Electroweak interactions in nuclei

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NUCLEI Nuclear Computational Low-Energy Initiative

www.computingnuclei.org

U.S. DEPARTMENT OF ENERGY

NERSC National Energy Research Scientific Computing Center

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Motivation

At "nuclear" energies, understanding neutrino-nucleus interactions very challenging and important!

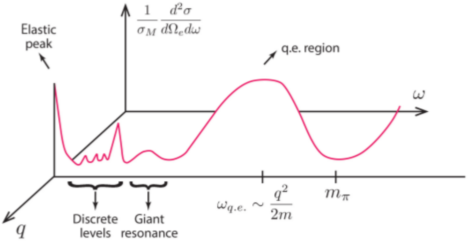
Understanding Nuclei:

- Nuclear interactions and structure
- Electroweak processes

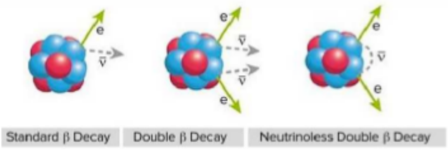
Relevance:

- Neutrino scattering in nuclei (neutrino oscillation experiments)
- Neutrinoless Double Beta Decay
- Neutrino interactions in supernovae and neutron stars, nucleosynthesis

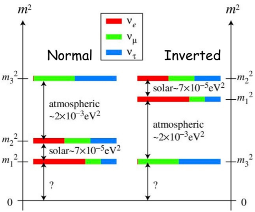
We need a coherent picture of ν-nucleus interactions



- $\omega \approx$ few MeV, $q \approx 0$: $\beta-$ and $\beta\beta-$decays
- $\omega \approx$ few MeV, $q \approx 10^2$ MeV: Neutrinoless $\beta\beta-$decays
- $\omega \lesssim$ tens MeV: Astrophysics
- $\omega \approx 10^2$ MeV: Accelerator neutrinos, ν-nucleus scattering



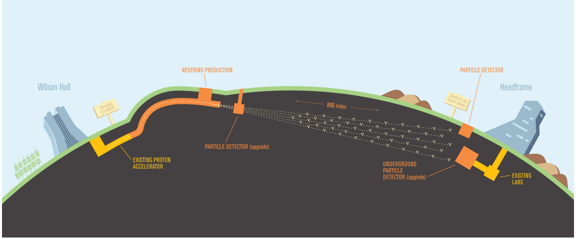
DUNE - Deep Underground Neutrino Experiment - to measure neutrino oscillations and CP violation



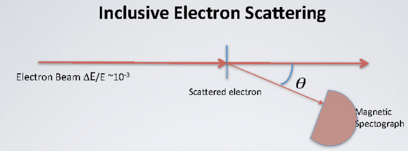
Simplified 2 flavors evolution (CP violation non included):

$$P_{\alpha\to\beta} = \sin^2(2\theta_{\alpha\beta})\sin^2\left(1.267\frac{\Delta m^2_{\alpha\beta}L}{E}\frac{GeV}{eV^2 km}\right)$$

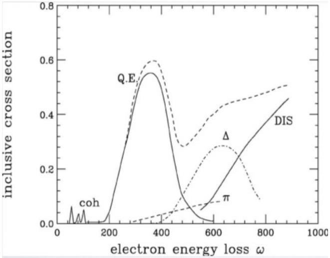
Need to know E!



Electron energy easy to know:



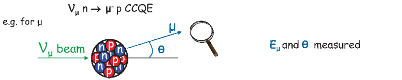
Electron scattering in nuclei:



Benhar, Day, Sick, RMP (2008)

Introduction: neutrino energy and cross-section

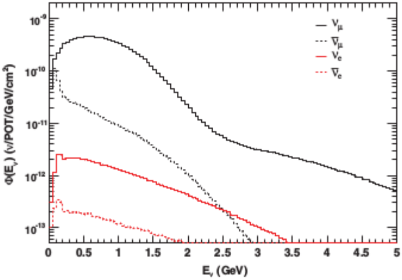
E_ν difficult to reconstruct. Example: CCQE process



$$\overline{E_\nu} = \frac{E_\mu - m_\mu^2/(2M)}{1 - (E_\mu - P_\mu \cos\theta)/M}$$

Neutral current process even more difficult.

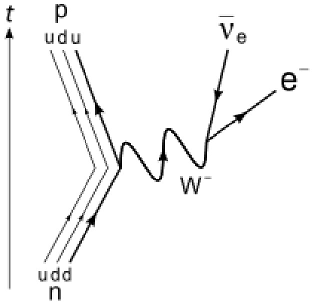
Simulation of neutrino energy distribution:

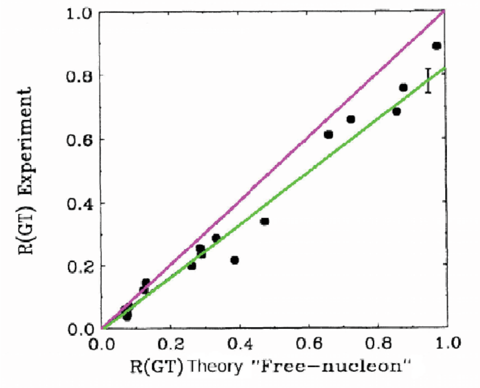


MiniBooNE Coll., PRD (2009)

Knowledge of cross-section
+ near detector
= determination of E_ν

The "quenching"-g_A problem





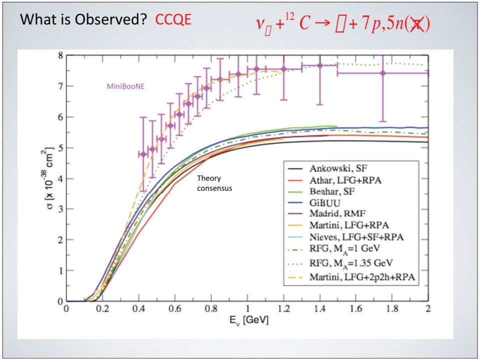
$$g_A^{\text{eff}} \simeq 0.70\, g_A$$

Chou et al., PRC 47, 163 (1993)

What's the origin (or is there a **need**) of g_A quenching?

Charge-change quasi-elastic cross-section in ^{12}C

Experimental vs theory disagreement:



Alvarez-Ruso arXiv:1012.3871

Currents inconsistent with the Hamiltonian.

Nucleon-nucleon correlations and two-body processes approximately accounted for. These models do not describe electron-scattering!!!

Need of g_A "unquenching"???

Nuclear Hamiltonian

Model: non-relativistic nucleons strongly interacting with a nucleon-nucleon (NN) and three-nucleon interaction (TNI).

$$H = -\frac{\hbar^2}{2m}\sum_{i=1}^{A}\nabla_i^2 + \sum_{i<j} v_{ij} + \sum_{i<j<k} V_{ijk}$$

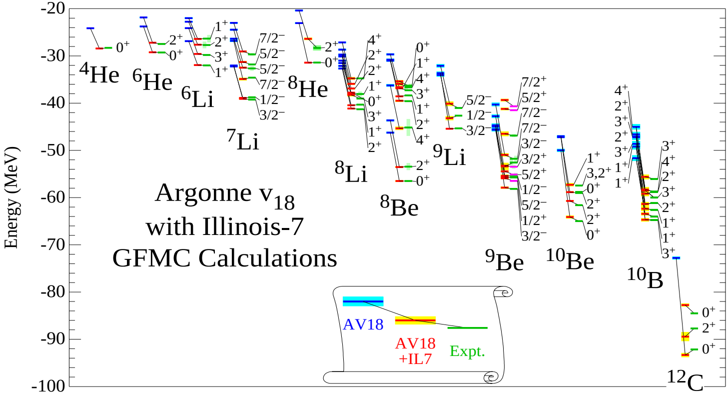
v_{ij} NN fitted on scattering data and TNI to properties of light nuclei.

Quantum Monte Carlo methods used to solve the many-body Schroedinger equation in imaginary time t:

$$H\,\psi(\vec{r}_1 \ldots \vec{r}_N) = E\,\psi(\vec{r}_1 \ldots \vec{r}_N) \qquad \psi(t) = e^{-H\,t}\psi(0)$$

Ground-state extracted in the limit of $t \to \infty$.

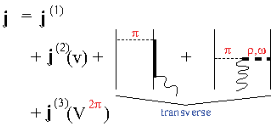
Light nuclei spectrum computed with GFMC



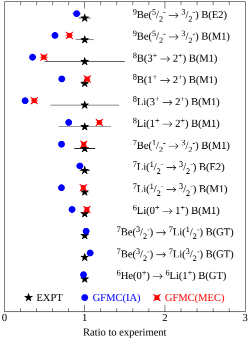
Carlson, Gandolfi, Pederiva, Pieper, Schiavilla, Schmidt, Wiringa, RMP (2015)

Also radii, densities, matrix elements, ...

Two-body processes

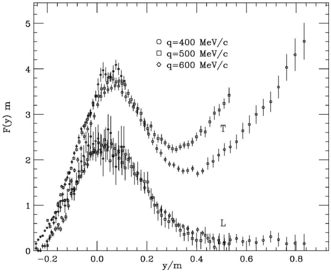


Low-momentum, transitions:



Pastore *et* al, PRC 2014

High-momentum, e^- scattering: rescaled longitudinal vs transverse electromagnetic response in ^{12}C

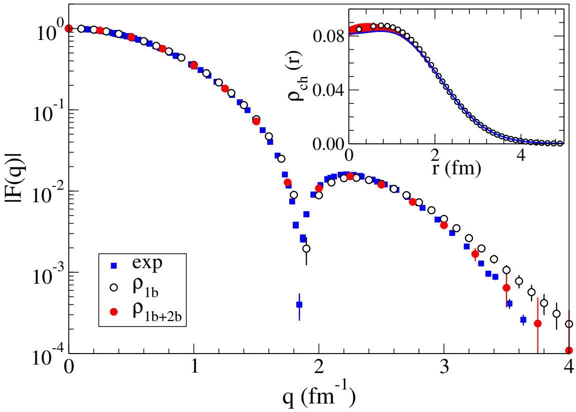


Benhar, Day, Sick, RMP (2008)

Without two-body processes, the longitudinal and transverse response is about the same

Charge form factor of ^{12}C

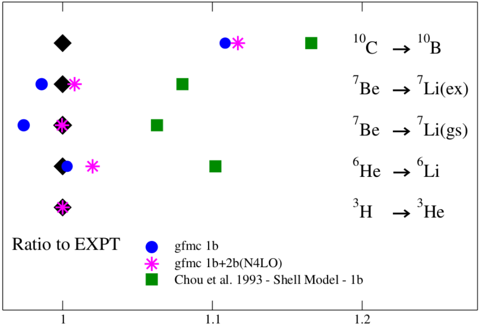
$$|F(q)| = \langle\psi|\rho_q|\psi\rangle \qquad \rho_q = \sum_i \rho_q(i) + \sum_{i<j} \rho_q(ij)$$



Lovato, Gandolfi, Butler, Carlson, Lusk, Pieper, Schiavilla, PRL (2013)

β-decays in light nuclei

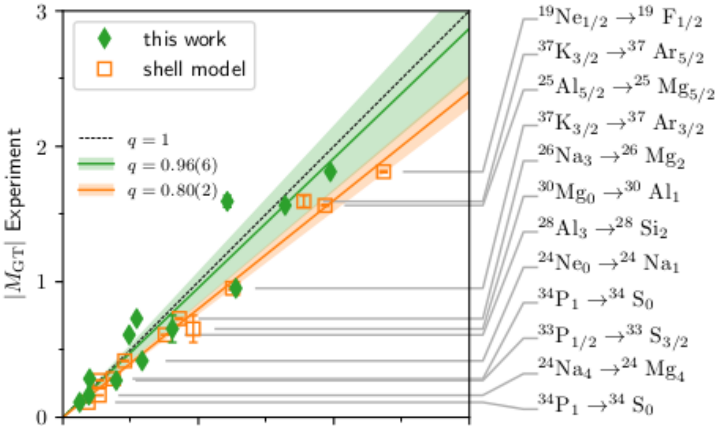
QMC calculations using a correlated wave function compared to shell-model calculations using the AV18+IL7 Hamiltonian and chiral currents.



Pastore, et al., PRC 97, 022501 (2018).

The effect of correlations in the nuclear wave function is critical!

VS-IMSRG calculations using NN-N^{4}LO+3N$_{lnl}$



Gysbers et al., Nature Physics (2019).

Inclusive scattering

Electron scattering:

$$\left(\frac{\mathrm{d}^2\sigma}{\mathrm{d}\epsilon'\mathrm{d}\Omega}\right)_{\nu/\overline{\nu}} = \left(\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}\right)_M \left[\frac{Q^4}{q^4} R_L(q,\omega) + \left(\frac{Q^2}{2q^2} + \tan^2\frac{\theta}{2}\right) R_T(q,\omega)\right]$$

R_T and R_L transverse and longitudinal response functions.

Neutrino scattering:

$$\left(\frac{\mathrm{d}^2\sigma}{\mathrm{d}\epsilon'\mathrm{d}\Omega}\right)_{\nu/\overline{\nu}} = \frac{G^2}{2\pi^2} k'\epsilon' \cos^2\frac{\theta}{2}\left[R_{00}(q,\omega) + \frac{\omega^2}{q^2} R_{zz}(q,\omega) - \frac{\omega}{q} R_{0z}(q,\omega) + \left(\tan^2\frac{\theta}{2} + \frac{Q^2}{2\,q^2}\right) R_{xx+yy}(q,\omega) \mp \tan\frac{\theta}{2}\sqrt{\tan^2\frac{\theta}{2} + \frac{Q^2}{q^2}}\, R_{xy}(q,\omega)\right]$$

R_{00}, R_{zz}, R_{0z}, R_{xx+yy}, and R_{xy} neutrino response functions.
R_{xy} is important for ν vs $\bar{\nu}$ processes.

Response functions

$$R(q,\omega) = \sum_n \langle \Psi | j^\dagger(q) | n \rangle \langle n | j(q) | \Psi \rangle \delta(\omega - E_n + E_0)$$
$$= \int \mathrm{d}t \langle \Psi | j^\dagger(q) \exp[i(H-\omega)t] j(q) | \Psi \rangle$$
$$= \int \mathrm{d}t \, E(q,\tau)$$

Using QMC we can calculate **exactly** $E(q,\tau)$ and then reconstruct $R(q,\omega)$.

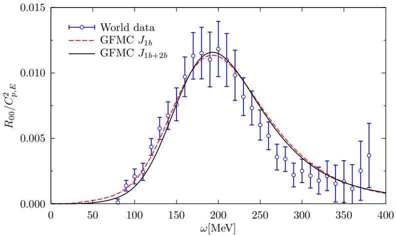
Ingredients:

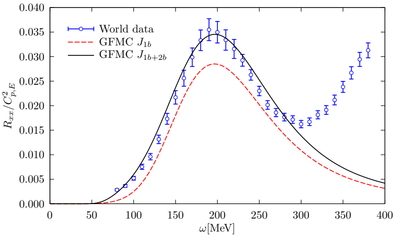
- Hamiltonian H
- Ground-state Ψ (H)
- Currents described by the electroweak operators $\mathbf{j}(q)$, constructed consistently with H.

Response functions

Using the maximum entropy method, we can reconstruct the response functions.

Longitudinal and transverse response functions of ^{4}He (q=600 MeV)

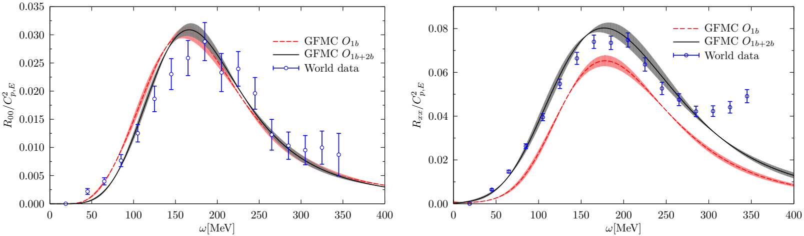




Lovato, Gandolfi, Carlson, Pieper, Schiavilla, PRC (2015)

Similar agreement also with other kinematics, q=400, 500, and 700 MeV.

Electromagnetic longitudinal and transverse response functions of ^{12}C (q=570 MeV)

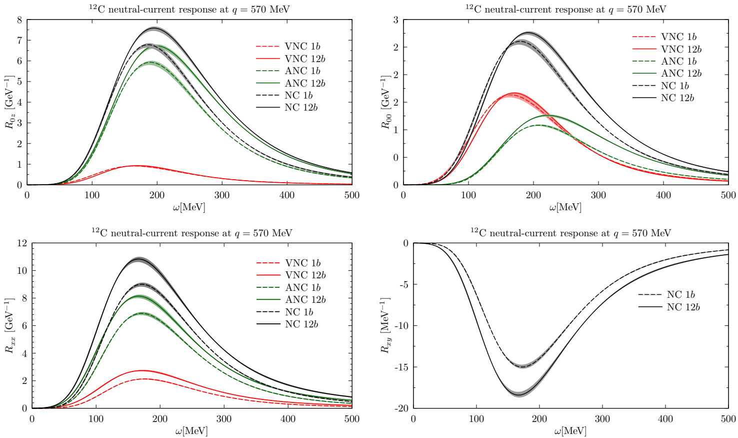


Lovato, Gandolfi, et al., PRL (2016).

Role of two-nucleon currents very important (as expected).

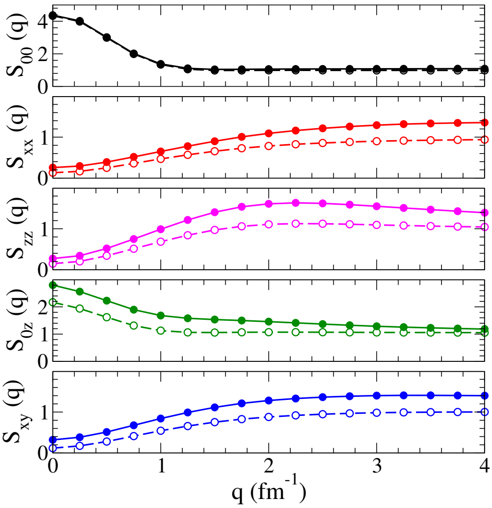
Neutral Electroweak response functions of ^{12}C

Transverse vector, axial, and neutral current of ^{12}C (q=570 MeV)



Lovato, Gandolfi, et al., PRC 97, 022502 (2018)

Neutral Electroweak sum-rules in ^{12}C

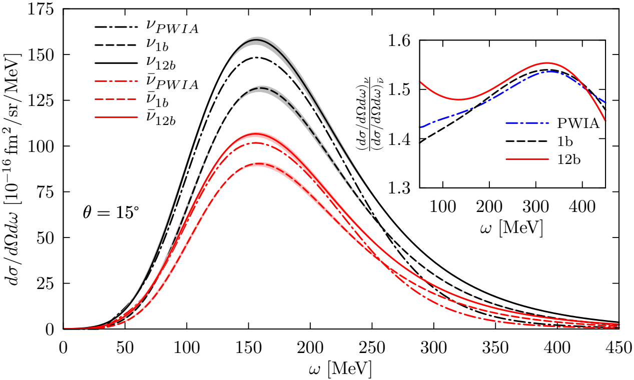


Lovato, Gandolfi, Carlson, Pieper, Schiavilla, PRL (2014).

Two-body operators enhance sum-rules up to 50%.

Neutral Electroweak cross-section of ^{12}C

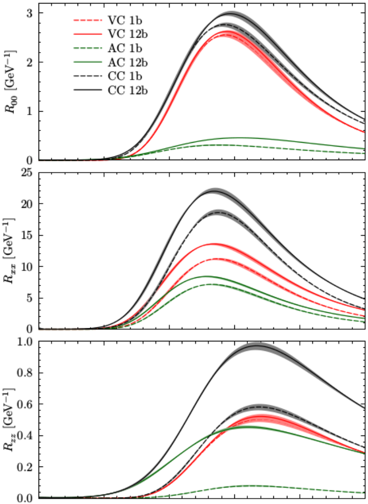
From the response functions, we can reconstruct the cross-section:

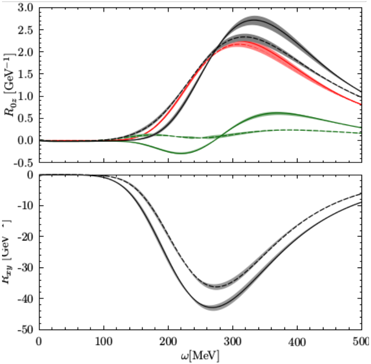


Lovato, Gandolfi, et al., PRC 97, 022502 (2018)

PRELIMINARY!

Vector, axial, and charge changing current of ^{12}C, q=700 MeV

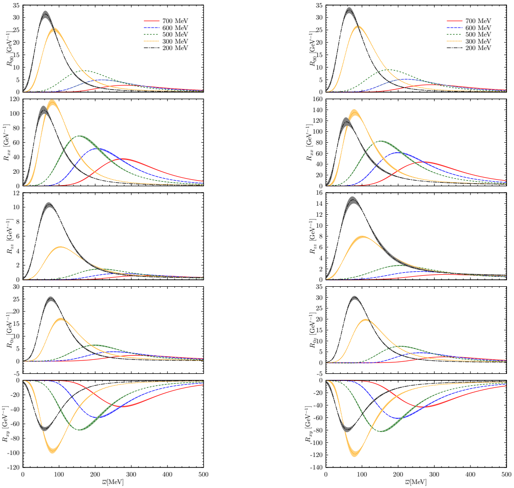




Lovato, Rocco, Carlson, Gandolfi, Schiavilla, in preparation.

PRELIMINARY!

Vector, axial, and charge changing current of ^{12}C



Lovato, Rocco, Carlson, Gandolfi, Schiavilla, in preparation.

$$R_\alpha(q,\omega) = \sum_f \delta(\omega + E_0 - E_f) \langle 0 | O_\alpha^\dagger(\mathbf{q}) | f \rangle \langle f | O_\alpha(\mathbf{q}) | 0 \rangle$$

$$R_\alpha(q,\omega) = \int dt \langle 0 | O_\alpha^\dagger(\mathbf{q})\, e^{i(H-\omega)t}\, O_\alpha(\mathbf{q}) | 0 \rangle$$

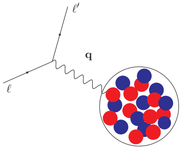
At short time, expand $P(t) = e^{i(H-\omega)t}$ and keep up to 2b-terms

$$H \sim \sum_i t_i + \sum_{i<j} v_{ij}$$

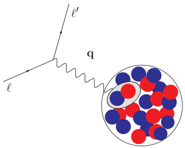
and

$$O_i^\dagger P(t) O_i + O_i^\dagger P(t) O_j + O_i^\dagger P(t) O_{ij} + O_{ij}^\dagger P(t) O_{ij}$$

1b



2b



PWIA vs Short-time-approximation

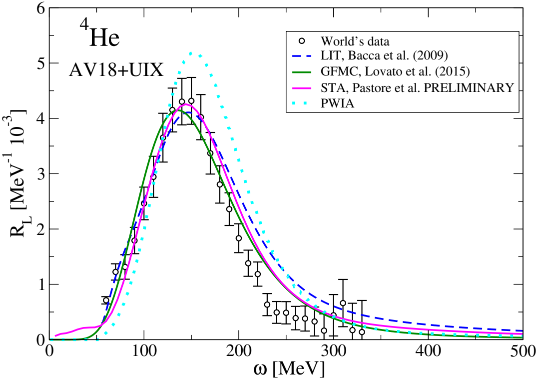
PWIA: Response functions given by incoherent scattering off single nucleons that propagate freely in the final state (plane waves)

STA: Response functions are given by the scattering off pairs of fully interacting nucleons that propagate into a correlated pair of nucleons

$$R_\alpha(q,\omega) = \sum_f \delta\left(\omega + E_0 - E_f\right) \langle\, 0|O_\alpha^\dagger(\mathbf{q})|f\,\rangle\langle\, f|O_\alpha(\mathbf{q})|0\,\rangle$$
$$O_\alpha(\mathbf{q}) = O_\alpha^{(1)}(\mathbf{q}) + O_\alpha^{(2)}(\mathbf{q}) = \mathrm{1b} + \mathrm{2b}$$
$$|\, f\,\rangle \sim |\psi_{p,P,J,M,L,S,T,M_T}(r,R)\rangle = \mathrm{correlated\ two-nucleon\ w.f.}$$

* We retain two-body physics consistently in the nuclear interactions and electroweak currents
* $R_\alpha(q,\omega)$ requires only direct calculation of g.s. $|0\rangle$ w.f.'s *
* STA can be implemented to accommodate for more two-body physics, *e.g.*, pion-production induced by e and ν

The Short-Time Approximation

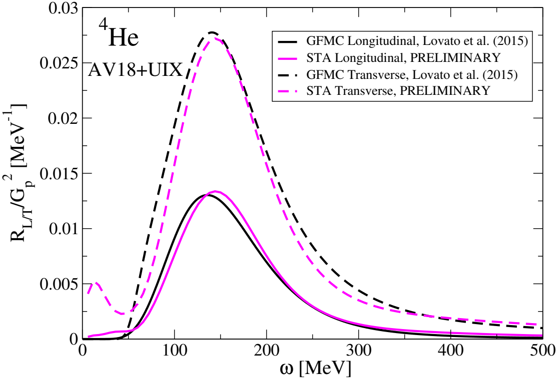


Longitudinal Response function at $q = 500$ MeV

Excellent agreement with full GFMC and EXPT at q>500 MeV

Pastore, Carlson, et al., arXiv:1909.06400.

The Short-Time Approximation



Longitudinal vs Transverse Response Function at $q = 500$ MeV

Pastore, Carlson, et al., arXiv:1909.06400.

Summary and future work

Conclusions:

- "Quenching" of g_A *maybe* understood. Two-body currents and nuclear correlations very important.
- Electron scattering in ^{12}C calculated using GFMC. Good agreement with experiments. One- and two-body vector currents tested.
- Two-body axial currents show a similar enhancement in response functions and sum rules.
- STA approximation beyond PWIA, very powerful, promising results.

In progress/future work:

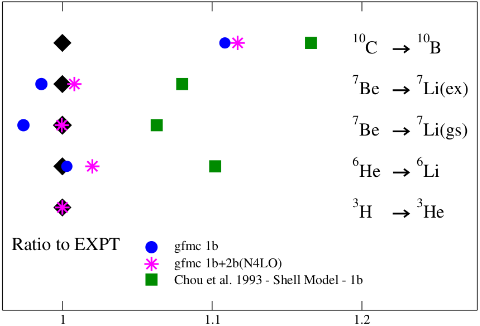
- Calculation of charge changing weak currents almost complete. Cross-section next.
- Extension to larger nuclei with STA.
- Extension to exclusive processes.

Acknowledgments:

- J. Carlson (LANL)
- S. Pastore (WUSTL)
- A. Lovato, N. Rocco, S. Pieper (ANL)
- R. Schiavilla (Jlab/ODU)

Extra slides

QMC calculations using a correlated wave function compared to shell-model calculations using the AV18+IL7 Hamiltonian and chiral currents.

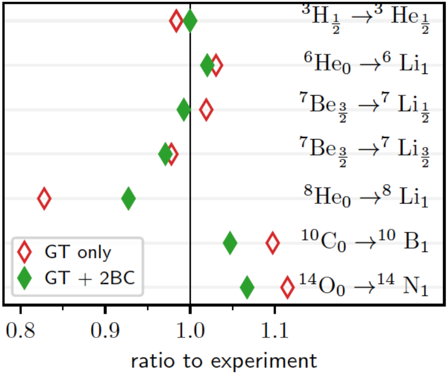


Pastore, et al., PRC 97, 022501 (2018).

The effect of correlations in the nuclear wave function is critical!

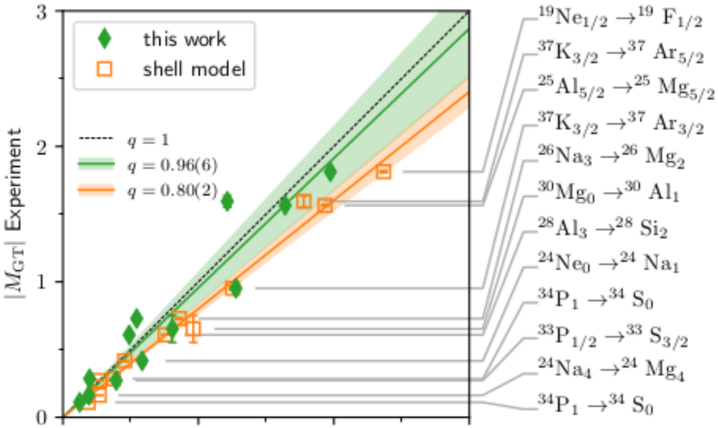
β-decays in light nuclei

NCSM calculations using NN-N^{4}LO+3N$_{lnl}$



Gysbers et al., Nature Physics (2019).

VS-IMSRG calculations using NN-N^{4}LO+3N$_{lnl}$



Gysbers et al., Nature Physics (2019).

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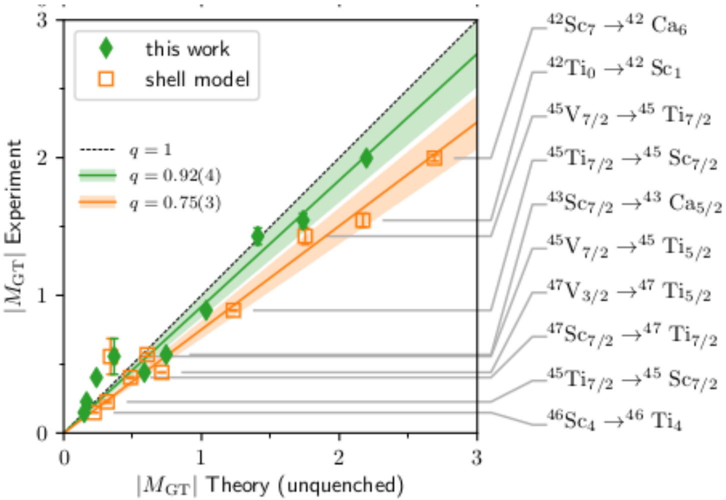
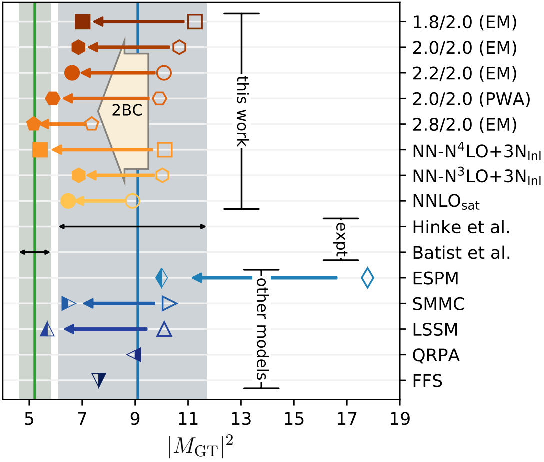


Gysbers et al., Nature Physics (2019).

β-decay in ^{100}Sn



ESPM: Extreme Single Particle Model

SMMC: Shell Model MC

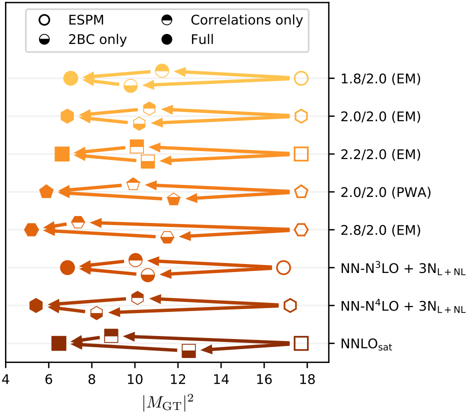
LSSM: Large Space Shell Model

QRPA: quasiparticle random phase approximation

FFS: finite Fermi systems

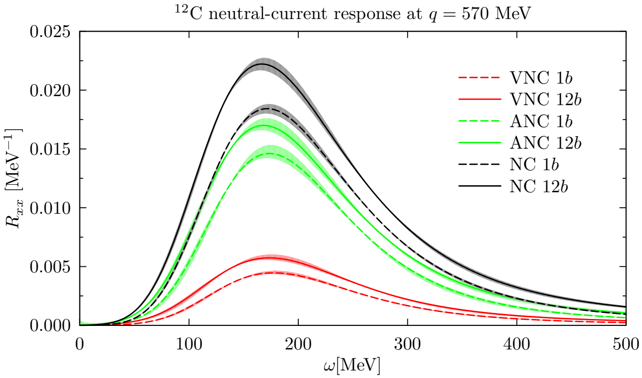
Gysbers et al., Nature Physics (2019).

Role of correlations vs 2BC



Gysbers et al., Nature Physics (2019).

Transverse vector, axial, and neutral current of ^{12}C (q=570 MeV)

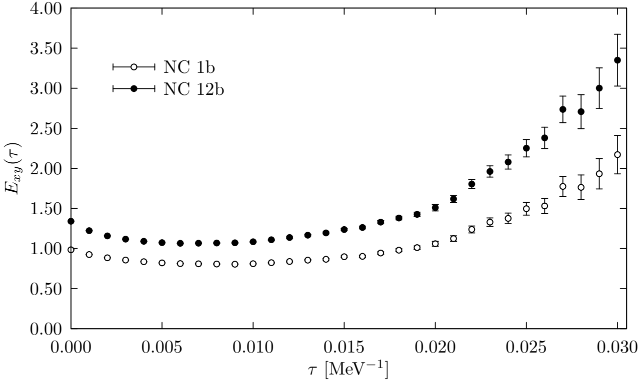


Axial currents give the largest contribution.

Role of axial form factor?

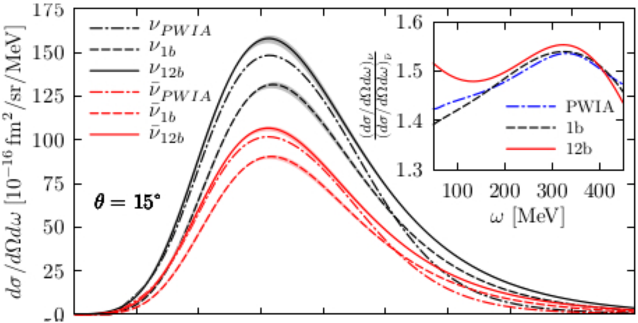
Euclidean electroweak response functions of ^{12}C

R_{xy} term responsible for ν vs $\bar{\nu}$ response. ^{12}C, q=570 MeV



Lovato, Gandolfi, Carlson, Pieper, Schiavilla, PRC (2015)

From the response functions, we can calculate the cross-section:



Lovato, et al., PRC 97, 022502 (2018)

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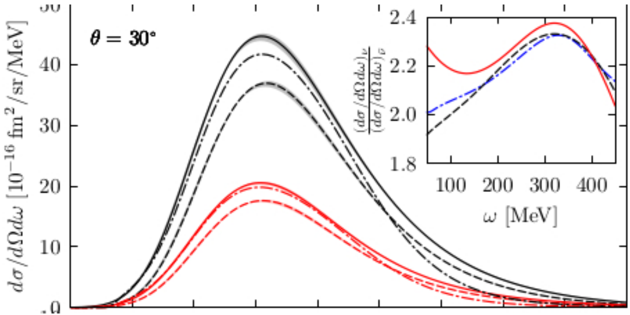

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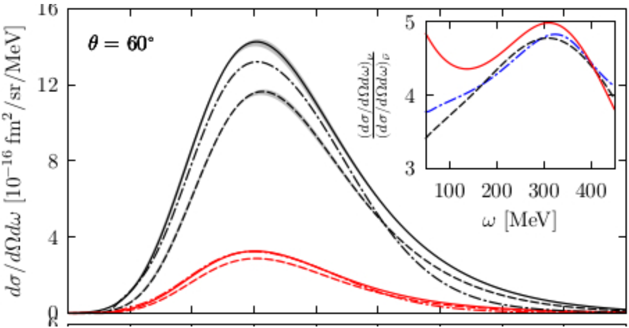
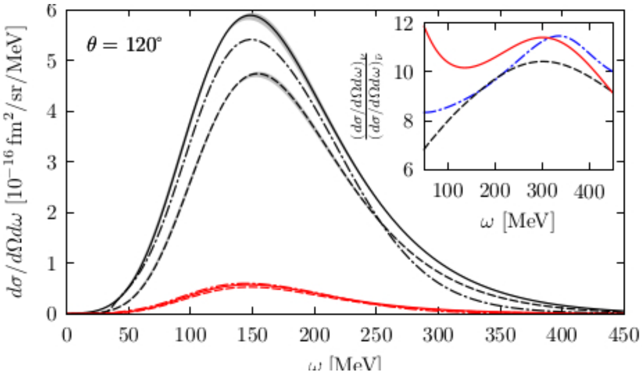


Lovato, et al., PRC 97, 022502 (2018)

Electroweak cross-section of ^{12}C

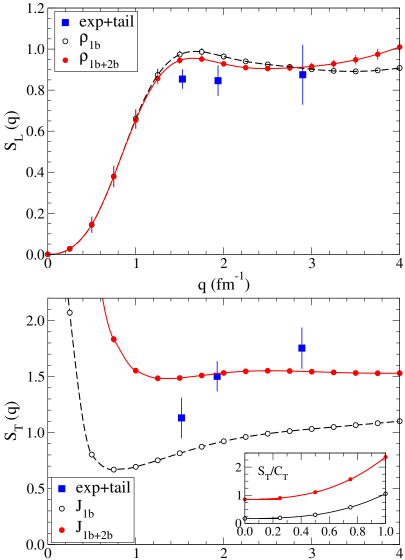
From the response functions, we can calculate the cross-section:



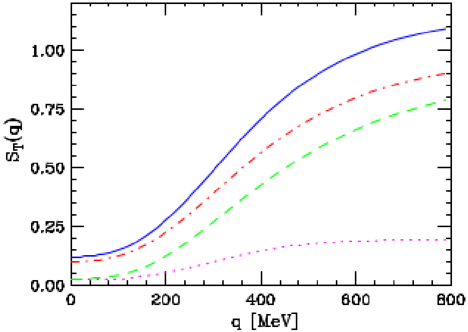
Lovato, et al., PRC 97, 022502 (2018)

Electromagnetic sum-rules in ^{12}C

Sum rules: $S_{L,T}(q) = C_{L,T} \int R_{L,T}(\omega, q) d\omega$



Transverse sum rule of ^{12}C

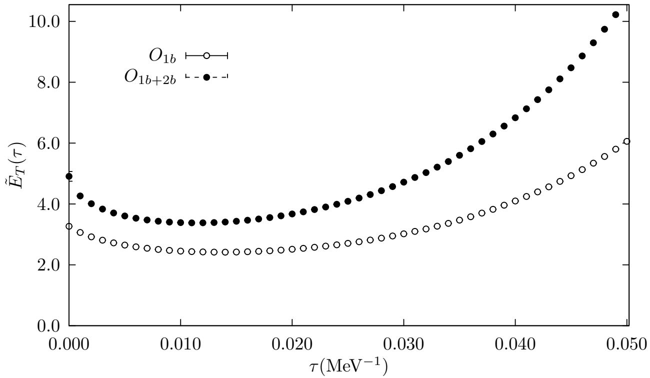


- Full response, $\langle\Psi|(j_1+j_2)^\dagger(j_1+j_2)\Psi\rangle$
- $\langle\Psi|j_1^\dagger j_1 + j_2^\dagger j_2|\Psi\rangle$
- $\langle\Psi|j_1^\dagger j_1|\psi\rangle$
- interference

Benhar, Lovato, Rocco, PRC (2015)

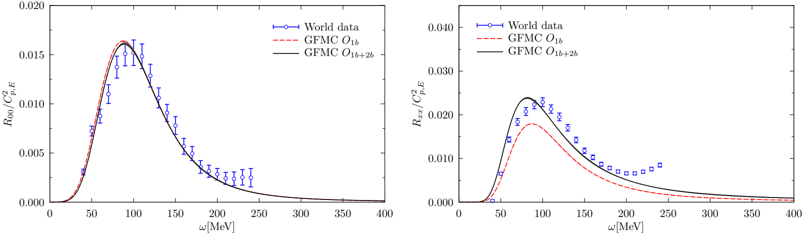
Euclidean response

Transverse electromagnetic (euclidean) response functions of ^{4}He (q=500 MeV)



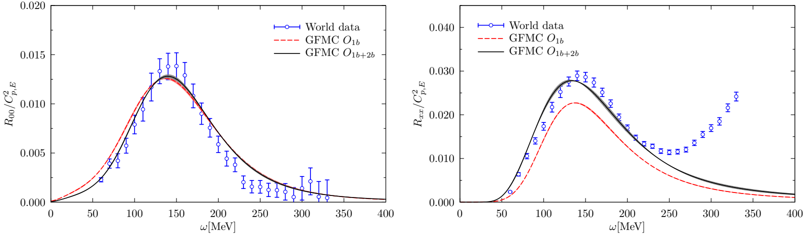
Note: results multiplied by $\exp(\tau q^2/2m)$

Longitudinal and transverse electromagnetic response functions of ^{4}He (q=400 MeV)



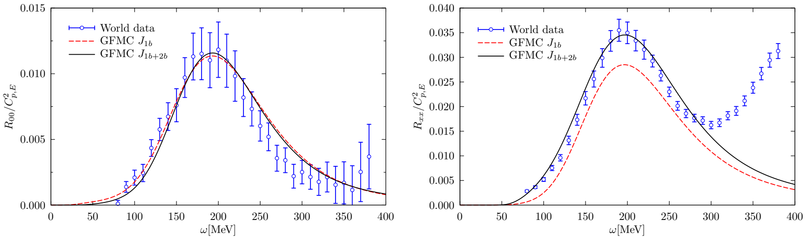
Note: results multiplied by $\exp(\tau q^2/2m)$

Longitudinal and transverse electromagnetic response functions of ^{4}He (q=500 MeV)



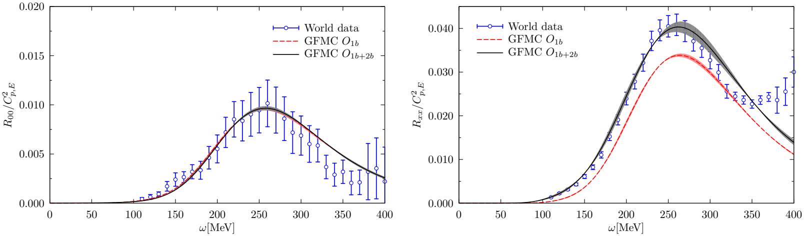
Note: results multiplied by $\exp(\tau q^2/2m)$

Longitudinal and transverse electromagnetic response functions of ^{4}He (q=600 MeV)



Note: results multiplied by $\exp(\tau q^2/2m)$

Longitudinal and transverse electromagnetic response functions of ^{4}He (q=700 MeV)



Note: results multiplied by $\exp(\tau q^2/2m)$

Transverse electromagnetic response functions of ^{4}He (q=500 MeV).
Role of the interference: