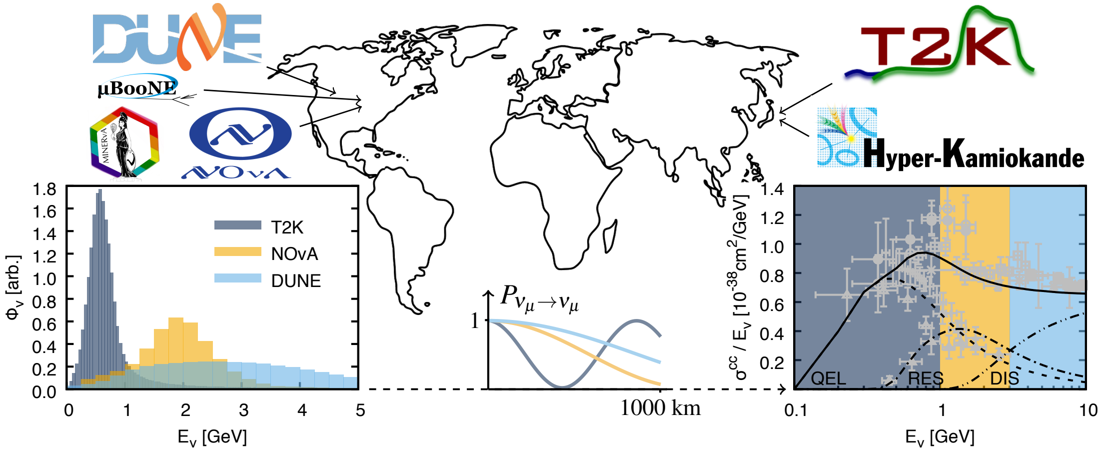
Multinucleon knock-out in lepton-nucleus scattering

Kajetan Niewczas



$$P(\nu_\mu \to \nu_e) \simeq \sin^2(2\theta)\sin^2\left(1.27\frac{\Delta m^2 L}{E_\nu}\right)$$

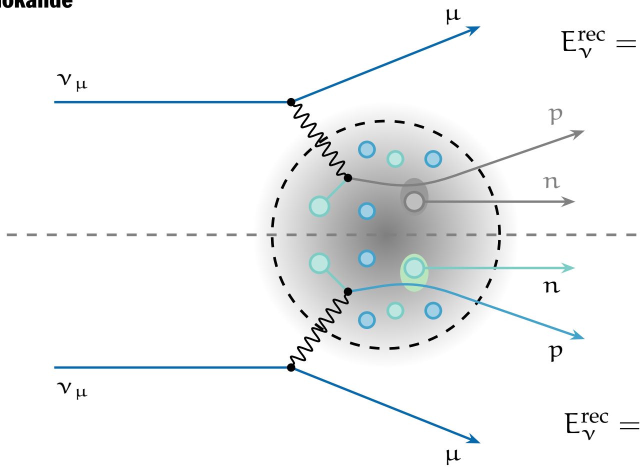
oscillation — amplitude — frequency

$$A_{CP} = \frac{P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e)}$$

asymmetry — oscillation ratio

Kinematical energy reconstruction

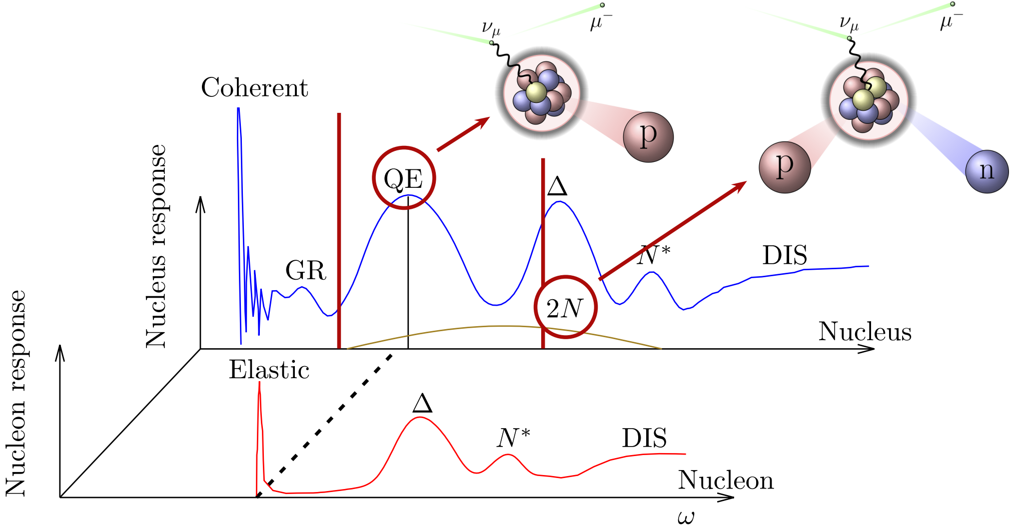
$$E_\nu^{rec} = \frac{2M_N E_\mu - {m_\mu}^2 + M_{N'}^2 - M_N^2}{2(M_N - E_\mu + p_\mu \cos\theta)}$$



$$E_\nu^{rec} = E_\mu - E_B + \sum_{nucl.} T_i + \sum_{mes.} E_j$$

Calorimetric energy reconstruction

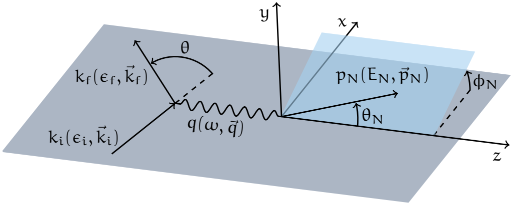
Nuclear response in the quasielastic and Δ regions



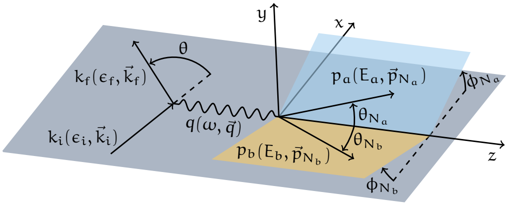
→ Mostly influenced by **one- and two-body physics** at nucleon and Δ levels

Kinematics

One-nucleon knock-out (1p1h)



Two-nucleon knock-out (2p2h)



Inclusive cross section

Electron scattering

$$\frac{d\sigma^{\gamma}}{d\epsilon_f d\Omega_f} = 4\pi\sigma^{\mathrm{Mott}}[\mathcal{V}_L^e \mathcal{W}_L + \mathcal{V}_T^e \mathcal{W}_T]$$

Neutrino scattering

$$\frac{d\sigma^{W}}{d\epsilon_f d\Omega_f} = 4\pi\sigma^{W}\zeta[\mathcal{V}_{CC}\mathcal{W}_{CC} + \mathcal{V}_{CL}\mathcal{W}_{CL} + \mathcal{V}_{LL}\mathcal{W}_{LL} + \mathcal{V}_T\mathcal{W}_T + h\mathcal{V}_{T'}\mathcal{W}_{T'}]$$

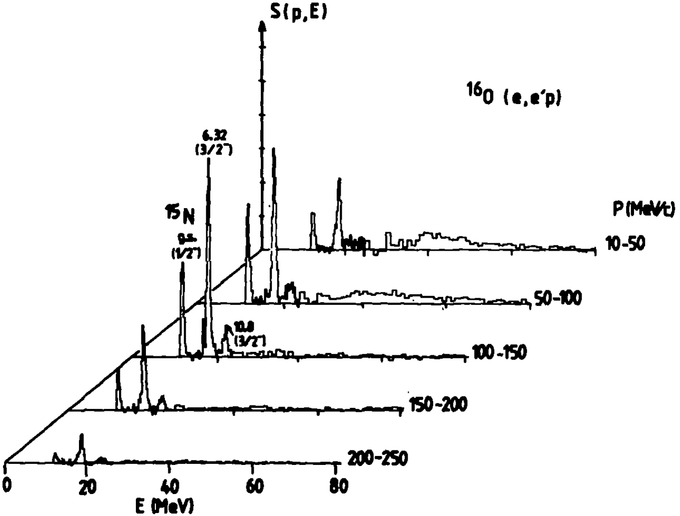
$\mathcal{V}_x$ - leptonic factors; $\mathcal{W}_x$ - hadronic responses; L/T - longitudinal/transverse relative to $\vec{q}$

Nuclear mean-field model

→ Nucleons exhibit discrete energy states characteristic of the **mean-field potential** picture

→ The redistribution of shell strength is caused by the **nucleon-nucleon correlations**

→ Residual nuclei can be excited above the **two-nucleon knock-out** threshold



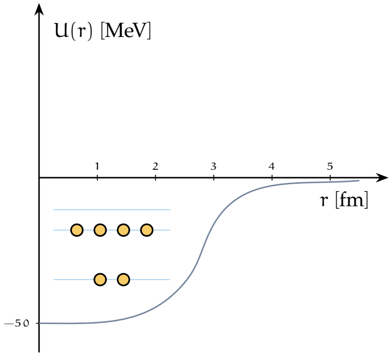
J. Mougey, Nucl.Phys. A 335 (1980) 35

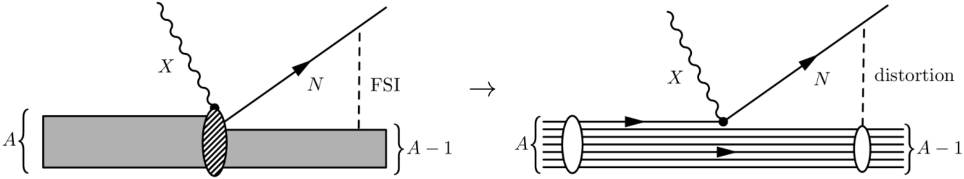
Our nuclear framework

→ Nucleons are solutions to the Schrödinger equation in a **mean-field potential**

→ We calculate single-particle states with the **Hartree-Fock** procedure and SkE2 NN force

→ We describe outgoing nucleons as **continuum states** of the nuclear potential





Impulse approximation

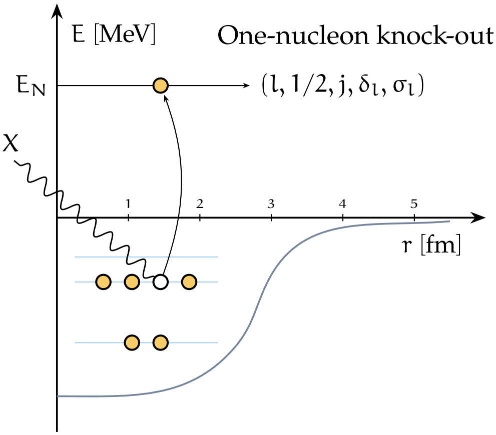
→ We evaluate the following **hadronic transition** currents

$$\mathcal{J}(\vec{r})^{\text{had}}_{\nu} = \langle \Psi_f \,|\, \hat{\mathcal{J}}(\vec{r})^{\text{had}}_{\nu} \,|\, \Psi_i \rangle$$

→ The nuclear many-body current is a sum of **one-body operators**

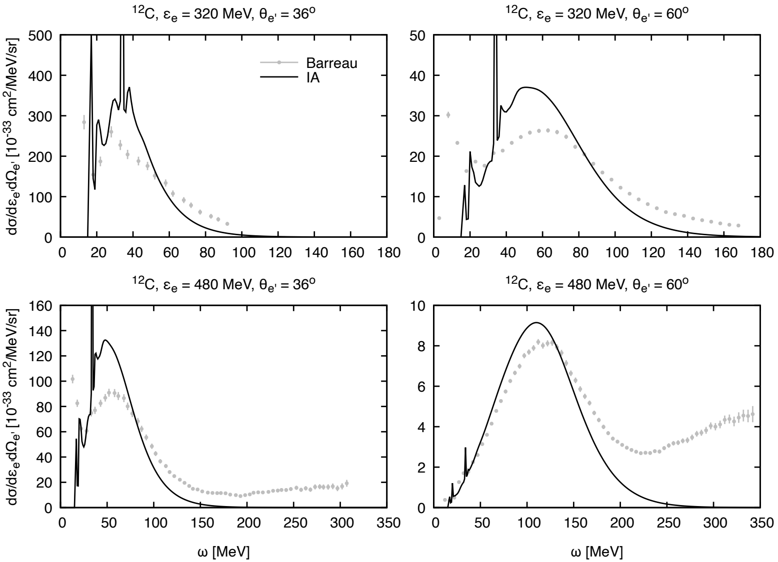
$$\hat{\mathcal{J}}(\vec{r})^{\text{had}}_{\nu} \simeq \hat{\mathcal{J}}(\vec{r})^{\text{IA}}_{\nu} = \sum_{j=1}^{A} \hat{\mathcal{J}}(\vec{r}_j)^{[1]}_{\nu} \delta^{(3)}(\vec{r} - \vec{r}_j)$$

→ We control numerical precision using a **multipole decomposition**

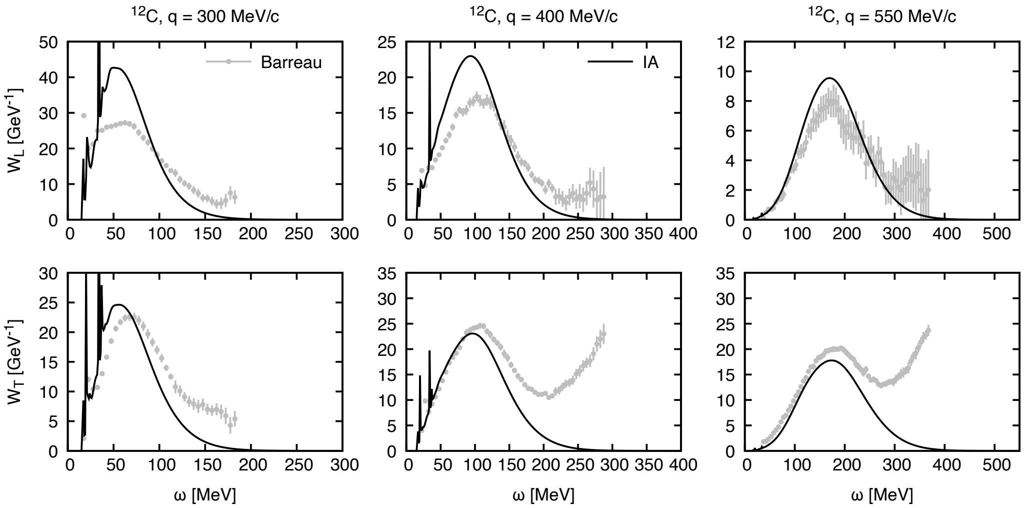


→ Comparing to **inclusive electron scattering data** allows for benchmarking of the model

Impulse approximation: electron scattering

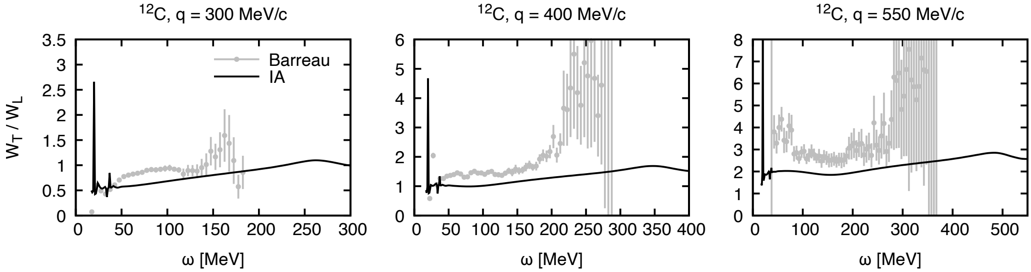


Impulse approximation: electron scattering



→ Calculation using **one-body currents** is fairly accurate

Impulse approximation: electron scattering



→ Overestimation of the longitudinal and the underestimation of the transverse responses

Short-range correlations

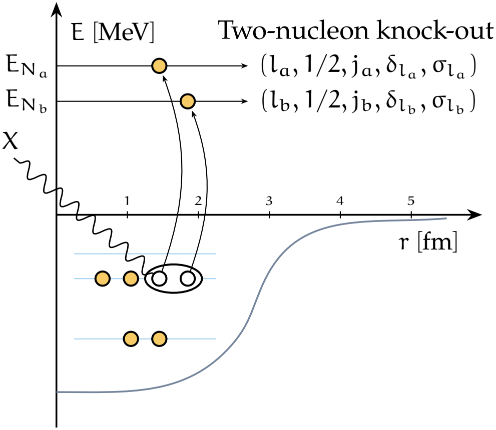
→ Nucleons with strongly **overlapping wave functions** for a short period of time

$$\hat{J}^{\text{eff}}_{\nu} \simeq \sum_{i=1}^{A} \hat{J}^{[1]}_{\nu}(i) + \sum_{i<j}^{A} \hat{J}^{[1],\text{SRC}}_{\nu}(i,j)$$

with

$$\hat{J}^{[1],\text{SRC}}_{\nu}(i,j) = \left[\hat{J}^{[1]}_{\nu}(i) + \hat{J}^{[1]}_{\nu}(j)\right] \hat{l}(i,j)$$

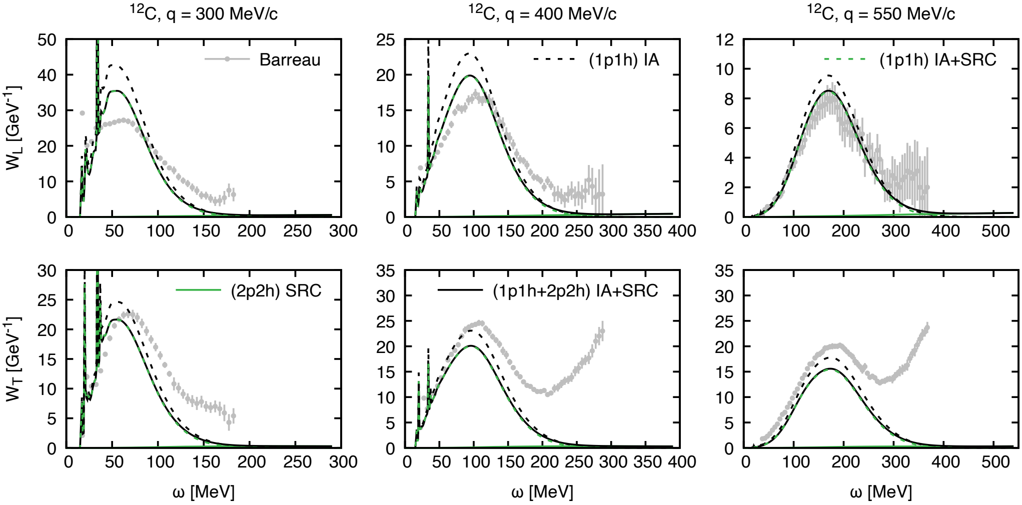
→ The correlation operator $\hat{l}(i,j)$ includes **central**, **tensor**, and **spin-isospin correlations**



→ First corrections to the **independent-particle model** picture for 1p1h

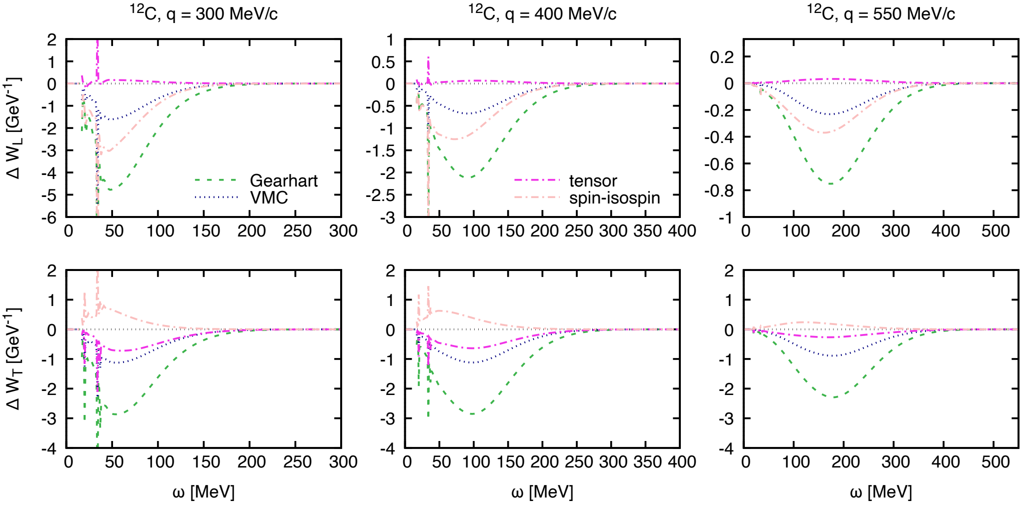
→ **Two-body currents** also leading to **two-nucleon knock-out** reactions

Short-range correlations: electron scattering



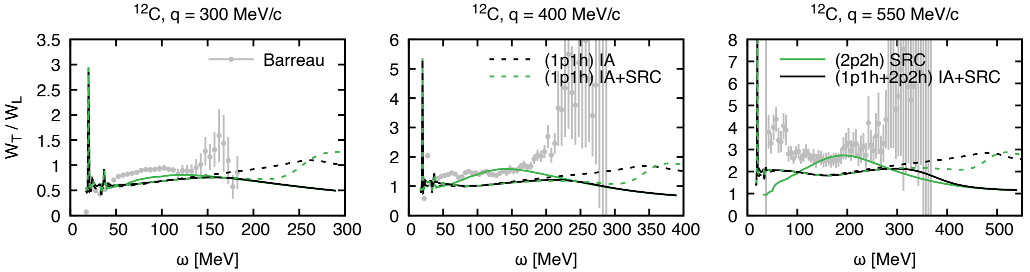
→ Significant **reduction of the 1p1h strength** and a minor 2p2h contribution

Short-range correlations: electron scattering



→ Interplay between different correlation effects

Short-range correlations: electron scattering

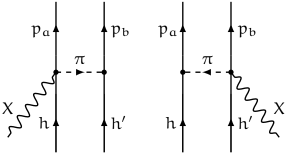


→ Including correlation effects does not fix the ratio

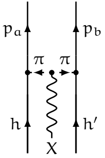
Meson-exchange currents

Explicit **two-body currents** contributing to both **1p1h** and **2p2h** final-states:

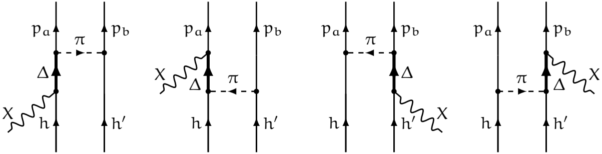
→ **Seagull** currents

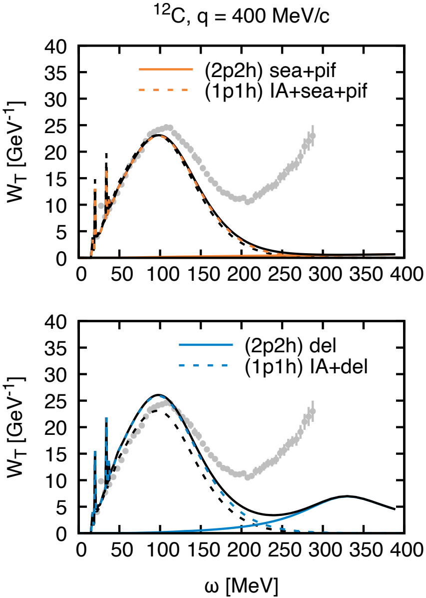


→ **Pion-in-flight** current

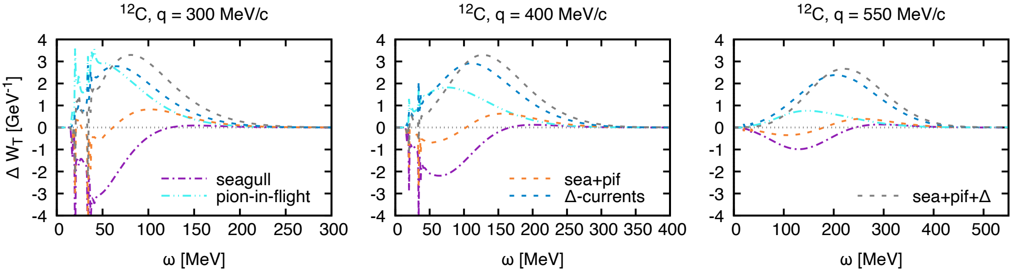


→ **Δ-isobar** degrees of freedom



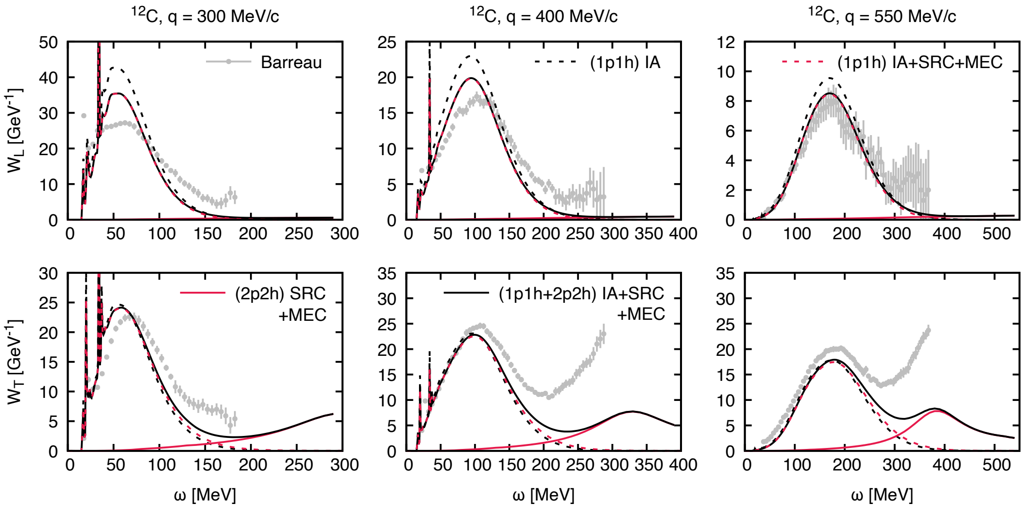


Meson-exchange currents: electron scattering



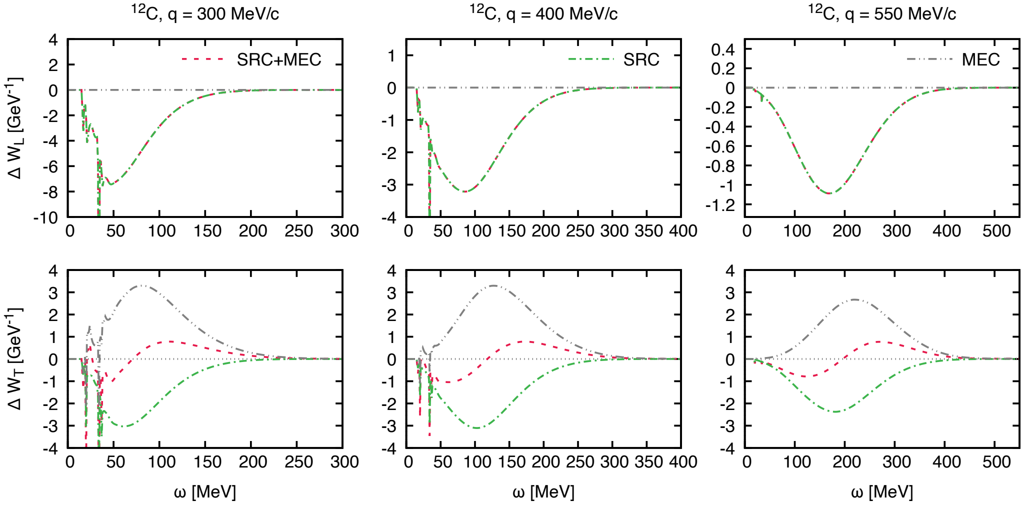
→ Meson-exchange currents **enhance the transverse response**

Consistent modeling of two-body currents: electron scattering



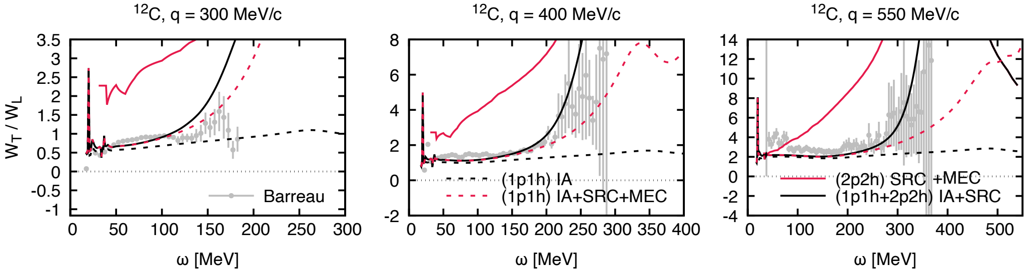
→ **Coherent sum of SRC and MEC** enhances our predictions

Consistent modeling of two-body currents: electron scattering



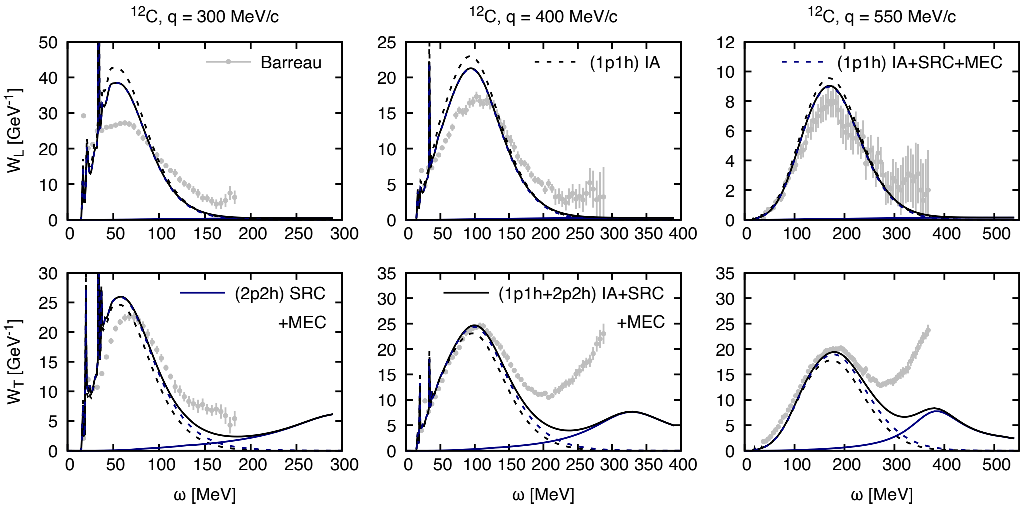
→ Interplay between SRC and MEC effects in the transverse response

Consistent modeling of two-body currents: electron scattering



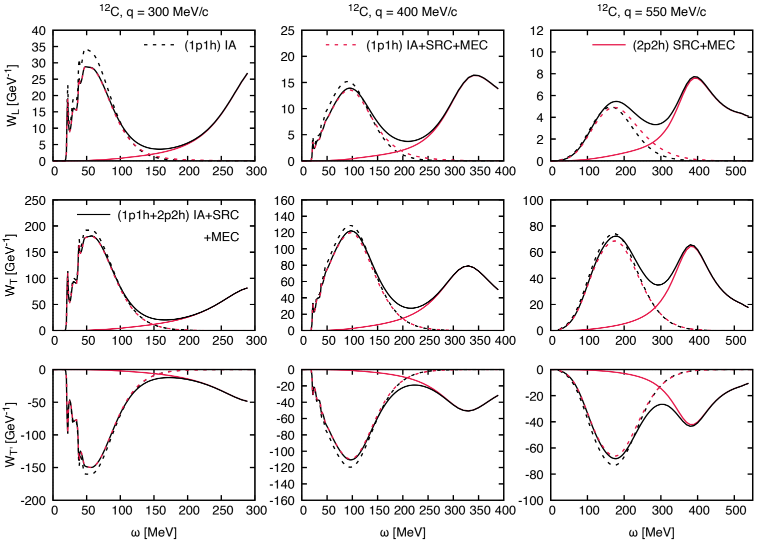
→ Meson-exchange currents are neccessary to fix the ratio

Consistent modeling of two-body currents: electron scattering



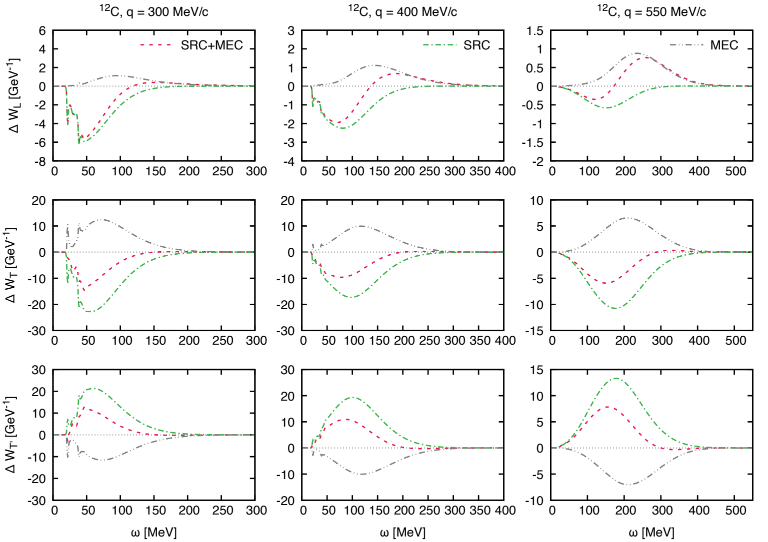
→ **Softer correlations** enhance the comparison for larger momentum transfer

Consistent modeling of two-body currents: neutrino scattering



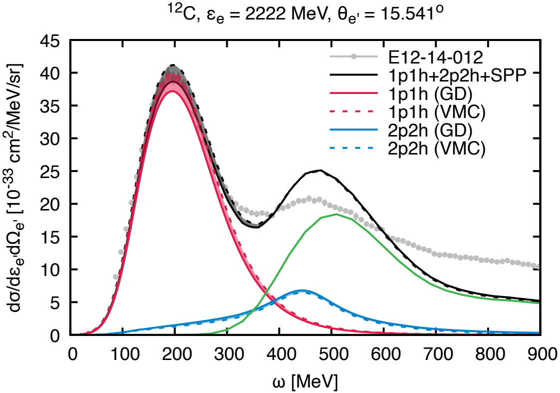
→ **Pronounced Δ peaks** for both longitudinal and transverse responses

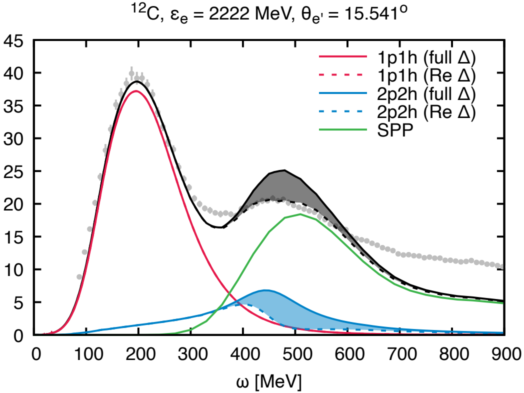
Consistent modeling of two-body currents: neutrino scattering



→ The enhancement appears only in the longitudinal response

JLab Hall A data

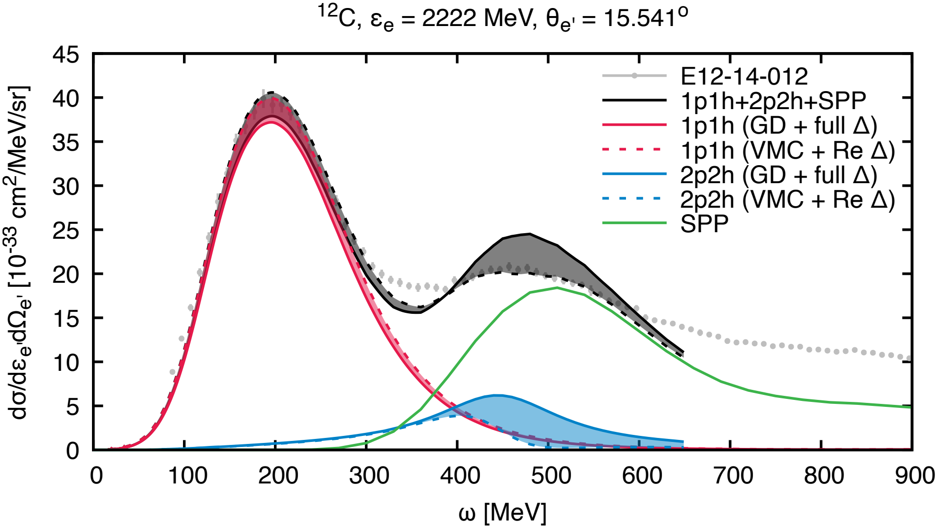




→ The choice of the different **central correlation functions** modifies the **QE peak strength** (GD–stronger, VMC–weaker)

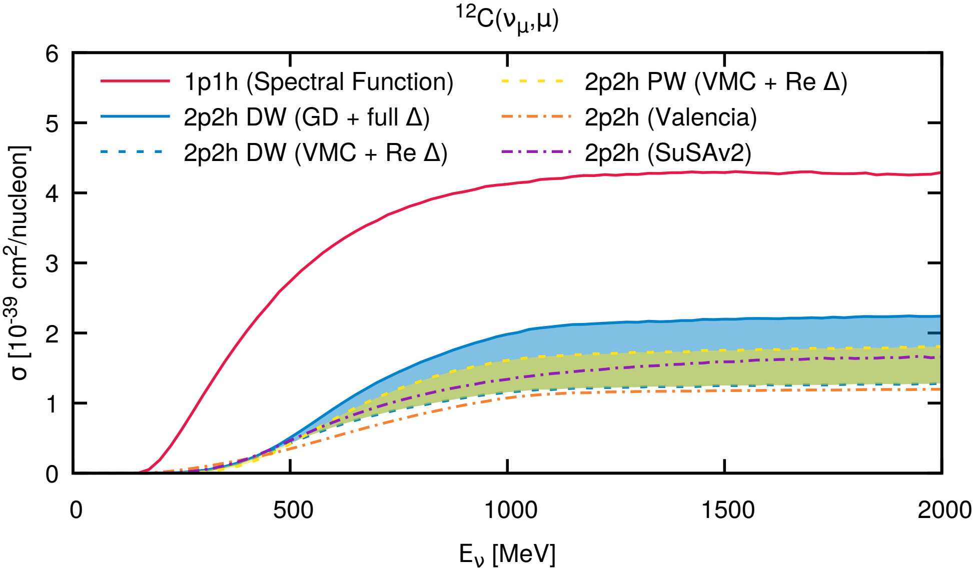
→ Modifying the Δ-propagator governs the **overlap between MEC and SPP** around the Δ peak (Re Δ–only the real part)

JLab Hall A data

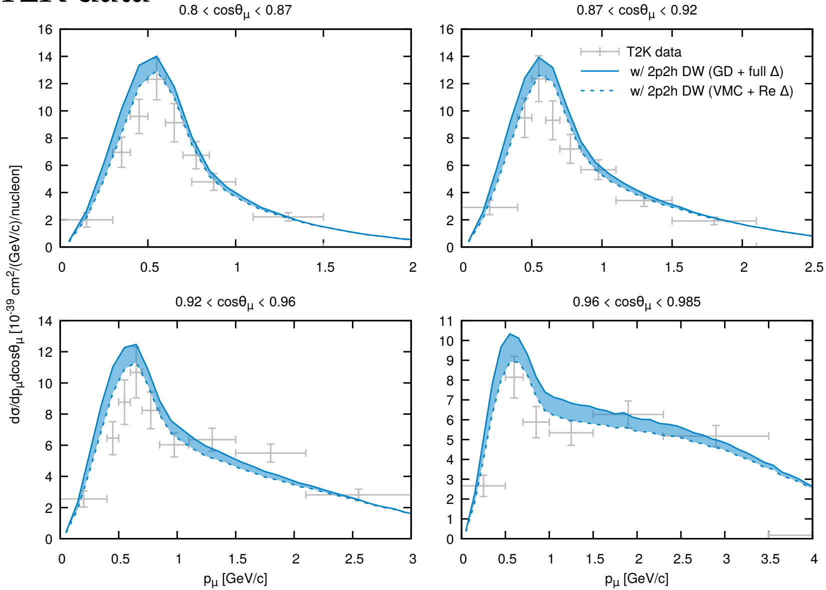


→ Combining variation in given d.f. provides **flexibility in describing QE and Δ peaks**

Inclusive NuWro implementation

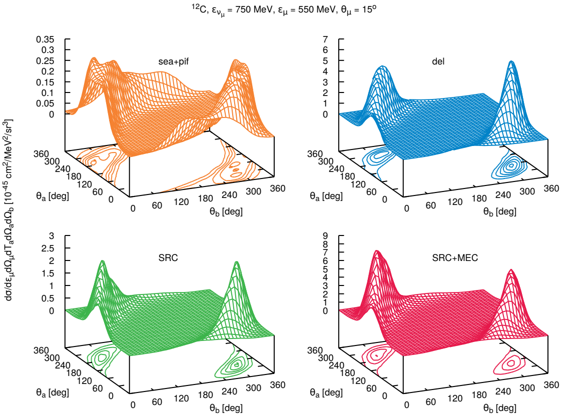


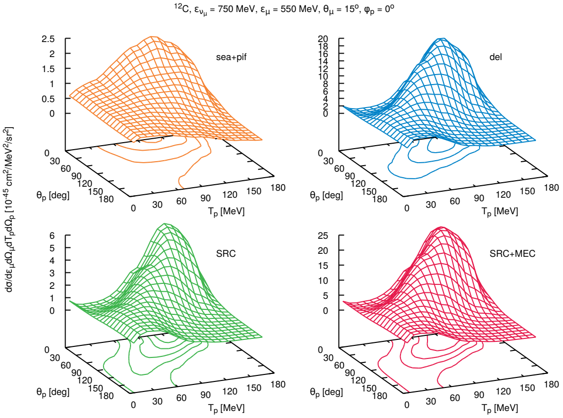
Inclusive T2K data



Going more exclusive... in neutrino scattering

Exclusive two-nucleon knock-out





Semi-inclusive two-nucleon knock-out

Conclusions

- The Ghent group has developed the lepton-nucleus scattering model predicting the influence of **one- and two-body** currents in **one- and two-nucleon knockout** reactions

- Our model has **passed the validation stage** and is ready to provide meaningful results

- The internal, **theoretical d.f.** give enough **flexibility** to compare to inclusive electron scattering data

- The entry, **inclusive implementation** in NuWro **requires more consistency** between the modeled interaction channels

Future plans

- Finding the **optimal choice of parameters**, as compared to **inclusive electron scattering**
- Releasing the entry **NuWro implementation for public use** (consistent parametrization)
- Incorporating the **CRPA** calculations of **long-range correlations** into the 1p1h+2p2h framework
- Exploring **exclusive 1p1h** and **semi-inclusive 2p2h** reactions in electron- and neutrino-scattering