Present Status of the NN Weak Interaction and Recent Results

Jason Fry

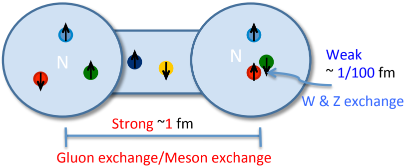
Institute of Nuclear and Particle Physics, University of Virginia

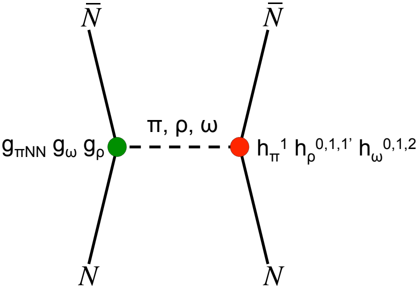
December 11, 2018

Particle Physics with Neutrons at the ESS

UNIVERSITY of VIRGINIA

Hadronic Weak Interaction: Connections to QCD

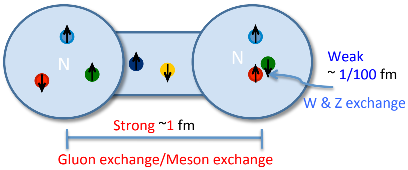


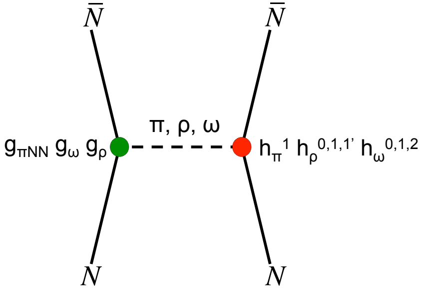


relative scale $\sim m_\pi / m_W \sim 10^{-7}$

- The range for W and Z exchange between quarks (10^{-2}fm) is small compared to the nucleon size (1fm) $\rightarrow$ **HWI is sensitive to short range quark-quark correlations in hadrons!**

Hadronic Weak Interaction: Connections to QCD

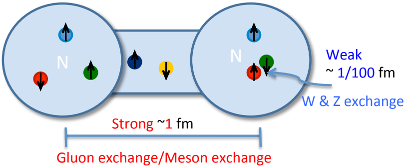


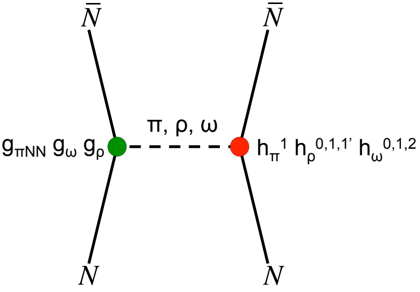


relative scale $\sim m_\pi / m_W \sim 10^{-7}$

- The range for W and Z exchange between quarks (10^{-2}fm) is small compared to the nucleon size (1fm) $\rightarrow$ **HWI is sensitive to short range quark-quark correlations in hadrons!**
- HWI has the potential to connect quark-quark correlations in the non-perturbative strongly interacting limit of QCD while accessing to the underlying weak interaction at the nucleon level as predicted by the SM. **"Inside out" probe of QCD**

Hadronic Weak Interaction: Connections to QCD





relative scale $\sim m_\pi / m_W \sim 10^{-7}$

- The range for W and Z exchange between quarks (10^{-2}fm) is small compared to the nucleon size (1fm) $\rightarrow$ **HWI is sensitive to short range quark-quark correlations in hadrons!**
- HWI has the potential to connect quark-quark correlations in the non-perturbative strongly interacting limit of QCD while accessing to the underlying weak interaction at the nucleon level as predicted by the SM. **"Inside out" probe of QCD**
- Ratio of weak to strong amplitudes is 10^{-7} $\rightarrow$ Use Parity Violation

Hadronic Weak Interaction: Theories

An Overview:

- DDH meson exchange model: PV potential π, ρ, and ω with strong and weak vertex. 7 Weak couplings h_π^1, $h_\rho^{0,1,2}$, $h_\rho^{1\prime}$, and $h_\omega^{0,1}$
  - B. Desplanques, J. F. Donoghue, and B. R. Holstein, Annals of Physics, 124 (1980)
  - W. C. Haxton and B. R. Holstein, Progress in Particle and Nuclear Physics (2013)

Hadronic Weak Interaction: Theories

An Overview:

- DDH meson exchange model: PV potential π, ρ, and ω with strong and weak vertex. 7 Weak couplings h_π^1, $h_\rho^{0,1,2}$, $h_\rho^{1\prime}$, and $h_\omega^{0,1}$
  - B. Desplanques, J. F. Donoghue, and B. R. Holstein, Annals of Physics, 124 (1980)
  - W. C. Haxton and B. R. Holstein, Progress in Particle and Nuclear Physics (2013)
- EFT($\not\pi$, π), χEFT: 5 LEC constants, model independent
  - 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

Hadronic Weak Interaction: Theories

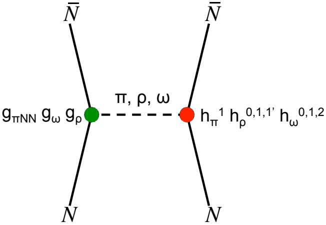
An Overview:

- DDH meson exchange model: PV potential π, ρ, and ω with strong and weak vertex. 7 Weak couplings h_π^1, $h_\rho^{0,1,2}$, $h_\rho^{1\prime}$, and $h_\omega^{0,1}$
  - B. Desplanques, J. F. Donoghue, and B. R. Holstein, Annals of Physics, 124 (1980)
  - W. C. Haxton and B. R. Holstein, Progress in Particle and Nuclear Physics (2013)
- EFT($\not\pi$, π), χEFT: 5 LEC constants, model independent
  - 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
- $1/N_c$ expansions: $N_c \to$ large gives hierarchy of couplings
  - D. Phillips, D. Samart, and C. Schat, PRL 114 (2015) 062301
  - M. R. Schindler, R. P. Springer, and J. Vanasse, PRC 93 (2016) 025502
  - Gardner, Haxton, Holstein, ARNPS 67, 69 (2017)

Hadronic Weak interaction: DDH

- Low energy NN interaction in terms of the lowest energy mesons in which the pseudoscalar π meson and ρ and ω vector mesons couple a weak vertex to a strong vertex
- To relate to observables, need to calculate matrix elements. DDH used quark model, SU(6) symmetry, and non-leptonic hyperon decays to make estimates of the couplings

$$
\begin{aligned}
V^{PV}_{DDH}(\vec{r}) = {} & i\frac{h^1_\pi g_{\pi NN}}{\sqrt{2}} \bigg(\frac{\boldsymbol{\tau_1}\times\boldsymbol{\tau_2}}{2}\bigg)_z (\boldsymbol{\sigma_1}+\boldsymbol{\sigma_2})\cdot\bigg[\frac{\boldsymbol{p_1}-\boldsymbol{p_2}}{2m_N}, w_\pi(\boldsymbol{r})\bigg] \\
& - g_\rho \bigg(h^0_\rho \boldsymbol{\tau_1}\cdot\boldsymbol{\tau_2} + h^1_\rho \bigg(\frac{\boldsymbol{\tau_1}\times\boldsymbol{\tau_2}}{2}\bigg)_z + \frac{h^2_\rho}{2\sqrt{6}}((3\boldsymbol{\tau_1}\cdot\boldsymbol{\tau_2})_z - \boldsymbol{\tau_1}\cdot\boldsymbol{\tau_2}) \bigg) \\
& \times \bigg((\boldsymbol{\sigma_1}-\boldsymbol{\sigma_2})\cdot\bigg\{\frac{\boldsymbol{p_1}-\boldsymbol{p_2}}{2m_N}, w_\rho(\boldsymbol{r})\bigg\} + i(1+\chi_V)\boldsymbol{\sigma_1}\times\boldsymbol{\sigma_2}\cdot\bigg[\frac{\boldsymbol{p_1}-\boldsymbol{p_2}}{2m_N}, w_\rho(\boldsymbol{r})\bigg]\bigg) \\
& - g_\omega \bigg(h^0_\omega + h^1_\omega \bigg(\frac{\boldsymbol{\tau_1}\times\boldsymbol{\tau_2}}{2}\bigg)_z \bigg) \\
& \times \bigg((\boldsymbol{\sigma_1}-\boldsymbol{\sigma_2})\cdot\bigg\{\frac{\boldsymbol{p_1}-\boldsymbol{p_2}}{2m_N}, w_\omega(\boldsymbol{r})\bigg\} + i(1+\chi_S)\boldsymbol{\sigma_1}\times\boldsymbol{\sigma_2}\cdot\bigg[\frac{\boldsymbol{p_1}-\boldsymbol{p_2}}{2m_N}, w_\omega(\boldsymbol{r})\bigg]\bigg) \\
& + \bigg(\frac{\boldsymbol{\tau_1}\times\boldsymbol{\tau_2}}{2}\bigg)_z (\boldsymbol{\sigma_1}+\boldsymbol{\sigma_2})\cdot \bigg) g_\rho h^1_\rho \bigg\{\frac{\boldsymbol{p_1}-\boldsymbol{p_2}}{2m_N}, w_\rho(\boldsymbol{r})\bigg\} - g_\omega h^1_\omega \bigg\{\frac{\boldsymbol{p_1}-\boldsymbol{p_2}}{2m_N}, w_\omega(\boldsymbol{r})\bigg\}\bigg) \\
& - i g_\rho h^{1'}_\rho \bigg(\frac{\boldsymbol{\tau_1}\times\boldsymbol{\tau_2}}{2}\bigg)_z (\boldsymbol{\sigma_1}+\boldsymbol{\sigma_2})\cdot\bigg[\frac{\boldsymbol{p_1}-\boldsymbol{p_2}}{2m_N}, w_\rho(\boldsymbol{r})\bigg]
\end{aligned}
$$



B. Desplanques, J. F. Donoghue, and B. R. Holstein, Annals of Physics, vol. 124, no. 2, pp. 449 - 495, 1980

Hadronic Weak Interaction: DDH

- Attractive theory: can use experimental data and symmetry from the SM to try and predict couplings, calculate few and many body
- Benchmark for 20 years. Created “reasonable range" and “best values" (not fits or actual determinations!) Strong interactions dominate range; take them lightly (error $\sim$ 100%)

Coupling	DDH Reasonable Range	DDH Best Value	DZ	FCDH
h_π^1	0.0 $\longleftrightarrow$ 11.4	4.6	1.1	2.7
h_ρ^0	-30.8 $\longleftrightarrow$ 11.4	-11.4	-8.4	-3.8
h_ρ^1	-0.38 $\longleftrightarrow$ 0.0	-0.19	0.4	-0.4
h_ρ^2	-11.0 $\longleftrightarrow$ -7.6	-9.5	-6.8	-6.8
h_ω^0	-10.3 $\longleftrightarrow$ 5.7	-1.9	-3.8	-4.9
h_ω^1	-1.9 $\longleftrightarrow$ -0.8	-1.1	-2.3	-2.3

Hadronic Weak Interaction: DDH

- Attractive theory: can use experimental data and symmetry from the SM to try and predict couplings, calculate few and many body
- Benchmark for 20 years. Created “reasonable range" and “best values" (not fits or actual determinations!) Strong interactions dominate range; take them lightly (error $\sim$ 100%)

Coupling	DDH Reasonable Range	DDH Best Value	DZ	FCDH
h_π^1	0.0 $\longleftrightarrow$ 11.4	4.6	1.1	2.7
h_ρ^0	-30.8 $\longleftrightarrow$ 11.4	-11.4	-8.4	-3.8
h_ρ^1	-0.38 $\longleftrightarrow$ 0.0	-0.19	0.4	-0.4
h_ρ^2	-11.0 $\longleftrightarrow$ -7.6	-9.5	-6.8	-6.8
h_ω^0	-10.3 $\longleftrightarrow$ 5.7	-1.9	-3.8	-4.9
h_ω^1	-1.9 $\longleftrightarrow$ -0.8	-1.1	-2.3	-2.3

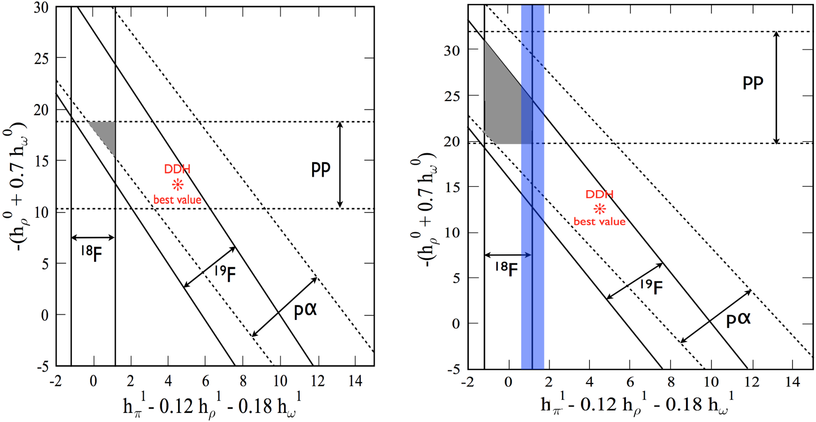
- Initially thought $\Delta I = 1$ could be large $\rightarrow$ motivated various experiments (including NPDGamma, $A_\gamma = -0.107 h_\pi^1$)

B. Desplanques, J. F. Donoghue, and B. R. Holstein, Annals of Physics, **124**, 2 (1980)

Extracting the Couplings from Observables in DDH?

Heavy Nuclei had a natural basis:

$$X_{N(n,p)} = 5.5(h_\pi^1 \pm 0.12 h_\rho^1 \pm 0.18 h_\omega^1) - 1.1(h_\rho^0 + 0.7 h_\omega^0)$$



- 6→2 projection proved to be incompatible: too much theoretical error

W. C. Haxton and B. R. Holstein, Progress in Particle and Nuclear Physics, 2013

Hadronic Weak interaction: Pionless EFT

Pionless EFT (EFT($\not\pi$))

- Below pion production, can choose photons and nucleons (instead of gluons, which are in bound states) as the only dynamical degrees of freedom, non-relativistic

Hadronic Weak interaction: Pionless EFT

Pionless EFT (EFT($\not\pi$))

- Below pion production, can choose photons and nucleons (instead of gluons, which are in bound states) as the only dynamical degrees of freedom, non-relativistic

$$\mathcal{L}_{PV} = -\Big[\mathcal{C}^{(^3S_1-^1P_1)}\left(N^T\sigma^2\vec{\sigma}\tau^2N\right)^\dagger\cdot\left(N^T\sigma^2\tau^2 i\overleftrightarrow{D}N\right)$$
$$+\mathcal{C}^{(^1S_0-^3P_0)}_{(\Delta I=0)}\left(N^T\sigma^2\tau^2\vec{\tau}N\right)^\dagger\left(N^T\sigma^2\vec{\sigma}\cdot\tau^2\vec{\tau}i\overleftrightarrow{D}N\right)$$
$$+\mathcal{C}^{(^1S_0-^3P_0)}_{(\Delta I=1)}\epsilon_{3ab}\left(N^T\sigma^2\tau^2\tau^aN\right)^\dagger\left(N^T\sigma^2\vec{\sigma}\cdot\tau^2\tau^b\overleftrightarrow{D}N\right)$$
$$+\mathcal{C}^{(^1S_0-^3P_0)}_{(\Delta I=2)}\mathcal{I}_{ab}\left(N^T\sigma^2\tau^2\tau^aN\right)^\dagger\left(N^T\sigma^2\vec{\sigma}\cdot\tau^2\tau^b i\overleftrightarrow{D}N\right)$$
$$+\mathcal{C}^{(^3S_1-^3P_1)}\epsilon_{ijk}\left(N^T\sigma^2\sigma^i\tau^2N\right)^\dagger\left(N^T\sigma^2\sigma^k\tau^2\tau^3\overleftrightarrow{D}^jN\right)\Big] + \text{H.c.}\,,$$

- 5 LECs. Can only use two-body systems

M. Schindler, R. Springer, Progress in Particle and Nuclear Physics (2013)
M. Schindler, R. Springer, J. Vanasse, PRC (2016)

Hadronic Weak Interaction: $1/N_c$ hierarchy

- Basic principle: find LO, NLO, NNLO... in $1/N_c$ expansion
- Can estimate the couplings to 30%! Terms can come in as $\mathcal{O}(N_c)$ or $\mathcal{O}(1/N_c)$ along with factors of $\sin^2(\theta_W)$, which come along from the Lagrangian

Hadronic Weak Interaction: $1/N_c$ hierarchy

- Basic principle: find LO, NLO, NNLO... in $1/N_c$ expansion
- Can estimate the couplings to 30%! Terms can come in as $\mathcal{O}(N_c)$ or $\mathcal{O}(1/N_c)$ along with factors of $\sin^2(\theta_W)$, which come along from the Lagrangian
- First, Phillips et al used the $1/N_c$ expansion of QCD to tackle the PV NN force in the DDH framework

$$h_\rho^0 \sim \sqrt{N_c}, \qquad h_\rho^2 \sim \sqrt{N_c}$$

$$\frac{h_\rho^{1'}}{\sin^2\theta_W} \lesssim \sqrt{N_c}, \qquad \frac{h_\omega^1}{\sin^2\theta_W} \sim \sqrt{N_c}$$

$$\frac{h_\rho^1}{\sin^2\theta_W} \lesssim \frac{1}{\sqrt{N_c}}, \qquad \frac{h_\pi^1}{\sin^2\theta_W} \lesssim \frac{1}{\sqrt{N_c}}, \qquad h_\omega^0 \sim \frac{1}{\sqrt{N_c}}$$

D. Phillips, D. Samart, and C. Schat, PRL 114 (2015) 062301

Hadronic Weak Interaction: $1/N_c$ hierarchy EFT

- First developed by Schindler et al in EFT($\not\pi$) (5 couplings), with LEC $\mathcal{C}$'s (related to the DDH couplings and the Λ's in the following)
- Showed that the two isoscalar terms are related to one another by a factor of 3 up to $\mathcal{O}(1/N_c^2)$ corrections. Can go from 5 → 4 effective couplings

$$\begin{aligned}
\mathcal{C}^{(^3S_1-^1P_1)} &\sim N_c \;, \\
\mathcal{C}^{(^1S_0-^3P_0)}_{(\Delta I=0)} &\sim N_c \;, \\
\mathcal{C}^{(^1S_0-^3P_0)}_{(\Delta I=1)} &\sim N_c^0 \sin^2\theta_W \;, \\
\mathcal{C}^{(^1S_0-^3P_0)}_{(\Delta I=2)} &\sim N_c \;, \\
\mathcal{C}^{(^3S_1-^3P_1)} &\sim N_c^0 \sin^2\theta_W \;.
\end{aligned} \tag{33}$$

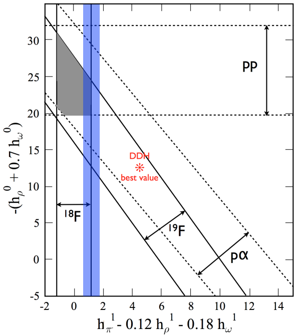
As before, the two isoscalar terms are not independent at leading order in the large-N_c counting, but up to $1/N_c^2$ corrections are related by

$$\mathcal{C}^{(^3S_1-^1P_1)} = 3\,\mathcal{C}^{(^1S_0-^3P_0)}_{(\Delta I=0)} \;. \tag{34}$$

M. R. Schindler, R. P. Springer, and J. Vanasse, PRC 93 (2016) 025502

Hadronic Weak Interaction: $1/N_c$ hierarchy EFT

- A recent review by Gardner, Haxton, and Holstein (GHH) finds a new basis of LO and makes predictions using a mapping from DDH



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

→

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

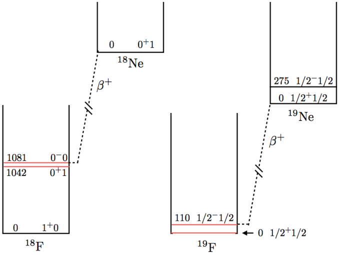
Gardner, Haxton, Holstein, ARNPS 67, 69 (2017)

Hadronic Weak Interaction: Theory Outlook

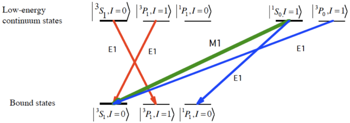
- DDH is an important theoretical framework. It is model dependent, but can still be used to describe experiments
- Lots of theoretical work has been done and ongoing. $1/N_c$ hierarchy is a great step forward
- pionless EFT, 2-body, 4 (5-1) LECs = at least 4 experiments
  - $\vec{n} + p \to d + \gamma$ spin-angular asymmetry (completed, $\sim$47% error)
  - $\vec{n} + p \to d + \gamma$ circular polarization (large error)
  - $n - p$ spin rotation
  - $p - p$ longitudinal asymmetry (completed, $\sim$16% error)
  - $\vec{\gamma} + d \to n + p$ (difficult, not bright enough γ source)
- EFT, GHH, DDH equivalent
  - Few- and many-body calculations ongoing
  - Difficult theory, but can express observables in the theory

Experimental approaches:

- **Heavy Nuclei**:
  - Small level spacings → large PV signals
  - Theoretical interpretations more difficult



- **Few-body**:
  - Large level spacings → small PV signals
  - Little or no theoretical error



Experiments with too much theoretical uncertainty?

γ Circular Polarization of Heavy Nuclei:

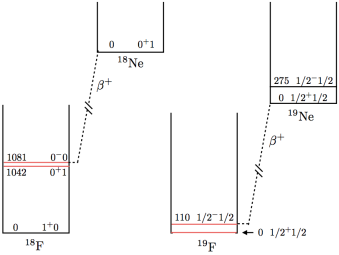
- E.g. ^{40}K, ^{175}Lu, ^{181}Ta
- All in the basis $X_{N(n,p)} = 5.5(h_\pi^1 \pm 0.12 h_\rho^1 \pm 0.18 h_\omega^1) - 1.1(h_\rho^0 - 0.7 h_\omega^0)$

^{133}Cs, ^{205}Tl anapole moment

- Theory of nuclear anapole moment? (W. S. Wilburn, J. D. Bowman, Phys.Rev. C, **57** (1998))

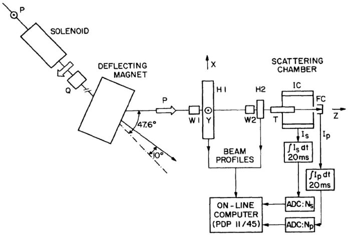
Hadronic Weak interaction: Heavy Nuclei Experiments

- ^{18}F: $P_\gamma = 12 \pm 38 \times 10^{-5}$ (Caltech/Seattle, Mainz, Florence, Queens)
  - Mixing of the 0^+, $\Delta I = 1$ decay into the 0^-, $\Delta I = 0$ state gives circular polarization in the 1.081 MeV γ emitted: $\rightarrow=$ pure $\Delta I = 1$ transition
  - Small mass difference between the two states acts as a nuclear amplifier
  - Couplings: $4385 h^1_\pi - 492 h^1_\rho - 833 h^1_\omega$, or $\Lambda_1^{^3S_1-^3P_1} + 2.42\Lambda_1^{^1S_0-^3P_0}$
- ^{19}F: $A_\gamma = 7.4 \pm 1.9 \times 10^{-5}$ (Seattle, Mainz)
  - Angular asymmetry in the polarized excited $1/2^-$ to the $1/2^+$ ground state
  - Couplings: $\Lambda_0^{^1S_0-^3P_0} + 0.67\Lambda_1^{^1S_0-^3P_0} + 0.43\Lambda_0^{^3S_1-^1P_1} + 0.29\Lambda_1^{^3S_1-^3P_1}$



Gardner, Haxton, Holstein, ARNPS 67, 69 (2017)

Hadronic Weak interaction: Few-body Experiments



$\vec{p} - \vec{p}$ scattering: best constraints still

- A_L = -0.93 $\pm$ 0.21 (13 MeV, Bonn), -1.7 $\pm$ 0.8 (15 MeV, LANL), -1.57 $\pm$ 0.23 $\times 10^{-7}$ (45 MeV, PSI)
  - Longitudinal analyzing power of polarized protons on an un-polarized target
  - GHH: $\Lambda_0^{^1S_0-^3P_0} + \Lambda_1^{^1S_0-^3P_0} + \frac{1}{\sqrt{6}}\Lambda_2^{^1S_0-^3P_0} = 419 \pm 43$
  - DDH: $-(h_\rho^0 - 0.7 h_\omega^0) = 25 \pm 6.1$

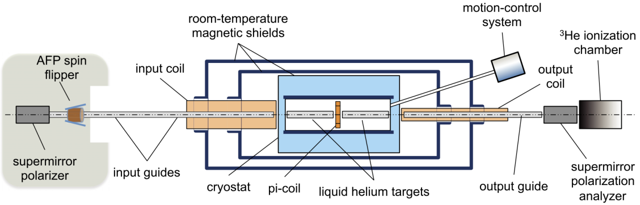
Hadronic Weak interaction: Few-body Experiments

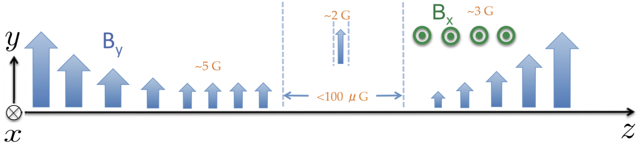
$\vec{p} - \vec{\alpha}$ scattering

- $A_L = 3.3 \pm 0.9 \times 10^{-7}$ (46 MeV, PSI)
  - Longitudinal analyzing power of protons on ^{4}He target
  - GHH: $\Lambda_0^{^1S_0-^3P_0} + 0.89\Lambda_1^{^1S_0-^3P_0} + 0.75\Lambda_0^{^3S_1-^1P_1} + 0.32\Lambda_1^{^3S_1-^3P_1} = 930 \pm 253$
  - DDH: $-0.34h_\pi^1 - 0.05h_\rho^1 - 0.06h_\omega^1 + 0.14h_\rho^0 + 0.06h_\omega^0 = 3.3 \pm 0.9$
  - Similar combination as ^{19}F

Hadronic Weak interaction: Few-body Experiments

Neutron Spin Rotation in ^{4}He to begin soon at NIST: $\frac{d\phi}{dz}$ LO: Λ_0^+

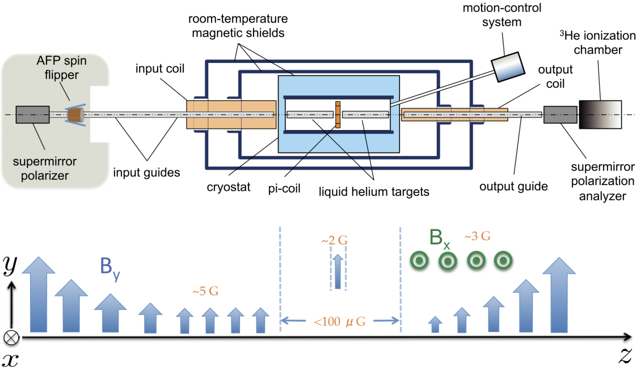




- Previous result statistics limited: $+1.7 \pm 9.1$ (stat) ± 1.4 (sys) $\times 10^{-7}$ rad/m
- $\vec{\sigma} \cdot \vec{k}$ interaction causes an accumulation of phase: corkscrew motion!
- Use various configurations of magnetic fields to isolate the effect
- 5th force program at LANL using same apparatus (sans ^{4}He) finished, published in PRB https://doi.org/10.1016/j.physletb.2018.06.066

Hadronic Weak interaction: Few-body Experiments

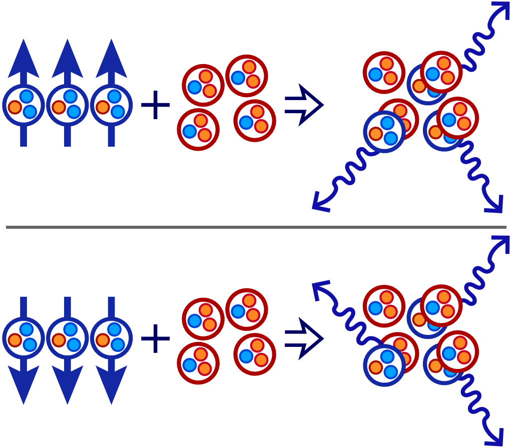
Neutron Spin Rotation in $n-p$: $\frac{d\phi}{dz}$ LO: $\Lambda_0^+ + 2.7\Lambda_2^{^1S_0-^3P_0}$



- Motivation for $n-p$ spin rotation:
  - Sensitive to leading order $\Delta I = 0,2$
  - One of the 4 experiments needed for pionless EFT
  - Could have a large signal (expectation based on experimental data now)

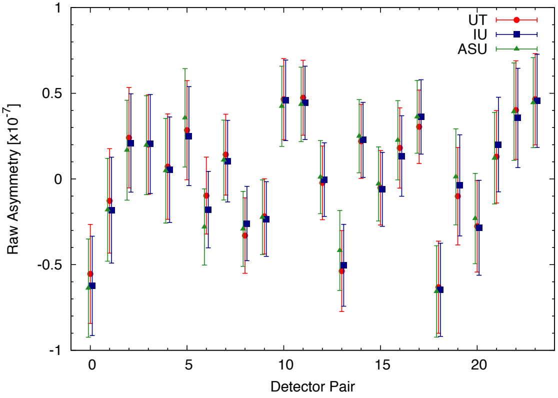
Hadronic Weak interaction: NPDGamma

NPDGamma $(\vec{\sigma} \cdot \vec{k})$ at the SNS at ORNL, goal: $h_\pi^1 \sim 1 \times 10^{-7}$



- Flipping the neutron polarization is equivalent to a parity transformation
- Large statistics! Must collect 10^{16} photons to see 10^{-8} asymmetry!

Final Results: accepted for publication in PRL!



- Three separate analyses agreed at the few 10^{-10} level!

$$\boxed{A_\gamma = -3.0 \pm 1.4 \times 10^{-8}}$$

- h_π^1 = (2.6 $\pm$ 1.2) $\times 10^{-7}$, $C^{3^S_1 \to ^3P_1}/C_0 = -7.4 \pm 3.5 \times 10^{-11}$ MeV^{-1}, $\Lambda_1^{^3S_1 - ^3P_1}$ = 810 $\pm$ 380 $\times 10^{-7}$

Final Results: accepted for publication in PRL!

PHYSICAL REVIEW LETTERS **VOL..XX,** 000000 (XXXX)

Editors' Suggestion

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. Penttilä,[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,[13,6] Z. Tang,[4,6] X. Tong,[7] D. J. Turkoglu,[28] R. Whitehead,[5] and W. S. Wilburn[6]

(NPDGamma Collaboration)

[1]Arizona State University, Tempe, Arizona 85287, USA
[2]High Energy Physics Division, Argonne National Laboratory, Argonne, Illinois 60439, USA
[3]University of Virginia, Charlottesville, Virginia 22904, USA
[4]Indiana University, Bloomington, Indiana 47405, USA
[5]University of Tennessee, Knoxville, Tennessee 37996, USA
[6]Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA
[7]Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831, USA
[8]Horia Hulubei National Institute for Physics and Nuclear Engineering, Magurele 077125, Romania
[9]Instituto de Física, Universidad Nacional Autónoma de México, Apartado Postal 20-364, 01000, Mexico
[10]University of Nevada, Las Vegas, Nevada 89154, USA
[11]University of New Hampshire, Durham, New Hampshire 03824, USA
[12]University of Michigan, Ann Arbor, Michigan 48109, USA
[13]University of Kentucky, Lexington, Kentucky 40506, USA
[14]University of Manitoba, Winnipeg, Manitoba, Canada R3T 2N2
[15]University of Tennessee, Chattanooga, Tennessee 37403 USA
[16]Physics Department, North Carolina State University, Raleigh, North Carolina 27695, USA
[17]Mississippi State University, Mississippi State, Mississippi 39759, USA
[18]Northwestern University Feinberg School of Medicine, Chicago, Illinois 60611, USA
[19]Paul Scherrer Institut, CH-5232 Villigen, Switzerland
[20]Middle Tennessee State University, Murfreesboro, Tennessee 37132, USA
[21]High Energy Accelerator Research Organization (KEK), Tukuba-shi, 305-0801, Japan
[22]Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA
[23]Western Kentucky University, Bowling Green, Kentucky 42101, USA
[24]Bhabha Atomic Research Centre, Trombay, Mumbai 400085, India
[25]Saarland University, Institute of Experimental Ophthalmology, Kirrberger Str. 100, Bldg. 22, 66424 Homburg/Saar, Germany
[26]Triangle Universities Nuclear Lab, Durham, North Carolina 27708, USA
[27]Joint Institute for Nuclear Research, Dubna 141980, Russia
[28]National Institute of Standards and Technology, Gaithersburg, Maryland 20899, USA

How does this result fit into the big picture and with ^{18}F?

Comparing NPDGamma and ^{18}F (DDH framework, the only way!), units of 10^{-7}

- ^{18}F
  - Experiment: $|P_\gamma| < 5100$
  - **Theory: $4385 h^1_\pi$ - $492 h^1_\rho$ - $833 h^1_\omega$**
- $\vec{n} + p \rightarrow d + \gamma$
  - NPDGamma Experiment: A_γ = -3.0 $\pm$ 1.4
  - **Theory: $-0.11 h^1_\pi$ - $0.001 h^1_\rho$ + $0.004 h^1_\omega$**

How does this result fit into the big picture and with ^{18}F?

Comparing NPDGamma and ^{18}F (DDH framework, the only way!), units of 10^{-7}

- ^{18}F
  - Experiment: $|P_\gamma| < 5100$
  - **Theory: 4385h^1_π - 492h^1_ρ - 833h^1_ω**
- $\vec{n} + p \rightarrow d + \gamma$
  - NPDGamma Experiment: A_γ = -3.0 $\pm$ 1.4
  - **Theory: -0.11h^1_π - 0.001h^1_ρ + 0.004h^1_ω**
- The ρ and ω $\Delta I = 1$ couplings are suppressed by a factor of 10 or more in NPDGamma! In the 2D projection, the reasonable ranges of the other ΔI = 1 couplings are adding to inflate the central value and error. This gave a false sense that h^1_π should be zero.

How does this result fit into the big picture and with ^{18}F?

Comparing NPDGamma and ^{18}F (DDH framework, the only way!), units of 10^{-7}

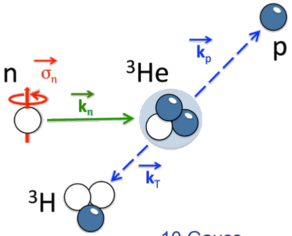
- ^{18}F
  - Experiment: $|P_\gamma| < 5100$
  - **Theory: 4385h^1_π - 492h^1_ρ - 833h^1_ω**
- $\vec{n} + p \rightarrow d + \gamma$
  - NPDGamma Experiment: A_γ = -3.0 $\pm$ 1.4
  - **Theory: -0.11h^1_π - 0.001h^1_ρ + 0.004h^1_ω**
- The ρ and ω ΔI = 1 couplings are suppressed by a factor of 10 or more in NPDGamma! In the 2D projection, the reasonable ranges of the other ΔI = 1 couplings are adding to inflate the central value and error. This gave a false sense that h^1_π should be zero.
- If we take both experiments at face value, we find a new linear combination of (0.4h^1_ρ + 0.6 h^1_ω) = 8.5 $\pm$ 5.0. This is larger than the DDH reasonable range would predict. More evidence to question the reasonable range.
- This **could** fit into the $1/N_c$ hierarchy. (h^1_ω favored, h^1_ρ and h^1_π disfavored)

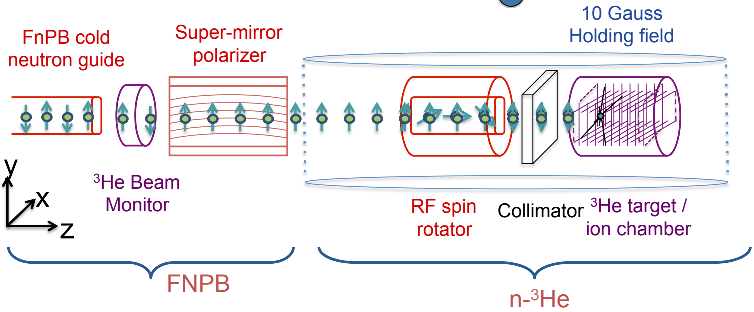
Hadronic Weak interaction: Few-body Experiments

n-3He at the SNS at ORNL: $-\Lambda_0^+ + 0.227\Lambda_2^{^1S_0 - ^3P_0}$

$$\sigma_\pm = \sigma_0 (1 \pm A_{PC}\, \hat{\boldsymbol{k}}_n \times \hat{\boldsymbol{\sigma}}_n \cdot \hat{\boldsymbol{k}}_p \pm A_{PV}\, \underbrace{\hat{\boldsymbol{\sigma}}_n \cdot \hat{\boldsymbol{k}}_p}_{G_{\substack{\mathrm{LR}\\\mathrm{UD}}}})$$

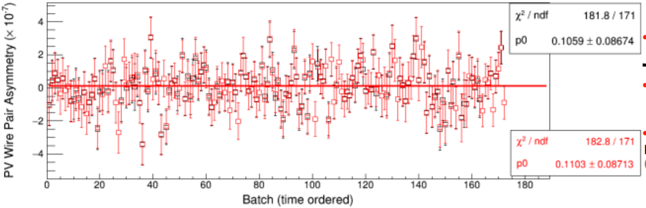
$$P_n A_{\substack{\mathrm{PC}\\\mathrm{PV}}} G_{\substack{\mathrm{LR}\\\mathrm{UD}}} = \frac{Y_+ - Y_-}{Y_+ + Y_-}$$

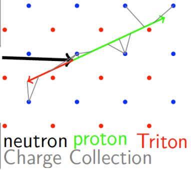


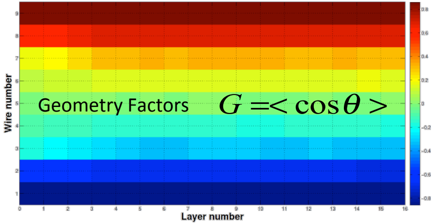


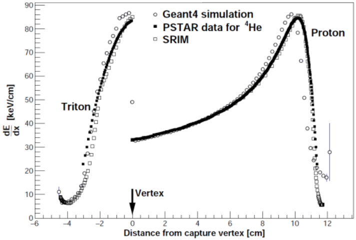
Hadronic Weak interaction: Few-body Experiments

n-3He at the SNS at ORNL: $-\Lambda_0^+ + 0.227\Lambda_2^{{}^1S_0-{}^3P_0}$









$$A_{PV} = 1.2 \pm 1.0 \times 10^{-8}$$

$$437 \pm 364 = (-\Lambda_0^+ + 0.227\Lambda_2^{{}^1S_0-{}^3P_0}) \text{ at LO}$$

Hadronic Weak interaction: GHH hierarchy

The review by Gardner et al finds a new basis of LO and makes predictions using a mapping from DDH and $1/N_c$ hierarchy EFT expectations

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

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

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

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

$$\left[|\Lambda_1^{^3S_1-^3P_1}|\right] < \epsilon\, 270 \qquad A_\gamma(\vec{\mathrm{n}}\mathrm{p} \to \mathrm{d}\gamma)$$

Observable	Exp. Status	LO Expectation	LO LEC Dependence
$A_\mathrm{p}(\vec{\mathrm{n}} + ^3\mathrm{He} \to ^3\mathrm{H}+\mathrm{p})$	ongoing	-1.8×10^{-8}	$-\Lambda_0^+ + 0.227\Lambda_2^{^1S_0-^3P_0}$
$A_\gamma(\vec{\mathrm{n}} + \mathrm{d} \to \mathrm{t} + \gamma)$	8×10^{-6} (see text) [58]	7.3×10^{-7}	$\Lambda_0^+ + 0.44\Lambda_2^{^1S_0-^3P_0}$
$P_\gamma(\mathrm{n} + \mathrm{p} \to \mathrm{d} + \gamma)$	$(1.8 \pm 1.8) \times 10^{-7}$ [57]	1.4×10^{-7}	$\Lambda_0^+ + 1.27\Lambda_2^{^1S_0-^3P_0}$
$\frac{d\phi^n}{dz}\big\vert_{\mathrm{parahydrogen}}$	none	9.4×10^{-7} rad/m	$\Lambda_0^+ + 2.7\Lambda_2^{^1S_0-^3P_0}$
$\frac{d\phi^n}{dz}\big\vert_{^4\mathrm{He}}$	$(1.7 \pm 9.1 \pm 1.4) \times 10^{-7}$ [56]	6.8×10^{-7} rad/m	Λ_0^+
$A_L(\vec{\mathrm{p}} + \mathrm{d})$	$(-3.5 \pm 8.5) \times 10^{-8}$ [43]	-4.6×10^{-8}	$-\Lambda_0^+$

M. R. Schindler, R. P. Springer, and J. Vanasse, PRC 93 (2016)
Gardner, Haxton, Holstein, ARNPS 67, 69 (2017)

Hadronic Weak interaction: GHH hierarchy

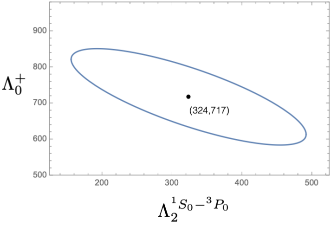
Prior to NPDGamma more severe conflict with DDH “best values”

$$\left\{ \begin{array}{c} {}^{\mathrm{DDH}}\Lambda_0^+ \\ {}^{\mathrm{DDH}}\Lambda_2^{^1S_0-^3P_0} \end{array} \right\} = \left\{ \begin{array}{c} 319 \\ 151 \end{array} \right\} \qquad \left\{ \begin{array}{c} {}^{\mathrm{DDH}}\Lambda_0^- \\ {}^{\mathrm{DDH}}\Lambda_1^{^1S_0-^3P_0} \\ {}^{\mathrm{DDH}}\Lambda_1^{^3S_1-^3P_1} \end{array} \right\} = \left\{ \begin{array}{c} -70 \\ 21 \\ 1340 \end{array} \right\}$$

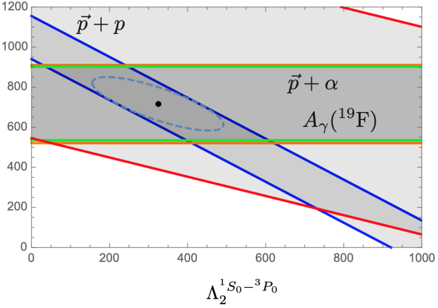
Also consistent with old conclusion that isoscalar strength is about twice DDH

LO theory consistent with experiment

$$\left\{ \begin{array}{c} 717 \\ 324 \end{array} \right\}$$



PRIOR to NPDGamma assuming $A_\gamma \lesssim 10^{-8}$



W. C. Haxton, CIPANP 2018: https://conferences.lbl.gov/event/137/session/18/contribution/2/material/slides/0.pdf

Hadronic Weak interaction: GHH hierarchy

After NPDGamma conflict with DDH "best values" somewhat mitigated

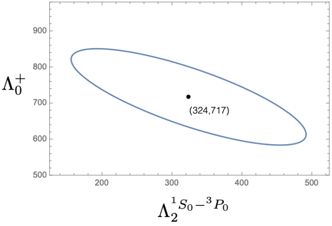
$$\left\{ \begin{array}{c} {}^{\rm DDH}\Lambda_0^+ \\ {}^{\rm DDH}\Lambda_2^{^1S_0-^3P_0} \end{array} \right\} = \left\{ \begin{array}{c} 319 \\ 151 \end{array} \right\} \qquad \left\{ \begin{array}{c} {}^{\rm DDH}\Lambda_0^- \\ {}^{\rm DDH}\Lambda_1^{^1S_0-^3P_0} \\ {}^{\rm DDH}\Lambda_1^{^3S_1-^3P_1} \end{array} \right\} = \left\{ \begin{array}{c} -70 \\ 21 \\ 1340 \end{array} \right\}$$

~ 810

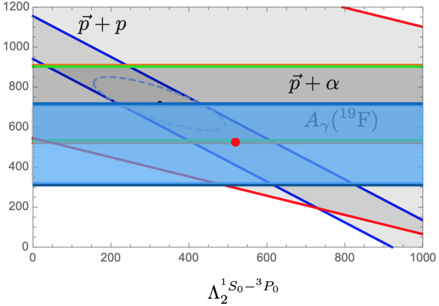
Also consistent with old conclusion that isoscalar strength is about twice DDH

LO theory consistent with experiment

$$\left\{ \begin{array}{c} \sim 520 \\ \sim 510 \end{array} \right\}$$

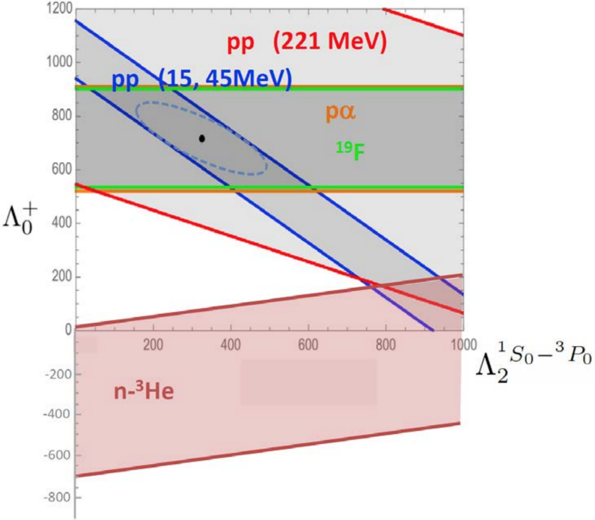


With NPDGamma constraint on NNLO corrections



W. C. Haxton, CIPANP 2018: https://conferences.lbl.gov/event/137/session/18/contribution/2/material/slides/0.pdf

After n-^{3}He... need more experiments to clean up the landscape



M. Gericke, CIPANP 2018: https://conferences.lbl.gov/event/137/session/18/contribution/178/material/slides/0.pdf

Hadronic Weak interaction: What Exps Should We Pursue?

Wouldn't it be nice to have a 10% measurement of LO couplings?

NPDGamma and n-^{3}He shows us how NLO and NNLO can affect LO. Need more experiments!

Completed, can be done with more precision

Done, does not contribute to the determination of the couplings

Not attempted

$\vec{n} + {}^3\text{He} \rightarrow {}^3\text{H} + p$

$\vec{n} + d \rightarrow t + \gamma$

$n + p \rightarrow d + \gamma$

$\vec{n} - p$ SR

$\vec{n}$–^{4}He SR

$\vec{p} + d$

Normed Observable	LO Expression	NNLO Correction
$\frac{364}{10^{-8}} A_\text{p}$	$-\Lambda_0^+ + 0.227\Lambda_2^{^1S_0-^3P_0}$	$-\left[3.82\Lambda_0^- + 8.18\Lambda_1^{^1S_0-^3P_0} + 2.27\Lambda_1^{^3S_1-^3P_1}\right]$
$\frac{118}{10^{-7}} A_\gamma$	$\Lambda_0^+ + 0.44\Lambda_2^{^1S_0-^3P_0}$	$-\left[1.86\Lambda_0^- + 0.65\Lambda_1^{^1S_0-^3P_0} + 0.42\Lambda_1^{^3S_1-^3P_1}\right]$
$\frac{825}{10^{-7}} P_\gamma$	$\Lambda_0^+ + 1.27\Lambda_2^{^1S_0-^3P_0}$	$\left[0.47\Lambda_0^-\right]$
$\frac{180}{10^{-7}} \frac{d\phi^\text{n}}{dz}\Big\vert_\text{parahydrogen}$	$(\Lambda_0^+ + 2.82\Lambda_2^{^1S_0-^3P_0})$ rad/m	$-\left[3.15\Lambda_0^- + 1.94\Lambda_1^{^3S_1-^3P_1}\right]$ rad/m
$\frac{105}{10^{-7}} \frac{d\phi^\text{n}}{dz}\Big\vert_{^4\text{He}}$	Λ_0^+ rad/m	$-\left[1.61\Lambda_0^- + 0.92\Lambda_1^{^1S_0-^3P_0} + 0.35\Lambda_1^{^3S_1-^3P_1}\right]$ rad/m
$\frac{156}{10^{-8}} A_L$	$-\Lambda_0^+$	$+\left[1.75\Lambda_0^- - 1.09\Lambda_1^{^1S_0-^3P_0} - 1.25\Lambda_1^{^3S_1-^3P_1}\right]$

W. C. Haxton, CIPANP 2018: https://conferences.lbl.gov/event/137/session/18/contribution/2/material/slides/0.pdf

Summary and Outlook

- Now have 3 few-body experiments (NPDGamma, n—^{3}He, and $p-p$)
- The community is developing a plan on the next steps for the theory and experiment:
  - Workshop at KITP in March 2018
  - Considering a workshop at ORNL
- What can we do going forward?
  - $\vec{n}$—^{4}He spin rotation experiment is planned at NIST
  - $\vec{n}-p$ spin rotation
  - $n+p\rightarrow d+\gamma$ spin-angular and circular polarization
  - $\vec{n}+d\rightarrow t+\gamma$
  - $\vec{n}+^3\text{He}\rightarrow ^3\text{H}+p$
  - LQCD calculations of $\Delta I=2$ might be possible!