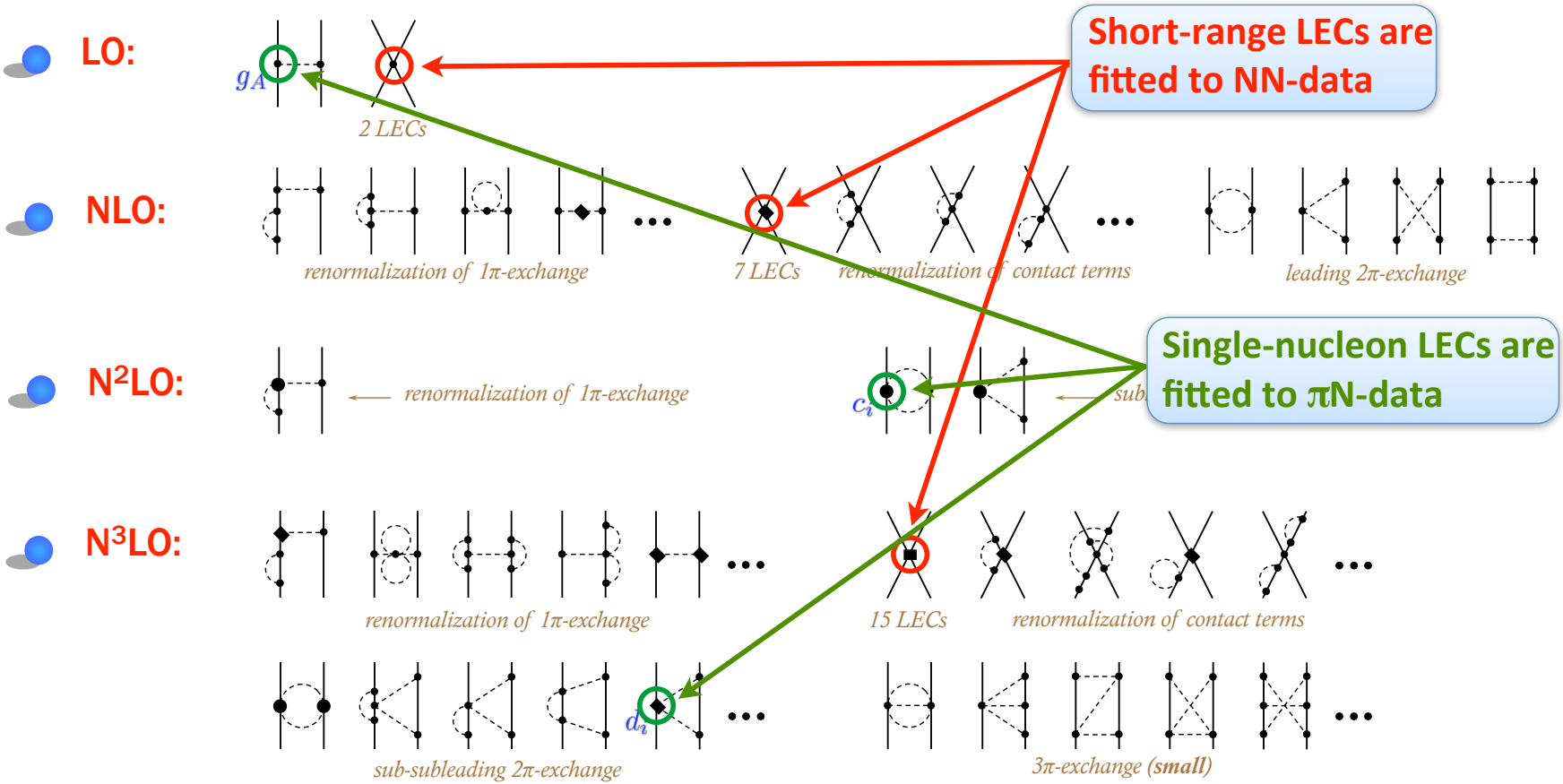
Nucleon-nucleon force up to N^{3}LO

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: $V_{2N} = V_{2N}^{(0)} + V_{2N}^{(2)} + V_{2N}^{(3)} + V_{2N}^{(4)} + \ldots$

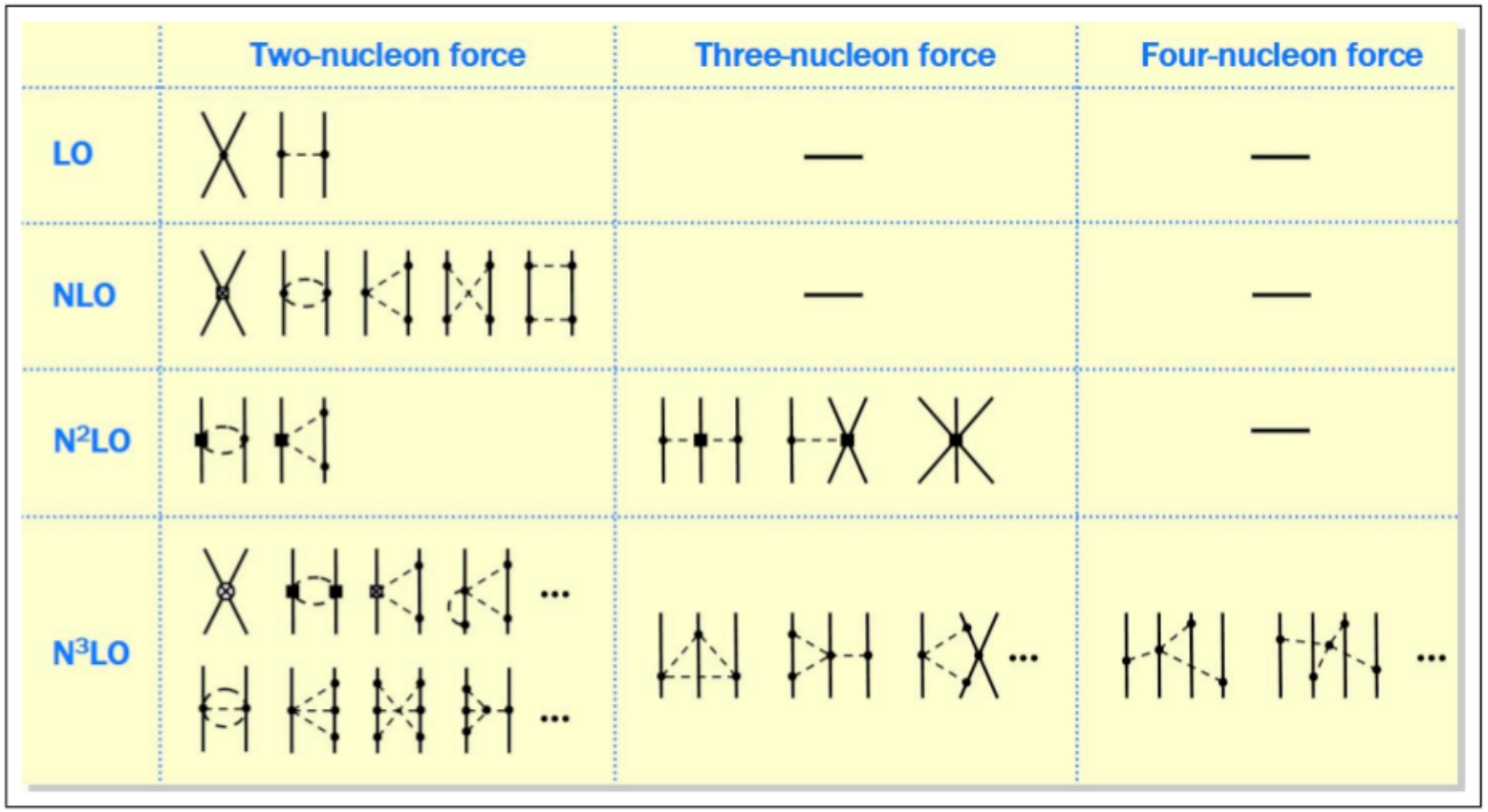


+ 1/m and isospin-breaking corrections…

figure from H. Krebs

Hierarchy of nuclear forces in chiral EFT

breakdown scale $\Lambda_b = \Lambda_\chi \sim 500\text{-}1000$ MeV



$\mathcal{O}((q/\Lambda_\chi)^0)$

$\mathcal{O}((q/\Lambda_\chi)^2)$

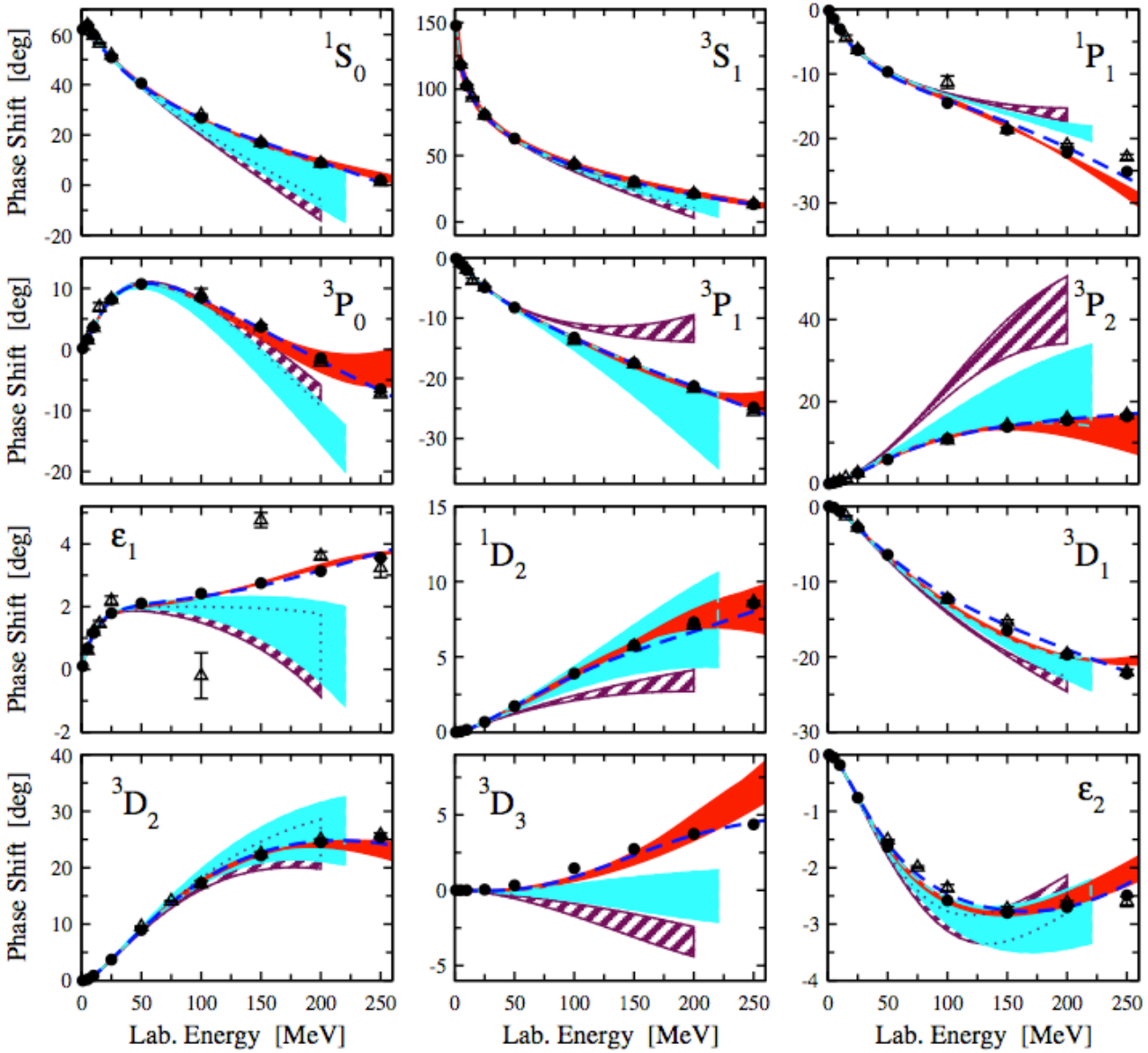
$\mathcal{O}((q/\Lambda_\chi)^3)$

$\mathcal{O}((q/\Lambda_\chi)^4)$

two-nucleon force $\gg$ three-nucleon force $\gg$ four-nucleon force

figure from U.-G. Meißner

neutron-proton S-, P-, D-wave phase shifts in chiral EFT



- legend:
  - NLO
  - N^2LO
  - N^3LO
  - Nijm. PWA
  - △ VPI PWA
  - —— EM N^3LO

bands from cutoff variation (estimates higher-order short-range parts)

figure from U.-G. Meißner

Neutron-proton phase shifts at N^{3}LO

Entem, Machleidt '04; Epelbaum, Glöckle, Meißner '05

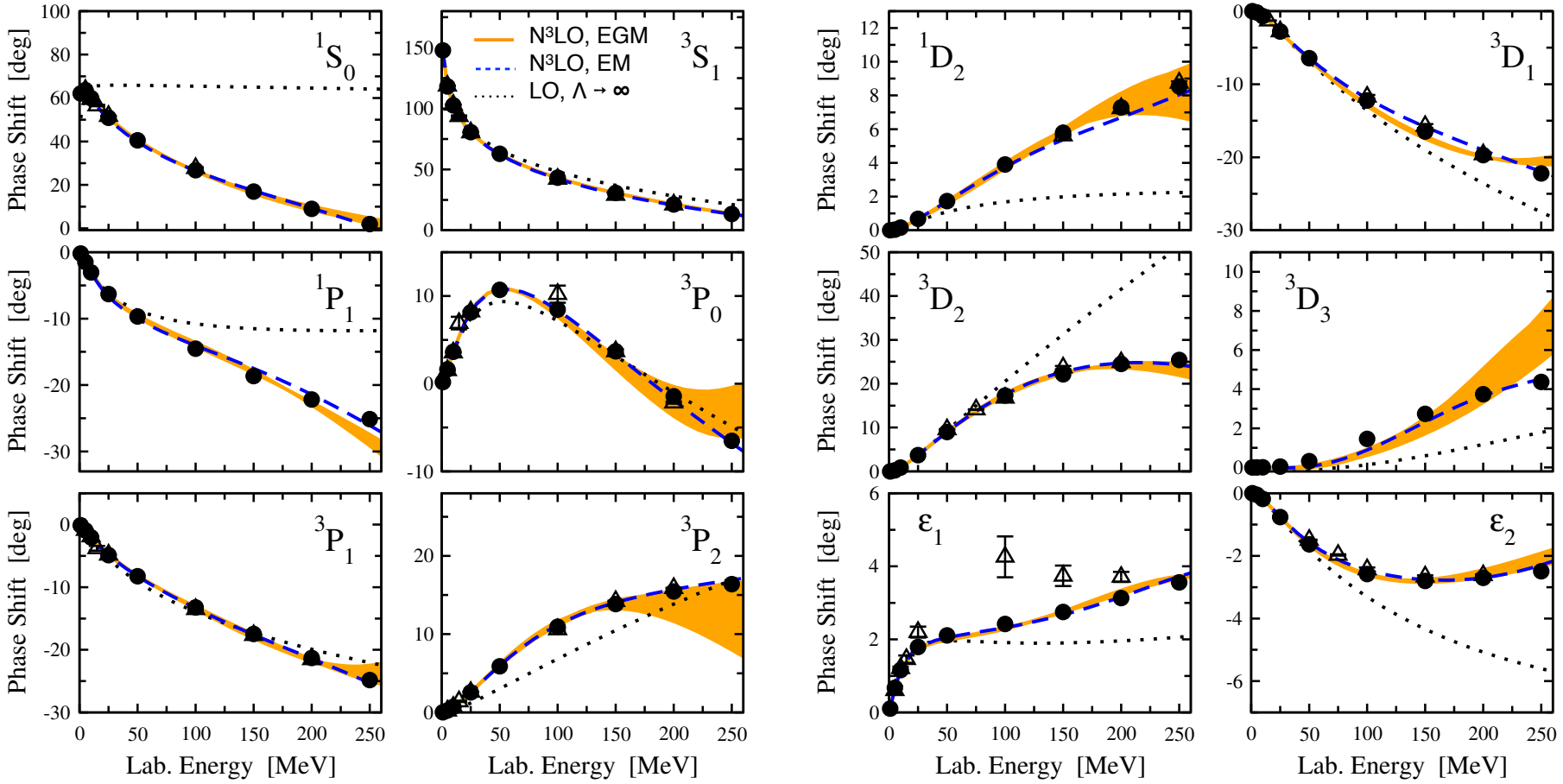


figure from H. Krebs

Range of c_i couplings

	c_1	c_3	c_4	
Fettes *et al.* (1998) (Fit 1)	-1.2	-5.9	3.5	πN
Büttiker and Meißner (2000)	-0.8	-4.7	3.4	πN
Meißner (2007)	-0.9	-4.7	3.5	πN
Rentmeester *et al.* (2003)	-0.8	-4.8	4.0	NN
Entem and Machleidt (2002)	-0.8	-3.4	3.4	NN
Entem and Machleidt (2003)	-0.8	-3.2	5.4	NN
Epelbaum *et al.* (2005)	-0.8	-3.4	3.4	NN
Bernard *et al.* (1997)	-0.9	-5.3	3.7	res

High-order analysis Krebs et al. (KGE) (2012)

	c_1 [GeV^{-1}]	c_3 [GeV^{-1}]
N^{2}LO/N^{3}LO EGM NN [31, 32]	-0.81	-3.40
N^{3}LO EM NN [33, 34]	-0.81	-3.20
N^{2}LO KGE [39]	$-(0.26-0.58)$	$-(2.80-3.14)$
'N^{2}LO' KGE (recom.) [39]	$-(0.37-0.73)$	$-(2.71-3.38)$
N^{3}LO KGE [39]	$-(0.75-1.13)$	$-(4.77-5.51)$

neutron-deuteron scattering

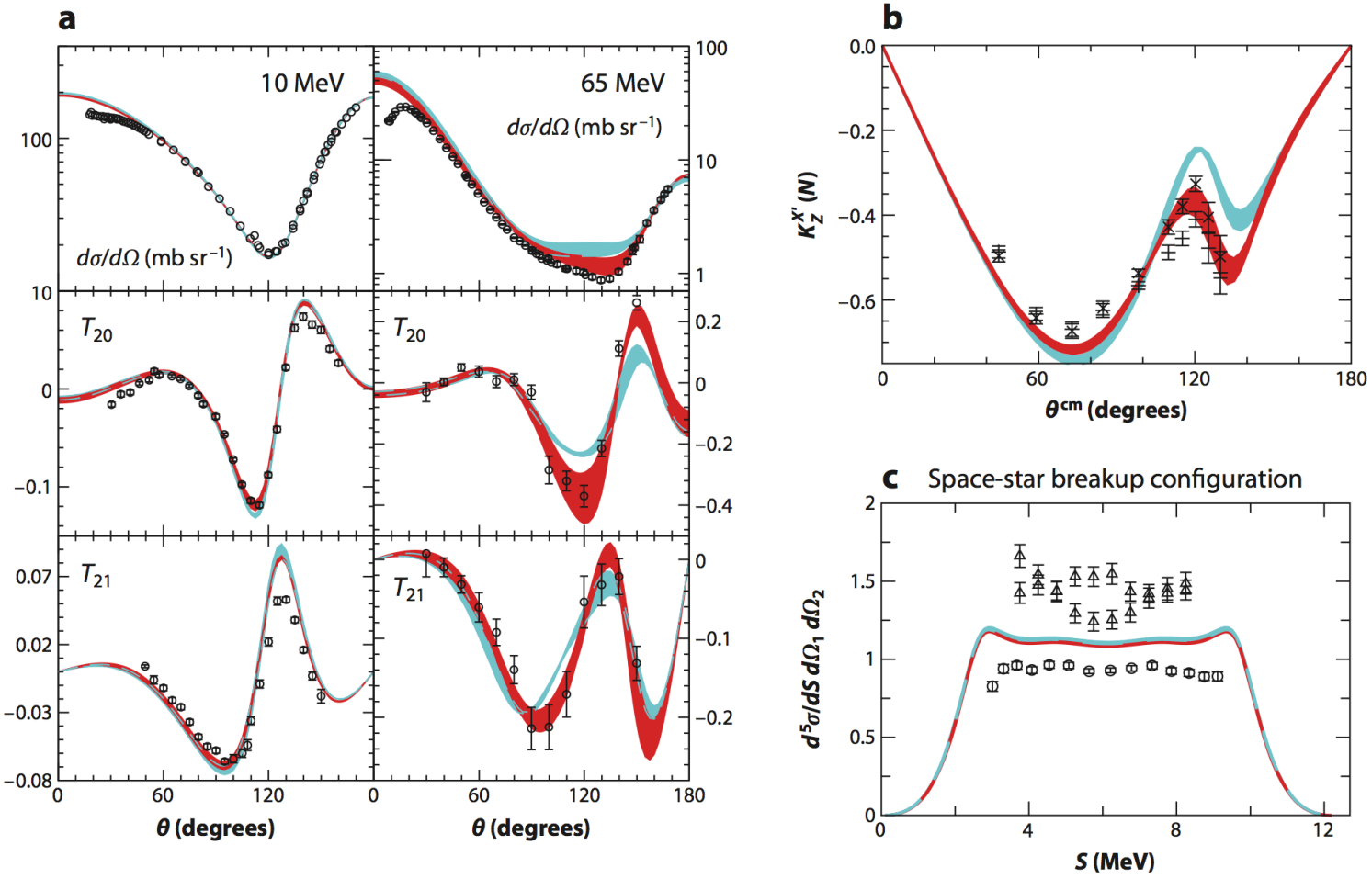


Figure 6

(*a*) Differential cross section and tensor analyzing powers T_{20} and T_{21} for elastic nucleon-deuteron (*Nd*) scattering at $E_{\text{lab}}^N = 10$ and 65 MeV. (*b*) The nucleon-to-nucleon polarization transfer coefficient in elastic *Nd* scattering at $E_{\text{lab}}^N = 22.7$ MeV [the proton-deuteron (*pd*) data are from Reference 72]. (*c*) *Nd* breakup cross section in the space-star configuration (upper sets of data, *nd*; lower sets of data, *pd*). The blue and red shaded bands show the results from the chiral effective field theory at next-to-leading order and next-to-next-to-leading order, in order. The precise kinematical description and references to data can be found in Reference 70.

figure from E. Epelbaum and U.-G. Meißner, experiment in a and b is Coulomb corrected p-d

3N forces in different EFTs

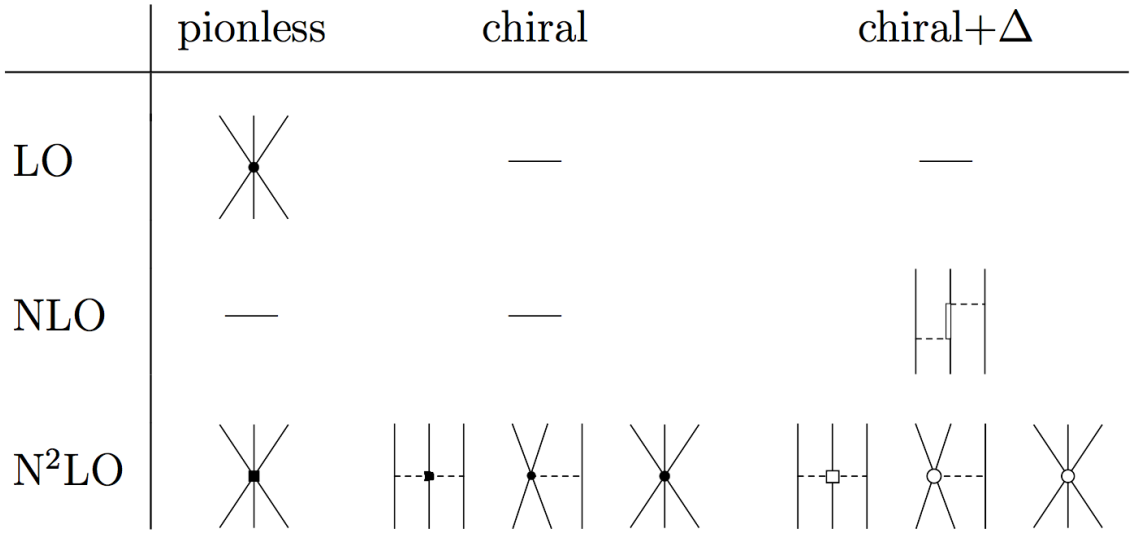


FIG. 23 Order of 3NF contributions in pionless and chiral EFT and in EFT with explicit Δ degrees of freedom (chiral+Δ). Open vertices in the last column indicate the differences of the low-energy constants in chiral and chiral+Δ EFT.