Electroweak Interactions in Nuclei

FRIB Dialogues on Nuclear Physics - 14 July 2020

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Computational Resources awarded by the DOE ALCC and INCITE programs

Nuclei for Fundamental Symmetries & Neutrinos

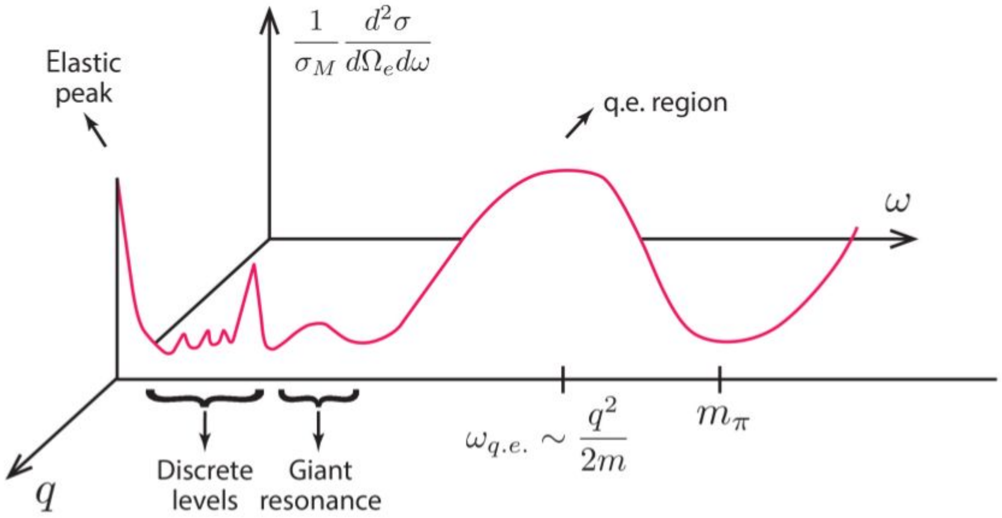
Nuclei are used for precision tests of the standard model and in searches for physics beyond the standard model.

An accurate understanding of nuclear structure and dynamics in a wide range of energy and momentum transferred is required in order to disentangle new physics from nuclear effects.

In this talk, I will focus on the role of two- and three-body correlations and currents in selected nuclear electroweak observables at different kinematics.

The emphasis will be on light nuclei ($A \leq 12$). For these systems Variational and Green's Function Monte Carlo methods allow to retain many-body effects and provide results with a computational accuracy (in most cases) of the order of few percents.

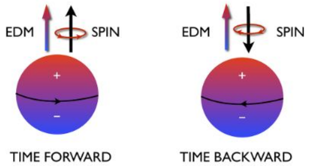
Electron-Nucleus Scattering Cross Section



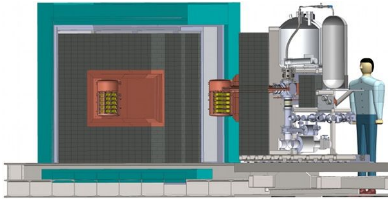
Energy and momentum transferred (ω,q)

Current and planned experimental programs rely on theoretical calculations at different kinematics

Ground States' Electroweak Moments, Form Factors, Radii



Neutrinoless Double Beta Decay, Muon-Capture



Accelerator Neutrino Experiments, Lepton-Nucleus XSecs

(ω,q)~0 MeV

ω~few MeVs q~0 MeV

ω~few MeVs q~10^2 MeV

ω~tens of MeVs

ω~10^2 MeV

FRIB

Electromagnetic Decay, Beta Decay, Double Beta Decay & inverse processes

JINA-CEE

Nuclear Rates for Astrophysics

DUNE

Jefferson Lab

Strategy

Validate the Nuclear Model against available data for strong and electroweak observables

- Energy Spectra, Electromagnetic Form Factors, Electromagnetic Moments, ...
- Electromagnetic and Beta decay rates, ...
- Muon Capture Rates, ...
- Electron-Nucleus Scattering Cross Sections, ...

Use attained information to make (accurate) predictions for BSM searches and precision tests

- EDMs, Anapole Moments, Hadronic PV, ...
- BSM searches with beta decay, ...
- Neutrinoless double beta decay, ...
- Neutrino-Nucleus Scattering Cross Sections, ...
- ...

Microscopic (or *ab initio*) Description of Nuclei

Goal:

Comprehensive theory that describes quantitatively and predictably nuclear structure and reactions

Requirements:

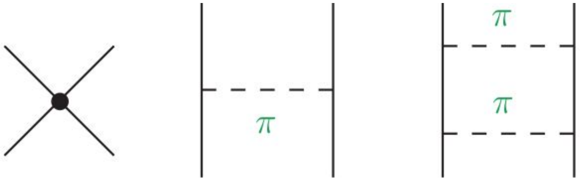
- Accurate understanding of the interactions/correlations between nucleons in paris, triplets, ... (two- and three-nucleon forces)
- Accurate understanding of the electroweak interactions of leptons with nucleons, correlated nucleon-pairs, … (one- and two-body electroweak currents)
- Computational methods to solve the many-body nuclear problem of strongly interacting particles

Many-body Nuclear Interactions

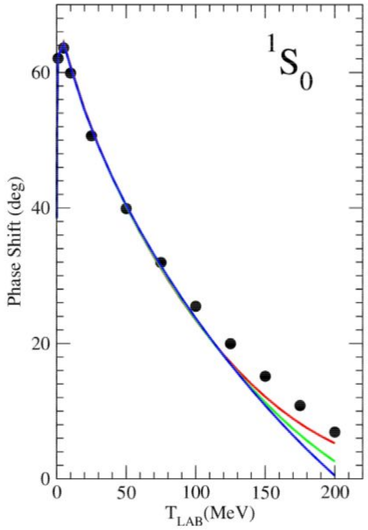
Many-body Nuclear Hamiltonian

$$H = T + V = \sum_{i=1}^{A} t_i + \sum_{i<j} v_{ij} + \sum_{i<j<k} V_{ijk} + \ldots$$

v_{ij} and V_{ijk} are two- and three-nucleon operators based on experimental data fitting; fitted parameters subsume underlying QCD dynamics



Contact term: short-range
Two-pion range: intermediate-range $r \propto (2\, m_\pi)^{-1}$
One-pion range: long-range $r \propto m_\pi^{-1}$



SP et al. PRC80(2009)034004

In Quantum Monte Carlo methods we use:

AV18+UIX; AV18+IL7 Wiringa, Schiavilla, Pieper *et al.*
chiral πN N2LO+N2LO Gerzelis, Tews, Lynn *et al.*
chiral πNΔ N3LO+N2LO Piarulli *et al.* Norfolk Models

Quantum Monte Carlo Methods

Minimize the expectation value of the nuclear Hamiltonian: H = T + v_{ij} + V_{ijk}

$$E_V = \frac{\langle \Psi_V | H | \Psi_V \rangle}{\langle \Psi_V | \Psi_V \rangle} \geq E_0$$

using the trial wave function:

$$|\Psi_V\rangle = \left[\mathcal{S} \prod_{i<j} (1 + U_{ij} + \sum_{k \neq i,j} U_{ijk}) \right] \left[\prod_{i<j} f_c(r_{ij}) \right] |\Phi_A(JMTT_3)\rangle$$

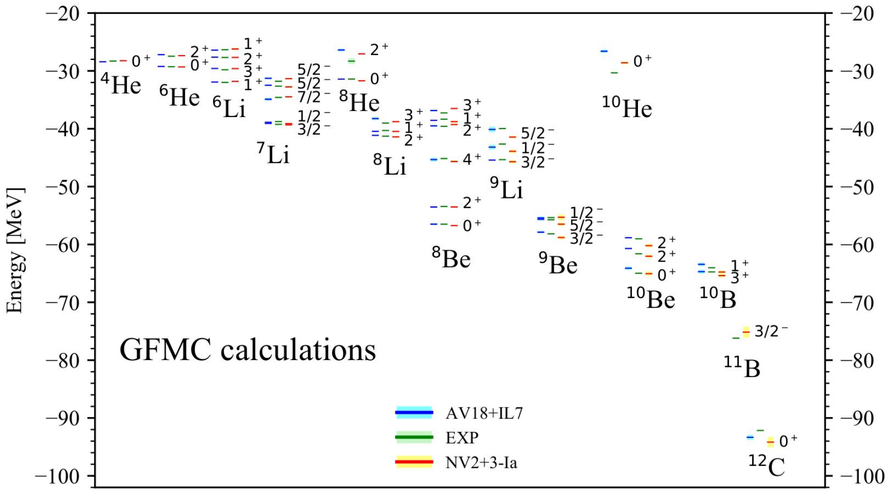
Further improve the trial wave function by eliminating spurious contaminations via a Green's Function Monte Carlo (GFMC) propagation in imaginary time

$$\Psi(\tau) = \exp[-(H - E_0)\tau] \Psi_V = \sum_n \exp[-(E_n - E_0)\tau] a_n \psi_n$$

$$\Psi(\tau \to \infty) = a_0 \psi_0$$

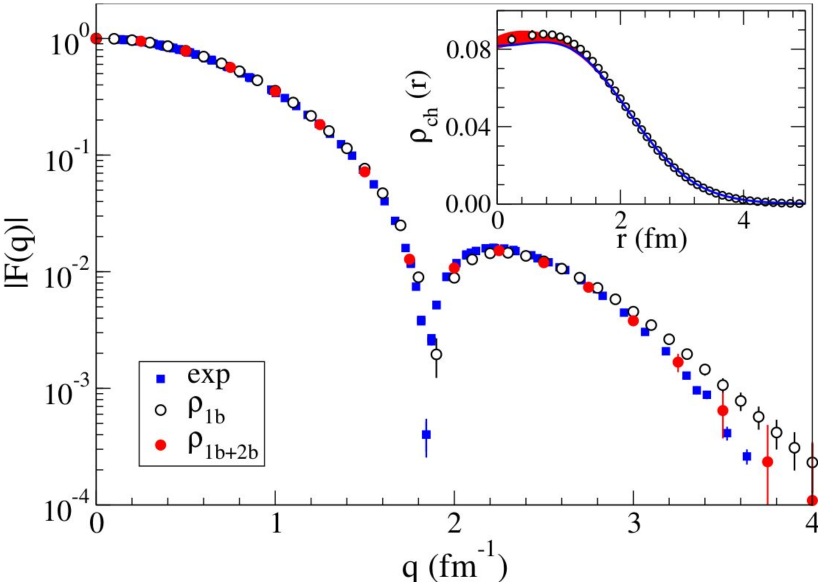
AV18+UIX; AV18+IL7 Wiringa, Schiavilla, Pieper *et al*.
chiral πN N2LO+N2LO Gerzelis, Tews, Lynn *et al*.
chiral πNΔ N3LO+N2LO Piarulli *et al*. Norfolk Models

Energies and Shapes of Nuclei

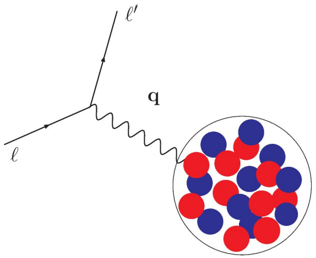


Spectra of light nuclei
Piarulli *et al.* PRL120(2018)052503

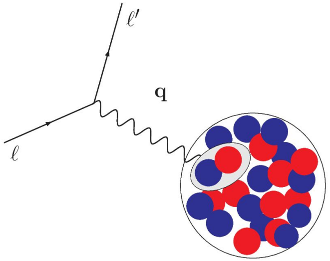
Charge form factor ^{12}C
Lovato *et al.* PRL111(2013)092501



Many-body Nuclear Electroweak Currents



one-body



two-body

- One-body currents: non-relativistic reduction of covariant nucleons' currents
- Two-body currents are a manifestation of two-nucleon correlations
- Electromagnetic two-body currents are required to satisfy current conservation

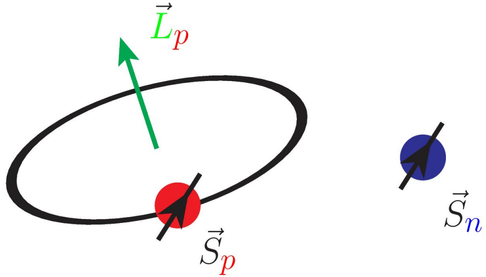
$$\mathbf{q}\cdot\mathbf{j} = [\,H,\ \rho\,] = [t_i + v_{ij} + V_{ijk},\ \rho\,]$$

Nuclear Charge Operator

$$\rho = \sum_{i=1}^{A} \rho_i + \sum_{i<j} \rho_{ij} + \ldots$$

Nuclear (Vector) Current Operator

$$\mathbf{j} = \sum_{i=1}^{A} \mathbf{j}_i + \sum_{i<j} \mathbf{j}_{ij} + \ldots$$



Magnetic Moment: Single Particle Picture

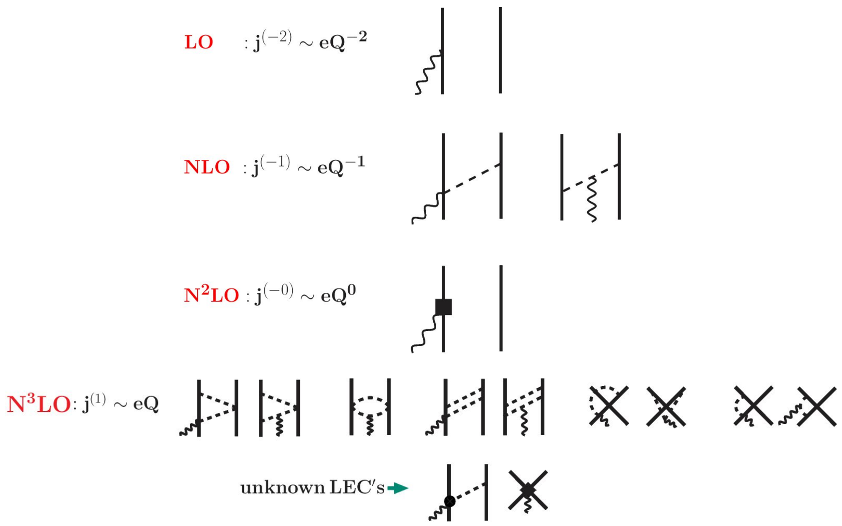
Many-body Currents: Available Models

- **Meson Exchange Currents** (MEC)

Constrain the MEC current operators by imposing that the current conservation relation is satisfied with the given two-body potential

- **Chiral Effective Field Theory Currents**

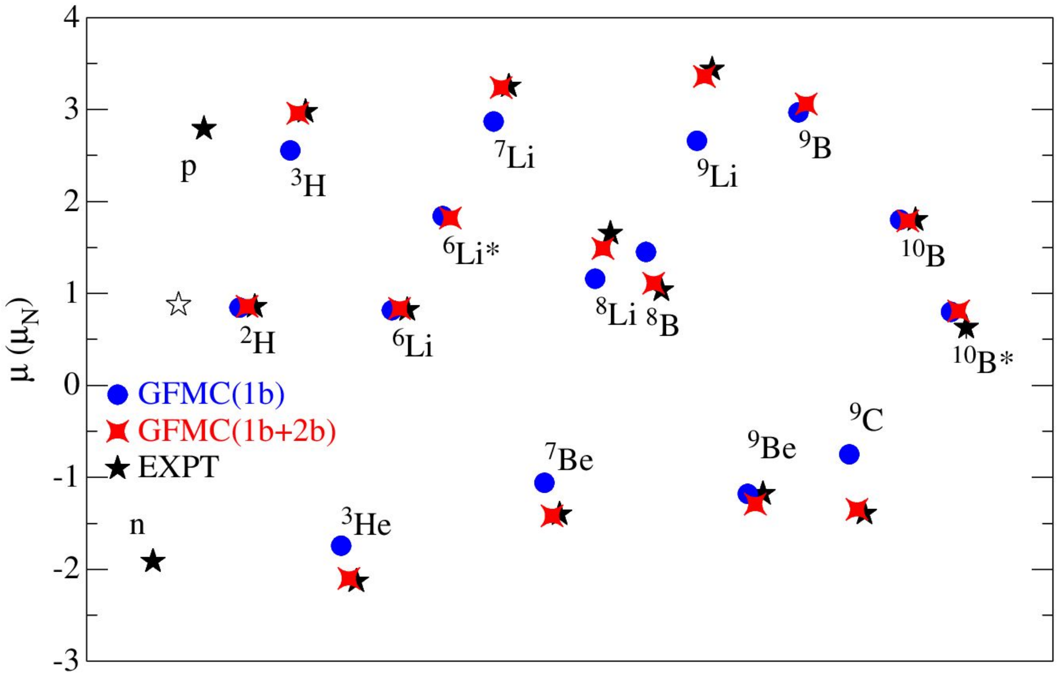
Are constructed consistently with the two-body chiral potential; Unknown parameters, or Low Energy Constants (LECs), need to be determined by either fits to experimental data or by QCD calculations



Electromagnetic Current Operator

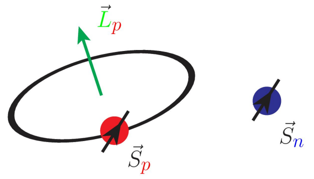
SP *et al.* PRC78(2008)064002, PRC80(2009)034004, PRC84(2011)024001, PRC87(2013)014006
Park *et al.* NPA596(1996)515, Phillips (2005)
Kölling *et al.* PRC80(2009)045502 & PRC84(2011)054008

Magnetic Moments of Light Nuclei



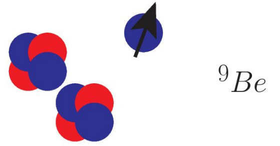
SP *et al*. PRC87(2013)035503

Single particle picture

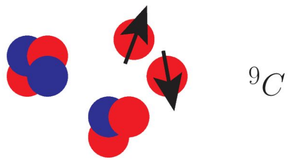


$$\mu_N(1\mathrm{b}) = \sum_i [(L_i + g_p S_i)(1+\tau_{i,z})/2 + g_n S_i (1-\tau_{i,z})/2]$$

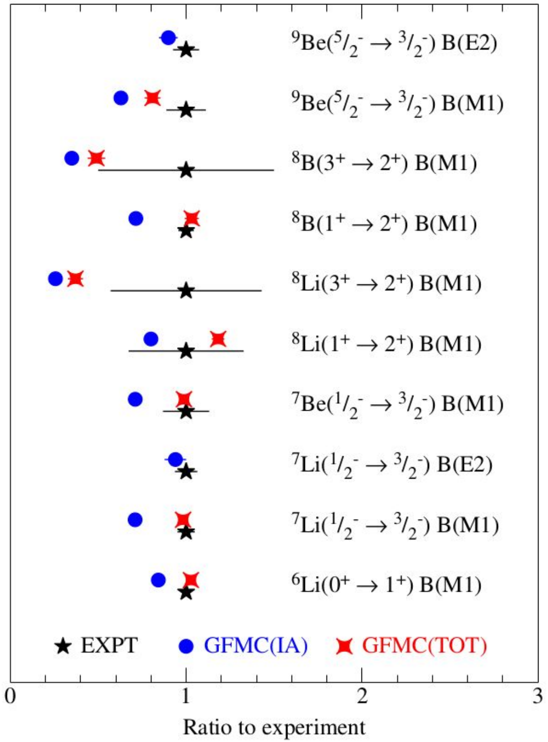
Small two-body current effects



Large two-body current effects



Electromagnetic Transitions in Low-lying States

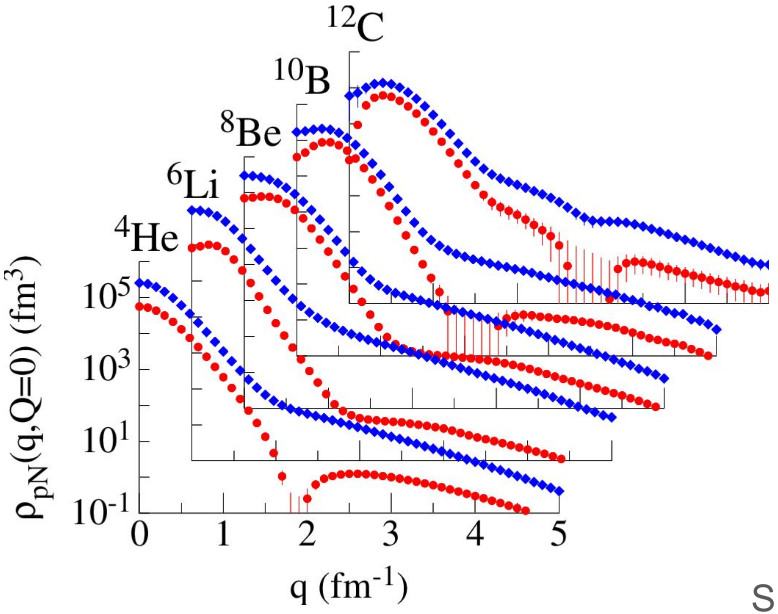


SP *et al*. PRC87(2013)035503

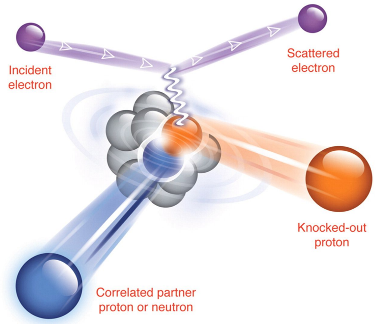
- Two-body electromagnetic currents bring the theory in a better agreement with the experimental data
- Significant corrections found in ^{9}Be and ^{9}C's magnetic moments where two-body currents provide a ~ 40% contribution
- In electromagnetic transitions in low-lying nuclear states, two-body currents are at the 10-20% level

Electron-Nucleus Scattering

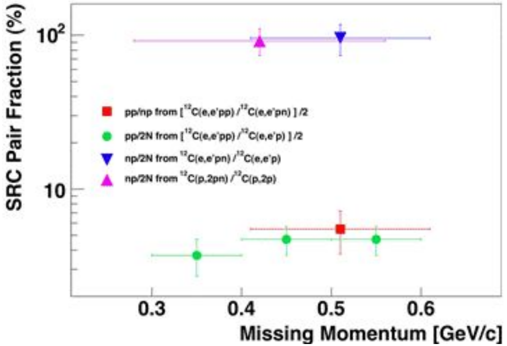
Two-body momentum distribution
Wiringa *et al.* PRC89(2014)024305



pp-pairs; np-pairs



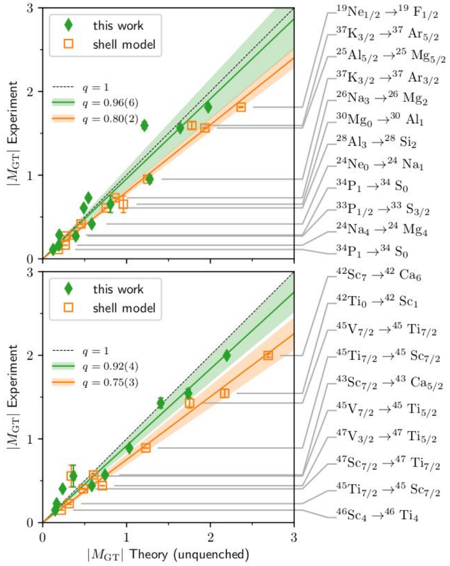
Nuclear properties are strongly affected by two-body correlations and currents in a wide range of energy and momentum transfer



Subedi et al. Science320(2008)1475

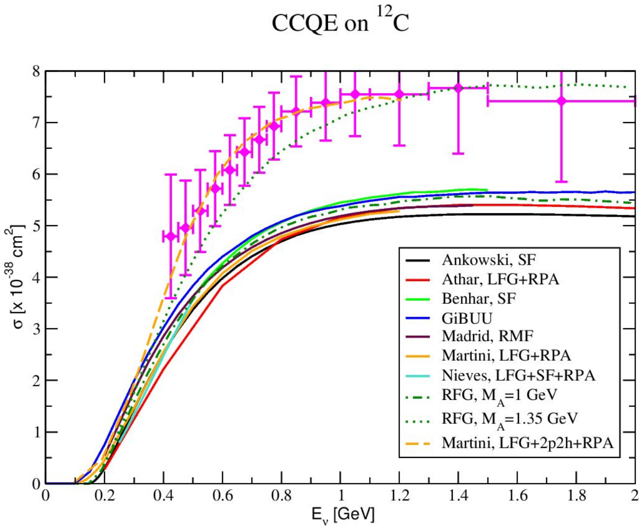
Neutrino-Nucleus Interactions

Low energy and momentum:
Beta Decay Matrix Elements



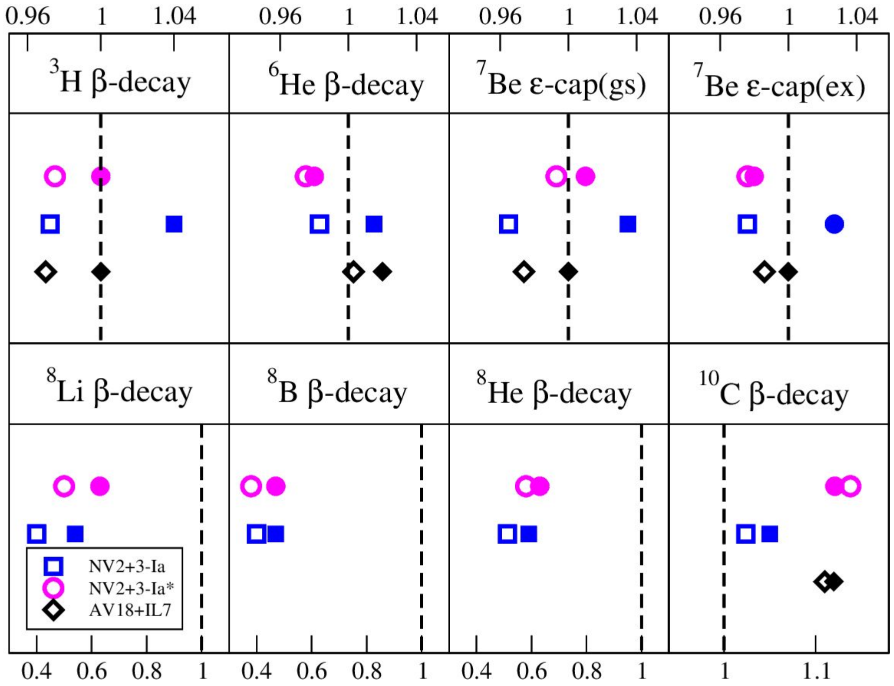
Gysbers *et al.* NaturePhys15(2019)

High Energy (on Nuclear Physics Scale):
Neutrino-Nucleus Cross Section



Alvarez-Ruso arXiv:1012.3871

Beta Decay and Electron Capture in Light Nuclei



G. King *et al.* to appear in PRC(2020) arXiv:2004.05263

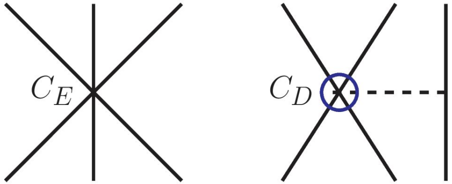
Calculations based on

- chiral interactions and currents
  NV2+3-Ia Norfolk unstarred
  NV2+3-Ia* Norfolk* starred
  Piarulli *et al.* PRL120(2018)052503
  Baroni *et al.* PRC98(2018)044003

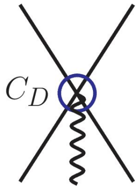
- phenomenological **AV18+IL7** potential and chiral axial currents (hybrid calculation)

Two-body currents are small/negligible;
Results for A=6-7 are within 2% of data;
Results for A=8 are off by a 30-40%;
Results for A=10 are affected by the second $J^{\pi}=(1^{+})$ state in ^{10}B

Three-body Force and the Axial Contact Current



Three-body force



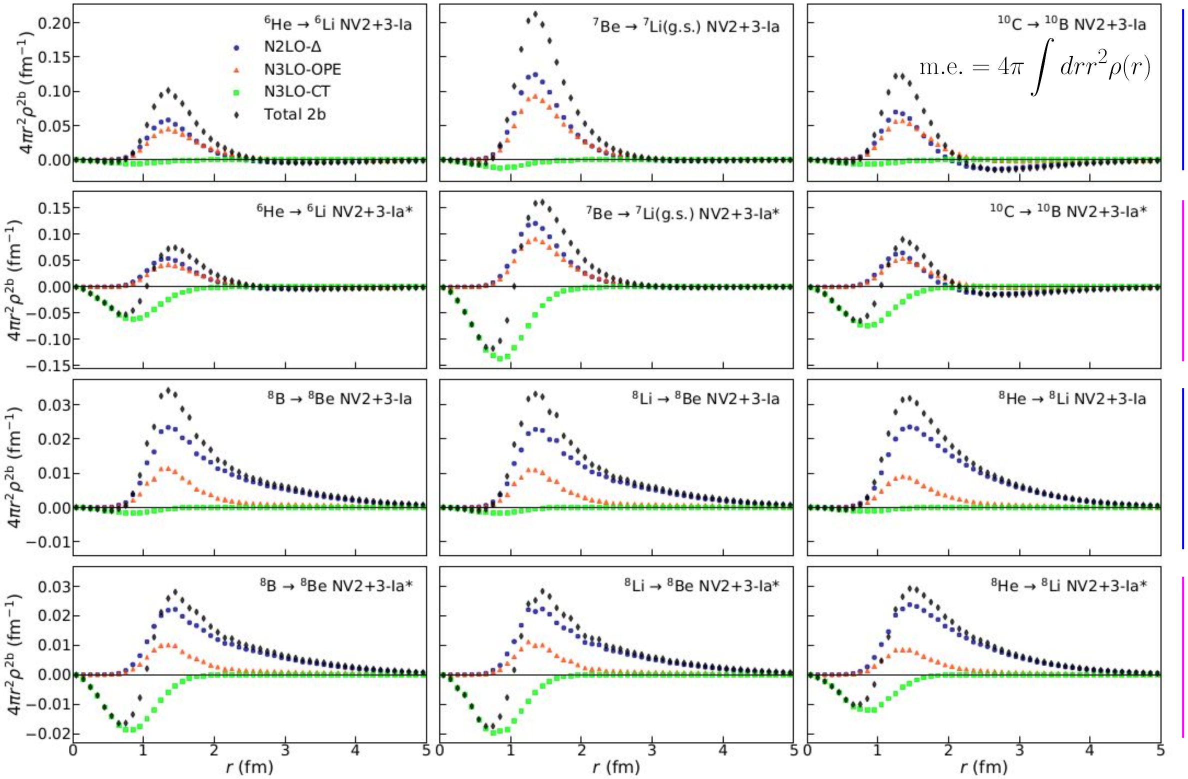
Axial two-body contact current

LECs $\boldsymbol{c_D}$ and $\boldsymbol{c_E}$ are fitted to:

- trinucleon B.E. and *nd* doublet scattering length in **NV2+3-Ia**
- trinucleon B.E. and Gamow-Teller matrix element of tritium **NV2+3-Ia***

Baroni *et al.* PRC98(2018)044003

Axial Two-body Transition Density



G. King *et al.* to appear in PRC(2020) arXiv:2004.05263

NV2+3-Ia ; **NV2+3-Ia***

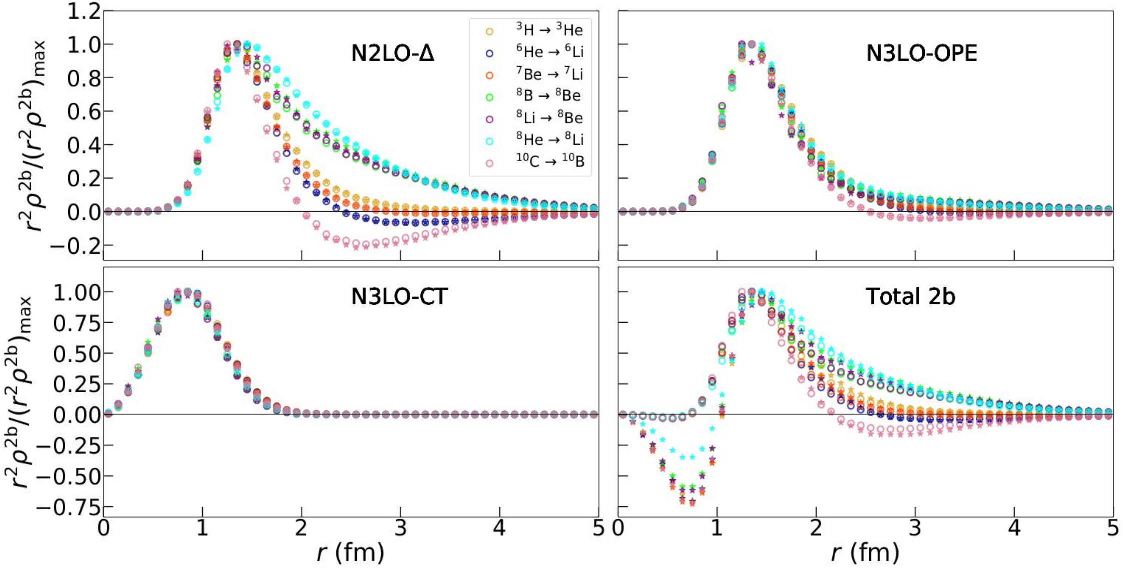
enhanced contribution from contact current in the starred model gives rise to nodes in the two-body transition density

Two-body axial currents

long-range at N2LO and N3LO

contact current at N3LO

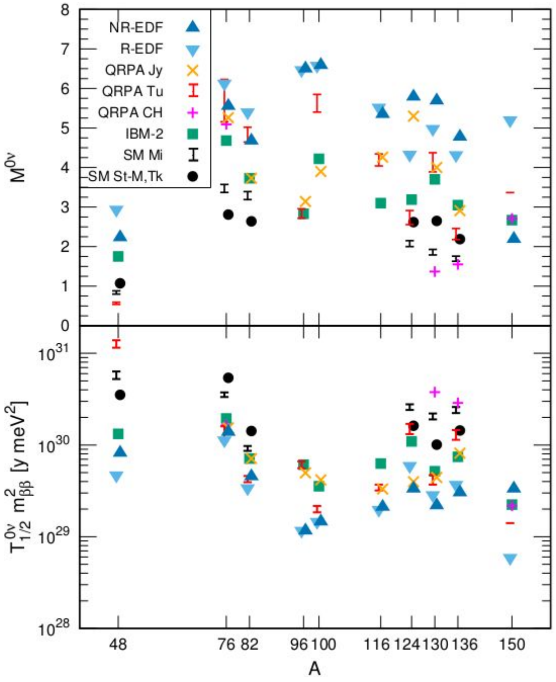
Scaling and Universality of Short-Range Dynamics



G. King *et al.* to appear in PRC(2020) arXiv:2004.05263

NV2+3-Ia empty circles; NV2+3-Ia* stars
Different colors refer to different transitions

Neutrinoless Double Beta Decay



Engel & Menéndez
Rep.Progr.Phys80(2017)046301

Nuclear matrix elements for neutrinoless double beta decay are required to extract the neutrino parameters from the decay rate (if the process is observed)

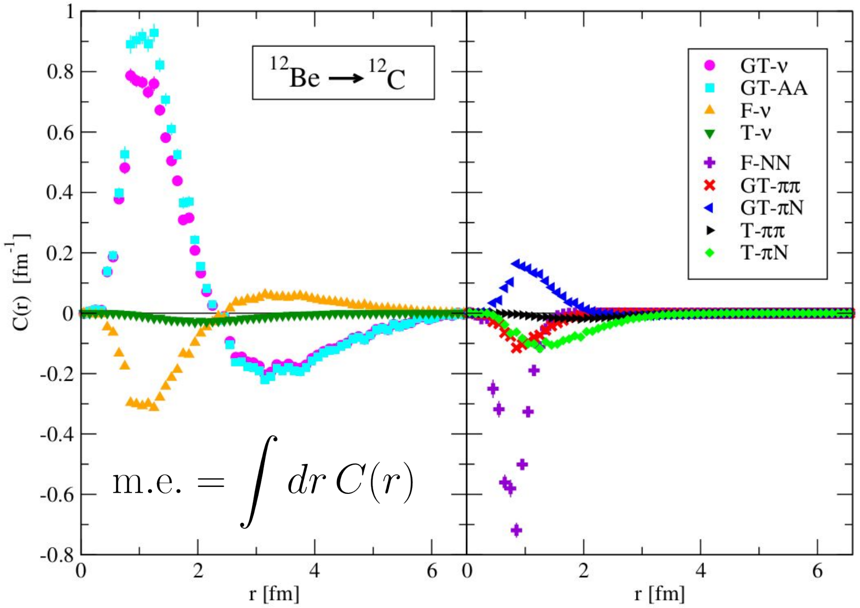
Matrix elements for nuclei of experimental interest are currently affected by large uncertainties due to truncation in the model space and partial (or missing) inclusion of many-body effects

We study neutrinoless double beta decay in **light nuclei** that have been successfully described by *ab initio* models where correlations and currents can be fully accounted for

These studies serve as benchmark and to establish the relevance of the various two-body (or more) dynamics inducing the decay

Neutrinoless Double Beta Decay Matrix Elements

Long-range One-pion & short range

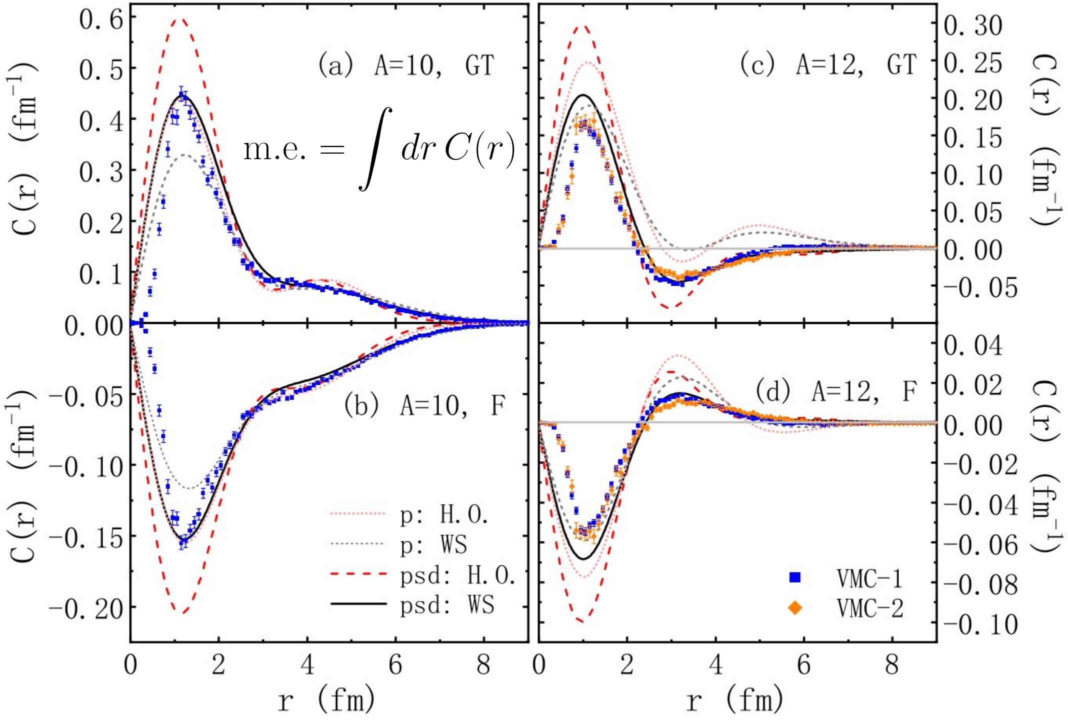


SP *et al.* PRC97(2018)014606

Cirigliano Dekens DeVries Graesser Mereghetti *et al.*
PLB769(2017)460, JHEP12(2017)082, PRC97(2018)065501

- Leading operators in neutrinoless double beta decay are two-body operators
- These observables are particularly sensitive to short-range and two-body physics
- Transition densities calculated in momentum space indicate that the momentum transfer in this process is of the order of ~ 200 MeV

Comparison with Shell-Model Calculations



X. Wang *et al.* PLB798(2019)134974

Closer agreement between Shell-Model calculations with Variational Monte Carlo results is reached by

- Increasing the size of the model space
- Wood-Saxon single particle wave functions are superion in describing the tails of the densities wrt harmonic oscillator wave functions
- Phenomenological Short-Range-Correlations functions further improve the agreement

Lepton-Nucleus scattering: Inclusive Processes

Electromagnetic Nuclear Response Functions

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

Longitudinal response induced by the charge operator $O_L = \rho$
Transverse response induced by the current operator $O_T = \boldsymbol{j}$
5 Responses in neutrino-nucleus scattering

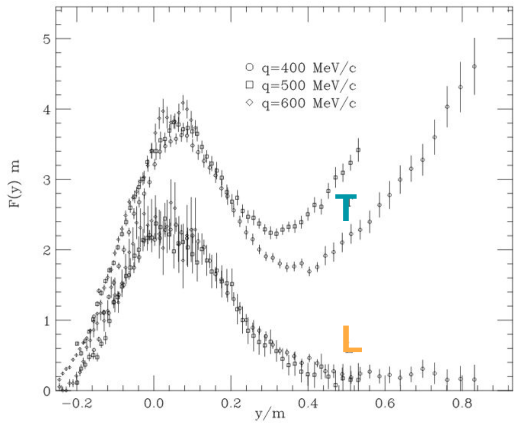
The Quantum Monte Carlo community at LANL, ANL, JLAB delivered calculations of inclusive responses of both electron and neutrino scattering from nuclei with mass number A≤12

For a recent review see Rocco *Front.inPhys.*8 (2020)116

Lepton-Nucleus scattering: Data

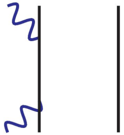
Transverse Sum Rule

$$S_T(q) \propto \langle 0|\mathbf{j}^\dagger\ \mathbf{j}|0\rangle \propto \langle 0|\mathbf{j}_{1b}{}^\dagger\ \mathbf{j}_{1b}|0\rangle + \langle 0|\mathbf{j}_{1b}{}^\dagger\ \mathbf{j}_{2b}|0\rangle + \ldots$$



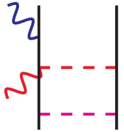
^{12}C Electromagnetic Data
Benhar *et al.* RMP80(2008)198

Observed transverse enhancement explained by the combined effect of two-body correlations and currents in the interference term



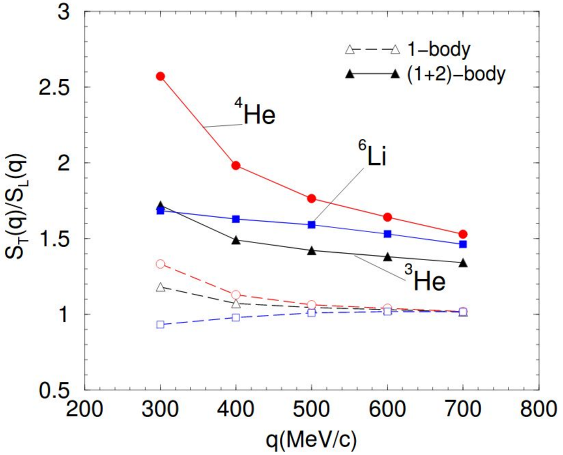
$\langle \mathbf{j}^\dagger_{1b}\ \ \mathbf{j}_{1b}\rangle > 0$

Leading one-body term



$\langle \mathbf{j}^\dagger_{1b}\ \mathbf{j}_{2b}\ v_\pi\rangle \propto \langle v_\pi^2\rangle > 0$

Interference term

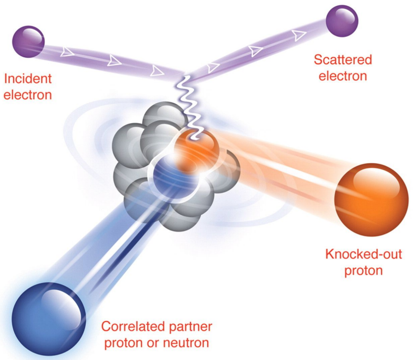


Transverse/Longitudinal Sum Rule
Carlson *et al.* PRC65(2002)024002

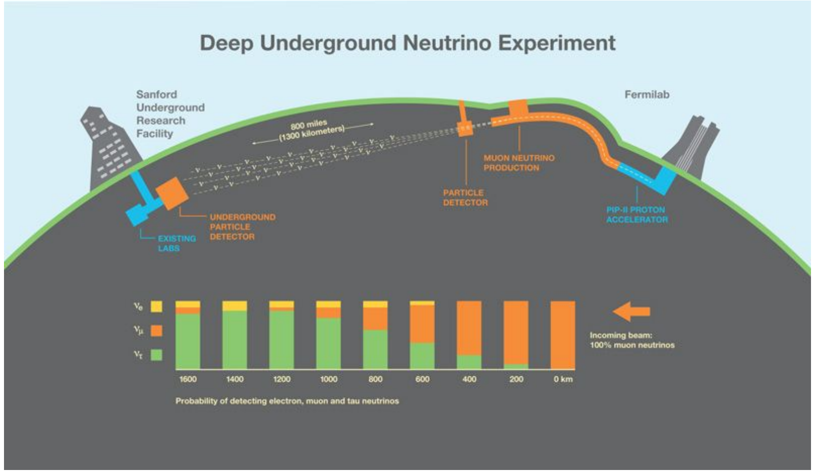
Beyond Inclusive: Short-Time-Approximation

Short-Time-Approximation Goals:

- Describe electroweak scattering from A > 12 without losing two-body physics
- Account for exclusive processes
- Incorporate relativistic effects

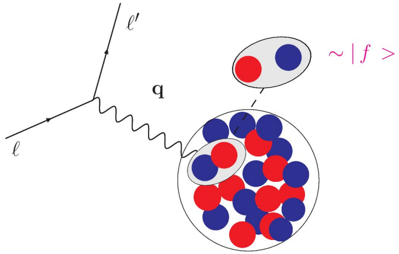


Subedi et al. Science320(2008)1475



[Stanford Lab article]

Short-Time-Approximation



Short-Time-Approximation:

- Based on Factorization
- Allows to retain both two-body correlations and currents at the vertex
- Provides "more" exclusive information in terms of nucleon-pair kinematics via the Response Densities
- Response functions are given by the scattering from pairs of fully interacting nucleons that propagate into a correlated pair of nucleons
- Correctly accounts for interference

Response Functions

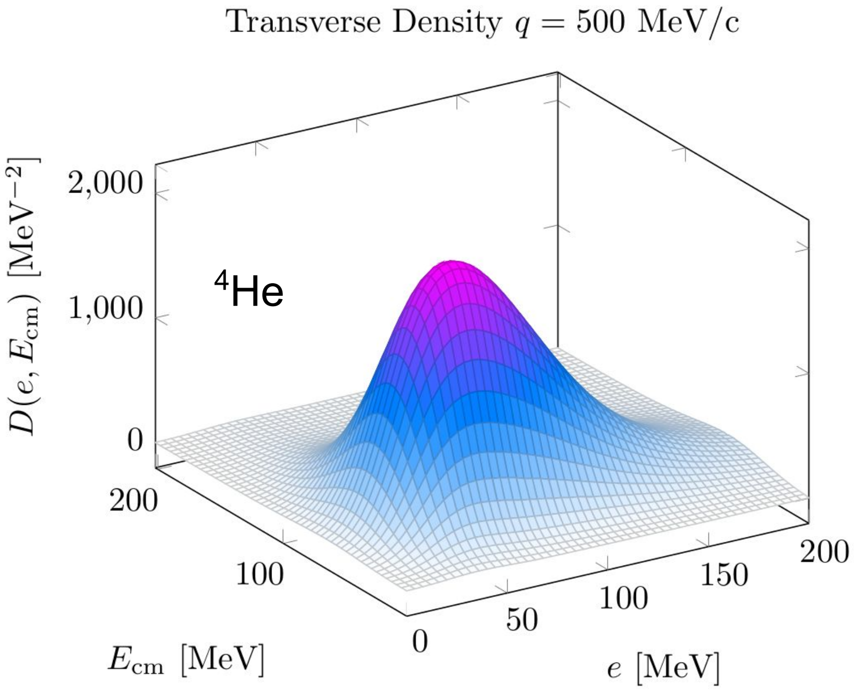
$$R_\alpha(q,\omega) = \sum_f \delta\left(\omega + E_0 - E_f\right) |\langle f|O_\alpha(\mathbf{q})|0\rangle|^2$$

Response Densities

$$R(q,\omega) \sim \int \delta\left(\omega + E_0 - E_f\right) dP'\, dp' \mathcal{D}(p', P'; q)$$

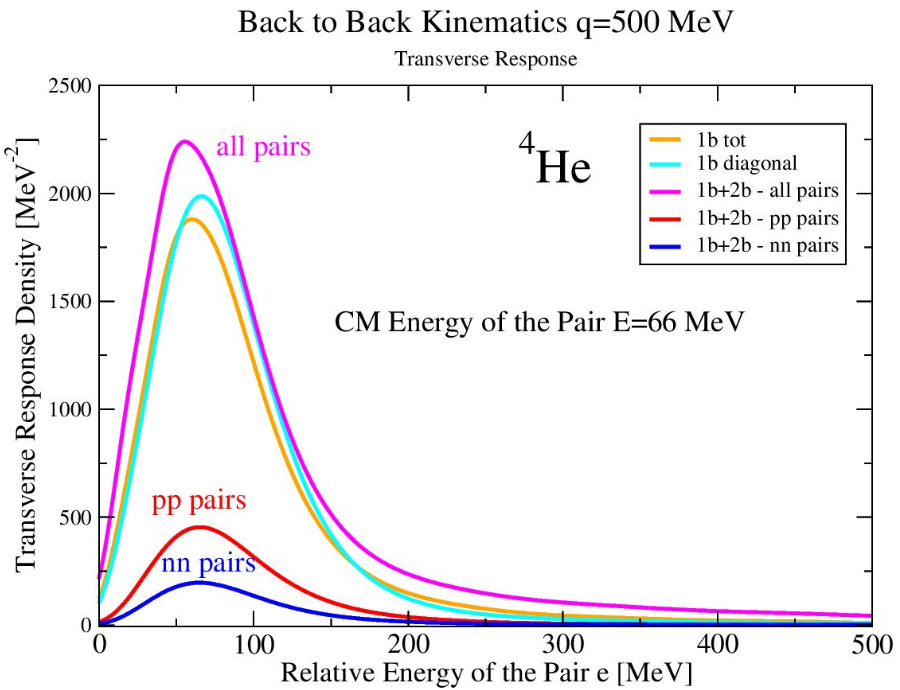
P' and *p'* are the CM and relative momenta of the struck nucleon pair

Transverse Response Density: *e*-^{4}He scattering



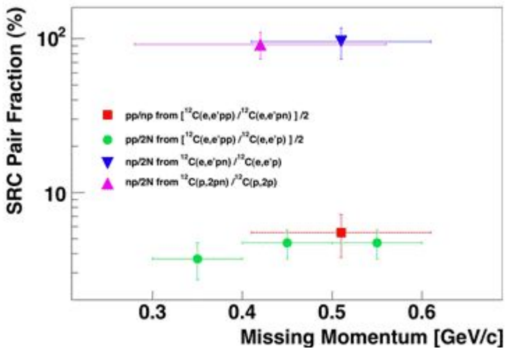
SP *et al.* PRC101(2020)044612

e-^{4}He scattering in the back-to-back kinematic



SP *et al.* PRC101(2020)044612

- pp pairs
- nn pairs
- all pairs 1body
- all pairs tot



Subedi et al. Science320(2008)1475

Summary and Outlook

Ab initio calculations of light nuclei yield a picture of nuclear structure and dynamics where many-body effects play an essential role to explain available data.

This is found in a wide range of energy and momentum transferred and in both static and dynamical observables.

Light to low and medium mass nuclei are promising candidates for precision tests and studies of fundamental symmetries and neutrino physics.

In these systems, the existing computational methods allow to retain the complexity of many-body correlations and currents.

The QMC community is addressing larger nuclear systems, developing new algorithms that allow to retain two-body physics (correlations and currents) in lepton-nucleus scattering, and studying observables in kinematic regions of interest to experimental programs in BSM and precision physics.

Strategy

Validate the Nuclear Model against available data for strong and electroweak observables

- Energy Spectra, Electromagnetic Form Factors, Electromagnetic Moments, ...
- Electromagnetic and Beta decay rates, ...
- Muon Capture Rates, ...
- Electron-Nucleus Scattering Cross Sections, ...

Use attained information to make (accurate) predictions for BSM searches and precision tests

- EDMs, Anapole Moments, Hadronic PV, ...
- BSM searches with beta decay, ...
- Neutrinoless double beta decay, ...
- Neutrino-Nucleus Scattering Cross Sections, ...
- ...

Collaborators

WashU: **Andreoli Bub King** Piarulli
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Salento U: Girlanda
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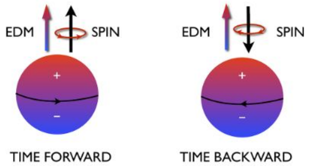
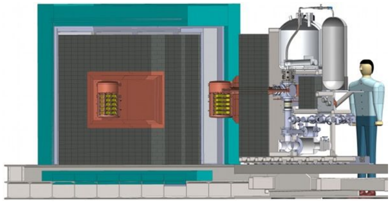
Ground States' Electroweak Moments, Form Factors, Radii



Neutrinoless Double Beta Decay, Muon-Capture



Accelerator Neutrino Experiments, Lepton-Nucleus XSecs

(ω,q)~0 MeV → **ω~few MeVs, q~0 MeV** → **ω~few MeVs, q~10^2 MeV** → **ω~tens of MeVs** → **ω~10^2 MeV**

FRIB

Electromagnetic Decay, Beta Decay, Double Beta Decay & inverse processes

JINA-CEE

Nuclear Rates for Astrophysics

DUNE

Jefferson Lab