Synergy between Electron Scattering and Neutrino Physics

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Outline

- ★ Motivation
- ★ Electron scattering
    - ▹ Measured double-differential nuclear cross sections
    - ▹ Theoretical description: impulse approximation
- ★ Neutrino-nucleus interactions
    - ▹ Flux averaged cross section
    - ▹ The axial mass puzzle
- ★ Synergy*

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*The interaction or cooperation of two or more organizations, substances, or other agents to produce a combined effect greater than the sum of their separate effects (Oxford Dicionary).

Motivation

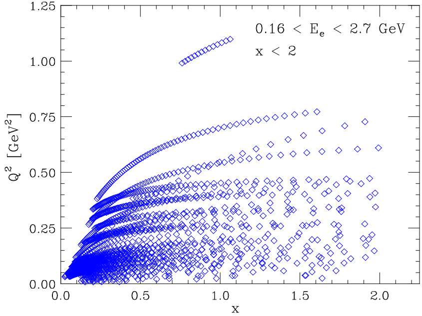
- ★ The interpretation of the signals detected by most neutrino experiments require a quantitative understanding of the nuclear response to electroweak interaction
- ★ Over the past decades electron scattering has provided a wealth of information that need to be fully exploited in the analysis of neutrino data
  - ▹ Nucleon form factors
  - ▹ Double differential inclusive cross sections
  - ▹ Coincidence, semi-inclusive, cross sections
- ★ More electron scattering data will be needed for the analysis of future, high precision, neutrino experiment
- ★ The combined information coming from electron and neutrino data may help to shed light on unresolved nuclear physics issues

Information from inclusive measurements

- ★ Vast supply of precise data available

$$Q^2 = 4E_eE_{e'}\sin^2\frac{\theta_e}{2} \quad , \quad x = \frac{Q^2}{2M\omega}$$

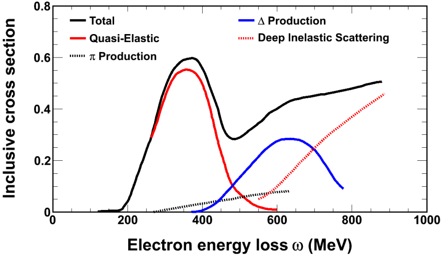
- ★ Carbon target, $x < 2$



- ★ Different rection mechanisms contributimg to the mesured cross sections can be readily identified

$$e + A \rightarrow e' + X$$

$$E_e \sim 1 \text{ GeV}$$



The lepton-nucleus x-section

- ★ Double differential cross section

$$\frac{d\sigma_A}{d\Omega_{k'}dk'_0} \propto L_{\mu\nu} W_A^{\mu\nu}$$

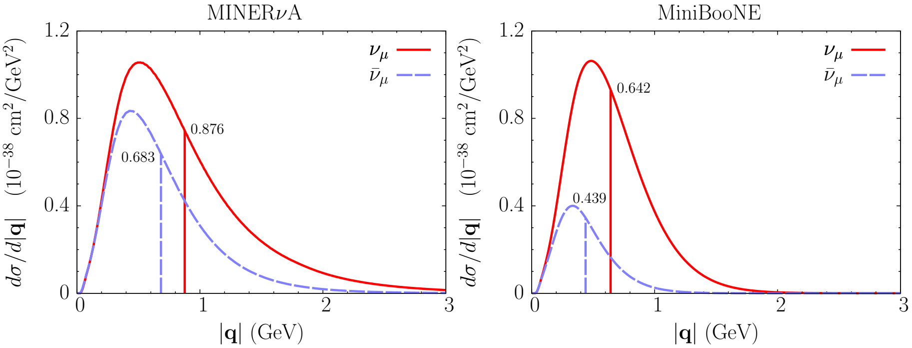
  - ▹ $L_{\mu\nu}$ is fully specified by the lepton kinematical variables, $k \equiv (k_0, \mathbf{k})$ and $k \equiv (k'_0, \mathbf{k}')$. Same as in lepton-nucleon scattering.
  - ▹ The determination of the target response tensor

$$W_A^{\mu\nu} = \sum_N \langle 0|J_A^{\mu\,\dagger}(q)|N\rangle\langle N|J_A^\nu(q)|0\rangle \delta^{(4)}(P_0 + q - P_N)$$

where $q = k - k' \equiv (\omega, \mathbf{q})$, requires a *consistent* description of the initial and final states, as well as of the nuclear current operator

$$J_A^\mu(q) = \sum_i j_i^\mu(q) + \sum_{j>i} j_{ij}^\mu(q_1, q_2) \quad , \quad q = q_1 + q_2$$

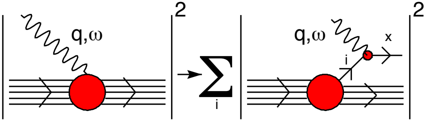
Why worry about relativity (courtesy of A. Ankowsky)



- ★ Unlike the initial state, the nuclear current and the final hadronic state *can not* be described using non relativistic many-body theory
- ★ Owing to flux average, in neutrino experiments low- and large-$|\mathbf{q}|$ contributions to the observables are inextricably tangled

Impulse approximation and factorization *ansatz*

- ⋆ At $|\mathbf{q}|^{-1} \ll d \sim 1.2$ fm the impulse approximation (IA) regime sets in



- ▹ In the quasi elastic channel, the one-body current is written in terms of the measured vector and axial-vector nucleon form factors

$$J^{\mu}_{A}(q) \approx \sum_{i} j^{\mu}_{i}(q)$$

- ▹ the nuclear final state is written in the factorized form

$$|N\rangle \to |\mathbf{p}\rangle \otimes |n_{(A-1)}, \mathbf{p_n}\rangle \quad , \quad |n_{(A-1)}, \mathbf{p_n}\rangle = |1h\rangle\ ,\ |2h1p\rangle \ldots$$

- ▹ at zero-th order, final state interactions (FSI) between the outgoing nucleon and the spectator particles are neglected (can be included as corrections)

Spectral function

- within the IA scheme the nuclear matrix element of the one-nucleon current reduces to

$$\langle N|J^{\mu}_{A}(q)|0\rangle = A\int d^3k\, M_m(\mathbf{k})\,\langle \mathbf{p}|j^{\mu}_{1}(q)|\mathbf{k}\rangle\ ,$$

  with

$$M_n(\mathbf{k}) = \{\langle n_{(A-1)}, \mathbf{p}_n| \otimes \langle \mathbf{k}|\}\,|0\rangle\ .$$

- The nuclear spectral function, yielding the probability of removing a nucleon of momentum $\mathbf{k}$ leaving the residual system with excitation energy E, is defined as

$$P(\mathbf{k}, E) = \sum_n |M_n(\mathbf{k})|^2 \delta(E_0 + E - E_n)$$

Local Density Approximation (LDA)

$$P(\mathbf{k},E) = P_{MF}(\mathbf{k},E) + P_{\rm corr}(\mathbf{k},E)$$

- ⋆ $P_{MF}(\mathbf{k},E) \to$ from $(e,e'p)$ data
- ⋆ $P_{\rm corr}(\mathbf{p},E) \to$ from uniform nuclear matter calculations at different densities:

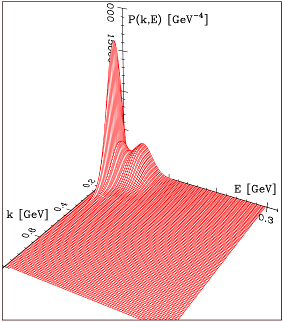
$$P_{MF}(\mathbf{k},E) = \sum_n Z_n |\phi_n(\mathbf{k})|^2 \ F_n(E-E_n)$$

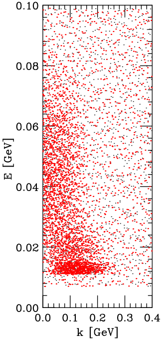
$$P_{\rm corr}(\mathbf{k},E) = \int d^3r \, \rho_A(r) \, P^{NM}_{\rm corr}(\mathbf{k},E;\rho=\rho_A(r))$$

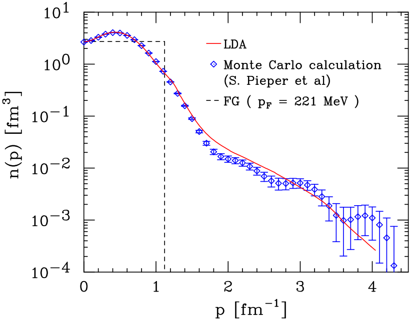
- ⋆ In the mean firld approximation $Z_n \to 1$, $F_n(E-E_n) \to \delta(E-E_n)$ and $\phi_n(\mathbf{k})$ reduces to the wave function of a shell model state

Nucleon energy and momentum distribution in ^{16}O

$$n(k) = \int dE \, P(\mathbf{k}, E)$$



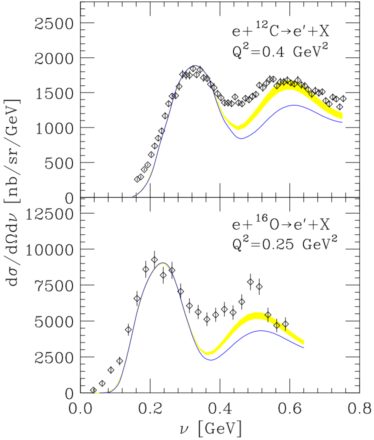


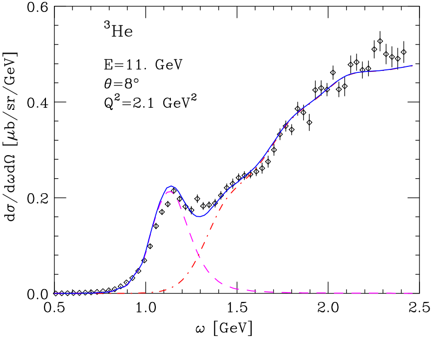


- ★ shell model states account for ~ 80% of the strenght
- ★ the remaining ~ 20%, arising from NN correlations, is located at high momentum *and* large removal energy ($\mathbf{k} \gg k_F, E \gg \epsilon$)

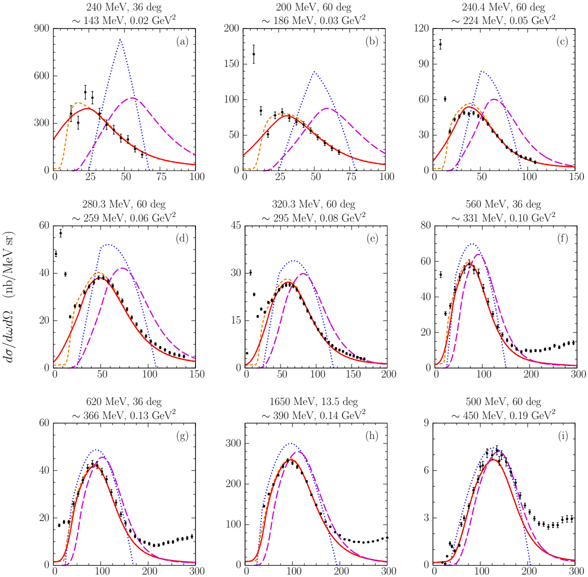
Theory *vs* data

- ★ Nuclear x-section $d\sigma_A = \int d^3k dE \, d\sigma_N \, P(\mathbf{k}, E)$
- ★ Recall: no adjustable parameters





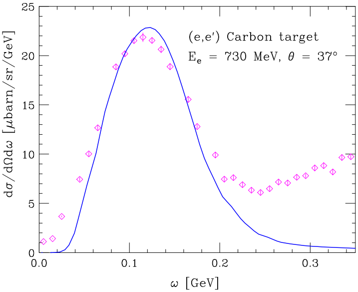
Quasi elastic channel - carbon target

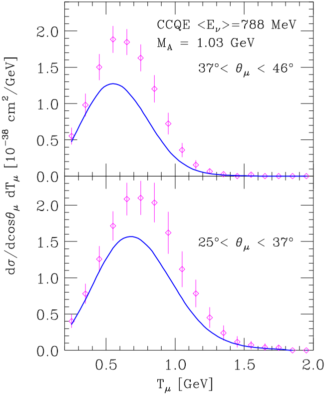


Quasi elastic channel: electron vs neutrino

- ⋆ Double differential CCQE neutrino x-section (MiniBooNE)

$$\frac{d\sigma_A}{dT_\mu d\cos\theta_\mu} = \frac{1}{N_\Phi}\int dE_\nu \Phi(E_\nu)\frac{d\sigma_A}{dE_\nu dT_\mu d\cos\theta_\mu}$$





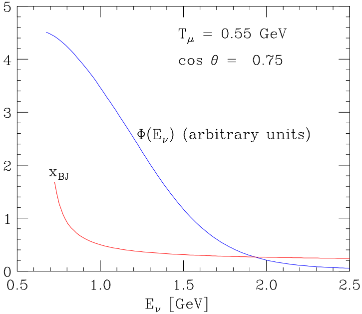
- ⋆ Nucleon axial mass set to $M_A = 1.03$ GeV

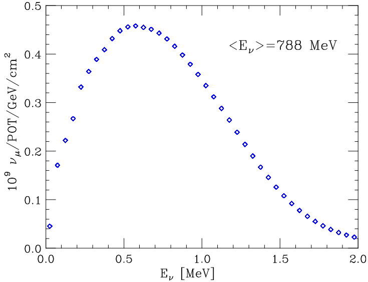
The axial mass puzzle

- ⋆ To bring the MiniBooNE data into agreement with the results of Monte Carlo simulations (based on the Fermi gas model of the nucleus), the axial mass must be increased from the value measued in deuteron, $M_A = 1.05 \pm 0.02(\mathrm{stat}) \pm 0.06(\mathrm{syst})$, to $M_A \sim 1.35$ GeV
- ⋆ It has been suggested that the large value of M_A may be interpreted as an *effective* axial mass, including *medium effects* not taken into acount by the Fermi gas model
- ⋆ Using a realistic spectral function only makes things worse. $M_A \sim 1.6$ GeV needed to reproduce the data
- ⋆ K2K also reported $M_A \sim 1.2$ GeV, extracted from the analysis of neutrino-oxygen interactions
- ⋆ The analysis of the sample of CCQE events collected by the NOMAD collaboration at $\langle E_\nu \rangle \sim 26$ GeV using a carbon target yieds a value compatible with the deuteron data: $M_A = 1.05 \pm 0.02(\mathrm{stat}) \pm 0.06(\mathrm{syst})$

The issue of flux average

- ⋆ The flux-averaged cross sections at fixed T_μ and $\cos\theta_\mu$ picks up contributions at different beam energies, corresponding to different reaction mechanisms not taken into account in the IA scheme

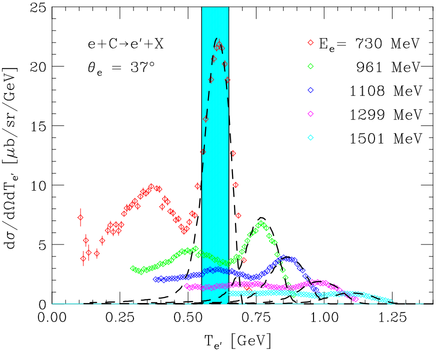




- ▹ $x = 1 \rightarrow E_\nu$ 0.788 GeV , $x = 0.5 \rightarrow E_\nu$ 0.975 GeV
- ▹ $\Phi(0.975)/\Phi(0.788) = 0.83$

“Flux averaged” electron-nucleus x-section

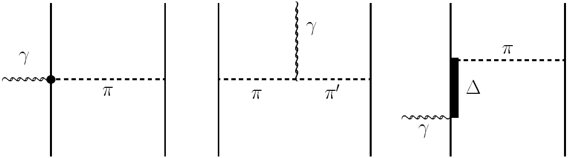
- ★ The electron scattering x-section off Carbon at θ_e= 37 deg has been measured for a number of beam energies



- ★ MIT-Bates data at different energies, plotted as a function of the energy of the scattered electron

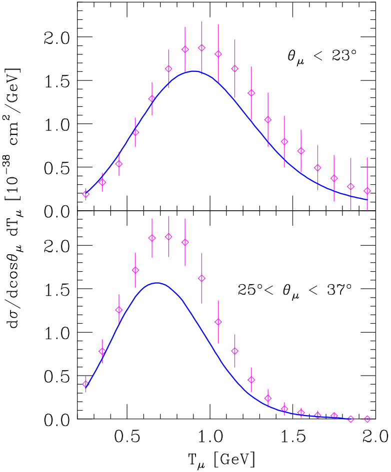
Where does the additional strength come from?

- It has been suggested that 2p2h final states provide a large contribution to the measured neutrino cross section
- Two particle-two hole final states may be produced through different mechanisms
  - Initial state correlations : lead to the tail extending to large energy loss, clearly visible in the calculated quasi elastic cross section.
  - Final state interactions : lead to a redistribution of the inclusive strength, from the region of the quasi free peak to the tails of the energy loss distribution
  - Coupling to the two-body, meson-exchange, currents (mostly in the transverse channel)



Dependence of the CCQE excess strength on θ_μ

★ θ_μ -dependence of the CCQE excess strength



2p2h transition matrix element

- ⋆ In interacting many body systems 2p2h states can be excited by both one- and two-body transition operators

$$
\begin{aligned}
|\langle 2p2h|\, J\, |0\rangle|^2 = |\langle 2p2h|\, J_1\, |0\rangle|^2 + |\langle 2p2h|\, J_2\, |0\rangle|^2 \\
+ 2\, \mathrm{Re}\, \langle 2p2h|\, J_1\, |0\rangle^\star \langle 2p2h|\, J_2\, |0\rangle
\end{aligned}
$$

- ⋆ In the mean field approximation

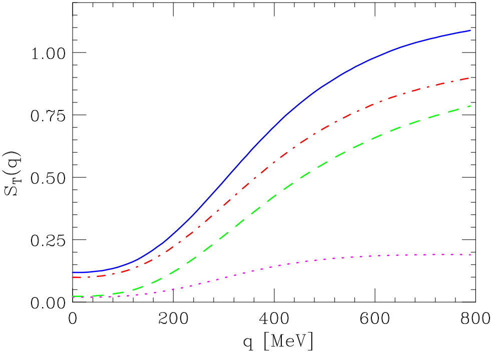
$$\langle 2p2h|\, J_1\, |0\rangle = 0$$

- ⋆ The occurrence of sizable interference contributions would be a clear signature of nucleon-nucleon correations

Sum rule of the transverse electromagnetic response

- ⋆ Exact non relativistic calculation for carbon

$$S_T(\mathbf{q}) = \frac{2m^2}{Z\mu_p + N\mu_n} \frac{1}{|\mathbf{q}|^2} \int_{\omega_{th}}^{\infty} d\omega R_T(\mathbf{q}, \omega)$$



- ⋆ Interference contributions are large (similar result for the neutral weak current)

Consistent description of one- and two-nucleon currents

- ⋆ Generalize the factosization *ansatz*: rewrite the final state $|N\rangle$ in the form

$$|N\rangle \rightarrow |\mathbf{p},\mathbf{p}'\rangle \otimes |n_{(A-2)},\mathbf{p}_n\rangle$$

implying

$$\langle N|\, j_{ij}{}^{\mu}\, |0\rangle \rightarrow \int d^3k d^3k' M_n(\mathbf{k},\mathbf{k}')\, \langle \mathbf{p}\mathbf{p}'|\, j_{ij}{}^{\mu}\, |\mathbf{k}\mathbf{k}'\rangle$$

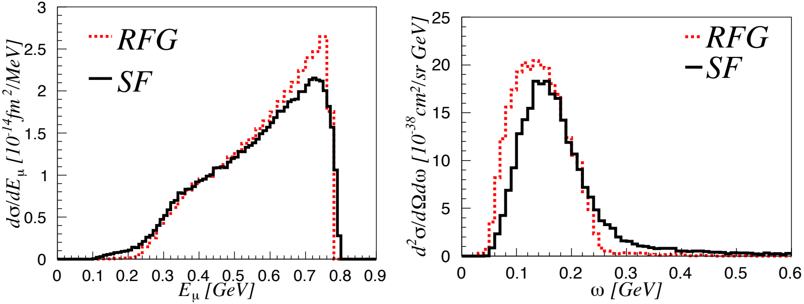
The amplitude

$$M_n(\mathbf{k},\mathbf{k}') = \{\langle n_{(A-2)}|\langle \mathbf{k},\mathbf{k}'|\} \otimes |0\rangle$$

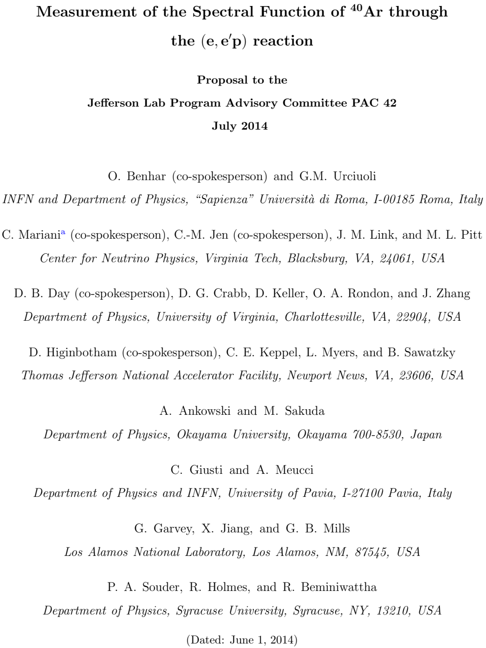
can be obtained from non relativistic many-body theory, while the matrix element of the two-body current can be computed using the fully relativistic expression

Synergies

- ★ Electron scattering data have provided the input needed to obtain the spectral functions of carbon and oxygen, which are currently being implemented in the neutrino event generator GENIE



- ★ The availability of comparable data for argon will be needed for the interpretation of the signal detected by liquid argon detectors.



Measurement of the Spectral Function of ^{40}Ar through the $(e,e'p)$ reaction

Proposal to the

Jefferson Lab Program Advisory Committee PAC 42

July 2014

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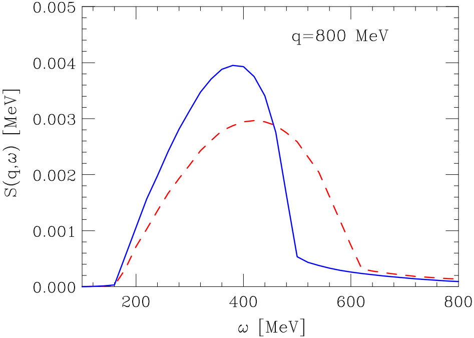
(Dated: June 1, 2014)

Synergies (continued)

- ⋆ The analysis of the double differential CCQE neutrino cross section may provide new information, and shed light on unresolved nuclear structure issues that have been extensively investigated in electron scattering experiments, such as the role of correlations and meson-exchange currents
- ⋆ If the contribution of processes involving 2p2h final state will be firmly established, the double differential CCQE neutrino cross section will provide a clean and strong signature of correlation effects.
- ⋆ The availability of a multi-GeV electron beam may also be instrumental to pin down the source of the disagreement between the values of the axial mass reported by NOMAD ($\langle E_\nu \rangle \sim 26$ GeV) and MiniBooNE ($\langle E_\nu \rangle \sim 800$ MeV)

Backup slides

Relativistic vs non relativistic kinematics



- ★ Response of uniform isospin symmetric nuclear matter to a scalar probe delivering momentum $|\mathbf{q}| = 800$ MeV.
- ★ Calculation carried out using a realistic spectral function. Solid line: relativistic kinematics. Dashed line: non relativistic kinematics

Two-nucleon spectral function

- ⋆ Calculations have been carried out for uniform isospin-symmetric nuclear matter using CBF perturbation theory [PRC 62, 034304 (2000)]

$$P(\mathbf{k},\mathbf{k}',E) = \sum_n |M_n(k,k')|^2 \delta(E + E_0 - E_n)$$

$$n(\mathbf{k},\mathbf{k}') = \int dE \, P(\mathbf{k},\mathbf{k}',E)$$

- ⋆ Relative momentum distribution

$$n(\mathbf{Q}) = 4\pi|\mathbf{Q}|^2 \int d^3q \, n\left(\frac{\mathbf{Q}}{2} + \mathbf{q}, \frac{\mathbf{Q}}{2} - \mathbf{q}\right)$$

$$\mathbf{q} = \mathbf{k} + \mathbf{k}' \ \ , \ \ \mathbf{Q} = \frac{\mathbf{k} - \mathbf{k}'}{2}$$