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

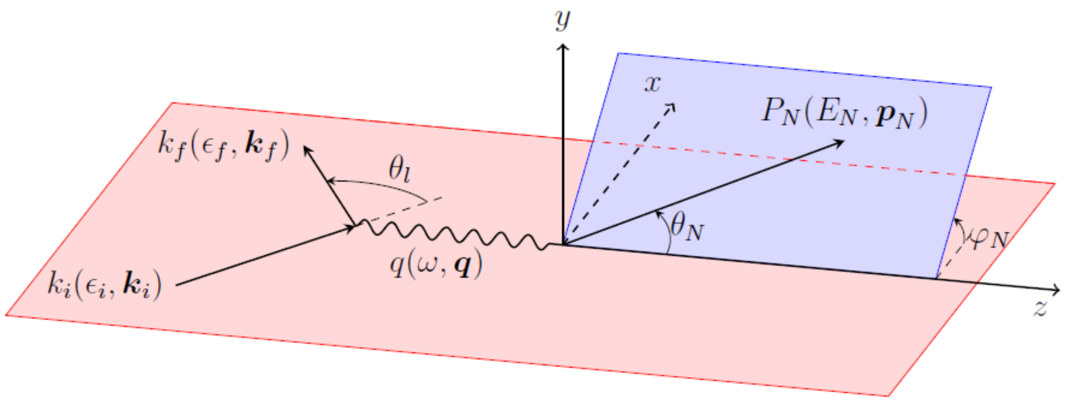
BriX

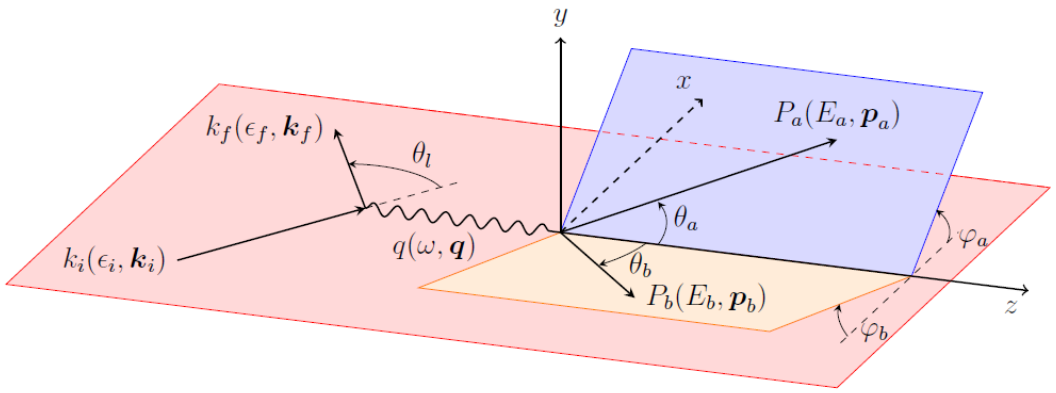
Outline

- 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
- effect of relativity and comparison with RMF models

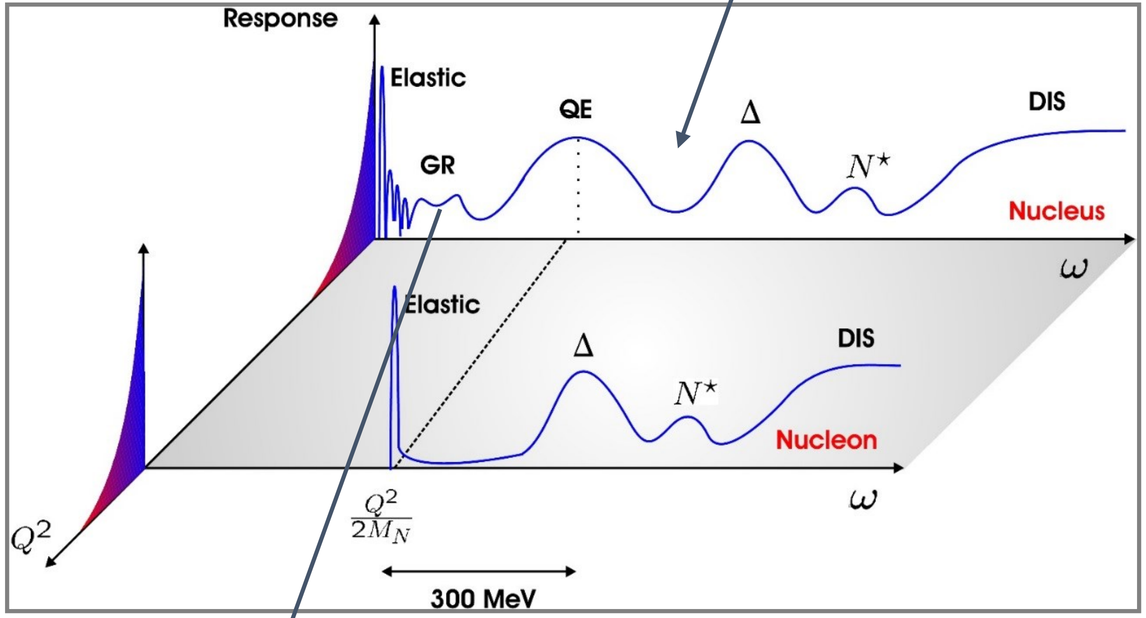
- Scheme-dependent separation
- Double counting

Neutrino-hadron scattering

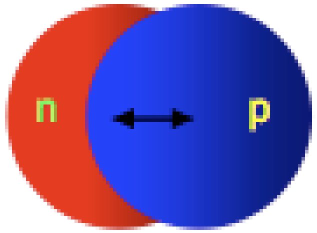


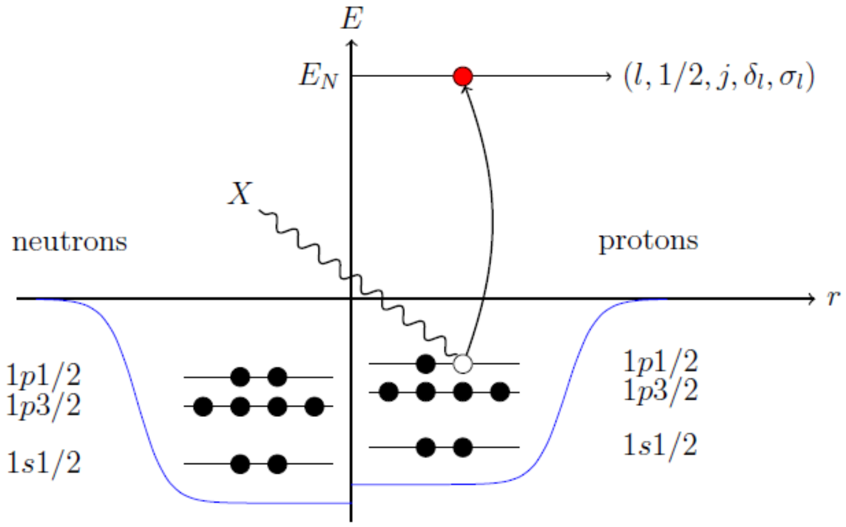


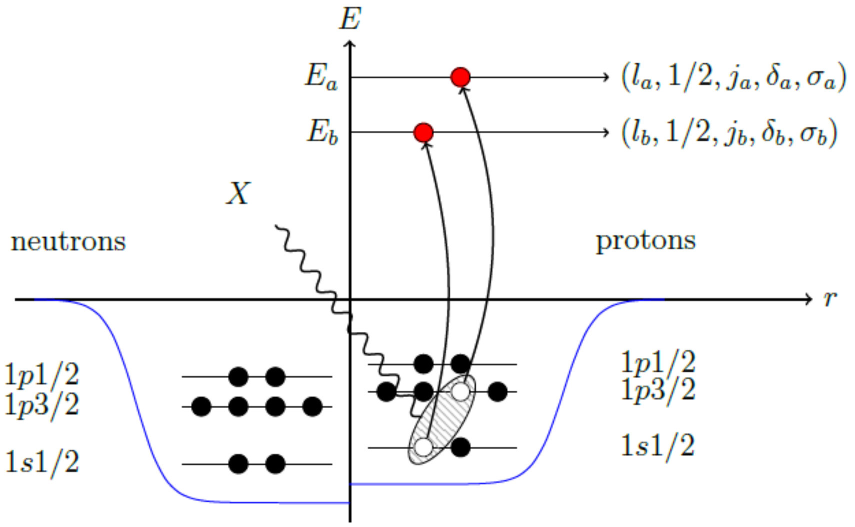
Dip region : multinucleon mechanisms



e.g.



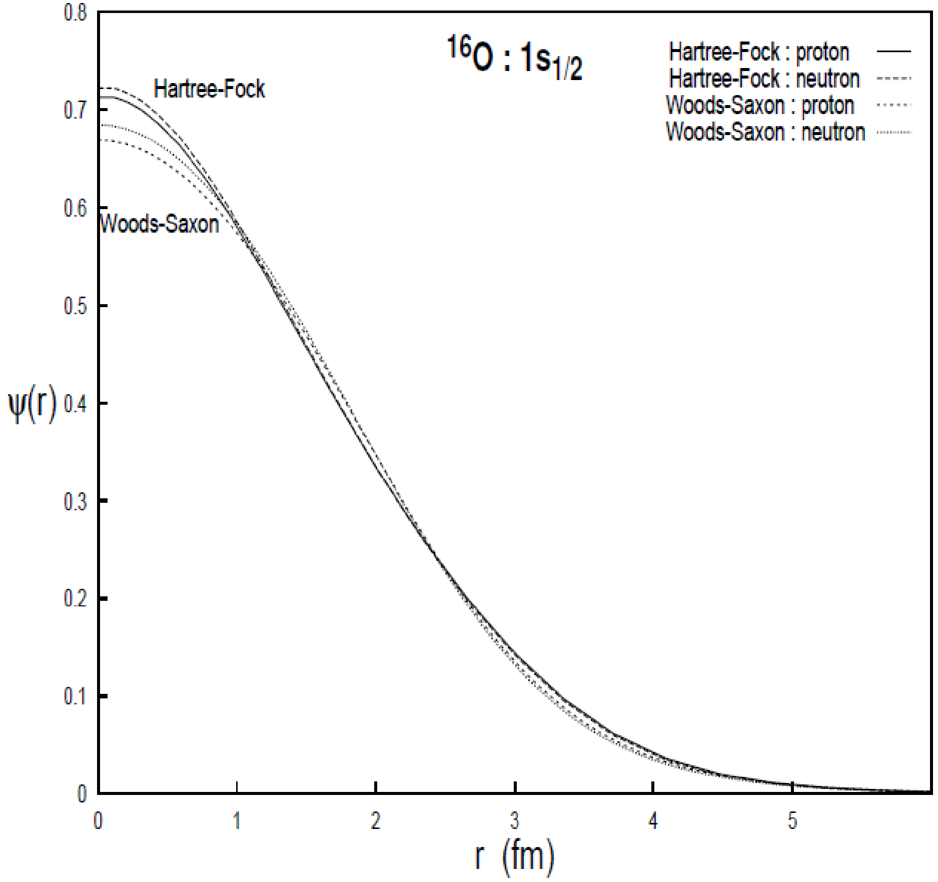


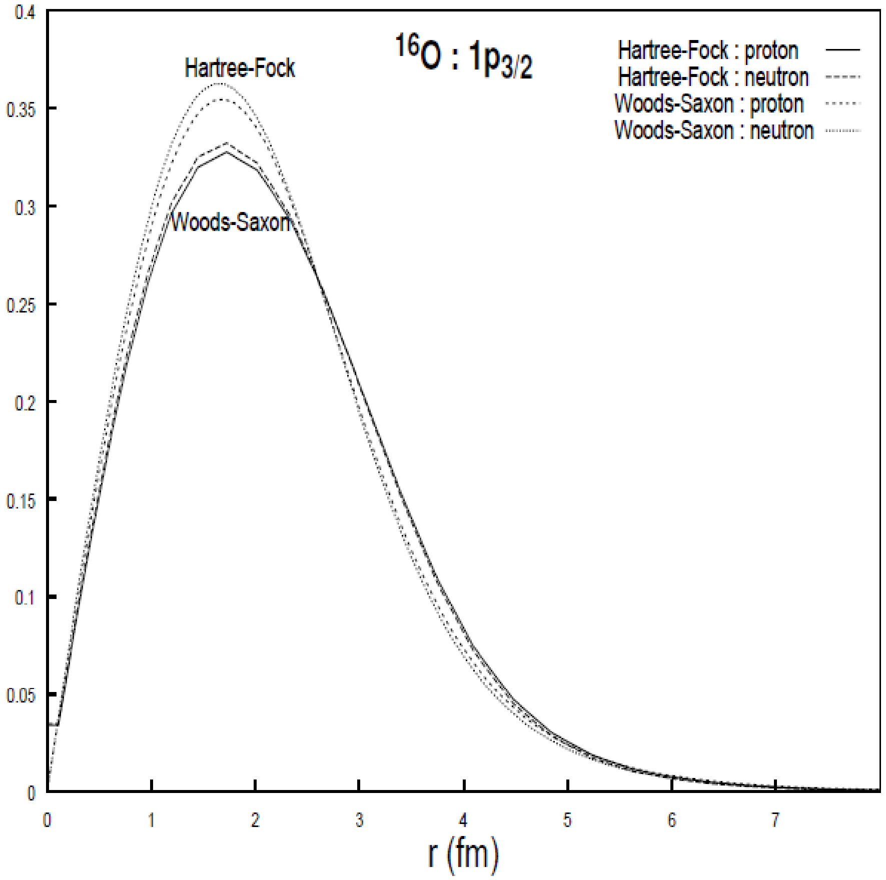


Cross section calculations

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

Bound state wave functions

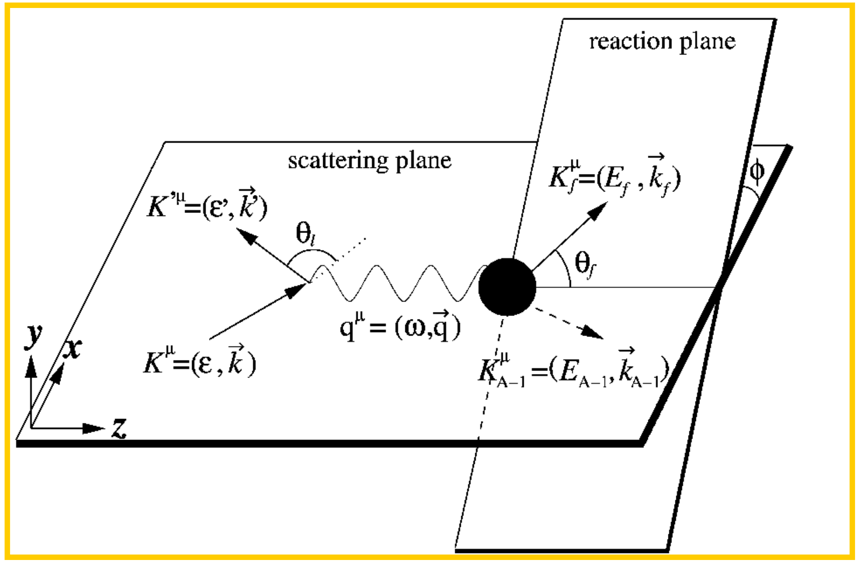




Hartree-Fock single-particle wave functions (Skyrme)

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

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

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

with

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

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

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

$$J_V^{0,\alpha}(\vec{x}) = \rho_V^{\alpha}(\vec{x}) = \sum_{i=1}^{A} G_E^{i,\alpha}\,\delta(\vec{x}-\vec{x}_i),$$

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

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

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

1-nucleon knockout cross sections

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

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

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

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

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 :

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

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

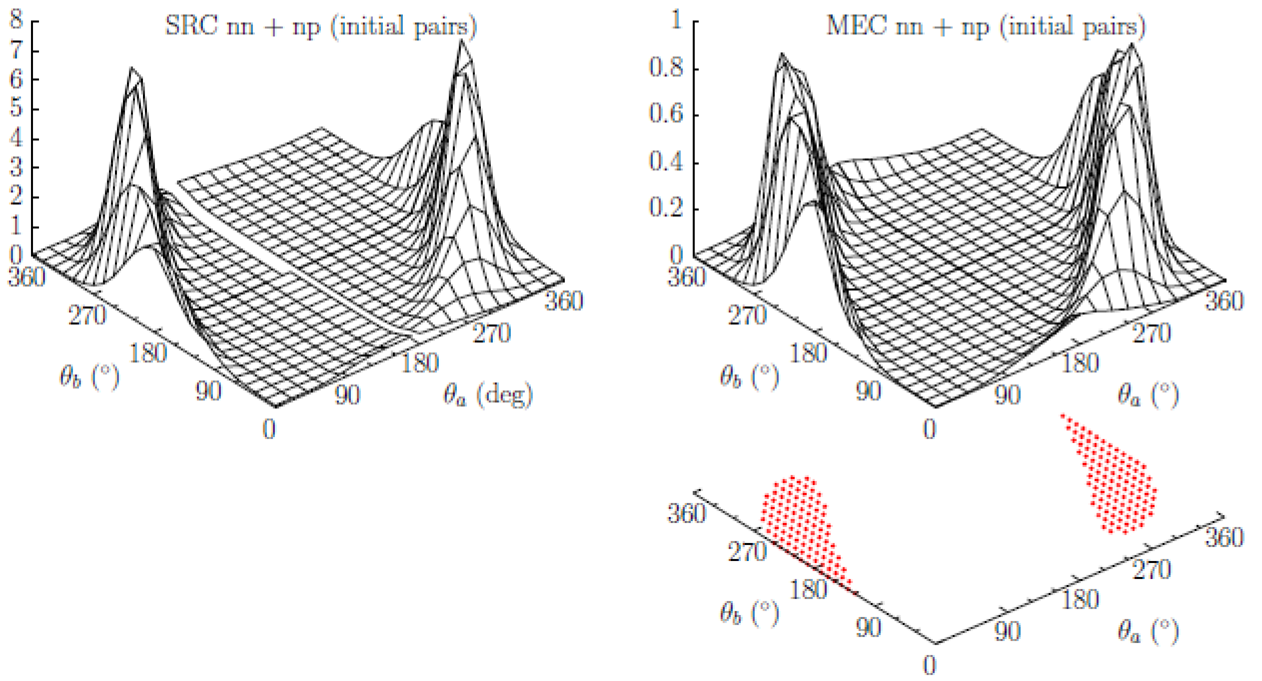
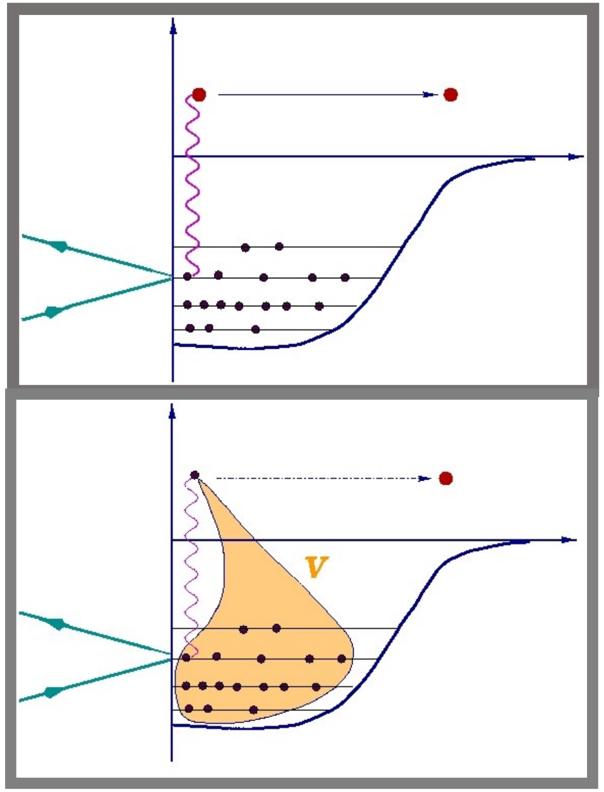


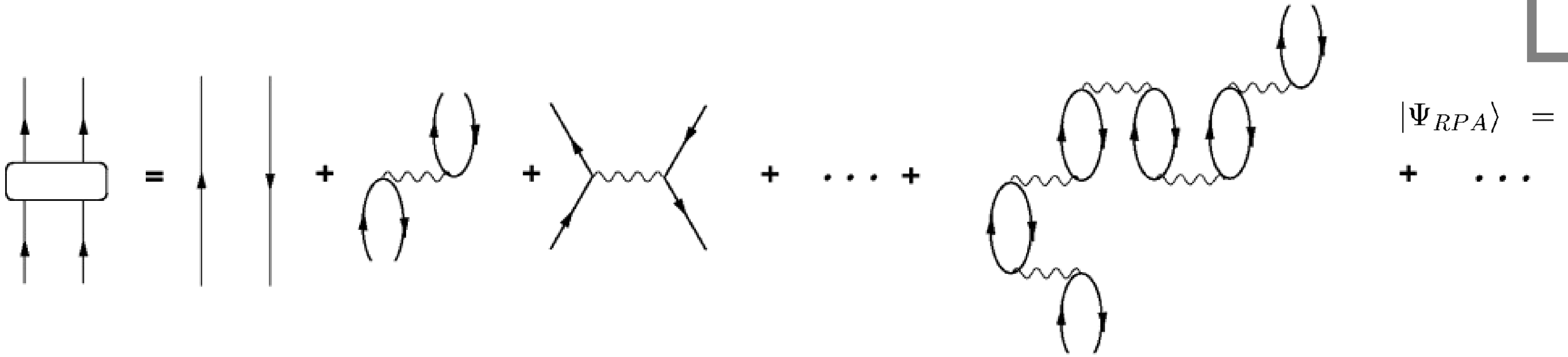
Figure 4.5: The $^{12}C(\nu_\mu, \mu^- N_a N_b)$ cross section (N_a = p, N_b = p′, n) at ϵ_{ν_μ} = 750 MeV, ϵ_μ = 550 MeV, $\theta_\mu = 15°$ and T_p = 50 MeV for in-plane kinematics. Left with SRCs, right with MECs, the bottom plot shows the (θ_a, θ_b) regions with $P_{12} < 300$ MeV/c.

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

Long-range correlations : Continuum RPA

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





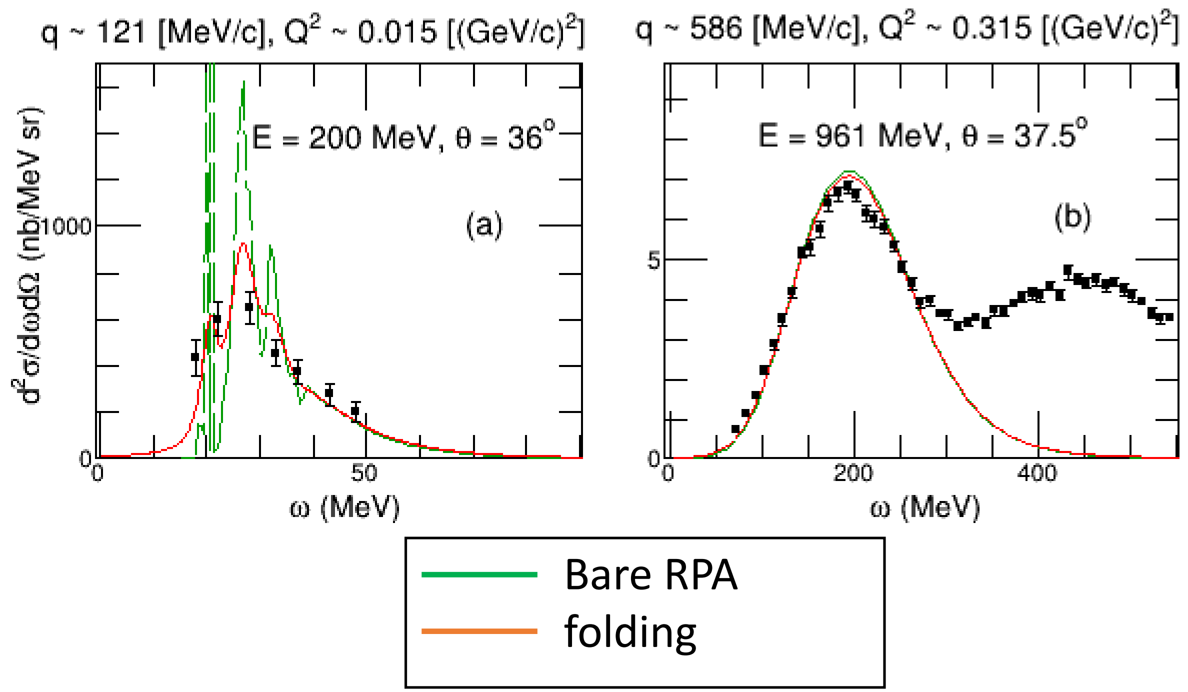
$$|\Psi_{RPA}\rangle = \sum_{c} \left\{ X_{(\Psi,C)} \left|ph^{-1}\right\rangle - Y_{(\Psi,C)} \left|hp^{-1}\right\rangle \right\} + \ \ldots$$

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

- 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

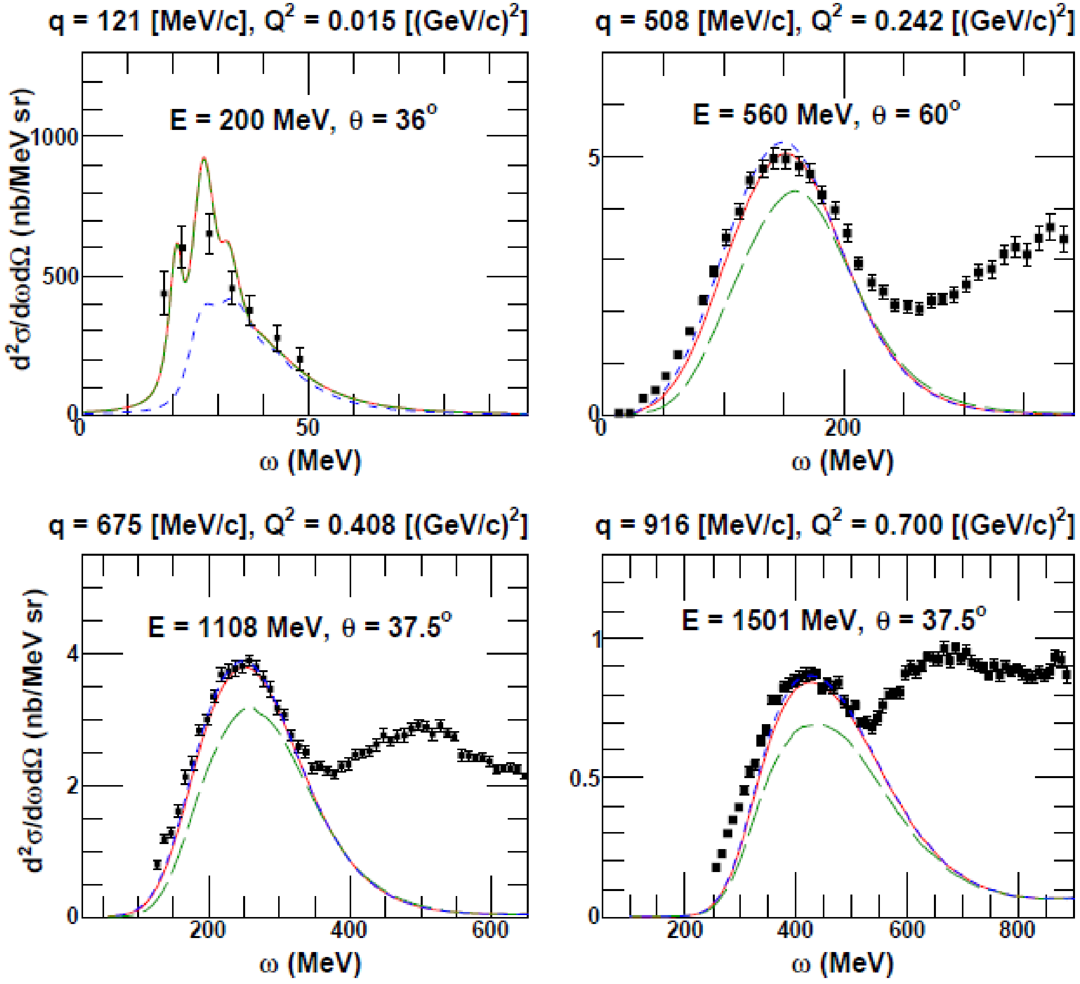
-influence of the spreading width of the particle states is implemented through a folding procedure



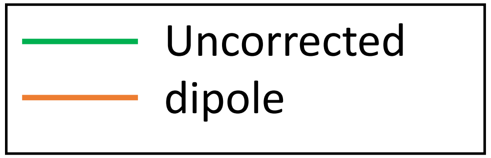
$$R'(q,\omega') = \int_{-\infty}^{\infty} d\omega \; R(q,\omega) \; L(\omega,\omega'),$$

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

•Regularization of the residual interaction :



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



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

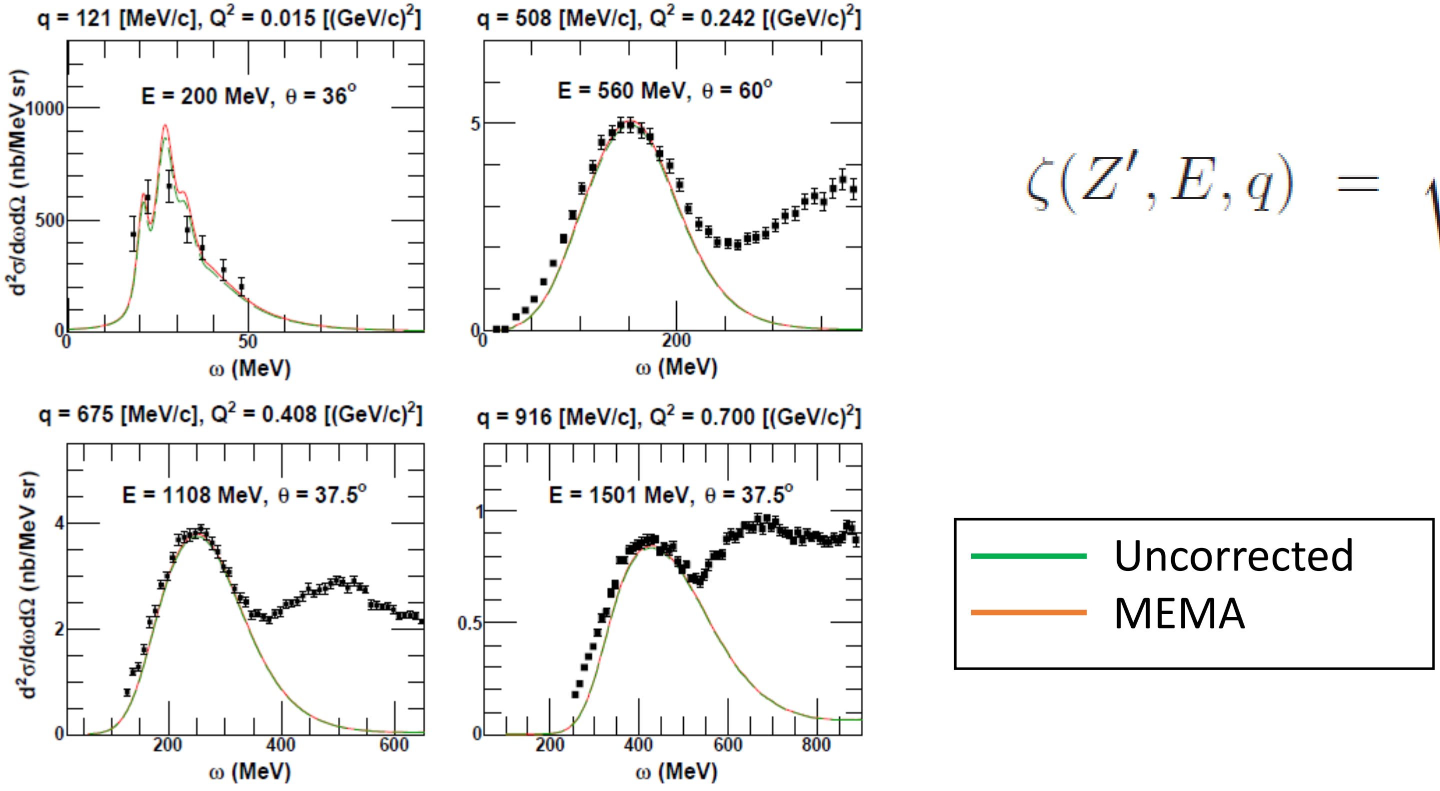
- ✓ Low energies : Fermi function

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

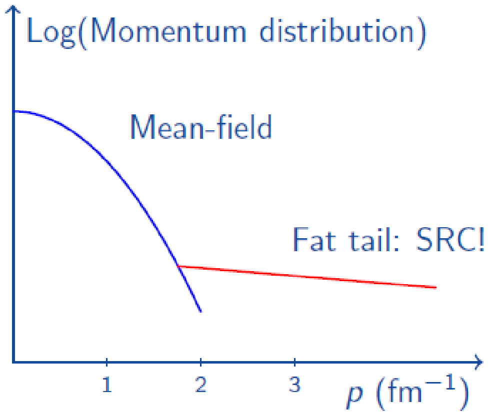
- ✓ High energies : modified effective momentum approximation (J. Engel, PRC57,2004 (1998))

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

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

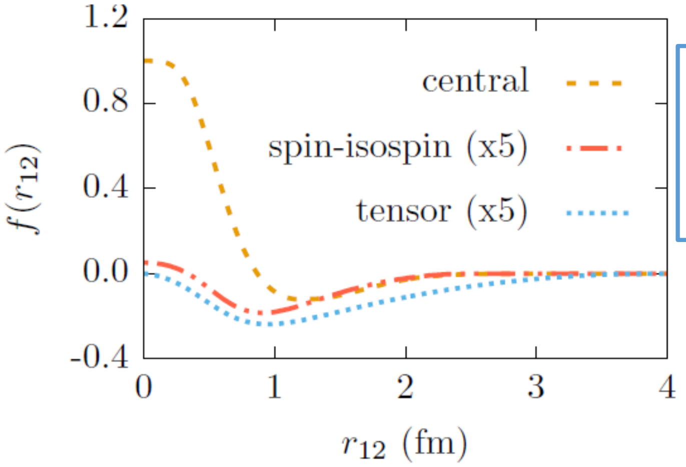


Short-range correlations



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

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

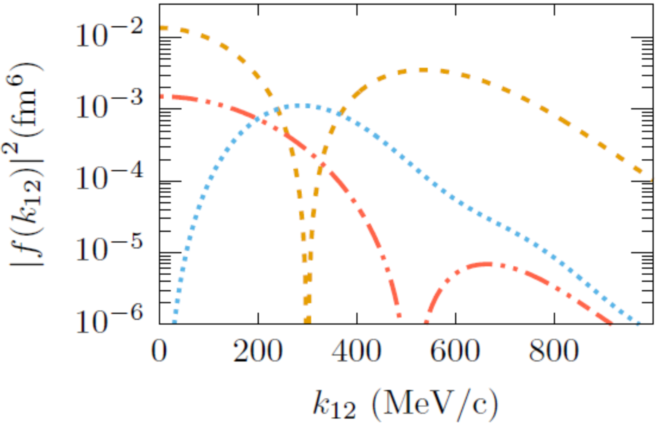


Shifting the complexity induced by correlations from the wave functions to the operators

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

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

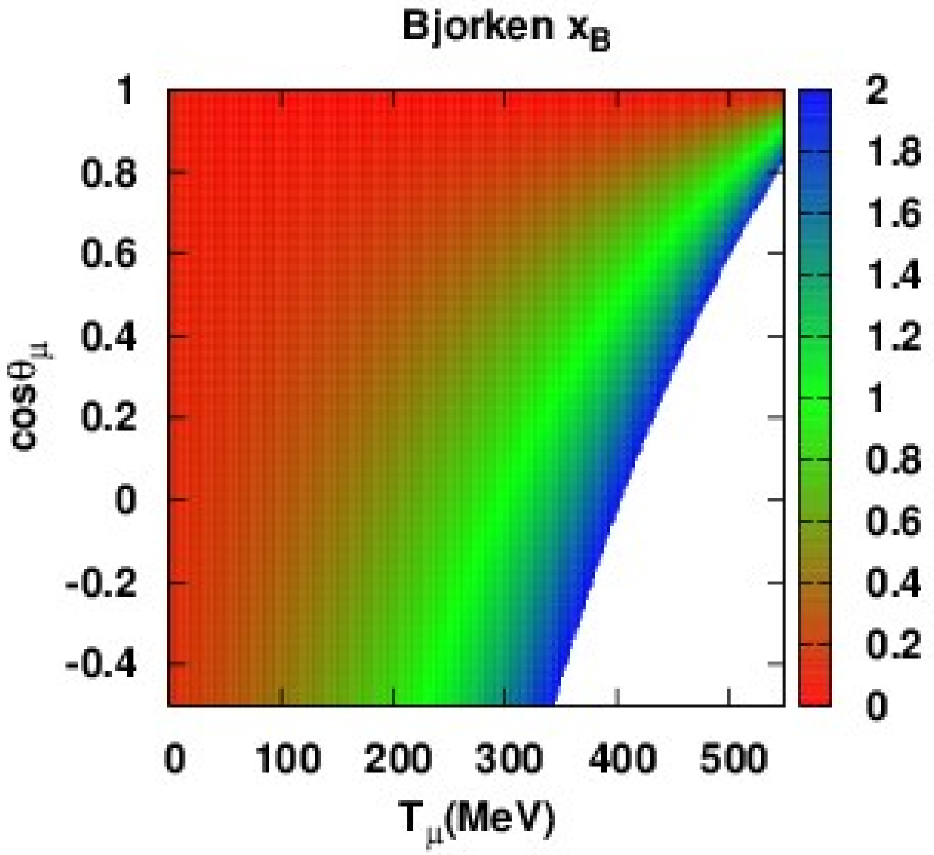
$$\widehat{J}^{[1],\mathrm{in}}_{\mu}(i,j) = \left[\widehat{J}^{[1]}_{\mu}(i) + \widehat{J}^{[1]}_{\mu}(j)\right]\widehat{l}(i,j)$$

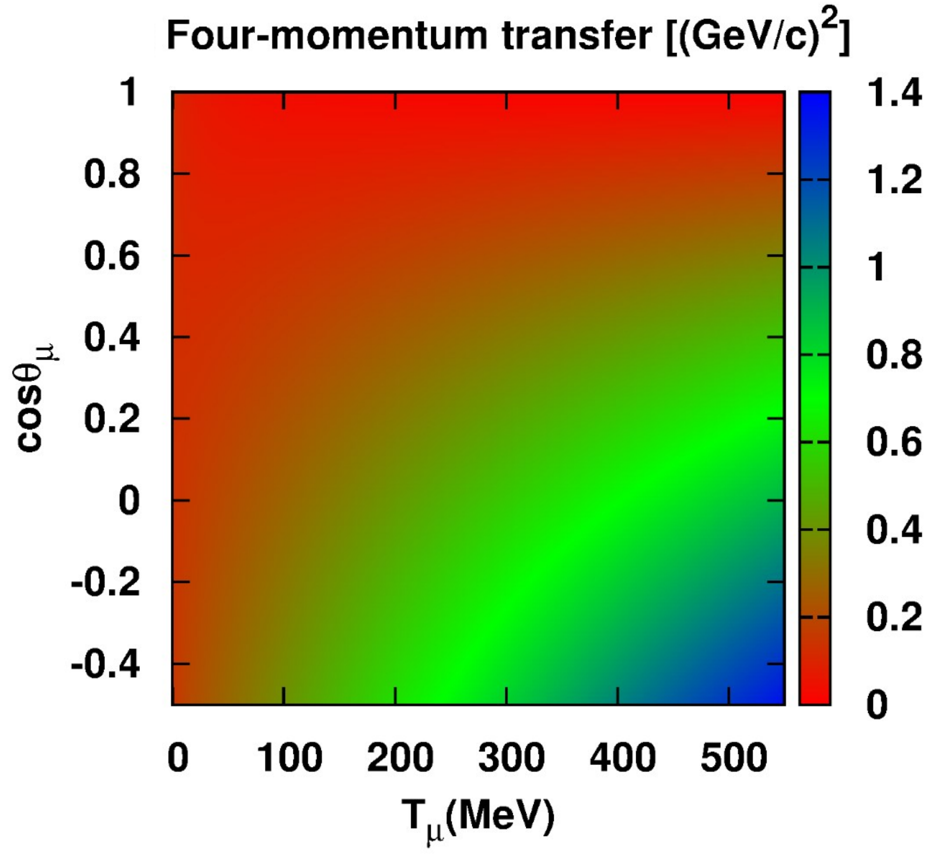


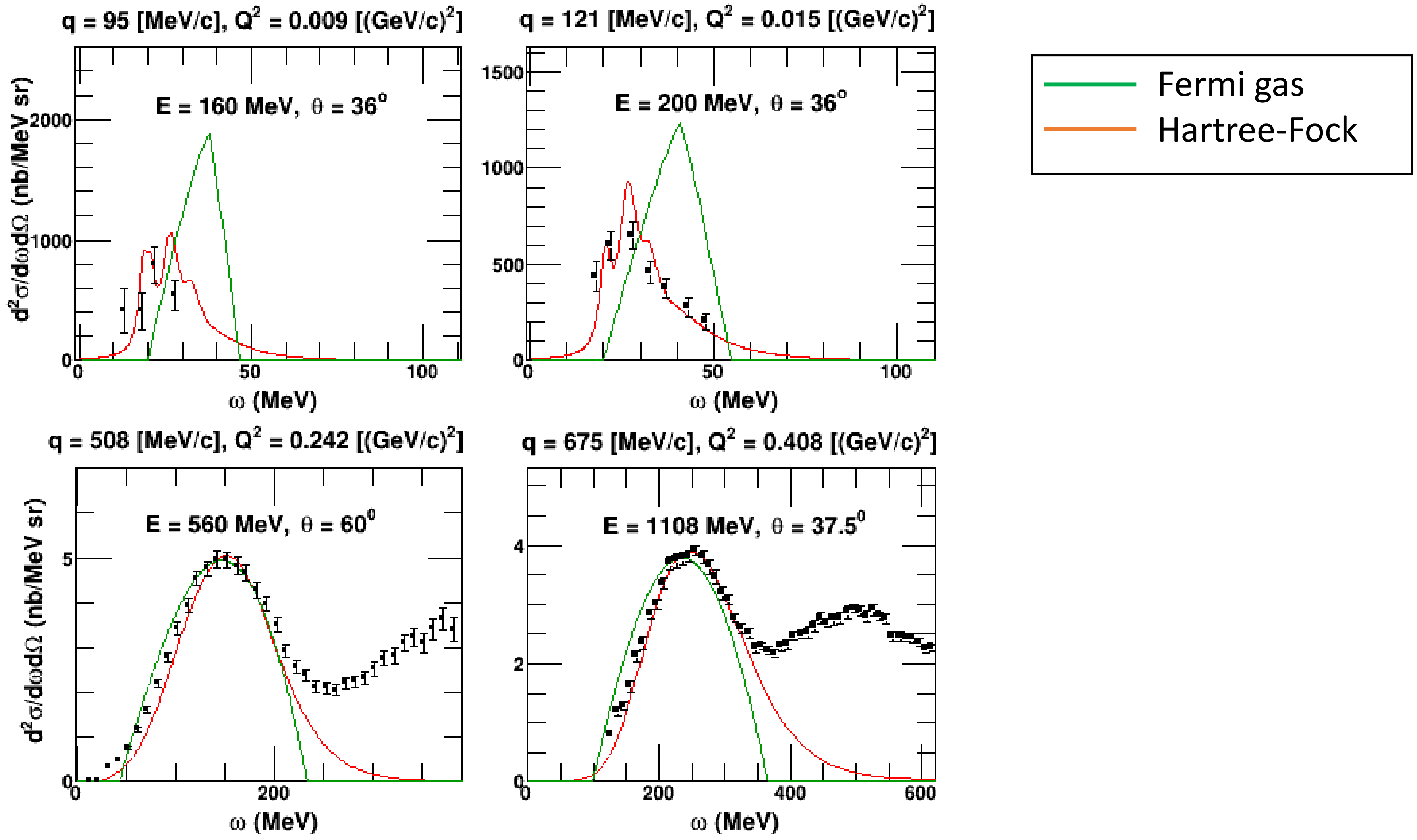
Gearheart (1994) Pieper (1992)

What kinematic region are we aiming at ?

E_ν=700MeV



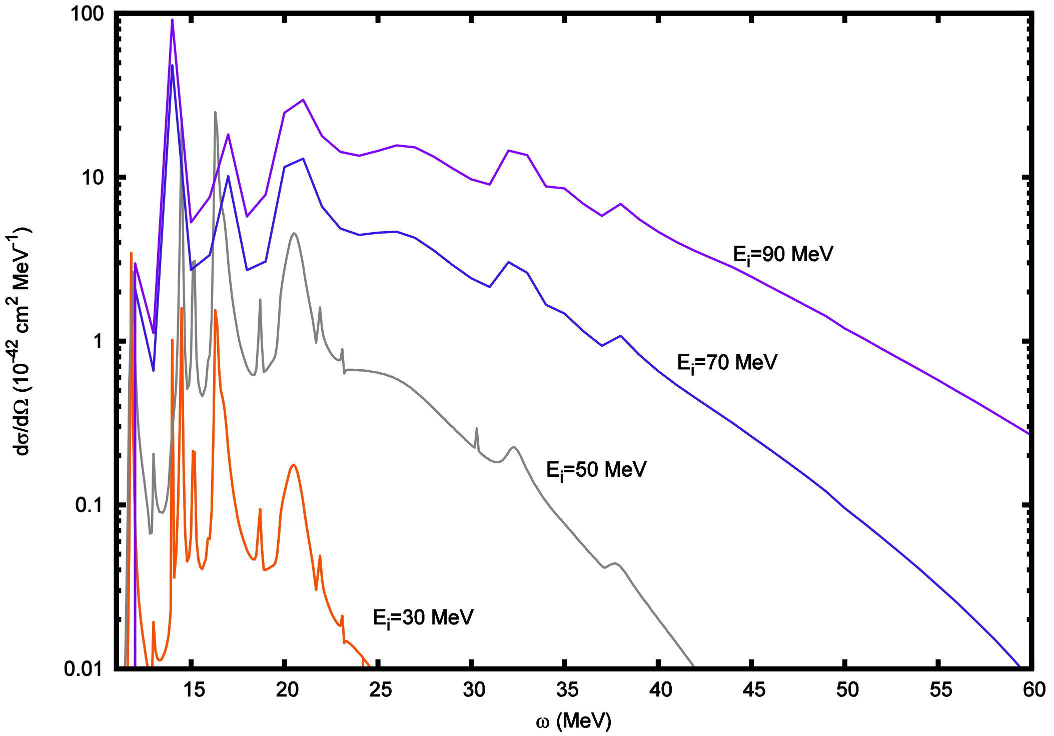


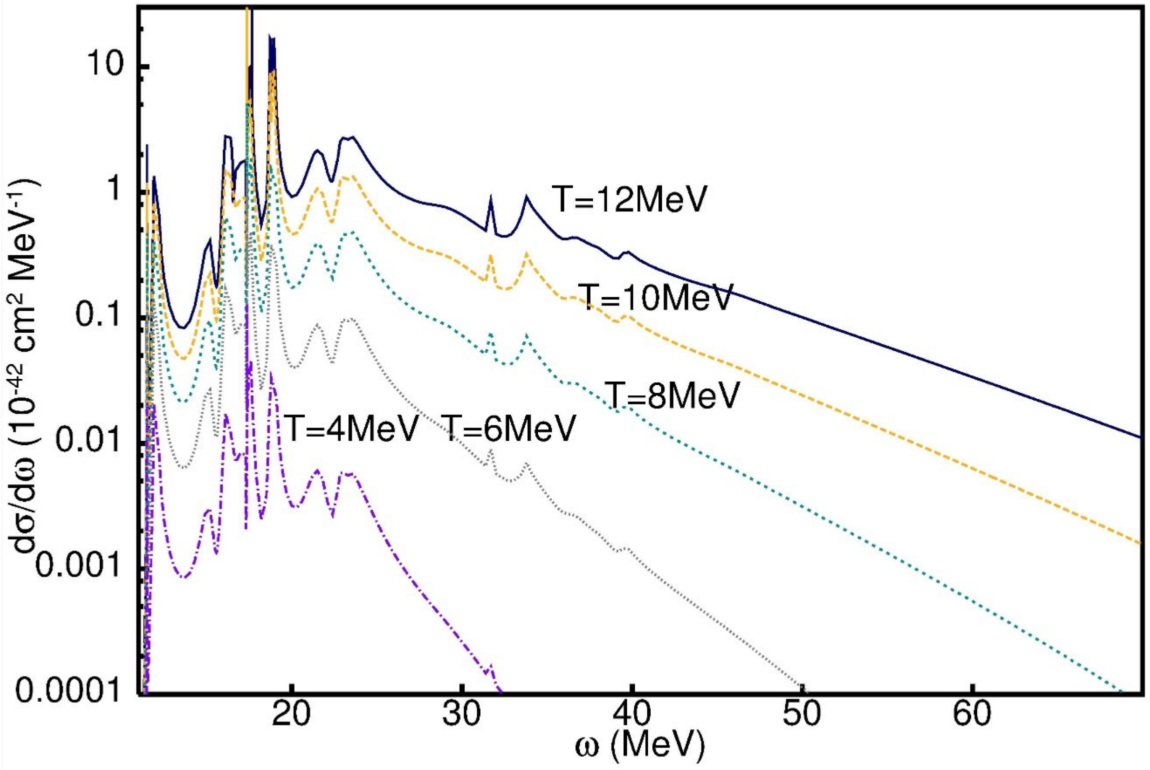

q = 95 [MeV/c], Q^2 = 0.009 [(GeV/c)^2]
E = 160 MeV, θ = 36°
q = 121 [MeV/c], Q^2 = 0.015 [(GeV/c)^2]
E = 200 MeV, θ = 36°
q = 508 [MeV/c], Q^2 = 0.242 [(GeV/c)^2]
E = 560 MeV, θ = 60°
q = 675 [MeV/c], Q^2 = 0.408 [(GeV/c)^2]
E = 1108 MeV, θ = 37.5°
d²σ/dωdΩ (nb/MeV sr)
ω (MeV)
Fermi gas
Hartree-Fock

Neutrino scattering results at low energies :

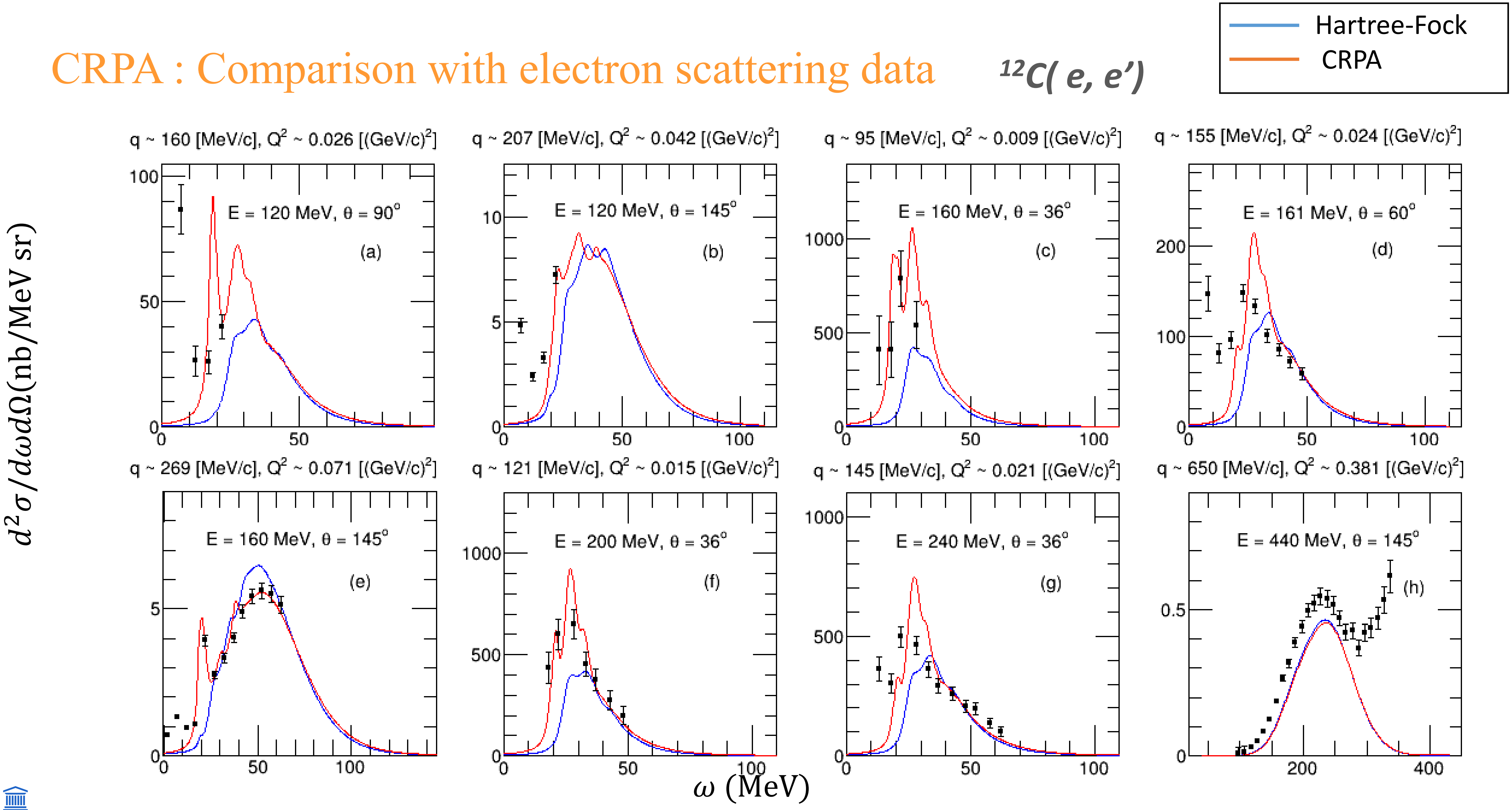
$^{16}O(\nu, \nu')\, ^{16}O^*$

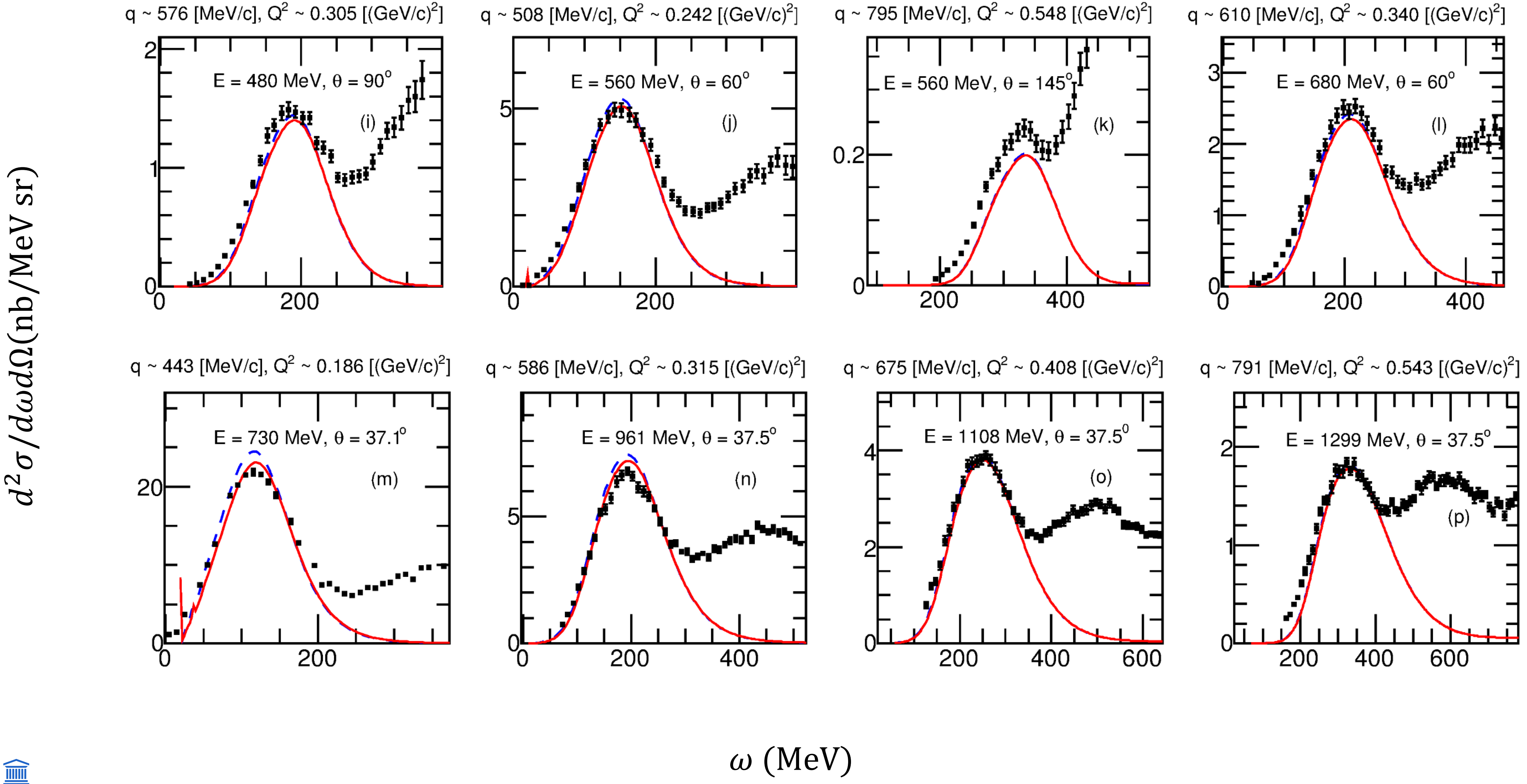
Folded cross sections supernova neutrino spectra :



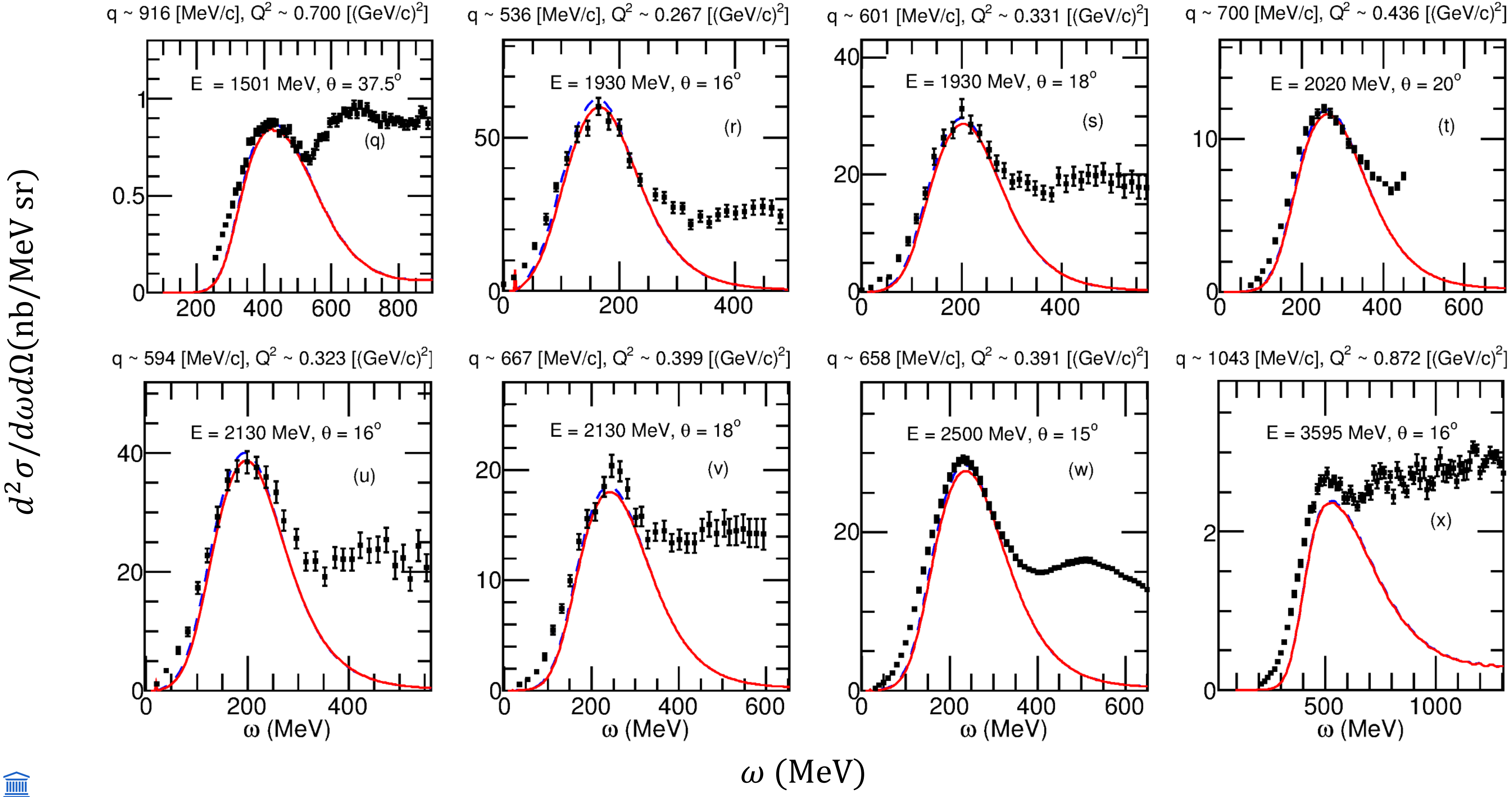


CRPA : Comparison with electron scattering data



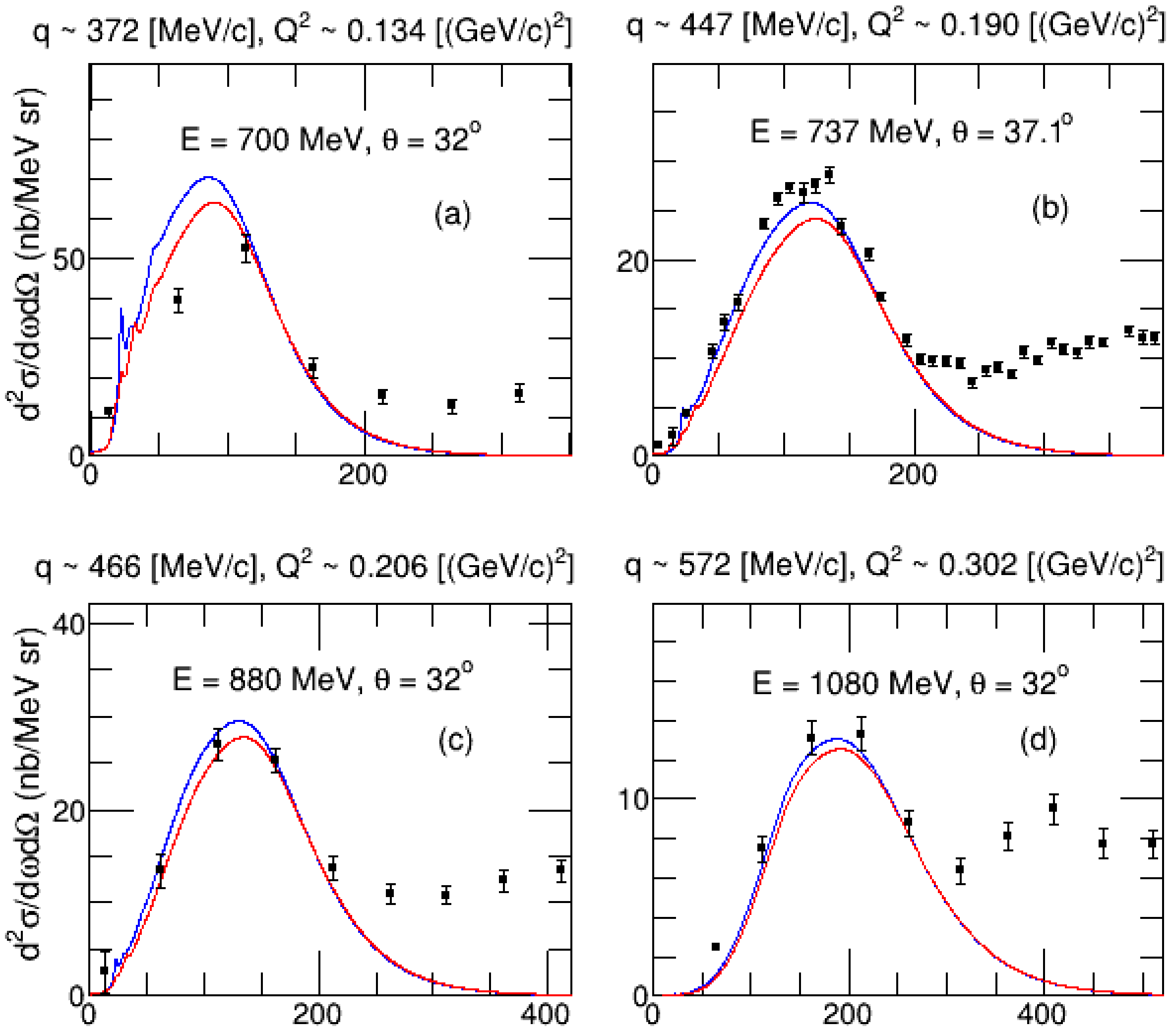


q ~ 576 [MeV/c], Q^2 ~ 0.305 [(GeV/c)^2]
E = 480 MeV, θ = 90°
(i)
q ~ 508 [MeV/c], Q^2 ~ 0.242 [(GeV/c)^2]
E = 560 MeV, θ = 60°
(j)
q ~ 795 [MeV/c], Q^2 ~ 0.548 [(GeV/c)^2]
E = 560 MeV, θ = 145°
(k)
q ~ 610 [MeV/c], Q^2 ~ 0.340 [(GeV/c)^2]
E = 680 MeV, θ = 60°
(l)
q ~ 443 [MeV/c], Q^2 ~ 0.186 [(GeV/c)^2]
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)
d²σ/dωdΩ(nb/MeV sr)
ω (MeV)



q ~ 916 [MeV/c], Q^2 ~ 0.700 [(GeV/c)^2]
E = 1501 MeV, θ = 37.5°
(q)
q ~ 536 [MeV/c], Q^2 ~ 0.267 [(GeV/c)^2]
E = 1930 MeV, θ = 16°
(r)
q ~ 601 [MeV/c], Q^2 ~ 0.331 [(GeV/c)^2]
E = 1930 MeV, θ = 18°
(s)
q ~ 700 [MeV/c], Q^2 ~ 0.436 [(GeV/c)^2]
E = 2020 MeV, θ = 20°
(t)
q ~ 594 [MeV/c], Q^2 ~ 0.323 [(GeV/c)^2]
E = 2130 MeV, θ = 16°
(u)
q ~ 667 [MeV/c], Q^2 ~ 0.399 [(GeV/c)^2]
E = 2130 MeV, θ = 18°
(v)
q ~ 658 [MeV/c], Q^2 ~ 0.391 [(GeV/c)^2]
E = 2500 MeV, θ = 15°
(w)
q ~ 1043 [MeV/c], Q^2 ~ 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)

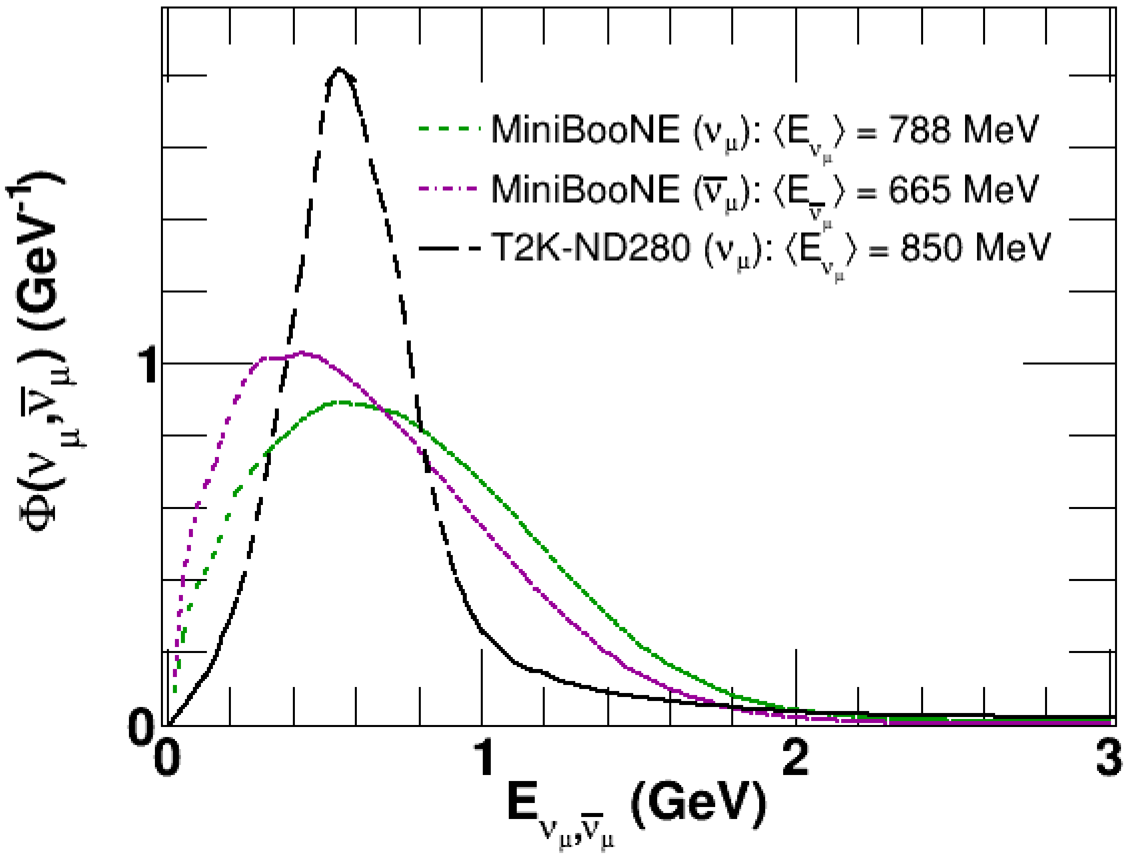
$^{16}O(e, e')$

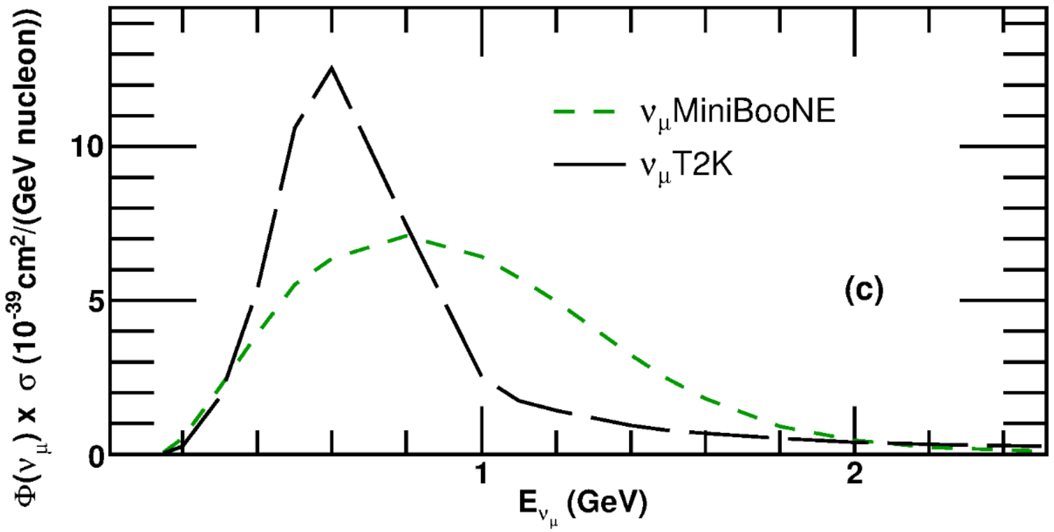


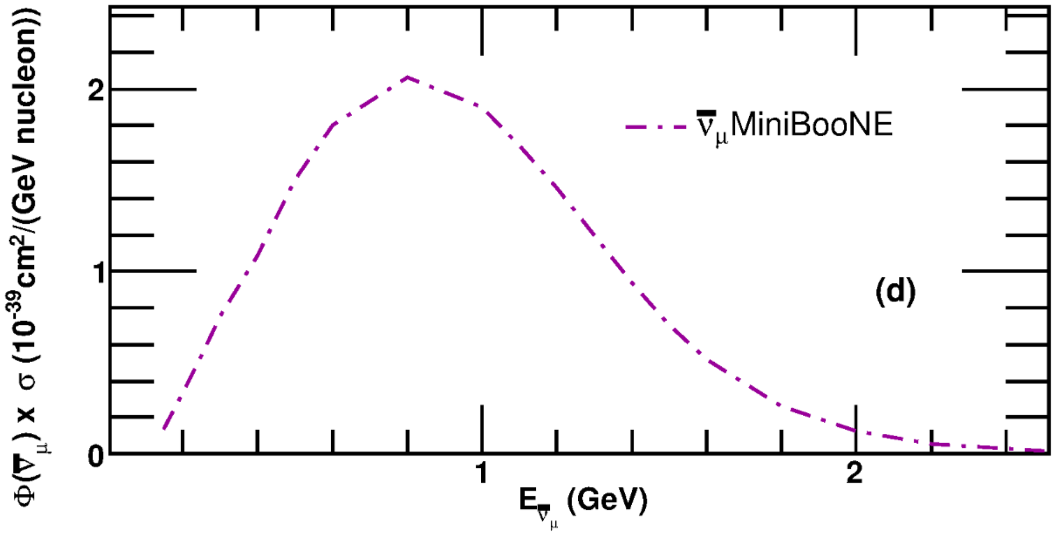
- Good overall agreement with e-scattering data

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).

CRPA : Comparison with neutrino data

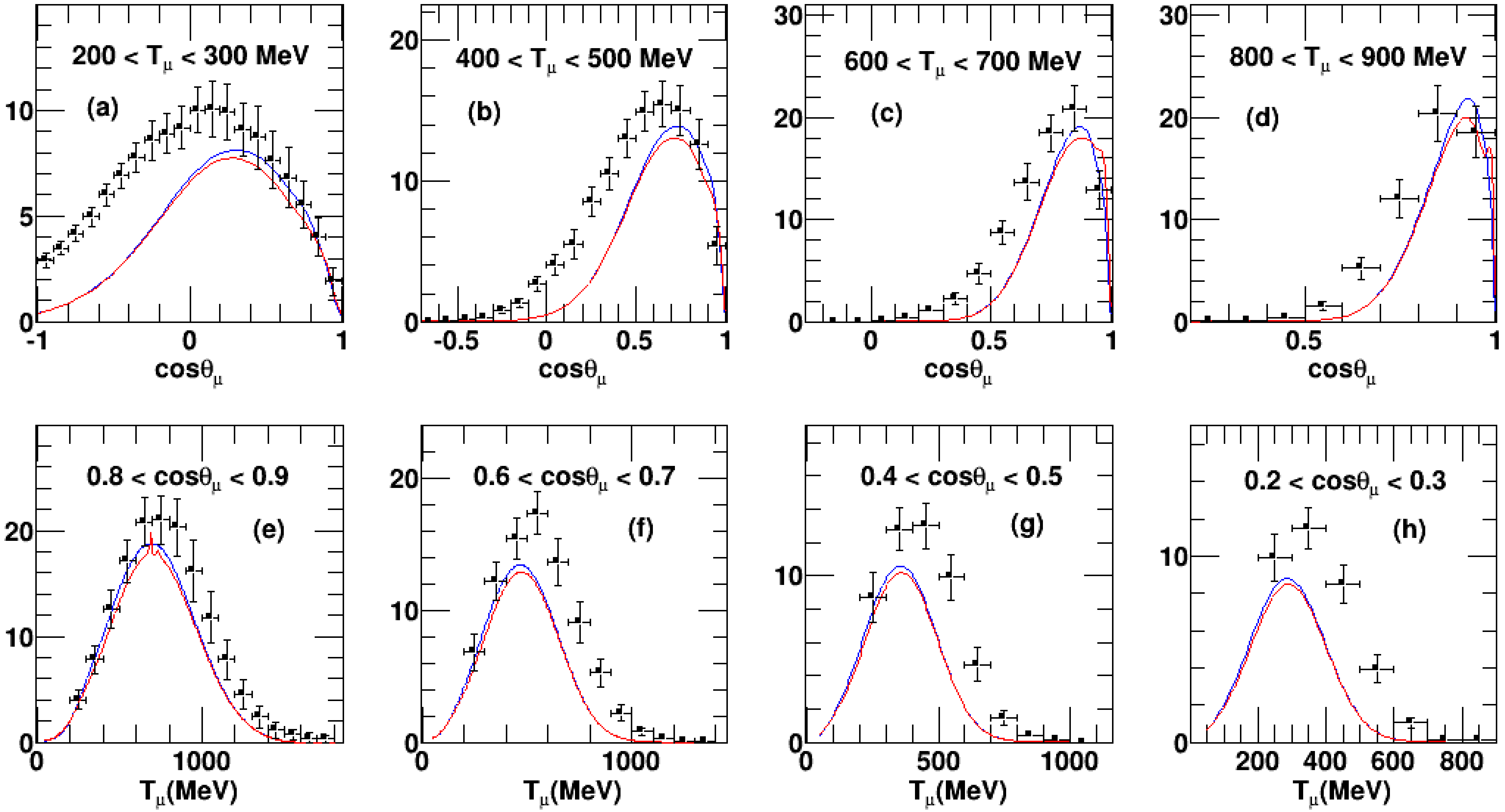






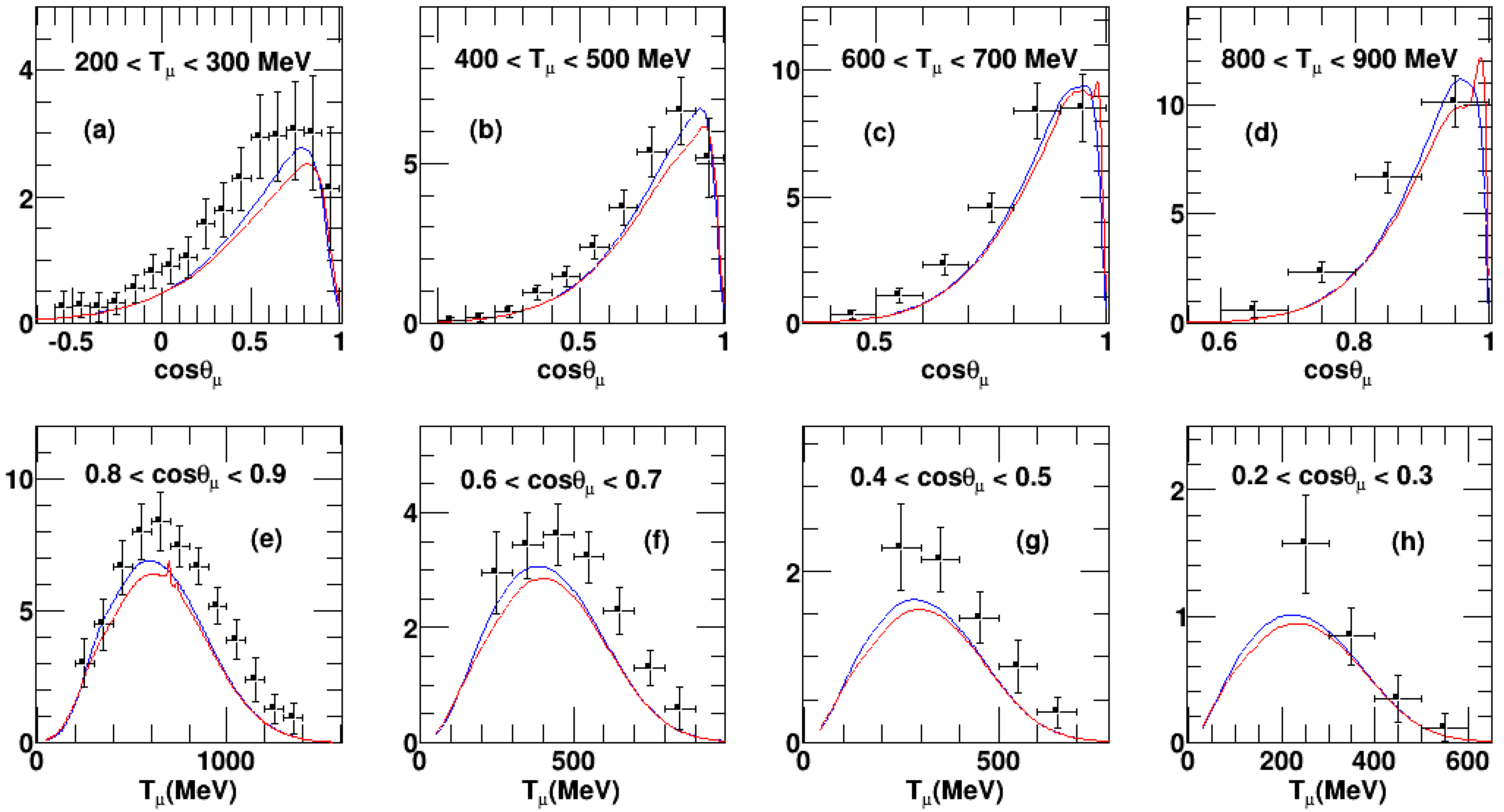
MiniBooNe ν_μ

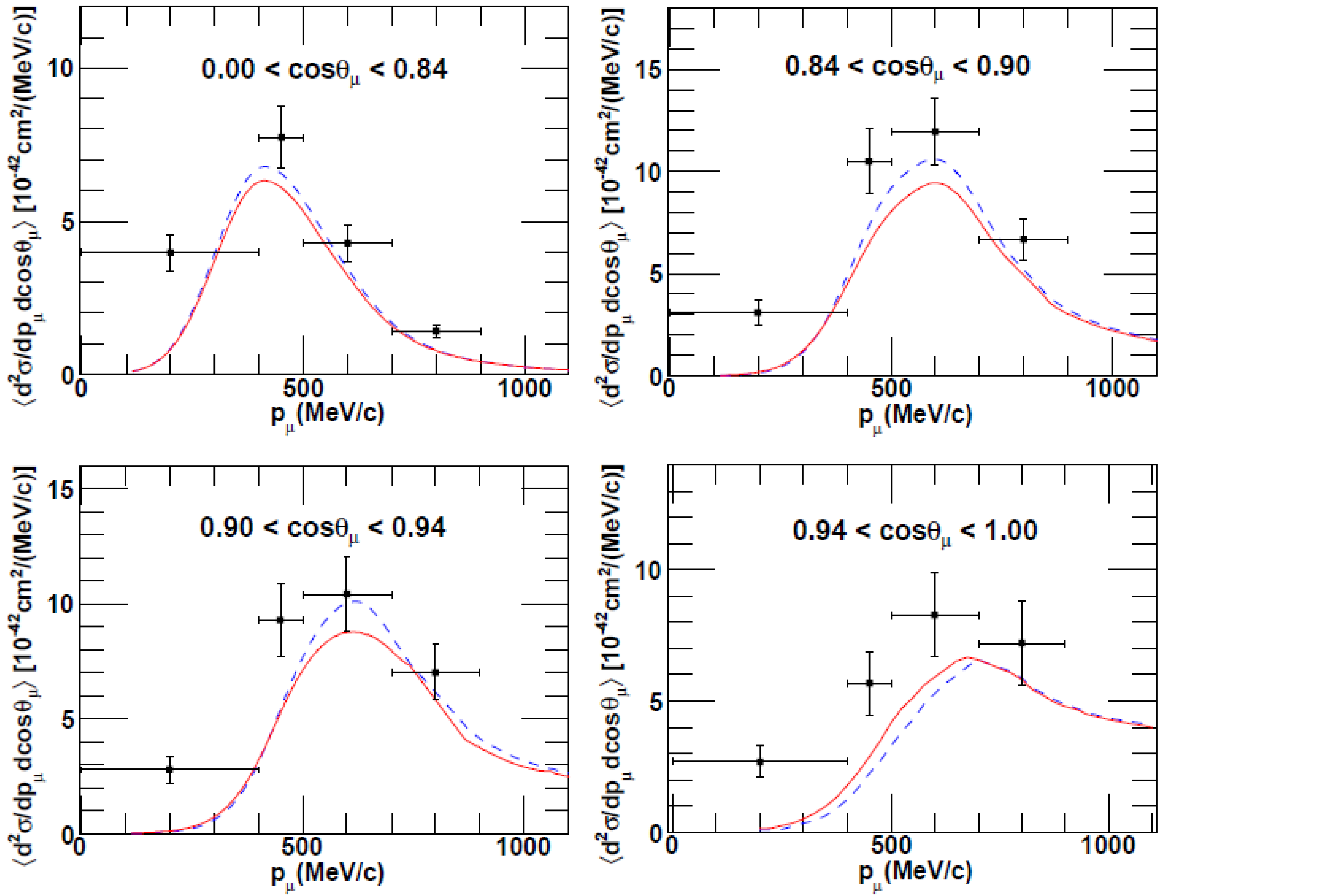
- Satisfactory general agreement
- Good agreement for forward scattering
- Missing strength for low T_μ, backward scattering



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

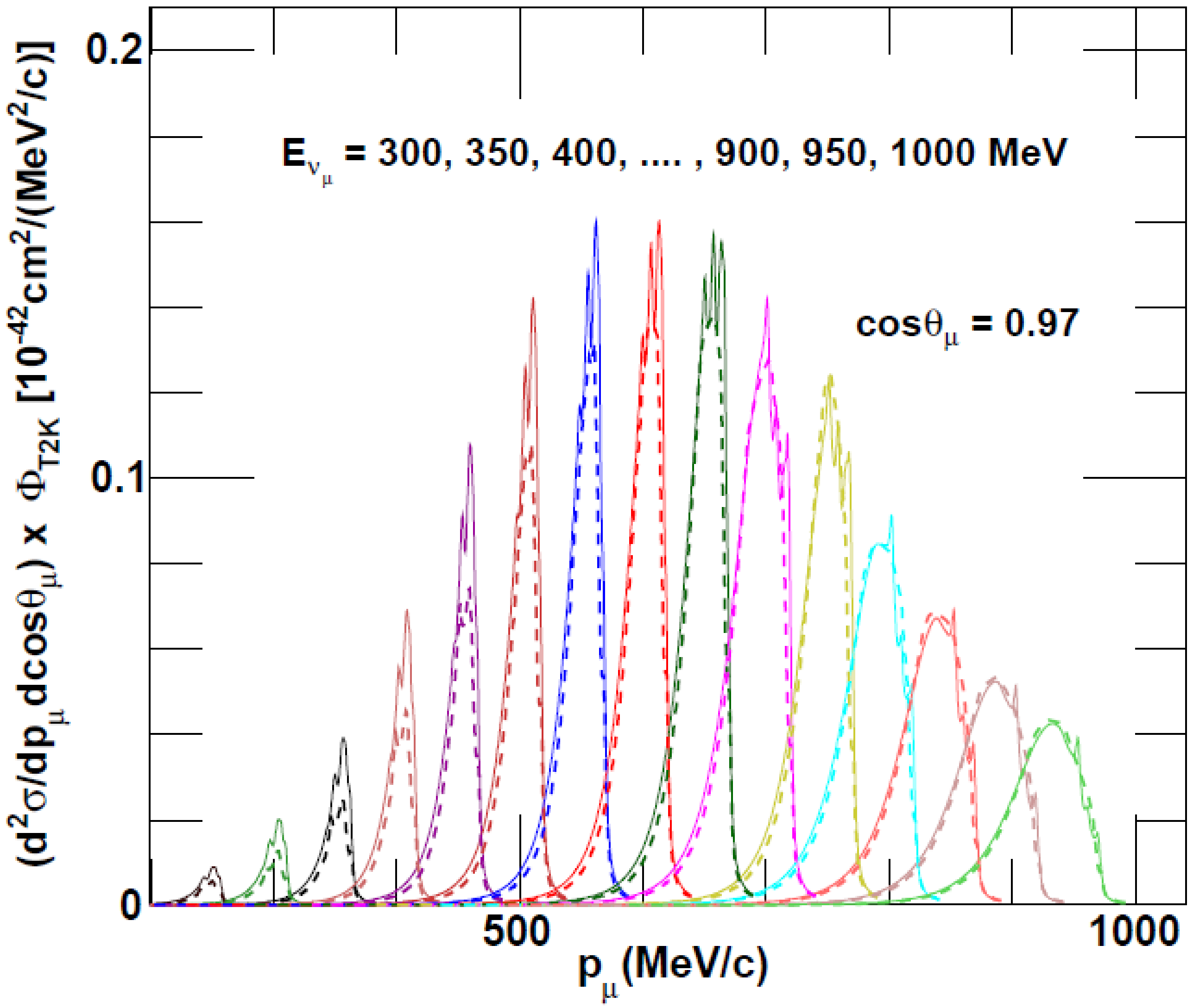




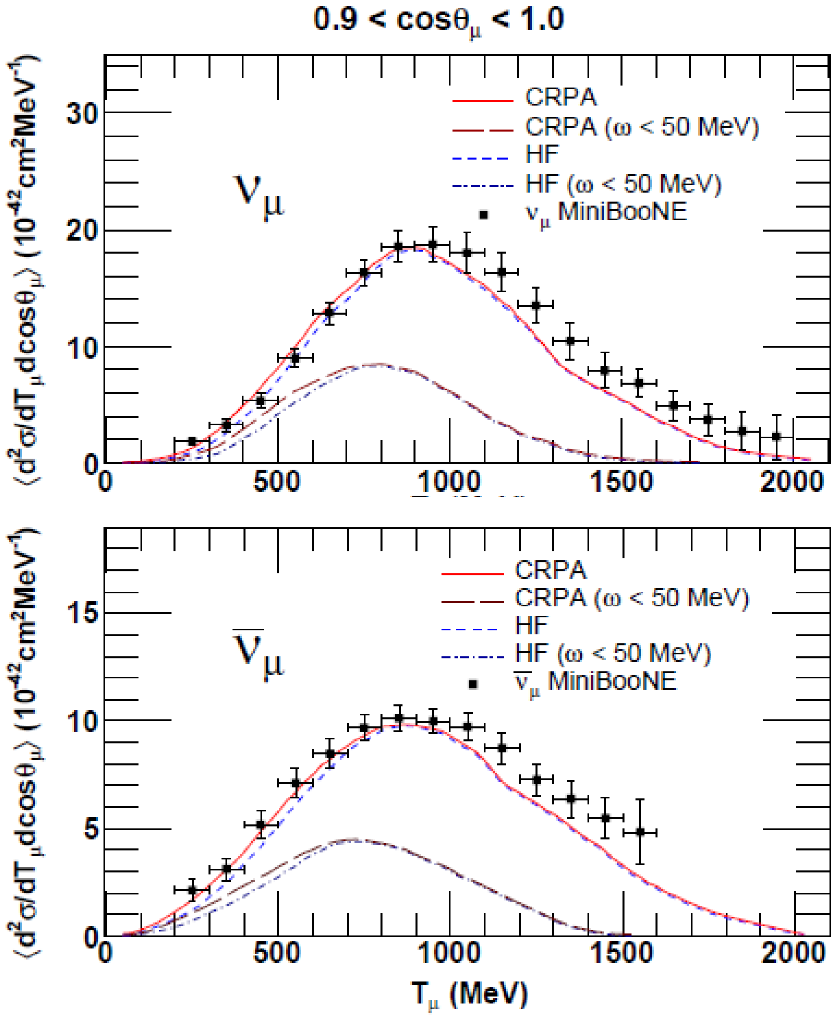
T2K ν_μ

- General agreement quite good
- Missing strength for low p_μ

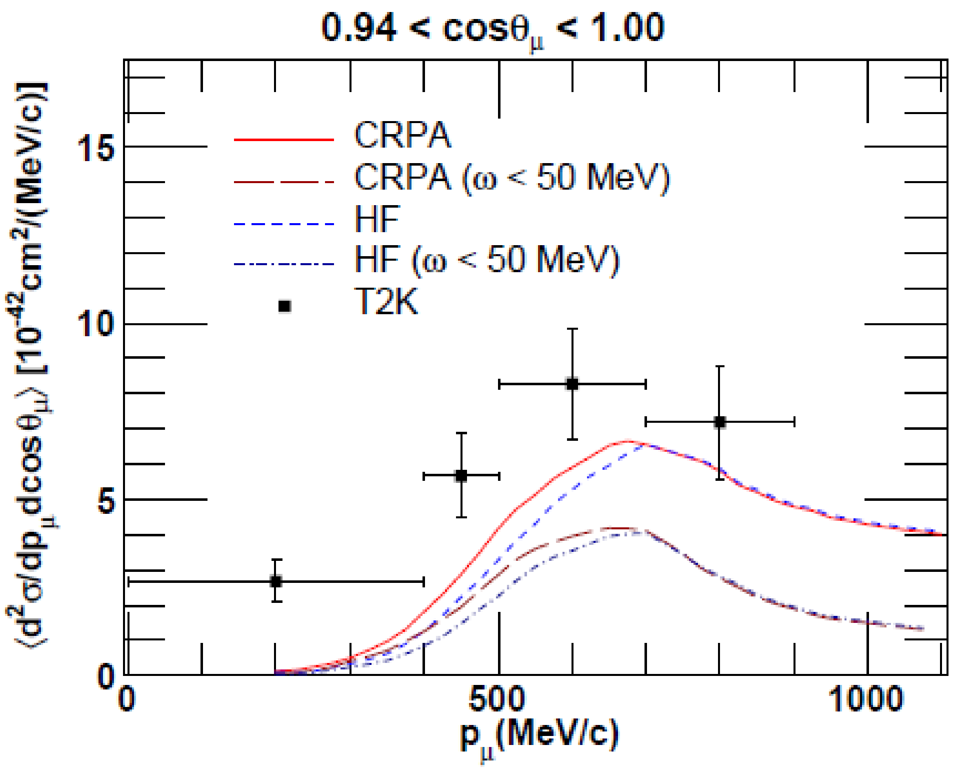
Forward scattering



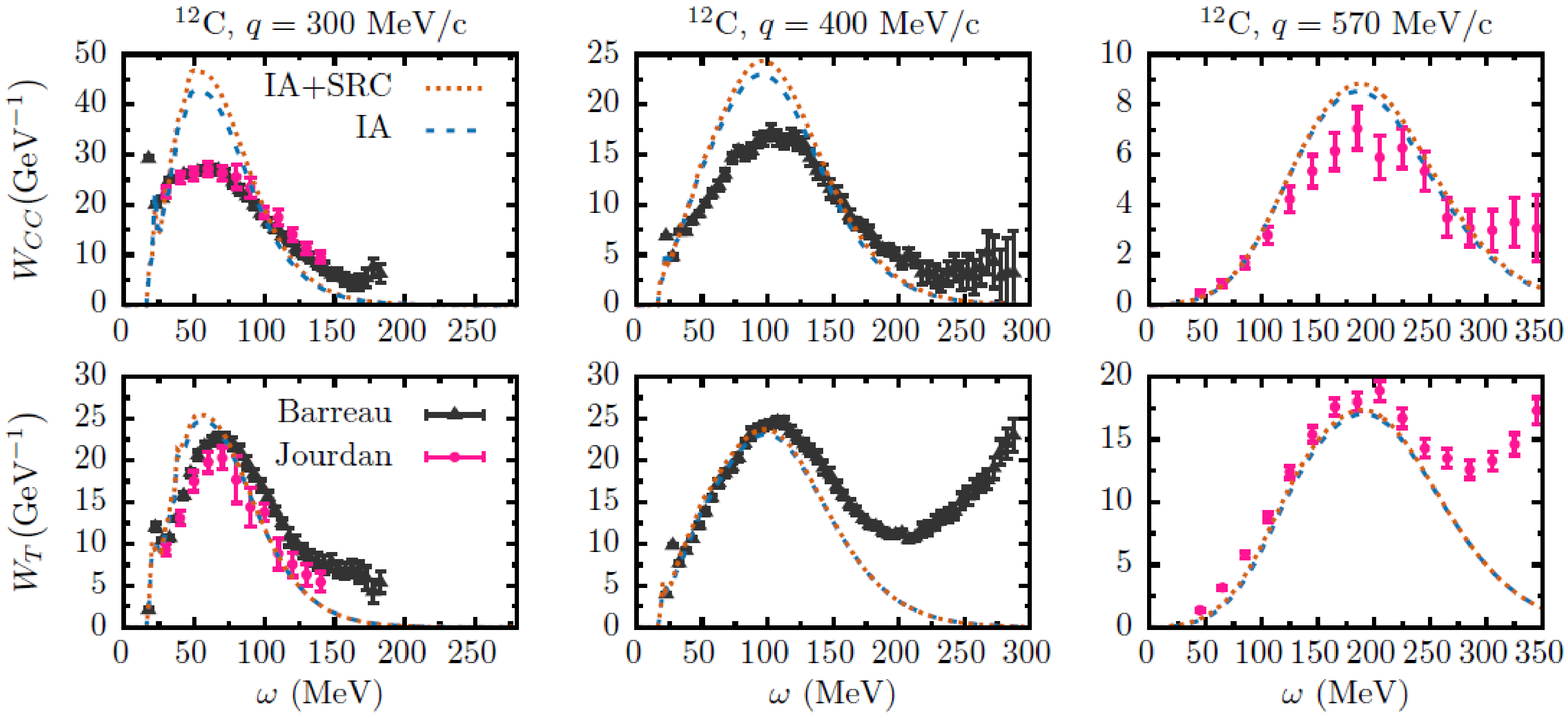
MiniBooNe

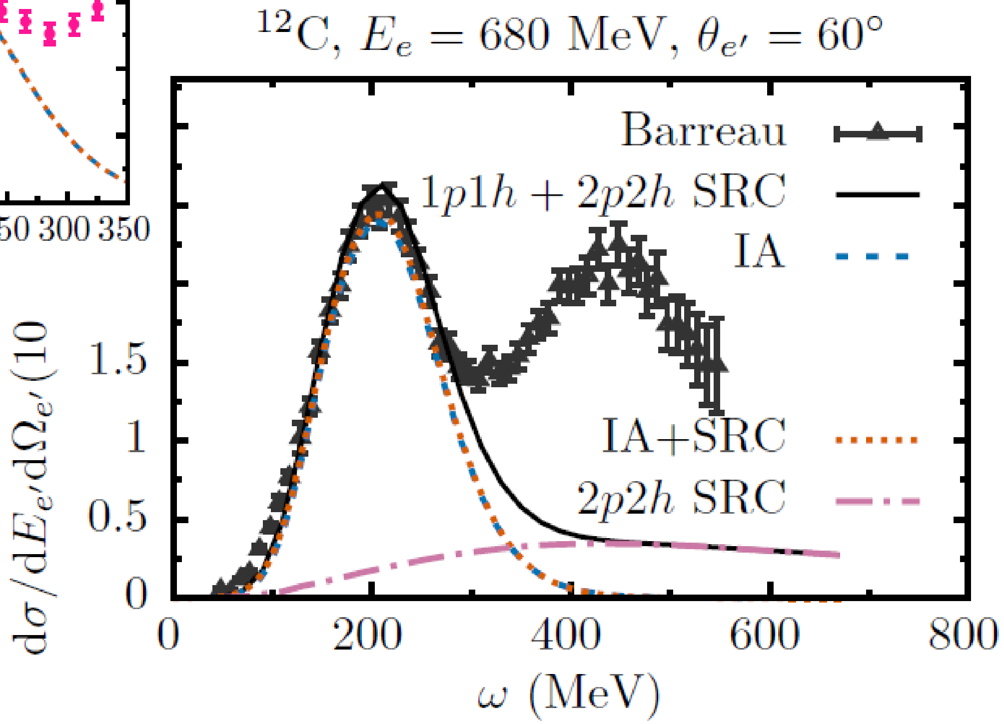


T2K

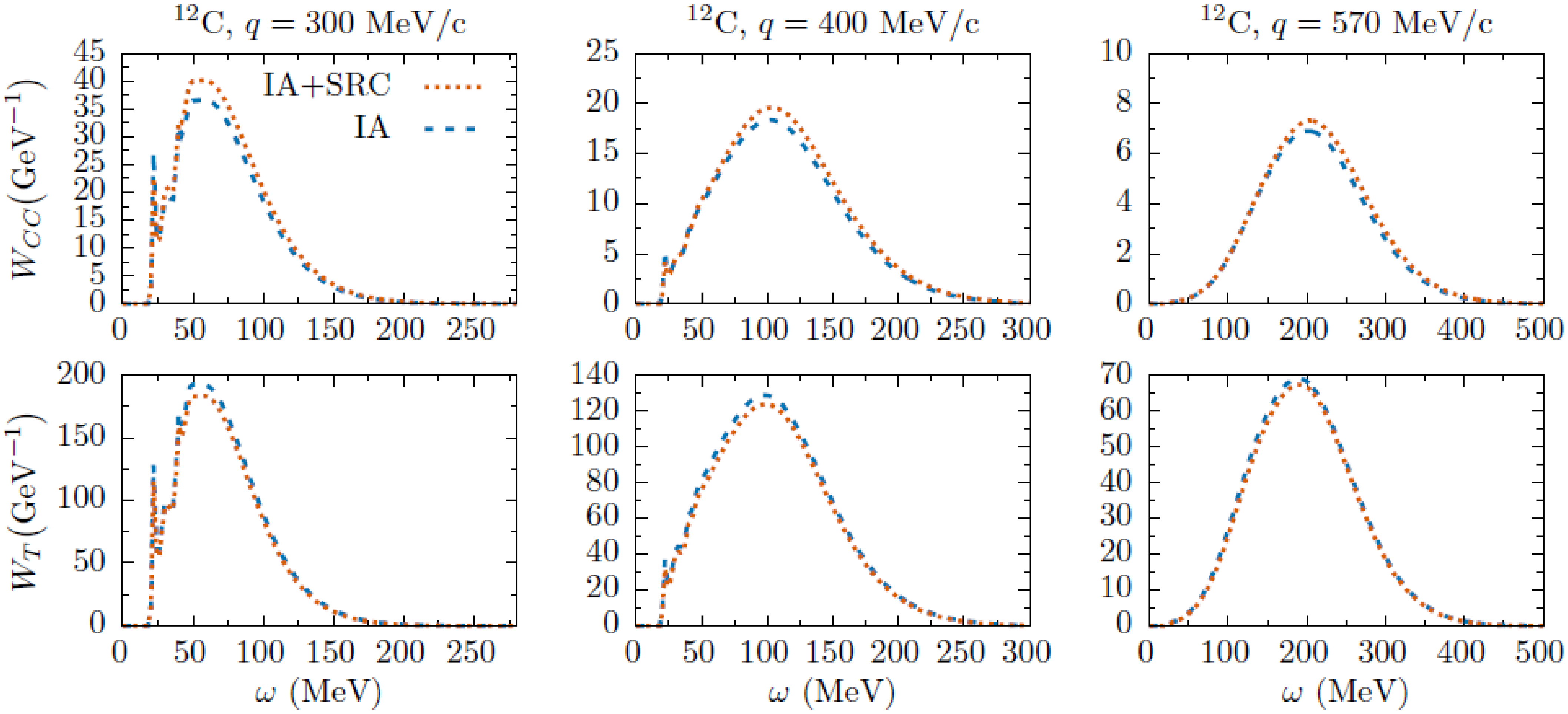


SRC electrons

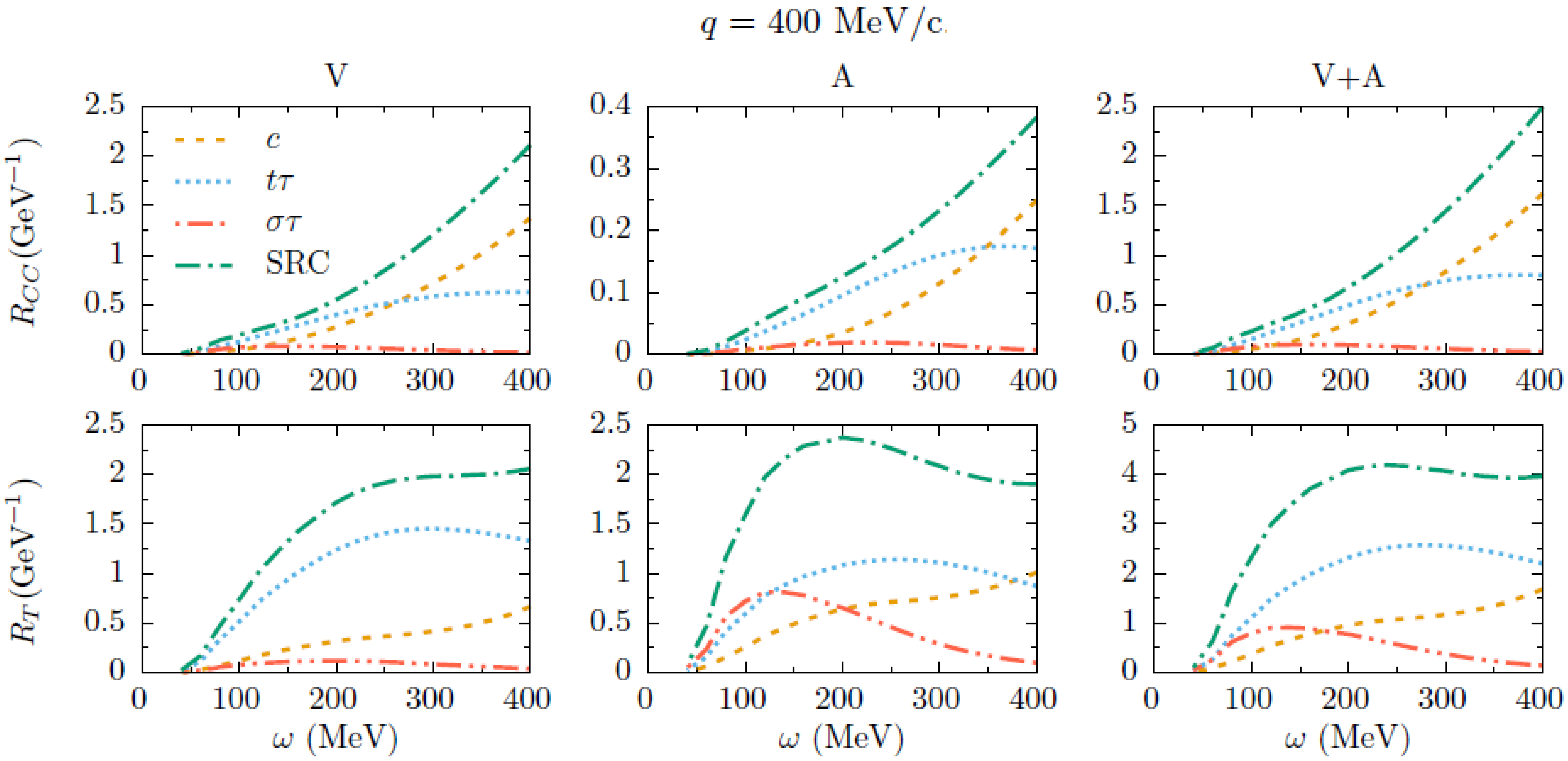


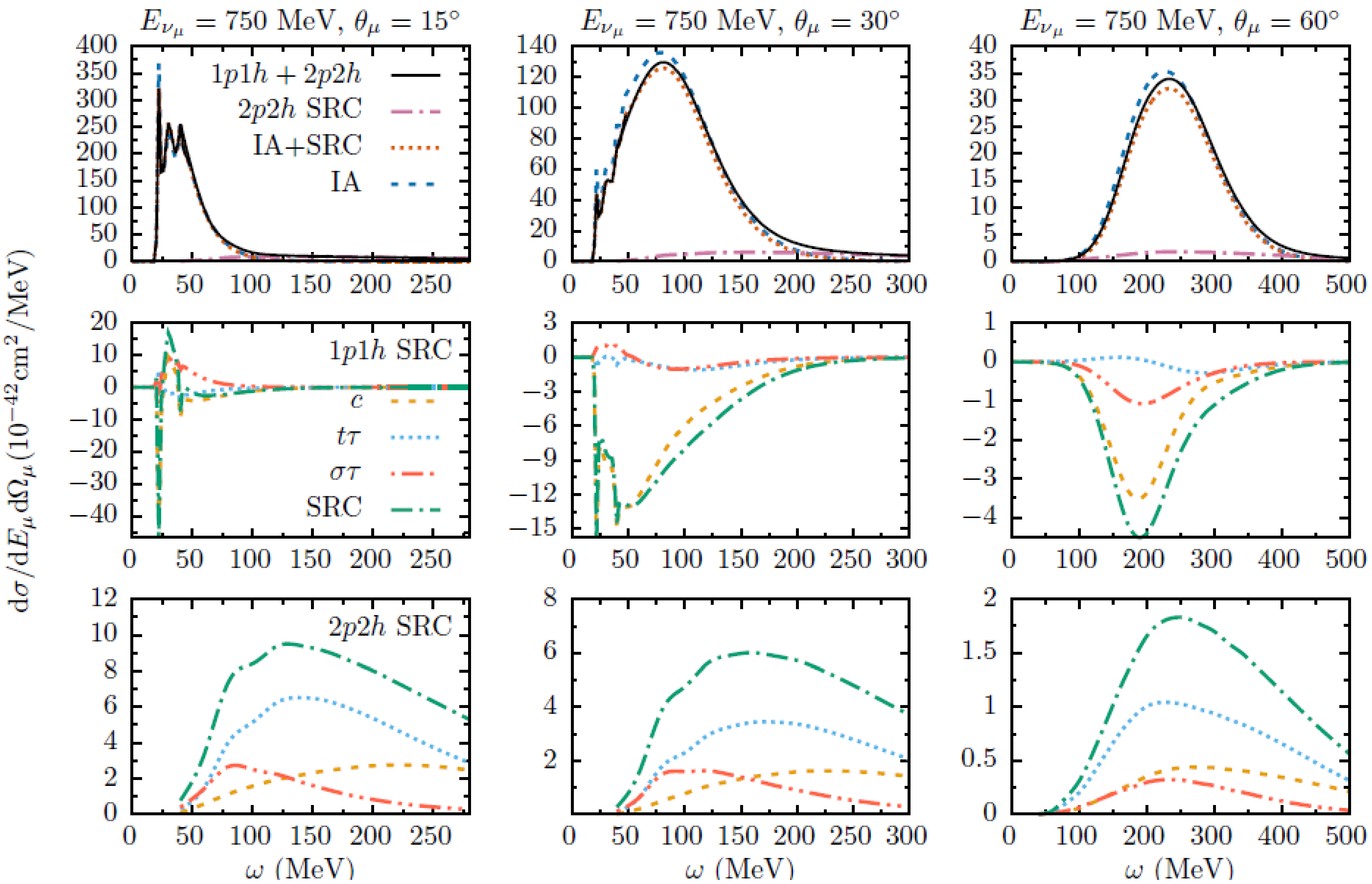


SRC neutrinos 1p1h



SRC neutrinos 2p2h





SRC
neutrinos
1p1h+2p2h

Start from :

- non-relativistic wave functions
- Non-relativistic description of the hadron dvnamics

The nucleus is a relativistic system …
but when do we notice?

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

$\langle\varphi_n|\hat{j}^\mu|\varphi_n\rangle$

Retain only lowest order contributions in $\frac{E}{M}$

$$\vec{J}_V^\alpha(\vec{x}) = \vec{J}^\alpha_{convection}(\vec{x}) + \vec{J}^\alpha_{magnetization}(\vec{x})$$

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

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

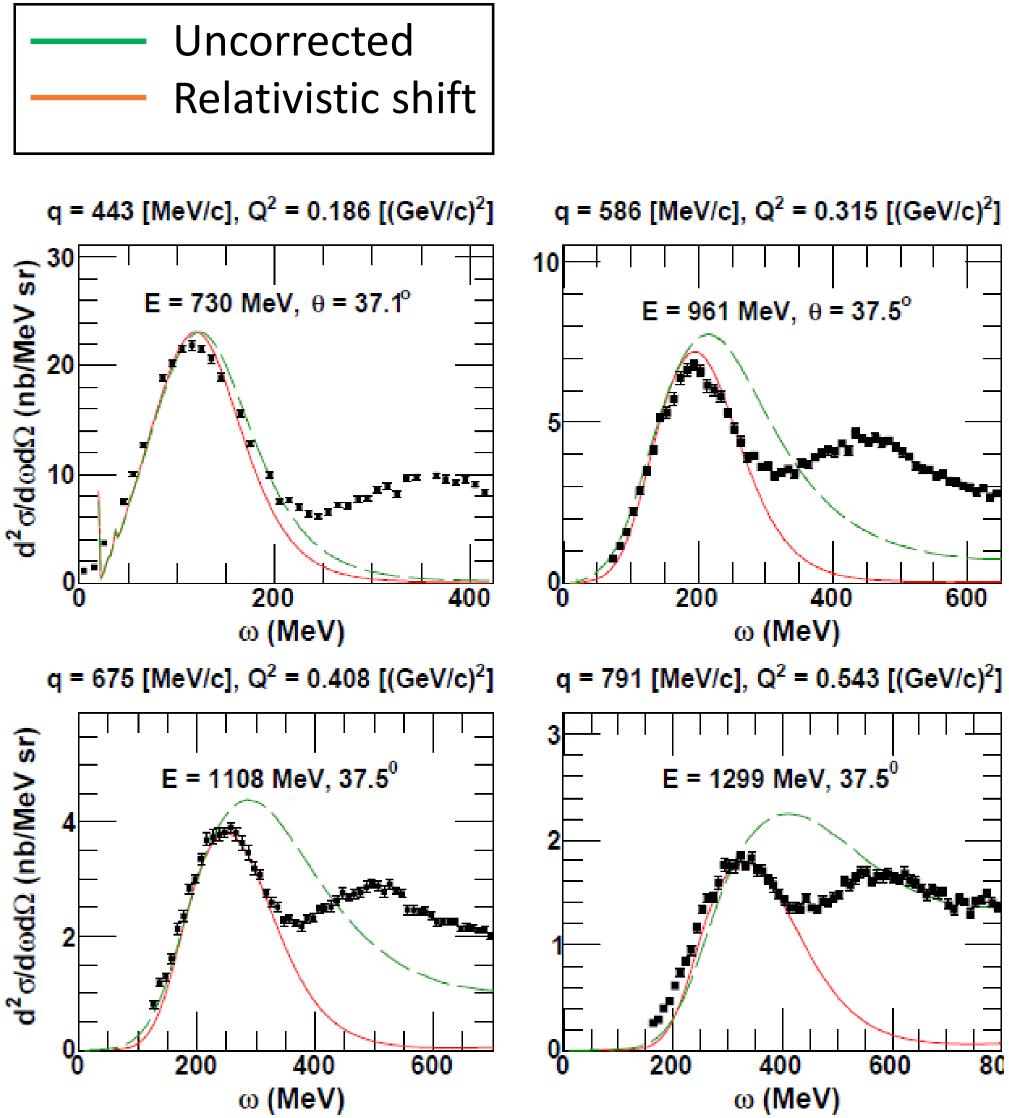
$$\vec{J}_A^\alpha(\vec{x}) = \sum_{i=1}^{A} G_A^{i,\alpha}\,\vec{\sigma}_i\,\delta(\vec{x}-\vec{x}_i),$$

$$J_V^{0,\alpha}(\vec{x}) = \rho_V^\alpha(\vec{x}) = \sum_{i=1}^{A} G_E^{i,\alpha}\,\delta(\vec{x}-\vec{x}_i),$$

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

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

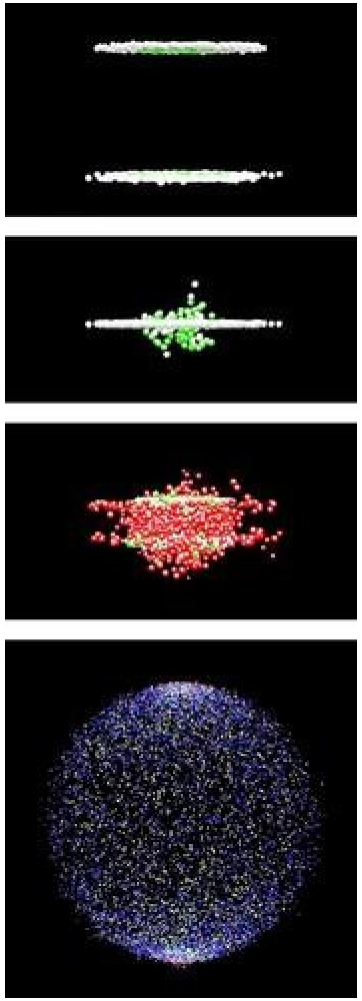
•Relativistic corrections at higher energies (J. Jeschonnek and T. Donnelly, PRC57, 2438 (1998)):



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 :

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

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

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

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

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

Interactions :

Skyrme SkE2 : $$\begin{aligned} V(\vec{r_1},\vec{r_2}) \;=\; & t_0\,(1+x_0\hat{P}_\sigma)\,\delta(\vec{r}_1-\vec{r}_2) \\ & -\frac{1}{8}t_1\left[(\overleftarrow{\nabla}_1-\overleftarrow{\nabla}_2)^2\,\delta(\vec{r}_1-\vec{r}_2)+\delta(\vec{r}_1-\vec{r}_2)\,(\overrightarrow{\nabla}_1-\overrightarrow{\nabla}_2)^2\right] \\ & +\frac{1}{4}t_2(\overleftarrow{\nabla}_1-\overleftarrow{\nabla}_2)\,\delta(\vec{r}_1-\vec{r}_2)\,(\overrightarrow{\nabla}_1-\overrightarrow{\nabla}_2) \\ & +iW_0\,(\overrightarrow{\sigma}_1+\overrightarrow{\sigma}_2)\cdot(\overleftarrow{\nabla}_1-\overleftarrow{\nabla}_2)\times\delta(\vec{r}_1-\vec{r}_2)\,(\overrightarrow{\nabla}_1-\overrightarrow{\nabla}_2) \\ & +\frac{1}{6}t_3\,(1-x_3)\,(1+\hat{P}_\sigma)\,\rho\,\frac{(\vec{r}_1+\vec{r}_2)}{2}\,\delta(\vec{r}_1-\vec{r}_2) \\ & +\frac{e^2}{|\vec{r}_1-\vec{r}_2|}\;+\;x_3t_3\,\delta(\vec{r}_1-\vec{r}_2)\,\delta(\vec{r}_1-\vec{r}_3) \\ & -\frac{1}{24}t_4\left\{\left[(\overleftarrow{\nabla}_1-\overleftarrow{\nabla}_2)^2+(\overleftarrow{\nabla}_2-\overleftarrow{\nabla}_3)^2+(\overleftarrow{\nabla}_3-\overleftarrow{\nabla}_1)^2\right]\right\} \\ & \qquad \delta(\vec{r}_1-\vec{r}_2)\,\delta(\vec{r}_1-\vec{r}_3)+\;\delta(\vec{r}_1-\vec{r}_2)\,\delta(\vec{r}_1-\vec{r}_3) \\ & \qquad \left\{\left[(\overrightarrow{\nabla}_1-\overrightarrow{\nabla}_2)^2+(\overrightarrow{\nabla}_2-\overrightarrow{\nabla}_3)^2+(\overrightarrow{\nabla}_3-\overleftarrow{\nabla}_1)^2\right]\right\}. \end{aligned}$$

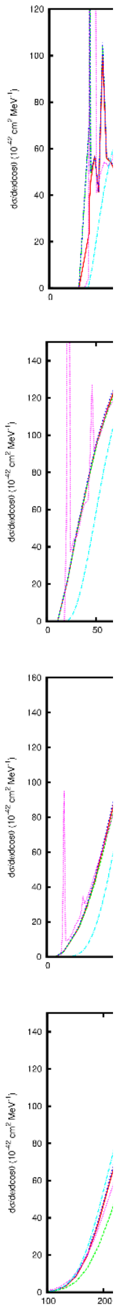
Total

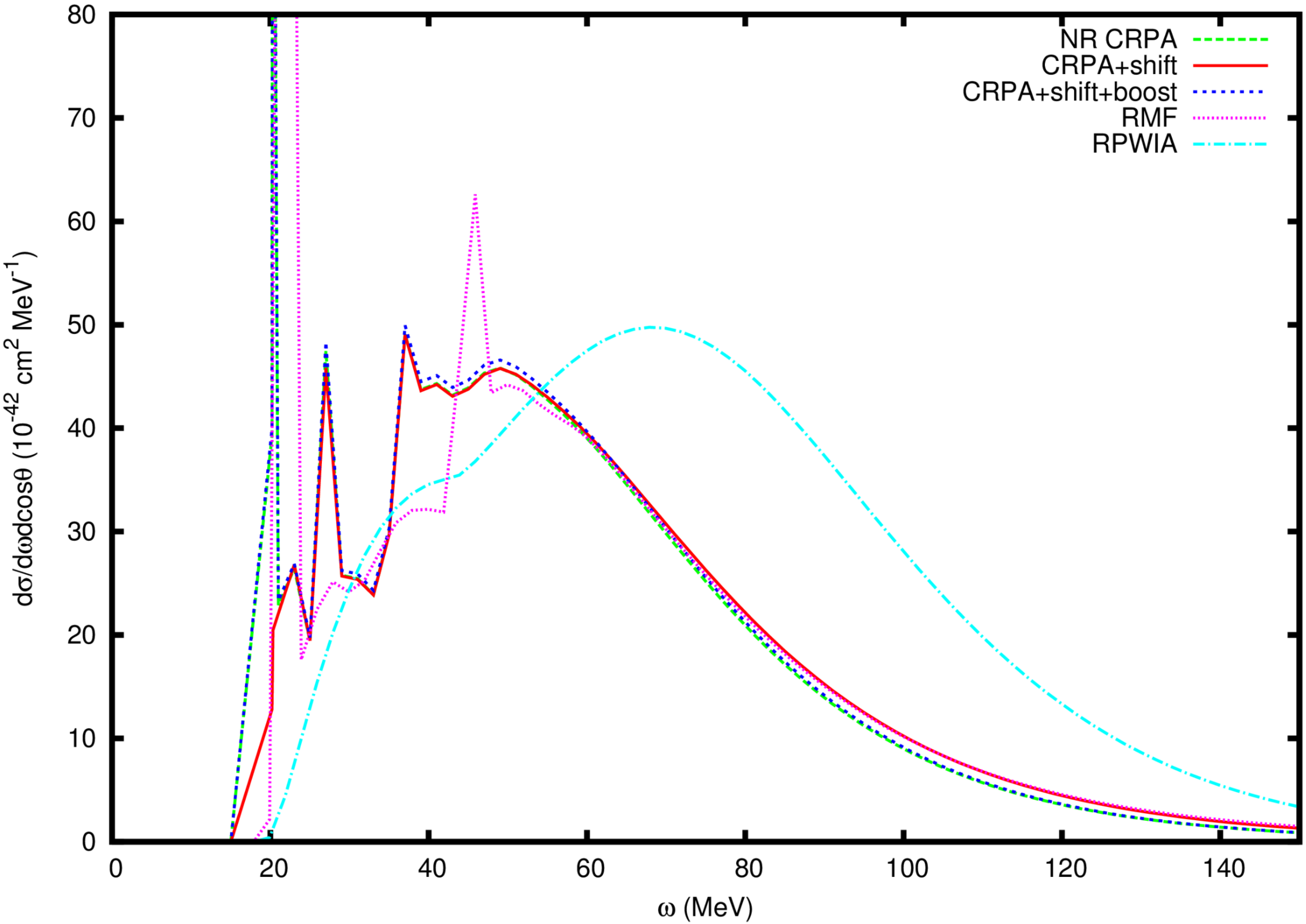
E=500 MeV

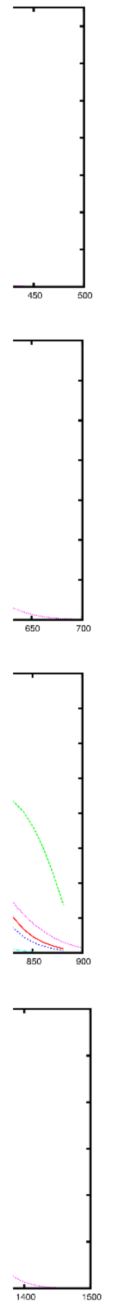
E=750 MeV

E=1000 MeV

E=1500 MeV







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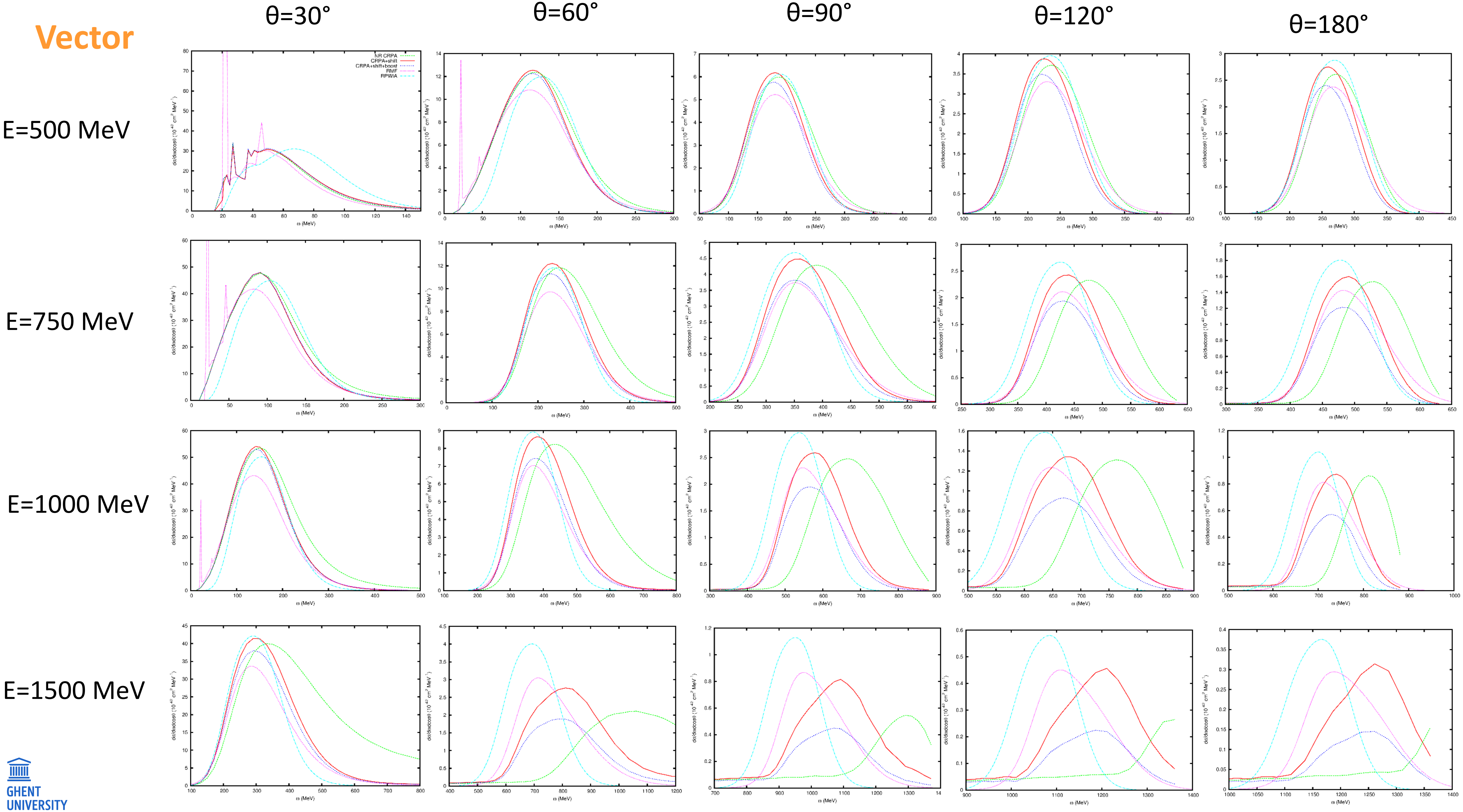

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Axial

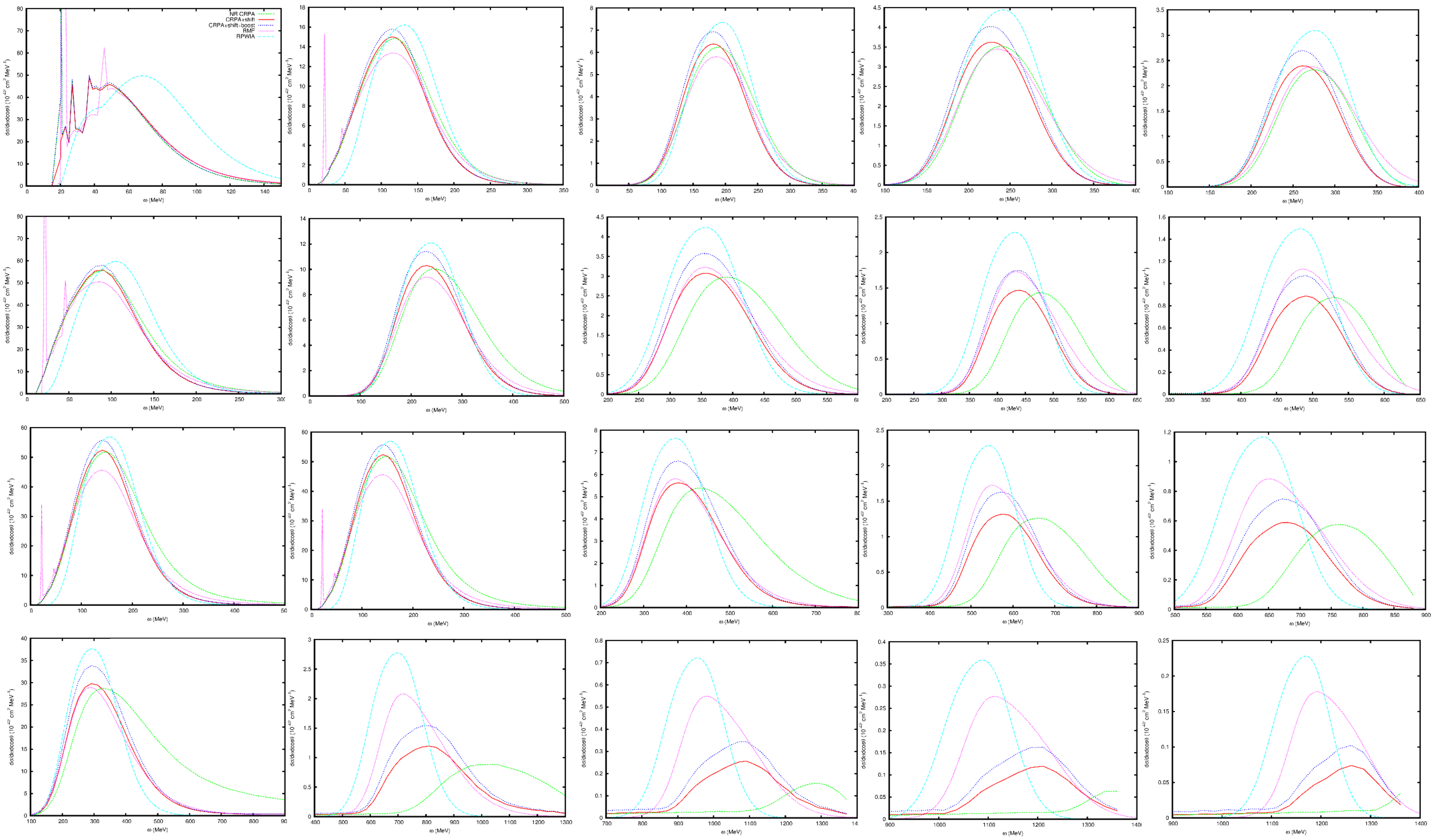
θ=30° θ=60° θ=90° θ=120° θ=180°

E=500 MeV

E=750 MeV

E=1000 MeV

E=1500 MeV



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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 and T2K
- SRC affect 1- and 2-nucleon knockout processes
- Relativistic corrections are under control for the kinematics most relevant for MiniBooNe and T2K