Evgeny Epelbaum, Ruhr University Bochum

Symmetry-violating nuclear properties, CEA Saclay, 23-27 June 2025

Parity- & time-reversal-violating nuclear forces

Based on: de Vries, EE, Girlanda, Gnech, Mareghetti, Viviani, Front. In Phys. 8 (2020)

- Chiral EFT in a nutshell
- PVTC and PVTV nuclear interactions
- Selected applications in the few-N sector
- Chiral EFT and the Δ(1232) isobar
- Chiral EFT and lattice QCD
- Summary

cea
ESNT
European Research Council
Ministerium für Kultur und Wissenschaft des Landes Nordrhein-Westfalen
ERATO
Exploratory Research for Advanced Technology

Framework in a nutshell

Standard Model (EFT)

Schwinger-Dyson , large-N_c, …

approximate chiral $SU(2)_L \times SU(2)_R$ symmetry of QCD

effective chiral Lagrangian $\mathscr{L}_{\text{eff}}(\pi, N)$

EFT (ChPT): $Q \in \{M_\pi/\Lambda_b,\ |\vec{p}\,|/\Lambda_b\}$

Lattice QCD

TOPT, MUT, S-matching ⟶

— S-matrix ($\pi\pi$, πN, $\pi\pi$N, …)
— nuclear forces and currents

$$\left[\sum_i \frac{-\vec{\nabla}_i^2}{2m} + \hat{V}_{2N} + \hat{V}_{3N} + \ldots\right]|\Psi\rangle = E|\psi\rangle$$

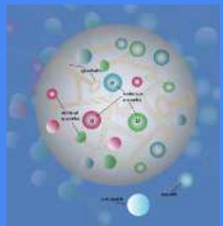
(finite-cutoff) chiral EFT

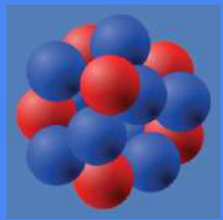
E_{FV}

EFT

finite-volume methods

Hadron/nuclear structure and dynamics

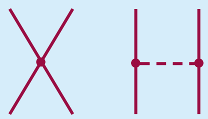
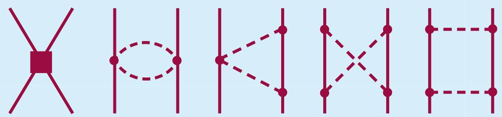
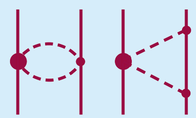
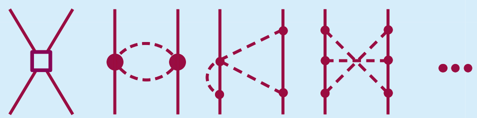
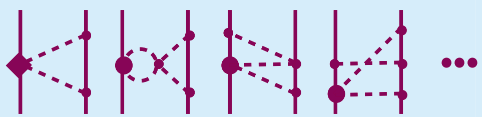

proton


nuclei


neutron stars

PCTC interactions

(NDA, chiral EFT with pions and nucleons as the only DoF)

	Two-nucleon force
LO (Q^0)	 Weinberg '90
NLO (Q^2)	
N^{2}LO (Q^3)	 van Kolck et al. '94 Friar, Coon '94 Kaiser et al. '97 Epelbaum et al. '98
N^{3}LO (Q^4)	 Kaiser '00-'02
N^{4}LO (Q^5)	 Entem, Kaiser, Machleidt, Nosyk '15

Variety of N^{2}LO and N^{3}LO NN potentials:
N^{2}LO$_{\mathrm{sat}}$, N^{2}LO$_{\mathrm{opt}}$, Δ-N^{2}LO, Norfolk, relativistic, …

— different DoF, regulators (local vs non-local) and fitting strategies

Most accurate N^{4}LO$^+$ potentials:

— **Idaho**: non-locally regularized Entem et al., '17

— **Bochum**: semil-local (SMS) Reinert et al., '18

$$V_{1\pi}(q) = \frac{\alpha}{\vec{q}^{\,2} + M_\pi^2}\, e^{-\frac{\vec{q}^{\,2}+M_\pi^2}{\Lambda^2}} + \text{subtraction},$$

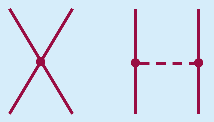
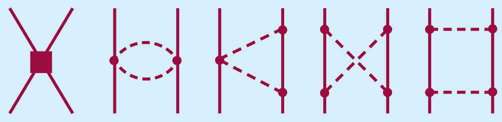
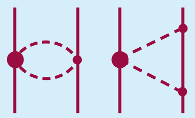
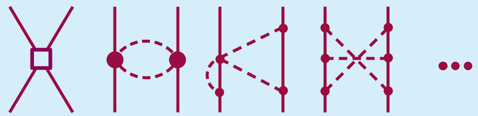
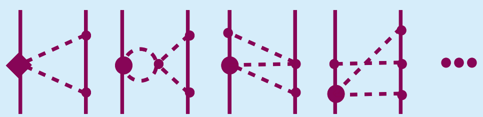
$$V_{2\pi}(q) = \frac{2}{\pi}\int_{2M_\pi}^{\infty} d\mu\,\mu\, \frac{\rho(\mu)}{\vec{q}^{\,2}+\mu^2}\, e^{-\frac{\vec{q}^{\,2}+\mu^2}{2\Lambda^2}} + \text{subtr.}$$

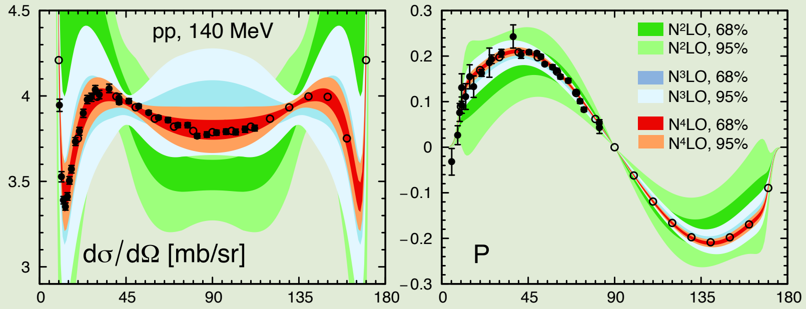
no long-range finite-cutoff artifacts

⇒ keeps pion physics intact!

PCTC interactions

(NDA, chiral EFT with pions and nucleons as the only DoF)

	Two-nucleon force
LO (Q^0)	 Weinberg '90
NLO (Q^2)	
N^{2}LO (Q^3)	 van Kolck et al. '94 Friar, Coon '94 Kaiser et al. '97 Epelbaum et al. '98
N^{3}LO (Q^4)	 Kaiser '00-'02
N^{4}LO (Q^5)	 Entem, Kaiser, Machleidt, Nosyk '15



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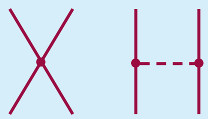
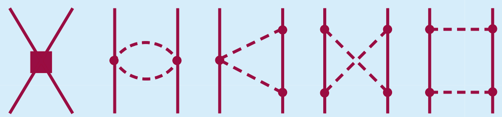
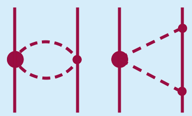
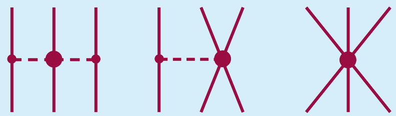
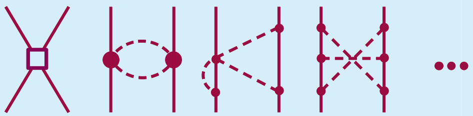
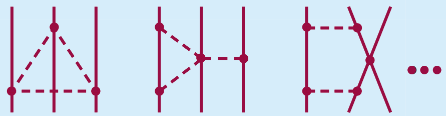
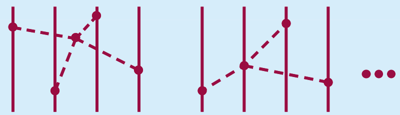
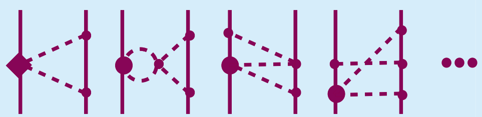
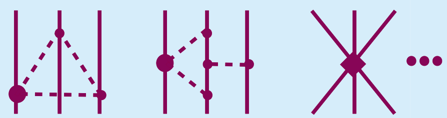
no long-range finite-cutoff artifacts

⇒ keeps pion physics intact!

PCTC interactions

(NDA, chiral EFT with pions and nucleons as the only DoF)

	Two-nucleon force	Three-nucleon force	Four-nucleon force
LO (Q^0)	 Weinberg '90	—	—
NLO (Q^2)		—	—
N²LO (Q^3)	 van Kolck et al. '94 Friar, Coon '94 Kaiser et al. '97 Epelbaum et al. '98	 van Kolck '94; Epelbaum et al. '02	—
N³LO (Q^4)	 Kaiser '00-'02	 Bernard, Epelbaum, Krebs, Meißner '08, '11	 Epelbaum '06, '07
N⁴LO (Q^5)	 Entem, Kaiser, Machleidt, Nosyk '15	 Girlanda et al.'11, Krebs et al. '11,'13	—

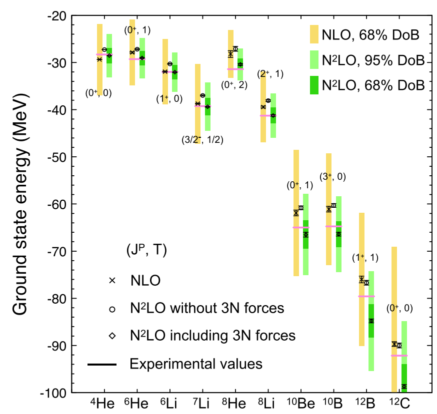
Symmetry-preserving regularization (in progress…)

PCTC interactions

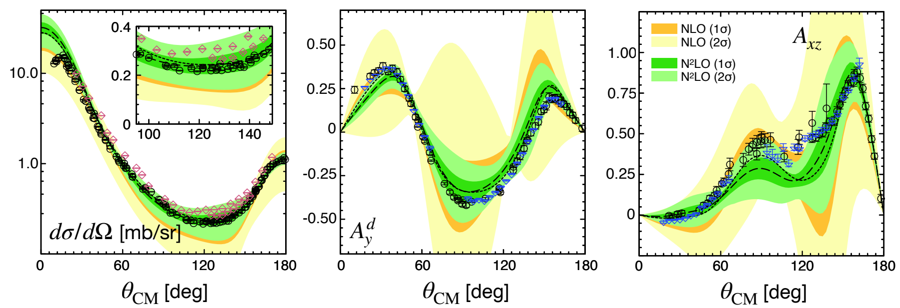
(NDA, chiral EFT with pions and nucleons as the only DoF)

	Two-nucleon force	Three-nucleon force
LO (Q^0)	Weinberg '90	—
NLO (Q^2)		—
N^{2}LO (Q^3)	van Kolck et al. '94 Friar, Coon '94 Kaiser et al. '97 Epelbaum et al. '98	van Kolck '94; Epelbaum et al. '02
N^{3}LO (Q^4)	Kaiser '00-'02	
N^{4}LO (Q^5)	Entem, Kaiser, Machleidt, Nosyk '15	

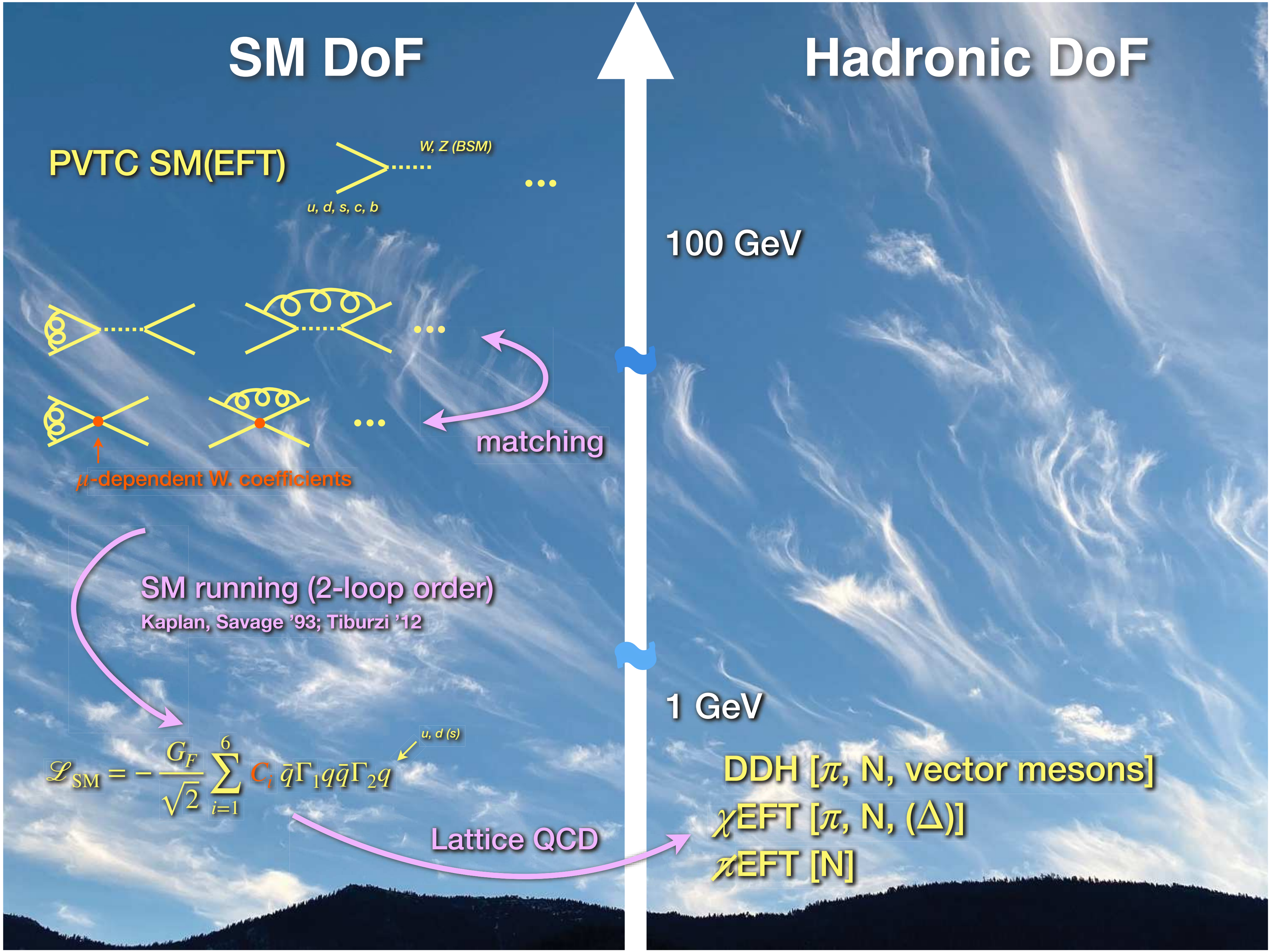
Selected p-shell nuclei



Elastic Nd scattering at 135 MeV



PVTC and PVTV interactions



SM DoF
Hadronic DoF
PVTC SM(EFT)
W, Z (BSM)
u, d, s, c, b
100 GeV
matching
μ-dependent W. coefficients
SM running (2-loop order)
Kaplan, Savage '93; Tiburzi '12
1 GeV
$\mathscr{L}_{\rm SM} = -\frac{G_F}{\sqrt{2}}\sum_{i=1}^{6} C_i\, \bar{q}\Gamma_1 q \bar{q}\Gamma_2 q$
u, d (s)
Lattice QCD
DDH [π, N, vector mesons]
χEFT [π, N, (Δ)]
$\not\pi$EFT [N]

The PVTC chiral Lagrangian

NDA: $h^1_\pi \sim G_F F_\pi \Lambda_\chi \sim 10^{-6}$

DDH: $h^1_\pi = 4.56 \times 10^{-7}$ (best value)
$h^1_\pi = (0 - 11.4) \times 10^{-7}$ (recommended range)

LQCD: $h^1_\pi = (1.1 \pm 0.5) \times 10^{-7}$ ($M_\pi = 390$) Wasem '12
$h^1_\pi = (8.08 \pm 0.98) \times 10^{-7}$ ($M_\pi = 260$) Petschlies et al. '24

— pion-nucleon Lagrangian:

$$\mathcal{L}^{(0)}_{\pi N} = \frac{h^1_\pi}{\sqrt{2}} N^\dagger [\boldsymbol{\pi} \times \boldsymbol{\tau}]^3 N + \ldots ,$$

$$\mathcal{L}^{(1)}_{\pi N} = -\frac{h^0_V}{2F_\pi} N^\dagger \boldsymbol{\tau} \cdot \dot{\boldsymbol{\pi}} N - \frac{h^1_V}{F_\pi} N^\dagger N \dot{\pi}^3 - \frac{2h^2_V}{F_\pi} \mathcal{I}_{ab} N^\dagger \tau^a N \dot{\pi}^b$$
$$- \frac{h^1_A}{F^2_\pi} N^\dagger \vec{\sigma} N \cdot [\boldsymbol{\pi} \times \vec{\nabla} \boldsymbol{\pi}]^3 + \frac{h^2_A}{F^2_\pi} \mathcal{I}_{ab} N^\dagger \vec{\sigma} \cdot \left([\boldsymbol{\pi} \times \vec{\nabla} \boldsymbol{\pi}]^a \tau^b + (\vec{\nabla} \pi^a) [\boldsymbol{\pi} \times \boldsymbol{\tau}]^b \right) N + \ldots ,$$

$\mathcal{I} = \mathrm{diag}(-1, -1, +2)$

NDA: $h_{V,A} \sim G_F F^2_\pi \sim 10^{-7}$

Kaplan, Savage '93; Kaplan, Savage, Springer '99; Zhu et al., '05; Girlanda et al.'08; de Vries et al. '14; Viviani et al. '14

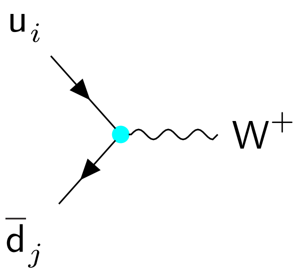
— nucleon-nucleon Lagrangian:

$$\mathcal{L}^{(1)}_{NN} = \frac{1}{\Lambda^2_\chi F_\pi} \Big[\frac{C_1}{2} \vec{\nabla} \times (N^\dagger \vec{\sigma} N) \cdot N^\dagger \vec{\sigma} N + \frac{C_2}{2} \vec{\nabla} \times (N^\dagger \vec{\sigma} \boldsymbol{\tau} N) \cdot \cdot N^\dagger \vec{\sigma} \boldsymbol{\tau} N$$
$$+ C_3 \epsilon_{ab3} \vec{\nabla} \cdot (N^\dagger \vec{\sigma} \tau^a N) N^\dagger \tau^b N + C_4 \vec{\nabla} \times (N^\dagger \vec{\sigma} \tau_3 N) \cdot N^\dagger \vec{\sigma} N + \frac{C_5}{2} \mathcal{I}_{ab} \vec{\nabla} \times (N^\dagger \vec{\sigma} \tau_a N) \cdot N^\dagger \vec{\sigma} \tau_b N \Big]$$

NDA: $C_i \sim G_F F_\pi \Lambda_\chi \sim 10^{-6}$

PVTV in the SM

Standard Model (dimension-4):



$\longleftarrow$ $$V_{\rm CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$ $\longleftarrow$ 3 mixing angles +1 complex phase $\delta_{\rm CP}$

$$\mathcal{L}^{\theta}_{PVTV} = -\theta \frac{g_s^2}{64\pi^2} \varepsilon^{\mu\nu\alpha\beta} G^a_{\mu\nu} G^a_{\alpha\beta} \quad \longrightarrow \quad \mathcal{L}^{\theta}_{PVTV} = \frac{m_u m_d}{m_u + m_d} \bar{\theta}\, \bar{q} i \gamma_5 q$$

Baluni '79; Crewther et al.'79

The strong CP problem: $\bar{\theta} \lesssim 10^{-10}$ (bounds on the neutron EDM…)

Both SM mechanisms are insufficient to explain the observed matter-antimatter asymmetry of the Universe Gavela et al., Huet et al.

PVTV beyond the SM

Beyond Standard Model physics:

— Dominant effects are expected to be induced by dimension-6 operators
Khriplovich, Lamoreaux; Pospelov, Ritz; Dekens, de Vries; Engel, Ramsey-Musolf, van Kolck, …

Tree-level matching onto the hadronic scale $\mu = 1$ GeV
de Vries et al.'13; Jenkins et al. '18; Mereghetti '18

— Most relevant operators:

depend on $\tilde{c}_\gamma^{(q)}$, $\tilde{c}_g^{(q)}$

$$\mathcal{L}_{PVTV}^{6,\mathrm{hadr}} = \frac{g_s \tilde{C}_G}{6v^2} f^{abc}\epsilon^{\mu\nu\alpha\beta} G^a_{\alpha\beta} G^b_{\mu\rho} G^{c\,\rho}_{\nu} - \frac{1}{2v^2}\left(\bar{q}\,[d_E]\, i\sigma^{\mu\nu}\gamma_5 q\, eF_{\mu\nu} + \bar{q}\,[d_{CE}]\, i\sigma^{\mu\nu}\, g_s G_{\mu\nu}\gamma_5 q\right)$$
$$-\frac{4G_F}{\sqrt{2}}\left\{\Sigma_1^{(ud)}(\bar{d}_L u_R \bar{u}_L d_R - \bar{u}_L u_R \bar{d}_L d_R) + \Sigma_2^{(ud)}(\bar{d}_L^\alpha u_R^\beta\, \bar{u}_L^\beta d_R^\alpha - \bar{u}_L^\alpha u_R^\beta\, \bar{d}_L^\beta d_R^\alpha)\right\}$$
$$-\frac{4G_F}{\sqrt{2}}\left\{\Xi_1^{(ud)}\bar{d}_L\gamma^\mu u_L\, \bar{u}_R\gamma_\mu d_R + \Xi_2^{(ud)}\bar{d}_L^\alpha\gamma^\mu u_L^\beta\, \bar{u}_R^\beta\gamma_\mu d_R^\alpha\right\}$$

Scaling of the W. coefficients: $\tilde{C}_G,\ \tilde{c}^{(q)}_{\gamma,g},\ \Sigma^{(ud)}_{1,2},\ \Xi^{(ud)}_{1,2} \sim \left[\frac{\text{Higgs VeV } v = 246 \text{ GeV}}{\text{Scale of new physics}}\right]^2$

(Remember: $G_F = 1.17 \times 10^{-5}$ GeV^{-2})

PVTV chiral Lagrangian

$$\mathcal{L}_{\pi}^{(0)} = M\bar{\Delta}\pi^3\,\boldsymbol{\pi}\cdot\boldsymbol{\pi} \,+\, \ldots$$

$$\mathcal{L}_{\pi N}^{(0)} = \bar{g}_0 N^\dagger \boldsymbol{\pi}\cdot\boldsymbol{\tau} N \,+\bar{g}_1 N^\dagger \pi^3 N \,+\bar{g}_2 N^\dagger \pi^3\tau^3 N + \ldots, \qquad \mathcal{L}_{\gamma N} = -\frac{1}{2}N^\dagger(\bar{d}_0 + \bar{d}_1\tau^3)\sigma^i N\,(F_{0i} - F_{i0})$$

$$\mathcal{L}_{NN}^{(1)} = \frac{1}{\Lambda_\chi^2 F_\pi}[\bar{C}_1\vec{\nabla}\cdot(N^\dagger\vec{\sigma}N)\,N^\dagger N + \bar{C}_2\vec{\nabla}\cdot(N^\dagger\vec{\sigma}\boldsymbol{\tau}N)\cdot N^\dagger\boldsymbol{\tau}N$$
$$+\;\bar{C}_3\vec{\nabla}\cdot(N^\dagger\vec{\sigma}\tau^3N)N^\dagger N + \bar{C}_4\vec{\nabla}\cdot(N^\dagger\vec{\sigma}N)N^\dagger\tau^3 N + \bar{C}_5\mathcal{I}_{ab}\,\vec{\nabla}\cdot(N^\dagger\vec{\sigma}\tau^a N)\,N^\dagger\tau^b N]$$

Mereghetti, Hockings, van Kolck, de Vries, Timmermans, Bsaisou, Hanhart, Liebig, Meißner, Minossi, Nogga, Wirzba, …

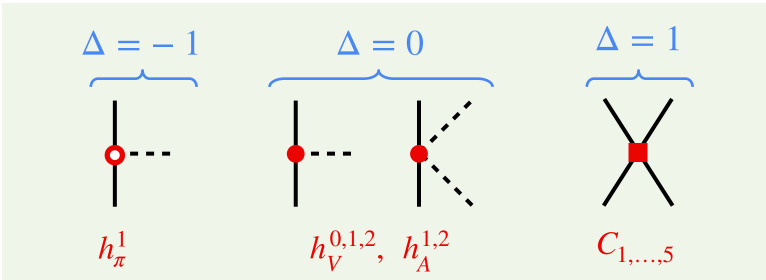
Scaling of the LECs:

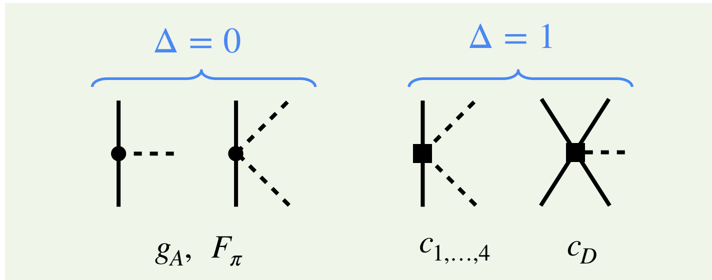
	$(4\pi\epsilon_{m_\pi})\bar{\theta}$	$(4\pi\epsilon_{m_\pi})\epsilon_v\tilde{c}_g^{(u,d)}$	$(4\pi\epsilon_{m_\pi})\epsilon_v\tilde{c}_\gamma^{(u,d)}$	$4\pi\epsilon_v\tilde{C}_G$	$\epsilon_v\Xi_{1,2}^{(ud)}/(4\pi)$	$\epsilon_v\Sigma_{1,2}^{(ud)}/(4\pi)$
$\bar{\Delta}$	ϵ_{m_π}	ϵ_{m_π}	–	$\varepsilon\epsilon_{m_\pi}^2$	1	ϵ_{m_π}
$\bar{g}_0$	1	1	–	ϵ_{m_π}	$\varepsilon\epsilon_{m_\pi}$	ϵ_{m_π}
$\bar{g}_1$	$\varepsilon\epsilon_{m_\pi}$	1	–	$\varepsilon\epsilon_{m_\pi}$	1	$\varepsilon\epsilon_{m_\pi}$
$\bar{g}_2$	$\varepsilon^2\epsilon_{m_\pi}^2$	$\varepsilon\epsilon_{m_\pi}$	–	$\varepsilon^2\epsilon_{m_\pi}^2$	$\varepsilon\epsilon_{m_\pi}$	$\varepsilon^2\epsilon_{m_\pi}^2$
$\bar{d}_{0,1}f_\pi$	$e\,\epsilon_\chi$	$e\,\epsilon_\chi$	$e\,\epsilon_\chi$	$e\,\epsilon_\chi$	$e\,\epsilon_\chi$	$e\,\epsilon_\chi$
$\bar{C}_{1,2}$	1	1	–	1	$\varepsilon\epsilon_{m_\pi}$	1
$\bar{C}_{3,4}$	$\varepsilon\epsilon_{m_\pi}$	1	–	$\varepsilon\epsilon_{m_\pi}$	1	$\varepsilon\epsilon_{m_\pi}$
$\bar{C}_5$	$\varepsilon^2\epsilon_{m_\pi}^2$	$\varepsilon\epsilon_{m_\pi}$	–	$\varepsilon^2\epsilon_{m_\pi}^2$	$\varepsilon\epsilon_{m_\pi}$	$\varepsilon^2\epsilon_{m_\pi}^2$

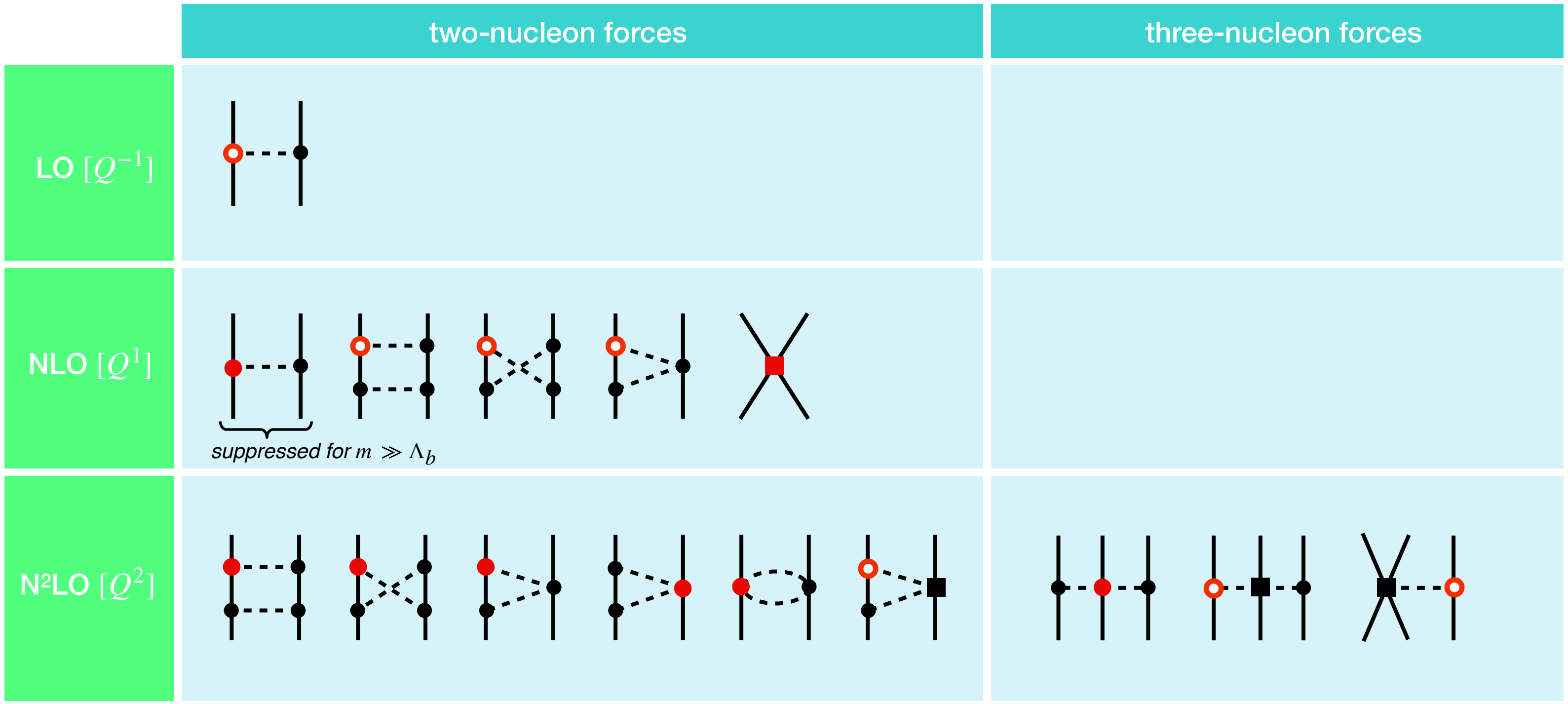
$$\epsilon \equiv \frac{m_d - m_u}{m_d + m_u} \sim \frac{1}{3} \qquad \epsilon_{m_\pi} \equiv \frac{m_\pi^2}{\Lambda_\chi^2} \sim 10^{-2} \qquad \epsilon_\chi \equiv \frac{F_\pi^2}{\Lambda_\chi^2} = \frac{1}{(4\pi)^2} \sim 10^{-2} \qquad \epsilon_v \equiv \frac{\Lambda_\chi^2}{v^2} \sim 10^{-5}$$

PVTC nuclear forces

Power counting $[Q^n]$: $n = -4 + 2N + 2L + \sum V_i \Delta_i$, where $\Delta_i = d_i + n_i/2 - 2$



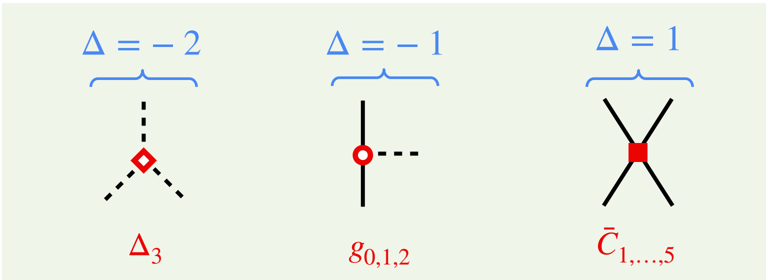


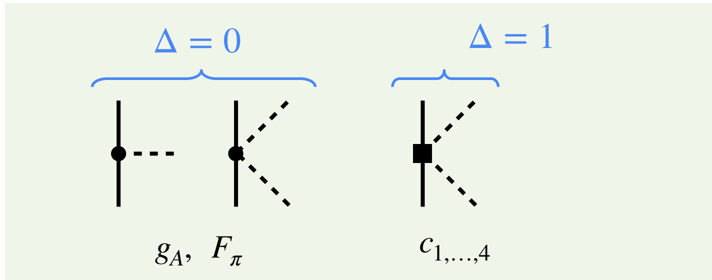


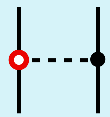
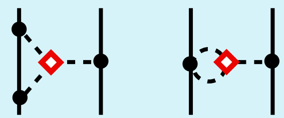
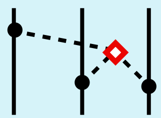
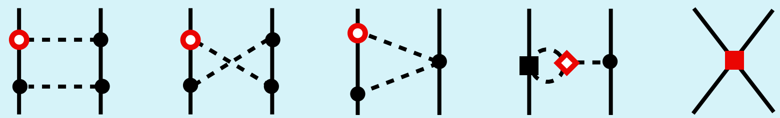
Zhu, Maekawa, Holstein, Ramsey-Musolf, van Kolck, de Vries, Li, Meißner, Nogga, EE, Kaiser, Gnech, Viviani, Baroni, Girlanda, Kievsky, Marcucci, Schiavilla, …

PVTV nuclear forces

Power counting $[Q^n]$: $n = -4 + 2N + 2L + \sum V_i \Delta_i$, where $\Delta_i = d_i + n_i/2 - 2$





	two-nucleon forces	three-nucleon forces
LO $[Q^{-1}]$		
NLO $[Q^{0}]$		
N²LO $[Q^{1}]$		

Maekawa, Mereghetti, de Vries, van Kolck, Bsaisou, Hanhart, Liebig, Meißner, Minossi, Nogga, Wirzba, …

Selected results

Selected results

- PV longitudinal asymmetry in $\vec{n}p \rightarrow d\gamma$

$$A_\gamma(\theta) = \frac{d\sigma_+(\theta) - d\sigma_-(\theta)}{d\sigma_+(\theta) + d\sigma_-(\theta)} = a_\gamma \cos\theta$$

Data from Oak Ridge: $a_\gamma = (-3.0 \pm 1.4 \pm 0.2) \cdot 10^{-8}$

Blyth et al. [NPDGamma Collab.], PRL 121 (18)

Insensitive to short-range interactions [Desplanques'75,'80, McKellar '75, Schiavilla et al.'04] $\Rightarrow$ good probe of h_π^1

NLO calculation (including 2-body PC and PV currents): $a_\gamma = (-0.11 \pm 0.05)\, h_\pi^1 \Rightarrow h_\pi^1 = (2.7 \pm 1.8) \times 10^{-7}$

de Vries, Li, Meißner, Nogga, EE, Kaiser, PLB 747 (15)

- PV $\vec{p}p$ scattering

$$A_z(E,\theta) = \frac{\sigma_+(\theta,E) - \sigma_-(\theta,E)}{\sigma_+(\theta,E) + \sigma_-(\theta,E)}$$

Several measurements exist:

Nagle et al. '79; Kystrin et al. '87; Eversheim et al. '91; Berdoz et al. '03

E **(MeV)**	$\bar{A}_z$ **(10^{-7})**	**(θ_1, θ_2)**
13.6	-0.97 ± 0.20	$(20^\circ, 78^\circ)$
45	-1.53 ± 0.21	$(23^\circ, 52^\circ)$
221	$+0.84 \pm 0.34$	$(5^\circ, 90^\circ)$

Chiral EFT calculations:

— NLO de Vries, Meißner, EE, Kaiser '13; de Vries, Li, Meißner, Kaiser, Liu, Zhu '14; Viviani, Baroni, Girlanda, Kievsky, Marcucci, Schiavilla '14

— N^{2}LO de Vries, EE, Girlanda, Gnech, Mereghetti, Viviani '20;

Selected results

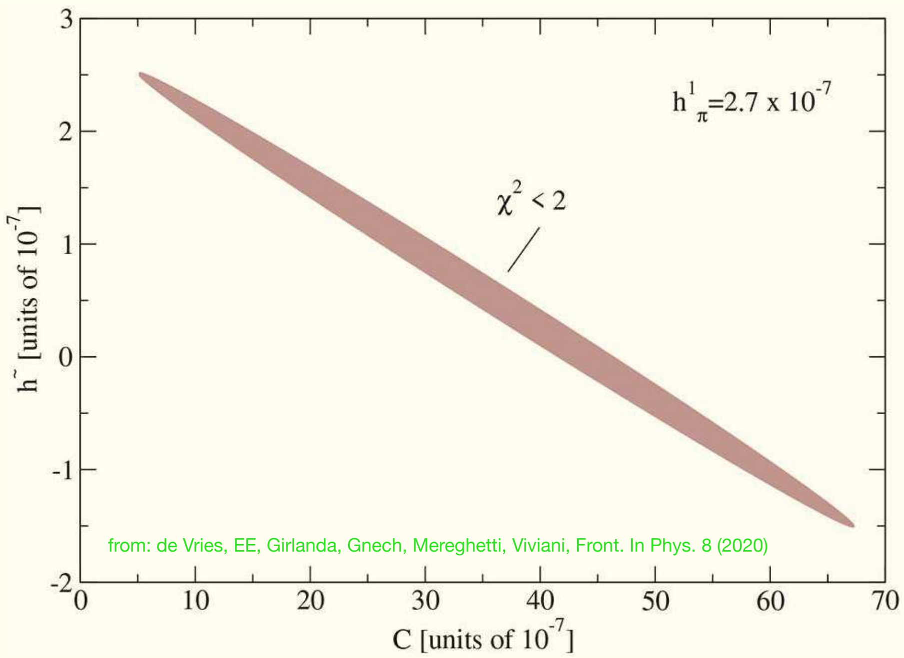
$$\overline{A}_z = \underbrace{h_\pi^1\, a_0^{(pp)} + C\, a_1^{(pp)}}_{\text{NLO}} + \underbrace{\tilde{h}\, a_2^{(pp)}}_{\text{N}^2\text{LO}}$$

with the linear combinations of LECs:

$$C = C_1 + C_2 + 2\,(C_4 + C_5)$$

$$\tilde{h} = \frac{5g_A}{4}h_V^0 + 2\left(\frac{g_A}{4}h_V^1 - h_A^1\right) - 2\left(\frac{g_A}{3}h_V^2 + h_A^2\right)$$

Unfortunately, the strongly correlated low-energy data do not allow to fix all 3 LECs…



from: de Vries, EE, Girlanda, Gnech, Mereghetti, Viviani, Front. In Phys. 8 (2020)

- PV longitudinal asymmetry in $\vec{n}\,^3\mathrm{He} \;\rightarrow\; p\,^3\mathrm{H}$

Recent data from Oak Ridge: $a_z \;=\; (1.58 \pm 0.97\,(\mathrm{stat}) + 0.24\,(\mathrm{sys})) \times 10^{-8}$ Gericke et al. [n3He Collab.] PRL 125 (2020)

NLO calculation Viviani et al., PRC 89 (2014): $a_z = h_\pi^1 a_0^{(nh)} + C_1 a_1^{(nh)} + C_2 a_2^{(nh)} + C_3 a_3^{(nh)} + C_4 a_4^{(nh)} + C_5 a_5^{(nh)}$

$a_0^{(nh)}$ (TOT)	$a_1^{(nh)}$	$a_2^{(nh)}$	$a_3^{(nh)}$	$a_4^{(nh)}$	$a_5^{(nh)}$
–0.1444	0.0061	0.0226	–0.0199	–0.0174	–0.0005

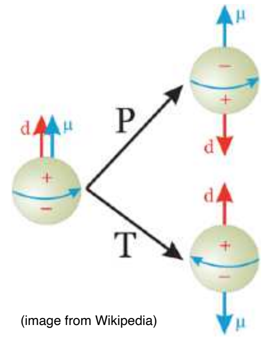
Selected results

- Electric dipole moments of light nuclei

Experimental searches for EDMs Chupp, Fierlinger, Ramsey-Musolf, Singth, RMP 91 (2019)

— neutron & nuclear: PSI, TRIUMF, SNS@ORNL, ILL, COSY, LANL, …

— experiments with muons, atoms, ions, molecules, …



Theory de Vries et al., PRC 84 (2011); Bsaisou et al., EPJA 49 (2013), JHEP 03 (2015); Yamanaka, Hiyama, PRC 91 (2015)

$$d^A = \left\langle \Psi^A_{\rm P-even} \right| \sum_i \frac{[(d_p + d_n) + (d_p - d_n)\tau_i^z]\vec{\sigma}_i}{2} \left| \Psi^A_{\rm P-even} \right\rangle + 2 \left\langle \Psi^A_{\rm P-even} \right| \sum_i e \frac{1+\tau_i^z}{2} \vec{r}_i \left| \Psi^A_{\rm P-odd} \right\rangle$$

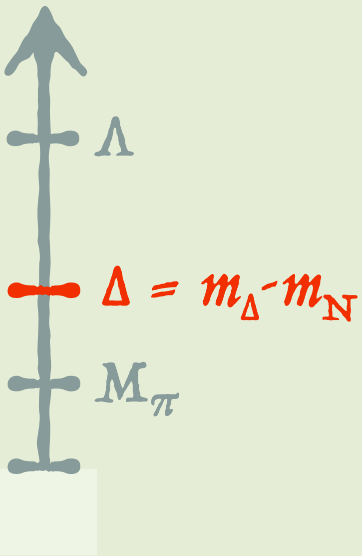
$$= \underbrace{d_p a_p + d_n a_n}_{\text{nucleon EDM}} + \underbrace{\bar{g}_0 a_0 + \bar{g}_1 a_1 + \bar{g}_2 a_2}_{\pi\text{N PVTV LECs}} + \underbrace{\bar{C}_1 A_1 + \bar{C}_2 A_2 + \bar{C}_3 A_3 + \bar{C}_4 A_4 + \bar{C}_5 A_5}_{\text{NN PVTV LECs}} + \underbrace{\bar{\Delta} a_\Delta}_{3\pi \text{ PVTV LECs}}$$

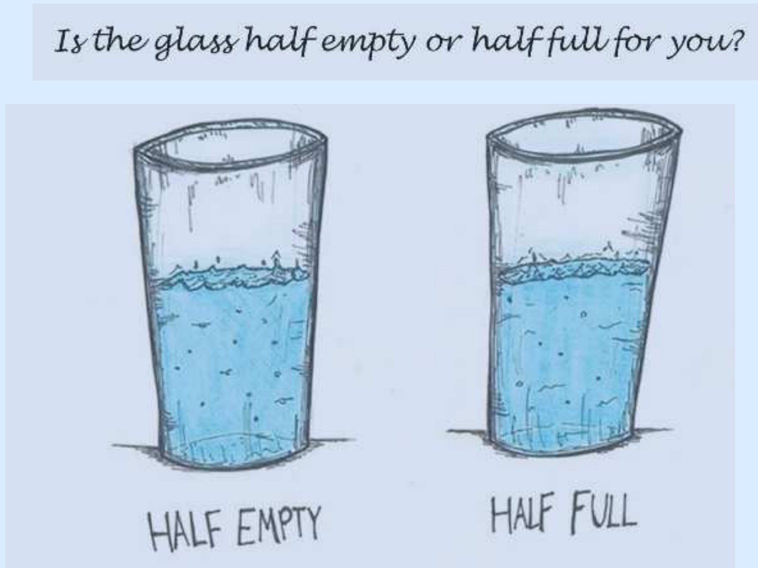
Numerical results:

	^{2}H	^{3}H	^{3}He
a_n	0.939	−0.033	0.908
a_p	0.939	0.909	−0.033
a_0 [fm]	—	−0.053	0.054
a_1 [fm]	0.200	0.158	0.158
a_2 [fm]	—	−0.119	0.119
A_1 [fm]	—	0.006	−0.006
A_2 [fm]	—	−0.010	0.010
A_3 [fm]	0.013	−0.008	−0.008
A_4 [fm]	−0.013	0.013	0.013
A_5 [fm]	—	−0.022	0.022
a_Δ [fm]	−0.304	−0.343	−0.339

de Vries, EE, Girlanda, Gnech, Mereghetti, Viviani, Front. In Phys. 8 (2020)

Chiral EFT and the Δ(1232) isobar





$\Delta \sim M_\pi$ $\Delta \sim \Lambda$

The small-scale (ε) expansion [Th. Hemmert et al. '98]

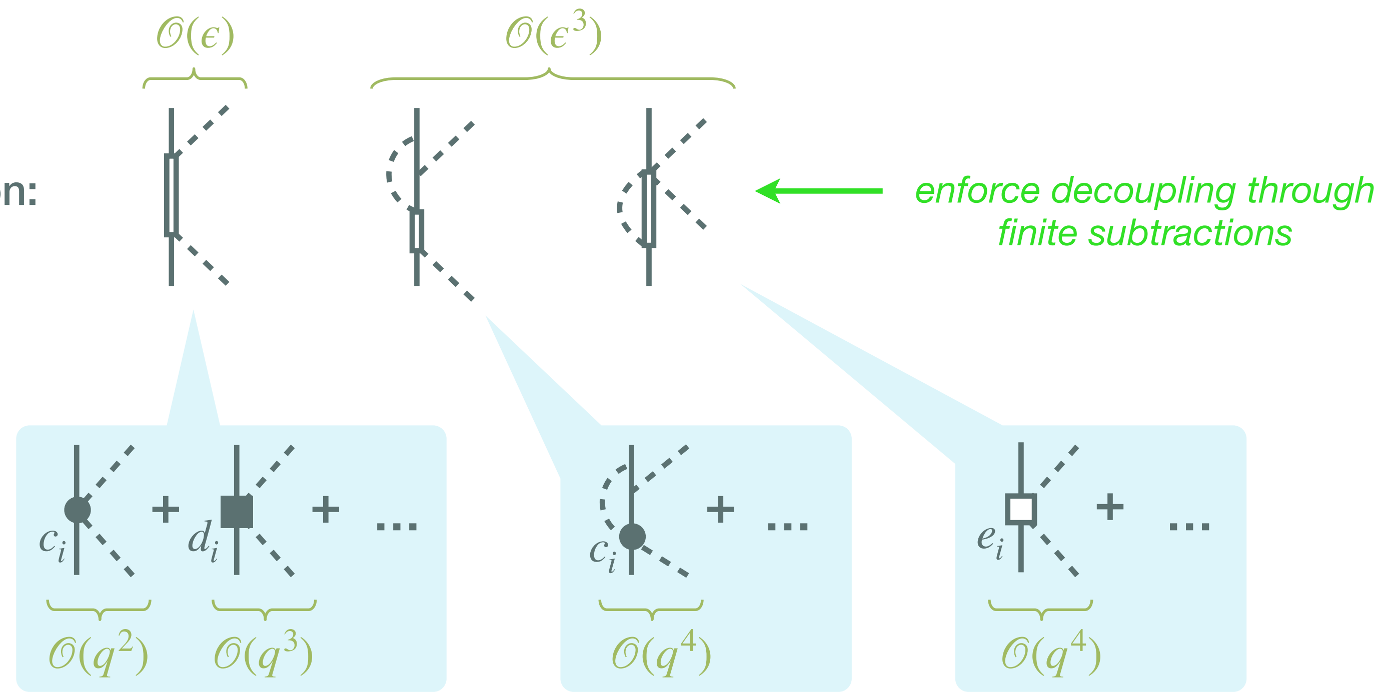
The strategy: Re-sum $1/\Delta^n$-contributions from $p \sim \Delta$ by including Δ(1232) in $\mathscr{L}_{\rm eff}$ and counting $\Delta \sim M_\pi = \mathcal{O}(\epsilon)$ while $\sqrt{m_N \Delta} = \mathcal{O}(1)$ (no coupled channels)

Potential concern: slow(er) convergence of χEFT due to Δ/Λ_b being twice as large as M_π/Λ_b?

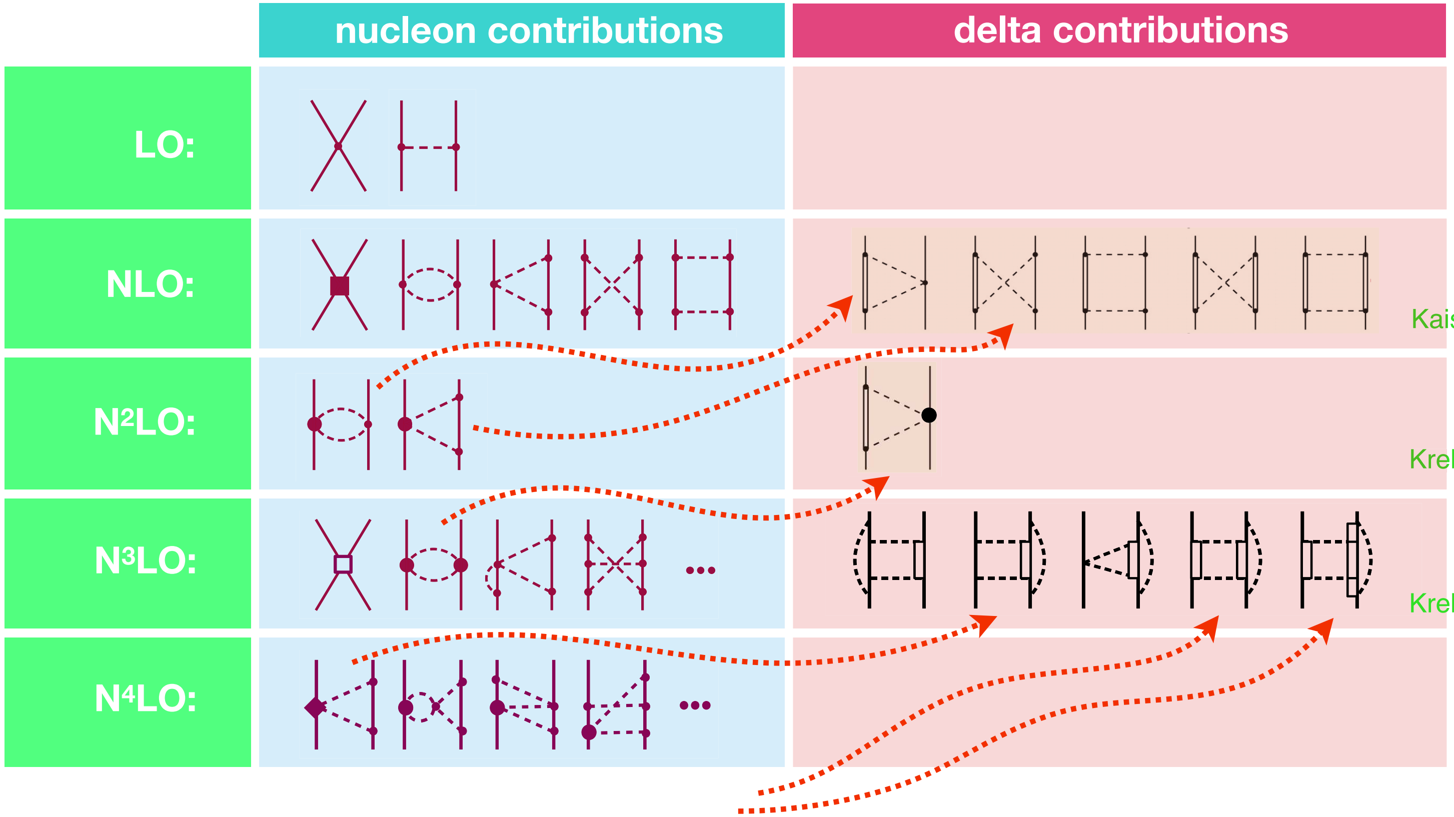
The Appelquist-Carrazone decoupling Theorem: Effects of heavy particles go into local terms in an EFT, either in renormalizable or in non-renormalizable suppressed by powers of the heavy mass

Small-scale expansion:

Chiral expansion:



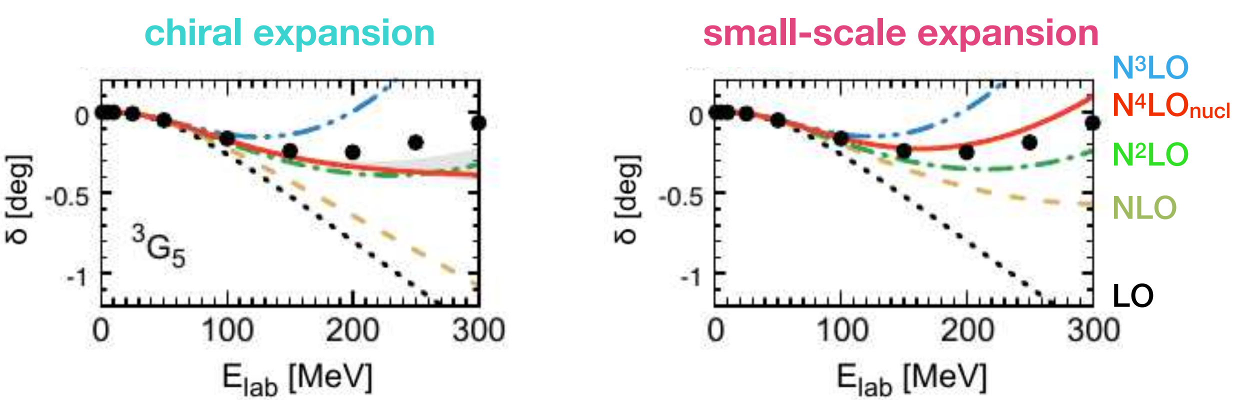
NN force in the small-scale expansion



Kaiser, Gerstendorfer, Weise '98

Krebs, EE, Meißner '07

Krebs, Gasparyan, EE, in prep.



Δ(1232)-contributions to CP-violating nuclear forces

Lukas Gandor, Hermann Krebs and EE, EPJA 60 (2024)

Searches for CP-violation in/beyond the SM with light nuclei (e.g., EDMs)

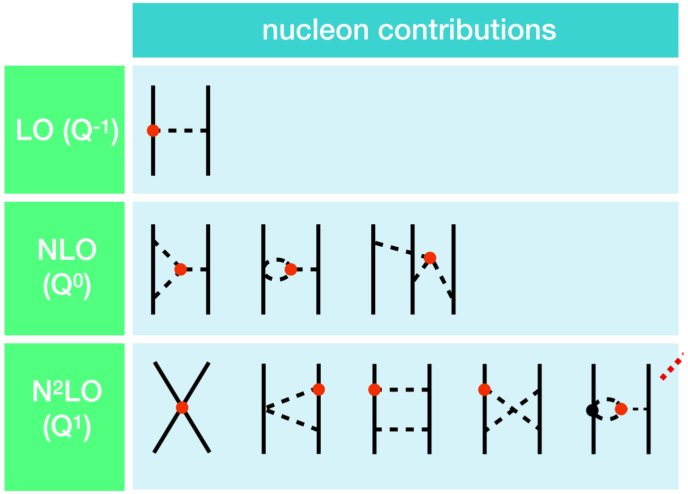
Bsaisou, Meißner, Nogga, Wirzba, de Vries, Gnech, Viviani, …

LO time-reversal violating vertices:

$$\mathcal{L}_{\text{TRV}}^{3\pi\,(0)} = M\Delta_3\pi_3\pi^2$$

$$\mathcal{L}_{\text{TRV}}^{\pi N\,(0)} = g_0\overline{\psi}\vec{\pi}\cdot\vec{\tau}\psi + g_1\overline{\psi}\pi_3\psi + g_2\overline{\psi}\pi_3\tau_3\psi$$

$$+\ 5\ NN\ contact\ terms$$



no sense to go beyond N²LO (more LECs…)

No LO CP-violating πNΔ-couplings

⇒ re-sum the 1/Δn-contributions to the PVTV nuclear forces without introducing additional parameters

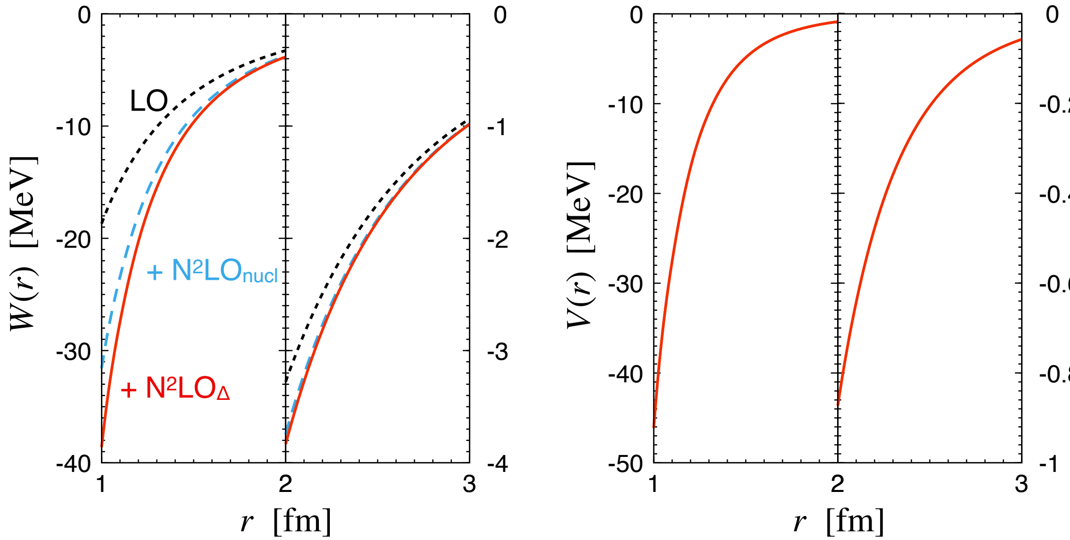
E.g., suppose the main source of CP violation is the QCD θ-term

$$\Rightarrow \quad \Delta_3, g_1, g_2 \ll g_0$$

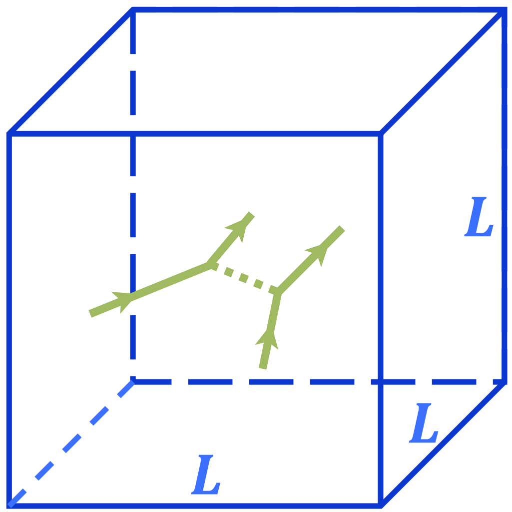
and the long-range potential involves just two structures:

$$V(r)\ \hat{r}\cdot(\vec{\sigma}_1-\vec{\sigma}_2)$$

$$+\ W(r)\ \vec{\tau}_1\cdot\vec{\tau}_2\ \hat{r}\cdot(\vec{\sigma}_1-\vec{\sigma}_2)$$



Chiral EFT and lattice QCD



Lattice QCD for two nucleons

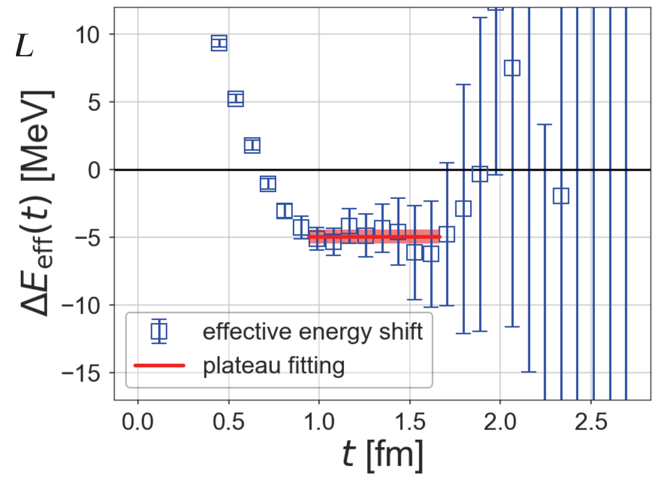
Lattice QCD studies for few-B systems: **HAL QCD, NPLQCD, PACS, CalLat, BaSc**

— truly first-principles approach

— finite-volume energies from 2-point correlators

$$C(t) = \langle 0 | \mathcal{O}(t+t_0)\mathcal{O}^\dagger(t_0) | 0 \rangle = \sum_{n=0}^{\infty} |\langle 0 | \mathcal{O} | n \rangle|^2 e^{-E_n t}$$

Lüscher's method: $\det \Big[\underbrace{M^{(\Gamma,\boldsymbol{P})}_{ln,l'n'}}_{\text{known matrix (depends on FV energies)}} - \delta_{ll'}\delta_{nn'} \cot \delta_l \Big] = 0$



from: Iritani, LATTICE2018

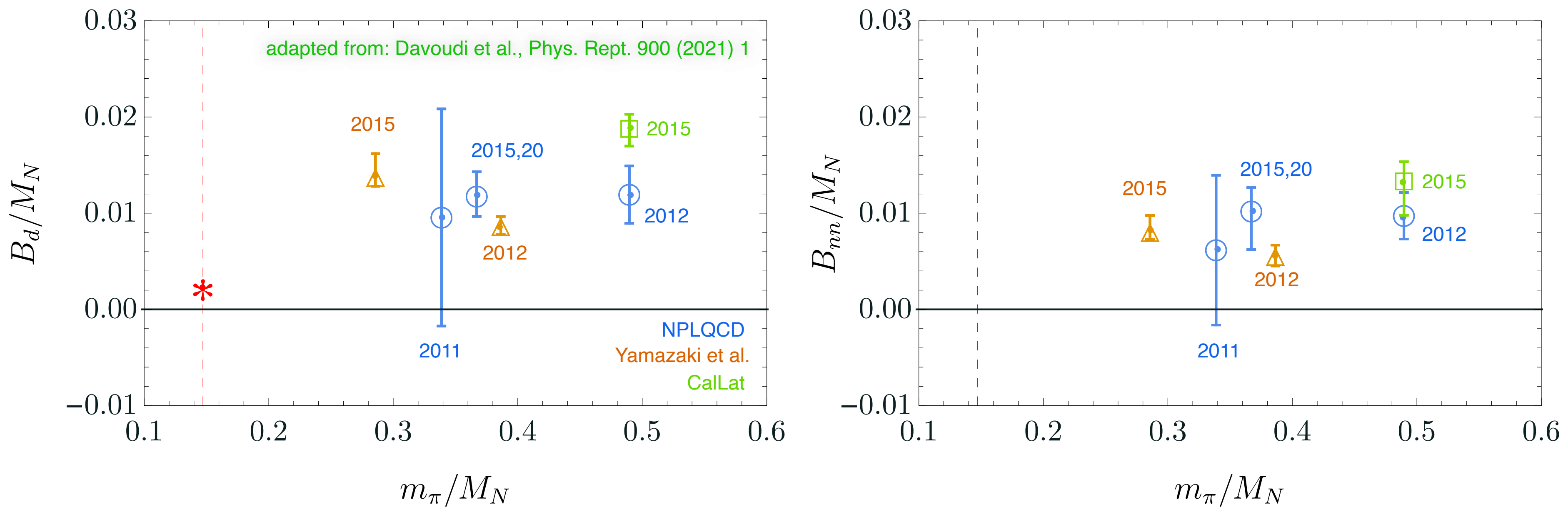
— Signal-to-Noise ratio: $\sim \exp\left[-A \left(m_B - \frac{3}{2} m_M \right) t \right]$ Parisi '84

— An alternative method [HAL QCD]: potentials from Nambu-Bethe-Salpeter wave functions (derivative expansion under control? see e.g. 1808.06299)

— Situation in the NN sector starts becoming less controversial

Lattice QCD for two nucleons

Lattice QCD studies for few-B systems: **HAL QCD, NPLQCD, PACS, CalLat, BaSc**



— HAL QCD sees NO bound states for all M_π—values

— also CalLat [2009.11825] strongly disfavors bound states at $M_\pi \sim 714$ MeV

— BaSc: „Di-nucleons do not form bound states at heavy pion mass", [2505.05547]

— Situation in the NN sector starts becoming less controversial

Chiral EFT and lattice QCD

Lattice-QCD

input for few-B systems (crucial for $S \neq 0$, BSM MEs and variable m_q)

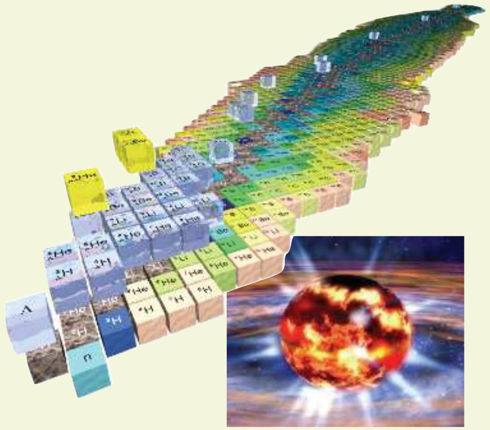
Experiment

Data for 2B & 3B observables at physical m_q

Chiral EFT

(Hyper-) nuclear interactions & current operators derived from the effective chiral Lagrangian

(Hyper-) nuclear physics, neutron stars, …



FAIR Jefferson Lab J-PARC

Finite volume energy spectra as an efficient interface between lattice-QCD and chiral EFT

Lu Meng, EE, JHEP 10 (21); Lu Meng, Baru, EE, Filin, Gasparyan, PRD 109 (24); Lu Meng et al., PRD 111 (2025) 3, 3

— infinite-V extrapolations without Lüscher

— solves the t-channel cut problem

— partial wave mixing included

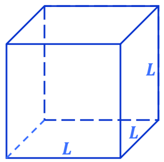
$$\underbrace{\det\left[\overbrace{M^{(\Gamma,\boldsymbol{P})}_{ln,l'n'}}^{\text{known function of FV energies}} - \delta_{ll'}\delta_{nn'}\cot\delta_l\right] = 0}_{\text{Lüscher's quantization condition is not valid below the left-hand cut}}$$

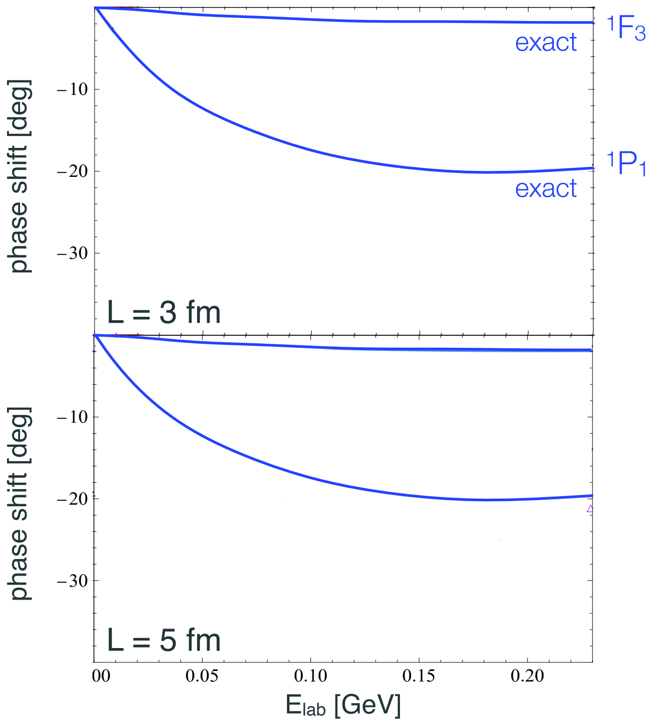
Two nucleons in a finite box (spin-0 channels)

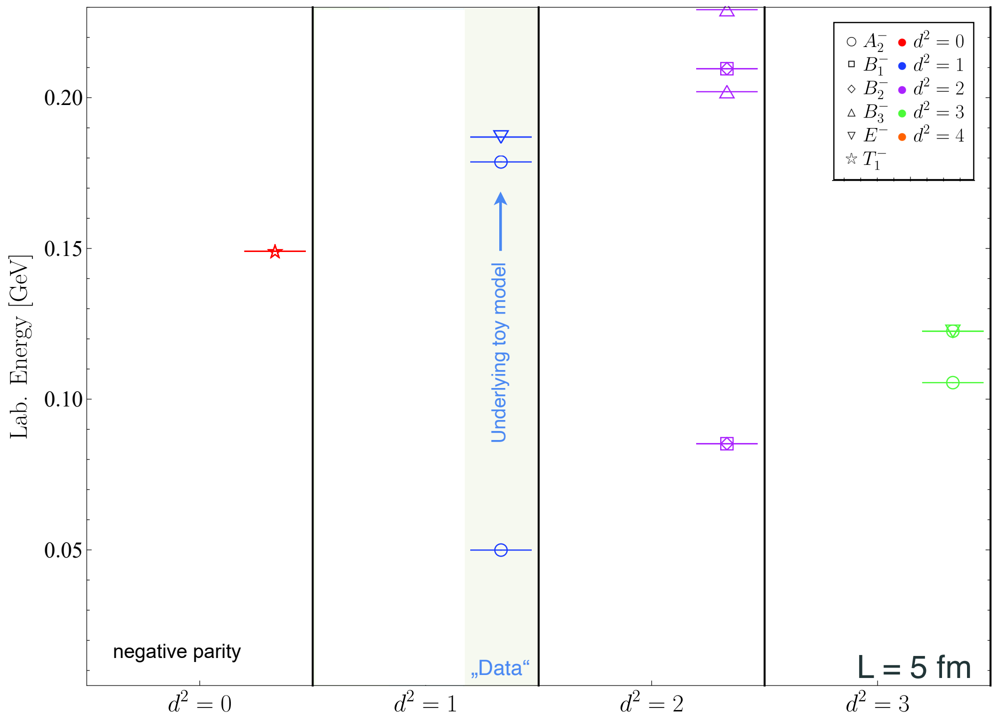
Lu Meng, EE, JHEP 10 (2021) 051

- As an illustration, consider the Hamiltonian $V_{\rm toy} = \underbrace{-\left(\frac{g_A}{2F_\pi}\right)^2 \frac{M_\pi^2}{\boldsymbol{q}^2+M_\pi^2}\boldsymbol{\tau}_1\cdot\boldsymbol{\tau}_2}_{\textit{long-range}} + \underbrace{(c_{h1}+c_{h2}\boldsymbol{\tau}_1\cdot\boldsymbol{\tau}_2)\frac{1}{\boldsymbol{q^2}+m_h^2}}_{\textit{short-range}}$

Infinite volume







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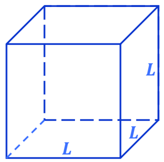
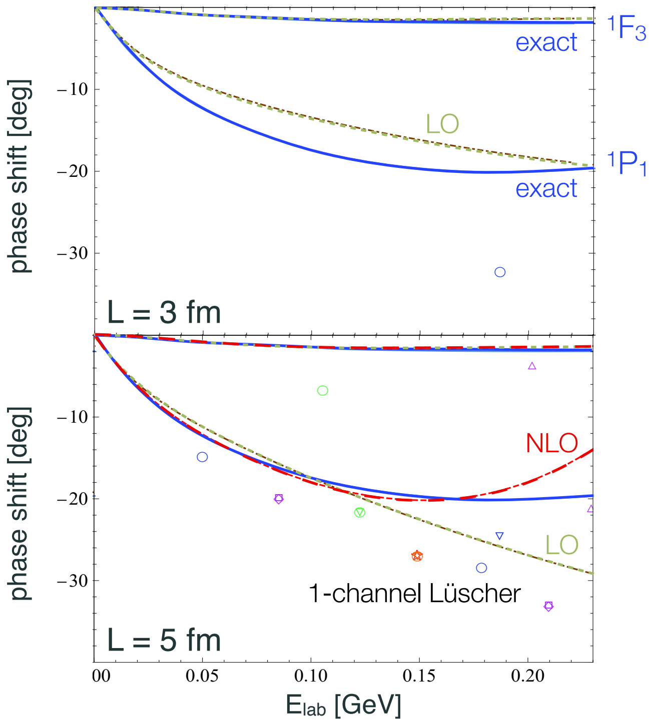
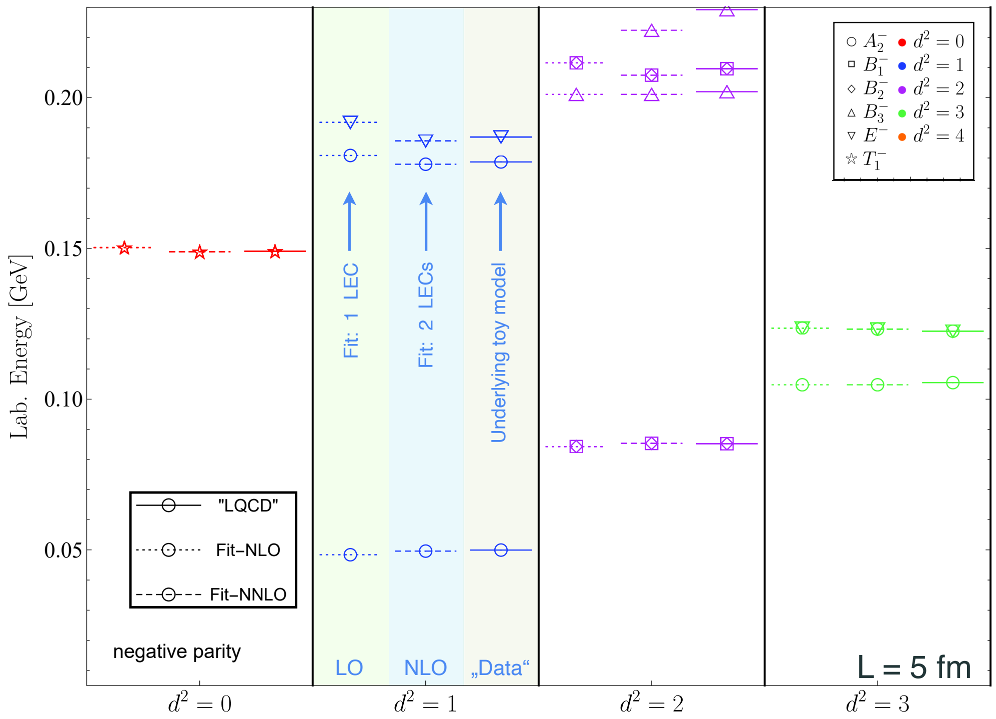
Infinite volume







Summary and outlook

- Good progress in describing few-nucleon P- and CP-violating observables in chiral EFT to N²LO (at this level already ~ 2×10 LECs…)
- PVTC LECs estimated from complementary observables, would be great to have data on longitudinal asymmetries in n-^{2}H scattering
- PVTV LECs have been translated to EDMs of light nuclei — waiting for signals…

Future:

More *ab-initio* studies of P-violating observables (also beyond few-N systems)

Symmetry-preserving gradient flow regularization from the PC sector Krebs, EE

More reliable uncertainty quantification see talk by Christian

Matching to lattice QCD

Thank you for your attention