Fundamental Physics with Nuclei

MAYORANA International Workshop

13 July 2023

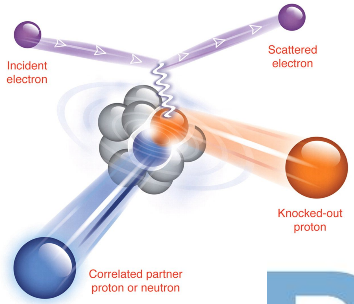
Saori Pastore

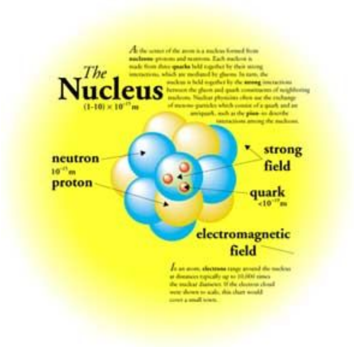
https://physics.wustl.edu/quantum-monte-carlo-group

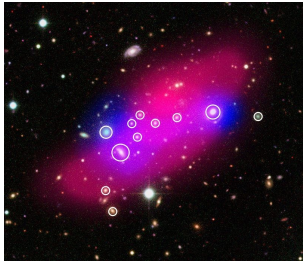
Quantum Monte Carlo Group @ WashU
Lorenzo Andreoli (PD) Jason Bub (GS) Graham Chambers-Wall (GS) Garrett King (GS)
Anna McCoy (FRIB TA Fellow)
Maria Piarulli and Saori Pastore

Computational Resources awarded by the DOE ALCC, INCITE and SciDAC programs

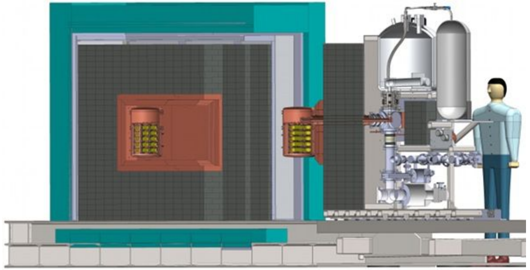
Understand Nuclei to Understand the Cosmos



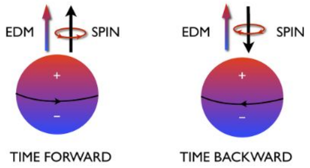




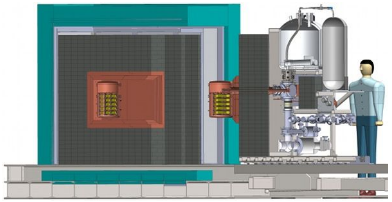
ESA, XMM-Newton, Gastaldello, CFHTL



Ground States' Electroweak Moments, Form Factors, Radii



Neutrinoless Double Beta Decay, Muon-Capture



Accelerator Neutrino Experiments, Lepton-Nucleus XSecs

(ω,q)~0 MeV

ω~few MeVs
q~0 MeV

ω~few MeVs
q~10^2 MeV

ω~tens of MeVs

ω~10^2 MeV

FRIB

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

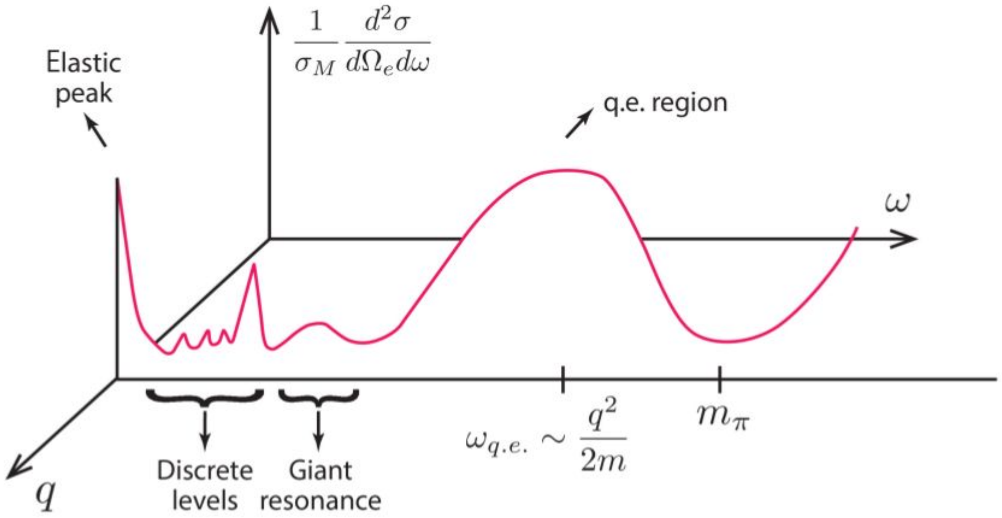
JINA-CEE

Nuclear Rates for Astrophysics

DUNE

Jefferson Lab

Electron-Nucleus Scattering Cross Section



Energy and momentum transferred (ω,q)

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

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

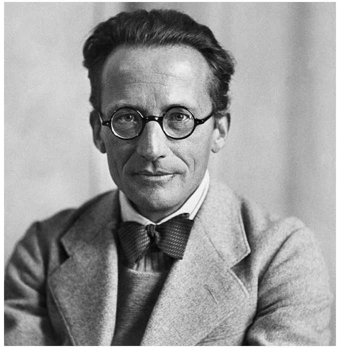
- EDMs, Hadronic PV, ...
- BSM searches with beta decay, ...
- Neutrinoless double beta decay, ...
- Neutrino-Nucleus Scattering Cross Sections, ...
- ...

Microscopic (or *ab initio*) Description of Nuclei

Comprehensive theory that describes quantitatively and predictably nuclear structure and reactions

Requirements:

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



Erwin Schrödinger

$$H\Psi = E\Psi$$

Many-body Nuclear Problem

http://exascaleage.org/np/

Nuclear Many-body Hamiltonian

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

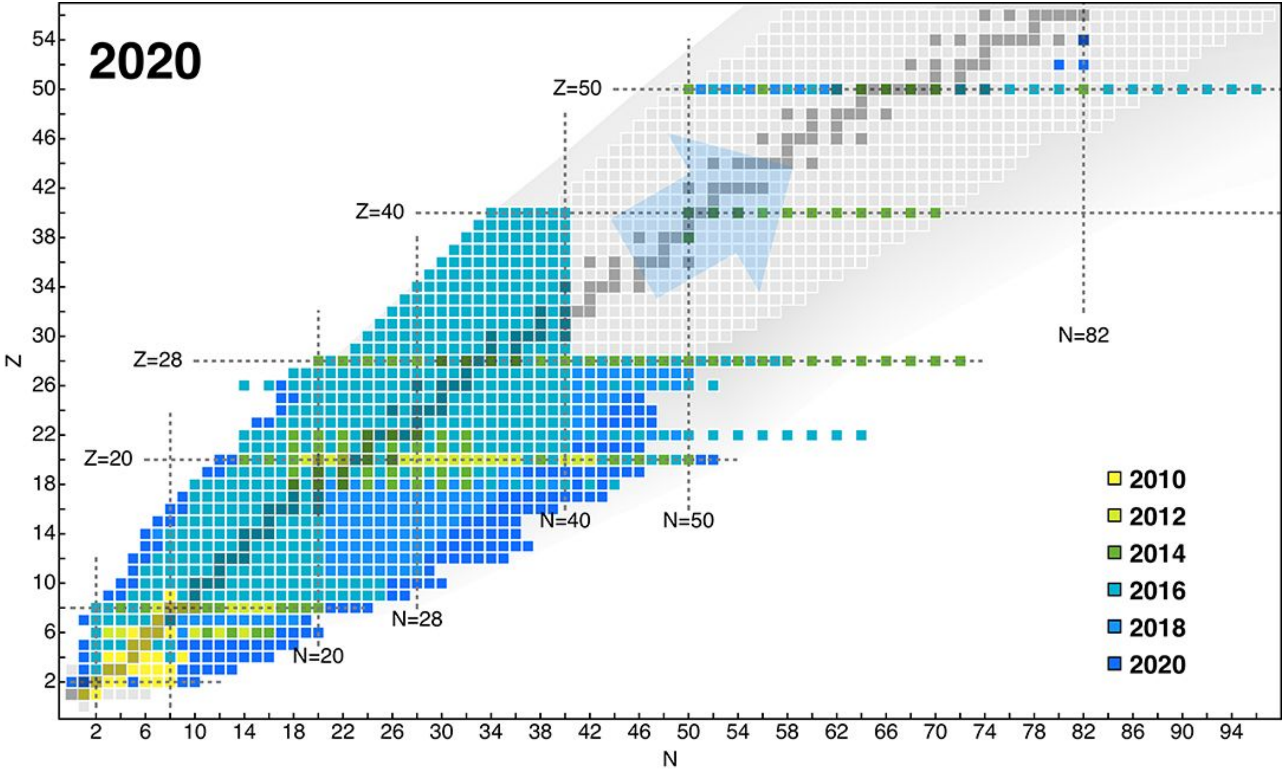
$$\Psi(\mathbf{r}_1, \mathbf{r}_2, \ldots, \mathbf{r}_A, s_1, s_2, \ldots, s_A, t_1, t_2, \ldots, t_A)$$

Ψ are spin-isospin vectors in 3A dimensions with $2^A \times \frac{A!}{Z!(A-Z)!}$ components

^{4}He : 96
^{6}Li : 1280
^{8}Li : 14336
^{12}C : 540572

Develop Computational Methods to solve (numerically) exactly or within approximations that are under control the many-body nuclear problem

Current Status



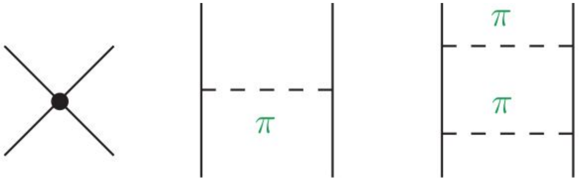
H. Hergert
Front. Phys.
07 October 2020

Many-body Nuclear Interactions

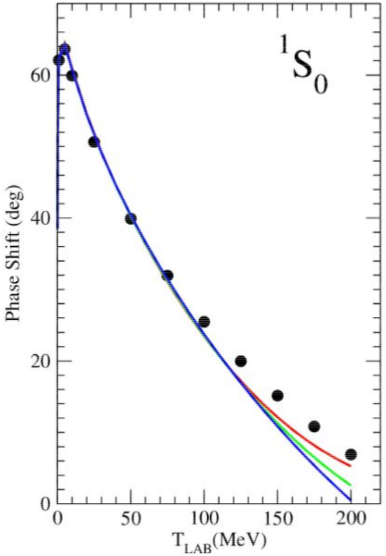
Many-body Nuclear Hamiltonian

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

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



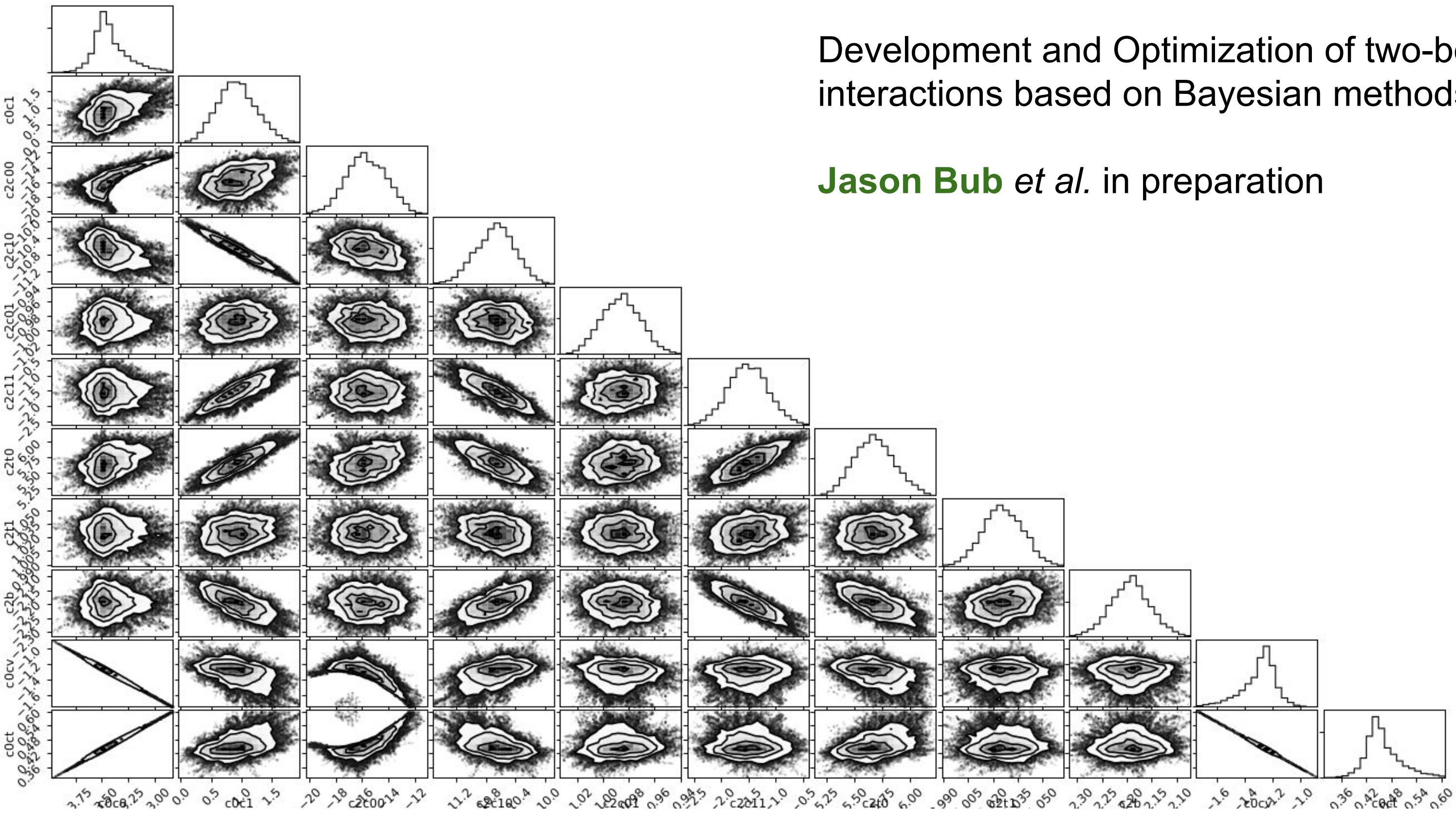
SP et al. PRC80(2009)034004

Hideki Yukawa

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

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

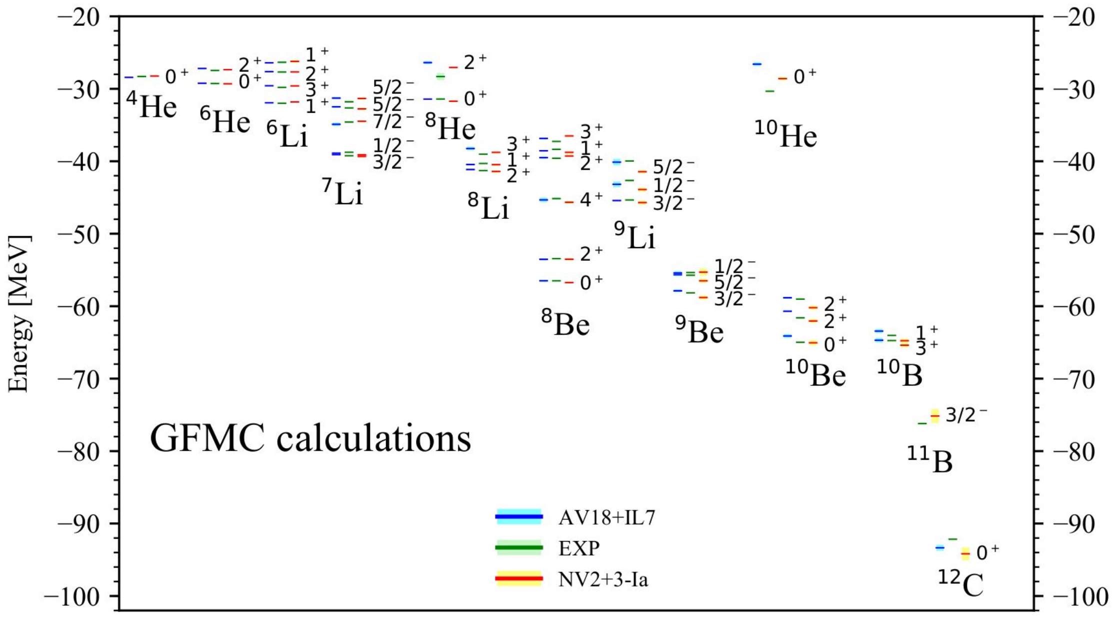
Optimization of Nuclear Two-body Interactions



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

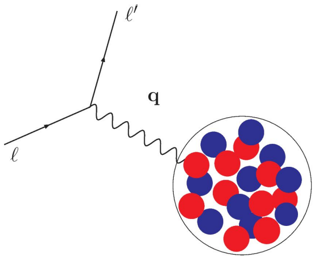
Jason Bub *et al.* in preparation

Energies

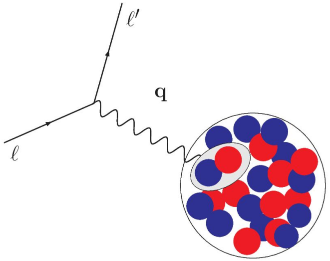


Piarulli *et al.* PRL120(2018)052503

Many-body Nuclear Electroweak Currents



one-body



two-body

Nuclear Charge Operator

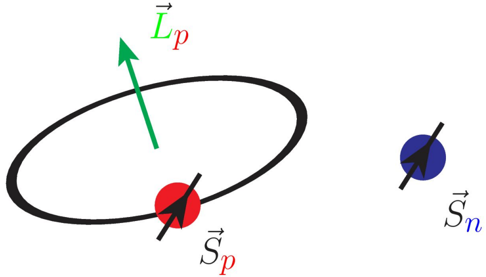
$$\rho = \sum_{i=1}^{A} \rho_i + \sum_{i<j} \rho_{ij} + \ldots$$

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

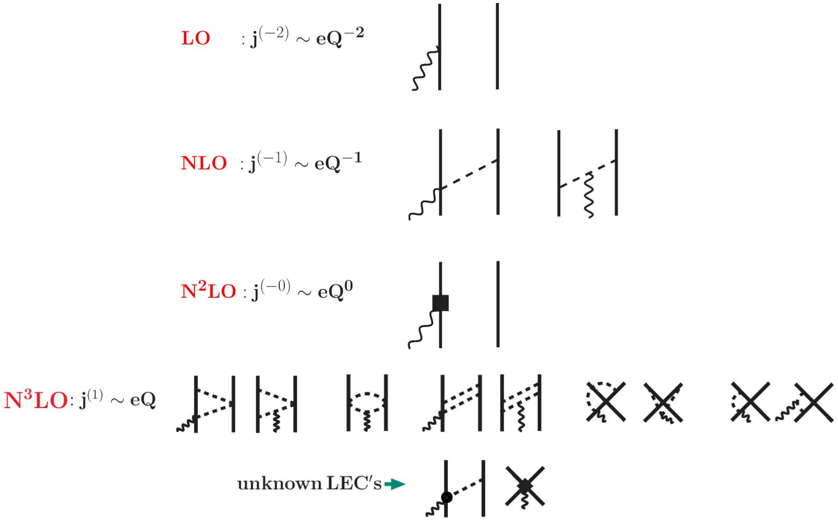
Many-body Currents

- **Meson Exchange Currents** (MEC)

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

- **Chiral Effective Field Theory Currents**

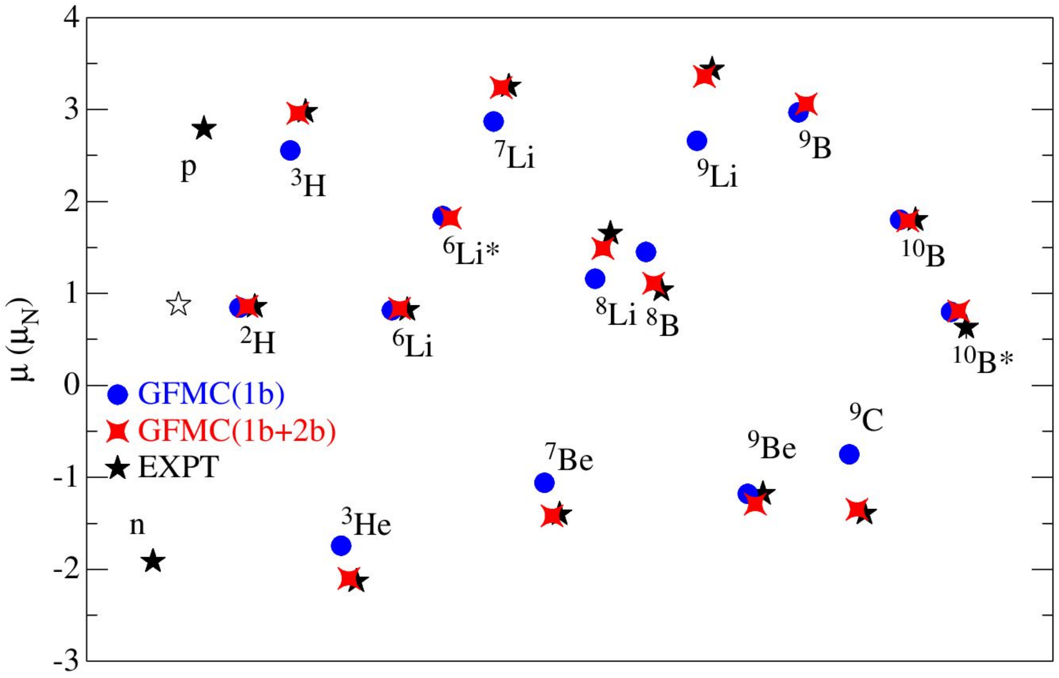
Are constructed consistently with the two-body chiral potential; Unknown parameters, or Low Energy Constants (**LECs**), need to be **determined by either fits to experimental data or by Lattice QCD calculations**



Electromagnetic Current Operator

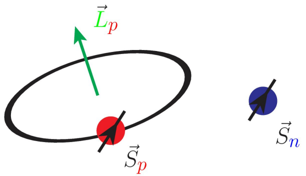
SP *et al.* PRC78(2008)064002, PRC80(2009)034004, PRC84(2011)024001, PRC87(2013)014006
Park *et al.* NPA596(1996)515, Phillips (2005)
Kölling *et al.* PRC80(2009)045502 & PRC84(2011)054008

Magnetic Moments of Light Nuclei



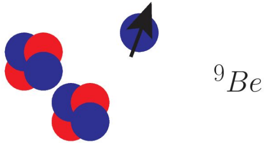
SP *et al*. PRC87(2013)035503

Single particle picture

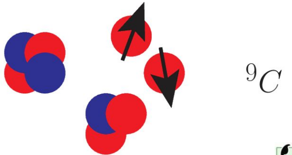


$$\mu_N(1\text{b}) = \sum_i [(L_i + g_p S_i)(1+\tau_{i,z})/2 + g_n S_i(1-\tau_{i,z})/2]$$

Small two-body current effects

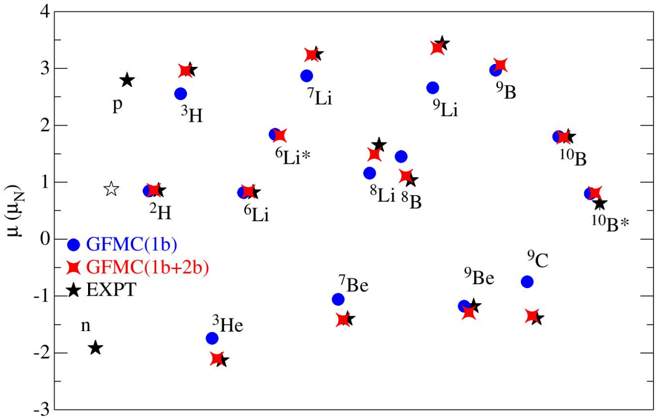


Large two-body current effects



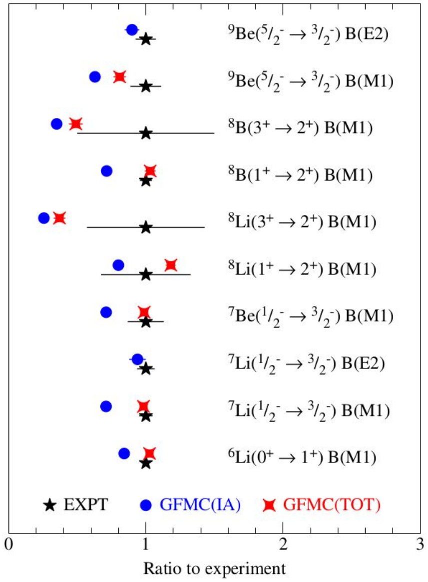
Electromagnetic Observables

Magnetic moments

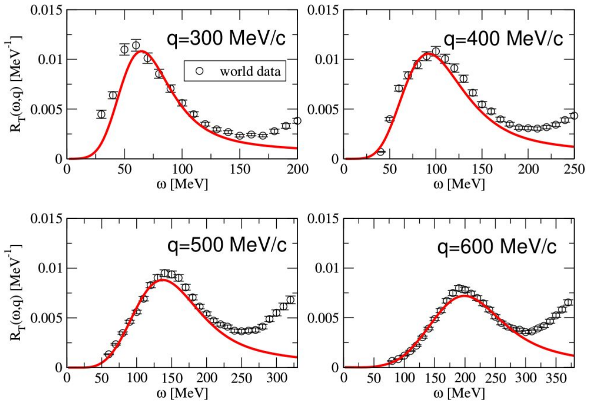


SP *et al*. PRC87(2013)035503, PRC101(2020)044612

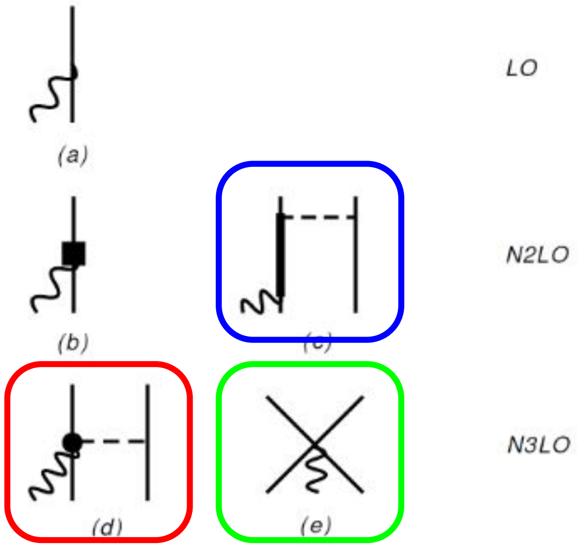
EM decay



e-^{4}He particle scattering



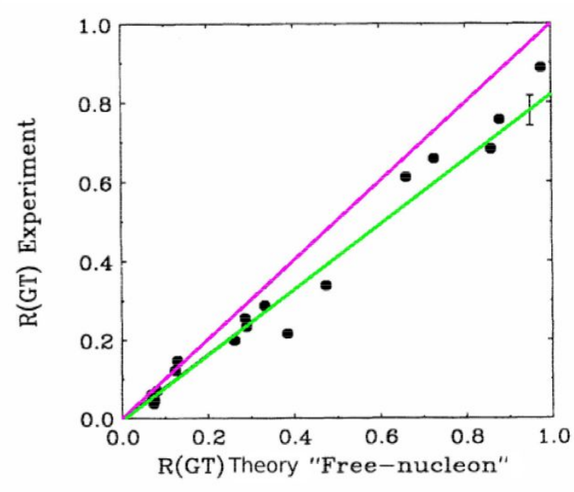
Axial currents with Δ at tree-level



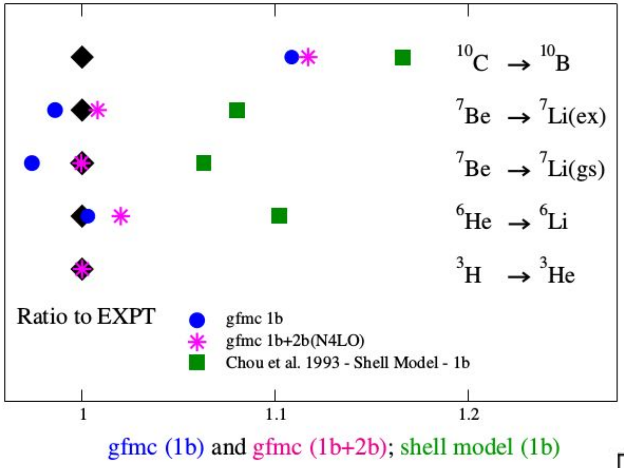
Two body currents of one pion range (red and blue) with c_3 c_4 from Krebs *et al.* Eur.Phys.J.(2007)A32

Contact current involves the LEC c_D

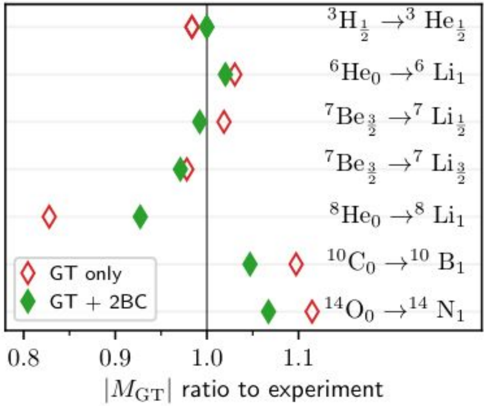
Beta decay



Chou et al. PRC47(1993)163

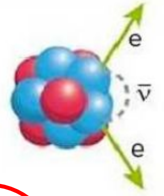


SP *et al*. PRC97(2018)022501



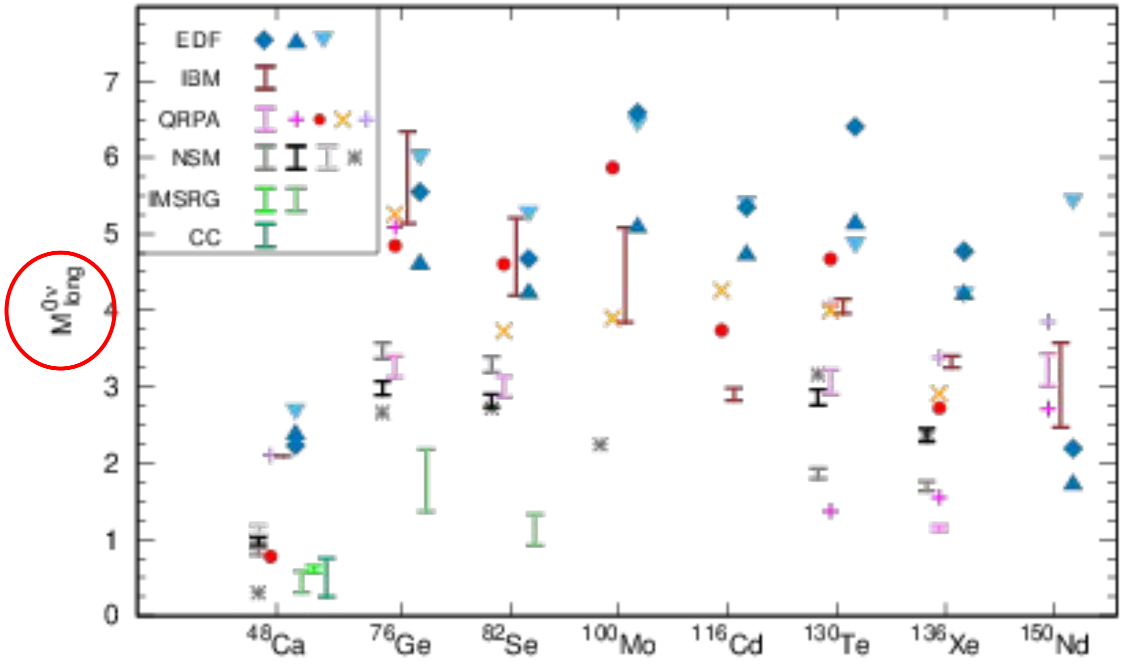
P. Gysbers *Nature Phys.* 15 (2019)

Neutrinoless Double Beta Decay

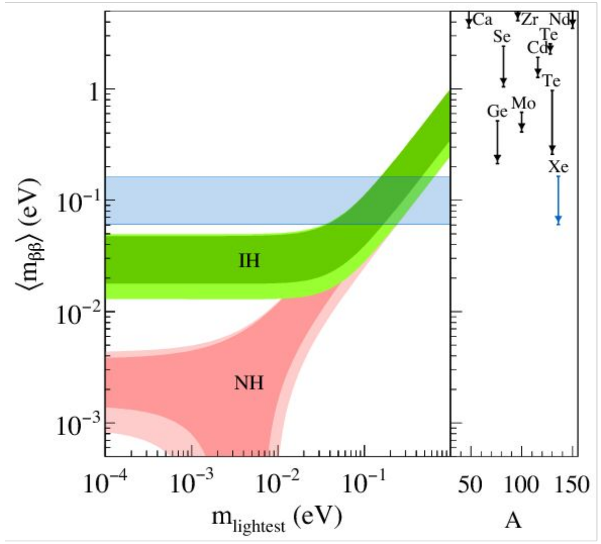


$$[T_{1/2}^{0\nu}]^{-1} = G_{0\nu}(Q,Z)\,|M_{0\nu}|^2\, m_{\beta\beta}^2$$

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



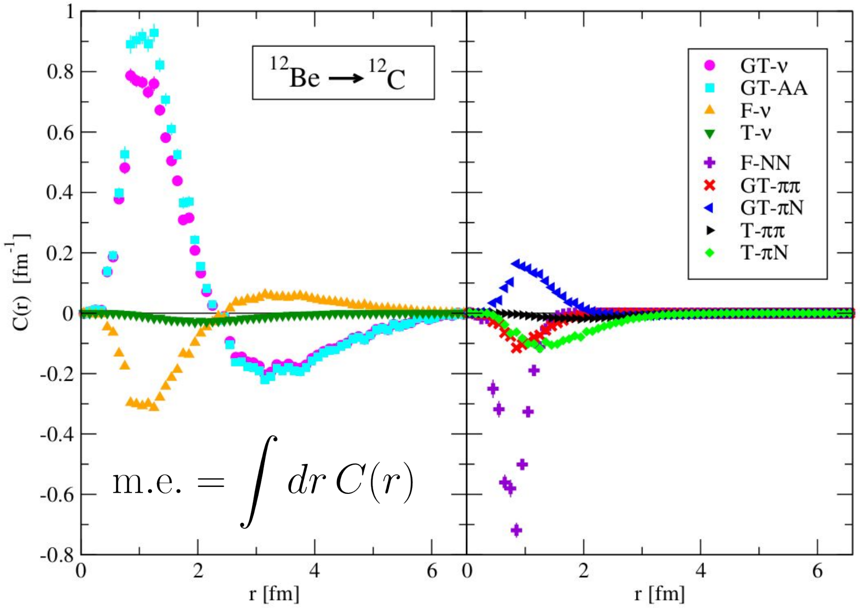
Menéndez Vissani et al. *Rev.Mod.Phys.* 95 (2023) 2, 025002



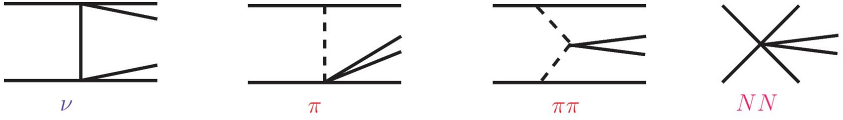
Neutrinoless Double Beta Decay Matrix Elements

Long-range

One-pion & short range



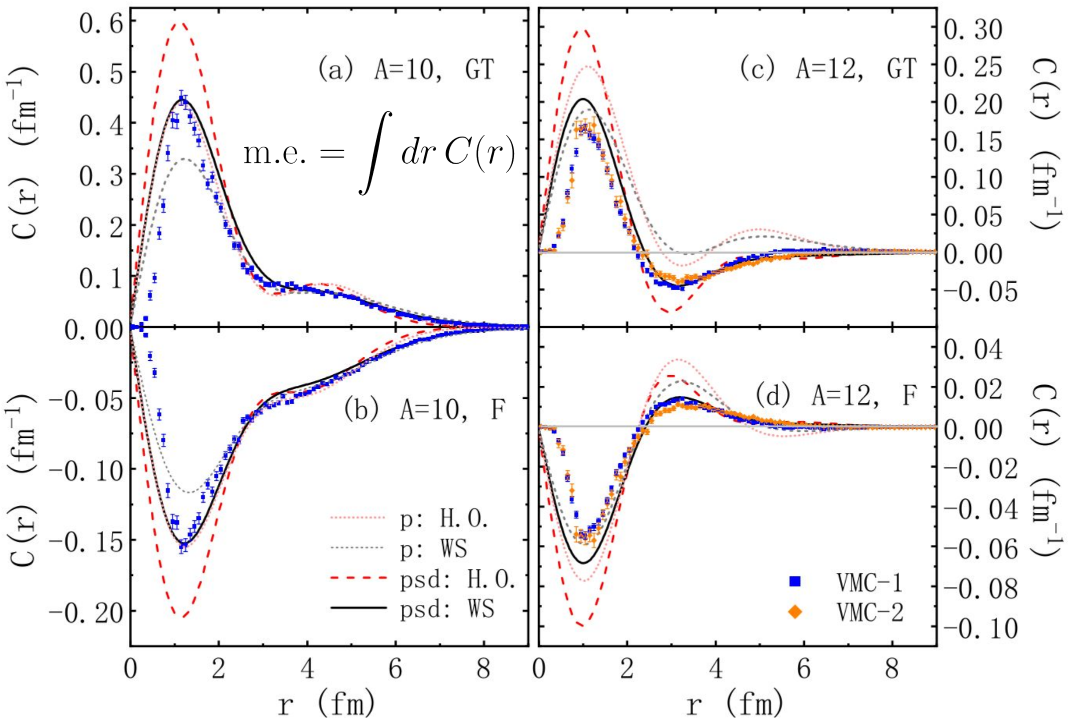
SP *et al.* PRC97(2018)014606



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

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

Comparison with Shell-Model Calculations

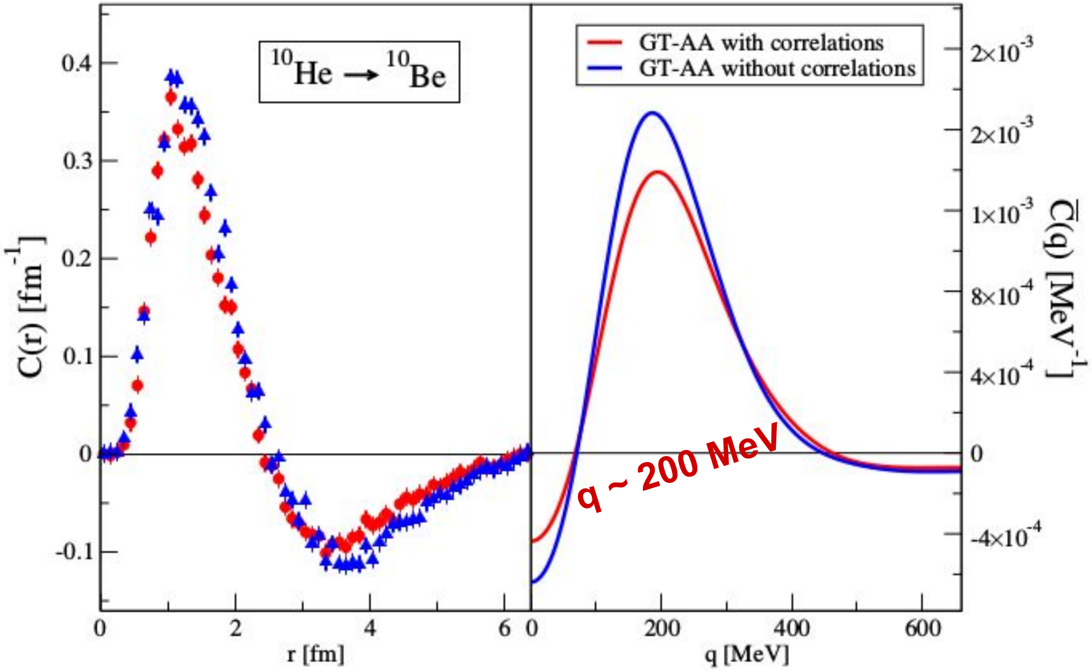


X. Wang *et al.* PLB798(2019)134974

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

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

Correlations in neutrinoless double beta decay ME



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)

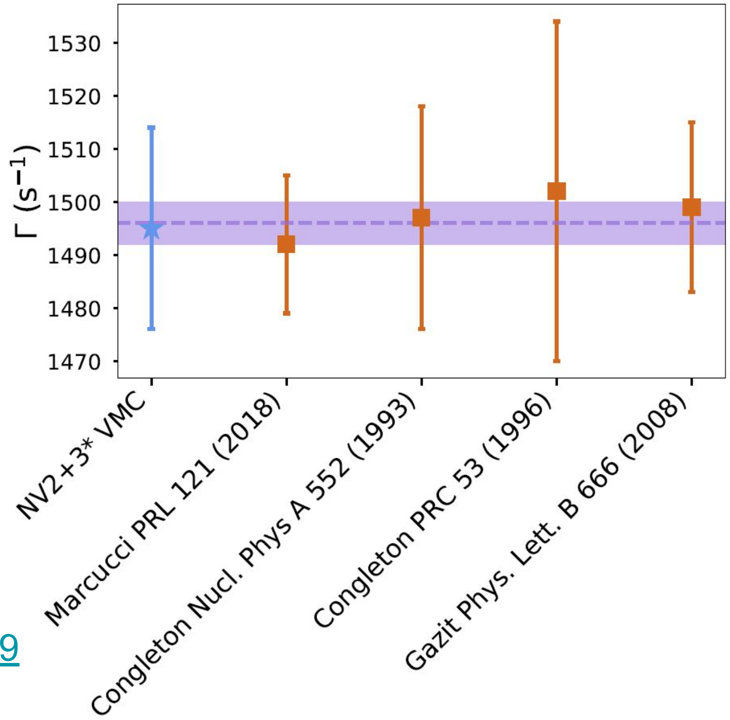
Momentum transfer **q~ 100 MeV**

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

Garrett King *et al.* PRC2022

Review by Measday [Physics Reports 354 (2001) 243–409]

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



Partial muon capture rates: VMC calculations

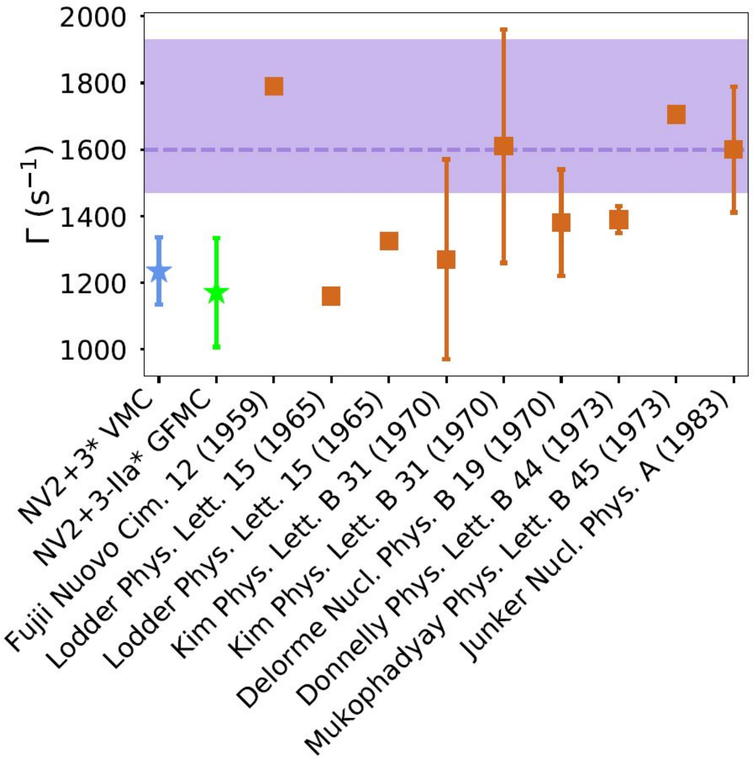
$\Gamma_{VMC}(\text{avg.}) = 1235\ s^{-1} \pm 101\ s^{-1}$
$\Gamma_{GFMC}(\text{IIa*}) = 1171\ s^{-1} \pm 164\ s^{-1}$
$\Gamma_{expt} = 1600\ s^{-1}\ +330/-129\ s^{-1}$

Deutsch *et al.* PLB26(1968)315

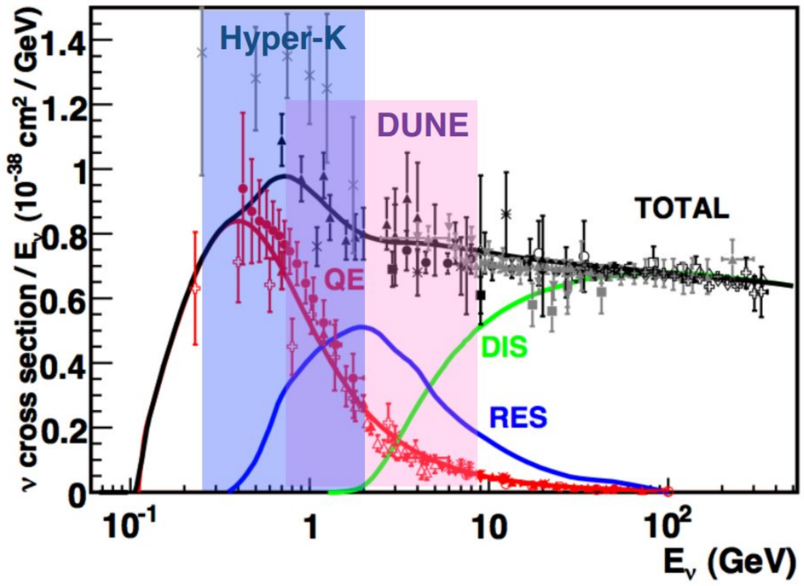
Garrett King *et al.* PRC2022

With FRIB experimentalist colleagues:
Gamow-Teller strength in A=11;
Schmitt et al. PRC106(2022)

$^{6}\text{Li}(1^{+};0) \rightarrow {}^{6}\text{He}(0^{+};1)$



Neutrino cross section anatomy



Formaggio & Zeller

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**

A challenge for achieving precise neutrino-nucleus cross-section is **reliably bridging the transition regions which use different degrees of freedom**

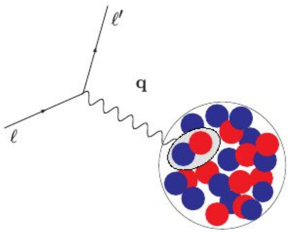
Lepton-Nucleus scattering: Inclusive Processes

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

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

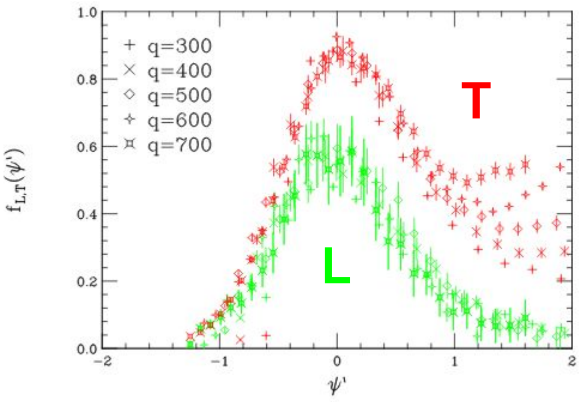


For a recent review on QMC, SF methods see
Rocco *Front. In Phys.*8 (2020)116

Lepton-Nucleus scattering: Data

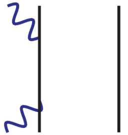
Transverse Sum Rule

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



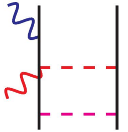
^{4}He Electromagnetic Data
Carlson *et al.* PRC65(2002)024002

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



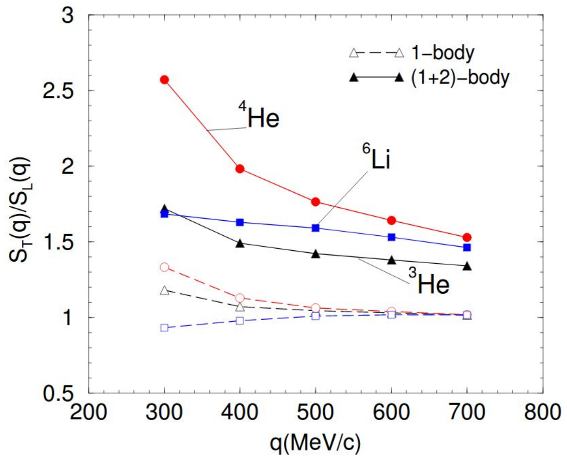
$\langle \mathbf{j}_{1b}^\dagger\ \ \mathbf{j}_{1b}\rangle\ > 0$

Leading one-body term



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

Interference term

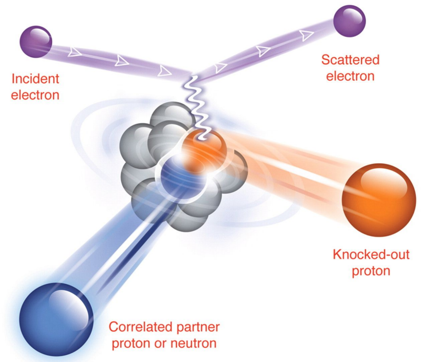


Transverse/Longitudinal Sum Rule
Carlson *et al.* PRC65(2002)024002

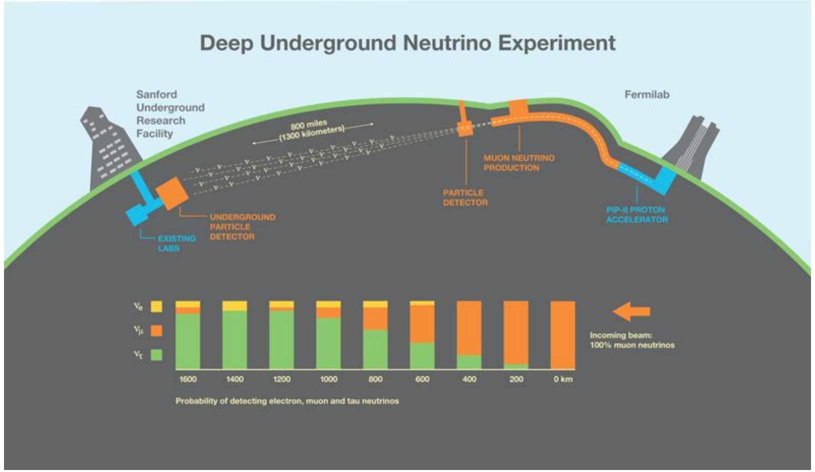
Beyond Inclusive: Short-Time-Approximation

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

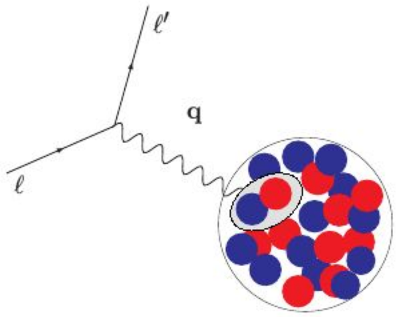


[Stanford Lab article]

[e4u collaboration]

e4V

Short-Time-Approximation



Short-Time-Approximation:

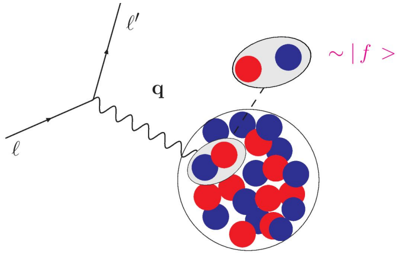
- Based on Factorization
- Retains two-body physics
- Correctly accounts for interference

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

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

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

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

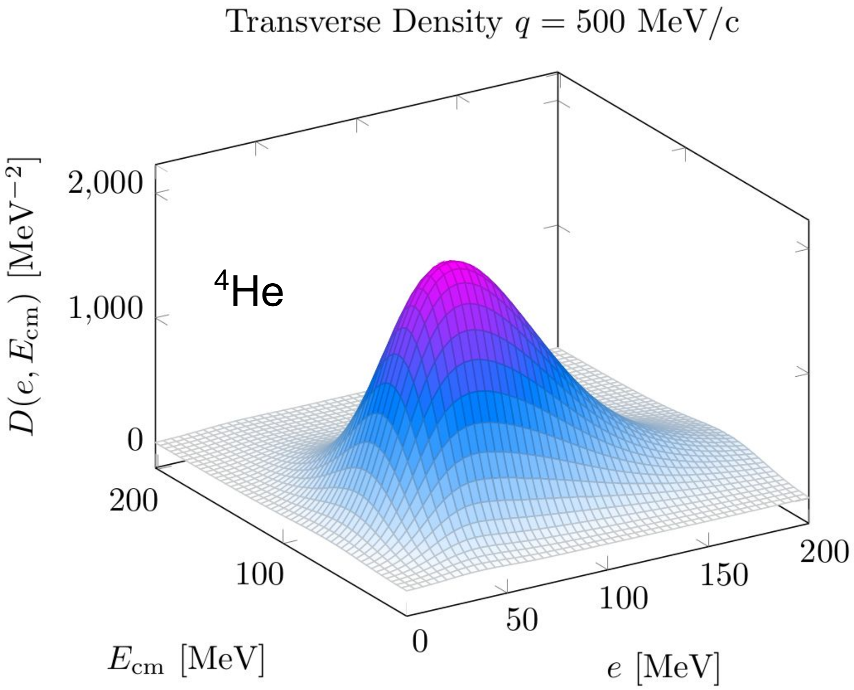
$$R_\alpha(q,\omega) = \sum_f \delta\left(\omega + E_0 - E_f\right) |\langle f|O_\alpha(\mathbf{q})|0\rangle|^2$$

Response ***Densities***

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

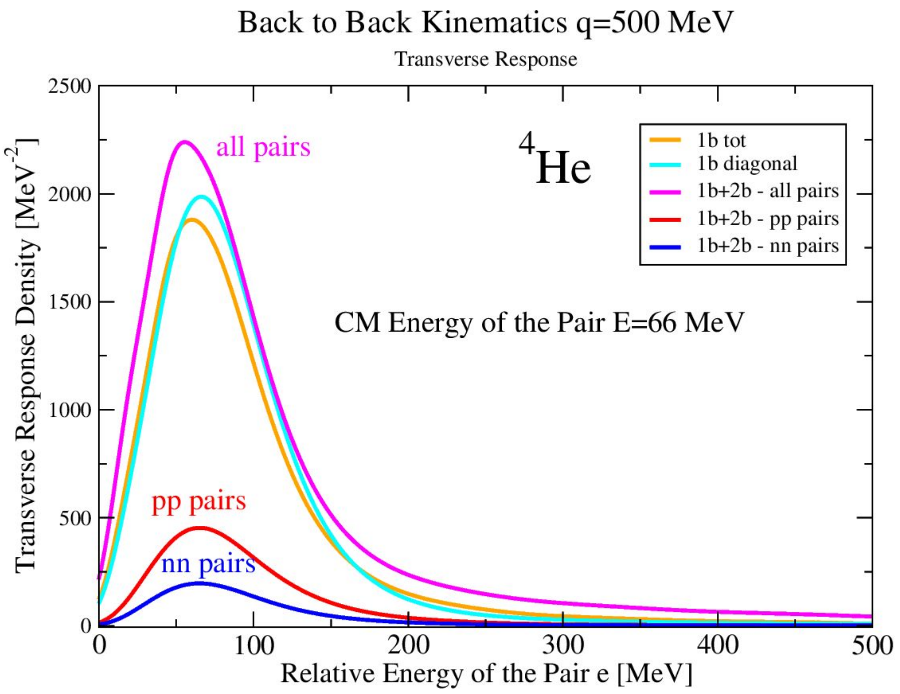
P’ and *p’* are the CM and relative momenta of the struck nucleon pair

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



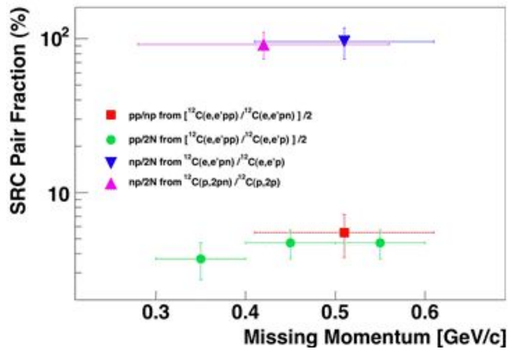
SP *et al.* PRC101(2020)044612

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



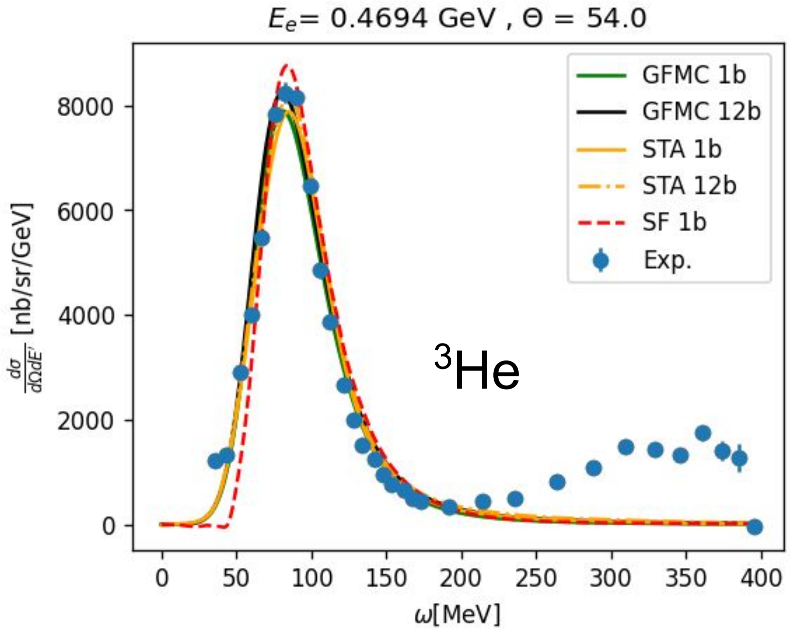
SP *et al.* PRC101(2020)044612

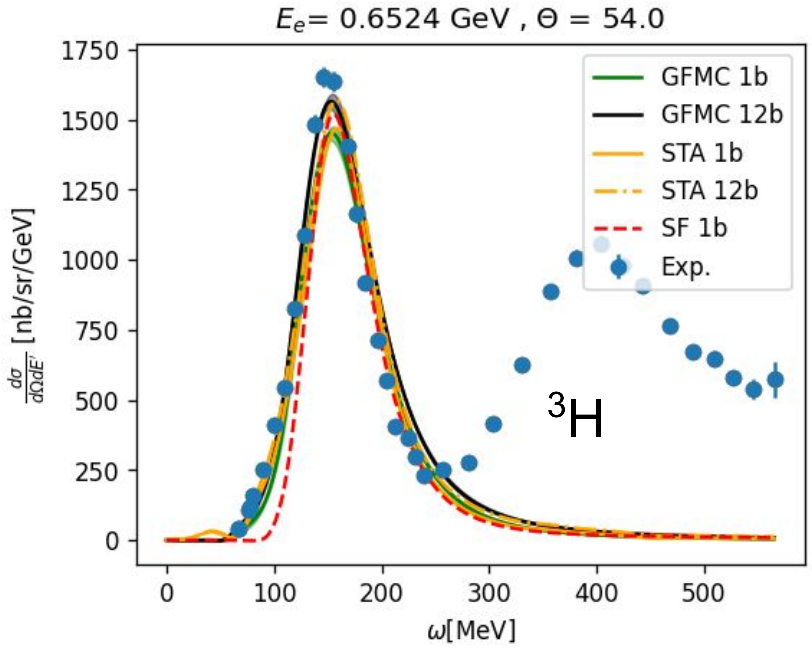
- pp pairs
- nn pairs
- all pairs 1body
- all pairs tot



Subedi et al. Science320(2008)1475

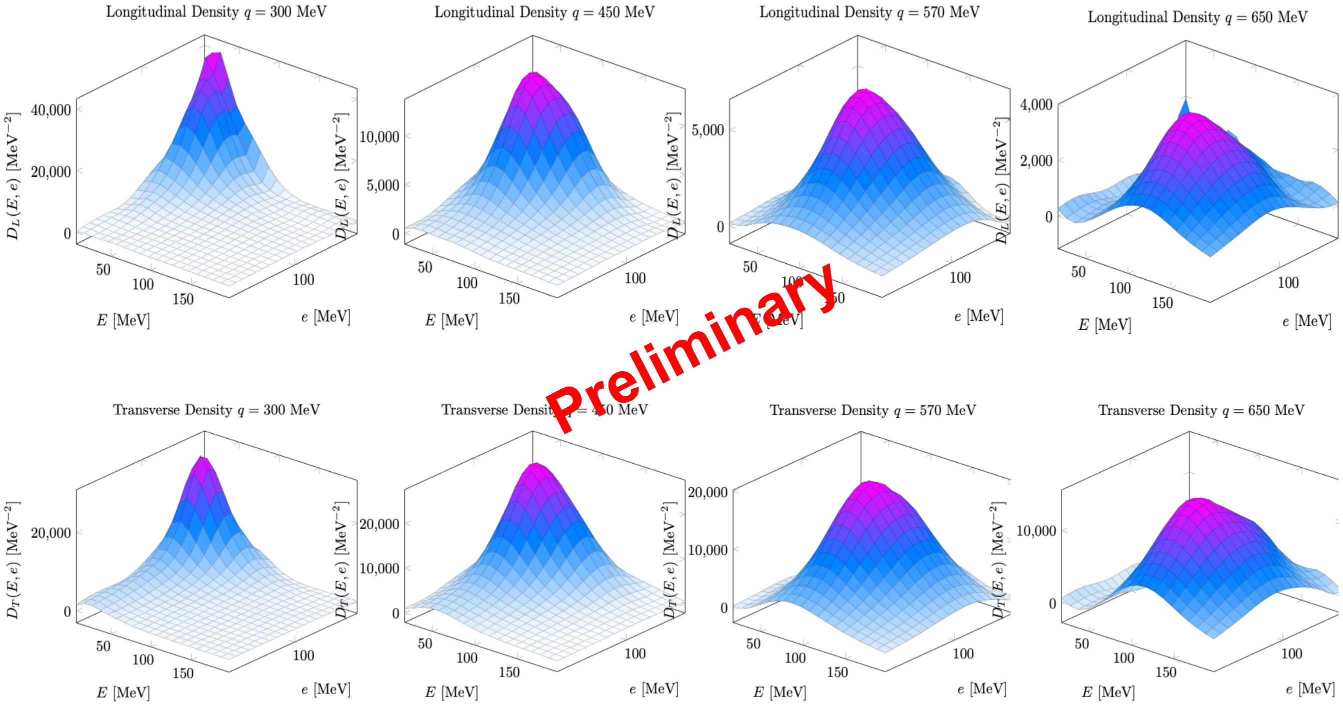
GFMC SF STA: Benchmark & error estimate





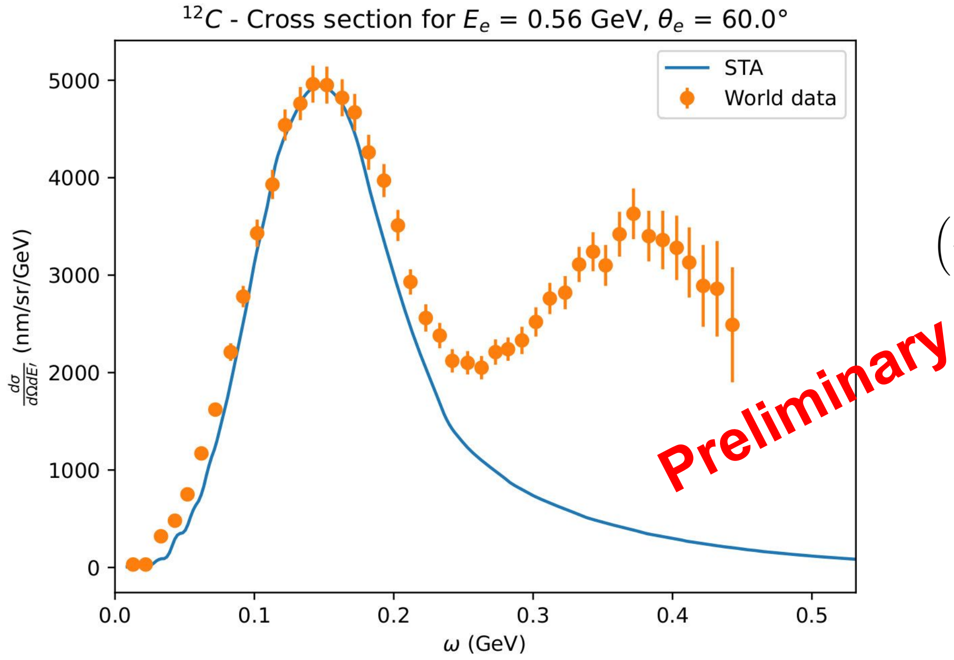
Lorenzo Andreoli, *et al.* PRC 2021

^{12}C Response Densities

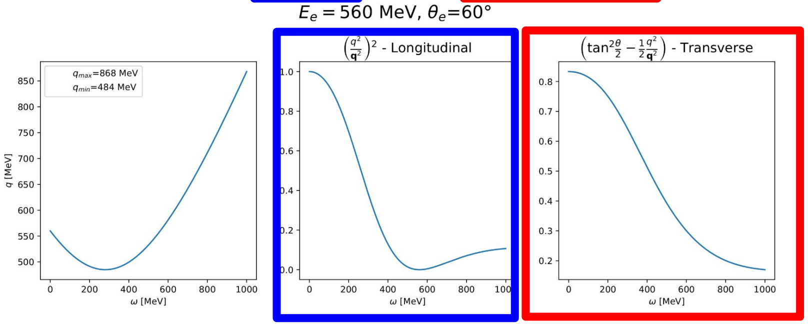


Lorenzo Andreoli *et al.* in preparation

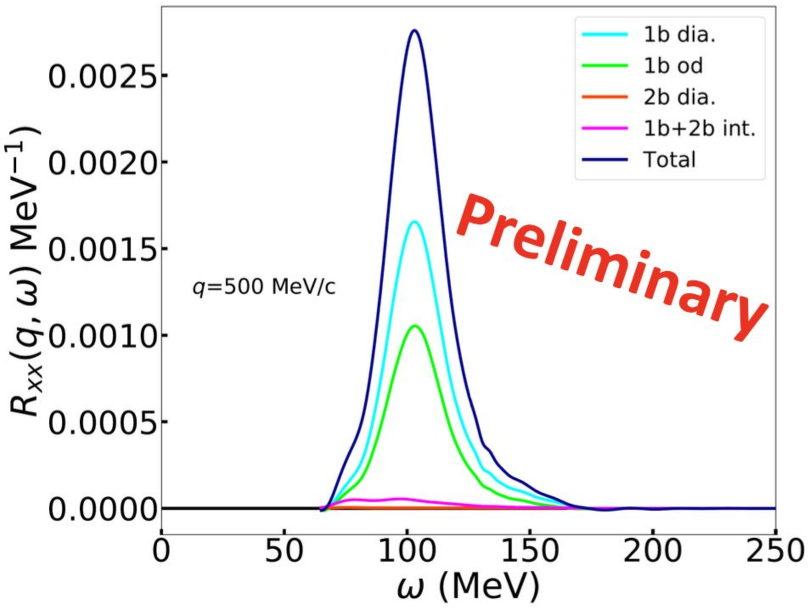
^{12}C cross sections



$$\left(\frac{d^2\sigma}{dE'd\Omega'}\right)_e = \left(\frac{d\sigma}{d\Omega'}\right)_{\mathrm{M}} \left[\left(\frac{q^2}{\mathbf{q}^2}\right)^2 R_L(|\mathbf{q}|,\omega) + \left(\tan^2\frac{\theta}{2} - \frac{1}{2}\frac{q^2}{\mathbf{q}^2}\right) R_T(|\mathbf{q}|,\omega)\right]$$



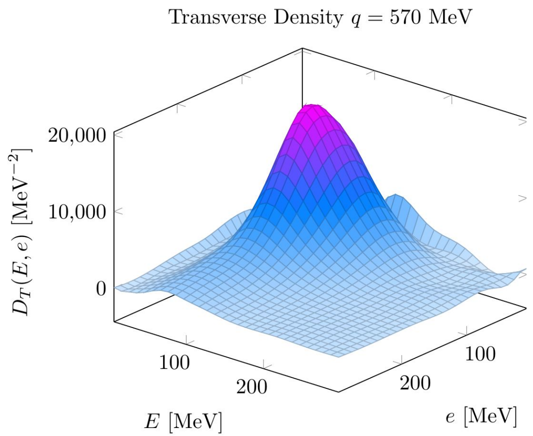
NC processes on deuteron with STA

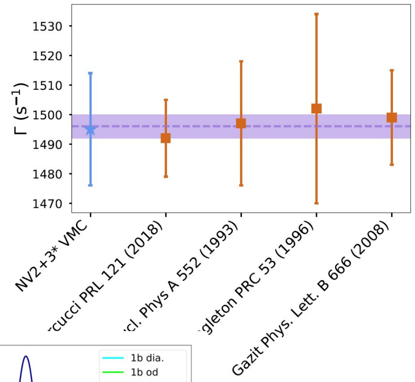


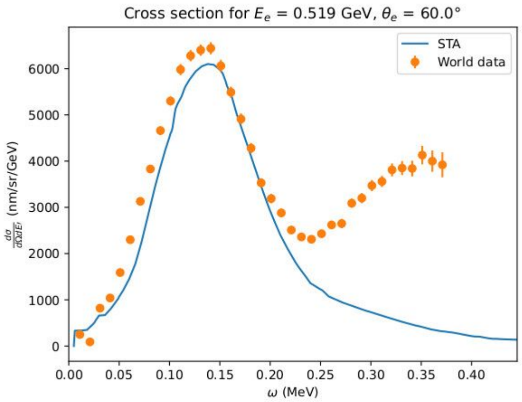
Garrett King *et al.* in preparation

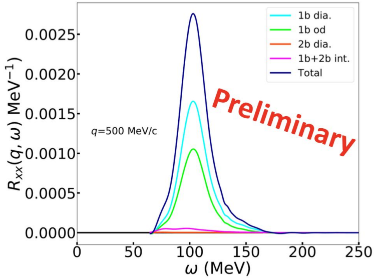
Summary

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.









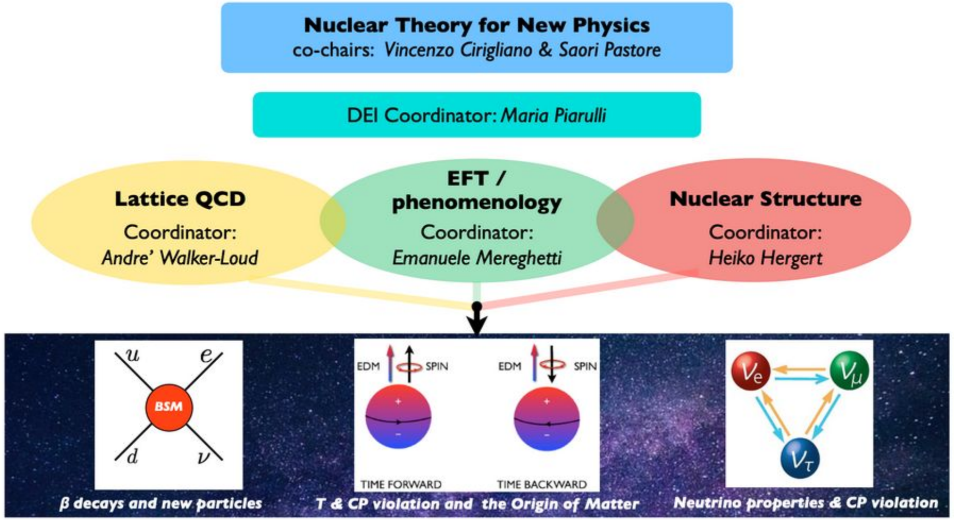
Close **collaborations** between **NP**, **LQCD**, **Pheno**, **Hep**, **Comp**, **Expt**, …
are required to progress
e.g., NP is represented in the Snowmass process

It's a very exciting time!

Nuclear Theory for New Physics NP&HEP TC

Nuclear Theory for New Physics

- About Us
- 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, …

Collaborators

WashU: **Andreoli Bub Chambers-Walls King McCoy Piarulli**
LANL: Baroni Carlson Cirigliano Gandolfi Hayes Mereghetti
JLab+ODU: Schiavilla Gnech
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

Theory Alliance
FACILITY FOR RARE ISOTOPE BEAMS

U.S. DEPARTMENT OF ENERGY
INCITE
LEADERSHIP COMPUTING

Los Alamos
NATIONAL LABORATORY
EST. 1943

Argonne
NATIONAL LABORATORY

U.S. DEPARTMENT OF
ENERGY
Office of Science

McDonnell Center
for the Space Sciences

Fermilab

Washington University in St. Louis
Arts & Sciences

Department of Physics

McDonnell Center for the Space Sciences

Quantum Monte Carlo Group for Nuclear Physics

https://physics.wustl.edu/quantum-monte-carlo-group

Lorenzo Andreoli
Postdoctoral Research Associate

landreoli@wustl.edu

Jason Bub
Graduate Student

jason.bub@wustl.edu

Garrett King
Graduate Student

kingg@wustl.edu

Anna McCoy
FRIB Theory Fellow

&