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Understanding Neutrino Cross Sections: An Experimental Renaissance

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Accelerator long-baseline neutrino oscillation experiments rely critically on accurate modeling of neutrino interaction cross sections to achieve their scientific goals. Improving cross section knowledge, however, faces significant challenges, ranging from complex nuclear effects to broad beam energy ranges and detector limitations. Over the last two decades, substantial effort has been directed toward improving cross sections, which has led to an experimental renaissance in the field. Innovations in analysis methods, coupled with advancements in detector technologies and increased statistics, have led to rapid progress. This review first discusses the most pressing accelerator neutrino cross section knowledge gaps for future long-baseline oscillation experiments, DUNE and Hyper-Kamiokande, and second, it highlights several of the most important recent experimental developments in this renaissance and their roles in addressing these challenges.

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1. Motivation

Oscillation experiments, specifically accelerator long-baseline (LBL) experiments, rely heavily on precise knowledge of neutrino interaction cross sections. This presents a challenge for current experiments. In many recent results, for example from T2K [1] and NOvA [2], neutrino cross section modeling is a significant source of uncertainty. This challenge will be exacerbated for future LBL experiments, DUNE and Hyper-Kamiokande (HK), which will have much higher event rates than present experiments and be systematics-limited [3].

A study by HK [4], for instance, highlights the importance of improved $\nu_e/\overline{\nu}_e$ cross section knowledge: a reduction of the current tolerance, from 4.9% to 2.7%, is predicted to reduce the run time required for δ_{cp} significance by O(years) and is a requirement for reaching significance for certain values of δ_{cp}. Showing the importance of improved cross section modeling in a different way, a DUNE study [5] demonstrates that a consequence of an alternative, but plausible interaction model, one which shifts 20% of visible proton energy into neutrons while retaining the p_P distribution, would result in $O(5\%)$ shifts in measured oscillation parameters.

While advancement in cross sections is critical for the success of these programs, in the last ~15 years there has been a proliferation of experimental techniques to meet the challenge. This paper has two parts. First, it discusses in more detail how cross section knowledge poses this challenge to oscillation measurements. And second, it discusses recent advancements in cross section measurements that are driving a renaissance in this field.

2. Challenges in Neutrino Interaction Cross Sections

Oscillation experiments must extract neutrino energy and flavor for each event. Event counts at near and far detectors are a convolution of effects. For a ν_μ disappearance measurement, for example:

$$N_\mu^{ND}(E_\nu) = \Phi_\mu^{ND}(E_\nu) \otimes \sigma_\mu(E_\nu) \otimes \epsilon_\mu^{ND}(\vec{x}) \tag{1}$$

$$N_\mu^{FD}(E_\nu) = \Phi_\mu^{FD}(E_\nu) \otimes \sigma_\mu(E_\nu) \otimes \epsilon_\mu^{FD}(\vec{x}) \otimes P_{\nu_\mu \to \nu_\mu}(E_\nu) \tag{2}$$

where Φ is beam flux, σ is neutrino cross section in the considered interaction channels, and ϵ is the detector efficiency. Constraints from the near detector mitigate flux and cross section uncertainties, but they don't fully cancel. In a ν_e appearance measurement, for example, the ν_e flux at the near detector is determined differently than at the far detector, i.e. $\Phi_{\nu_e}^{ND} \neq \Phi_{\nu_\mu}^{ND} \times P(\nu_\mu \to \nu_e)$.

Models are relied upon not just for the ND $\to$ FD extrapolation, but also for detector acceptance, efficiency, and energy smearing. DUNE simulations [6] have shown, for example, that ν_μCC muons have strikingly different acceptances in E_ν-Q^2 space between an ND-LAr and the FD. Regarding energy smearing, equations 1 and 2 are implicitly in terms of true neutrino energy, and there is the additional challenge of modeling energy smearing to map the observed event in reconstructed space to true space. Different detector designs or nuclear targets further compound model reliance. These difficulties require accurate models of total cross sections, as well as cross section ratios $\sigma_{\nu_\alpha}/\sigma_{\nu_\beta}$, across the E_ν spectra, which currently do not exist. In a comparison study of several event generator and model predictions of the total ν_μ cross section on Ar as a function of E_ν [7], shape disagreements surpassing 10% are commonplace.

Progress in cross section knowledge currently faces challenges from four critical areas: (1) complex theory of the nuclear environment, (2) electron neutrinos and antineutrinos, (3) experimental limitations, and (4) development and use of event generators.

The nuclear environment presents a significant challenge for understanding neutrino cross sections, particularly in the phase space relevant to long-baseline experiments, $E_\nu \sim 0.1$ - 20 GeV and energy transfer $q_0 \leq 1$ GeV. Here, multiple nuclear response modes – elastic scattering, quasielastic scattering, and inelastic processes such as resonance, shallow inelastic scattering, and hadronization – contribute simultaneously. The overlap of these processes makes it difficult to disentangle their individual contributions. Moreover, nuclear modeling must account for both initial nuclear momentum and complex final state interactions (FSIs). Altogether the modeling challenge is significant – interaction channels "can't be cleanly separated and models can't approximate away nuclear structure nor final state degrees of freedom" [8].

Electron neutrino and antineutrino knowledge poses a challenge in large part due to the scarcity of direct measurements compared with ν_μ. While much of the understanding of electron neutrinos is extrapolated from ν_μ data, this approach fails to capture radiative corrections [9] and nuclear medium effects. Likewise neutrino and antineutrino interaction theory is still developing particularly in the context of the two-particle–two-hole (2p2h) process and random phase approximation (RPA) effects [10].

In direct measurements of cross sections, flavor and energy determination remain an experimental challenge. Energy reconstruction is inherently smeared by hadronic energy loss and FSIs, and flavor misidentification occurs, for example when mistaking a ν_μCCπ^0 event, where the second photon is lost due to detector efficiencies, for a ν_e interaction. FSIs can further obscure the primary interaction channel by redistributing energy among final-state particles.

Finally, the reliance on neutrino interaction generators introduces technical challenges that are central to experimental analyses. Generators encode theoretical approximations and data-driven corrections but often, necessarily, they simplify or overgeneralize key processes. Limited phase space coverage and inclusive reaction models can obscure critical discrepancies between data and theoretical predictions. While data highlights these deficiencies, it doesn't explain their origin, making iterative development of generators both essential and labor-intensive. Experimentally, it is critical that generators closely resemble data to avoid introducing systematic biases, but the ongoing development of these tools remains a bottleneck for progress.

3. A Renaissance in Cross Section Experiment

The field of neutrino cross section measurements has been undergoing a period of concentrated innovation since the early 2000's, beginning with NOMAD and MiniBooNE experiments, and driven by beam improvements, increased statistics, improved detector technologies, and advances in experimental techniques. Table 1, for example, shows the event count growth in the ν_μCC$1\pi^+$ channel from old bubble chamber experiments, to the beginning of this renaissance, to today. Altogether, the advancements have solved many problems while uncovering new ones. The following sections highlight recent advancements in key areas.

Experiment	FNAL 15' BC (1978) [11]	MiniBooNE (2011) [12]	MINERvA (2024) [13]
ν_μ**CC1**π^+ **Event Count**	~ 300	~ 40,000	~ 100,000

Table 1: The recent increase in ν_μCC1π^+ cross section event counts, driven by advancements in beams, detector technology, and analysis methods, is representative of rapid progress in cross section experimental techniques more broadly.

3.1 Neutrons

Neutron final states have posed a persistent and significant challenge for neutrino experiments, contributing to undetected energy losses and complicating neutrino-antineutrino separation in CCQE and resonance interactions. Recent efforts have begun to improve the situation, notably in detectors not specifically optimized for neutron detection. SNO [14], T2K [15], MINERvA [16], and MicroBooNE [17] have all made significant progress in neutron tagging and event counting, and results from the Super Fine Grained Scintillator (Super-FGD) detector, a component of T2K's recent ND upgrade [18], are highly anticipated [19].

MINERvA has made also notable advancements beyond tagging. It performed the first-ever multi-neutron cross section measurement on a CH target [20] and a groundbreaking extraction of the axial form factor (F_A) through $\bar{\nu}_\mu$ interactions on hydrogen within a CH target [21]. Using the distinct two-body neutron kinematics of $\bar{\nu}_\mu$ H interactions, MINERvA isolated $\bar{\nu}_\mu$ H events and measured F_A, providing a direct probe of the weak sector and a benchmark for lattice QCD calculations.

3.2 Transverse Kinematic Imbalance (TKI) Variables

Transverse kinematic imbalance variables, most commonly δp_T and $\delta\alpha_T$, are powerful tools for disentangling initial nuclear state effects, such as Fermi motion, from FSIs and multi-nucleon contributions in neutrino-nucleus interactions. δp_T is the sum of the components of the muon and proton momenta perpendicular to the neutrino direction and measures the transverse momentum lost to FSI's and multi-nucleon effects. $\delta\alpha_T$ encodes the orientation of δp_T and is expected to be uniformly distributed in the absence of FSIs, due to isotropic Fermi motion. These variables enable the initial nuclear state to be studied while controlling for FSI's (e.g. near $\delta p_T \sim 0$), and, when δp_T and $\delta\alpha_T$ are measured together, they can separate FSI's from multi-nucleon effects.

TKI variables were first measured as differential cross sections by T2K [22] and MINERvA [23] and have since become standard observables in the field. T2K and MINERvA have made additional measurements in [24] and [25], MicroBooNE has recently introduced "generalized kinematic imbalance" variables, which extend TKI variables into alternate coordinate systems for heightened sensitivity to FSIs [26]. Many experiments have extended their measurements into multiple dimensions, further isolating these nuclear effects within smaller regions of phase space.

3.3 Shallow Inelastic Scattering (SIS) Region

The shallow inelastic scattering region represents an intermediate kinematic regime "between" resonant (RES) and deep inelastic scattering (DIS) processes, characterized by the production of mesons through both resonant and non-resonant mechanisms [27]. This region is somewhat loosely defined but typically covers invariant mass values just above the Δ resonance and below the onset of DIS. Modeling this region is challenging – event generators feature discontinuities at model transitions, and there are significant discrepancies between generator predictions [28]. Understanding this regime is crucial for DUNE, where SIS interactions will constitute more than 50% of events. MINERvA has recently performed the first measurement of SIS interactions since the bubble chamber era, highlighting poor agreement between data and generator predictions, particularly at low Q^2 [29].

3.4 ν_e and $\bar{\nu}_e$

Electron neutrino and antineutrino cross sections are among the most challenging to measure due to the low fraction (<1%) of ν_e and $\bar{\nu}_e$ in accelerator beams dominated by ν_μ. Many of the existing measurements have appeared in the last five years, reflecting growing statistical samples, an increase in ν_e-capable detectors, and critical advancements in ν_e analysis methods. These measurements can be categorized by key features such as the separation of ν_e and $\bar{\nu}_e$, the interaction channel (e.g. inclusive vs. 0π), the nuclear target (e.g. argon vs. scintillator), and total vs (multi-)differential cross sections. ArgoNeuT [30] and MicroBooNE [31] have contributed the first measurements of $\nu_e + \bar{\nu}_e$ cross sections on argon. NOvA's recent measurement is multi-dimensional with large statistics [32]. T2K has followed up on its 2014 result [33] with increased statistics, improved analysis methods, and separate ν_e and $\bar{\nu}_e$ differential cross sections [34]. MINERvA has measured the 0π channel and ratios to ν_μ [35], and recently, separate ν_e and $\bar{\nu}_e$ differential inclusive cross sections [36], with anticipated ν_μ ratio results.

3.5 Correlated Measurements

Correlated measurements are a powerful way to understand the relationships between interaction channels, nuclear targets, and detector configurations. By holding certain experimental conditions constant, such as beam energy or nuclear target material, multiple measurements can be performed in a way that cancels or significantly reduces systematic uncertainties through ratios, thereby isolating specific physics effects and enhancing model sensitivity. MINERvA has performed several correlated analyses in its nuclear target ratio measurements, a complete pion suite of ν_μ and $\bar{\nu}_\mu$ CC1π^X cross sections, and ν_e and $\bar{\nu}_e$ studies [37]. T2K has conducted joint $\nu/\bar{\nu}$ analyses [38], combined on- and off-axis measurements [39], and studies linking nuclear targets with flavor-separated cross sections [40, 41]. With its recent near detector upgrade, T2K is poised to further expand correlated measurement capabilities with more nuclear targets, detector configurations, and energy spectra. Correlated measurement best practices are rapidly evolving, and the technique will certainly play a growing role in advancing cross section knowledge in the years leading up to DUNE and Hyper-Kamiokande.

3.6 Data Preservation & Analysis Software

Data preservation and open science have long been critical priorities for European organizations and CERN/LHC groups, with significant resources dedicated to initiatives such as HEPData [42], a repository for published high-energy physics data established in 1980, and the Institute for

Research and Innovation in Software for High Energy Physics (IRIS-HEP) [43], launched in 2018 to develop "software to address the analysis challenges of the LHC." In contrast, the Fermilab neutrino community lags in providing comparable access to data and in developing general analysis tools. MINERvA has taken significant steps with its data preservation program [44], which includes an experiment-agnostic HEP analysis toolkit [45, 46] and will incorporate its complete preserved dataset by 2025. MINERvA's dataset holds the potential for further studies, including searches for nonstandard interactions, insights into nuclear effects, and other model probes to bridge the time and data gaps before DUNE and Hyper-Kamiokande begin. Looking ahead, the Fermilab neutrino community will benefit from increasing coordinated efforts in data preservation and analysis infrastructure. While SBN and DUNE are beginning to coalesce around shared systems/tools, continued coordination in high-level development and planning will enhance the efficiency and effectiveness of future analyses.

3.7 Generators

Event generators are a critical yet imperfect tool for HEP experiments, and they present significant challenges for the imminent LBL experiments. The various neutrino experiment generators each encode different physics and often disagree in key observables, including oscillation parameter measurements, and the community must prepare for the reality that a fully "correct" model will not exist for DUNE and Hyper-Kamiokande. A core issue lies in the "serial" nature of event simulation, where interactions are modeled as a convolution of effects beginning with the initial nuclear state, through primary interactions and hadronization, and concluding with hadron transport and FSIs. Efforts like the GENIE DUNE Tune [47, 48] attempt to match models to data through aggressive parameter tuning. Tunes however face limitations, often requiring mismodeled physics to be absorbed into arbitrary model knobs. Experiments will benefit from rethinking their relationship to generators and exploring ways to reduce their reliance on them or, for example, ways of encoding the serial simulation process into an uncertainty. Addressing these challenges warrants greater investment in generator development, dedicated resources, and continued collaboration between generator developers and experimentalists to improve the integration of models with experimental data and needs. Progress will also require more sympathetic experimentalists who engage with the nuances of generator limitations and provide data in forms that better support tuning and validation. The experimental renaissance discussed in this review has further created an urgent need for input from theorists and model builders more generally.

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Material from Section 2 draws generally on excellent presentations in [49, 50] as well as [3, 48, 51].

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