Hadronic parity violation in chiral EFT

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by CAS, PIFI

by DFG, SFB 1639

by ERC, EXOTIC

by NRW-FAIR

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Short Introduction

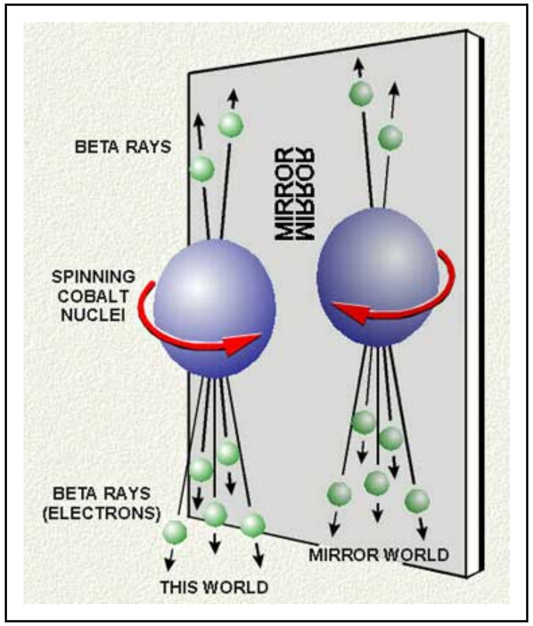
Parity-violation in the Standard Model

- Parity-violation (PV) is an integral part of the Standard Model
- Important Chinese contributions to establish it:

Prediction of PV in the weak interactions

T.-D. Lee and C.-N. Yang, Phys. Rev. **104** (1956) 254

$\hookrightarrow$ Nobel prize 1957



Experimental verification in ^{60}Co decay

C.S. Wu et al., Phys. Rev. **105** (1957) 1413

$\hookrightarrow$ no Nobel prize, why?

Parity-violation in the Standard Model cont'd

- Parity-violation (PV) is an integral part of the Standard Model

  ↪ effective four-Fermion operators at low energies — Fermi 1933

- Hadronic/nuclear PV in most cases effectively masked: $G_F M_\pi^2 \sim 10^{-7}$

  ↪ look for observables that vanish for PC interactions

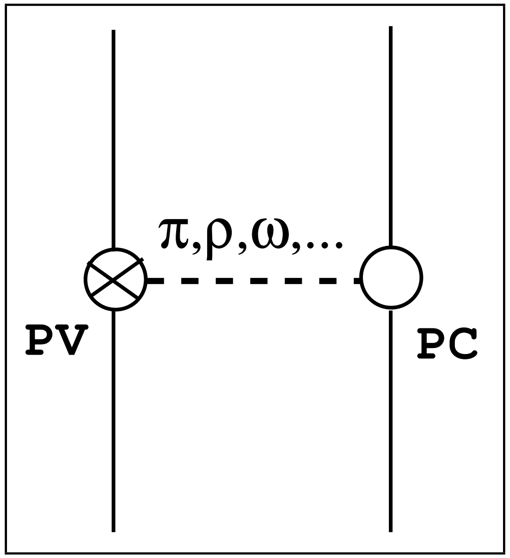
- Theory mostly based on boson-exchange models

  ... Desplanques, Donoghue, Holstein 1980 and many others

  ↪ uncertainties hard to specify

  ↪ only consistent model for PV/PC int. is the vector-meson stabilized Skyrmion

  Kaiser, UGM 1990; UGM, Weigel 1999



Status of hadronic PV A.D. 2016

- Various experimental determinations

  $\hookrightarrow$ consistent picture?

  Haxton, Wieman 2001

- inconsistency in h_π
  (weak pion-nucleon coupling $\to$ slide)

- consistency of DDH approach?

- power counting ?

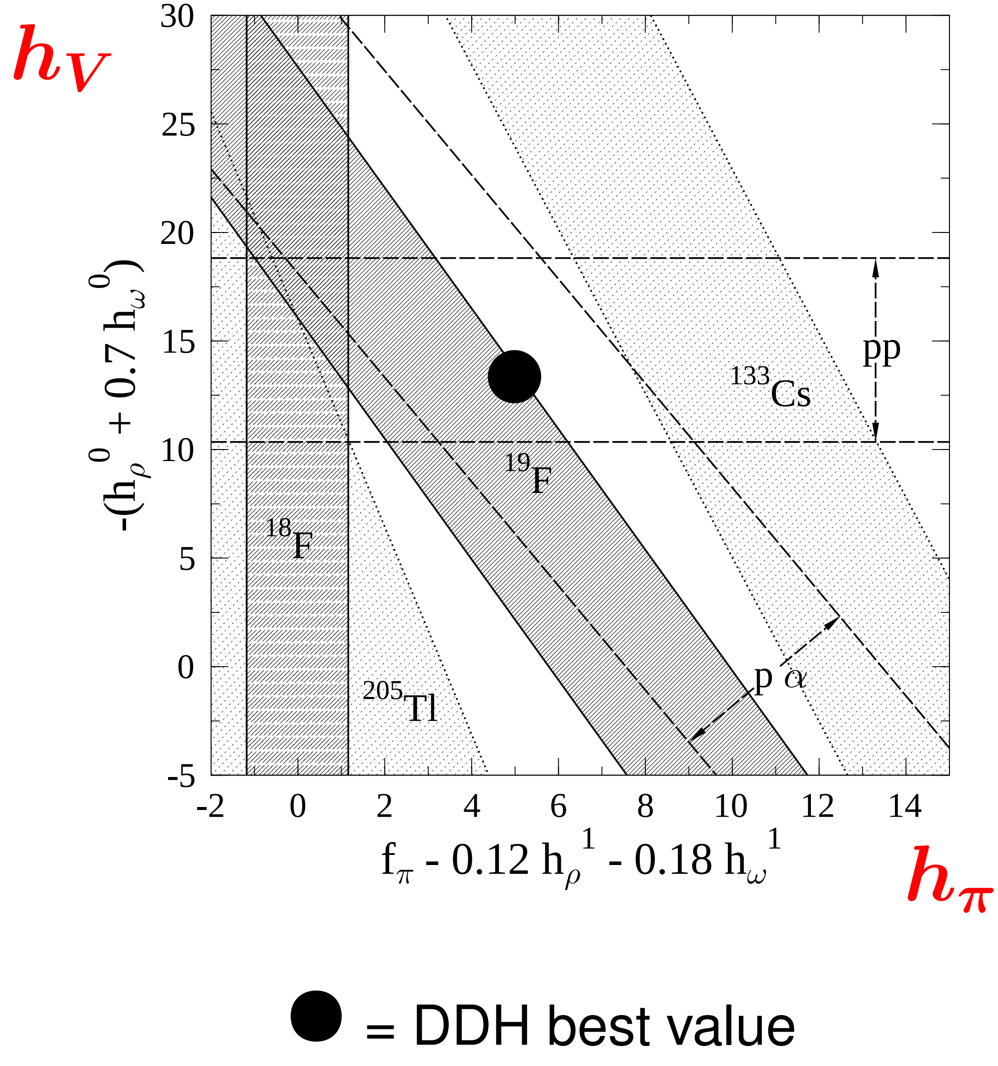
- link to QCD ?

$\Rightarrow$ can do better these days

$\Rightarrow$ chiral nuclear EFT

[pionless approach can also be used]

Schindler, Springer, Prog. Part. Nucl. Phys. **72** (2013) 1



= DDH best value

Estimates & limits on h_π A.D. 2016

- Naive dimensional analysis (NDA):

$$h_\pi \sim \mathcal{O}(G_F F_\pi \Lambda_\chi) \sim 10^{-6}$$

- DDH best value [range]: Desplanques, Donoghue, Holstein 1980

$$h_\pi = 4.6 \cdot 10^{-7} \quad [0 \leq h_\pi \leq 1.2 \cdot 10^{-6}]$$

- SU(3) Skyrme model: $h_\pi = (1.0^{+0.3}_{-0.2}) \cdot 10^{-7}$ UGM, Weigel 1999

- Lattice (connected diagrams, $M_\pi = 389$ MeV):

$$h_\pi = (1.10 \pm 0.50_{\rm sys} \pm 0.06_{\rm stat}) \cdot 10^{-7}$$ Wasem 2012

- γ-ray emission from ^{18}F: $h_\pi < 1.3 \cdot 10^{-7}$ Adelberger et al 1983; Page et al. 1987

The framework

Manifestations of PV at low energies

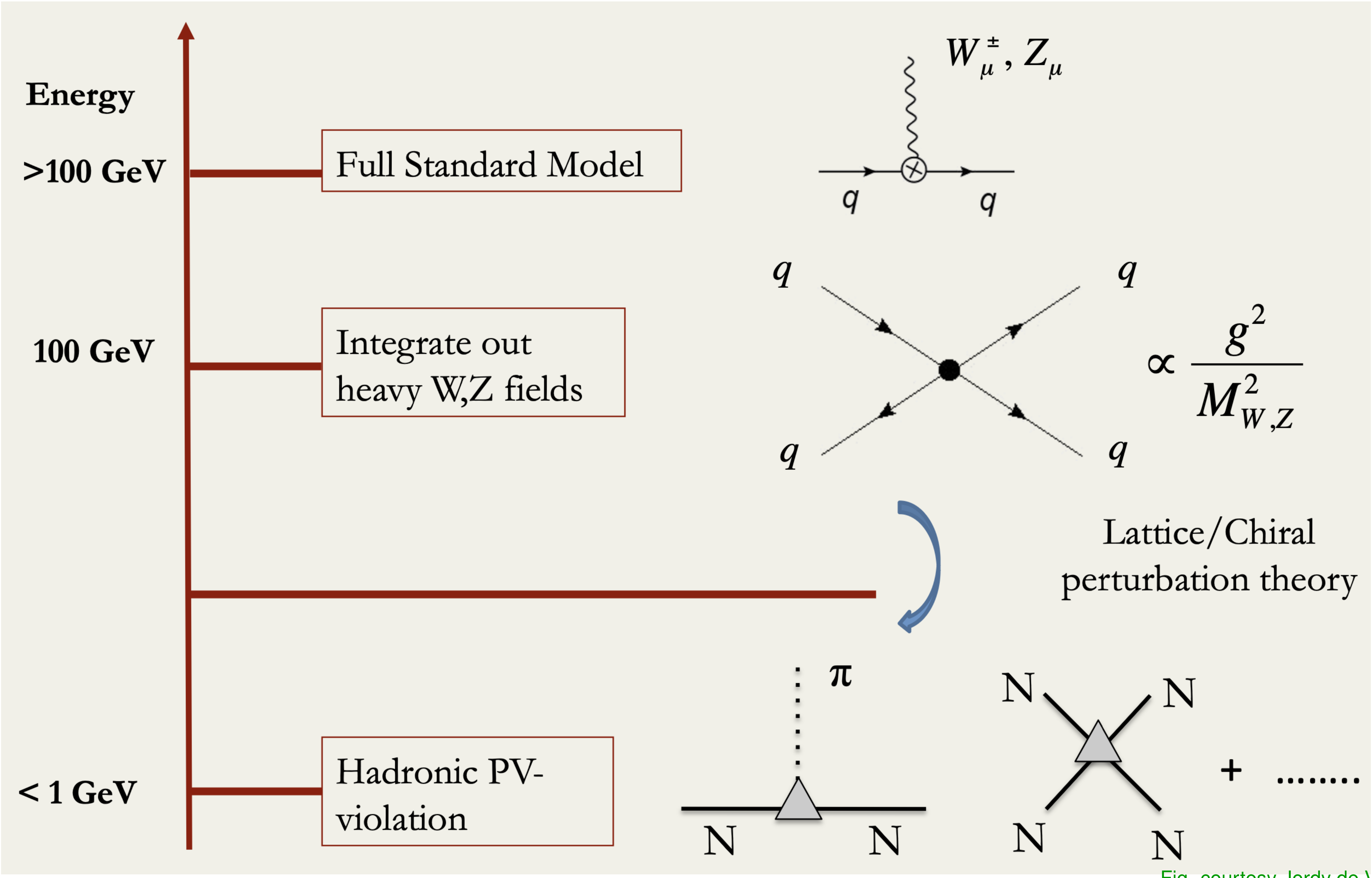


Fig. courtesy Jordy de Vries

Chiral nuclear EFT

Weinberg, Gasser, Leutwyler, van Kolck, Epelbaum, Bernard, Kaiser, UGM, . . .

- explore the symmetries of QCD (chiral, C, P, T . . .)

  $\hookrightarrow$ chiral effective Lagrangians in terms of pions and nucleons

$$\mathcal{L}_{\rm QCD} \to \mathcal{L}_{\rm EFF} = \mathcal{L}_{\pi\pi} + \mathcal{L}_{\pi N} + \mathcal{L}_{NN} + \ldots$$

- power counting in Q/Λ_χ (Q = external momentum, pion mass)
- perturbative expansion of the scattering amplitudes for the pion and pion-nucleon sectors (CHPT)
- perturbative expansion of the potential $V = V_{\rm NN} + V_{\rm NNN} + \ldots$
- extremely successfull in the parity-conserving (PC) sector

Epelbaum, Hammer, UGM, Rev. Mod. Phys. **81** (2009) 1773

Parity-odd chiral Lagrangian

- Write down terms that break P but have different chiral properties:

Kaplan, Savage 1993

$$\mathcal{L} = \frac{G_F}{\sqrt{2}}\left[\left(\frac{1}{2} - \frac{1}{3}s_{\rm W}^2\right)\underbrace{V_\mu \cdot A^\mu}_{\mathbf{F_0}} - \frac{1}{3}s_{\rm W}^2\,\underbrace{I_\mu \cdot A_3^\mu}_{\mathbf{F_1}} - s_{\rm W}^2\,\underbrace{\left(V_3^\mu A_\mu^3 - \frac{1}{3}V_a^\mu A_\mu^a\right)}_{\mathbf{F_2}}\right]$$

$\mathbf{F_0}$: chiral scalar (conserves chiral symmetry)

$\mathbf{F_1}$: isovector

$\mathbf{F_2}$: isotensor

$$V_\mu^a = \bar{q}\gamma^\mu\tau^a q$$
$$A_\mu^a = \bar{q}\gamma^\mu\gamma^5\tau^a q$$
$$I_\mu = \bar{q}\gamma^\mu q$$
$$q = (u\ d)^T$$
$$s_{\rm W}^2 = \sin^2\theta_{\rm W} \simeq 1/5$$

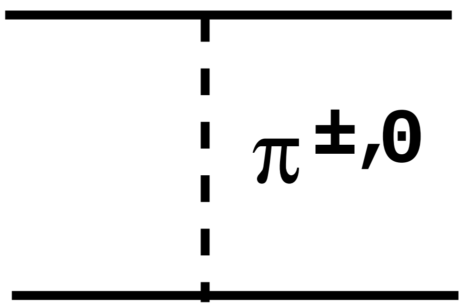
- Only $\mathbf{F_1}$ induces a leading-order pion-nucleon coupling:

$$\boxed{\mathcal{L}_{\rm PV} = \frac{h_\pi}{\sqrt{2}}\bar{N}(\vec{\tau}\times\vec{\pi})^3 N}$$

PC and PV interaction hierarchy

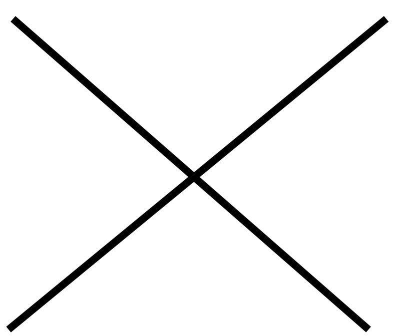
- PC

$$\frac{g_A}{2F_\pi}\bar{N}(\gamma_\mu\gamma_5\partial^\mu\pi^a)\tau^a N$$



$$\sim \frac{(g_A Q)^2}{Q^2} \sim Q^0$$

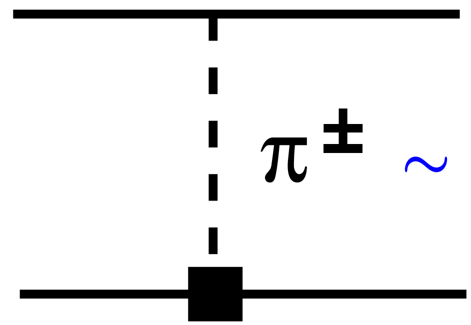
$$\bar{N}N\,\bar{N}N$$



$$\sim Q^0$$

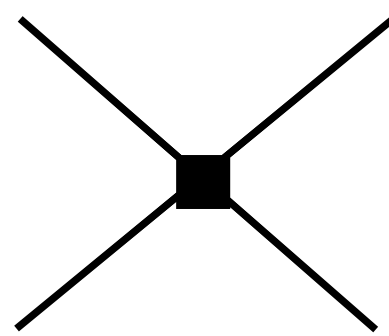
- PV

$$\frac{h_\pi}{\sqrt{2}}\bar{N}(\vec{\tau}\times\vec{\pi})^3 N$$



$$\sim \frac{(g_A Q)h_\pi}{Q^2} \sim Q^{-1}$$

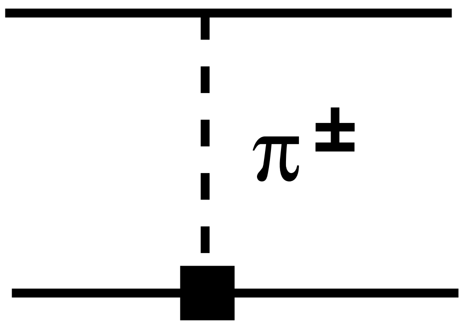
$$\epsilon^{ijk}(\bar{N}\sigma^i N)\partial^k(\bar{N}\sigma^j N)$$



$$\sim Q^1$$

PV chiral NN potential at NLO

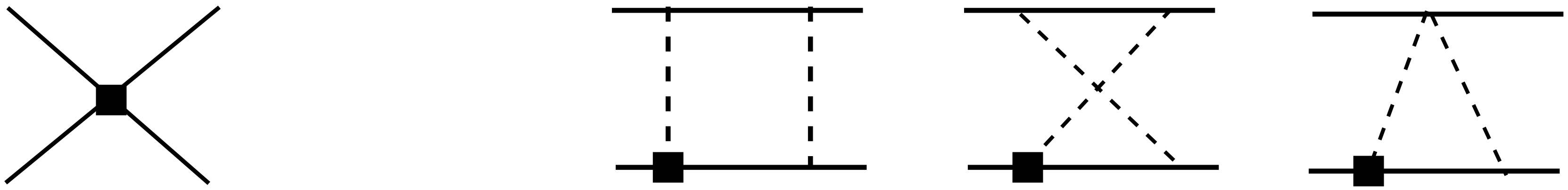
- Leading order $\mathcal{O}(Q^{-1})$ Kaplan, Savage 1993



$$-\left(\frac{g_A h_\pi}{2\sqrt{2}F_\pi}\right) i(\vec{\tau}_1 \times \vec{\tau}_2)^3 \frac{(\vec{\sigma}_1 + \vec{\sigma}_2)^3 \cdot \vec{q}}{\vec{q}^{\,2} + M_\pi^2}$$

One-pion exchange (large uncertainty in the coupling constant h_π)

- Next-to-leading order $\mathcal{O}(Q^1)$ Zhu et al. 2005, Kaiser 2007, Girlanda 2008, Viviani et al. 2014



NN contact terms (5) but also: two-pion exchange, **not** in the DDH framework !

- For small values of h_π, must also consider NNLO $\mathcal{O}(Q^2)$

NLO contact interactions

- Leading order contact terms:

Girlanda, Phys. Rev. C **77** (2008) 067001
Phillips, Schindler, Springer, Nucl. Phys. A **822** (2009) 1
de Vries, Li, UGM, Kaiser, Liu, Zhu, Eur. Phys. J. A **50** (2014) 108

$$\begin{aligned} V_{\rm CT}^{\rm NLO} &= \frac{C_0}{F_\pi \Lambda_\chi^2}(\vec{\sigma}_1 - \vec{\sigma}_2)\cdot(\vec{p}+\vec{p}\,') + \frac{C_4}{F_\pi \Lambda_\chi^2} i(\vec{\tau}_1 \times \vec{\tau}_2)^3 (\vec{\sigma}_1 + \vec{\sigma}_2)\cdot \vec{q} \\ &+ \frac{1}{F_\pi \Lambda_\chi^2}\left(C_1 + C_2 \frac{(\vec{\tau}_1 + \vec{\tau}_2)^3}{2} + C_3 \frac{\vec{\tau}_1\cdot\vec{\tau}_2 - 3\tau_1^3\tau_2^3}{2}\right) i(\vec{\sigma}_1 \times \vec{\sigma}_2)\cdot \vec{q} \end{aligned}$$

- Can be easily understood: There are five possible $S \leftrightarrow P$ couplings:

  $\Delta I = 0$: one ${}^3S_1 \leftrightarrow {}^1P_1$ transition, one ${}^3S_1 \leftrightarrow {}^3P_1$ transition,

  $\Delta I = 1$: three ${}^1S_0 \leftrightarrow {}^3P_0$ transitions (one for each value of m_t)

- LECs C_i can be estimated via resonance saturation, see later

NNLO corrections to the potential

Kaplan, Savage 1993; de Vries, UGM, Kaiser, Li, Zhu 2014, Viviani et al. 2014

- no contact terms at this order (require two more derivatives for $P \leftrightarrow D$ transitions)

- new πN operators [+ recoil corrections from these terms]:

$$\mathcal{L}_{\rm PV} = h_0^v (v\cdot\partial\vec{\pi})\cdot\bar{N}\vec{\tau}N + h_1^v(v\cdot\partial\pi^3)\bar{N} + h_2^v(v\cdot\partial\pi^3)\bar{N}\tau^3 N + \frac{h_\pi^{(2)}}{\sqrt{2}}\bar{N}(\partial^2\vec{\pi}\times\vec{\tau})^3 N + \frac{h_m M_\pi^2}{\sqrt{2}}\bar{N}(\vec{\pi}\times\vec{\tau})^3 N + \cdots$$

- new $\pi\pi N$ operators:

$$\mathcal{L}_{\rm PV} = \frac{h_1^{\pi\pi}}{F_\pi}(\vec{\pi}\times\partial\vec{\pi})^3\bar{N}S^\mu N - \frac{h_2^{\pi\pi}}{F_\pi}\left[\partial_\mu\pi^3\bar{N}(\vec{\tau}\times\vec{\pi})^3 S^\mu N + \ldots\right]$$

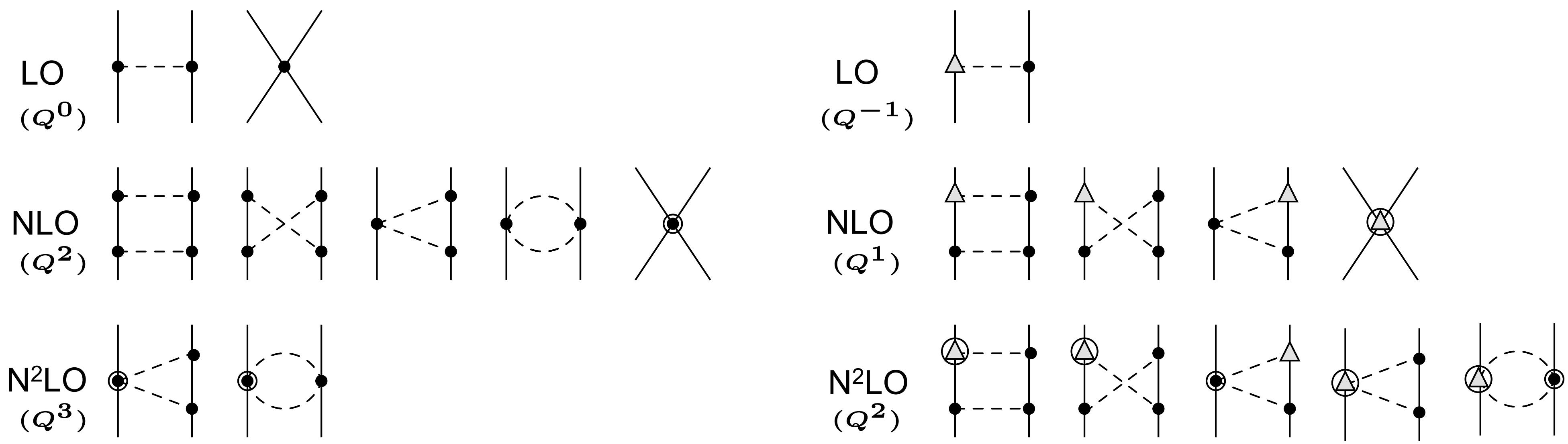
- a three-pion operator: $\mathcal{L}_{\rm PV} = \Delta_\pi(\vec{\pi}\times\partial_\mu\vec{\pi})^3\partial^\mu\pi^3$

$\Rightarrow$ in principle, 8 new LECs (in practice, much less per process + renormalization)

NNLO corrections continued

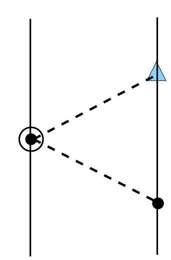
de Vries, UGM, Kaiser, Li, Zhu 2014

- pertinent diagrams (cf. also PC case):



PC dim 1 • PC dim 2 ⊙ PV dim 0 △ PV dim 1 ⊛

- for later numerical estimates, we only consider the dominant graph $\sim \pi c_4 h_\pi \sim 10 h_\pi$ $[\mathrm{GeV}^{-1}]$



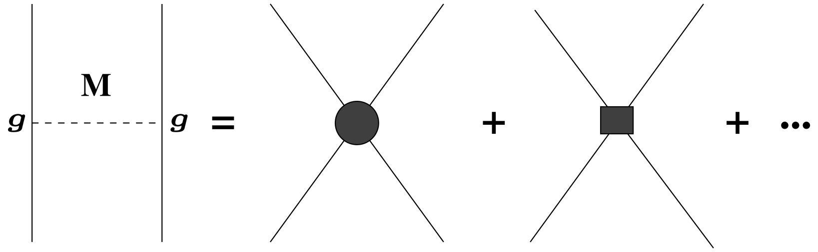
Resonance saturation: DDH in view of EFT

Resonance saturation

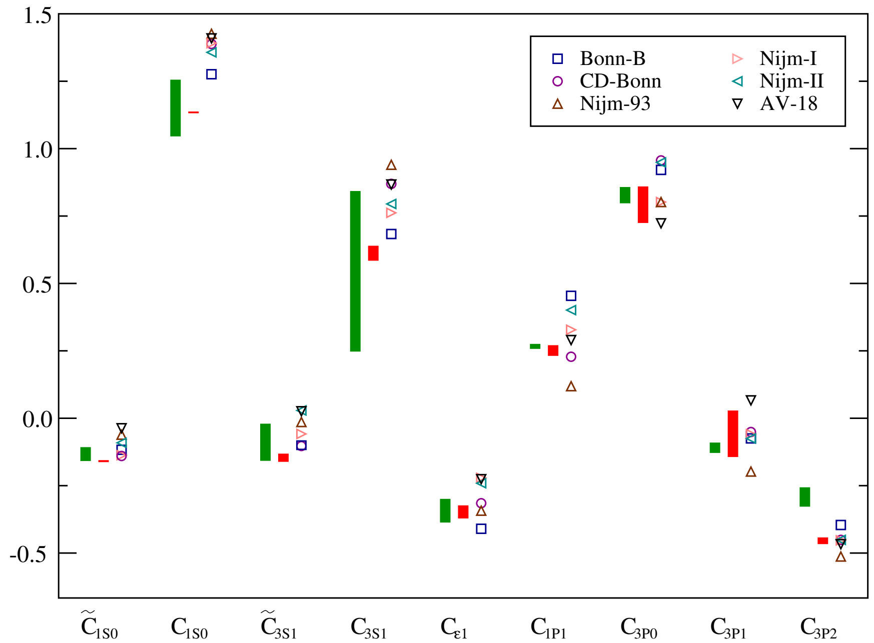
- Contact interactions modeled by heavy meson exchanges

Epelbaum, UGM, Glöckle, Elster 2002

- must include form factor and subtract TPE contributions



$$\frac{g^2}{t-M^2} = -\frac{g^2}{M^2} - \frac{g^2\, t}{M^4} + \ldots$$



- quite successfull in the PC case, can be extended to PV

- provides dictionary between EFT and OBE models

Dictionary

Carlson et al. 2002; Haxton, Holstein 2013; de Vries et al. 2014

- LO contact terms ($S \leftrightarrow P$ transitions)

$$
\begin{aligned}
\frac{C_0 + C_1}{F_\pi \Lambda_\chi^2} &\sim \frac{1}{m_N}\left[\frac{g_\omega h_\omega^0 \chi_S}{m_\omega^2} c_\omega(0,\Lambda_\omega) - \frac{3 g_\rho h_\rho^0 \chi_V}{m_\rho^2} c_\rho(0,\Lambda_\rho)\right] \\
\frac{-C_0 + C_1}{F_\pi \Lambda_\chi^2} &\sim \frac{1}{m_N}\left[\frac{g_\omega h_\omega^0 (2+\chi_S)}{m_\omega^2} c_\omega(0,\Lambda_\omega) + \frac{g_\rho h_\rho^0 (2+\chi_V)}{m_\rho^2} c_\rho(0,\Lambda_\rho)\right] \\
\frac{C_2}{F_\pi \Lambda_\chi^2} + \frac{g_A^3 h_\pi}{2\sqrt{2} F_\pi} \frac{8}{(4\pi F_\pi)^2} \frac{s}{\Lambda_S} &\sim \frac{1}{m_N}\left[\frac{g_\omega h_\omega^1 (2+\chi_S)}{m_\omega^2} c_\omega(0,\Lambda_\omega) + \frac{g_\rho h_\rho^1 (2+\chi_V)}{m_\rho^2} c_\rho(0,\Lambda_\rho)\right] \\
\frac{C_3}{F_\pi \Lambda_\chi^2} &\sim -\frac{1}{m_N} \frac{g_\rho h_\rho^2 (2+\chi_V)}{\sqrt{6}\, m_\rho^2} c_\rho(0,\Lambda_\rho) \\
\frac{C_4}{F_\pi \Lambda_\chi^2} - \frac{g_A h_\pi}{2\sqrt{2} F_\pi} \frac{(2g_A^2 - 1)}{(4\pi F_\pi)^2} \frac{s}{\Lambda_S} &\sim \frac{1}{m_N}\left[\frac{g_\omega h_\omega^1}{m_\omega^2} c_\omega(0,\Lambda_\omega) + \frac{g_\rho (h_\rho^{1\prime} - h_\rho^1)}{m_\rho^2} c_\rho(0,\Lambda_\rho)\right] \\
c_V(q^2,\Lambda_V) &= \left(\frac{\Lambda_V^2 - m_V^2}{\Lambda_V^2 + q^2}\right)^2, \quad V = \rho, \omega
\end{aligned}
$$

- C_2 and C_4 sensitive to TPE corrections (Λ_S = spectral function cut-off)

- can be used to estimate the LECs (better than NDA)

Numerical values for the LECs

de Vries et al. 2014

- Use various model values for the couplings and deduce values for the LECs

Coupling	DDH 'best' value	KMW
h_π	$4.6 \cdot 10^{-7}$	$1.0 \cdot 10^{-7}$
h_ρ^0	$-11.4 \cdot 10^{-7}$	$-1.9 \cdot 10^{-7}$
h_ρ^1	$-0.19 \cdot 10^{-7}$	$-0.02 \cdot 10^{-7}$
h_ρ^2	$-9.5 \cdot 10^{-7}$	$-3.8 \cdot 10^{-7}$
$h_\rho^{1\prime}$	0	$-2.2 \cdot 10^{-7}$
h_ω^0	$-1.9 \cdot 10^{-7}$	$-1.1 \cdot 10^{-7}$
h_ω^1	$-1.1 \cdot 10^{-7}$	$-1.0 \cdot 10^{-7}$

DDH: Desplanques, Donoghue, Holstein, Ann. Phys. **124** (1980) 449

KMW: Kaiser, UGM, Nucl. Phys. A **499** (1989) 699

UGM, Weigel, Phys. Lett. B **447** (1999) 1

LEC	DDH 'best' value	KMW
C_0	$4.7 \cdot 10^{-6}$	$0.89 \cdot 10^{-6}$
C_1	$1.2 \cdot 10^{-6}$	$0.11 \cdot 10^{-6}$
C_2	$-2.2 \cdot 10^{-6}$	$-0.66 \cdot 10^{-6}$
C_3	$1.0 \cdot 10^{-6}$	$0.41 \cdot 10^{-6}$
C_4	$0.25 \cdot 10^{-6}$	$-0.049 \cdot 10^{-6}$

Parity-violating proton-proton scattering

The longitudinal asymmetry

- The longitudinal asymmetry in $\vec{p}p$ scattering:

$$A_L(\theta_1,\theta_2,E) = \frac{\displaystyle\int d\Omega(\sigma_+ - \sigma_-)}{\displaystyle\int d\Omega(\sigma_+ + \sigma_-)}$$

$\pm$ = proton helicity

- vanishes for PC interactions, expected size $\sim 10^{-7}$

- only three (low-energy) data points (Bonn/PSI/TRIUMF):

angular range

$A_L(14\,\mathrm{MeV}) = -(0.93 \pm 0.21)\cdot 10^{-7}$ $(20^\circ - 78^\circ)$ Eversheim et al. 1991

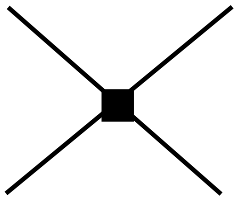
$A_L(45\,\mathrm{MeV}) = -(1.50 \pm 0.22)\cdot 10^{-7}$ $(23^\circ - 52^\circ)$ Kistryn et al. 1987

$A_L(221\,\mathrm{MeV}) = +(0.84 \pm 0.34)\cdot 10^{-7}$ $(2^\circ - 90^\circ)$ Berdoz et al. 2001

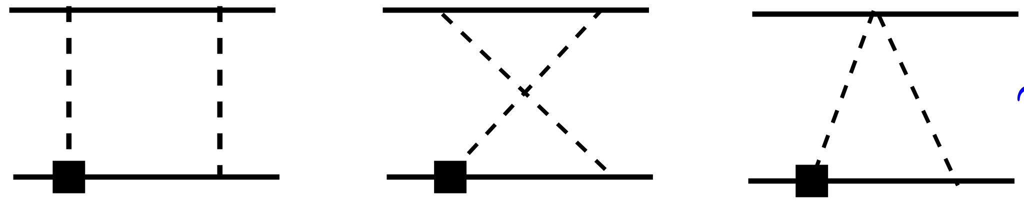
Theory of the longitudinal asymmetry

- No contribution of OPE as its M.E. is $\sim (t' - t)$ (with t = total isospin)

- In EFT, A_L depends on two LECs: h_π and $C = (-C_0 + C_1 + C_2 - C_3)$



$\sim C$



$\sim h_\pi$

- Solve the LS eq.: $\boxed{T = V + VG_0T}$ $\qquad V = V_{\rm strong} + V_{\rm weak} + V_{\rm Coulomb}$

  $\hookrightarrow$ Strong and weak potential **consistently** derived in chiral EFT

  $\hookrightarrow$ Weak potential can be treated perturbatively

  $\hookrightarrow$ Coulomb important in forward direction

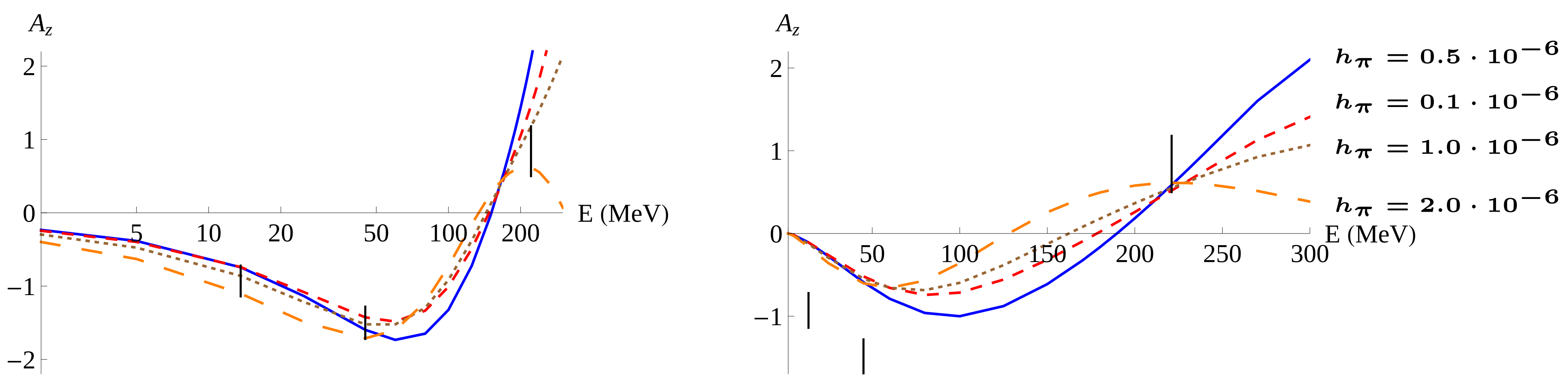
Driscoll, Miller 1989; Driscoll, UGM 1990; Carlson et al. 2002; de Vries, UGM, Epelbaum, Kaiser 2013

Fits to low-energy data

de Vries, UGM, Epelbaum, Kaiser, Eur. Phys. J. A **49** (2013) 149

- Fits to the first two data and predict the third [chosen to be sensitive to ρ exchange]

$$h_\pi = (1.1 \pm 2.0) \cdot 10^{-6} \qquad C = (-9.3 \pm 10) \cdot 10^{-6}$$



$(20^\circ - 78^\circ)$ $(2^\circ - 90^\circ)$

- well described, but large uncertainties due to lack of data

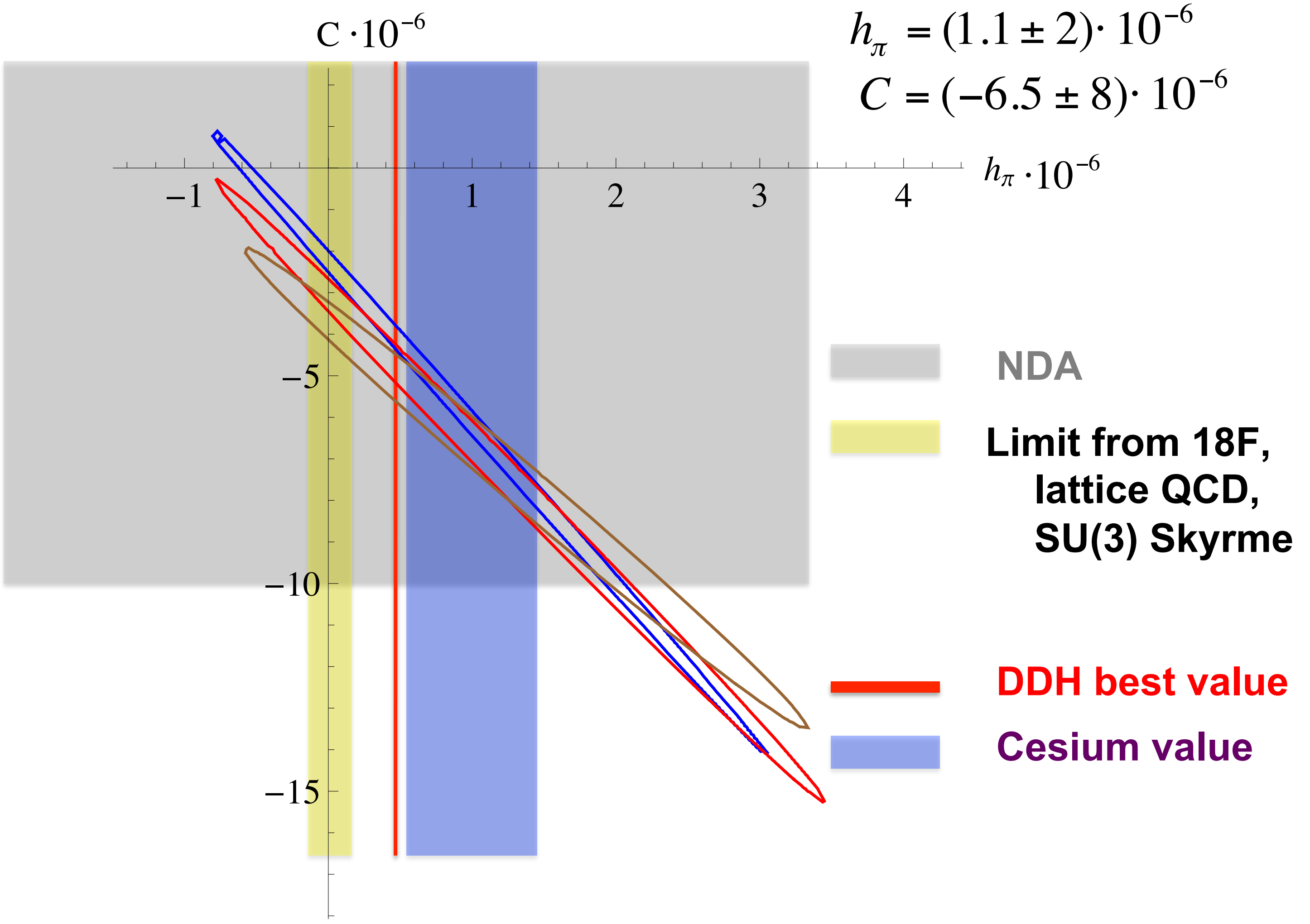
- largest sensitivity to h_π for $E = 100 \ldots 150$ MeV

Fits to all low-energy data

de Vries et al. EPJA **49**: 149 (2013)

- Fit to all data at 90% conf. level:

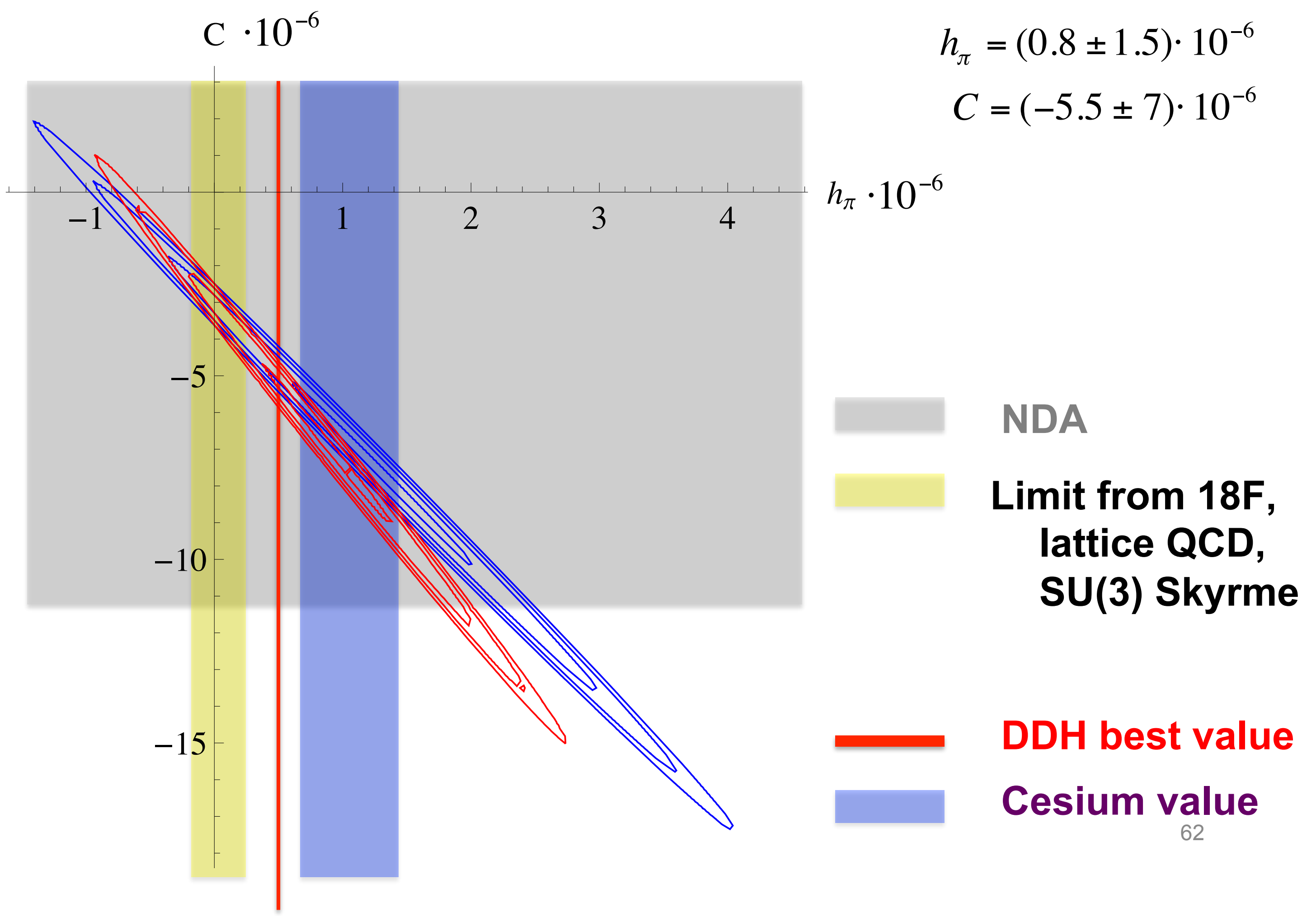
$$h_\pi = (1.1 \pm 2)\cdot 10^{-6}$$
$$C = (-6.5 \pm 8)\cdot 10^{-6}$$



Sanity check

de Vries, Li, UGM, Kaiser, Liu, Zhu, Eur. Phys. J. A **50** (2014) 108

- Go to NNLO, include **dominant** TPE correction $\sim \pi c_4 h_\pi$, $c_4 = 3.4\,\text{GeV}^{-1}$:



$h_\pi = (0.8 \pm 1.5) \cdot 10^{-6}$

$C = (-5.5 \pm 7) \cdot 10^{-6}$

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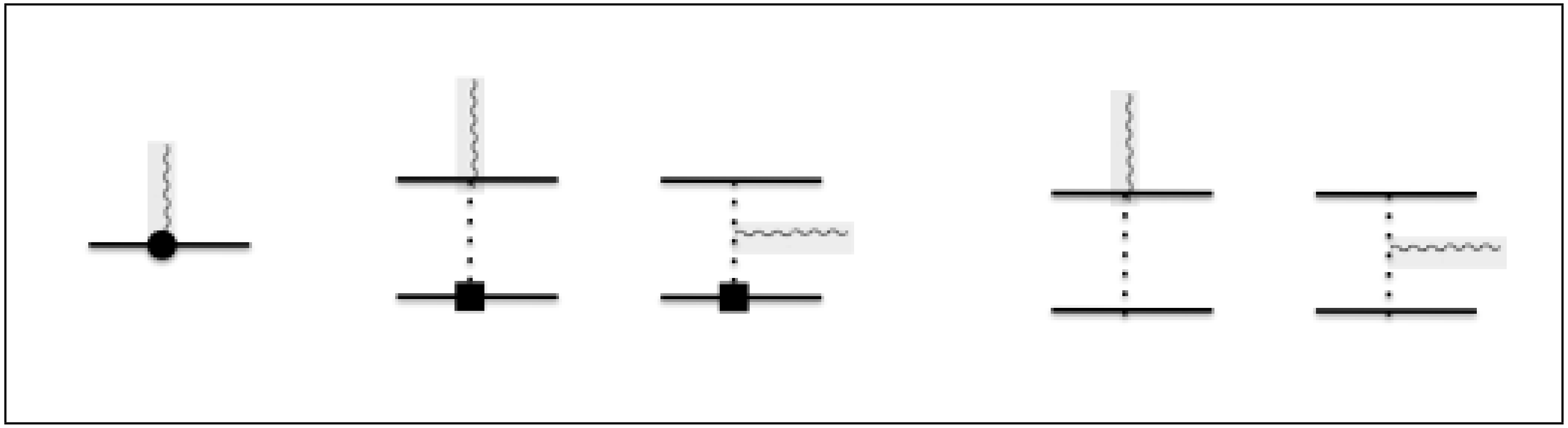
Parity-violating neutron-proton fusion

Theory of the longitudinal asymmetry

- LA in $\vec{n}p \to d\gamma$: $$A_\gamma(\theta) = \frac{d\sigma_+(\theta) - d\sigma_-(\theta)}{d\sigma_+(\theta) + d\sigma_-(\theta)} = a_\gamma \cos\theta$$

$\pm$ = neutron helicity

- $A_\gamma(\theta) \sim \vec{s}_n \cdot \vec{k}_\gamma \to$ requires interference between E1 and M1 currents
- LO calculation: sensitive to h_π through meson exchange currents



$\hookrightarrow$ cancellations between the three contributions [PC $\mu_V \times$ ...]

- NLO calculation: sensitive to h_π and the LEC C_4

LO analysis

- LO + NLO PC currents: iv magnetic moment plus MECs at thermal energies:

$$\sigma = (319 \pm 5)\ \text{mb} \quad [(334.2 \pm 0.5)\ \text{mb}]$$

$\hookrightarrow$ remaining discrepancy from higher orders ✓

- PV current at LO: $\vec{J}_{PV} = \frac{e g_A h_\pi}{2\sqrt{2} F_\pi} \left(\vec{\tau}_1 \cdot \vec{\tau}_2 - \tau_1^3 \tau_2^3\right) \times f(\vec{k}; \vec{q}, \vec{\sigma}_i)$

$\Rightarrow$ LO analyzing power: $\boxed{a_\gamma = -(0.11 \pm 0.05) h_\pi}$

$\hookrightarrow$ cancellations between different contributions causes uncertainty

- Experimental uncertainty still larger (2016 not final value):

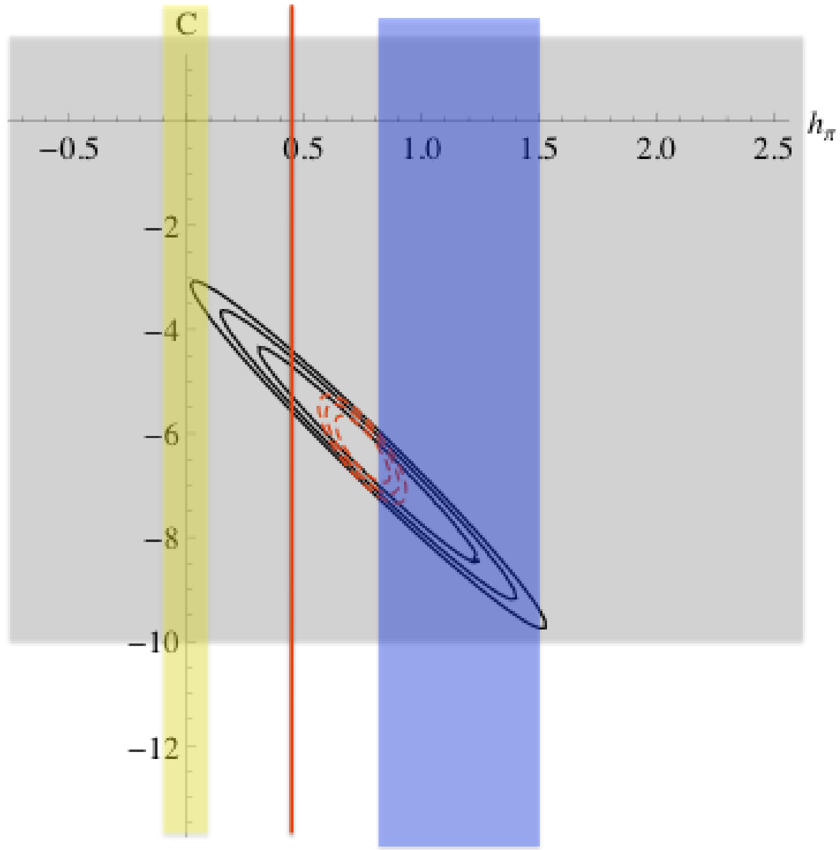
$$a_\gamma = -(0.72 \pm 0.44) \cdot 10^{-7}$$

- Expected exp. uncertainty: $\delta a_\gamma = \pm 1 \cdot 10^{-8}$ NPDGamma Coll.

Combined fit

de Vries, Li, UGM, Nogga, Epelbaum, Kaiser, Phys. Lett. **B 747** (2015) 299

- Combine pp data with upcoming $\vec{n}p \to d\gamma$ experiment



– – – upcoming sensitivity

note: central value might shift

- h_π from present data:

$$h_\pi = (0.75 \pm 0.45) \cdot 10^{-6}$$

$\Rightarrow$ need NLO analysis

[published value inconclusive: $(-1.8 \pm 1.9 \pm 0.2) \cdot 10^{-7}$]

NPDG Coll., Gericke et al., Phys. Rev C **83** (2011) 015505

NLO analysis

- NLO current [h_π small]: $\vec{J}_{\text{PV,NLO}} = -\frac{C_4}{F_\pi \Lambda_\chi^2}\left(\vec{\tau}_1 \cdot \vec{\tau}_2 - \tau_1^3 \tau_2^3\right)\left(\vec{\sigma}_1 + \vec{\sigma}_2\right)$

- Result for the asymmetry: $a_\gamma = (-0.11 \pm 0.05) h_\pi + (0.055 \pm 0.025) C_4$

- Resonance saturation for C_4: $C_4 = \frac{F_\pi \Lambda_\chi^2}{2 m_N}\left[\frac{g_\omega h_\omega^1}{m_\omega^2} + \frac{g_\rho (h_\rho^{1\,\prime} - h_\rho^1)}{m_\rho^2}\right]$

$$\to C_4 = (-0.8 \pm 0.4) \cdot 10^{-7}$$

⇒ NLO prediction for A_γ: $\boxed{a_\gamma = (-0.11 \pm 0.05) h_\pi - (0.5 \pm 0.5) \times 10^{-8}}$

⇒ Short-distance effects larger than originally thought, include into the error budget

Schiavilla et al. (1998), Liu (2007), Gericke et al. (2011)

⇒ for fixed h_π, strong correlation between C_4 and C (from pp data)

⇒ need more data to fit all LECs separately

Recent developments

Experimental result for $np \to d\gamma$

- Finally, the NPDG collaboration published their final result

PHYSICAL REVIEW LETTERS **121,** 242002 (2018)

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)

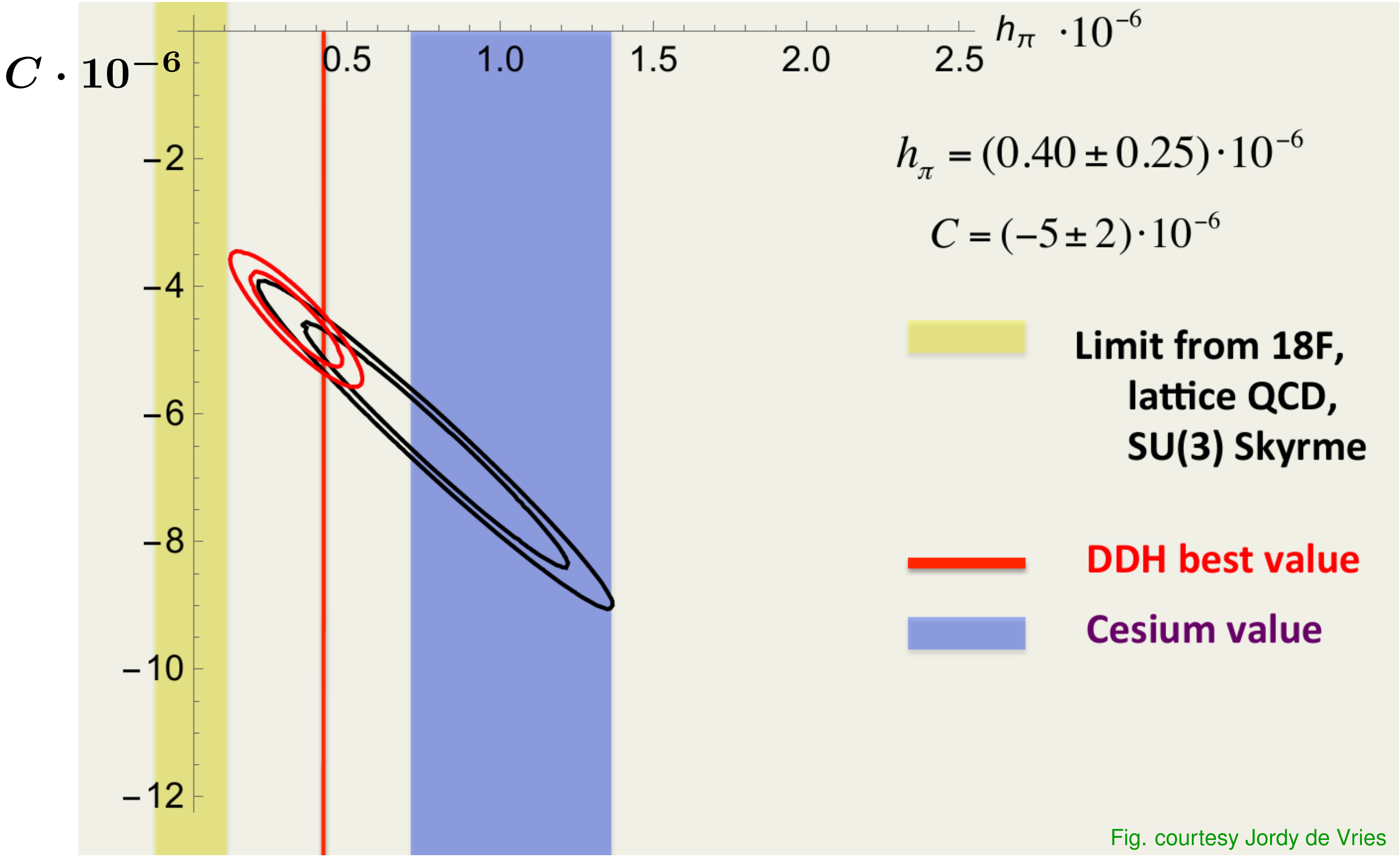
$$\boldsymbol{A_\gamma = [-3.0 \pm 1.4(\text{stat.}) \pm 0.2(\text{syst.})] \cdot 10^{-8}}$$

$\hookrightarrow$ Using our the discussed formalism [ct in the error budget]

$$\boldsymbol{h_\pi = (0.27 \pm 0.18) \cdot 10^{-6}}$$

de Vries et al., Front.in Phys. **8** (2020) 218

New combined fit



- Sizeable shift from the old (intermediate) result (black ellipses)

Further few-body reactions I

- The Pisa group has performed chiral EFT calculations for spin-rotation measurements in n-p, n-^{2}H, n-^{3}He and on the LA in n + ^{3}He $\to$ p + ^{3}H

$$A_L = -(0.14 \pm 0.01)h_\pi + (0.017 \pm 0.003)C_0 - (0.007 \pm 0.001)C_1$$
$$+ (0.008 \pm 0.001)C_2 + (0.018 \pm 0.002)C_4$$

Viviani et al., 2014

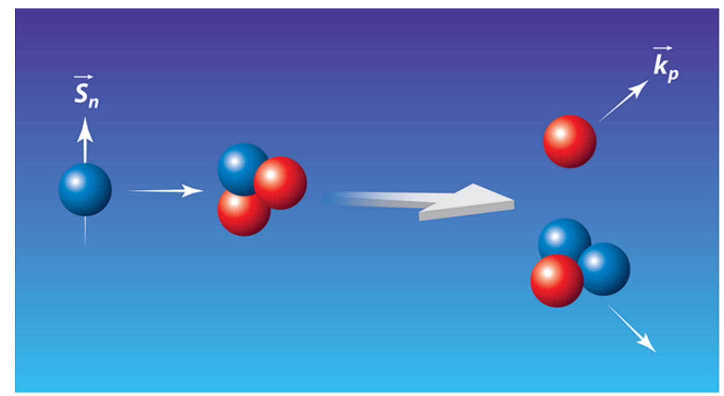
PHYSICAL REVIEW LETTERS **125,** 131803 (2020)

Featured in Physics

First Precision Measurement of the Parity Violating Asymmetry in Cold Neutron Capture on ^{3}He

M. T. Gericke,[1,*] S. Baeßler,[2,3] L. Barrón-Palos,[4] N. Birge,[5] J. D. Bowman,[3] J. Calarco,[6] V. Cianciolo,[3] C. E. Coppola,[5] C. B. Crawford,[7] N. Fomin,[5] I. Garishvili,[5] G. L. Greene,[5,3] G. M. Hale,[8] J. Hamblen,[9] C. Hayes,[5] E. Iverson,[3] M. L. Kabir,[7] M. McCrea,[1,10] E. Plemons,[5] A. Ramírez-Morales,[4] P. E. Mueller,[3] I. Novikov,[11] S. Penttila,[3] E. M. Scott,[5] J. Watts,[9] and C. Wickersham[9]

(n^3He Collaboration)



$$A_L = [1.55 \pm 0.97(\text{stat.}) \pm 0.24(\text{syst.})] \cdot 10^{-8}$$

$\hookrightarrow$ not yet conclusive due to the partial determinations of the LECs

$\hookrightarrow$ combine with spin rotation $d\phi/dz(\vec{n}p, \vec{n}d)$ & all other measurements

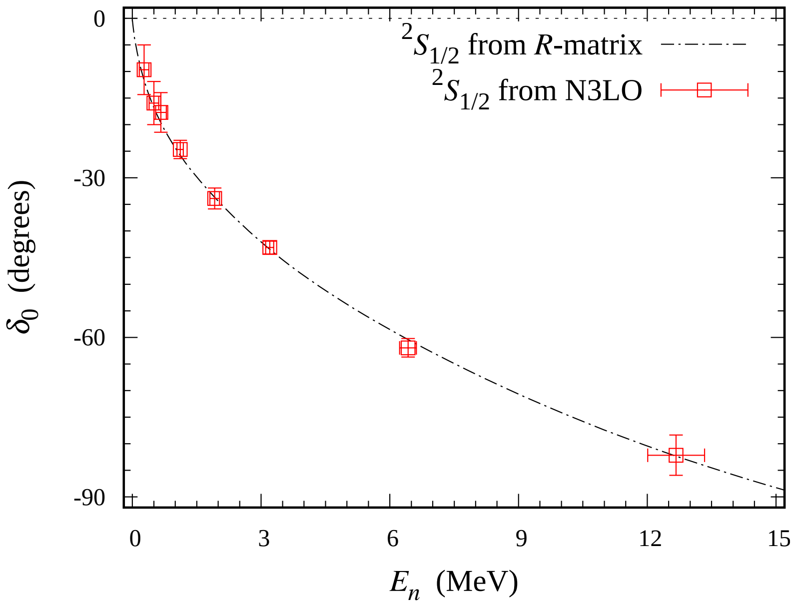
Further few-body reactions II

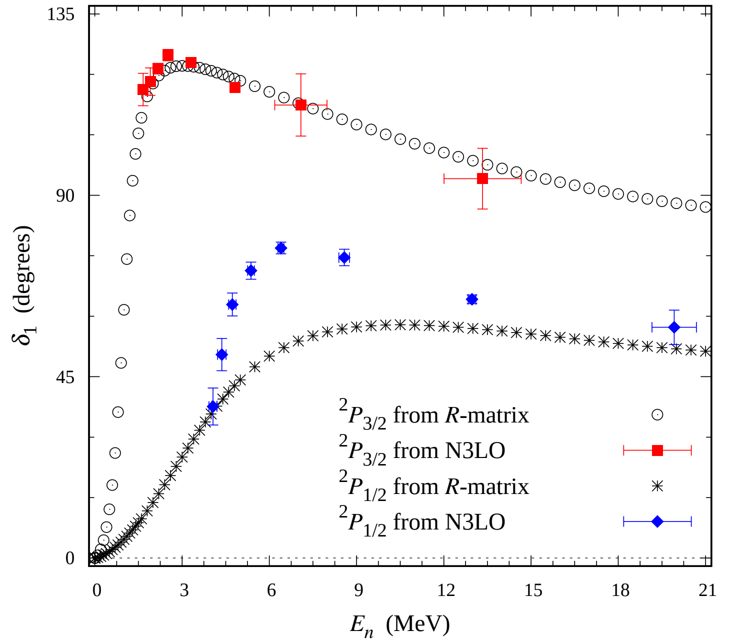
- Non-zero measurement in p-^{4}He scattering:
  Henneck et al. (1982), Lang et al. (1985)

$$A_L(46\ \mathrm{MeV}) = -(3.3 \pm 0.9) \cdot 10^{-7}$$

- sensitive to OPE $\sim h_\pi$
- presently investigated in NLEFT
- along the lines of *ab initio* α-α scattering
  Elhatisari et al., Nature **528** (2015) 111
- first results of PC n-^{4}He scattering using the recent wavefunction matching method with chiral EFT at N3LO
  Elhatisari et al., Nature **630** (2024) 59

$\hookrightarrow$ some fine-tuning of the 3NFs needed





Elhatisari, Hildenbrand, UGM, in preparation

A new lattice QCD approach

PHYSICAL REVIEW LETTERS **120,** 181801 (2018)

Novel Soft-Pion Theorem for Long-Range Nuclear Parity Violation

Xu Feng,[1,2,3] Feng-Kun Guo,[4,5] and Chien-Yeah Seng[6,*]

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[6]*INPAC, Shanghai Key Laboratory for Particle Physics and Cosmology, MOE Key Laboratory for Particle Physics, Astrophysics and Cosmology, School of Physics and Astronomy, Shanghai Jiao-Tong University, Shanghai 200240, China*

$$\boxed{F_\pi h_\pi^1 \simeq -\frac{(\delta m_N)_{4q}}{\sqrt{2}}}$$

$$(\delta m_N)_{4q} = \frac{1}{m_N}\langle p|\mathcal{L}^w_{\rm PC}(0)|p\rangle = -\frac{1}{m_N}\langle n|\mathcal{L}^w_{\rm PC}(0)|n\rangle$$

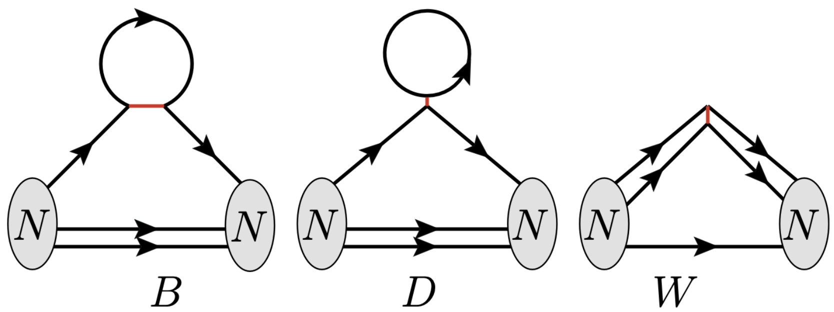
- This relation is not new, was already known in the days of CA
- Main result of FGS: Chiral corrections to this relations are $\sim (M_\pi/\Lambda_\chi)^2 \sim 1\%$

$\hookrightarrow$ Local four-quark operators of the PC weak Hamiltonian are easier computable in LQCD than h_π^1 directly

$\hookrightarrow$ This was taken up in project **A.10** in the CRC 110 (Bonn lattice group)

Status of the LQCD calculation

Petschlies, Schlage, Sen, Urbach, Eur. Phys. J. A **60**:9 (2024)



- 3 different topolgies of the 4q insertion
- $M_\pi = 261$ MeV, $a = 0.091$ fm, $L = 3.1$ fm
- Weak interactions treated in perturbation theory

$$m_{\rm eff}^{(\lambda)}(t|\tau) = m_{\rm eff}(t|\tau) + \frac{\lambda}{2}(\delta m)_{4q} + \mathcal{O}(\lambda^2)$$

- Operator renormalization not yet done, can only calculate the bare value of class W

$$\boxed{h_\pi^1(W, \text{bare}) = 8.08(98) \cdot 10^{-7}}$$

↪ of reasonable size, comparable to the earlier result of Wasem

↪ waiting for the fully renormalized result including all three topologies

Summary & outllok

- The extracted values of h_π still show a sizeable spread

  $\hookrightarrow$ a better lattice QCD calculation is under way

- Evaluation of all data from few-nucleon systems still to be done

  $\hookrightarrow$ a few more measurements are under way ($\vec{\gamma} d \to np, \vec{n} d \to t\gamma, \ldots$)

- An $\vec{p}p$ scattering experiment around 125 MeV could give more information

- How about many-body systems?

- PV measured in other systems, but theoretically difficult (F, Cs, La, Hf, . . .)

  $\hookrightarrow$ NLEFT at N3LO might be the way to go

- For more details, see the reviews

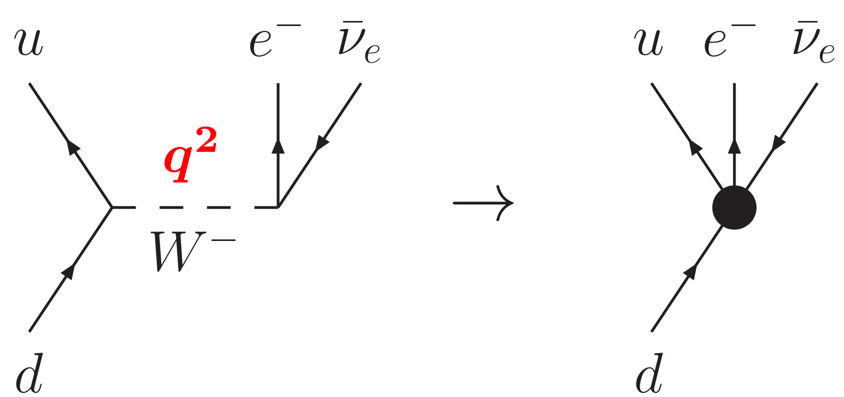
  de Vries, UGM, Int. J. Mod. Phys. E **25** (2016) 1641008

  de Vries, Epelbaum, Girlanda, Gnech, Mereghetti, Viviani, Front. in Phys. **8** (2020) 218

SPARES

REMINDER: FERMI THEORY

- Weak decays
  - mediated by the charged W bosons, $M_W \simeq 80$ GeV
  - energy release in neutron β-decay $\simeq 1$ MeV $[n \to p e^- \nu_e]$
  - energy release in kaon decays $\simeq$ a few 100 MeV $[K \to \pi \, \ell \, \nu]$



$$\frac{e^2}{8\sin\theta_W} \times \frac{1}{M_W^2 - q^2} \xrightarrow{q^2 \ll M_W^2} \frac{e^2}{8 M_W^2 \sin\theta_W}\left\{1 + \frac{q^2}{M_W^2} + \ldots\right\}$$
$$= \frac{G_F}{\sqrt{2}} + \mathcal{O}\left(\frac{q^2}{M_W^2}\right)$$

$\Rightarrow$ Fermi's current-current interaction w/ Fermi constant G_F

PREDICTING the LECs

- Leading order contact terms:

$$V_{\rm CT} = \frac{C_0}{F_\pi \Lambda_\chi^2}(\vec{\sigma}_1 - \vec{\sigma}_2)\cdot(\vec{p}+\vec{p}\,') + \frac{C_4}{F_\pi \Lambda_\chi^2} i(\vec{\tau}_1 \times \vec{\tau}_2)^3(\vec{\sigma}_1 + \vec{\sigma}_2)\cdot \vec{q}$$
$$+ \frac{1}{F_\pi \Lambda_\chi^2}\left(C_1 + C_2\frac{(\vec{\tau}_1+\vec{\tau}_2)^3}{2} + C_3\frac{\vec{\tau}_1\cdot\vec{\tau}_2 - 3\tau_1^3\tau_2^3}{2}\right) i(\vec{\sigma}_1 \times \vec{\sigma}_2)\cdot\vec{q}$$

- Predictions of the LECs C_i using resonance saturation

LEC	DDH best values	KMW soliton model
C_0	$4.7\cdot 10^{-6}$	$0.89\cdot 10^{-6}$
C_1	$1.2\cdot 10^{-6}$	$0.22\cdot 10^{-6}$
C_2	$-2.2\cdot 10^{-6}$	$-0.66\cdot 10^{-6}$
C_3	$1.0\cdot 10^{-6}$	$0.41\cdot 10^{-6}$
C_4	$0.25\cdot 10^{-6}$	$-0.05\cdot 10^{-6}$

DDH: Desplanques, Donoghue, Holstein, Ann. Phys. **124** (1980) 449

KMW: Kaiser, UGM, Nucl. Phys. A **499** (1989) 699

UGM, Weigel, Phys. Lett. B **447** (1999) 1