Wick Haxton, UC Berkeley and LBL

Large N_c HPNC Analyses post NPDGamma

13th Conference on the Intersections of Particle and Nuclear Physics

<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

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

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

↕ ΔI=1 ↕ ΔI=1/2

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

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

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↕ ↕

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

↕ ↕

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

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

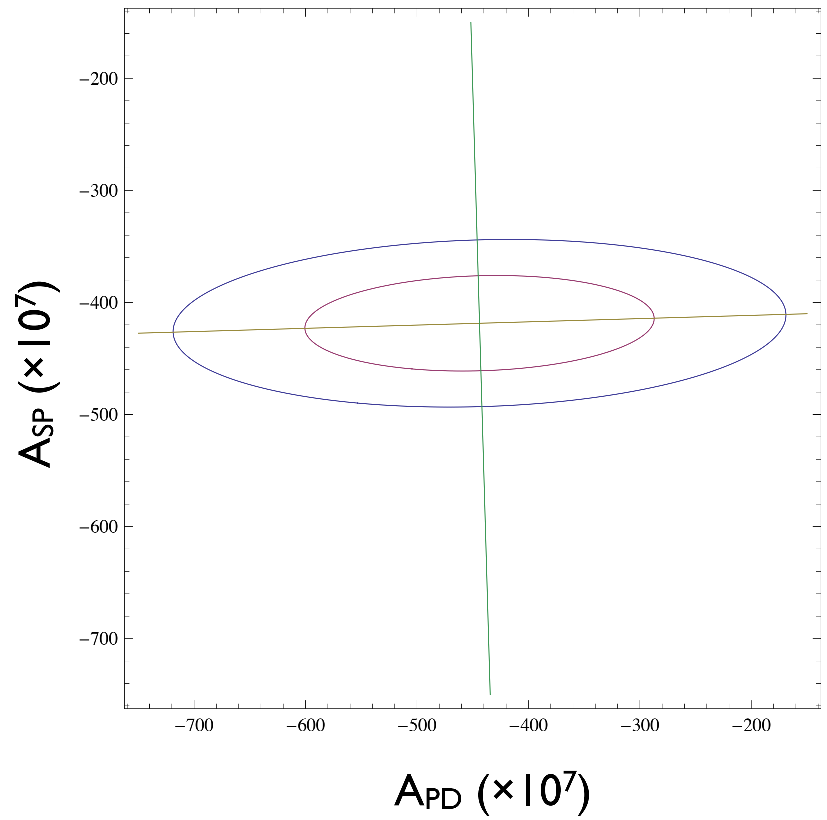
and $1/N_c$ approaches
- D. Phillips, D. Samart, and C. Schat, PRL 114 (2015) 062301
- M. R. Schindler, R. P. Springer, and J. Vanasse, PRC 93 (2016) 025502

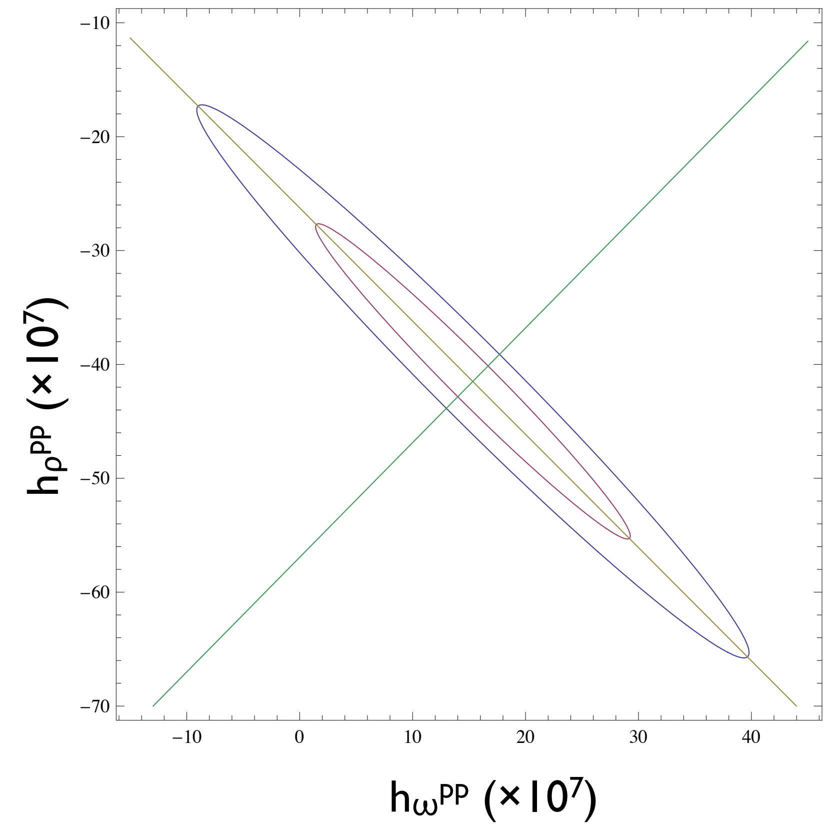
Coeff	DDH	Girlanda	Zhu
$\Lambda_{0\ DDH}^{1S_0-3P_0}$	$-g_\rho h_\rho^0(2+\chi_V) - g_\omega h_\omega^0(2+\chi_S)$	$2(\mathcal{G}_1+\tilde{\mathcal{G}}_1)$	$2(\mathcal{C}_1+\tilde{\mathcal{C}}_1+\mathcal{C}_3+\tilde{\mathcal{C}}_3)$
$\Lambda_{0\ DDH}^{3S_1-1P_1}$	$g_\omega h_\omega^0\chi_S - 3g_\rho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

Lack of data has been one challenge

$\vec{p}+p$ asymmetry:

at 13.6, 45, 221 MeV





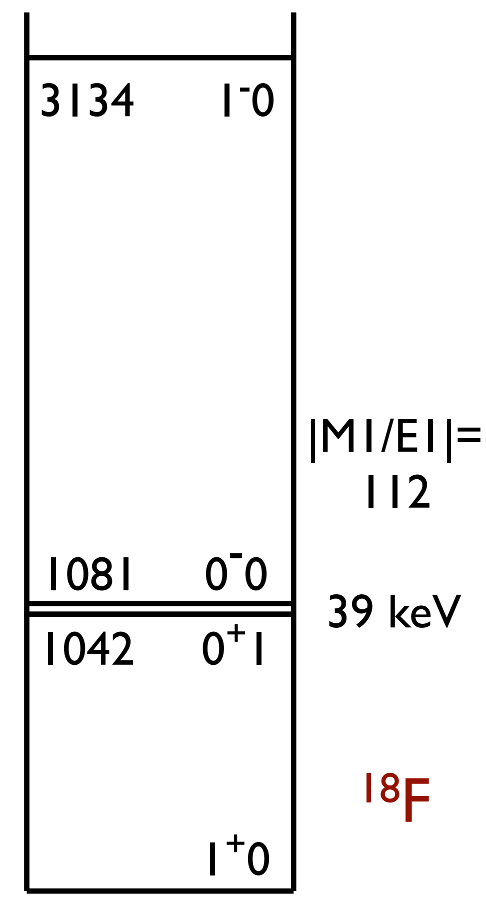
some of the most reliable constraints

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

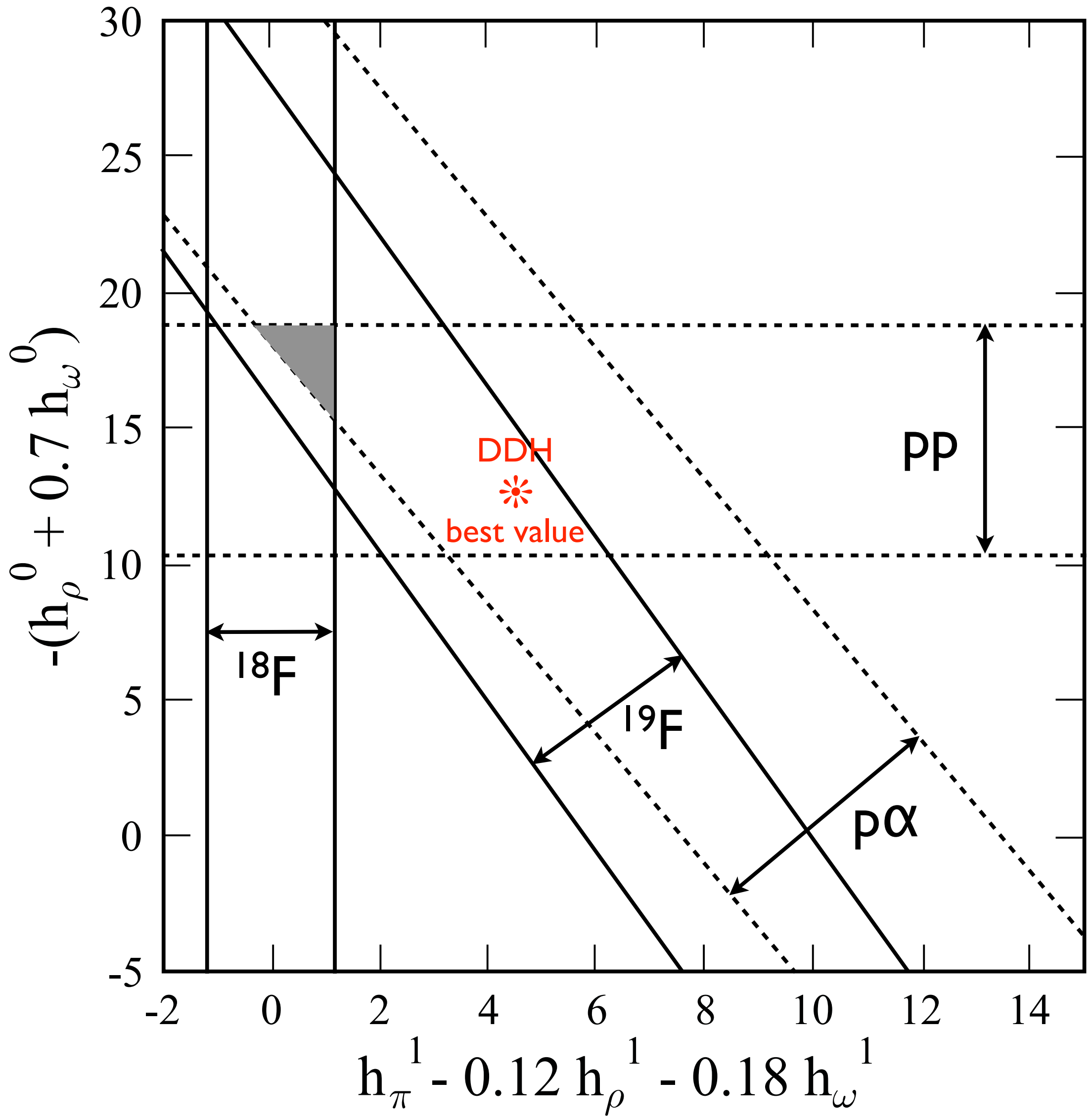
$$A_L^{\vec{p}+\alpha}(46\,\mathrm{MeV}) = (-3.34 \pm 0.93) \times 10^{-7}$$

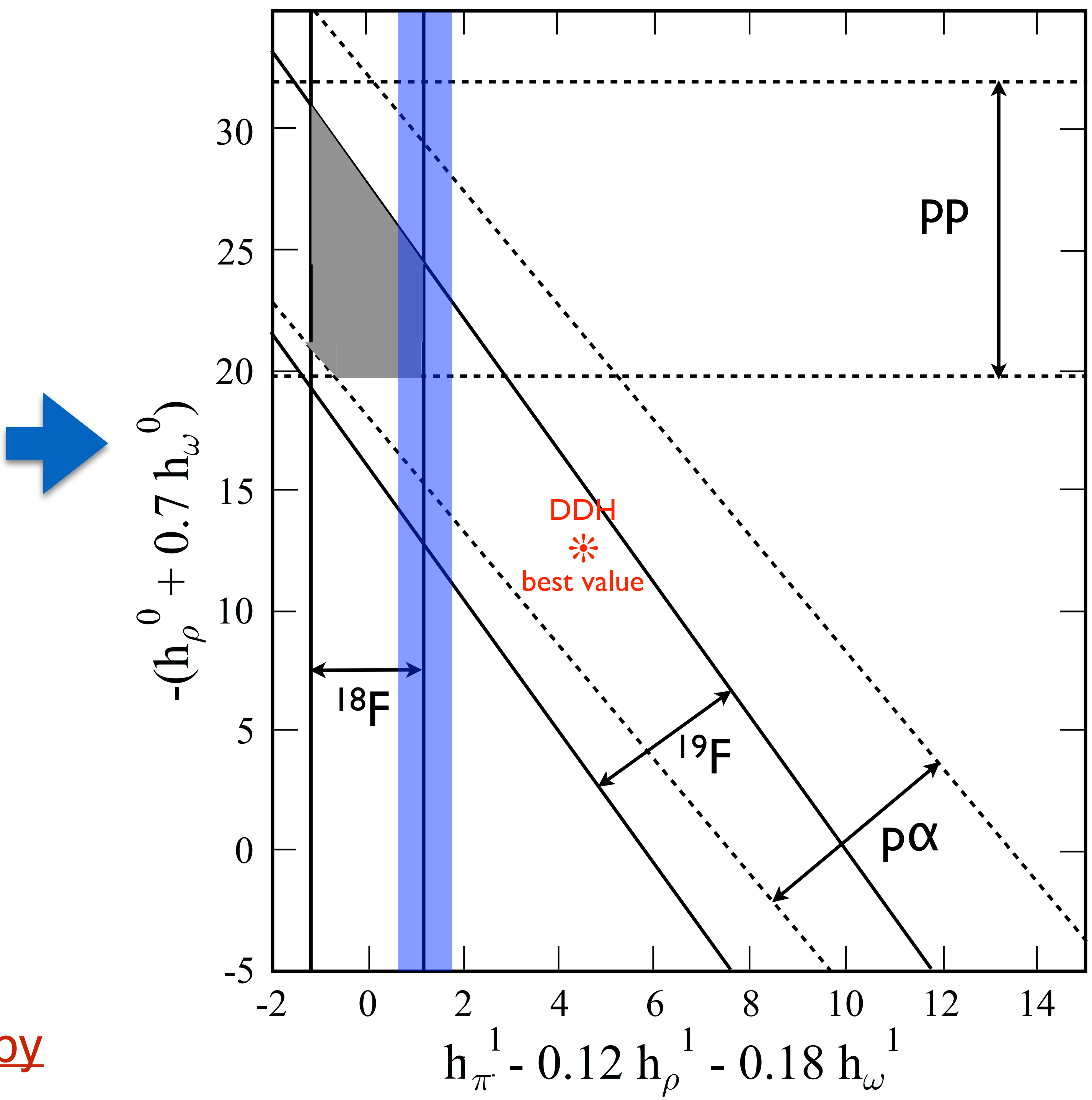
$$P_\gamma^{^{18}\mathrm{F}}(1081\,\mathrm{keV}) = (12 \pm 38) \times 10^{-5}$$

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



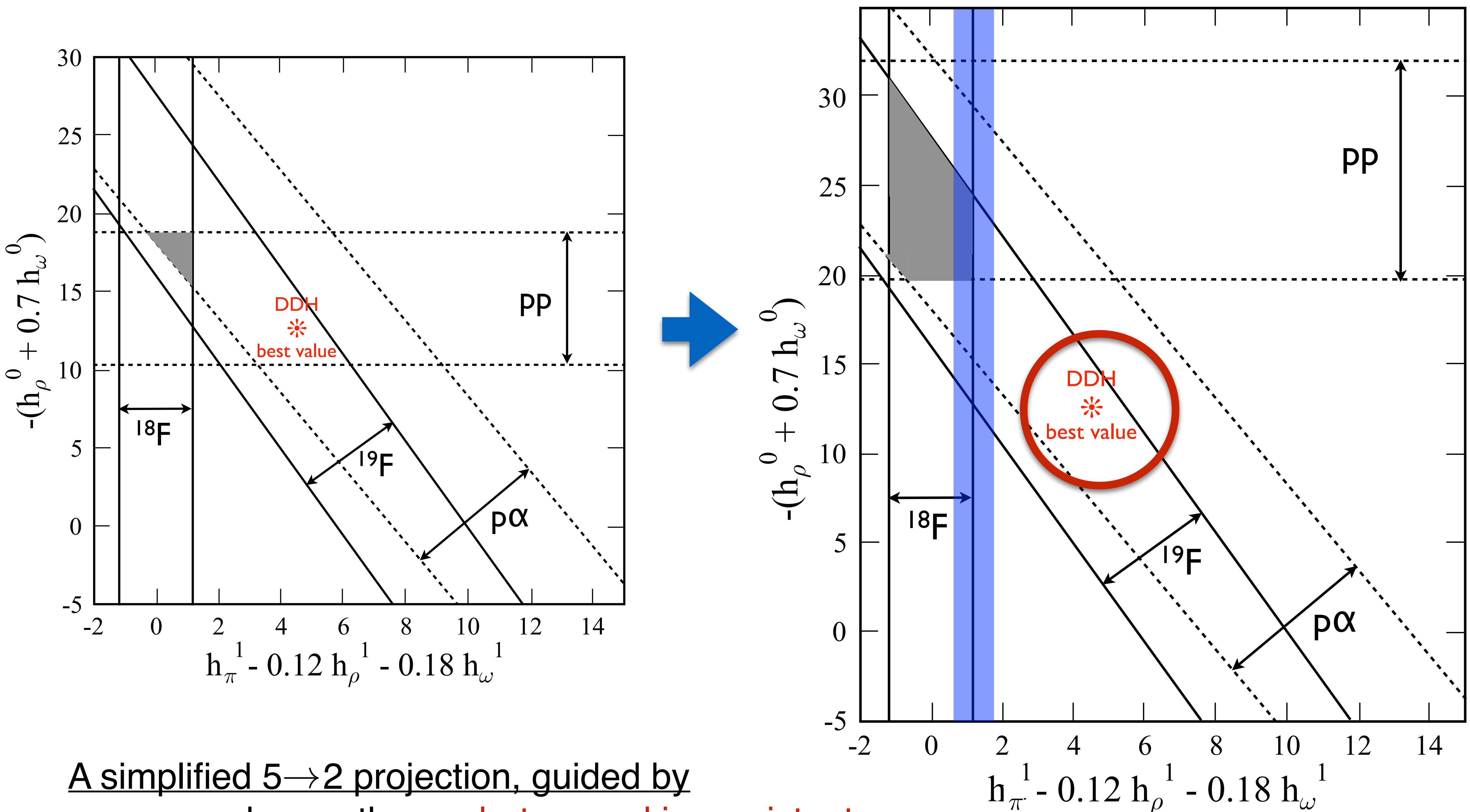
Another has been the need to combine calculations of different types, vintages





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

Effectively the isoscalar/isovector 2D projection collapses to 1D

The alternative offered by the large Nc analysis argues for a different projection — onto a space spanned by one isoscalar interaction and one isotensor

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

Schindler et al.

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

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

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

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

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

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

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

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

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

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

$$\Lambda_1^{^3S_1-^3P_1} = 810 \pm 380 \qquad A_\gamma(\vec{\mathrm{n}}\mathrm{p} \to \mathrm{d}\gamma)$$

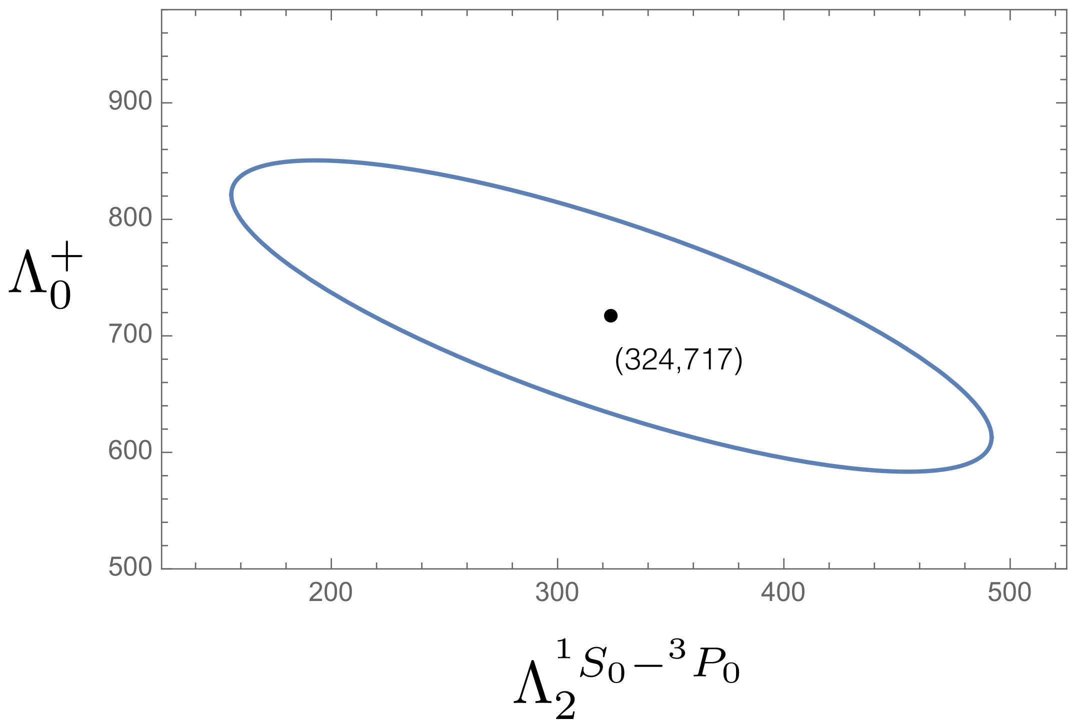
Prior to NPDGamma more severe conflict with DDH "best values"

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

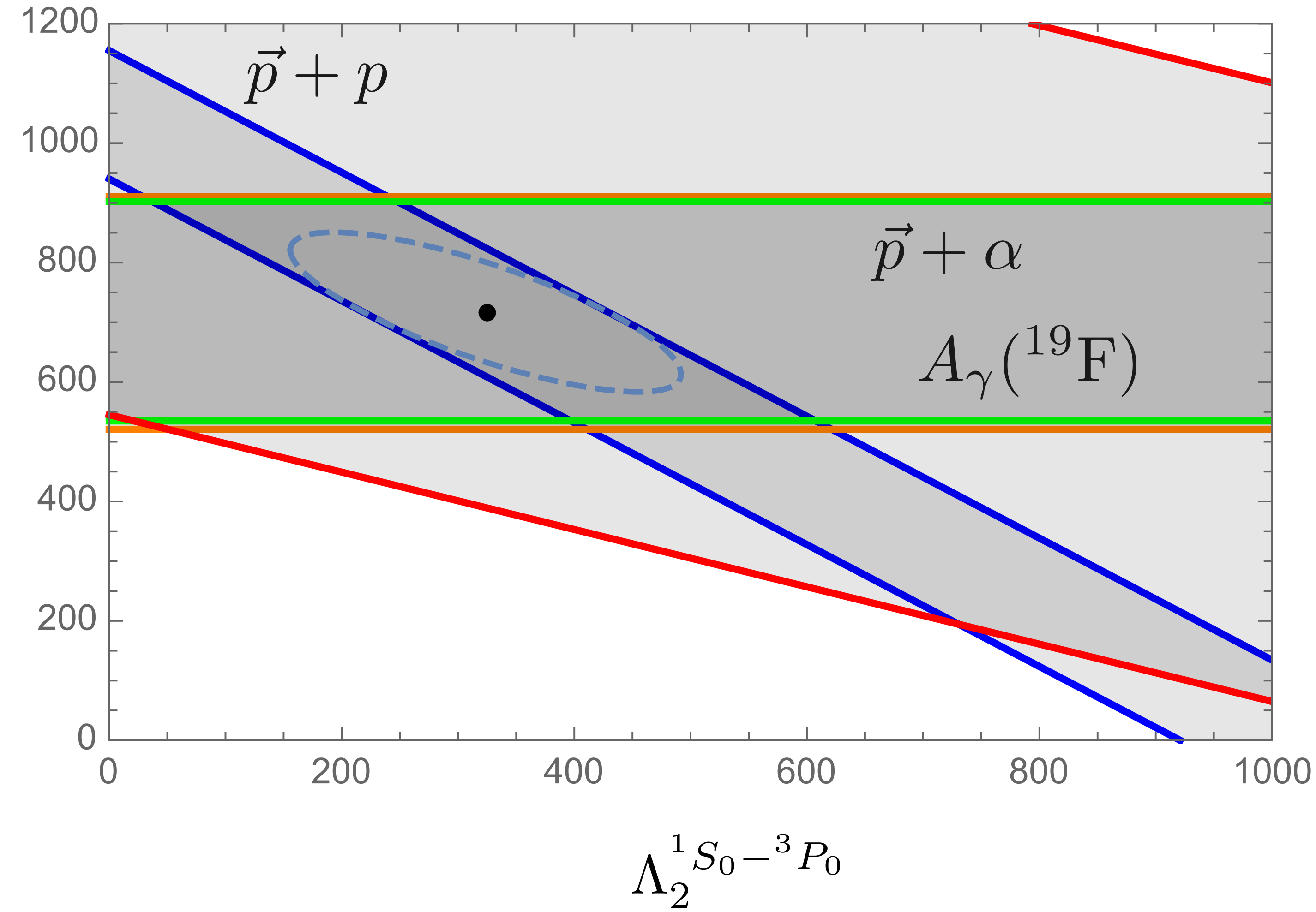
Also consistent with old conclusion that isoscalar strength is about twice DDH

LO theory consistent with experiment

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



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



After NPDGamma conflict with DDH “best values” somewhat mitigated

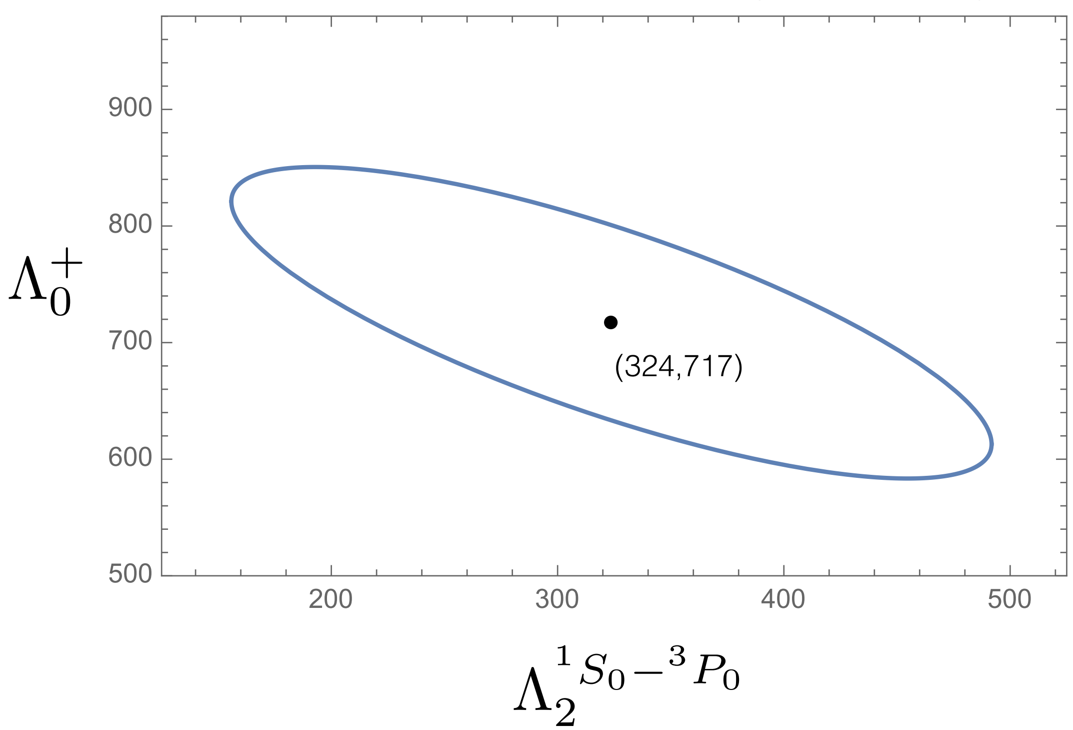
$$\left\{\begin{array}{c} {}^{\mathrm{DDH}}\Lambda_0^+ \\ {}^{\mathrm{DDH}}\Lambda_2^{{}^1S_0-{}^3P_0} \end{array}\right\} = \left\{\begin{array}{c} 319 \\ 151 \end{array}\right\} \qquad \left\{\begin{array}{c} {}^{\mathrm{DDH}}\Lambda_0^- \\ {}^{\mathrm{DDH}}\Lambda_1^{{}^1S_0-{}^3P_0} \\ {}^{\mathrm{DDH}}\Lambda_1^{{}^3S_1-{}^3P_1}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

~ 810

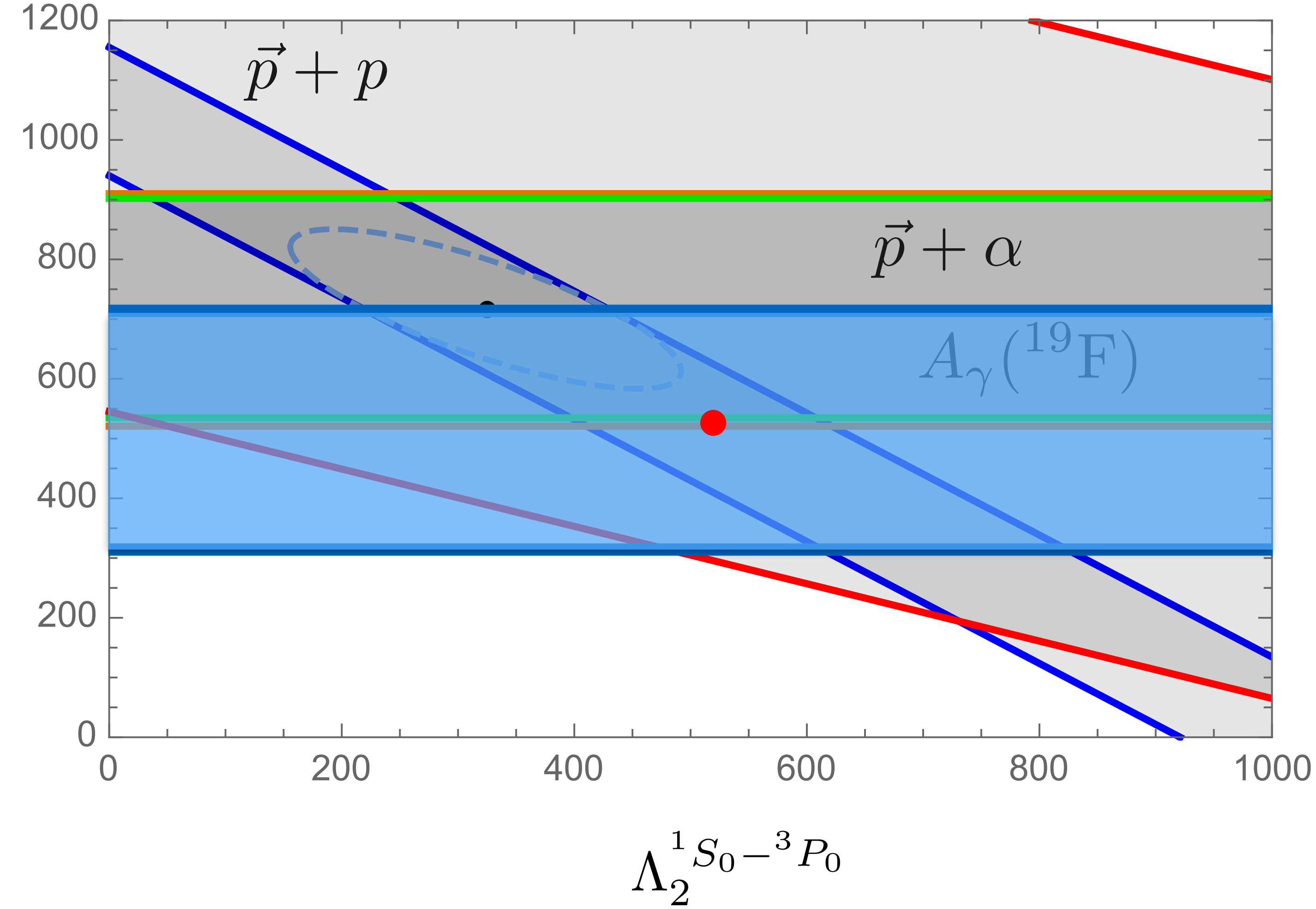
Also consistent with old conclusion that isoscalar strength is about twice DDH

LO theory consistent with experiment

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

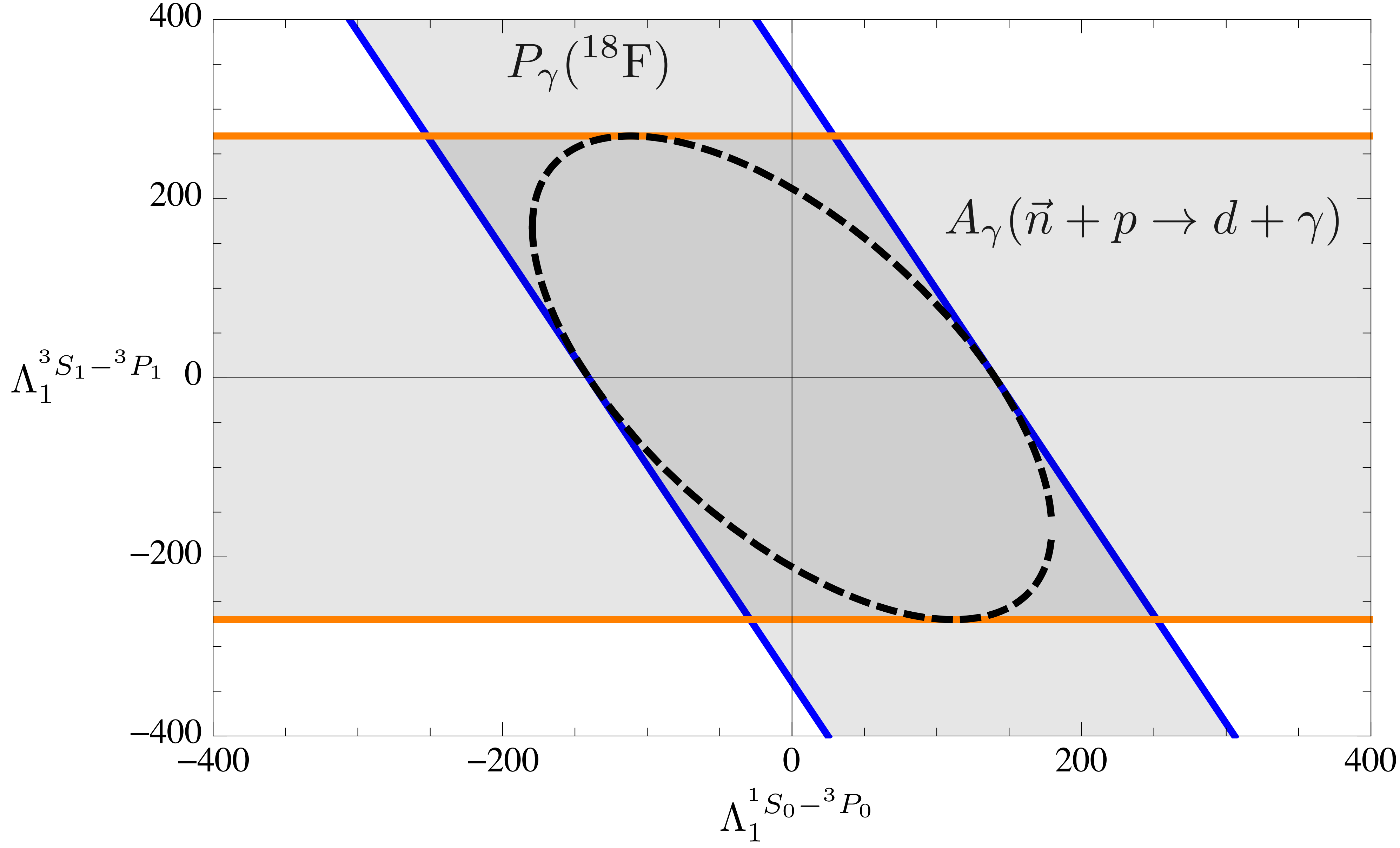


With NPDGamma constraint on NNLO corrections

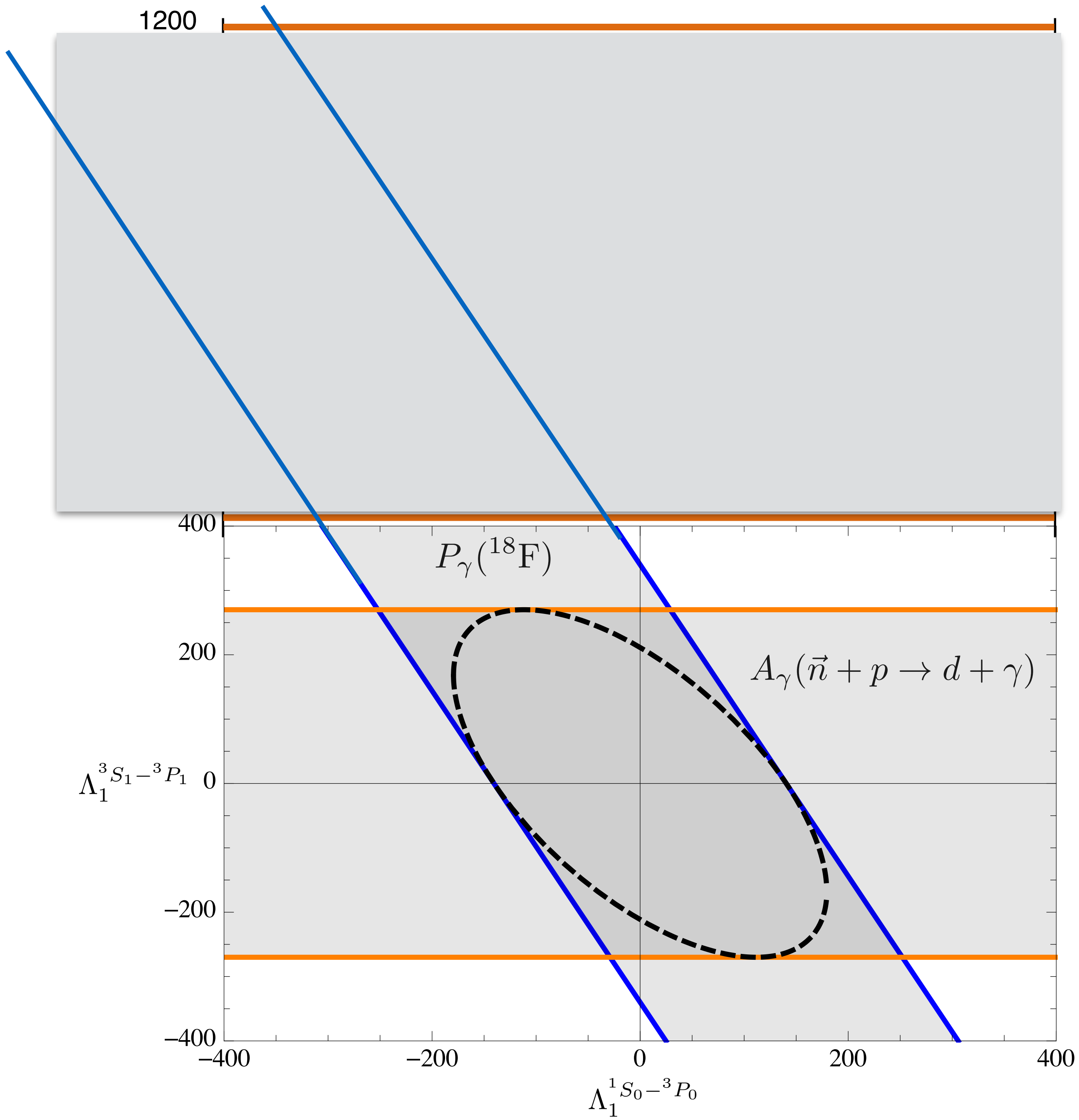


NNLO couplings: alters the relationship between ^{18}F, NPDGamma

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



Now complementary: nothing is learned about NNLO couplings without both

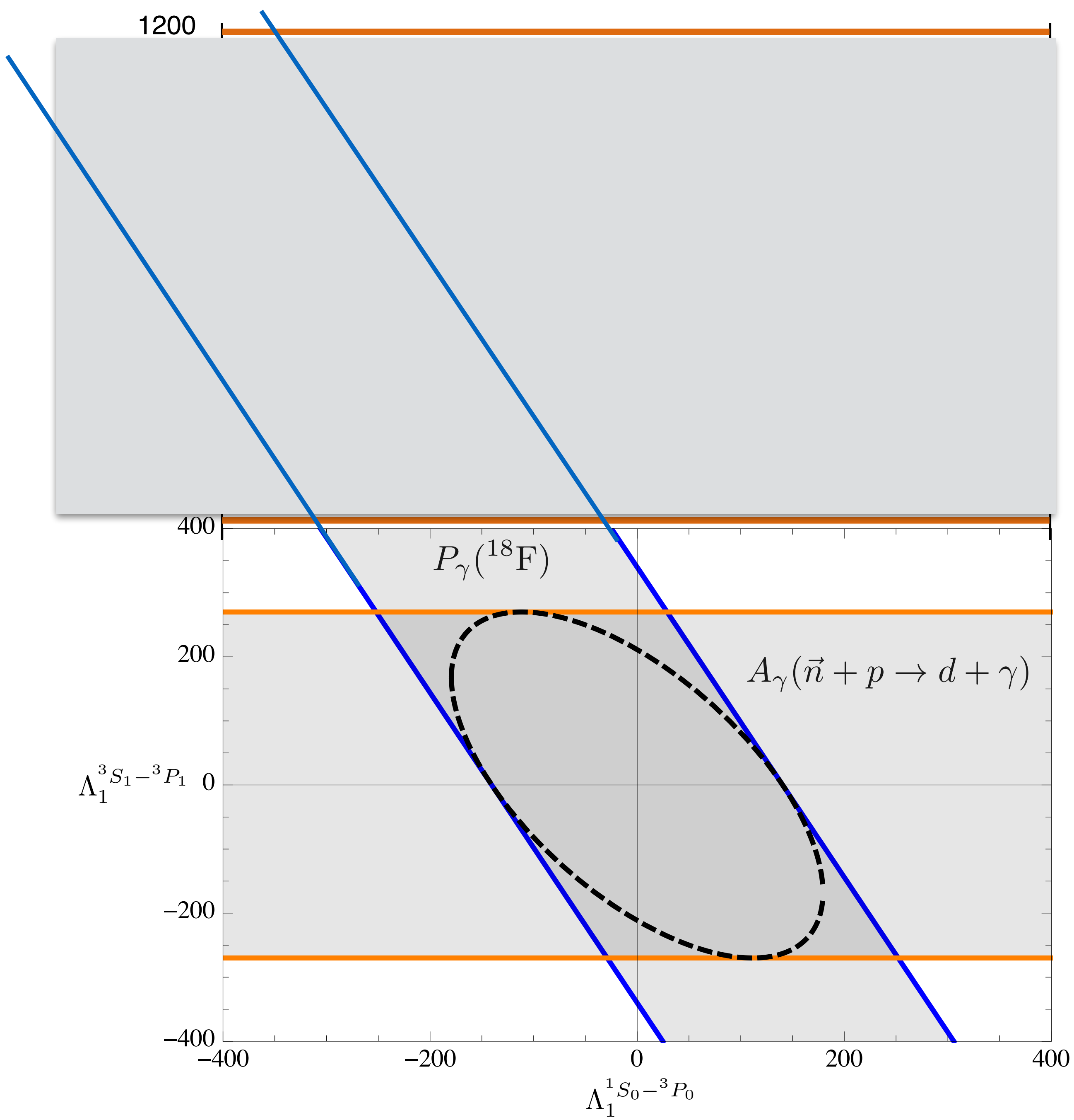


bottom line:

this preliminary analysis appears to delete much of the hierarchy of couplings that the large Nc analysis suggests

couplings generically ~ 500

18F drives $\Lambda_1^{{}^1S_0-{}^3P_0}$ negative, typically -325



bottom line:

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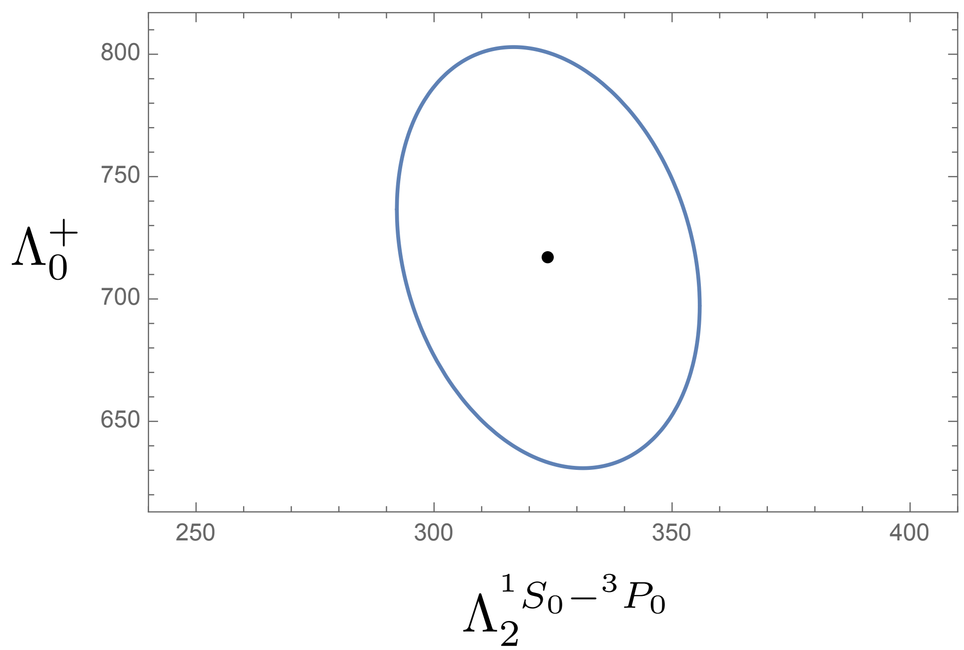
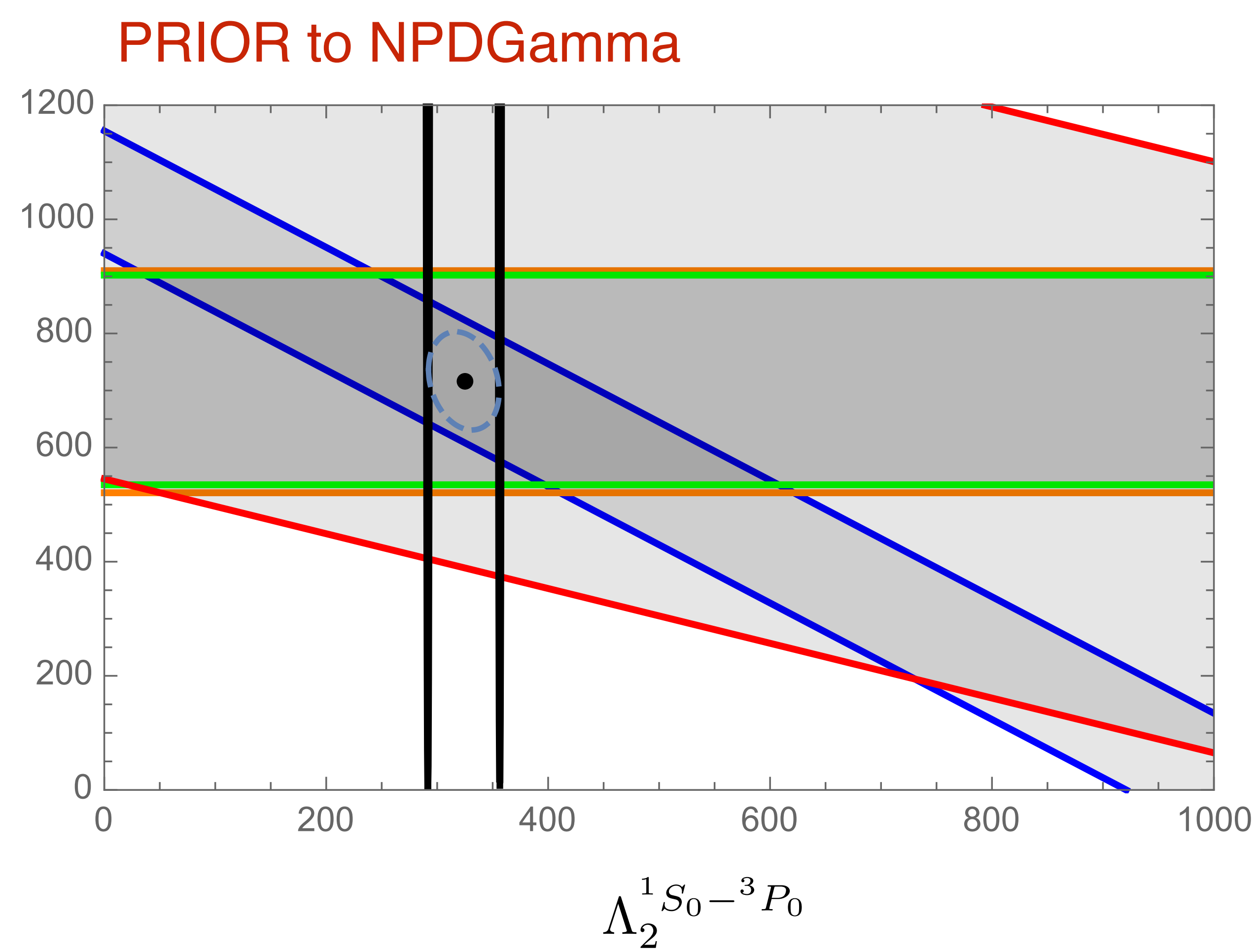
couplings generically ~ 500

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

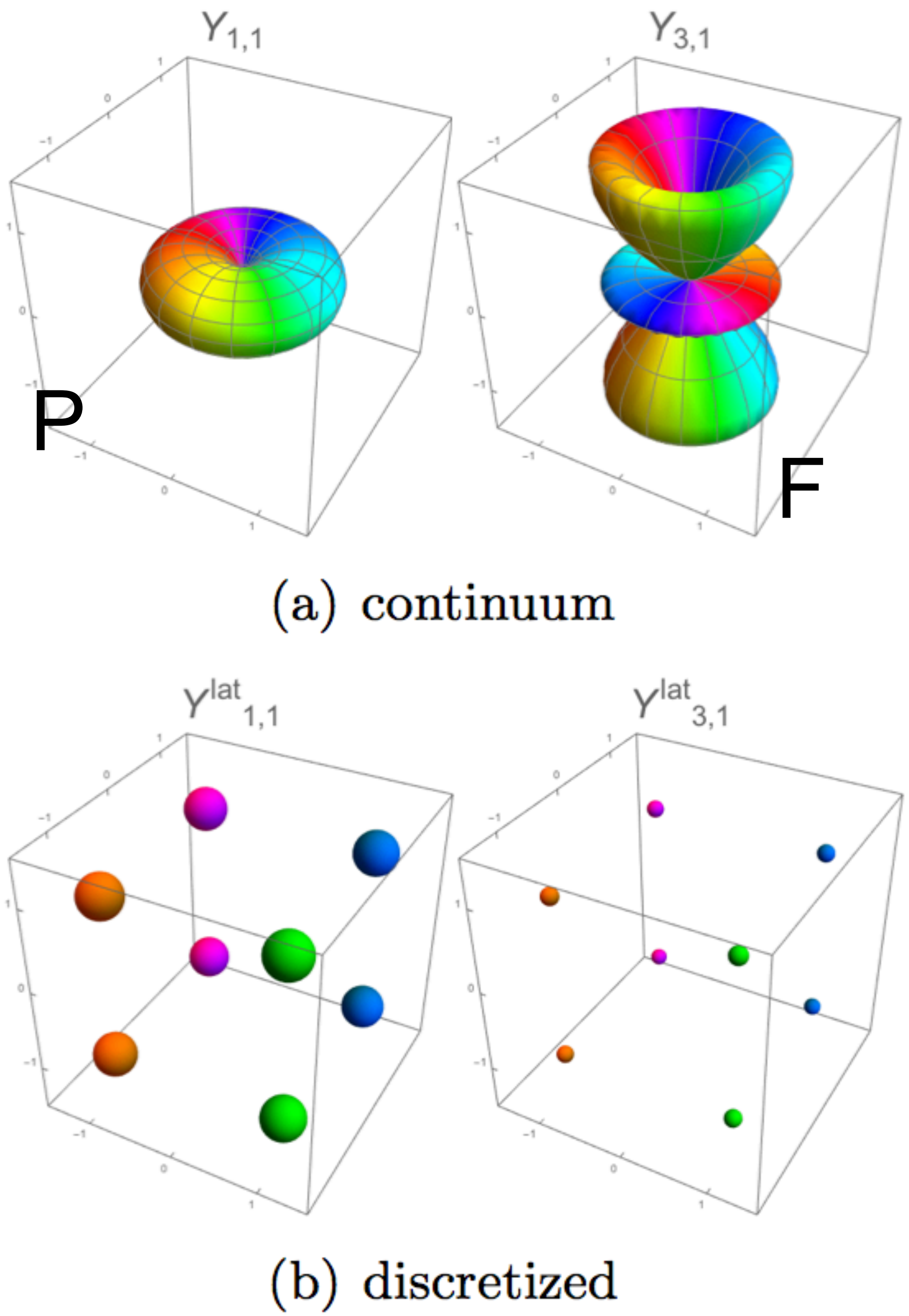
LO couplings: need a 10% measurement to complement $\vec{p} + p$



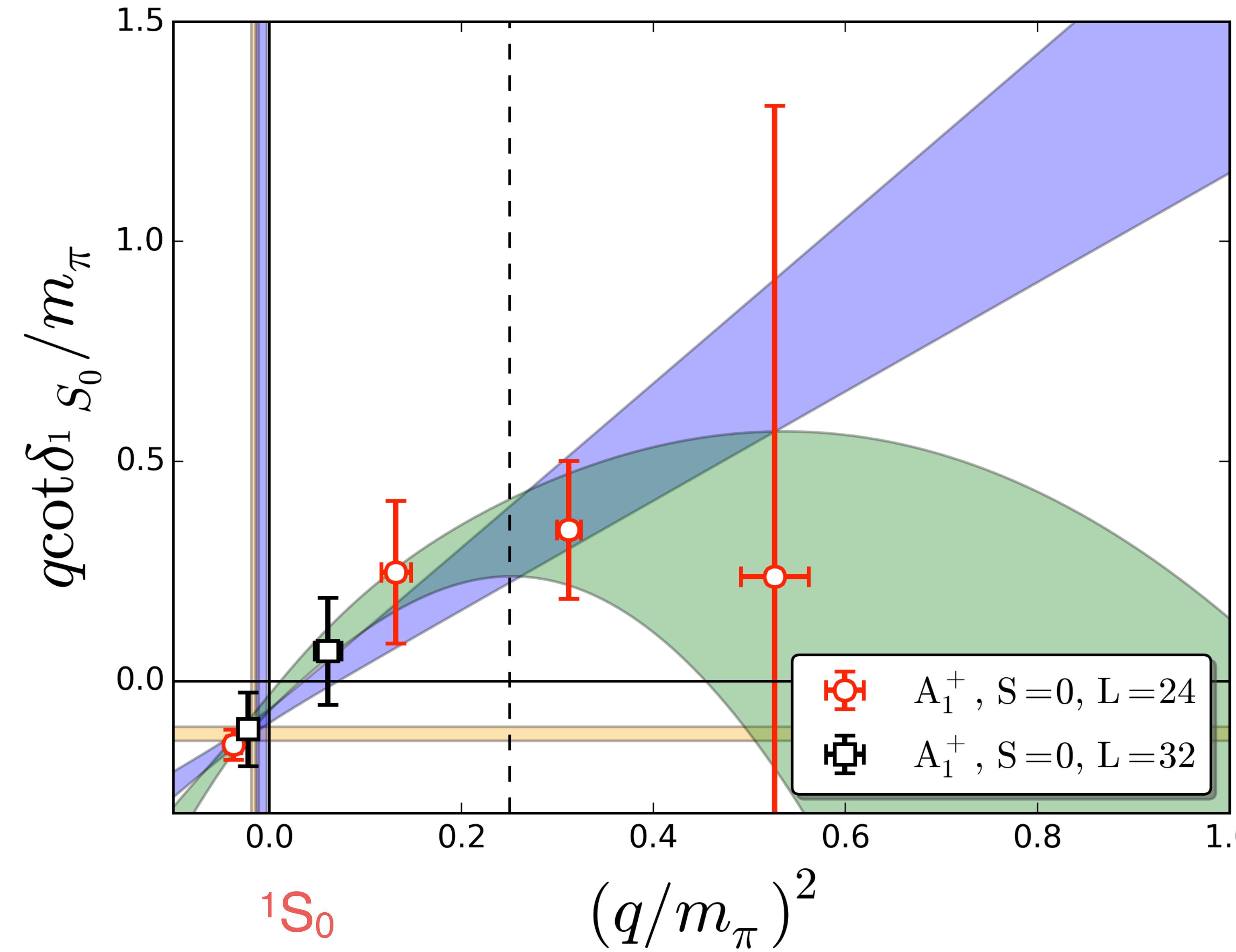


Impact of an LQCD calculation of the I=2 amplitude (Walker-Loud talk)

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



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

PRIOR to NPDGamma

Observable	Exp. Status	LO Expectation
$A_{\rm p}(\vec{\rm n} + ^3{\rm He} \to ^3{\rm H}+{\rm p})$	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}
$\frac{d\phi^{\rm n}}{dz}\Big\rvert_{\rm parahydrogen}$	none	9.4×10^{-7} rad/m
$\frac{d\phi^{\rm n}}{dz}\Big\rvert_{^4{\rm He}}$	$(1.7 \pm 9.1 \pm 1.4) \times 10^{-7}$	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}

wrong sign

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

or pursue "new" experiments sensitive to LO couplings

post NPDGamma

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

$\to +1.2 \times 10^{-8}$

driven by 18F/ NPDGamma comparison

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

Summary

- 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

- now have NPDGamma, n+^{3}He

- The switch to the large-N_c LO couplings $\Lambda_0^+,\ \Lambda_2$ attractive
  - based on reasonable theoretical arguments
  - consistent with previous work in that the iso scalar coupling is about 1.5 DDH best value, consistent with DDH broad reasonable range
  - Λ_2 become NLO, exceeds DDH reasonable range
  - more careful analysis needed, but the nonzero NPDGamma result appears to wash out most of the large-Nc hierarchy
  - more careful analysis needed, but NPDGamma/18F constraint then significantly impacts n+3He

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