Electroweak responses of nuclei

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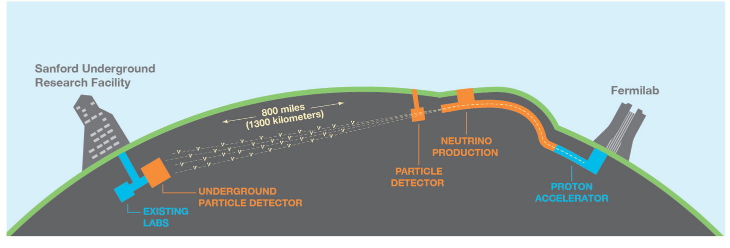
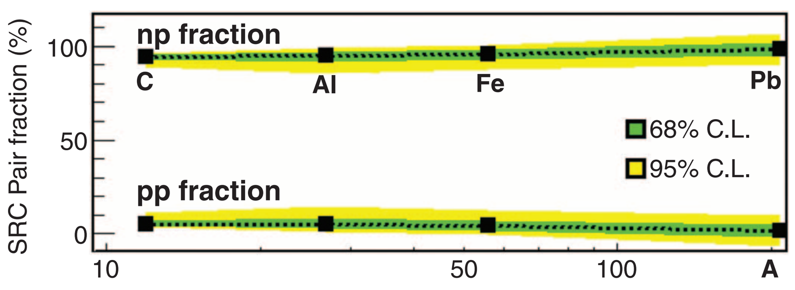
Introduction



- Neutrino physics is entering a precision era. The long- and short-baseline programs will provide definitive answers on neutrino fundamental properties
- The success of these experiments greatly relies on the precision with which nuclear structure and electroweak response functions are calculated

- Electron- and proton-nucleus scattering experiments allow to study the high momentum component of the nuclear wave function. This is dominated by the presence of short range correlated pairs of nucleons
- Observed dominance of np-over-pp pairs for a variety of nuclei is ascribed to the tensor part of the nuclear force
- An accurate description of short-range correlated pairs appears to be relevant for the understanding of the EMC effect

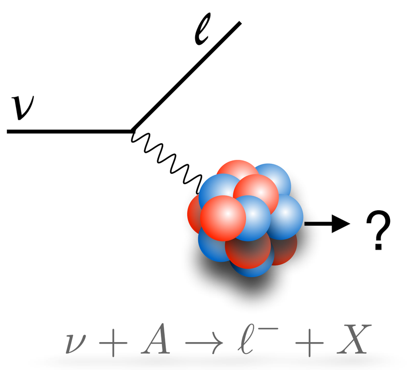


Subedi et al., Science 320, 1476 (2008)

Theory of nuclear electroweak interactions

The differential cross section for inclusive lepton-nucleus scattering reads

$$\frac{d^2\sigma}{dE'd\Omega'} = \frac{1}{16\pi^2}\frac{G^2}{2}L^{\alpha\beta}R_{\alpha\beta}$$



The hadron tensor describes the response of the nucleus

$$R_{\alpha\beta} = \sum_f \langle 0|J_\alpha^\dagger(q)|f\rangle\langle f|J_\beta(q)|0\rangle\delta^{(4)}(p_0+q-p_f)$$

The initial and final state are given by

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

Nuclear dynamics is described by:

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

Theoretical approaches:

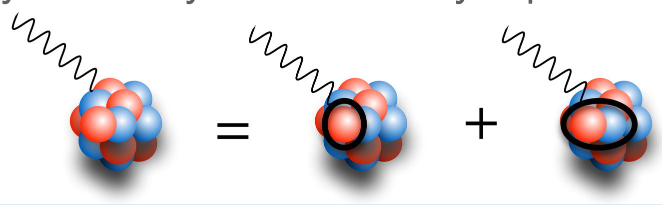
- Phenomenological: two body AV18 + three body IL7
- Chiral effective field theory: two- and three-body chiral interactions

In electromagnetic processes the current operator is conserved:

$$\partial_\mu J^\mu = 0 \longleftrightarrow \nabla\cdot\mathbf{J} + i[H, J^0] = 0$$

Two body currents are necessary to satisfy the continuity equation

$$J^\mu = \sum_i j_i^\mu + \sum_{i<j} j_{ij}^\mu + \ldots$$



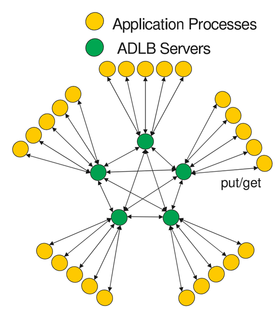
Green's Function Monte Carlo

- GFMC algorithms use imaginary-time projection technique to enhance the ground-state component of a starting (correlated) trial wave function.

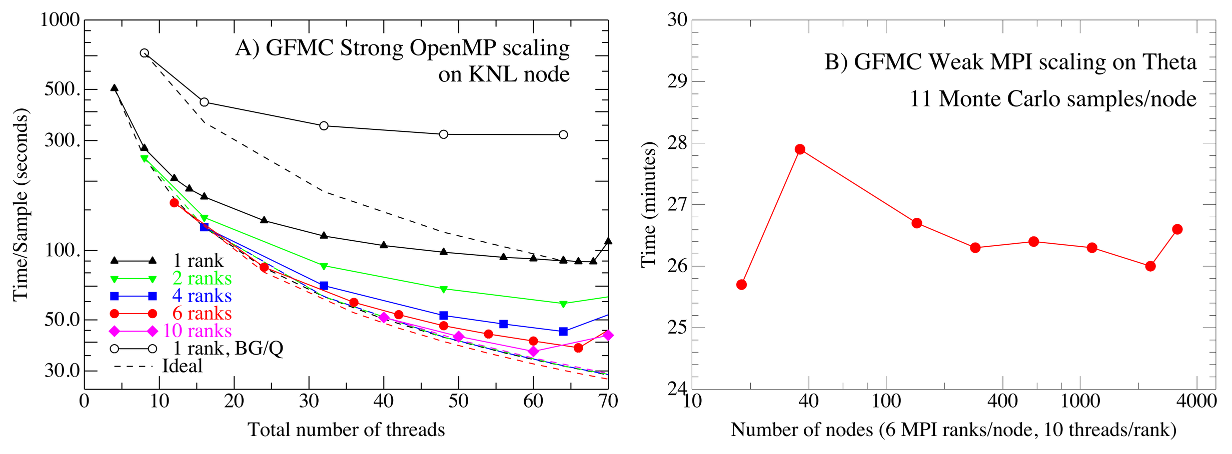
$$|\Psi_0\rangle = \lim_{\tau\to\infty} e^{-(H-E_0)\tau}|\Psi_T\rangle$$

All the nucleon spin and isospin degrees of freedom are retained, the computational cost grows exponentially with A. To deal with this level of complexity: both MPI and OpenMP parallelism are used

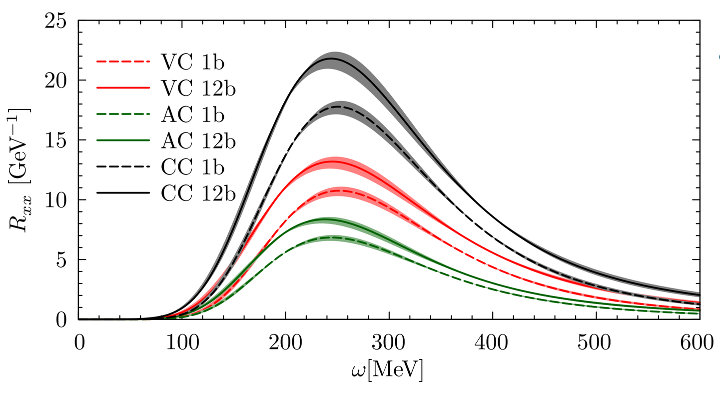
- Asynchronus Dynamic Load Balancing (ADLB) is a library that handles computational load balancing by accepting work packages from any MPI rank and distributing them to ranks that need work to do



- Distributed Memory (DMEM) carries out memory load balancing by storing large arrays on any node with enough memory and subsequently fetching them when needed.



✤ Scaling of GFMC calculations on KNL nodes and Theta



- GFMC calculation of the charged-current electroweak response of ^{12}C at **q**=700 MeV: one- and two-body currents are included

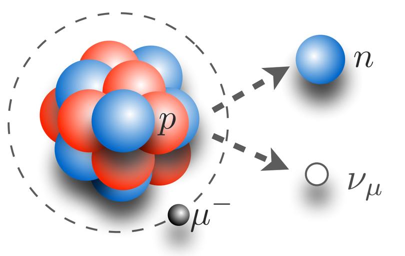
Accurate calculation of the Euclidean response within GFMC

Maximum Entropy technique is used to obtain the nuclear response function

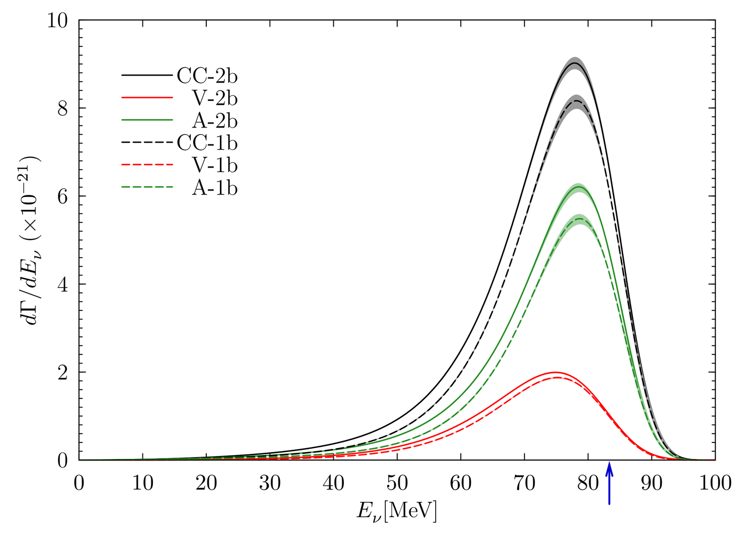
$$E_{\alpha\beta}(\sigma,\mathbf{q}) = \int d\omega K(\sigma,\omega)R_{\alpha\beta}(\omega,\mathbf{q}) = \langle\Psi_0^A|J_\alpha^\dagger(\mathbf{q})K(\sigma, H-E_0)J_\beta(\mathbf{q})|\Psi_0^A\rangle$$

- GFMC calculation of muon capture on ^{4}He and ^{3}H

Muons can be captured by the nucleus: inverse process of charge current neutrino scattering



	CC-1B	CC-12B	exp
Γ(s-1)	265±9	306±9	336±75

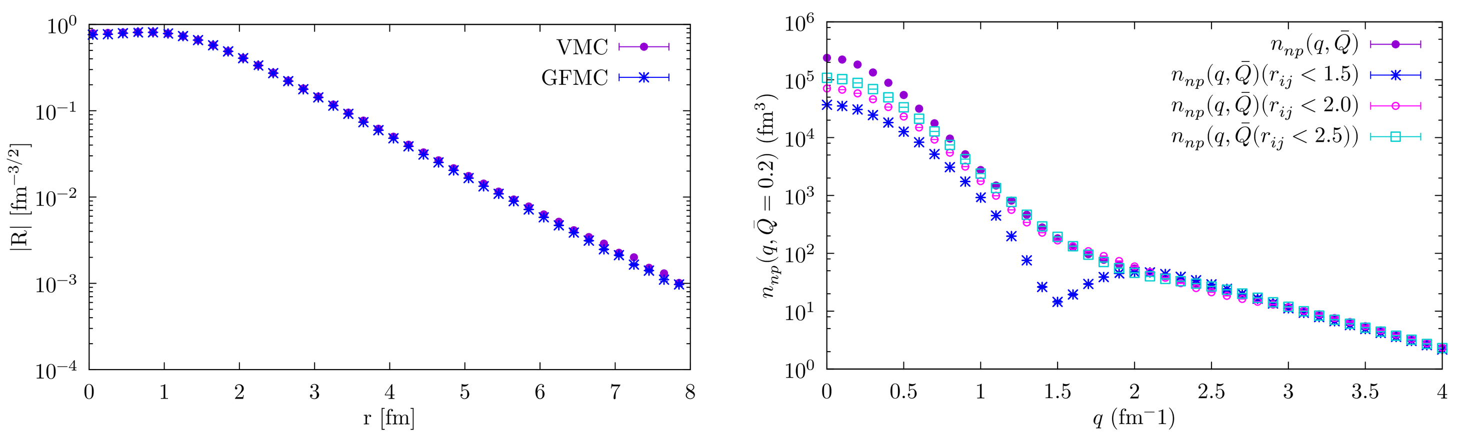


✤ Total (left) and differential (right) capture rate of ^{4}He obtained within GFMC including one-and two-body currents. The measured rate is taken from Nuovo Cimento 33, 1497 (1964).

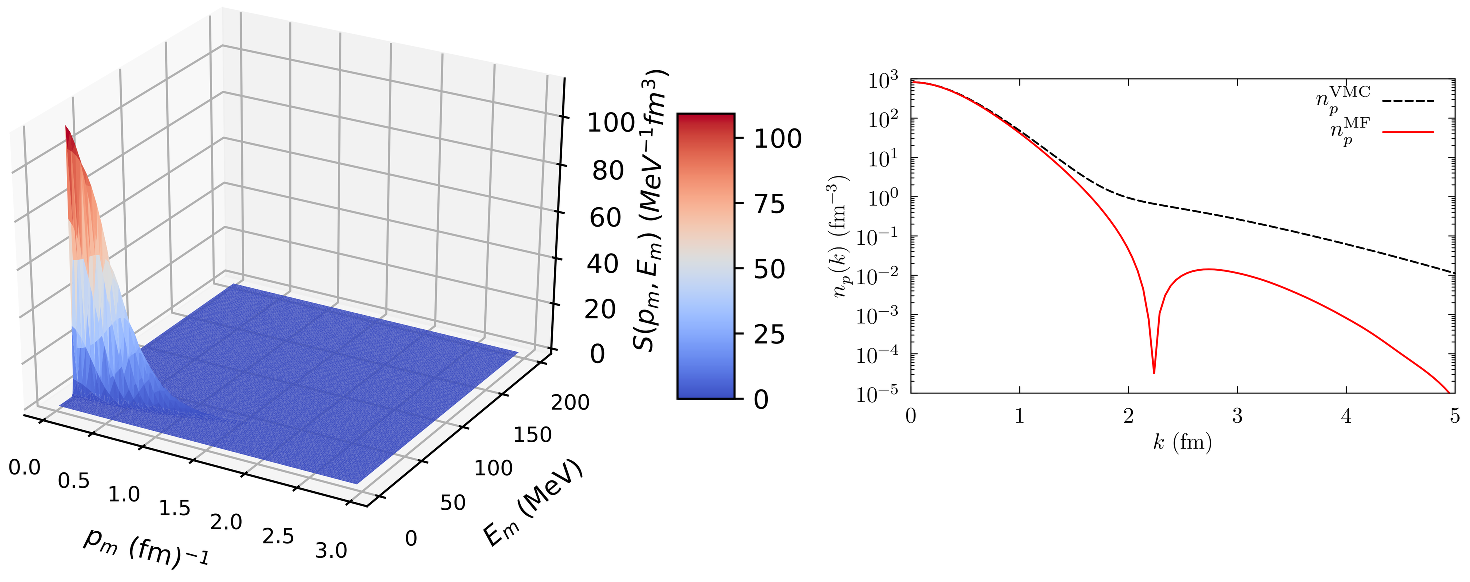
Variational Monte Carlo Spectral Function

- The Spectral Function yields the probability distribution of removing a nucleon with a given momentum and energy

$$P_N(\mathbf{k},E) = P_N^{\rm MF}(\mathbf{k},E) + P_N^{\rm corr}(\mathbf{k},E)$$

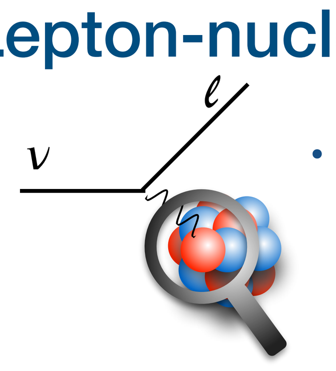


✤ The Mean Field part (left) is obtained from VMC estimates of single-nucleon overlaps. The VMC two-nucleon momentum distributions are utilized to describe the short-distance and high-momentum component of the nuclear wave-function



✤ Total spectral function of ^{4}He (left) and single nucleon momentum distribution, obtained integrating over E (right). Both the total and MF contribution are shown

Lepton-nucleus scattering using factorization



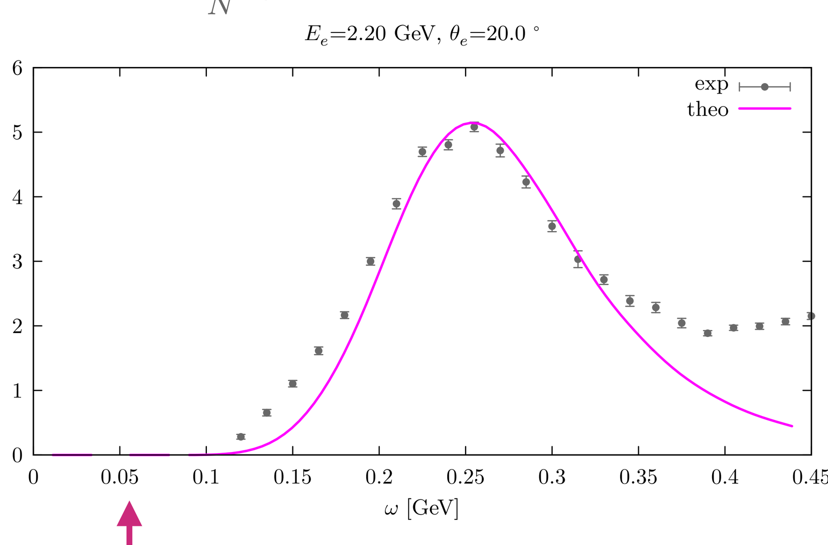
- In the limit of moderate **q**, one can factorize the interaction vertex and use a Spectral Function to describe the internal nuclear dynamics

The matrix element of the current can be written in the factorized form

$$\langle 0|J_\alpha(\mathbf{q})|f\rangle \to \sum_k \langle\Psi_0^A|[|\psi_k^N\rangle\otimes|\Psi_f^{A-1}\rangle]\langle\psi_k^N|\sum_i j_\alpha^i(\mathbf{q})|\psi_p^{N'}\rangle$$

leading to a simplified expression for the nuclear cross section

$$d\sigma_A = \sum_N \int dE d^3k\, P_N(\mathbf{k},E)d\sigma_N$$ given in terms of the elementary one



✤ Electron-^{4}He (top left) differential cross section obtained using the VMC spectral function. Only one-body current is included

✤ Charge current neutrino-^{12}C (bottom right) differential cross section. We included one- and two-body current, π production