Impact of tensor and short-range correlations in nuclear physics

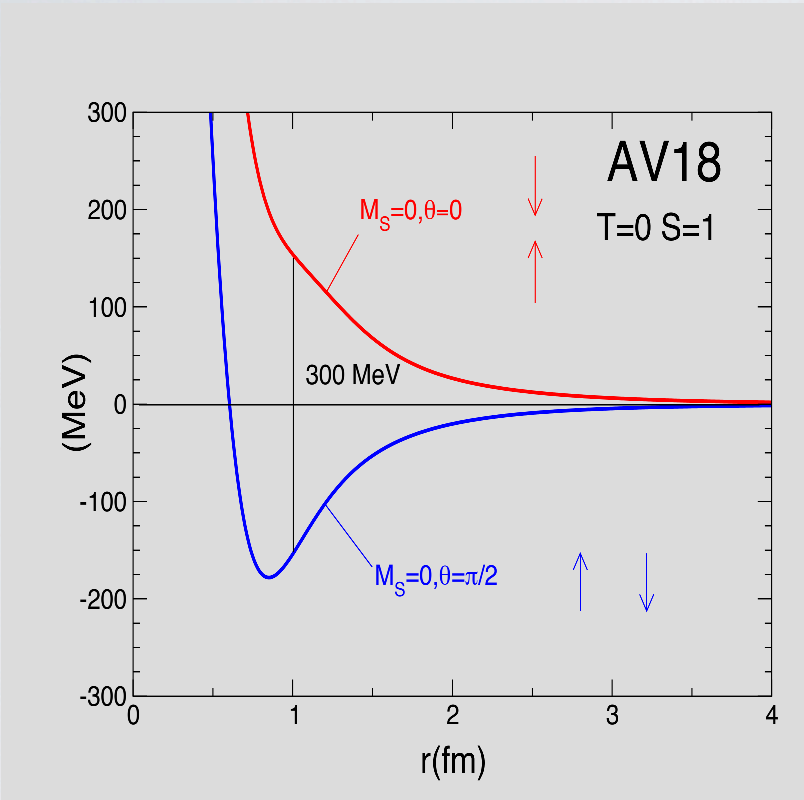
J Carlson, LANL

Santa Fe Plaza Dec 9

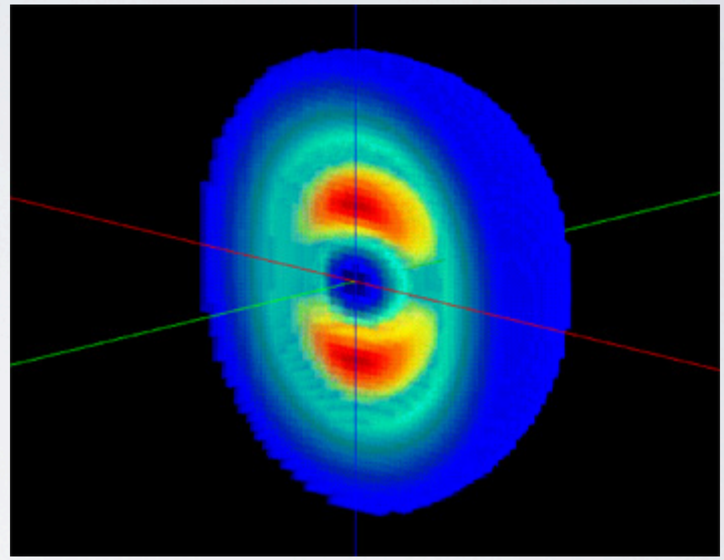
Tensor Force
Deuteron
T20
Nuclear density matrix
Three-nucleon interactions
JLAB/BNL correlated pairs
Inclusive electron/neutrino scattering
Neutrino emissivity in neutron matter

work with: Wiringa, Schiavilla, Pieper, Shen, Reddy, Gandolfi,...

Tensor force (and spin-orbit) couple spin to space



diagonal elements of force in different spatial directions (Forest, PRC, 1996)



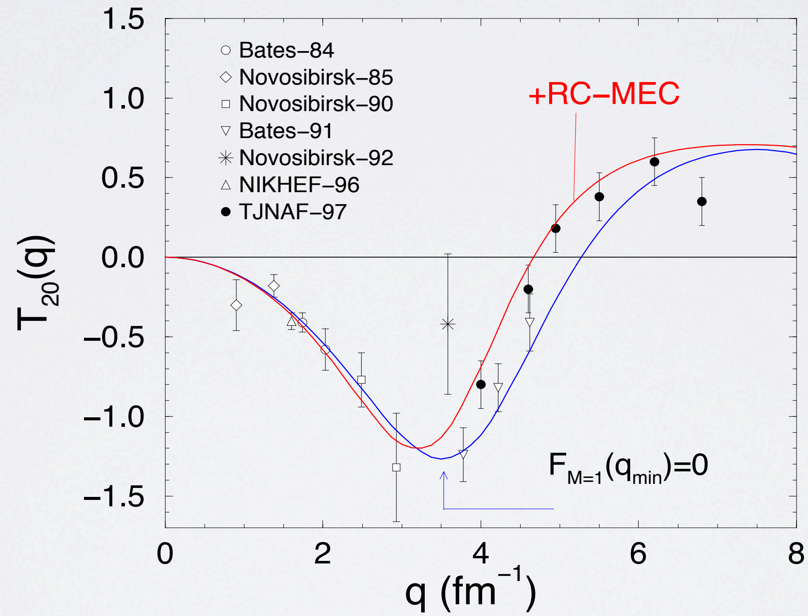
Intrinsic shape of the deuteron (Jlab); low density in interior (repulsion) and exterior. Intermediate behavior is strongly space-dependent

$$Q_d = 0.286\ \mathrm{fm}^2$$

JLab measurement of T20 in elastic electron scattering

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

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

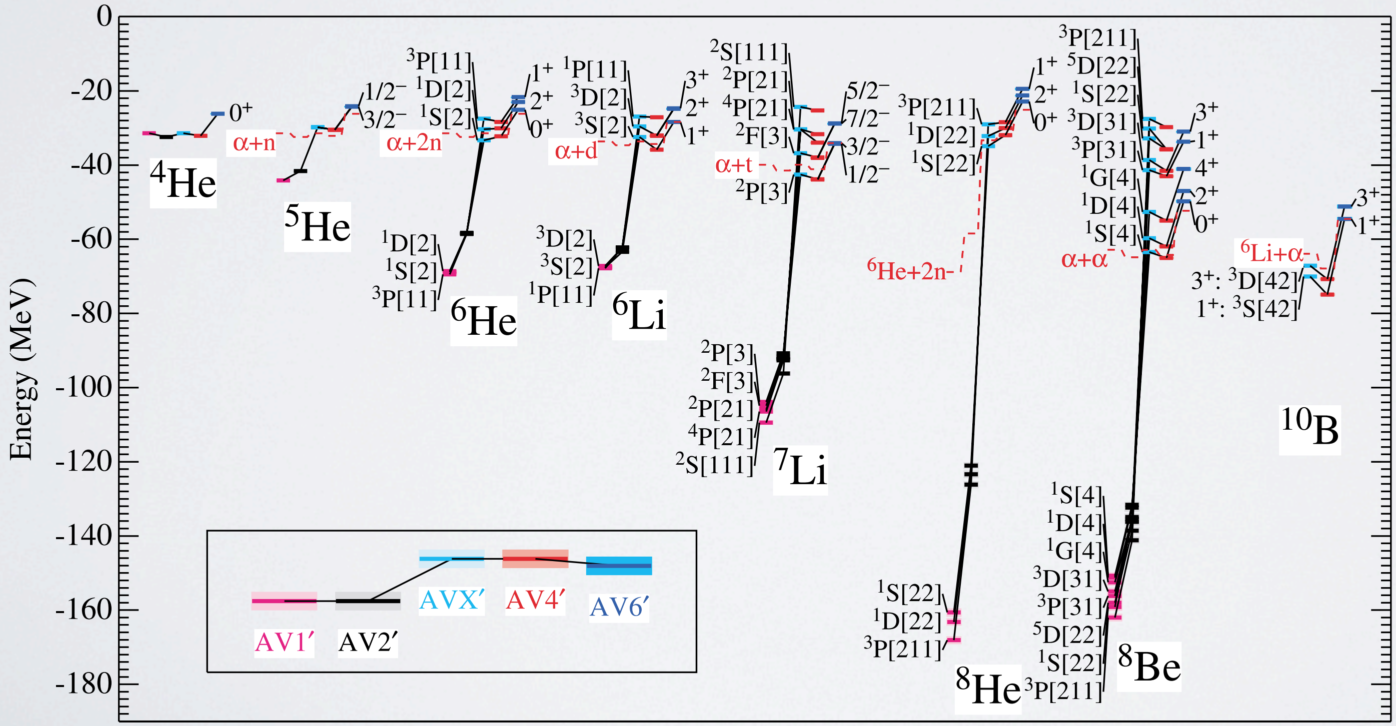


Roy Holt Bonner Prize

Tensor correlations in A>2

Much more difficult to `see' in larger nuclei.
Typical matrix elements (eg. energy) involve S_{ij}^2

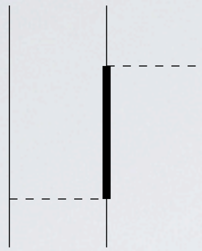
Light nuclei spectra, though, require a `realistic' force



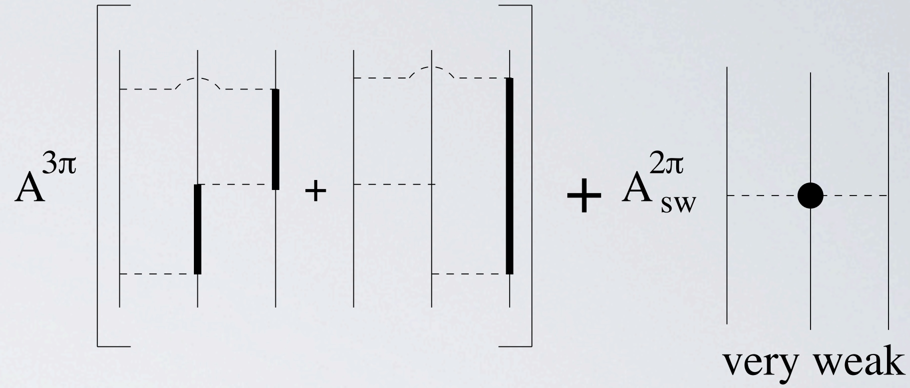
Pieper and Wiringa, PRL 2002

alpha-n phase shifts

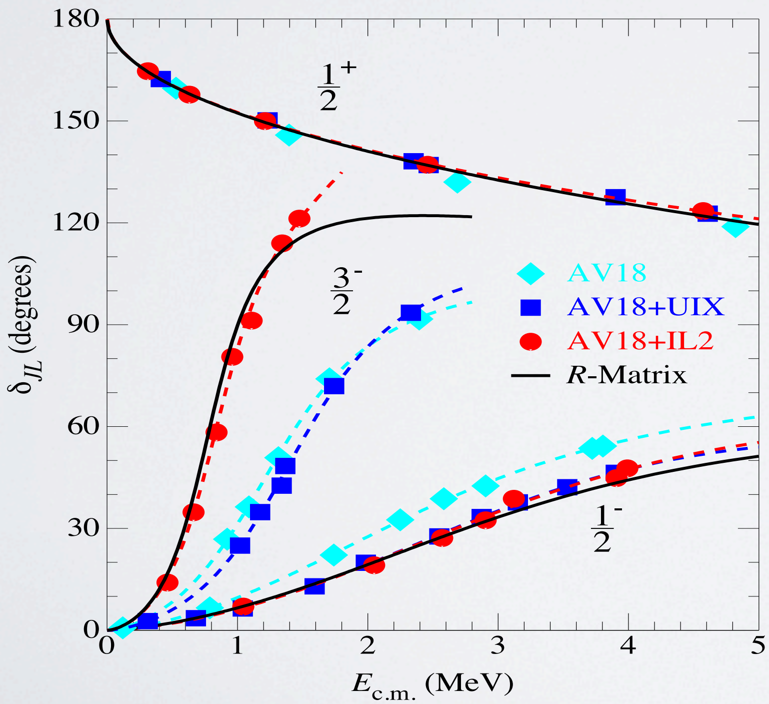
3-nucleon interaction: UIX



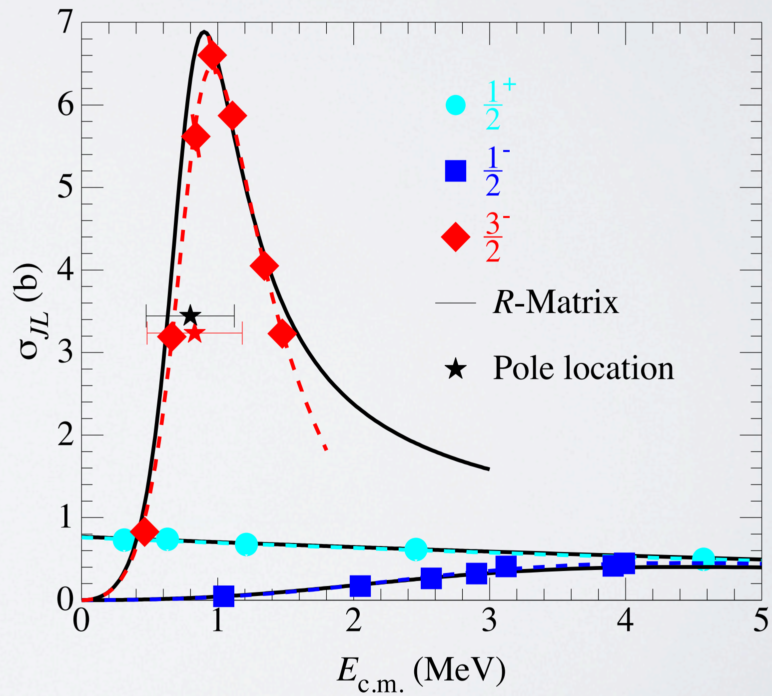
IL7:



Phase Shifts



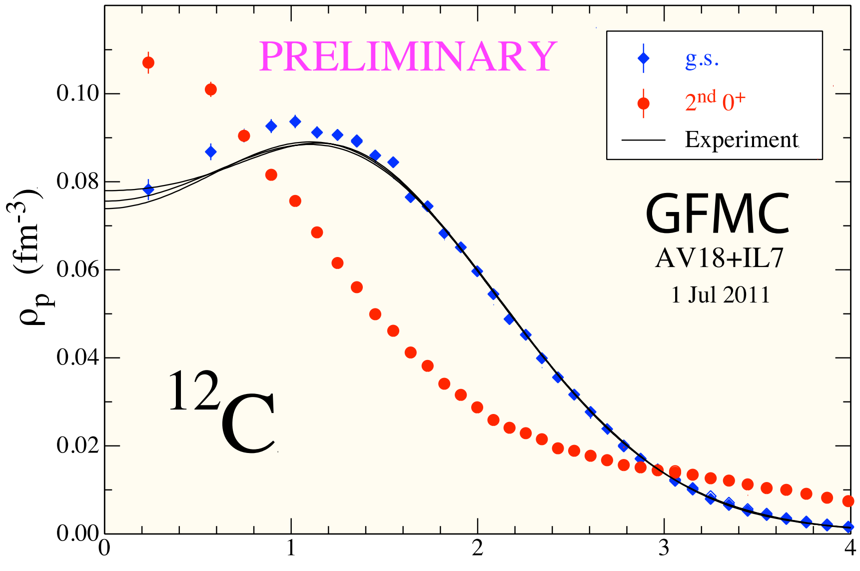
Cross Sections (AV18/IL2)



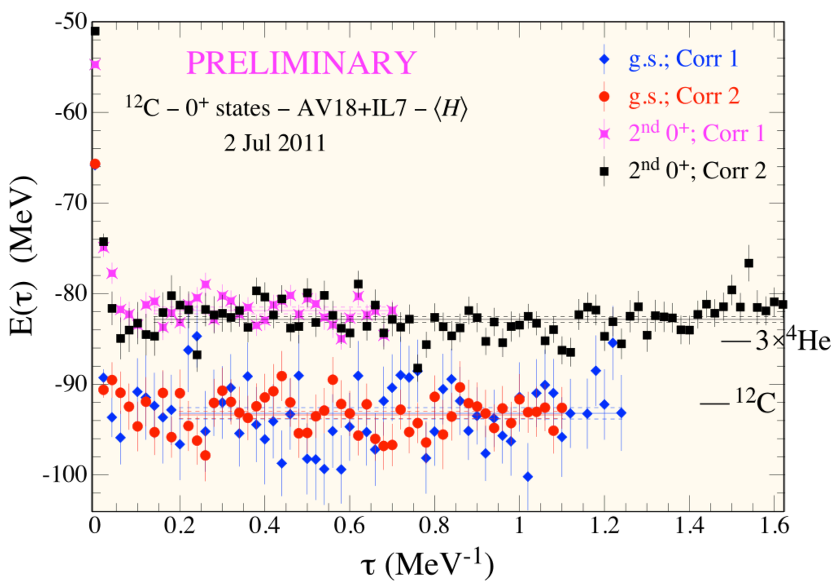
Nollett, et al., PRL 2007

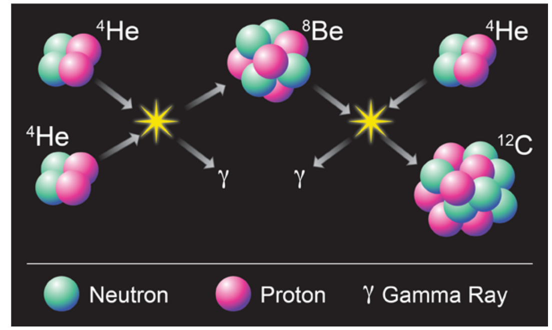
Long-range correlations (clustering) in Carbon-12

GFMC (Pieper et al.)



The ADLB (Asynchronous Dynamic Load-Balancing) library & GFMC. GFMC energy 93.5(6) MeV; expt. 92.16 MeV. GFMC pp radius 2.35 fm; expt. 2.33 fm.

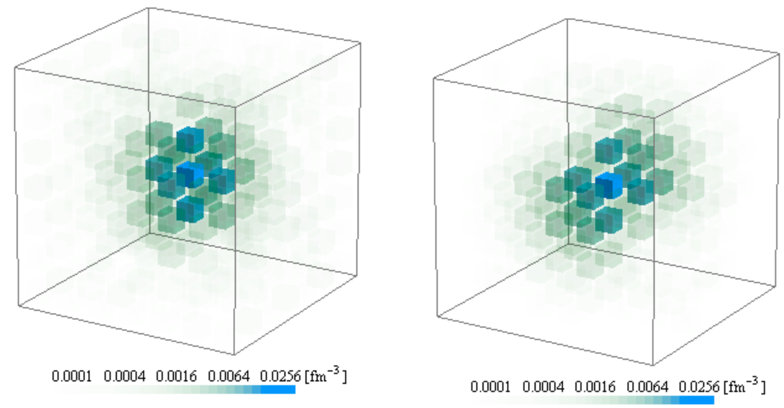




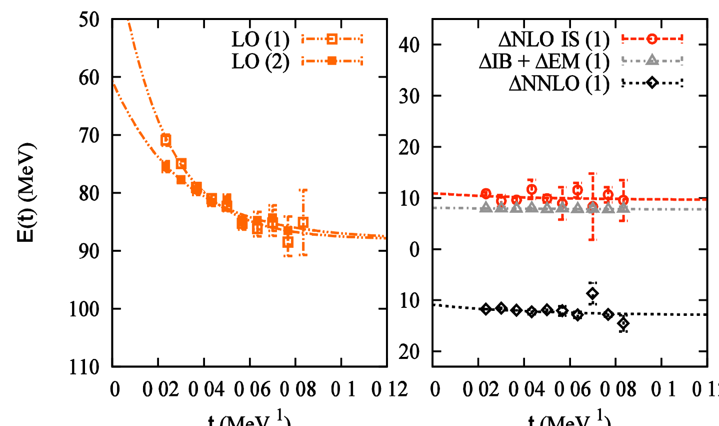
Lattice EFT (Lee, Epelbaum, Meissner,…)

0+(1) fpp

0+(2) fpp



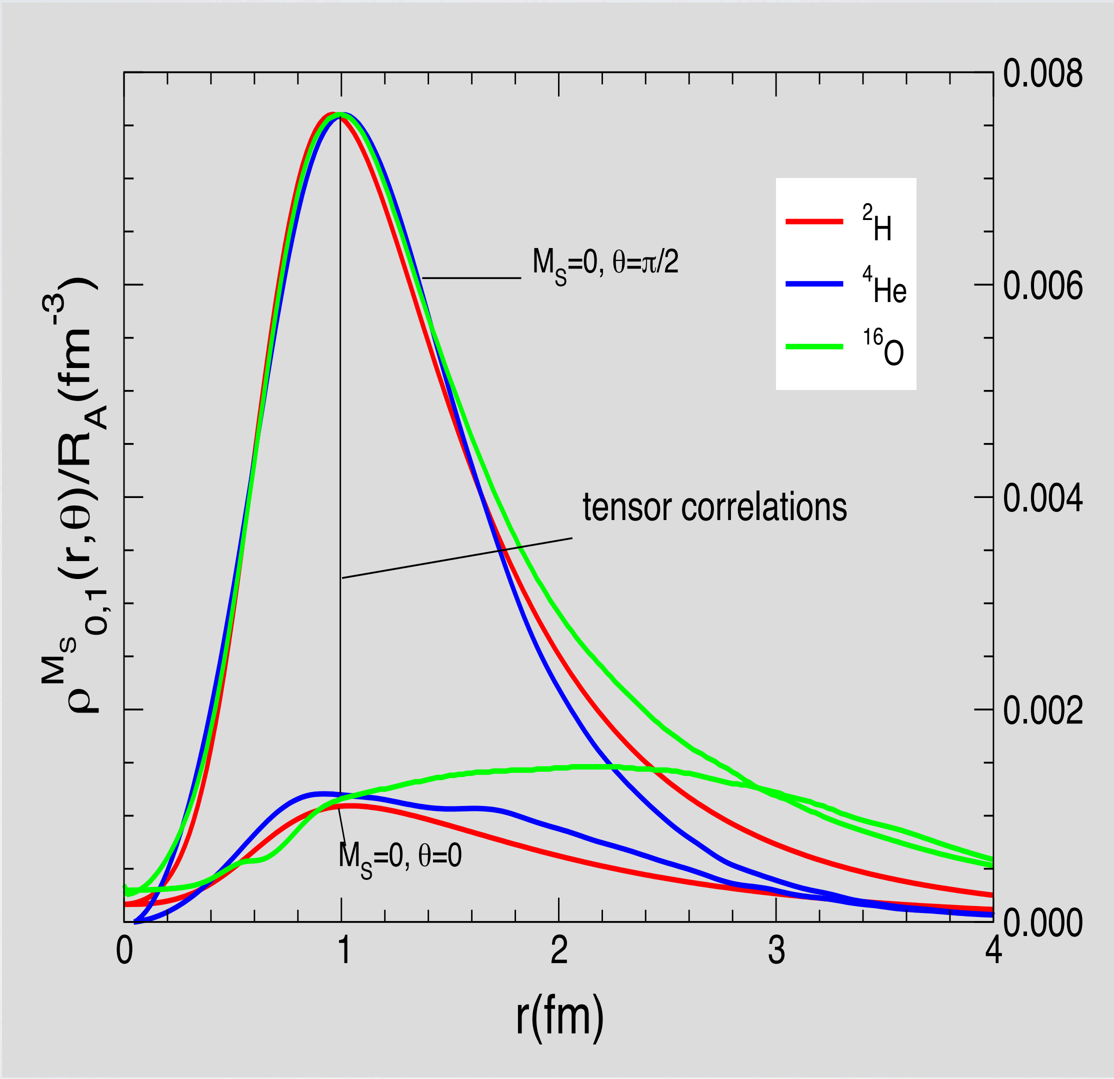
(A) (B)



Epelbaum et al., Phys. Rev. Lett. 106, 192501 (2011)

Shorter-range correlations
Tensor Force: higher momentum transfer:
Two-Nucleon Distribution Functions

T=0 S=1
`deuteron'
pairs



Expectation of short-range operator in T=0, S=1 pairs: scaling with nucleus

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		$\simeq 6.5(5)$

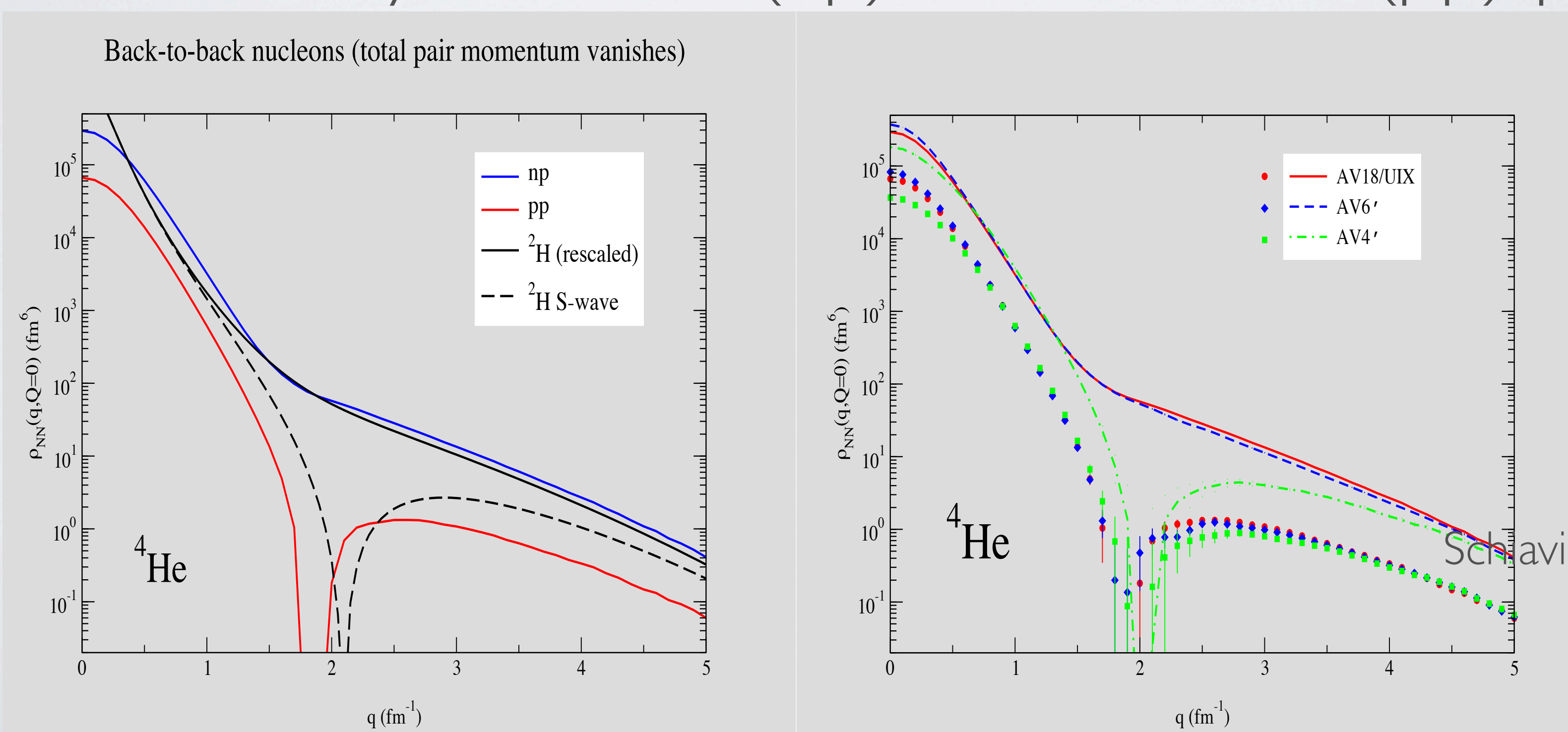
Two-nucleon momentum distributions: Total P=0;   p1 ~ - p2

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

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

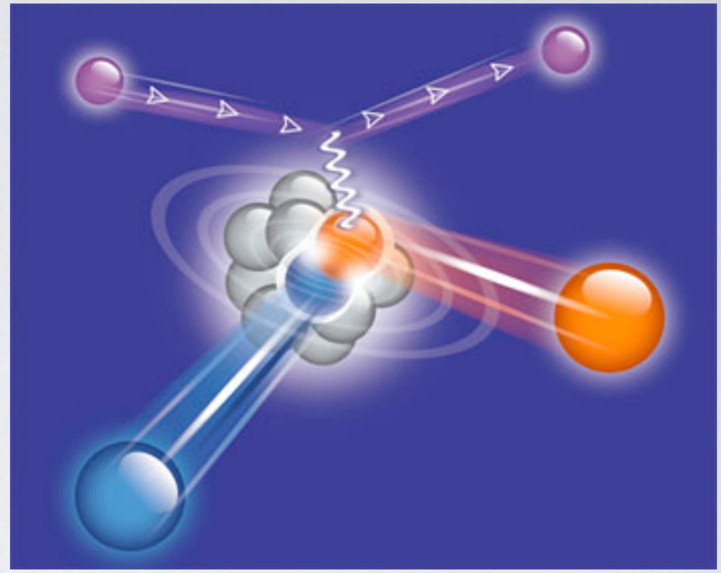
$$P_{ij}^{NN}(\mathbf{q},\mathbf{Q}) \equiv \delta(\mathbf{k}_{ij}-\mathbf{q})\delta(\mathbf{K}_{ij}-\mathbf{Q})\, P_{NN}(ij)$$

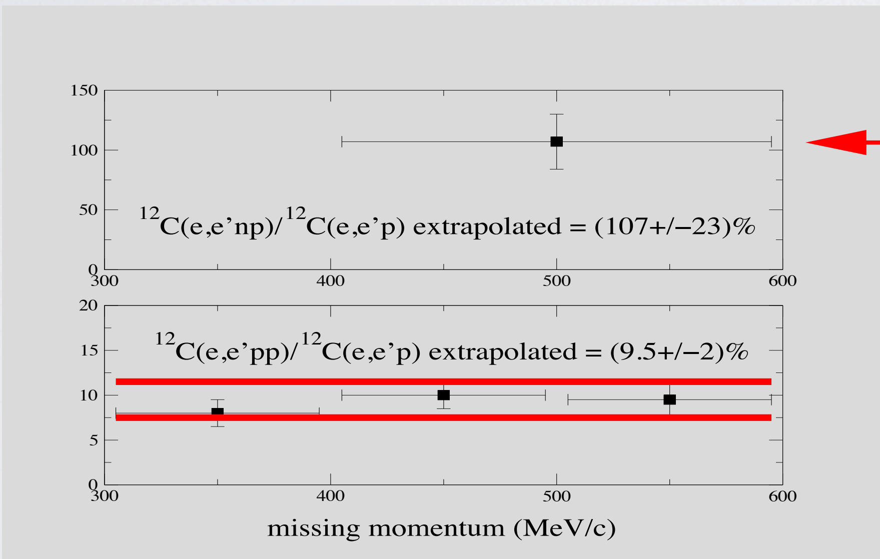
Dominated by T=0,S=1 (np) and T=1,S=0 (pp) pairs



Schiavilla, PRL 2007

np correlations correlations in back-to-back nucleon knockout: observed at BNL, Jlab



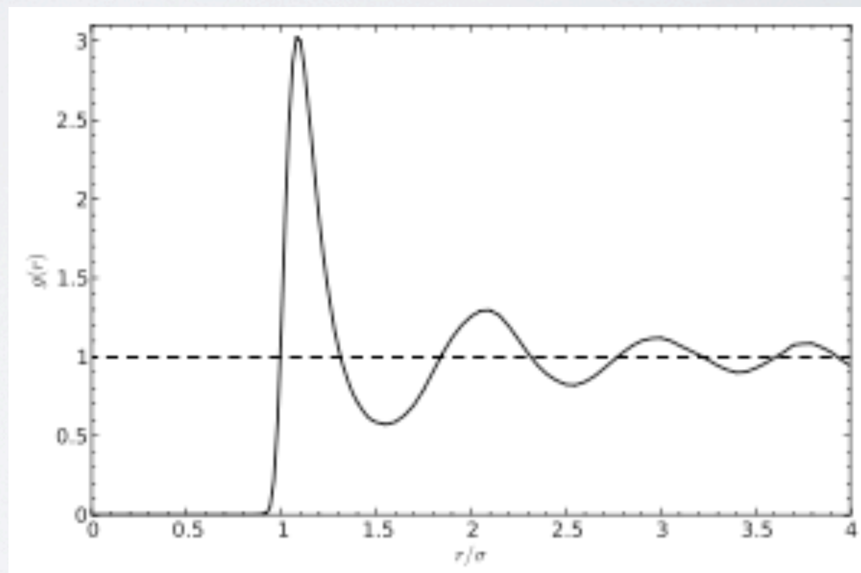


Analysis of BNL data:
$P_{pn} / P_{pX} = 92^{+8}_{-18}\%$

[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)

Typical method to study correlations, inclusive scattering

Liquid Helium, ... neutron scattering



pair distribution function
Lennard-Jones model fluid

Electron and Neutrino Scattering

$$S(q,\omega) \ = \ \sum_f \langle 0|O^\dagger(q)|f >< f|O(q)|0\rangle \ \delta(\omega - (E_f - E_0))$$

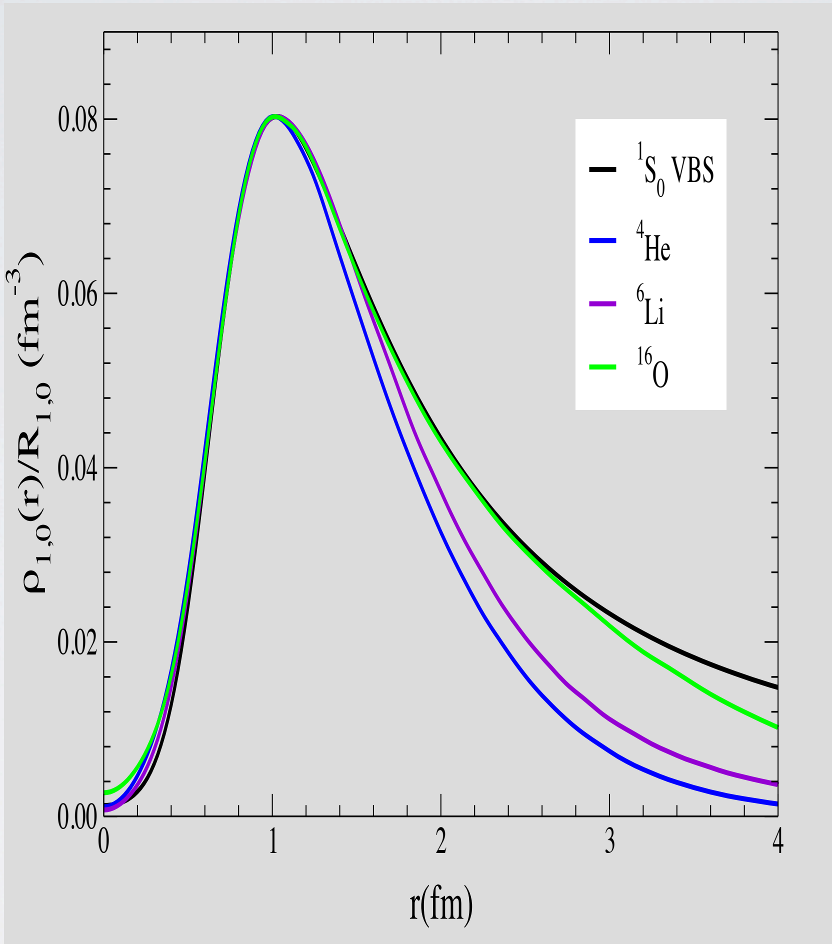
Longitudinal (Charge) scattering

$$O(q) = \sum_i P_p(i) \exp[i\mathbf{q}\cdot r]$$

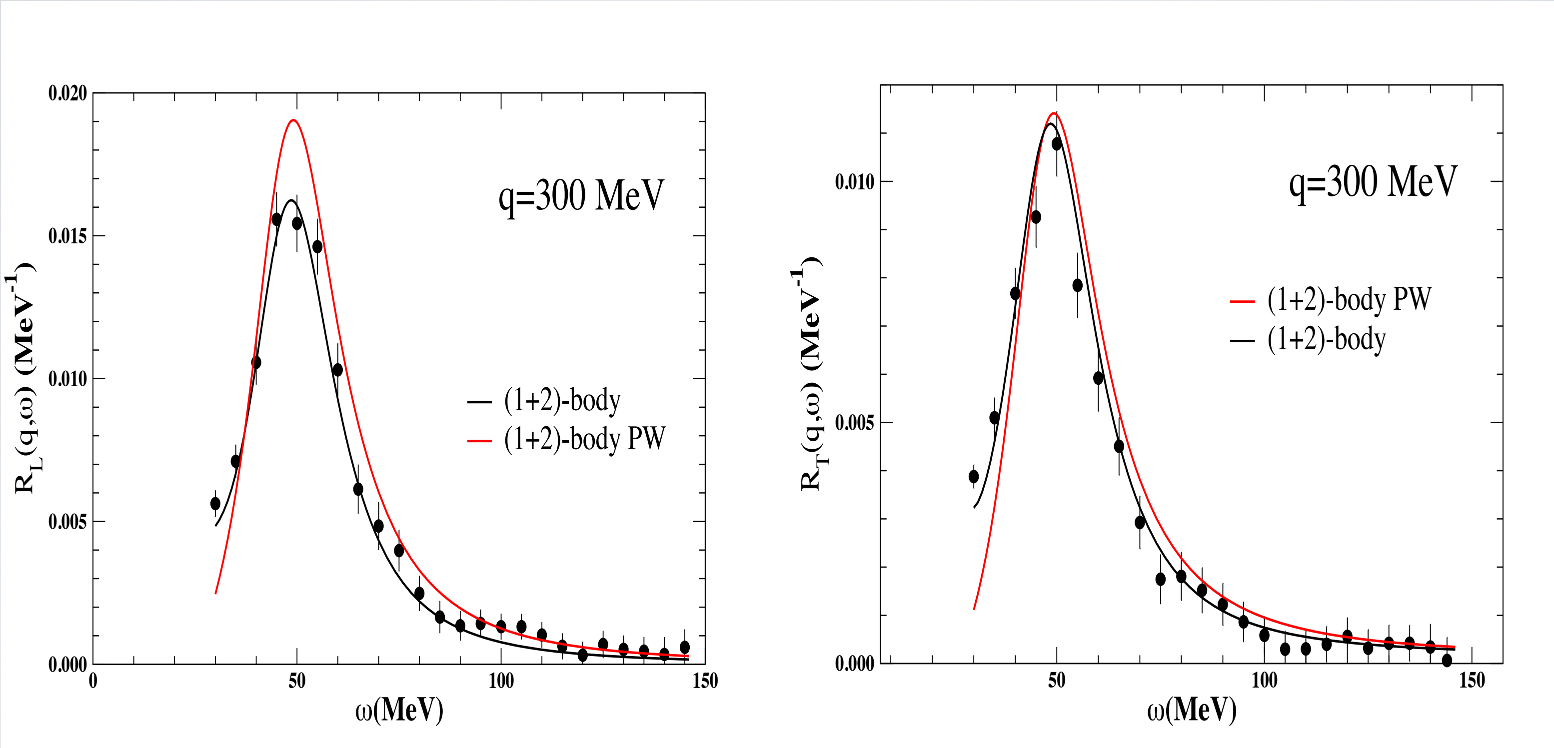
Transverse (Current Scattering)

$$O(q) = \sum_i \mu(i) \exp[i\mathbf{q}\cdot \mathbf{r_i}] + P_p(i)\mathbf{p_i} \exp[\mathbf{iq}\cdot \mathbf{r_i} \ \mathbf{p}(\mathbf{i}) + \ \sum_{\mathbf{i<j}} \ \mathbf{j_{ij}}(\mathbf{q})$$

Inclusive Electron Scattering and spin 0, T=1 pairs (pp, nn)



Inclusive electron scattering on the deuteron



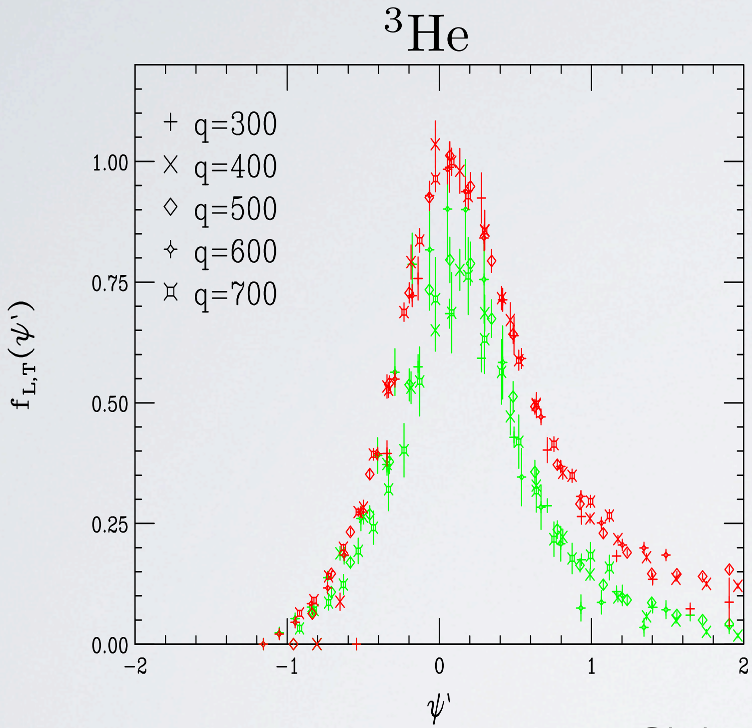
$$R_\alpha(q,\omega) = \sum_{f\neq 0} \delta(\omega + E_0 - E_f)\, |\, \langle f\, |\, O_\alpha(\mathbf{q})\, |0\rangle\, |^2 \qquad \alpha = L, T$$

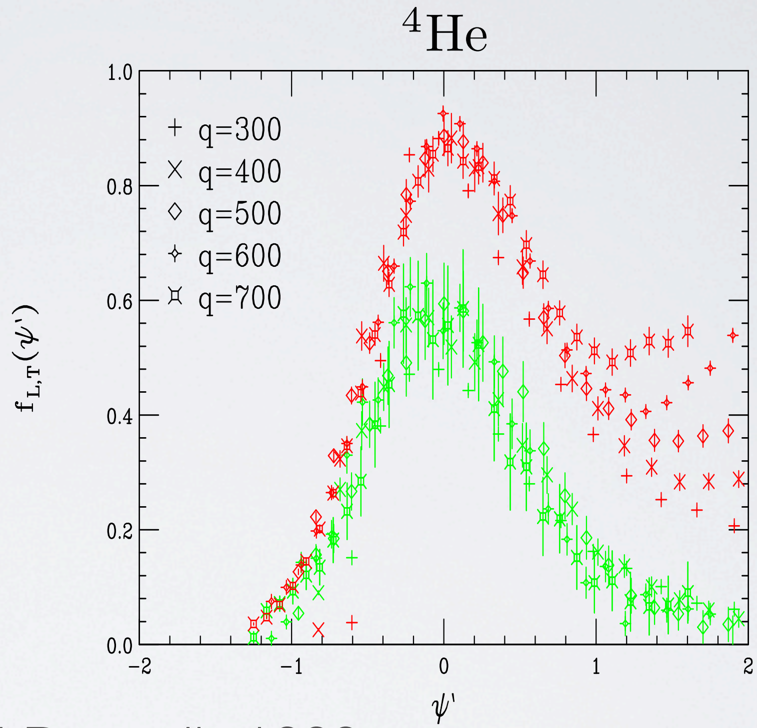
require knowledge of continuum states: hard to calculate for $A \geq 3$

- Sum rules: integral properties of response functions
- Integral transform techniques

$$E(q,\tau) = \int_0^\infty \mathrm{d}\omega\, K(\tau,\omega)\, R(q,\omega)$$

Inclusive Electron Scattering





Sick and Donnelly, 1999

Carlson, Schiavilla, Sick, 2002

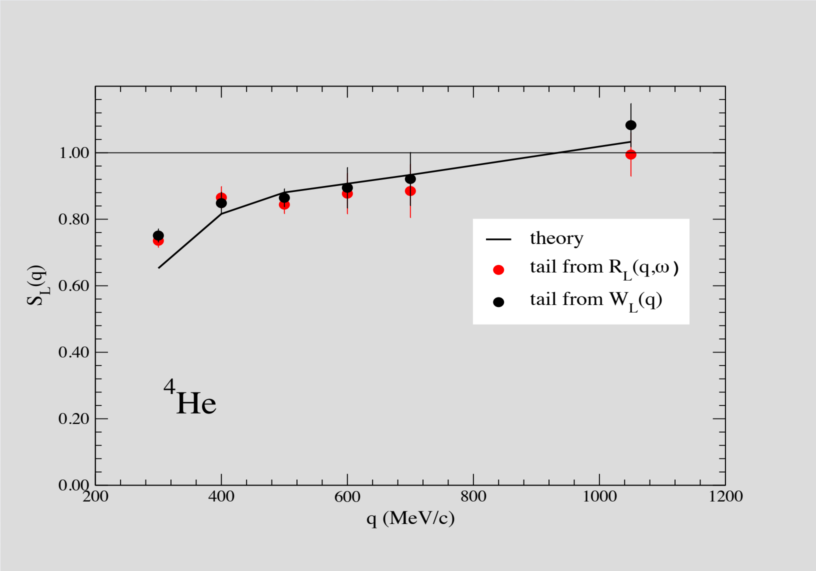
Longitudinal sensitive to pp correlations

Transverse sensitive to np correlations

Measuring charge-charge ('pp') correlations

The ^{4}He Coulomb Sum Rule

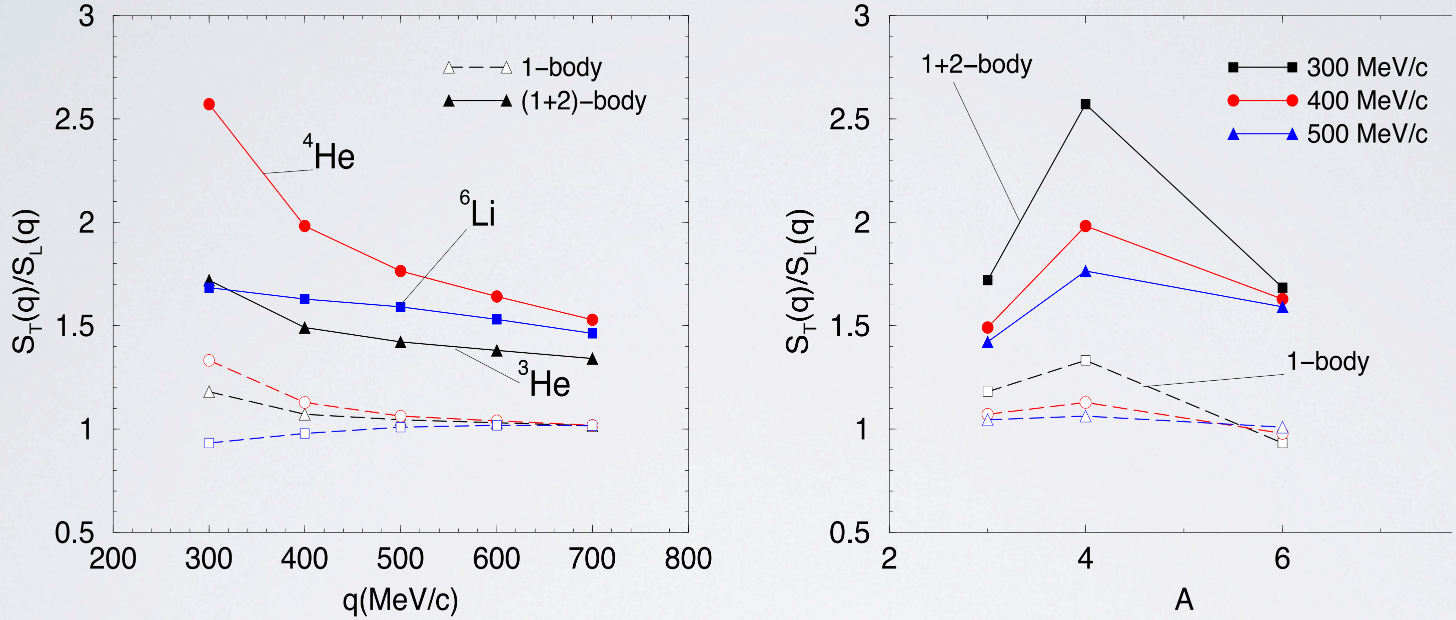
- RC/MEC (small) contributions to $S_L(q)$ tend to cancel out
- Theory and experiment in agreement when using free G_{Ep}



$$W_L(q) = \frac{1}{Z}\int_{\omega_{\rm th}^+}^{\infty} {\rm d}\omega\, \omega\, \frac{R_L(q,\omega)}{G_{Ep}^2(q,\omega)} = \frac{1}{2Z}\langle 0|\left[\rho^\dagger(\mathbf{q})\,,\left[H\,,\rho(\mathbf{q})\right]\right]|0\rangle$$

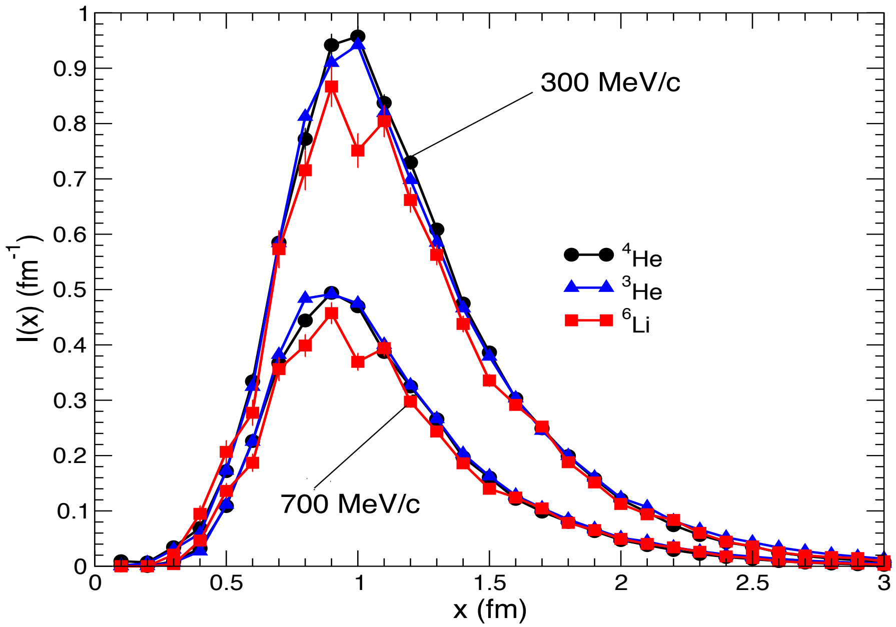
Transverse Channel: 1 + 2-nucleon currents

Excess Transverse Strength



- How much of the excess transverse strength $\Delta S_T = S_T - S_T^{1b}$ in the quasi-elastic peak region?
- Can we understand the A-dependence of ΔS_T?

A-Scaling Property



$$\int_0^\infty \mathrm{d}x\, I(x) = \Delta S_T \propto R_A / \left(Z\,\mu_p^2 + N\,\mu_n^2\right)$$

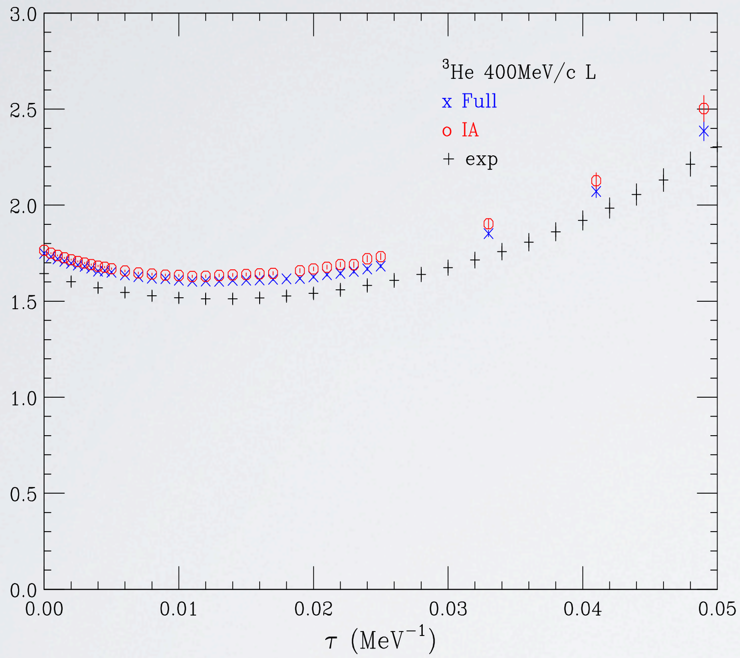
Euclidean Response Functions

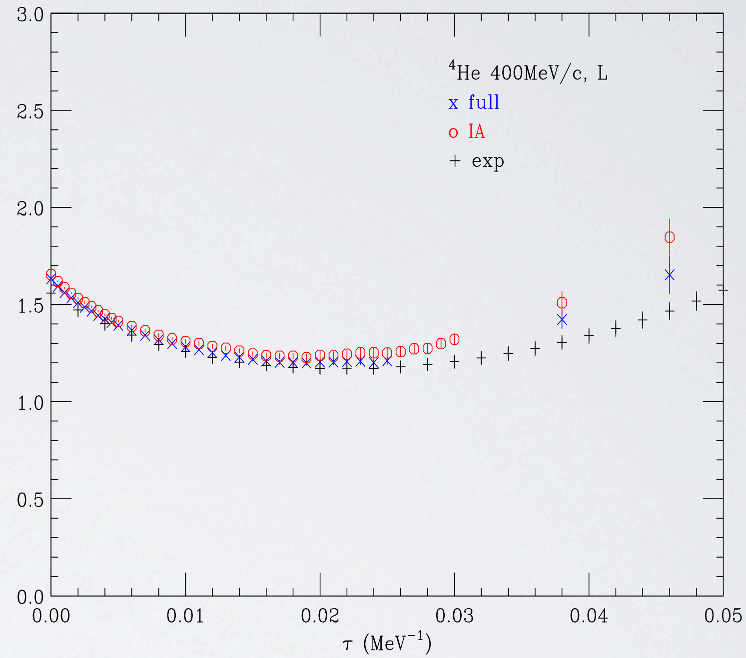
Carlson and Schiavilla (1992,1994)

$$\widetilde{E}_\alpha(q,\tau) = \int_{\omega_{\rm th}^+}^{\infty} {\rm d}\omega\, {\rm e}^{-\tau(\omega-E_0)} \frac{R_\alpha(q,\omega)}{G_{Ep}^2(q,\omega)}$$
$$= \langle 0|\, O_\alpha^\dagger(\mathbf{q}){\rm e}^{-\tau(H-E_0)}O_\alpha(\mathbf{q})\,|0\rangle - (\text{elastic term})$$

- ${\rm e}^{-\tau(H-E_0)}$ evaluated stochastically with QMC
- No approximations made, exact
- At $\tau=0$, $\widetilde{E}_\alpha(q;0) \propto S_\alpha(q)$; as τ increases, $\widetilde{E}_\alpha(q;\tau)$ is more an more sensitive to strength in quasi-elastic region
- Inversion of $\widetilde{E}_\alpha(q;\tau)$ is a numerically ill-posed problem; Laplace-transform data instead

^{3}He and ^{4}He Longitudinal Euclidean Response Functions

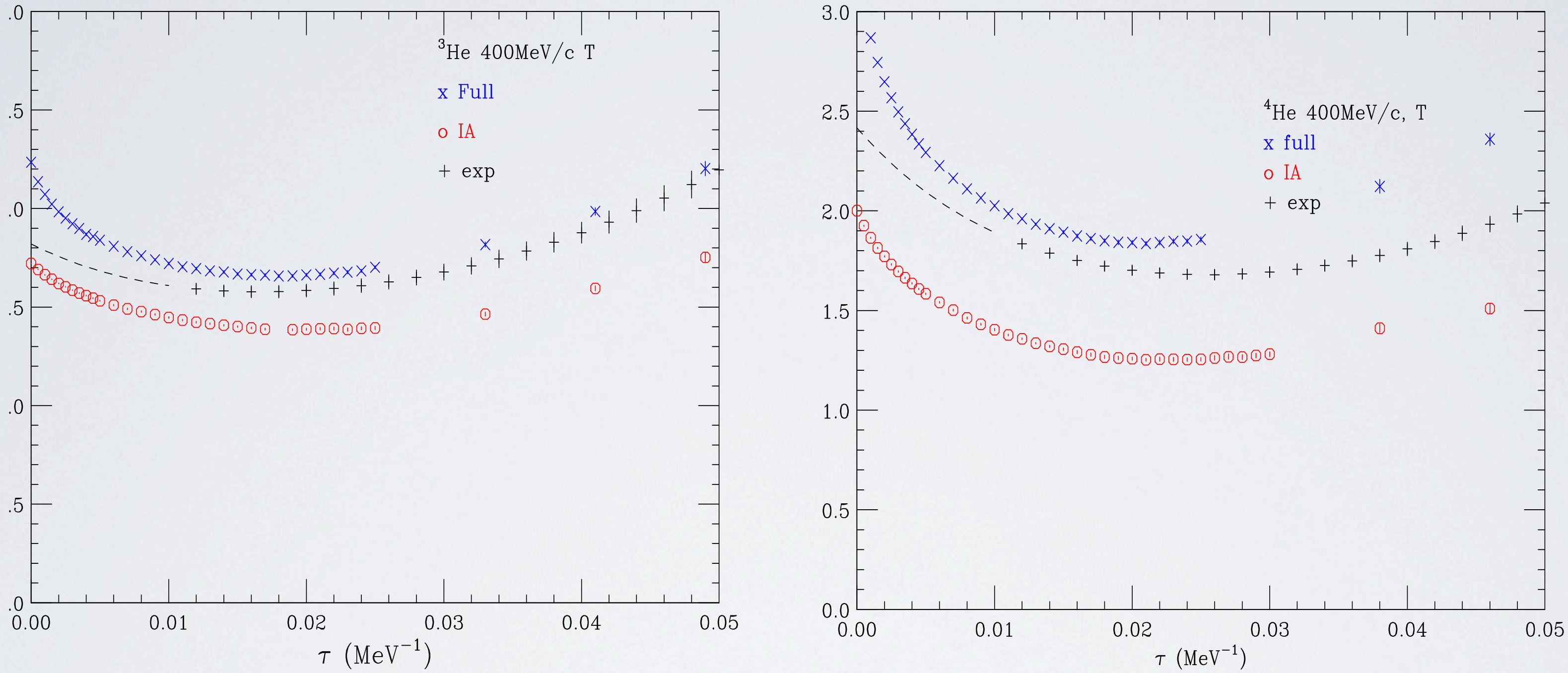




$$E_\alpha(q,\tau) = \exp\left[\tau\, q^2/(2\,m)\right]\ \widetilde{E}_\alpha(q,\tau)$$

and $E_L(q,\tau) \to Z$ for a collection of protons initially at rest

^{3}He and ^{4}He Transverse Euclidean Response Functions

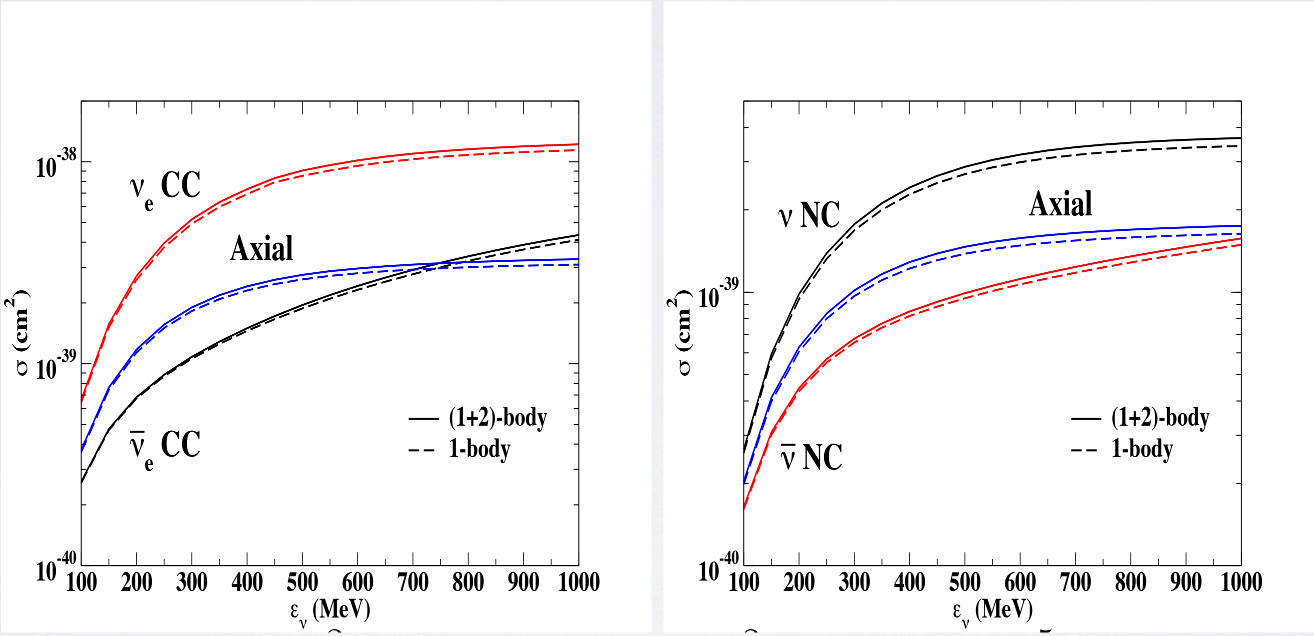


- Excess strength in quasielastic region ($\tau > 0.01$ MeV^{-1})
- Larger in $A = 4$ than in $A = 3$, as already inferred from S_T

What happens in ~GeV neutrino scattering?

ν-Deuteron Scattering up to GeV Energy

Shen *et al.* (2012)

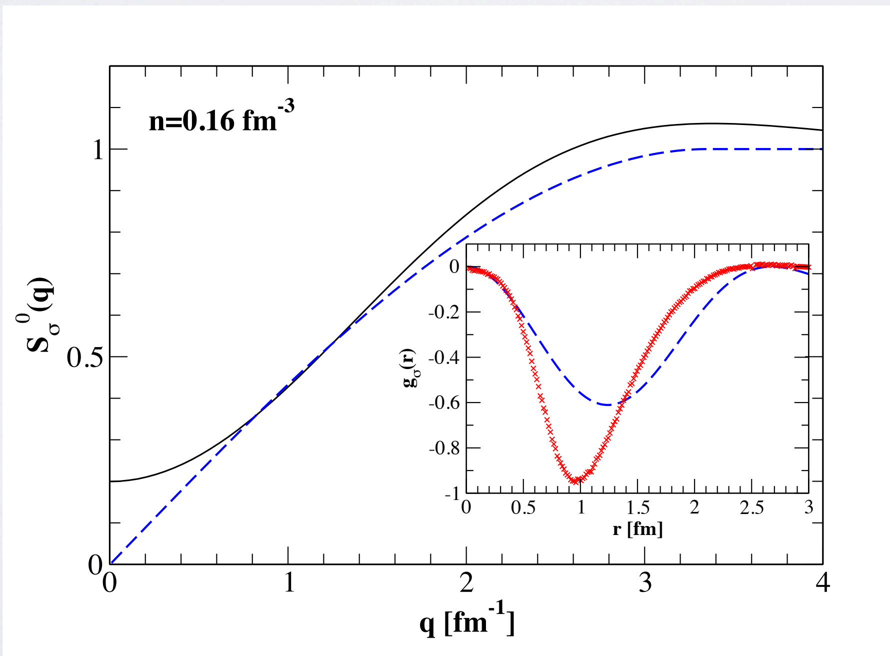


Potentially important in Mini-Boone, LBNE,...

Spin Response in Neutron Matter requires tensor and/or spin-orbit interactions at q=0

$$S_\sigma(\omega, \mathbf{q}) = \frac{4}{3n}\frac{1}{2\pi}\int_{-\infty}^{\infty} dt e^{i\omega t}\langle \mathbf{s}(t,\mathbf{q})\cdot \mathbf{s}(0,-\mathbf{q})\rangle$$
$$= \frac{4}{3n}\sum_f \langle 0|s(\mathbf{q})|f\rangle \cdot \langle f|s(-\mathbf{q})|0\rangle \delta(\omega - (E_f - E_0))$$

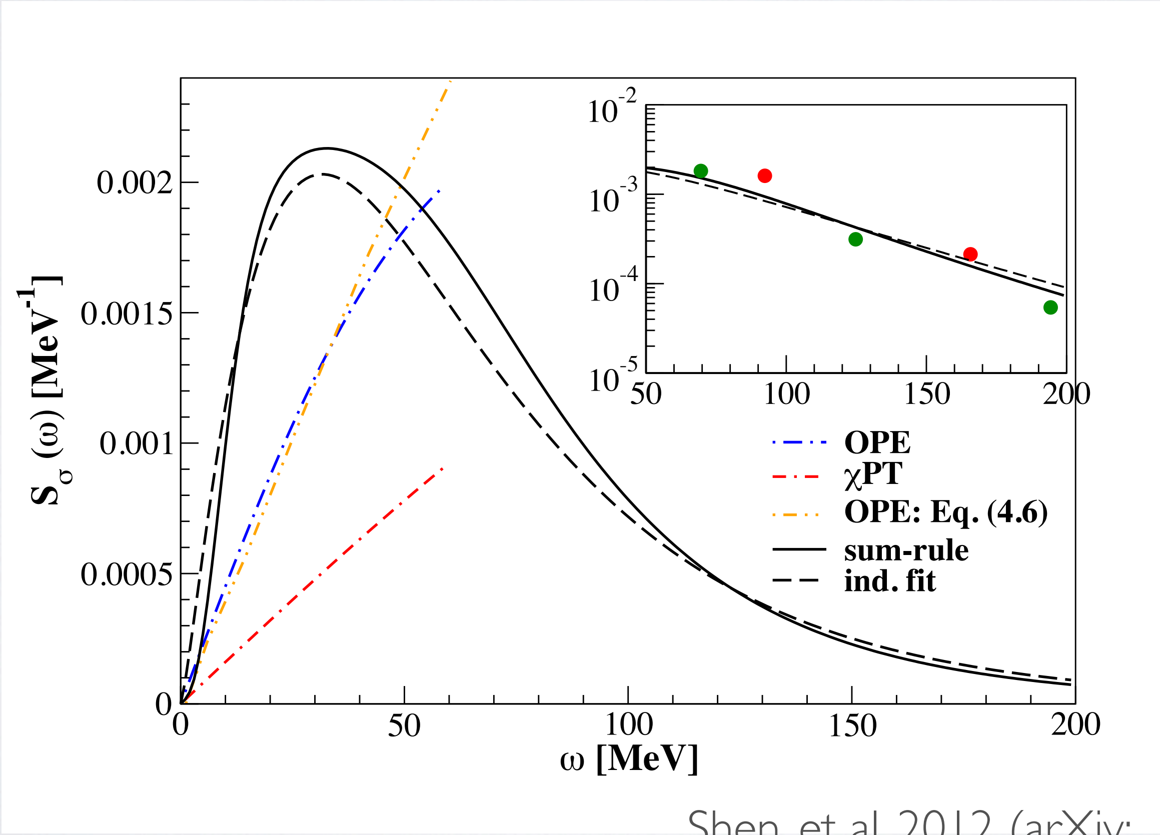
$$Q = \frac{C_A^2 G_F^2 n}{20\pi^3}\int_0^\infty d\omega\ \omega^6\ e^{-\omega/T} S_\sigma(\omega)\,,$$



Sum Rules (inc. spin susceptibility) give measure of overall stength, position and width of peak

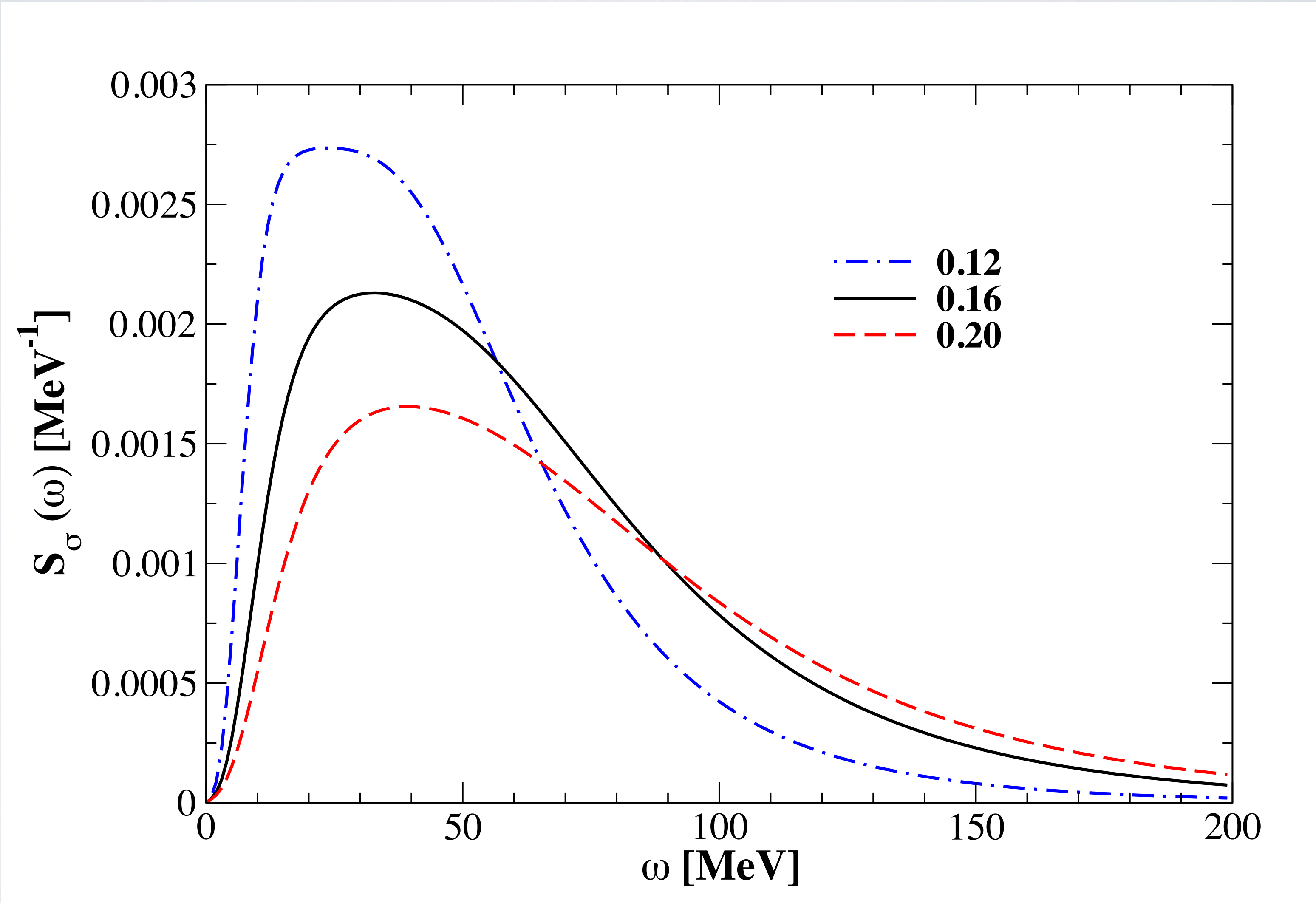
Table I: AFDMC results for the sum-rules

Density (fm^{-3})	S_σ^{-1} (MeV^{-1})	S_σ^0	S_σ^{+1} (MeV)	$\bar{\omega}_0$ (MeV)	$\bar{\omega}_1$ (MeV)
$n = 0.12$	0.0057(9)	0.20(1)	8(1)	35(9)	40(8)
$n = 0.16$	0.0044(7)	0.20(1)	11(1)	46(11)	55(8)
$n = 0.20$	0.0038(6)	0.18(1)	14(1)	47(12)	78(10)

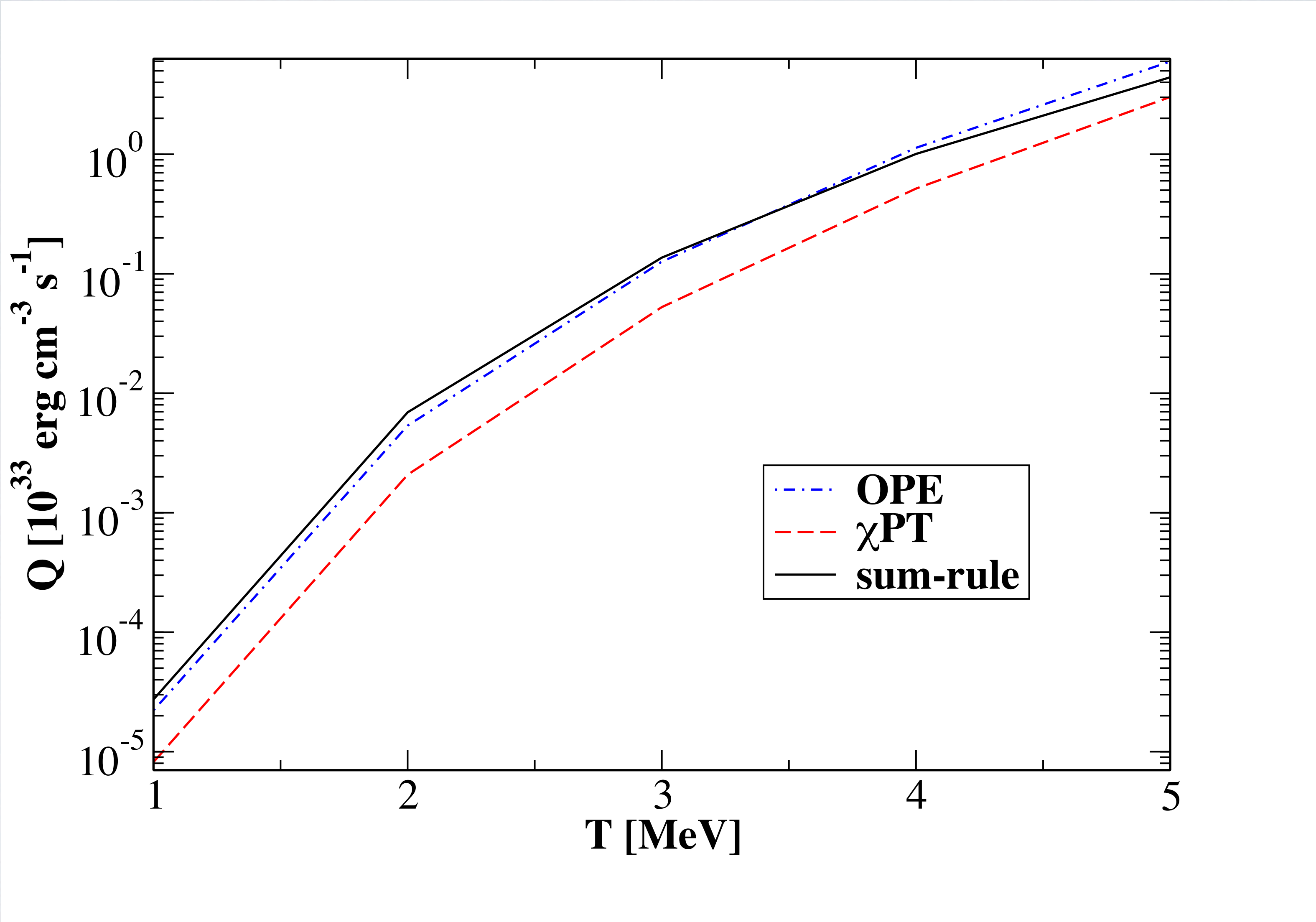


Shen, et al, 2012 (arXiv:

Density dependence of response



Energy loss rate Q



Conclusions:

Tensor (and other) correlations critical in nuclear physics

Obvious impacts in the deuteron (Q,T20,...),
but for larger nuclei, impact not often seen in
low-energy observables (spectra, etc.)

Tensor correlations more important in spin observables

More obvious impact at higher momenta:
np vs. pp back-to-back in electron scattering
inclusive electron and neutrino scattering

Can impact astrophysically relevant behavior:
neutrino propagation, 3P2 pairing, ...