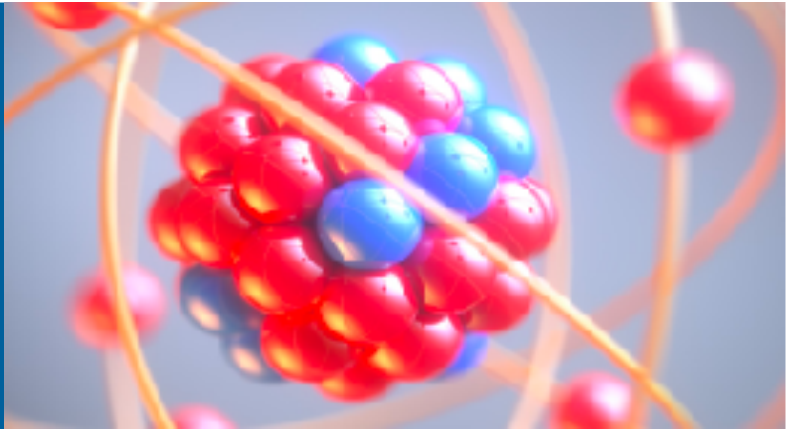
QUANTUM MONTE CARLO BASED APPROACH TO INTRANUCLEAR CASCADES



Joshua Isaacson, William Jay, Alessandro Lovato, Pedro Machado, Noemi Rocco,

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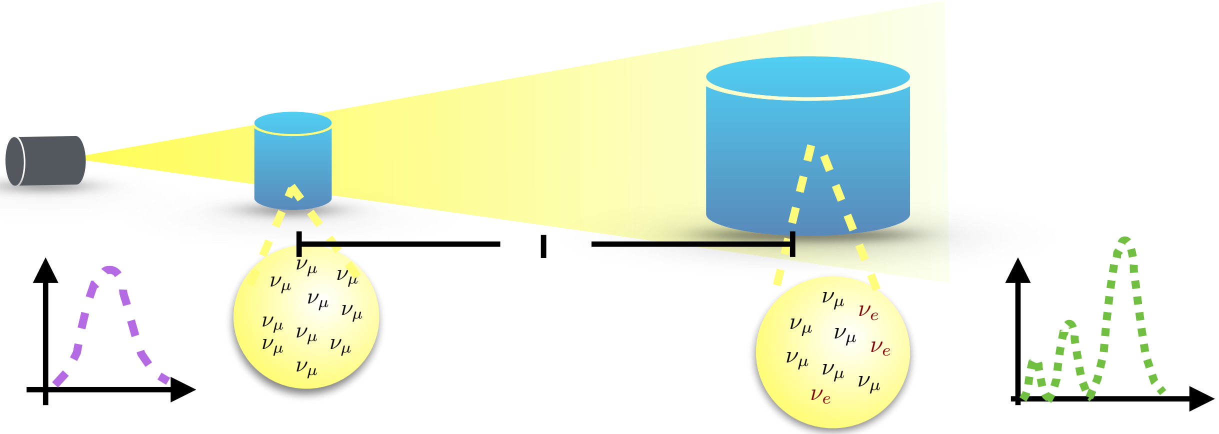
17 March 2021

New Directions in Neutrino-Nucleus Scattering
NUSTEC Workshop

INTRODUCTION

Extracting oscillation parameters requires comparing the neutrino flux at near and far detectors



The flux is extracted from the measured neutrino-nucleus interactions in a detector

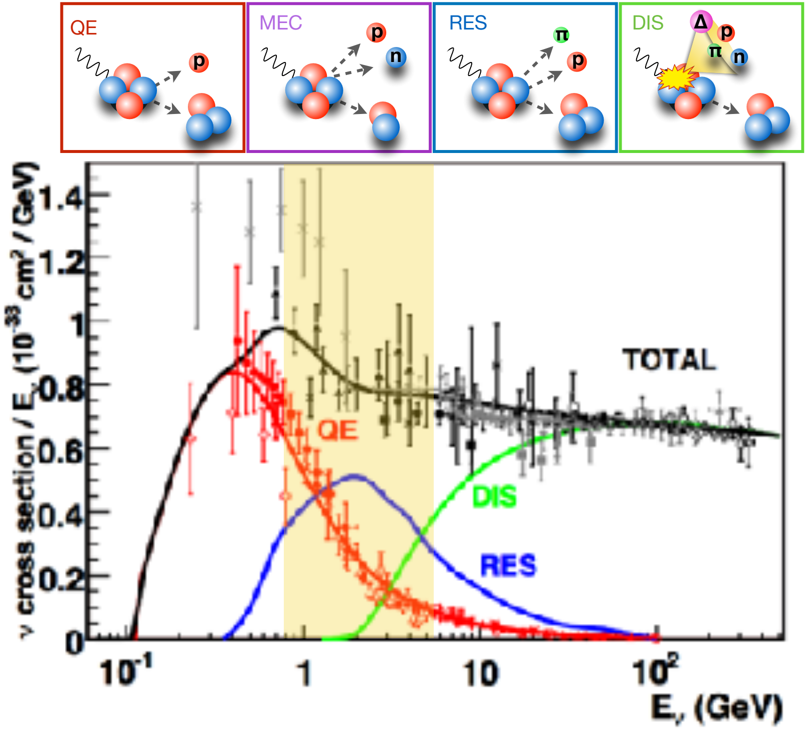
$$N_e(E_{\rm rec}, L) \propto \sum_i \Phi_e(E, L)\sigma_i(E) f_{\sigma_i}(E, E_{\rm rec}) dE$$

Knowledge of the neutrino-nucleus cross section → Precision on neutrino-oscillation parameters

INTRODUCTION

Achieving a robust description of the reaction mechanisms at play in the DUNE energy regime is a **formidable nuclear-theory challenge**

- Realistic description of nuclear correlations
- Relativistic effects in the current operators and kinematics
- Description of resonance-production and DIS region



INTRODUCTION

The exclusive neutrino-nucleus cross section can be schematically expressed as

$$d\sigma \propto L^{\mu\nu} \langle 0 | J_\mu^\dagger | f \rangle \langle f | J_\nu | 0 \rangle$$

- The initial target state can be “exactly” computed within nuclear many-body theory

$$H|\Psi_0^A\rangle = E_0|\Psi_0^A\rangle \quad \longleftrightarrow \quad H = \sum_i \frac{\mathbf{p}_i^2}{2m} + \sum_{i<j} v_{ij} + \sum_{i<j<j} V_{ijk}$$

- The final state can contain real pions and particles other then protons and neutrons

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

- Detailed information on the hadron final state are crucial for the neutrino energy reconstruction

- A quantum mechanical treatment of exclusive process involves prohibitive difficulties

QUANTUM MONTE CARLO

Our intra-nuclear cascade algorithm is based on quantum Monte Carlo calculations

- First, we perform a variational Monte Carlo calculation

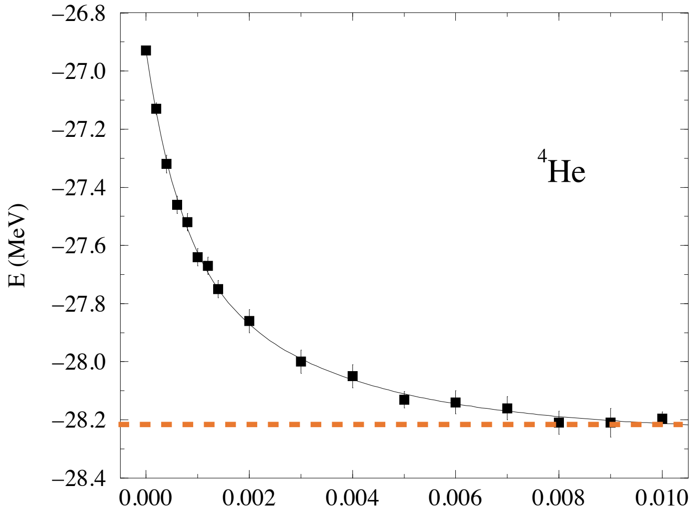
$$|\Psi_T\rangle = \left(1 + \sum_{ijk} F_{ijk}\right)\left(\mathcal{S}\prod_{ij} F_{ij}\right)|\Phi\rangle \quad \longleftrightarrow \quad E_T = \langle\Psi_T|H|\Psi_T\rangle \geq E_0$$

- Then, Green's function Monte Carlo projects out the lowest-energy state

$$|\Psi_T\rangle = \sum_n c_n |\Psi_n\rangle$$

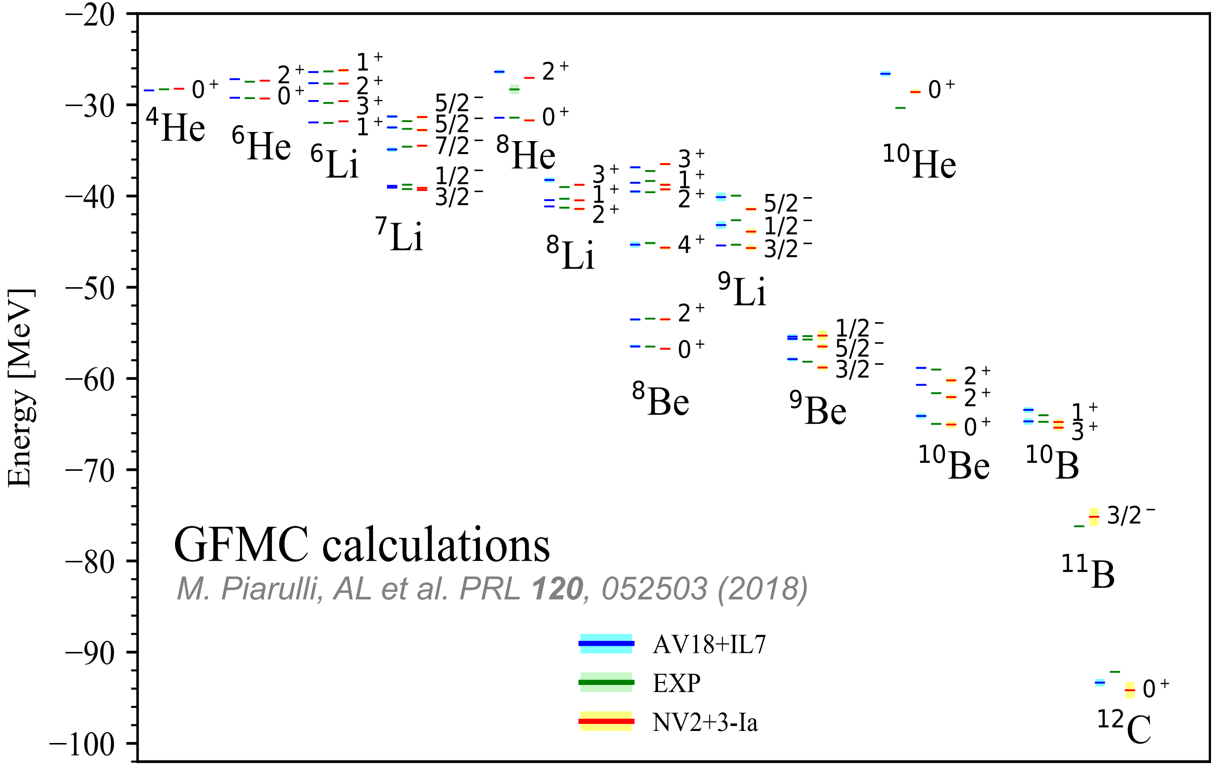
$$\lim_{\tau\to\infty} e^{-(H-E_0)\tau}|\Psi_T\rangle = c_0|\Psi_0\rangle$$

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



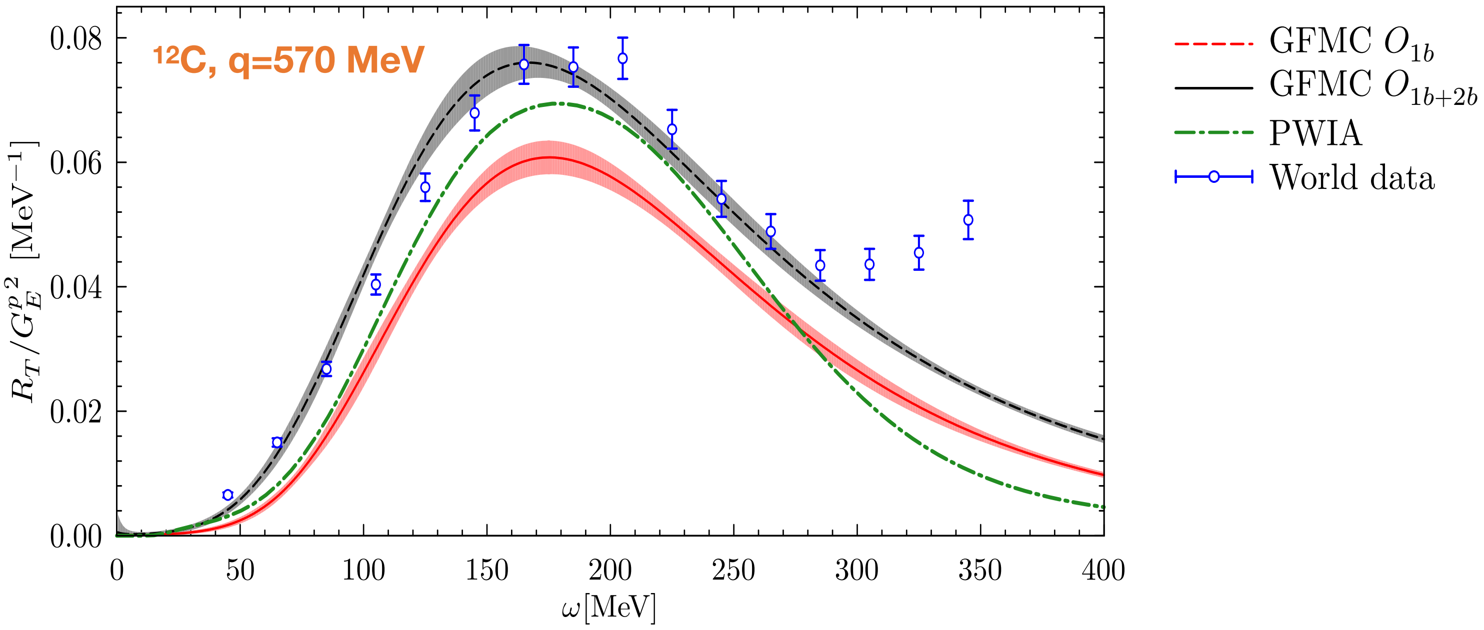
QUANTUM MONTE CARLO

GFMC solves the spectrum of light nuclei with percent-level accuracy



ELECTRON SCATTERING FROM QMC

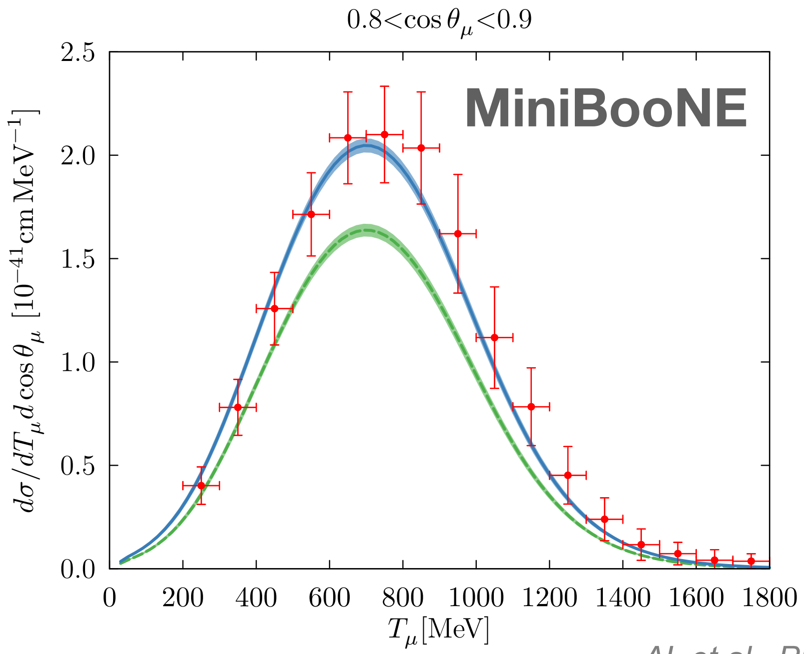
Besides the spectrum of light nuclei, QMC has been used to compute a variety of electroweak transitions and responses

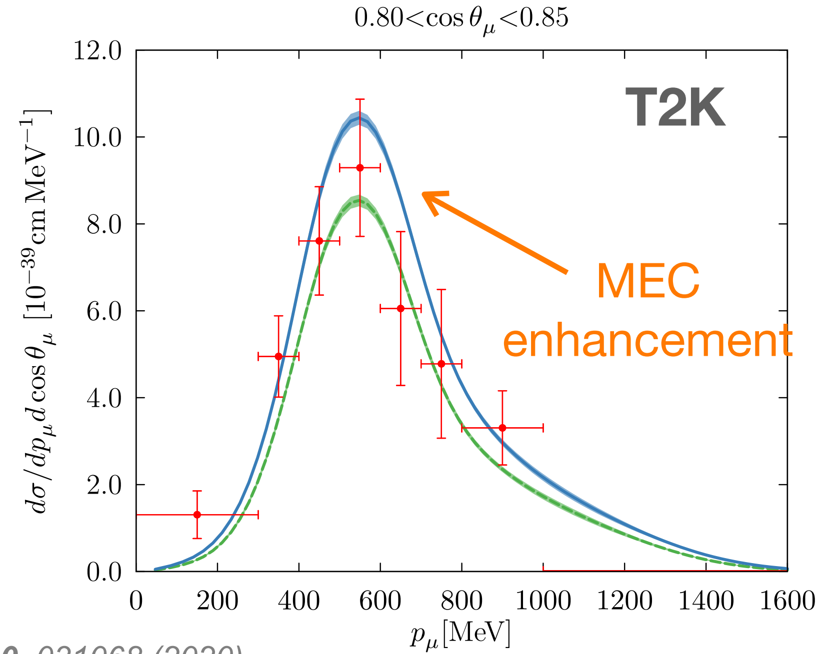


*AL et al. PRL **117** 082501 (2016)*

NEUTRINO SCATTERING FROM QMC

We recently carried out first-principle calculation of neutrino-nucleus cross section and confronted with MiniBooNE and T2K data





*AL et al., PRX **10**, 031068 (2020)*

QMC-BASED INTRANUCLEAR CASCADE

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

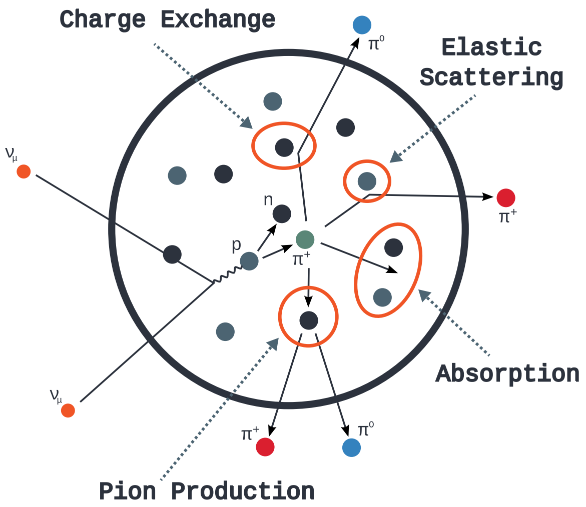


Figure from T. Golan

Ingredients:

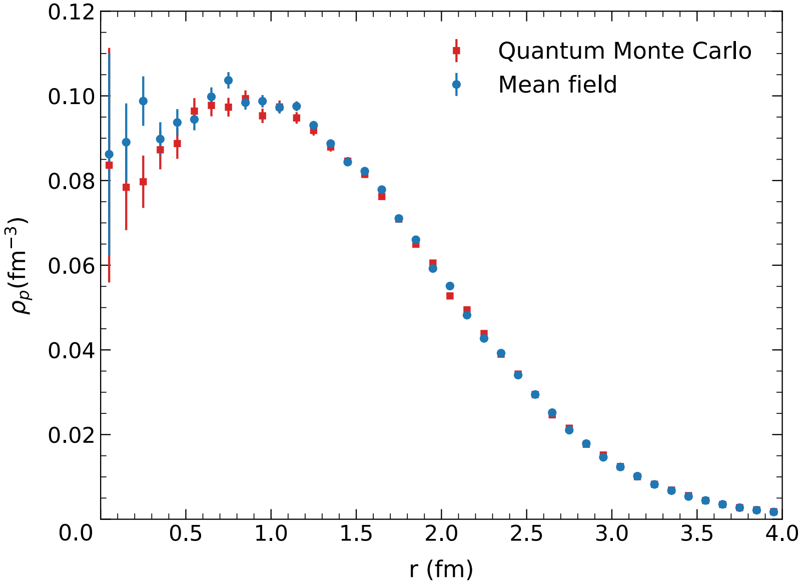
- Propagation of particles
- Elastic scattering
- Pion Production
- Pion Absorption

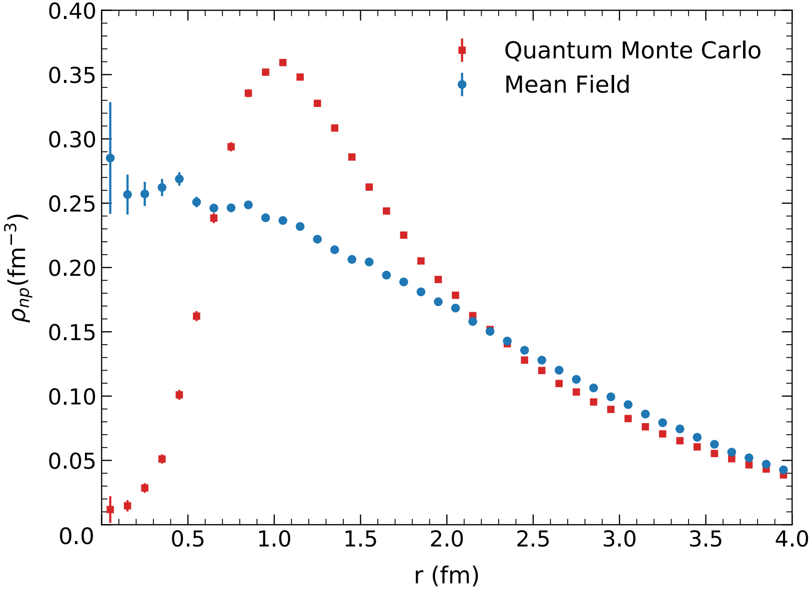
We have developed a semi-classical intra-nuclear cascade (INC) that assume classical propagation between consecutive scatterings and use QMC configurations as inputs;

QMC-BASED INTRANUCLEAR CASCADE

The nucleons’ positions are sampled from GFMC configurations. For benchmark purposes we also sampled mean-field (MF) configurations from the single-proton distribution.

The differences between GFMC and MF configurations induced by nuclear correlations are apparent when comparing the two-body density distributions





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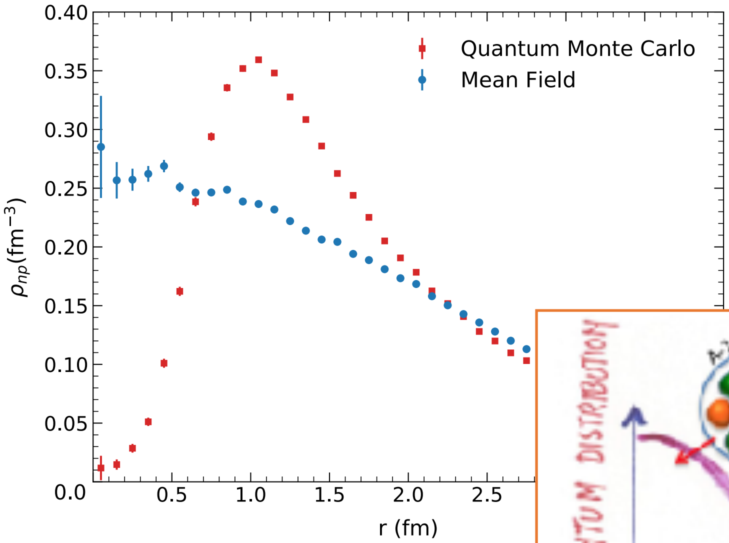
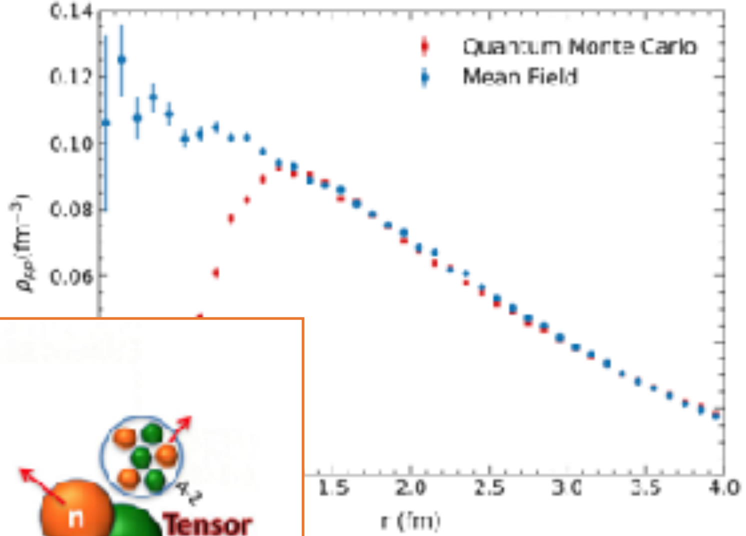
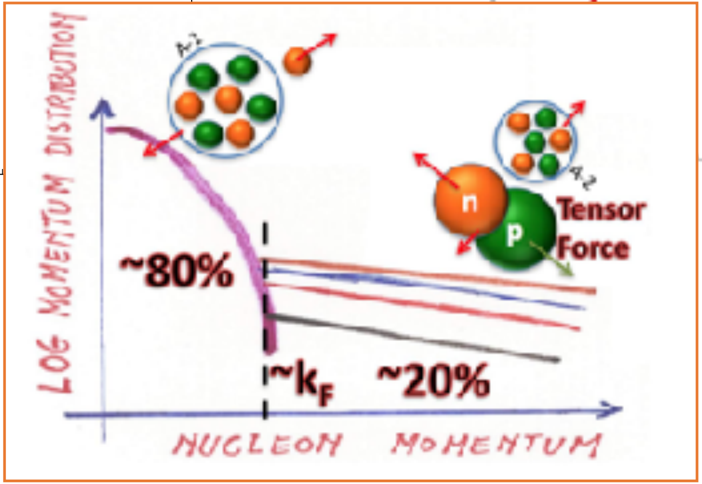
QMC-BASED INTRANUCLEAR CASCADE

There is an enhancement of the neutron-proton two-body density distribution, consistent with the dominance of neutron-proton over proton-proton SRC pairs for a variety of nuclei





O. Hen, et al. RMP **89**, 4 (2017)

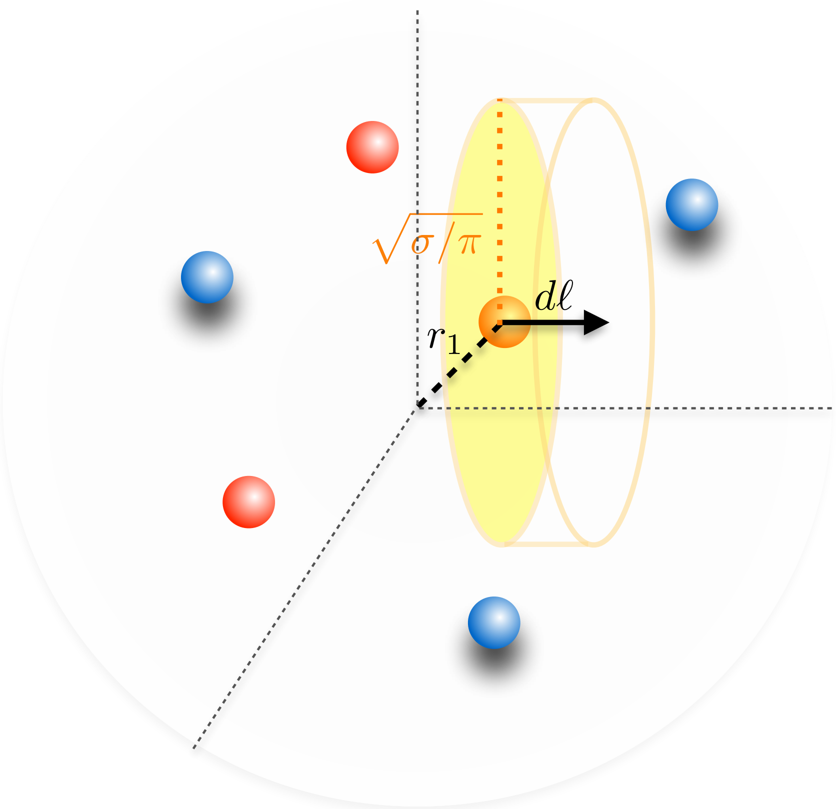


QMC-BASED INTRANUCLEAR CASCADE

To check whether an interaction has occurred we consider an accept/reject algorithm based on a "cylinder" and a "gaussian" distributions

$$P_{\rm cyl}(b) = \theta(\sigma/\pi - b^2)$$

$$P_{\rm Gau}(b) = \exp\left(-\frac{\pi b^2}{\sigma}\right)$$



We have also implemented a standard mean free path approach

$$P_{\rm int} = (\rho_p \sigma_p + \rho_n \sigma_n) d\ell$$

PROTON-CARBON CROSS SECTION

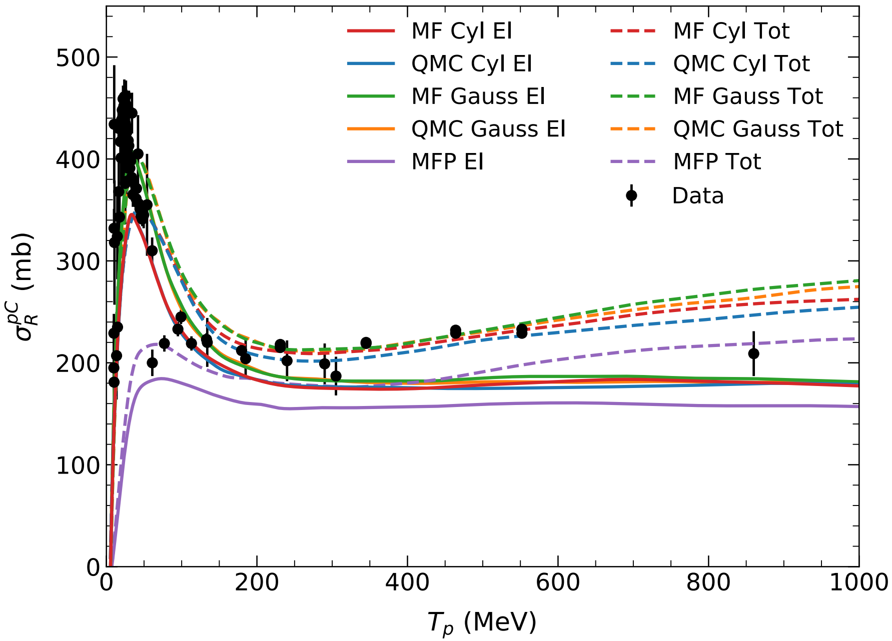
J. Isaacson, et al., PRC ***103****, 015502 (2021)*

Reproducing proton-nucleus cross section measurements is an important test for INC.

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

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

See also S. Dytman et al., 2103.07535



Solid lines: elastic NN cross-section
Dashed lines: total NN cross section

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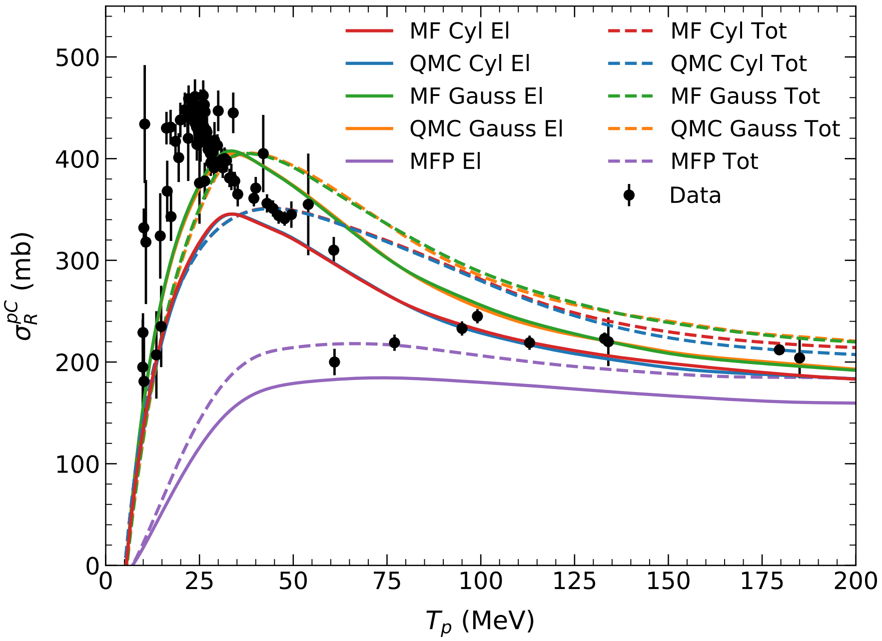


Solid lines: elastic NN cross-section
Dashed lines: total NN cross section

NUCLEAR TRANSPARENCY

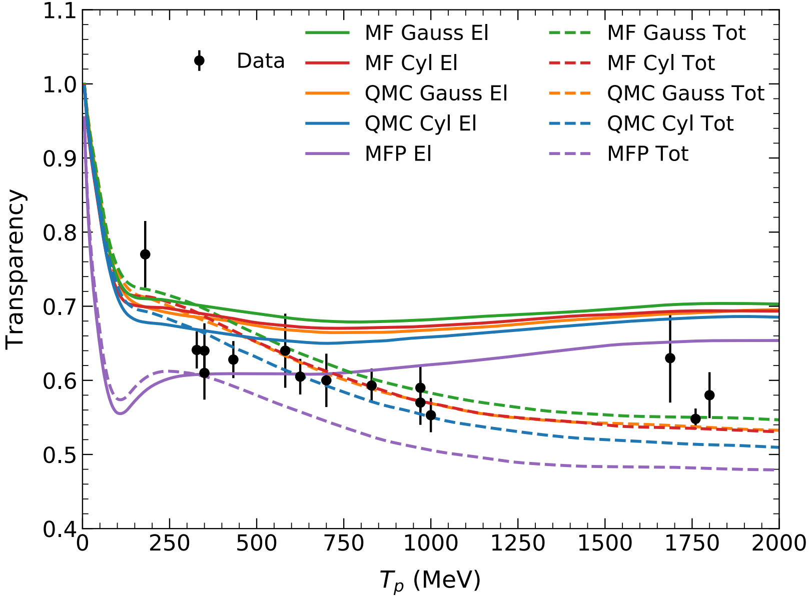
The nuclear transparency yields the average probability that a struck nucleon leaves the nucleus without interacting with the spectator particles

- The nuclear transparency is measured in (e,e'p) scattering experiments
- Simulation: we randomly sample a nucleon inside the nucleus from our configurations
- We give this nucleon a kinetic energy T_p and propagate it through the nuclear medium

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

See also S. Dytman et al., 2103.07535

*J. Isaacson, et al., PRC **103**, 015502 (2021)*

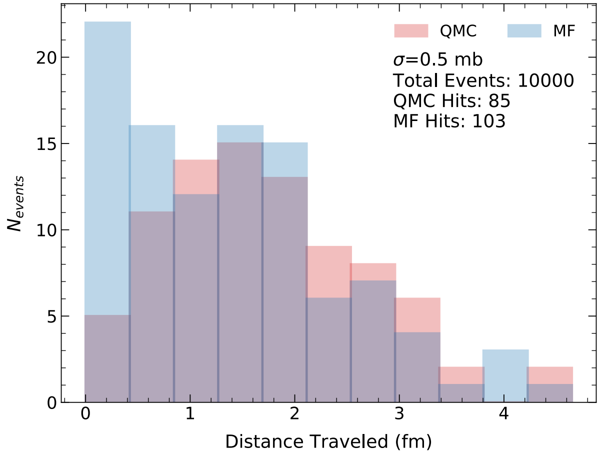


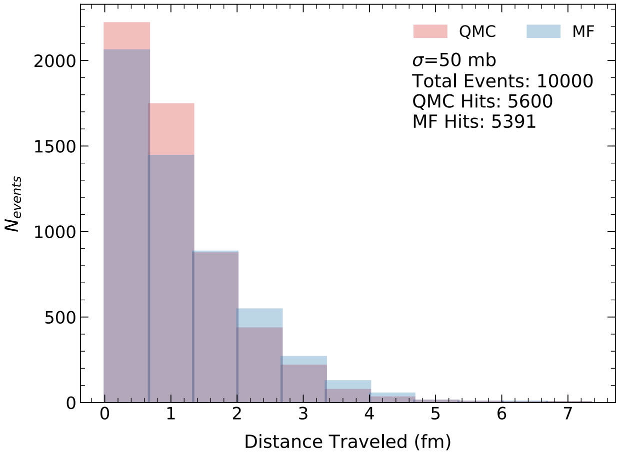
Solid lines: elastic NN cross-section
Dashed lines: total NN cross section

NUCLEAR TRANSPARENCY

Nuclear correlations in the final state do not seem to play a key role in the transparency;

- We generate histograms of the distance traveled by a struck particle before the first interaction takes place
- When using QMC configurations, the hit nucleon is surrounded by a short-distance correlation hole
- For σ=0.5 mb the MF distribution peaks toward smaller distances than the QMC one;
- For σ=50 mb large cylinder, the base of the cylinder covers the correlations hole;

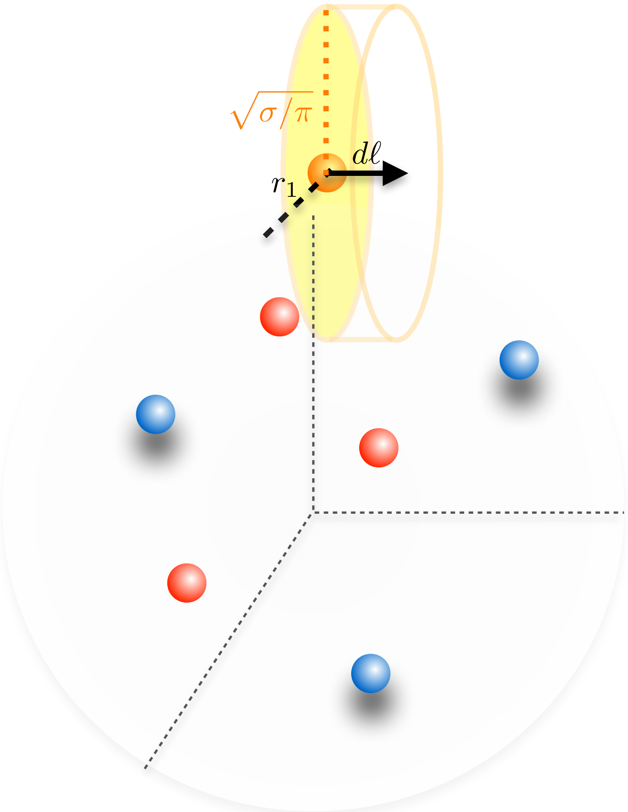


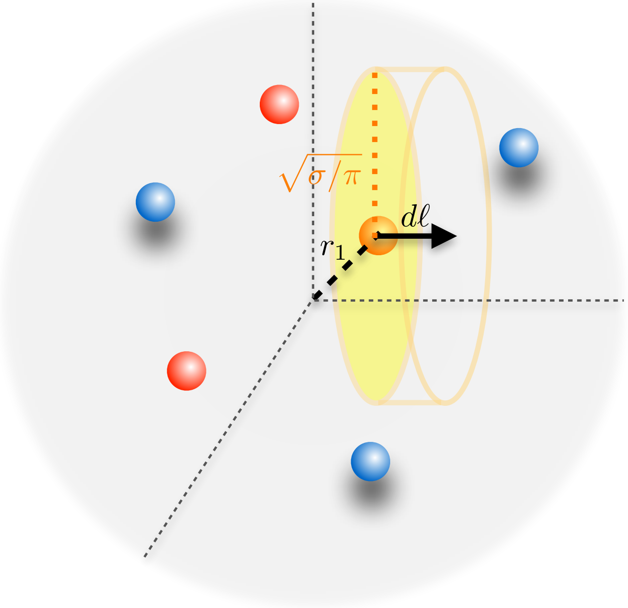


FUTURE DIRECTIONS

- Implement the “hard interaction” using the spectral-function formalism to better simulate transparency. Encouraging preliminary results (inclusive cross section reproduced)
- Better treatment of in-medium effects (binding, effective masses, position-dependent momentum distributions);
- Inclusion of pion-production in the elementary vertex and of pion-nucleon interactions in the propagation;
- Use QMC configurations to include quantum effects in the propagation (Glauber Theory)

SCATTERING VS TRANSPARENCY





INPUT CROSS SECTION

We use the nucleon-nucleon cross sections from the SAID (elastic) database obtained using GEANT4, or from the NASA (total) parametrization.