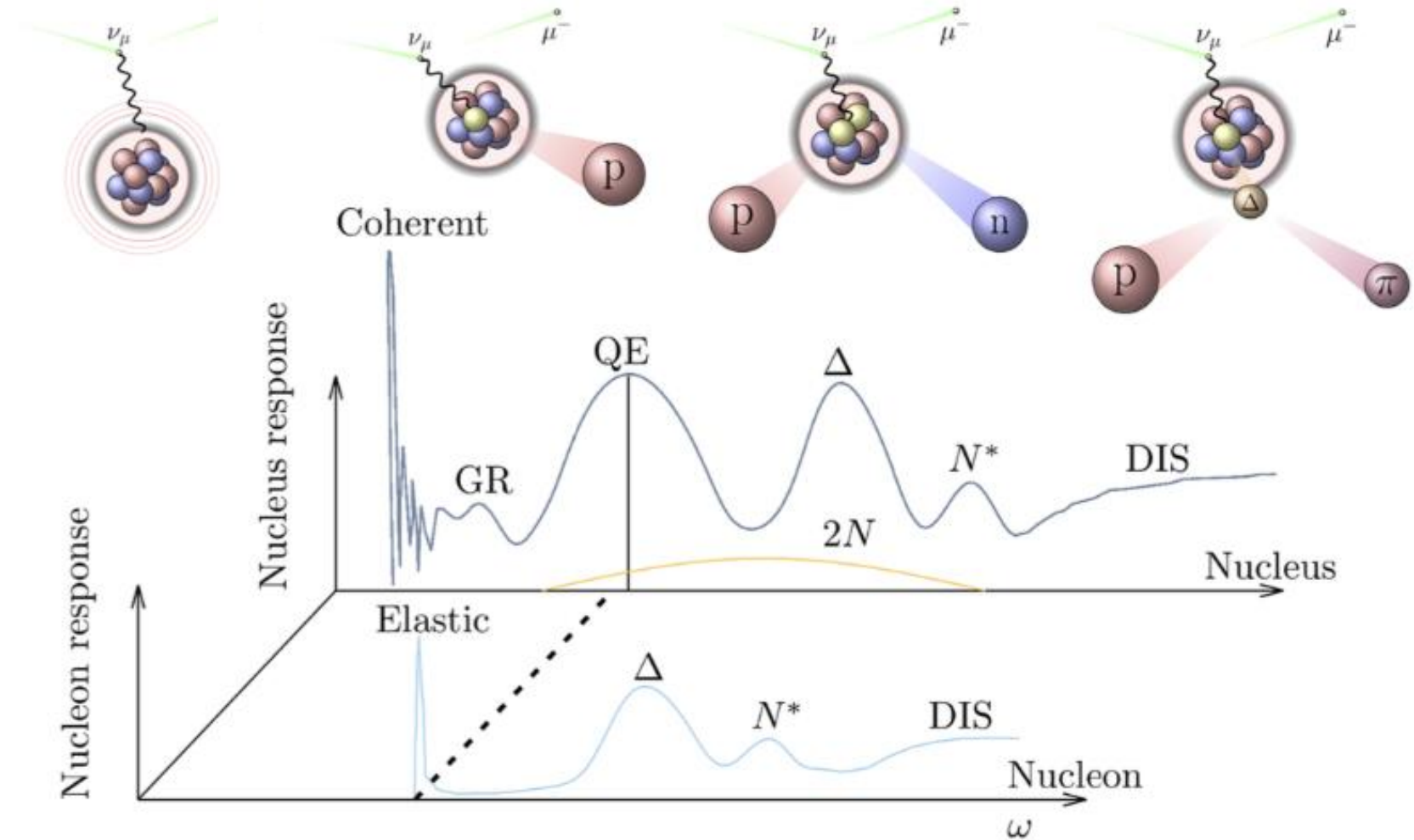
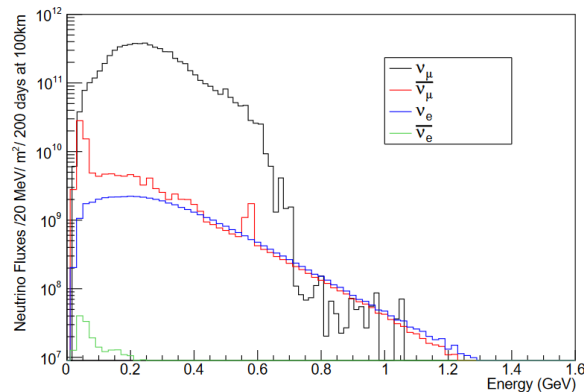
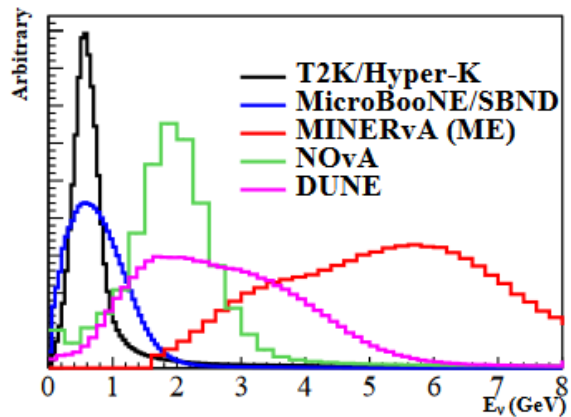


Two-nucleon effects at ESSnuSB energies

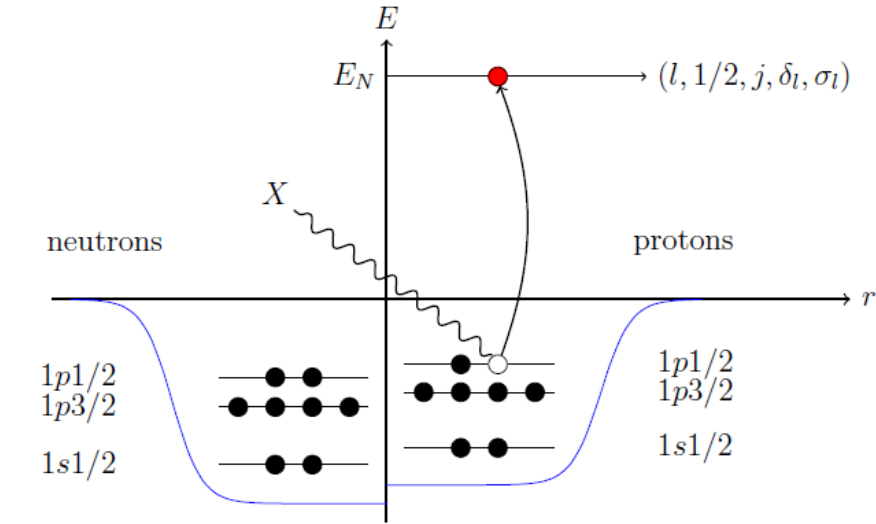
Natalie Jachowicz, Ashish Kumar Jha, Dries Kallaert, Kajetan Niewczas, Marco Vanderpoorten

Lepton-nucleus reaction mechanisms

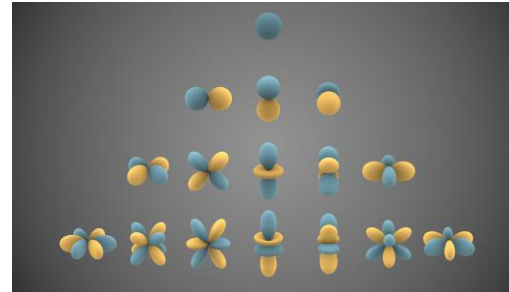
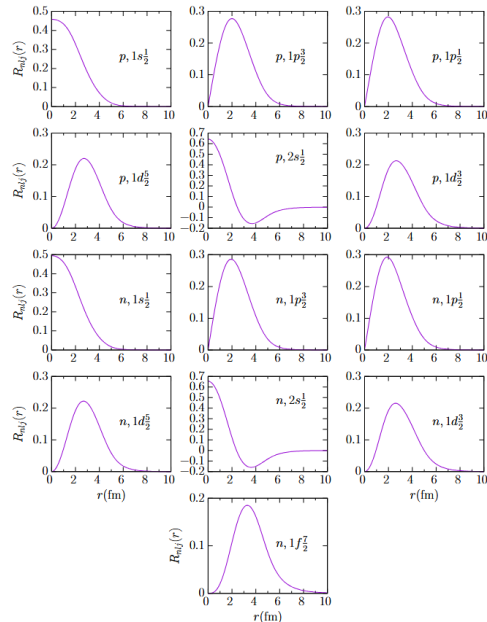


A Mean Field for the nucleus

- Starting point : mean-field nucleus with Hartree-Fock single-particle wave functions
- Binding energies for the different shells
- Pauli blocking fully implemented quantummechanically
- Distortion of the final nucleon : wave functions for initial bound and final nucleon calculated in the same potential
- Skyrme SkE2 force used to build the potential : effective interaction optimized to reproduce low-energy properties of closed-shell nuclei



3s	2d _{3/2}	4
2d	3s _{1/2}	2
	1g _{7/2}	8
1g	2d _{5/2}	6
	1g _{9/2}	10
	2p _{1/2}	2
2p	1f _{5/2}	6
1f	2p _{3/2}	4
	1f _{7/2}	8
		28
2s	1d _{3/2}	4
1d	2s _{1/2}	2
	1d _{5/2}	6
		20
1p	1p _{1/2}	2
	1p _{3/2}	4
		8
1s	1s _{1/2}	2
		2

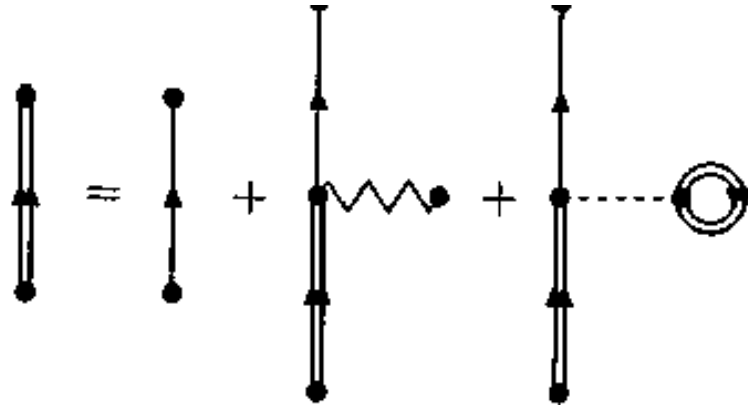


$$\begin{aligned}\hat{V}_{ij}^{(2)} = & t_0(1 + x_0 P_\sigma) \delta^{(3)}(\mathbf{r}_i - \mathbf{r}_j) \\ & + \frac{1}{2} t_1 \left(\delta^{(3)}(\mathbf{r}_i - \mathbf{r}_j) k_{ij}^2 + k_{ij}'^2 \delta^{(3)}(\mathbf{r}_i - \mathbf{r}_j) \right) \\ & + t_2 \mathbf{k}_{ij}' \cdot \delta^{(3)}(\mathbf{r}_i - \mathbf{r}_j) \mathbf{k}_{ij} \\ & + i W_0 (\boldsymbol{\sigma}_i + \boldsymbol{\sigma}_j) \cdot (\mathbf{k}_{ij}' \times \delta^{(3)}(\mathbf{r}_i - \mathbf{r}_j) \mathbf{k}_{ij}) \\ & + \frac{1}{6} t_3 (1 - x_3) (1 + P_\sigma) \rho \left(\frac{\mathbf{r}_i + \mathbf{r}_j}{2} \right) \delta^{(3)}(\mathbf{r}_i - \mathbf{r}_j) \\ & + V_{ij}^{Coul}\end{aligned}$$

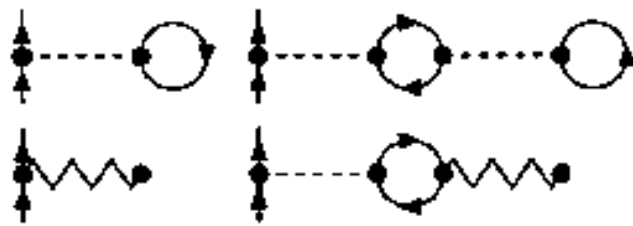
$$\begin{aligned}\hat{V}_{ijk}^{(3)} = & x_3 t_3 \delta^{(3)}(\mathbf{r}_i - \mathbf{r}_j) \delta^{(3)}(\mathbf{r}_i - \mathbf{r}_k) \\ & + \frac{1}{6} t_4 \left[(k_{ij}'^2 + k_{jk}'^2 + k_{ki}'^2) \delta^{(3)}(\mathbf{r}_i - \mathbf{r}_j) \delta^{(3)}(\mathbf{r}_i - \mathbf{r}_k) \cdot \right. \\ & \left. + \delta^{(3)}(\mathbf{r}_i - \mathbf{r}_j) \delta^{(3)}(\mathbf{r}_i - \mathbf{r}_k) (k_{ij}^2 + k_{jk}^2 + k_{ki}^2) \right]\end{aligned}$$

Hartree-Fock Mean Field

$$G^{HF}(\alpha, \beta; E) = G^{(0)}(\alpha, \beta; E) + \sum_{\gamma, \delta} G^{(0)}(\alpha, \gamma; E) \Sigma^{HF}(\gamma, \delta) G^{HF}(\delta, \beta; E)$$



$$\Sigma^{HF}(\gamma, \delta; E) = -\langle \gamma | U | \delta \rangle - i \int \frac{dE'}{2\pi} \sum_{\mu\nu} \langle \gamma\mu | V | \delta\nu \rangle G^{HF}(\nu\mu; E')$$



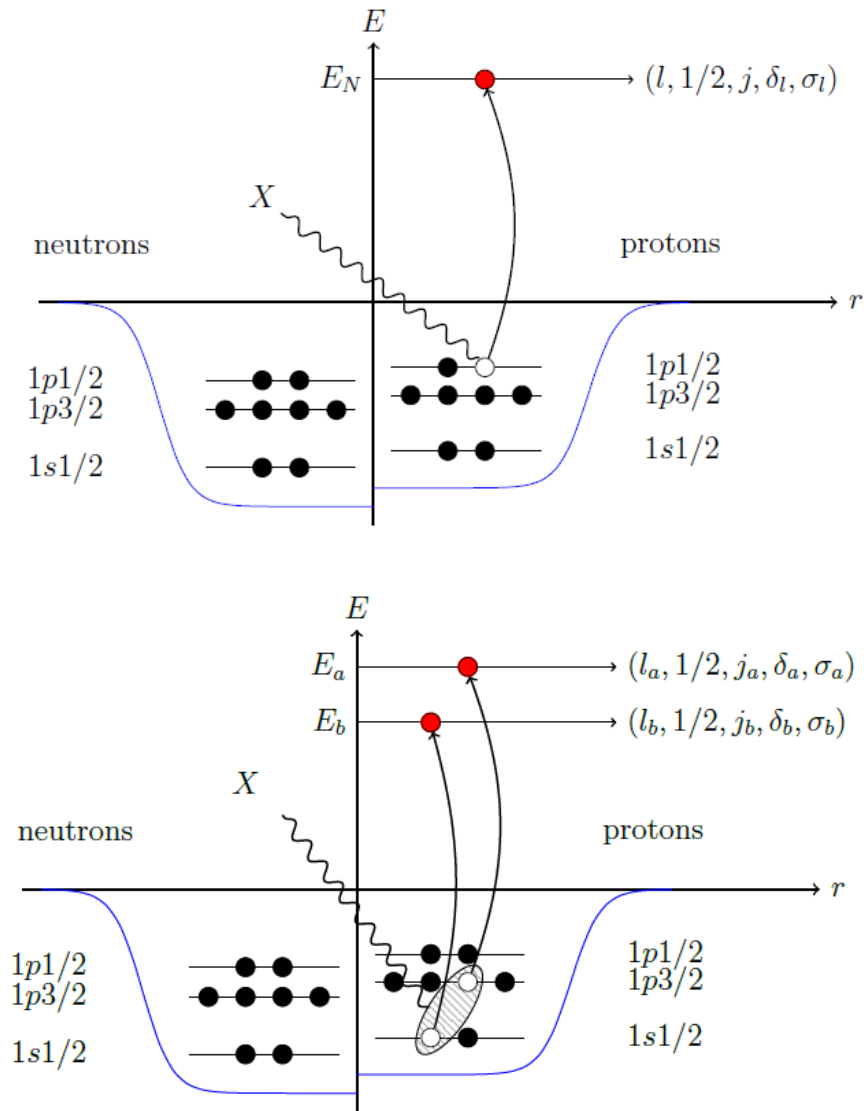
Mean field already contains a lot of correlations !

Multinucleon mechanisms

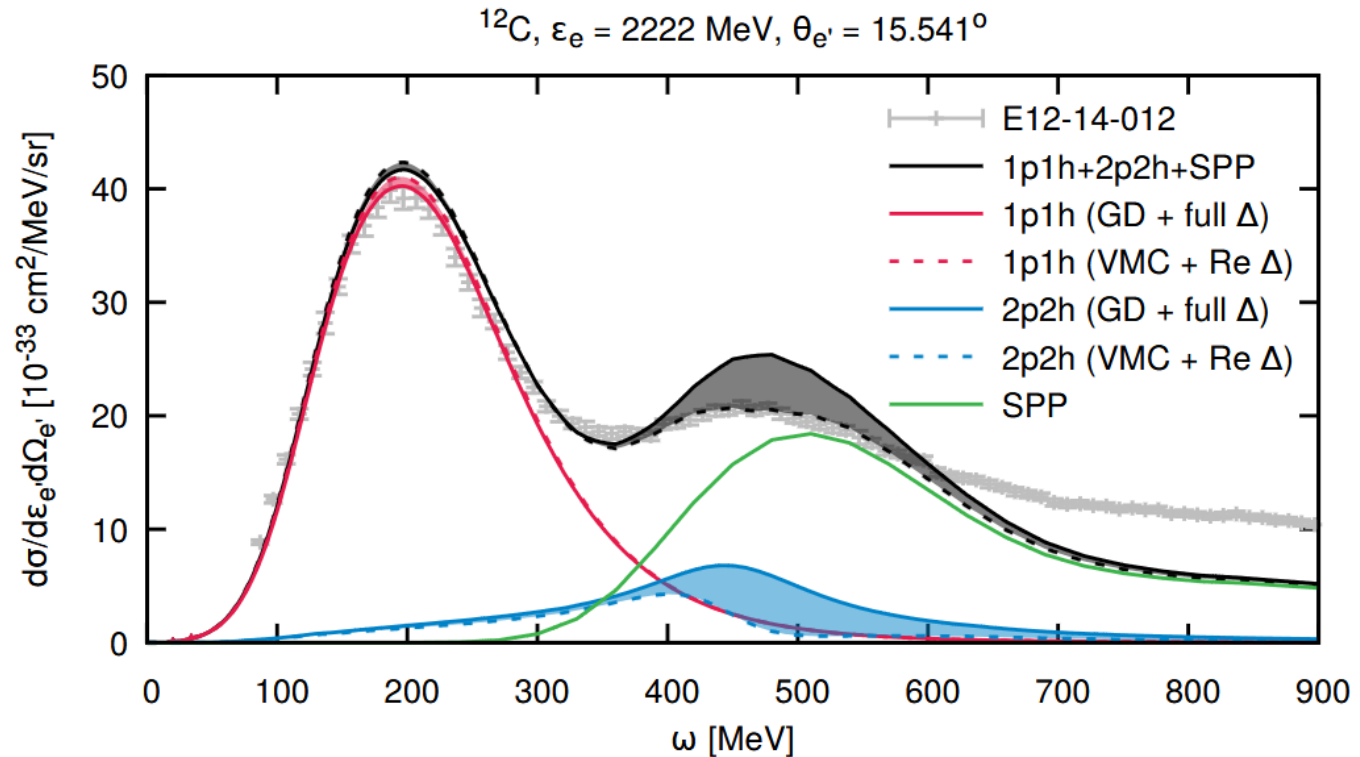
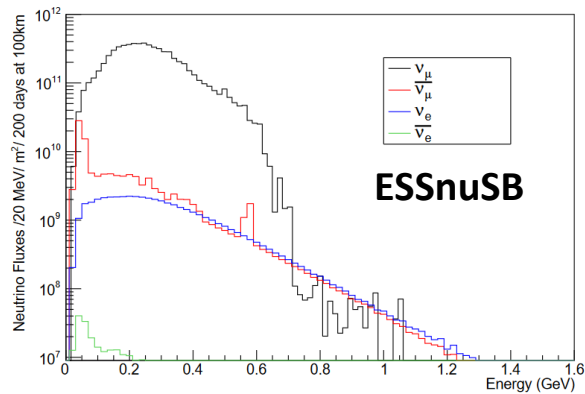
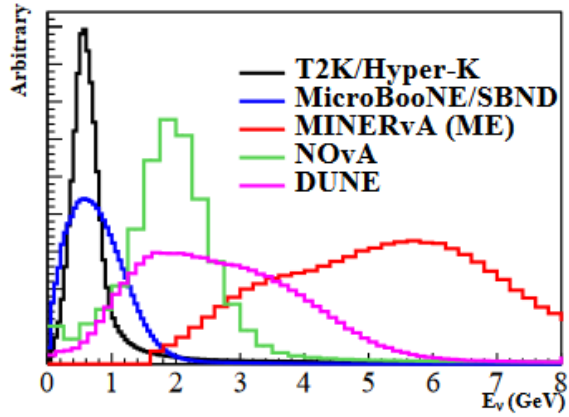
Cross section calculations

Nuclear model

- 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 correlations
- **Short-range correlations**
- **Meson-Exchange Currents**
- **2p2h effects result in 2-nucleon knockout processes and affect 1p1h cross sections**

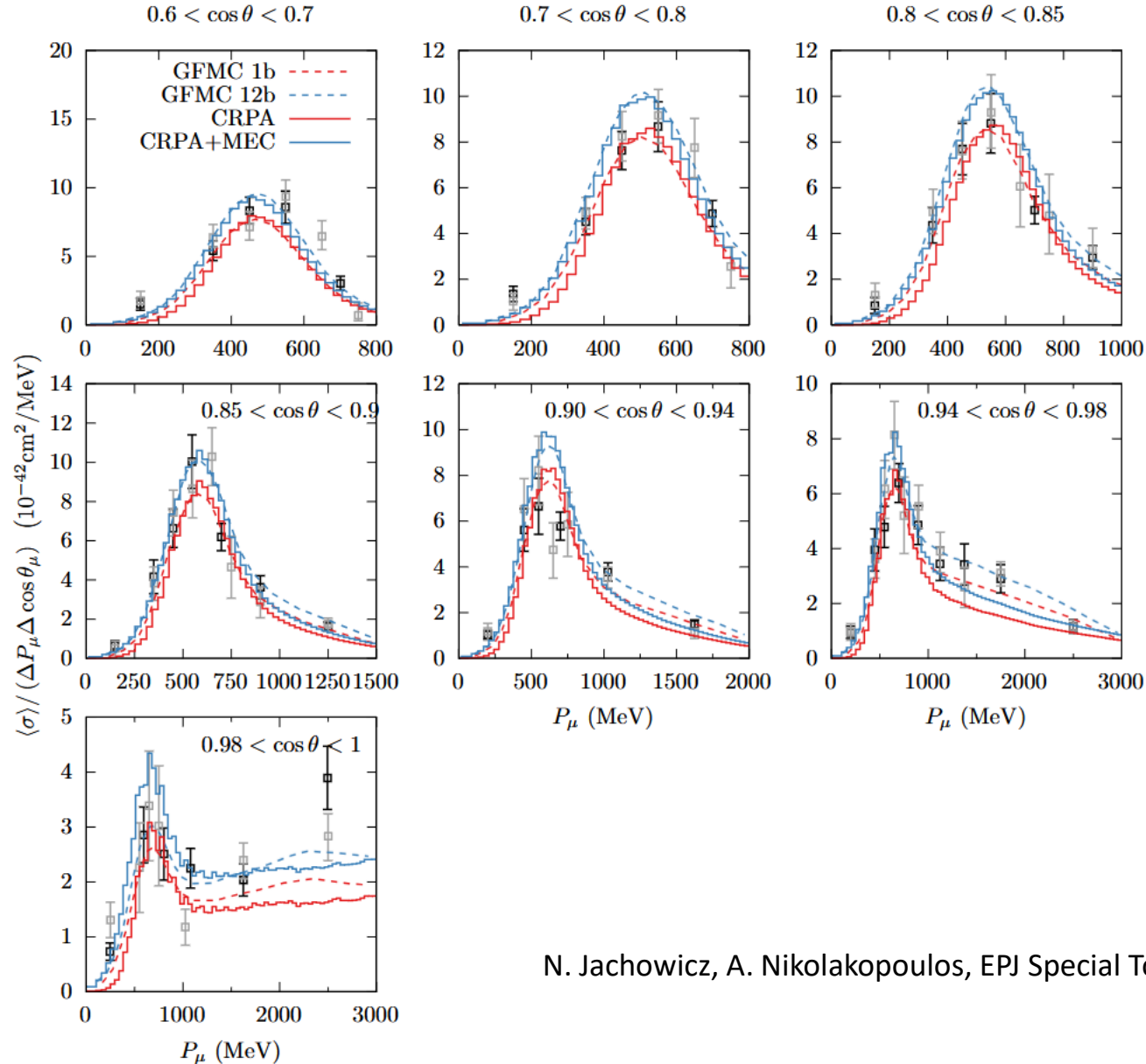


Multinucleon mechanisms : experimental evidence



- Multinucleon effects are crucial to explain experimental data, especially in the dip region
- ESSnuSB energy range allows for 2p2h knockout processes
- In the lower energy range of the ESSnuSB flux, nuclear effects will be relevant

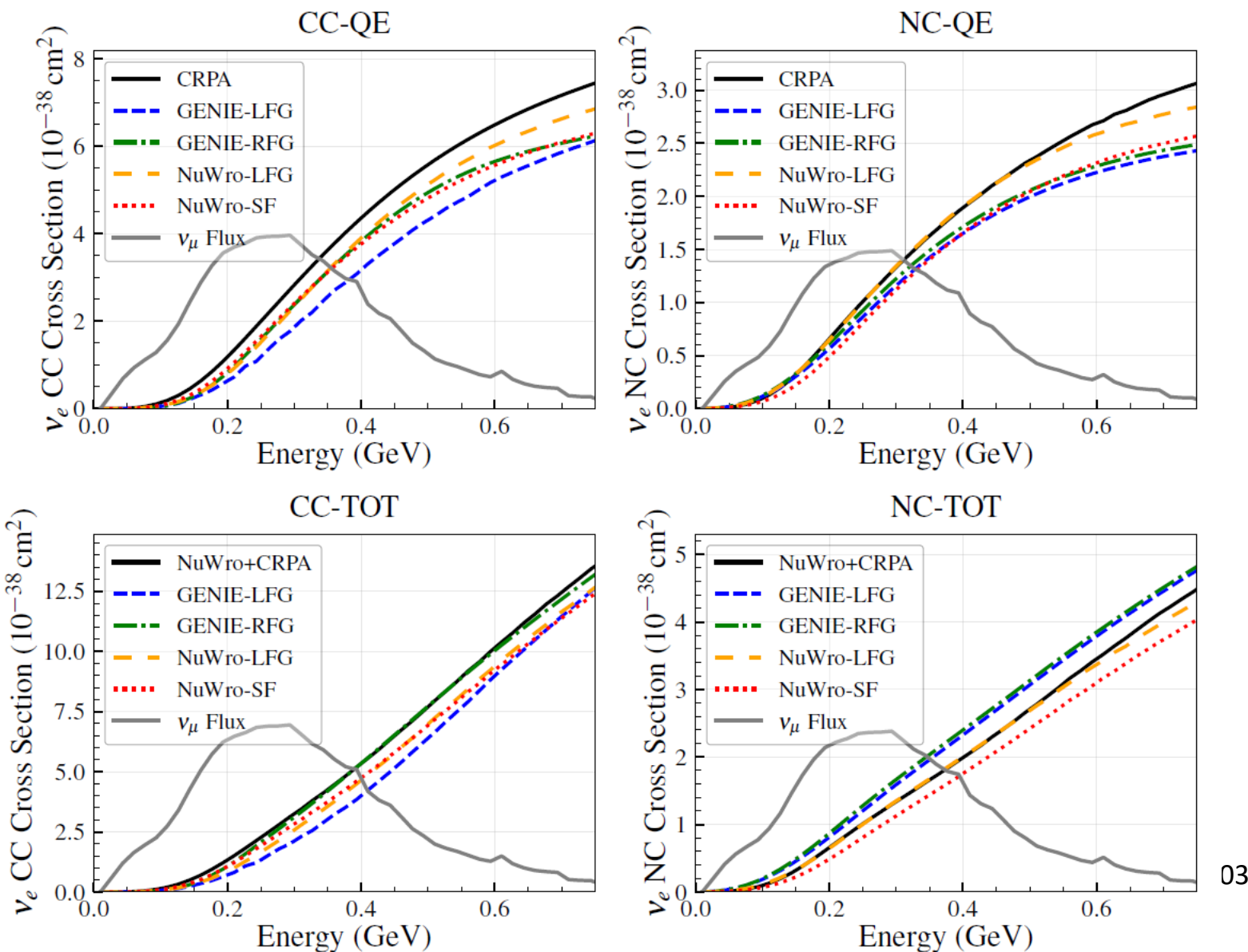
T2K flux-folded inclusive cross sections



- T2K flux-folded double differential cross sections per target neutron for ν_μ -CCQE scattering on ^{12}C
- Comparing ab-initio calculations with mean-field-based calculations
- Include long-range correlations in CRPA and added (SuSA) 2p-2h contributions

N. Jachowicz, A. Nikolakopoulos, EPJ Special Topics 230, 7803

ESSnuSB cross sections

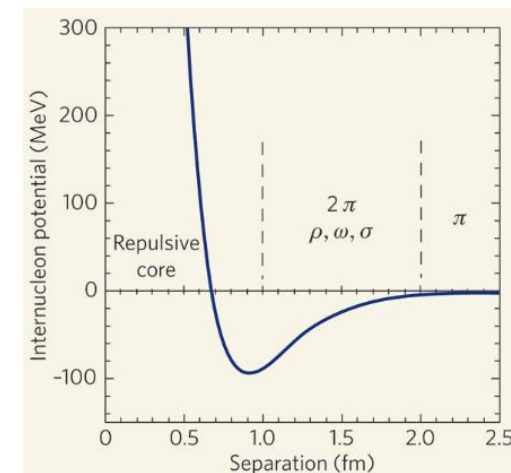
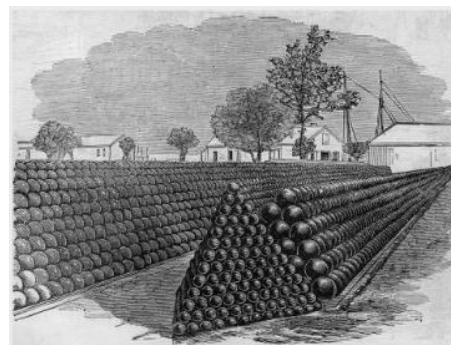


- At various incoming energies, different reaction mechanisms are active and can contribute to the 'same' final state
- It is difficult to identify the precise reaction mechanism and reconstruct the energy transfer at the primary vertex
- Still, reconstructing the incoming neutrino energy is crucial for the oscillation analysis
- Different generators provide different predictions for beyond-QE strength
- Studying processes beyond the QE mechanism is crucial for a good understanding of the signal in the detector

03

Multinucleon effects (1) : Short range correlations

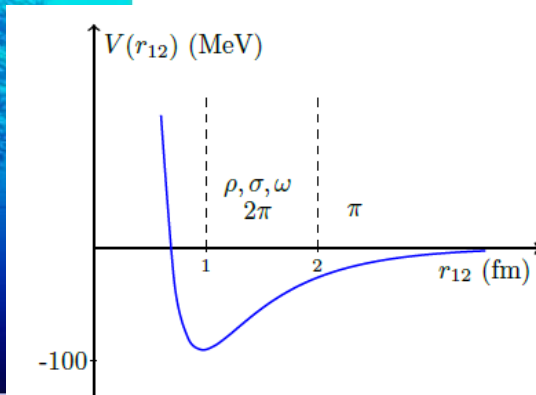
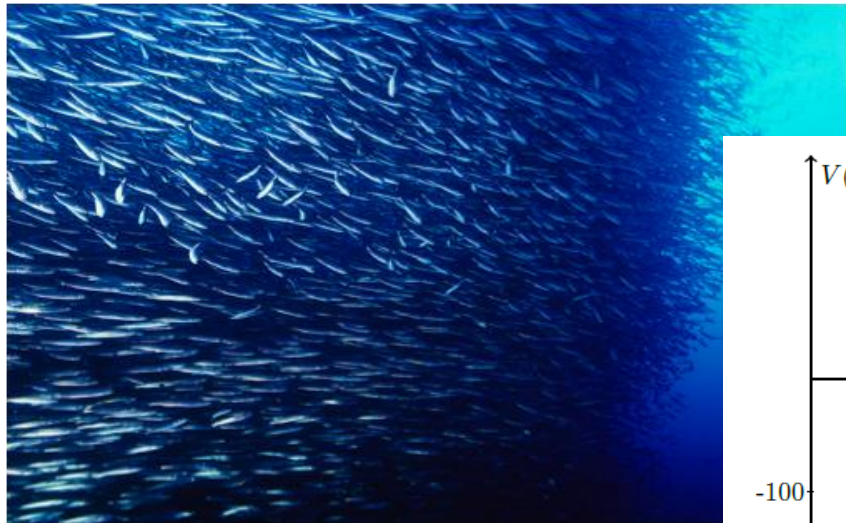
- ▶ Nuclear radius $\approx 1.2A^{\frac{1}{3}}$ fm
- ▶ Nucleon is a diffuse system
 - Hard core (repulsion) ≈ 0.5 fm
 - RMS charge radius from (e,e') = 0.897(18) fm
- ▶ $0.07 \lesssim \text{NPF} \lesssim 0.42$
 - closest packing fraction of spheres ≈ 0.74
 - packing fraction of Argon liquid ≈ 0.032
 - packing fraction of Argon gas $\approx 3.75 \cdot 10^{-5}$
- ▶ The nuclear medium is a rather **dense quantum liquid**



C. Colle, PhD, UGent 2017



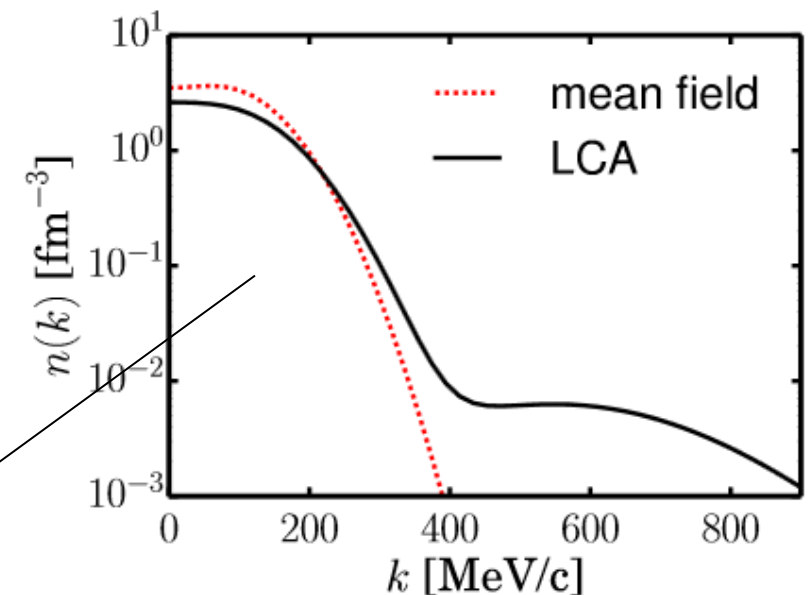
Multinucleon effects (1) : short range correlations



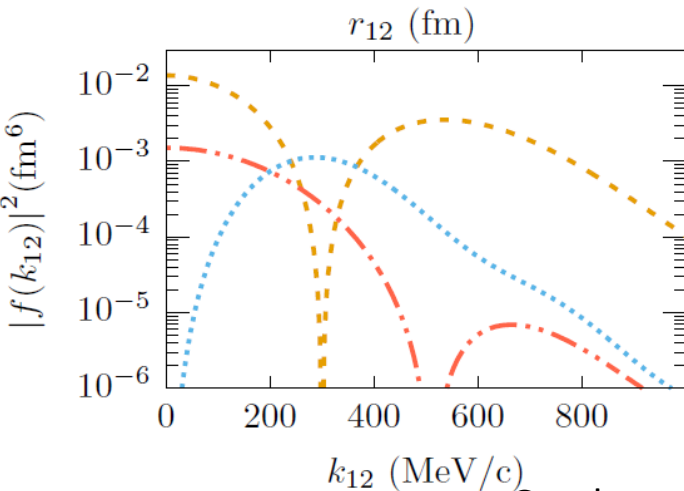
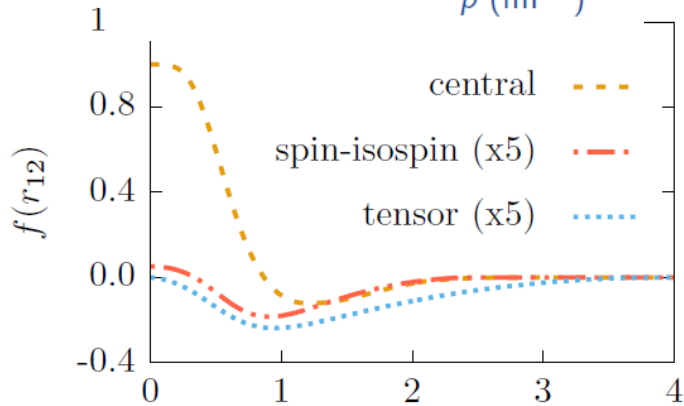
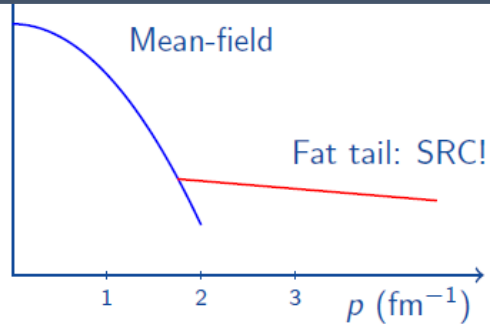
- SRC : short-range repulsive, tensor component of the nuclear force
- Individual nucleons receive large momenta compared to the Fermi momentum

IPM single-particle orbitals are depleted by SRC and higher energy levels are populated

- The short-range repulsive character of the nuclear force, which correlates with the Pauli exclusion principle, results in a large mean free path of the nucleons with respect to the size of the nucleus
- In an independent particle model nucleons move independently from each other in a mean field
- This approach fails to capture short-range features of nucleon-nucleon correlations



Quasi elastic versus multinucleon mechanisms : short range correlations



Gearheart (1994) Pieper (1992)

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

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

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

$$\langle \Psi_f | \hat{J}_\mu^{\text{nuc}} | \Psi_i \rangle = \frac{1}{\sqrt{\mathcal{N}_i \mathcal{N}_f}} \langle \Phi_f | \hat{J}_\mu^{\text{eff}} | \Phi_i \rangle$$

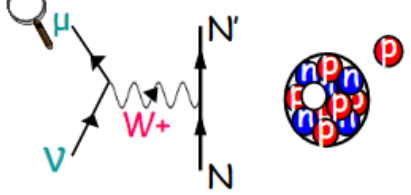
$$\hat{J}_\mu^{\text{eff}} \approx \sum_{i=1}^A \hat{J}_\mu^{[1]}(i) + \sum_{i<j}^A \hat{J}_\mu^{[1],\text{in}}(i, j) + \left[\sum_{i<j}^A \hat{J}_\mu^{[1],\text{in}}(i, j) \right]^\dagger$$

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

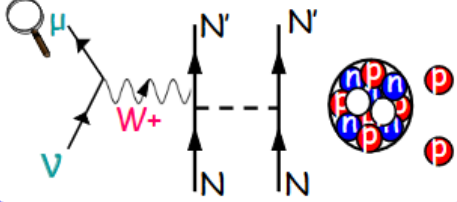
Multinucleon effects (2) : MECs

Meson-exchange currents

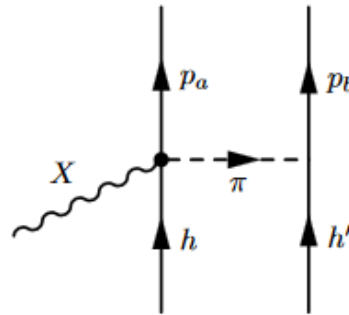
Genuine CCQE (1p-1h)



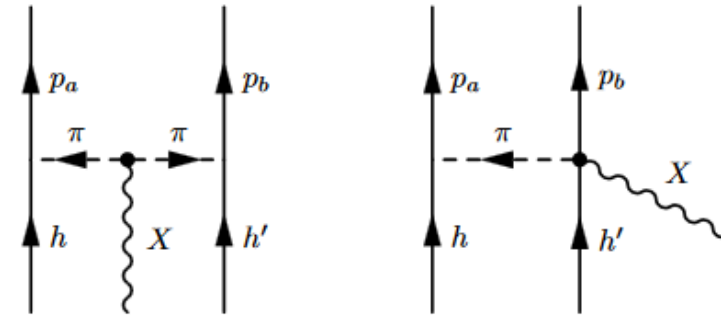
Two particles-two holes (2p-2h)



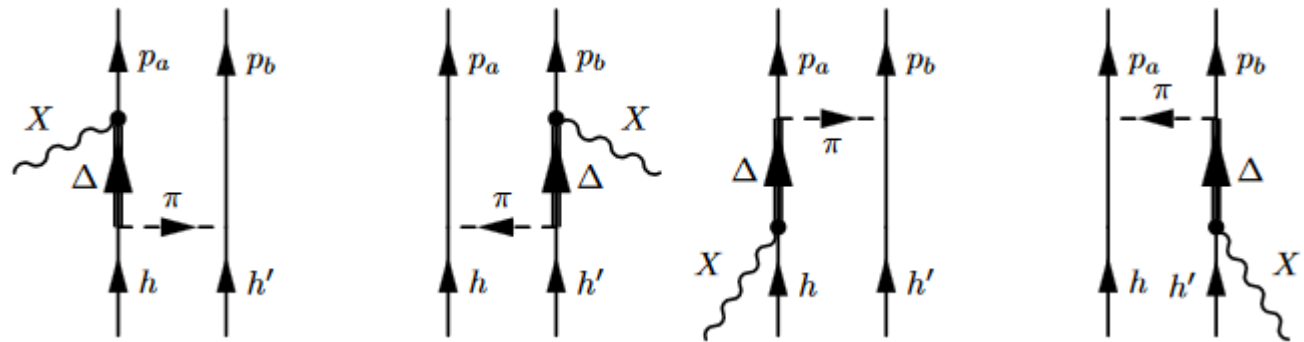
Seagull



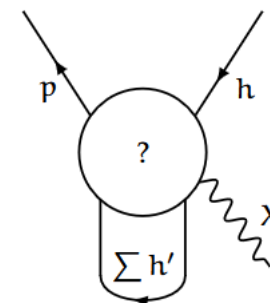
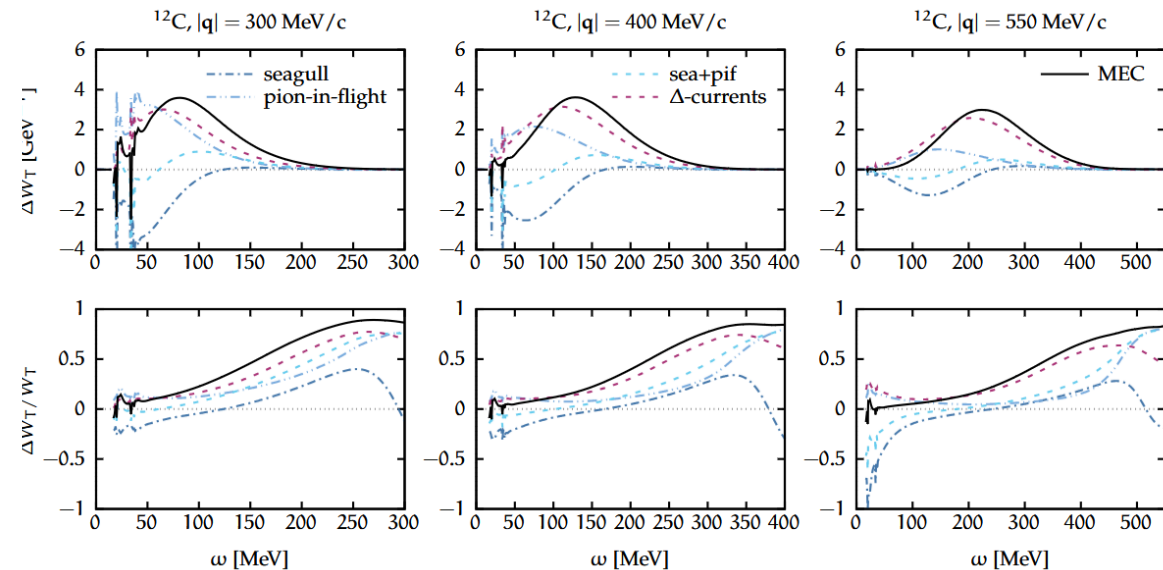
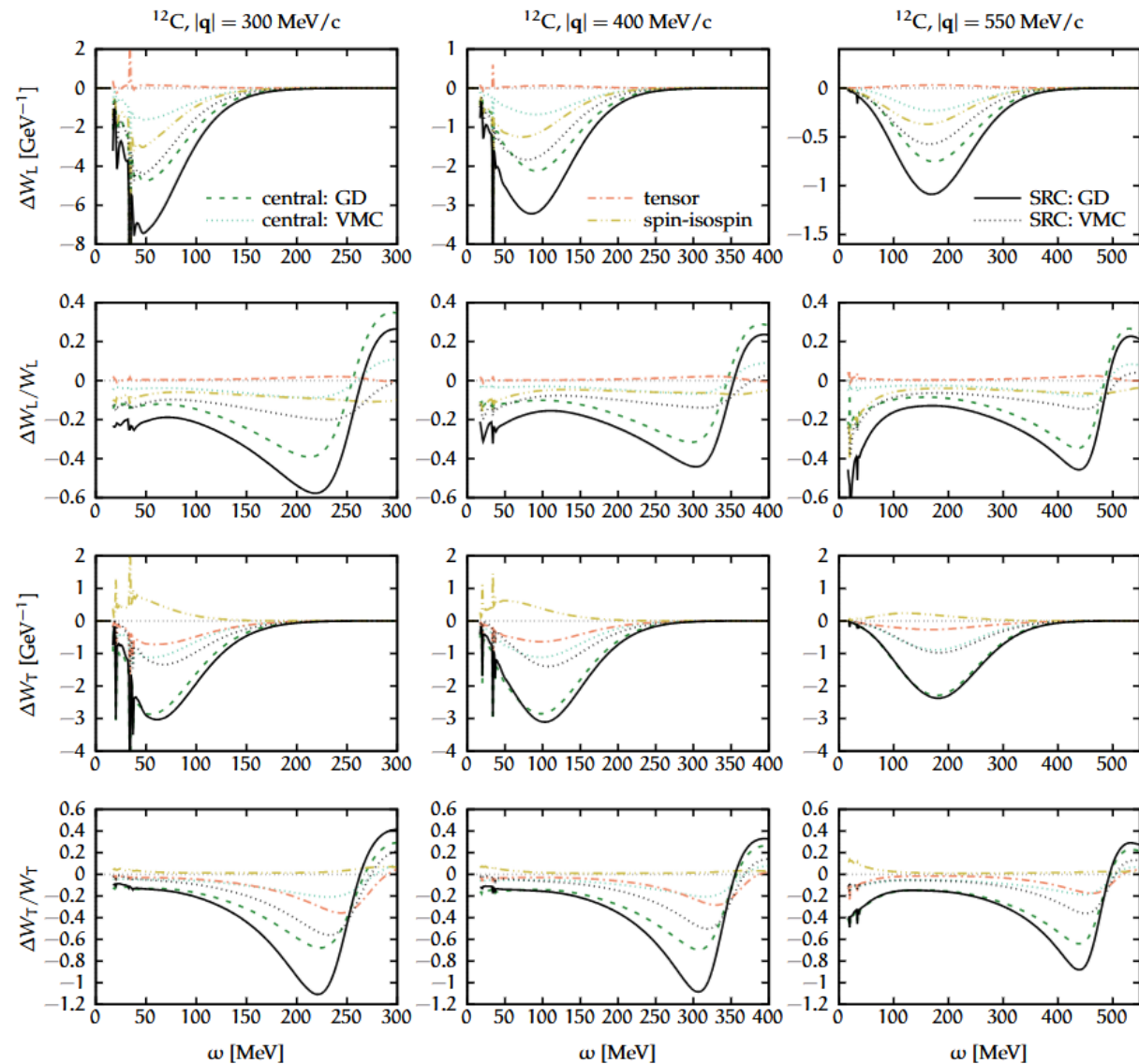
Pion in flight



Delta currents



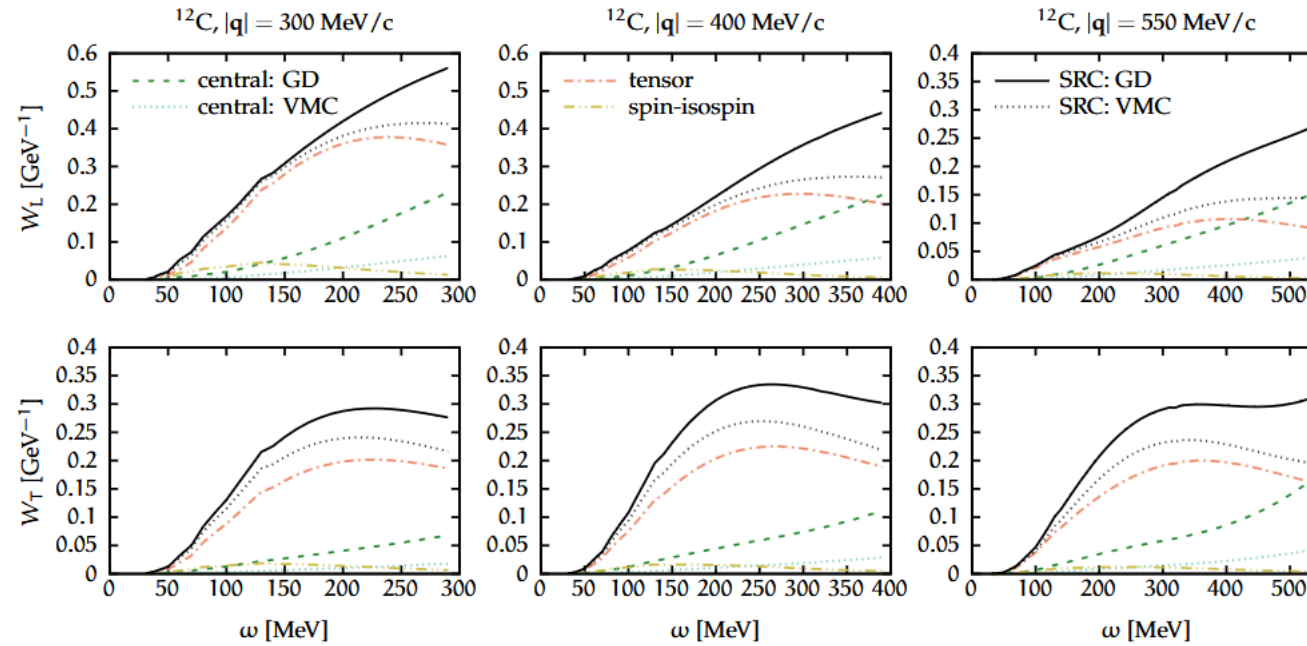
1p1h including SRC & MECs : e-scattering



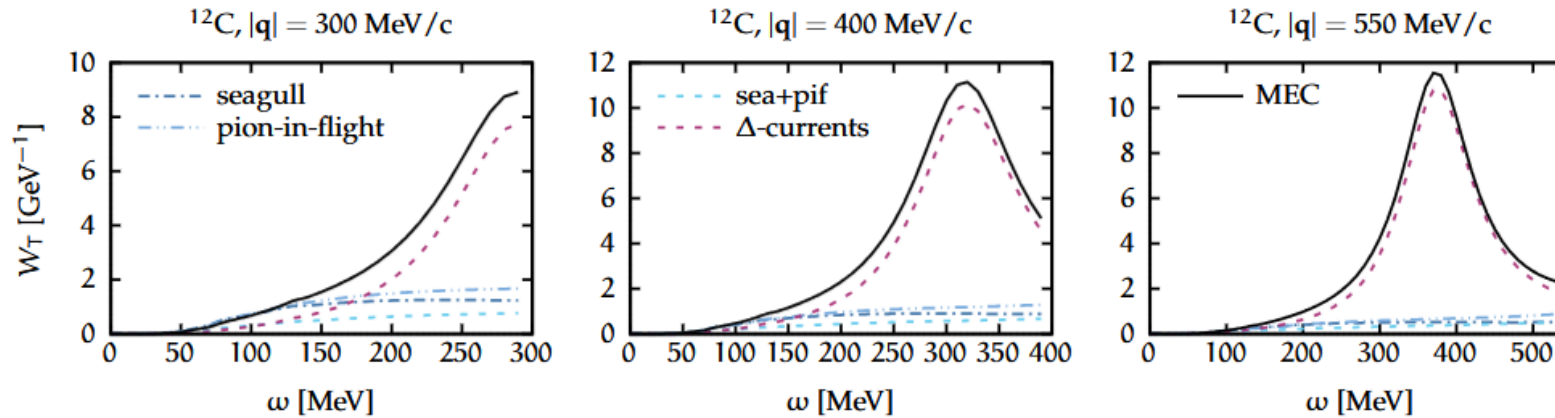
Kajetan Niewczas et al. arXiv2608.31044

2p2h e-scattering

SRC :

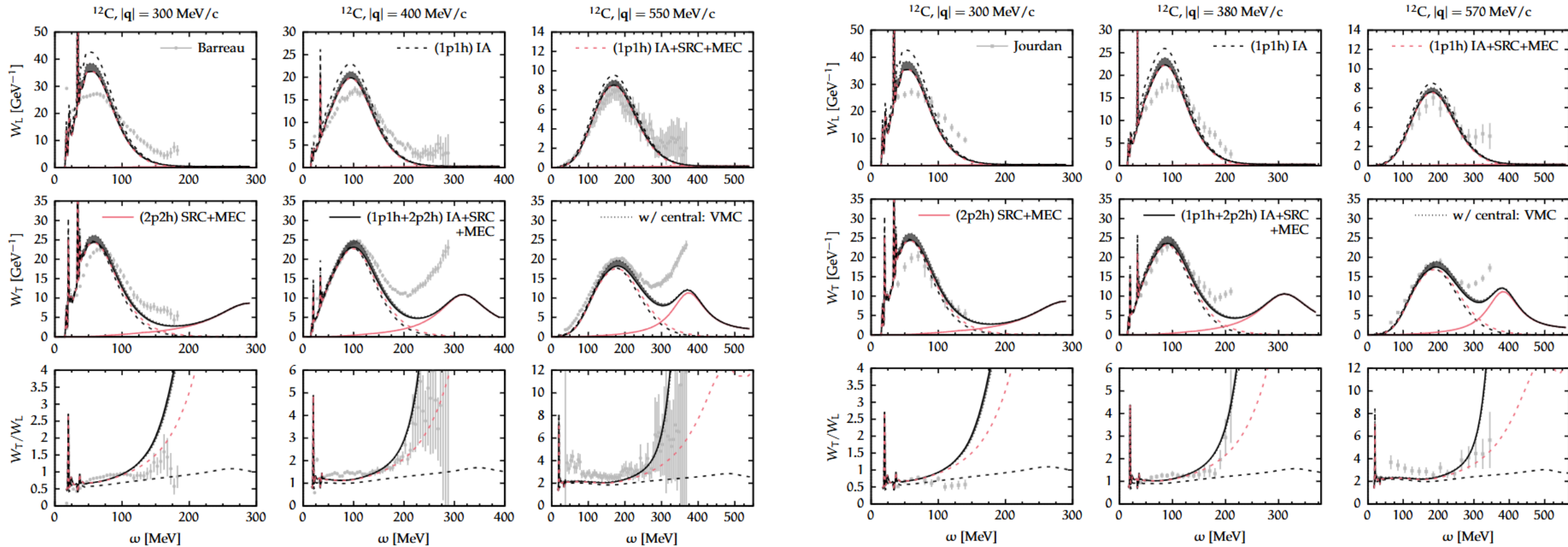


MECs :



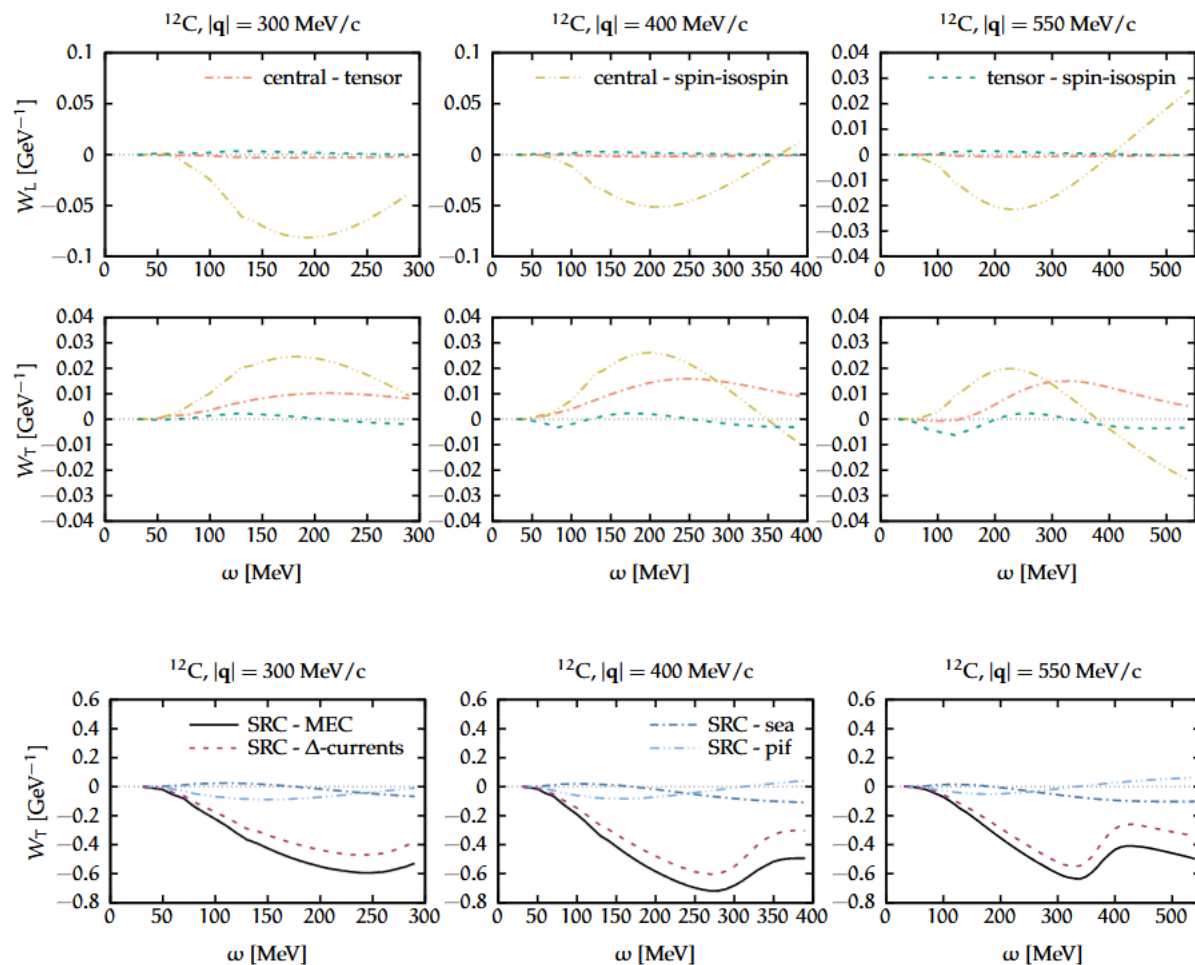
Kajetan Niewczas et al. arXiv2608.31044

1p1h+2p2h inclusive e-scattering



Kajetan Niewczas et al. arXiv2608.31044

2p2h inclusive e-scattering

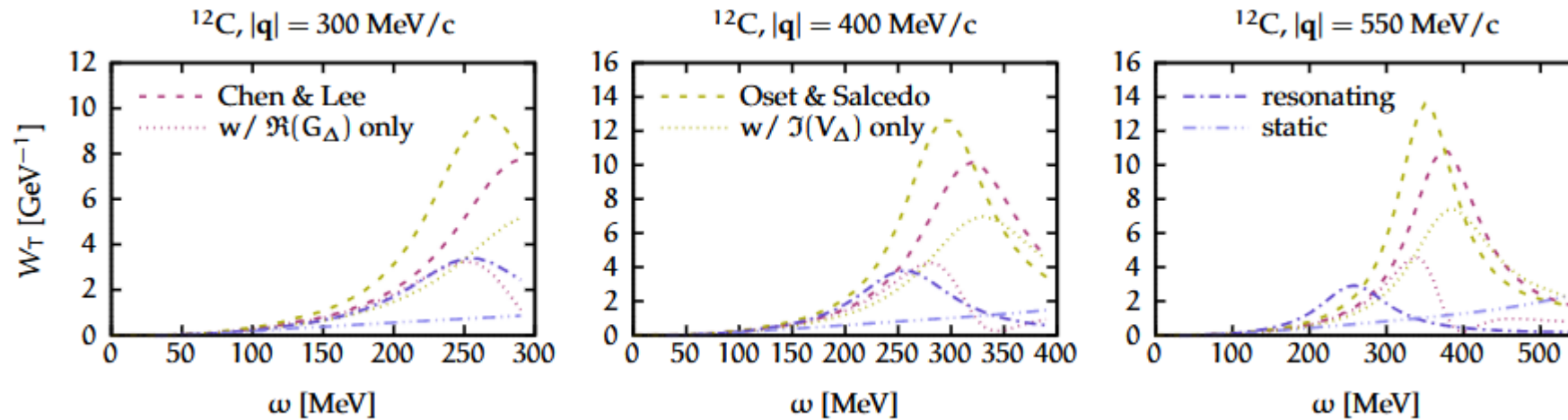


- Interference between SRCs and Δ MECs is substantial and destructive
- Need for a detailed microscopic modelling of effects



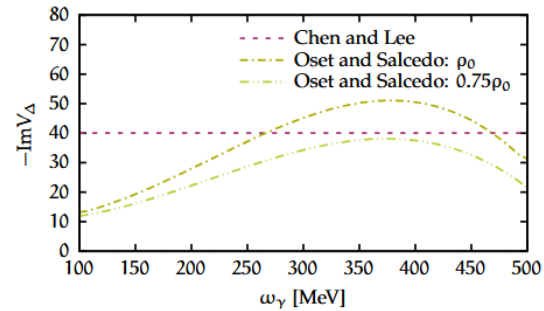
Kajetan Niewczas et al. arXiv2608.31044

2p2h inclusive e-scattering



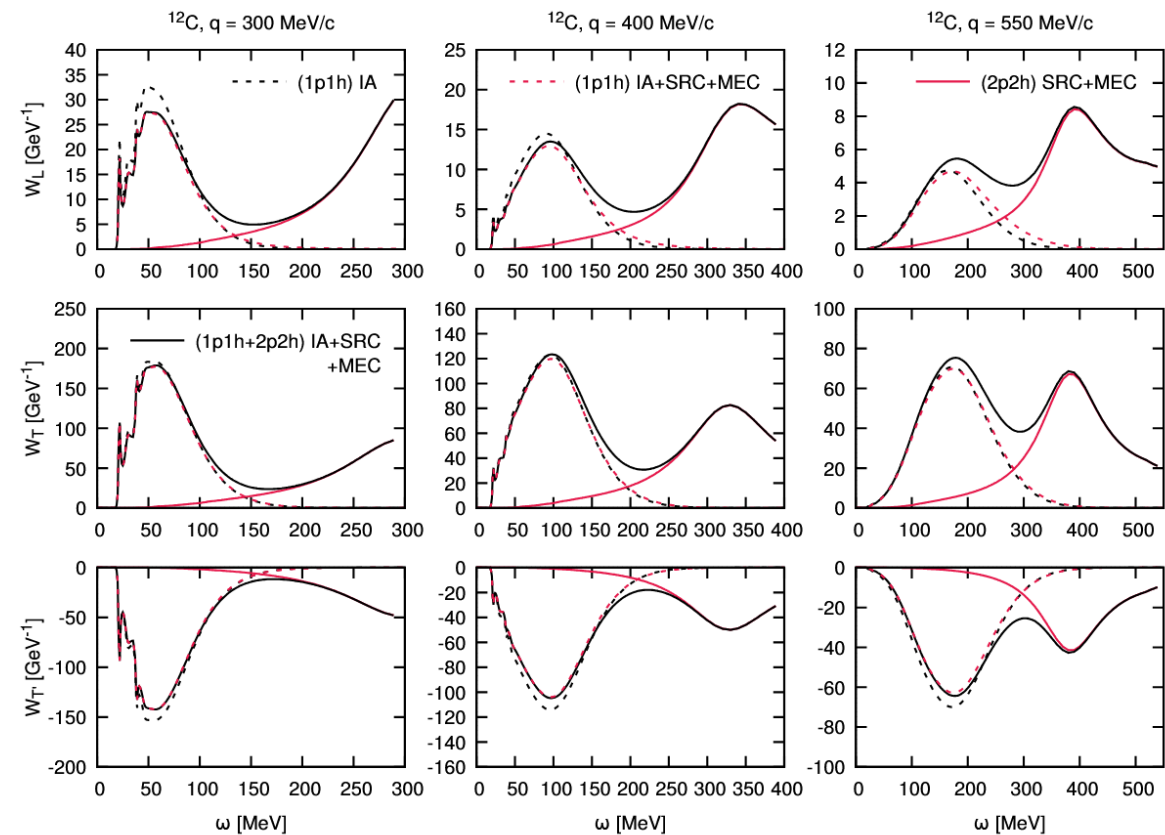
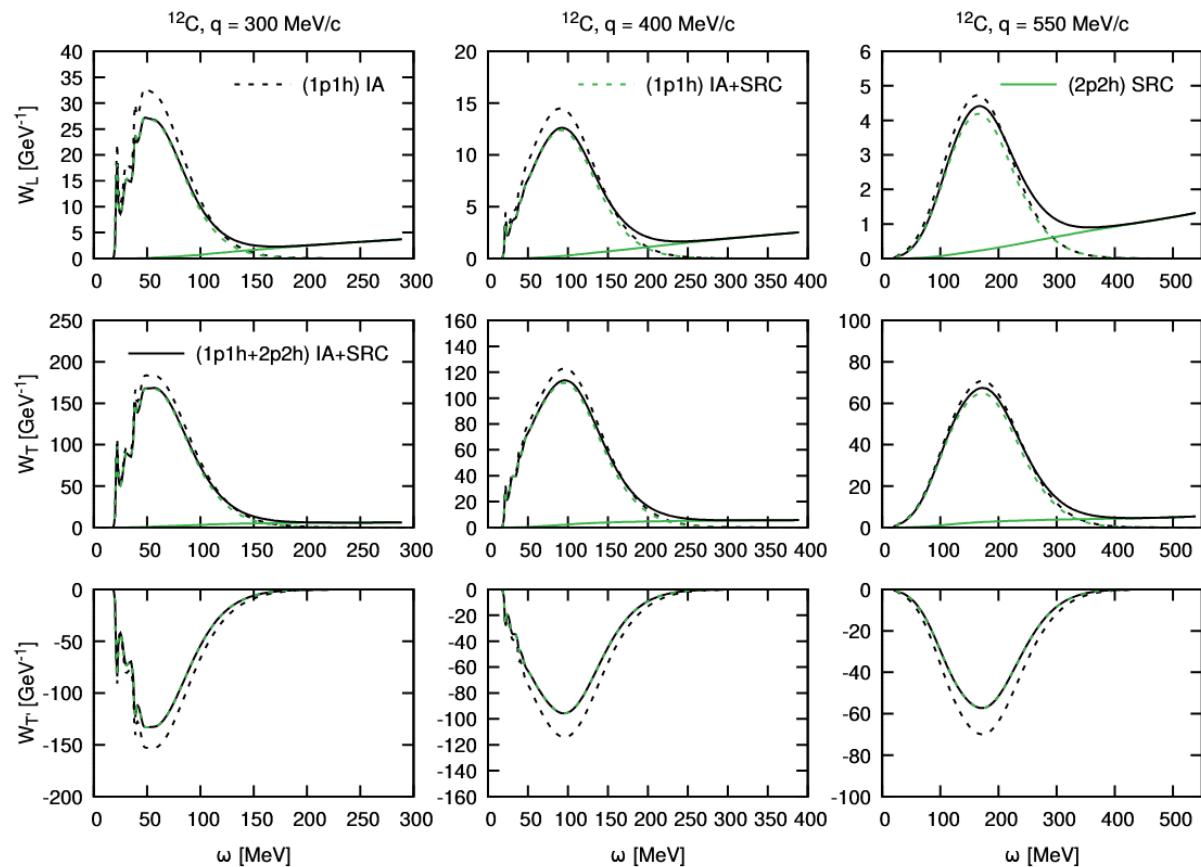
$$G_{\Delta}^{\text{res}} = \frac{1}{M_{\Delta} - \sqrt{s} - i/2\Gamma_{\Delta}^{\text{res}} + V_{\Delta}}$$

$$V_{\Delta}^{\text{Chen\&Lee}} = -30 - i40$$



Kajetan Niewczas et al. arXiv2608.31044

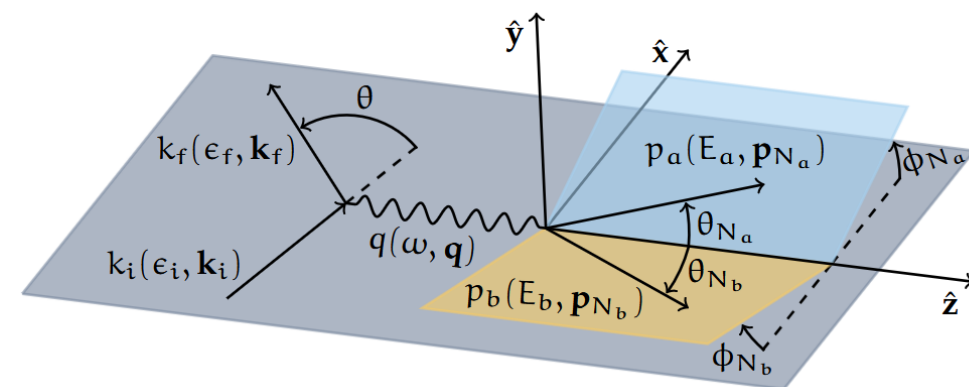
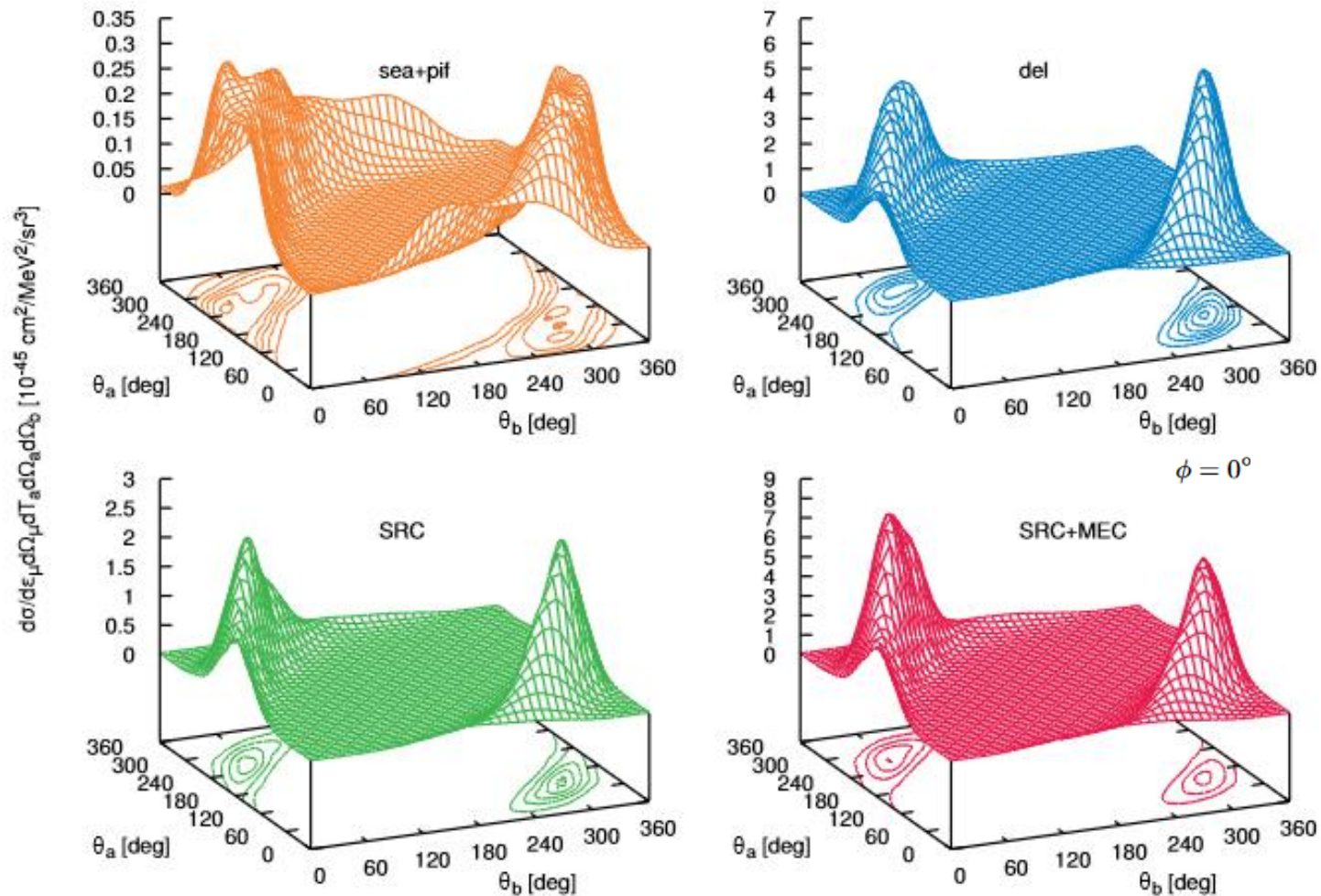
SRC & MECs : neutrinos



Kajetan Niewczas PhD Thesis 2023

2p2h cross sections : exclusive 2-nucleon knockout

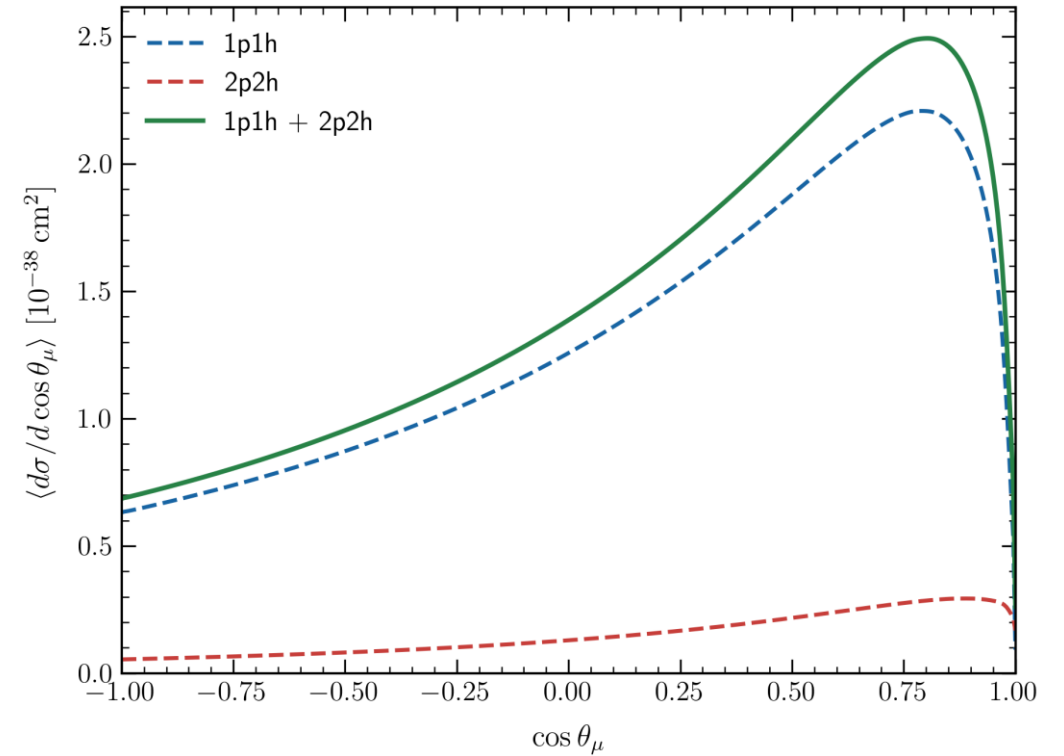
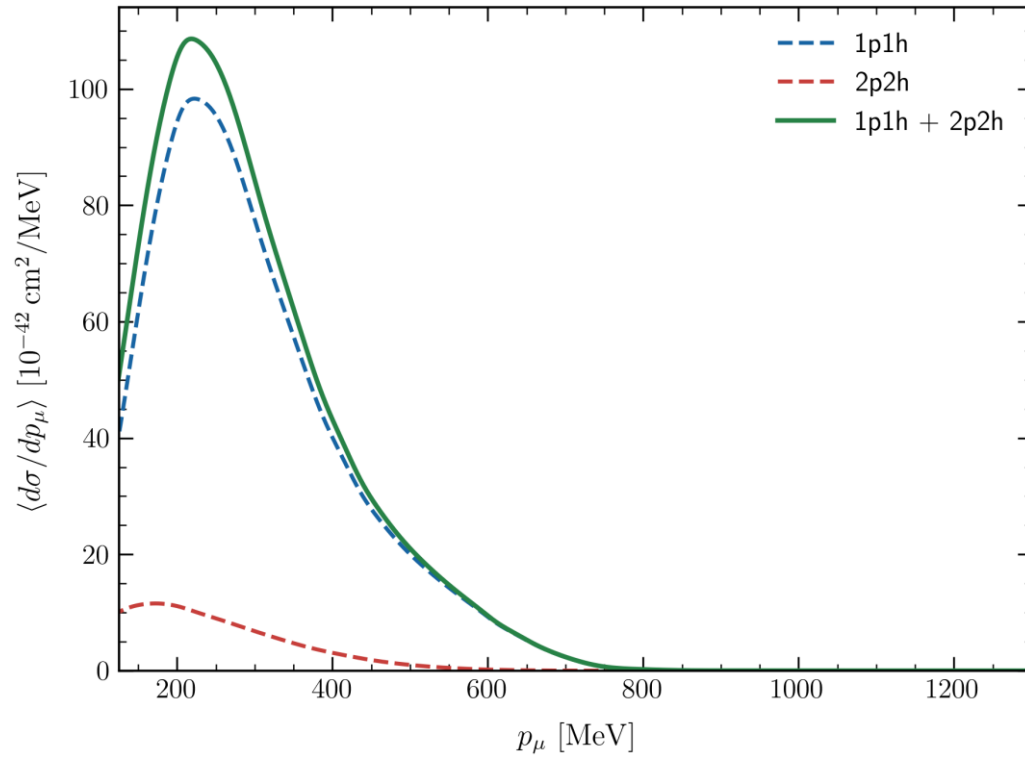
^{12}C , $\varepsilon_{\nu\mu} = 750 \text{ MeV}$, $\varepsilon_{\mu} = 550 \text{ MeV}$, $\theta_{\mu} = 15^\circ$



Kajetan Niewczas PhD Thesis 2023

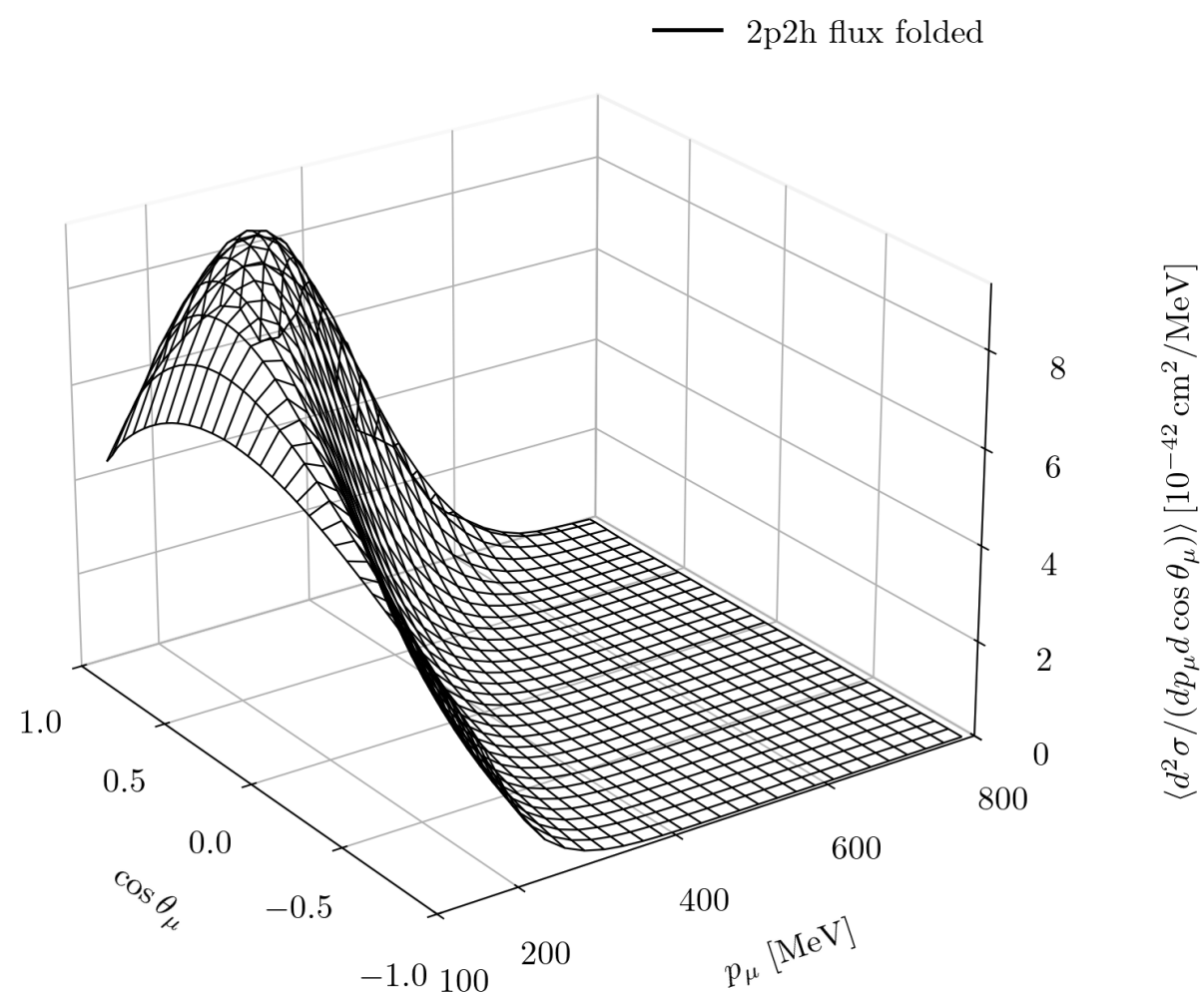
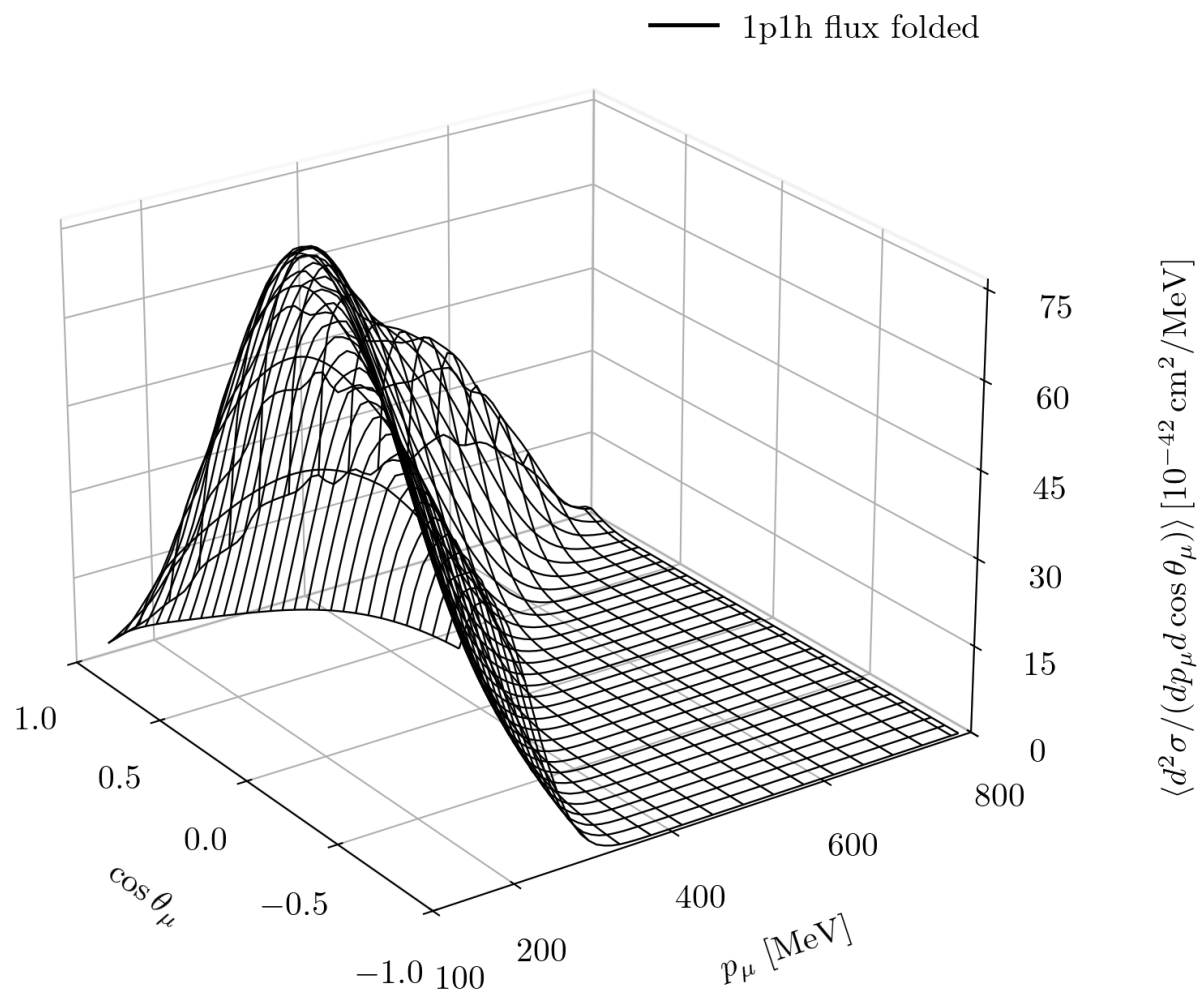
2-nucleon knockout for ESSnuSB

Flux-folded cross sections on as a function of lepton kinematics :

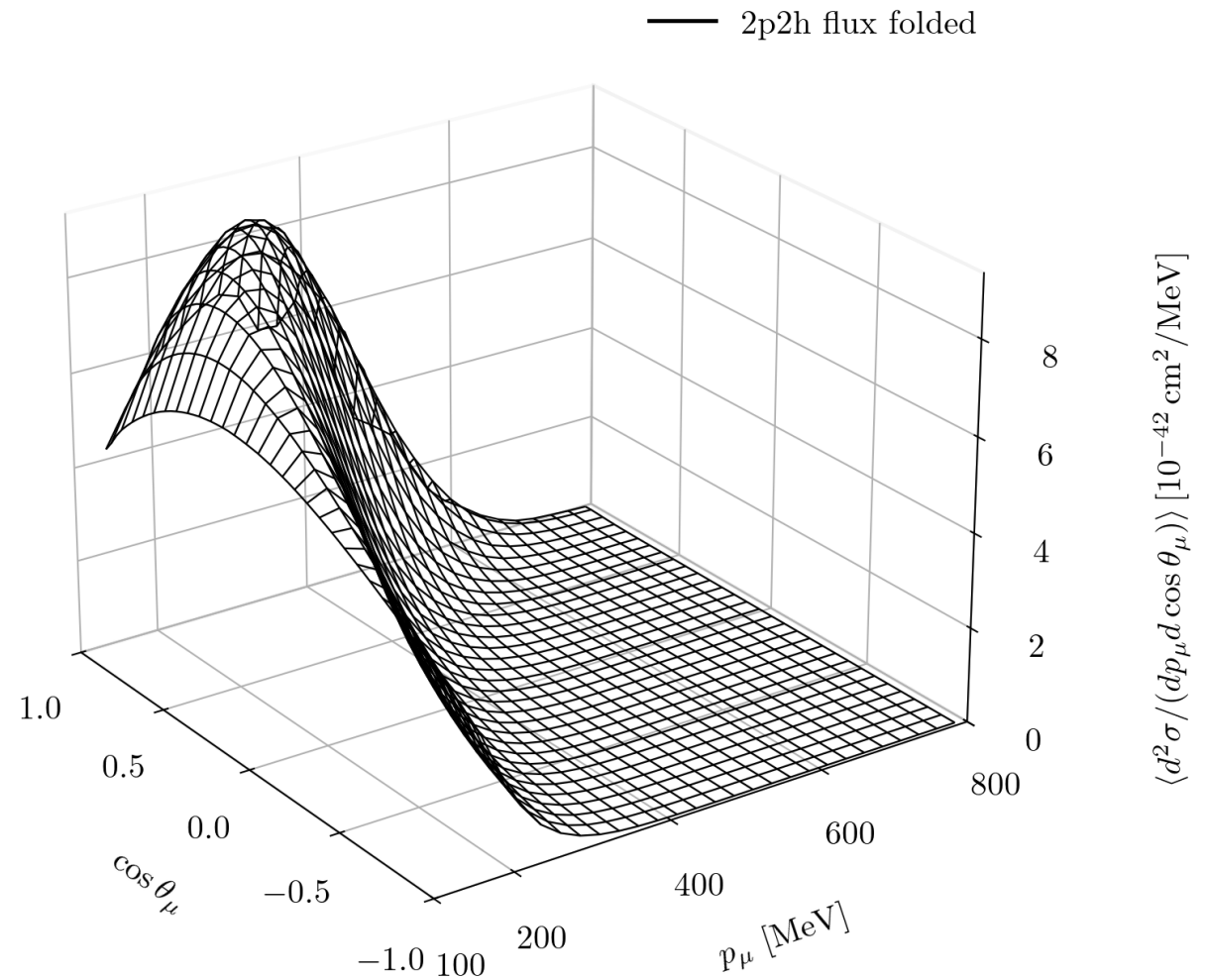
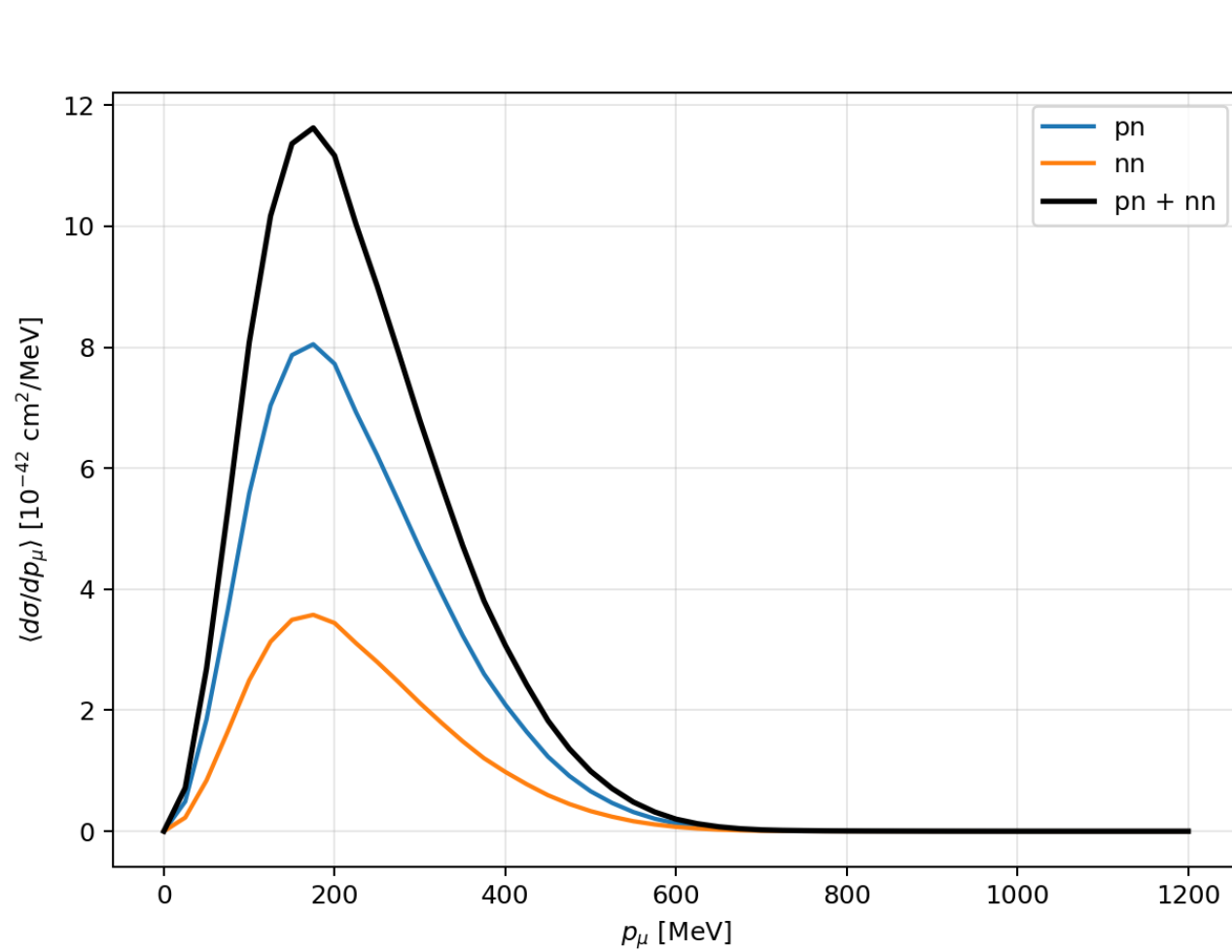


- 2-nucleon knockout constitutes a non-trivial part of the cross section
- 2-nucleon processes tend to result in leptons that are on average lower in energy and more forward than QE processes

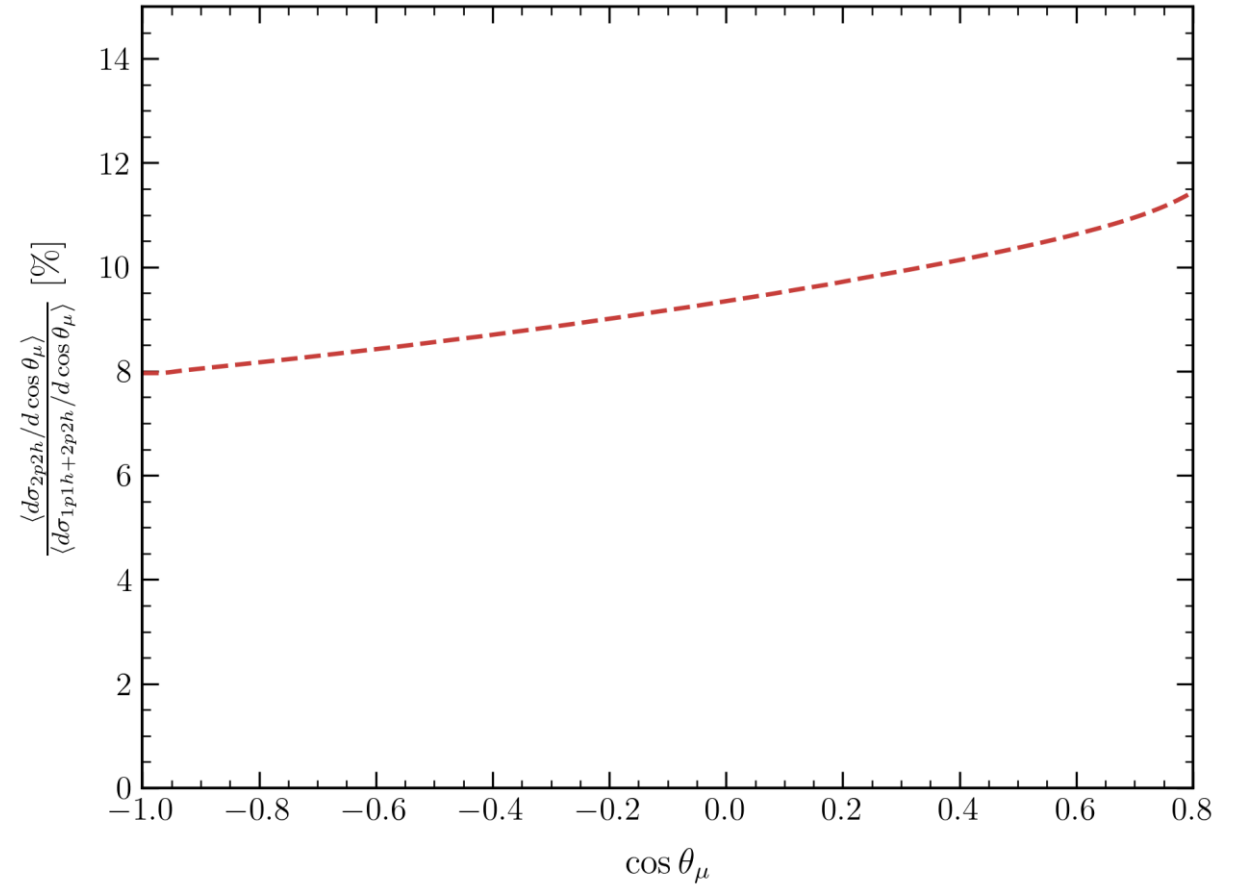
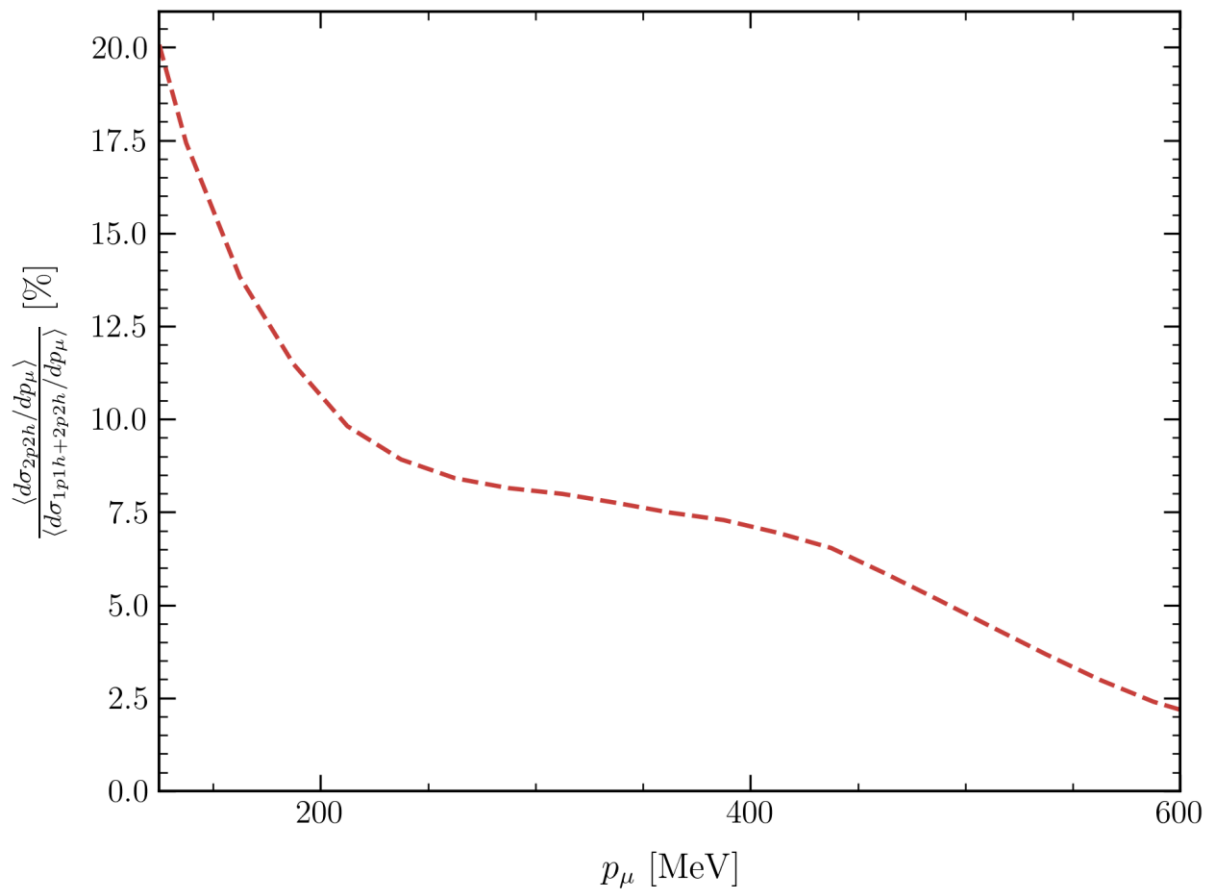
2-nucleon knockout for ESSnuSB



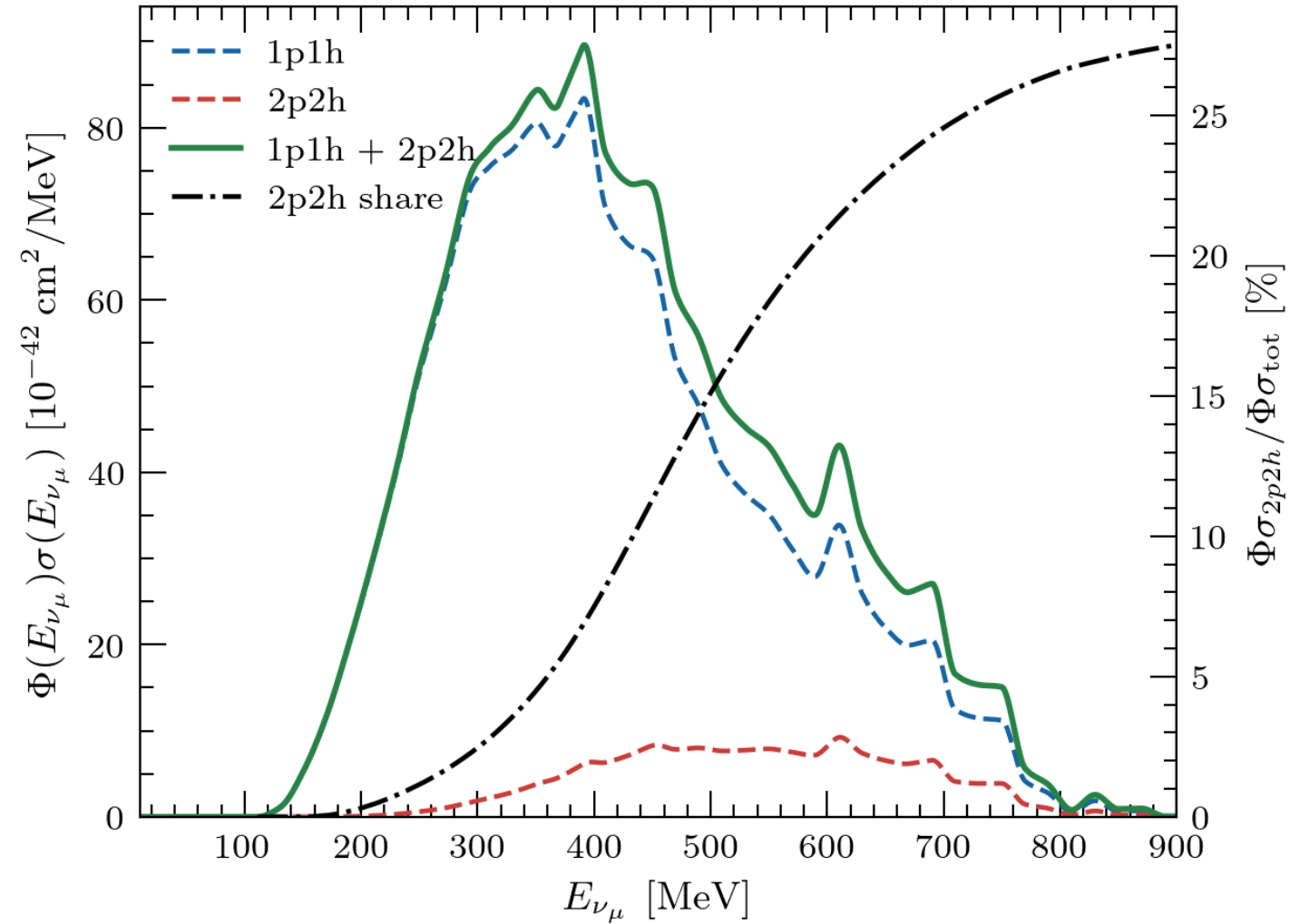
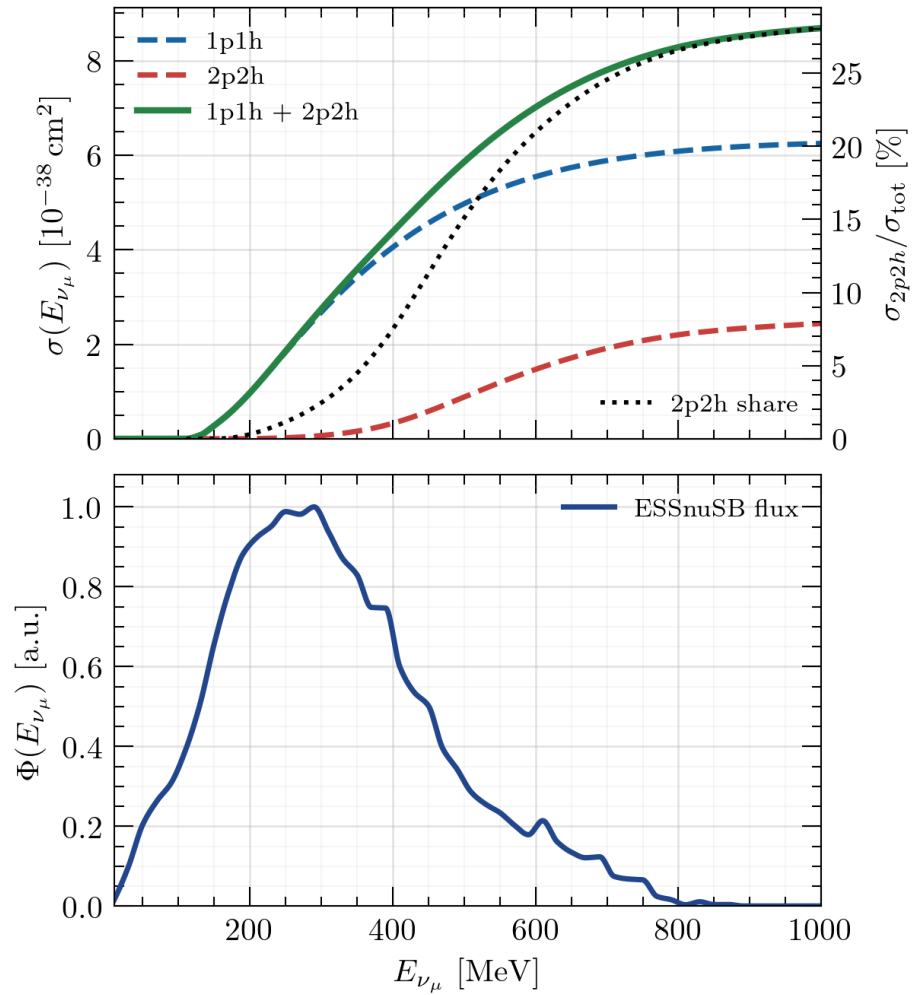
2-nucleon knockout for ESSnuSB



2-nucleon knockout for ESSnuSB

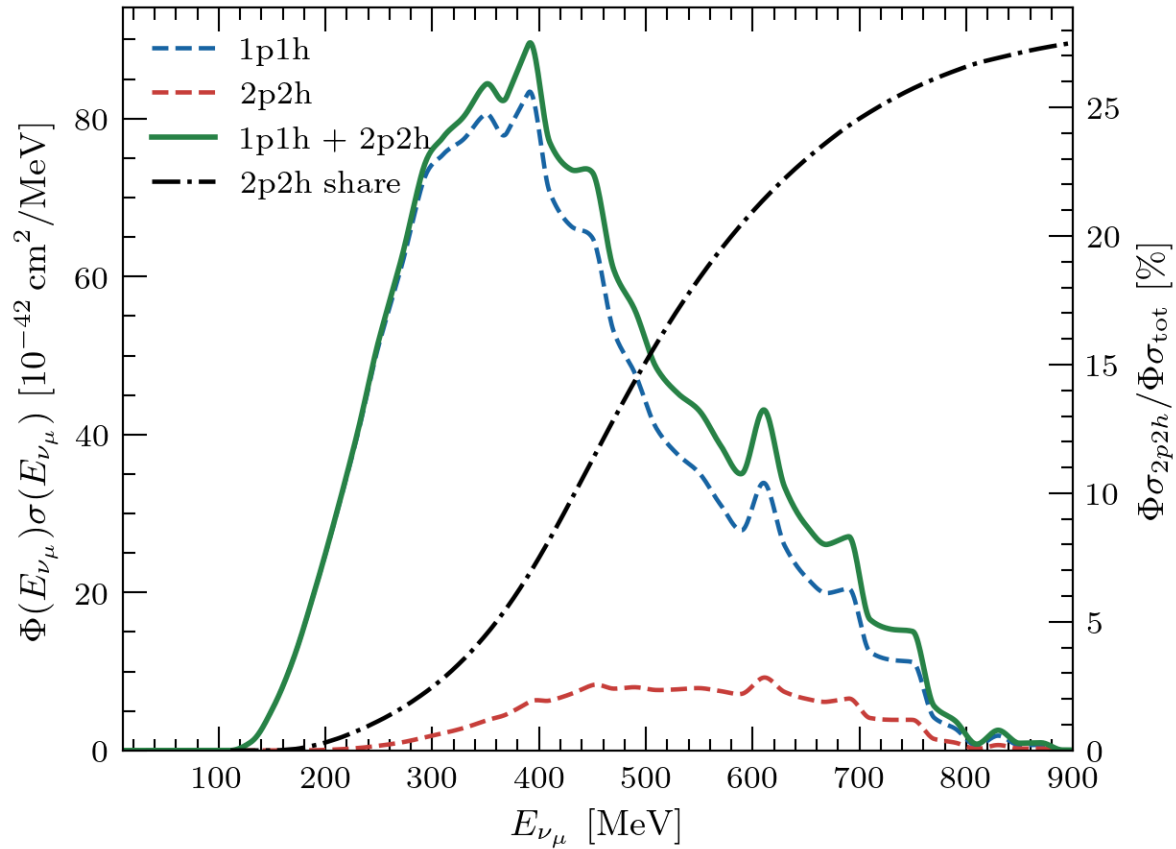


2-nucleon knockout for ESSnuSB

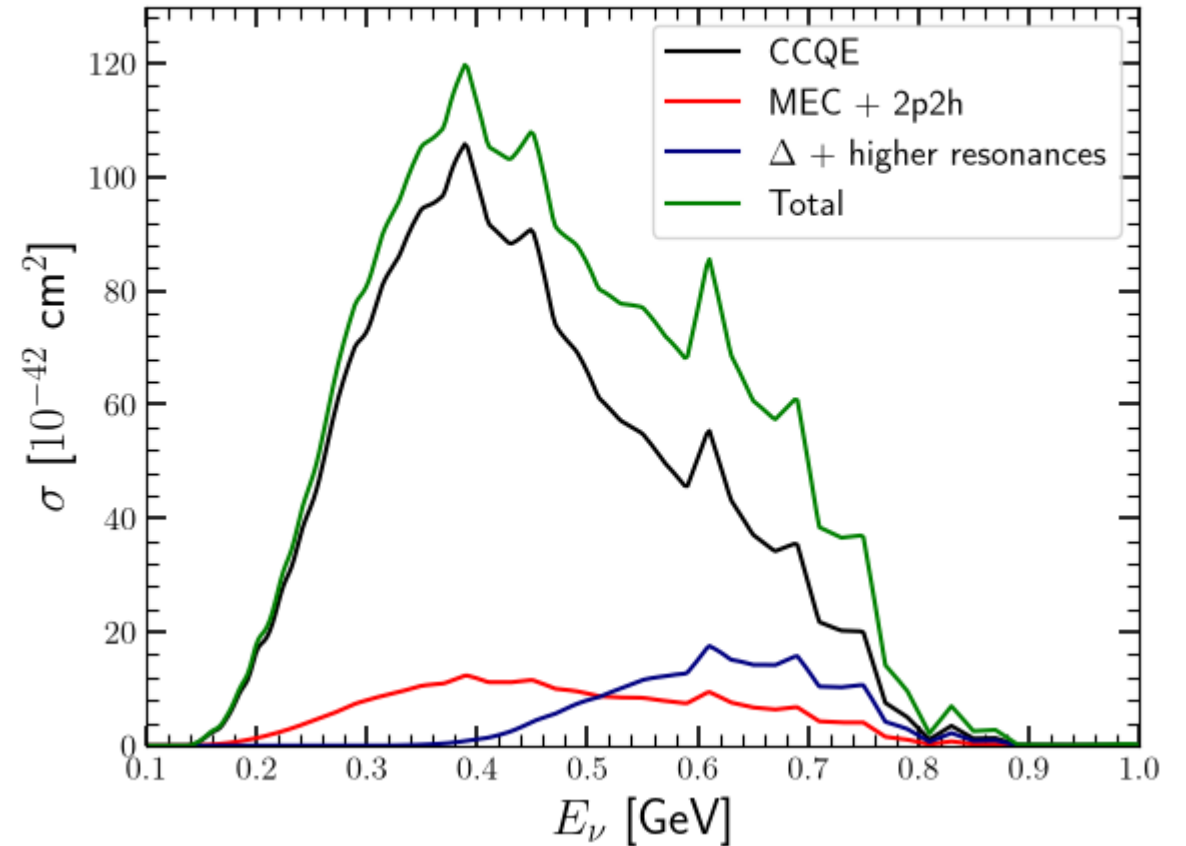


2-nucleon knockout for ESSnuSB

Mean Field + SRC + MECs :

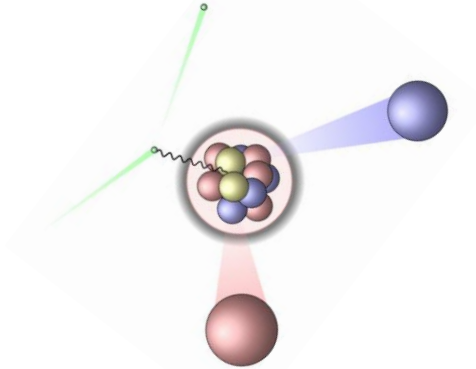


GENIE :



Summarizing ...

- 2-nucleon knockout processes constitute a non-negligible contribution to neutrino interaction cross sections in the energy range of few 100 MeVs
- If only the outgoing lepton is detected or when one of the nucleons is reabsorbed or goes otherwise undetected, the process will mimic a QE event and complicate energy reconstruction



- The energy range covered by the ESSnuSB flux presents some challenges with regards to the cross section modeling since nuclear effects are more prevailing than for experiments at higher energies
- Out-of-the-box generator studies are likely to fail to capture the details of these processes
- The lack of experimental constraints constitutes an important challenge for detailed microscopic modeling of SRC and MEC processes
- The energy range and intensity of the ESSnuSB flux offer unique opportunities for studying these processes and provide cross section information for the neutrino community