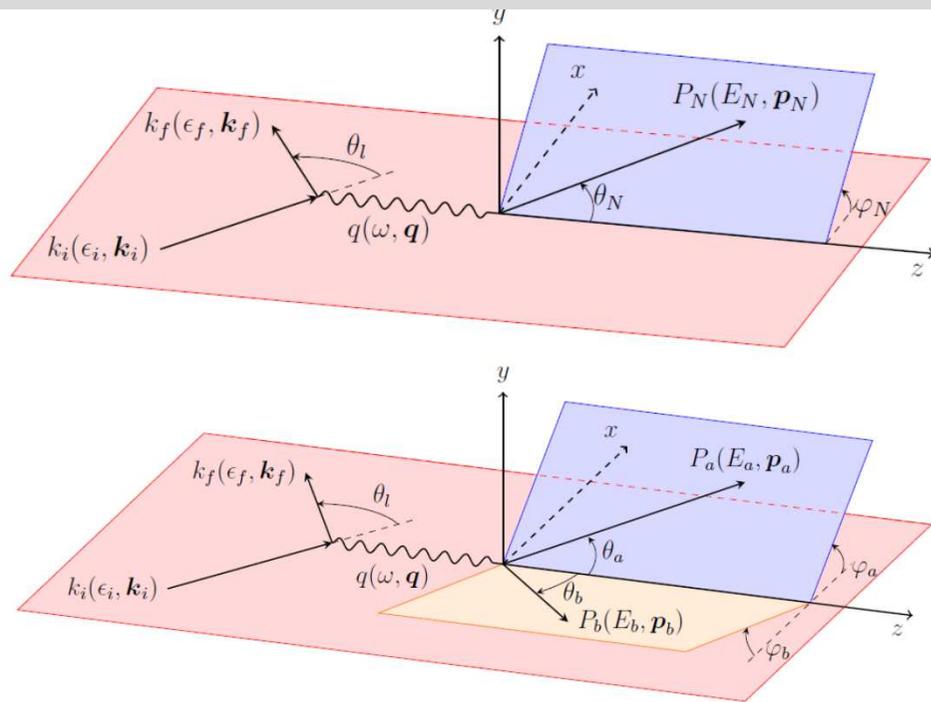


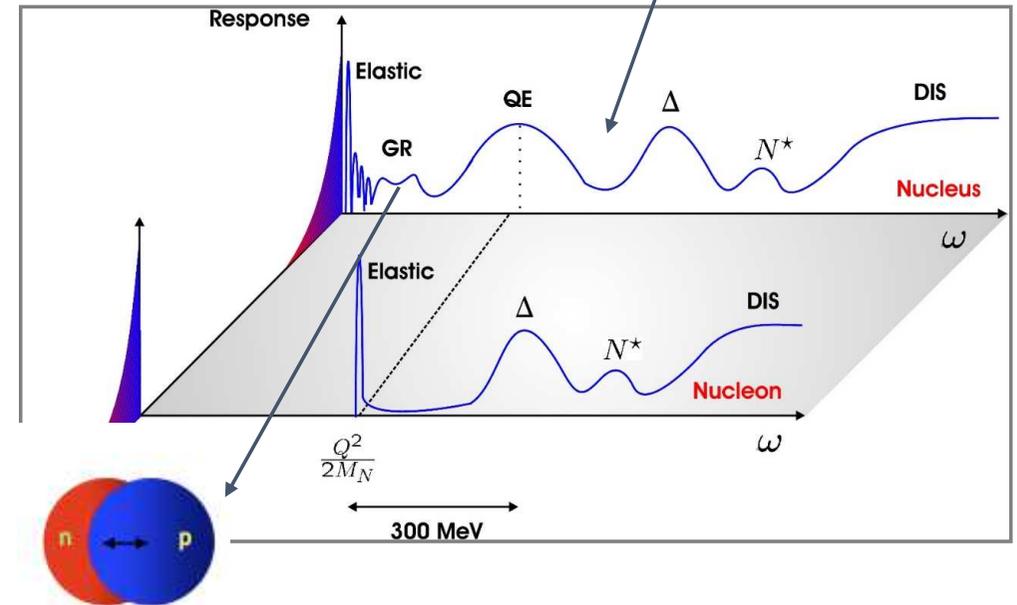
# NEUTRINO-NUCLEUS SCATTERING IN A HF- CRPA APPROACH

Natalie Jachowicz, N. Van Dessel, S. Wauthier, T. Van Cuyck, R. González-Jimenez, N. Van Dessel, V. Pandey

# Outline



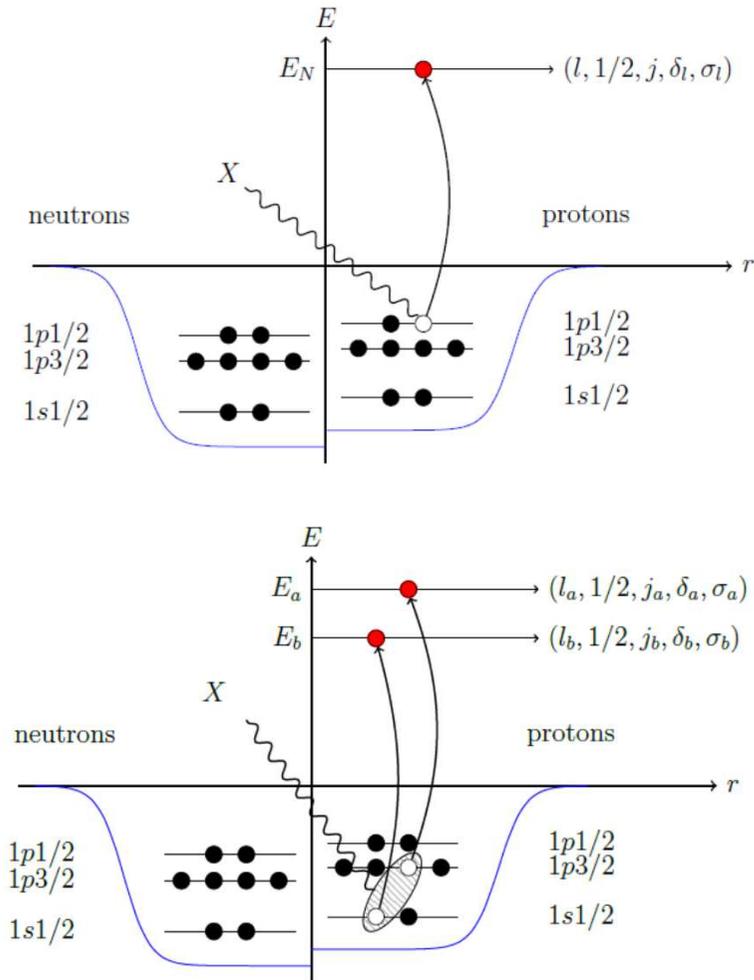
Dip region : multinucleon mechanisms



e.g.

- Detailed microscopic cross sections calculations for QE(-like) scattering over broad energy range
- Coherent cross sections in consistent framework

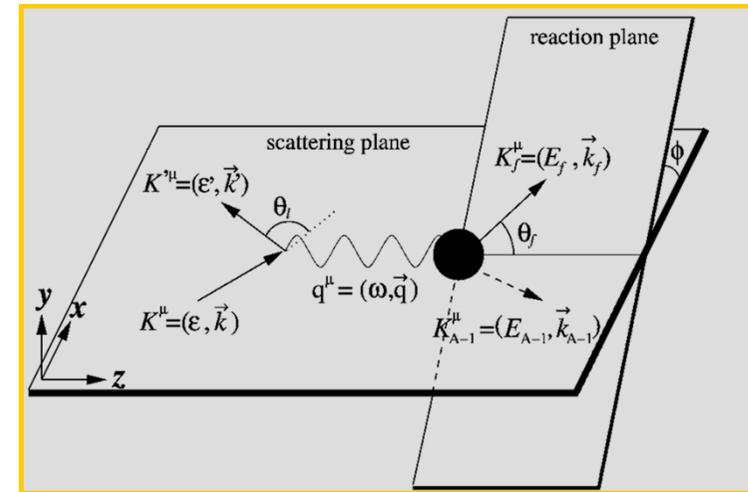
# Cross Section Calculations



- Starting point : mean-field nucleus with Hartree-Fock single-particle wave functions
- Skyrme SkE2 force used to build the potential
- Pauli blocking
- Binding
- Long-range RPA correlations
- (Short-range correlations, MEC contributions in 1- and 2-nucleon knockout processes)

# Neutrino-nucleus interaction

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



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

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

## QE cross section

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

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

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

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

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

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

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

for NC reactions

$$G_E^{V,0} = \left( \frac{1}{2} - \sin^2 \theta_W \right) \tau_3 - \sin^2 \theta_W,$$

$$G_M^{V,0} = \left( \frac{1}{2} - \sin^2 \theta_W \right) (\mu_p - \mu_n) \tau_3 - \sin^2 \theta_W (\mu_p + \mu_n)$$

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

---

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 :

## QE cross section

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

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

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

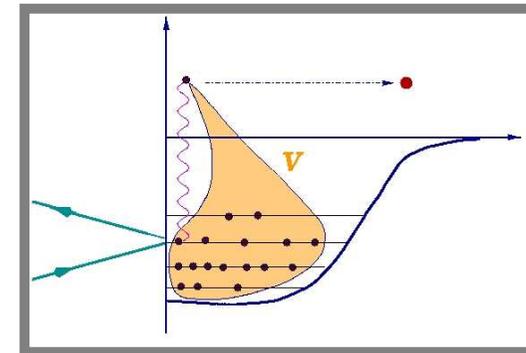
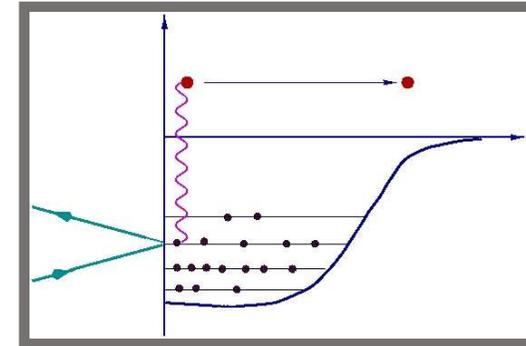
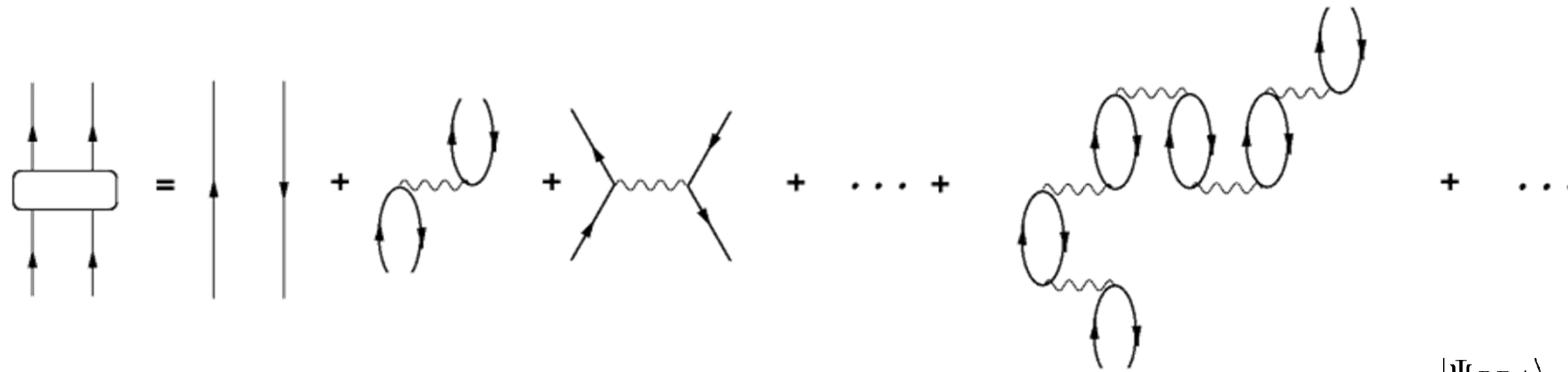
$$\sigma_T^J = \left( -\frac{q_\mu^2}{2|\vec{q}|^2} + \tan^2 \left( \frac{\theta}{2} \right) \right) \left[ \left| \left\langle J_f \left\| \hat{\mathcal{J}}_J^{mag}(\kappa) \right\| J_i \right\rangle \right|^2 + \left| \left\langle J_f \left\| \hat{\mathcal{J}}_J^{el}(\kappa) \right\| J_i \right\rangle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

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

# Long-range correlations : Continuum RPA

## CRPA

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



$$|\Psi_{RPA}\rangle = \sum_c \{ X_{(\Psi,C)} |ph^{-1}\rangle - Y_{(\Psi,C)} |hp^{-1}\rangle \}$$

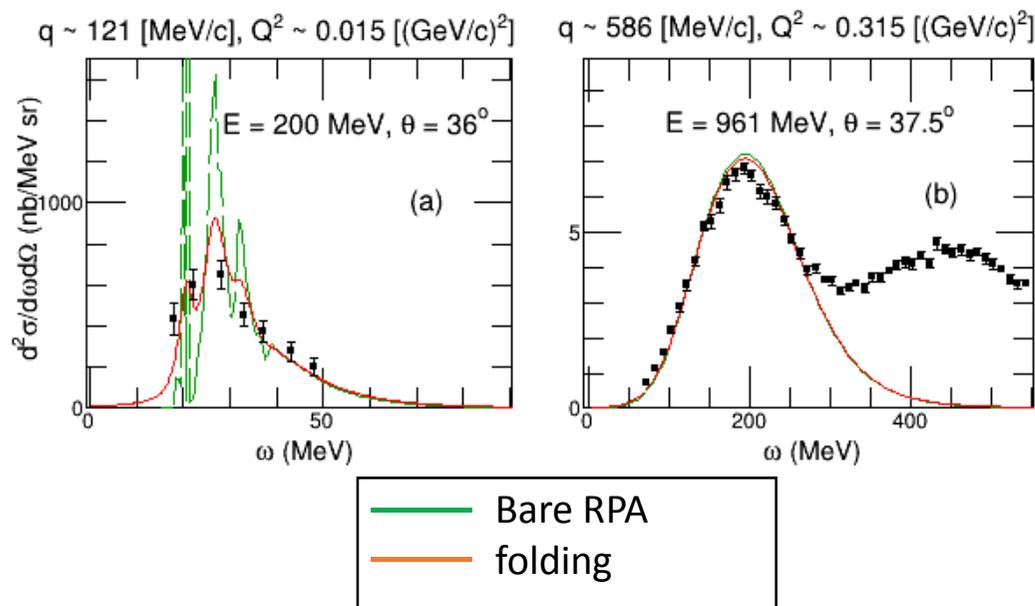
$$\Pi^{(RPA)}(x_1, x_2; \omega) = \Pi^{(0)}(x_1, x_2; \omega) + \frac{1}{\hbar} \int dx \int dx' \Pi^{(0)}(x_1, x; \omega) \tilde{V}(x, x') \Pi^{(RPA)}(x', x_2; \omega)$$

## Long-range correlations : Continuum RPA

- 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



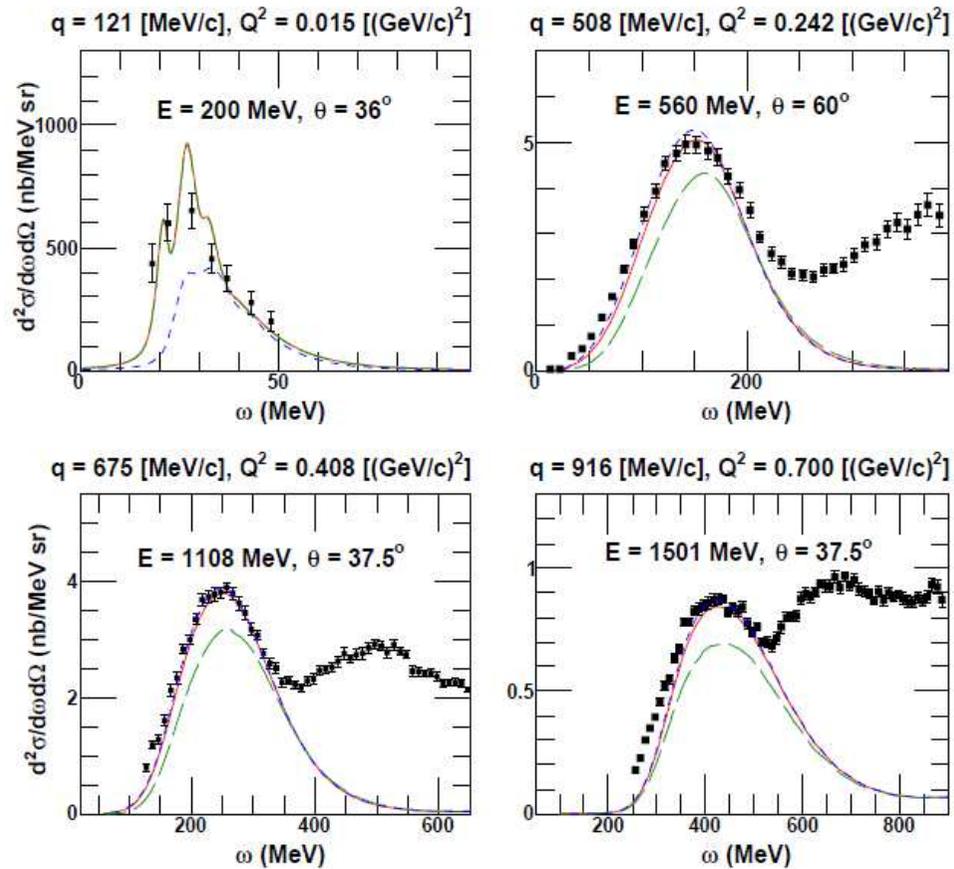
$$R'(q, \omega') = \int_{-\infty}^{\infty} d\omega R(q, \omega) L(\omega, \omega'),$$

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

# Long-range correlations : Continuum RPA

- Regularization of the residual interaction :

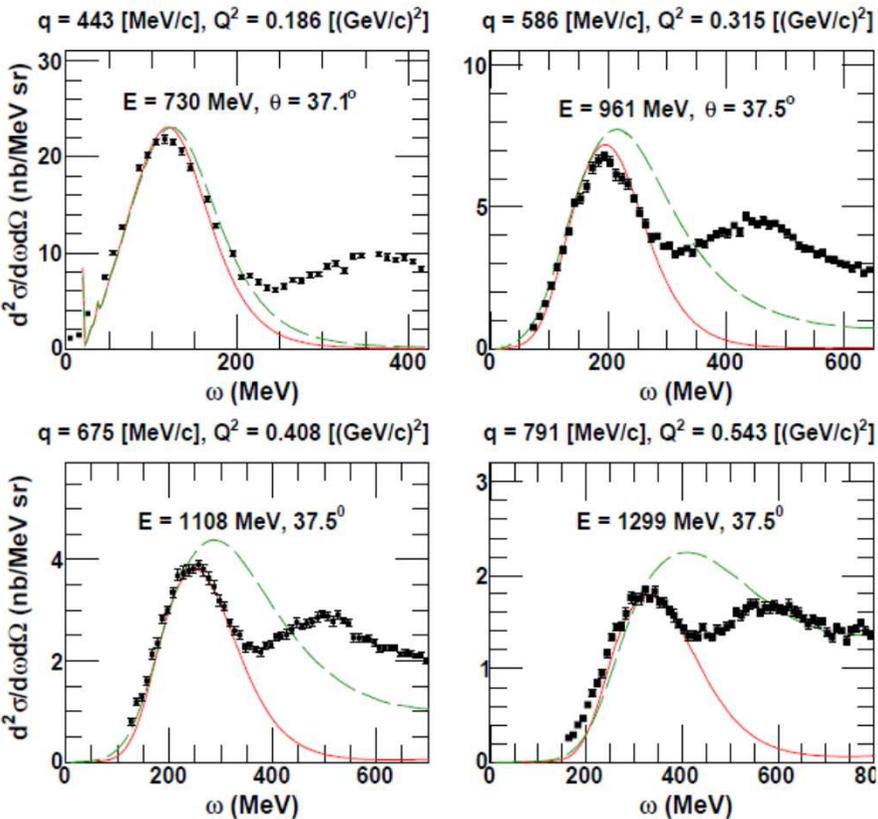
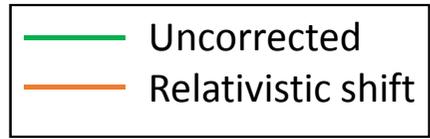
$$V(Q^2) \rightarrow V(Q^2 = 0) \frac{1}{\left(1 + \frac{Q^2}{\Lambda^2}\right)^2}$$



— Uncorrected  
— dipole

# Long-range correlations : Continuum RPA

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



Shift :

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

- The outgoing nucleon obtains the correct relativistic momentum
- Shifts the QE peak to the right relativistic position

Boost :

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

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

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

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

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

# Long-range correlations : Continuum RPA

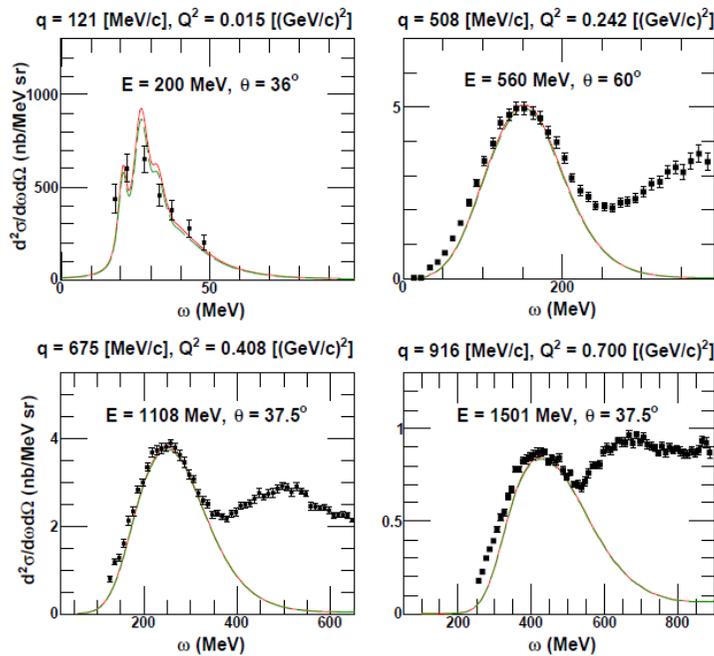
•Coulomb correction for the outgoing lepton in charged-current interactions :

✓ 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))

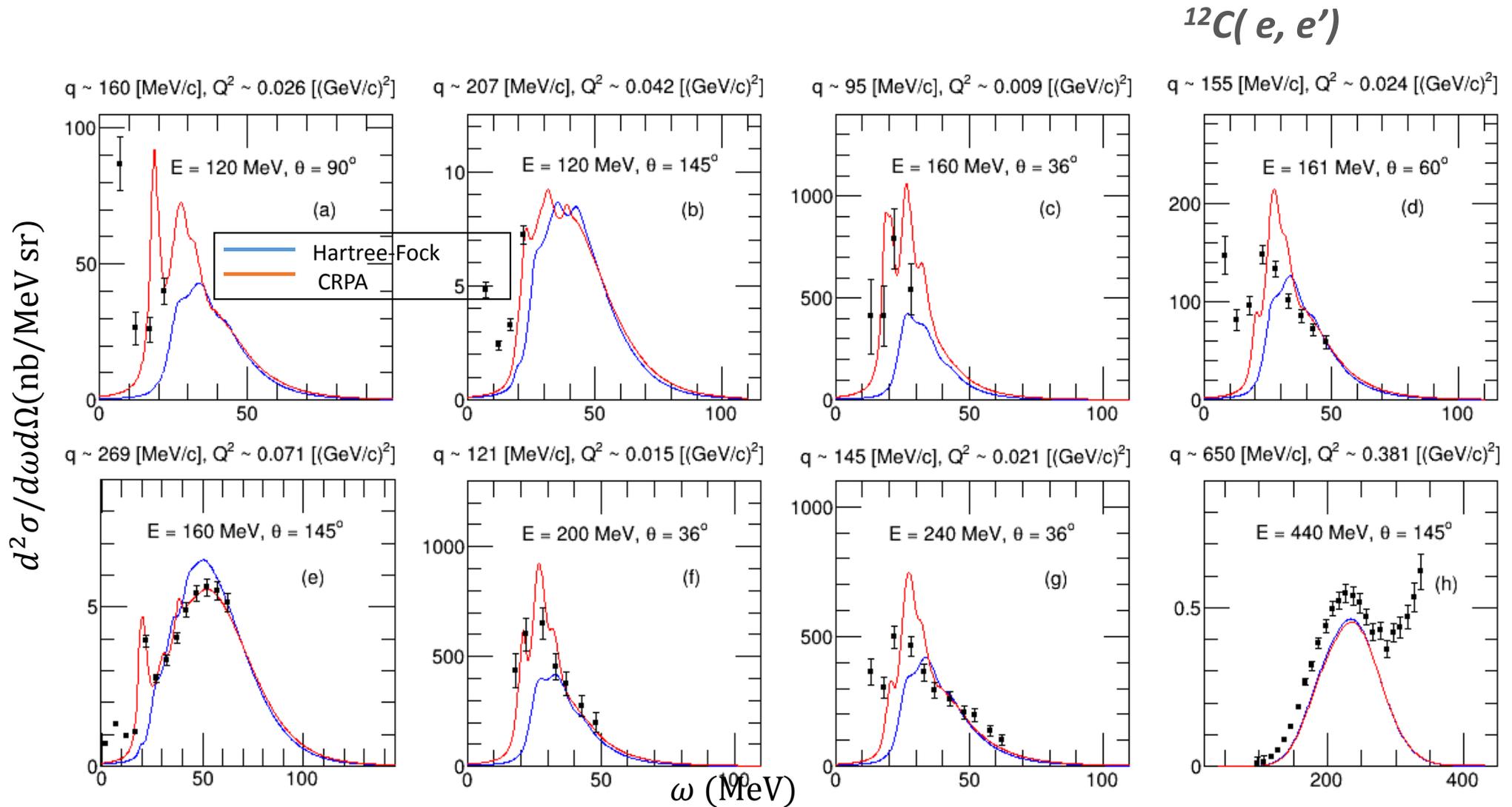
$$q_{eff} = q + 1.5 \left( \frac{Z' \alpha \hbar c}{R} \right), \quad \Psi_l^{eff} = \zeta(Z', E, q) \Psi_l,$$



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

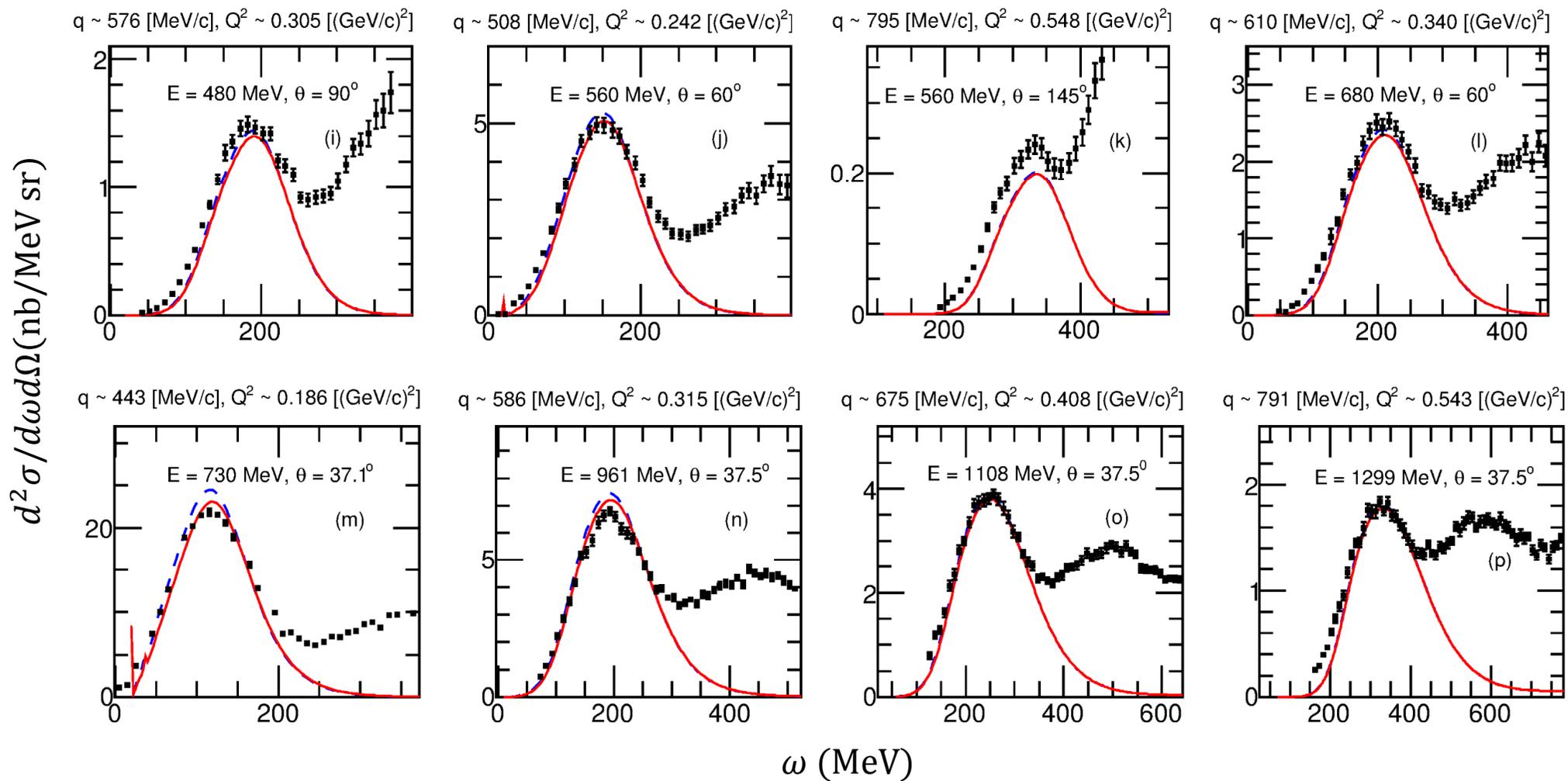


# Comparison with electron scattering data



VECLIPSE, KNOXVILLE, AUGUST 20-22 2017

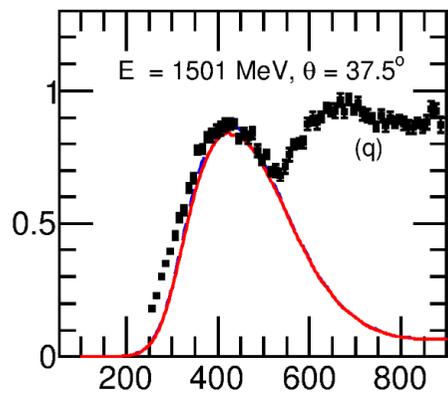
# Comparison with electron scattering data



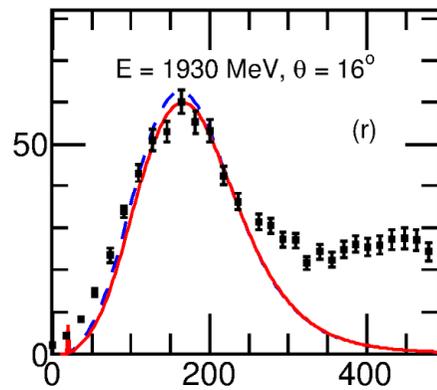
# Comparison with electron scattering data

$d^2\sigma/d\omega d\Omega$  (nb/MeV sr)

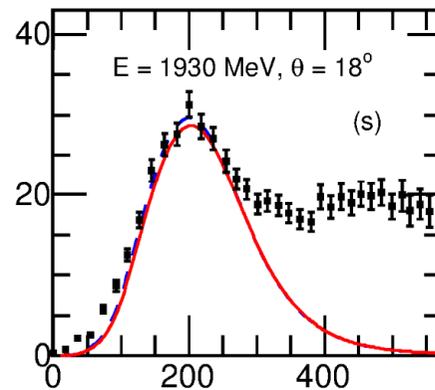
$q \sim 916$  [MeV/c],  $Q^2 \sim 0.700$  [(GeV/c) $^2$ ]



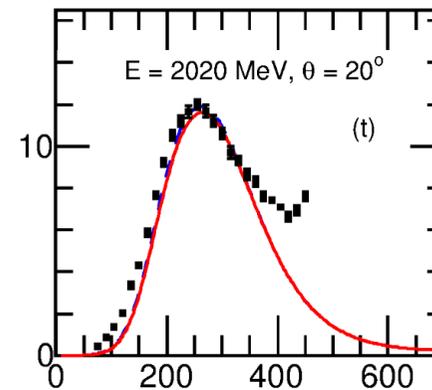
$q \sim 536$  [MeV/c],  $Q^2 \sim 0.267$  [(GeV/c) $^2$ ]



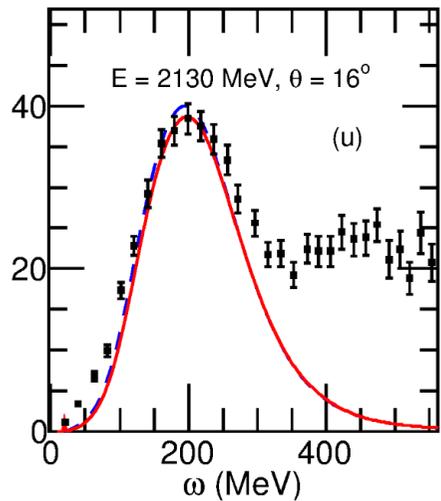
$q \sim 601$  [MeV/c],  $Q^2 \sim 0.331$  [(GeV/c) $^2$ ]



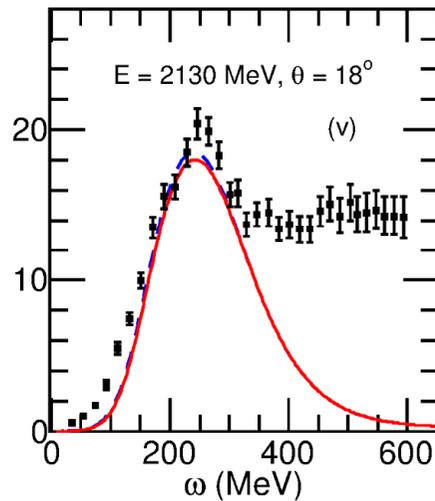
$q \sim 700$  [MeV/c],  $Q^2 \sim 0.436$  [(GeV/c) $^2$ ]



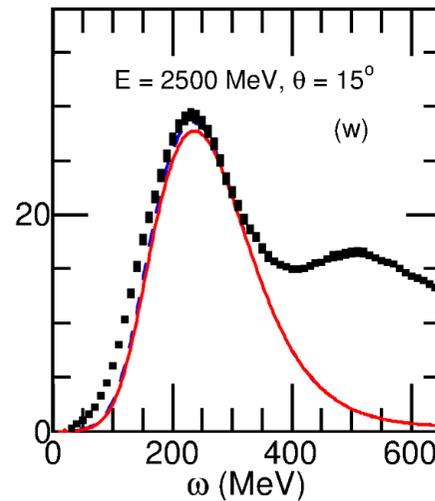
$q \sim 594$  [MeV/c],  $Q^2 \sim 0.323$  [(GeV/c) $^2$ ]



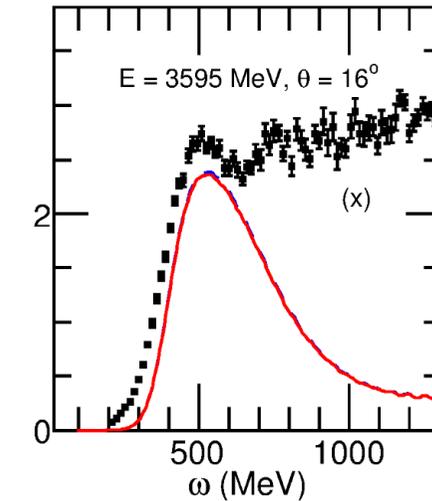
$q \sim 667$  [MeV/c],  $Q^2 \sim 0.399$  [(GeV/c) $^2$ ]



$q \sim 658$  [MeV/c],  $Q^2 \sim 0.391$  [(GeV/c) $^2$ ]



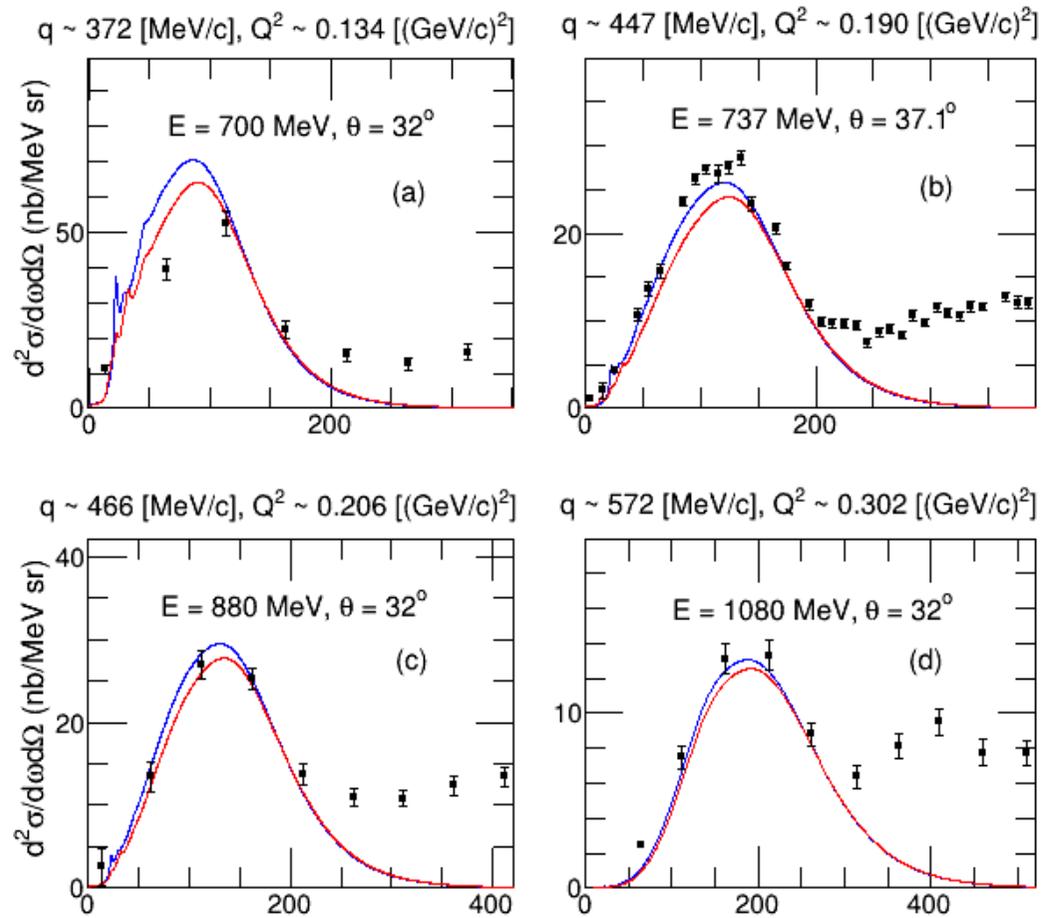
$q \sim 1043$  [MeV/c],  $Q^2 \sim 0.872$  [(GeV/c) $^2$ ]



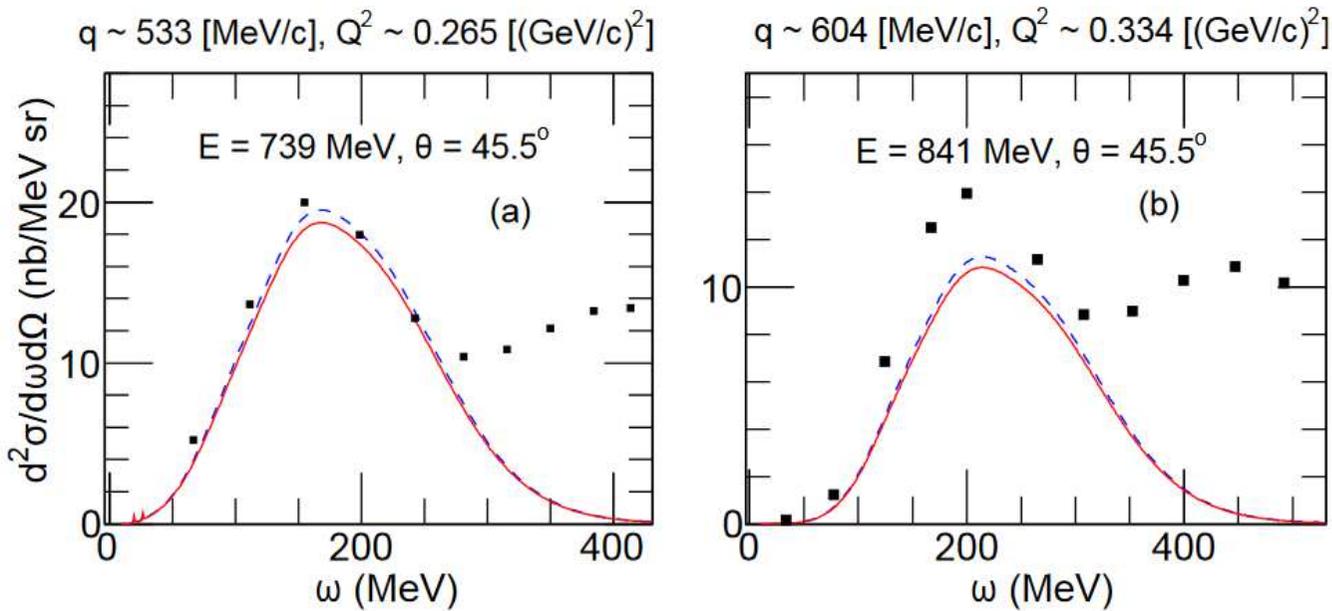
$\omega$  (MeV)

# Comparison with electron scattering data

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



## Comparison with electron scattering data



$^{40}\text{Ca}(e, e')$

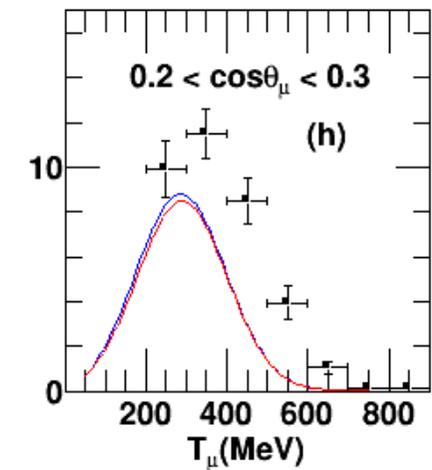
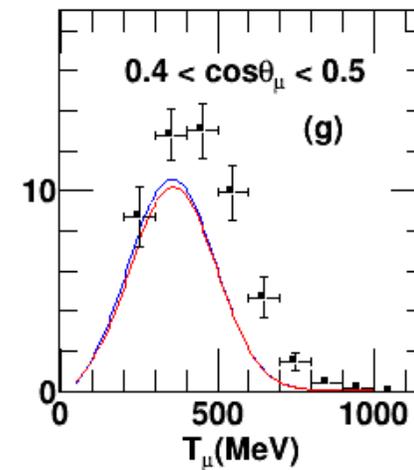
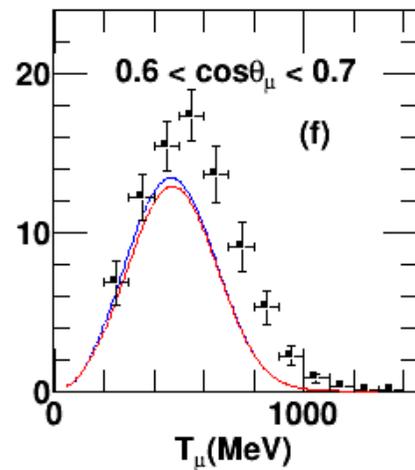
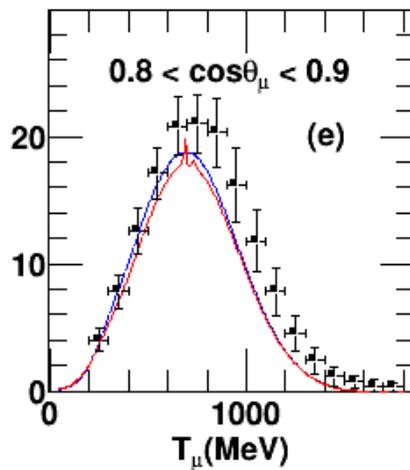
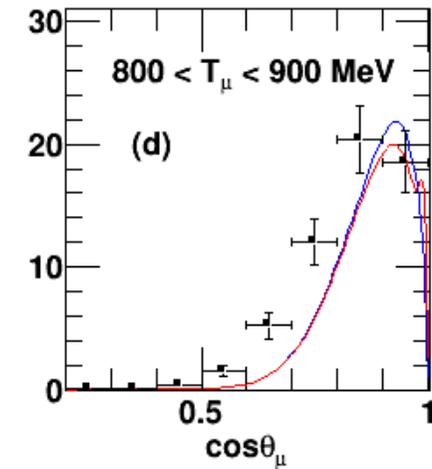
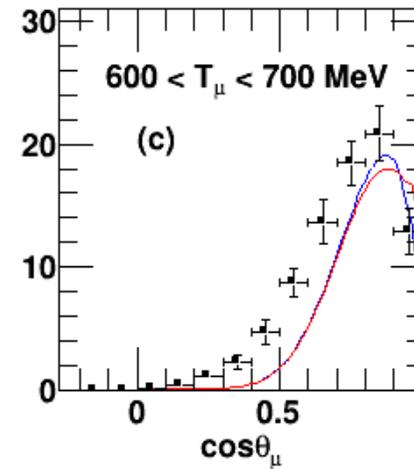
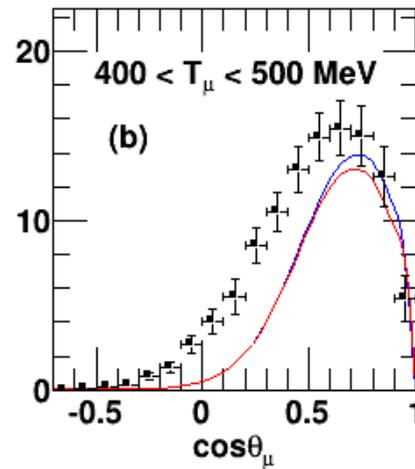
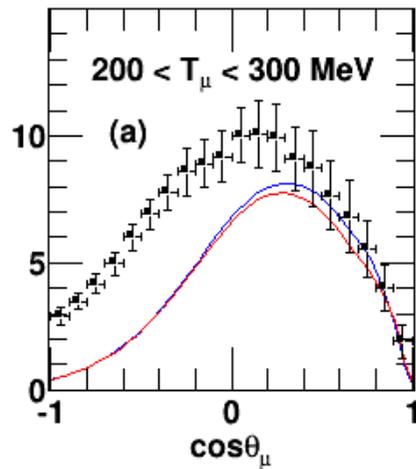
- Good overall agreement with e-scattering data

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).

## Comparison with neutrino scattering data

MiniBooNe  $\nu_\mu$

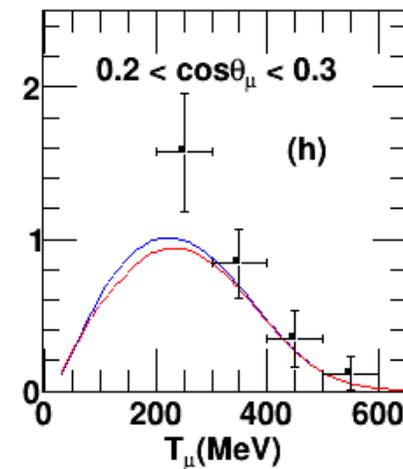
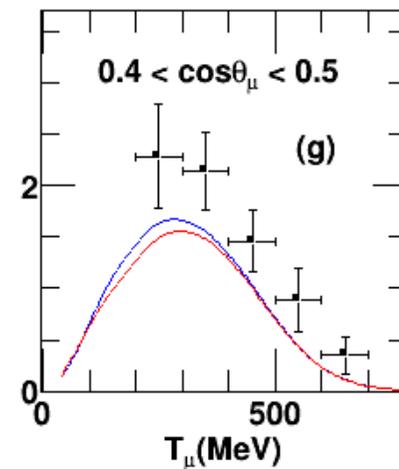
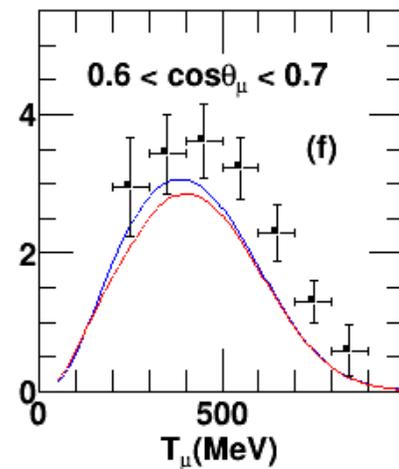
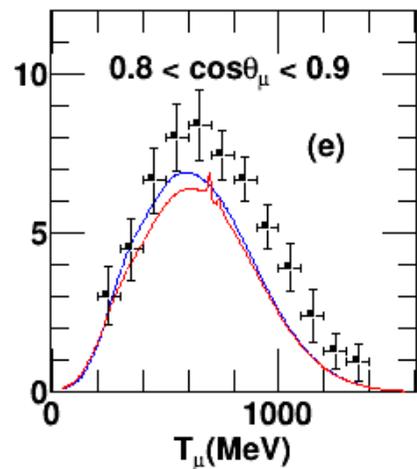
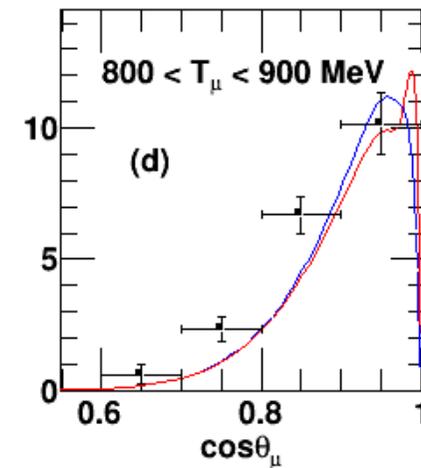
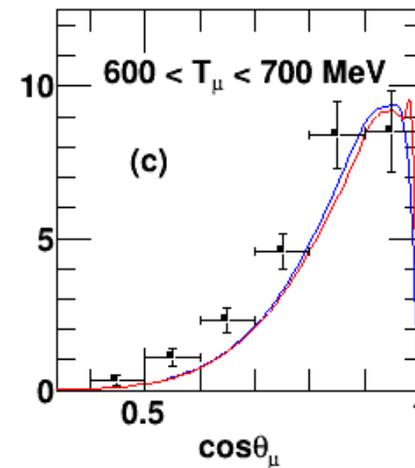
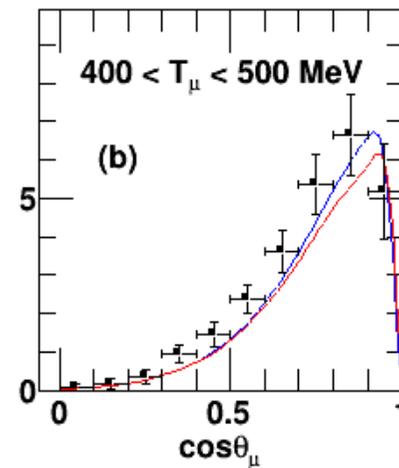
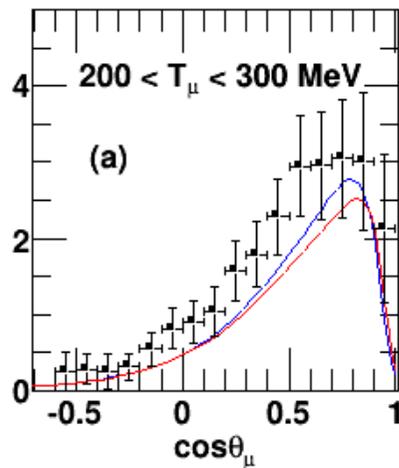
- Satisfactory general agreement
- Good agreement for forward scattering
- Missing strength for low  $T_\mu$ , backward scattering



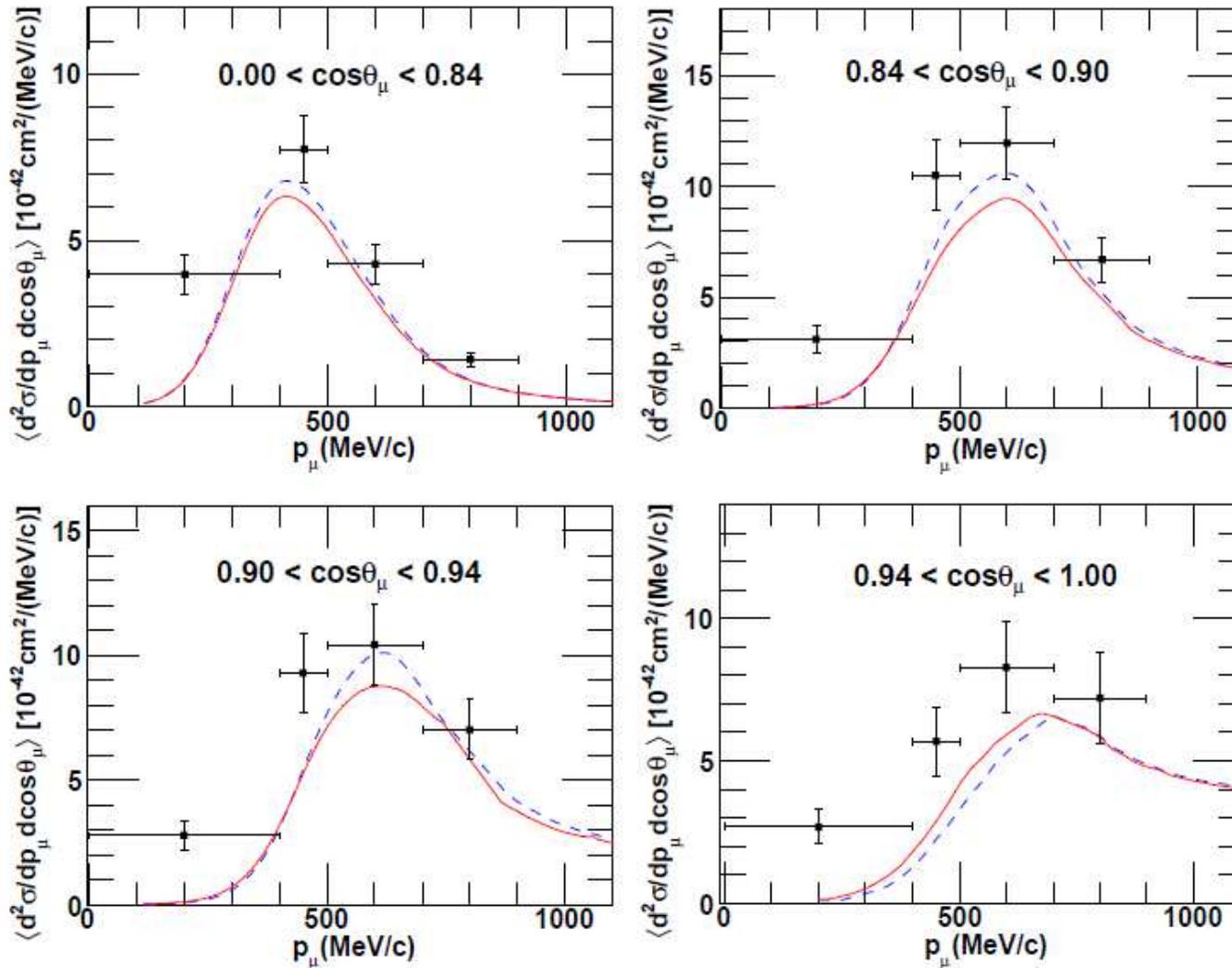
## Comparison with antineutrino scattering data

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

- Good general agreement
- Good agreement for forward scattering
- Missing strength for high  $T_\mu$ , backward scattering
- Better agreement with data than neutrino cross sections



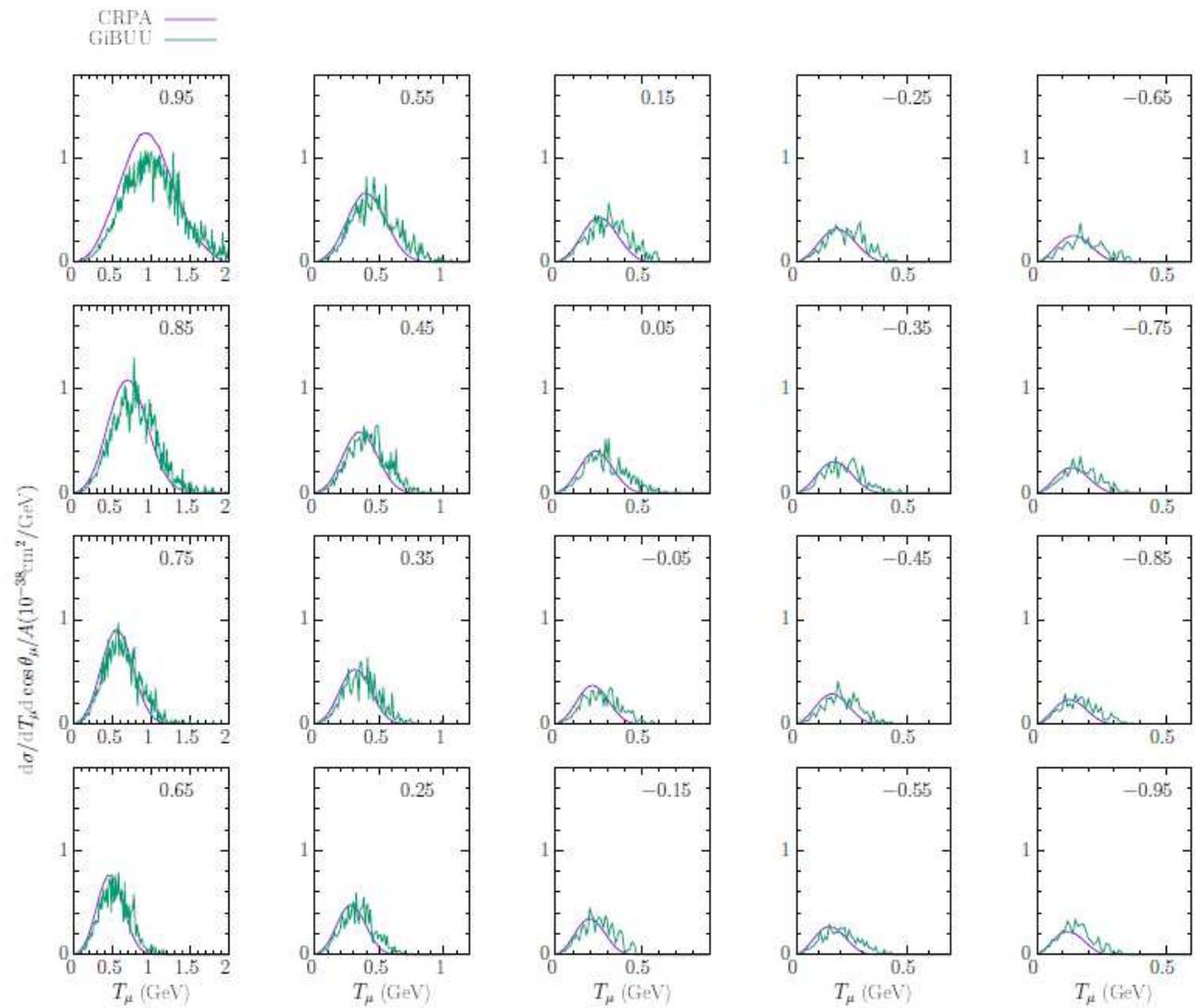
## Comparison with neutrino scattering data



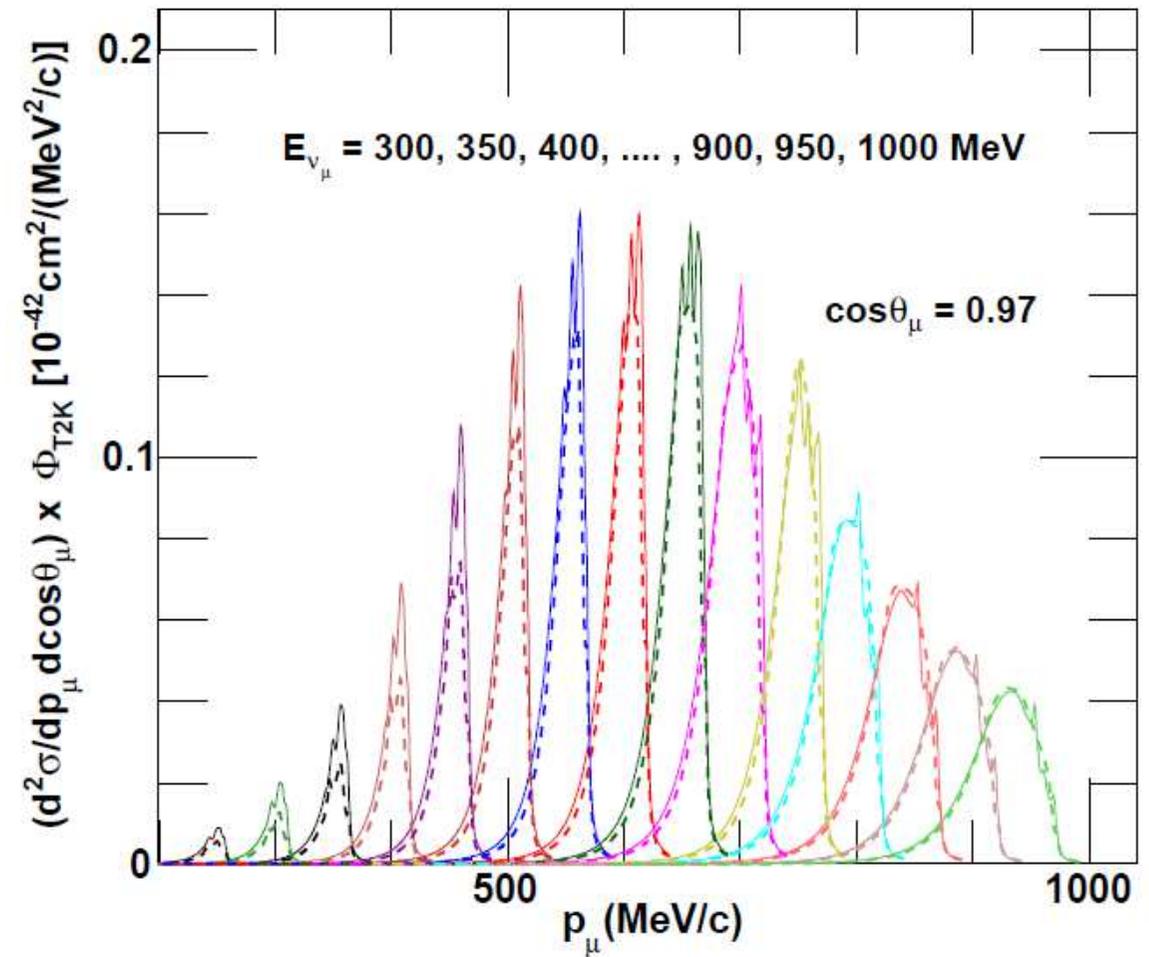
T2K  $\nu_\mu$

- General agreement quite good
- Missing strength for low  $p_\mu$

<sup>40</sup>Ar

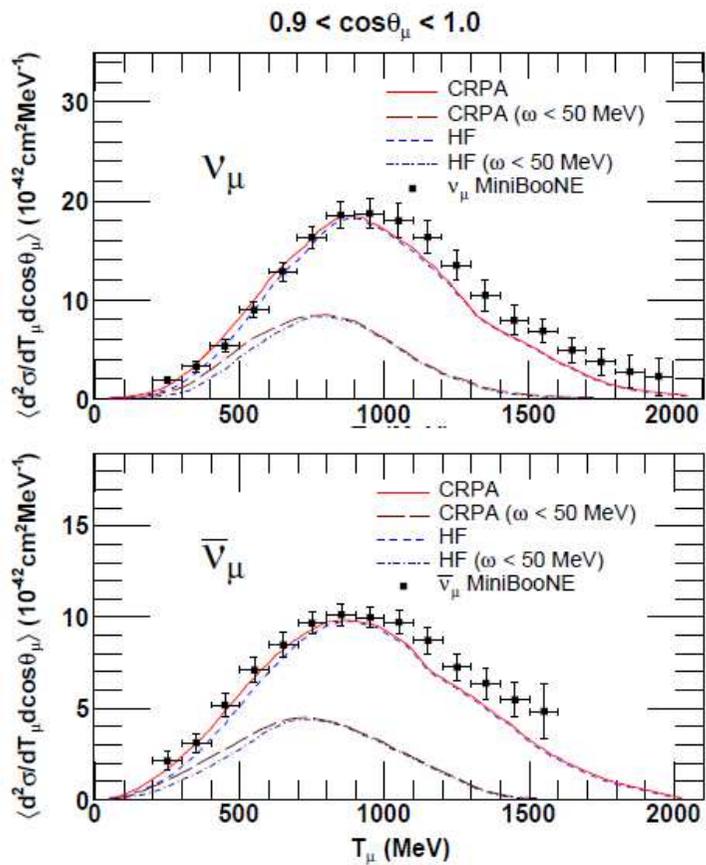


# Forward scattering at intermediate energies ...

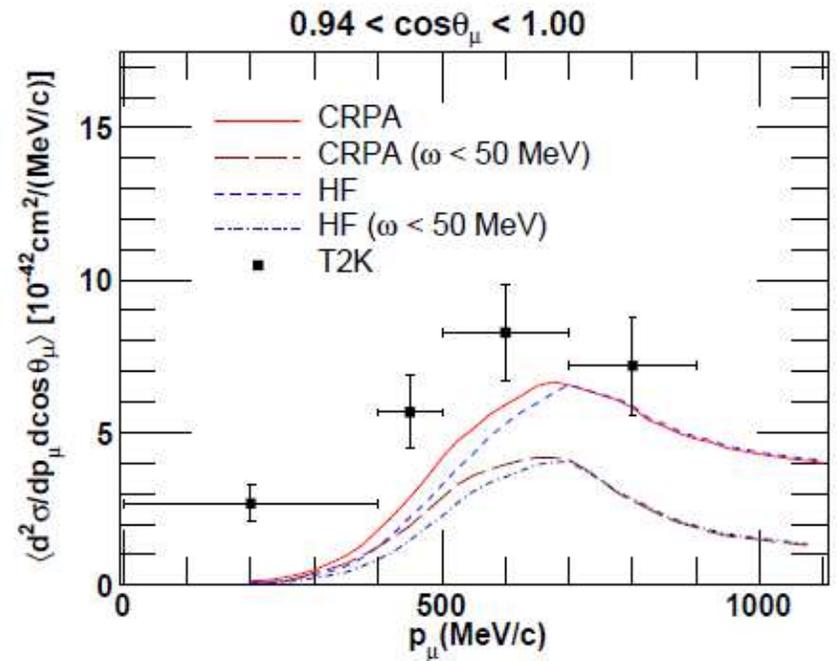


# Forward scattering at intermediate energies ...

MiniBooNe

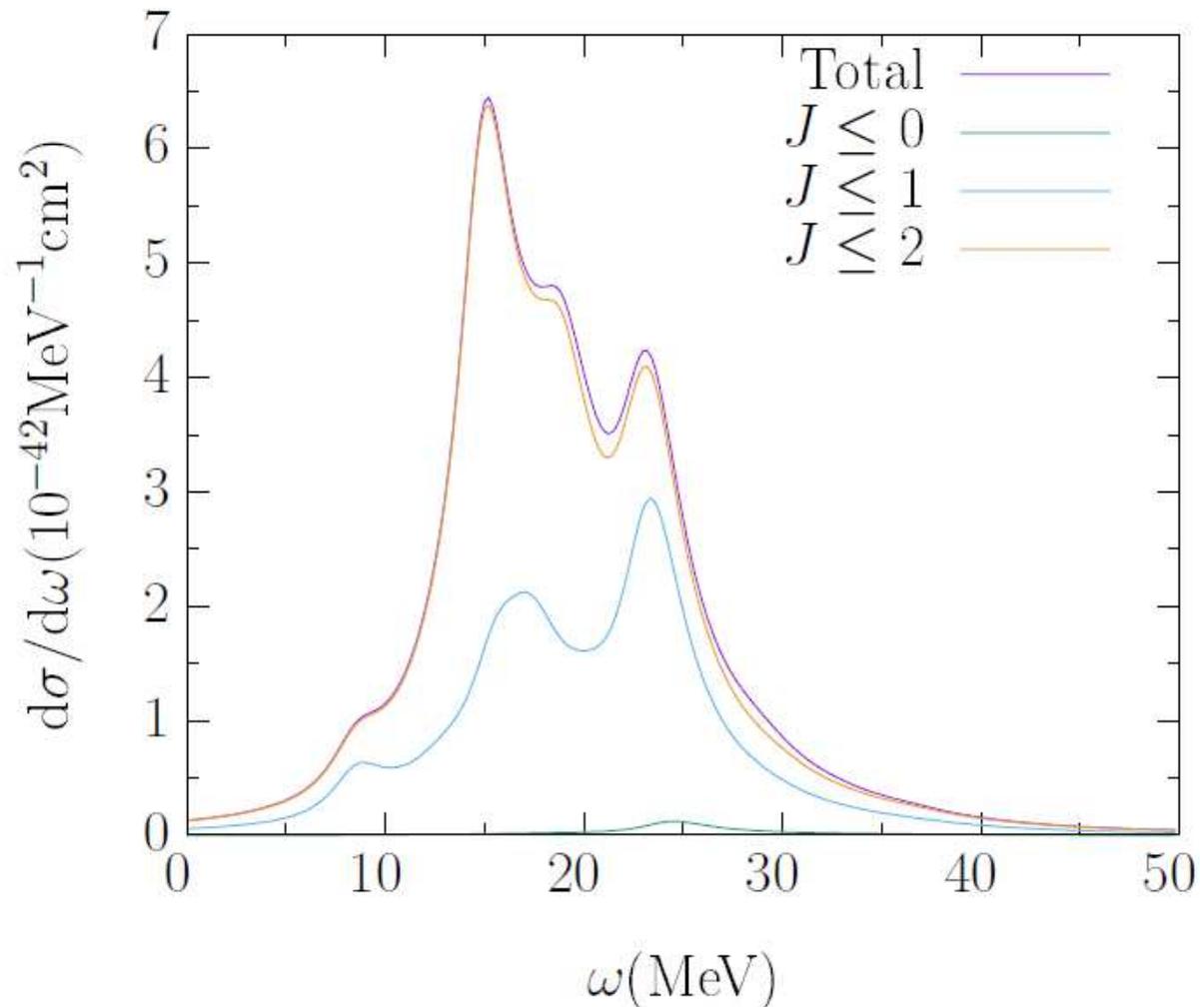


T2K

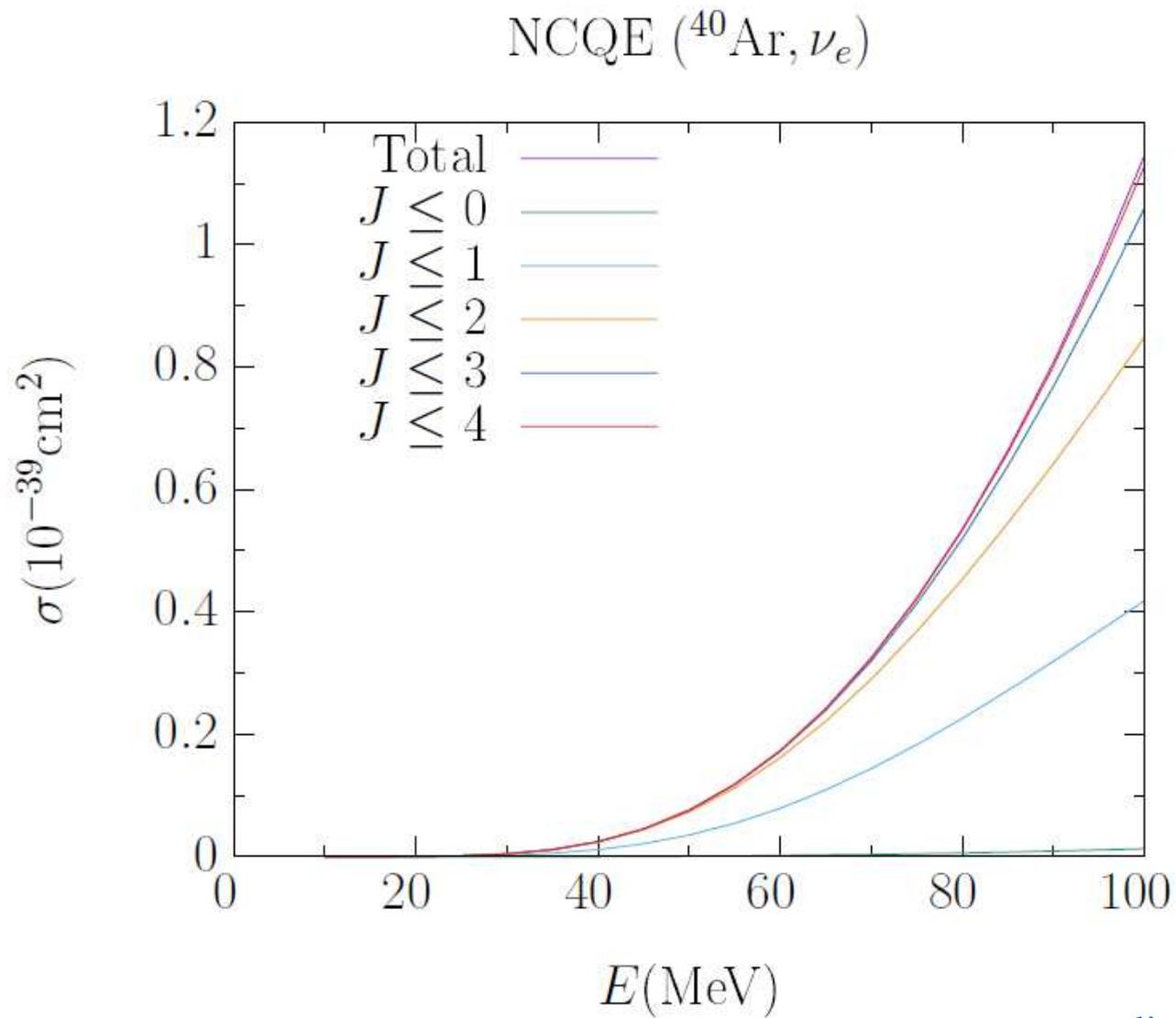


# Low energy cross sections - Ar

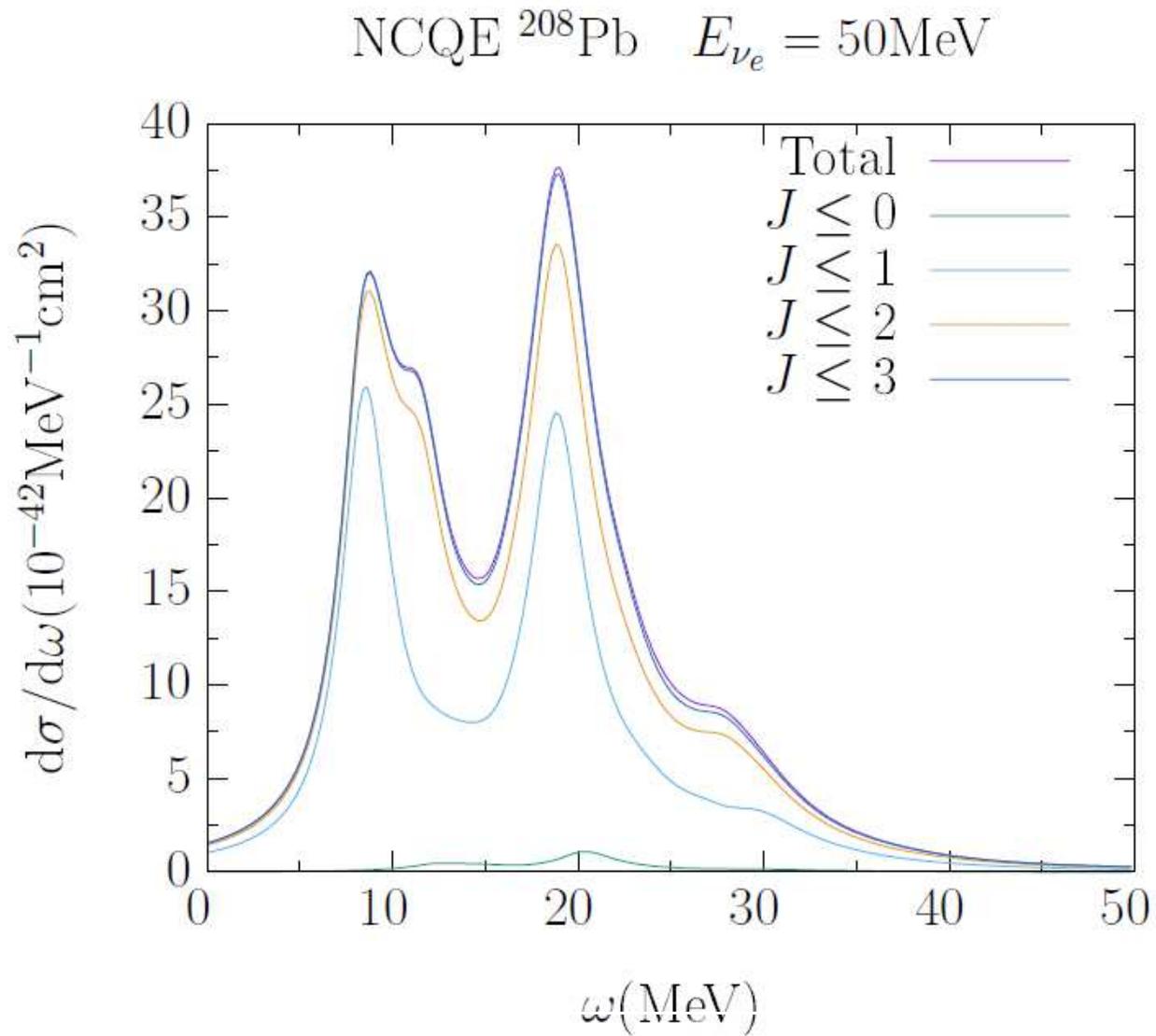
NCQE  $^{40}\text{Ar}$   $E_{\nu_e} = 50\text{MeV}$



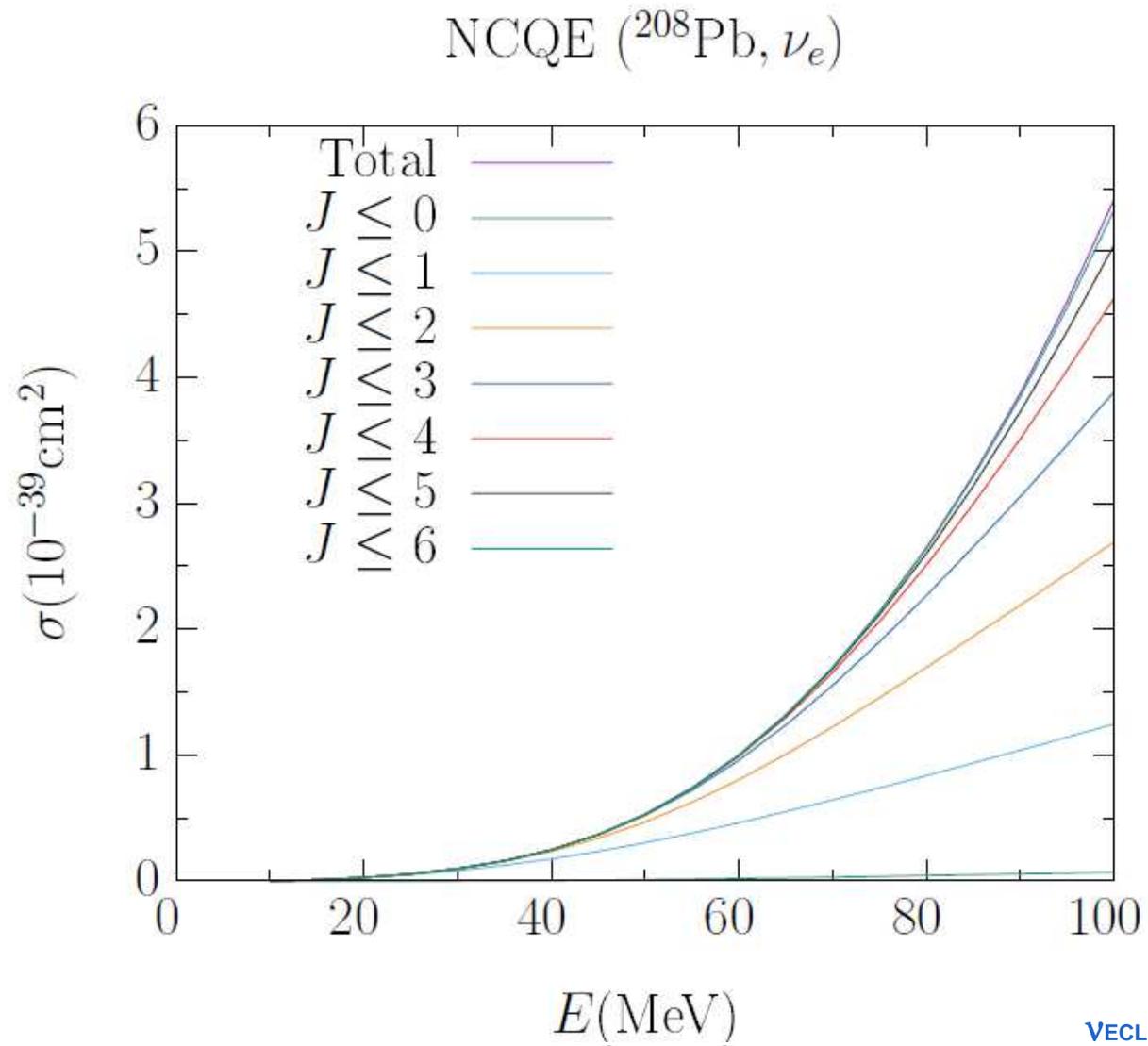
## Low energy cross sections - Ar



# Low energy cross sections - Pb

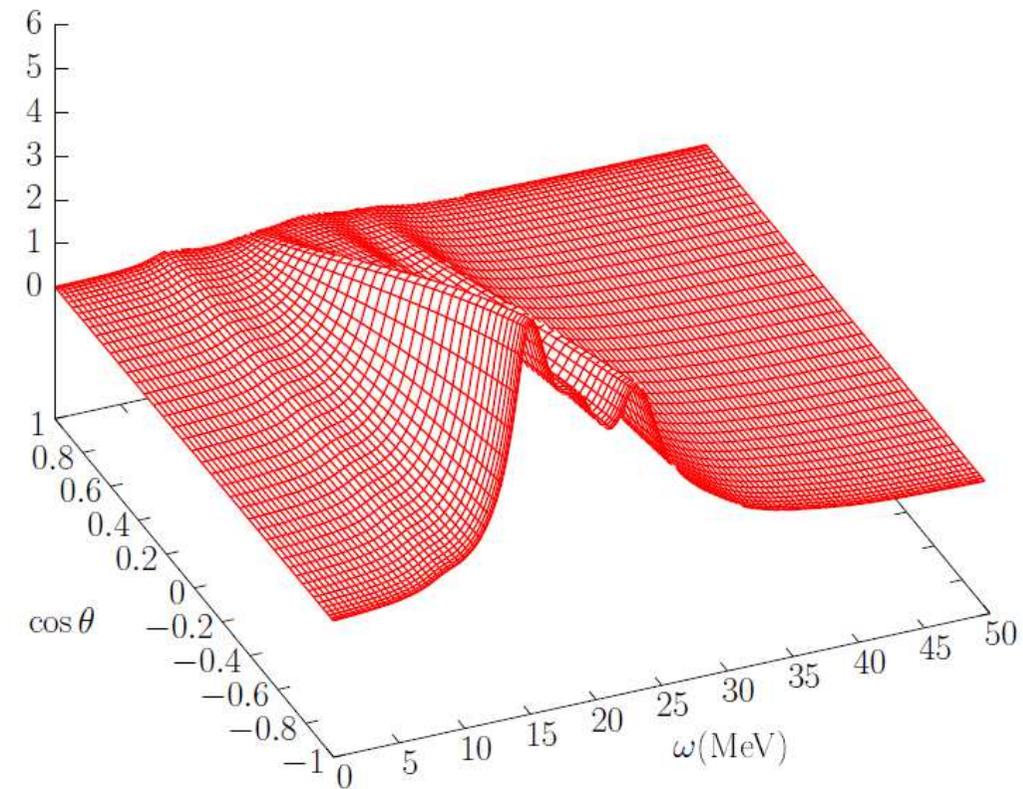


# Low energy cross sections - Pb

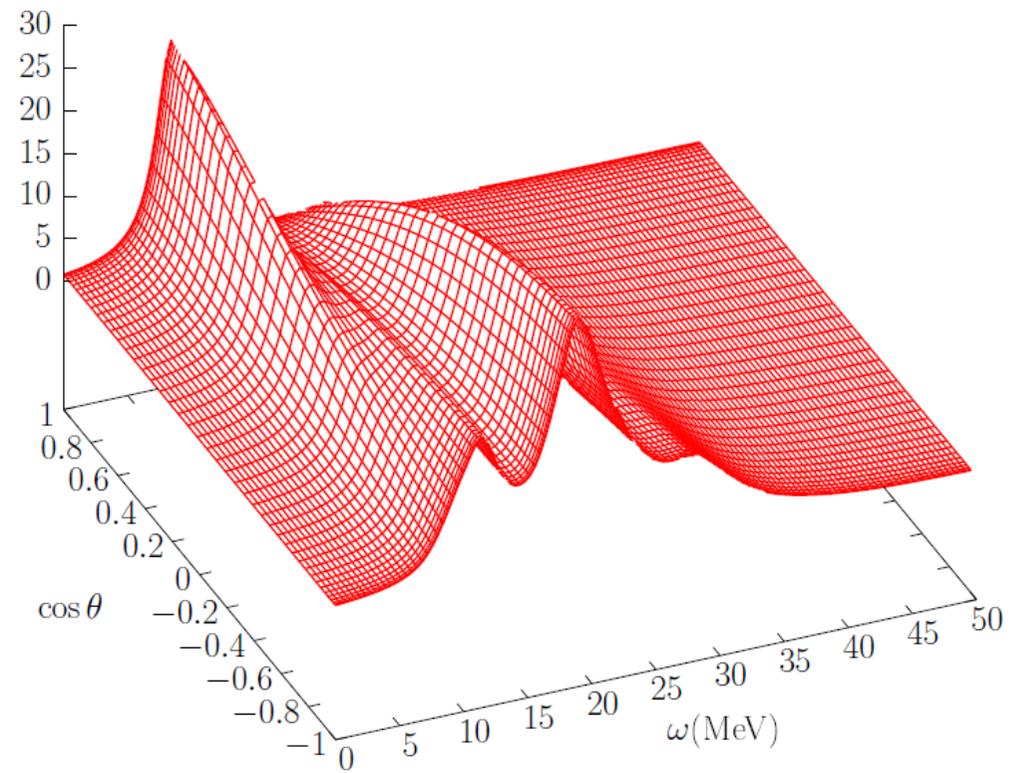


# Low energy cross sections

NCQE  $^{40}\text{Ar}$   $E_{\nu_e} = 50\text{MeV}$   $d^2\sigma/d\omega d\cos\theta(10^{-42}\text{cm}^2\text{MeV}^{-1})$

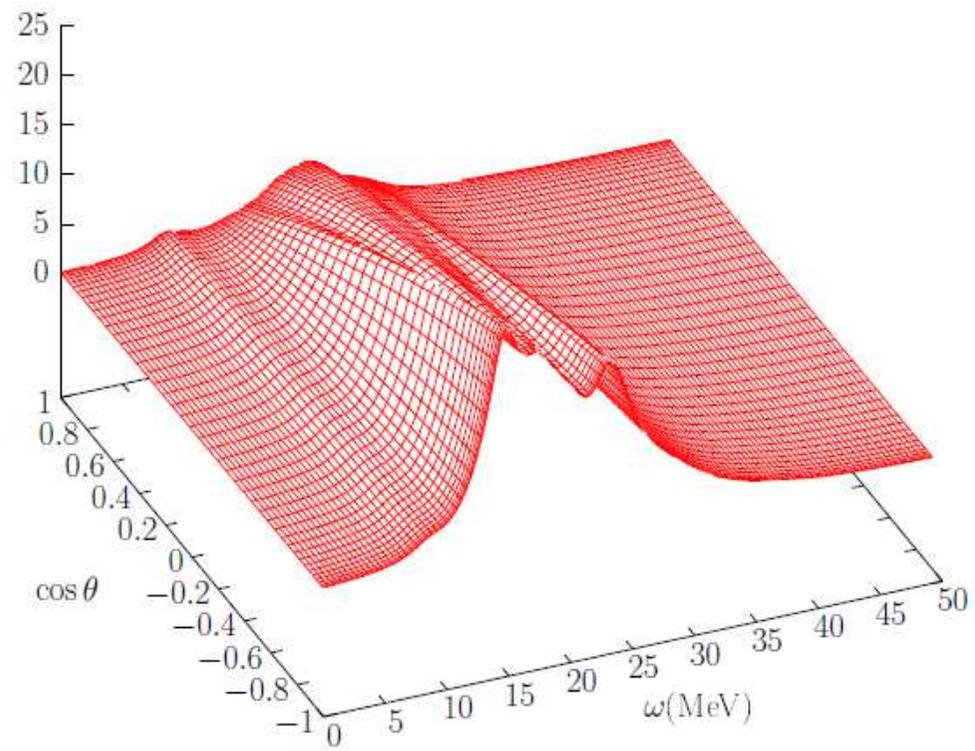


NCQE  $^{208}\text{Pb}$   $E_{\nu_e} = 50\text{MeV}$   $d^2\sigma/d\omega d\cos\theta(10^{-42}\text{cm}^2\text{MeV}^{-1})$

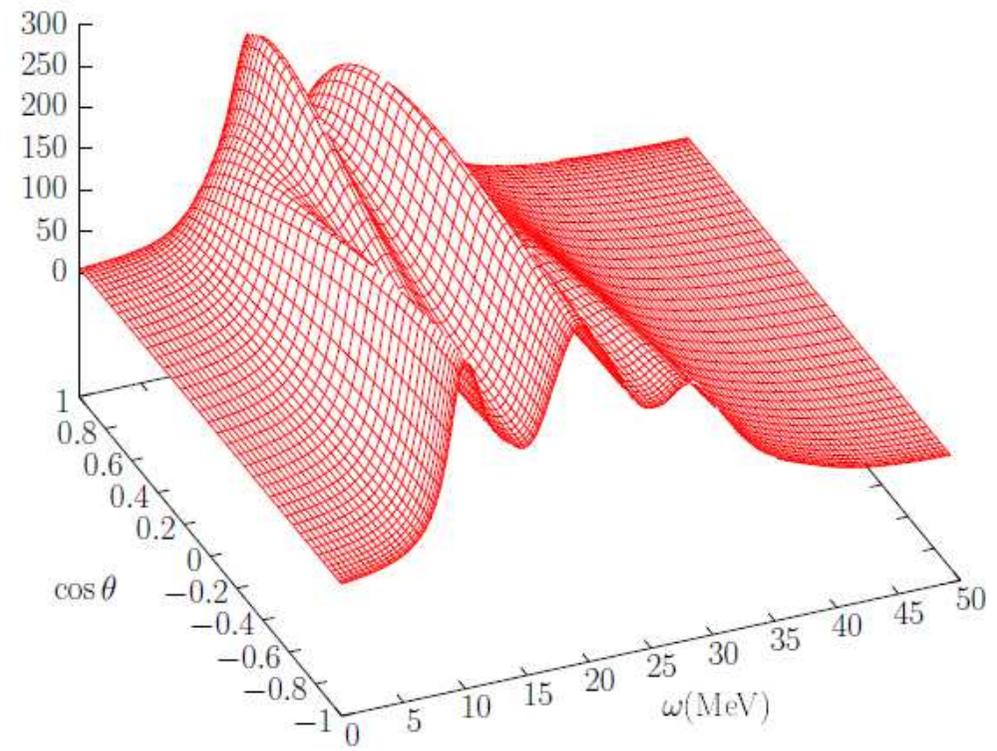


# Low energy cross sections

CCQE  $^{40}\text{Ar}$   $E_{\nu_e} = 50\text{MeV}$   $d^2\sigma/d\omega d\cos\theta (10^{-42}\text{cm}^2\text{MeV}^{-1})$

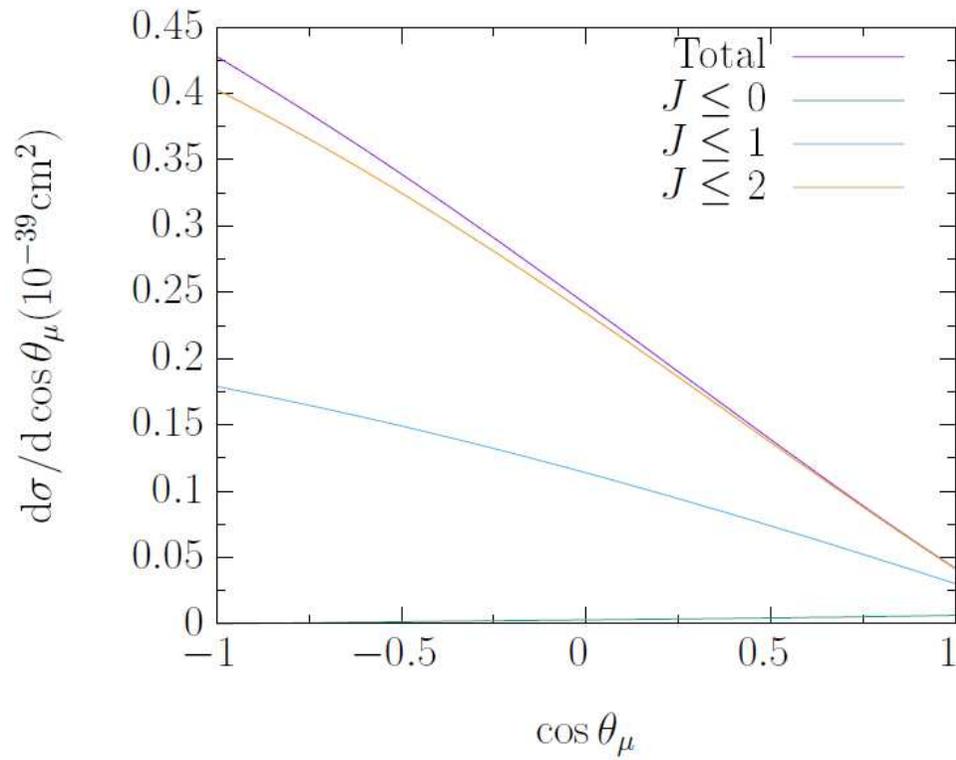


CCQE  $^{208}\text{Pb}$   $E_{\nu_e} = 50\text{MeV}$   $d^2\sigma/d\omega d\cos\theta (10^{-42}\text{cm}^2\text{MeV}^{-1})$

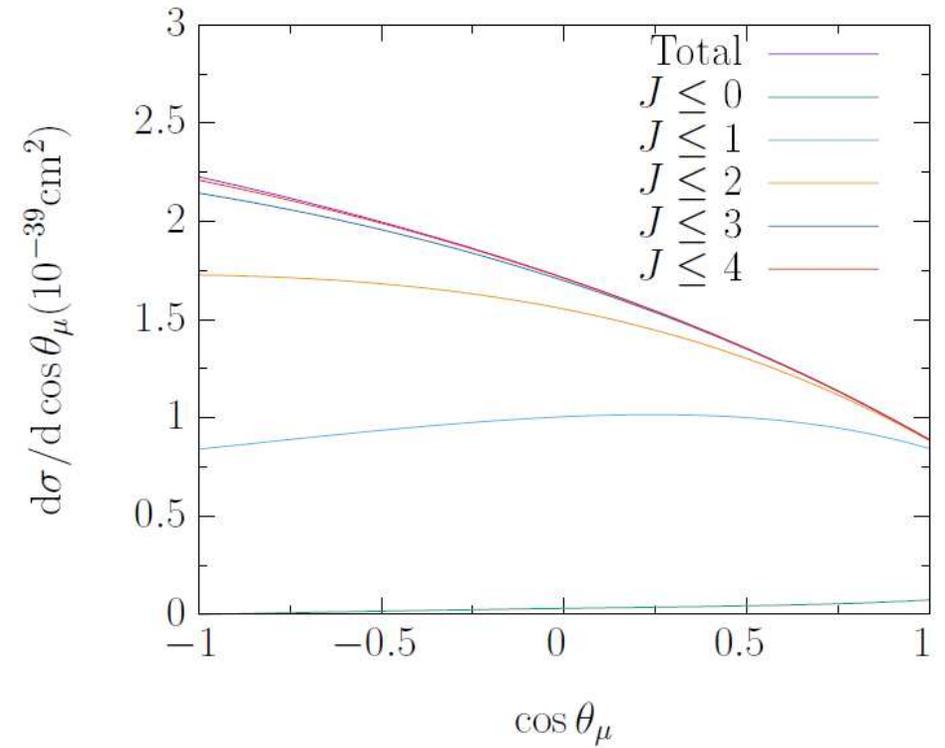


# Low energy cross sections

NCQE  $^{40}\text{Ar}$   $E_{\nu_e} = 50\text{MeV}$



NCQE  $^{208}\text{Pb}$   $E_{\nu_e} = 50\text{MeV}$

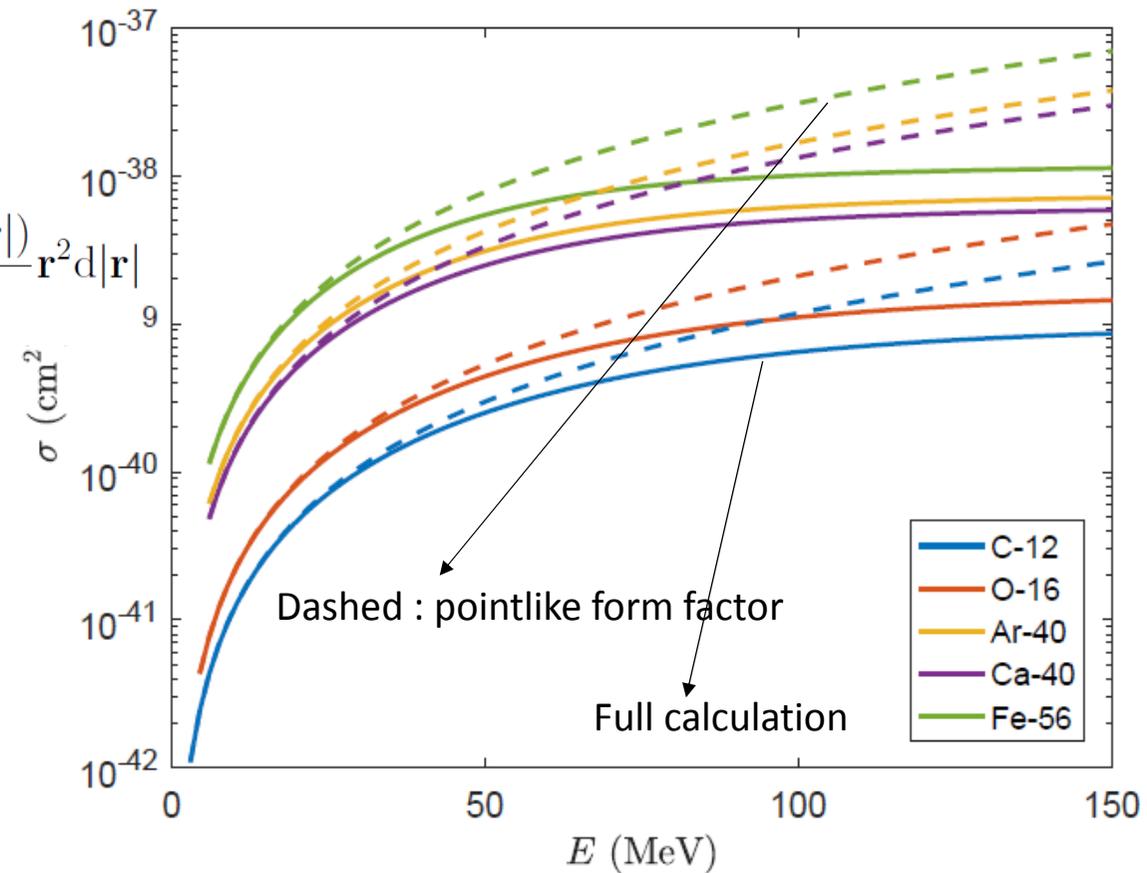


# Coherent

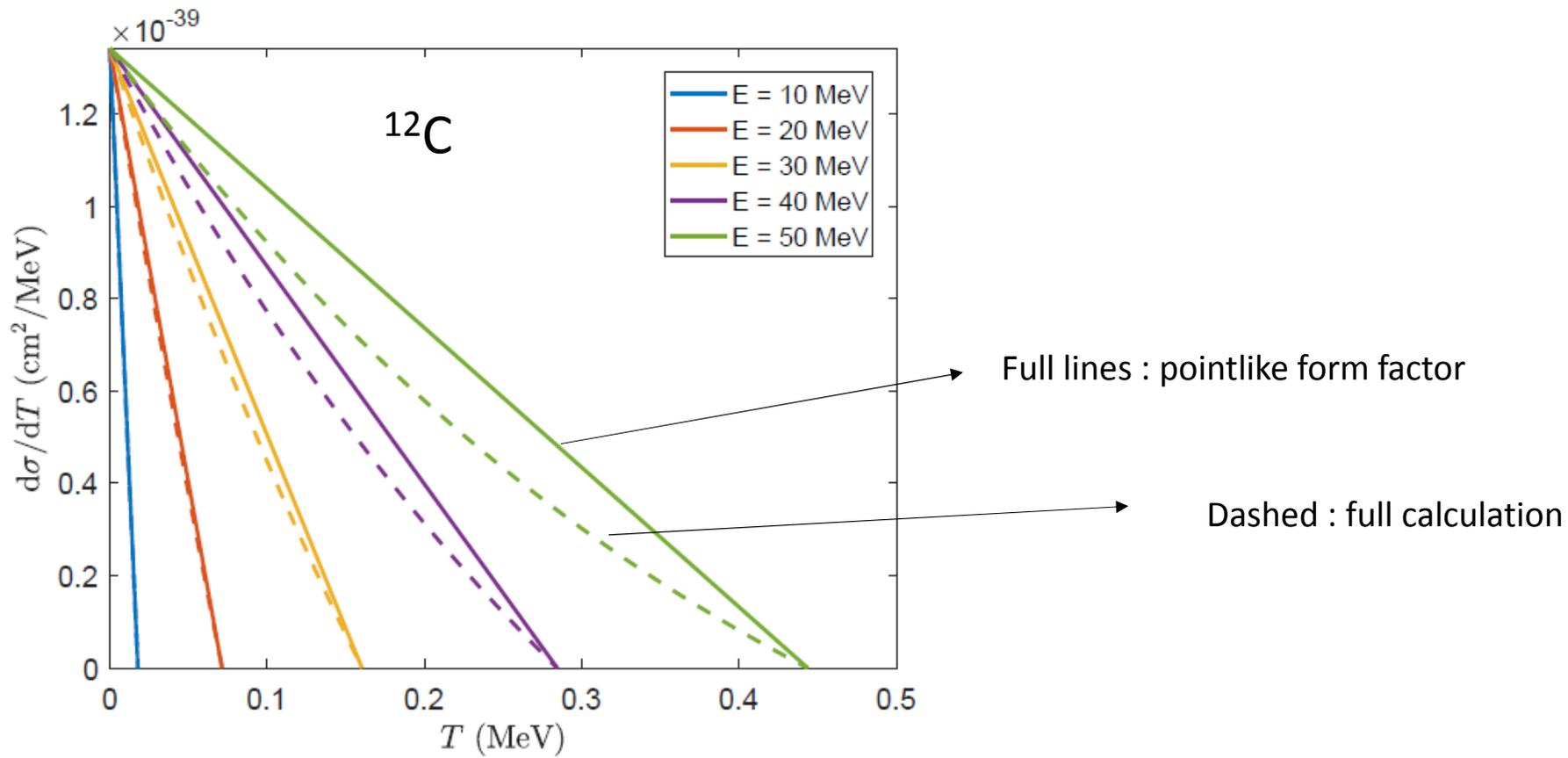
$$\frac{d\sigma}{dT} = \frac{G_F^2}{4\pi} Q_W^2 |F(-2MT)|^2 M \left( 1 - \frac{T}{E} - \frac{MT}{2E^2} \right)$$

$$F(q^2) = \frac{4\pi}{Q_W} \int ((1 - 4 \sin^2 \theta_W) \rho_p(|\mathbf{r}|) - \rho_n(|\mathbf{r}|)) \frac{\sin(|\mathbf{q}||\mathbf{r}|)}{|\mathbf{q}||\mathbf{r}|} \mathbf{r}^2 d|\mathbf{r}|$$

$$\rho_\tau(|\mathbf{r}|) = \frac{1}{4\pi|\mathbf{r}|^2} \sum_{\alpha} (2j_{\alpha} + 1) R_{\alpha}^2(|\mathbf{r}|)$$



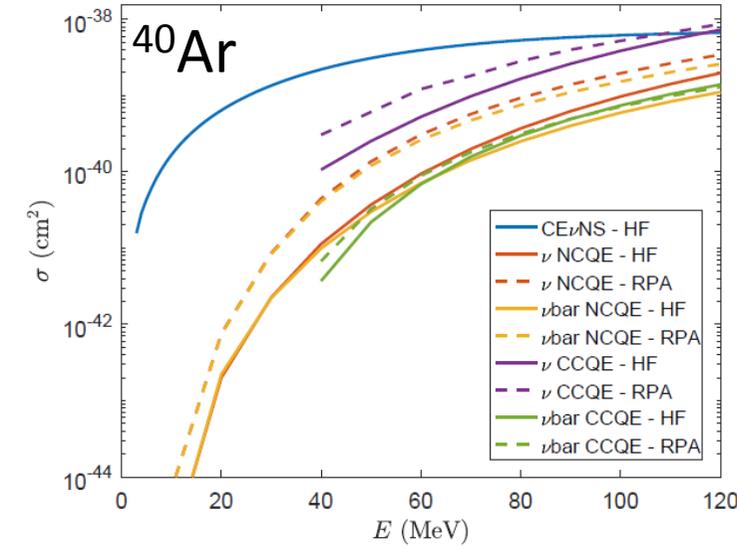
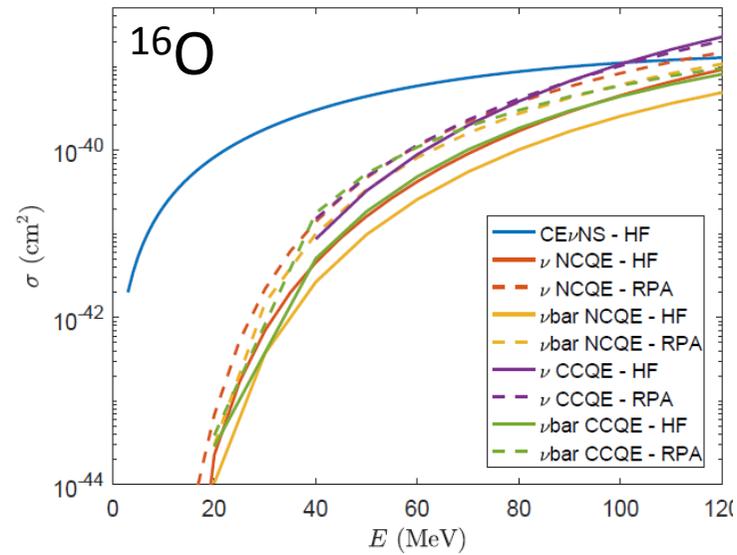
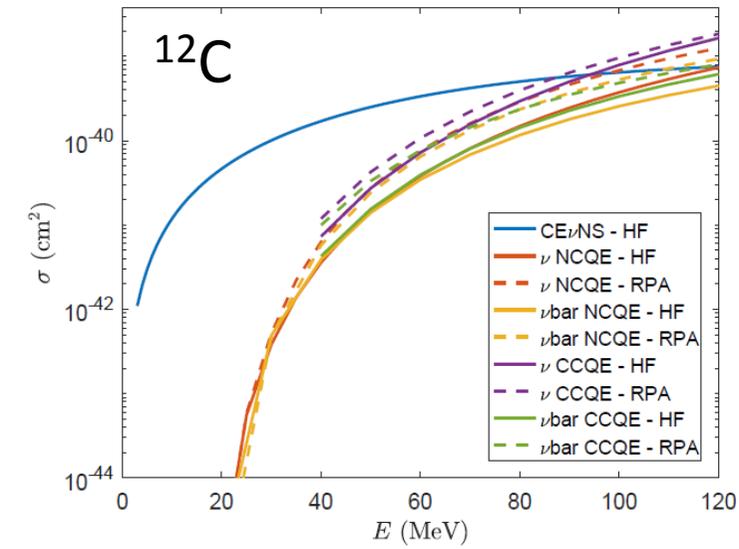
# Coherent



Full lines : pointlike form factor

Dashed : full calculation

# Coherent – consistent comparison with other processes



➤ Strong mass dependence of coherent cross section