Towards a Unified Description of Neutrino-Nucleus Interactions

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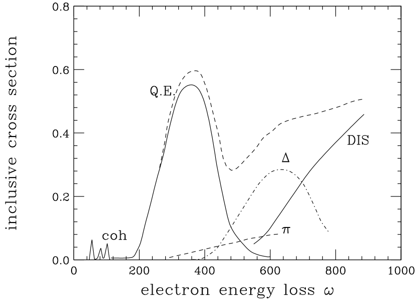
OUTLINE

- Motivation: unraveling the flux-averaged cross section
- Lessons learned from studies of electron-nucleus interactions: emergence of factorisation in the impulse approximation (IA) regime
- Extensions & corrections: two-nucleon meson-exchange currents (MEC) and final state interactions (FSI)
- Generalisation to neutrino-nucleus interactions
- Exploiting the full potential of factorisation: the E12-14-012 $^{40}\mathrm{Ar}(e,e'p)$ experiment at Jefferson Lab
- Summary & Outlook
- Epilogue

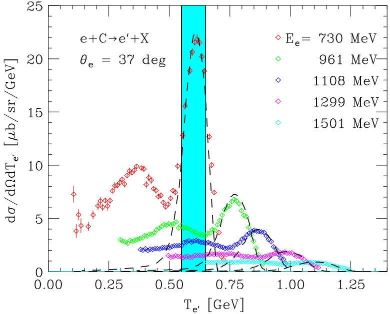
Interpretation of the flux–averaged cross section

⋆ $e + {}^{12}\mathrm{C} \to e' + X$ x-sections at fixed beam energy and scattering angle

- beam energy ∼1 GeV



- beam energies between ∼ 0.7 and ∼1.5 GeV.

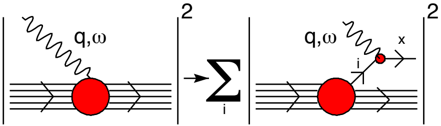


⋆ The averaged cross section at fixed energy and scattering angle of the outgoing lepton picks up contributions from different mechanisms

⋆ All reaction channels must be included within a consistent theoretical framework

Impulse approximation and factorisation

- for $\lambda \sim 1/|\mathbf{q}| \ll d_{\rm NN} \sim 1.6$ fm, the average nucleon-nucleon distance in the target nucleus, nuclear scattering reduces to the incoherent sum of scattering processes involving individual nucleons



- Basic assumptions
  - $J^\mu_A(q) \approx \sum_i j^\mu_i(q)$: single-nucleon coupling
  - $|X\rangle \to |x(\mathbf{p})\rangle \otimes |n_{(A-1)}, \mathbf{p_n}\rangle$: factorisation of the final state
- Corrections arising from te occurrence of FSI and processes involving MEC can be consistently included
- Striking evidence of the onset of factorisation is provided by the occurrence of y-scaling in inclusive electron-nucleus scattering

THE IA CROSS SECTION

- Factorisation allows to rewrite the nuclear transition matrix element as

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

  - The nuclear amplitude $M_n = \langle n | a_{\mathbf{k}} | 0 \rangle$ is independent of momentum transfer. It can be accurately calculated within non relativistic many-body theory
  - The matrix element of the current describes the transition of a nucleon of momentum $\mathbf{k}$ to a hadronic final state of momentum $\mathbf{k} + \mathbf{q}$

- Nuclear x-section

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

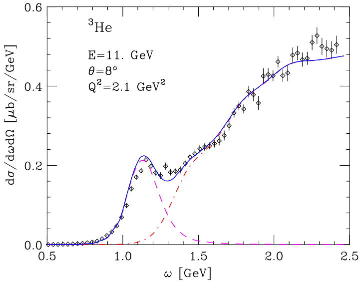
- The lepton-nucleon cross section $d\sigma_N$ can be obtained from proton and deuteron data, theoretical models, or lattice calculations

- The spectral function $P_h(\mathbf{k}, E)$ describes the probability of removing a nucleon of momentum $\mathbf{k}$ from the nuclear ground state, leaving the residual system with excitation energy E

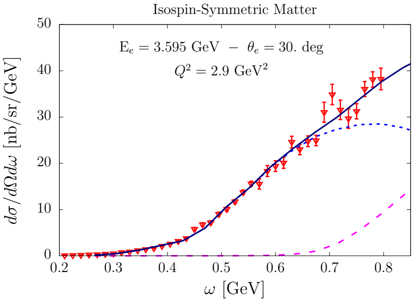
Inclusive electron-nucleus scattering: $e + A \to e' + X$

- ⋆ elastic and inelastic (RES + DIS) processes consistently taken into account (Bodek & Ritchie parametrisation of SLAC data)
- ⋆ spectral functions obtained from *ab initio* microscopic calculations

- $A = 3$ SLAC data
  Day *et al*, PRL 43,1143 (1979)

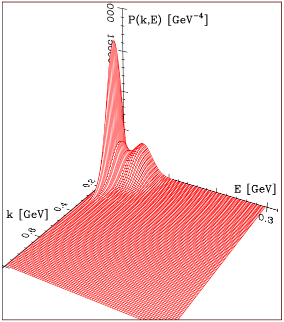


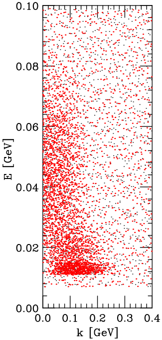
- $A \to \infty$ extrapolation of SLAC data, taken using targets with $4 \leq A \leq 197$
  Day *et al*, PRC 40, 1011 (1989)

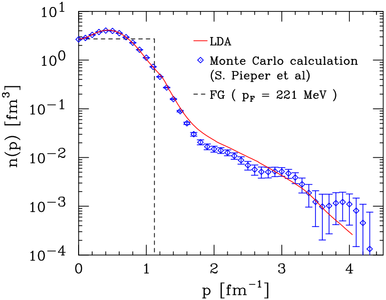


Spectral Function of complex nuclei

- Phenomenological model: theory + electron scattering data. Oxygen as an example, similar results available for Carbon and Iron



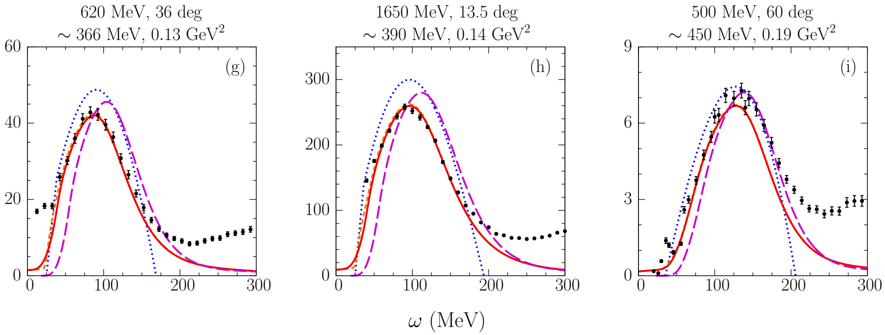




- Fermi gas model: $P(\mathbf{p}, E) \propto \theta(p_F - |\mathbf{p}|)\, \delta(E - \sqrt{|\mathbf{p}|^2 + m^2} + \epsilon)$
- shell model states account for $\sim$ 80% of the strength
- the remaining $\sim$ 20% is pushed at high momentum and removal energy

INTERACTION EFFECTS (QE ONLY, NO MEC)

- Initial state (spectral function)
  - nuclear mean field → cross section shifted
  - nucleon-nucleon correlations → appearance of two particle-two-hole . Peak quenched, appearance of tails at both low and high energy transfer, ω.
- FSI (folding approximatioon) → cross section shifted and broadened

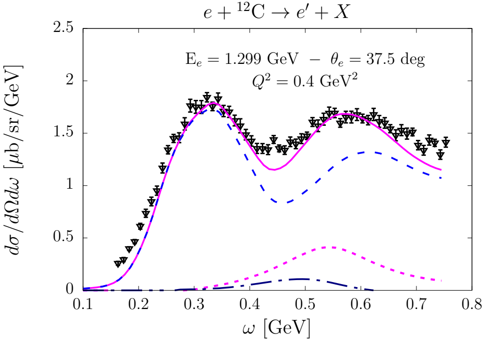


A. Ankowski *et al*, PRD **91** 033005, (2015)

EXTENDED FACTORISATION

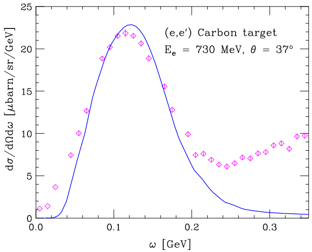
- ⋆ Factorisation of the nuclear cross section can be extended to treat one- and two-body current contributions consistently, using one- and two-nucleon spectral functions obtained from a realistic microscopic model of nuclear dynamics and fully relativistic current operators

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

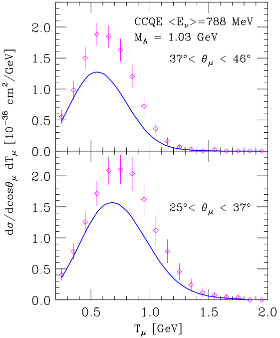


COMPARING e- AND ν_μ-CARBON 0π CROSS SECTIONS

▷ Electron scattering



▷ MiniBooNe CCQE cross section



- Theoretical calculations carried out using the same formalism
- Failure to explain the data to be ascribed to flux average & form factors

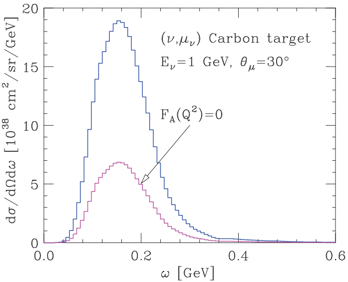
The axial form factor of the nucleon

- The contribution of the axial-vector current is large

⋆ Jen *et al.* PRD **90**, 093004 (2014); dipole axial form factor

$$F_A(Q^2) = \frac{g_A}{(1 + Q^2/M_A^2)} \, ,$$

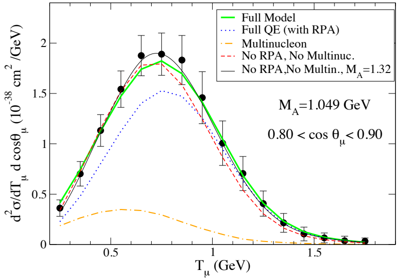
Canonical axial mass:
$M_A = 1.03$ GeV



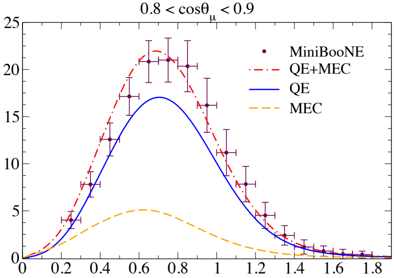
- The MiniBoone data can be explained using the Fermi gas (FG) model if the value of the axial mass is increased to $M_A = 1.35$ MeV
- The MiniBooNE paper suggests that the large axial mass is meant to parametrise nuclear effects not taken into account by the FG model
- More advanced models of the nuclear cross section appear to provide a good a description of the data, although their ability to explain electron scattering data is not fully established

VALENCIA MODEL *vs* SUPERSCALING

- Nieves *et al*



- Megias *et al*



⋆ The result of Nieves et al show a significant contribution arising from the excitation of nuclear collective modes (RPA), which is not included in the phenomenological approach of Megias et al. Both models use $M_A = 1.03$ GeV

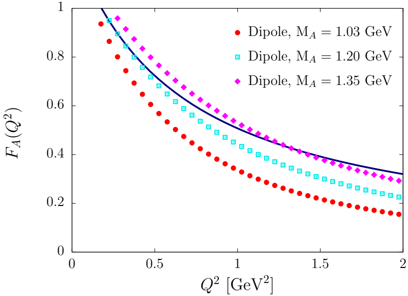
⋆ Large MEC contribution needed to describe the data, even though a clear cut identification of the relevant nuclear effects is still missing

Determination of $F_A(Q^2)$ from lattice calculations

- ⋆ The results of lattice calculations recently reported by the NME Collaboration point to a Q^2-dependence significantly different from that predicted by the dipole parametrisation

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

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

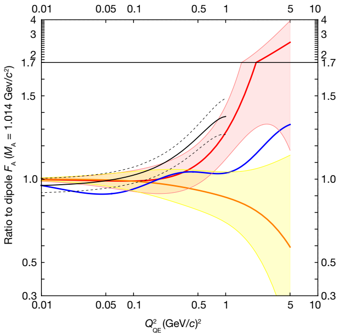


- ⋆ At $Q^2 \lesssim 0.5$ GeV^2 the dipole fit with $M_A = 1.2$ GeV is remarkably close to the lattice results

New experimental determination of $F_A(Q^2)$

- ⋆ 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)

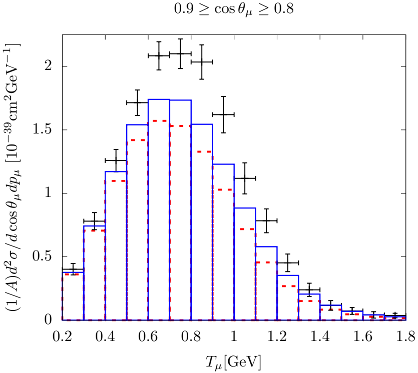
- Ratio between the axial form factor extracted from the MINERνA measurements and the dipole parametrisation with $M_A = 1.014$ GeV



Impact of Lattice (& Minerνa?) Results

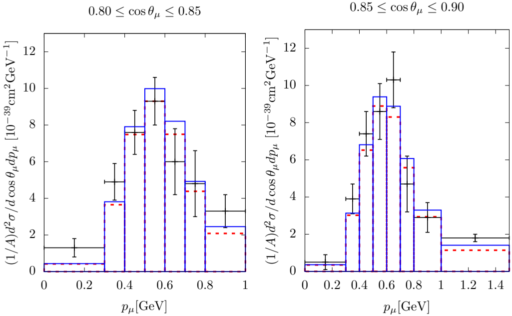
- Calculations performed the carbon spectral function employed to describe electron scattering data
- Replacing the $M_A = 1.03$ MeV dipole parametrisation with the lattice axial form factor of Parks *et al.* leads to a $\sim 10 - 15\%$ enhancement of the single-nucleon knock out cross section, entailing a corresponding reduction of the missing strength

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



Similar 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)

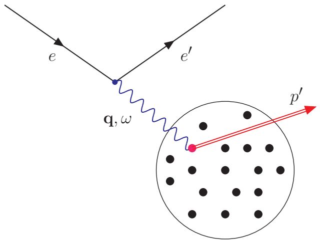
THE JEFFERSON LAB E12-14-012 $^{40}\mathrm{Ar}(e, e'p)$ EXPERIMENT

- Consider the process $e + A \to e' + p + (A-1)$ in which both the scattered electron and the knocked-out proton are detected in coincidence

Missing momentum and missing energy

$$\mathbf{p}_m = \mathbf{p}' - \mathbf{q}$$

$$E_m = \omega - T_{\mathbf{p}'} - T_{A-1} \approx \omega - T_{\mathbf{p}'}$$



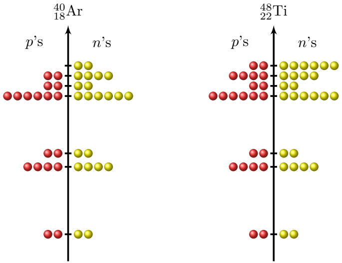
- Assuming that FSI be negligible, the spectral function of the target nucleus can be obtained from

$$\frac{d\sigma_A}{dE_{e'} d\Omega_{e'} dE_p d\Omega_p} \propto \sigma_{ep} P(p_m, E_m)$$

Determination of the Argon spectral function

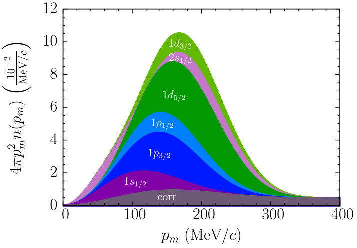
- ⋆ The distortion arising from FSI have been taken into account using the well established framework of Distorted Wave Impulse Approximation (DWIA)

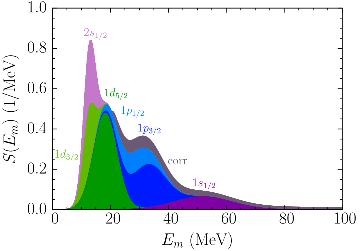
- ⋆ The $\mathrm{Ar}(e, e'p)$ cross section only provides information on protons. Useful information on the neutron distributions have been obtained from $\mathrm{Ti}(e, e'p)$ data, by exploiting the similarity between the proton spectrum of $^{48}_{22}\mathrm{Ti}$ and the neutron spectrum of $^{40}_{18}\mathrm{Ar}$



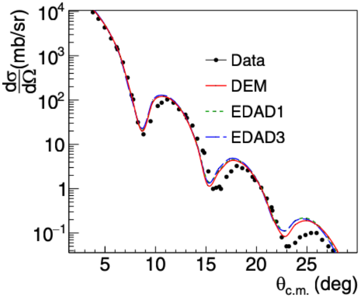
Main Elements of the Argon Analysis

Missing momentum (top) and missing energy (bottom) distributions





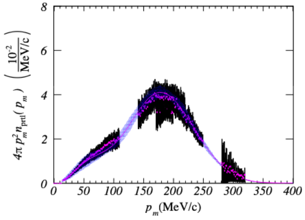
Differential cross section for elastic scattering of 800 MeV protons on Argon. Theoretical results obtained from the optical potential employed in the analysis



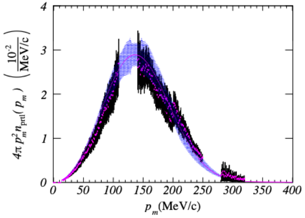
Step 1: Analysis of Momentum Distribution

- The spectroscopic factors have been determined from momentum distributions—obtained from integration over three missing energy ranges—using constraints from previous experiments

		All priors	w/o p_m	w/o corr.
α	N_α		S_α	
$1d_{3/2}$	2	0.89 ± 0.11	1.42 ± 0.20	0.95 ± 0.11
$2s_{1/2}$	2	1.72 ± 0.15	1.22 ± 0.12	1.80 ± 0.16
$1d_{5/2}$	6	3.52 ± 0.26	3.83 ± 0.30	3.89 ± 0.30
$1p_{1/2}$	2	1.53 ± 0.21	2.01 ± 0.22	1.83 ± 0.21
$1p_{3/2}$	4	3.07 ± 0.05	2.23 ± 0.12	3.12 ± 0.05
$1s_{1/2}$	2	2.51 ± 0.05	2.05 ± 0.23	2.52 ± 0.05
Corr.	0	3.77 ± 0.28	3.85 ± 0.25	Excluded
$\sum_\alpha S_\alpha$		17.02 ± 0.48	16.61 ± 0.57	14.12 ± 0.42
d.o.f		206	231	232
χ^2/d.o.f.		1.9	1.4	2.0



(a) $0 < E_m < 30$ MeV



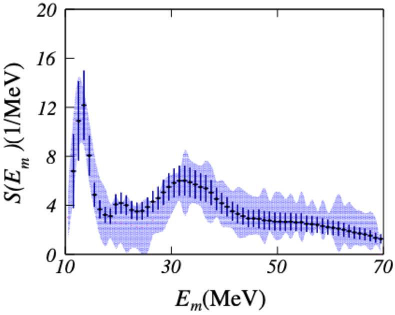
(b) $30 < E_m < 54$ MeV

Step 2: Analysis of Missing Energy Distribution

- The energies and widths of the shell-model states have been determined from the missing energy distributions, using the priors obtained from the momentum distribution analysis

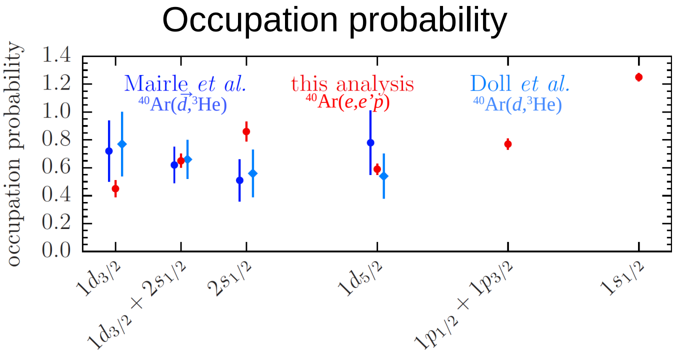
$15 \leq p_m \leq 110$ MeV

	E_α (MeV)		σ_α (MeV)	
α	w/ priors	w/o priors	w/ priors	w/o priors
$1d_{3/2}$	12.53 ± 0.02	10.90 ± 0.12	1.9 ± 0.4	1.6 ± 0.4
$2s_{1/2}$	12.92 ± 0.02	12.57 ± 0.38	3.8 ± 0.8	3.0 ± 1.8
$1d_{5/2}$	18.23 ± 0.02	17.77 ± 0.80	9.2 ± 0.9	9.6 ± 1.3
$1p_{1/2}$	28.8 ± 0.7	28.7 ± 0.7	12.1 ± 1.0	12.0 ± 3.6
$1p_{3/2}$	33.0 ± 0.3	33.0 ± 0.3	9.3 ± 0.5	9.3 ± 0.5
$1s_{1/2}$	53.4 ± 1.1	53.4 ± 1.0	28.3 ± 2.2	28.1 ± 2.3
Corr.	24.1 ± 2.7	24.1 ± 1.7	…	…



Comparison with Previous Argon Data

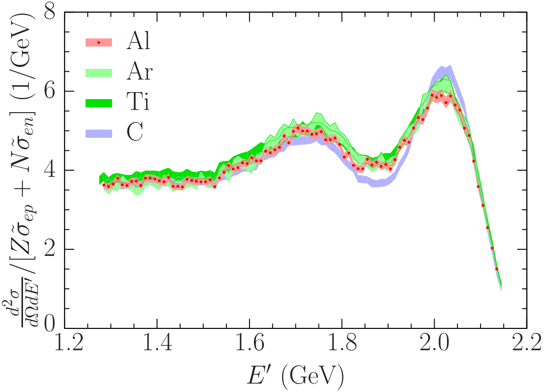
- Nucleon knock-out from Argon has been also studied in the proton pick-up reaction $^{40}\mathrm{Ar}(^{2}\mathrm{H},^{3}\mathrm{He})$ using both inpolarised and polarised deuteron beams



- The results of present analysis turn out to be largely compatible with previous data

A bonus from E12-14-012: inclusive Cross Sections

- Beam energy $E = 2.22$ GeV, electron scattering angle $\theta_e = 15.54$ deg



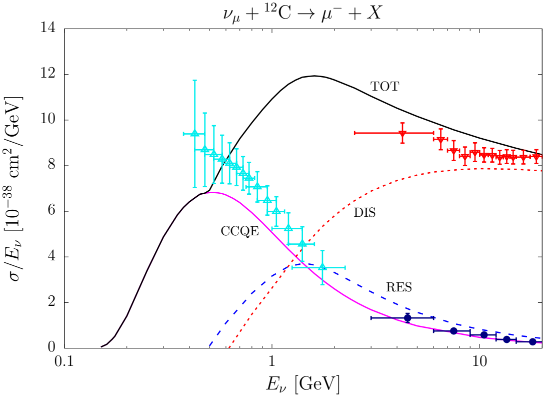
- Consistency with previous inclusive data confirmed by y-scaling and superscaling analysis

SUMMARY & OUTLOOK

- ⋆ Despite the difficulties arising from flux average, a consistent description of the neutrino-nucleus cross in both elastic and inelastic channels appears to be possible using factorisation
- ⋆ Most theoretical models of neutrino-nucleus interactions involve some level of factorisation. However, to fully exploit its potential, this scheme must be implemented using spectral functions providing an accurate description of the initial state
- ⋆ A better understanding of the interaction vertices, involving vector and axial form factors, and structure functions in the resonance production and DIS regions, is needed
- ⋆ The present development of the treatment of FSI, while being adequate for inclusive processes in the 0π sector, need to be improved and generalised to treat more complex final states and exclusive processes
- ⋆ Long-range correlations and the breakdown of factorisation at low momentum transfer need to be carefully investigated

EPILOGUE

⋆ A unified framework for the description of neutrino-nucleus interaction is emerging



- Theory: E. Vagnoni *et al*, PRL 118, 142502 (2017)
- σ_{CCQE}: NOMAD, PLB 660, 19 (2008), MiniBooNE, PRD 81, 092005 (2010)
- σ_{TOT}: NOMAD, EPJC 63, 555 (2009)

Abstract

The achievement of the goals of the ongoing and future accelerator-based neutrino experiments—notably the determination of CP violating phase in the lepton sector—will require the development of advanced models of neutrino-nucleus interactions. In this talk, I summarise the present status of theoretical models of lepton-nucleus scattering, highlighting the importance of exploiting the information obtained from processes involving electrons, and discuss the developments and perspectives of the approach based on factorisation of the nuclear cross section, which has recently emerged as a promising framework for the description of the variety of processes contributing to the flux-integrated neutrino cross section. The experimental implications of factorisation and the measurement of the argon spectral function performed iat Jefferson Lab by the E12-14-012 Collaboration, are also discusssed.

Results obtained in collaboration with

A.M. Ankowski, C. Mariani, D. Meloni, N. Rocco,
M. Sakuda, and E. Vagnoni

Talk based on the review by OB and C. Mariani: EPJA **59**, 85 (2023)
https://doi.org/10.1140/epja/s10050-023-00995-9