Fermilab Proton Driver Neutrino Scattering Physics Working Group Report

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1 Introduction

The Fermilab proton driver, with high-intensity neutrino and antineutrino beams produced from 8 and 120 GeV protons, will offer a unique opportunity to explore neutrino scattering processes with unprecedented precision. While there will have been significant progress made in this area with current and currently planned experiments, existing beams will lack the intensity needed to make the precision measurements required for complete understanding of the physics.

The pre-proton-driver experiments will provide measurements of charged-current (CC) and neutral-current (NC) (quasi)elastic scattering and CC and NC production of pions and strange particles on nuclear targets. It will remain for the proton-driver to make high-precision measurements of these processes with antineutrino beams and with nucleon targets. Neutrino-electron elastic scattering requires a proton-driver class neutrino beam. For this program of measurements, high intensity, low duty-factor neutrino and antineutrino beams from both 8 and 120 GeV proton sources are required. The details of the physics case for this is made in the following sections.

The 8 and 120 GeV beams are complementary and both are required for the full physics program. The 8 GeV beam will provide a low-energy narrow-band beam to allow for measurements of reaction channels where it is crucial to minimize backgrounds resulting from high-energy component of the beam. The 120 GeV beam will provide higher rates from low cross section processes due to the higher energy component of the beam and can explore the deep-inelastic scattering regime.

It is assumed in the following sections, that these current and near-future experiments will have completed relevant measurements by the time of start-up of the proton driver:

- Auxiliary experiments to predict the neutrino flux such as HARP, BNL E910, and MIPP;
- Jefferson lab high precision elastic scattering experiments for precision determination of the vector form factors;
- The K2K suite of near detector experiments including the SCIBAR experiment;
- The MiniBooNe experiment;
- The MINERνA experiment running parasitically to MINOS;

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- The proposed FINeSSE experiment running on an $E_\nu \approx 1$ GeV neutrino beamline; and
- T2K-I, although details of a neutrino scattering detector are not yet known.

A review of what we expect to be the state of knowledge of neutrino scattering physics and what will still be awaiting experimentation is summarized below.

1.1 Neutrino Scattering Physics Program

Neutrino and antineutrino scattering measurements are of interest for a variety of reasons. Charged Current (CC) Quasi-Elastic (QE) scattering probes the structure of the nucleon and the binding of nucleons within the nucleus. Neutral Current (NC) elastic scattering probes the strange quark contribution to the spin structure of the nucleon. Resonance production and the transition region to deeply inelastic scattering (DIS) provides tests of non-perturbative QCD. The study of nuclear effects with neutrino interactions permits the determination of quark-flavor dependent nuclear effects and a better understanding of the role of coherence length in nuclear shadowing. Strange particle production measurements are needed to better understand backgrounds important in proton decay searches, and neutrino-electron elastic scattering can be used to search for physics beyond the Standard Model. In more detail:

(i) **Parton Distribution Functions** The study of the partonic structure of the nucleon, using the neutrino's weak probe, could complement the on-going study of this subject with electromagnetic probes at Jlab. The unique ability of the neutrino to "taste" only particular flavors of quarks enhances any study of parton distribution functions.

With the high statistics foreseen with the Fermilab proton driver as well as the special attention to minimizing neutrino beam systematics, it should be possible for the first time to determine the separate structure functions $2F_1^{\nu N}(x,Q^2)$,$2F_1^{\bar{\nu} N}(x,Q^2)$, $F_3^{\nu N}(x,Q^2)$ and $F_3^{\bar{\nu} N}(x,Q^2)$ where N is an isoscalar target. In leading order QCD (used for illustrative purposes) these four structure functions are related to the parton distribution functions by:

$$\begin{aligned}
2F_1^{\nu N}(x,Q^2) &= u(x)+d(x)+s(x)+\bar{u}(x)+\bar{d}(x)+\bar{c}(x)\\
2F_1^{\bar{\nu} N}(x,Q^2) &= u(x)+d(x)+c(x)+\bar{u}(x)+\bar{d}(x)+\bar{s}(x)\\
xF_3^{\nu N}(x,Q^2) &= u(x)+d(x)+s(x)-\bar{u}(x)-\bar{d}(x)-\bar{c}(x)\\
xF_3^{\bar{\nu} N}(x,Q^2) &= u(x)+d(x)+c(x)-\bar{u}(x)-\bar{d}(x)-\bar{s}(x)
\end{aligned}$$

Note that taking differences and sums of these structure functions would then allow extraction of individual parton distribution functions in a given x, Q^2 bin:

$$\begin{aligned}
2F_1^{\nu N}-2F_1^{\bar{\nu} N} &= [s(x)-\bar{s}(x)]+[\bar{c}(x)-c(x)]\\
2F_1^{\nu N}-xF_3^{\nu N} &= 2[\bar{u}(x)+\bar{d}(x)+\bar{c}(x)]\\
2F_1^{\bar{\nu} N}-xF_3^{\bar{\nu} N} &= 2[\bar{u}(x)+\bar{d}(x)+\bar{s}(x)]\\
xF_3^{\nu N}-xF_3^{\bar{\nu} N} &= [\bar{s}(x)+s(x)]-[\bar{c}(x)+c(x)]
\end{aligned}$$

Our knowledge of the the parton distributions is still very incomplete. For example, although we know that the net number of strange quarks is zero, there is no reason for $s(x) = \bar{s}(x)$. A global analysis to determine the strange sea asymmetry as a function of x shows moderate deviations from zero at higher

Q^2. Differences between s and $\bar{s}$ can have a significant impact on the extraction of $\sin^2\theta_W$ from $\nu, \bar{\nu}$ data [37]. Even the valence PDFs are not well known at large x. The ratio of d/u is normally determined by comparing scattering from the proton and neutron. However, because no free neutron target exists, the deuteron is used as a neutron target. Although this makes little difference in the extracted value at small x, uncertainties in the nuclear corrections become substantial for x larger than about 0.6, and make determination of the ratio essentially impossible for x larger than about 0.8, as shown in Fig. 1. The ratio of d/u can be determined without any nuclear structure effect corrections by using neutrino and antineutrino scattering on hydrogen, as the ratio $F_2^{\nu p}/F_2^{\bar{\nu} p}$ is equal to d/u. Hence, a MW-scale Proton Driver would enable progress in obtaining a more complete knowledge of the parton distributions within the nucleon.

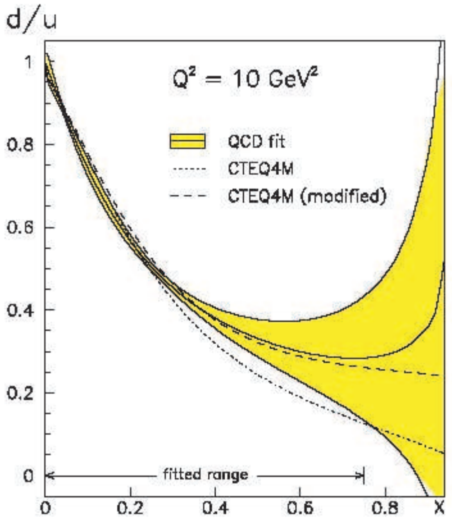

Figure 1: The d/u ratio showing the uncertainty due to nuclear effects in the deuteron. Figure taken from Ref. [38].

With the proposed Fermilab Proton Driver, the expected POT per year is expected to be at least 20x10^{20}. As will be summarized shortly, the expected number of DIS events per ton of detector would be (units of 1 K events): ME - 2170, HE - 5100, $\bar{M}E$ - 565, $\bar{H}E$ - 1210. Note that without the Proton Driver, the statistics for the $\overline{\nu}$ case would be reduced by a factor of 5 necessitating multi-year exposures to accumulate sufficient statistics at high x.

(ii) **Generalized Parton Distribution Functions** One of the most exciting developments in the theory of the structure of the nucleon has been the introduction of generalized parton distributions (GPDs) [47, 48, 49, 50, 51]. The usual PDFs are sensitive only to the longitudinal momentum distributions of the parton. In contrast, the elastic form factors integrate over the longitudinal distributions of the partons and describe the spatial distribution. The GPDs give a more complete picture of the nucleon in which the spatial distribution can be determined as a function of the longitudinal momentum distribution. However, the GPDs are difficult to access experimentally because they require measurement of exclusive final states. The most promising reaction to date is deeply virtual Compton scattering (DVCS), i.e. $p(e, e'\gamma p)$. These measurements are either underway or planned at JLab. However, a complete determination of the GPDs requires flavor separation which can only be accomplished using neutrinos and anti-neutrinos. Because of the requirement that exclusive final states be measured, the reaction is difficult to perform on nuclei. Although MINERνA will measure GPDs on carbon, due to nuclear effects this is considerably inferior to measurement on the proton. A true GPD measurement would

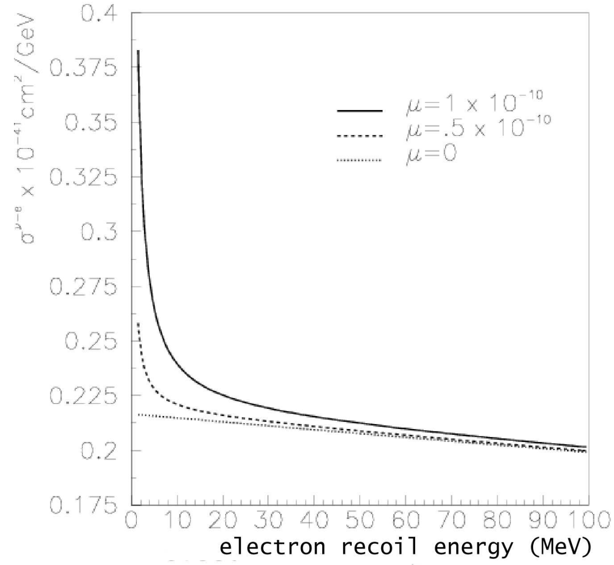

Figure 2: Differential cross section versus electron recoil kinetic energy, T, for $\nu e \to \nu e$ events. The electroweak contribution is linear in T (bottommost line), while contributions from nonzero neutrino magnetic moments yield sharp rises at low T.

require measurement of the $p(\bar{\nu}, \mu\gamma n)$ reaction using a free proton (i.e. hydrogen) target or $n(\nu, \mu\gamma p)$ reaction using a free neutron target (in practice, a deuteron target). Estimates for this "weak DVCS" process are currently being made by A. Psaker [52]. The CC cross section is of order 10^{-41}cm^2 and the NC about 10 times smaller. These small cross sections will clearly require higher intensity neutrino beams than are available at NuMI if measurements on hydrogen are to be performed.

(iii) **Strange Quarks and the Spin Structure of the Nucleon** The NC elastic scattering of neutrinos and antineutrinos on nucleons ($\nu N \to \nu N$, $\bar{\nu} N \to \bar{\nu} N$) provides information about the spin structure of the nucleon. In particular, these scattering processes are sensitive to the isoscalar spin structure that results from strange quark contributions. Determination of the strange quark contribution to the nucleon Δs has been a major component of the JLab program. Note that Δs, has been measured to be ≈ -0.1 in deep-inelastic scattering (DIS) polarized lepton experiments [6]. NC elastic scattering measures the flavor non-singlet combination of all flavors. However, recent work by Bass *et al.* [**?**] has shown it is possible to eliminate the heavy flavor contribution. Combined with this, a precise measurement of NC elastic scattering would provide a direct measurement of Δs that is insensitive to theoretical assumptions. The ideal measurement would be of the ($\nu p \to \nu p$)/($\nu n \to \mu p$) cross-section ratio on a deuterium target. The proposed FINeSSE experiment was designed to determine Δs by making an accurate measurement of this cross-section ratio using the Fermilab Booster neutrino beam and a carbon target (liquid scintillator). The ultimate goal in this program requires measuring NC elastic scattering with both neutrinos and antineutrinos, with a large event sample, on *nucleon* targets, which will require a MW-scale proton source to produce a narrow band neutrino beam of high intensity.

(iv) **Neutrino-Electron Elastic Scattering and the Neutrino Magnetic Moment** The Standard Model predictions for neutrino-electron elastic scattering have little theoretical uncertainty, and a measurement of $\nu e \to \nu e$ scattering can therefore be used in principle to precisely determine $\sin^2\theta_W$, and search for physics beyond the Standard Model. However, absolute cross-section measurements with the required precision are challenging, and may not be possible, even with a proton-driver class neutrino beam. An alternative strategy is to measure the well-predicted energy-dependent shape of the cross section. This would enable a search for physics beyond the Standard Model. As an example, consider a search for a finite neutrino magnetic moment, which is theoretically possible since we now know that neutrinos have finite masses. Within the Standard Model, modified to include finite neutrino masses, neutrinos may acquire a magnetic moment via radiative corrections. With $m_\nu = 1$ eV, the resulting magnetic moment would be $\approx 3 \times 10^{-19}\mu_B$ where $\mu_B = e/2m_e$ is the Bohr magneton. This value is too small to be detected or to affect astrophysical processes. Hence, a search for a finite neutrino magnetic moment is a search for physics beyond the Standard Model. The current best limit on the muon neutrino magnetic moment is $\mu_{\nu_\mu} \leq 6.8 \times 10^{-10}\mu_B$ from LSND $\nu_\mu e$ elastic scattering [10]. This sensitivity may be substantially improved, perhaps to the level of some beyond-the- Standard-Model predictions (which in some cases are as large as $10^{-11}\mu_B$), by precisely measuring the elastic scattering rate as a function of electron recoil energy. An electromagnetic contribution to the cross section from the magnetic moment will show up as an increase in event rate at low electron recoil energies (see Figure 2). The needed sensitivity requires a MW-class Proton Driver to produce a sufficiently intense neutrino beam, and a precise tracking detector with a low electron energy threshold. Depending on the energy threshold, a gain of 10-30 over the LSND measurement is possible.

(v) **Elastic Form Factors** The distributions of charge and magnetism within the nucleus can be parameterized using two elastic form factors: the electric form factor G_E and the magnetic form factor G_M. For many years it was assumed that both the charge and magnetic distributions fall exponentially. With this assumption it can be shown that G_E and G_M are described by the "dipole" form. However, precision measurements at JLab [33, 34] have shown that this is not the case; the electric form factor has a distinctly different form, and drops more quickly than the magnetic form factor (Fig. 3), indicating that the charge distribution has a broader spatial distribution than the distribution of magnetism. In the language of particle physics, Perturbative QCD predicts that the ratio Q^2F_1/F_2 should be constant. Instead it appears QF_1/F_2 approaches a constant. Although the reason for this is not understood, it

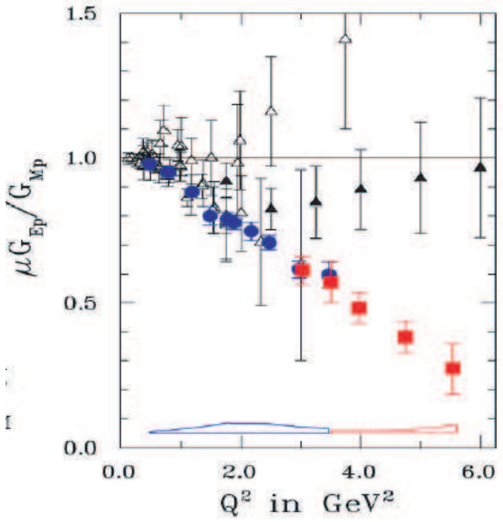

Figure 3: Ratio of the electric to magnetic form factor measured using polarization transfer. Data taken from Ref. [34].

does appear to be an indication of angular momentum between the quarks. To understand this more deeply it is desirable to precisely measure the weak form factor. This can be measured through parity violation in electron-nucleon scattering, with limited precision. Neutrino-nucleon elastic (or quasi-elastic) scattering depends on both the electromagnetic form factors and the weak form factor. Nearly half the cross section is due to the weak form factor, making neutrino-nucleon scattering a good probe. Proposed measurements of the weak form factor (e.g. the MINERνA experiment) use scattering from nucleons in nuclei. Although the statistical precision will be reasonably good, there is an uncertainty in both extracting the form factor from scattering from a bound nucleon due to final state interactions and other conventional effects, as well as the possibility of modification of the form factor by the nuclear medium. Thus, measurement of the form factor using neutrino scattering on hydrogen and deuterium is essential. This will require the intensity available at a MW-scale Proton Driver.

(vi) **Duality and Resonance Production** Although QCD appears to provide a good description of the strong interaction, we have a very poor understanding of the transition from the domain where quarks and gluons are the appropriate degrees of freedom to the domain best described using baryons and mesons. In the region of modest Q^2 (1-10 GeV^2) the scattering of electrons on nucleons is dominated by resonance production, and can also be described using the same formalism as DIS. However, there is no obvious reason to expect the structure functions measured in the resonance region from correlated partons forming the nucleon should be related to the DIS structure functions. Despite this, experiments at JLab [39] have found that the F_2 structure function measured in the resonance region closely follows that measured in the DIS region. The phenomenon, called quark-hadron duality, has also been observed in other processes, such as e^+e- annihilation into hadrons. The origins of duality are not well understood [40, 41, 42, 43, 44, 45, 46, **?**]. However, as discussed in Ref. [**?**], duality does appear to be a general feature of QCD. Duality is expected to exist for neutrino scattering, although it may manifest itself quite differently than for electron scattering. Of particular interest would be a measurement of the ratio of neutron to proton nuetrino structure functions as large x, where similar valence quark dynamics as in charged lepton scattering are probed, but with different sensitivity to quark flavors. An uncertain aspect of duality is the relationship be resonant and nonresonant backgrounds in the onset of duality. Neutrino and antineutrion scattering would provide an important consistency check as well as additional information on this aspect of duality because of the dramatically different resonance production response of the nucleon for neutrino and electron scattering. The next decade of experiments, especially with MINERνA, should provide some information on the validity of duality using neutrinos. However, high precision measurements using anti-neutrinos and nucleon (hydrogen and deuterium) targets will be required in order to fully explore the origins of duality.

(vii) **Strange Particle Production** Measurements of the production of strange mesons and hyperons in neutrino NC and CC processes (e.g. $\nu_\mu n \to \mu^- K^+ \Lambda^0$ and $\nu_\mu p \to \nu_\mu K^+ \Lambda^0$) provide input to test the theoretical models of neutrino induced strangeness production [9, **?**]. In addition, neutrino induced strangeness production is a significant background in searches for proton decay based on the SUSY-inspired proton decay mode $p \to \nu \Lambda K^+$. The existing experimental data on these channels consists of only a handful of events from bubble chamber experiments. There are plans to measure these reactions using the existing K2K data and the future MINERνA data. MINERνA will collect a large sample ($\approx 10,000$) of fully constrained $\nu_\mu n \to \mu^- K^+ \Lambda^0$ events. However, the antineutrino measurements will require a more intense (MW-scale) proton source.

1.2 Expected Event Rates with the Fermilab Proton Driver

With the Fermilab Proton Driver we expect order 20x10^{20} PoT per year.

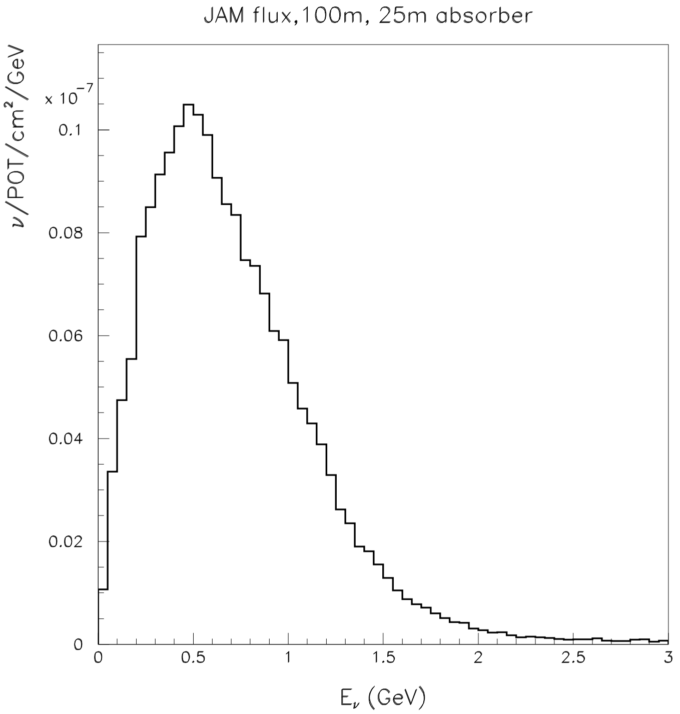

Figure 4: Calculated ν_μ flux at a 100m location on the booster neutrino beamline.

CC Events/10^{20} PoT/ton			
Beam	CC ν_μ	CC $\overline{\nu}_{mu}$	ν in $\overline{\nu}$ beam
LE	60 K	20 K	26 K
ME	230 K	60 K	10.7 K
HE	525 K	125 K	18.6 K

Table 1: NuMI charged-current interactions per ton, per 10^{20} protons on target.

1.3 The Need for a High Intensity Proton Beam at 8 GeV

The Fermilab long-baseline neutrino oscillation program utilizes the NUMI beamline, and hence protons at MI energies. It is important to stress that the desired neutrino scattering program at a MW-class proton driver would utilize both the upgraded MI beam and the high-intensity lower energy proton beam at 8 GeV. The measurements using high-intensity neutrino and antineutrino beams of mean energy $\approx$ 1 GeV are particularly important. These measurements require that the beam have no high-energy tail (above $\approx$ 2 GeV) so that backgrounds from multipion and deep-inelastic scattering processes do not overwhelm the signal reactions of interest. The energy distribution of the booster neutrino beam, currently in operation at Fermilab, is ideal for these studies (Fig. 4). An 8 GeV MW-class proton-driver beam that uses a MiniBooNE-like horn-focusing system would satisfy the beam requirements. A 2 MW beam at 8 GeV would enable a 64-fold increase in intensity with respect to MiniBooNE. This is the rough factor required to enable precision neutrino and antineutrino measurements using nucleon targets. In addition to the highest intensities practical, it is also important for the neutrino beam to have a very low duty-factor. This will require a buncher using either the recycler ring or a new dedicated storage ring. Note that beam-unrelated cosmic-ray-induced backgrounds

Event Rates per ton						
CC Process	LE	ME	HE	$L\bar{}E$	$M\bar{}E$	$H\bar{}E$
Quasi-Elastic	6.6 K	22.8 K	46.2 K	2.8 K	7.6 K	14.0 K
Resonance	12.5 K	43.2 K	93.0 K	3.3 K	8.9 K	17.5 K
Transition	13.2 K	53.1 K	125.5 K	4.5 K	14.1 K	30.5 K
DIS	27,1 K	108.6 K	255.1 K	9.0 K	28.2 K	60.5 K
Coherent	0.6 K	2.3 K	5.2 K	0.4 K	1.2 K	2.5 K

Table 2: NuMI CC samples per 10^{20} PoT - ton for various processes.

increase with the duty-factor. Many of the desired neutrino measurements require low backgrounds for low energy final states (e.g. NC elastic scattering and neutrino-electron elastic scattering). These measurements would be limited with a high duty-factor neutrino beam.

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