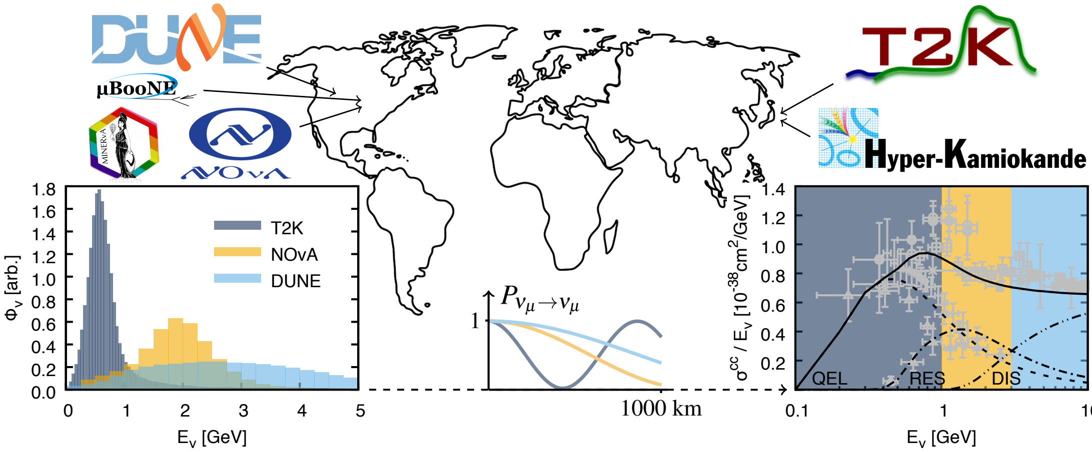
Current Capabilities and Future Plans for Lepton Scattering Uncertainties in NuWro and their Implications for Global Neutrino Oscillation Experiments

Kajetan Niewczas



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

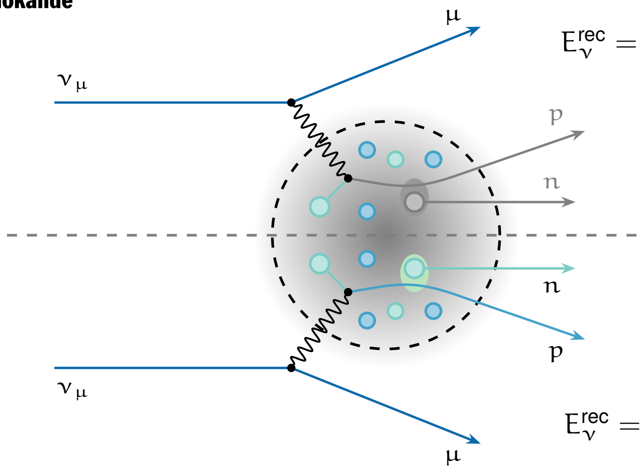
oscillation — amplitude — frequency

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

asymmetry — oscillation ratio

Kinematical energy reconstruction

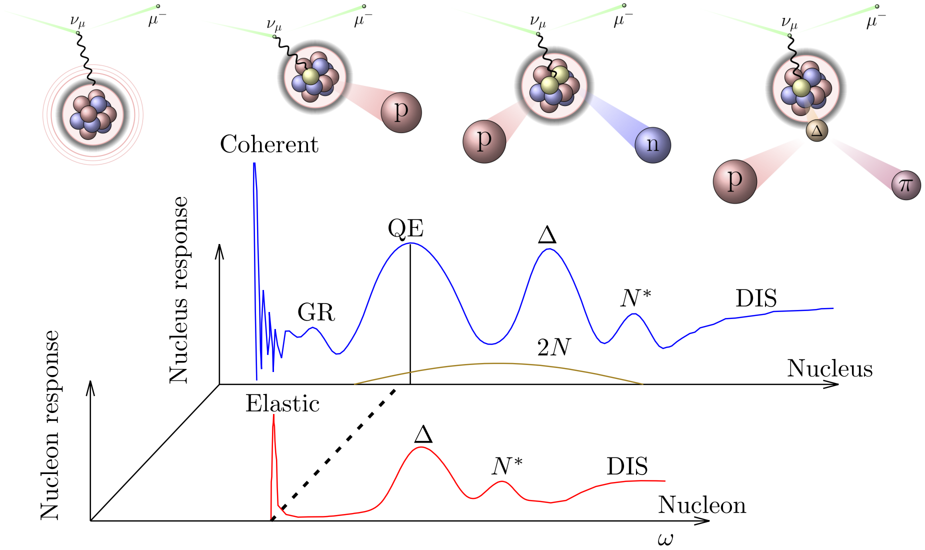
$$E_\nu^{\text{rec}} = \frac{2M_N E_\mu - m_\mu{}^2 + M_{N'}^2 - M_N^2}{2(M_N - E_\mu + p_\mu \cos\theta)}$$



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

Calorimetric energy reconstruction

Nuclear response



Outline

(6) Brief characteristics of NuWro

(2) Challenges in modeling quasielastic scattering

(4) Understanding the current meson-exchange currents implementations

(3) Enhancing sensitivity to angular distributions in single-pion production

(5) Testing the cascade model against nuclear transparency

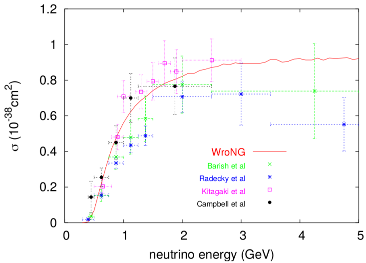
(1) **The future beyond franken-models**

Standard NuWro assumptions

- Nuclei are composed of nucleons → **Nucleon** degrees of freedom
- One-photon exchange (BA, IA) → $(L_{\mu\nu}W^{\mu\nu})$ separation
- Plane-wave impulse approximation → $(\sigma_{\nu A} \propto P(E, p)\sigma_{\nu N})$ **factorization**
- In-medium propagation $(\bar{\lambda} \ll d < \lambda < R)$ → **Cascade model** for inelastic FSI

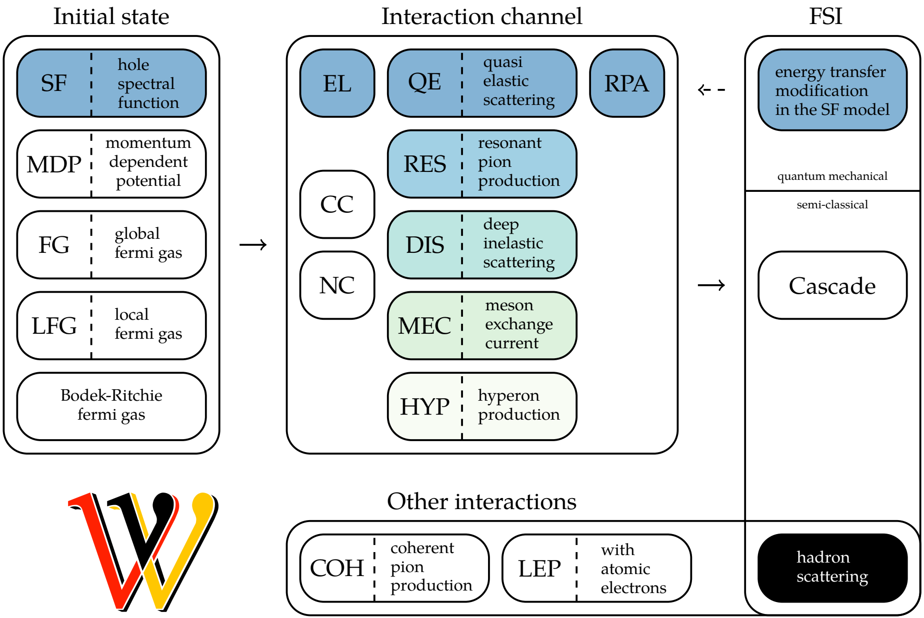
More *WroNG* assumptions

- Not fully relativistic, no distorted waves
- Factorization of the inclusive cross section
- *Frankenstein; or, The Modern Prometheus*



J.T. Sobczyk et al., Nucl.Phys.B Proc.Suppl. 139 (2005) 266-271

NuWro
Monte Carlo event generator



Intranuclear cascade

- **Propagates particles** through the nuclear medium

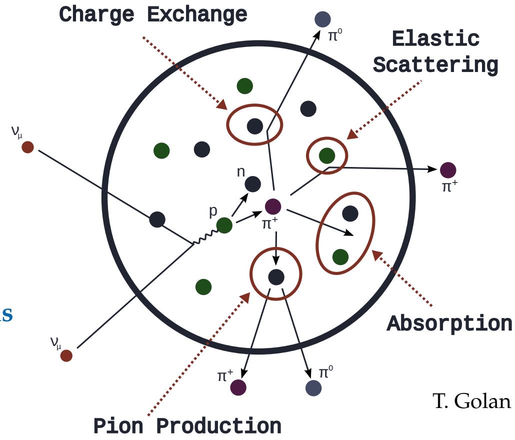
- **Probability** of passing a distance λ:

$$P(\lambda) = e^{-\lambda/\tilde{\lambda}}$$

where $\tilde{\lambda} \equiv (\rho\sigma)^{-1}$ and
ρ - local density
σ - cross section

→ Implemented for **nucleons**, **pions** and **kaons**

T. Golan, C. Juszczak, J.T. Sobczyk, Phys.Rev. C 86 (2012) 015505



T. Golan

Uncertainties of concern

Coming from **models**:

- Form factors, nuclear dynamics, and in-medium effects ...
- Model validity, meaningful degrees of freedom ...

Coming from **event generators**:

- Model implementations, simplifications ...
- Double counting of physical effects and dynamics ...

Factorization of the cross section calculation

Plane-wave impulse approximation

$$\frac{d^2\sigma}{d\omega d|\vec{q}|} = K \int dE\, d^3\vec{p}\; S(E, |\vec{p}|)\; L_{\mu\nu} H^{\mu\nu}$$

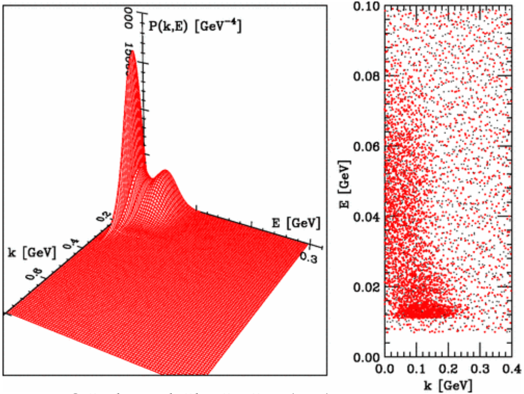
→ effective optical potential prescription

or the **Llewellyn-Smith** formula

$$\frac{d\sigma}{dQ^2} = K \left[A(Q^2) - B(Q^2) \left(\frac{s-u}{M^2} \right) + C(Q^2) \left(\frac{s-u}{M^2} \right)^2 \right]$$

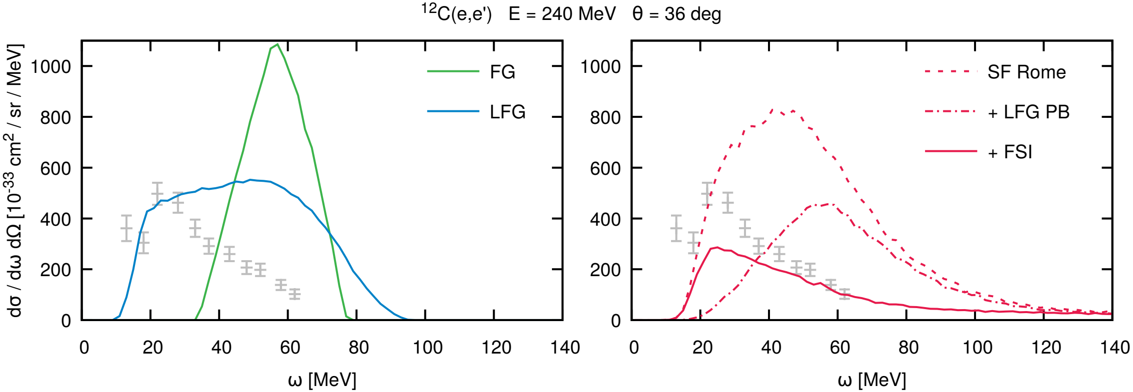
→ after boosting to the N-rest frame

→ folded with nuclear model distributions



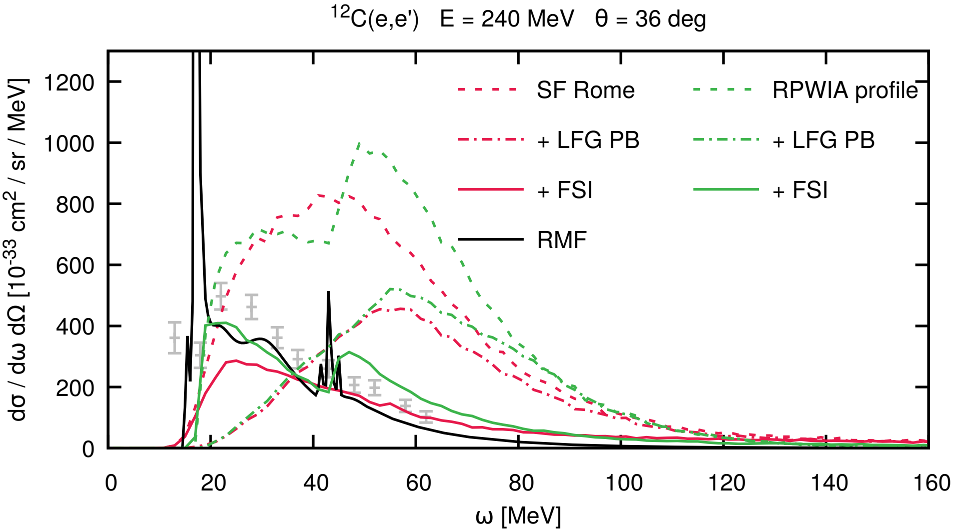
O. Benhar et al., Phys.Rev.D 72 (2005) 053005

Factorization of the cross section calculation



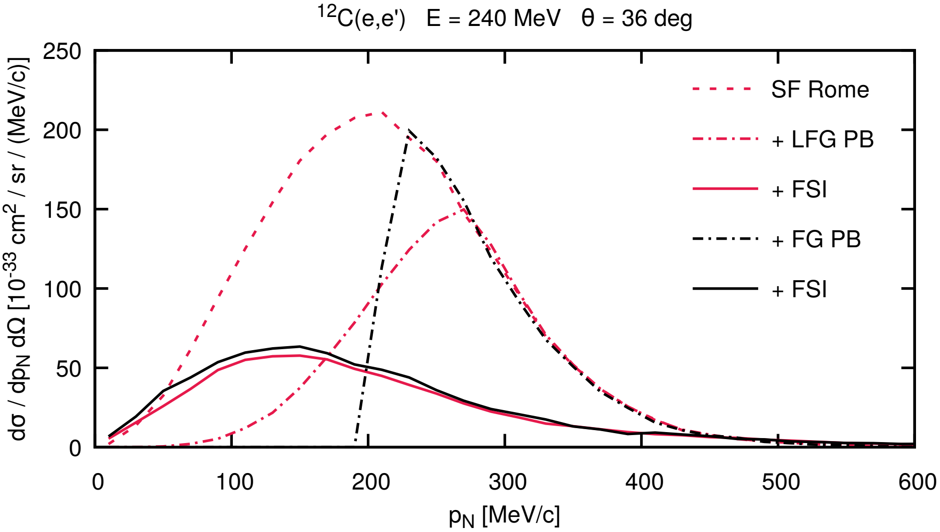
→ **FG** and **LFG** do not reproduce the inclusive electron results

Factorization of the cross section calculation



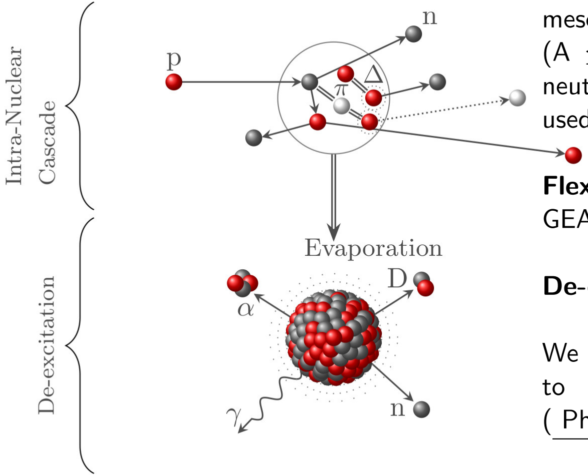
→ For inclusive cross sections, the **correction is fine**

Factorization of the cross section calculation



→ The procedure is **inconsistent for exclusive observables**

NuWro + INCL + ABLA



Projectiles: baryons (nucleons, Λ, Σ), mesons (pions and Kaons) or light nuclei (A $\leq$ 18). **No neutrinos** yet! We use neutrino vertex from **NuWro** (widely used ν-nucleus MC generator).

Flexible tool: has been implemented in GEANT4 and GENIE

De-excitation: ABLA, SMM, GEMINI

We will use **ABLA**, since it proved to work for the **light nuclei** (Phys. J. Plus 130, 153 (2015))

First neutrino simulation results: Phys.Rev.D 106, 3 (2022)

Anna Ershova, NuFACT 2023

NuWro + INCL + ABLA

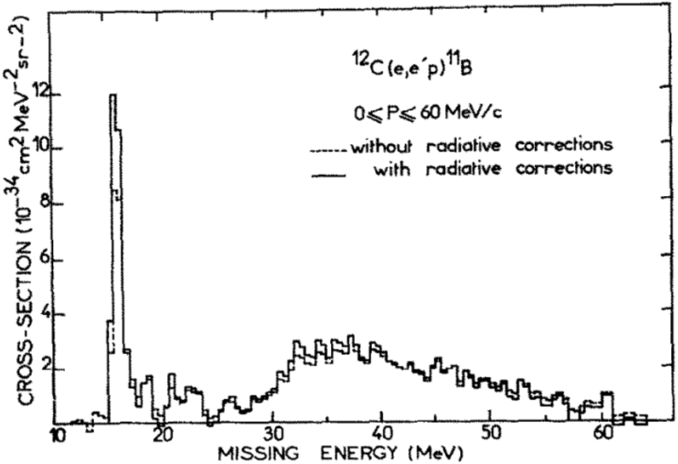
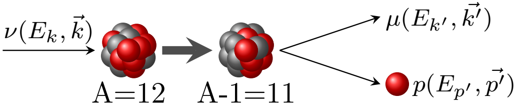


Fig. 7. Energy spectrum of the $^{12}C(e, e'p)$ reaction before and after the radiative corrections.

Anna Ershova, NuFACT 2023

NuWro + INCL + ABLA



Experimental definition:

$$E_x^{\text{exp}} = E_{missing} - (M_A - M_{A-1} - M)$$

- A constant shift of missing energy by $\sim$15.4 MeV leads to **non-physical, negative values**
- We use experimental data (J. Phys. G: Nucl. Part. Phys. 16 507 (1999)) to simulate discrete levels
- We assume all strength below the peak comes from the symmetric $\mathbf{1p_{3/2}}$ **shell**

Anna Ershova, NuFACT 2023

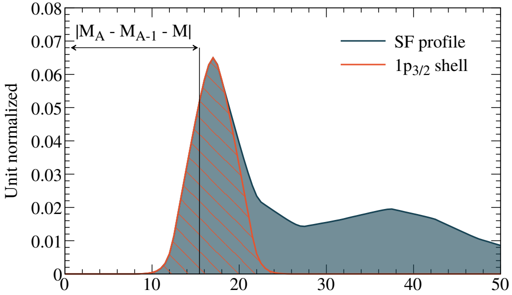
M_{A-1} is the rest mass of the $A-1$ nucleus

M_A is the rest mass of the initial A nucleus

M is the rest mass of the target nucleon

$E_{missing}$ is the missing energy

For interaction on carbon,
$M_A - M_{A-1} - M = 15.4$ MeV



NuWro + INCL + ABLA

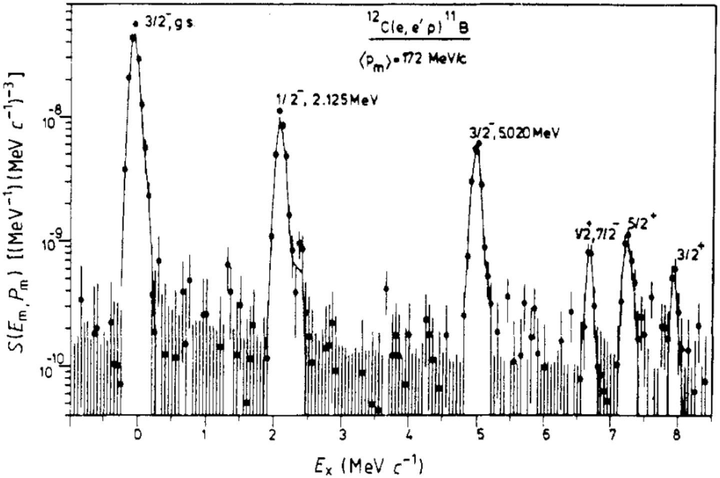
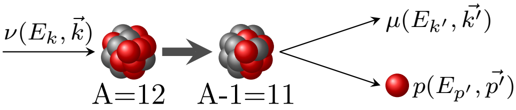


Figure 22. Excitation-energy spectrum of ^{11}B observed in the reaction $^{12}C(e,e'p)$. Both negative and positive-parity final states are shown.

Anna Ershova, NuFACT 2023

NuWro + INCL + ABLA



For the continuous spectrum part, we can calculate excitation energy as:

$$E_x = M_R^* - M_R, \text{where:}$$

$$M_R^* = \sqrt{(E_k + M_A - E_{k'} - E_{p'})^2 - |\vec{p}_{missing}|^2}$$

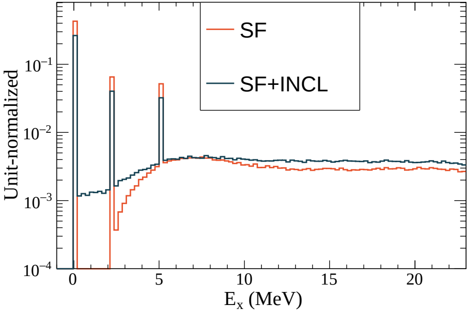
Otherwise, we model **3 discrete peaks** with strength of 79%, 12%, and 9% (**p-shell**)

M_R^* is the mass of the excited remnant

M_R is the rest mass of the remnant

T_R is the kinetic energy of the excited remnant

$p_{missing}$ is the missing momentum



Anna Ershova, NuFACT 2023

NuWro + INCL + ABLA

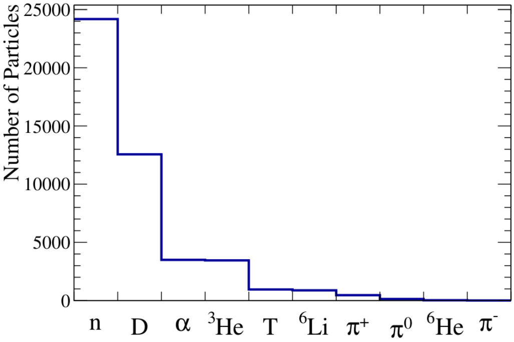


FIG. 11: Particles leaving the nucleus in events without proton in the final state in INCL.

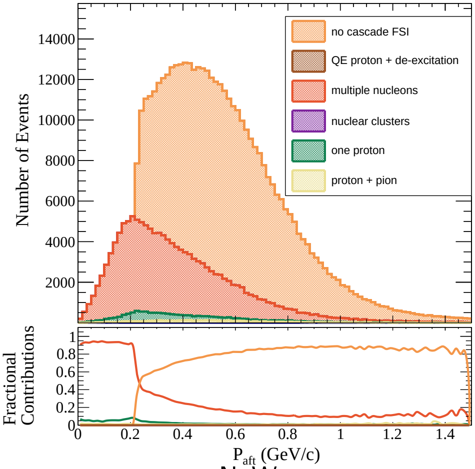
In the last paper: Phys.Rev.D 106, 3 (2022) we show the **nuclear cluster production for the first time** in FSI.

Now we study the impact of the subsequent **de-excitation modelling**, that predicts **more nuclear clusters**.

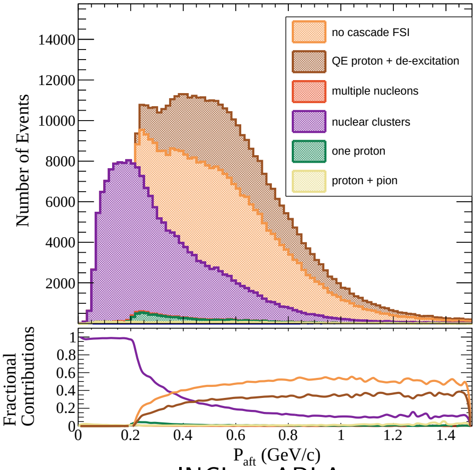
Anna Ershova, NuFACT 2023

NuWro + INCL + ABLA

INCL+ABLA simulation features **massive difference** in nucleon kinematics in comparison to NuWro



NuWro

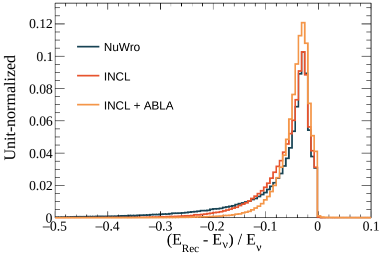


INCL + ABLA

Anna Ershova, NuFACT 2023

A. Ershova et al., arXiv:2309.05410 (accepted for publication in PRD)

Using $\mu + p$ is **better** than using muon only, but here we show that we gain even **higher precision** by using all subleading particles



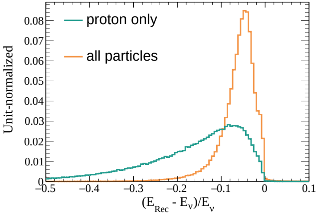
"all particles" reconstruction

proton only:

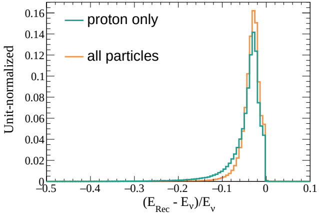
$$E_{rec} = E_\mu + T_p$$

all particles (including clusters)

$$E_{rec} = E_\mu + \sum_i T_i$$



INCL+ABLA cascade FSI



INCL+ABLA no cascade FSI

Anna Ershova, NuFACT 2023

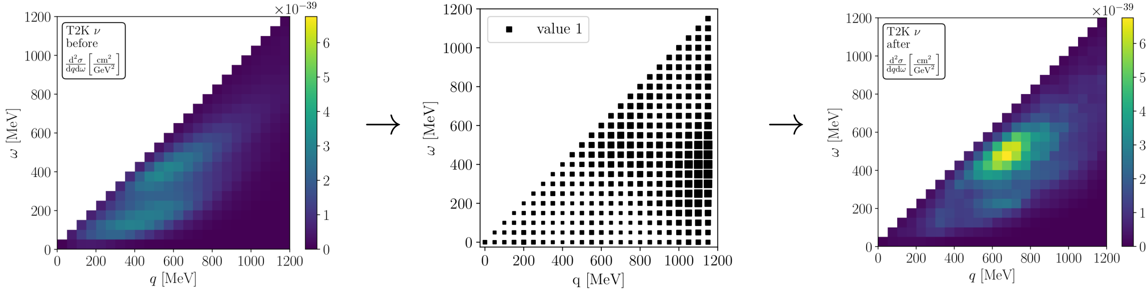
Phenomenological 2p2h model

A simultaneous fit to the T2K and MINERvA CC0π data

→ ansatz: the **whole error comes from 2p2h**

→ **Valencia 2p2h** model as the **prior** ($|\vec{q}| \leqslant 1.2$ GeV/c)

Experiment	D.O.F.	Non-scaled	Scaled
MINERvA ν_μ	156	462.8	358.2
MINERvA $\bar{\nu_\mu}$	60	65.1	62.2
T2K ν_μ	58	143.7	83.9
T2K $\bar{\nu_\mu}$	58	101.2	98.0
Sum	332	772.8	619.6



→ the **data** favor contributions from **higher momentum transfers**

T. Bonus, J.T. Sobczyk, M. Siemaszko, and C. Juszczak, Phys.Rev. C 102 (2020) 015502

Single-pion production

$$\nu + N \to l^- + N' + \pi$$

- **Single-pion production** (SPP) is an essential dynamics for accelerator-based experiments
- There many measurements sensitive to **pion angular distributions** ($\cos\theta_\pi$)

$$\nu + N \to l^- + (\Delta \to N' + \pi)$$

- **NuWro** models the **Δ-resonance** excitation
  → it decays according to the ANL/BNL angular fits

$$\frac{d^2\sigma_\Delta}{dQ^2 dW} \to \frac{d^4\sigma_\pi}{dQ^2 dW} \times \frac{df_\Delta(Q^2)}{d\Omega^*_\pi}$$

- The nonresonant background is extrapolated from the DIS formalism into the lower regions of W, Q^2

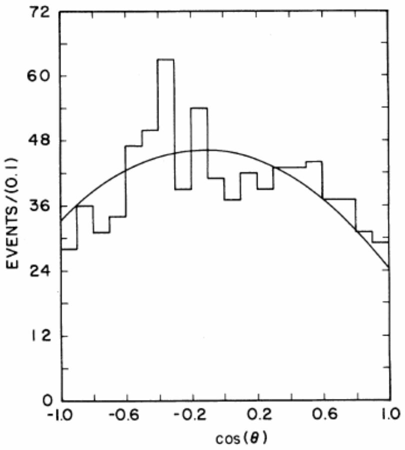


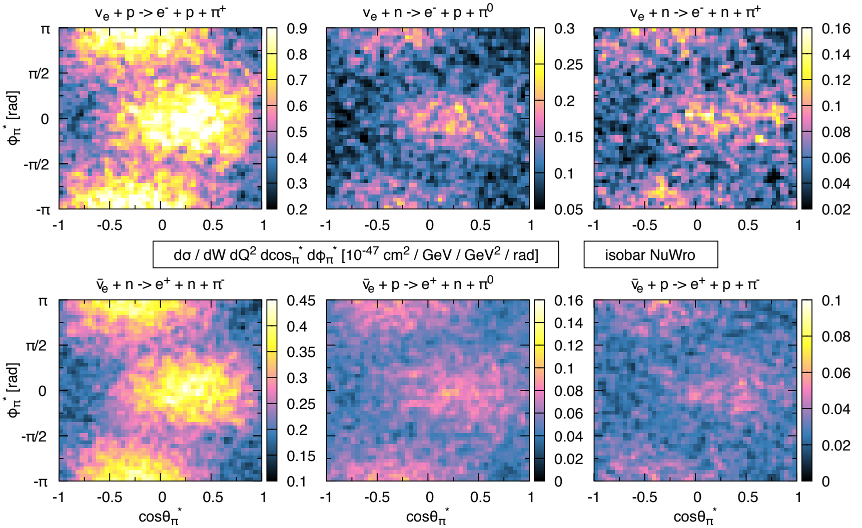
FIG. 15. Distribution of events in the pion polar angle $\cos\theta$ for the final state $\mu^- p \pi^+$, with $M(p\pi^+) < 1.4$ GeV. The curve is the area-normalized prediction of the Adler model.

Radecky et al. [ANL Collaboration], Phys.Rev. D 25 (1982) 1161

Pion angular distributions

- **Default NuWro**
- Free nucleon
- Fixed kinematics:

$$E = 1\text{ GeV}$$
$$Q^2 = 0.1\text{ GeV}^2$$
$$W = 1230\text{ MeV}$$



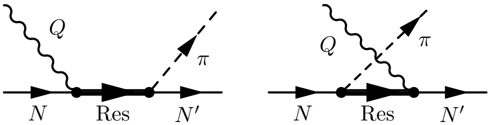
(total number of 10^7 **events** over the **whole phase space**)

Ghent low energy model of SPP

- The model of Ref. [**R. González-Jiménez et al., Phys.Rev. D 95 (2017) 113007**]
- The **low-energy** part based on the **Valencia model**

Resonances

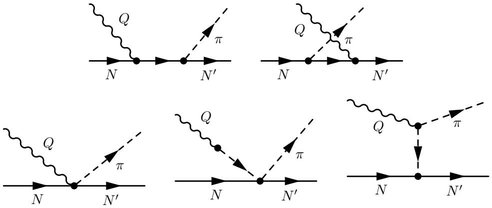
$P_{33}(1232)$, $P_{11}(1440)$, $D_{13}(1520)$, $S_{11}(1535)$



based on [PRD 76 033005, PRD 87 113009, PRD 93 014016]

+

ChPT background



- **Bottleneck** for the implementation is the code **execution time**
- Adding a **nuclear model** will further increase the complexity of the implementation

Implementation

- Working in the **Adler frame**, generating an event requires the value of

$$\frac{d^4\sigma}{dQ^2 dW d\Omega_\pi^*} = \frac{\mathcal{F}^2}{(2\pi)^4}\frac{k_\pi^*}{k_l^2}\left[A + B\cos(\phi_\pi^*) + C\cos(2\phi_\pi^*) + D\sin(\phi_\pi^*) + E\sin(2\phi_\pi^*)\right]$$

  → that is **time consuming** and the MC sampling has an **efficiency** of 10 − 15 %

- Sampling Q^2, W from **precomputed arrays** allows to build the **muon kinematics**
- Then, $\cos\theta_\pi^*$ is given by the A function that is mostly **parabolic** (fit using 3-7 points)
- Finally, for other variables fixed, ϕ_π^* is given by an **analytical expression**

$$\frac{d^2\sigma}{dQ^2 dW} \xrightarrow[\text{numerical}]{\text{fix } Q^2, W} \frac{d^3\sigma}{dQ^2 dW d\cos\theta_\pi^*} \xrightarrow[\text{numerical / analytical}]{\text{fix } \cos\theta_\pi^*} \frac{d^4\sigma}{dQ^2 dW d\Omega_\pi^*} \xrightarrow[\text{analytical}]{\text{fix } \phi_\pi^*} \text{event...}$$

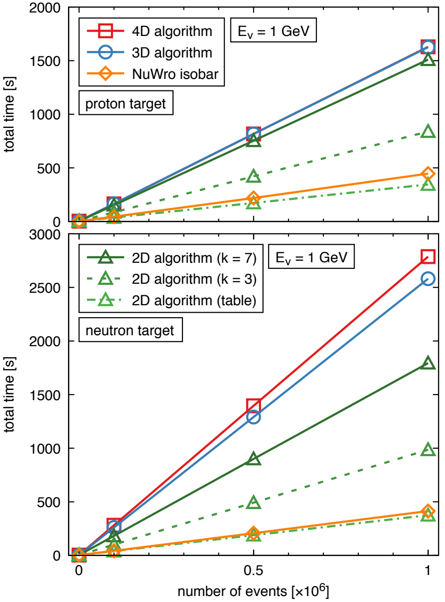
K.N. et al., Phys.Rev.D 103 (2021) 053003

Performance

We propose:

- **4D algorithm**: sampling $(Q^2, W, \cos\theta^*_\pi, \phi^*_\pi)$ together
  (1 cross section calculation per accepted event)
- **3D algorithm**: sampling $(Q^2, W, \cos\theta^*_\pi)$ together
  $+\ \phi^*_\pi$ analytical
  (2 cross section calculation per accepted event)
- **2D algorithm**: sampling (Q^2, W) from tables
  $+ \cos\theta^*_\pi$ from k points or from tables
  $+\ \phi^*_\pi$ analytical
  $(k+1$ cross section calculation per accepted event)

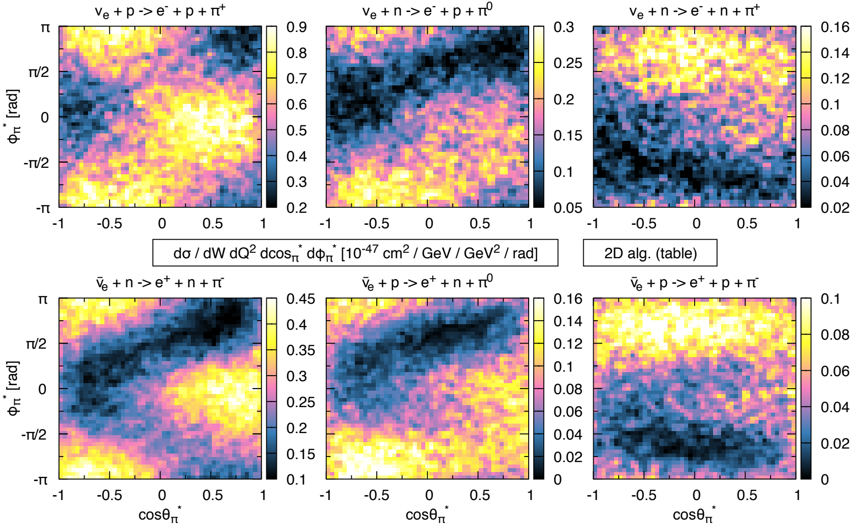
→ $\nu - n$ scattering requires one more code evaluation because it has two channels $(p+\pi^0, n+\pi^+)$



Pion angular distributions

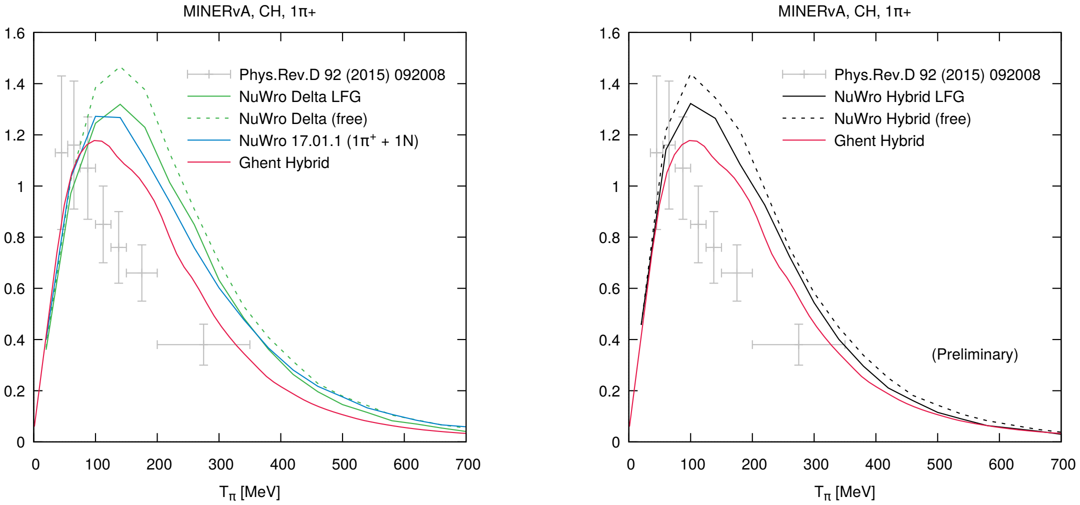
- **Ghent LEM**
- Free nucleon
- Fixed kinematics:

$$E = 1\,\text{GeV}$$
$$Q^2 = 0.1\,\text{GeV}^2$$
$$W = 1230\,\text{MeV}$$



(total number of 10^7 **events** over the **whole phase space**)

Hybrid model on the nucleus



R. González-Jiménez et al., Phys.Rev.D 97 (2018) 013004; *Q. Yan et al., in preperation*

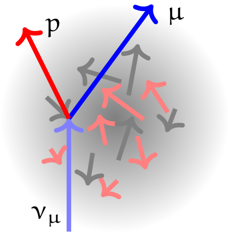
Nuclear transparency

Definition

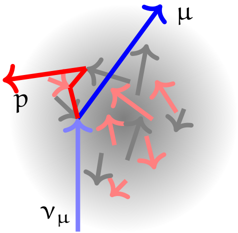
Nuclear transparency is the average **probability** for a knocked-out **proton** to **escape** the nucleus **without significant reinteraction**.

e.g. measured for Carbon: $T \simeq 0.60$ [D. Abbott *et al.*, PRL 80 (1998), 5072]

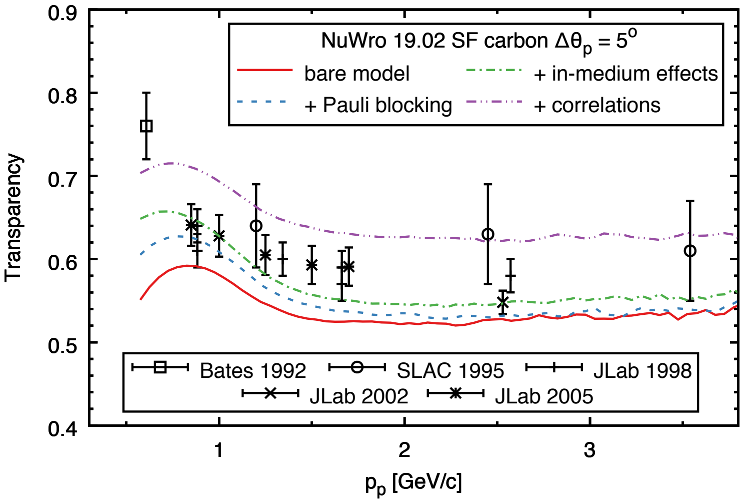
$\sim 60\%$ without FSI



$\sim 40\%$ with FSI

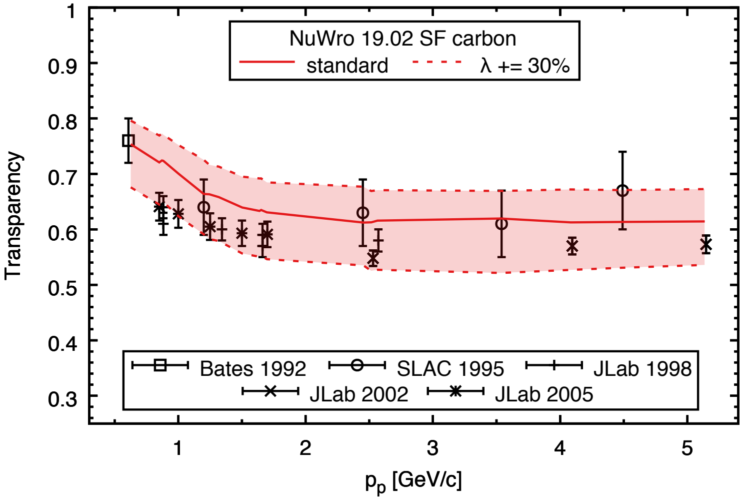


Nuclear transparency



K. Niewczas, J. Sobczyk, Phys.Rev. C 100 (2019) 015505

Nuclear transparency

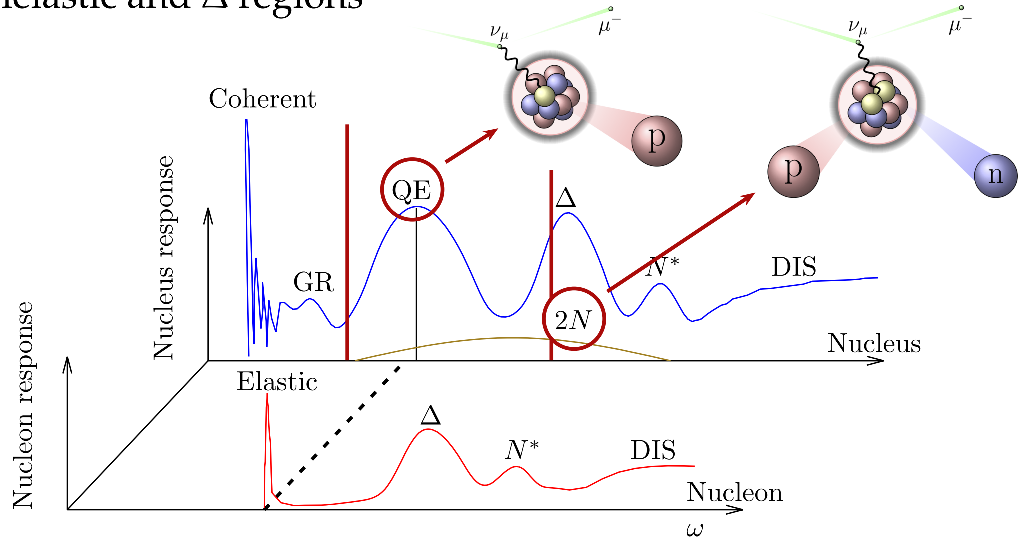


K. Niewczas, J. Sobczyk, Phys.Rev. C 100 (2019) 015505

The future beyond franken-models...

with UNIVERSITEIT GENT

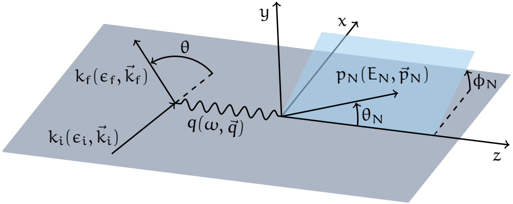
Quasielastic and Δ regions



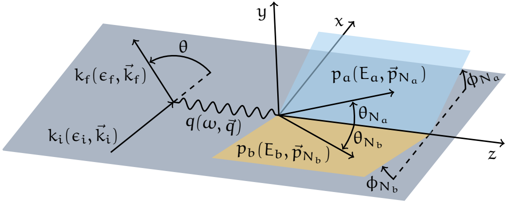
→ Mostly influenced by **one- and two-body physics** at nucleon and Δ levels

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

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

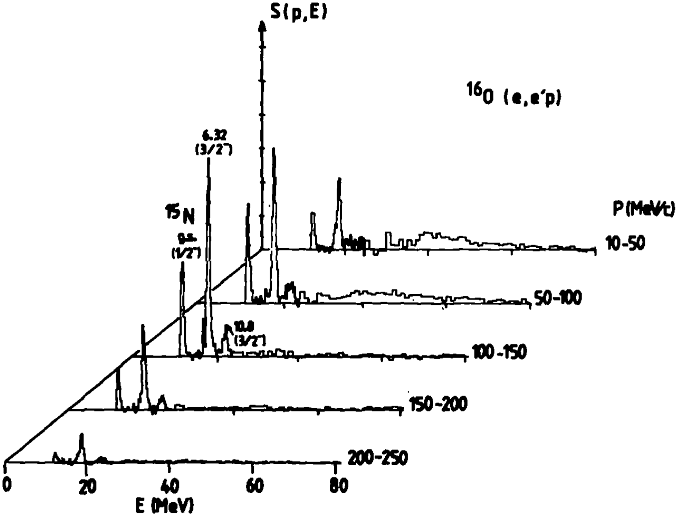
$\mathcal{V}_x$ - leptonic factors; $\mathcal{W}_x$ - hadronic responses; L/T - longitudinal/transverse relative to $\vec{q}$

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



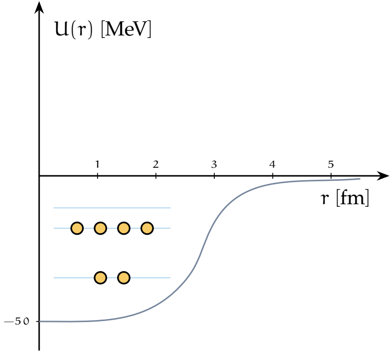
J. Mougey, Nucl.Phys. A 335 (1980) 35

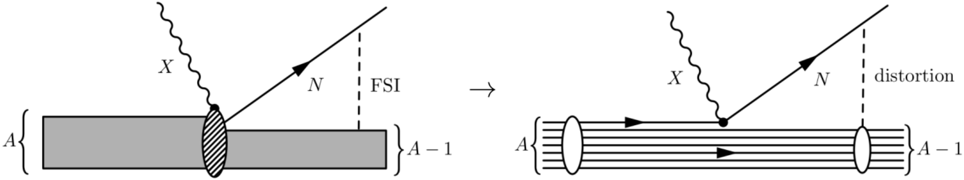
Our nuclear framework

→ 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

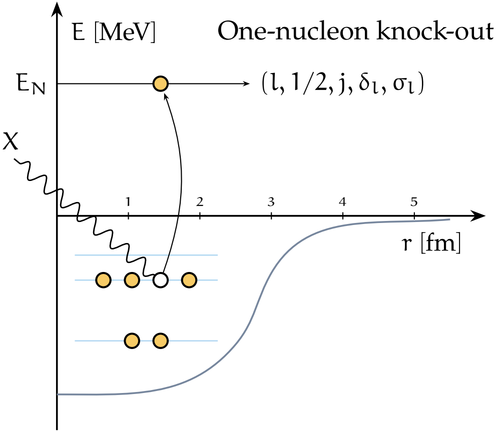
→ We evaluate the following **hadronic transition** currents

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

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

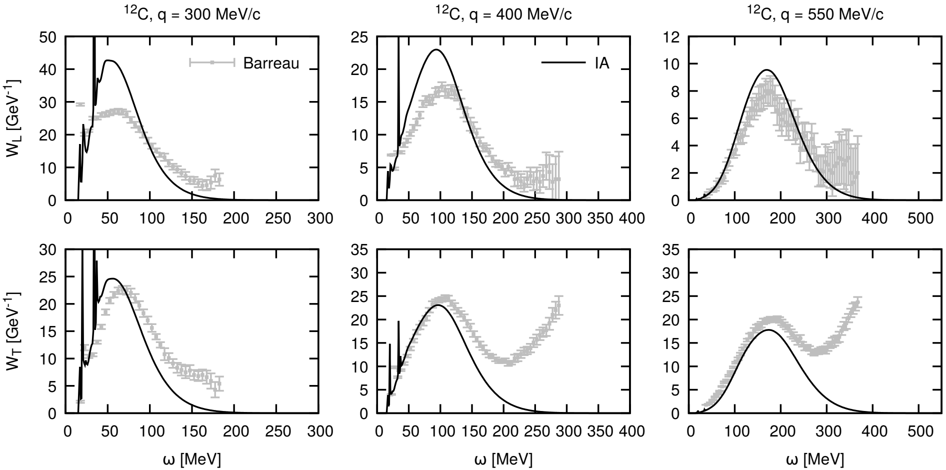
$$\hat{\mathcal{J}}(\vec{r})^{\text{had}}_{\nu} \simeq \hat{\mathcal{J}}(\vec{r})^{\text{IA}}_{\nu} = \sum_{j=1}^{A} \hat{\mathcal{J}}(\vec{r}_j)^{[1]}_{\nu} \delta^{(3)}(\vec{r} - \vec{r}_j)$$

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



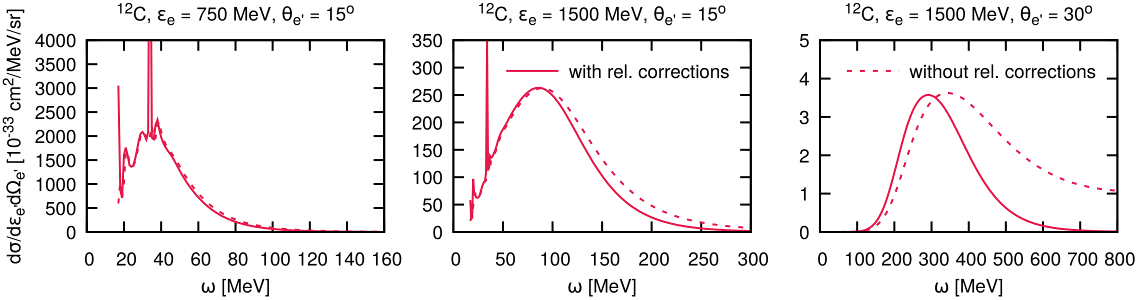
→ Comparing to **inclusive electron scattering data** allows for benchmarking of the model

Impulse approximation: electron scattering



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

Relativistic corrections



Fixing the **relativistic** position of the **quasielastic peak**

$$\omega \to \omega\left(1 + \frac{\omega}{2M_N}\right), \quad \text{then} \quad \omega_{QE} = \frac{|\vec{q}|^2}{2M_N} \to \frac{Q^2}{2M_N}$$

Short-range correlations

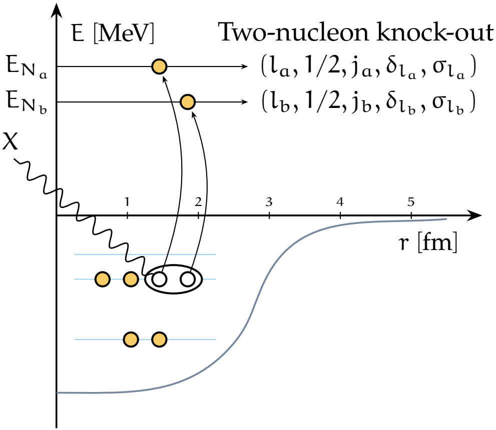
→ Nucleons with strongly **overlapping wave functions** for a short period of time

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

with

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

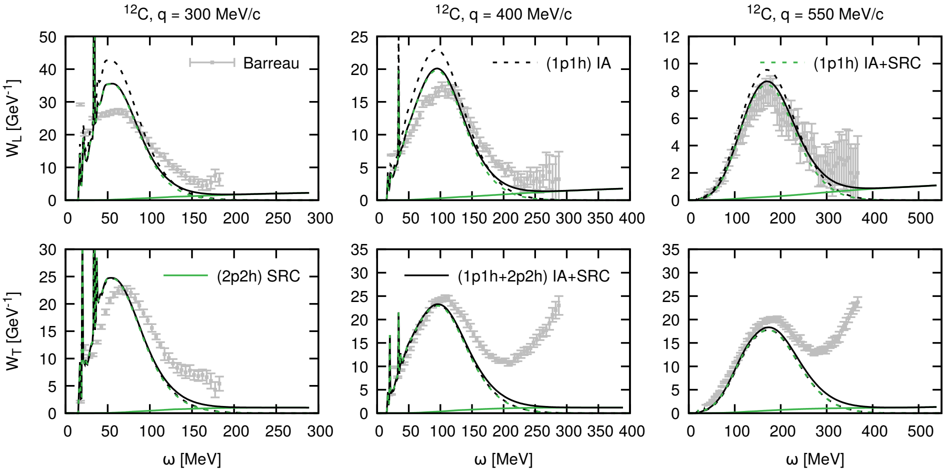
→ The correlation operator $\hat{l}(i,j)$ includes **central**, **tensor**, and **spin-isospin correlations**



→ 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

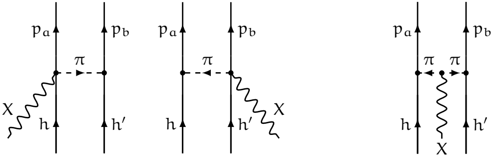


→ Significant reduction of the **longitudinal 1p1h strength** and a minor 2p2h contribution

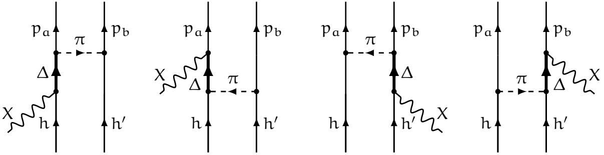
Meson-exchange currents

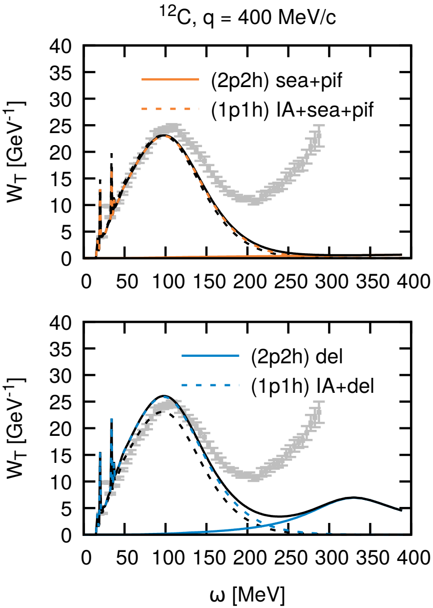
Explicit **two-body currents** contributing to both **1p1h** and **2p2h** final-states:

→ **Seagull** currents → **Pion-in-flight** current

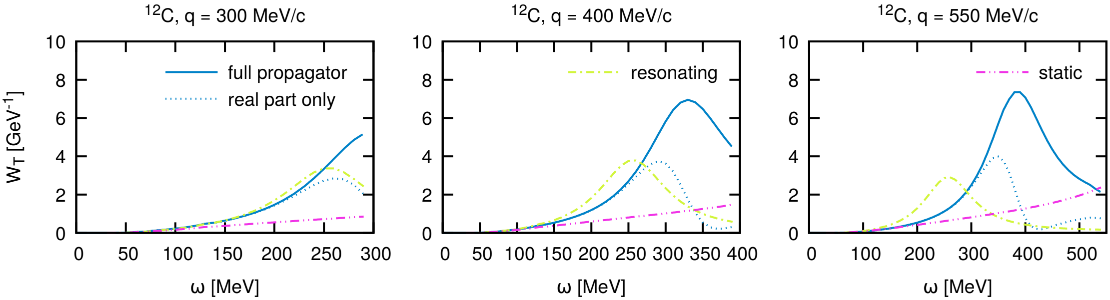


→ **Δ-isobar** degrees of freedom





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

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

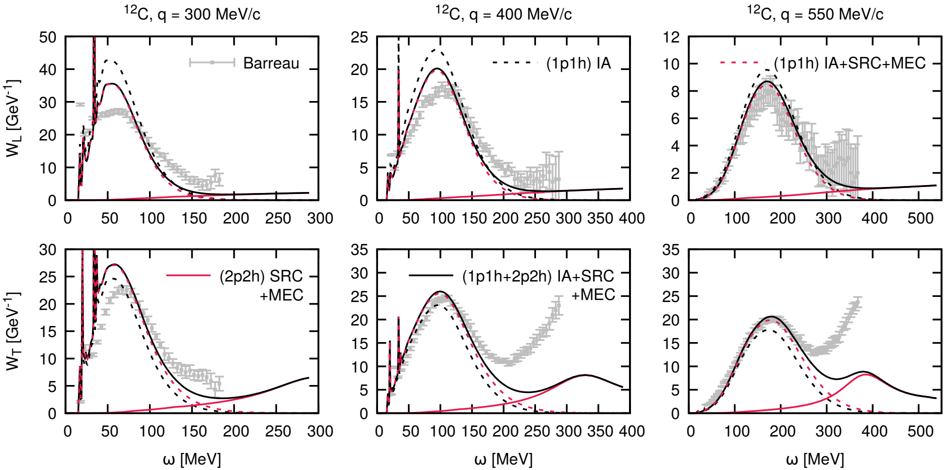
$$G_\Delta^{\text{nres}} = 0$$

Resonating approximation

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

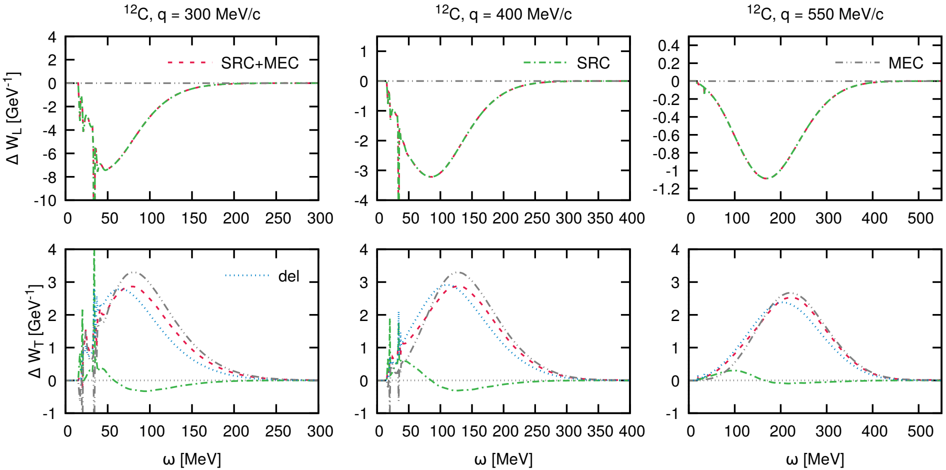
$$G_\Delta^{\text{res}} - G_\Delta^{\text{nres}} = 0 \qquad + \frac{1}{M_\Delta - M_N + \omega}$$

Consistent modeling of two-body currents: electron scattering



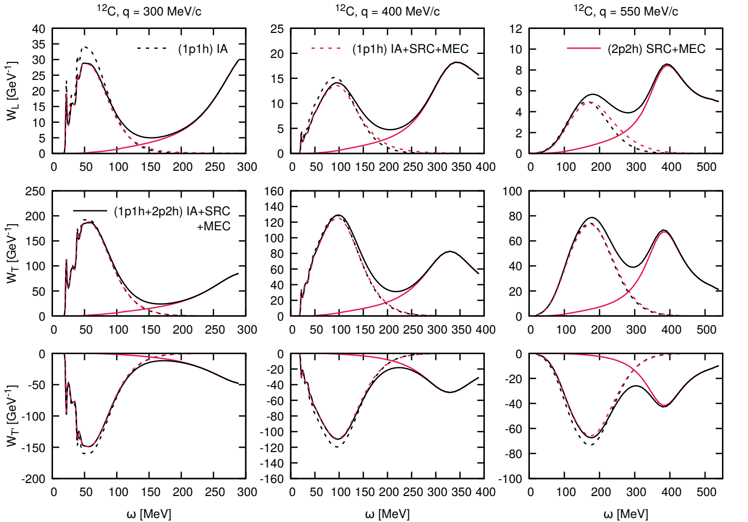
→ **Coherent sum of SRC and MEC** enhances our predictions

Consistent modeling of two-body currents: electron scattering



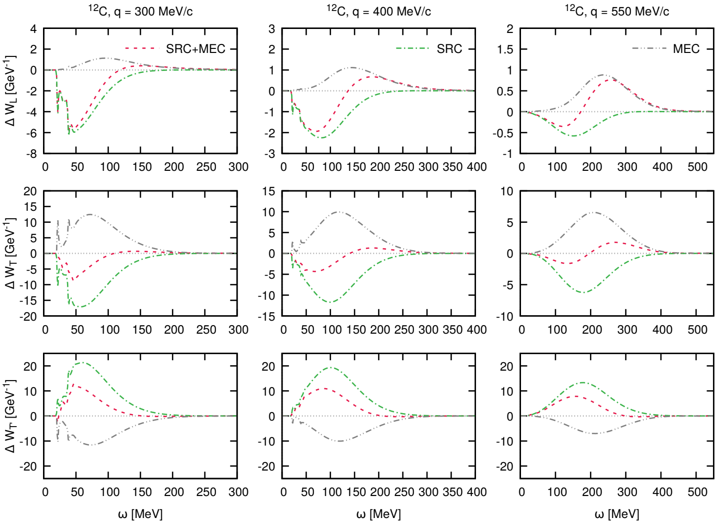
→ **Two-body currents** modify the one-nucleon knock-out responses

Consistent modeling of two-body currents: neutrino scattering



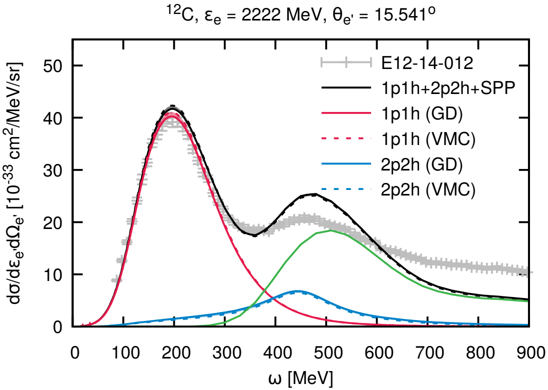
→ **Pronounced Δ peaks** for both longitudinal and transverse responses

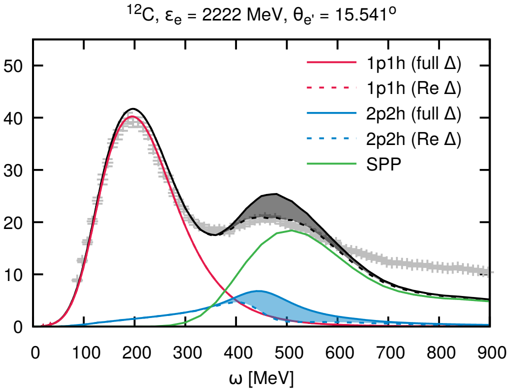
Consistent modeling of two-body currents: neutrino scattering



→ **SRC** provides quenching in the longitudinal and transverse responses

JLab Hall A data

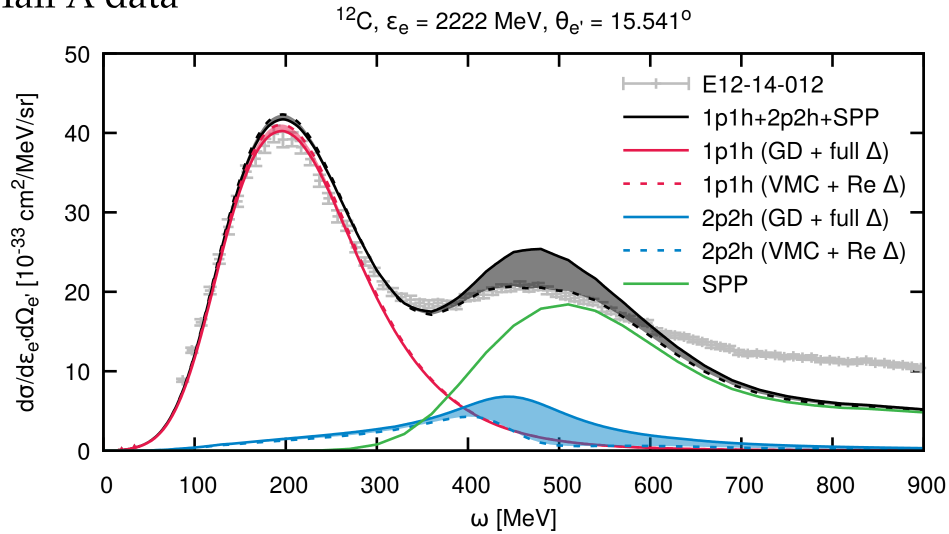




→ The choice of the different **central correlation functions** modifies the **QE peak strength** (GD–stronger, VMC–weaker)

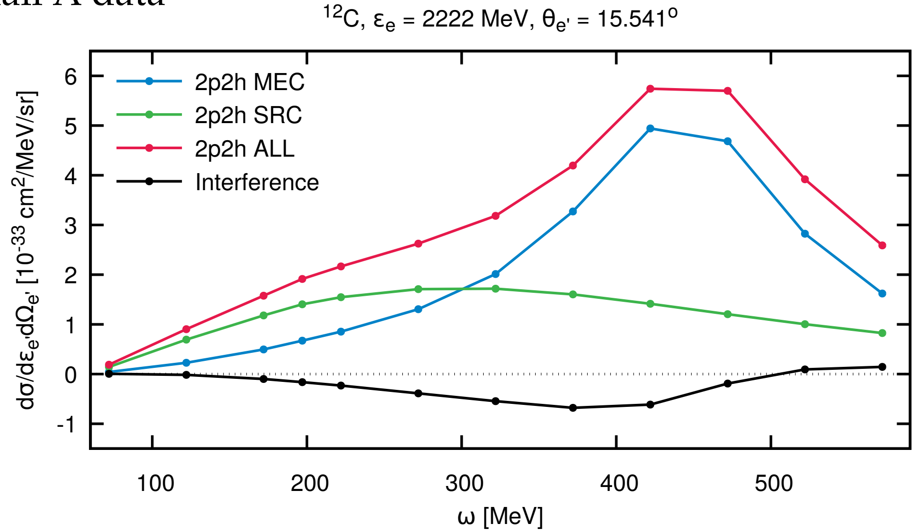
→ Modifying the Δ-propagator governs the **overlap between MEC and SPP** around the Δ peak (Re Δ–only the real part)

JLab Hall A data



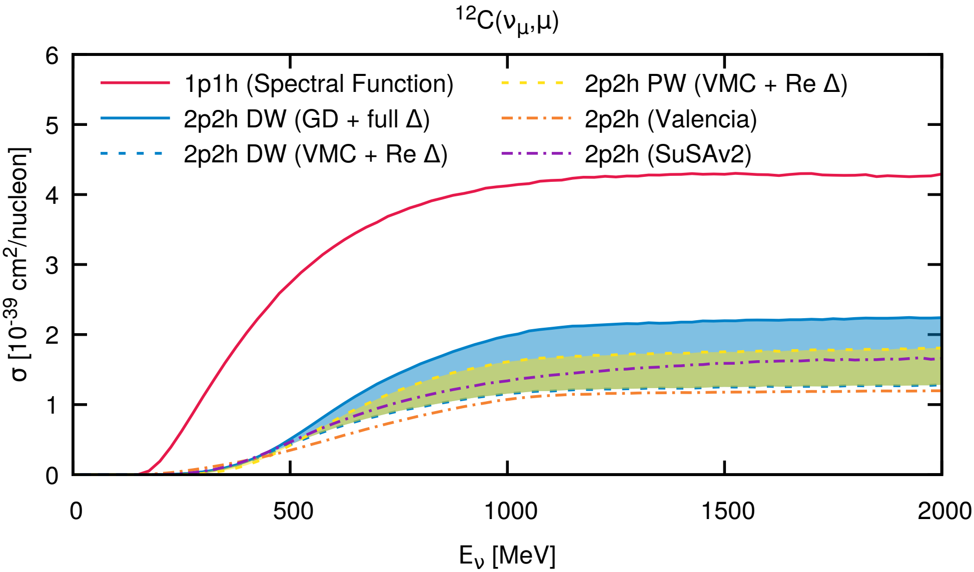
→ Combining variation in given d.f. provides **flexibility in describing QE and Δ peaks**

JLab Hall A data

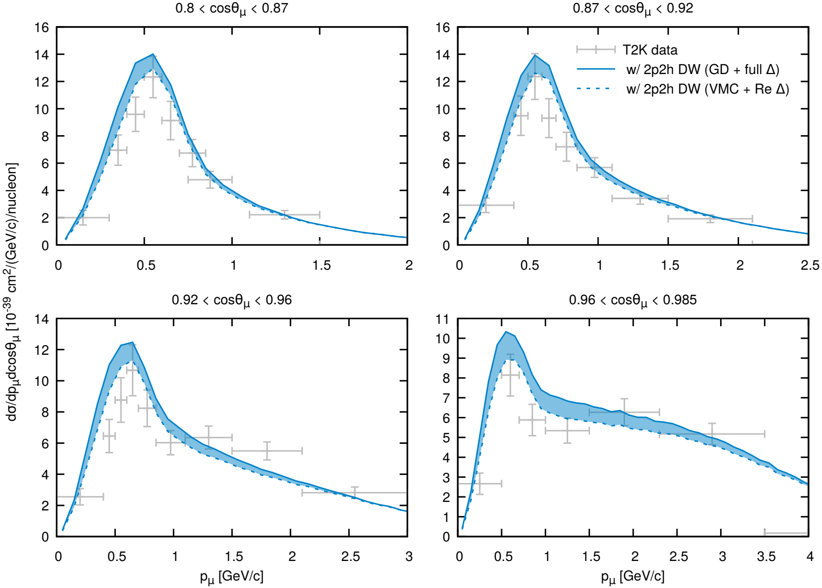


→ We see a siginificant **negative interference** between the SRC and MEC contributions

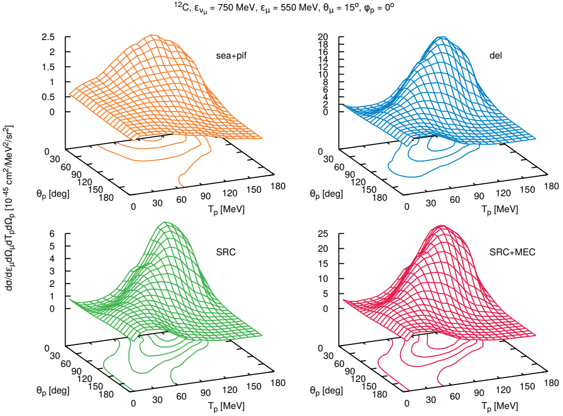
Inclusive NuWro implementation



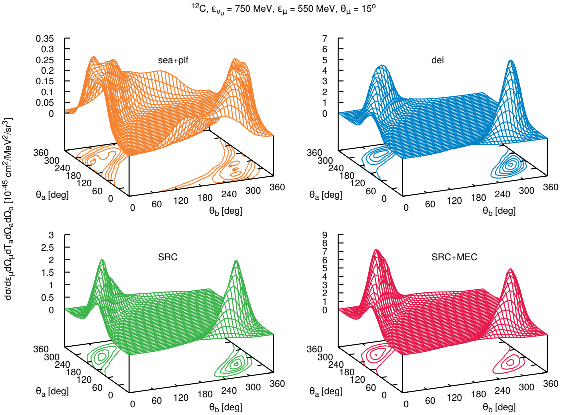
Inclusive T2K data



Going more exclusive... in neutrino scattering



Exclusive two-nucleon knock-out



Semi-inclusive two-nucleon knock-out

Conclusions

- The current generator methods face **significant challenges**
- We are moving towards precision **exclusive processes modeling**
- More **refined implementation methods** become available
- We are **moving forward**, leaving franken-models behind

You, theoreticians, want consistency. We, experimentalists, want flaxibility.

Stephen Dolan, NuXTract 2023