Nuclei as a laboratory for beyond the Standard Model physics

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International School of Nuclear Physics
45th Course
Nuclei in the Laboratory and in Stars
Erice-Sicily
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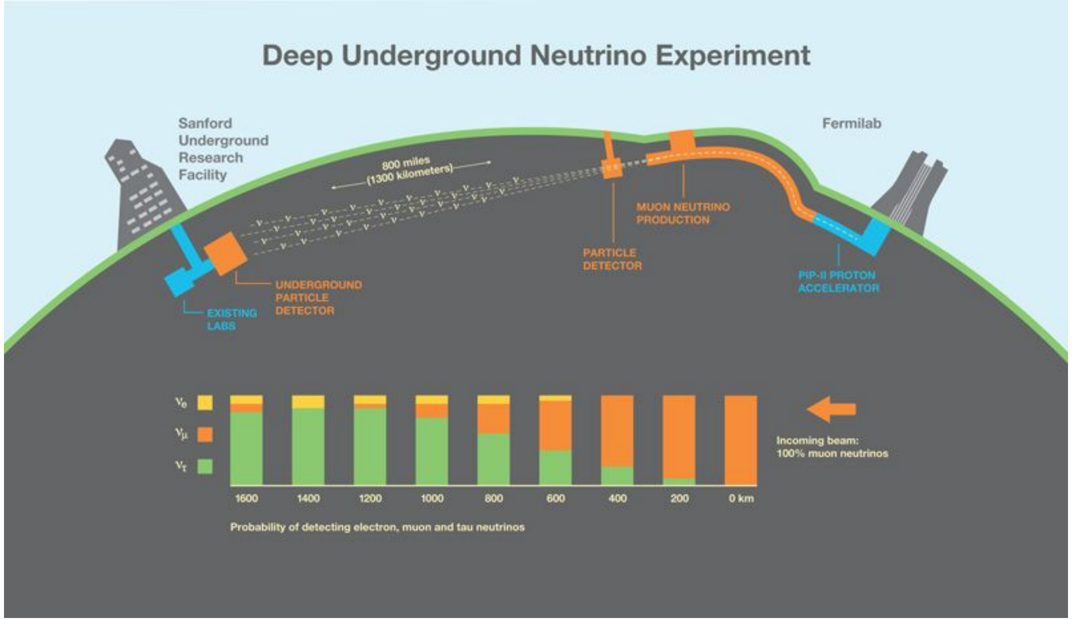
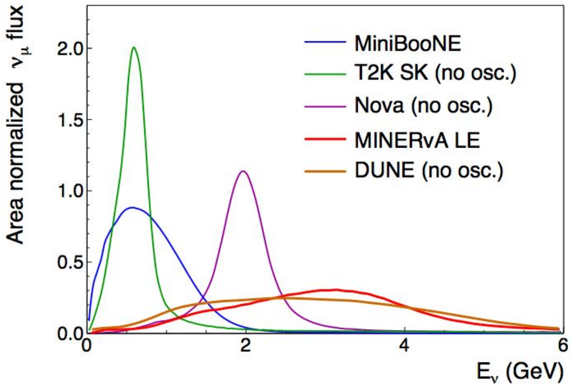
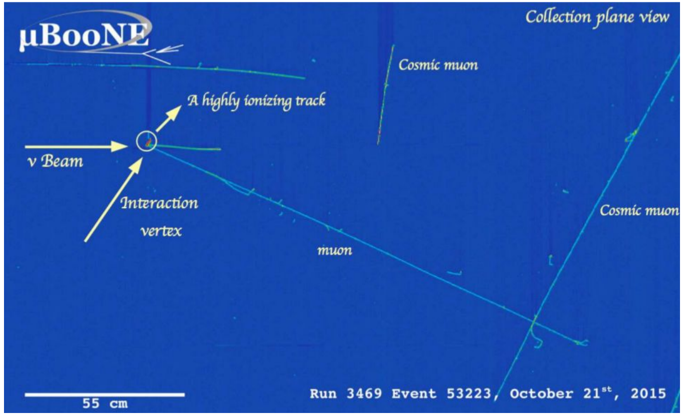
Blackett Institute (San Domenico)

Accelerator Neutrinos' Experiments

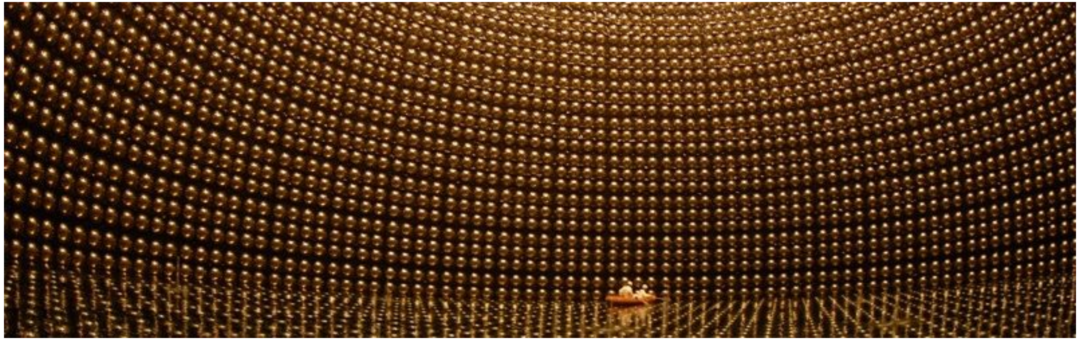


DUNE - Fermilab

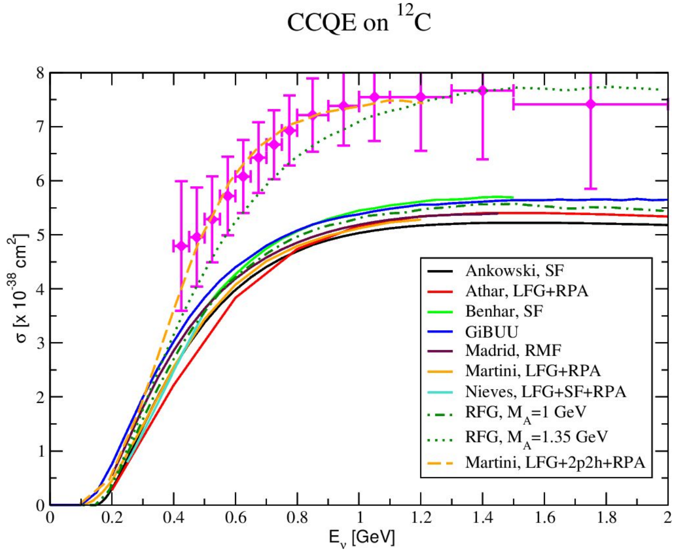




Nuclei for Neutrino Oscillations' Experiments

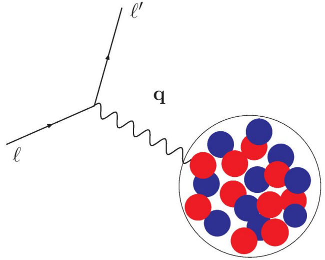


Neutrino-^{12}C cross section



Alvarez-Ruso arXiv:1012.3871

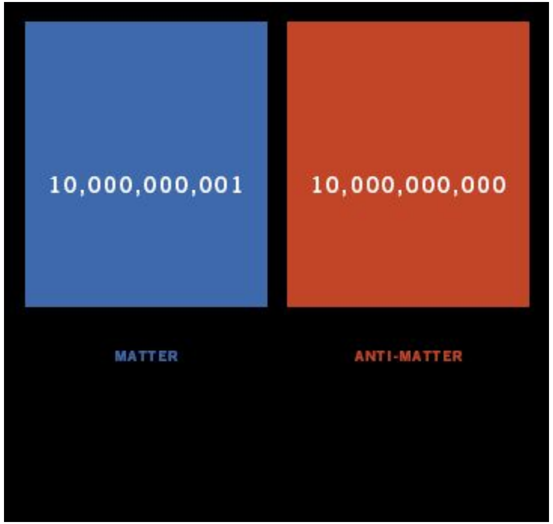
$$P(\nu_\mu \rightarrow \nu_e) = sin^2 2\theta sin^2 \left(\frac{\Delta m_{21}^2 L}{2E_\nu} \right)$$



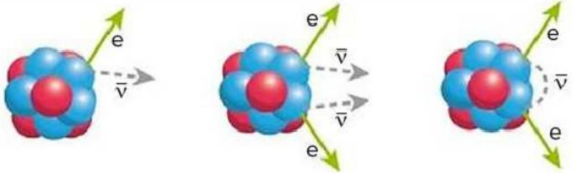
Nuclei are the active material in the detectors

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

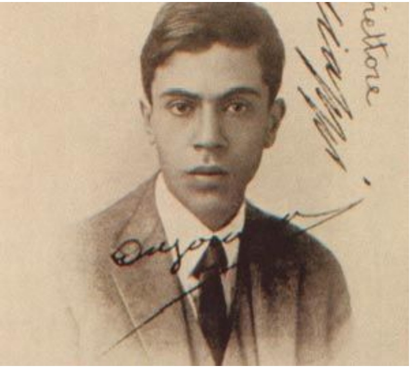
Neutrinoless double beta decay



Hitoshi Murayama



2015 Long Range Plan for Nuclear Physics

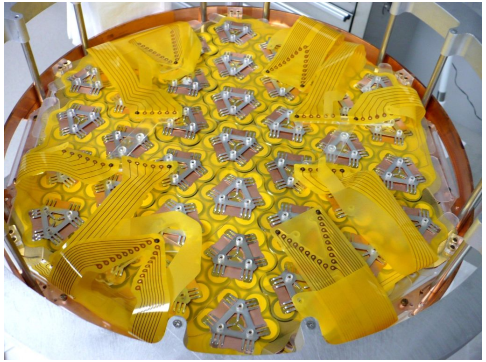


Ettore Majorana

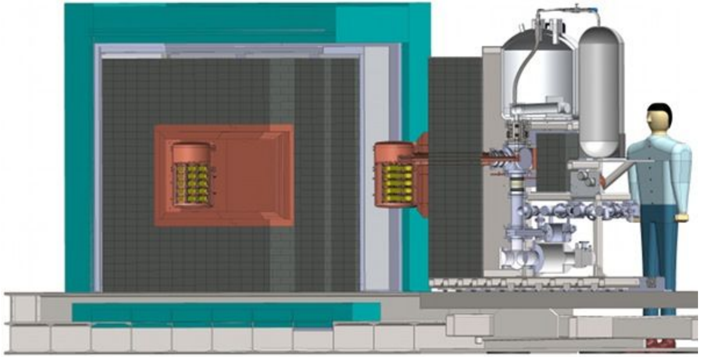
$$(Z, N) \rightarrow (Z+2, N-2) + 2e$$

Here the lepton number is not conserved

Nuclear Physics for Neutrinoless Double Beta Programs



EXO-200 Collaboration



Majorana Demonstrator

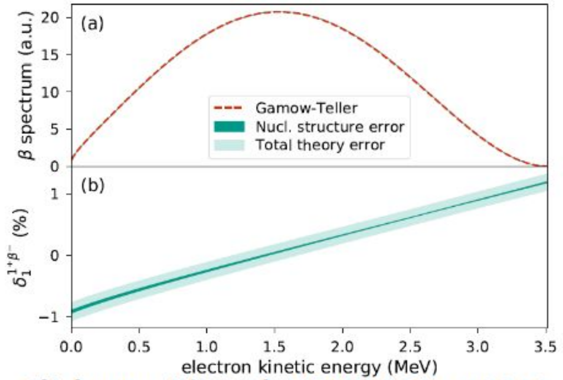
Neutrinoless double beta decay half-life $T_{1/2} \gtrsim 10^{25}$ years (age of the universe 1.4×10^{10} years)
1 ton of material is required to see few events per year

Decay Rate $\propto$ (**nuclear matrix element**)^2 x $(m_{\beta\beta})^2$

Beta decay spectrum

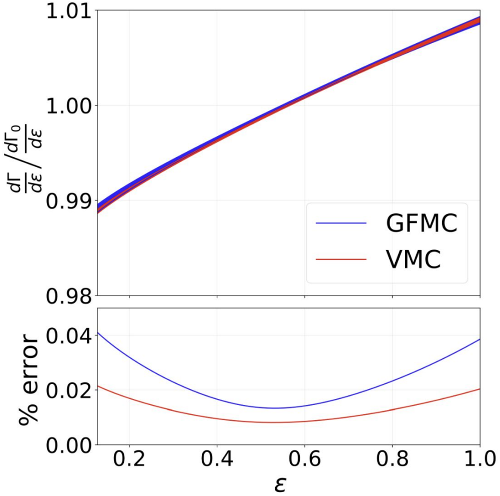
^{6}He Beta decay spectrum for BSM searches with NCSL, He6-CRES, LPC-Caen

^{6}He beta-decay spectrum from NCSM



Glick-Magid et al. arXiv:2107.10212

Standard Model spectrum for ^{6}He

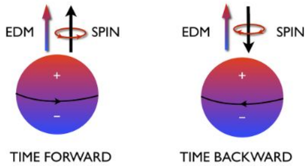


$$\varepsilon = \frac{E_e}{\omega}$$

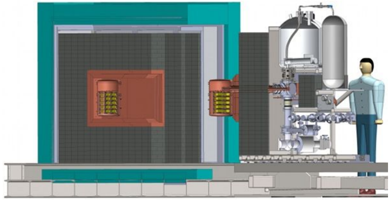
King, Mereghetti, SP et al. PRC22

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

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

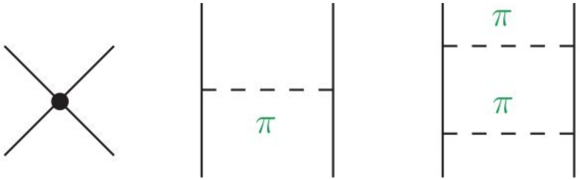
- EDMs, Hadronic PV, ...
- BSM searches with beta decay, ...
- Neutrinoless double beta decay, ...
- Neutrino-Nucleus Scattering Cross Sections, ...
- ...

Many-body Nuclear Interactions

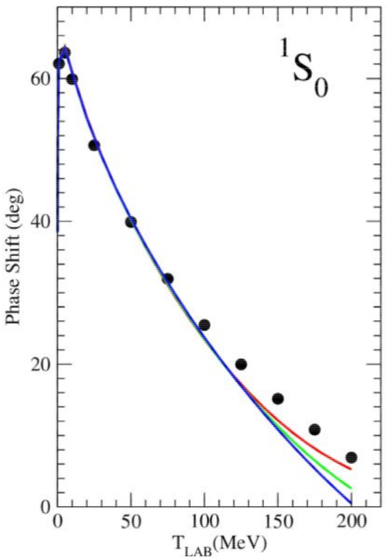
Many-body Nuclear Hamiltonian

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

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



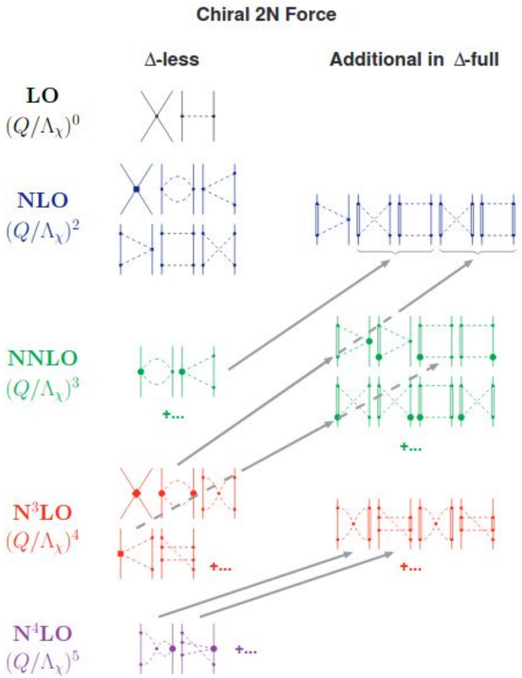
SP et al. PRC80(2009)034004

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

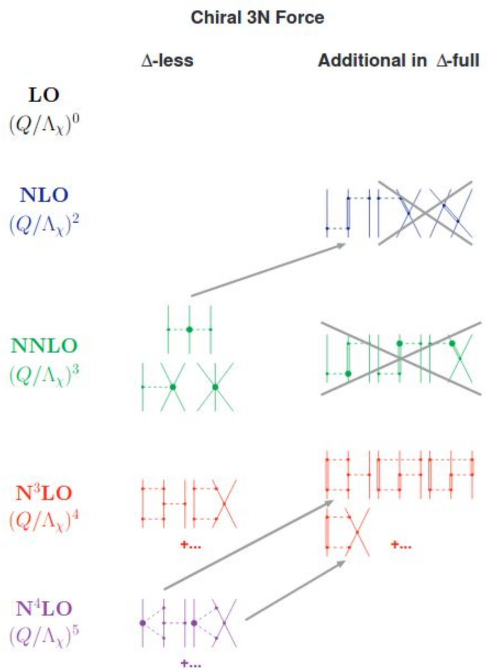
NV2: two-body

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

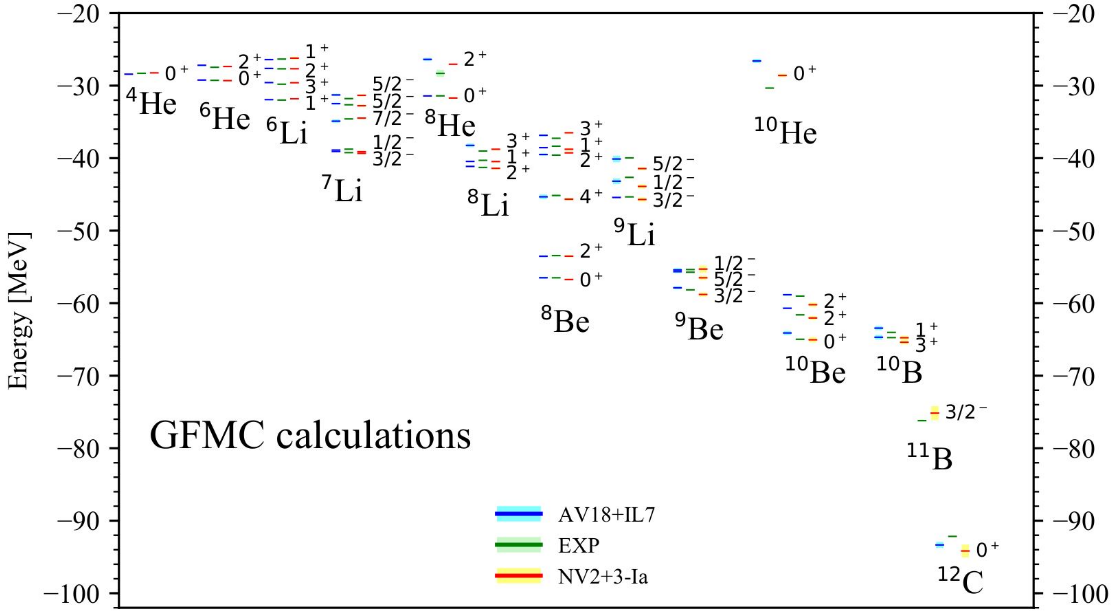
2 LECs

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



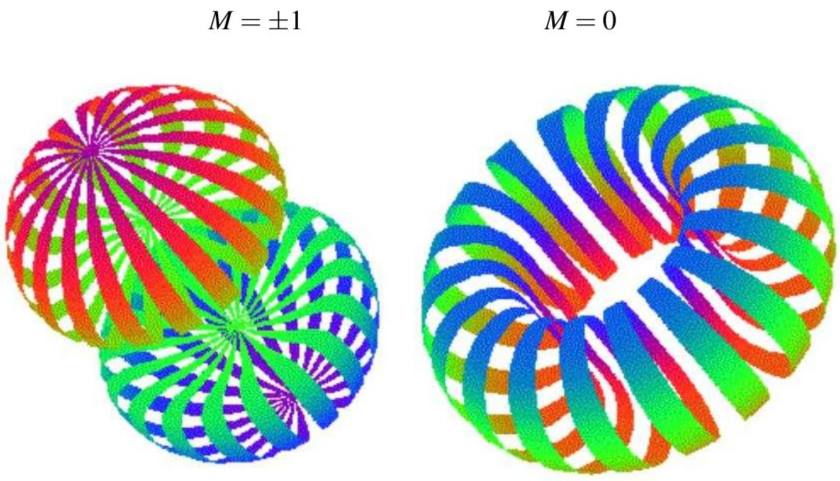
Figs. credit Entem and Machleidt Phys.Rept.503(2011)1

Energies



Piarulli *et al.* PRL120(2018)052503

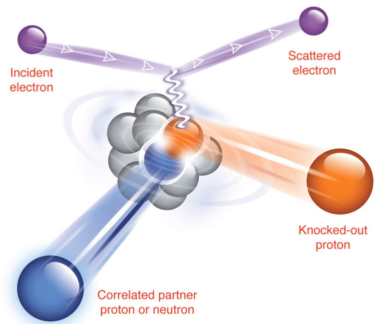
Two-nucleon correlation & the deuteron shape

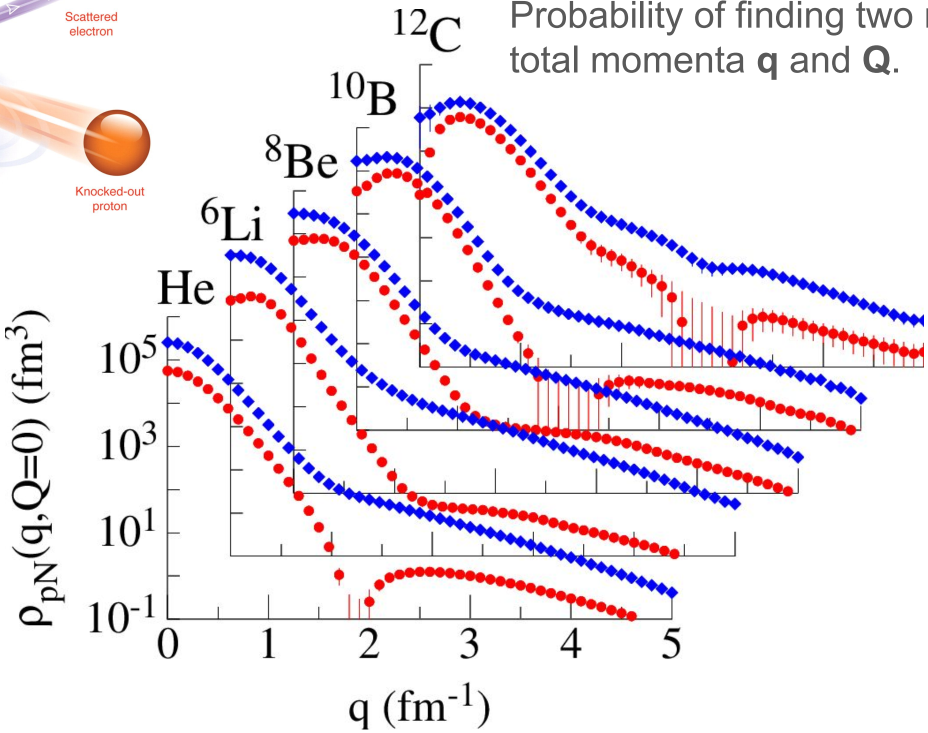


Constant density surfaces for a polarized deuteron in the $M = \pm 1$ (left) and $M = 0$ (right) states

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

Two-nucleon correlations & momentum distributions





pp-pairs; np-pairs

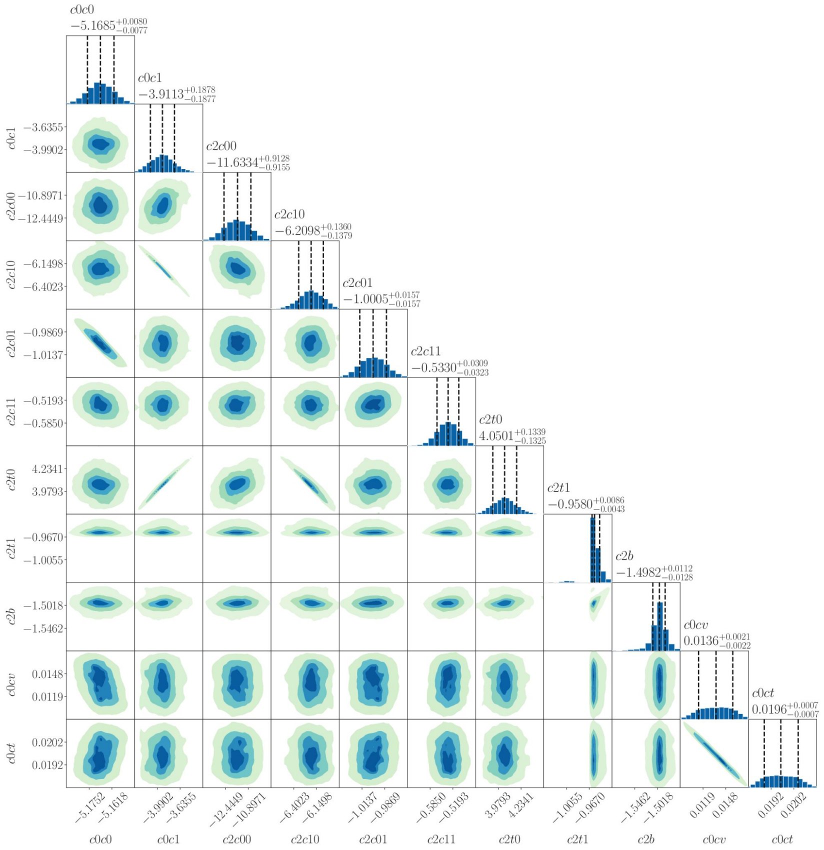
Probability of finding two nucleons with relative and total momenta **q** and **Q**.

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)

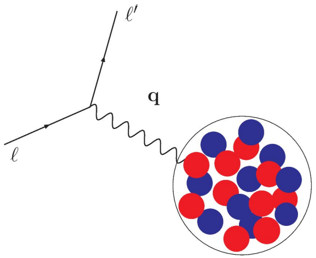
Optimization of Nuclear Two-body Interactions



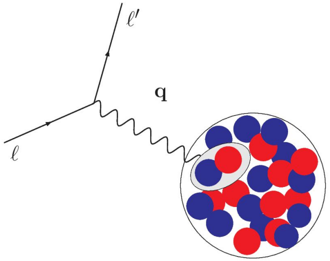
Development and Optimization of two-body interactions based on Bayesian methods

Jason Bub *et al.* arxiv:2408.02480 2024

Many-body Nuclear Electroweak Currents



one-body



two-body

Nuclear Charge Operator

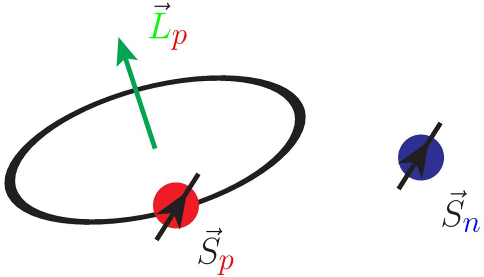
$$\rho = \sum_{i=1}^{A} \rho_i + \sum_{i<j} \rho_{ij} + \ldots$$

Nuclear (Vector) Current Operator

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

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

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



Magnetic Moment: Single Particle Picture

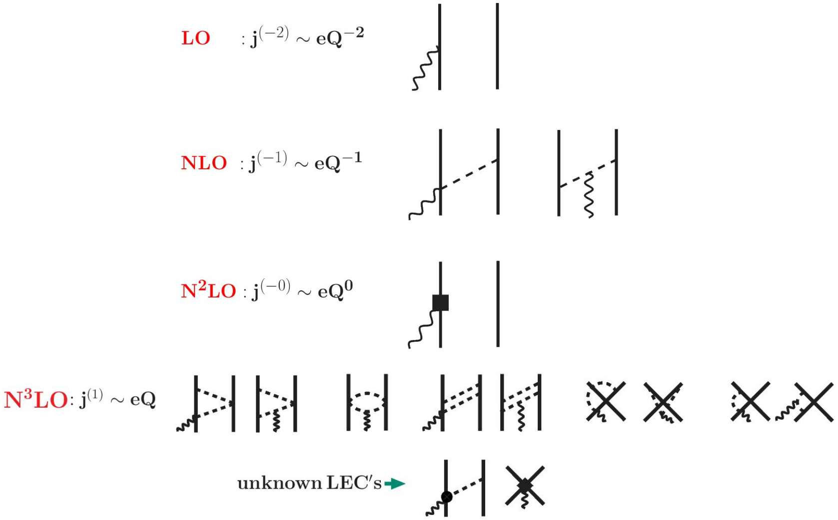
Many-body Currents

- **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**

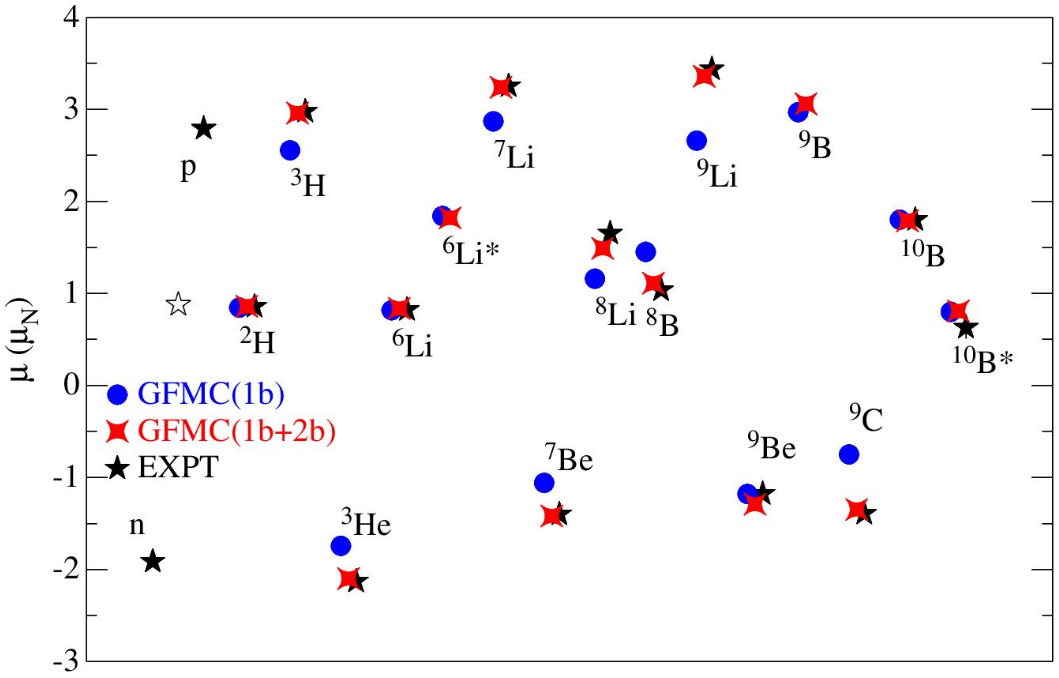
Are constructed consistently with the two-body chiral potential; Unknown parameters, or Low Energy Constants (**LECs**), need to be **determined by either fits to experimental data or by Lattice QCD calculations**



Electromagnetic Current Operator

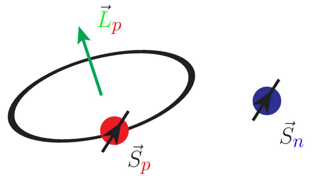
SP *et al.* PRC78(2008)064002, PRC80(2009)034004, PRC84(2011)024001, PRC87(2013)014006
Park *et al.* NPA596(1996)515, Phillips (2005)
Kölling *et al.* PRC80(2009)045502 & PRC84(2011)054008

Magnetic Moments of Light Nuclei



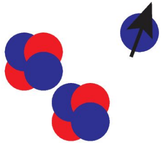
SP *et al*. PRC87(2013)035503

Single particle picture



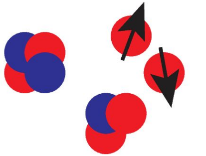
$$\mu_N(1\mathrm{b}) = \sum_i [(L_i + g_p S_i)(1+\tau_{i,z})/2 + g_n S_i (1-\tau_{i,z})/2]$$

Small two-body current effects



^9Be

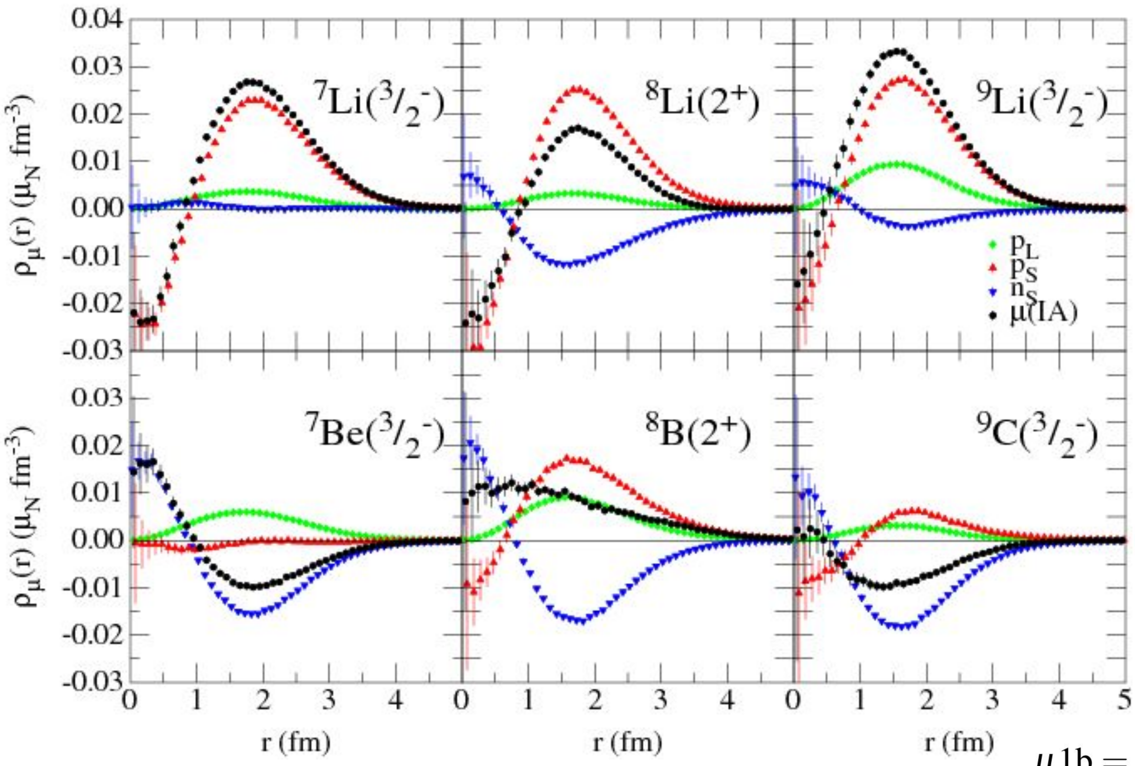
Large two-body currents ~40%



^9C

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

One-body magnetic density

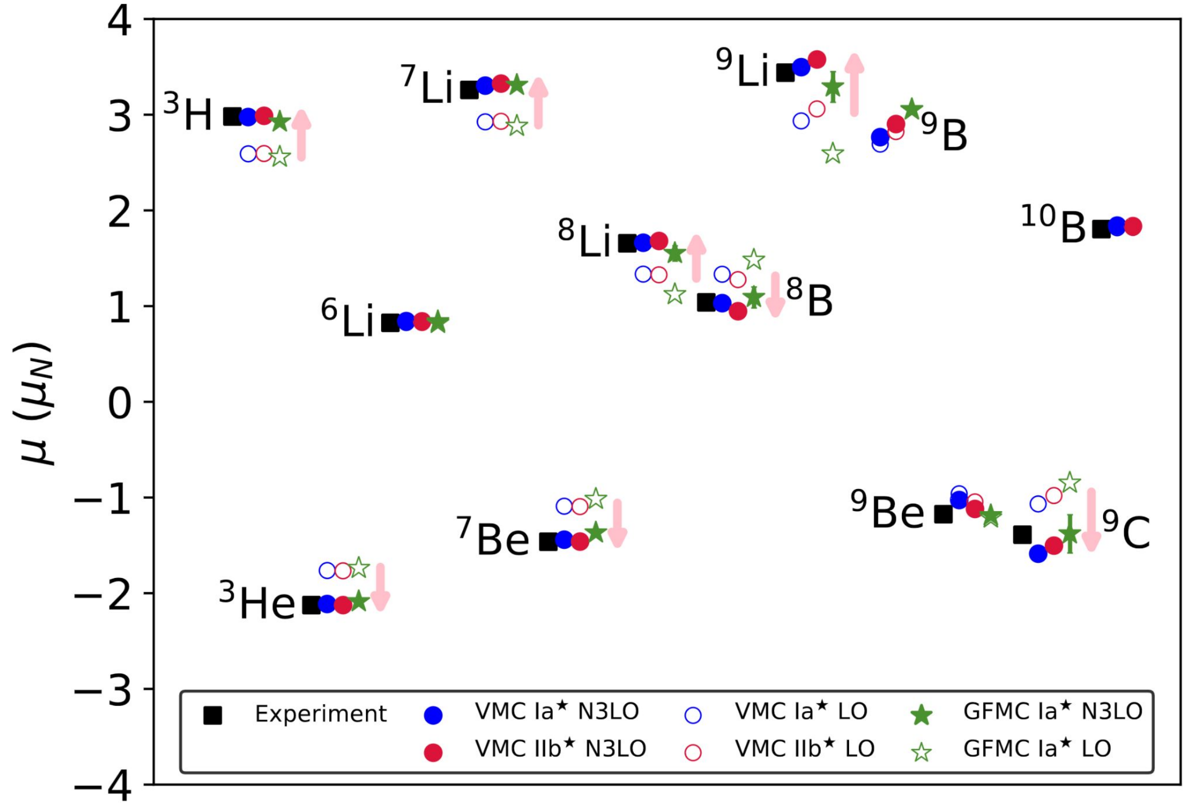


$$\mu^{1b} \propto \int \rho_M^{1b}(r)dr$$

r single particle coordinate from the c.m.

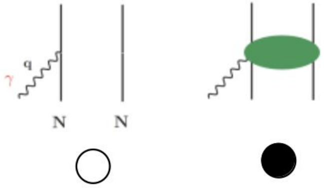
$$\mu 1\text{b} = \mu_N \sum_i [(L_i + g_p S_i)(1+\tau_{i,z})/2 + g_n S_i (1-\tau_{i,z})/2]$$

Magnetic moments in light nuclei

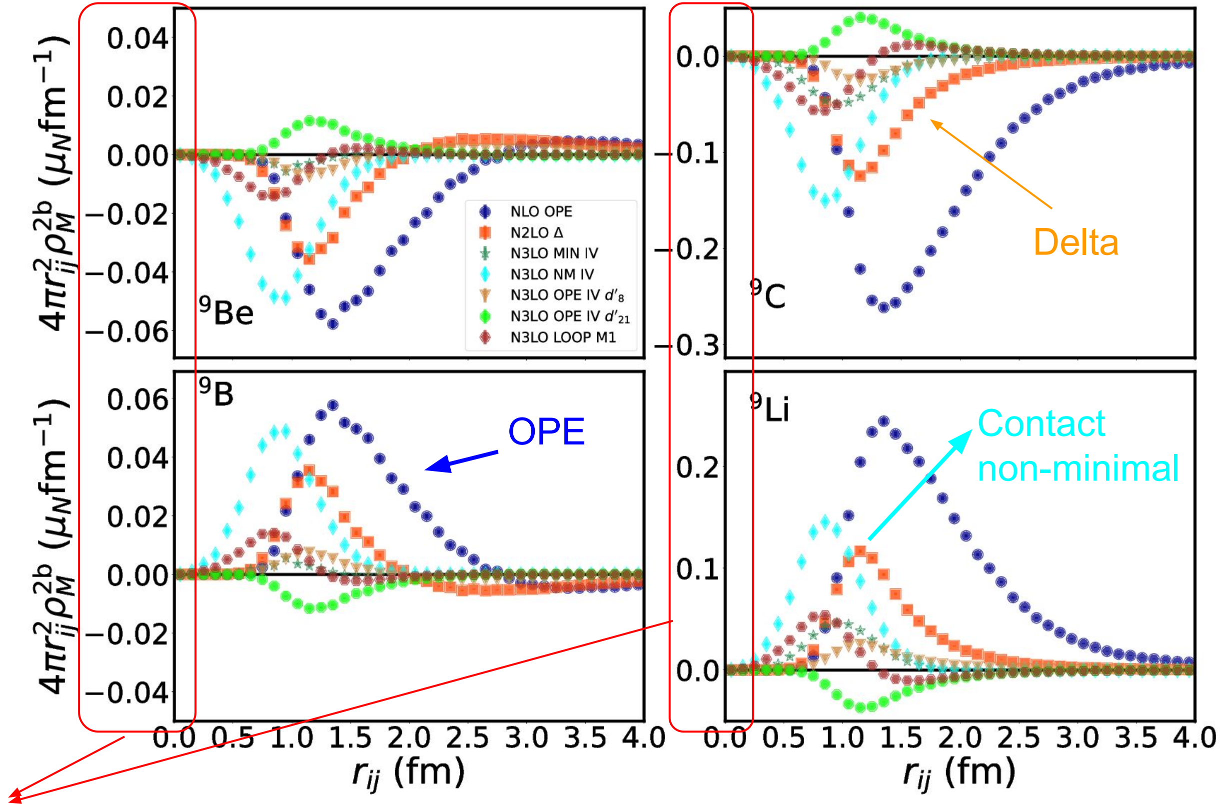


Chambers-Wall, King, Gnech et al. PRL 2024 [2407.03487]

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



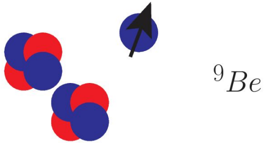
Two-body magnetic densities



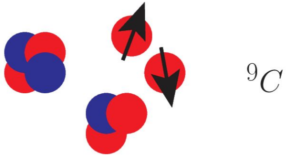
Note the scale

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

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



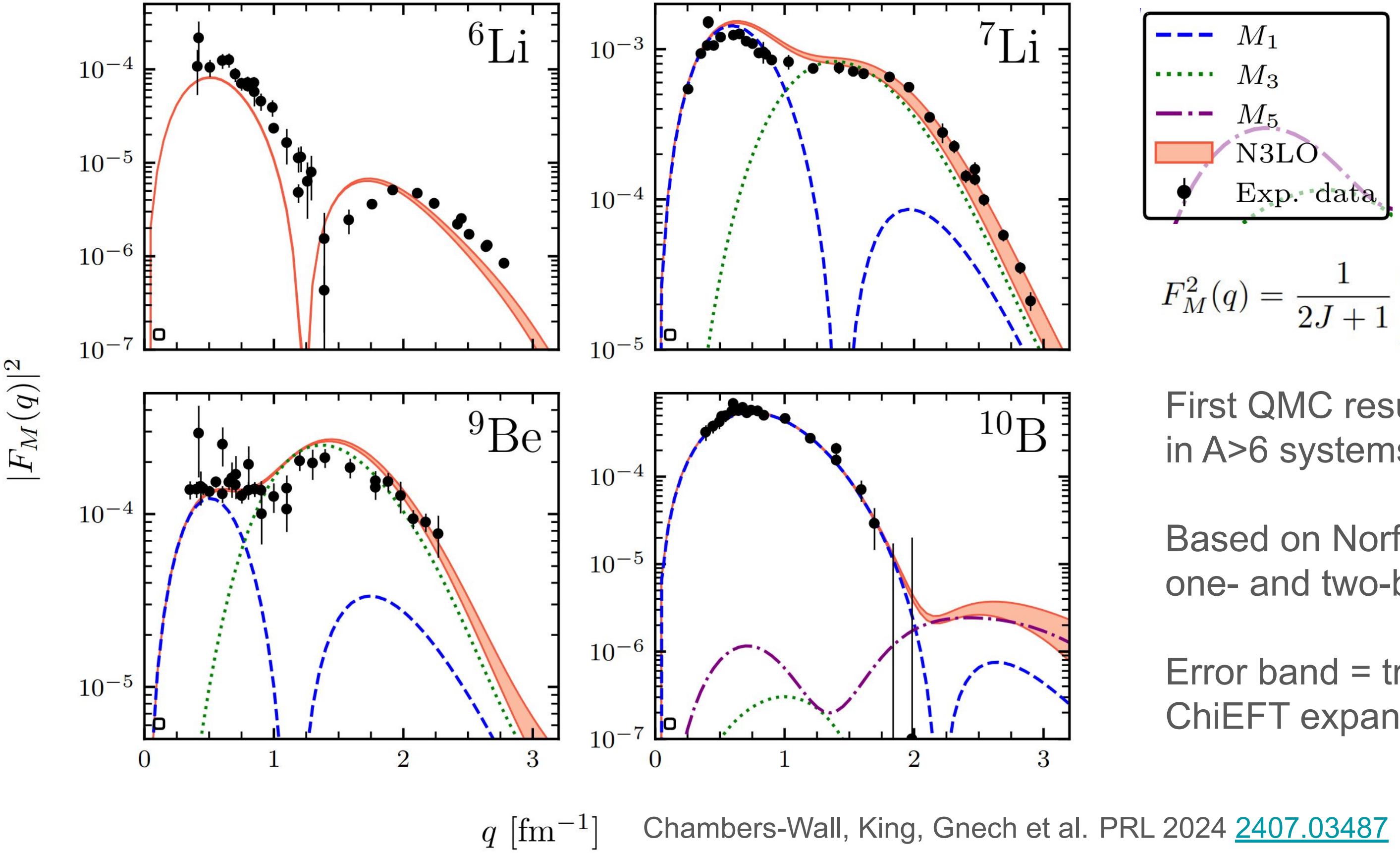
$[441] = [\alpha, \alpha, n(p)]$



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

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

Magnetic form factors: comparison with the data



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

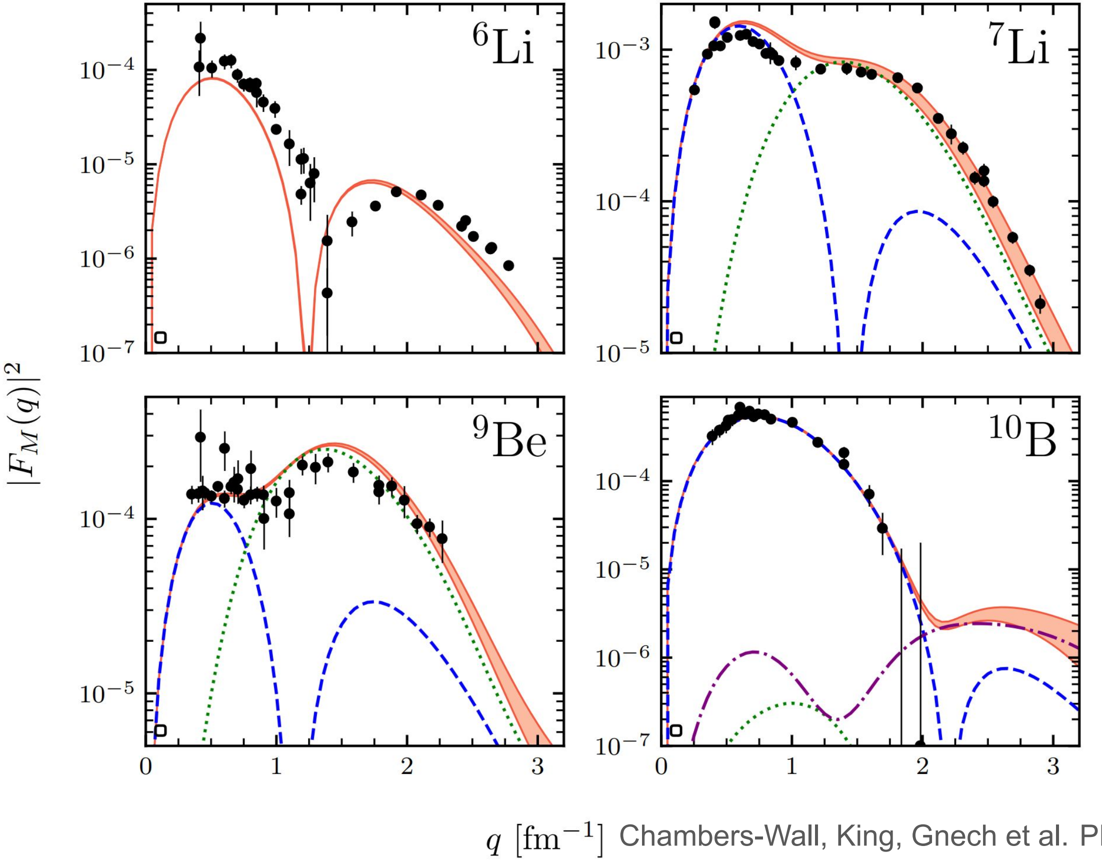
First QMC results for form factors in A>6 systems.

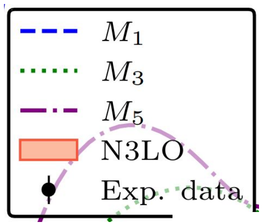
Based on Norfolk interactions and one- and two-body currents.

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

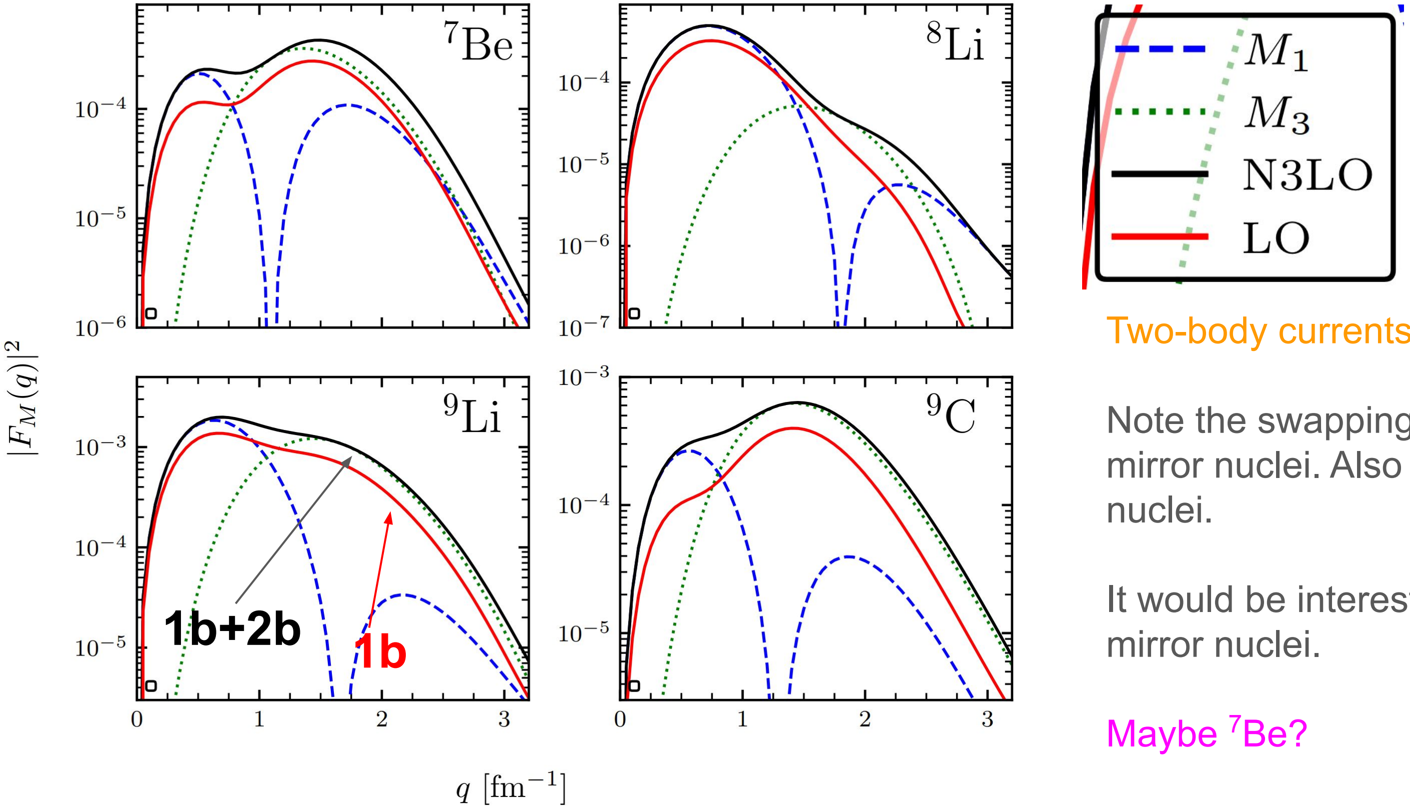




Chambers-Wall, King, Gnech et al. PRL 2024 2407.03487

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%.

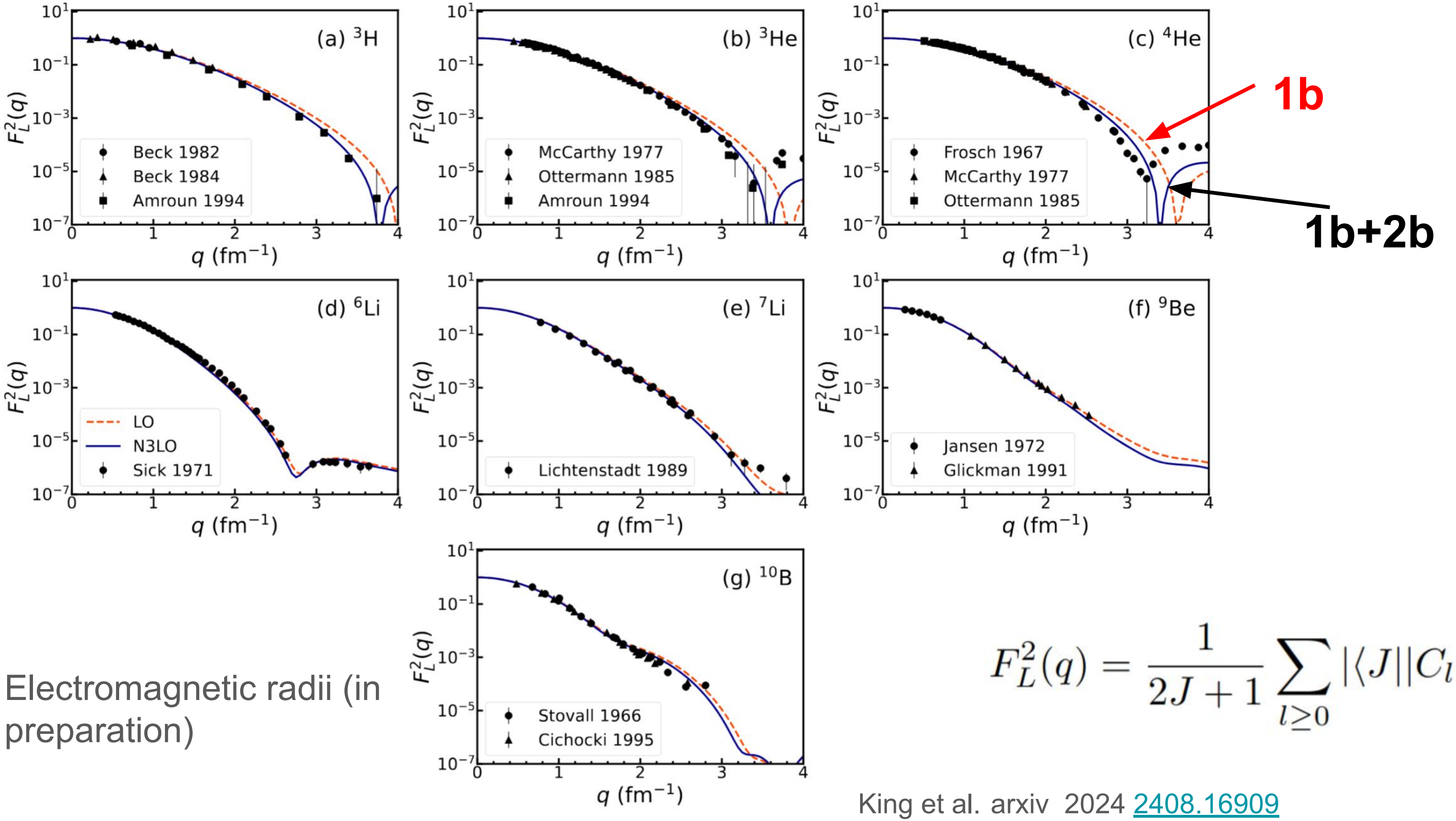
Note the swapping of M1 and M3 in mirror nuclei. Also observed in A=7 nuclei.

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



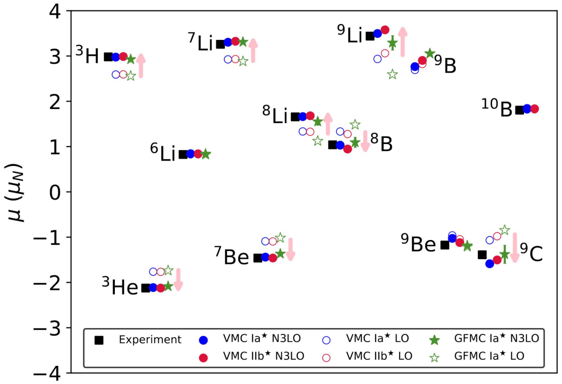
Electromagnetic radii (in preparation)

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

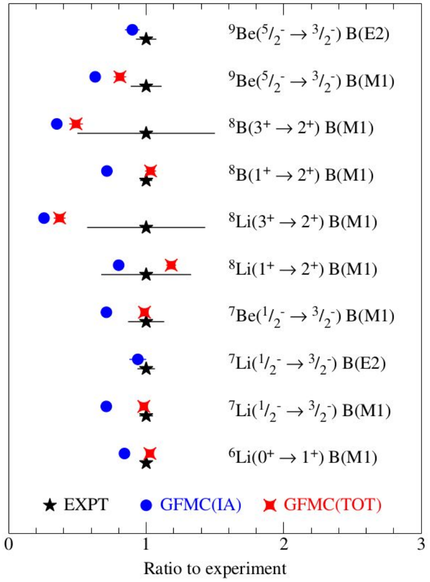
King et al. arxiv 2024 2408.16909

Electromagnetic Observables

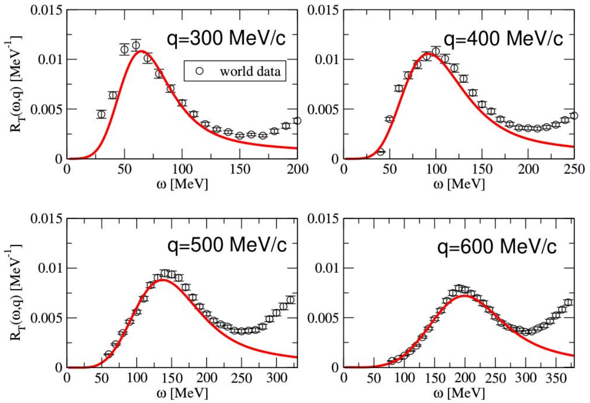
Magnetic moments



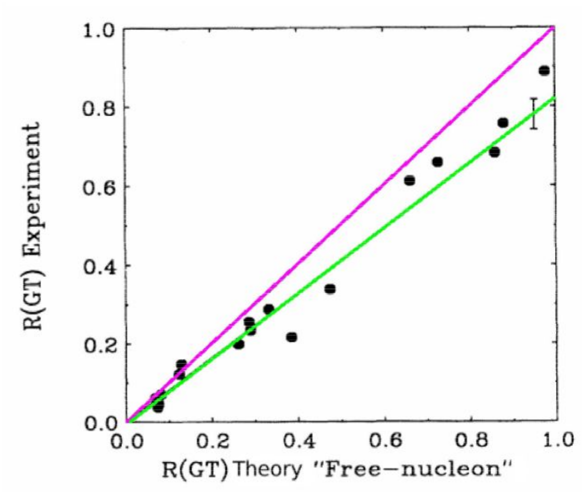
EM decay



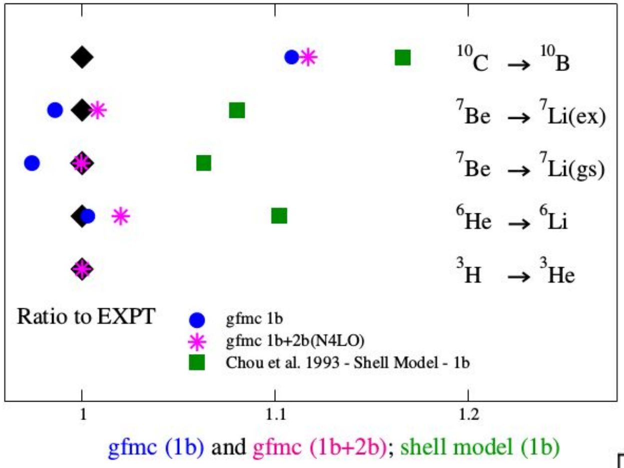
e-^{4}He particle scattering



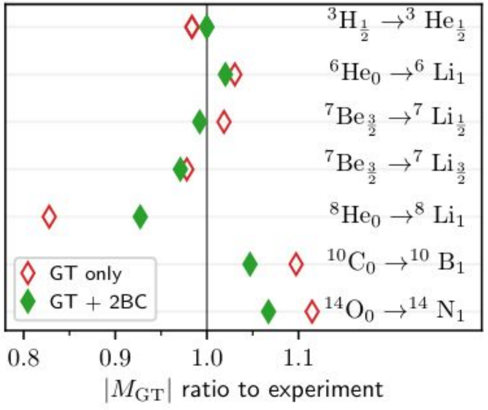
Beta decay



Chou et al. PRC47(1993)163

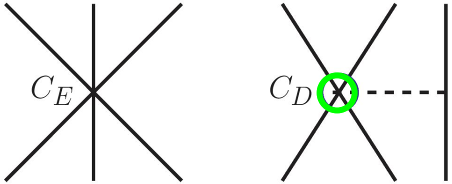


SP *et al*. PRC97(2018)022501

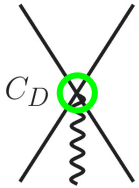


P. Gysbers *Nature Phys.* 15 (2019)

Three-body Force and the Axial Contact Current



Three-body force



Axial two-body contact current

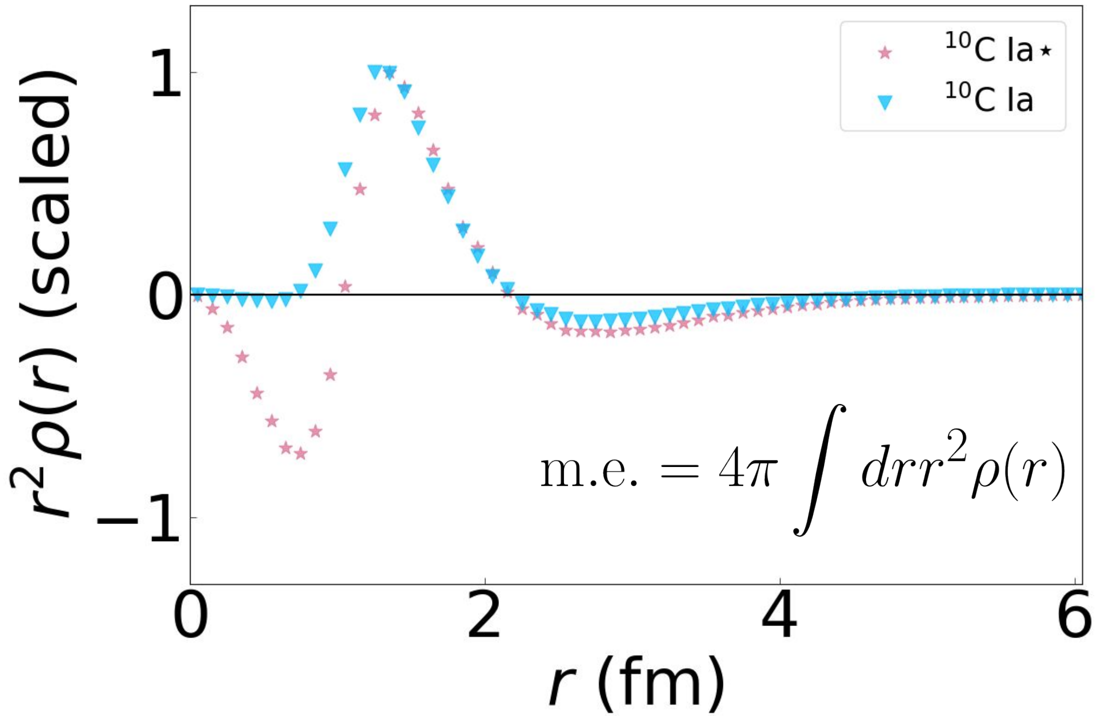
LECs c_D and c_E are fitted to:

- **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.

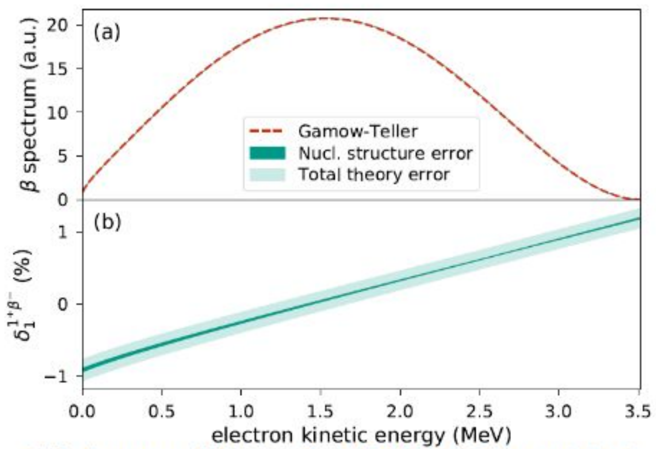
Garrett King *et al.* PRC102(2020)025501

Beta decay spectrum

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

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:

$$\frac{d\Gamma_\beta}{dE_e} = \frac{d\Gamma_0}{dE_e}\left[1 + \boxed{b}\frac{m_e}{E_e}\right]$$

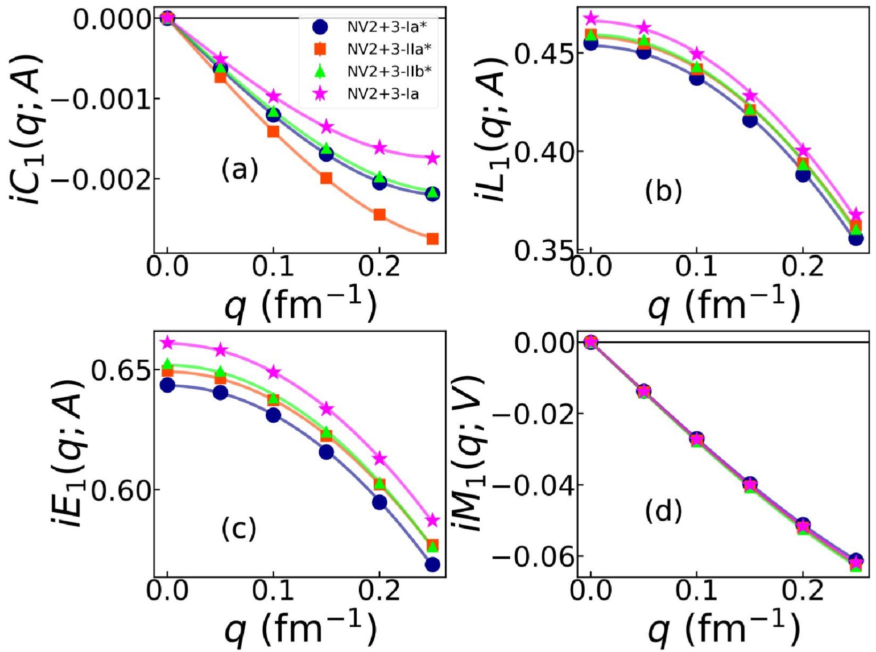
SM (q→0):

$$b = 0$$

SM (with recoil):

$$b = 0 + \Delta b$$

Beta Decay Spectrum



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

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

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

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

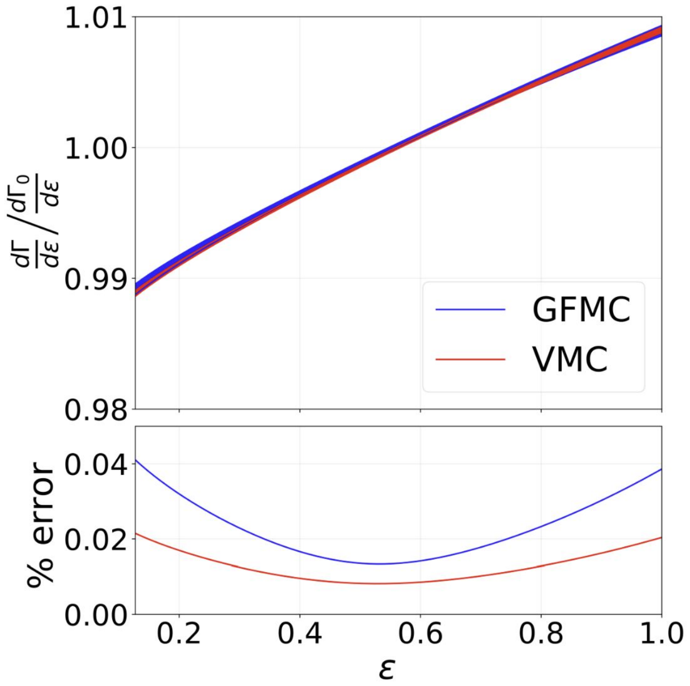
Model dependencies determined with the Norfolk interactions and one- plus two-body currents.

Garrett King et al. PRC (2023)

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

Beta Decay Spectrum

Standard Model spectrum for ^6He



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

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)

Partial muon capture rates: VMC calculations

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

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

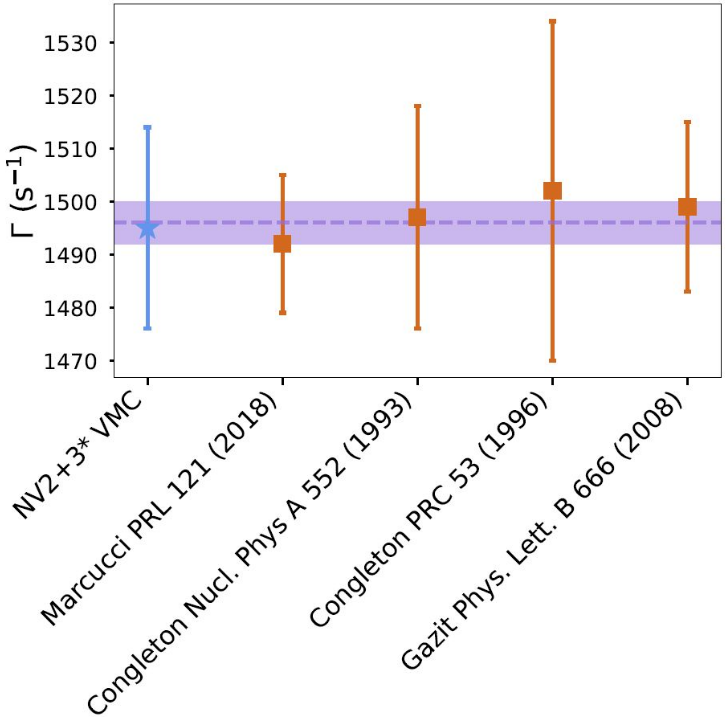
Ackerbauer *et al.* PLB417, 224(1998)

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

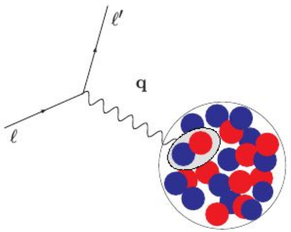
Lepton-Nucleus scattering: Inclusive Processes

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

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

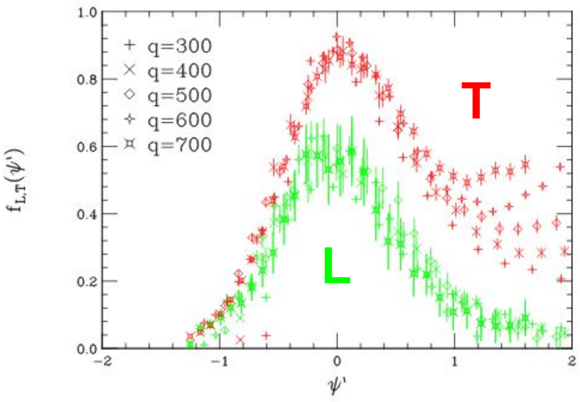


For a recent review on QMC, SF methods see
Rocco *Front. In Phys.*8 (2020)116

Lepton-Nucleus scattering: Data

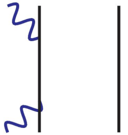
Transverse Sum Rule

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



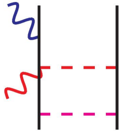
^{4}He Electromagnetic Data
Carlson *et al.* PRC65(2002)024002

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



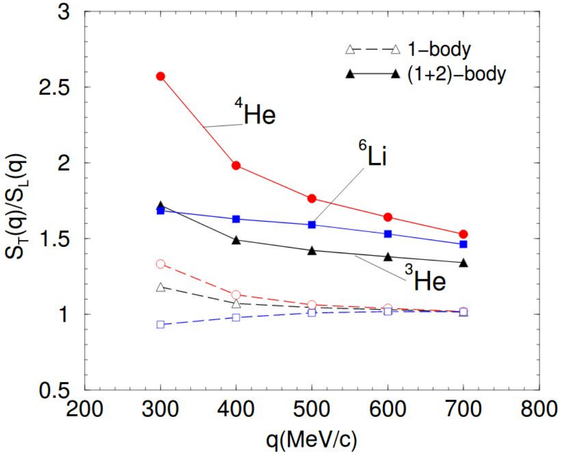
$\langle \mathbf{j}_{1b}^\dagger \;\; \mathbf{j}_{1b}\rangle \;\; > 0$

Leading one-body term



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

Interference term

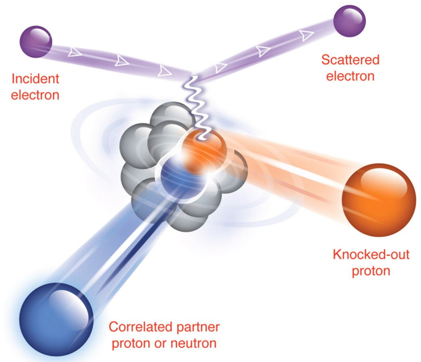


Transverse/Longitudinal Sum Rule
Carlson *et al.* PRC65(2002)024002

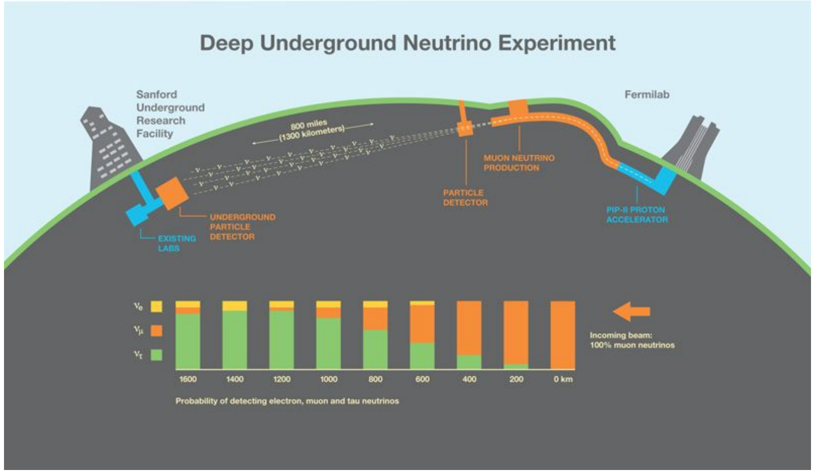
Beyond Inclusive: Short-Time-Approximation

Short-Time-Approximation Goals:

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



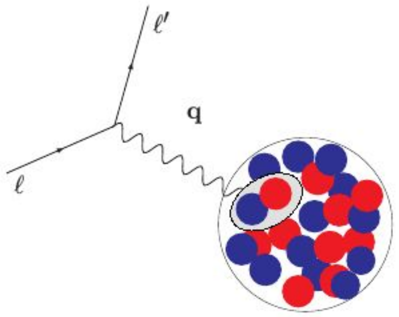
Subedi et al. Science320(2008)1475



[Stanford Lab article]

[e4u collaboration]

Short-Time-Approximation



Short-Time-Approximation:

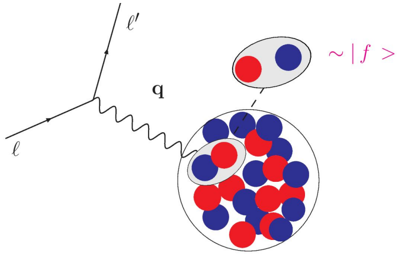
- Based on Factorization
- Retains two-body physics
- Correctly accounts for interference

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

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

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

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

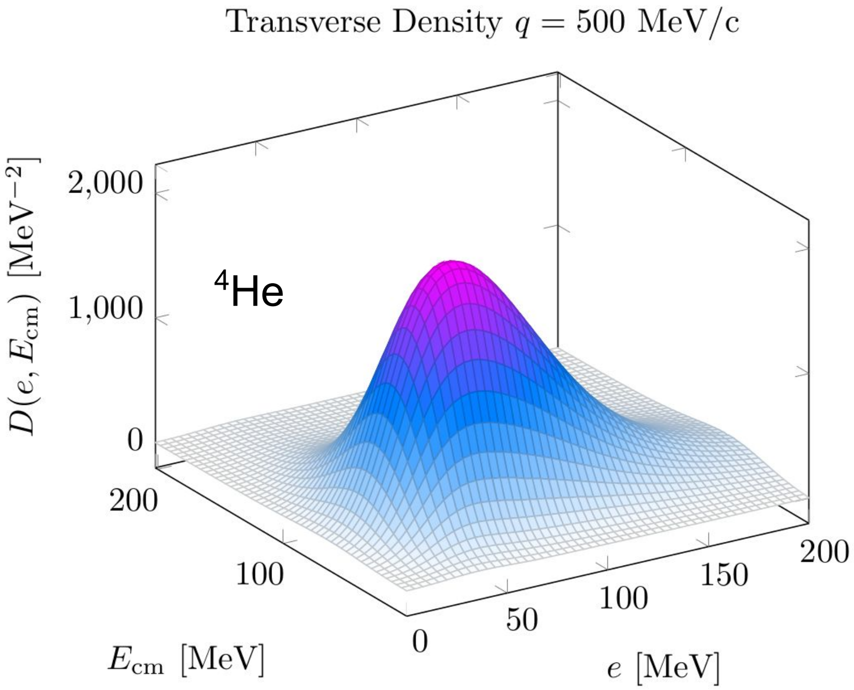
$$R_\alpha(q,\omega) = \sum_f \delta\left(\omega + E_0 - E_f\right) |\langle f|O_\alpha(\mathbf{q})|0\rangle|^2$$

Response ***Densities***

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

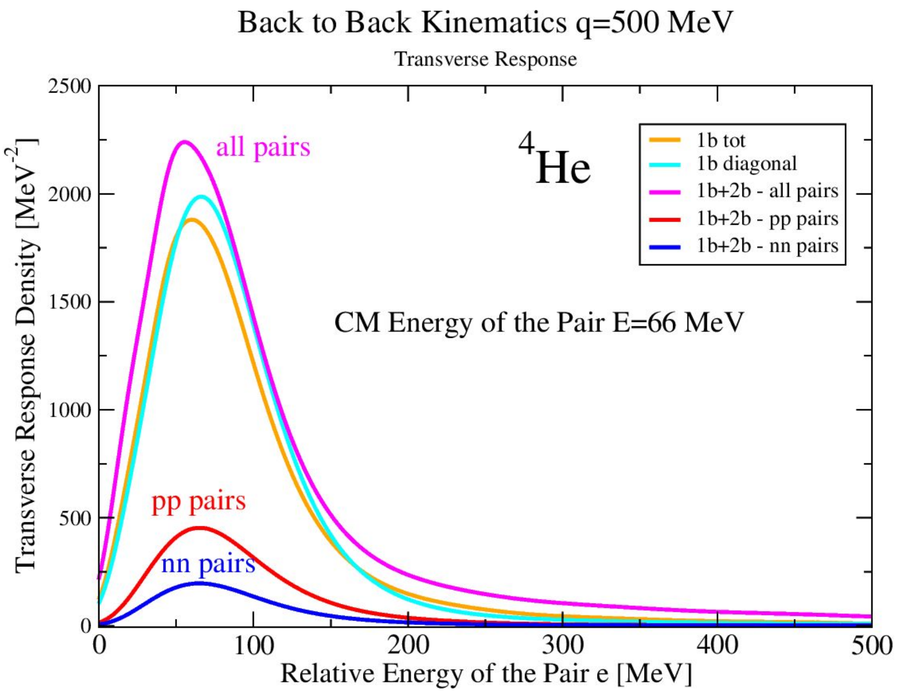
P' and *p'* are the CM and relative momenta of the struck nucleon pair

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



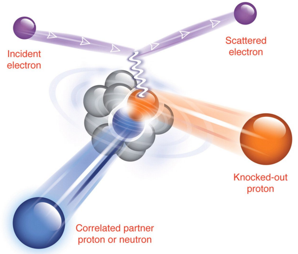
SP *et al.* PRC101(2020)044612

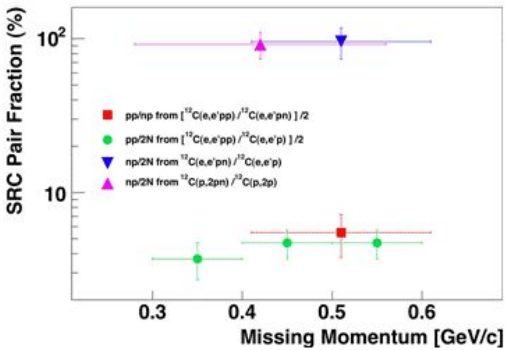
e-^{4}He scattering in the back-to-back kinematic



SP *et al.* PRC101(2020)044612

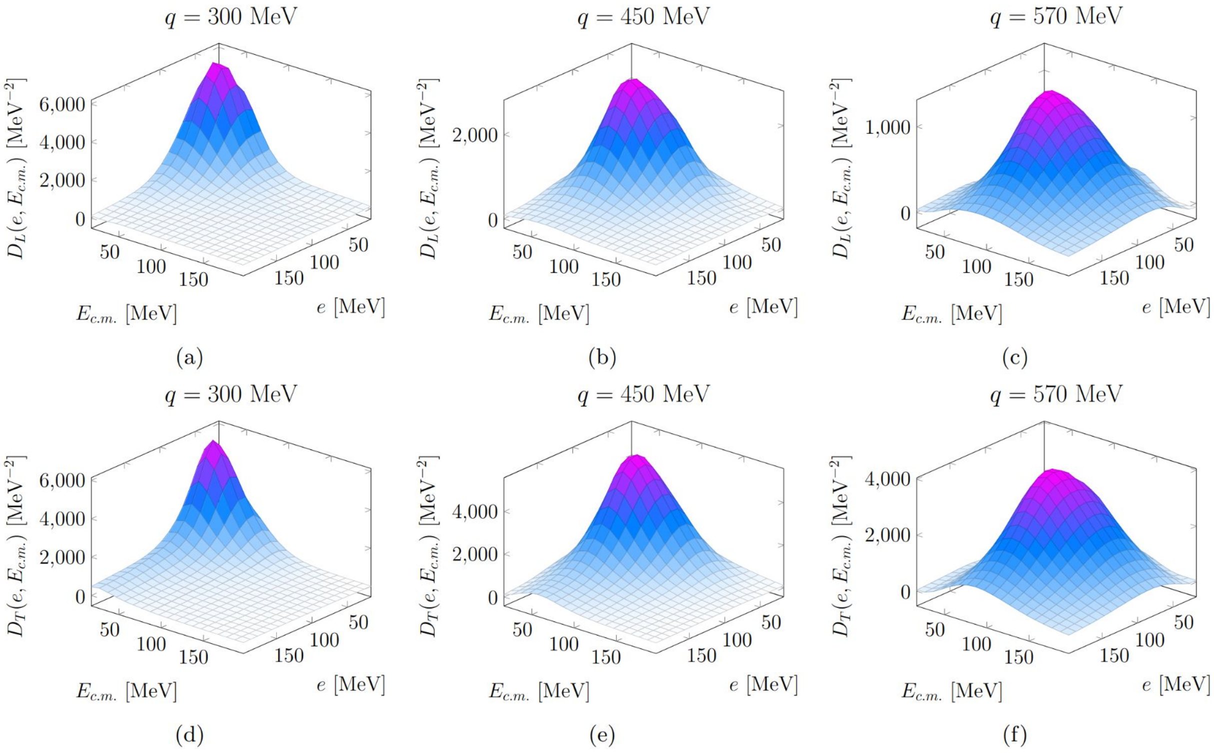
- pp pairs
- nn pairs
- all pairs 1body
- all pairs tot





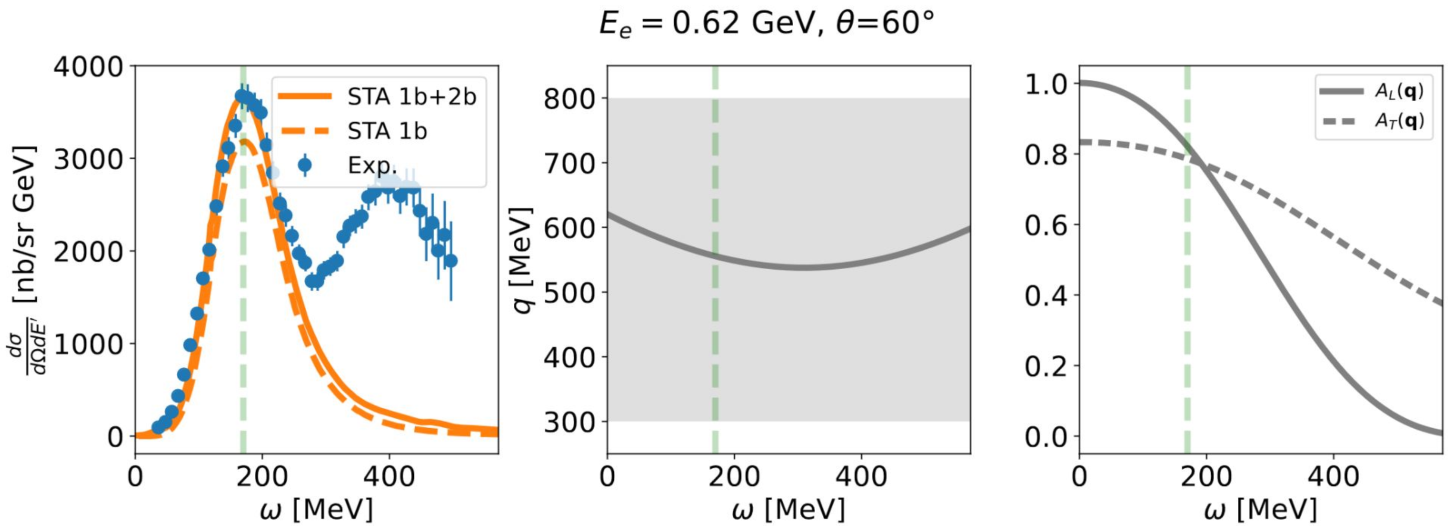
Subedi et al. Science320(2008)1475

^{12}C Response Densities



Lorenzo Andreoli *et al.* arXiv:2407.06986 2024

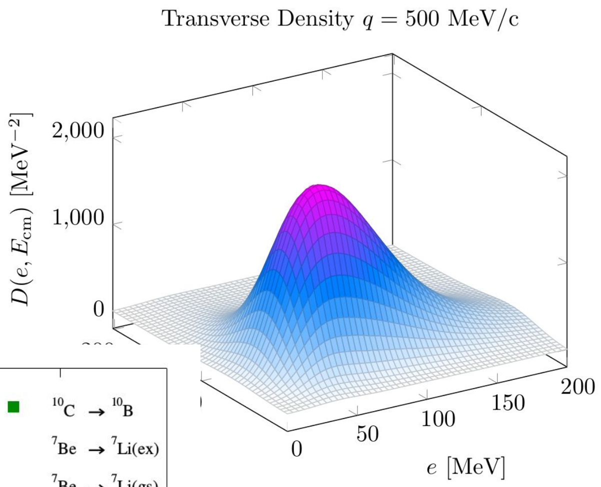
^{12}C cross sections

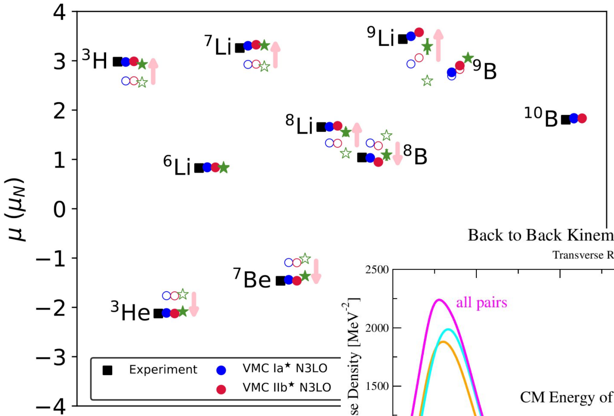


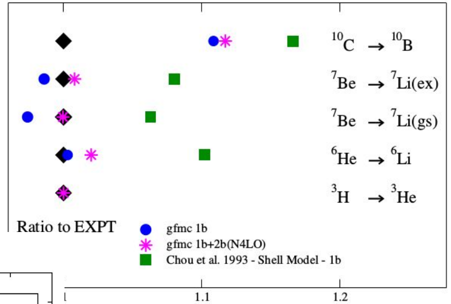
Lorenzo Andreoli *et al.* arXiv:2407.06986 2024

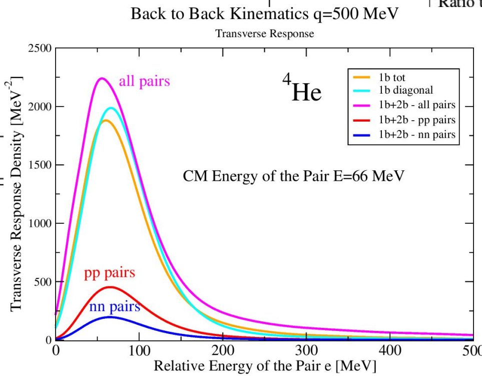
Summary

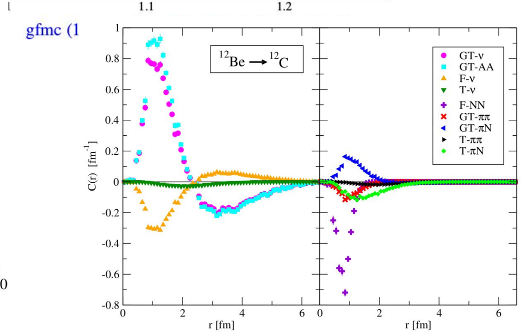
Ab initio calculations of light nuclei yield a picture of nuclear structure and dynamics where many-body effects play an essential role to explain available data.











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 Novario Piarulli**
LANL: Carlson Gandolfi King Hayes Mereghetti
JLab+ODU: Schiavilla Gnech Andreoli
ANL: Lovato Rocco Wiringa
UCSD/UW: Cirigliano 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

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McDONNELL CENTER FOR THE SPACE SCIENCES

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