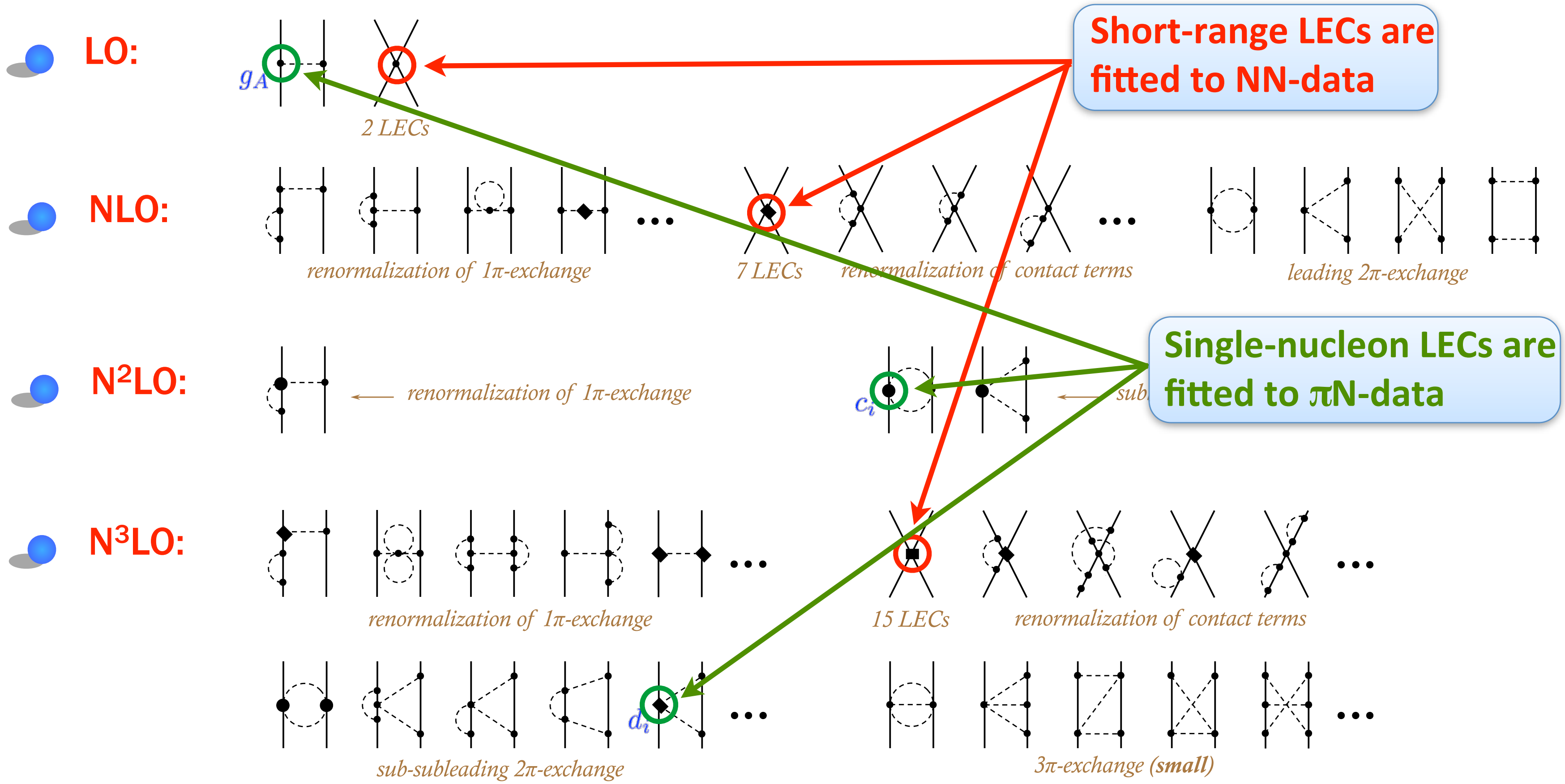
Nucleon-nucleon force up to N^{3}LO

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

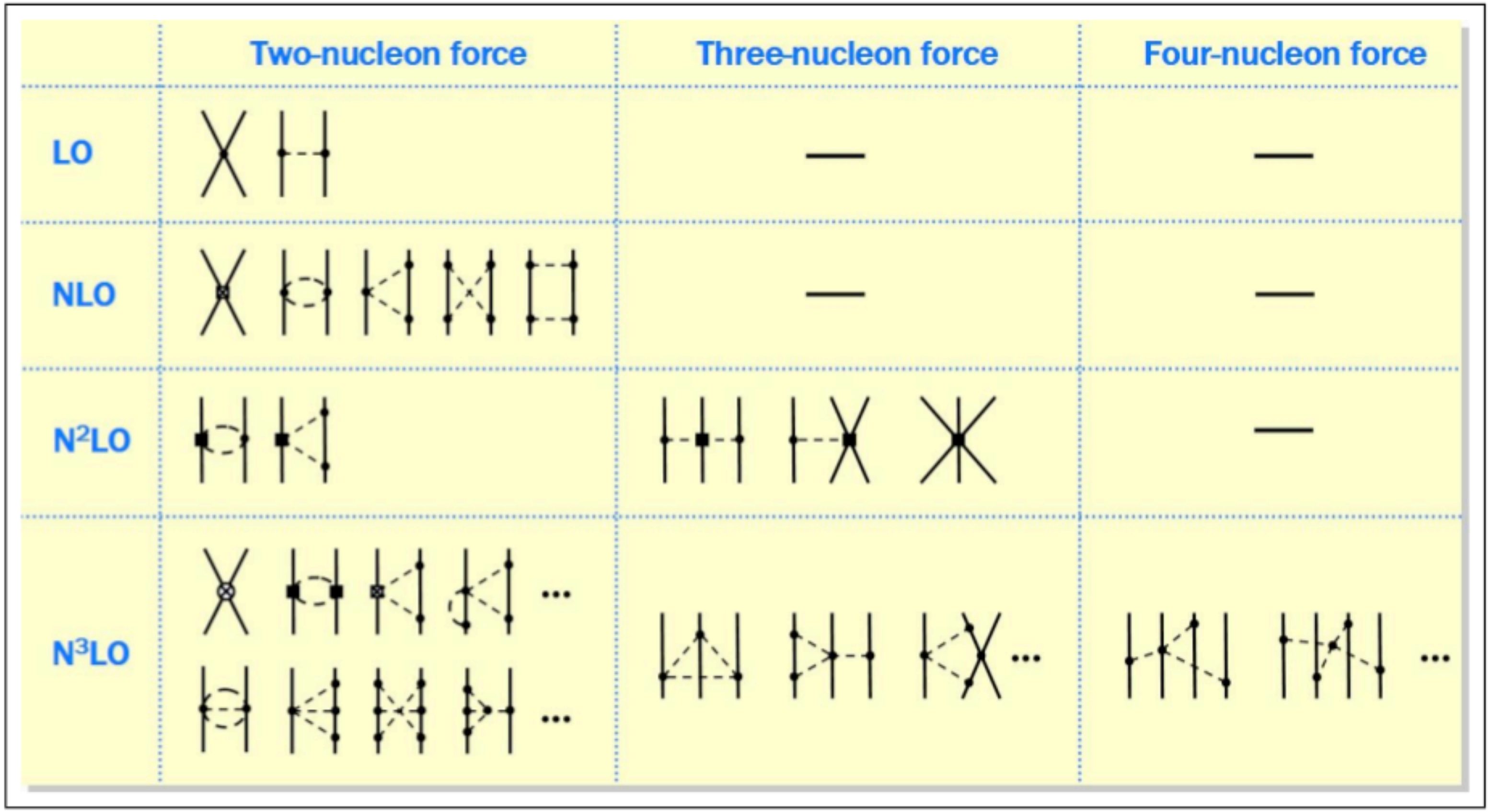


+ 1/m and isospin-breaking corrections…

figure from H. Krebs

Hierarchy of nuclear forces in chiral EFT

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



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

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

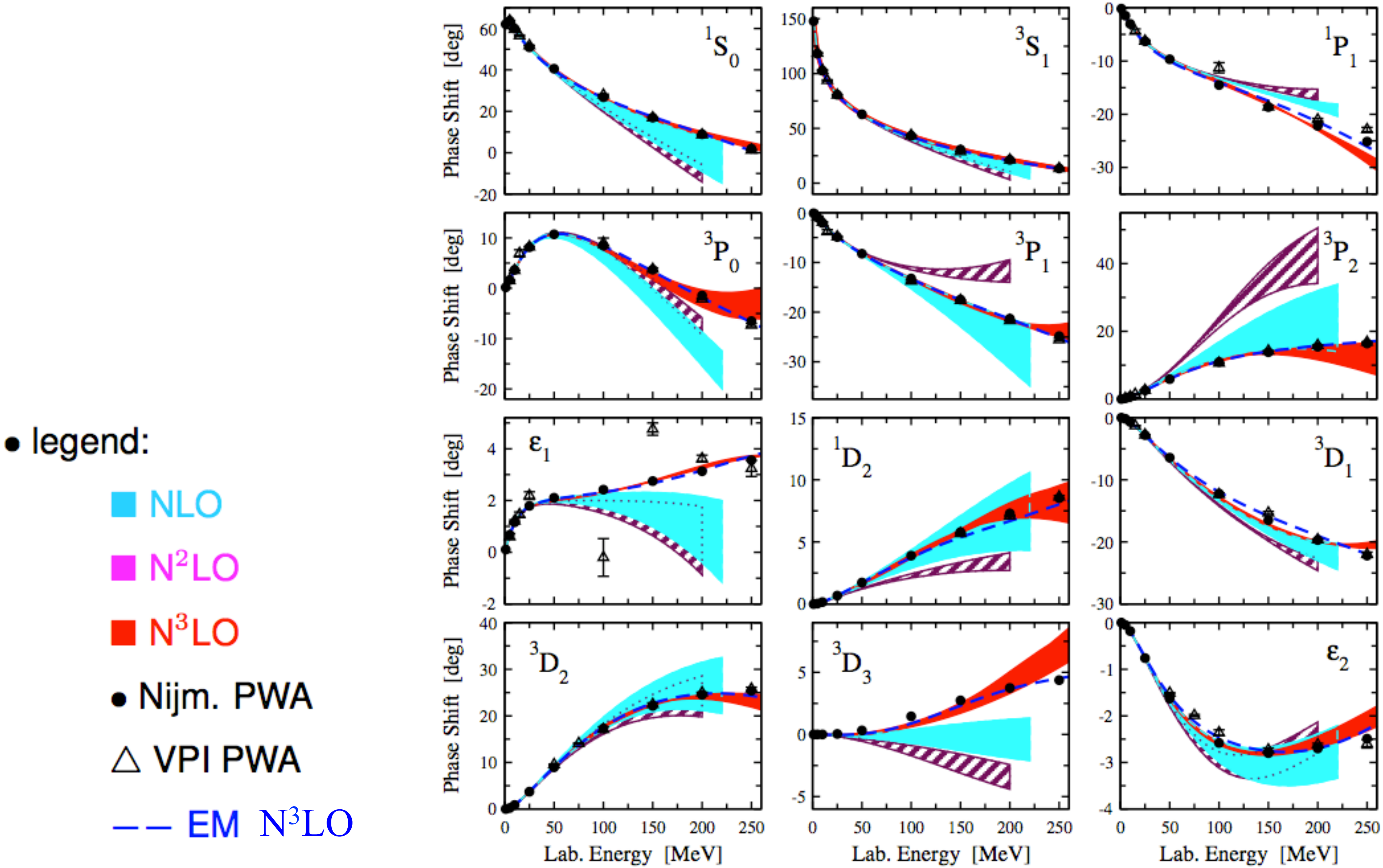
$\mathcal{O}((q/\Lambda_\chi)^3)$

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

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



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

figure from U.-G. Meißner

Neutron-proton phase shifts at N^3LO

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

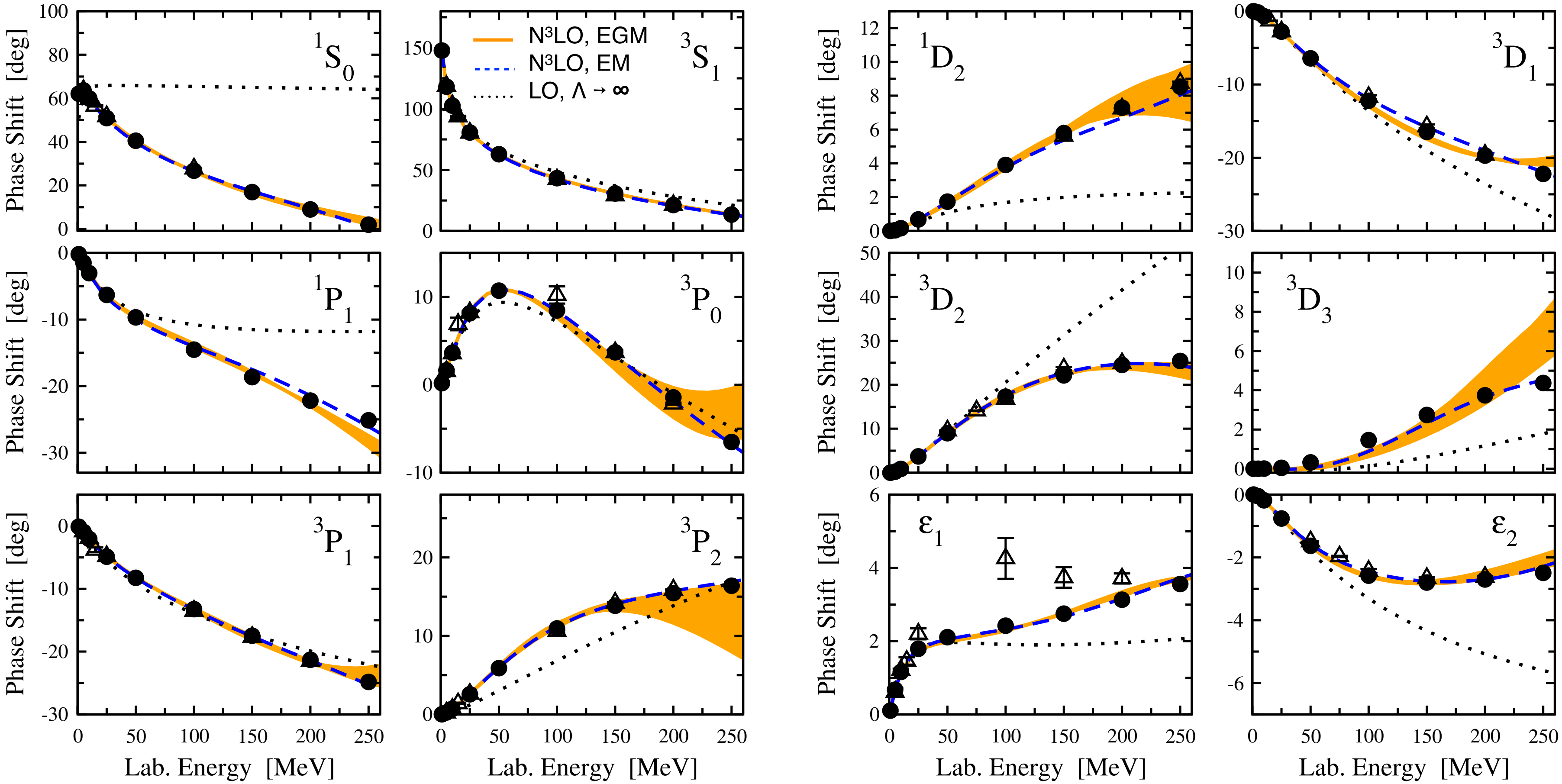


figure from H. Krebs

neutron-proton scattering

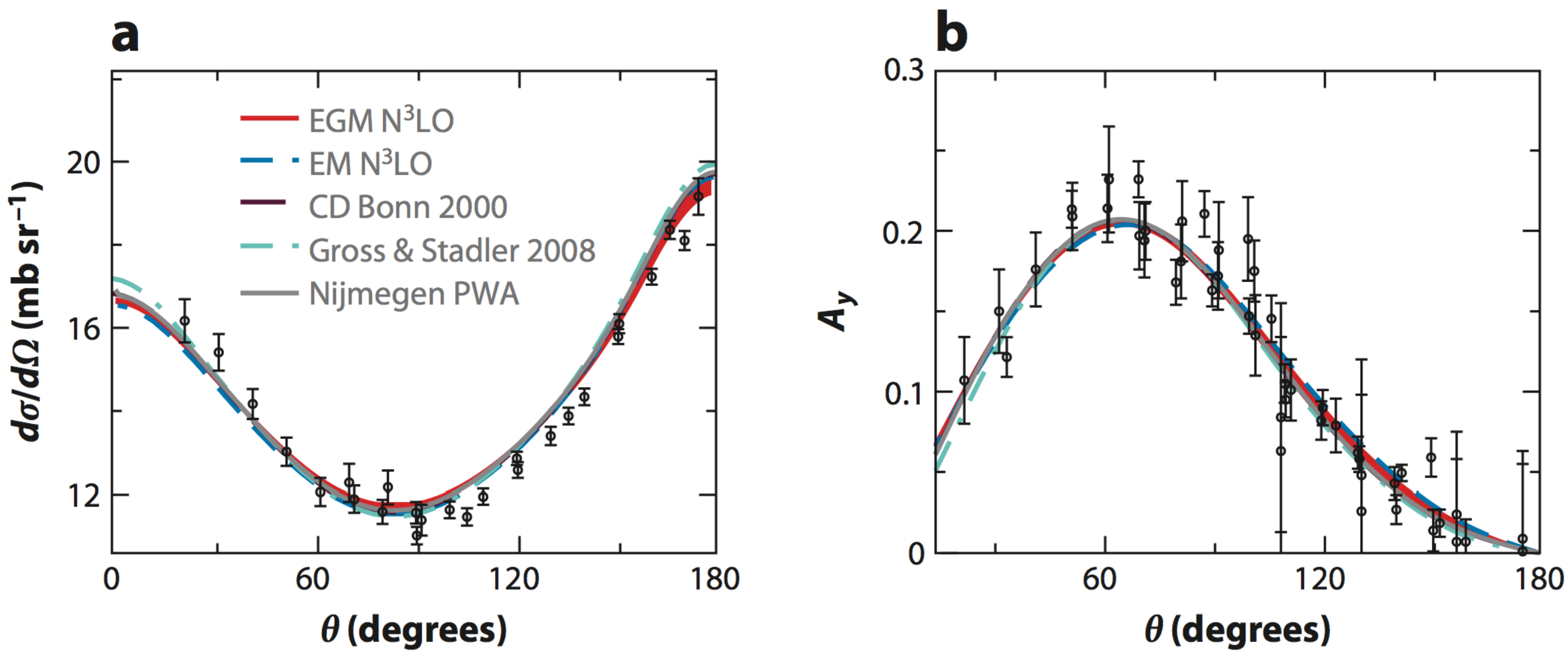
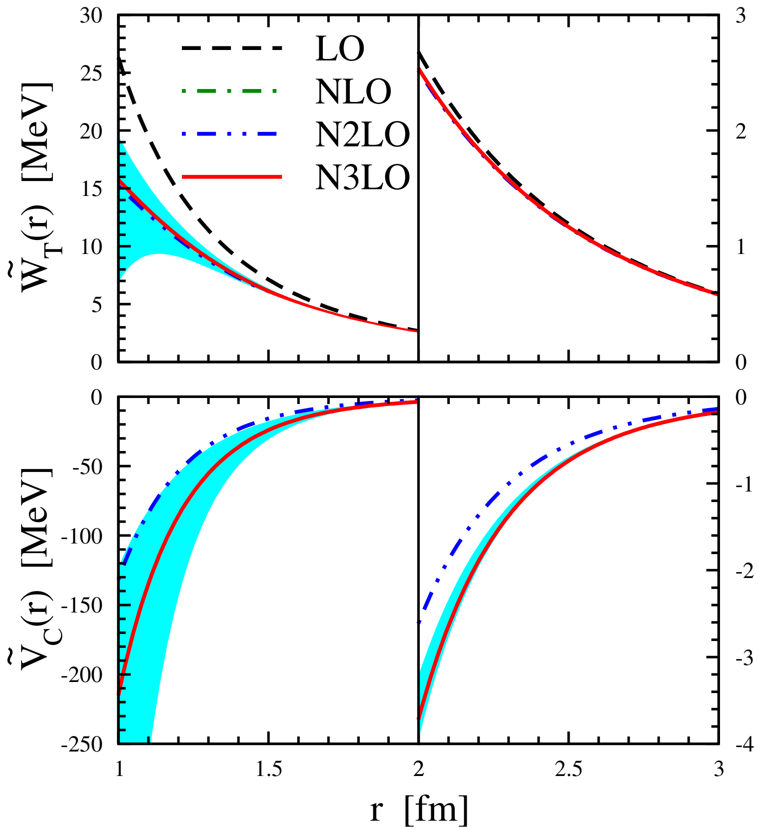


Figure 4

(*a*) Neutron-proton differential cross section and (*b*) analyzing power at $E_{\mathrm{lab}} = 50$ MeV, calculated by use of the chiral effective field theory, the CD Bonn 2000 potential (44), and the potential developed by Gross & Stadler (45). Also shown are results from the Nijmegen partial-wave analysis (PWA). References to data can be found at **http://nn-online.org**. EGM and EM refer to the potentials constructed by Epelbaum, Glöckle & Meißner and by Entem & Machleidt in References 37 and 43, respectively.

figure from E. Epelbaum and U.-G. Meißner

Chiral expansion of NN force



Epelbaum, Meißner Ann. Rev. Nucl. Part. Sci 62 (12) 159

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

Bands ($800 \text{ MeV} \leq \tilde{\Lambda}$) visualize estimated scheme-dependence for separation between short- and long-range contributions

Long-range behavior at $r \geq 2\,\text{fm}$ of

- $\tilde{W}_T$ is governed by 1π-exchange
- $\tilde{V}_C$ is governed by subleading 2π-exchange

figure from H. Krebs

band = scheme dependence from cutoff variation in pion loops
(uses spectral function regularization)

isovector-tensor (top) dominated by one-pion exchange
ioscalar-central (bottom) attraction due to two-pion exchange