Evgeny Epelbaum, Ruhr-Universität Bochum

NN Meeting, Mumbai, Nov. 2010

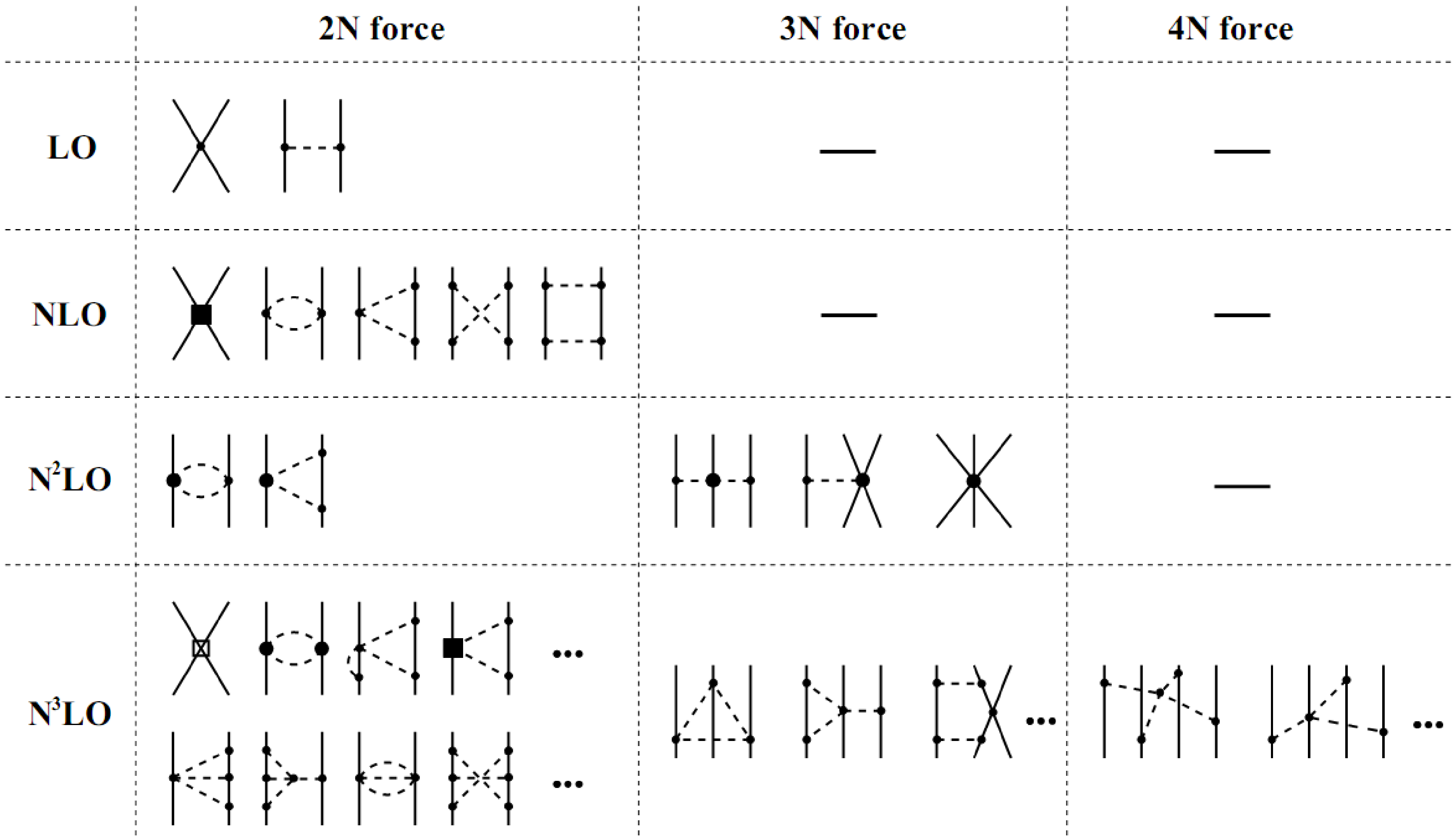
RUB

Nuclear Forces and Light Nuclei: (Some) Recent Developments

Outline

- 3N scattering at N^2LO
- Chiral EFT for nuclear forces with explicit Δ(1232)
- Pion production in NN collisions
- Probing light nuclei with photons
- Nuclear lattice simulations
- Summary and outlook

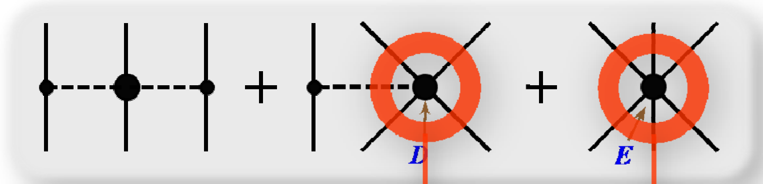
Nuclear forces in Δ-less EFT



Three-nucleon force at N^{2}LO

First nonvanishing 3N-force contribution appears at next-to-next-to-leading order

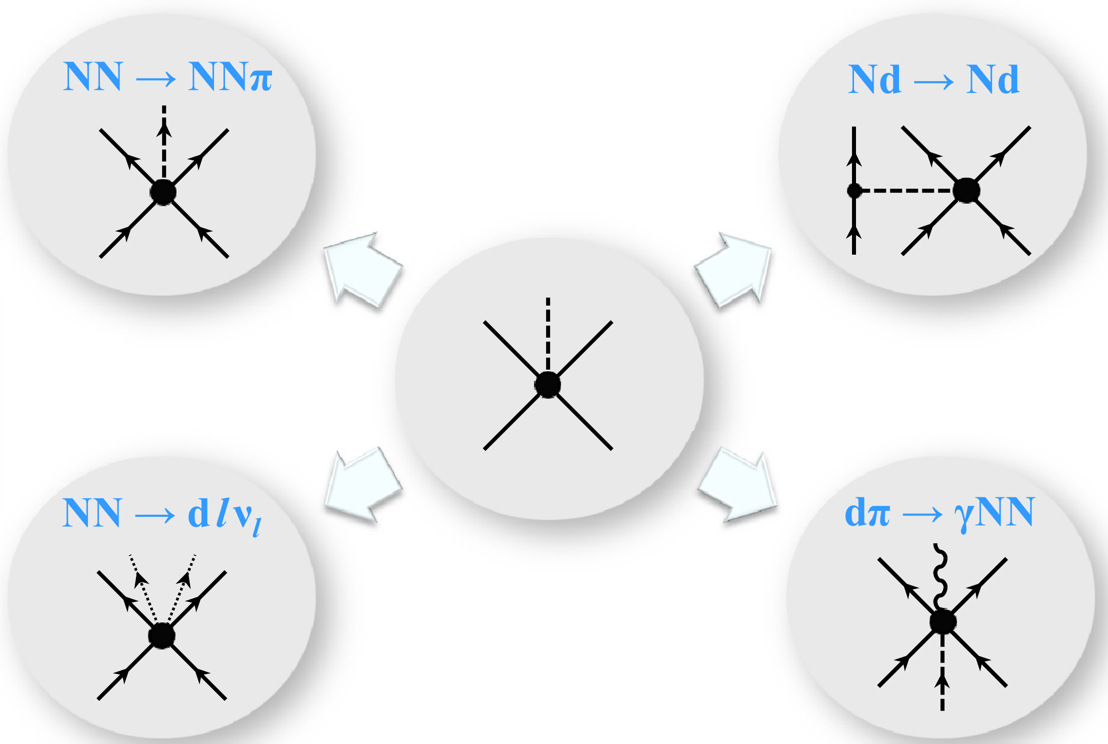
Cannot be fixed in the NN system



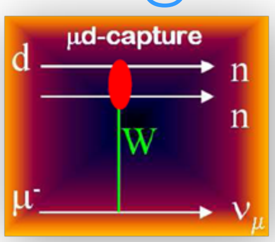
D-term figures prominently in various reactions

Hanhart et al.'00,
Baru et al.'09,
Filin et al.'09,
...

E.E. et al.'02,
Nogga et al.'05,
Navratil et al.'07



MuSun@PSI



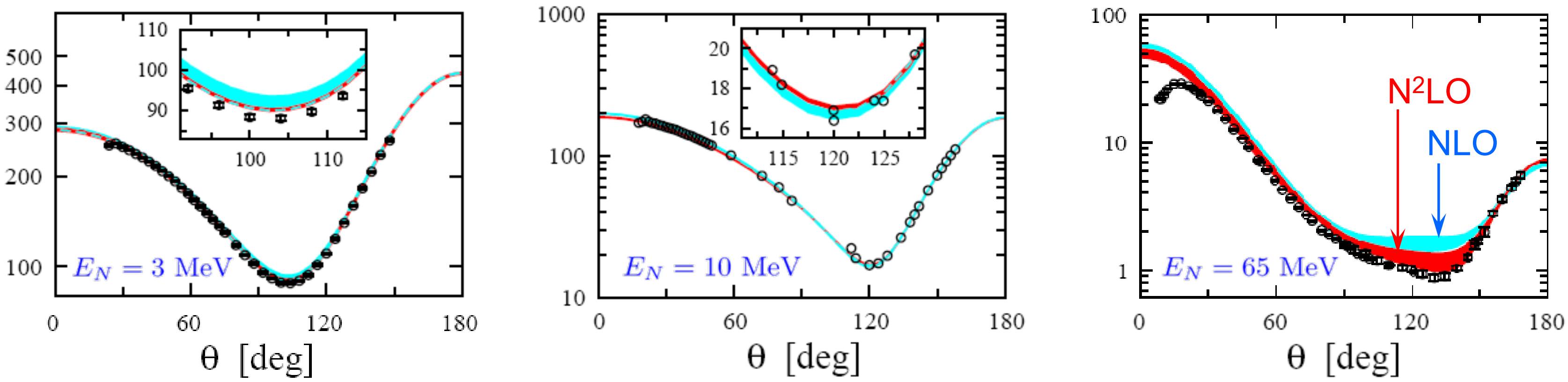
Park et al. '03,
Ando et al.'02,'03,
Nakamura et al.'07

Lensky et el.'05,'07
Gardestig et al.'06

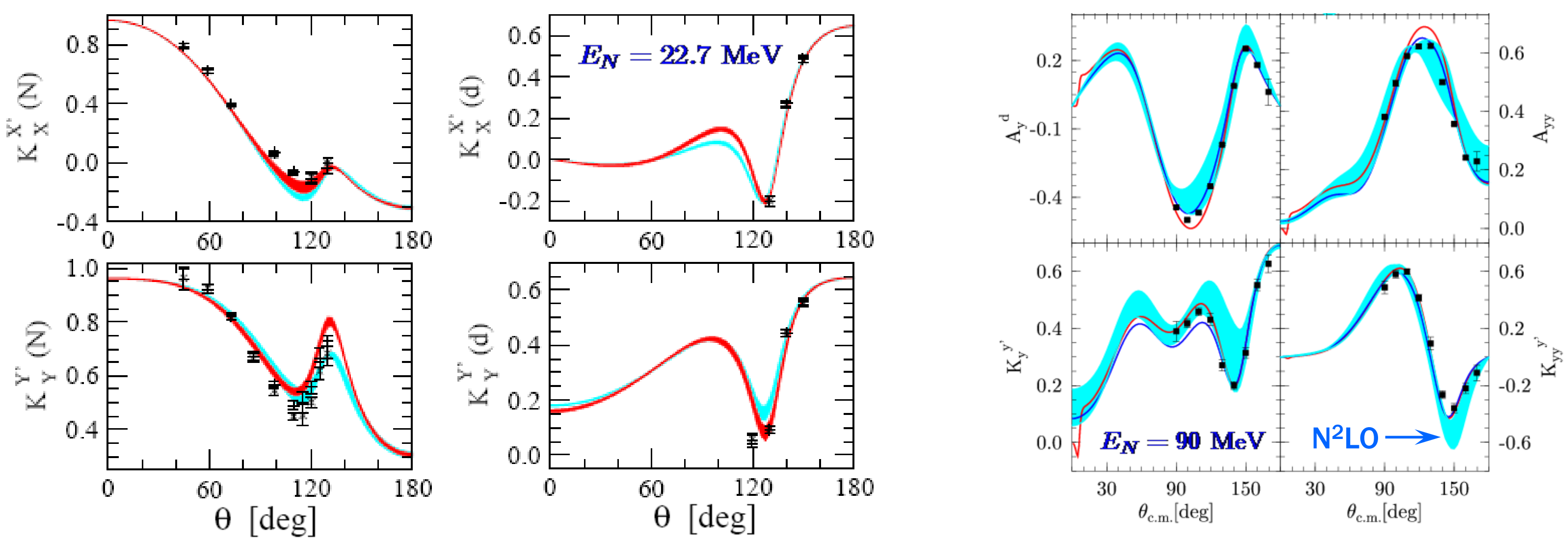
Three nucleons up to N^2LO

E.E. et al.'02; Kistryn et al.'05; Witala et al.'06; Ley et al.'06; Stephan et al.'07; ...

Differential cross section in elastic Nd scattering

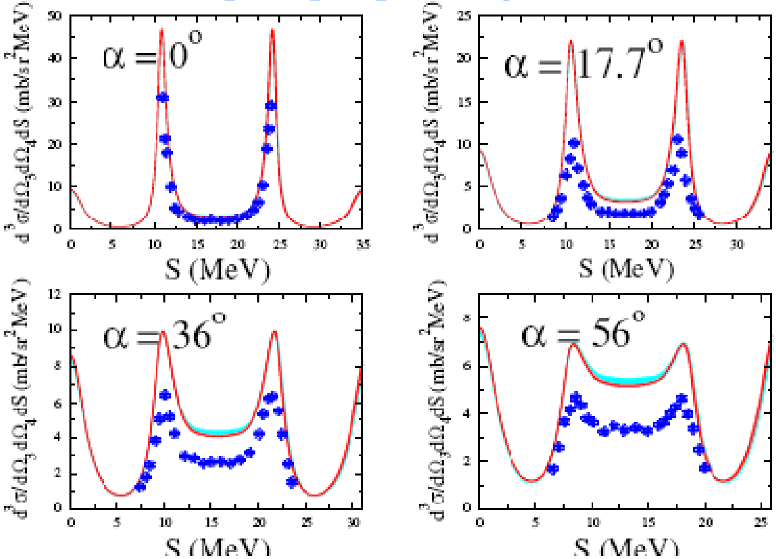


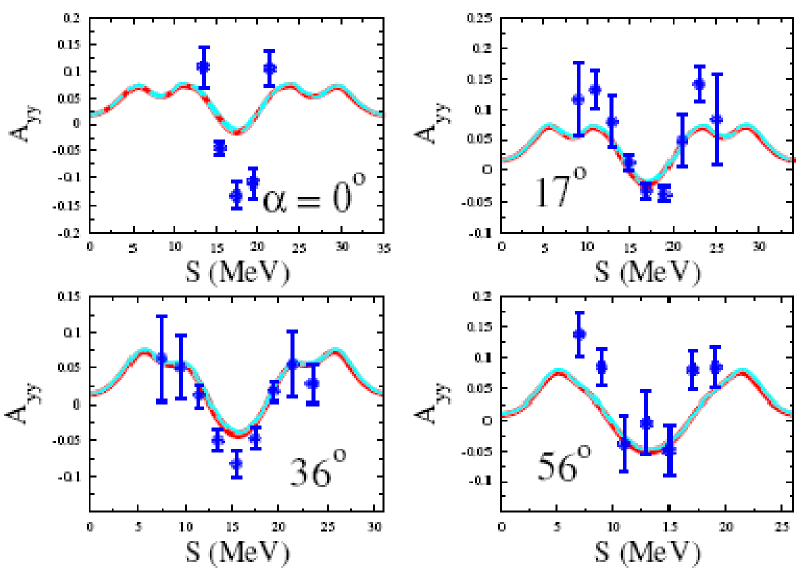
Polarization observables in elastic Nd scatering



Deuteron breakup at N^2LO

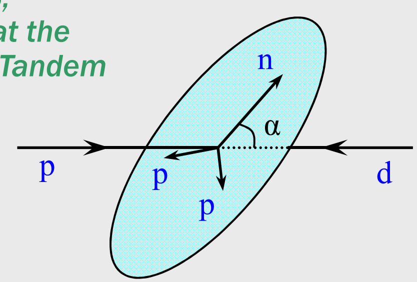
$\vec{d} + p \rightarrow p + p + n$ @ 19 MeV



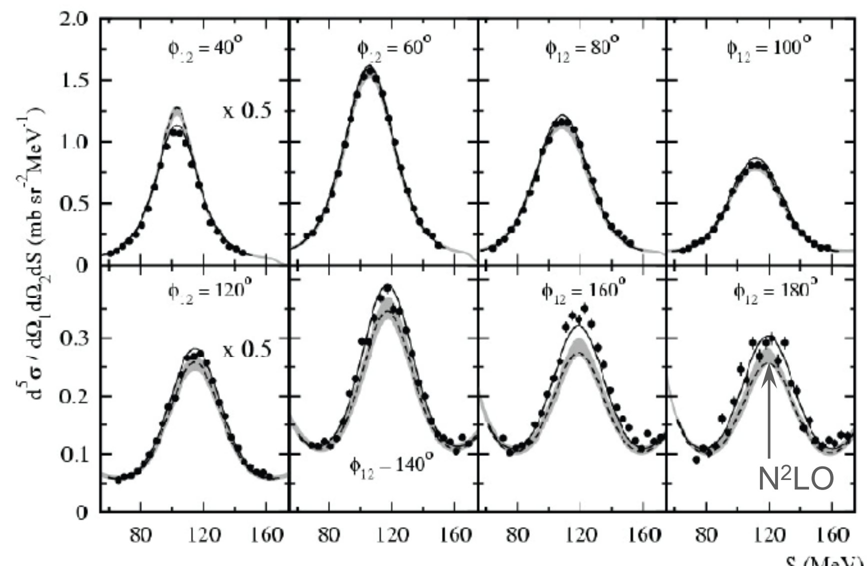


The so-called Symmetric-Constant-Energy geometry

Ley et al.'06;
data taken at the
Cologne FN Tandem
accelerator



$d + p \rightarrow p + p + n$ @ 130 MeV



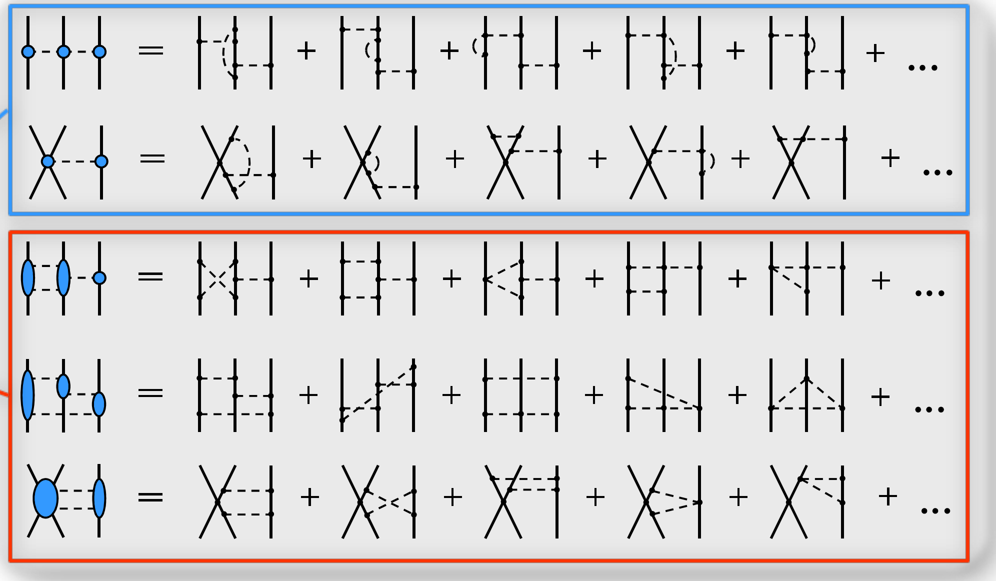
Kistryn et al.'05, KVI data

3N force: first corrections (N^{3}LO)

Three-nucleon force at N^{3}LO

Ishikawa, Robilotta '07;
Bernard, E.E., Krebs, Meißner '07, to appear

- parameter-free
- mainly finite shifts of c_i, D
- new structures (also from 1/m-terms)
- 3N scattering in progress...



Partial-wave decomposition

Too many terms (> 100 !) for doing PWD "manually" ⟹ let computer do the job…
Golak et al.'09

$$\underbrace{\langle p' q' \alpha' | V | p q \alpha \rangle}_{\text{matrix, } \sim 10^5 \times 10^5} = \int \underbrace{d\hat{p}'\, d\hat{q}'\, d\hat{p}\, d\hat{q}}_{\text{can be reduced to 5 dim. integral}} \sum_{m_l, \ldots} \big(\text{CG coeffs.}\big)\big(Y_{l,m_l}(\hat{p})\, Y_{l',m_l'}(\hat{p}') \ldots\big) \underbrace{\langle m_{s_1}' m_{s_2}' m_{s_3}' | V | m_{s_1} m_{s_2} m_{s_3} \rangle}_{\text{depends on } \vec{p}, \vec{q}, \vec{p}', \vec{q}', \text{ spin \& isospin}}$$

⟹ feasible task for modern supercomputers, work in progress…

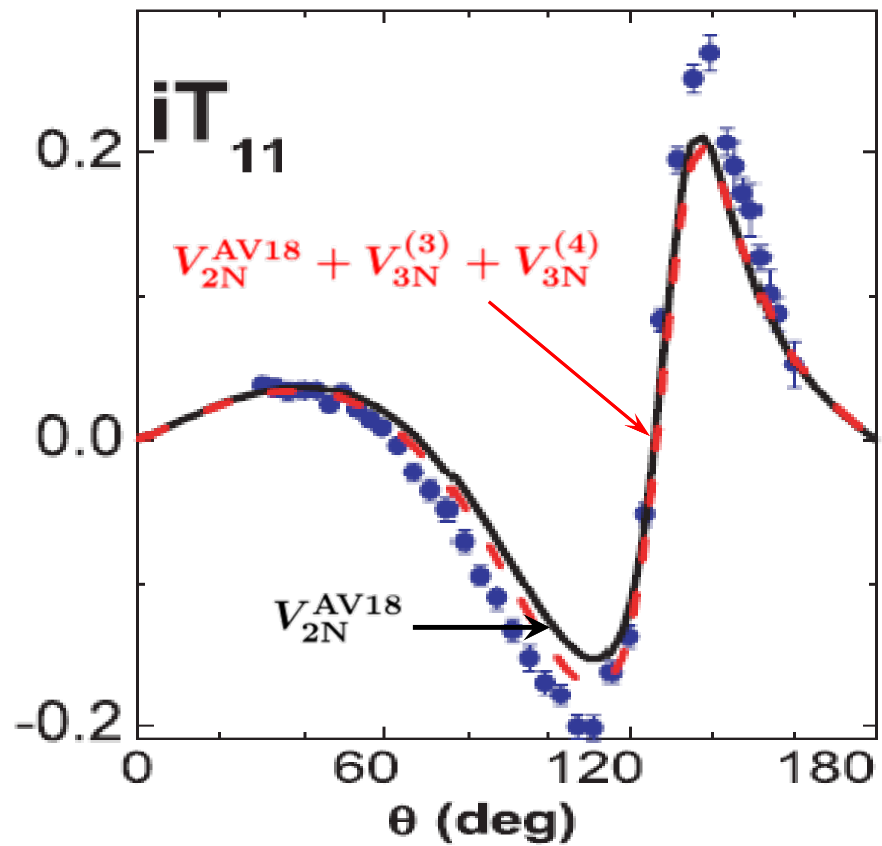
Faddeev equations without PWD ?

talk by Charlotte Elster

3N force: first corrections (N^{3}LO)

Elastic Nd scattering at 28 MeV

Ishikawa, Robilotta '07



Preliminary results (incomplete) indicate that the two-pion exchange corrections at N^{3}LO are rather small

Nuclear forces from chiral EFT with explicit Δ(1232)

in collaboration with *Hermann Krebs* *(Bochum)*
Ulf-G. Meißner *(Bonn/Jülich)*

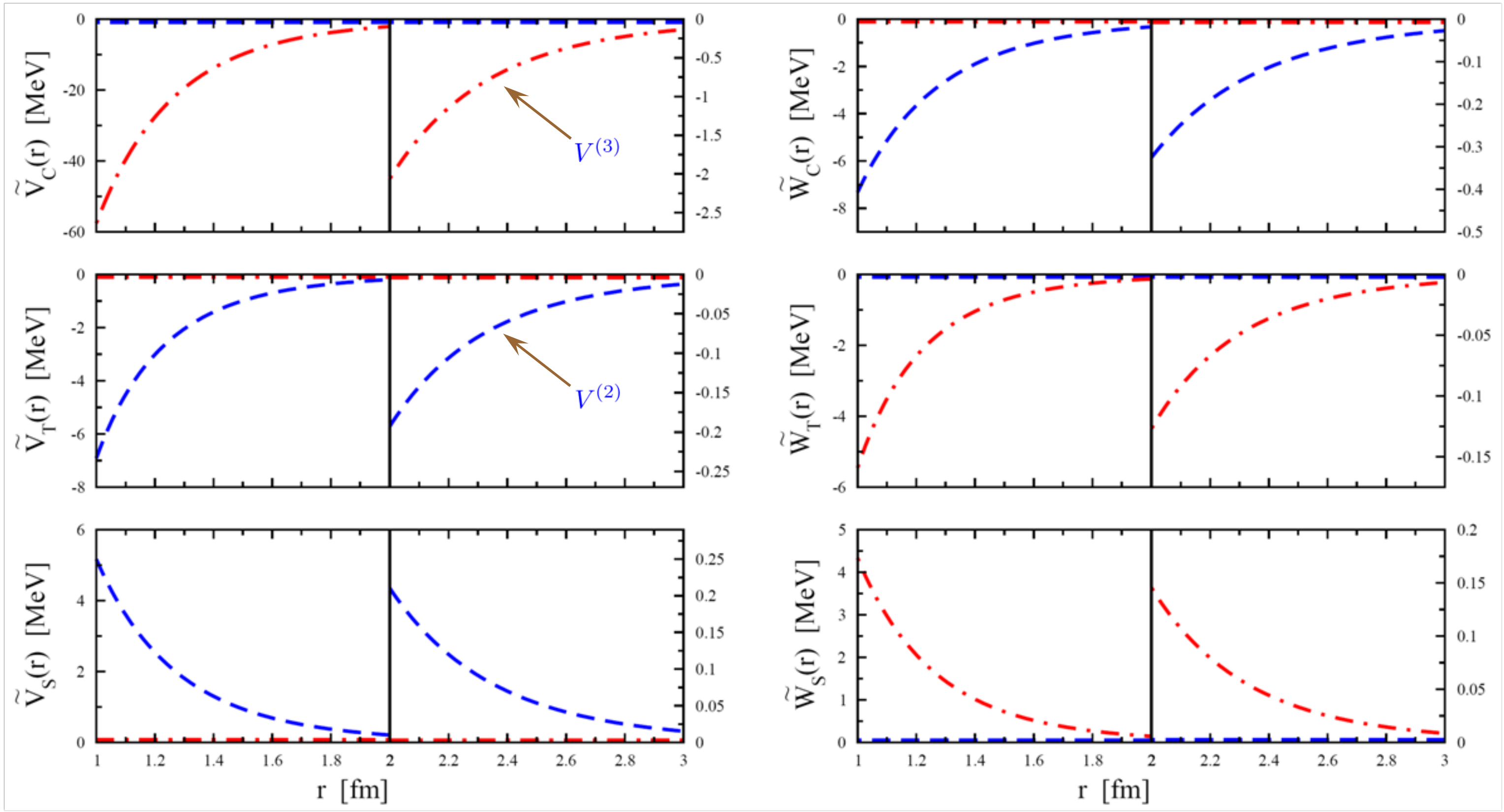
Inclusion of the Δ: Motivation

Chiral expansion of the NN force up to NNLO (Q^3): $V = V_{1\pi} + V_{2\pi} + V_{\rm cont}$

where $V_{1\pi} = V_{1\pi}^{(0)} + \underbrace{V_{1\pi}^{(2)} + V_{1\pi}^{(3)}}_{\textit{renormalize LECs}} + \ldots\,; \quad V_{2\pi} = V_{2\pi}^{(2)} + V_{2\pi}^{(3)} + \ldots\,; \quad V_{\rm cont} = \underbrace{V_{\rm cont}^{(0)} + V_{\rm cont}^{(2)}}_{\textit{contribute to S- and P-waves}} + \ldots$

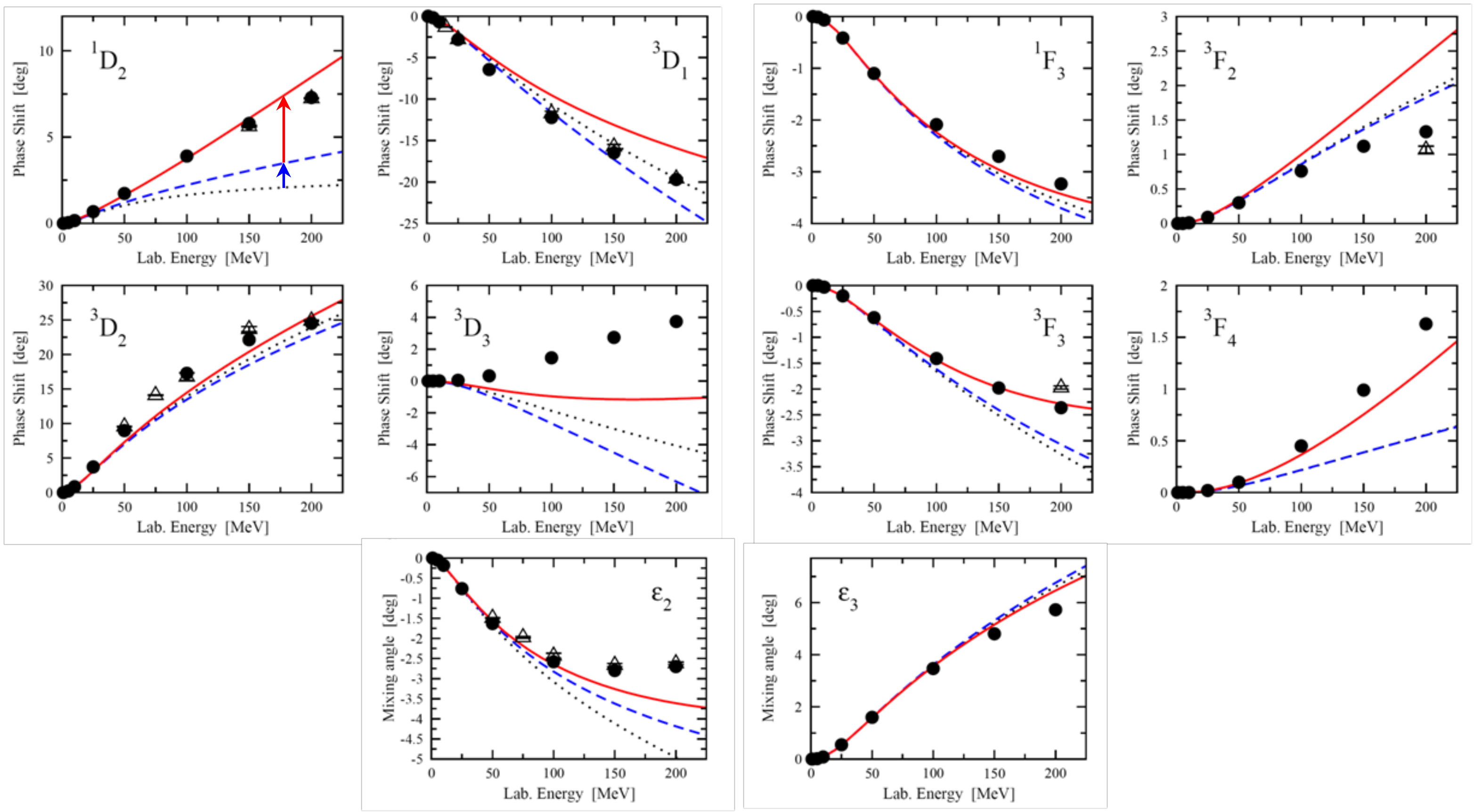
The 2π-exchange potential in coordinate space has the structure:

$$V(r) = \tilde{V}_C + \tilde{W}_C\, \boldsymbol{\tau}_1\cdot\boldsymbol{\tau}_2 + [\tilde{V}_S + \tilde{W}_S\, \boldsymbol{\tau}_1\cdot\boldsymbol{\tau}_2]\, \vec{\sigma}_1\cdot\vec{\sigma}_2 + [\tilde{V}_T + \tilde{W}_T\, \boldsymbol{\tau}_1\cdot\boldsymbol{\tau}_2]\, (3\vec{\sigma}_1\cdot\hat{r}\, \vec{\sigma}_2\cdot\hat{r} - \vec{\sigma}_1\cdot\vec{\sigma}_2)$$



Inclusion of the Δ: Motivation

Neutron-proton peripheral phase shifts up to N^{2}LO (Born approximation)

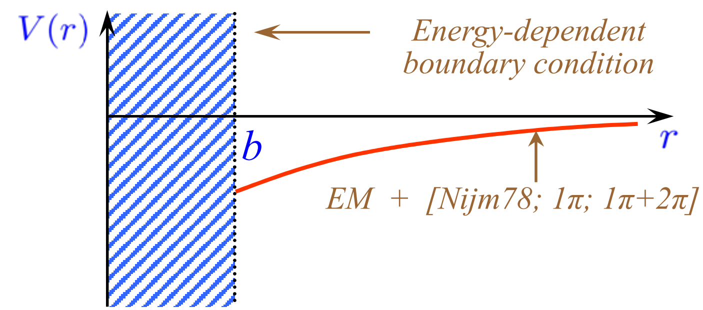


⇨ big corrections at NNLO

Inclusion of the Δ: Motivation

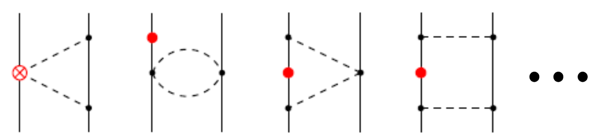
- **Similar observation made by the Nijmegen Group**
  Rentmeester et al. '99, '03

	#BC	$\chi^2_{\min}$
Nijm78	19	1968.7
OPE	31	2026.2
OPE + TPE(l.o.)	28	1984.7
OPE + χTPE	23	1934.5

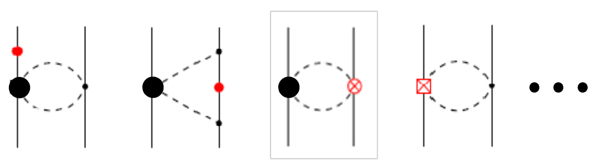


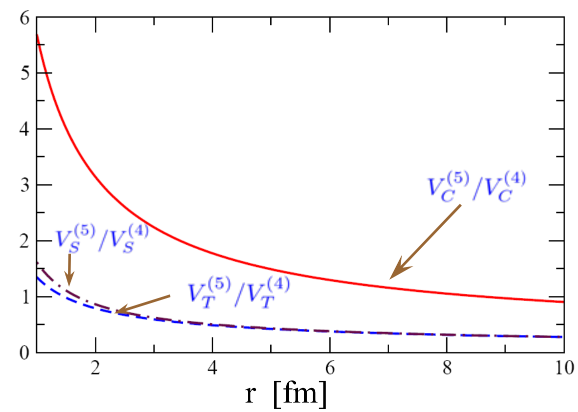
- **Similar convergence pattern for charge-symmetry breaking 2π-exchange**
  E.E., Meißner '05

Order Q^4:



Order Q^5:





- **Similar convergence pattern for 3π-exchange and 2πγ-exchange**
  Kaiser '01, '06

Inclusion of the Δ: Motivation

Why is the order-Q^3 (i.e. subleading) 2π–exchange NN potential so strong?

- Loop integrals at order Q^3 yield accidentally one power of π less than expected in the denominator (chiral expansion is an expansion in $Q^2/(4\pi F_\pi)^2$)
- Unnaturally large LECs c_3 and c_4 — understood in terms of resonance saturation. In particular, Δ-isobar yields an important contribution:

$$\delta c_3 = -2\delta c_4 = -\frac{4h_A^2}{9\Delta}$$ *(Bernard, Kaiser & Meißner '97)*

⟹ including Δ as an explicit DOF is expected to yield a more natural size of LECs, better convergence & applicability at higher energies

caveats: calculations more involved; more LECs…

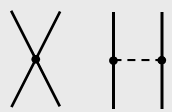
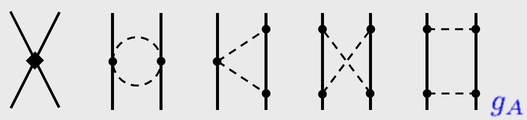
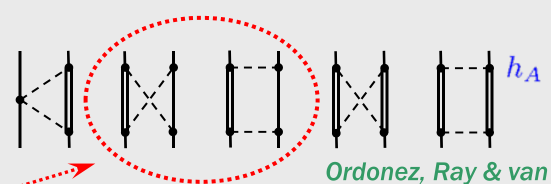
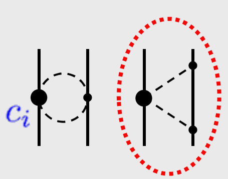
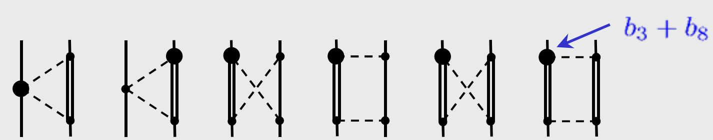
- standard chiral expansion: $Q \sim M_\pi \ll \Delta \equiv m_\Delta - m_N = 293 \text{ MeV}$
- small-scale expansion: $Q \sim M_\pi \sim \Delta$ *(Hemmert, Holstein & Kambor '98)*

To be studied: convergence of the EFT expansion, effects beyond resonance saturation of c_i, isospin violating effects, …

Δ-isobar & the two-nucleon force

Krebs, E.E., Meißner EPJA 32 (2007) 127

Two-nucleon force in EFT with and without Δ

	Δ-less theory	Δ-full theory: additional graphs
LO		—
NLO		 *Ordonez, Ray & van Kolck.'96, Kaiser, Gerstendorfer & Weise '98*
N^2LO		 *Krebs, E.E., Meißner EPJA 32 (2007) 127*

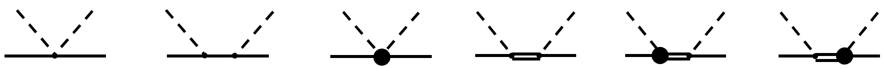
Notice: Δ-contributions to the OPEP and contact interactions only lead to shifts in the corresponding low-energy constants

Δ-isobar & the two-nucleon force

Krebs, E.E., Meißner EPJA 32 (2007) 127

Determination of the LECs from πN threshold coefficients

πN amplitude up to NLO:



Input:

- fit 1: $h_A = \frac{3 g_A}{2\sqrt{2}} \sim 1.34$ *(SU(4), large N_c)*
- fit 2: $h_A = 1.05$ *(Fettes & Meißner '01)*

We found:

- improved description of P-wave threshold parameters when Δ is included;
- resulting c_i's depend strongly on h_A while the thresh. param. do not
- strongly reduced values for c_i's;

Determinations of the LECs

LECs	Q^2, no Δ	Q^2, fit 1	Q^2, fit 2
c_1	-0.57	-0.57	-0.57
c_2	2.84	-0.25	0.83
c_3	-3.87	-0.79	-1.87
c_4	2.89	1.33	1.87
h_A	–	$1.34^\star$	$1.05^\star$
$b_3 + b_8$	–	1.40	2.95

Values of the S- and P-wave threshold param.

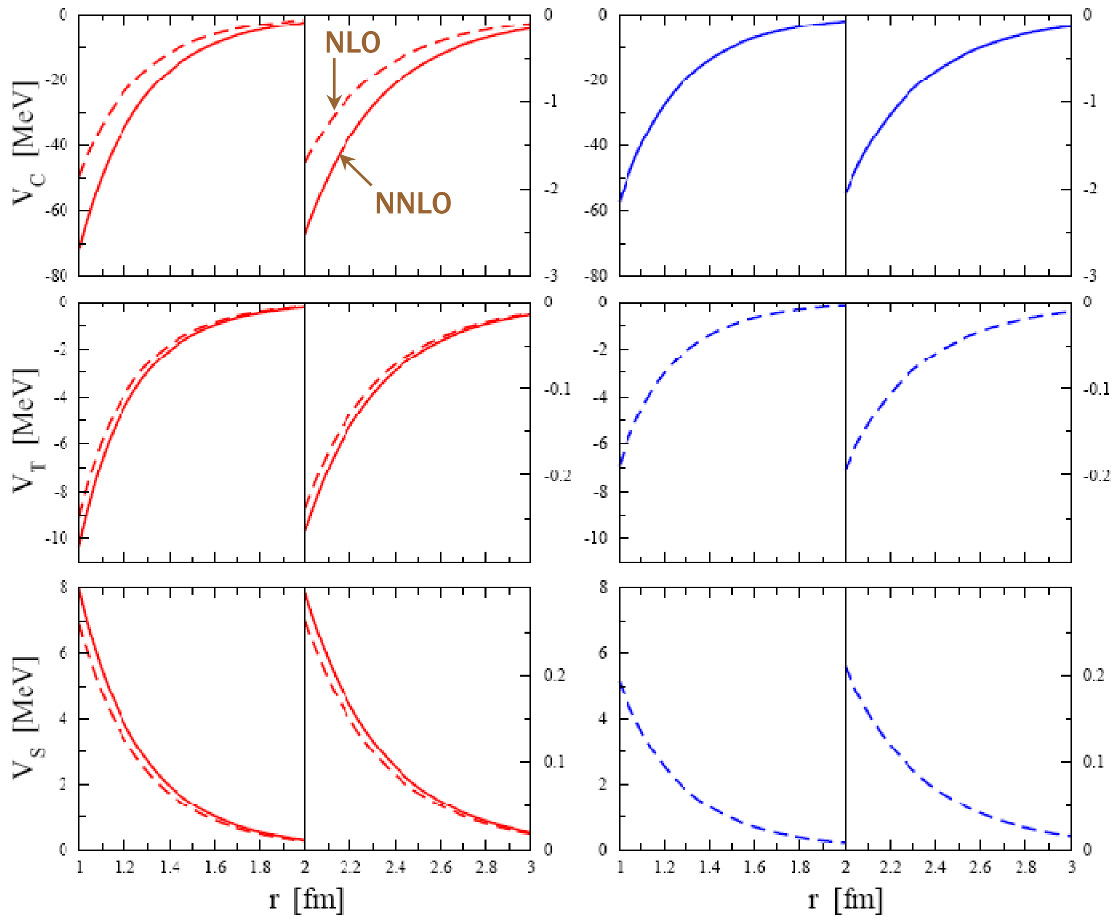
	Q^2, no Δ	Q^2 fits 1, 2	EM98
a_{0+}^+	0.41	0.41	0.41 ± 0.09
b_{0+}^+	-4.46	-4.46	-4.46
a_{0+}^-	7.74	7.74	7.73 ± 0.06
b_{0+}^-	3.34	3.34	1.56
a_{1-}^-	-0.05	-1.32	-1.19 ± 0.08
a_{1-}^+	-2.81	-5.30	-5.46 ± 0.10
a_{1+}^-	-6.22	-8.45	-8.22 ± 0.07
a_{1+}^+	9.68	12.92	13.13 ± 0.13

all values in units $10^{-2} M_\pi^{-n}$

Δ-isobar & the two-nucleon force

Krebs, E.E., Meißner EPJA 32 (2007) 127

Chiral 2π-exchange up to NNLO with and without explicit Δ

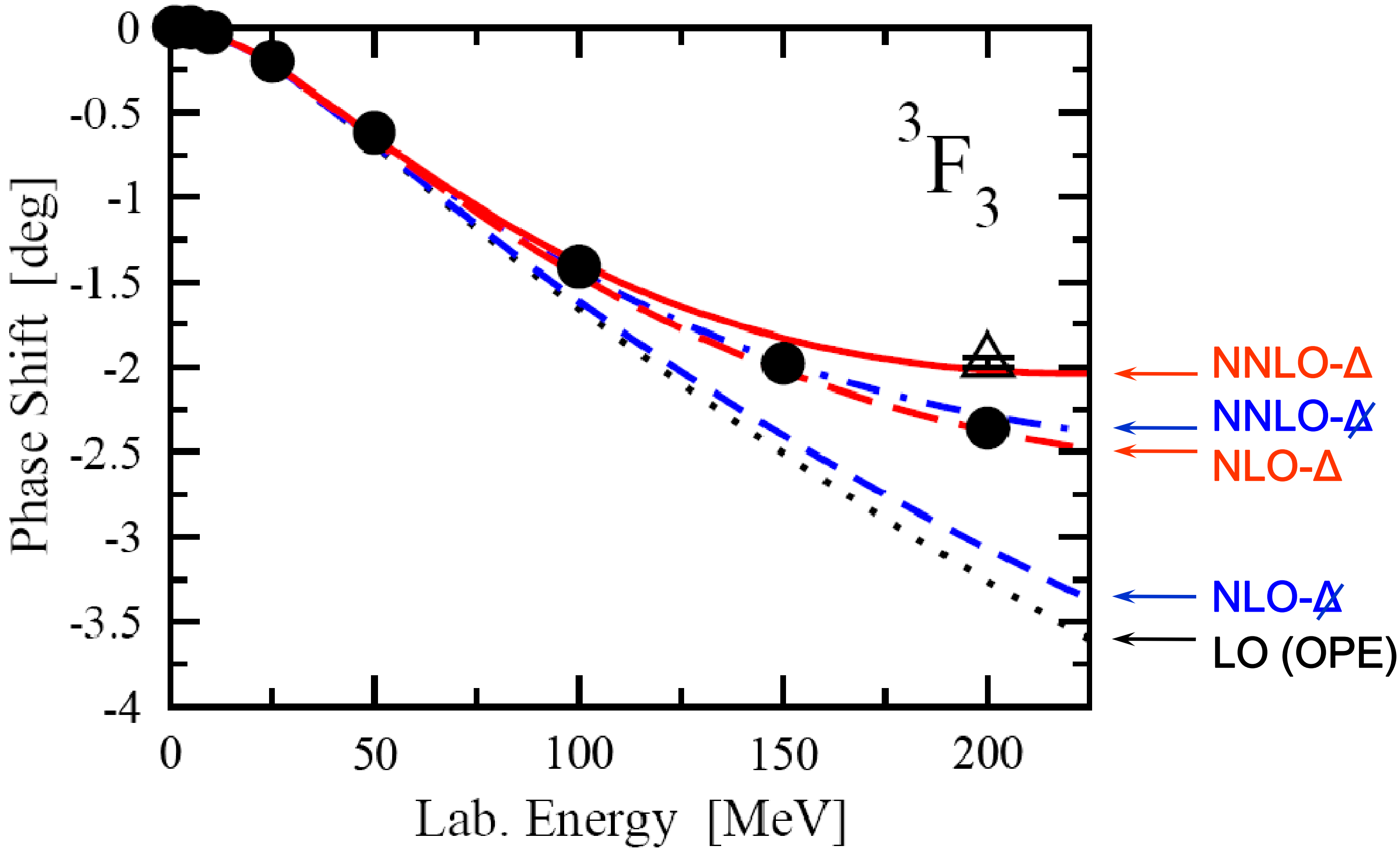


much better convergence when Δ is included explicitly!

Δ-isobar & the two-nucleon force

Krebs, E.E., Meißner EPJA 32 (2007) 127

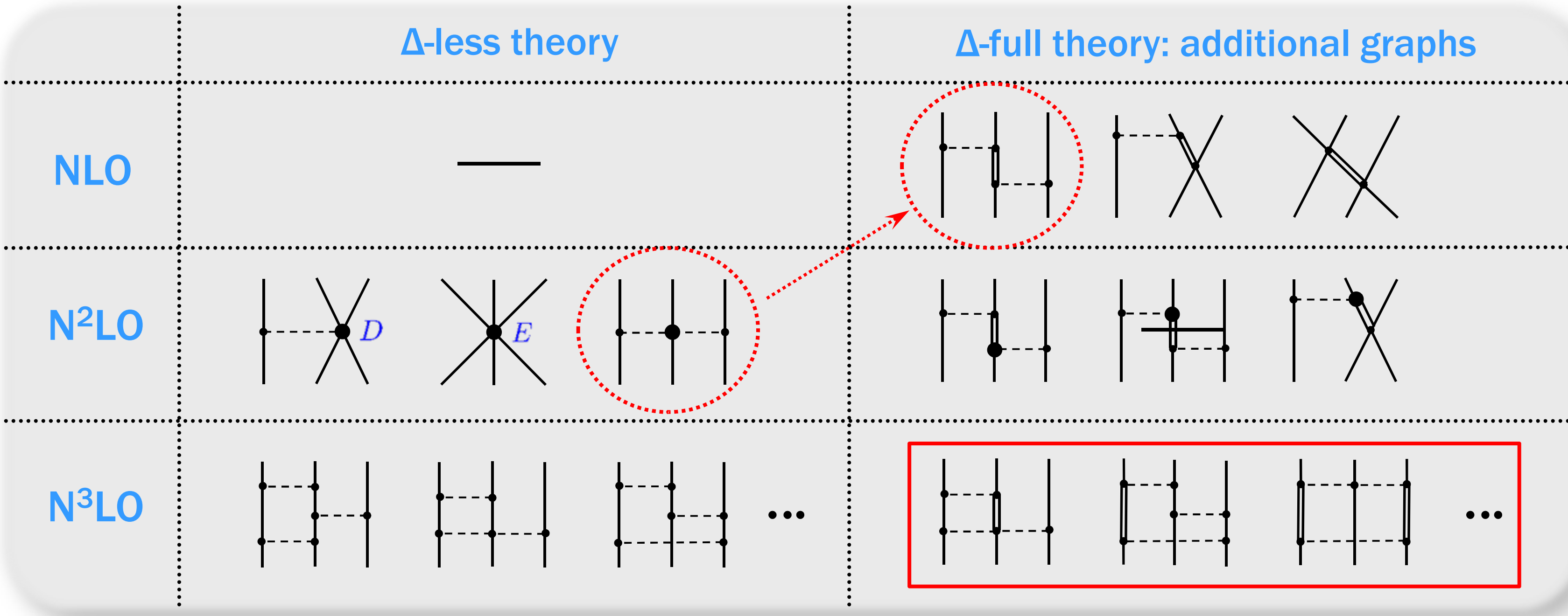
$^3F_3$ partial waves up to NNLO with and without Δ



(calculated in the first Born approximation)

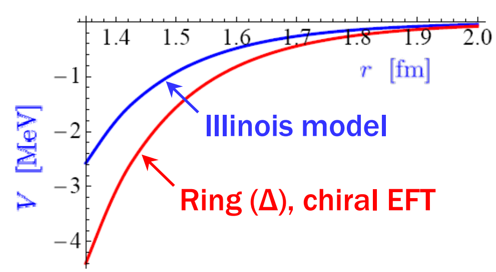
Δ-isobar & the three-nucleon force

E.E., Krebs, Meißner NPA 806 (2008) 65

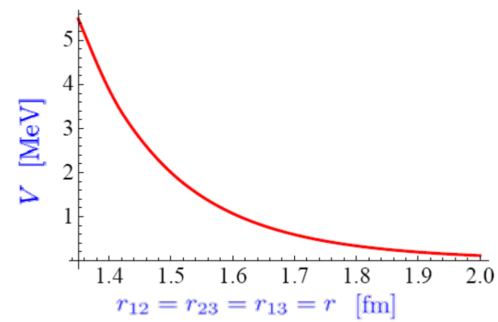


- Δ contributions at N^{3}LO are large!
- Long-range part is parameter free
- Much richer spin/isospin structure compared to the Illinois model
- Complete analysis still to be done
  Krebs, E.E., in progress

isoscalar central potential



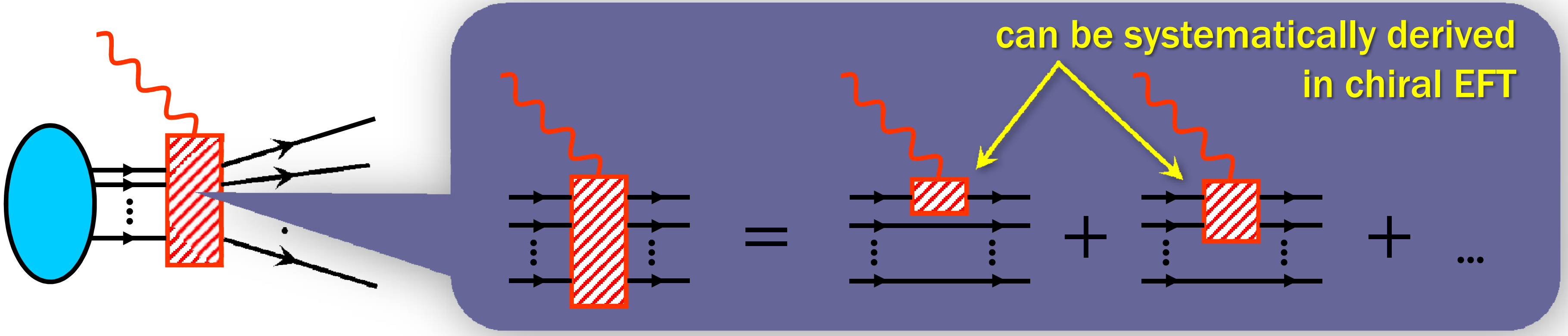
$\vec{\sigma}_2 \cdot \hat{r}_{12} \times \hat{r}_{23}\, \vec{\sigma}_3 \cdot \hat{r}_{13} \times \hat{r}_{23}$



Electromagnetic currents

in collaboration with *Stefan Kölling* *(Jülich/Bonn)*
Hermann Krebs *(Bochum)*
Dagmara Rozpedzik, Jacek Golak *(Cracow)*
Ulf-G. Meißner *(Bonn/Jülich)*

Probing few nucleons with photons



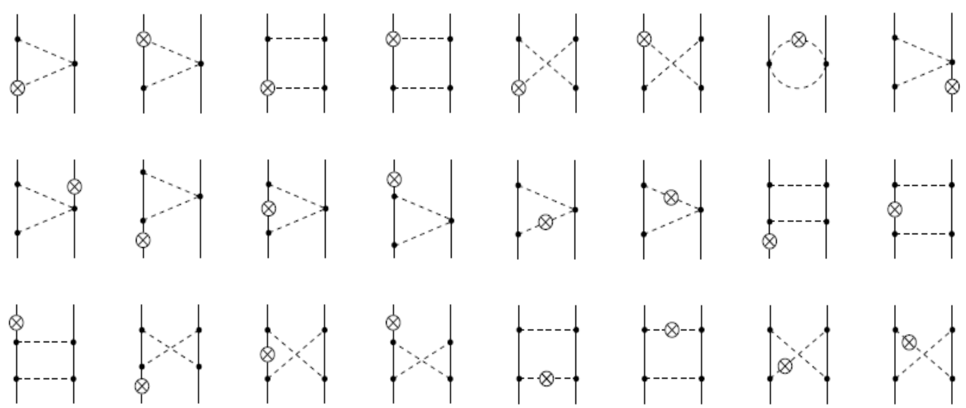
- Leading 1-loop expressions for exchange currents in the threshold kinematics known since long time *(Park, Min, Rho)* Application to $np \to d\gamma$ at threshold:

$\sigma_{1N} = 306.6 \text{ mb} \quad \longrightarrow \quad \sigma_{1N+2N} = 334 \pm 3 \text{ mb}$ to be compared with $\sigma_{\exp} = 334.2 \pm 0.5 \text{ mb}$

- Leading 2π-exchange charge and current densities worked out (parameter-free)
  Pastore, Schiavilla, ... ; Kölling, Krebs, E.E., Meißner

- 1π-exchange and short-range contributions to one loop in progress
  (Kölling et al., in preparation)

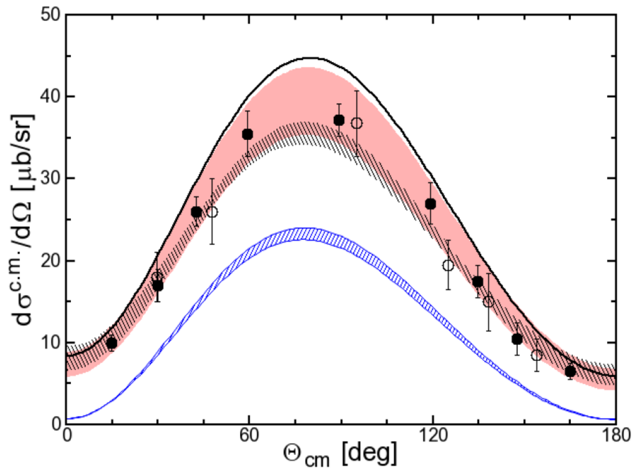
Leading 2π-exchange contributions to 2N current

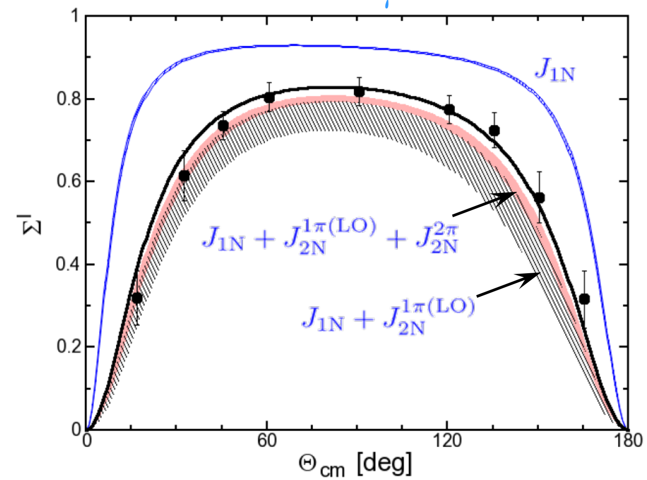


Deuteron photodisintegration

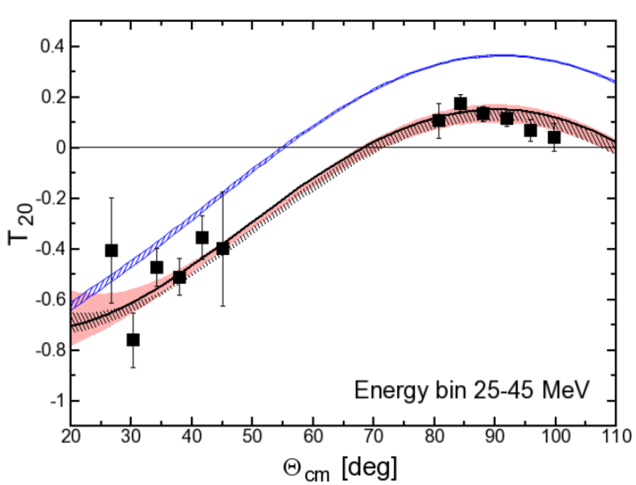
Rozpedzik et al. ’10

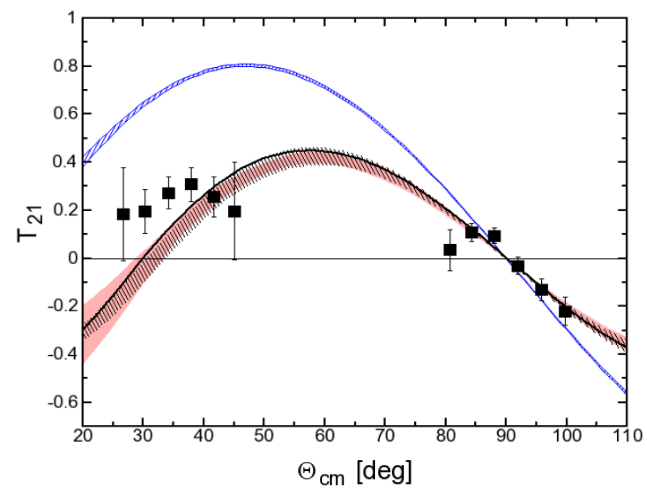
Cross section and photon analyzing power at E_γ =30 MeV





Deuteron tensor analyzing powers



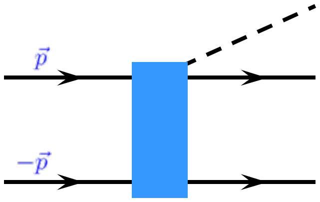


large sensitivity to MEC; short-range & 1π-exchange terms still to be taken into account

Pion production in NN collisions

in collaboration with *Vadim Baru, Arseny Filin, Christoph Hanhart,*
Johan Haidenbauer (Jülich)
Vadim Lensky (Manchester)
Alexander Kudryavtsev (Moscow)
Ulf-G. Meißner (Bonn/Jülich)

Pion production in NN collisions

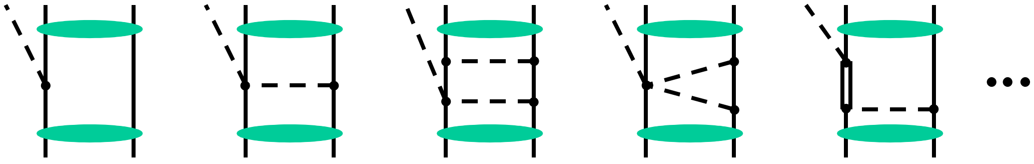


Considerably more challenging due to the appearance of a new „soft“ scale $|\vec{p}| \gtrsim \sqrt{M_\pi m_N} \sim 350$ MeV

⟹ slower convergence of the chiral expansion (expansion parameter $\sqrt{M_\pi m_N}/\Lambda_\chi$ vs M_π/Λ_χ in the few-N sector)

Current state-of-the-art

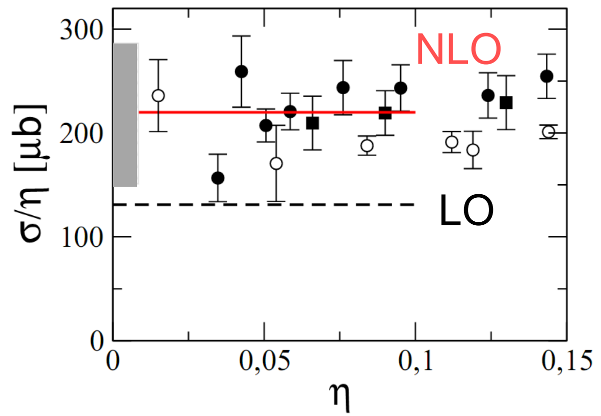
- Hybrid approach (EFT description of the 2N system for $|\vec{p}| \sim \sqrt{M_\pi m_N}$ not yet available)
- Δ(1232) isobar plays an important role ⟹ must be included as an explicit DOF
- s-wave pion production worked out up to NLO
  Cohen et al.'96; Dmitrasinovic et al.'99; da Rocha et al.'00; Hanhart et al.'01,'02



Proper separation of irred. contributions crucial!
Lensky et al. '01

Near threshold: $\sigma = \alpha\eta + \mathcal{O}(\eta^3)$ with $\eta \equiv k_\pi/M_\pi$

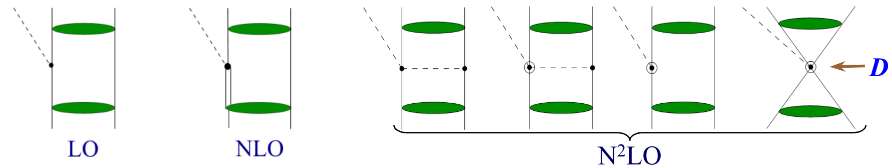
results for $pp \to d\pi^+$



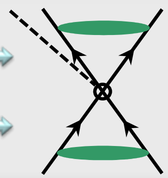
p-wave π-production and the D-term

Hanhart, van Kolck, Miller '00; Baru, EE, Haidenbauer, Hanhart, Kudryavtsev, Lensky, Meißner '09

- Loops start to contribute at N^{3}LO
- Up to N^{2}LO, D is the only unknown LEC
- Simultaneous description of
  $pn \to pp\pi^-$, $pp \to pn\pi^+$ and $pp \to d\pi^+$ ⟹ nontrivial consistency check of chiral EFT



- In the future: implications for the 3NF and for weak reactions with light nuclei

$|\vec{p}\,'| \sim M_\pi$ ⟹  ⟸ $^1S_0$ for $pp \to pn\pi^+$, $pp \to d\pi^+$; $^3S_1$ for $pn \to pp\pi^-$

$|\vec{p}| \sim \sqrt{M_\pi m_N}$ ⟹ ⟸ $^3S_1$ for $pp \to pn\pi^+$, $pp \to d\pi^+$; $^1S_0$ for $pn \to pp\pi^-$

Reaction $pp \to d\pi^+$

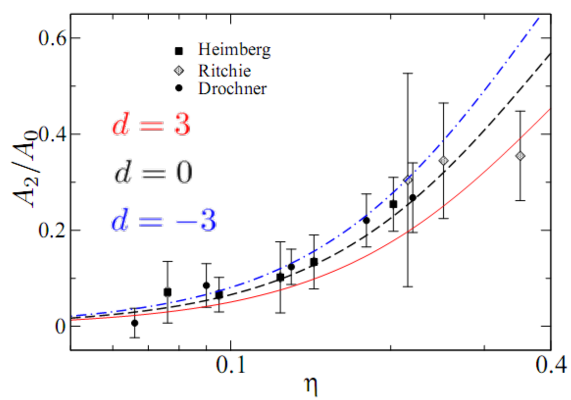
Near threshold:

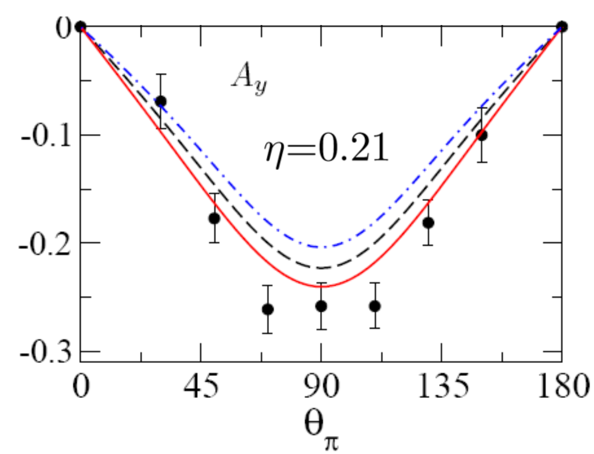
$$\frac{d\sigma}{d\Omega} \simeq A_0 + A_2\, P_2(\cos\theta_\pi)$$

Natural units for D:

$$D = \frac{d}{F_\pi^2\, m_N}$$

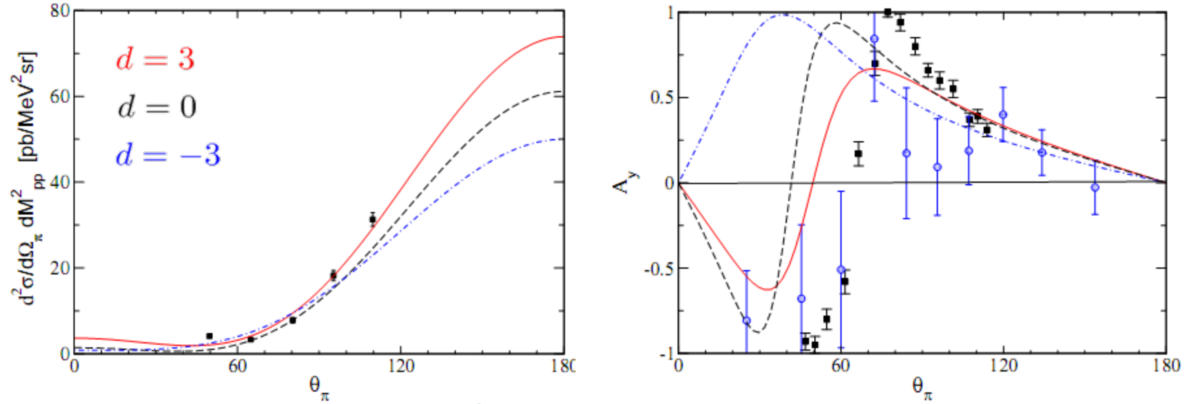
d ← *dimensionless coefficient ~ 1*





p-wave π-production and the D-term

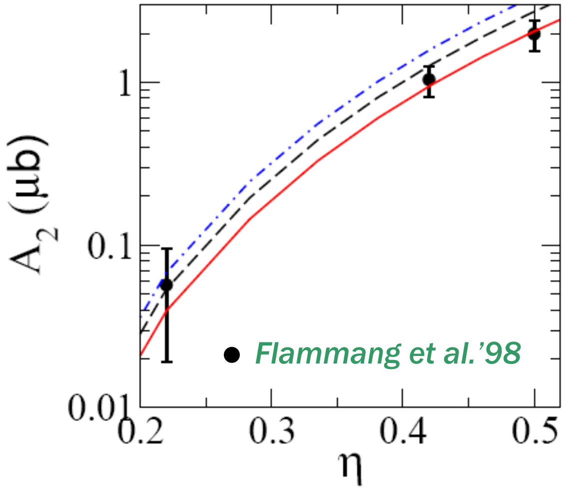
- **Reaction** $pn \longrightarrow pp\pi^-$
  - The final *pp* relative momentum is restricted to be: $|\vec{p}\,'| < 38$ MeV ⟹ *pp* p-waves suppressed
  - Data only available at $\eta = 0.66$ ⟹ expect only qualitative description...



Data from TRIUMF and PSI

New data at lower energies will be taken at COSY.

- **Reaction** $pp \longrightarrow pn\pi^+$
  - The relevant amplitude ($^1S_0 \rightarrow {}^3S_1p$) is suppressed compared to the dominant $^1D_2 \rightarrow {}^3S_1p$ amplitude ⟹ minor sensitivity to the D-term…

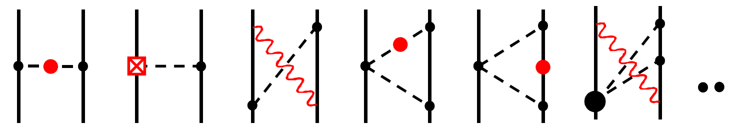


Overall best results are achieved for d ~ 3

Isospin breaking & few-N systems

$$\mathcal{L}_{\rm QCD} = -\frac{1}{4} G^a_{\mu\nu} G^{\mu\nu,\,a} + \bar{q}(i\gamma_\mu D^\mu - \underbrace{\mathcal{M} - A_\mu \gamma^\mu Q_q}_{\text{isospin-breaking}})q \;\Longrightarrow\; \mathcal{L}_{\rm eff} = \mathcal{L}_{\rm eff}^{\rm conserv} + \underbrace{\mathcal{L}_{\rm eff}^{\rm breaking}}_{\text{hard / soft } \gamma\text{'s + terms } \propto\, m_u - m_d}$$

- IB 2NF, 3NF worked out up to high orders, long-range contributions largely driven by $M_{\pi^\pm} - M_{\pi^0}$, $(m_p - m_n)^{\rm str}$ and $(m_p - m_n)^{\rm em}$



van Kolck et al. '93,'96; Friar et al. '99,'03,'04; Niskanen '02; Kaiser '06; E.E. et al. '04,'05,'07; ...

- Charge-symmetry-breaking nuclear forces and BE differences in ^{3}He – ^{3}H

Coulomb	Breit	K.E.	Two-Body	Three-body	Theory	Experiment
648	28	14	65(22)	5	760(22)	764

Friar et al. PRC 71 (2005) 024003

- $dd \to \alpha\pi^0$ measured at IUCF: $\sigma = 12.7 \pm 2.2 \,/\, 15.1 \pm 3.1$ pb @ 228.5 / 231.8 MeV

Stephenson et al. '03

Theoretical analysis challenging; first estimations yield the right order of magnitude.

Gardestig et al. '04; Nogga et al.'06

- CSB forward-backward asymmetry in $np \to d\pi^0$ @ 279.5 MeV at TRIUMF

$$A_{\rm fb} = \frac{\int [d\sigma/d\Omega(\theta) - d\sigma/d\Omega(\pi-\theta)]\, d[cos\theta]}{\int [d\sigma/d\Omega(\theta) + d\sigma/d\Omega(\pi-\theta)]\, d[cos\theta]} = \Big[17.2 \pm 8({\rm stat}) \pm 5.5({\rm sys})\Big] \times 10^{-4}$$

(Opper et al. '03)

$np \to d\pi^0$ & the np mass difference

Niskanen '99; van Kolck et al. '00; Bolton, Miller '09; Filin, Baru, E.E., Haidenbauer, Hanhart, Kudryavtsev, Meißner '09

The goal: use A_{fb} measured at TRIUMF to extract the strong/em contributions to the neutron-to-proton mass shift.

$$\begin{cases} \delta m_N^{\rm str} \equiv (m_n - m_p)^{\rm str} = 2.05 \pm 0.3 \text{ MeV} \\ \delta m_N^{\rm em} \equiv (m_n - m_p)^{\rm em} = -0.76 \pm 0.3 \text{ MeV} \end{cases}$$

Gasser, Leutwyler '82 (based on the Cottingham sum rule)

$$\frac{d\sigma}{d\Omega} = A_0 + \underbrace{A_1 P_1(\cos\theta_\pi)} + A_2 P_2(\cos\theta_\pi) + \ldots \quad \Longrightarrow \quad A_{fb} \simeq \frac{A_1}{2A_0}$$

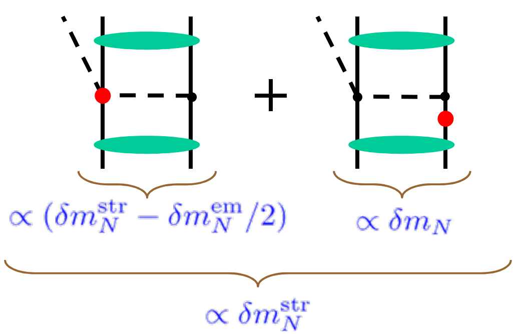
gives rise to A_{fb}, nonzero only for $pn \to d\pi^0$ *due to interference of IB and IC amplitudes*

- A_0 can be determined from the pionic deuterium lifetime measurement @ PSI:

$$\sigma(np \to d\pi^0) = \frac{1}{2}\sigma(nn \to d\pi^-) = \frac{1}{2} \times 252^{+5}_{-11}\, \eta \; [\mu\text{b}] \quad \Longrightarrow \quad A_0 = 10.0^{+0.2}_{-0.4}\, \eta \; [\mu\text{b}]$$

- A_1 at LO in chiral EFT: $A_1 = \frac{1}{128\pi^2}\frac{\eta M_\pi}{p(M_\pi + m_d)^2}\Re\Big[\underbrace{\Big(M_{^1S_0 \to {}^3S_1,\,p} + \frac{2}{3}M_{^1D_2 \to {}^3S_1,\,p}\Big)}M^*_{^1P_1 \to {}^3S_1,\,s}\Big]$

IC amplitudes calculated at NLO Baru et al.'09



Our result: $A_{\rm fb}^{\rm LO} = (11.5 \pm 3.5) \times 10^{-4}\; \delta m_N^{\rm str}/\text{MeV}$

$$\Longrightarrow \quad \boxed{\delta m_N^{\rm str} = 1.5 \pm 0.8\,(\text{exp.}) \pm 0.5\,(\text{th.}) \text{ MeV}}$$

Lattice: $\delta m_N^{\rm str} = 2.26 \pm 0.57 \pm 0.42 \pm 0.10 \text{ MeV}$

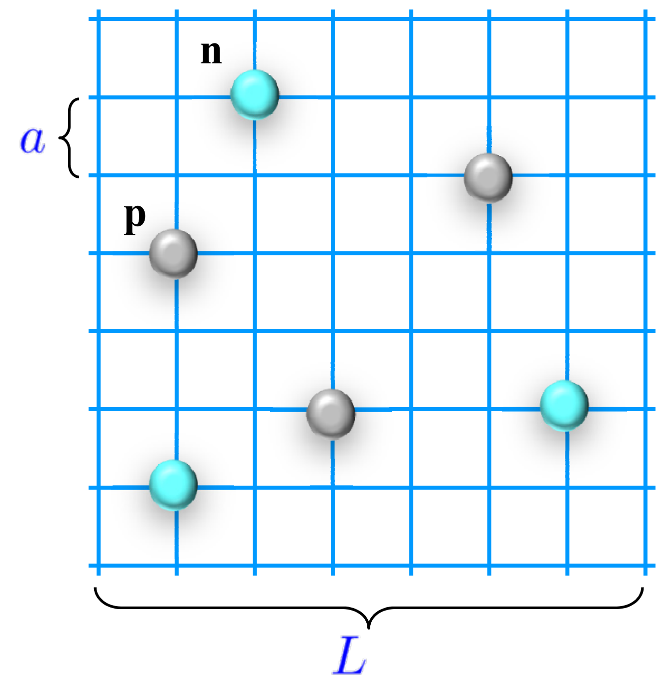
Beane et al.'07

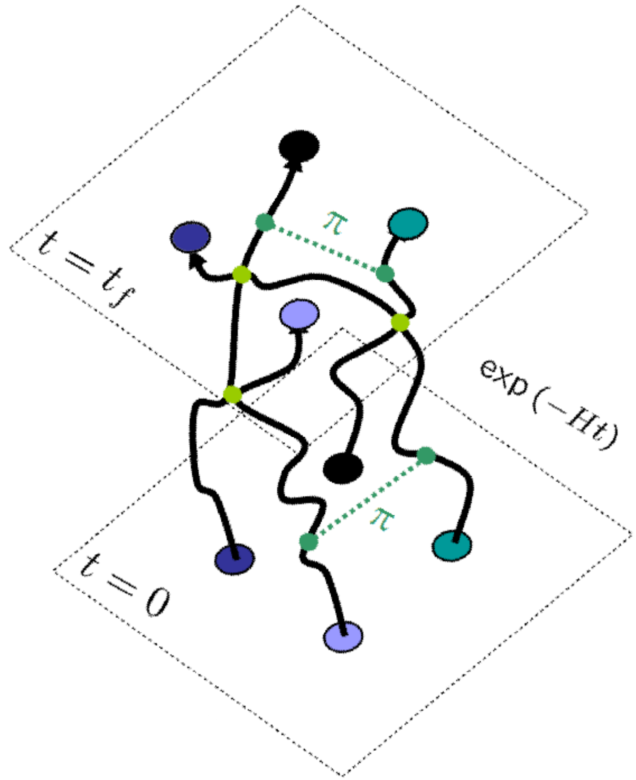
Nuclear lattice simulations

in collaboration with **Dean Lee** *(North Carolina)*
Kermann Krebs *(Bochum)*
Ulf-G. Meißner *(Bonn/Jülich)*

Nuclear Lattice Simulations

Lee, E.E., Krebs, Meißner





- Pions and nucleons as point-like particles on the lattice (typical lattice size ~ 20 fm)
- Use Monte Carlo to evaluate path integral

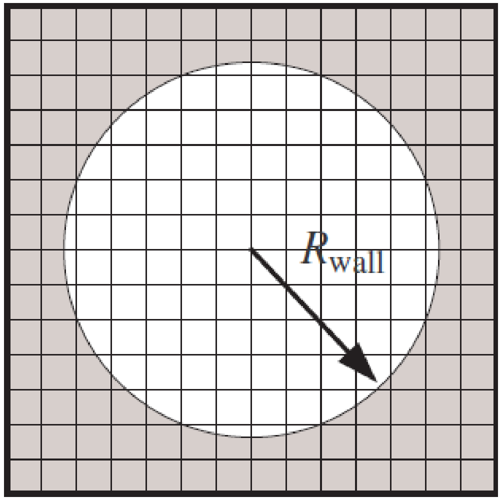
$$Z_A(t) = \langle \Psi_A^0 | \exp(-tH) | \Psi_A^0 \rangle \qquad E_A^0 = \lim_{t\to\infty} \left[-\frac{d}{dt} \ln Z_A(t) \right]$$

⟹ systematic ab initio approach to few- & many-nucleon systems

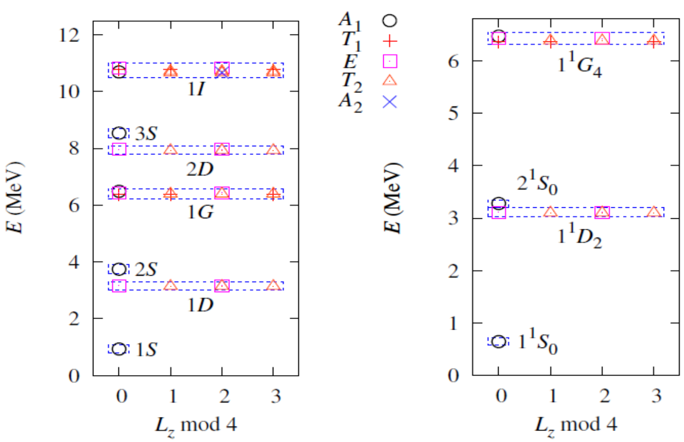
Two-particle scattering: spherical wall method

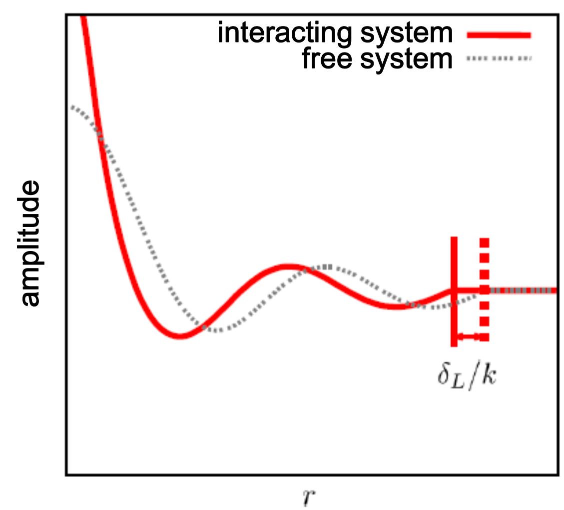
Borasoy, E.E., Krebs, Lee, Meißner, EPJA 34 (2007) 185

Place a wall at sufficiently large R. Phase shifts & mixing angles can be extracted by measuring energy shifts from free-particle values.

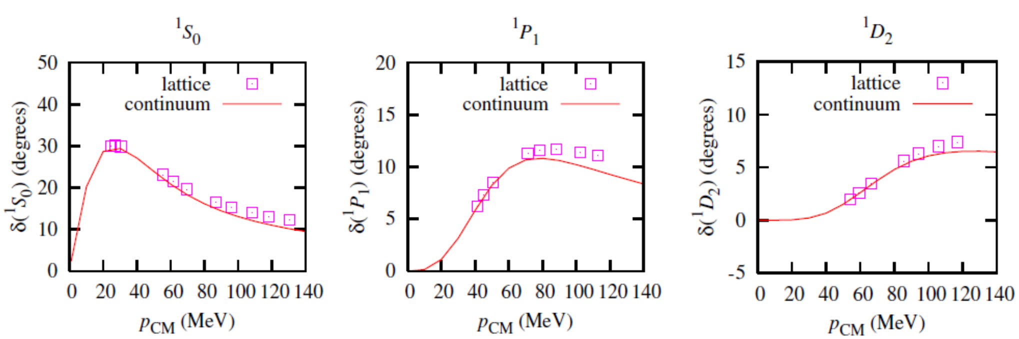


free system | interacting system





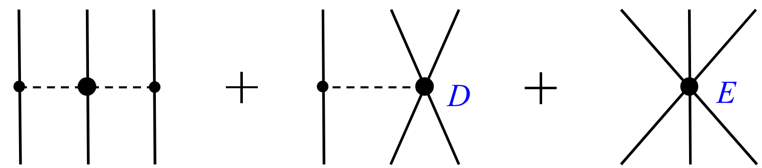
Phase shifts for a toy model potential



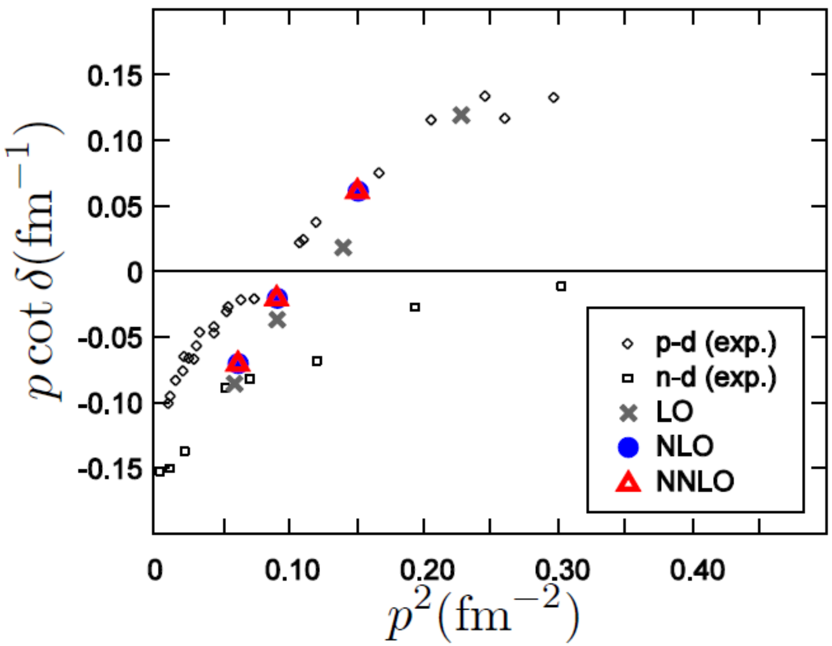
Inclusion of the 3N force

E.E., Krebs, Lee, Meißner '09

The unknown LECs D and E fixed from the ^{3}H binding energy and nd doublet S-wave.

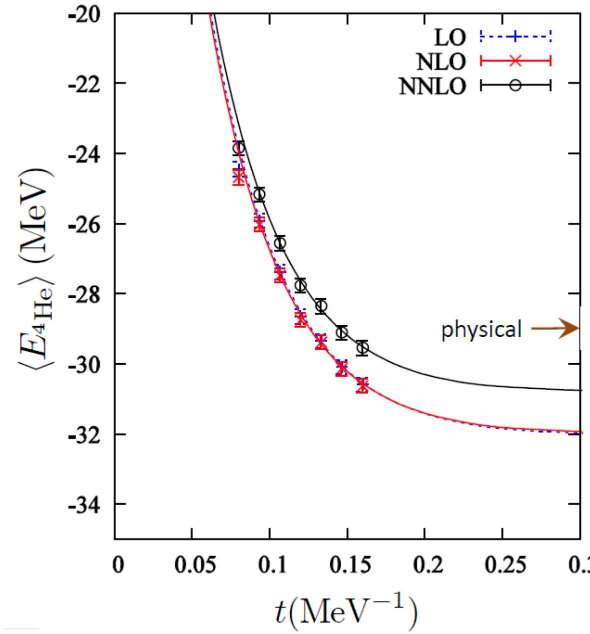


Neutron-deuteron spin-3/2 channel



- fast convergence
- results consistent with the data

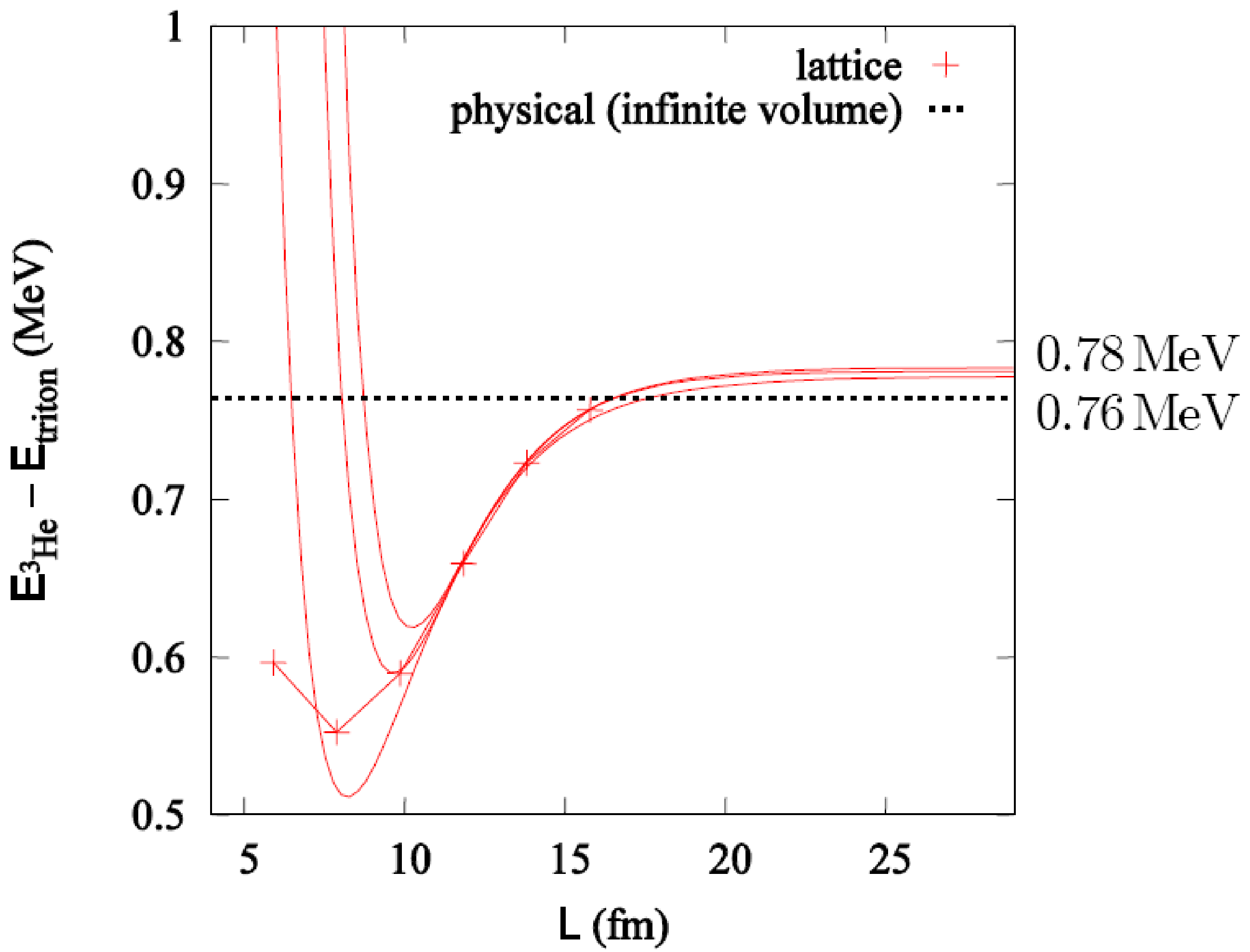
^{4}He BE vs. Euclidean time



- about 5% overbinding

^3H-^3He binding energy difference (NNLO)

E.E., Krebs, Lee, Meißner '10



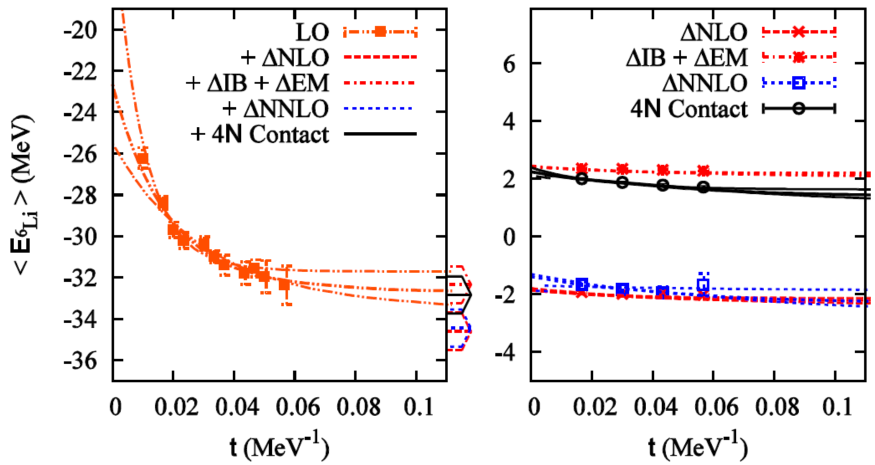
Infinite-volume extrapolations via: $E(L) = E(\infty) - \frac{C}{L} e^{-L/L_0} + \mathcal{O}\left(e^{-\sqrt{2}L/L_0}\right)$

Lüscher '86

Lattice simulations of light nuclei

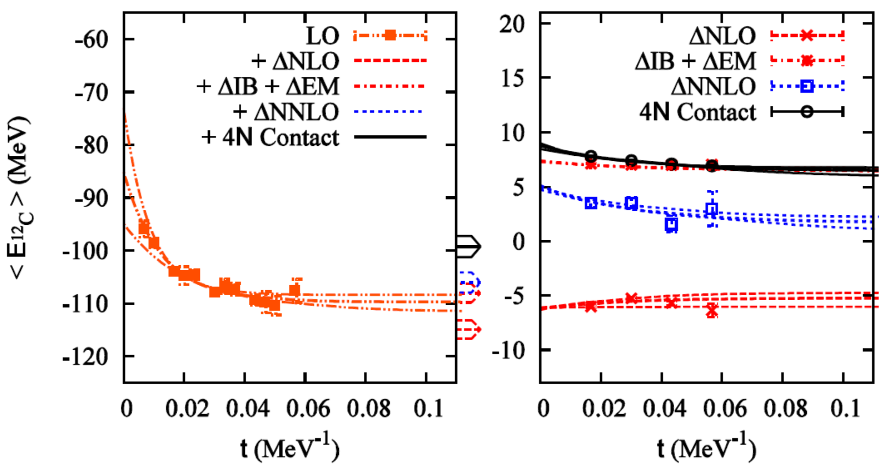
E.E., Krebs, Lee, Meißner '10

Simulations for ^{6}Li, L=9.9 fm



LO	−32.6(9) MeV
NLO	−34.6(9) MeV
NLO + IB + EM	−32.4(9) MeV
NNLO + IB + EM	−34.5(9) MeV
NNLO + IB + EM + 4N_{contact}	−32.9(9) MeV
Physical (infinite volume)	−32.0 MeV

Simulations for ^{12}C, L=13.8 fm



LO	−109(2) MeV
NLO	−115(2) MeV
NLO + IB + EM	−108(2) MeV
NNLO + IB + EM	−106(2) MeV
NNLO + IB + EM + 4N_{contact}	−99(2) MeV
Physical (infinite volume)	−92.2 MeV

Summary

- Nd scattering at N^2LO
  - Promising results at N^2LO; N^3LO in progress…
- Chiral EFT for nuclear forces with explicit Δ(1232)
  - Improved convergence of the chiral expansion for nuclear forces verfied
  - Expect large contributions for 3NF at N3LO (work in progress)
- Pion production in NN collisions
  - Important consistency check from studying different channels
  - $\delta m_N^{\rm str} = 1.5 \pm 0.8\,(\rm exp.) \pm 0.5\,(\rm th.)\ \rm MeV$ extracted from A_{fb} in $np \to d\pi^0$ consistent with the value obtained using the Cottingham sum rule and Lattice QCD
- Probing light nuclei with photons
  - NN exchange current worked out to leading one loop, applications in progress…
- Nuclear lattice simulations
  - formulated continuum EFT on space-time lattice
  - promising results for NN scattering and light nuclei up to N^2LO