Connecting QCD to neutrino-nucleus scattering

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Abstract

The energy spectrum of neutrinos at DUNE is peaked in the few GeV region, where quantifying nuclear model uncertainties arising from nonperturbative quantum chromodyanmics (QCD) effects is particularly challenging. A coherent set of theoretical frameworks is required to describe neutrino interactions with nuclei with the level of accuracy needed for the success of DUNE and other precision neutrino oscillation experiments. We envision developments in lattice and perturbative QCD, nuclear effective field theory, and many-body methods that will be incorporated in neutrino event generators to significantly improve the accuracy of neutrino event reconstruction. This letter of interest outlines strategies for interfacing between these frameworks and constructing a pipeline for robustly connecting the neutrino-nucleus cross-sections relevant for neutrino-oscillation experiments to QCD.

Topical Groups:
■ (NF6) Neutrino cross sections
■ (TF11) Theory of neutrino physics
■ (CompF2) Theoretical Calculations and Simulation
■ (TF05) Lattice Gauge Theory

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Introduction — Neutrino oscillations are the only beyond the Standard Model (BSM) physics processes that have been definitively observed in terrestrial experiments. Understanding the nature of neutrino mass and possible violation of CP and lepton number symmetries in the neutrino sector will provide insights into the physics behind neutrino masses and mixing, and possibly the origin of the matter-antimatter asymmetry of the universe[2]. Future long-baseline neutrino experiments, such as the Deep Underground Neutrino Experiment (DUNE), aim at addressing these fundamental questions[3]. This experiment will utilize liquid-argon time-projection chamber technology, which exploits scattering of neutrinos off ^{40}Ar nuclei contained in the detectors. For this reason providing accurate predictions of neutrino-nucleus (νA) interactions supplemented by reliable estimates of theoretical uncertainty will be crucial in this era of high-precision physics. To fully exploit DUNE's high statistics and unique capabilities in probing standard and beyond standard physics, it is essential that calculations of νA scattering are grounded in the Standard Model (SM) of particle physics and rely on controlled approximations to QCD, the fundamental theory of quark and gluon interactions.

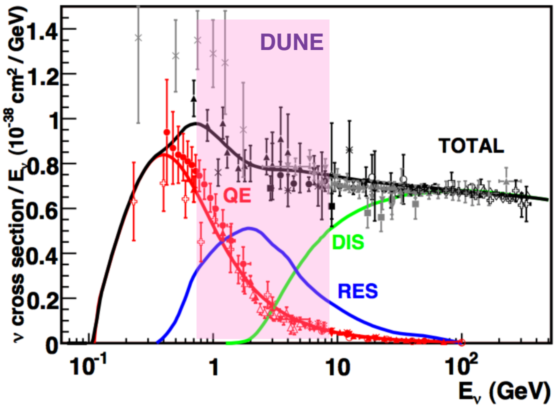

Figure 1: Total neutrino per nucleon charge current cross section adapted from Ref.[1].

Neutrino-nucleus scattering — The relative importance of the reaction mechanisms at play in νA scattering depends upon the incident neutrino energy[1;4;5], as shown in Fig. 1. Different theoretical frameworks are needed to properly describe them. For low incident neutrino energies $E_\nu \ll 1$ GeV in the quasielastic region, hadronic effective field theories (EFTs) with nucleons, pions, and sometimes hadronic resonances as explicit degrees of freedom can be used to parametrize νA scattering amplitudes using convergent low-energy expansions[6–11]. For large incident neutrino energies $E_\nu \gg 1$ GeV in the deep-inelastic scattering (DIS) region, QCD factorization can be used to model νA scattering amplitudes as convolutions of hard scattering amplitudes that are perturbatively calculable in QCD and nonperturbative but process-independent parton distribution functions (PDFs). In both cases, the nonperturbative QCD properties required as inputs to these expansions can be constrained using results from eA, νA, and hadron scattering experiments or computed using lattice QCD (LQCD) or a combination of LQCD and EFT. For energies of order 1 GeV in the resonance and shallow inelastic regions, nonperturbative QCD effects lead to large corrections to either low-energy or high-energy expansions of νA scattering amplitudes, and LQCD calculations are required to describe νA scattering directly from the SM. Phenomenological nuclear models can be used to smoothly interpolate between low-energy and high-energy descriptions of νA scattering and describe this transition region in practice[12;13], but quantifying the uncertainties of phenomenological nuclear models is challenging and requires validation with accurate results from experiment and LQCD.

Interplay between LQCD and EFT — The role of LQCD in νA scattering calculations will be to provide accurate results for electroweak processes in the nucleon and few-nucleon systems that can be used to constrain nuclear EFTs and phenomenological models, as recently outlined in a whitepaper by the USQCD Collaboration[14]. Low-energy EFTs exploit a hierarchy of nuclear forces in which two-nucleon forces and one-nucleon currents dominate, three-nucleon forces and two-nucleon currents provide subdominant corrections, and additional higher-body effects are further suppressed[15–19]. Some vector current form factors are well-known experimentally from electron scattering, but νA scattering is also sensitive to axial currents and different quark flavor structures. In these cases, LQCD calculations of elastic form factors are already achieving phenomenologically relevant precision[20–26], and with increased control of statistical and systematic uncertainties future nucleon form factor calculations will provide valuable input for nuclear EFT studies of νA scattering. Inelastic electroweak transition amplitudes involving π or other meson production or hadronic resonances such as the Δ are also required as inputs to EFT descriptions of nuclei involving explicit π and Δ degrees of freedom relevant for multi-hundred-GeV incident neutrinos and are less well-known experimentally than elastic nucleon form factors[27;28]. Although LQCD calculations are limited to finite-volume Euclidean correlation functions, there has been significant progress in extracting resonance physics from finite-volume observables[29] and in particular formalism has been developed for relating multi-hadron finite-volume matrix elements to infinite-volume resonant electroweak transition amplitudes[30–36]. LQCD results for finite-volume energy levels and matrix elements can also be matched directly to corresponding EFT results in order to constrain the parameters governing resonance production[37]. Calculations of the nucleon hadron tensor governing inclusive νA scattering are also being explored in which spectral reconstruction techniques are used to related Euclidean and Minkowski correlation functions[38].

LQCD calculations of electroweak transition rates in light nuclei will also provide critical inputs to low-energy nuclear EFT — in particular two-body currents — and will be essential for constraining and validating phenomenological models needed to describe νA scattering at higher energies where chiral EFT does not converge[39]. Exploratory LQCD calculations of nuclear matrix elements for electroweak processes such as $np \to d\gamma$ and $pp \to de^+\nu$ have demonstrated the feasibility of using LQCD to constrain two-nucleon currents in EFT[40;41]. With increased computing and algorithmic advances, future LQCD calculations will provide precise continuum-extrapolated predictions for electroweak nuclear matrix elements and form factors at physical quark masses. In particular, predictions of the muon capture rates of light nuclei in LQCD and EFT can be compared to constrain one- and two-body axial currents in the low-momentum region where EFT is applicable[42–44], while calculations of electroweak transition amplitudes at at 1 to few GeV energies will provide critical inputs for nuclear models of the poorly constrained shallow inelastic region.

For high energies in the DIS region, it is advantageous to exploit factorization and describe νA scattering at the quark-and-gluon level in terms of perturbative QCD amplitudes and PDFs[1]. Some PDFs are precisely constrained using data from the Large Hadron Collider (LHC) and other experiments, but the electroweak interactions involved in νA scattering probe additional spin and flavor combinations of PDFs that are more poorly constrained. LQCD can be used to constrain the required PDFs in these cases by computing PDF moments related to nucleon and nuclear matrix elements of local operators and by using recently developed methods such as large momentum effective theory (LaMET) and related methods to directly constrain the x-dependence of PDFs[45;46]. Using LQCD constraints on PDFs in one- and few-nucleon systems, EFT can be used to constrain additional aspects of nuclear PDFs and extrapolate LQCD constraints to larger nuclei of experimental relevance[47;48].

Event generators play a key role in simulating the propagation of particles produced in the primary interaction vertex throughout the nuclear medium, hence connecting theoretical predictions to experimental data[49–52]. Nuclear many-body methods based on EFT Hamiltonians can provide realistic inputs to these simulations, such as nucleon distributions in coordinate and momentum space, as well as optical potentials. Concurrently, LQCD calculations of $N \to N\pi$ and $N\pi \to N\pi$ amplitudes will provide valuable constraints on the phenomenological models currently employed in event generators to describe these processes. As these and other examples highlight, the interplay between LQCD and nuclear EFT will grow in the coming years and play an essential role in our quantitative understanding νA scattering.

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