Assessing the Role of Meson-Exchange Currents in Neutrino-Nucleus Interactions

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Outline

- ⋆ Preamble: the paradigm of Nuclear Many-Body Theory
- ⋆ Qualitative features of MEC contributions emerging from early studies of electron-nucleus scattering
- ⋆ Studies based on more realistic models of electron-nucleus scattering
  - Factorisation and Spectral Function formalism
  - y-scaling and superscaling
  - Green function Monte Carlo
- ⋆ Specific issues associated with the description of neutrino-nucleus scatteing
  - Flux average
  - Contribution of axial current
- ⋆ Results of recent studies
- ⋆ Summary & Outlook

PREAMBLE

- ⋆ Nuclear Many-Body Theory is based on the tenet—strongly supported by low-energy nuclear phenomenology—that nucleon dynamics can be described by the Hamiltonian

$$H_A = \sum_{i=1}^{A} \frac{\mathbf{p}_i^2}{2m} + \sum_{j>i=1}^{A} v_{ij} + \sum_{k>j>i=1}^{A} V_{ijk} ,$$

  and the associated electro-weak current operator

$$J(q) = \sum_{i=1}^{A} j_i + \sum_{j>i=1}^{A} j_{ij} + \ldots .$$

- ⋆ The electromagnetic current—trivially connected to the vector component of the weak current—is related the nuclear Hamiltonian through the continuity equation

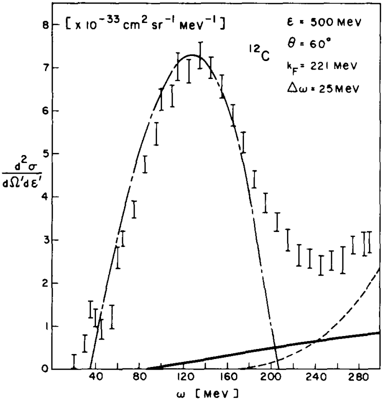
$$\boldsymbol{\nabla} \cdot \boldsymbol{J}_{\rm em} + i[H, J^0_{\rm em}] = 0$$

Early Electron Scattering Studies

- In the late 1970s, significant two-nucleon meson-exchange current (MEC) contributions, leading to the excitation of 2p2h final states, were advocated to explain the discrepancy between the measured $A(e,e')$ cross sections and the predictions of the Relativistic Fermi Gas (RFG) model in the *dip* region, between the quasi-elastic and Δ-production peaks, corresponding to $\omega \sim Q^2/m$

- Calculations by T.W. Donnellly *et al.*, PLB **76**, 393 (1978). RFGM + MEC

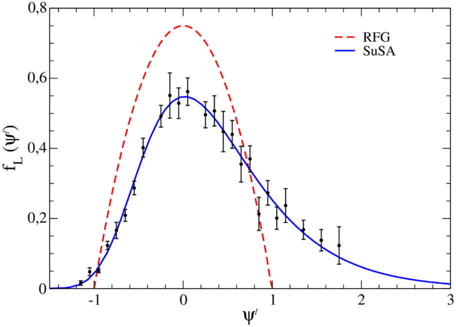
- Data from E.J. Moniz *et al.*, PRL **26**, 445 (1971)



Enter Nuclear Dynamics

- ⋆ Taking into account the effects of nuclear dynamics not included in the RFGM leads to the appearance of sizeable asymmetric tails, originating from both initial state dynamics—primarily Short-Range Correlations (SRC)—and Final State Interactions (FSI)

- ⋆ Nuclear electromagnetic response in the longitudinal channel, unaffected by MEC
- ⋆ J.E. Amaro *et al.*, Eur. Phys. J. Spec. Top. **230**, 4321 (2021)
- ⋆ Data from J. Jourdan, NPA **603**, 17 (1996)

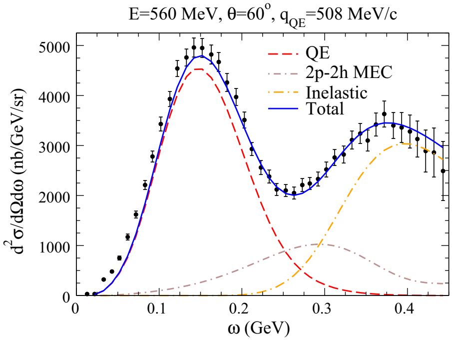


- ⋆ One- and two-nucleon current contributions must be treated consistently, within a realistic unified model

A Popular Semi-Phenomenological Model

- ⋆ In the superscaling model (SuSA) the single-nucleon knock out contribution to the cross section is obtained from inclusive data
- ⋆ MEC contributions computed within the RFGM, including only transitions to 2p2h final states

- ⋆ J.E. Amaro *et al.*, Eur. Phys. J. Spec. Top. **230**, 4321 (2021)
- ⋆ Carbon data from P. Barreau *et al.*, NPA **402**, 515 (1983)

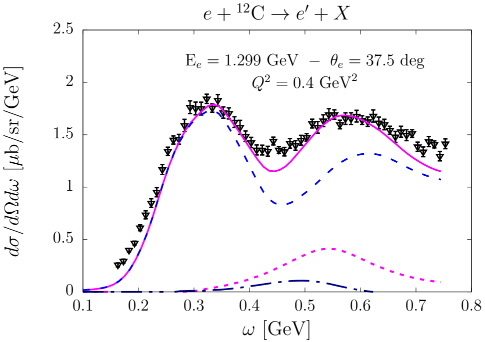


- ⋆ The SuSA model is inherently unable to take into account interference between 1p1h and 2p2h amplitudes

A More Advanced Model: Factorisation

- ⋆ Factorisation of the nuclear cross section allows to treat one- and two-body current contributions within a consistent framework, using spectral functions obtained from a state-of-the-art microscopic model of nuclear dynamics and fully relativistic current operators

- ⋆ N. Rocco *et al.*, PRL **116**, 192501 (2016)
- ⋆ Carbon data from R. Sealock *et al.*, PRL **62**, 1350 (1989)

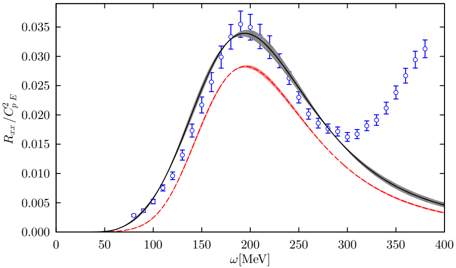


- ⋆ Transitions to 1p1h final state induced by the two-nucleon current are neglected

Green Function Monte Carlo

- ⋆ The Green Function Monte Carlo (GFMC) technique allows one to perform *ab initio* calculations of the nuclear response in the non relativistic regime. All one- and two-body current contributions, including interference, consistently taken into account

- ⋆ Lovato *et al.*, PRC **91**, 062501 (2015); red: one-body current only; blue: full calculation
- ⋆ Transvere response of Carbon at $q = 600$ MeV from J. Carlson *et al.* PRC **65**, 024002 (2002);

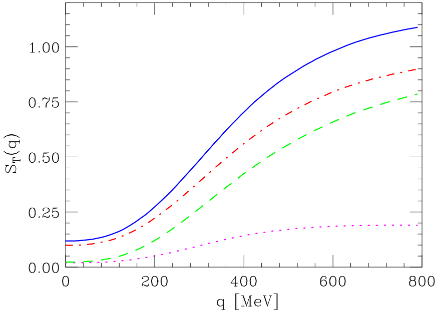


- ⋆ The contribution of MEC, critical to explain the data, peaks at energy transfer $\omega \approx Q^2/2m$, corresponding to single nucleon knock-out. MEC appear to mainly play a role through transitions to 1p1h final states

One- and Two-Nucleon Currents in GFMC

- ⋆ OB, A. Lovato and N. Rocco, PRC **92**, 024602 (2015). Green: one-body current only; red: one-body + two-body, no interference; blue: full calculation
- ⋆ Transvere response of Carbon at $q = 600$ MeV from J. Carlson *et al.* PRC **65**, 024002 (2002);

- ⋆ Transverse sum rule of ^{12}C



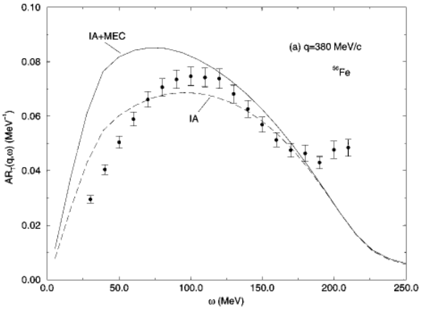
- ⋆ Interference terms appear to play a critical role. However the sum rule does not allow identify the energy dependence of their contribution

PIONEERING NUCLEAR MATER STUDIES

- ⋆ In the late 1990s, the transverse electromagnetic response of nuclear matter was obtained from a realistic Hamiltonian and the associated MEC using the formalism of Correlated Basis Function (CBF) perturbation theory; A. Fabrocini, PRC **55**, 338 (1997)

- ⋆ Non relativistic calculation, performed including only contributions of 1p1h final states
- ⋆ Iron data from J. Jourdan, NPA **603**, 117 (1996)

- ⋆ Comparison to Iron data at $q = 380$ MeV



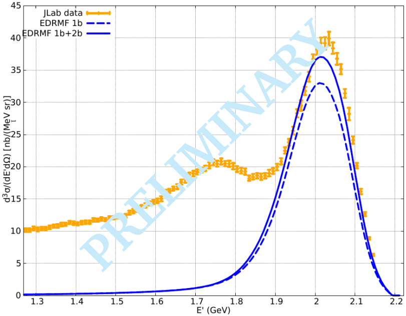
- ⋆ More nuclear matter calculations performed within CBF perturbation theory are under way

RECENT RMF STUDIES

- ⋆ Relativistic Mean-Field Model, extended to consistently describe Final State Interactions and corrected to account for ground-state correlations; T. Franco-Munoz *et al.* arXiv:2203.09996 [nucl-th]
- ⋆ Fully relativistic current operator, only transitions to 1p1h final states included

- ⋆ Figure courtesy of Raul Gonzáles-Jiménez
- ⋆ Data from JLab expt E12-14-012; H. Dai *et al.*, PRC **99**, 054608 (2019)
- ⋆ The two-body current contribution, yielding $\sim$ 20% of the full cross section, peaks at $\omega \approx Q^2/2m$

- ⋆ Argon target
  $E_e = 2.2$ GeV, $\theta_e = 15.5$ deg



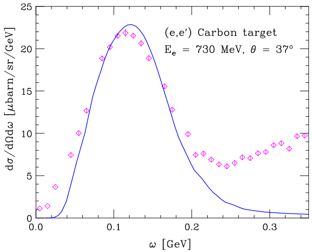
Summary of Electron Scattering Results

- ⋆ MEC give sizable contributions to the electron-nucleus scattering cross section over a broad kinematic range
- ⋆ MEC play an important role in both the 1p1h and 2p2h sectors. The corresponding cross sections exhibit distinctive energy dependences
- ⋆ Interference between contributions play a significant role, and must be described in a consistent fashion using a realistic dynamical model

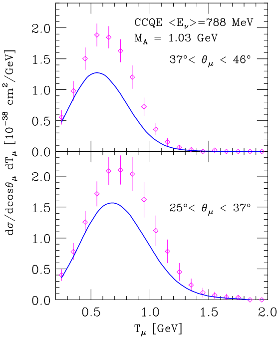
NEUTRINO-NUCLEUS INTERACTIONS IN THE 0π CHANNEL

- OB, P. Coletti and D. Meloni, PRL **105**, 132301 (2010)

- Electron scattering data taken at MIT-Bates; J. S. O'Connell *et al.*, PRC **35**, 1063 (1987)



- MiniBooNe data; A.A. Aguilar-Arevalo *et al.*, PRD **81**, 092005 (2010)

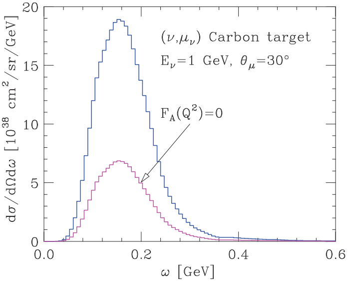


- Processes involving MEC—often misleadingly referred to as 2p2h contributions—have been advocated as the main source of the missing strength

Electron and Neutrino-Nucleus Interactions

- ⋆ Compared to the electron-nucleus cross sections, the measured neutrino-nucleus cross sections involve two important differences:
  - the average over a broad neutrino flux, which severely hampers a clear-cut identification of different reaction mechanisms
  - a large contribution of the axial-vector current

- ⋆ Jen *et al.* PRD **90**, 093004 (2014); dipole fit with $M_A = 1.03$ GeV



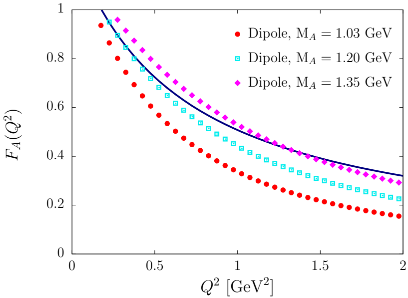
- ⋆ The size of the contribution from two-nucleon currents is strongly affected by the uncertainty on the axial structure of the nucleon

Q^2-dependence of the Axial Form Factor

- ⋆ The available data, from both MiniBooNE and T2K, can be explained using the dipole parametisation of the axial form factor and a nucleon axial mass significantly larger than the *canonical* value $M_A = 1.03$ GeV
- ⋆ The results of lattice calculations recently reported by the NME Collaboration point to a significantly different Q^2 dependence

- ▶ Comparison between the results of Park *et al.*, PRD **105**, 054505 (2022), obtained from lattice calculations and the dipole parametrisation

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

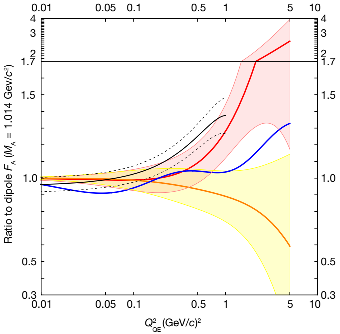


- ⋆ At $Q^2 \lesssim 0.5$ GeV^2 the dipole fit with $M_A = 1.2$ GeV is remarkably close to the lattice results

Recent Experimental Developments

⋆ The MINERνA collaboration has recently reported the results of an analysis aimed at obtaining the axial form factor from the cross section of the process $\overline{\nu} + p \to \mu^+ + n$; T. Cai *et al.*, Nature **614**, 48 (2023)

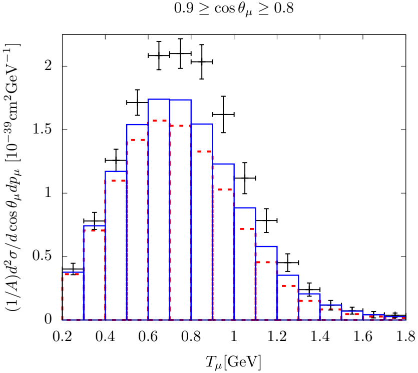
- Ratio between the axial form factor extracted from the MINERνA measurements and the dipole parametrisation with $M_A = 1.014$ GeV



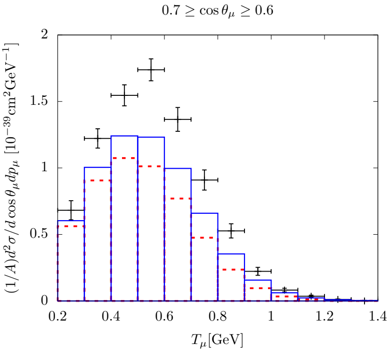
Impact of Lattice (& MINERνA) Results

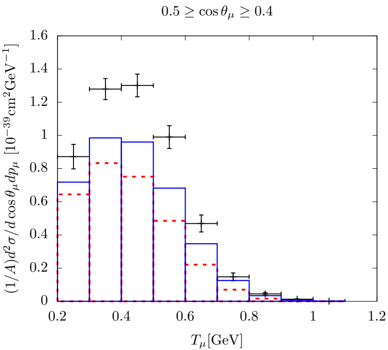
- ⋆ Replacing the $M_A = 1.03$ MeV dipole parametrisation with the lattice axial form factor of Parks *et al.* leads to a $\sim 10 - 15\%$ enhancement of the single-nucleon knock out cross section, entailing a corresponding reduction of the missing strength

- ⋆ Theoretical calculations carried out using the same carbon spectral function as in PRL **105**, 132301 (2010)



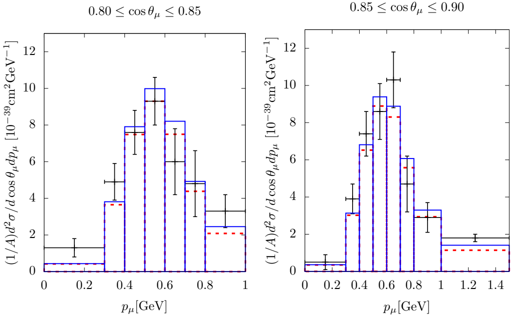
★ Similar pattern observed at all muon emission angles





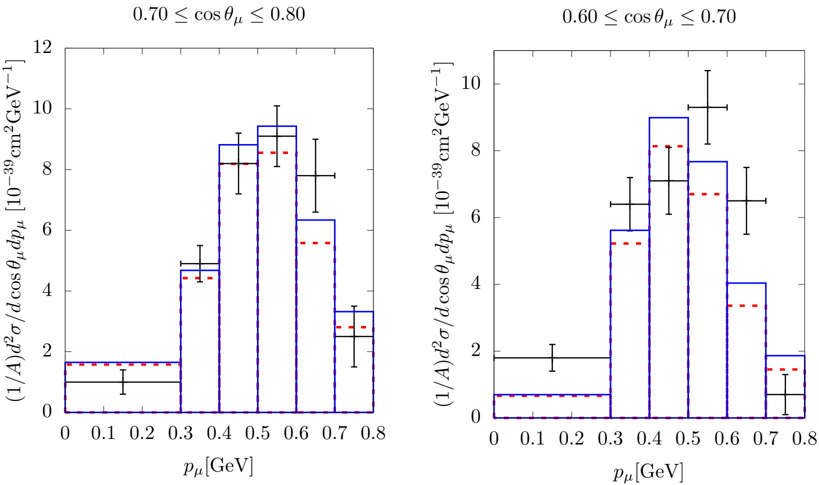
Comparison to T2K Data

- ⋆ 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



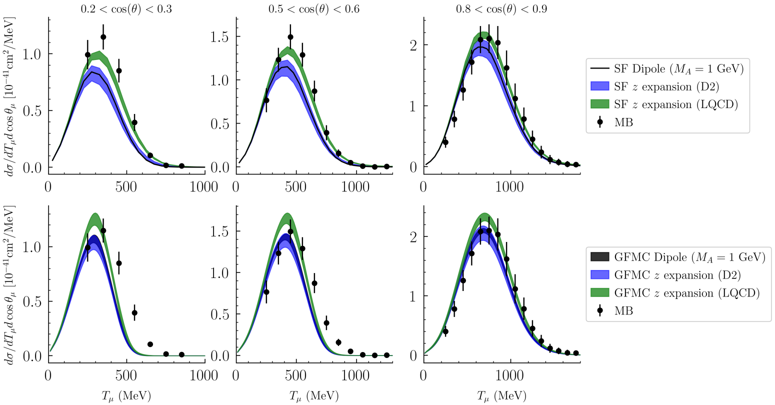
- ⋆ This observation is consistent with the results of the analysis of T2K data based on the dipole parametrisation of the axial form factor, yielding $M_A = 1.26$ GeV (to be compared with $M_A = 1.35$ GeV reported by MiniBooNE)

⋆ Similar pattern observed at all muon emission angles



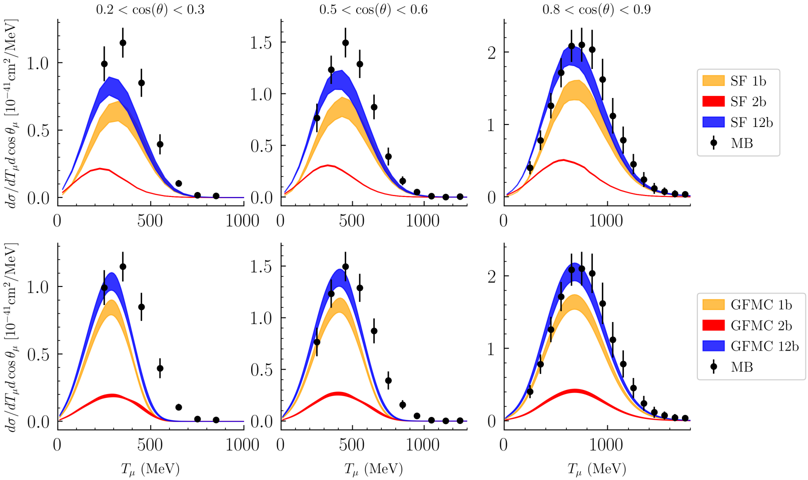
Similar analysis by Simons *et al.* (arXiv:2210.02455 [hep-ph])

- ⋆ MiniBooNE data analysed using the GFMC and SF formalisms and different prescriptions for the axial form factor

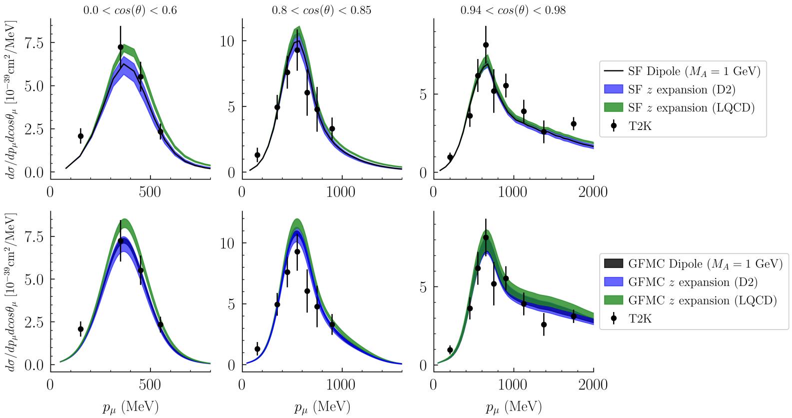


One- and two-nucleon current contributions

★ SF results do not include interference



Comparison to T2K data



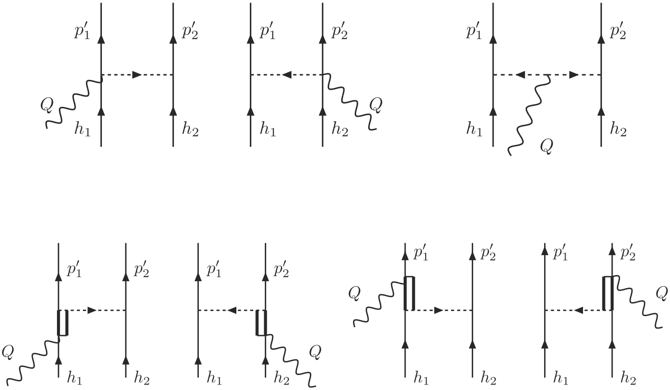
Summary & Outlook

- ⋆ The disagreement between the first measured double-differential neutrino-nucleus cross section and the prediction of simulation codes led to the development of theoretical models including large MEC contributions in the 2p2h sector, which appeared to be needed to explain the data
- ⋆ Theoretical studies of electron-nucleus scattering performed using realistic dynamical models provide convincing evidence that the use of oversimplified or incomplete models may be very misleading
- ⋆ In interacting many-body systems, processes driven by one- and two-nucleon currents lead to the appearance of both 1p1h and 2p2h final states. Interference plays an important role, and must be taken into account realistic model
- ⋆ A firm assessment of the role of MEC in neutrino interactions requires that the contribution of processes driven by the axial one-body current be under control at quantitative level
- ⋆ The impact of the recent determinations of the axial form factor must be carefully investigated

Thank you!

Backup slides

PROCESSES INVOLVING TWO-NUCLEON CURRENTS



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 . As a consequence, different reaction mechanisms contribute to the cross section at fixed muon energy and emission angle
- ⋆ This problem clearly emerges from the analysis of electron-scattering data corresponding to different beam energies