Lepton-nucleus scattering: from the quasi-elastic to the DIS region

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Neutrino Seminar series—Virtual Seminar
Fermilab
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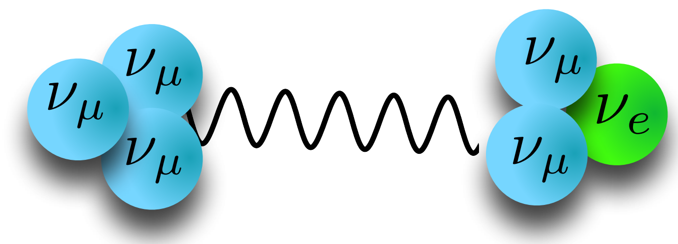
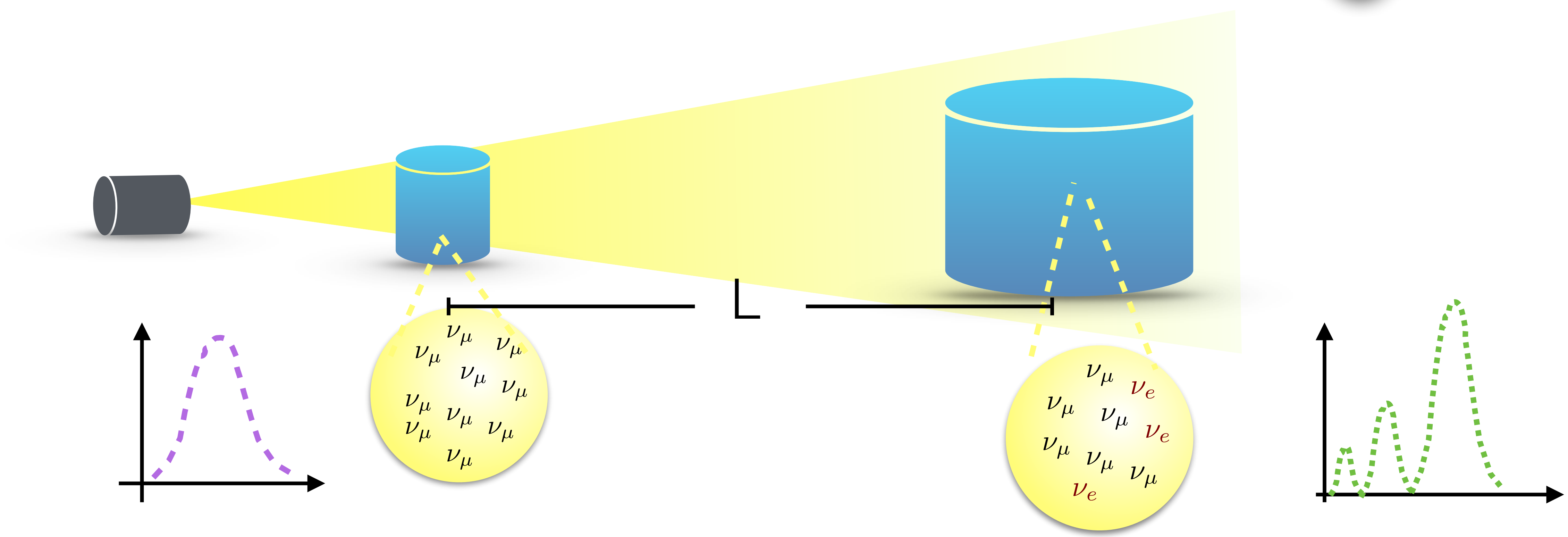
Addressing Neutrino-Oscillation Physics

$$P_{\nu_\mu \to \nu_e}(E, L) \sim \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E}\right) \to \Phi_e(E, L)/\Phi_\mu(E, 0)$$





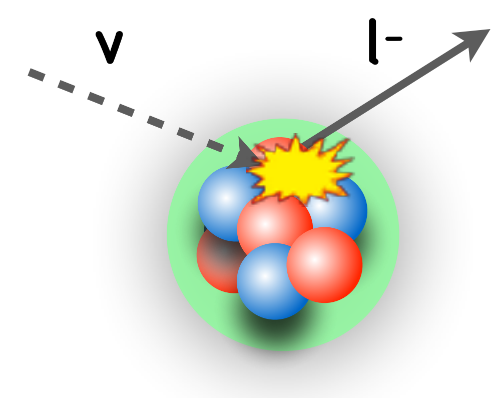
Detectors measure the neutrino interaction rate:

$$N_e(E_{\text{rec}}, L) \propto \sum_i \Phi_e(E, L)\sigma_i(E) f_{\sigma_i}(E, E_{\text{rec}}) dE$$

Reconstructed
ν energy

Cross Section

Smearing
matrix



A quantitative knowledge of σ(E) and f_σ(E) is crucial to precisely extract ν oscillation parameters

To study neutrinos we need nuclei

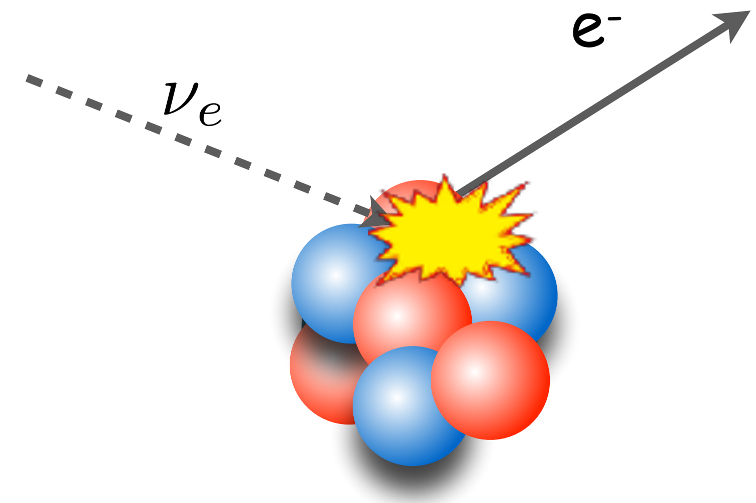
? Where does Nuclear Physics come into play

Number of Interactions = $\sigma \times \Phi \times N$

Cross Section

Neutrino Flux

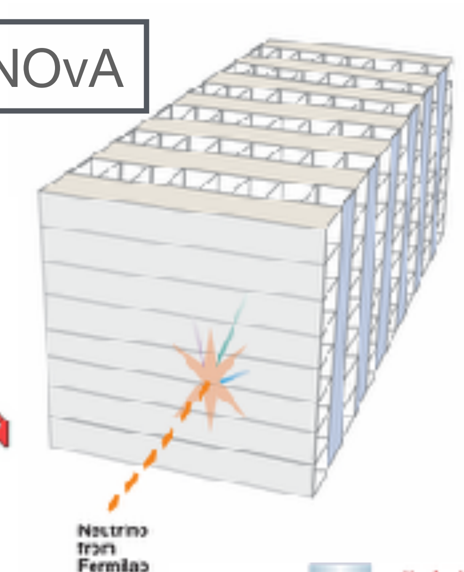
Targets

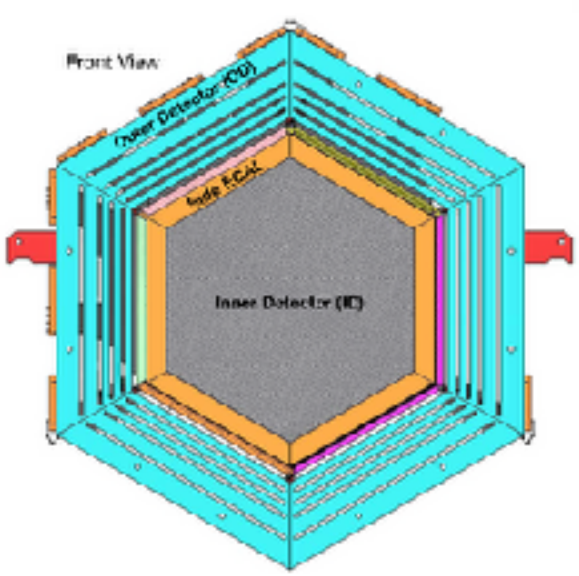


Utilize heavy target in neutrino detectors to maximize interactions→ understand nuclear structure

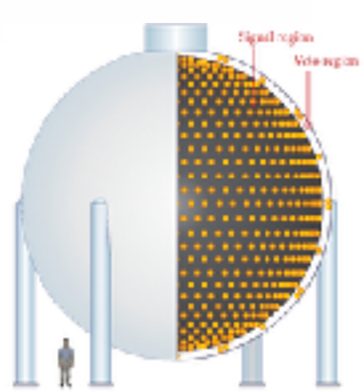
Carbon

NOvA



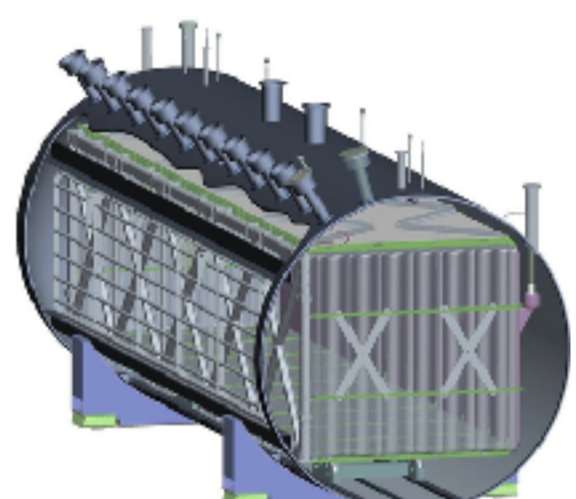


MINERvA



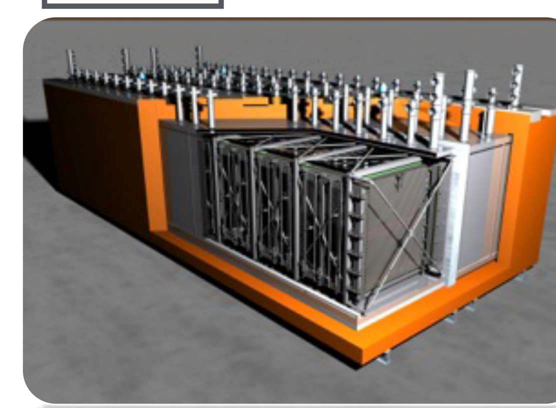
MiniBooNE

Liquid Argon

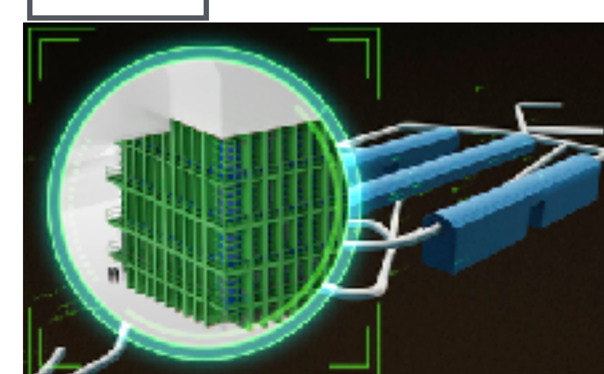


MicroBooNE

Icarus

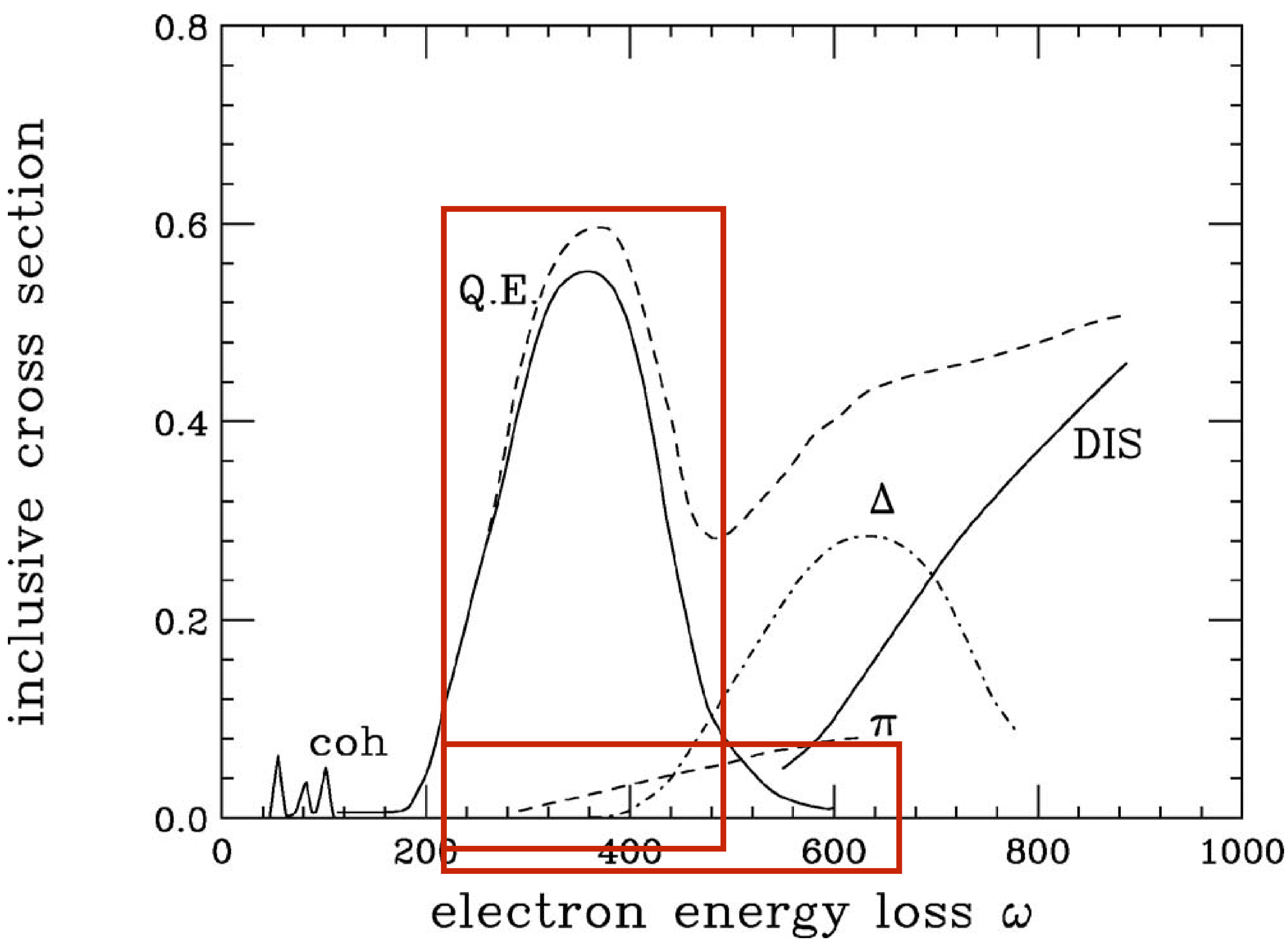


DUNE



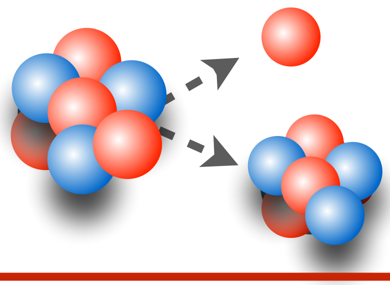
Outline of the talk

1st Part of the Presentation



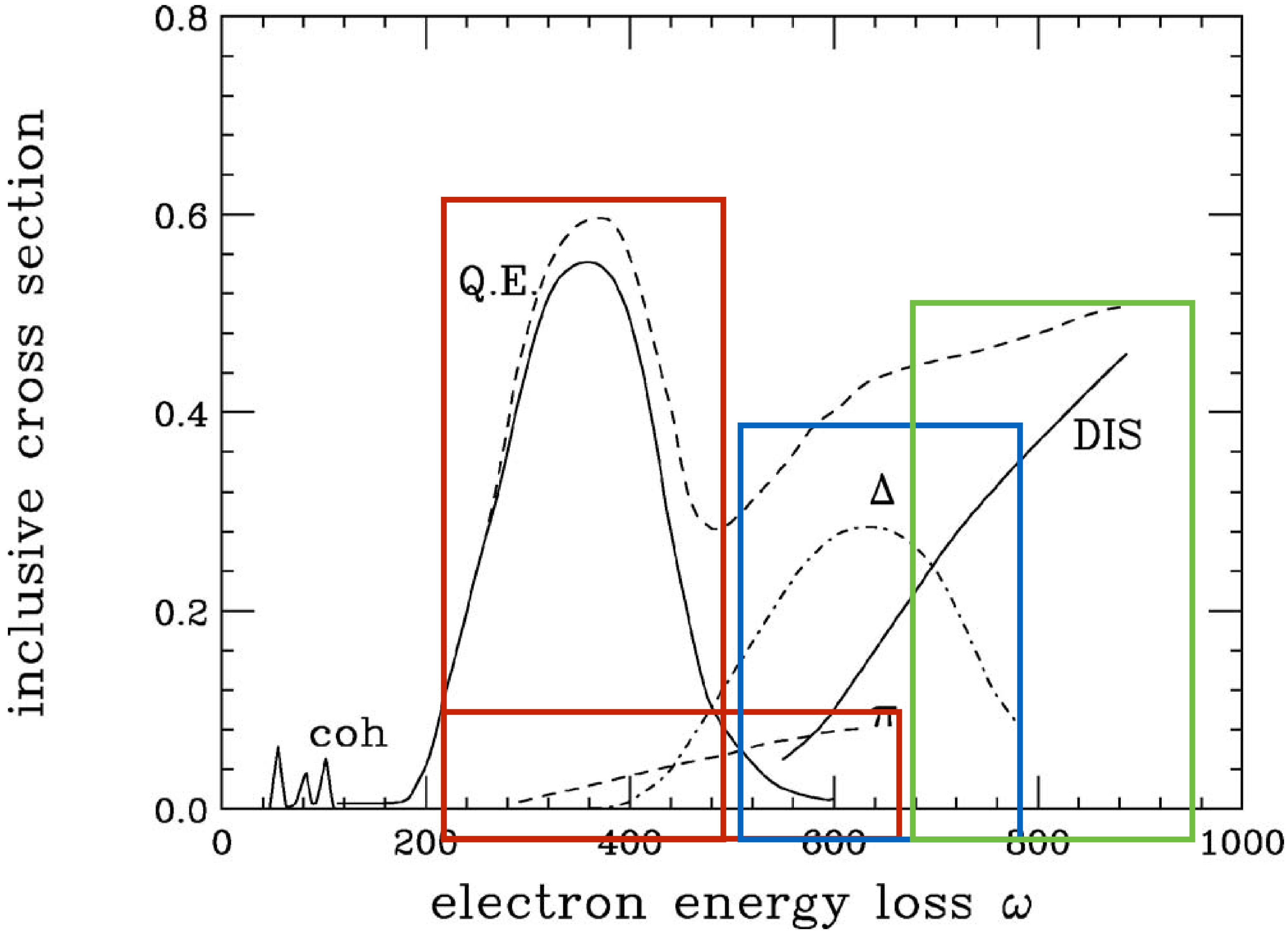
- Ab-initio calculations (GFMC)—able to describe how nuclei emerge starting from neutron and proton interactions—provide an accurate predictions of the QE region including one- and two-body currents

Quasielastic scattering on a nucleus:



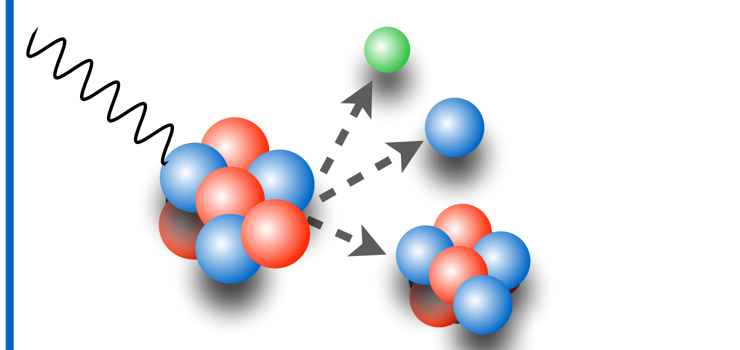
Outline of the talk

2nd Part of the Presentation

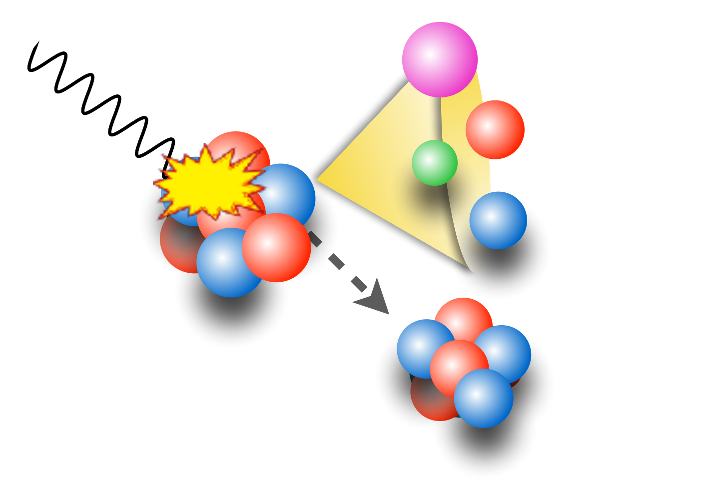


- More approximate approach: Extended Factorization scheme + Semi-phenomenological SF have been introduced to tackle QE, dip and π-production regions.

Pion production: RES

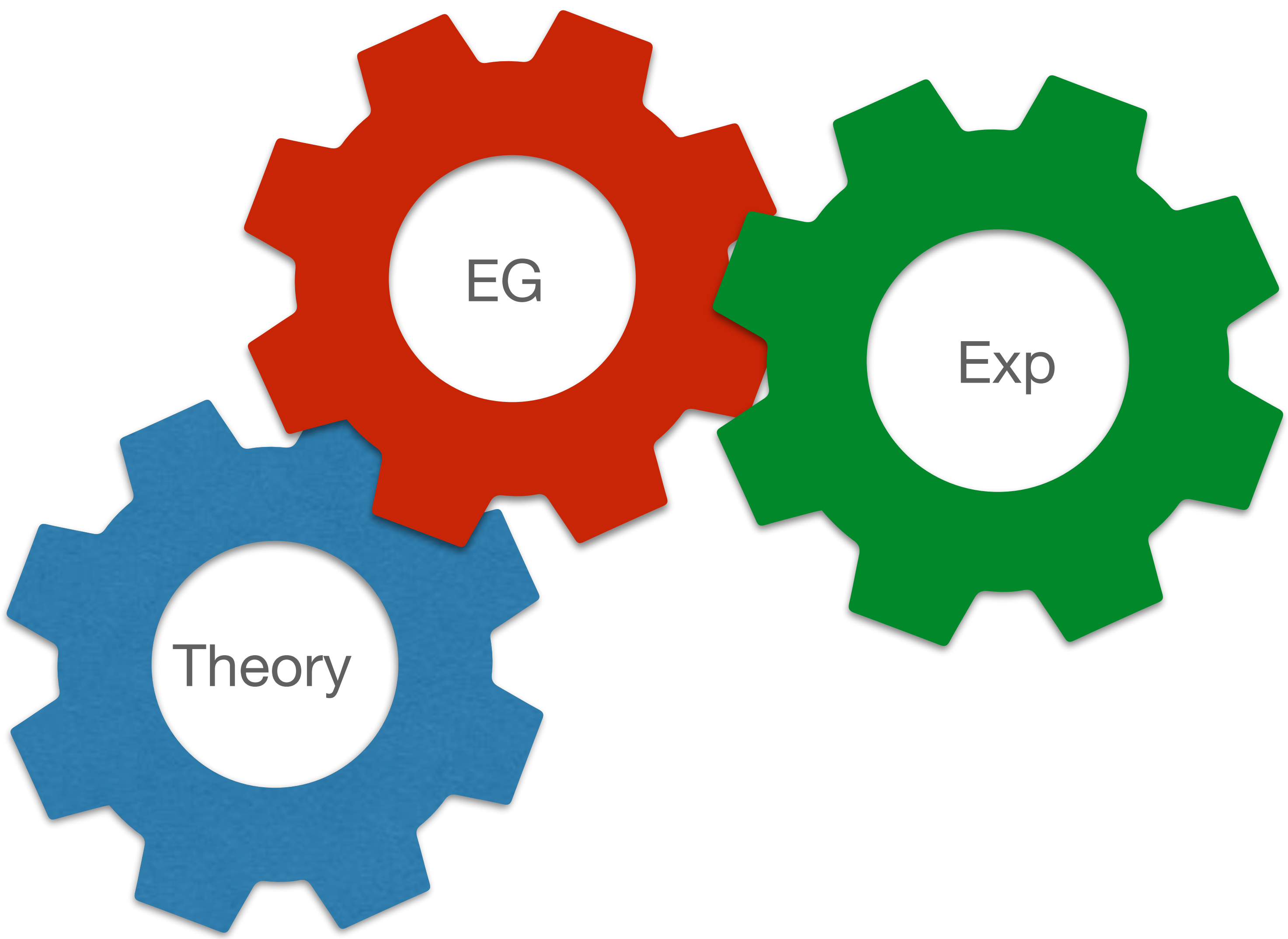


DIS



Outline of the talk

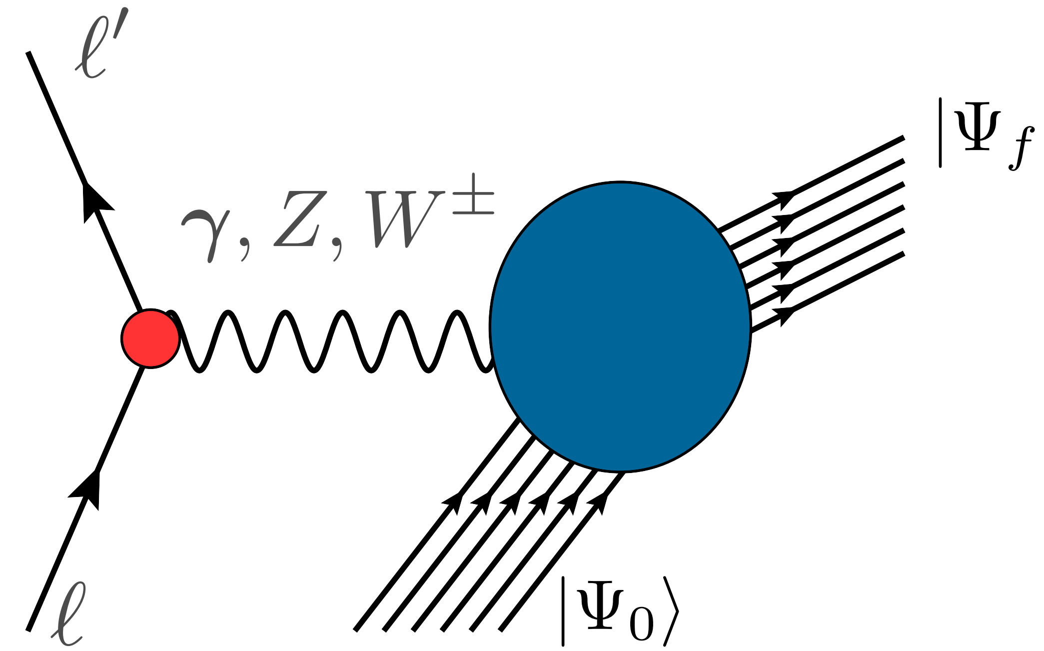
3nd Part of the Presentation



Synergistic effort among these three components:

what we are doing / plan to do for the event-generator component

Theory of lepton-nucleus scattering



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

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

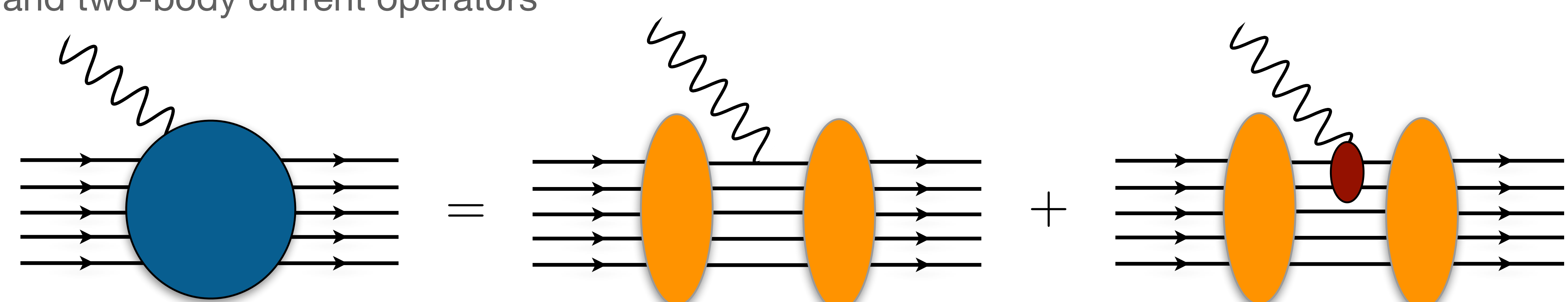
Nuclear response to the electroweak probe:

$$R_{\alpha\beta}(\omega, \mathbf{q}) = \sum_f \langle 0|J_\alpha^\dagger(\mathbf{q})|f\rangle\langle f|J_\beta(\mathbf{q})|0\rangle\delta(\omega - E_f + E_0)$$

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

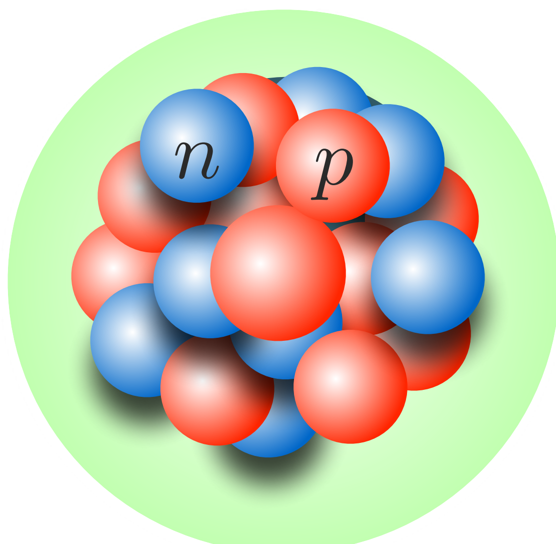
$$|0\rangle = |\Psi_0^A\rangle \; , |f\rangle = |\Psi_f^A\rangle, |\psi_p^N, \Psi_f^{A-1}\rangle, |\psi_k^\pi, \psi_p^N, \Psi_f^{A-1}\rangle \ldots$$

One and two-body current operators



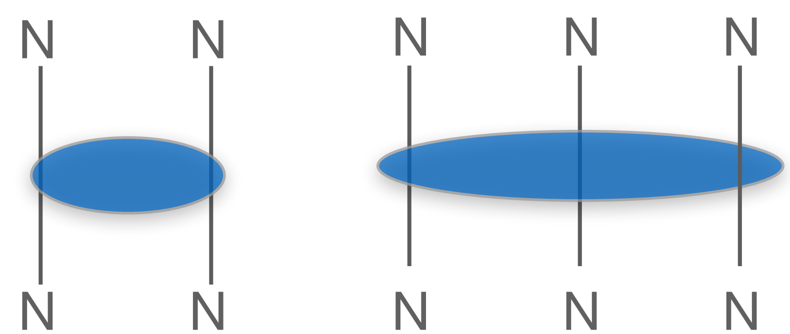
The basic model of nuclear theory

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



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

1-body **2-body** **3-body**

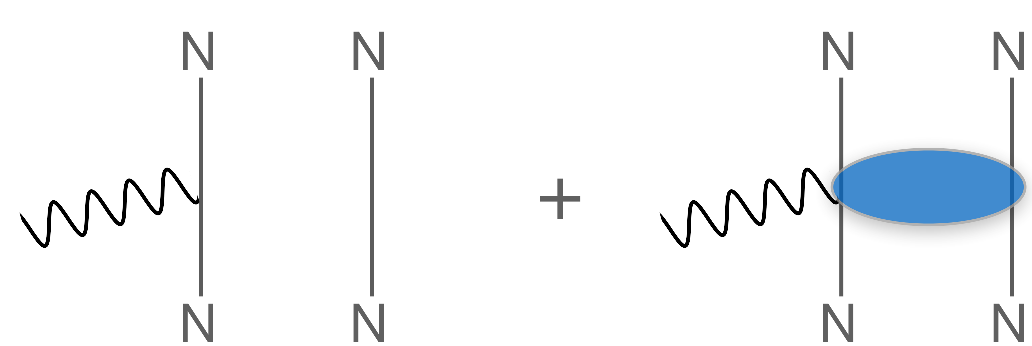


The electromagnetic current is constrained by the Hamiltonian through the **continuity equation**

$$\nabla \cdot \mathbf{J}_{\mathrm{EM}} + i[H, J^0_{\mathrm{EM}}] = 0 \qquad [v_{ij}, j_i^0] \neq 0$$

The above equation implies that the current operator includes one and two-body contributions

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



Quantum Monte Carlo approach

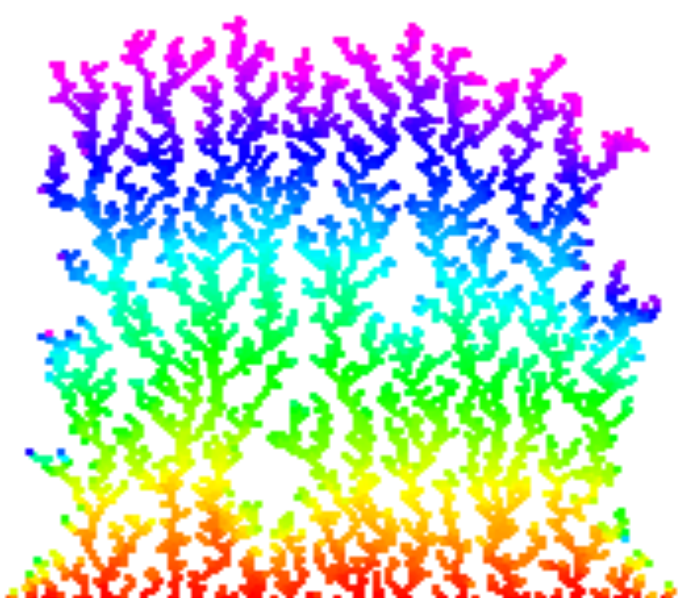
We want to solve the Schrödinger equation

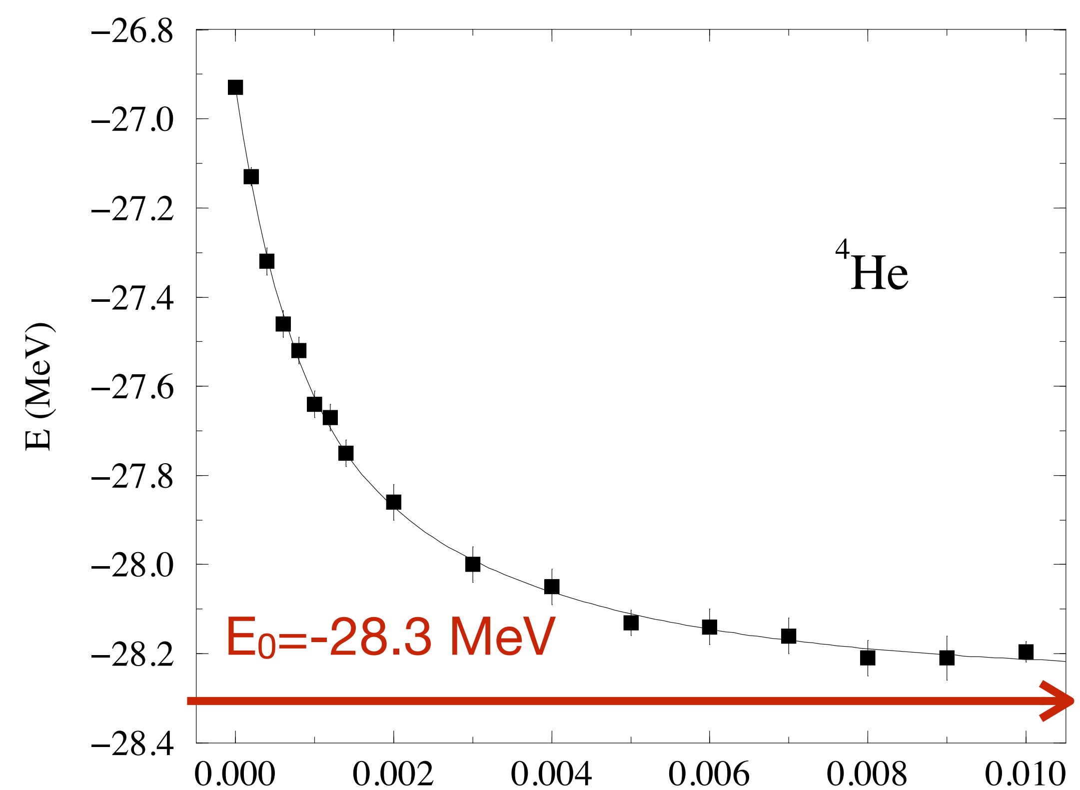
$$H\Psi(\mathbf{R}; s_1 \ldots s_A, \tau_1 \ldots \tau_A) = E\Psi(\mathbf{R}; s_1 \ldots s_A, \tau_1 \ldots \tau_A)$$

Any trial wave function can be expanded in the complete set of eigenstates of the the Hamiltonian according to

$$|\Psi_T\rangle = \sum_n c_n |\Psi_n\rangle \qquad\qquad H|\Psi_n\rangle = E_n|\Psi_n\rangle$$

QMC techniques **projects out the exact lowest-energy state:** $e^{-(H-E_0)\tau}|\Psi_T\rangle \rightarrow |\Psi_0\rangle$





The system is cooled down by evolving it in time

✐ B. Pudliner et al., PRC **56**, 1720 (1997)

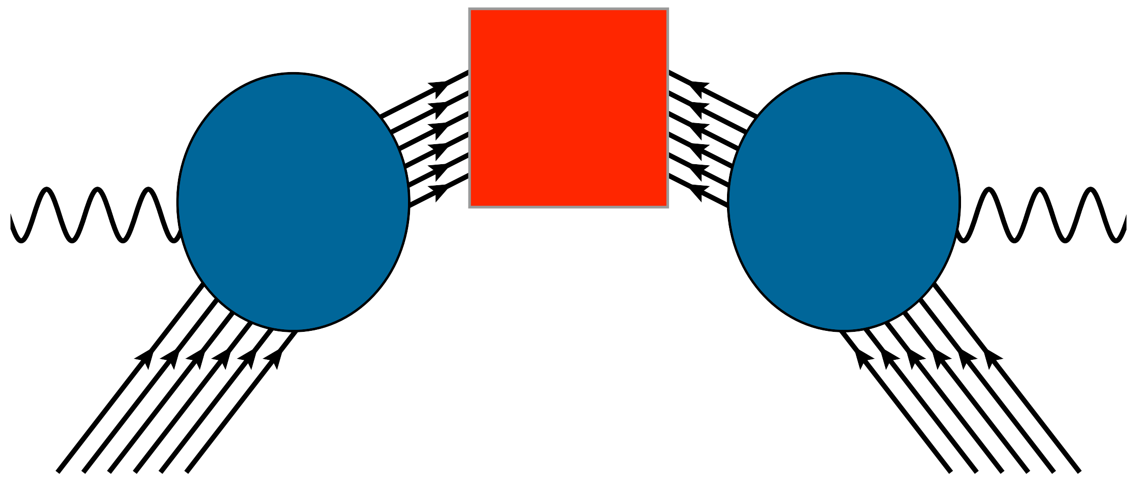
Integral Transform Techniques

- Nuclear responses obtained with QMC techniques (more in detail Greens' Function Monte Carlo)

$$R_{\alpha\beta}(\omega,\mathbf{q}) = \sum_f \langle 0|J_\alpha^\dagger(\mathbf{q})|f\rangle\langle f|J_\beta(\mathbf{q})|0\rangle\delta(\omega - E_f + E_0)$$

Valuable information can be obtained from the integral transform of the response function

$$E_{\alpha\beta}(\sigma,\mathbf{q}) = \int d\omega K(\sigma,\omega)R_{\alpha\beta}(\omega,\mathbf{q}) = \langle\psi_0|J_\alpha^\dagger(\mathbf{q})K(\sigma,H-E_0)J_\beta(\mathbf{q})|\psi_0\rangle$$

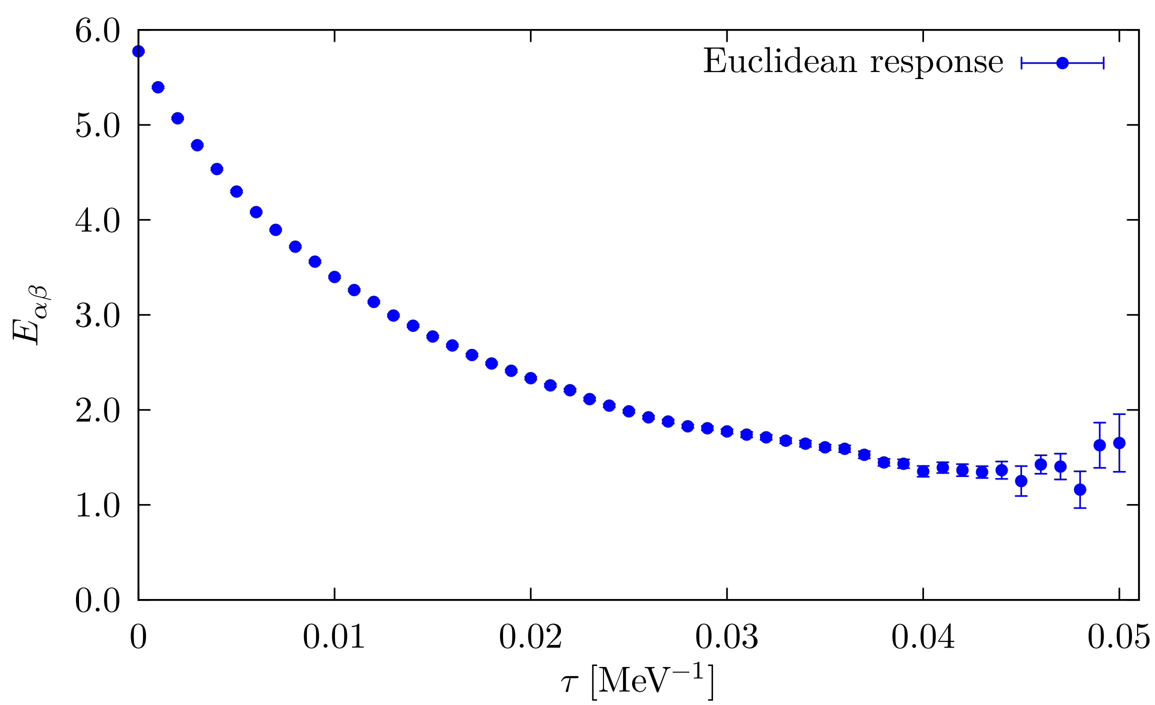


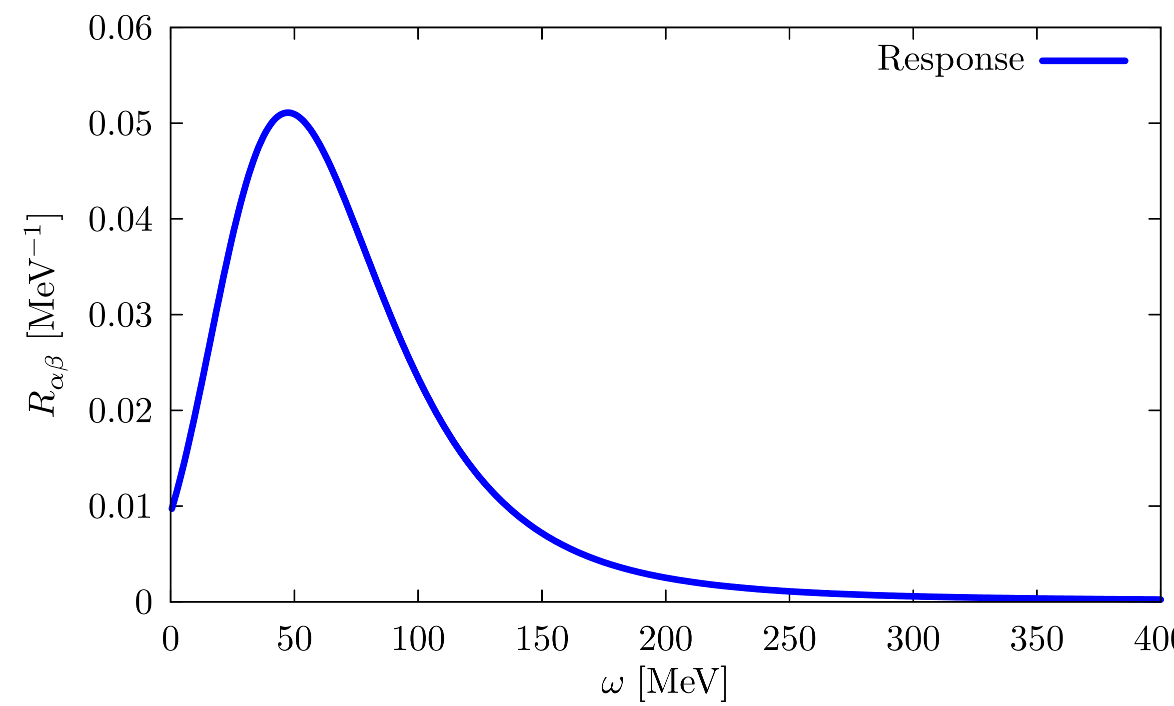
Integral Transform Techniques

$E(\sigma, \mathbf{q}) \xrightarrow{?} R(\omega, \mathbf{q})$

Inverting the integral transform is a complicated problem

$E_{\alpha\beta}(\tau, \mathbf{q}) \longrightarrow R_{\alpha\beta}(\omega, \mathbf{q})$





Current solution for the quasielastic region: Maximum Entropy Techniques

A. Lovato et al, Phys.Rev.Lett. 117 (2016), 082501, Phys.Rev. C97 (2018), 022502

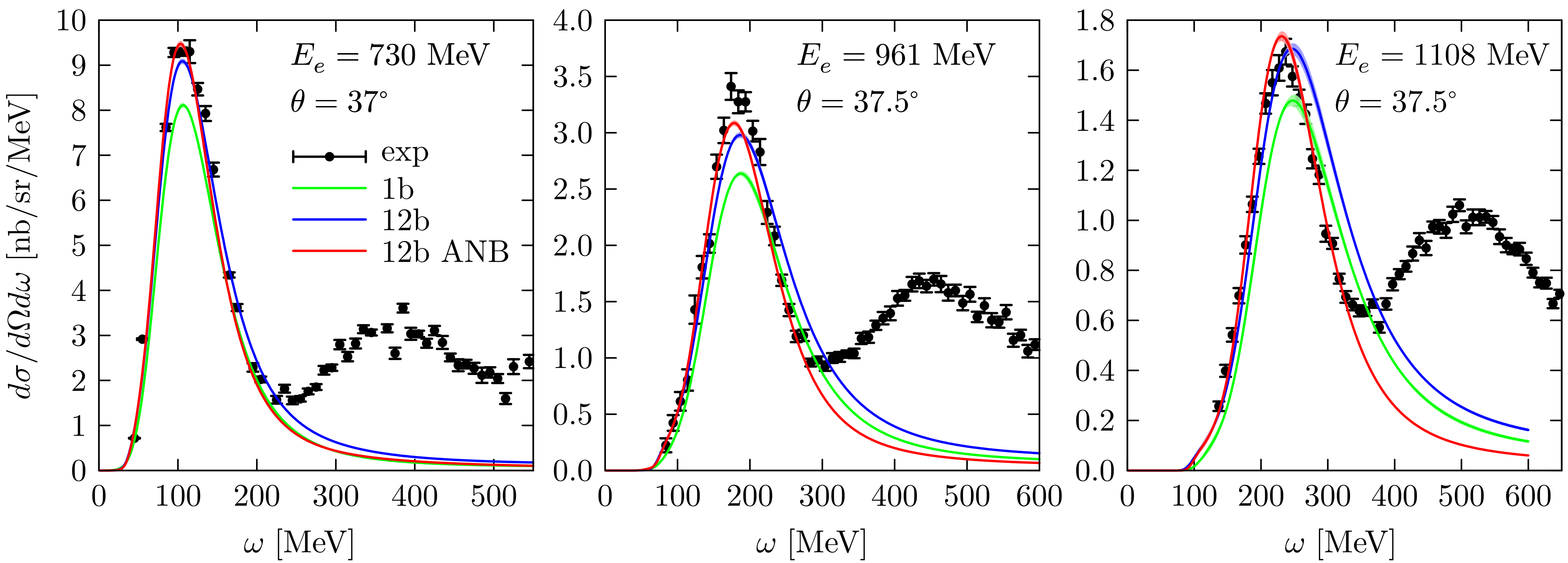
We are now exploring new strategies, based on **machine learning techniques**, to improve the accuracy of the inversion and to better estimate the associated uncertainties

GFMC electron ^{4}He-cross sections

Virtually exact results for 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

N.R, W. Leidemann, et al PRC 97 (2018) no.5, 055501

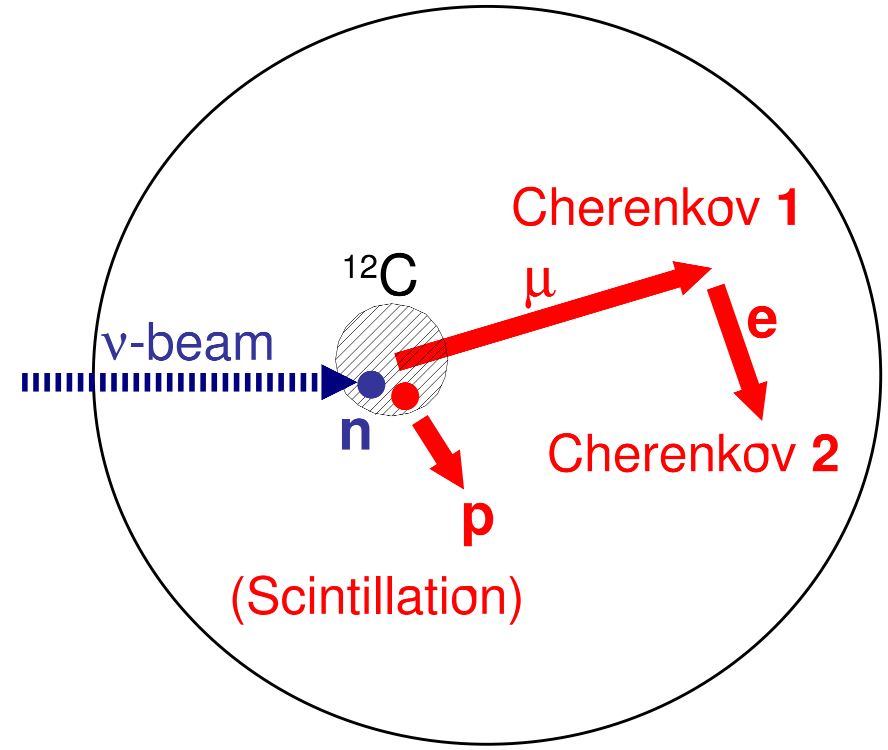


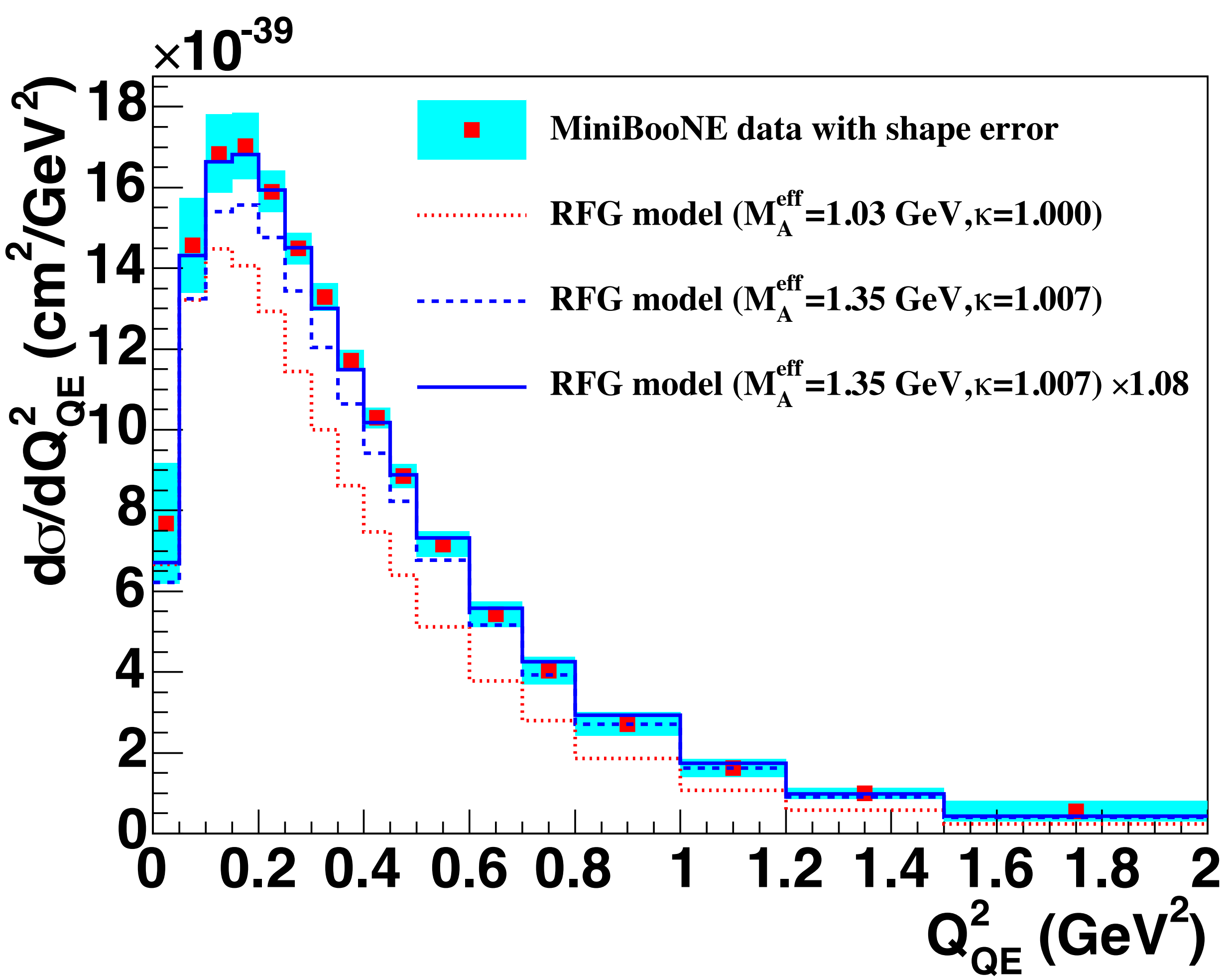
- Very good agreement in the quasielastic region when: one- and two-body currents are included
- Peak on the right: π production can not be described within this approach

MiniBooNE: the axial mass puzzle

- In MiniBooNE data analysis, an event is labeled as CCQE if **no final state pions** are detected in **addition to the outgoing muon.**

- To reproduce the data: M_A~1.35 GeV is incompatible with former measurements: M_A~1.03 GeV





✐ MiniBooNE collaboration, PRDD81 (2010) 092005

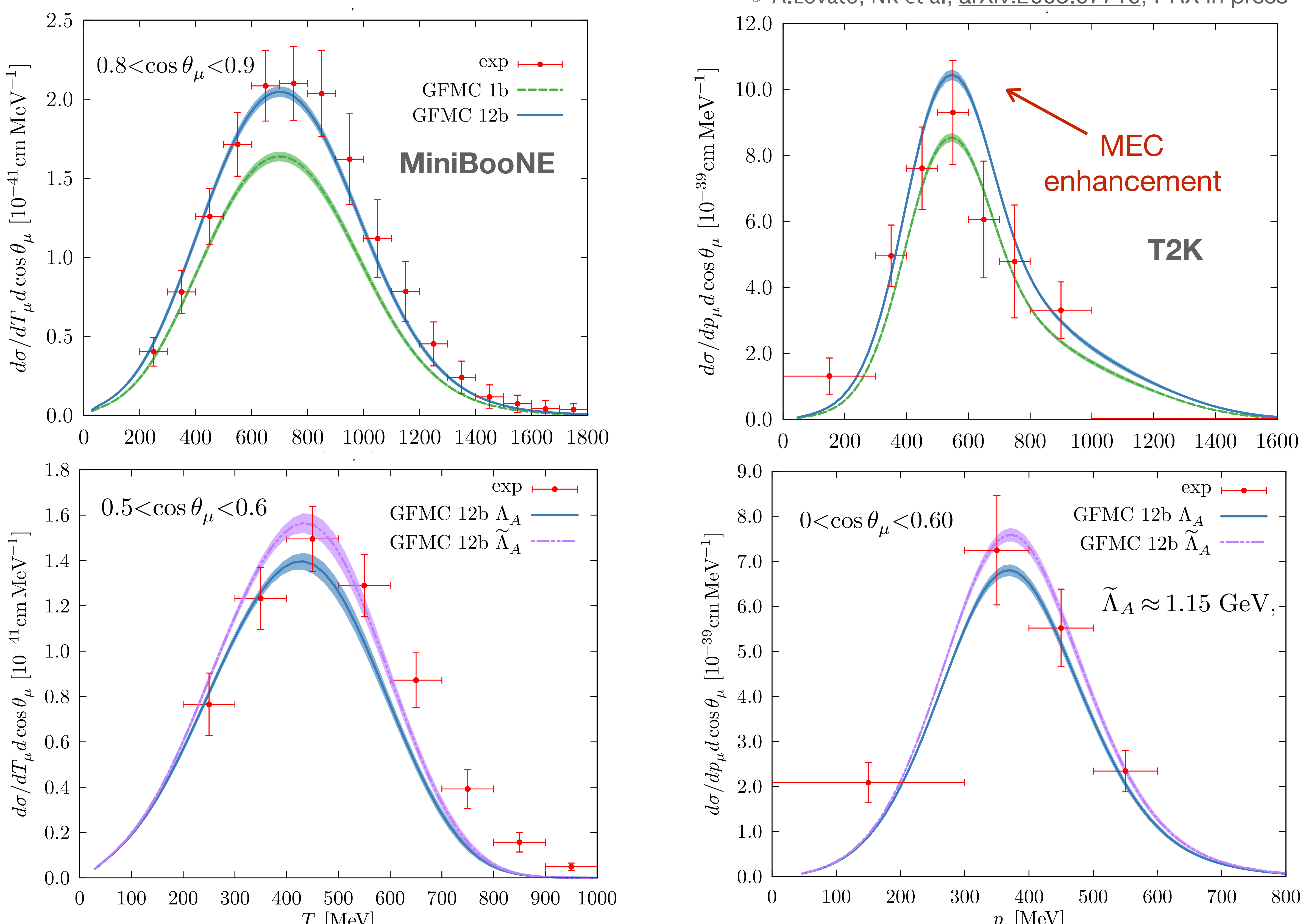
Nuclear effects might explain the axial mass puzzle

We have to include **meson-exchange currents**

—two nucleon emission: CCQE-like

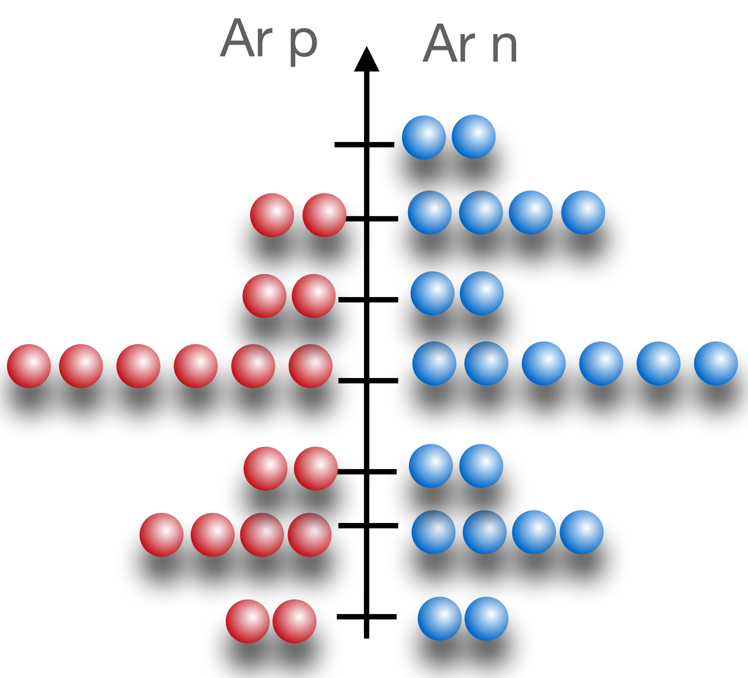
GFMC CC ν_μ ^{12}C-cross sections

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



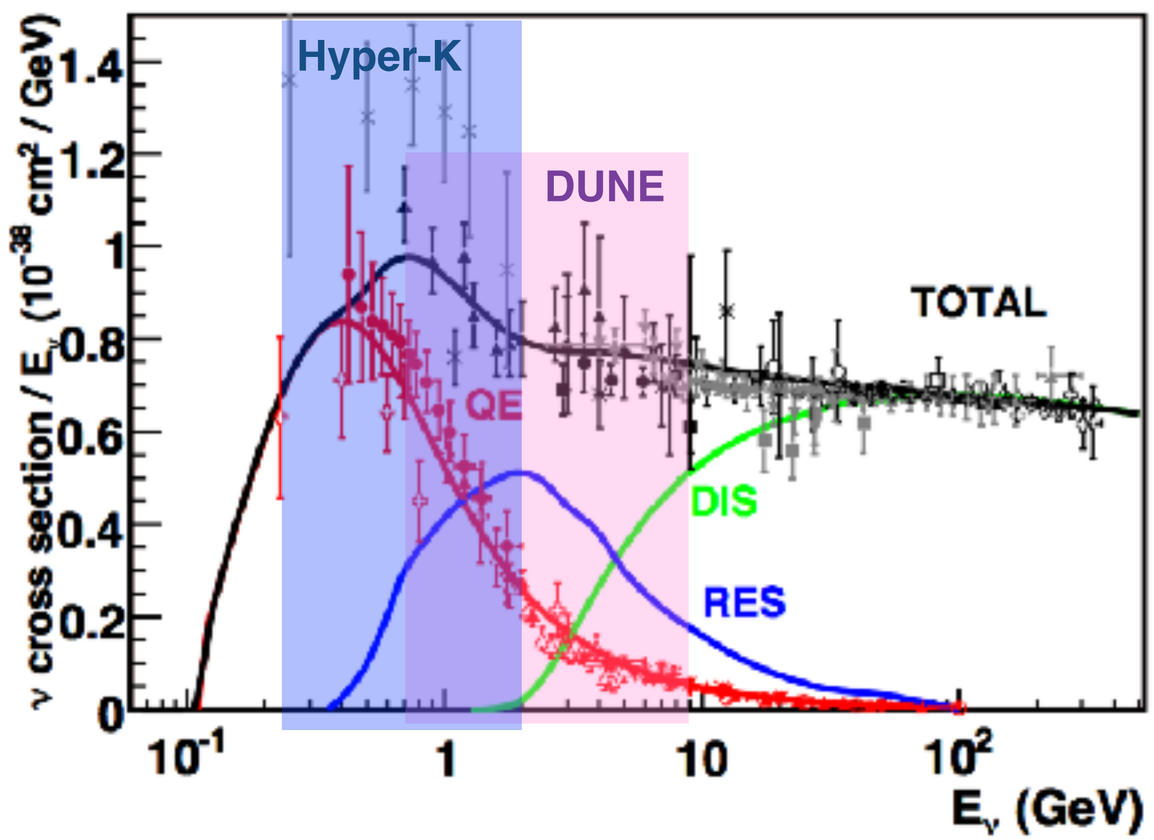
Addressing future precision experiments

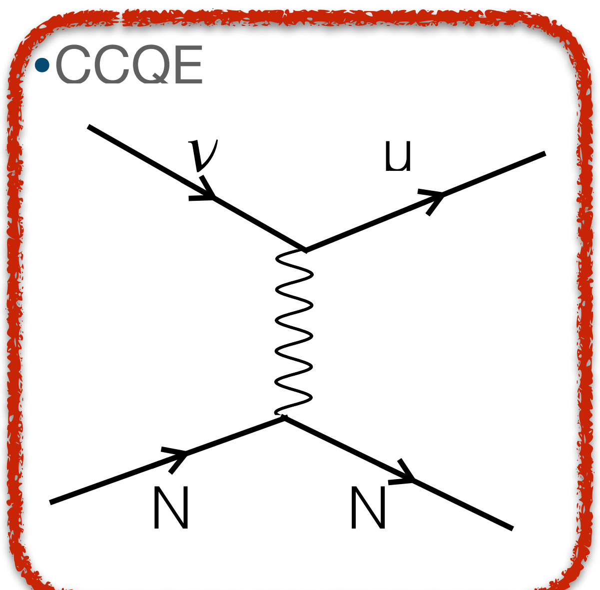
- Liquid Argon TPC Technology

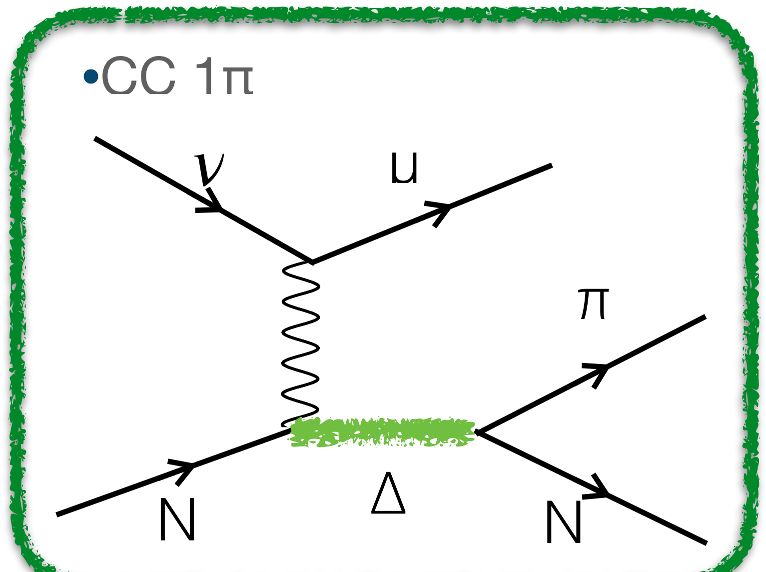


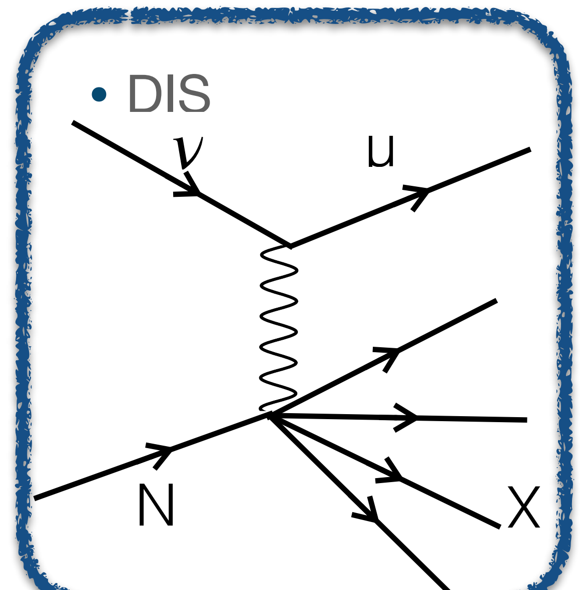
- Ar has a complicated structure, out of the reach of most of the ab initio methods

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









- The dominant reaction mechanism changes dramatically over the region of interest to oscillation experiment

Factorization Scheme and Spectral Function

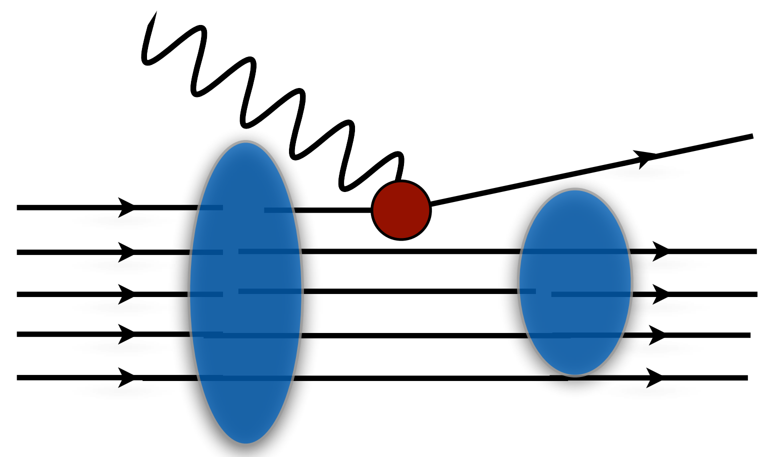
For sufficiently large values of |**q**|, the **factorization scheme** can be applied under the assumptions

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

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

$\rightarrow$

$|\Psi_0\rangle$

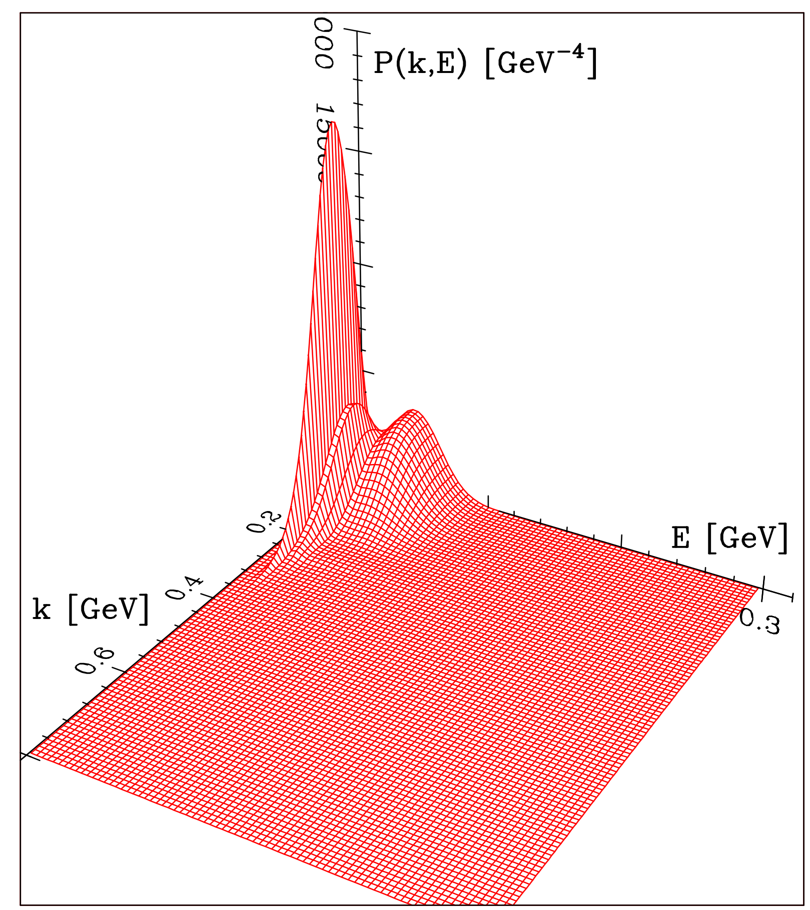


$|p\rangle$

$|\Psi_f\rangle_{A-1}$

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

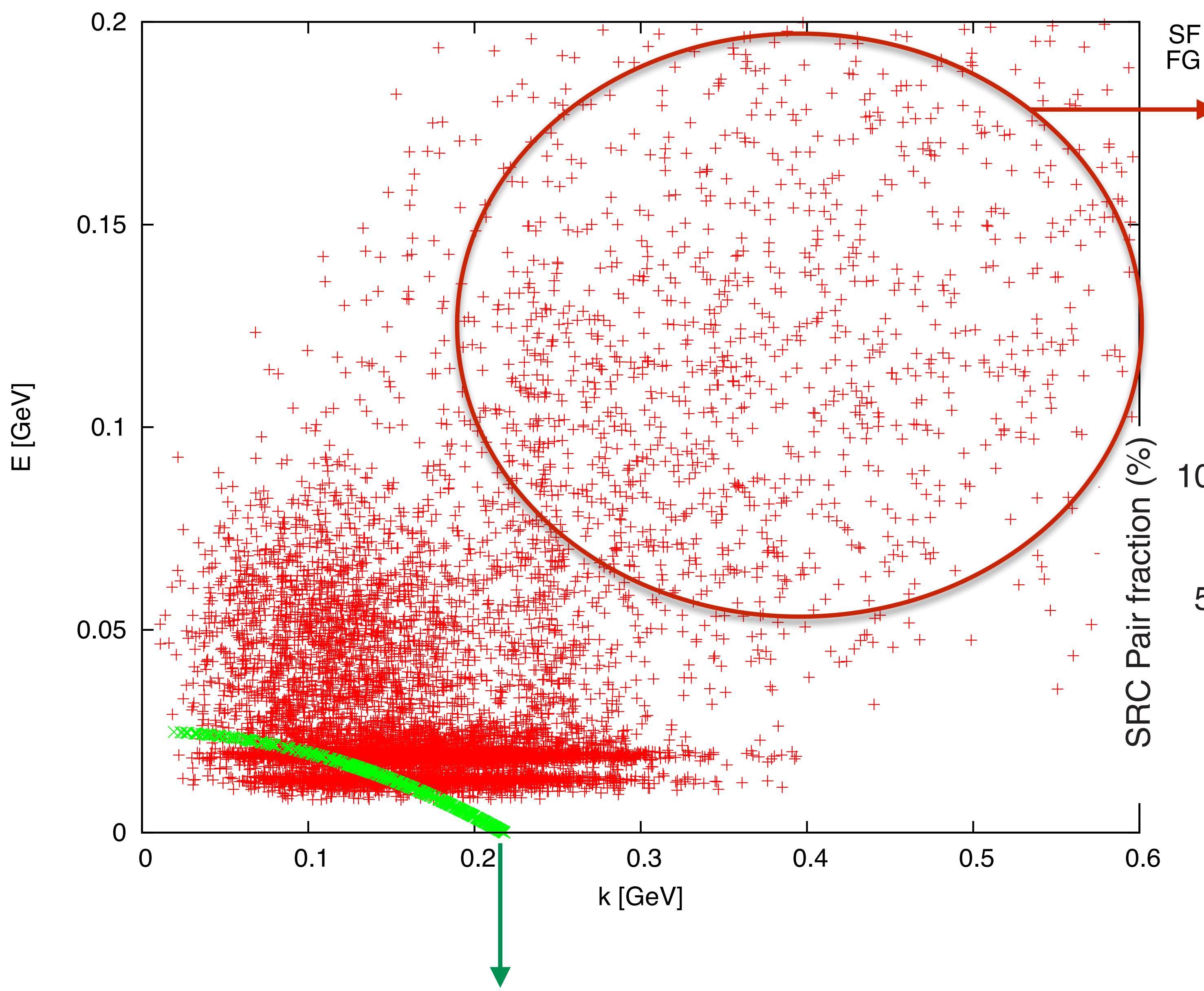
$$\boxed{d\sigma_A = \int dE d^3k \; d\sigma_N P(\mathbf{k}, E)}$$



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

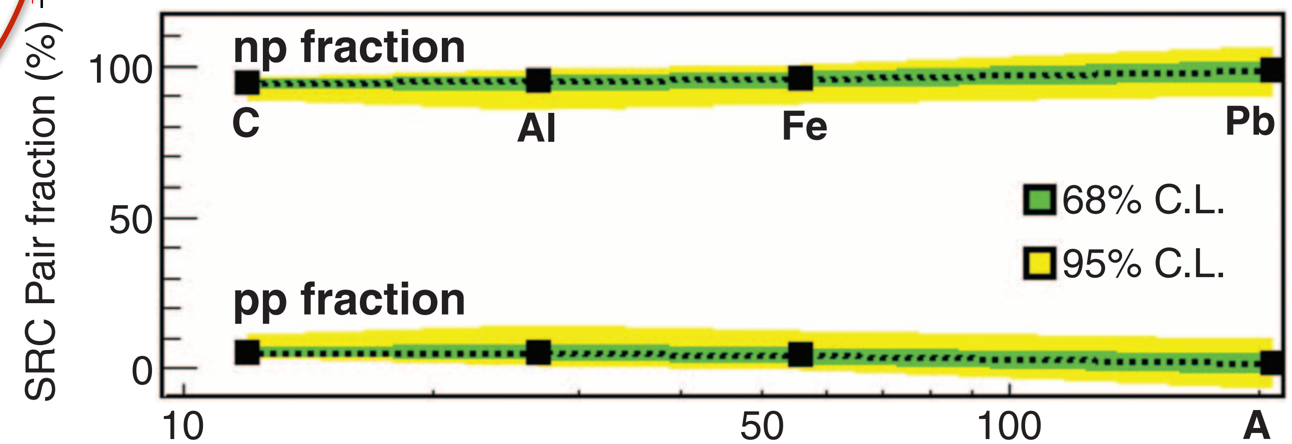
The one-nucleon Spectral Function

P(**k**,E) provides the **probability distribution** of removing a nucleon with momentum **k** from the target nucleus, leaving the residual (A – 1)-nucleon system with an **excitation energy E**.



High energy and momentum correlated pairs

Observed **dominance of np-over-pp** pairs for a variety of nuclei



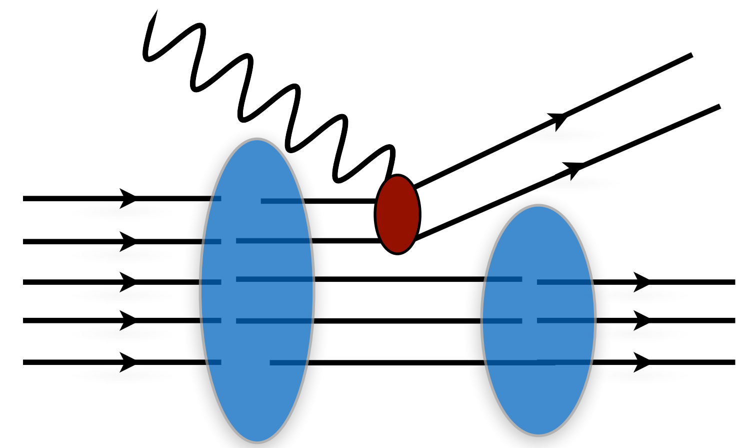
Consequence of the **tensor component of the nucleon-nucleon interaction**

Fermi gas contribution : $P_{\rm FG}(\mathbf{k},E) = \delta(E-\epsilon_B)\theta(k_F-|\mathbf{k}|)$

Extended Factorization Scheme

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

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



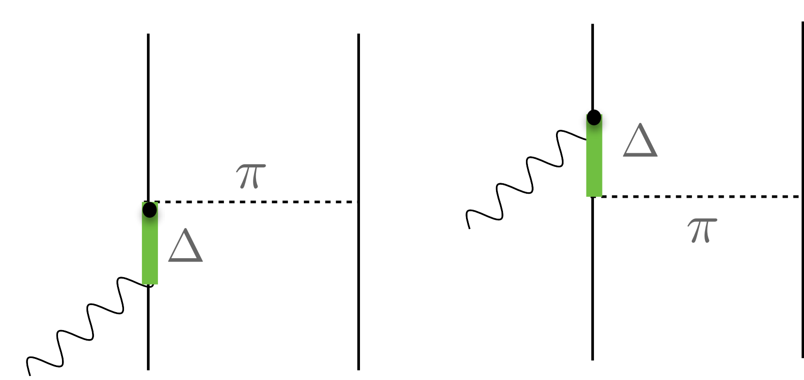
The hadronic tensor for two-body current processes reads

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

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

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

Relativistic two-body currents

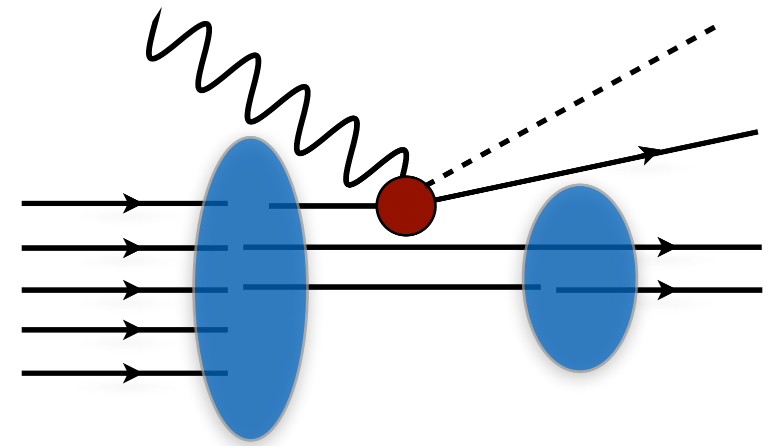


Dedicated code that **automatically** carries out the calculation of the **MEC spin-isospin matrix elements**, performing the integration using the Metropolis MC algorithm

Extended Factorization Scheme

- Production of real π in the final state

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

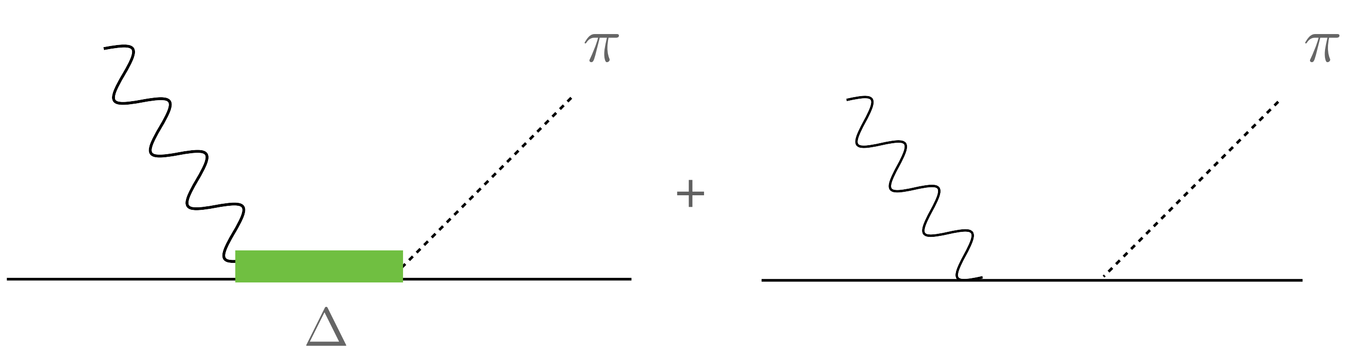


The hadronic tensor for two-body current processes reads

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

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



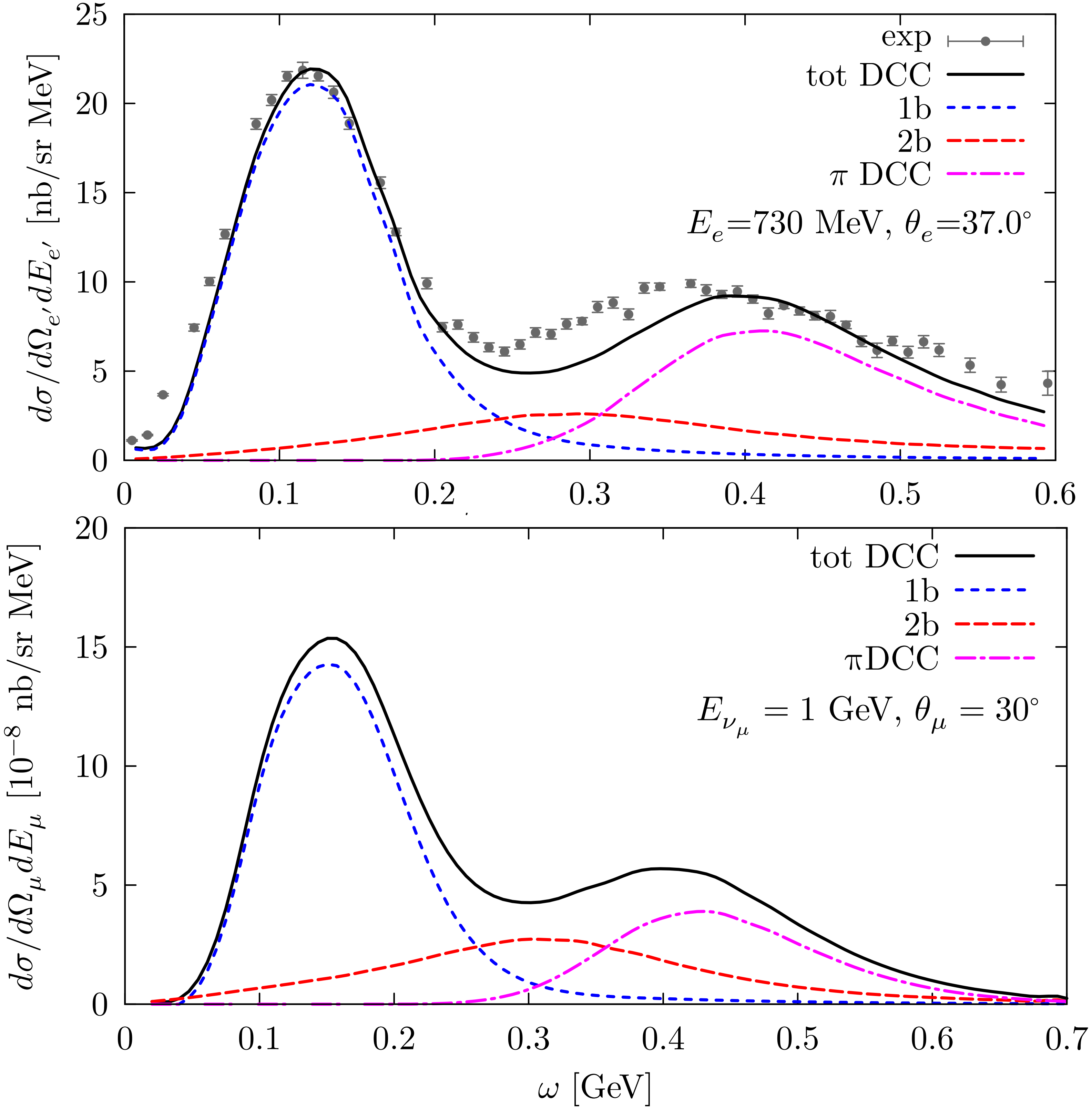
NR, et al, PRC100 (2019) no.4, 045503

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

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

Electron and neutrino -^{12}C cross sections-SF

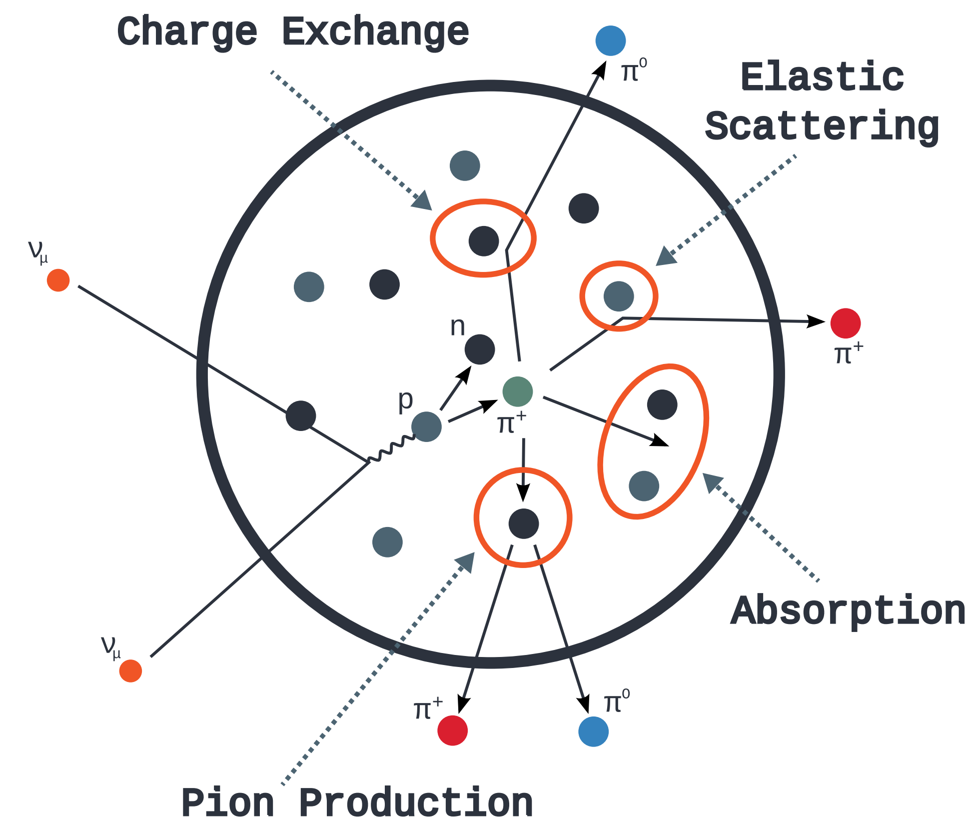
NR, S. Nakamura, T.S.H. Lee, A. Lovato, PRC100 (2019) no.4, 045503



- We included in the Extended Factorization Scheme the **one-** and **two-body current** contributions and the **pion production** amplitudes.
- Good agreement with electron scattering data when all reaction mechanisms are included
- Ongoing calculation of flux folded cross sections

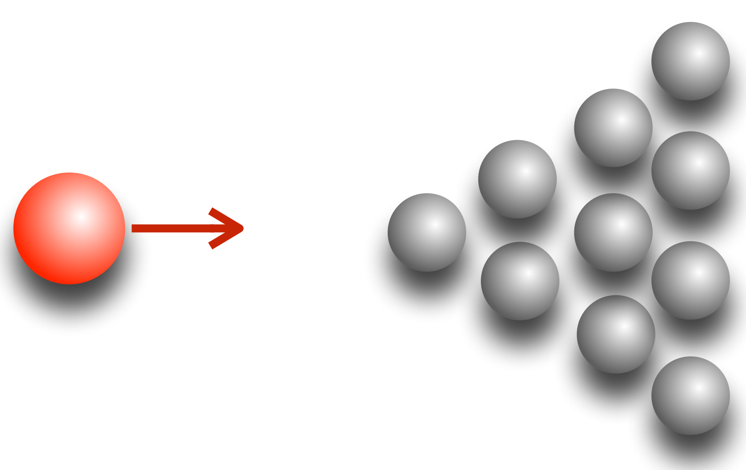
A QMC based approach to intranuclear cascade

Figure by T. Golan



The propagation of **nucleons** through the **nuclear medium** is crucial in the analysis of electron-nucleus scattering and neutrino oscillation experiments.

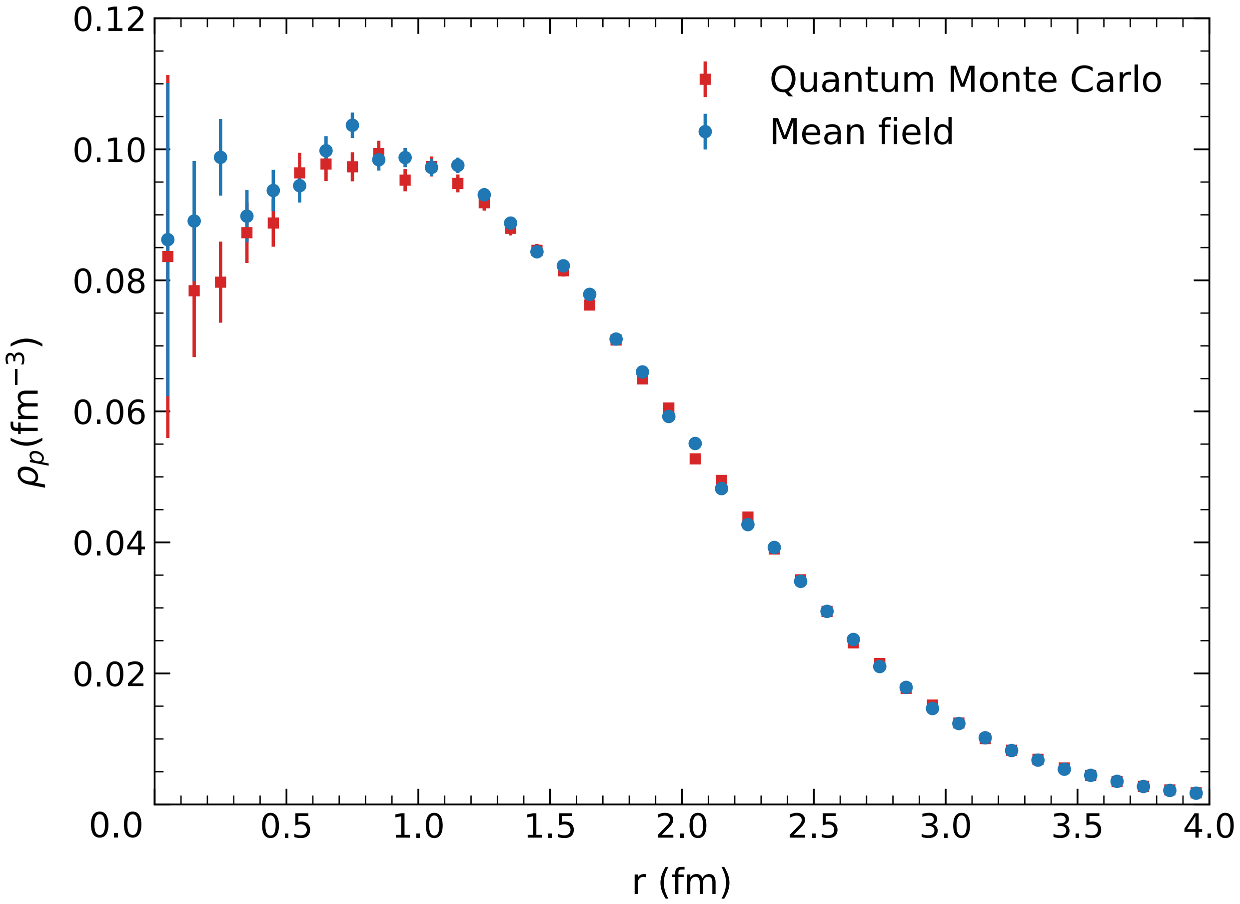
Describing nucleons' propagation in the nuclear medium would in principle require a fully quantum-mechanical description of the hadronic final state.

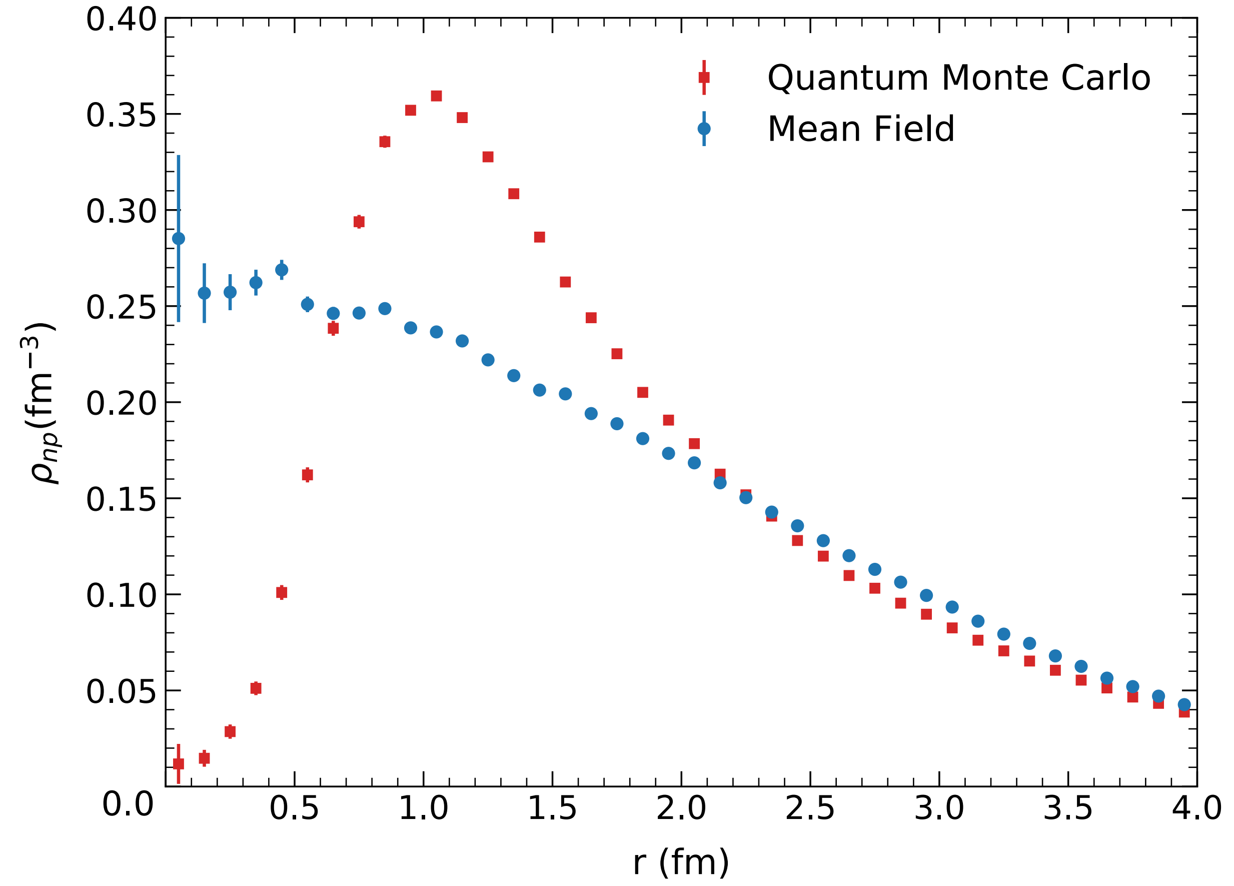


Due to its tremendous difficulty we follow a seminal work of Metropolis and develop a **semi-classical intranuclear cascade** (INC) that assume classical propagation between consecutive scatterings

J.Isaacson, W. Jay, P. Machado, A. Lovato, NR, arXiv:2007.15570

Sampling nucleon configurations



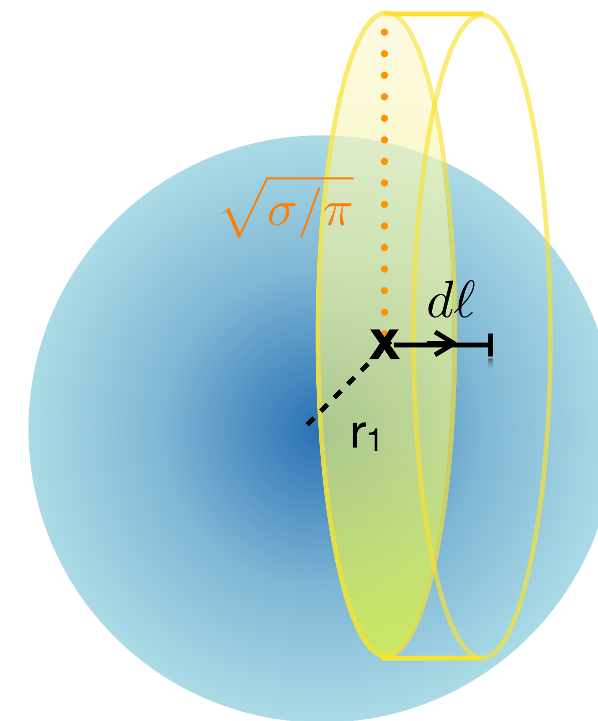


The nucleons' positions utilized in the INC are sampled from **36000 GFMC configurations**. For benchmark purposes we also sampled **36000 mean-field (MF) configurations** from the single-proton distribution.

The differences between GFMC and MF configurations are apparent when comparing the **two-body density distributions**: repulsive nature of two-body interactions reduced the probability of finding two particles close to each other

Probability of interaction

To check if an interaction between nucleons occurs an accept-reject test is performed on the closest nucleon according to a probability distribution.



We use a **cylinder probability distribution**, this mimics a more classical billiard ball like system where each billiard ball has a radius
In addition we consider a **gaussian probability distribution**

For benchmark purposes, we also implemented the **mean free path approach**, routinely used in event generators

$P = \sigma\bar{\rho}d\ell$ where a constant density is assumed $\rho(r_1) \sim \rho(r_1 + d\ell) \sim \bar{\rho}$

we sample a number $0 \leq x \leq 1$

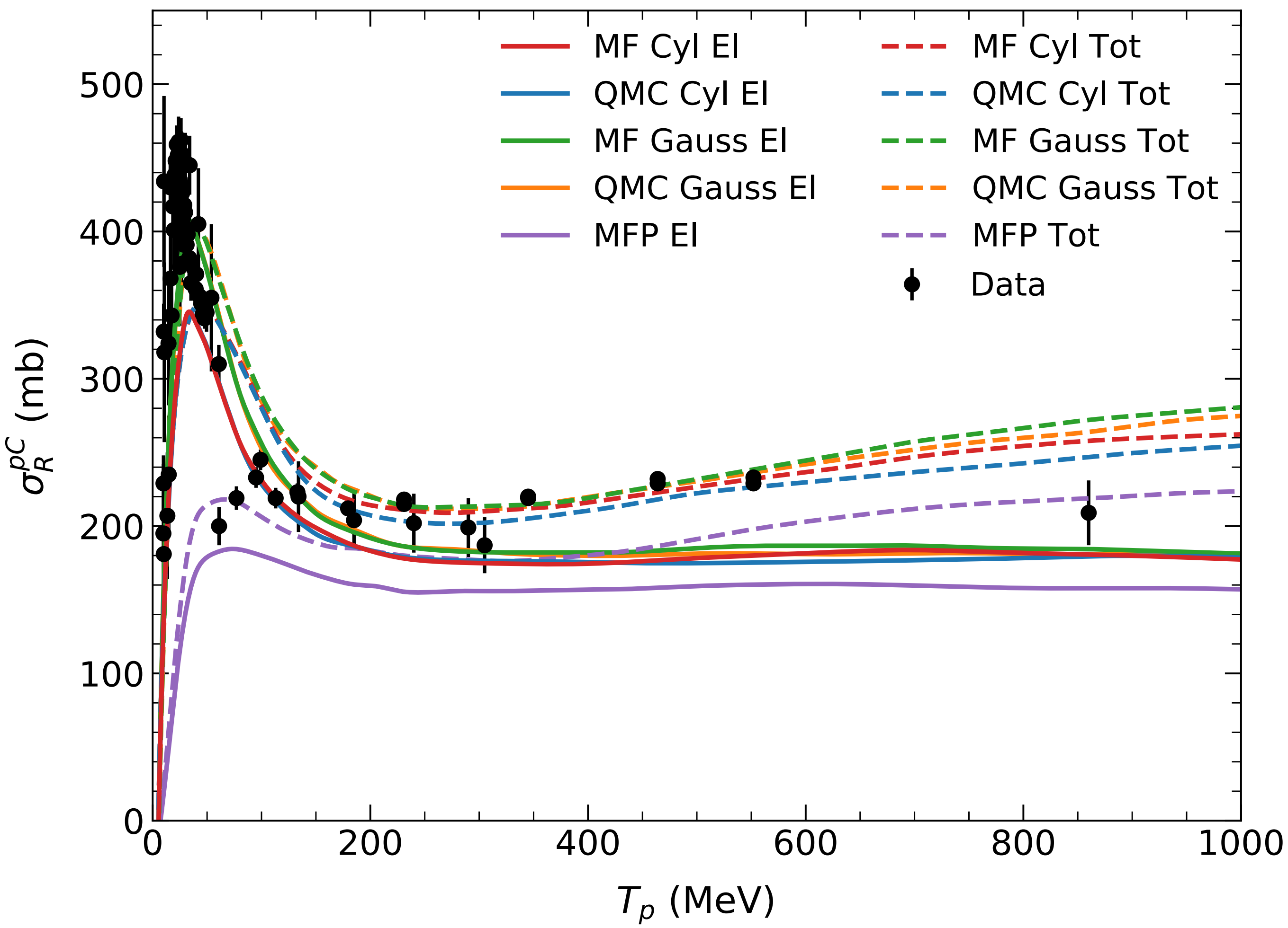
$$\begin{cases} x < P & \checkmark \text{ the interaction occurred, check Pauli blocking} \\ x > P & \times \text{ the interaction DID NOT occur} \end{cases}$$

Results: proton-Carbon cross section

Reproducing proton-nucleus cross section measurements is an important test of the accuracy of the INC model.

- We define a beam of protons with energy E, uniformly distributed over an area A.
- We propagate each proton in time and check for scattering at each step.
- The Monte Carlo cross section is defined as:

$$\sigma_{\mathrm{MC}} = A\frac{N_{\mathrm{scat}}}{N_{\mathrm{tot}}}$$



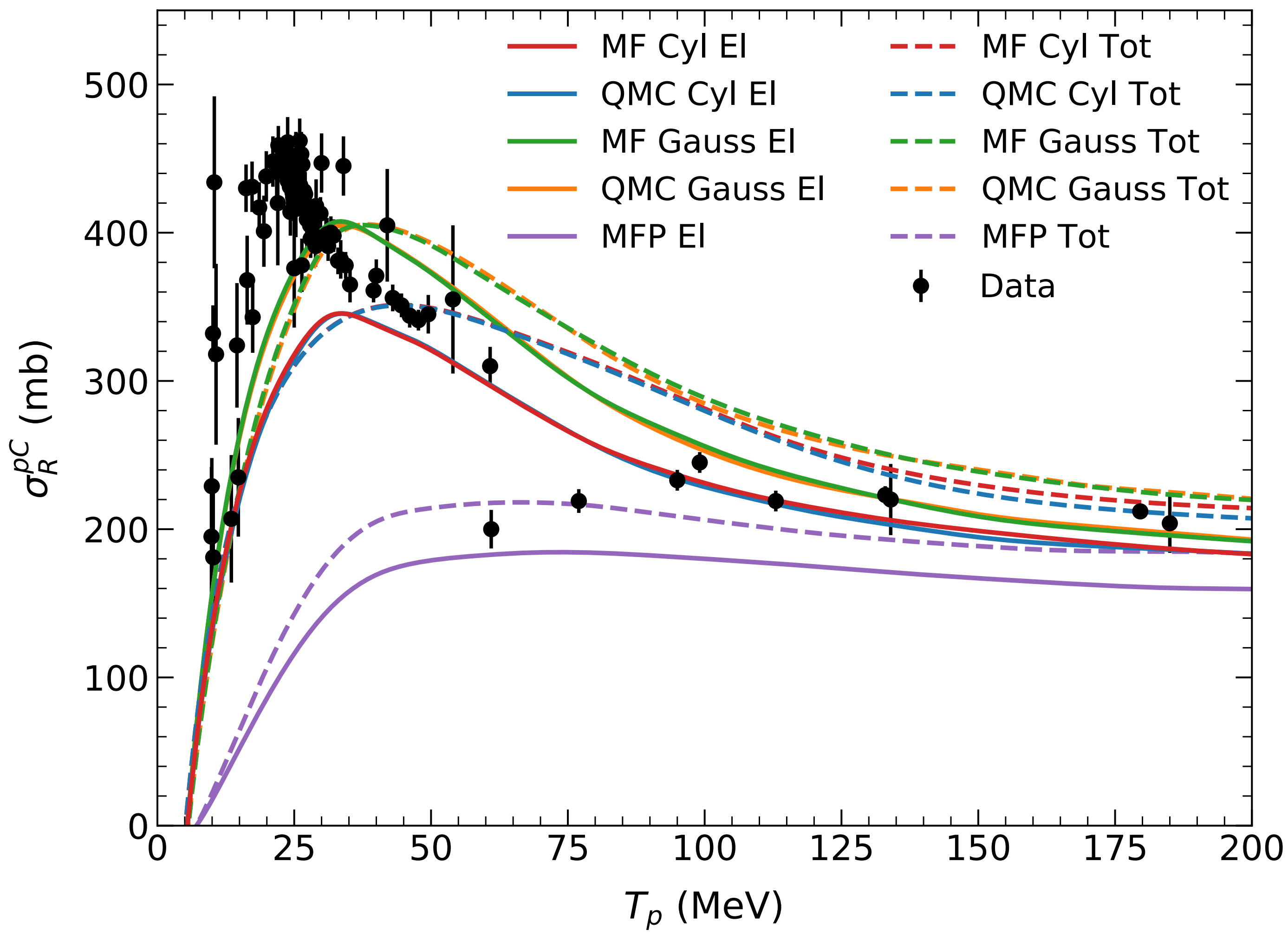
The **solid lines** have been obtained using the nucleon- nucleon cross sections from the **SAID database** in which only the **elastic contribution** is retained. The **dashed lines** used the **NASA parameterization** , which includes **inelasticities**.

Results: proton-Carbon cross section

The **Gauss** and **cylinder probability** distribution yield **similar results**

Large difference with the mean-free-path implementation: conceptual differences with respect to the previous cases

QMC and MF distribution lead to almost identical results: this observable does not depend strongly on correlations among the nucleons



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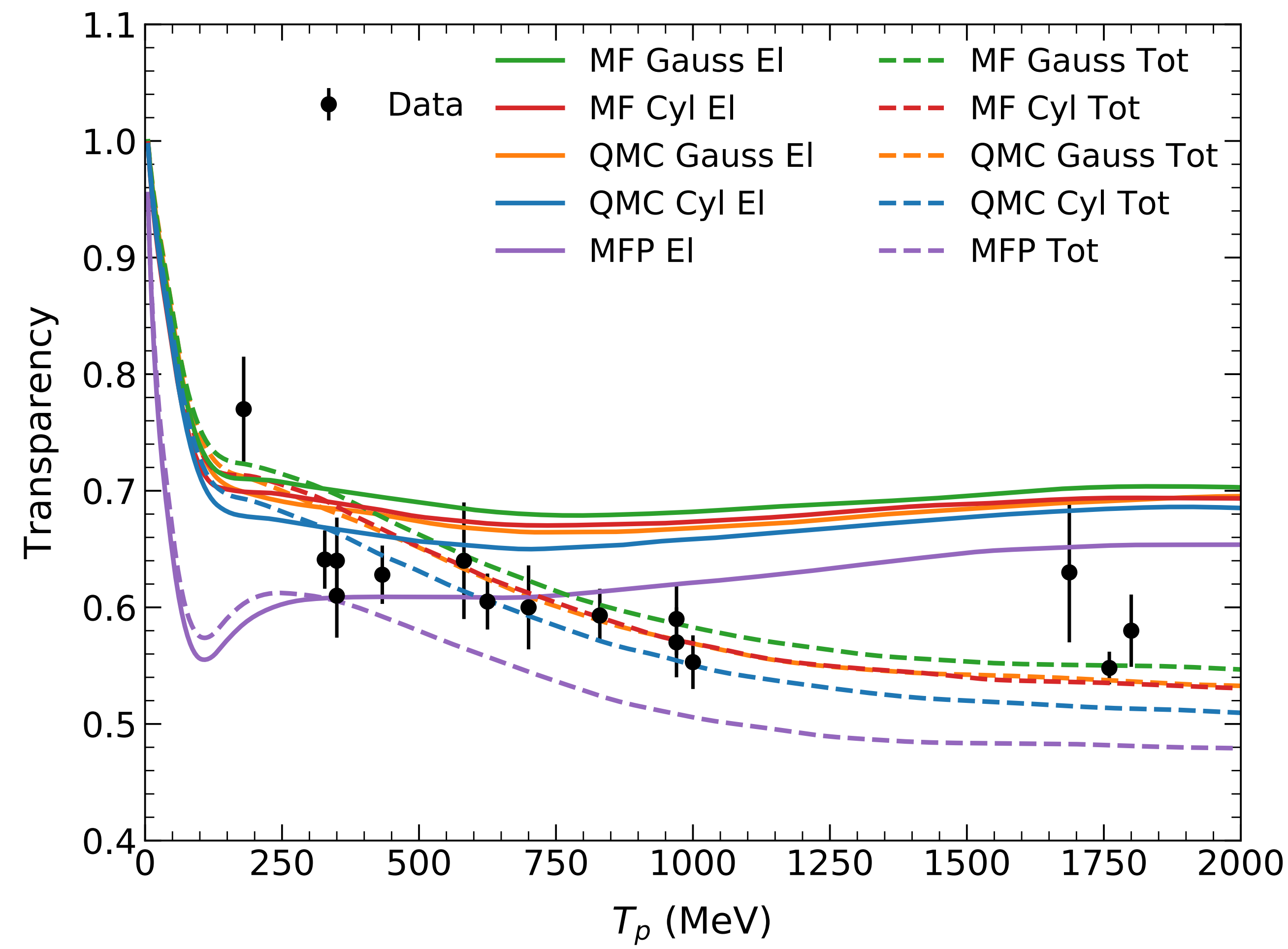
Results: nuclear transparency

The **nuclear transparency** yields the average probability that a struck nucleon leaves the nucleus without interacting with the spectator particles

Nuclear transparency is **measured in (e,e’p) scattering** experiments

Simulation: we randomly sample a nucleon with kinetic energy Tp and propagate it through the nuclear medium

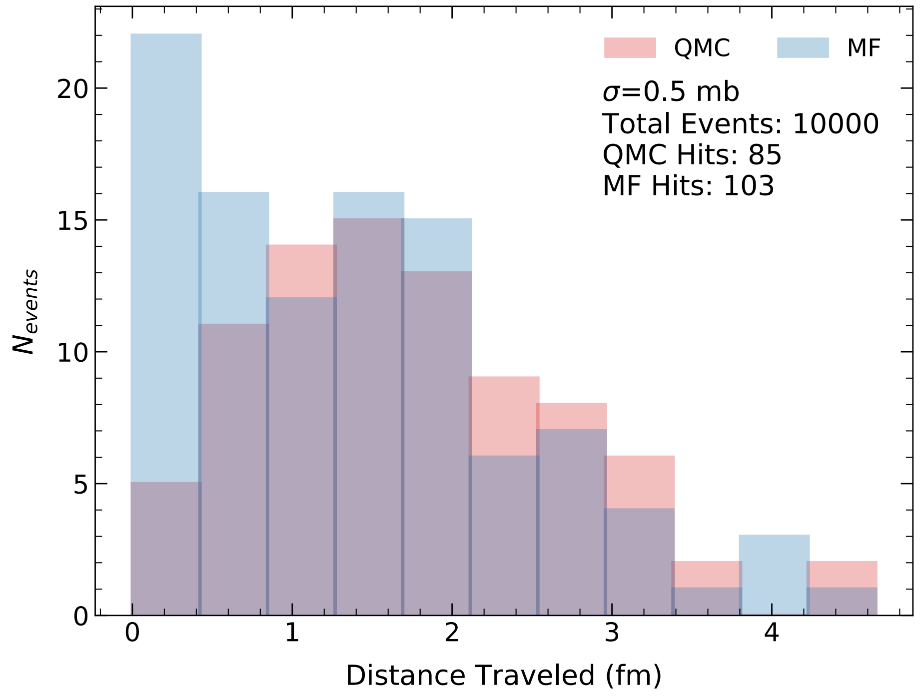
$$T_{\mathrm{MC}} = 1 - \frac{N_{\mathrm{hits}}}{N_{\mathrm{tot}}}$$



Gaussian and cylinder curves are consistent and correctly reproduces the data. Correlations do not seem to play a big role.

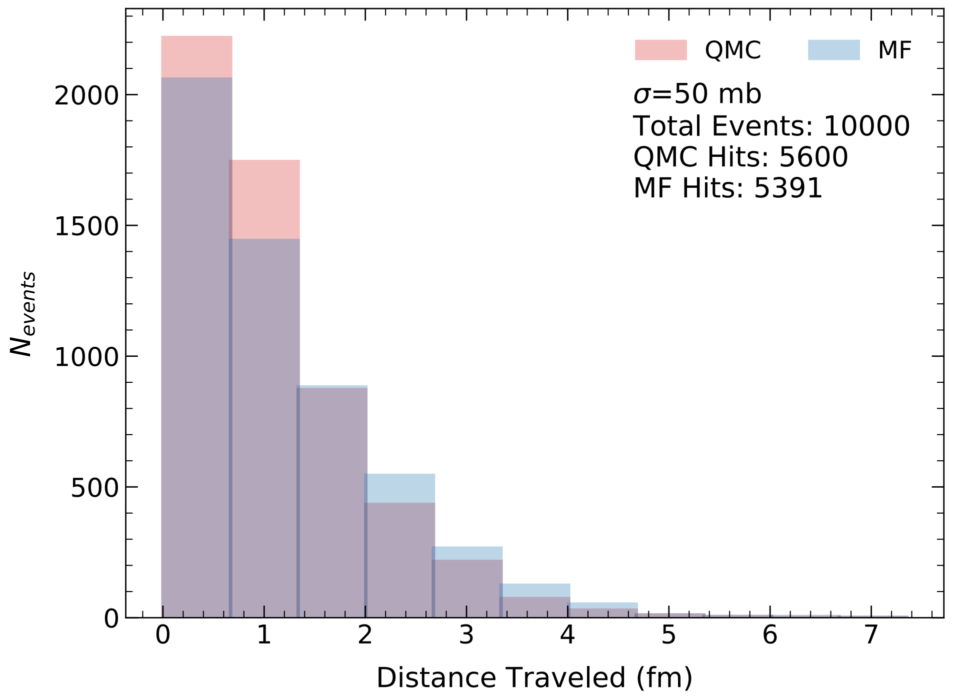
Results: correlation effects

Histograms of the **distance traveled** by a struck particle **before the first interaction** takes place for different values of the interaction cross section



When using **QMC configurations**, the hit nucleon is surrounded by a short-distance **correlation hole**: expected to propagate freely for ~ 1 fm before interacting

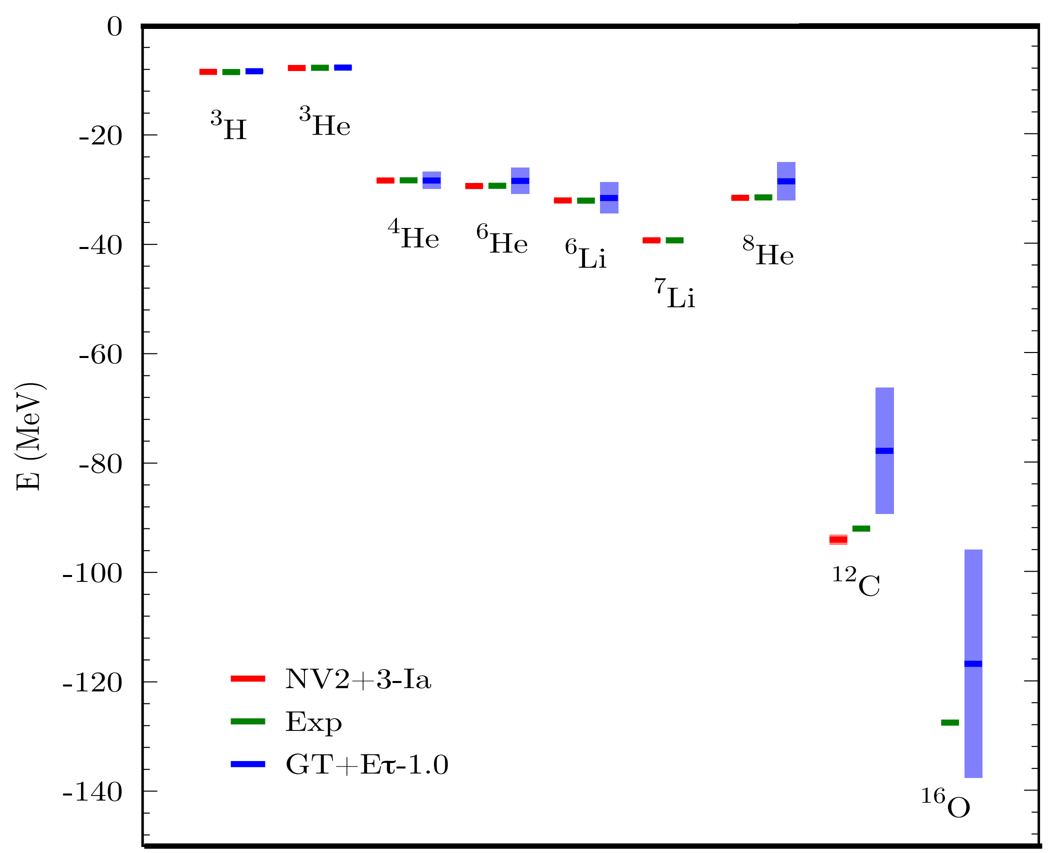
For **σ=0.5 mb** the **MF distribution peaks toward smaller distances than the QMC one**: originates from the repulsive nature of the nucleon-nucleon potential



For **σ=50 mb** large cylinder, **MF and QMC distributions become similar.** The propagating particle is less sensitive to the local distribution of nucleons and more sensitive to the integrated density over a larger volume, reducing the effect of correlations

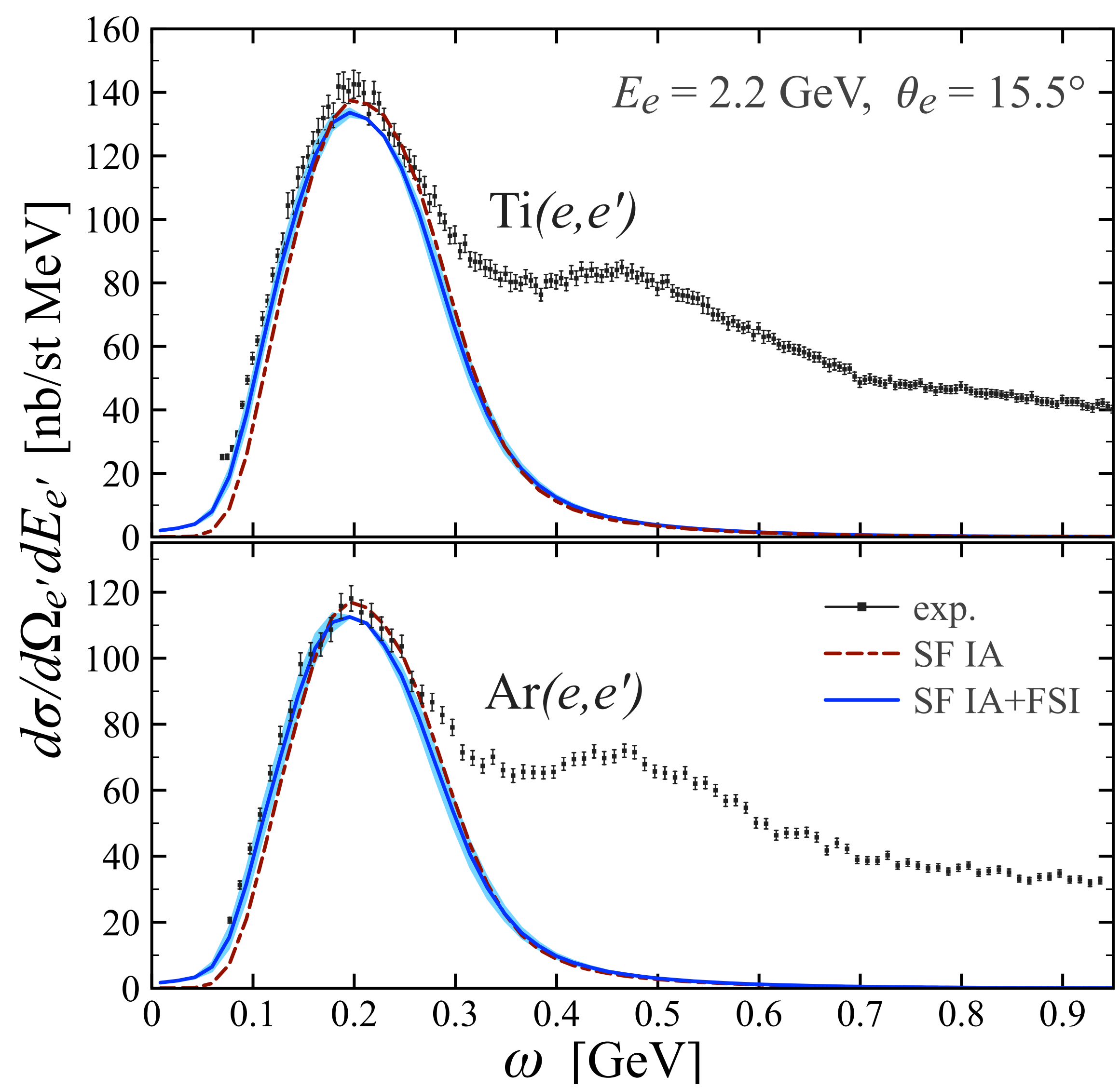
Future theory efforts

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



Theoretical uncertainty estimate: truncation of the chiral expansion and statistical uncertainty of the ab-initio method

Devise an **hybrid QMC** approach able to describe larger nuclei such as ^{16}O and use machine learning algorithms to obtain cross sections



✐ C.Barbieri, NR, V.Somà, PRC 100 (2019) 6, 062501

Using more approximate methods, **calculation of lepton-Ar cross sections. Extend** the factorization scheme to the **DIS**

Intranuclear cascade: include **π degrees of freedom**: π production, absorption and elastic scattering as well as **in medium corrections**

Thank you for your attention!