Neutrino-Nucleus Cross Sections and Neutrino Oscillations

J. Carlson, S. Pastore, S. Gandolfi: LANL
A. Lovato, S. Pieper, R. B. Wiringa: ANL
R. Schiavilla: Jlab/ODU,

(many slides taken from R. Schiavilla)

General Issues for extracting Neutrino Oscillation Parameters

- In accelerator neutrino experiments
  initial neutrino energy E reconstructed from
  outgoing lepton (+ nucleon + pion + …) tracks

$$R^{\alpha}_{\beta}(E_{\rm obs}) = N \int dE\, \Phi_{\alpha}(E)\, \overline{\sigma}_{\beta}(E, E_{\rm obs})\, P(\nu_\alpha \to \nu_\beta; E)$$

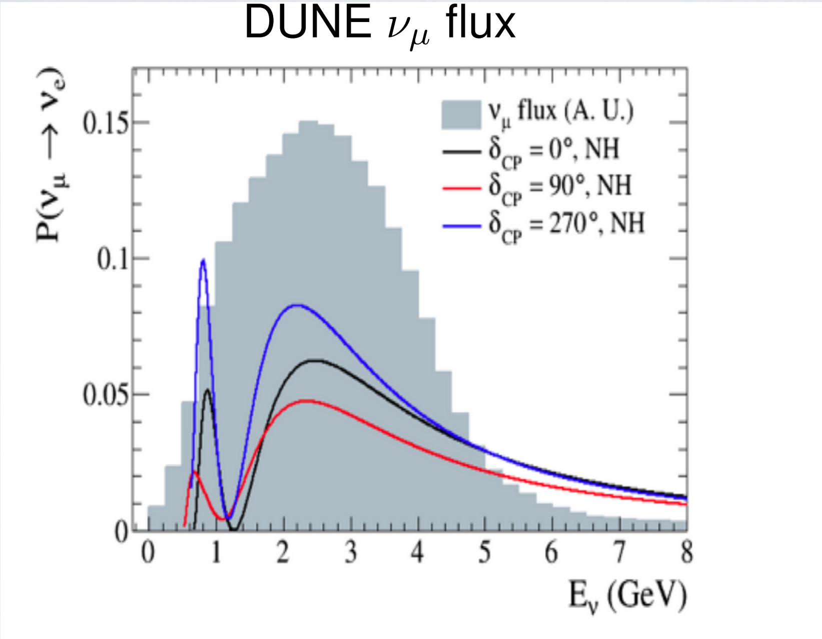
- Extracting oscillation parameters (CP violating phase,
  mass hierarchy) requires an accurate reconstruction of E:
  depends upon an accurate knowledge of cross sections and flux Φ

- Near plus far detectors sufficient (in principle) to determine if there
  are oscillations, but not sufficient to determine oscillation parameters
  without knowledge of flux and cross section to reconstruct E

  also: fluxes different at near and far detectors
  detectors not identical

- **Experimental analysis performed using event generators which
  encode our knowledge of cross sections (inclusive and exclusive)
  typically classical, until recently based upon RFG**

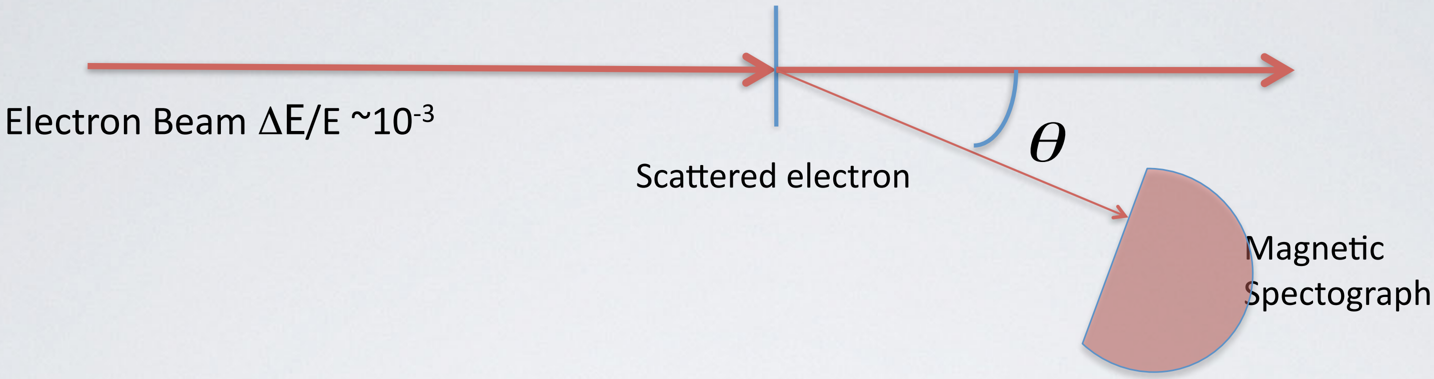
An accurate description over a wide range of kinematics is required

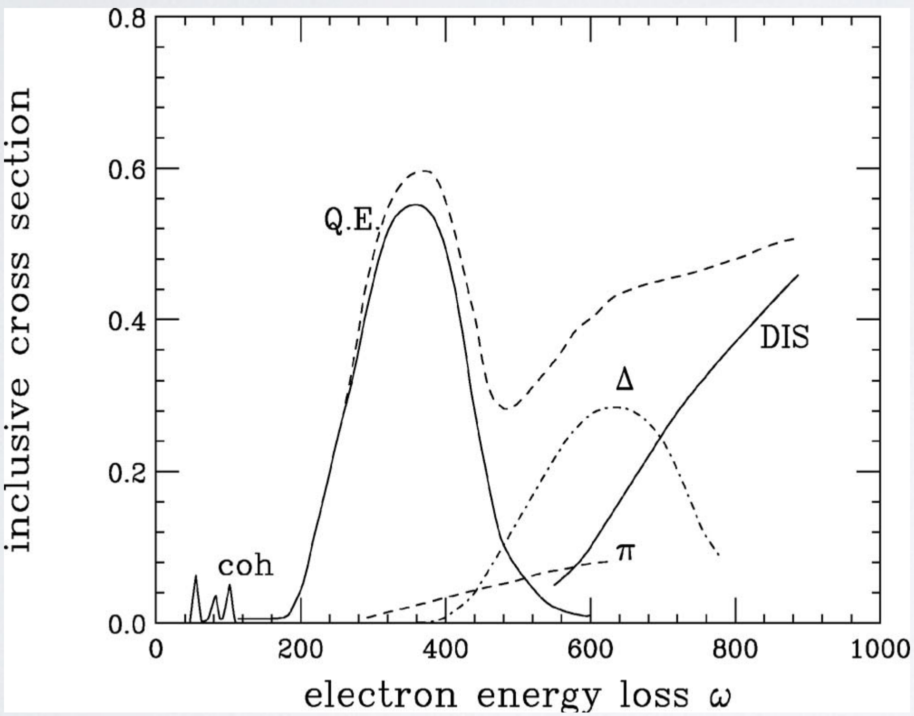


- Event generators (EGs) are one of the most important components in the analysis of neutrino experiments
- Estimate flux-averaged cross section by modeling the nucleus
- Assuming the nuclear model is correct, EGs provide
  - information on how signal and background events appear
  - means for estimating systematic errors
  - estimates of final state composition

- GENIE is the most widely used event generator
  - Argoneut, MINOS, MicroBooNE, Minerva, Nova T2K, SBND, DUNE

Inclusive Electron / Neutrino Scattering





$$(E,0,0,p),\ \ (E',p'\sin\theta,0,p'\cos\theta)$$

$$\omega \equiv E - E'$$

$$\vec{q} = \vec{p} - \vec{p}\,'$$

Thus q and ω are precisely known <u>without any reference to the nuclear final state</u>

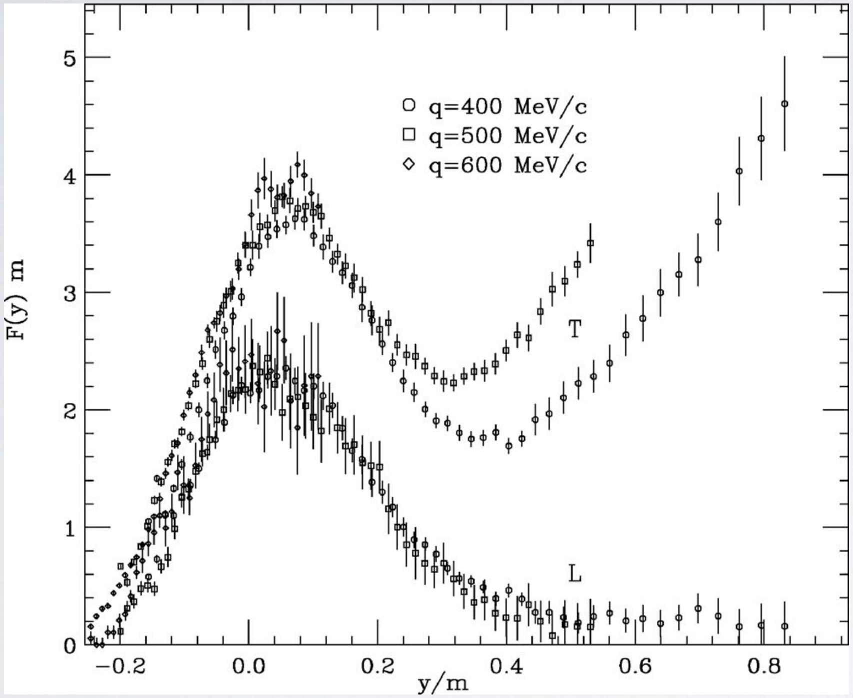
from Benhar, Day, Sick, RMP 2008

- **Many different physical processes contribute for different E, q**

Simple Models fail to describe e, ν scattering

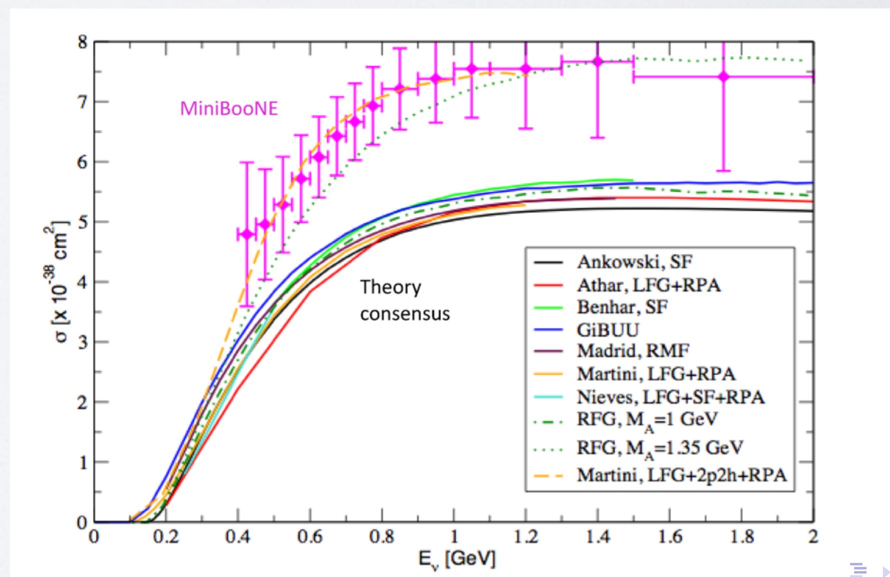
Scaling ≠ Single-Nucleon Process

Longitudinal / Transverse separation in ^{12}C



electron scattering

neutrino scattering



Realistic Model of neutrino scattering must:

- Provide a realistic model of size (fermi momentum) and binding of nuclei, and simultaneouslu include two-nucleon correlations and currents (CVC and PCAC): dominantly from pion exchange

- Describe electron scattering data

- Reproduce known neutrino / anti-neutrino scattering data

Our model: microscopic Quantum treatment of interacting nucleons including one- and two-nucleon currents

For ground states or low-lying excitations: path integral algorithm

$$\Psi_0 = \exp\left[-H\tau\right]\,\Psi_T$$

Monte Carlo used to sample path integral

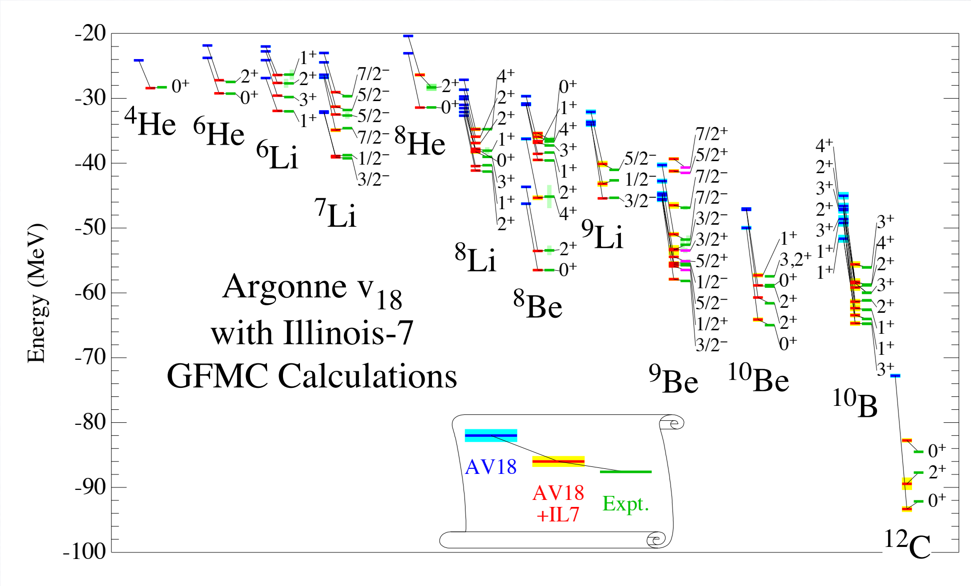


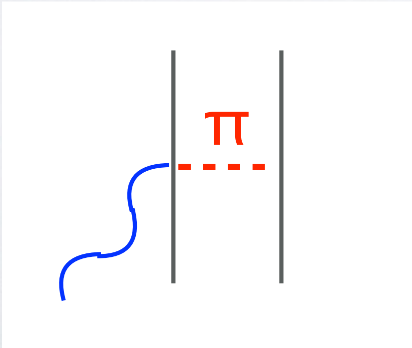
FIG. 2 GFMC energies of light nuclear ground and excited states for the AV18 and AV18+IL7 Hamiltonians compared to experiment.

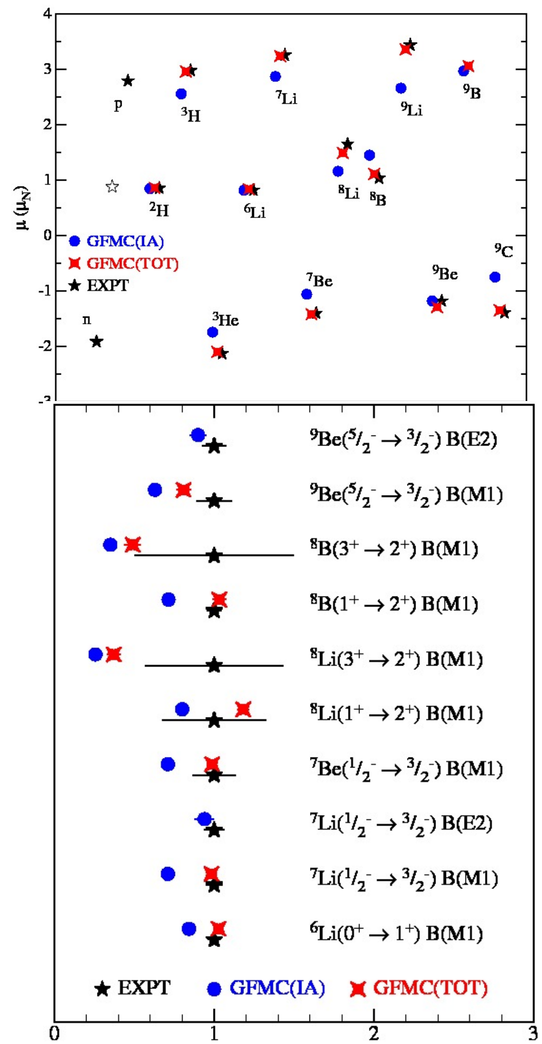
Nuclear Electroweak Currents

$$\mathbf{j} = \sum_i \mathbf{j}_i + \sum_{i<j} \mathbf{j}_{ij} + \ldots$$

one-body currents
j_i: nucleon form factors, taken from data

two-body currents associated with pion exchange plus… required for current conservation





Magnetic Moments

Transitions

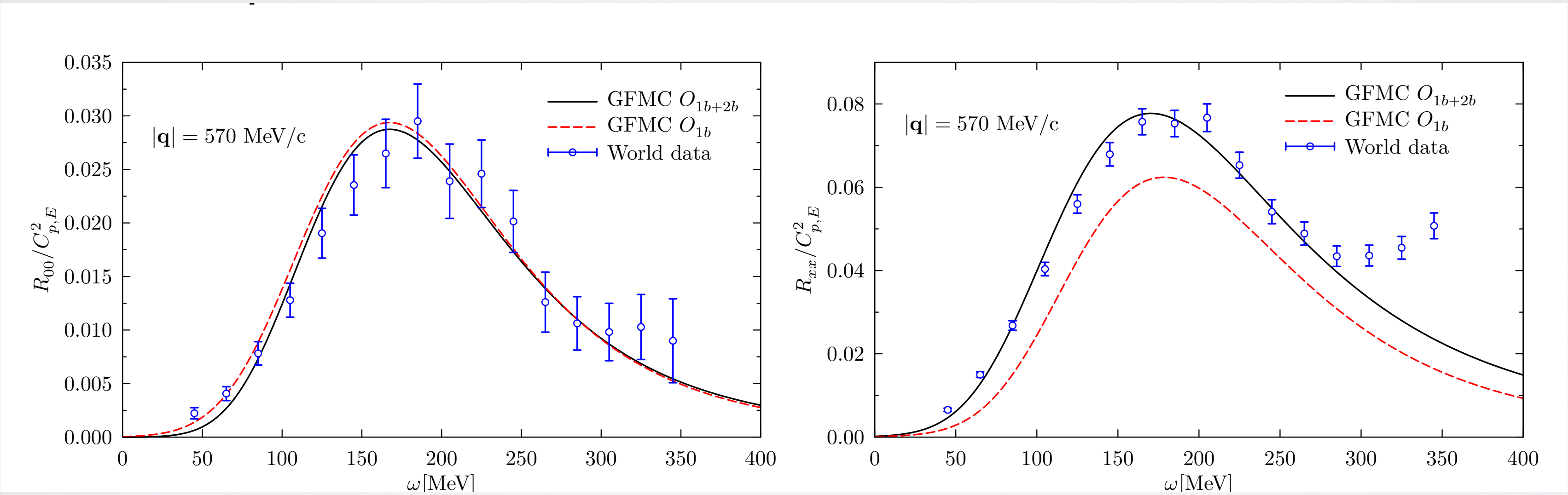
Method:

Evaluate imaginary-time correlation functions (Euclidean Response):

$$\tilde{R}(q,\tau) \;=\; \langle 0|\; \mathbf{j}^{\dagger} \;\; \exp[-(\mathbf{H} - \mathbf{E_0} - \mathbf{q^2}/(\mathbf{2m}))\tau] \;\; \mathbf{j}\; |\mathbf{0}\rangle >$$

Quantum Monte Carlo: similar to ground-state methods
Maximum Entropy Methods to invert to real-time response

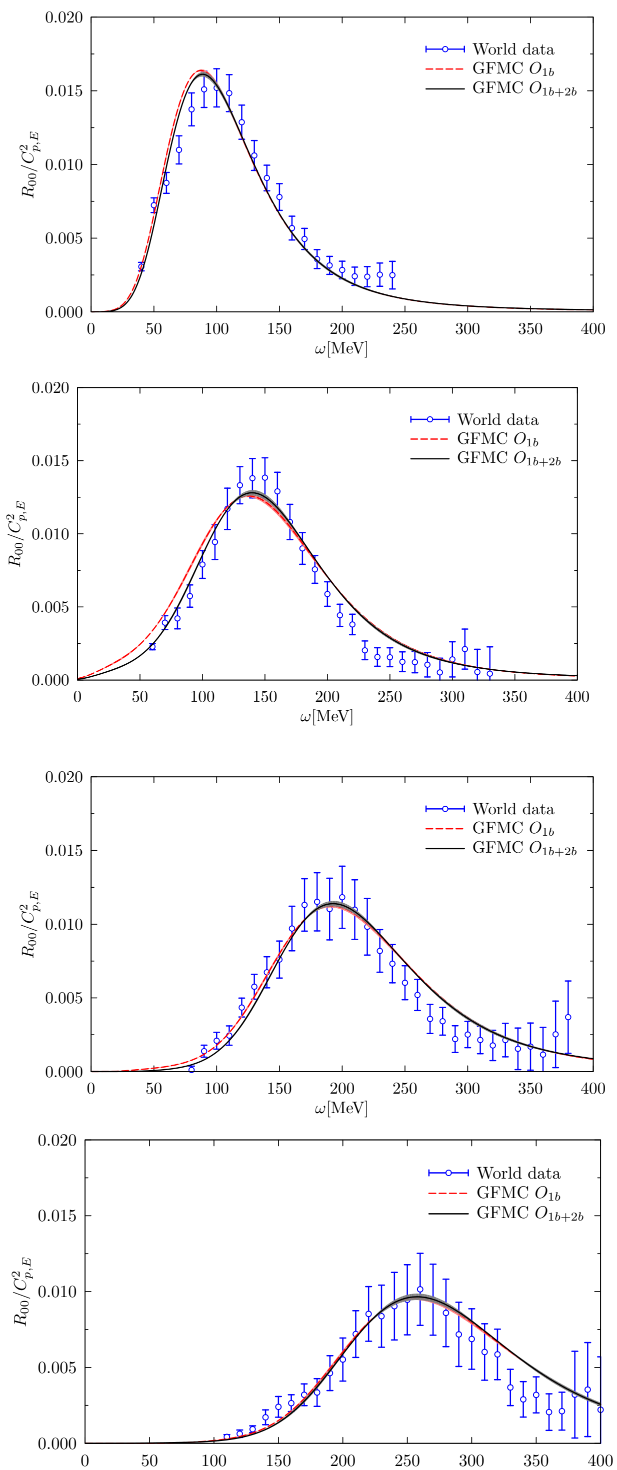
Method `exact' given input nuclear interaction and one- and two-nucleon currents



Electron Scattering (Longitudinal and Transverse) in ^{12}C

^{4}He EM

Longitudinal



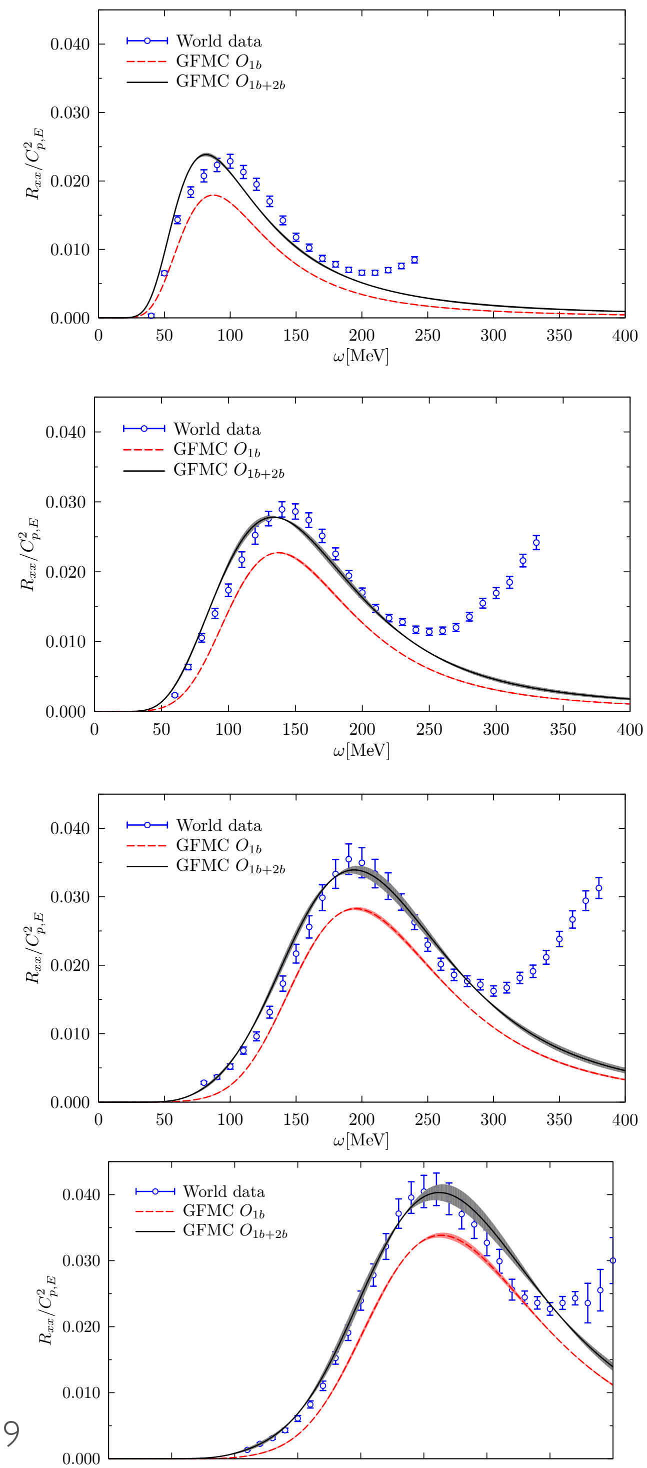
q=400

500

600

700

Transverse



Lovato, 2015 (prelim)

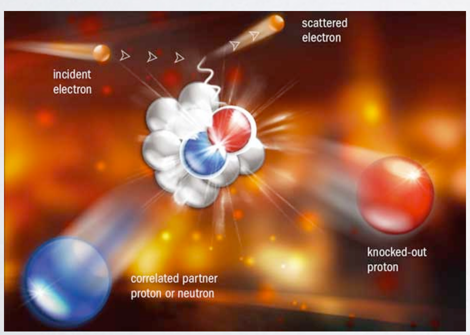
Neutrino / Anti-neutrino cross section involves 5 response functions

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\epsilon_l' \mathrm{d}\Omega_l} = \frac{G^2}{8\,\pi^2}\,\frac{k_l'}{\epsilon_l}\left[v_{00}\,R_{00} + v_{zz}\,R_{zz} - v_{0z}\,R_{0z} + v_{xx}\,R_{xx} \mp v_{xy}\,R_{xy}\right]$$

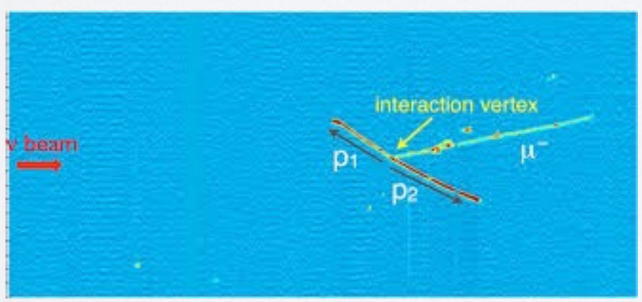
$$R_{\alpha\beta}(q,\omega) \sim \overline{\sum_i} \sum_f \delta(\omega + m_A - E_f) \langle f \,|\, j_\alpha \,|i\rangle^* \langle f \,|\, j_\beta \,|i\rangle$$

Method for inclusive cross-section, exclusive cross section requires more information on final states

From calculations to date: both vector and axial vector (and interference) enhanced by two-nucleon correlations / currents



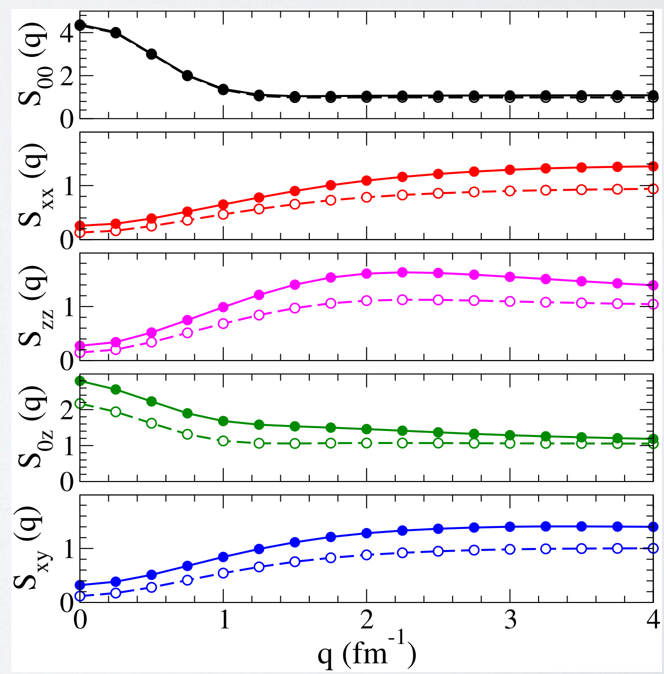
Jlab



Argoneut

Sum rules in ^{12}C

Lovato, et al., PRL 2014



Our Present and Future Efforts:

(1) complete NC and CC calculations of ^{12}C
(2) interface with GENIE:

certainly including constraints on inclusive cross section
can we include more quantum information into
final-state propagation by event generators?

in RFG, struck nucleon with a given momentum
can we specify momentum and energy (and isospin) of a pair?

(3) extensions to heavier nuclei (AFDMC, CVMC)
(4) relativistic kinematics and pion production

Interfaces with other efforts:

- Input from experiment, Lattice Gauge Theory on nuclear currents: (single nucleon form factors, 2-nucleon currents, …)
- Working with GENIE event generator
- Interface w/ pion, resonance production, …