Challenges in Few- to Many-Nucleon Physics

Outline

- Static Properties, Discrete Transitions:
  Ground States, Elastic/ Transition Form Factors
- Low-Energy Properties:
  Electroweak Capture, Parity Violation, ...
- Intermediate Energy Properties: Electron Scattering
- Larger Systems: Neutron Matter

Collaborators

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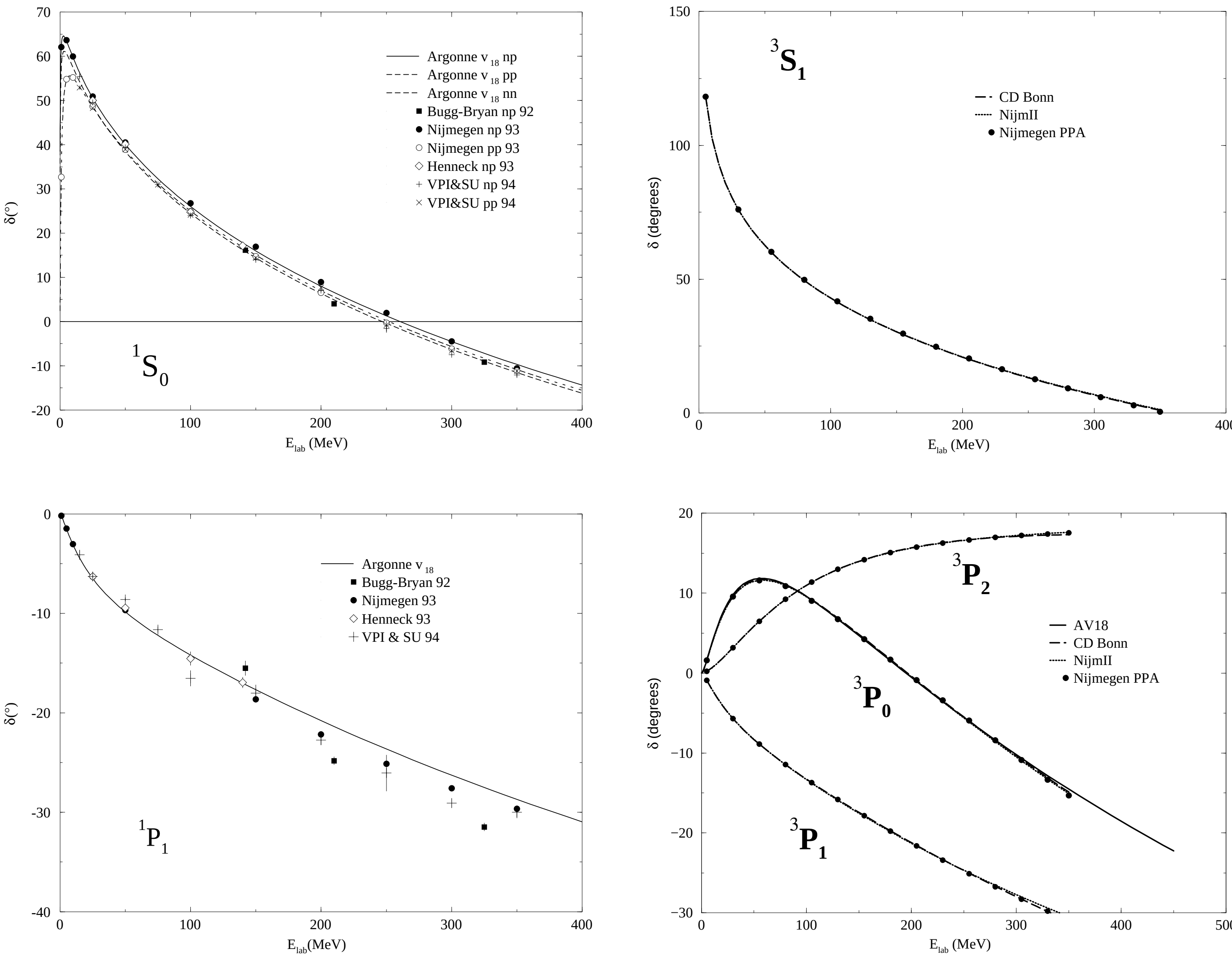
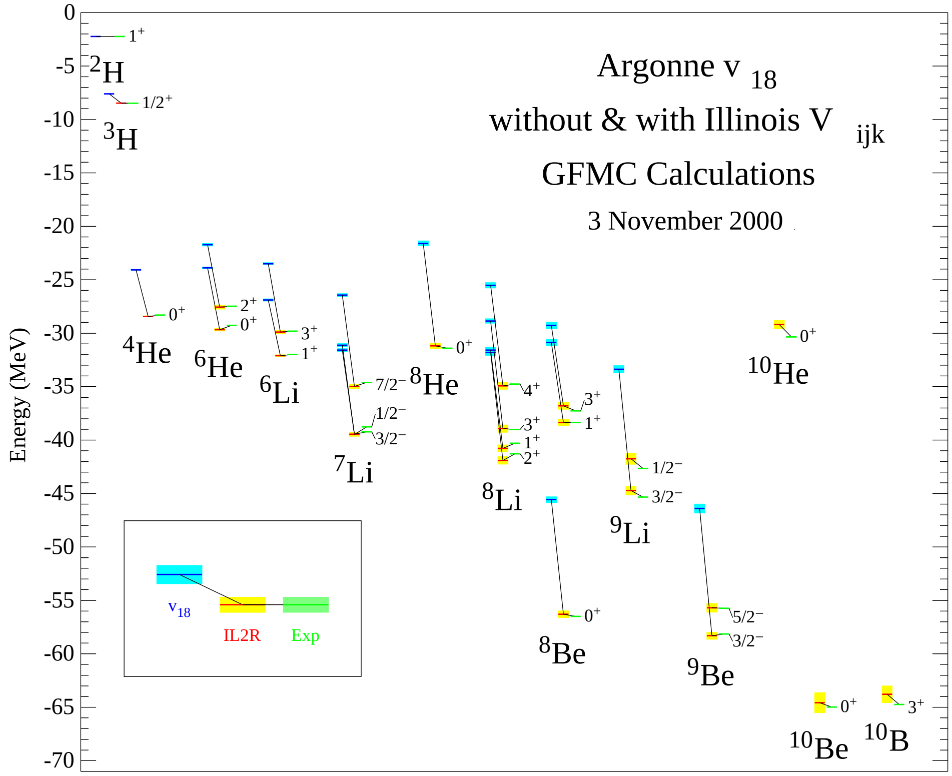
Ingredients:

- Interactions - (Largely Known)
- Currents - (mostly known)
- Non-Perturbative Solutions - (some things known)

Interaction:



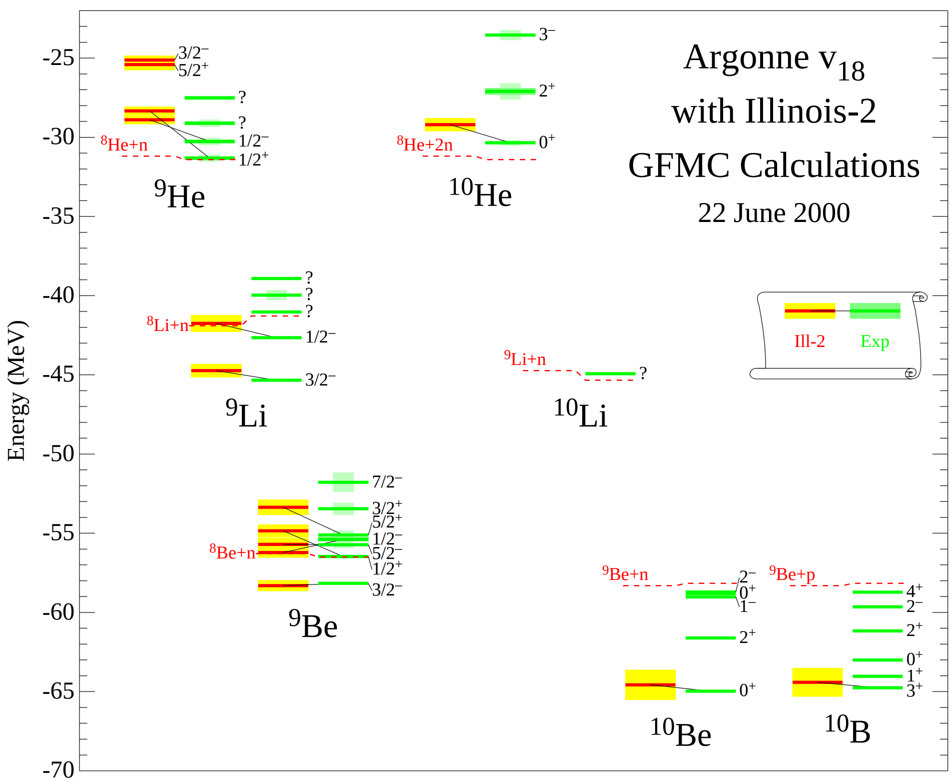
Interaction:



Caveats:

- Chiral Two-Pion Exchange in NN interaction Models
- Alternative Three-Nucleon Interactions
- To what extent do these affect physical observables?

Interaction: Mass 9-10 Spectra from Illinois Vijk



Neutron Matter: Test of Integral Equation Variational Methods
14N w/ PBC

- nearly identical one-body density matrix
- Importance of elementary diagrams
- Accuracy of variational wvfn
- Test of short-distance physics

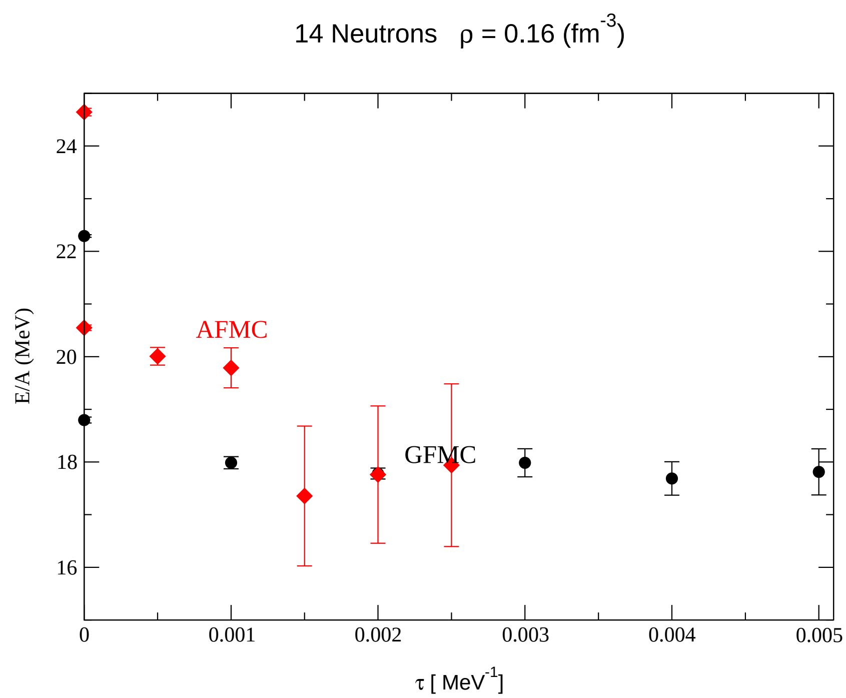
FHNC vs. GFMC (pbc)

	ρ=0.16			$\rho = 0.24 fm^{-3}$		
H	FHNC	GFMC	Δ(%)	FHNC	GFMC	Δ(%)
V4	21.9	21.2(1)	-3	34.9	34.4(1)	-1.5
V4LS	18.5	19.3(3)	4	28.2	29.8(6)	5
V6	21.2	20.0(2)	-6	34.5	32.1(1)	-7.5
V8'	17.7	17.9(2)	1	27.4	29.1(3)	6

- Errors range up to $\approx$ 10%.
- Larger errors in $< V >$ at $\rho = 0.24$; primarily OPEP - needs to be sorted out

AFDMC : Schmidt and Fantoni

- Samples path integrals over coordinates AND spin/isospins
- Large systems possible (up to 100)
- Approximate constraint on Path Integral needed



Electroweak Transitions: Current Operators

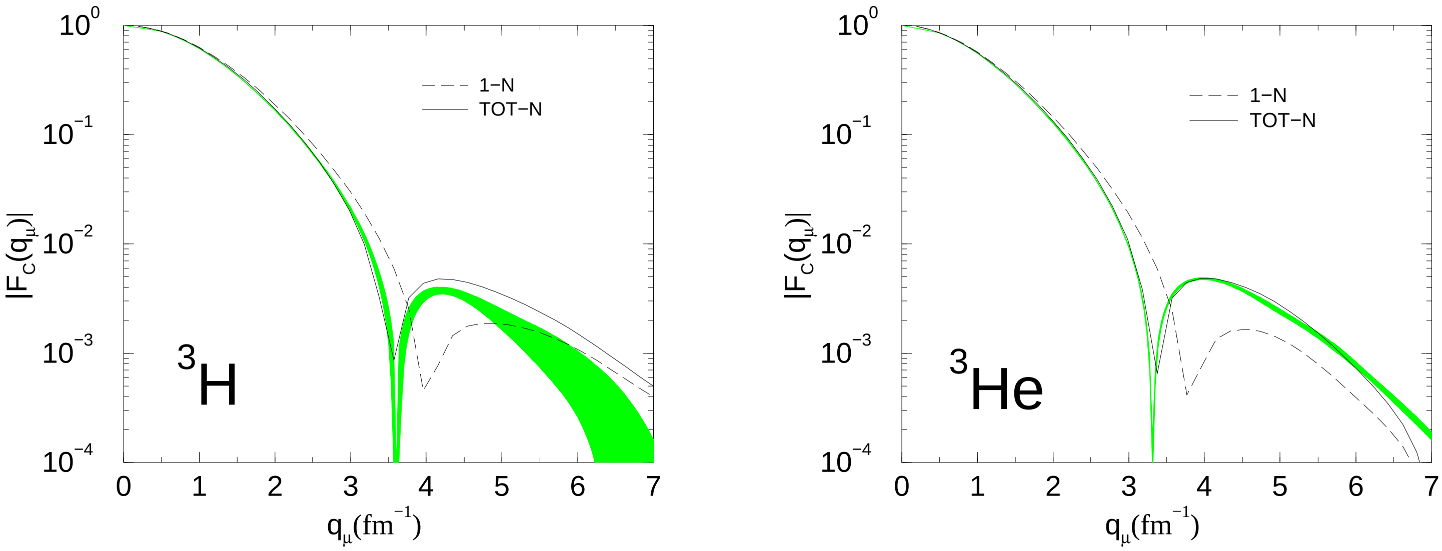
$$\rho(\mathbf{q}) = \sum_i \rho_i^1 + \sum_{i<j>} \rho_{ij}^2 + \ldots$$

$$\rho_i^{(1)}(\mathbf{q}) = \rho_{i,\mathrm{NR}}^{(1)}(\mathbf{q}) + \rho_{i,\mathrm{RC}}^{(1)}(\mathbf{q}) \ ,$$

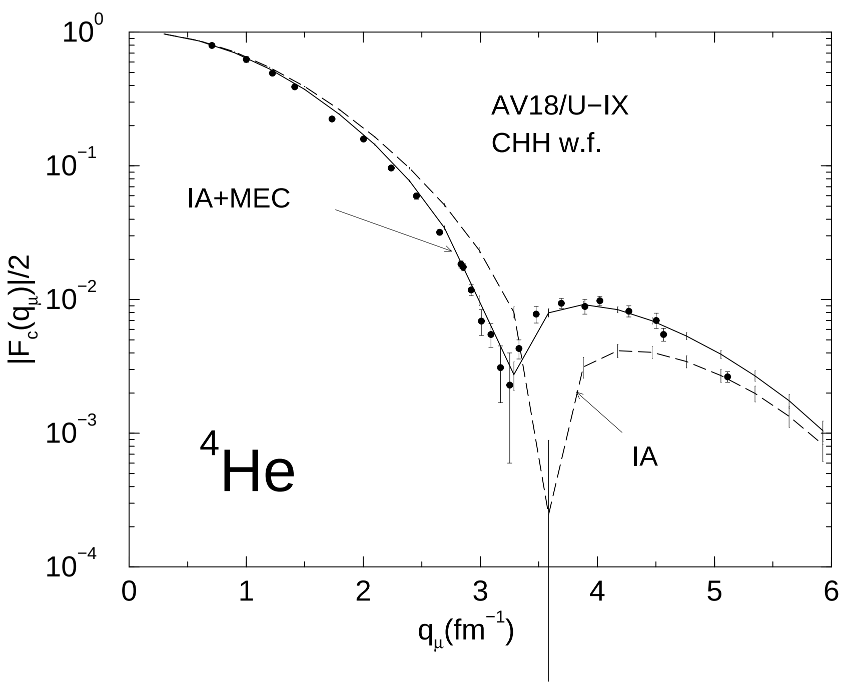
$$\rho_{i,\mathrm{NR}}^{(1)}(\mathbf{q}) = \epsilon_i \, \mathrm{e}^{\mathbf{i}\mathbf{q}\cdot\mathbf{r}_i}$$

$$\begin{aligned}\rho_{i,\mathrm{RC}}^{(1)}(\mathbf{q}) = {} & \left(\frac{1}{\sqrt{1+Q^2/4m^2}} - 1\right) \epsilon_i \, \mathrm{e}^{\mathbf{i}\mathbf{q}\cdot\mathbf{r}_i} \\ & - \frac{\mathbf{i}}{4m^2} \left(2\,\mu_i - \epsilon_i\right) \mathbf{q} \cdot \left(\sigma_i \times \mathbf{p}_i\right) \mathrm{e}^{\mathbf{i}\mathbf{q}\cdot\mathbf{r}_i}\end{aligned}$$

$$\begin{aligned}\rho_{ij,\pi}(\mathbf{k}_i, \mathbf{k}_j) = {} & \frac{3}{2m} \Big[\left[F_1^S(Q^2) \tau_i \cdot \tau_j + F_1^V(Q^2) \tau_{z,j} \right] \\ & v_\pi(k_j) \sigma_i \cdot \mathbf{q} \, \sigma_j \cdot \mathbf{k}_j \\ & + \left[F_1^S(Q^2) \tau_i \cdot \tau_j + F_1^V(Q^2) \tau_{z,i} \right] \\ & v_\pi(k_i) \sigma_i \cdot \mathbf{k}_i \, \sigma_j \cdot \mathbf{q} \Big] \ ,\end{aligned}$$



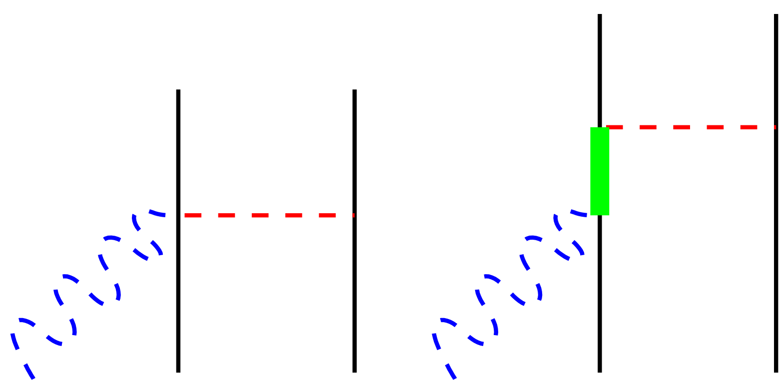
CHARGE FORM FACTOR



EM Currents

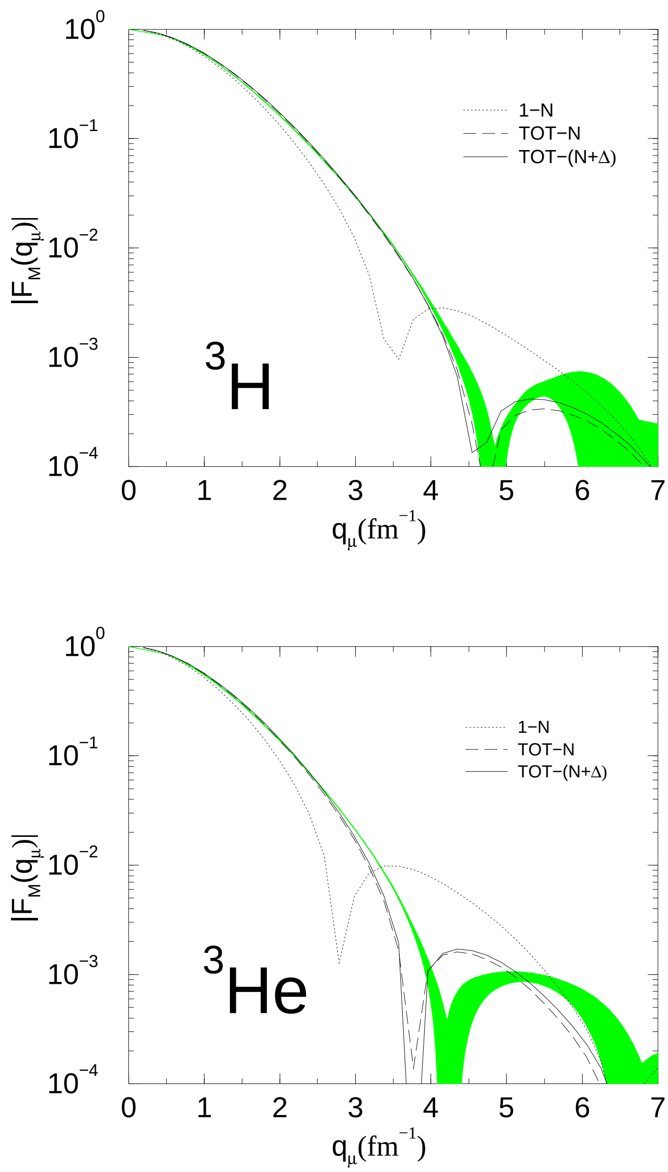
$$\mathbf{j}_i^{(1)}(\mathbf{q}) = \frac{1}{2m}\epsilon_i \left\{\mathbf{p}_i \,,\, \mathrm{e}^{\mathrm{i}\mathbf{q}\cdot\mathbf{r}_i}\right\} - \frac{\mathrm{i}}{2m}\mu_i\, \mathbf{q} \times \sigma_i\, \mathrm{e}^{\mathrm{i}\mathbf{q}\cdot\mathbf{r}_i}$$

$$\mathbf{j}_{ij,\pi}^{(2)}(\mathbf{k}_i,\mathbf{k}_j) = 3\mathrm{i}(\tau_i \times \tau_j)_z\, G_E^V(Q^2) \left[v_\pi(k_j)\sigma_i(\sigma_j \cdot \mathbf{k}_j) - v_\pi(k_i)\sigma_j(\sigma_i \cdot \mathbf{k}_i)\right]$$



$$\mathbf{j}_{\Delta_{\rm PT},ij} = \mathbf{j}_i(\mathbf{q};\Delta \to N)\frac{v_{NN\to\Delta N,ij}}{m - m_\Delta} + \frac{v_{\Delta N\to NN,ij}}{m-m_\Delta}\mathbf{j}_i(\mathbf{q}; N \to \Delta) + i \rightleftharpoons j$$

$$\ldots$$



10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
$|F_M(q_\mu)|$
1−N
TOT−N
TOT−(N+Δ)
^{3}H
0 1 2 3 4 5 6 7
$q_\mu(fm^{-1})$
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
$|F_M(q_\mu)|$
1−N
TOT−N
TOT−(N+Δ)
^{3}He
0 1 2 3 4 5 6 7
$q_\mu(fm^{-1})$

A=6 Form Factors

Fig.1 Wiringa & Schiavilla

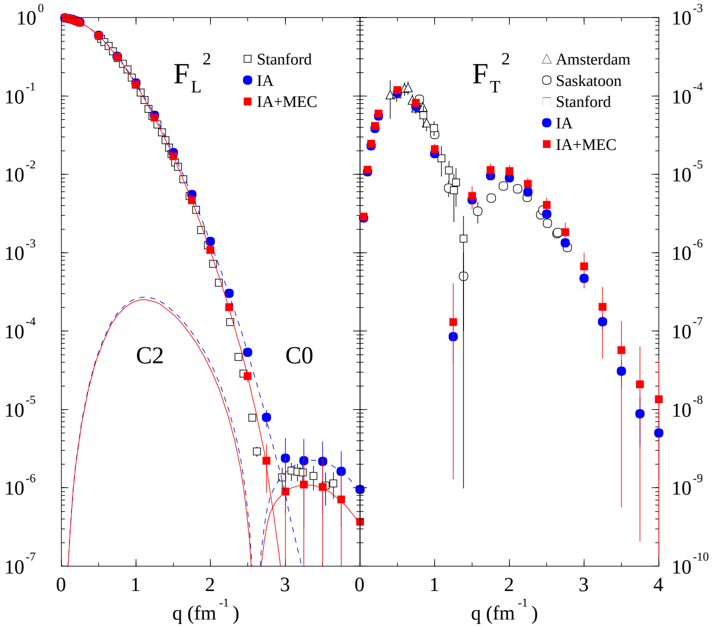
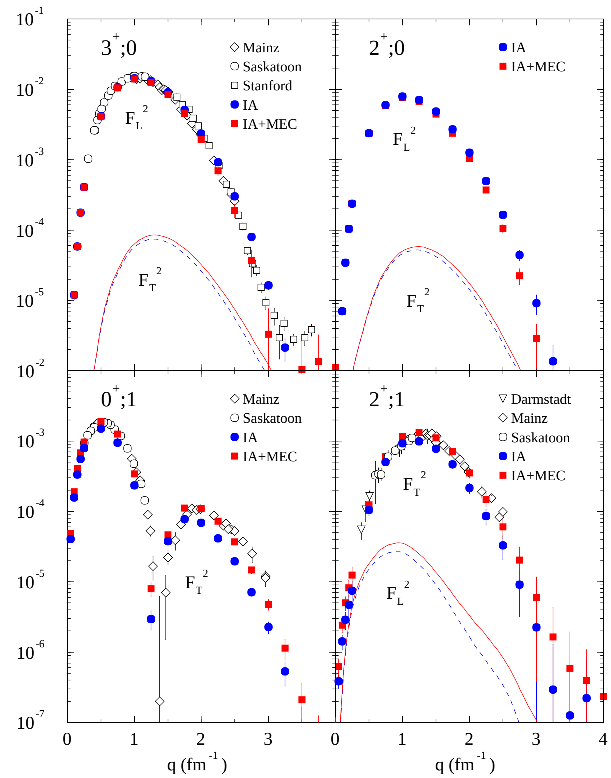


Fig.2 Wiringa & Schiavilla

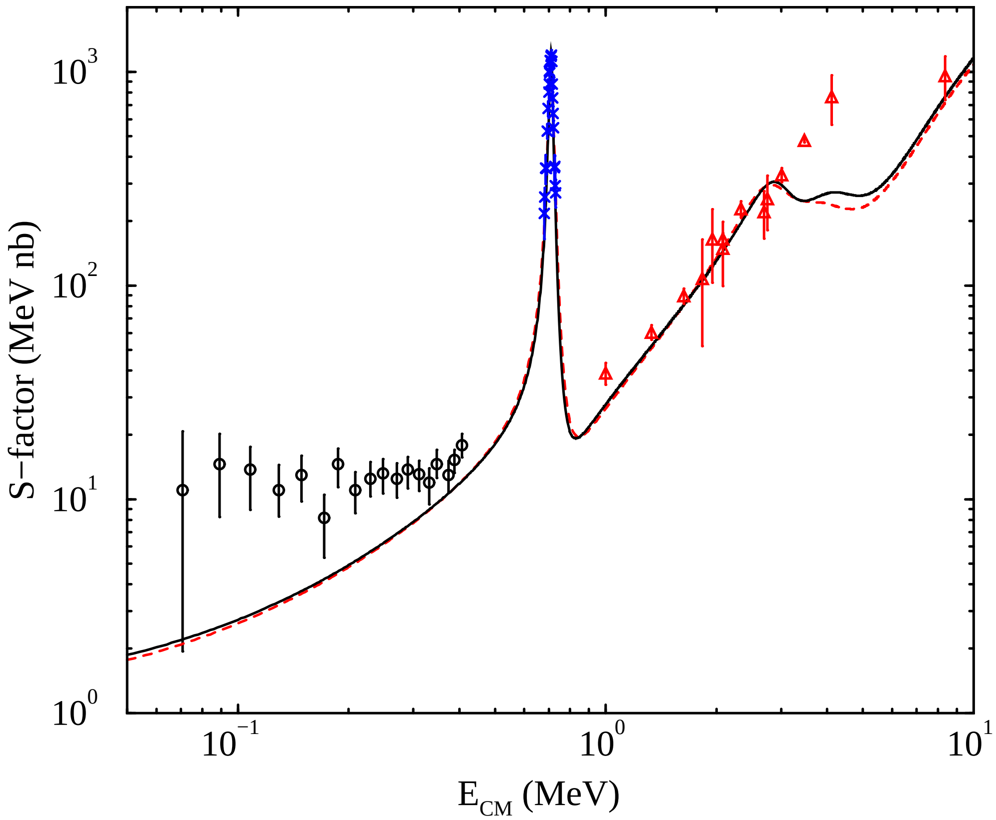


Caveats

- Relativistic Treatment consistent with charge operator
- Experimental constraints on currents beyond Pion
- Electroweak Currents...

Low Energy Scattering: α-d capture

R. B. Wiringa and K. Nollett

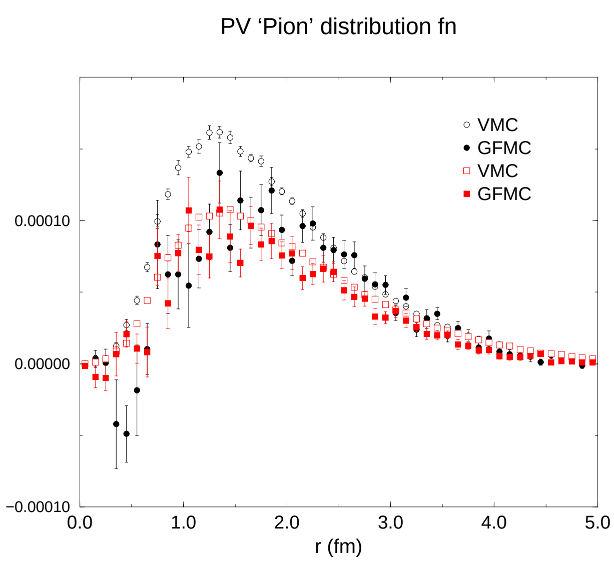


Calculation:

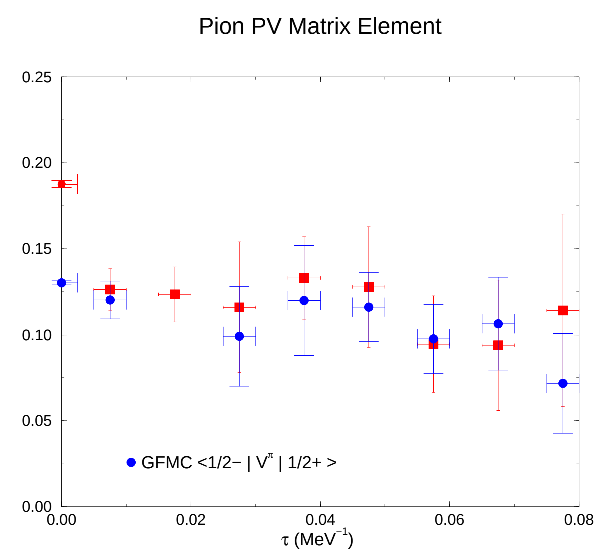
- VMC calculation of α, ^{6}Li wave functions
- Include careful attention to asymptotic boundary conditions
- Optical Model Potential for α-d scattering
- Consistent with Microscopic Interaction ?

Low Energy Scattering:
Parity-Violation in $\vec{n} - \alpha$

Radial Dependence



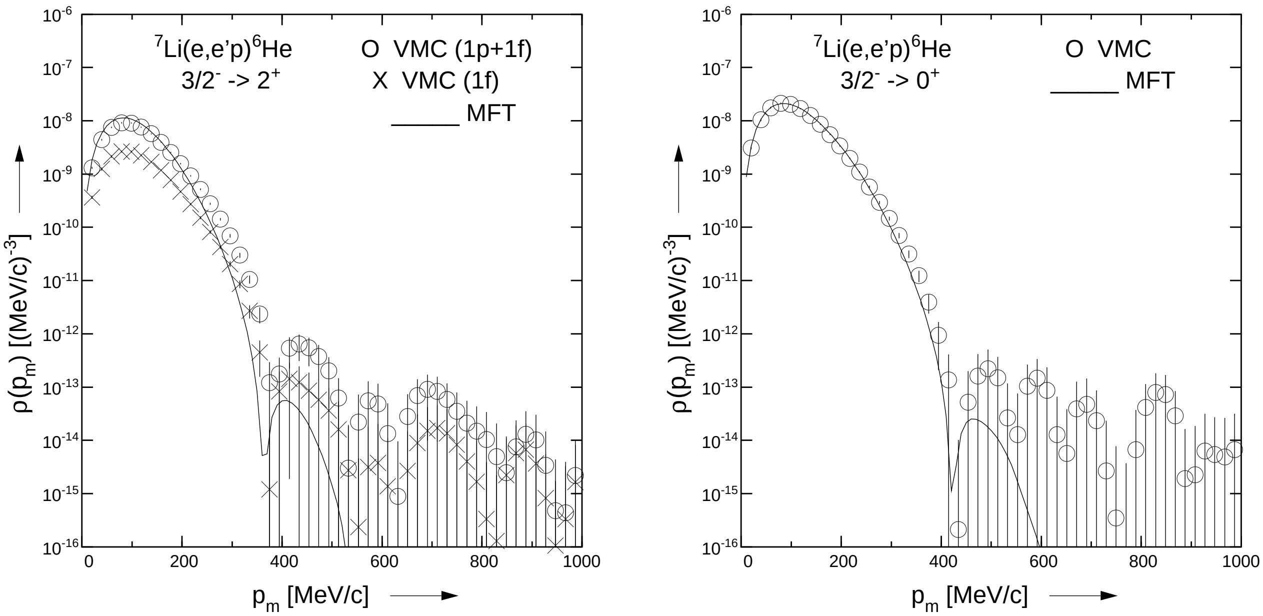
Matrix Element Convergence



Calculation:

- Extract Pion PV (and other) contributions to $\vec{n} - \alpha$
- Similar Efforts underway in β-decay of p-shell nuclei spin rotation.

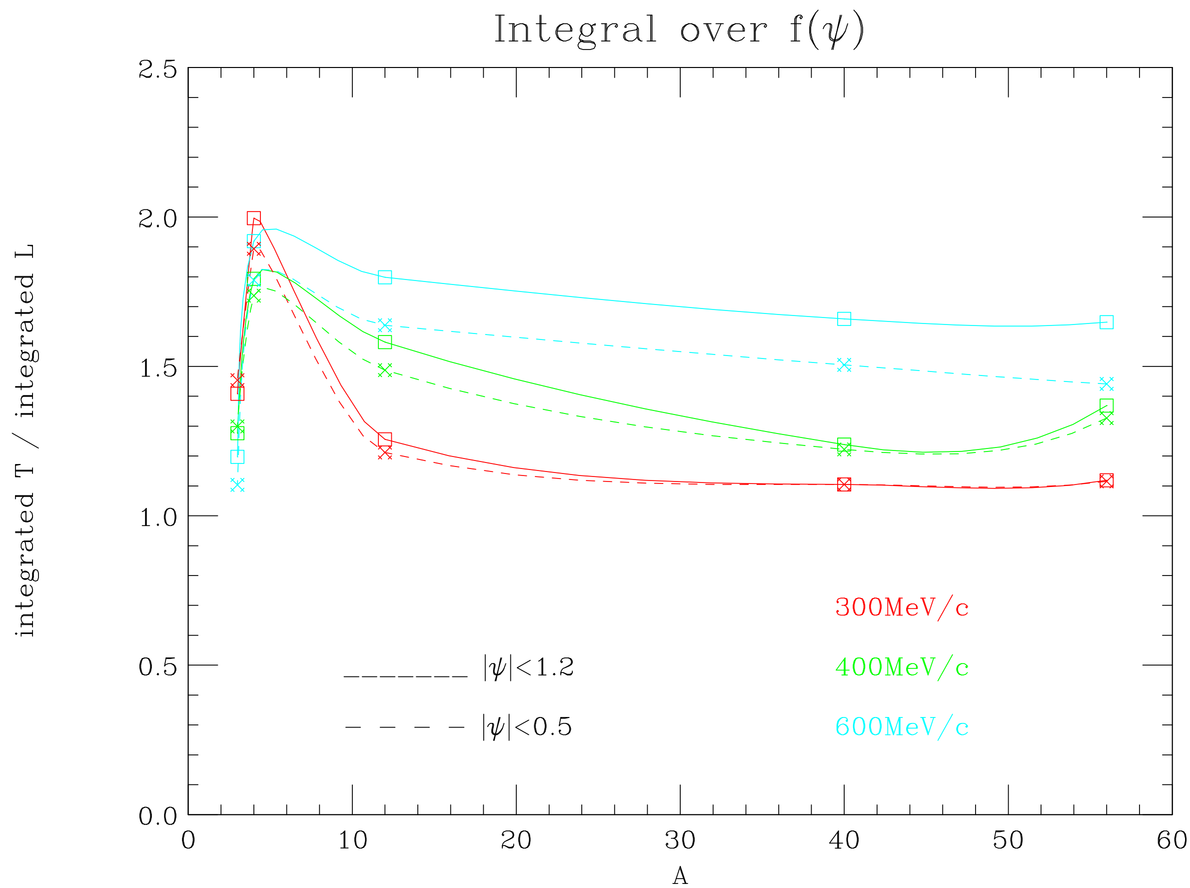
Electron Scattering: (e,e'p)



Calculation:

- Microscopic calculations of nuclear wvfns, overlaps
- Optical Potential Treatment
- Challenges: Microscopic determination of exclusive scattering, studies of energy dependence, etc.

Inclusive Response: Integrated Transverse / Longitudinal Strength



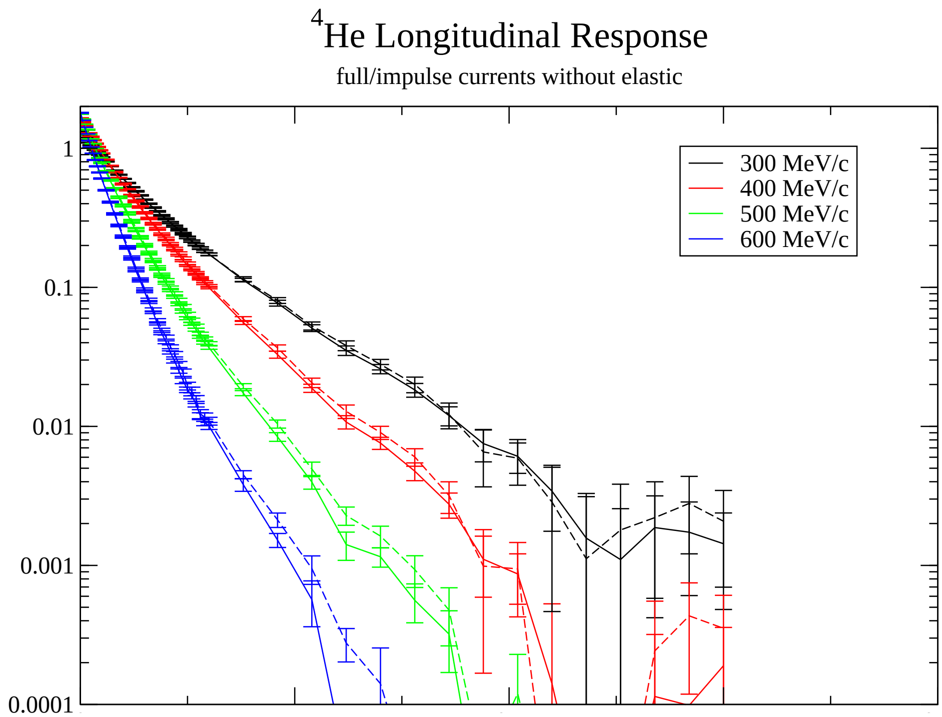
Inclusive Response

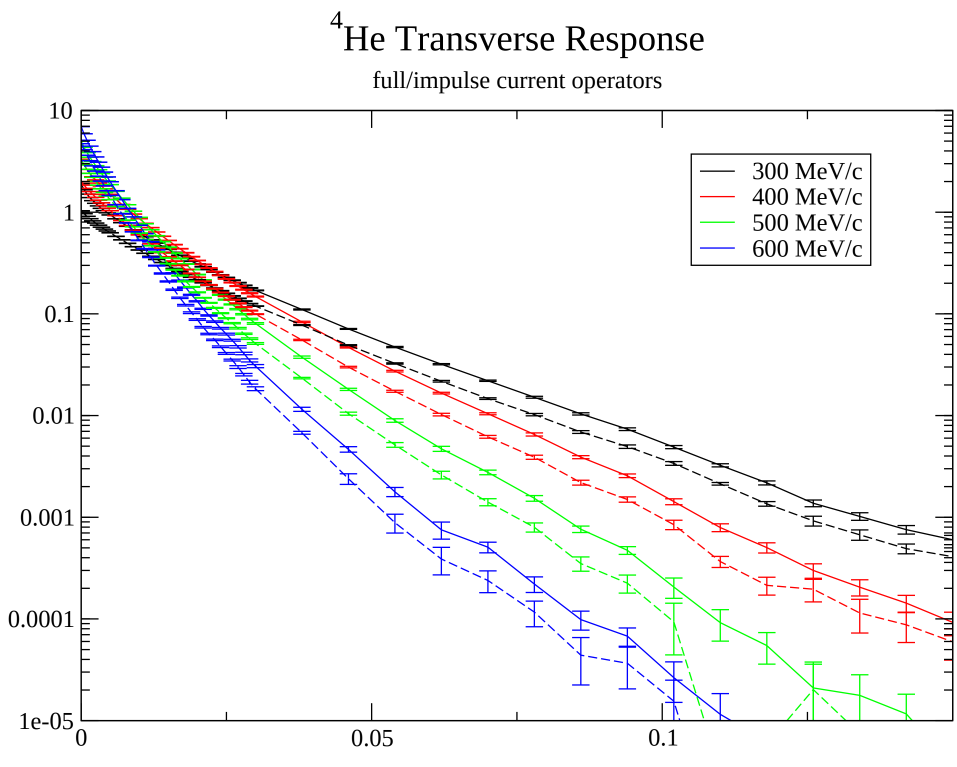
Longitudinal / Transverse Sum Rules

$$
\begin{aligned}
S_L(q) &= \langle 0|\rho^\dagger(\mathbf{q})\rho(\mathbf{q})|0> - |\langle 0_\mathbf{q}|\rho(\mathbf{q})|0\rangle|^2 \\
S_T(q) &= \langle 0|\mathbf{J}^\dagger(\mathbf{q})\mathbf{J}(\mathbf{q})|0> - |\langle 0_\mathbf{q}|\mathbf{J}(\mathbf{q})|0\rangle|^2
\end{aligned}
$$

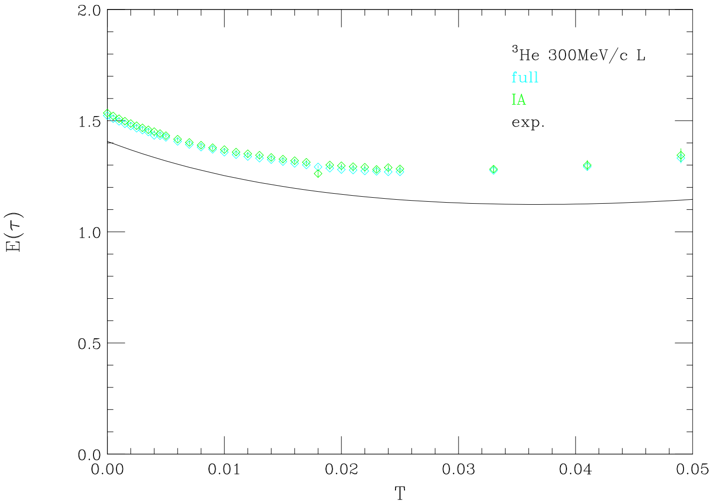
Euclidean Response

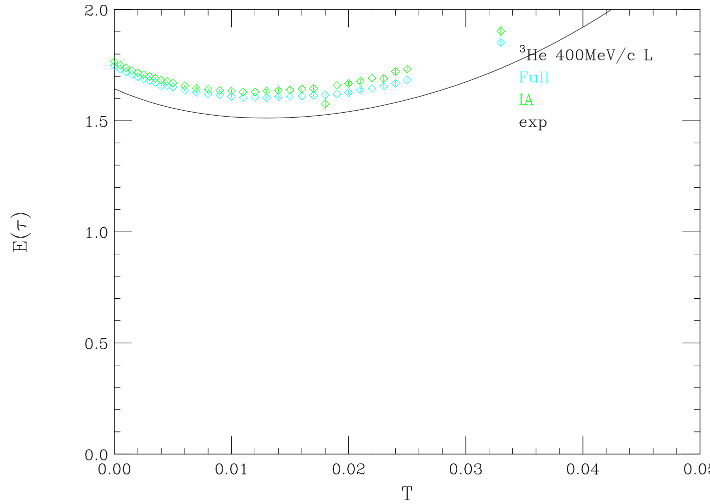
$$
\begin{aligned}
E_L(q) &= \langle 0|\rho^\dagger(\mathbf{q})\exp[-(H - E_0 - q^2/(2m))\tau]\rho(\mathbf{q})|0> \\
&\quad -|\langle 0_\mathbf{q}|\rho(\mathbf{q})|0\rangle|^2 \exp[-E_r\tau] \\
&= \int d\omega \ S_L(q,\omega) \ \exp(-\omega\tau) \\
E_T(q) &= \langle 0|\mathbf{J}^\dagger(\mathbf{q})\exp[-(H - E_0 - q^2/(2m))\tau]\mathbf{J}(\mathbf{q})|0> \\
&\quad -|\langle 0_\mathbf{q}|\mathbf{J}(\mathbf{q})|0\rangle|^2 \exp[-(E_r - q^2/(2m)\tau] \\
&= \int d\omega \ S_T(q,\omega) \ \exp(-(\omega - q^2/(2m)\tau)
\end{aligned}
$$


4He Longitudinal Response
full/impulse currents without elastic
300 MeV/c
400 MeV/c
500 MeV/c
600 MeV/c
1
0.1
0.01
0.001
0.0001

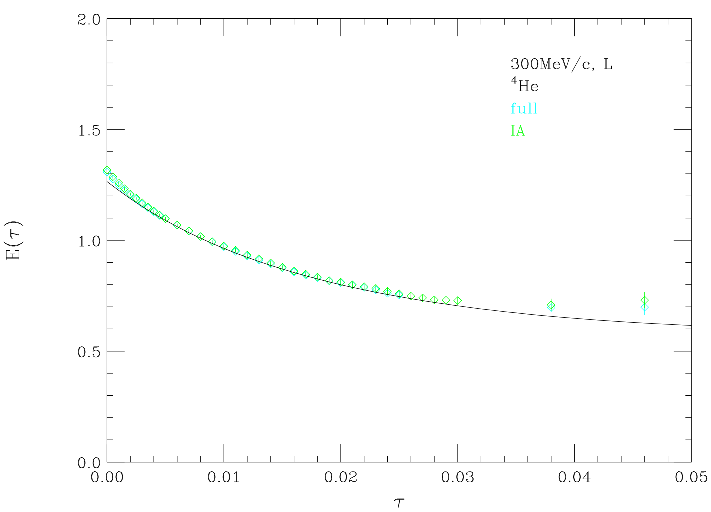

4He Transverse Response
full/impulse current operators
300 MeV/c
400 MeV/c
500 MeV/c
600 MeV/c
10
1
0.1
0.01
0.001
0.0001
1e-05
0
0.05
0.1

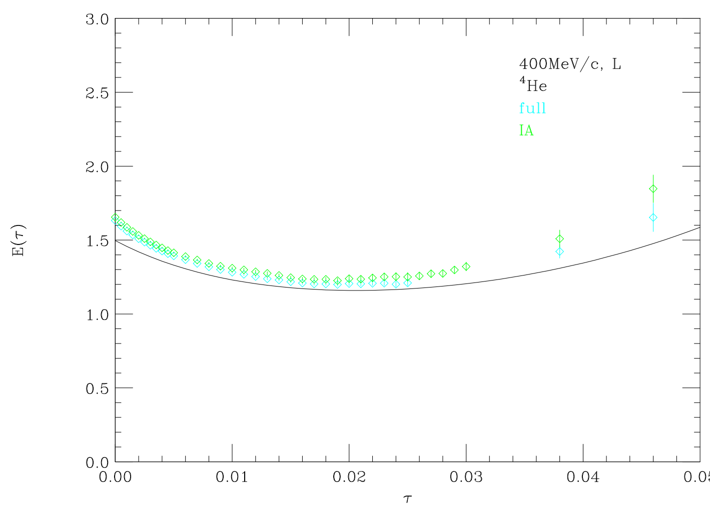
^{3}He Longitudinal Theory vs. Exp



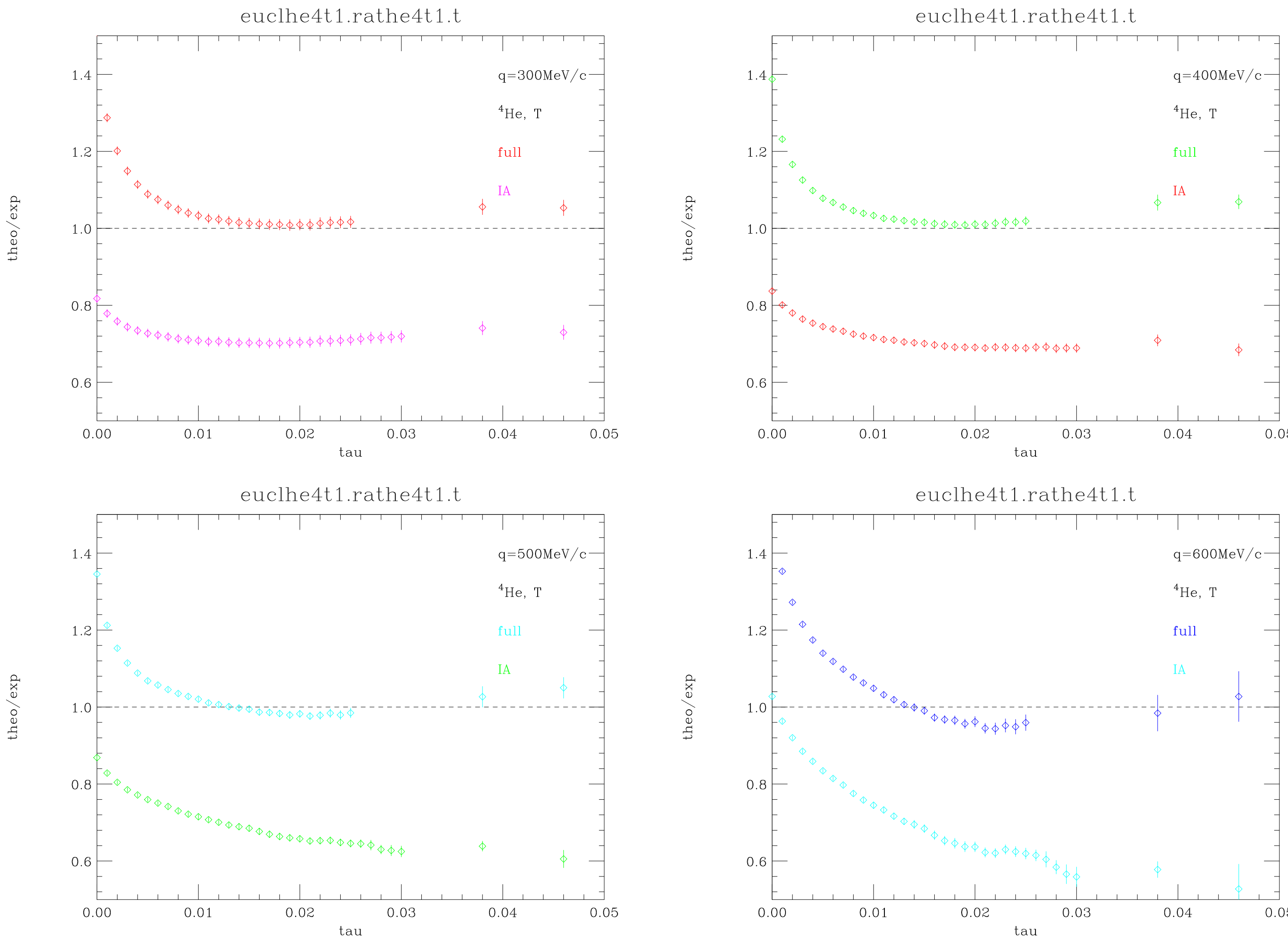


^{4}He Longitudinal Theory vs. Exp

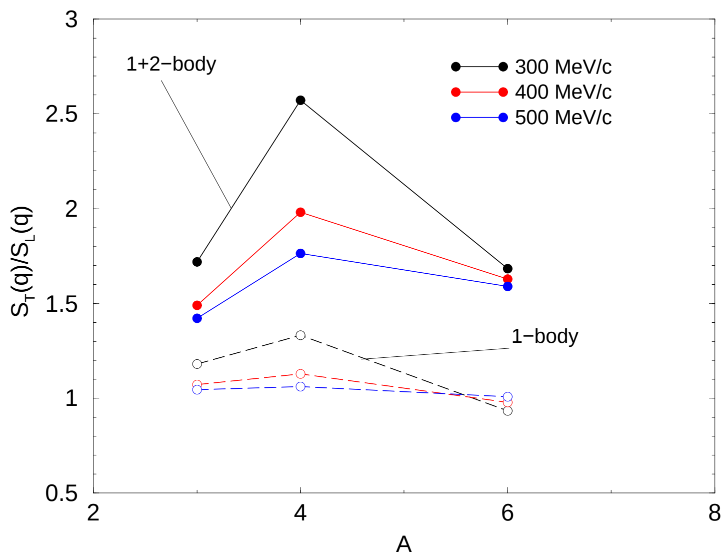




^{4}He Transverse Theory / Exp



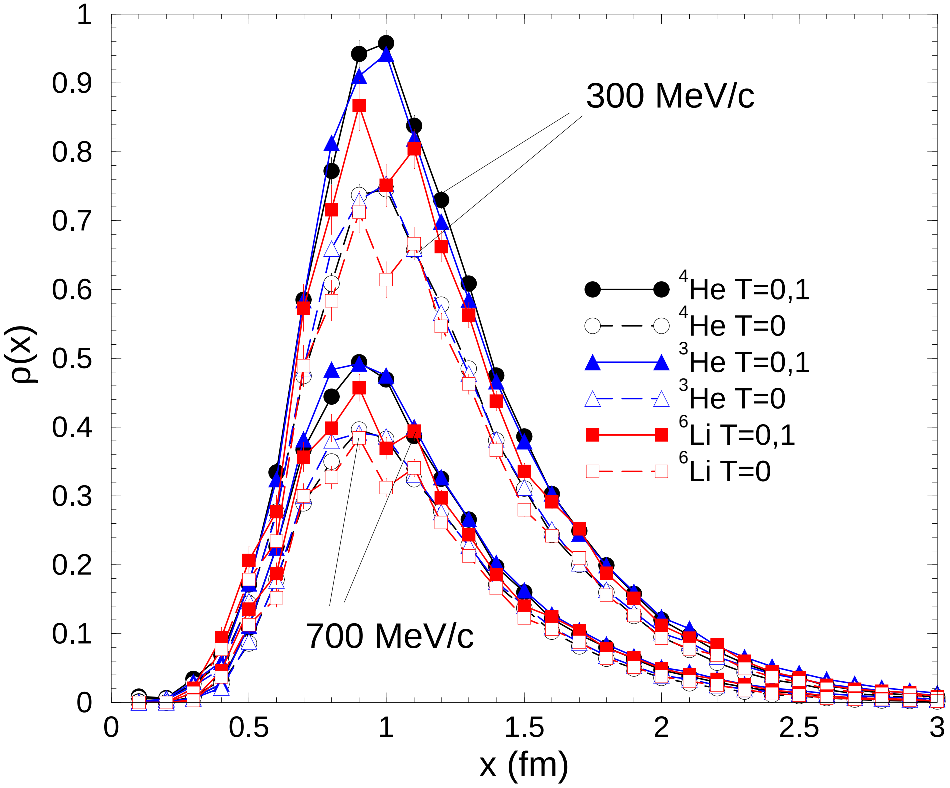
Inclusive Response Beyond A=4
‘Excess’ Strength from T/L Sum Rules



- Strength comes from $\mathbf{j}_{ij}^{\dagger}\mathbf{j}_{ij}$ terms and from single-particle two-nucleon current interference
- Pion exchange current plus currents from Delta dominate
- Transverse strength comes from np pairs
- Conjecture: can scale ‘excess strength’ beyond 1-body from np pair dist (90 % level)

Inclusive Response: Scaling Results

Assume scaling applies to each element of pair distribution fn:



Sum rule indicates that np pairs dominate exchange current effects; larger distances more important at finite τ.

Can explain sum rules in A=6 by this scaling.

Does this qualitatively explain scaling for large Nuclei?

Challenges

- Spectra / Static Properties:
  - Larger Nuclei (GFMC up to 12; AFDMC beyond)
  - Neutron & Nuclear Matter: EOS, Long-Distance Properties
  - β decay of p-shell nuclei
- Low Energy Scattering:
  - Hadronic Reactions as tests of interaction
  - Electroweak Capture Reactions (BBN, solar, ...)
  - PV processes
  - Resonance properties in p-shell states
- Response and Beyond
  - Mass Dependence of EM response in nuclei
  - Inclusive Neutrino scattering
  - Polarizabilities, ...