Nuclear forces and their impact on structure, reactions and astrophysics

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July, 2013

Lectures for Week 2

- **M.** Chiral EFT 1 (as); χ-symmetry in NN scattering, QCD 2 (rjf)
- **T.** Chiral EFT 2 (rjf); Three-nucleon forces 1 (as)
- **W.** Renormalization group 1 (rjf);
  Forces from LQCD, hyperon-nucleon (as)
- **Th.** Renormalization group 2 (rjf);
  Nuclear forces and electroweak interactions (as)
- **F.** Many-body overview (rjf); Three-nucleon forces 2 (as)

Outline

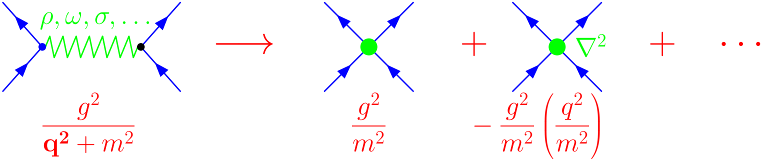
NDA, naturalness, and resonance saturation

Including Δs in chiral EFT (from H. Krebs)

Chiral EFT: Resonance Saturation

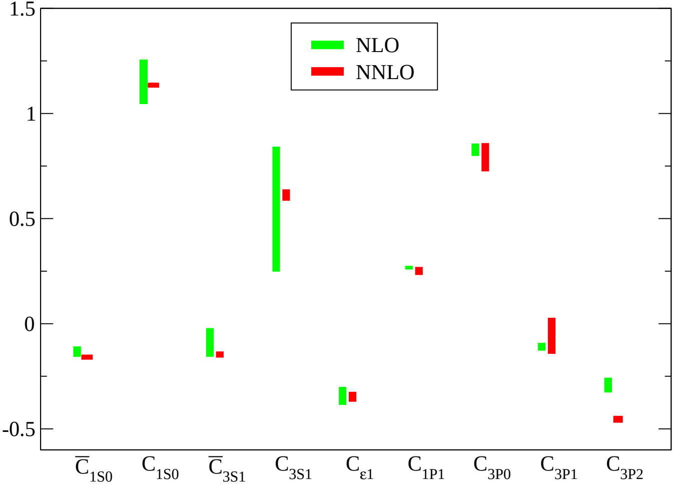
[Epelbaum et al. (2002)]

- How is chiral EFT potential related to phenomenological NN potentials based on one-boson exchange?
- Boson exchange $\Longrightarrow$ model of short-distance physics
  $\Longrightarrow$ unresolved in chiral EFT (except for pion)
  $\Longrightarrow$ encoded in coefficients of contact terms



Chiral EFT: Resonance Saturation (cont.)

- Compare coefficients from phenomenological models to low-energy constants of chiral EFT:



Chiral EFT: Resonance Saturation (cont.)

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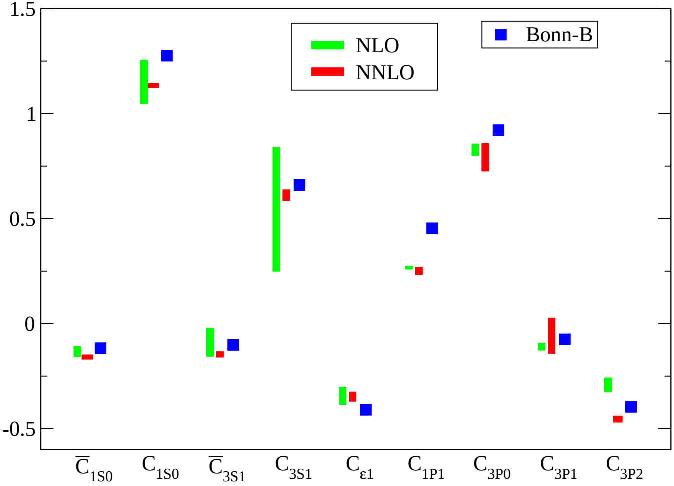

Chiral EFT: Resonance Saturation (cont.)

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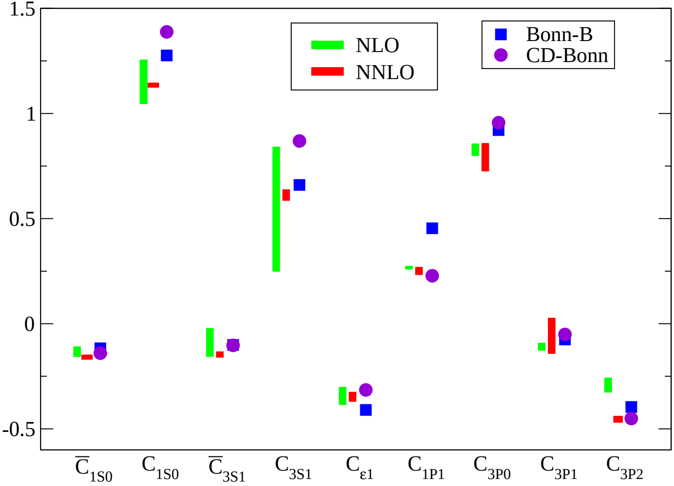

Chiral EFT: Resonance Saturation (cont.)

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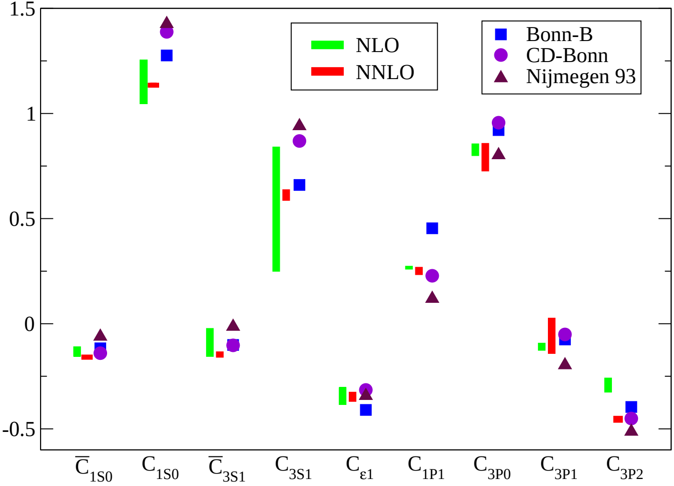


Outline

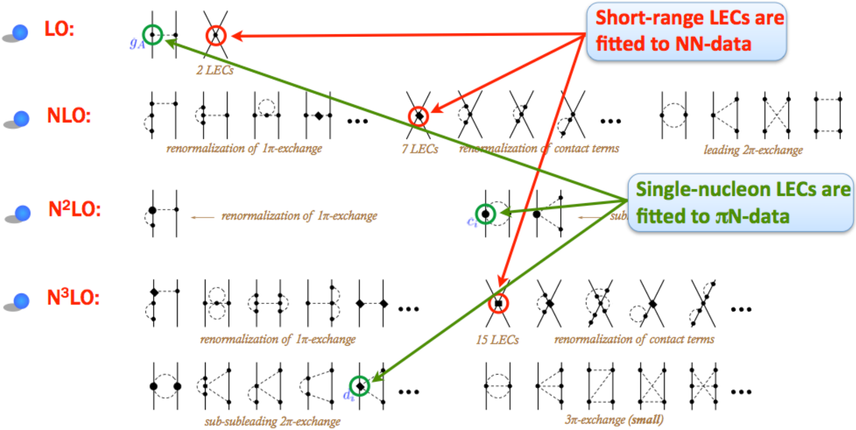
NDA, naturalness, and resonance saturation

Including Δs in chiral EFT (from H. Krebs)

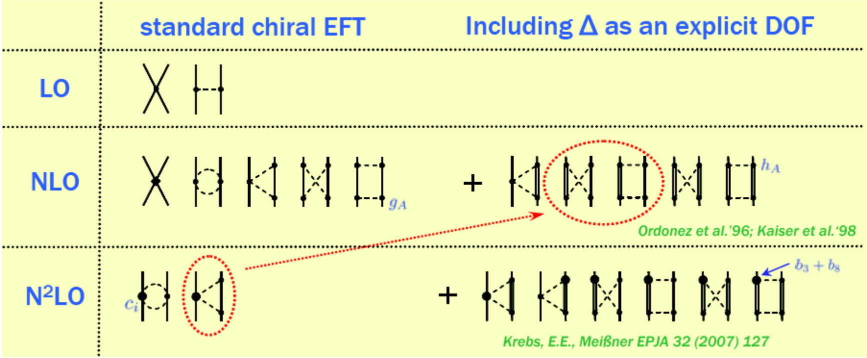
Nucleon-nucleon force up to N^{3}LO

Ordonez et al. '94; Friar & Coon '94; Kaiser et al. '97; Epelbaum et al. '98,'03; Kaiser '99-'01; Higa et al. '03; ...

Chiral expansion for the 2N force: $V_{2N} = V_{2N}^{(0)} + V_{2N}^{(2)} + V_{2N}^{(3)} + V_{2N}^{(4)} + \ldots$



+ 1/m and isospin-breaking corrections…

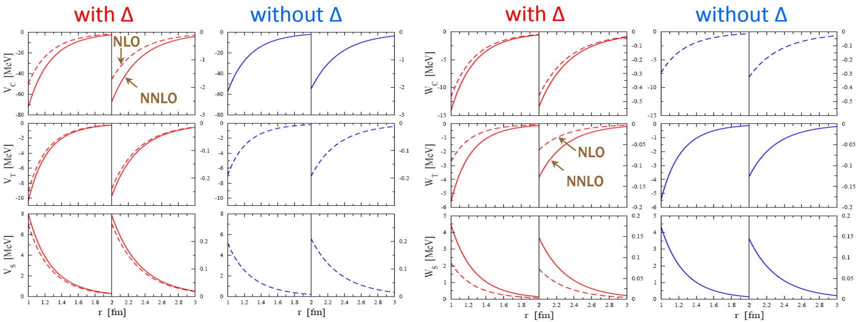

standard chiral EFT
Including Δ as an explicit DOF
LO
NLO
g_A
+
h_A
Ordonez et al.'96; Kaiser et al.'98
N²LO
c_i
+
$b_3 + b_8$
Krebs, E.E., Meißner EPJA 32 (2007) 127

NN potential with explicit Δ

Epelbaum, H.K., Meißner, Eur. Phys. J. A32 (2007) 127

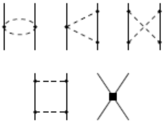
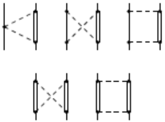
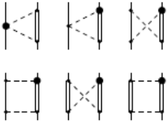
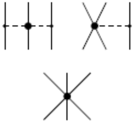
$$V_{\rm eff} = V_C + W_C \vec{\tau}_1 \cdot \vec{\tau}_2 + [V_S + W_S \vec{\tau}_1 \cdot \vec{\tau}_2] \vec{\sigma}_1 \cdot \vec{\sigma}_2 + [V_T + W_T \vec{\tau}_1 \cdot \vec{\tau}_2](3\, \vec{\sigma}_1 \cdot \hat{r} \vec{\sigma}_2 \cdot \hat{r} - \vec{\sigma}_1 \cdot \vec{\sigma}_2)$$

Chiral 2π- exchange potential up to NNLO

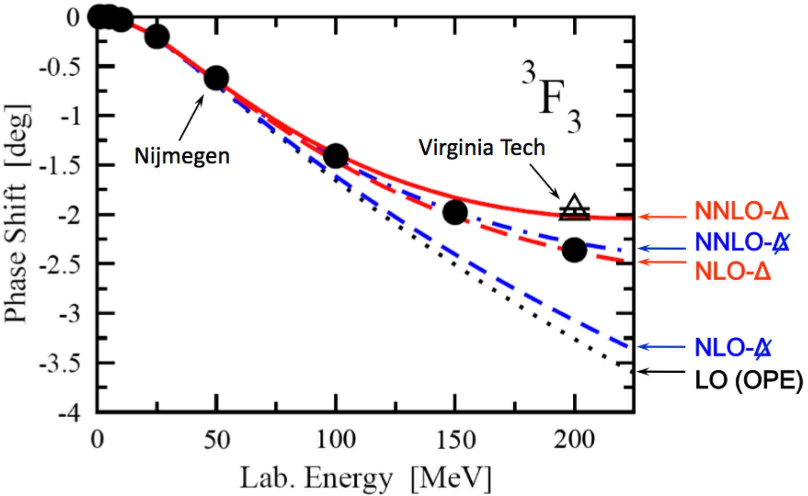


Advantages when Δ is included explicitly

- Dominant contributions already at NLO
- Much better convergence in all potentials

	Two–nucleon force		Three–nucleon force	
	Δ–less EFT	Δ–contributions	Δ–less EFT	Δ–contributions
LO		—	—	—
NLO		 Ordonez et al.'96, Kaiser et al. '98	—	
NNLO		 H.K., Epelbaum & Meißner '07		—

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



(calculated in the first Born approximation)