

# Hadronic Parity Violation

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UMass

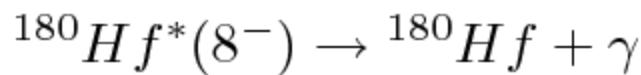
# Our Problem:

Parity violating effects in strong

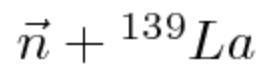
and electromagnetic hadronic interactions.

Examples:

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



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



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

# Theory

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

1964 → 2014

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

## 1980: DDH Approach

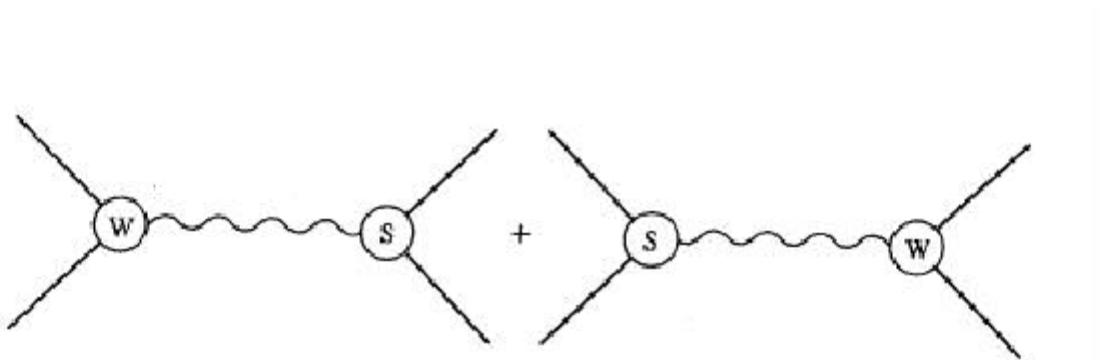
Basic idea:

Meson exchange gives good picture of PC NN interaction, with

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

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

so use for PV NN



Then define general PV weak couplings:

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

$$+ \bar{N} \left( h_\rho^0 \tau \cdot \rho^\mu + h_\rho^1 \rho_3^\mu + \frac{h_\rho^2}{2\sqrt{6}} (3\tau_3 \rho_3^\mu - \tau \cdot \rho^\mu) \right) \gamma_\mu \gamma_5 N$$
$$+ \bar{N} (h_\omega^0 \omega^\mu + h_\omega^1 \tau_3 \omega^\mu) \gamma_\mu \gamma_5 N - h_\rho'^1 \bar{N} (\tau \times \rho^\mu)_3 \frac{\sigma_{\mu\nu} k^\nu}{2M} \gamma_5 N$$

Yields two-body PV NN potential

$$V^{\text{PNC}} = i \frac{f_\pi^1 g_{\pi NN}}{\sqrt{2}} \left( \frac{\tau_1 \times \tau_2}{2} \right)_3 (\sigma_1 + \sigma_2) \cdot \left[ \frac{\mathbf{p}_1 - \mathbf{p}_2}{2M}, f_\pi(r) \right]$$

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

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

$$|N\rangle \sim b_{qs}^\dagger b_{q's'}^\dagger b_q^\dagger |0\rangle$$

$$|M\rangle \sim b_{qs}^\dagger d_{q's'}^\dagger |0\rangle$$

and

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

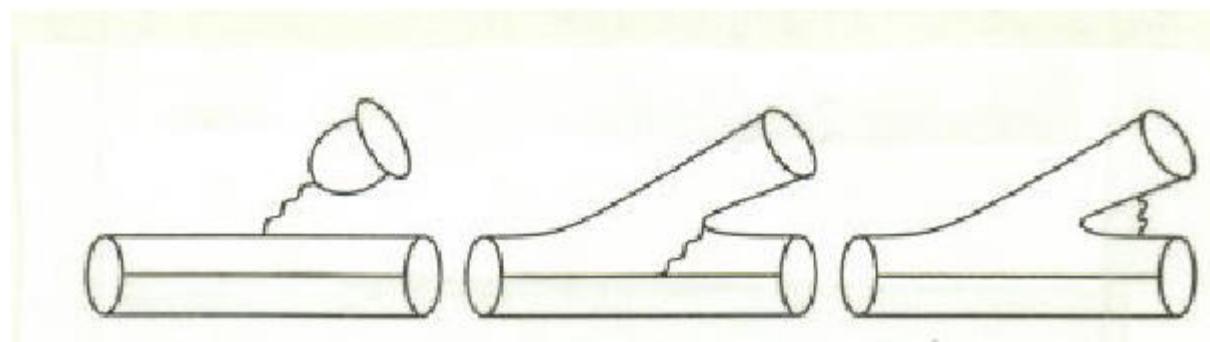
Then structure of weak matrix element is

$$\begin{aligned} < MN | \mathcal{H}_{\text{wk}} | N > = \frac{G}{\sqrt{2}} < 0 | (b_{qs} b_{q's'}^\dagger b_{q''s''}) (b_{qs} d_{q's'}) \\ &\times \bar{\psi} \mathcal{O} \psi \bar{\psi} \mathcal{O}' \psi (b_{qs}^\dagger b_{q's'}^\dagger b_{q''s''}^\dagger) | 0 > \times R \end{aligned}$$

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

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

Find three basic structures



Here first is factorization, but two additional diagrams

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

Coupling	DDH 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

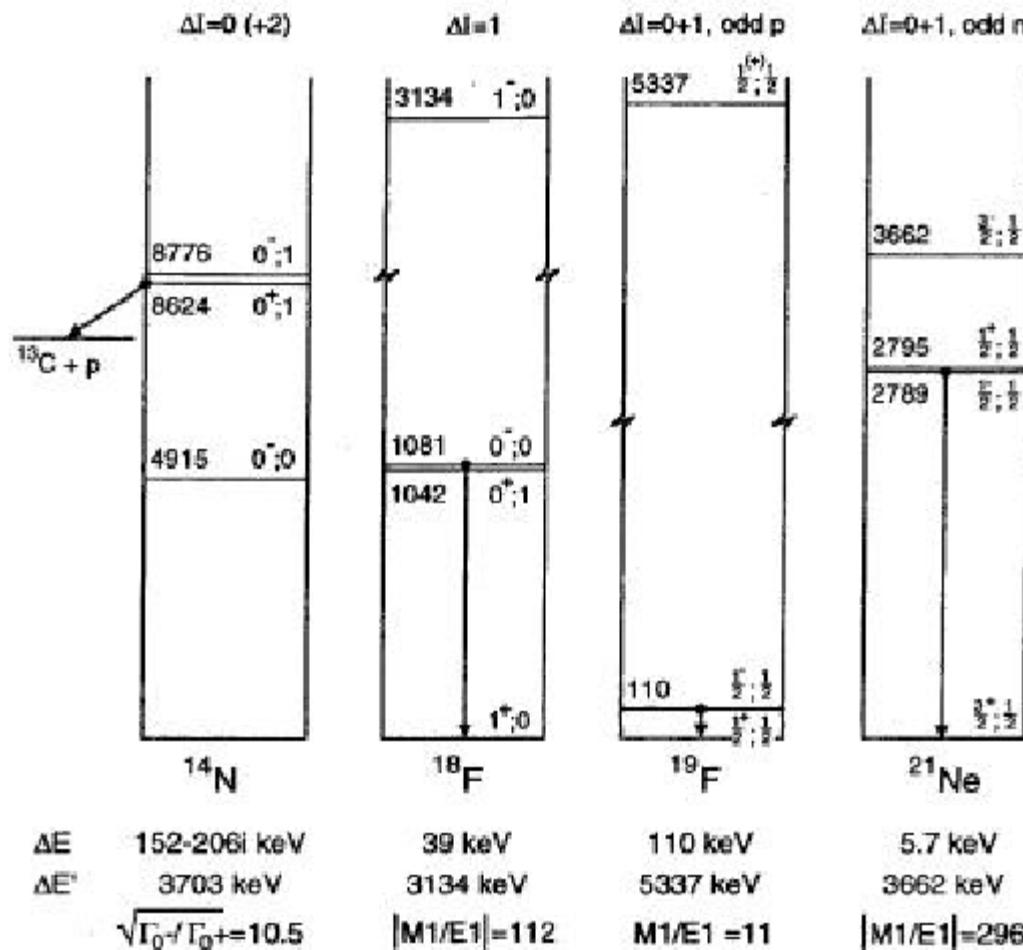
$$|\psi_{J^+}\rangle \simeq |\phi_{J^+}\rangle + \frac{|\phi_{J^-}\rangle \langle \phi_{J^-}| \mathcal{H}_{\text{wk}} | \phi_{J^+}\rangle}{E_+ - E_-}$$

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

$$|\psi_{J^-}\rangle \simeq |\phi_{J^-}\rangle + \frac{|\phi_{J^+}\rangle \langle \phi_{J^+}| \mathcal{H}_{\text{wk}} | \phi_{J^-}\rangle}{E_- - E_+}$$

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

Then enhancement if  $\Delta E \ll$  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

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

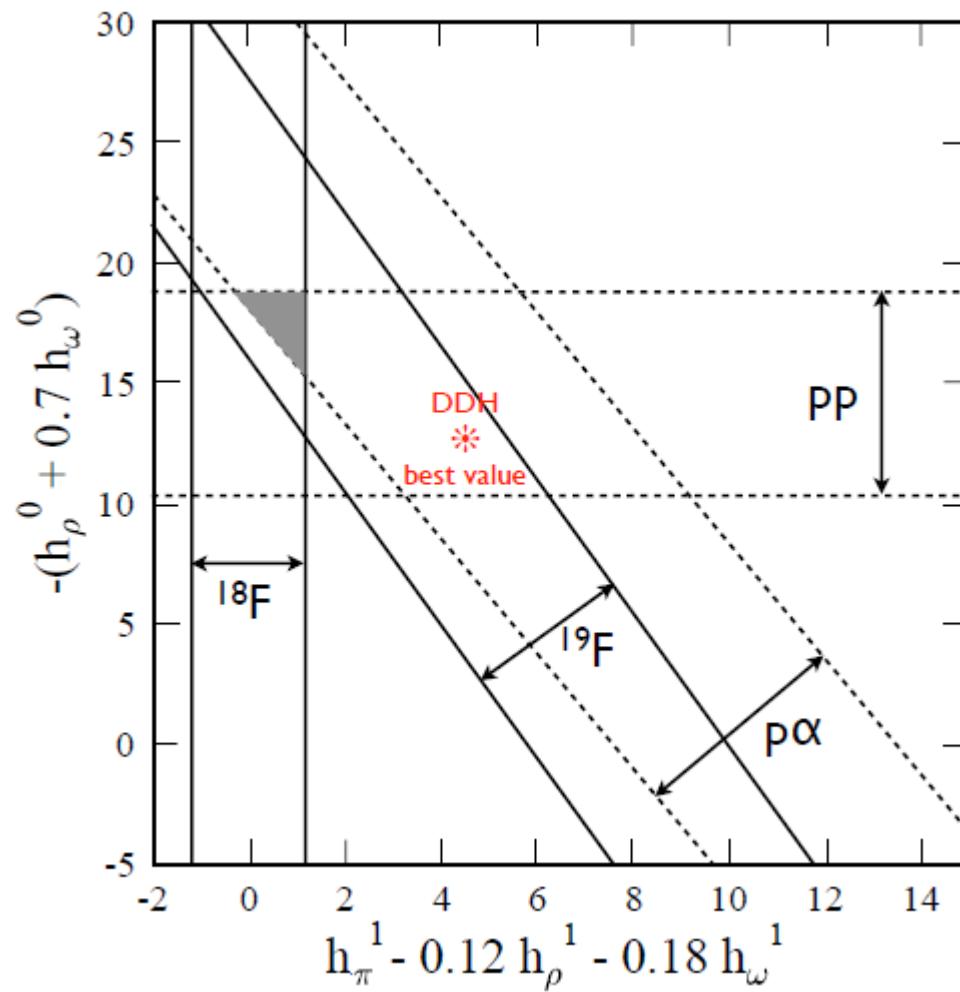
Also results on NN systems which are not enhanced:

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

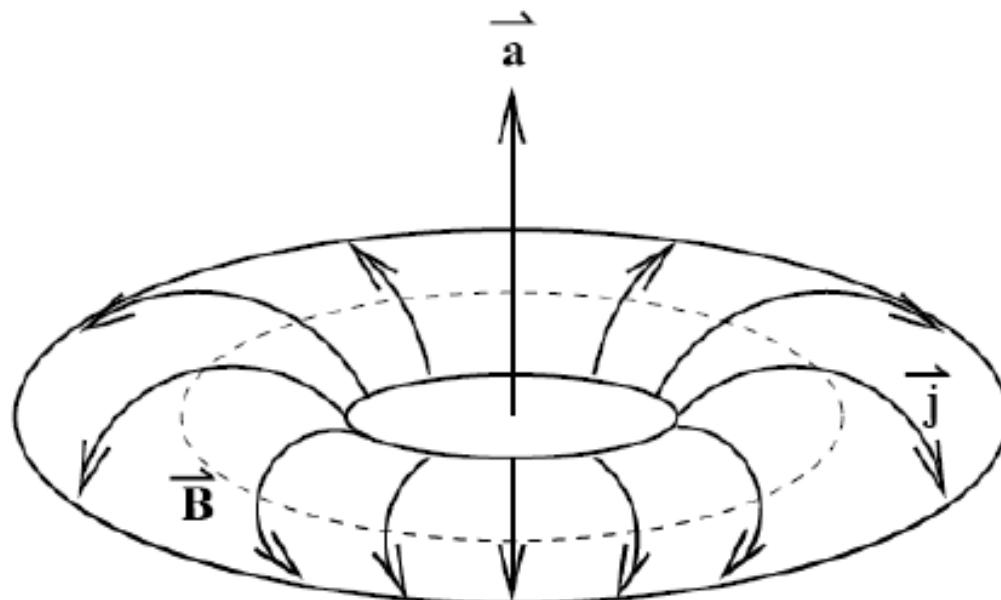
## Traditional Plot



## 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:

$$\begin{aligned} < f | V_\mu^{em} | i > = \bar{u}(p_f) [F_1(q^2)\gamma_\mu - F_2(q^2)\frac{i\sigma_{\mu\nu}q^\nu}{2M} \\ + F_3(q^2)\frac{1}{4M^2}(\gamma_\mu\gamma_5q^2 - q_\mu q^\nu\gamma_5) + F_4(q^2)\frac{i\sigma_{\mu\nu}q^\nu\gamma_5}{2M}] u(p_i) \end{aligned}$$

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  $6S$ - $7S$   $^{133}\text{Cs}$  transitions.

Effective interaction is

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

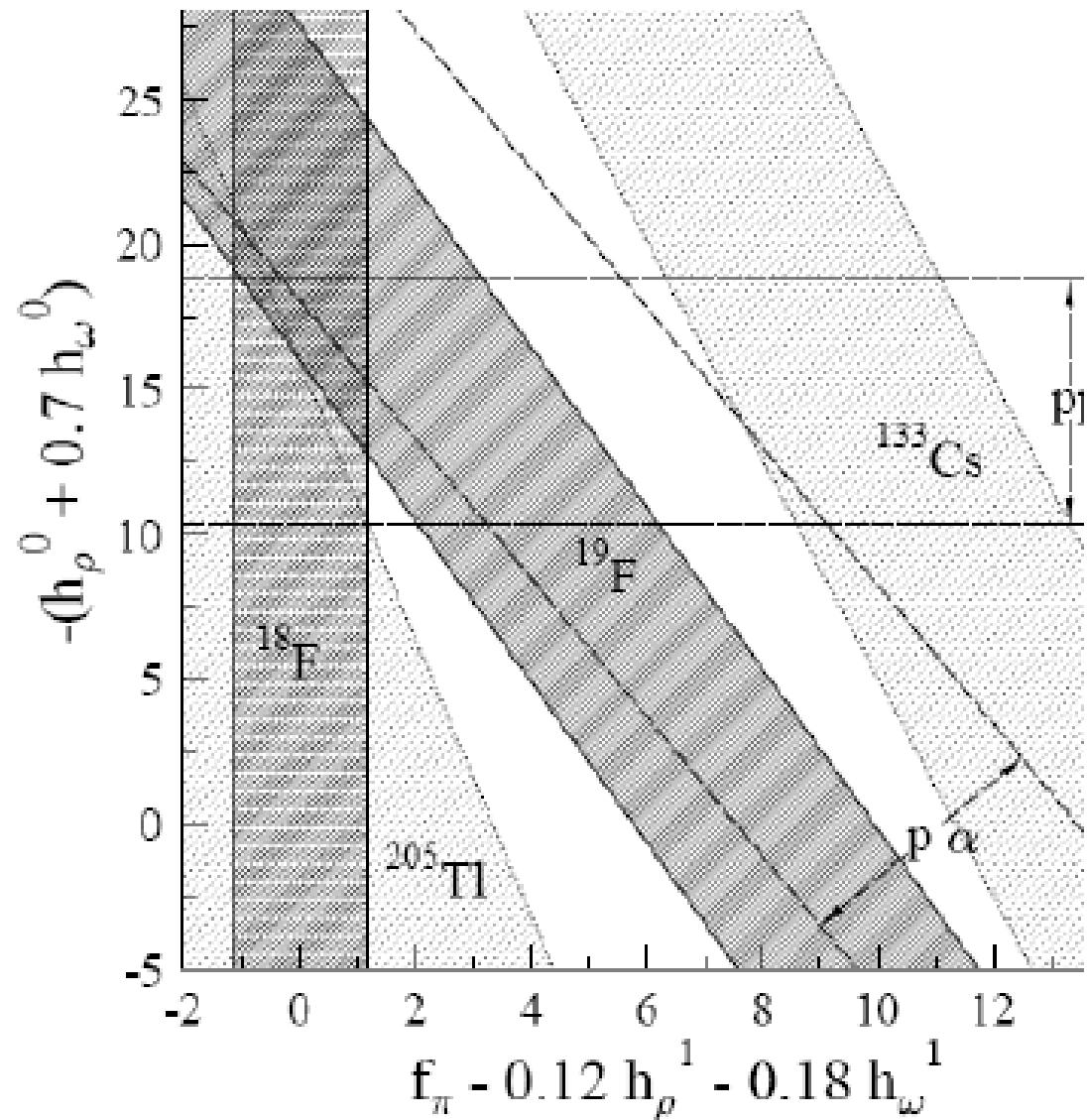
Here  $\kappa_Z = 0.013$  is direct Z-exchange term and

$$\kappa_a = 0.112 \pm 0.016$$

is anapole moment

In terms of DDH

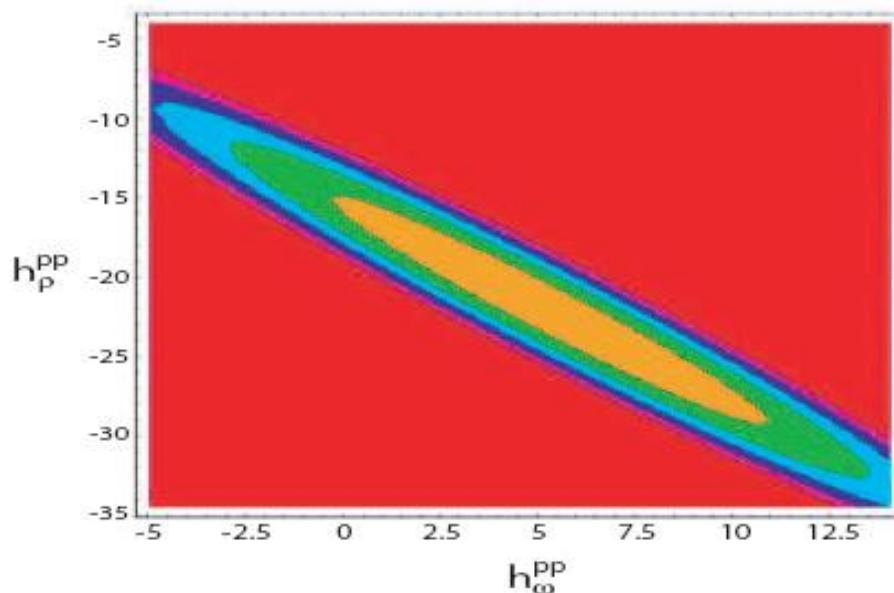
$$h_\pi - 0.21(h_\rho^0 + 0.6h_\omega^0) = (0.99 \pm 0.16) \times 10^{-6}$$



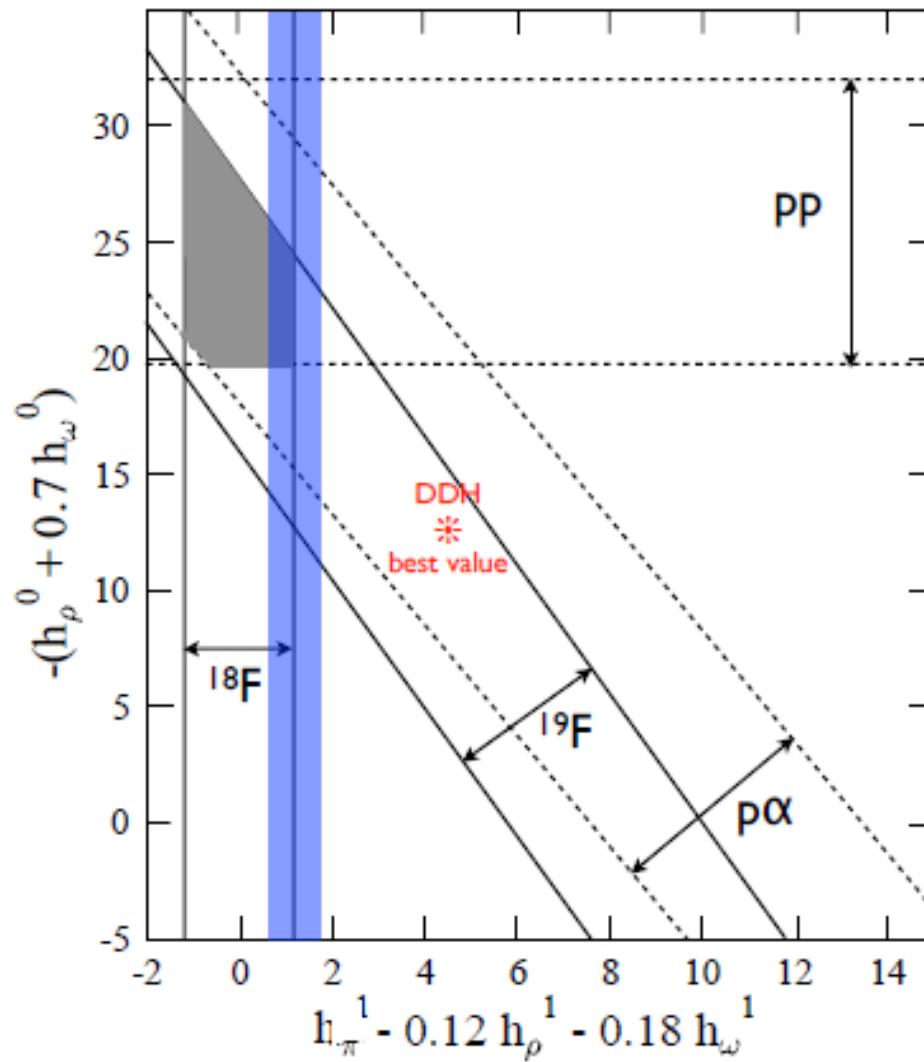
## TRIUMF E497

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

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



## New plot



## 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

$$\begin{aligned}\mathcal{L} = & N^\dagger \left( i\partial_0 + \frac{\vec{\nabla}^2}{2M} \right) N - \frac{1}{8} \mathcal{C}_0^{(1S_0)} (N^T \tau_2 \tau_a \sigma_2 N)^\dagger (N^T \tau_2 \tau_a \sigma_2 N) \\ & - \frac{1}{8} \mathcal{C}_0^{(3S_1)} (N^T \tau_2 \sigma_2 \sigma_i N)^\dagger (N^T \tau_2 \sigma_2 \sigma_i N) + \dots,\end{aligned}$$

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

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

## 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

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

so

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

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

$$\mathcal{O}_1 = \bar{\psi} \gamma^\mu \psi \bar{\psi} \gamma_\mu \gamma_5 \psi$$

$$\mathcal{O}_2 = \bar{\psi} \gamma^\mu \psi \bar{\psi} \tau_3 \gamma_\mu \gamma_5 \psi$$

$$\mathcal{O}_3 = \bar{\psi} \tau_a \gamma^\mu \psi \bar{\psi} \tau^a \gamma_\mu \gamma_5 \psi$$

$$\mathcal{O}_4 = \bar{\psi} \tau_3 \gamma^\mu \psi \bar{\psi} \gamma_\mu \gamma_5 \psi$$

$$\mathcal{O}_5 = \mathcal{I}_{ab} \bar{\psi} \tau_a \gamma^\mu \psi \bar{\psi} \tau_b \gamma_\mu \gamma_5 \psi$$

$$\mathcal{O}_6 = i \epsilon_{ab3} \bar{\psi} \tau_a \gamma^\mu \psi \bar{\psi} \tau_b \gamma_\mu \gamma_5 \psi$$

$$\tilde{\mathcal{O}}_1 = \bar{\psi} \gamma^\mu \gamma_5 \psi \partial^\nu (\bar{\psi} \sigma_{\mu\nu} \psi)$$

$$\tilde{\mathcal{O}}_2 = \bar{\psi} \gamma^\mu \gamma_5 \psi \partial^\nu (\bar{\psi} \tau_3 \sigma_{\mu\nu} \psi)$$

$$\tilde{\mathcal{O}}_3 = \bar{\psi} \tau_a \gamma^\mu \gamma_5 \psi \partial^\nu (\bar{\psi} \tau^a \sigma_{\mu\nu} \psi)$$

$$\tilde{\mathcal{O}}_4 = \bar{\psi} \tau_3 \gamma^\mu \gamma_5 \psi \partial^\nu (\bar{\psi} \sigma_{\mu\nu} \psi)$$

$$\tilde{\mathcal{O}}_5 = \mathcal{I}_{ab} \bar{\psi} \tau_a \gamma^\mu \gamma_5 \psi \partial^\nu (\bar{\psi} \tau_b \sigma_{\mu\nu} \psi)$$

$$\tilde{\mathcal{O}}_6 = i \epsilon_{ab3} \bar{\psi} \tau_a \gamma^\mu \gamma_5 \psi \partial^\nu (\bar{\psi} \tau_b \sigma_{\mu\nu} \psi)$$

With Fierz transformation and EOM find six conditions

$$\mathcal{O}_3 = \mathcal{O}_1$$

$$\mathcal{O}_2 - \mathcal{O}_4 = 2\mathcal{O}_6$$

$$\tilde{\mathcal{O}}_3 + 3\tilde{\mathcal{O}}_1 = 2M(\mathcal{O}_1 + \mathcal{O}_3)$$

$$\tilde{\mathcal{O}}_2 + \tilde{\mathcal{O}}_4 = M(\mathcal{O}_2 + \mathcal{O}_4)$$

$$\tilde{\mathcal{O}}_2 - \tilde{\mathcal{O}}_4 = -2M\mathcal{O}_6 - \tilde{\mathcal{O}}_6$$

$$\tilde{\mathcal{O}}_5 = \mathcal{O}_5$$

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

## Hadronic PV Rosetta Stone

Coeff	DDH	Girlanda	Zhu
$\Lambda_0^{1S_0-3P_0}_{DDH}$	$-g_\rho h_\rho^0(2+\chi_V) - g_\omega h_\omega^0(2+\chi_S)$	$2(\mathcal{G}_1 + \tilde{\mathcal{G}}_1)$	$2(\mathcal{C}_1 + \tilde{\mathcal{C}}_1 + \mathcal{C}_3 + \tilde{\mathcal{C}}_3)$
$\Lambda_0^{3S_1-1P_1}_{DDH}$	$g_\omega h_\omega^0 \chi_S - 3g_\rho h_\rho^0 \chi_V$	$2(\mathcal{G}_1 - \tilde{\mathcal{G}}_1)$	$2(\mathcal{C}_1 - \tilde{\mathcal{C}}_1 - 3\mathcal{C}_3 + 3\tilde{\mathcal{C}}_3)$
$\Lambda_1^{1S_0-3P_0}_{DDH}$	$-g_\rho h_\rho^1(2+\chi_V) - g_\omega h_\omega^1(2+\chi_S)$	$\mathcal{G}_2$	$(\mathcal{C}_2 + \tilde{\mathcal{C}}_2 + \mathcal{C}_4 + \tilde{\mathcal{C}}_4)$
$\Lambda_1^{3S_1-3P_1}_{DDH}$	$\frac{1}{\sqrt{2}}g_{\pi NN}h_\pi^1 \left(\frac{m_\rho}{m_\pi}\right)^2 + g_\rho(h_\rho^1 - h_\rho^{1'}) - g_\omega h_\omega^1$	$2\mathcal{G}_6$	$(2\tilde{\mathcal{C}}_6 + \mathcal{C}_2 - \mathcal{C}_4)$
$\Lambda_2^{1S_0-3P_0}_{DDH}$	$-g_\rho h_\rho^2(2+\chi_V)$	$-2\sqrt{6}\mathcal{G}_5$	$2\sqrt{6}(\mathcal{C}_5 + \tilde{\mathcal{C}}_5)$

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)  $^{18}\text{F}$  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)  $\vec{n}p \rightarrow d\gamma$  measurement at SNS— $A_\gamma \simeq -0.11h_\pi^1$
- v) Triton asymmetry in  $^6\text{Li}(n, \alpha)^3\text{H}$ — $|h_\pi^1| < 3.0$

Challenge then is to identify heavy meson couplings

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

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

$$g_{\pi NN} h_\pi^1 \rightarrow g_{\pi NN} h_\pi^1 + \eta$$

$$g_\rho h_\rho^1 \rightarrow g_\rho h_\rho^1 - \frac{\eta m_\rho^2}{\sqrt{2}m_\pi^2} \frac{2 + \mu_S}{4 + \mu_S + \mu_V}$$

$$g_\rho h_\omega^1 \rightarrow g_\rho h_\omega^1 + \frac{\eta m_\rho^2}{\sqrt{2}m_\pi^2} \frac{2 + \mu_V}{4 + \mu_S + \mu_V}$$

Must be determined from experiment—

From  $\vec{p}p$  scattering

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

and

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

Here

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

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

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

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

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

From neutron spin rotation in  ${}^4He$

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

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

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

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

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

## Future Possibilities:

Analyzing power in  $\vec{p}d$

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

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

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

## Neutron spin rotation in hydrogen

$$\begin{aligned}\frac{d\phi^{nH}}{dz} &= [-0.23g_{\pi NN}h_\pi^1 - 0.082g_\rho h_\rho^0 - 0.011g_\rho h_\rho^1 - 0.090g_\rho h_\rho^2 \\ &\quad - 0.027g_\omega h_\omega^0 + 0.011g_\omega h_\omega^1] \text{ rad/m} \\ &= [0.015\Lambda_0^{1S_0-3P_0} - 0.011\Lambda_1^{3S_1-3P_1} + 0.016\Lambda_2^{1S_0-3P_0}] \text{ rad/m}\end{aligned}$$

## Asymmetry in polarized photodisintegration



possible flagship Higs2 experiment—

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

## 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