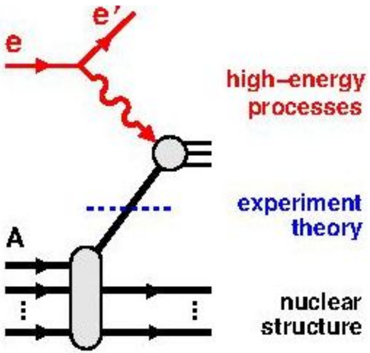
Effective Field Theory methods for nuclear interactions

Saori Pastore
Washington University in St Louis



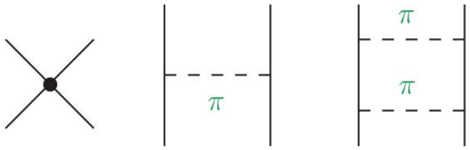
Jun 19 – 27, 2025
Florida International University, Miami, FL

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. They correlate nucleons in pairs and triplets.

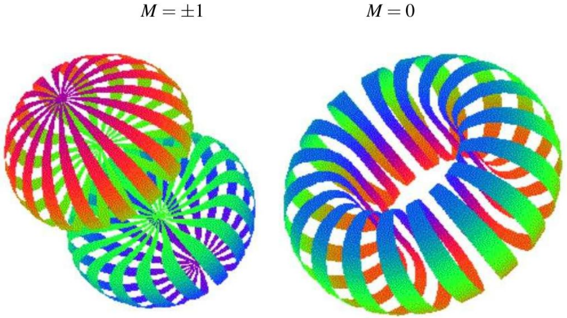


$r \propto m_\pi^{-1}$ $\quad r \propto (2\,m_\pi)^{-1}$

Contact term: short-range
Two-pion range: intermediate-range
One-pion range: long-range

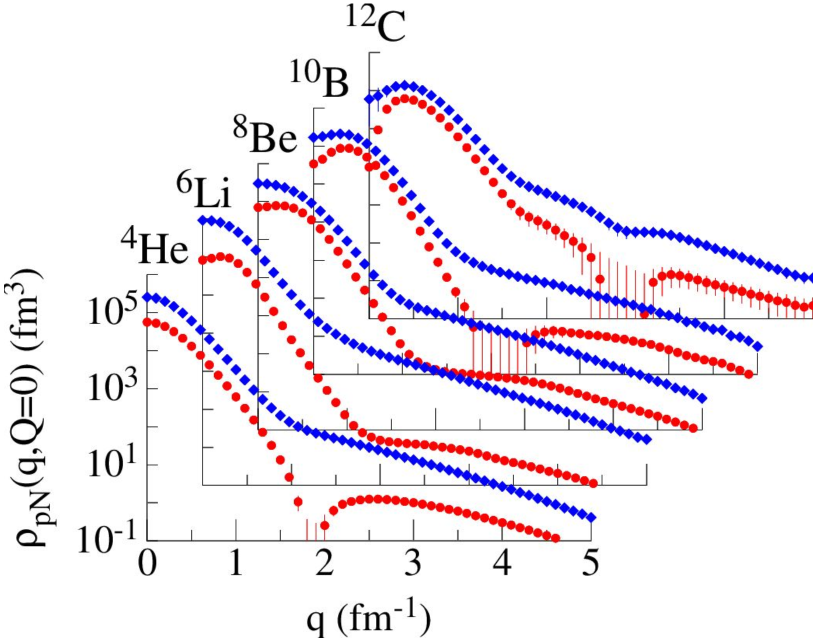
1. Phenomenological potentials AV18+UIX; AV18+IL7 Wiringa, Schiavilla, Pieper *et al.*
2. Chiral EFT potentials with πNΔ N3LO+N2LO Piarulli *et al.* **Norfolk Models**

Two-nucleon physics



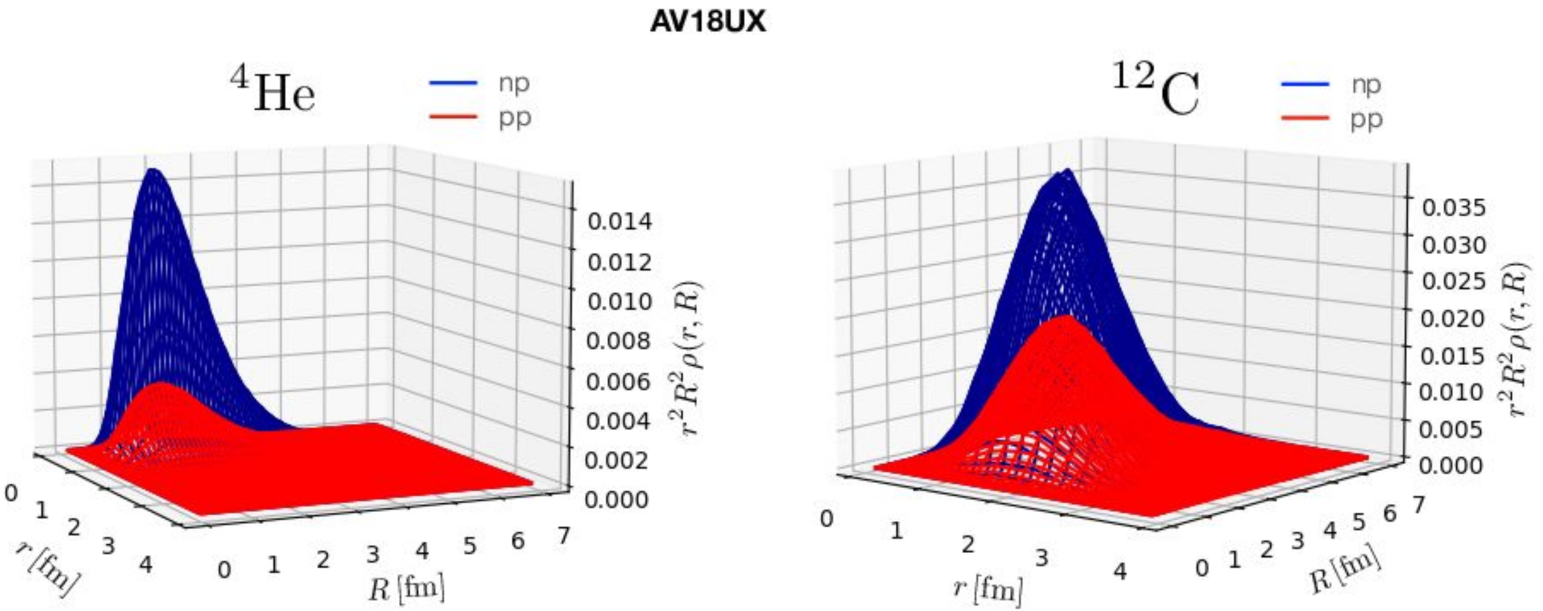
Constant density surfaces for a polarized deuteron in the $M = \pm 1$ (left) and $M = 0$ (right) states

Carlson and Schiavilla Rev.Mod.Phys.70(1998)743



Schiavilla Carlson Wiringa Pieper
PRL98(2007) & PRC89(2014)

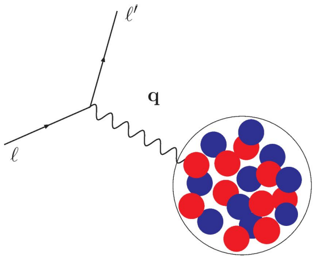
Two-body densities



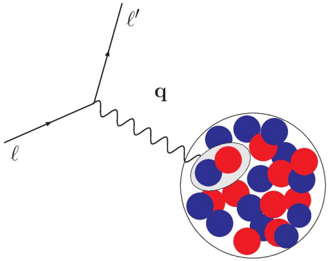
Piarulli, SP, Wiringa PRC (2023)

data

Many-body Nuclear Electroweak Currents



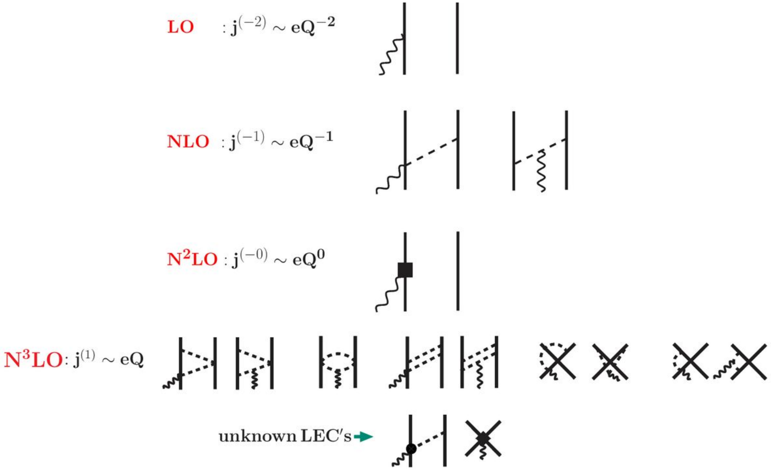
one-body



two-body

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

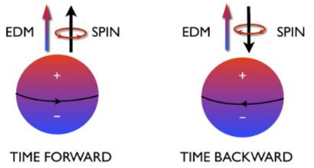
$$\mathbf{j} = \sum_{i=1}^{A} \mathbf{j}_i + \sum_{i<j} \mathbf{j}_{ij} + \ldots$$



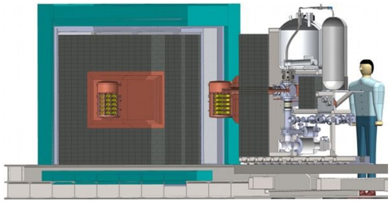
Electromagnetic Current Operator

1. Phenomenological meson exchange currents consistent with the AV18 interaction Schiavilla *et al.*
2. Chiral EFT currents with LECs fixed from expt data SP, Schiavilla, Baroni et al.

Ground States' Electroweak Moments, Form Factors, Radii



Neutrinoless Double Beta Decay, Muon-Capture



Accelerator Neutrino Experiments, Lepton-Nucleus XSecs

T2K

(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

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

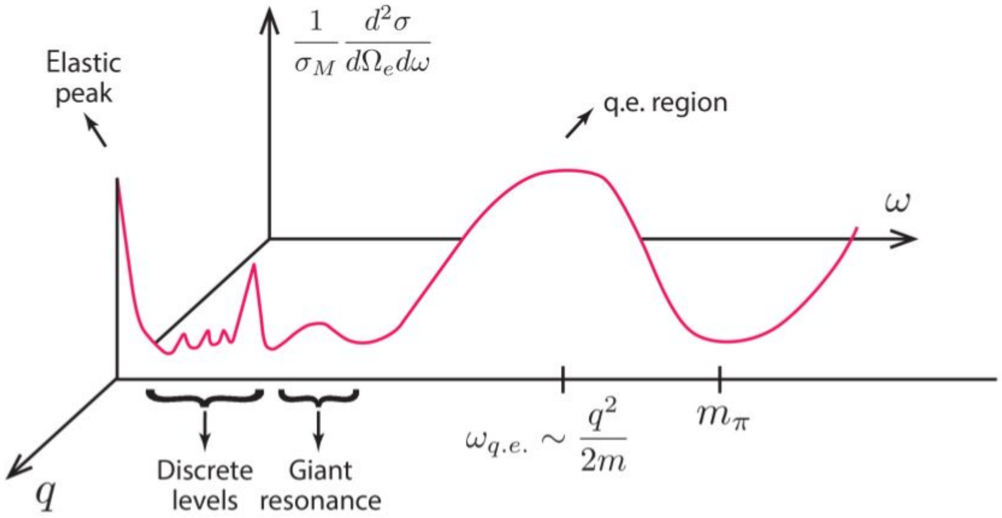
JINA-CEE

Nuclear Rates for Astrophysics

DUNE

Jefferson Lab

Electron-Nucleus Scattering Cross Section



Energy and momentum transferred (ω,q)

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

Electromagnetic observables at low-energies

Electromagnetic structure of nuclei

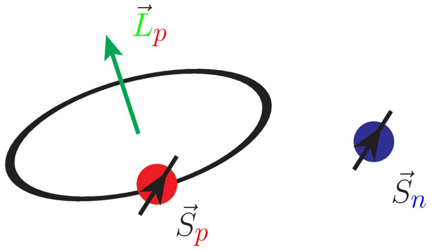
Magnetic structure of nuclei

Magnetic moment

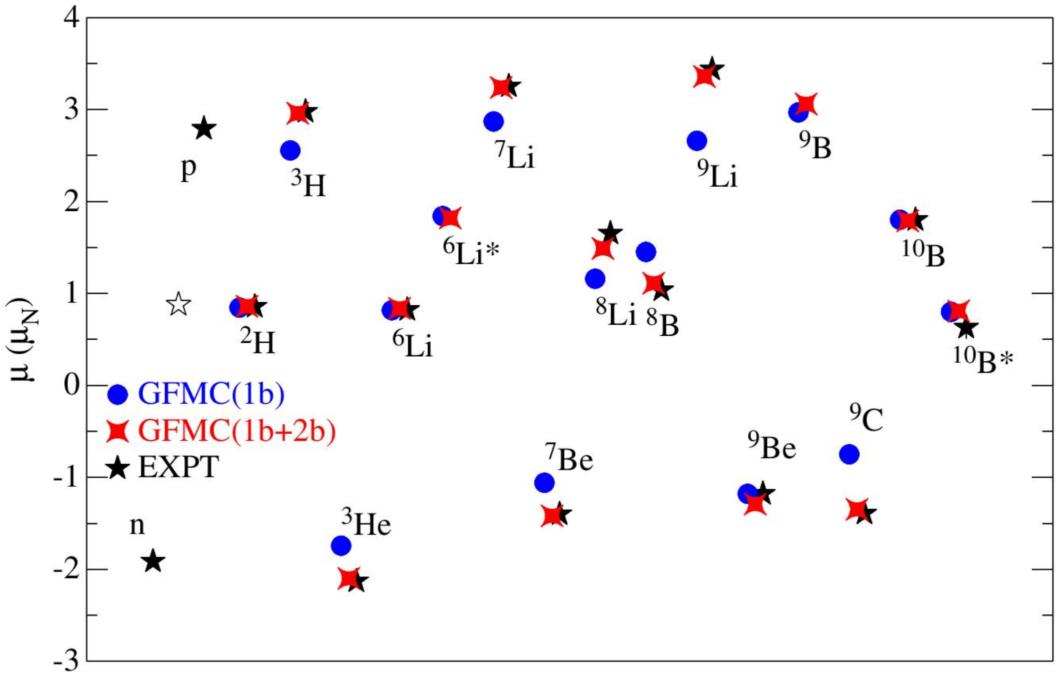
$$\mu = \lim_{q\to 0} -i\frac{2m_N}{q}\langle JJ|\mathrm{j}_y(q\hat{\mathbf{x}})|JJ\rangle$$

Magnetic moment in the single particle picture

$$\mu_i = \mu_N\left[(L_i + g_p S_i)\frac{1+\tau_{i,z}}{2} + g_n S_i\frac{1-\tau_{i,z}}{2}\right]$$

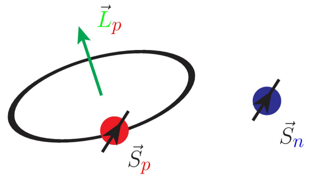


Magnetic Moments of Light Nuclei



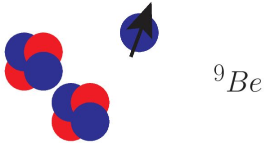
SP *et al*. PRC87(2013)035503

Single particle picture

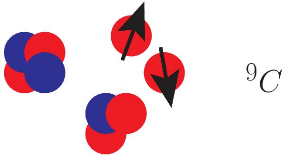


$$\mu_N(1b) = \sum_i [(L_i + g_p S_i)(1+\tau_{i,z})/2 + g_n S_i (1-\tau_{i,z})/2]$$

Small two-body current effects

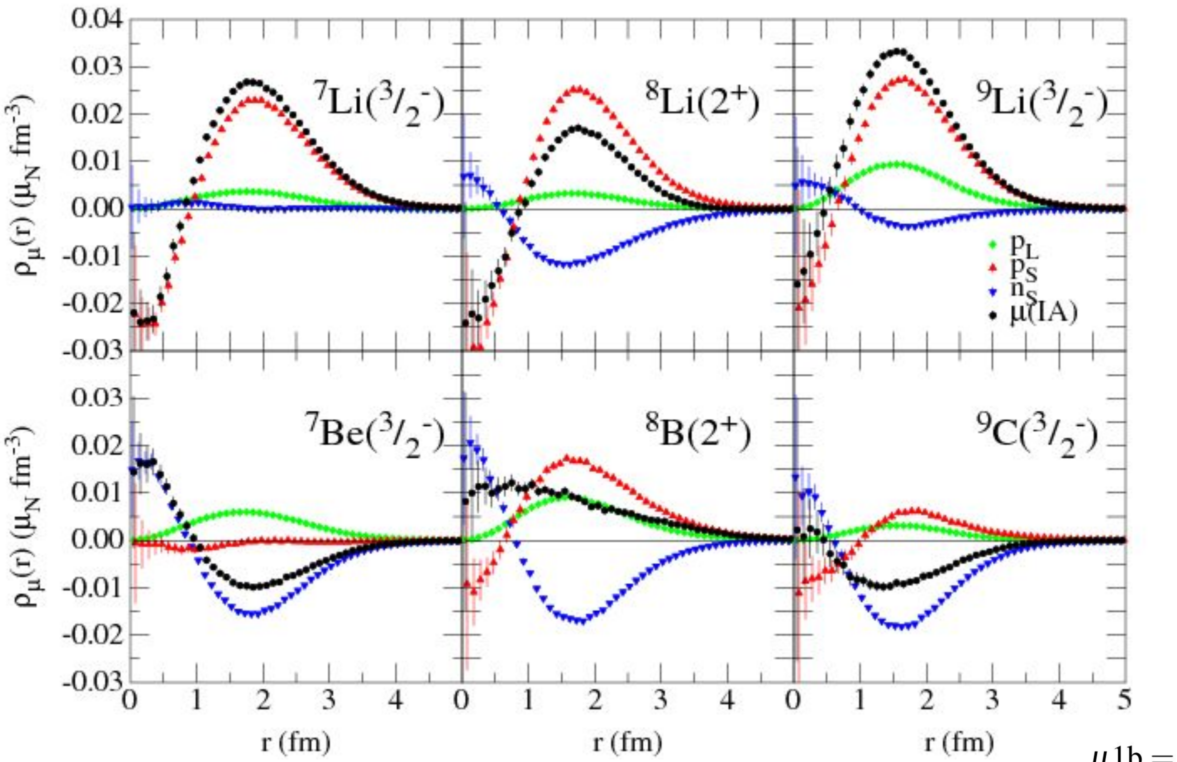


Large two-body currents ~40%



Hybrid approach: AV18+IL7 and chiEFT currents; predictions are for A>3 nuclei

One-body magnetic density

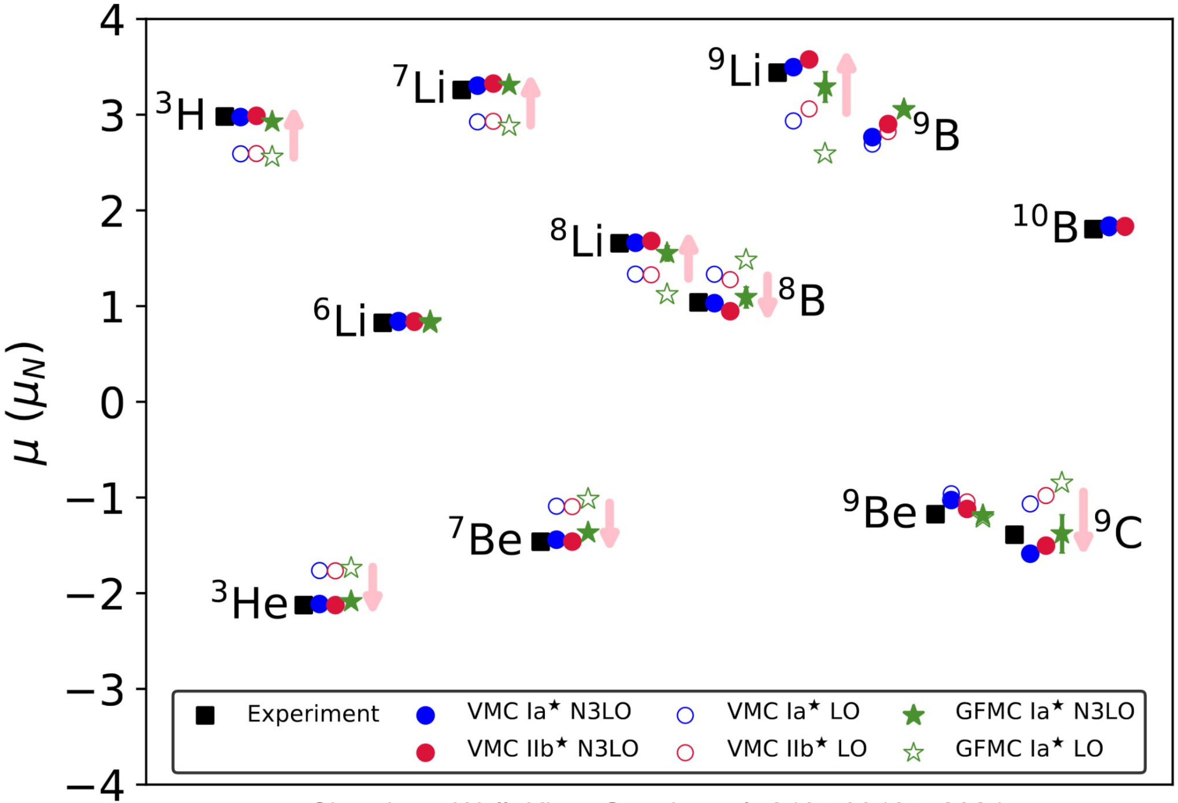


$$\mu^{1b} \propto \int \rho_M^{1b}(r)dr$$

r single particle coordinate from the c.m.

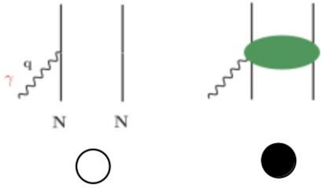
$$\mu 1\mathrm{b} = \mu_N \sum_i [(L_i + g_p S_i)(1+\tau_{i,z})/2 + g_n S_i (1-\tau_{i,z})/2]$$

Magnetic moments in light nuclei

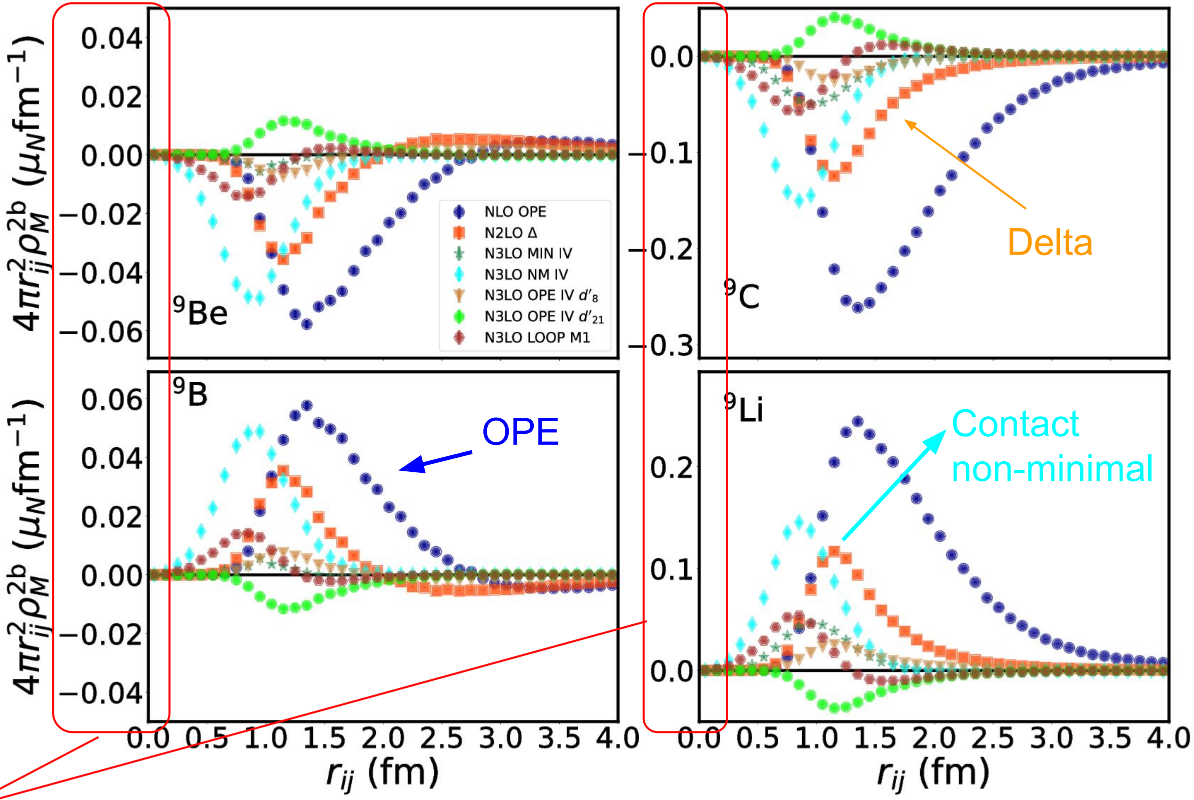


Chambers-Wall, King, Gnech et al. [2407.03487](https://arxiv.org/abs/2407.03487) 2024

Based on Norfolk interactions and one- plus two-body currents



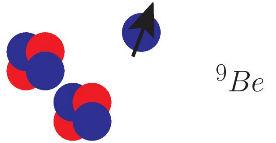
Two-body magnetic densities



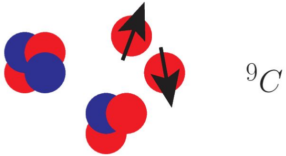
Note the scale

$$\mu^{2b} = \int dr_{ij} 4\pi r_{ij}^2 \rho_M^{2b}(r_{ij})$$

Cluster effects suppress the two-body contribution for A=9,T=1/2



$[441] = [\alpha, \alpha, n(p)]$



$[432] = [\alpha, {}^3\mathrm{He}({}^3\mathrm{H}), pp(nn)]$

Chambers-Wall, King, Gnech et al. 2407.03487 2024

Elastic scattering

Cross section

$$\frac{d\sigma}{d\Omega} = 4\pi\sigma_M f_{\mathrm{rec}}^{-1} \left[\frac{Q^4}{q^4} F_L^2(q) + \left(\frac{Q^2}{2q^2} + \tan^2\theta_e/2 \right) F_T^2(q) \right]$$

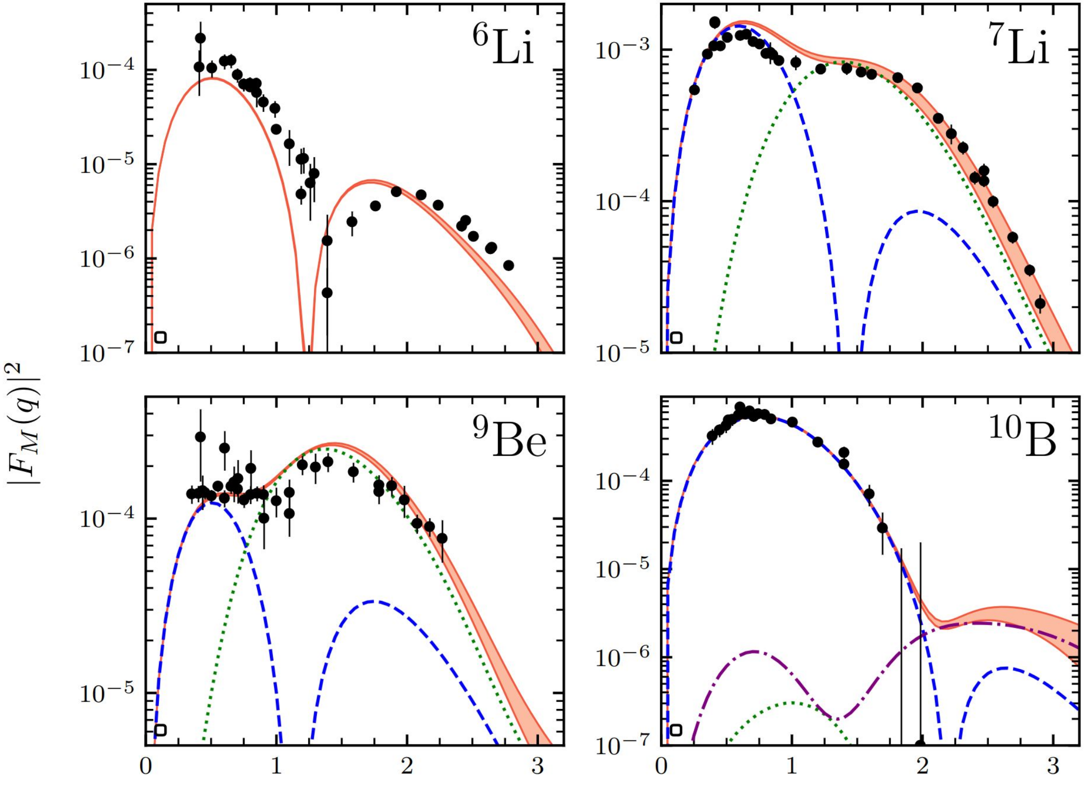
$$F_T^2(q) = F_M^2(q) = \frac{1}{2J_i+1} \sum_{L=1}^{\infty} |\langle J_f || M_L(q) || J_i \rangle|^2$$

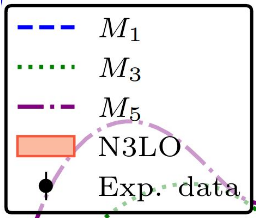
$$F_L^2(q) = \frac{1}{2J_i+1} \sum_{L=0}^{\infty} |\langle J_f || C_L(q) || J_i \rangle|^2$$

Magnetic and Charge Form Factors

$\langle JJ | \mathrm{j}_y(q\hat{\boldsymbol{x}}) | JJ \rangle$ $\langle J_f M | \rho^\dagger(q) | J_i M \rangle$

Magnetic form factors: comparison with the data





$$F_M^2(q) = \frac{1}{2J+1}\sum_{L=1}^{\infty} |\langle J||M_L(q)||J\rangle|^2$$

First QMC results for form factors in A>6 systems.

Based on Norfolk interactions and one- and two-body currents.

Error band = truncation error in the ChiEFT expansion.

q [fm^{-1}] Chambers-Wall, King, Gnech et al. 2407.03487 2024

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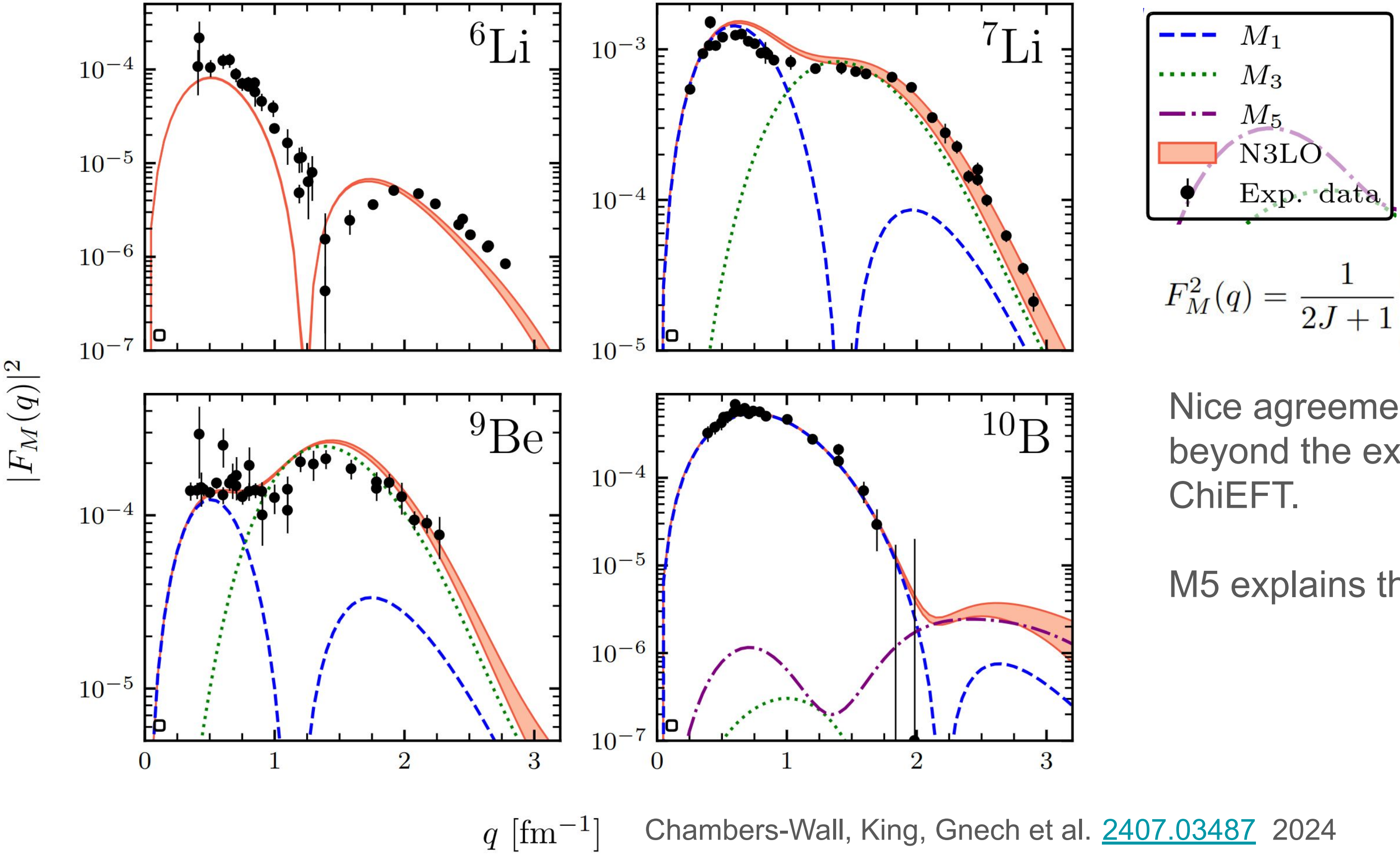


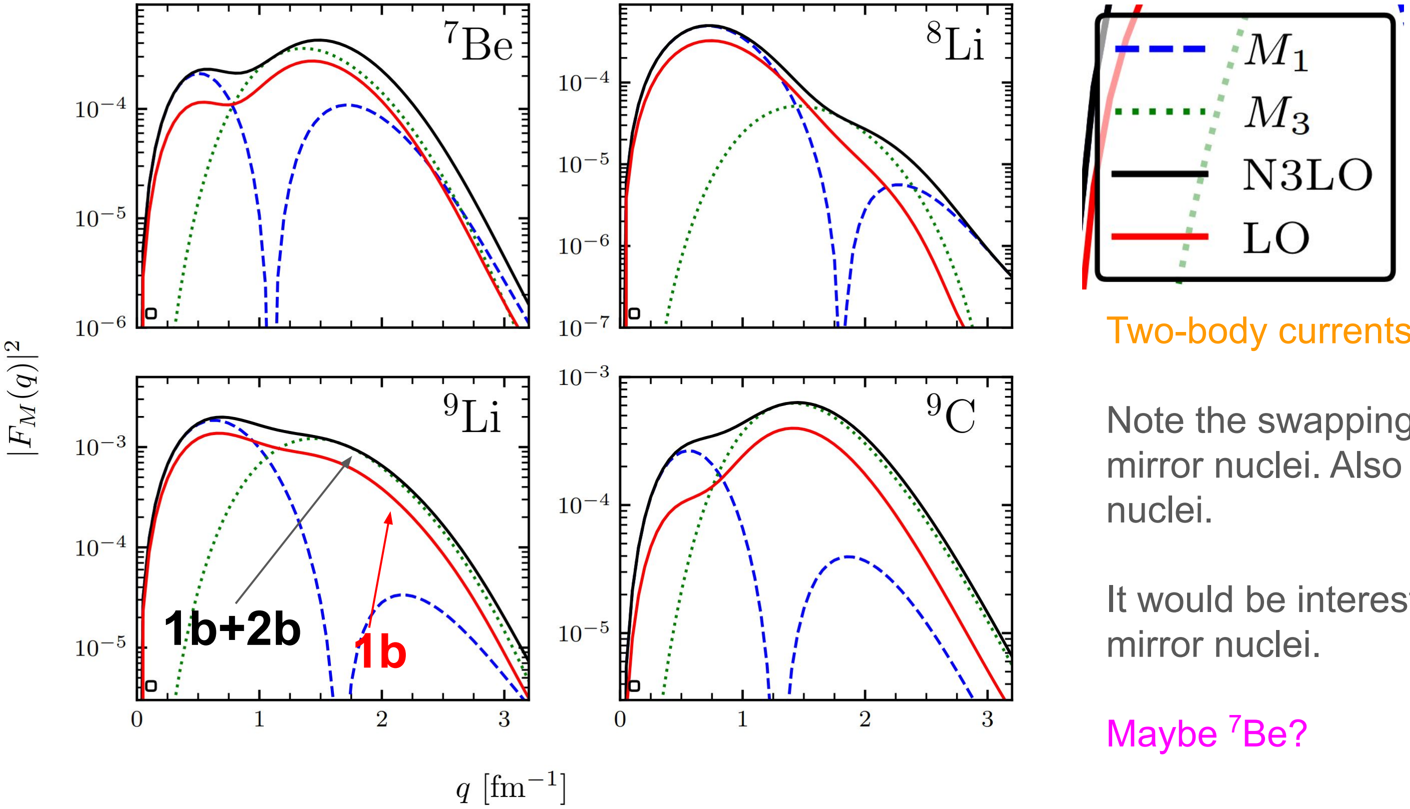
$$F_M^2(q) = \frac{1}{2J+1} \sum_{L=1}^{\infty} |\langle J||M_L(q)||J\rangle|^2$$

Nice agreement with the data beyond the expected validity of ChiEFT.

M5 explains the dip in ^{10}B at high q.

Chambers-Wall, King, Gnech et al. 2407.03487 2024

Magnetic form factors: predictions



Two-body currents provide 40-60%.

Note the swapping of M1 and M3 in mirror nuclei. Also observed in A=7 nuclei.

It would be interesting to have data for mirror nuclei.

Maybe ^{7}Be?

Chambers-Wall, King, Gnech et al. 2407.03487 2024

A comment on the data

Nucleus	Reference	Data type	ratio/method
^{3}H	Sick 2001 [89]	N	1
^{3}He	Sick 2001 [89]	N	1
^{6}Li	Peterson 1962 [90]	N	Eq. (C2)
	Goldemberg 1963 [91]	N	Eq. (C2)
	Rand 1966 [92]	N	Eq. (C1)
	Lapikas 1978 [93]	D	$1/4\pi$
	Bergstrom 1982 [94]	N	$Z^2/4\pi$
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^{9}Be	Goldemberg 1963 [91]	N	Eq. (C2)
	Vanpraet 1965 [98]	N	Eq. (C1)
	Rand 1966 [92]	N	Eq. (C1)
	Lapikas 1975 [97]	N	Eq. (C2)
^{10}B	Goldemberg 1963 [91]	N	Eq. (C2)
	Goldemberg 1965 [100]	N	Eq. (C2)
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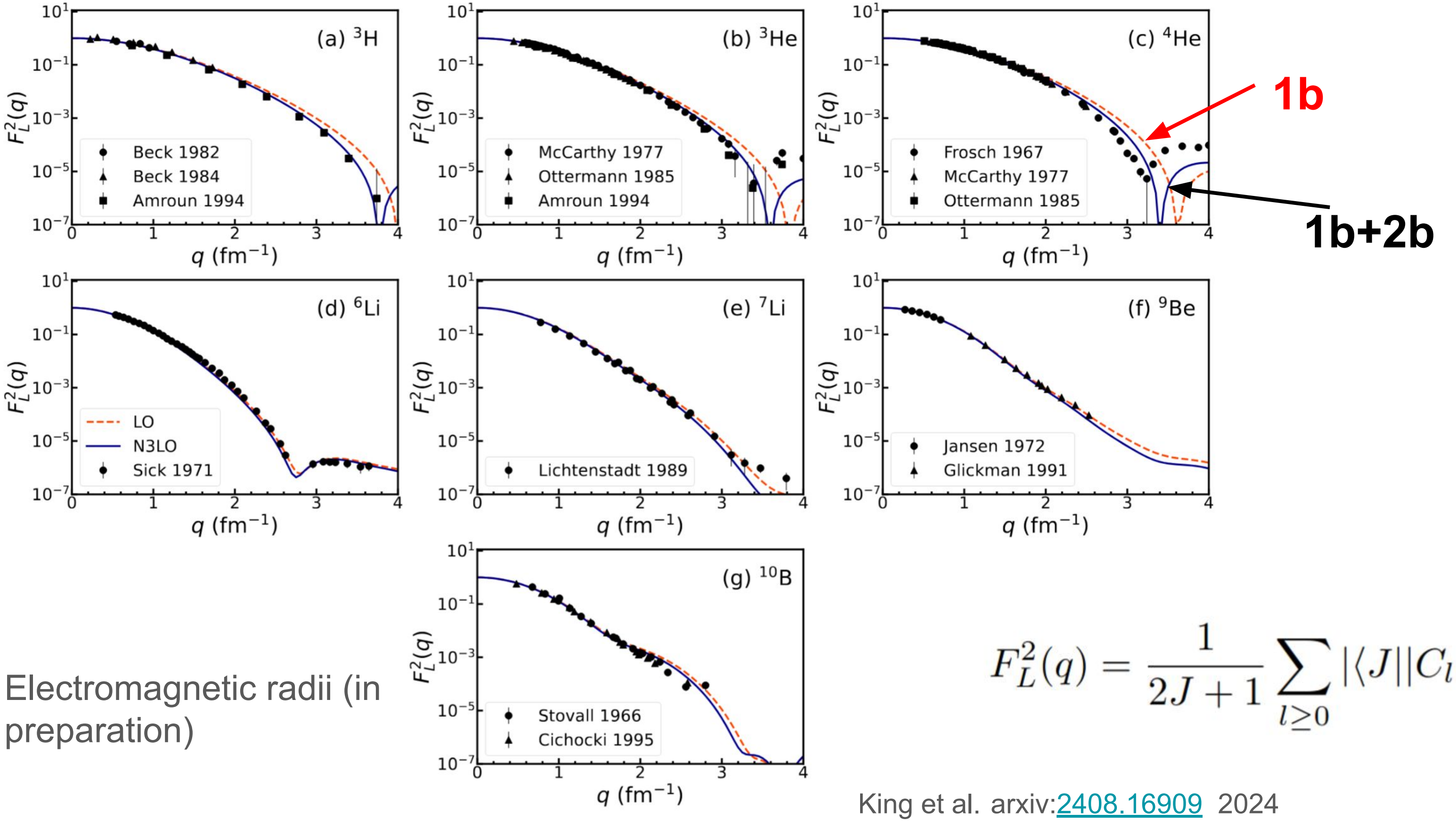
Available data to date.

Charge form factors

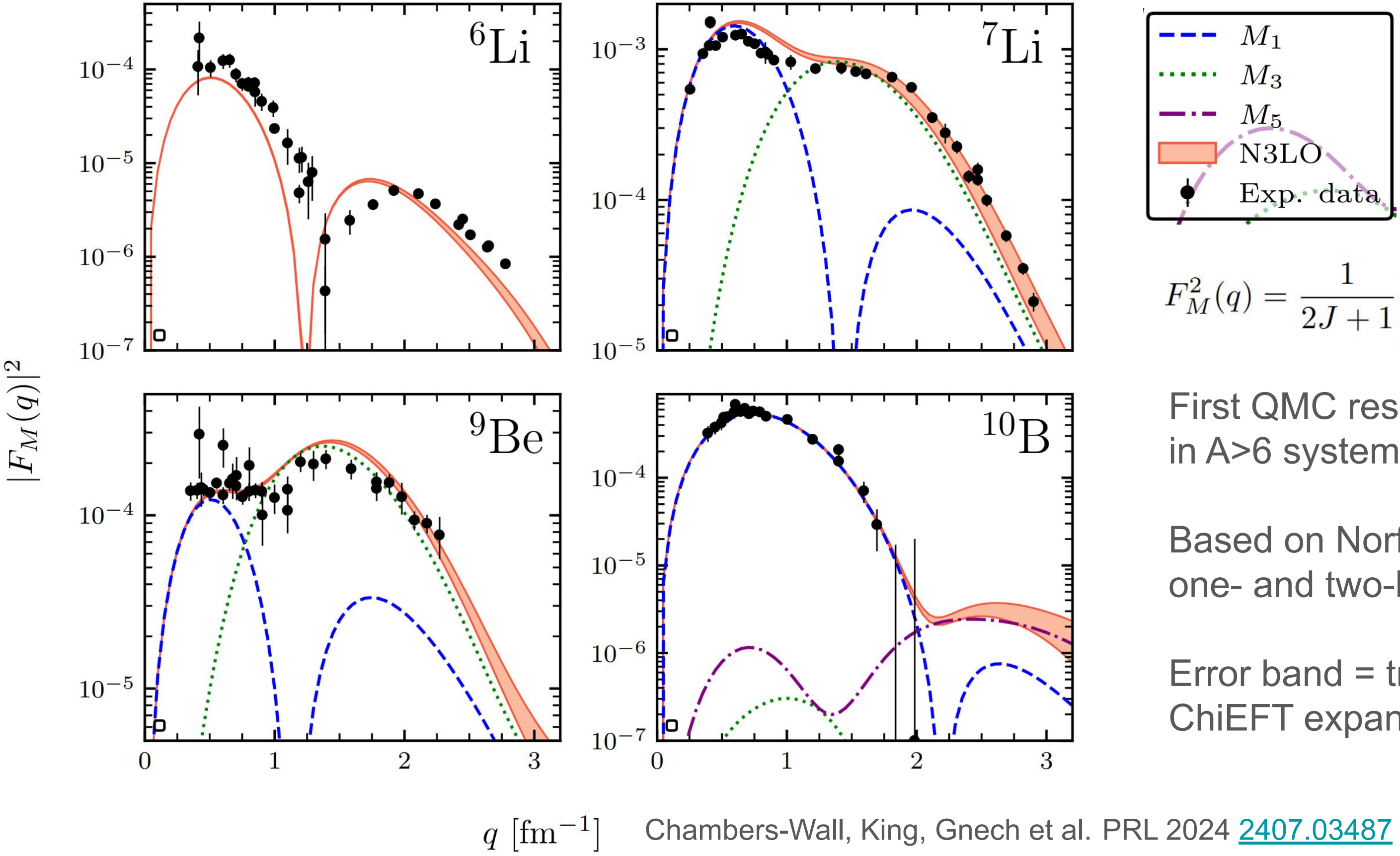


Electromagnetic radii (in preparation)

$$F_L^2(q) = \frac{1}{2J+1} \sum_{l \geq 0} |\langle J || C_l(q) || J \rangle|^2$$

King et al. arxiv:2408.16909 2024

Magnetic form factors: comparison with the data



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Chambers-Wall, King, Gnech et al. PRL 2024 2407.03487

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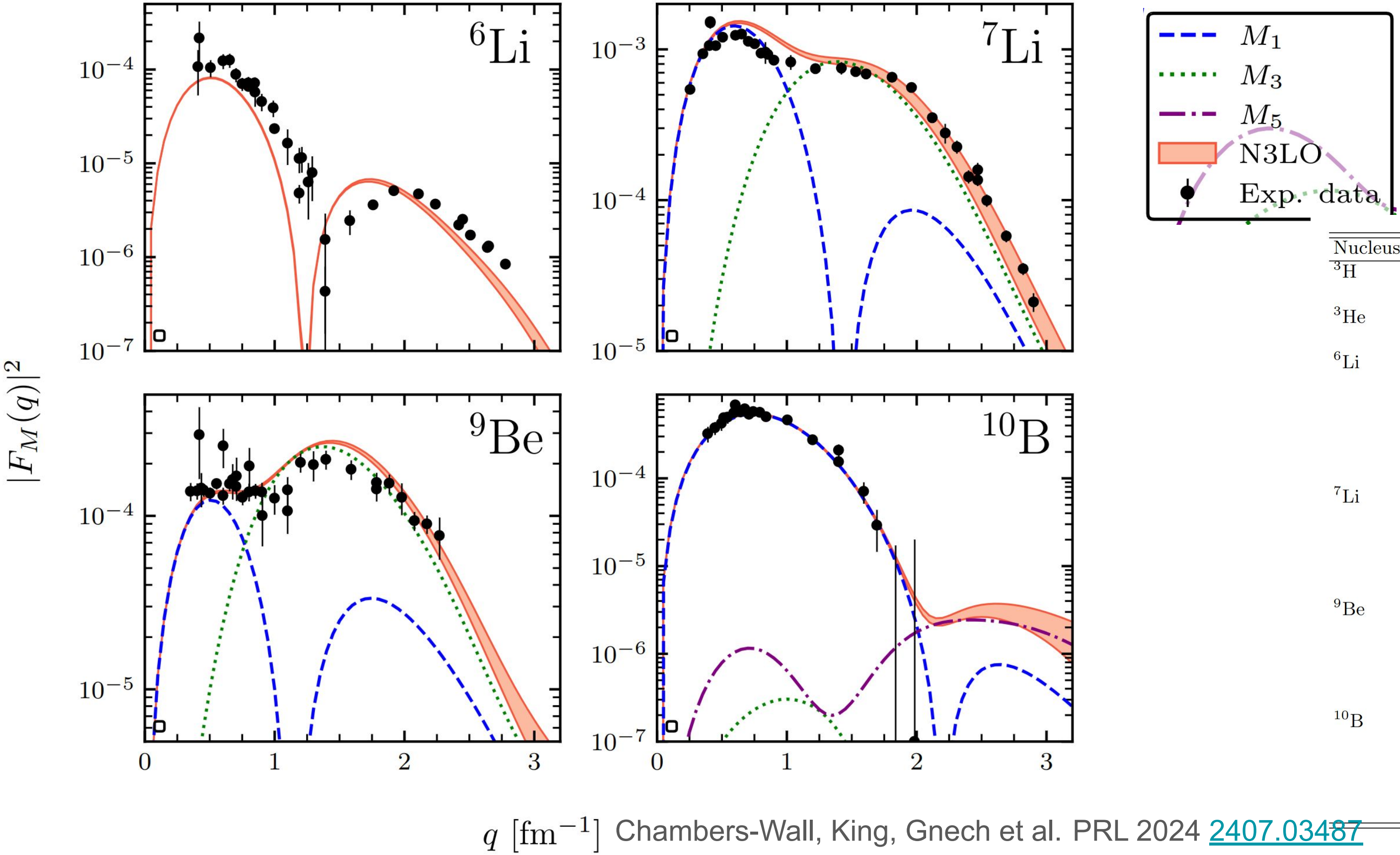

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Chambers-Wall, King, Gnech et al. PRL 2024 2407.03487

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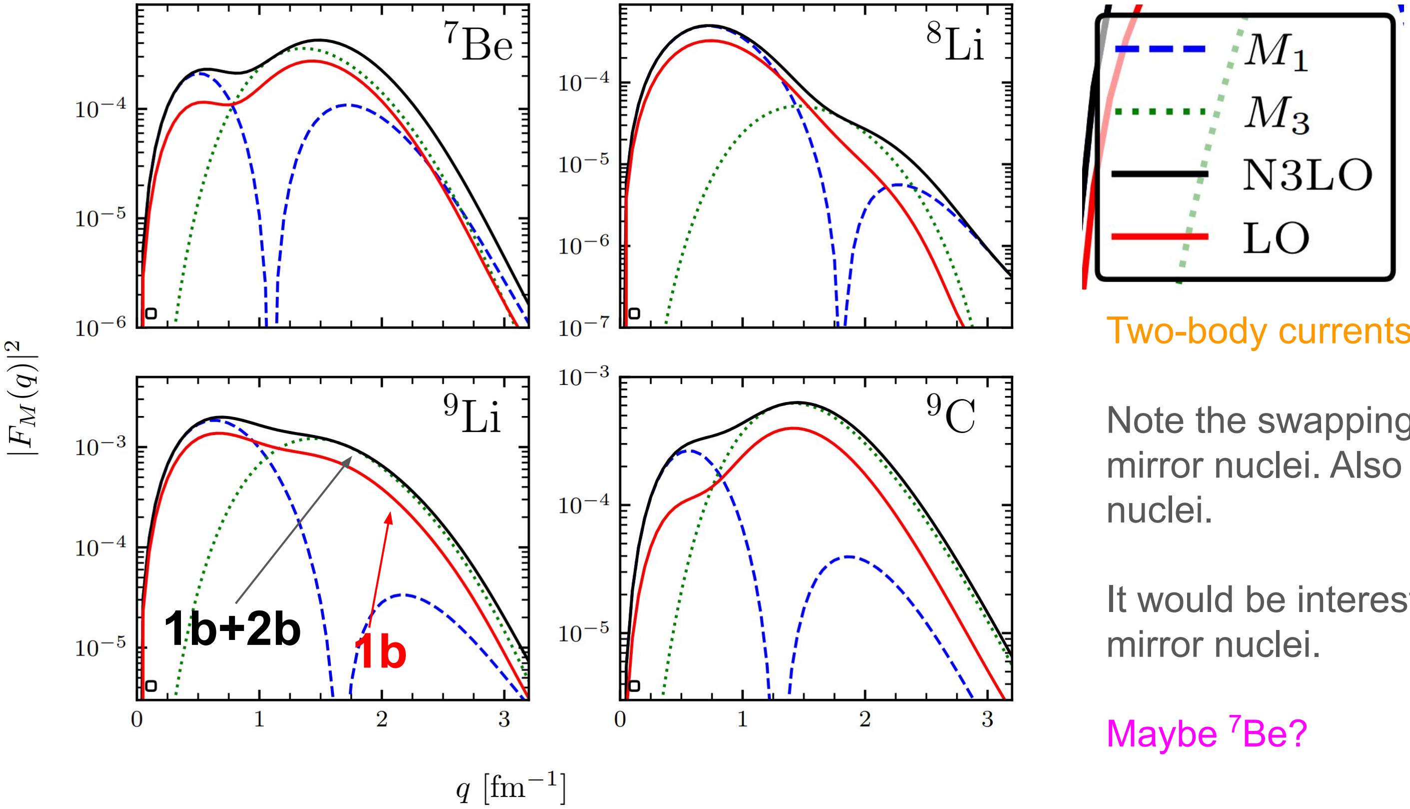

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Chambers-Wall, King, Gnech et al. PRL 2024 2407.03487

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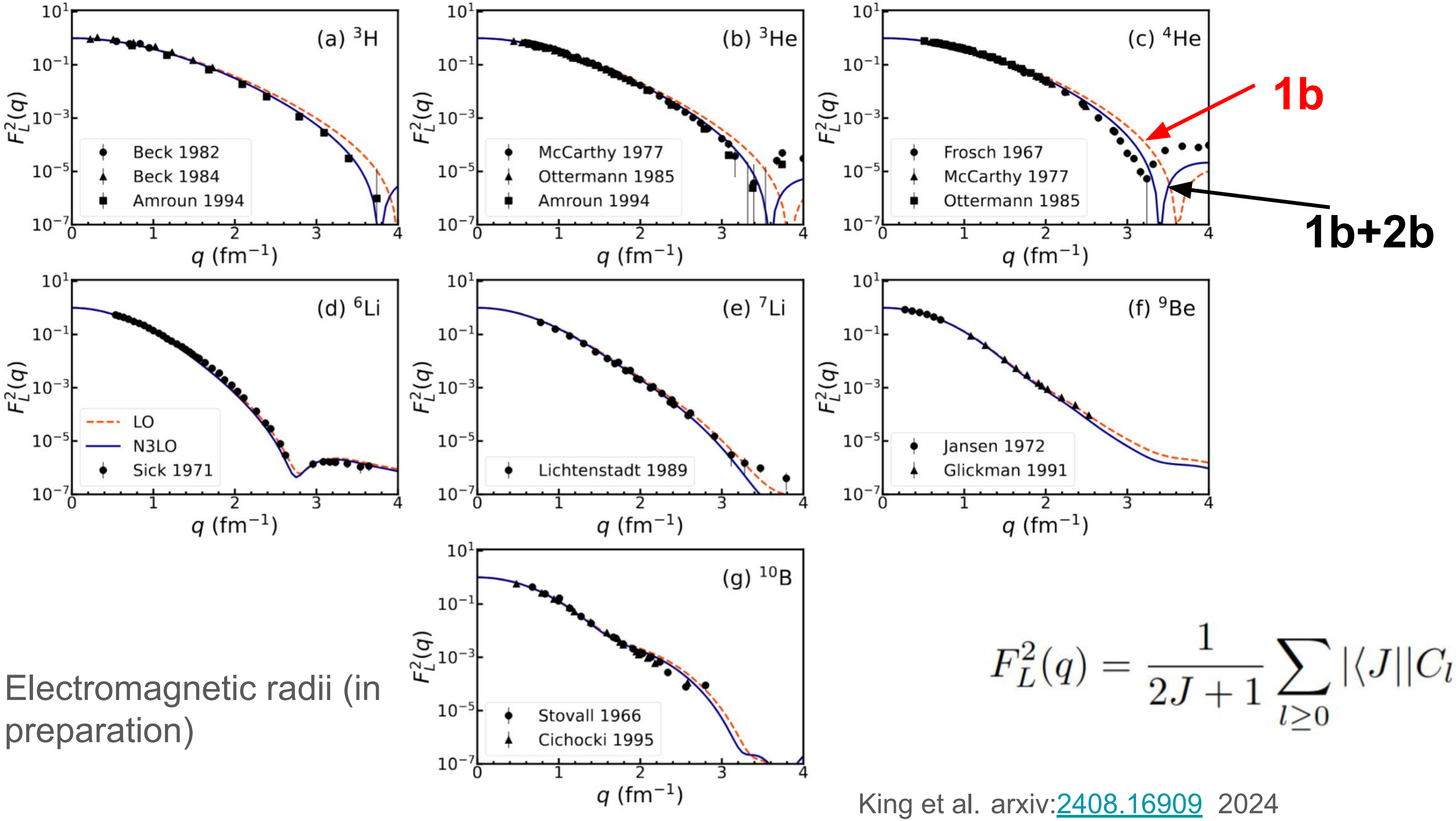

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King et al. arxiv:2408.16909 2024

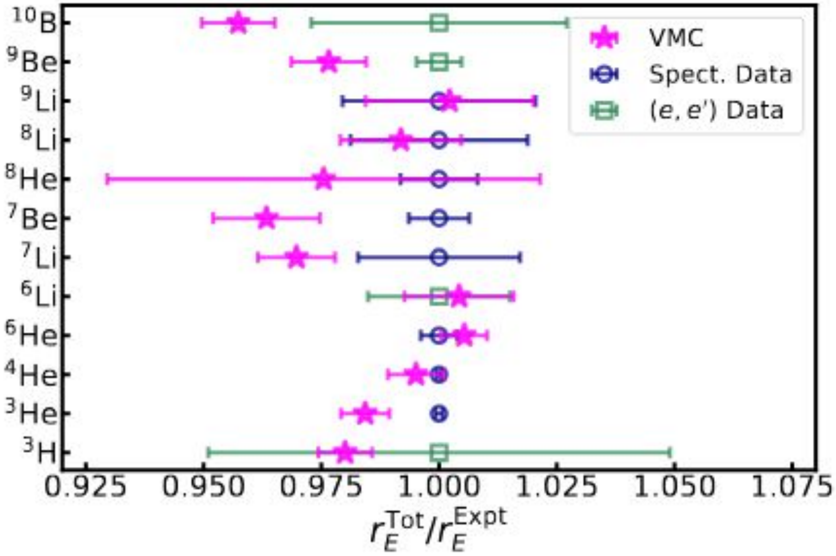
Charge radii

Extracted from low-momentum transfer behavior of form factor.

$$\frac{1}{Z}\langle JJ|\rho(q\hat{\mathbf{z}})|JJ\rangle \approx 1 - \frac{1}{6}r_E^2 q^2 + \mathcal{O}(q^4)$$

Accounts for two-body correlations, finite size/nucleon level corrections via nucleonic form factors.

Agreement of ~5% or better.



King *et al*. submitted to PRC 2025

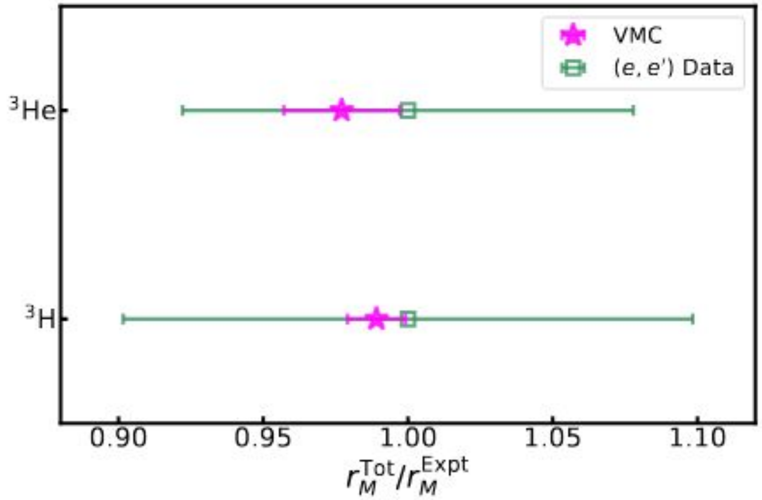
Magnetic radii

Extracted from low-momentum transfer behavior of form factor.

$$-i\frac{2m}{q\mu}\langle JJ|\mathrm{j}_y(q\hat{\mathbf{x}})|JJ\rangle \approx 1-\frac{1}{6}r_M^2q^2+\mathcal{O}(q^4)$$

Accounts for two-body currents, finite size/nucleon level corrections via nucleonic form factors.

Limited data, predictions available for A up to 10.

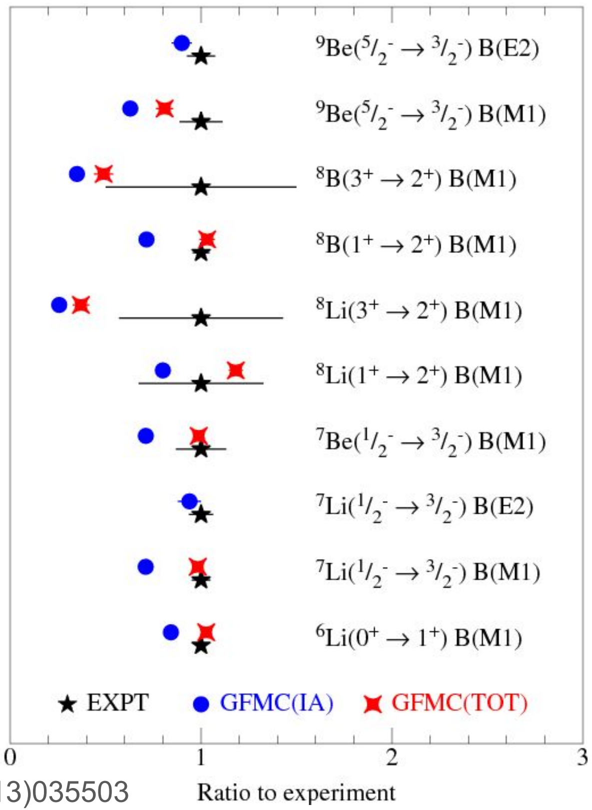


King *et al*. submitted to PRC 2025

Electromagnetic transitions

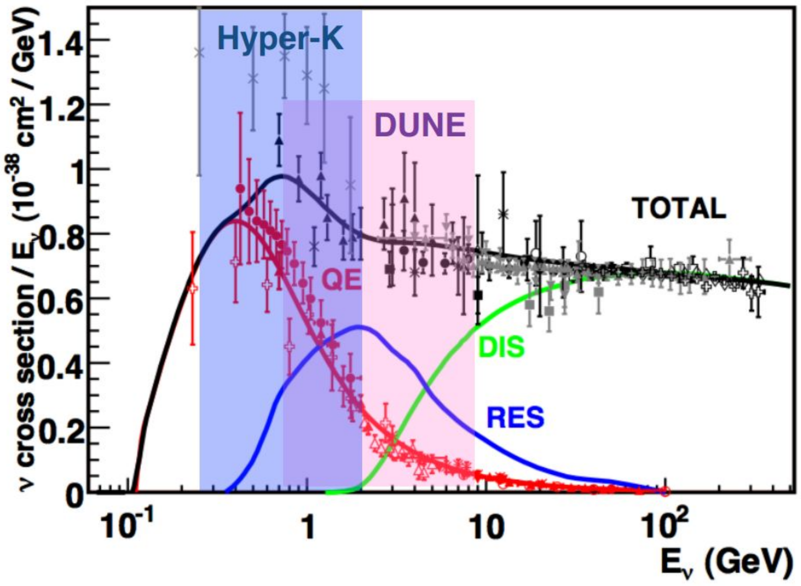
Two-body electromagnetic currents bring the theory in agreement with the data

~ 60 − 70% of total two-body current is due to one-pion-exchange currents



SP *et al*. PRC87(2013)035503

Neutrino cross section anatomy



Formaggio & Zeller

The neutrino program is in need of accurate determinations of neutrino nucleus cross sections in a wide range of energies.

Quasi-elastic: dominated by single-nucleon knockout

Resonance: excitation to nucleonic resonant states which decay into mesons

Deep-inelastic scattering: where the neutrino resolves the nucleonic quark content

Each of these regimes requires knowledge of both the **nuclear ground state** and the **electroweak coupling** and **propagation of the struck nucleons, hadrons, or partons**

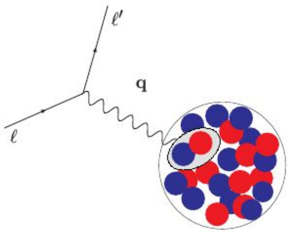
Lepton-Nucleus scattering: Inclusive Processes

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

$$\frac{d^2\sigma}{d\omega d\Omega} = \sigma_M \left[v_L R_L(\mathbf{q},\omega) + v_T R_T(\mathbf{q},\omega)\right]$$

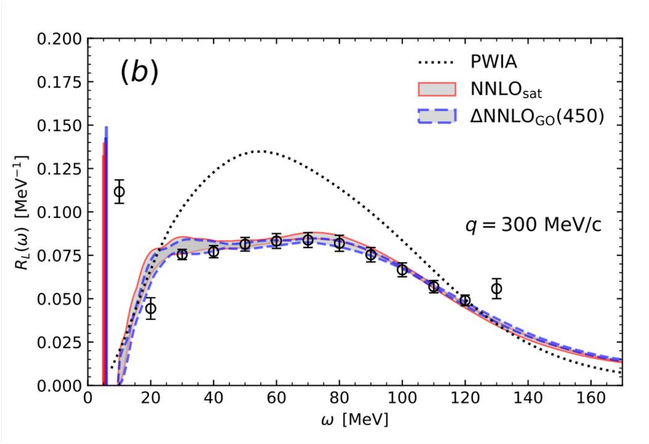


For a recent review on QMC, SF methods see
Rocco *Front. In Phys.*8 (2020)116

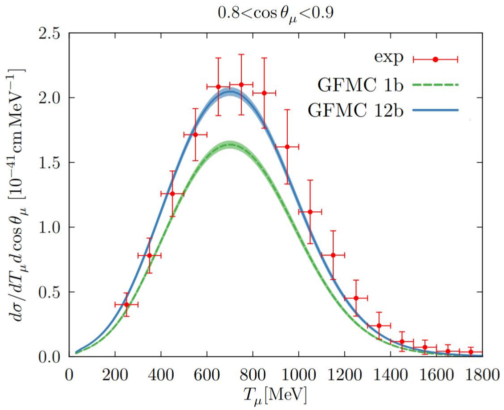
Inclusive Cross Sections with Integral Transforms

Exploit integral properties of the response functions and closure to avoid explicit calculation of the final states (Lorentz Integral Transform **LIT**, **Euclidean**, …)

$$S(q,\tau) = \int_0^\infty d\omega\, K(\tau,\omega)\, R_\alpha(q,\omega)$$



Sobczyk et al, PRL127 (2021)

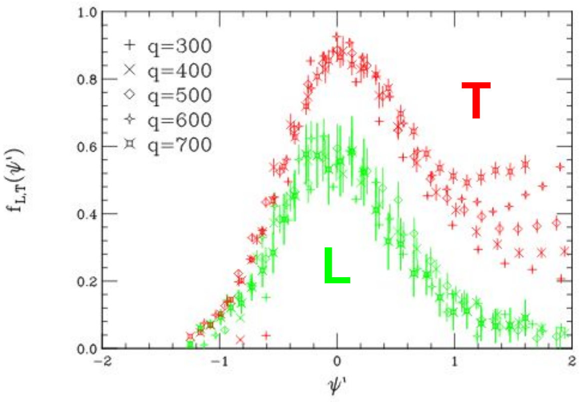


Lovato et al. PRX10 (2020)

Lepton-Nucleus scattering: Data

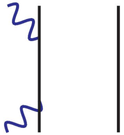
Transverse Sum Rule

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



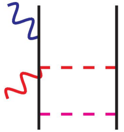
^{4}He Electromagnetic Data
Carlson *et al.* PRC65(2002)024002

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



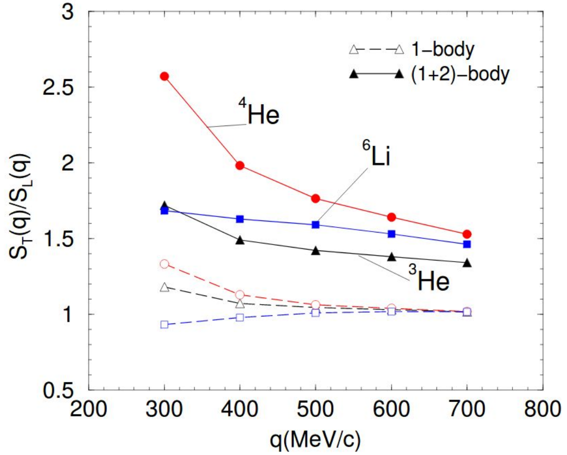
$\langle \mathbf{j}_{1b}^\dagger\ \ \mathbf{j}_{1b}\rangle\ > 0$

Leading one-body term



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

Interference term

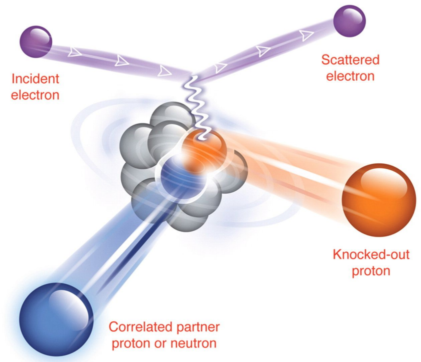


Transverse/Longitudinal Sum Rule
Carlson *et al.* PRC65(2002)024002

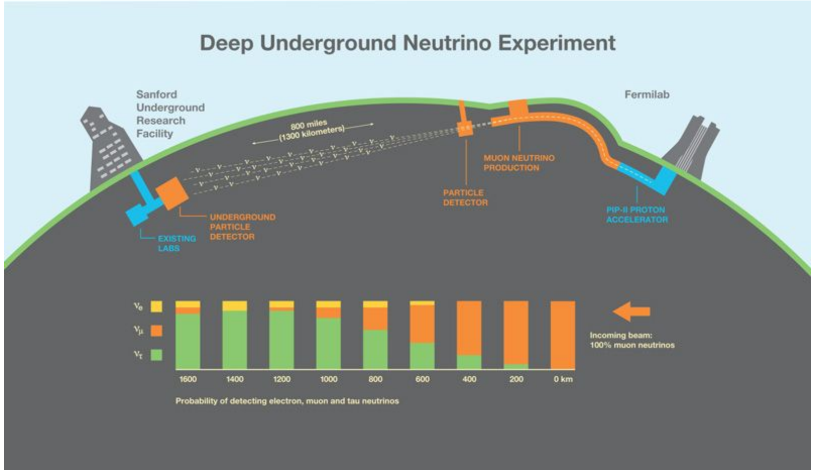
Beyond Inclusive: Short-Time-Approximation

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

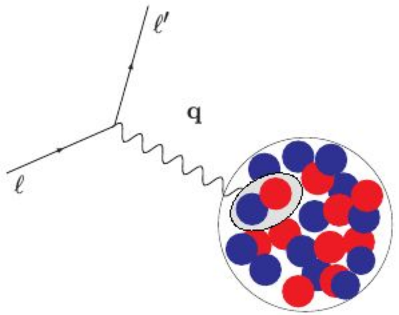


[Stanford Lab article]

[e4u collaboration]

e4V

Short-Time-Approximation



Short-Time-Approximation:

- Based on Factorization
- Retains two-body physics
- Correctly accounts for interference

$$R(q,\omega) = \int_{-\infty}^{\infty} \frac{dt}{2\pi} e^{i(\omega+E_0)t} \langle 0|O^\dagger e^{-iHt} O|0\rangle$$

$$O_i^\dagger e^{-iHt} O_i + O_i^\dagger e^{-iHt} O_j + \boxed{O_i^\dagger e^{-iHt} O_{ij}} + O_{ij}^\dagger e^{-iHt} O_{ij}$$

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

STA: regime of validity

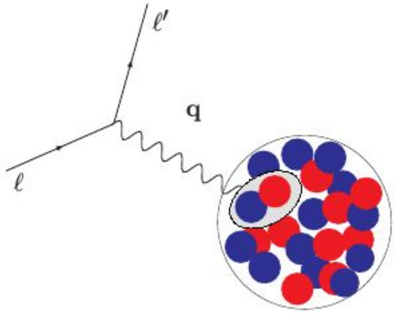
The typical (conservative estimate) energy (time) scale in a nucleus with A correlated nucleons in pairs is

$\varepsilon_{pair} \sim 20$ MeV $\quad (t \sim 1/\varepsilon_{pair})$

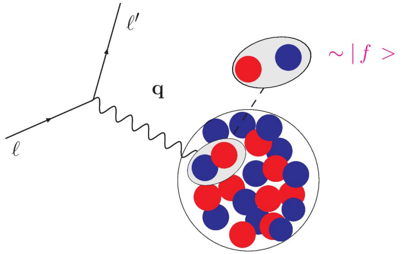
This sets a natural expansion parameter in the QE region characterized by ω_{QE}

$\varepsilon_{pair} / \omega_{QE}$

The STA neglects terms of order $\mathcal{O}((\varepsilon_{pair} / \omega_{QE})^2)$



Short-Time-Approximation



Short-Time-Approximation:

- Based on Factorization
- **Retains two-body physics**
- Response functions are given by the **scattering from pairs of fully interacting nucleons** that propagate into a correlated pair of nucleons
- 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 ∝ Cross Sections

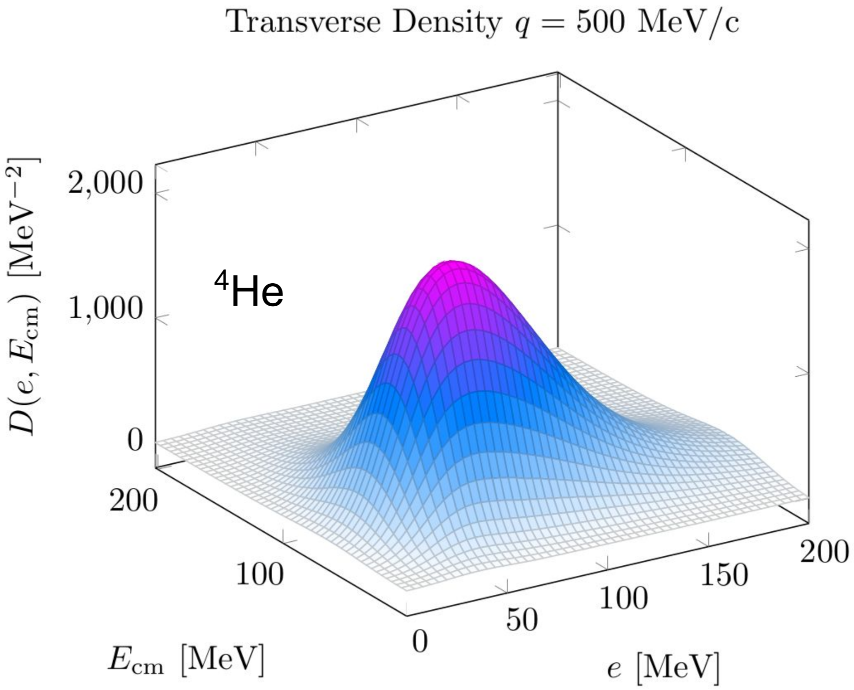
$$R_\alpha(q,\omega) = \sum_f \delta\left(\omega + E_0 - E_f\right) |\langle f|O_\alpha(\mathbf{q})|0\rangle|^2$$

Response ***Densities***

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

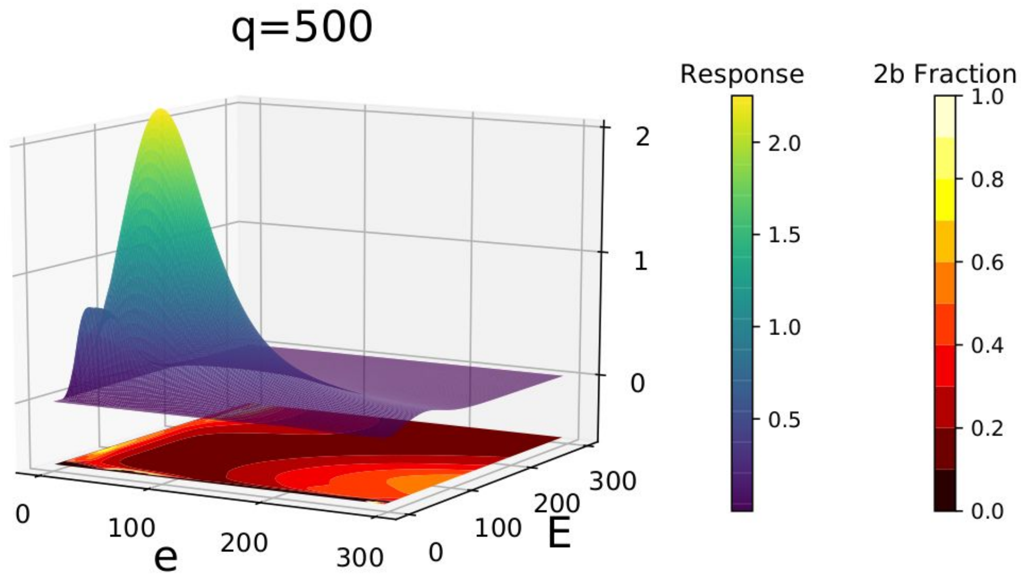
P’ and *p’* are the CM and relative momenta of the struck nucleon pair

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

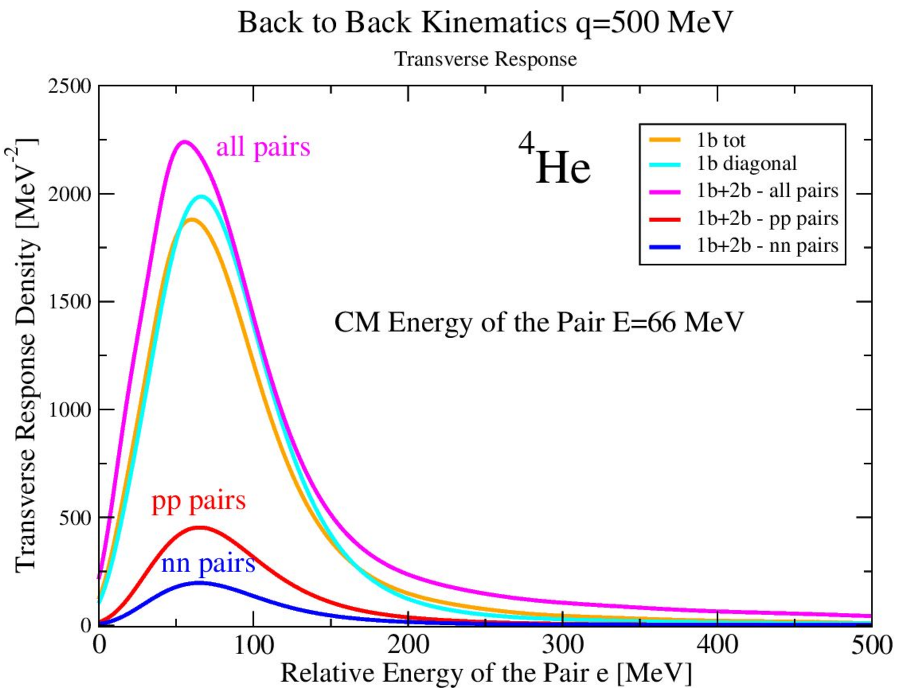


SP *et al.* PRC101(2020)044612

Transverse Response Density: two-body physics

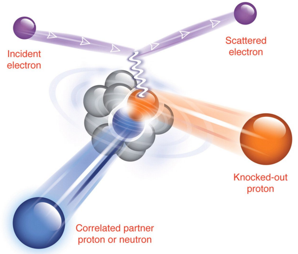


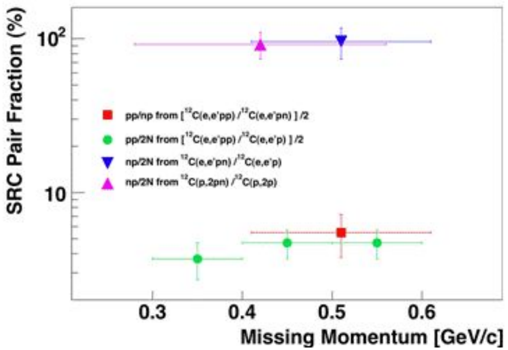
e-^{4}He scattering in the back-to-back kinematic



SP *et al.* PRC101(2020)044612

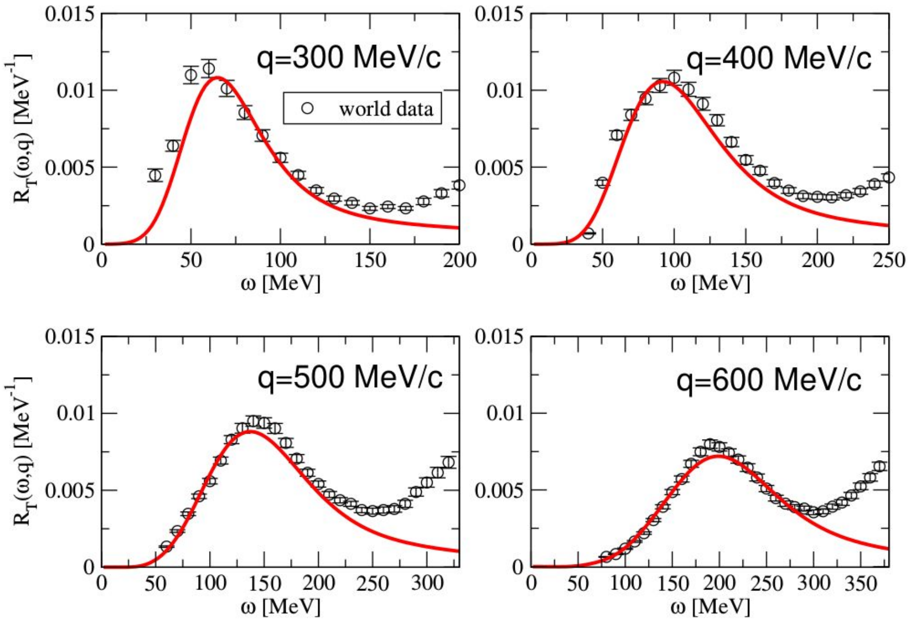
- pp pairs
- nn pairs
- all pairs 1body
- all pairs tot

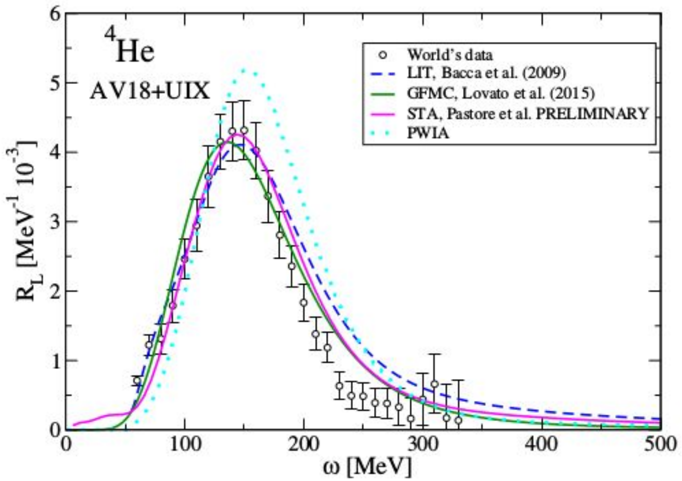




Subedi et al. Science320(2008)1475

Helium-4: data & model dependence

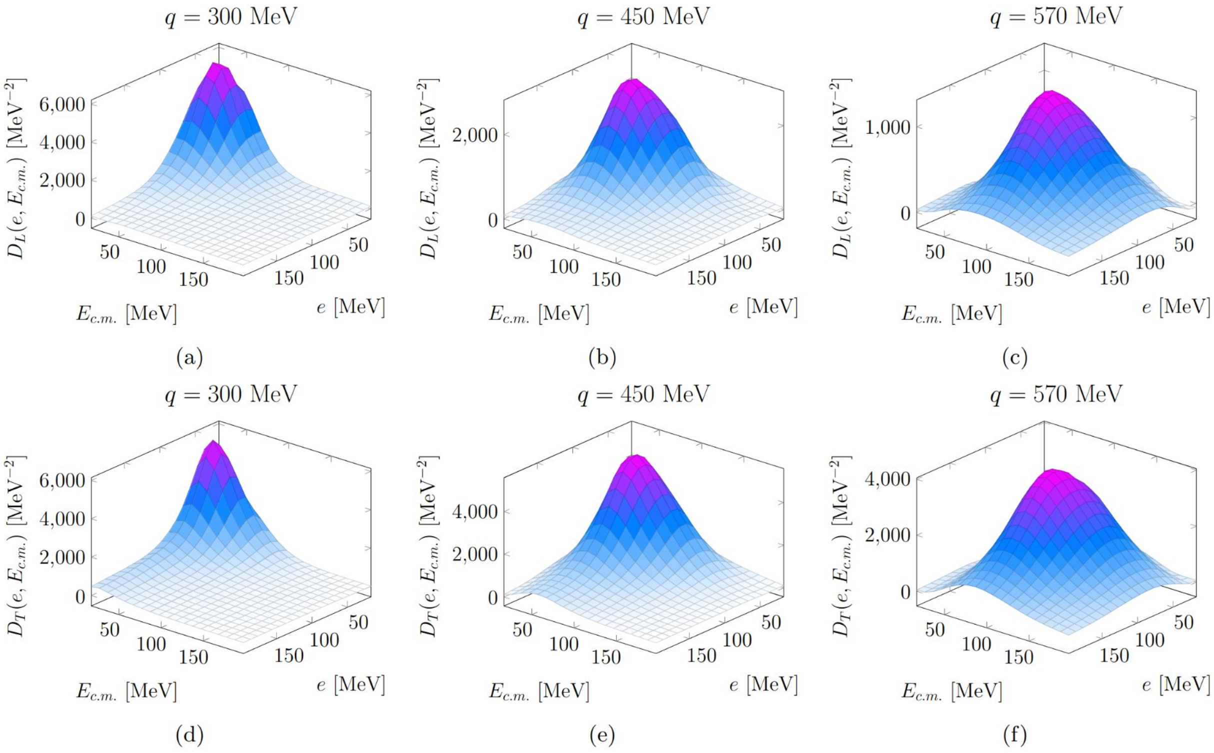




Benchmark in ^{4}He

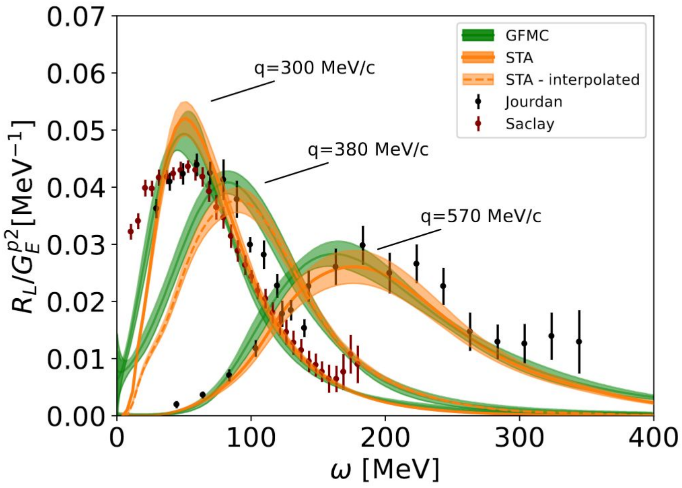
SP *et al.* PRC101(2020)044612

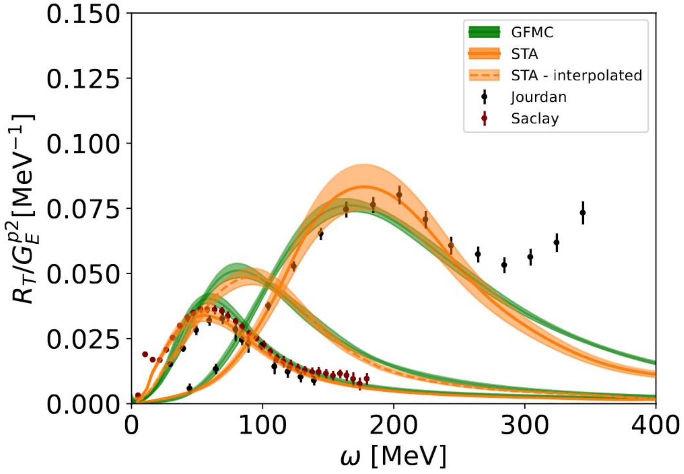
^{12}C Response Densities



Andreoli *et al.* *Phys.Rev.C* 110 (2024) 6, 064004 arXiv:2407.06986

^{12}C response functions



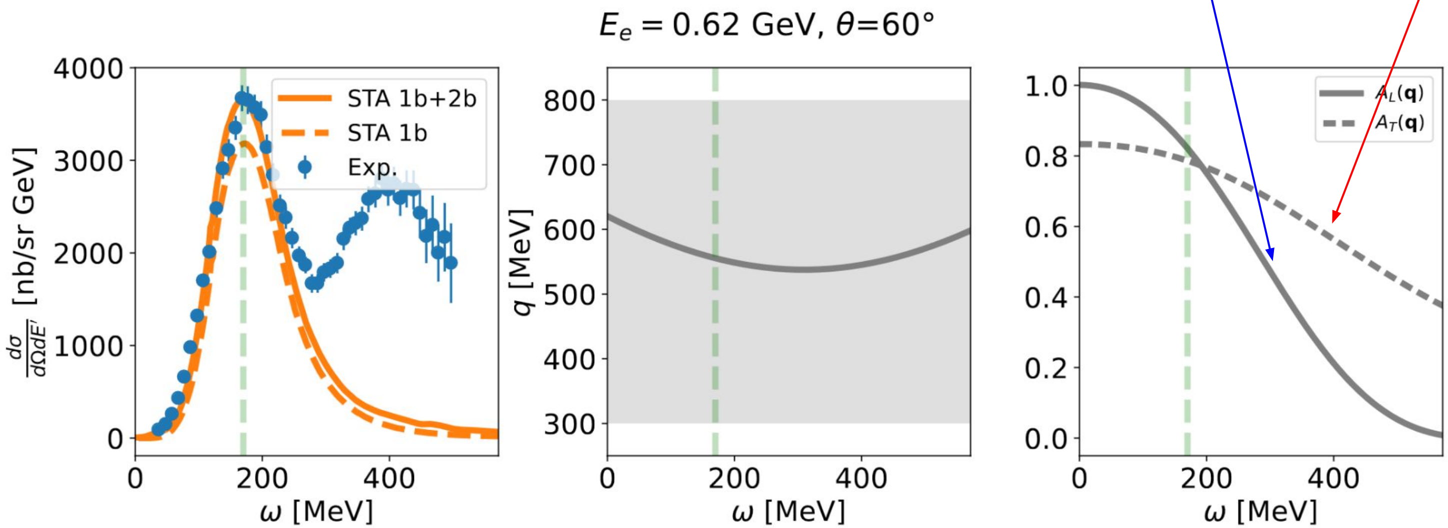


$$\frac{d^2\,\sigma}{d\,\omega d\,\Omega} = \sigma_M\,\left[v_L\,R_L(\mathbf{q},\omega) + v_T\,R_T(\mathbf{q},\omega)\right]$$

Andreoli *et al.* *Phys.Rev.C* 110 (2024) 6, 064004 arXiv:2407.06986

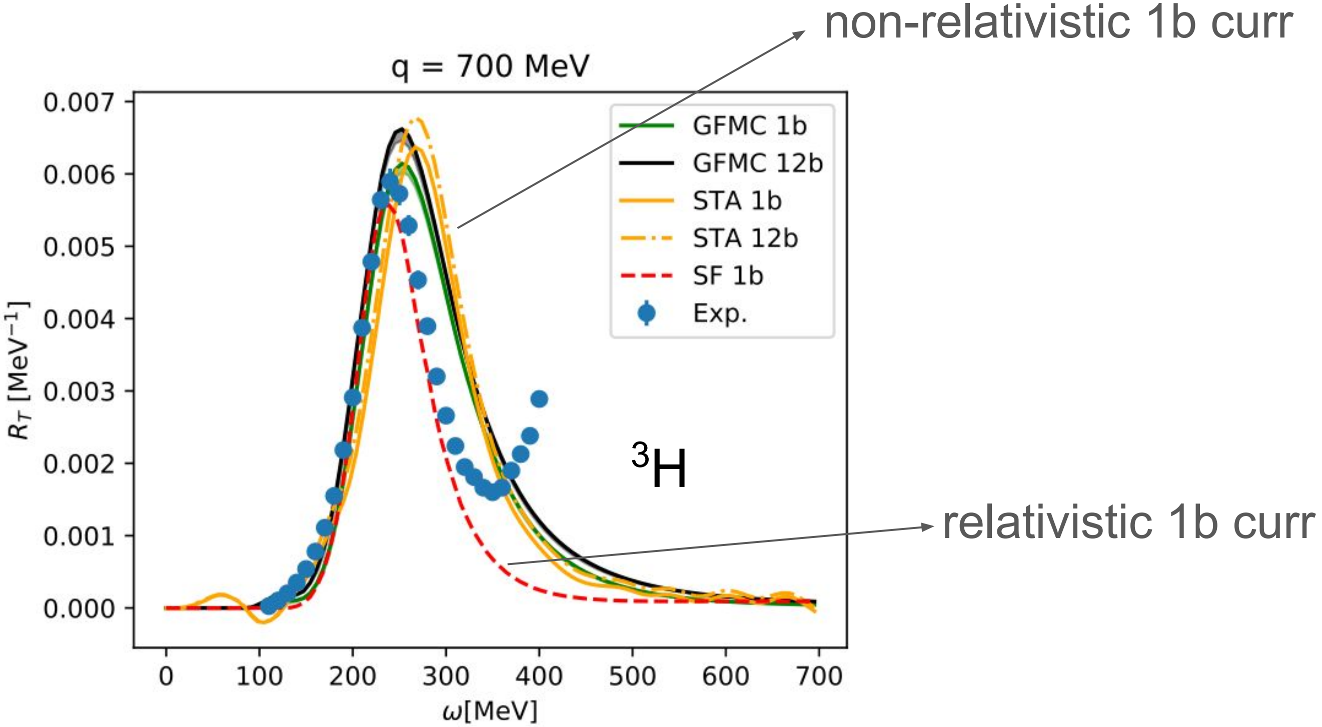
^{12}C cross sections

$$\frac{d^2\sigma}{d\omega d\Omega} = \sigma_M \left[v_L R_L(\mathbf{q},\omega) + v_T R_T(\mathbf{q},\omega)\right]$$



Andreoli *et al.* *Phys.Rev.C* 110 (2024) 6, 064004 arXiv:2407.06986
Data From https://discovery.phys.virginia.edu/research/groups/qes-archive/index.html

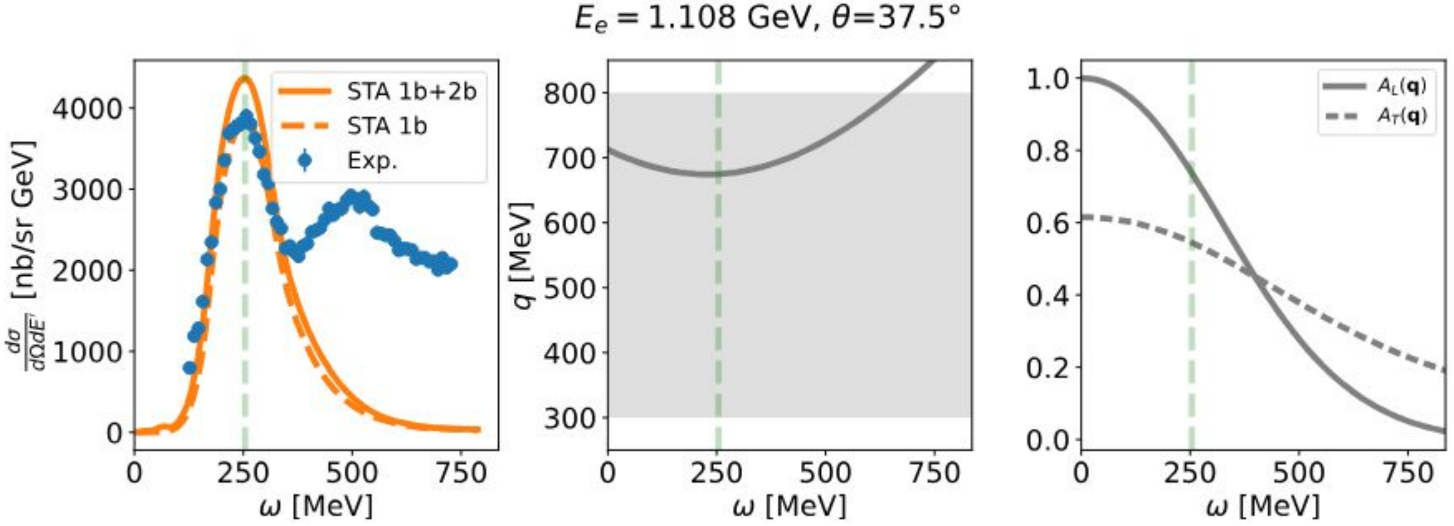
Relativistic effects in e-^{3}H scattering



Andreoli *et al. Phys.Rev.C* 105 (2022) 1, 014002

Relativistic effects in e-^{12}C scattering

$$\frac{d^2\,\sigma}{d\,\omega d\,\Omega} = \sigma_M\;\left[v_L\,R_L(\mathbf{q},\omega) + v_T\,R_T(\mathbf{q},\omega)\right]$$



Andreoli *et al.* *Phys.Rev.C* 110 (2024) 6, 064004 arXiv:2407.06986

Relativistic corrections

With Ronen Weiss and Lorenzo Andreoli
In preparation

Traditional non relativistic expansion of the covariant single nucleon electromagnetic current assumes initial and final nucleon momentum small.

$$j^{\mu} = e\bar{u}(\boldsymbol{p}'s')\left(e_N\gamma^{\mu} + \frac{i\kappa_N}{2m_N}\sigma^{\mu\nu}q_{\nu}\right)u(\boldsymbol{p}s)$$

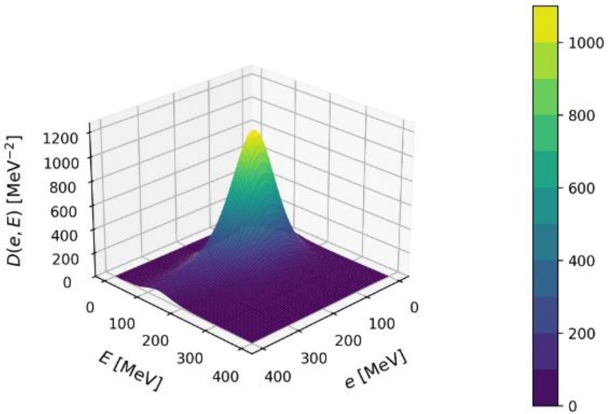
$$\boldsymbol{p}' = \boldsymbol{p} + \boldsymbol{q}$$

New paradigme where the relativistic correction is obtained expanding the covariant one-nucleon current for high values of momentum transfer, and small values of initial nucleon momentum p. This changed:

1. Expression of the one-body operator
2. Energy conserving delta function

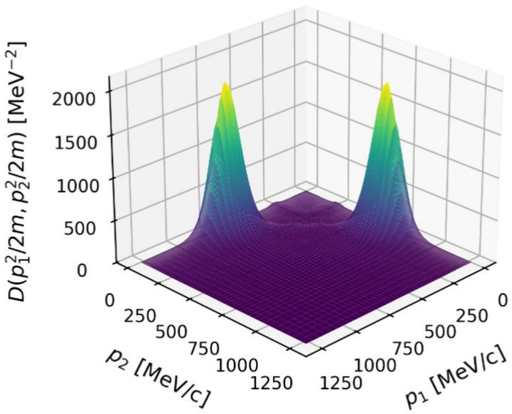
Ronen Weiss
Ed Jaynes Fellow at WashU

Implementation single nucleon current

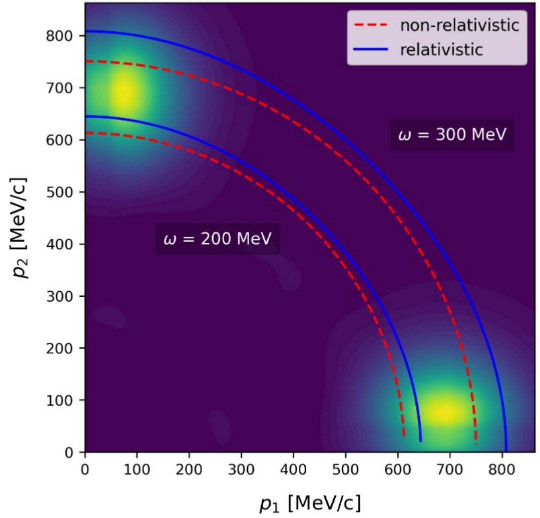


Response density vs relative and c.m. energy of the struck pair

^{4}He Transverse response density at q = 700 MeV/c

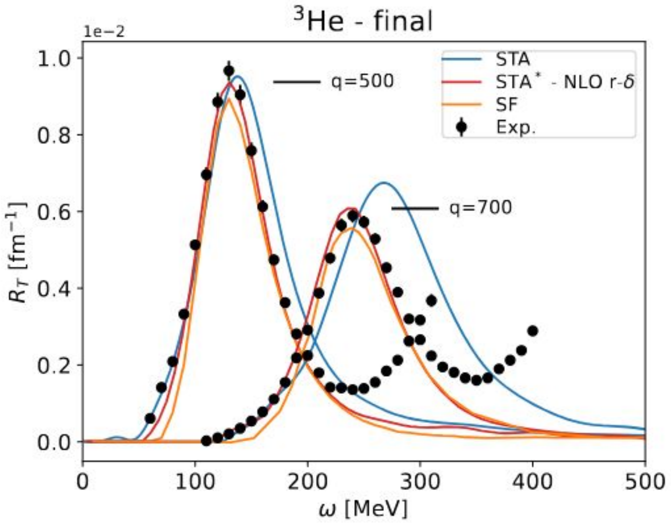


Response density vs momenta of individual nucleons



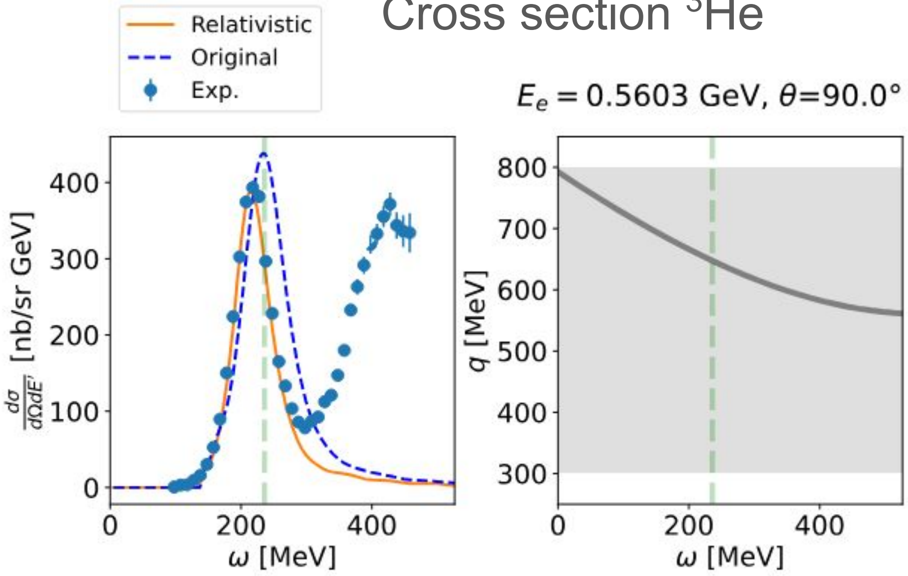
Preliminary

Application to e-^{3}H scattering

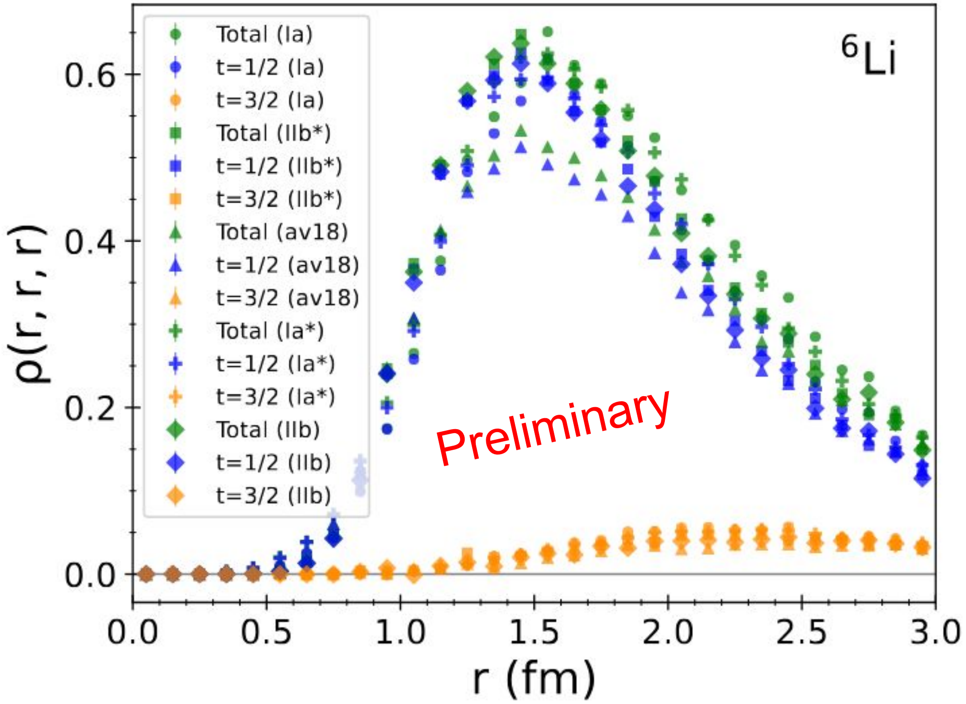


Preliminary

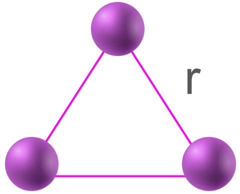
Cross section ^{3}He

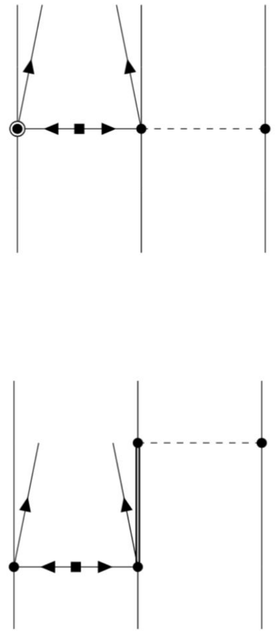


Three-body densities



Graham Chambers-Wall in preparation

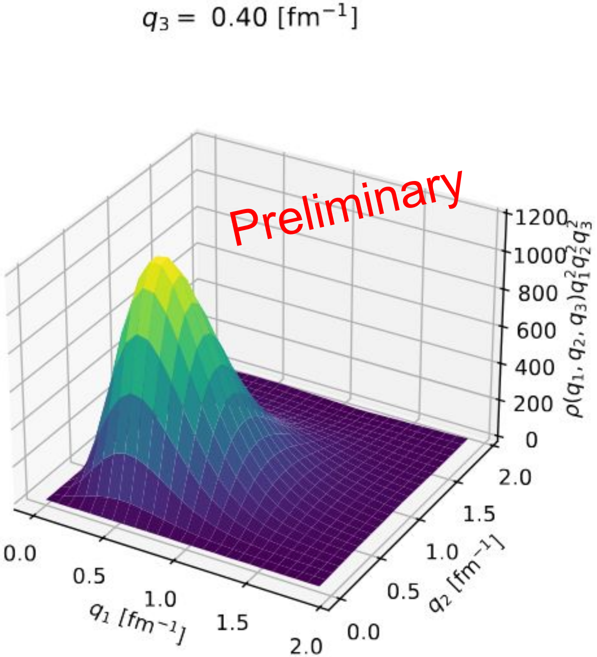


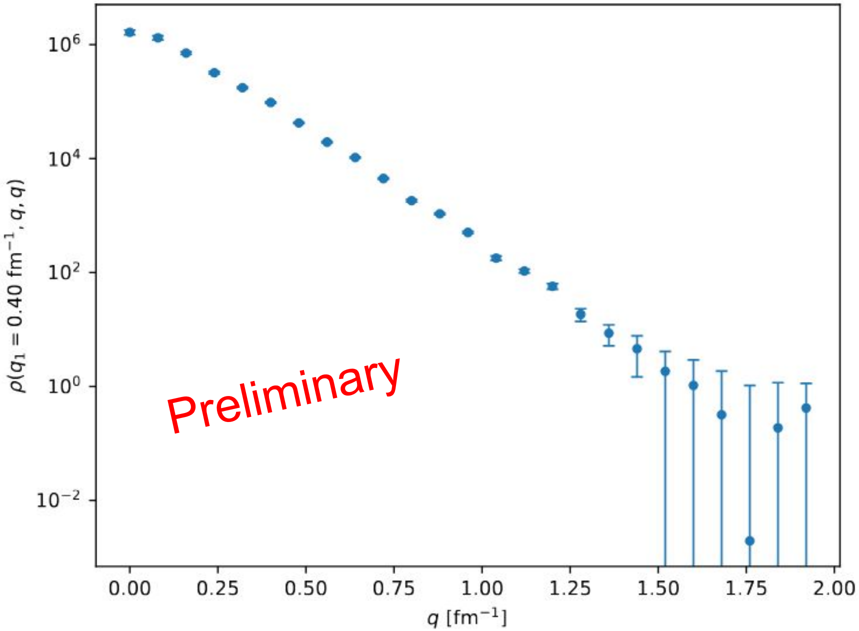


Ronen Weiss, and Stefano Gandolfi *Phys.Rev.C* 108 (2023) 2, L021301

With AFDMC

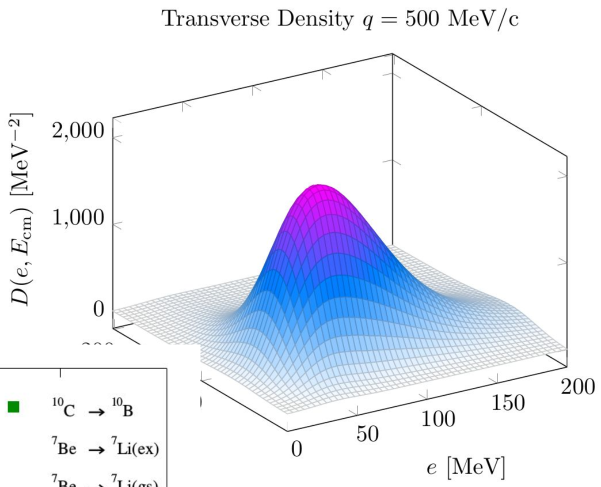
^{4}He Three-Body Momentum Distribution

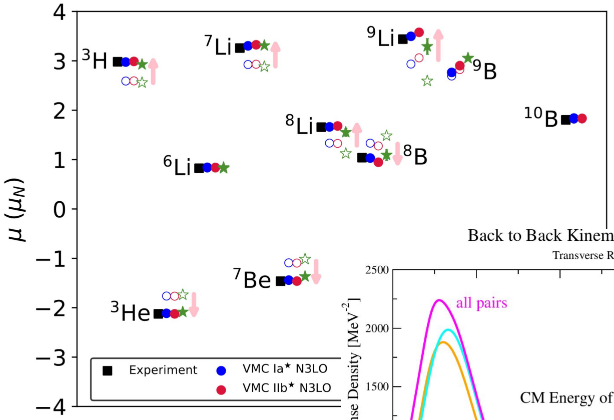


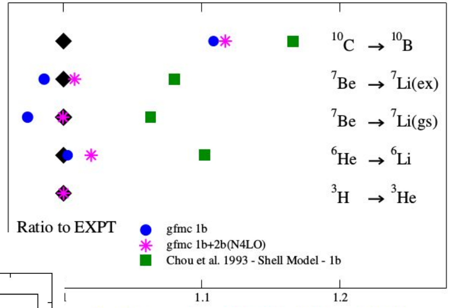


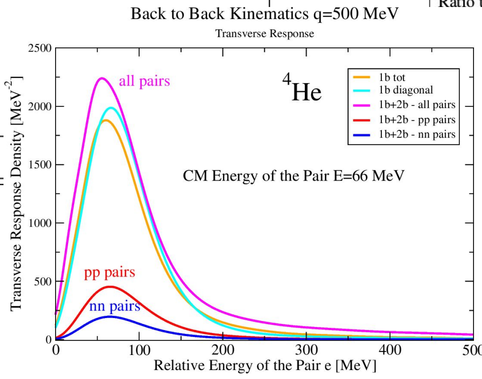
Summary

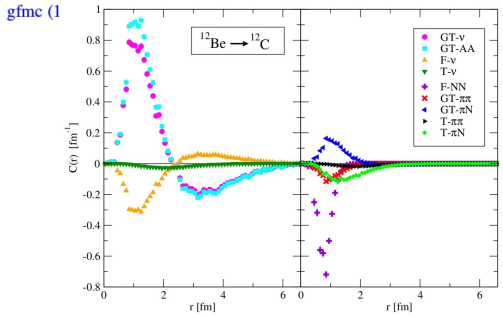
Ab initio calculations of light nuclei yield a picture of nuclear structure and dynamics where many-body effects play an essential role to explain available data.











Close **collaborations** between **NP**, **LQCD**, **Pheno**, **Hep**, **Comp**, **Expt**, …
are required to progress
e.g., NP is represented in the Snowmass process

It's a very exciting time!

Graham Chambers-Wall
(WashU GS)

Garrett King
(LANL PD)

Lorenzo Andreoli
(ODU/JLab PD)

King *et al.* PRC 110 (2024) 5, 054325; *Ann.Rev.Nucl.Part.Sci. 74* (2024) 343
Chambers-Wall, Gnech, King *et al*. PRL 133 (2024) 21, 212501; PRC 110 (2024) 5, 054316
Andreoli *et al*. *PRC 110* (2024) 6, 064004

Collaborators

WashU: **Bub Chambers-Wall Flores Novario Piarulli Weiss**
LANL: Carlson Gandolfi Hayes **King** Mereghetti
JLab+ODU: **Andreoli Gnech** Schiavilla
ANL: McCoy Lovato Wiringa
UW/INT: Cirigliano Dekens
Pisa U/INFN: Kievsky Marcucci Viviani
Salento U: Girlanda
Huzhou U: Dong Wang
Fermilab: Gardiner Betancourt Rocco
MIT: Barrow

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McDONNELL CENTER FOR THE SPACE SCIENCES

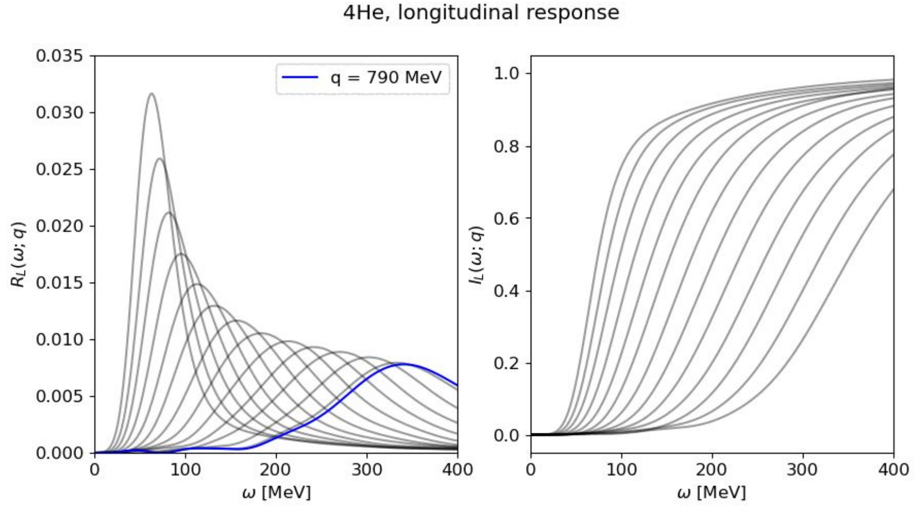
Fermilab

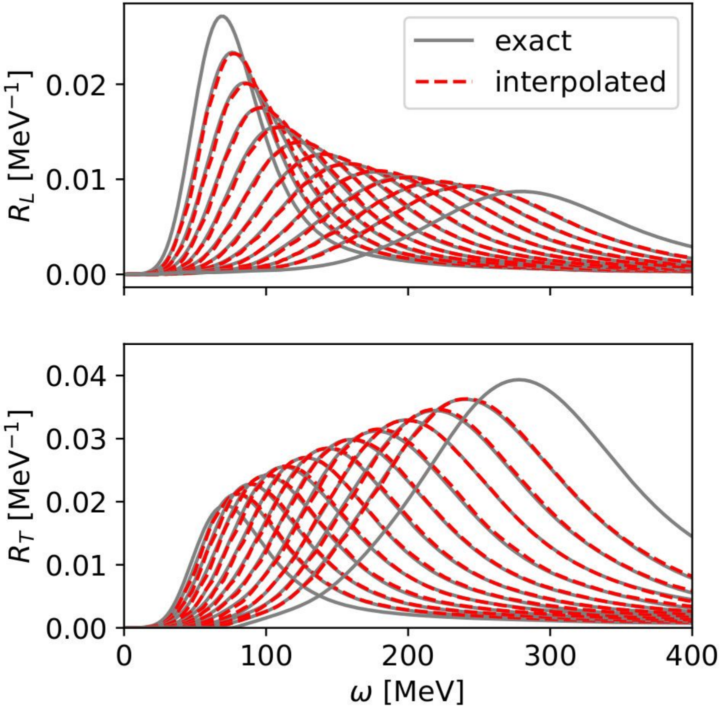
NERSC

^{12}C cross sections: interpolation scheme

We have coarse grid in q for ^{12}C. We use an interpolation scheme tested on He4.

$$I_{L/T}(\omega;\mathbf{q}) = \frac{\int_0^{\omega} R_{L/T}(\omega';\mathbf{q})d\omega'}{\int_0^{\infty} R_{L/T}(\omega';\mathbf{q})d\omega'}$$



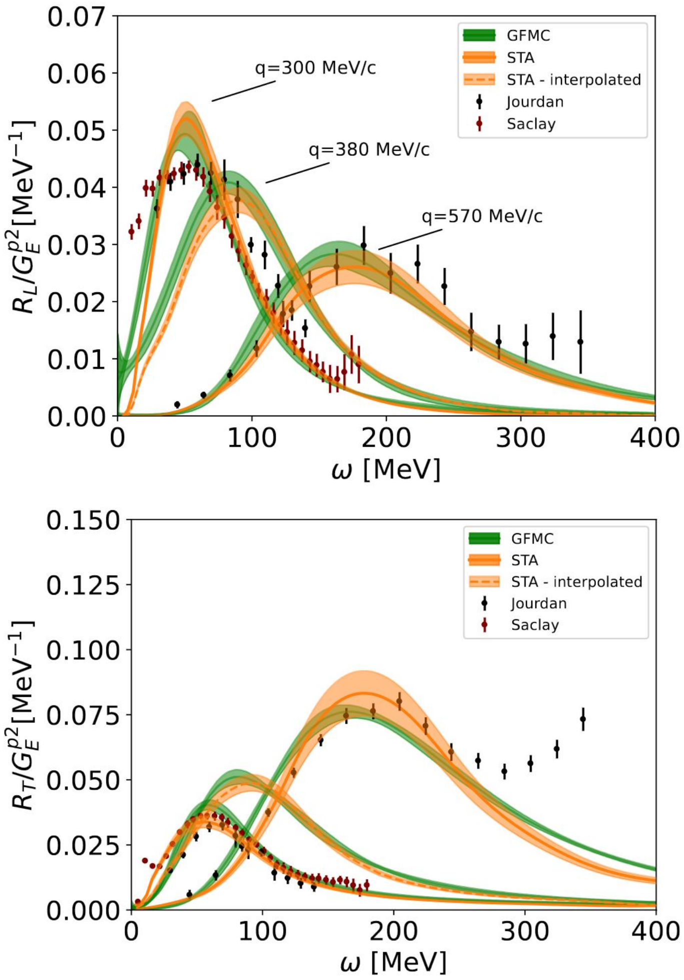


Lorenzo Andreoli *et al.* arXiv:2407.06986

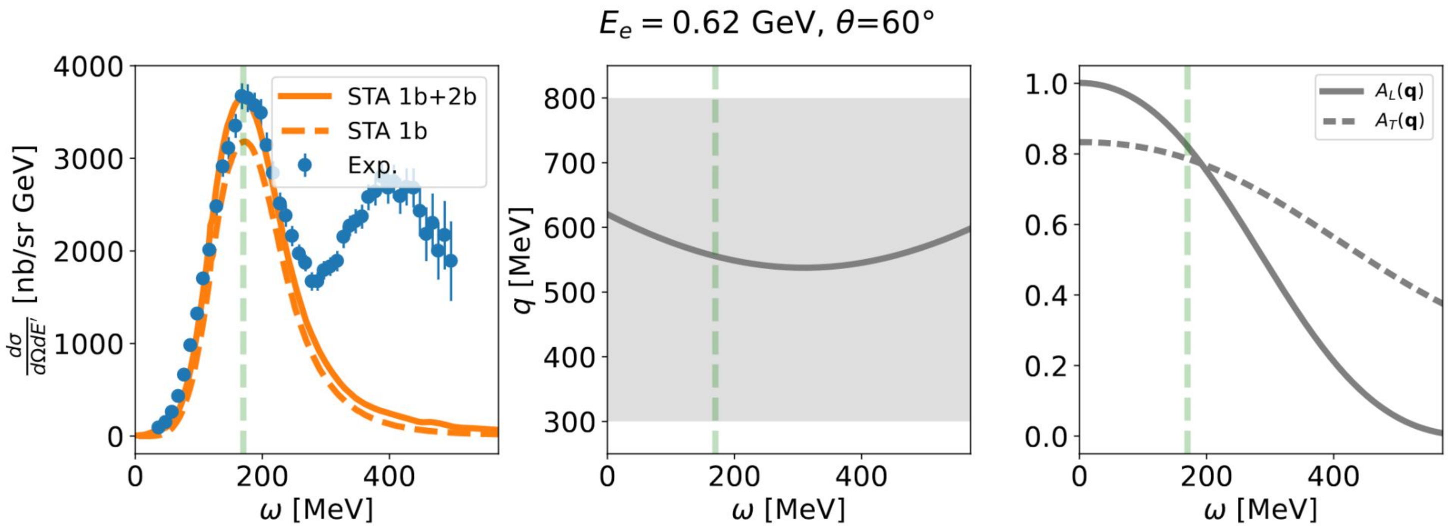
^{12}C response functions

$$\frac{d^2\sigma}{d\omega d\Omega} = \sigma_M \left[v_L R_L(\mathbf{q},\omega) + v_T R_T(\mathbf{q},\omega) \right]$$

Lorenzo Andreoli *et al.* [arXiv:2407.06986](https://arxiv.org/abs/2407.06986)

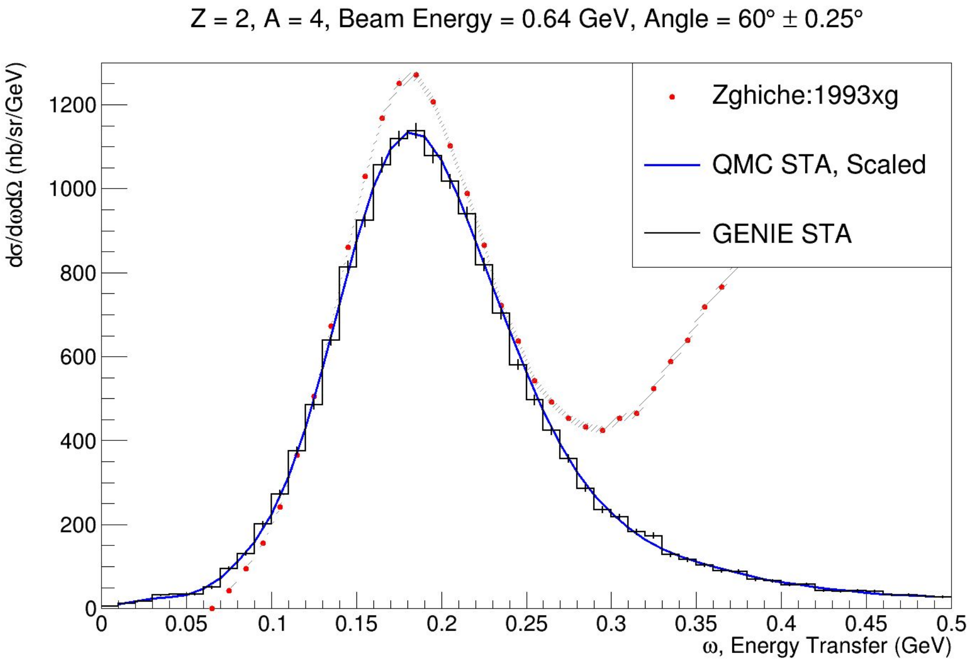


^{12}C cross sections



Lorenzo Andreoli *et al.* arXiv:2407.06986

GENIE validation using e-scattering

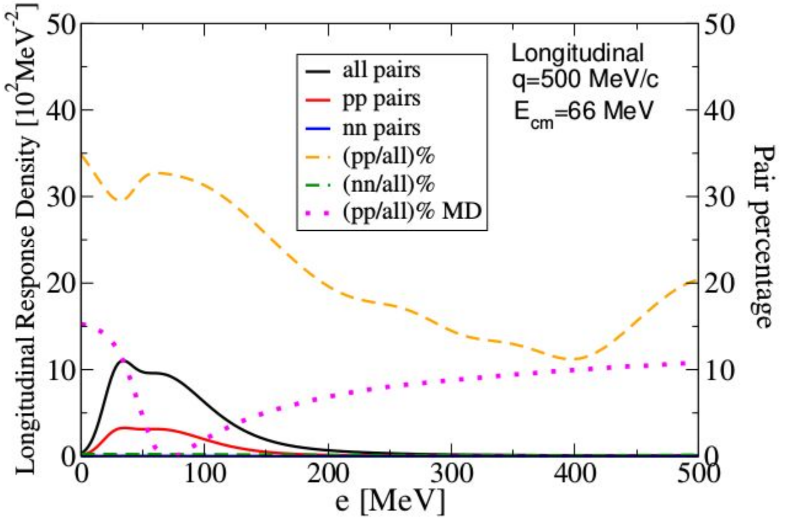


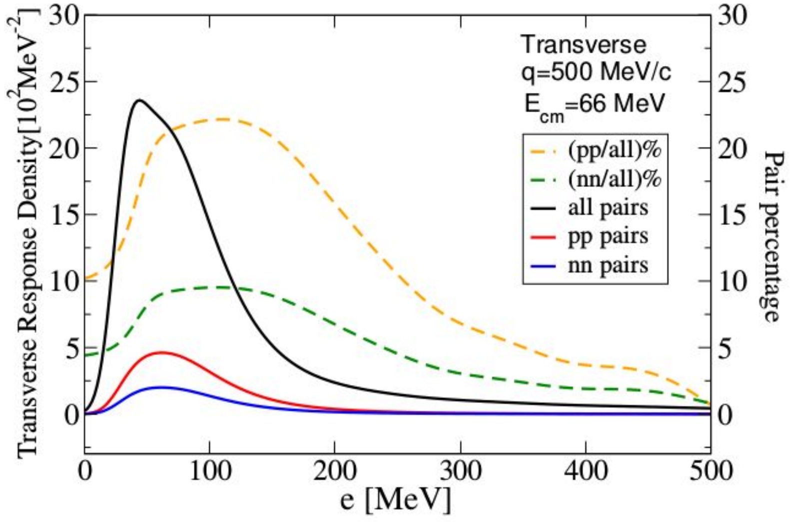
Barrow, Gardiner, SP et al. PRD 103 (2021) 5, 052001

- STA responses used to build the cross sections
- Cross sections are used to generate events in GENIE (a Monte Carlo neutrino event generator)
- Here, we use electromagnetic processes (for which data are available) to validate the generator

$$\frac{d^2\sigma}{d\omega d\Omega} = \sigma_M \left[v_L R_L(\mathbf{q},\omega) + v_T R_T(\mathbf{q},\omega) \right]$$

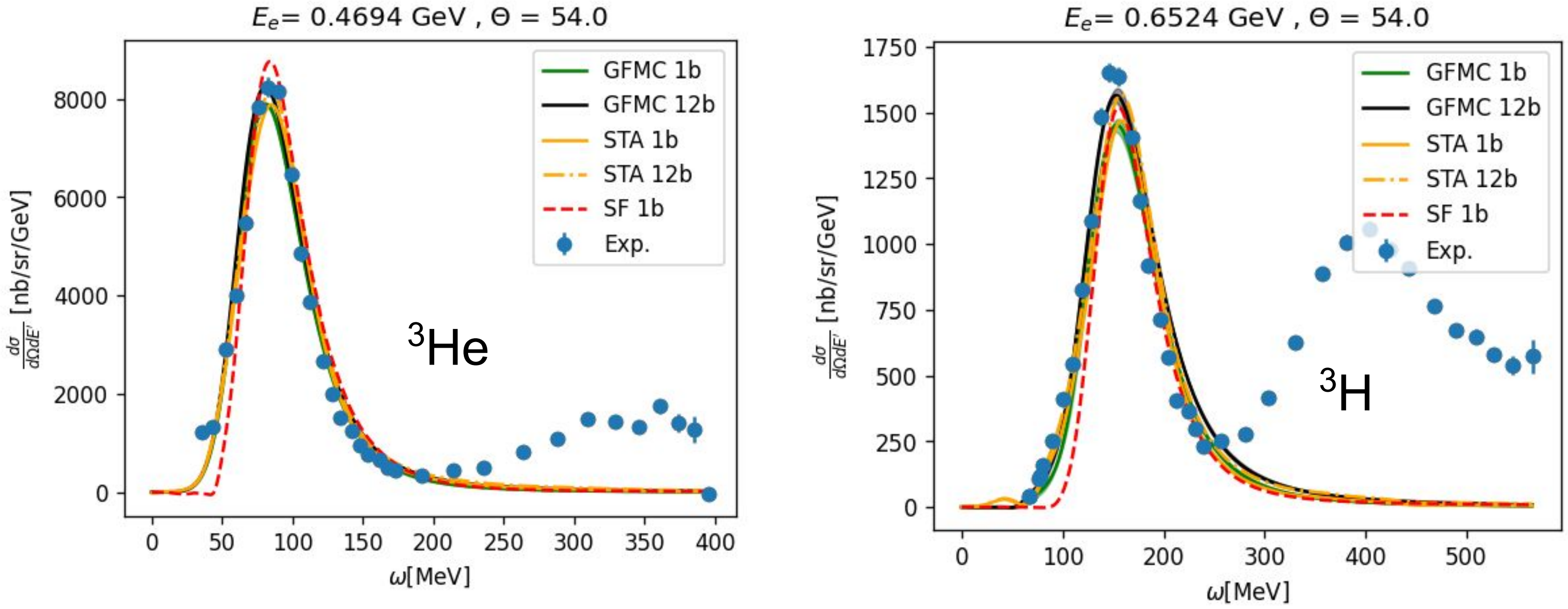
Back to back scattering and particle identity





tot
pp nn
pp/all % pp/all % from momentum distributions
nn/all %

GFMC SF STA: Benchmark & error estimate



Lorenzo Andreoli, *et al.* PRC 2021