Fundamental Physics with Nuclei

Neutrino Scattering at Low and Intermediate Energies

30 June 2023
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https://physics.wustl.edu/quantum-monte-carlo-group

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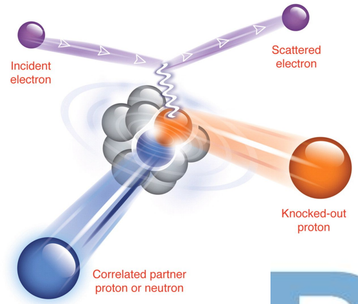
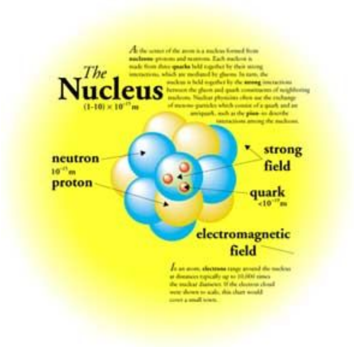
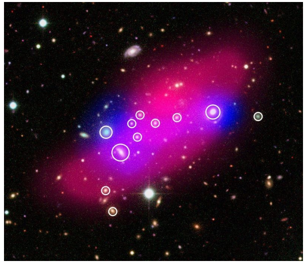
Anna McCoy (FRIB TA Fellow)
Maria Piarulli and Saori Pastore

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

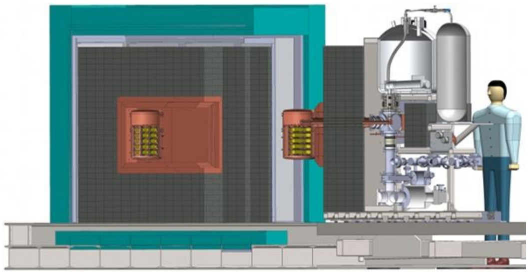
Understand Nuclei to Understand the Cosmos



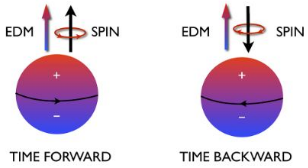




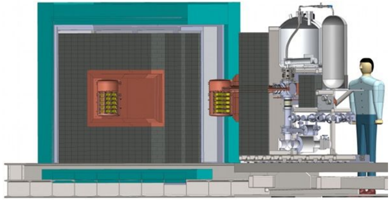
ESA, XMM-Newton, Gastaldello, CFHTL



Ground States' Electroweak Moments, Form Factors, Radii



Neutrinoless Double Beta Decay, Muon-Capture



Accelerator Neutrino Experiments, Lepton-Nucleus XSecs

$(\omega, q) \sim 0$ **MeV**

$\omega \sim$ **few MeVs** $q \sim 0$ **MeV**

$\omega \sim$ **few MeVs** $q \sim 10^2$ **MeV**

$\omega \sim$ **tens of MeVs**

$\omega \sim 10^2$ **MeV**

FRIB

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

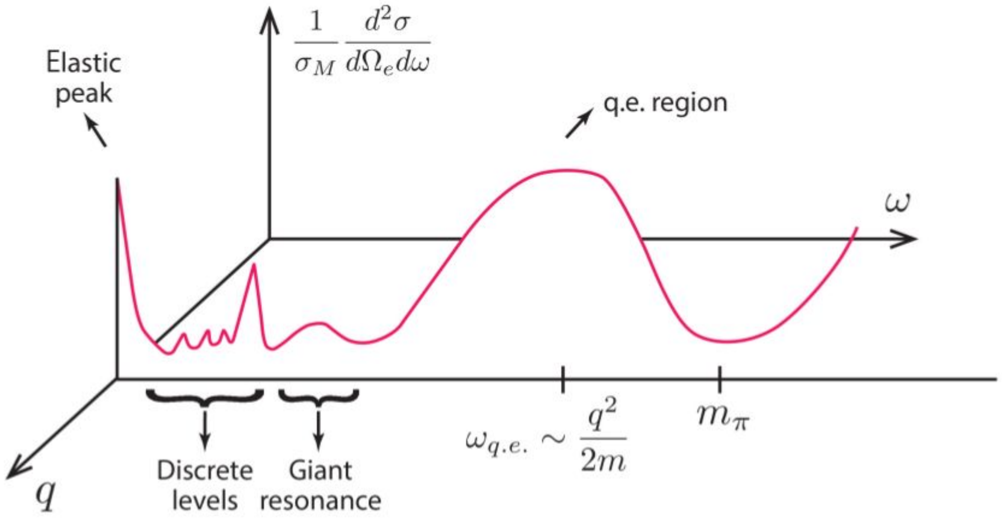
JINA-CEE

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

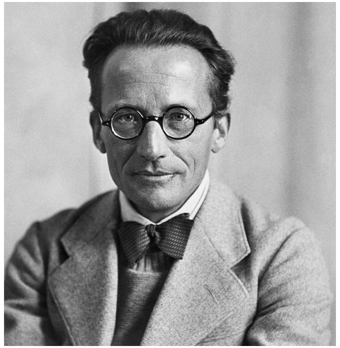
- EDMs, Hadronic PV, ...
- BSM searches with beta decay, ...
- Neutrinoless double beta decay, ...
- Neutrino-Nucleus Scattering Cross Sections, ...
- ...

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

Nuclear Many-body Hamiltonian

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

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

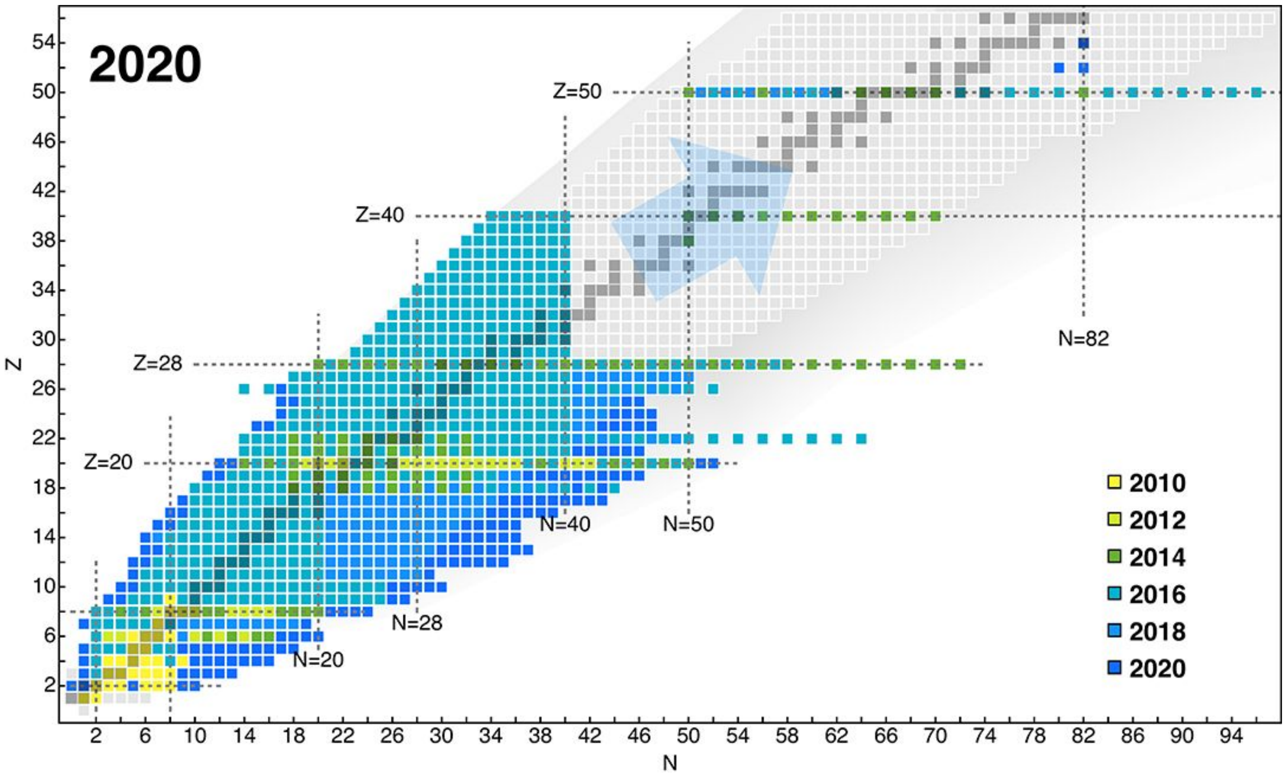
Ψ are spin-isospin vectors in 3A dimensions with $2^A \times \frac{A!}{Z!(A-Z)!}$ components

^{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

http://exascaleage.org/np/

Current Status



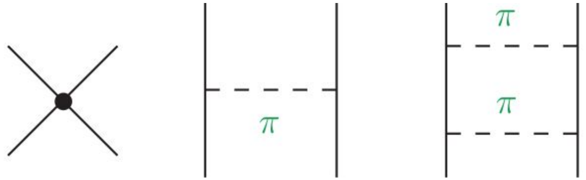
H. Hergert
Front. Phys.
07 October 2020

Many-body Nuclear Interactions

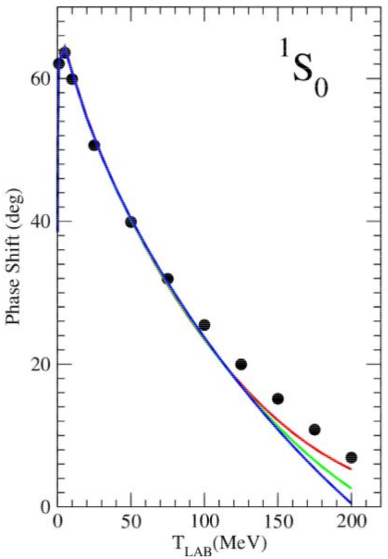
Many-body Nuclear Hamiltonian

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

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



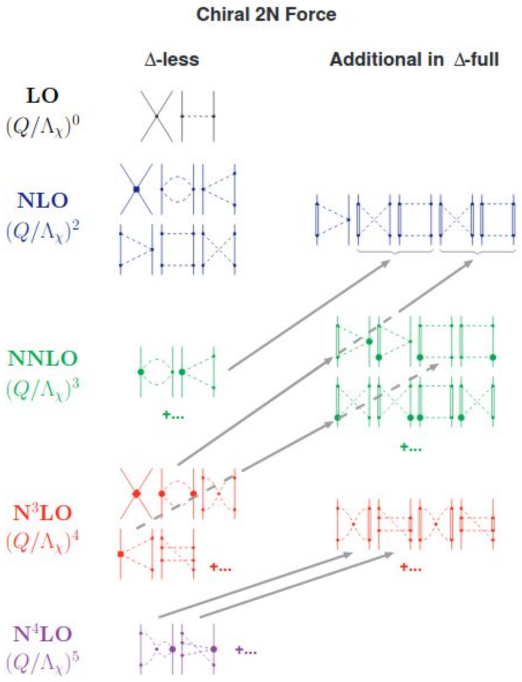
SP et al. PRC80(2009)034004

Hideki Yukawa

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

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

Norfolk Two- and Three-body Potentials

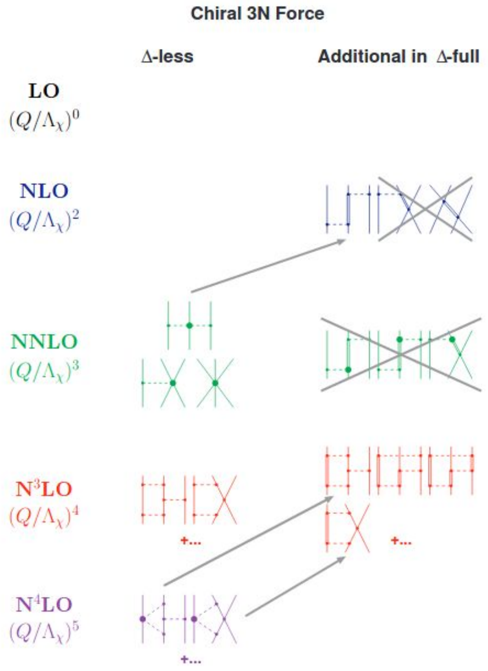


Norfolk Chiral Potentials

NV2+3

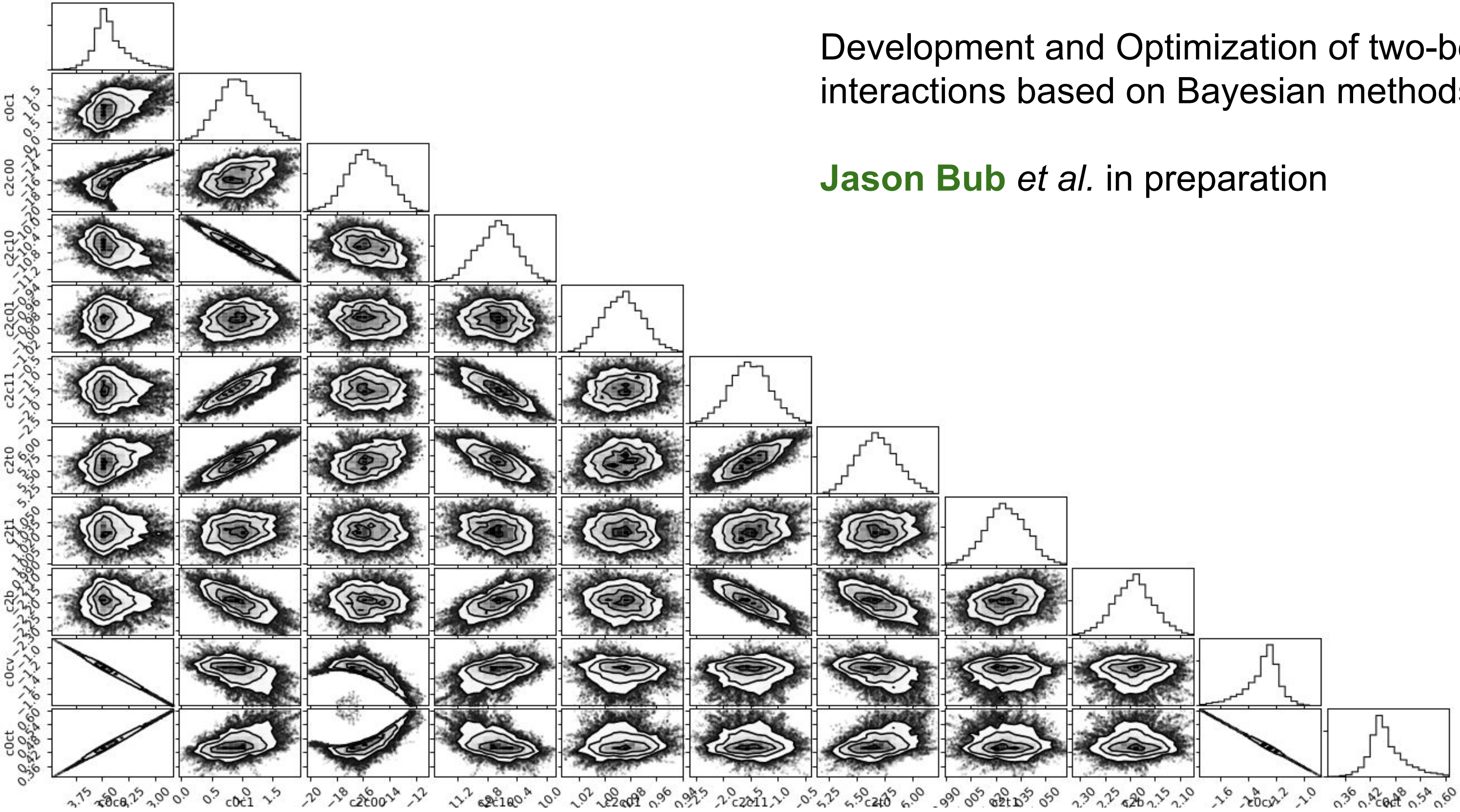
developed in Piarulli *et al*.
PRC91(2015)024003
PRC94(2016)054007

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



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

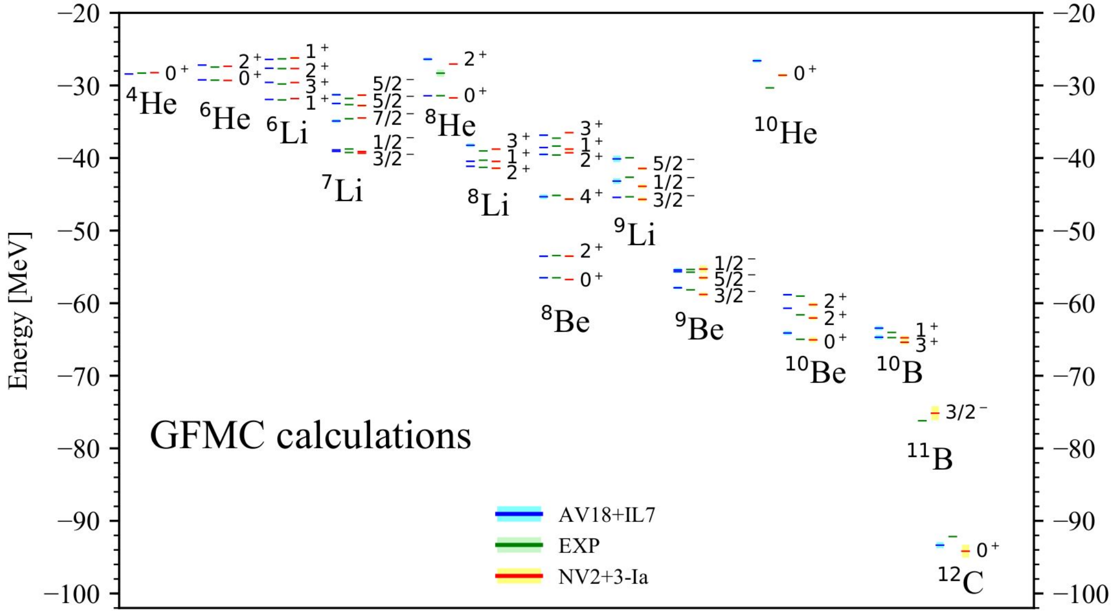
Optimization of Nuclear Two-body Interactions



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

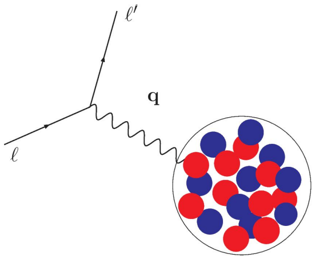
Jason Bub *et al.* in preparation

Energies

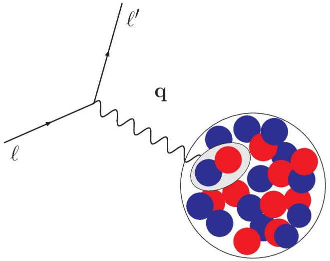


Piarulli *et al.* PRL120(2018)052503

Many-body Nuclear Electroweak Currents



one-body



two-body

Nuclear Charge Operator

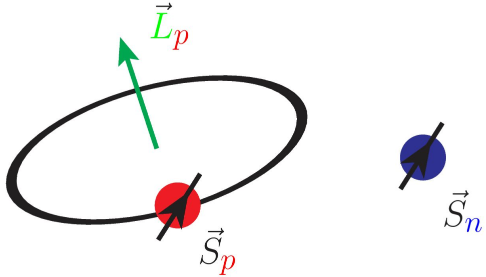
$$\rho = \sum_{i=1}^{A} \rho_i + \sum_{i<j} \rho_{ij} + \ldots$$

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

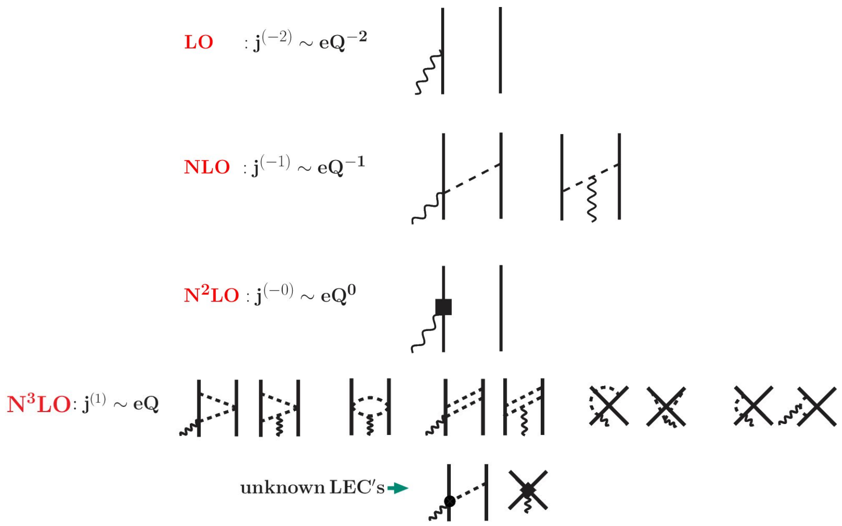
Many-body Currents

- **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**

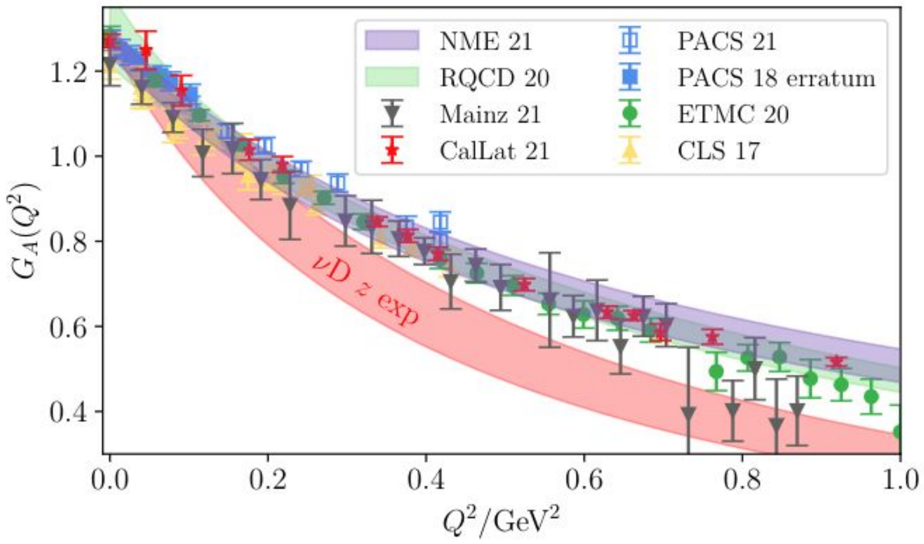
Are constructed consistently with the two-body chiral potential; Unknown parameters, or Low Energy Constants (**LECs**), need to be **determined by either fits to experimental data or by Lattice QCD calculations**



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

LCQD inputs for neutrino-nucleus scattering



Snowmass WP: Theoretical tools for neutrino scattering: interplay between lattice QCD, EFTs, nuclear physics, phenomenology, and neutrino event generators; arXiv:2203.09030

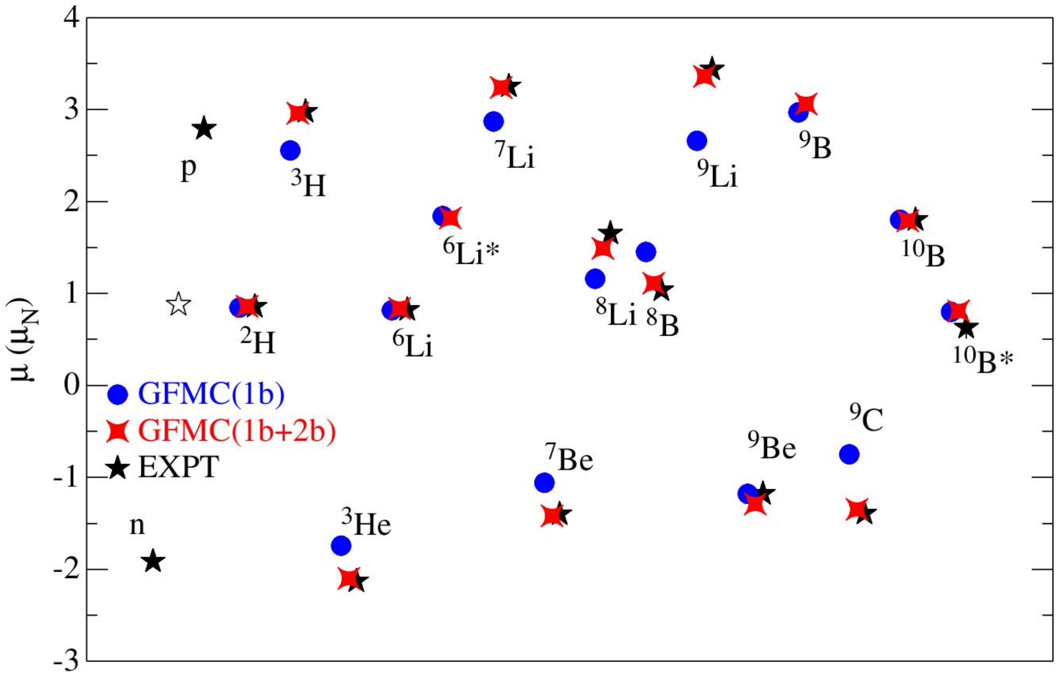
Meyer, Walker-Loud, Wilkinson (2022)

Building blocks of ab initio nuclear approaches:

Nucleonic form factors
Transition form factors
Pion production amplitudes
Two-nucleon couplings (strong and EW)
…

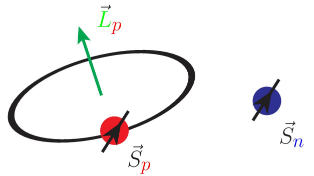
Taken from data where available, or from theory

Magnetic Moments of Light Nuclei



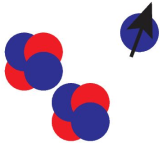
SP *et al*. PRC87(2013)035503

Single particle picture



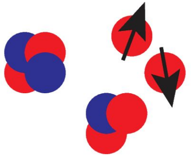
$$\mu_N(1\text{b}) = \sum_i [(L_i + g_p S_i)(1+\tau_{i,z})/2 + g_n S_i(1-\tau_{i,z})/2]$$

Small two-body current effects



^9Be

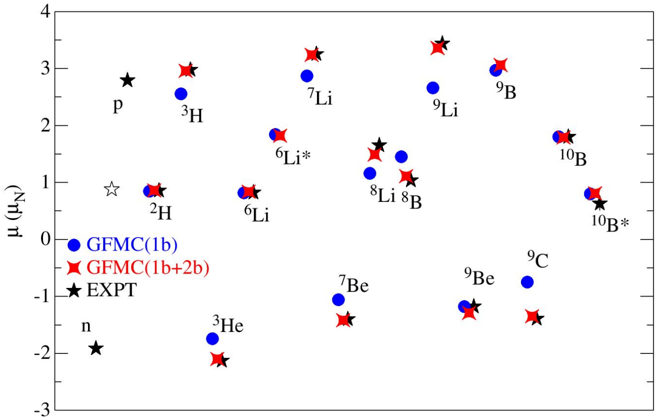
Large two-body current effects



^9C

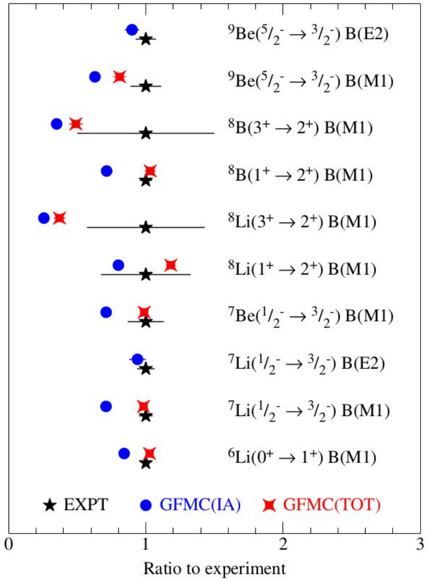
Electromagnetic Observables

Magnetic moments

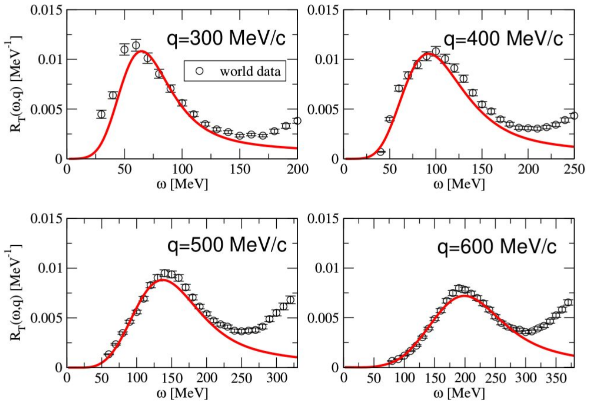


SP *et al*. PRC87(2013)035503,
PRC101(2020)044612

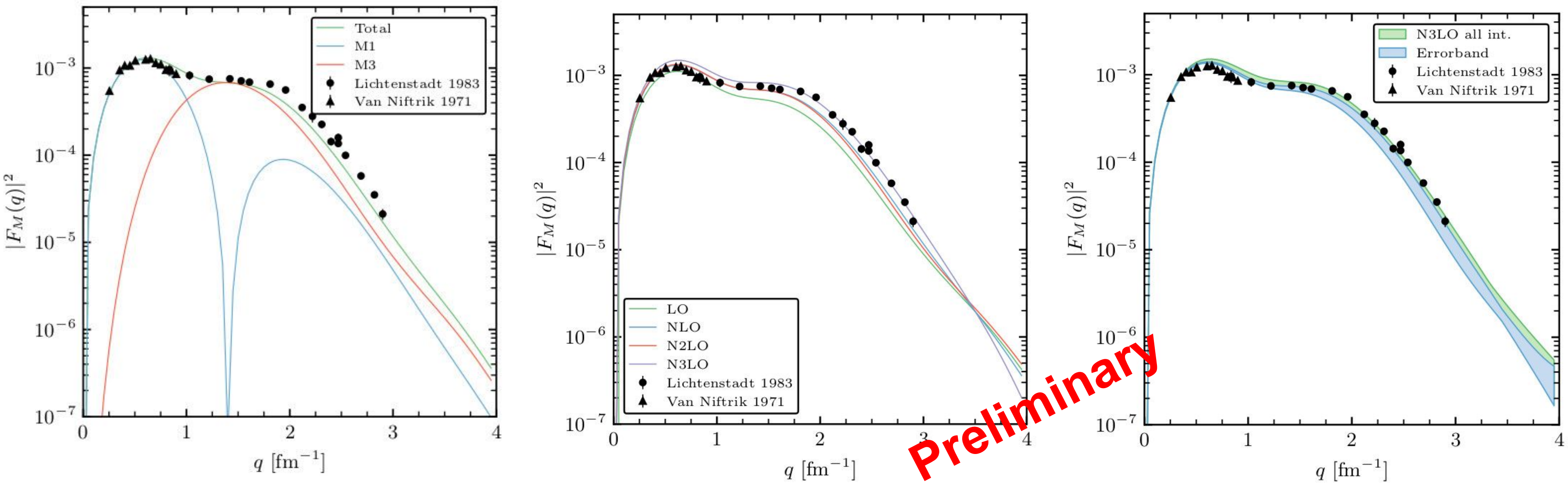
EM decay



e-^{4}He particle scattering

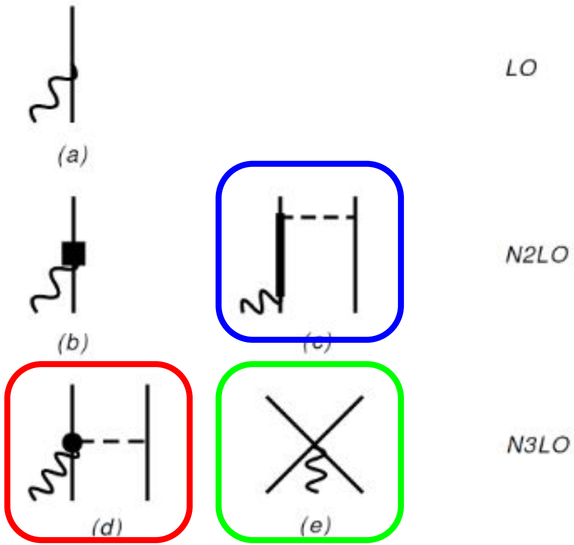


Electromagnetic form factors from chiEFT



^{7}Li magnetic form factor - A. Gnech, G. Chambers-Wall, G. King *et al.* (in preparation)

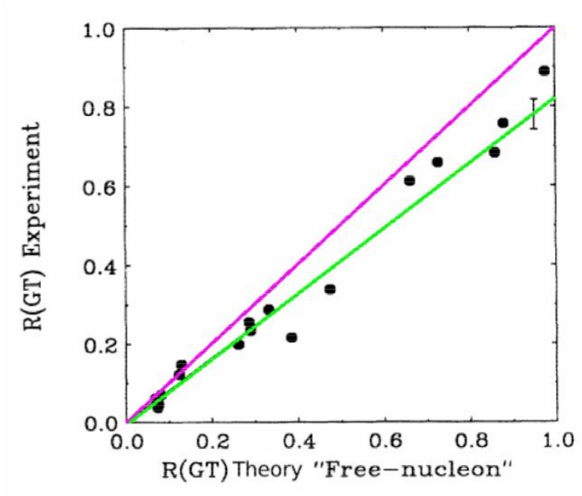
Axial currents with Δ at tree-level



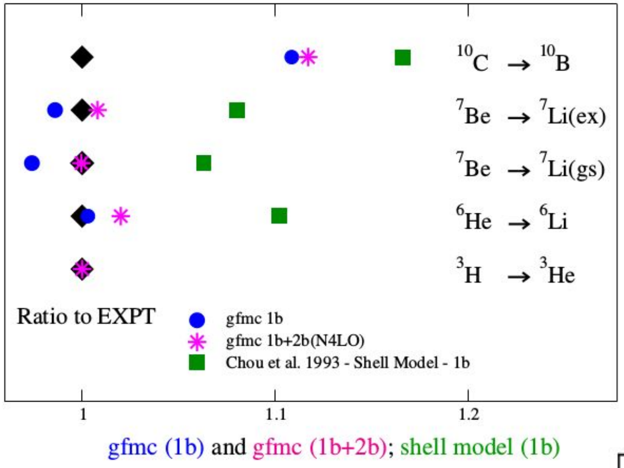
Two body currents of one pion range (red and blue) with c_3 c_4 from Krebs *et al.* Eur.Phys.J.(2007)A32

Contact current involves the LEC c_D

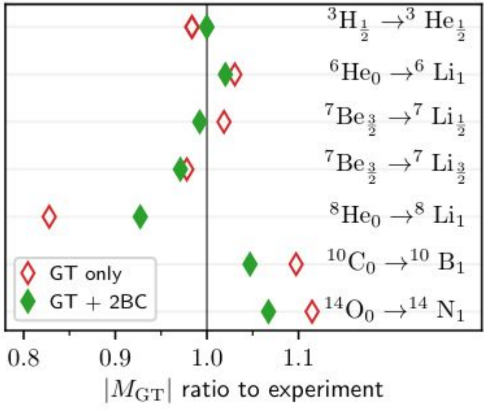
Beta decay



Chou et al. PRC47(1993)163

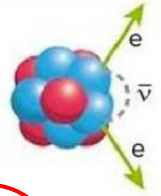


SP *et al*. PRC97(2018)022501



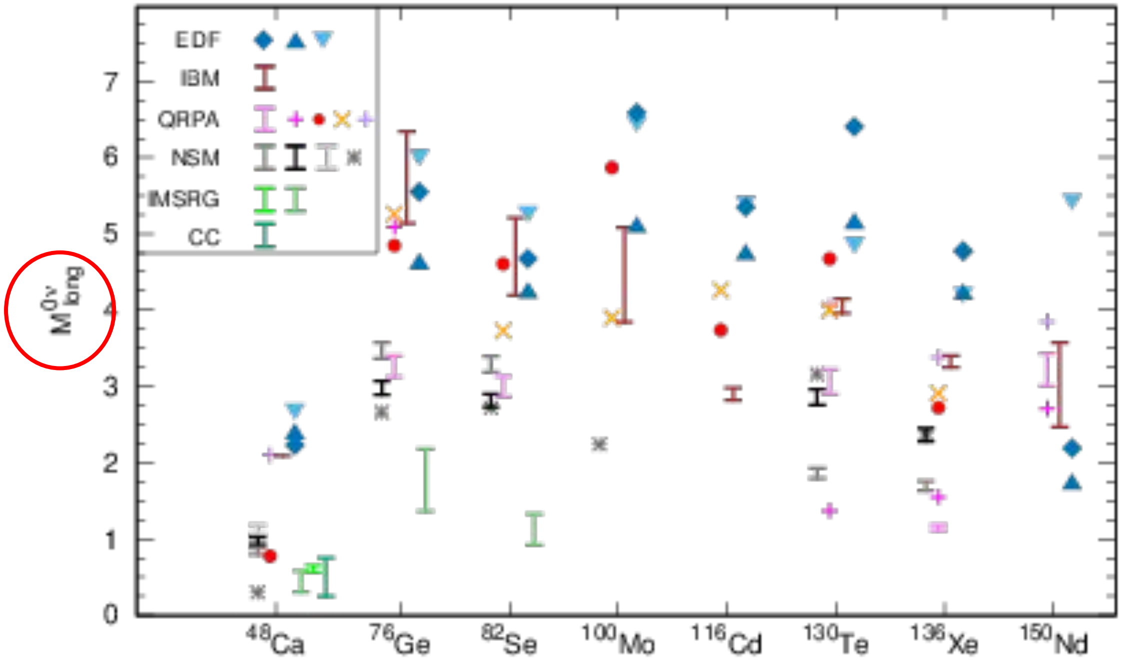
P. Gysbers *Nature Phys.* 15 (2019)

Neutrinoless Double Beta Decay

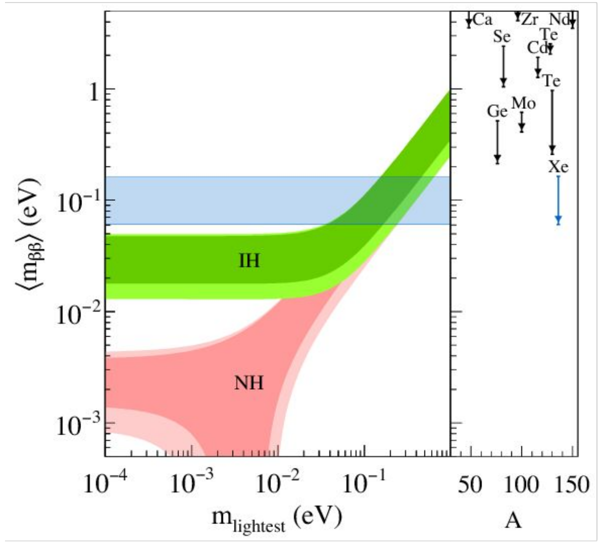


$$[T^{0\nu}_{1/2}]^{-1} = G_{0\nu}(Q,Z)\,|M_{0\nu}|^2\, m^2_{\beta\beta}$$

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



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



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)

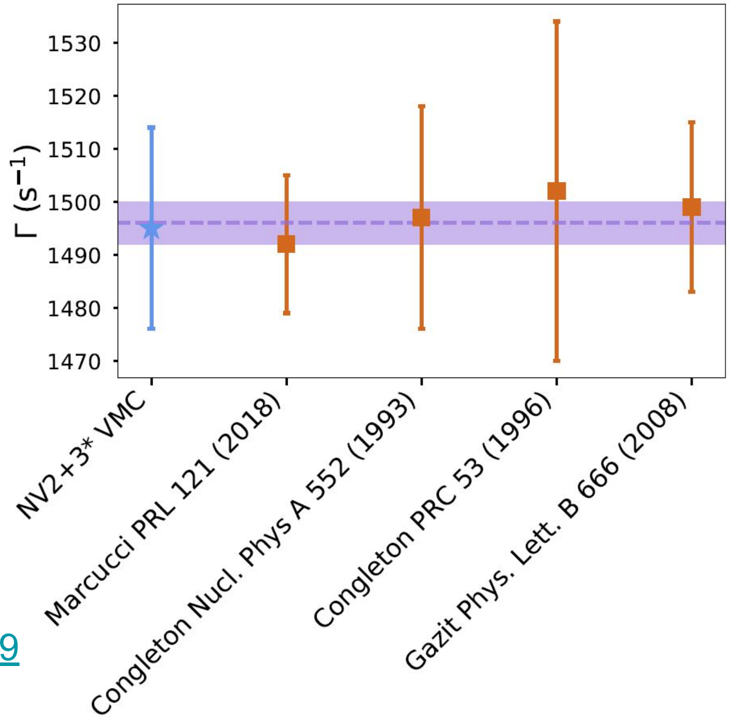
Momentum transfer **q~ 100 MeV**

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

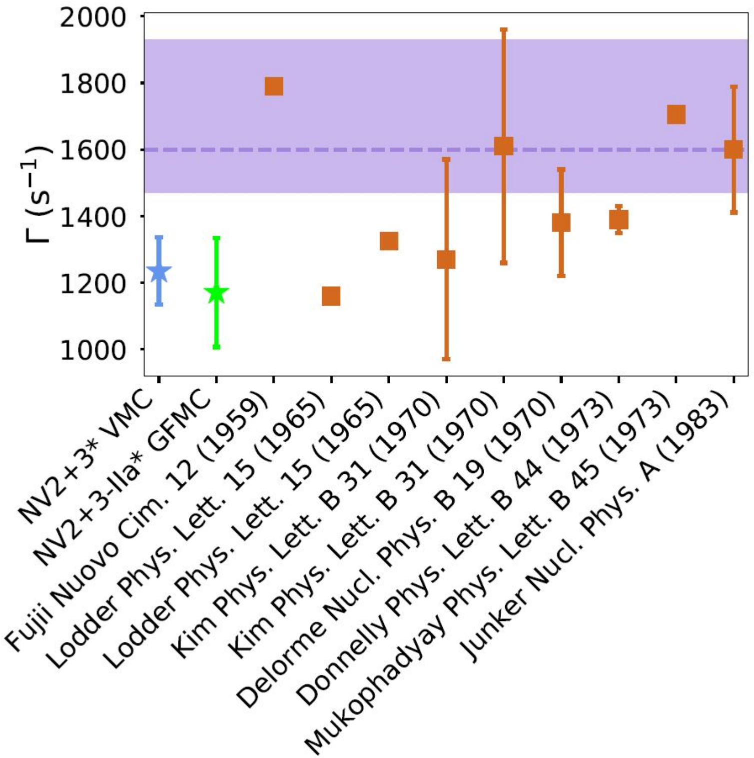
$\Gamma_{VMC}(\text{avg.}) = 1235\ s^{-1} \pm 101\ s^{-1}$
$\Gamma_{GFMC}(\text{IIa*}) = 1171\ s^{-1} \pm 164\ s^{-1}$
$\Gamma_{expt} = 1600\ s^{-1}\ +330/-129\ s^{-1}$

Deutsch *et al.* PLB26(1968)315

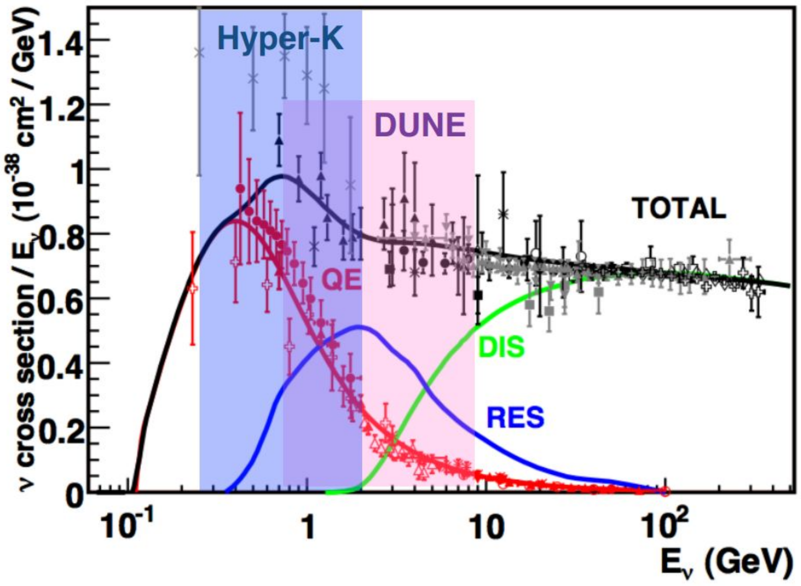
Garrett King *et al.* PRC2022

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**

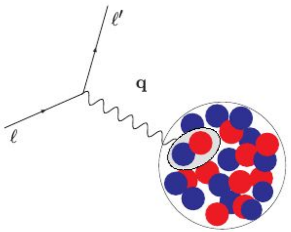
Lepton-Nucleus scattering: Inclusive Processes

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

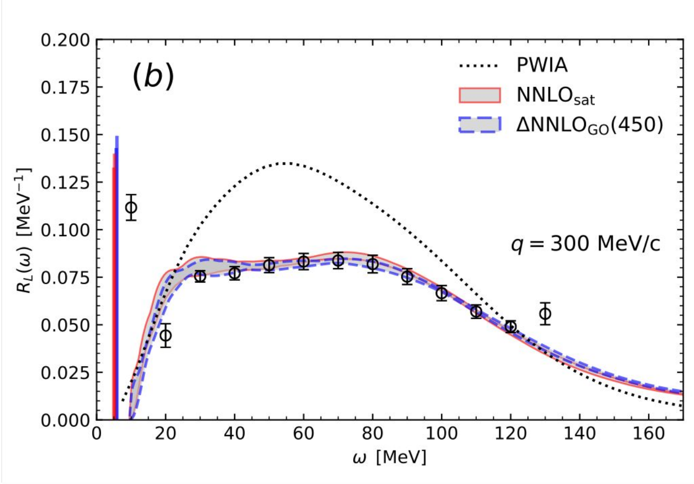
$$\frac{d^2\sigma}{d\omega d\Omega} = \sigma_M \left[v_L R_L(\mathbf{q},\omega) + v_T R_T(\mathbf{q},\omega)\right]$$



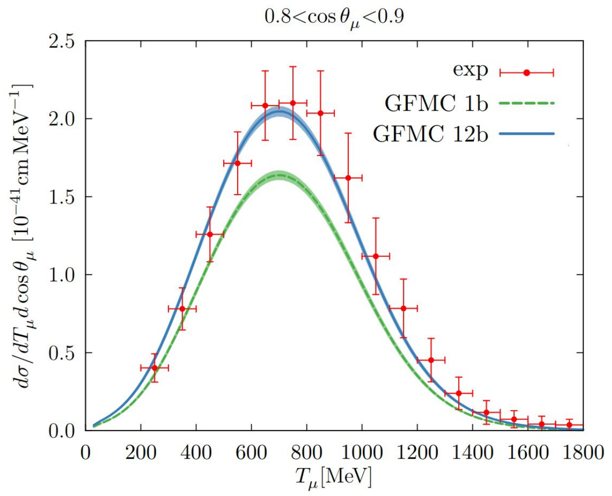
For a recent review on QMC, SF methods see
Rocco *Front. In Phys.*8 (2020)116

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**, …)



Sobczyk et al, PRL127 (2021)

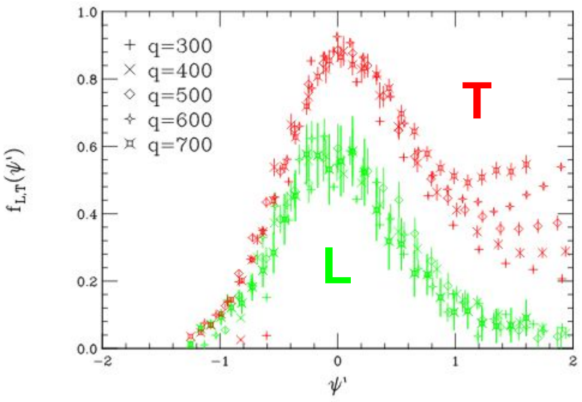


Lovato et al. PRX10 (2020)

Lepton-Nucleus scattering: Data

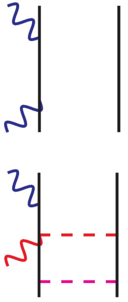
Transverse Sum Rule

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



[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

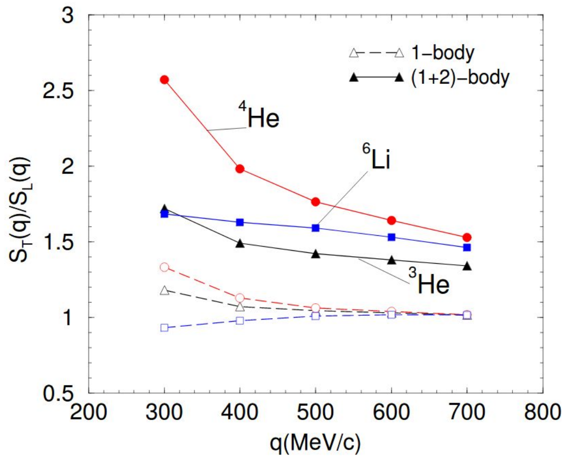


$\langle \mathbf{j}^\dagger_{1b}\ \ \mathbf{j}_{1b}\rangle\ > 0$

Leading one-body term

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

Interference term

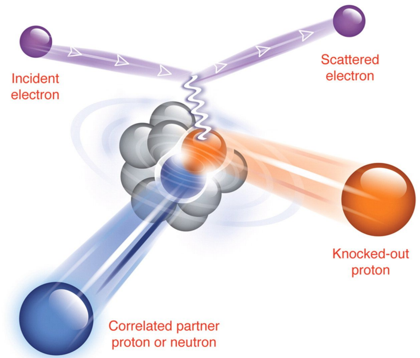


Transverse/Longitudinal Sum Rule
Carlson *et al.* PRC65(2002)024002

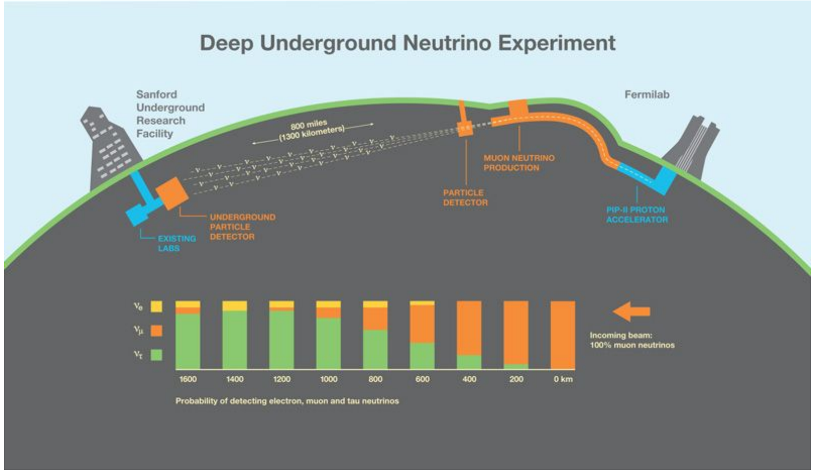
Beyond Inclusive: Short-Time-Approximation

Short-Time-Approximation Goals:

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



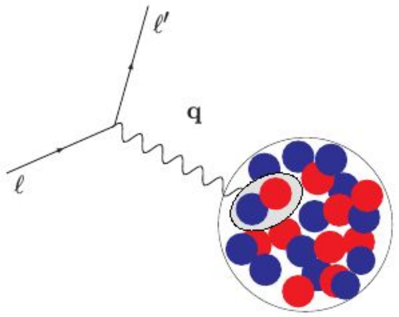
Subedi et al. Science320(2008)1475



[Stanford Lab article]

[e4u collaboration]

Short-Time-Approximation



Short-Time-Approximation:

- Based on Factorization (for SF see Noemi's talk)
- Retains two-body physics
- Correctly accounts for interference

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

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

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

STA: regime of validity

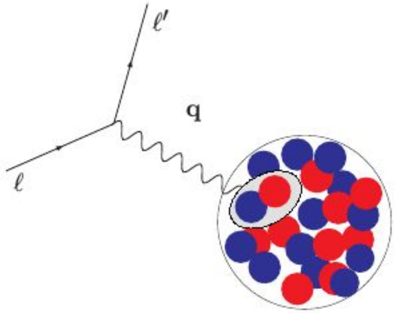
The typical (conservative estimate) energy (time) scale in a nucleus with A correlated nucleons in pairs is

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

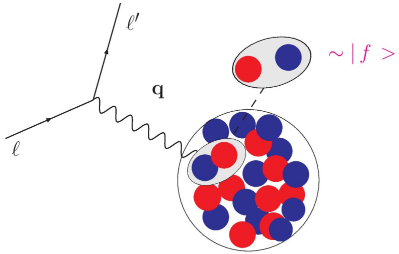
This sets a natural expansion parameter in the QE region characterized by ω_{QE}

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

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

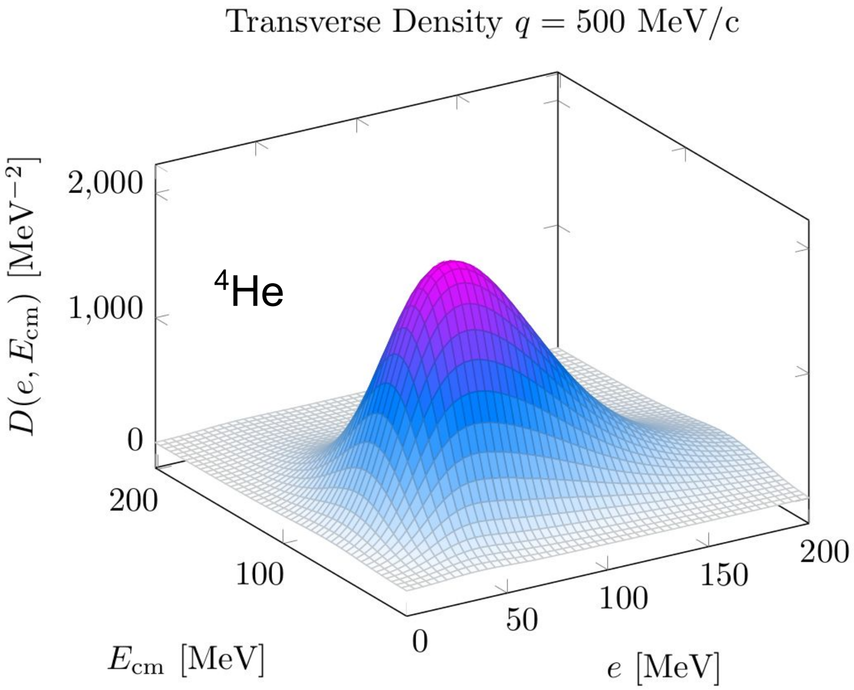
$$R_\alpha(q,\omega) = \sum_f \delta\left(\omega + E_0 - E_f\right) |\langle\, f|O_\alpha(\mathbf{q})|0\rangle|^2$$

Response ***Densities***

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

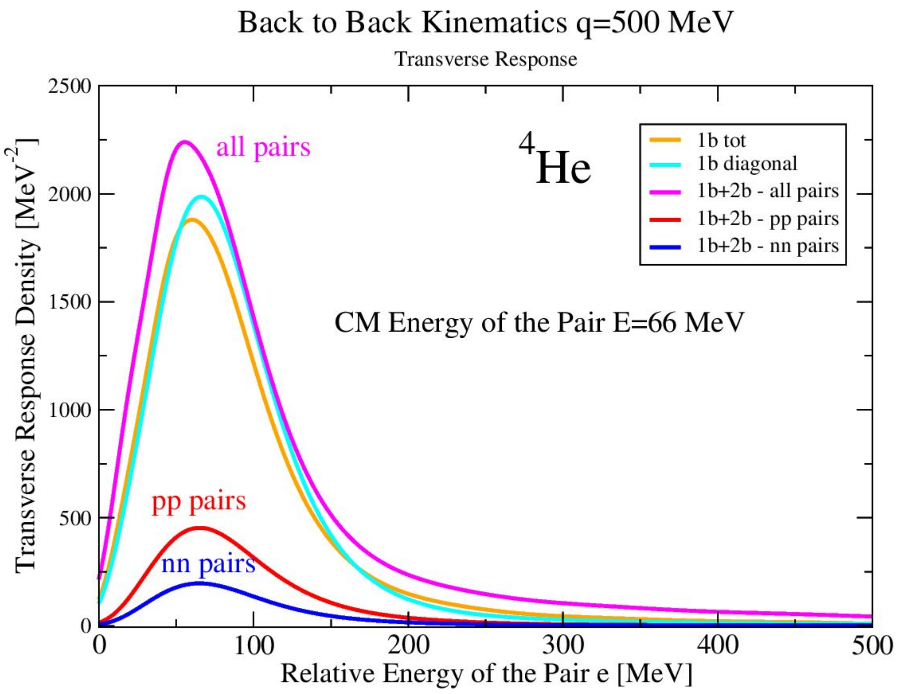
P' and *p'* are the CM and relative momenta of the struck nucleon pair

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



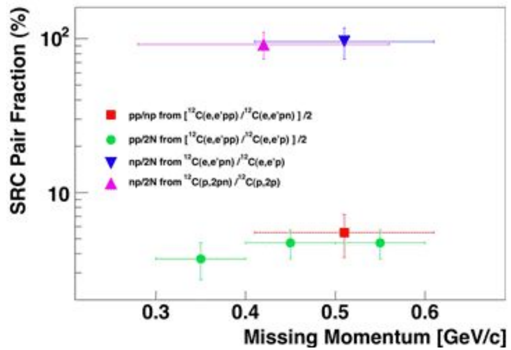
SP *et al.* PRC101(2020)044612

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



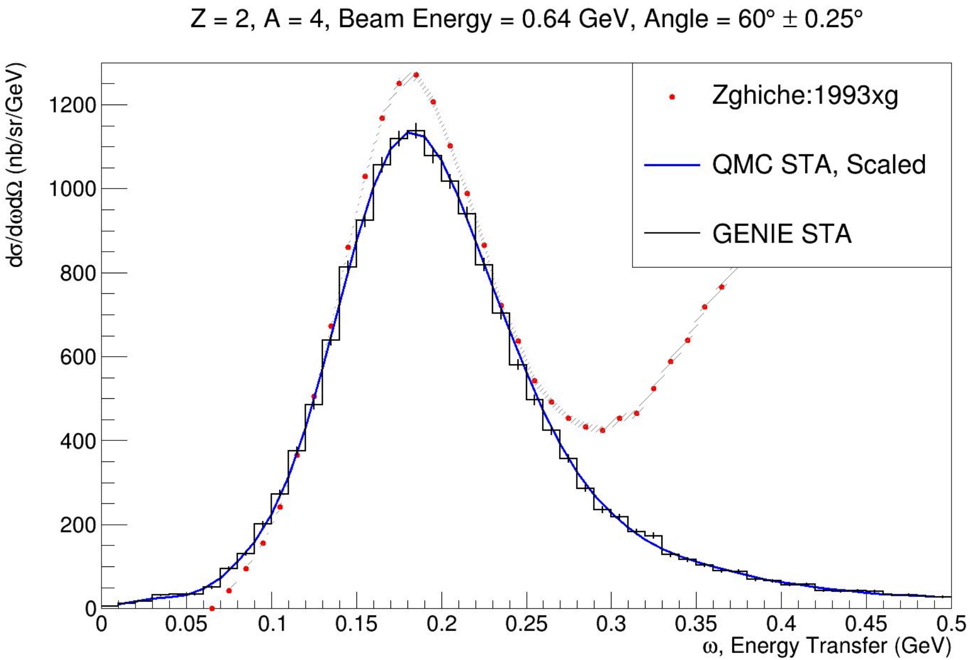
SP *et al.* PRC101(2020)044612

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



Subedi et al. Science320(2008)1475

GENIE validation using e-scattering

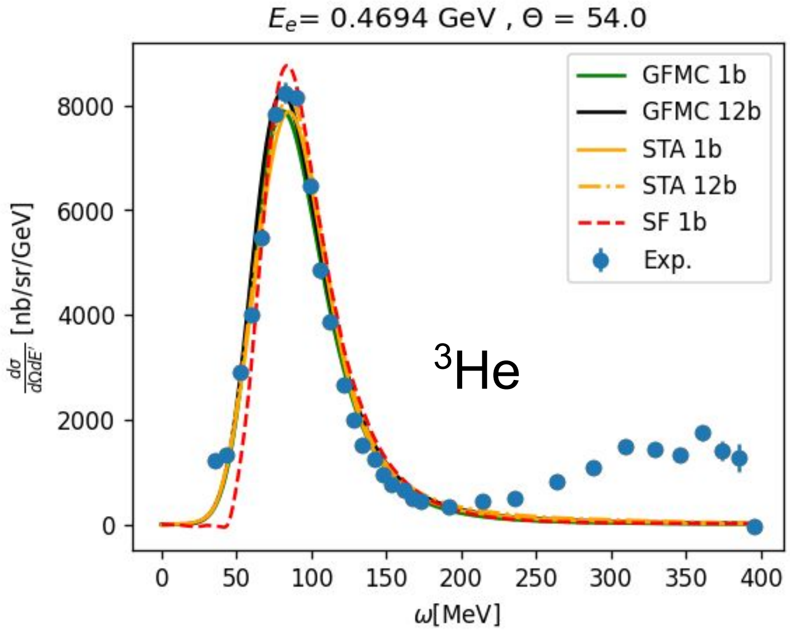


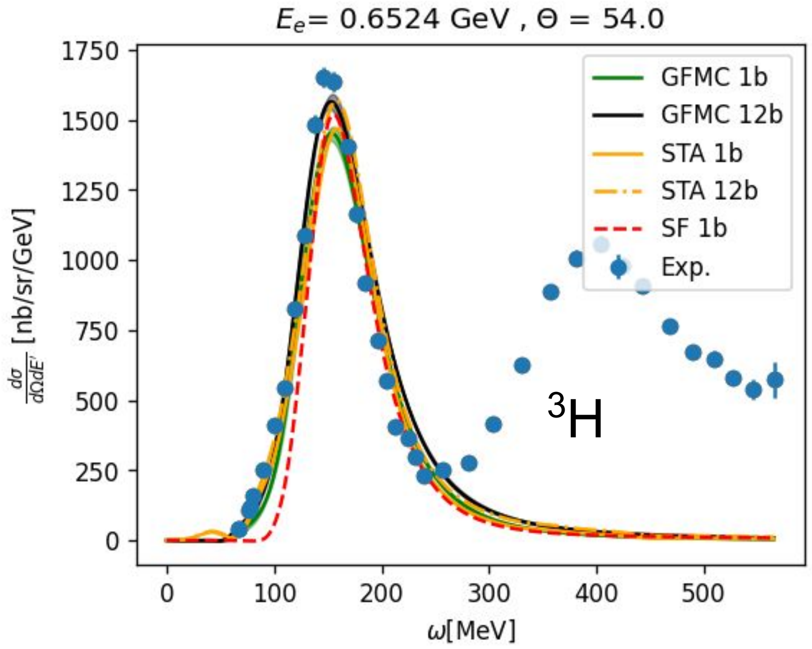
Barrow, Gardiner, SP et al. PRD 103 (2021) 5, 052001

- 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

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

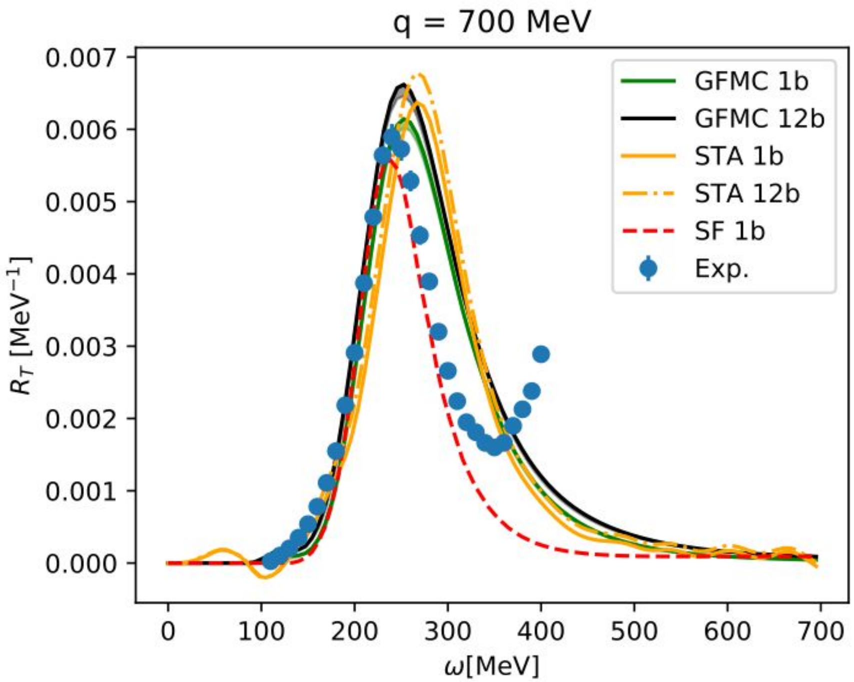
GFMC SF STA: Benchmark & error estimate





Lorenzo Andreoli, *et al.* PRC 2021

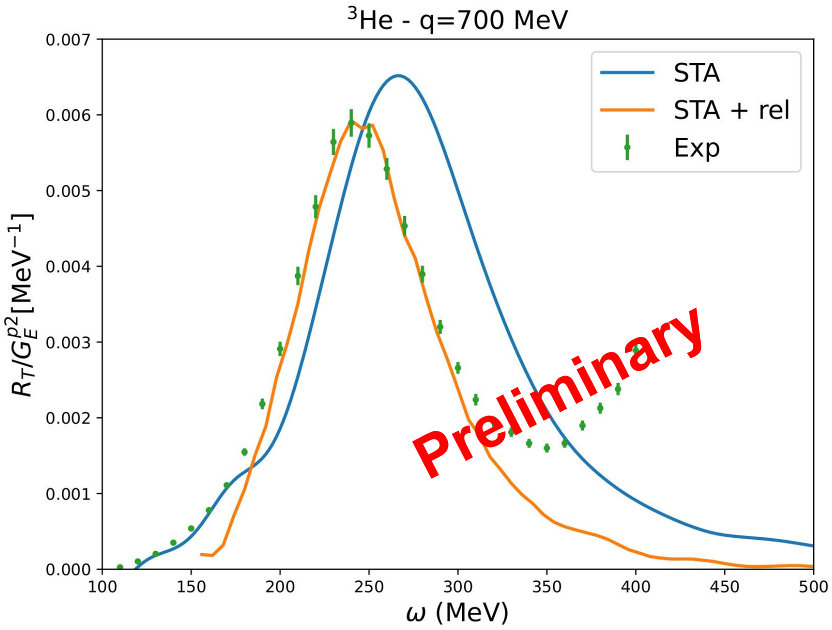
Importance of relativistic corrections



Lorenzo Andreoli, *et al.* PRC 2021

Relativistic corrections

So far we used non relativistic reduction of the single nucleon covarian current (low-momentum expansion both p and p')



WIth Ronen Weiss

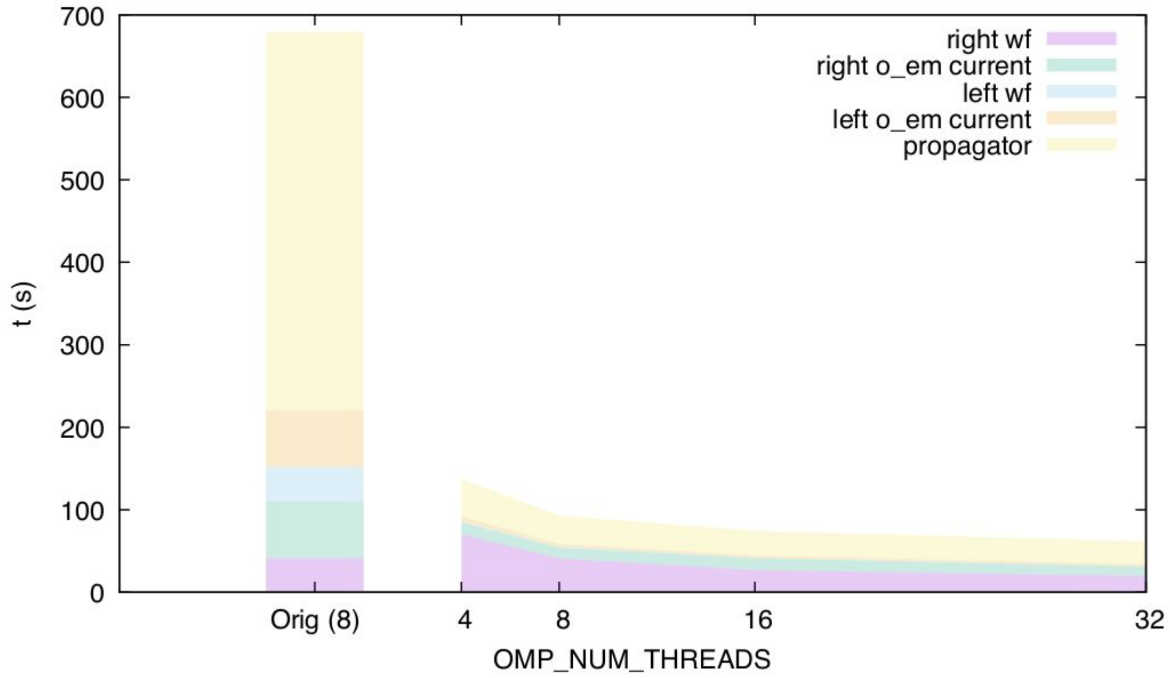
Relativistic corrections obtained expanding the covariant one-nucleon current for high values of momentum transfer **q**

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

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

R. Weiss & L. Andreoli *et al.* (in preparation)

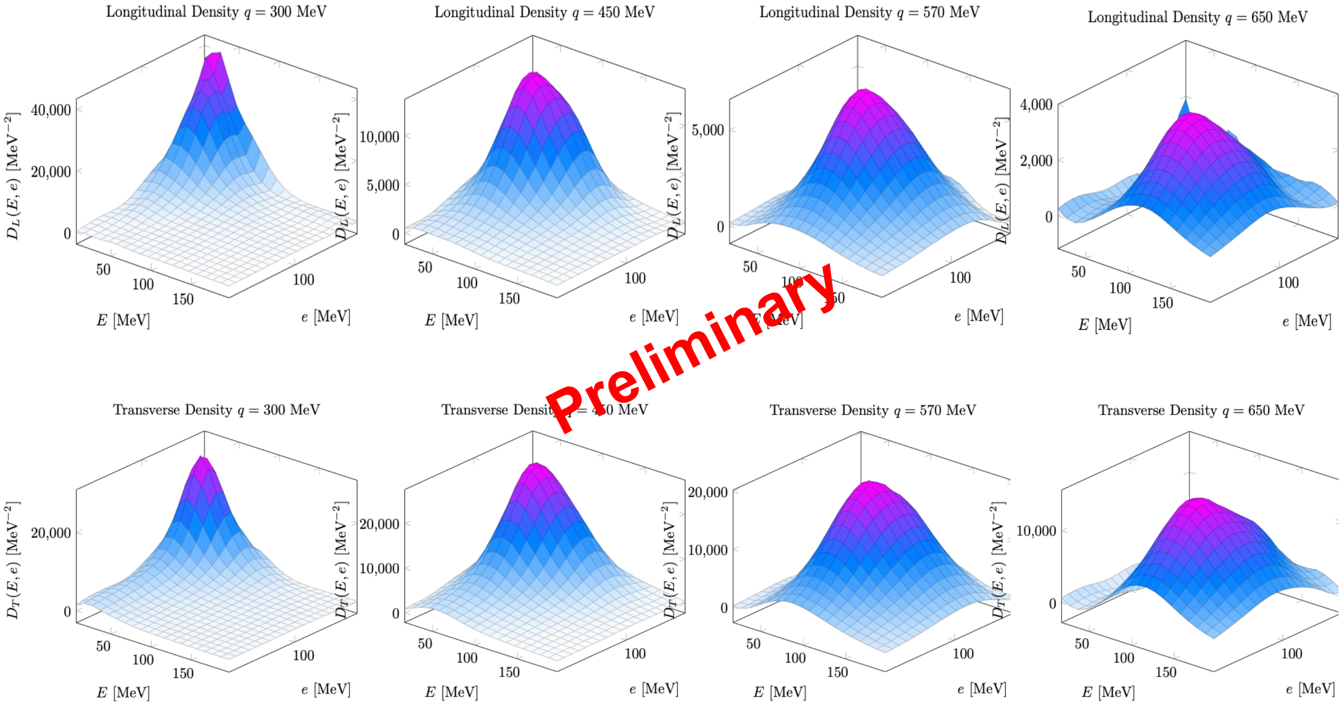
Towards A=12



Lorenzo Andreoli
et al. in preparation

$$R_\alpha(q,\omega) = \int_{-\infty}^{\infty} \frac{dt}{2\pi} e^{i(\omega+E_i)t} \langle \Psi_i | O_\alpha^\dagger(\mathbf{q}) e^{-iHt} O_\alpha(\mathbf{q}) | \Psi_i \rangle$$

^{12}C Response Densities

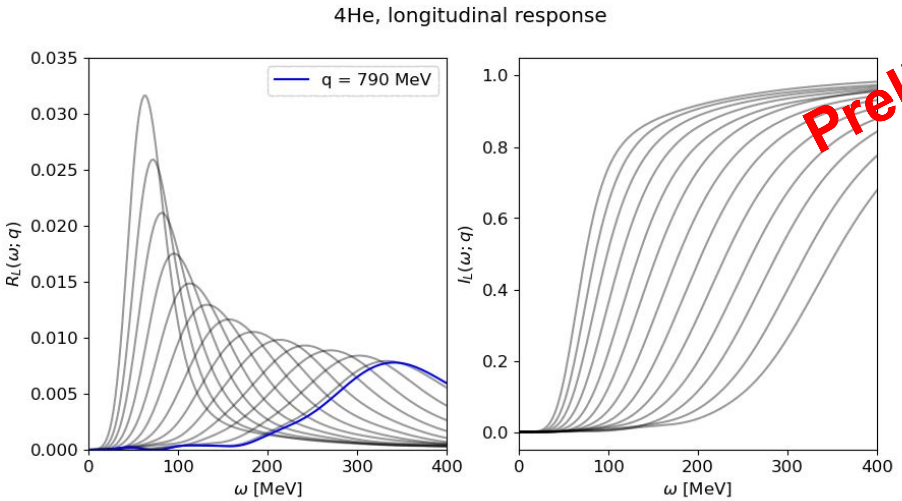


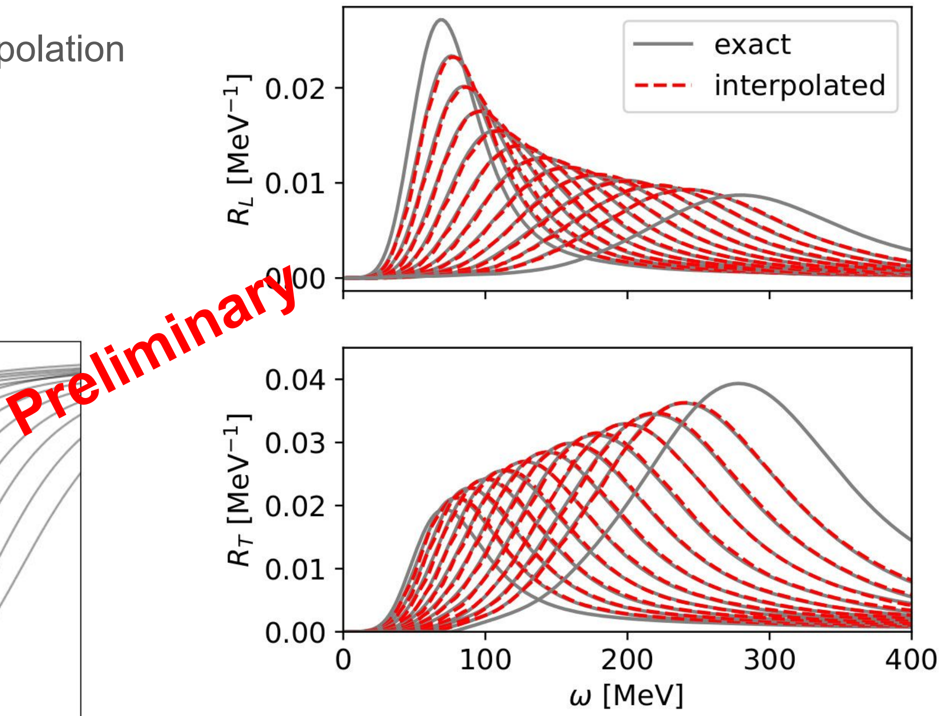
Lorenzo Andreoli *et al.* in preparation

^{12}C cross sections: interpolation scheme

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

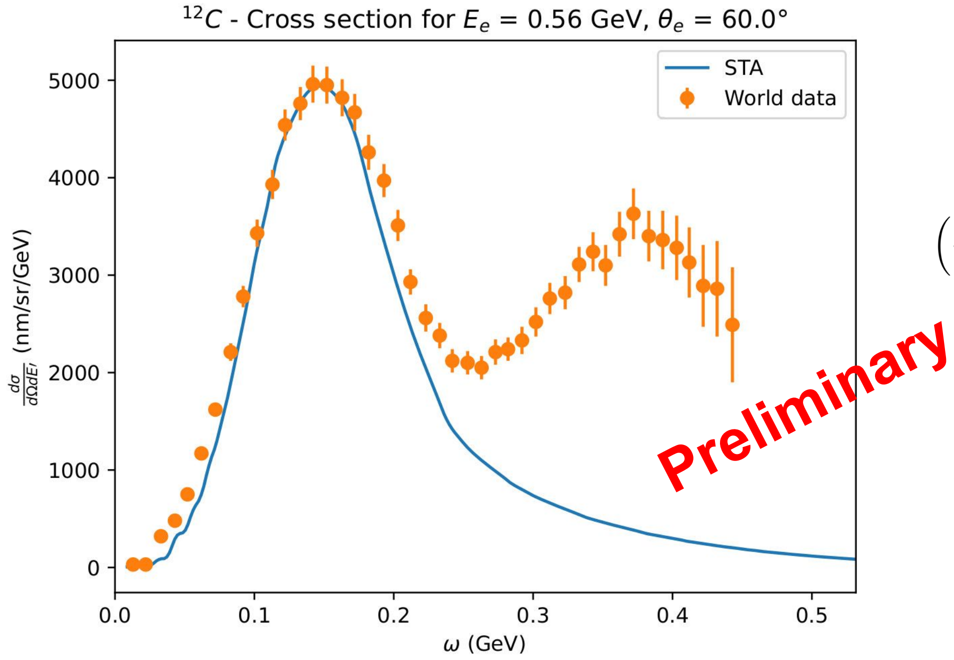
$$I_{L/T}(\omega;\mathbf{q}) = \frac{\int_0^\omega R_{L/T}(\omega';\mathbf{q})d\omega'}{\int_0^\infty R_{L/T}(\omega';\mathbf{q})d\omega'}$$



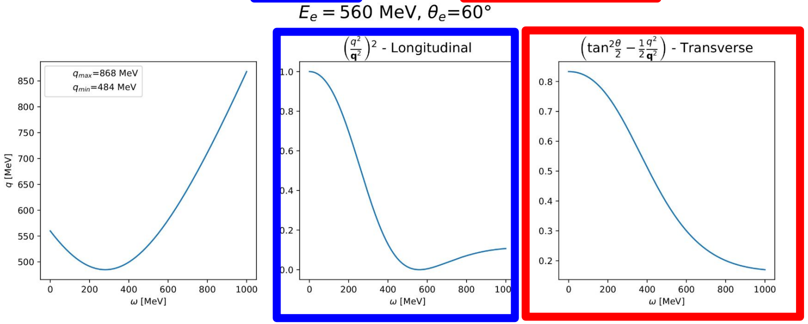


Lorenzo Andreoli *et al.* in preparation

^{12}C cross sections

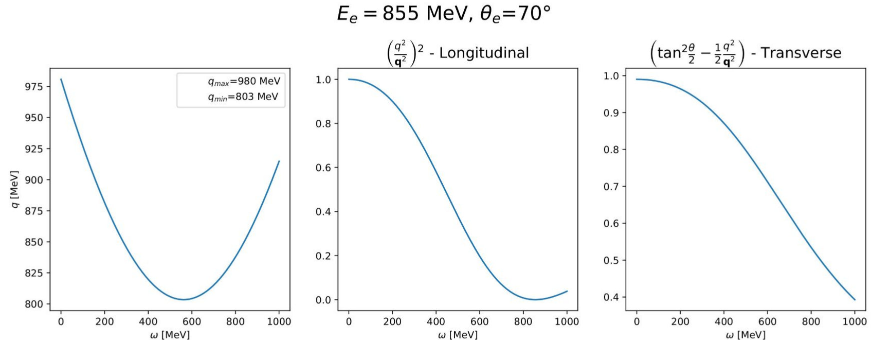


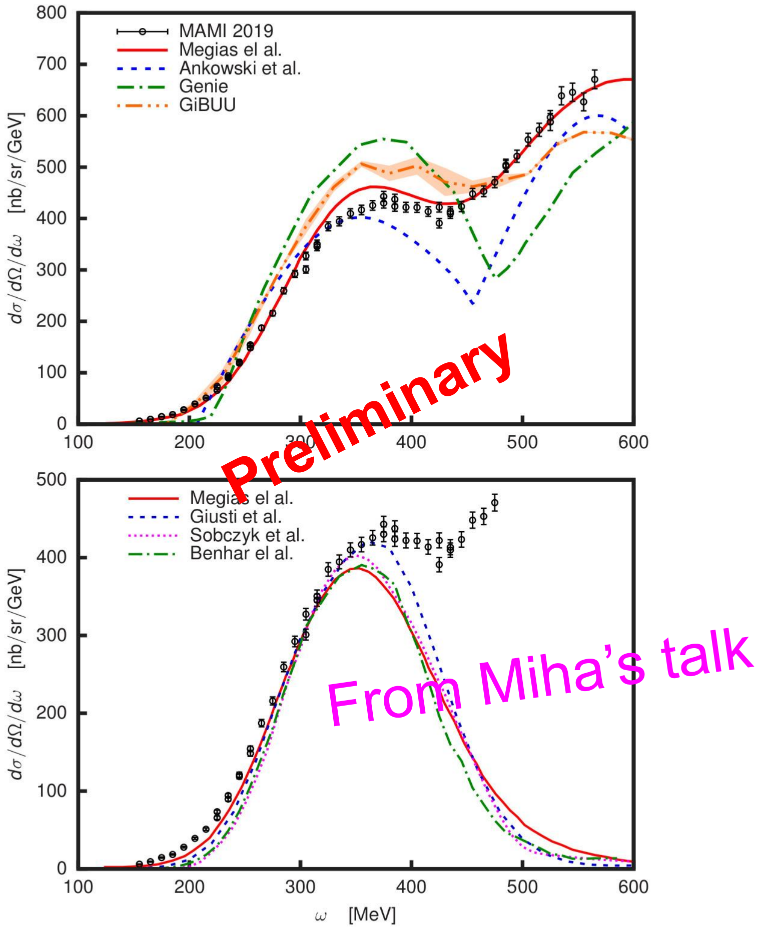
$$\left(\frac{d^2\sigma}{dE'd\Omega'}\right)_e = \left(\frac{d\sigma}{d\Omega'}\right)_{\mathrm{M}} \left[\left(\frac{q^2}{\mathbf{q}^2}\right)^2 R_L(|\mathbf{q}|,\omega) + \left(\tan^2\frac{\theta}{2} - \frac{1}{2}\frac{q^2}{\mathbf{q}^2}\right) R_T(|\mathbf{q}|,\omega)\right]$$



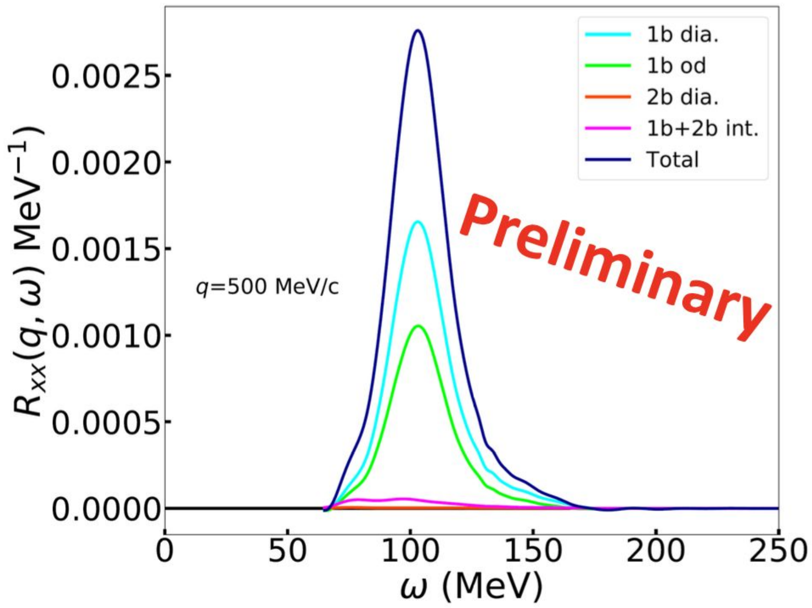
(Available) Mainz kinematics

E_e = 855 MeV θ_e = 70





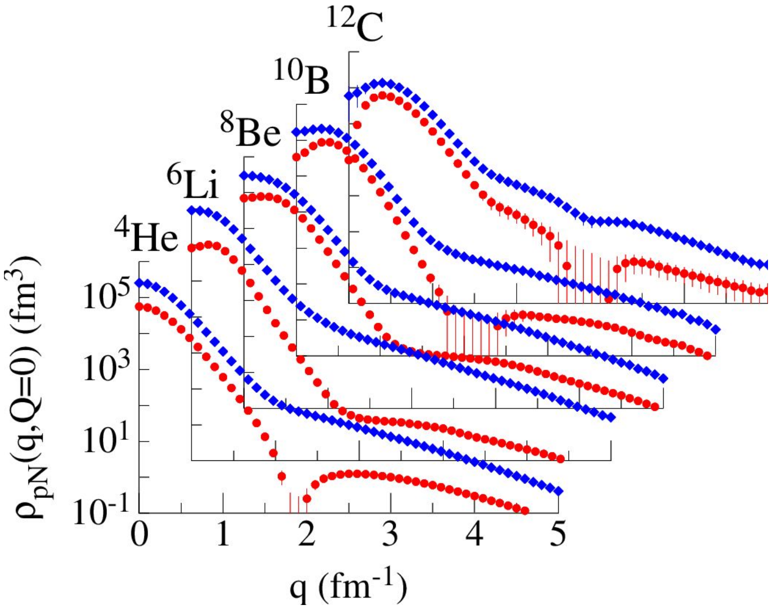
NC processes on deuteron with STA



Garrett King *et al.* in preparation

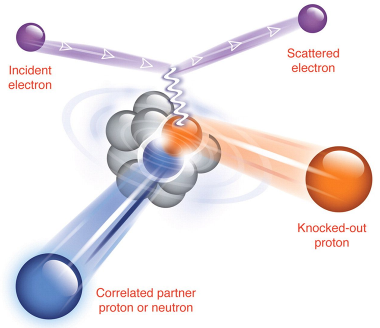
Momentum distributions

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



pp-pairs; np-pairs

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

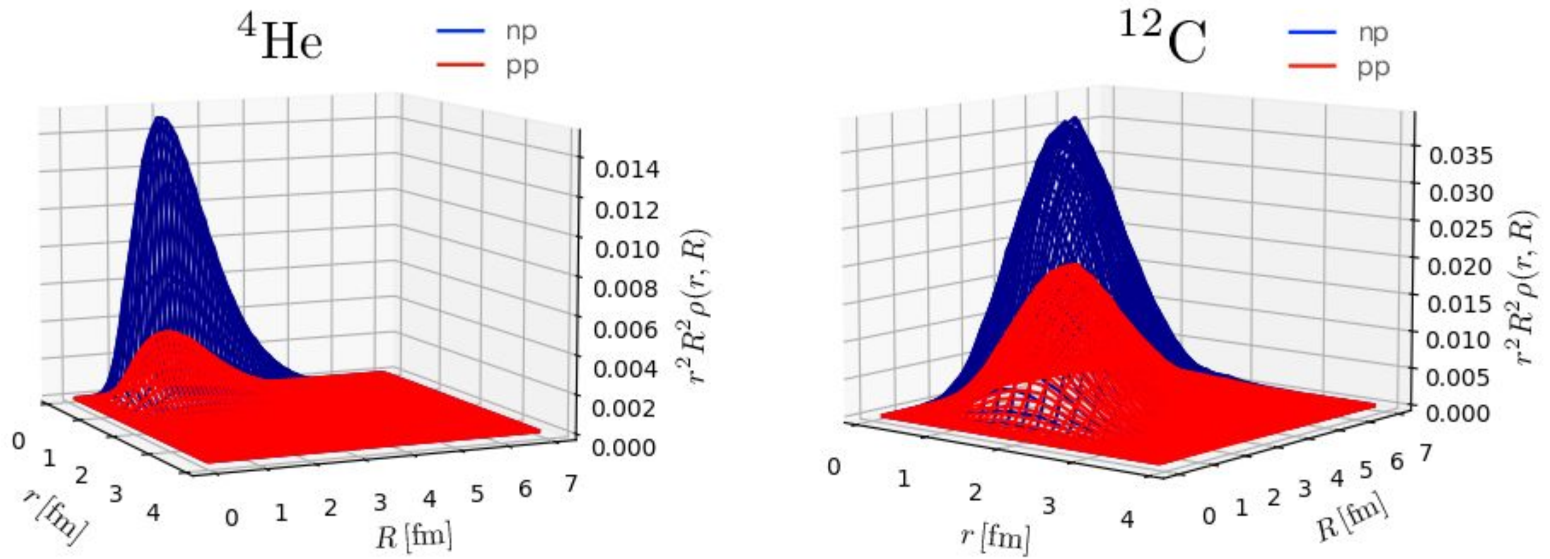


New two-body momentum distributions from chiEFT potentials

Piarulli, SP, Wiringa PRC (2023)

Two-body densities

AV18UX

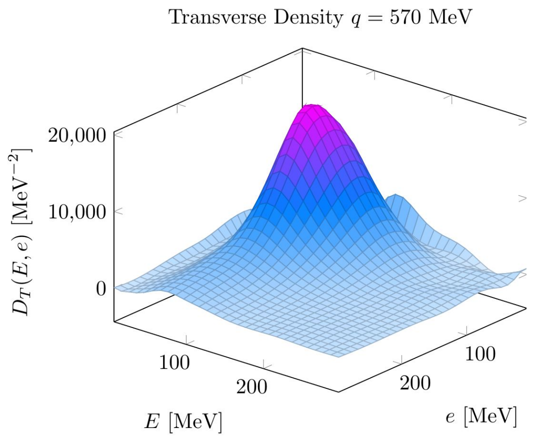


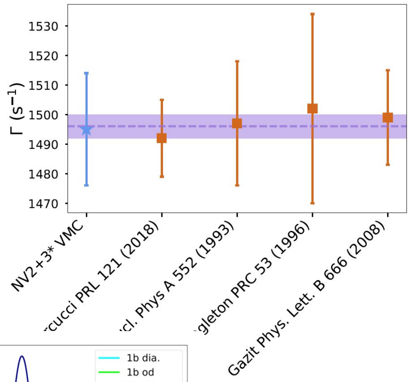
Piarulli, SP, Wiringa PRC (2023)

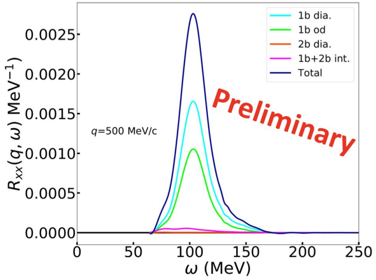
[data]

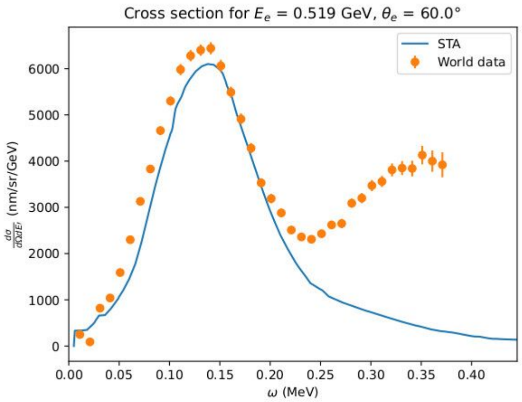
Summary

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.









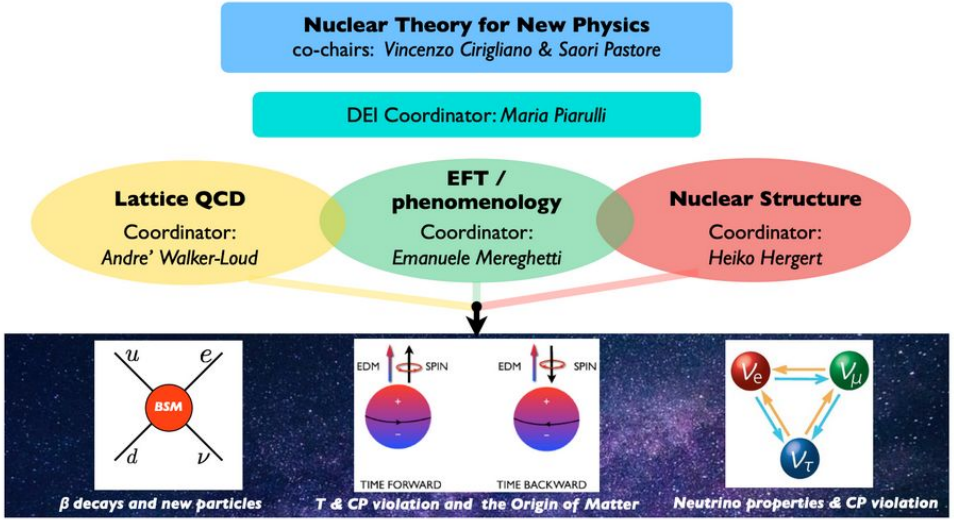
Close **collaborations** between **NP**, **LQCD**, **Pheno**, **Hep**, **Comp**, **Expt**, …
are required to progress
e.g., NP is represented in the Snowmass process

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, …

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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

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