# NTNP: Neutrino-Nucleus Scattering

2024 Topical Collaboration Principal Investigators’ Exchange Meeting

May 2nd, 2024

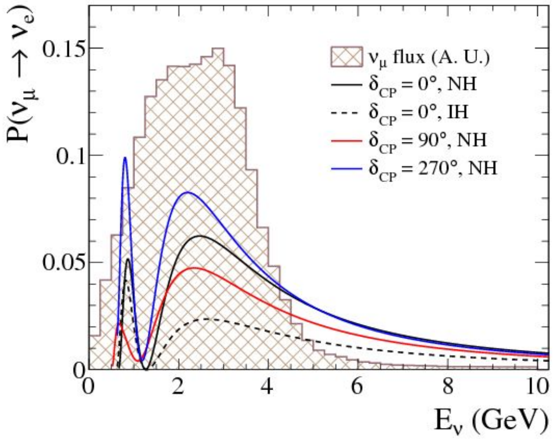
# NTNP Thrust 3: Objectives & Timeline

**XSEC 4**: Compute electroweak (electron and neutrino) cross sections in A=4-12 using Green's Function Monte Carlo (GFMC), Short-Time Approximation (STA), Spectral Function (SF) formalisms.

**XSEC 5**: Investigate exclusive reactions and relativistic effects induced by electrons and neutrinos in the STA and SF formalism.

| **Activities** | Yr 1 | Yr 2 | Yr 3 | Yr 4 | Yr 5 |
|---|---|---|---|---|---|
| **XSEC**: *Neutrino-nucleus scattering* | | | | | |
| XSEC-1 Nucleon elastic form factors with sLapH [CM, AN, AS, AWL] | | | | | |
| XSEC-2 $N \rightarrow \Delta$ transitions with sLapH [CM, AN, AS, AWL] | | | | | |
| XSEC-4 Inclusive processes with QMC, STA, SF [JC, BD, SG, AL, SP, MP, NR, RS, IT] | | | | | |
| XSEC-5 Exclusive processes with STA and SF [JC, SG, AL, SP, MP, NR, RS] | | | | | |

# Neutrino Oscillations Systematics

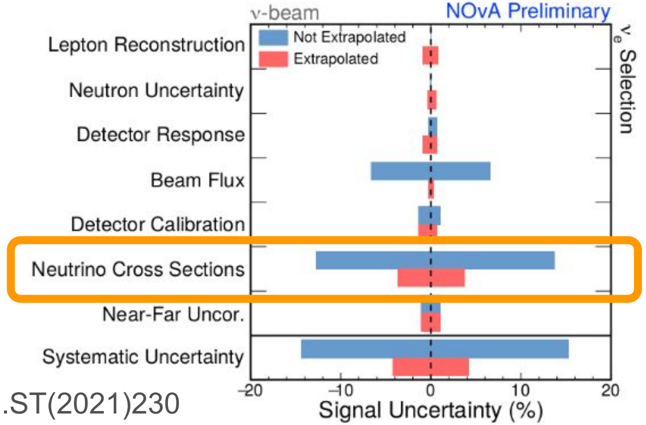



DUNE CP violation sensitivity
Ann.Rev.Nucl.Part.Sci. 66

Unprecedented theoretical accuracy in ν-Ar cross section required to achieve sensitivity to **CP violation at DUNE**.

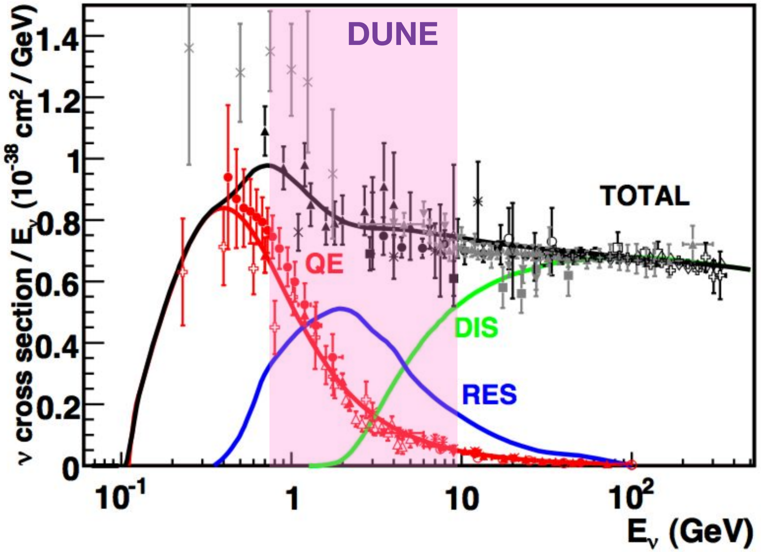
**A precise determination of neutrino-nucleus cross sections is required to extract ν-oscillation parameters.**

Oscillation experiments report large systematic uncertainties associated with neutrino-nucleus interactions.



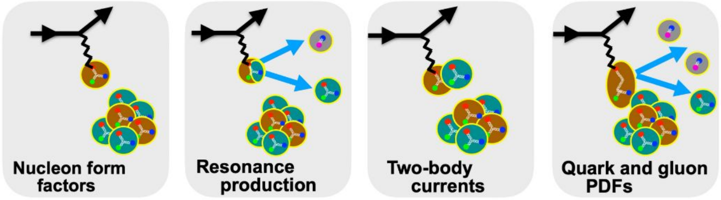

NOvA Eur.Phys.J.ST(2021)230

# Neutrino Cross Section Anatomy




Formaggio & Zeller, Rev. Mod. Phys. 84,

Multi-scale problem covering a broad range of energies with different reaction mechanisms



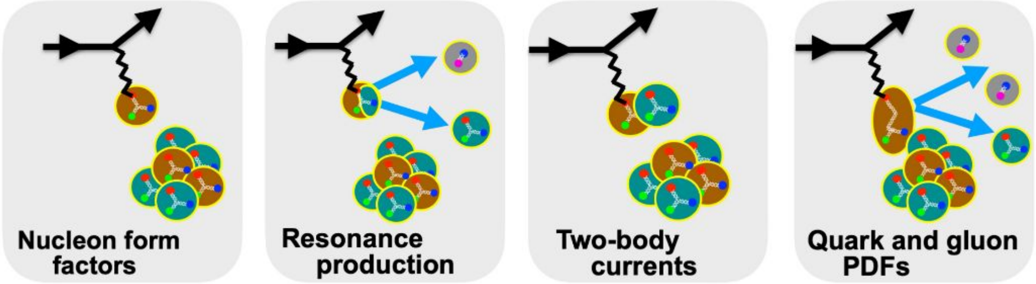

Courtesy of M. Wagman

NP + HEP effort

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

# Building Blocks from LQCD

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




Courtesy of M. Wagman

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

# Quantum Monte Carlo Methods

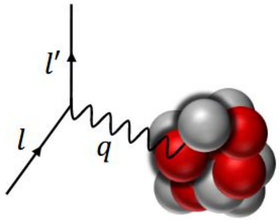
Variational (VMC) and Green's Function Monte Carlo (GFMC) Methods solve the many-body Schrodinger equation, retain the complexity of many-nucleon correlations

$$H = \sum_i -\frac{\hbar^2}{2m}\nabla_i^2 + \sum_{i<j} v_{ij} + \sum_{i<j<k} V_{ijk}$$

And many-nucleon electroweak currents

$$O_\alpha(\mathbf{q}) = \sum_i O_i^{(\alpha)}(\mathbf{q}) + \sum_{i<j} O_{ij}^{(\alpha)}(\mathbf{q}) + \cdots$$

Two-body operators describe the interaction of the probe with pairs of correlated nucleons



# Lepton-Nucleus Scattering

QMC's effort has been extensively addressed to study inclusive QE electroweak processes

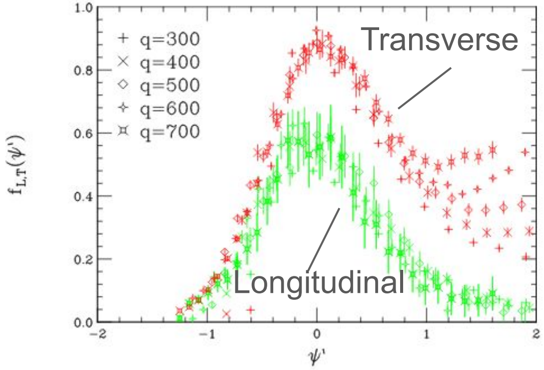
Nuclear Response Function

$$R_\alpha(q,\omega) = \overline{\sum_{M_i}} \sum_f \langle \Psi_i | O_\alpha^\dagger(\mathbf{q}) | \Psi_f \rangle \langle \Psi_f | O_\alpha(\mathbf{q}) | \Psi_i \rangle \, \delta(E_f - E_i - \omega)$$

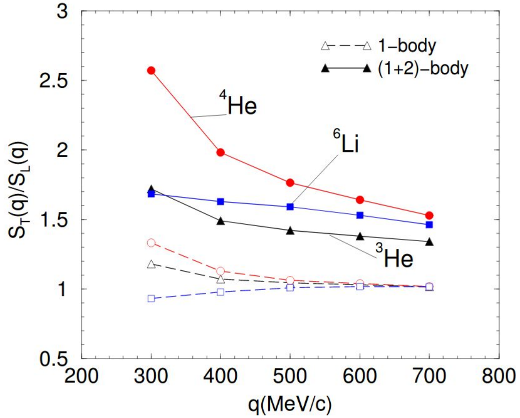
$$\left.\begin{array}{ll} \text{Longitudinal Response} & O^{(L)}(\mathbf{q}) = \rho(\mathbf{q}) \\ \text{Transverse Response} & O^{(T)}(\mathbf{q}) = \mathbf{j}(\mathbf{q}) \end{array}\right\} \text{Electron scattering}$$

Two-nucleon correlations and currents required to explain electron scattering data in the QE region, including the *Interference* term

one + two-body interference $\langle \mathbf{j}_i \, \mathbf{j}_{ij} \, v_{ij} \rangle > 0$




$^4$He Electromagnetic Data




Transverse/Longitudinal

Carlson *et al.* PRC65(2002)024002

# Green's Function Monte Carlo Method

Exploits integral properties of the Response Function to avoid calculations of the final states. The Response Function is obtained inverting the integral Laplace transform.

$$\widetilde{R}_\alpha(q,\tau) = \int_{\omega_{\rm el}}^{\infty} d\omega\, \mathrm{e}^{-\omega\tau}\, R_\alpha(q,\omega)$$

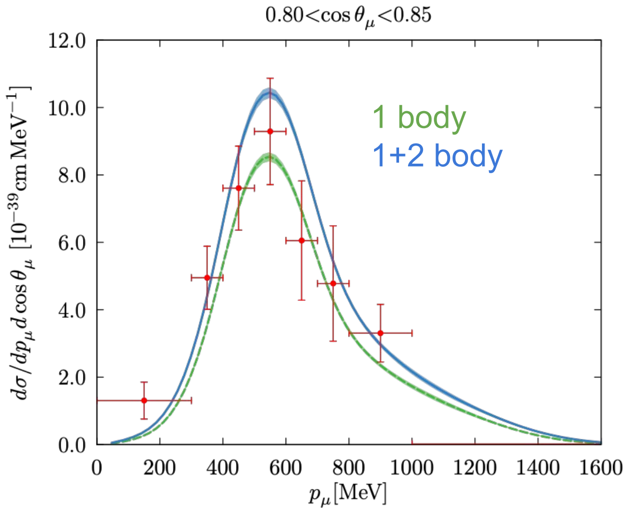
GFMC exact in the QE region

Two-body currents give the enhancement

Based on a non-relativistic approximation

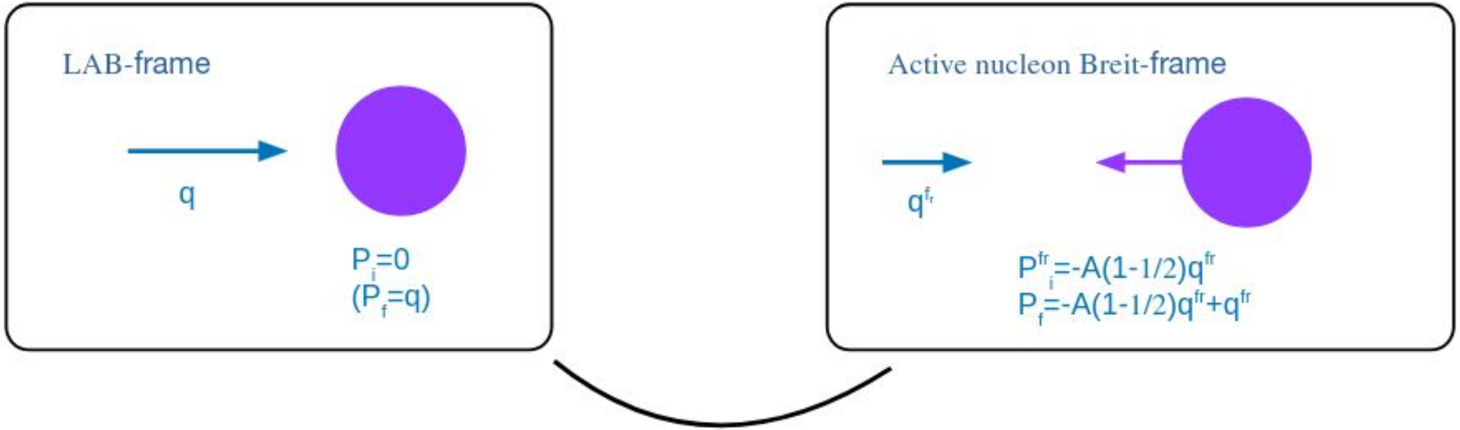
Treats only inclusive processes

CC neutrino-$^{12}$C scattering




Lovato, Rocco et al , PRX.10 (2020)

# GFMC Recent Developments




Lorentz Boost connects the two frames

$$R^{\mu\nu}_{LAB}(\omega, q) = B^{\mu}{}_{\alpha}\,[\beta]\,B^{\nu}{}_{\beta}\,[\beta]\,R^{\alpha\beta}_{fr}(\omega^{fr}, \mathbf{q}^{fr})$$

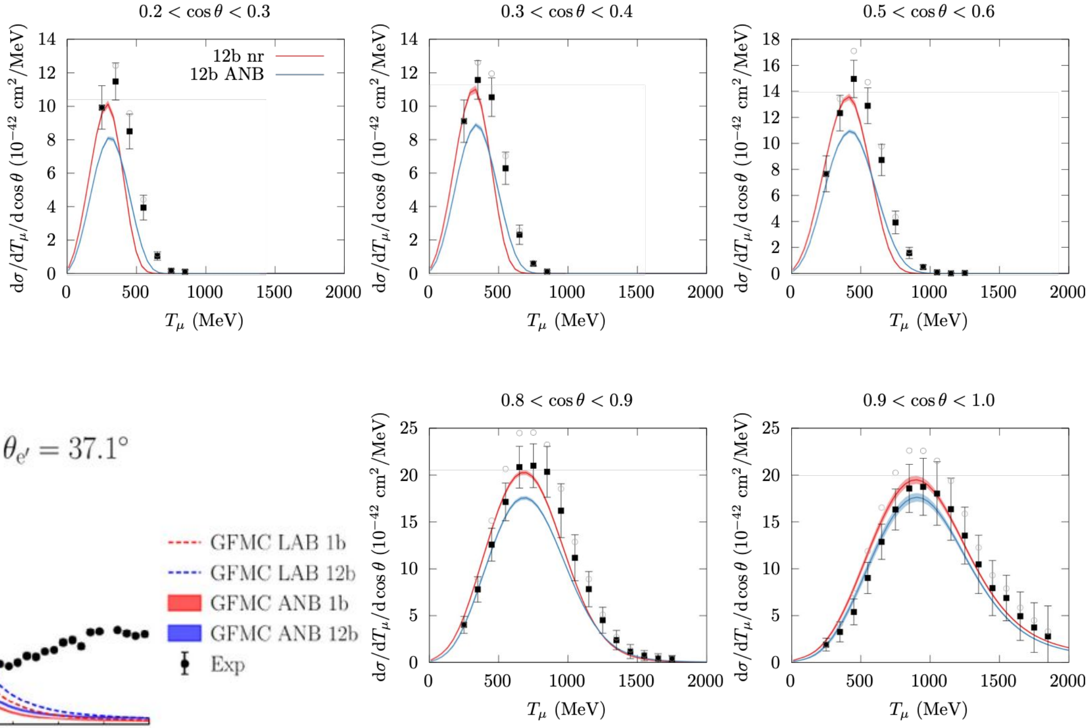
Inclusion of relativistic effects in GFMC inclusive response functions

Lovato, Rocco et al

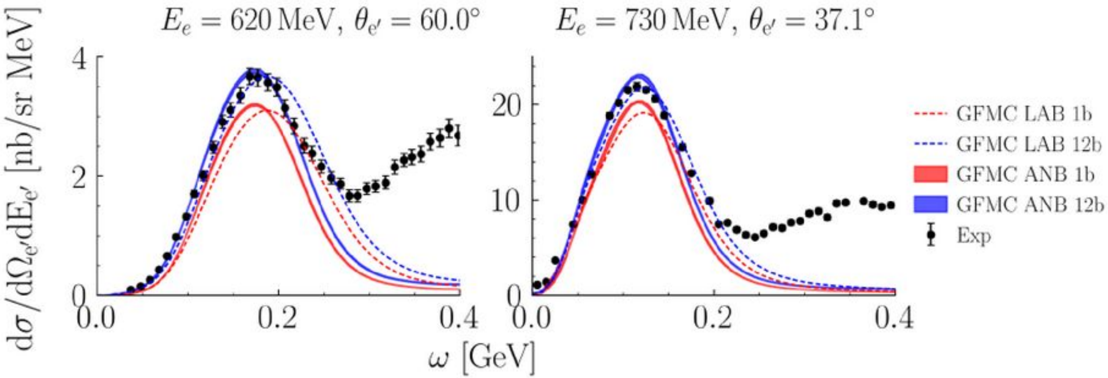
# GFMC New Results

Nikolakopoulos, Lovato, and Rocco, PRC109(**2024**)

## Neutrino-$^{12}$C scattering vs MiniBoone

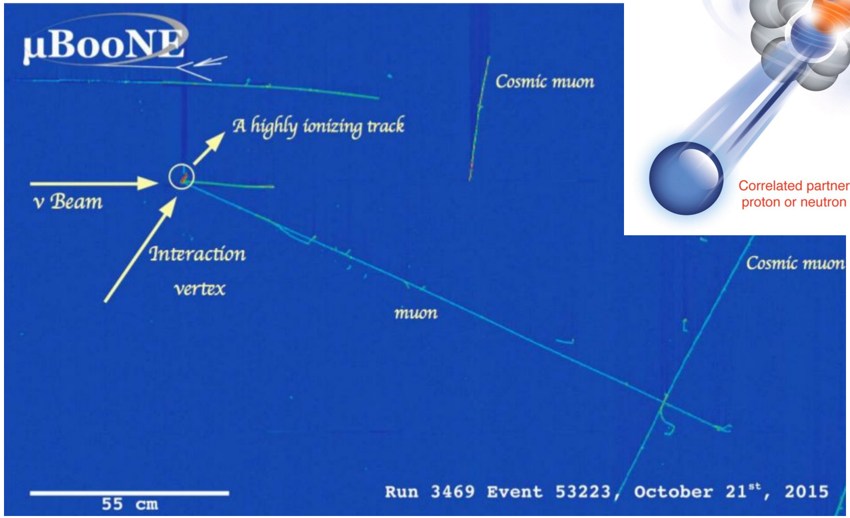


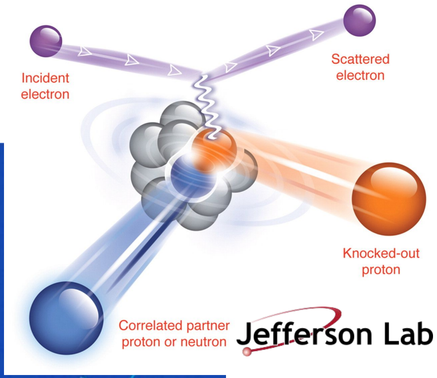

## Electron-$^{12}$C scattering




* pion-production not included

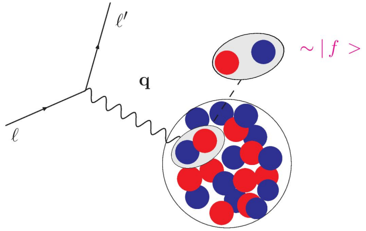
# Beyond Inclusive Processes




Current effort directed to include **relativistic effects** and accommodate for **exclusive processes**

# Short-Time Approximation




Use VMC in the STA to calculate the Nuclear Response Function in real time, propagating only pairs of correlated nucleons.

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

Is in good agreement with exact GFMC in the QE region

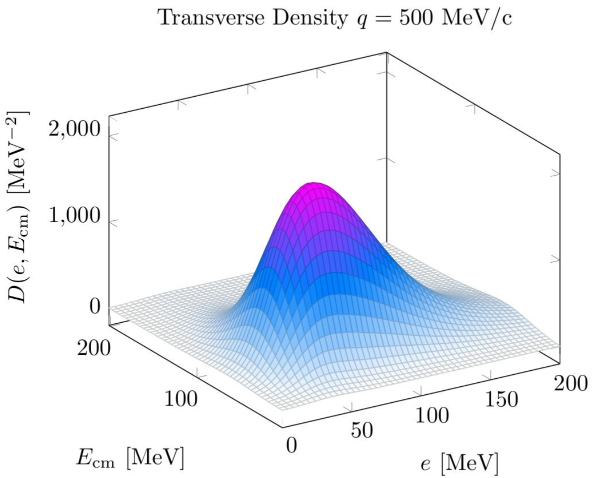
Two-nucleon dynamics (correlation & currents) accounted for

Allows to examine two-nucleon final state dynamics

Can be extended to describe exclusive channels

Can accommodate for relativistic effects at the vertex

Electron scattering from $^4$He

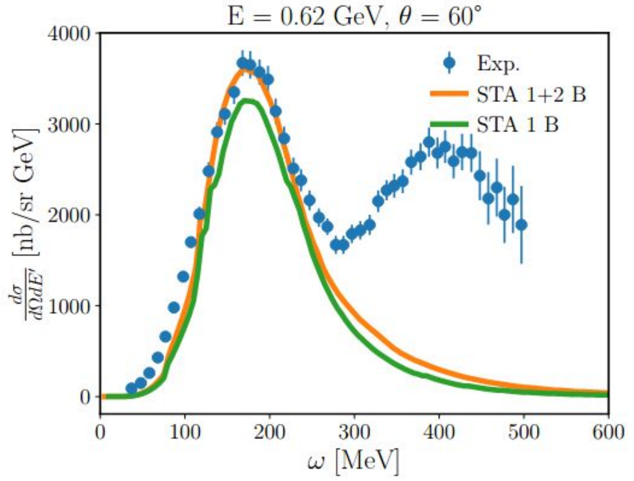


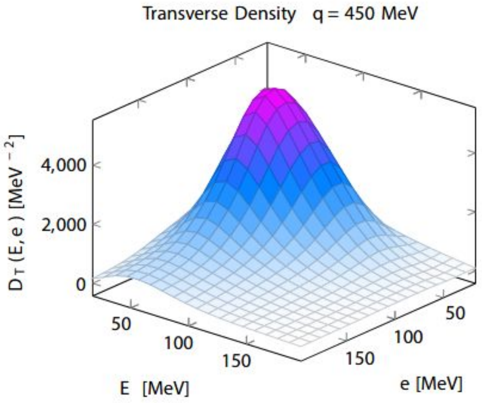

Pastore et al. PRC101(2020)044612

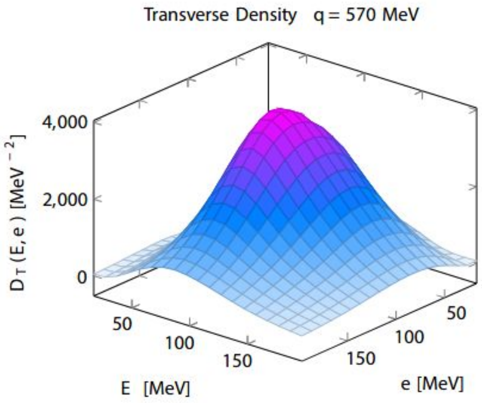
# STA New Results

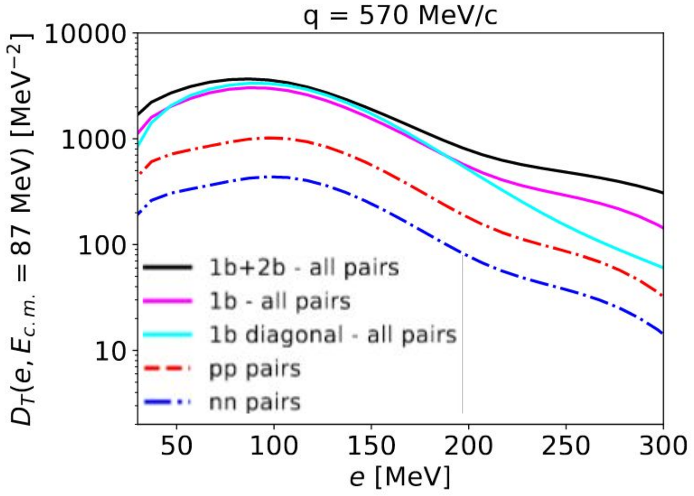
Andreoli et al. (**2024**)

Electron-$^{12}$C Response Densities, Cross Sections, and Back-to-Back Response




* pion-production not included

# Spectral Function

Uses a factorization scheme to calculate the nuclear cross section in terms of cross sections for single-bound nucleons.

$$d\sigma_A = \int dE d^3k \; d\sigma_N P(\mathbf{k}, E)$$

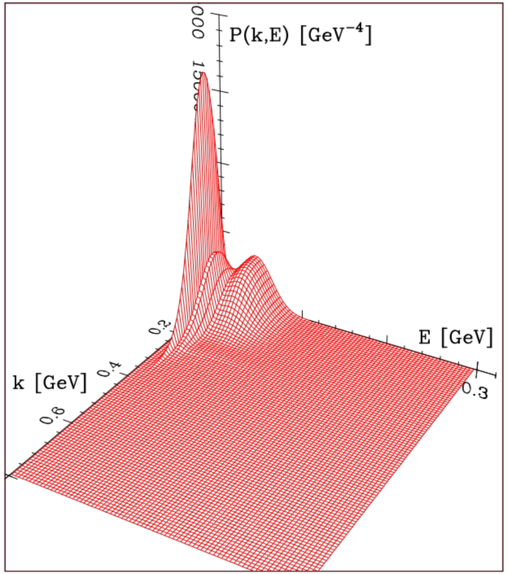
$P(\mathbf{k},E)$ encodes the intrinsic properties of the nucleus

$P(\mathbf{k},E)$ is calculated using QMC methods

Relativistic effects fully accounted for at the vertex

Can describe exclusive processes (pion-prodroduction ✅)

Rocco et al



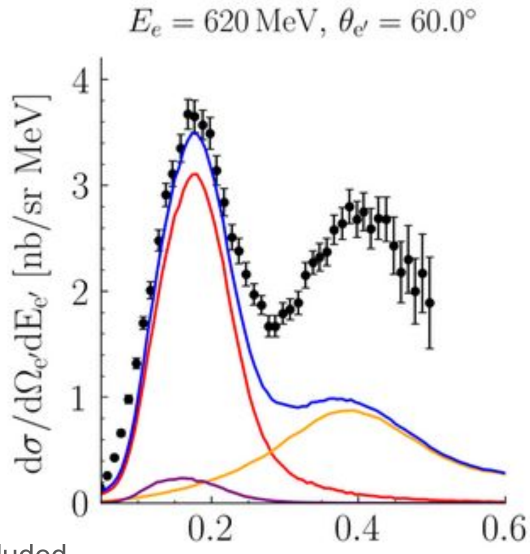

O. Benhar et al, Rev.Mod.Phys. 80 (2008)

# SF New Results

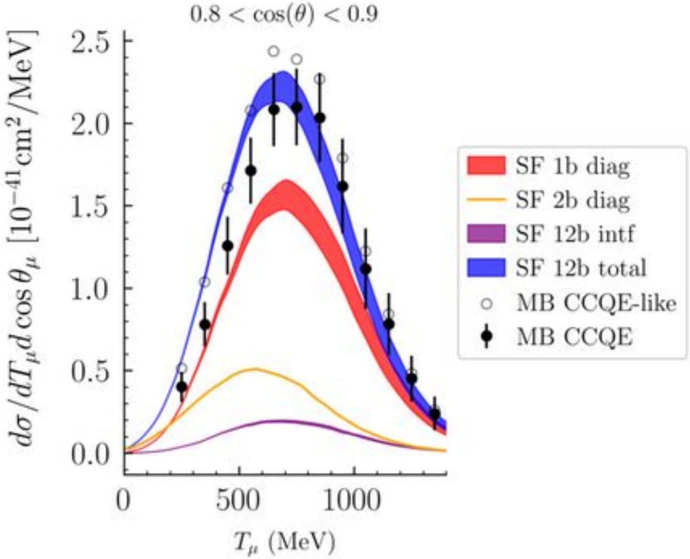
Steinberg, Rocco, and Lovato, arxiv:2312.12545 (**2024**)

Inclusion of *Interference* term in the *Extended SF Formalism*

Electron-12C scattering




$-\nu_\mu -^{12}$ C flux folded




* pion-production not included

# Summary

**XSEC 4**: Compute electroweak (electron and neutrino) cross sections in A=4-12 using Green's Function Monte Carlo (GFMC), Short-Time Approximation (STA), Spectral Function (SF) formalisms. On trak

**XSEC 5**: Investigate exclusive reactions and relativistic effects induced by electrons and neutrinos in the STA and SF formalism. On track

**ToDOs:** AFDMC calculations of xsec in A>12 systems, Exploit SF and STA to study exclusive processes (e.g., pion-production and resonance region)

**Needs**: precise inputs for hadronic dynamics (electroweak & strong couplings, nucleonic form factors, transition form factors …)

Thank you!

| **Activities** | Yr 1 | Yr 2 | Yr 3 | Yr 4 | Yr 5 |
|---|---|---|---|---|---|
| **XSEC**: *Neutrino-nucleus scattering* | | | | | |
| XSEC-1 Nucleon elastic form factors with sLapH [CM, AN, AS, AWL] | | | | | |
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