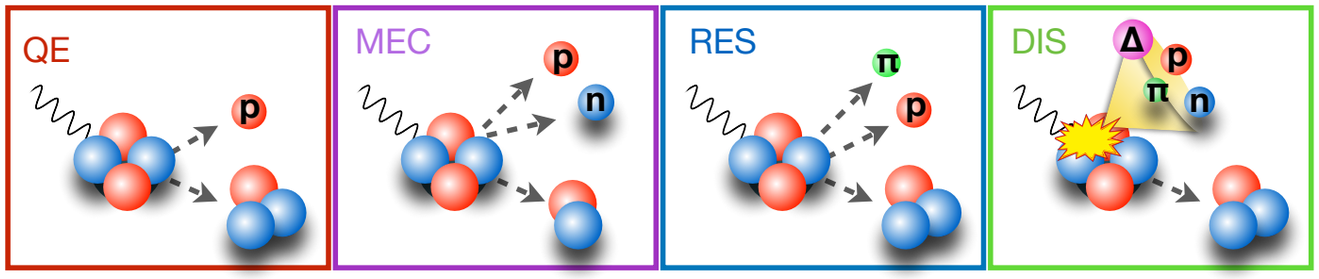
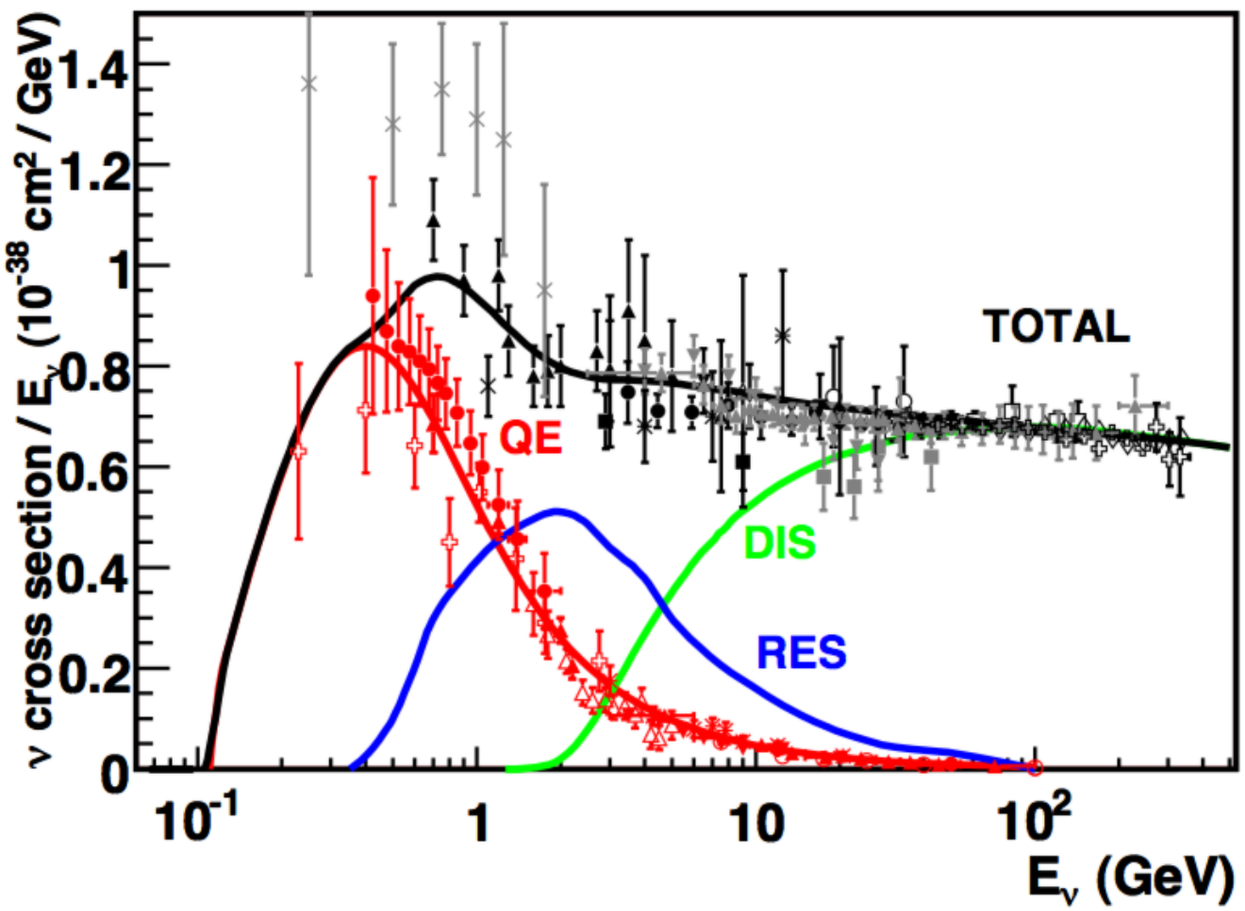
Neutrino-nucleus cross sections





- Accelerator neutrino flux covers a **broad range of energies** and a variety of reaction mechanisms. Need for **specialized event generators applicable** in the 100 MeV to few GeV energy range

- **Theoretical challenge:** develop a unified nuclear framework to describe all different reaction mechanisms. Significant progress over the last few years.

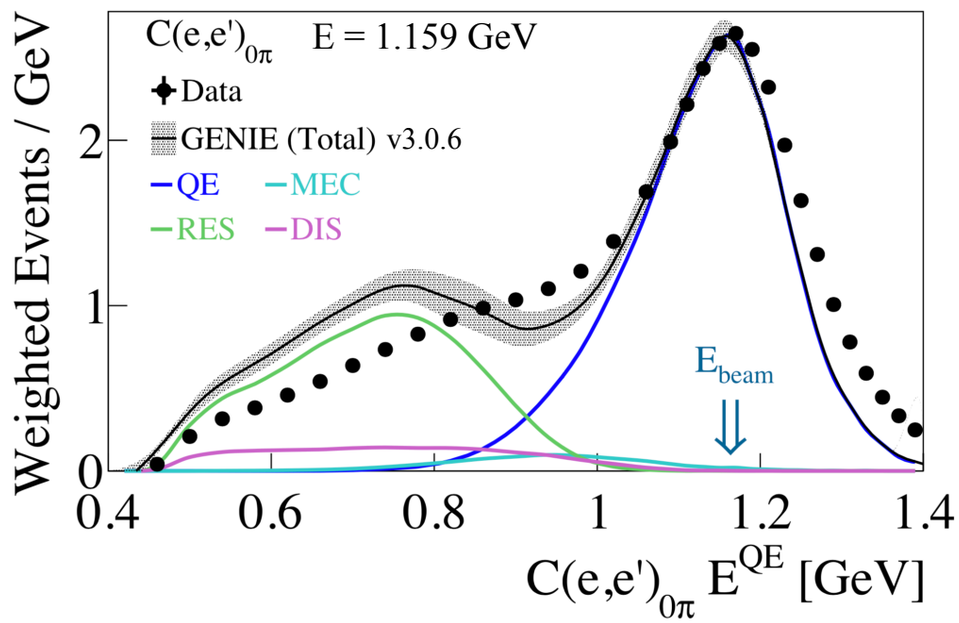
- **Factorization of the interaction vertex** is the approximation used to include relativistic effect, have access to exclusive channels, and connect the theory model to the intra-nuclear cascade

- Implementation of **state-of-the-art nuclear theoretical model** in event generators is crucial to compare with neutrino data

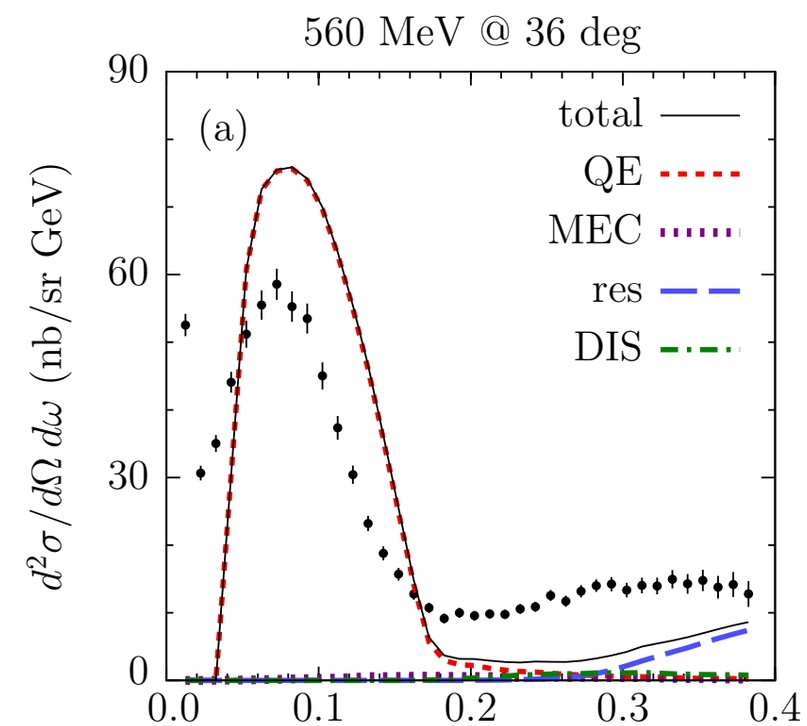
- Currently, event generators stitch together different (and ofter inconsistent) approaches (the so called ‘Frankenstein’ models)

Establishing benchmarks

Ashkenazi for e4v Collaboration @Neutrino2020

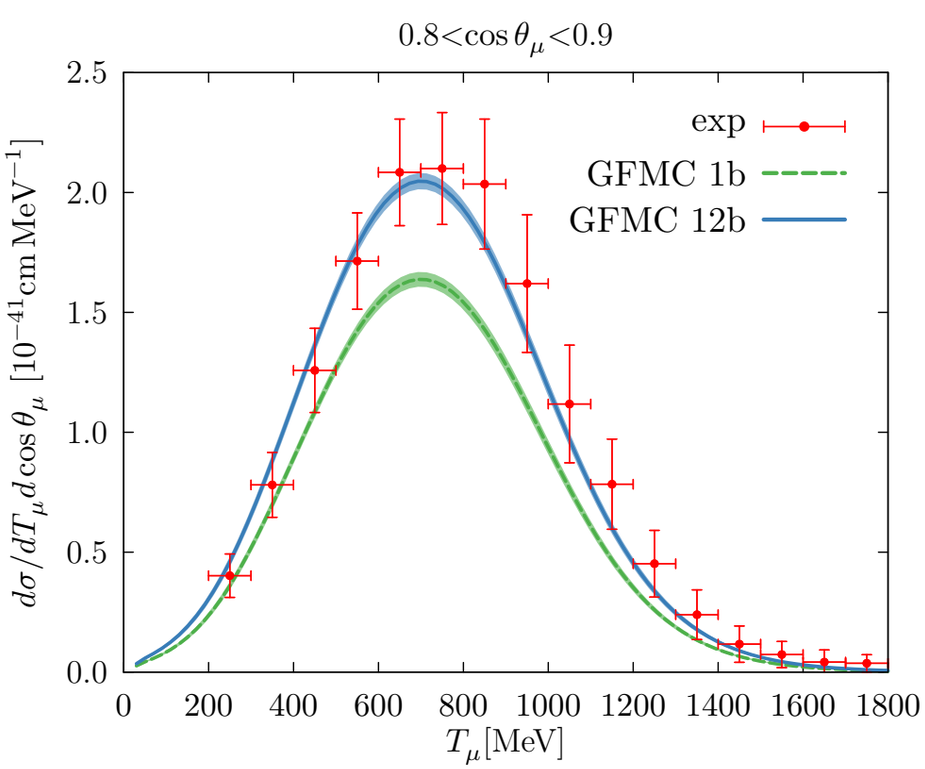


- **Test the accuracy** of the theoretical model and the event generator in the **electron sector** where the beam energy and scattering kinematics are known



Ankowski, Friedland PRD 102 (2020)

- Establish a validation procedure able to disentangle and separately test the different physical processes



- In the quasielastic region "virtually exact' predictions are obtained using ab-initio methods. Use them to quantify the **uncertainties inherent to the factorization of the final state** and have **more controlled approximations** of the many-body method

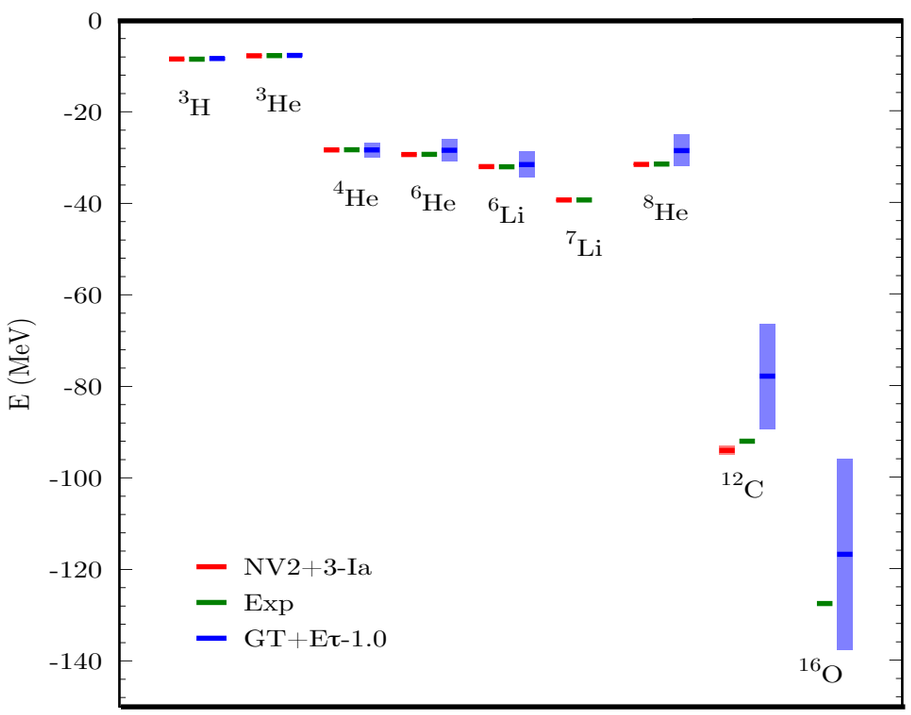
Lovato et al, PRX 10 (2020) 3

Physics opportunities

- Modular event generators—capitalize on the LHC experience— in which:

  Decouple the leptonic tensor from nuclear physics: allows to readily incorporate and test BSM scenarios

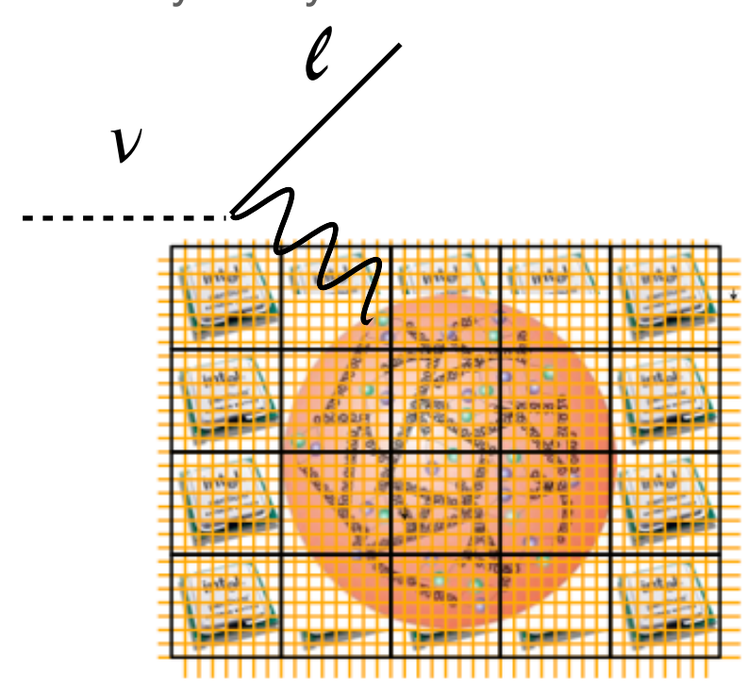
  Seamlessly use electron scattering data to perform common validation benchmarks and estimate the theoretical uncertainty



Gandolfi, Lonardoni et al, *Front.Phys.* 8 (2020) 117

- Estimate the **uncertainty of the theoretical calculation.**

- Combination of truncation of chiral-EFT expansion and numerical uncertainty of the many-body method



- **Interplay between Lattice-QCD and EFT:** nucleon form factors, inelastic electroweak transition amplitudes involving π crucial in the description of RES regions and in the cascade.

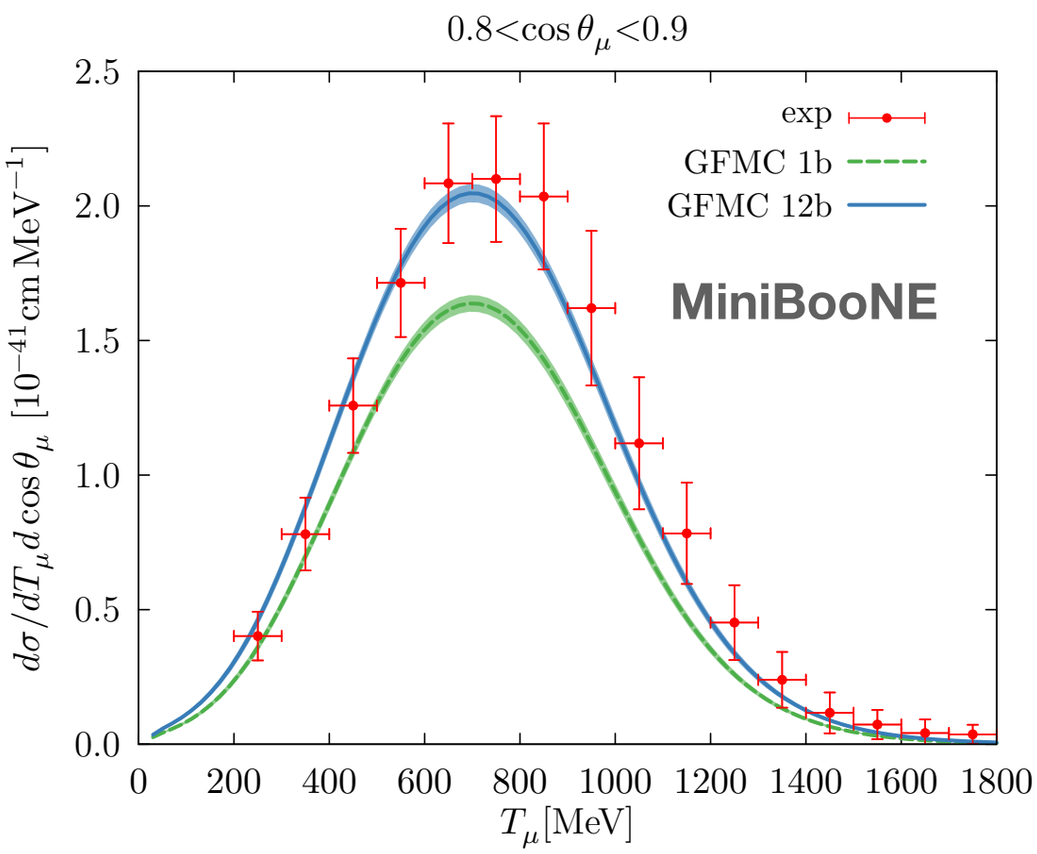
Thank you for your attention!

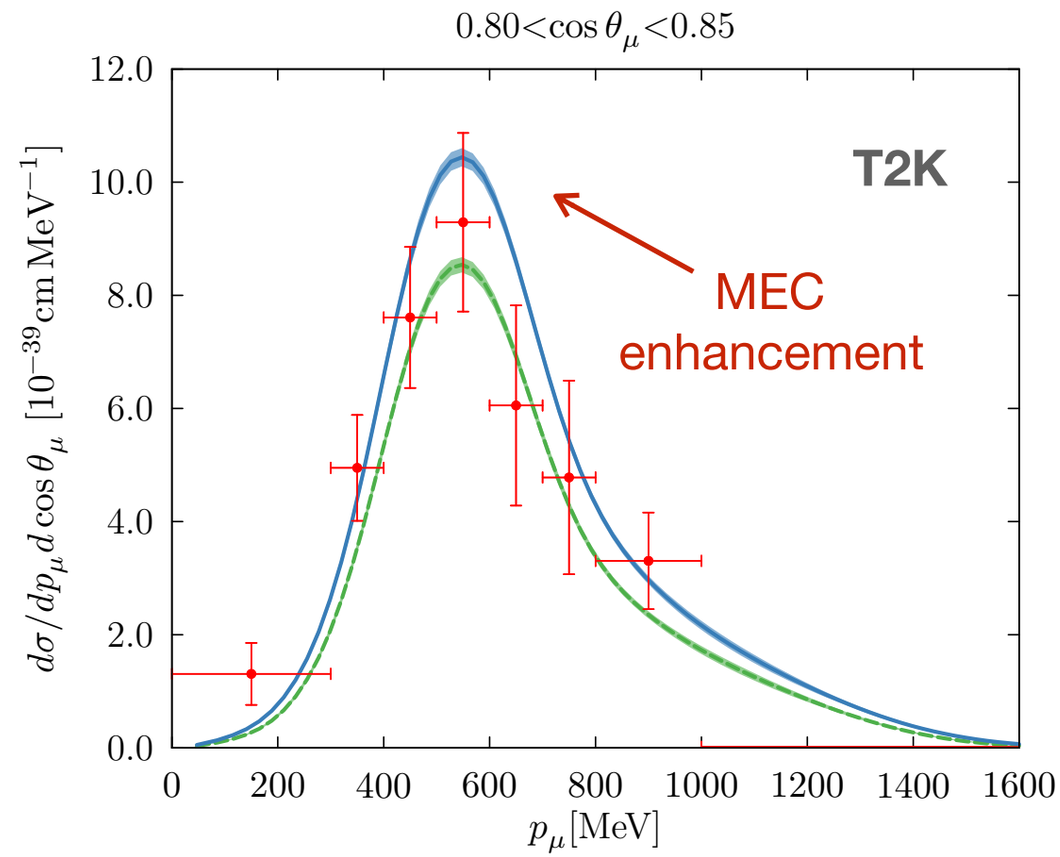
Green's Function Monte Carlo

Virtually exact results for **inclusive** nuclear electroweak responses in the **quasi-elastic region** up to moderate values of **q**.
Initial and **final state interactions** fully accounted for.

Computational cost grows exponentially with the number of particles: currently limited to ^{12}C

✐A.Lovato, NR, et al, arXiv:2003.07710, PRX in press



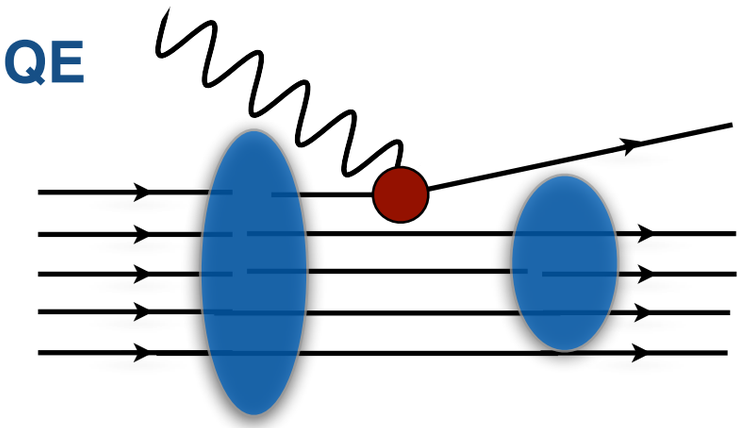


- Two-body currents are needed in the quasi-elastic to reproduce ν data
- Within the GFMC it is difficult to include fully-relativistic kinematics and currents.

Factorization Scheme and Spectral Function

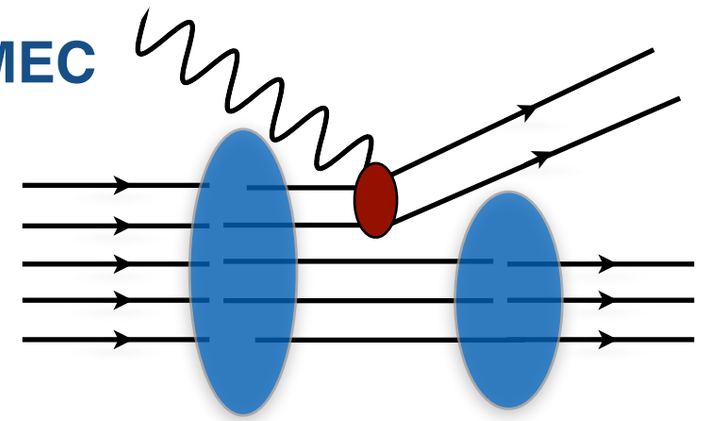
For sufficiently large values of |**q**|, the **factorization scheme** can be applied

QE



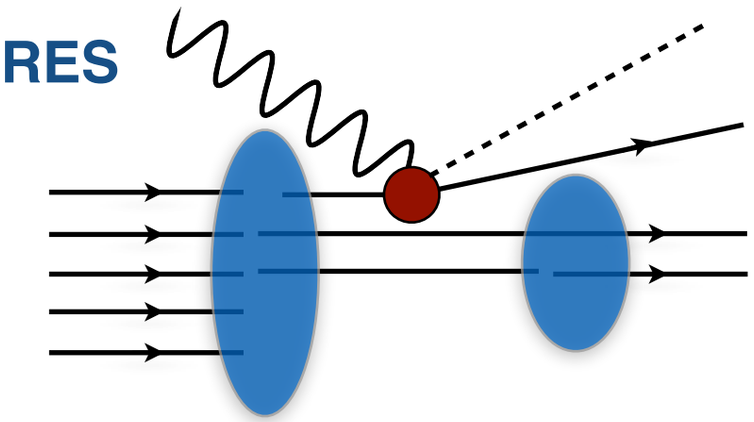
$$|f\rangle \to |p\rangle \otimes |f_{A-1}\rangle$$

MEC



$$|f\rangle \to |pp'\rangle_a \otimes |f_{A-2}\rangle$$

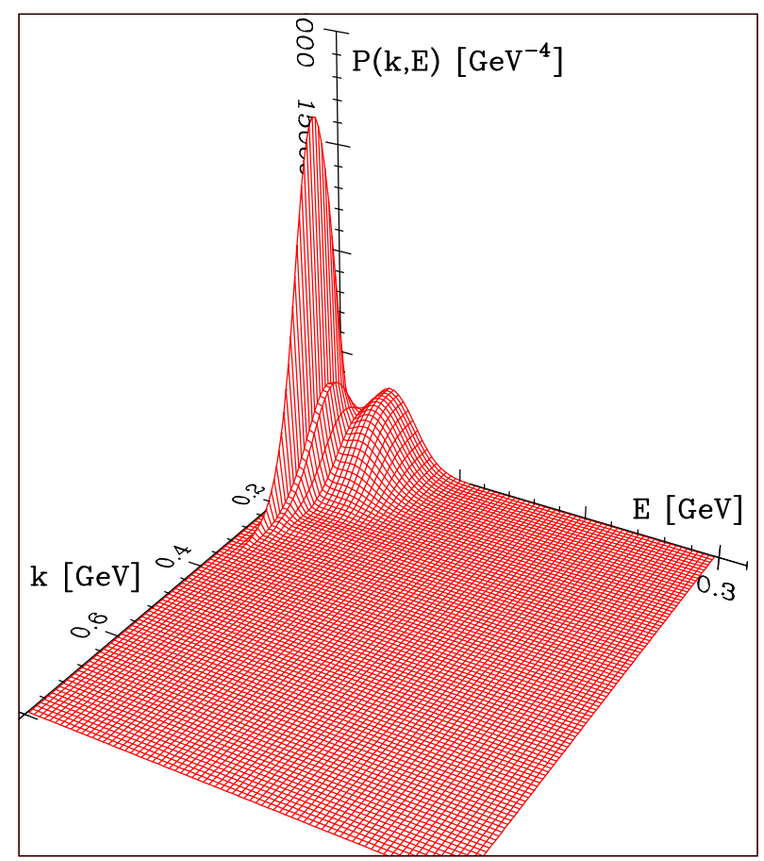
RES



$$|f\rangle \to |p_\pi p\rangle \otimes |f_{A-1}\rangle$$

The intrinsic properties of the nucleus are described by the **Spectral Function**→ effective field theory and nuclear many-body methods

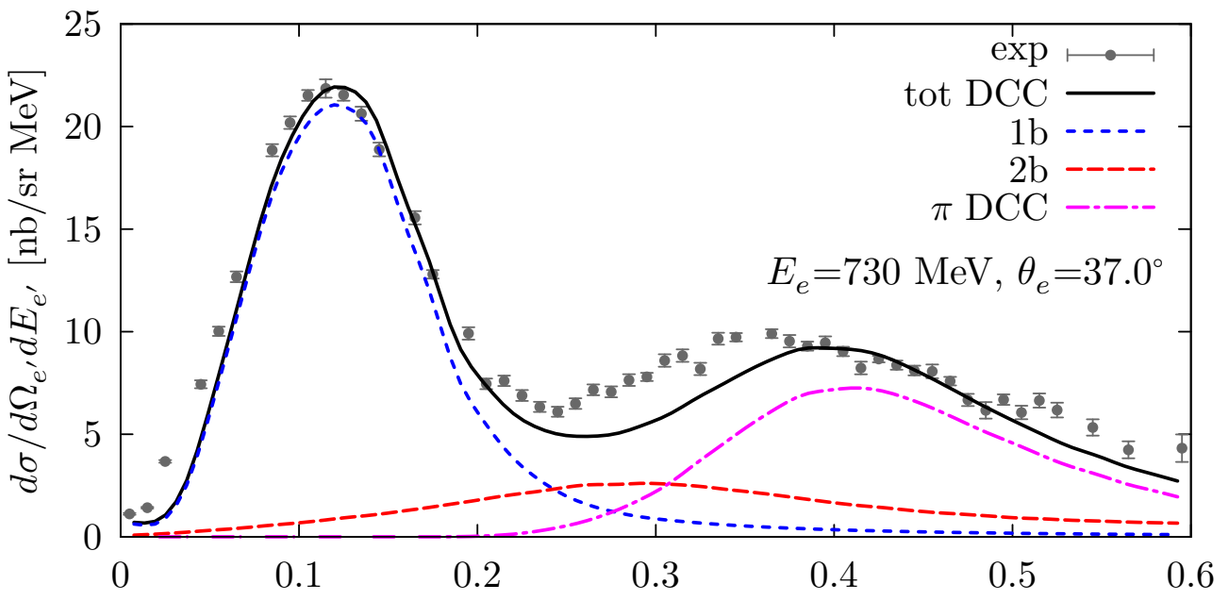
$$d\sigma_A = \int dE d^3k \; d\sigma_N P(\mathbf{k}, E)$$

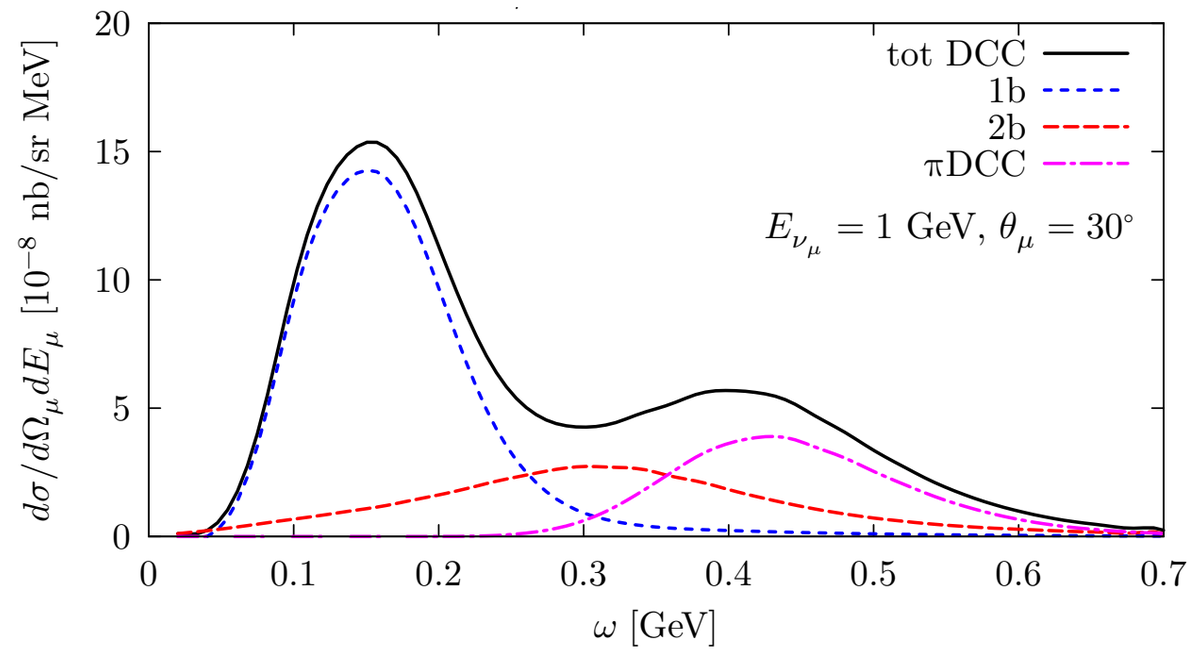


✐ O. Benhar, A. Fabrocini, and S. Fantoni, Nucl. Phys. A505, 267 (1989).

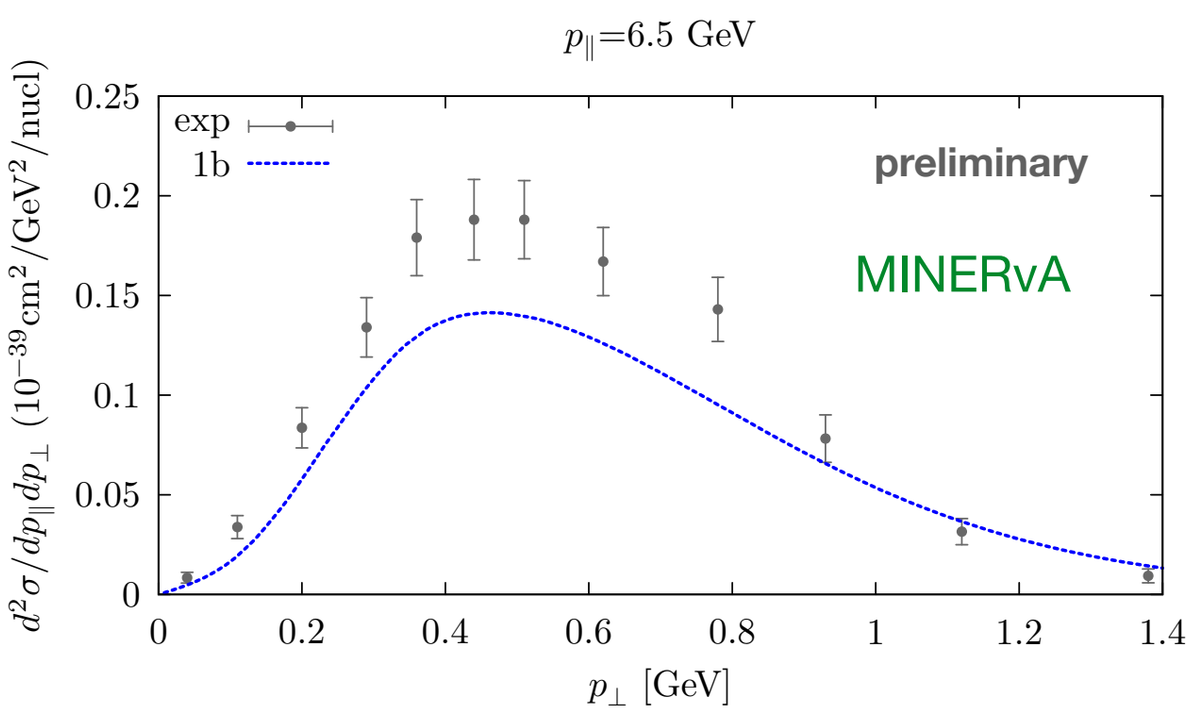
Factorization Scheme and Spectral Function

✐ NR, et al, Phys. Rev. C 100 (2019) no.4, 045503



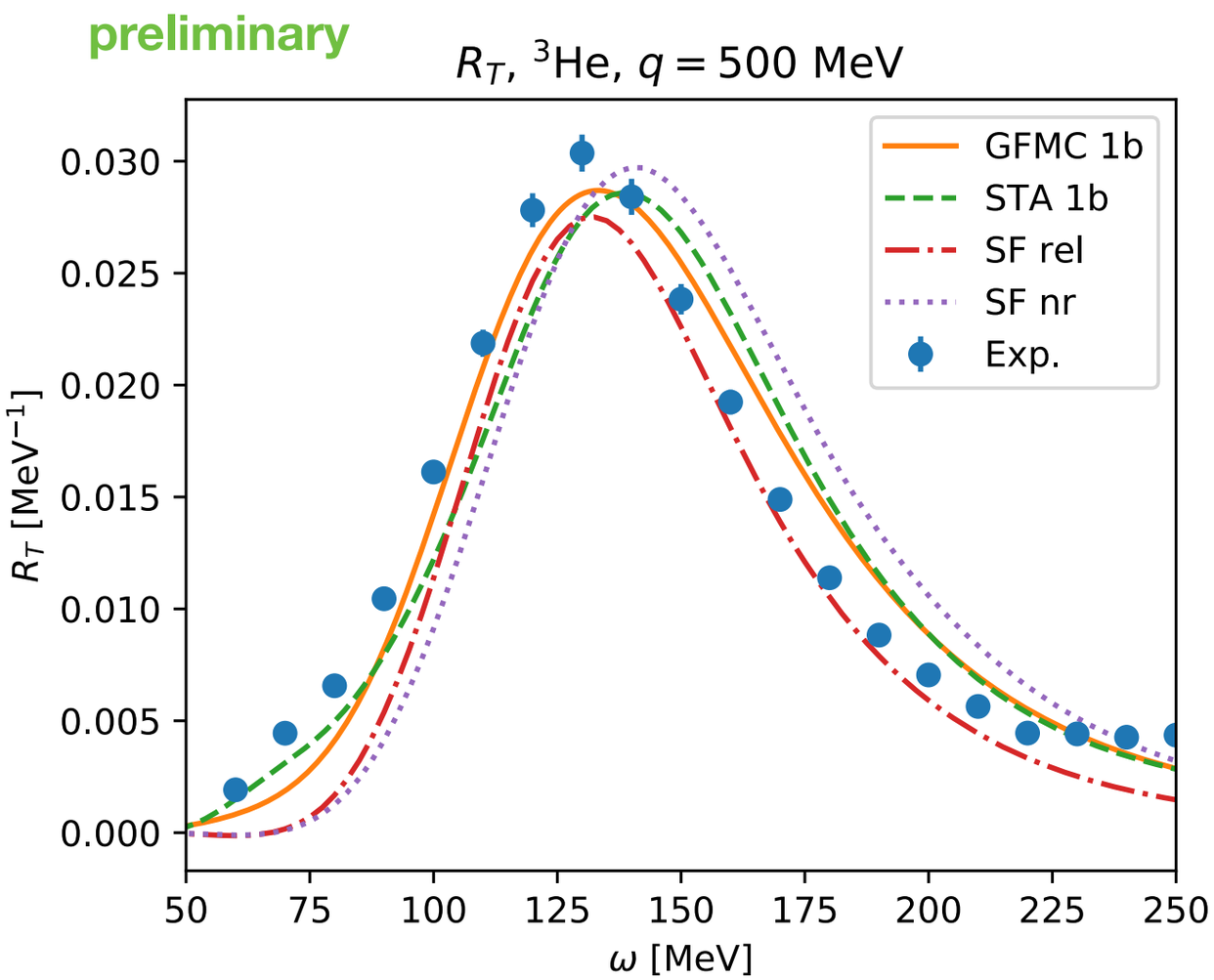


- Spectral function formalism including the **one-** and **two-body current** contributions and the **pion production** amplitudes (ANL-Osaka model) for electron and neutrino ^{12}C-scattering



Preliminary comparison with CC0π data on ^{12}C from MINERvA using μ kinematics. Only the one body current operator has been included. Next steps: **inclusion of MEC and π production and absorption**

Future experiments and theory efforts



- Comparisons among QMC, SF, and STA approaches to precisely quantify the **uncertainties inherent to the factorization of the final state**. Determine the importance of relativistic effects in the whole energy region relevant for oscillation experiments.
- Use the STA and the SF methods to attain information on the hadronic final states and on the response densities to **tackle exclusive processes** and achieve a consistent treatment of the different reaction mechanisms including **resonance and pion-production**

- Implement these microscopic approaches in commonly used **event generators**. Perform extensive **validation with electron scattering data**, and use the attained information to accurately study neutrino-scattering and precisely compare with experiments.