Interpretation of ν-Nucleus Interactions

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OUTLINE

⋆ The good news

- The surge of activity of the past two decades—which may be referred to as the NuInt age —has led to the development of highly refined models of lepton-nucleus interactions
- Several models appear to be capable to provide an accurate description of *selected* electron- and/or neutrino-scattering data

⋆ The bad news

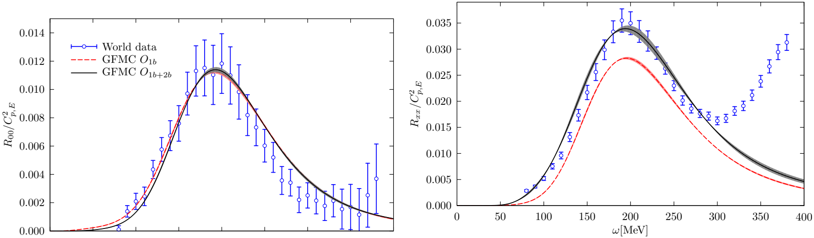
- Models based on different—in some instances even conflicting—assumptions yield similar results

⋆ Outlook

- Resolving the the degeneracy between different models and assessing their predictive power will require the analysis of electron scattering data other than the inclusive cross section

GREEN'S FUNCTION MONTE CARLO (GFMC)

- Longitudinal (left) and transverse (right) electromagnetic responses of $^{12}\mathrm{C}$ at $|\mathbf{q}| = 570$ MeV

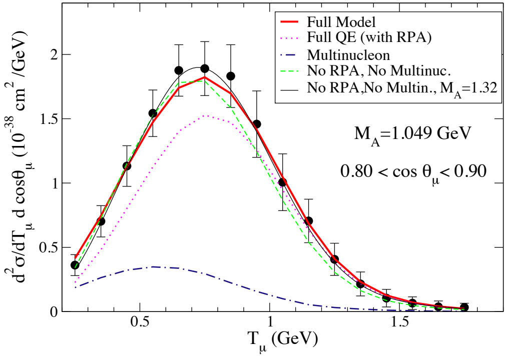


A, Lovato *et al* PRL 117, 082501 (2016)

- Full *ab initio* calculation based on a realistic nuclear Hamiltonian
  - Inherently non relativistic
  - Does not allow to pin down the role of all different reaction mechanisms

VALENCIA MODEL

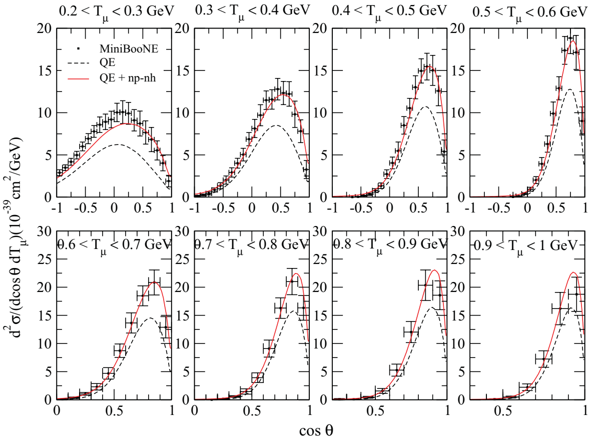
- Single and multinucleon emission included. Long range correlations included within the Random Phase Approximation (RPA)
- Flux intergated double differential neutrino-carbon cross section in the CCQE channel



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

MARTINI-ERICSON-MARTEAU MODEL

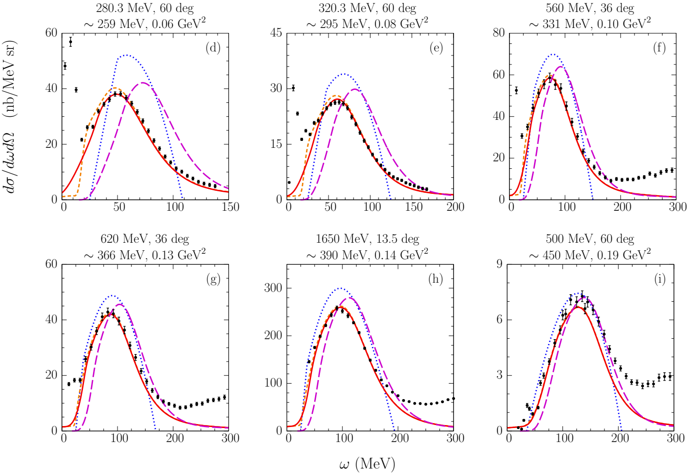
- Single and multinucleon emission and RPA correlations included
- Flux intergated double differential neutrino-carbon cross section in the CCQE channel compared to MiniBooNE data



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

SPECTRAL FUNCTION FORMALISM

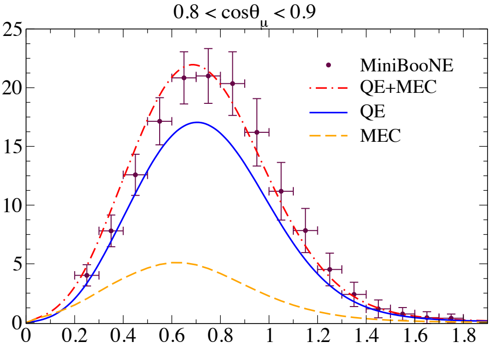
- $e + {}^{12}\mathrm{C} \to e' + X$ cross section computed within the impulse approximation including ground state correlations and final state interactions



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

SUPERSCALING APPROACH

- Phenomenological scaling analysis of electron scattering data in the single-nucleon knock-out sector. Contribution of Meson-Exchange Currents (MEC) added within the Relativistic Fermi Gas Model (RFGM)
- 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 CROSS-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

- In the kinematical regime in which relativistic effects become important, approximations—involving both the reaction mechanism and the underlying dynamics—are needed.

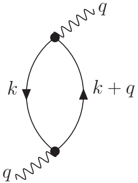
THE ONE-PARTICLE–ONE-HOLE $(1p1h)$ SECTOR

- 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

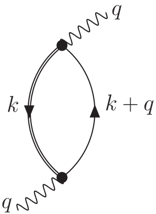
$$G_h(k,E) = \frac{\theta(k-k_F)}{E - e_0(k) + i\eta} \;,\; G_p = \frac{\theta(k_F - k)}{E - e_0(k) - i\eta}$$

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

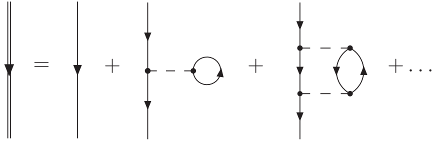
$$e_0(k) = \sqrt{k^2 + m^2} + \epsilon$$

- Including nucleon-nucleon interactions in the initial state

$W_A^{\mu\nu} =$



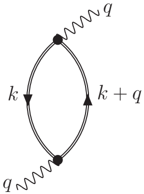
$G_h(k, E) =$



- Note thatthe *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 final state interactions may be taken into account in a consistent fashion, using

$W_A^{\mu\nu}$ =



However, in general the propagation of the outgoing nucleon, described by the Green's function $G_p(\mathbf{k}+\mathbf{q},E)$, requires the use of a relativistically consistent scheme, such as the eikonal approximation

- The 1p1h sector has been extensively studied measuring the cross section of the process

$$e + A \to e' + p + (A-1)_B$$

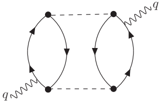
THE TWO-PARTICLE–TWO-HOLE SECTOR

- 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 coupling to the ground state

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

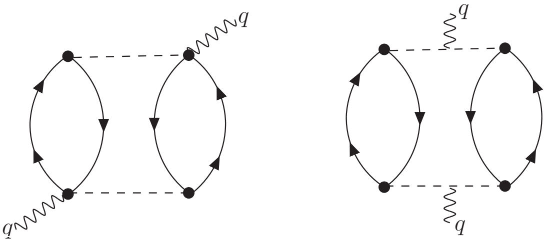


- These contributions exhibit a specific energy dependence, and give rise to a characteristic event geometry
- Note: in interacting many body systems the excitation of 2p2h states *does not* require a two-nucleon current

MESON-EXCHANGE CURRENTS (MEC)

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

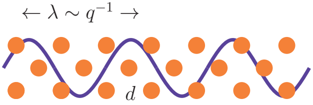
$$W_A^{\mu\nu} =$$



as well as through similar processes involving the excitation of the Δ-resonance
- Note: amplitudes involving one- and two-body currents and the same final state state give rise to interference terms

LONG-RANGE CORRELATIONS

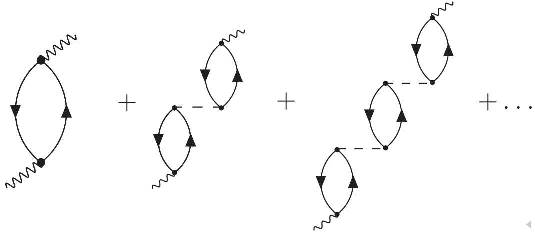
- ⋆ At low momentum transfer the space resolusion of the neutrino becomes much larger than the average NN separation distance (~ 1.5 fm), and the interaction involves many nucleons



- ⋆ Write the nuclear final state as a superposition of 1p1h states

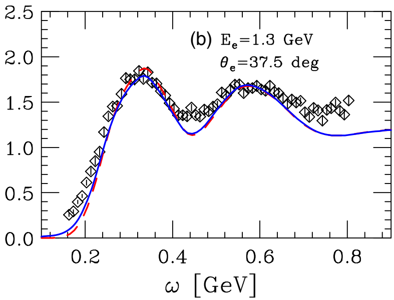
$$|n\rangle = \sum^{N} C_i \, |p_i h_i)$$

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

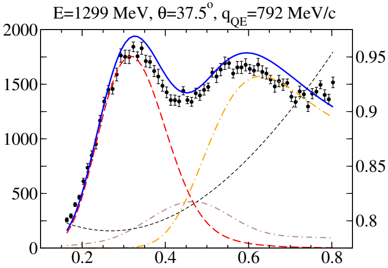


THE DEGENERACY ISSUE: e–A SCATTERING

- Same data. Different theoretical models, based on different assumptions. Comparable agreement between theory and experiment



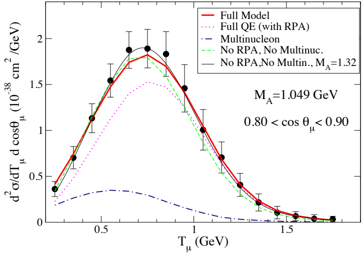
- Spectral function approach. Correlations and MEC consistently taken into account. Significant interference terms included

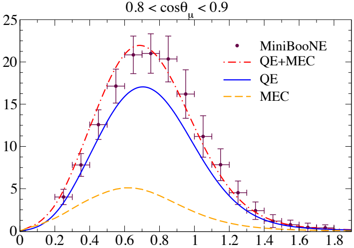


- SuSAv2+MEC approach. Superscaling analysis, MEC added within the RFGM. Interference terms not included

THE DEGENERACY ISSUE: ν–A SCATTERING

- Flux integrated double-differential cross section in the CCQE channel predicted by the Valencia Model and the SuSav2+MEC approach

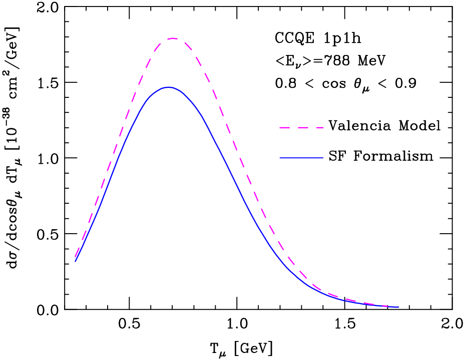




- Note that RPA contributions, which turn out to be significant within the Valencia Model to the nuclear responsibility *do not* exhibit *y*-scaling. Therefore, they are *not* included in the SuSav2+MEC analysis

WHY WORRY?

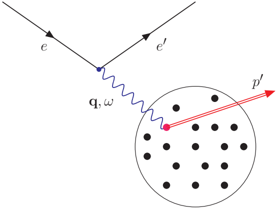
- Compare the results of the Valencia Model to those obtained using the spectral function formalism



- The effects of RPA corrections appear to be comparable to the quenching of the normalization of shell model states, arising from ground-state correlations. How do we assess the predictive power of the different models?

THE $(e, e'p)$ REACTION

- Consider the process $e + A \to e' + p + (A-1)$ in which both the outgoing electron and the proton, carrying momentum p', are detected in coincidence



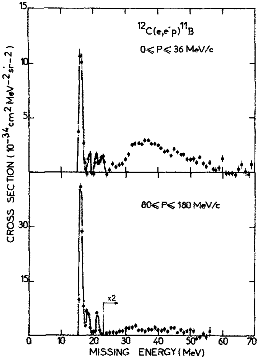
- In the absence of final state interactions (FSI), the initial energy and momentum of the knocked out nucleon can be identified with the *measured* missing momentum and energy, respectively

$$\mathbf{p}_m = \mathbf{p}' - \mathbf{q} \quad , \quad E_m = \omega - T_{\mathbf{p}'} - T_{A-1} \approx \omega - T_{\mathbf{p}'}$$

- FSI effects can be taken into account as corrections

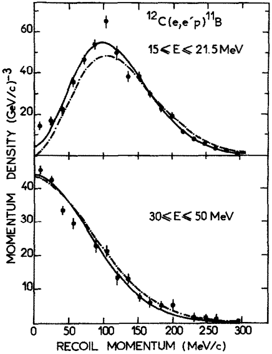
$(e, e'p)$ CROSS SECTION

- ⋆ Low missing energy region: single nucleon knock out from shell model states



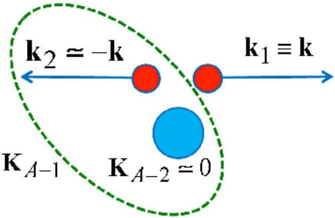
- Contribution of shell model states clearly seen. Normalizations, or spectroscopic strengths, significantly lower than shell model predictions

- Momentum distributions of carbon $p-$ and $s-$states



WHERE IS THE MISSING SPECTROSCOPIC STRENGTH?

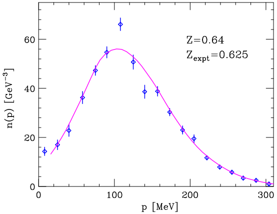
- ⋆ The missing strength is pushed to the two-nucleon emission sector by processes involving high momentum nucleons, with $|\mathbf{p}_m| \gtrsim 400$ MeV. The relevant missing energy scale can be easily understood considering that momentum conservation requires



$$E_m = E_{\rm thr} + \sqrt{|\mathbf{p}_m|^2 + m^2} - m$$

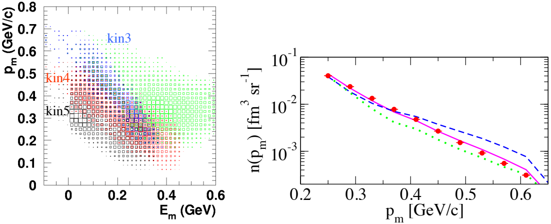
- ⋆ Scattering off a nucleon belonging to a correlated pair entails a strong energy-momentum correlation

$(e, e'p)$ within the Spectral Function Approach



- After correcting for FSI, both shape and normalization of the valence *p*-state of carbon are accurately reproduced using the CBF spectral function

- The correlation strenght at large missing energy and missing momentum is also consistently accounted for



Experiment	0.61 ±0.06
Greens function theory [3]	0.46
CBF theory [2]	0.64
SCGF theory [4]	0.61

SUMMARY AND OUTLOOK

- ⋆ Bottom line: an accurate description of the two-nucleon emission sector sector, providing $\sim 20\%$ of the nuclear cross section in the quasi elastic channel, is only relevant to the extent to which the remaining $\sim 80\%$, arising from processes single-nucleon knock out processes, is fully understood. In this context, consistency is a key issue

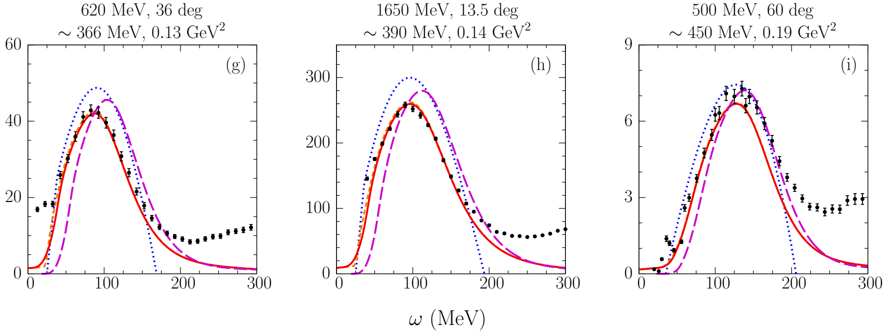
- ⋆ Studies of the $(e, e'p)$ cross section, giving access to the nuclear spectral function, have greatly contributed to identify processes involving different nuclear final states

- ⋆ The availability of $(e, e'p)$ data must be exploited to resolve the degeneracy between model of neutrino nucleus-interactions based on different—or even conflicting—assumptions on both nuclear dynamics and the relevant reaction mechanisms

Backup slides

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)

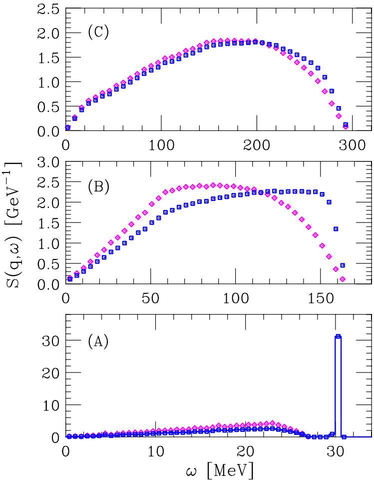
EFFECTS OF LONG-RANGE CORRELATIONS

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

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

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

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



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