A Novel Approach to Neutrino-Hydrogen Measurements

H. Duyang, B. Guo, S.R. Mishra and R. Petti

Department of Physics and Astronomy,
University of South Carolina, Columbia, South Carolina 29208, USA

Abstract

The lack of high statistics samples of (anti)neutrino-hydrogen interactions has been a longstanding impediment for neutrino physics. We propose a practical way to achieve accurate (anti)neutrino-hydrogen measurements, solving some of the principal limitations of neutrino experiments. Interactions on hydrogen are extracted by subtracting measurements on a dedicated graphite (pure C) target from those on a dedicated polypropylene (CH$_2$) target within a highly segmented detector. A statistics of $\mathcal{O}(10^6)$ can be realistically achieved for the various $\nu(\bar{\nu})$-H event topologies, with efficiencies exceeding 90% and purities around 80-92%. The availability of such samples allows a determination of neutrino and antineutrino fluxes with unprecedented precision, as well as, by contrasting these samples to corresponding measurements on heavy materials, a measurement of initial and final state nuclear effects. The systematic uncertainties associated with both the fluxes and the nuclear smearing are crucial for modern long-baseline neutrino oscillation experiments. (Anti)neutrino-hydrogen interactions also provide an ideal tool for a wide range of precision tests of fundamental interactions.

PACS numbers: 13.60.Hb, 12.38.Qk
I. INTRODUCTION

In order to collect a sizable statistics, neutrino experiments typically use massive nuclear targets, which are particularly relevant in long-baseline oscillation experiments because of the reduced flux at the far site [1, 2]. An understanding of the structure and interactions of hadrons inside the nuclear targets is therefore crucial to achieve accurate measurements of neutrino interactions. The existing uncertainties in the modeling of the nuclear effects modifying the neutrino cross-sections, as well as final state interactions within the nucleus are not consistent with the precisions required by next-generation neutrino experiments [3].

Modern (anti)neutrino beams can deliver high intensity fluxes, thus alleviating one of the primary limitations of past experiments from the available statistics. This fact allows the use of high resolution detectors with a relatively small fiducial mass of a few tons to obtain a more accurate reconstruction of (anti)neutrino interactions. However, all of these improvements are voided without a control of the configuration, chemical composition, size, and mass of the neutrino targets comparable to the one traditionally achieved in electron scattering experiments. Furthermore, available measurements of various (anti)neutrino exclusive processes and cross-sections on nuclei indicate many outstanding discrepancies among different experiments, as well as with existing theoretical models [3]. The limited resolution of some of those measurements, together with the complexity of the weak current (compared to the electromagnetic one) and of the nuclear effects on the interactions can play a role in the observed discrepancies. To this end, in addition to the high experimental resolution and a complete control of the (anti)neutrino target, a necessary condition for any program of high precision measurements with (anti)neutrino interactions is to have a (complementary) target free from nuclear effects, i.e. hydrogen $^1$H (free proton).

The only available data from $\nu(\bar{\nu})$-H interactions were collected by the early bubble chamber experiments ANL [4], BNL [5], BEBC [6, 7], and FNAL [8, 9]. In spite of the excellent experimental resolution of those measurements, the overall statistics is limited to about 16,000 events and is insufficient for current needs. Since then safety requirements related to the underground operation and practical considerations favoring modern electronic detectors have prevented new experimental measurements of high statistics $\nu(\bar{\nu})$-H samples.

In this paper we propose a novel approach for precision measurements of $\nu(\bar{\nu})$-H interactions, which is both simple and safe to implement. Interactions on hydrogen are extracted by subtracting measurements on a dedicated graphite (pure C) target from those on a dedicated CH$_2$ plastic target. This concept appears to be the only realistic opportunity to obtain a clean selection of high statistics samples of (anti)neutrino interactions on hydrogen.

This paper is organized as follows. In Sec. II we discuss how we can achieve a control of (anti)neutrino targets comparable to electron scattering experiments, as well as the basic concept of the subtraction between CH$_2$ and C targets. In Sec. III we present a detailed kinematic selection of $\nu(\bar{\nu})$-H interactions from the CH$_2$ plastic target for various event topologies. In Sec. IV we discuss our results and in Sec. V we summarize our findings.

---

$^1$ Elastic scattering off electrons (mainly NC) can also provide complementary information free from nuclear effects. However, the substantially smaller statistics and the additional smearing associated to the outgoing neutrino and the beam divergence limit the physics sensitivity of this channel.
II. CONTROL OF NEUTRINO TARGETS

All detectors for neutrino interactions suffer from a tension between the opposing requirements of a large target mass versus the detector resolution necessary to achieve the physics goals. Furthermore, in most fine-grained neutrino detectors the active detector, consisting of several different materials, also provides the target mass. A drawback of this configuration is the difficulty to precisely control the target chemical composition and size, limiting the ultimate precision achievable in the measurements. Solving these outstanding issues requires an innovative detector design for neutrino physics. The neutrino target must be physically separated from the actual tracking system, which should have a negligible overall mass compared to the former. In order to achieve high resolution measurements, the target mass should be spread out uniformly throughout the entire tracking volume, by keeping the average density low enough to have a detector transparent (about one radiation length) to final state particles produced in neutrino interactions.

An example of multi-purpose neutrino detector matching the above design principles is described in the CDR of the DUNE experiment [2]. The key element is a central tracker inserted in a 0.4-0.6 T magnetic field, surrounded by a 4π electromagnetic calorimeter (ECAL). This detector concept is rather flexible and its main operating parameters can be adapted to different detector configurations. The base tracking technology is provided by low-mass straws similar to the ones used in many modern experiments for precision physics or the search for rare processes [10–13]. Thin layers of various target materials (100% chemical purity) are alternated with straw layers so that they represent more than 95% of the total detector mass (5% being the mass of the straw tracker). This feature, combined with the excellent vertex, angular, momentum, and timing resolutions are key factors to correctly associate neutrino interactions to each target material, as well as for an accurate measurement of the four-momenta of the final state particles. As a result, we can achieve a control of the configuration, chemical composition, size, and mass of the (anti)neutrino targets in a way similar to what is typically done in electron scattering experiments.

In this paper we will focus on two specific materials to be used as (anti)neutrino targets within the detector concept described above: polypropylene (C₃H₆)n and graphite (pure C). The former is one of the plastic materials with the highest hydrogen content and can be easily manufactured in thin foils of arbitrary size. Both targets can be integrated within the tracking detector by ensuring that they result in similar detector acceptances for final state particles. We further assume that they are exposed simultaneously to the same (anti)neutrino beam. By performing a statistical subtraction between the data collected from the CH₂ plastic and the ones collected from the graphite, we can in principle obtain (anti)neutrino interactions on a hydrogen target, i.e. on free protons. Given the purity (100%) of the CH₂ and C targets and the accuracy in associating the interactions to each target, the normalization of the H signal and the C background is based upon the corresponding relative abundances in CH₂. This technique can be safely implemented and can offer a relatively large (∼ 0.7 ton with 5 tons of CH₂) target mass of hydrogen. The main issues to address are the physics sensitivity achievable and whether the uncertainties associated to the subtraction procedure allow competitive $\nu(\bar{\nu})$-H measurements. In the following we will present detailed studies of the corresponding event selection with realistic assumptions for the detector smearing and the physics modeling.
FIG. 1. Comparison of the reconstructed $p_T$ asymmetry $R_{mH}$ in three-track $\mu p\pi$ CC topologies from H and C targets. Results for both neutrino (left panel) and antineutrino (right panel) interactions are shown. All distributions are normalized to unit area.

III. SELECTION OF $\nu(\bar{\nu})$-H INTERACTIONS

The detection technique described in Sec. II allows a complete control of the (anti)neutrino targets in both size and material(s), as well as an accurate location of the interaction vertices within each target material. However, the H content by weight in the CH$_2$ target is only 14.4% of the total and most of the interactions are still originated from the C nucleus.

We can improve the signal/background ratio in the selection of H interactions by exploiting the event kinematics. Since the H target is at rest, the Charged Current (CC) events are expected to be perfectly balanced in a plane transverse to the beam direction (up to the tiny beam divergence) and the muon and hadron vectors are back-to-back in the same plane. Instead, events from nuclear targets are affected by the smearing with the energy-momentum distribution of bound nucleons (Fermi motion and binding), the off-shell modifications of bound nucleons, meson exchange currents and nuclear shadowing [14–16], as well as by final state interactions (FSI). These nuclear effects result in a significant missing transverse momentum and a smearing of the transverse plane kinematics. The use of transverse plane variables and event kinematics to select various Neutral Current (NC) and CC (anti)neutrino topologies was pioneered by the NOMAD experiment [17]. The analysis described in this paper is largely based upon the variables and techniques developed and validated with NOMAD data [18–20].

A. Kinematic analysis

We simulate (anti)neutrino interactions on CH$_2$, H, and C targets with three different event generators: NuWro [21], GiBUU [22], and GENIE [23]. While we use NuWro as our default generator, we compare our results with both GiBUU and GENIE to check the sensitivity of our analysis to the details of the input modeling. The studies of nuclear FSI by the MINER$\nu$A and
FIG. 2. Correlations between kinematic variables used to construct $\ln \lambda^H$ for H signal (left plots) and C background (right plots) $\mu^- p \pi^+$ CC events.
Table I. Efficiency and purity for the kinematic selection of H interactions from the CH$_2$ plastic target using simple cuts on $R_{mH}$ and $p_{T\perp}^H$ (described in the text), as well as on the multi-variate likelihood ratio $\ln \lambda^H$. The cuts on $\ln \lambda^H$ are chosen to retain a fixed 90% signal efficiency.

T2K experiments [24, 25] have found an unphysical excess of $hA$ elastic scattering processes in the FSI simulated by GENIE, which is in disagreement with (anti)neutrino data. We follow the corresponding prescriptions by MINER$\nu$A and T2K and discard such elastic $hA$ FSI processes in GENIE. We generate inclusive CC interactions including all processes available in the event generators with input (anti)neutrino spectra similar to the ones expected in the DUNE experiment. We then use the GEANT4 [26] program to evaluate detector effects and apply to all final state particles a parameterized reconstruction smearing consistent with the NOMAD data [17].

In order to illustrate the potential of the technique we propose for the measurement of H interactions, we start from an analysis based upon simple kinematic cuts. We will focus initially on the cleanest topologies $\nu p \rightarrow \mu^- p\pi^+$ and $\bar{\nu} p \rightarrow \mu^+ p\pi^-$, mainly originated from resonance production. All final state particles from these processes on H can be accurately reconstructed in the detector described in Sec. II, thus resulting in an excellent measurement of all the relevant kinematic variables. We will discuss later a more refined kinematic analysis, as well as the selection of other CC event topologies.

The most powerful kinematic variable to separate H interactions from the ones originated in nuclear targets is $R_{mH} \equiv (p_{mT}^H - p_T^H)/(p_{mT}^H + p_T^H)$, the asymmetry between the missing transverse momentum, $p_{mT}^H$, and the transverse momentum of the hadron vector, $p_T^H$. For H interactions $p_{mT}^H$ is consistent with zero up to reconstruction effects and hence we expect $R_{mH} \approx -1$. Instead, if the interactions occur inside a nuclear target we expect a substantial $p_{mT}^H$ together with smaller values of $p_T^H$, due to the nuclear smearing. Furthermore, the missing transverse momentum is mainly generated inside the hadron system and it is expected to be correlated with the latter. All these nuclear effects result in much larger values of $R_{mH}$. As shown in Fig. 1, this variable can be efficiently used to separate H interactions, as well as to probe various aspects of the nuclear smearing. Another useful variable is the magnitude of the component of the hadron transverse momentum perpendicular to the transverse momentum of the lepton, $p_{T\perp}^H$. In H interactions the transverse momenta of the lepton and of the hadron system are back-to-back, thus resulting in a sharp peak around zero in $p_{T\perp}^H$. Interactions from nuclear targets have a much broader distribution originating from the nuclear smearing. The use of this variable to study H interactions within composite targets was suggested in Ref. [27]. Since $p_{T\perp}^H$ is selecting topologies in which the transverse momenta of the lepton and the hadron system are back-to-back, the effect of this variable is similar to the use of the angle between those transverse vectors, $\Phi_{TH}$. Used as a single variable in the H selection, $p_{T\perp}^H$ has less discriminating power than both $R_{mH}$ and the other kinematic variables discussed in
FIG. 3. Distributions of ln $\lambda_H$ for the H signal, the C background, and the CH$_2$ plastic (sum) for the exclusive $\mu^- p \pi^+$ CC topologies. The multiple peaks are the effect of the binning used to build $L^H$. The H and C distributions are normalized to the expected relative abundance in CH$_2$.

this section. However, it provides information complementary to $R_{mH}$, so that the combined effect of both these variables improves the overall selection efficiency.

The use of simple cuts $R_{mH} < -0.6$ and $p_H^{T\perp} < 0.03$ GeV/c provides a clean selection of $\nu p \rightarrow \mu^- p \pi^+$ H interactions from the CH$_2$ plastic with an efficiency of 93% and a purity of 86%, including non-resonant backgrounds as well as higher order resonances above $\Delta$. Similarly, we can select the equivalent $\bar{\nu} p \rightarrow \mu^+ p \pi^-$ topology with a purity of 84% and an efficiency of 89%. Table I summarizes the results of the kinematic selection.

We can further improve the selection of H interactions by using multivariate techniques exploiting the complete event kinematics [18–20]. Assuming the two momentum vectors of the lepton and hadron system, we have in total 3 transverse and 2 longitudinal degrees of freedom in the event selection, due to the invariance for an arbitrary rotation in the transverse plane. Since we want to separate the same CC events with and without nuclear effects, we can further assume that the overall reconstructed energy spectra are similar (up to the nuclear smearing), thus somewhat reducing the rejection power of one of the longitudinal variables. As a result, we can define a complete kinematic set as 3 transverse plus one longitudinal variables. We select this latter as the angle between the total visible momentum vector and the incident neutrino direction ($z$ axis), $\theta_{\nu T}$. This variable is expected to be close to zero in H interactions, up to the tiny beam divergence, while it is much larger in interactions originated from nuclear targets.

We use a likelihood function incorporating multi-dimensional correlations among kinematic variables. An optimization of the kinematic selection suggests the following function:

$$L^H \equiv \left[ [ R_{mH}, p_T^{H T\perp}, \theta_{\nu T}], p_T^m, \Phi_{lH} \right]$$

(1)

where the square brackets denote correlations (Fig. 2). The $L^H$ function is over-constrained in the transverse plane to compensate for the missing correlations, binning, etc. A function
based upon a complete set of kinematic variables is the four-dimensional likelihood function $\mathcal{L}_4^H = [R_{mH}, p_{T\perp}^H, p_T^m, \theta_{\nu T}]$. Although the use of this function requires a larger statistics to achieve a sensible binning, we used it to cross-check our kinematic selection and obtained results comparable to $\mathcal{L}^H$. We build the $\mathcal{L}^H$ probability density functions (pdf) for the two test hypotheses of H interactions (signal) and C interactions (background). The individual pdf are properly smoothed and are built with samples independent from the test ones to avoid large statistical biases. As it is common practice, the logarithm of the final likelihood ratio between signal and background hypotheses, $\ln \lambda^H$, is used.

The distributions of $\ln \lambda^H$ for the H signal and the C background in $\mu^- p \pi^+$ topologies are shown in Fig. 3. The corresponding purity and efficiency achievable in the kinematic H selection as a function of the $\ln \lambda^H$ cut are given in Fig. 4 for both the $\mu^- p \pi^+$ and $\mu^+ p \pi^-$ samples. Both the efficiency and the purity appear relatively uniform as a function of the neutrino energy (Fig. 5). Table I summarizes the results for a fixed kinematic efficiency of 90%. The use of a multi-variate selection further reduces the background levels with respect to the simple cut analysis, without dramatically changing the overall results. A key advantage of this approach is that the likelihood function allows to assign, on an event-by-event basis, the probability that a given (anti)neutrino interaction detected originated from either the hydrogen or the carbon nucleus. Furthermore, it provides a better control of the selection procedure by easily varying the efficiency/purity and by offering relatively clean control samples.
Efficiency/Purity

FIG. 5. Efficiency (solid line) and purity (dashed-dotted line) as a function of neutrino energy for the kinematic selection of the exclusive $\nu_\mu p \rightarrow \mu^- p \pi^+$ CC topologies on hydrogen from the CH$_2$ polypropylene target. The same cut on $\ln \lambda^H$ as in Table I is applied.

B. Results for different event topologies

In Sec. III A we showed that our kinematic analysis can efficiently select $\nu p \rightarrow \mu^- p \pi^+$ and $\bar{\nu} p \rightarrow \mu^+ p \pi^-$ interactions on the hydrogen embedded inside the CH$_2$ plastic. These topologies are minimally affected by the detector smearing, which is given by the momentum resolution of the three final state particles.

Another important exclusive process is the quasi-elastic (QE) $\bar{\nu} \rightarrow \mu^+ n$ on hydrogen. The reconstruction of this topology is more complex because of the presence of the neutron in the final state and a single charged track. Detailed GEANT4 simulations show that 25-30% of neutrons interact inside the tracker and can be detected. Another 45-60% of the neutrons can be detected in the ECAL surrounding the tracker [2], thus allowing a combined detection of 70-90% of the neutrons. For events with a single charged track the resolution on the position of the primary vertex is worse than for multi-track events and is essentially defined by the thickness of a single CH$_2$ (or C) target plane by noting the absence of straw tube hits preceding the presumed target. However, events can still be efficiency associated to the correct target material, due to the lightness of the tracking straws and the purity of the target itself. The corresponding uncertainty is given by the ratio between the thickness of the straw walls and the thickness of a single CH$_2$ target, resulting in an efficiency $>99\%$. From the positions of the primary vertex and of the neutron interaction within the detector we can reconstruct the neutron direction. Assuming that the target proton is at rest, we calculate the energy of the incoming antineutrino as:

$$E_\nu \equiv \frac{M_n^2 - M_\mu^2 + 2E_\mu M_\mu - M_p^2}{2[M_p - E_\mu + p_\mu \cos \theta_\mu]}$$  \hspace{1cm} (2)

where $M_p, M_n, m_\mu$ are the masses of the proton, neutron, and muon, respectively, and $p_\mu, E_\mu$ and $\theta_\mu$ are the momentum, energy and the angle of the outgoing muon. The energy of the neutron is $E_n = E_\nu - E_\mu$ and the momentum vector of the neutron is obtained from the
FIG. 6. Ratio between the relative statistical uncertainty $\Delta_{\text{stat}}$ on the H sample obtained after the C background subtraction and the corresponding ideal uncertainty from the H statistics in CH$_2$ as a function of the ratio between the fiducial masses of the graphite and CH$_2$ targets, $M_C/M_{CH_2}$. The curves for a H purity of 90% (solid line) and 60% (dashed-dotted line) and 90% efficiency are shown to illustrate the impact of the kinematic selection (see text for details).

neutron direction and energy. We note that Eq. (2) is correct only for interactions on hydrogen and not for the ones on carbon, due to nuclear effects. We can then reconstruct the complete event kinematics for $\bar{\nu} \rightarrow \mu^+ n$ interactions on hydrogen and apply the same kinematic selection described in Sec. III A. The use of simple cuts $R_{mH} < -0.7$ and $p_{H \perp} < 0.02$ GeV/c provides a clean selection of $\bar{\nu} \rightarrow \mu^+ n$ H interactions from the CH$_2$ plastic with an efficiency of 95% and a purity of 80% (Tab. I).

The kinematic selection of inclusive Deep Inelastic Scattering (DIS) events $\nu p \rightarrow \mu^- X$ and $\bar{\nu} p \rightarrow \mu^+ X$ on hydrogen is less efficient than for the exclusive processes discussed above, due to the higher multiplicity and the incomplete reconstruction of some of the DIS topologies. The larger detector smearing directly affects the reconstruction of the key kinematic variables, thus somewhat reducing their discriminating power. However, these effects are even larger for the DIS interactions originated in nuclear targets, primarily because of the final state interactions. We can therefore still achieve an adequate separation of DIS interactions on hydrogen from the main carbon background in the CH$_2$ plastic target. As an illustration, by using simple cuts on the $R_{mH}$ and $p_{H \perp}$ reconstructed variables we obtain a purity of about 73% and and efficiency of 83% with the inclusive $\nu_\mu$ CC sample on hydrogen. Table I summarizes the results of our kinematic selection for the various topologies.
TABLE II. Number of events expected in the selection of various processes on H with (anti)neutrino beams similar to the ones available in DUNE [1, 2], assuming 5+5 years of data taking with the neutrino and antineutrino beam polarities. The first two columns (CH$_2$ and H targets) refer to the initial statistics, while the last two include all selection cuts described in this paper. For the CH$_2$ and C targets the numbers refer to the given final state topologies originated from either $p$ or $n$ interactions. For the $\mu^+n$ topologies the first line refers to the events with $n$ identified in the tracker (25%) and the second to the ones with $n$ identified in ECAL (45%). See the text for details.

| Process             | CH$_2$ target | H target | CH$_2$ selected | C bkgnd |
|---------------------|---------------|----------|----------------|---------|
| $\nu_\mu$ CC $\mu^- p\pi^+$ | 3,924,000     | 2,484,000 | 2,430,000      | 194,000 |
| $\nu_\mu$ CC inclusive | 34,900,000    | 3,591,000 | 4,140,000      | 1,160,000 |
| $\bar{\nu}_\mu$ CC $\mu^+ p\pi^-$ | 836,000       | 373,000   | 365,000        | 29,100  |
| $\nu_\mu$ CC $\mu^+ n$ | 4,960,000     | 1,240,000 | 648,000        | 126,000 |
| $\bar{\nu}_\mu$ CC inclusive | 13,000,000    | 2,882,000 |                 |         |

C. Achievable statistics

In the following we will assume an overall fiducial mass of 5 tons for the CH$_2$ targets. This value is realistically achievable with the detector technology discussed in Sec. II and a relatively compact tracking volume around 50 m$^3$ (without fiducial cuts), depending upon the specific configuration of the main detector parameters. The measured distributions of the generic kinematic variables $\vec{x} \equiv (x_1, x_2, \ldots, x_n)$ in $\nu(\bar{\nu})$-H interactions are obtained as:

$$N_H(\vec{x}) \equiv N_{CH_2}(\vec{x}) - N_C(\vec{x}) \times \frac{M_C/CH_2}{M_C}$$

(3)

where $N_{CH_2}$ and $N_C$ are the data from the CH$_2$ plastic and graphite (C) targets. The interactions from this latter are normalized by the ratio between the total fiducial masses of C within the graphite and CH$_2$ targets, $M_C/CH_2/M_C$. The subtraction in Eq.(3) is performed after all the selection cuts including the kinematic analysis described above, resulting in the purities and efficiencies summarized in Tab. I. Practical considerations require the graphite targets to be smaller than the actual amount of C inside the CH$_2$ plastic, thus resulting in a statistical penalty associated with the subtraction procedure. Figure 6 illustrates how the total statistical uncertainty on $N_H$ from Eq.(3) compares to the ideal one expected from a pure H$_2$ sample equivalent to the statistics of H interactions within CH$_2$. For a given efficiency, the purity of the H samples achievable by the kinematic selection is crucial for the feasibility of this technique. Our analysis suggests that a fiducial mass for the graphite targets of about 600 kg (i.e. $M_C/M_{CH_2} = 0.12$) provides a reasonable compromise with a statistical penalty less than 30%. We note that this statistical penalty can be further reduced by analytically smoothing the measured distributions from the graphite target.

As an example of application of our technique, we consider neutrino and antineutrino beam spectra similar to the ones expected in the DUNE experiment. To this end, we assume a nominal beam power of 1.07 MW with $1.47 \times 10^{21}$ pot/year and a total running time of 5+5 years with the neutrino and antineutrino beam polarities [1, 2]. Table II summarizes the total number of events expected for the various topologies and targets. The planned upgrades
TABLE III. Comparison of the efficiency and purity for the kinematic selection of H interactions from the CH\textsubscript{2} plastic target using simple cuts on $R_{mH}$ and $p_{T\perp}^H$ with the NuWro [21], GiBUU [22], and GENIE [23] event generators. The same selection cuts as in Tab. I are used in all cases.

| Process          | NuWro Efficiency | Purity | GiBUU Efficiency | Purity | GENIE Efficiency | Purity |
|------------------|------------------|--------|------------------|--------|------------------|--------|
| $\nu_{\mu}p \rightarrow \mu^-p\pi^+$ | 93%              | 86%    | 93%              | 84%    | 93%              | 91%    |
| $\bar{\nu}_{\mu}p \rightarrow \mu^+p\pi^-$ | 89%              | 84%    | 89%              | 87%    | 89%              | 89%    |

of the beam intensity to a nominal power of 2.4 MW would more than double the available statistics. Similarly, the high-energy beam option designed to detect the $\nu_\tau$ appearance in the far detector would increase the available statistics by another factor of 2.4 with a much harder spectrum [28].

IV. DISCUSSION

A. Systematic uncertainties

The kinematic analysis described in Sec. III allows to identify all the main $\nu(\bar{\nu})$-H CC topologies within the CH\textsubscript{2} plastic target with little residual backgrounds $\sim$\%20\% from interactions on the carbon nucleus. This selection dramatically reduces not only the statistical uncertainty from the background subtraction procedure (Sec. III C), but also the impact of systematic uncertainties on the modeling of nuclear effects in carbon [3]. These latter are further reduced by the model-independent background subtraction using the data obtained from the dedicated graphite target. The CH\textsubscript{2} plastic can be considered as an effective tank filled with hydrogen, while the graphite represents the empty tank. This technique is similar to what has been done for decades in electron scattering experiments, in which a cryogenic tank is filled with a liquid H\textsubscript{2} target and special runs with the empty tank are taken for background subtraction \(\textsuperscript{2}\). Since the CH\textsubscript{2} and C targets are configured as thin layers spread out uniformly over the tracking volume, the corresponding corrections for the detector acceptance are small and, most importantly, similar for both targets. The impact of possible model dependencies through these corrections is therefore negligible on $\nu(\bar{\nu})$-H measurements, as they would appear as third order effects on the data-driven subtraction of small backgrounds.

In order to check the sensitivity of our results to the details of the interaction modeling we repeat the event selection based upon simple cuts on $R_{mH}$ and $p_{T\perp}^H$ with three event generators: NuWro [21], GiBUU [22], and GENIE [23]. These generators use different assumptions for the (anti)neutrino-nucleon cross-sections, as well as for the nuclear modeling of both initial and final state interactions. As shown in Tab. III, our kinematic selection of H interactions from the plastic CH\textsubscript{2} targets is rather stable and we obtain comparable efficiencies and purities with all the three event generators used.

Reconstruction effects on the four-momenta of the final state particles can in principle degrade the kinematic selection. For this reason in our studies we used a realistic detector

\(\textsuperscript{2}\) One of the dominant systematic uncertainties in electron scattering experiments on hydrogen is typically given by the knowledge of the density/mass of the cryogenic target. Our technique for measuring $\nu(\bar{\nu})$-H interactions allows a more precise knowledge of the actual target mass.
smearing and checked its consistency with GEANT4 simulations. Furthermore, we validated the effects of the detector acceptance, smearing, and track reconstruction with NOMAD data [17], although the NOMAD detector had worse acceptance, granularity, and resolutions compared to the one we are considering. We also note that similar kinematic selections were successfully demonstrated by NOMAD in more severe background conditions (rejections up to $10^5$) in various published analyses [18–20], as well as in single track measurements of $\bar{\nu}_\mu$ QE and inverse muon decay [29].

The use of a likelihood function in the kinematic analysis (Sec. III A) provides a simple way to vary the purity and efficiency of the selected samples (Fig. 4) to validate the background subtraction and the selection procedure through appropriate control samples.

B. Unique option for $\nu(\bar{\nu})$-H

The technique we propose appears to have no practical alternatives for the experimental detection of high statistics samples of $\nu(\bar{\nu})$-H interactions. The only technology ideally able to deliver more precise measurements (including both statistics and resolution) would be a dedicated liquid H$_2$ bubble chamber with a volume $> 10^3$ m$^3$. However, modern safety requirements for underground experimental halls make this option unfeasible. Filling a large time-projection chamber (TPC) with high pressure H$_2$ gas, besides safety/cost concerns, would result in an insufficient statistics for any sensible physics measurement. The use of a plastic scintillator target cannot deliver the precision required for the detection of $\nu(\bar{\nu})$-H interactions via subtraction with a graphite target. In addition to the smaller hydrogen content (CH vs. CH$_2$), the coarser vertex, angular, and momentum resolution achievable introduce larger systematic uncertainties in the location of $\nu(\bar{\nu})$-H interactions and higher backgrounds from the kinematic selection (Fig. 6). Furthermore, the many impurities from glue, fibers, coatings, etc. make the subtraction of nuclear components problematic in relation to the small H content of about 7%.

C. Physics Measurements

The availability of high statistics samples of $\nu(\bar{\nu})$-H interactions can represent a significant advancement for neutrino physics in general, and for long-baseline experiments in particular. In this section we briefly outline some of the key physics measurements, which will be discussed in details elsewhere [30].

Historically, the limited knowledge of the incoming fluxes has always been a bottleneck for neutrino experiments. The samples of $\nu(\bar{\nu})$-H interactions described in Sec. III C can provide the most precise measurements of (anti)neutrino fluxes, possibly superseding any other technique using nuclear targets. To this end, two types of processes are relevant. The exclusive $\nu(\bar{\nu})p$ resonant topologies at small hadronic energy $\nu < 0.5$ GeV offer a clean measurement of the relative fluxes as a function of energy with negligible hadronic uncertainties. The measurement of the $\bar{\nu}p$ quasi-elastic process at small momentum transfer $Q$ allows an absolute measurement of fluxes since the corresponding cross-section in the limit $Q \to 0$ is a constant known to high accuracy from neutron $\beta$ decay.

---

3 Following the NOMAD procedure, the momentum scale for charged tracks can be calibrated to better than 0.2% in the detector being considered using the constraint from the mass of the reconstructed $K_{0S}$.

4 A total TPC volume of about 2,500 m$^3$ filled with H$_2$ gas at 10 atm would be required to match the statistics achievable with our technique.
A comparison of $\nu(\bar{\nu})$-H interactions with the corresponding ones from nuclear targets provides a direct measurement/constraint of nuclear effects, which typically result in a substantial smearing of the observed interactions. This study can be performed with both inclusive CC events and with various exclusive topologies. Constraining the nuclear smearing from initial and final state interactions is required to reduce the uncertainties in the unfolding of data collected from heavy targets and to calibrate the reconstructed neutrino energy scale.

The possibility to control the (anti)neutrino target and the input fluxes to an unprecedented accuracy would open up a sensible program of precision tests of fundamental interactions [28]. An example is given by the Adler sum rule [31],

$$S_A = \int_0^1 \frac{dx}{x} \left( F_{2p}^{\bar{\nu}p} - F_{2p}^{\nu p} \right) = 2,$$

which is based upon current algebra and was tested only by BEBC [32] with a few thousand events. Similarly, by exploiting the isospin symmetry $F_{2n}^{\nu n} = F_{2p}^{\bar{\nu}p}$, we can obtain a model-independent measurement of the free neutron structure functions, as well as a measurement of the large $x$ behavior of the $d/u$ quark ratio [33]. These measurements can also be used for precision tests of the isospin (charge) symmetry and would help to elucidate the flavor structure of the nucleon [34].

V. SUMMARY

We presented a novel approach to achieve precision measurements of $\nu(\bar{\nu})$-hydrogen interactions via subtraction between dedicated CH$_2$ plastic and graphite (pure C) targets, embedded within a low mass tracker allowing a complete control of the targets. We used an efficient kinematic selection to reduce backgrounds from the carbon nucleus in the CH$_2$ measurements to the a 8-20% level, depending upon the specific event topology considered. The measurement of this background is entirely data-driven by subtracting it using the corresponding graphite target measurements.

The possibility to have large samples of $\nu(\bar{\nu})$-H is a necessary condition for any program of precision measurements with (anti)neutrino interactions, as well as to achieve the precisions required by next-generation long-baseline oscillation experiments. The simple and safe approach we proposed appears to be the only realistic opportunity to obtain such high statistics samples, since safety and practical arguments make other techniques unfeasible.

The selected $\nu(\bar{\nu})$-H interactions can provide the most precise measurements of (anti)neutrino fluxes, possibly superseding any other technique using nuclear targets. In combination with nuclear targets, they also allow the first direct measurement of nuclear effects affecting the smearing of observed $\nu(\bar{\nu})$-nucleus interactions. Finally, they represent the key to access a sensible program of precision tests of fundamental interactions.

ACKNOWLEDGMENTS

The authors express their gratitude to the LBNE and DUNE experiments for the use of some detector simulation tools to check the physics performance with the CDR reference detector. We thank L. Camilleri and X. Lu for fruitful discussions. This work was supported by Grant No. de-sc0010073 from the Department of Energy, USA.

[1] R. Acciarri et al. (DUNE), (2015), arXiv:1512.06148 [physics.ins-det].
16-20, 2018 (2018) arXiv:1808.06871 [hep-ph].