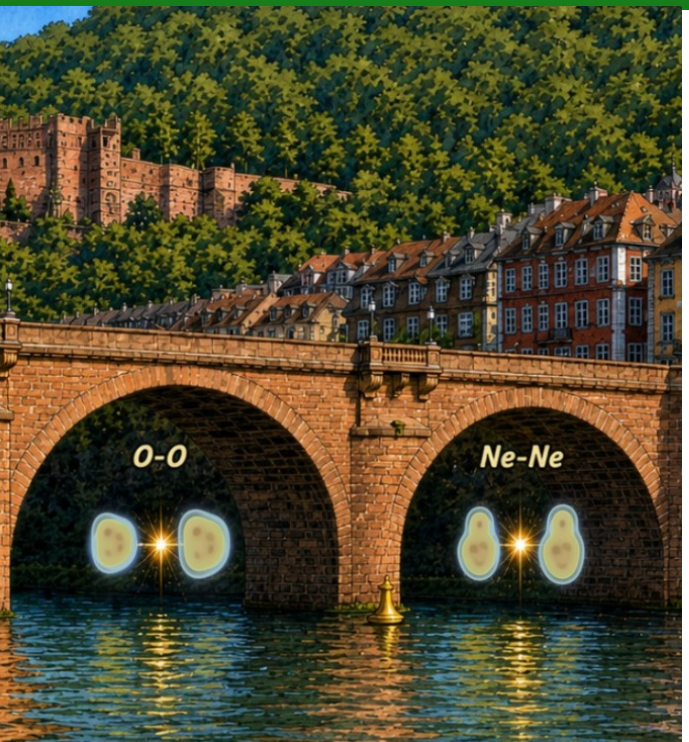
Evgeny Epelbaum, Ruhr University Bochum

EMMI Workshop on Light-Ion Collisions
KIP, Heidelberg, 21-25 Sep 2026

Nuclear forces from QCD

(using chiral EFT)



- Where do we stand with understanding nuclear interactions?
- What is the role of chiral symmetry?
- Precision nuclear physics from first principles?

erc European Research Council
Ministerium für Kultur und Wissenschaft des Landes Nordrhein-Westfalen
TOMOE

Nuclear Physics from First Principles

$$\mathcal{L}_{\mathrm{QCD}} = -\frac{1}{4} G_a^{\mu\nu} G_{a,\mu\nu} + \bar{q}(i\gamma^\mu D_\mu - \mathcal{M})q$$

Nuclear Physics from First Principles

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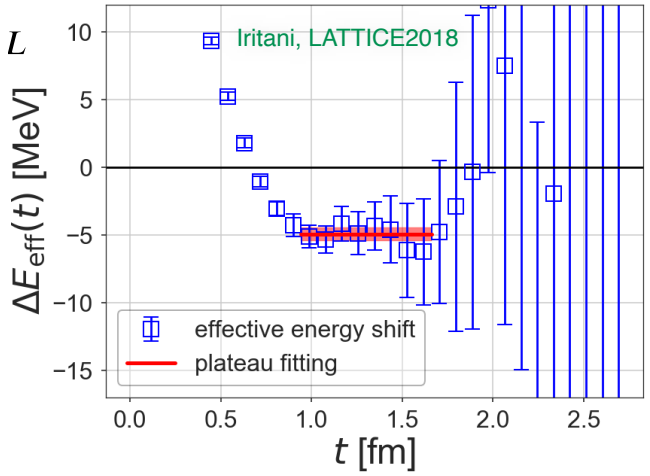
Lattice QCD (finite-volume discretized Euclidean space-time)

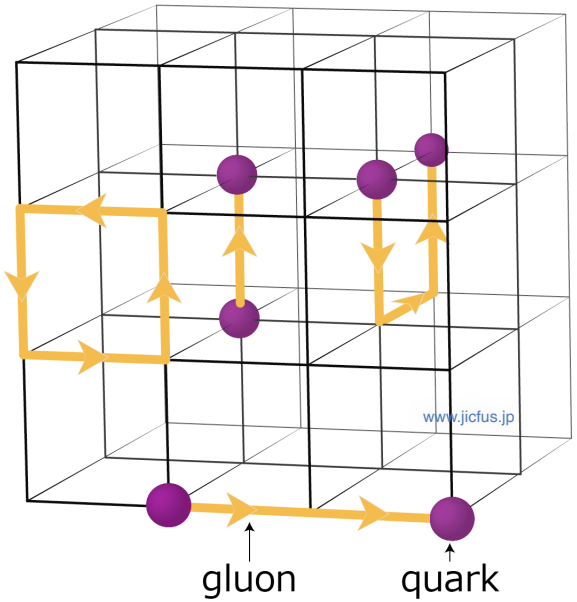
$$C(t) = \langle 0 \,|\, \mathcal{O}(t+t_0)\mathcal{O}^\dagger(t_0) \,|\, 0 \rangle = \sum_{n=0}^{\infty} |\langle 0 \,|\, \mathcal{O} \,|\, n \rangle|^2 \, e^{-E_n t}$$

sink (↑ $\mathcal{O}(t+t_0)$) source (↑ $\mathcal{O}^\dagger(t_0)$)

$\Rightarrow$ FV energies E_n $\Rightarrow$ hadron properties…

(continuum, volume and m_q extrapolations…)





Nuclear Physics from First Principles

$$\mathcal{L}_{\rm QCD} = -\frac{1}{4} G_a^{\mu\nu} G_{a,\mu\nu} + \bar{q}(i\gamma^\mu D_\mu - \mathcal{M})q$$

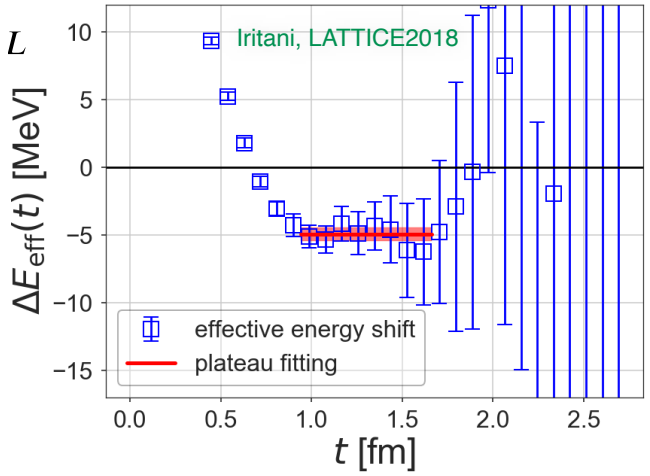
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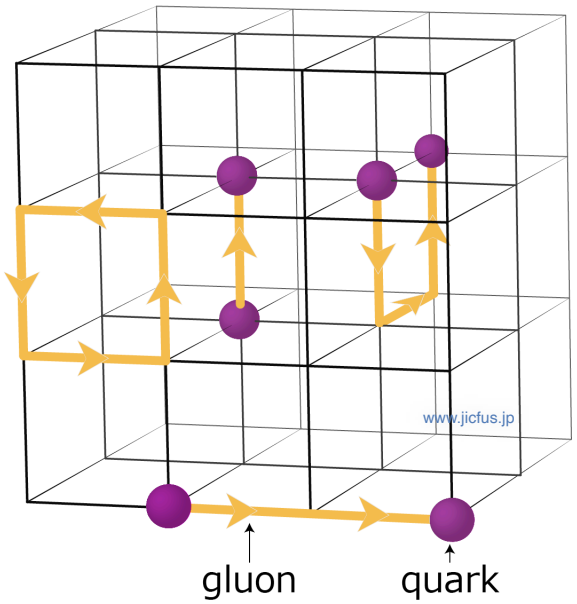
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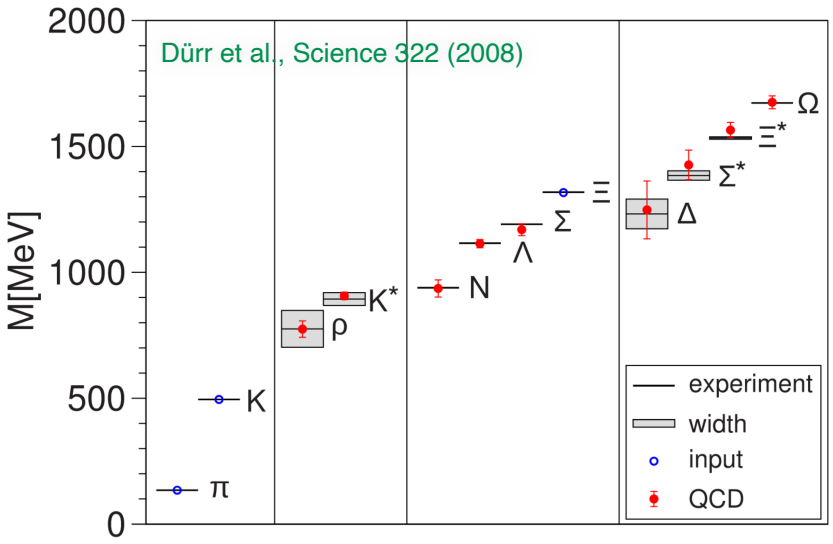
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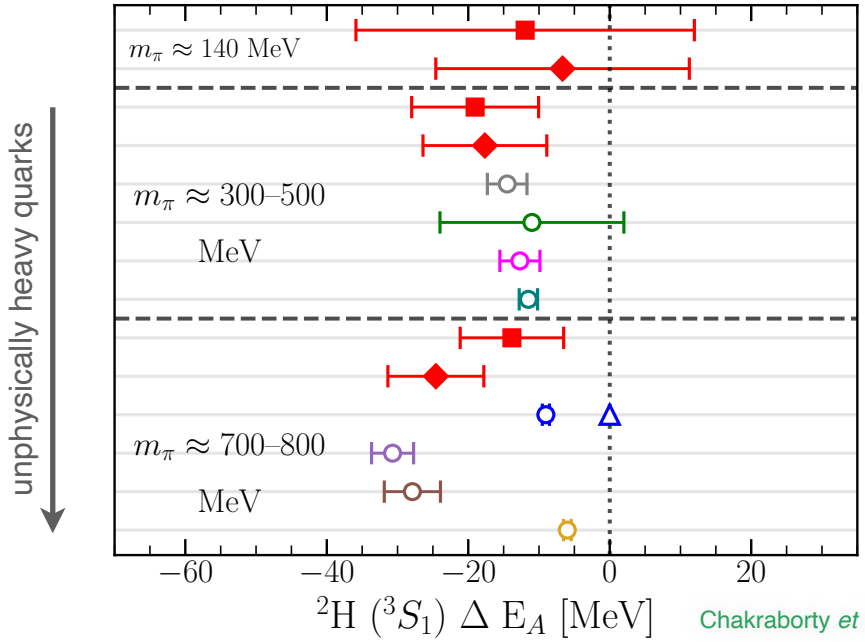


Works beautifully for hadrons, but how about nuclei?

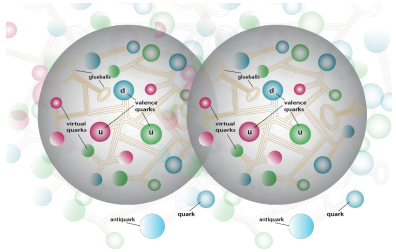
Nuclear Physics from First Principles

$$\mathcal{L}_{\rm QCD} = -\frac{1}{4} G_a^{\mu\nu} G_{a,\mu\nu} + \bar{q}(i\gamma^\mu D_\mu - \mathcal{M})q$$

Lattice QCD results for the deuteron HALQCD, NPLQCD, CalLat, PACS, BaSc, …



Chakraborty *et al.*, 2603.28872 [hep-lat]



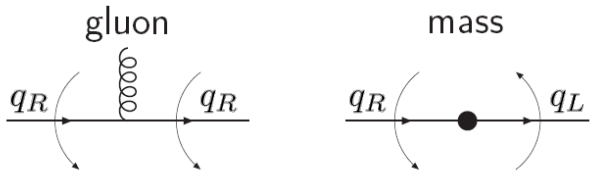
…and no bound states at heavy quark masses using the HALQCD method…

— exponential scaling of the signal-to-noise ratio with the baryon number

— complicated systematics (choice of interpolation operators, discretization effects, …)

Nuclear Physics from First Principles

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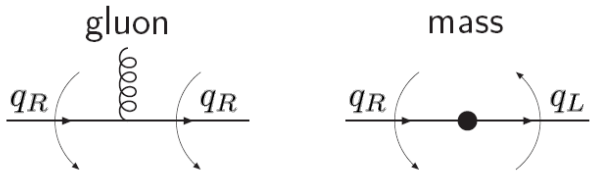
Chiral perturbation theory Weinberg, Gasser, Leutwyler, …

$$\langle 0,\,\text{out}|0,\,\text{in}\rangle_{\text{v,a,s,p}} \;=\; Z[v,a,s,p] \;=\; \int [DG_\mu][Dq][D\bar{q}]\, e^{i\int d^4x \mathcal{L}(q,\bar{q},G_{\mu\nu};\,v,a,s,p)}\Big|_{\text{low energy}}$$

$$= \int \underbrace{[DU]}_{\text{pion fields}}\, e^{i\int d^4x \mathcal{L}_{\rm eff}(U;\,v,a,s,p)}\Big|_{\text{low energy}} \xrightarrow[Q \;=\; p/\Lambda_b \sim\; M_\pi/\Lambda_b]{\text{chiral expansion in}} \text{S-matrix}$$

Nuclear Physics from First Principles

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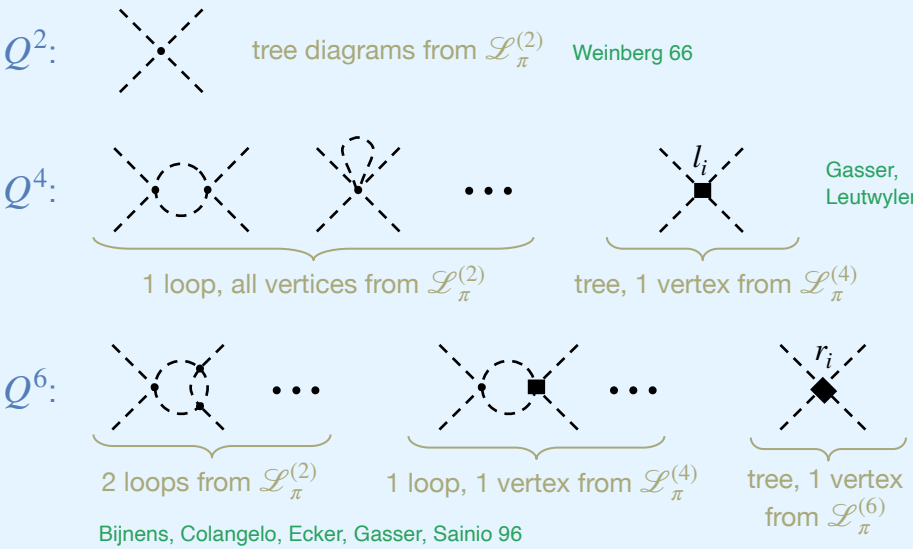


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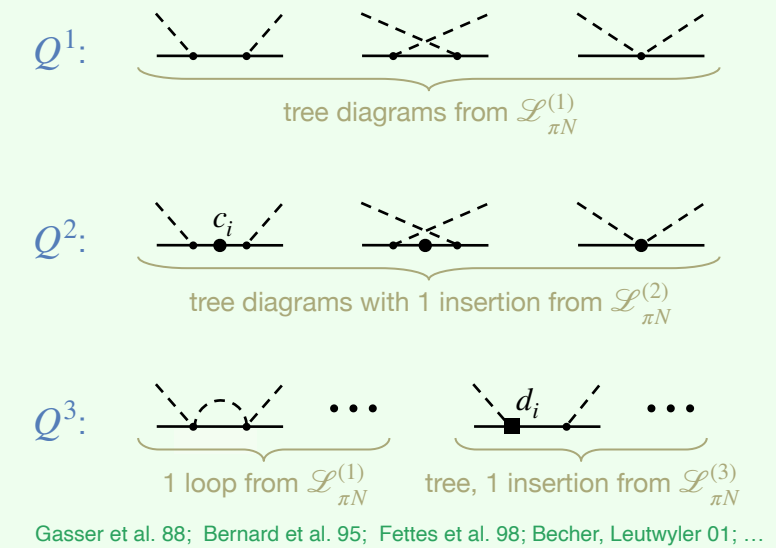
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Pion-pion scattering



Pion-nucleon scattering

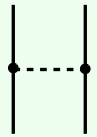


Nuclear Physics from First Principles

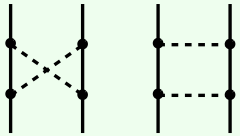
Nucleon-nucleon scattering shallow virtual/bound states ⇒ must go beyond perturbation theory…

Weinberg 90, 91

Q^0:



Q^2:

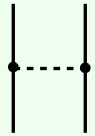


Nuclear Physics from First Principles

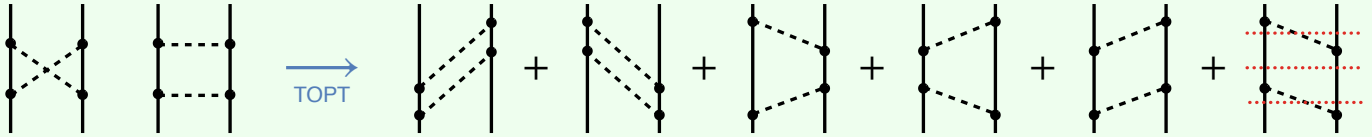
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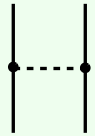


Nuclear Physics from First Principles

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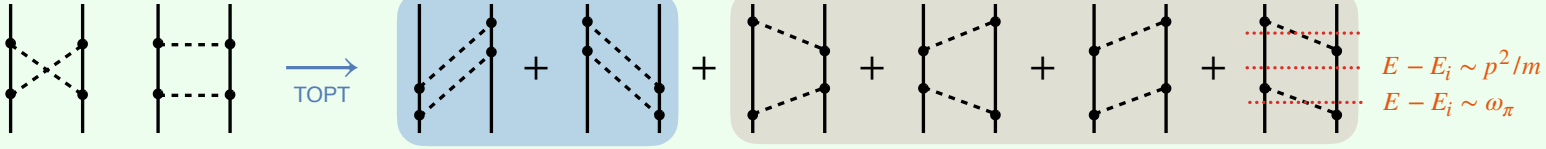
Q^0:



scales according to NDA

enhanced compared to NDA

Q^2:

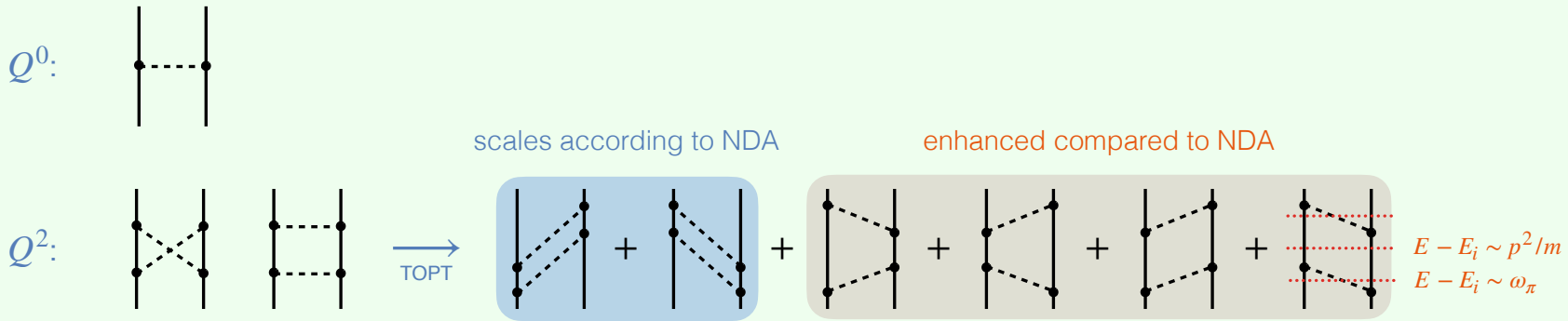


$V_{1\pi}\, G_0\, V_{1\pi}$ ⇒ get resummed by solving the Schrödinger equation

Nuclear Physics from First Principles

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$V_{1\pi}\, G_0\, V_{1\pi}$ ⇒ get resummed by solving the Schrödinger equation

Chiral EFT: The Standard Model of Nuclear Physics Weinberg, van Kolck, Kaiser, EE, Meißner, Machleidt, …

— non-perturbative re-summation of ladder diagrams

$$\left[\left(\sum_{i=1}^{A}\frac{-\vec{\nabla}_i^2}{2m_N}+\mathcal{O}(m_N^{-3})\right)+\underbrace{V_{2N}+V_{3N}+V_{4N}+\ldots}_{\text{derived in ChPT (systematically improvable)}}\right]|\Psi\rangle = E|\Psi\rangle$$

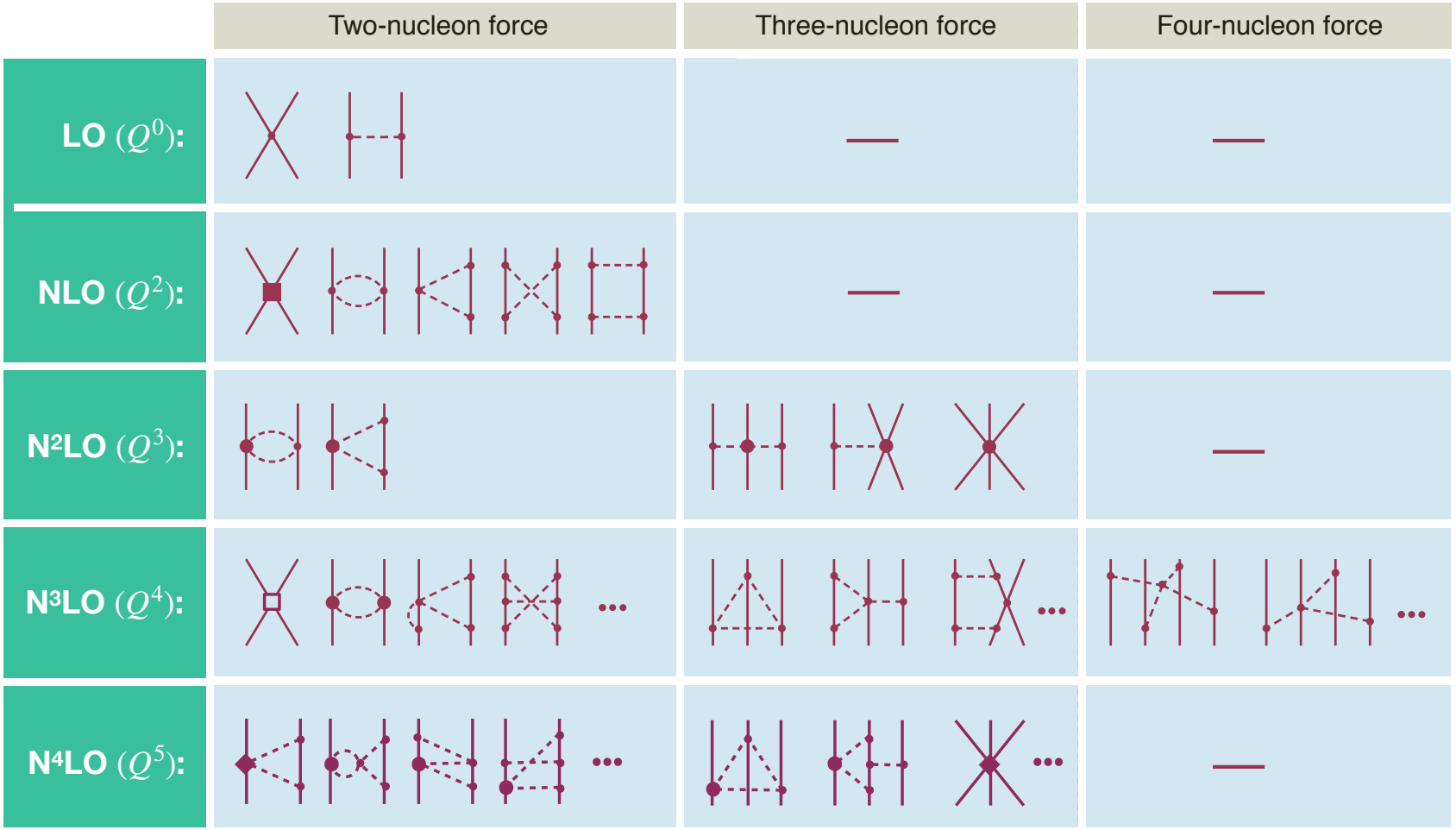
— analytic results for (scheme-dependent!) nuclear forces & currents derived from $\mathscr{L}_{\text{eff}}$

— (finite) cutoff needed to regularize the Schrödinger equation Lepage, EE, Meißner, Gasparyan, Gegelia

— Quantum A-body problem talks by Gaute and Dean, calibration of LECs talk by Andreas

The Standard Model of Nuclear Physics

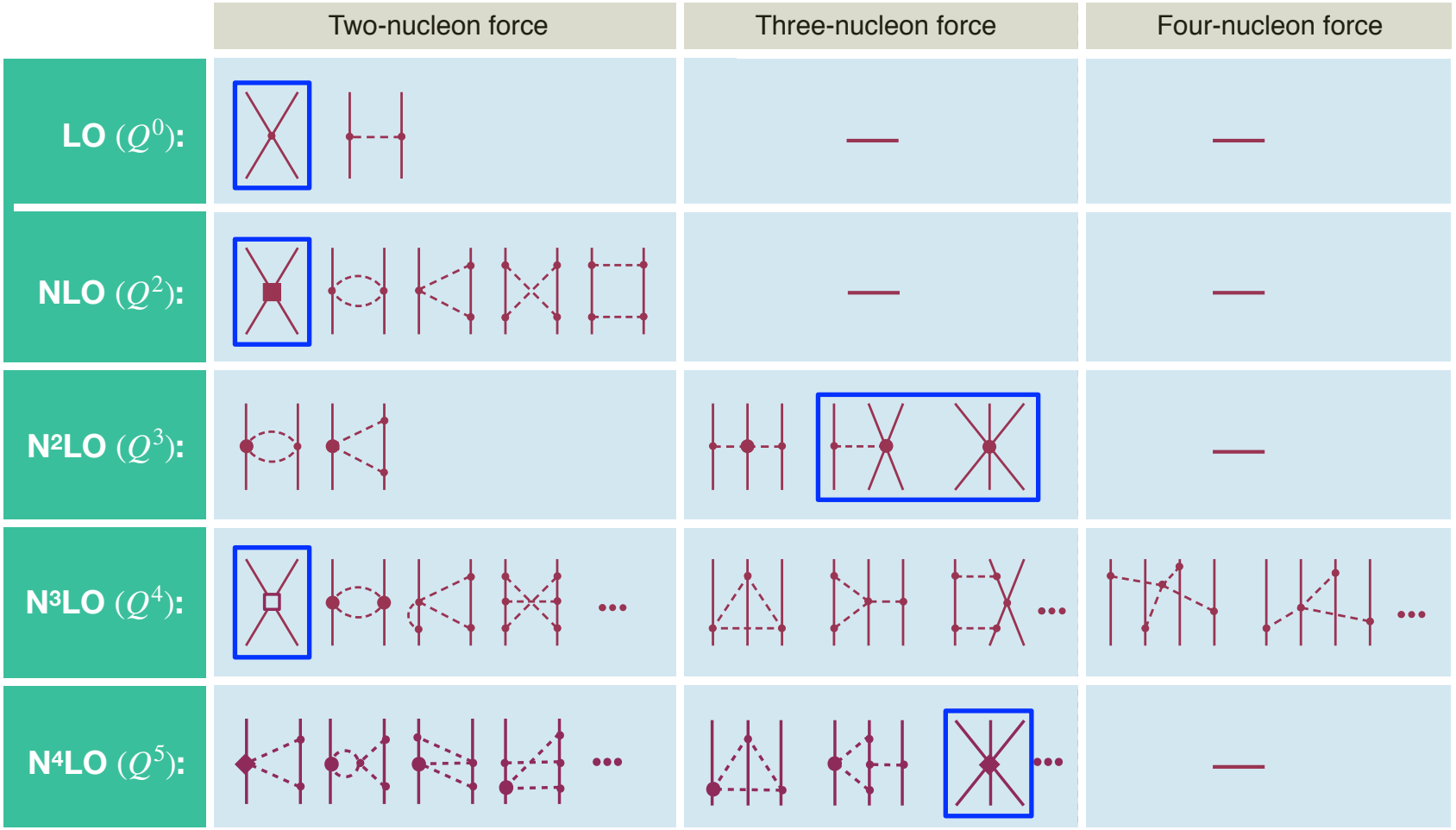
(Weinberg counting scheme, pions and nucleons as the only DoF)



Weinberg 90; van Kolck *et al.* 94; Friar, Coon 94; van Kolck 94; Kaiser, Brockmann, Weise 97; EE *et al.* 98; Kaiser 00-02; EE *et al.* 02; EE 06, 07; Bernard, EE, Krebs, Meißner 08, 11; Girlanda *et al.* 11; Krebs, Gasparyan, EE 11, 13; Entem, Kaiser, Machleidt, Nosyk 15; Huesmann, Krebs, EE 25

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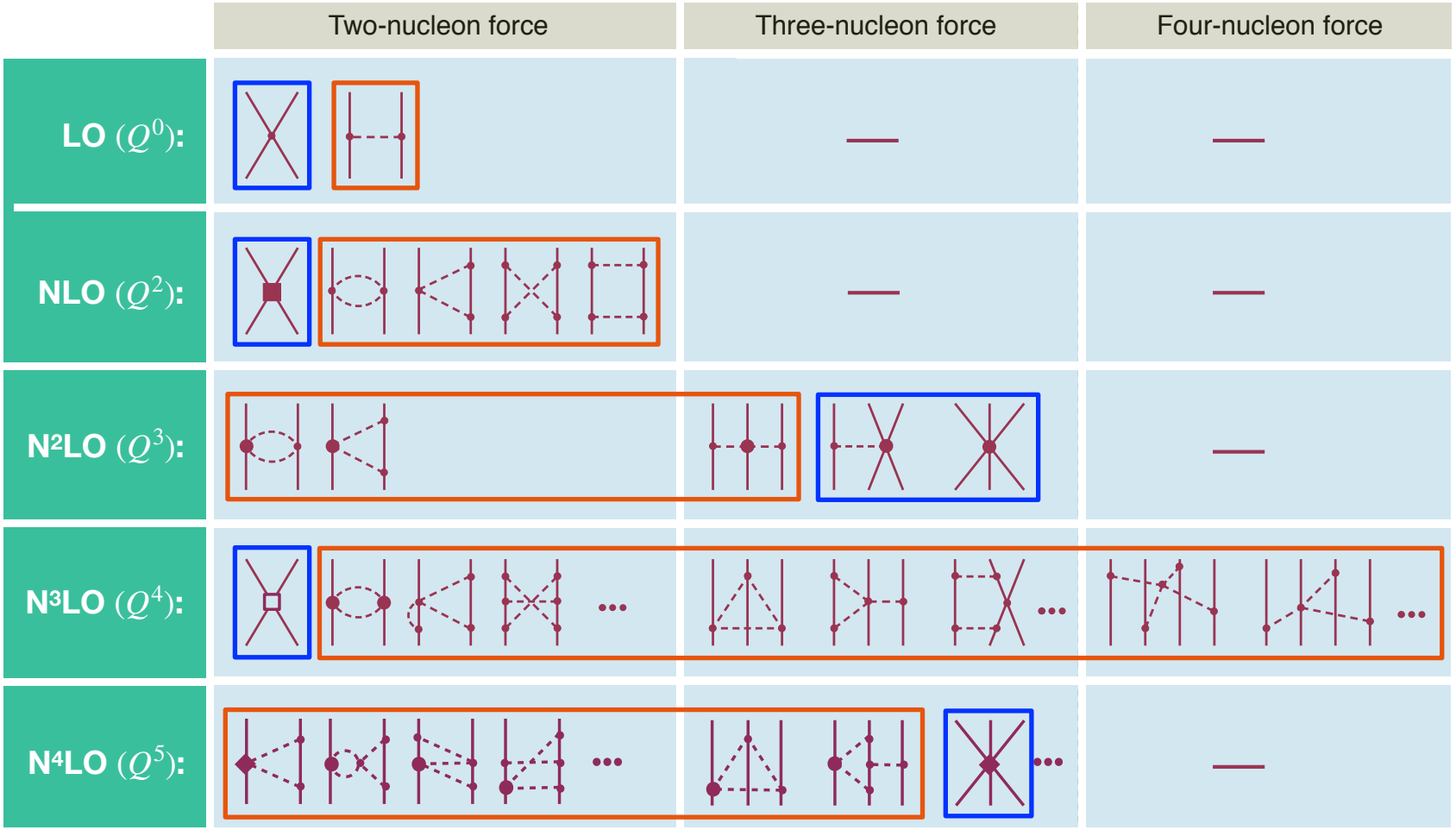


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Short-range few-N interactions are tuned to experimental data

The Standard Model of Nuclear Physics

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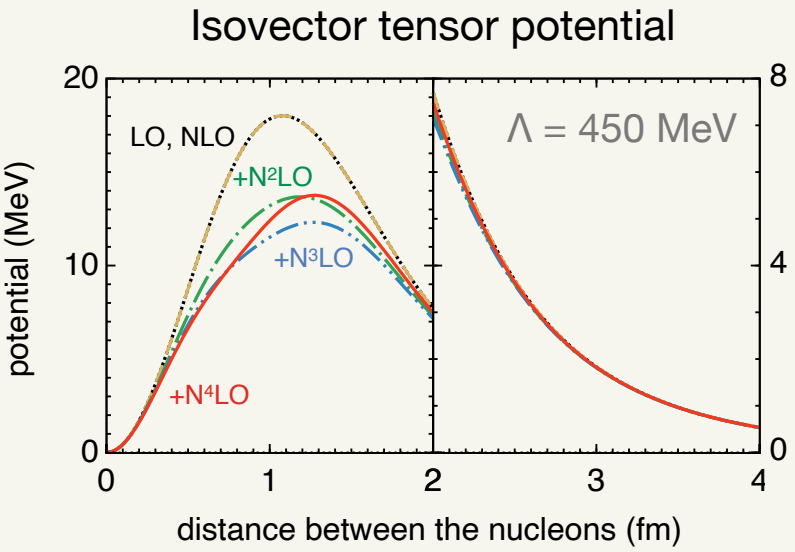
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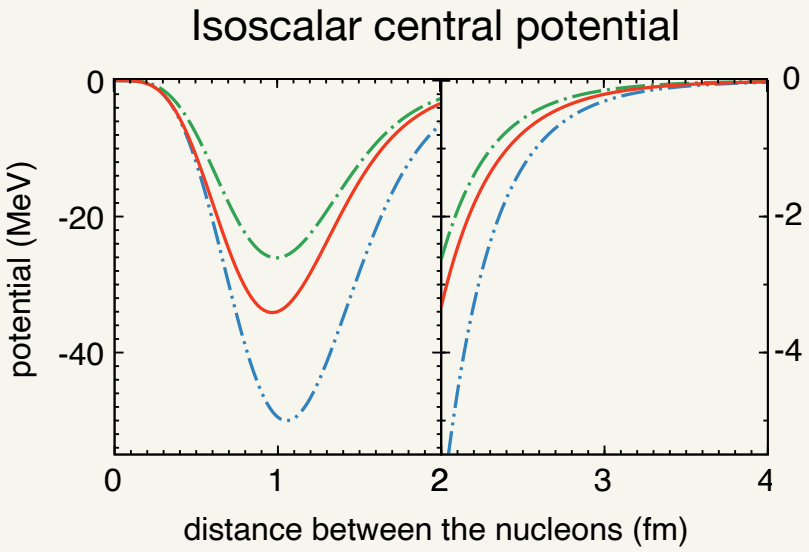
Short-range few-N interactions are tuned to experimental data

Chiral dynamics: Long-range interactions are predicted in terms of on-shell amplitudes



Chiral expansion of the long-range NN force



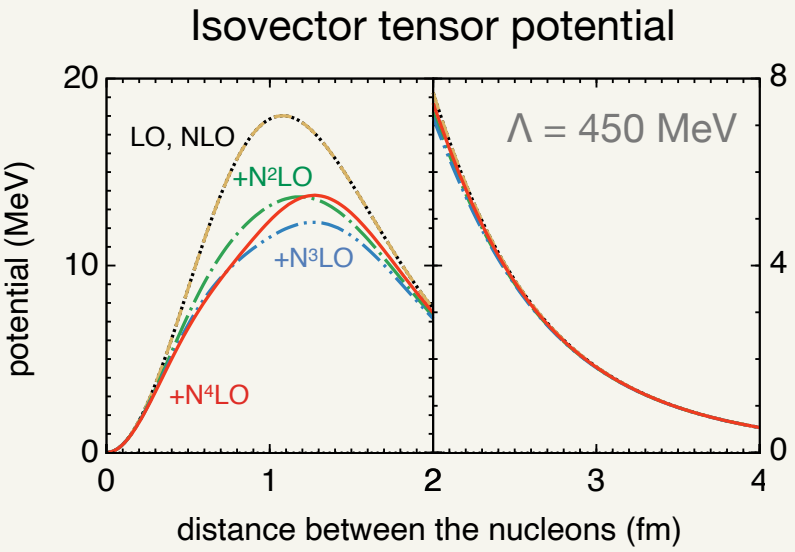


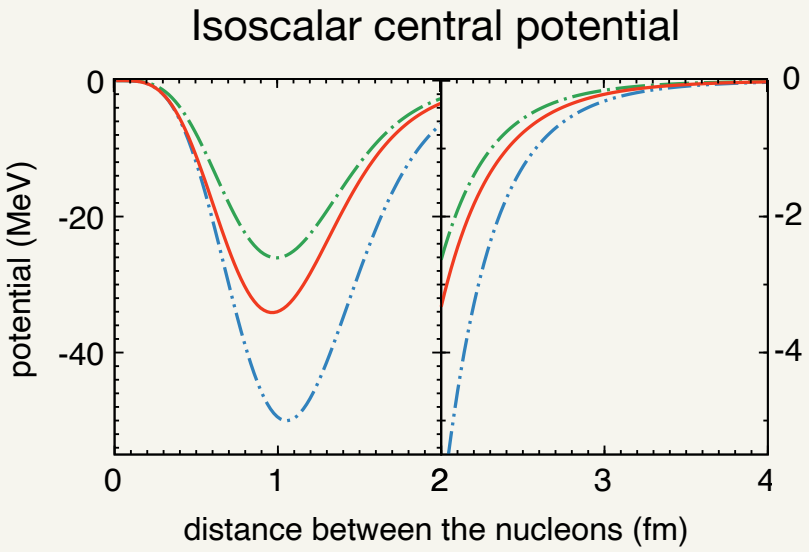
SMS NN potentials Reinert, Krebs, EE, EPJA 54 (2018) 86; PRL 126 (2021) 092501

$$V_{1\pi}(q) = \frac{\alpha}{\vec{q}^2 + M_\pi^2} \; e^{-\frac{\vec{q}^2 + M_\pi^2}{\Lambda^2}} + \text{subtraction}, \qquad V_{2\pi}(q) = \frac{2}{\pi}\int_{2M_\pi}^{\infty} d\mu\,\mu \frac{\rho(\mu)}{\vec{q}^2 + \mu^2} \; e^{-\frac{\vec{q}^2 + \mu^2}{2\Lambda^2}} + \text{subtractions}$$

+ nonlocal (Gaussian) cutoff for contacts

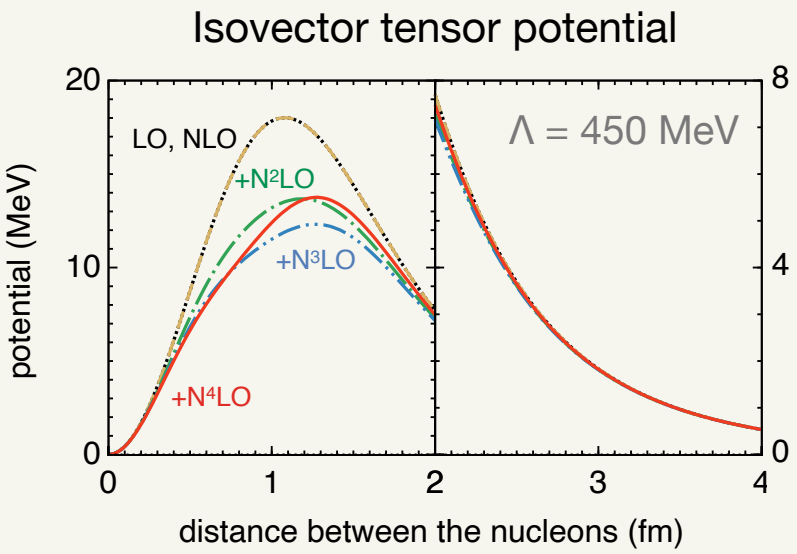
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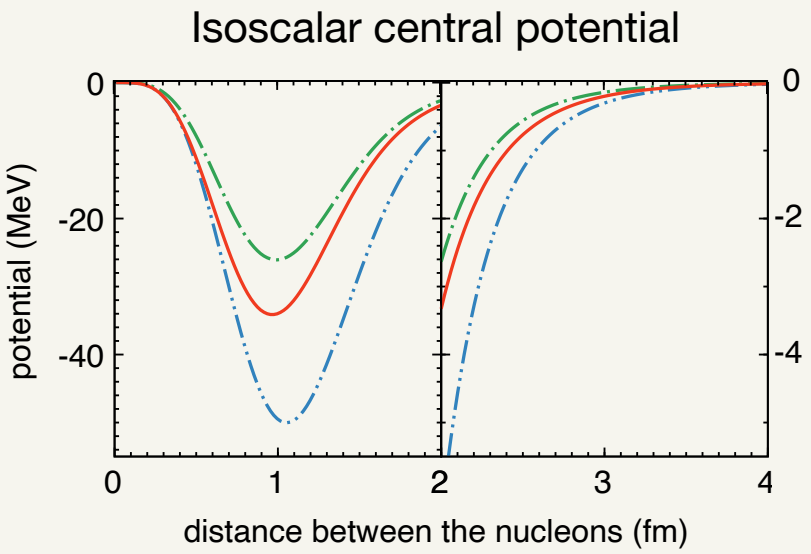




Can these predictions be tested in NN scattering?

Chiral expansion of the long-range NN force





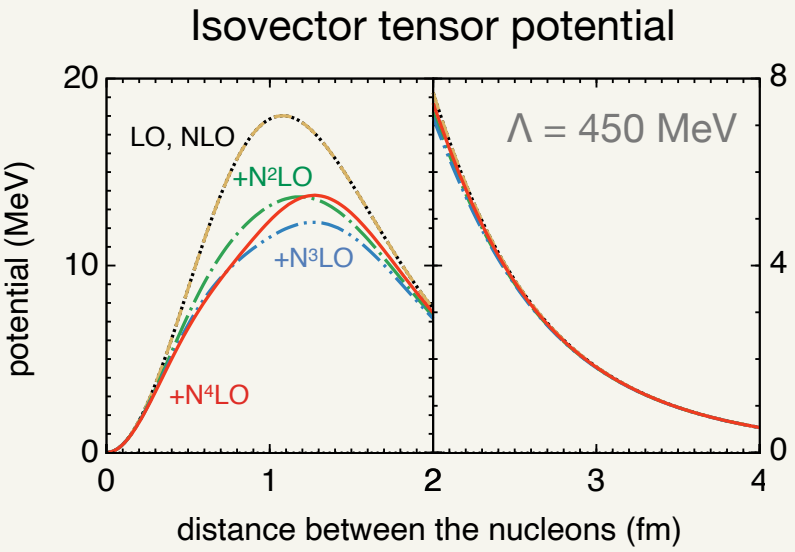
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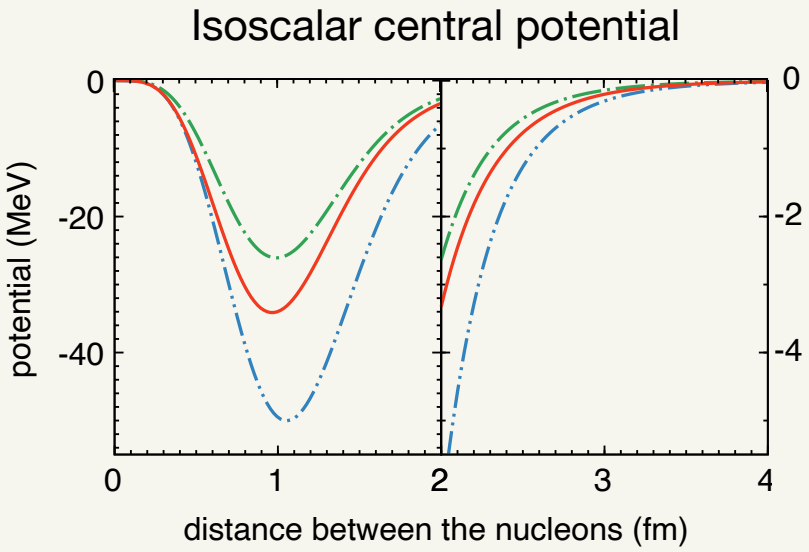
$\chi^2_{\rm datum}$ for the description of neutron-proton and proton-proton scattering data

E_{lab} bin	CD Bonn	Nijm I	Nijm II	Reid 93	Bochum N⁴LO⁺
0-300 MeV	1.042	1.061	1.070	1.078	1.013

~ 40% less adjustable parameters
(2π exchange physics!)

Chiral expansion of the long-range NN force





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Switching off the 2π-exchange leads to $\chi^2_{\rm datum} \sim 1.99$ (i.e., 50σ away!), consistent fits only for $E_{\rm lab} \leq 135$ MeV…

Precision chiral EFT: Neutron charge radius

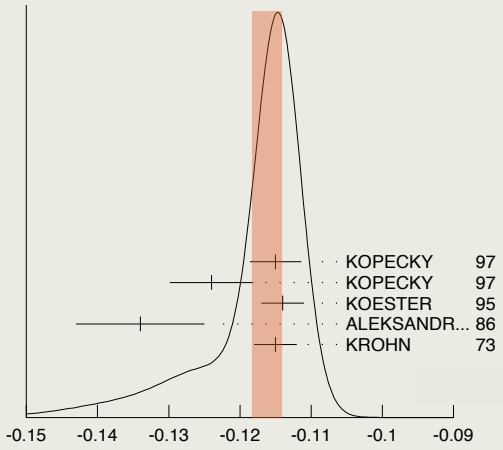
Filin, Möller, Baru, EE, Krebs, Reinert, PRL 124 (2020) 082501; PRC 103 (2021) 024313

The charge and structure radius of the deuteron:

$$r_d^2 = (-6)\frac{\partial G_C(Q^2)}{\partial Q^2}\bigg|_{Q^2=0} = r_{str}^2 + r_p^2 + r_n^2 + \frac{3}{4m_p^2}$$

isotope-shift measurement $r_d^2 - r_p^2 = 3.82007(65)\,\mathrm{fm}^2$

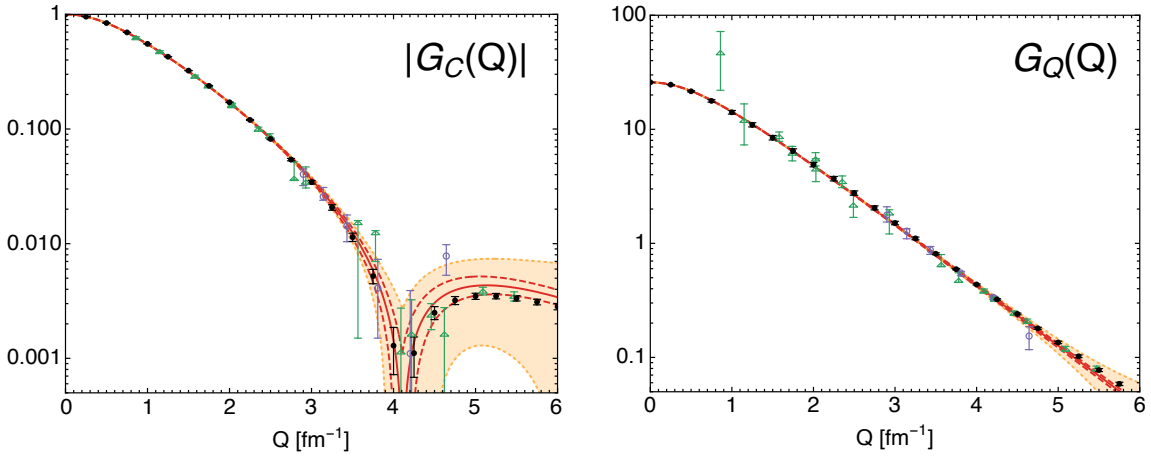
PDG: $r_n^2 = -0.1161(22)\ \mathrm{fm}^2$



Precision chiral EFT: Neutron charge radius

Filin, Möller, Baru, EE, Krebs, Reinert, PRL 124 (2020) 082501; PRC 103 (2021) 024313

Charge and quadrupole form factors of the deuteron at N⁴LO



Extracted quadrupole moment:

$$Q_\mathrm{d} = 0.2854^{+0.0038}_{-0.0017}\ \mathrm{fm}^2$$

EFT truncation, choice of fitting range, NN, πN and γNN LECs

to be compared with experiment

$$Q_\mathrm{d}^\mathrm{exp} = 0.285\,699(15)(18)\ \mathrm{fm}^2$$

Puchalski et al., PRL 125 (2020)

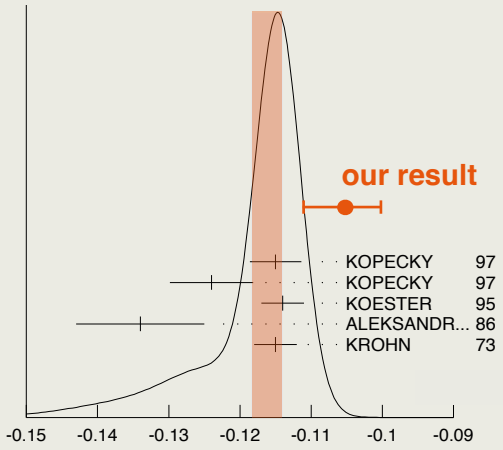
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Combining our result $r_\mathrm{str} = 1.9729^{+0.0015}_{-0.0012}\,\mathrm{fm}$ with the high-precision isotope-shift measurement $r_d^2 - r_p^2 = 3.82007(65)\,\mathrm{fm}^2$, we determine the neutron m.s. charge radius:

$$r_n^2 = -0.105^{+0.005}_{-0.006}\ \mathrm{fm}^2$$

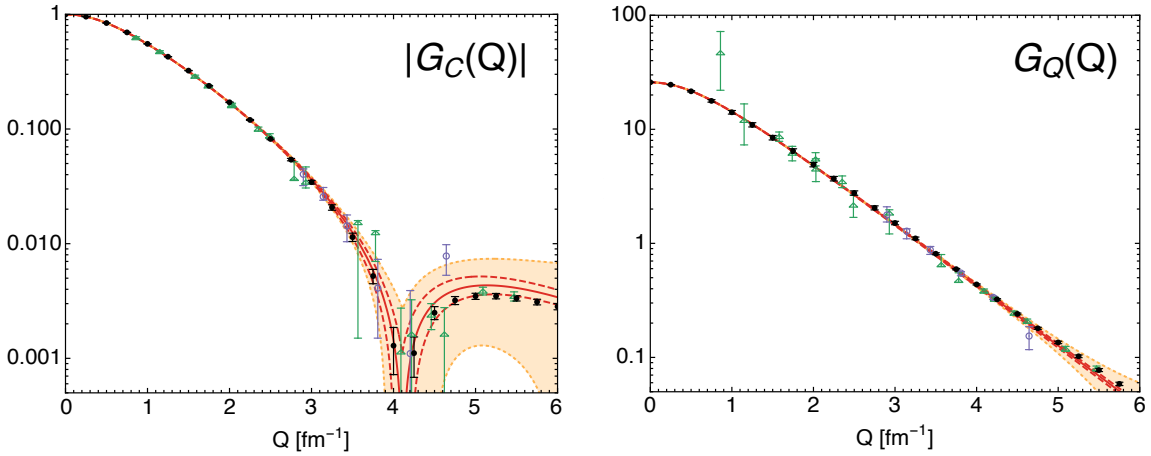
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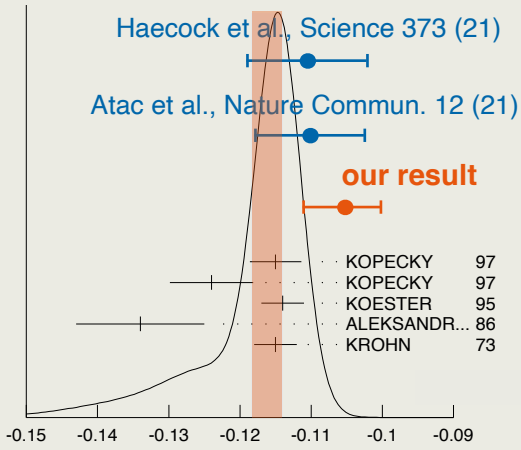
The charge and structure radius of the deuteron:

$$r_d^2 = (-6)\frac{\partial G_C(Q^2)}{\partial Q^2}\bigg|_{Q^2=0} = r_{str}^2 + r_p^2 + r_n^2 + \frac{3}{4m_p^2}$$

Combining our result $r_\mathrm{str} = 1.9729^{+0.0015}_{-0.0012}\,\mathrm{fm}$ with the high-precision isotope-shift measurement $r_d^2 - r_p^2 = 3.82007(65)\,\mathrm{fm}^2$, we determine the neutron m.s. charge radius:

$$r_n^2 = -0.105^{+0.005}_{-0.006}\ \mathrm{fm}^2$$

PDG: $r_n^2 = -0.1161(22)\ \mathrm{fm}^2$



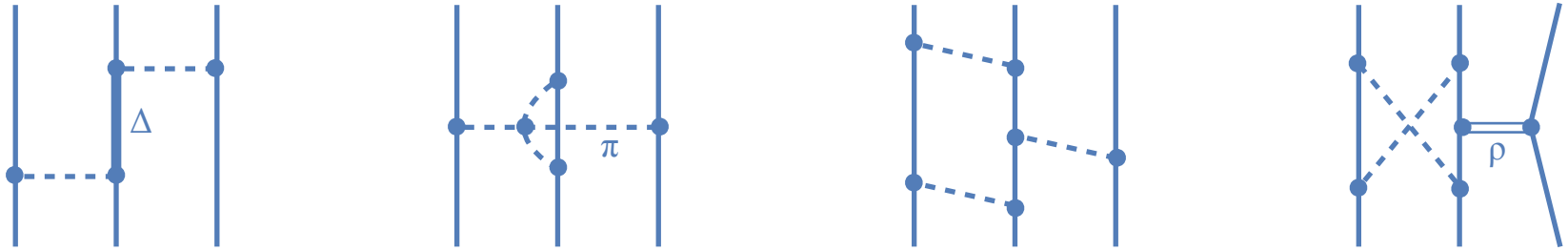
Three-nucleon force



3-body force: A frontier in nuclear & atomic physics

Endo, EE, Naidon, Nishida, Sekiguchi, Takahashi, EPJA 61 (2025) 9

- Three-nucleon forces (3NF) are small but important corrections to the dominant NN forces
- 3NF mechanisms:



intermediate Δ-excitation
Fujita, Miyazawa '57

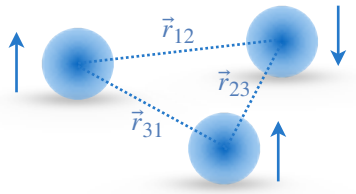
multi-pion interactions

off-shell behavior of the V_{NN}
$V_{\rm ring} = \mathscr{A}_{3\pi} - V_\pi G_0 V_\pi G_0 V_\pi$

short-range

⇒ 3NF are not directly measurable and depend on the scheme (DoF, off-shell V_{NN}, …)

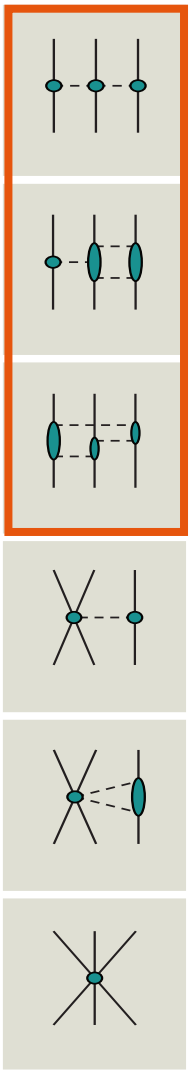
- Still poorly understood (in spite of extensive research) Kalantar-Nayestanaki, EE, Messchendorp, Nogga, Rept. Prog. Phys. 75 (12)
- 3NF have extremely rich and complex structure
  - — most general ***local*** 3NF: $V_{3N} = \sum_{i=1}^{20} O_i\, f_i(r_{12}, r_{23}, r_{31}) + \text{permutations}$
    EE, Gasparyan, Krebs, Schat '15
  - — most general ***nonlocal*** 3NF: **320 (!)** operators Topolnicki '17



⇒ Guidance from theory indispensable — an opportunity for χEFT!

Three-body force: A frontier in nuclear physics

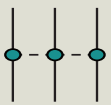
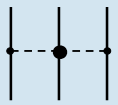
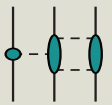
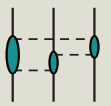
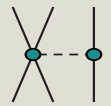
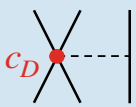
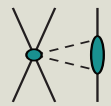
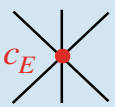
Endo, EE, Naidon, Nishida, Sekiguchi, Takahashi, EPJA 61 (2025) 9



3N potentials at large distances
come as parameter-free predictions based
on χ symmetry of QCD + exp. information on πN system

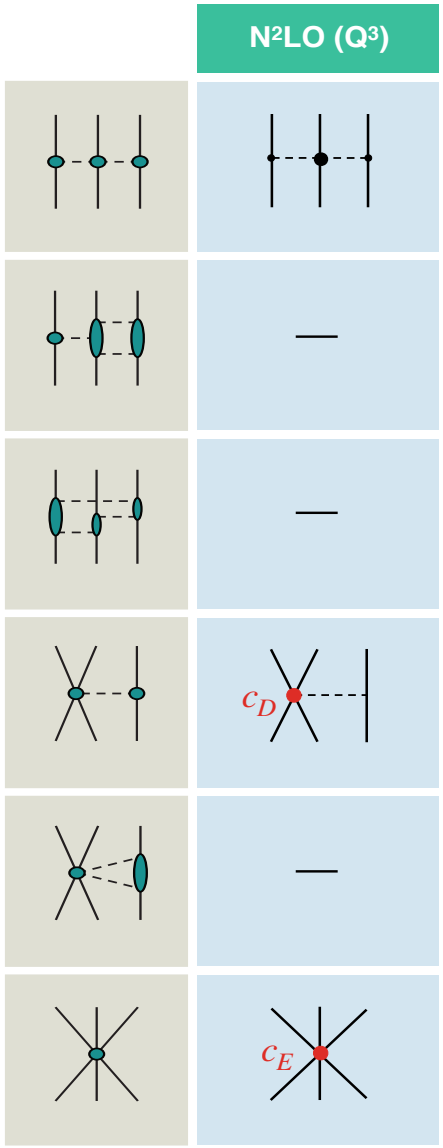
Three-body force: A frontier in nuclear physics

Endo, EE, Naidon, Nishida, Sekiguchi, Takahashi, EPJA 61 (2025) 9

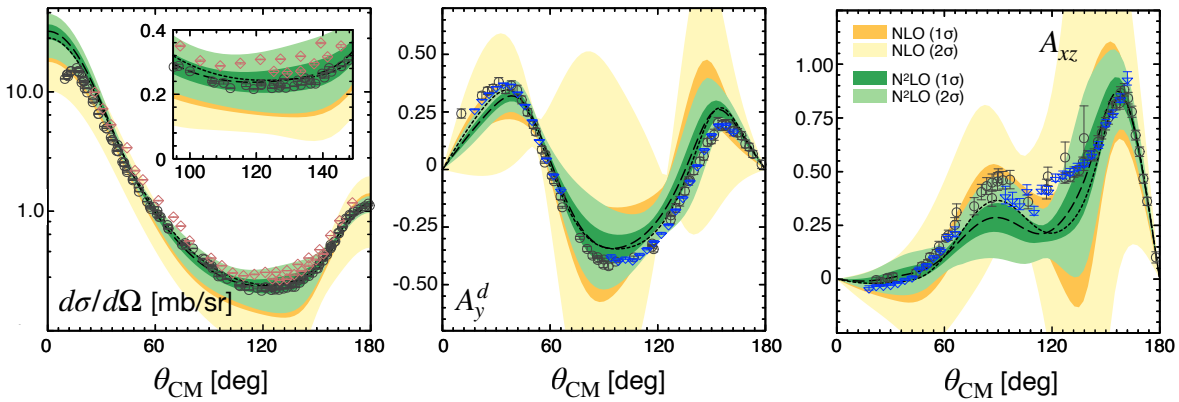
	N^{2}LO (Q^3)
	
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Three-body force: A frontier in nuclear physics

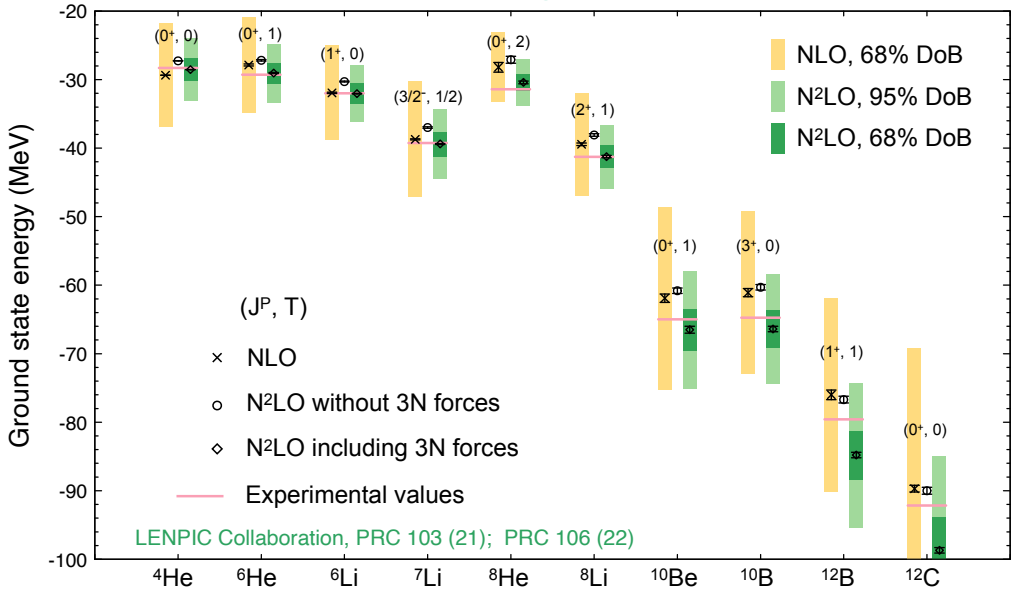
Endo, EE, Naidon, Nishida, Sekiguchi, Takahashi, EPJA 61 (2025) 9



Elastic Nd scattering at 135 MeV



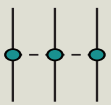
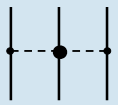
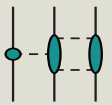
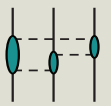
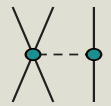
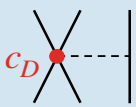
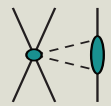
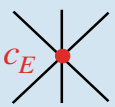
Predictions for light p-shell nuclei



LENPIC

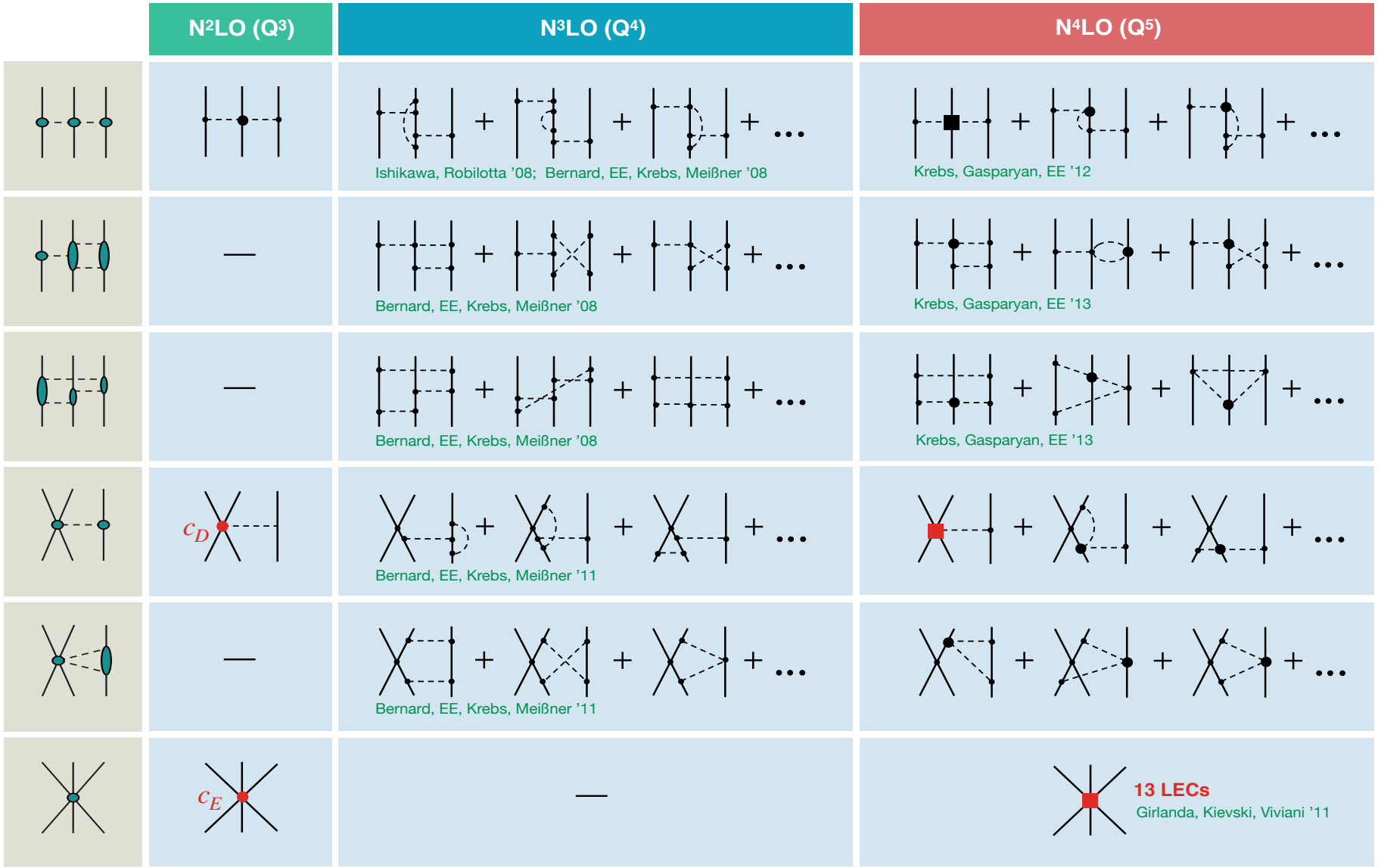
Three-body force: A frontier in nuclear physics

Endo, EE, Naidon, Nishida, Sekiguchi, Takahashi, EPJA 61 (2025) 9

	N^{2}LO (Q^3)
	
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Three-body force: A frontier in nuclear physics

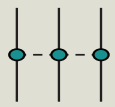
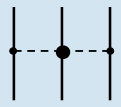
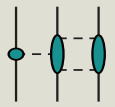
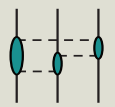
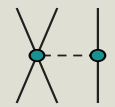
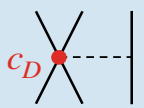
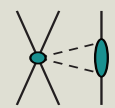
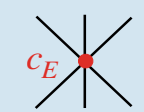
Endo, EE, Naidon, Nishida, Sekiguchi, Takahashi, EPJA 61 (2025) 9



New experiment @RIKEN will measure spin-transfer coefficients in elastic d-p scattering Sekiguchi et al.

Three-body force: A frontier in nuclear physics

Endo, EE, Naidon, Nishida, Sekiguchi, Takahashi, EPJA 61 (2025) 9

	N²LO (Q^3)	N³LO (Q^4)	N⁴LO (Q^5)
		 Ishikawa, Robilotta '08; Bernard, EE, Krebs, Meißner '08	 Krebs, Gasparyan, EE '12
	—	 Bernard, EE, Krebs, Meißner '08	 Krebs, Gasparyan, EE '13
	—	 Bernard, EE, Krebs, Meißner '08	 Krebs, Gasparyan, EE '13
		 Bernard, EE, Krebs, Meißner '11	
	—	 Bernard, EE, Krebs, Meißner '11	
			

mixing DimReg with Cutoff regularization in the Schrödinger equation violates χ-symmetry

EE, Krebs, Reinert, Front. in Phys. 8 (2020)



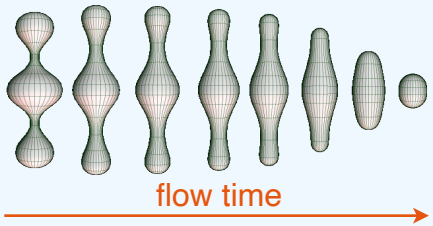
DANGER: momentum cutoff for pions breaks chiral symmetry!

INSTITUTE for NUCLEAR THEORY

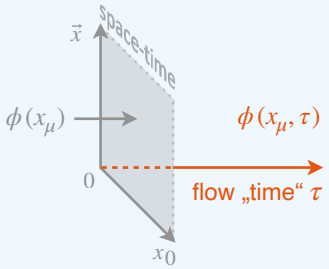
Chiral gradient flow

Hermann Krebs, EE, PRC 110 (2024) 044003; PRC110 (2024) 044003

Gradient flows: methods for smoothing manifolds
(e.g., Ricci flow used in the proof of the Poincaré conjecture)



Gradient flow as a regulator in field theory



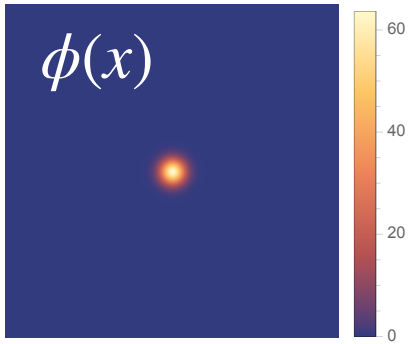
Flow equation: $\dfrac{\partial}{\partial\tau}\phi(x,\tau) = -\dfrac{\delta S[\phi]}{\delta\phi(x)}\Big|_{\phi(x)\to\phi(x,\tau)}$

subject to the boundary condition $\phi(x,0) = \phi(x)$

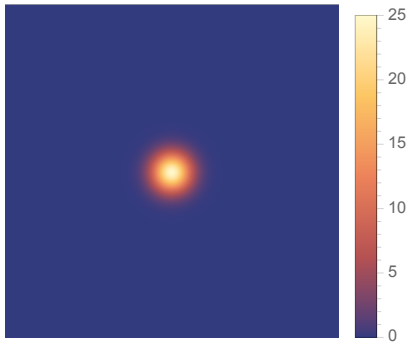
Free scalar field:

$$G(x,\tau) = \frac{\theta(\tau)}{16\pi^2\tau^2} e^{-\frac{x^2+4M^2\tau^2}{4\tau}}$$

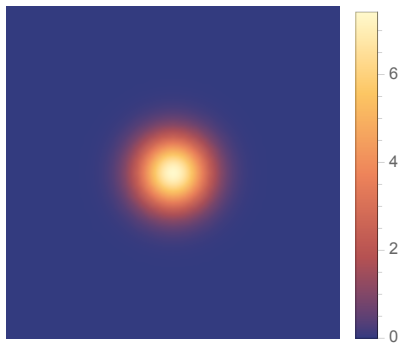
$$\left[\partial_\tau - (\partial_\mu^x\partial_\mu^x - M^2)\right]\phi(x,\tau) = 0 \quad \Rightarrow \quad \phi(x,\tau) = \int d^4y \underbrace{G(x-y,\tau)}_{\text{heat kernel}}\phi(y) \quad \Rightarrow \quad \tilde{\phi}(q,\tau) = e^{-\tau(q^2+M^2)}\tilde{\phi}(q)$$



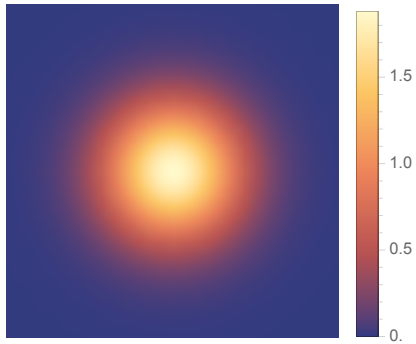
$\tau = 0$



$\tau = 1$



$\tau = 2$

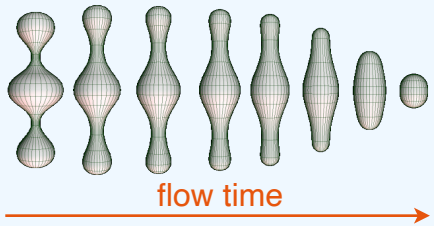


$\tau = 4$

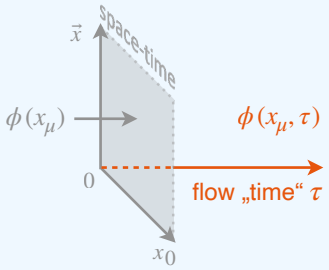
Chiral gradient flow

Hermann Krebs, EE, PRC 110 (2024) 044003; PRC110 (2024) 044003

Gradient flows: methods for smoothing manifolds
(e.g., Ricci flow used in the proof of the Poincaré conjecture)



Gradient flow as a regulator in field theory



Flow equation: $\dfrac{\partial}{\partial\tau}\phi(x,\tau) = -\dfrac{\delta S[\phi]}{\delta\phi(x)}\Big|_{\phi(x)\to\phi(x,\tau)}$

subject to the boundary condition $\phi(x,0) = \phi(x)$

Free scalar field:

$$G(x,\tau) = \frac{\theta(\tau)}{16\pi^2\tau^2}e^{-\frac{x^2+4M^2\tau^2}{4\tau}}$$

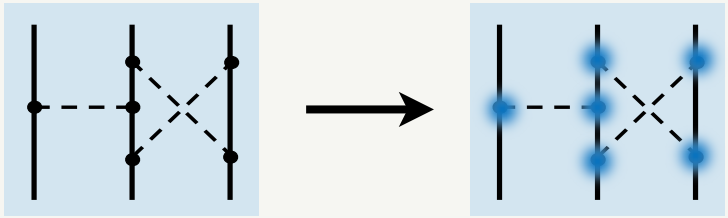
$$\left[\partial_\tau - (\partial_\mu^x\partial_\mu^x - M^2)\right]\phi(x,\tau) = 0 \quad\Rightarrow\quad \phi(x,\tau) = \int d^4y \underbrace{G(x-y,\tau)}_{\text{heat kernel}}\phi(y) \quad\Rightarrow\quad \tilde{\phi}(q,\tau) = e^{-\tau(q^2+M^2)}\tilde{\phi}(q)$$

YM gradient flow Narayanan, Neuberger ’06, Lüscher, Weisz ’11: $\partial_\tau A_\mu(x,\tau) = D_\nu G_{\nu\mu}(x,\tau)$ ← extensively used in LQCD

Chiral gradient flow **Hermann Krebs**, EE, PRC 110 (2024) 044003 PRC 110 (2024) 044004

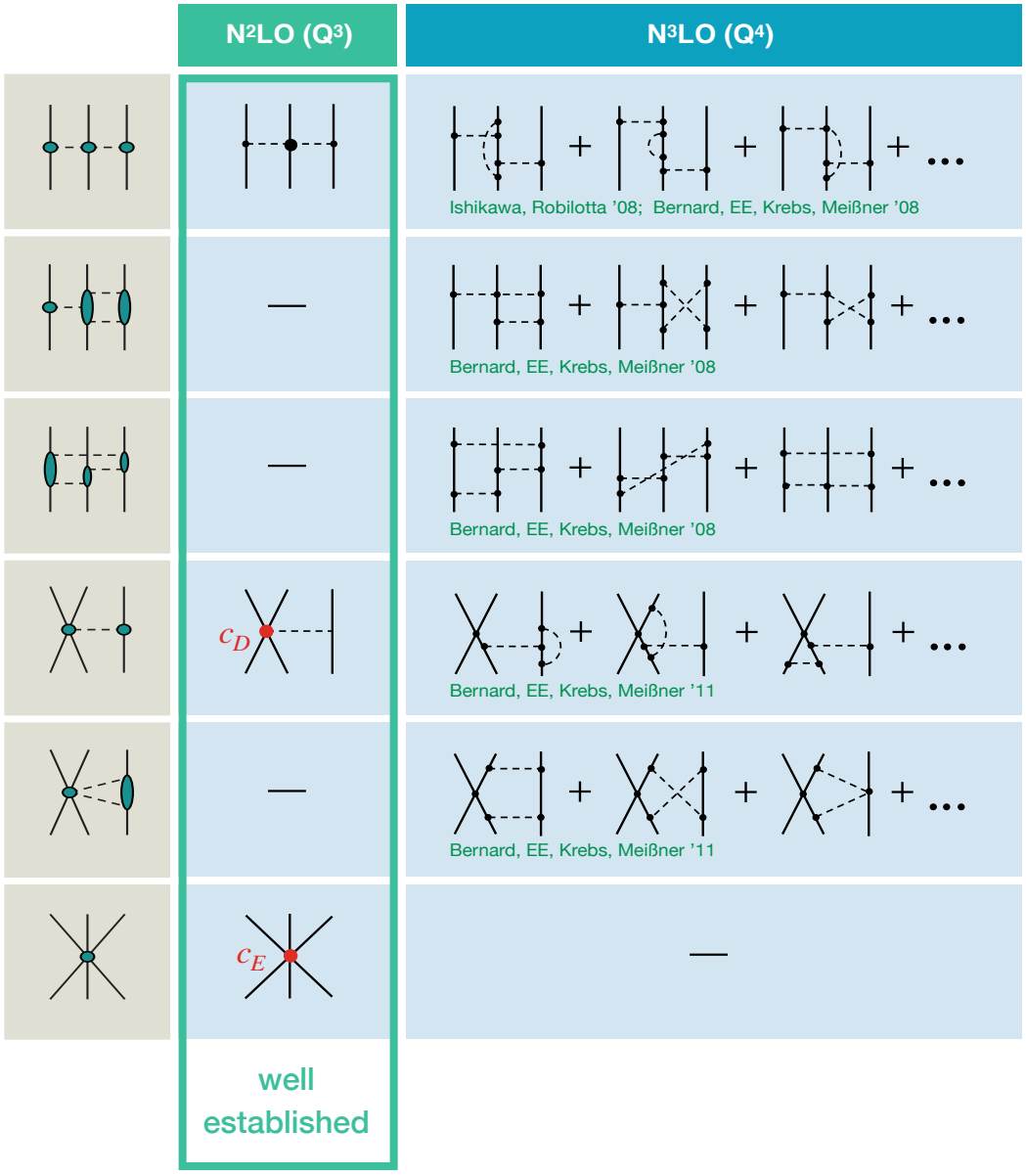
Generalize $U(x)$, $U(x)\to RU(x)L^\dagger$ to $W(x,\tau)$:

$$\partial_\tau W = -i\underbrace{w}_{\sqrt{W}}\,\mathrm{EOM}(\tau)\,w, \quad W(x,0) = U(x)$$



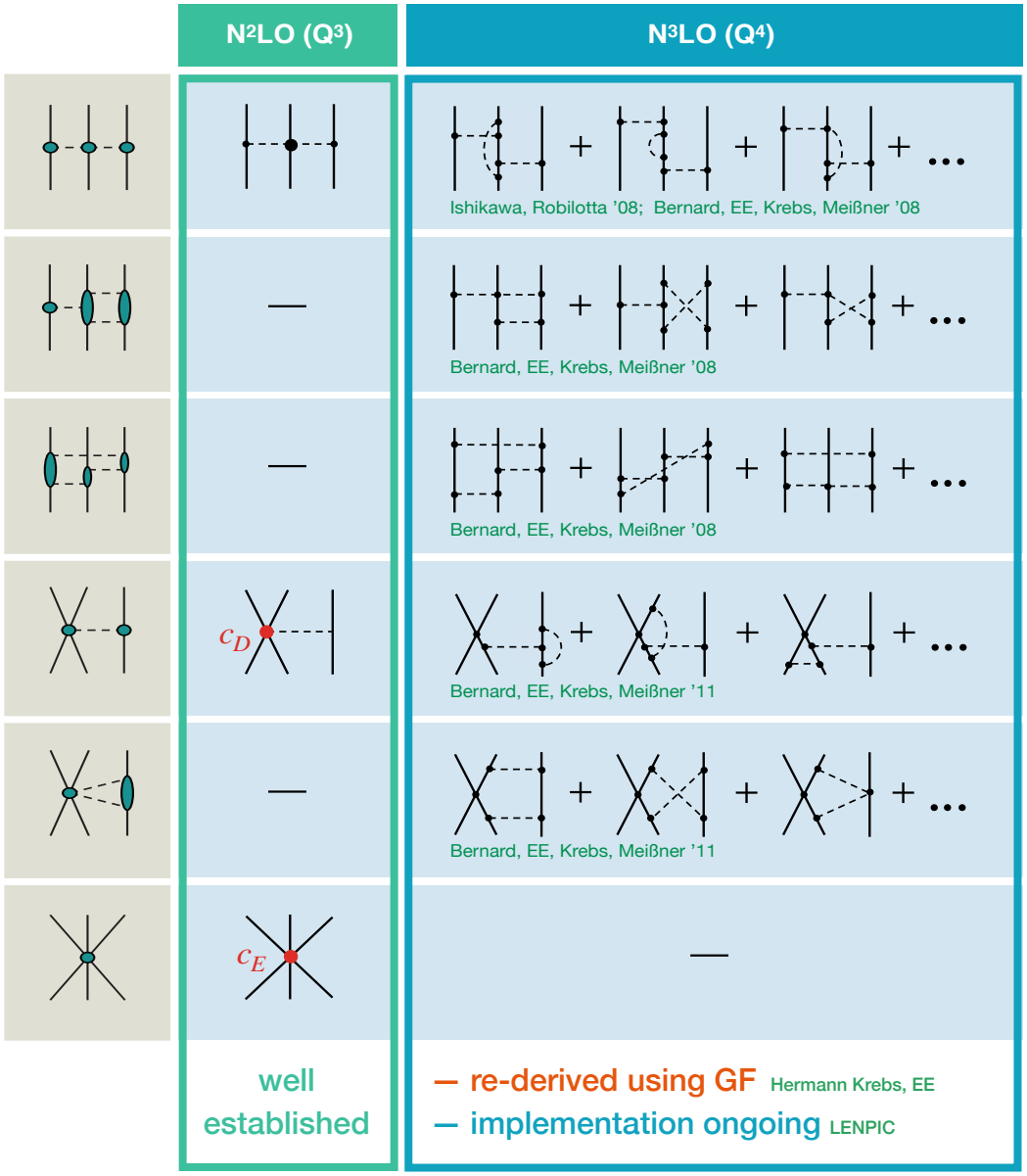
Consistent 3NF at N³LO using Gradient Flow

LENPIC, work in progress

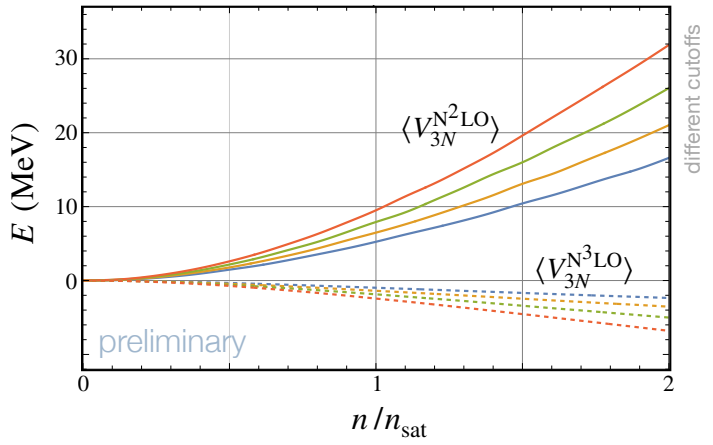


Consistent 3NF at N³LO using Gradient Flow

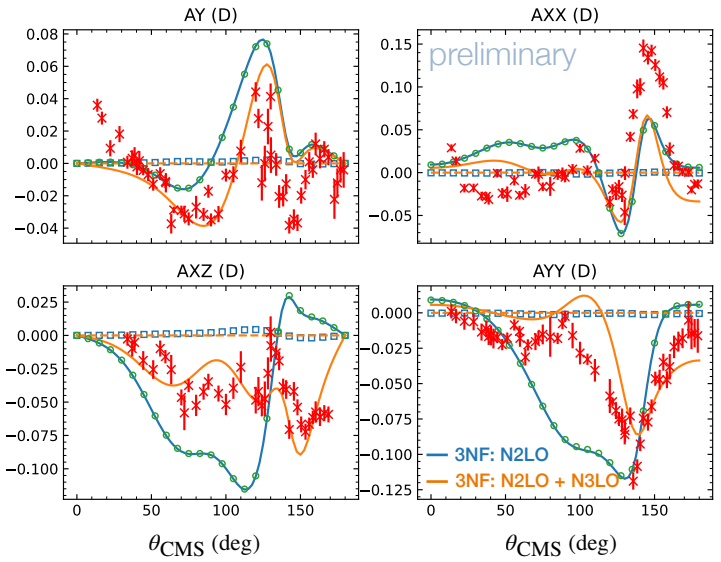
LENPIC, work in progress



Contributions to symmetric nuclear matter

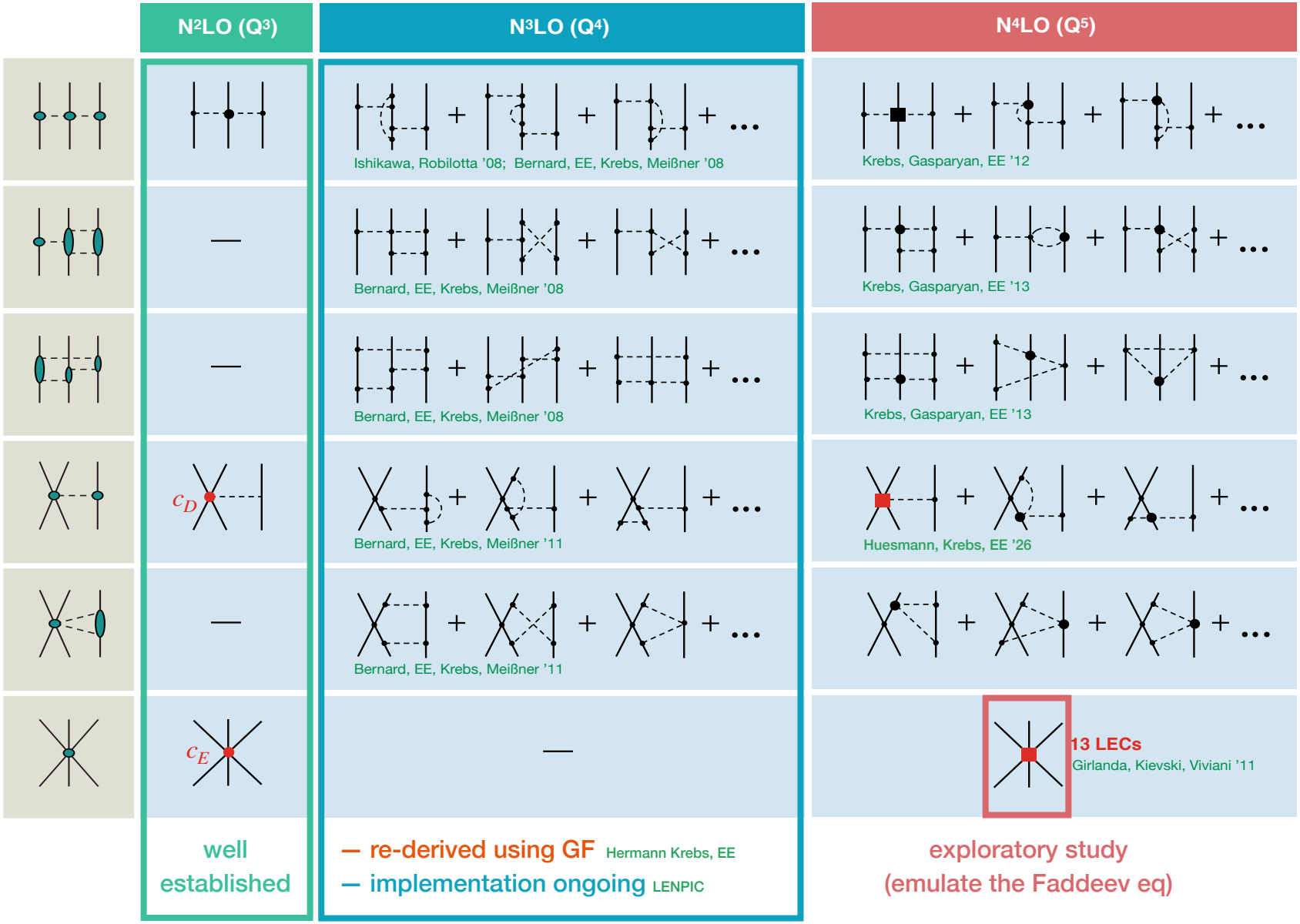


Deuteron analyzing powers at $E_N = 70$ MeV



Consistent 3NF at N³LO using Gradient Flow

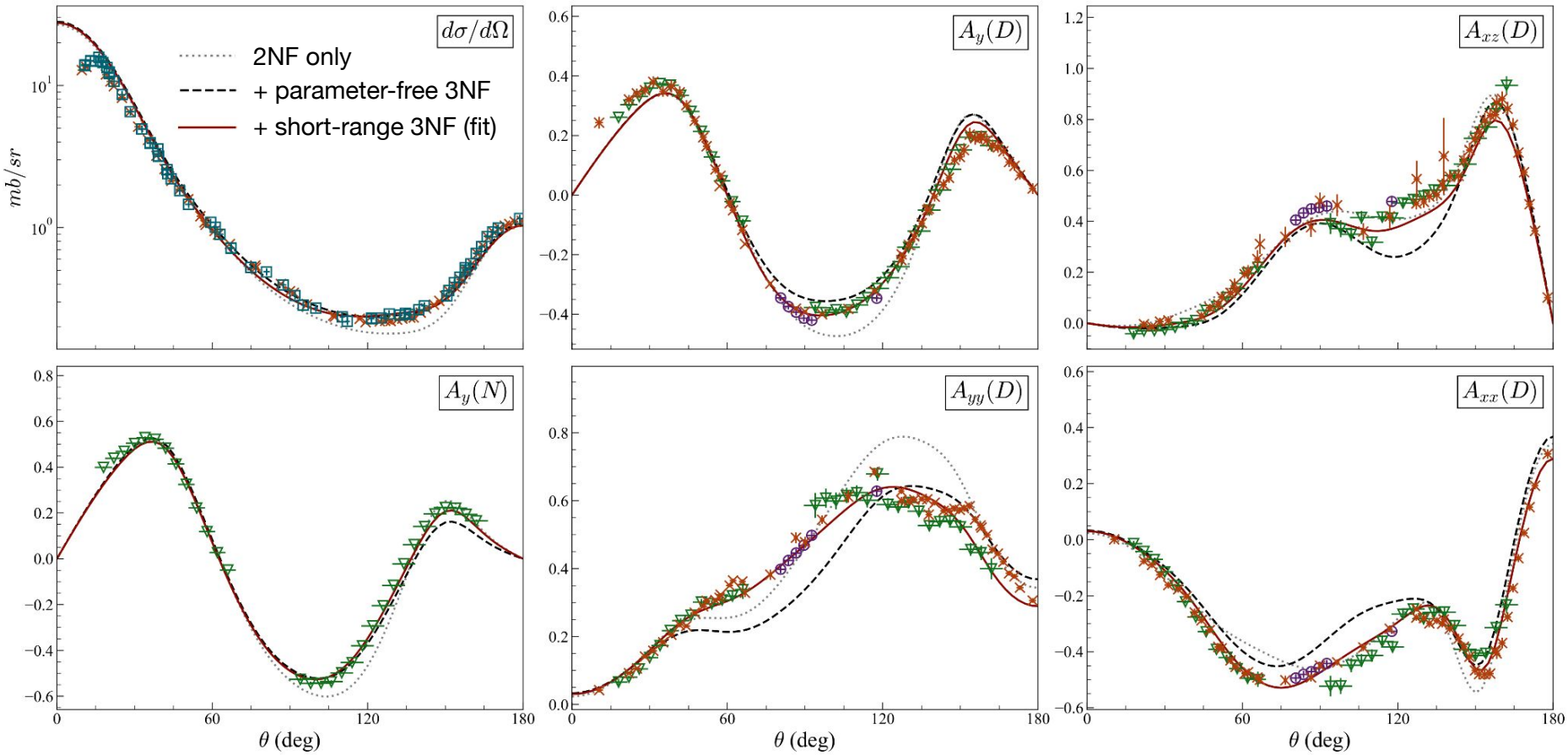
LENPIC, work in progress



Exploratory study of short-range 3NF@N⁴LO

Josep Solà Cava, Arseniy A. Filin, Sven Heihoff, Henri Paul Huesmann, EE, e-Print: 2607.26958

Selected Nd elastic scattering observables at $E_N = 135$ MeV



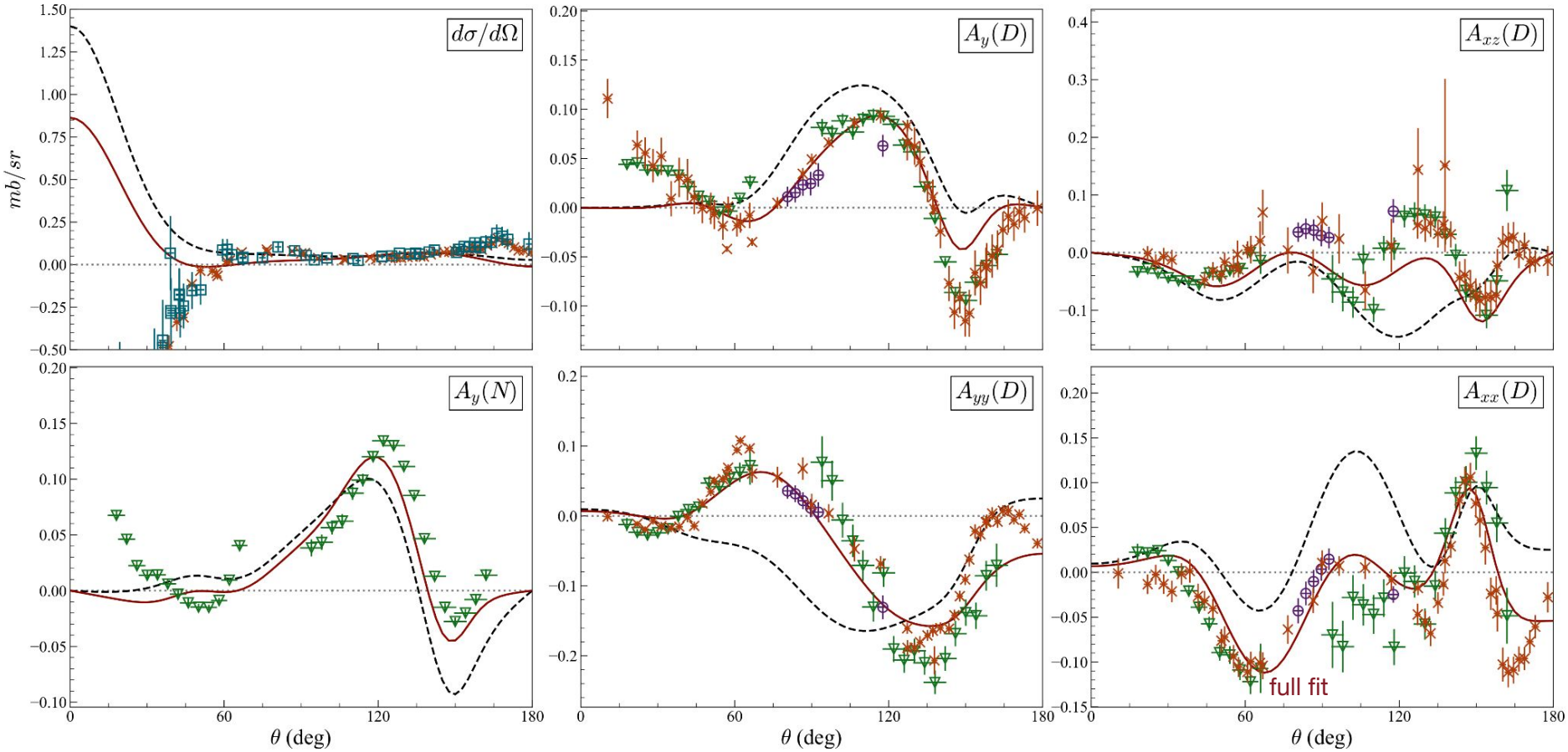
— Developed *exact* emulator for scattering and bound states Heihoff, Filin, EE, e-Print: 2604.25792

— Fitted 9 N⁴LO LECs to Nd data (cs + analyzing powers) at 10, 70 and 135 MeV

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Same but with the 2NF contribution subtracted



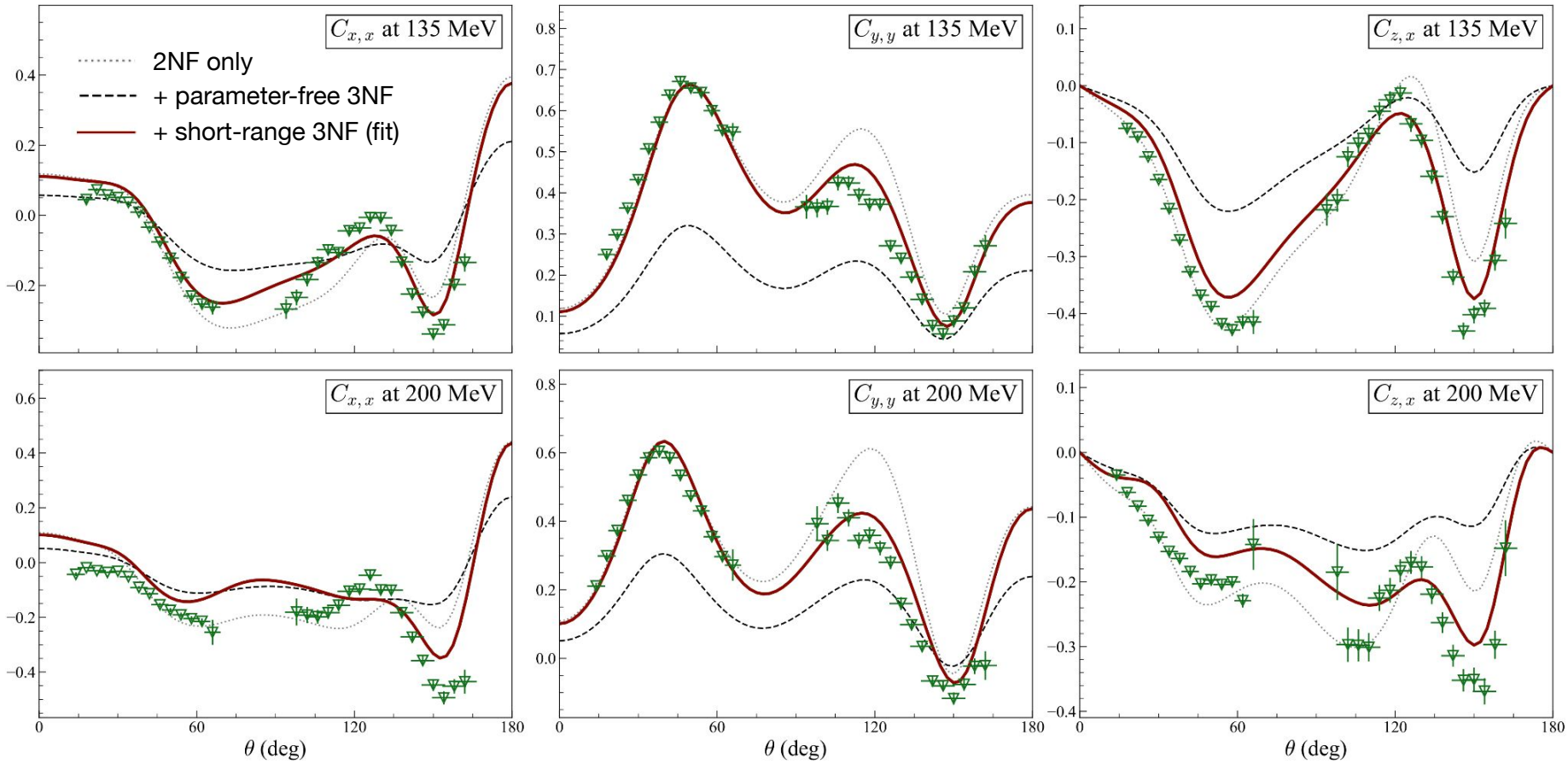
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Selected *predictions*



— Developed *exact* emulator for scattering and bound states Heihoff, Filin, EE, e-Print: 2604.25792

— Fitted 9 N⁴LO LECs to Nd data (cs + analyzing powers) at 10, 70 and 135 MeV

Summary and outlook

- The chiral symmetry of QCD and its breaking pattern play the key role for understanding low-energy nuclear physics
- Chiral EFT has already been developed into a precision tool in the NN sector!

Frontiers and challenges:

- Precision physics beyond 2N: Need to tackle the 3NF challenge
  - Chiral EFT reformulated (gradient flow): Consistent 3NFs and currents
  - Precision tests with light nuclei: Spectra, transitions, FFs, …
  - *Ab-initio* theory for heavier nuclei and reactions
- Chiral EFT as a tool to deal with nuclear effects (SM and BSM): PV, EDM, 0νββ,…
- EFT and lattice-QCD

Thank you for your attention