F

ii) ^{19}F

iii) $\vec{p}+{}^{4}$He

be redone with higher precision?

After six decades of study, still more work needs to be done.