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Neutrino Cross Section Theory for future Oscillation Experiments

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The next generation of oscillation experiments will require considerable efforts towards more precise modeling of neutrino cross sections. In this context, neutrino-interaction theory is in the position to play a pivotal role in the success of the experimental program, providing accurate predictions and meaningful theoretical uncertainties. There is ongoing progress in lattice QCD, effective field theories and phenomenological models. It is bound to have a direct impact in planning, running and analyzing future experiments, maximizing their discovery potential.

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Motivation Neutrinos are revealed through their interactions with matter. A good understanding of detector responses to these interactions is therefore critical for the success of oscillation experiments [1]. Depending on the typical neutrino energies in a given experiment, many different reaction mechanisms can occur, ranging from coherent elastic scattering on nuclei as a whole to deep-inelastic scattering on subnuclear partons. For accelerator neutrinos in the few-GeV region quasi-elastic (QE) and inelastic processes on one or more nucleons lead to a variety of final states.

While precise cross section measurements using neutrino but also electron beams are instrumental in achieving the experimental goals, the importance of state-of-the-art strong interaction theory cannot be underestimated. Oscillation analyses rely on theory-based simulations for neutrino flux calibrations, background subtractions, efficiency and acceptance determinations, neutrino energy reconstruction and cross section extrapolations between different target materials or neutrino flavors (for example, to infer ν_e cross sections from better experimentally constrained ν_μ ones).

In the case of future experiments, realistic hadron and nuclear models can allow to perform more realistic projections. For illustration let us consider Ref. [2], which quantifies DUNE's expected sensitivity to long-baseline neutrino oscillations, using the accelerator neutrino beam. For this purpose, the study considers detailed uncertainties due to, among others, the "neutrino interaction model". As anticipated, several different interaction mechanisms and degrees of freedom should be taken into account; a detailed account is given in Sec. 3 of Ref. [2]. In spite of its known deficiencies, the initial state is described by a global Fermi gas although it is approximately improved with short and long-range nuclear correlations. According to the error budget listed in tables 1-4, to the "Fermi surface momentum for Pauli blocking", p_F a $\pm 30\%$ uncertainty is assigned. However, recalling that according to Fermi statistics, the density is proportional to p_F^3, one can see that a $\pm 30\%$ variation in p_F corresponds to $0.3\rho_0 \lesssim \rho \lesssim 2.2\rho_0$, where ρ_0 is the nuclear matter saturation density. The lowest values densities in this interval are met in the outer layers of nuclei, while the highest ones can only be found in the densest neutron stars. The assumed uncertainty is therefore unrealistically large. In spite of this and other model deficiencies, the experiment is robust: Ref. [2] concludes that DUNE should be able to determine the neutrino mass ordering and observe CP violation. Nevertheless, an artificial inflation of errors can be dangerous because potentially interesting new physics, might remain undisclosed under error bars. Ultimately, a more efficient management of the resources would be possible if advanced neutrino interaction physics is taken into account.

Theory tool box. The physics of electroweak interactions on nucleons and nuclei relies on different approaches and techniques. The theory tool box includes: quantum chromodynamics (on the lattice), effective field theory and phenomenological models.

Lattice QCD. At high energy and momentum transfers, neutrino scattering takes place on quasi-free quarks, and can be studied using perturbative QCD but for most of the phase space relevant for oscillation experiments the relevant degrees of freedom are hadronic and perturbation theory is not applicable. Lattice QCD (LQCD) computes correlation or Green's functions in Euclidean time. At large times, unwanted excited states decay away while signal-to-noise ratios degrade. These computationally expensive calculations are performed in ensembles with fixed lattice spacing, volume and quark masses. Extrapolations to zero lattice spacing, infinite volume and physical quark masses, with a careful error assessment, are required to obtain physical matrix elements. They provide non-perturbative input for effective field theory and phenomenological models.

A valuable for neutrino physics deliverable of LQCD is the nucleon axial form factor, $F_A(q^2)$, whose dependence on the four-momentum transfer squared $q^2 = -Q^2$ is poorly constrained by experiment. Indeed, nuclear corrections prevent modern neutrino scattering experiment from extracting the nucleon axial form factor in a model independent way. Empirical knowledge of $F_A(q^2)$ therefore comes from neutrino scattering in old bubble chamber experiments with low statistics and poorly understood fluxes. The present situation is summarized in a plot published in Ref. [3] and reproduced in Fig 1. It shows the tension between LQCD and empirical determinations.

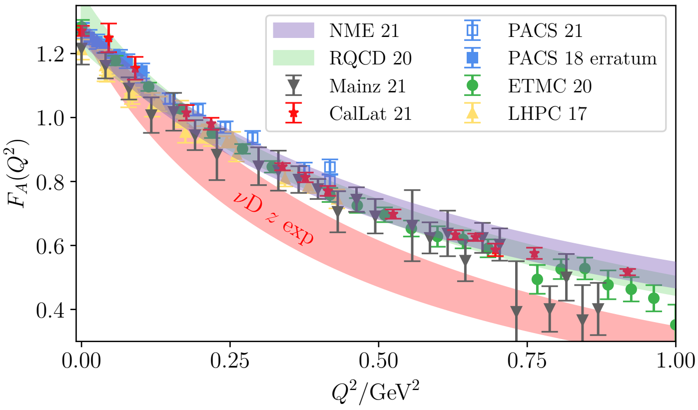

Figure 1: $F_A(Q^2)$ obtained in recent LQCD studies displayed together with its determination from bubble chamber data on deuterium using the z-expansion parametrization [4]. Plot taken from Ref. [3].

It is unclear if this discrepancy is caused by deficiencies in the old experiments or still unaccounted systematics in the LQCD results. On the experimental side, new direct or indirect (using subtraction techniques and targets containing hydrogen) determinations of the neutrino-nucleon cross sections are highly awaited. Lattice practitioners expect to have the resources to compute the nucleon axial form factor with a few-percent accuracy in the next five years [5].

LQCD can provide input not only to QE scattering but also to inelastic processes in the form of $N \to N\pi$ matrix elements, $N - \Delta$ and $N - N^*$ transition form factors (FF). So far, only for the N–$\Delta(1232)$ transition LQCD computations of axial FF with heavy quark masses are available [6]. In the case of nucleon-to-resonance transitions, control over the systematic uncertainties is challenging but FF computations should become available in five to ten years [5]. The study of two/few-nucleon currents in LQCD is still in its infancy although pioneering studies of axial-current matrix elements at high quark masses have been reported. Results close to physical masses and with robust continuum extrapolations could be obtained within five to ten years given sufficient computing resources [5].

Effective field theory. Effective field theory (EFT) provides a low-energy realization of QCD in terms of hadrons (pions, nucleons and $\Delta(1232)$). Heavier degrees of freedom are integrated out and accounted by low-energy constants (LEC) to be determined from data. EFT is valid at low four momenta compared to the chiral symmetry breaking scale $\Lambda \sim 0.7 - 1$ GeV. In this low-energy regime perturbation theory is applicable so that the accuracy of the calculations can be (at least in principle) systematically improved. The EFT of QCD a low energies is chirally symmetric in the limit of massless quarks and is known as chiral perturbation theory (ChPT).

There is a powerful synergy between LQCD and EFT. LQCD can provide LECs which might be difficult to obtain from experiment. On the other hand, EFT predicts the light-quark mass dependence of physical quantities, allowing for model independent extrapolations to the physical point. For example, the light-quark mass dependence of the axial coupling $g_A = F_A(q^2 = 0)$ was investigated in Ref. [7] using relativistic ChPT. Differences between next and next-to-next to leading order calculations provided an estimate for errors from the truncation of the perturbative series. This theory was used to extrapolate a set of recent LQCD to the physical point, leading to a better agreement with the experimental value than the one obtained by the Flavor Lattice Averaging Group (FLAG) in 2021. When extended to finite (but low) $Q^2 < 0.36$ GeV^2, the axial radius could be extracted from LQCD [8]. The obtained value $\langle r_A^2 \rangle = 0.291(52)$ fm^2 (corresponding to a dipole mass $M_A = 1.27(11)$ GeV) is within errorbars but much lower than the central value of the empirical determination of [4], in line with the scenario displayed in Fig. 1.

In nuclear systems, EFT allows to treat two and three-nucleon interactions and the corresponding currents consistently, being an input for a variety of many-body calculations. EFT can also be used to study inelastic neutrino interactions, whose onset is marked by single pion production. The first comprehensive study of CC pion production using relativistic ChPT was reported in Ref. [9]. The amplitude is given in terms of LECs, many of which have been determined from other process and, in particular, using threshold pion photo and electroproduction data [10]. The rest could be determined from neutrino-nucleon scattering data.

The perturbative EFT approach is limited to small four-momenta and therefore not applicable at the full kinematic region probed in oscillation experiments. Nevertheless, EFT calculations provide a benchmark for phenomenological models, as can be seen in Figs. 5 of Ref. [9]. Furthermore, an appealing possibility is to use pion production as a standard candle for neutrino-flux determination at DUNE with controlled theoretical errors using the *solid hydrogen* concept [11].

Phenomenological models. A theoretical description covering the whole kinematics available with few-GeV neutrinos is out of reach for EFT and demands phenomenological modeling. This is particularly the case for inelastic processes. The kinematic region with invariant masses of the final hadronic system above the $\Delta(1232)$ and below the onset of deep inelastic scattering ($1.3 \lesssim W \lesssim 2$ GeV) is theoretically challenging, with several overlapping resonances, non-trivial interferences and coupled channels. Unitarization becomes important but, for neutrino interactions, unitarization in coupled channels has only been implemented by the dynamical coupled-channel model [12] and in the strangeness $\Delta S = -1$ sector within a chiral unitary approach [13]. This region is very important for the future: its prevalence is shown in Fig. 2 at $E_\nu = 3$ GeV, which is a typical energy for the expected neutrino flux at DUNE.

Phenomenological models rely on data for input and validation. The role of photon and electron scattering data is often stressed. Indeed, isospin symmetry implies that the vector part of the weak current can be related to the electromagnetic one, for which extensive experimental information is available. The connection to pion-nucleon scattering is less emphasized but no less important. Owing to the conservation of the axial current in the chiral limit (PCAC) and the

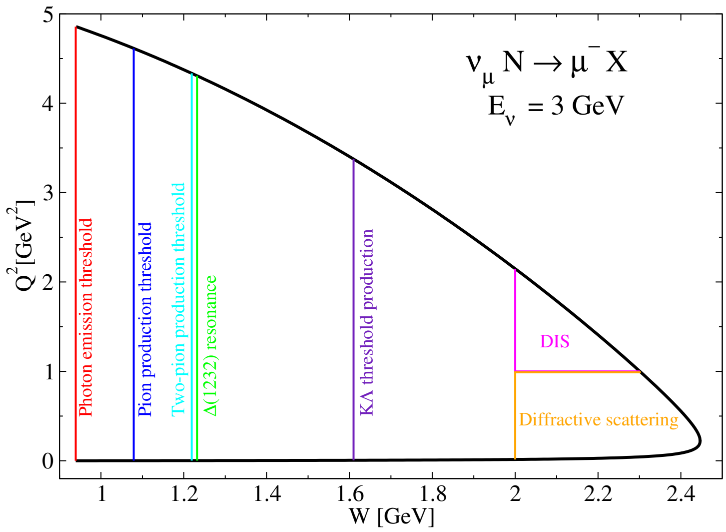

Figure 2: (W, Q^2) *landscape* for neutrino-nucleon scattering at a laboratory energy $E_\nu = 3$ GeV.

pion-pole dominance of pseudoscalar FF at low q^2, relations between the axial current and πN scattering amplitudes can be derived (Goldberger-Treiman relations). One then finds that at $Q^2 = 0$ (reachable only for massless outgoing leptons) and up to terms vanishing in the chiral limit

$$\frac{d\sigma}{dWdQ^2}(Q^2 = 0) = \frac{a}{2\pi^2} G_F^2 f_\pi^2 \frac{E_l}{E_\nu} \frac{1}{q_0} \frac{W}{m_N} \sigma_{\pi N}(\sqrt{s} = W) . \tag{1}$$

Here $a = 2V_{ud}^2(1)$ for CC(NC); E_l is the laboratory energy of the outgoing charged lepton or neutrino; $q_0 = E_\nu - E_l$. This relation is valid for both inclusive and exclusive hadronic final states provided that $\sigma_{\pi N}$ is chosen accordingly. It poses a strong constraint to axial current models but only at $Q^2 = 0$ [14]. Away from this limit the available information about the axial current is very scarce which, as advocated above, calls for new measurements of neutrino-nucleon cross sections.

At the neutrino energies of oscillation experiments, a sizable part of the nuclear response is dominated by nucleon knockout. Over the last 10-15 years, considerable efforts have been devoted to improving models in a variety of frameworks and using different descriptions of the nuclear initial state: local and global Fermi gas models, mean field and Green's function approaches, superscaling, spectral functions (see Refs. [1, 5] and references therein). Although discrepancies in the details persist, there is a consensus that two-nucleon currents play a significant role in explaining MiniBooNE and T2K scattering data without pions in the final state. This has been confirmed by *ab-initio* Green's function Monte Carlo calculations on ^{12}C [15]. The scenario is less clear in experiments that probe higher energy and momentum transfers such as MINERvA and NOvA, where significant discrepancies with theory or, at least, with the theory implementations in event generators, have been observed. The signature of two-nucleon mechanisms in the exclusive final states and their role in calorimetric neutrino energy measurements are still far from being understood. This is not a minor issue for neutrino physics because mismodeling of two-nucleon reaction mechanisms leads to a bias in E_ν reconstruction that impacts oscillation analyses.

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