Neutrino interactions in nuclei

Stefano Gandolfi

Los Alamos National Laboratory (LANL)

Atomic nuclei as laboratories for BSM physics,
April 15-19, 2019, ECT*, Trento, Italy

Los Alamos NATIONAL LABORATORY EST.1943
LDRD

NUCLEI
Nuclear Computational Low-Energy Initiative
www.computingnuclei.org

U.S. DEPARTMENT OF ENERGY

NERSC National Energy Research Scientific Computing Center

U.S. DEPARTMENT OF ENERGY INCITE LEADERSHIP COMPUTING

Motivation

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

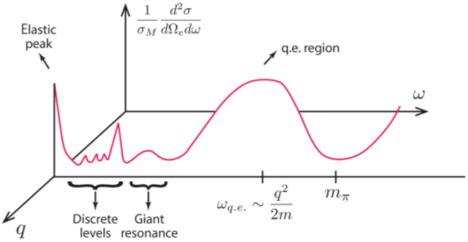
Understanding Nuclei:

- Nuclear interactions and structure
- Exotic nuclei - neutron rich
- Electroweak processes

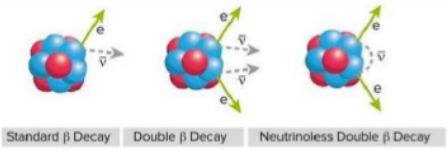
Relevance:

- 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



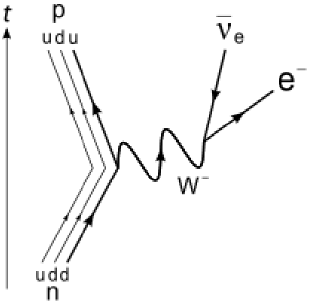
- $\omega \approx$ few MeV, $q \approx 0$: $\beta-$ and $\beta\beta-$decays
- $\omega \approx$ few MeV, $q \approx 10^2$ MeV: Neutrinoless $\beta\beta-$decays
- $\omega \lesssim$ tens MeV: Astrophysics
- $\omega \approx 10^2$ MeV: Accelerator neutrinos, ν-nucleus scattering

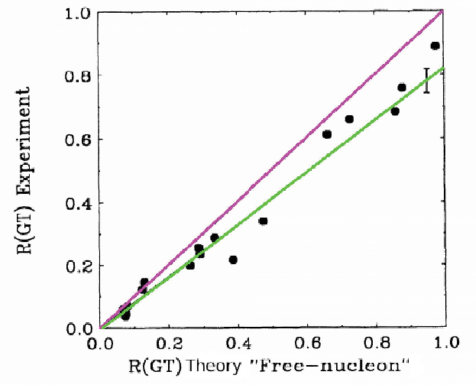


Outline

- The "g_A quenching" puzzle
- Evidence of the importance of two-body currents
- The nuclear Hamiltonian, currents and QMC method
- β-decay in nuclei
- Electron scattering
- ν-nucleus scattering

The "quenching"-g_A problem





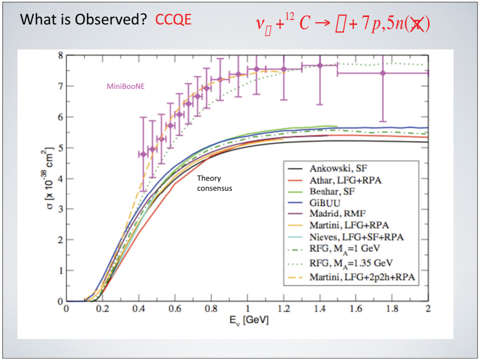
$$g_A^{\text{eff}} \simeq 0.70\, g_A$$

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:



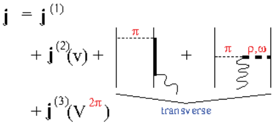
Alvarez-Ruso arXiv:1012.3871

Currents inconsistent with the Hamiltonian.

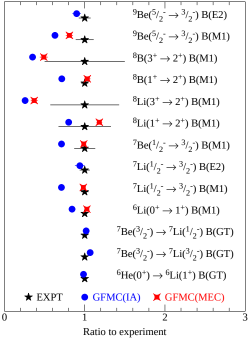
Nucleon-nucleon correlations and two-body processes approximately accounted for.

Need of g_A "unquenching"???

Two-body processes

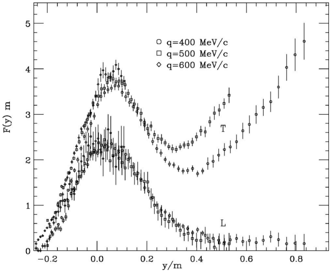


Low-momentum, transitions:



Pastore *et* al, PRC 2014

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

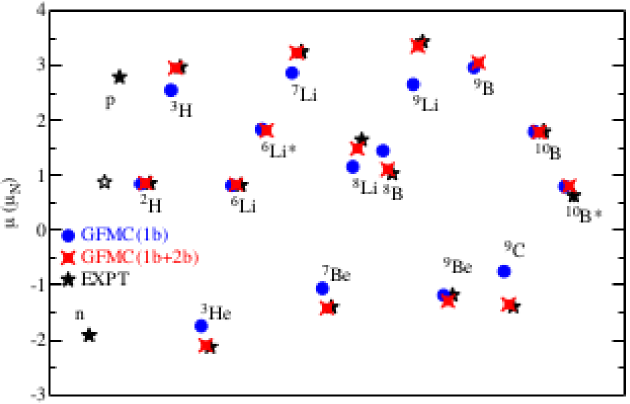


Benhar, Day, Sick, RMP (2008)

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

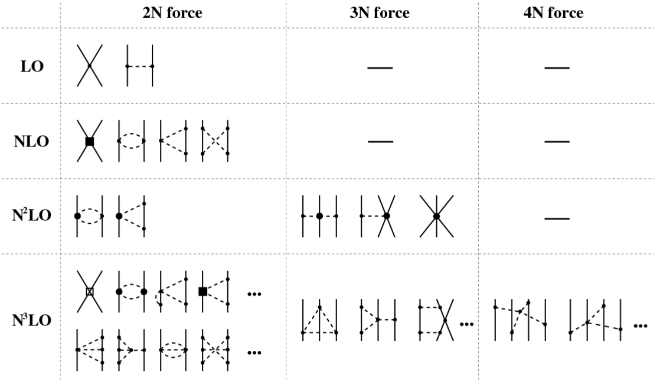
Electromagnetic two-body processes

Magnetic moments in light nuclei:



Pastore *et* al, PRC 2013

Nuclear Hamiltonian (only pions)



Expansion in powers of Q/Λ, Q$\sim$100 MeV, Λ $\sim$1 GeV.

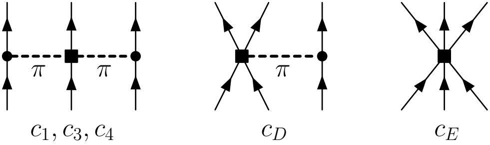
Long-range physics given by pion-exchanges (no free parameters).

Short-range physics: contact interactions (LECs) to fit.

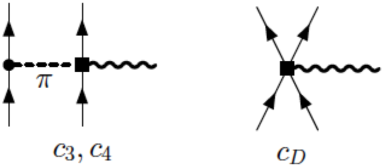
Operators need to be regulated $\rightarrow$ cutoff dependency!

Order's expansion provides a way to quantify uncertainties!

Chiral three-body forces at N^{2}LO:



Chiral two-body currents:



NN and NNN often use different regulators and cutoffs (local vs non-local, or a mix).

Hamiltonian-currents consistency?

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:

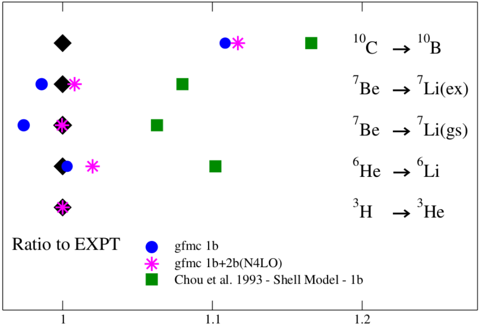
$$H\,\psi(\vec{r}_1\ldots\vec{r}_N) = E\,\psi(\vec{r}_1\ldots\vec{r}_N) \qquad \psi(t) = e^{-H\,t}\psi(0)$$

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

No more details! Ask if interested...

β-decays in light nuclei

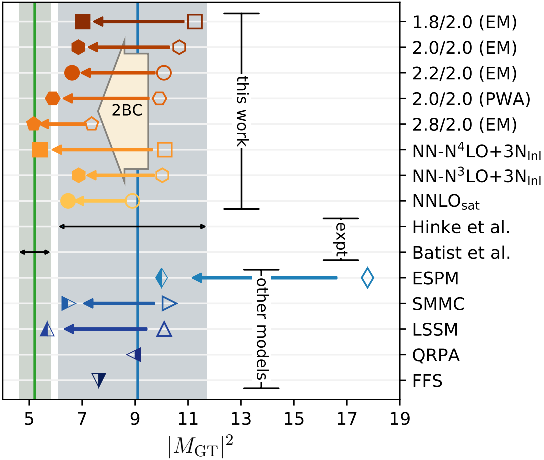
QMC calculations using a correlated wave function compared to shell-model calculations using the AV18+IL7 Hamiltonian and chiral currents.



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

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

β-decay in ^{100}Sn



Gysbers et al., Nature Physics (2019).

ESPM: Extreme Single Particle Model

SMMC: Shell Model MC

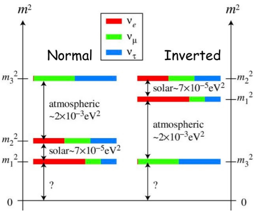
LSSM: Large Space Shell Model

QRPA: quasiparticle random phase approximation

FFS: finite Fermi systems

Motivation

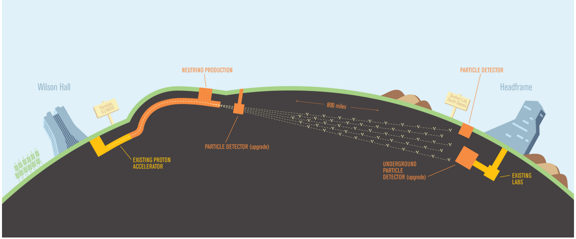
DUNE - Deep Underground Neutrino Experiment - to measure neutrino oscillations and CP violation



Simplified 2 flavors evolution (CP violation non included):

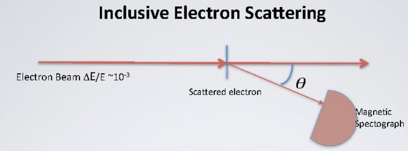
$$P_{\alpha\to\beta} = \sin^2(2\theta_{\alpha\beta})\sin^2\left(1.267\frac{\Delta m^2_{\alpha\beta}L}{E}\frac{GeV}{eV^2 km}\right)$$

Need to know E!

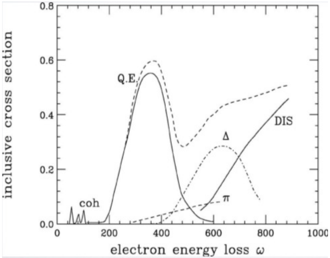


Introduction: electron energy and cross-section

Electron energy easy to know:

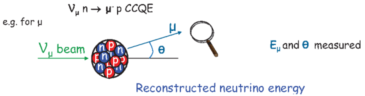


Electron scattering in nuclei:



Benhar, Day, Sick, RMP (2008)

E_ν difficult to reconstruct. Example: CCQE process

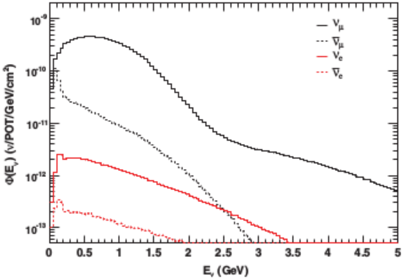


$$\overline{E_\nu} = \frac{E_\mu - m_\mu^2/(2M)}{1 - (E_\mu - P_\mu \cos\theta)/M}$$

via two-body kinematics

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

Inclusive scattering

Electron scattering:

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

R_T and R_L transverse and longitudinal response functions.

Neutrino scattering:

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

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

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

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

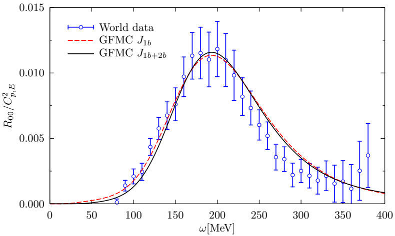
Ingredients:

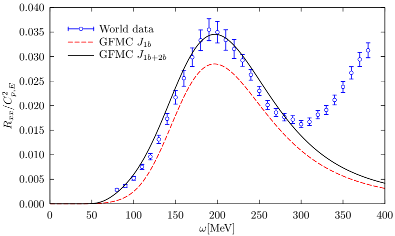
- Hamiltonian H
- Ground-state Ψ (H)
- Currents described by the electroweak operators $\mathbf{j}(q)$, constructed consistently with H.

Response functions

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

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

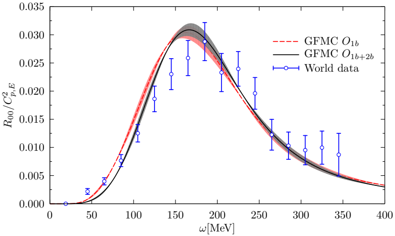


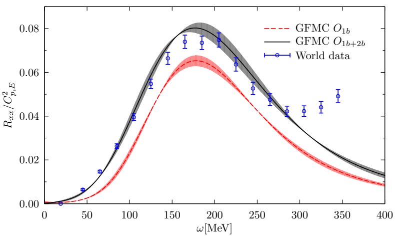


Lovato, Gandolfi, Carlson, Pieper, Schiavilla, PRC (2015)

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

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



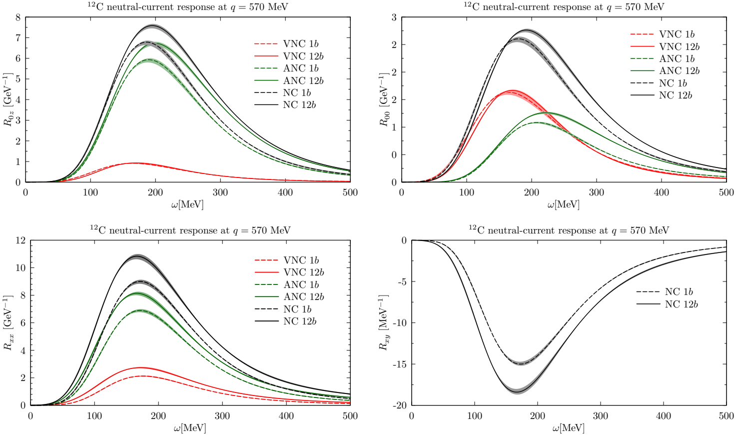


Lovato et al., PRL (2016).

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

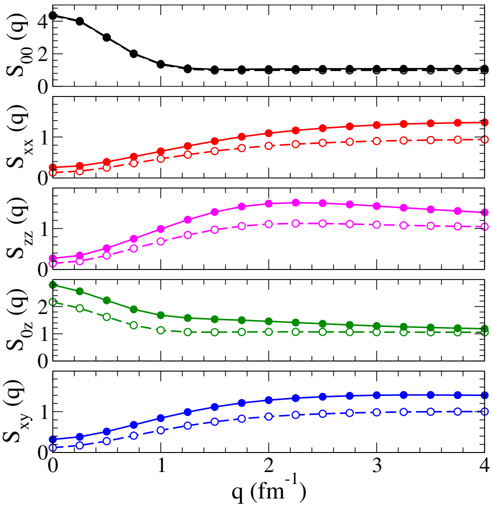
Electroweak response functions of ^{12}C

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



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

Electroweak sum-rules in ^{12}C

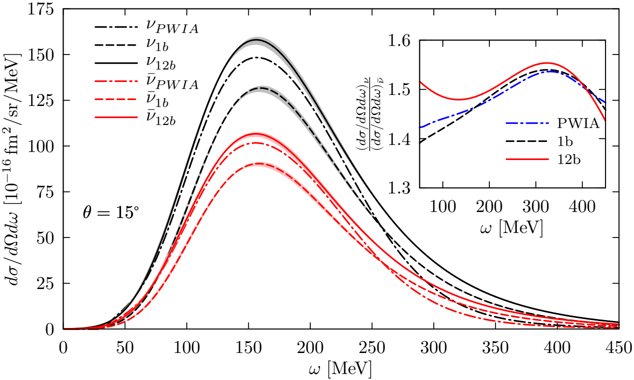


Lovato, Gandolfi, Carlson, Pieper, Schiavilla, PRL (2014).

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

Electroweak cross-section of ^{12}C

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



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

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.

In progress/future work:

- Calculation of charge changing weak currents.
- Extension to larger nuclei.

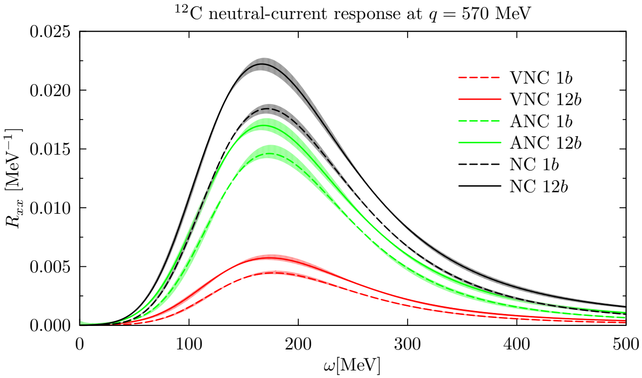
Acknowledgments:

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

Extra slides

Euclidean electroweak response functions of ^{12}C

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

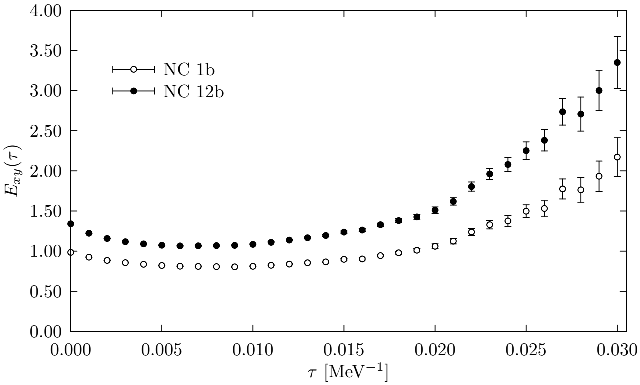


Axial currents give the largest contribution.

Role of axial form factor?

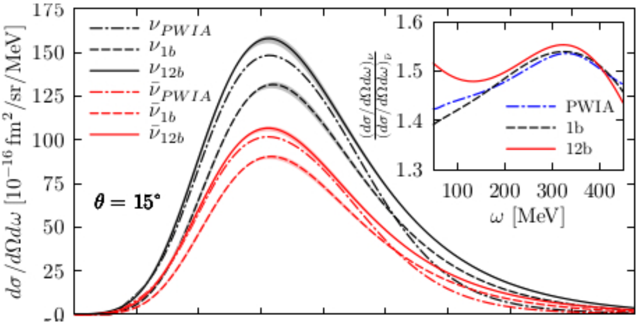
Euclidean electroweak response functions of ^{12}C

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



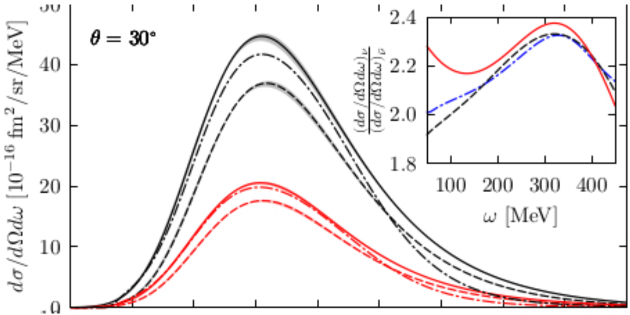
Lovato, Gandolfi, Carlson, Pieper, Schiavilla, PRC (2015)

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



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

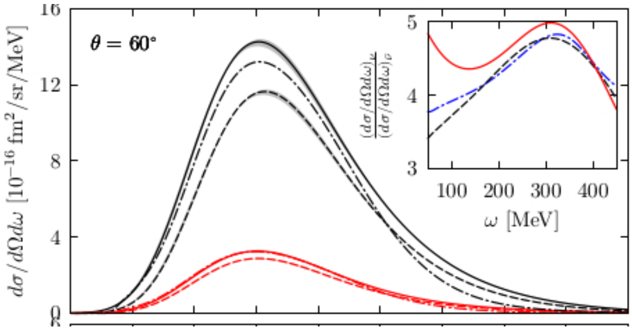
From the response functions, we can calculate the cross-section:



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

Electroweak cross-section of ^{12}C

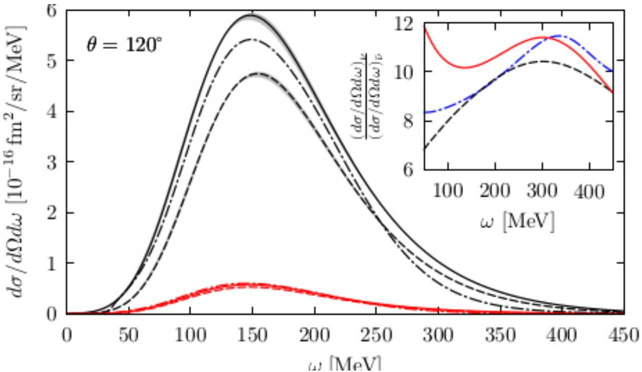
From the response functions, we can calculate the cross-section:



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

Electroweak cross-section of ^{12}C

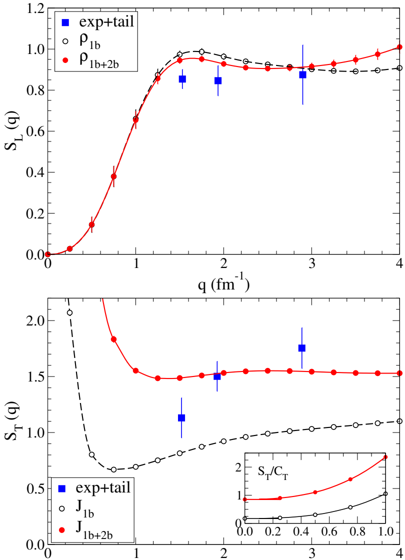
From the response functions, we can calculate the cross-section:



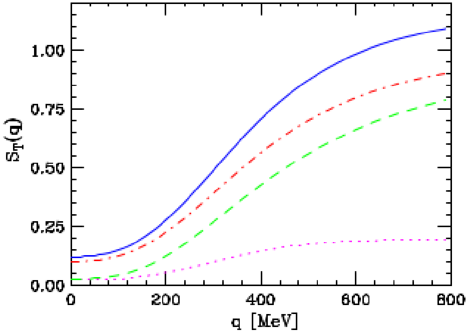
Lovato, et al., PRC 97, 022502 (2018)

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

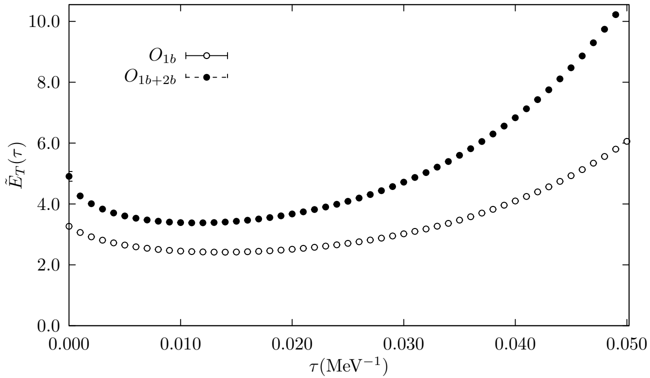


- Full response, $\langle\Psi|(j_1 + j_2)^\dagger (j_1 + j_2)\Psi\rangle$
- $\langle\Psi|j_1^\dagger j_1 + j_2^\dagger j_2|\Psi\rangle$
- $\langle\Psi|j_1^\dagger j_1|\psi\rangle$
- interference

Benhar, Lovato, Rocco, PRC (2015)

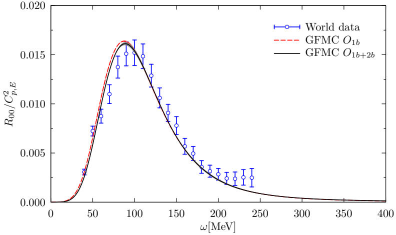
Euclidean response

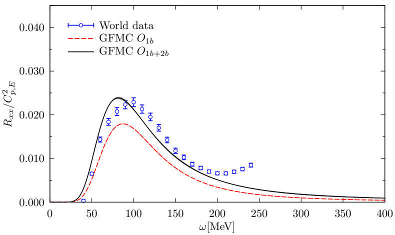
Transverse electromagnetic (euclidean) response functions of ^{4}He (q=500 MeV)



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

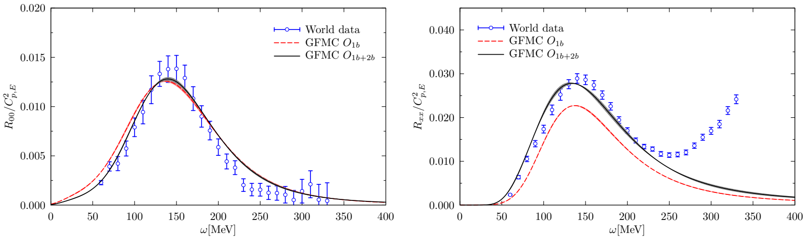
Longitudinal and transverse electromagnetic response functions of ^{4}He (q=400 MeV)





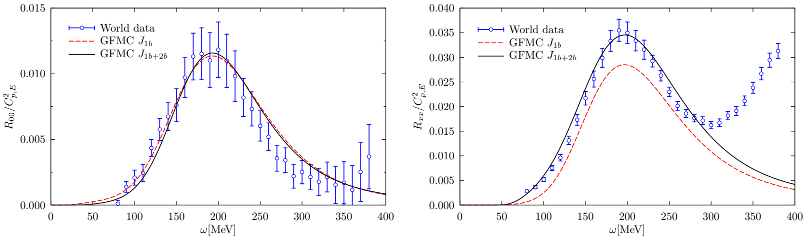
Note: results multiplied by $\exp(\tau q^2/2m)$

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



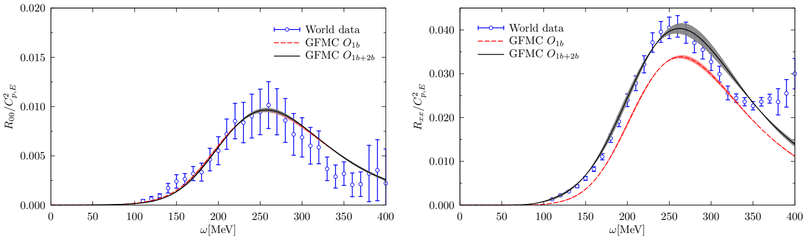
Note: results multiplied by $\exp(\tau q^2/2m)$

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



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

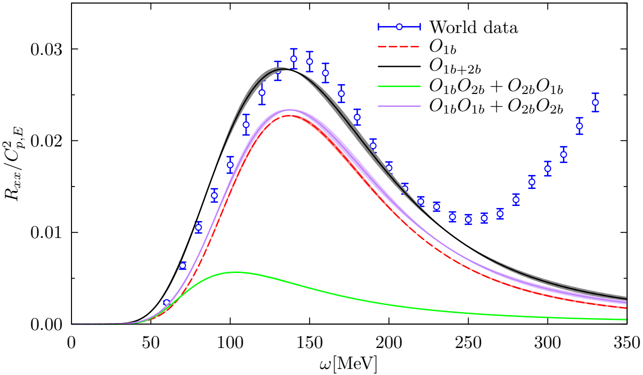
Longitudinal and transverse electromagnetic response functions of ^{4}He (q=700 MeV)



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

Transverse response response

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



Electromagnetic sum-rules in ^{12}C

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