Relativistic meson-exchange currents in lepton-nucleus scattering

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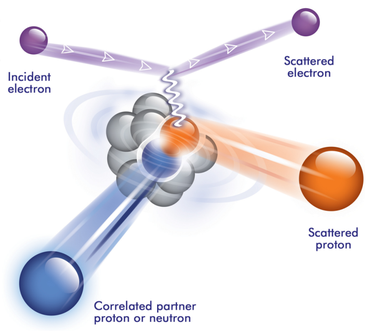
Formalism

When a lepton interacts with a nucleus two -or more- nucleons in the same interaction can be ejected, yielding to a $np-nh$ process. This is a pure nuclear effect. Specifically, we focus on the $2p2h$, based on RFG.
The nuclear tensor contains matrix elements:

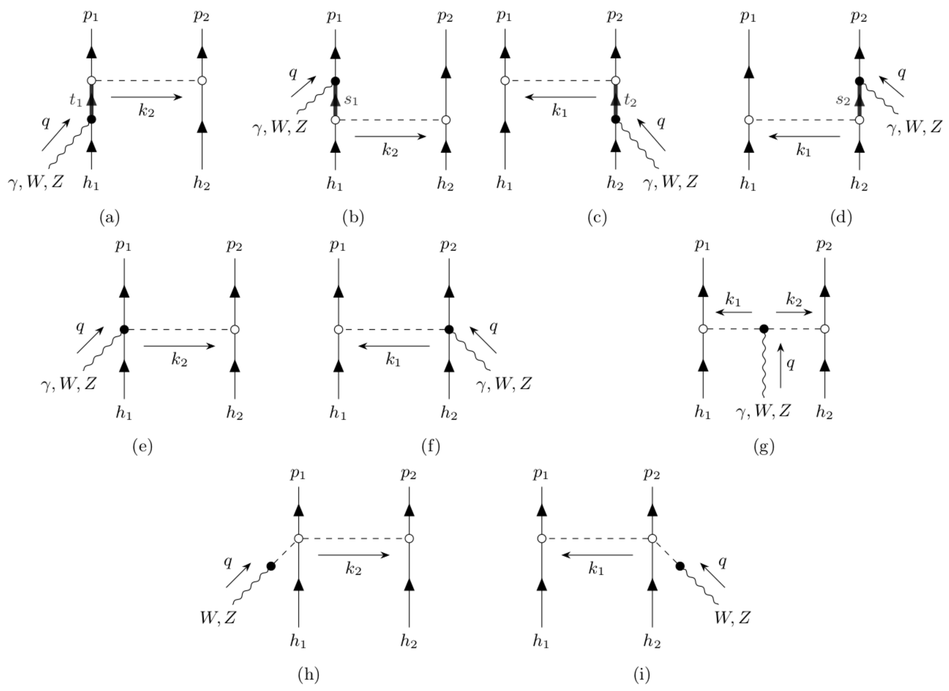
$$w_{\mu\nu} \propto \langle F|\hat{J}^{2b\dagger}_{\mu}|2p2h\rangle\langle 2p2h|\hat{J}^{2b}_{\nu}|F\rangle$$

with $|F\rangle$ the Fermi sphere and $|2p2h\rangle$ the $2p2h$ state.
$\hat{J}^{2b}_{\mu}$ is a two-body current, that is obtained following the Meson Exchange Currents (MEC) formalism.



Subedi et al., Science 320, 1476 (2008)

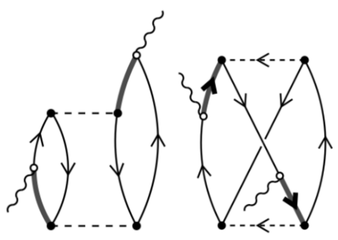
Meson Exchange Currents



MEC for the EM-EW interaction, related to Δ resonance -a,b,c,d-, 'contact' -e,f-, 'pion-in-flight' -g- and 'pion-pole' -h,i- currents.

J^{2b}_{μ} is a fully relativistic two-body current, corresponding to the coupling of the virtual boson to a pair of nucleons exchanging a pion. It is derived from the Non-Linear σ-model Lagrangian investigated in [1], where the Δ resonance is incorporated *ad hoc*.

On the right exempla of *direct* and *exchange* many-body diagrams, included in our computations, obtained combining two MEC currents.



Inclusive process

In an inclusive lepton-nucleus scattering only the outgoing lepton is detected: the $2p2h$ cross section is obtained including every possible hadronic final state with two ejected nucleons.
Lepton-nucleus inclusive cross-section:

$$\frac{\mathrm{d}^2\sigma}{\mathrm{dE_{e'}d\Omega_{e'}}} = \sigma_0 \frac{L_{\mu\nu}}{\nu_0} W_A^{\mu\nu} \qquad W_A,\ L \text{ nuclear and leptonic tensor}$$

We described the $2p2h$ hadronic tensor in a RFG framework, hence:

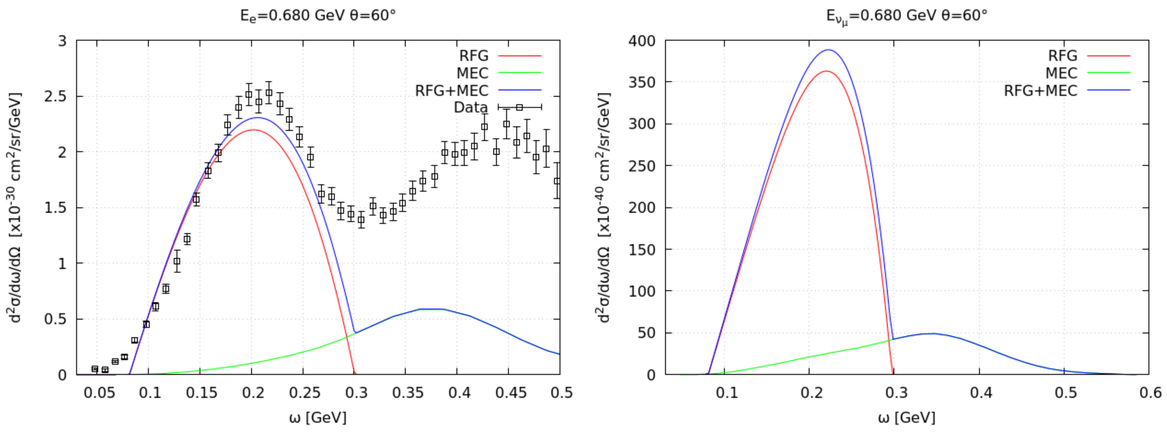
$$W^{\mu\nu}_{(2p2h)} = \frac{1}{4}\frac{V}{(2\pi)^9} \sum_{\substack{s_1,s_2,s_1',s_2' \\ t_1,t_2,t_1',t_2'}} \int_{\substack{\mathbf{h_i}<k_F \\ \mathbf{p_i}>k_F}} d\mathbf{h_1}\, d\mathbf{h_2}\, d\mathbf{p_1}\, d\mathbf{p_2}\, \delta^4(p_1+p_2-h_1-h_2-\tilde{q})\, w_{\mu\nu}$$

$$\tilde{q} := (\tilde{\omega}, \mathbf{q}), \quad \tilde{\omega} := \omega - E_s^{2p2h}, \qquad \text{for } {}^{12}C \Rightarrow E_s^{2p2h} = 40 \text{ MeV}, k_F = 228 \text{ MeV}$$

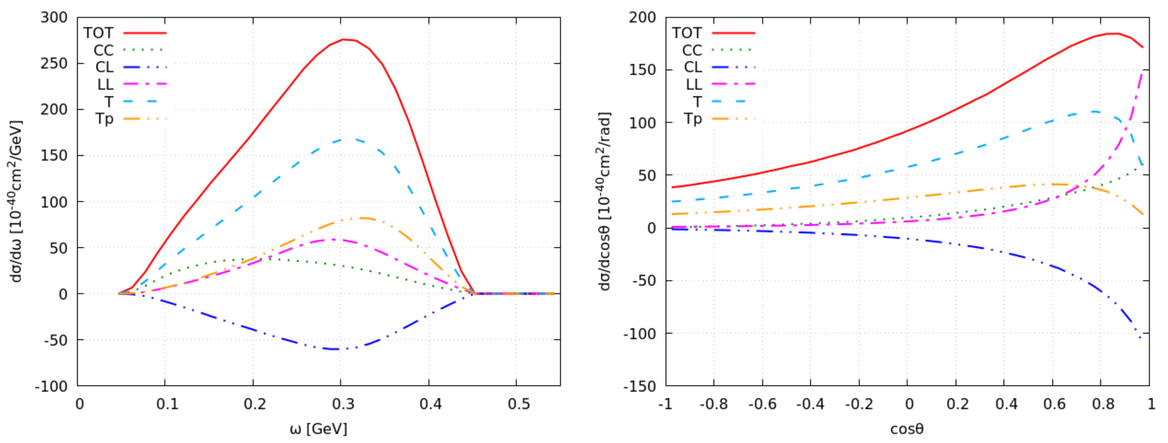
Integration over holes and particles momenta $\Rightarrow$ less non-vanishing hadronic contributions

Results

We tested our model with previous inclusive calculations for the electron [2] and for the CC neutrino [3] scattering.

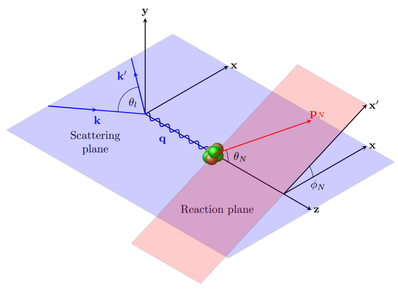


Double differential cross section for $e\,{}^{12}C$ and $\nu_\mu\,{}^{12}C$, with quasi-elastic contribution evaluated using RFG nuclear model and the 2p2h, computed using MEC. Electron data are also shown, from archive $10.48550/arXiv.nucl-ex/0603032$.



Inclusive EW differential cross section as a function of the scattering angle and the energy transfer ω. Incident neutrino energy $E_{\nu_\mu} = 550$ MeV, corresponding to T2K ND flux peak.

Semi-inclusive process



J.M. Franco-Patiño, PhD Thesis (2024)

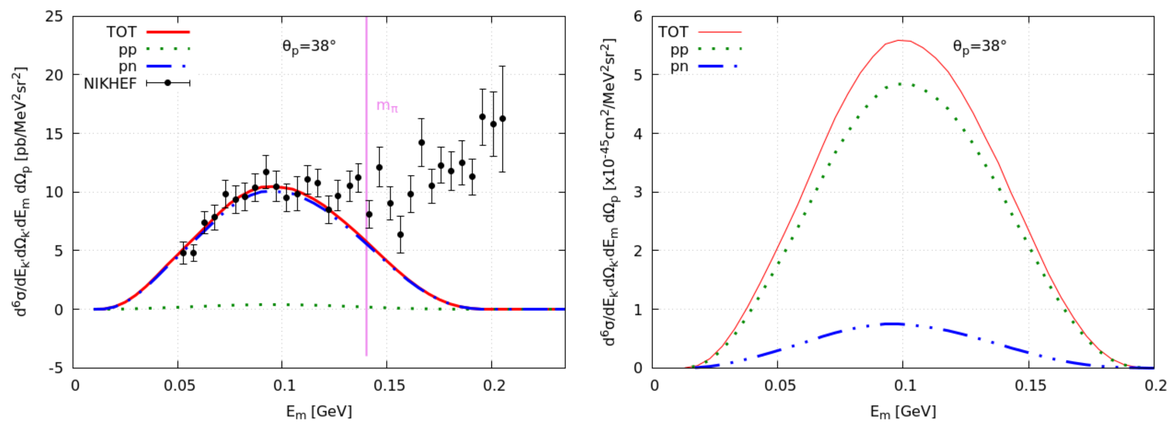
In a semi-inclusive lepton-nucleus scattering an outgoing nucleon is detected in addition to the final lepton.We computed theoretical predictions for detected nucleon p_1 lying on the scattering plane, $\phi_{p_1} = 0$.
Lepton-nucleus semi-inclusive cross-section:

$$\frac{d^6\sigma}{d\omega d\Omega_{e'} dE_m d\Omega_{p_1}} = \frac{p_1 E_{p_1}}{(2\pi)^3}\sigma_0 \frac{L_{\mu\nu}}{\nu_0} W^{\mu\nu}_{A(N)}$$

$$W^{\mu\nu}_{A(N)} := \frac{d\,W^{\mu\nu}_A}{d\mathbf{p_1}} \qquad E_m = \omega - E_{p_1} + m_N$$

Integration over holes and one particle only momenta $\Rightarrow$ numerous non-vanishing hadronic contributions

Results



Semi-inclusive predictions, with incident lepton energy E=478 MeV, energy transfer ω=263 MeV, momentum transfer q=303 MeV/c and proton scattering angle θ_p. Left: electron-carbon scattering, in violet the pion production threshold, data from [4]; right: CC muonic neutrino-carbon scattering, similar predictions can be found in *J. Niewczas, PhD Thesis (2023)*. The isospin separation for ejected nucleons in final state is performed.

Conclusion

We computed the $2p2h$ contribution for the inclusive and semi-inclusive lepton-carbon scattering, showing preliminary weak predictions.
In particular, we tested the EM-MEC formalism comparing with available semi-inclusive data focused in the 'dip' region. For details, see [5].

Currently the $2p2h$ component of the cross section is simulated in event generators on the basis of inclusive calculations, necessarily relying on strong approximations. The model aims to provide a reliable description of neutrino-nucleus semi-inclusive $2p2h$ process, for which a complete microscopic and fully relativistic computation is still absent in the literature, although it is strongly needed for the correct interpretation of neutrino data.

References

[1] E. Hernandez, J. Nieves and M. Valverde, *"Weak Pion Production off the Nucleon"*, Phys. Rev. D 76, 033005 (2007), hep-ph/0701149.

[2] A. De Pace, M. Nardi, W. M. Alberico, T. W. Donnelly and A. Molinari, *"Role of 2p - 2h MEC excitations in superscaling"*, Nucl. Phys. A 741, 249 (2004), nucl-th/0403023.

[3] G. D. Megias, J. E. Amaro, M. B. Barbaro, J. A. Caballero, T. W. Donnelly and I. Ruiz Simo, *"Charged-current neutrino-nucleus reactions within the superscaling meson-exchange current approach"*, Phys. Rev. D 94, 093004 (2016), arxiv:1607.08565.

[4] J. Ryckebusch, V. Van der Sluys, M. Waroquier, L. J. H. M. Kester, W. H. A. Hesselink, E. Jans and A. Zondervan, *"Two nucleon knockout contributions to the ${}^{12}C$ (e, e' p) reaction in the dip and Δ (1232) regions"*, Phys. Lett. B 333, 310 (1994), nucl-th/9406015.

[5] V. Belocchi, M. B. Barbaro, A. De Pace and M. Martini, *"Relativistic meson-exchange currents in semi-inclusive lepton scattering"*, Phys. Rev. C 109, 065502 (2024), https://link.aps.org/doi/10.1103/PhysRevC.109.065502.