Modeling quasielastic neutrino-nucleus scattering in MiniBooNe and T2K
From very low energies to the quasielastic peak

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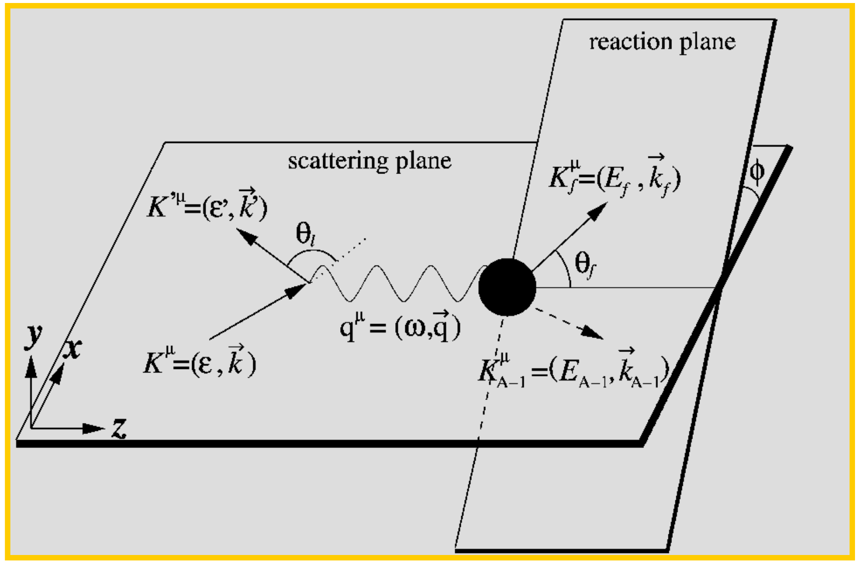
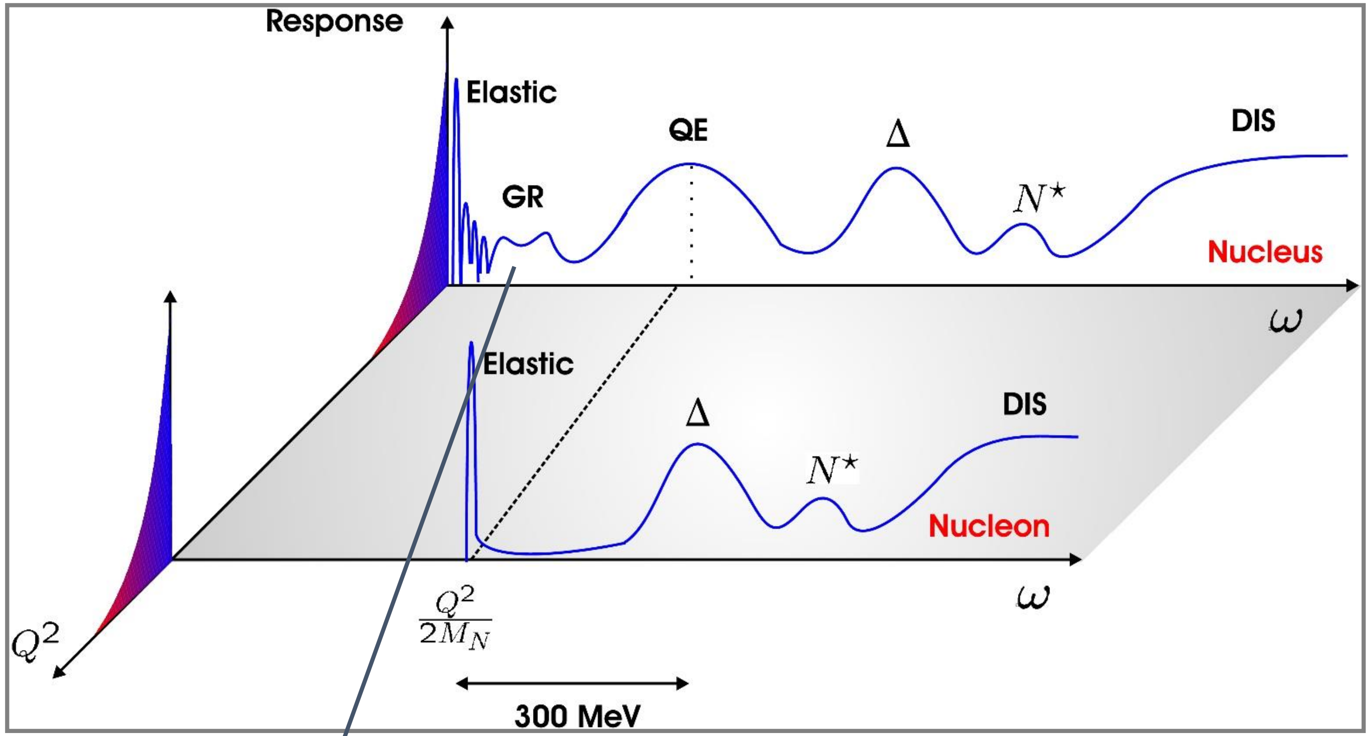
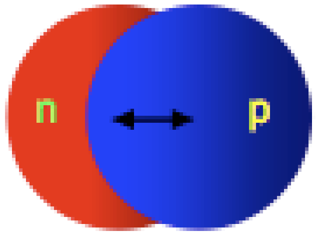
Neutrino-hadron scattering





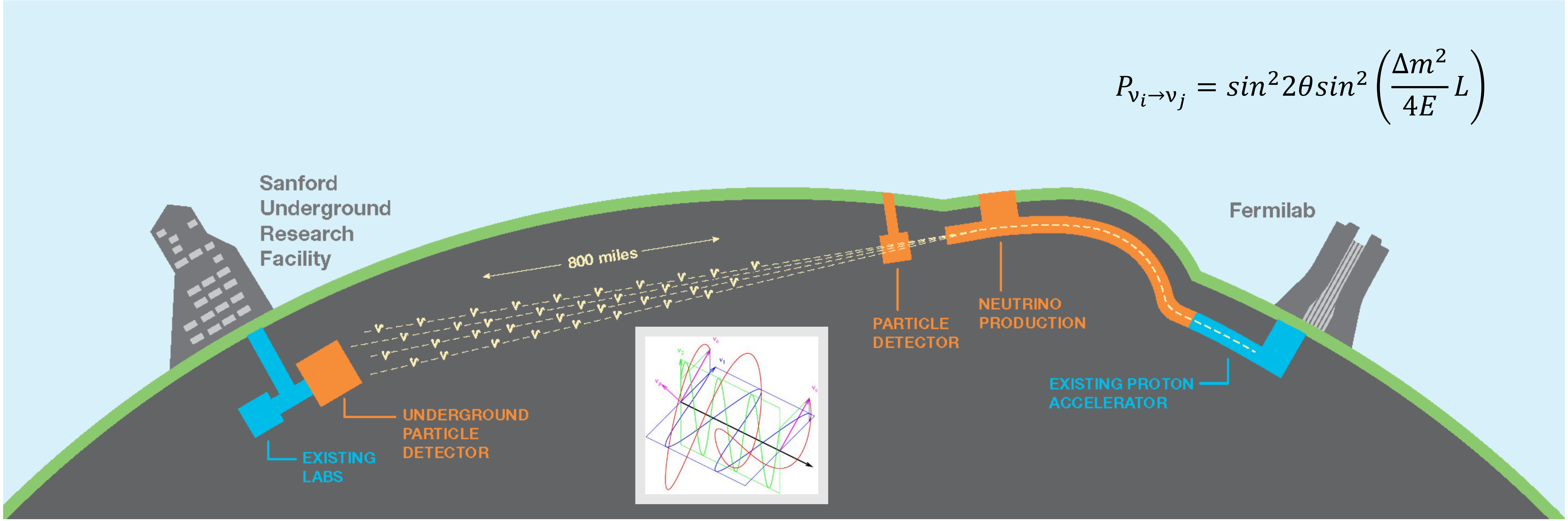
e.g.

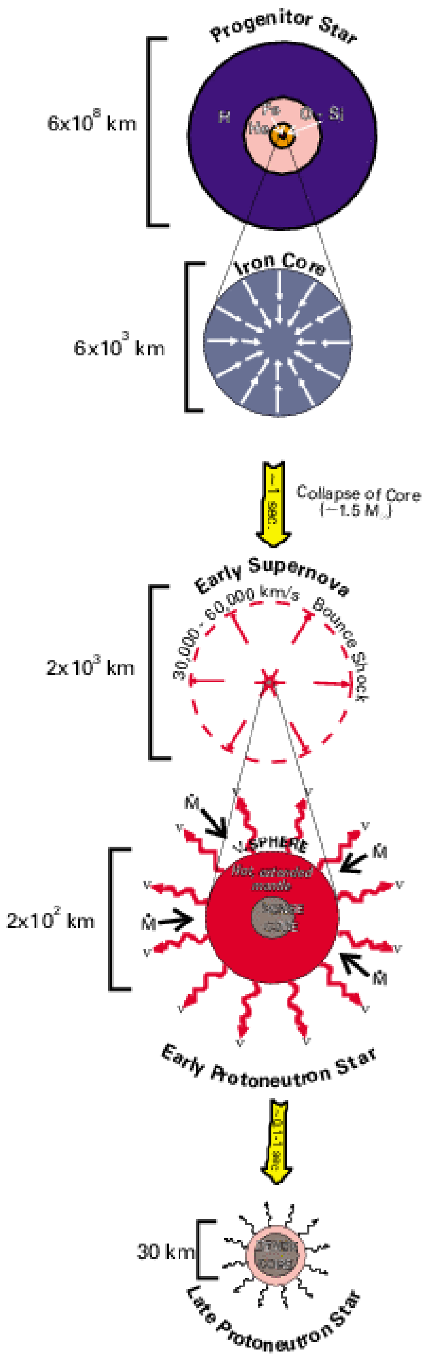


Motivation I : Neutrino-oscillation experiments

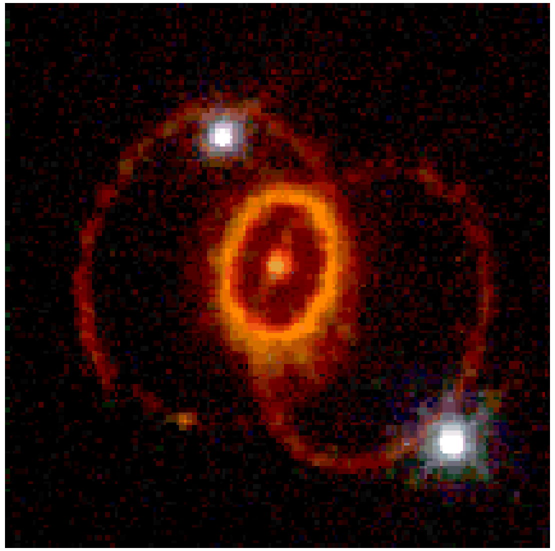
- ν_μ are produced, part of them is detected in the near detector
- Neutrinos propagate from near to far detector, neutrino oscillations occur underway
- Neutrinos are detected in the far detector
- Count different neutrino flavors at near and far detector
- Extract information about mass differences and mixing angles from the differences between near and far detector

$$P_{\nu_i \to \nu_j} = sin^2 2\theta sin^2 \left(\frac{\Delta m^2}{4E} L \right)$$

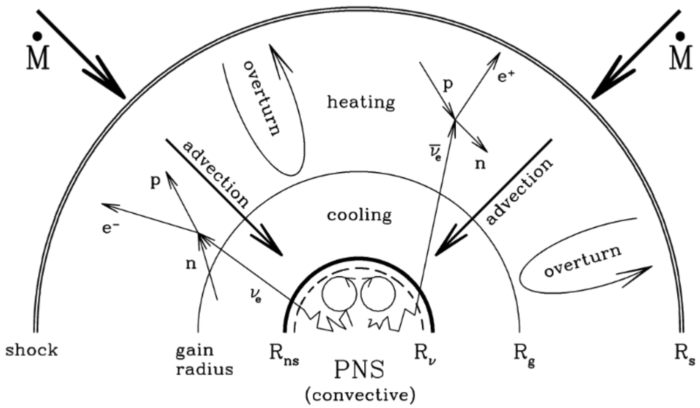




Motivation II : Neutrinos in a core-collapse supernova



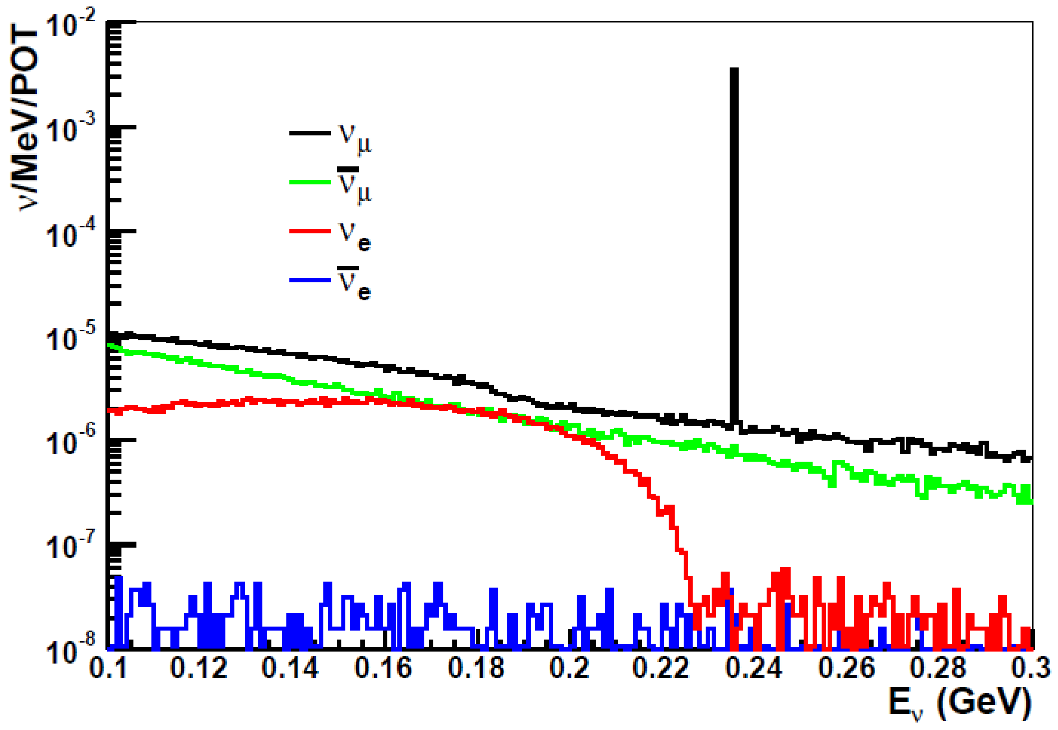
- weak interactions are important
- neutrinos are produced in the neutronization processes characterizing the gravitational collapse
- neutrinos are responsible for the cooling of the proto-neutron star
- neutrinonucleosynthesis
- energy deposition by neutrinos might reheat the stalled shock wave and cause a delayed explosion
- terrestrial detection of supernova neutrinos



H.-T. Janka astro-ph/0008432

Motivation III … : 236 MeV neutrinos

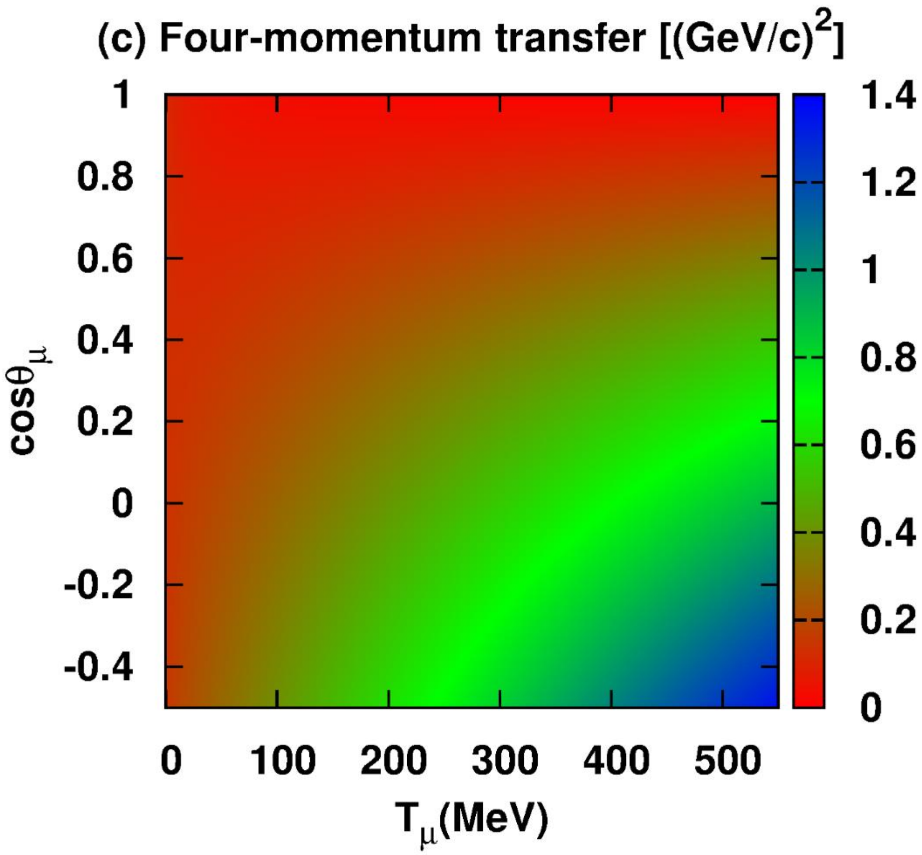
- Protons on Carbon generate Kaons
- Kaons-at-rest- decay … primarily in ν_μ
- with an energy of 236 MeV



Joshua Spitz PRD89 073007

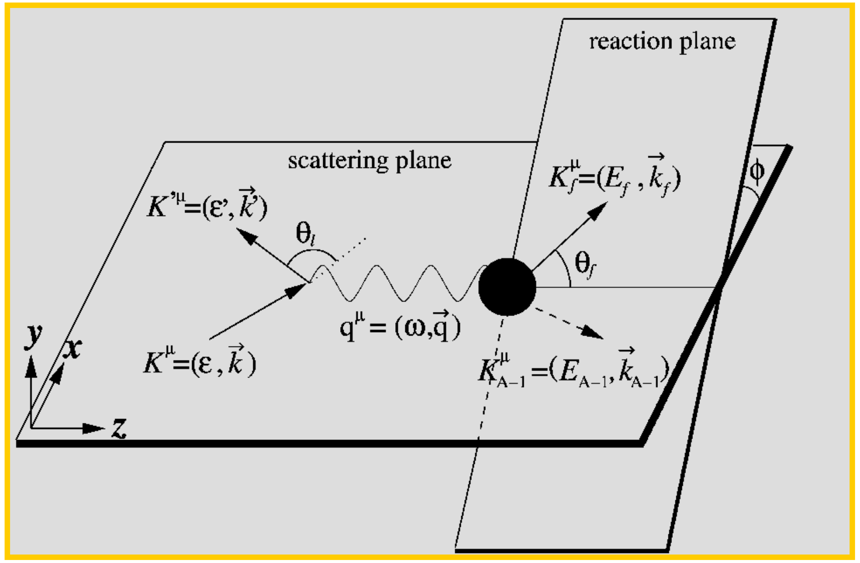
What is ‘low energy’ ?

E_ν=700MeV



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

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

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

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

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

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

for NC reactions

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

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

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

for CC reactions

$$G^{V,\pm}_{E} = \tau_\pm$$

$$G^{V,\pm}_{M} = (\mu_p-\mu_n)\,\tau_\pm$$

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

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

Cross section

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

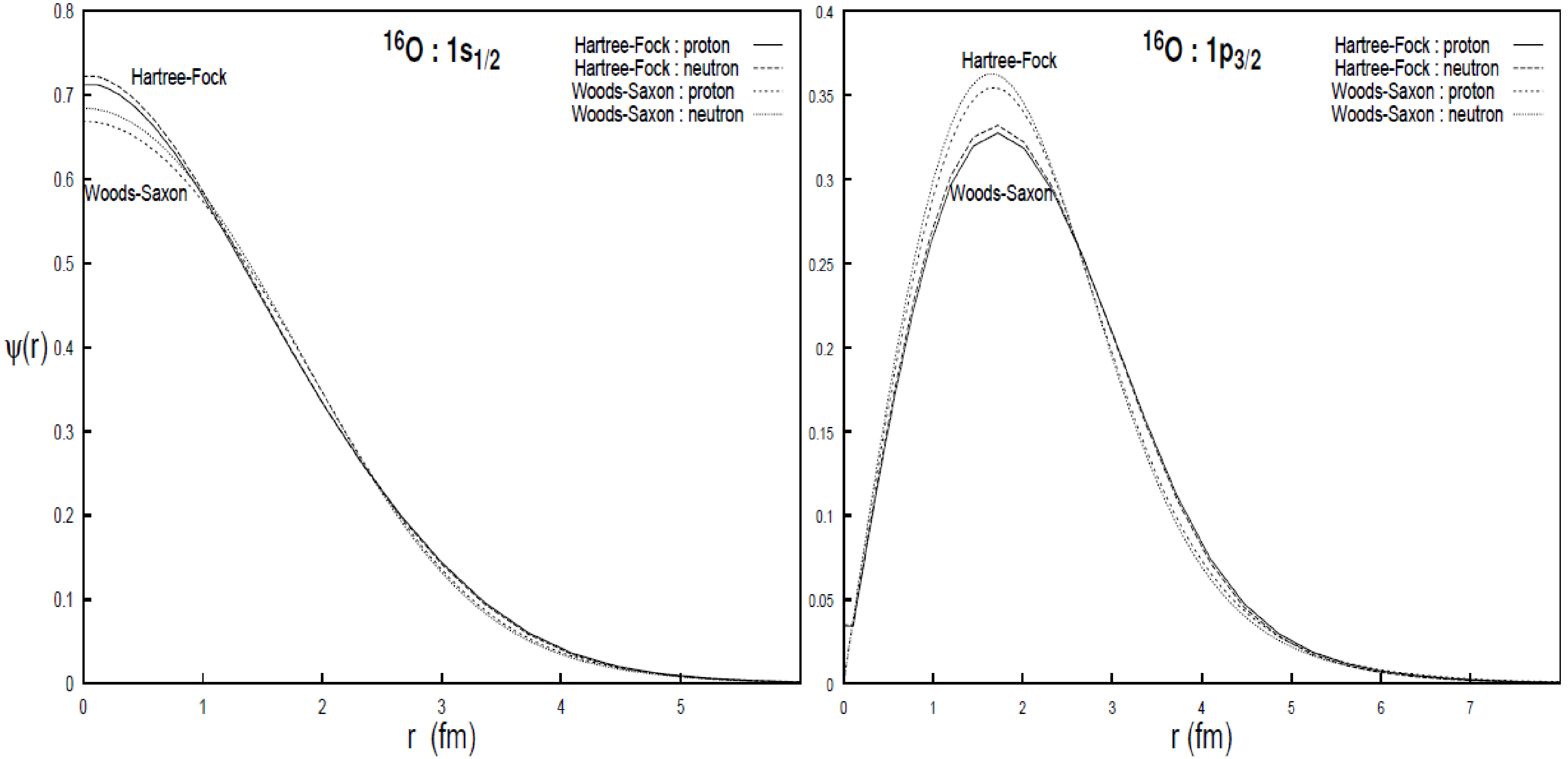
$$\left(\frac{d^2\sigma_{i\to f}}{d\Omega d\omega} \right)_{\frac{\nu}{\bar{\nu}}} = \frac{G^2 \varepsilon_f^2}{\pi} \frac{2\cos^2\left(\frac{\theta}{2}\right)}{2J_i + 1} \left[\sum_{J=0}^{\infty} \sigma_{CL}^J + \sum_{J=1}^{\infty} \sigma_T^J \right]$$

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

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

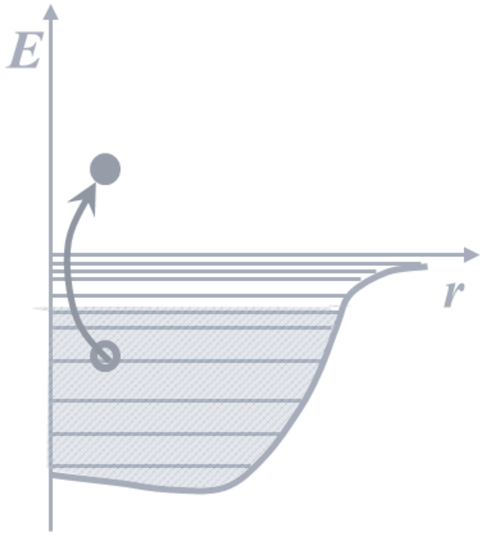
$$\mp \tan\left(\frac{\theta}{2}\right) \sqrt{-\frac{q_\mu^2}{|\vec{q}|^2} + \tan^2\left(\frac{\theta}{2}\right)} \left[2\Re\left(\left\langle J_f \left\| \widehat{\mathcal{J}}_J^{mag}(\kappa) \right\| J_i \right\rangle \left\langle J_f \left\| \widehat{\mathcal{J}}_J^{el}(\kappa) \right\| J_i \right\rangle^*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

Bound state wave functions



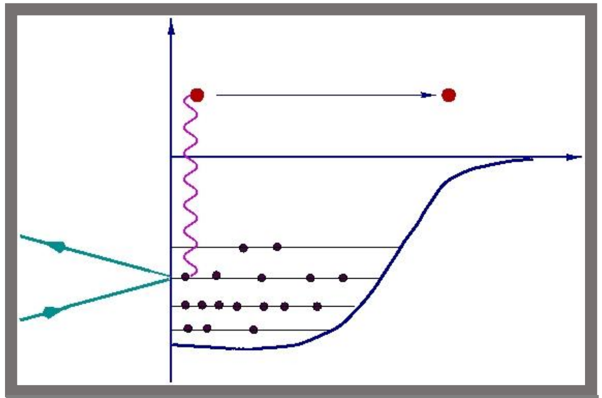
Hartree-Fock single-particle wave functions (Skyrme)

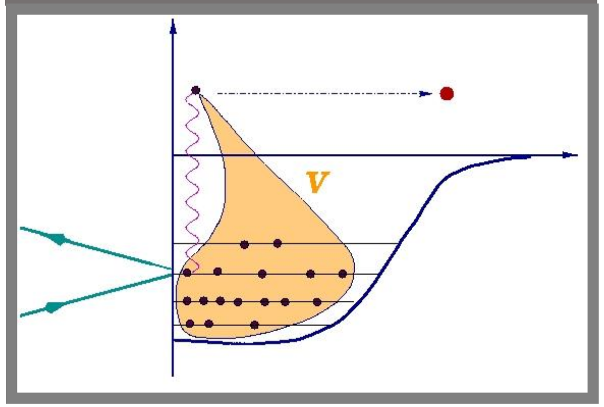
- Pauli blocking
- binding

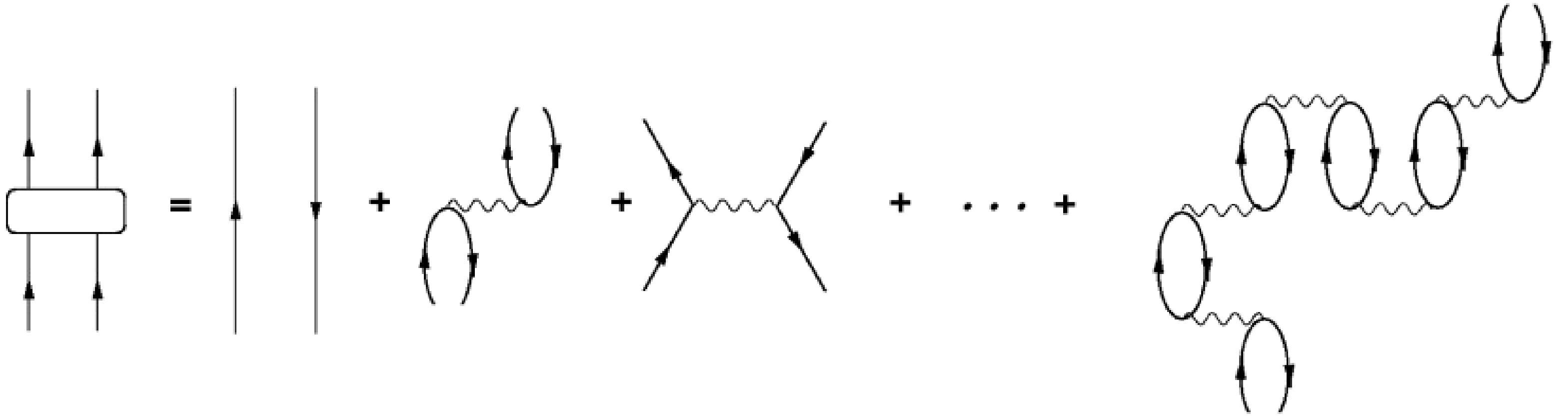


Continuum RPA

- Accounts for long-range correlations
- Green's function approach
- Skyrme SkE2 residual interaction
- ground state : Hartree-Fock single-particle wave functions (Skyrme)
- self-consistent calculations







$$|\Psi^{C}_{RPA}\rangle = \sum_{C'} \left[X_{C,C'} \; |p'h'^{-1}\rangle - \; Y_{C,C'} \; |h'p'^{-1}\rangle \right]$$

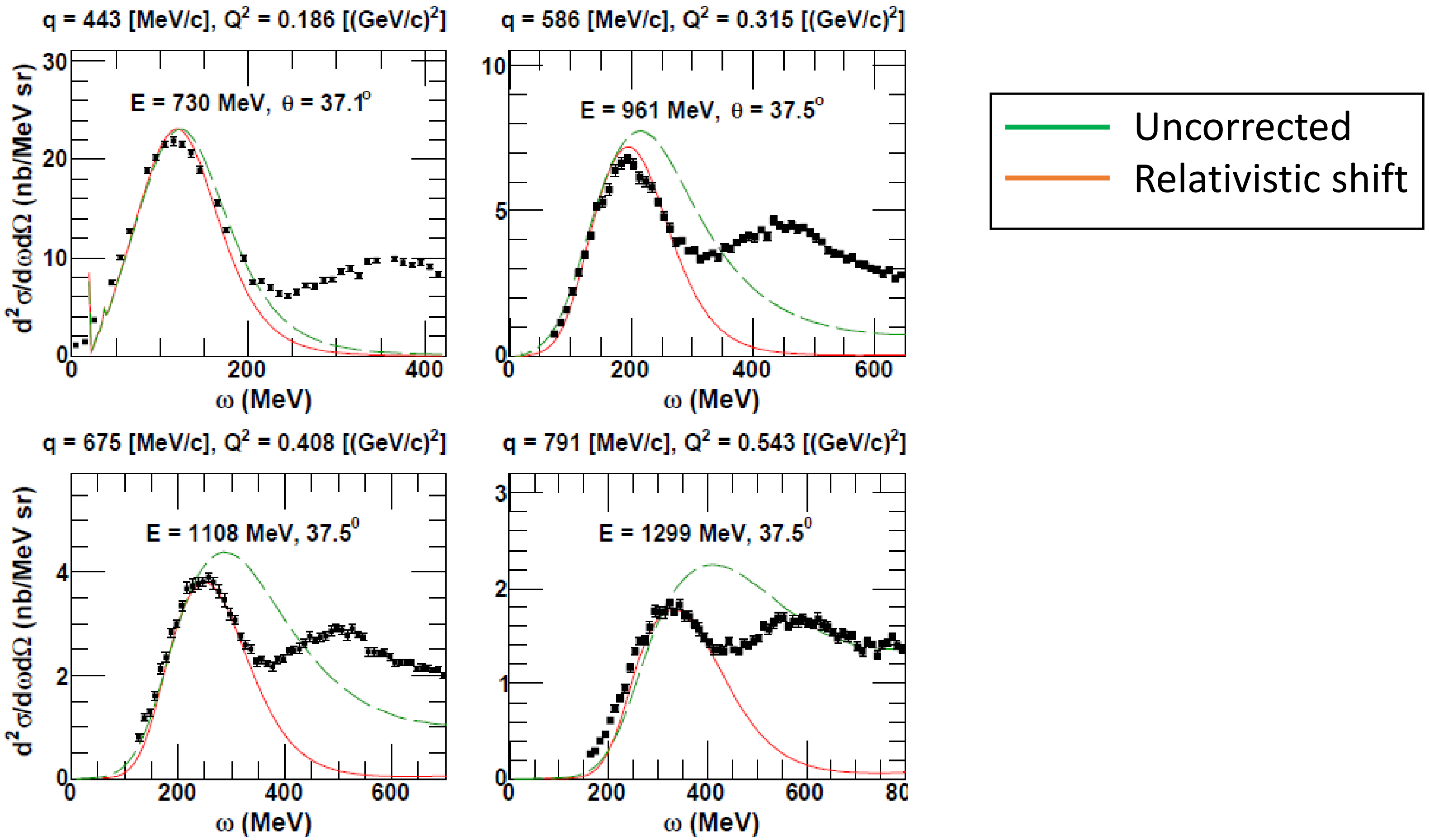
\+ . . .

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

Extra ingredients of the model

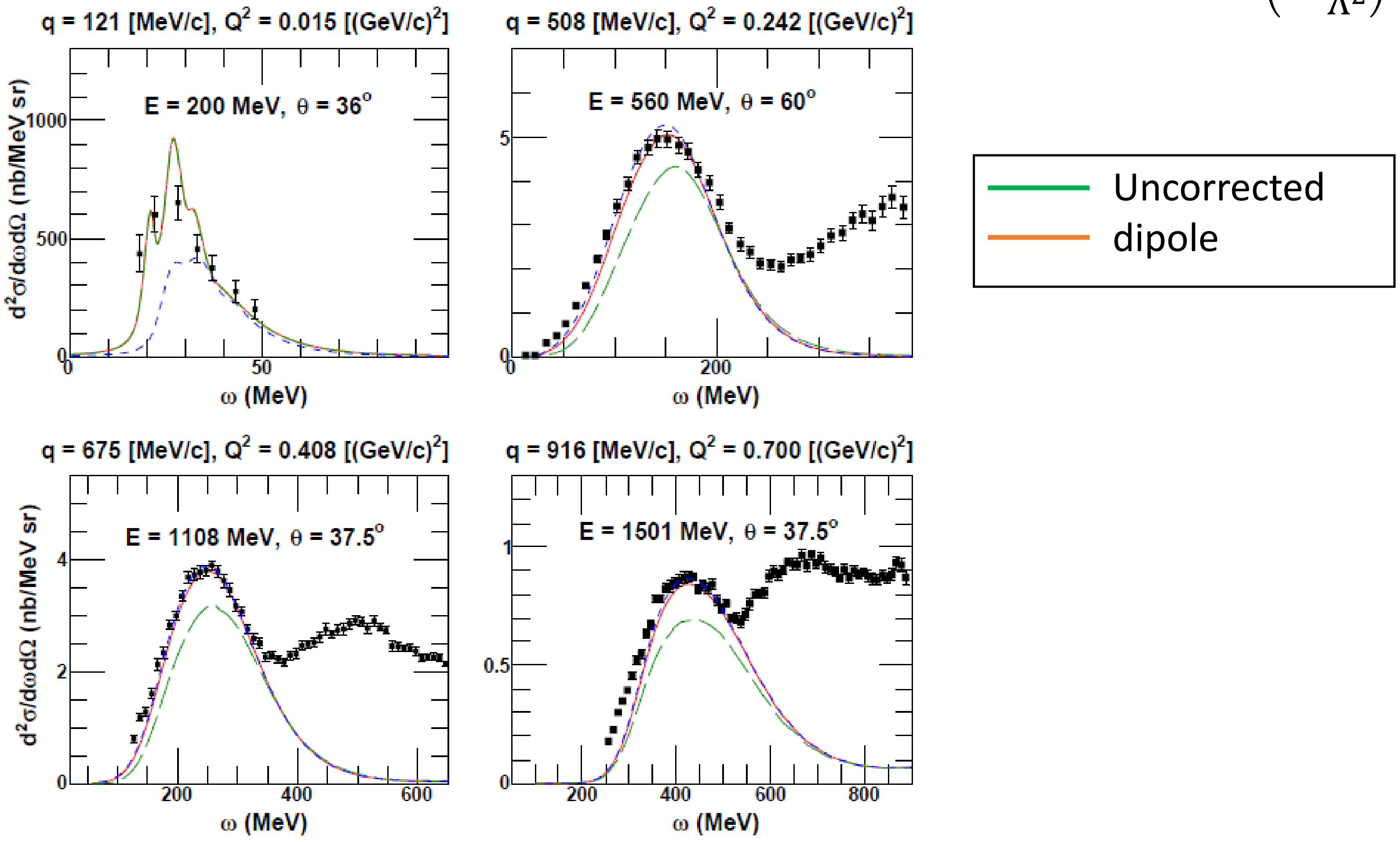
- I. Relativistic corrections at higher energies (J. Jeschonnek and T. Donnelly, PRC57, 2438 (1998)):

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



•II.Regularization of the residual interaction :

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



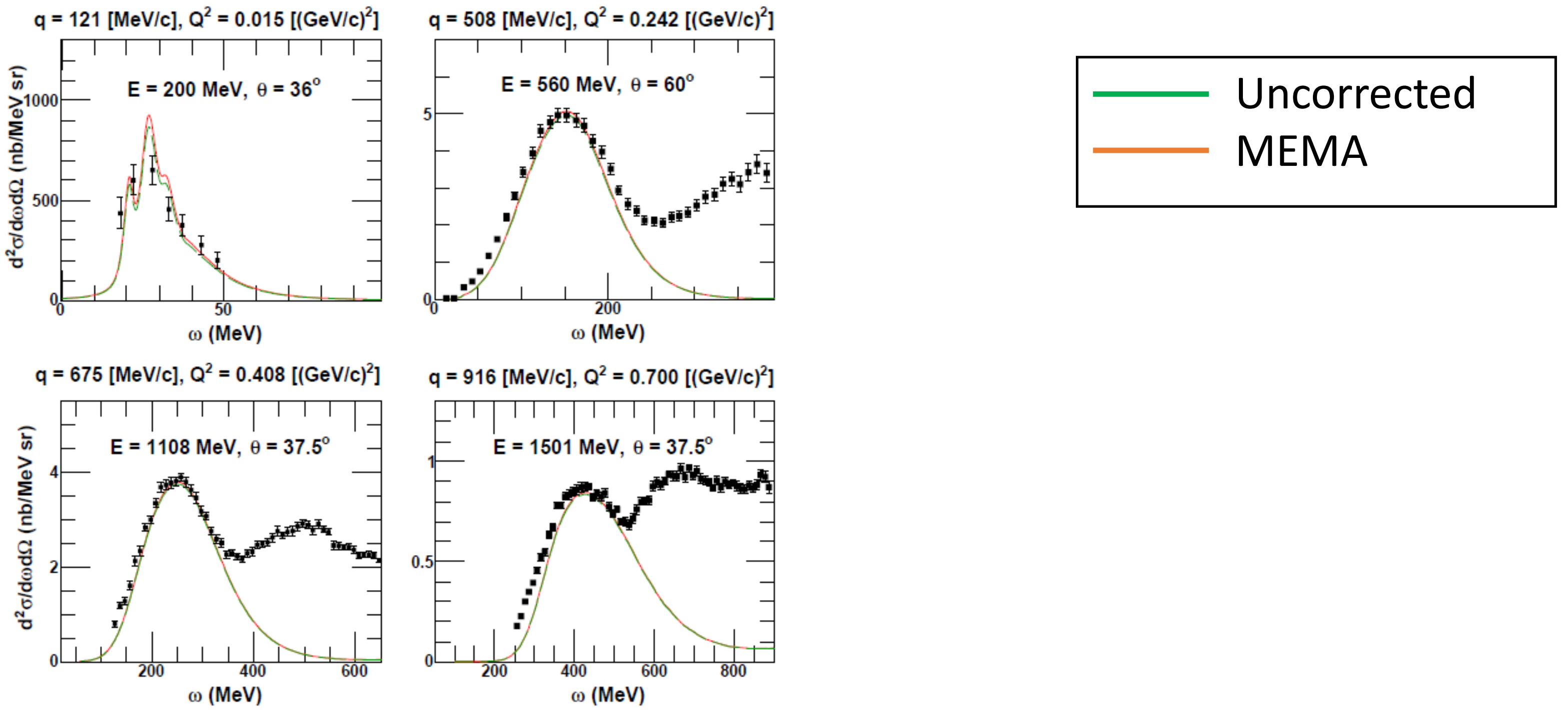
•III.Coulomb correction for the outgoing lepton in charged-current interactions :

- ✓ Low energies : Fermi function

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

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

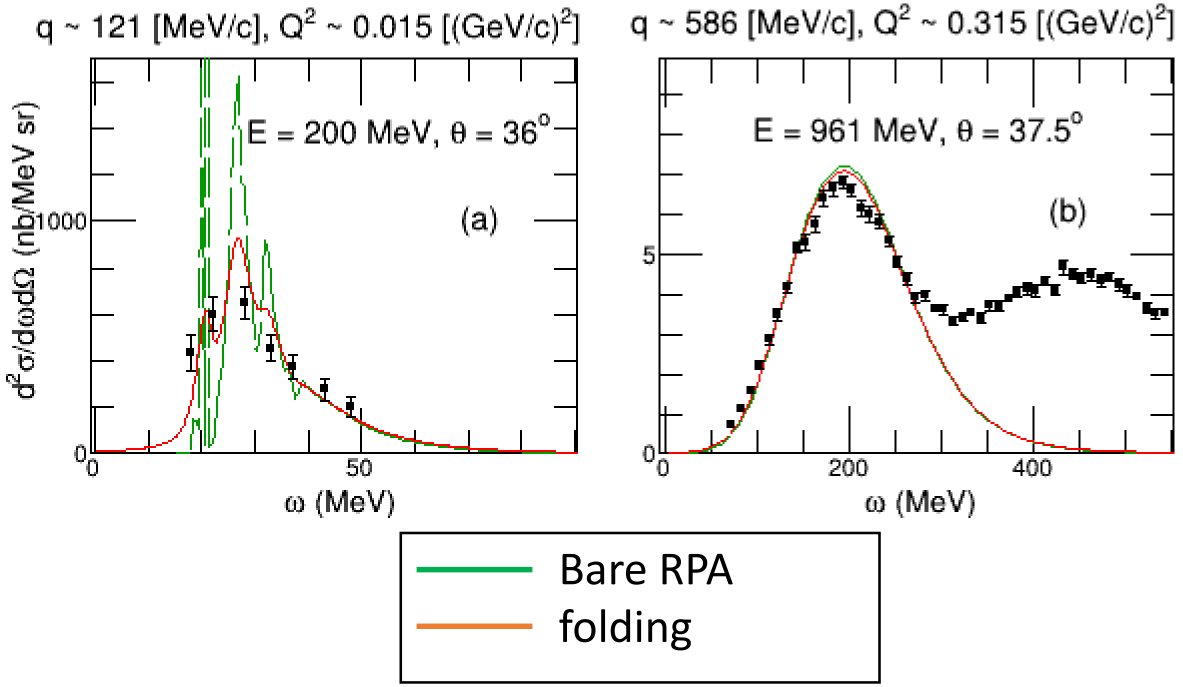
$$q_{eff} = q + 1.5\left(\frac{Z'\alpha\hbar c}{R}\right) \quad \Psi_l^{eff} = \zeta(Z', E, q)\,\Psi_l \quad \zeta(Z', E, q) = \sqrt{\frac{q_{eff}E_{eff}}{qE}}$$



- IV. 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

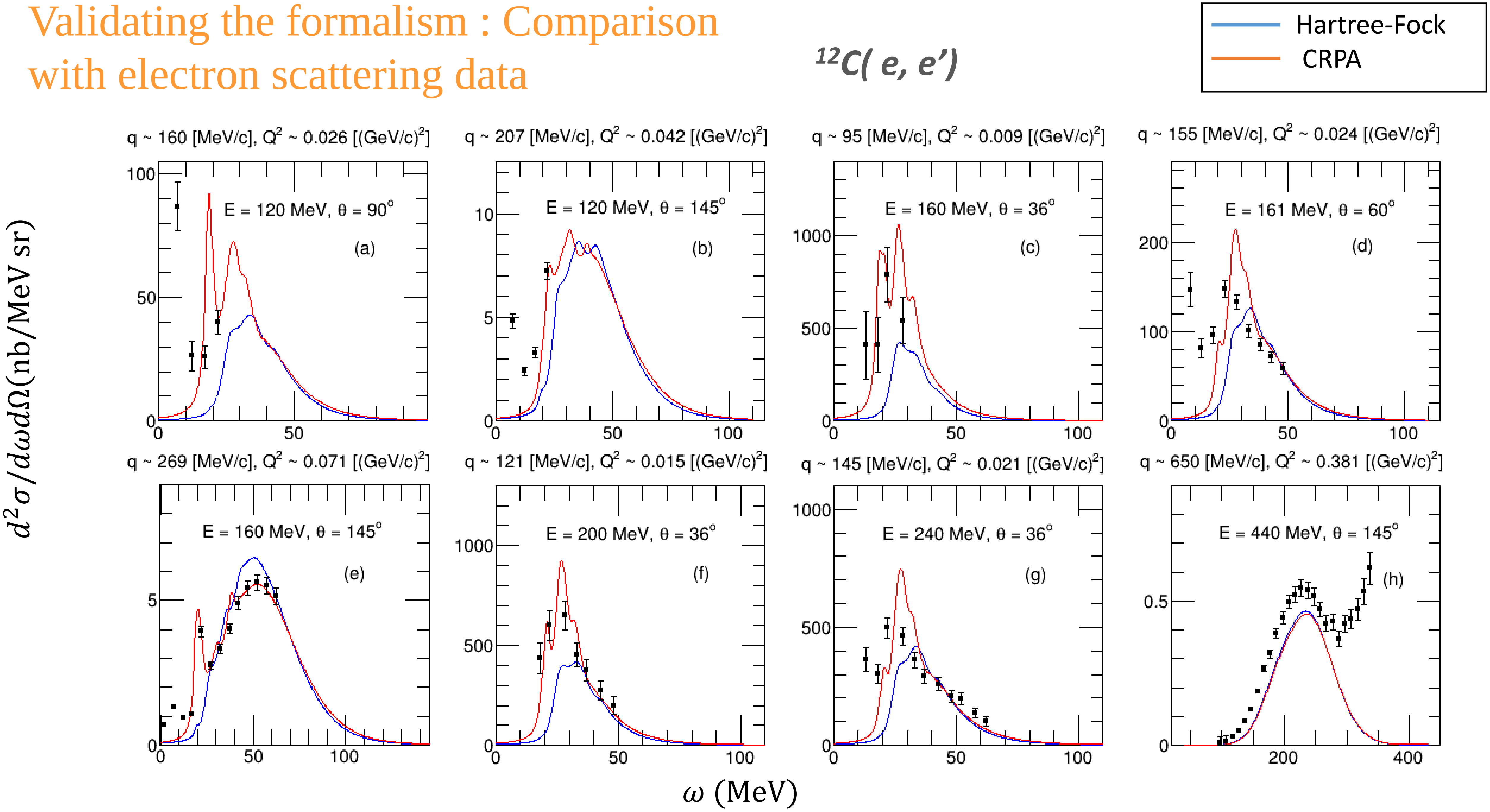
-influence of the spreading width of the particle states is implemented through a folding procedure



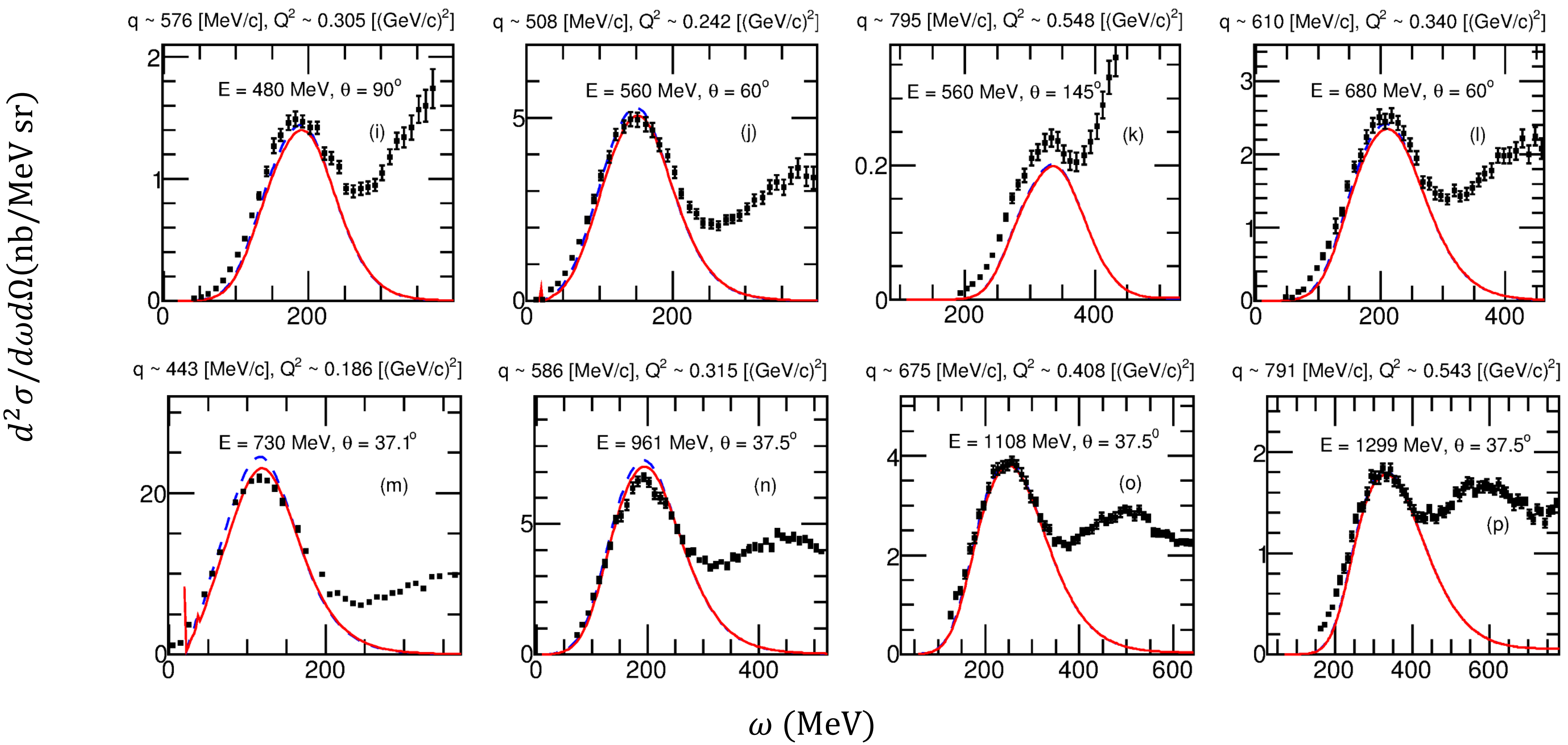
$$R'(q,\omega') = \int_{-\infty}^{\infty} d\omega \; R(q,\omega) \; L(\omega,\omega')$$

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

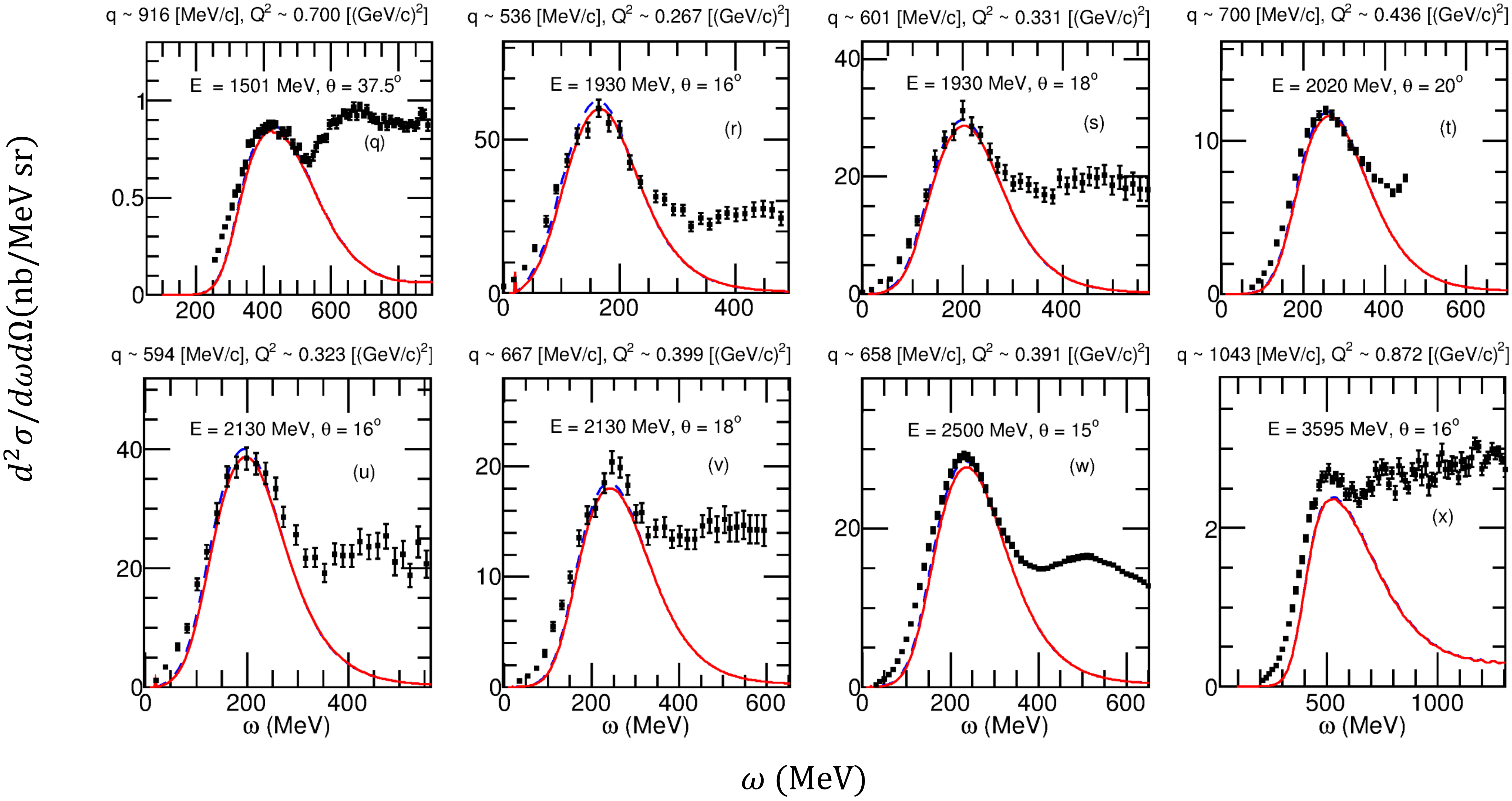
Validating the formalism : Comparison with electron scattering data



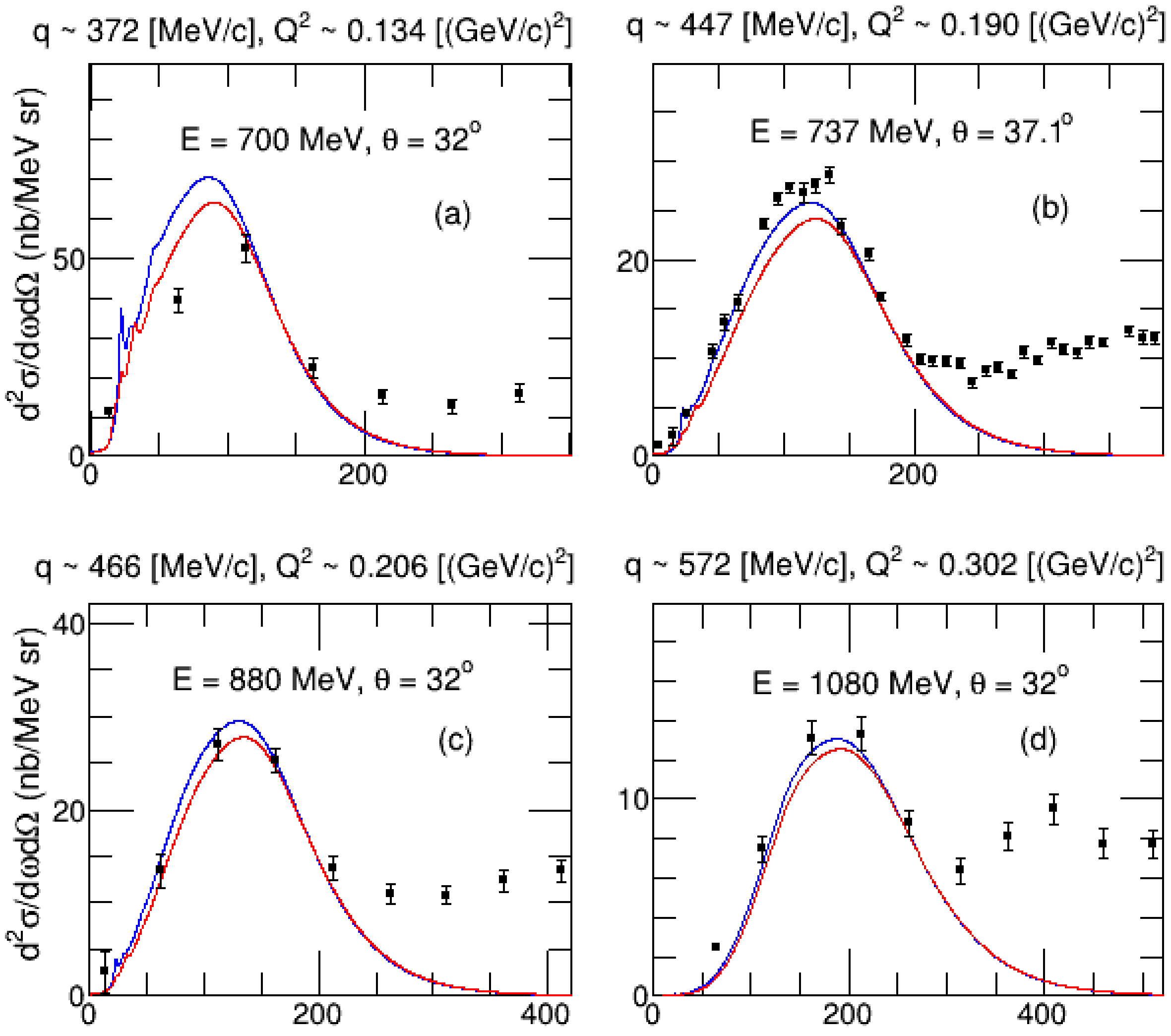
$^{12}C(e, e')$ … continued



^{12}C(e, e') … continued



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

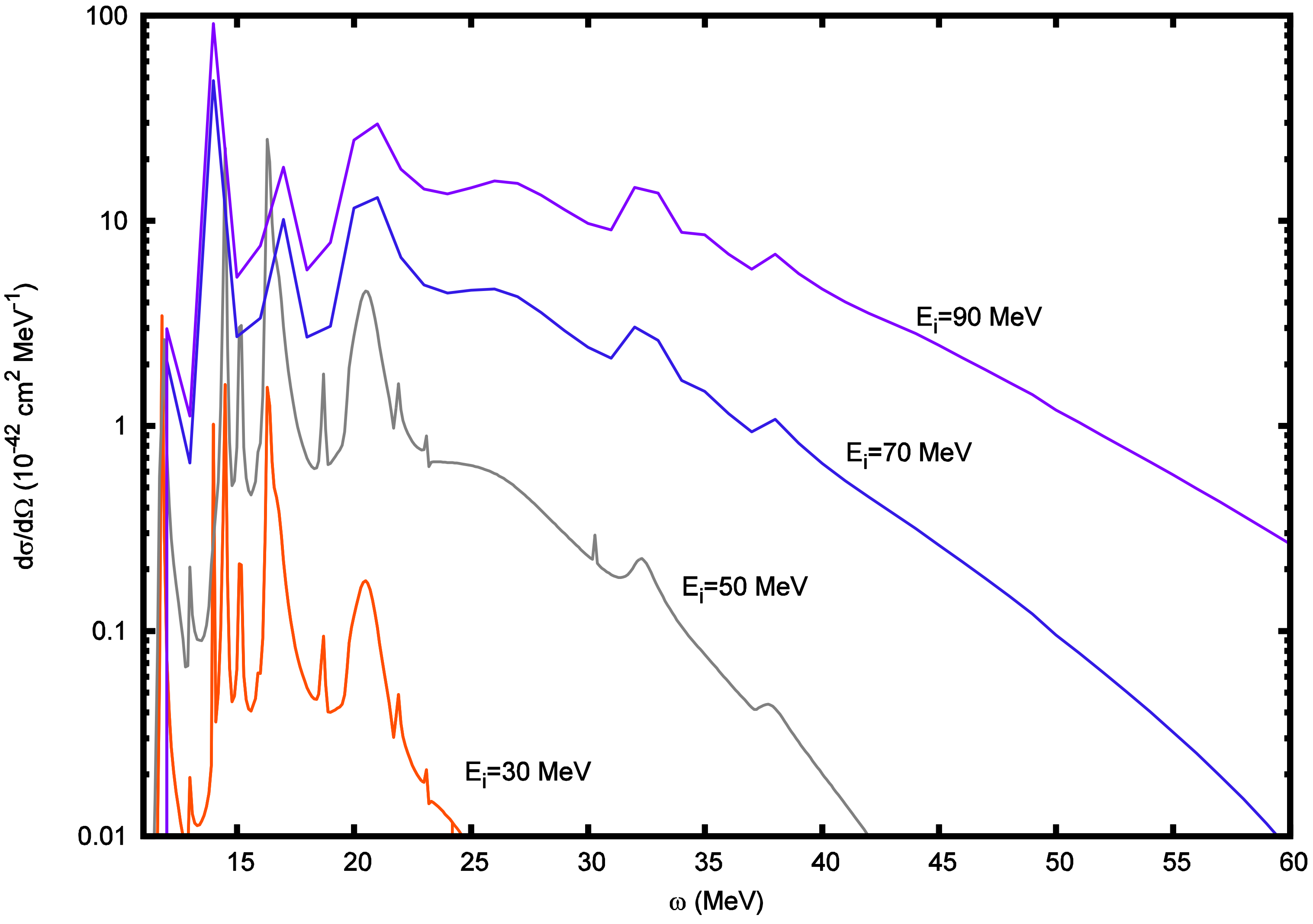


- Good overall agreement with e-scattering data

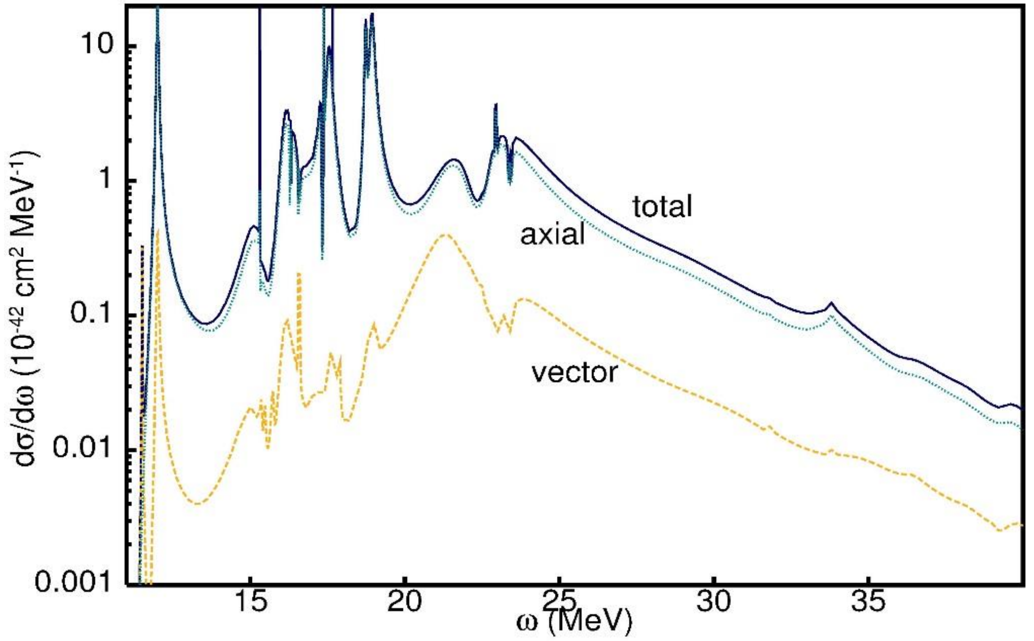
P. Barreau et al., Nucl. Phys. A402, 515 (1983), J. S. O'Connell et al., Phys. Rev. C35, 1063 (1987), R. M. Sealock et al., Phys. Rev. Lett.62, 1350 (1989).,D. S. Bagdasaryan et al., YERPHI-1077-40-88 (1988),D. B. Day et al., Phys. Rev. C 48, 1849 (1993).,D. Zeller, DESY-F23-73-2 (1973).

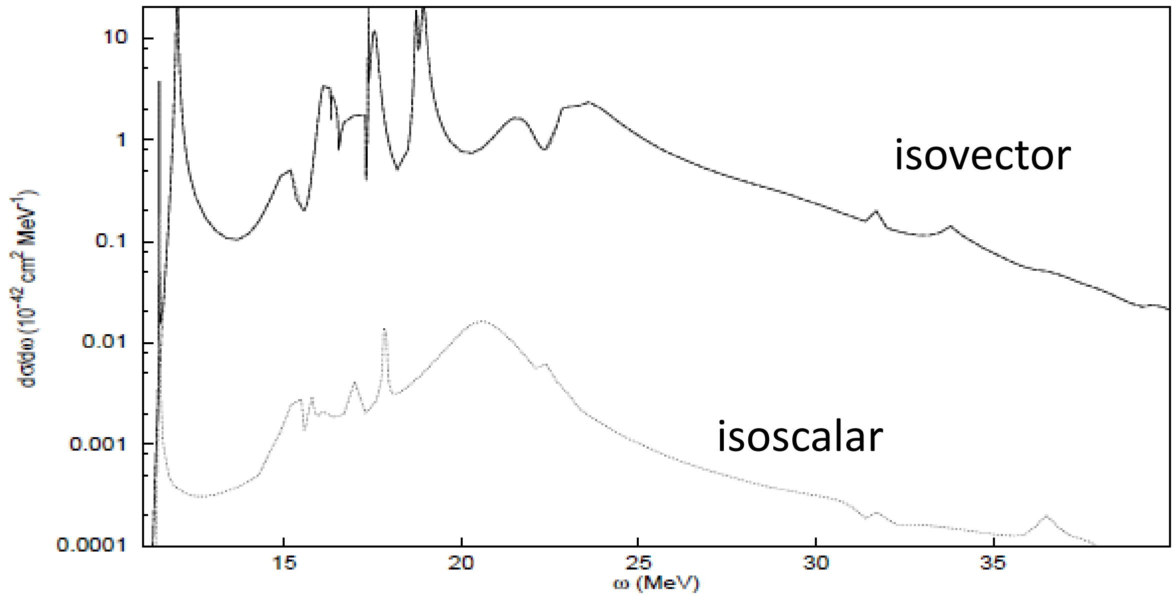
Low energy neutrino scattering results :

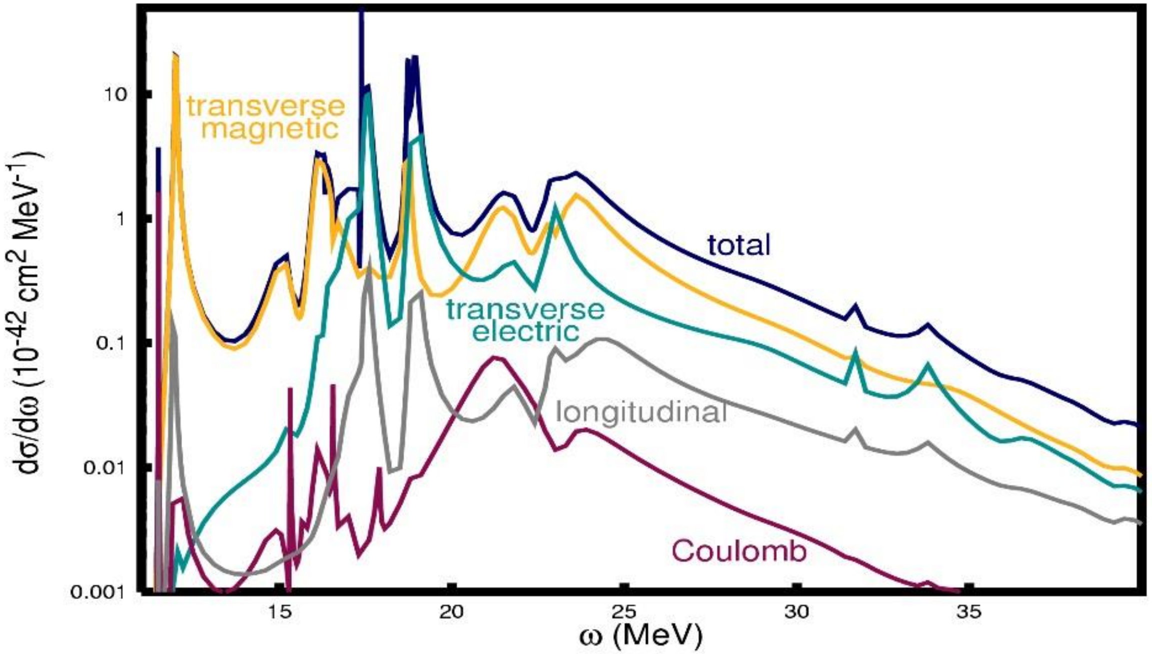
$^{16}O(\nu, \nu')\, ^{16}O^*$



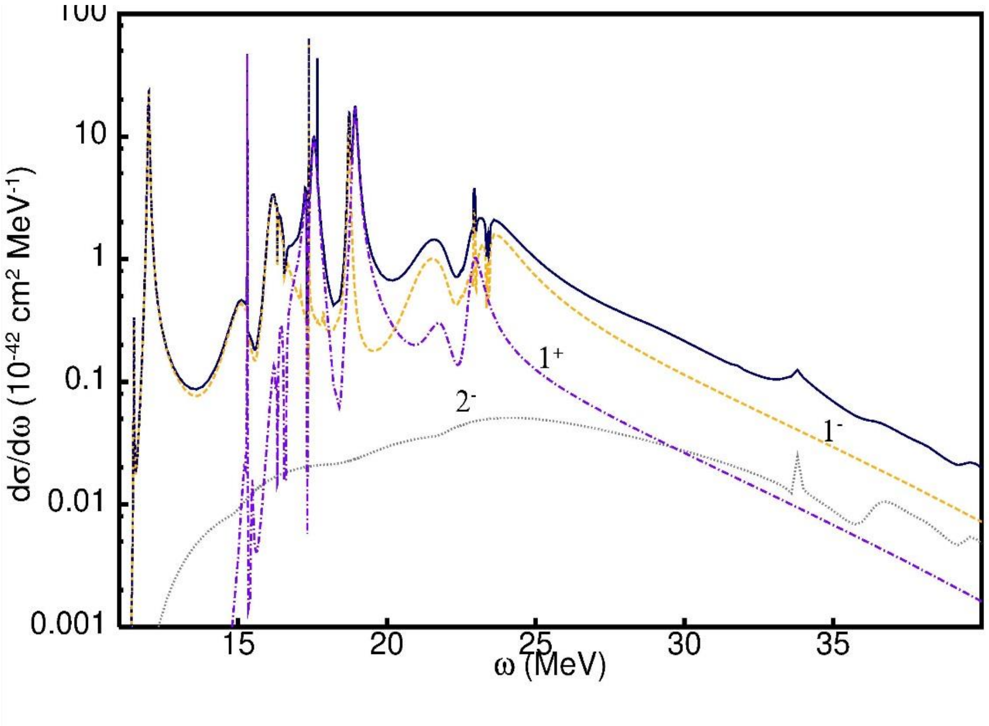
$^{16}O(\nu_{50\,MeV}, \nu')\,^{16}O^*$



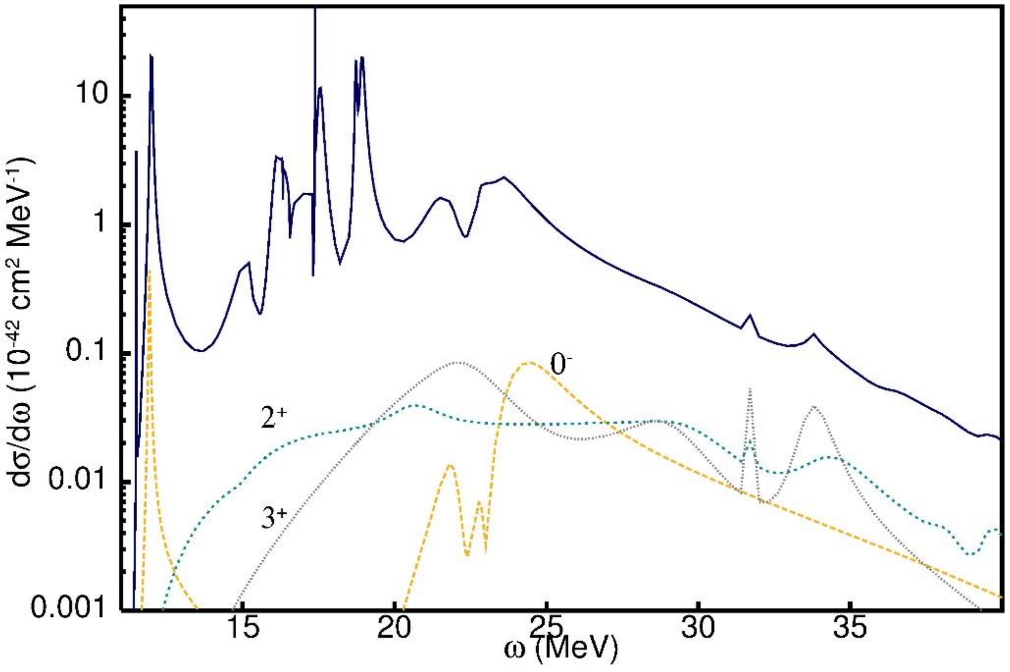




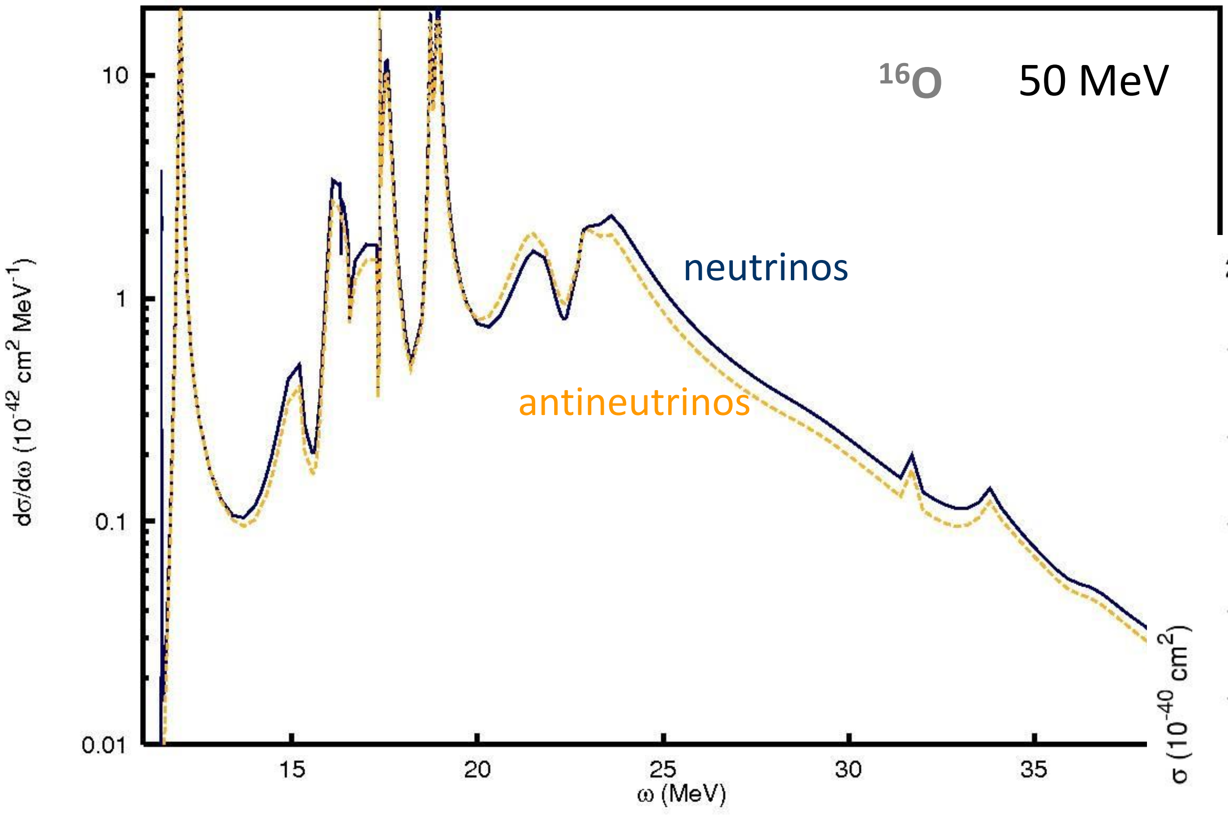
Multipole contributions :

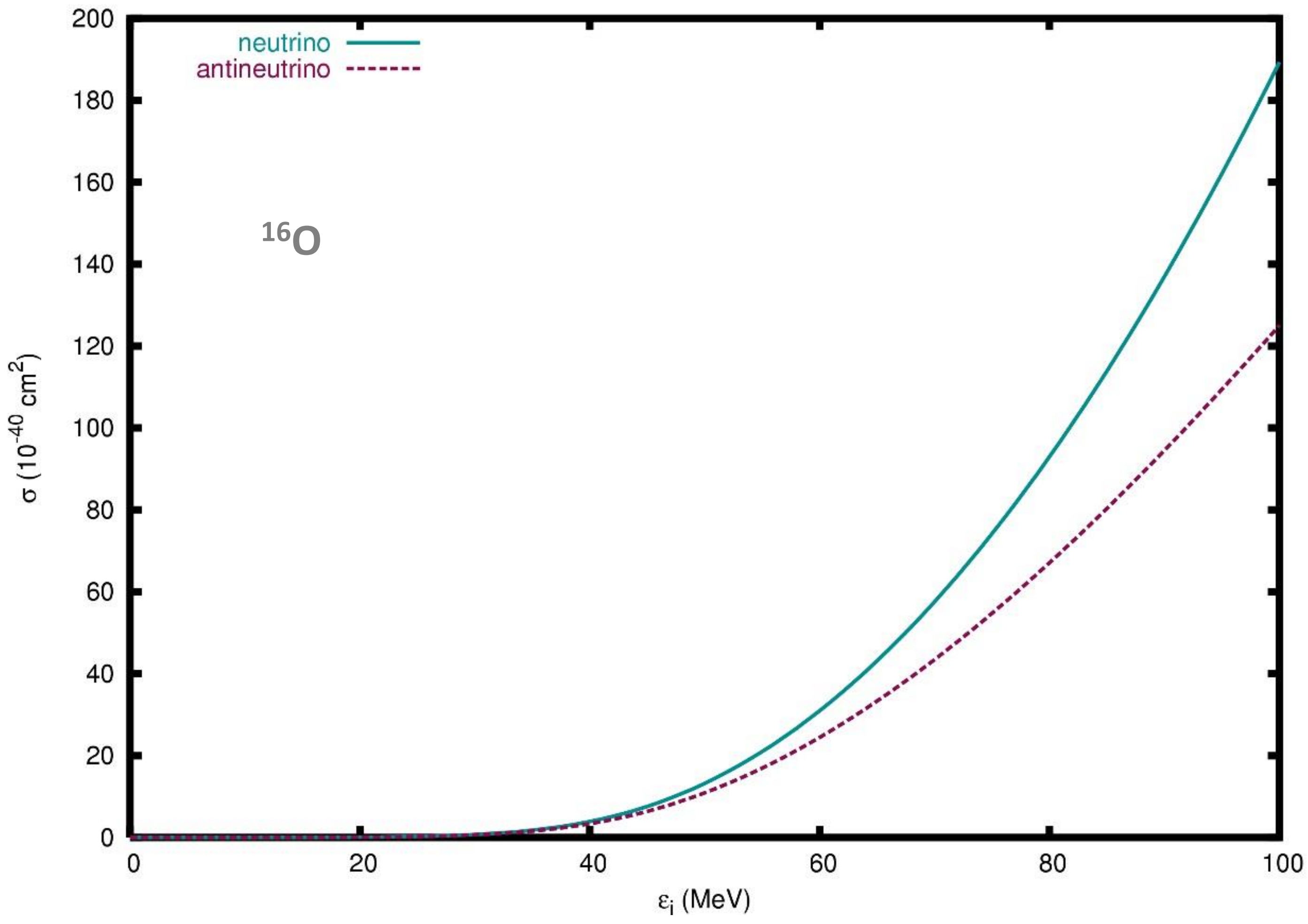


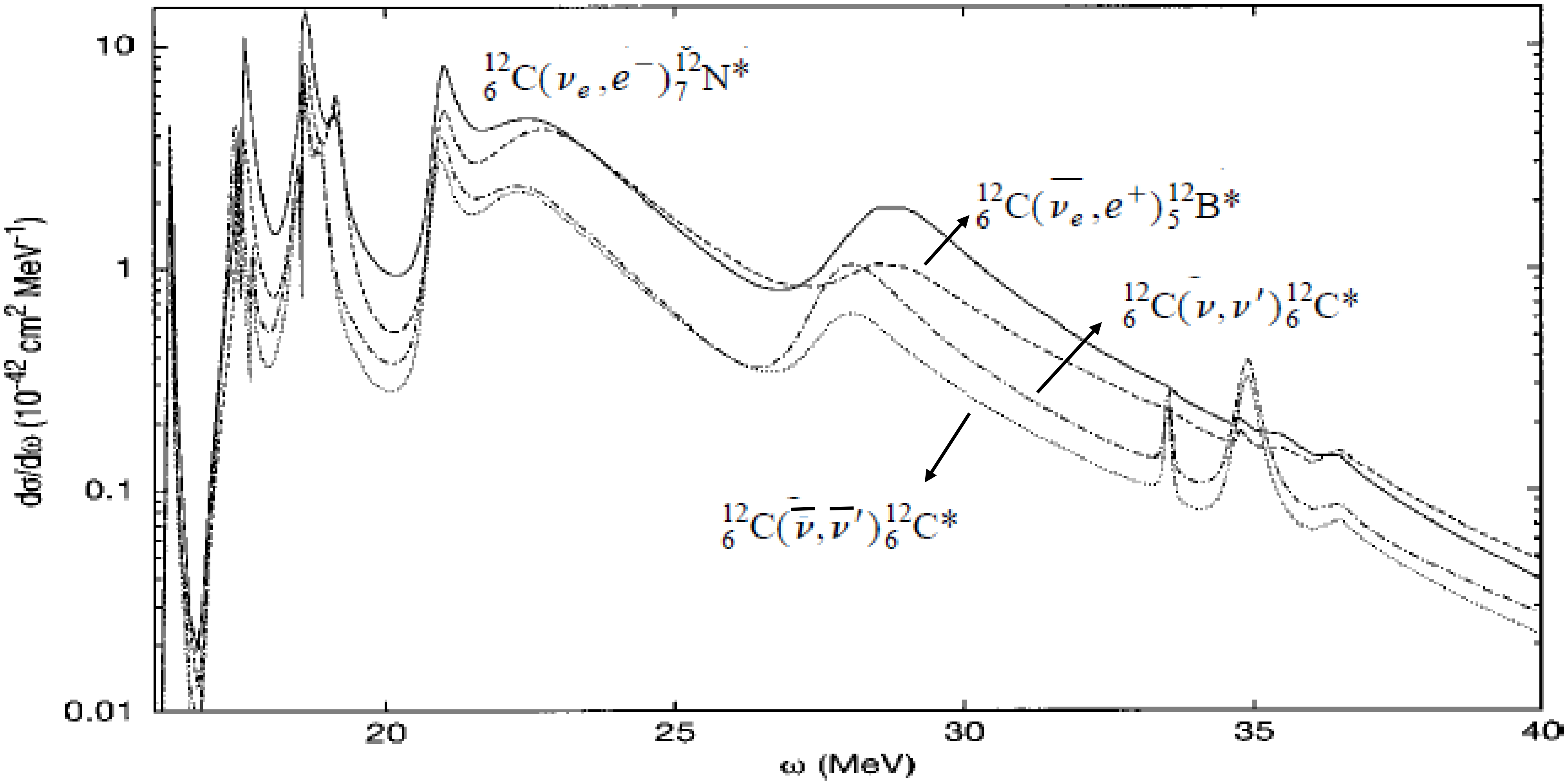
^{16}O



Neutrinos versus antineutrinos

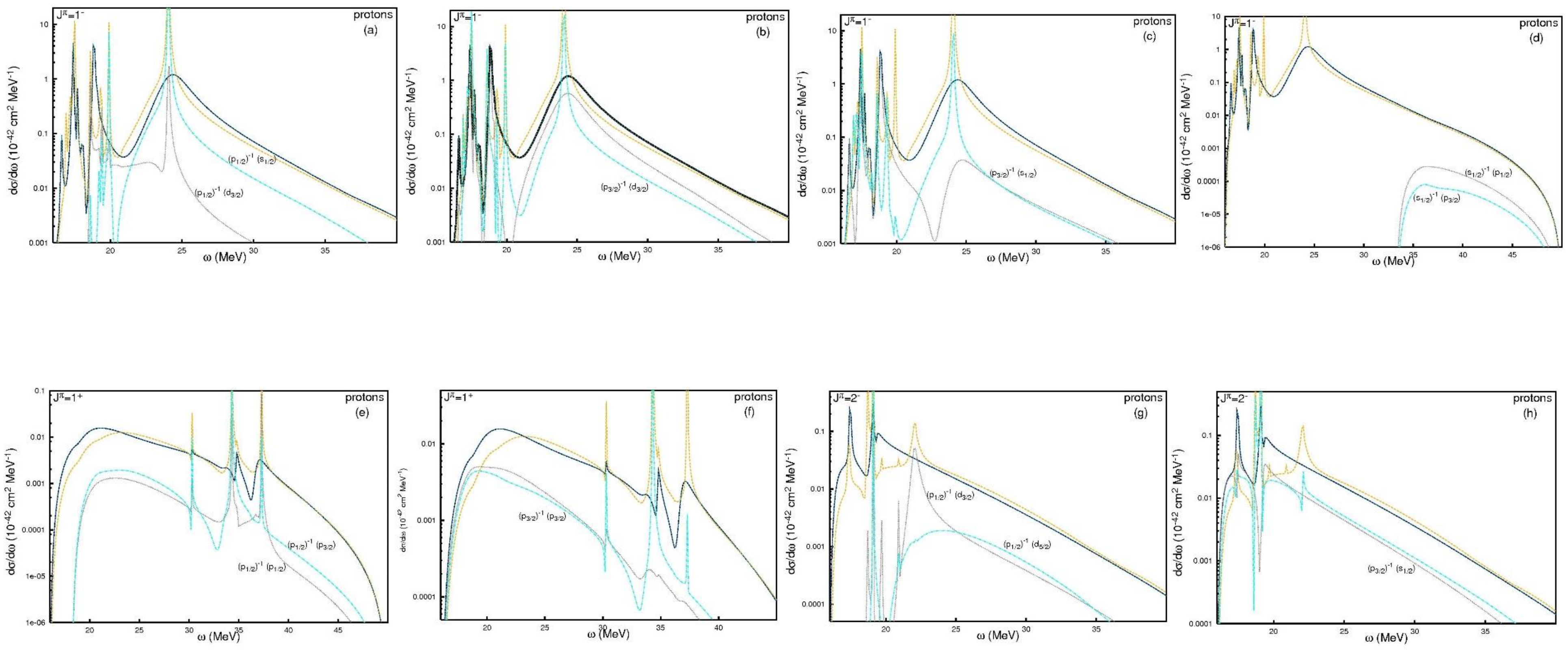






$^{12}_{6}C(\nu_e, e^-)^{12}_{7}N^*$
$^{12}_{6}C(\overline{\nu_e}, e^+)^{12}_{5}B^*$
$^{12}_{6}C(\nu, \nu')^{12}_{6}C^*$
$^{12}_{6}C(\overline{\nu}, \overline{\nu}')^{12}_{6}C^*$
10
1
0.1
0.01
20
25
30
35
40
dσ/dω (10^{-42} cm^2 MeV^{-1})
ω (MeV)

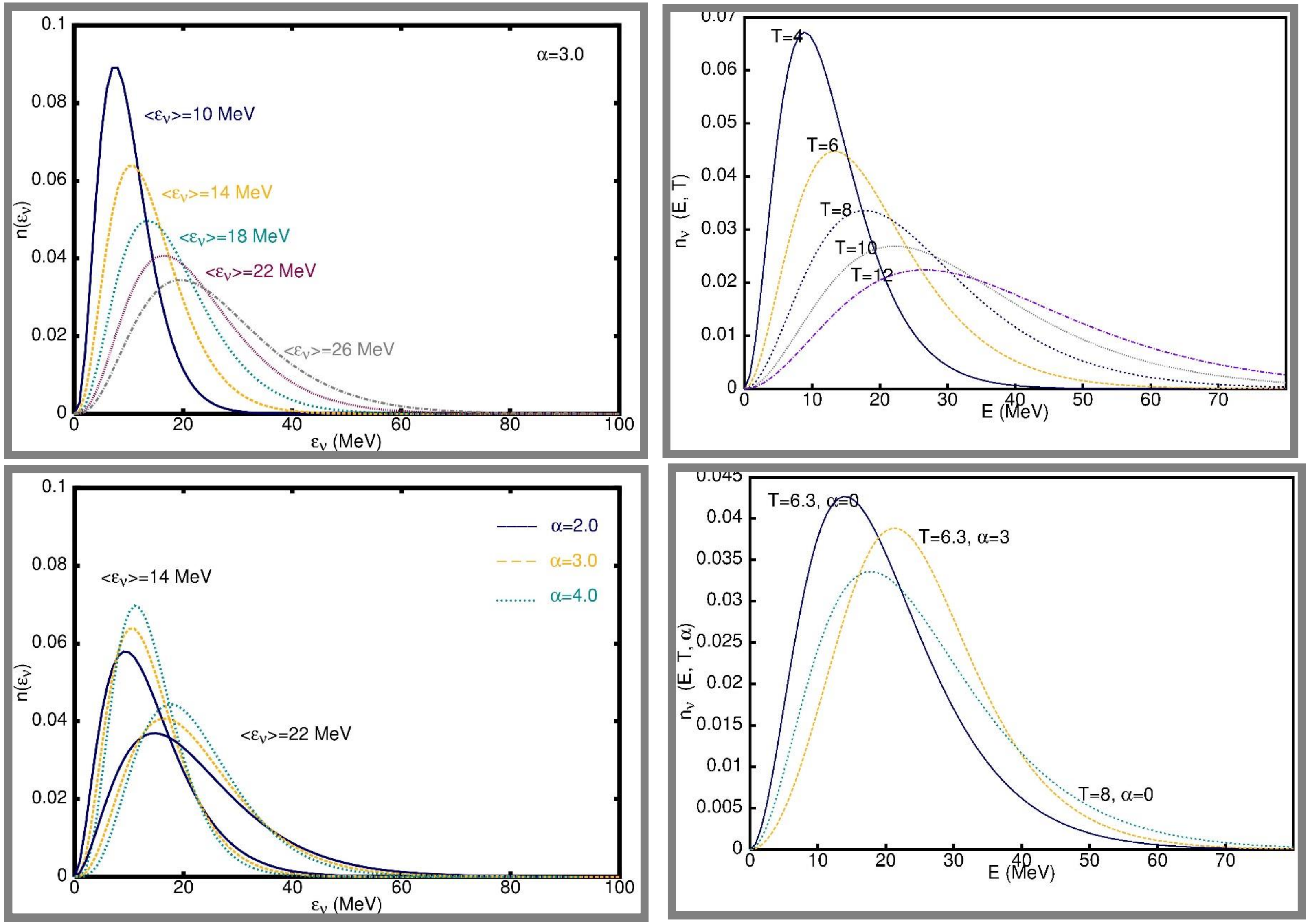
Contribution of different single-particle channels in ^{12}C



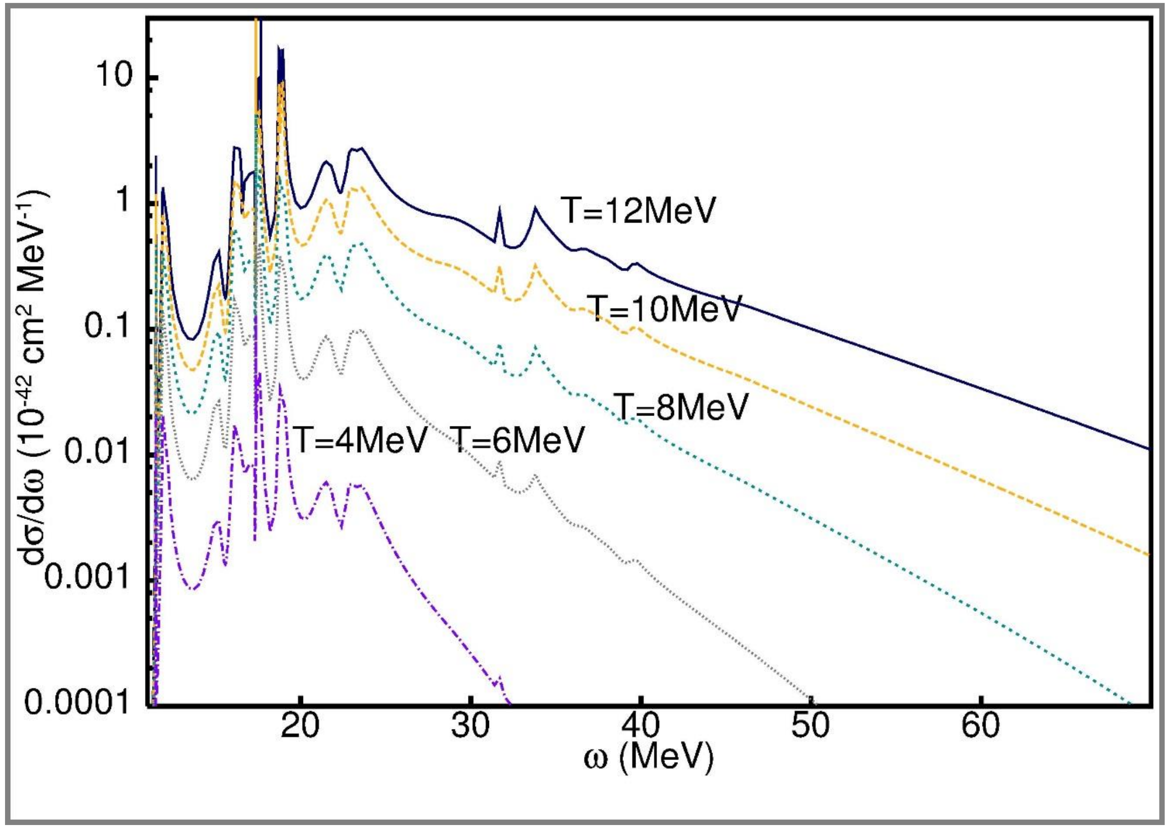
Supernova neutrinos

$$n_{SN[\langle\varepsilon\rangle,\alpha]}(\varepsilon) = \left(\frac{\varepsilon}{\langle\varepsilon\rangle}\right)^{\alpha} e^{-(\alpha+1)\frac{\varepsilon}{\langle\varepsilon\rangle}}$$

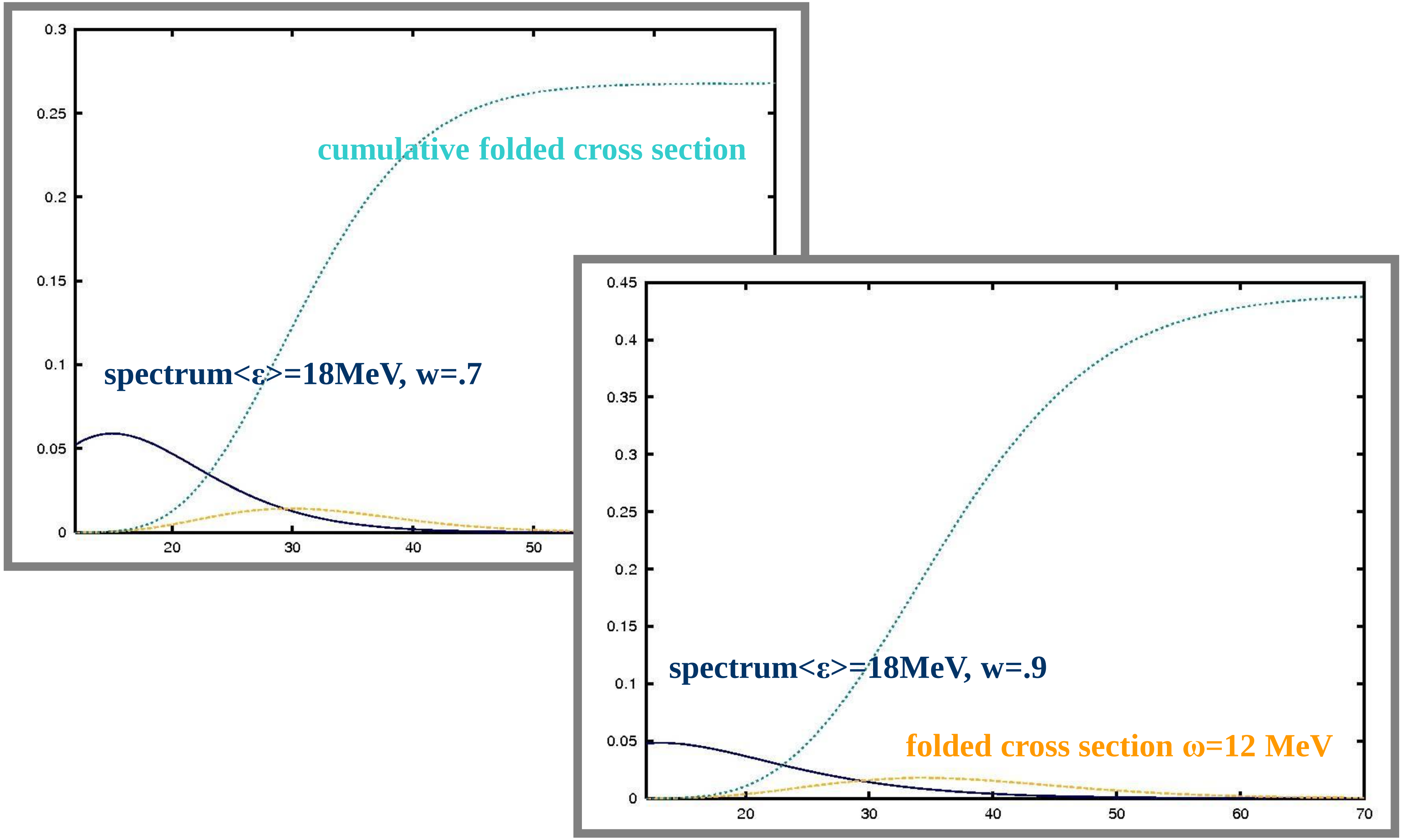
Spectra

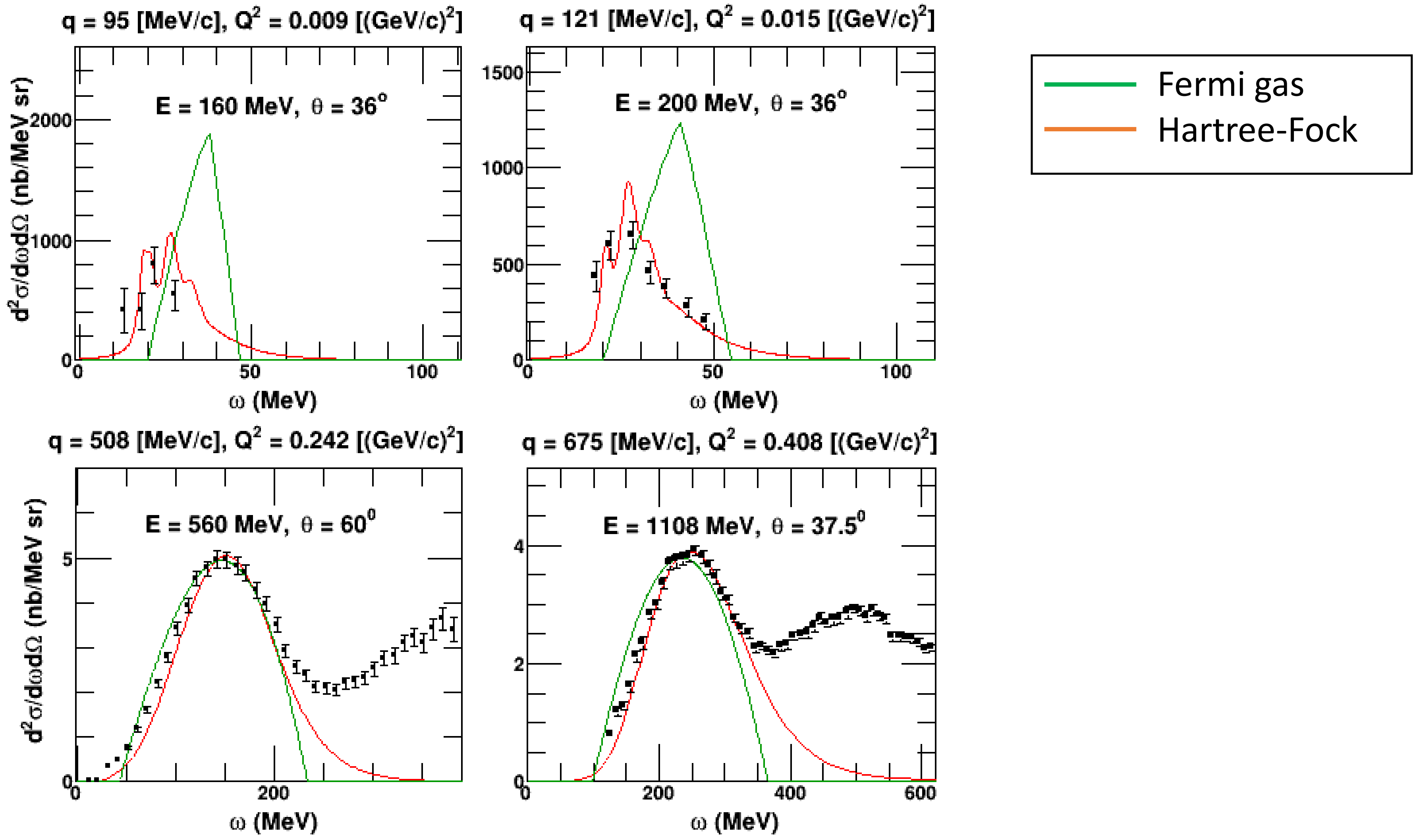


Folded cross sections supernova neutrino spectra :



Cumulative folded cross sections:





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°
d^{2}σ/dωdΩ (nb/MeV sr)
ω (MeV)
Fermi gas
Hartree-Fock

Strangeness in the nucleon

Axial form factor :

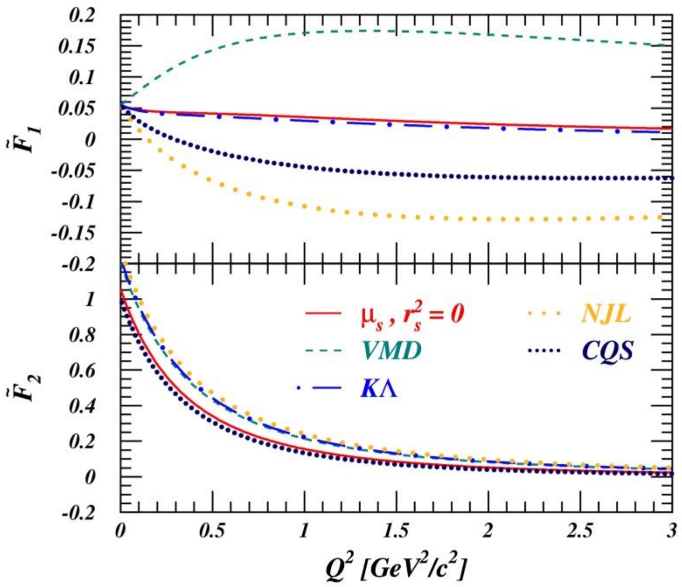
$$G_A(Q^2) = -\frac{(\tau_3 g_A - g_A^s)}{2} G(Q^2), \qquad g_A = 1.262$$

$$G(Q^2) = (1 + Q^2/M^2)^{-2}, \qquad M = 1.032$$

Weak vector form factors :

$$F_1^s = \frac{1}{6} \frac{-r_s^2 Q^2}{(1 + Q^2/M_1^2)^2}, \qquad M_1 = 1.3$$

$$F_2^s = \frac{\mu_s}{(1 + Q^2/M_2^2)^2}, \qquad M_2 = 1.26$$



Model	$\mu_s(\mu_N)$	$r_s^2(\text{fm}^2)$
VMD	-0.31	0.16
$K\Lambda$	-0.35	-0.007
NJL	-0.45	-0.17
CQS (K)	0.115	-0.095

Traditionally :

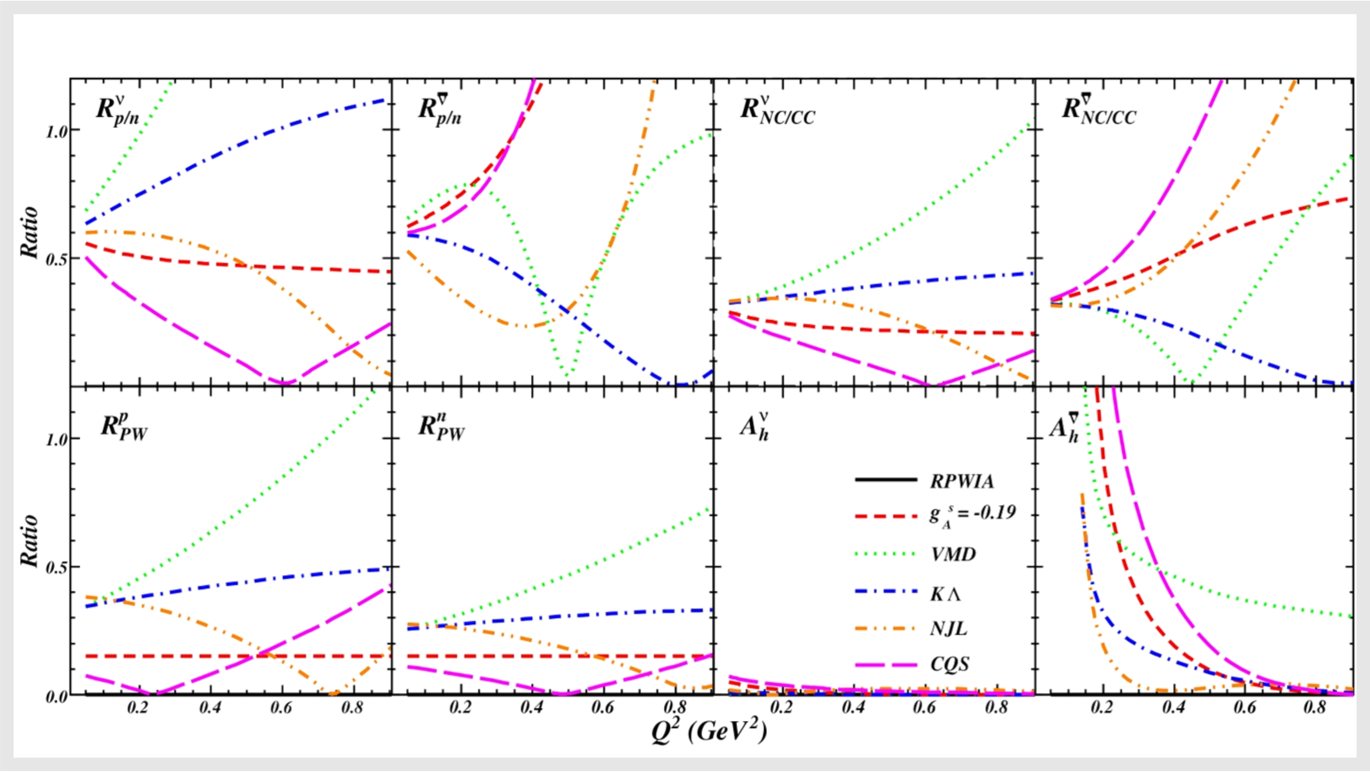
•strangeness contribution to the ***weak vector formfactors*** : Parity Violating Electron Scattering (Sample, Happex, G0, …)

Correlated !

•strangeness contribution to the ***axial current*** : neutrino scattering

-vector current contributions are suppressed

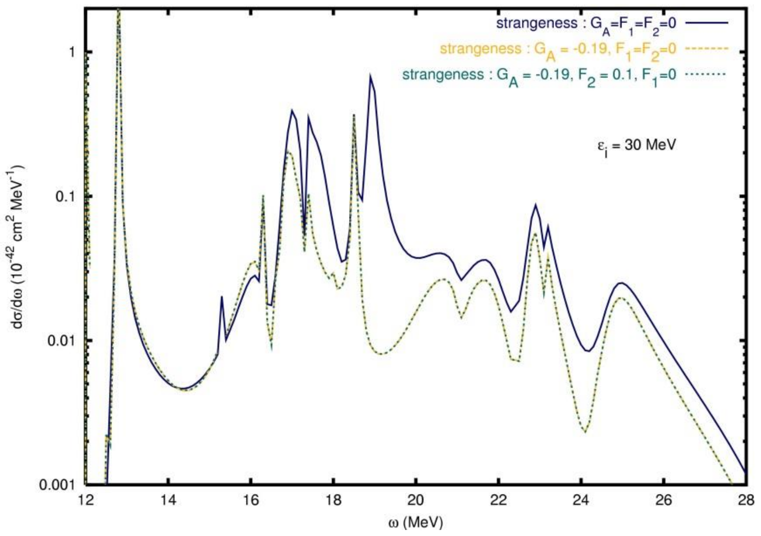
-no radiative corrections

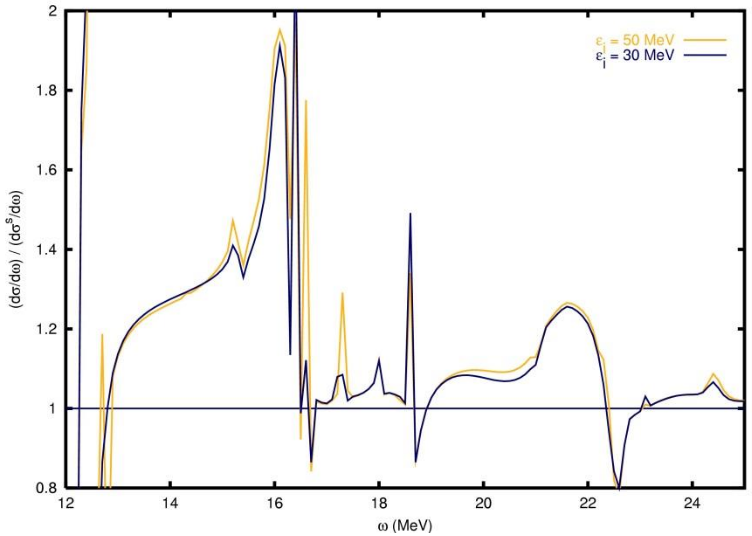


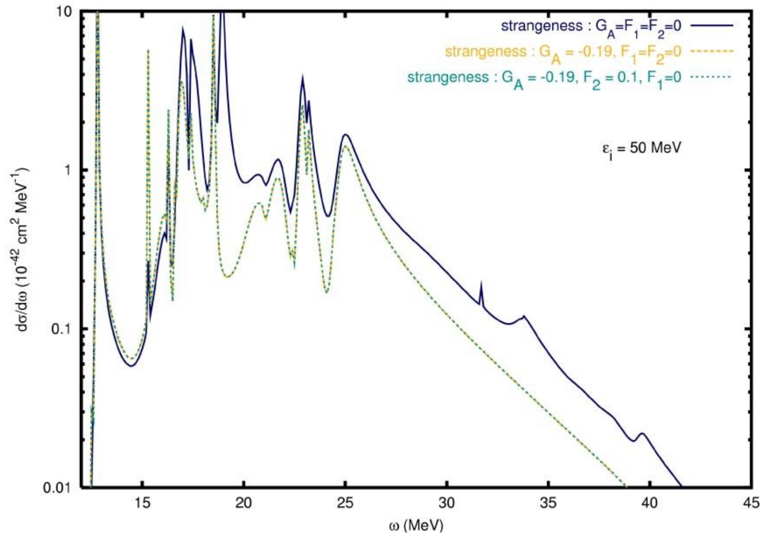
N.J., P. Vancraeyveld, P. Lava, J. Ryckebusch, PRC76, 055501 (2007).

Neutrino cross sections including strangeness

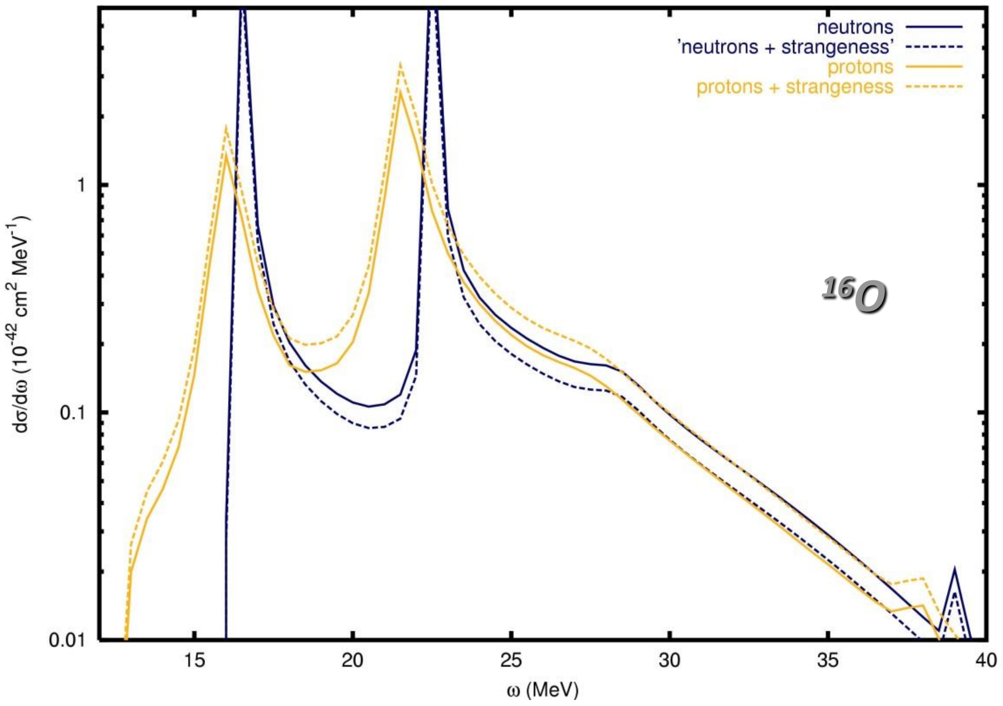
- Generally : net strangeness effect vanishes for isoscalar targets
- close to particle knockout threshold the influence becomes larger due to binding energy differences between protons and neutrons
- differential cross sections differ, energy of reaction products can be very different





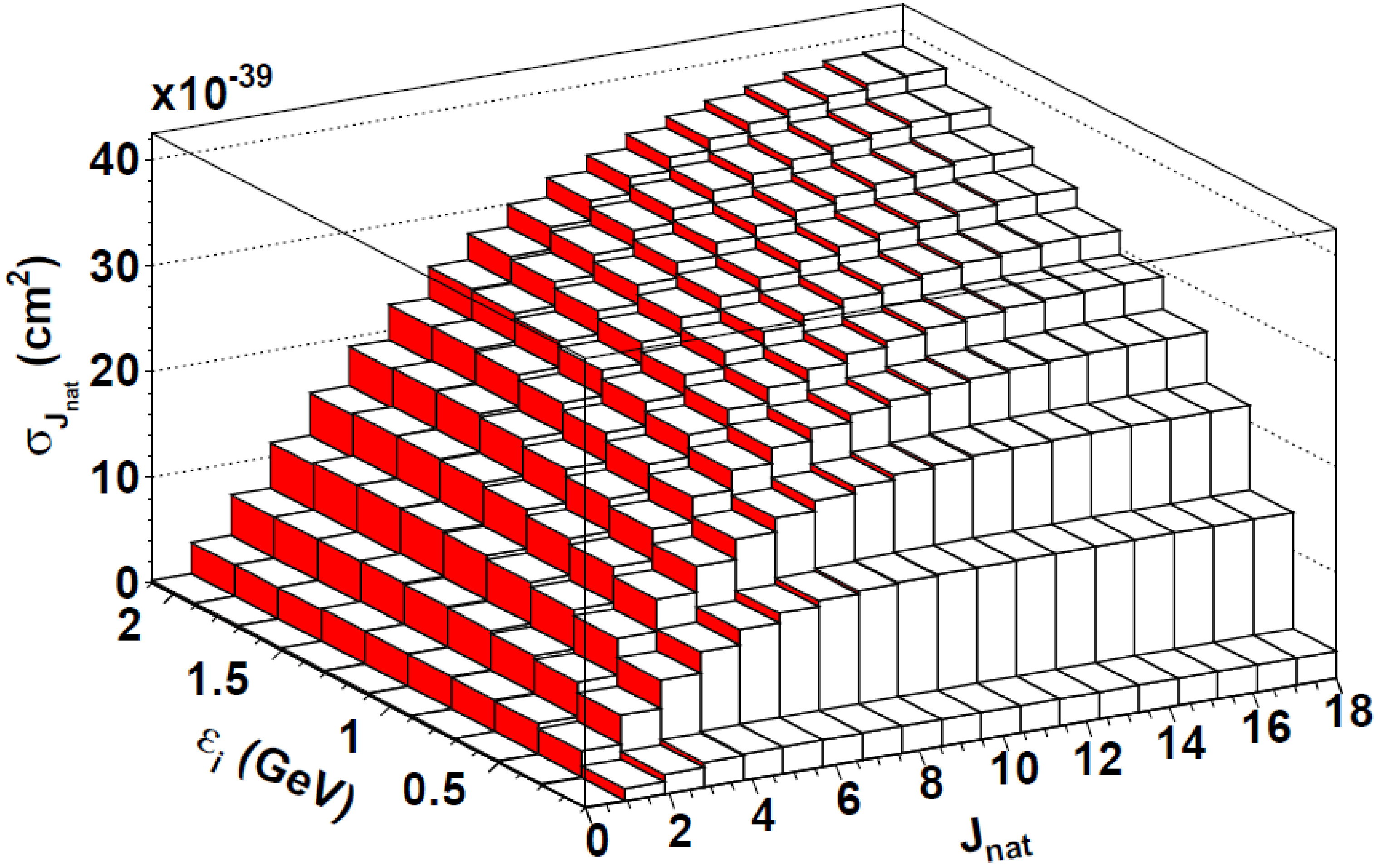


proton/neutron cross sections



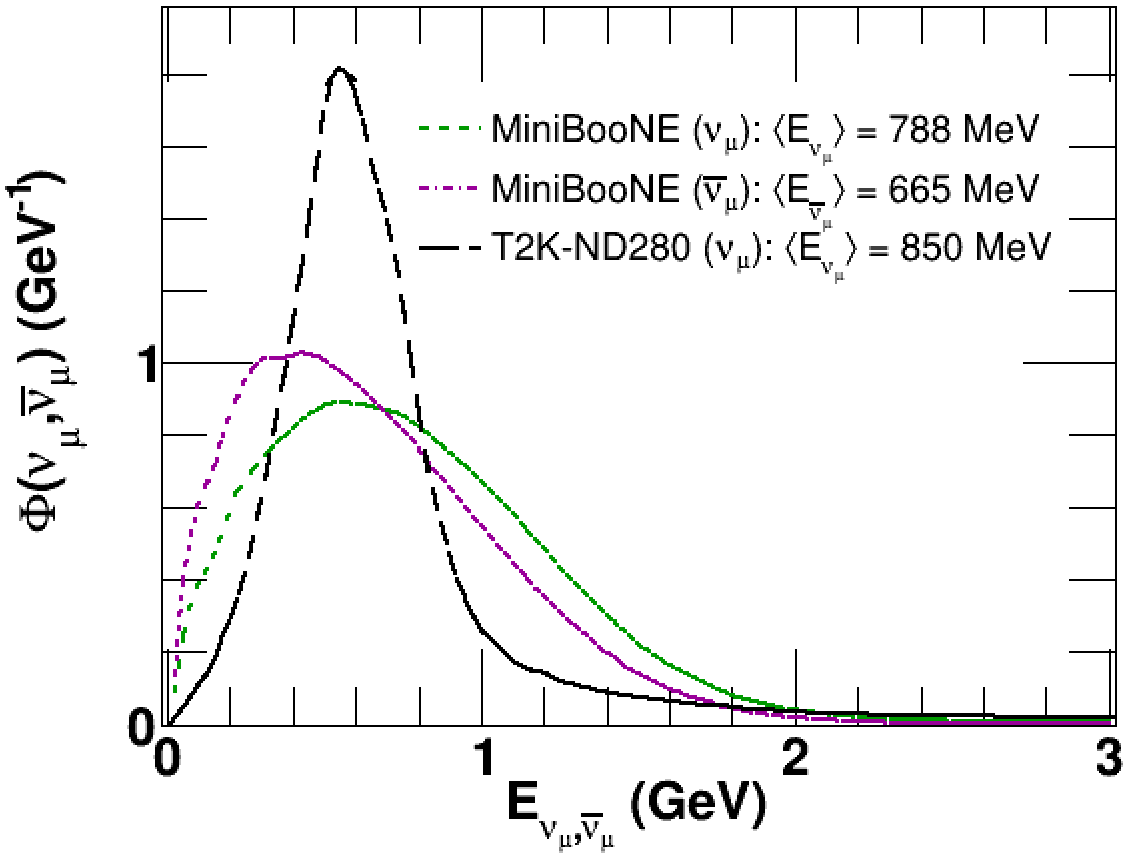
- differences up to 20%
- opposite effect for protons and neutrons

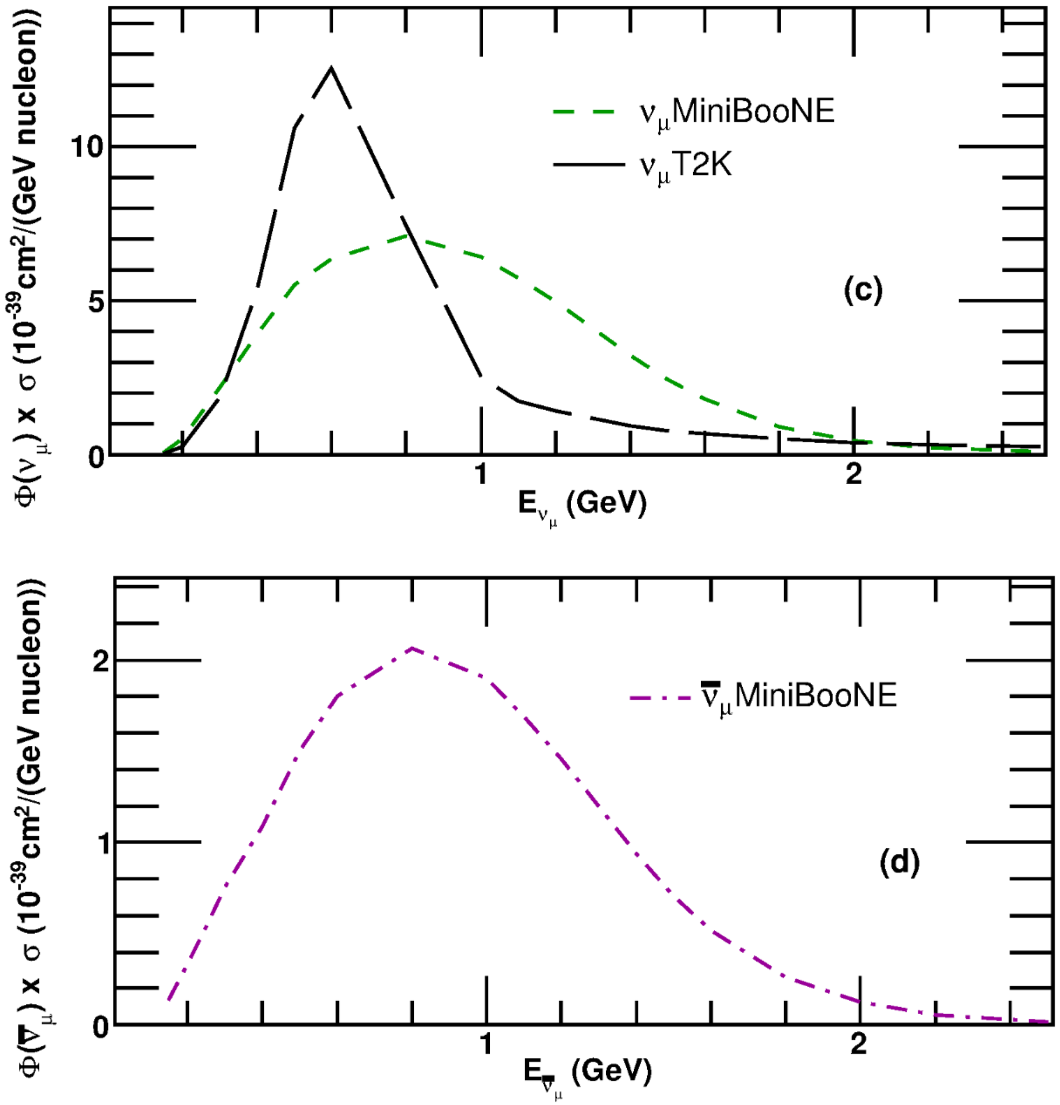
Higher incoming energies



Multipole distribution

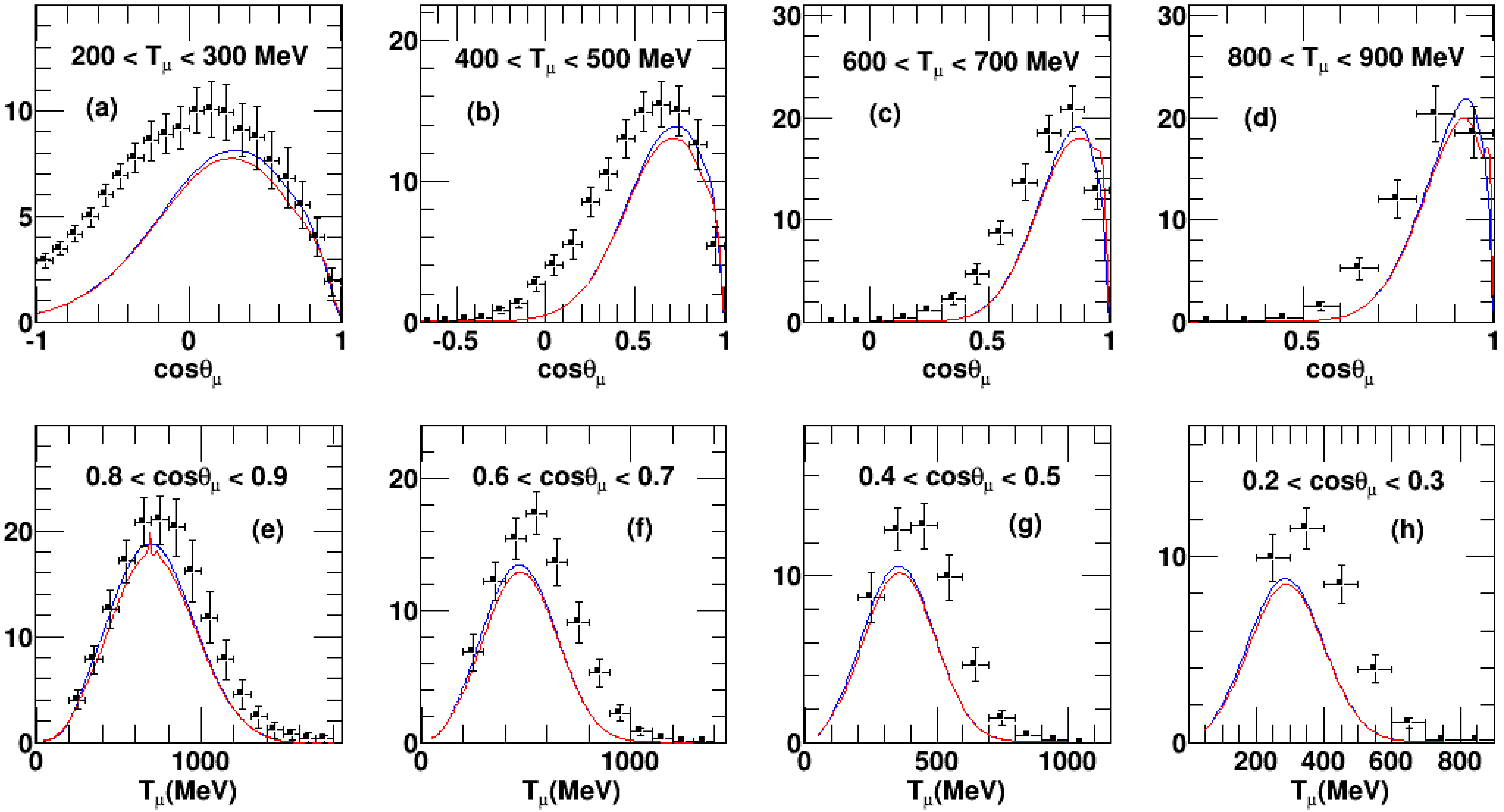
Comparison with neutrino data

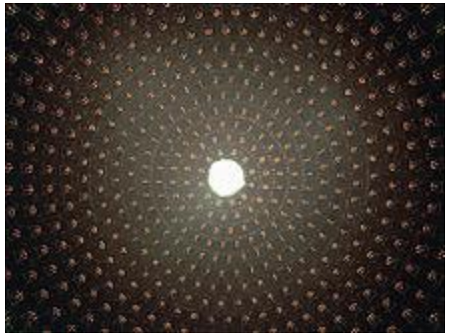




MiniBooNe ν_μ

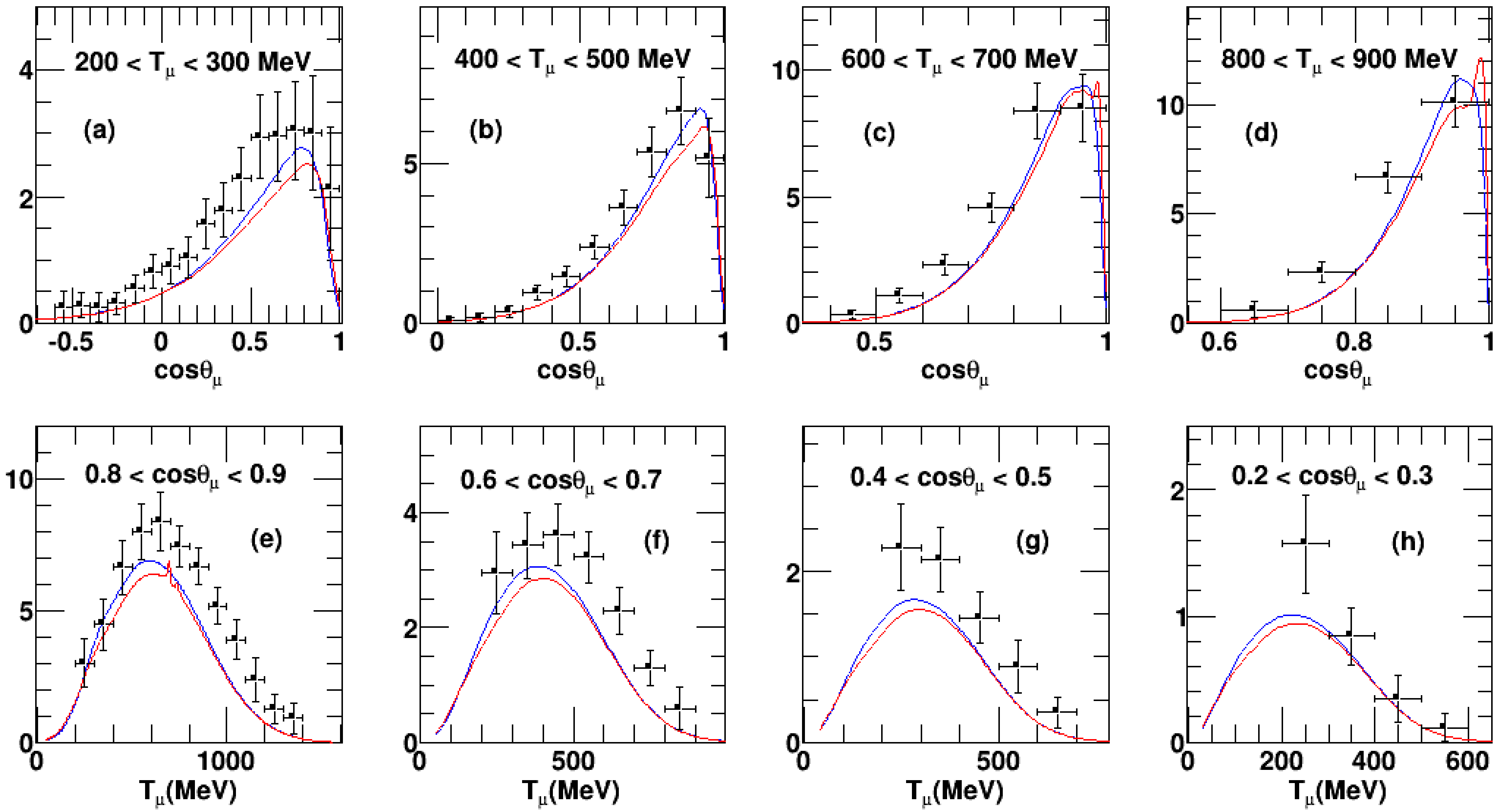
- Satisfactory general agreement
- Good agreement for forward scattering
- Missing strength for low T_μ, backward scattering

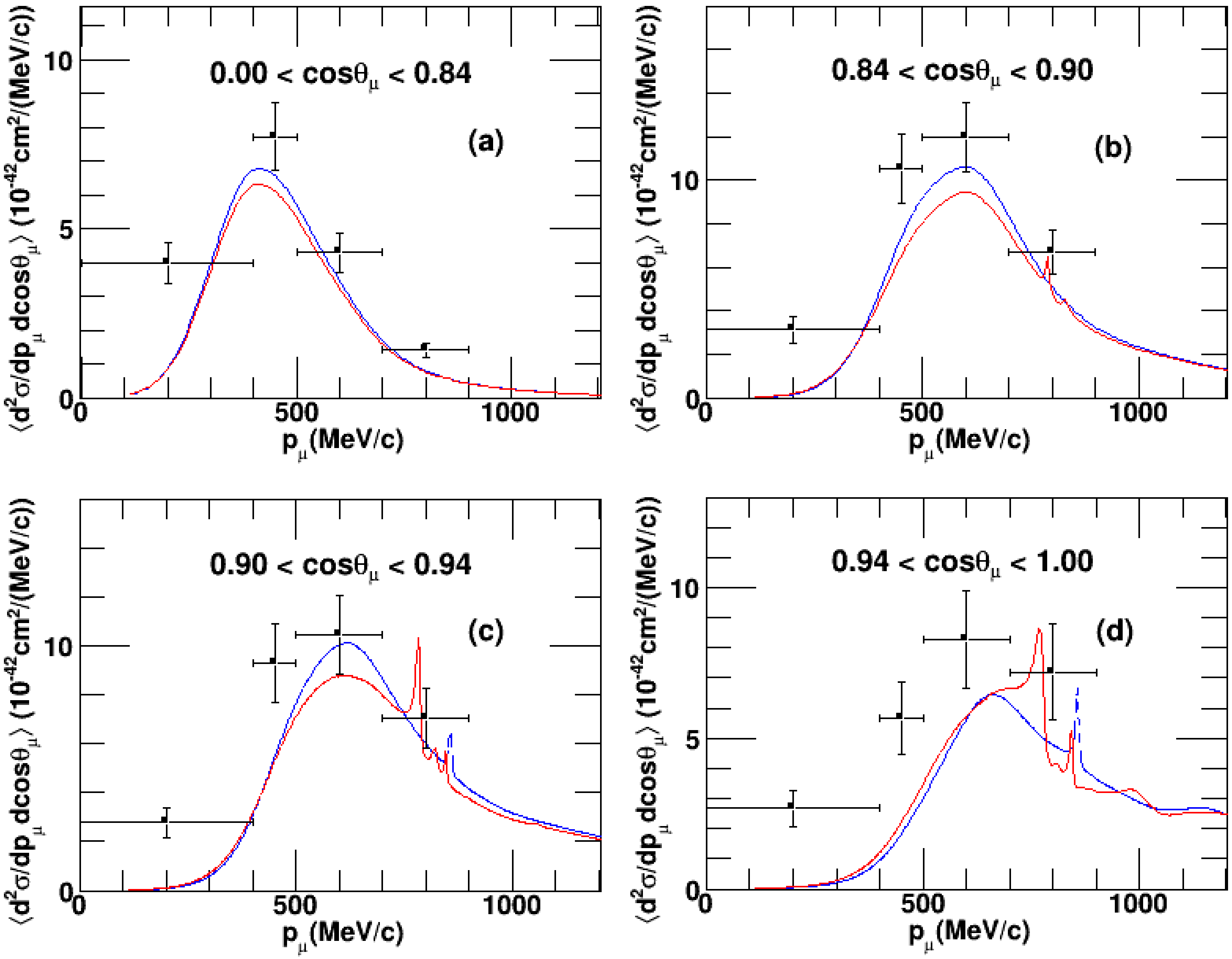




MiniBooNe $\bar{\nu}_\mu$

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





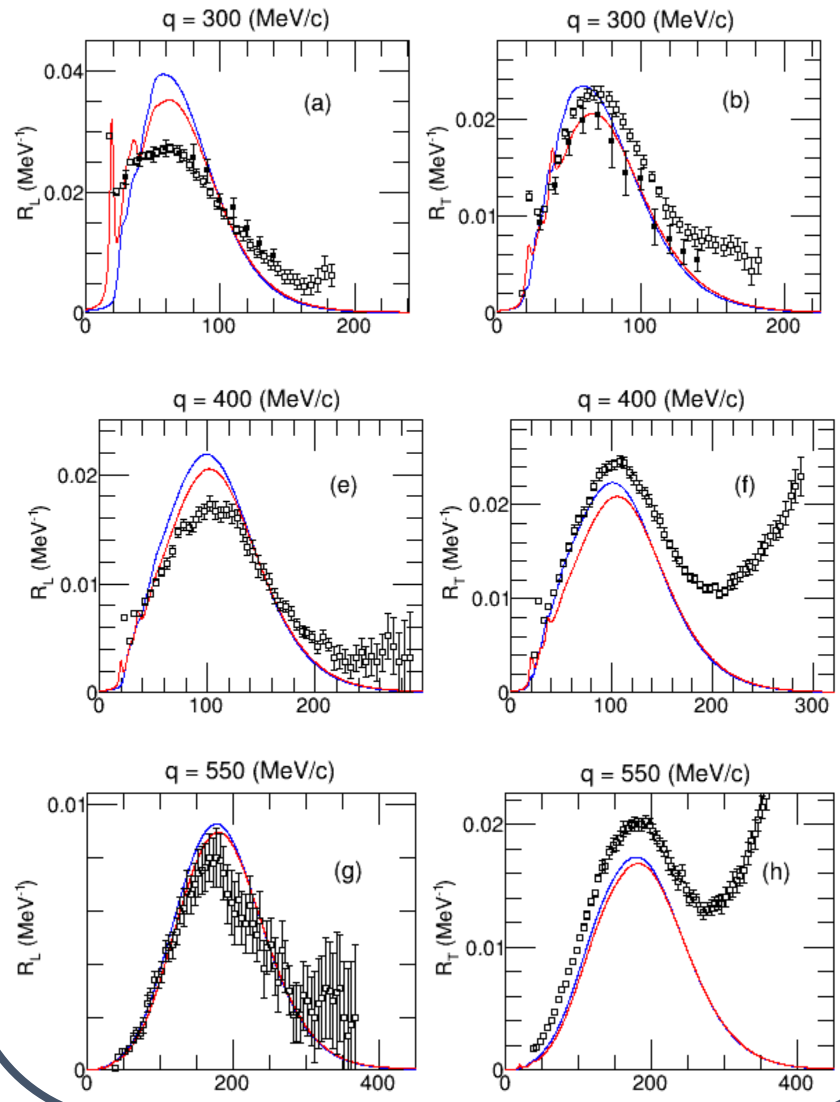
T2K ν_μ

- General agreement quite good
- Missing strength for low p_μ

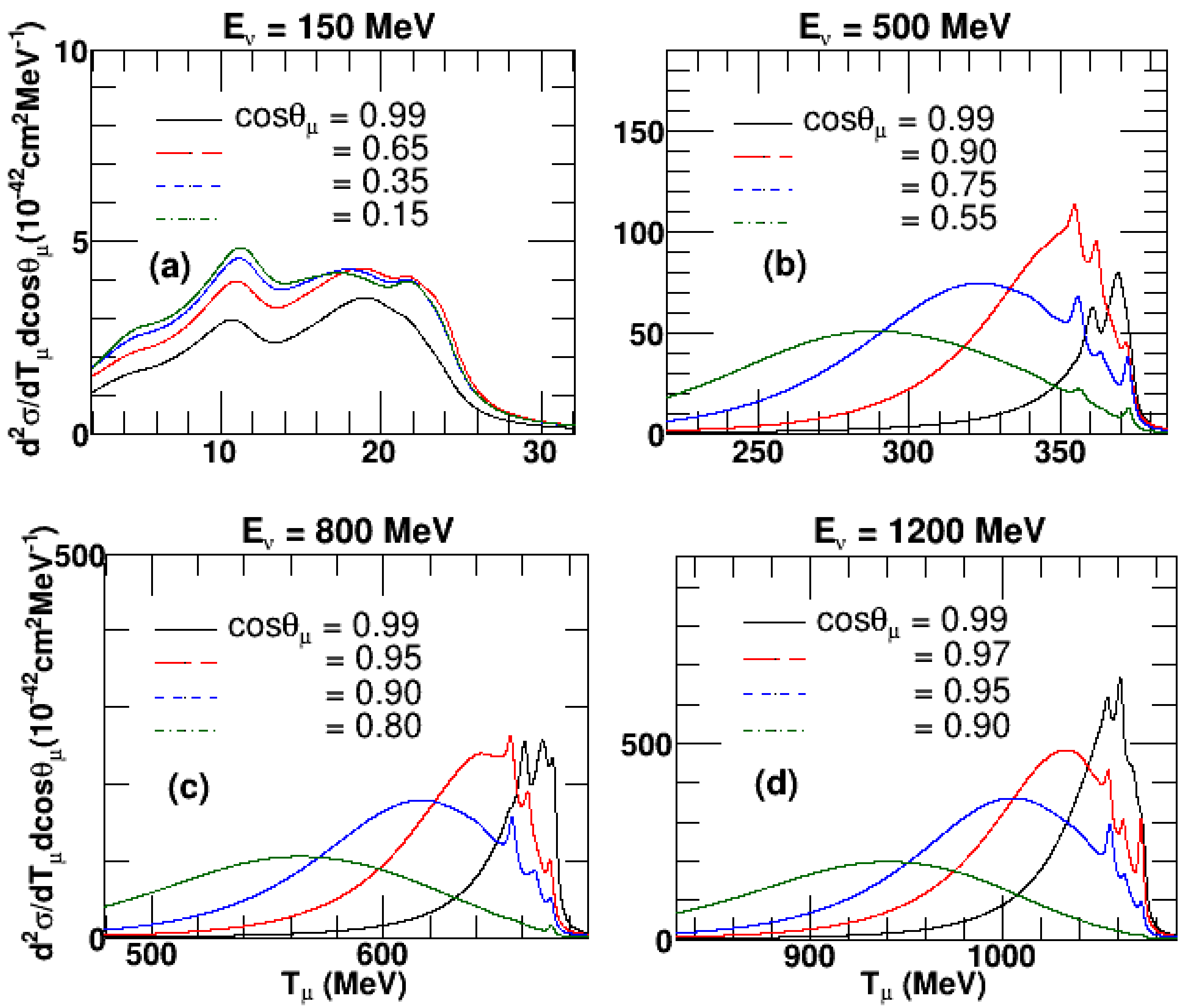
More detailed cross section contributions

- Missing strength mainly attributed to transverse responses

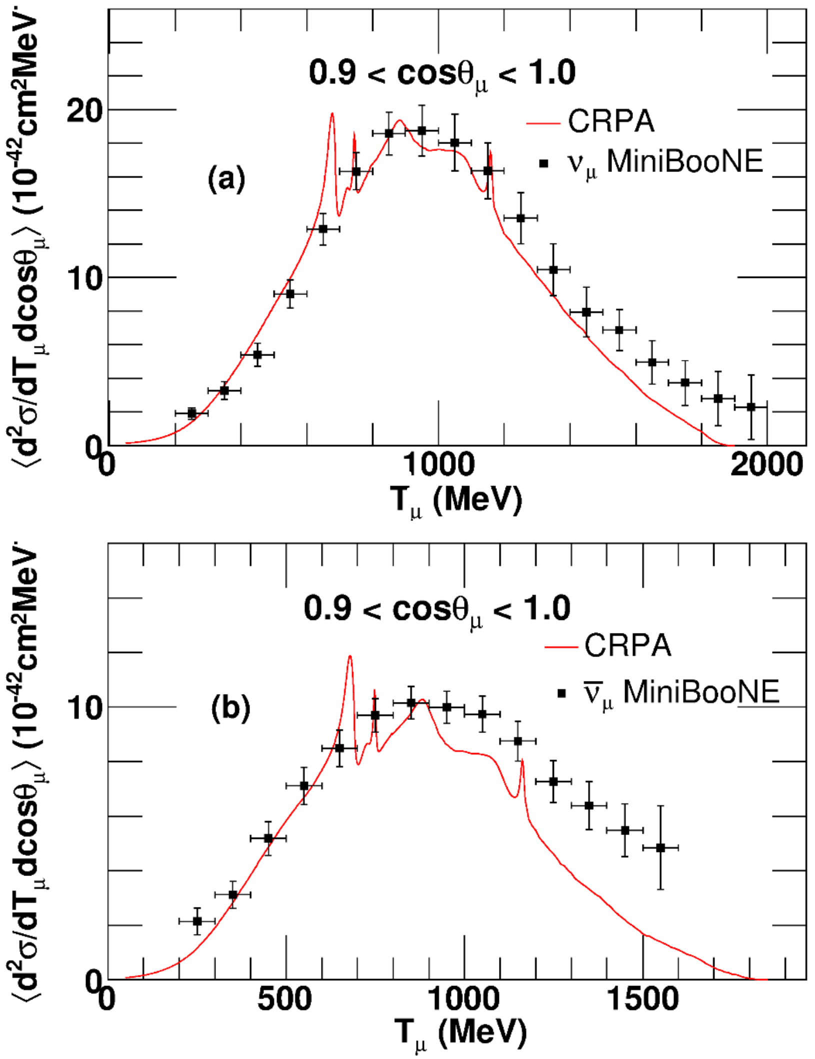
Transverse/longitudinal structure



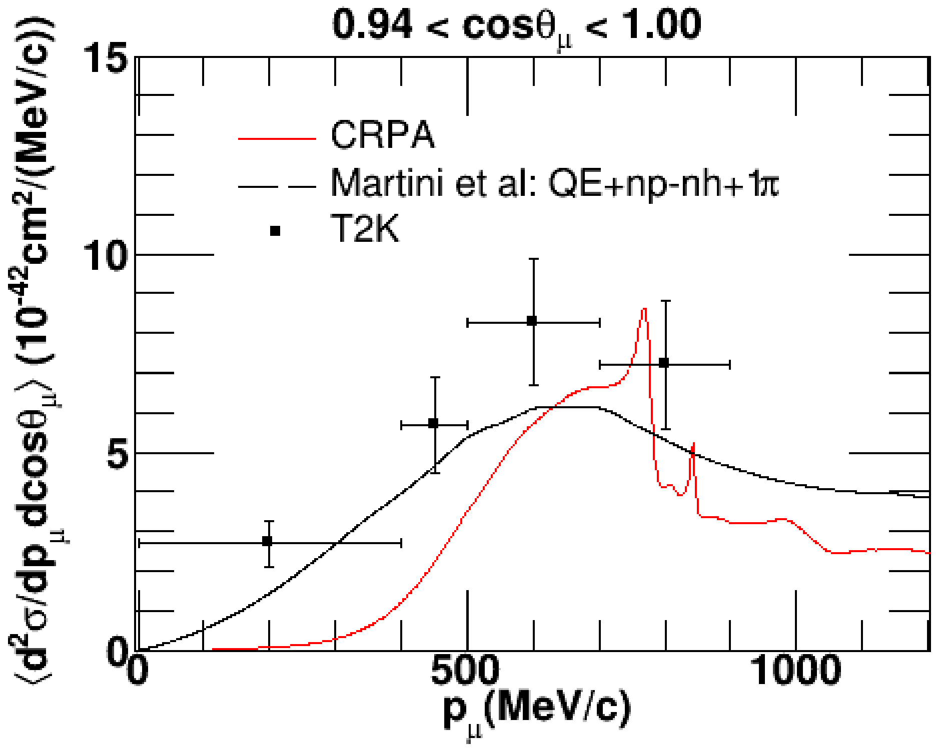
Forward scattering



MiniBooNe

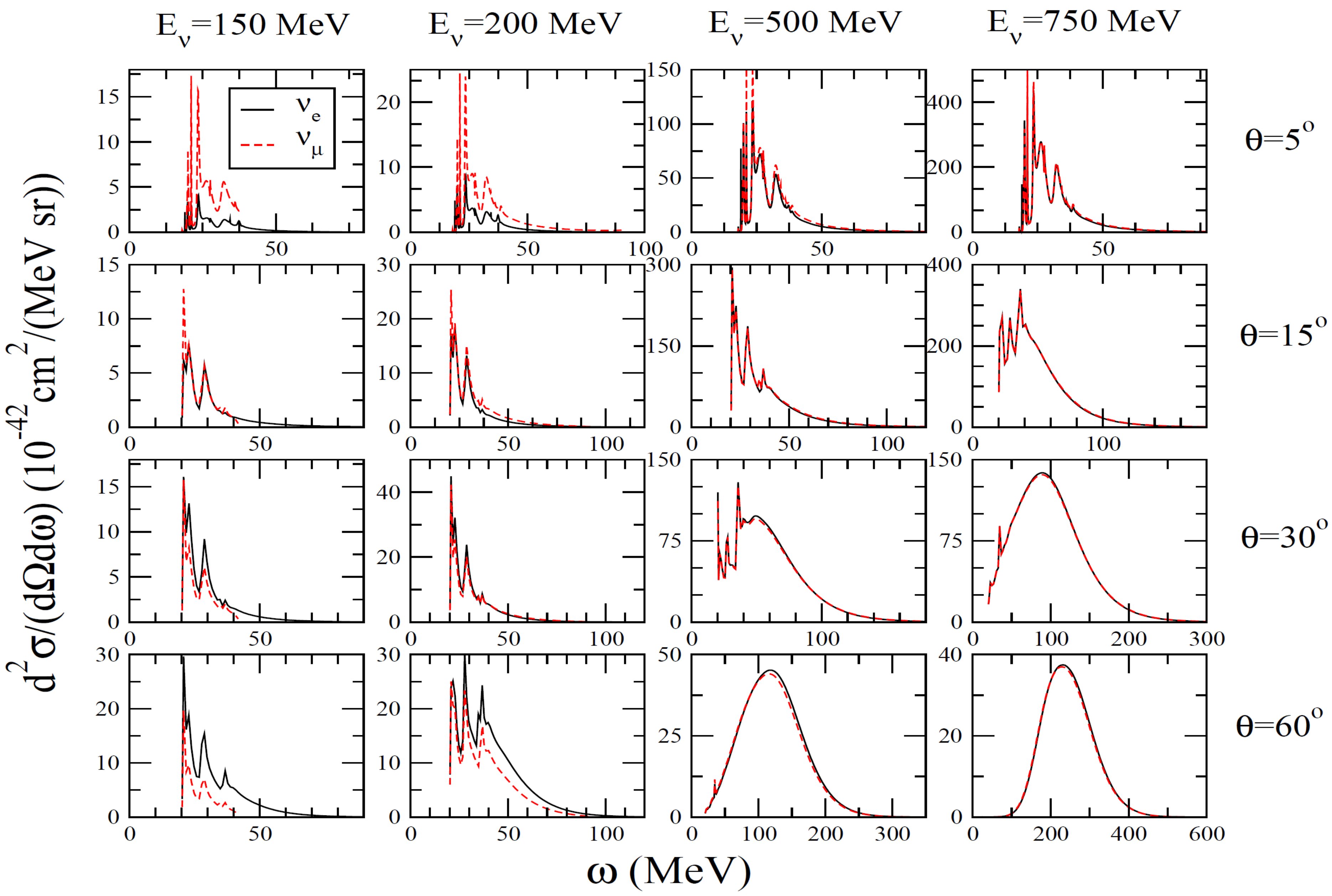


T2K

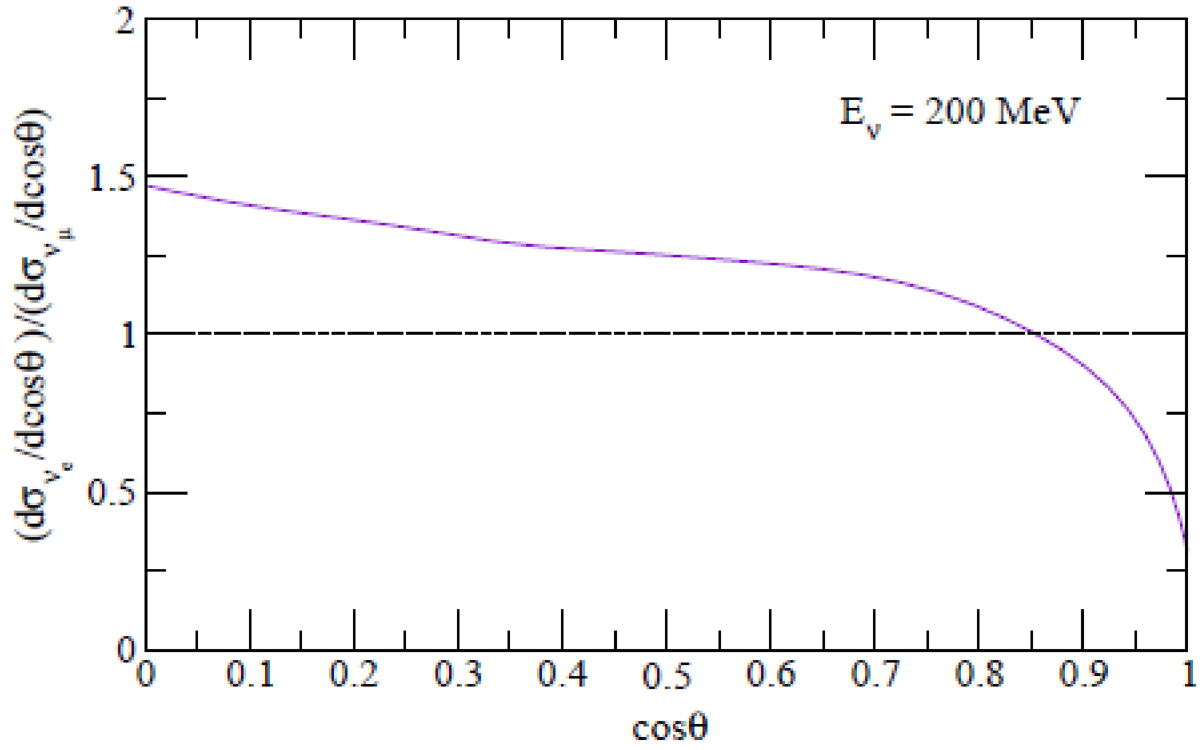


- Collective excitations at low energies generate some extra strength

Electronneutrino
vs
muonneutrino
Cross sections

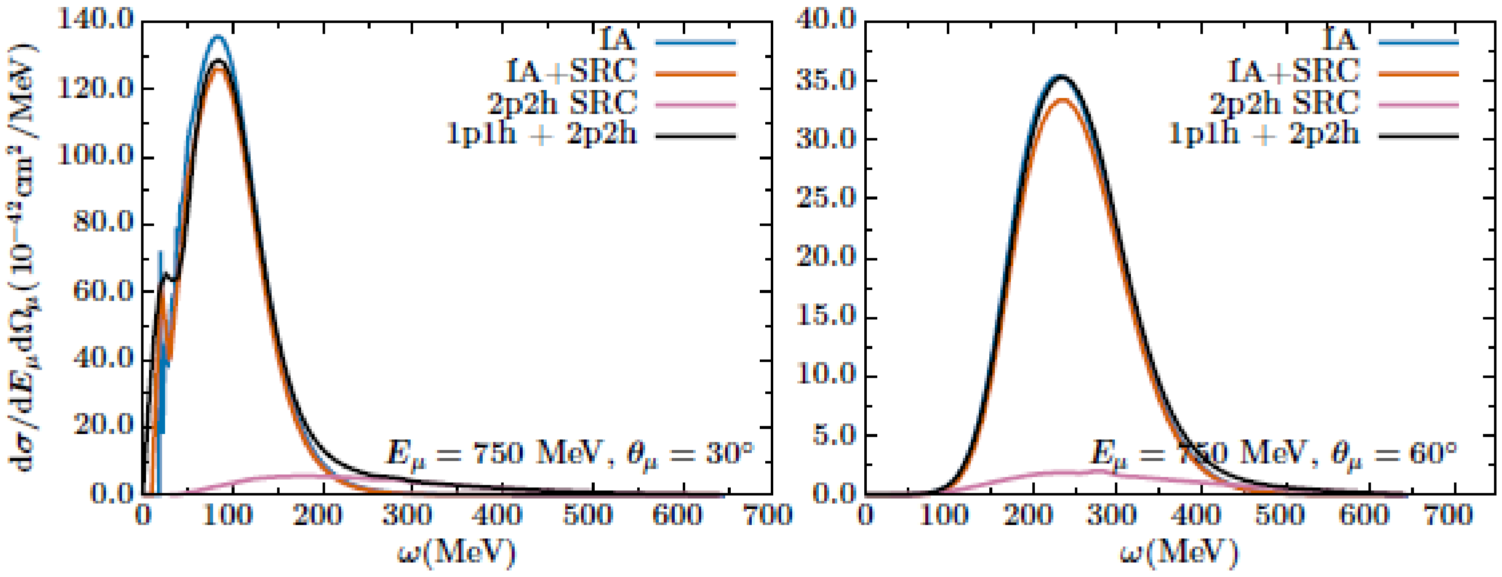


Cross section ratio :



Outlook :

- short-range correlations in QE region



- MEC

Summary

- Inelastic neutrino cross sections at (very) low energies :
  - ✓ Heavily depend on incoming energy
  - ✓ Are dominated by axial, isovector, $J^{\pi}=1^{-}$ contributions
  - ✓ Are sensitive to axial strangeness contributions

- Supernova neutrino cross sections are dominated by interactions with neutrinos from the tail of the spectrum

- Strangeness content of the nucleon affects neutral current cross sections and cross section ratios

- At intermediate energies, 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

- Refs. : V. Pandey, N. Jachowicz et al : PRC89,024601, PRC92,024606.