Tensor Forces and the Structure of Nuclei

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- Strong interactions in nuclei
- Tensor forces and nuclear structure
- Summary

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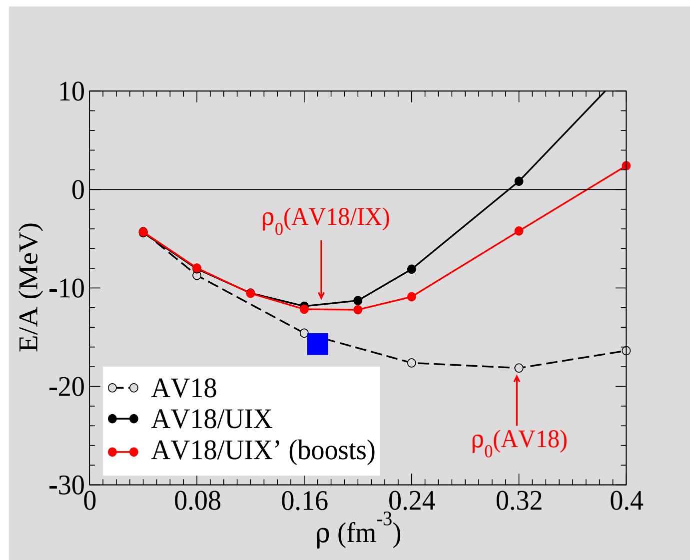
S. Pastore	S. Pieper	M. Viviani	R. Wiringa

Nuclear Interactions: an Update

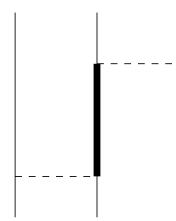
Nuclear Interactions

- NN interactions alone fail to predict:
  1. spectra of light nuclei
  2. Nd scattering
  3. nuclear matter $E_0(\rho)$



- 2π-NNN interactions:

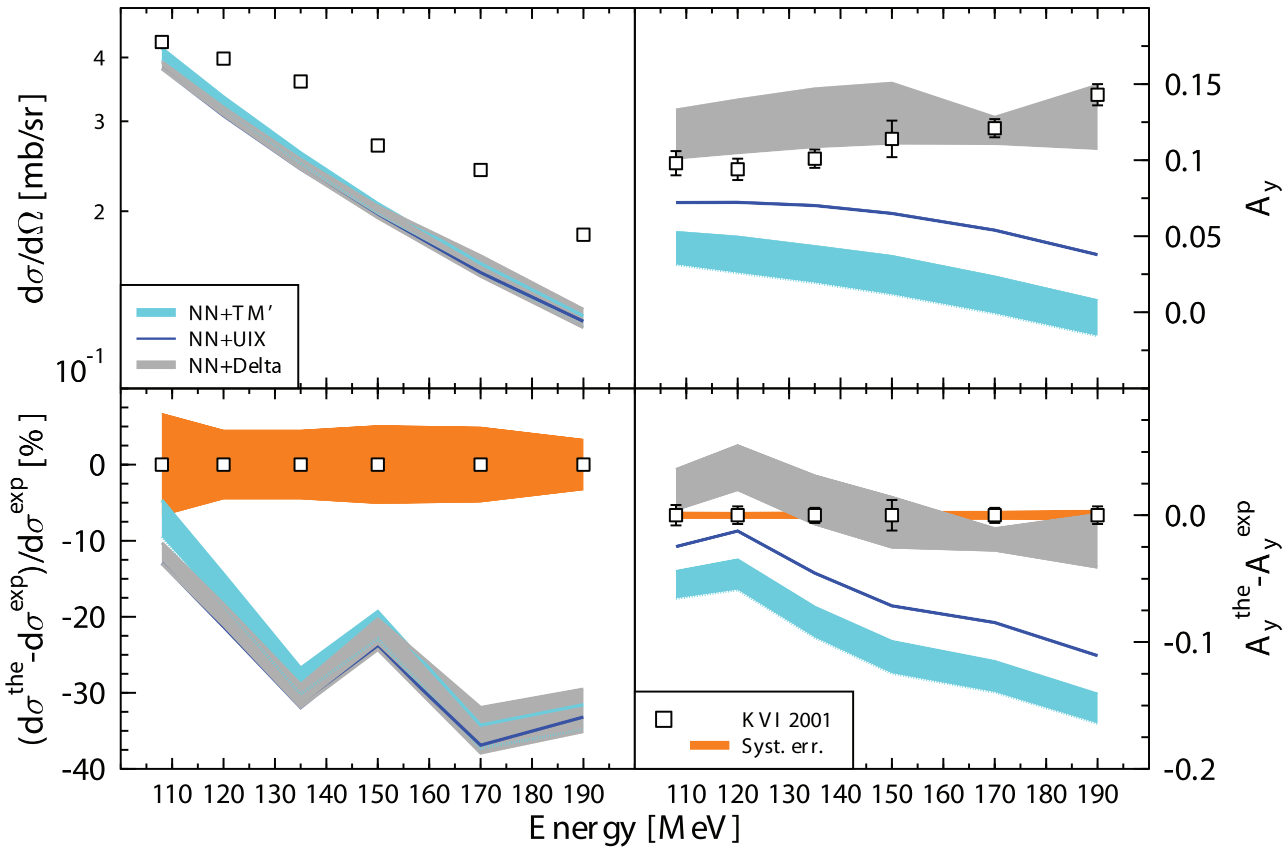
$$\mathrm{UIX}^{2\pi} = A^{2\pi}_{pw}$$



$$+\, A^{R} \sum_{cyc} T^2(r_{ij})\, T^2(r_{jk})$$

Proton-Deuteron Elastic Scattering

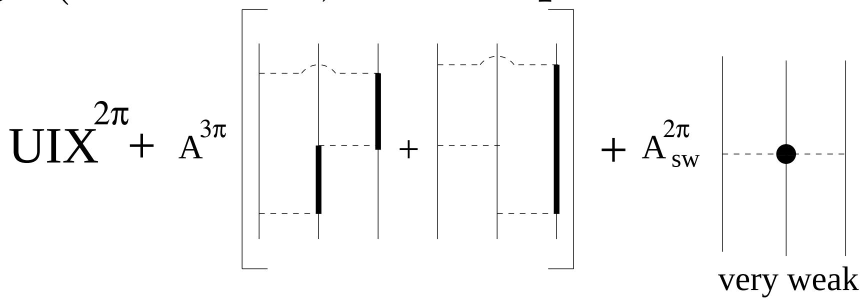
- $V^{2\pi}$ alone is not enough: spectra of p-shell nuclei, ...



Ermisch *et al.* (KVI collaboration), PRC**71**, 064004 (2005)

Kalantar-Nayestanaki, private communication

Beyond 2π-exchange (IL2 model, with important $T = 3/2$ terms)



parameters (~ 3) fixed by a best fit to the energies of low-lying states (~ 17) of nuclei with $A \leq 8$

AV18/IL2 Hamiltonian reproduces well:

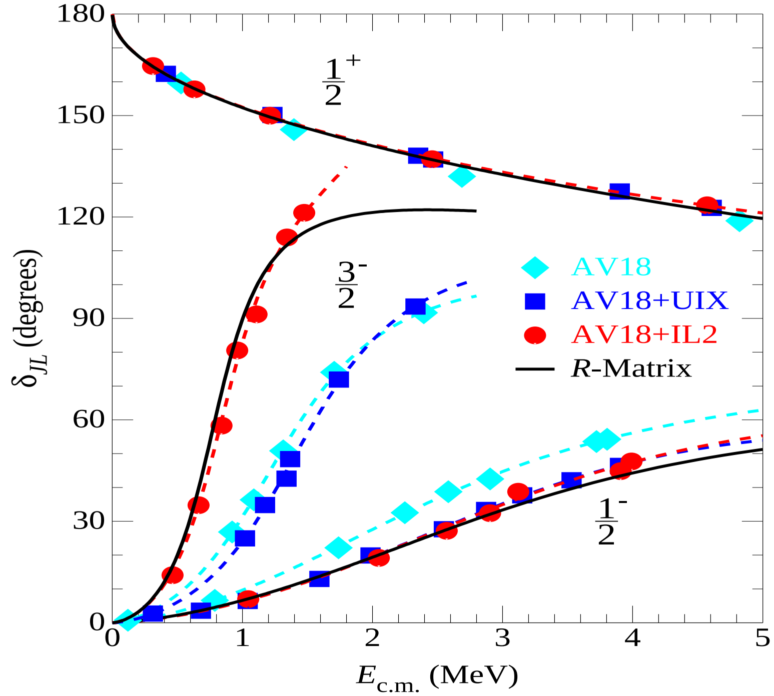
- spectra of A=6–10 nuclei (attraction provided by IL2 in $T = 3/2$ triplets crucial for p-shell nuclei)
- low-lying p-wave resonances with J^π=$3/2^-$ and $1/2^-$ respectively, as well as low-energy s-wave ($1/2^+$) scattering

<u>but</u> some discrepancies persist in A=3 and 4 scattering observables

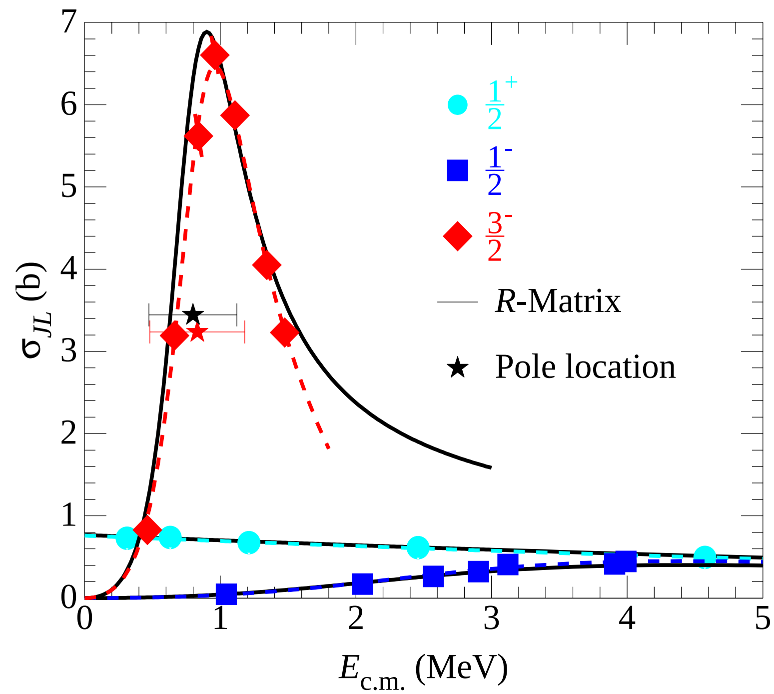
QMC Calculations of Low Energy n-α Scattering

Nollett *et al.*, PRL**99**, 022502 (2007)

Phase Shifts



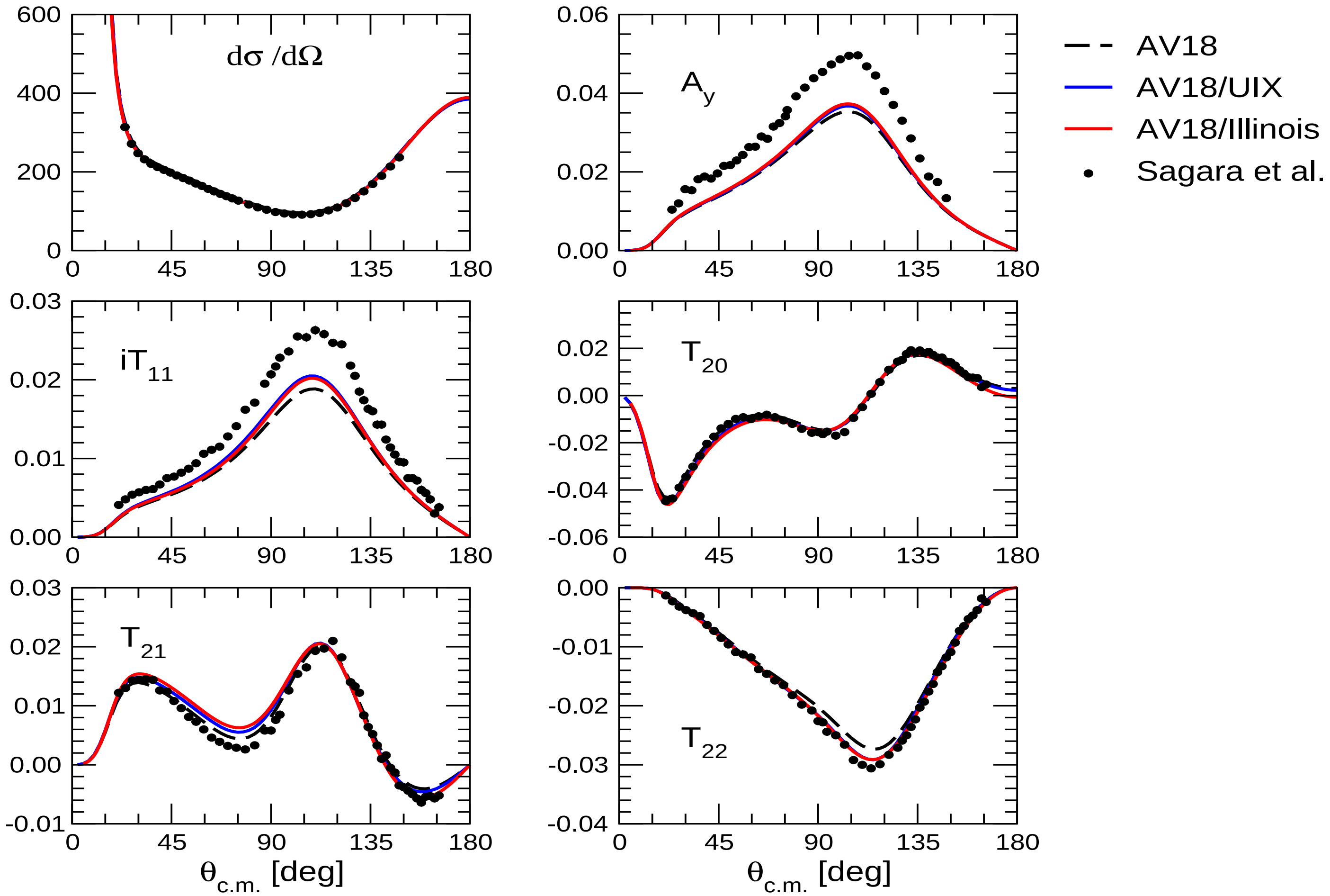
Cross Sections (AV18/IL2)



AV18, AV18/IX, and AV18/IL2 phase shifts compared to experimental determinations from *R*-matrix fits

HH Calculations of Low Energy (2 MeV) p-d Scattering

Girlanda, Kievsky, Marcucci, and Viviani, private communication



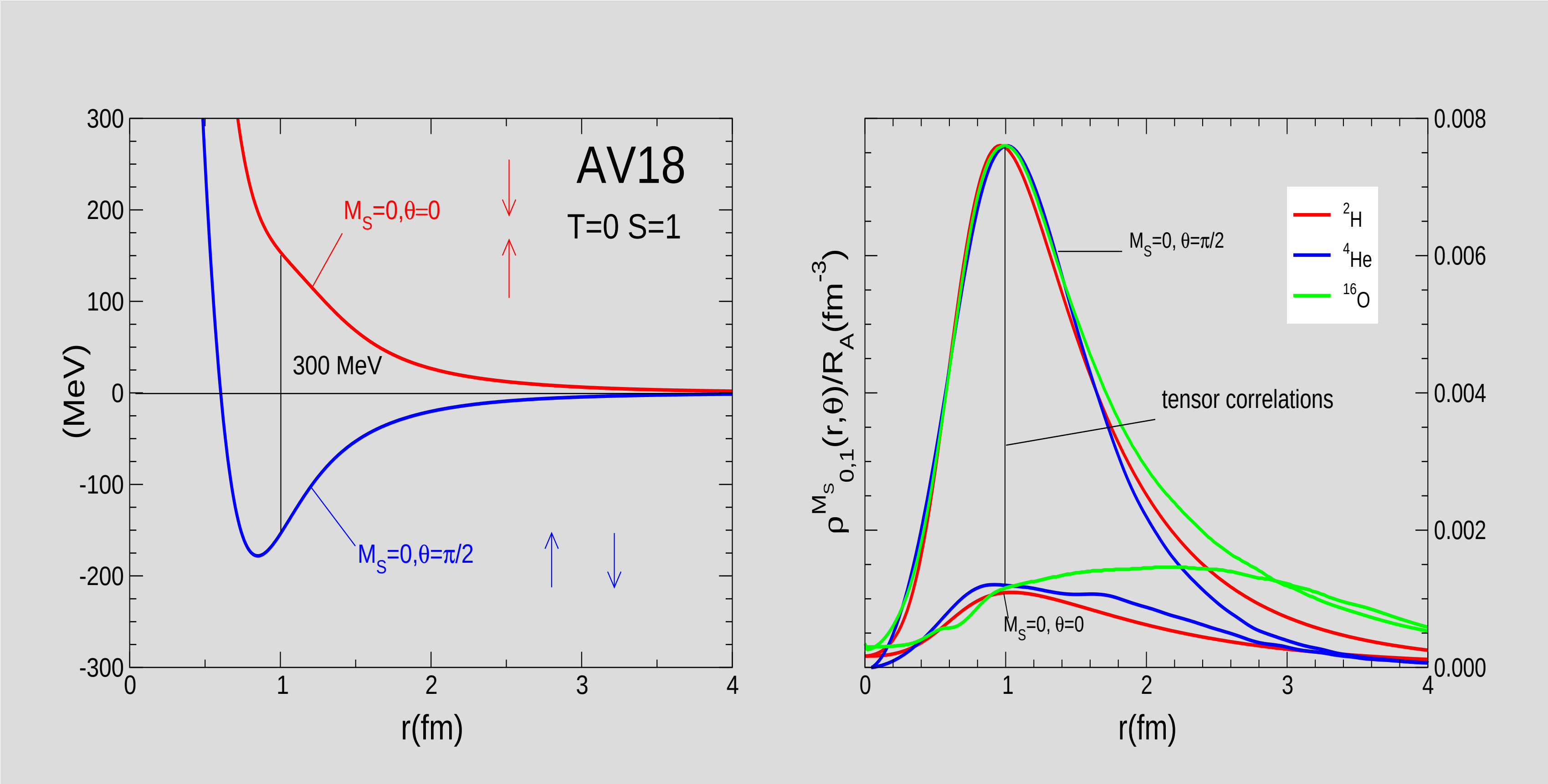
Summary (I)

- Energy spectra and n-α scattering well described by two- and three-nucleon interactions (AV18/IL2)
- $3N$ and $4N$ scattering as a crucial testing ground for three-nucleon interactions
- Derivation of NNN interaction in χEFT at N3LO is in progress: will it resolve present problems?

Tensor Forces and Nuclear Structure

Preeminent features of v_{ij}:

- <u>short-range repulsion (common to many systems)</u>
- <u>intermediate- to long-range tensor character (unique to nuclei)</u>



Forest *et al.*, PRC**54**, 646 (1996)

- At small separation, np relative w.f. in a nucleus $\propto$ deuteron w.f., but scaling factor $R_A >$ number of T, S=0,1 pairs
- $\langle O \rangle_A \simeq R_A \, \langle O \rangle_d$, where O is any short-range operator effective in the $T = 0, S = 1$ channel[a]

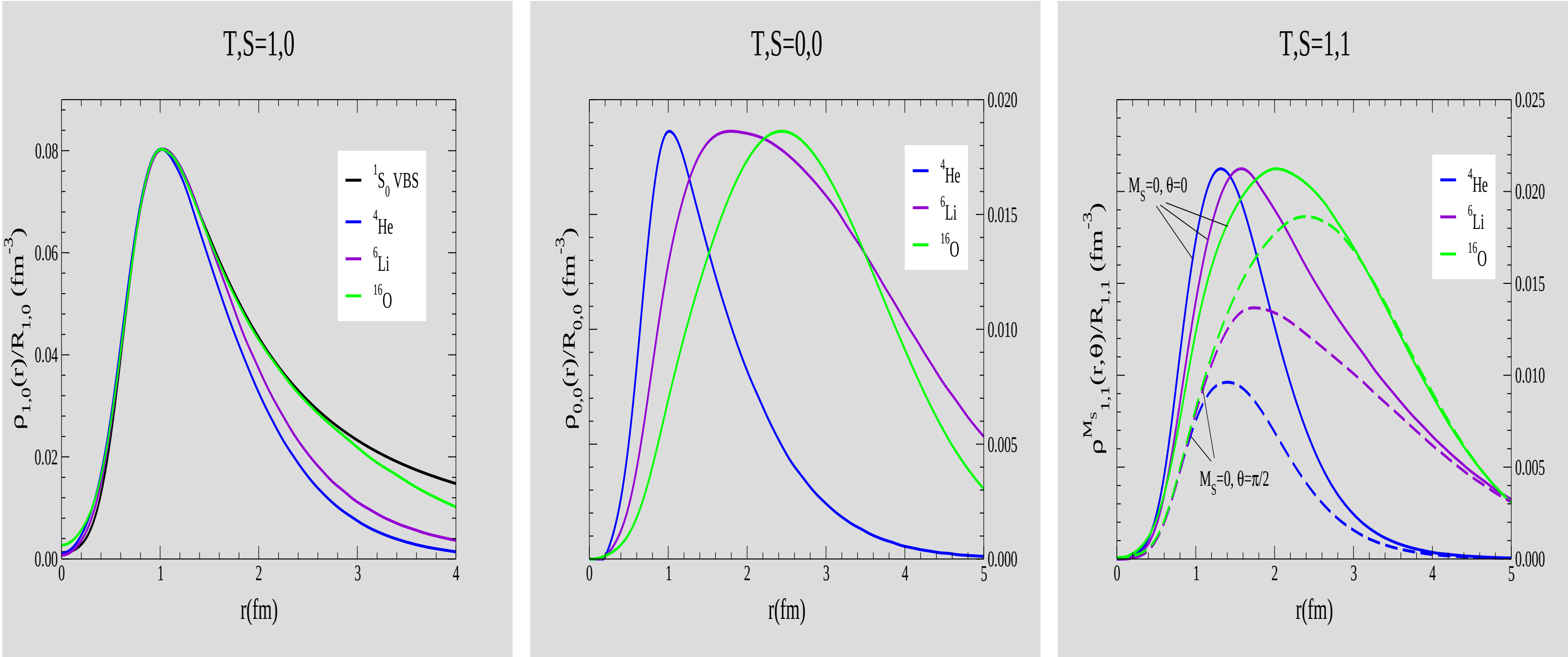
Scaling

	R_A	$\langle v^\pi \rangle_A / \langle v^\pi \rangle_d$	$\sigma^\pi_A / \sigma^\pi_d$	$\sigma^\gamma_A / \sigma^\gamma_d$
^{3}He	2.0	2.1	2.4(1)	$\simeq 2$
^{4}He	4.7	5.1	4.3(6)	$\simeq 4$
^{6}Li	6.3	6.3		
^{7}Li	7.2	7.8		$\simeq 6.5(5)$

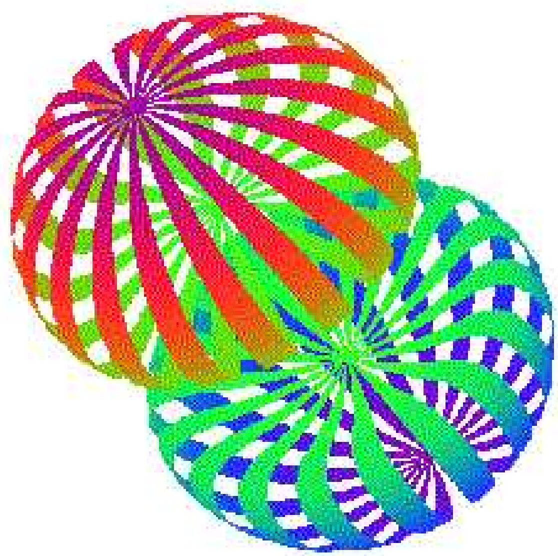
[a] *e.g.*, m.e. of axial two-body currents in pp weak capture and ^{3}H β-decay are $\propto$ to each other $\rightarrow$ model independent prediction of pp cross section [Schiavilla *et al.*, PRC**58**, 1263 (1998)]

Two-Nucleon Density Profiles in $T, S \neq$0,1 States

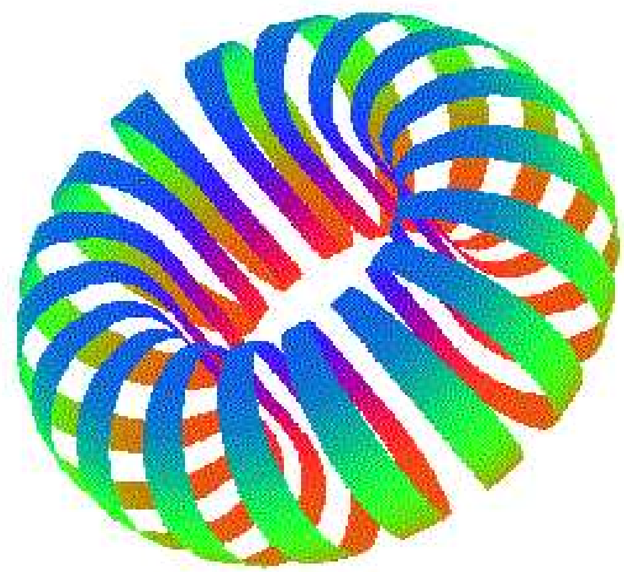
- Scaling persists in T, S=1,0 channel (^{1}S$_0$ state) for $r \leq 2$ fm
- But no scaling occurs in remaining channels (interaction either repulsive or weakly attractive)



Two-Nucleon Density Profiles in T,S=0,1 States



$M_S = \pm 1$



$M_S = 0$

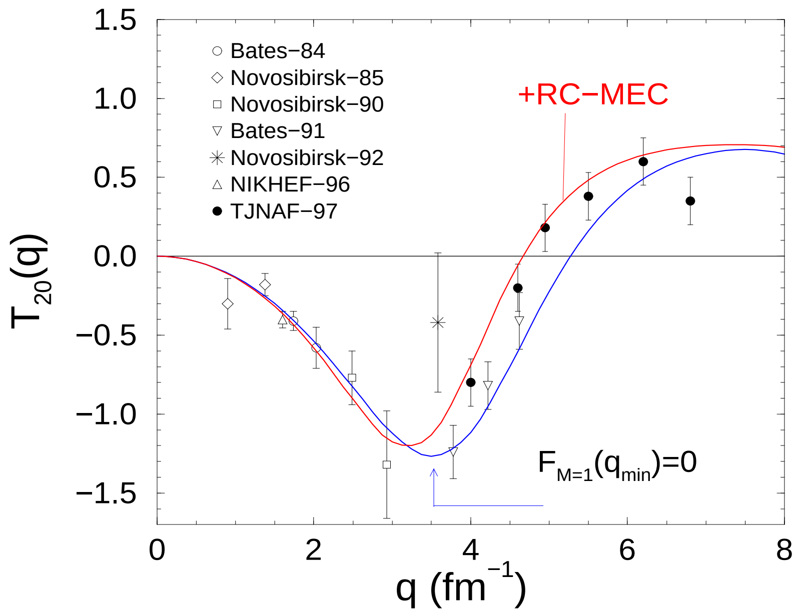
- Hole due to short-range repulsion, angular confinement due to tensor force
- Size of torus: $d \simeq 1.4$ fm, $t \simeq 0.9$ fm (at $\approx$ half-max density)
- Confirmed by e-d elastic scattering measurements

- In deuteron $\rho^{M_S}_{T=0,S=1}(\mathbf{r})|_d \propto \rho^M_d(\mathbf{r}' = \mathbf{r}/2)$, where $\rho^M_d(\mathbf{r}')$ is the matter density, *i.e.* the charge density in T=0 states

- Fourier transforms of $\rho^M_d(\mathbf{r}')$ "measured" in elastic e-scattering:

$$A(q) \simeq |F_{M=0}(q)|^2 + 2\,|F_{M=1}(q)|^2$$

$$T_{20}(q) \simeq -\sqrt{2}\,\frac{|F_{M=0}(q)|^2 - |F_{M=1}(q)|^2}{|F_{M=0}(q)|^2 + 2\,|F_{M=1}(q)|^2}$$



Evidence for Tensor Correlations in $A > 2$ Nuclei

Several nuclear properties influenced by tensor forces including:

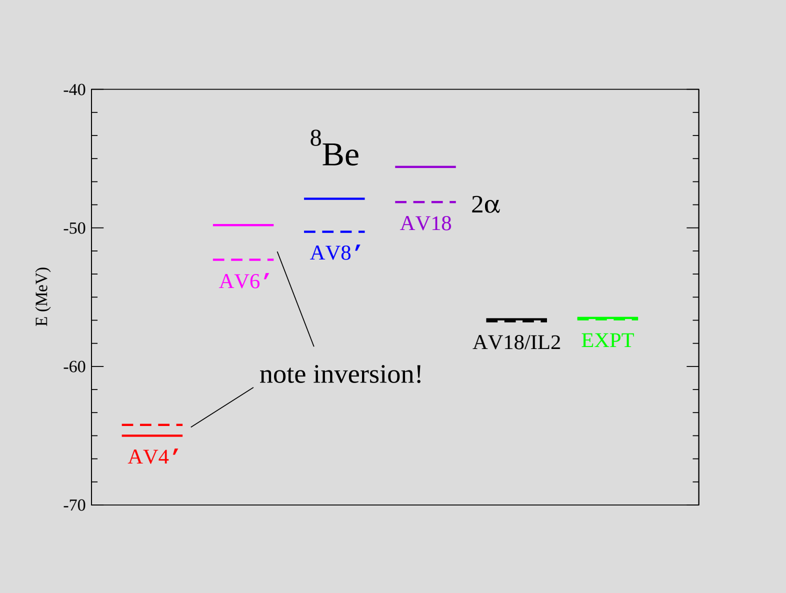
- Ordering of levels in low-energy spectra of light nuclei and absence of stable A=8 nuclei
- Momentum distributions $N(k)$ and spectral functions $S(k,E)$ at high k and E
- Radiative (and weak) capture processes involving few-nucleon systems, *e.g.* ${}^2\mathrm{H}(n,\gamma){}^3\mathrm{H}$, ${}^3\mathrm{He}(n,\gamma){}^4\mathrm{He}$, ${}^2\mathrm{H}(d,\gamma){}^4\mathrm{He}$, ...
- and more

However, effects of tensor correlations are generally subtle, and are not easily isolated in the experimental data

Absence of Stable A=8 Nuclei

Build series of potentials designed to reproduce as many features of the deuteron and elastic NN scatttering as feasible at each stage

1. $AV4' = [1\,,\,\boldsymbol{\sigma}_1\cdot\boldsymbol{\sigma}_2]\otimes[1\,,\,\boldsymbol{\tau}_1\cdot\boldsymbol{\tau}_2]$
2. $AV6' = AV4'$+tensor
3. $AV8' = AV6'$+spin-orbit, ...



Wiringa and Pieper, PRL **89**, 182501 (2002)

Tensor Correlations and Two-Nucleon Momentum Distributions

$$\rho^{NN}(\mathbf{q},\mathbf{Q}) = \frac{1}{2J+1}\sum_{M_J}\langle\psi_{JM_J} \mid \sum_{i<j} P_{ij}^{NN}(\mathbf{q},\mathbf{Q}) \mid \psi_{JM_J}\rangle$$

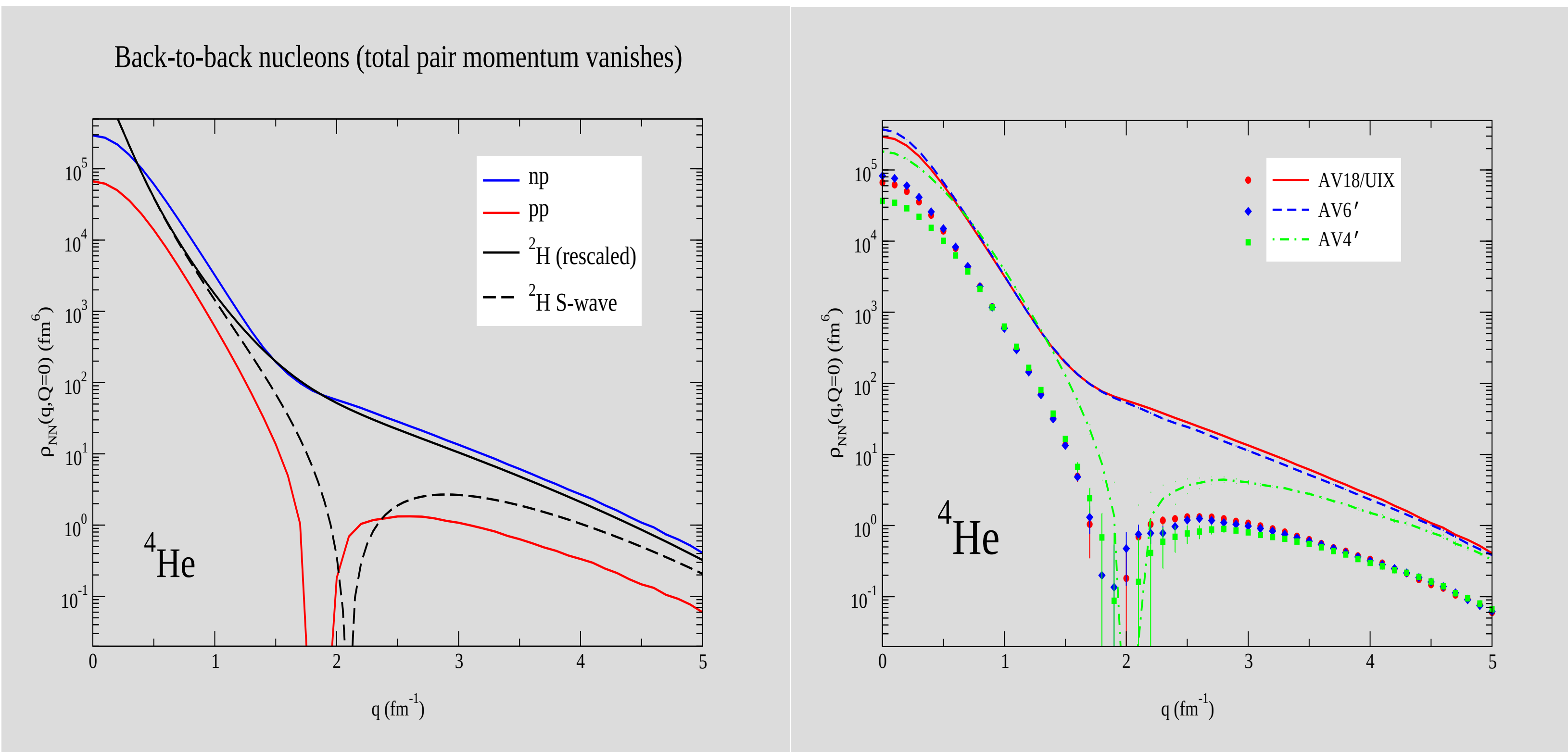
where $\mathbf{q}$ and $\mathbf{Q}$ are respectively the relative and total momenta of the NN pair, and

$$P_{ij}^{NN}(\mathbf{q},\mathbf{Q}) \equiv \delta(\mathbf{k}_{ij}-\mathbf{q})\delta(\mathbf{K}_{ij}-\mathbf{Q})\, P_{NN}(ij)$$

- np (pp) pairs predominantly in T=0 deuteron-like (T=1 $^1\mathrm{S}_0$) state→ large differences between ρ^{np} and ρ^{pp}
- Pair-momentum distributions can be used to estimate NN-knockout x-sections
- ρ^{NN} can be calculated exactly with QMC

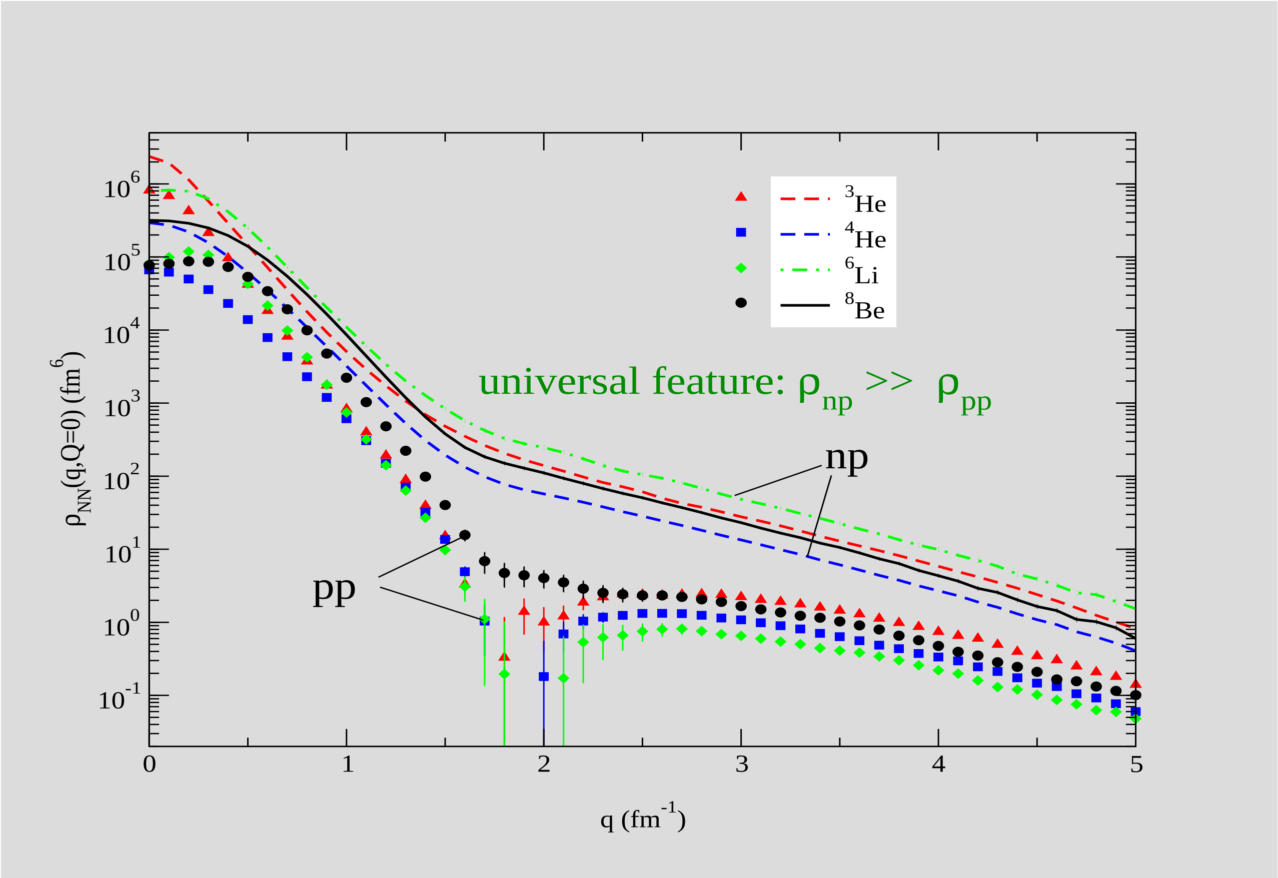
NN momentum distributions at Q=0 (back-to-back)

- Scaling is (again!) seen between deuteron $\rho^d(q)$ and nucleus $\rho^{np}(q, Q = 0)$



New Opportunities for Observing Tensor Correlations

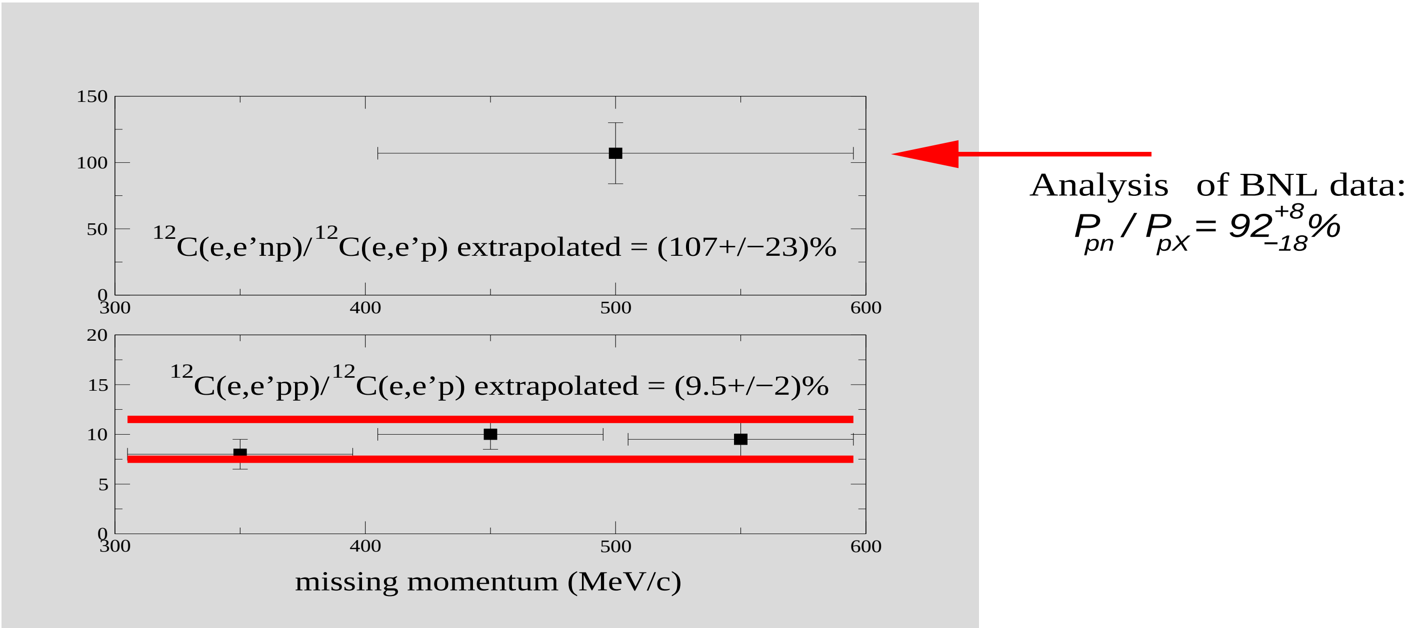
These differences have been observed in (back-to-back) two-nucleon knock-out processes, such as $A(e, e'np)$ and $A(e, e'pp)$



Schiavilla, Wiringa, Pieper, and Carlson, PRL**98**, 132501 (2007)

Experimental Evidence for the Effects of Tensor Correlations

- JLab measurements on ^{12}C$(e,e'pp)$[a] and $(e,e'np)$[b]
- Analysis of ^{12}C(p,pp) and (p,ppn) BNL data[c]
- Possibly also seen in π-absorption: $\sigma(\pi^-,np)/\sigma(\pi^+,pp) \ll 1$[d]



[a] Shneor *et al.*, PRL**99**, 072501 (2007); [b] Subedi *et al.*, Science **320**, 1476 (2008); [c] Piasetzky *et al.*, PRL**97**, 162504 (2006); [d] Ashery *et al.*, PRL**47**, 895 (1981)

Summary (II)

- Tensor correlations affect subtly a variety of nuclear properties: two-nucleon densities, energy spectra, radiative captures, ...
- But they lead to order of magnitude differences between the (back-to-back) *np*- and *pp*-pair momentum distributions
- This isospin dependence has been observed in *np*- and *pp*-knockout processes at JLab (and BNL)