Modelling neutrino-nucleus interactions: status and perspectives

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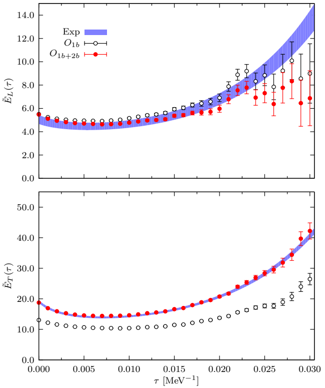
Outline

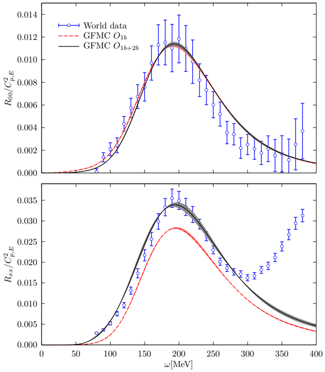
- The good news
  - *Ab initio* approaches—based on a nuclear hamiltonian fitted to the properties of the two- and three-nucleon systems—provide a remarkably accurate account of electron scattering data.
  - Several models appear to be capable to provide a semi-quantitative description of selected electron- and/or neutrino-scattering data in the quasi elastic (QE, or 0π) sector.
- The bad news
  - There is a degree of degeneracy between models based on different—and in some instances even conflicting—assumptions for both the reation mechanisms and the underlying dynamical model.
  - While the relevant mechanisms have been probably identified, the assessment of their importance is still hindered by the uncertainty associated with nuclear dynamics.
- Summary & Outlook

GREEN'S FUNCTION MONTE CARLO (GFMC)

- Longitudinal (upper panel) and transverse (lower panel) euclidean electromagnetic responses of ^{12}C at $|\mathbf{q}| = 570$ MeV



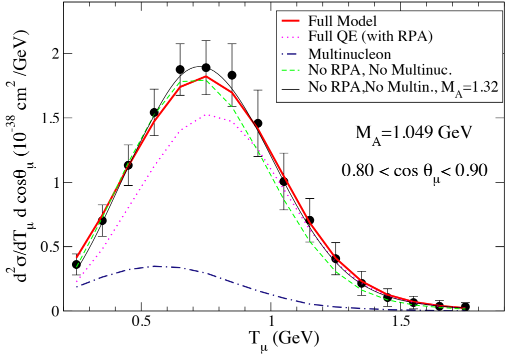
- Longitudinal (upper panel) and transverse (lower panel) electromagnetic responses of ^{4}He at $|\mathbf{q}| = 600$ MeV



A.Lovato *et al* PRC **91**, 034325 (2015)

VALENCIA MODEL

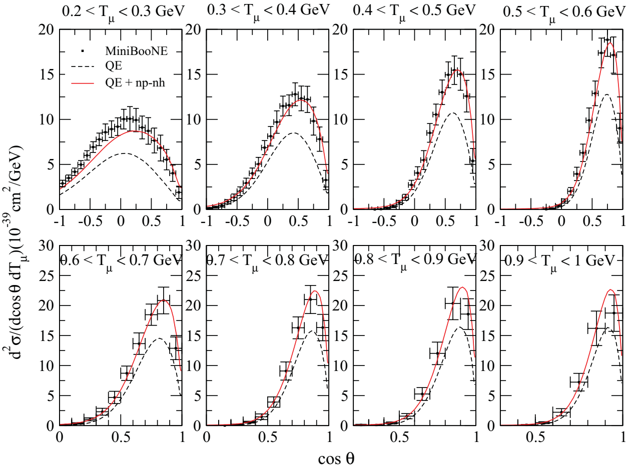
- Flux intergated double differential neutrino-carbon cross section in the CCQE channel (MiniBoone data rescaled by a factor 0.9)



J. Nieves *et al* PLB **707**, 072 (2012)

MARTINI-ERICSON-MARTEAU MODEL

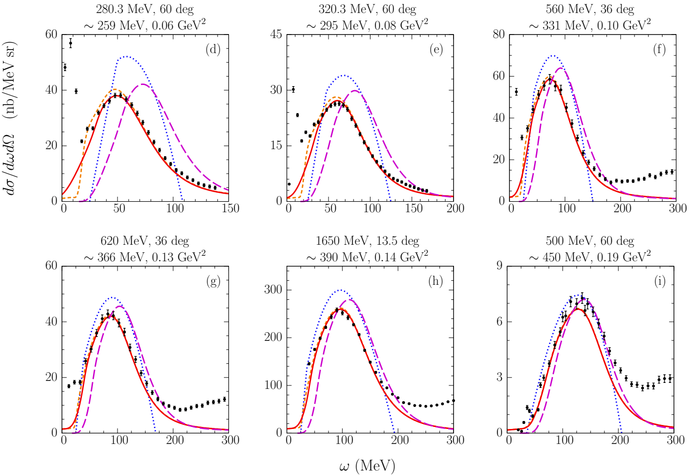
- Flux intergated double differential neutrino-carbon cross section in the CCQE channel compared to MiniBooNE data



M. Martini *et al* PRC **84**, 055502 (2011)

Spectral function formalism

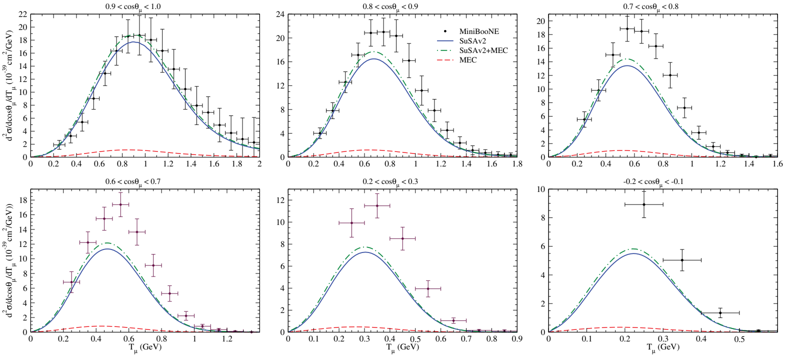
- $e + {}^{12}\mathrm{C} \rightarrow e' + X$ cross section computed within the impulse approximation and including final state interactions.



A. Ankowski *et al*, PRD **91** 033005, (2015)

SUPERSCALING APPROACH

- Flux intergated double differential neutrino-carbon cross section in the CCQE channel



G.D. Megias *et al* PRD **91**, 073004 (2015)

Preamble: the lepton-nucleus x-section

⋆ Double differential cross section of the process $\ell + A \to \ell' + X$

$$\frac{d\sigma_A}{d\Omega_{k'} dk'_0} \propto L_{\mu\nu} W_A^{\mu\nu}$$

- $L_{\mu\nu}$ is fully specified by the lepton kinematical variables
- The determination of the nuclear response tensor

$$W_A^{\mu\nu} = \sum_N \langle 0 | J_A^{\mu\,\dagger} | N \rangle \langle N | J_A^{\nu} | 0 \rangle \delta^{(4)}(P_0 + k - P_N - k')$$

$$J_A^{\mu} = \sum_i j_i^{\mu} + \sum_{j>i} j_{ij}^{\mu} + \ldots$$

  requires a consistent description of the target initial and final states and the nuclear current. Fully consistent *ab initio* calculations are feasible in the non relativistic regime, corresponding to $|\mathbf{q}| \lesssim 500$ MeV.
- In the kinematical regime in which relativistic effects become important, approximations—involving both the reaction mechanism and the underlying dynamics—are needed.

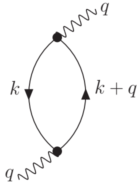
THE ONE-PARTICLE–ONE-HOLE $(1p1h)$ SECTOR

- Consider a $^{12}\mathrm{C}$ target as an example

$$|N\rangle = |p, {}^{11}\mathrm{C}\rangle \; , \; |n, {}^{11}\mathrm{B}\rangle$$

  - The infamous Relativistic Fermi Gas Model (RFGM)

$$W_A^{\mu\nu} =$$



No nucleon-nucleon interaction, mean field described by a constant binding energy ϵ. Oriented lines represent the Green's functions

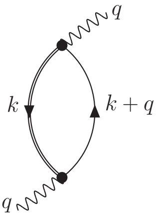
$$G_h(k, E) = \frac{\theta(k - k_F)}{E - e_0(k) + i\eta} \; , \; G_p = \frac{\theta(k_F - k)}{E - e_0(k) - i\eta}$$

where $\eta = 0^+$, k_F is the Fermi momentum and

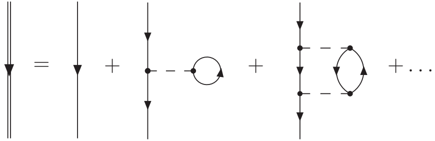
$$e_0(k) = \sqrt{k^2 + m^2} + \epsilon$$

- Including nucleon-nucleon interactions in the initial state

$W_A^{\mu\nu} =$



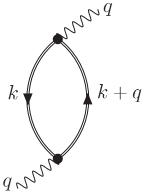
$G_h(k, E) =$



- the *bare* nucleon-nucleon interaction cannot be used for perturbation theory in the basis of eigenstates of the non-interacting system. Eiher the interaction or the basis states need to be "renormalized" using G-matrix or Correlated Basis Function (CBF) perturbation theory.

- In principle, the effects of nucleon-nucleon interactions in the final state may be taken into account in a consistent fashion, using

$W_A^{\mu\nu}$ =



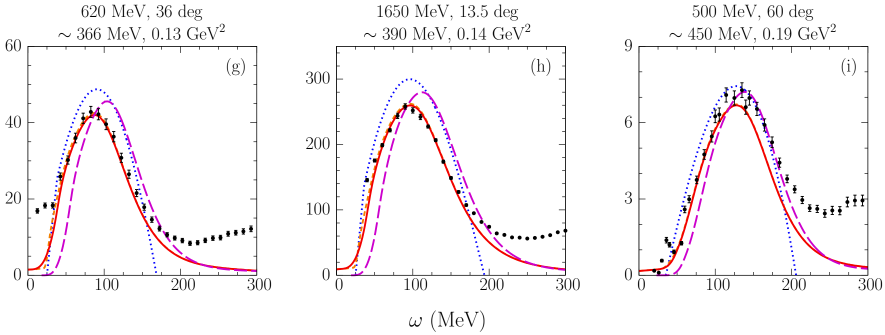
However, the propagation of the outgoing nucleon, described by the Green's function $G_p(\mathbf{k}+\mathbf{q}, E)$, requires either a relativistic model of nuclear dynamics or an approximation scheme based on nucleon-nucleon and nucleon-nucleus scattering data

- Recall that the spectral functions are trivially reated to Green's functions through

$$P_h(k,E) = \frac{1}{\pi}\text{Im}\, G_h(k, e_F - E) \ , \ \ P_p(k,E) = -\frac{1}{\pi}\text{Im}\, G_p(k, e_F + E)$$

INTERACTIONS EFFECTS

- nuclear mean field → cross section shifted
- nucleon-nucleon correlations → coupling between 1p1h and 2p2h final states. Peak quenched, appearance of tails at both low and high energy transfer, ω.



A. Ankowski *et al*, PRD **91** 033005, (2015)

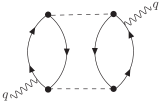
The two-particle–two-hole sector

- Interactions couple the 1h (1p) states of the residual nucleon to 2h1p (2p1h) states, in which one of the spectator nucleons is excited to the continuum. This mechanism leads to the appearance of 2p2h final states

$$|N\rangle = |pp, {}^{10}\mathrm{B}\rangle \ , \ |np^{10}\mathrm{C}\rangle \ldots$$

- In addition, 2p2h states appear through their couplig to the ground state

$$W_A^{\mu\nu} =$$

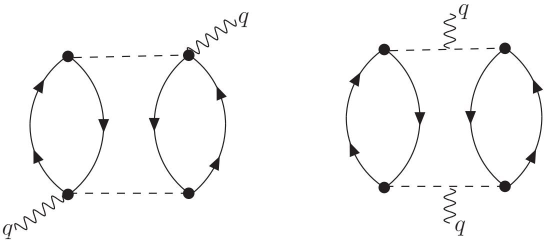


- These contributions exhibit a specific energy dependence, and give rise to a characteristic event geometry
- Note: in interacting many body systems the excitation of 2p2h states *does not* require a two-nucleon current

Meson-exchange currents (MEC)

- Two-nucleon currents naturally couple the nuclear ground state to 2p2h final states, e.g. through the processes

$$W_A^{\mu\nu} =$$



as well as through similar processes involving the excitation of a Δ-resonance

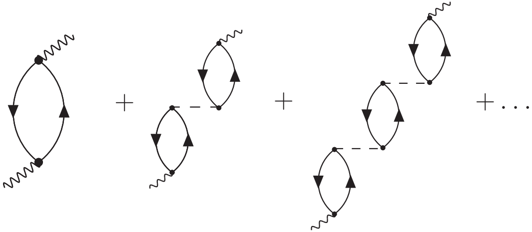
- Note: amplitudes involving one- and two-body currents and the same 2p2h state give rise to interference

LONG-RANGE CORRELATIONS

- At low momentum transfer, processes involving many nucleons may become important. Within the Tamm-Dancoff (ring) approximation the nuclear final state is written in the form

$$|N\rangle = \sum_i C_i |p_i h_i\rangle$$

$W_A^{\mu\nu} =$



Note: the Random-Phase-Approximation (RPA) is a generalization of the above scheme

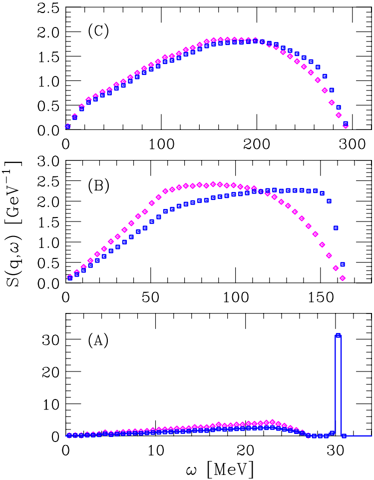
Effects of long-range correlations

- $|\mathbf{q}|$-evolution of the density-response of isospsin-symmetric nuclear matter. Calculation carried out within CBF using a realistic nuclear hamiltonian.

$|\mathbf{q}| \approx 480\,\mathrm{MeV}$

$|\mathbf{q}| \approx 300\,\mathrm{MeV}$

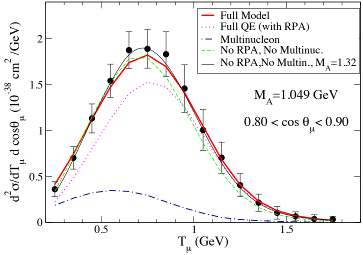
$|\mathbf{q}| \approx 60\,\mathrm{MeV}$

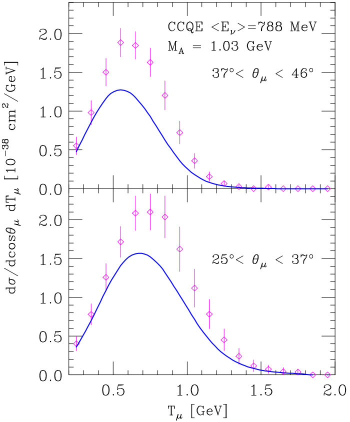


OB and N. Farina, PLB **680** 305, (2009)

Why worry

- Approaches based on different reaction mechanisms and dynamical models yield similar results





- From the numerical point of view, RPA effects appear to be similar to the quenching of the normalization of 1h states arising from nucleon-nucleon correlations

SUMMARY & OUTLOOK

- ⋆ Despite the significant progresses of the past decade, a clearcut interpretation of the observed neutrino-nucleus cross section in the QE (0π) channel is still missing.
- ⋆ While it is arguable that the relevant reaction mechanisms have been identified, their role and possible interplay depend on the description of nuclear dynamics.
- ⋆ The degeneracy between different models may be resolved exploiting the available experimental information. For example, the analysis of the two-proton emission events observed in the ArgoNeut detector may help to discriminate between different treatments of short-range nucleon-nucleon correlations.
- ⋆ Comparison with GFMC results in the non relativistic regime may also provide valuable complementary information.