# Hadronic Parity Violation

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# Our Problem:

Parity violating effects in strong

and electromagnetic hadronic interactions.

Examples:

First experiment—PV in $^{19}F(p,\alpha)^{16}O$ by Tanner (1957)—no effect seen

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

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

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

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

# Theoretical Clues

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

1964 $\longrightarrow$ 2013

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 $J_\mu^{\rm hadron} \times J^\mu_{\rm hadron}$

# 1980: DDH Approach

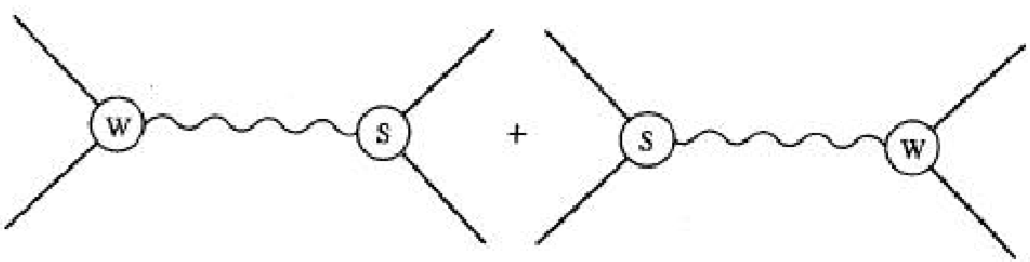
Basic idea:

Meson exchange gives good picture of PC NN interaction, with

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

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

so use for PV NN



Then define general PV weak couplings:

$$\mathcal{H}_{\rm wk} = \frac{f_\pi^1}{\sqrt{2}}\bar{N}(\tau\times\pi)_3 N$$

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

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

Yields two-body PV NN potential

$$
\begin{aligned}
V^{\mathrm{PNC}} = {} & i\frac{f_\pi^1 g_{\pi NN}}{\sqrt{2}}\left(\frac{\tau_1\times\tau_2}{2}\right)_3(\sigma_1+\sigma_2)\cdot\left[\frac{\mathbf{p}_1-\mathbf{p}_2}{2M}, f_\pi(r)\right] \\
& -g_\rho\left(h_\rho^0\tau_1\cdot\tau_2 + h_\rho^1\left(\frac{\tau_1+\tau_2}{2}\right)_3 + h_\rho^2\frac{(3\tau_1^3\tau_2^3-\tau_1\cdot\tau_2)}{2\sqrt{6}}\right) \\
& \times((\sigma_1-\sigma_2)\cdot\left\{\frac{\mathbf{p}_1-\mathbf{p}_2}{2M}, f_\rho(r)\right\} \\
& +i(1+\chi_V)\sigma_1\times\sigma_2\cdot\left[\frac{\mathbf{p}_1-\mathbf{p}_2}{2M}, f_\rho(r)\right]) \\
& -g_\omega\left(h_\omega^0 + h_\omega^1\left(\frac{\tau_1+\tau_2}{2}\right)_3\right) \\
& \times((\sigma_1-\sigma_2)\cdot\left\{\frac{\mathbf{p}_1-\mathbf{p}_2}{2M}, f_\omega(r)\right\} \\
& +i(1+\chi_S)\sigma_1\times\sigma_2\cdot\left[\frac{\mathbf{p}_1-\mathbf{p}_2}{2M}, f_\omega(r)\right]) \\
& -(g_\omega h_\omega^1 - g_\rho h_\rho^1)\left(\frac{\tau_1-\tau_2}{2}\right)_3(\sigma_1+\sigma_2)\cdot\left\{\frac{\mathbf{p}_1-\mathbf{p}_2}{2M}, f_\rho(r)\right\} \\
& -g_\rho h_\rho^{1'} i\left(\frac{\tau_1\times\tau_2}{2}\right)_3(\sigma_1+\sigma_2)\cdot\left[\frac{\mathbf{p}_1-\mathbf{p}_2}{2M}, f_\rho(r)\right]
\end{aligned}
$$

where

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

Key problem is to evaluate seven weak couplings

## 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

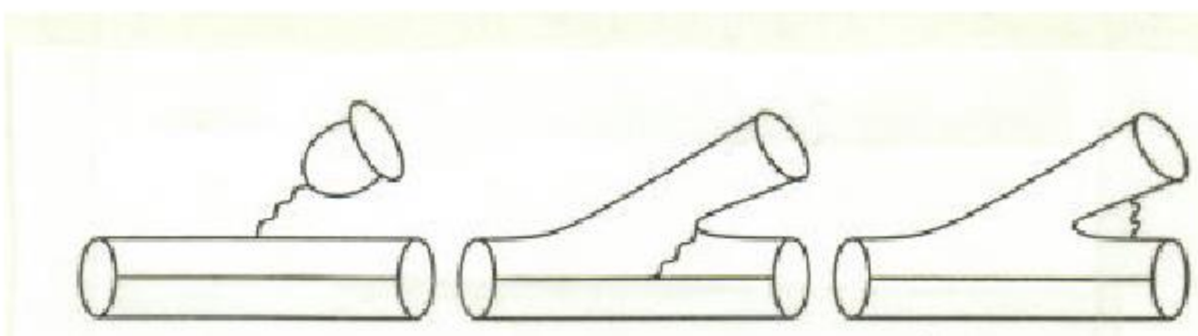
$$< MN|\mathcal{H}_{\rm wk}|N >= \frac{G}{\sqrt{2}} < 0|(b_{qs}b_{q's'}b_{q``s"})(b_{qs}d_{q's'})$$

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

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

$< MN|\mathcal{H}_{\rm wk}|N >\sim$ 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 Reasonable Range | DDH "Best" Value |
|---|---|---|
| $f_\pi^1$ | $0 \rightarrow 30$ | 12 |
| $h_\rho^0$ | $30 \rightarrow -81$ | -30 |
| $h_\rho^1$ | $-1 \rightarrow 0$ | -0.5 |
| $h_\rho^2$ | $-20 \rightarrow -29$ | -25 |
| $h_\omega^0$ | $15 \rightarrow -27$ | -5 |
| $h_\omega^1$ | $-5 \rightarrow -2$ | -3 |

all times "sum rule value" $3.8 \times 10^{-8}$

# Experimental

Can use nucleus as amplifier—first order perturbation theory

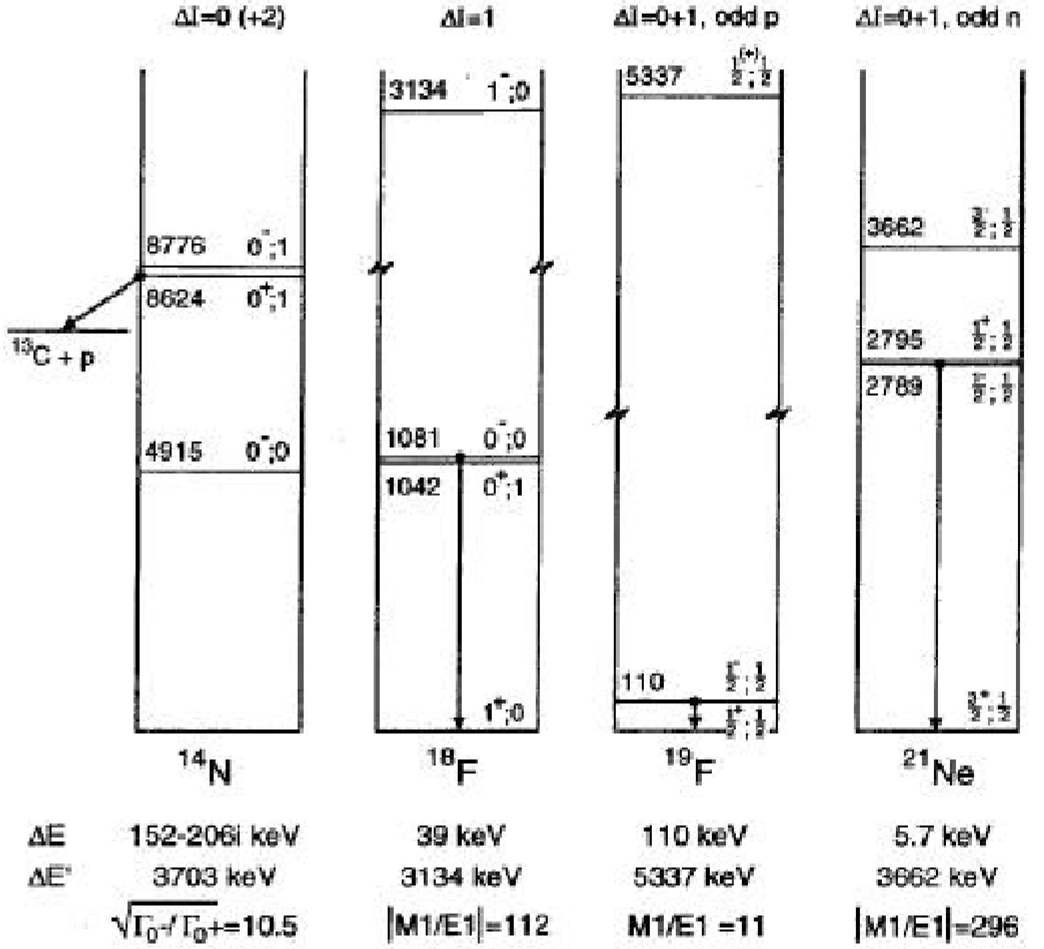
$$|\psi_{J^+}> \simeq |\phi_{J^+}> + \frac{|\phi_{J^-}><\phi_{J^-}|\mathcal{H}_{\rm wk}|\phi_{J^+}>}{E_+ - E_-}$$

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

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

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

Then enhancement if $\Delta E$ << typical spacing. Examples are



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

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

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

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

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

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

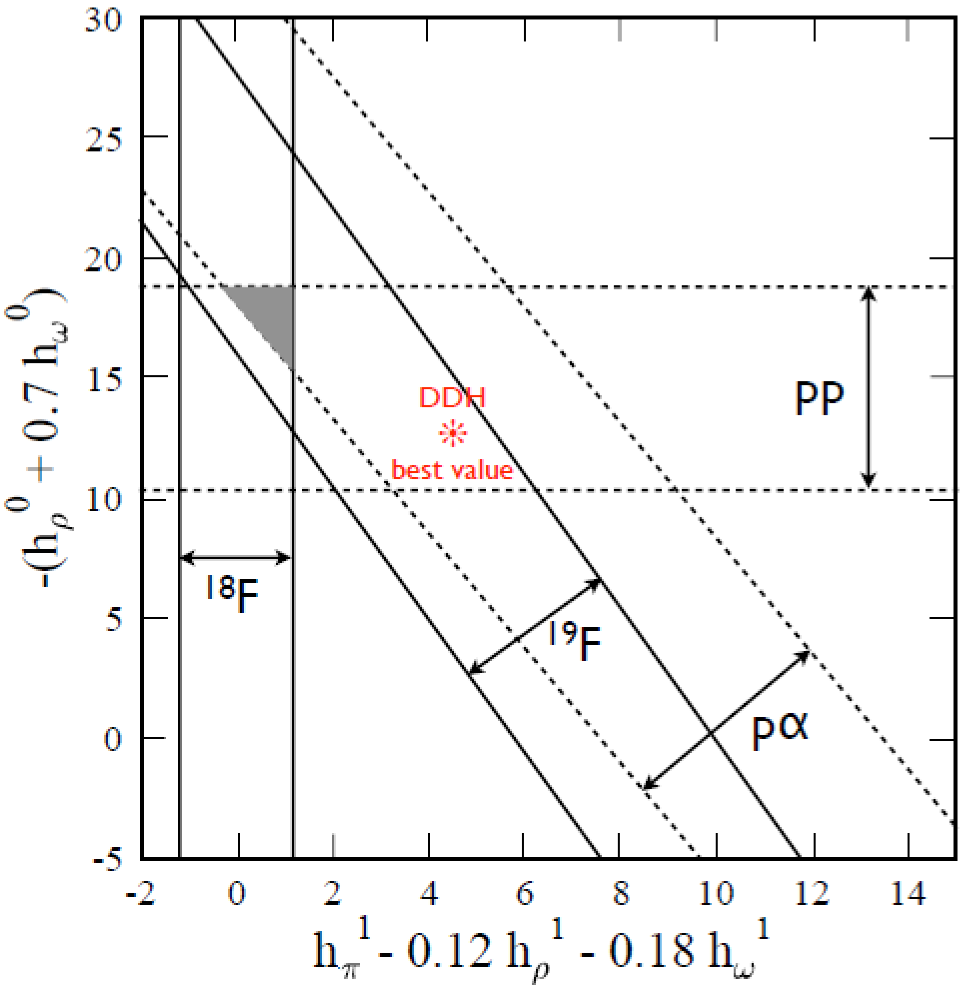
Also results on NN systems which are not enhanced:

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

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

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

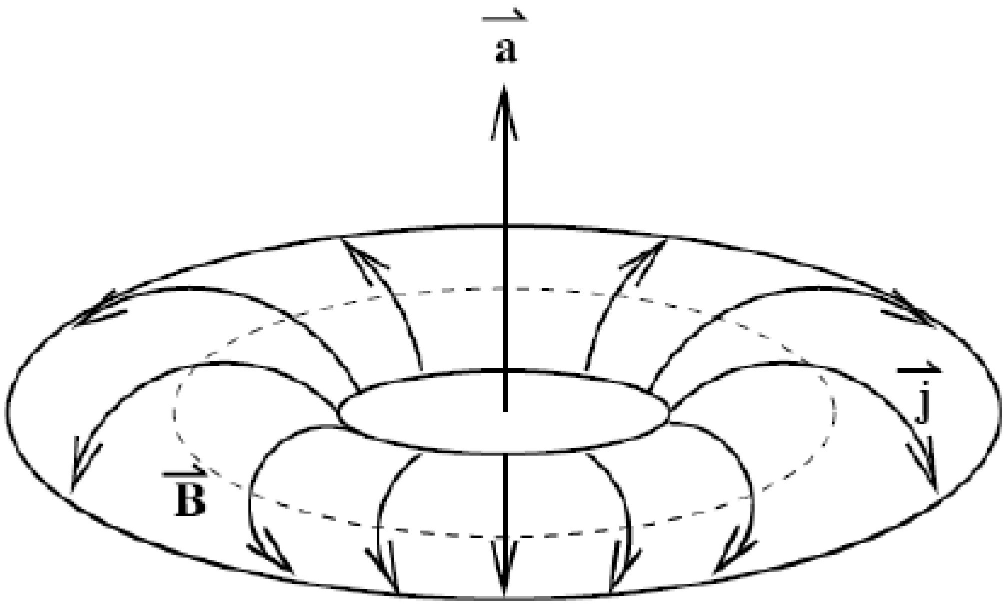
# Traditional Plot



## 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 $V_\mu^{em}$ 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

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

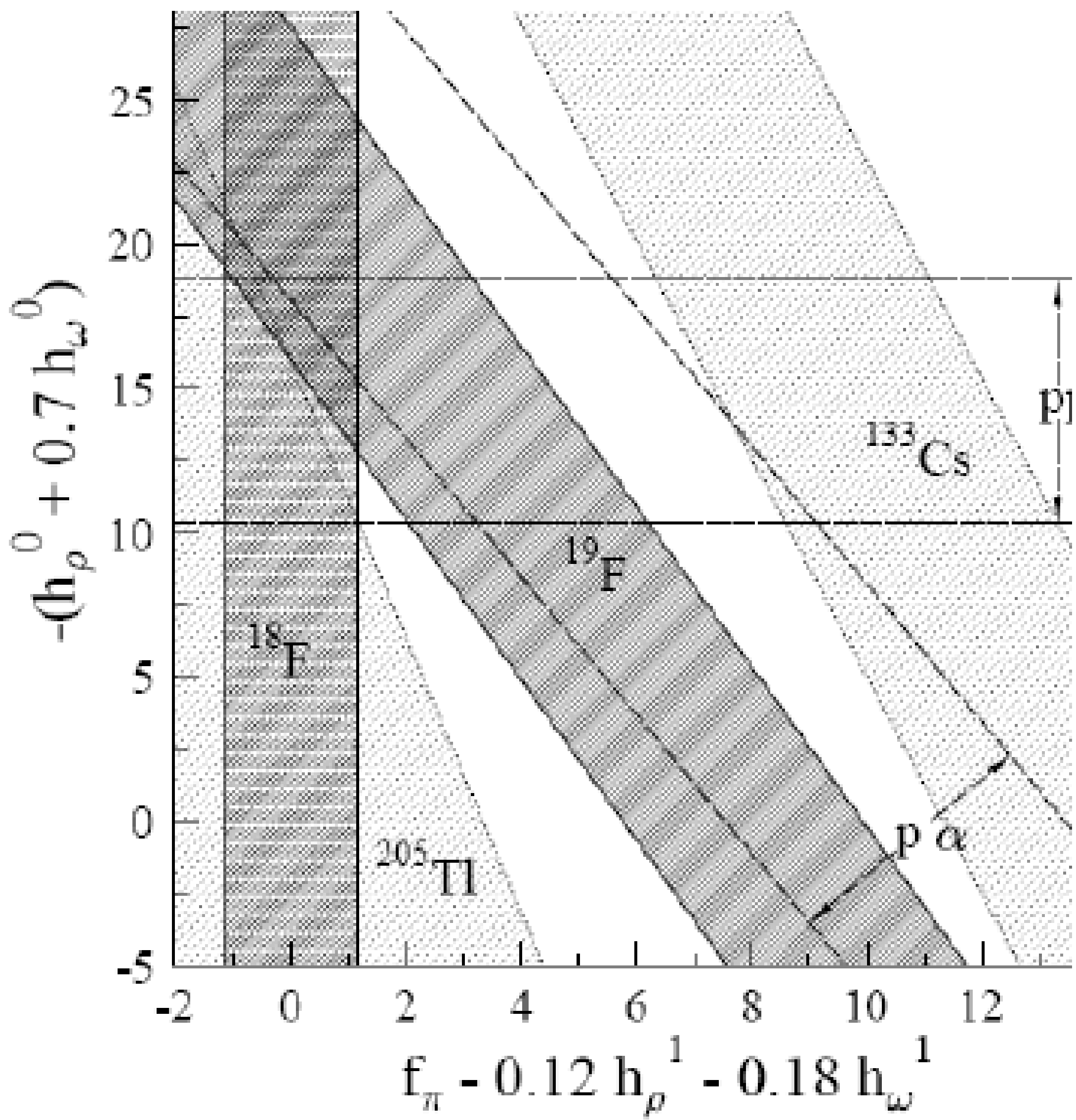
Here $\kappa_Z = 0.013$ is direct Z-exchange term and

$$\kappa_a = 0.112 \pm 0.016$$

is anapole moment

In terms of DDH

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

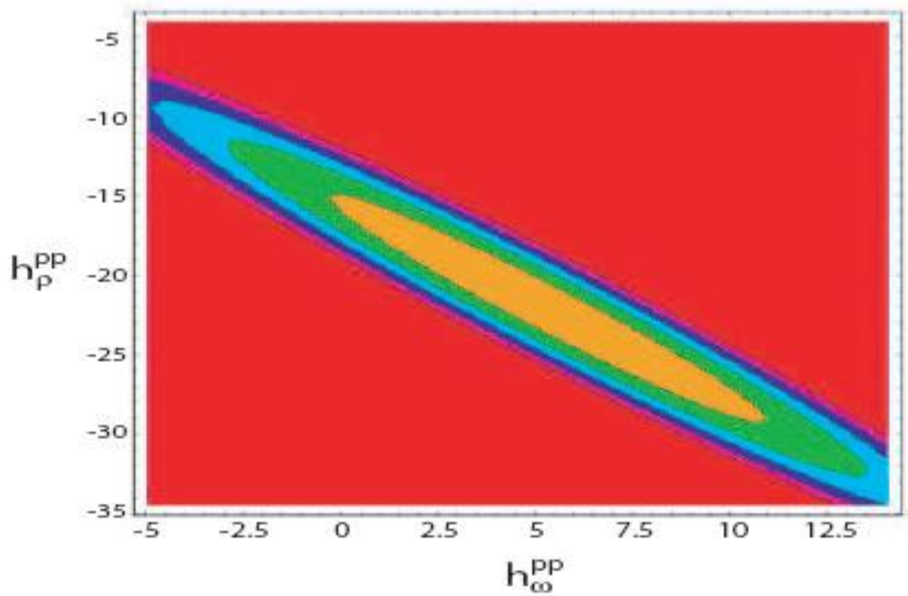


-(h$_\rho$$^0$ + 0.7 h$_\omega$$^0$)
f$_\pi$ - 0.12 h$_\rho$$^1$ - 0.18 h$_\omega$$^1$
$^{133}$Cs
$^{19}$F
$^{18}$F
$^{205}$Tl
p α
p

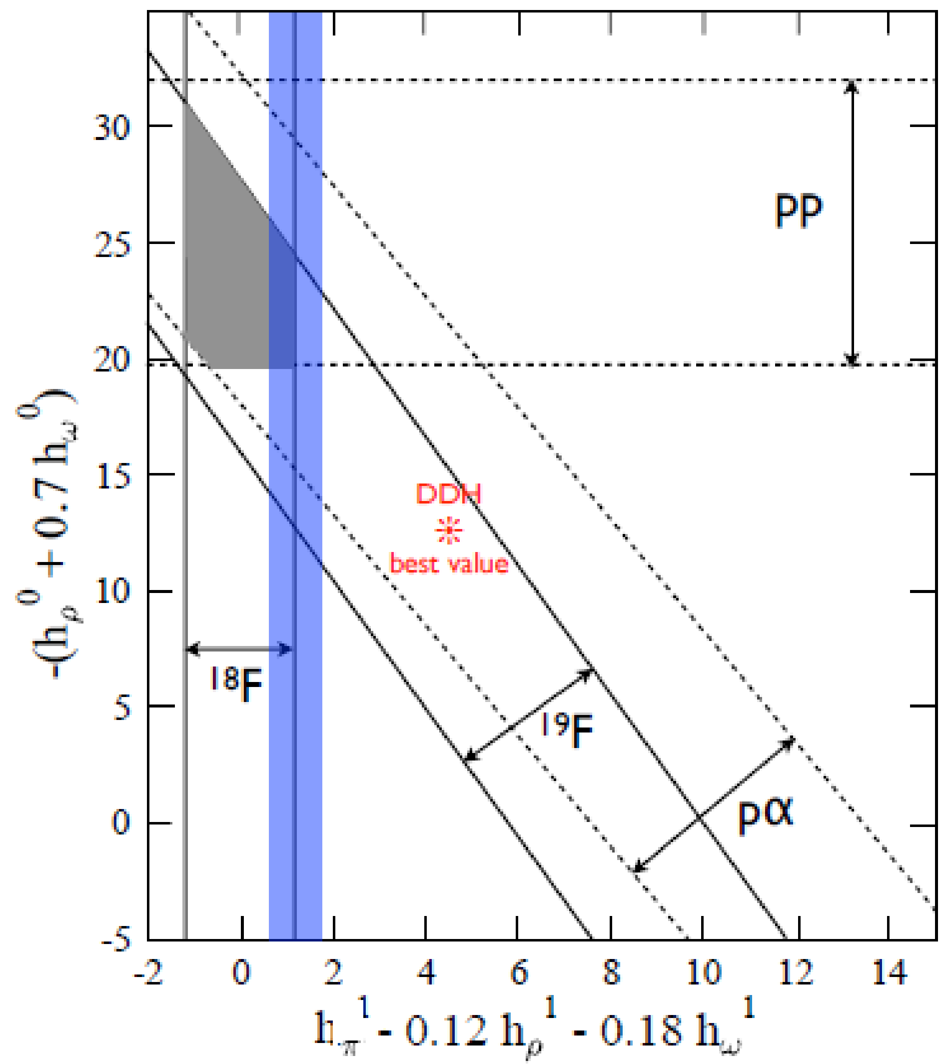
# TRIUMF E497

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

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



# New plot



PP
DDH
best value
$^{18}$F
$^{19}$F
pα
$-(h_\rho^0 + 0.7\,h_\omega^0)$
$h_\pi^1 - 0.12\,h_\rho^1 - 0.18\,h_\omega^1$

## EFT Approach

Note that in *parity conserving* sector low energy NN interaction characterized by just *two* numbers—$^3S_1$ and $^1S_0$ scattering lengths. Described via effective Lagrangian

$$\mathcal{L} = N^\dagger(i\partial_0 + \frac{\vec{\nabla}^2}{2M})N - \frac{1}{8}\mathcal{C}_0^{(^1S_0)}(N^T\tau_2\tau_a\sigma_2N)^\dagger(N^T\tau_2\tau_a\sigma_2N)$$
$$- \frac{1}{8}\mathcal{C}_0^{(^3S_1)}(N^T\tau_2\sigma_2\sigma_iN)^\dagger(N^T\tau_2\sigma_2\sigma_iN) + \ldots,$$

Connection to scattering lengths is

$$C = \frac{4\pi}{M}\frac{1}{1/a - \mu}$$

In *parity violating* sector low energy NN interaction characterized by *five* S-P wave couplings

$$\begin{aligned}
\mathcal{L}_{PV} = -\Big[&\mathcal{C}^{(^3S_1-^1P_1)}\left(N^T\sigma_2\,\vec{\sigma}\tau_2 N\right)^\dagger\cdot\left(N^T\sigma_2\tau_2 i\overleftrightarrow{D}N\right)\\
&+\mathcal{C}^{(^1S_0-^3P_0)}_{(\Delta I=0)}\left(N^T\sigma_2\tau_2\vec{\tau}N\right)^\dagger\left(N^T\sigma_2\,\vec{\sigma}\cdot\tau_2\vec{\tau}i\overleftrightarrow{D}N\right)\\
&+\mathcal{C}^{(^1S_0-^3P_0)}_{(\Delta I=1)}\;\epsilon^{3ab}\left(N^T\sigma_2\tau_2\tau^a N\right)^\dagger\left(N^T\sigma_2\,\vec{\sigma}\cdot\tau_2\tau^b\overleftrightarrow{D}N\right)\\
&+\mathcal{C}^{(^1S_0-^3P_0)}_{(\Delta I=2)}\;\mathcal{I}^{ab}\left(N^T\sigma_2\tau_2\tau^a N\right)^\dagger\left(N^T\sigma_2\,\vec{\sigma}\cdot\tau_2\tau^b i\overleftrightarrow{D}N\right)\\
&+\mathcal{C}^{(^3S_1-^3P_1)}\;\epsilon^{ijk}\left(N^T\sigma_2\sigma^i\tau_2 N\right)^\dagger\left(N^T\sigma_2\sigma^k\tau_2\tau_3\overleftrightarrow{D}^j N\right)\Big]+h.c.
\end{aligned}$$

# A New Approach:

Note low energy NN PV characterized by five amplitudes:

i) $d_t(k) - - - {}^3S_1 - -{}^1P_1$ mixing: $\Delta I = 0$

ii) $c_t(k) - - - {}^3S_1 - -{}^3P_1$ mixing: $\Delta I = 1$

iii) $d_s^{0,1,2}(k) - - - {}^1S_0 - - - {}^3P_0$ mixing: $\Delta I = 0, 1, 2$

Unitarity requires

$$d_{s,t}(k) = |d_{s,t}(k)| \exp i(\delta_S(k) + \delta_P(k))$$

Danilov suggests

$$d_i(k) \approx \lambda_i m_i(k)$$

with

$$m_i(k) = \frac{1}{k} e^{i\delta_i(k)} \sin \delta_i(k) \xrightarrow{k \to 0} a_i$$

so

$$\lim_{k \to 0} c_t(k), d_t(k), d_s^{0,1,2}(k) = \rho_t a_t, \lambda_t a_t, \lambda_s^{0,1,2} a_s$$

## Described in various languages. First was Zhu et al.

$$
\begin{aligned}
V_{LO}^{Zhu} = & -2\frac{\tilde{\mathcal{C}}_6}{\Lambda_\chi^3} i(\vec{\tau}_1 \times \vec{\tau}_2)_z(\vec{\sigma}_1 + \vec{\sigma}_2) \cdot \frac{1}{i}\overleftrightarrow{\nabla}_S \delta(\vec{r}) + 2\frac{\mathcal{C}_3}{\Lambda_\chi^3}(\vec{\tau}_1 \cdot \vec{\tau}_2)(\vec{\sigma}_1 - \vec{\sigma}_2) \cdot \frac{1}{i}\overleftrightarrow{\nabla}_A \delta(\vec{r}) \\
& -2\frac{\tilde{\mathcal{C}}_3}{\Lambda_\chi^3}(\vec{\tau}_1 \cdot \vec{\tau}_2) i(\vec{\sigma}_1 \times \vec{\sigma}_2) \cdot \frac{1}{i}\overleftrightarrow{\nabla}_S \delta(\vec{r}) + \frac{\mathcal{C}_4}{\Lambda_\chi^3}(\tau_1^z + \tau_2^z)(\vec{\sigma}_1 - \vec{\sigma}_2) \cdot \frac{1}{i}\overleftrightarrow{\nabla}_A \delta(\vec{r}) \\
& -\frac{\tilde{\mathcal{C}}_4}{\Lambda_\chi^3}(\tau_1^z + \tau_2^z) i(\vec{\sigma}_1 \times \vec{\sigma}_2) \cdot \frac{1}{i}\overleftrightarrow{\nabla}_S \delta(\vec{r}) + 2\sqrt{6}\frac{\mathcal{C}_5}{\Lambda_\chi^3}(\tau_1 \otimes \tau_2)_{20}(\vec{\sigma}_1 - \vec{\sigma}_2) \cdot \frac{1}{i}\overleftrightarrow{\nabla}_A \delta(\vec{r}) \\
& -2\sqrt{6}\frac{\tilde{\mathcal{C}}_5}{\Lambda_\chi^3}(\tau_1 \otimes \tau_2)_{20} i(\vec{\sigma}_1 \times \vec{\sigma}_2) \cdot \frac{1}{i}\overleftrightarrow{\nabla}_S \delta(\vec{r}) + 2\frac{\mathcal{C}_1}{\Lambda_\chi^3}(\vec{\sigma}_1 - \vec{\sigma}_2) \cdot \frac{1}{i}\overleftrightarrow{\nabla}_A \delta(\vec{r}) \\
& -2\frac{\tilde{\mathcal{C}}_1}{\Lambda_\chi^3} i(\vec{\sigma}_1 \times \vec{\sigma}_2) \cdot \frac{1}{i}\overleftrightarrow{\nabla}_S \delta(\vec{r}) + \frac{\mathcal{C}_2}{\Lambda_\chi^3}(\tau_1^z + \tau_2^z)(\vec{\sigma}_1 - \vec{\sigma}_2) \cdot \frac{1}{i}\overleftrightarrow{\nabla}_A \delta(\vec{r}) \\
& -\frac{\tilde{\mathcal{C}}_2}{\Lambda_\chi^3}(\tau_1^z + \tau_2^z) i(\vec{\sigma}_1 \times \vec{\sigma}_2) \cdot \frac{1}{i}\overleftrightarrow{\nabla}_S \delta(\vec{r}) + \frac{(\mathcal{C}_2 - \mathcal{C}_4)}{\Lambda_\chi^3}(\tau_1^z - \tau_2^z)(\vec{\sigma}_1 + \vec{\sigma}_2) \cdot \frac{1}{i}\overleftrightarrow{\nabla}_A \delta(\vec{r})
\end{aligned}
$$

# Partial wave approach

$$\begin{aligned}
V_{LO}^{PNC}(\vec{r}) &= \Lambda_0^{^1S_0-^3P_0}\left(\frac{1}{i}\frac{\overleftrightarrow{\nabla}_A}{2m_N}\frac{\delta(\vec{r})}{m_\rho^2}\cdot(\vec{\sigma}_1-\vec{\sigma}_2)-\frac{1}{i}\frac{\overleftrightarrow{\nabla}_S}{2m_N}\frac{\delta(\vec{r})}{m_\rho^2}\cdot i(\vec{\sigma}_1\times\vec{\sigma}_2)\right)\\
&+ \Lambda_0^{^3S_1-^1P_1}\left(\frac{1}{i}\frac{\overleftrightarrow{\nabla}_A}{2m_N}\frac{\delta(\vec{r})}{m_\rho^2}\cdot(\vec{\sigma}_1-\vec{\sigma}_2)+\frac{1}{i}\frac{\overleftrightarrow{\nabla}_S}{2m_N}\frac{\delta(\vec{r})}{m_\rho^2}\cdot i(\vec{\sigma}_1\times\vec{\sigma}_2)\right)\\
&+ \Lambda_1^{^1S_0-^3P_0}\frac{1}{i}\frac{\overleftrightarrow{\nabla}_A}{2m_N}\frac{\delta(\vec{r})}{m_\rho^2}\cdot(\vec{\sigma}_1-\vec{\sigma}_2)(\tau_1^z+\tau_2^z)\\
&+ \Lambda_1^{^3S_1-^3P_1}\frac{1}{i}\frac{\overleftrightarrow{\nabla}_A}{2m_N}\frac{\delta(\vec{r})}{m_\rho^2}\cdot(\vec{\sigma}_1+\vec{\sigma}_2)(\tau_1^z-\tau_2^z)\\
&+ \Lambda_2^{^1S_0-^3P_0}\frac{1}{i}\frac{\overleftrightarrow{\nabla}_A}{2m_N}\frac{\delta(\vec{r})}{m_\rho^2}\cdot(\vec{\sigma}_1-\vec{\sigma}_2)(\vec{\tau}_1\otimes\vec{\tau}_2)_{20}
\end{aligned}$$

## Girlanda technique

Write effective Lagrangian as (Girlanda form)

$$\mathcal{L} = \sum_{i=1}^{6} (C_i \mathcal{O}_i + \tilde{C}_i \tilde{\mathcal{O}}_i)$$

where

$$\begin{aligned}
\mathcal{O}_1 &= \bar{\psi}\gamma^{\mu}\psi\bar{\psi}\gamma_{\mu}\gamma_5\psi \\
\mathcal{O}_2 &= \bar{\psi}\gamma^{\mu}\psi\bar{\psi}\tau_3\gamma_{\mu}\gamma_5\psi \\
\mathcal{O}_3 &= \bar{\psi}\tau_a\gamma^{\mu}\psi\bar{\psi}\tau^a\gamma_{\mu}\gamma_5\psi \\
\mathcal{O}_4 &= \bar{\psi}\tau_3\gamma^{\mu}\psi\bar{\psi}\gamma_{\mu}\gamma_5\psi \\
\mathcal{O}_5 &= \mathcal{I}_{ab}\bar{\psi}\tau_a\gamma^{\mu}\psi\bar{\psi}\tau_b\gamma_{\mu}\gamma_5\psi \\
\mathcal{O}_6 &= i\epsilon_{ab3}\bar{\psi}\tau_a\gamma^{\mu}\psi\bar{\psi}\tau_b\gamma_{\mu}\gamma_5\psi
\end{aligned}
\qquad
\begin{aligned}
\tilde{\mathcal{O}}_1 &= \bar{\psi}\gamma^{\mu}\gamma_5\psi\partial^{\nu}(\bar{\psi}\sigma_{\mu\nu}\psi) \\
\tilde{\mathcal{O}}_2 &= \bar{\psi}\gamma^{\mu}\gamma_5\psi\partial^{\nu}(\bar{\psi}\tau_3\sigma_{\mu\nu}\psi) \\
\tilde{\mathcal{O}}_3 &= \bar{\psi}\tau_a\gamma^{\mu}\gamma_5\psi\partial^{\nu}(\bar{\psi}\tau^a\sigma_{\mu\nu}\psi) \\
\tilde{\mathcal{O}}_4 &= \bar{\psi}\tau_3\gamma^{\mu}\gamma_5\psi\partial^{\nu}(\bar{\psi}\sigma_{\mu\nu}\psi) \\
\tilde{\mathcal{O}}_5 &= \mathcal{I}_{ab}\bar{\psi}\tau_a\gamma^{\mu}\gamma_5\psi\partial^{\nu}(\bar{\psi}\tau_b\sigma_{\mu\nu}\psi) \\
\tilde{\mathcal{O}}_6 &= i\epsilon_{ab3}\bar{\psi}\tau_a\gamma^{\mu}\gamma_5\psi\partial^{\nu}(\bar{\psi}\tau_b\sigma_{\mu\nu}\psi)
\end{aligned}$$

With Fierz transformation and EOM find six conditions

$$
\begin{aligned}
&\mathcal{O}_3 = \mathcal{O}_1 \\
&\mathcal{O}_2 - \mathcal{O}_4 = 2\mathcal{O}_6 \\
&\tilde{\mathcal{O}}_3 + 3\tilde{\mathcal{O}}_1 = 2M(\mathcal{O}_1 + \mathcal{O}_3) \\
&\tilde{\mathcal{O}}_2 + \tilde{\mathcal{O}}_4 = M(\mathcal{O}_2 + \mathcal{O}_4) \\
&\tilde{\mathcal{O}}_2 - \tilde{\mathcal{O}}_4 = -2M\mathcal{O}_6 - \tilde{\mathcal{O}}_6 \\
&\tilde{\mathcal{O}}_5 = \mathcal{O}_5
\end{aligned}
$$

$$V_{LO}^{Girlanda} = \left[-2\tilde{\mathcal{G}}_1\right] \frac{1}{i}\overleftrightarrow{\nabla}_S\, \delta(\vec{r}) \cdot i(\vec{\sigma}_1 \times \vec{\sigma}_2) + [2\mathcal{G}_1] \frac{1}{i}\overleftrightarrow{\nabla}_A\, \delta(\vec{r}) \cdot (\vec{\sigma}_1 - \vec{\sigma}_2)$$
$$+ [\mathcal{G}_2] \frac{1}{i}\overleftrightarrow{\nabla}_A\, \delta(\vec{r}) \cdot (\vec{\sigma}_1 - \vec{\sigma}_2)(\tau_1^z + \tau_2^z) + [2\mathcal{G}_6] \frac{1}{i}\overleftrightarrow{\nabla}_A\, \delta(\vec{r}) \cdot (\vec{\sigma}_1 + \vec{\sigma}_2)(\tau_1^z - \tau_2^z)$$
$$+ \left[-2\sqrt{6}\mathcal{G}_5\right] \frac{1}{i}\overleftrightarrow{\nabla}_A\, \delta(\vec{r}) \cdot (\vec{\sigma}_1 - \vec{\sigma}_2)(\tau_1 \otimes \tau_2)_{20}$$

# Hadronic PV Rosetta Stone

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

Evidence mounting that PV pion coupling $h_\pi^1$ is small, compared to DDH best value—${}^{DDH}h_\pi^1 = 12$ (in units of $g_\pi = 3.8 \times 10^{-8}$):

i) ${}^{18}$F experiments supplemented by meson-exchange argument—$|h_\pi^1| < 3.4$

ii) Lattice estimate by Wasem—$h_\pi^1 = 2.9 \pm 1.4 \pm 1.4$

iii) Skyrme model calculation by Meissner and Wiegel—$2.0 < h_\pi^1 < 3.4$

iv) $\vec{n}p \to d\gamma$ measurement at SNS—$A_\gamma \simeq -0.11 h_\pi^1$

v) Triton asymmetry in ${}^6Li(n,\alpha)^3H$—$|h_\pi^1| < 3.0$

Challenge then is to identify heavy meson couplings

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

Note there is overcounting here since I=1 couplings can be reparameterized via

$$\begin{aligned}
g_{\pi NN} h_\pi^1 &\rightarrow g_{\pi NN} h_\pi^1 + \eta \\
g_\rho h_\rho^1 &\rightarrow g_\rho h_\rho^1 - \frac{\eta\ m_\rho^2}{\sqrt{2} m_\pi^2} \frac{2+\mu_S}{4+\mu_S+\mu_V} \\
g_\rho h_\omega^1 &\rightarrow g_\rho h_\omega^1 + \frac{\eta\ m_\rho^2}{\sqrt{2} m_\pi^2} \frac{2+\mu_V}{4+\mu_S+\mu_V}
\end{aligned}$$

Must be determined from experiment—

From $\vec{p}p$ scattering

$$\Lambda_{pp}^{^1S_0-^3P_0} \equiv \Lambda_0^{^1S_0-^3P_0} + \Lambda_1^{^1S_0-^3P_0} + \frac{\Lambda_2^{^1S_0-^3P_0}}{\sqrt{6}} = (4.19 \pm 0.43) \times 10^{-5} \ (68\%\mathrm{c.l.})$$

and

$$g_\rho h_\rho^{pp} \chi_V + g_\omega h_\omega^{pp} \chi_S = -(4.4 \pm 1.6) \times 10^{-5} \ (68\%\mathrm{c.l.})$$

Here

$$h_V^{pp} = h_V^0 + h_V^1 + \sqrt{\frac{1}{6}} h_V^2$$

## From $\vec{p}^4 He$ scattering

$$
\begin{aligned}
A_L(\vec{\mathrm{p}}\alpha,\,46\,\mathrm{MeV}) &= -0.025 g_{\pi NN} h_\pi^1 + 0.050 g_\rho h_\rho^0 + 0.017 g_\rho h_\rho^1 + 0.007 g_\omega h_\omega^0 \\
&\quad +0.007 g_\omega h_\omega^1 \\
&\sim -0.00355 \Lambda_0^{^1S_0-^3P_0} - 0.00317 \Lambda_1^{^1S_0-^3P_0} \\
&\quad -0.00268 \Lambda_0^{^3S_1-^1P_1} - 0.00114 \Lambda_1^{^3S_1-^3P_1} \\
&= -(3.3 \pm 0.9) \times 10^{-7}
\end{aligned}
$$

From $A_\gamma$ in $^{19}\vec{F}$ decay

$$
\begin{aligned}
A_\gamma(^{19}\mathrm{F}) &= -7.00 g_{\pi NN} h_\pi^1 + 12.2 g_\rho h_\rho^0 + 3.65 g_\rho h_\rho^1 + 2.31 g_\omega h_\omega^0 + 2.02 g_\omega h_\omega^1 \\
&\sim -1.12 \Lambda_0^{^1S_0 - ^3P_0} - 0.75 \Lambda_1^{^1S_0 - ^3P_0} - 0.48 \Lambda_0^{^3S_1 - ^1P_1} - 0.32 \Lambda_1^{^3S_1 - ^3P_1} \\
&= -(7.4 \pm 1.9) \times 10^{-5}
\end{aligned}
$$

From neutron spin rotation in $^4He$

$$
\begin{aligned}
\frac{d\phi^{n\alpha}}{dz} &= \left[-0.072 g_{\pi NN} h_\pi^1 - 0.115 g_\rho h_\rho^0 + 0.039 g_\rho h_\rho^1 - 0.026 g_\omega h_\omega^0 + \right. \\
&\qquad \left. + 0.026 g_\omega h_\omega^1\right] \mathrm{rad/m} \\
&\sim \left[0.0138 \Lambda_0^{^1S_0-^3P_0} - 0.0087 \Lambda_1^{^1S_0-^3P_0} + 0.0033 \Lambda_0^{^3S_1-^1P_1} \right. \\
&\qquad \left. - 0.0033 \Lambda_1^{^3S_1-^3P_1}\right] \mathrm{rad/m} \\
&= (1.7 \pm 9.1 \pm 1.4) \times 10^{-7} \mathrm{rad/m}
\end{aligned}
$$

From the photon asymmetry in $\vec{n}p \to d\gamma$

$$
\begin{aligned}
A_\gamma(\vec{n}p \to d+\gamma) &= -0.0080 g_{\pi NN} h_\pi^1 - 0.0005 g_\rho h_\rho^1 + 0.0005 g_\omega h_\omega^1 \\
&\sim -(3.7 \times 10^{-4}) \Lambda_1^{^3S_1 - ^3P_1} \\
&= \begin{cases} (0.6 \pm 2.1) \times 10^{-7} \\ (-1.2 \pm 1.9 \pm 0.2) \times 10^{-7} \end{cases}
\end{aligned}
$$

From the circular polarization of photons emitted in $np \to d\vec{\gamma}$

$$
\begin{aligned}
P_\gamma(np \to d+\gamma) &= -0.011 g_\rho h_\rho^0 - 0.0088 g_\rho h_\rho^2 + 0.0001 g_\omega h_\omega^0 \\
&\sim -0.00012 \Lambda_0^{{}^1S_0-{}^3P_0} + 0.00105 \Lambda_0^{{}^3S_1-{}^1P_1} + 0.00154 \Lambda_2^{{}^1S_0-{}^3P_0} \\
&= (1.8 \pm 1.8) \times 10^{-7}
\end{aligned}
$$

## Future Possibilities:

Analyzing power in $\vec{p}d$

$$
\begin{aligned}
A_L(\vec{p}+d)\Big|_{15\ \mathrm{MeV}} &= -0.0171 g_{\pi NN} h_\pi^1 + 0.0085 g_\rho h_\rho^0 + 0.0035 g_\rho h_\rho^1 \\
&\quad + 0.002 g_\omega h_\omega^0 + 0.0015 g_\omega h_\omega^1 \\
&\sim -0.0010 \Lambda_0^{^1S_0-^3P_0} - .0007 \Lambda_1^{^1S_0-^3P_0} \\
&\quad -0.0002 \Lambda_0^{^3S_1-^1P_1} - 0.0008 \Lambda_1^{^3S_1-^3P_1} \\
&= -(0.35 \pm 0.85) \times 10^{-7}
\end{aligned}
$$

## Photon asymmetry in $\vec{n}d \to t\gamma$

$$
\begin{aligned}
A_\gamma(\vec{n}+d \to t+\gamma) &= 0.051 g_{\pi NN} h_\pi^1 - 0.12 g_\rho h_\rho^0 + 0.036 g_\rho hrho^1 + 0.020 g_\rho h_\rho^2 \\
&\quad -0.027 g_\omega h_\omega^0 + 0.007 g_\omega h_\omega^1 \\
&\sim 0.0139 \Lambda_0^{{}^1S_0-{}^3P_0} - 0.0055 \Lambda_1^{{}^1S_0-{}^3P_0} + 0.0037 \Lambda_0^{{}^3S_1-{}^1P_1} \\
&\quad +0.0024 \Lambda_1^{{}^3S_1-{}^3P_1} - 0.0035 \Lambda_2^{{}^1S_0-{}^3P_0}
\end{aligned}
$$

## Neutron spin rotation in hydrogen

$$\frac{d\phi^{n\mathrm{H}}}{dz} = \left[-0.23 g_{\pi NN} h_\pi^1 - 0.082 g_\rho h_\rho^0 - 0.011 g_\rho h_\rho^1 - 0.090 g_\rho h_\rho^2 -0.027 g_\omega h_\omega^0 + 0.011 g_\omega h_\omega^1\right] \mathrm{rad/m}$$

$$= \left[0.015 \Lambda_0^{{}^1S_0 - {}^3P_0} - 0.011 \Lambda_1^{{}^3S_1 - {}^3P_1} + 0.016 \Lambda_2^{{}^1S_0 - {}^3P_0}\right] \mathrm{rad/m}$$

Asymmetry in polarized photodisintegration

$$\vec{\gamma} d \to np$$

possibile flagship Higs2 experiment—

$$\begin{aligned} A_L &= -0.011 g_\rho h_\rho^0 - 0.0088 g_\rho h_\rho^2 + 0.0001 g_\omega h_\omega^0 \\ &\sim -0.00012 \Lambda_0^{{}^1S_0 - {}^3P_0} + 0.00105 \Lambda_0^{{}^3S_1 - {}^1P_1} + 0.00154 \Lambda_2^{{}^1S_0 - {}^3P_0} \end{aligned}$$

## Future Goals

i) (Over?) Determine the five S-P (Danilov) couplings experimentally

ii) Calculate the five S-P couplings via the lattice

iii) Use results to understand nuclear results