Evgeny Epelbaum, Ruhr University Bochum

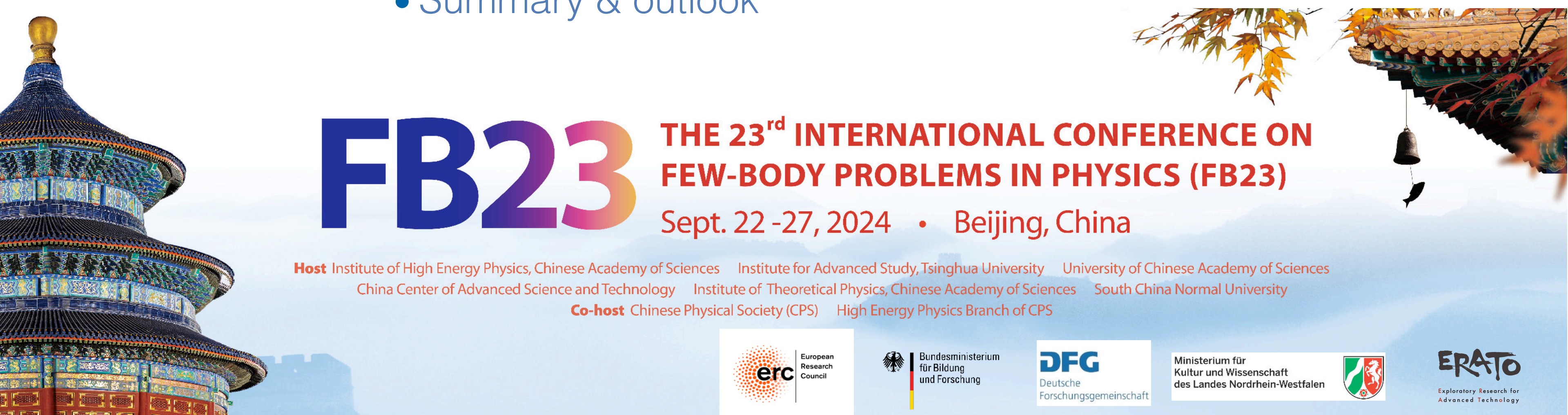
RUB

Chiral EFT using Gradient Flow

based on work done in collaboration with Hermann Krebs, e-Prints: 2311.10893; 2312.13932
(both papers accepted for publication in PRC)

…opens an avenue for accurate χEFT calculations beyond the 2N system

- Introduction & state-of-the-art
- The need for a symmetry-preserving regulator
- Chiral EFT using gradient flow
- Summary & outlook



Deuteron as a bound state of quarks and gluons

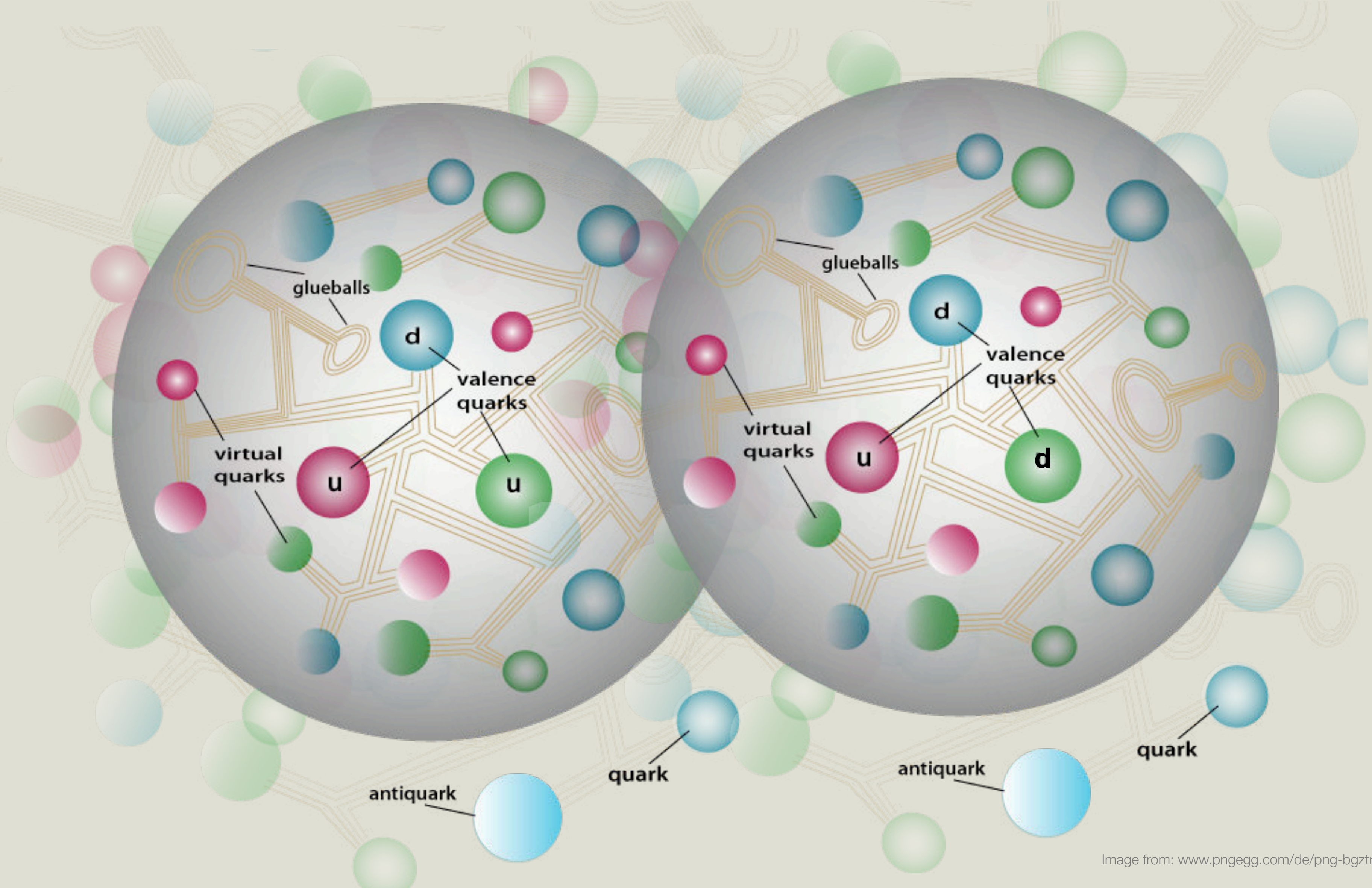
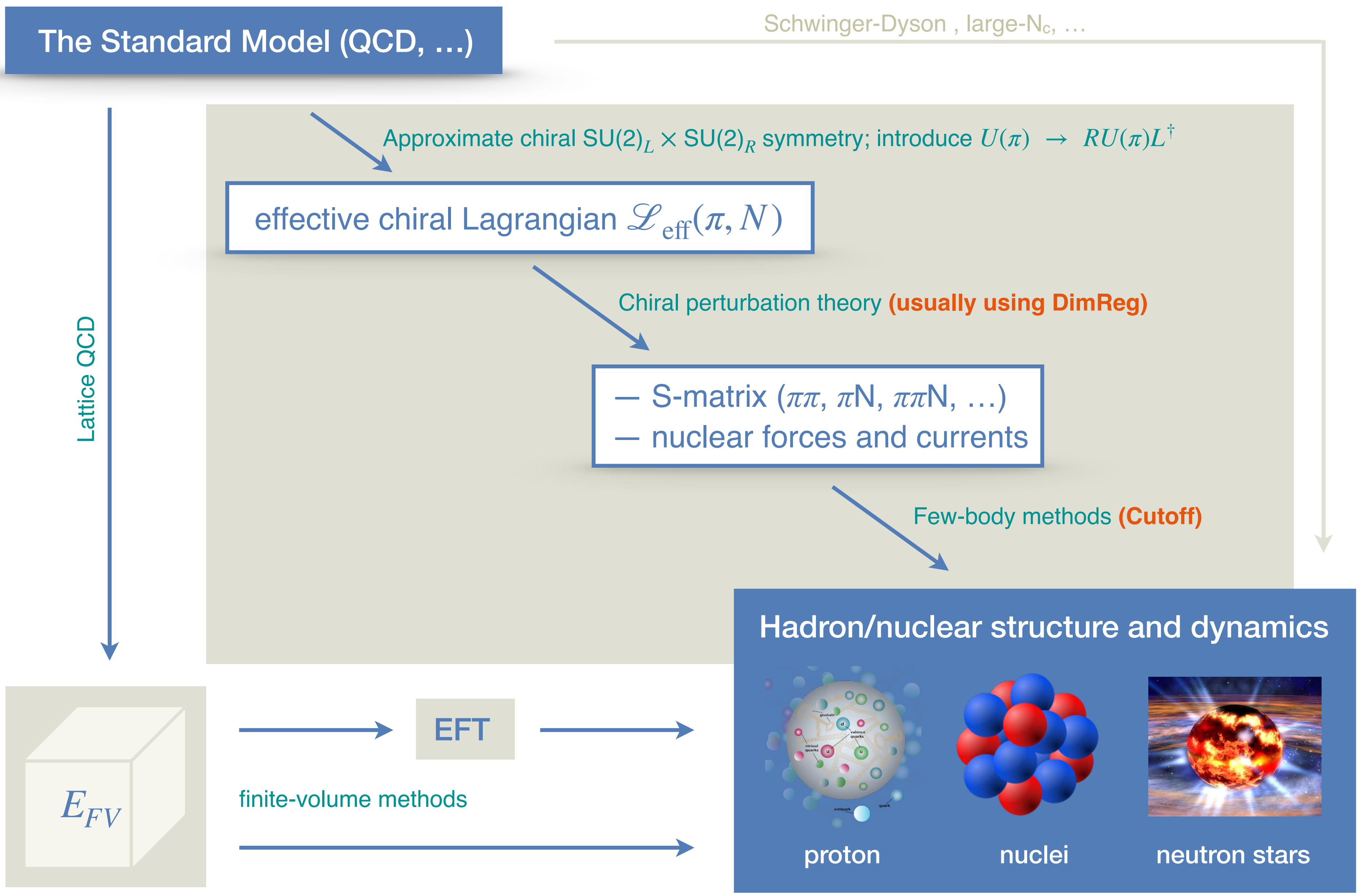


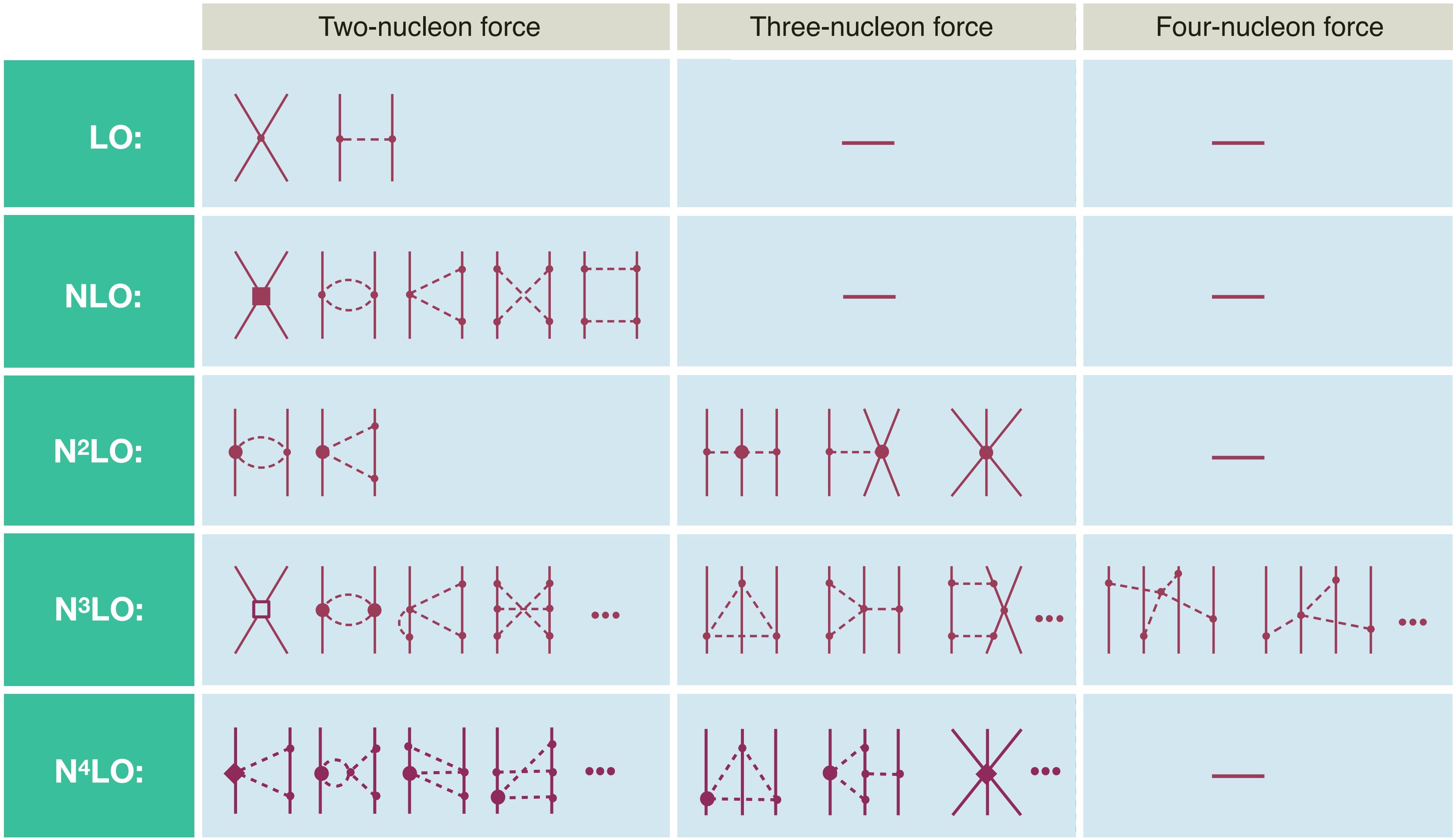
Image from: www.pngegg.com/de/png-bgztr

Is there a way to simplify the picture (without losing connection to QCD)?

Chiral Effective Field Theory



Chiral expansion of nuclear forces



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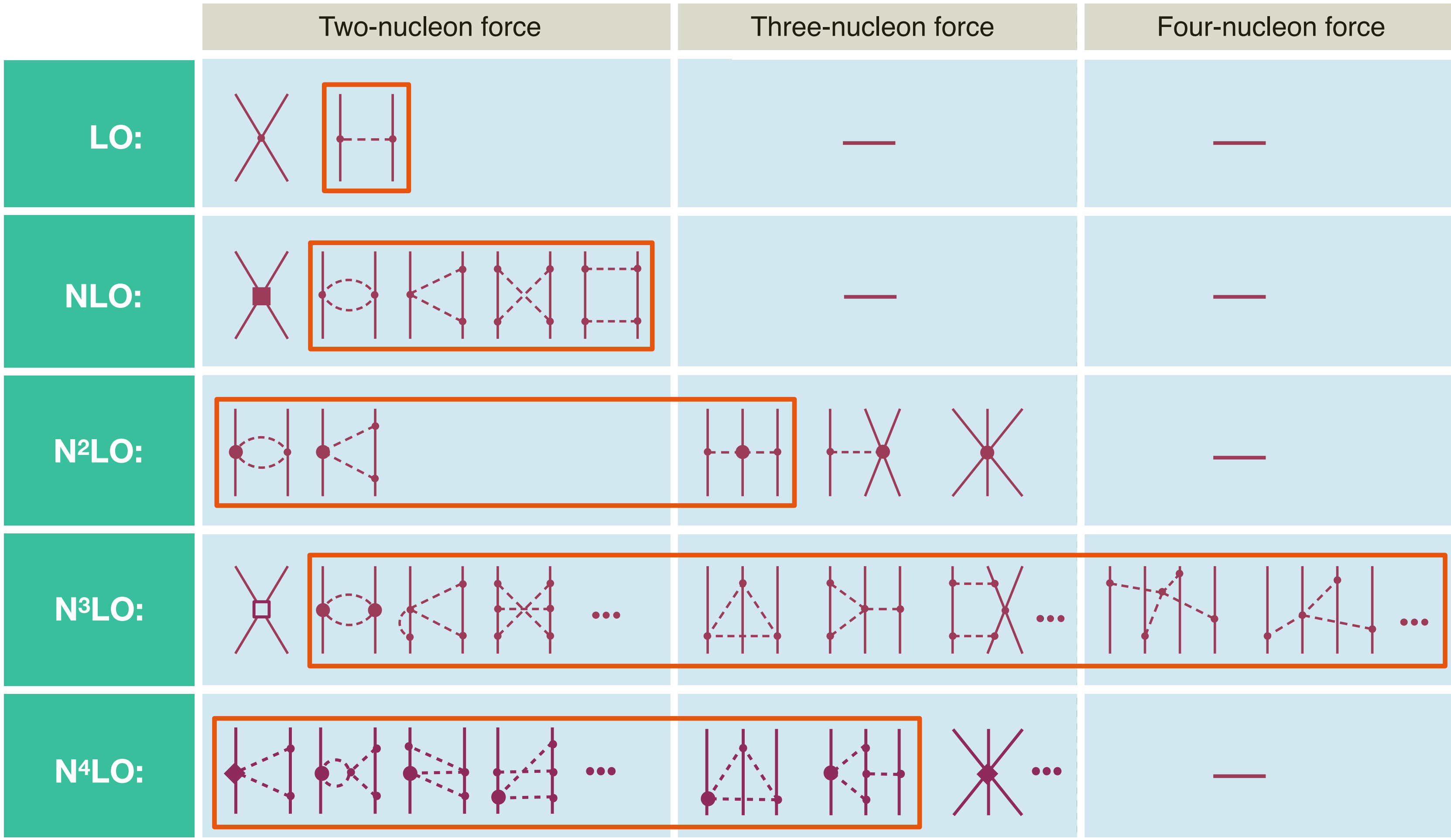
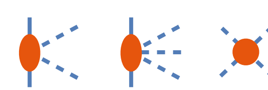


Chiral dynamics: Long-range interactions are predicted in terms of on-shell amplitudes



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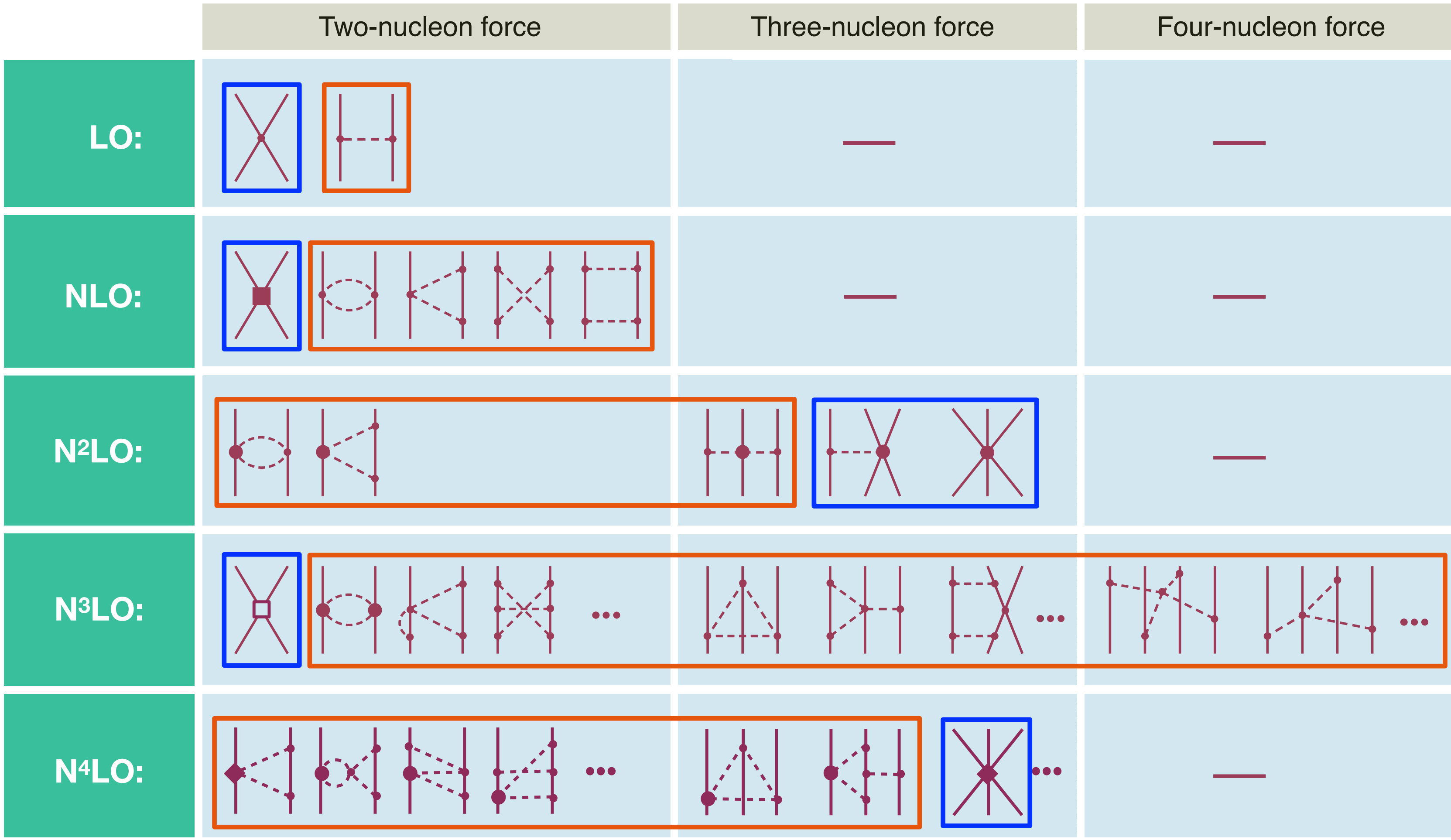
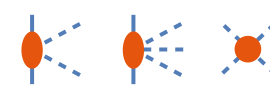
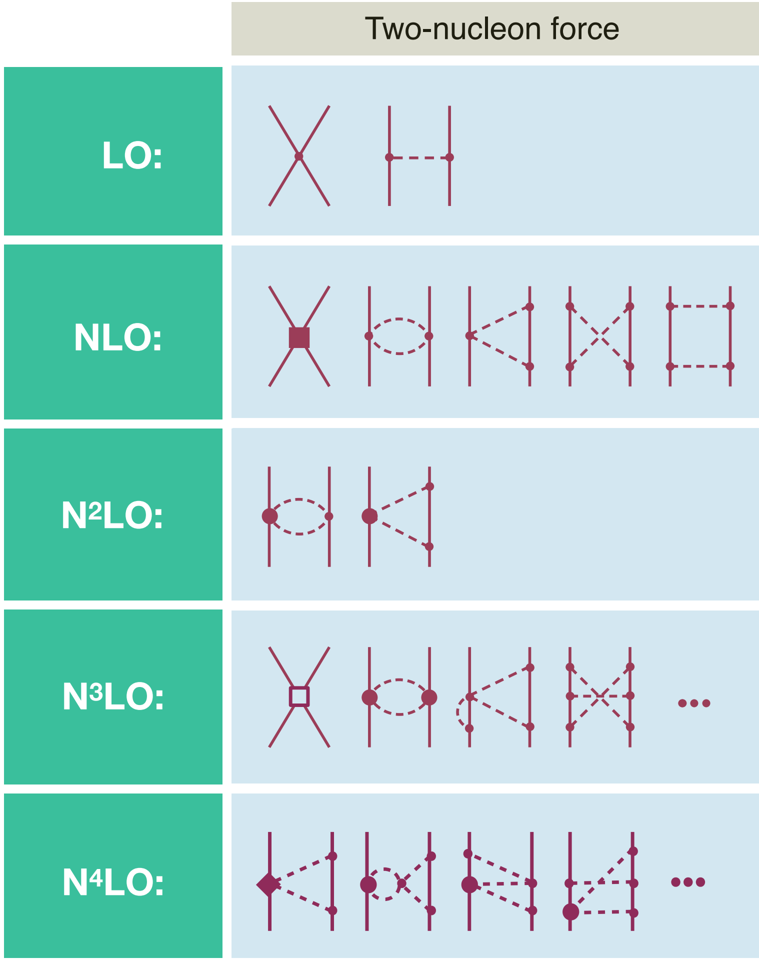


Chiral dynamics: Long-range interactions are predicted in terms of on-shell amplitudes 

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

Chiral expansion of nuclear forces

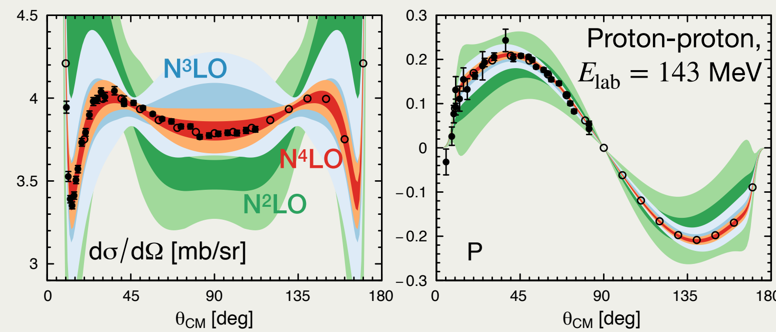


χEFT as a precision tool in the 2N sector

— N⁴LO⁺: currently most accurate and precise NN interactions on the market

— clear evidence of the TPEP from NN data

— Bayesian truncation-error estimation



— almost no residual cutoff dependence

⇒ precision 2N physics from χEFT

Semi-local regularization in momentum space Reinert, Krebs, EE, EPJA 54 (2018) 86; PRL 126 (2021) 092501

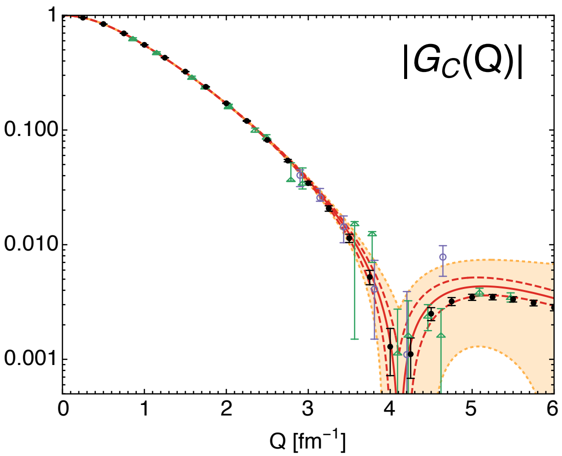
$$V_{1\pi}(q) = \frac{\alpha}{\vec{q}^2 + M_\pi^2}\, e^{-\frac{\vec{q}^2 + M_\pi^2}{\Lambda^2}} + \text{subtraction,} \qquad V_{2\pi}(q) = \frac{2}{\pi}\int_{2M_\pi}^{\infty} d\mu\,\mu\, \frac{\rho(\mu)}{\vec{q}^2 + \mu^2}\, e^{-\frac{\vec{q}^2 + \mu^2}{2\Lambda^2}} + \text{subtractions}$$

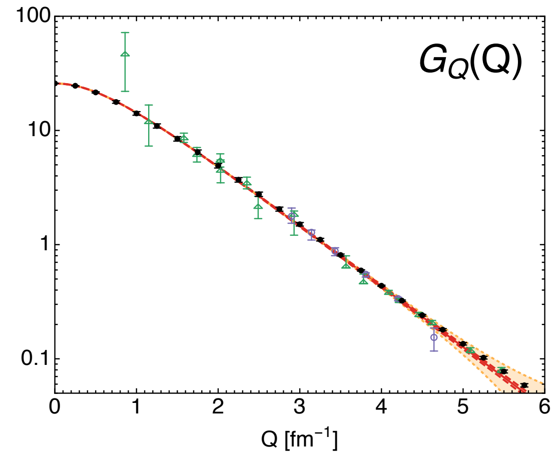
+ nonlocal (Gaussian) cutoff for contacts

Precision 2N physics: Deuteron FFs

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:

$$Q_d = 0.2854^{+0.0038}_{-0.0017}\ \text{fm}^2$$

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

to be compared with experiment

$$Q_d^{exp} = 0.285\,699(15)(18)\ \text{fm}^2$$

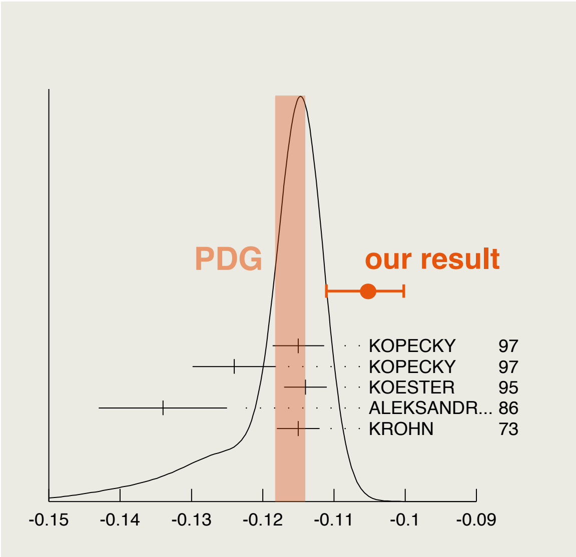
Puchalski et al., PRL 125 (2020)

The charge and structure radius:

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

Combining our result $r_{str} = 1.9729^{+0.0015}_{-0.0012}$ fm with very precise isotope-shift spectroscopy data for $r_d^2 - r_p^2$, we determine the neutron m.s. charge radius:

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



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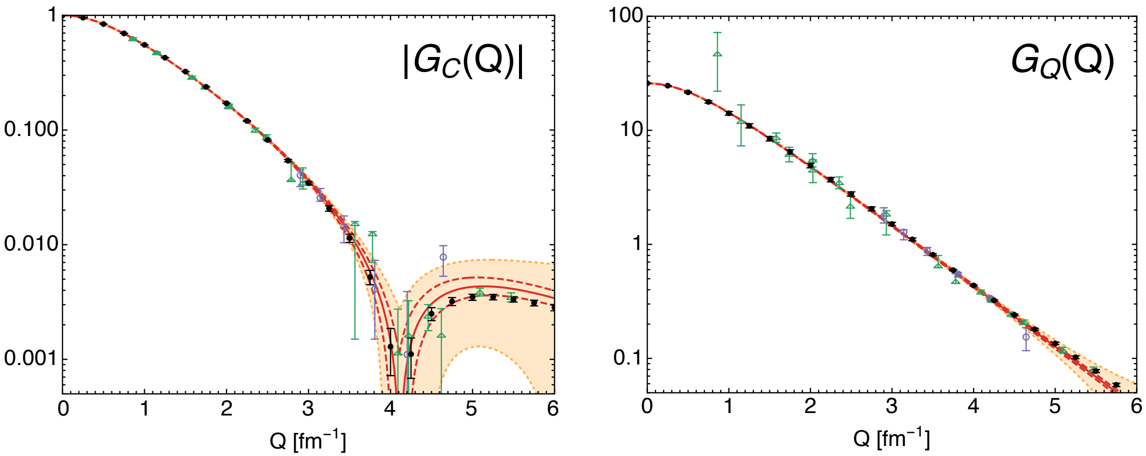

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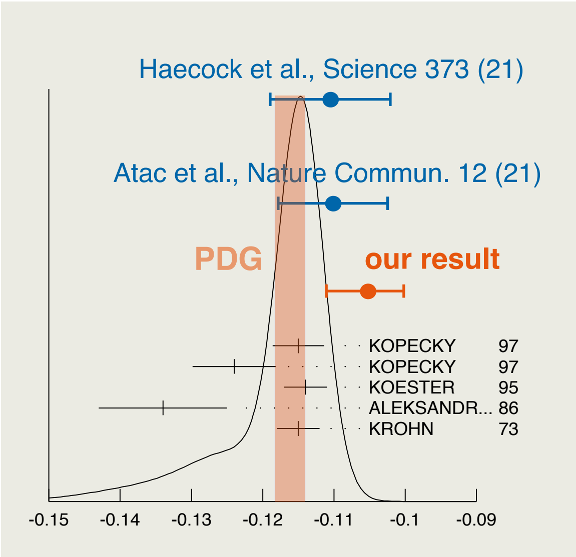
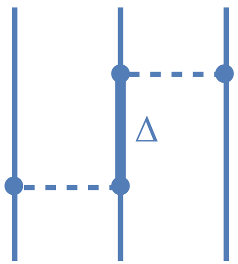


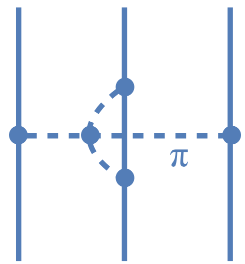
3-body force: A frontier in nuclear & atomic physics

Endo, EE, Naidon, Nishida, Sekiguchi, Takahashi, e-Print: 2405.09807 [nucl-th]

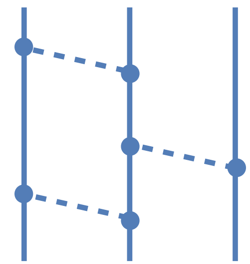
- Three-nucleon forces (3NF) are small **<u>but important</u>** corrections to the dominant NN forces
- 3NF mechanisms:



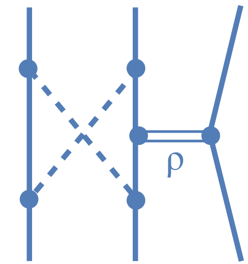
intermediate Δ-excitation
Fujita, Miyazawa ’57



multi-pion interactions



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



short-range

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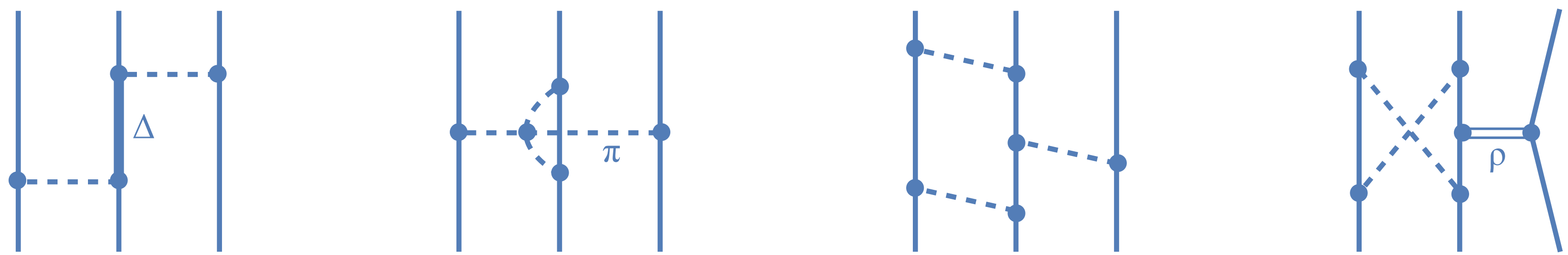

intermediate Δ-excitation — Fujita, Miyazawa '57 | multi-pion interactions | off-shell behavior of the V_{NN}: $V_{\rm ring} = \mathscr{A}_{3\pi} - V_\pi G_0 V_\pi G_0 V_\pi$ | short-range

- **Difficult to model: None of the existing 3NFs allow to describe of 3N data…**
  - — scarcer database compared to the NN sector ← talk by Kimiko Sekiguchi
  - — high computational cost of solving the Faddeev equation
  - — complicated structure:

$$V_{3N}^{\rm non-local} = \sum_{i=1}^{320} O_i \times f_i = \sum_{i=1}^{68} O_i \times \tilde{f}_i + \text{perm.} \xrightarrow{\text{antisymm.}} \sum_{i=1}^{14} O_i \times \tilde{\tilde{f}}_i + \text{perm.}$$

Topolnicki '17; spin-momentum-isospin (O_i); functions of 5 momenta ($\tilde{\tilde{f}}_i$); Krebs, EE, in preparation

⇒ Guidance from theory indispensable — an opportunity for χEFT!

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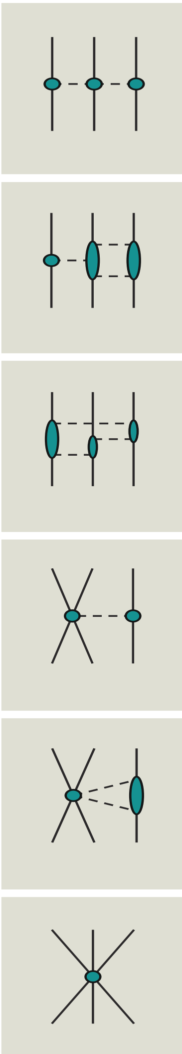

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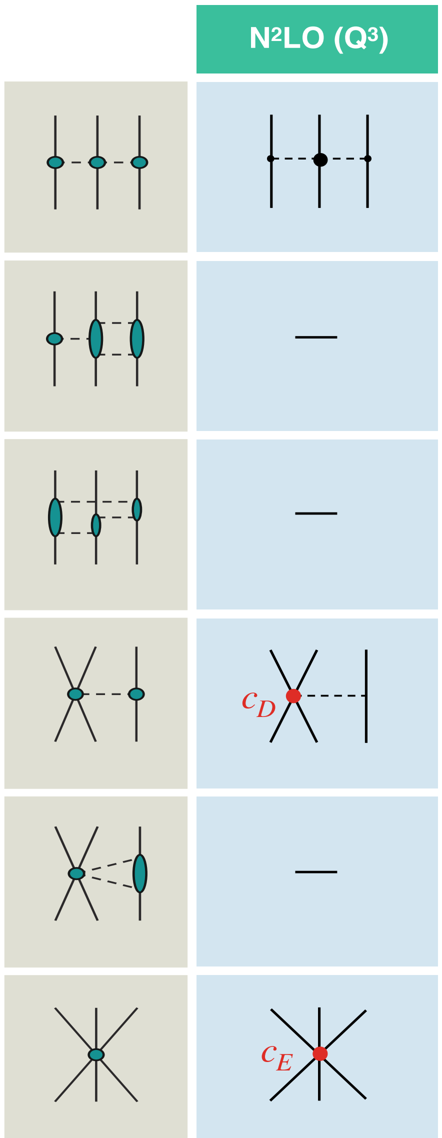

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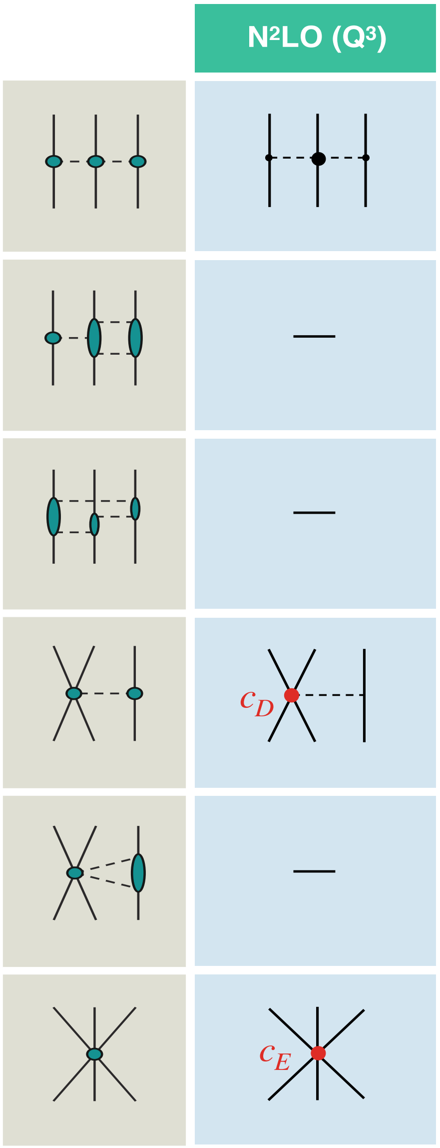
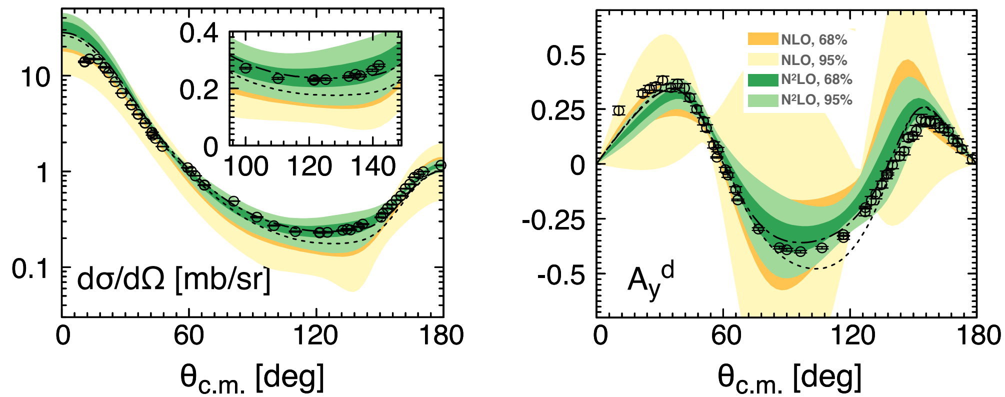
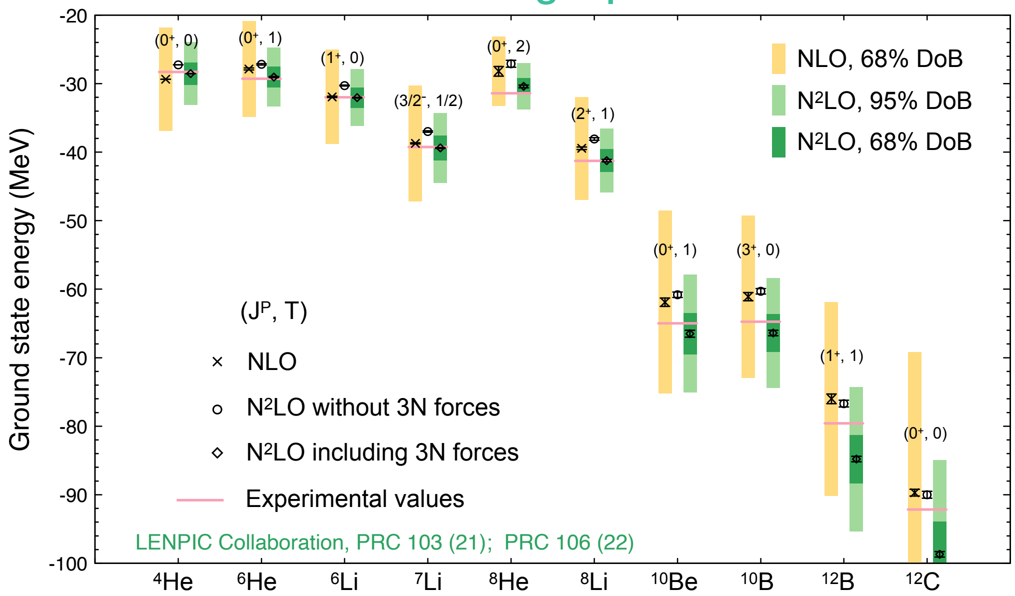


Elastic Nd scattering at 135 MeV



Predictions for light p-shell nuclei



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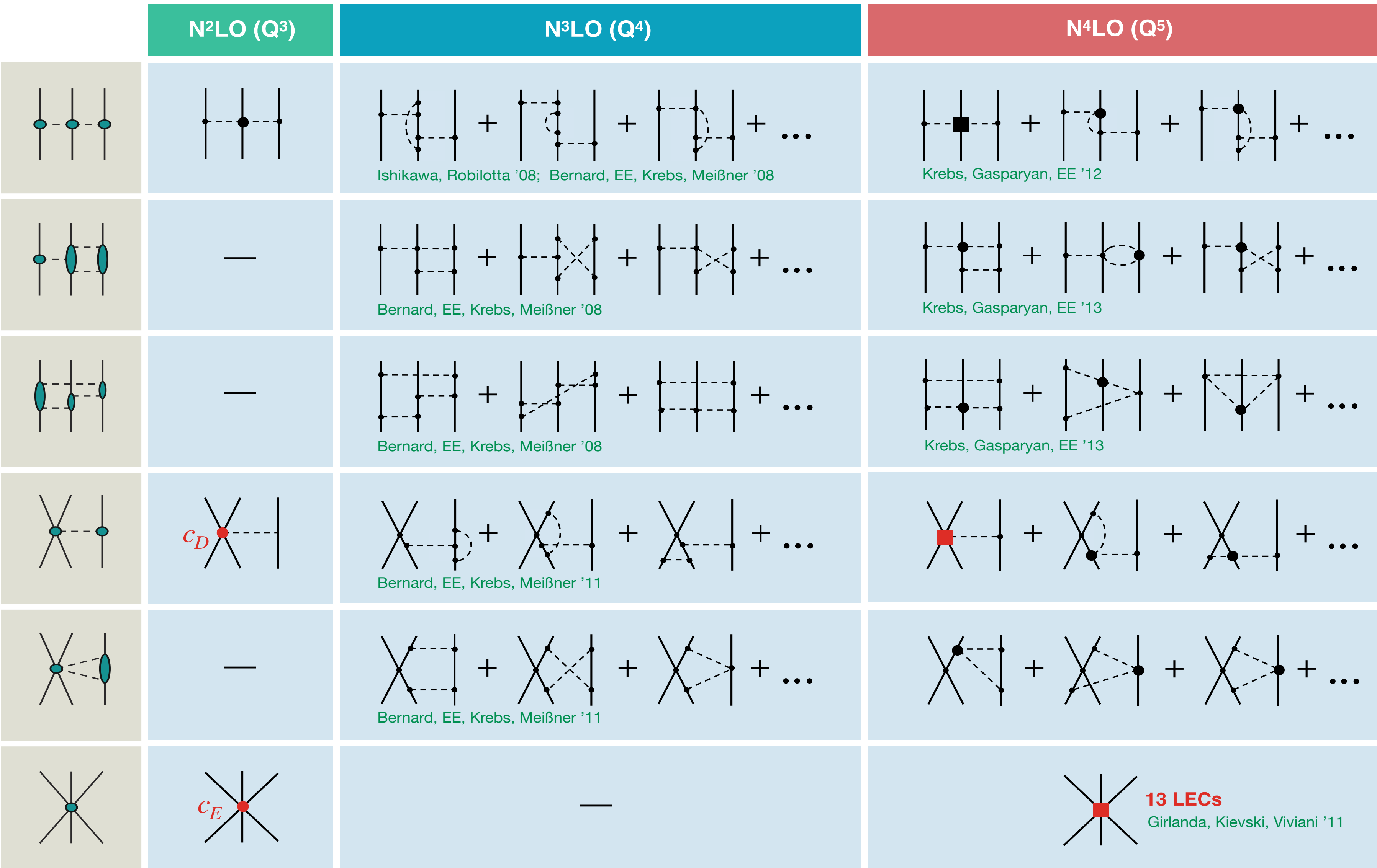

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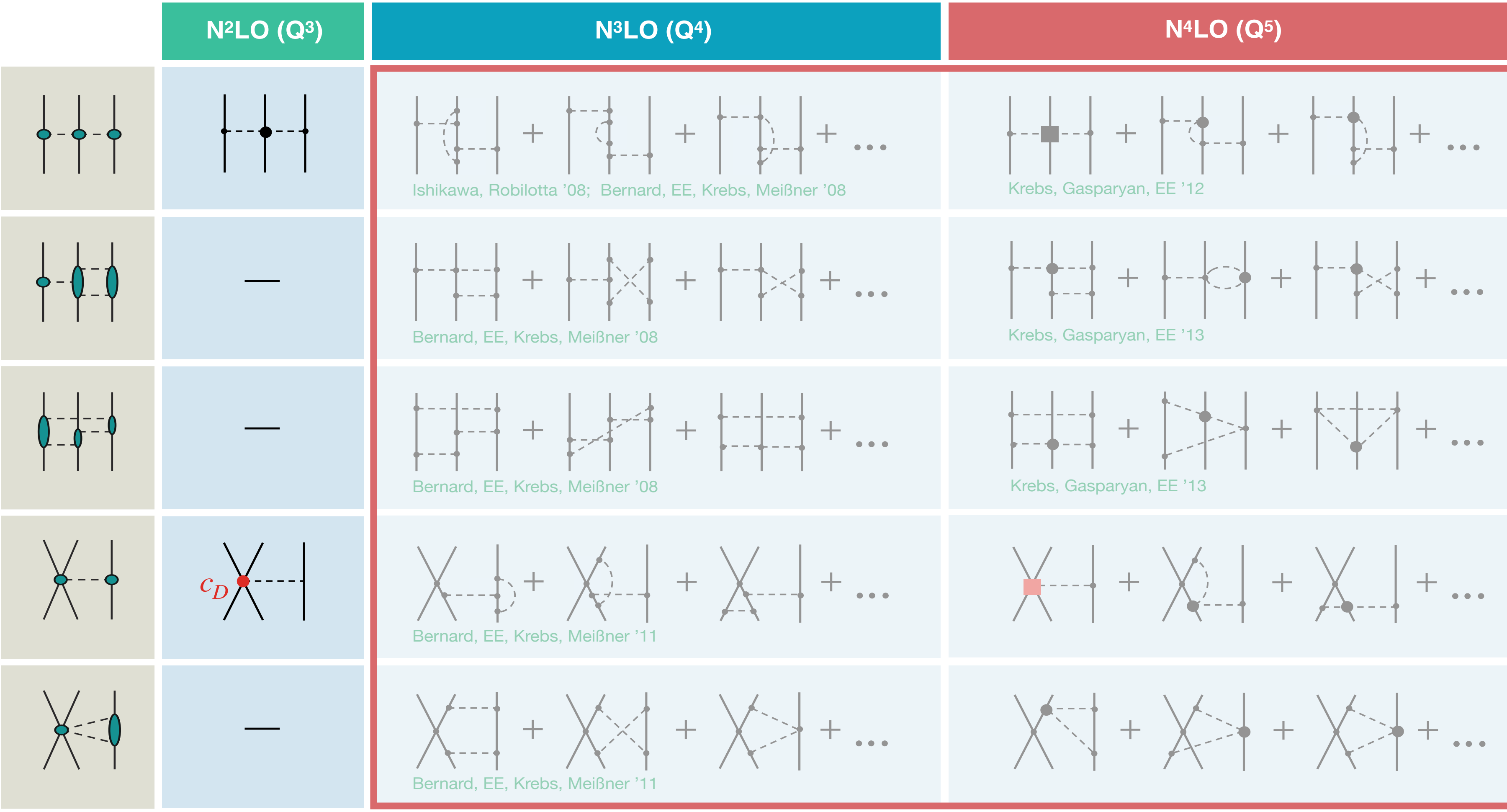


mixing DimReg with Cutoff in the Schrödinger equation breaks χ-symmetry [EE, Krebs, Reinert '19]

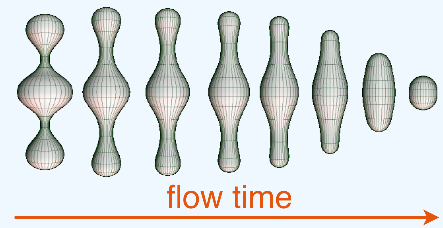
⇒ **need to be re-derived using symmetry-preserving Cutoff regularization**

(also applies to nuclear currents at N³LO and beyond…)

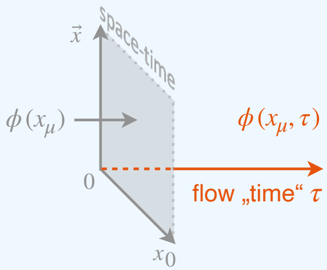
DANGER: momentum cutoff for pions breaks chiral symmetry!

Gradient flow

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: $\frac{\partial}{\partial \tau}\phi(x,\tau) = - \left.\frac{\delta S[\phi]}{\delta \phi(x)}\right|_{\phi(x)\to\phi(x,\tau)}$

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

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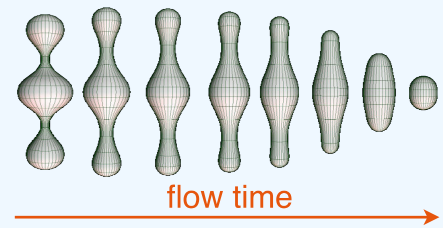

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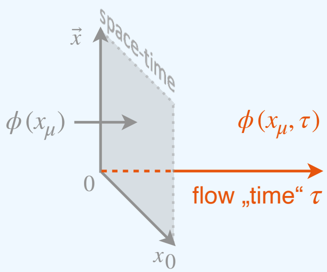

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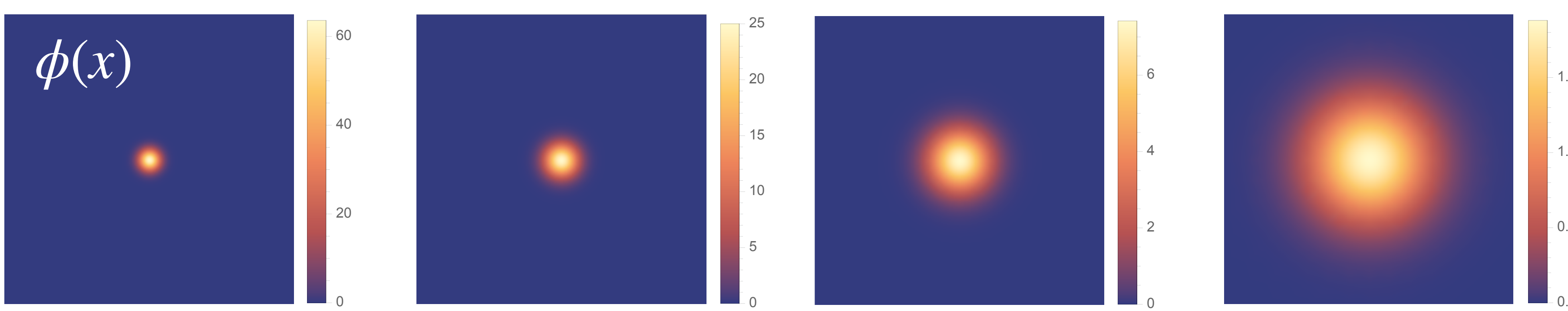
Free scalar field:

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

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



$\tau = 0$ $\tau = 1$ $\tau = 2$ $\tau = 4$

Gradient flow

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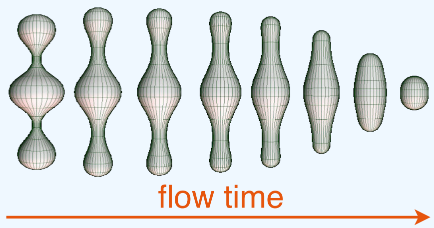

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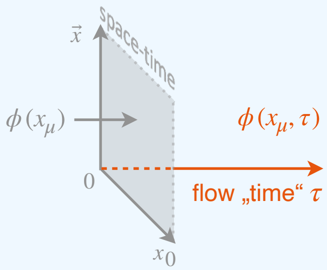

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YM gradient flow Narayanan, Neuberger ’06, Lüscher, Weisz ’11: $\partial_\tau A_\mu(x,\tau) = D_\nu G_{\nu\mu}(x,\tau)$ ← extensively used in LQCD

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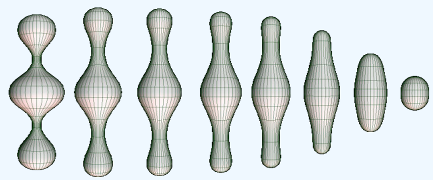

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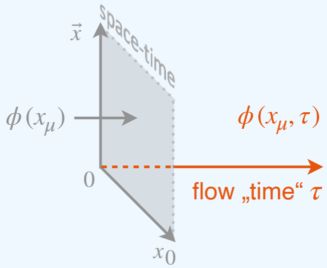

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Chiral gradient flow Krebs, EE, 2312.13932, to appear in PRC

Generalize $U(x)$, $U(x) \to RU(x)L^\dagger$ to $W(x,\tau)$: $\partial_\tau W = -i\underbrace{w}_{\sqrt{W}} \overbrace{\text{EOM}(\tau)}^{[D_\mu, w_\mu] + \frac{i}{2}\chi_-(\tau) - \frac{i}{4}\text{Tr}\,\chi_-(\tau)} w, \quad W(x,0) = U(x)$

We have proven $\forall\tau$: $W(x,\tau) \in \text{SU}(2)$, $W(x,\tau) \to RW(x,\tau)L^\dagger$

Chiral gradient flow

Solving the chiral gradient flow equation $\partial_\tau W = -iw\,\mathrm{EOM}(\tau)\,w$

— most general parametrization of U: $U = 1 + \frac{i}{F}\boldsymbol{\tau}\cdot\boldsymbol{\pi} - \frac{\boldsymbol{\pi}^2}{2F^2} - \alpha\frac{i}{F^3}\boldsymbol{\tau}\cdot\boldsymbol{\pi}\boldsymbol{\pi}^2 + \dots$

— similarly, write $W = 1 + i\boldsymbol{\tau}\cdot\boldsymbol{\phi} - \boldsymbol{\phi}^2 - i\,\alpha\,\boldsymbol{\tau}\cdot\boldsymbol{\phi}\boldsymbol{\phi}^2 + \dots$ and make an ansatz $\boldsymbol{\phi} = \sum_{n=0}^{\infty}\frac{\boldsymbol{\phi}^{(n)}}{F^n}$

$\Rightarrow$ recursive (perturbative) solution of the GF equation in $1/F$

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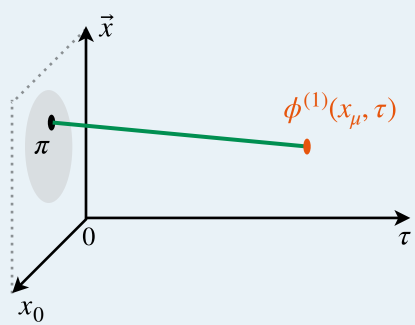
Leading order $\phi^{(1)}$ (no external sources):

$$\left.\begin{aligned}\left[\partial_\tau - (\partial^x_\mu\partial^x_\mu - M^2)\right]\boldsymbol{\phi}^{(1)}(x,\tau) &= 0\\ \boldsymbol{\phi}^{(1)}(x,0) &= \boldsymbol{\pi}(x)\end{aligned}\right\} \;\Rightarrow\; \boldsymbol{\phi}^{(1)}(x,\tau) = \int d^4y\,\overbrace{G(x-y,\tau)}^{G(x,\tau)=\frac{\theta(\tau)}{16\pi^2\tau^2}e^{-\frac{x^2+4M^2\tau^2}{4\tau}}}\boldsymbol{\pi}(y)$$

$\phi(x_\mu, \tau) \quad =$



$+$

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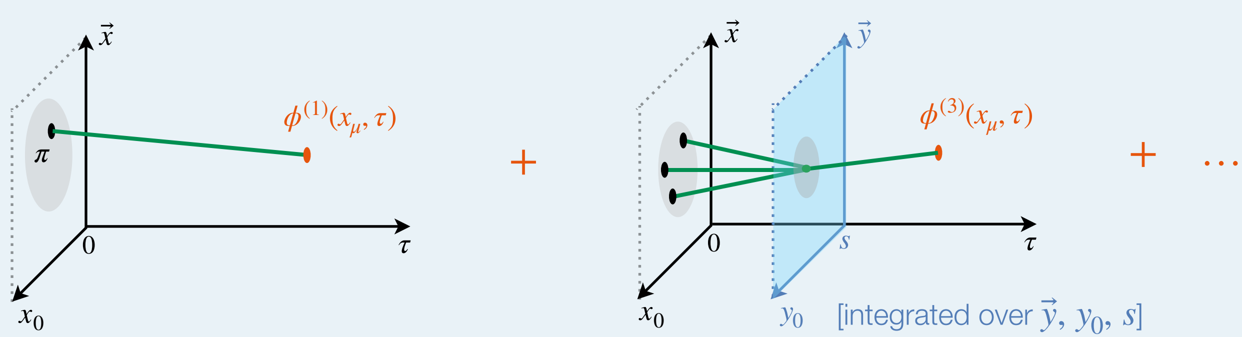
— similarly, write $W \;=\; 1 + i\boldsymbol{\tau}\cdot\boldsymbol{\phi} - \boldsymbol{\phi}^2 - i\,\alpha\,\boldsymbol{\tau}\cdot\boldsymbol{\phi}\boldsymbol{\phi}^2 + \ldots$ and make an ansatz $\boldsymbol{\phi} = \sum_{n=0}^{\infty}\frac{\boldsymbol{\phi}^{(n)}}{F^n}$

$\Rightarrow$ recursive (perturbative) solution of the GF equation in $1/F$

Leading order $\boldsymbol{\phi}^{(1)}$ (no external sources):

$$\left.\begin{aligned}\left[\partial_\tau - (\partial_\mu^x\partial_\mu^x - M^2)\right]\boldsymbol{\phi}^{(1)}(x,\tau) &= 0\\ \boldsymbol{\phi}^{(1)}(x,0) &= \boldsymbol{\pi}(x)\end{aligned}\right\} \quad\Rightarrow\quad \boldsymbol{\phi}^{(1)}(x,\tau) = \int d^4y\,\overbrace{G(x-y,\tau)}^{G(x,\tau)\,=\,\frac{\theta(\tau)}{16\pi^2\tau^2}e^{-\frac{x^2+4M^2\tau^2}{4\tau}}}\boldsymbol{\pi}(y)$$

$\phi(x_\mu,\tau) \;=$



Nuclear forces using chiral gradient flow

Regularization is achieved by requiring N to „live“ at a fixed τ: $\mathscr{L}_{\pi N} \;\rightarrow\; \mathscr{L}_{\phi N}(\tau) \;=\; \mathscr{L}_{\pi N}\Big|_{U \rightarrow W(\tau)}$

Notice: chiral symmetry manifest since $W(\tau) \;\rightarrow\; RW(\tau)L^\dagger$ for all τ.

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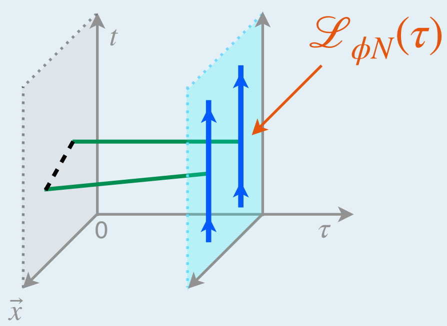
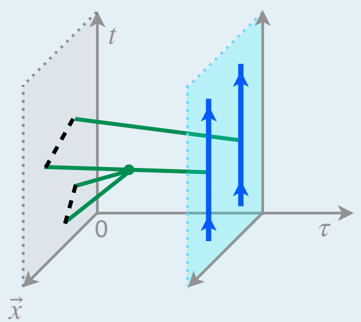
Local field theory in 5d





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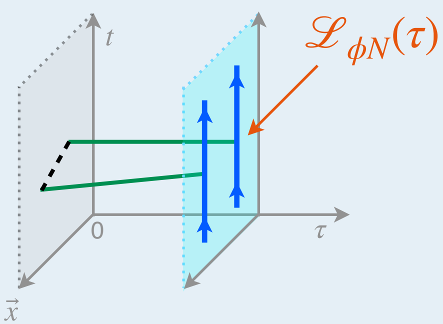
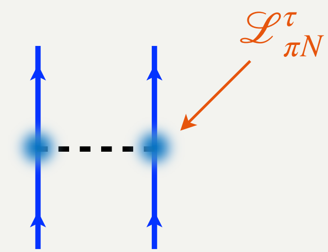
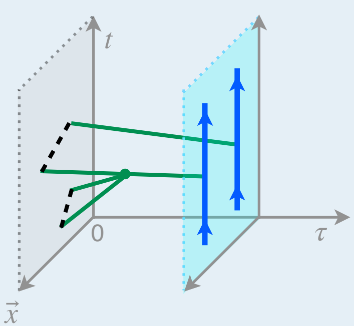
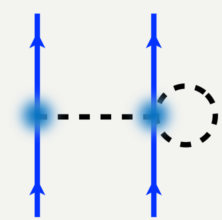
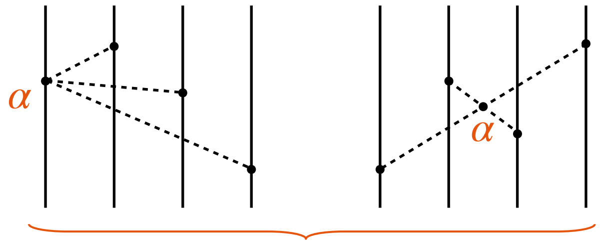
Local field theory in 5d	Smeared (non-local) theory in 4d
	
	

Chiral symmetry and the 4N force

unregularized



The sum of two diagrams ***must*** *be* α*-independent*

Unregularized expression for this 4NF EE, EPJA 34 (2007):

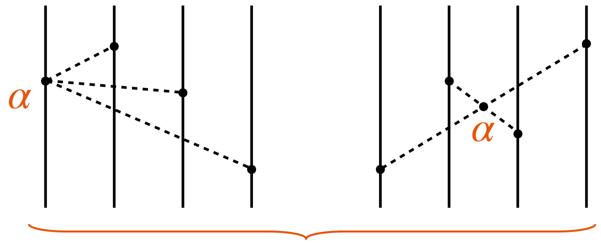
$$\hat{O}_{[\sigma_i,\tau_i,\vec{q}_i]} = \boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2 \boldsymbol{\tau}_3 \cdot \boldsymbol{\tau}_4 \, \vec{\sigma}_2 \cdot \vec{q}_2 \, \vec{\sigma}_3 \cdot \vec{q}_3 \, \vec{\sigma}_4 \cdot \vec{q}_4$$

$$V^{4N} = -\frac{g^4}{64F^6} \frac{\hat{O}_{[\sigma_i,\tau_i,\vec{q}_i]}}{(\vec{q}_2^{\,2}+M^2)(\vec{q}_3^{\,2}+M^2)(\vec{q}_4^{\,2}+M^2)} \vec{\sigma}_1 \cdot \vec{q}_{12}$$

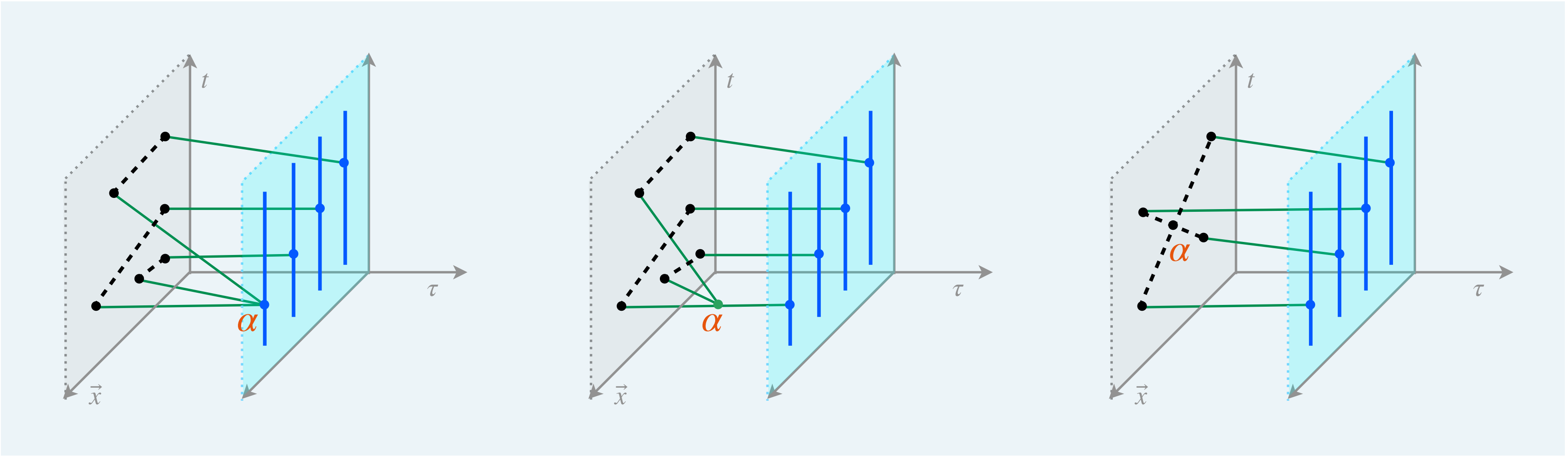
$$+ \frac{g^4}{128F^6} \frac{\vec{\sigma}_1 \cdot \vec{q}_1 \, \hat{O}_{[\sigma_i,\tau_i,\vec{q}_i]}}{(\vec{q}_1^{\,2}+M^2)(\vec{q}_2^{\,2}+M^2)(\vec{q}_3^{\,2}+M^2)(\vec{q}_4^{\,2}+M^2)} \left(M^2 + \vec{q}_{12}^{\,2}\right) + 23 \text{ perm.}$$

Chiral symmetry and the 4N force

unregularized



*The sum of two diagrams **must** be α-independent*



Chiral symmetry and the 4N force

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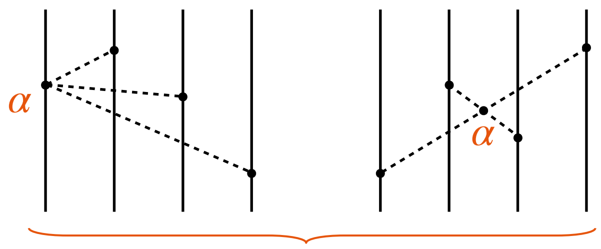

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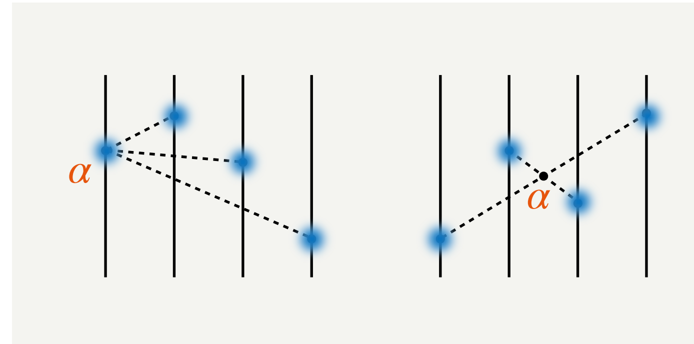
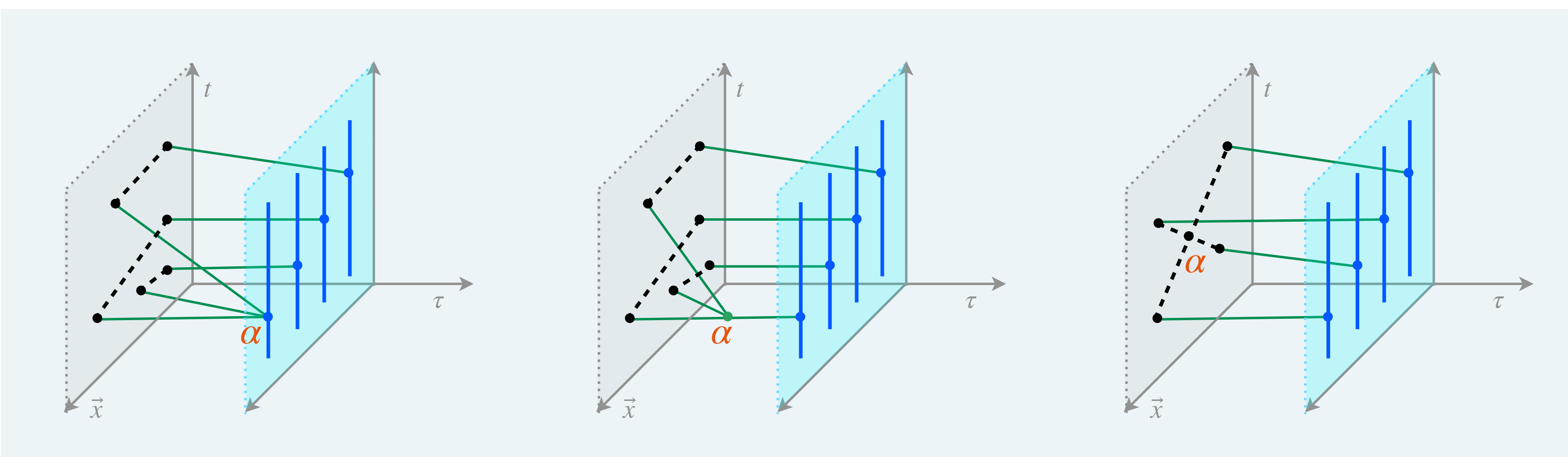
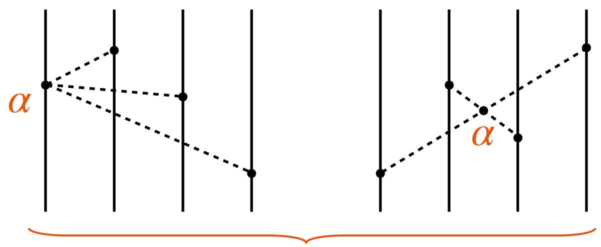




Chiral symmetry and the 4N force

unregularized



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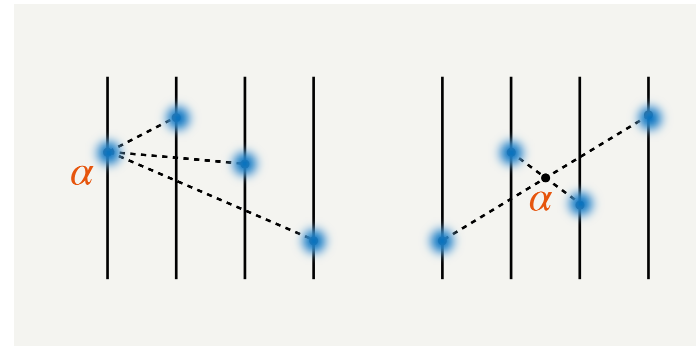

Regularized expression (ready to use in the A-body Schrödinger equation):

$$
\begin{aligned}
V_\Lambda^{4N} = \; & \frac{g^4}{64F^6} \frac{\hat{O}_{[\sigma_i,\tau_i,\vec{q}_i]}}{(\vec{q}_2^{\,2}+M^2)(\vec{q}_3^{\,2}+M^2)(\vec{q}_4^{\,2}+M^2)} \bigg[\vec{\sigma}_1 \cdot \vec{q}_1 \big(2g_\Lambda - 4 f_\Lambda^{123} + 2 f_\Lambda^{134} - f_\Lambda^{234} \big) - \vec{\sigma}_1 \cdot \vec{q}_2 f_\Lambda^{234} \\
& + 2 \vec{\sigma}_1 \cdot \vec{q}_1 \big(5M^2 + \vec{q}_1^{\,2} + \vec{q}_2^{\,2} + \vec{q}_3^{\,2} + \vec{q}_4^{\,2} + \vec{q}_{34}^{\,2} \big) \frac{g_\Lambda - f_\Lambda^{134}}{2M^2 + \vec{q}_1^{\,2} + \vec{q}_3^{\,2} + \vec{q}_4^{\,2} - \vec{q}_2^{\,2}} \\
& - 4 \vec{\sigma}_1 \cdot \vec{q}_1 \big(3M^2 + \vec{q}_1^{\,2} + \vec{q}_2^{\,2} + \vec{q}_3^{\,2} + \vec{q}_4^{\,2} - \vec{q}_{34}^{\,2} \big) \frac{g_\Lambda - f_\Lambda^{124}}{2M^2 + \vec{q}_1^{\,2} + \vec{q}_2^{\,2} + \vec{q}_4^{\,2} - \vec{q}_3^{\,2}} \bigg] \\
+ \; & \frac{g^4}{128F^6} \frac{\vec{\sigma}_1 \cdot \vec{q}_1 \, \hat{O}_{[\sigma_i,\tau_i,\vec{q}_i]}}{(\vec{q}_1^{\,2}+M^2)(\vec{q}_2^{\,2}+M^2)(\vec{q}_3^{\,2}+M^2)(\vec{q}_4^{\,2}+M^2)} \big(M^2 + \vec{q}_{12}^{\,2} \big) \big(4 f_\Lambda^{123} - 3 g_\Lambda \big) + 23 \text{ perm.},
\end{aligned}
$$

$$f_\Lambda^{ijk} = e^{-\frac{\vec{q}_i^{\,2}+M^2}{\Lambda^2}} e^{-\frac{\vec{q}_j^{\,2}+M^2}{\Lambda^2}} e^{-\frac{\vec{q}_k^{\,2}+M^2}{\Lambda^2}}$$

$$e^{-\frac{\vec{q}_1^{\,2}+M^2}{2\Lambda^2}} e^{-\frac{\vec{q}_2^{\,2}+M^2}{2\Lambda^2}} e^{-\frac{\vec{q}_3^{\,2}+M^2}{2\Lambda^2}} e^{-\frac{\vec{q}_4^{\,2}+M^2}{2\Lambda^2}}$$

(reduces to the unregularized result in the $\Lambda \to \infty$ limit)

Summary and outlook

New formulation of nuclear chiral EFT:

— gradient flow regularized formulation of chiral EFT Krebs, EE, 2312.13932, to appear in PRC

— path integral method to perform QM reduction of QFT Krebs, EE, 2311.10893, to appear in PRC

⇒ regularized 3N, 4N forces and currents, which are consistent with the SMS NN potentials and respect chiral & gauge symmetries

Already done:

— NN at N^{2}LO, long-range 3NF (still needs to be implemented…) and 4NF at N^{3}LO

Work in progress:

— πN scattering inside the Mandelstam triangle (LECs), 3N scattering at N^{3}LO

The new method can also be useful for improving convergence of SU(3) BChPT

Thank you for your attention