FACULTY OF SCIENCES

DEPARTMENT OF PHYSICS AND ASTRONOMY

CORRELATIONS IN QE(LIKE) NEUTRINO-NUCLEUS SCATTERING

Natalie Jachowicz, T. Van Cuyck, R. González-Jímenez, N. Van Dessel, V. Pandey

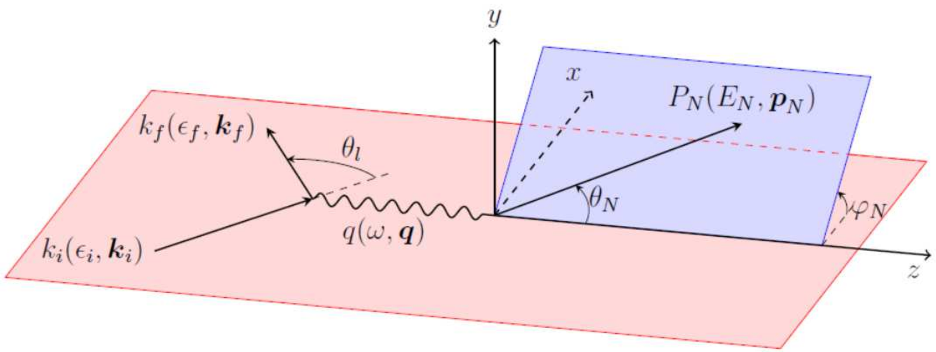
GHENT UNIVERSITY

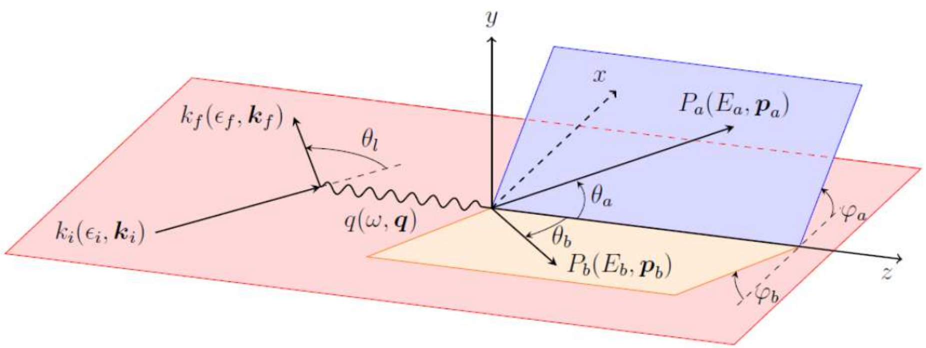
Outline

- Detailed microscopic cross sections calculations for QE(-like) scattering
- influence of long-range correlations
- influence of short-range correlations in 1- and 2-nucleon knockout processes
- Influence of seagull and pion-in-flight MEC contributions

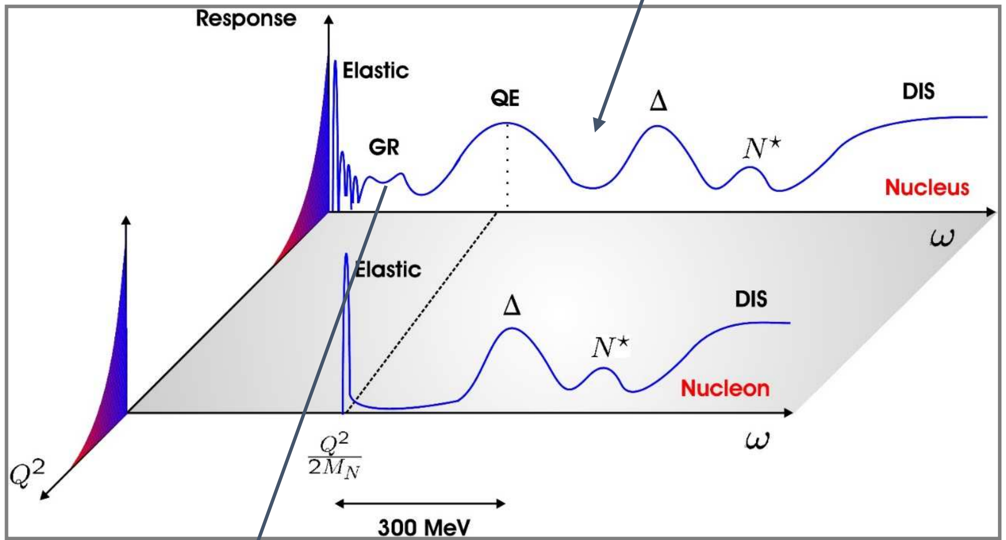
- Scheme-dependent separation
- Double counting

Neutrino-hadron scattering

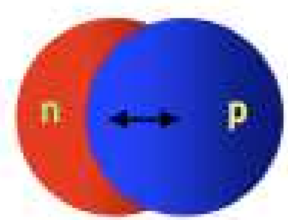


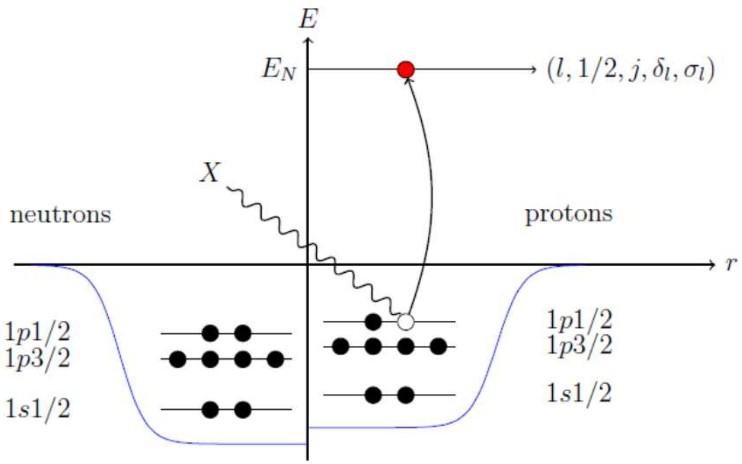


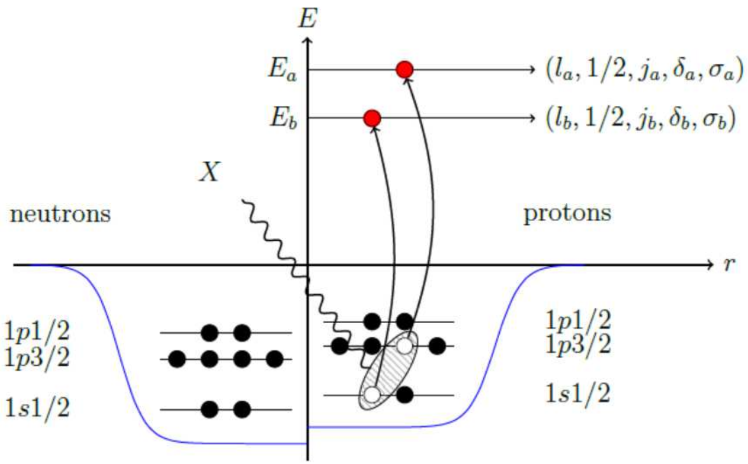
Dip region : multinucleon mechanisms



e.g.





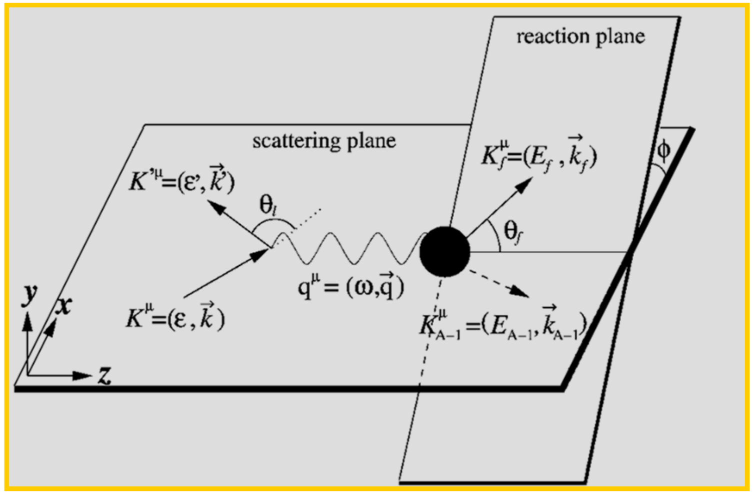


Cross section calculations

- Starting point : mean-field nucleus with Hartree-Fock single-particle wave functions
- Skyrme SkE2 force used to build the potential
- Pauli blocking
- Binding

Neutrino-nucleus interactions

$$\hat{H}_W = \frac{G}{\sqrt{2}} \int d\vec{x}\, \hat{J}_{\mu,lepton}(\vec{x})\, \hat{J}^{\mu,hadron}(\vec{x})$$



Hadron current

$$J^{\mu} = F_1(Q^2)\gamma^{\mu} + i\frac{\kappa}{2M_N}F_2(Q^2)\sigma^{\mu\nu}q_{\nu} + G_A(Q^2)\gamma^{\mu}\gamma_5 + \frac{1}{2M_N}G_P(Q^2)q^{\mu}\gamma_5$$

Lepton tensor

$$l_{\alpha\beta} \equiv \overline{\sum_{s,s'}}[\overline{u}_l\gamma_{\alpha}(1-\gamma_5)u_l]^{\dagger}[\overline{u}_{\nu}\gamma_{\beta}(1-\gamma_5)u_{\nu}]$$

$$\vec{J}^{\alpha}_{V}(\vec{x}) = \vec{J}^{\alpha}_{convection}(\vec{x}) + \vec{J}^{\alpha}_{magnetization}(\vec{x})$$

with $$\vec{J}^{\alpha}_{c}(\vec{x}) = \frac{1}{2Mi}\sum_{i=1}^{A} G_E^{i,\alpha}\left[\delta(\vec{x}-\vec{x}_i)\overrightarrow{\nabla}_i - \overleftarrow{\nabla}_i\,\delta(\vec{x}-\vec{x}_i)\right],$$

$$\vec{J}^{\alpha}_{m}(\vec{x}) = \frac{1}{2M}\sum_{i=1}^{A} G_M^{i,\alpha}\,\overrightarrow{\nabla} \times \vec{\sigma}_i\,\delta(\vec{x}-\vec{x}_i),$$

$$\vec{J}^{\alpha}_{A}(\vec{x}) = \sum_{i=1}^{A} G_A^{i,\alpha}\,\vec{\sigma}_i\,\delta(\vec{x}-\vec{x}_i),$$

$$J^{0,\alpha}_{V}(\vec{x}) = \rho^{\alpha}_{V}(\vec{x}) = \sum_{i=1}^{A} G_E^{i,\alpha}\,\delta(\vec{x}-\vec{x}_i),$$

$$J^{0,\alpha}_{A}(\vec{x}) = \rho^{\alpha}_{A}(\vec{x}) = \frac{1}{2Mi}\sum_{i=1}^{A} G_A^{i,\alpha}\,\vec{\sigma}_i\cdot\left[\delta(\vec{x}-\vec{x}_i)\overrightarrow{\nabla}_i - \overleftarrow{\nabla}_i\,\delta(\vec{x}-\vec{x}_i)\right]$$

$$J^{0,\alpha}_{P}(\vec{x}) = \rho^{\alpha}_{P}(\vec{x}) = \frac{m_\mu}{2M}\sum_{i=1}^{A} G_P^{i,\alpha}\,\vec{\nabla}\cdot\vec{\sigma}_i\,\delta(\vec{x}-\vec{x}_i)$$

for NC reactions

$$G_E^{V,o} = \left(\frac{1}{2} - \sin^2\theta_W\right)\tau_3 - \sin^2\theta_W,$$

$$G_M^{V,o} = \left(\frac{1}{2} - \sin^2\theta_W\right)(\mu_p - \mu_n)\,\tau_3 - \sin^2\theta_W\,(\mu_p + \mu_n)$$

$$G^{A,0} = g_a\,\frac{\tau_3}{2} = -\,\frac{1.262}{2}\,\tau_3$$

for CC reactions

$$G_E^{V,\pm} = \tau_\pm$$

$$G_M^{V,\pm} = (\mu_p - \mu_n)\,\tau_\pm$$

$$G^{A,\pm} = g_a\,\tau_\pm = -\,1.262\,\tau_\pm$$

$G = (1 + Q^2/M^2)^{-2}$ Q^2 dependence : dipole parametrization or BBBA07 :

Inclusive QE 1-nucleon knockout cross sections

$$\frac{d^2\sigma}{d\Omega\, d\omega} = (2\pi)^4\, k_f \varepsilon_f \sum_{s_f,s_i} \frac{1}{2J_i+1} \sum_{M_f,M_i} \left| \left\langle f \left| \widehat{H}_W \right| i \right\rangle \right|^2$$

$$\left(\frac{d^2\sigma_{i\to f}}{d\Omega d\omega}\right)_{\frac{\nu}{\bar\nu}} = \frac{G^2 \varepsilon_f^2}{\pi} \frac{2\cos^2\left(\frac{\theta}{2}\right)}{2J_i+1} \left[\sum_{J=0}^{\infty} \sigma_{CL}^J + \sum_{J=1}^{\infty} \sigma_T^J\right]$$

$$\sigma_{CL}^J = \left| \left\langle J_f \left\| \widehat{\mathcal{M}}_J(\kappa) + \frac{\omega}{|\vec{q}|} \widehat{\mathcal{L}}_J(\kappa) \right\| J_i \right\rangle \right|^2$$

$$\sigma_T^J = \left(-\frac{q_\mu^2}{2|\vec{q}|^2} + \tan^2\left(\frac{\theta}{2}\right)\right) \left[\left| \left\langle J_f \left\| \widehat{\mathcal{J}}_J^{mag}(\kappa) \right\| J_i \right\rangle \right|^2 + \left| \left\langle J_f \left\| \widehat{\mathcal{J}}_J^{el}(\kappa) \right\| J_i \right\rangle \right|^2 \right]$$

$$\mp \tan\left(\frac{\theta}{2}\right) \sqrt{-\frac{q_\mu^2}{|\vec{q}|^2} + \tan^2\left(\frac{\theta}{2}\right)} \left[2\Re \left(\left\langle J_f \left\| \widehat{\mathcal{J}}_J^{mag}(\kappa) \right\| J_i \right\rangle \left\langle J_f \left\| \widehat{\mathcal{J}}_J^{el}(\kappa) \right\| J_i \right\rangle^* \right) \right]$$

2-nucleon knockout cross sections

2-nucleon knockout :

$$\frac{\mathrm{d}\sigma^X}{\mathrm{d}E_f\mathrm{d}\Omega_f\mathrm{d}T_b\mathrm{d}\Omega_b\mathrm{d}\Omega_a} = \frac{p_a p_b E_a E_b}{(2\pi)^6} g_{rec}^{-1}\sigma^X\zeta$$
$$\times\big[v_{CC}W_{CC} + v_{CL}W_{CL} + v_{LL}W_{LL} + v_T W_T + v_{TT}W_{TT} + v_{TC}W_{TC}$$
$$+v_{TL}W_{TL} + h(v_{T'}W_{T'} + v_{TC'}W_{TC'} + v_{TL'}W_{TL'})\big],$$

with :

$$\mathcal{J}_\lambda = \langle\, \Phi_f^{(A-2)}(E^{exc}, J_R M_R);\, \boldsymbol{p}_a m_{s_a};\, \boldsymbol{p}_b m_{s_b} \,|\, \widehat{J}_\lambda(\boldsymbol{q}) \,|\, \Phi_{gs} \,\rangle$$

$$|\, \Phi^{2p2h} \,\rangle = |\, \Phi_f^{(A-2)}(E^{exc}, J_R M_R);\, \boldsymbol{p}_a m_{s_a};\, \boldsymbol{p}_b m_{s_b} \,\rangle_{as}$$

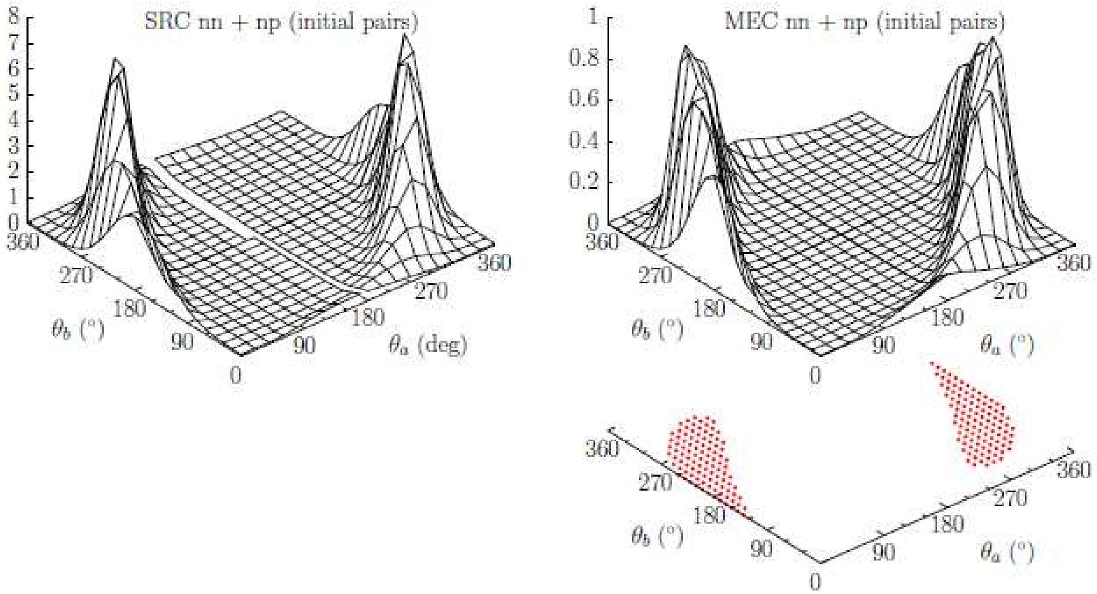
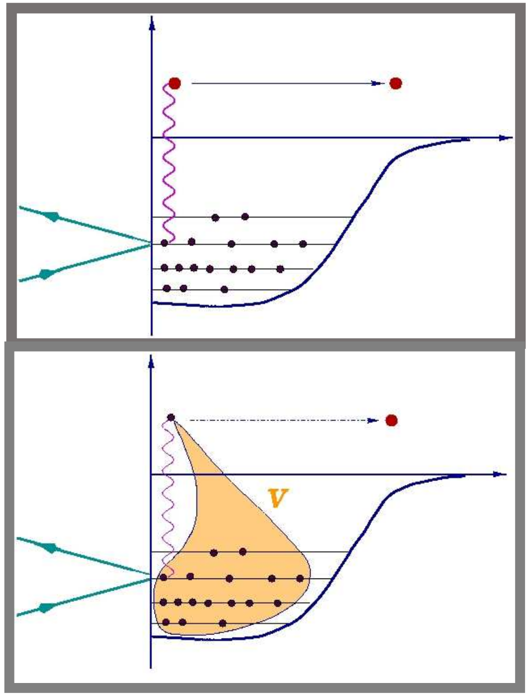


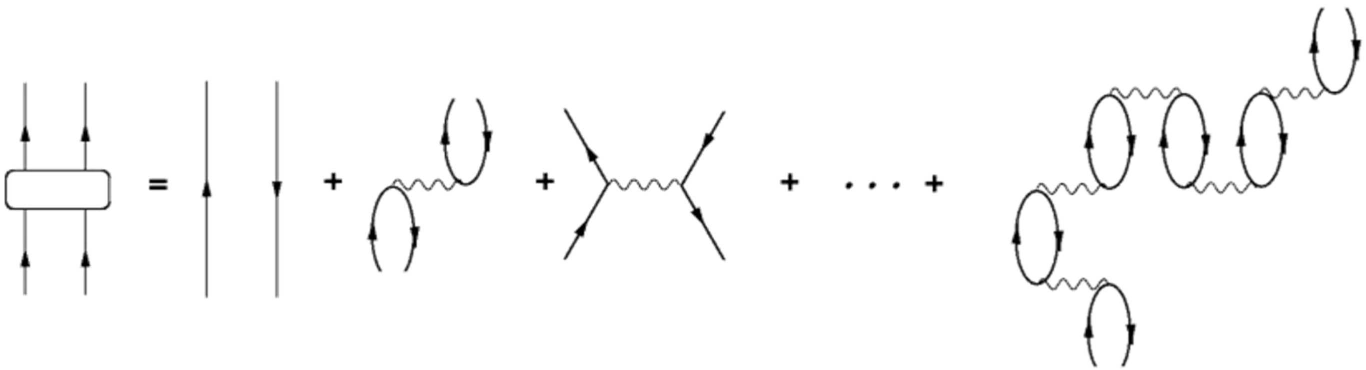
Figure 4.5: The ^{12}C$(\nu_\mu, \mu^- N_a N_b)$ cross section (N_a = p, N_b = p′, n) at ϵ_{ν_μ} = 750 MeV, ϵ_μ = 550 MeV, $\theta_\mu = 15°$ and T_p = 50 MeV for in-plane kinematics. Left with SRCs, right with MECs, the bottom plot shows the (θ_a, θ_b) regions with $P_{12} < 300$ MeV/c.

- Strength residing in restricted part of phase space
- $\boldsymbol{p}_b \approx \boldsymbol{p}_b^{ave}$
- Quasi-deuteron kinematics

Long-range correlations : Continuum RPA

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

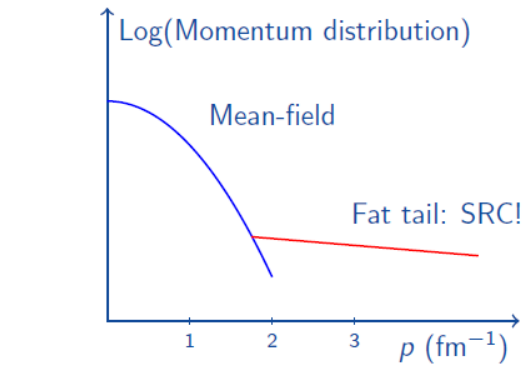


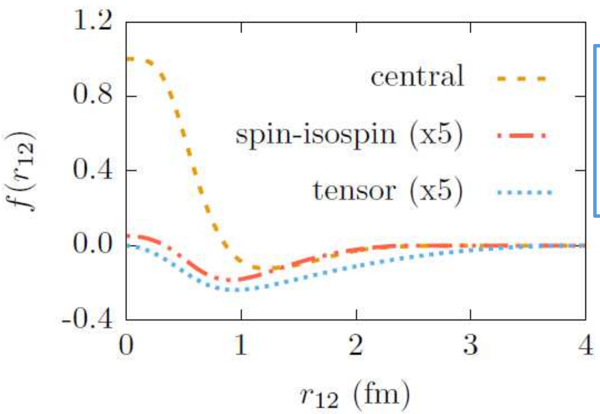


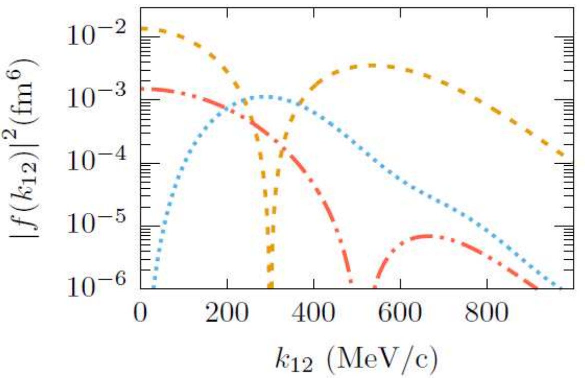
$$|\Psi_{RPA}\rangle = \sum_{c} \left\{ X_{(\Psi,C)} \left|ph^{-1}\right\rangle - Y_{(\Psi,C)} \left|hp^{-1}\right\rangle \right\} + \ldots$$

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

Short-range correlations







Gearheart (1994) Pieper (1992)

$$|\Psi\rangle = \frac{1}{\sqrt{\mathcal{N}}}\widehat{\mathcal{G}}|\Phi\rangle \qquad \text{with} \qquad \widehat{\mathcal{G}} \approx \widehat{\mathcal{S}}\left(\prod_{i<j}^{A}\left[1+\widehat{l}(i,j)\right]\right)$$

$$\widehat{l}(i,j) = -\,g_c(r_{ij}) + f_{\sigma\tau}(r_{ij})\,(\vec{\sigma}_i\cdot\vec{\sigma}_j)\,(\vec{\tau}_i\cdot\vec{\tau}_j) + f_{t\tau}(r_{ij})\widehat{S}_{ij}\,(\vec{\tau}_i\cdot\vec{\tau}_j)\,,$$

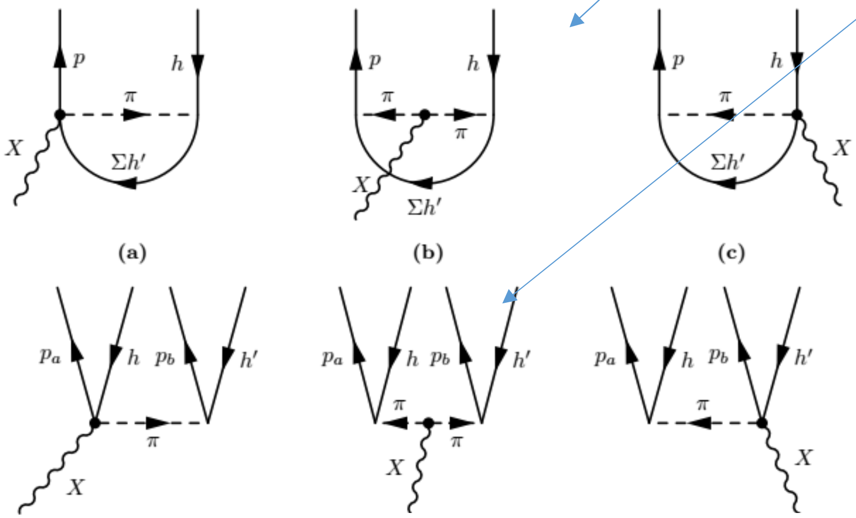
Shifting the complexity induced by correlations from the wave functions to the operators

$$\langle\Psi_{\mathrm{f}}|\widehat{J}^{\mathrm{nucl}}_{\mu}|\Psi_{\mathrm{i}}\rangle = \frac{1}{\sqrt{\mathcal{N}_{\mathrm{i}}\mathcal{N}_{\mathrm{f}}}}\langle\Phi_{\mathrm{f}}|\widehat{J}^{\mathrm{eff}}_{\mu}|\Phi_{\mathrm{i}}\rangle$$

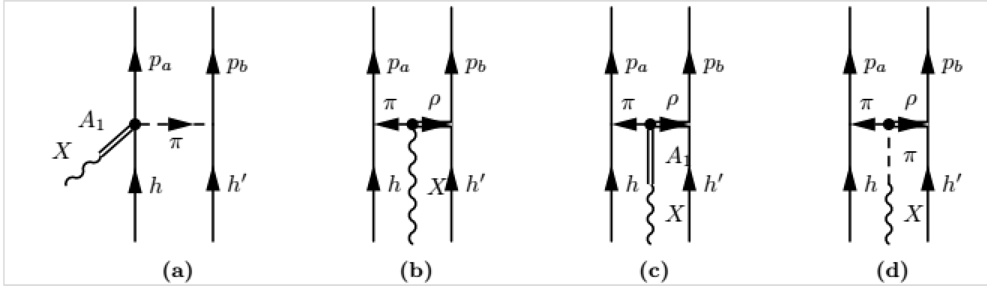
$$\widehat{J}^{\mathrm{eff}}_{\mu} \approx \sum_{i=1}^{A}\widehat{J}^{[1]}_{\mu}(i + \sum_{i<j}^{A}\widehat{J}^{[1],\mathrm{in}}_{\mu}(i,j) + \left[\sum_{i<j}^{A}\widehat{J}^{[1],\mathrm{in}}_{\mu}(i,j)\right]^{\dagger}$$

$$\widehat{J}^{[1],\mathrm{in}}_{\mu}(i,j) = \left[\widehat{J}^{[1]}_{\mu}(i) + \widehat{J}^{[1]}_{\mu}(j)\right]\widehat{l}(i,j)$$

III. MEC in 1p1h and 2p2h



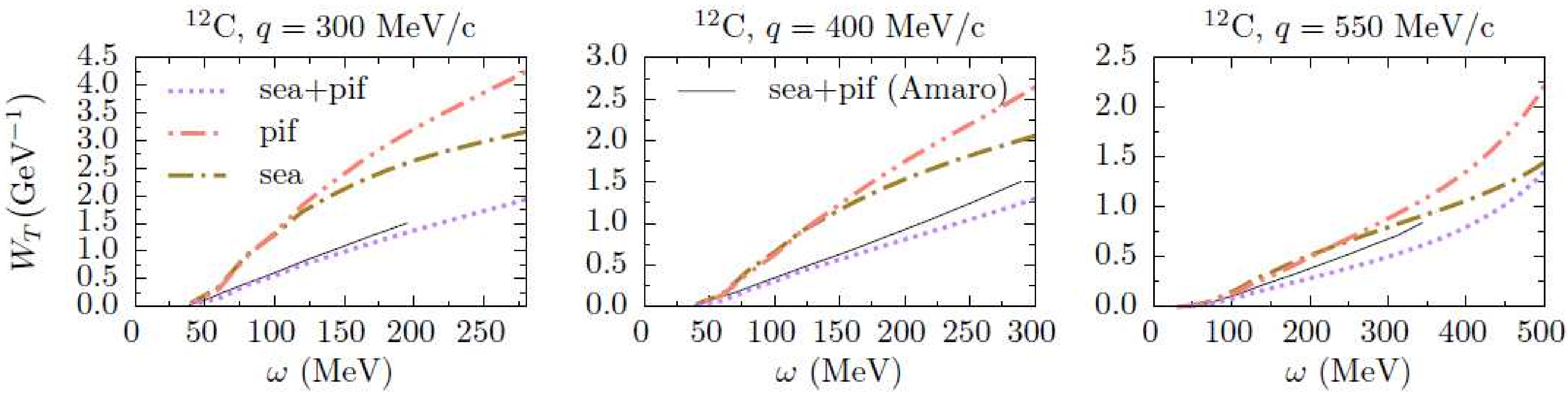
Axial contributions :



$$\hat{\rho}_A^{[2],\mathrm{axi}}(\boldsymbol{q}) = \frac{i}{g_A}\left(\frac{f_{\pi NN}}{m_\pi}\right)^2 (\boldsymbol{I}_V)\left(F_\pi(\boldsymbol{q}_2^2)\,\Gamma_\pi^2(\boldsymbol{q}_2^2)\frac{\boldsymbol{\sigma}_2\cdot\boldsymbol{q}_2}{\boldsymbol{q}_2^2+m_\pi^2} - F_\pi(\boldsymbol{q}_1^2)\,\Gamma_\pi^2(\boldsymbol{q}_1^2)\frac{\boldsymbol{\sigma}_1\cdot\boldsymbol{q}_1}{\boldsymbol{q}_1^2+m_\pi^2}\right)$$

I. Towner, Nucl. Phys.A542, 631 (1992)

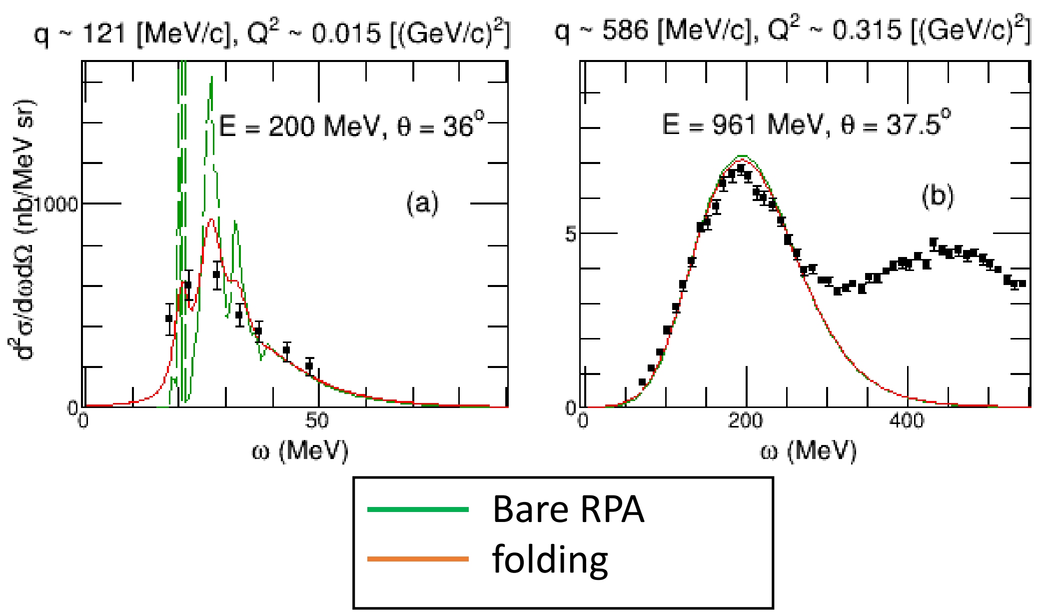
$^{12}C(e, e')$



- Final state interactions :

-taken into account through the calculations of the wave function of the outgoing nucleon in the (real) nuclear potential generated using the Skyrme force

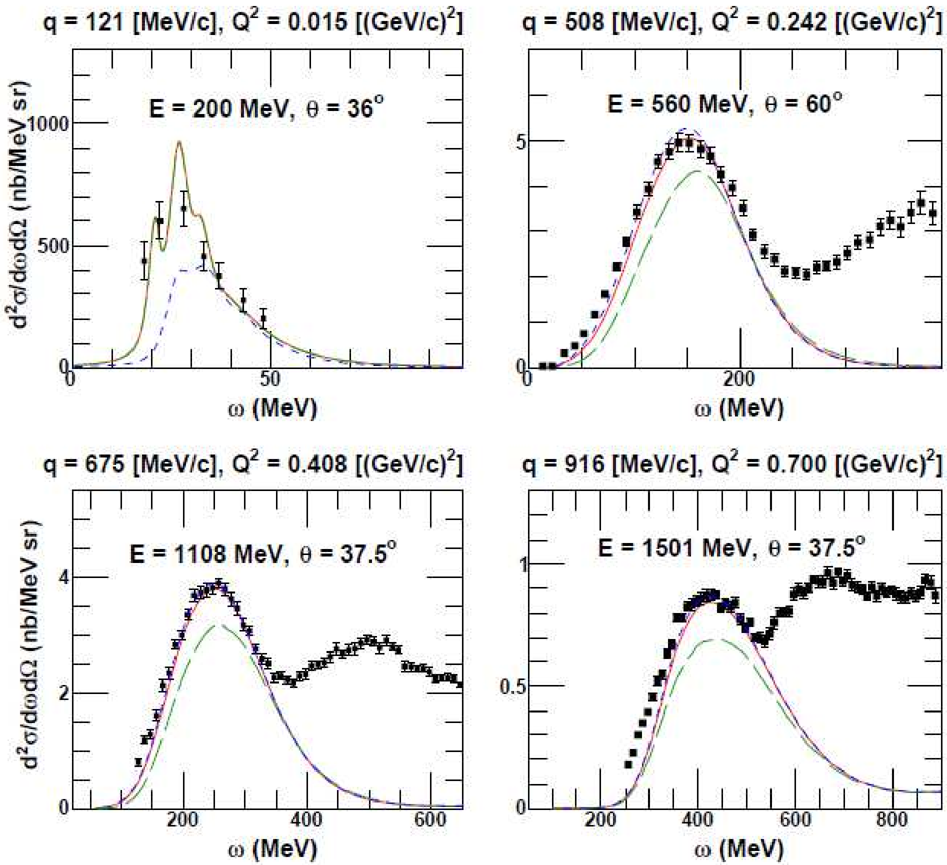
-influence of the spreading width of the particle states is implemented through a folding procedure



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

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

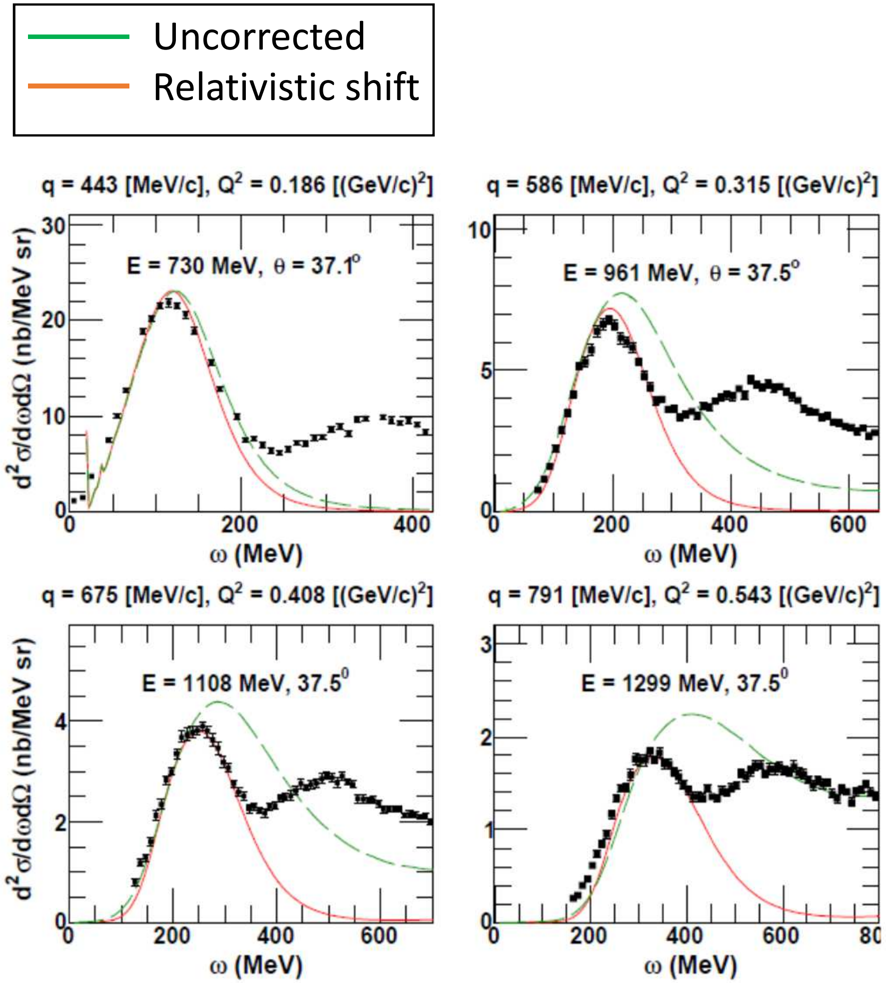
•Regularization of the residual interaction :



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

Uncorrected
dipole

•Relativistic corrections at higher energies (J. Jeschonnek and T. Donnelly, PRC57, 2438 (1998)):



Shift :

$$\lambda \to \lambda(\lambda + 1) \qquad \lambda = \omega/2M_N$$

- The outgoing nucleon obtains the correct relativistic momentum

$$p = \sqrt{T^2 + 2MT}$$

- Shifts the QE peak to the right relativistic position

Boost :

$$R^{\rm V}_{\rm CC}(q,\omega) \to \frac{q^2}{q^2-\omega^2} R^{\rm V}_{\rm CC}(q,\omega)\,,$$

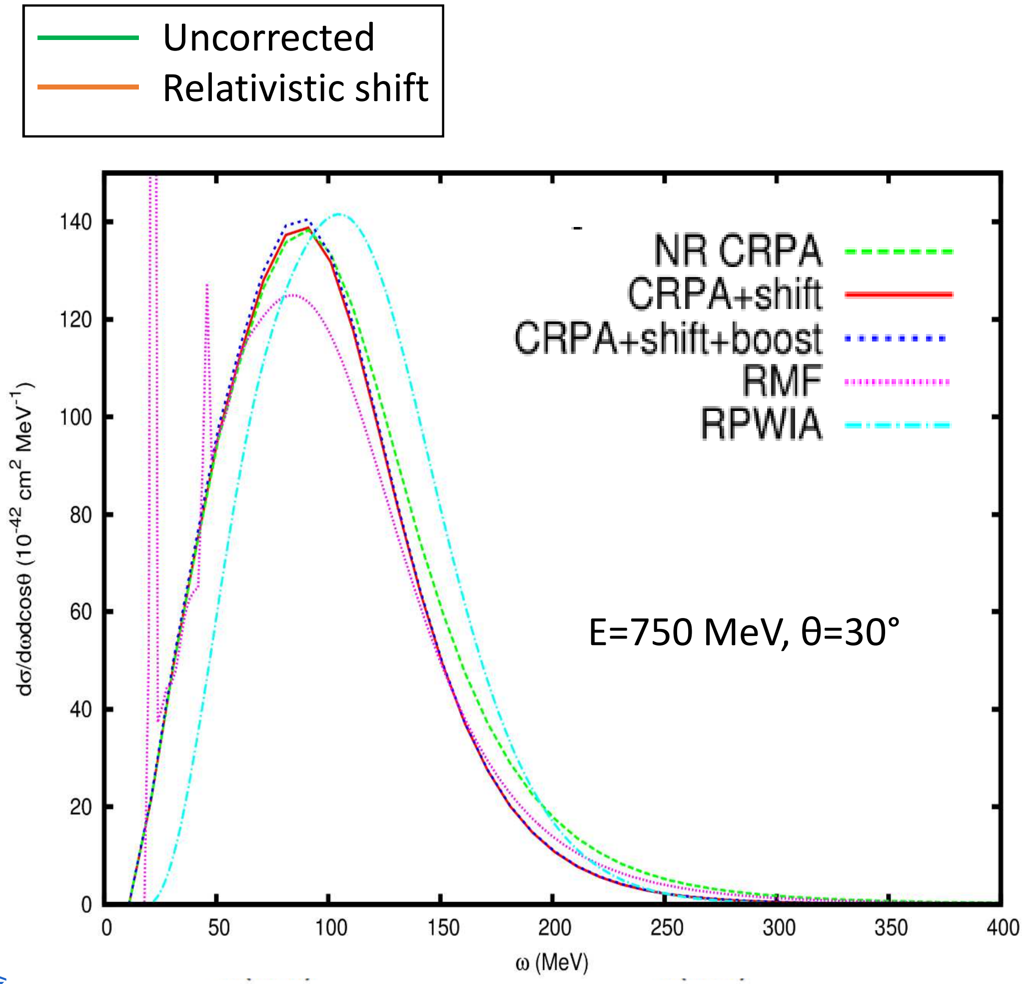
$$R^{\rm A}_{\rm LL}(q,\omega) \to \left(1 + \frac{q^2-\omega^2}{4m^2}\right) R^{\rm A}_{\rm LL}(q,\omega)\,,$$

$$R^{\rm V}_{\rm T}(q,\omega) \to \frac{q^2-\omega^2}{q^2} R^{\rm V}_{\rm T}(q,\omega)\,,$$

$$R^{\rm A}_{\rm T}(q,\omega) \to \left(1 + \frac{q^2-\omega^2}{4m^2}\right) R^{\rm A}_{\rm T}(q,\omega)\,,$$

$$R^{\rm VA}_{\rm T'}(q,\omega) \to \sqrt{\frac{q^2-\omega^2}{q^2}}\sqrt{1 + \frac{q^2-\omega^2}{4m^2}}\, R^{\rm VA}_{\rm T'}(q,\omega)\,.$$

•Relativistic corrections at higher energies (J. Jeschonnek and T. Donnelly, PRC57, 2438 (1998)):



Shift :

$$\lambda \rightarrow \lambda(\lambda+1) \qquad \lambda = \omega/2M_N$$

The outgoing nucleon obtains the correct relativistic momentum

$$p = \sqrt{T^2 + 2MT}$$

Shifts the QE peak to the right relativistic position

Boost :

$$R^{\mathrm{V}}_{\mathrm{CC}}(q,\omega) \rightarrow \frac{q^2}{q^2-\omega^2} R^{\mathrm{V}}_{\mathrm{CC}}(q,\omega),$$

$$R^{\mathrm{A}}_{\mathrm{LL}}(q,\omega) \rightarrow \left(1+\frac{q^2-\omega^2}{4m^2}\right) R^{\mathrm{A}}_{\mathrm{LL}}(q,\omega),$$

$$R^{\mathrm{V}}_{\mathrm{T}}(q,\omega) \rightarrow \frac{q^2-\omega^2}{q^2} R^{\mathrm{V}}_{\mathrm{T}}(q,\omega),$$

$$R^{\mathrm{A}}_{\mathrm{T}}(q,\omega) \rightarrow \left(1+\frac{q^2-\omega^2}{4m^2}\right) R^{\mathrm{A}}_{\mathrm{T}}(q,\omega),$$

$$R^{\mathrm{VA}}_{\mathrm{T'}}(q,\omega) \rightarrow \sqrt{\frac{q^2-\omega^2}{q^2}}\sqrt{1+\frac{q^2-\omega^2}{4m^2}}\, R^{\mathrm{VA}}_{\mathrm{T'}}(q,\omega).$$

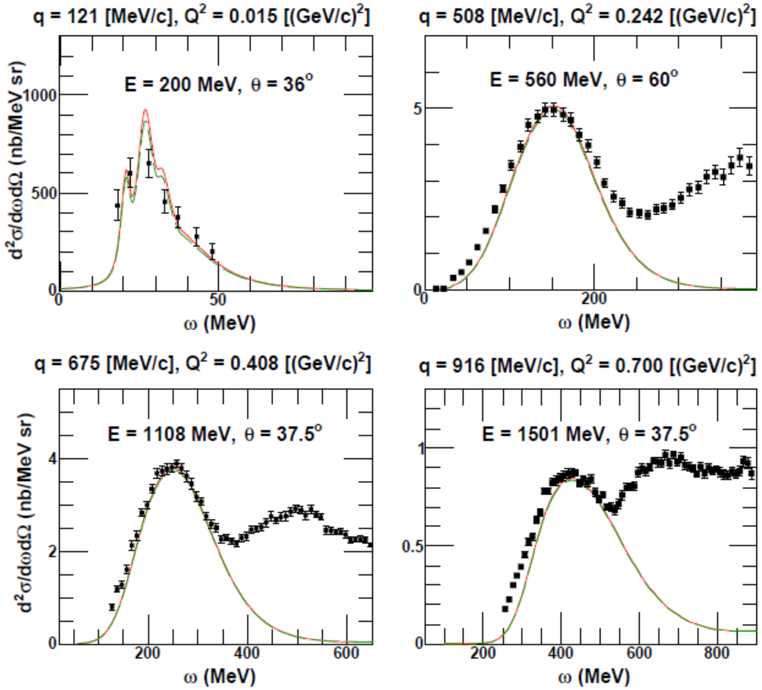
• Coulomb correction for the outgoing lepton in charged-current interactions :

✓ Low energies : Fermi function

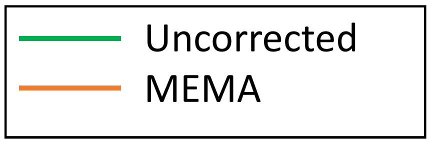
$$F(Z', E) = \frac{2\pi\eta}{1 - e^{-2\pi\eta}} \qquad \eta \sim \mp Z'\alpha$$

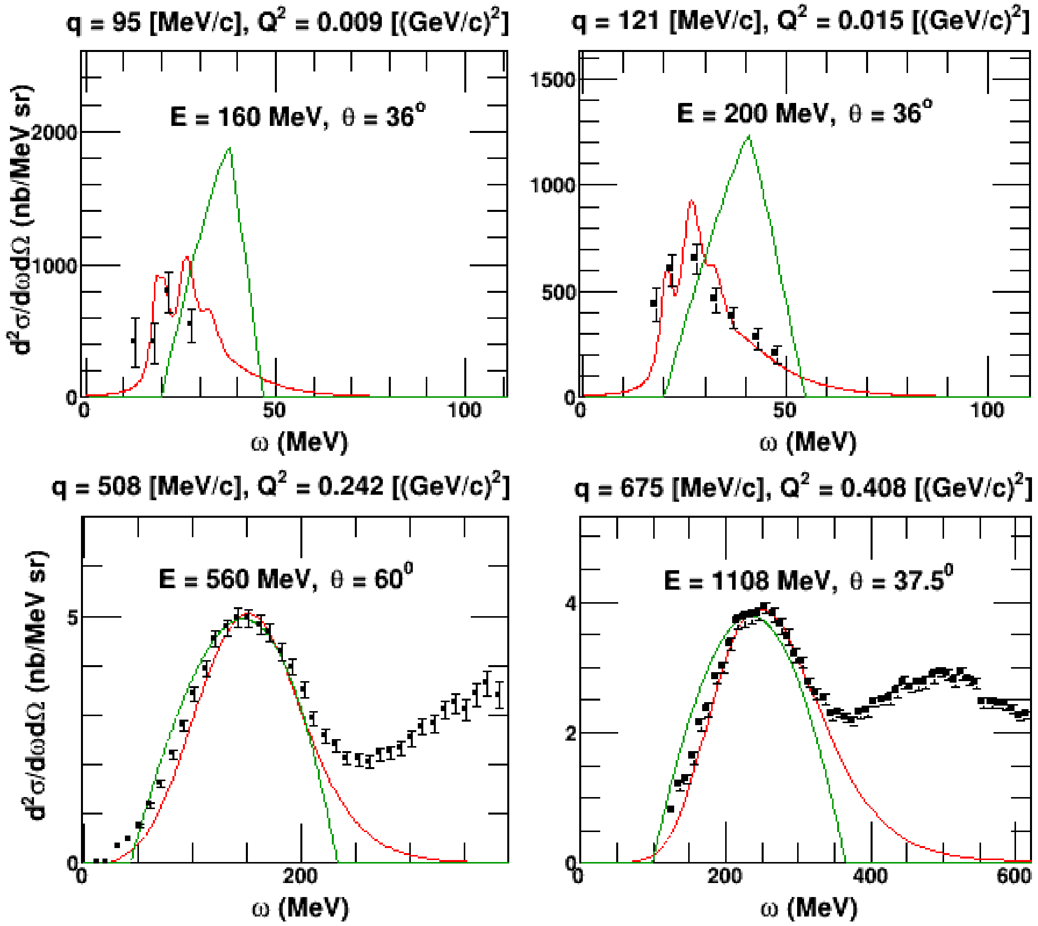
✓ High energies : modified effective momentum approximation (J. Engel, PRC57,2004 (1998))

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



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

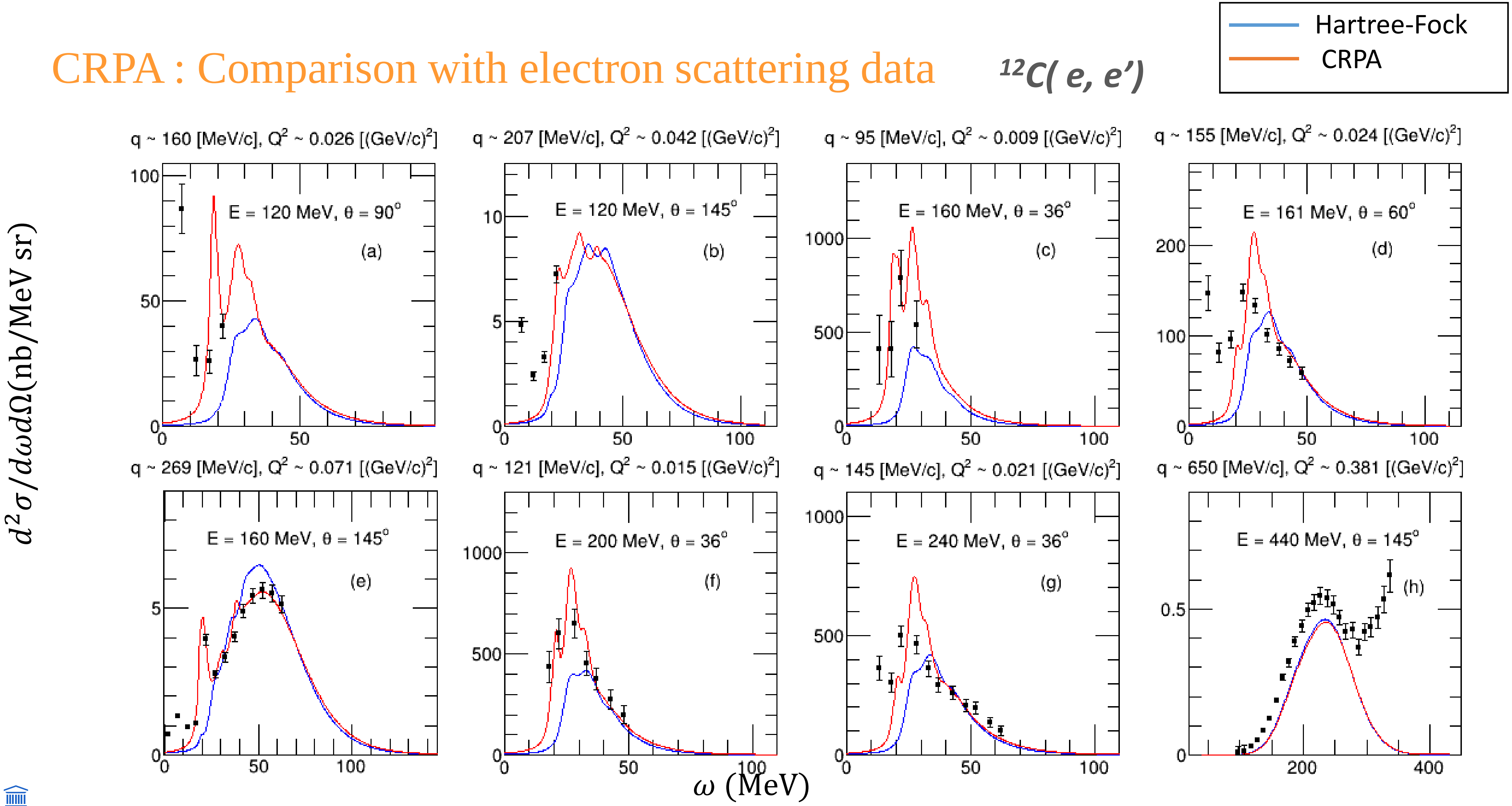


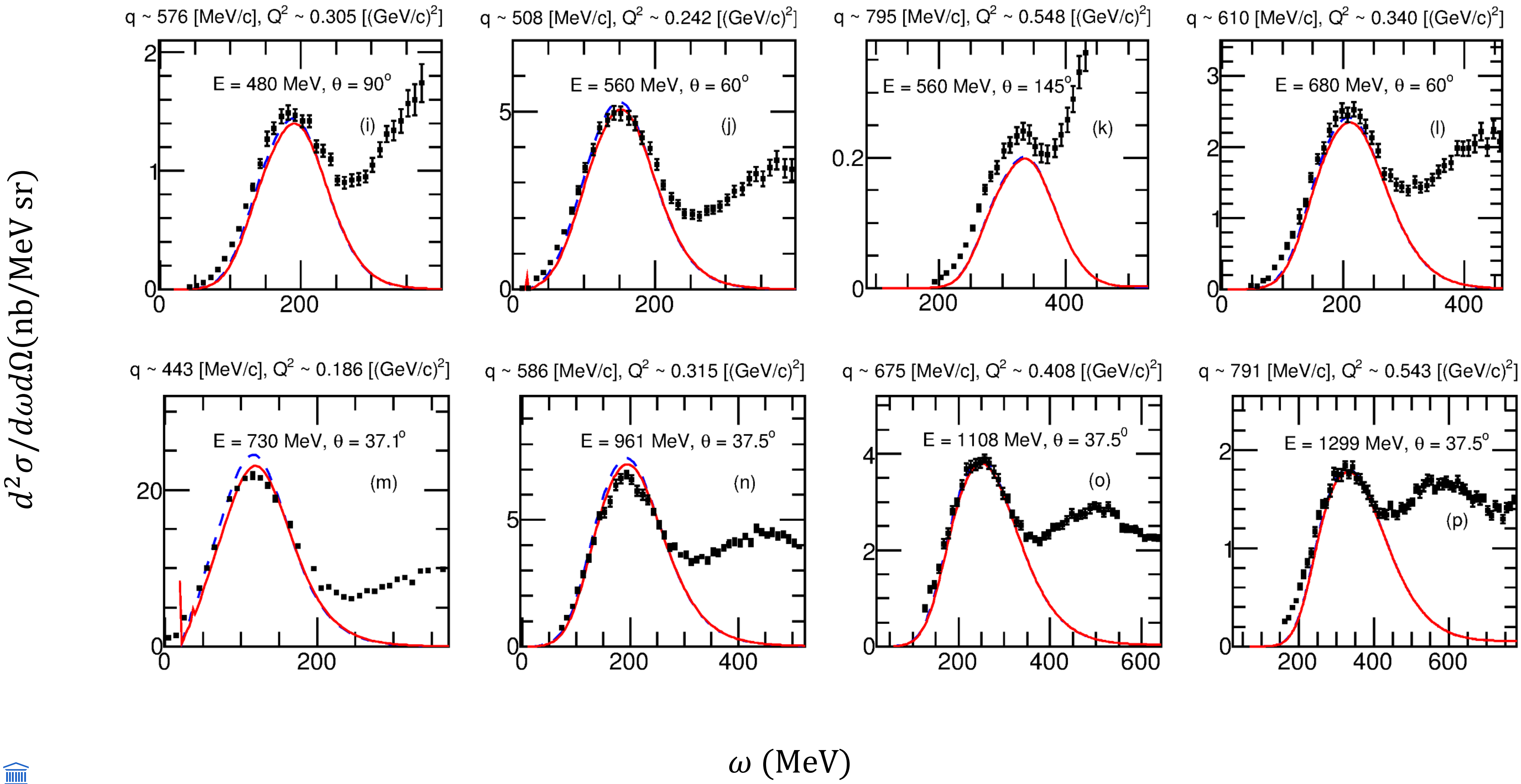

q = 95 [MeV/c], Q² = 0.009 [(GeV/c)²]
E = 160 MeV, θ = 36°
q = 121 [MeV/c], Q² = 0.015 [(GeV/c)²]
E = 200 MeV, θ = 36°
q = 508 [MeV/c], Q² = 0.242 [(GeV/c)²]
E = 560 MeV, θ = 60°
q = 675 [MeV/c], Q² = 0.408 [(GeV/c)²]
E = 1108 MeV, θ = 37.5°
d²σ/dωdΩ (nb/MeV sr)
ω (MeV)


Fermi gas
Hartree-Fock

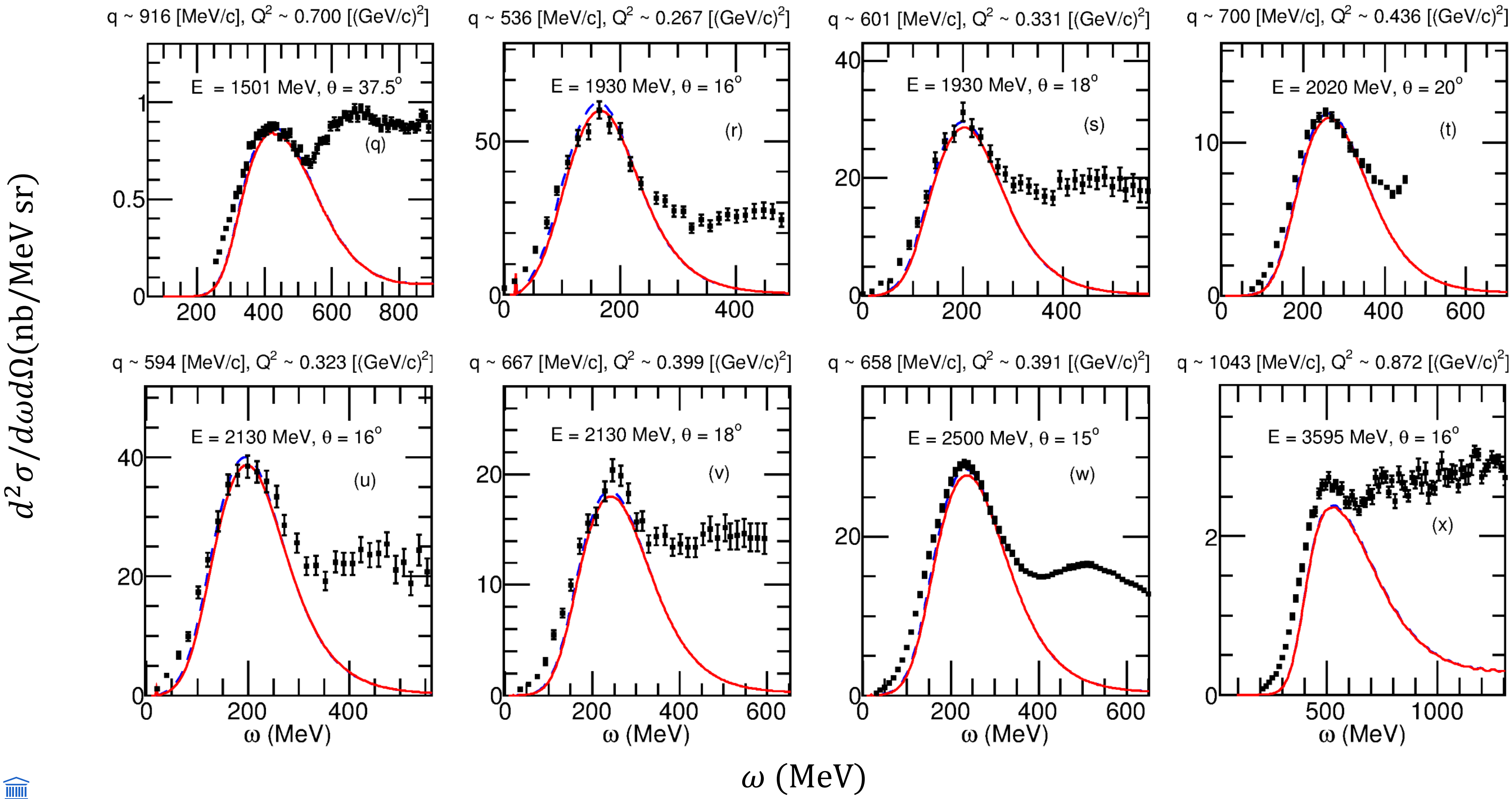
CRPA : Comparison with electron scattering data

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

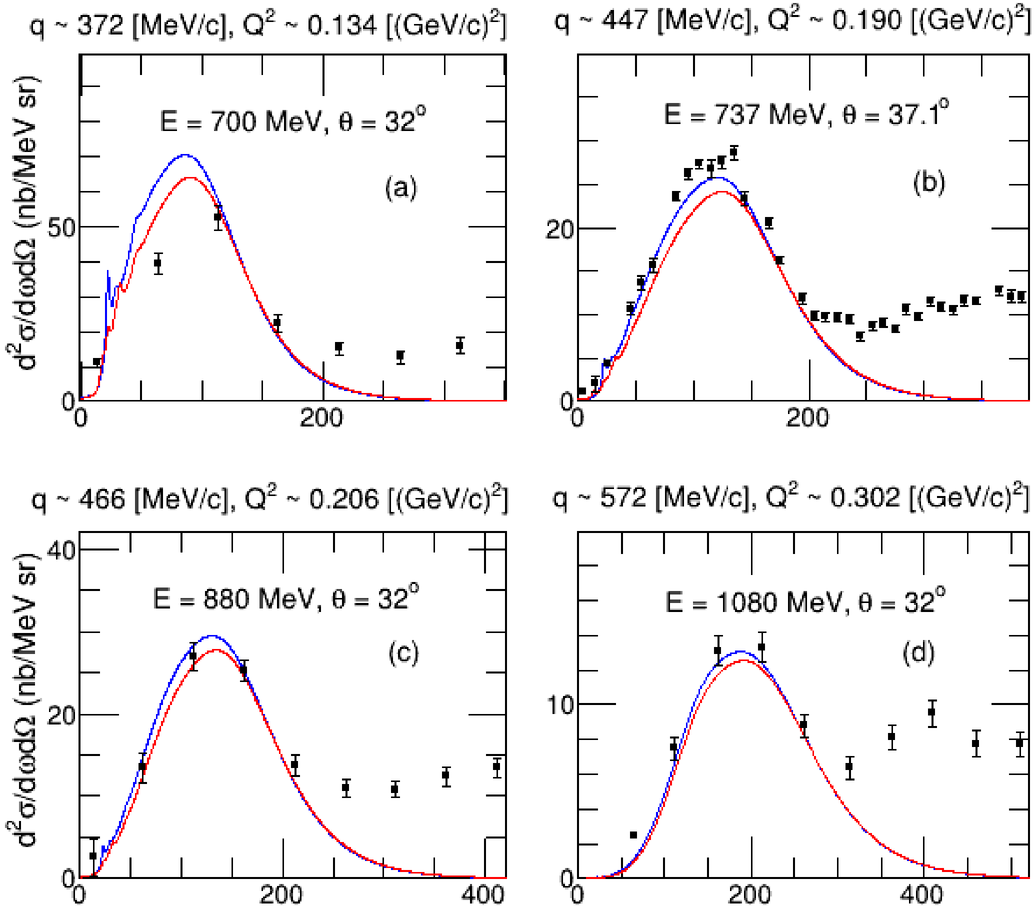




q ~ 576 [MeV/c], Q^2 ~ 0.305 [(GeV/c)^2]
E = 480 MeV, θ = 90°
(i)
q ~ 508 [MeV/c], Q^2 ~ 0.242 [(GeV/c)^2]
E = 560 MeV, θ = 60°
(j)
q ~ 795 [MeV/c], Q^2 ~ 0.548 [(GeV/c)^2]
E = 560 MeV, θ = 145°
(k)
q ~ 610 [MeV/c], Q^2 ~ 0.340 [(GeV/c)^2]
E = 680 MeV, θ = 60°
(l)
q ~ 443 [MeV/c], Q^2 ~ 0.186 [(GeV/c)^2]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


q ~ 916 [MeV/c], Q² ~ 0.700 [(GeV/c)²]
E = 1501 MeV, θ = 37.5°
(q)
q ~ 536 [MeV/c], Q² ~ 0.267 [(GeV/c)²]
E = 1930 MeV, θ = 16°
(r)
q ~ 601 [MeV/c], Q² ~ 0.331 [(GeV/c)²]
E = 1930 MeV, θ = 18°
(s)
q ~ 700 [MeV/c], Q² ~ 0.436 [(GeV/c)²]
E = 2020 MeV, θ = 20°
(t)
q ~ 594 [MeV/c], Q² ~ 0.323 [(GeV/c)²]
E = 2130 MeV, θ = 16°
(u)
q ~ 667 [MeV/c], Q² ~ 0.399 [(GeV/c)²]
E = 2130 MeV, θ = 18°
(v)
q ~ 658 [MeV/c], Q² ~ 0.391 [(GeV/c)²]
E = 2500 MeV, θ = 15°
(w)
q ~ 1043 [MeV/c], Q² ~ 0.872 [(GeV/c)²]
E = 3595 MeV, θ = 16°
(x)
ω (MeV)
$d^2\sigma/d\omega d\Omega$(nb/MeV sr)
ω (MeV)

$^{16}O(e, e')$

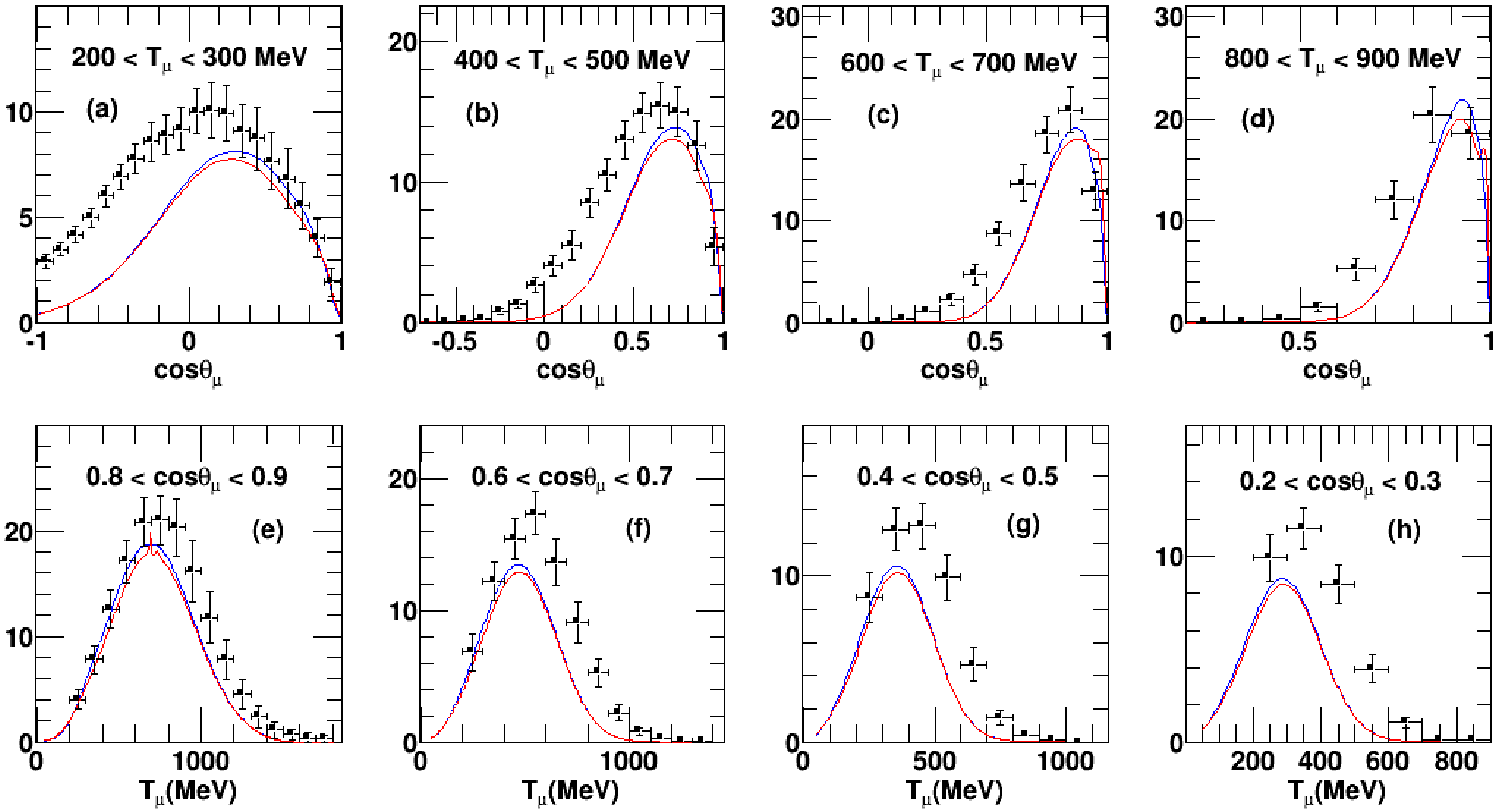


- Good overall agreement with e-scattering data

P. Barreau et al., Nucl. Phys. A402, 515 (1983), J. S. O'Connell et al., Phys. Rev. C35, 1063 (1987), R. M. Sealock et al., Phys. Rev. Lett.62, 1350 (1989).,D. S. Bagdasaryan et al., YERPHI-1077-40-88 (1988),D. B. Day et al., Phys. Rev. C 48, 1849 (1993).,D. Zeller, DESY-F23-73-2 (1973).

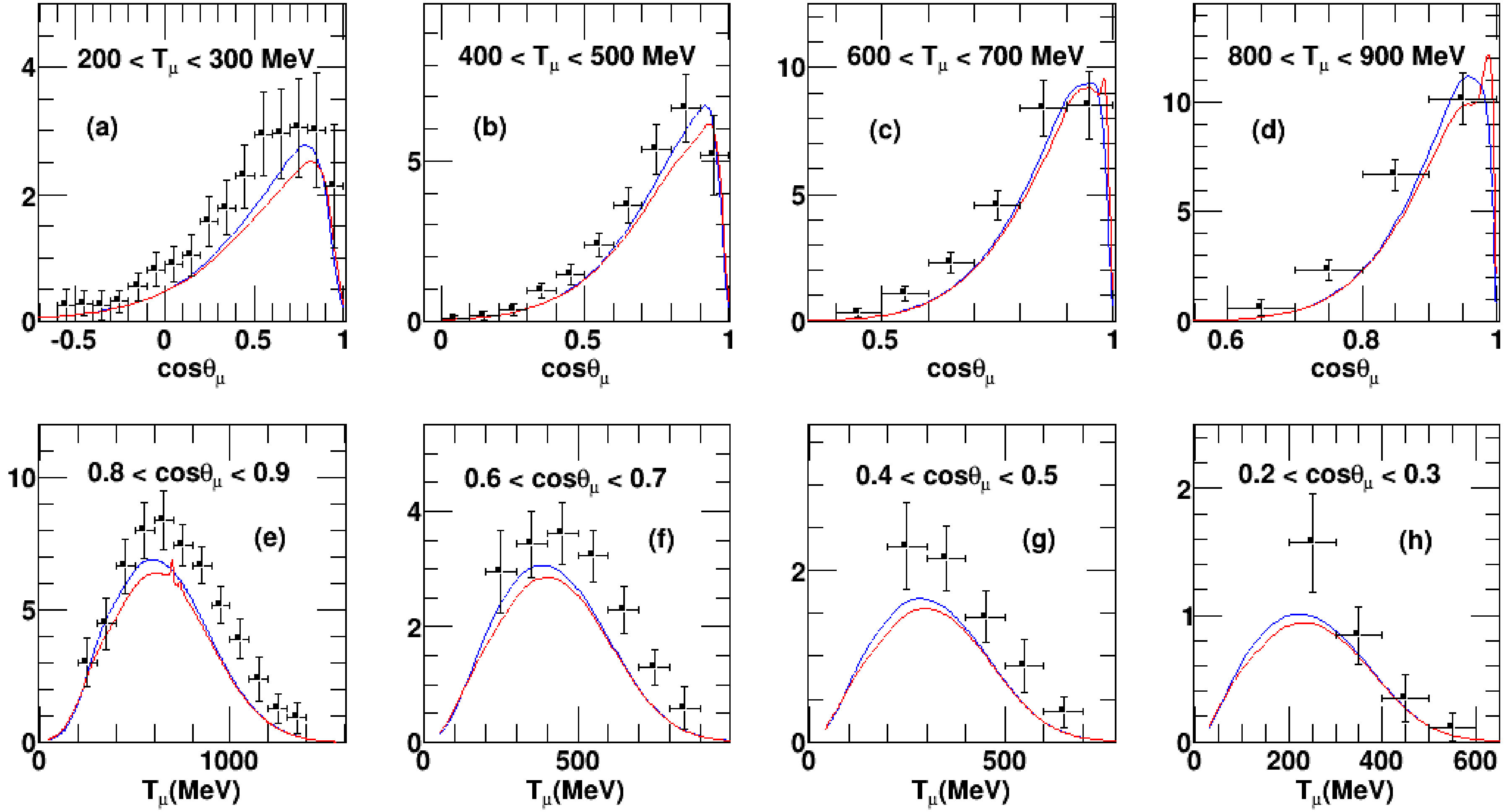
MiniBooNe ν_μ

- Satisfactory general agreement
- Good agreement for forward scattering
- Missing strength for low T_μ, backward scattering



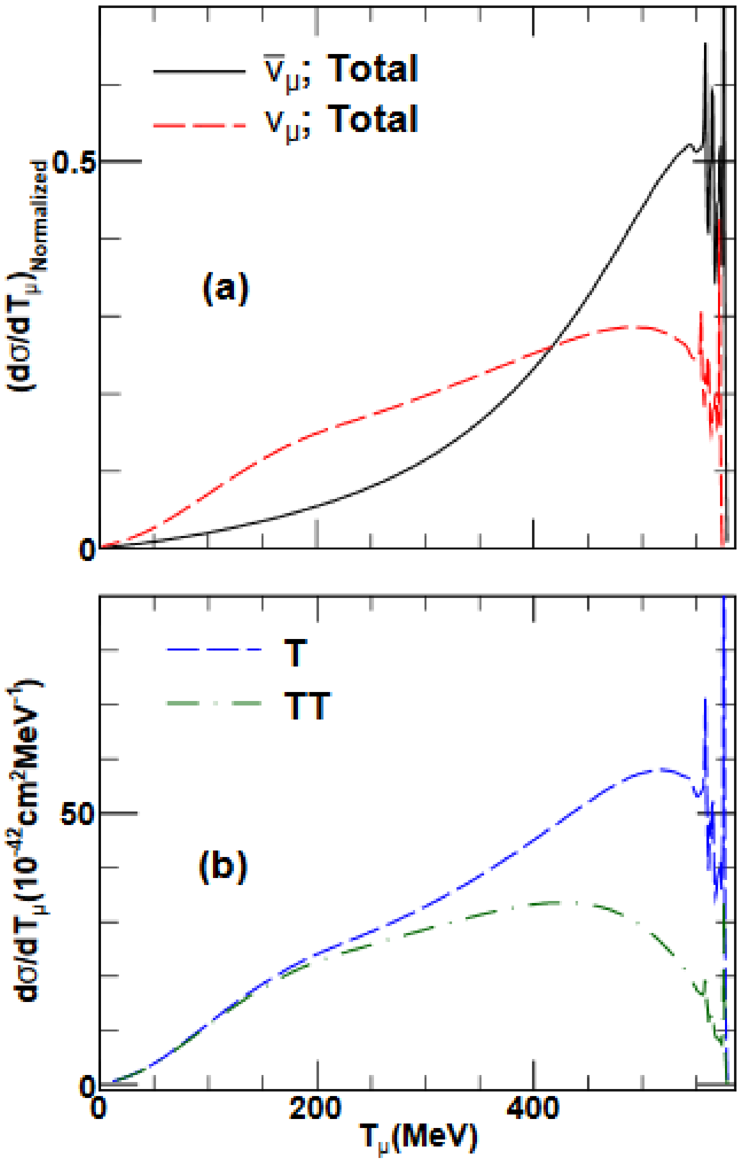
MiniBooNe $\bar{\nu}_\mu$

- Good general agreement
- Good agreement for forward scattering
- Missing strength for high T_μ , backward scattering
- Better agreement with data than neutrino cross sections

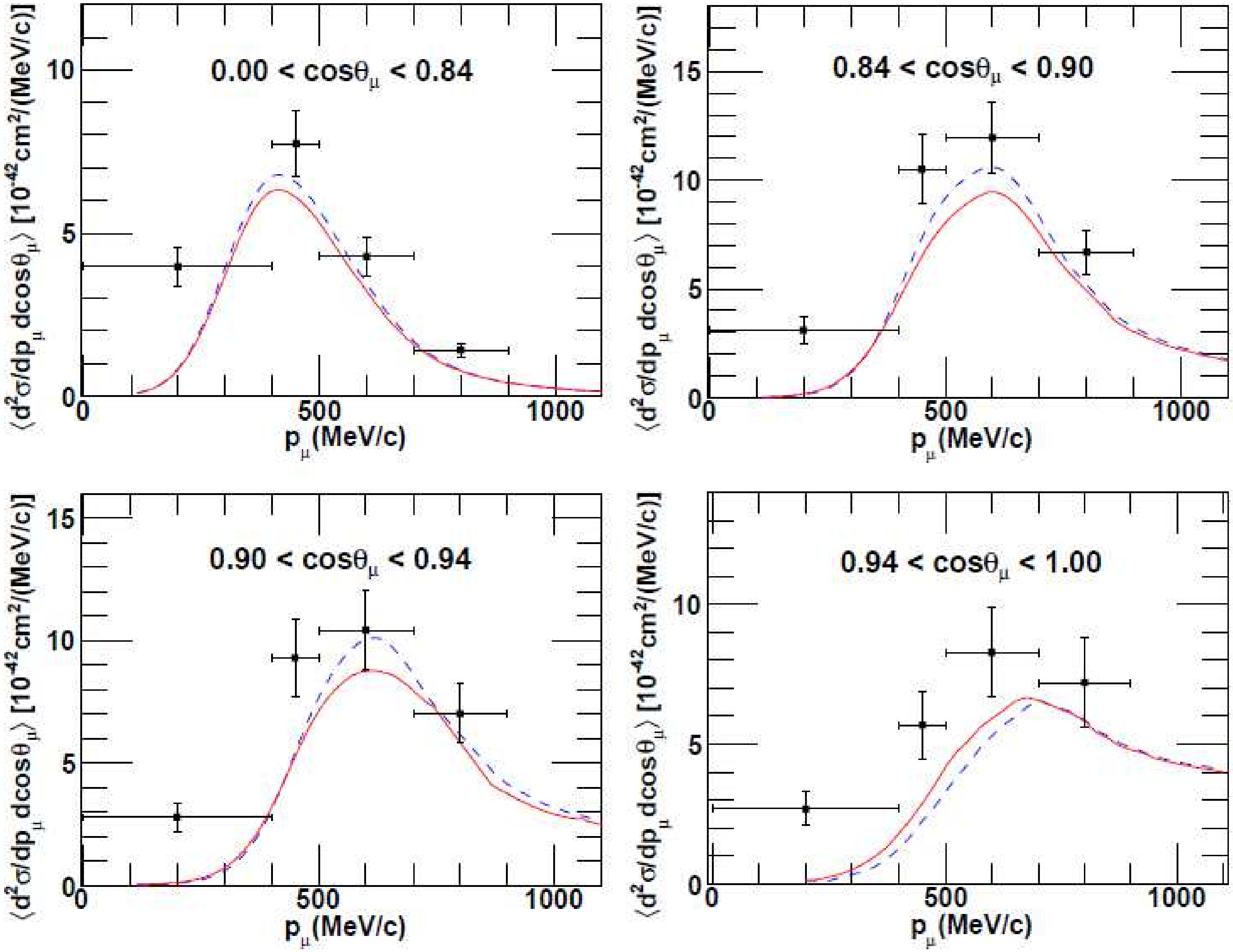


neutrino vs anti neutrinos

E=700 MeV



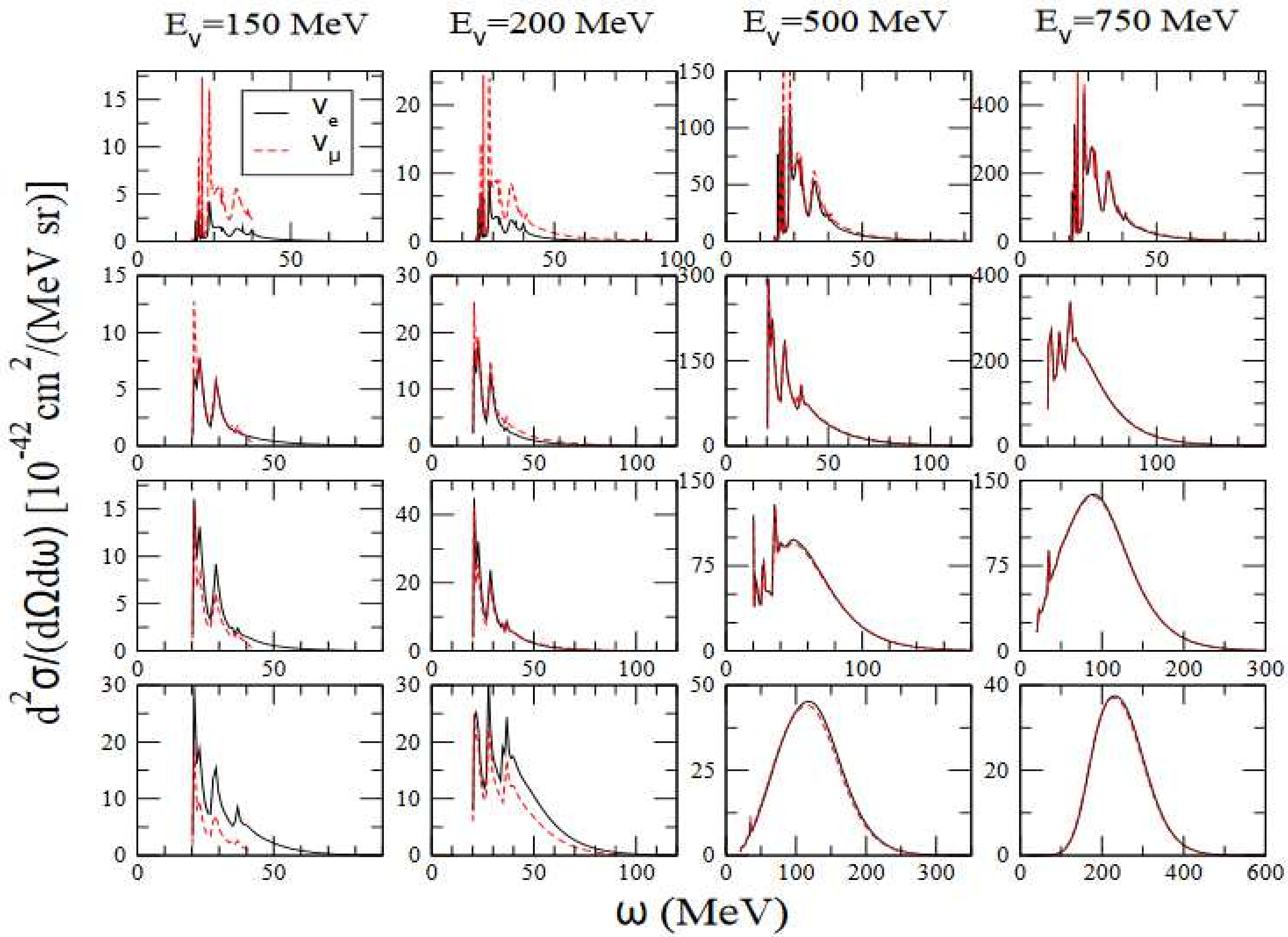
V. Pandey et al, Phys. Rev. C 92, 024606 (2015)

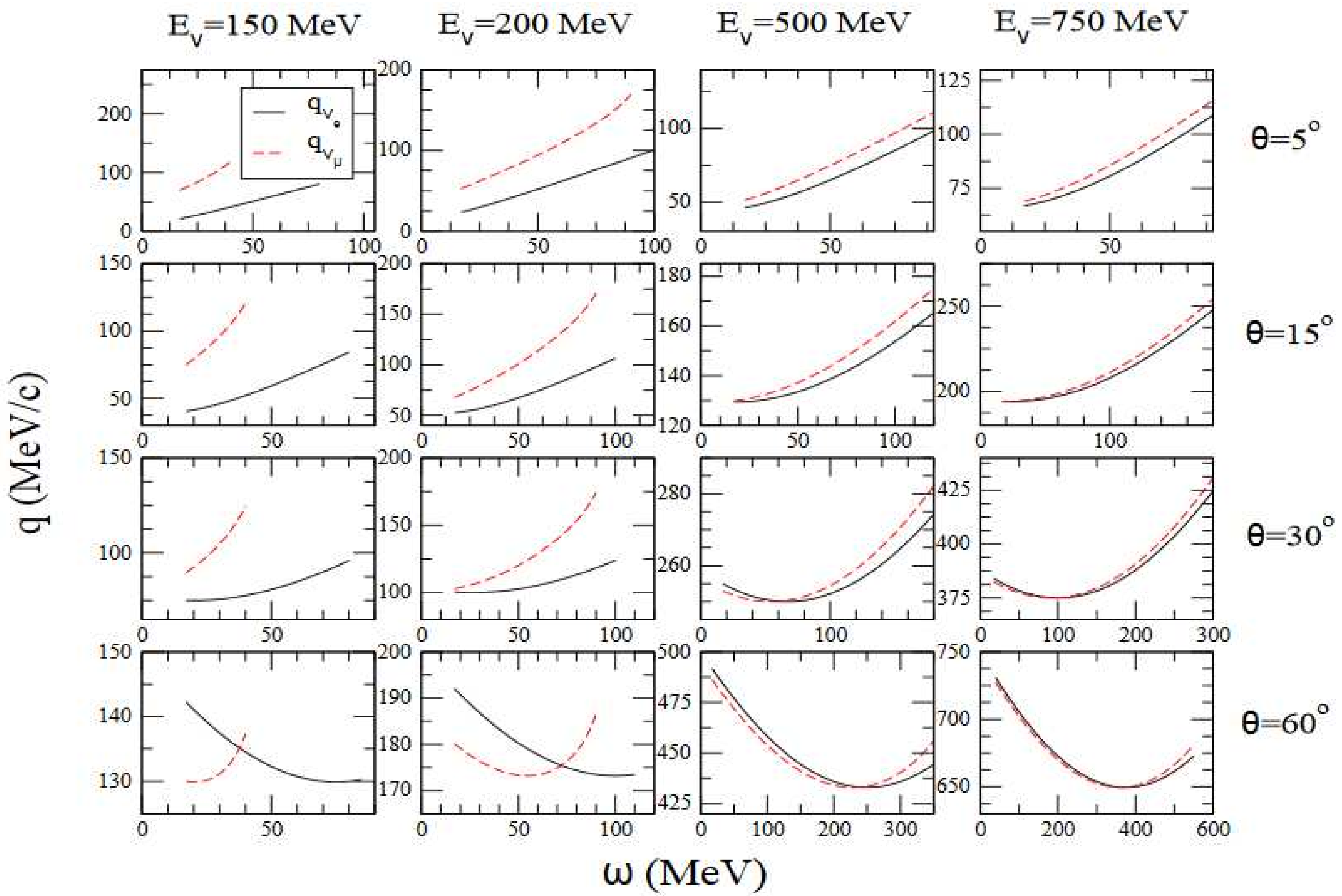


T2K ν_μ

- General agreement quite good
- Missing strength for low p_μ

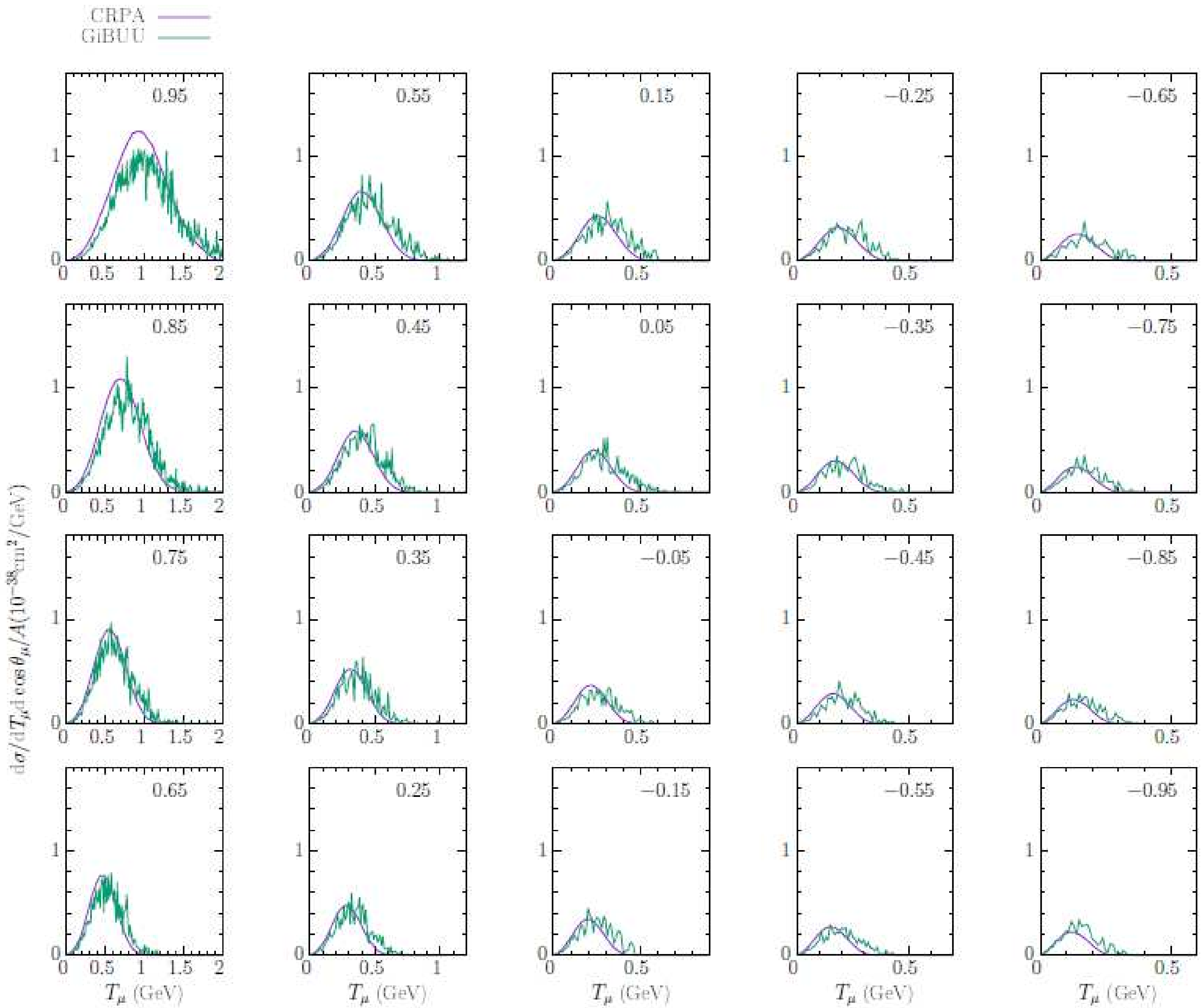
electron vs muon neutrinos



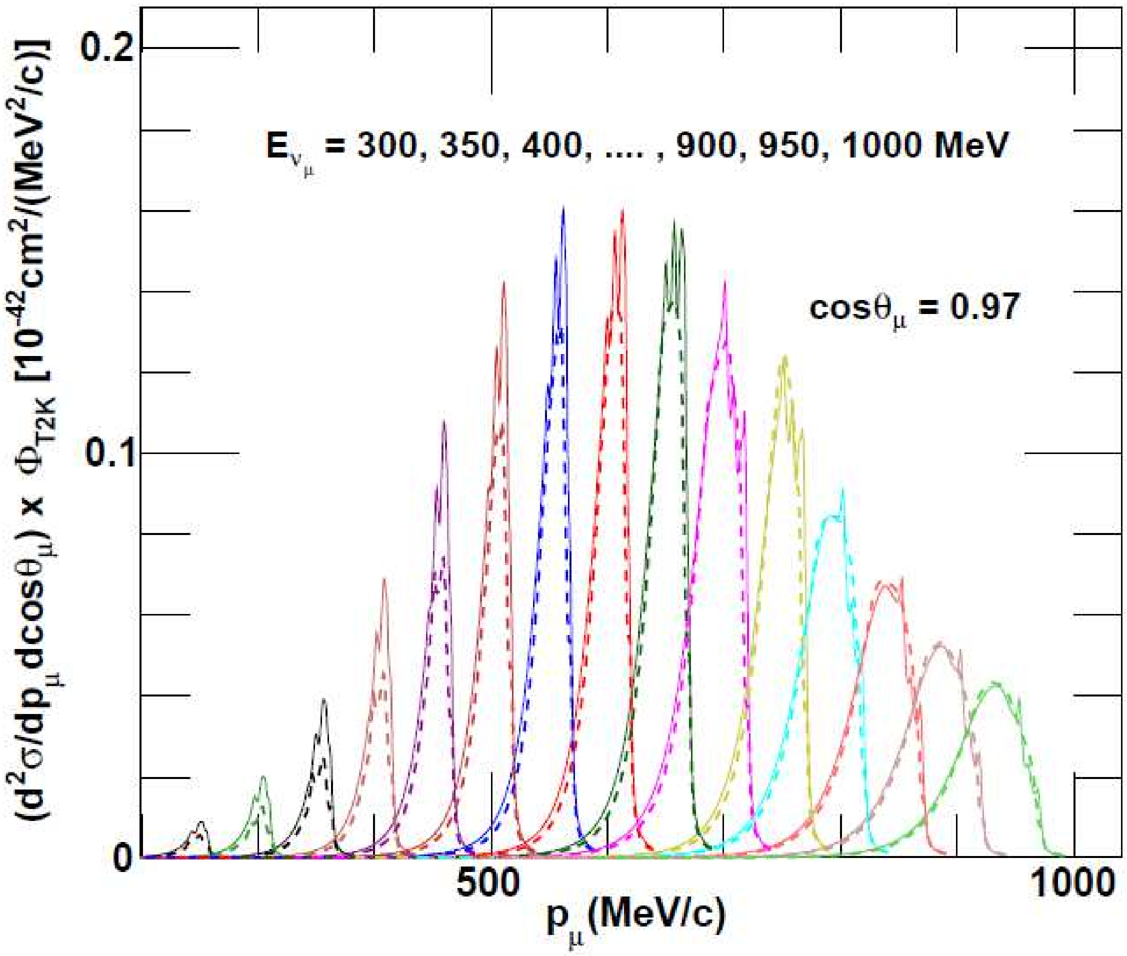


M. Martini et al, Phys.Rev. C94 (2016) no.1, 015501

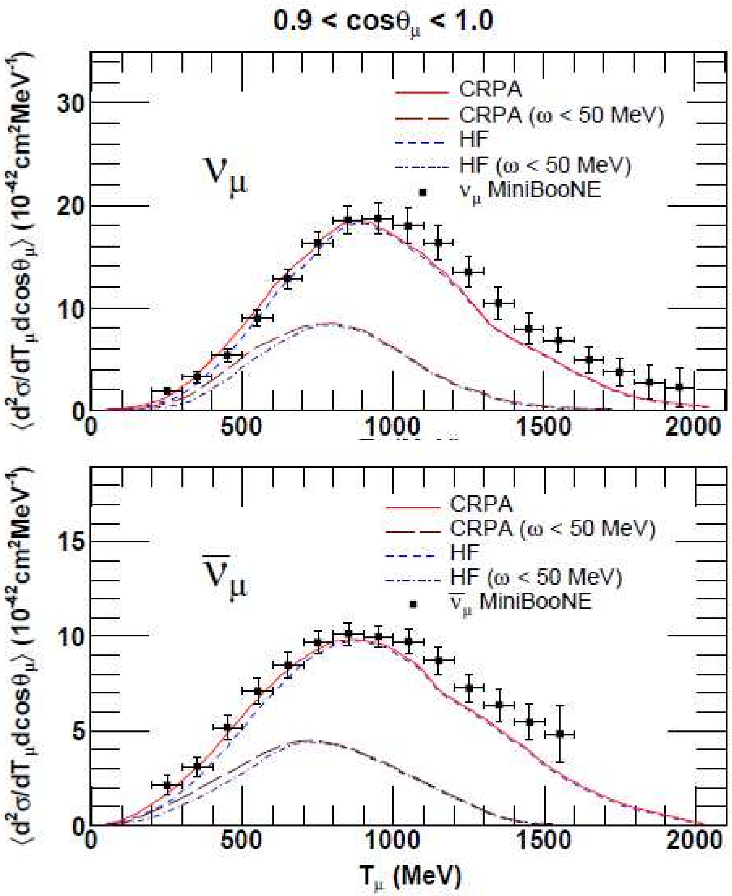
^{40}Ar


CRPA
GiBUU
0.95
0.55
0.15
−0.25
−0.65
0.85
0.45
0.05
−0.35
−0.75
0.75
0.35
−0.05
−0.45
−0.85
0.65
0.25
−0.15
−0.55
−0.95
dσ/dT_μ d cos θ_μ/A(10^−38 cm^2/GeV)
T_μ (GeV)

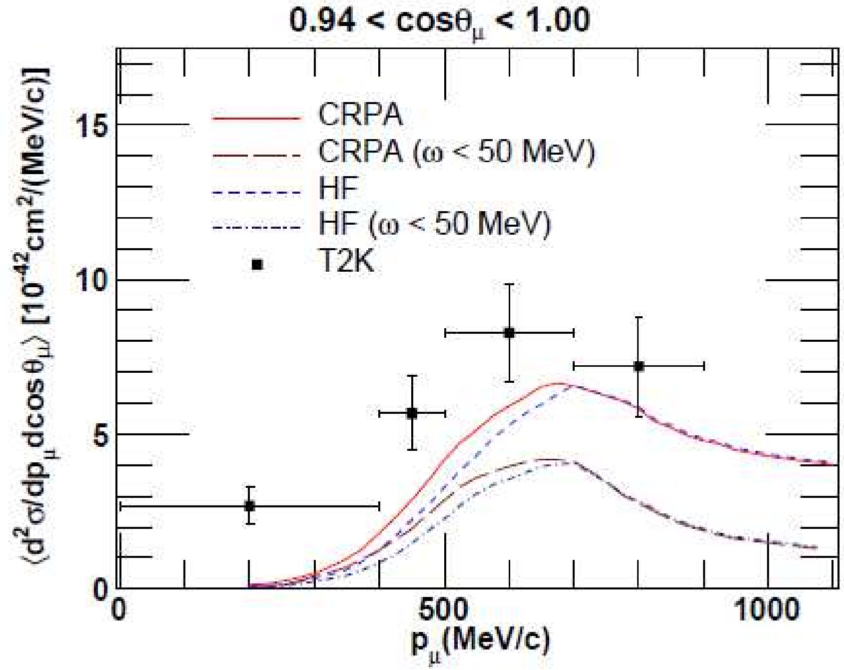
Forward scattering



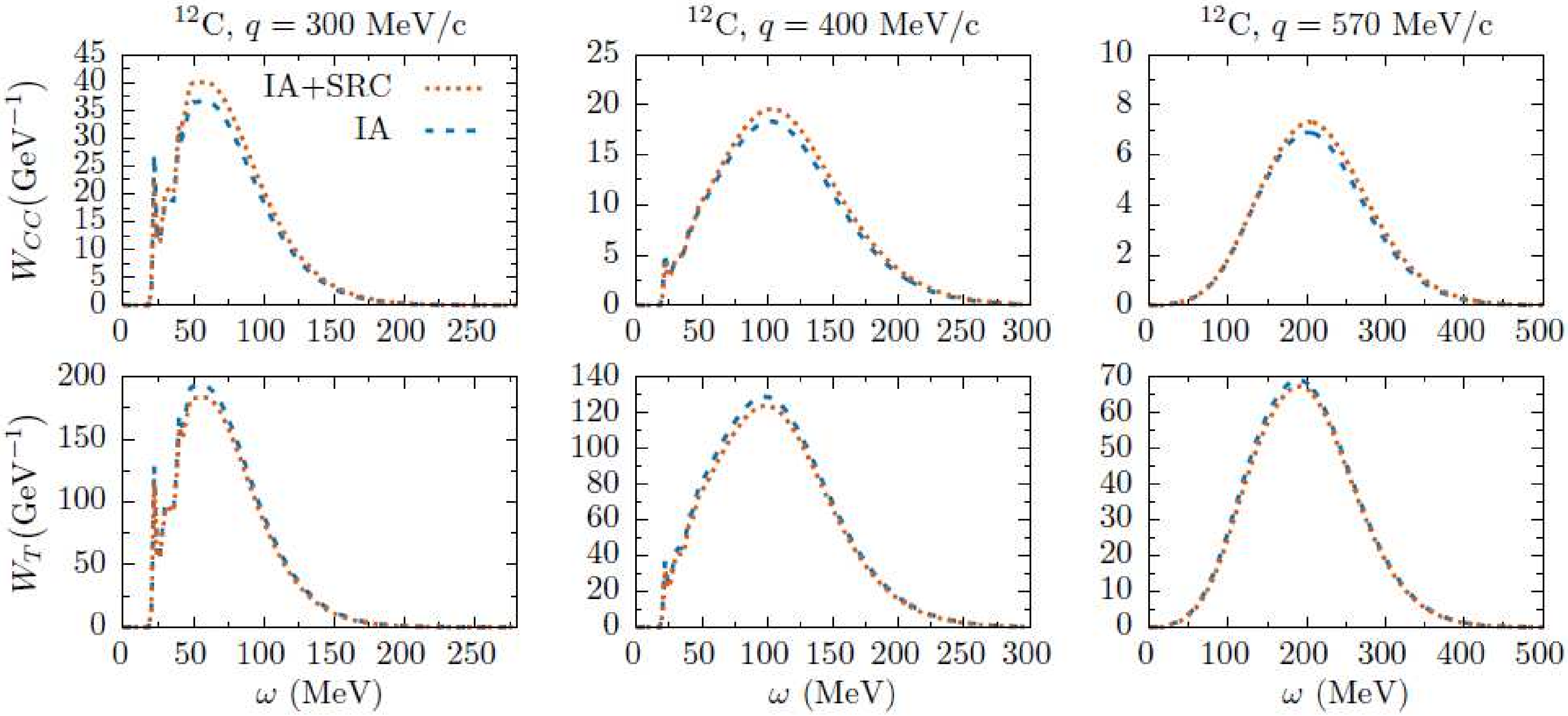
MiniBooNe



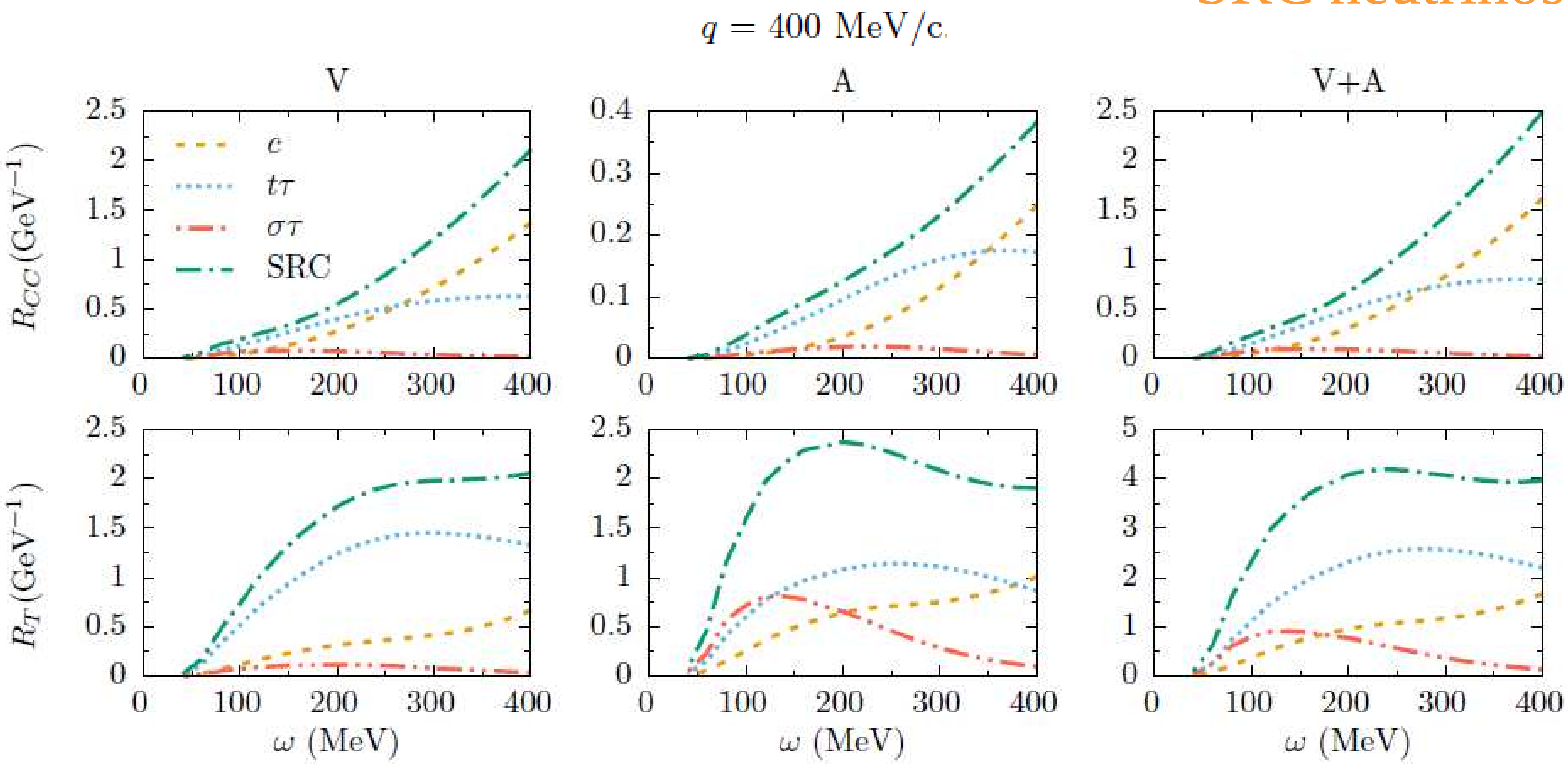
T2K

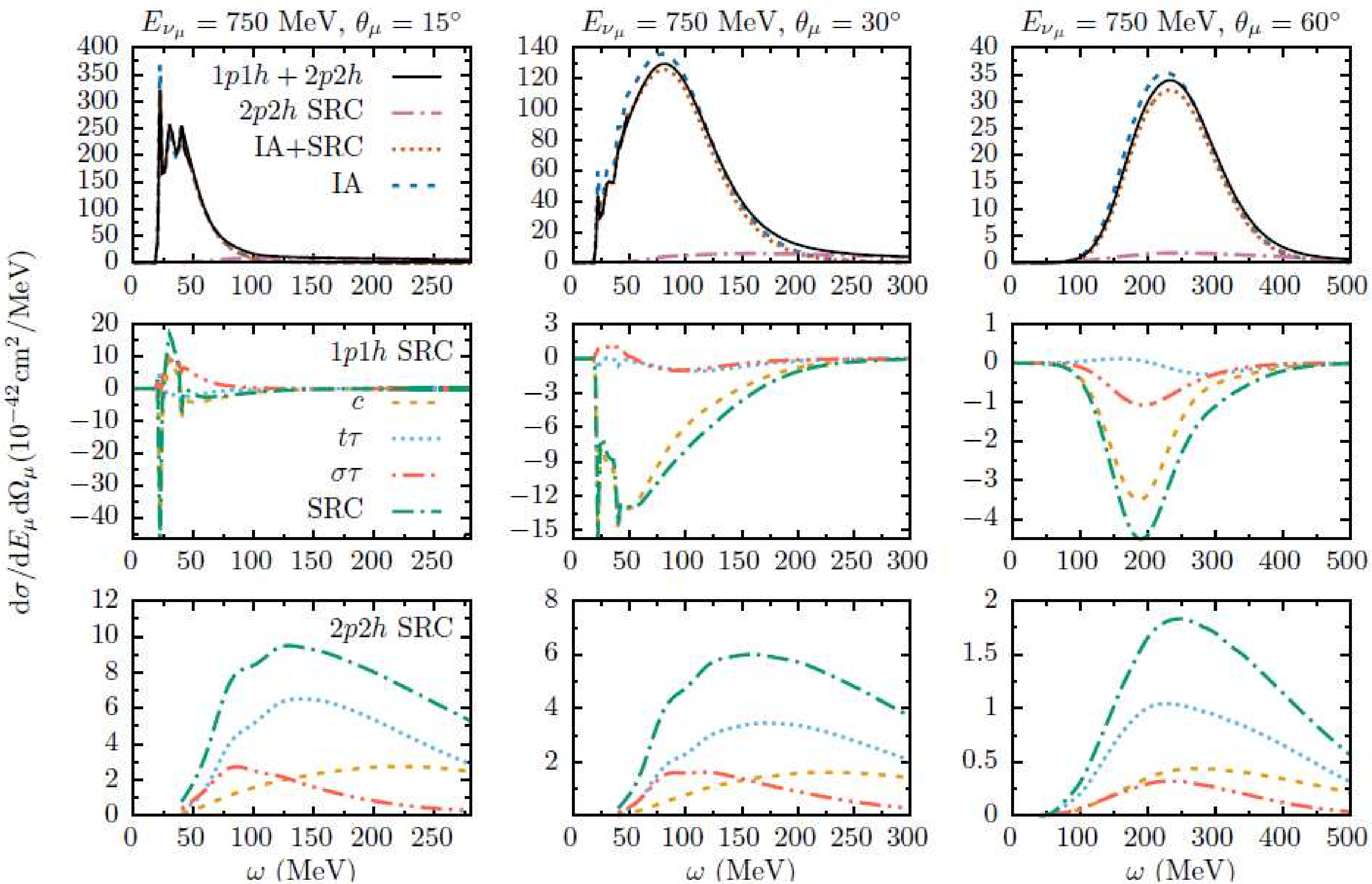


SRC neutrinos 1p1h



SRC neutrinos 2p2h

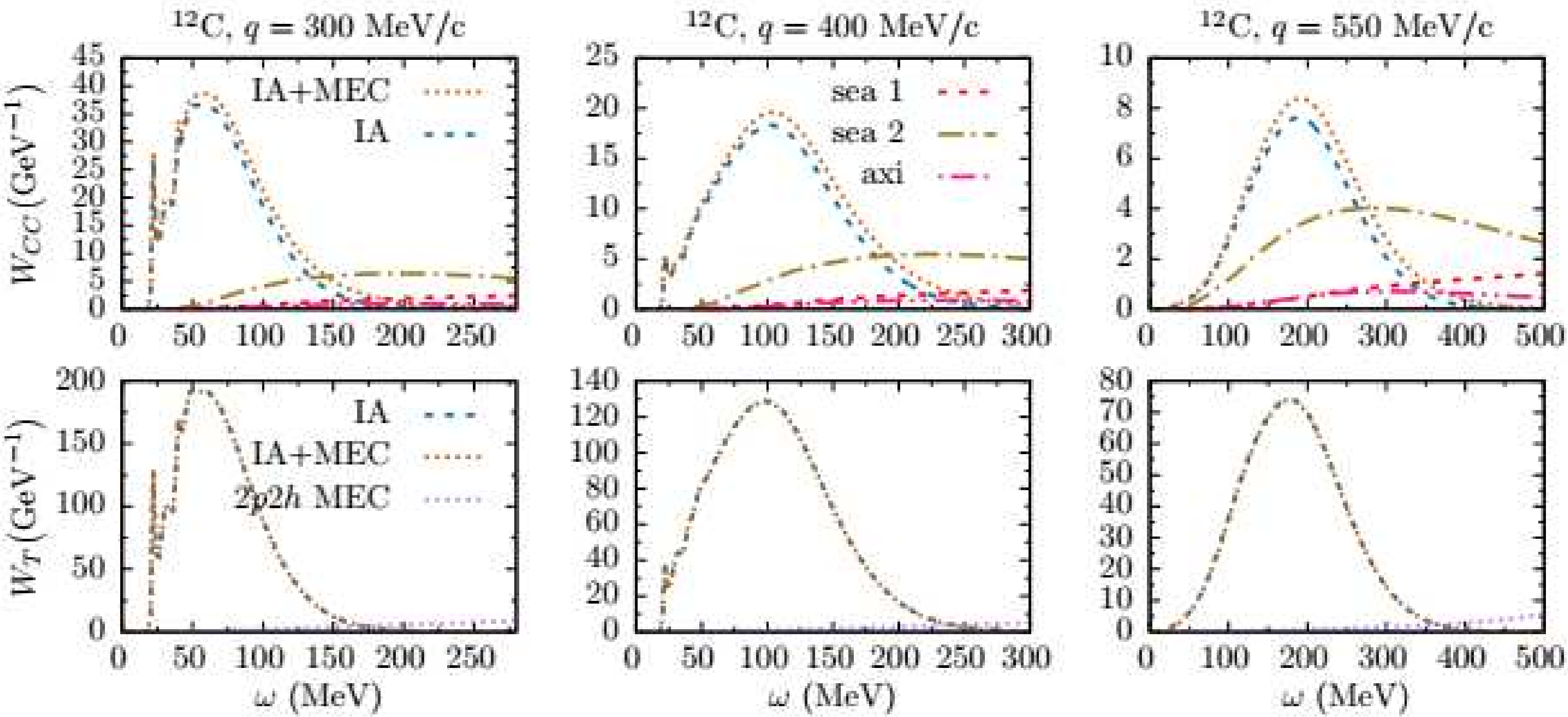




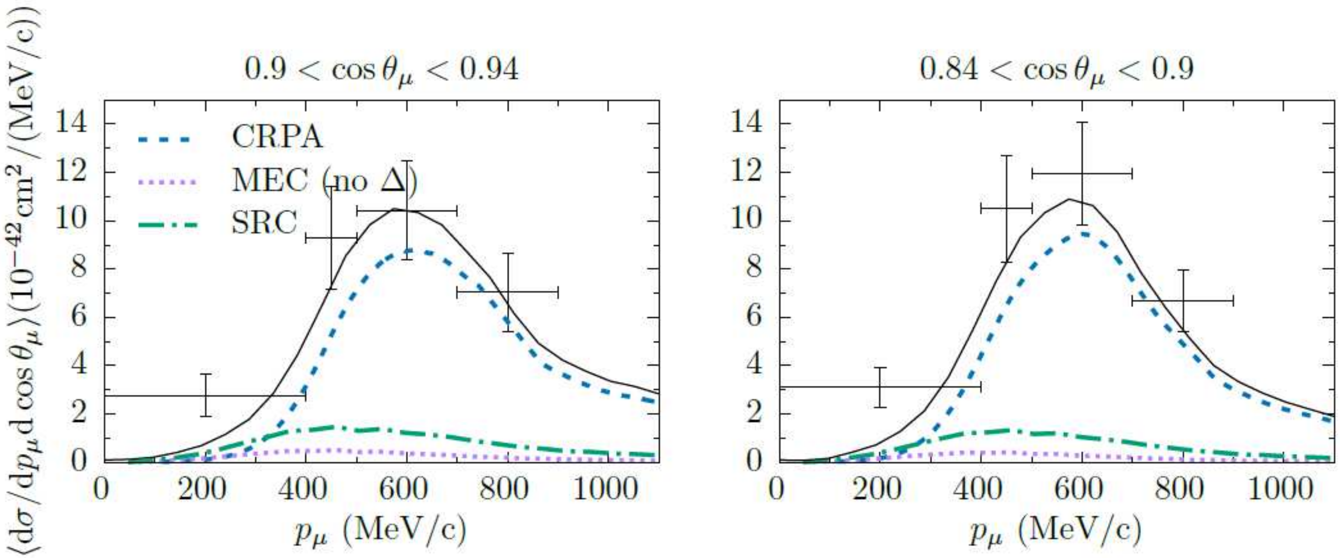
SRC
neutrinos
1p1h+2p2h

T. Van Cuyck et al
Phys. Rev. C 94,
024611 (2016)

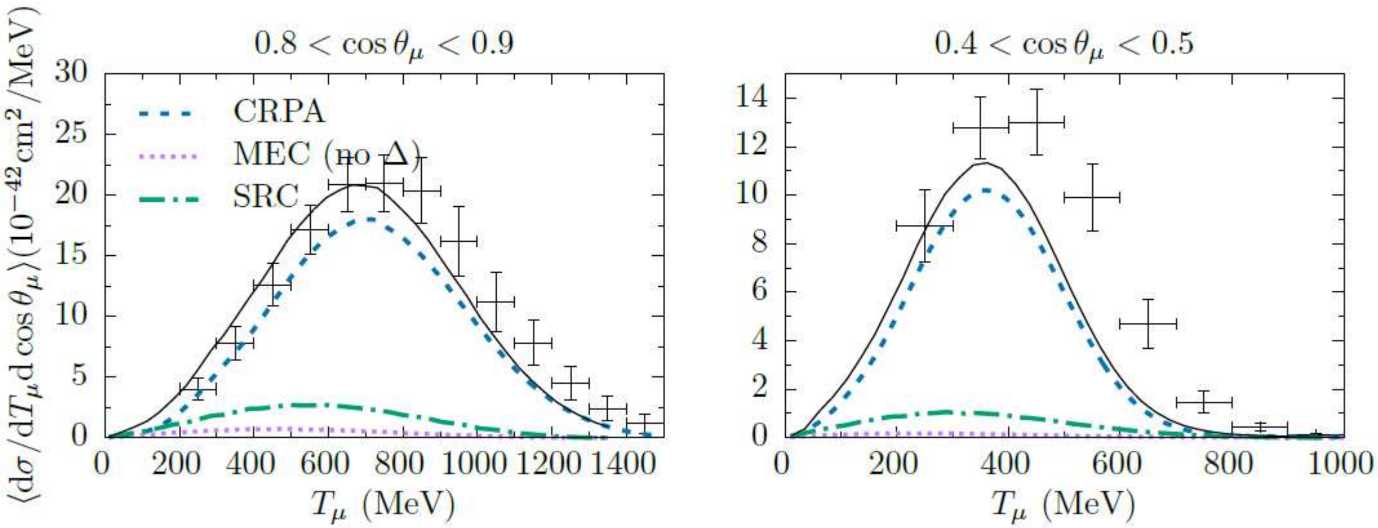
MEC neutrinos 2p2h



T2K



MiniBooNe



Summary

- Long- and short-range correlations in QE-like cross sections
- CRPA calculations provide extra strength for forward scattering arising from low-energy excitations
- This might affect CCQE neutrino cross sections as measured by MiniBooNe, T2K, …
- SRC and MEC affect 1- and 2-nucleon knockout processes