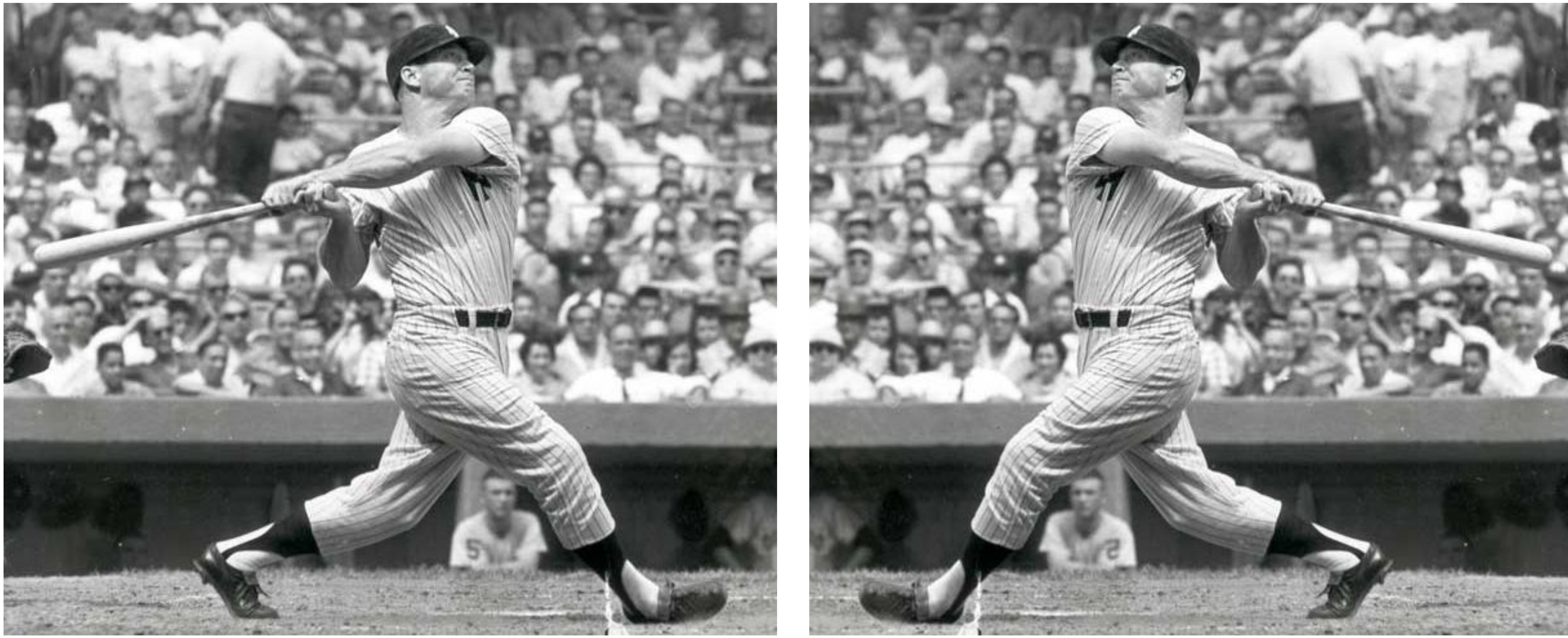
Wick Haxton, UC Berkeley and LBL

Large N_c Phenomenology: Workshop Goals

Workshop on Hadronic Parity Nonconservation

Sponsored by the National Science Foundation and KITP

Hadronic Parity Nonconservation



MM: nearly mirror symmetric
obp: 0.418 (LHed) 0.424 (RHed) - parity conserved at the 1% level

Parity as a good quantum label almost as old as QM itself: used by Wigner in 1927 as an atomic spectroscopy label

Found violated in weak interactions 1957: (Lee,Yang, MM (.365 BA) - all had good years)

<u>hadronic weak interactions:</u> as the weak neutral current is suppressed in $\Delta S \neq 0$ weak processes, neutral current can only be studied in $\Delta S = 0$ reaction

NN and nuclear reactions the only feasible possibilities

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

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

↕ ↕

ΔI=1 ΔI=1/2

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

↕ ↕

symmetric ⇒ ΔI=0,2 ΔI=1 but Cabibbo suppressed

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↕ symmetric ⇒ ΔI=0,2 ↕ ΔI=1 but Cabibbo suppressed

weak hadronic neutral current will dominate experiments sensitive to isovector PNC — the only SM current not yet isolated: led to a focus on h_π^1, which DDH predicted would be large

Largely equivalent DDH, Danilov, and Pionless EFT treatments

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

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

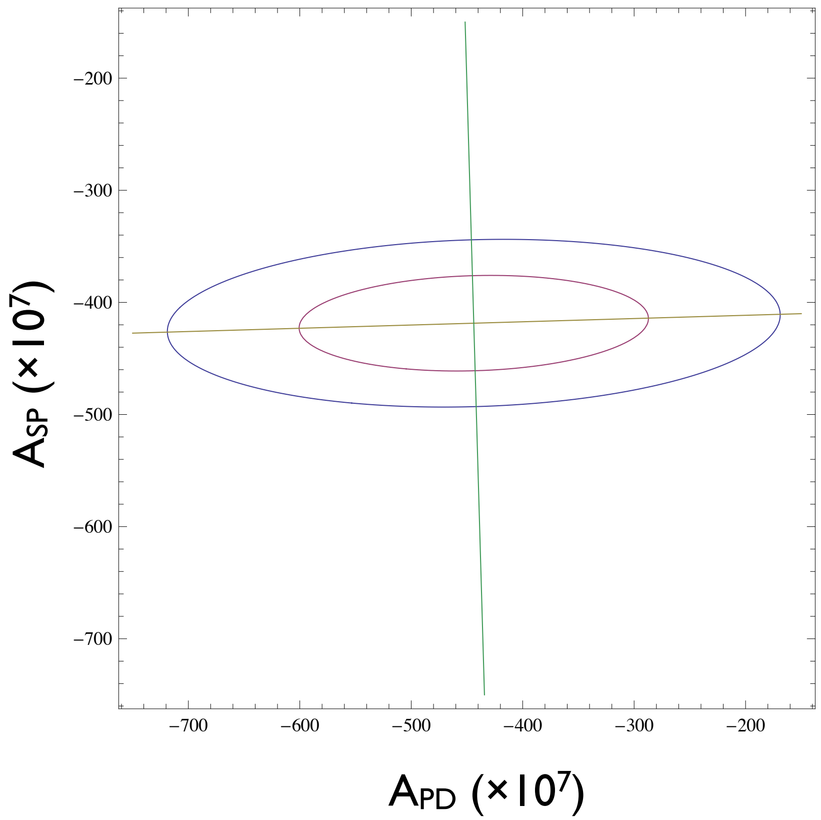
and $1/N_c$ approaches
- D. Phillips, D. Samart, and C. Schat, PRL 114 (2015) 062301
- M. R. Schindler, R. P. Springer, and J. Vanasse, PRC 93 (2016) 025502

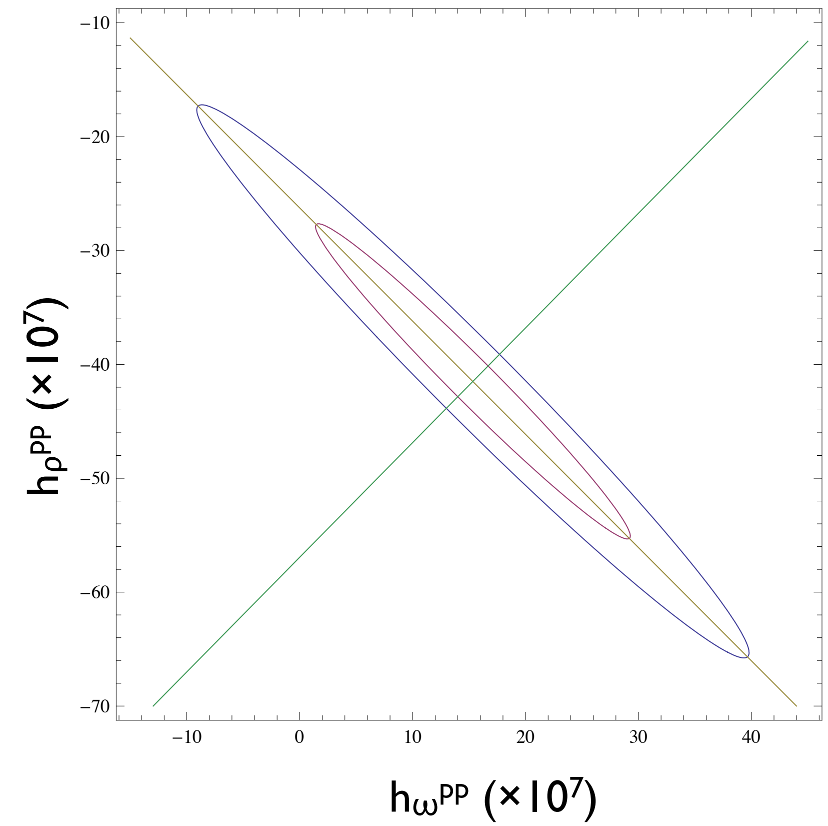
Coeff	DDH	Girlanda	Zhu
$\Lambda_{0\ DDH}^{^1S_0-^3P_0}$	$-g_\rho h_\rho^0(2+\chi_V) - g_\omega h_\omega^0(2+\chi_S)$	$2(\mathcal{G}_1+\tilde{\mathcal{G}}_1)$	$2(\mathcal{C}_1+\tilde{\mathcal{C}}_1+\mathcal{C}_3+\tilde{\mathcal{C}}_3)$
$\Lambda_{0\ DDH}^{^3S_1-^1P_1}$	$g_\omega h_\omega^0\chi_S - 3g_\rho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

Lack of data has been one challenge

$\vec{p}+p$ asymmetry:

at 13.6, 45, 221 MeV





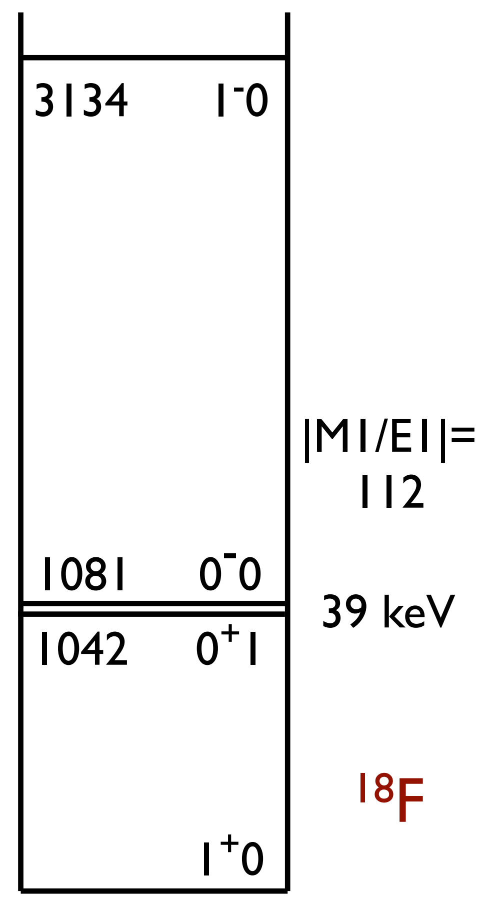
some of the most reliable constraints

$$A_L^{\vec{p}+p}(45\,\mathrm{MeV}) = (-1.57 \pm 0.23) \times 10^{-7}$$

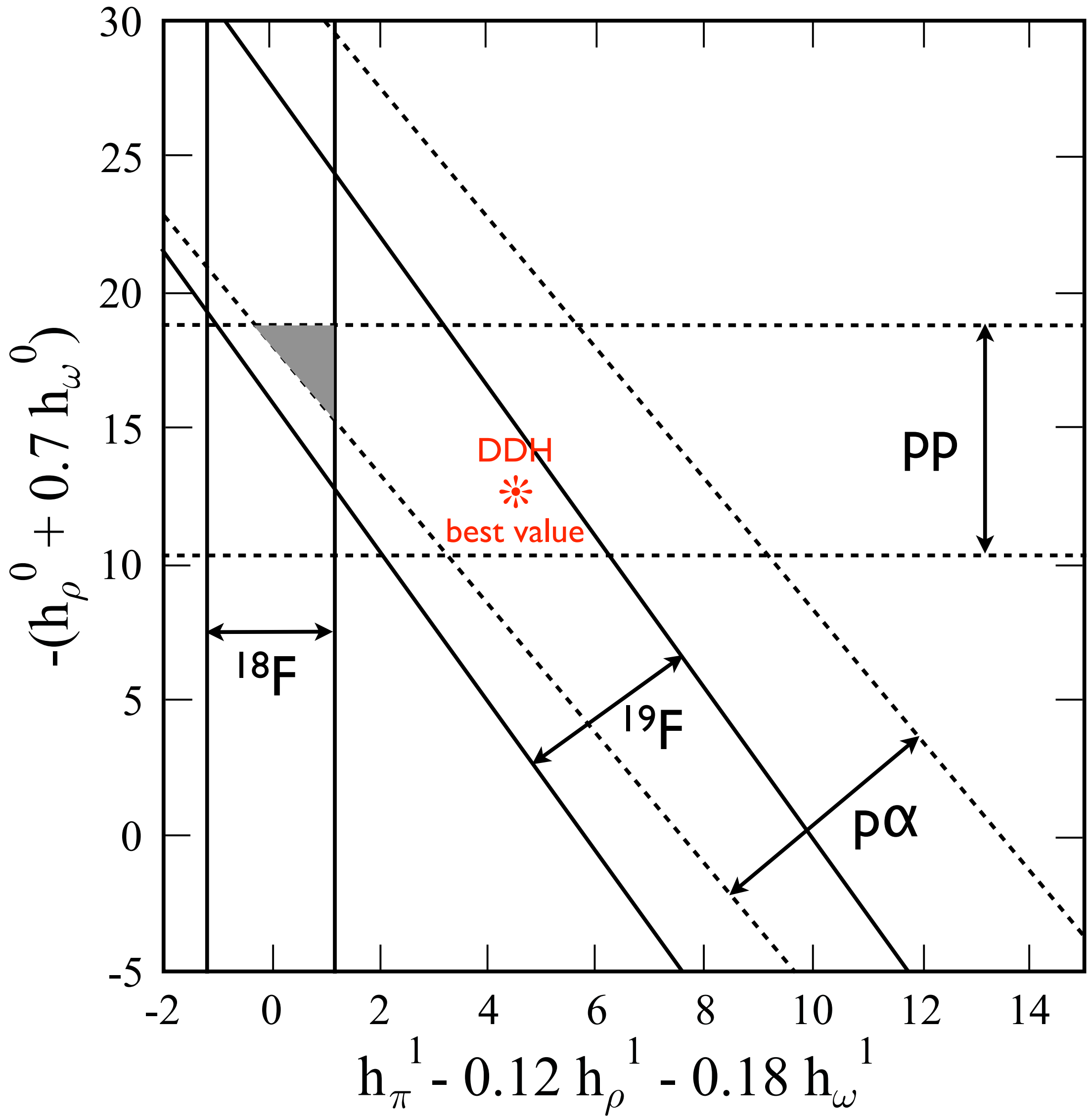
$$A_L^{\vec{p}+\alpha}(46\,\mathrm{MeV}) = (-3.34 \pm 0.93) \times 10^{-7}$$

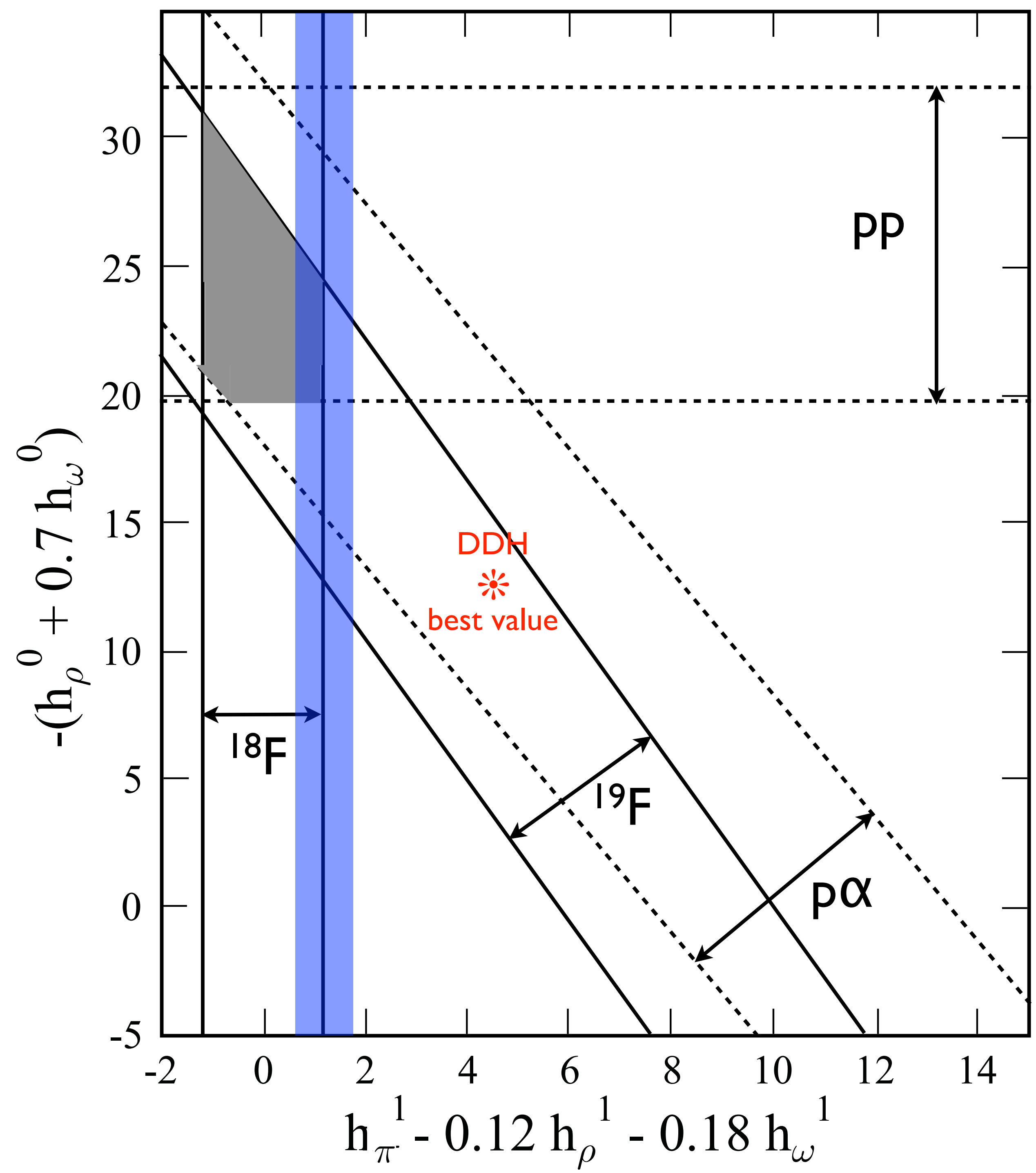
$$P_\gamma^{^{18}\mathrm{F}}(1081\,\mathrm{keV}) = (12 \pm 38) \times 10^{-5}$$

$$A_\gamma^{^{19}\mathrm{F}}(110\,\mathrm{keV}) = (-7.4 \pm 1.9) \times 10^{-5}$$



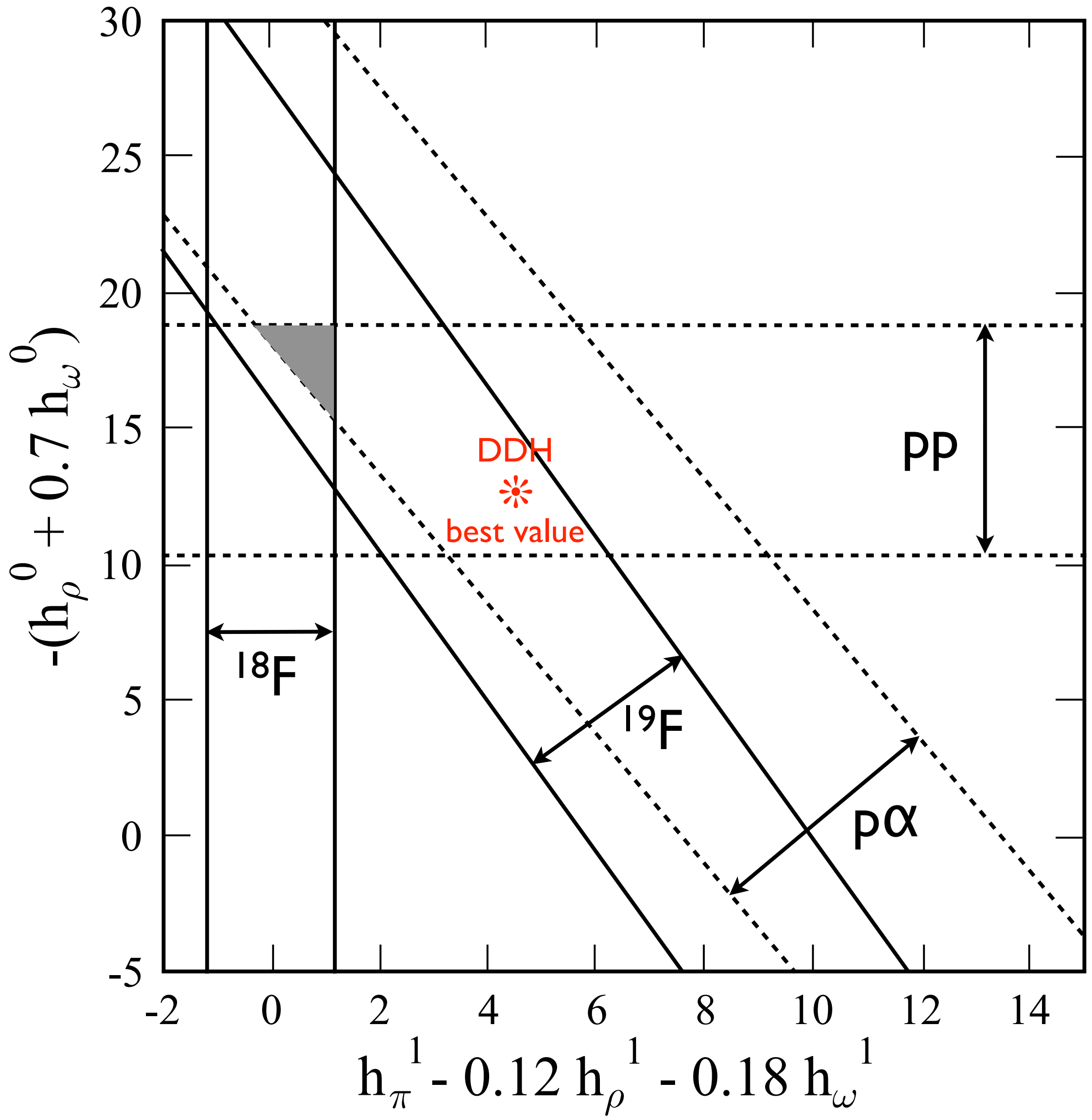
Another has been the need to combine calculations of different types, vintages

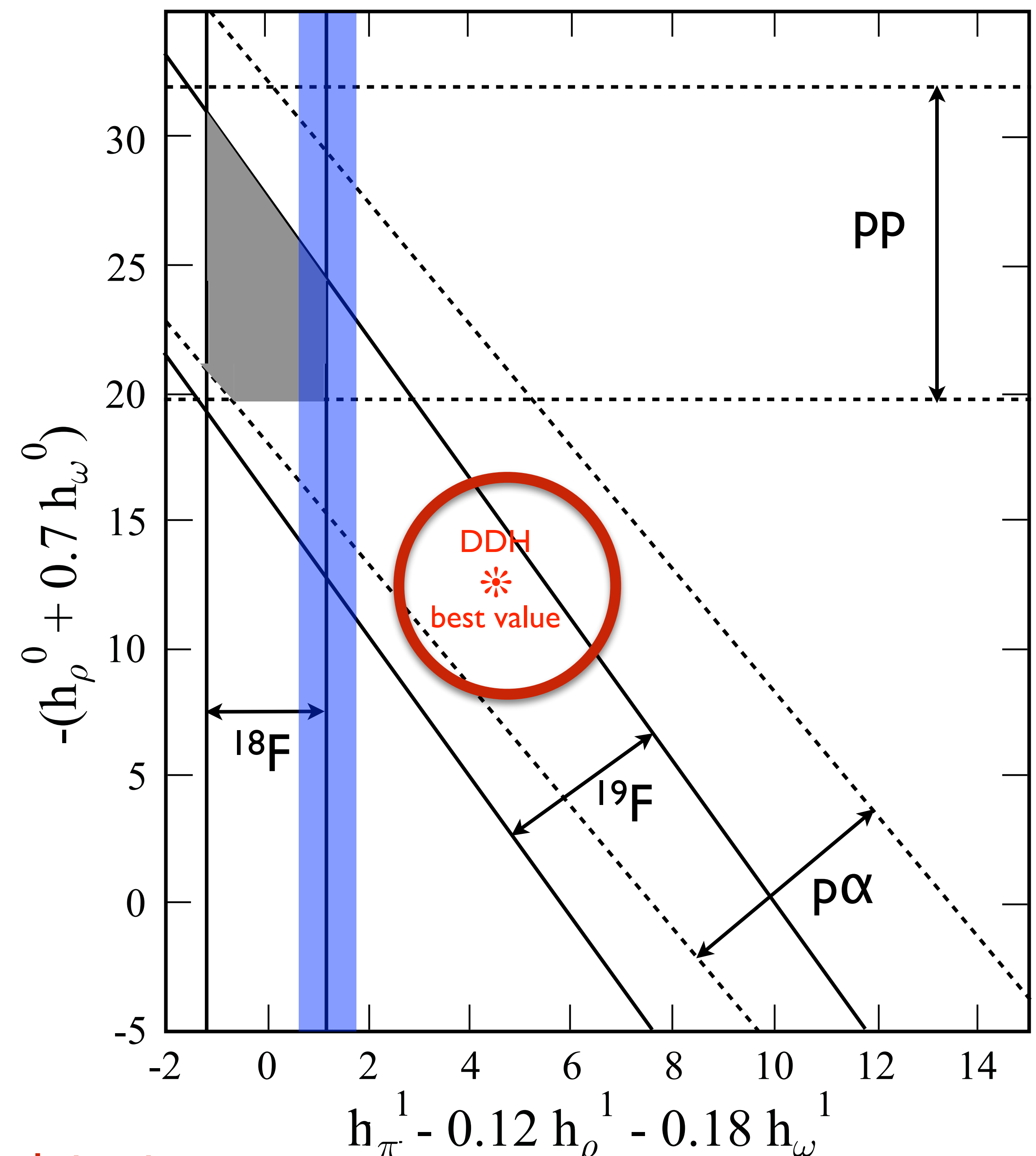




A simplified 5→2 projection, guided by meson-exchange theory

Another has come from combining calculations of different types, vintages





A simplified 5→2 projection, guided by meson-exchange theory: but proved inconsistent

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

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

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

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

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

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

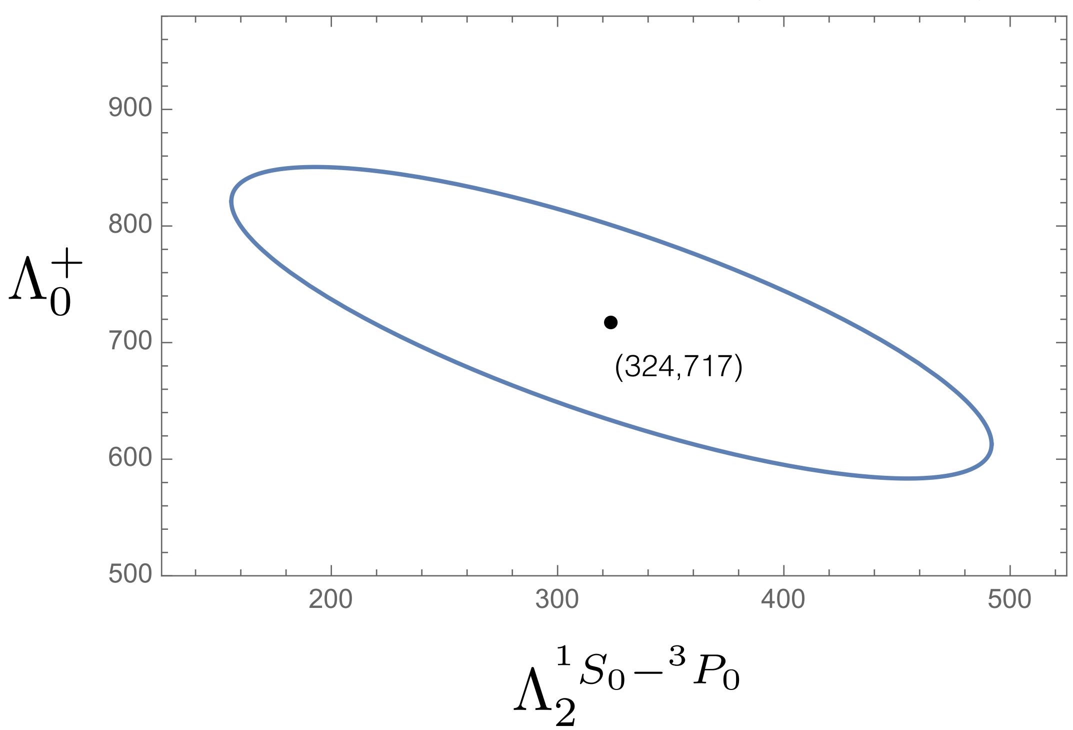
One area of conflict with DDH "best values"

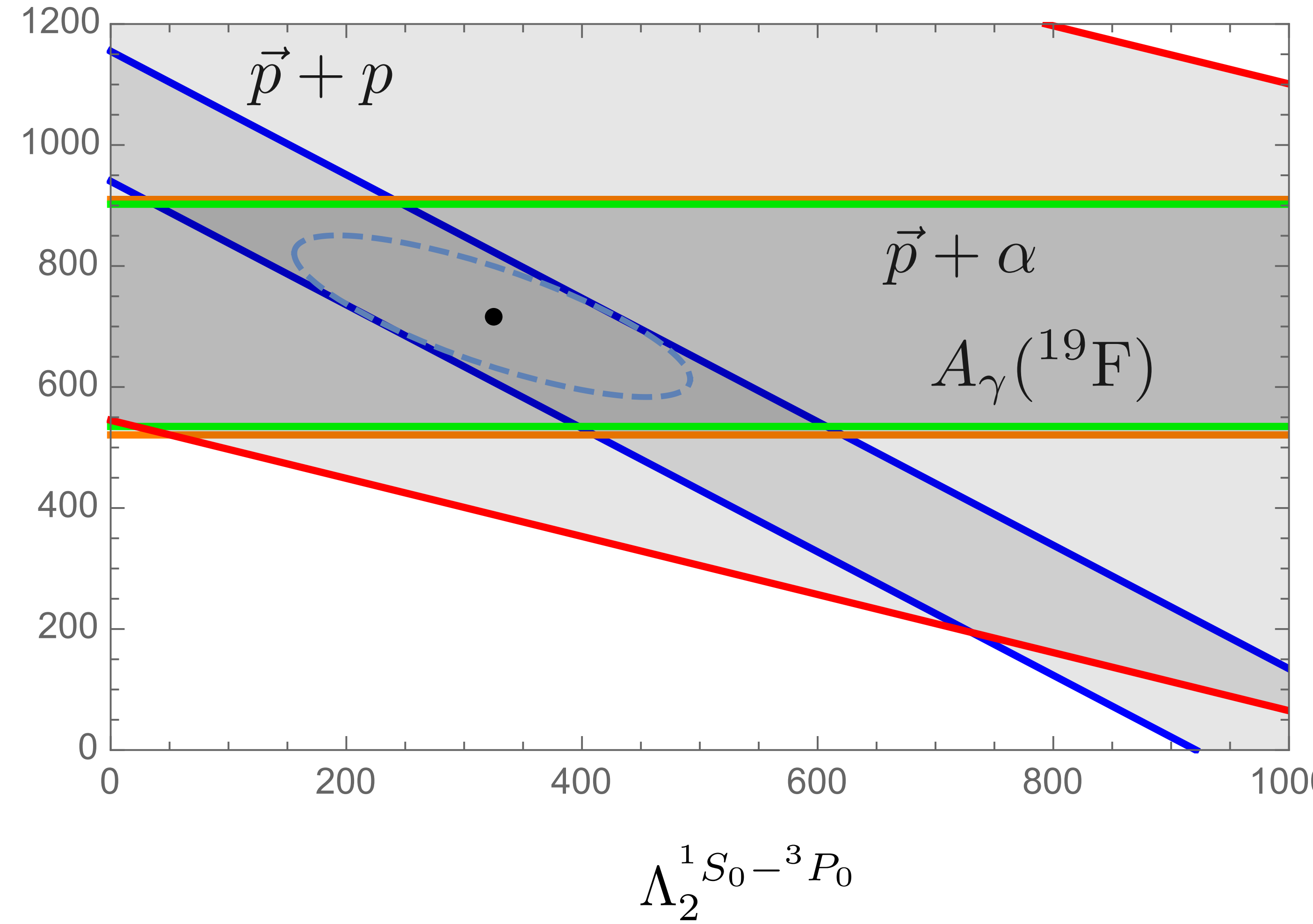
$$\left\{ \begin{array}{c} {}^{\mathrm{DDH}}\Lambda_0^+ \\ {}^{\mathrm{DDH}}\Lambda_2^{{}^1S_0-{}^3P_0} \end{array} \right\} = \left\{ \begin{array}{c} 319 \\ 151 \end{array} \right\} \qquad \left\{ \begin{array}{c} {}^{\mathrm{DDH}}\Lambda_0^- \\ {}^{\mathrm{DDH}}\Lambda_1^{{}^1S_0-{}^3P_0} \\ {}^{\mathrm{DDH}}\Lambda_1^{{}^3S_1-{}^3P_1}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

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

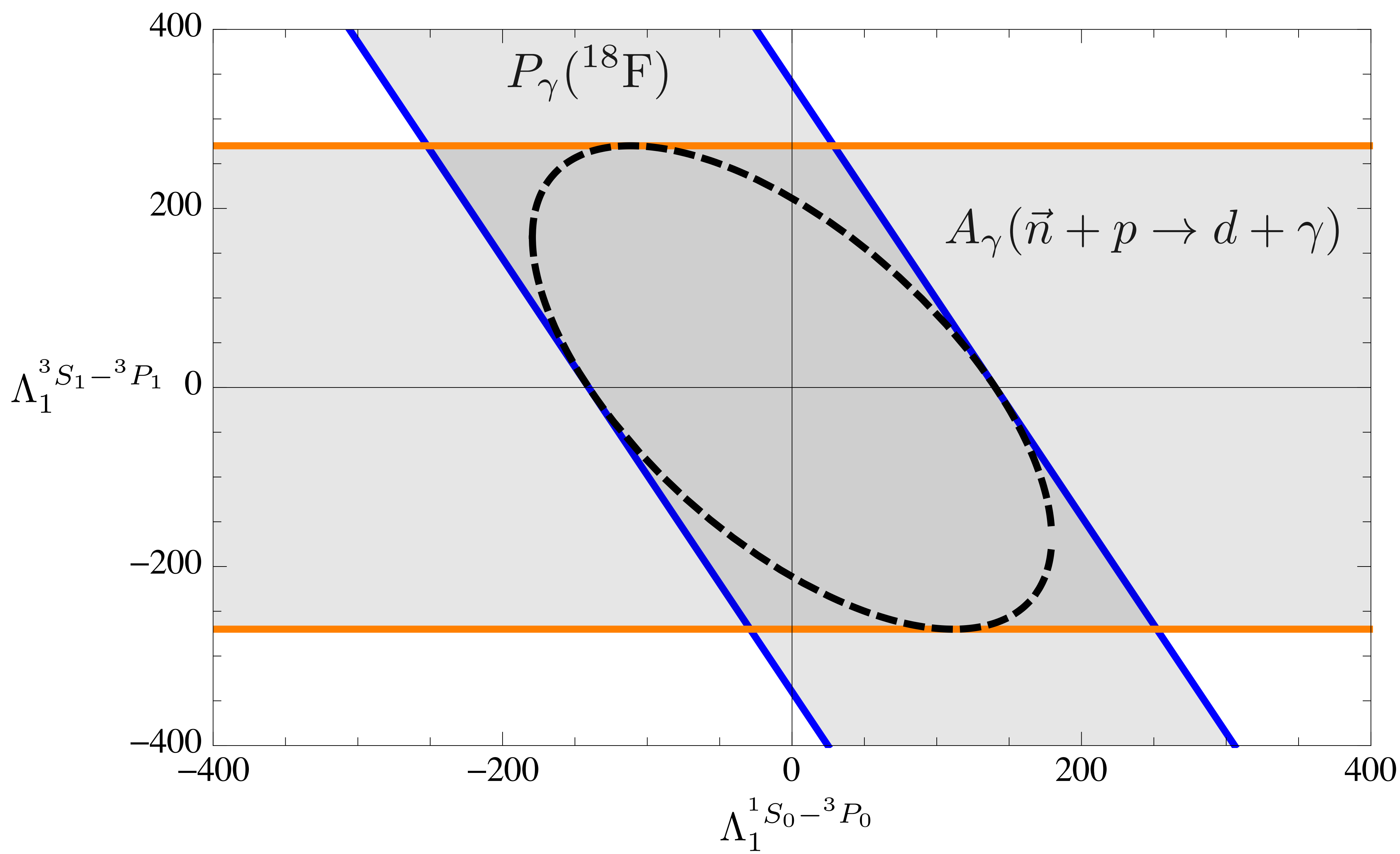
LO theory consistent with experiment

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





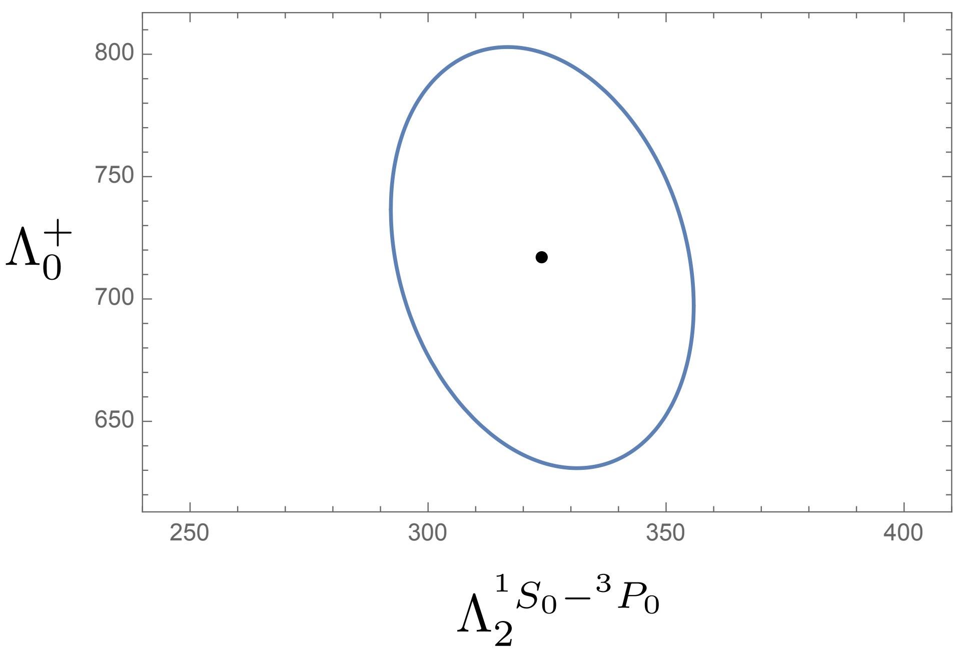
NNLO couplings: alters the relationship between ^{18}F, NPDGamma

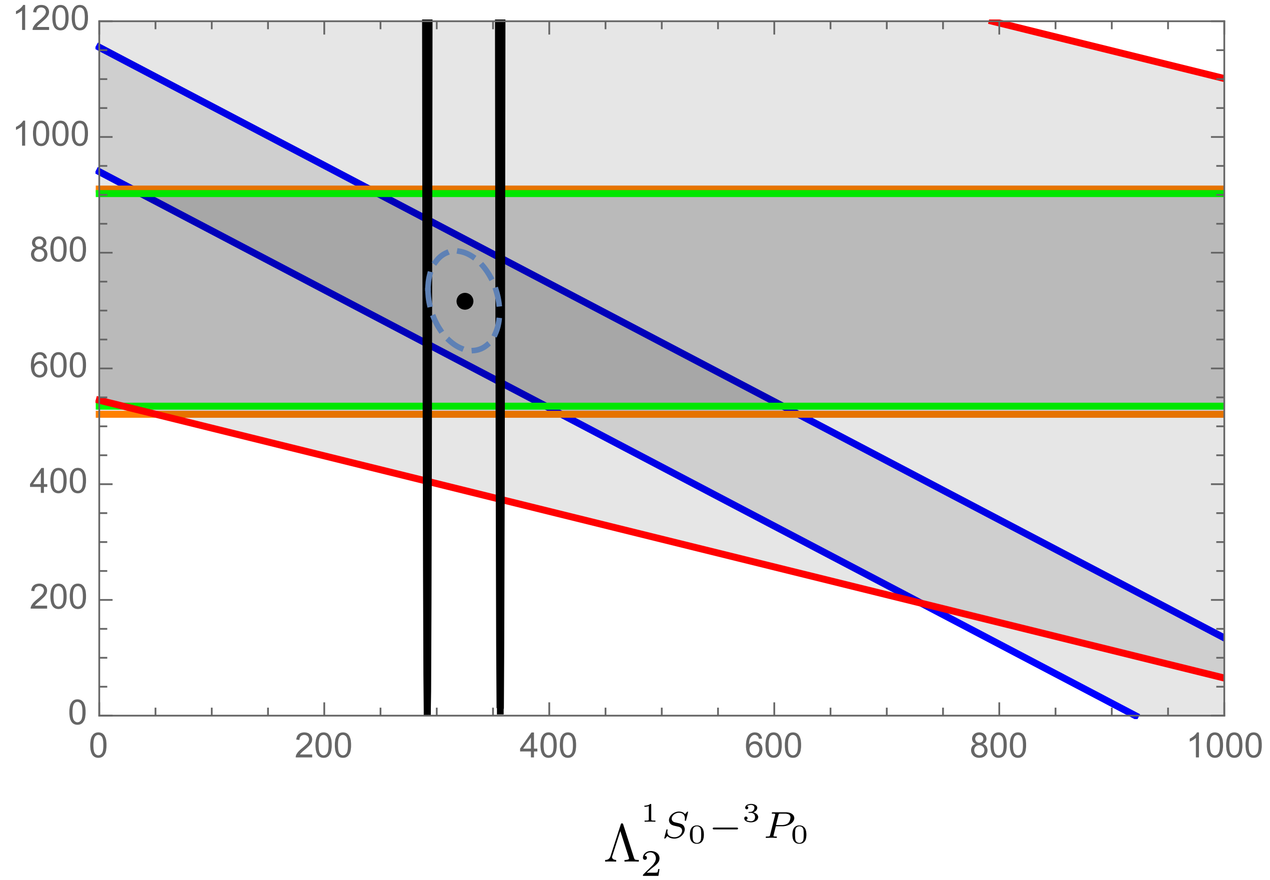


Now complementary: nothing is learned about NNLO couplings without both

With things beginning to align, one can see the experimental path forward

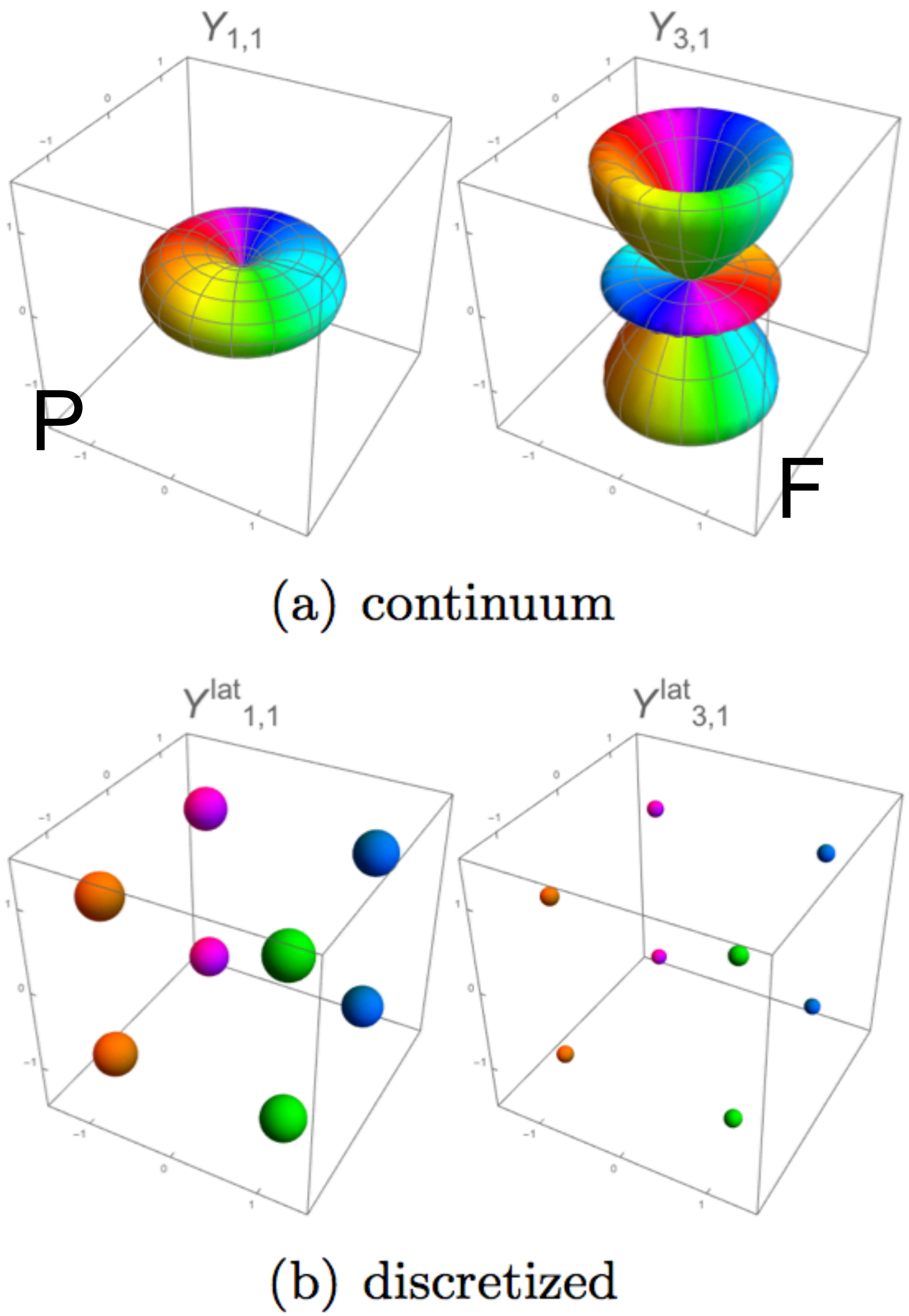
LO couplings: need a 10% measurement to complement $\vec{p} + p$



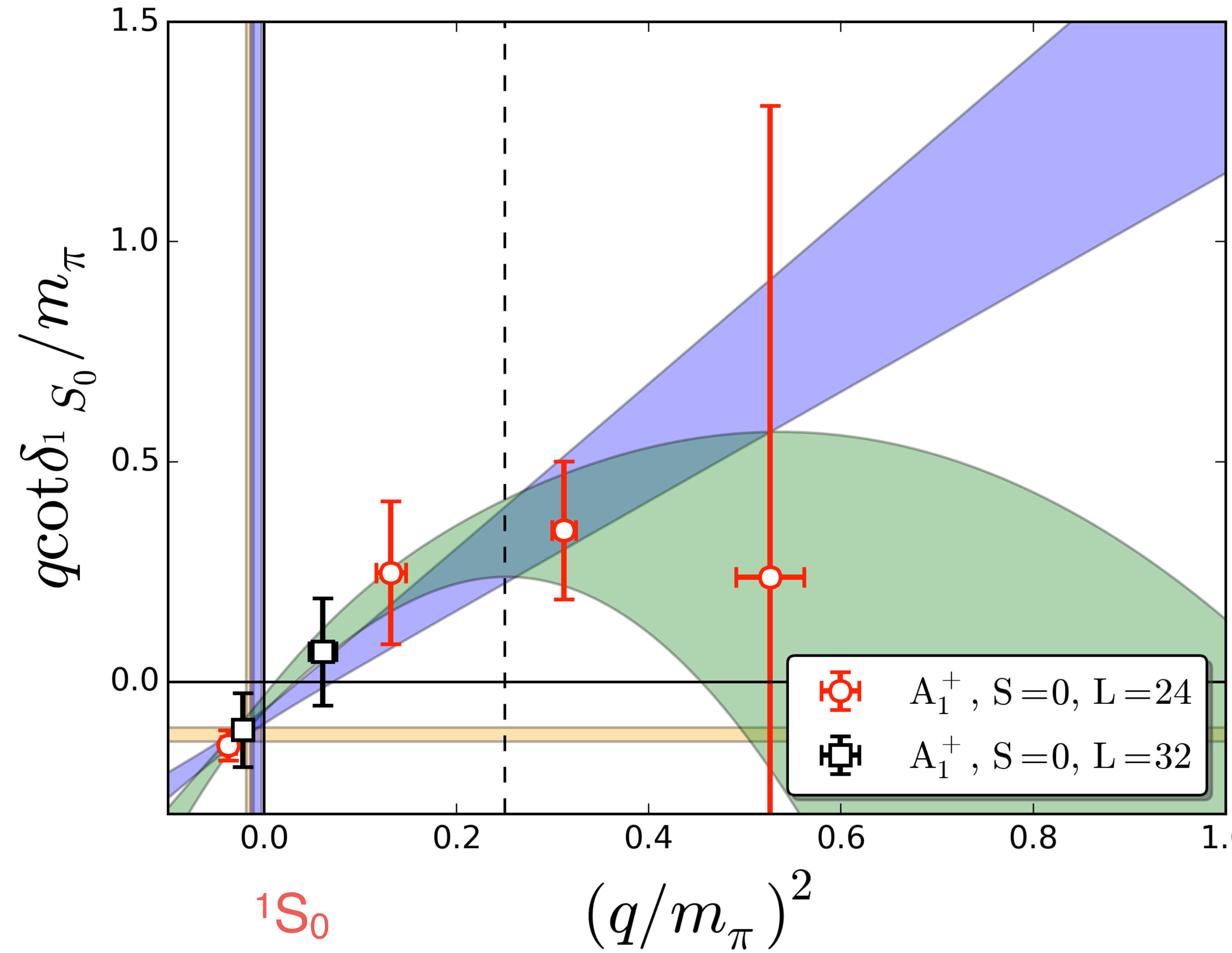


Impact of an LQCD calculation of the I=2 amplitude (Walker-Loud talk)

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



Cubic to rotational symmetry



$^1S_0$

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

Alternatively, can one of the existing odd-proton measurements be improved?

$$A_L(\vec{\mathrm{p}} + {}^4\,\mathrm{He}): \quad (-3.34 \pm 0.9) \times 10^{-7}$$

Lang et al., 1985
1.3 μA polarized beam
factor of 2.5 improvement?

$$A_\gamma({}^{19}\mathrm{F}) = \begin{cases} (-8.5 \pm 2.6) \times 10^{-5} \\ (-6.8 \pm 1.8) \times 10^{-5} \end{cases}$$

Seattle 1983
Zurich 1987

statistics limited
systematics ok at 10% level
0.4 μA 5 MeV polarized p beam

Significant improvements in the theory possible, as well

or pursue "new" experiments sensitive to LO couplings

Observable	Exp. Status	LO Expectation
$A_{\rm p}(\vec{\rm n} + {}^3\,{\rm He} \to {}^3{\rm H+p})$	ongoing	-1.8×10^{-8}
$A_\gamma(\vec{\rm n} + {\rm d} \to {\rm t} + \gamma)$	8×10^{-6}	7.3×10^{-7}
$P_\gamma({\rm n} + {\rm p} \to {\rm d} + \gamma)$	$(1.8 \pm 1.8) \times 10^{-7}$	1.4×10^{-7}
$\frac{d\phi^{\rm n}}{dz}\big\vert_{\rm parahydrogen}$	none	9.4×10^{-7} rad/m
$\frac{d\phi^{\rm n}}{dz}\big\vert_{^4{\rm He}}$	$(1.7 \pm 9.1 \pm 1.4) \times 10^{-7}$	6.8×10^{-7} rad/m
$A_L(\vec{\rm p} + {\rm d})$	$(-3.5 \pm 8.5) \times 10^{-8}$	-4.6×10^{-8}

Table 4: As in the previous table, but with the observable normalized as shown, then decomposed into its LO and NNLO contributions.

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

Summary and Workshop Goals

- HPNC progress over the past three decades has until recently been slow
  - only a few new experimental results
  - idea of selecting two LO couplings — isoscalar and h_π^1 — ran into the problem of a small h_π^1

- The switch to the large-N_c LO couplings $\Lambda_0^+,\ \Lambda_2$ appears to work well
  - based on reasonable theoretical arguments
  - consistent with previous work in that the iso scalar coupling is about twice DDH, but consistent with DDH broad reasonable range
  - Λ_2 is also somewhat larger than given by the DDH range
  - this I=2 coupling was "marginalized," in treating p+p

- This progress coincides with the advent of high flux cold neutron beams
  - so one can envision a period of rapid progress

Where do we go from here?

Theory

- formulas for relating observables to LECs vary greatly in their vintage and quality
  - e.g., $\vec{p} +^4 \mathrm{He}$

- we lack the analog of the cosmological "vanilla" model ΛCDM — a common baseline that allows us to combine results with confidence
  - different strong potentials
  - different treatments of the weak potential, e.g., the Bonn vs. DDH strong coupling differences that confused the analysis of $\vec{p} + p$

- ^{18}F,^{19}F remain important constraints
  - the axial-charge beta decay trick should yield "nucleon level" couplings
  - but a lot more could be done *today* to test the approach (C Johnson)

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

Appropriate for low-energy applications, but $\boldsymbol{\nabla}$ ill behaved at high q

Possibility: exploit the DDH potential $\leftrightarrow$ EFT equivalence to form the
“vanilla model”

$$
\begin{aligned}
V^{\mathrm{PNC}}_{DDH}(\vec{r}) = {} & i\frac{h^1_\pi g_{\pi NN}}{\sqrt{2}}\left(\frac{\vec{\tau}_1\times\vec{\tau}_2}{2}\right)_z(\vec{\sigma}_1+\vec{\sigma}_2)\cdot\left[\frac{\vec{p}_1-\vec{p}_2}{2m_N},w_\pi(r)\right] \\
& -g_\rho\left(h^0_\rho\vec{\tau}_1\cdot\vec{\tau}_2+h^1_\rho\left(\frac{\vec{\tau}_1+\vec{\tau}_2}{2}\right)_z+h^2_\rho\frac{(3\tau^z_1\tau^z_2-\vec{\tau}_1\cdot\vec{\tau}_2)}{2\sqrt{6}}\right) \\
& \quad\times\left((\vec{\sigma}_1-\vec{\sigma}_2)\cdot\left\{\frac{\vec{p}_1-\vec{p}_2}{2m_N},w_\rho(r)\right\}\right. \\
& + \left. i(1+\chi_V)\vec{\sigma}_1\times\vec{\sigma}_2\cdot\left[\frac{\vec{p}_1-\vec{p}_2}{2m_N},w_\rho(r)\right]\right) \\
& -g_\omega\left(h^0_\omega+h^1_\omega\left(\frac{\vec{\tau}_1+\vec{\tau}_2}{2}\right)_z\right) \\
& \quad\times\left((\vec{\sigma}_1-\vec{\sigma}_2)\cdot\left\{\frac{\vec{p}_1-\vec{p}_2}{2m_N},w_\omega(r)\right\}\right. \\
& + \left. i(1+\chi_S)\vec{\sigma}_1\times\vec{\sigma}_2\cdot\left[\frac{\vec{p}_1-\vec{p}_2}{2m_N},w_\omega(r)\right]\right) \\
& +\left(\frac{\vec{\tau}_1-\vec{\tau}_2}{2}\right)_z(\vec{\sigma}_1+\vec{\sigma}_2)\cdot\left(g_\rho h^1_\rho\left\{\frac{\vec{p}_1-\vec{p}_2}{2m_N},w_\rho(r)\right\}-g_\omega h^1_\omega\left\{\frac{\vec{p}_1-\vec{p}_2}{2m_N},w_\omega(r)\right\}\right)
\end{aligned}
$$

<u>A candidate interaction:</u>

uses DDH potential to predict P-D and higher partial waves

effectively determined by our large-Nc LECs

one additional degree of freedom chosen to be $0 < -g_\rho h^1_\rho < 0.106$ as DDH predicts a very small value

PLUS say av18 for all strong wave functions

$$
g_\rho h^0_\rho = -\frac{2}{5}\frac{(3+2\chi_S)\Lambda^+_0+(1-\chi_S)\Lambda^-_0}{\chi_S+3\chi_V+2\chi_S\chi_V} \qquad g_\omega h^0_\omega = \frac{2}{5}\frac{3\Lambda^+_0+(1+5\chi_V)\Lambda^-_0}{\chi_S+3\chi_V+2\chi_S\chi_V} \qquad g_\rho h^2_\rho = -\frac{\Lambda_2^{^1S_0-^3P_0}}{2+\chi_V}
$$

$$
g_\pi h^1_\pi = \frac{\sqrt{2}m^2_\pi}{(2+\chi_S)m^2_\rho}\left(\Lambda_1^{^1S_0-^3P_0}-(2+\chi_S)\Lambda_1^{^3S_1-^3P_1}+(\chi_S-\chi_V)g_\rho h^1_\rho\right)
$$

$$
g_\omega h^1_\omega = \frac{1}{2+\chi_S}\left(-\Lambda_1^{^1S_0-^3P_0}+(2+\chi_V)g_\rho h^1_\rho\right)
$$

Where do we go from here?

Experiments

- testing LO couplings at 10%
  - LQCD $\Delta I = 2$
  - ^{19}F or $\vec{p} + {}^4\,\mathrm{He}$ improvements
  - new experiments like $\vec{n} + {}^3\,\mathrm{He}$

- testing the NNLO couplings
  - lovely complementarity of ^{18}F and $\vec{n} + p \to d + \gamma$
  - impact of new neutron beams

Our challenge here: identifying the opportunities

Proposal: An effort for HPNC analogous to Solar Fusion I & II

This workshop

- decide on the format for such a study — the optimal structure of a white paper
- form the necessary working groups
- perform the necessary work
- draft a document

Our mission, should we decide to accept it…

Solar Fusion: important update for the field
helped to focus future work
had impact: 500 and 800 citations

RMP would be interested in publishing a similar document for HPNC