Consistency between low and high energy models

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Testing and improving models of neutrino nucleus interactions in generators,
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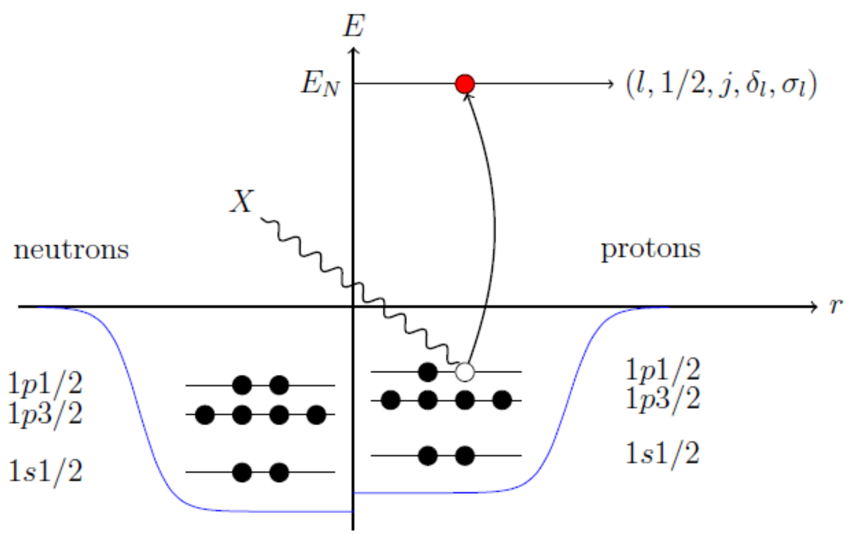
Outline

I. Description of the Ghent CRPA model

II. The influence of forbidden transitions in charged current scattering on Argon

III. Differences between electron and muon neutrino cross sections

The mean field approach (briefly)



The mean field potential and bound states are obtained in a self-consistent Hartree-Fock calculation with a realistic nucleon-nucleon force

All bound and scattering states are obtained by solving the Schrödinger (or Dirac) equation in a central mean field potential.

This means all states are consistent and orthogonal within this approach.

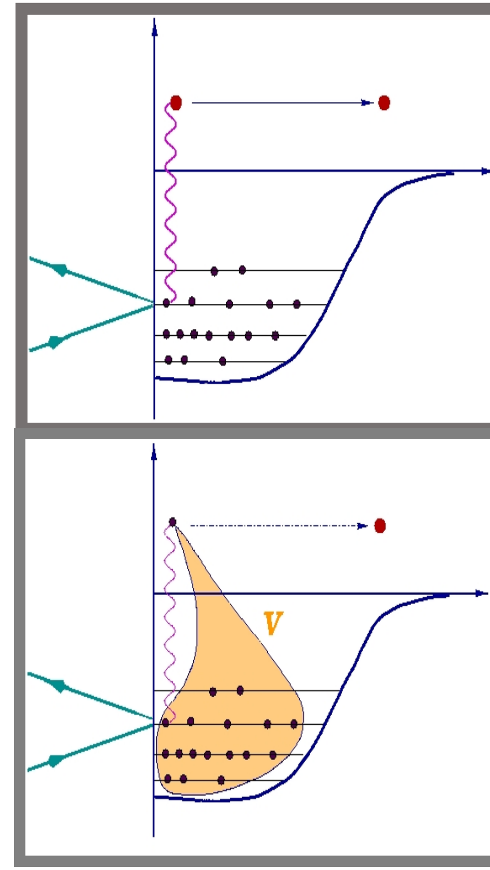
Naturally includes:

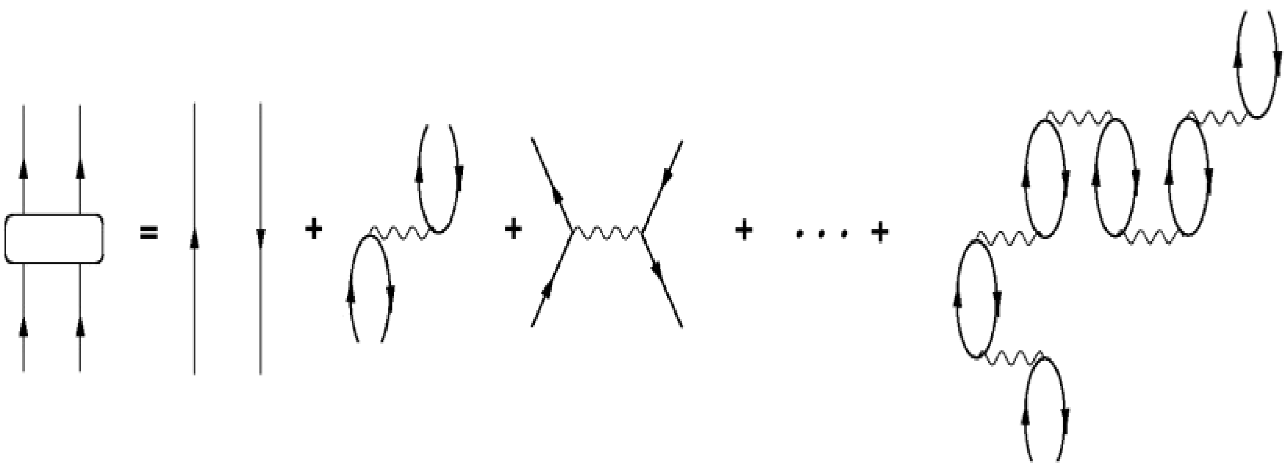
Binding
Fermi motion
Elastic Final state interactions
Pauli blocking
orthogonality

This approach captures the main nuclear effects in a consistent quantum mechanical way

Long-range correlations : Continuum RPA

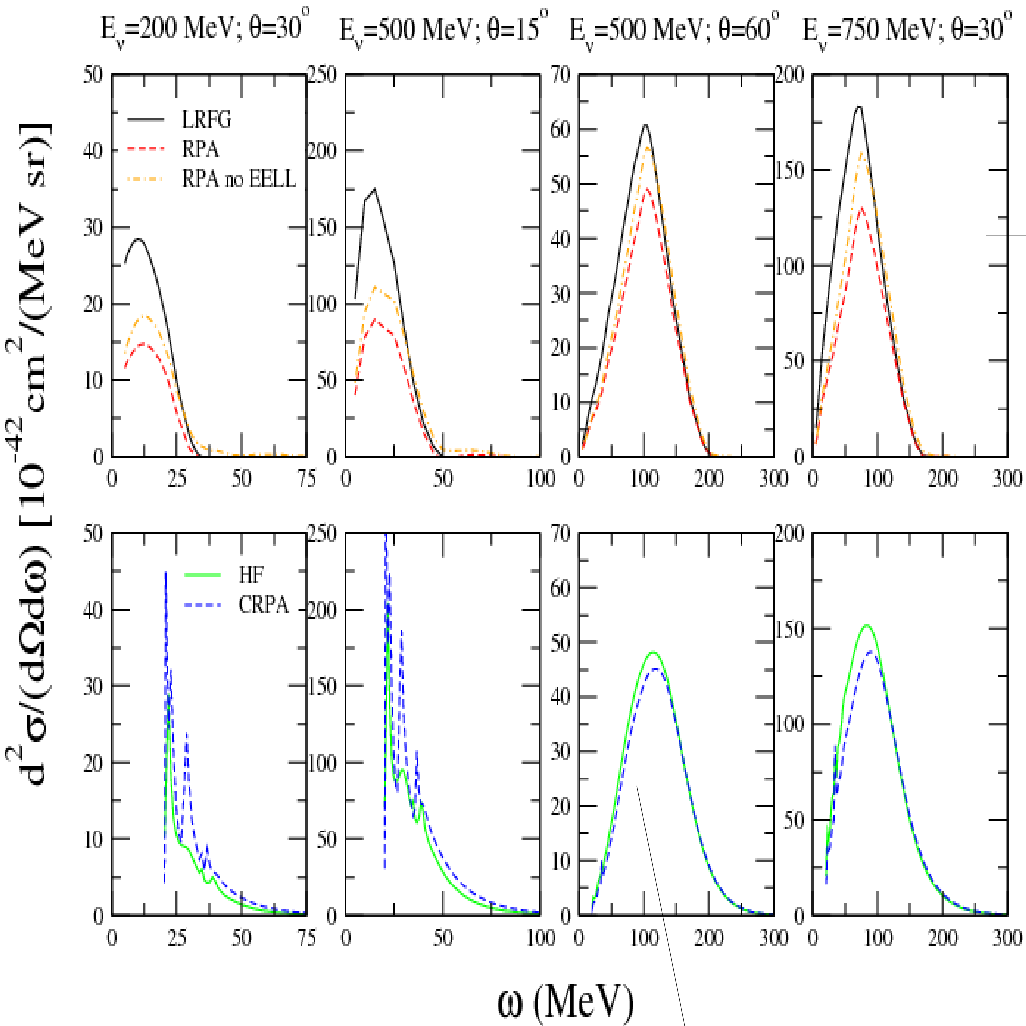
- Green's function approach
- Skyrme SkE2 residual interaction
- self-consistent calculations





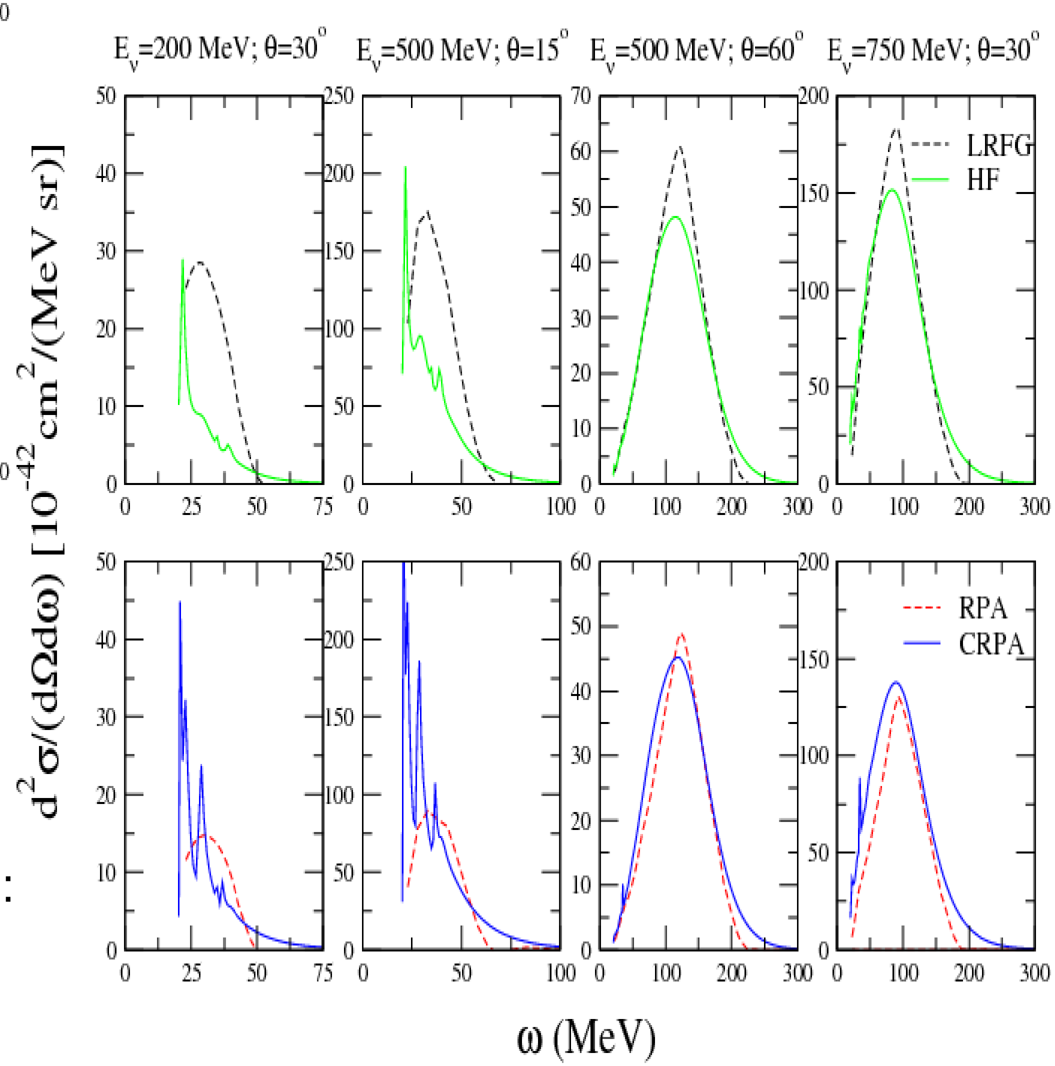
$$|\Psi_{RPA}\rangle = \sum_{c} \left\{ X_{(\Psi,C)} \left|ph^{-1}\right\rangle - Y_{(\Psi,C)} \left|hp^{-1}\right\rangle \right\} + \dots$$

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



- Start from (basically) free initial and final states

→ Large effect of RPA is needed to introduce interactions



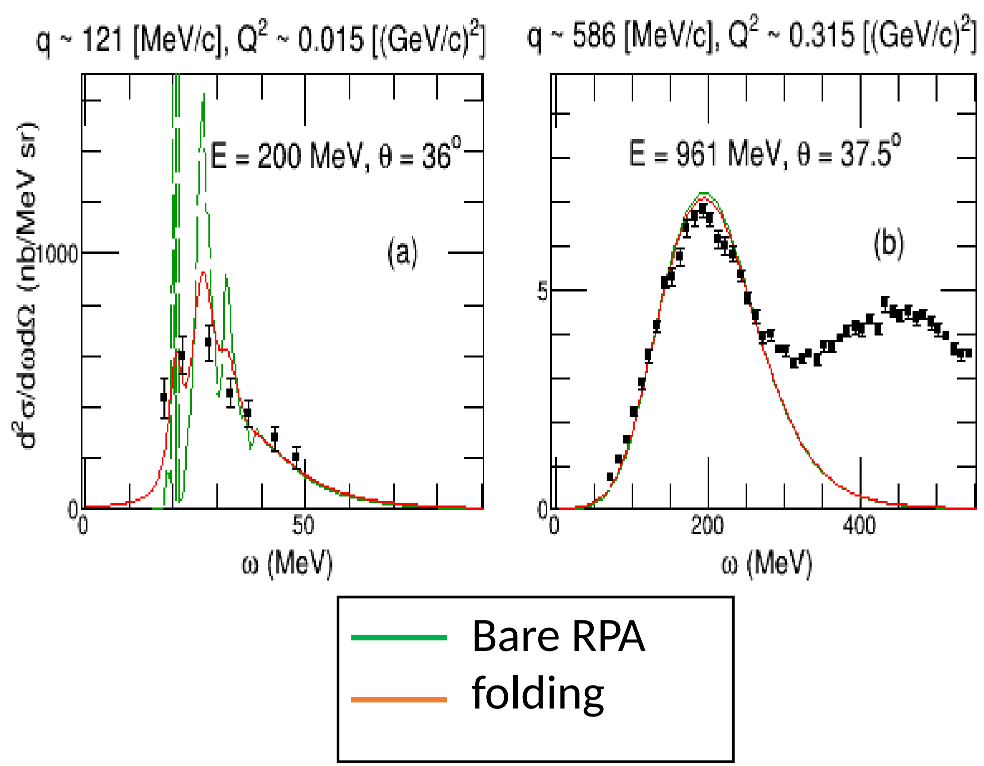
- MF initial and final states

→ Effect of RPA is smaller

Eventually the models 'converge':

Final state interactions

-Calculations of the wave function of the outgoing nucleon in the same (real) nuclear potential used for the initial state
-influence of the spreading width of the particle states is implemented through a folding procedure



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

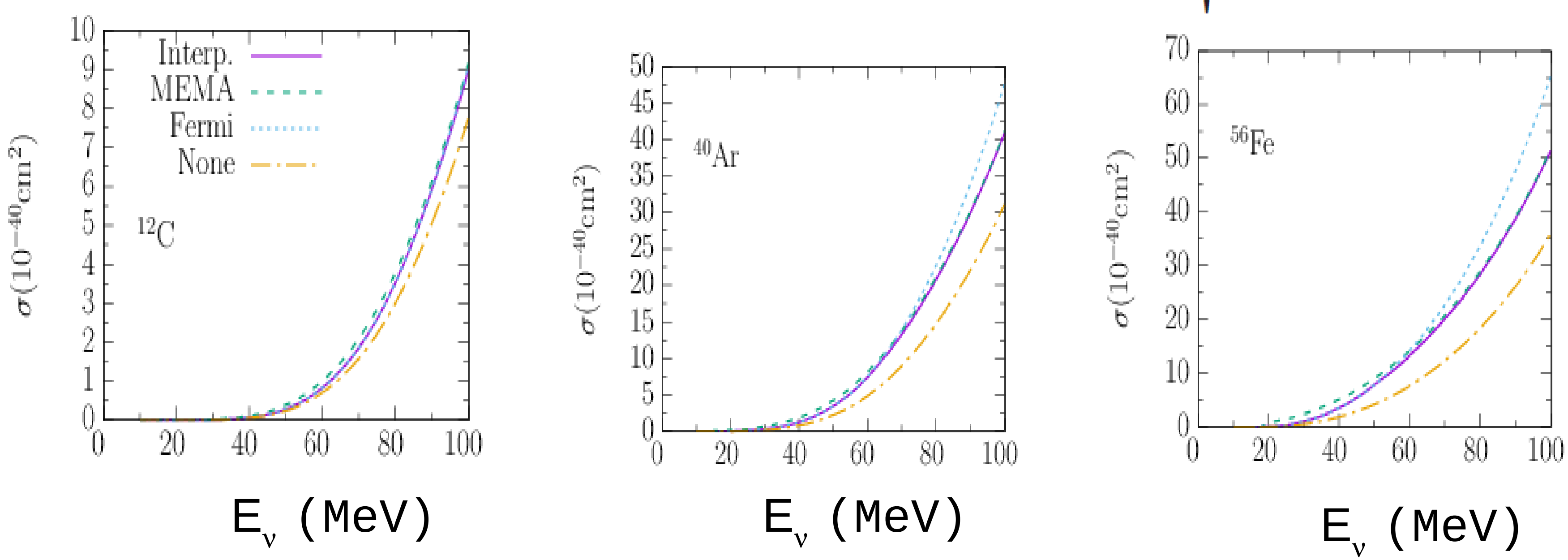
$$L(\omega,\omega') = \frac{1}{2\pi}\left[\frac{\Gamma}{(\omega-\omega')^2 + (\Gamma/2)^2}\right].$$

Coulomb corrections

- ✓ Low energies : Fermi function (s-wave correction factor) $F(Z',E) = \frac{2\pi\eta}{1-e^{-2\pi\eta}}$ $\qquad \eta \sim \mp Z'\alpha$
- ✓ High energies : modified effective momentum approximation (J. Engel, PRC57,2004 (1998))

$$q_{eff} = q + 1.5\left(\frac{Z'\alpha\hbar c}{R}\right), \qquad \Psi_l^{eff} = \zeta(Z',E,q)\,\Psi_l\,,$$

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



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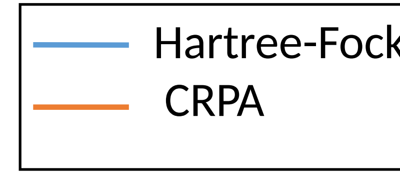
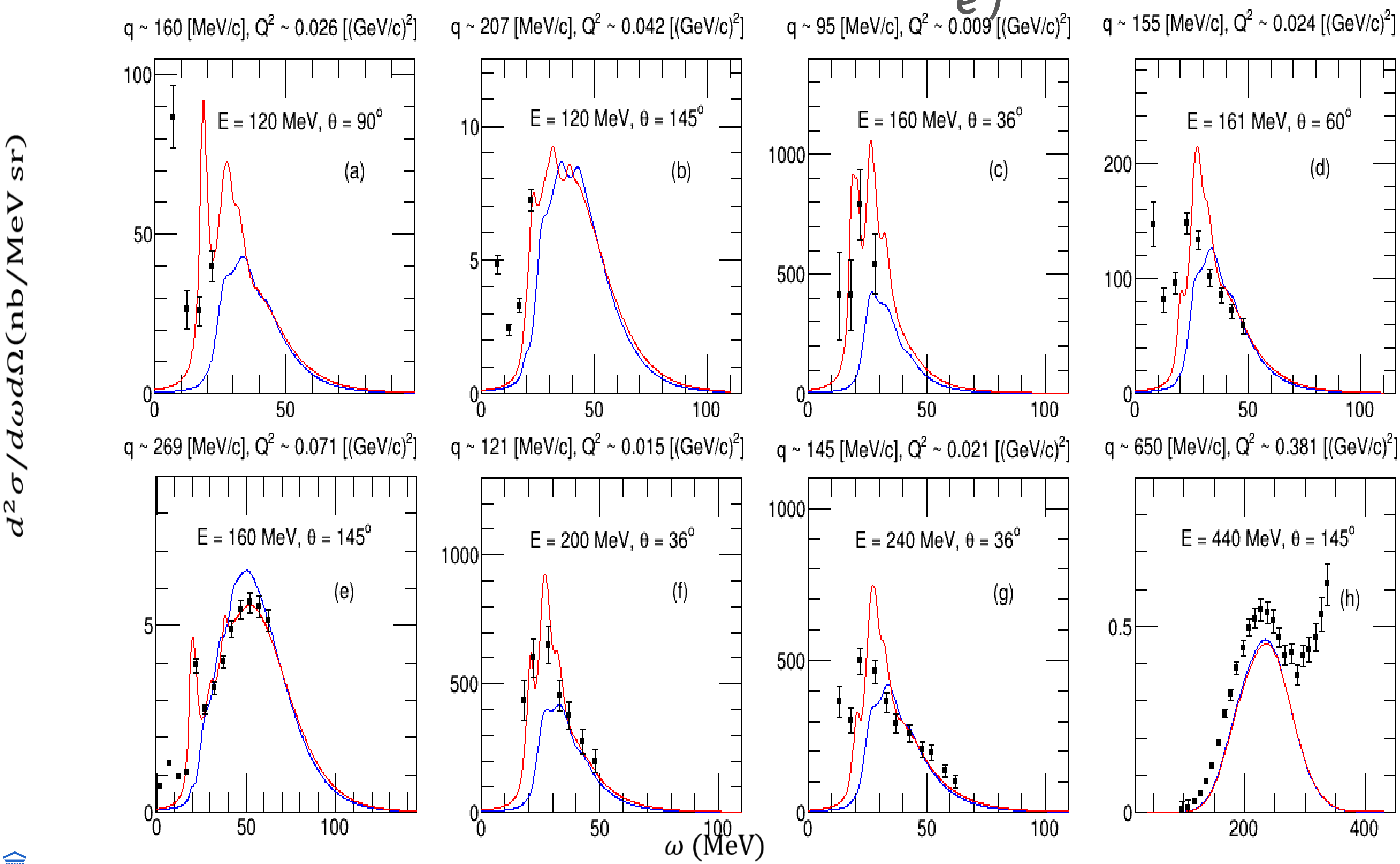
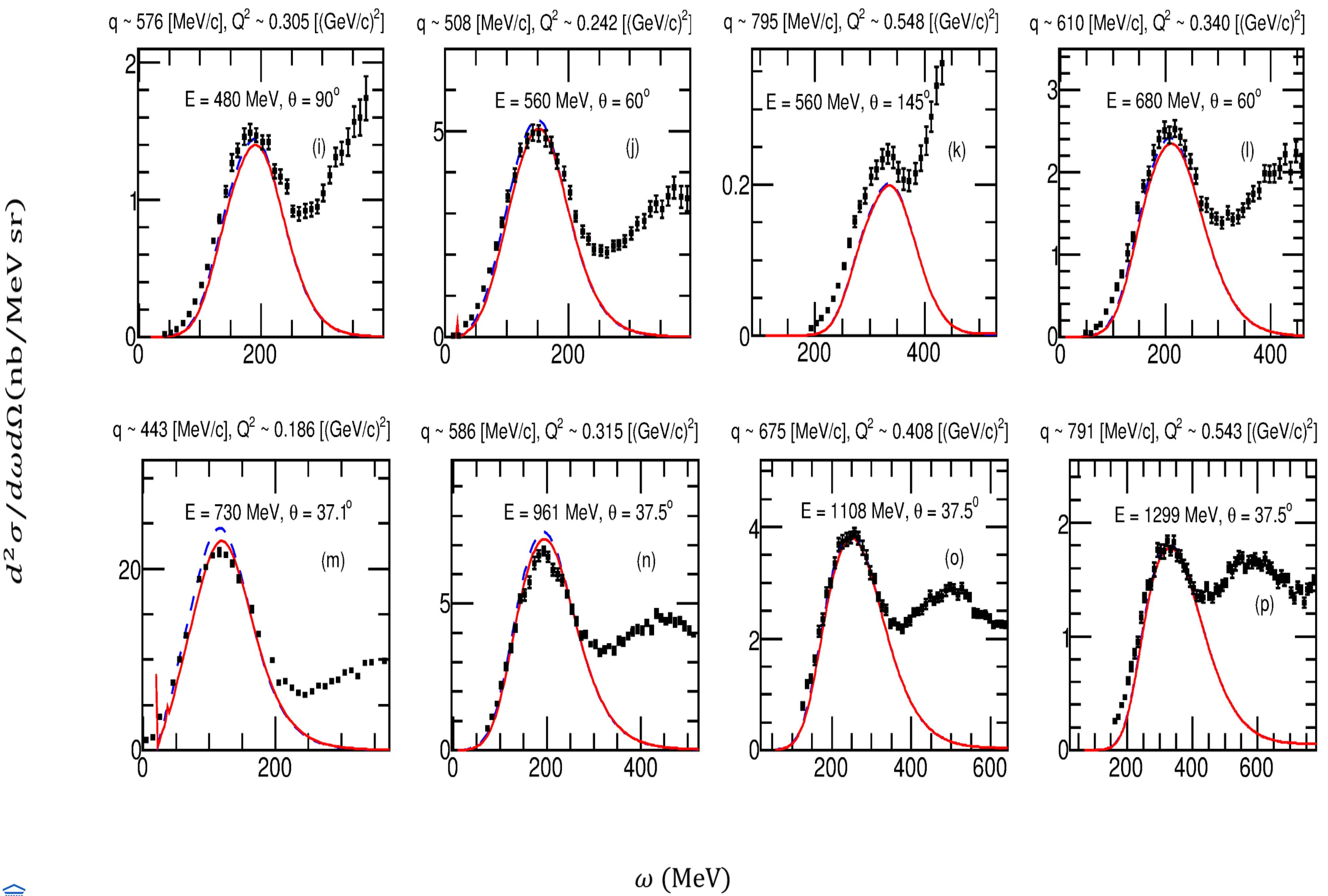
CRPA : Comparison with electron scattering data



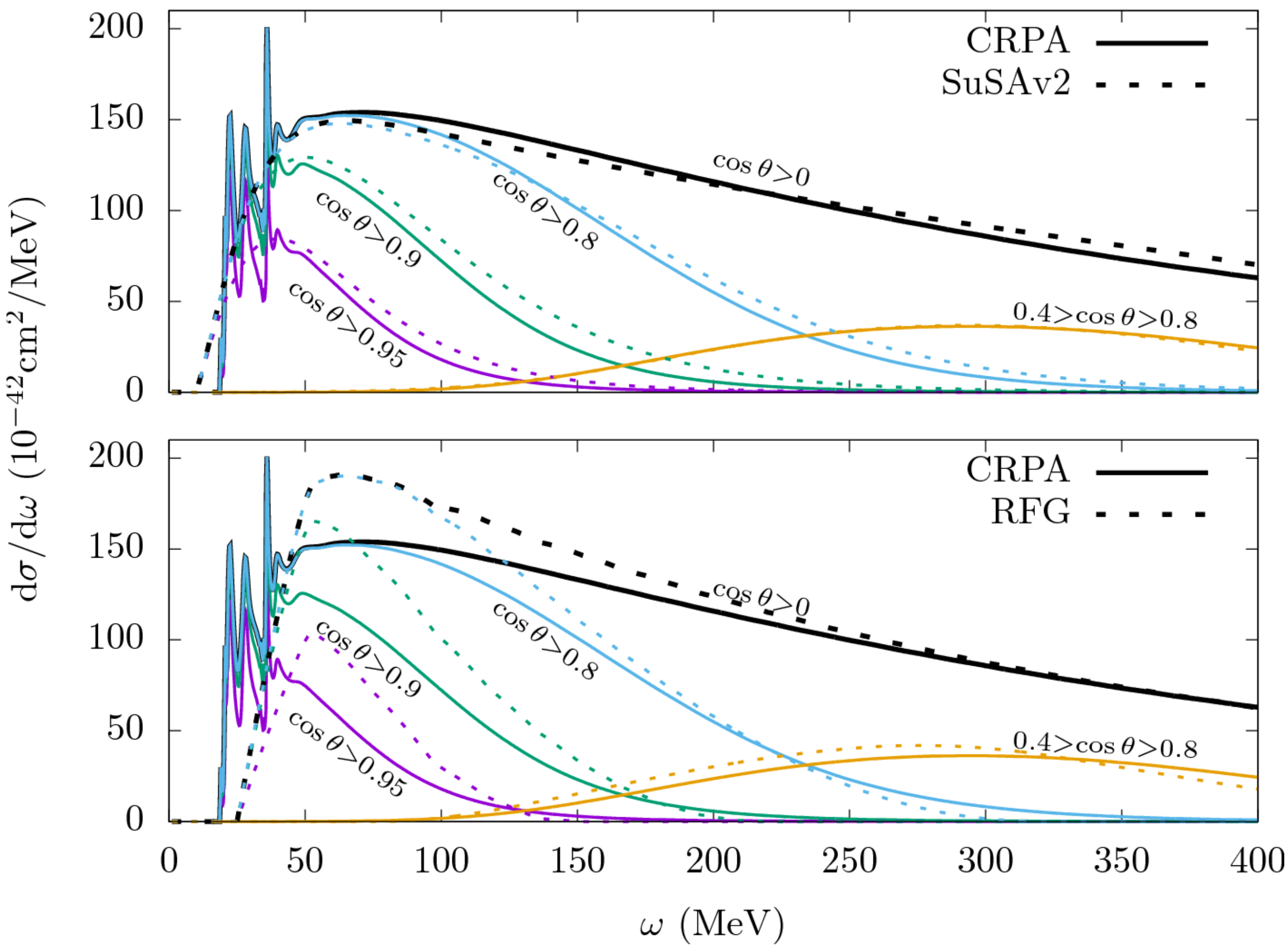
$^{12}C(e, e')$





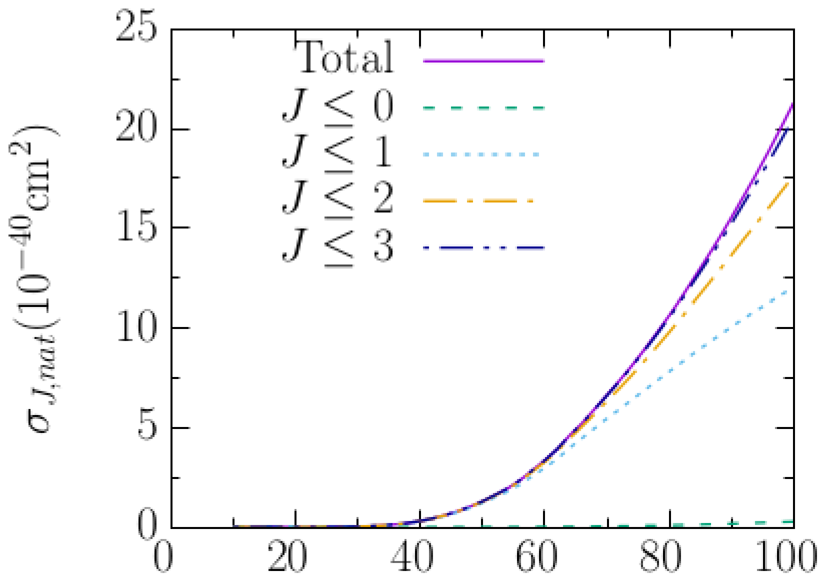
q ~ 576 [MeV/c], Q2 ~ 0.305 [(GeV/c)2]
E = 480 MeV, θ = 90°
(i)
q ~ 508 [MeV/c], Q2 ~ 0.242 [(GeV/c)2]
E = 560 MeV, θ = 60°
(j)
q ~ 795 [MeV/c], Q2 ~ 0.548 [(GeV/c)2]
E = 560 MeV, θ = 145°
(k)
q ~ 610 [MeV/c], Q2 ~ 0.340 [(GeV/c)2]
E = 680 MeV, θ = 60°
(l)
q ~ 443 [MeV/c], Q2 ~ 0.186 [(GeV/c)2]
E = 730 MeV, θ = 37.1°
(m)
q ~ 586 [MeV/c], Q2 ~ 0.315 [(GeV/c)2]
E = 961 MeV, θ = 37.5°
(n)
q ~ 675 [MeV/c], Q2 ~ 0.408 [(GeV/c)2]
E = 1108 MeV, θ = 37.5°
(o)
q ~ 791 [MeV/c], Q2 ~ 0.543 [(GeV/c)2]
E = 1299 MeV, θ = 37.5°
(p)
d²σ/dωdΩ(nb/MeV sr)
ω (MeV)

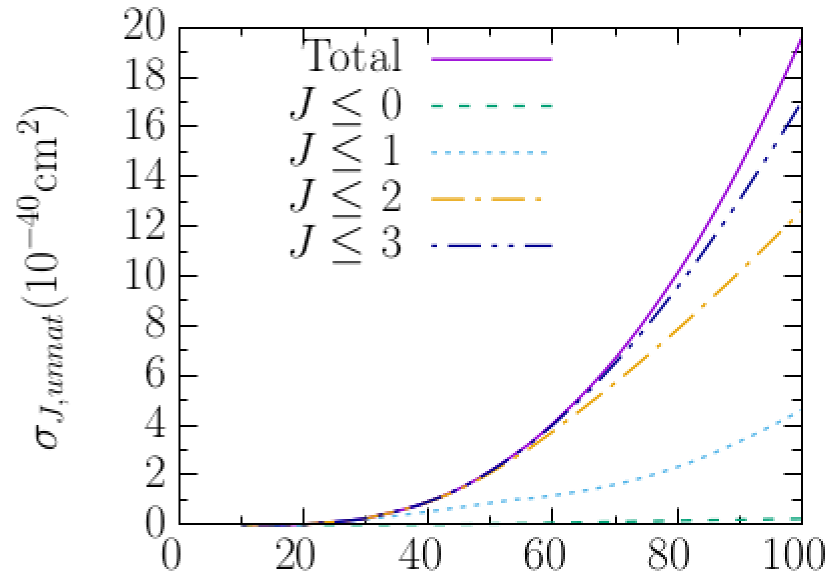
Low energy excitations at higher E_ν



CRPA takes into account in a satisfactory way the nuclear response for QE starting from low to intermediate ω and q

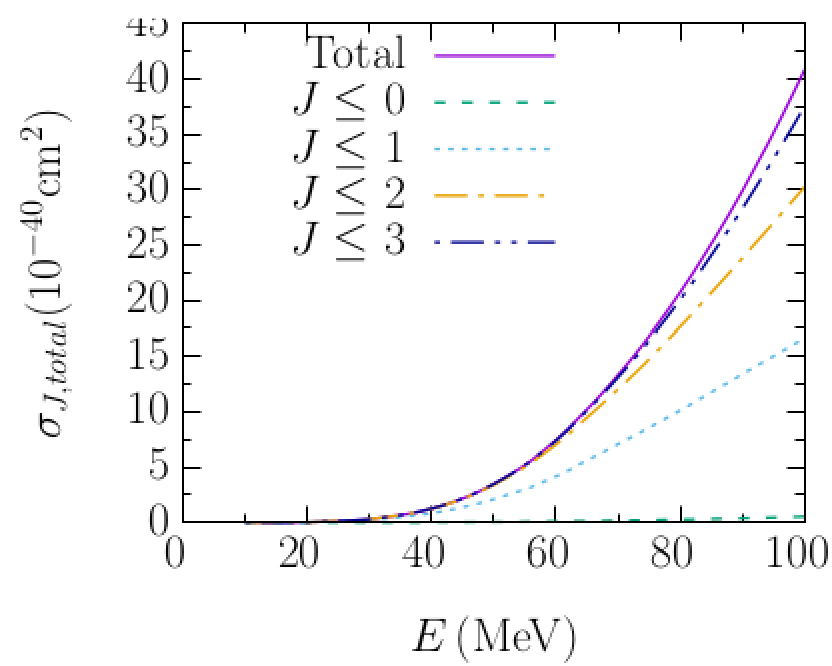
Multipole contributions to total CS

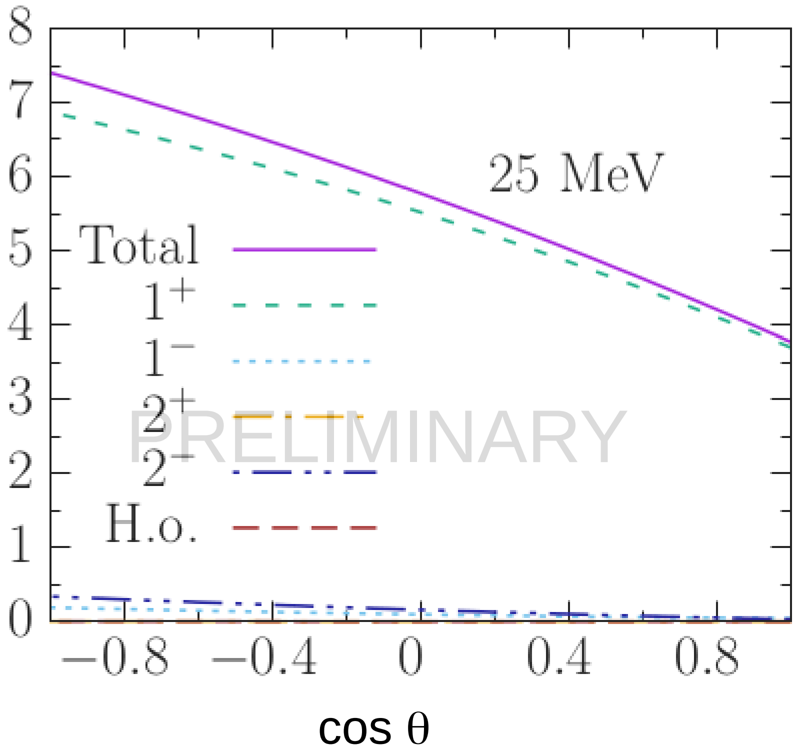


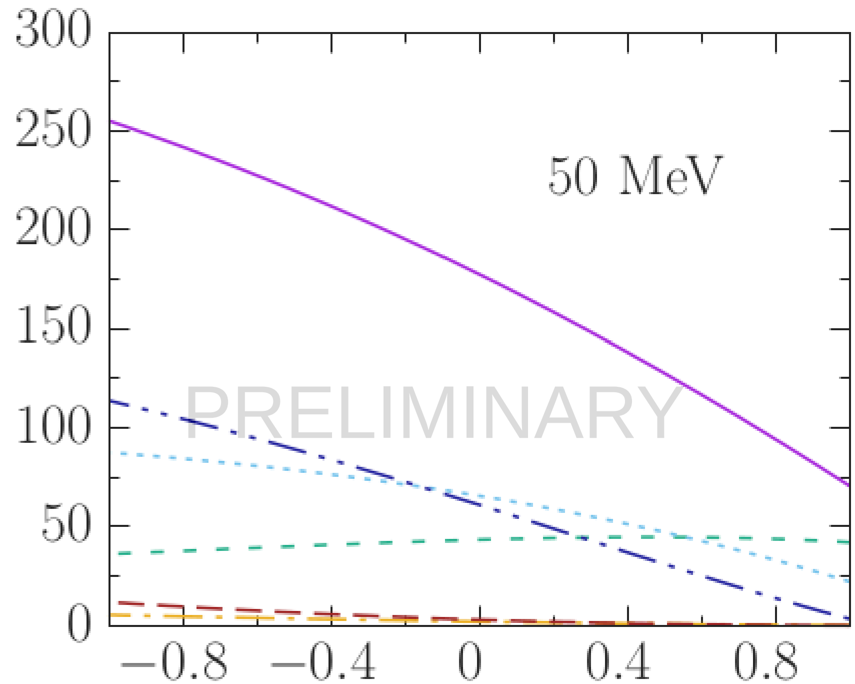


CC scattering of electron neutrinos neutrinos scattering on Argon.
Different multipoles shown cumulatively.

Forbidden transitions carry significant strength for continuum excitations!



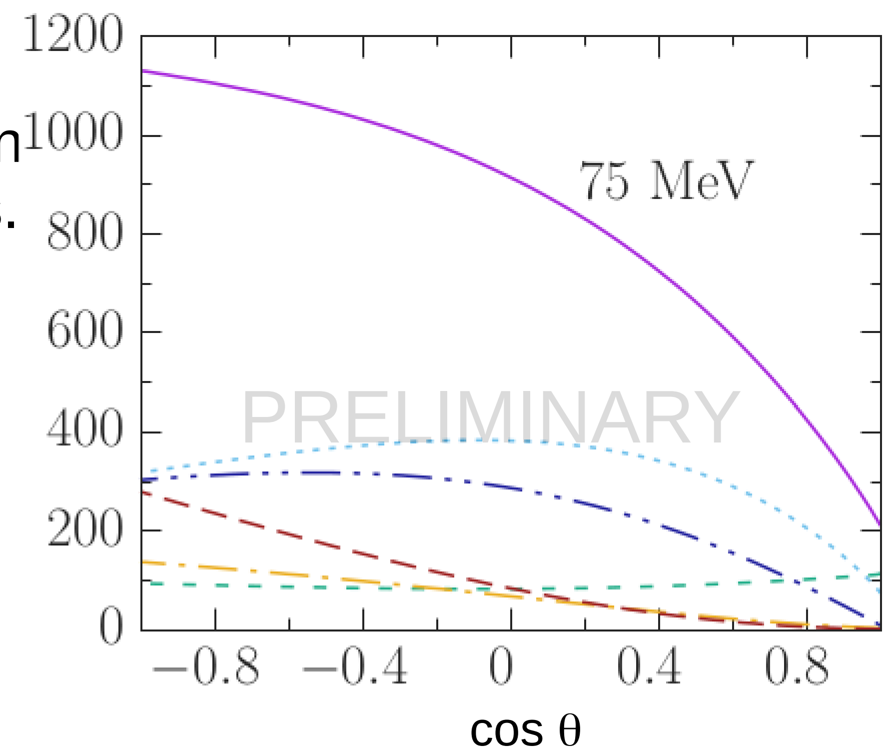


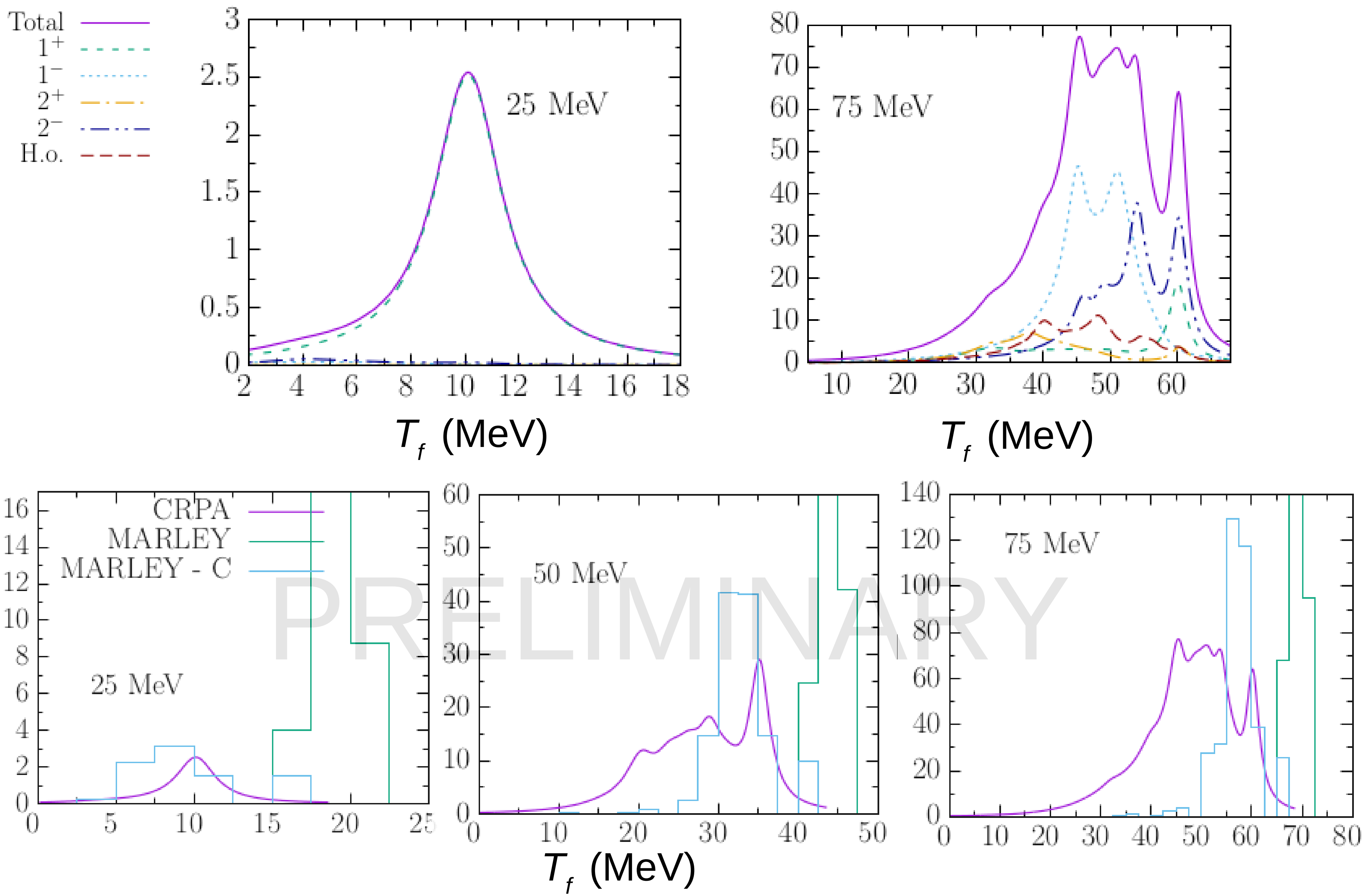


CC scattering of electron neutrino on argon at different incoming energies.

The angular distribution of the outgoing charged lepton for the allowed (1+) transition is flat.

Higher order multipoles heavily affect the shape of the differential cross section





The higher order multipoles give significant strength for low outgoing lepton energies

Electron versus muon neutrino induced cross sections in charged current quasi-elastic processes

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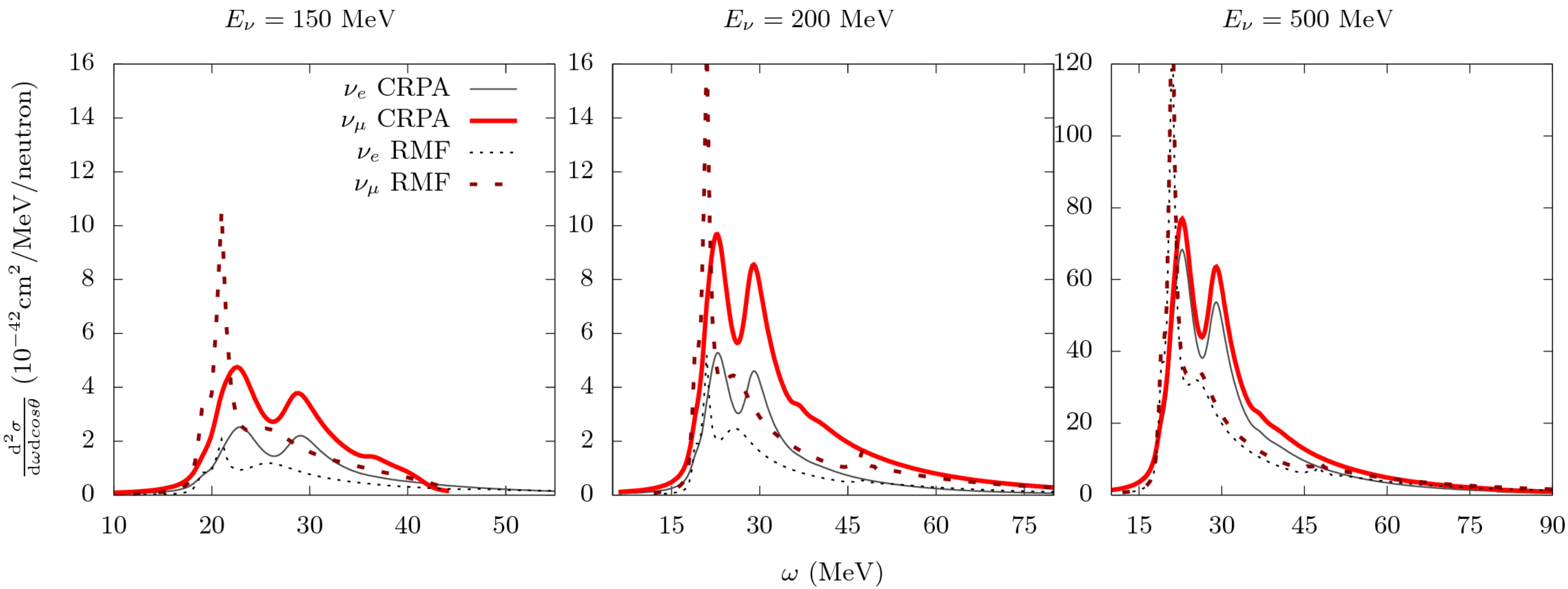
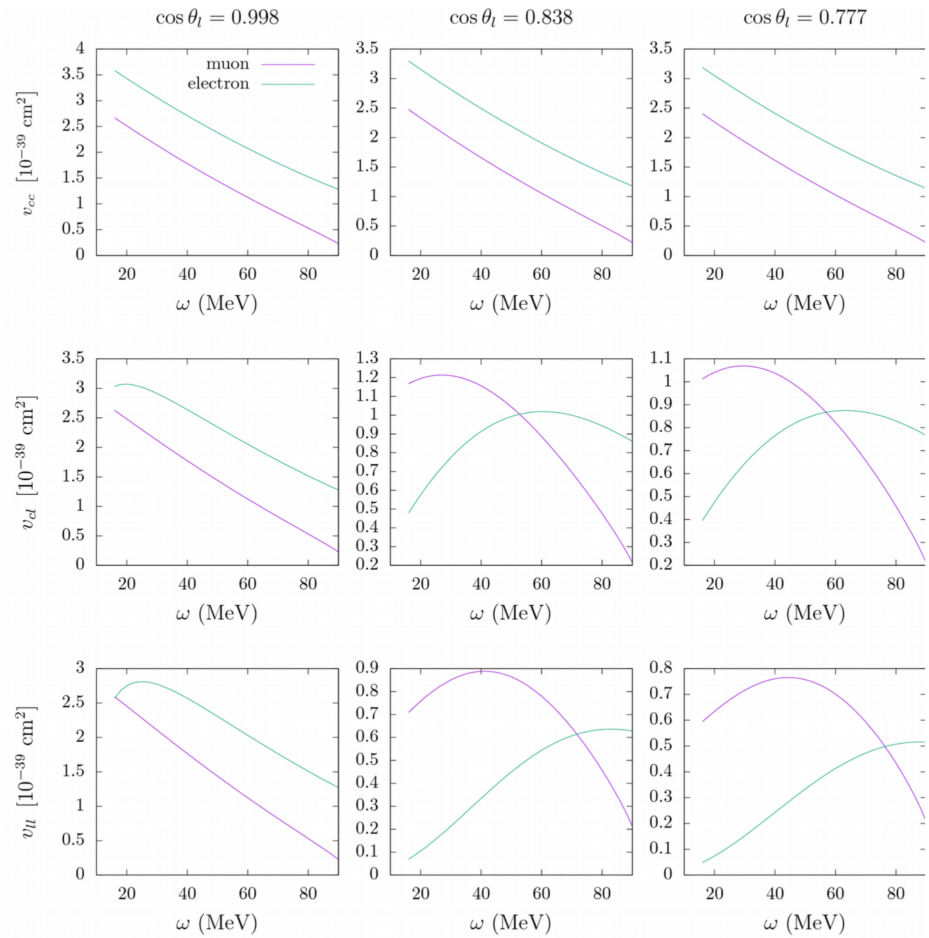


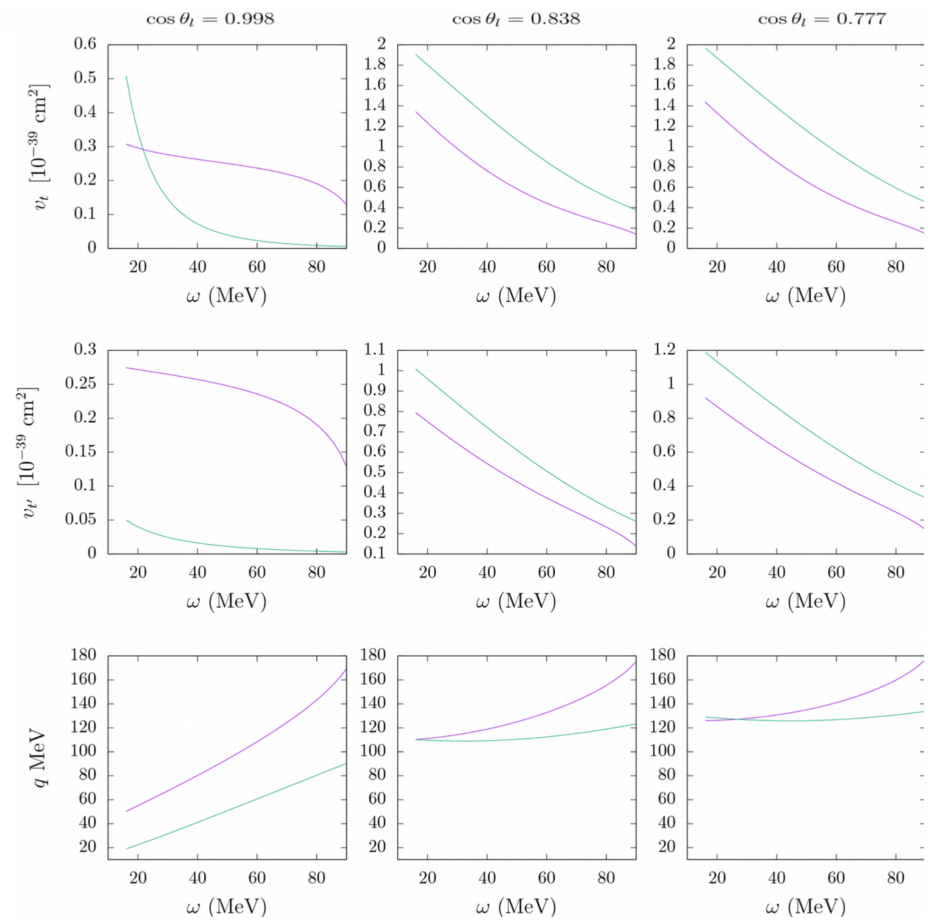
- Mean field models give larger ν_μ than ν_e cross sections for low ω and q
- Collective excitations add significant strength

Leptonic prefactors

Longitudinal

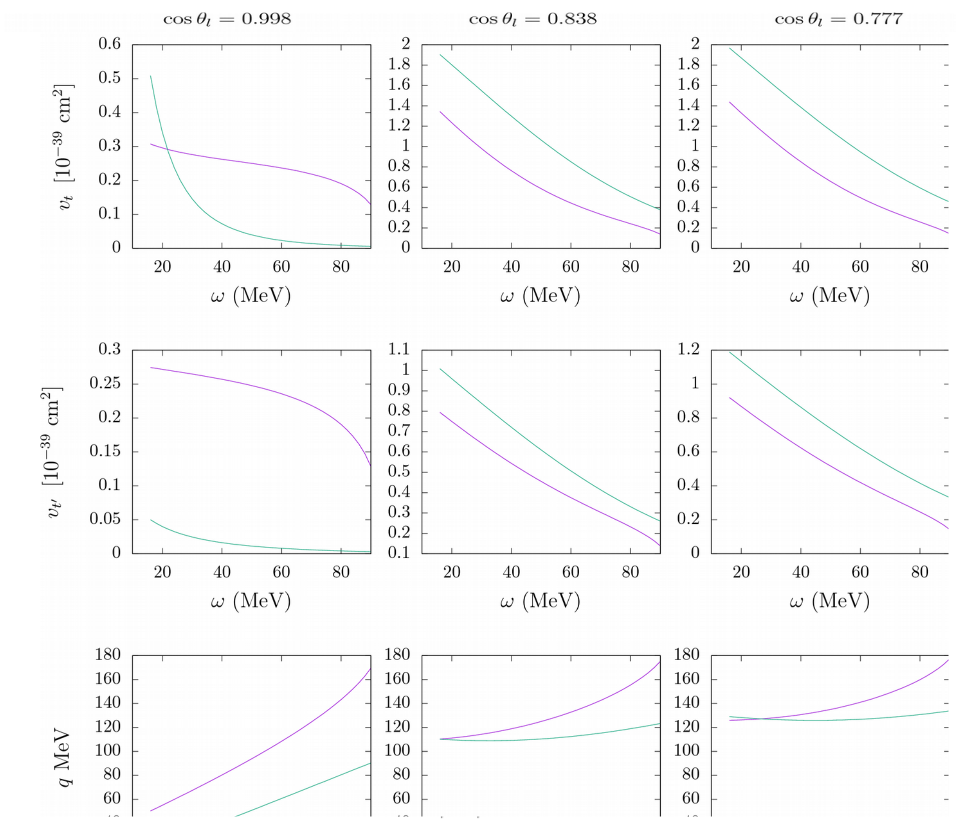


Transverse

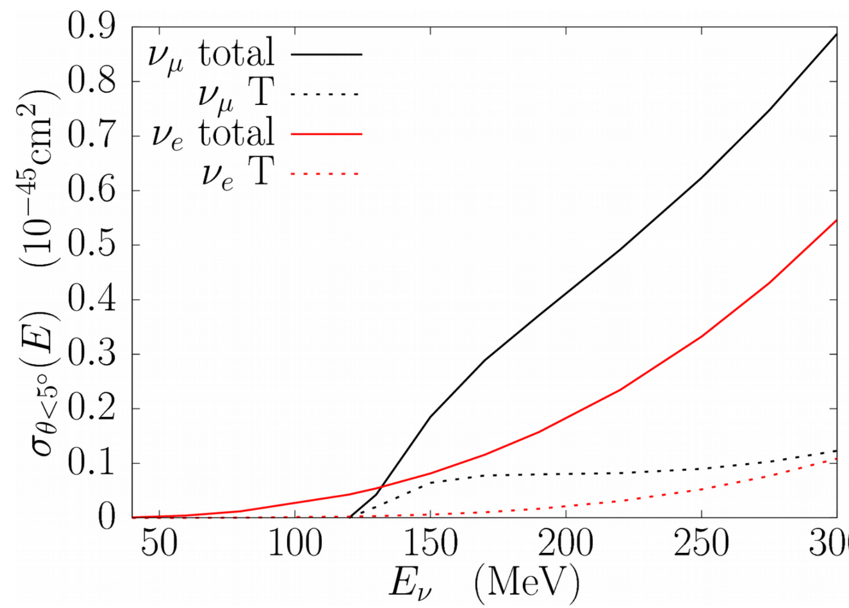


From the leptonic vertex one expects the electron neutrino to dominate

Leptonic prefactors



Caveat: close to threshold the muon gets transverse contributions.

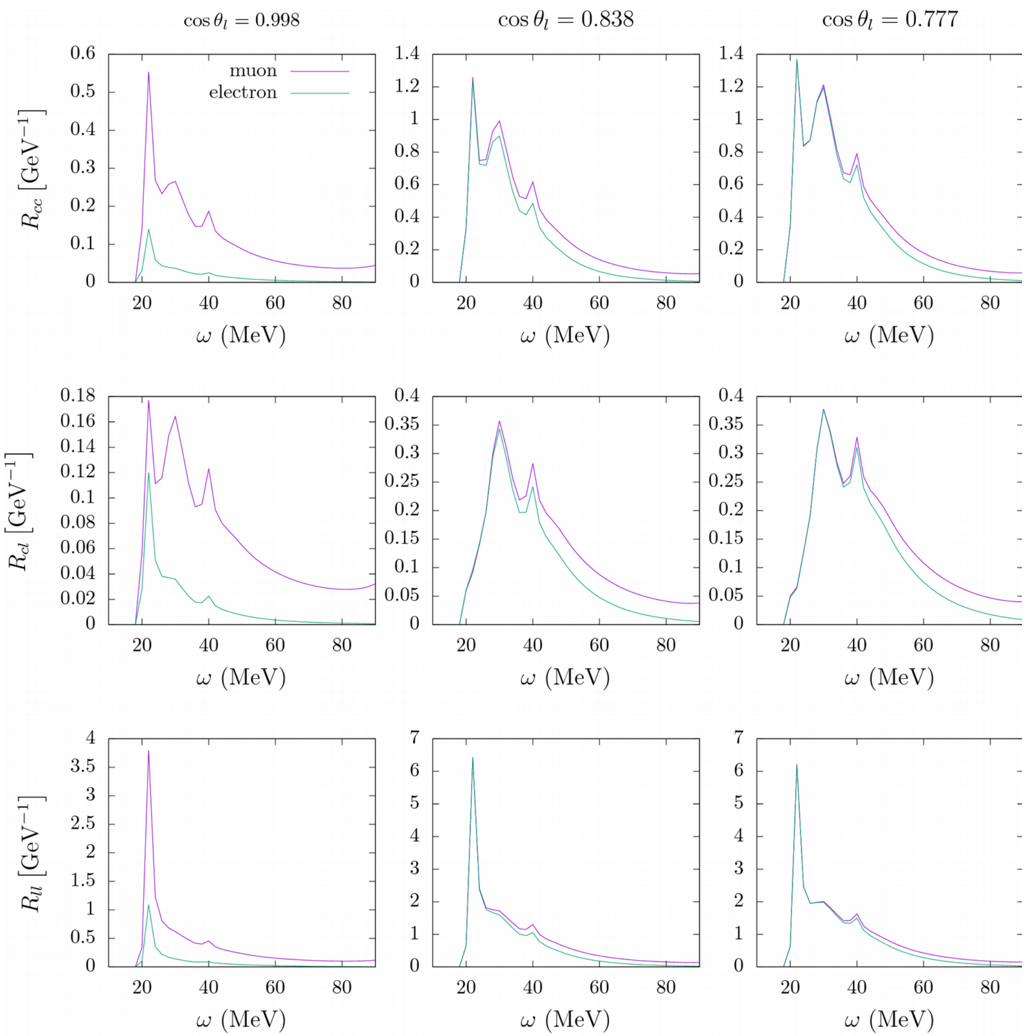


$$\omega_T W_T = \left\{ \frac{\epsilon_i k_f \sin^2\theta}{2|\vec{k}\,|^2} \cos(2\phi_F)\left(|J_{||}|^2 - |J_\perp|^2\right) + \left[\frac{\epsilon_i k_f \sin^2\theta}{2|\vec{k}\,|^2} - \frac{1}{2}\left(\frac{-\epsilon_f}{k_f} + \cos\theta\right)\right]\left(|J_{||}|^2 + |J_\perp|^2\right)\right\}$$

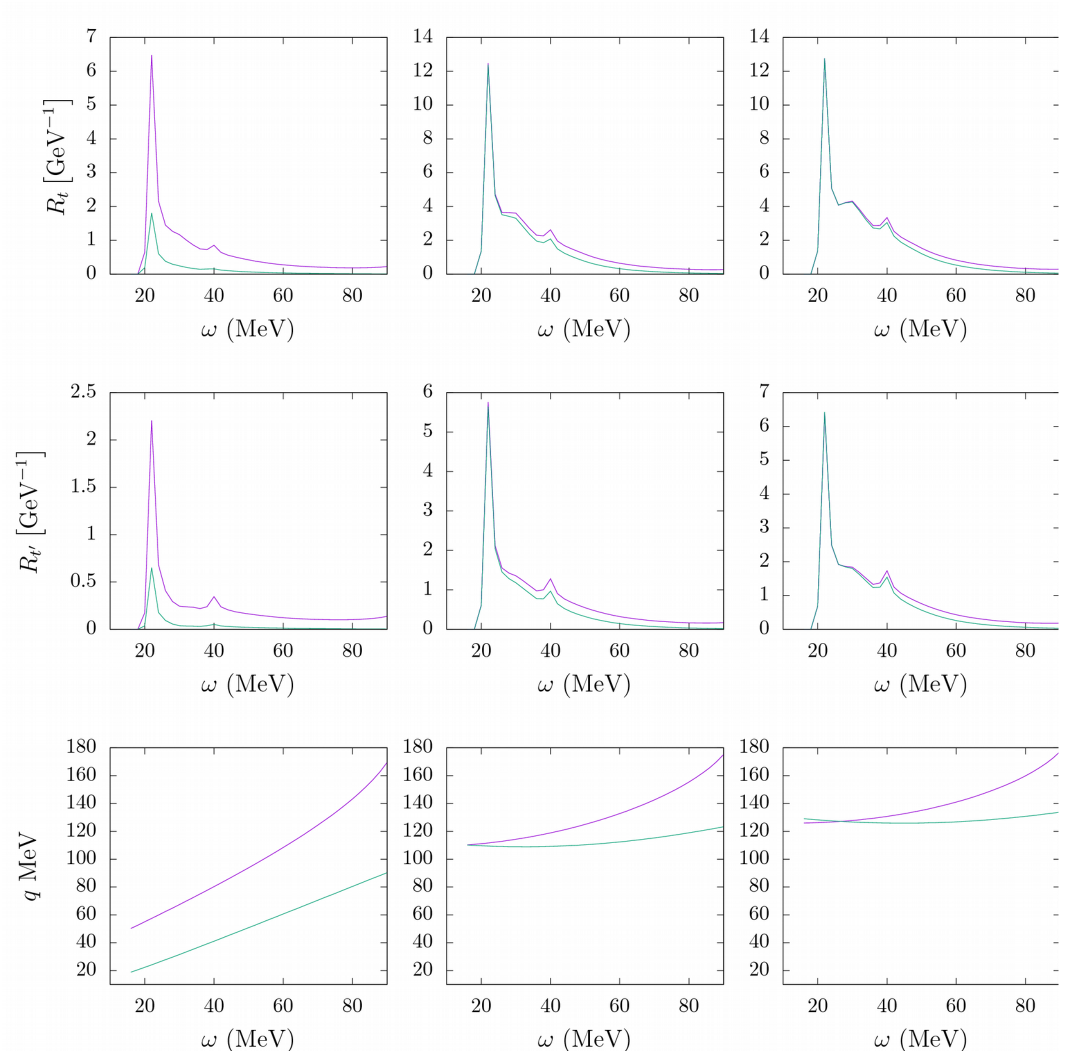
$$\omega_{TT'} W_{TT'} = -\frac{1}{|\vec{k}\,|}\left(\frac{\epsilon_i \epsilon_f}{k_f} + k_f - (\epsilon_i + \epsilon_f)\cos\theta\right) Im\left(J_{||} J_\perp^*\right)$$

Responses

Longitudinal

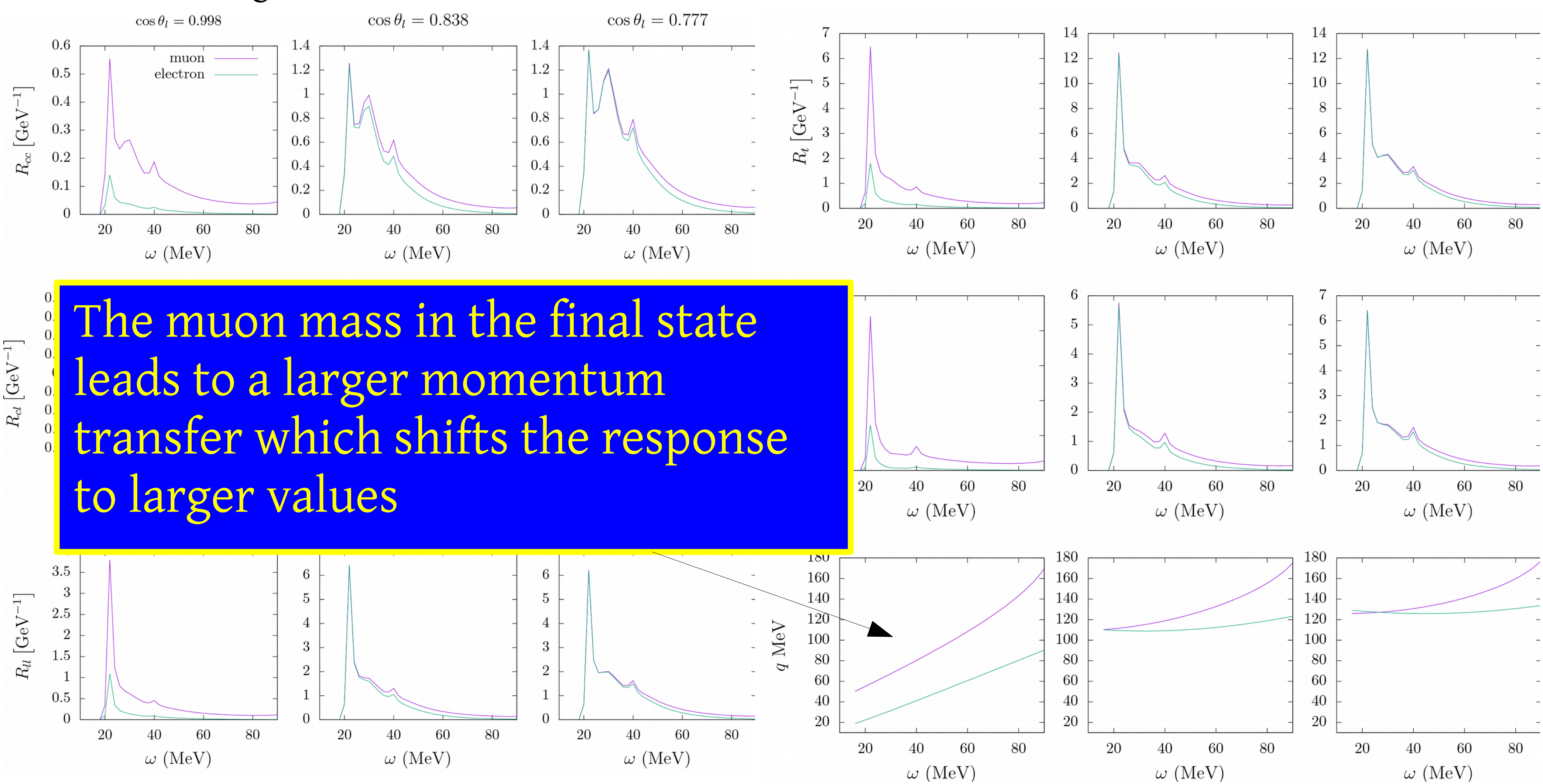


Transverse



Responses

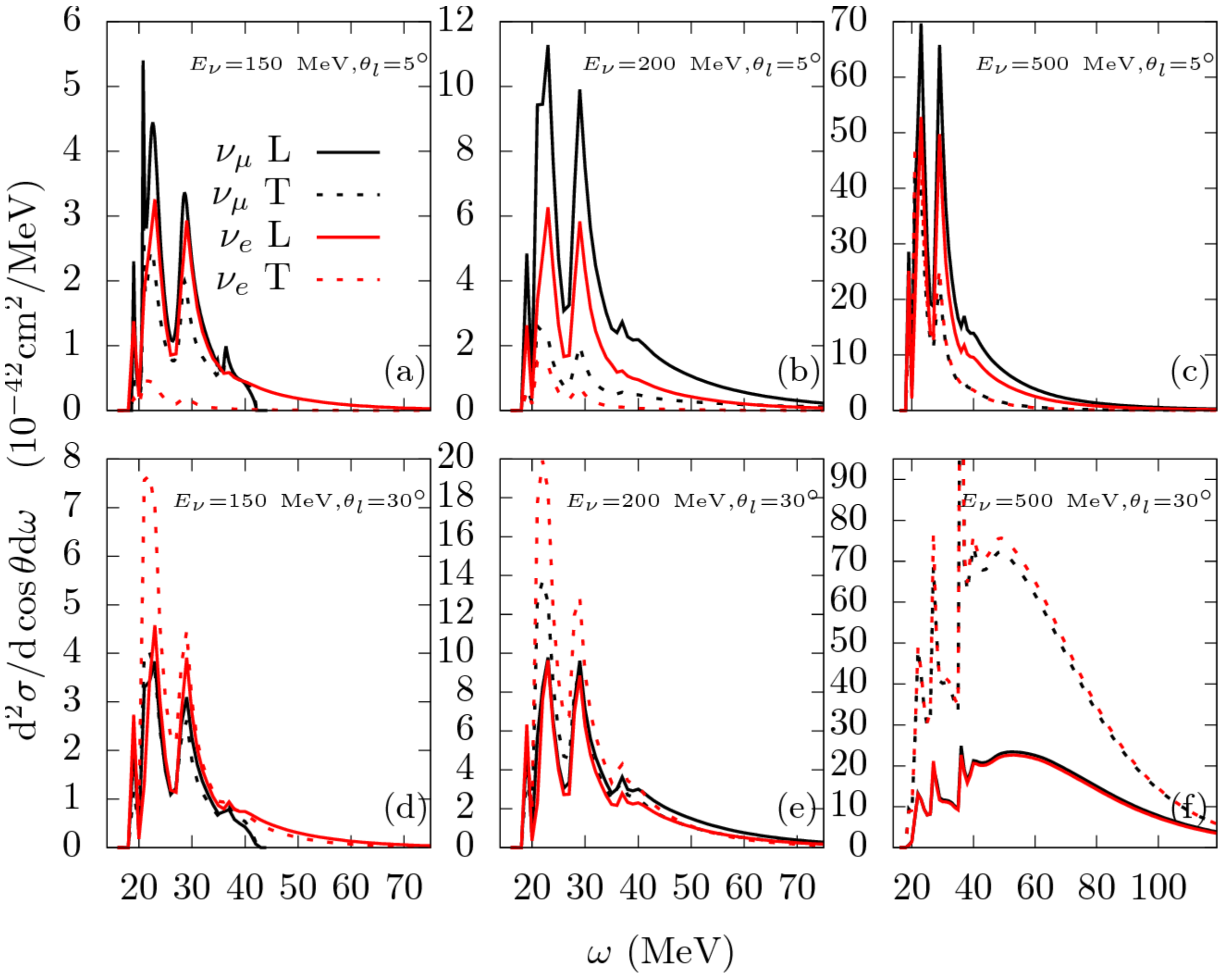
Longitudinal Transverse



The muon mass in the final state leads to a larger momentum transfer which shifts the response to larger values

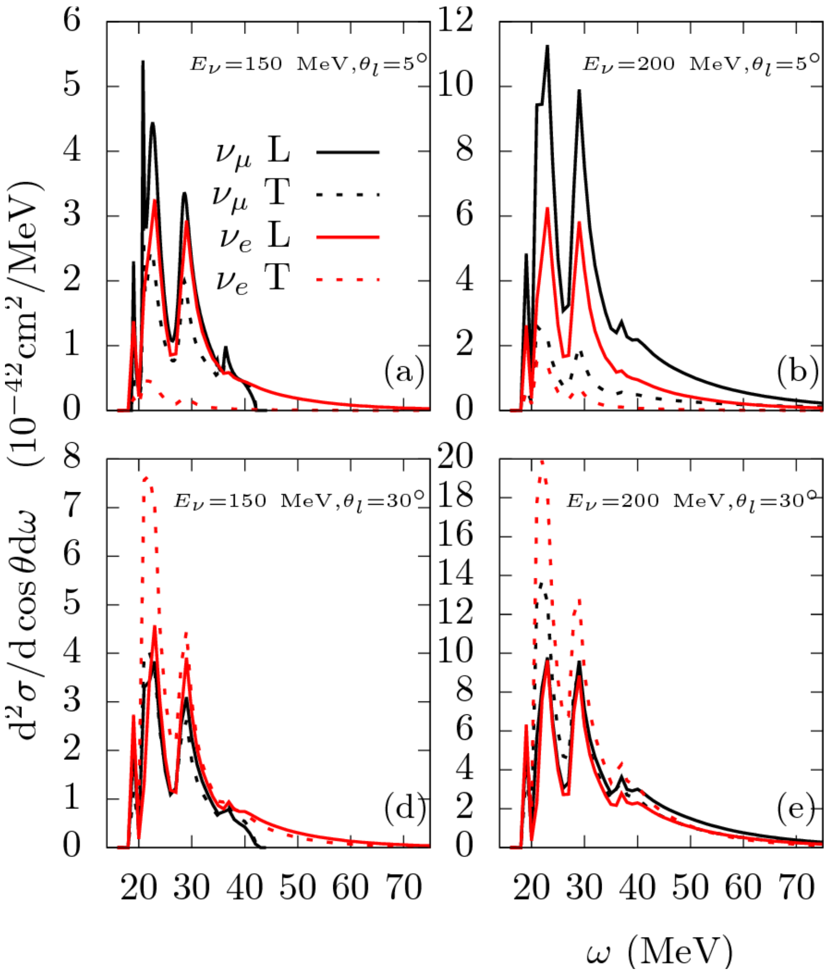
Leptonic x Responses

CRPA

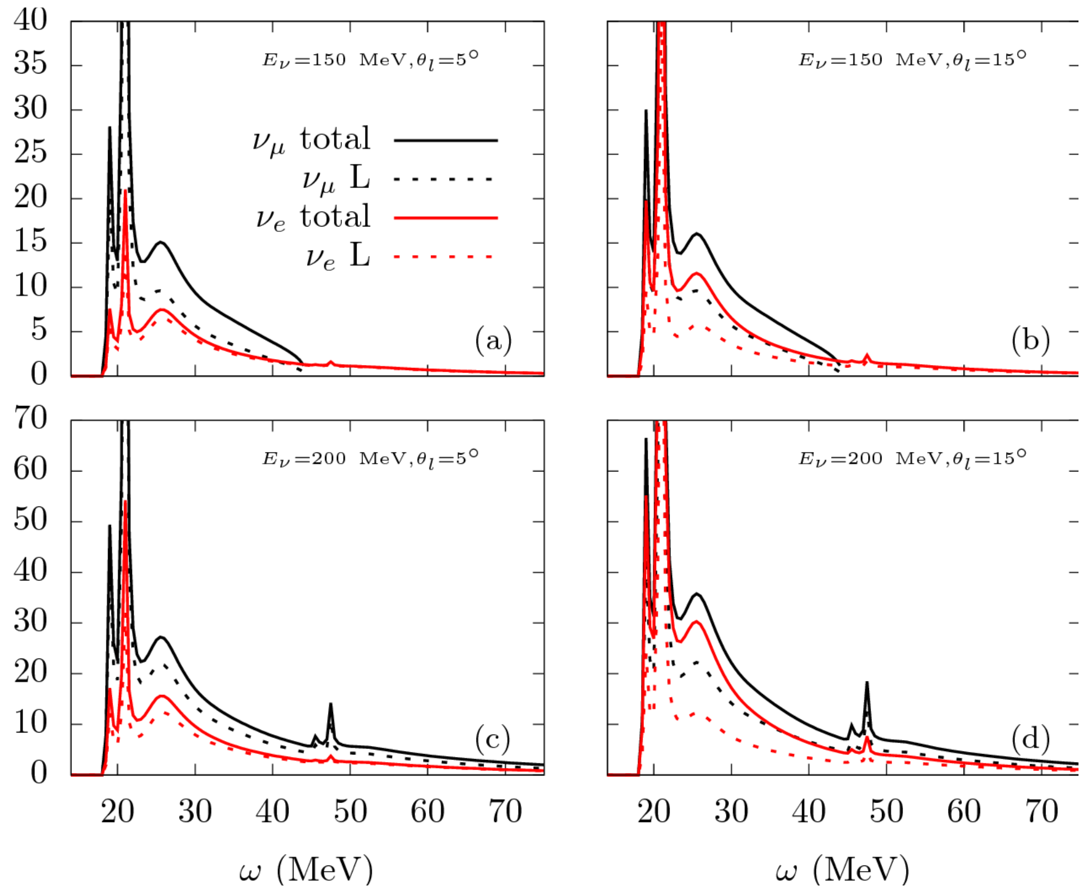


Leptonic x Responses

CRPA

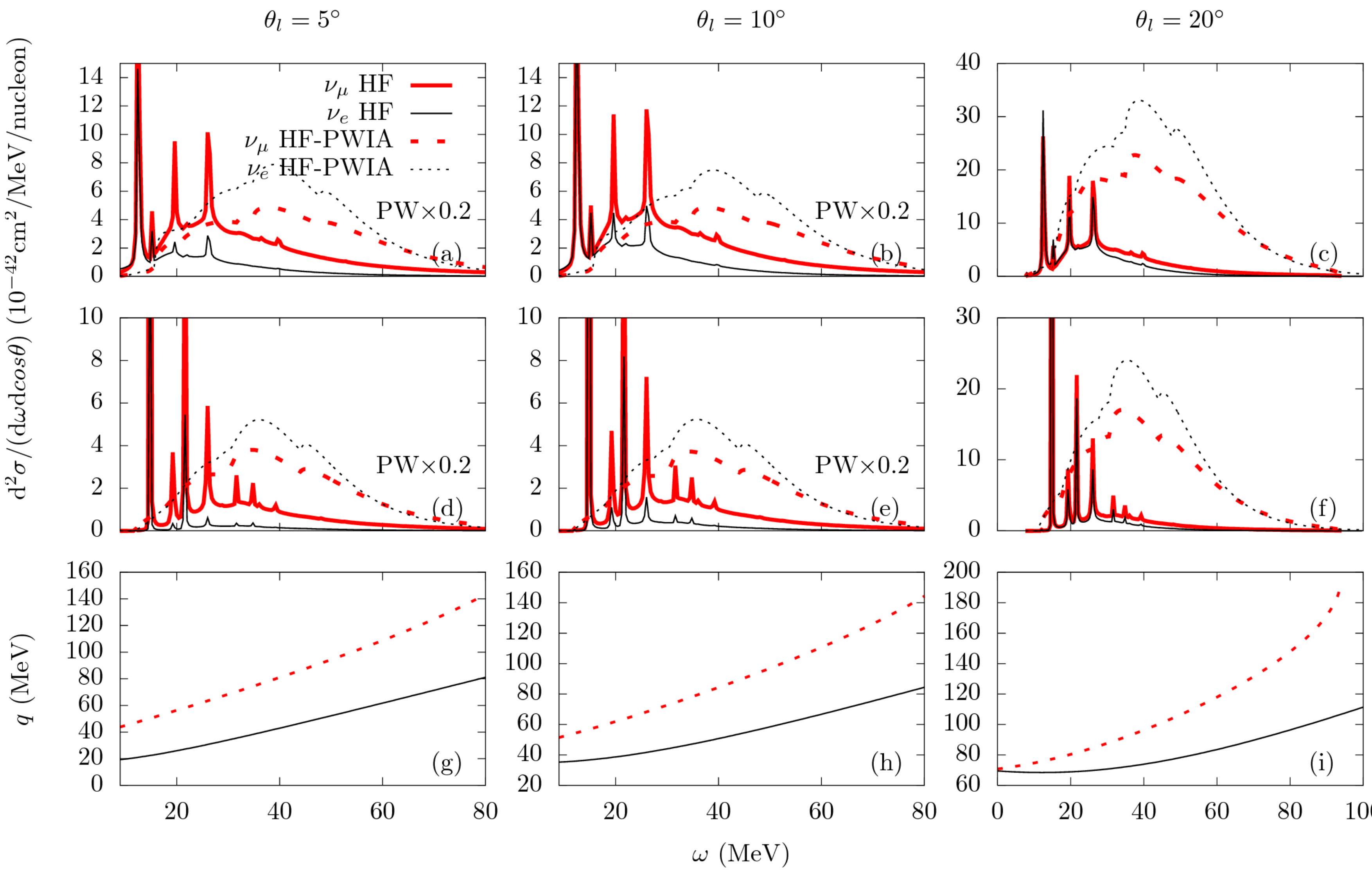


RMF



Comparison to PWIA

Large reduction at low ω and q with distorted waves



Orthogonality and Pauli-blocking

Pauli blocked RPWIA (PB-RPWIA) (arXiv:1904.10696, R. Gonzalez-Jimenez)

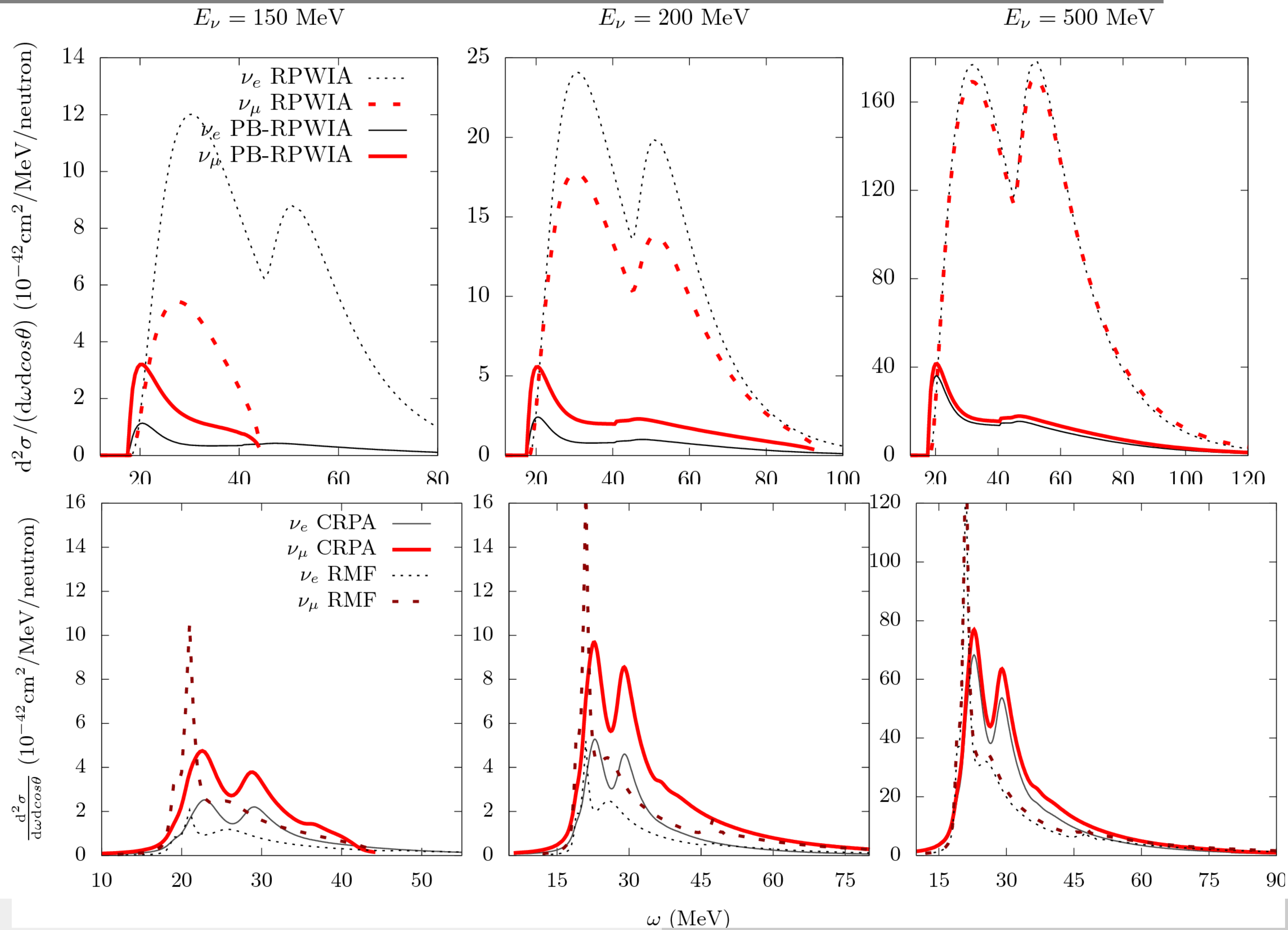
$$|\Psi^{s_N}(\mathbf{p}_N)\rangle = |\psi^{s_N}_{pw}(\mathbf{p}_N)\rangle - \sum_{\kappa,m_j} [C^{m_j,s_N}_{\kappa}(\mathbf{p}_N)]^\dagger \, |\psi^{m_j}_{\kappa}\rangle$$

$$C^{m_j,s_N}_{\kappa}(\mathbf{p}_N) = (2\pi)^{3/2}\sqrt{\frac{M}{VE_N}} \times u(\mathbf{p}_N, s_N)^\dagger \psi^{m_j}_{\kappa}(\mathbf{p}_N) \, .$$

Orthogonalize the relativistic plane wave with respect to the bound states of the nucleus.

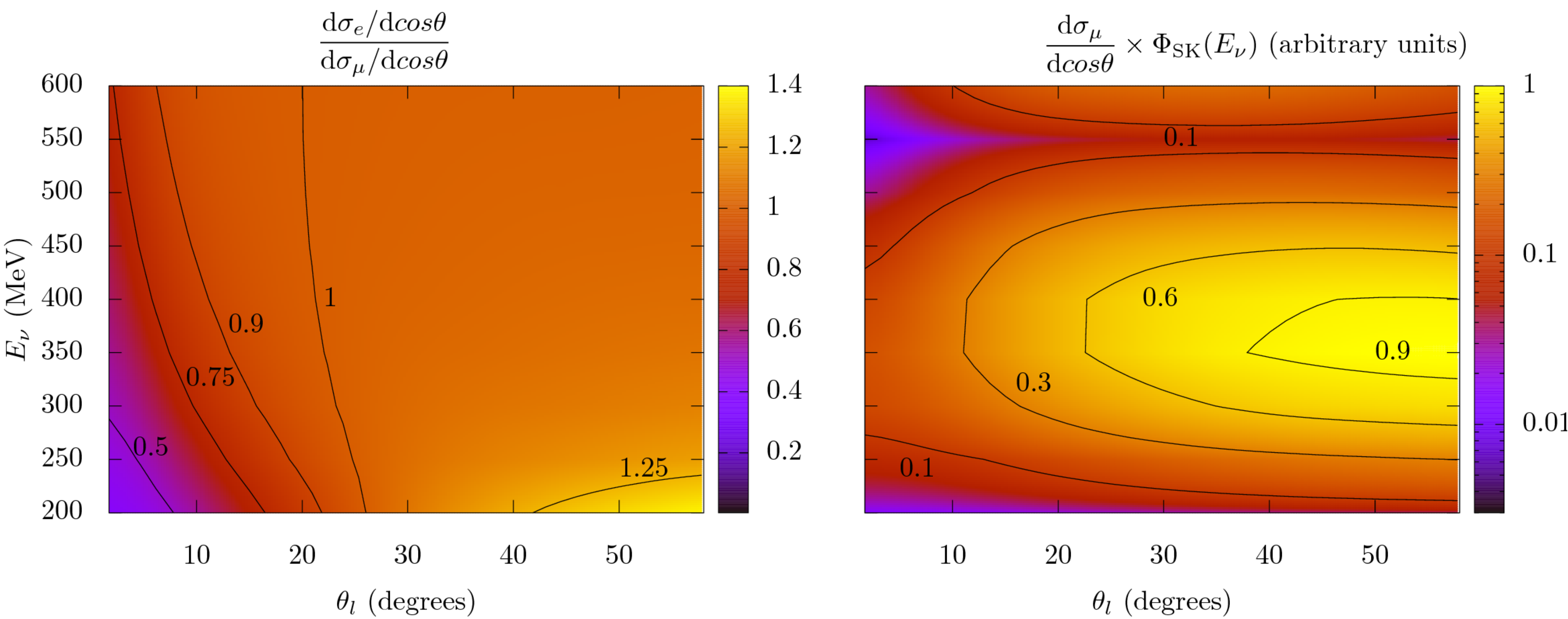
In a consistent model all nucleon states are orthogonal to eachother.
This implies Pauli-blocking as the nucleon wave function does not overlap with a bound state

Orthogonality and Pauli-blocking



Difference between ν_μ and ν_e

Non-trivial ratio of electron versus muon neutrino cross sections have a significant overlap with the T2K oscillated flux weighted cross section



Conclusions

I. The CRPA model is able to provide a consistent description of the CC scattering of neutrinos with nuclei from low to intermediate excitation energies

II. Forbidden transitions contribute considerably strength for scattering of low energy neutrinos on Argon

II. We find larger Responses for muon than for electron neutrinos for forward scattering angles if the initial and final state wave functions are treated consistently

III. By orthogonalization of the final state PW to the bound states of the nucleus we remove spurious non-orthogonal contributions and obtain the same ratio as in the full calculation.