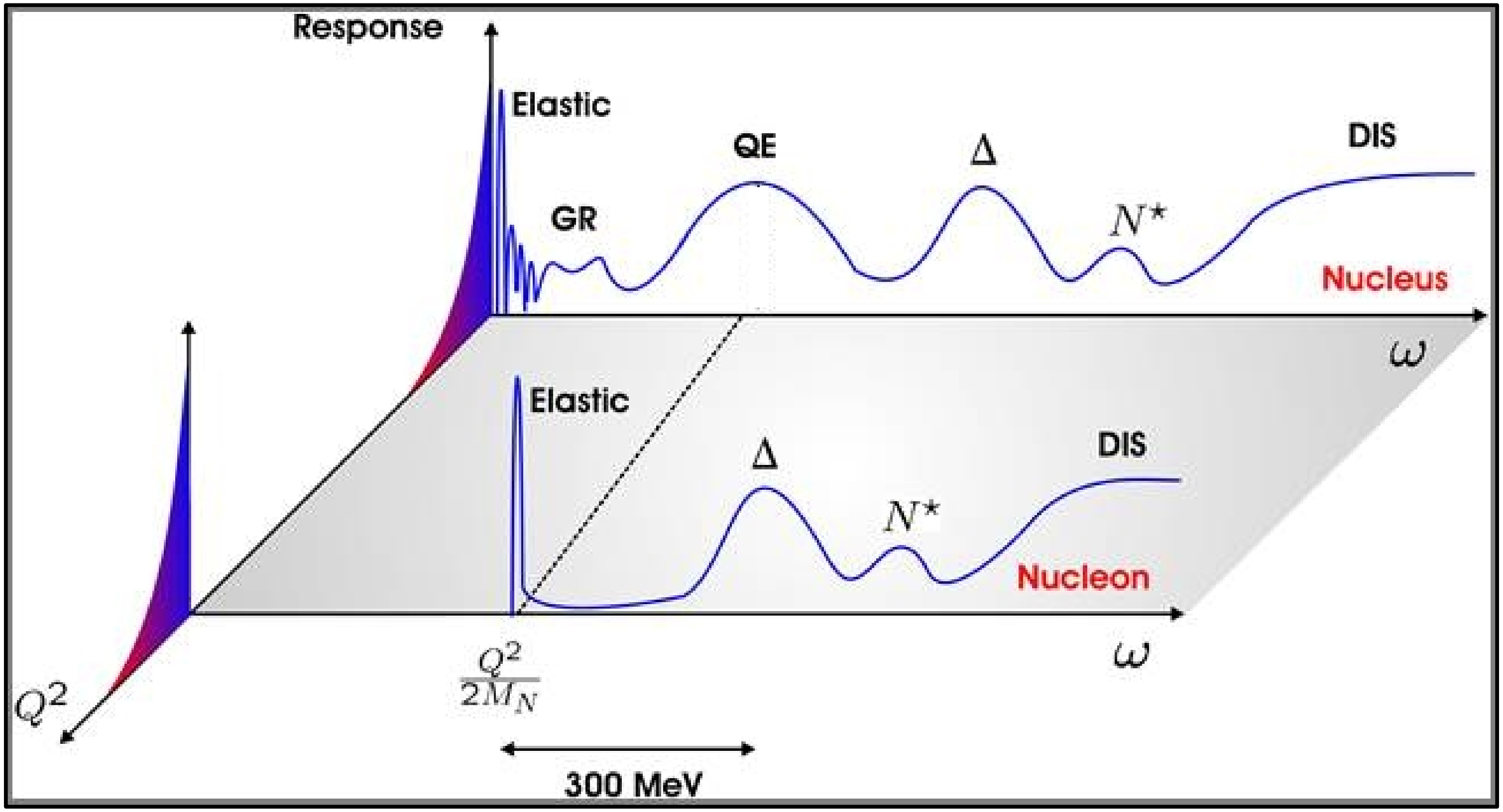
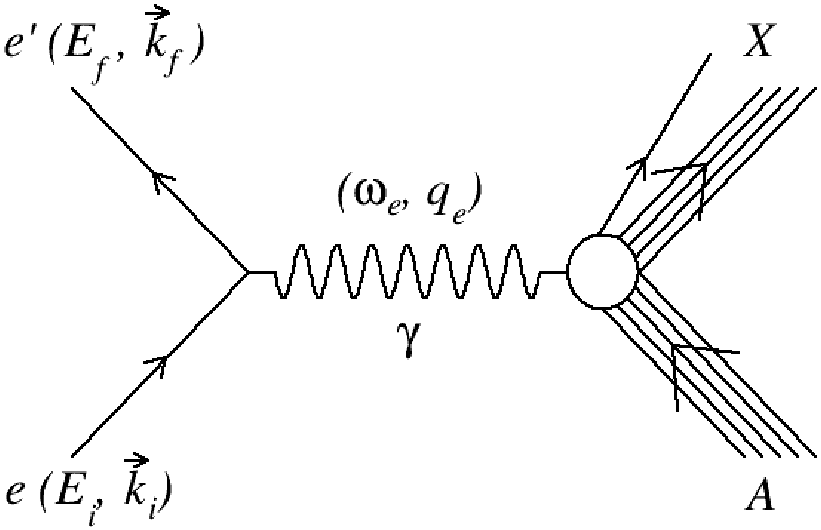
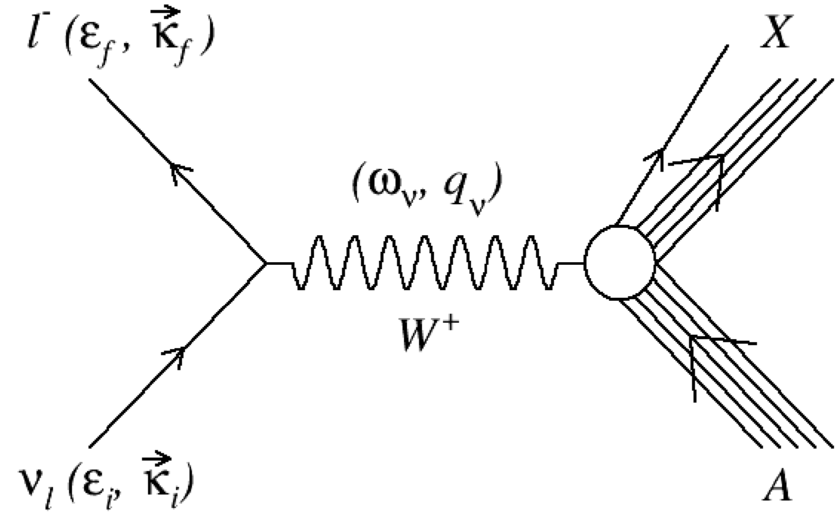
Low-energy excitations to quasielastic scattering



Vishvas Pandey
Department of Physics and Astronomy,
Ghent University, Ghent, Belgium

Quasielastic scattering





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

$$\sigma_{L,e} = v_e^L R_e^L$$

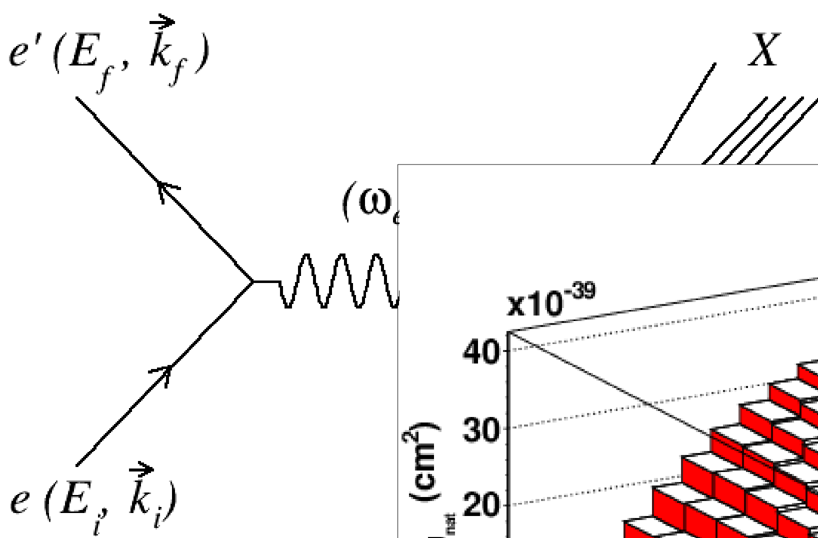
$$\sigma_{T,e} = v_e^T R_e^T$$

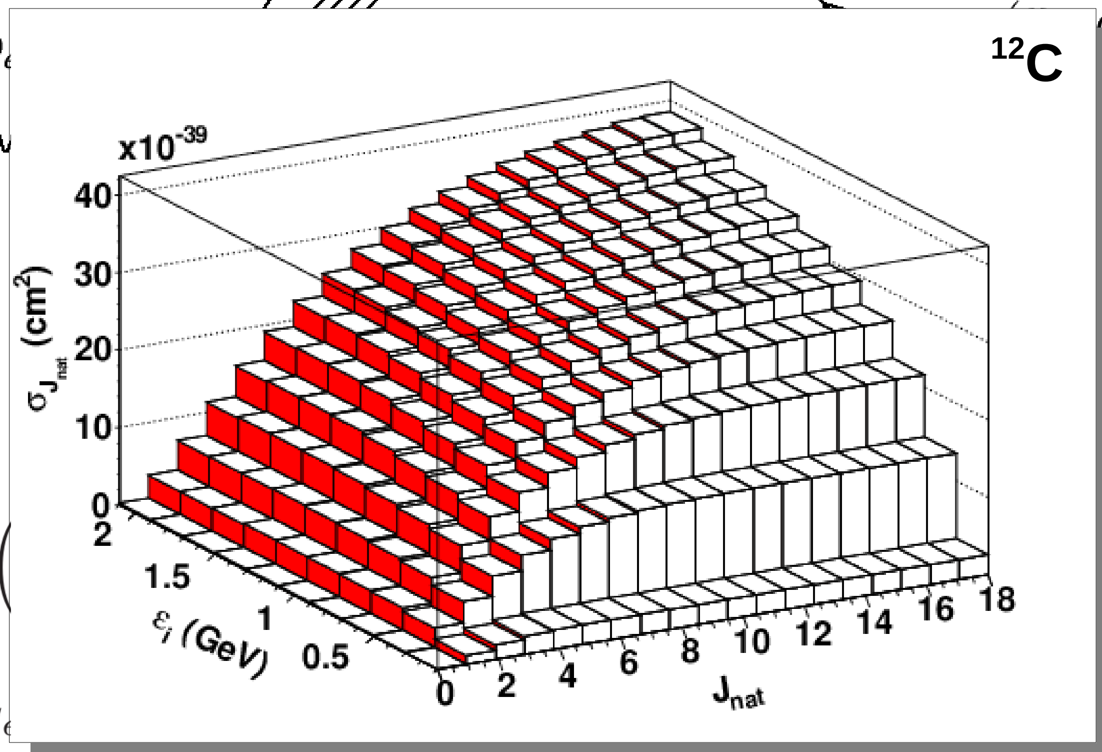
$$\left(\frac{d^2\sigma}{d\omega_\nu d\Omega}\right)_\nu = \frac{G_F^2 \cos^2\theta_c}{(4\pi)^2}\left(\frac{2}{2J_i+1}\right)\varepsilon_f \kappa_f \times \zeta^2(Z', \varepsilon_f, q_\nu)\left[\sum_{J=0}^{\infty}\sigma_{CL,\nu}^J + \sum_{J=1}^{\infty}\sigma_{T,\nu}^J\right]$$

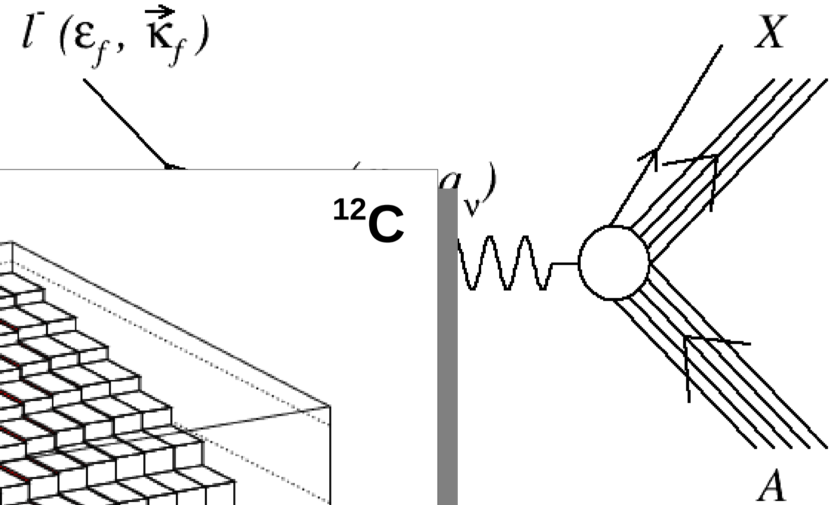
$$\sigma_{CL,\nu} = \left[v_\nu^{\mathcal{M}} R_\nu^{\mathcal{M}} + v_\nu^{\mathcal{L}} R_\nu^{\mathcal{L}} + 2\, v_\nu^{\mathcal{ML}} R_\nu^{\mathcal{ML}}\right]$$

$$\sigma_{T,\nu} = \left[v_\nu^T R_\nu^T \pm 2\, v_\nu^{TT} R_\nu^{TT}\right]$$

Quasielastic scattering







$$\left(\frac{d^2\sigma}{d\omega_e d\Omega}\right)_e = \frac{\alpha^2}{Q^4} \Bigg($$

$$\times\ \zeta^2(Z', E_f, q_e \quad \Bigg[\sum_{J=0} \qquad \sum_{J=1} \Bigg]$$

$${}^2\theta_c \left(\frac{2}{2J_i+1}\right) \varepsilon_f \kappa_f$$

$$\left[\sum_{J=0}^{\infty} \sigma^J_{CL,\nu} + \sum_{J=1}^{\infty} \sigma^J_{T,\nu}\right]$$

$$\sigma_{L,e} = v_e^L R_e^L$$

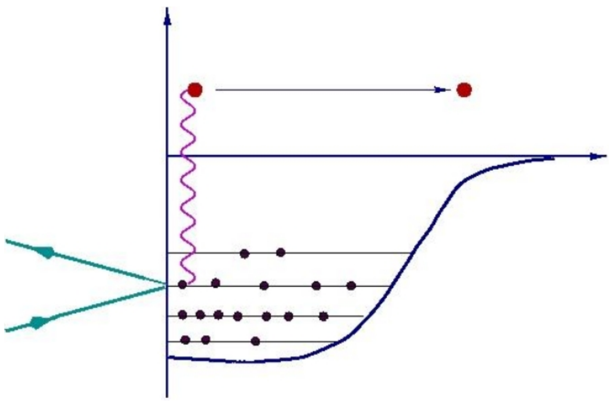
$$\sigma_{T,e} = v_e^T R_e^T$$

$$\sigma_{CL,\nu} = \left[v_\nu^{\mathcal{M}} R_\nu^{\mathcal{M}} + v_\nu^{\mathcal{L}} R_\nu^{\mathcal{L}} + 2\, v_\nu^{\mathcal{ML}} R_\nu^{\mathcal{ML}}\right]$$

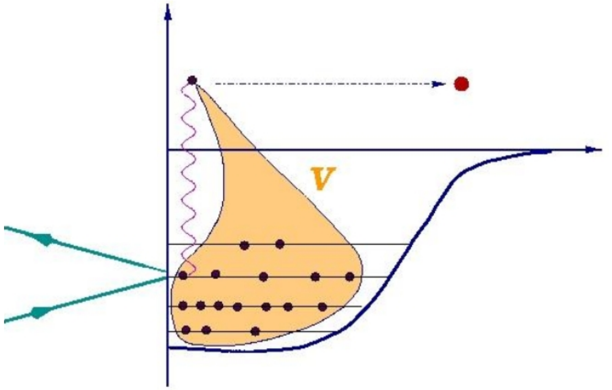
$$\sigma_{T,\nu} = \left[v_\nu^T R_\nu^T \pm 2\, v_\nu^{TT} R_\nu^{TT}\right]$$

Formalism: HF-CRPA approach

- 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).

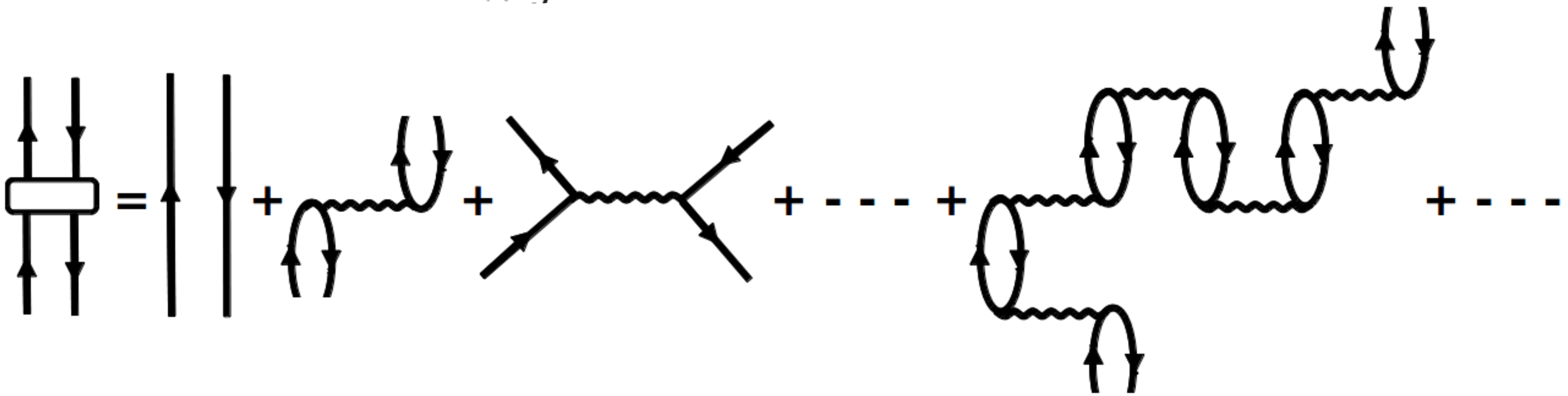


- RPA equations are solved using a Green's function approach.

Formalism: HF-CRPA 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 of the ejected nucleon waves, are taken into account.

Formalism: Folding procedure

- A limitation of RPA formalism at lower energies:
  - → energy position of the giant resonances is generally well predicted
  - → width is underestimated
  - → height is overestimated

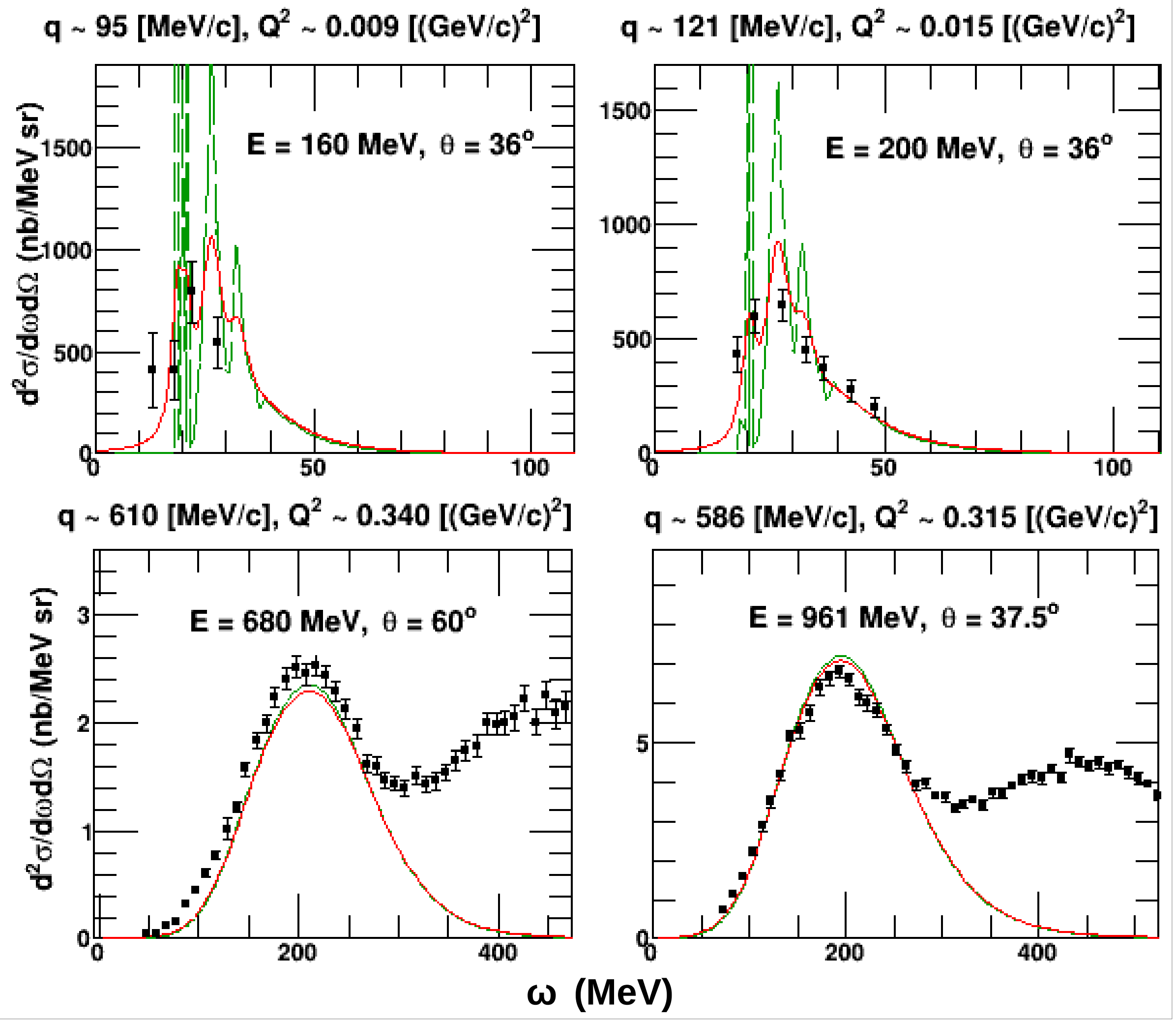
Folding

$$R'(q,\omega') = \int_{-\infty}^{\infty} d\omega R(q,\omega) L(\omega,\omega')$$

$$L(\omega,\omega') = \frac{1}{2\pi}\left[\frac{\Gamma}{(\omega-\omega')^2 + (\Gamma/2)^2}\right]$$

Γ = 3 MeV

CRPA: Without Folding, CRPA: With Folding



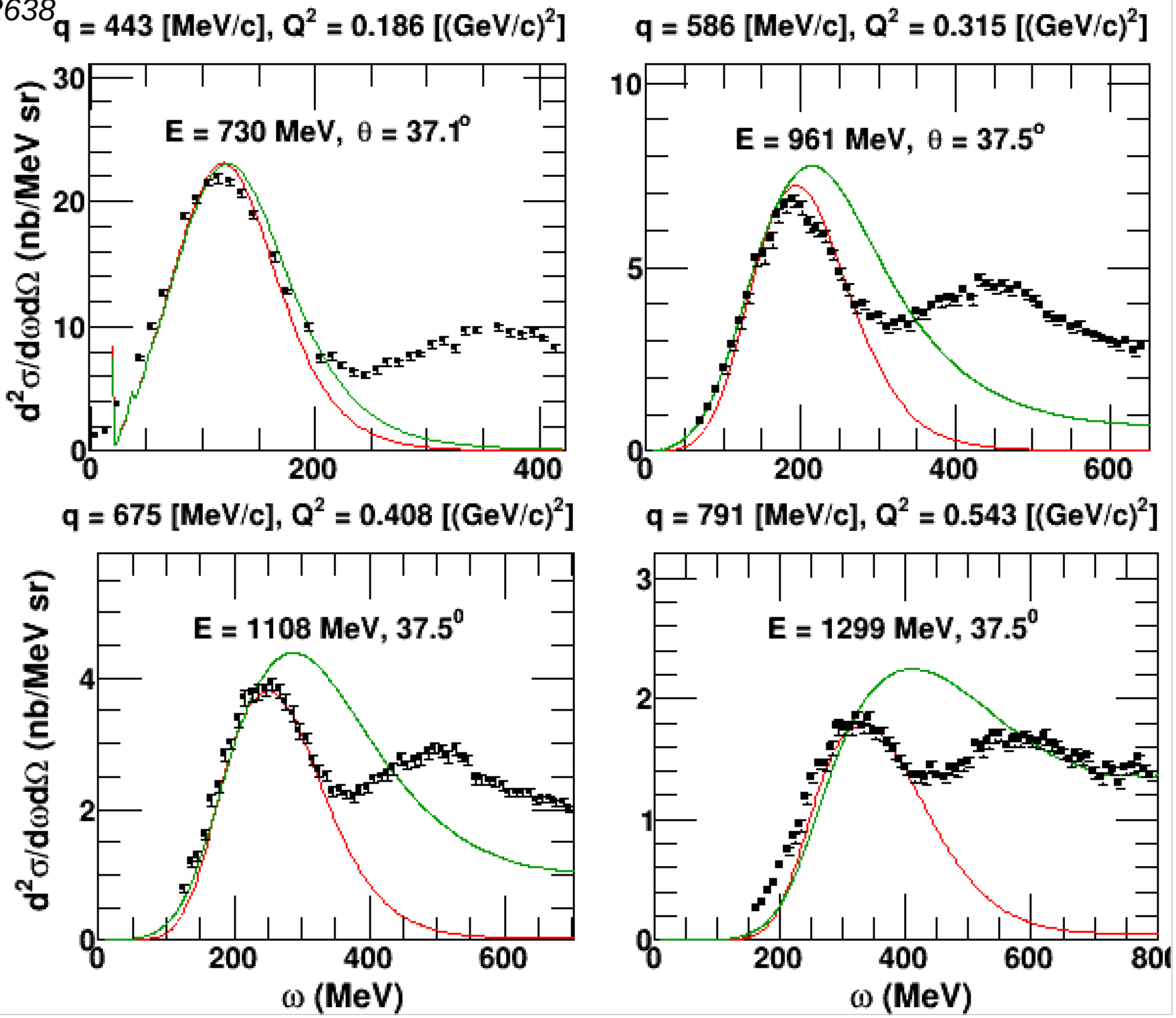
Formalism: Relativistic corrections

- Non-relativistic model → higher energies (~GeV) → problem!

'Semi-relativistic' modeling

(S. Jeschonnek and T. W. Donnelly, PRC57, 2638 (1998))

CRPA: Non-relativized, CRPA: Relativized



Kinematic effects:

- $\lambda \rightarrow \lambda(1+\lambda)$, $\lambda = \omega/2M_N$
- QE peak: $\omega = q^2/2M_N \Rightarrow Q^2/2M_N$

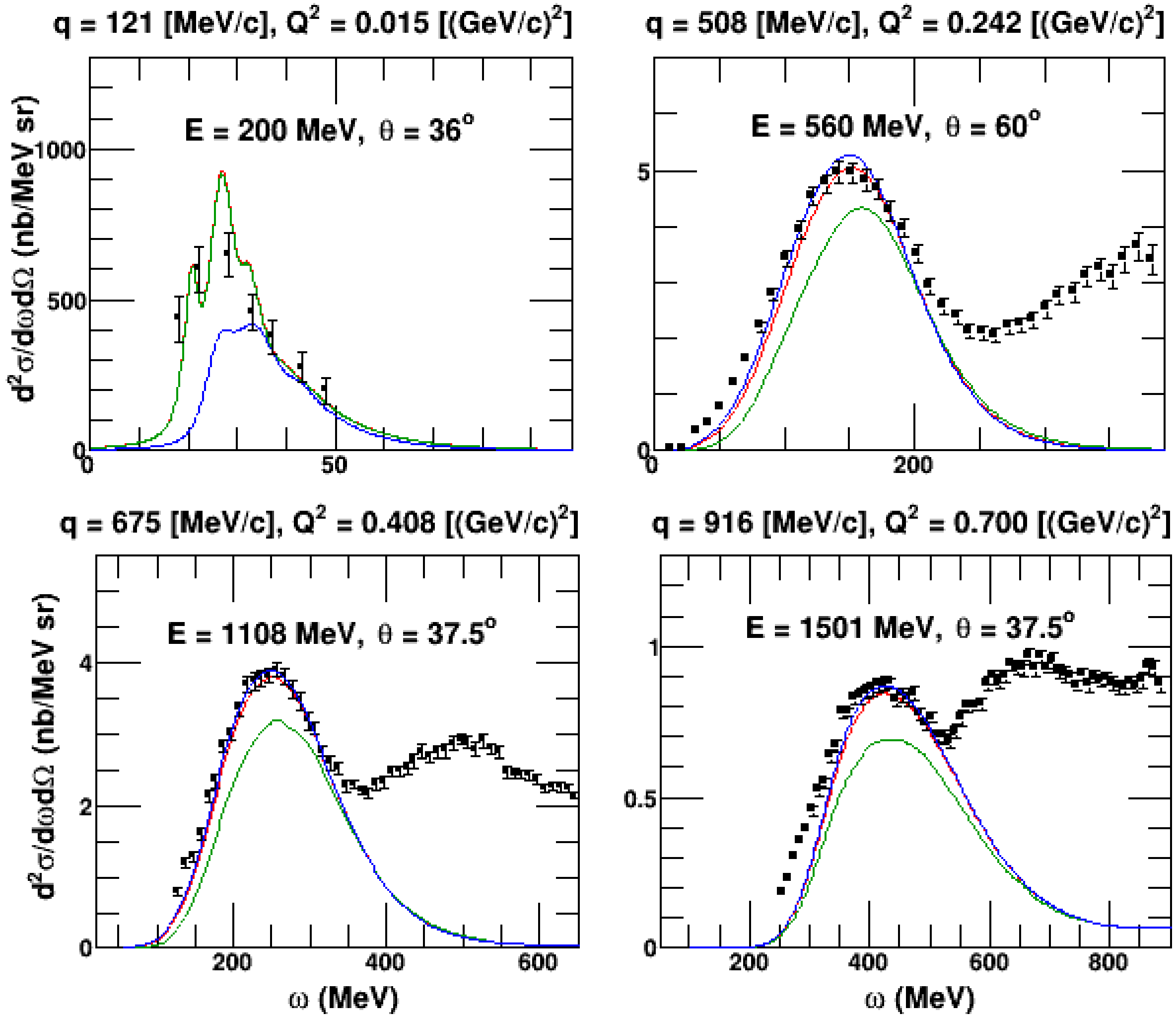
Formalism: Regularization of the residual interaction

- SkE2 interaction → optimized against ground-state and low-excitation energy properties
  → at higher Q^2, unrealistically strong!

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

With Λ = 455 MeV, optimized with a χ^2 fitting of theory-experiment comparison from low ω up to the QE peak, over broad set of available data on *A(e,e')* scattering.

CRPA: without dipole, CRPA: with dipole, HF



Formalism: Coulomb correction for outgoing lepton

- Effect of coulomb potential of the nucleus on the charged lepton:

→ Low energies: Fermi function $F(Z',E) = \frac{2\pi\eta}{1-e^{-2\pi\eta}}$ $\eta \sim \mp Z'\alpha$

→ High energies:

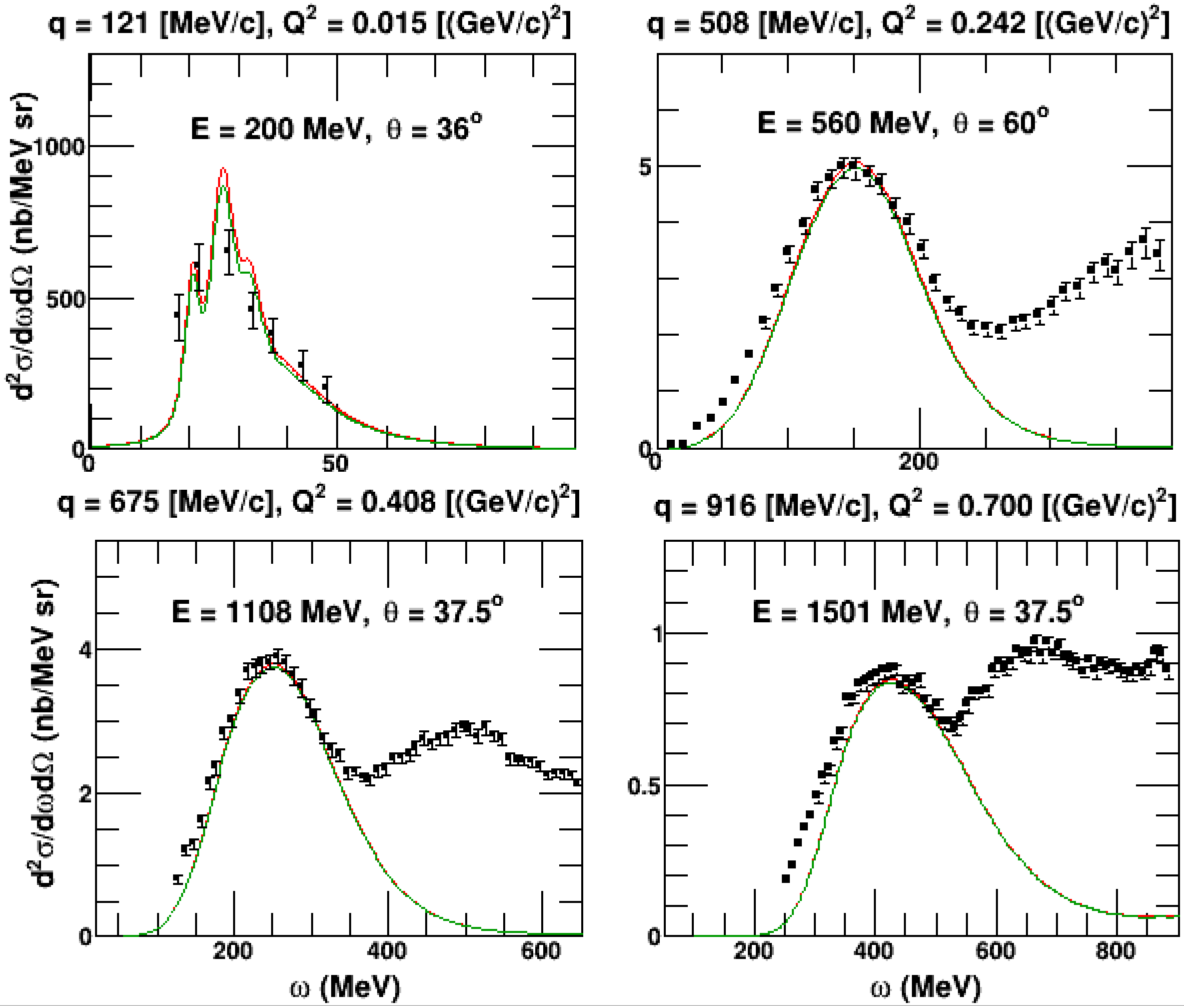
Modified effective momentum approximation

(J. Engel, PRC57,2004 (1998))

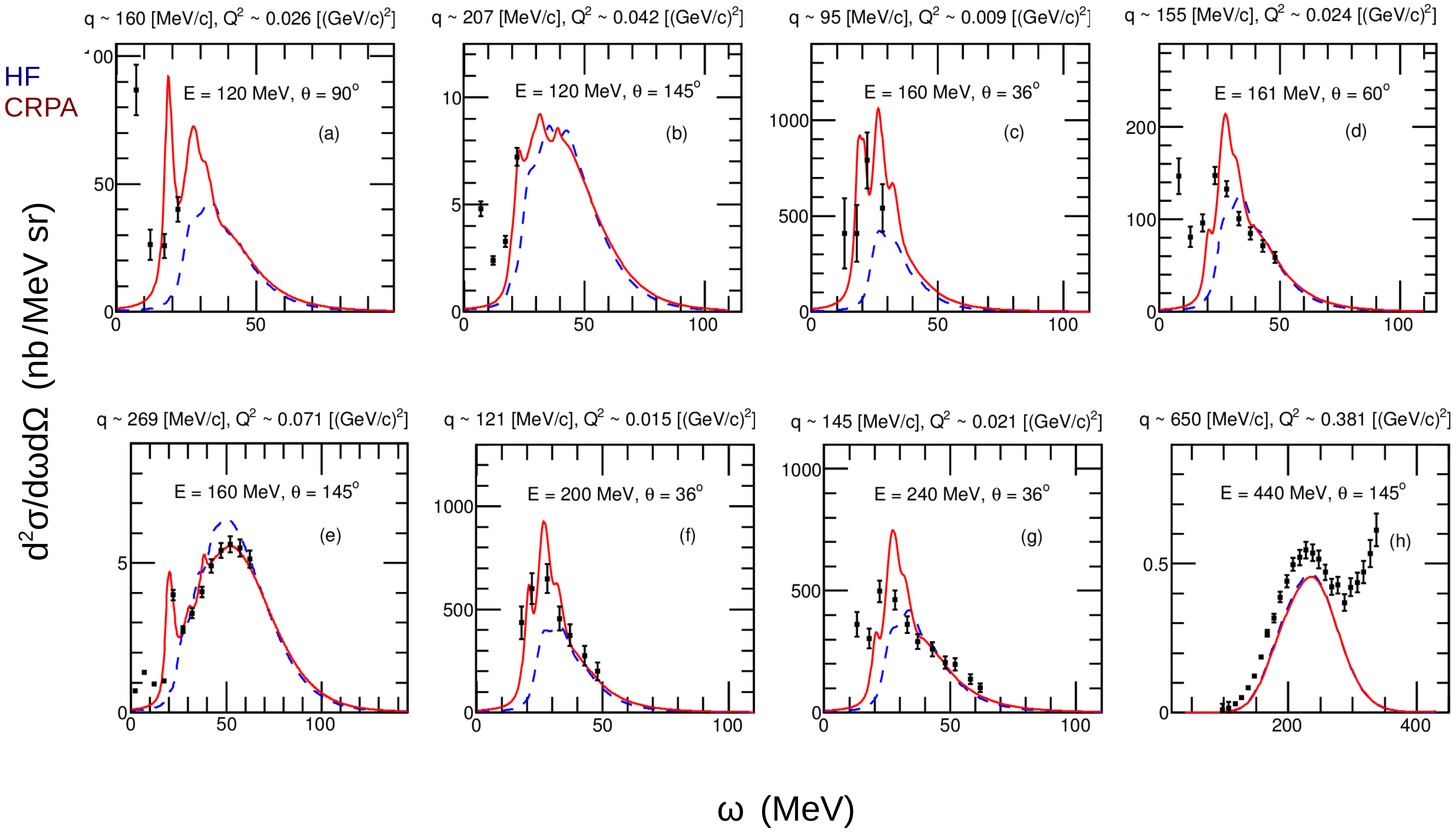
$$q_{\text{eff}} = q + 1.5\left(\frac{Z'\alpha\hbar c}{R}\right)$$

$$\zeta(Z',E,q) = \sqrt{\frac{q_{\text{eff}}E_{\text{eff}}}{qE}}$$

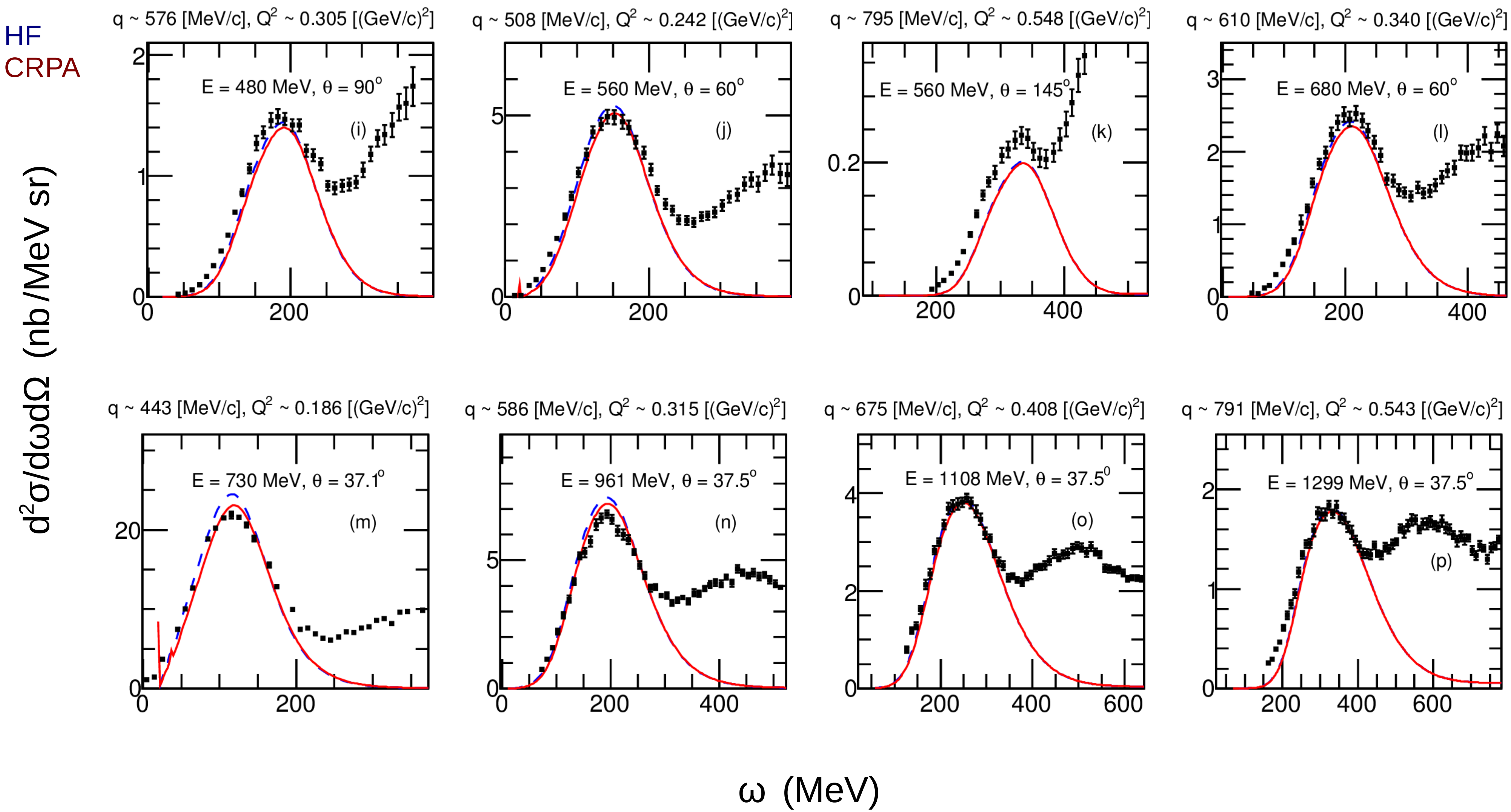
CRPA: without MEMA, CRPA: with MEMA



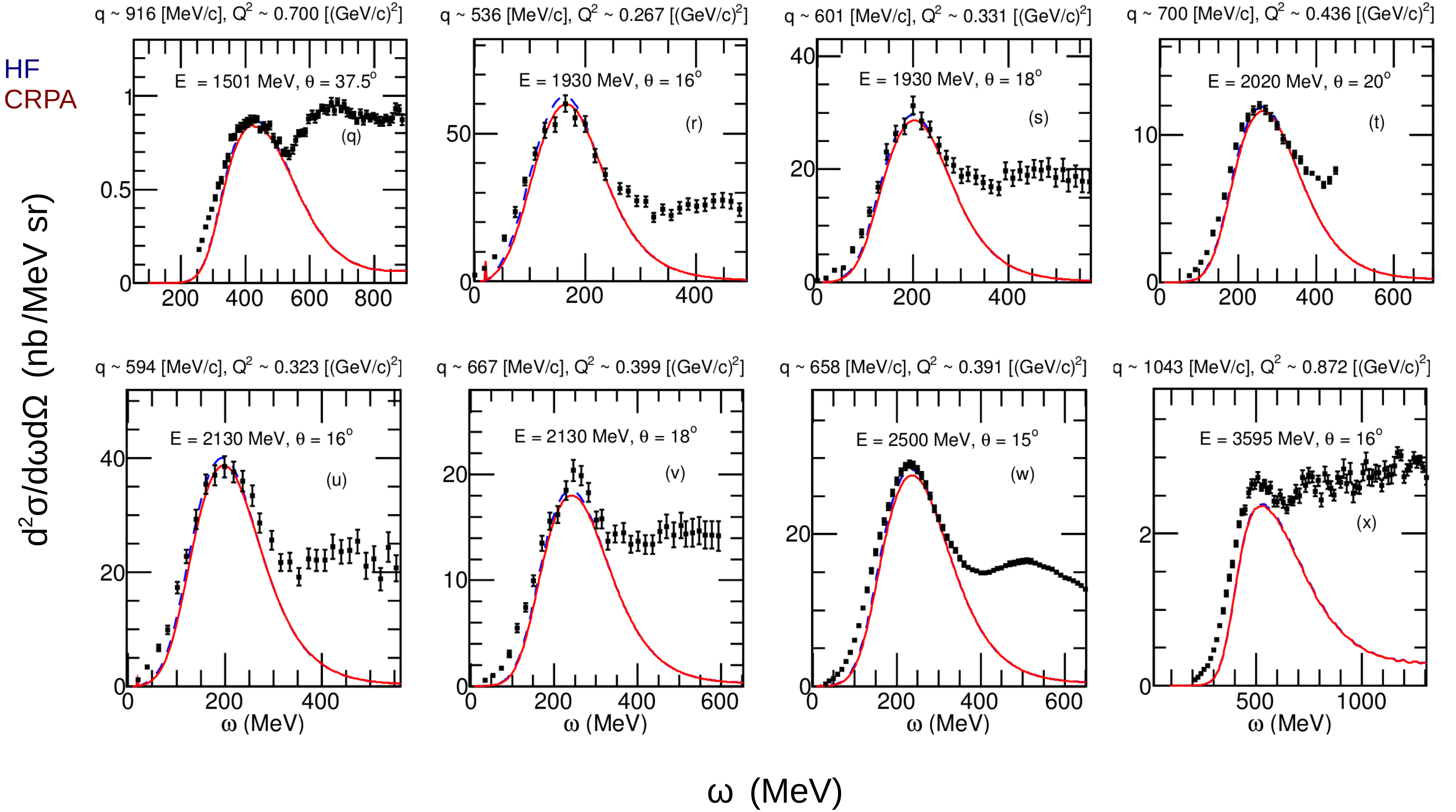
Comparison with electron scattering data: ^{12}C (e,e′)



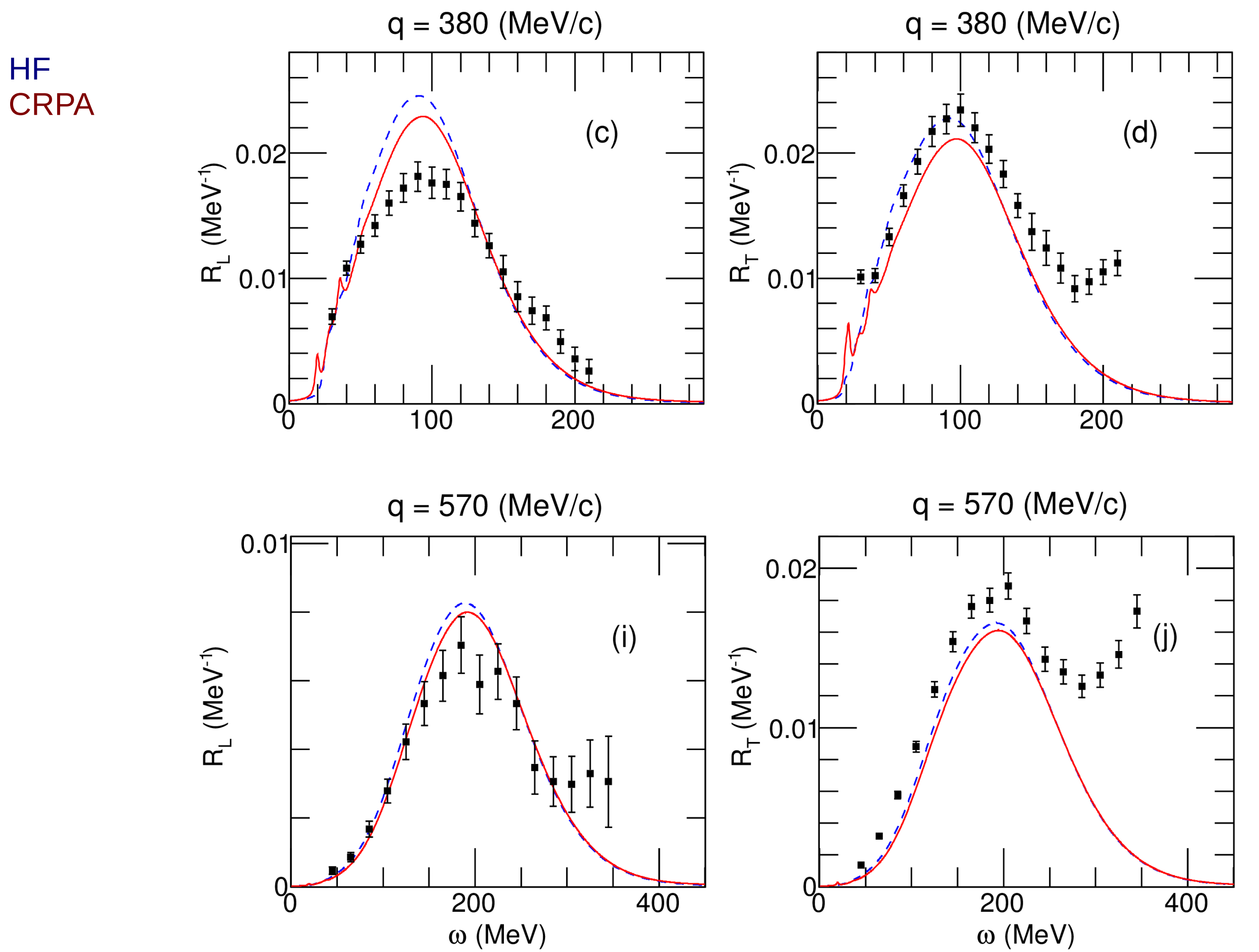
Comparison with electron scattering data: $^{12}C\ (e,e')$



Comparison with electron scattering data: ^{12}C (e,e′)

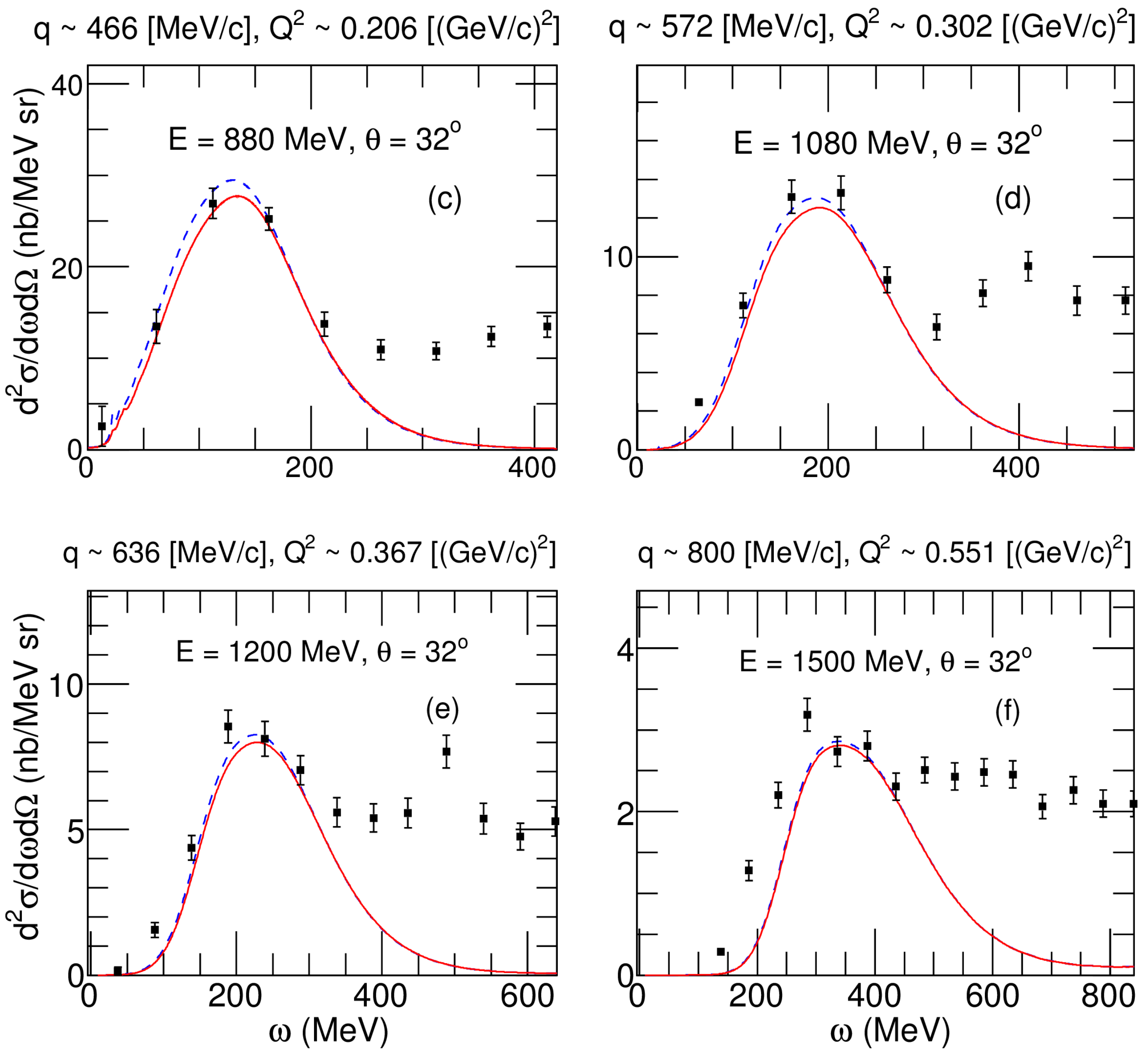


Longitudinal and Transverse structure for ^{12}C *(e,e')*

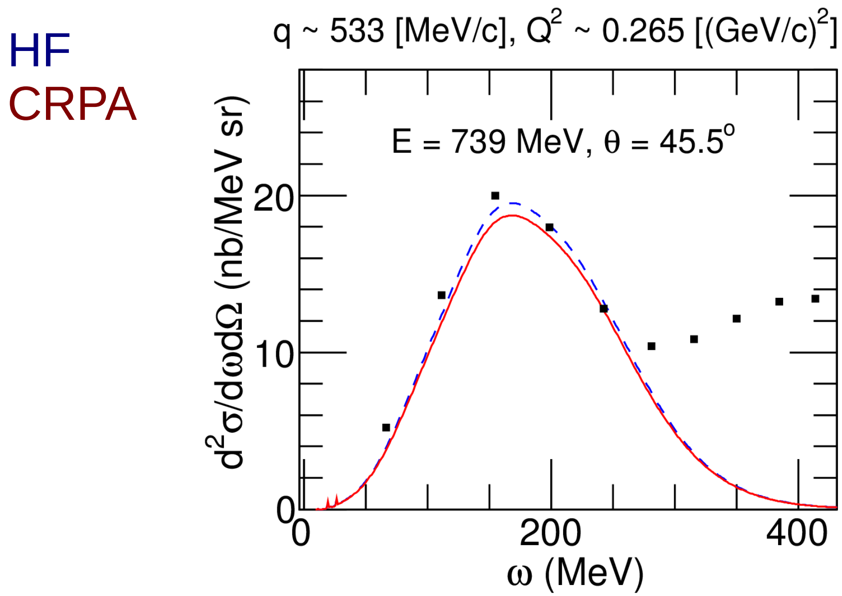


Comparison with electron scattering data: ^{16}O (e,e′)

HF
CRPA

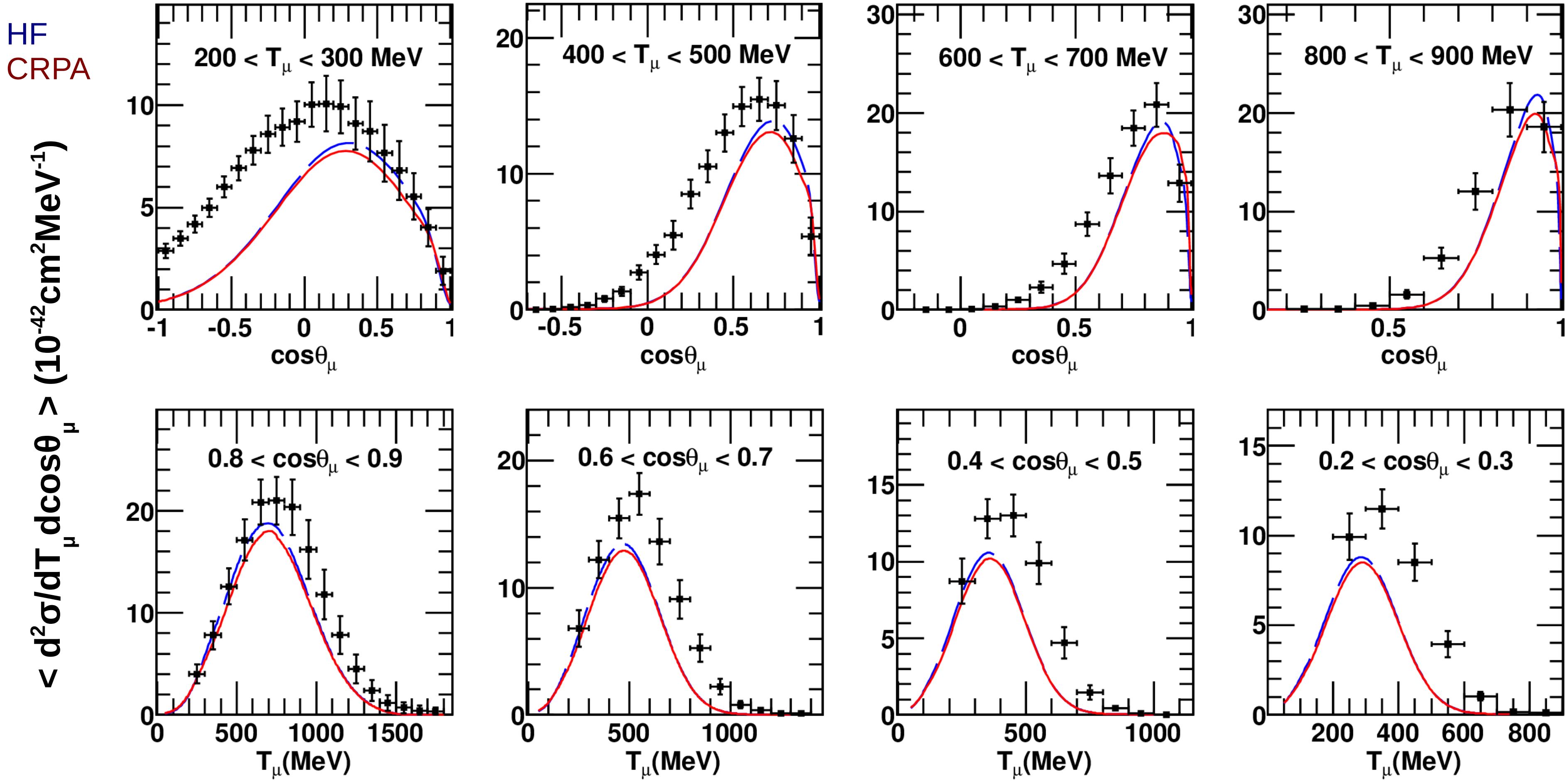


Comparison with electron scattering data: ^{26}Ca *(e,e')*

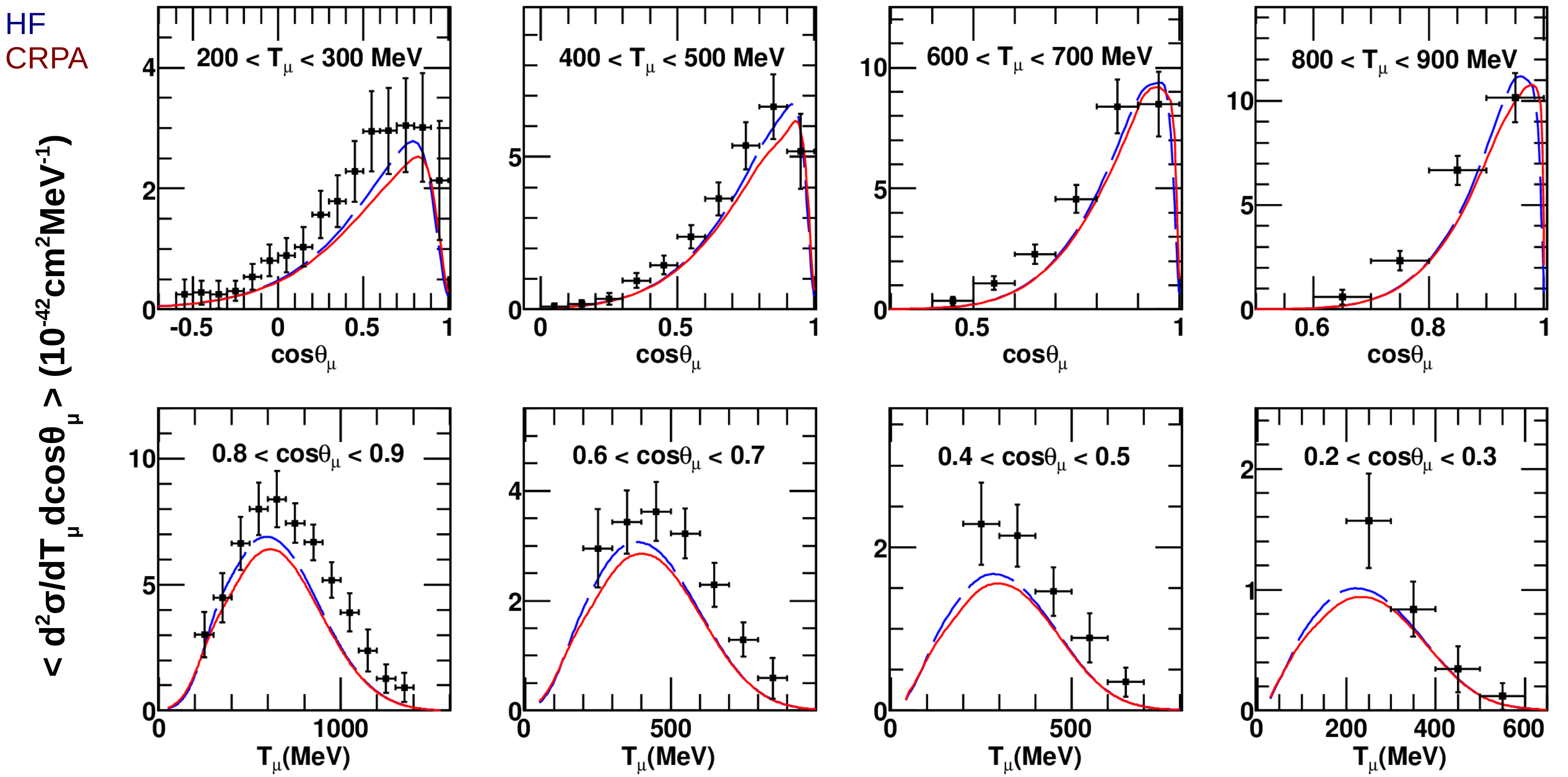


- Good overall agreement with electron scattering data on variety of nuclear target (^{12}C, ^{16}O, ^{26}Ca) from low-energy excitations to the QE region, validates the reliability of our approach.

Comparison with MiniBooNE ν_μ 'CCQE-like' data

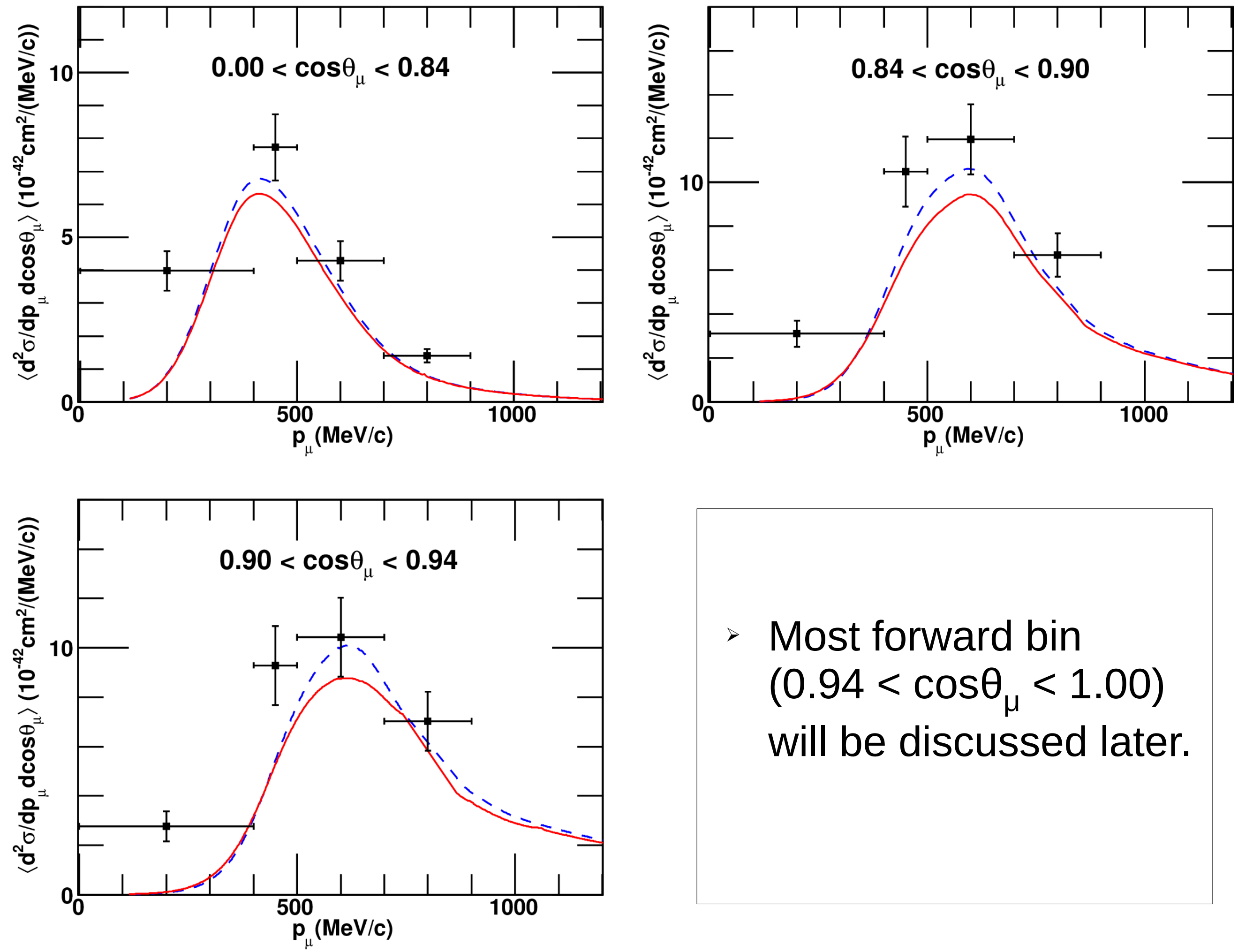


Comparison with MiniBooNE $\bar{\nu}_\mu$ 'CCQE-like' data



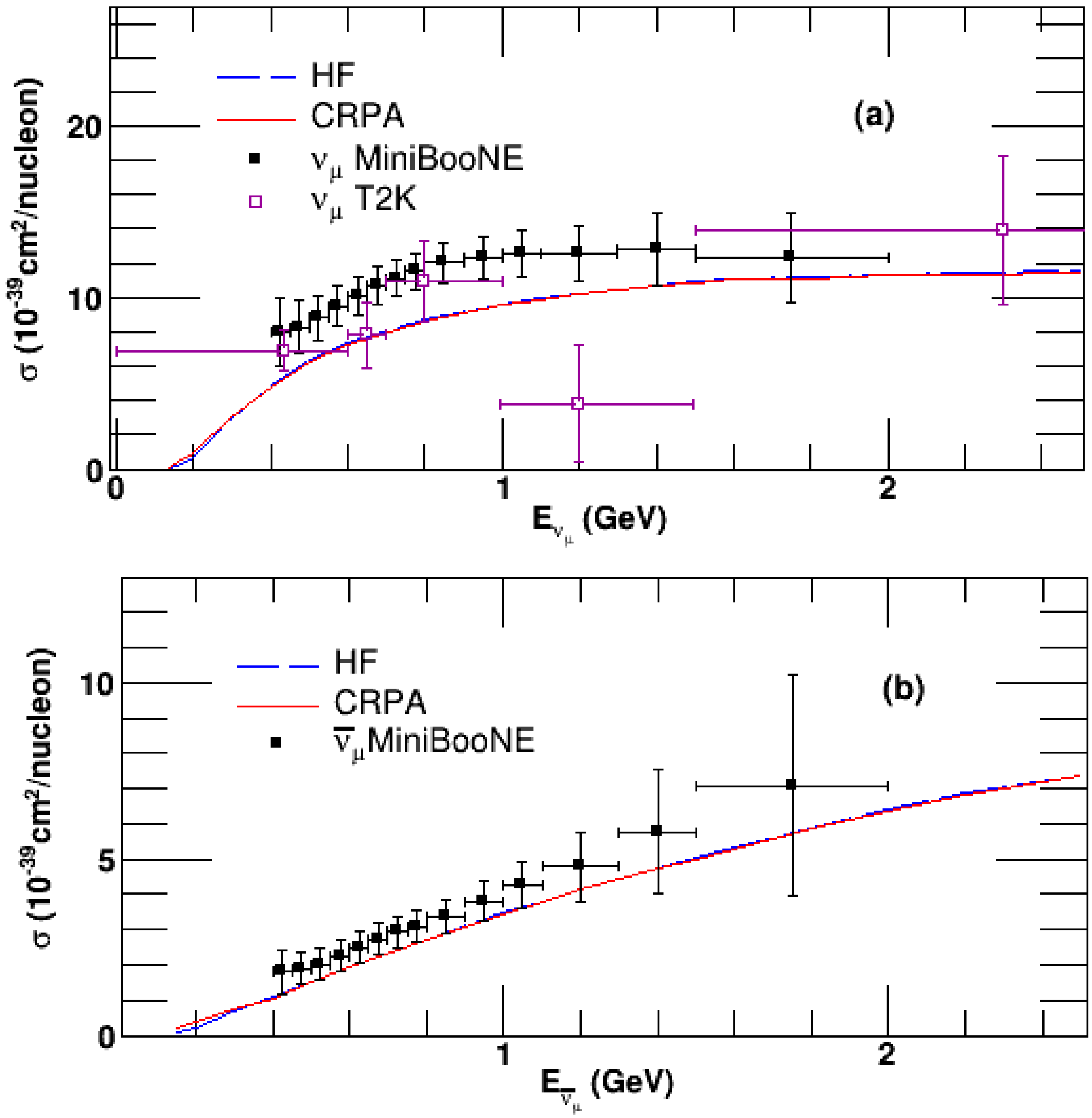
Comparison with T2K ν_μ inclusive QE data

HF
CRPA

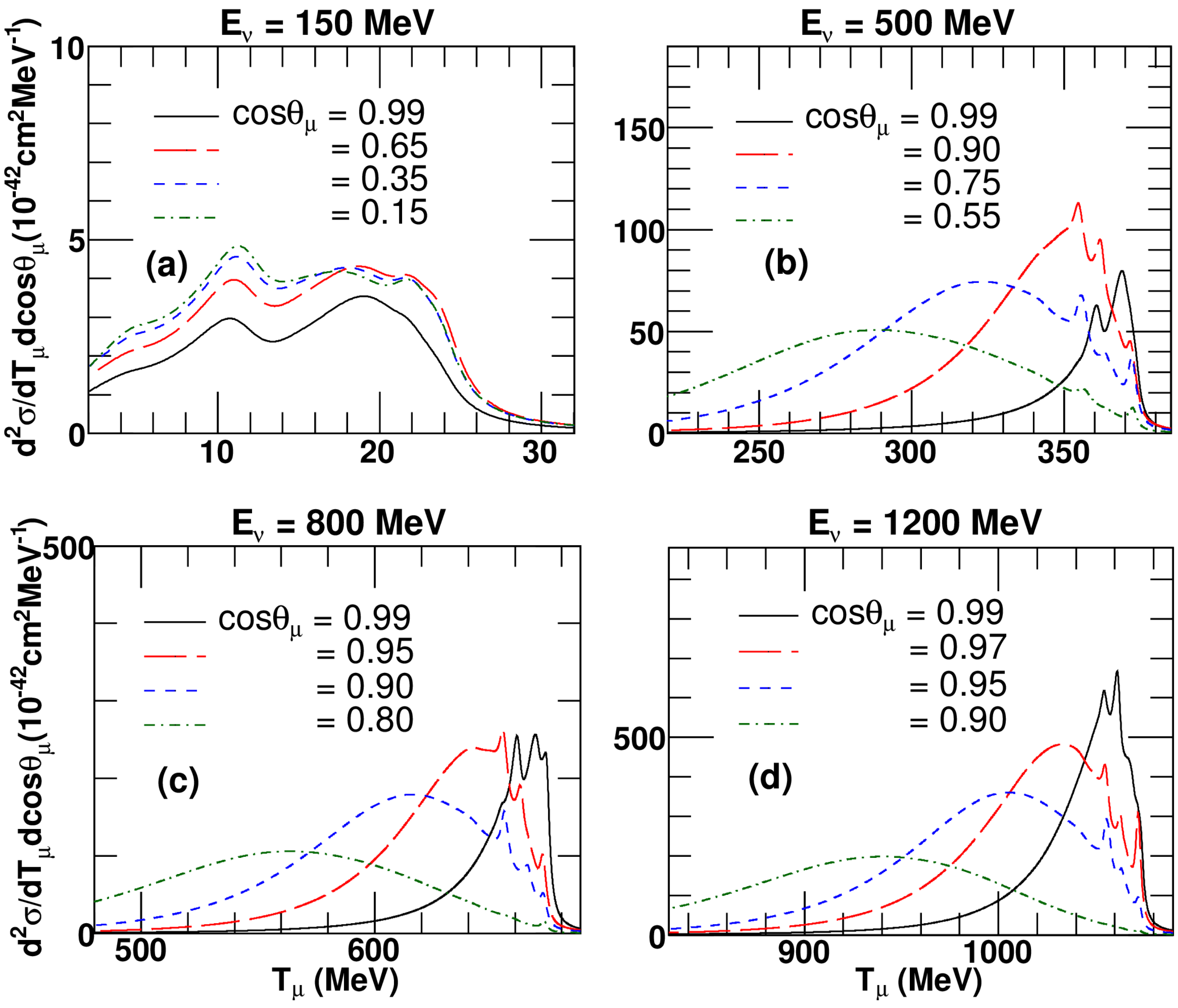


- Most forward bin ($0.94 < \cos\theta_\mu < 1.00$) will be discussed later.

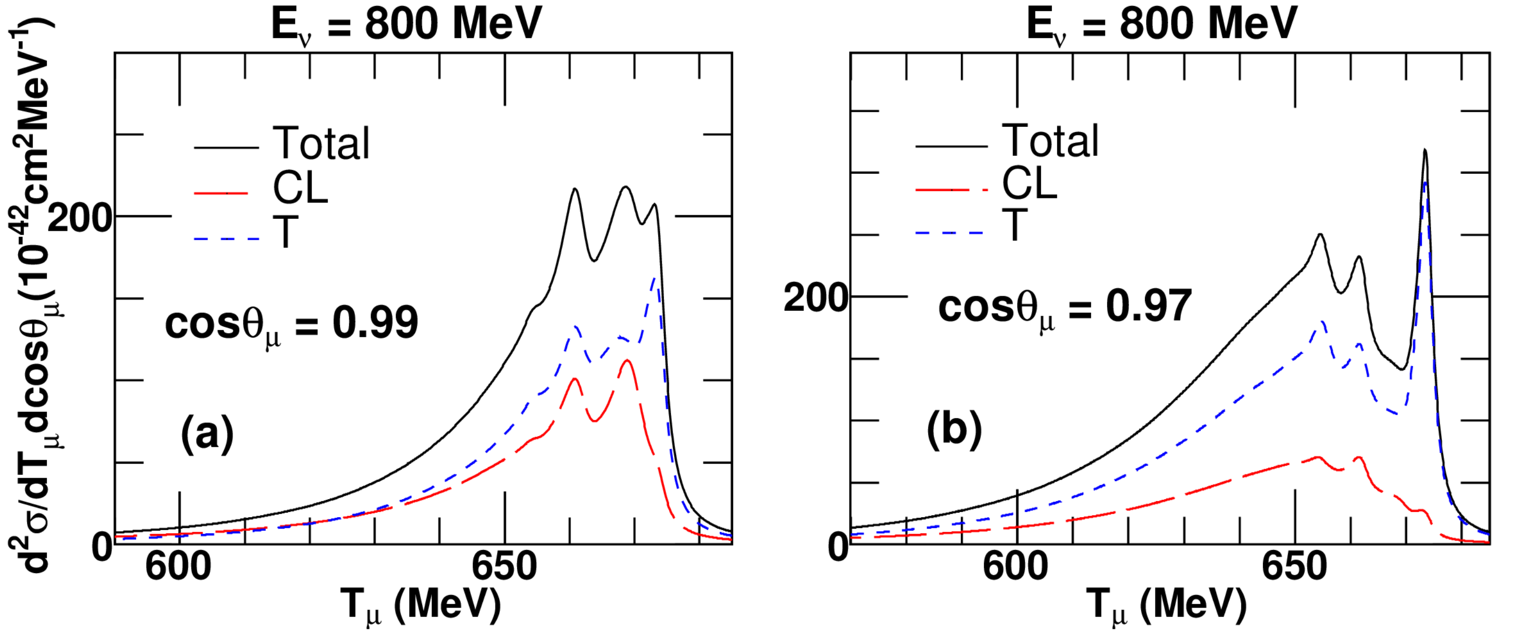
Total cross section: comparison with MiniBooNE and T2K CCQE data



Impact of low-energy excitations: Forward scattering (fixed energy)



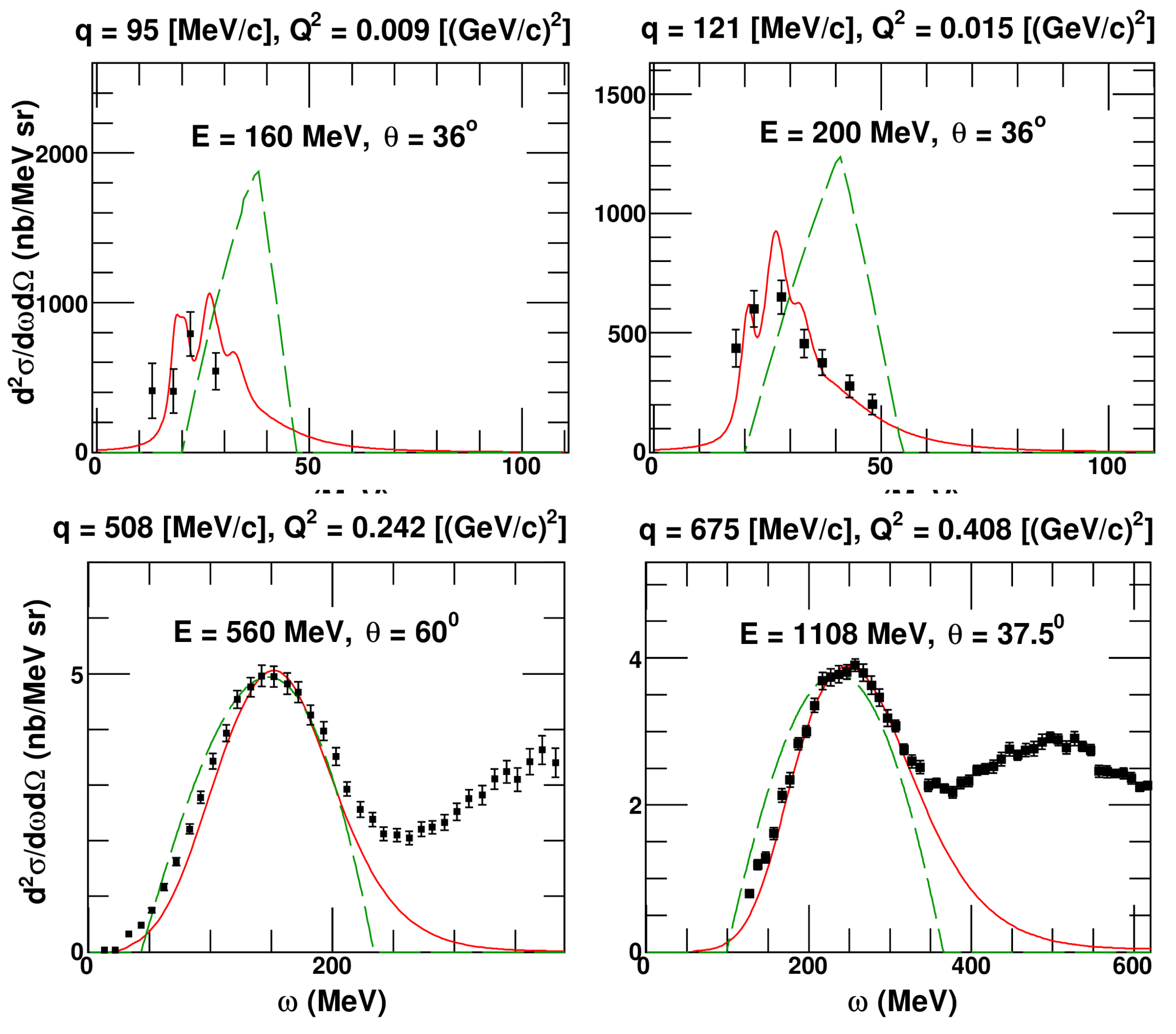
Impact of low-energy excitations: Forward scattering (CL *vs* T)



Impact of low-energy excitations: CRPA *vs* RgFG

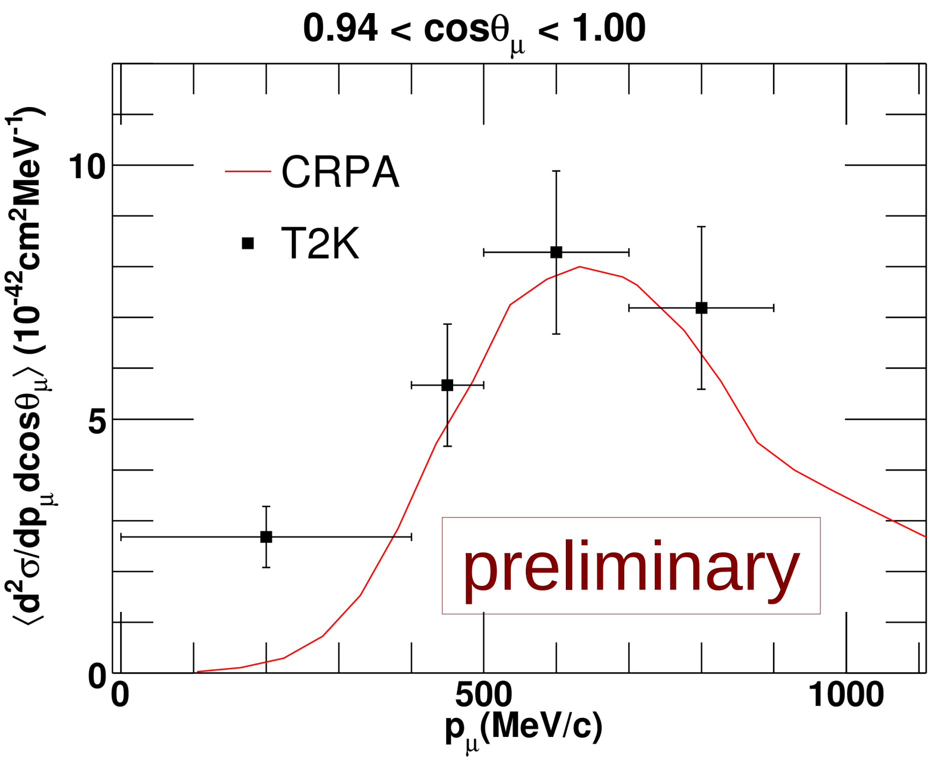
- Example from $^{12}C(e,e')$

CRPA
RgFG

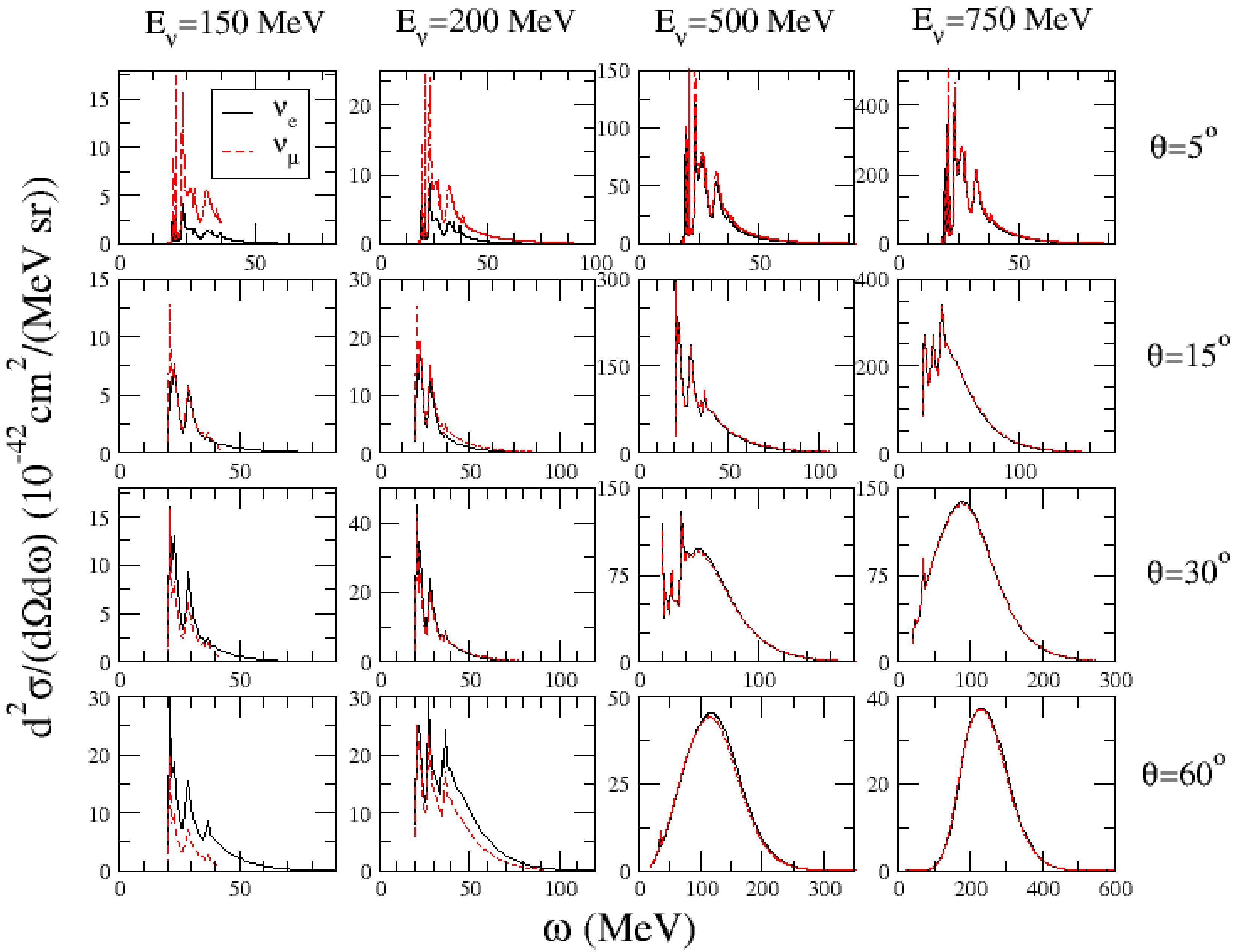


Impact of low-energy excitations: Forward scattering (flux-folded)

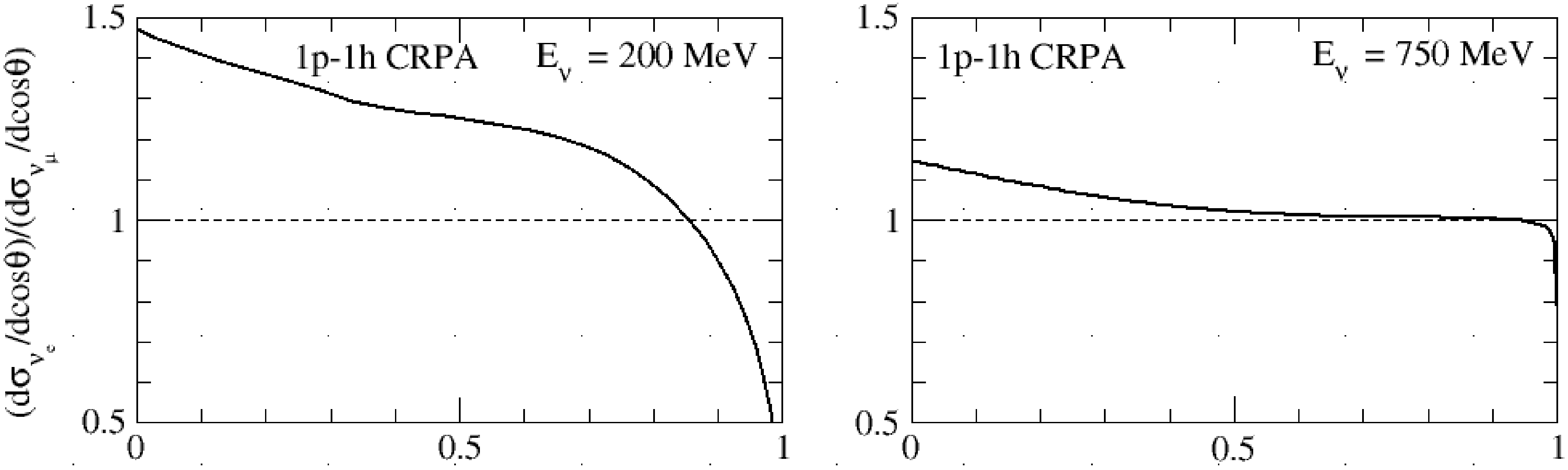
- Significant contribution is expected from low-energy nuclear excitation ($\omega < 50$ MeV).
- A quantitative analysis is underprogress.



Impact of low energies: ν_e *vs* ν_μ



Impact of low energies: ν_e *vs* ν_μ



Summary

- We present a CRPA approach for QE electron- and neutrino-nucleus scatterings. The model is validated against electron scattering data.

- We compare flux-folded neutrino-nucleus cross-section predictions with MiniBooNE and T2K experimental measurements. Our calculations successfully describe the gross feature of the measurements but underestimate the data. Missing strength can be associated to the processes beyond QE (np-nh, pion production, etc.), not present in our description.

Impact of low energies

- We draw special attention to the contributions emerging from low-energy nuclear excitations ($\omega < 50$ MeV), which remain inaccessible in the RFG-based Models, especially for forward scatterings.

- We compare electron-neutrino and muon-neutrino cross sections, relevant for $\nu_\mu \rightarrow \nu_e$ oscillation studies, we observed some non-trivial behavior at low energies.

References

[1] V. Pandey, N. Jachowicz, J. Ryckebusch, T. Van Cuyck, W. Cosyn, Phys.Rev. C89, 026601 (2), 2014.
[2] V. Pandey, N. Jachowicz, T. Van Cuyck, J. Ryckebusch, M. Martini, Phys.Rev. C92, 026606 (2), 2015.
[3] M. Martini, N. Jachowicz, M. Ericson, V. Pandey, T. Van Cuyck, N. Van Dessel, arXiv:1602.00230 [nucl-th].
[4] V. Pandey, N. Jachowicz, M. Martini, T. Van Cuyck, and J. Ryckebusch, 'CRPA approach to charged-current neutrino-nucleus scatterings at MiniBooNE and T2K kinematics', to be submitted.

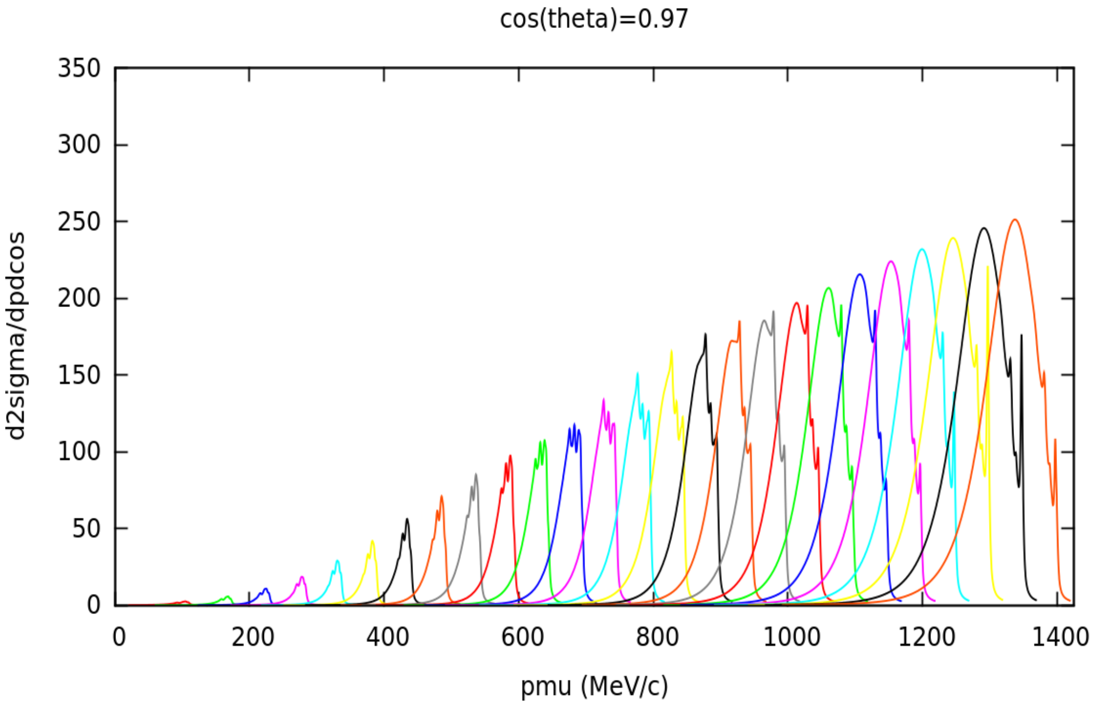
Electron-scattering data are from:

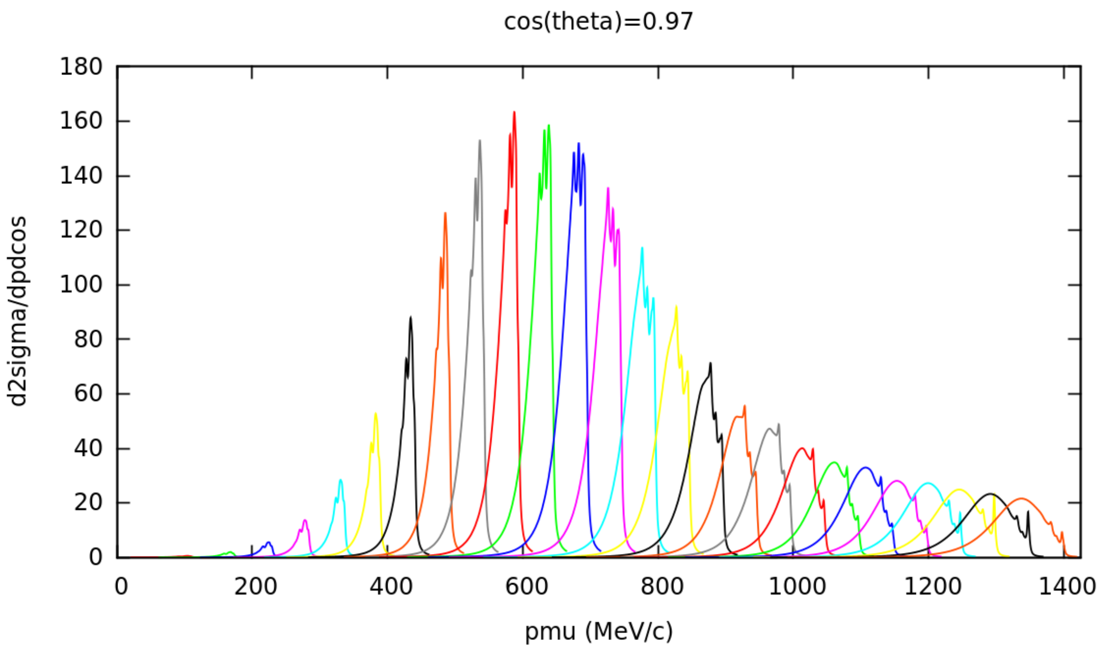
[1] P. Barreau et al., Nucl. Phys. A262, 515 (1983).
[2] J. S. O'Connell et al., Phys. Rev. C35, 1063 (1987).
[3] R. M. Sealock et al., Phys. Rev. Lett.62, 1350 (1989).
[4] D. S. Bagdasaryan et al., YERPHI-1077-26-88 (1988).
[5] D. B. Day et al., Phys. Rev. C 48, 1849 (1993).
[6] D. Zeller, DESY-F23-73-2 (1973).
[7] M. Anghinolfi et al., Nucl. Phys. A602, 265 (1996).
[8] C. F. Williamson et al., Phys. Rev. C56, 3152 (1997).
[9] J. Jourdan, Nucl. Phys. A603, 117 (1996).

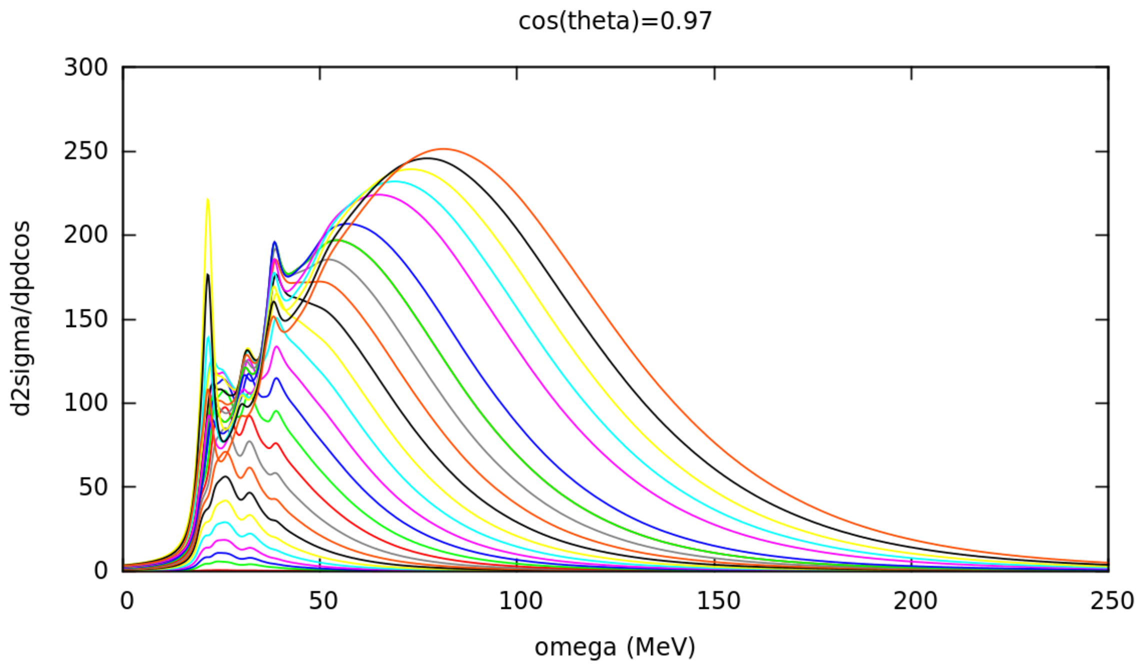
Neutrino-scattering data are from:

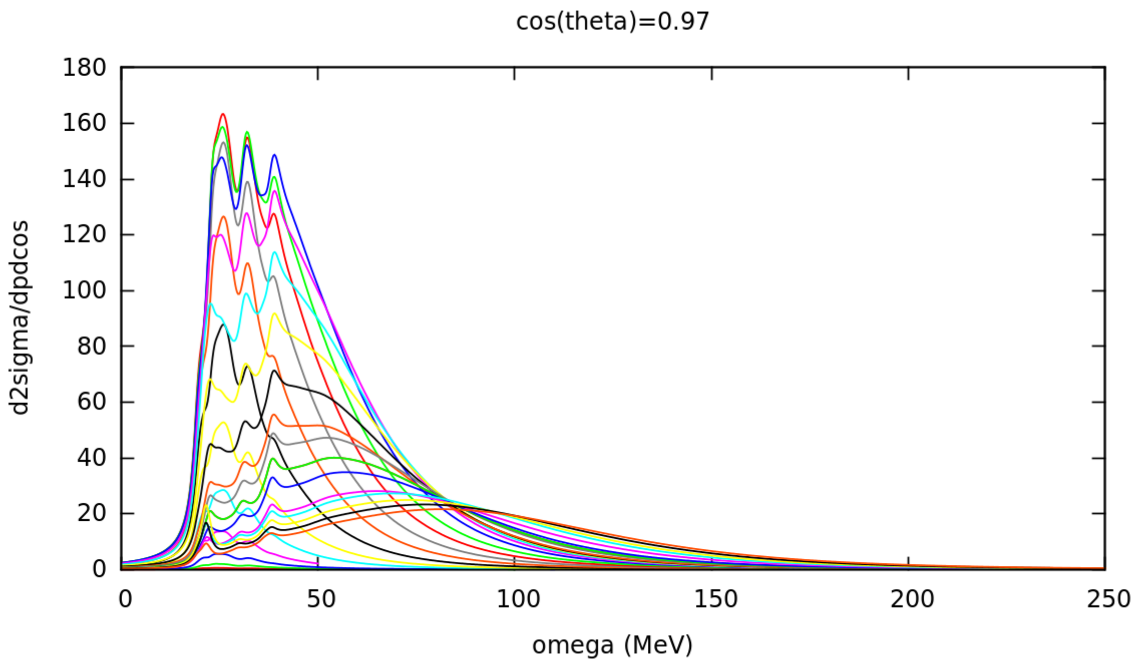
[1] A. A. Aguilar-Arevalo et al., (MiniBooNE Collaboration), Phys. Rev. D81, 092005 (2010).
[2] A. A. Aguilar-Arevalo et al., (MiniBooNE Collaboration), Phys. Rev. D88, 032001 (2013).
[3] K. Abe et al., (T2K Collaboration), Phys. Rev. D87, 092003 (2013).
[4] K. Abe et al., (T2K Collaboration), Phys. Rev. D92, 112003 (2015).

Back-up


cos(theta)=0.97
d2sigma/dpdcos
pmu (MeV/c)
0
50
100
150
200
250
300
350
0
200
400
600
800
1000
1200
1400


cos(theta)=0.97
d2sigma/dpdcos
pmu (MeV/c)
0
20
40
60
80
100
120
140
160
180
0
200
400
600
800
1000
1200
1400


cos(theta)=0.97
d2sigma/dpdcos
omega (MeV)
0
50
100
150
200
250
300


cos(theta)=0.97
d2sigma/dpdcos
omega (MeV)
0
20
40
60
80
100
120
140
160
180
50
150
200
250