Enhancing the LBNF/DUNE Physics Program

P. Bernardini[1], S. Bertolucci[2], M. Bhattacharjee[3], B. Bhuyan[3], S. Biagi[11], A. Caminata[13], A. Cervelli[6], S. Davini[13], S. Di Domizio[13], L. Di Noto[13], M. Diwan[4], C. Distefano[11], H. Duyang[5], F. Ferraro[13], A. Gabrielli[2], M. Guerzoni[6], B. Guo[5], M.A. Iliescu[12,14], G. Laurenti[6], G. Mandrioli[6], N. Mauri[2], S.R. Mishra[5], N. Moggi[2], A. Montanari[6], M. Pallavicini[13], L. Pasqualini[2], L. Patrizii[6], R. Petti[5],*
M. Pozzato[6], P. Sapienza[11], F. H. Sawy[7], G. Sirri[6], L. Stanco[8], A. Surdo[9], M. Tenti[10], F. Terranova[10], G. Testera[13], M. Torti[10], N. Tosi[6], R. Travaglini[6], and S. Zucchelli[2]

[1] *University of Salento and INFN, 73100 Lecce, Italy*

[2] *University of Bologna and INFN, 40127 Bologna, Italy*

[3] *Indian Institute of Technology Guwahati, Guwahati, 781039, India*

[4] *Brookhaven National Laboratory, Upton, NY 11973, USA*

[5] *University of South Carolina, Columbia, South Carolina 29208, USA*

[6] *INFN sezione di Bologna, 40127 Bologna, Italy*

[7] *University of Padova and INFN, 35131 Padova, Italy*

[8] *INFN sezione di Padova, 35131 Padova, Italy*

[9] *INFN sezione di Lecce, 73100 Lecce, Italy*

[10] *University of Milano Bicocca and INFN, 20126 Milano Bicocca, Italy*

[11] *INFN, Laboratori Nazionali del Sud, 95125 Catania, Italy*

[12] *INFN, Laboratori Nazionali di Frascati, 00044 Frascati, Italy*

[13] *University of Genova and INFN, 16146 Genova, Italy and*

[14] *CERN, European Organization for Nuclear Research 1211 Geneve 23, Switzerland*

* Corresponding Editor: Roberto.Petti@cern.ch

I. EXECUTIVE SUMMARY

The Long-Baseline Neutrino Facility (LBNF) offers a unique opportunity for neutrino physics due to the high intensity (anti)neutrino beam with a broad energy spectrum. The possibility to collect unprecedented exposures alleviates one of the primary limitations of past neutrino experiments. An experimental technique has been recently proposed [1, 2] to achieve a control of the configuration, chemical composition, size, and mass of the neutrino targets comparable to the electron scattering experiments. In particular, this technique allows precise measurements of high statistics samples of (anti)neutrino-hydrogen (H) interactions [1].

The availability of high statistics samples of $\nu(\bar{\nu})$-H interactions addresses three main systematic uncertainties affecting the Deep Underground Neutrino Experiment (DUNE) long-baseline oscillation analyses [3]: (a) determination of the neutrino and antineutrino fluxes $\Phi(E_\nu)$; (b) constraint of the nuclear smearing in Ar (response function) entering the event unfolding; (c) calibration of the reconstructed (anti)neutrino energy scale. Neutrino flux can be potentially measured at the percent level using various exclusive $\nu(\bar{\nu})$-H topologies. Such a precision cannot be achieved by other techniques [1].

A control of the neutrino target(s) similar to the one achieved in electron scattering experiments together with an accurate determination of the (anti)neutrino fluxes from $\nu(\bar{\nu})$-H and the unprecedented statistics would enable a sensible program of precision tests of fundamental interactions in the DUNE Near Detector (ND) [4]. This program includes a broad mixture of measurements of electroweak parameters, QCD and hadron structure of nucleons and nuclei, form factors, structure functions and cross-sections, as well as searches for new physics or verification of existing outstanding inconsistencies. It would produce hundreds of papers of varying importance and potentially add a substantial discovery potential to the DUNE physics program. This ND program would not require any additional cost with respect to what is needed to address the systematics of the long-baseline analyses. Such a program of precision measurements and searches would nicely complement the ongoing efforts in the collider, fixed-target and nuclear physics communities. In turn, it would elevate the near site of DUNE to a general physics facility much needed for a project of the size and duration of the DUNE experiment.

We propose to integrate the capability to obtain accurate $\nu(\bar{\nu})$-H measurements into the design of the ND complex currently considered in DUNE. The core technology needed for this enhancement of the physics potential is well established and has enough flexibility to be adapted to different detector geometries and configurations. This addition to the ND system can be accomplished either with a new self-contained complementary detector or an integrated sub-detector with minimal variations of the magnetized detector being considered. In particular, an interesting low-cost solution currently being studied for the former option includes the reuse of an existing magnet and electromagnetic calorimeter [5].

II. ADDITION TO THE DUNE NEAR DETECTOR

A. The Straw Tube Tracker

The detector concept we propose is based upon the reference ND design described in the DUNE Conceptual Design Report [2] and which successfully passed the technical and DOE CD1 reviews [6–8]. The neutrino targets are physically separated from the actual tracking system, which has a negligible overall mass compared to the former. In order to achieve high resolution measurements, the target mass is spread out uniformly throughout the entire tracking volume, by keeping the average density low enough to have a detector transparent (about one radiation length X_0) to final state particles produced in neutrino interactions.

The key detector element is a central Straw Tube Tracker (STT), which is inserted into a magnetic field and surrounded by a 4π electromagnetic calorimeter (ECAL). This detector concept is rather flexible and its main operating parameters can be adapted to different detector geometries and 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 [9–12]. 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. The main parameters of the proposed STT are the following: magnetic field $B = 0.6$ T, average density $\rho \sim 0.16$ g/cm^3, radiation length $X_0 \sim$ 3.5m, tracking sampling 0.15 (0.36)%X_0 $\perp$ ($\|$). The corresponding STT modules are based upon a compact design (Fig. 1) resulting in a total width of $\sim$ 5cm:

- The straws can be fabricated with either the ultrasonic welding or the traditional winding technologies [13]. Each module includes four straw layers XXYY with straw diameter 5mm, mylar walls with total thickness 20 μm and 1000 Angstroms Al coating, tungsten wire with 20 μm diameter.
- Each radiator target consists of 49 polypropylene $(C_3H_6)_n$ foils 15μm thick, interspaced by 120μm air gaps. The last radiator target (number 4) is preceded by a 4mm thick (tunable) polypropylene target foil.
- Various thin nuclear targets can be integrated into a STT module without radiator targets, followed by two additional STT modules without radiators for tracking. The most important nuclear targets for the measurement of $\nu(\bar{\nu})$-H interactions [1] are given by thin graphite (pure C) and Ca plates. In addition, a thin cryogenic liquid target ($< 1X_0$) can also be added in front of the STT assembly.

Most of the target mass is located either in the target foil within the last radiator or in the integrated nuclear target, which can be fine tuned to achieve the desired fiducial mass and resolutions. The mass of the radiator targets in the default configuration corresponds to about 95% of the total mass of the STT modules. All physics sensitivity studies are based upon a fiducial mass of 5 tons of CH_2 radiators and about 600 kg of graphite targets [1], which roughly corresponds to a total tracking volume of 3.5m $\times$ 3.5m $\times$ 4m = 49 m^3 (including module frames, etc.). Additional nuclear targets include Ar, Ca, Fe, etc.

The readout of the straws must provide a measurement of both the drift time (the straws can be operated in a common trigger/stop mode) and of the energy deposition within the active gas. An interesting solution is provided by the ASIC chip VMM3 (evolution of the earlier VMM1 [14]) developed at BNL and CERN for the muon chambers of LHC experiments to provide a general readout package for micro-pattern detectors. The VMM3 is composed of 64 linear front-end channels integrating enough functionality to be adapted for the STT readout. It is also a low power readout solution, making the detector easily movable.

The core technology required to build STT is well established [9–12] and we do not anticipate the need of major detector R&D. Similarly, the basic STT design was already successfully reviewed in the context of the DUNE ND [6–8]. A conservative requirement on the single hit space resolution $< 200\mu m$ is assumed for the straws. The STT provides excellent

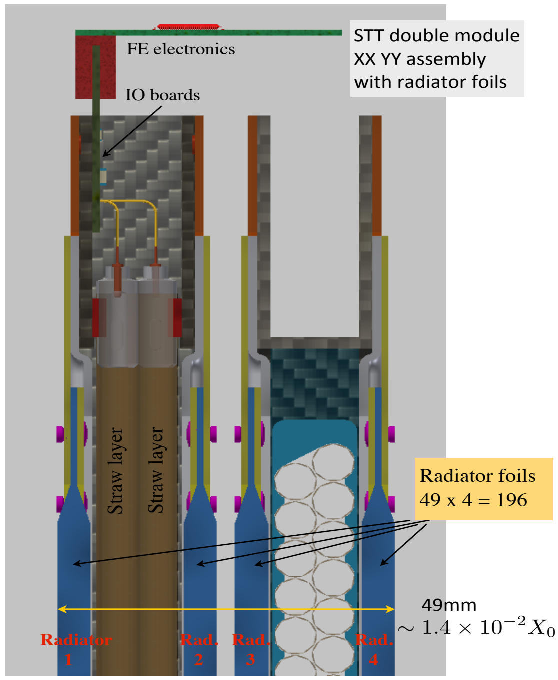

FIG. 1. Drawing of one compact STT double module including four thin polypropylene CH_2 targets. The plastic targets can be replaced with thin graphite (C) plates or any other solid nuclear target.

momentum ($\sim 3\%$) and angular (~ 2 mrad) resolutions, as well as particle identification exploiting both ionization signals dE/dx and the Transition Radiation produced by $e^{\pm}$ in the radiator foils. This latter capability offers π rejections $\sim 10^3$ for 90% electron efficiency.

B. Integration with the DUNE Near Detector

The proposed STT must be inserted into a magnetic field of 0.6 T and must be surrounded by a 4π ECAL to measure neutral particles not decaying/interacting within the STT volume. The overall magnetic volume required to accommodate the complete STT proposed is relatively compact at 49 m^3, allowing its integration as part of an additional self-contained detector in the DUNE ND complex. To this end, an interesting low-cost solution is offered by the reuse of the existing solenoidal magnet and ECAL from the KLOE experiment [5]. The performance of the proposed STT within this magnet is being evaluated with complete GEANT 4 simulations and is consistent with the physics performance expected from a similar detector within a dipole magnet.

Alternatively, the proposed STT can be integrated within the magnetic spectrometer currently planned for the DUNE ND complex, resulting in a hybrid detector including the high pressure Ar gas TPC (HPgTPC) and STT sharing the same magnetic volume. The geometry and configuration can be optimized based upon the magnet constraints and the desired physics performance.

The planned ND hall for DUNE is large enough to implement the possibility of a movable ND complex (DUNE-Prism). The size of this hall allows in principle the installation of the additional detector we propose either off-axis or on-axis once the other ND components are moved off-axis. We note that the overall volume occupied by the standalone detector with the compact STT is smaller than the magnetized detector currently considered.

Process	CP optimized beam FHC 1.2MW, 5y	CP optimized beam RHC 1.2MW, 5y	ν_τ optimized beam FHC 2.4MW, 2y	ν_τ optimized beam RHC 2.4MW, 2y
ν_μ CC on CH_2	34,300,000	5,500,000	65,570,000	3,810,000
$\bar{\nu}_\mu$ CC on CH_2	1,680,000	13,100,000	1,152,000	24,000,000
ν_e CC on CH_2	508,000	242,000	665,000	181,000
$\bar{\nu}_e$ CC on CH_2	85,700	187,000	70,000	190,000
ν_μ CC on H	3,360,000	542,000	6,510,000	375,000
$\bar{\nu}_\mu$ CC on H	308,000	2,490,000	210,000	4,330,000
ν_e CC on H	49,700	23,900	65,800	17,800
$\bar{\nu}_e$ CC on H	15,400	34,400	12,600	33,900

TABLE I. Number of events expected in the proposed STT for a fiducial mass of 5 tons $(C_3H_6)_n$ targets and 714 kg of hydrogen (within radiator targets). Results with two different LBNF beam options are shown: (a) default 3 horn beam optimized for the CP violation search (1.2 MW, 120 GeV, 1.1 $\times 10^{21}$ pot/year); (b) high energy option optimized for the ν_τ appearance (2.4 MW).

III. PHYSICS PROGRAM

In order to assess the physics sensitivity of the proposed detector we use as default the engineered 3 horn LBNF beams optimized for the CP violation search with 120 GeV protons, a 1.2 MW power, and 1.1 $\times 10^{21}$ pot/year. Table I lists the expected number of inclusive Charged Current (CC) events for the various beam components for a 5 year run with both the FHC neutrino and RHC antineutrino beam modes. A nominal fiducial mass of 5 tons of CH_2 radiator targets, providing about 714 kg of hydrogen, results in statistics large enough to achieve accurate measurements of all relevant physics processes discussed in the following. As discussed in Sec II A, various additional nuclear targets like C, Ar, Ca, Fe, etc. can further enhance the physics potential.

Another interesting option is provided by the LBNF beam optimized to detect the ν_τ appearance in the Far Detector. The corresponding energy spectrum is substantially higher than the one with the default beam configuration, resulting in an increase of the expected event rates by a factor 2.4 with respect to the default beam (Tab. I). A realistic scenario could be that after completing a data taking of 5 years with the standard FHC beam and 5 years with the standard RHC beam, we can have dedicated runs with the ν_τ optimized beam. Even a modest exposure of 2 years with FHC and 2 years with RHC in this configuration would substantially enhance the discovery potential of the precision tests of fundamental interactions described in Sec. III B. To this end, by the time we can realistically have dedicated runs with the ν_τ optimized beam (after 10 years of data taking with the standard beam) the LBNF beam intensity is expected to be upgraded from 1.2 MW to 2.4 MW.

A. Reduced Systematics for Long-baseline Oscillation Analyses

We summarize here the key advantages offered by the proposed detector for the DUNE long-baseline oscillation measurements. In particular, we focus on the unique features enabled by the capability to collect large samples of $\nu(\bar{\nu})$-H interactions [1]. Additional measurements to constrain the various systematic uncertainties with a similar technology can be found in the DUNE CDR [3].

1. Measurement of Neutrino and Antineutrino Fluxes $\Phi(E_\nu)$

A well established method commonly used by neutrino experiments to determine the shape of the ν_μ and $\bar{\nu}_\mu$ fluxes is known as low-ν_0 [15, 16]. However, all past experiments used inclusive CC interactions off various nuclear targets, resulting in intrinsic limitations in the achievable accuracy from the related nuclear smearing (neutrons, final state interactions, etc.) and the related detector acceptances.

The availability of large samples of $\nu(\bar{\nu})$-H interactions (Tab. I) has the potential to reduce hadronic uncertainties on the determination of the relative fluxes to negligible level. To this end, a key channel is represented by the exclusive $\nu(\bar{\nu})p$ resonant topologies with $\mu^\mp p\pi^\pm$ in the final state [1]. A cut $\nu < 0.5$ GeV reduces the phase space flattening the the energy dependence of the cross-section in the DUNE energy range, still retaining more than 540,000 events. As a result even sizable uncertainties on the H form factors have a small impact on the flux determination. We note that the H form factors can be directly measured/constrained by fitting the Q^2 differential distributions of the complete $\mu^\mp p\pi^\pm$ samples without ν cut.

Another important process for the flux determination is the $\bar{\nu}_\mu$ quasi-elastic (QE) on H, which can be efficiently selected by using the neutrons interacting either in the STT volume or in the surrounding ECAL [1]. This channel can provide both the relative and absolute $\bar{\nu}_\mu$ flux as a function of energy since in the limit $Q^2 = 0$ the QE cross-section becomes independent of energy and is completely defined by the neutron β-decay to a precision $\ll 1\%$. The flux can be extracted in STT by measuring low Q^2 QE interactions. Neutrons can be detected in STT up to a lower threshold than protons, thus enhancing the reconstruction efficiency of $\bar{\nu}_\mu$ QE on H at very small Q^2 values: we expect >130,000 QE events with $Q^2 < 0.05$ GeV^2.

Using the measurements with $\nu(\bar{\nu})$-H interactions described above we can potentially achieve a knowledge of neutrino and antineutrino fluxes $\Phi(E_\nu)$ at the percent level. No other technique currently known can offer comparable precisions.

2. Constraining the Nuclear Smearing and Calibrating the Neutrino Energy Scale

The use of an Ar target in the DUNE FD implies a large smearing on the reconstructed energy due to the nuclear effects in both the initial and final state interactions. Furthermore, the nuclear smearing is maximal and rapidly varying in the energy range most sensitive to the oscillations. We must therefore constrain experimentally in-situ the systematic uncertainties associated to the unfolding of the measured distributions. To this end, a project aiming at discoveries including physics beyond standard model like DUNE cannot rely entirely upon Monte Carlo tuning or model corrections.

The availability of large samples of $\nu(\bar{\nu})$-H interactions allows an in-situ measure/constraint of the nuclear effects relevant for the DUNE oscillation analyses by using a complementary Ar target within the ND complex. In H interactions the response function is essentially defined by the momentum resolution $\delta p/p$, which can be calibrated to 0.2% using the reconstructed K_0 mass peak. From a comparison of inclusive CC interactions from Ar and H targets we can therefore determine the product of the Ar cross-section times the corresponding (nuclear) response function. The inclusive samples effectively integrate over all visible topologies resulting in the actual average smearing for CC interactions on Ar.

The comparison of inclusive CC events in Ar and H described above can determine the nuclear smearing for the particular ND beam spectrum. The use of a complete set of kinematic variables sensitive to the smearing can constrain the physics response function and help resolving potential degeneracies. This latter point is particularly relevant given the fact that in the FD we will have a different beam spectrum. Additional handles include: (a) analysis of various exclusive CC topologies; (b) consider different bins in the momentum and angle of the outgoing muon; (c) simultaneous analysis of ν and $\bar{\nu}$ exploiting the isospin symmetry; (d) select Ar events with specific primary charged multiplicities.

B. Physics Facility for Precision Measurements and Searches

The collection of the statistics shown in Tab. I and the determination of the neutrino and antineutrino fluxes to unprecedented precision using $\nu(\bar{\nu})$-H interactions (Sec. III A 1) would solve the two main limitations of past neutrino experiments. We can then exploit the unique properties of the (anti)neutrino probe for the study of fundamental interactions with a broad program of precision measurements and searches [4] complementary to the ongoing efforts in the collider, fixed-target and nuclear physics communities. In this Section we outline a few examples of measurements part of this broader program, which for the most part is unique to the proposed detector.

1. Electroweak Precision Measurements

The interest of a precise determination of the weak mixing angle ($\sin^2\theta_W$) in (anti)neutrino scattering at the DUNE energies is twofold: (a) it provides a direct measurement of neutrino couplings to the Z boson and (b) it probes a different scale of momentum transfer than LEP did by virtue of not being at the Z boson mass peak.

The most precise measurement of $\sin^2\theta_W$ in neutrino deep inelastic scattering (DIS) comes from the NuTeV experiment, which reported a value that is 3σ from the Standard Model [17]. The proposed addition to the DUNE ND complex can determine $\sin^2\theta_W$ from the ratio of NC and CC DIS interactions induced by neutrinos $\mathcal{R}^\nu \equiv \sigma^\nu_{\rm NC}/\sigma^\nu_{\rm CC}$. A cut on the visible hadronic energy $E_{\rm had} > 5$ GeV (the CHARM experiment used $E_{\rm had} > 4$ GeV) is used to harden the Q^2 distribution. With an exposure of 5 years with the CP optimized beam and 2 years with the ν_τ optimized beam about 4×10^6 NC events are expected with this cut. The use of the high resolution STT significantly reduces the experimental systematic uncertainties compared to much coarser detectors like NuTeV. Two key advantages are the efficient identification of ν_e CC interactions and an event-by-event kinematic analysis separating NC and CC interactions.

The measurement of $\mathcal{R}^\nu$ will be dominated by theoretical systematic uncertainties [18–20] on the structure functions of the target nucleons. Assuming modest improvements over the NuTeV analysis it seems feasible to achieve a total relative uncertainty on the value of $\sin^2\theta_W$ extracted from νN DIS of 0.35%. We note that most of the model uncertainties will be constrained by dedicated in situ measurements using the large CC samples and employing improvements in theory that will have evolved over the course of the experiment.

A second independent measurement of $\sin^2\theta_W$ can be obtained from NC $\nu_\mu e$ elastic scattering. This channel is free from hadronic uncertainties but it is limited by the statistics due to its tiny cross section. The value of $\sin^2\theta_W$ can be extracted from the ratio $\mathcal{R}_{\nu e}(Q^2) \equiv \sigma(\overline{\nu}_\mu e \to \overline{\nu}_\mu e)/\sigma(\nu_\mu e \to \nu_\mu e)$ [21], in which systematic uncertainties related to the selection and the electron identification cancel out. The required fluxes are measured using $\nu(\bar{\nu})$-H

(Sec. III A 1) and coherent $\pi^{\pm}$ interactions. The proposed detector can select $\nu_\mu e$ elastic events with little backgrounds, which, most importantly, can be calibrated in-situ with data. In order to increase the available statistics we can perform a combined analysis of the events collected in STT and in the large LAr detector (fiducial volume of about 25 tons) present within the ND complex. The STT reduces systematic uncertainties while the LAr increases the statistics. An overall relative precision of $\sin^2\theta_W$ from ν-e of 1% or better seems feasible.

The DIS and ν-e elastic channels are characterized by substantially different scales of momentum transfer, providing a tool to test the running of $\sin^2\theta_W$ in a single experiment. To this end, another interesting channel is the NC elastic scattering off protons (Sec. III B 3) in which the Q^2 can be reconstructed and has scales intermediate between ν and DIS. Another channel is the coherent ρ production through the ratio $\mathcal{R}_\rho \equiv (\nu_\mu \mathcal{A} \to \nu_\mu \rho^0 \mathcal{A})/(\nu_\mu \mathcal{A} \to \mu^- \rho^+ \mathcal{A})$. Electroweak parameters including $\sin^2\theta_W$ and the couplings can be extracted from a global fit including all the different channels measured, similarly to what was done at LEP.

2. Tests of Isospin Physics and Sum Rules

A compelling physics topic with the proposed detector is isospin physics using both neutrino and antineutrino interactions. The availability of large samples of $\nu(\bar{\nu})$-H interactions [1] allows a precision test of the Adler sum rule [22] , $S_A = 0.5\int_0^1 dx/x\left(F_2^{\bar{\nu}p} - F_2^{\nu p}\right) = I_p$, which gives the isospin of the target and was tested only by BEBC [23] with a few thousand events. The Adler sum rule survives the strong-interaction effects because of the conserved vector current (CVC) and provides an exact relation to test the local current commutator algebra of the weak hadronic current. In the quark-parton model the Adler sum is the difference between the number of valence u and d quarks of the target. The value of S_A can be measured as a function of the momentum transfer Q^2 from the structure functions $F_2^{\bar{\nu}p}$ and $F_2^{\nu p}$ determined from the corresponding differential cross-sections on hydrogen. This measurement is sensitive to possible violations of the isospin (charge) symmetry, heavy quark (charm) production, and strange sea asymmetries $s - \bar{s}$. Furthermore, the measurement from H can be compared with the values of S_A obtained from the C target ($S_A = 0$) [20].

The Gross-Llewellyn-Smith (GLS) sum rule [24] $S_{GLS} = 0.5\int_0^1 dx/x\left(xF_3^{\bar{\nu}p} + xF_3^{\nu p}\right)$ can also be measured precisely as a function of Q^2 using $\nu(\bar{\nu})$-H interactions. The value of S_{GLS} in the quark-parton model gives the number of valence quarks in the nucleon. This sum rules receives both perturbative and non-perturbative QCD corrections and its Q^2 dependence can be used to extract the strong coupling constant $\alpha_s(Q^2)$. The most precise measurement of S_{GLS} was performed by CCFR on a Fe target at $Q^2 = 3$ GeV^2. The presence of both H and various nuclear targets in STT would allow an investigation of the isovector and nuclear corrections, adding a tool to test isospin (charge) symmetry.

The isospin symmetry implies that $F_{2,3}^{\bar{\nu}p} = F_{2,3}^{\nu n}$ and that for an isoscalar target $F_{2,3}^{\bar{\nu}} = F_{2,3}^{\nu}$. In the proposed detector we can perform various precision tests of isospin (charge) symmetry exploiting the unique combination of H and nuclear targets A. In particular, we can measure two structure function ratios as a function of Q^2 and Bjorken x: $R_{2,3}^H \equiv F_{2,3}^{\bar{\nu}p}/F_{2,3}^{\nu p} = F_{2,3}^{\nu n}/F_{2,3}^{\nu p}$ and $R_{2,3}^A \equiv F_{2,3}^{\bar{\nu}A}/F_{2,3}^{\nu A} - 1 = \Delta F_{2,3}^{\bar{\nu}-\nu}/F_{2,3}^{\nu}$, in which many systematic uncertainties cancel out. Since these ratios are sensitive to charm quark effects though the Cabibbo angle $\sin^2\theta_C$ and strange sea asymmetry $s - \bar{s}$ a combined analysis with charm production (Sec. III B 3) is needed. We can use three possible nuclear targets C, Ca, and Ar in order to disentangle nuclear effects from isospin effects in nucleon structure functions.

3. Measurements of the Strangeness Content of the Nucleon

The strange quark contribution to the vector and axial-vector currents of the nucleon, as well as to the nucleon spin, Δs, are important elements to improve our understanding of the nucleon structure. While the strange quark vector elastic form factors have been measured with good accuracy in parity-violating electron scattering (PVES) experiments, the strange axial-vector form factors are still poorly determined. The proposed detector can accurately determine the latter from a measurement of the NC elastic scattering off protons $\nu_\mu(\bar{\nu}_\mu)p \to \nu_\mu(\bar{\nu}_\mu)p$. In the limit $Q^2 \to 0$ the NC differential cross-section is proportional to the axial-vector form factor $d\sigma/dQ^2 \propto G_1^2 = (-G_A/2 + G_A^s/2)^2$, where G_A is the known axial form factor and G_A^s is the strange form factor. This process provides the most direct measurement of Δs by extrapolating the NC differential cross-section to $Q^2 = 0$ since in this limit $G_A^s \to \Delta s$.

We can measure the ratios of NC elastic scattering to the corresponding QE process $\mathcal{R}_{\nu p}(Q^2) \equiv \sigma(\nu_\mu p \to \nu_\mu p)/\sigma(\nu_\mu n \to \mu^- p)$ and $\mathcal{R}_{\bar{\nu} p}(Q^2) \equiv \sigma(\overline{\nu}_\mu p \to \overline{\nu}_\mu p)/\sigma(\overline{\nu}_\mu p \to \mu^+ n)$ over an extended Q^2 range, using the CC QE process to determine G_A. This latter can also be used to extract the axial current charge radius, which can be compared to the results from muon capture in hydrogen to investigate existing discrepancies on this quantity [25]. The QE process $\bar{\nu} p$ can be measured both with hydrogen and nuclear targets. With the statistics in Tab. I we expect to detect $\mathcal{O}(10^6)$ events in STT from NC elastic off proton for both ν_μ and $\bar{\nu}_\mu$. In addition, a combined analysis with PVES data (HAPPEX, G0, A4) would allow an accurate determination of all three strage form factors G_E^s, G_M^s, G_A^s.

The resolution of the proposed detector will enable precision measurements of exclusive decay modes of charmed hadrons (e.g., D^{*+}, D_s, Λ_c) and measurement of charm fragmentation and production parameters. In addition, the low density of STT will give access to both the $\mu\mu$ and μe inclusive semi-leptonic charm decay channels with a statistics more than one order of magnitude higher than the largest sample of charm dimuon events available from NOMAD [26]. The analysis of both neutrino and antineutrino induced charm production provides the most direct determination of the strange quark content of the nucleon [28].

4. Nucleon Structure and QCD Studies

The precise calibration of the energy scale uncertainties in the proposed detector and the unprecedented precision in the determination of the (anti)neutrino fluxes (Sec. III A 1) allow measurements of structure functions and cross-sections with accuracies comparable to electron scattering experiments. Using both neutrino and antineutrino DIS we can determine the different structure functions F_2, xF_3, F_L, F_T, elucidating the flavor structure of the nucleon [28]. We can perform global QCD analyses of (anti)neutrino data from the proposed detector to study parton distribution functions (PDFs) as well as perturbative and non-perturbative corrections (High Twists) in a broad range of Q^2 and Bjorken x, given the statistics (Tab. I) and energies available in DUNE. Data from both H and the various nuclear targets can be used to separate valence and sea quark distributions, d and u quark distributions, and the strange quark s and $\bar{s}$ distributions. A study of F_L will not only provide information on the gluon distribution (e.g. Altarelli-Martinelli relation) but also a determination of $R = F_L/F_T$, which is expected to have a different behavior at small Q^2 with respect to electromagnetic interactions [20] as a result of the partial conservation of the axial current (PCAC). All of these studies of the nucleon structure in the proposed detector can provide unique information, complementary to the ongoing programs at colliders and fixed-target electron DIS experiments.

The availability of large statistics samples of $\nu(\bar{\nu})$-H interactions (Tab. I) is crucial to study the structure of the nucleon disentangling nuclear effects. In particular, using the isospin symmetry we can obtain a direct model-independent measurement of the free neutron structure functions $F_{2,3}^{\nu n} \equiv F_{2,3}^{\bar{\nu} p}$ and $F_{2,3}^{\bar{\nu} n} \equiv F_{2,3}^{\nu p}$. All other determinations from charged lepton DIS suffer from various model systematic uncertainties, typically growing with Bjorken x. This measurement allows, in turn, a precise determination of the d quark distribution and of the corresponding d/u ratio up to values of Bjorken x close to 1, testing various model predictions for the limit at $x \to 1$.

The measurement of QE and resonance production on hydrogen allows precision measurements of elementary amplitudes and form factors [30]. A determination of the axial current charge radius from $\bar{\nu}p$ QE can be compared with the results from muon capture in hydrogen to investigate existing discrepancies [25] and test μ-e universality. The available QE statistics can be used to test radiative corrections to neutron and nuclear β decay and possible violations of CKM unitarity [31]. Single photon NC processes which could provide potential backgrounds for the MiniBooNE anomaly [32] can be measured.

5. *Studies of (Anti)Neutrino-Nucleus Interactions*

The possibility to integrate various thin nuclear targets within STT (Sec. II A) allows detailed studies of the nuclear structure and the related nuclear effects on structure functions, form factors, and cross-sections. An important issue is how the structure of a nucleon is modified when said nucleon is inside the medium of a heavy nucleus, including the determination of nuclear PDFs as well as non-perturbative effects. The study of final state interactions (FSI) is also relevant as FSI can introduce a substantial smearing of the kinematic variables reconstructed from the observed final-state particles. The flavor separation provided by the weak current and the availability of nuclear targets with the same atomic weight like Ar and Ca would clarify the flavor dependence of nuclear effects. All of these nuclear physics measurements offer unique and complementary information to the existing programs at JLab, heavy-ion, and electron-ion colliders.

A comparison between interactions on H and on the various nuclear targets available in STT can provide a direct model-independent measurement of nuclear effects. In particular, the isospin symmetry provides a determination of the free neutron structure function and hence the one of the average isoscalar nucleon $F_{2,3}^{\nu N} \equiv (F_{2,3}^{\nu p} + F_{2,3}^{\bar{\nu} p})/2$. We can then obtain the first direct measurement of the nuclear ratios $R_A \equiv F_{2,3}^{\nu A}/F_{2,3}^{\nu N}$. An interesting issue to study, in addition to the flavor dependence of nuclear effects, is the role of the axial-vector current and the corresponding differences with electromagnetic interactions. The precision achievable with the proposed detector can clarify the many outstanding discrepancies observed among different existing measurements, as well as with various theoretical models.

6. *Searches for New Physics*

The precision tests of fundamental interactions described in the previous Sections are sensitive to various new physics Beyond Standard Model (BSM), which would manifest as unexpected deviations from the SM predictions in the measured quantities. A complementary approach offered by the proposed detector is through many direct searches.

The excellent electron identification capability and resolution of STT offer a way to test the MiniBooNE low-energy anomaly with a different detector and at a different energies but similar L/E. To this end, several measurements are possible searching for anomalies in all the four spectra from $\nu_\mu, \bar{\nu}_\mu$ CC (disapperance) and $\nu_e, \bar{\nu}_e$ CC (appearance). Various explanations for the MiniBooNE anomaly can be tested including both SM and BSM physics. Oscillations with sterile neutrinos can be detected using both the CC ratios $\mathcal{R}_{e\mu}(L/E) \equiv (\nu_e N \to e^- X)/(\nu_\mu N \to \mu^- X)$ and $\bar{\mathcal{R}}_{e\mu}(L/E) \equiv (\bar{\nu}_e N \to e^+ X)/(\bar{\nu}_\mu N \to \mu^+ X)$ and the NC/CC ratios $\mathcal{R}_{\nu p}$ and $\mathcal{R}_{\bar{\nu} p}$ (Sec. III B 3) as a function of L/E. These latter provide additional handles to distinguish between appearance and disappearance. In addition, since the STT design is based upon the NOMAD concept, it provides an excellent sensitivity to ν_τ appearance [33] as a result of either oscillations with sterile neutrinos or non-standard interactions (NSI).

The proposed detector can further enhance the sensitivity of the ND complex to searches for Dark Sector physics including heavy sterile neutrinos (e.g. Majorana singlet fermions in νMSM models), axion-like particles, dark photons, light (sub-GeV) dark matter, etc.

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