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Lepton-nucleus interactions within the spectral function approach

Noemi Rocco

NuFact 2021: The 22nd International Workshop on Neutrinos from Accelerators
Working Group 2
September 9th, 2021

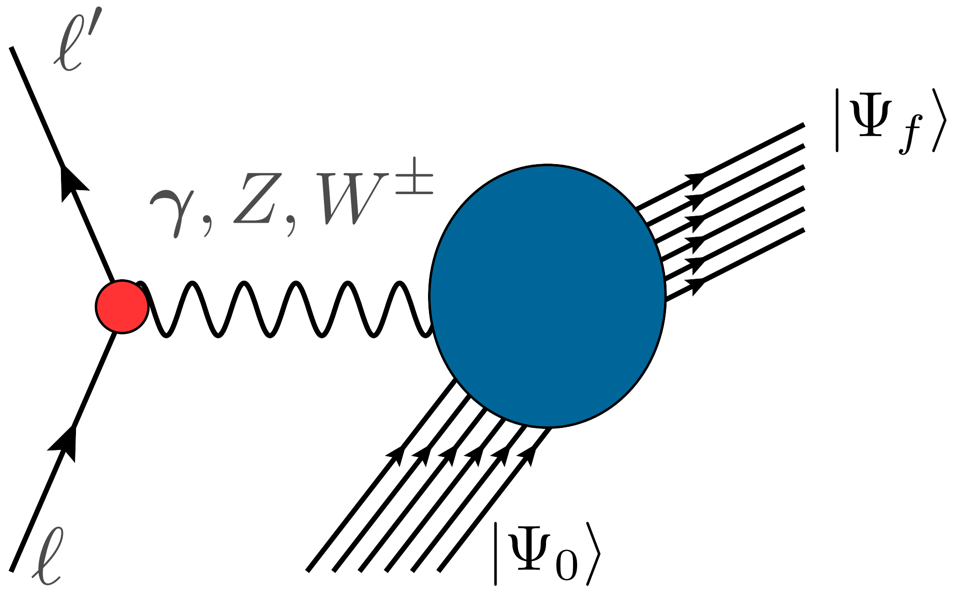
Theory of lepton-nucleus scattering

- The cross section of the process in which a lepton scatters off a nucleus is given by

$$d\sigma \propto L^{\alpha\beta} R_{\alpha\beta}$$

Leptonic Tensor: can include new physics models

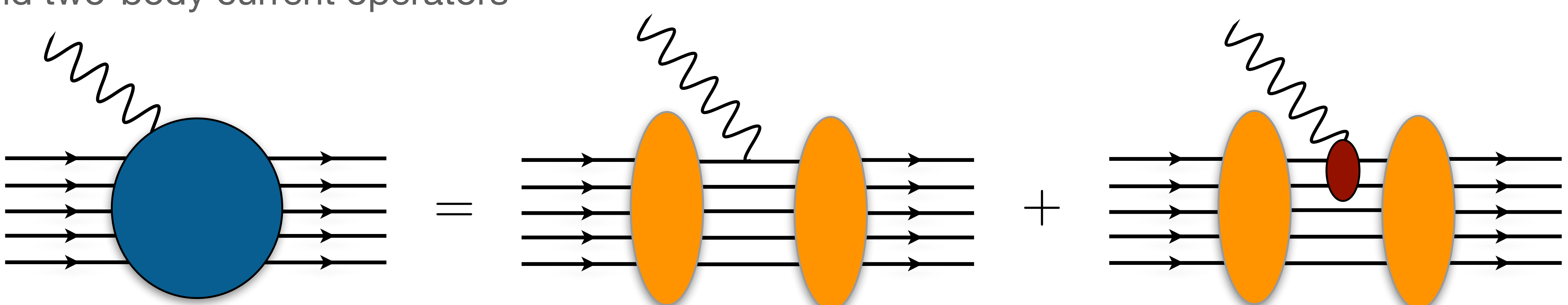
Hadronic Tensor: nuclear response function



The initial and final wave functions describe many-body states:

$$|0\rangle = |\Psi_0^A\rangle \;, |f\rangle = |\Psi_f^A\rangle, |\psi_p^N, \Psi_f^{A-1}\rangle, |\psi_k^\pi, \psi_p^N, \Psi_f^{A-1}\rangle \dots$$

One and two-body current operators



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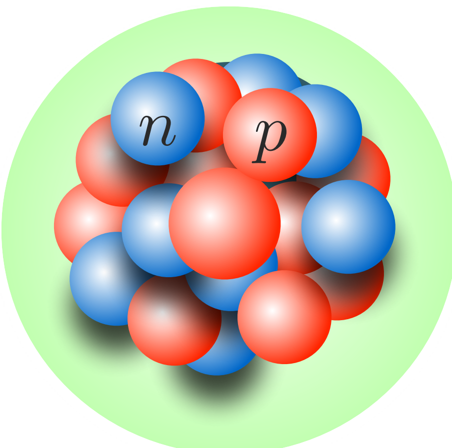
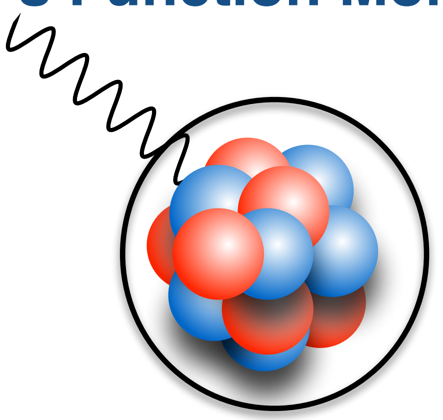
The basic model of nuclear theory



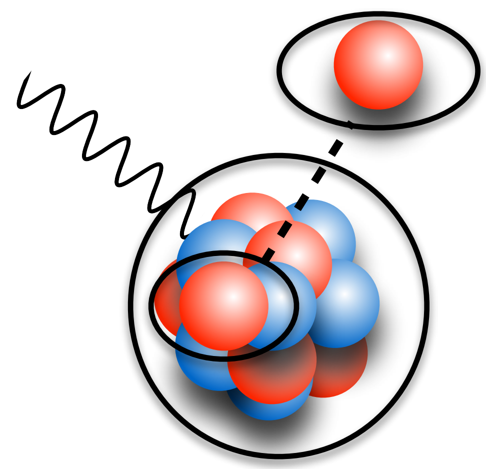
At low energy, the effective degrees of freedom are pions and nucleons:

$$H = \sum_i \frac{\mathbf{p}_i^2}{2m} + \sum_{i<j} v_{ij} + \sum_{i<j<k} V_{ijk} + \dots$$

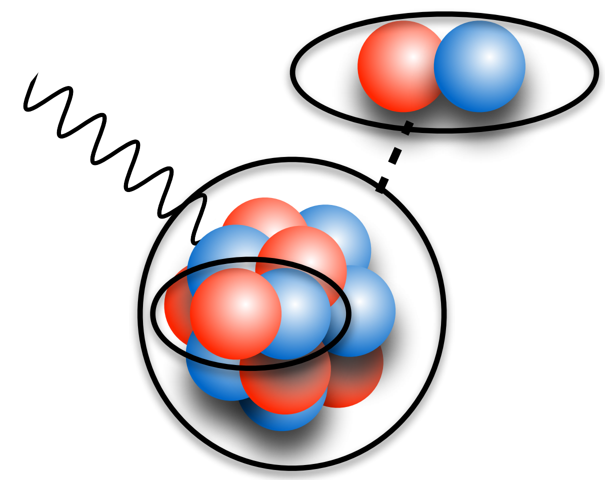
Green's Function Monte Carlo



Spectral Function (SF)

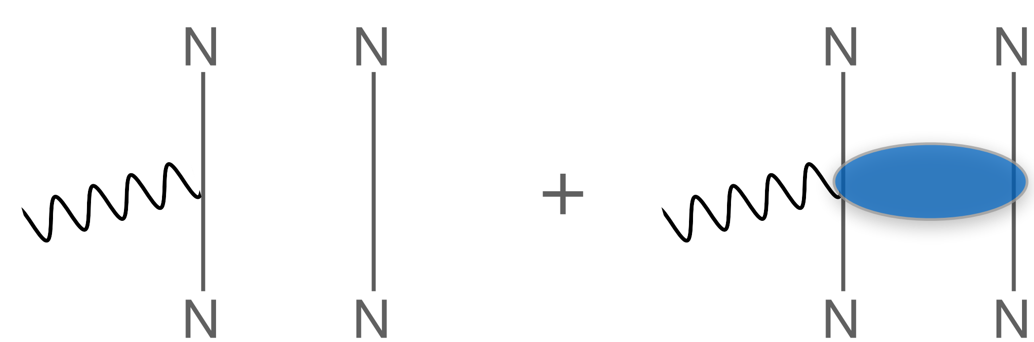


Short-time Approximation (STA)



The electromagnetic current is constrained by the Hamiltonian through the **continuity equation**

$$J^\mu(q) = \sum_i j_i^\mu + \sum_{i<j} j_{ij}^\mu + \dots$$



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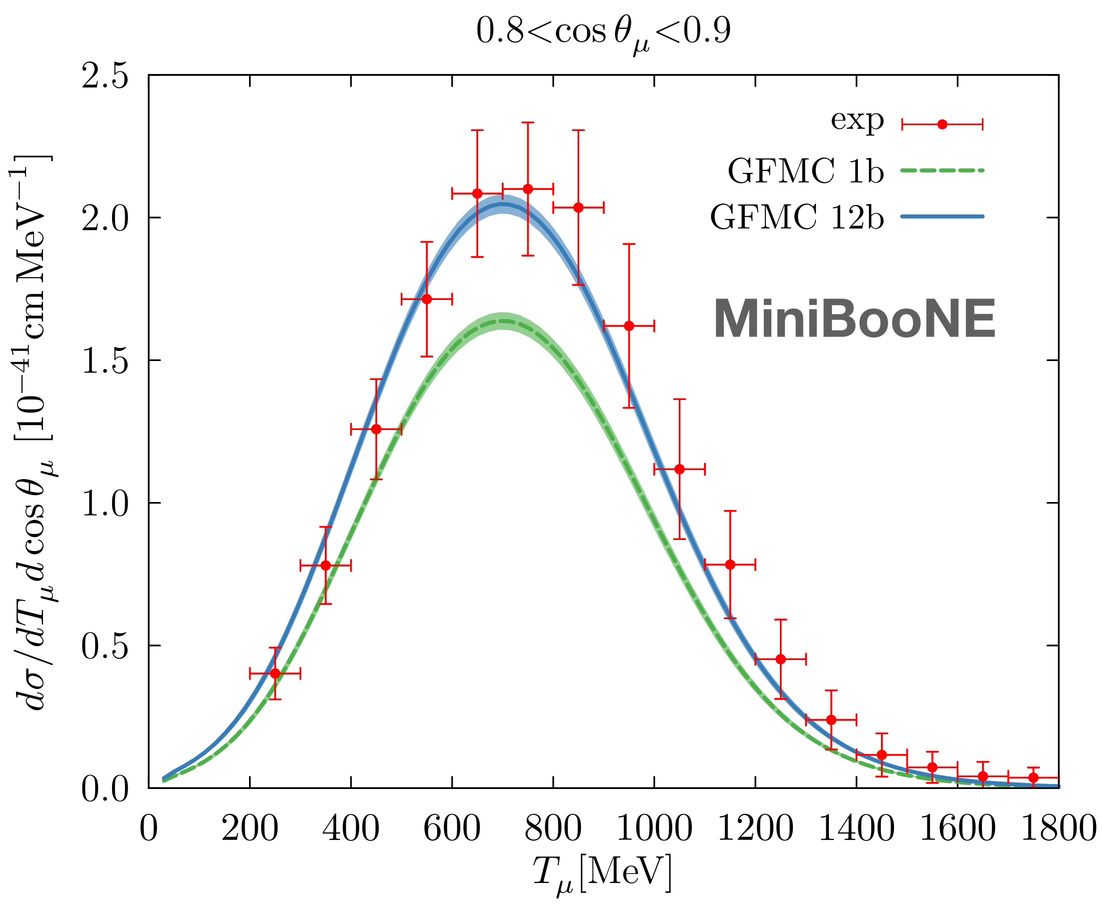
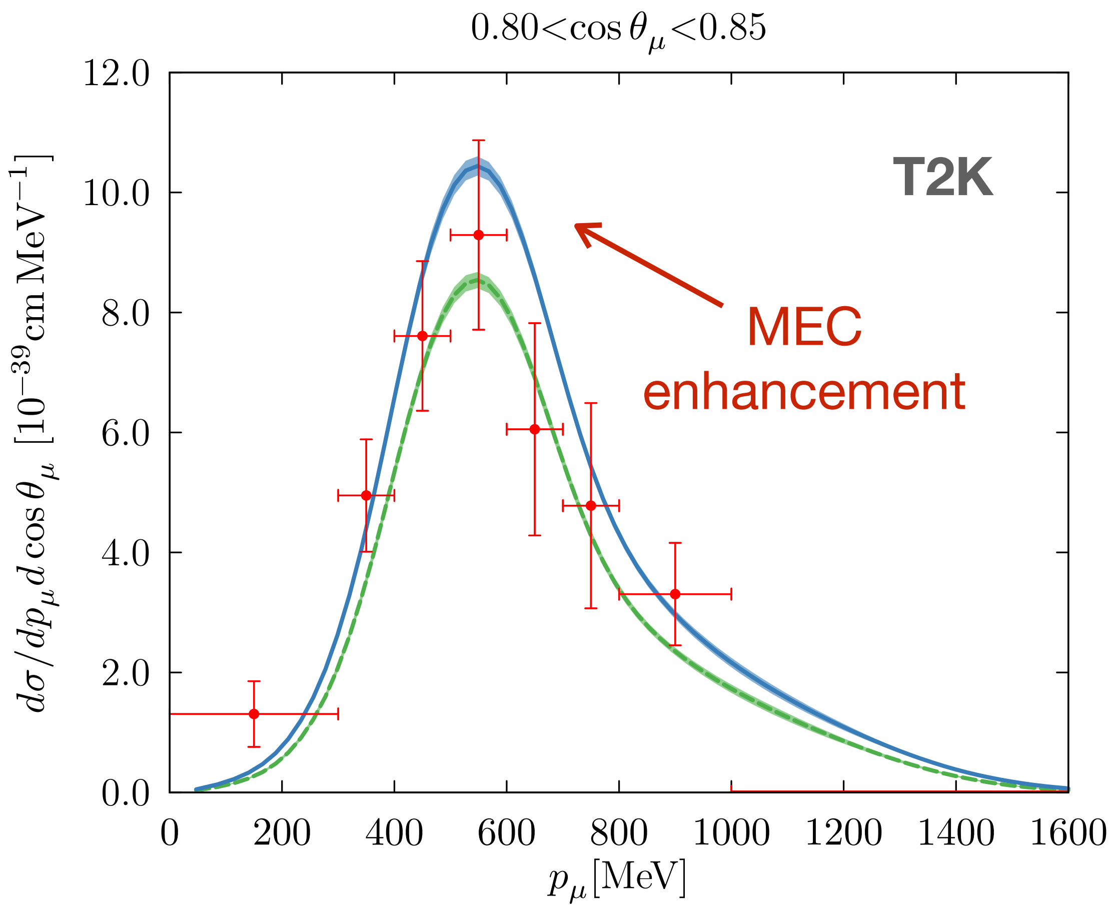
Cross sections: Green's Function Monte Carlo

GFMC accurately obtain the properties of nuclei to ^{12}C using high performance computing

Exact results for ν-cross sections in the **quasi-elastic region** up to moderate values of **q**.

✐A.Lovato, NR et al, Phys.Rev.X 10 (2020) 3, 031068





Limitations: high energy regions, pions can not be explicitly included

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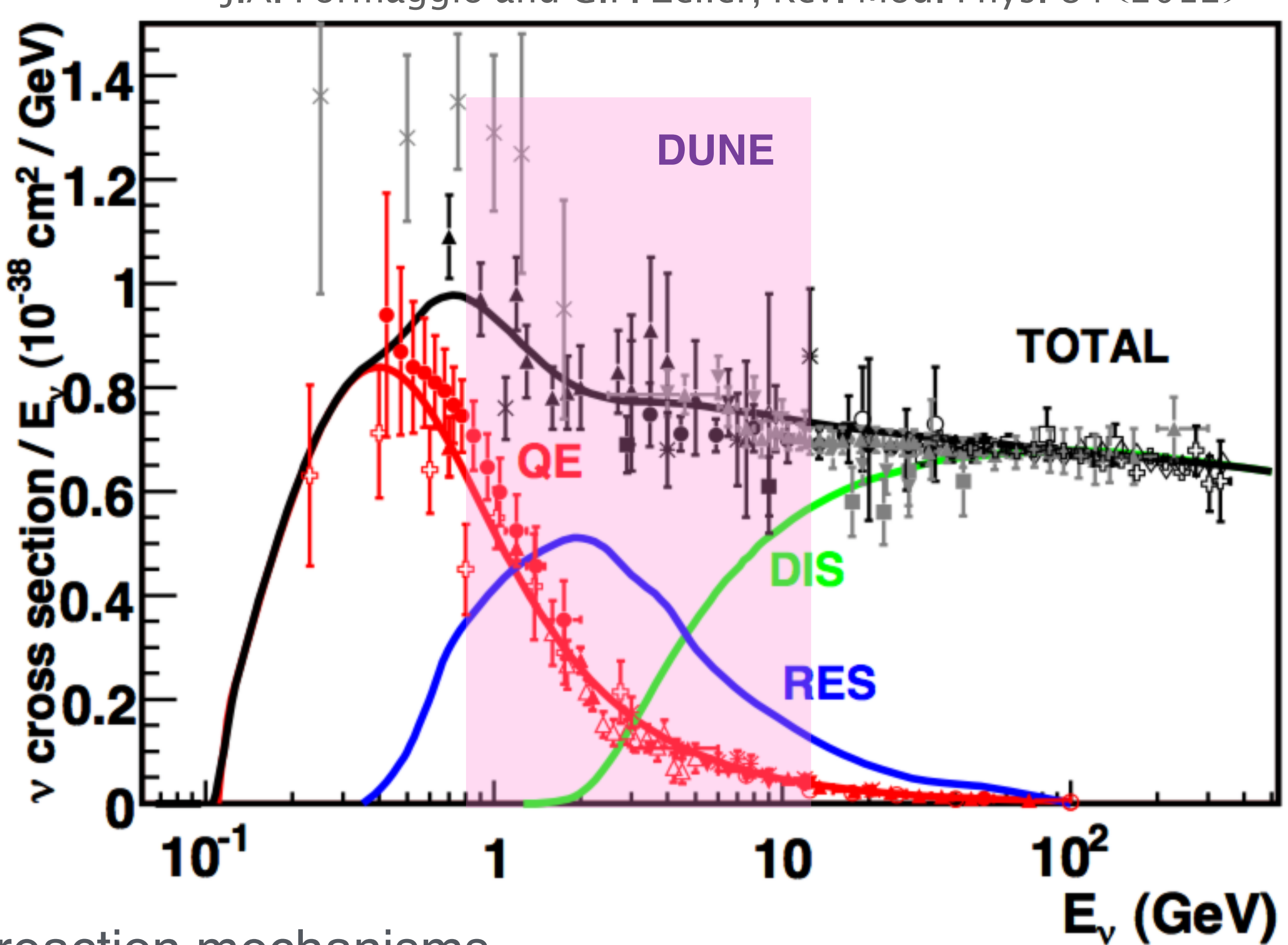
Addressing Neutrino-Oscillation Physics

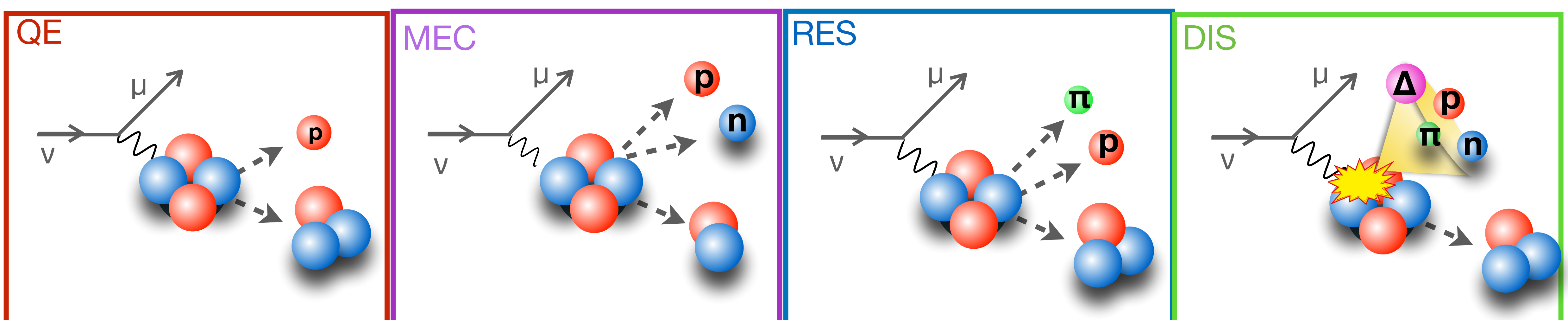
Unprecedented accuracy in the determination of **neutrino-argon cross section** is required to achieve design sensitivity to CP violation at DUNE

Current oscillation experiments report **large systematic uncertainties** associated with the neutrino- nucleus interaction models.

J.A. Formaggio and G.P. Zeller, Rev. Mod. Phys. 84 (2012)



Nuclei are complicated objects. Many different reaction mechanisms



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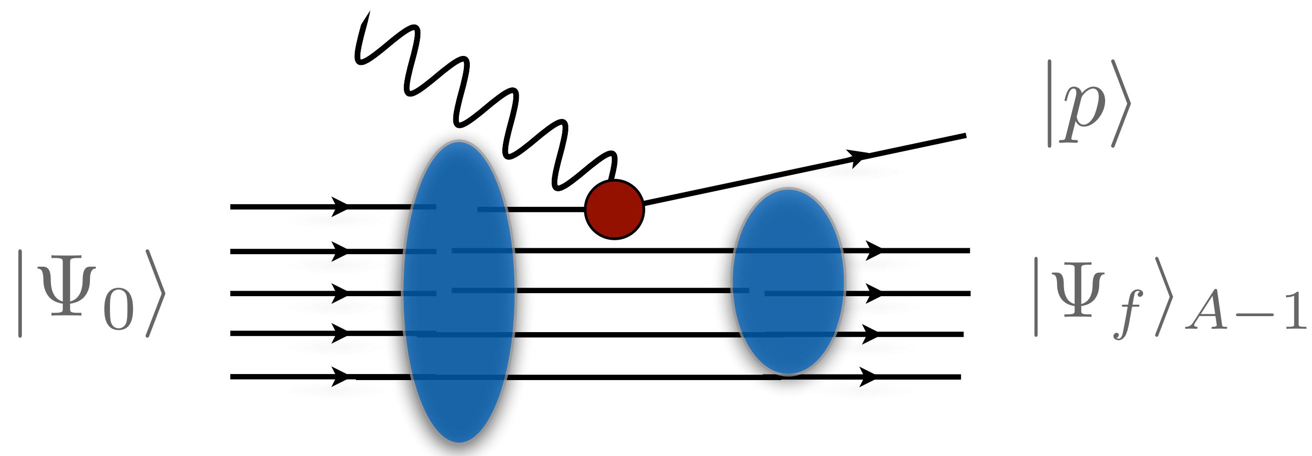
Cross sections: Spectral function approach

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

$$|\Psi_f\rangle \to |p\rangle \otimes |\Psi_f\rangle_{A-1}$$

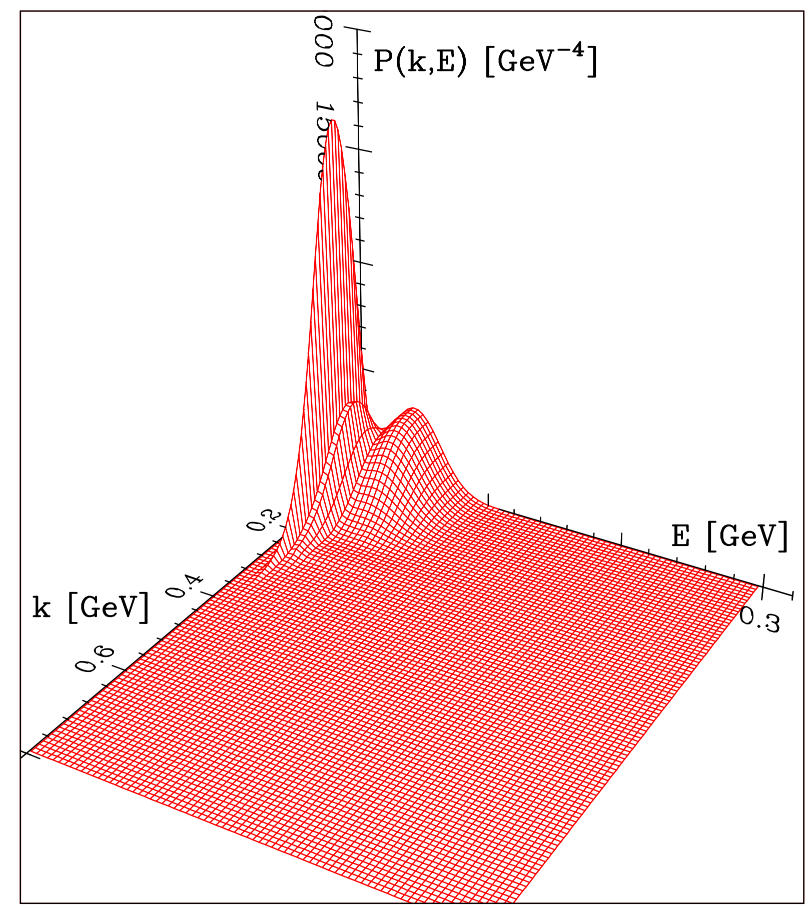
$$J_\alpha = \sum_i j_\alpha^i$$



The nuclear cross section is given in terms of the one describing the interaction with individual bound nucleons

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

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



O. Benhar et al, Rev.Mod.Phys. 80 (2008)

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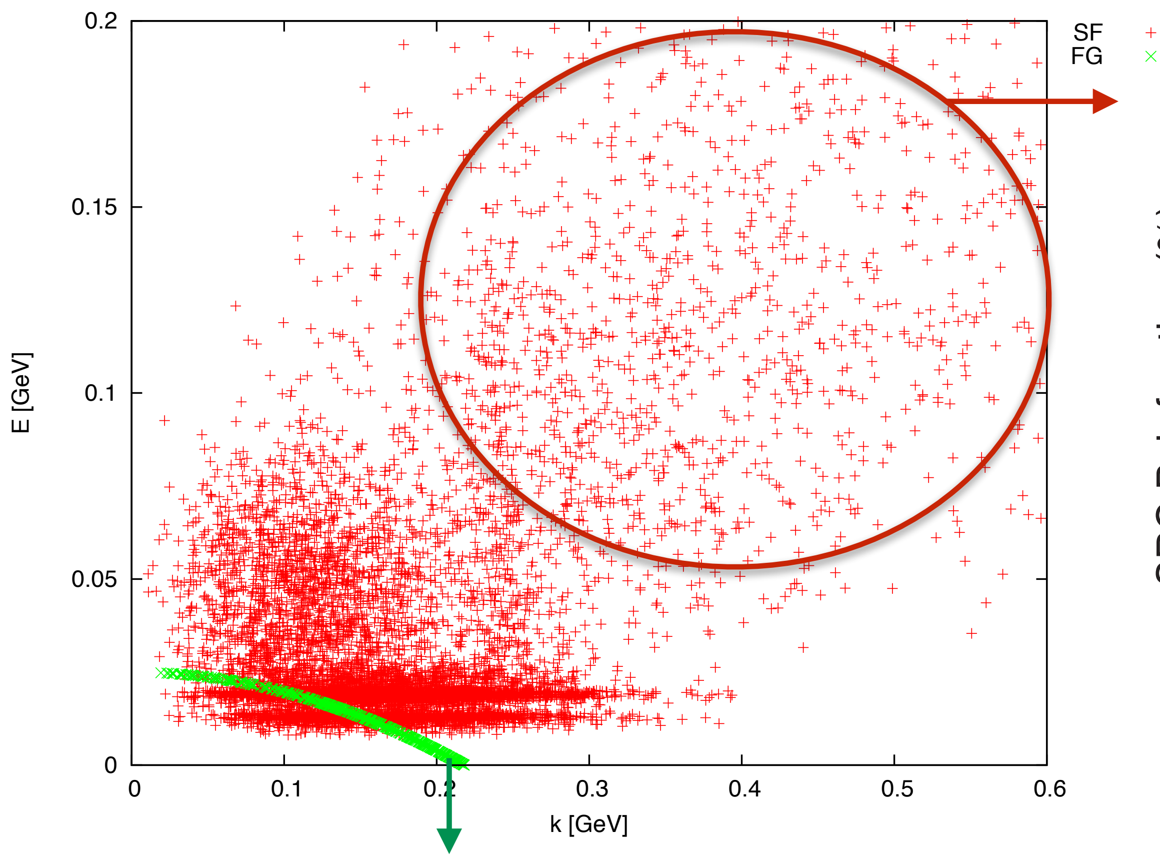
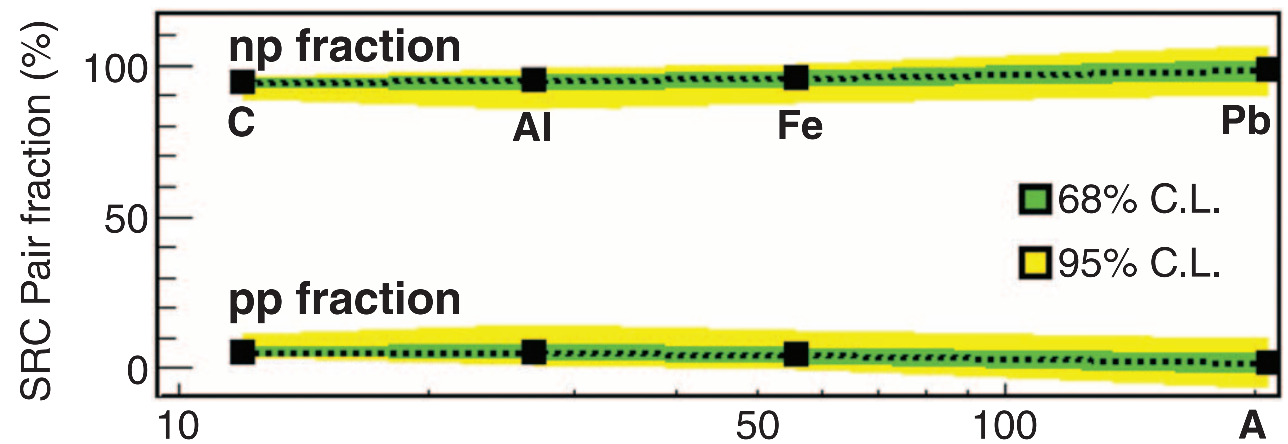
Cross sections: Spectral function approach

The one-nucleon Spectral function is the imaginary part of the **two-point Green's Function**



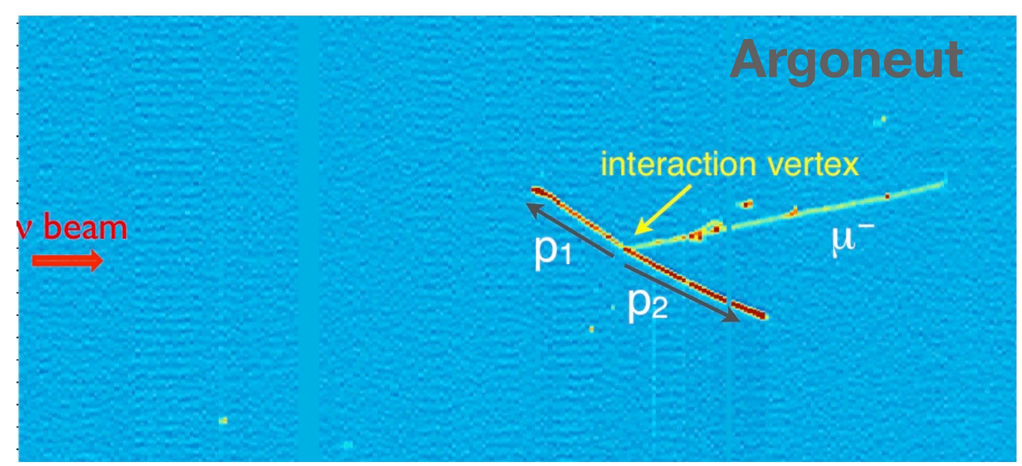
High energy and momentum correlated pairs

Fermi gas contribution



Observed **dominance of np-over-pp** pairs

Neutrino experiments are becoming more and more sensitive to the complexity of nuclear dynamics.



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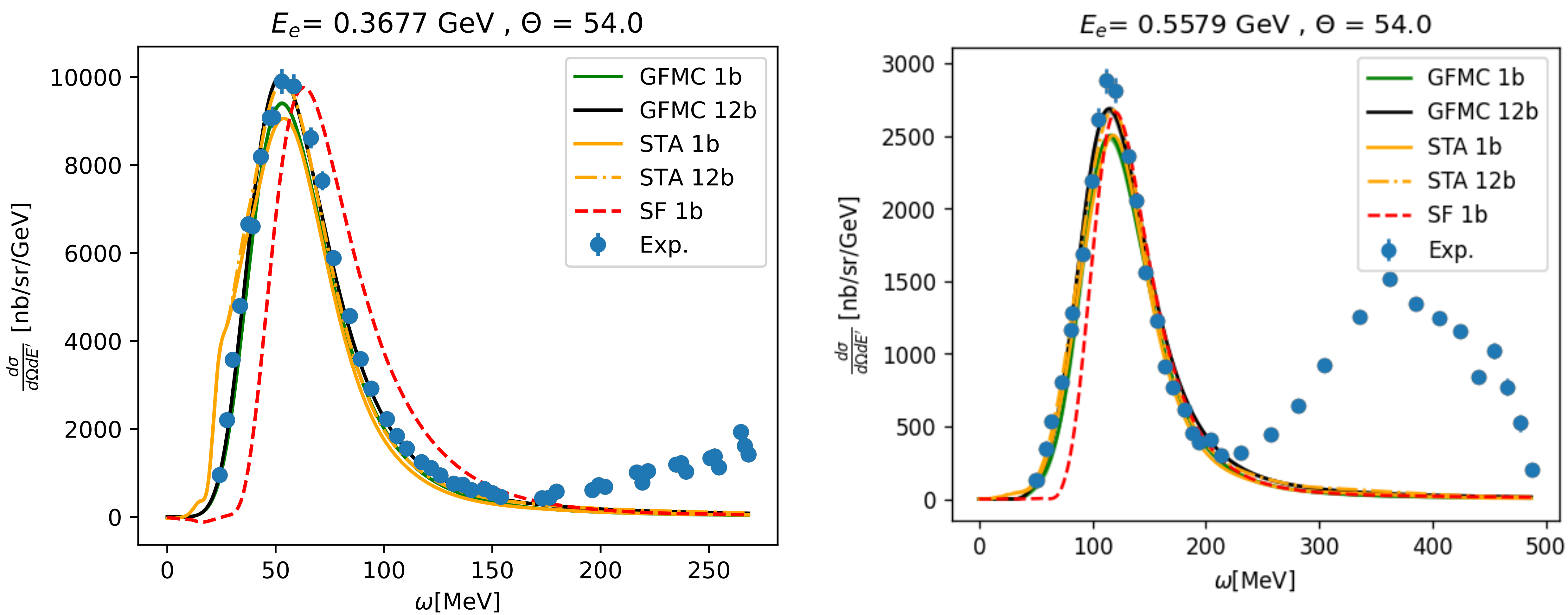
Comparing different many-body methods

- e -^{3}H: inclusive cross section

L. Andreoli, J. Carlson, A. Lovato, S. Pastore, NR, arXiv::2108.10824



- Comparisons among QMC, SF, and STA approaches: first step to precisely **quantify the uncertainties i**nherent to the factorization of the final state.

- Gauge the role of **relativistic effects** in the energy region relevant for neutrino experiments.

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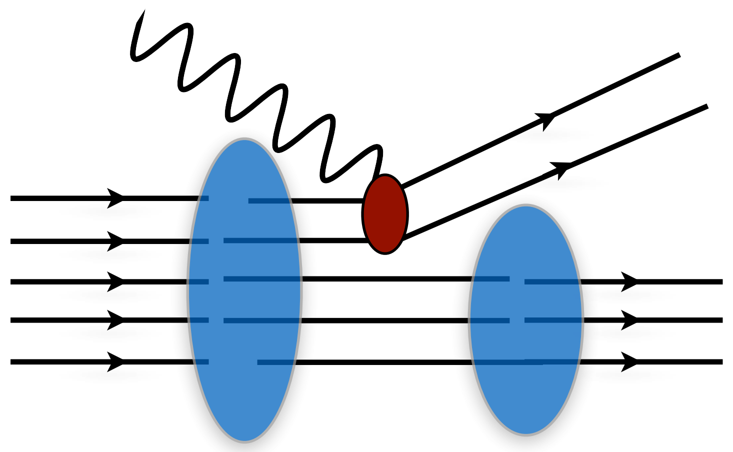
Extended Factorization Scheme

- Two-body currents are included rewriting the hadronic final state as

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



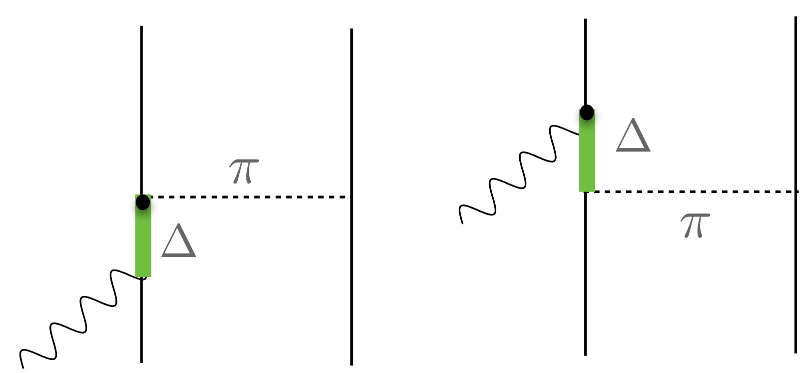
The hadronic tensor for two-body current processes reads

$$W^{\mu\nu}_{2b}(\mathbf{q},\omega) \propto \int dE \frac{d^3k}{(2\pi)^3}\frac{d^3k'}{(2\pi)^3}\frac{d^3p}{(2\pi)^3} P_h(\mathbf{k},\mathbf{k}',E)\, 2\sum_{ij} \langle k\, k'|j^{\mu\,\dagger}_{ij}|p\, p'\rangle_a$$
$$\times \langle p\, p'|j^{\nu}_{ij}|k\, k'\rangle \delta(\omega - E + 2m_N - e(\mathbf{p}) - e(\mathbf{p}')) .$$

✎ NR et al, Phys.Rev. C99 (2019) no.2, 025502

✎ NR et al, Phys. Rev. Lett. 116, 192501 (2016)

Relativistic two-body currents



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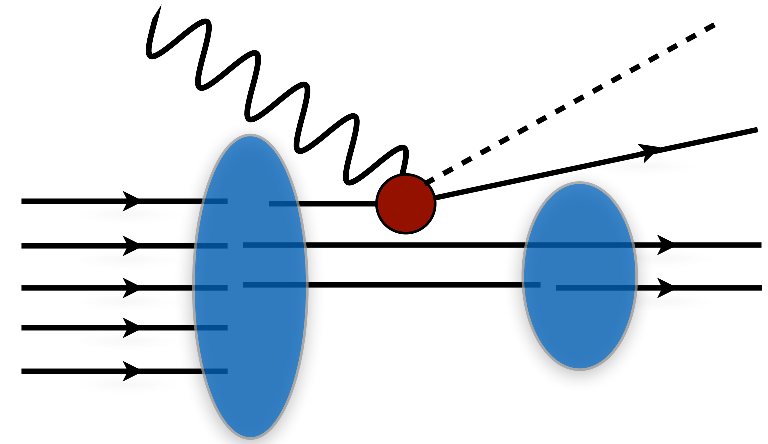
Extended Factorization Scheme

- Production of real π in the final state

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



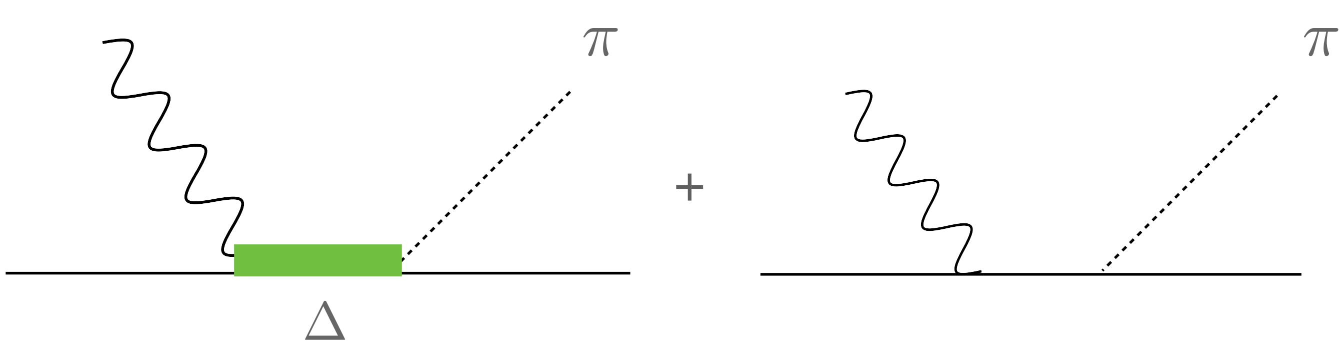
The hadronic tensor for two-body current processes reads

$$W^{\mu\nu}_{1b1\pi}(\mathbf{q},\omega) \propto \int \frac{d^3k}{(2\pi)^3} dE P_h(\mathbf{k},E) \frac{d^3p_\pi}{(2\pi)^3} \sum_i \langle k|j_i^{\mu\,\dagger}|p_\pi p\rangle\langle p_\pi p|j_i^\nu|k\rangle$$

$$\times\, \delta(\omega - E + m_N - e(\mathbf{p}) - e_\pi(\mathbf{p}_\pi))$$

Pion production elementary amplitudes derived within the extremely sophisticated **Dynamic Couple Chanel approach**; includes meson baryon channel and nucleon resonances up to W=2 GeV

- The diagrams considered resonant and non resonant π production



NR, et al, PRC100 (2019) no.4, 045503

H. Kamano et al, PRC 88, 035209 (2013)

S.X.Nakamura et al, PRD 92, 074024 (2015)

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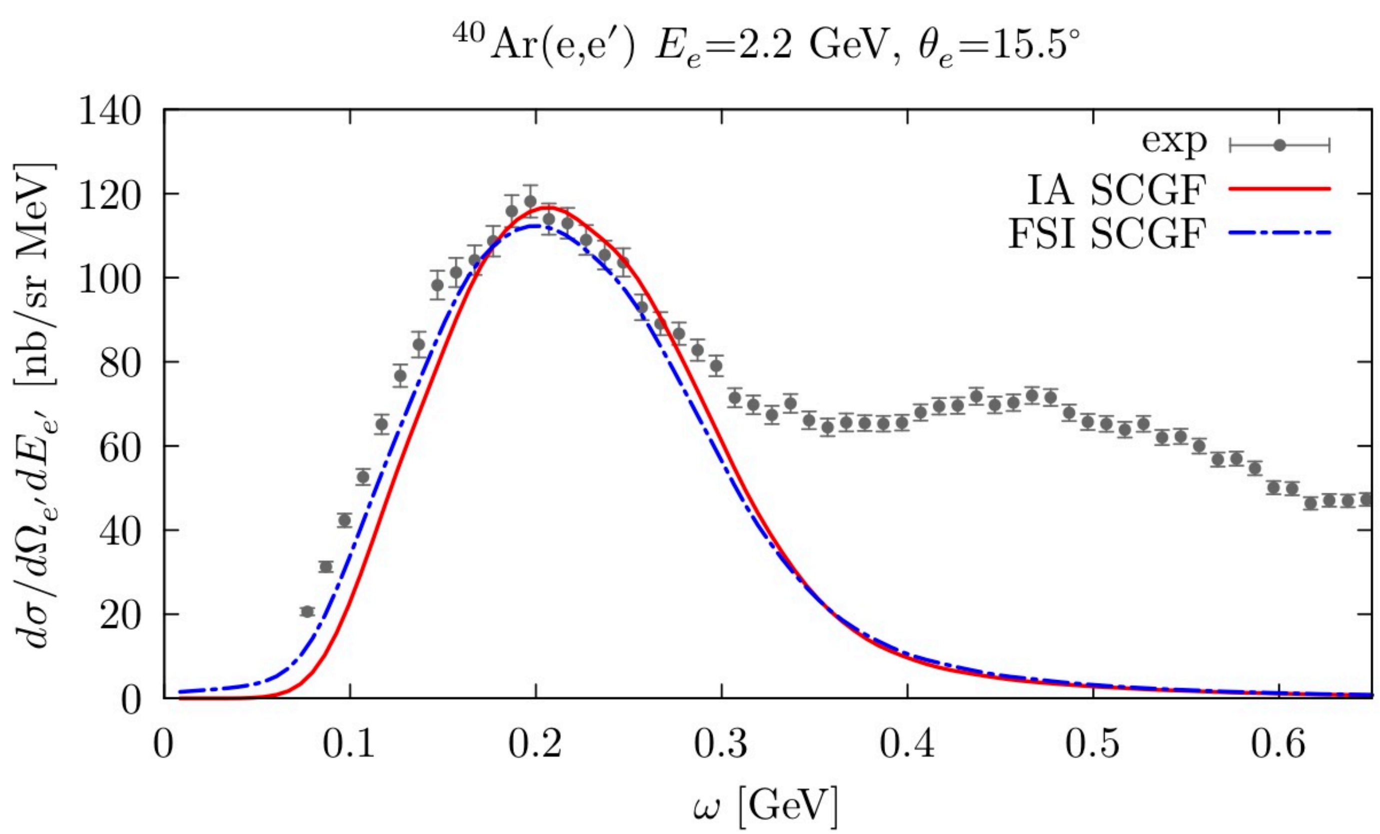
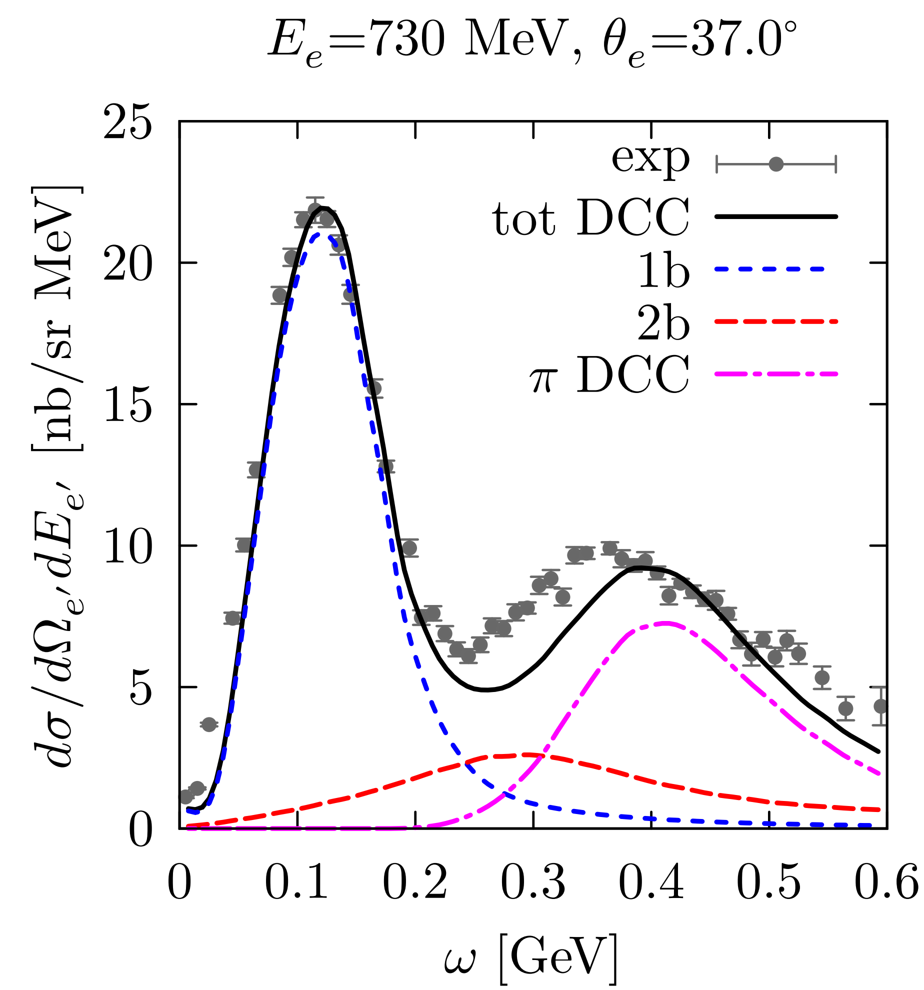
Cross sections: Spectral function approach

Spectral function formalism: unified framework able to describe the different reaction mechanisms retaining an accurate treatment of nuclear dynamics

- Work on **implementing the spectral function model in event generators** is currently ongoing

NR, Frontiers in Phys. 8 (2020) 116





- Good agreement with electron scattering data when all reaction mechanisms are included

Using electron scattering data to validate our predictions for ^{40}Ar

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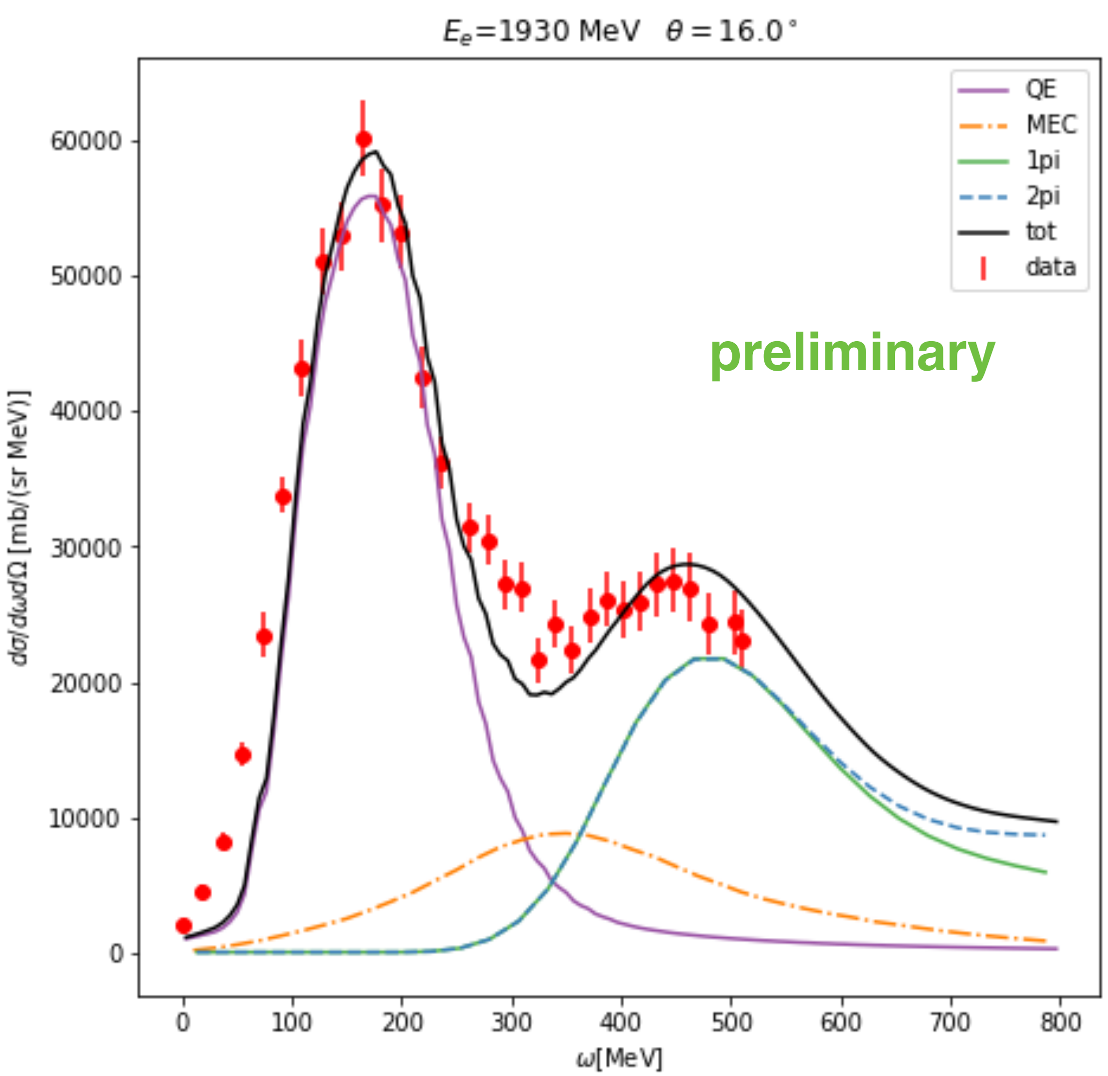
Cross sections: Spectral function approach

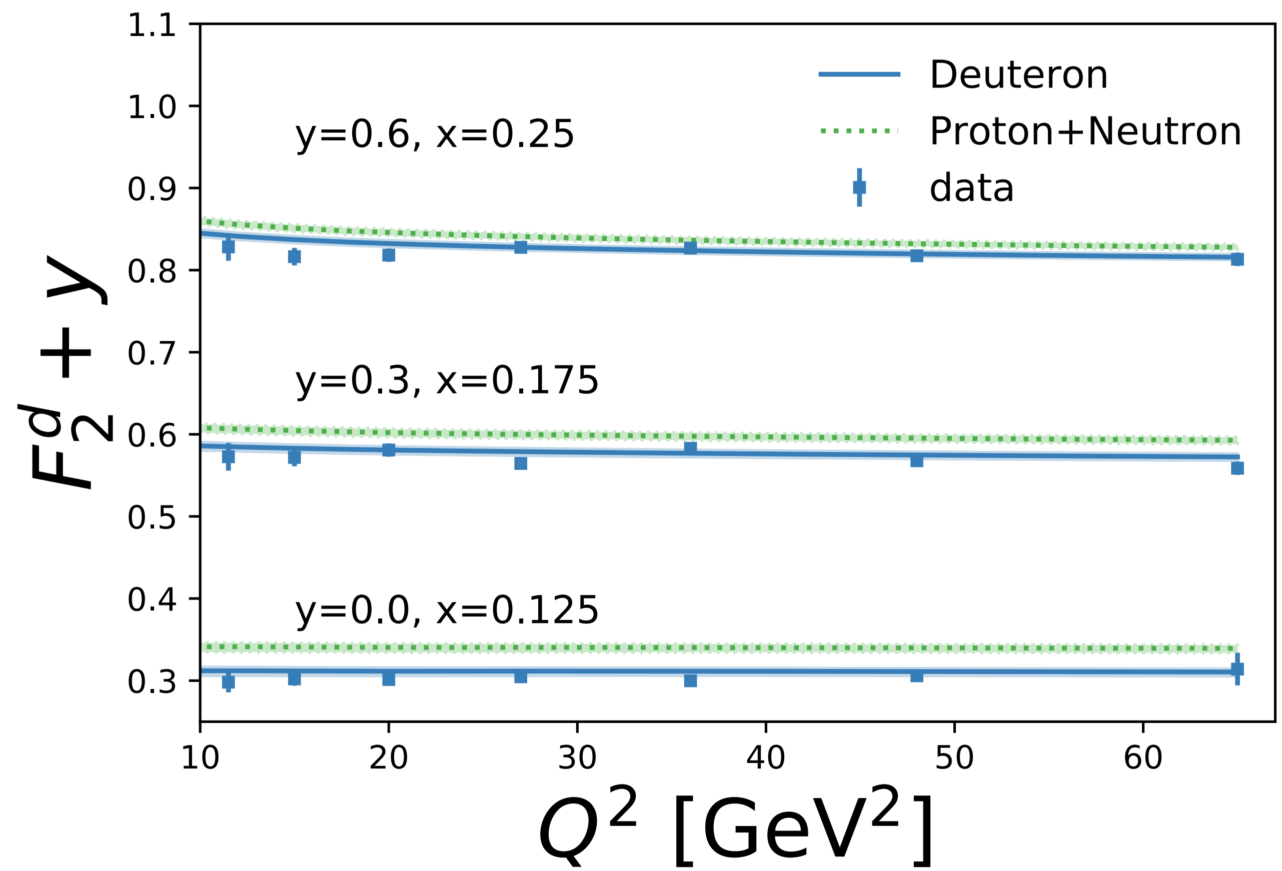
In preparation T. Sato, H. T-S Lee, O. Benhar, A. Lovato, N. Rocco



Inclusion of 2-pion production

Difficulties transition between RES-DIS

S. English, H. Haider, J. Isaacson, N. Rocco in preparation

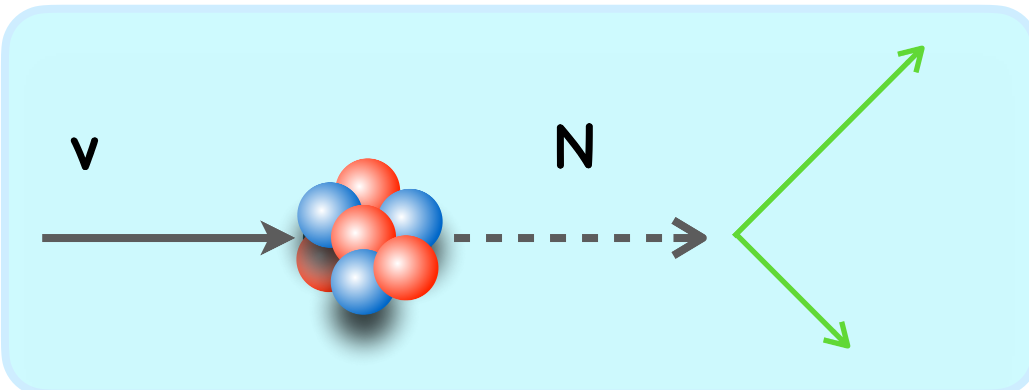


Deuteron electromagnetic structure function F_2 predictions for the DIS region. Convolution of the spectral function+nucleon pdf MMHT2014 at LO

Double Bang events from New Physics at DUNE

I. Martinez-Soler, NR, et al, arXiv:2105.09357

- New physics models allows for neutrinos to up-scatter into **heavier neutrino states N**



First bang: neutrino-nucleus interaction, production of heavy neutrino

Second bang: decay of heavy neutrino after propagating for some distance

- The number of DB events can be written as:

$$N_{DB} = \int dE_\nu dc_\theta \mathcal{B} \frac{d\phi_\nu}{dE_\nu dc_\theta} \frac{d\sigma_{\nu N}}{dE_\nu} P_d(L) V(L, c_\theta)$$

- $d\phi_\nu$ neutrino flux
- $P_d(L) = e^{-L/L_{lab}}/L_{lab}$ probability of **N** decaying after traveling a distance *L*
- $\mathcal{B}$ *branching ratio into visible final states*
- $d\sigma_{\nu N}/dE_\nu$ differential cross section

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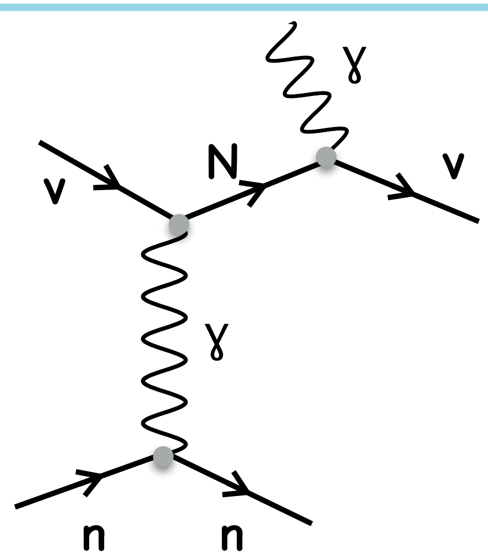
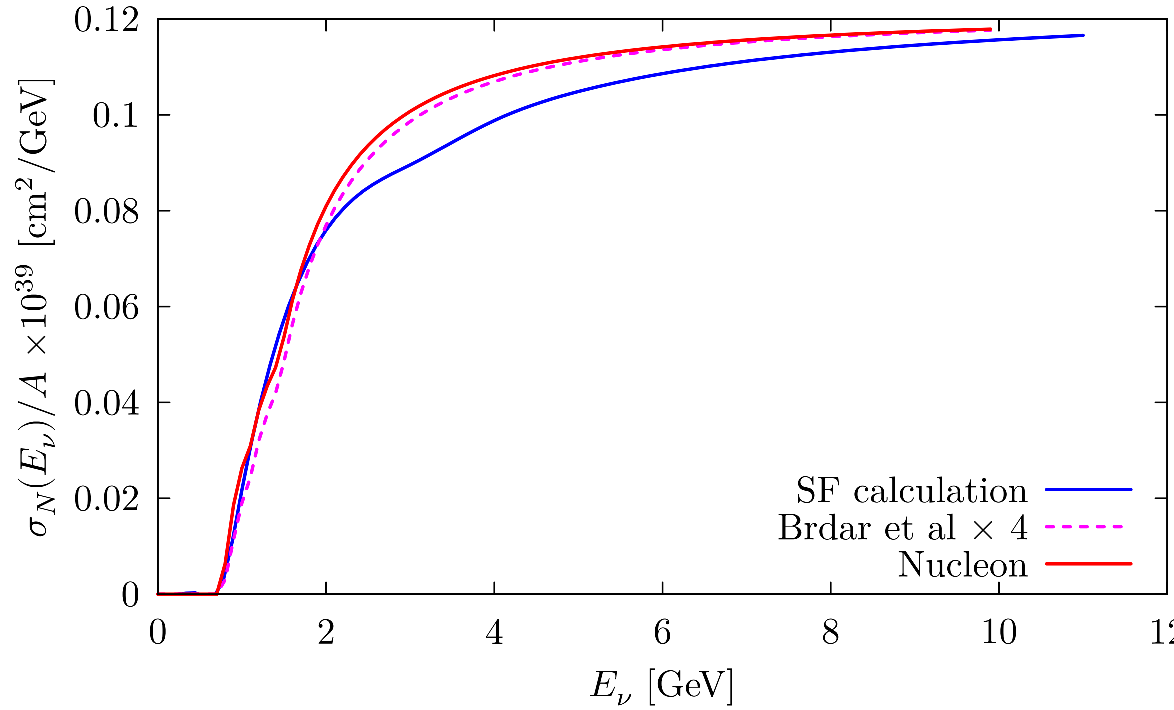
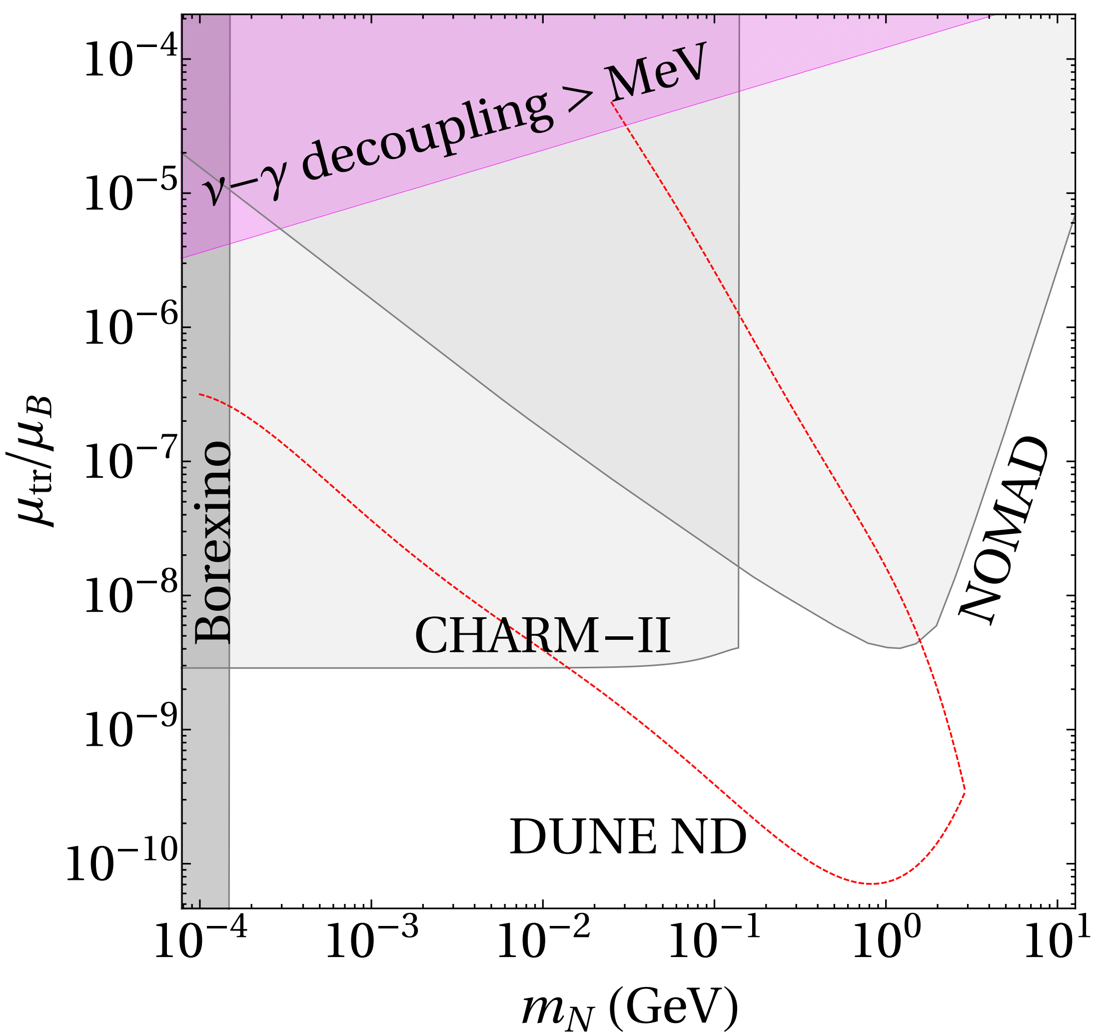
Double Bang events from New Physics at DUNE



- Production via magnetic moment
- Comparing different cross section models

More work on this topic: Harnik, Machado, Plestid, Brdar





- Expected sensitivity to the **transition magnetic moment ν_μ – N from DBs** signals in the DUNE LAr near detector
- Iso-contours: region of parameter space where more than one DB event is expected. The shaded regions are disfavored by previous experiments.

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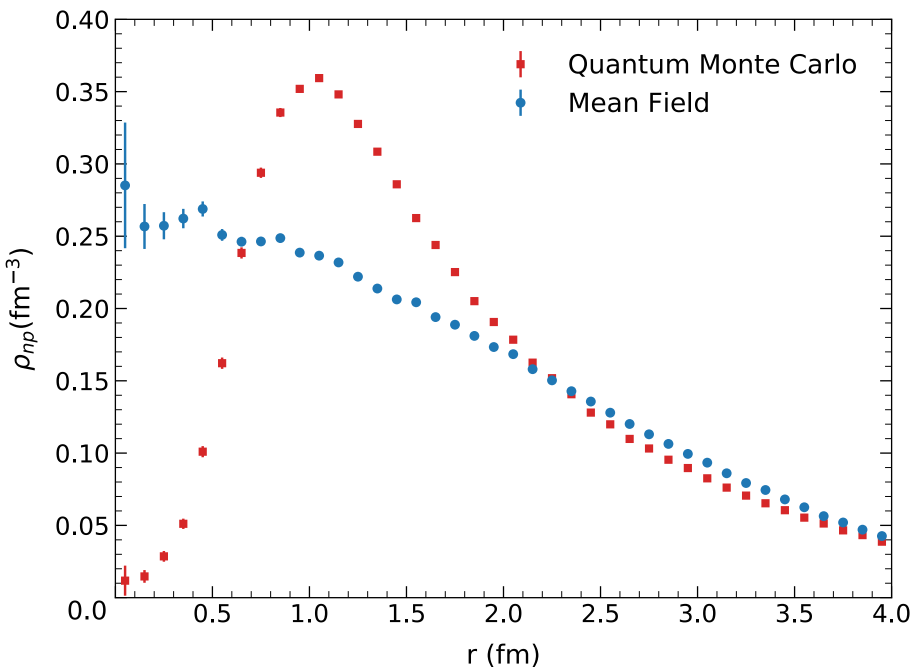
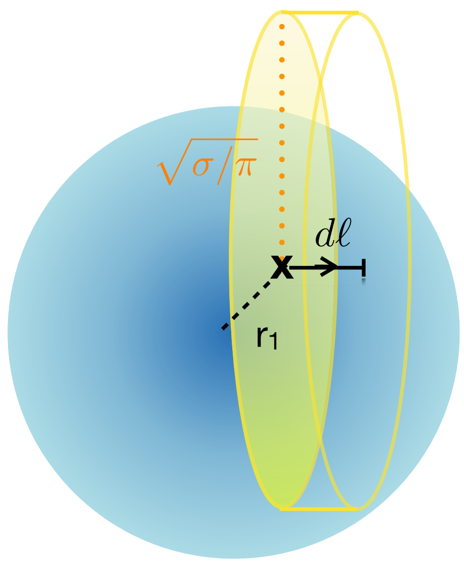
A Quantum Monte Carlo based cascade



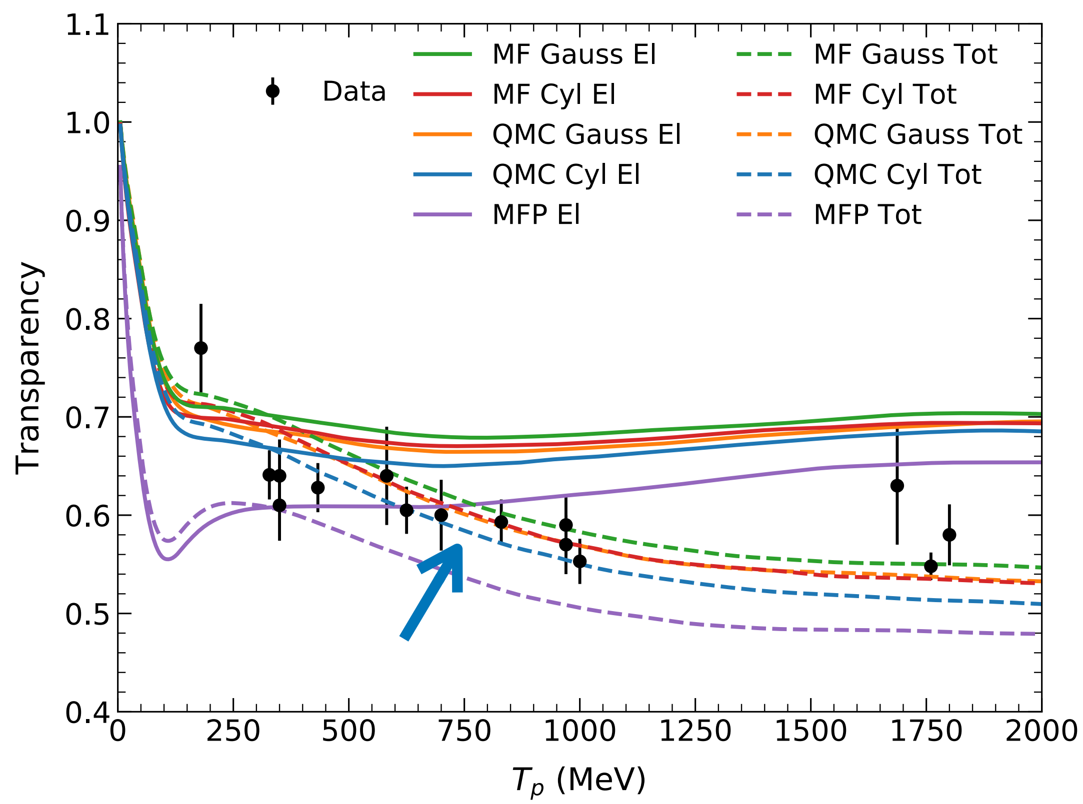
We investigated the role of nuclear effects in intra-nuclear cascade

*J.Isaacson, W Jay, A. Lovato, P Machado, NR, Phys. Rev. C **103**, 015502 (2021)*

The nucleons' positions are sampled from **36000 GFMC configurations**.



Check interaction: **accept-reject** test with a cylinder probability distribution.



- We computed different observables: p-^{12}C cross section, ^{12}C transparency and obtained a fair agreement with data
- Extend the model to include pion degrees of freedom and compare with exclusive observables.

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Summary and Future Prospects

- A comprehensive estimate of the **theoretical uncertainty**: can be achieved in QMC calculations. Work in this direction has been done for the energy spectra of light nuclei.

- Comparisons among different approaches is important to precisely quantify the **uncertainties inherent to the factorization of the final state and relevance of relativistic effects**

- **Spectral function** formalism allows for a consistent description of the different reaction mechanisms including short range correlation effects. Ongoing work to **extend** this approach to the **DIS region**

- We developed a **semi-classical intra-nuclear** cascade were nuclear effects are included. Using a cylinder probability distribution we correctly reproduce nuclear transparency.

- Next steps: include **π degrees of freedom**: π production, absorption and elastic scattering as well as **in medium corrections**

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Thank you for your attention!