Reassessing the theoretical description of neutrino-nucleus interactions

Omar Benhar

INFN and Department of Physics, “Sapienza” University
I-00185 Roma, Italy

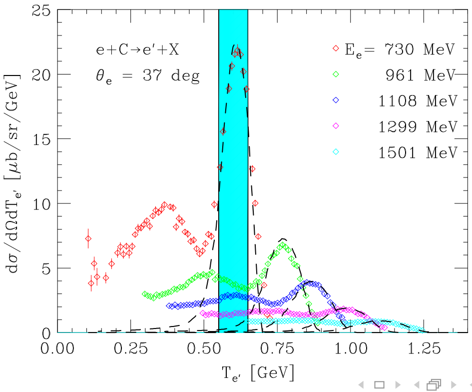
NUINT 2022
Seoul National University, October 24-29, 2022

OUTLINE

- ⋆ The riddle of the flux integrated neutrino-nucleus cross section
- ⋆ Identification of the reaction mechanisms relevant to the flux integrated cross section in the 0π channel
- ⋆ Quantitative assessment of their contributions: recent developments
- ⋆ Outlook

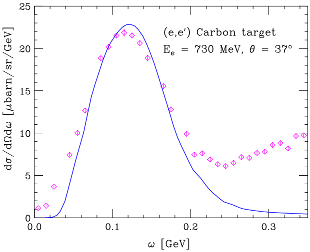
The trouble with flux average

- In neutrino-nucleus interactions, e.g. , $\nu_\mu + A \to \mu^- + X$, the beam energy is unknown, and so is the energy transfer
- different reaction mechanisms contribute to the cross section at fixed muon energy and emission angle
- This feature clearly emerges from the analysis of electron-scattering data corresponding to different beam energies

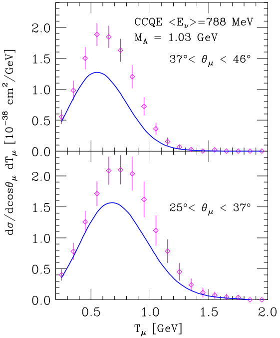


Comparing e- and ν_μ-Carbon cross sections

- Electron scattering, O'Connell et al., PRC 35, 1063 (1987)



- MiniBooNe CCQE cross section, PRD 81, 092005 (2010)

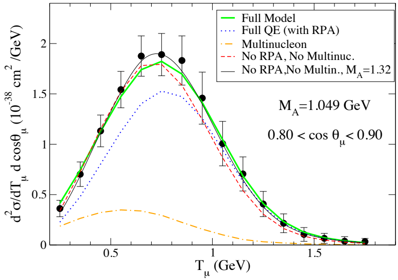


- Calculations performed using the same formalism, based on realistic nuclear spectral functions and phenomenological nucleon form factors
- Owing to flux average, reaction mechanisms other than single-nucleon knock out—leading to the appearance of 1p1h final states of the target nucleus—contribute to the neutrino cross section

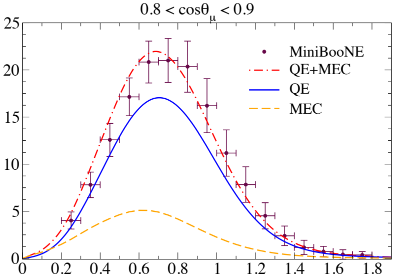
IDENTIFICATION OF DIFFERENT MECHANISMS

- ⋆ While involving somewhat different assumptions, several models agree in predicting that the MiniBooNE data can be explained taking into account the contribution of processes involving two-nucleon currrents (MEC), associated with 2p2h final states

- ▶ Valencia model: Nieves *et al*



- ▶ Superscaling: Megias *et al*



- ⋆ Assessing the role of the 2p2h sector requires an accurate description of the dominant single-nucleon knock out process

THE $\ell + A \to \ell' + X$ CROSS SECTION

- In the impulse approximation regime, factorisation allows to rewrite the nuclear transition amplitude as

$$\langle X|J_A^\mu|0\rangle \to \sum_i \int d^3k \; M_n(\mathbf{k})\langle \mathbf{k}+\mathbf{q}|j_i^\mu|\mathbf{k}\rangle$$

  - The nuclear amplitude $M_n = \langle n|a_{\mathbf{k}}|0\rangle$ describes initial sate properties, independent of the nature of the beam particle.
  - The matrix element of the current between free-nucleon states can be computed exactly using the fully relativistic expression

- Nuclear x-section

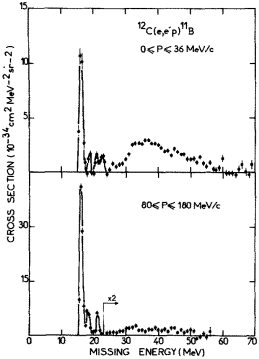
$$d\sigma_A = \int d^3k dE \; d\sigma_N \; P(\mathbf{k}, E)$$

- The spectral function $P(\mathbf{k}, E) = \text{ Im } G(\mathbf{k}, E)/\pi$ describes the energy and momentum distribution of the struck nucleon
- In the quasi elastic sector, the lepton-nucleon cross section $d\sigma_N$ involves phenomenological nucleon form factors
- Corrections to the impulse approximation can be consistently included

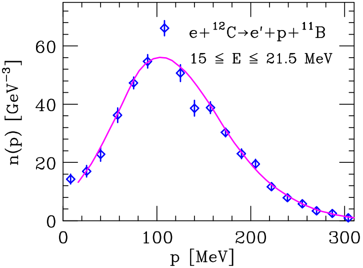
PINNING DOWN THE 1P1H CONTRIBUTION

⋆ $C(e, e'p)$ at Moderate Missing Energy: $e + {}^{12}C \rightarrow e' + p + {}^{11}B^*$

- Missing energy spectrum measured at Saclay (Mougey et al, 1976)

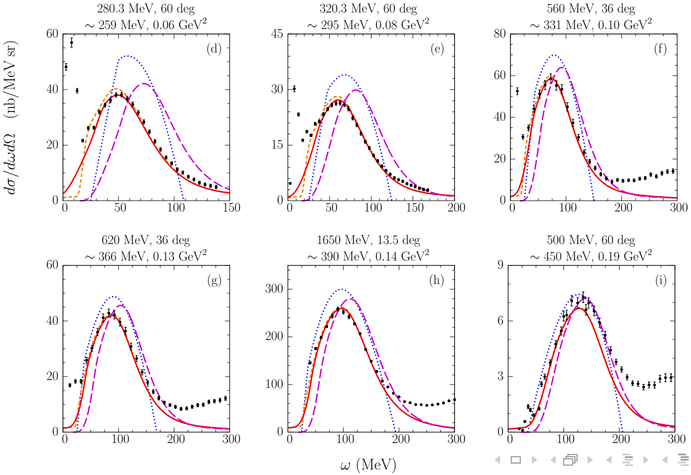


- P- state momentum distribution



⋆ The measured spectroscopic factors are $\sim 37\%$ lower than the predictions of the independent particle model. The missing strength is pushed at higher missing energy by nucleon-nucleon correlations

⋆ After inclusion of corrections arising from final state interactions (FSI), the spectral function derived from C$(e, e'p)$ data—used in conjunction with phenomenological nucleon form factors—provides a remarkably good description of electron-carbon cross sections in a broad kinematic range (Ankowski *et al.*, PRD 2015)



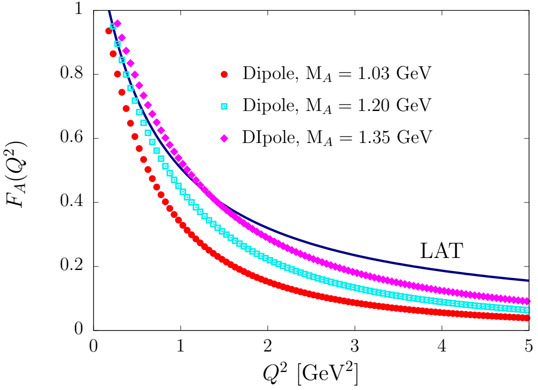
SINGLE NUCLEON KNOCK OUT IN ν-A INTERACTIONS

- ⋆ The availability of a carbon spectral function providing an accurate description of electron-induced single-nucleon knock out allows to carry out a meaningful analysis of the dependence of the CCQE $\nu_\mu + A \to \mu^- + X$ on the nucleon axial form factor
- ⋆ It is long known that MiniBooNE data can be explained by significantly increasing the axial mass—appearing in the dipole parametrisation of the axial form factor—from its canonical value $M_A = 1.03$ GeV. However, this procedure, lacking a compelling physics motivation, appears to be largely arbitrary
- ⋆ Recent results, showing that lattice QCD calculations provide a remarkably good description of the vector form factors of the nucleon [S. Park et al., Phys. Rev. D 105, 054505 (2022)], suggest that the axial form factor obtained from this approach can be reliably used to study neutrino-nucleus cross sections.

Q^2-DEPENDENCE OF THE AXIAL FORM FACTOR

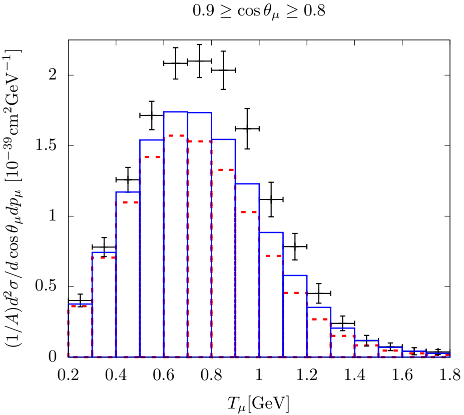
- Comparison between the lattice QCD results of Park et al. [Phys. Rev. D 105, 054505 (2022)] and those obtained using the dipole parametrisation

$$F_A(Q^2) = g_A\left(1 + Q^2/M_A^2\right)^{-1}$$

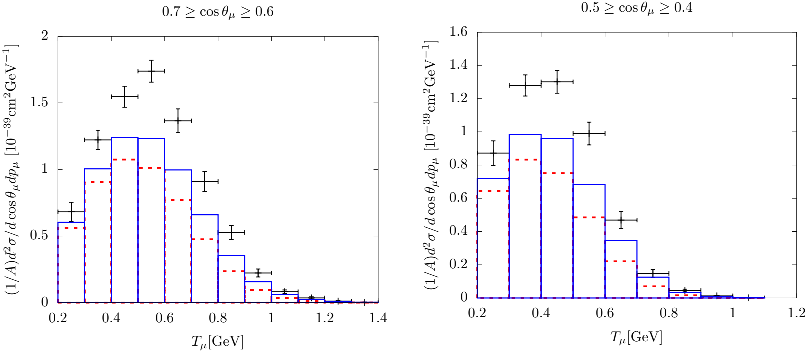


COMPARISON TO MINIBOONE DATA

- Replacing the $M_A = 1.03$ MeV dipole parametrisation with the lattice QCD axial form factor leads to a $\sim 10 - 15\%$ enhancement of the single-nucleon knock out cross section, suggesting a corresponding reduction of the MEC contribution

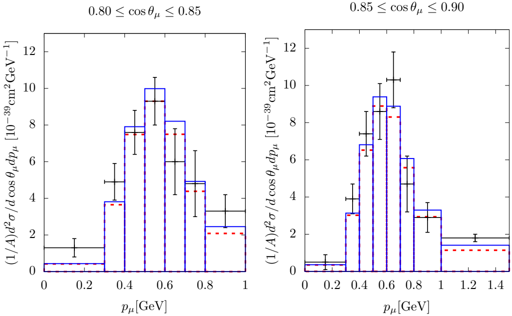


⋆ Same pattern observed at all muon emission angles



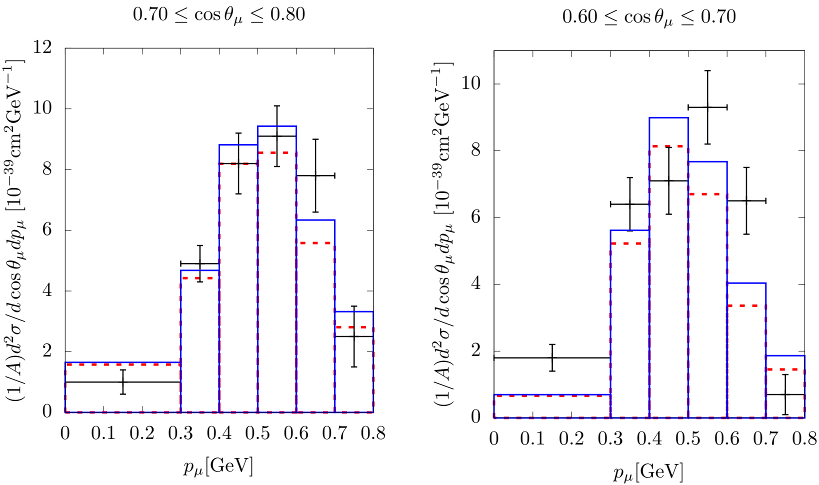
Comparison to T2K data

- ⋆ A comparison to T2K CCQE data [K. Abe et al.. PRD 93, 112012 (2016)] suggests in this instance there is less room for contributions other than single-nucleon knock out



- ⋆ This observation is consistent with the results of the analysis of T2K data based on the dipole parametrisation of the axial form factor, yielding $M_A = 1,20$ GeV (to be compared with $M_A = 1,35$ GeV reported by MiniBooNE)

⋆ Similar pattern observed at all muon emission angles



Summary & Outlook

- ⋆ Despite the significant progresses of the past decade, a firm interpretation of the flux-integrated neutrino-nucleus cross section in the CCQE sector is still missing
- ⋆ While it is arguable that the relevant reaction mechanisms have been identified, their role and possible interplay depend on both the description of nuclear dynamics and the uncertainty associated with the nucleon axial form factor
- ⋆ Use of the recent lattice QCD results in calculations of the flux-integrated cross sections (see also Simons et al. arXiv:2210.02455) suggest that the contribution of processes involving MEC may be smaller than previously believed
- ⋆ The effect of FSI on the flux integrated cross section must be carefully analysed
- ⋆ Comparison with the results of Green Function Monte Carlo calculations in the non relativistic regime may also provide valuable complementary information

- All in all, the present knowledge of neutrino interactions appears to be still comparable to the knowledge of the geography of North America around 1650