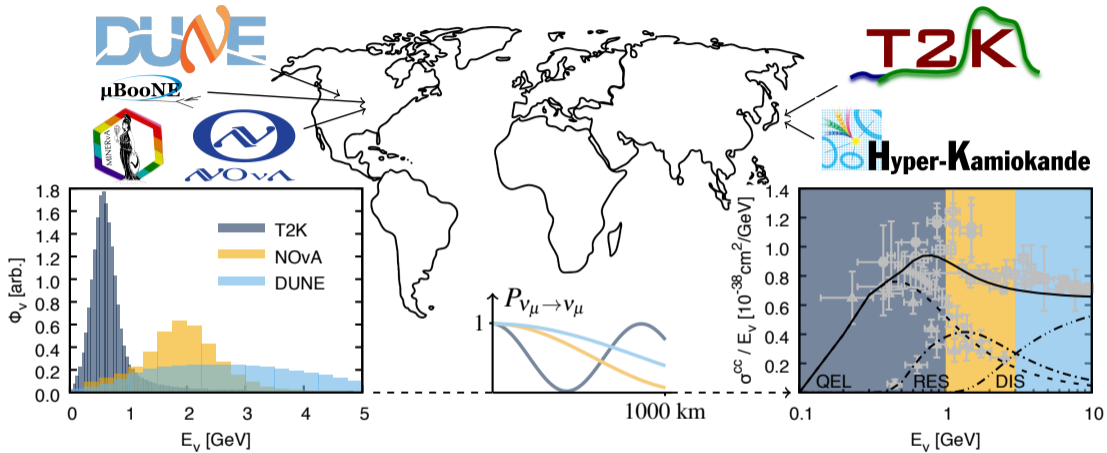


Multinucleon knock-out in lepton-nucleus scattering

Kajetan Niewczas





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

↑
oscillation

↑
amplitude

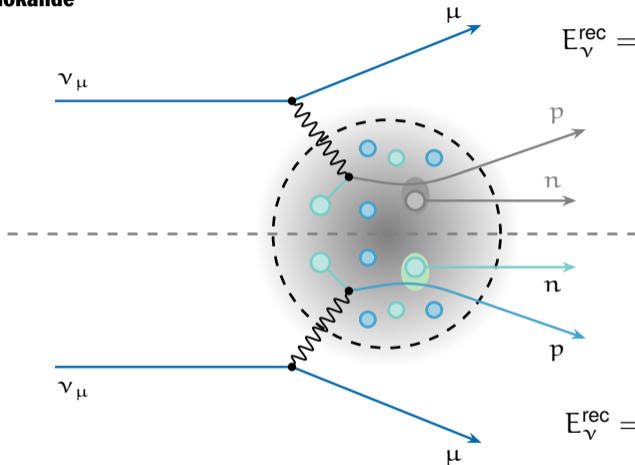
↑
frequency

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

↑
asymmetry

↑
oscillation ratio

Kinematical energy reconstruction



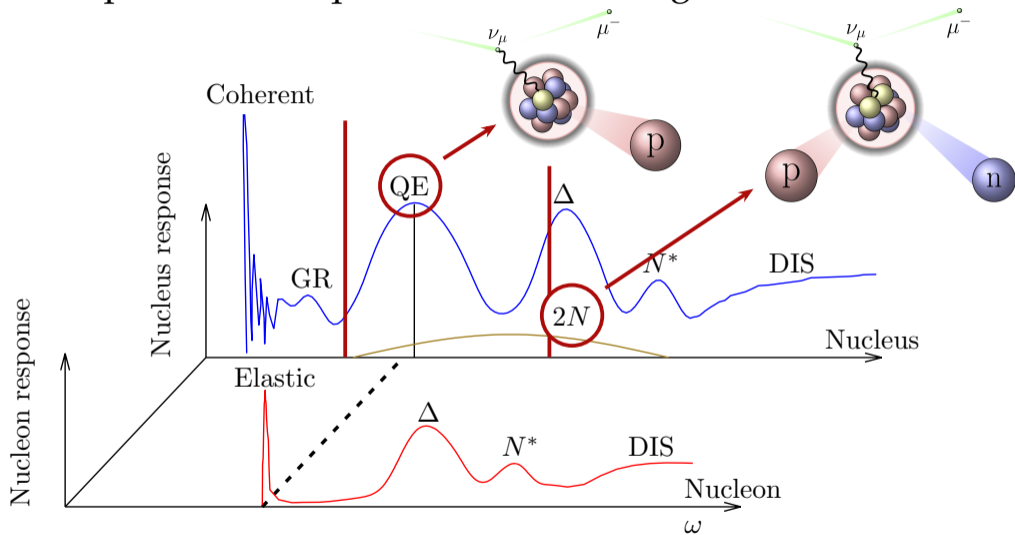
$$E_{\nu}^{\text{rec}} = \frac{2M_N E_{\mu} - m_{\mu}^2 + M_{N'}^2 - M_N^2}{2(M_N - E_{\mu} + p_{\mu} \cos \theta)}$$

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



Calorimetric energy reconstruction

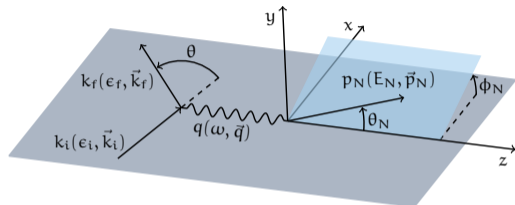
Nuclear response in the quasielastic and Δ regions



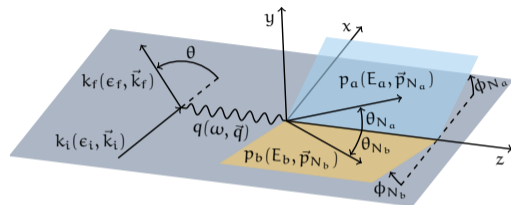
→ Mostly influenced by **one- and two-body physics** at nucleon and Δ levels

Kinematics

One-nucleon knock-out (1p1h)



Two-nucleon knock-out (2p2h)



Inclusive cross section

Electron scattering

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

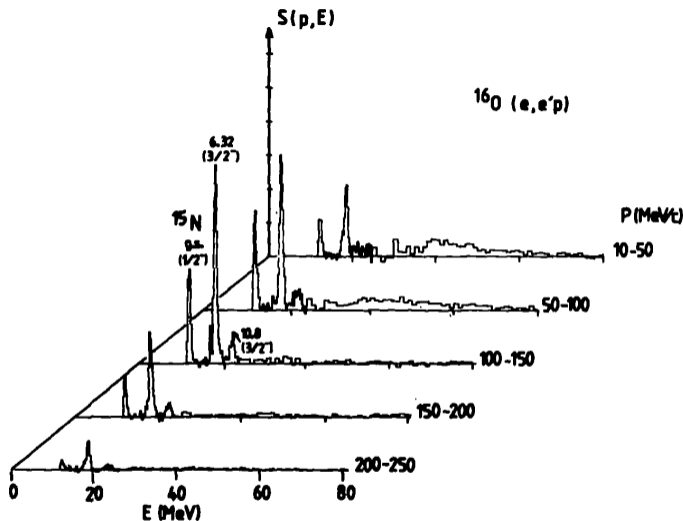
Neutrino scattering

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

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

Nuclear mean-field model

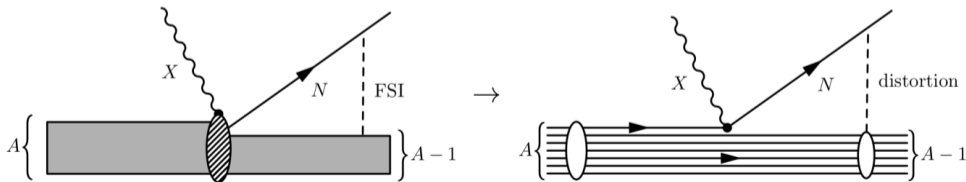
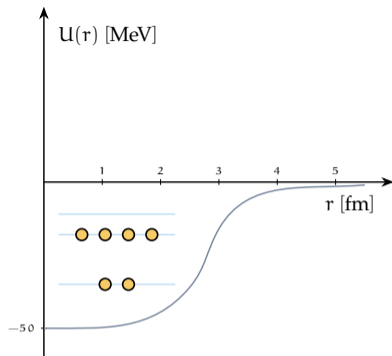
- Nucleons exhibit discrete energy states characteristic of the **mean-field potential** picture
- The redistribution of shell strength is caused by the **nucleon-nucleon correlations**
- Residual nuclei can be excited above the **two-nucleon knock-out** threshold



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**

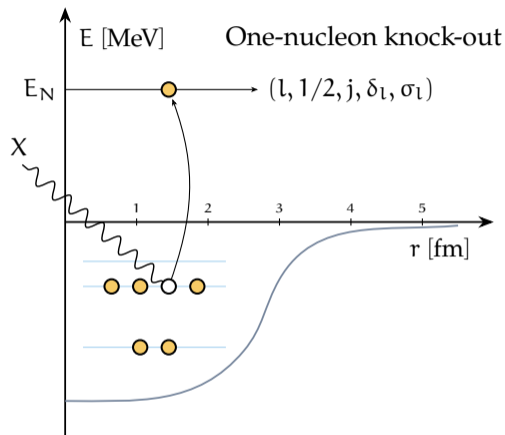
$$\hat{\mathcal{J}}(\vec{r})_{\nu}^{\text{had}} = \langle \Psi_f | \hat{\mathcal{J}}(\vec{r})_{\nu}^{\text{had}} | \Psi_i \rangle$$

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

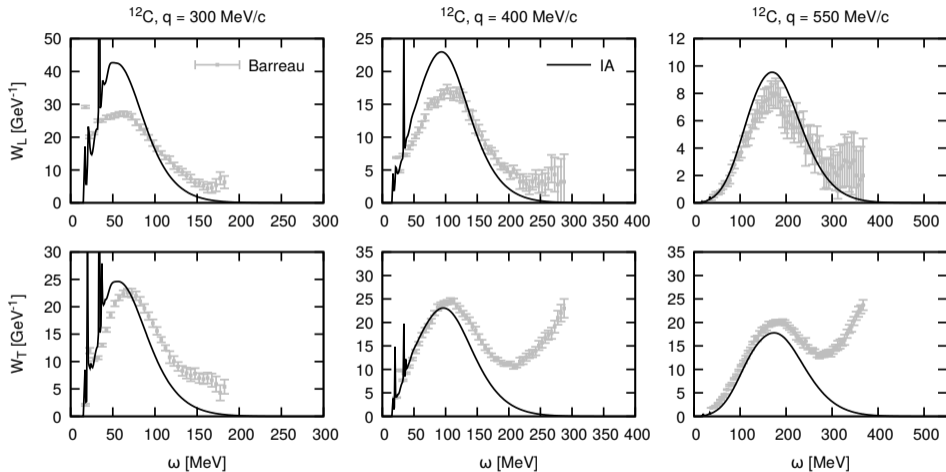
$$\hat{\mathcal{J}}(\vec{r})_{\nu}^{\text{had}} \simeq \hat{\mathcal{J}}(\vec{r})_{\nu}^{\text{IA}} = \sum_{j=1}^A \hat{\mathcal{J}}(\vec{r}_j)_{\nu}^{[1]} \delta^{(3)}(\vec{r} - \vec{r}_j)$$

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

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

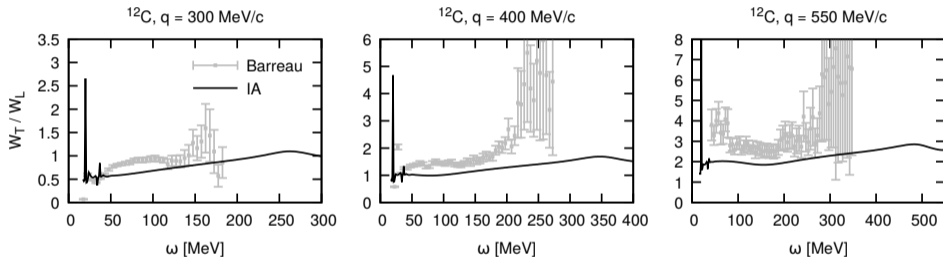


Impulse approximation: electron scattering



→ Calculation using **one-body currents** exhibits typical properties

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

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

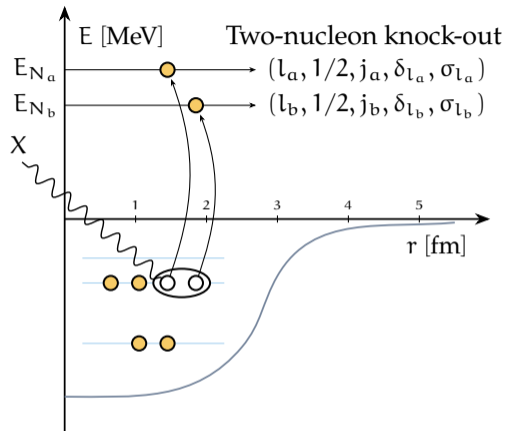
with

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

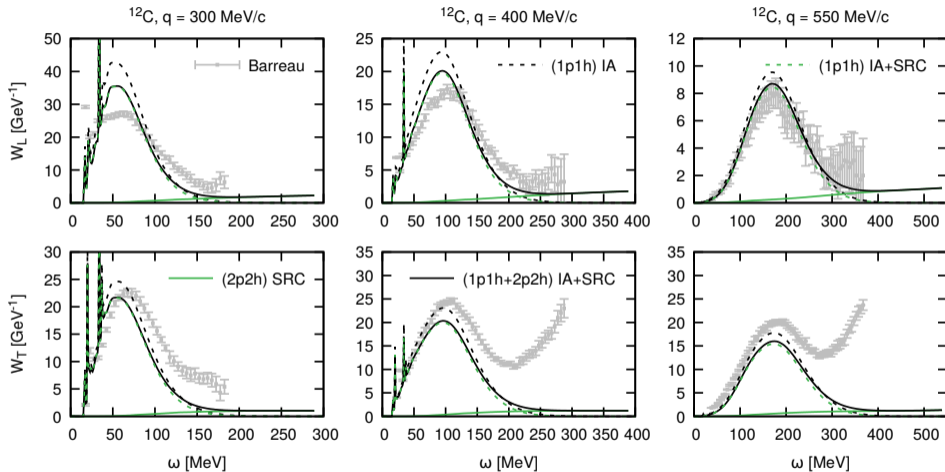
→ The correlation operator $\hat{l}(i,j)$ includes **central**, **tensor**, and **spin-isospin correlations**

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

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

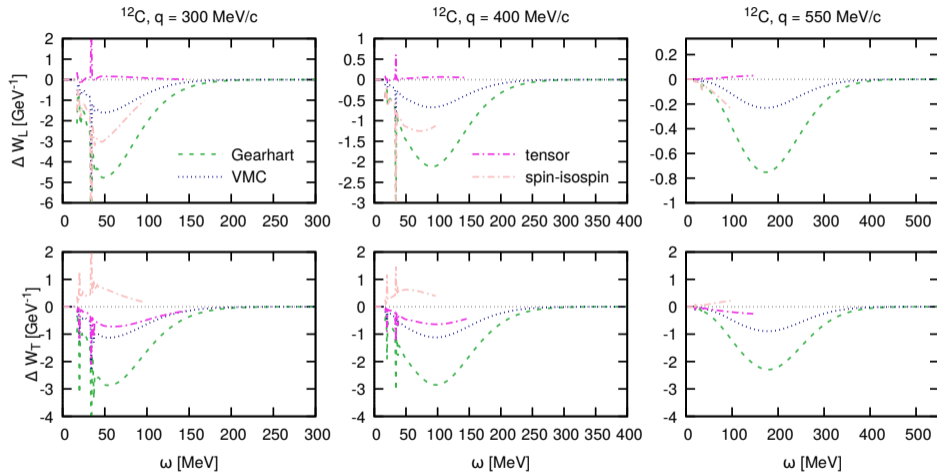


Short-range correlations: electron scattering



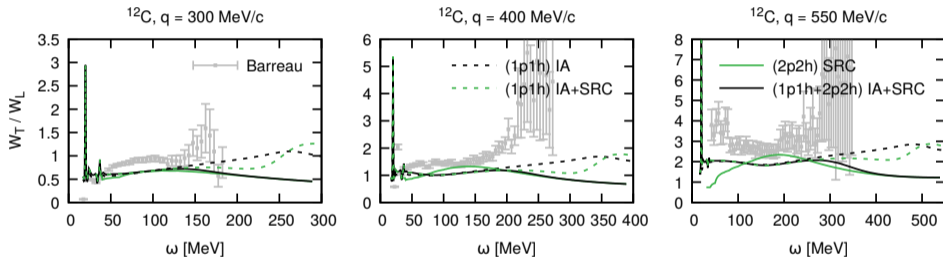
→ Significant **reduction of the 1p1h strength** and a minor 2p2h contribution

Short-range correlations: electron scattering



→ Interplay between different correlation effects

Short-range correlations: electron scattering

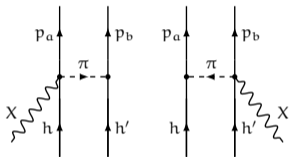


→ Including correlation effects does not fix the ratio

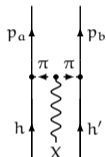
Meson-exchange currents

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

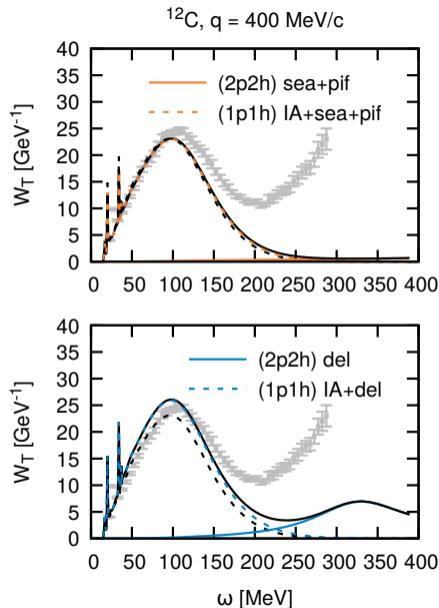
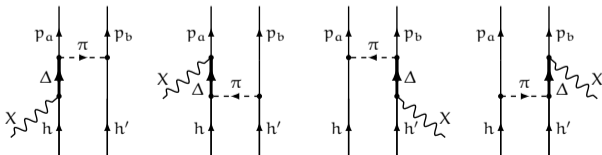
→ **Seagull** currents



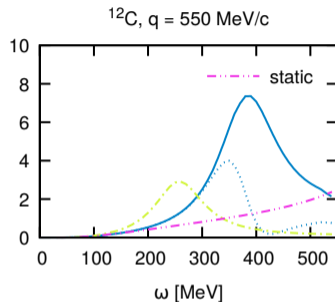
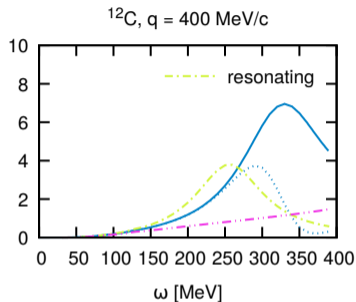
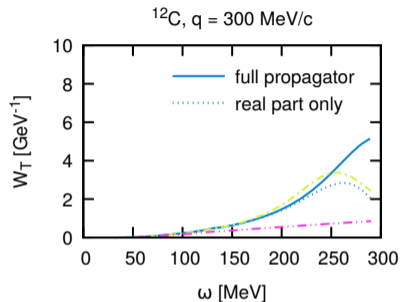
→ **Pion-in-flight** current



→ **Δ -isobar** degrees of freedom



Delta currents



Full propagators

$$G_{\Delta}^{\text{res}} = \frac{2M_{\Delta}}{M_{\Delta}^2 - s - iM_{\Delta}\Gamma_{\Delta}^{\text{res}} + 2M_{\Delta}V_{\Delta}}$$

$$G_{\Delta}^{\text{nres}} = \frac{2M_{\Delta}}{M_{\Delta}^2 - u}$$

Static approximation

$$G_{\Delta}^{\text{res}} = \frac{1}{M_{\Delta} - M_N}$$

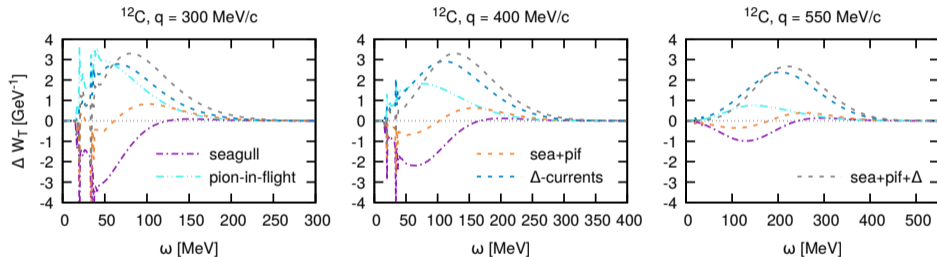
$$G_{\Delta}^{\text{nres}} = \frac{1}{M_{\Delta} - M_N}$$

Resonating approximation

$$G_{\Delta}^{\text{res}} + G_{\Delta}^{\text{nres}} = \frac{1}{M_{\Delta} - M_N - \omega - \frac{i}{2}\Gamma_{\Delta}^{\text{res}}}$$

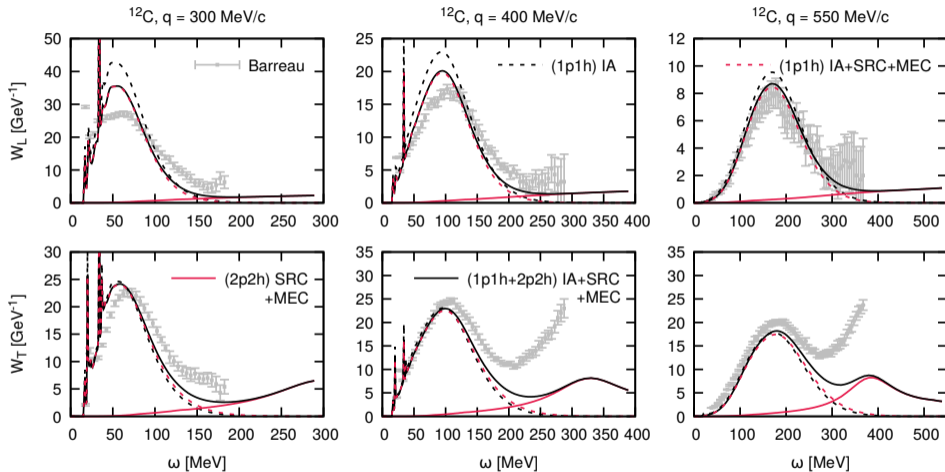
$$G_{\Delta}^{\text{res}} - G_{\Delta}^{\text{nres}} = 0 \quad + \frac{1}{M_{\Delta} - M_N + \omega}$$

Meson-exchange currents: electron scattering



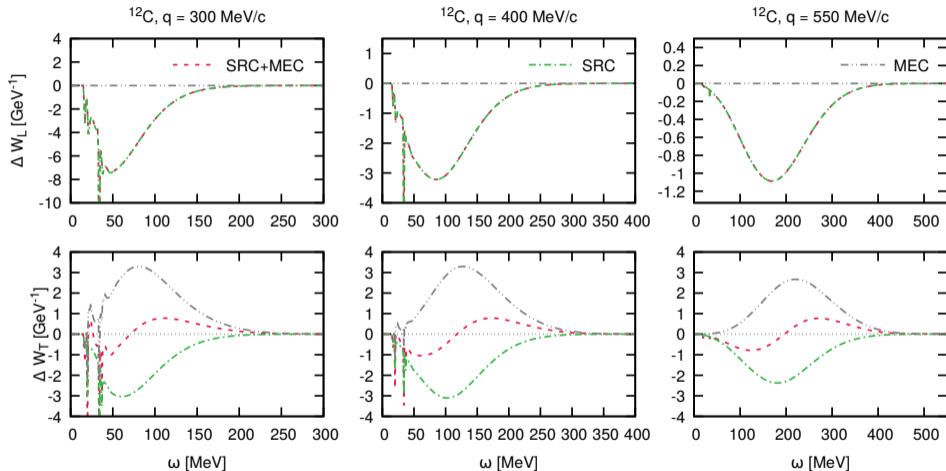
→ Meson-exchange currents **enhance the transverse response**

Consistent modeling of two-body currents: electron scattering



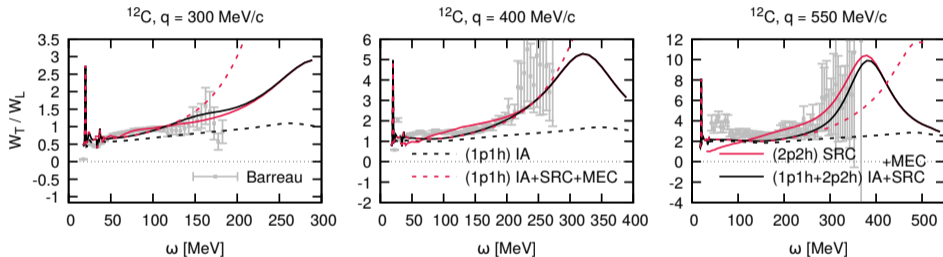
→ **Coherent sum of SRC and MEC** enhances our predictions

Consistent modeling of two-body currents: electron scattering



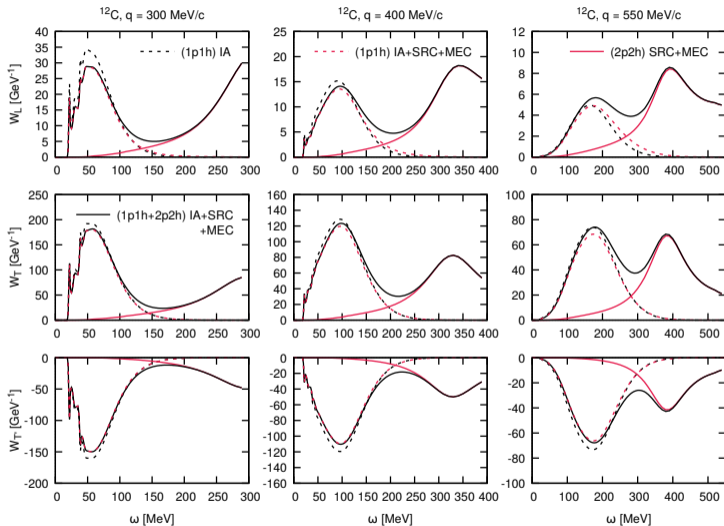
→ Interplay between SRC and MEC effects in the transverse response

Consistent modeling of two-body currents: electron scattering



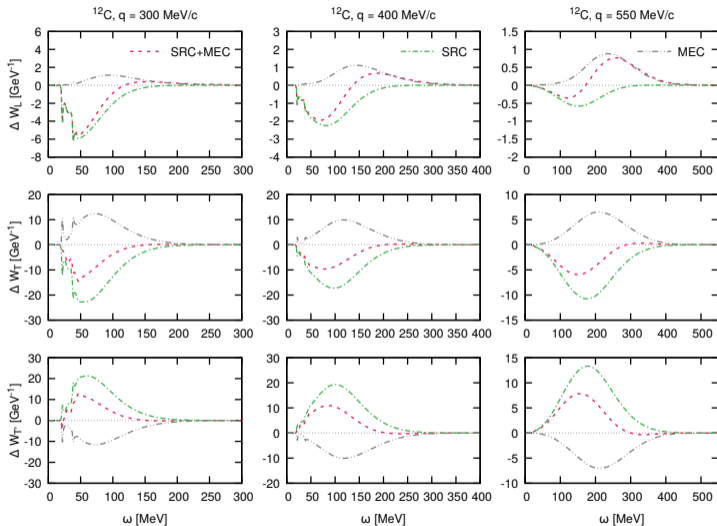
→ Meson-exchange currents are necessary to fix the ratio

Consistent modeling of two-body currents: neutrino scattering



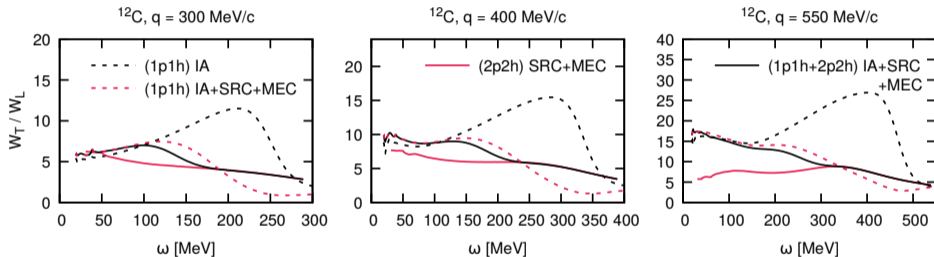
→ **Pronounced Δ peaks** for both longitudinal and transverse responses

Consistent modeling of two-body currents: neutrino scattering



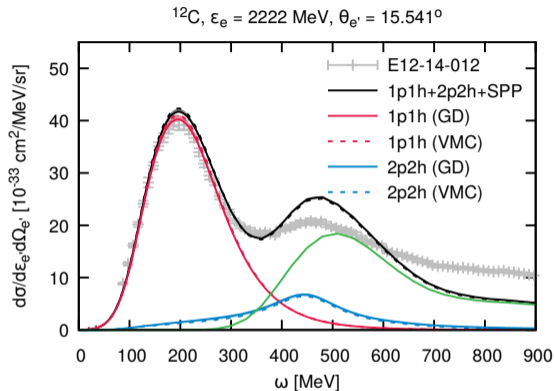
→ The enhancement appears only in the longitudinal response

Consistent modeling of two-body currents: neutrino scattering

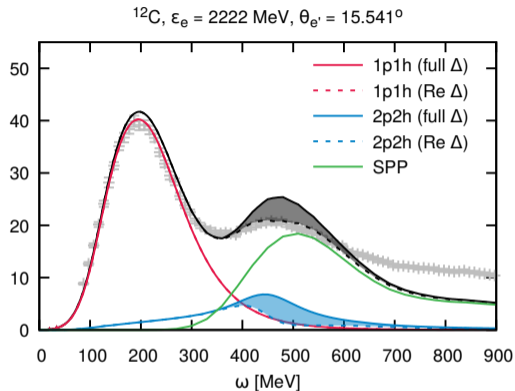


→ **Much more transverse**, but with the opposite energy dependence

JLab Hall A data



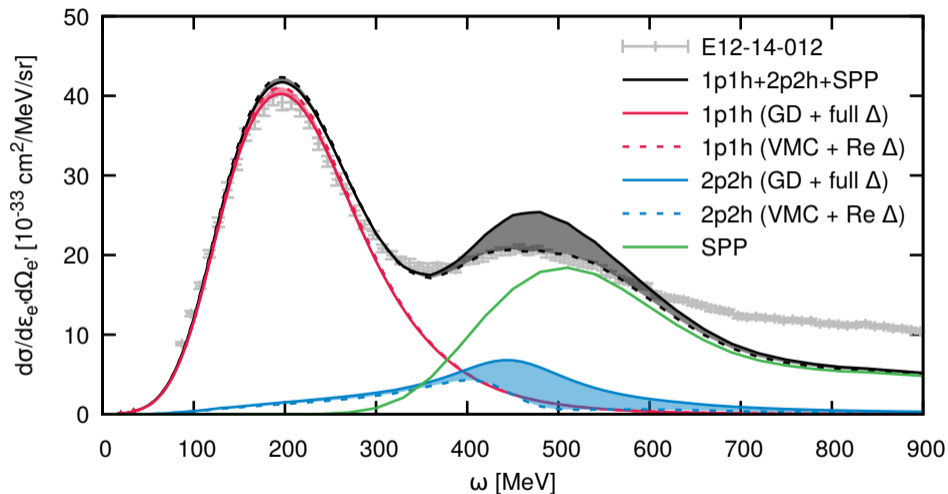
→ The choice of the different **central correlation functions** modifies the **QE peak strength** (GD–stronger, VMC–weaker)



→ 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

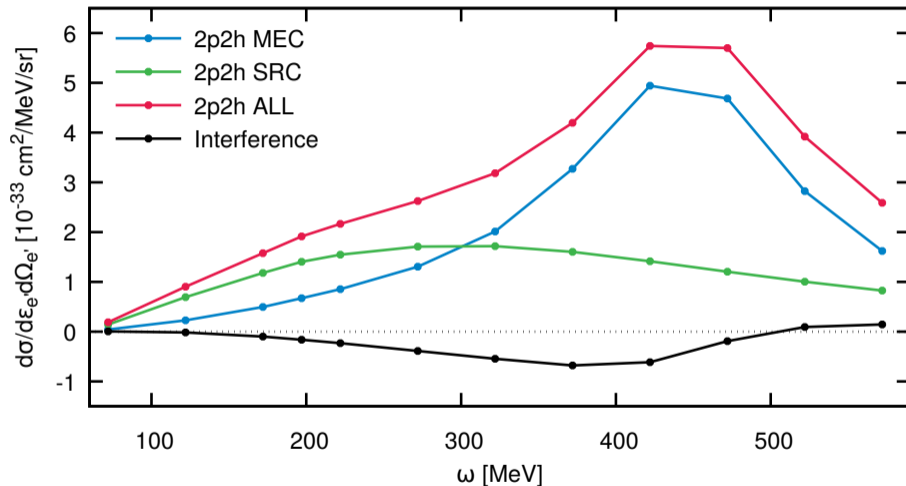
^{12}C , $\epsilon_e = 2222 \text{ MeV}$, $\theta_{e'} = 15.541^\circ$



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

JLab Hall A data

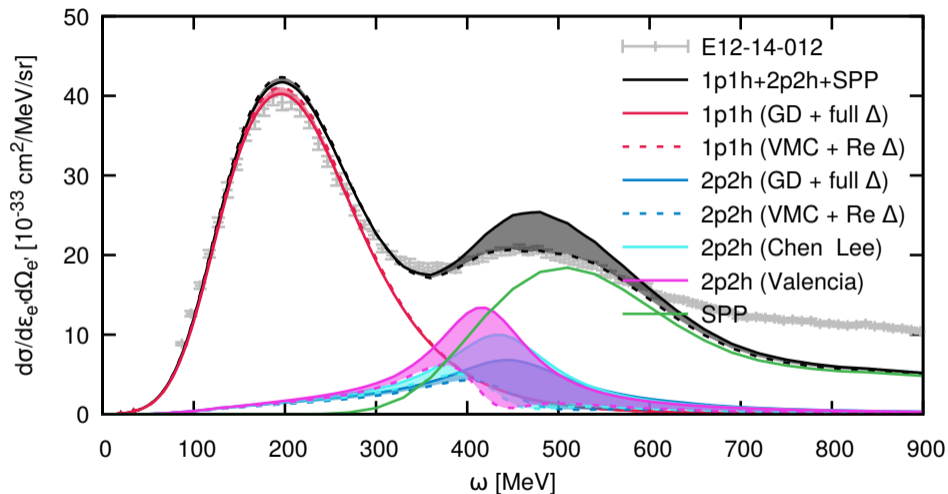
^{12}C , $\epsilon_e = 2222 \text{ MeV}$, $\theta_{e'} = 15.541^\circ$



→ We see a significant **negative interference** between the SRC and MEC contributions

JLab Hall A data

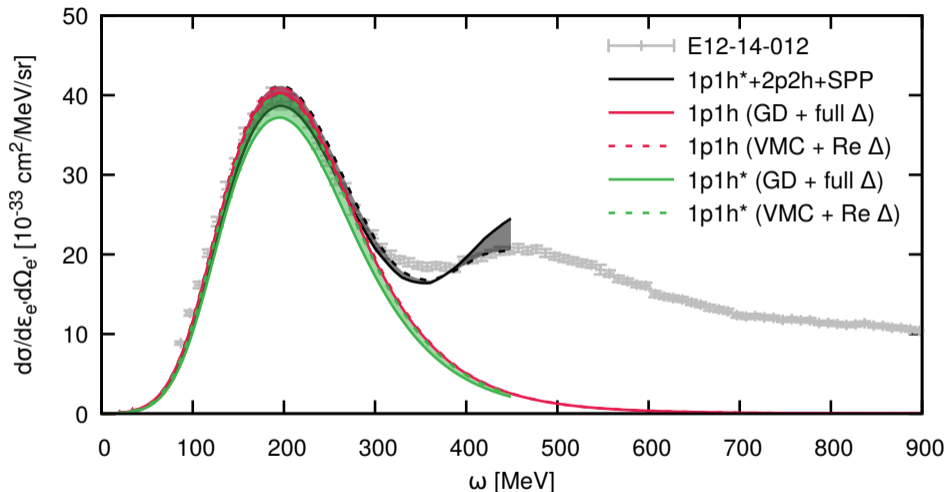
^{12}C , $\epsilon_e = 2222 \text{ MeV}$, $\theta_{e'} = 15.541^\circ$



→ Various parametrizations of the **in-medium Δ properties** bring vast differences

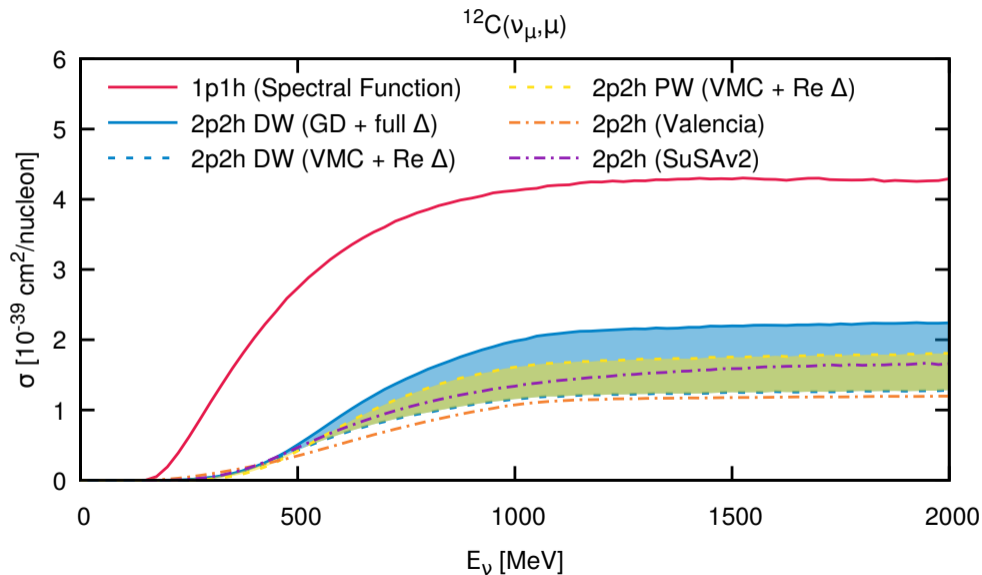
JLab Hall A data

^{12}C , $\epsilon_e = 2222 \text{ MeV}$, $\theta_{e'} = 15.541^\circ$

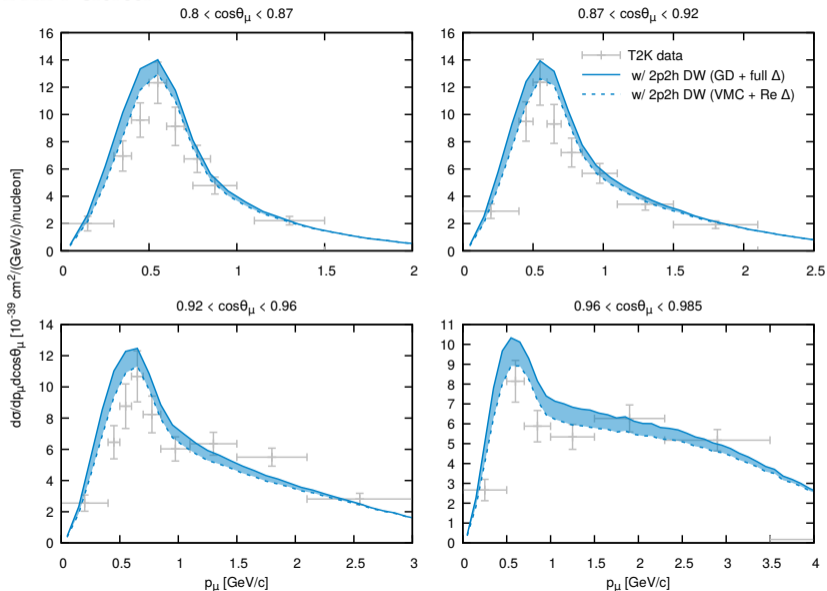


→ Fixing SRC issues resulted in a **reasonable quasielastic peak** description and more space in the dip region

Inclusive NuWro implementation

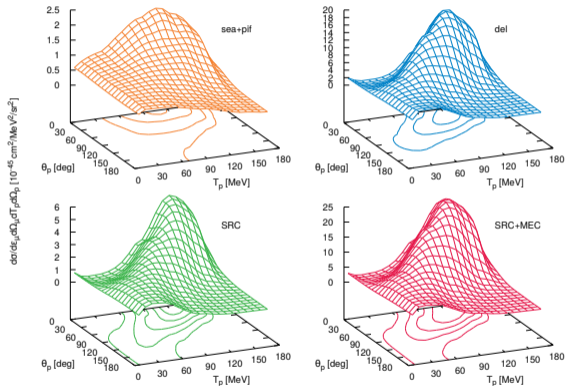


Inclusive T2K data



Going more exclusive... in neutrino scattering

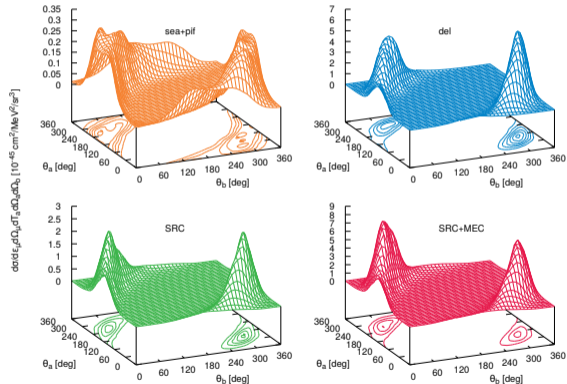
^{12}C , $\epsilon_{\nu\mu} = 750 \text{ MeV}$, $\epsilon_{\mu} = 550 \text{ MeV}$, $\theta_{\mu} = 15^\circ$, $\phi_p = 0^\circ$



Semi-inclusive two-nucleon knock-out

Exclusive two-nucleon knock-out

^{12}C , $\epsilon_{\nu\mu} = 750 \text{ MeV}$, $\epsilon_{\mu} = 550 \text{ MeV}$, $\theta_{\mu} = 15^\circ$



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