Quasielastic electron and neutrino-nucleus scattering in a continuum random phase approximation approach

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Outline

- Introduction
- CRPA Formalism
- Results:
  - Electron-nucleus scattering cross section
    - Comparison with measurements on ^{12}C, ^{16}O and ^{40}Ca
    - Comparison with measurements of R_L and R_T
  - Neutrino-nucleus scattering cross section
    - Comparison with MiniBooNE CCQE ν_μ & $\bar{\nu}_\mu$ measurements
    - Importance of low-energy nuclear excitations

NuFact2014, Glasgow

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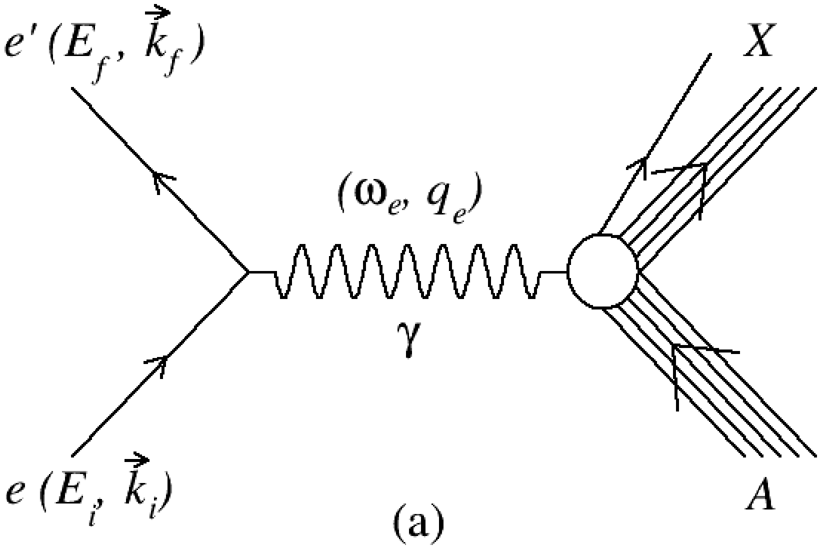
Introduction

- There has been substantial amount of progress in the understanding of the different processes involved in the signal of accelerator-based neutrino oscillation experiments.
- There still remains considerable amount of uncertainty in the measurements even for CCQE scattering cross sections (which account for a large share of the detected signal.)
- Major source of this uncertainty is associated with the nuclear structure details.
- Low-energy excitations in the nucleus can account for a non-negligible contribution in measurements even at high neutrino energies (and specially at forwarded scatterings), but remain inaccessible in RFG descriptions, need a microscopic investigation beyond RFG based models.

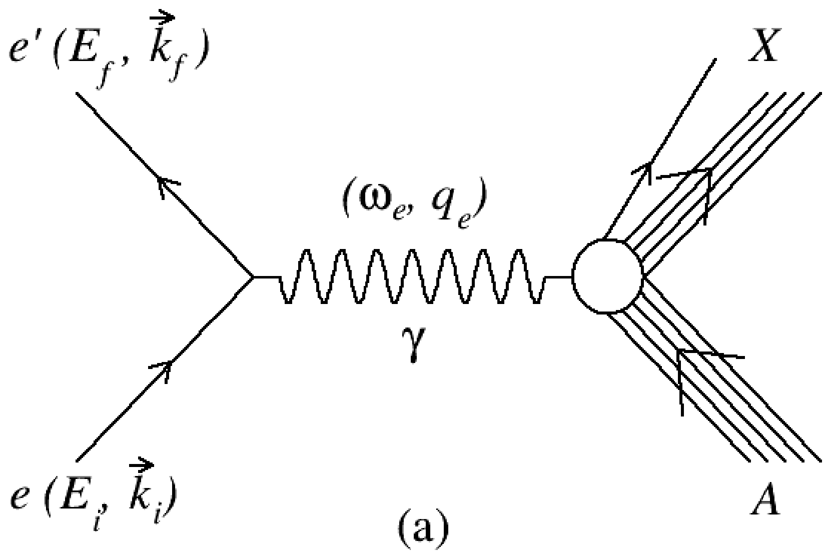
QE *(e,e')* scattering



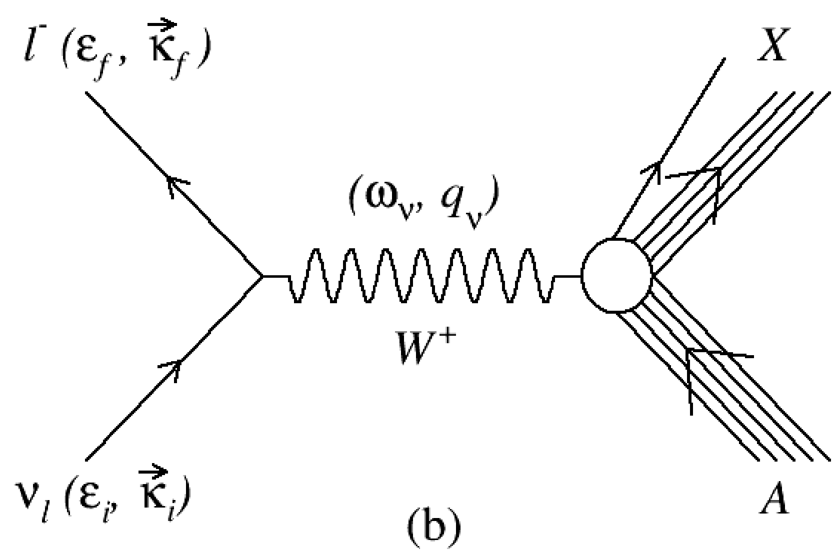
X is the undetected hadronic final state.

$$\left(\frac{d^2\sigma}{d\omega_e d\Omega}\right)_e = \frac{\alpha^2}{Q^4}\left(\frac{2}{2J_i+1}\right)\frac{1}{k_f E_i} \times \zeta^2(Z', E_f, q_e)\left[\sum_{J=0}^{\infty}\sigma_{L,e}^J + \sum_{J=1}^{\infty}\sigma_{T,e}^J\right]$$

QE (e,e') scattering



QE (ν_l, l^-) scattering



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$$\left(\frac{d^2\sigma}{d\omega_\nu d\Omega}\right)_\nu = \frac{G_F^2\ \cos^2\theta_c}{(4\pi)^2}\left(\frac{2}{2J_i+1}\right)\varepsilon_f\kappa_f \times \zeta^2(Z', \varepsilon_f, q_\nu)\left[\sum_{J=0}^{\infty}\sigma^J_{CL,\nu} + \sum_{J=1}^{\infty}\sigma^J_{T,\nu}\right]$$

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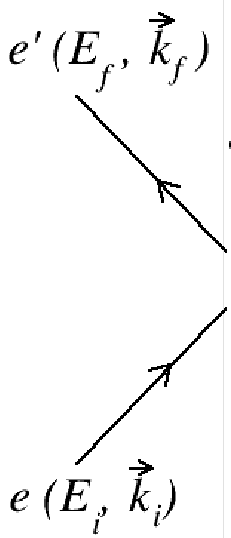

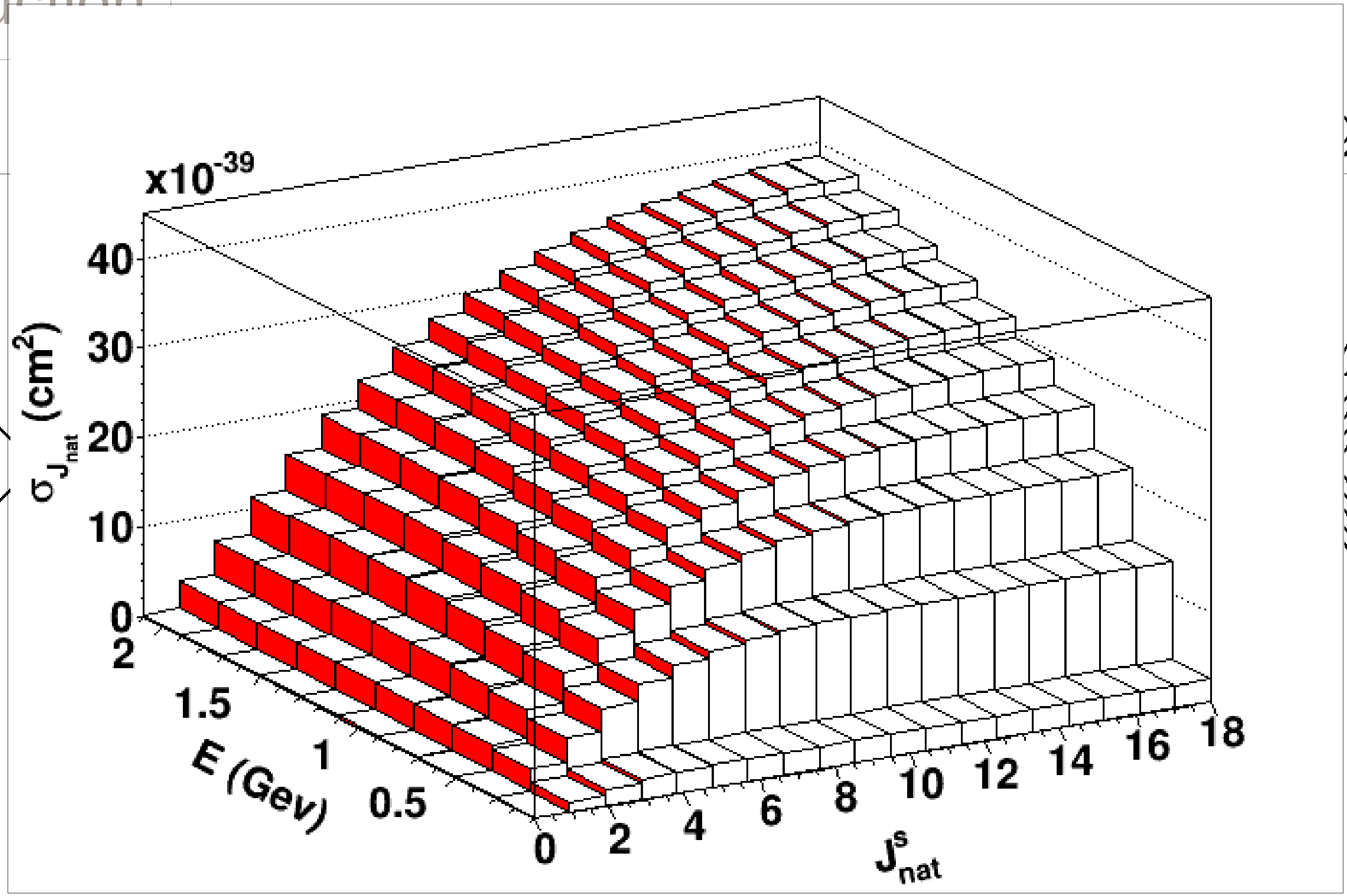

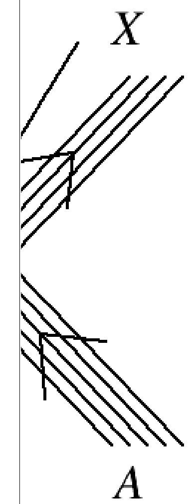

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Introduction

- However, unlike in the electron scattering case, the interacting neutrino energy is never sharply defined because neutrinos are produced as the secondary decay products of a primary beam.

- Reconstructing neutrino energies, using the kinematics of final outgoing lepton, results in a broadly distributed energy flux.

- The major part of the uncertainty in measurements arises from identifying the correct scattering process and reconstructing the neutrino energy accordingly.

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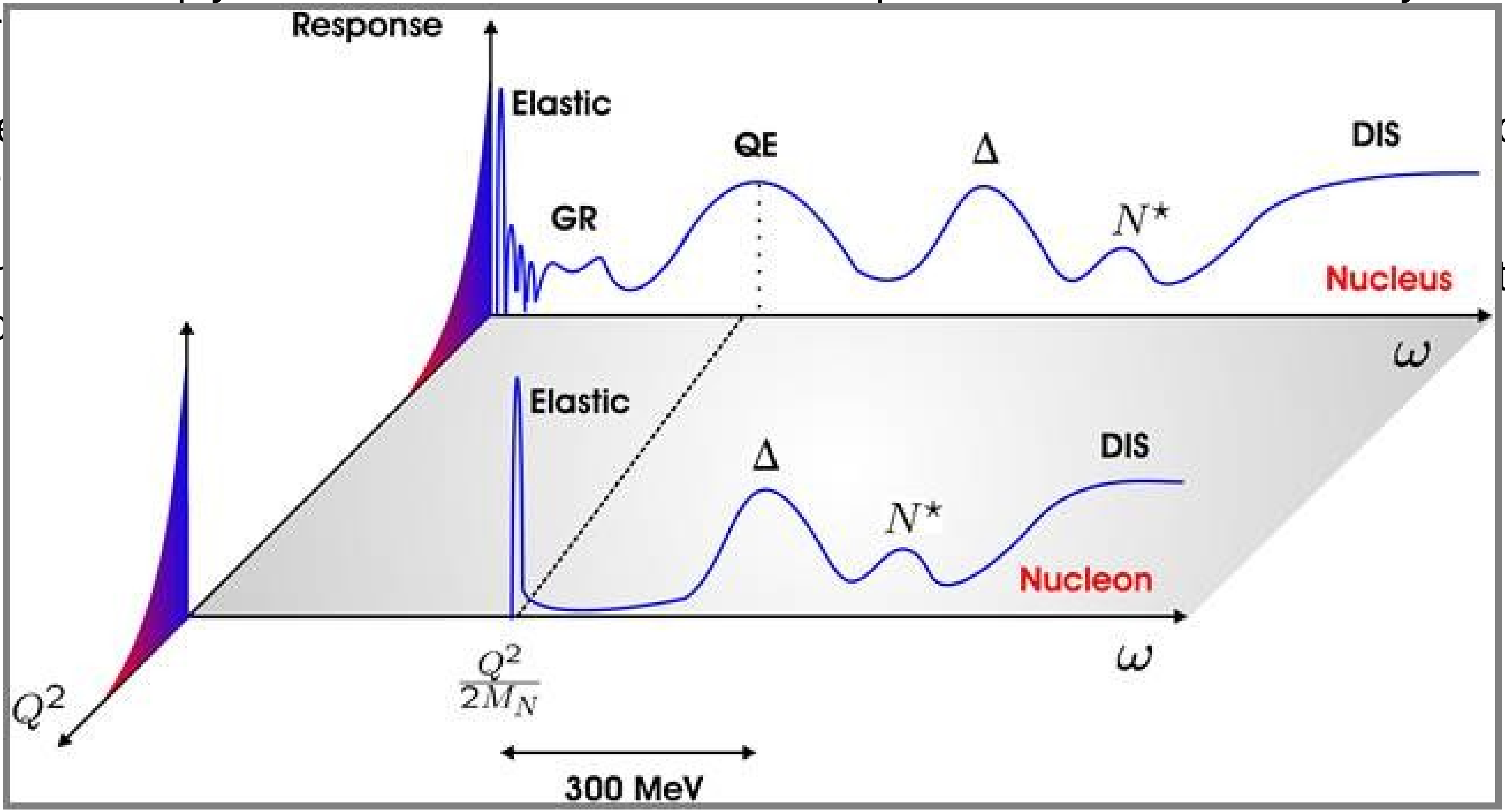

Introduction

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➢ The important issue is to find a microscopic nuclear structure model which can describe neutrino-nucleus scatterings at low and intermediate energies.

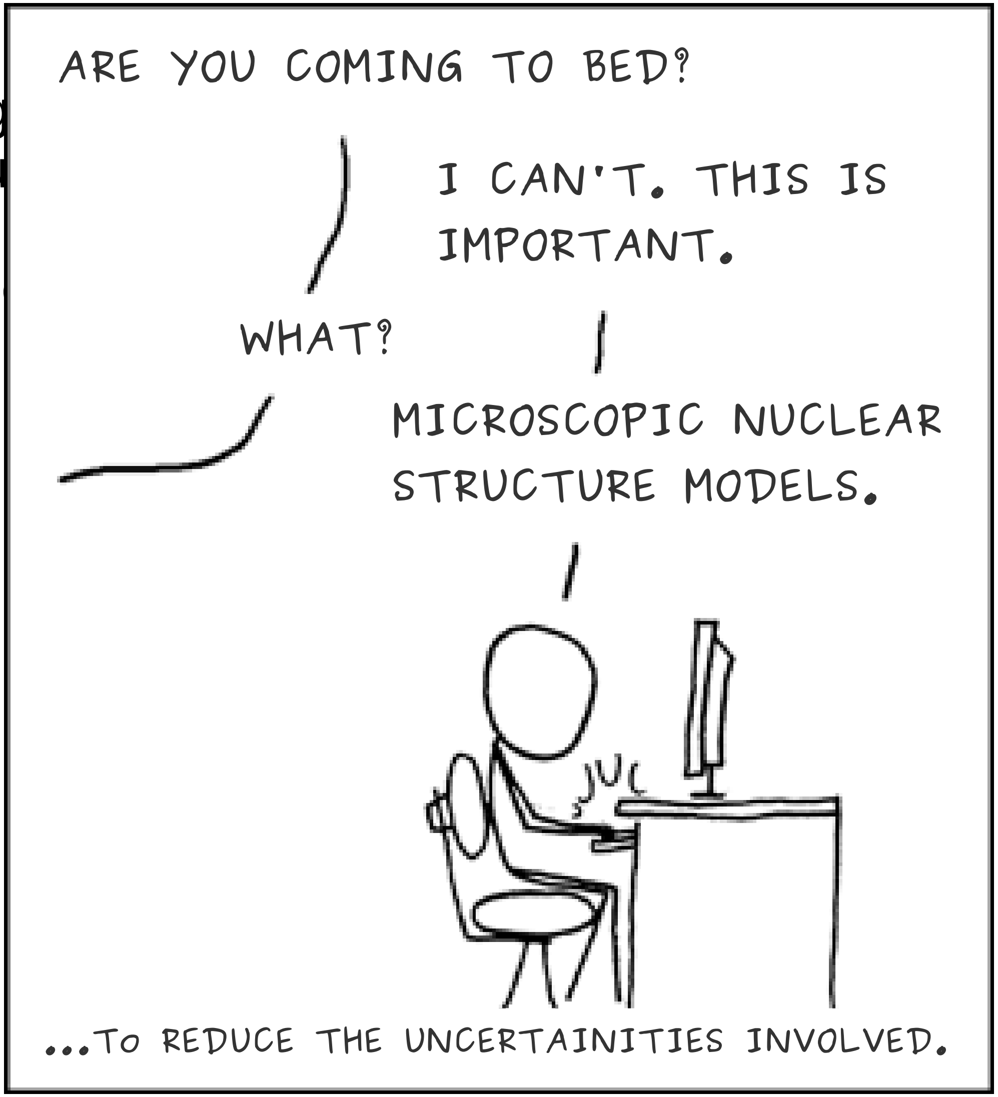

Image modified from xkcd

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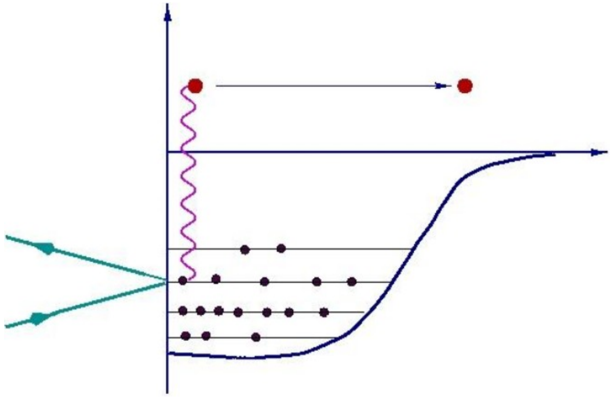
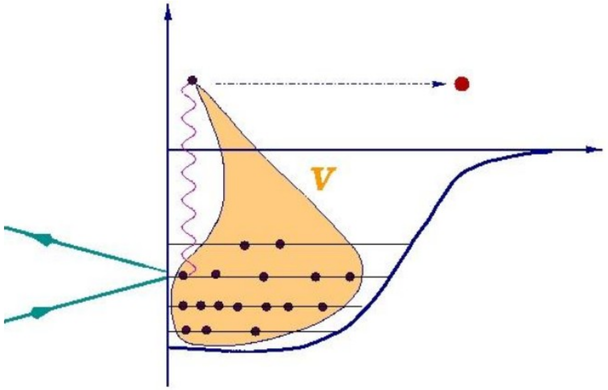
Formalism[1,2,3]



- We start by describing the nucleus with a Hartree-Fock (HF) approximation. The mean-field (MF) potential is obtained by solving the HF equations and using a Skyrme (SkE2) two-body interaction.



- Once we have bound and continuum single-nucleon wave functions, we introduce long-range correlations between the nucleons through a continuum Random Phase Approximation (CRPA).

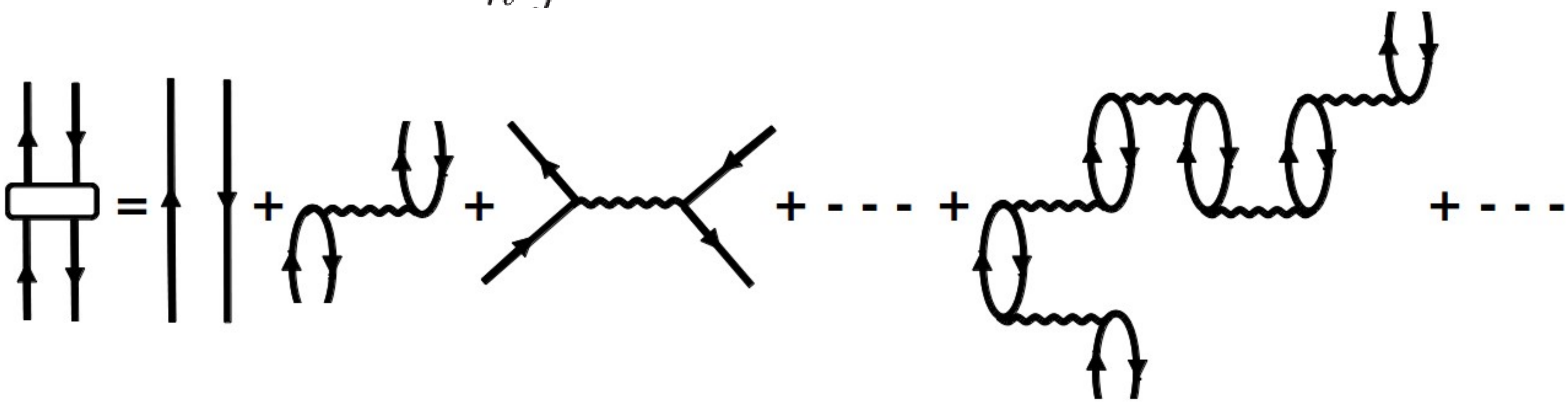
- RPA equations are solved using a Green's function approach.

[1] V. Pandey, N. Jachowicz, J. Ryckebusch, T. Van Cuyck, and W. Cosyn, Phys. Rev. C89, 024601 (2014).
[2] N. Jachowicz, K. Heyde, J. Ryckebusch, and S. Rombouts, Phys. Rev. C65, 025501 (2002).
[3] N. Jachowicz, K. Heyde, J. Ryckebusch, and S. Rombouts, Phys. Rev. C59, 3246 (1999).

Formalism

- In our approach, the Skyrme (SkE2) nucleon-nucleon interaction, which was used in the HF calculations, is also used to perform CRPA calculations. That makes our approach self-consistent.

$$\Pi^{(RPA)}(x_1,x_2;E_x) = \Pi^{(0)}(x_1,x_2;E_x) + \frac{1}{\hbar}\int dx dx' \Pi^0(x_1,x;E_x)\tilde{V}(x,x')\Pi^{(RPA)}(x',x_2;E_x)$$



- The effects of final state interactions (FSI) of the ejected nucleon with the residual nucleus, the distortion on the ejected nucleon waves and rescattering with the residual nucleons, are implemented.

- The pauli-blocking effects are included.

Formalism

- The Skyrme parameterization is designed for the description of ground-state properties of nuclei and for interactions at low energies. For reactions at high energies, its Q^2 behavior is not realistic and the effect of long-range correlations is overestimated. We remedy this shortcoming by introducing a dipole Q^2 running for the interaction:

$$V(Q^2) \;= V(Q^2=0)\;\frac{1}{(1+\frac{Q^2}{\Lambda^2})^2}$$

  Λ is determined, using standard X^2 test, against high-precision electron scattering data, as Λ = 335 MeV.

- We implemented a relativistic kinematic correction as suggested in Refs. [4,5,6], important for *q* > 500 MeV/c:

$$\lambda \;\rightarrow\; \lambda\,(1+\lambda), \quad \lambda = \omega/2M_N$$

[4] S. Jeschonnek, T.W. Donnelly, Phys. Rev. C57, 2438 (1998).
[5] J. E. Amaro, M. B. Barbaro, J. A. Caballero, T. W. Donnelly, and C. Maieron Phys. Rev. C71, 065501 (2005).
[6] J. E. Amaro, M. B. Barbaro, J. A. Caballero, T. W. Donnelly, and J. M. Udias Phys. Rev. C75, 034613 (2007).

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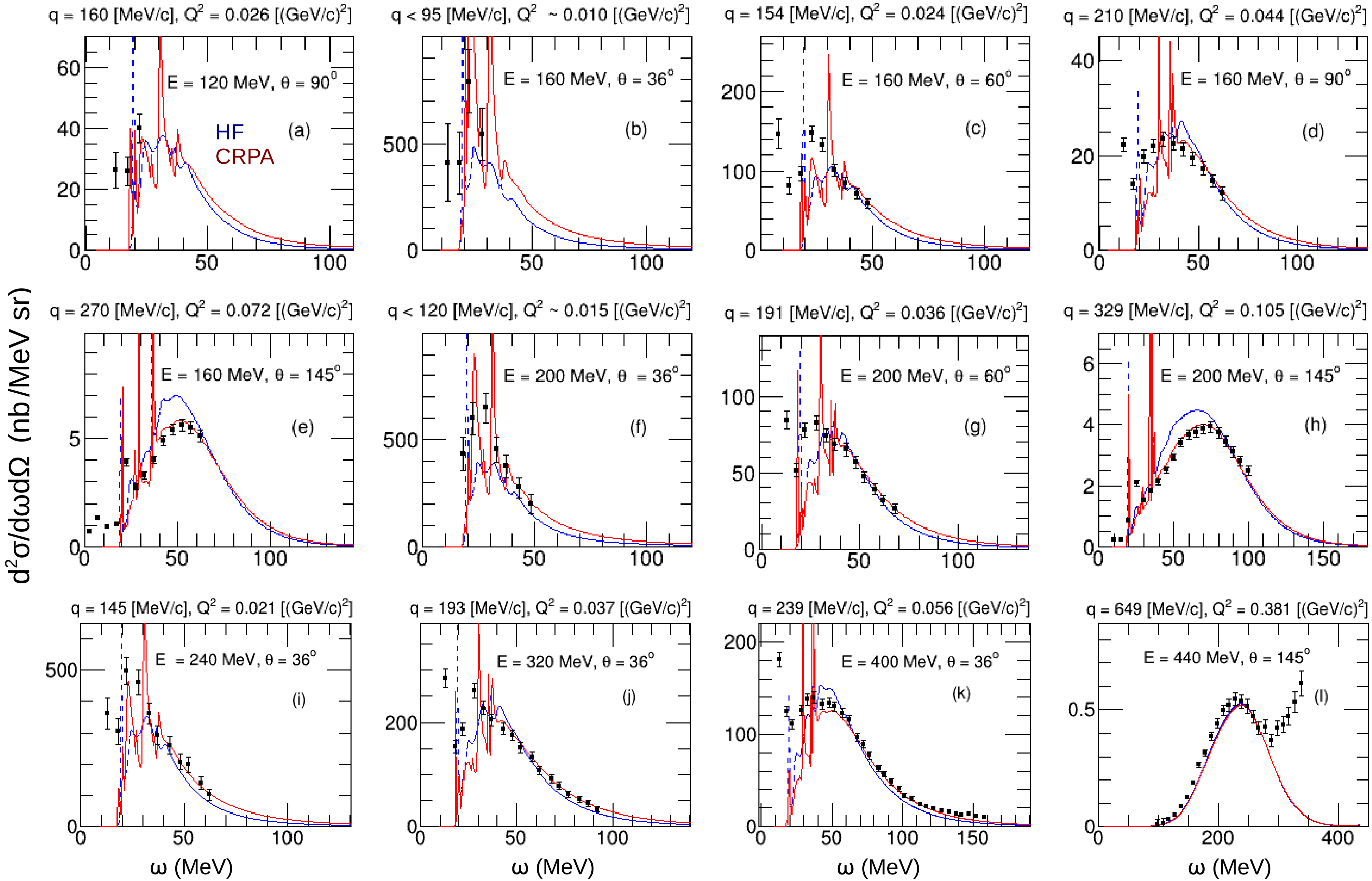
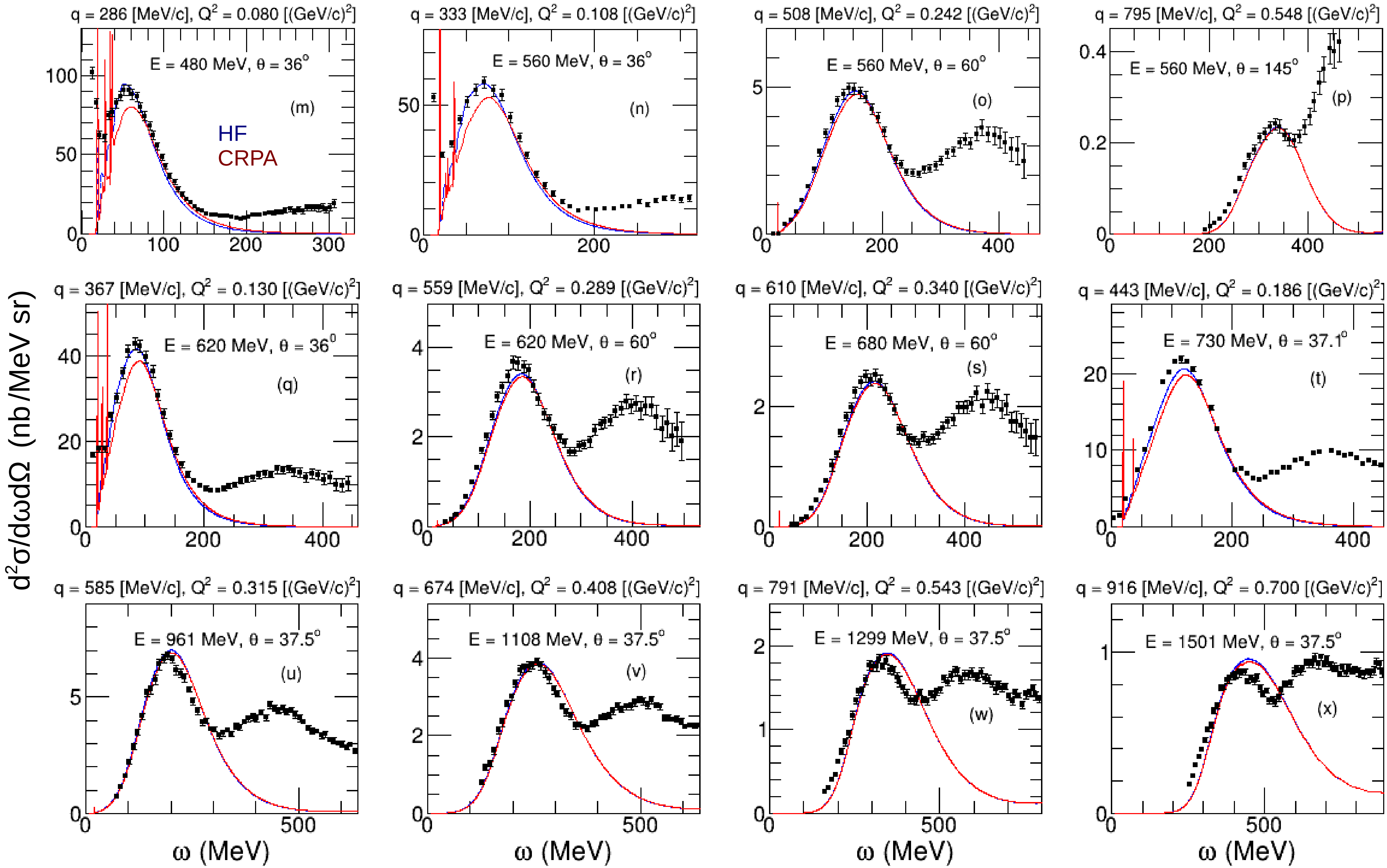
(e,e') scattering on ^{12}C



Data is taken from: [1] P. Barreau et al., Nucl. Phys. A402, 515 (1983). [2] J. S. O'Connell et al., Phys. Rev. C35, 1063 (1987). [3] R. M. Sealock et al., Phys. Rev. Lett.62, 1350 (1989).

(e,e′) scattering on ^{12}C



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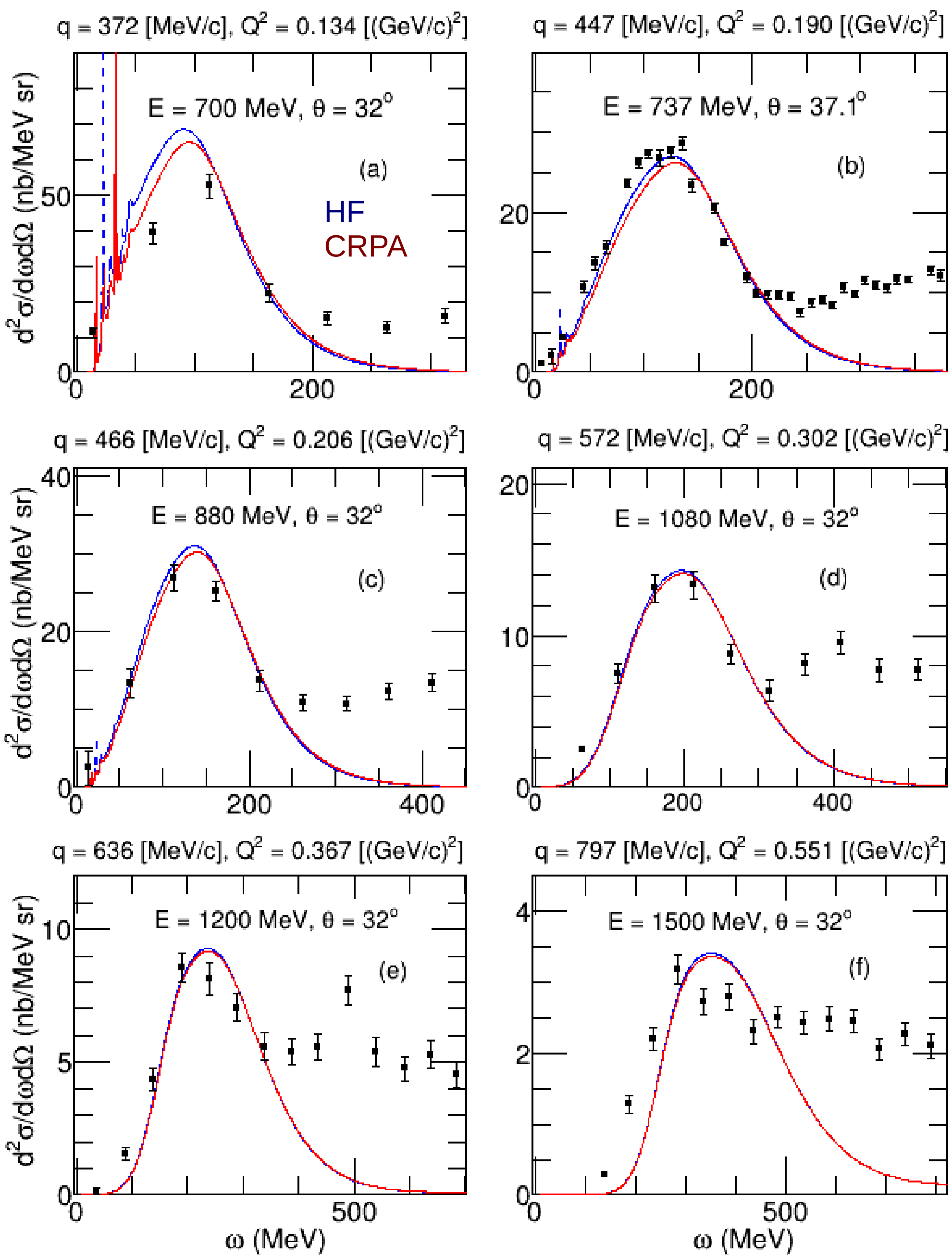
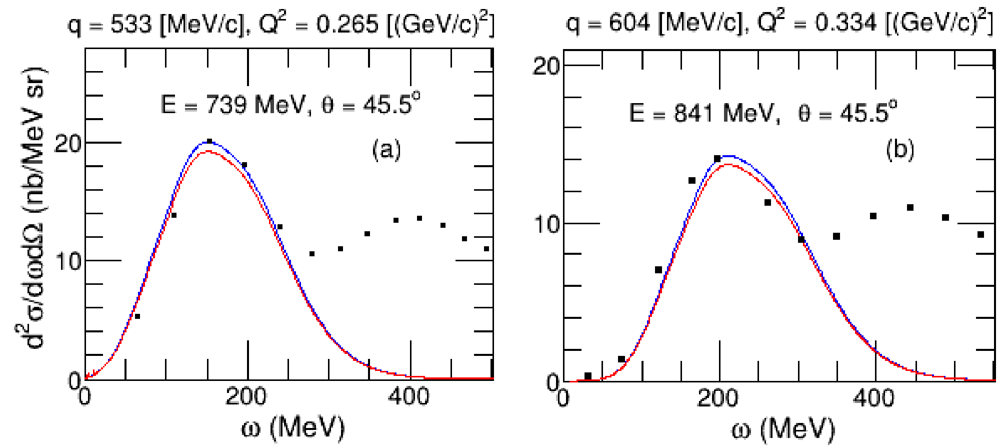
[3] R. M. Sealock et al., Phys. Rev. Lett.62, 1350 (1989).

(e,e') scattering on ^{16}O



(e,e') scattering on ^{40}Ca



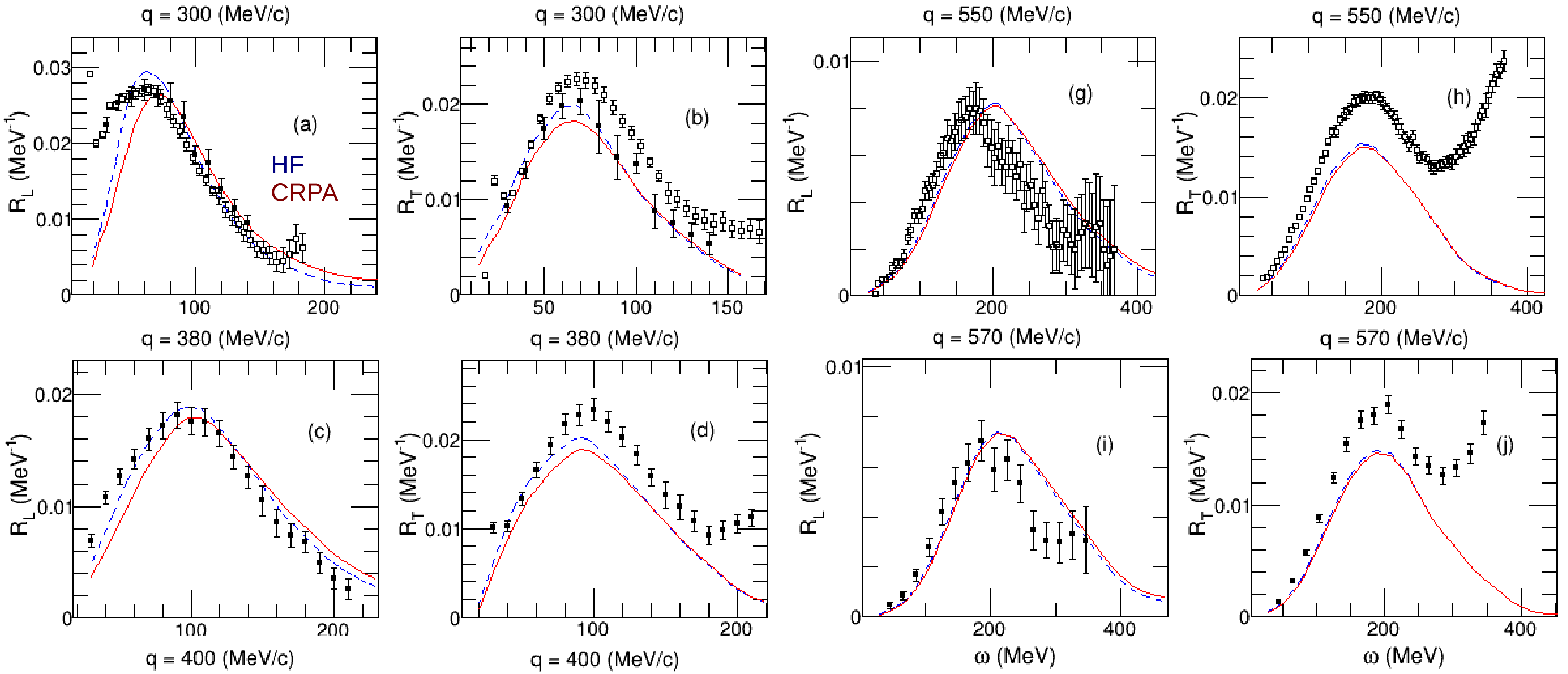
- Our formalism successfully predicts the *(e,e')* cross section on *^{12}C*, *^{16}O* and *^{40}Ca* for a kinematic range of: *10s of MeV < |q| < 1000 MeV*, where QE is expected to be the dominant process.

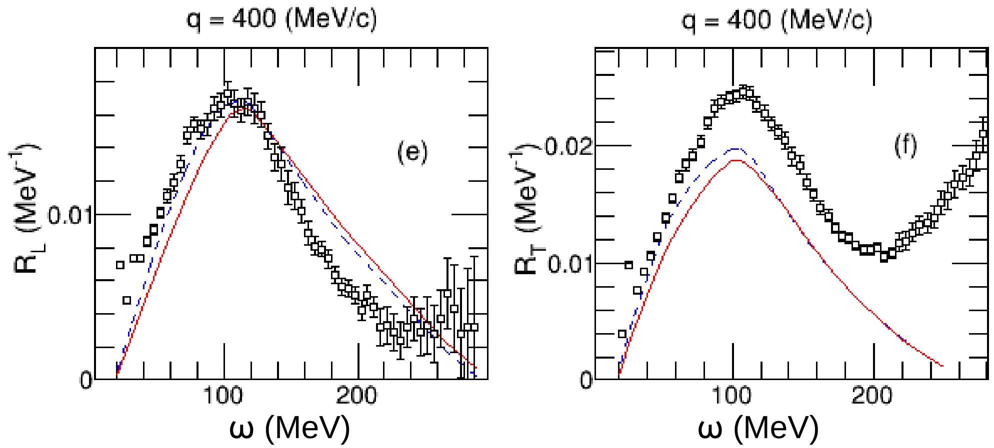
- Model successfully describes the low energy nuclear excitations, occur for *ω < 50 MeV*, where nuclear structure details are prominent.

Data is taken from:

[1] J. S. O'Connell et al., Phys. Rev. C35, 1063 (1987).
[2] M. Anghinolfi et al., Nucl. Phys. A602, 405 (1996).
[3] C. F. Williamsonet al., Phys. Rev. C56, 3152 (1997).

Longitudinal and transverse response for *(e,e')* scatterings on ^{12}C





Data is taken from: [1] P. Barreau et al., Nucl. Phys. A402, 515 (1983).
[2] J. Jourdan, Nucl. Phys. A603, 117 (1996).

- There is a discrepancy between different measurements, due to the intricate processes involved in separating the responses.
- Longitudinal response is dominated by single nucleon knock-out processes.
- Inclusion of contributions involving MEC currents are needed, in addition to the single nucleon processes, in order to explain the transverse response.

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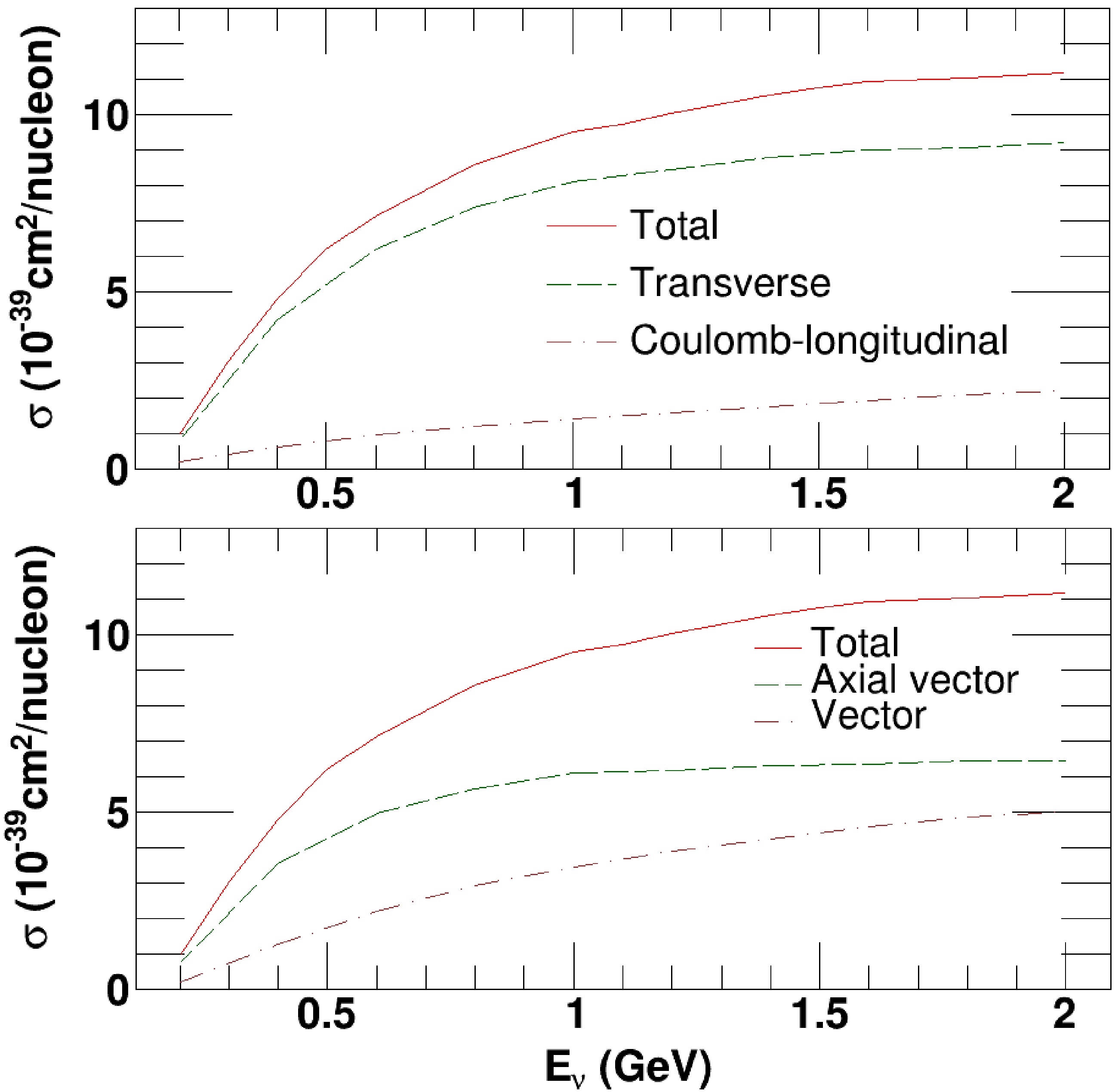
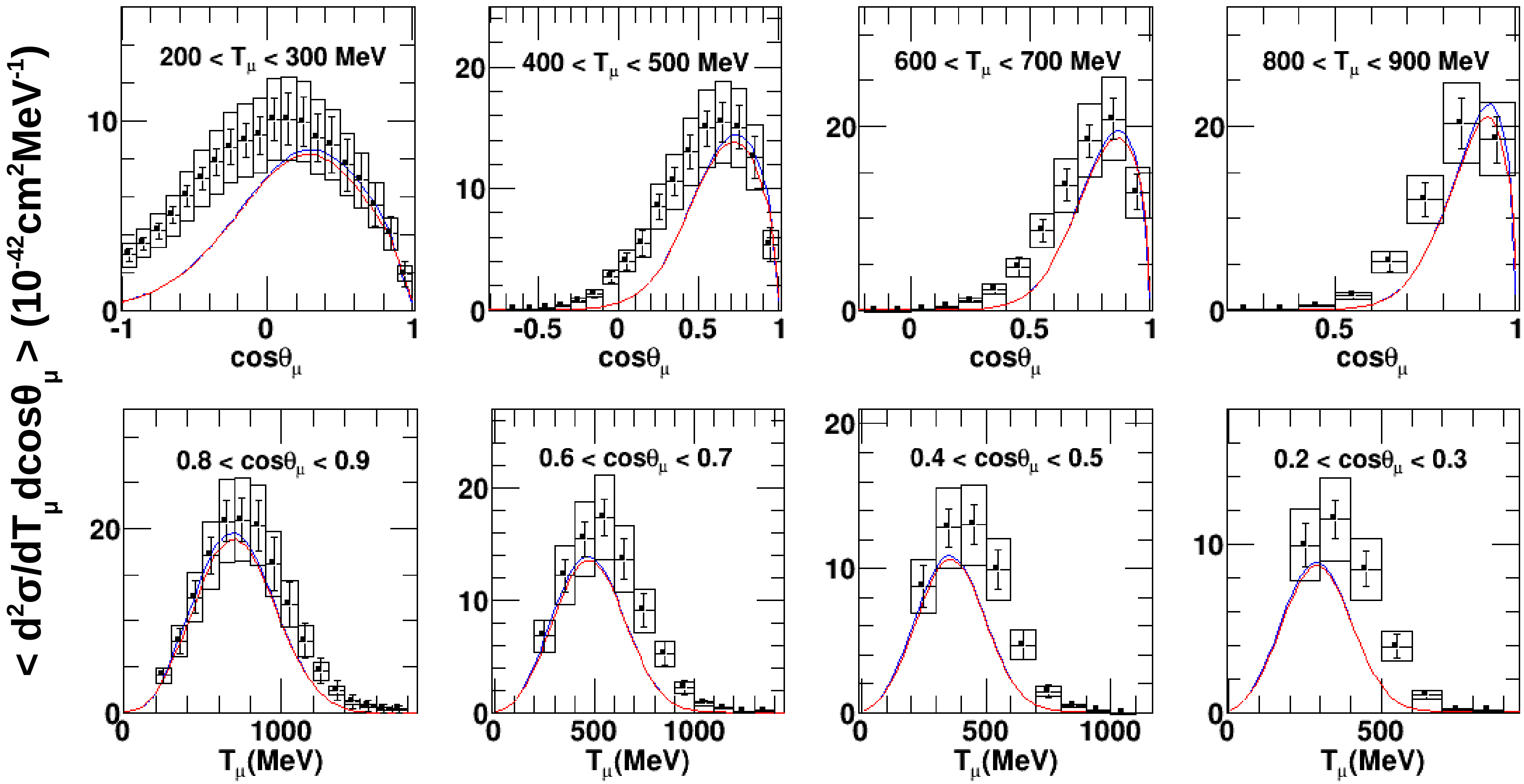
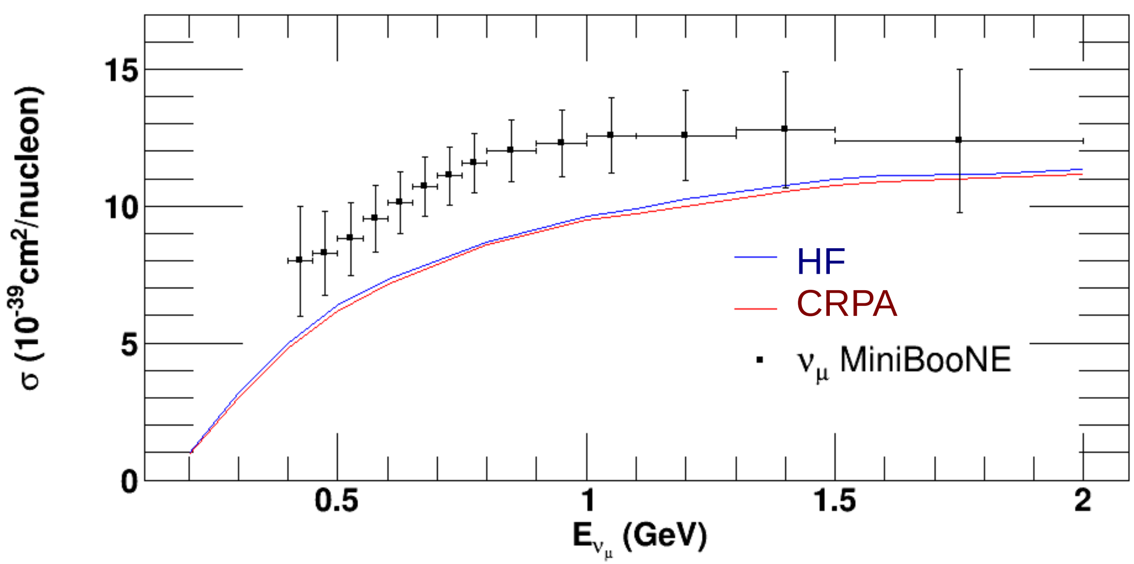
(ν_μ, μ^-) scatterings



Comparison with MiniBooNE CCQE neutrino (ν_μ) Measurements

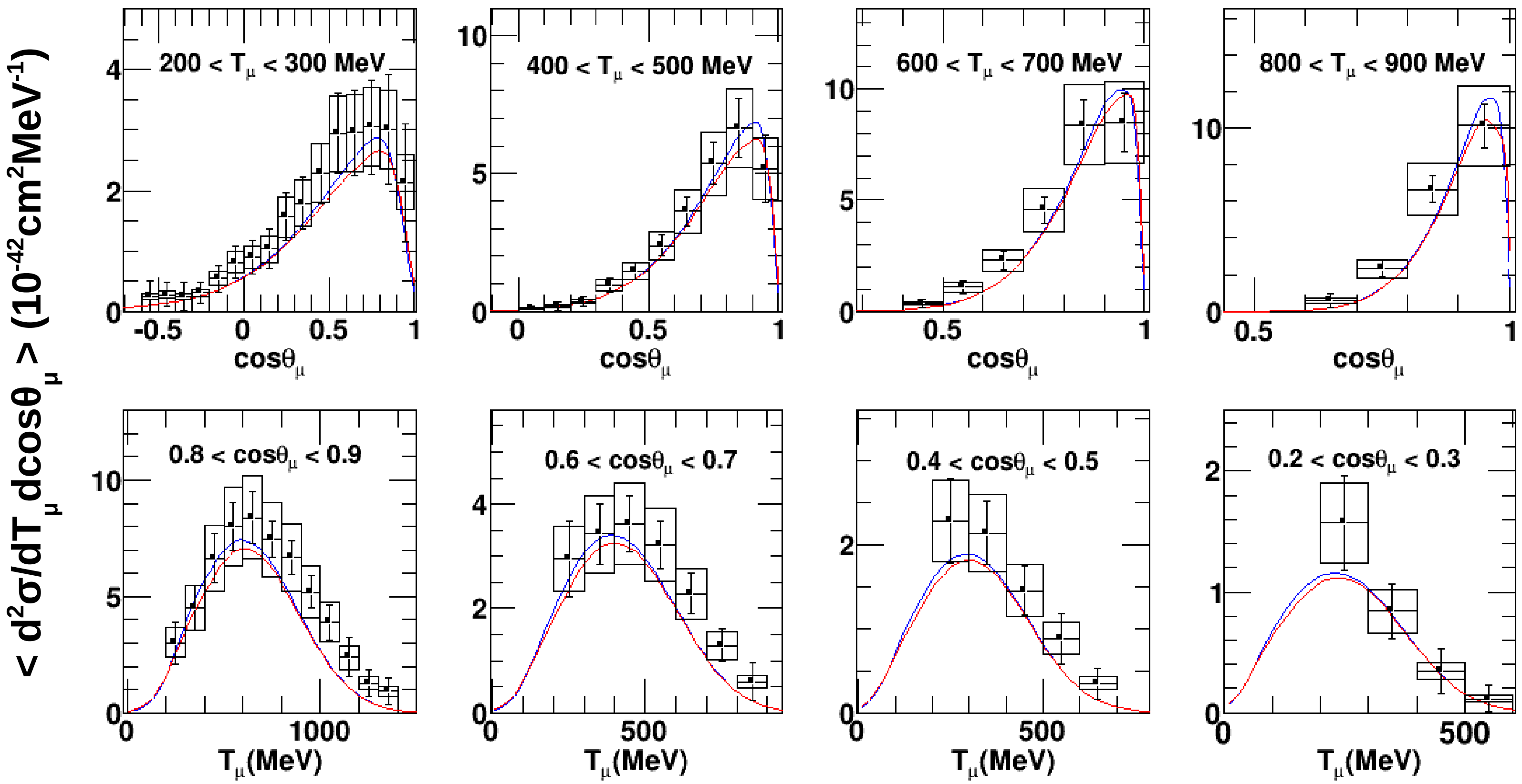


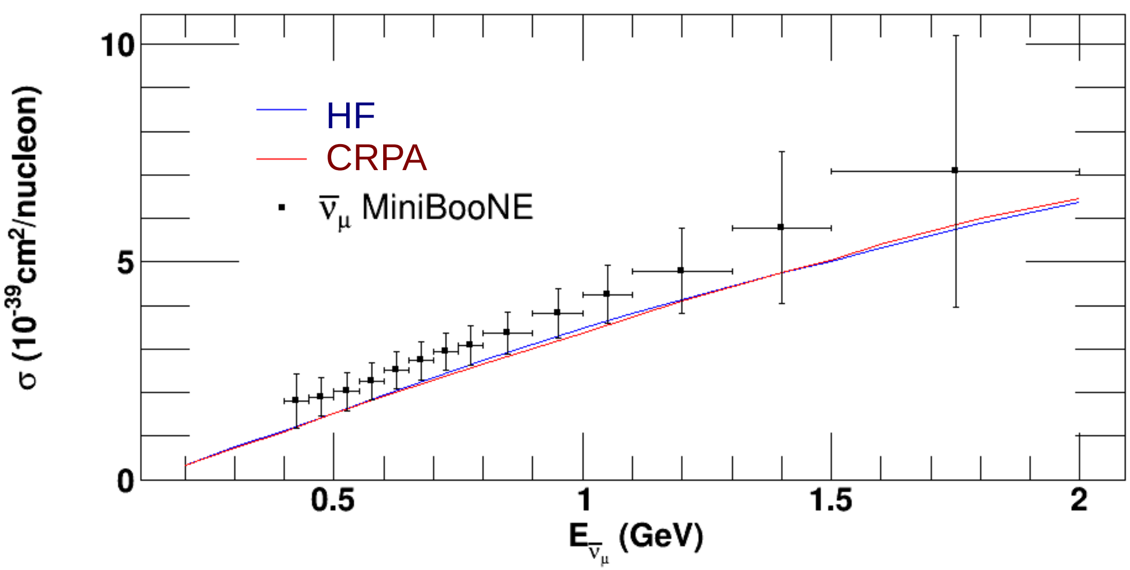


- Our predictions successfully describe the gross feature of the cross section.
- The missing strength can be associated with the contribution from multinucleon processes, not included here.

Data is taken from:
A. A. Aguilar-Arevalo et al., (MiniBooNE Collaboration), Phys. Rev. D81, 092005 (2010).

Comparison with MiniBooNE CCQE antineutrino ($\bar{\nu}_\mu$) Measurements



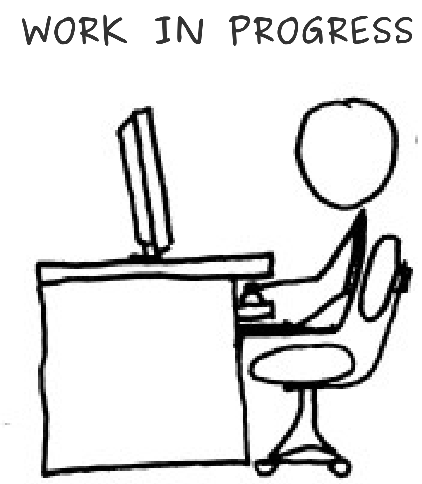


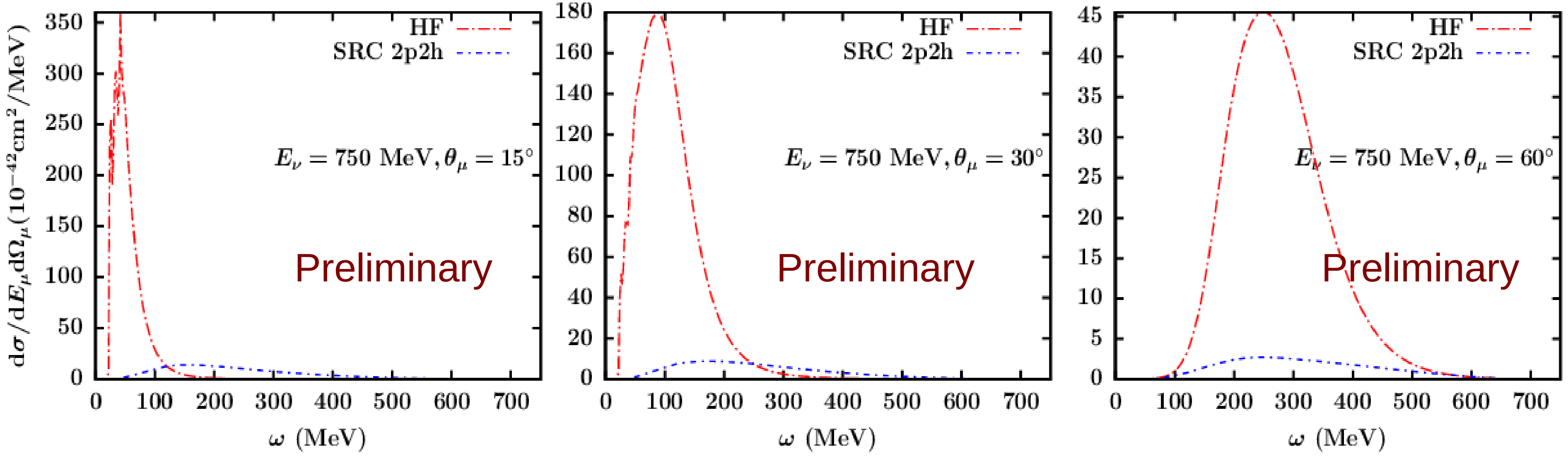
- Antineutrino predictions are better describing the data than the neutrino ones.
- But there seems to be still some strength missing.

Data is taken from:
A. A. Aguilar-Arevalo et al., (MiniBooNE Collaboraion), Phys. Rev. D88, 032001 (2013).

Multinucleon contributions: in progress

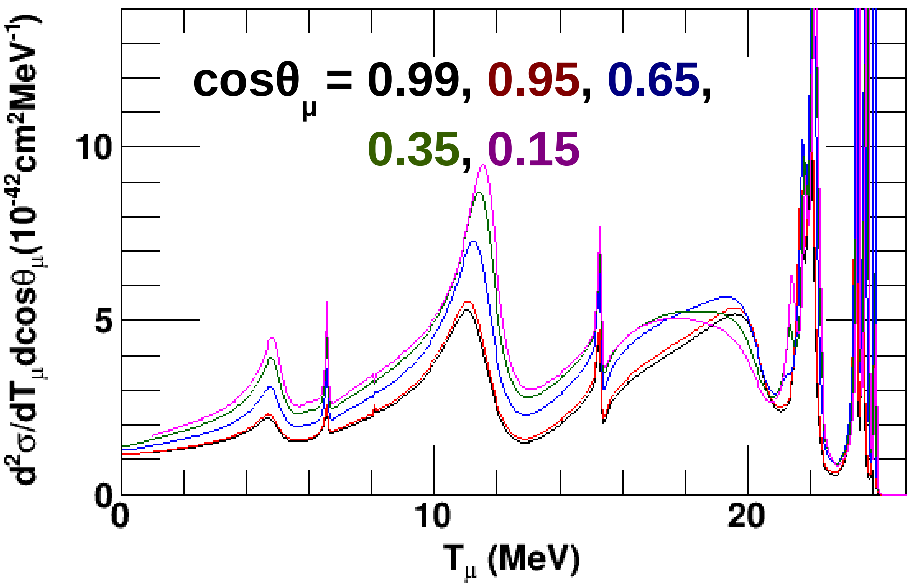
- Short-range correlations are introduced to go beyond the impulse approximation approach.
- These correlated pairs contribute to the QE-like cross section via two-nucleon knockout.





E_ν = 150 MeV

- Cross section is dominated by nuclear structure details.



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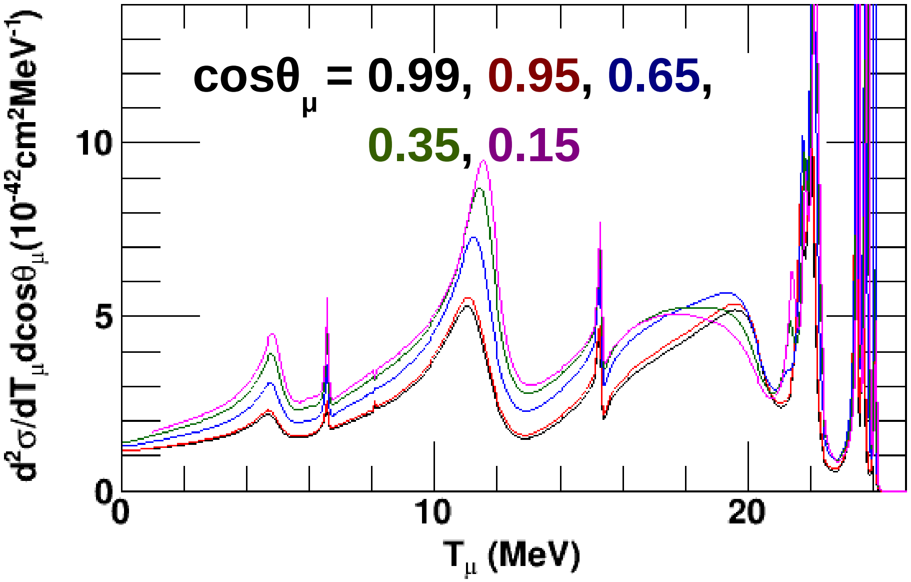
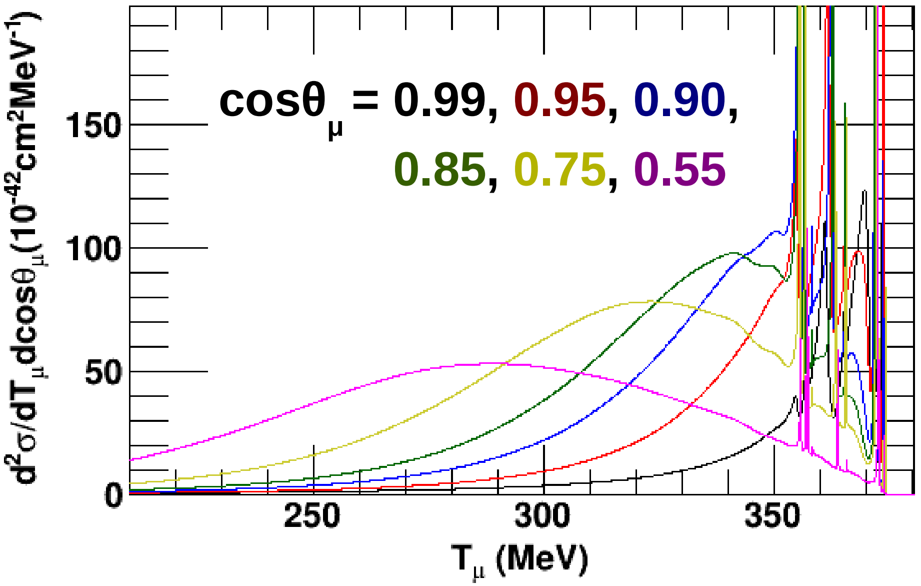


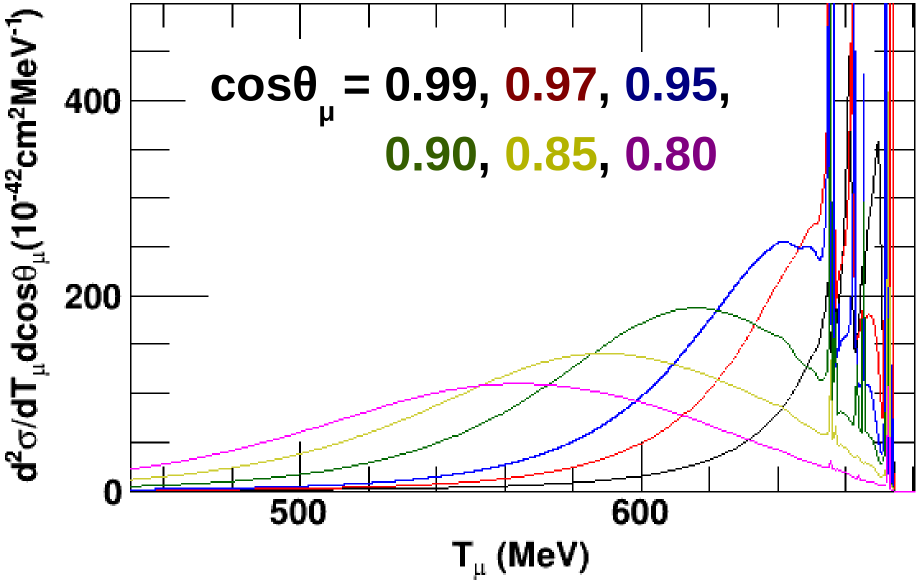
E_ν = 500 MeV

- Nuclear excitations are sizable at forward scatterings.



E_ν = 800 MeV

- Energy near to the mean energy of T2K ND280 and MiniBooNE ν_μ flux.
- Nuclear excitations are still sizable at forward scattering.



Low energy nuclear excitations in (ν_l, l^-) scatterings

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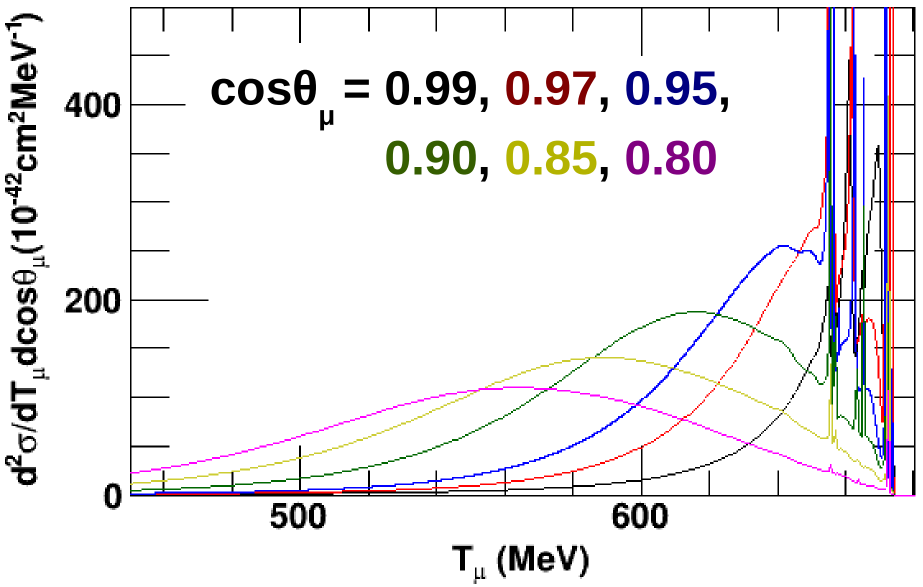
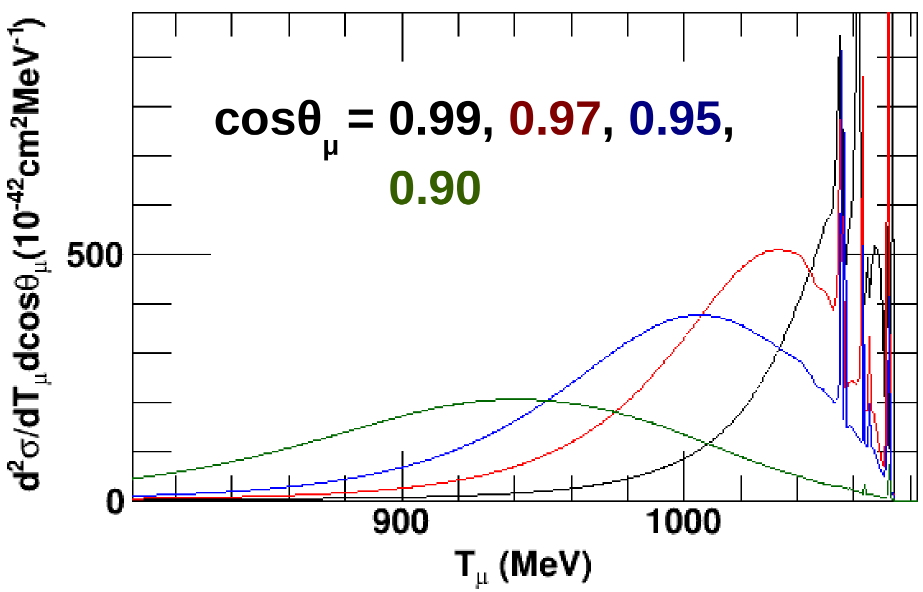


E_ν = 1200 MeV

- Nuclear excitations are still noticable at forward scattering.



Low energy nuclear excitations in (ν_l, l^-) scatterings

- At low neutrino energies, cross section is dominated by nuclear structure details.
- Even at higher neutrino energies, nuclear structure effects are still non-negligible especially for very forward scatterings.

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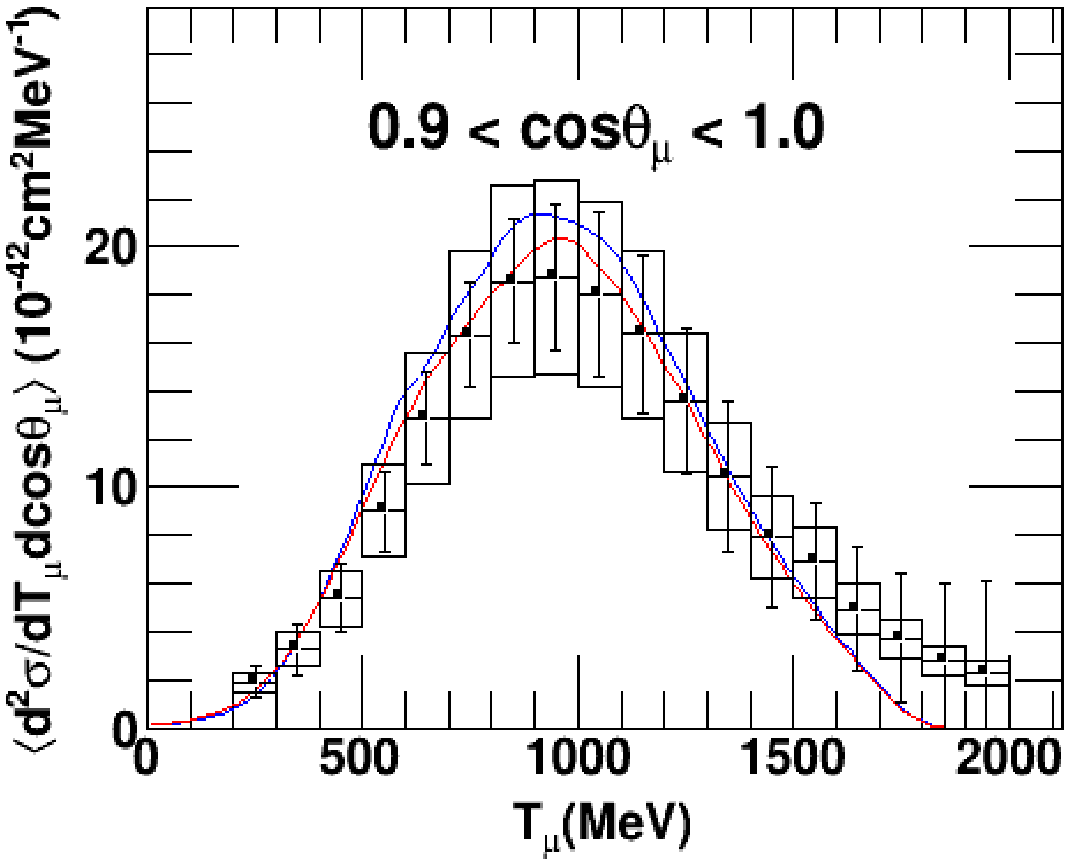

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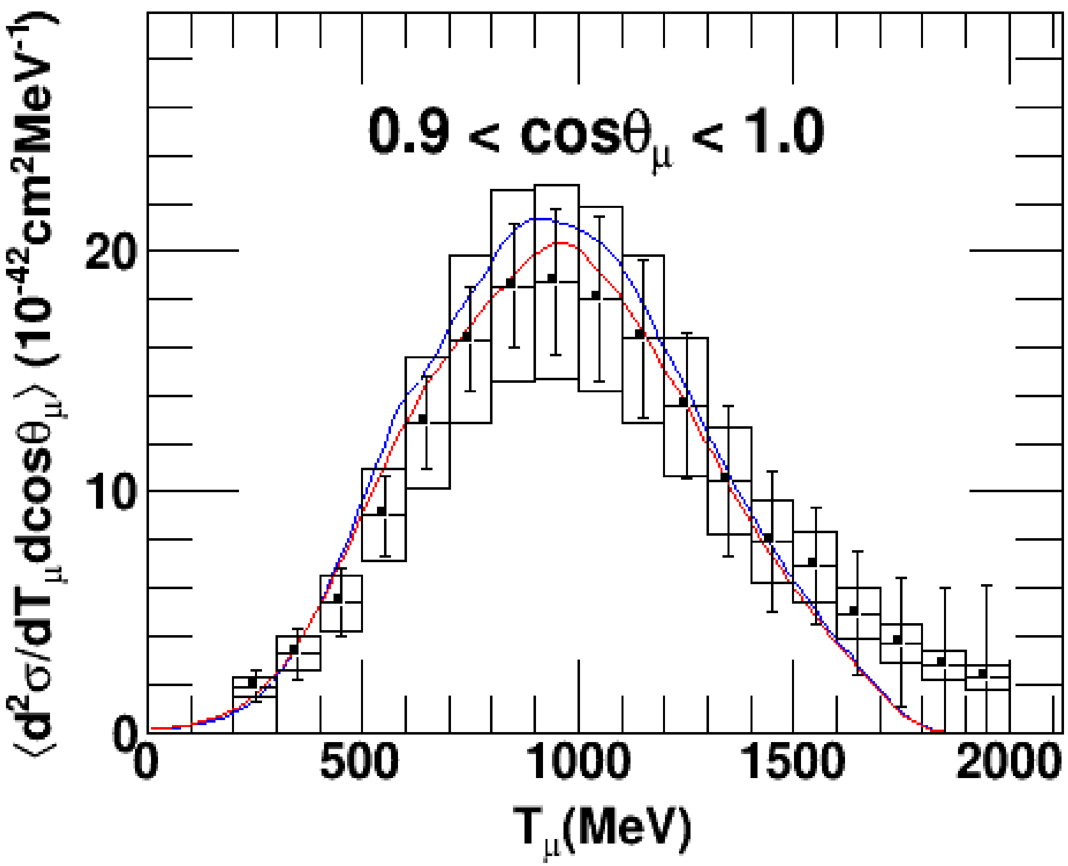

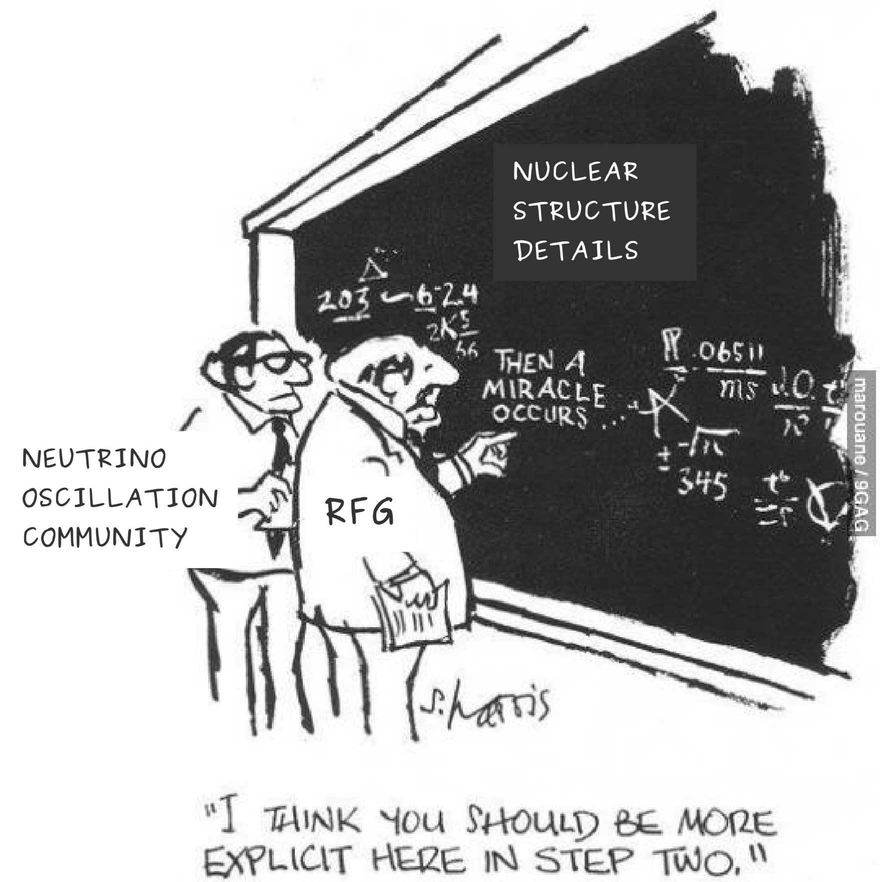

➢ Such effects, where nuclear structure details are important, are inaccessible in RFG based models.

Summary and Outlook

- We presented a CRPA approach for quasielastic neutrino-nucleus scattering, relevant for the accelerator based neutrino oscillation experiments.
- The model is validated against high precision electron scattering data for a variety of nuclear targets (^{12}C, ^{16}O, ^{40}Ca), in the kinematic region where quasielastic scattering is the dominant process.
- We calculated (MiniBooNE) flux-folded (anti)neutrino cross section and compared them against the MiniBooNE data. CRPA cross sections successfully describe the gross feature of the measured cross section.
- Further work on the influence of short-range correlations on one-nucleon and two-nucleon knockout is in progress.
- We draw special attention to the low-energy nuclear excitations, which seems to have non-negligible contribution even at high neutrino energies and forward scatterings but remain inaccessible in the RFG description.

**Most of the work presented here, will be submitted for publication soon.*