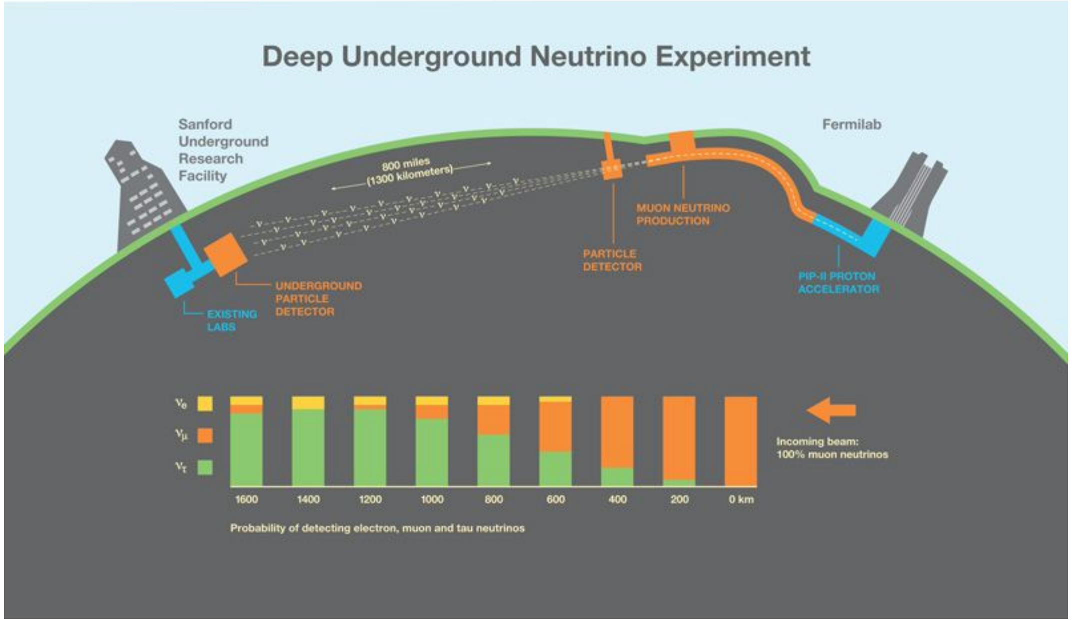
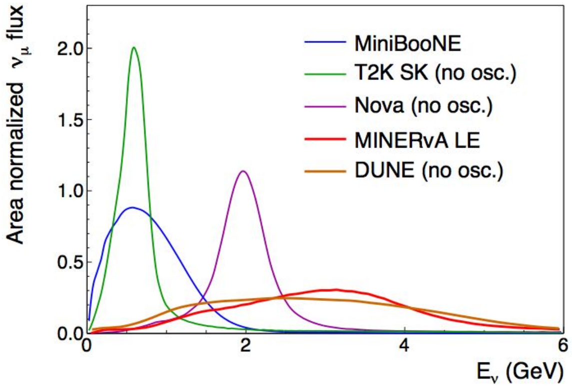
Precision electroweak physics with nuclei

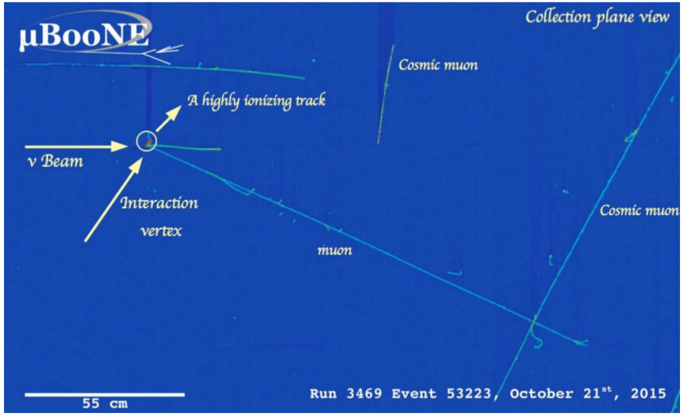
Saori Pastore
Washington University in St Louis

Accelerator Neutrinos' Experiments

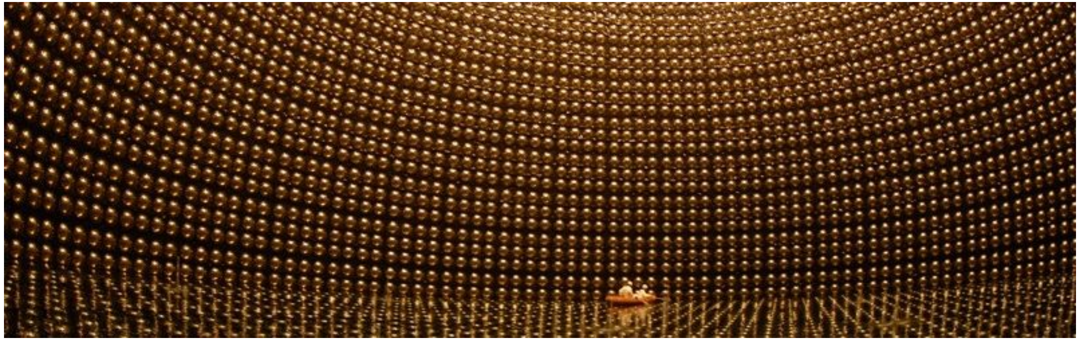


DUNE - Fermilab



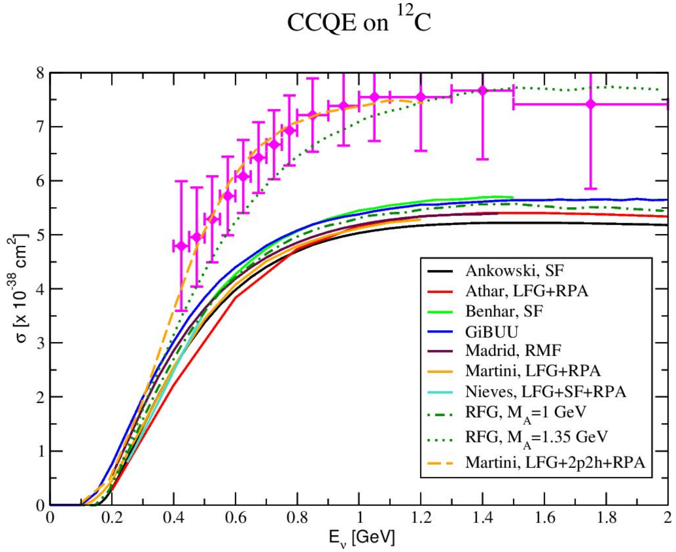


Nuclei for Neutrino Oscillations' Experiments



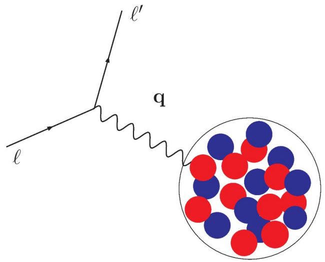
T2K

Neutrino-^{12}C cross section



Alvarez-Ruso arXiv:1012.3871

$$P(\nu_\mu \to \nu_e) = sin^2 2\theta sin^2\left(\frac{\Delta m^2_{21} L}{2E_\nu}\right)$$



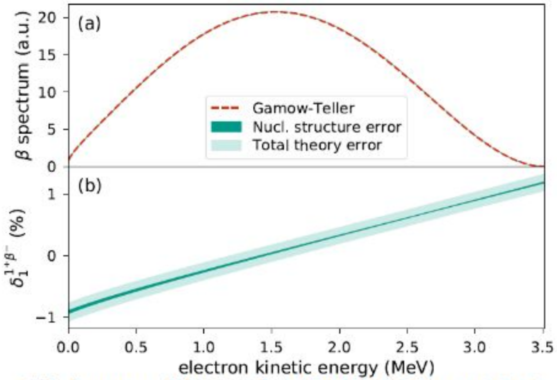
Nuclei are the active material in the detectors

moreover the energy of the incident neutrino is reconstructed from the observed final states

Beta decay spectrum

^{6}He Beta decay spectrum for BSM searches with NCSL, He6-CRES, LPC-Caen

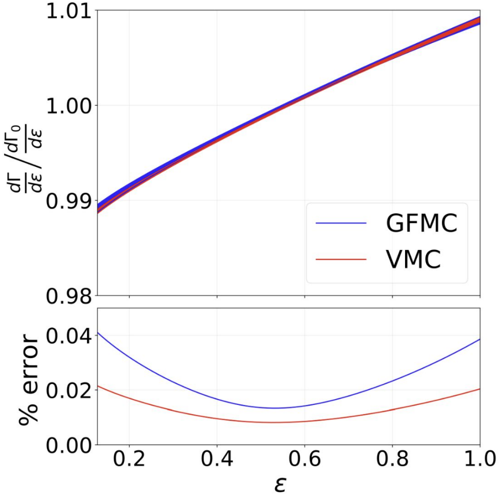
^{6}He beta-decay spectrum from NCSM



Glick-Magid et al. arXiv:2107.10212

Standard Model spectrum for ^{6}He

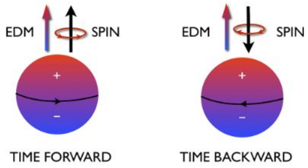
$$\varepsilon = \frac{E_e}{\omega}$$



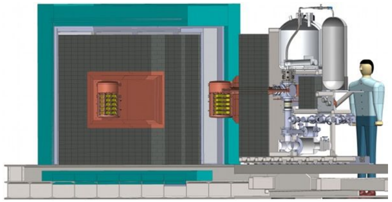
King, Mereghetti, SP et al. PRC 2022

$$\frac{d\Gamma}{d\varepsilon} = \frac{d\Gamma_0}{d\varepsilon} \times (1 + \text{corrections})$$

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

RIKEN NiSHiNA CENTER

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

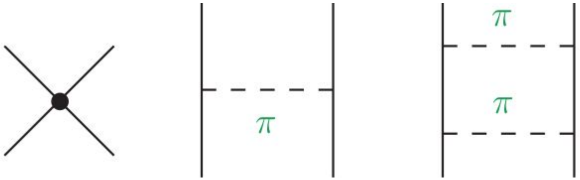
- EDMs, Hadronic PV, ...
- BSM searches with beta decay, ...
- Neutrinoless double beta decay, ...
- Neutrino-Nucleus Scattering Cross Sections, ...
- ...

Many-body Nuclear Interactions

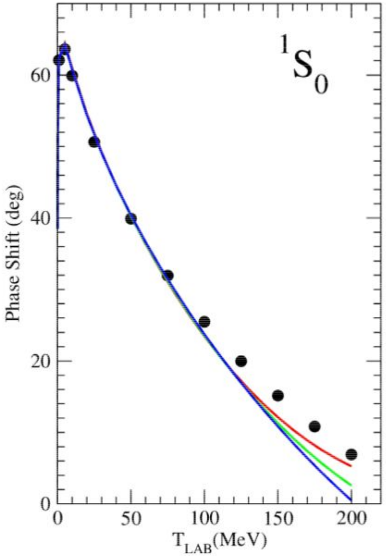
Many-body Nuclear Hamiltonian

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

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 $r \propto m_\pi^{-1}$



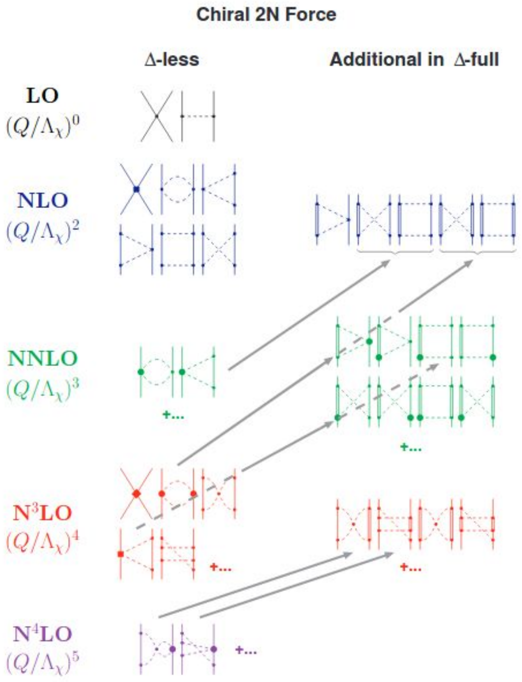
SP et al. PRC80(2009)034004

Hideki Yukawa

AV18+UIX; AV18+IL7
Wiringa, Schiavilla, Pieper *et al*.

chiral πNΔ
N3LO+N2LO Piarulli *et al*. **Norfolk Models**

Norfolk Two- and Three-body Potentials



Norfolk Chiral Potentials

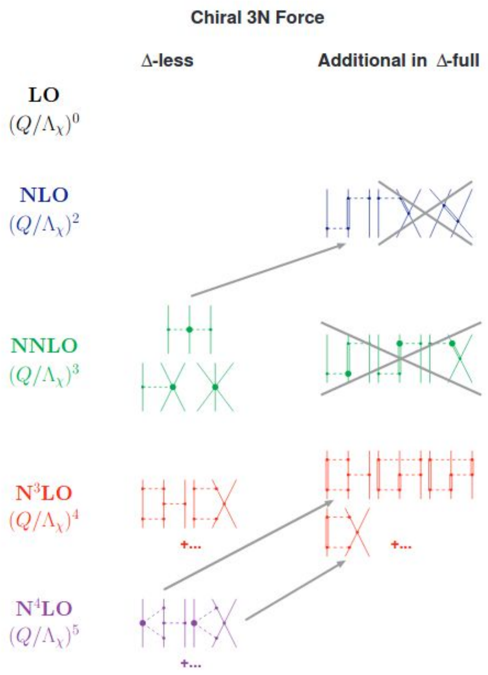
NV2: two-body

26 LECs fitted to np and pp Granada database (2700-3700 data points; lab energies up to 125-200 MeV) with a chi-square/datum ~1

NV3: three-body

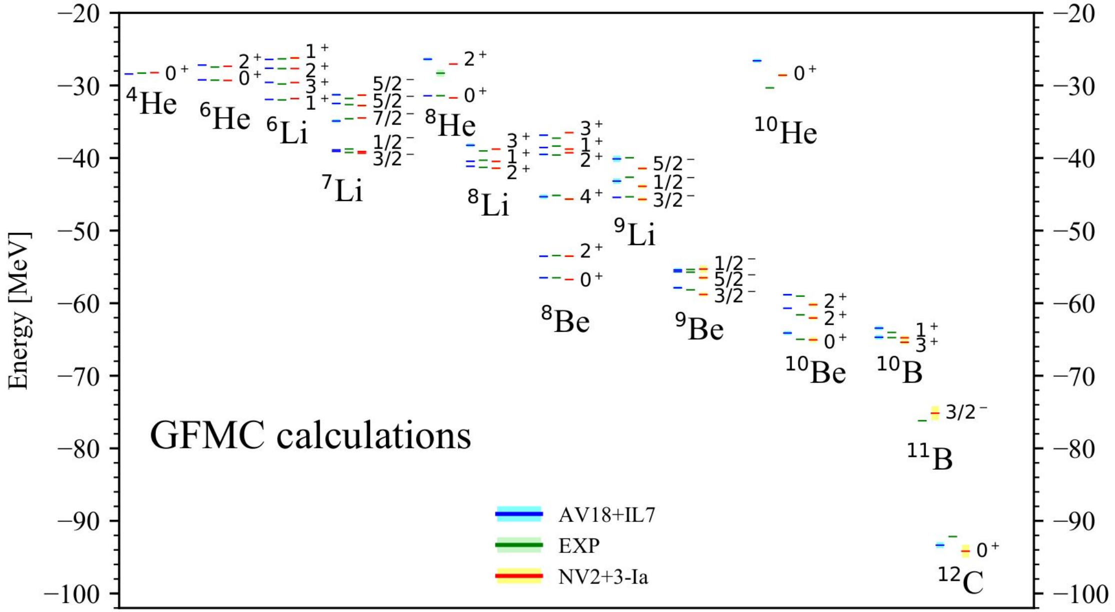
2 LECs

Piarulli *et al*. PRC91(2015) PRC94(2016)



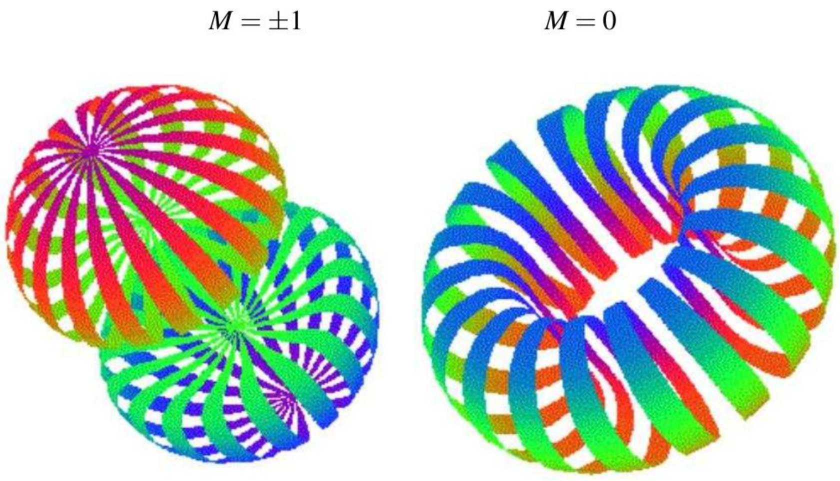
Figs. credit Entem and Machleidt Phys.Rept.503(2011)1

Energies



Piarulli *et al.* PRL120(2018)052503

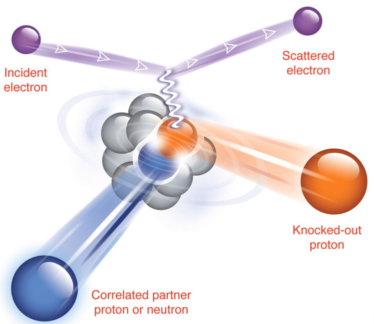
Two-nucleon correlation & the deuteron shape

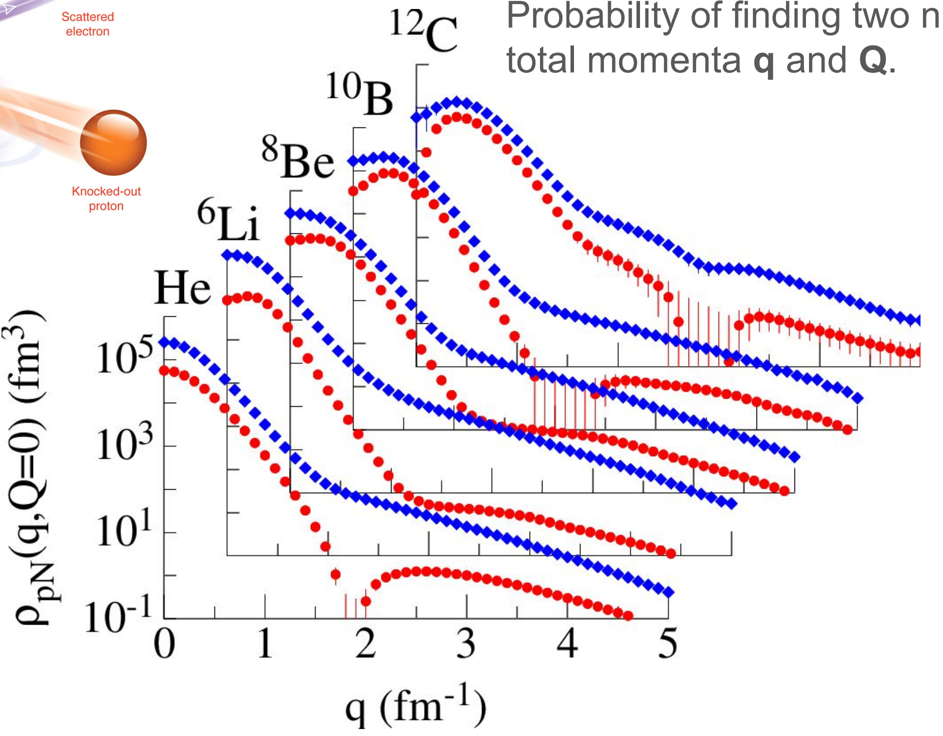


Constant density surfaces for a polarized deuteron in the $M = \pm 1$ (left) and $M = 0$ (right) states

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

Two-nucleon correlations & momentum distributions





pp-pairs; np-pairs

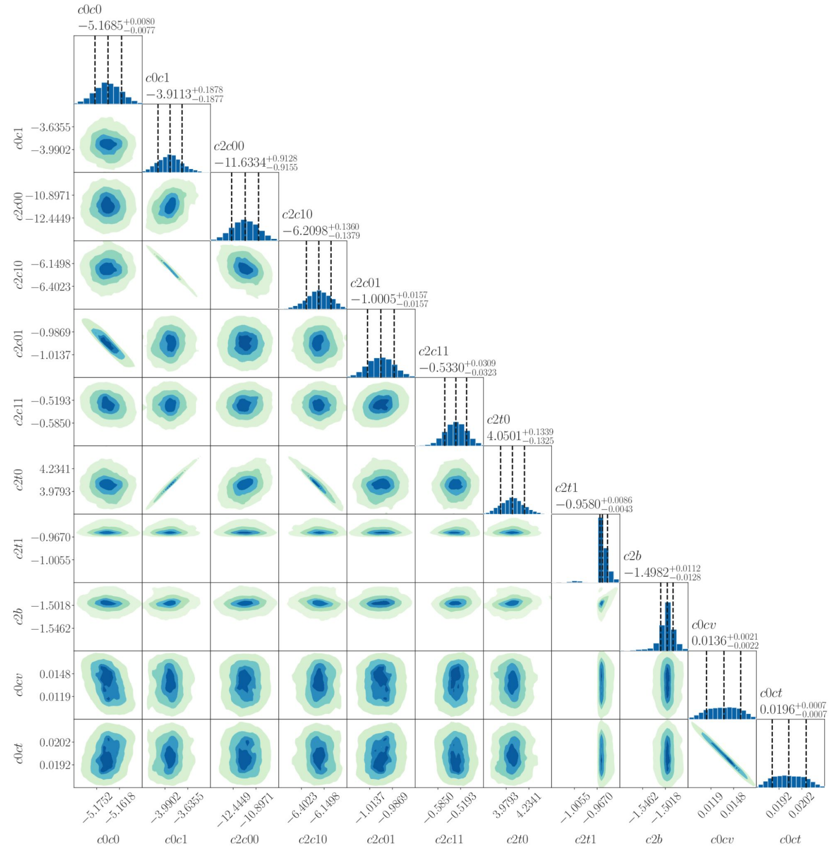
Probability of finding two nucleons with relative and total momenta **q** and **Q**.

Tensor correlations lead to large differences in the np versus pp distributions.

These differences are observed in A(e, e′np) and A(e, e′pp) reactions.

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

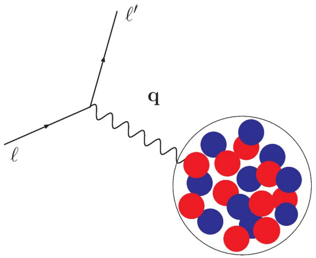
Optimization of Nuclear Two-body Interactions



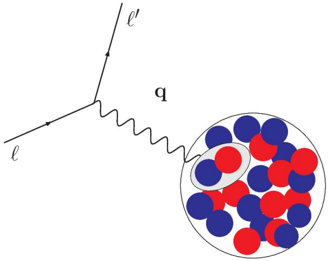
Development and Optimization of two-body interactions based on Bayesian methods

Jason Bub *et al.* arxiv:2408.02480 (2024)

Many-body Nuclear Electroweak Currents



one-body



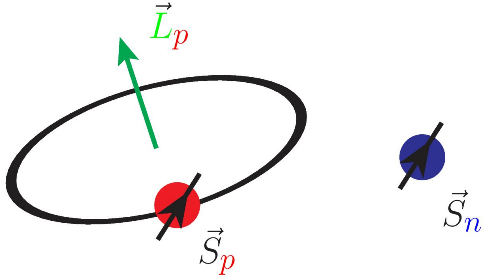
two-body

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

- Two-body currents are a manifestation of two-nucleon correlations
- Electromagnetic two-body currents are required to satisfy current conservation

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

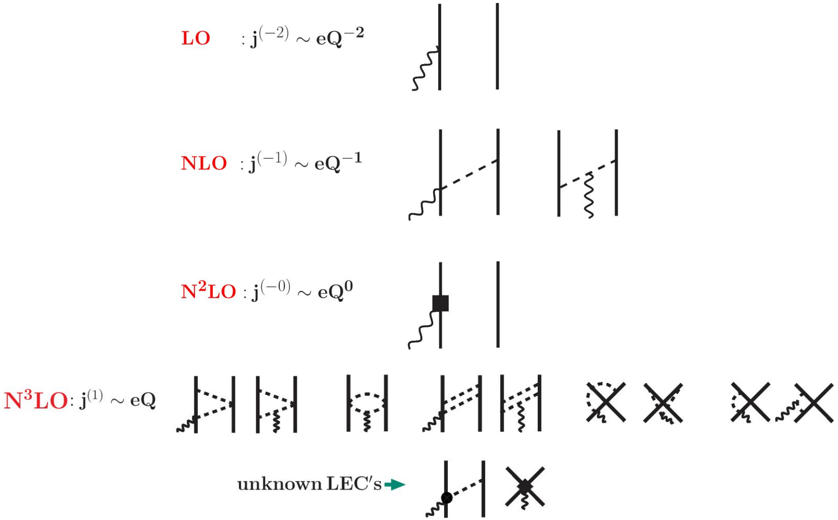
Many-body Currents

- **Meson Exchange Currents** (MEC)

Constrain the MEC current operators by imposing that the current conservation relation is satisfied with the AV18 two-body potential

- **Chiral Effective Field Theory Currents**

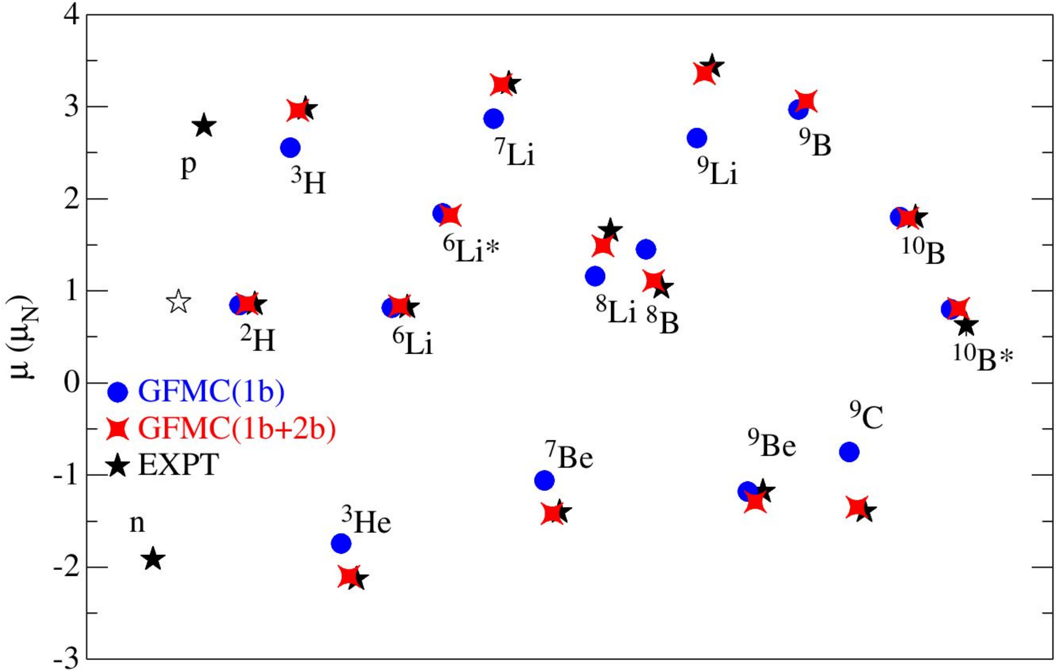
Are constructed consistently with the two-body chiral potential; Unknown parameters, or Low Energy Constants (**LECs**), need to be **determined by either fits to experimental data or by Lattice QCD calculations**



Electromagnetic Current Operator

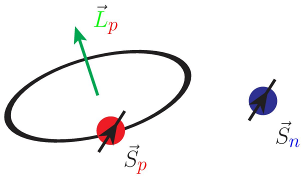
SP *et al.* PRC78(2008)064002, PRC80(2009)034004, PRC84(2011)024001, PRC87(2013)014006
Park *et al.* NPA596(1996)515, Phillips (2005)
Kölling *et al.* PRC80(2009)045502 & PRC84(2011)054008

Magnetic Moments of Light Nuclei



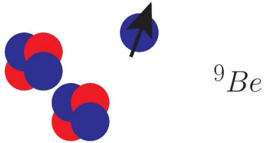
SP *et al*. PRC87(2013)035503

Single particle picture

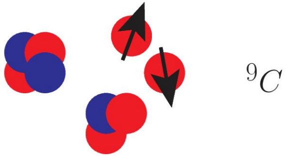


$$\mu_N(1b) = \sum_i [(L_i + g_p S_i)(1+\tau_{i,z})/2 + g_n S_i (1-\tau_{i,z})/2]$$

Small two-body current effects

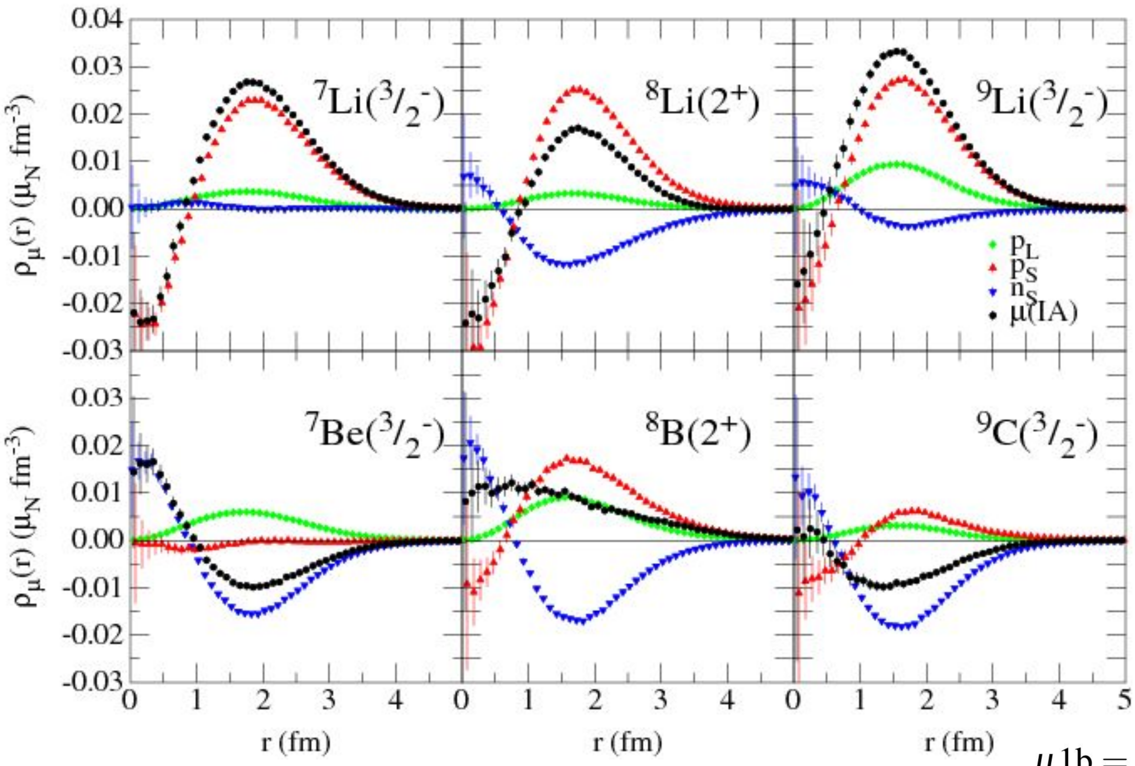


Large two-body currents ~40%



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

One-body magnetic density

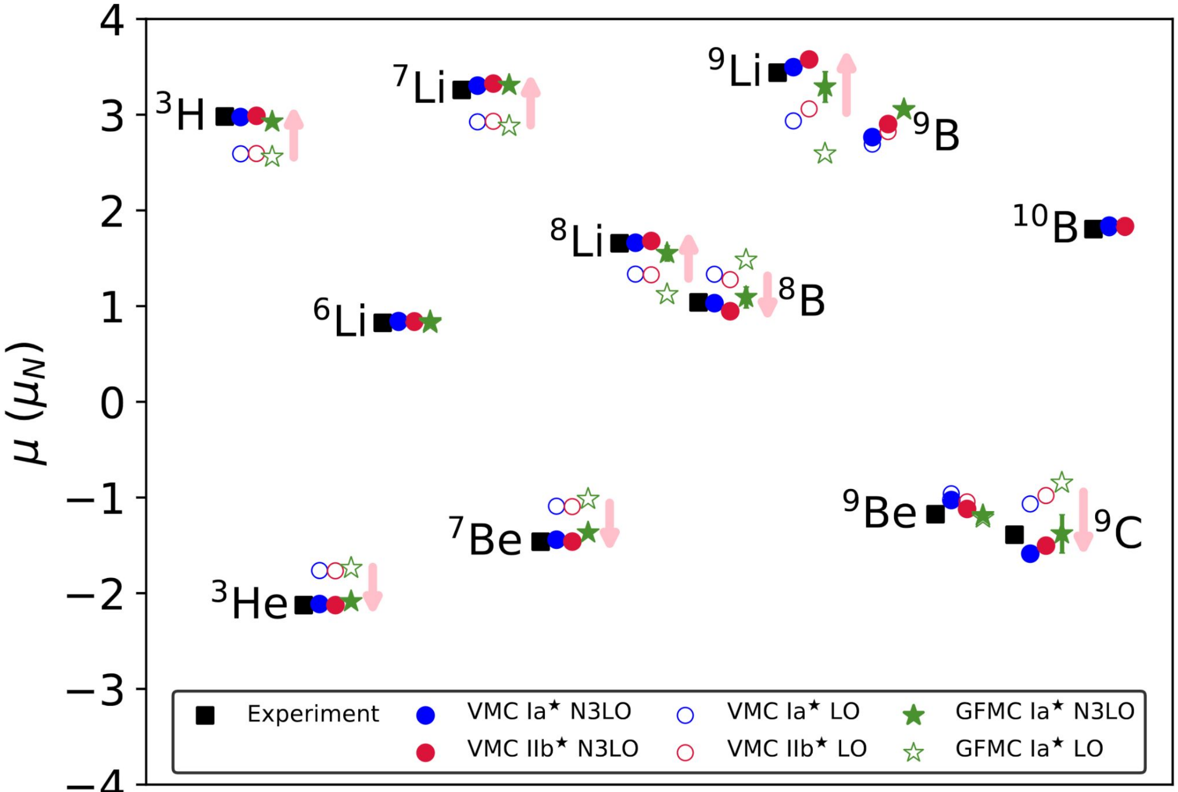


$$\mu^{1b} \propto \int \rho_M^{1b}(r) dr$$

r single particle coordinate from the c.m.

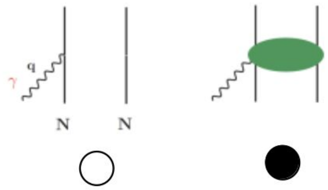
$$\mu 1\mathrm{b} = \mu_N \sum_i [(L_i + g_p S_i)(1+\tau_{i,z})/2 + g_n S_i (1-\tau_{i,z})/2]$$

Magnetic moments in light nuclei

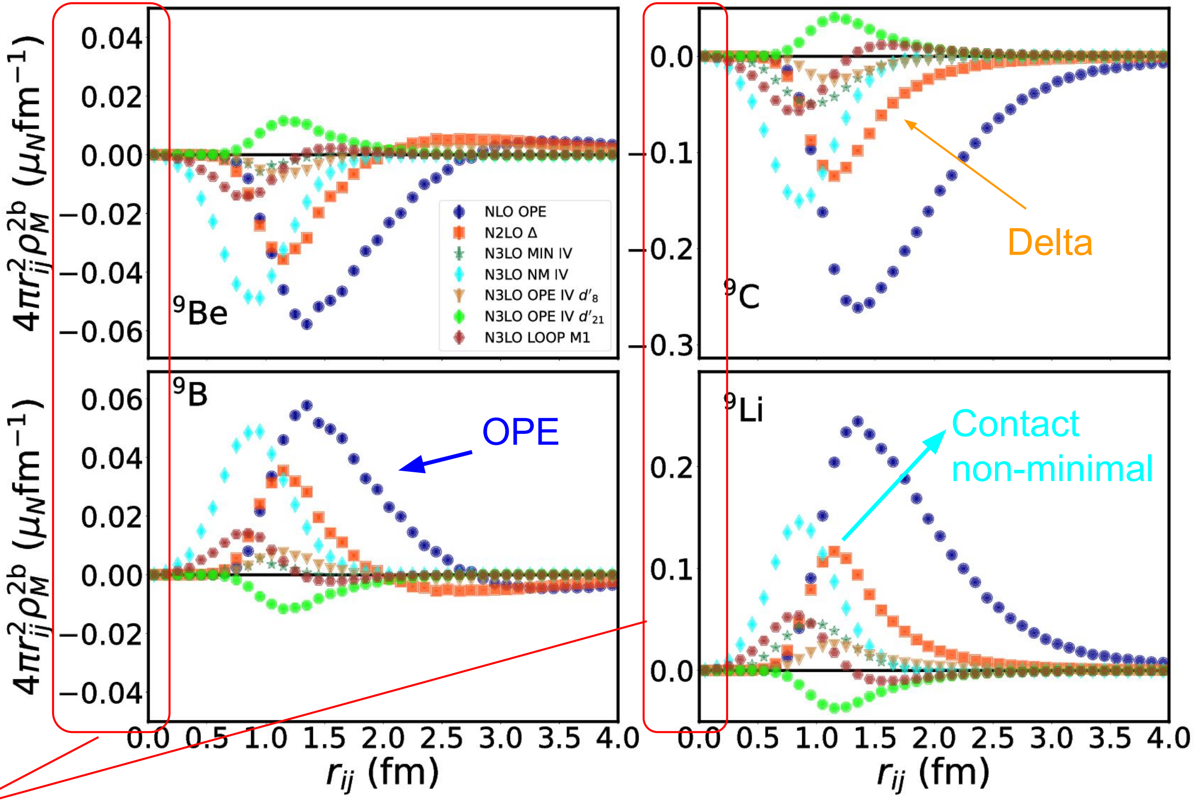


Chambers-Wall, King, Gnech et al. PRL 2024 [2407.03487]

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



Two-body magnetic densities

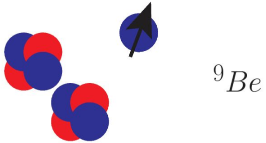


Note the scale

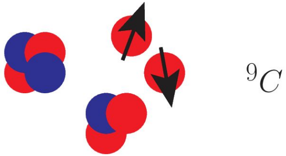
Chambers-Wall, King, Gnech et al. PRC 2024 2407.04744

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

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

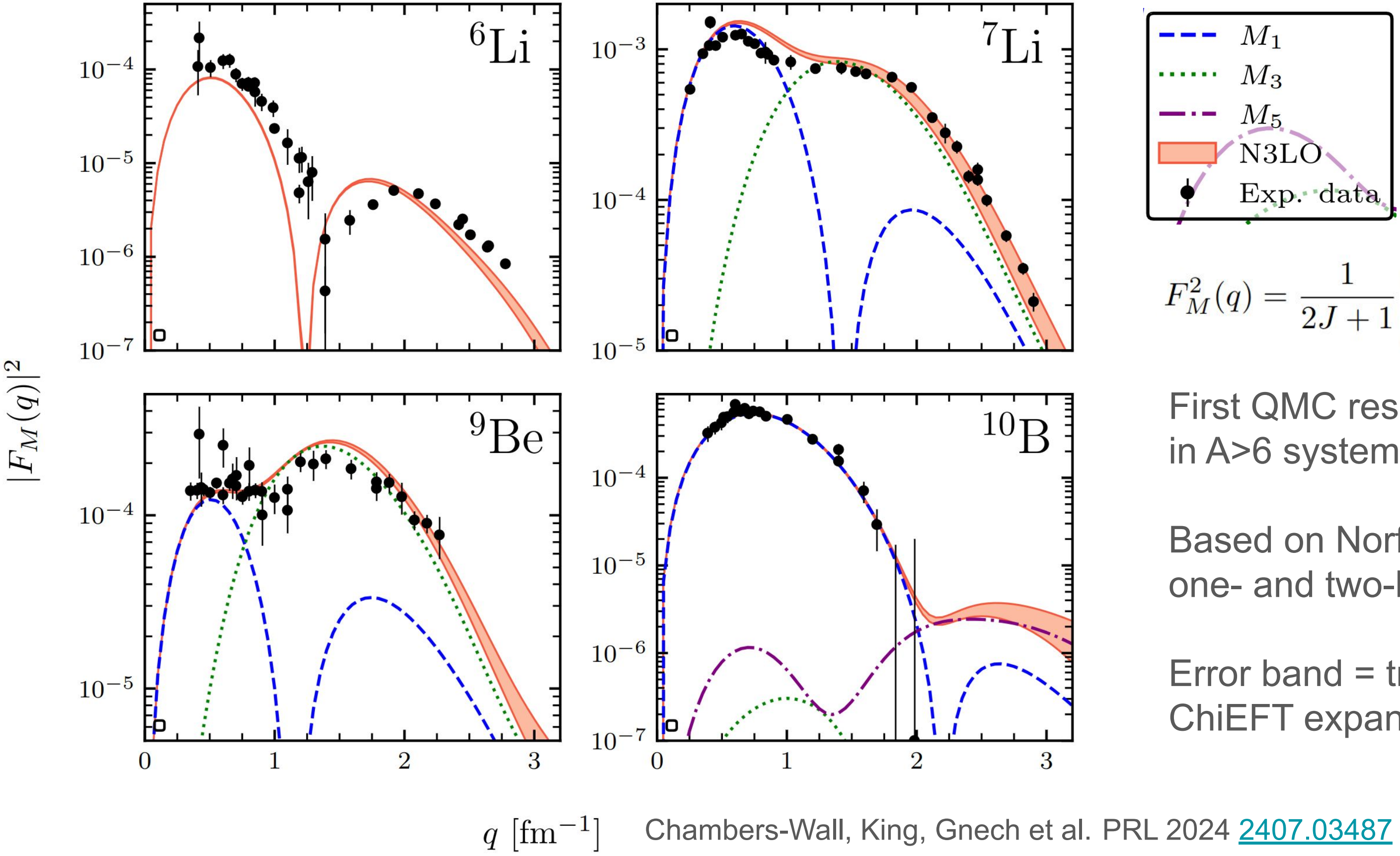


$[441] = [\alpha, \alpha, n(p)]$



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

Magnetic form factors: comparison with the data



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

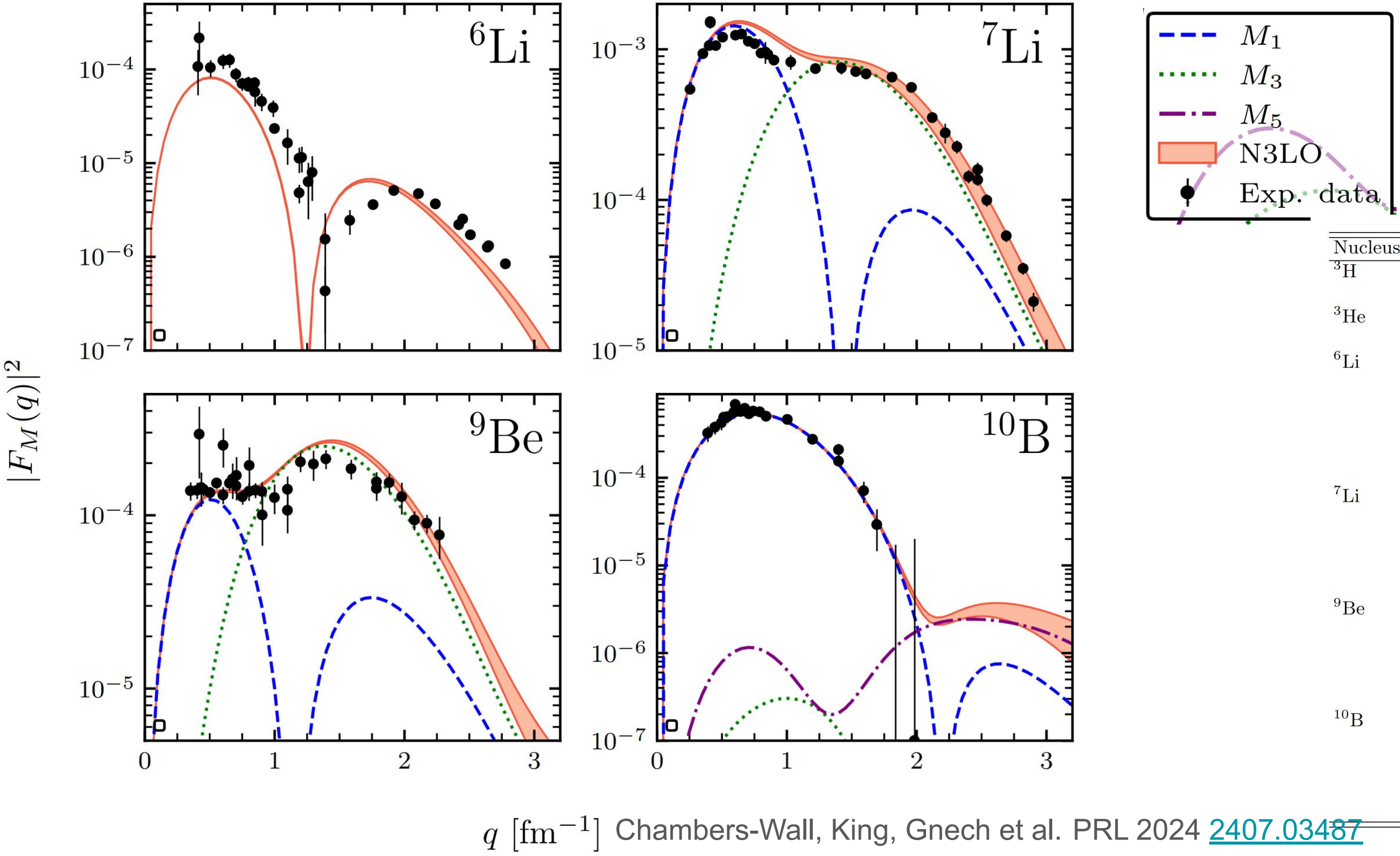
First QMC results for form factors in A>6 systems.

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

Error band = truncation error in the ChiEFT expansion.

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

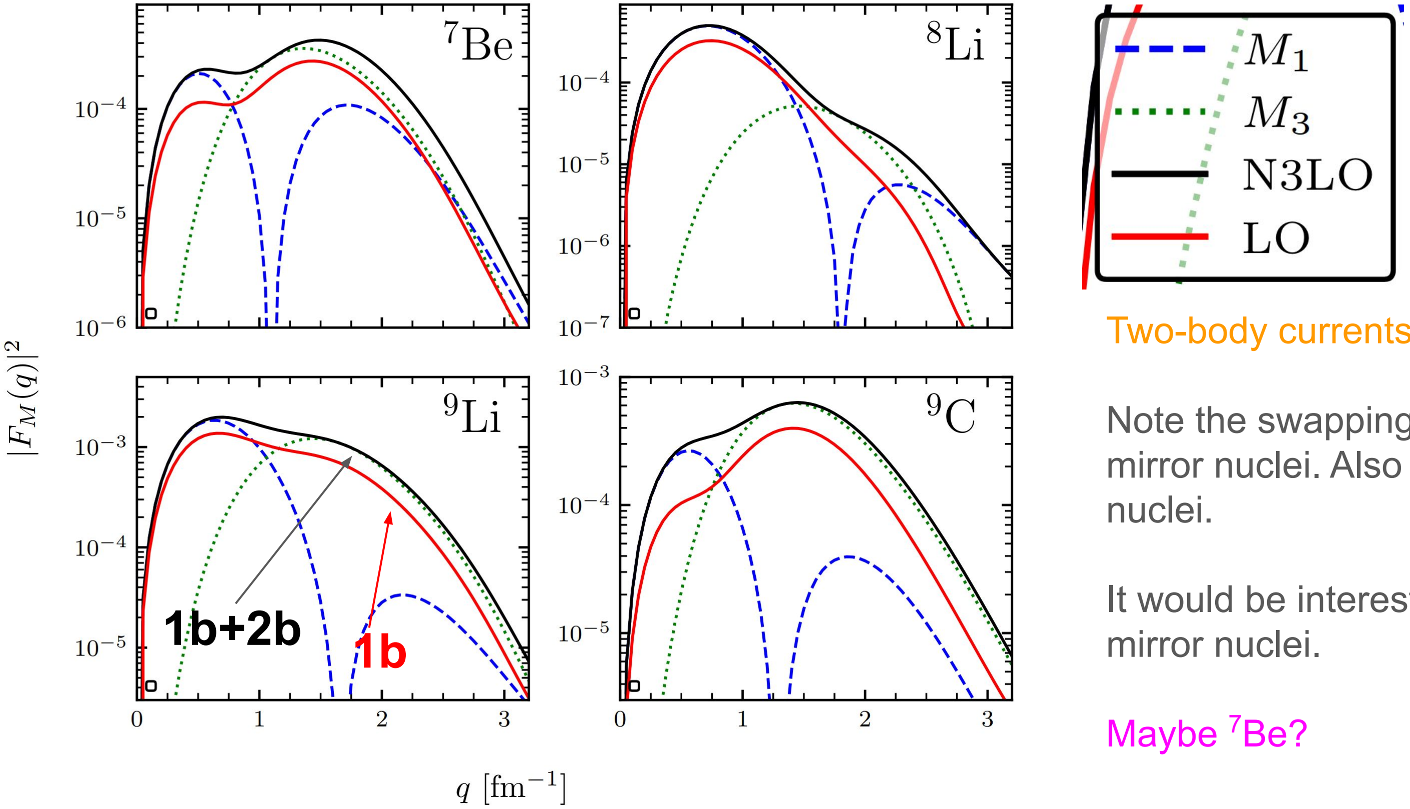
Magnetic form factors: comparison with the data



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

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	$Z^2/4\pi$
^{7}Li	Peterson 1962 [90]	N	Eq. (C2)
	Goldemberg 1963 [91]	N	Eq. (C2)
	Van Niftrik 1971 [95]	D	Eq. (C1)
	Lichtenstadt 1983 [96]	N	$Z^2/4\pi$
^{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)
	Vanpraet 1965 [98]	N	Eq. (C1)
	Rand 1966 [92]	N	Eq. (C1)
	Lapikas 1978 [93]	D	$1/4\pi$

Magnetic form factors: predictions



Two-body currents provide 40-60%.

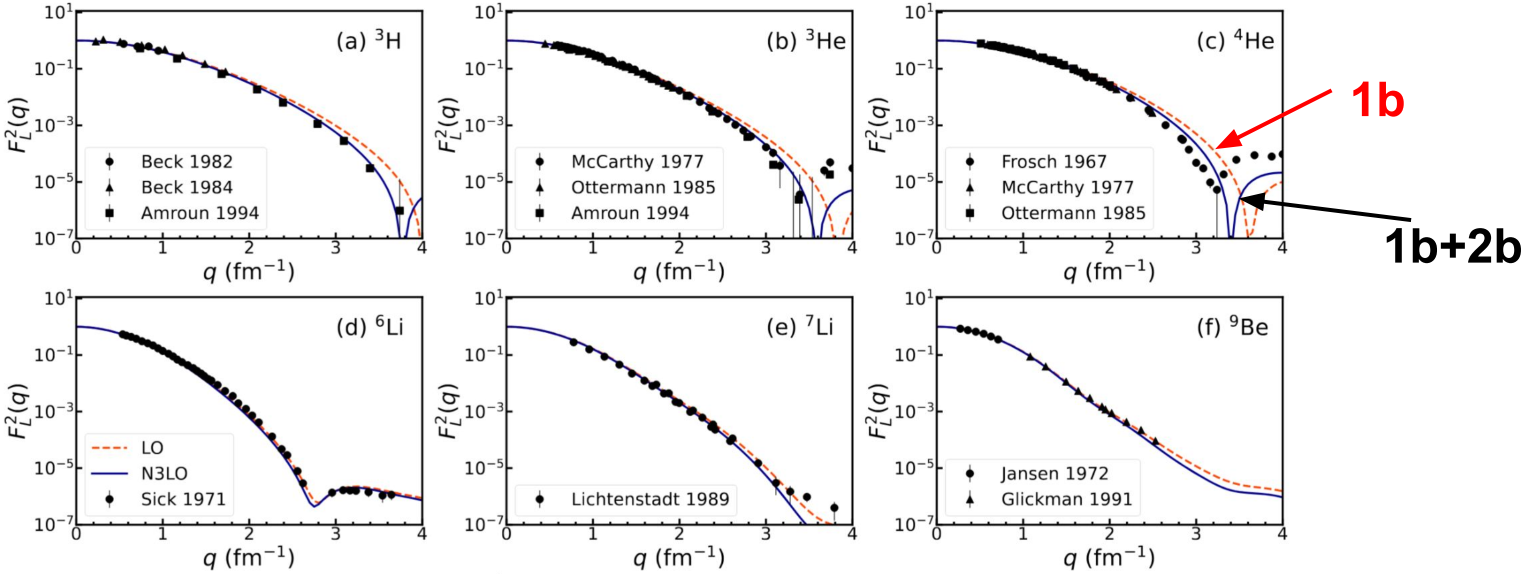
Note the swapping of M1 and M3 in mirror nuclei. Also observed in A=7 nuclei.

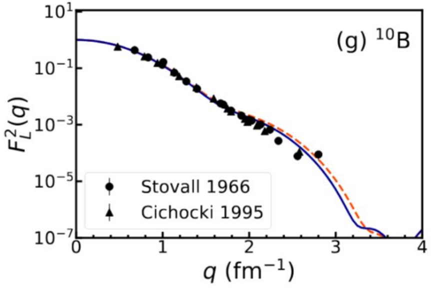
It would be interesting to have data for mirror nuclei.

Maybe ^{7}Be?

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

Charge form factors





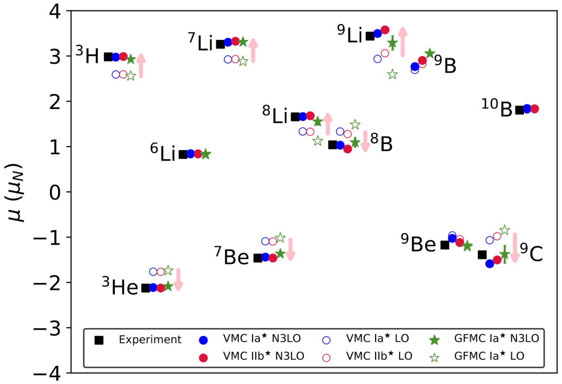
Electromagnetic radii (in preparation)

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

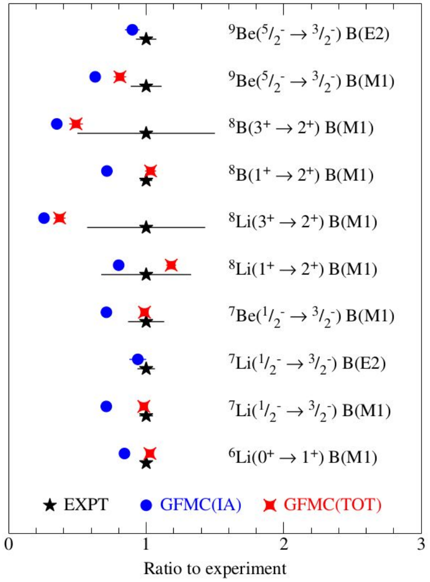
King et al. arxiv:2408.16909 2024

Electromagnetic Observables

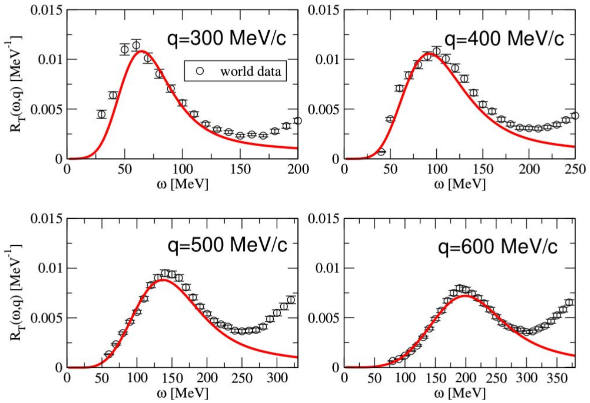
Magnetic moments



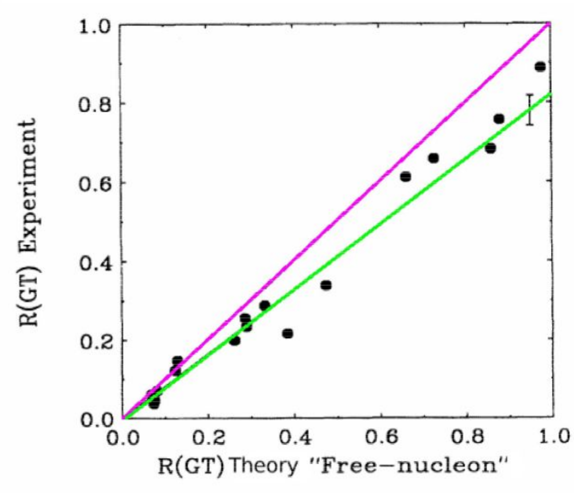
EM decay



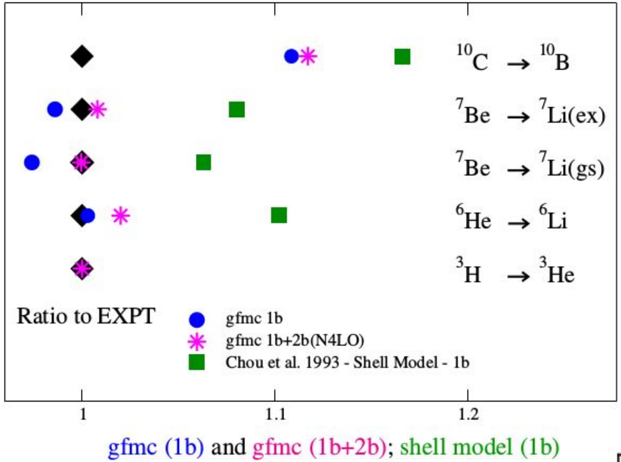
e-^{4}He particle scattering



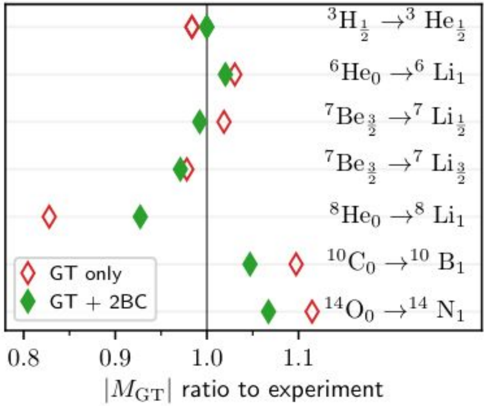
Beta decay



Chou et al. PRC47(1993)163

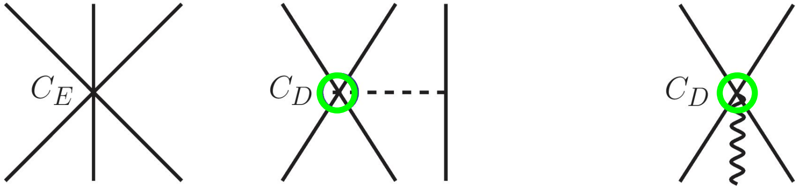


SP *et al*. PRC97(2018)022501



P. Gysbers et al. *Nature Phys.* 15 (2019)

Three-body Force and the Axial Contact Current



Three-body force   Axial two-body contact current

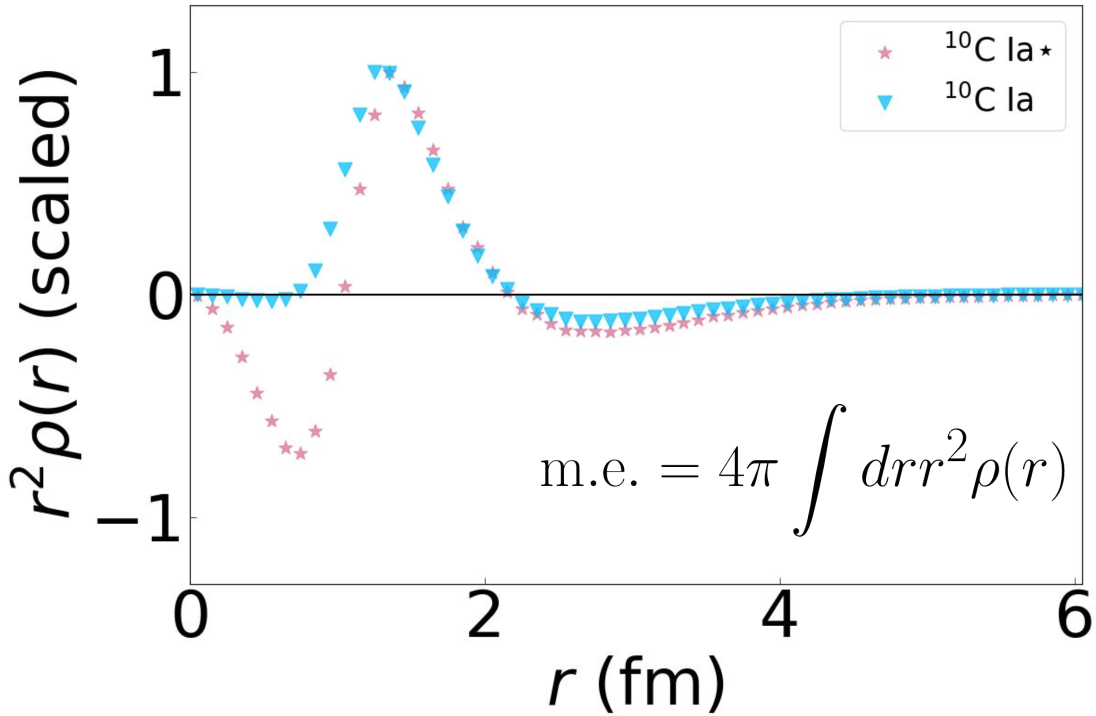
LECs $\boldsymbol{c_D}$ and $\boldsymbol{c_E}$ are fitted to:

- **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

Energies A=8-10 slightly better with non-starred models

Two-body transition densities



Different fitting procedures lead to different short range behaviours.

Garrett King *et al.* PRC102(2020)025501

Beta decay spectrum

^{6}He Beta decay spectrum for BSM searches with NCSL, He6-CRES, LPC-Caen

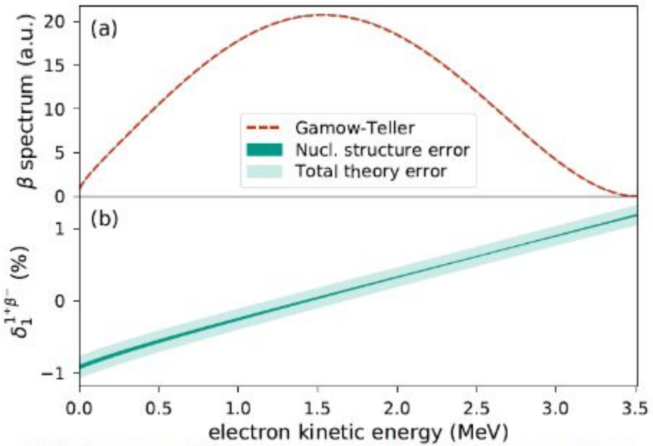
NSCL

He6 CRES

lpc caen

Experiments aim to <0.1% precision

^{6}He beta-decay spectrum from NCSM



Glick-Magid et al. arXiv:2107.10212

$$\frac{d\Gamma}{d\varepsilon} = \frac{d\Gamma_0}{d\varepsilon} \times (1 + \text{corrections})$$

^{6}He Beta Decay Spectrum

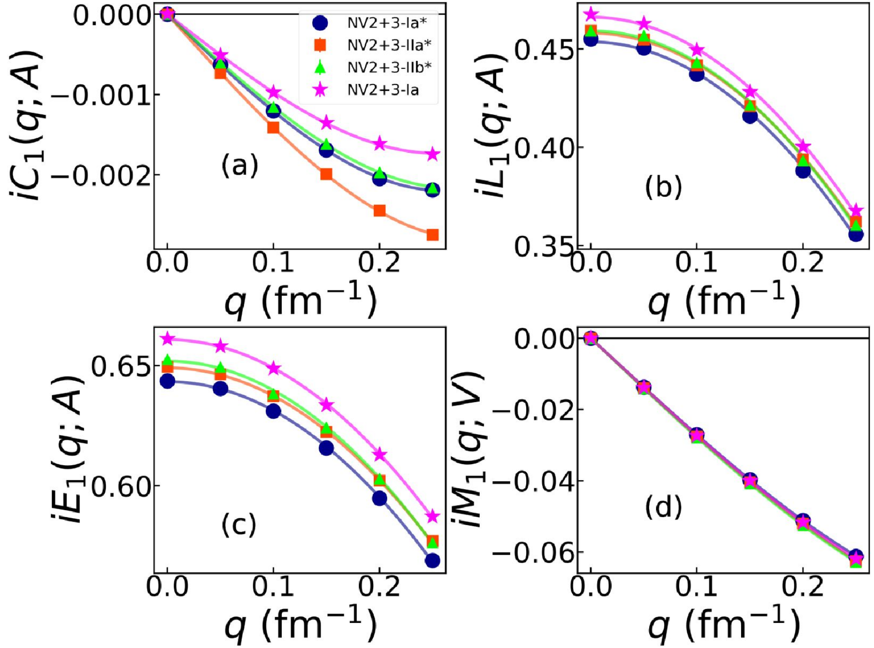
Differential rate: $$d\Gamma_\beta = |M_\beta(q)|^2 \times (\text{kinematic factors})$$

In the $q \to 0$ limit: $$\frac{d\Gamma_\beta}{dE_e} = \frac{d\Gamma_0}{dE_e}\left[1 + \boxed{b}\frac{m_e}{E_e}\right]$$

SM (q→0): $$b = 0$$

SM (with recoil): $$b = 0 + \Delta b$$

Beta Decay Spectrum



$$C_1(q;A) = \frac{i}{\sqrt{4\pi}} \langle {}^6\mathrm{Li}, 10 | \rho_+^\dagger(q\hat{\mathbf{z}};A) | {}^6\mathrm{He}, 00 \rangle$$

$$L_1(q;A) = \frac{i}{\sqrt{4\pi}} \langle {}^6\mathrm{Li}, 10 | \hat{\mathbf{z}} \cdot \mathbf{j}_+^\dagger(q\hat{\mathbf{z}};A) | {}^6\mathrm{He}, 00 \rangle$$

$$E_1(q;A) = -\frac{i}{\sqrt{2\pi}} \langle {}^6\mathrm{Li}, 10 | \hat{\mathbf{z}} \cdot \mathbf{j}_+^\dagger(q\hat{\mathbf{x}};A) | {}^6\mathrm{He}, 00 \rangle$$

$$M_1(q;V) = -\frac{1}{\sqrt{2\pi}} \langle {}^6\mathrm{Li}, 10 | \hat{\mathbf{y}} \cdot \mathbf{j}_+^\dagger(q\hat{\mathbf{x}};V) | {}^6\mathrm{He}, 00 \rangle$$

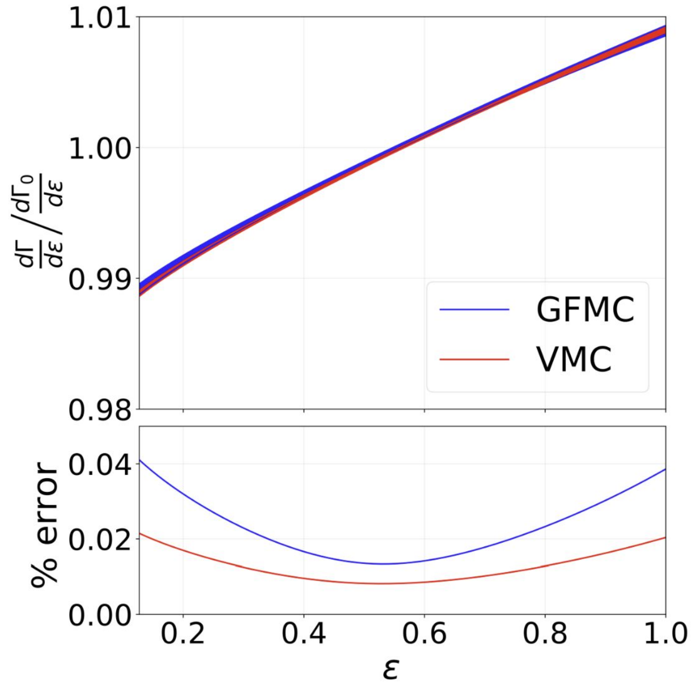
Model dependencies determined with the Norfolk interactions and one- plus two-body currents.

Dominant terms $L_1^{(0)}$ and $E_1^{(0)}$ have model dependence of ~1% to ~2%

Garrett King et al. PRC (2023)

Beta Decay Spectrum

Standard Model spectrum for ^{6}He



$$\varepsilon = \frac{E_e}{\omega}$$

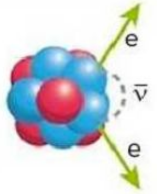
τ_{GFMC} = 808 +/- 24 ms

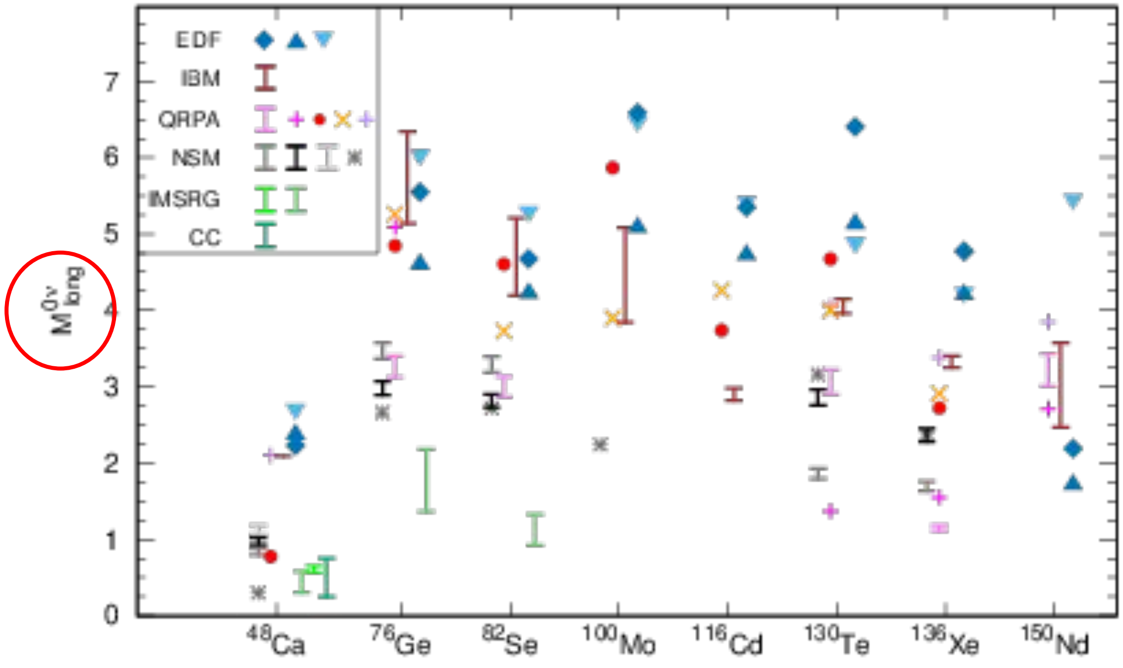
$\tau_{Expt.}$ = 807.25 +/- 0.16 +/- 0.11 ms

Accounting for model uncertainty and fully retaining two-body currents, required theory precision achieved

Garrett King et al. PRC (2023)

Neutrinoless Double Beta Decay





Menéndez Vissani et al. *Rev.Mod.Phys.* 95 (2023) 2, 025002

$$[T^{0\nu}_{1/2}]^{-1} = G_{0\nu}(Q,Z)|M_{0\nu}|^2 m^2_{\beta\beta}$$

$$(Z,N) \rightarrow (Z+2,N-2) + 2e$$

Ad: Three-body neutrino \`potentials' in the Jamboree

Partial muon capture rates

$\Gamma_{VMC}(\text{avg.}) = 1495\ s^{-1} \pm 19\ s^{-1}$

$\Gamma_{expt} = 1496.0\ s^{-1} \pm 4.0\ s^{-1}$

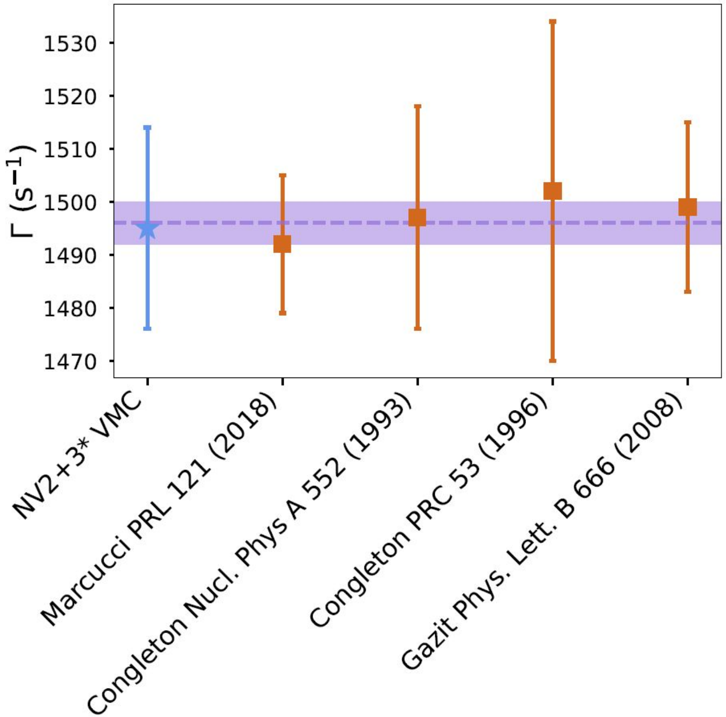
Ackerbauer *et al.* PLB417, 224(1998)

Momentum transfer **q~ 100 MeV**

Two-body correction is ~8% of total rate on average for A=3

- Cutoff: 0.5%
- Energy range of fit: 0.7%
- Three-body fit: 1.8%

$$^3\mathrm{He}(1/2^+;1/2) \rightarrow ^3\mathrm{H}(1/2^+;1/2)$$



Garrett King *et al.* PRC2022

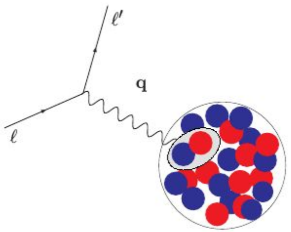
Lepton-Nucleus scattering: Inclusive Processes

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

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

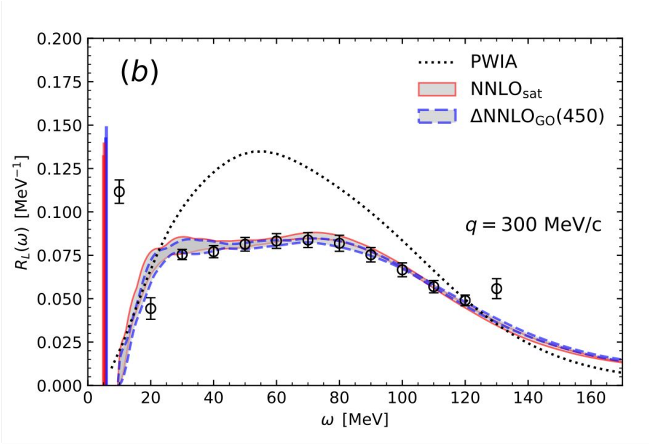


For a recent review on QMC, SF methods see
Rocco *Front. In Phys.*8 (2020)116

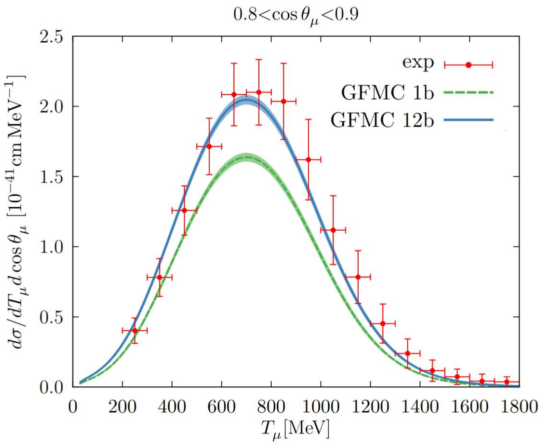
Inclusive Cross Sections with Integral Transforms

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)

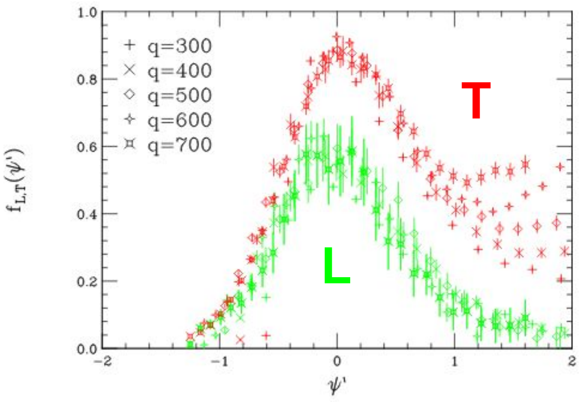


Lovato et al. PRX10 (2020)

Lepton-Nucleus scattering: Data

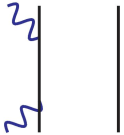
Transverse Sum Rule

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



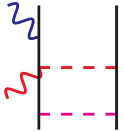
^{4}He Electromagnetic Data
Carlson *et al.* PRC65(2002)024002

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



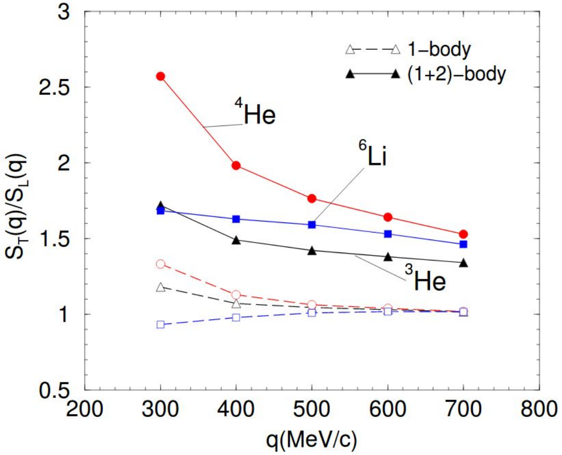
$\langle \mathbf{j}_{1b}^\dagger\ \ \mathbf{j}_{1b}\rangle\ > 0$

Leading one-body term



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

Interference term

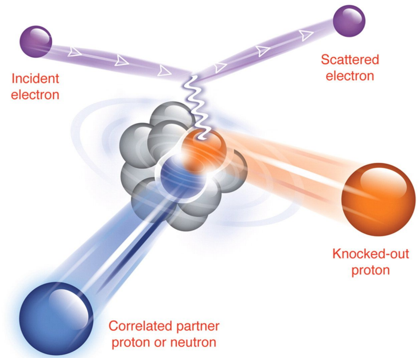


Transverse/Longitudinal Sum Rule
Carlson *et al.* PRC65(2002)024002

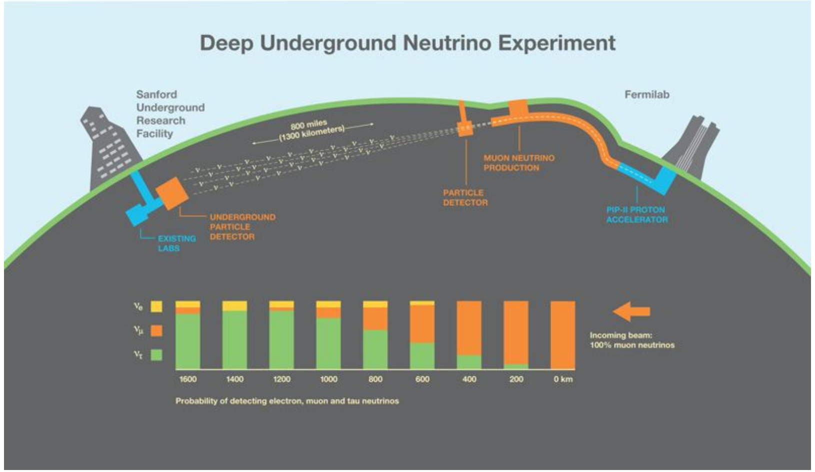
Beyond Inclusive: Short-Time-Approximation

Short-Time-Approximation Goals:

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



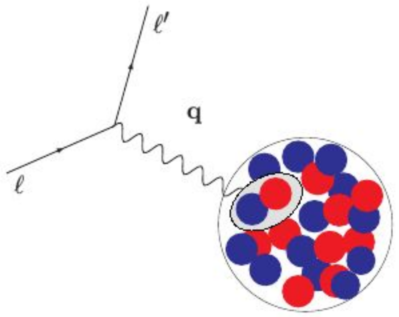
Subedi et al. Science320(2008)1475



Stanford Lab article

e4u collaboration

Short-Time-Approximation



Short-Time-Approximation:

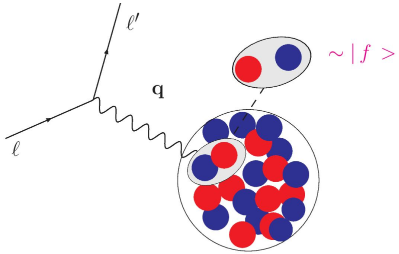
- Based on Factorization
- Retains two-body physics
- Correctly accounts for interference

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

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

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

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

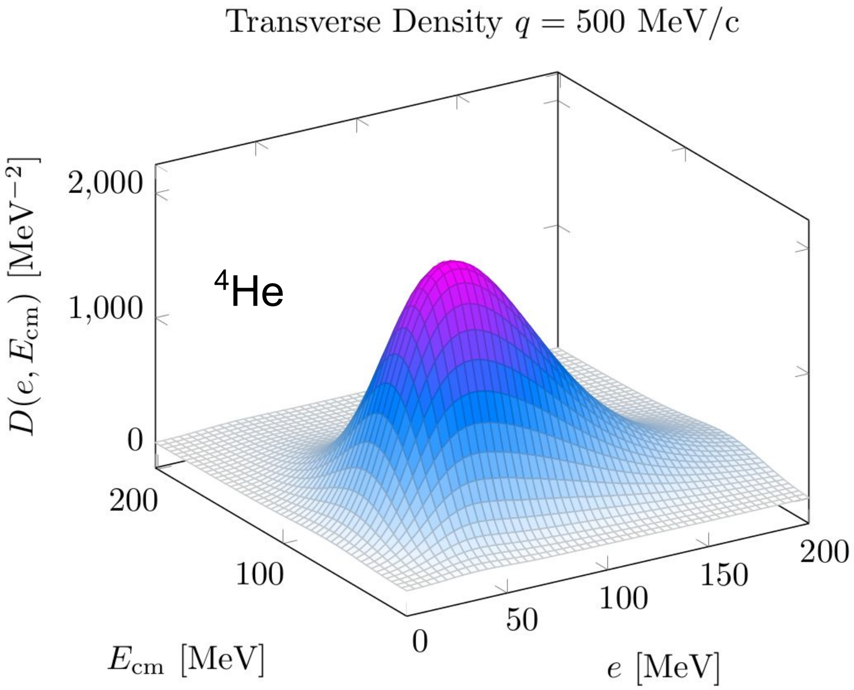
$$R_\alpha(q,\omega) = \sum_f \delta\left(\omega + E_0 - E_f\right) |\langle f | O_\alpha(\mathbf{q}) | 0 \rangle|^2$$

Response ***Densities***

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

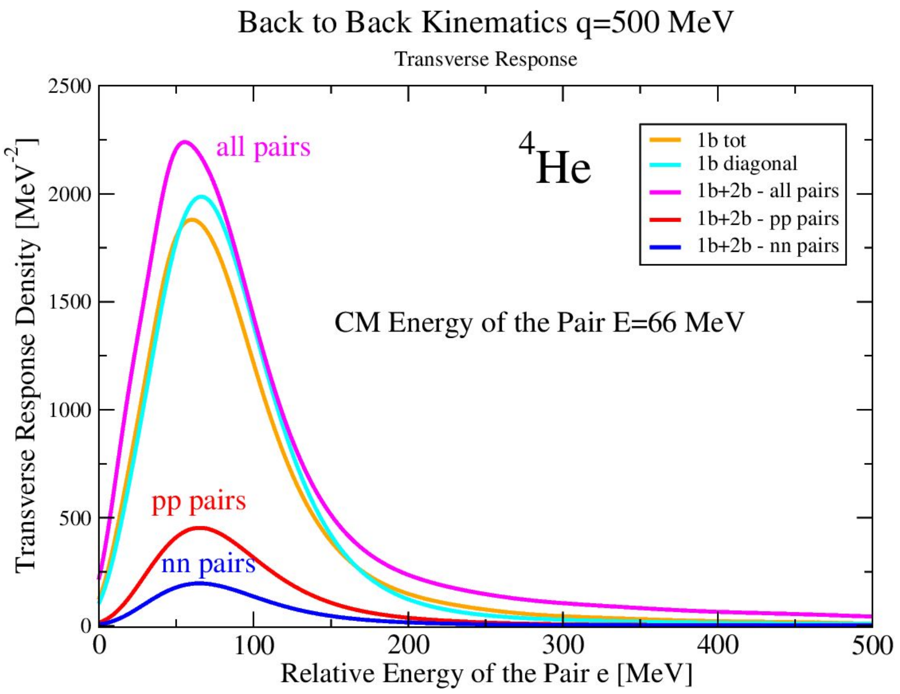
P’ and *p’* are the CM and relative momenta of the struck nucleon pair

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



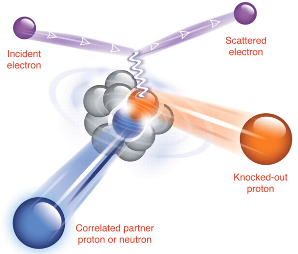
SP *et al.* PRC101(2020)044612

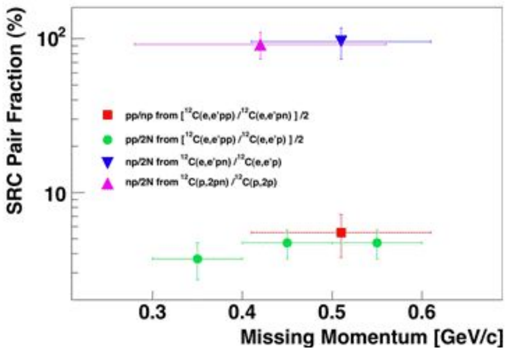
e-^{4}He scattering in the back-to-back kinematic



SP *et al.* PRC101(2020)044612

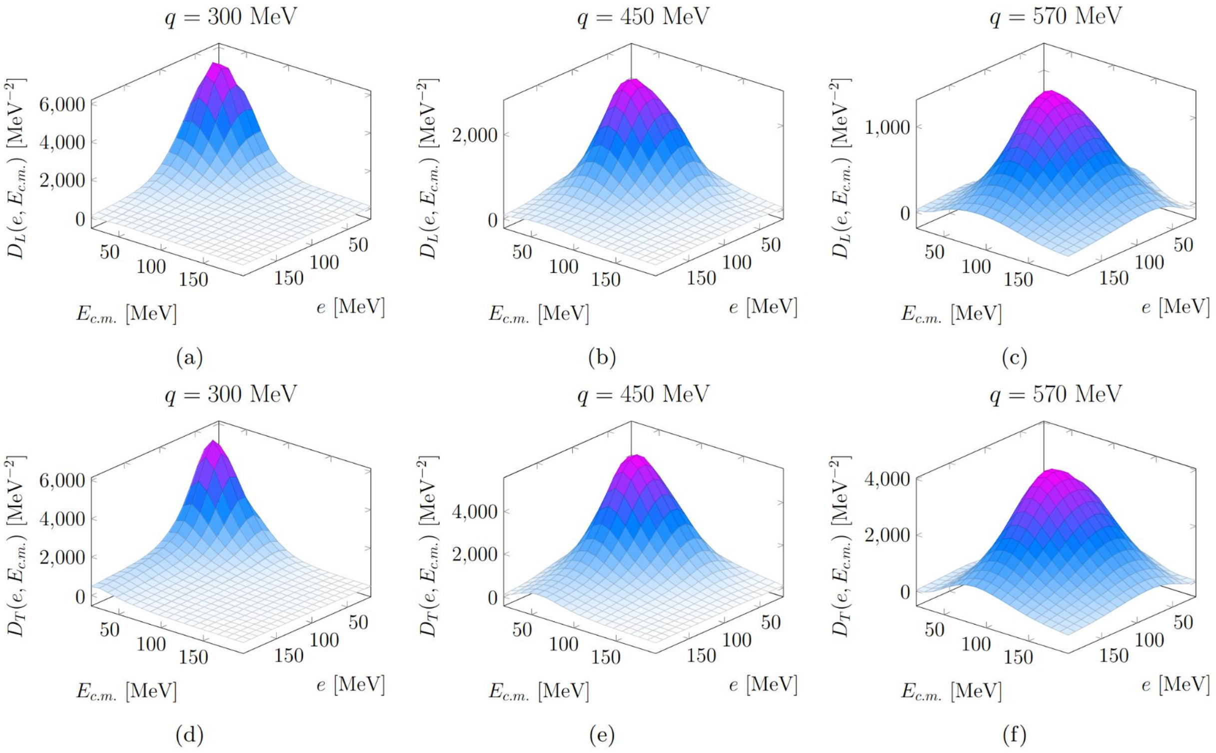
- pp pairs
- nn pairs
- all pairs 1body
- all pairs tot





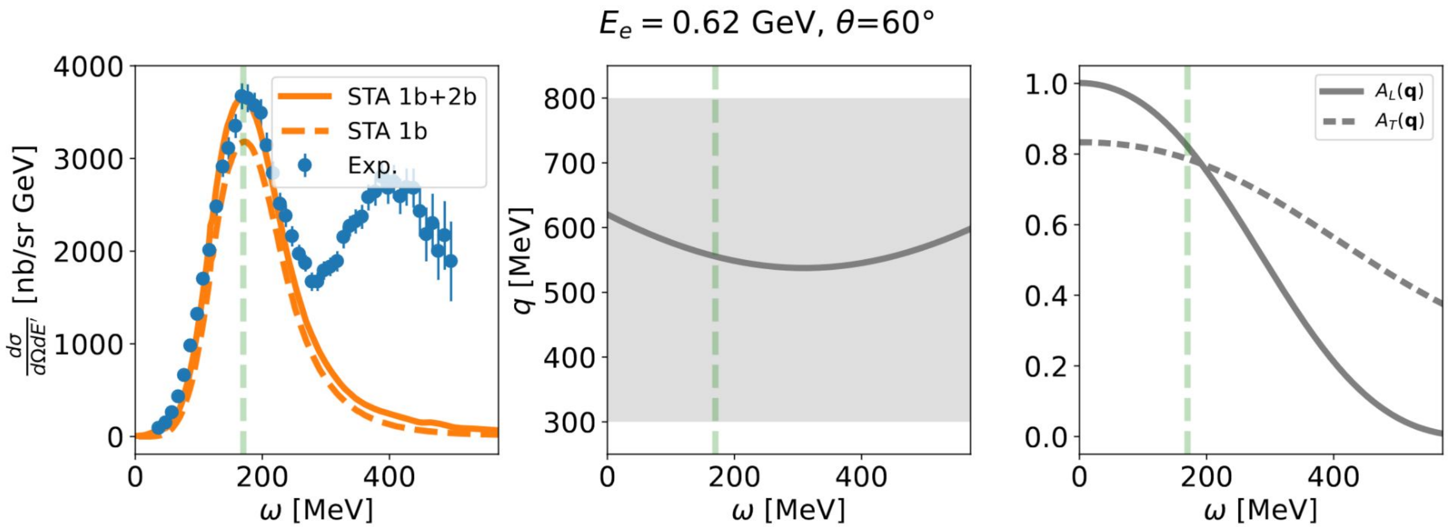
Subedi et al. Science320(2008)1475

^{12}C Response Densities



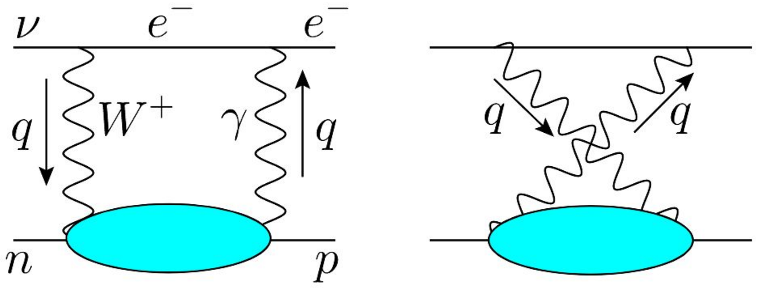
Lorenzo Andreoli *et al.* arXiv:2407.06986 2024

^{12}C cross sections



Lorenzo Andreoli *et al.* arXiv:2407.06986 2024

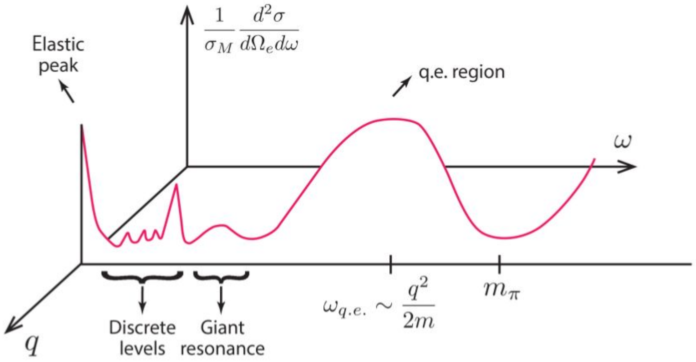
Ties to fundamental symmetry: CKM unitarity



Superallowed beta decay used to test CKM unitarity

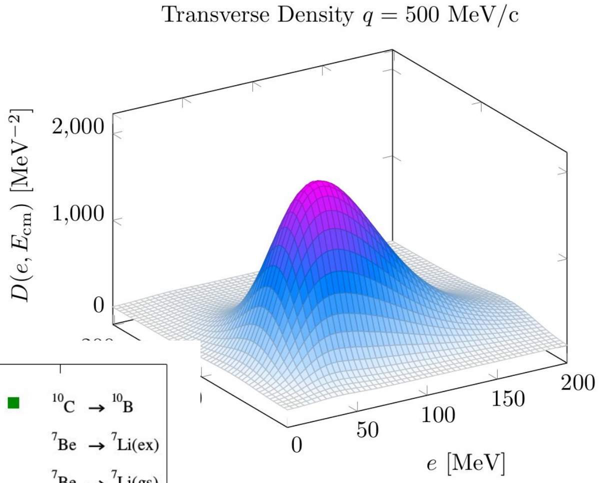
Radiative corrections receive contributions from the QE region

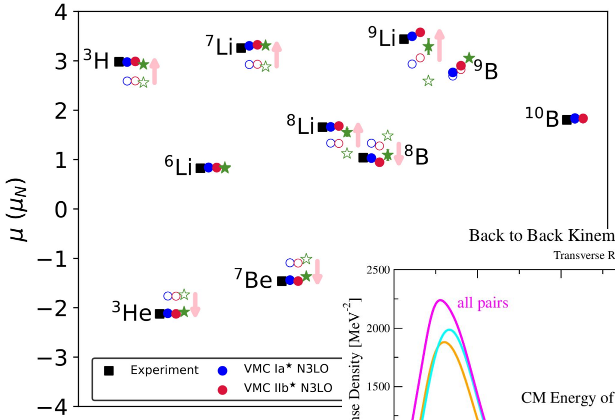
$$\frac{\log 2}{ft} = \frac{G_F^2 m_e^5 |V_{ud}|^2}{\pi^3}(1 + \Delta_R^V + \delta_R' + \delta_{NS} - \delta_C)$$

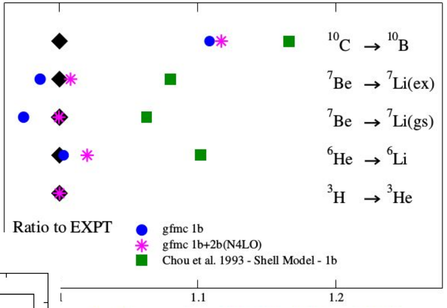


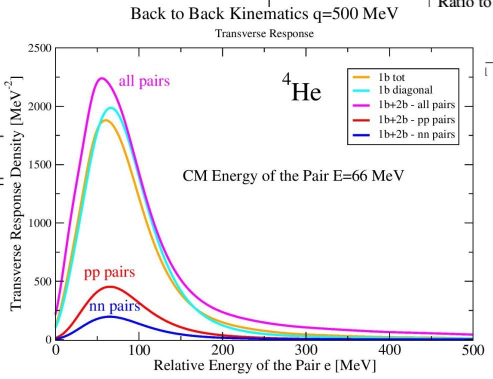
Summary

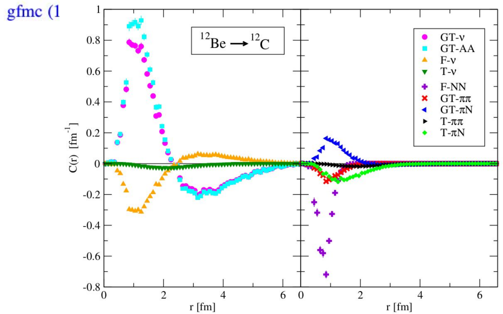
Ab initio calculations of light nuclei yield a picture of nuclear structure and dynamics where many-body effects play an essential role to explain available data.











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!

Collaborators

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

Washington University in St. Louis Arts & Sciences
U.S. Department of Energy INCITE Leadership Computing
NUCLEI Nuclear Computational Low-Energy Initiative
A SciDAC-5 Project
NTNP
U.S. Department of Energy Office of Science
McDonnell Center for the Space Sciences
Fermilab

Nuclear Theory for New Physics NP&HEP TC

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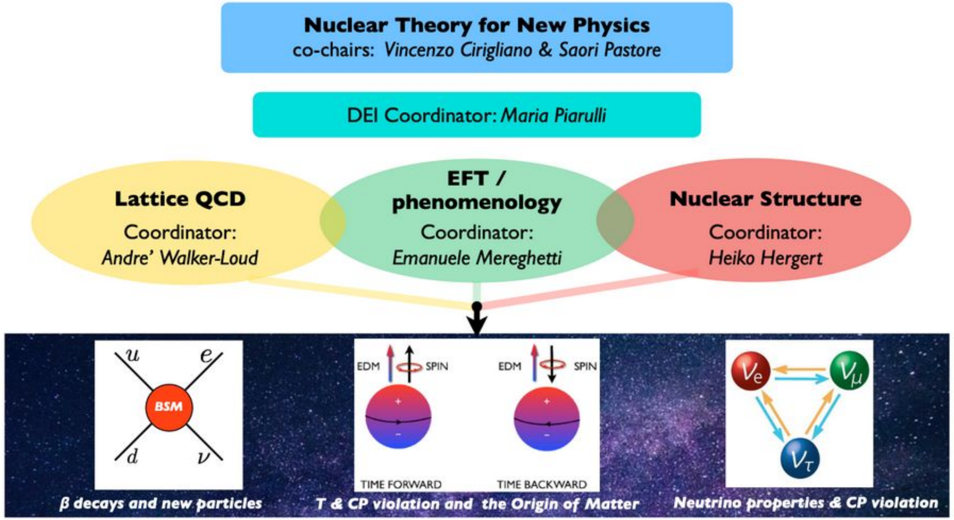
- Commitment to Diversity
- Funding Acknowledgement



Funding Acknowledgement

We are funded in part through The Department of Energy, Office of Science, Office of Nuclear Physics and the Office of High Energy Physics

NTNP

Snowmass:
Topical groups and Frontier Reports, Whitepapers, …

LRP:
White papers, 2301.03975, FSNN, …