Evgeny Epelbaum, RUB

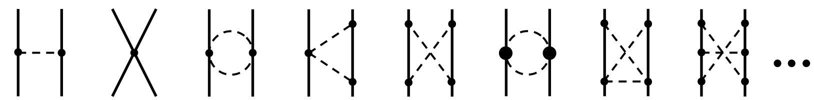
TR110 μWS on Strangeness and related topics, ECT*, Trento, Dec 5/6 2013

Chiral forces: reducing cutoff artifacts

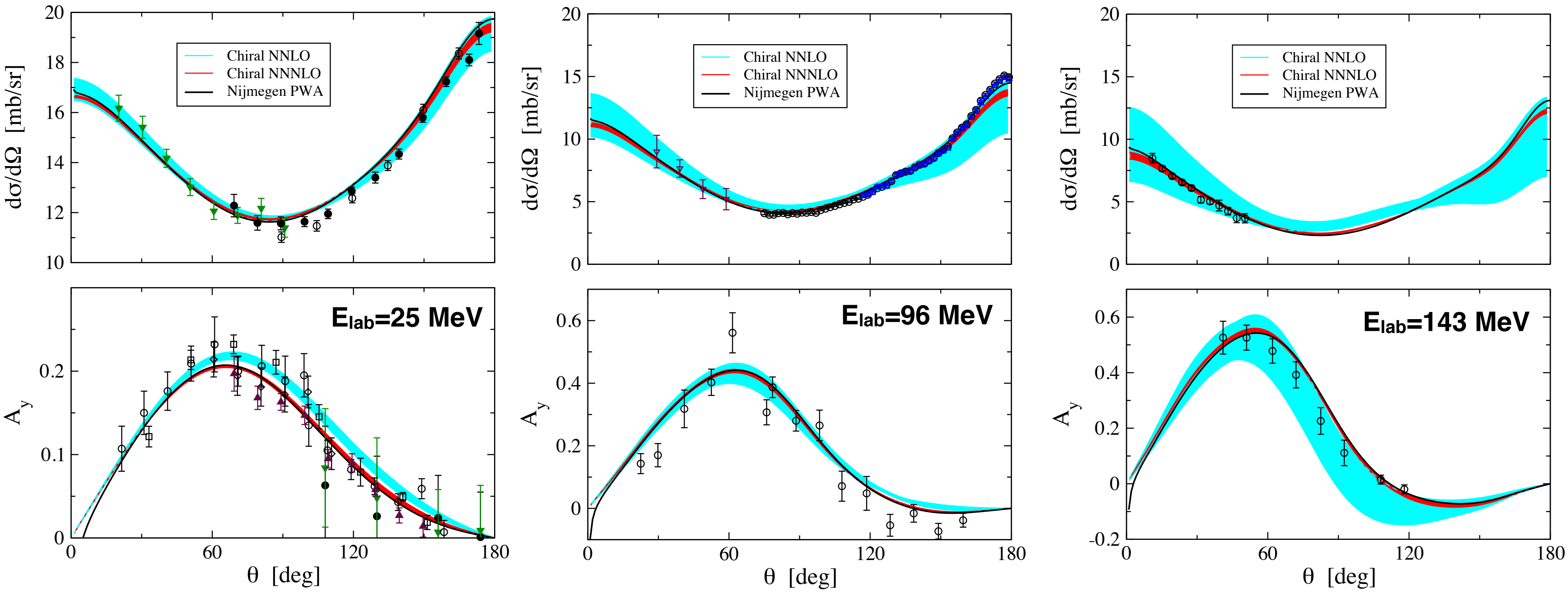
- Motivation
- Renormalizable chiral EFT for NN
- Local chiral nuclear forces
- Summary & outlook

Nucleon-nucleon potential at N^{3}LO

- Long-range: parameter-free (all LECs from πN)
- Short-range part: 24 LECs tuned to NN data
- At N^{3}LO, accurate description of NN data up to ~ 200 MeV   Entem-Machleidt, EE-Glöckle-Meißner

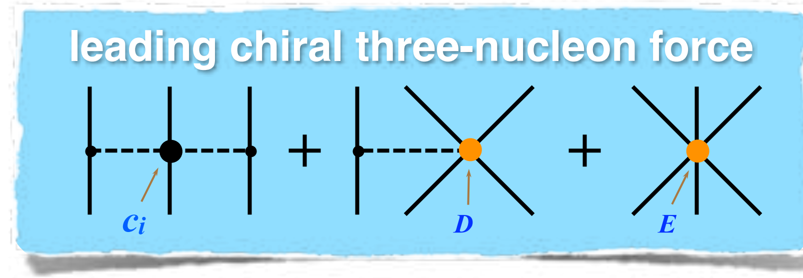


Neutron-proton diff. cross section & the analyzing power



Chiral 3NF & nd elastic scattering

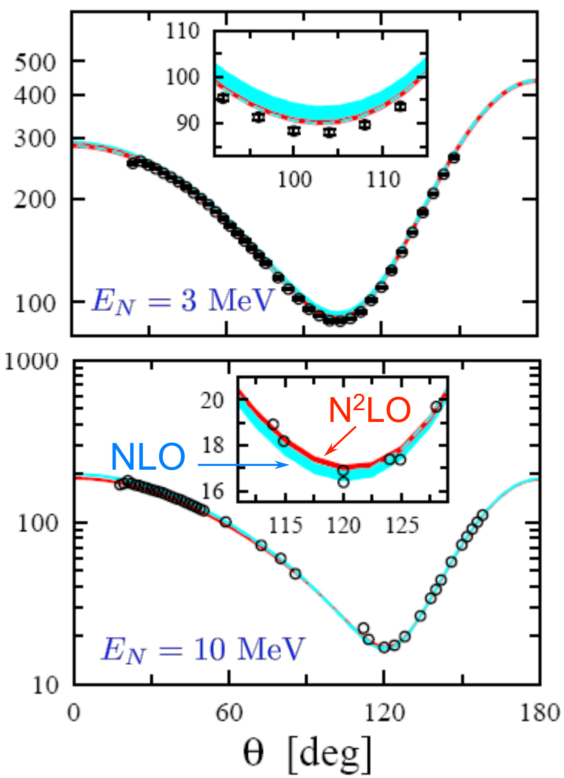
EE, Glöckle, Golak, Kamada, Nogga, Skibinski, Witala



The 3NF starts to contribute at N²LO

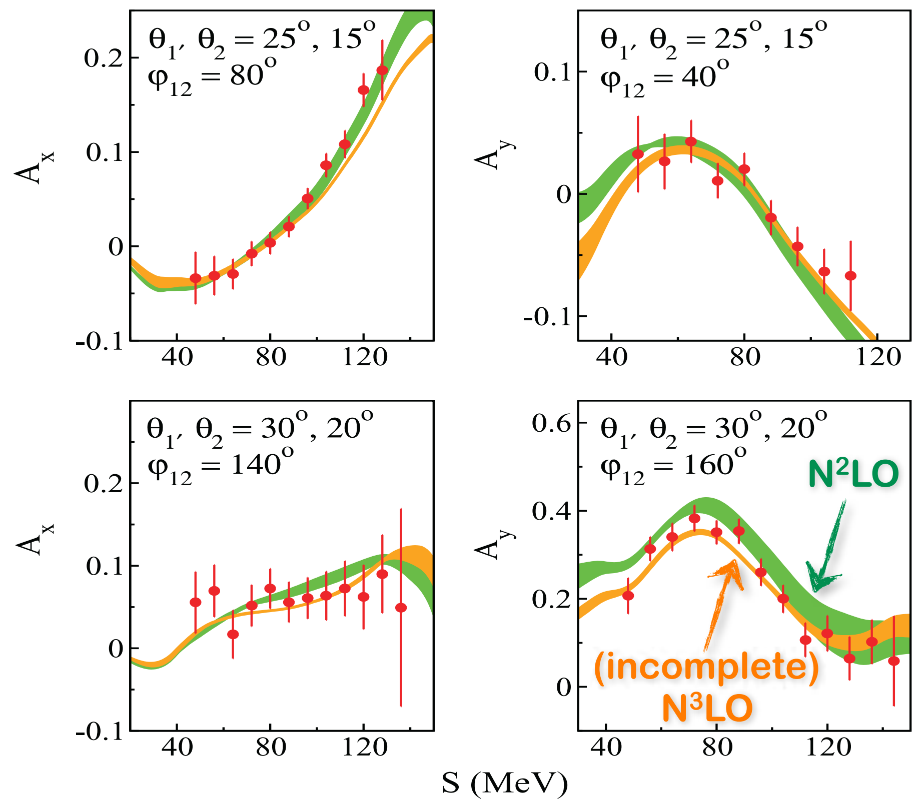
The LECs D,E can be fixed e.g. from ^{3}H BE and nd doublet scattering length

Nd elastic cross sections at low energies



Nd breakup at E_d=130 MeV

Stephan et al., PRC 82 (2010) 014003



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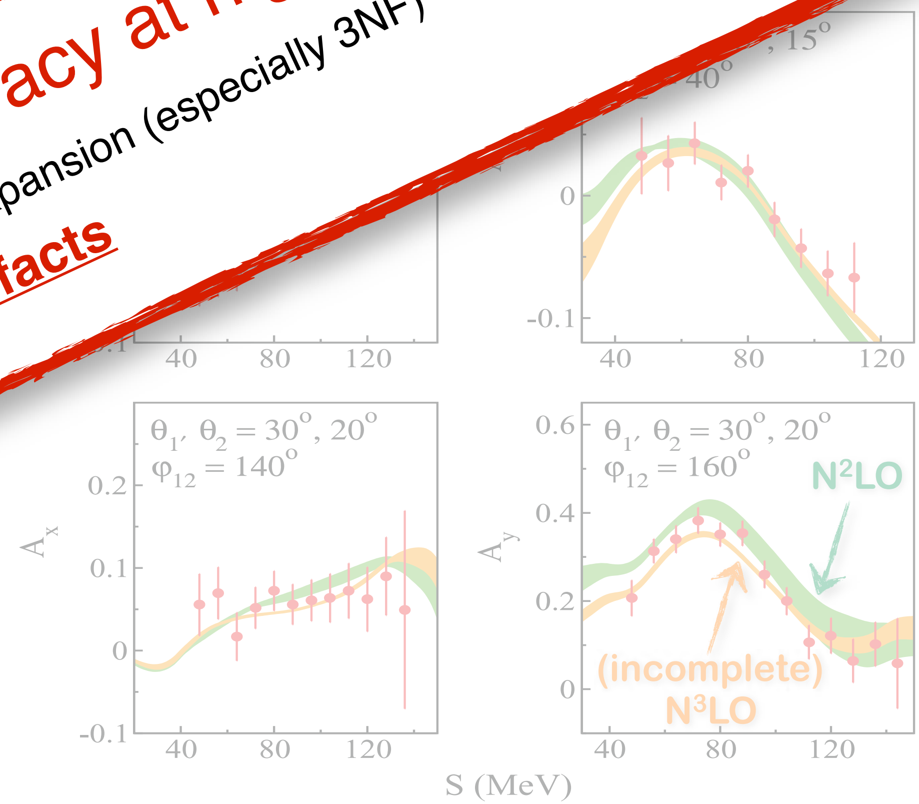


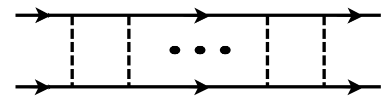
How to increase accuracy at higher energies?

- go to higher orders in the chiral expansion (especially 3NF)
- **reduce finite-cutoff artefacts**

The cutoff issue

Why cutoff?

$$T = \underbrace{V}_{\text{truncated at a given order in the expansion}} + VG_0T = \underbrace{V + VG_0V + VG_0VG_0V + \ldots}_{\text{increasingly UV divergent integrals are generated through iterations}}$$



Ideally, would like to calculate the integrals

$$T^{(n)} = V[G_0V]^{n-1} = m^{n-1} \int_0^{\Lambda} d^3l_1 \ldots d^3l_{n-1} \frac{V(\vec{p}\,', \vec{l}_1)\, V(\vec{l}_1, \vec{l}_2) \ldots V(\vec{l}_{n-1}, \vec{p})}{[p^2 - l_1^2 + i\epsilon] \ldots [p^2 - l_{n-1}^2 + i\epsilon]}$$

subtract the UV divergences ($\sim \log\Lambda;\ \Lambda;\ \Lambda^2; \ldots$) and take the limit $\Lambda \to \infty$. This is not possible in practice (except for pionless EFT) ⟶ let Λ finite and adjust bare C_i to exp data (= implicit renormalization). Λ should be not taken too high [Lepage, EE, Meißner, Gegelia], in practice $\max[\Lambda] \sim 600$ MeV (otherwise spurious BS...)

Price to pay: finite cutoff artifacts (i.e. terms $\sim 1/\Lambda;\ 1/\Lambda^2;\ 1/\Lambda^3; \ldots$), may become an issue at higher energies (e.g. $E_{lab} \sim 200$ MeV corresponds to $p \sim 310$ MeV/c)

Is it possible to eliminate or at least reduce finite cutoff artifacts?

1st option:
Renormalizable chiral EFT for NN ($\Lambda=\infty$)

Renormalizable chiral EFT for NN scattering

EE, Gegelia PLB 716 (2012) 338

Crucial observation: **non-renormalizability of the LS equation at LO [i.e. $V_{cont} + V_{OPE}$] is an artifact of the HB expansion of the propagators**

→ do not expand the integrand

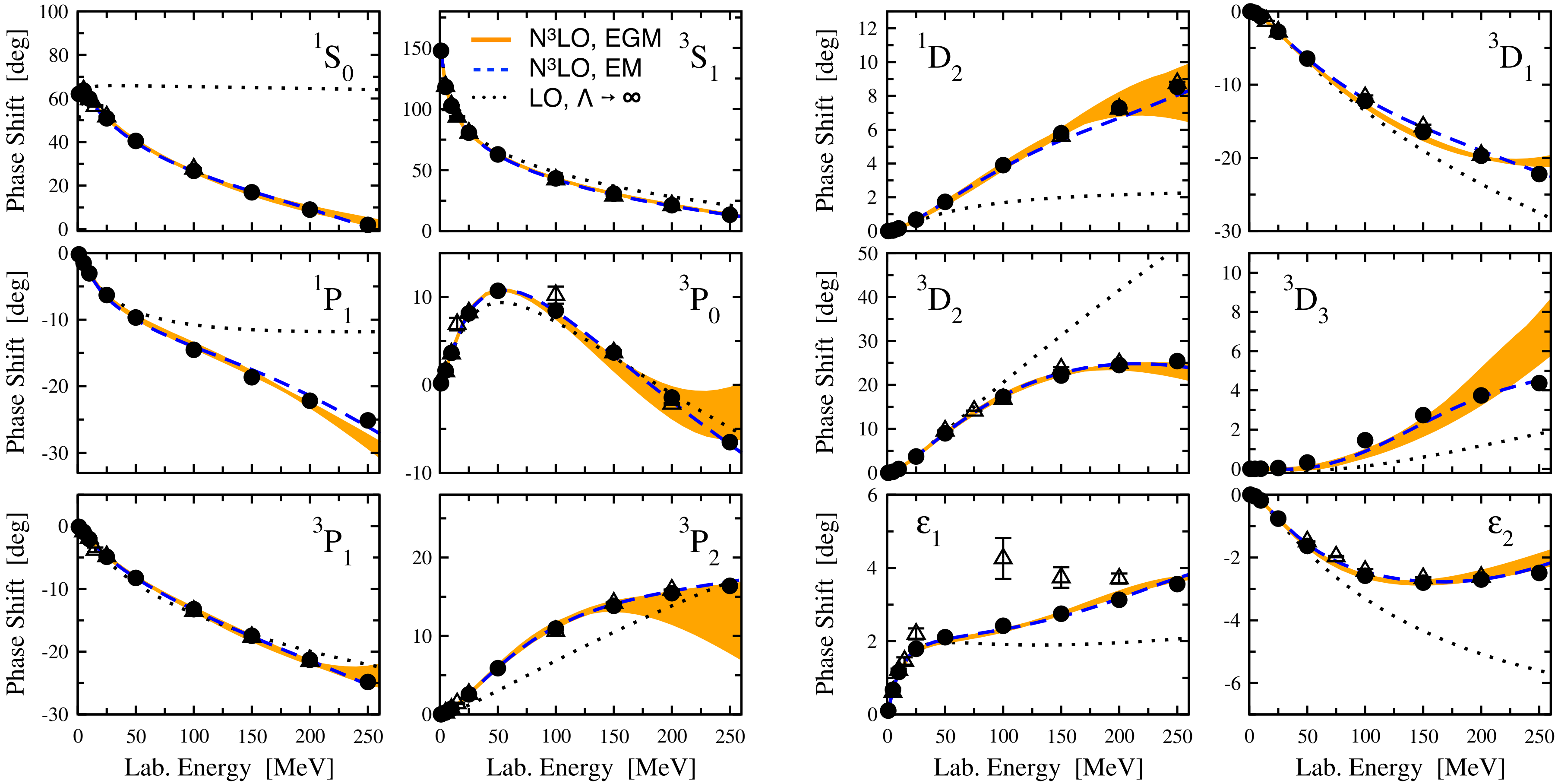
→ 3D equations which fulfill relativistic elastic unitarity, e.g.:

$$T(\vec{p}\,',\vec{p}) = V_{2N}^{(0)}(\vec{p}\,',\vec{p}) + \frac{m_N^2}{2}\int \frac{d^3k}{(2\,\pi)^3}\,\frac{V_{2N}^{(0)}(\vec{p}\,',\vec{k})\,T(\vec{k},\vec{p})}{(k^2+m_N^2)\,(E-\sqrt{k^2+m_N^2}+i\,\epsilon)}$$

Kadyshevsky '68

- LO equation is log-divergent (i.e. renormalizable) → can safely take $\Lambda \to \infty$!
- corrections beyond LO are to be included perturbatively
- power counting is restored by making additional subtractions (EOMS)
- benchmark for perturbative pions: reproduce KSW results EE, Gegelia PLB 716 (12) 338
- paramater-free results for m_q dependence of NN observables at LO EE, Gegelia PoS CD12 (13) 90

Neutron-proton phase shifts



- Higher-order corrections in progress

LETs: perturbative vs non-perturbative pions

Coeff. in the ERE are governed by π's (LETs): $k \cot\delta = -a^{-1} + \frac{1}{2} r k^2 + v_2 k^4 + v_3 k^6 + v_4 k^8 + \ldots$

Predictions for coefficients in the ERE in the $^1S_0$ channel

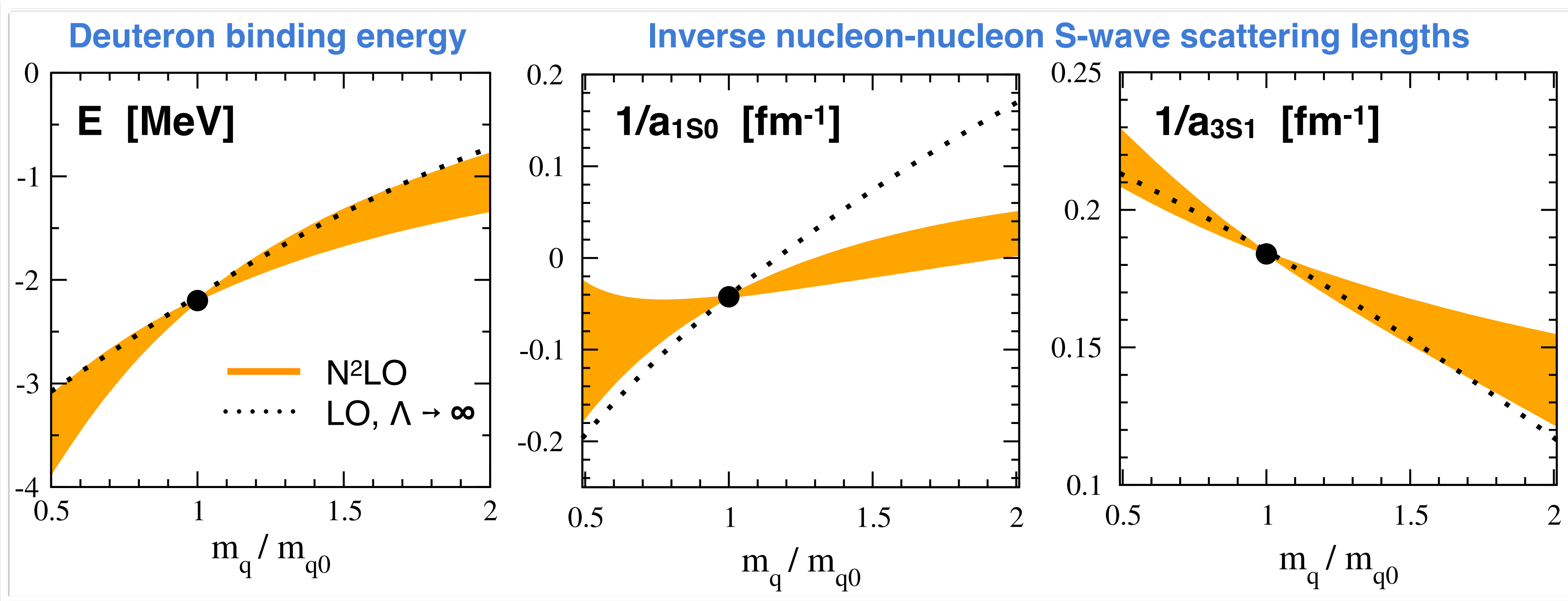
$^1S_0$ partial wave	a [fm]	r [fm]	v_2 [fm^3]	v_3 [fm^5]	v_4 [fm^7]
NLO KSW from Ref. [23]	fit	fit	-3.3	18	-108
LO Weinberg	fit	1.50	-1.9	8.6(8)	$-37(10)$
Nijmegen PWA	-23.7	2.67	-0.5	4.0	-20

Predictions for coefficients in the ERE in the $^3S_1$ channel

$^3S_1$ partial wave	a [fm]	r [fm]	v_2 [fm^3]	v_3 [fm^5]	v_4 [fm^7]
NLO KSW from Ref. [23]	fit	fit	-0.95	4.6	-25
LO Weinberg	fit	1.60	-0.05	0.8(1)	$-4(1)$
Nijmegen PWA	5.42	1.75	0.04	0.67	-4.0

Quark mass dependence of the NN force

Berengut, EE, Flambaum, Hanhart, Meißner, Nebreda, Pelaez ’13; EE, Gegelia PoS CD12 (13)



In terms of K-factors $K_X^q \equiv \frac{m_q}{X}\frac{\partial X}{\partial m_q}\bigg|_{m_q^{\rm phys}}$ we find: $K_{a_s}^q = 2.3^{+1.9}_{-1.8}, \quad K_{a_t}^q = 0.32^{+0.17}_{-0.18}$

to be compared with earlier calculations:

$K_{a_s}^q = 5 \pm 5, \quad K_{a_t}^q = 1.1 \pm 0.9$ (W, NLO) EE et al. ’03

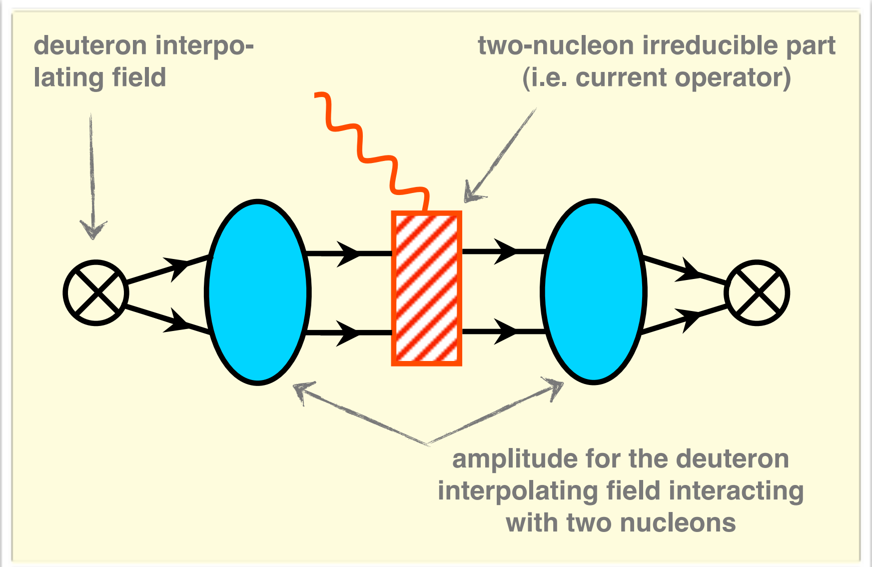
$K_{a_s}^q = 2.4 \pm 3.0, \quad K_{a_t}^q = 3.0 \pm 3.5$ (KSW, NLO) Beane, Savage ’03

Impact on BBN: limits on m_q variation at the time of BBN: $\delta m_q / m_q = 0.02 \pm 0.04$

Deuteron form factors at LO

EE, Gasparyan, Gegelia, Schindler, arXiv:1311.7164 [nucl-th]

Follow the lines of:
Kaplan, Savage, Wise PRC 59 (99) 617
but with nonperturbative pions
and without 1/m-expansion



Interpolating fields for the deuteron:

$$\mathcal{D}_i \equiv N^T P_i N, \quad P_i \equiv \frac{1}{\sqrt{8}} \sigma_2 \sigma_i \tau_2$$

Current MEs in terms of 3-point function (LSZ):

$$\langle \mathbf{P}', j | J^\mu_{em} | \mathbf{P}, i \rangle = -\frac{1}{Z} \left[\left(P^2 - M_d^2\right) \left(P'^2 - M_d^2\right) G^\mu_{ij}(P, P') \right]_{P^2, P'^2 \to M_d^2}$$

where $Z = \mathcal{Z}(M_d^2)$ is the residue of the propagator and

$$G^\mu_{ij}(P, P') = \int d^4x\, d^4y\, e^{-iP\cdot x} e^{iP'\cdot y} \langle 0 | T \left[\mathcal{D}_i^\dagger(x) J^\mu_{em}(0)\, \mathcal{D}_j(y) \right] | 0 \rangle$$

⟵ 3-point function

The 3-point function can be expressed in terms of the scattering amplitude obtained by solving the Kadyshevsky equation (solved in 3d without partial wave decomposition)

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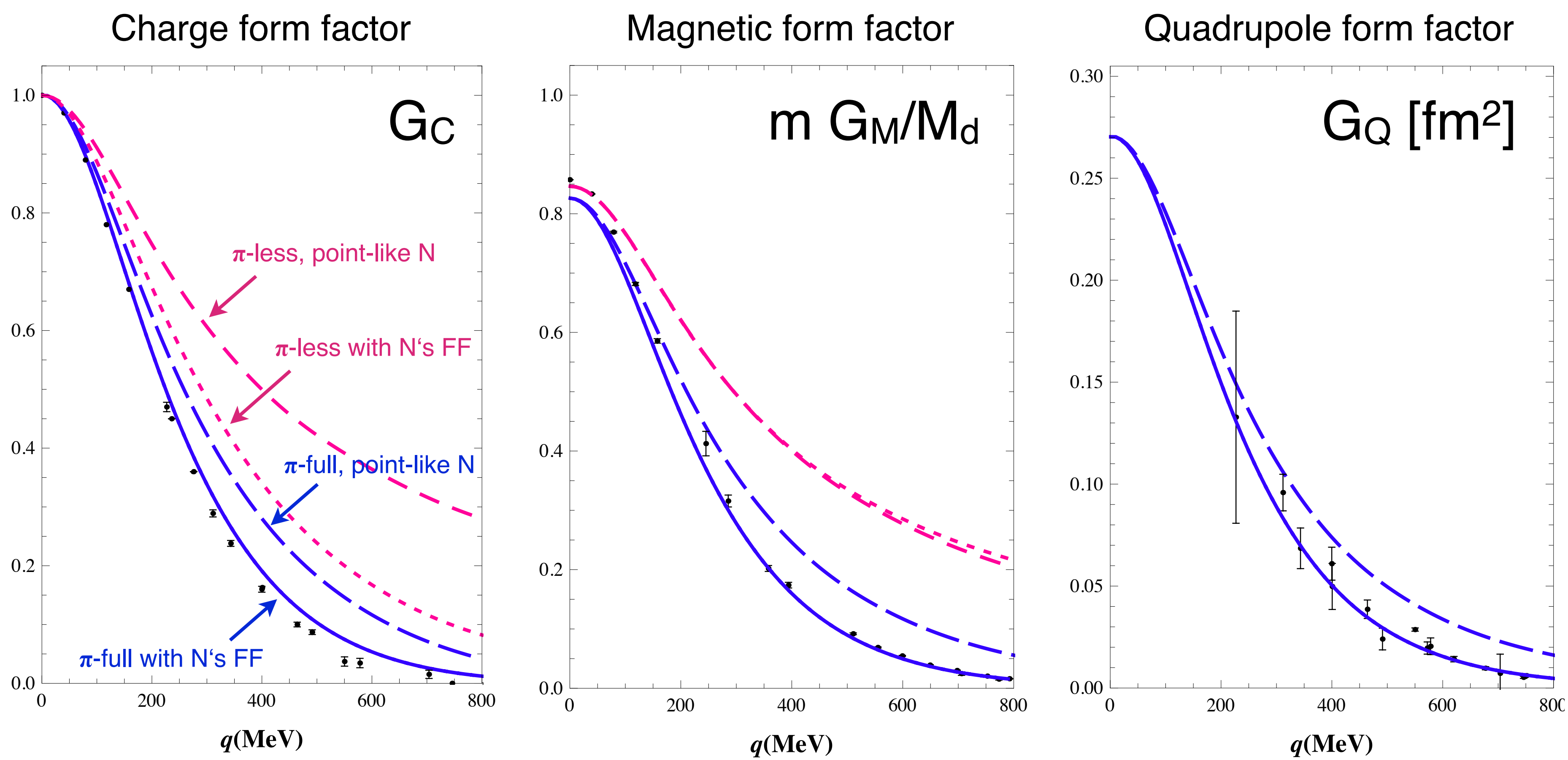

Magnetic moment of the deuteron: $\mu^{\rm LO} = 0.826\ (e/(2m))$ to be compared with $\mu^{\rm exp} = 0.85741\ (e/(2m))$

Quadrupole moment of the deuteron: $Q_d^{\rm LO} = 0.271\ {\rm fm}^2$ to be compared with $Q_d^{\rm exp} = 0.2859\ {\rm fm}^2$

2nd option:

Keep Λ finite but reduce Λ-artifacts by a properly chosen regularization

Regularization of the chiral NN potentials

order of the chiral expansion

$$\langle \vec{p}\,'|\, V^{\rm NNLO}\,|\vec{p}\,\rangle = \left[V_{1\pi}^{(0)} + V_{2\pi}^{(2)} + V_{2\pi}^{(3)} + V_{\rm cont}^{(0)} + V_{\rm cont}^{(2)}\right] e^{\frac{-p'^4 - p^4}{\Lambda^4}}$$

The cutoff Λ should not be chosen too large (spurious bound states, nonlinearities, nonrenormalizable theory) Lepage'97, EE., Meißner '06, EE, Gegelia '09. On the other hand, smaller values of Λ introduce unnecessary errors.

Typical choice: Λ = 450...600 MeV [N^3LO potentials by EGM, EM]

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Claim: while the above nonlocal regulator simplifies the determination of the LECs, it cuts off some model-independent long-range physics one would like to keep and leaves some model-dependent short-range physics one would like to cut off...

Given that $V_{1\pi}^{(0)} + V_{2\pi}^{(2)} + V_{2\pi}^{(3)}$ is local, local regulator does a better job!

Reminder:

$$V_{\rm local}(\vec{p}\,', \vec{p}\,) \equiv \langle \vec{p}\,' | V_{\rm local} | \vec{p} \rangle = V(\vec{p}\,' - \vec{p}\,) \quad \longrightarrow \quad V(\vec{r}\,', \vec{r}\,) \equiv \langle \vec{r}\,' | V | \vec{r} \rangle = \delta^3(\vec{r}\,' - \vec{r}\,) V(\vec{r}\,)$$

Regularization of the chiral NN potentials

Peripheral NN scattering as a long-range filter: insensitive to short-range physics and determined by the model-independent long-range interaction ($V_{1\pi}$). Can be computed using Born approximation: $T_{\alpha'\alpha}(p) \equiv \langle p, \alpha' | T | p, \alpha \rangle = \langle p, \alpha' | V_{1\pi} | p, \alpha \rangle$

where $V_{1\pi}(\vec{q}) = -\frac{g_A^2}{4F_\pi^2} \frac{(\vec{q} \cdot \vec{\sigma}_1)(\vec{q} \cdot \vec{\sigma}_2)}{\vec{q}^{\,2} + M_\pi^2} \boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2$

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- **Standard, nonlocal regularization** $V_{1\pi}^{\rm reg}(\vec{q}) = V_{1\pi}(\vec{q}) \; F\left(\frac{p'}{\Lambda}, \frac{p}{\Lambda}\right)$

  Partial-wave decomposition: $\langle p', \alpha' | V_{1\pi}^{\rm reg} | p, \alpha \rangle = \langle p', \alpha' | V_{1\pi} | p, \alpha \rangle \; F\left(\frac{p'}{\Lambda}, \frac{p}{\Lambda}\right)$

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- **Local regularization**

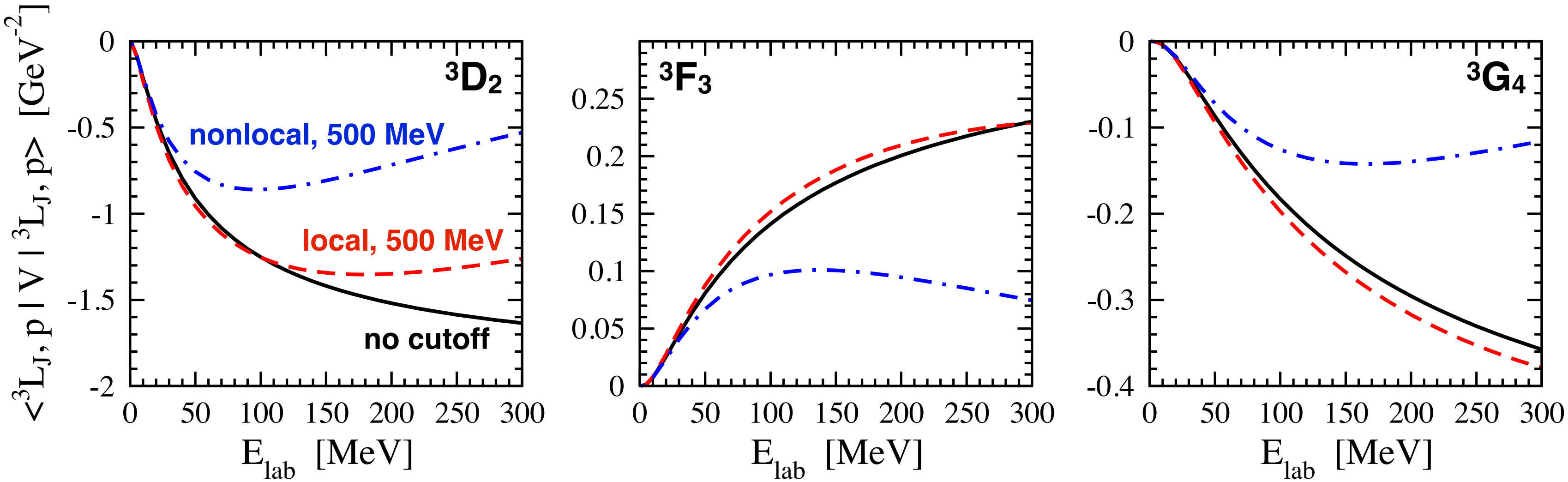
  $V_{1\pi}^{\rm reg}(\vec{q}) = V_{1\pi}(\vec{q})\; F\left(\frac{q}{\Lambda}\right)$ or, alternatively, $V_{1\pi}^{\rm reg}(\vec{r}) = V_{1\pi}(\vec{r})\; F(r/R_0)$

  Partial-wave matrix elements in momentum space:

$$\langle p', \alpha' | V_{1\pi}^{\rm reg} | p, \alpha \rangle \sim \underbrace{\int r^2 dr\, j_{l'}(p'r) \left[V_{1\pi}^{\alpha'\alpha}(r) F(r/R_0) \right] j_l(pr)}_{\text{becomes insensitive to } F \text{ for high } \boldsymbol{l},\ \boldsymbol{l'}}$$

Regularization of the chiral NN potentials

PW projected MEs of the OPEP: $\exp[-(p'^2+p^2)/\Lambda^2]$ versus $\exp[-q^2/\Lambda^2]$ for Λ = 500 MeV



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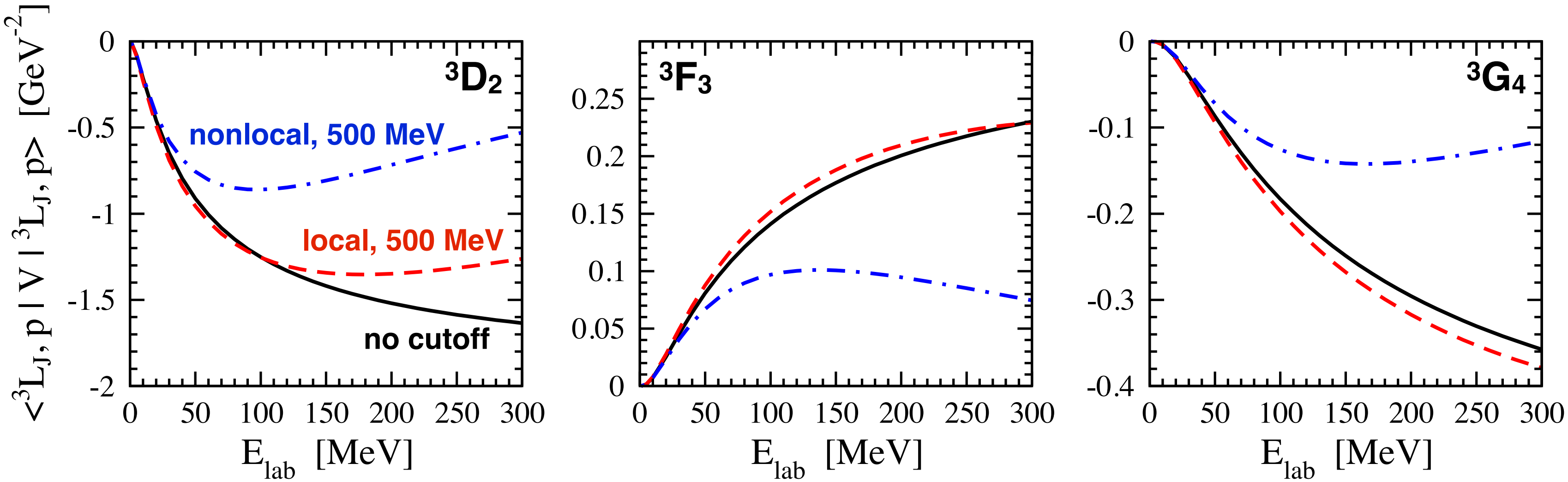
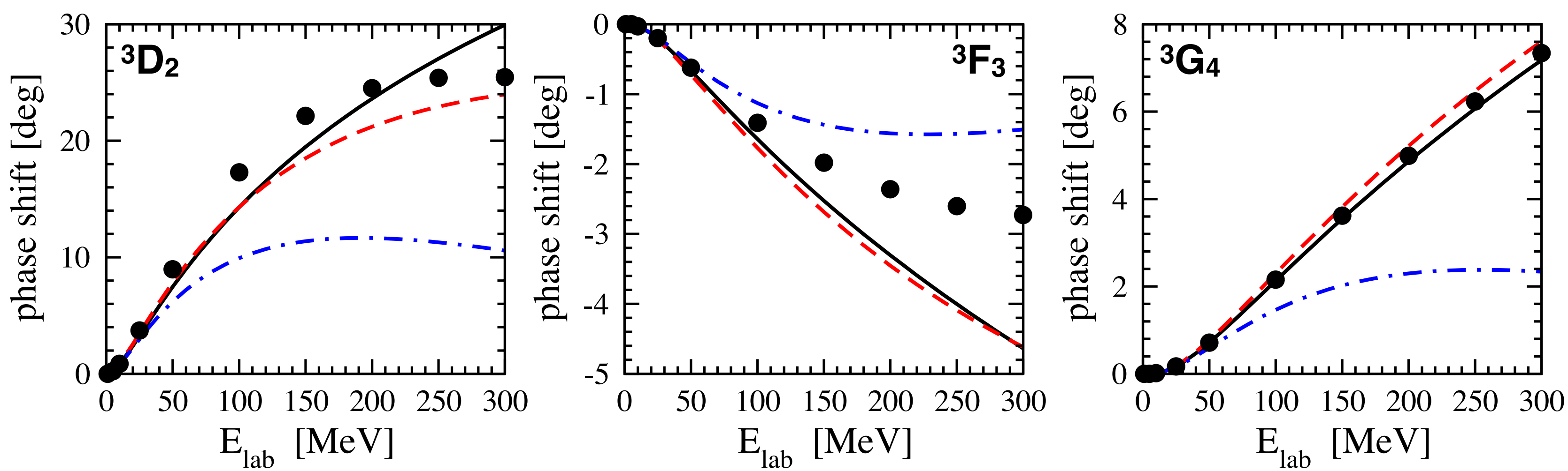
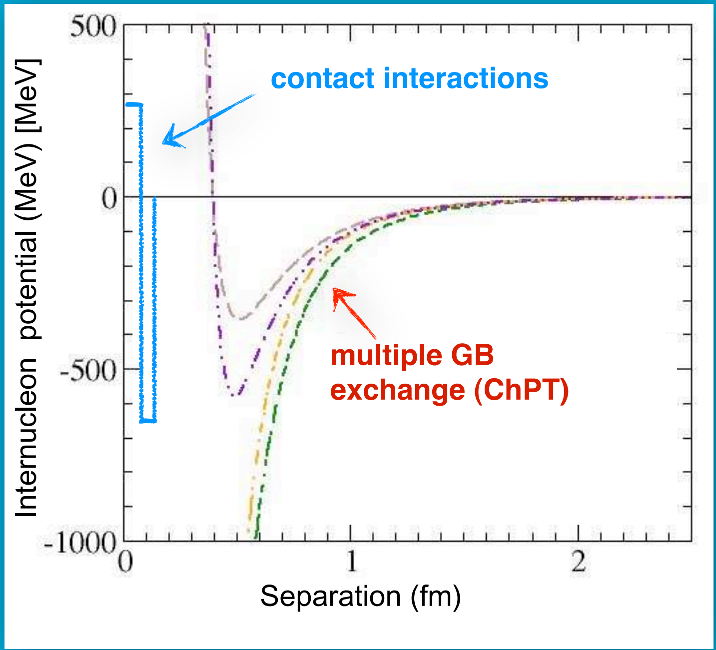


Peripheral partial waves based on the OPE potential (Born approx.)



Choice of the cutoff

What is the breakdown distance of the chiral expansion of the multiple-pion exchange ?



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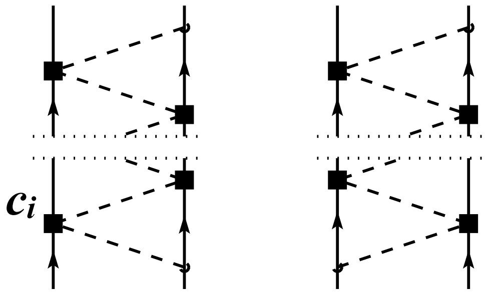
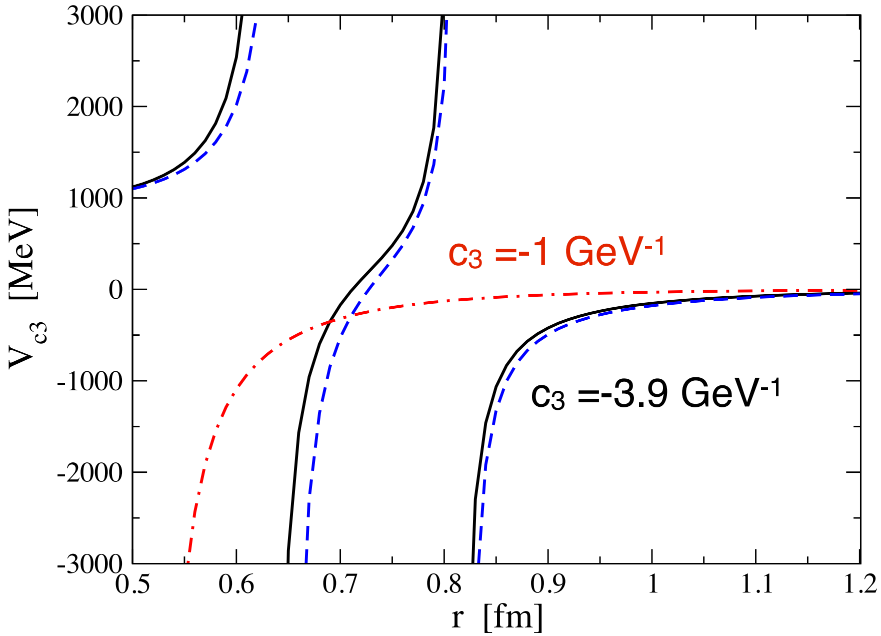
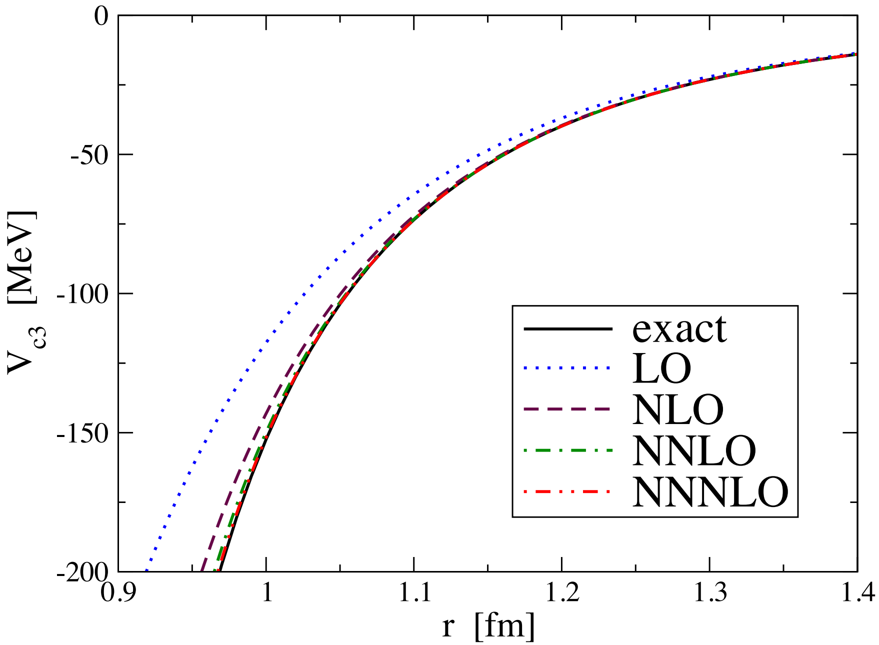


Certain classes of multiple-pion exchange diagrams (MSS) can be calculated analytically to an infinite order and resummed

Baru, EE, Hanhart, Hoferichter, Kudryavtsev, Phillips, EPJA 48 (12) 69

Resummed central potential generated by multi-pion exchange (c_3-part)





pole(!) ar r ~ 0.81fm but good convergence of the chiral expansion for r > 1fm

Construction of the potential

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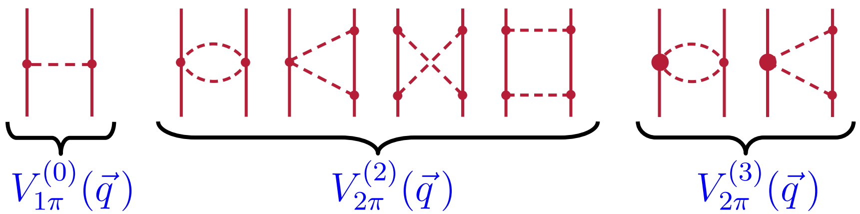
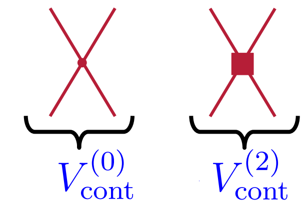
Long-range:



Short-range:



There are 9 isospin-concerving contact terms whose choice is not unique. Standard:

$$V_{\rm cont}^{(0)} = C_S + C_T(\vec{\sigma}_1 \cdot \vec{\sigma}_2)$$

$$V_{\rm cont}^{(2)} = C_1 q^2 + C_2 k^2 + C_3 q^2(\vec{\sigma}_1 \cdot \vec{\sigma}_2) + C_4 k^2(\vec{\sigma}_1 \cdot \vec{\sigma}_2) + \frac{iC_5}{2}(\vec{\sigma}_1 + \vec{\sigma}_2) \cdot \vec{q} \times \vec{k} + C_6(\vec{\sigma}_1 \cdot \vec{q})(\vec{\sigma}_2 \cdot \vec{q}) + C_7(\vec{\sigma}_1 \cdot \vec{k})(\vec{\sigma}_2 \cdot \vec{k})$$

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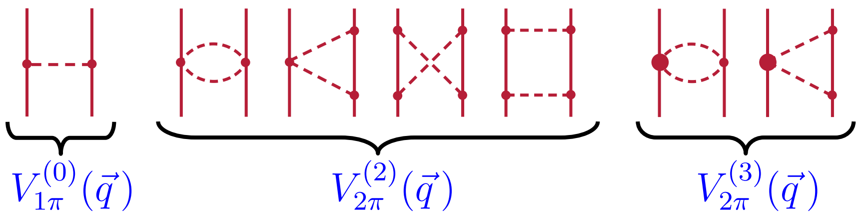

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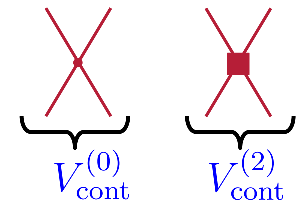

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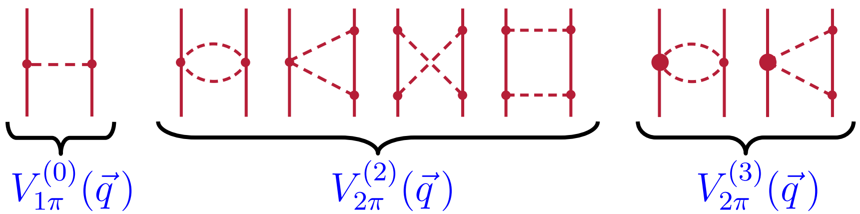

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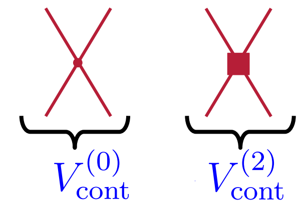

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One can choose instead a local basis:

$$V_{\rm cont}^{(2)} = C_1 q^2 + C_2 q^2(\boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2) + C_3 q^2(\vec{\sigma}_1 \cdot \vec{\sigma}_2) + C_4 q^2(\vec{\sigma}_1 \cdot \vec{\sigma}_2)(\boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2) + \frac{iC_5}{2}(\vec{\sigma}_1 + \vec{\sigma}_2) \cdot \vec{q} \times \vec{k}$$
$$+ \; C_6(\vec{\sigma}_1 \cdot \vec{q})(\vec{\sigma}_2 \cdot \vec{q}) + C_7(\vec{\sigma}_1 \cdot \vec{q})(\vec{\sigma}_2 \cdot \vec{q})(\boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2)$$

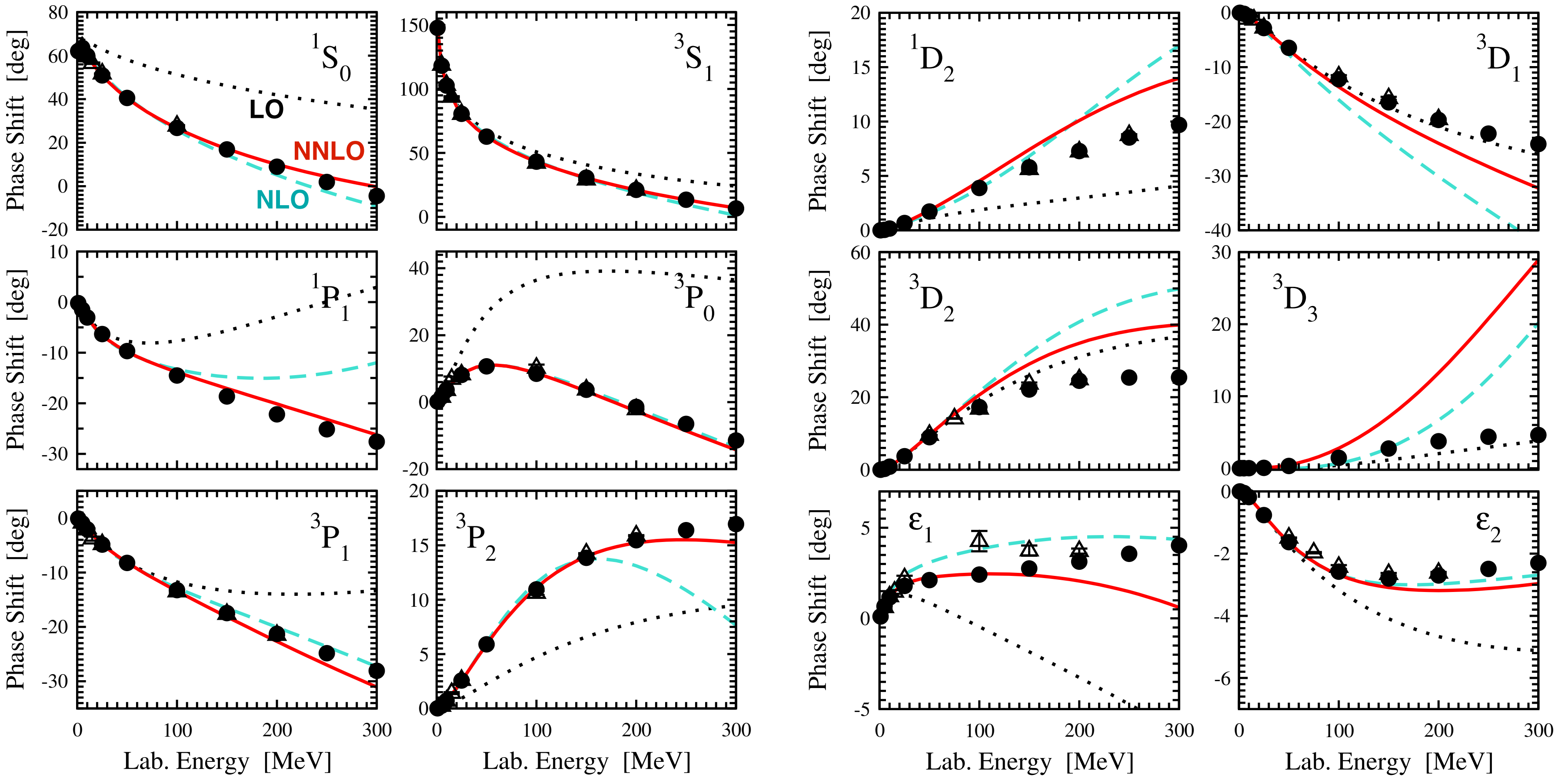
Make Fourier Transform and regularize in configuration space, e.g.:

$$V_{\rm long}(\vec{r}) \; \rightarrow \; V_{\rm long}(\vec{r})\left[1 - e^{-r^4/R_0^4}\right]$$ and $$\delta^3(\vec{r}) \; \rightarrow \; \alpha e^{-r^4/R_0^4}$$ where $$\alpha = \frac{1}{\pi \Gamma(3/4) R_0^3}$$

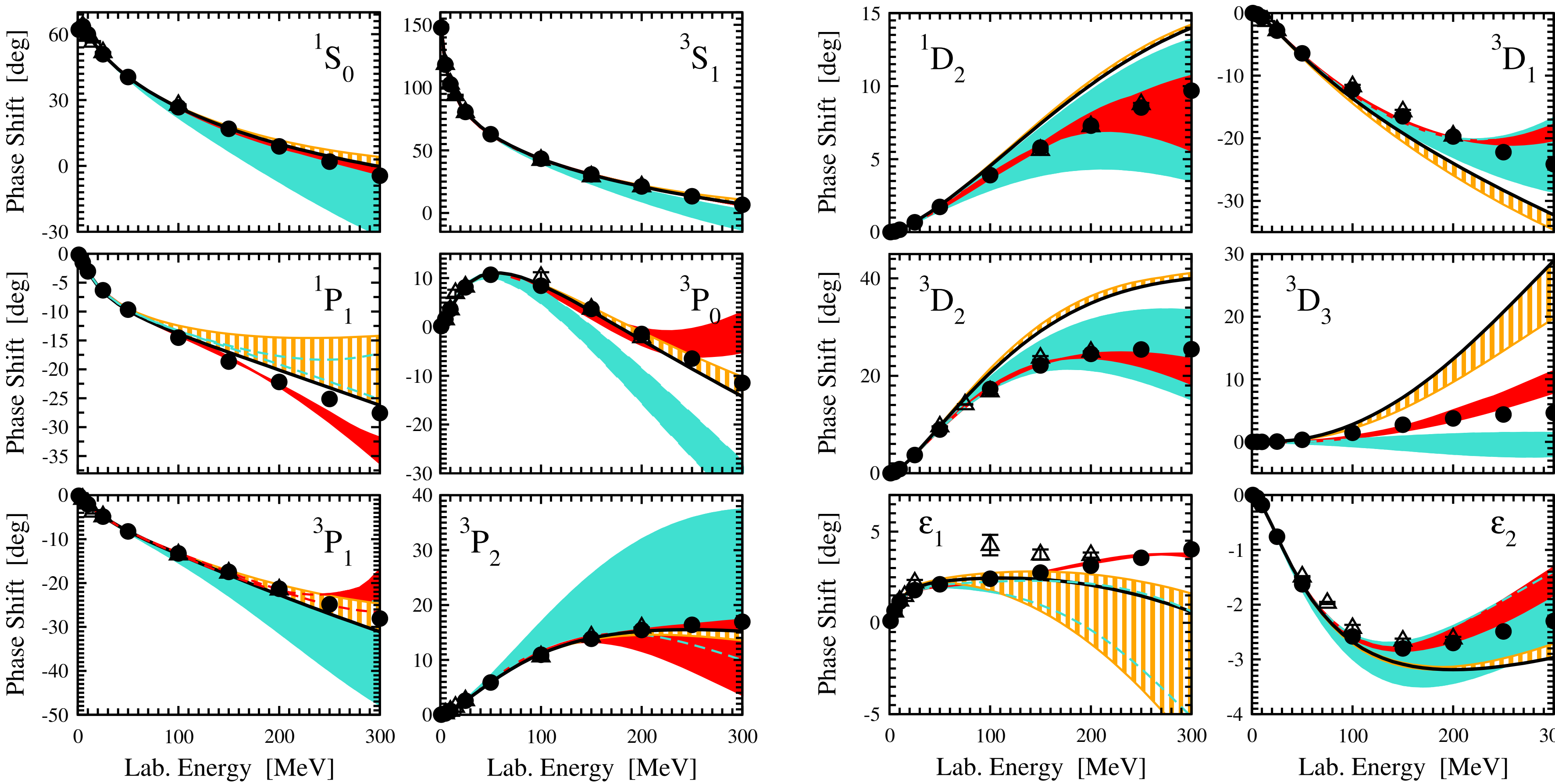
The LECs are determined from NN S-, P-waves and the mixing angle ε_1

Results

np phase shifts: Order-by-order improvement



np phase shifts: Cutoff dependence at NNLO



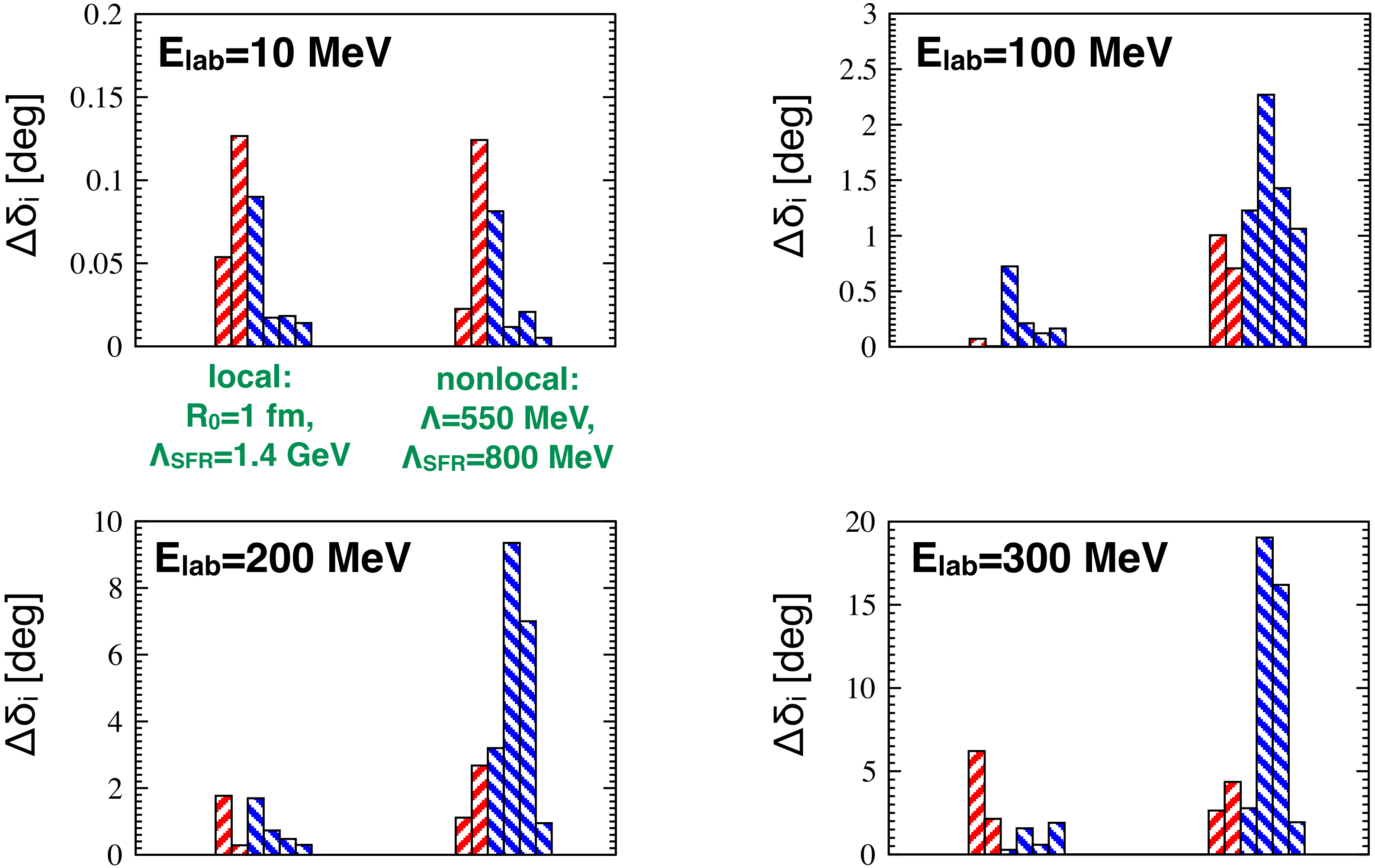
nonlocal N²LO [EGM]

nonlocal N³LO [EGM]

local N²LO, R_0 = 1...1.2 fm, Λ_{SFR} = 1...2 GeV

Error budget: local vs nonlocal regulators

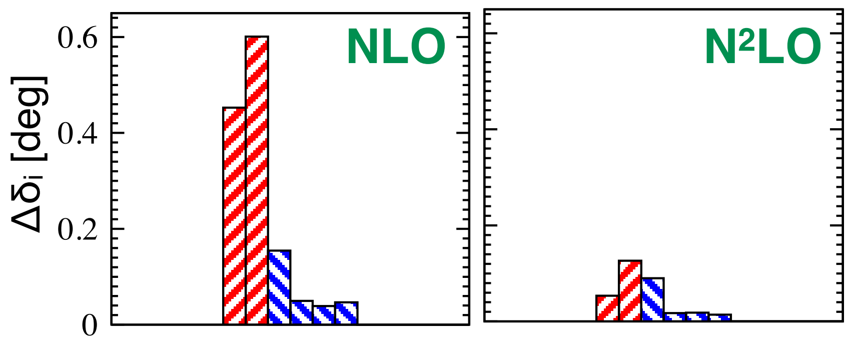
Absolute errors in S- and P-wave phase shifts at N^{2}LO



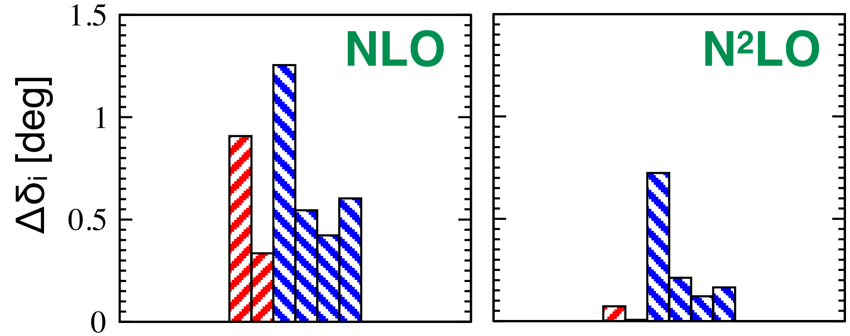
Ordering of partial waves: $^1S_0$, $^3S_1$, $^1P_1$, $^3P_0$, $^3P_1$, $^3P_2$

Error budget: NLO vs N^2LO (R_0=1fm, Λ_{SFR}=1.4 GeV)

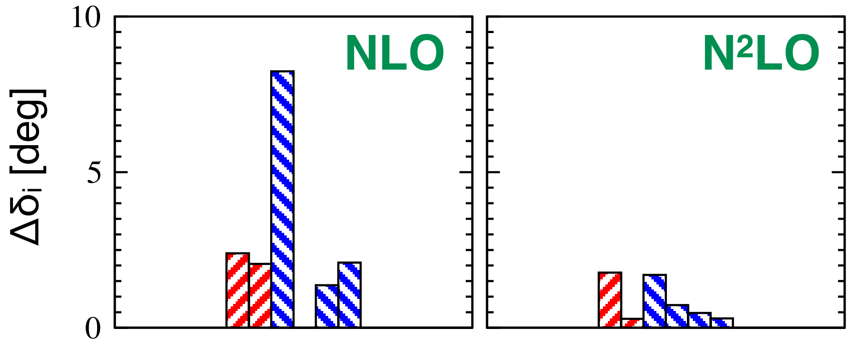
Absolute errors at E_{lab}=10 MeV



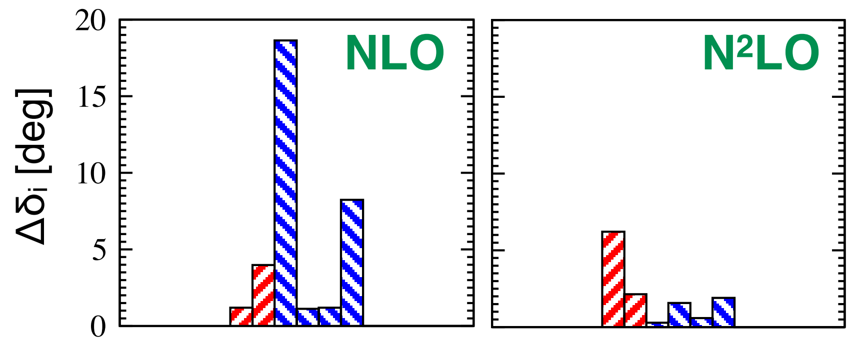
Absolute errors at E_{lab}=100 MeV



Absolute errors at E_{lab}=200 MeV



Absolute errors at E_{lab}=300 MeV

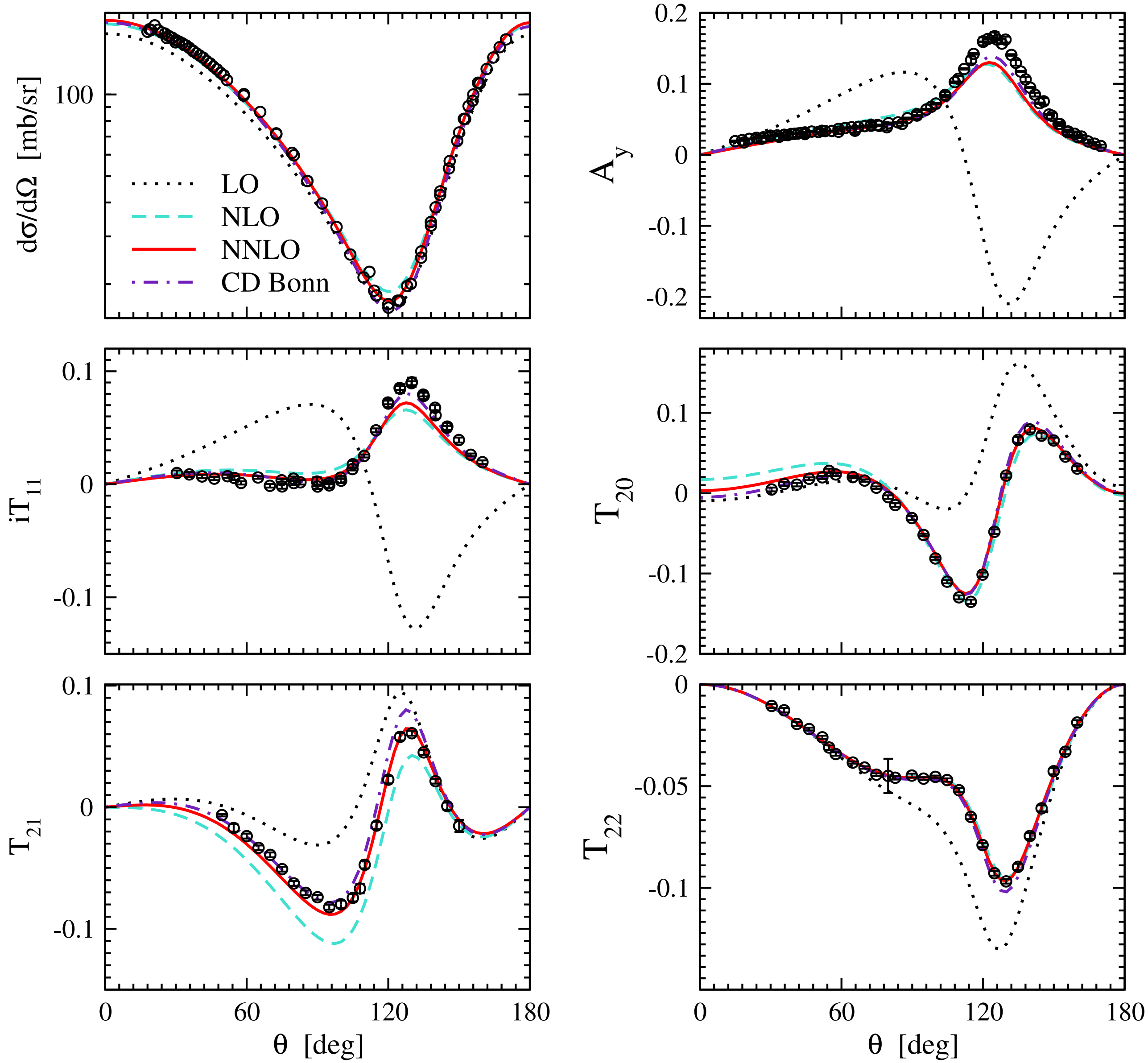


Ordering of partial waves: $^1S_0$, $^3S_1$, $^1P_1$, $^3P_0$, $^3P_1$, $^3P_2$

The improvement when going from NLO to N^2LO is entirely due to subleading TPEP

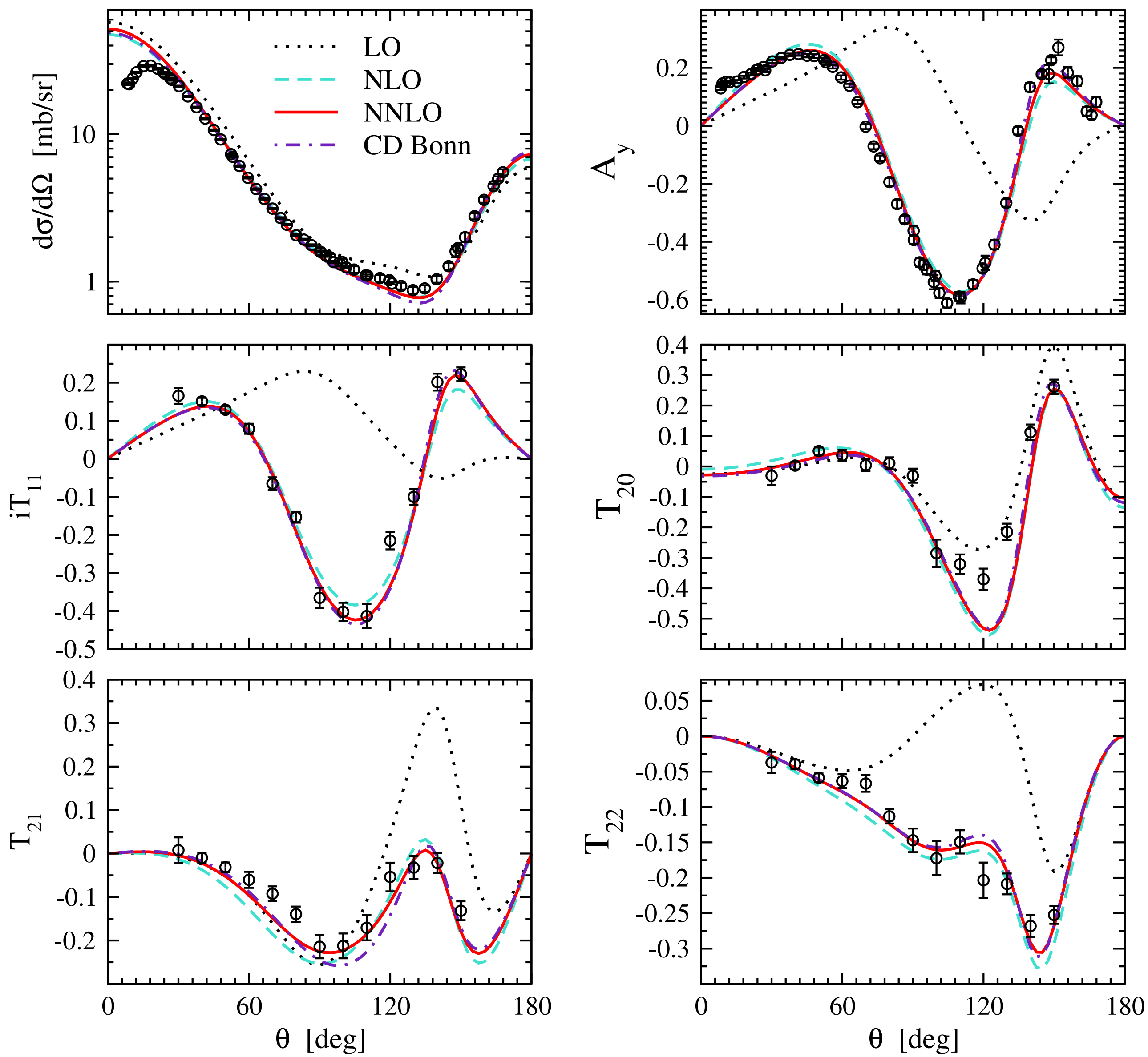
Elastic nd scattering order-by-order

3 MeV:



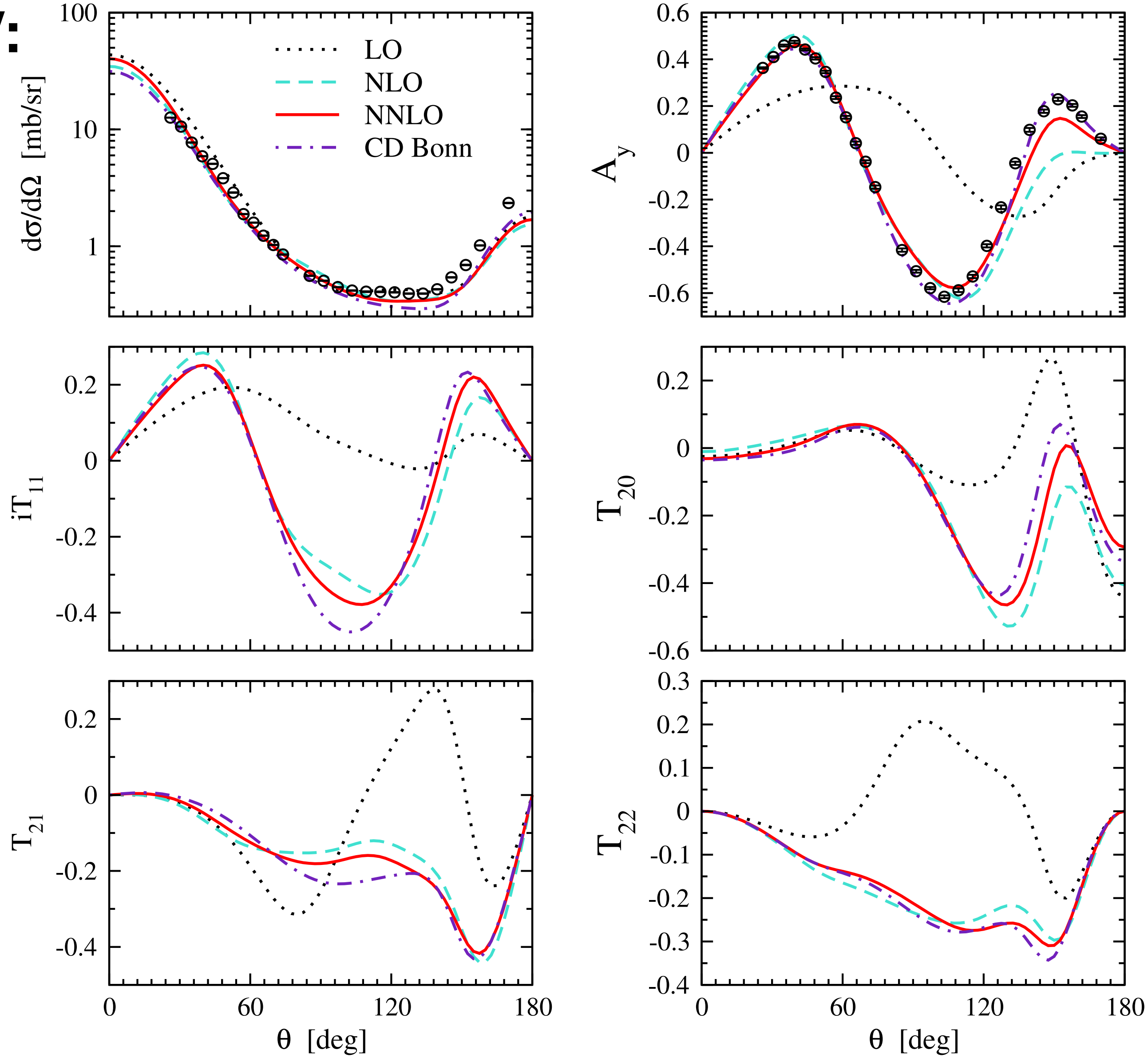
Elastic nd scattering order-by-order

65 MeV:



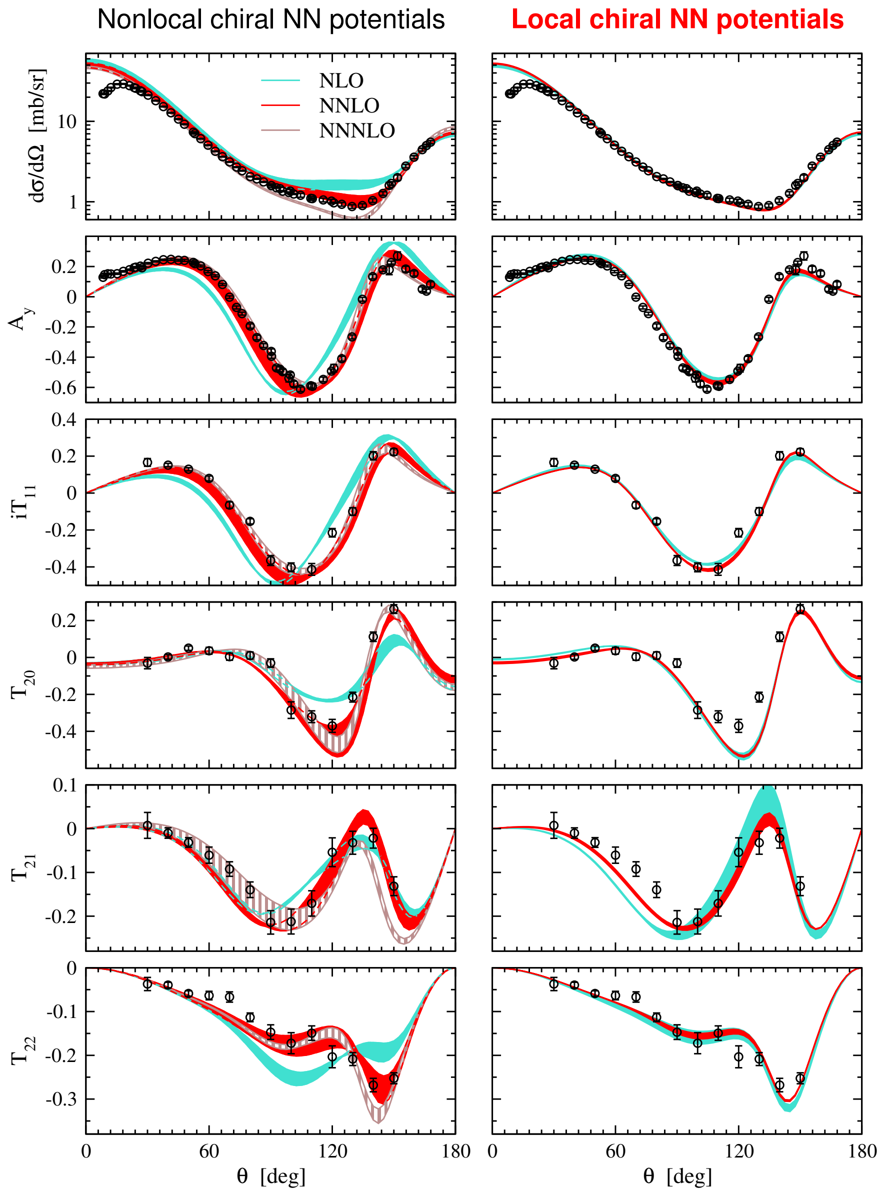
Elastic nd scattering order-by-order

108 MeV:



Elastic nd scattering: Cutoff dependence

65 MeV:

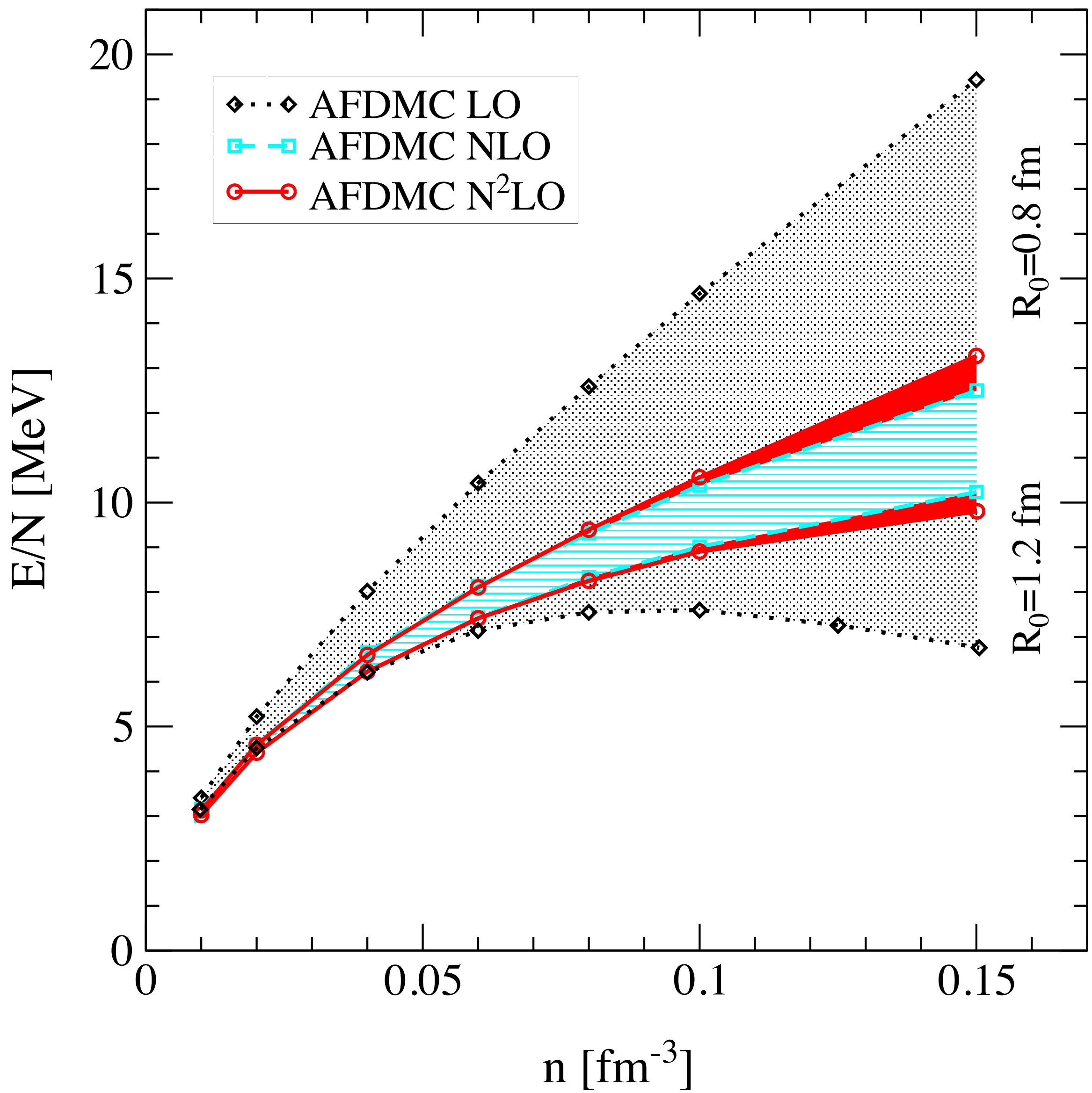


nonlocal NLO/N²LO/N³LO:
Λ = 450...600 MeV,
Λ_{SFR} = 500...500 MeV

local NLO/N²LO:
R_0 = 1...1.2 fm,
Λ_{SFR} = 1...2 GeV

Neutron matter with local chiral NN forces (QMC)

Gezerlis, Tews, EE, Gandolfi, Hebeler, Nogga, Schwenk, PRL 111 (2013) 032501; in preparation



Summary and outlook

It is possible to eliminate or at least substantially decrease Λ artefacts and thus to considerably increase the applicability range of nuclear chiral EFT!

Renormalizable approach

Summary: Promising results for NN scatt, deut. FF & chiral extrapolations at LO

Pro: Conceptually clean (no cutoff!), well suited for chiral extrapolations

Contra: Derivation of the kernel rather involved (TOPT), cannot directly use in few-/many-body codes (corrections included perturbatively)

To be done: higher orders, strange baryon-baryon systems, 3N,...

Local nuclear forces

Summary: New NN potential at N^2LO allows for excellent description of S- and P-waves even at high energies, promising results for 3N scattering

Pro: Transparent physical picture, no need for SFR, can use c_i from πN scattering, can be used in standard codes, accessible for QMC

Contra: Fits require more work, PWD of the 3NF has to be re-done

To be done: Nd with 3NF at N^2LO, detailed studies of c_i, explicit Δ, N^3LO,...