Light Nuclei from keV to GeV Energies: a Review

Rocco Schiavilla (JLab/ODU)

- Strong and electromagnetic interactions in nuclei
- Relativistic descriptions of few-nucleon dynamics
- Tensor forces and ground-state structure
- Inferring nucleon properties from nuclear experiments
- Summary(ies)
- Future prospects

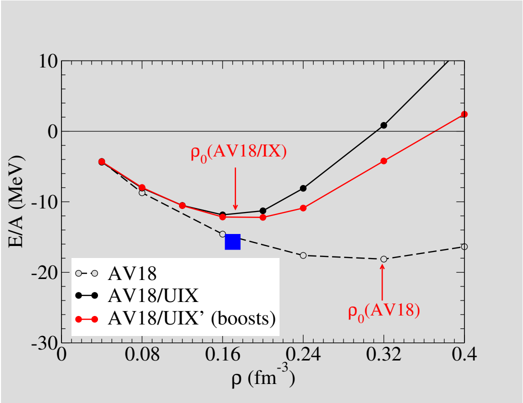
In collaboration with:

J. Carlson	A. Kievsky	L. Marcucci	K. Nollett
S. Pieper	M. Viviani	R. Wiringa	

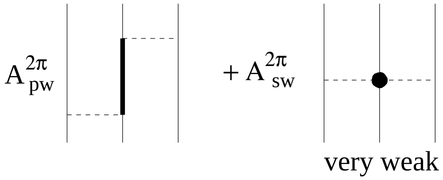
Nuclear Interactions and Currents: an Update

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 [EFT w/o explicit Δ's overestimates strength of $V^{2\pi}_{\rm pw}$, Pandharipande *et al.*, PRC**71**, 064002 (2005)]:

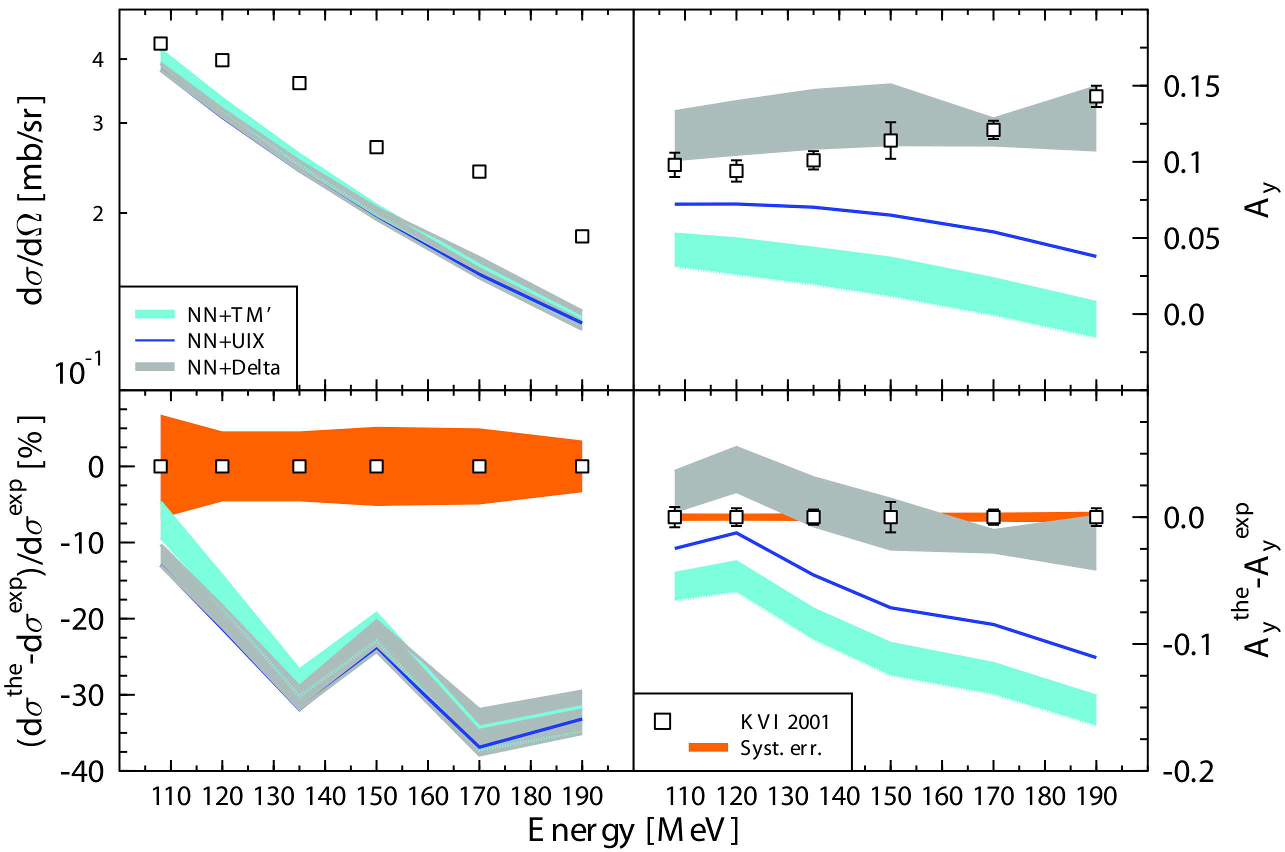


- $V^{2\pi}$ alone does not fix problems above

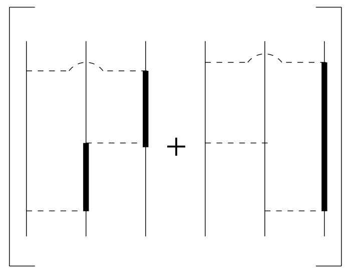
Proton-Deuteron Elastic Scattering

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

Kalantar-Nayestanaki, private communication



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

$V^{2\pi} + A^{3\pi}$  $+ A^{R} \sum_{cyc} T^2(r_{ij}) T^2(r_{jk})$

parameters (~ 3) fixed by a best fit to the energies of low-lying states (~ 17) of nuclei with $A \leq 8$ (IL2 presently under revision ...)

AV18/IL2 Hamiltonian reproduces well:

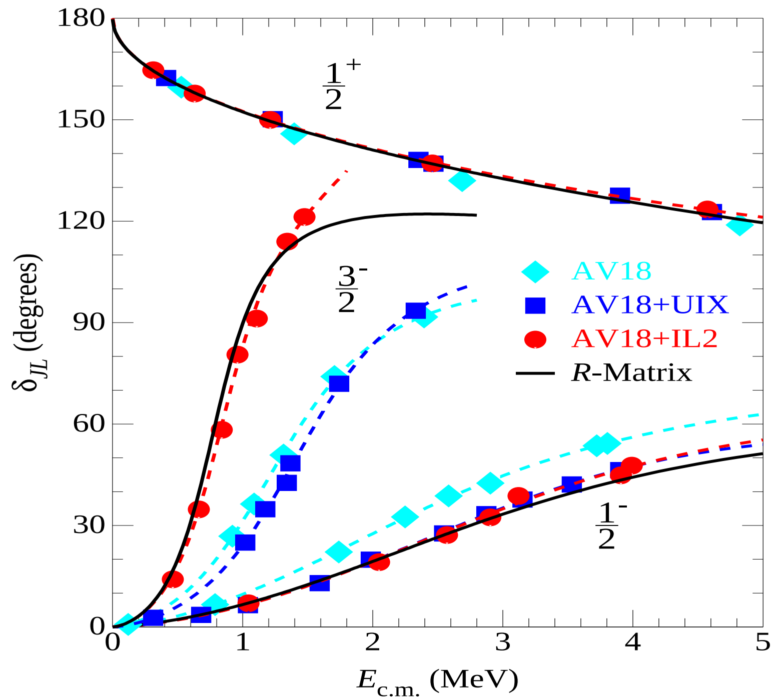
- spectra of A=9–12 nuclei (attraction provided by IL2 in $T = 3/2$ triplets crucial for p-shell nuclei)
- low-lying p-wave resonances with J^π=$3/2^-$ and $1/2^-$ respectively, as well as low-energy s-wave ($1/2^+$) scattering

<u>but</u> needs to be tested in three- and four-nucleon scattering (work by the Pisa group is in progress)

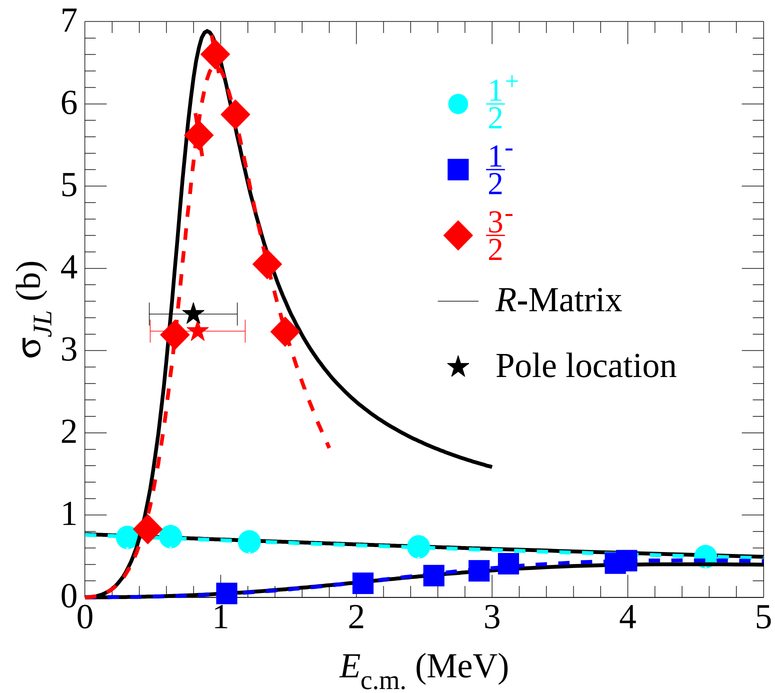
QMC Calculations of Low Energy n-α Scattering

Nollett *et al.*, nucl-th/0612035, PRL in press

Phase Shifts



Cross Sections (AV18/IL2)



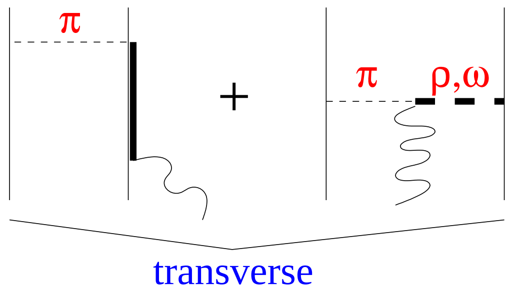
AV18, AV18/IX, and AV18/IL2 phase shifts compared to experimental determinations from *R*-matrix fits

Nuclear Electromagnetic Currents

Marcucci *et al.*, PRC**72**, 014001 (2005)

$$\mathbf{j} = \mathbf{j}^{(1)}$$

$$+ \mathbf{j}^{(2)}(v) +$$



$$+ \mathbf{j}^{(3)}(V^{2\pi})$$

- Gauge invariant:

$$\mathbf{q} \cdot \left[\mathbf{j}^{(1)} + \mathbf{j}^{(2)}(v) + \mathbf{j}^{(3)}(V^{2\pi})\right] = \left[T + v + V^{2\pi}\, ,\, \rho\right]$$

ρ is the nuclear charge operator

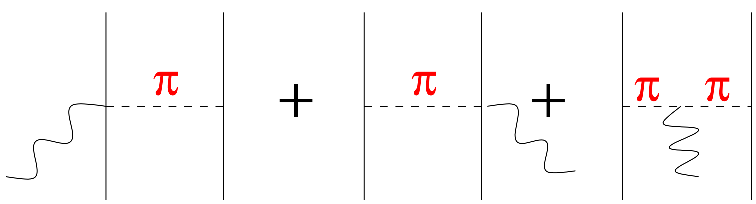
- Terms from static part v_0 of v (and $V^{2\pi}$) assumed to arise from pion-like (PS) and rho-like (V) exchanges:

$$\begin{aligned}\mathbf{j}_{ij}(v_0;PS) &= \mathrm{i}\,(\boldsymbol{\tau}_i\times\boldsymbol{\tau}_j)_z\Big[v_{PS}(k_j)\boldsymbol{\sigma}_i\,(\boldsymbol{\sigma}_j\cdot\mathbf{k}_j) \\ &+ \frac{\mathbf{k}_i-\mathbf{k}_j}{k_i^2-k_j^2}v_{PS}(k_i)\,(\boldsymbol{\sigma}_i\cdot\mathbf{k}_i)\,(\boldsymbol{\sigma}_j\cdot\mathbf{k}_j)\Big]+i\leftrightharpoons j\end{aligned}$$

with $v_{PS}=v^{\sigma\tau}-2\,v^{t\tau}$

- Terms from velocity-dependent part v_1 of v by minimal substitution: $\mathbf{p}_i\rightarrow\mathbf{p}_i-e\,\mathbf{A}(\mathbf{r}_i)$

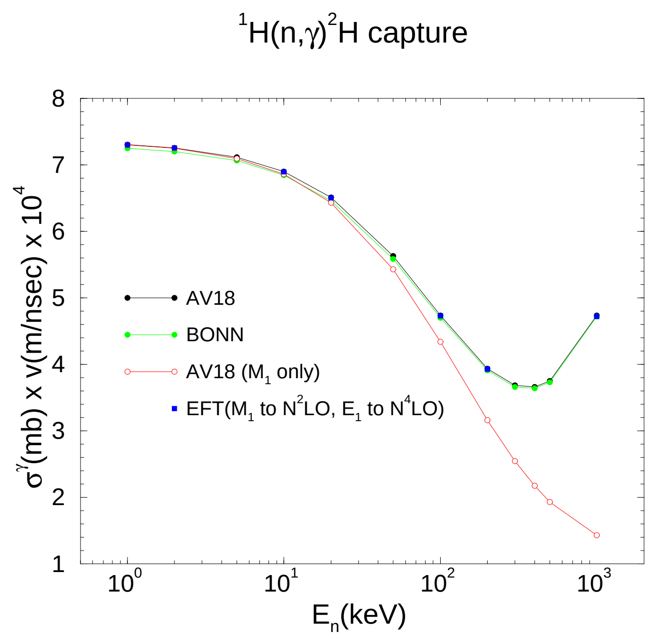
- $\mathbf{j}^{(2)}(v)$ satisfies:

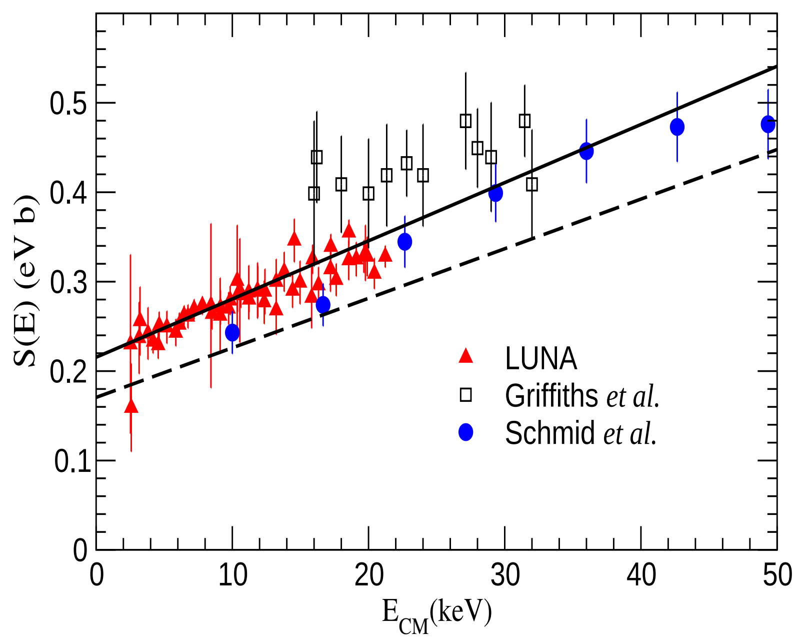
$\mathbf{j}^{(2)}(\mathrm{v})$ $\xrightarrow{\text{long range}}$ 

Radiative Captures in A=2 and 3 Systems

Marcucci *et al.*, PRC**72**, 014001 (2005)

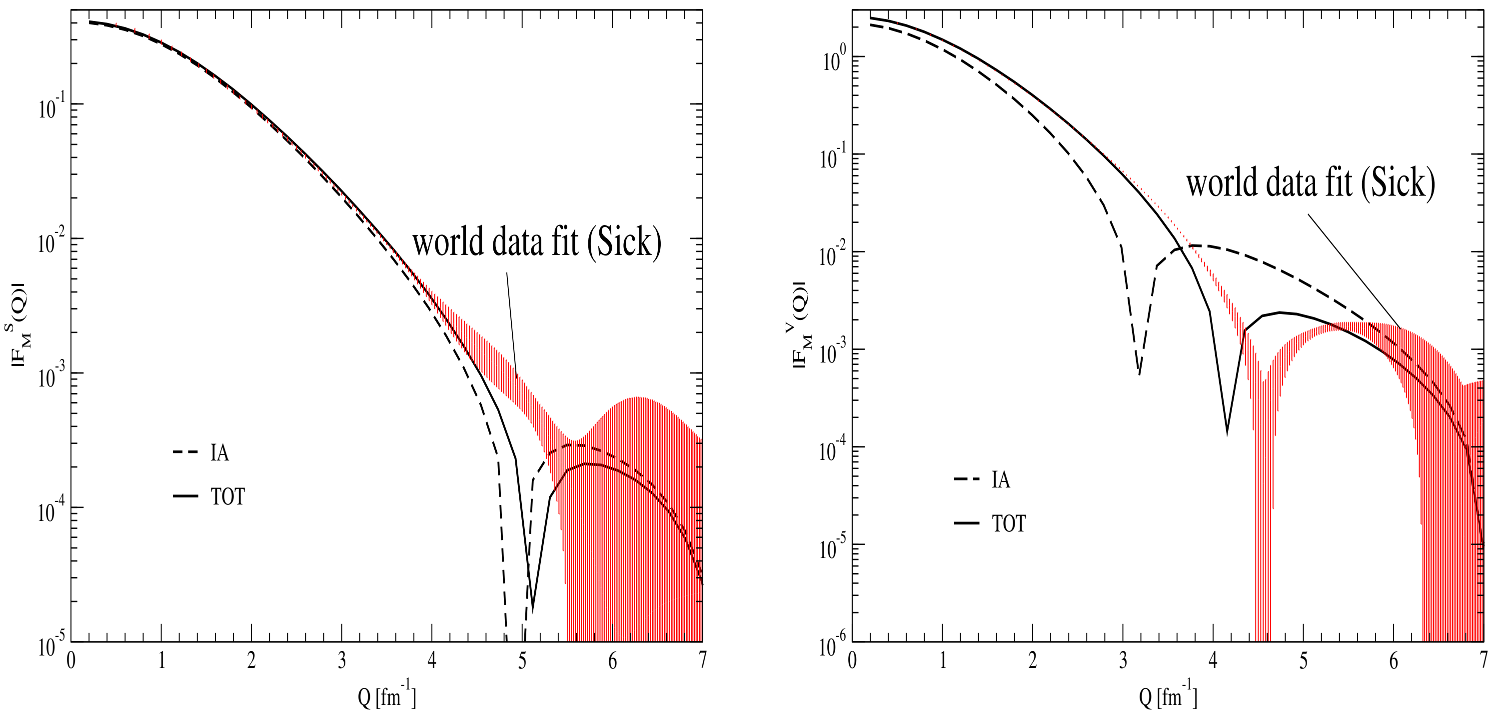
$^{2}\mathrm{H}(p,\gamma)^{3}\mathrm{He}$ capture





- however, theory overpredicts $^{2}\mathrm{H}(n,\gamma)^{3}\mathrm{H}$ and $^{3}\mathrm{He}(n,\gamma)^{4}\mathrm{He}$ x-sections at thermal energies by 9% and $\approx$ 30% respectively

Isoscalar and Isovector Magnetic Structure in A=3 Nuclei



- diffraction region in F_M^V "problematic" for theory: similar trend seen in deuteron threshold e-disintegration

(Arriaga and Schiavilla, arXiv:0704.2514, PRC in press)

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 (tests of IL2 are in progress)
- Constructed current (and charge) operators, which reproduce well a variety of light-nuclei EM observables (charge f.f.'s, inclusive (e,e') and exclusive $(e,e'p)$ responses, $\ldots$)
- But a few discrepancies persist: nd (and n^3He) radiative capture(s), diffraction region in $F_M^V(q)$, $\ldots$

Approaches to Relativistic Dynamics

Hamiltonian Dynamics

(Instant-form) Hamiltonian dynamics [Krajcik and Foldy, PRD**10**, 1777 (1974); Carlson, Pandharipande, and Schiavilla, PRC**47**, 484 (1993)]:

$$H = \sum_i \sqrt{\mathbf{p}_i^2 + m^2} + \sum_{i<j} \left[v_{ij} + \delta v_{ij}(\mathbf{P}_{ij}) \right] + \ldots$$

- v is the rest frame interaction (fitted to NN data)
- $\delta v(\mathbf{P})$ ("boost interaction") depends on pair momentum $\mathbf{P}$, and is determined from v via (Poincaré group) $\left[\hat{\mathbf{K}} \, , \, \hat{H} \right] = i \, \hat{\mathbf{P}}$:

$$\delta v(\mathbf{P}) = -\frac{P^2}{8m^2} v + \frac{i}{8m^2} [\mathbf{P} \cdot \mathbf{r} \, \mathbf{P} \cdot \mathbf{p} \, , \, v] + \frac{i}{8m^2} [(\boldsymbol{\sigma}_i - \boldsymbol{\sigma}_j) \times \mathbf{P} \cdot \mathbf{p} \, , \, v]$$

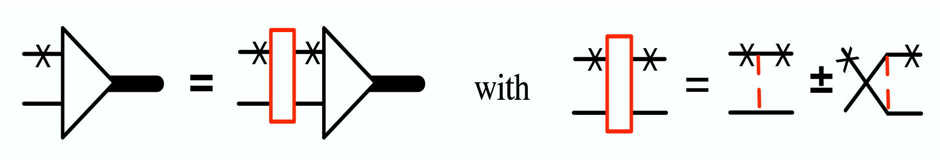
- Boosting (two-body, for example) states from the rest frame to a frame moving with velocity $\boldsymbol{\beta}$:

$$\psi_{\boldsymbol{\beta}}(\mathbf{p}) = \frac{1}{\sqrt{\gamma}} \left[1 - \frac{i}{4m} \boldsymbol{\beta} \cdot (\boldsymbol{\sigma}_i - \boldsymbol{\sigma}_j) \times \mathbf{p} \right] \psi_0(\mathbf{p}_{\parallel}/\gamma, \mathbf{p}_{\perp})$$

Spectator Formalism

Spectator formalism, aka Gross equation[a]: explicit N and $\overline{N}$ d.o.f. (consequently, deuteron develops P-wave components)

- Bound state obtained from:



- v is a high-quality (χ^2=1) OBE model with effective I=0 and 1, J^π=$0^+, 0^-, 1^-$ exchanges; it includes off-shell couplings[b]:

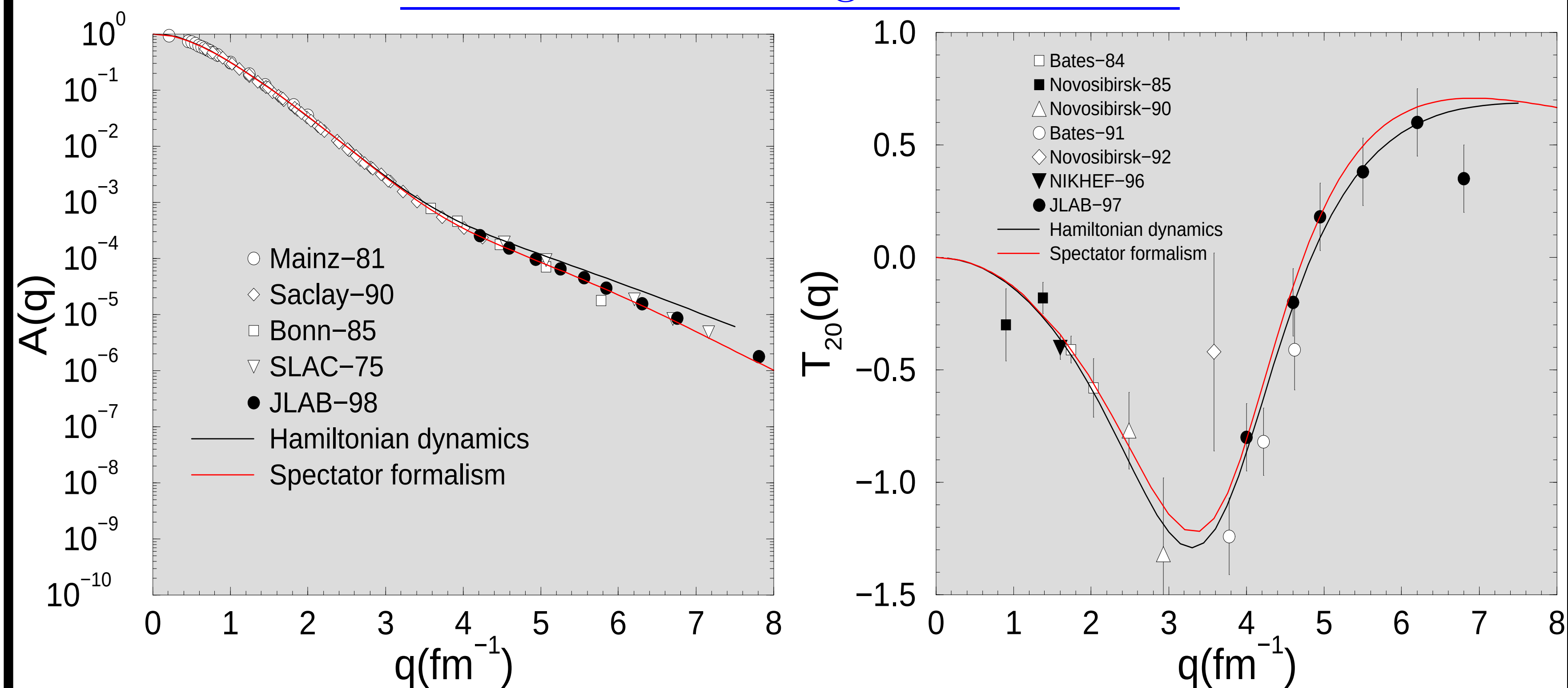
$$\text{scalar vertex} = g_S - \nu_S \left[(m - \not{p})/(2m) + (m - \not{k})/(2m)\right]$$

- v reproduces $E_0(^3\text{H})$: crucial off-shell couplings simulate NNN interaction effects[b]

- Boosts are kinematical and exactly accounted for

[a] Gross, PR**186**, 1448 (1969); [b] Gross and Stadler, arXiv:0704.1229 and PRL**78**, 26 (1997)

Deuteron Electromagnetic Structure



Hamiltonian dynamics (HD): Schiavilla and Pandharipande, PRC**65**, 064009 (2002)

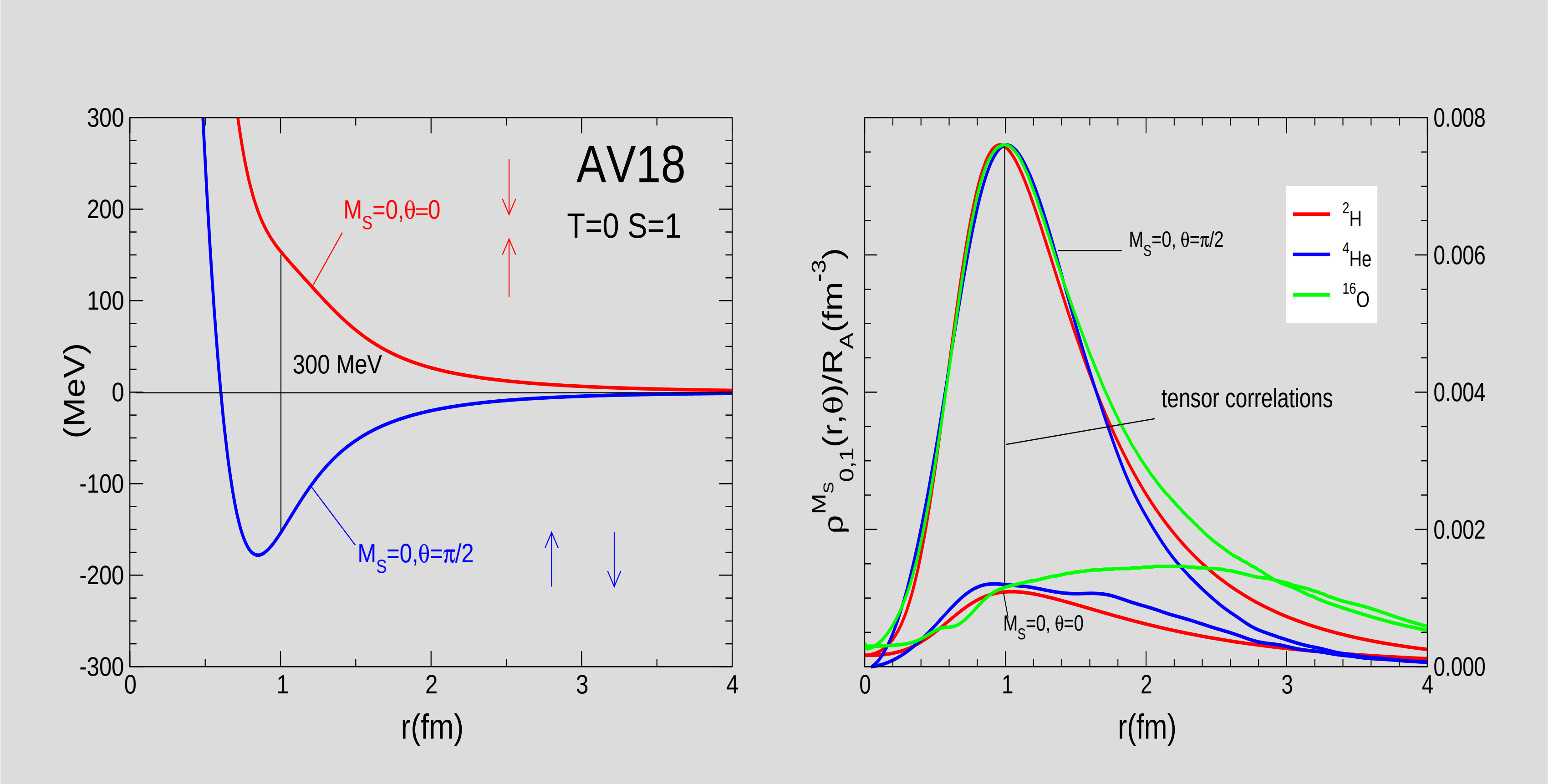
Spectator formalism (SF): Van Orden, Devine, and Gross, PRL**75**, 4369 (1995), older OBE model

- HD and SF represent drastically different approaches, yet lead to equally satisfactory description of *e*-*d* elastic scattering

Tensor Forces and Ground-State Structure

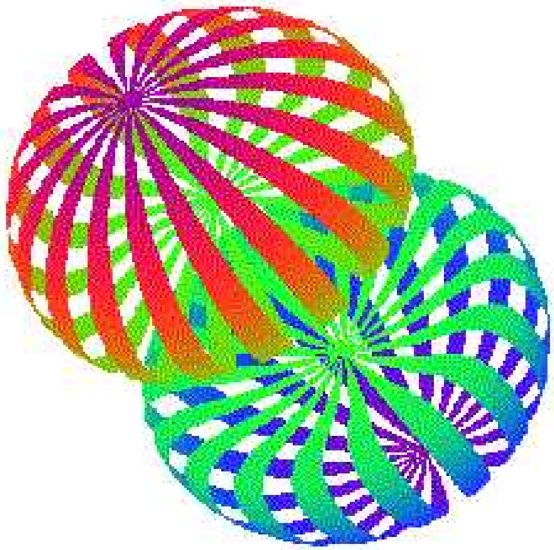
Preeminent features of v_{ij}:

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

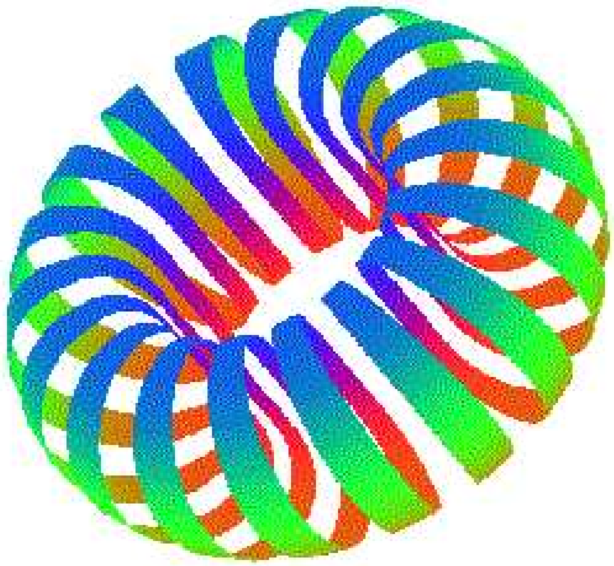


Forest *et al.*, PRC**54**, 646 (1996)

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



$M_S = \pm 1$

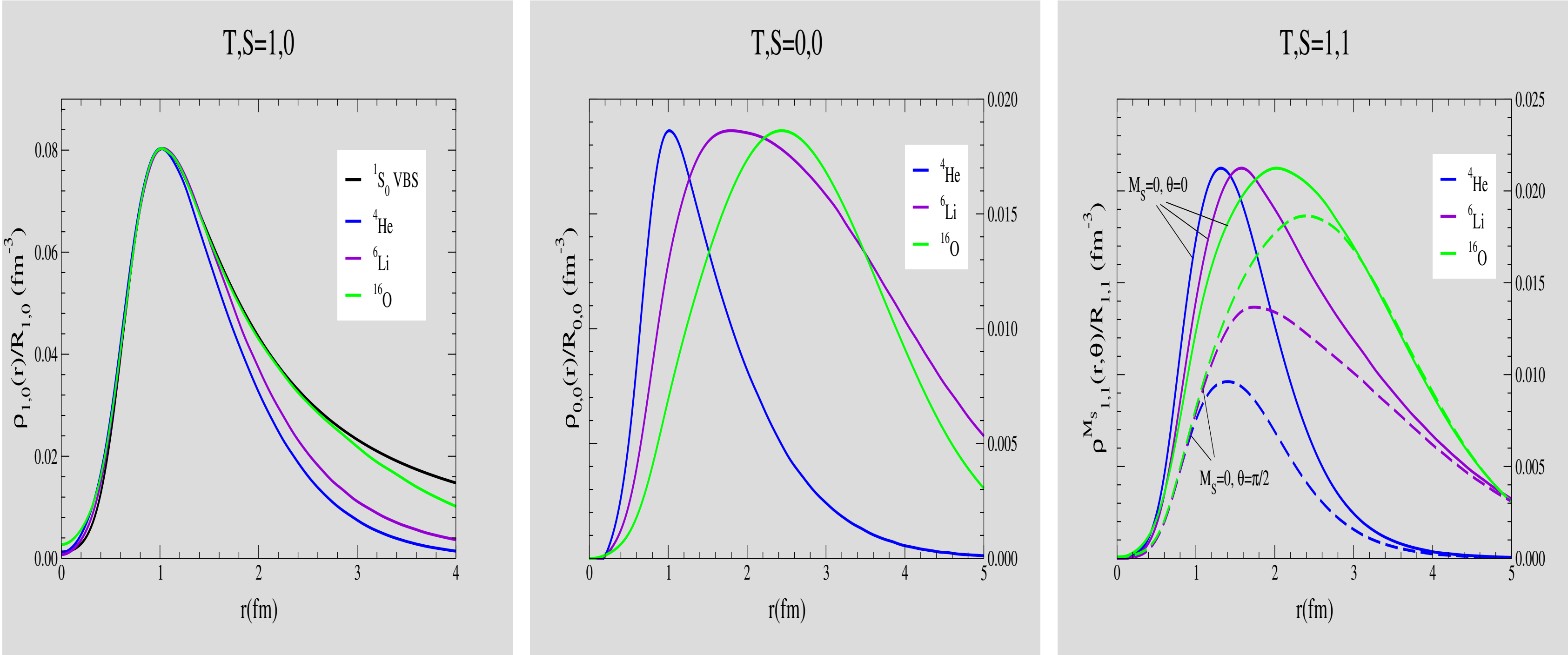


$M_S = 0$

- 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

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

- Scaling persists in T, S=1,0 channel (quasibound $^1S_0$ state) for $r \leq 2$ fm
- But no scaling occurs in remaining channels (interaction either repulsive or weakly attractive)

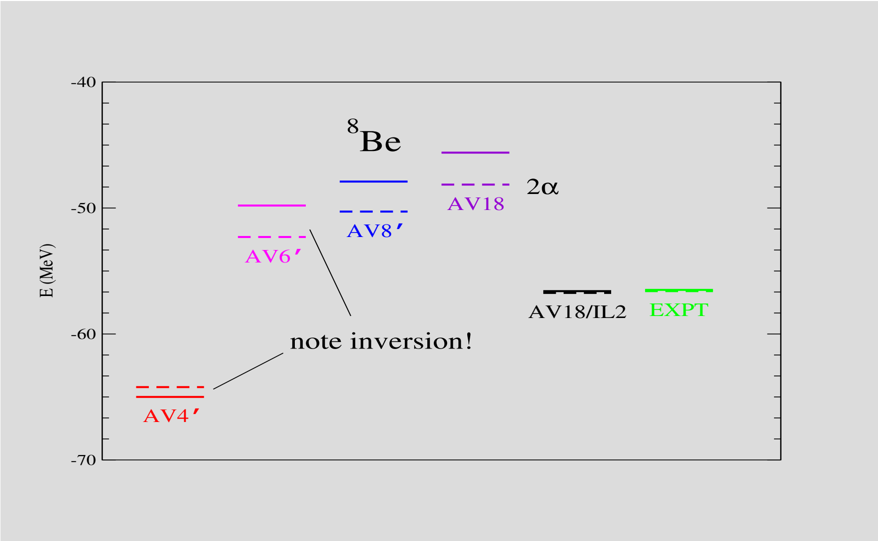


Experimental Evidence for Tensor Correlations in $A > 2$ Nuclei

While many nuclear properties are affected by tensor correlations, their effects are generally subtle, and not easily isolated in data

For example, absence of stable A=8 nuclei:

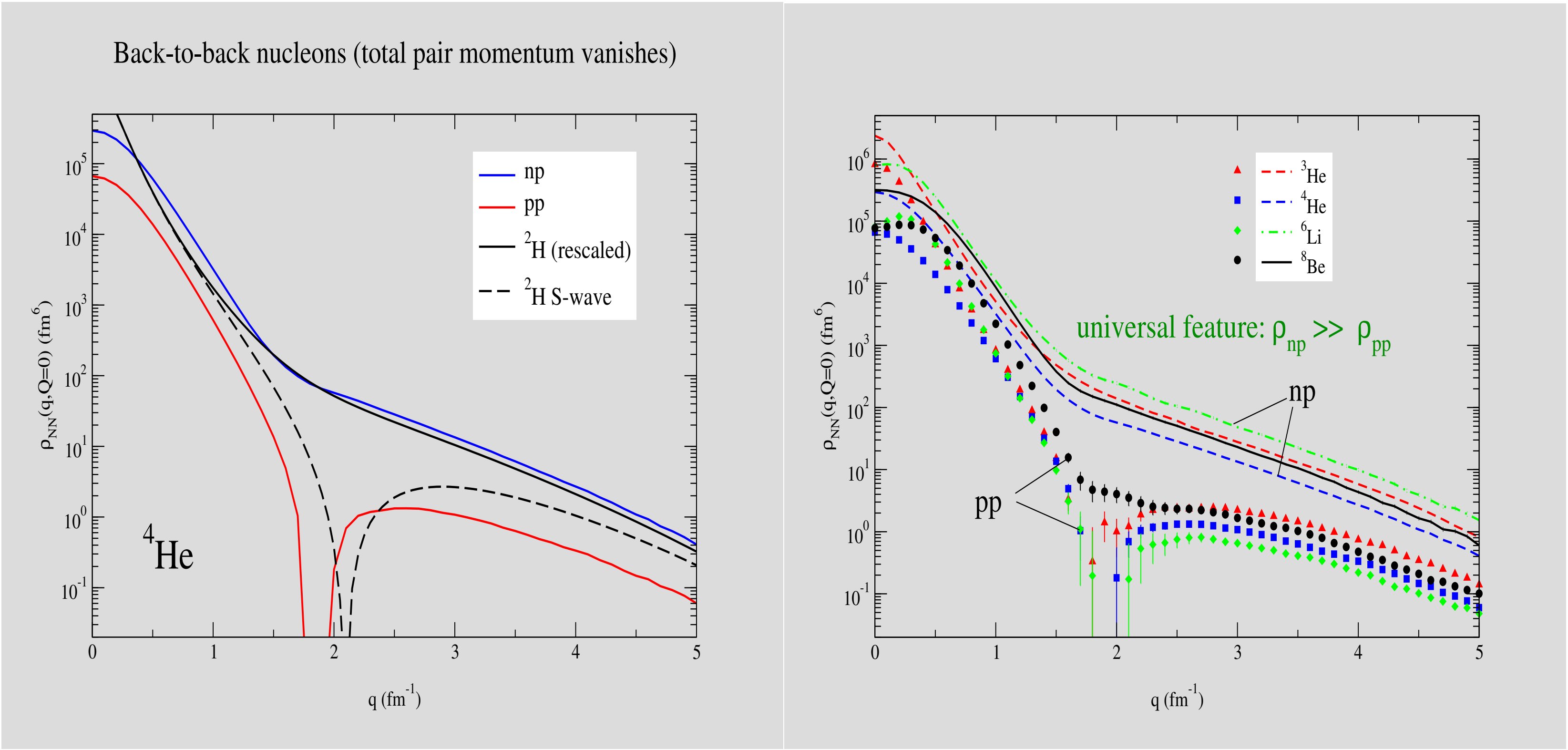
1. $AV4' = [1\,,\, \boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2] \otimes [1\,,\, \boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2]$
2. $AV6' = AV4'$+tensor
3. $AV8' = AV6'$+spin-orbit, ...



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

New Opportunities for Observing Tensor Correlations

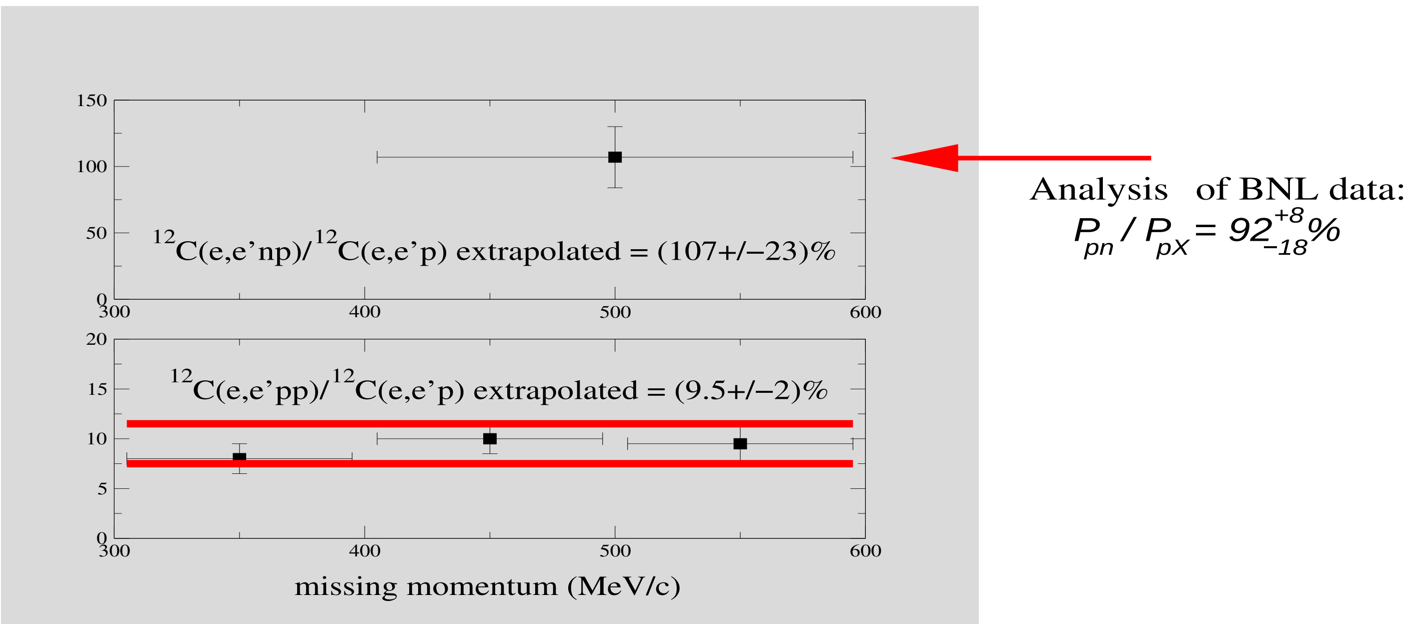
np and *pp* pairs predominantly in deuteron-like and $^1S_0$ states:
large differences between *np*- and *pp*-pair momentum distributions



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

Two-Nucleon Knockout Processes and Tensor Correlations

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

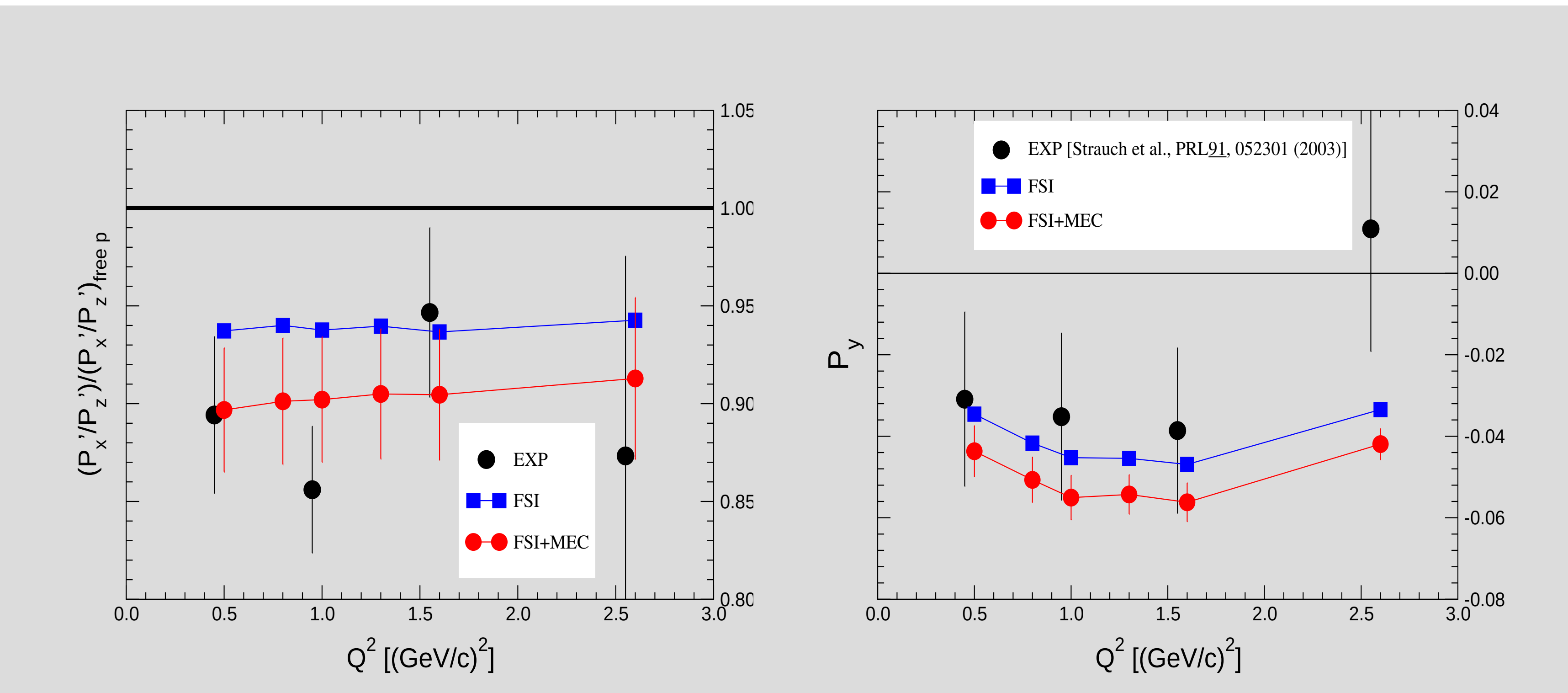


[a] Shneor *et al.*, nucl-ex/0703023, submitted to PRL; [b] Subedi *et al.*, in preparation; [c] Piasetzky *et al.*, PRL **97**, 162504 (2006); [d] Ashery *et al.*, PRL **47**, 895 (1981)

Nucleon Properties from Nuclear Experiments

Medium-Modified p f.f.: the $^4\text{He}(\vec{e}, e'\vec{p})^3\text{H}$ process

- In PWIA: $P'_x/P'_z \propto (G_{Ep}/G_{Mp})$
- FSI effects and MEC contributions explain measured ratio: no in medium modification is required

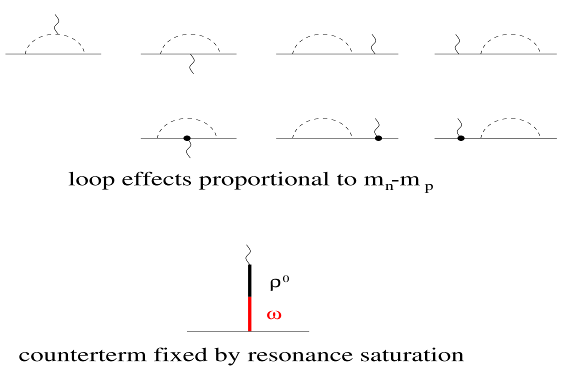


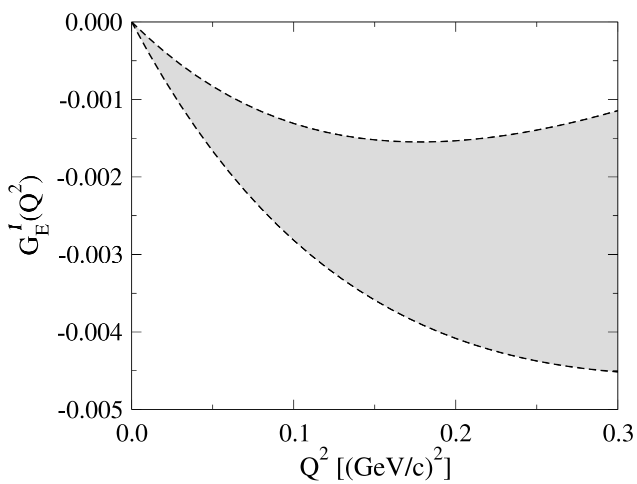
Schiavilla, Benhar, Kievsky, Marcucci, and Viviani, PRL**94**, 072303 (2005)

Parity-Violating $^4\mathrm{He}(\vec{e},e')^4\mathrm{He}$ Scattering and G_E^s

$$A_{\mathrm{PV}} = \frac{G_\mu Q^2}{4\pi\alpha\sqrt{2}}\left[4\sin^2\theta_W - 2\,\frac{F^{(1)}(q)}{F^{(0)}(q)} - \frac{2\,G_E^{\not 1} - G_E^s}{(G_E^p + G_E^n)/2} + \mathrm{RC/MEC}\right]$$

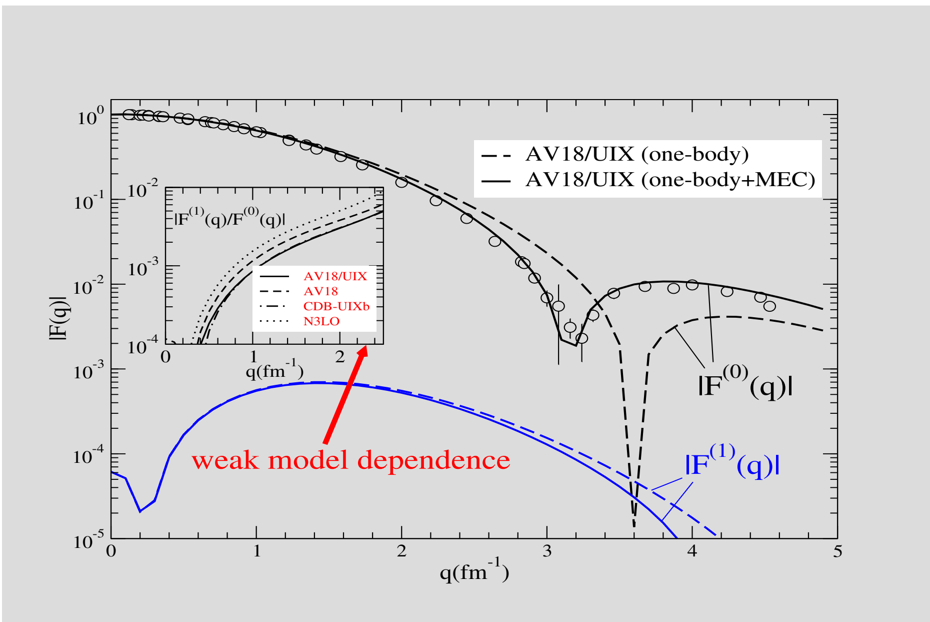
- $G_E^{\not 1}$ parameterizes nucleonic isospin symmetry breaking (ISB): $(G_E^p + G_E^n)/2 = G_E^0 + G_E^{\not 1}$, $G_E^{\not 1}$ obtained up to NLO in ChPT[a]
- $F^{(1)}$ nuclear ISB, would vanish if $|^4\mathrm{He}\rangle$ pure $T=0$ state
- At low Q^2, RC/MEC contributions calculated to be tiny[b]





[a] Kubis and Lewis, PRC**74**, 015204 (2006); [b] Musolf, Schiavilla, and Donnelly, PRC**50**, 2173 (1994)

- Nuclear ISB: i) EM interactions (Coulomb, ...), ii) n-p mass difference in kinetic energy, and iii) CD/CA strong interactions
- Calculated A=3–8 isomultiplet energies in good agreement with experiment [Pieper, Pandharipande, Wiringa, and Carlson, PRC**64**, 014001 (2001)]

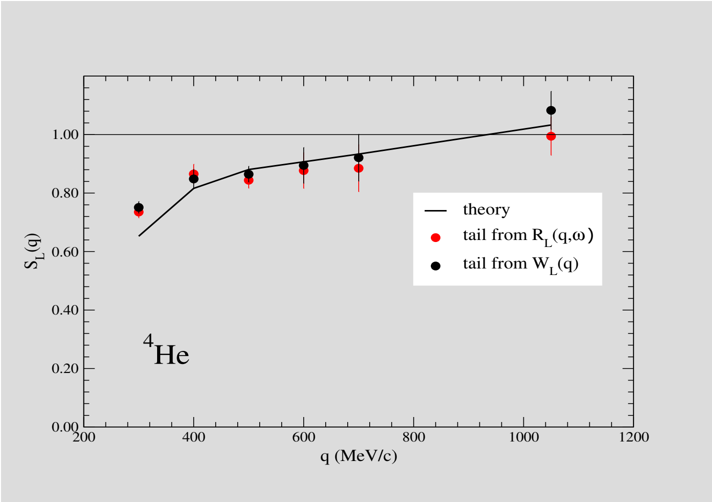


Viviani *et al.*, nucl-th 0703051

$-2\,G_E^{\not{1}}/[(G_E^p+G_E^n)/2]\approx 0.008$ and $-2\,F^{(1)}(q)/F^{(0)}(q)\approx 0.00314$ in HAPPEX $A_{\rm PV}$ give $G_E^s\left[Q^2=0.077\,({\rm GeV/c})^2\right]=-0.001\pm 0.016$

Summary (II)

- Conventional nuclear effects explain suppression of $(P'_x/P'_z)_{^4\mathrm{He}}$
- Present and Coulomb sum rule analysis indicate no in-medium modification for G_{Ep} and G_{Mp}



Carlson, Jourdan, Schiavilla, and Sick, PLB**553**, 191 (2003)

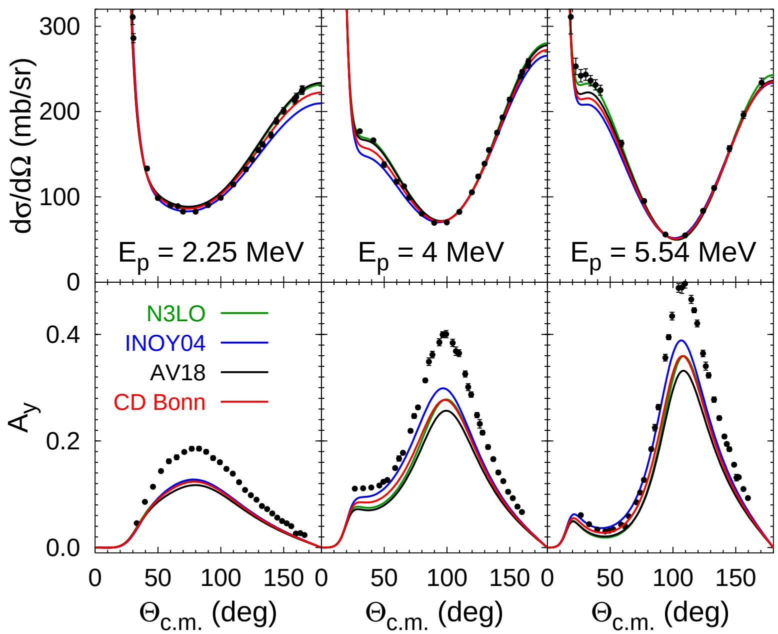
- $|G_E^s| \lesssim |\mathrm{ISB}|$: measuring ISB admixtures?
- Inferred G_E^s consistent (in magnitude!) with estimate obtained by using LQCD input [Leinweber *et al.*, PRL**97**, 022001 (2006)]

New Frontiers

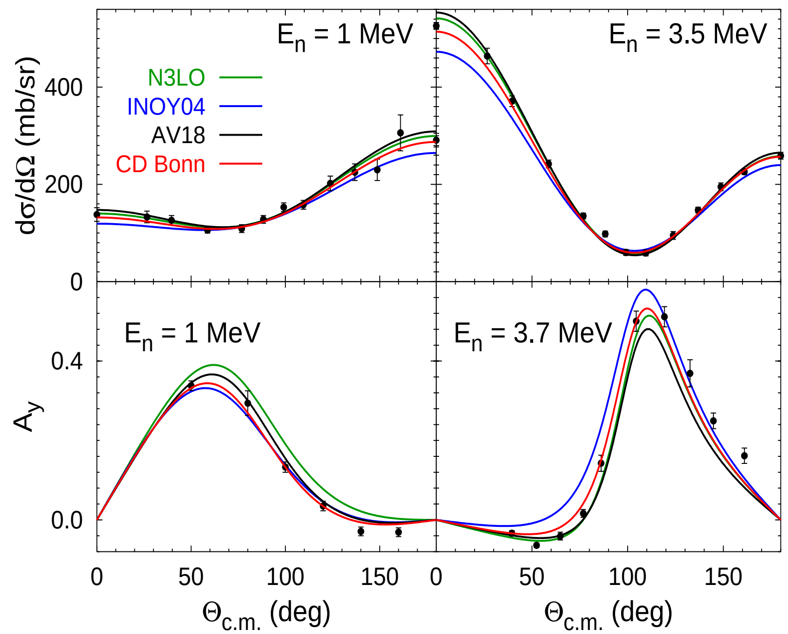
AGS formulation of 4-body scattering including channel couplings

[Deltuva and Fonseca, PRL**98**, 162502 (2007) and nucl-th/0703066]

p-^{3}He

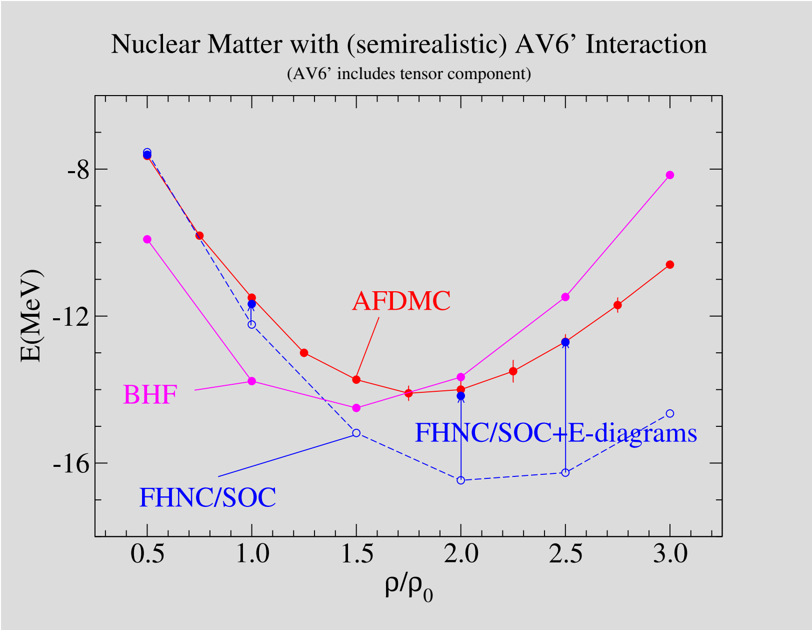


n-^{3}He



- NN interactions only (for the time being)
- A_y puzzle in 4-body scattering: strong isospin dependence, theory underestimate in ^{3}He-p (T=1) much reduced relative to ^{3}He-n and ^{3}H-p (T=0 and T=1 superpositions)

Auxiliary-Field-Diffusion-Monte-Carlo (AFDMC) calculations of nuclear matter and of $A \leq 40$ nuclei



Gandolfi, Pederiva, Fantoni, and Schmidt, PRL**98**, 102503 (2007); arXiv:0704.1774

- In AFDMC spin-isospin variables are sampled rather than summed over explicitly as in GFMC
- Power-law rather than exponential growth with A (^{12}C GFMC calculations presently require $\simeq 70,000$ processor hours)