Precision Measurements with (Anti)Neutrinos at LBNF

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Neutrino Physics Frontier Topical Groups:

- (NF1) Neutrino oscillations
- (NF2) Sterile neutrinos
- (NF3) Beyond the Standard Model
- (NF5) Neutrino properties
- (NF6) Neutrino interaction cross sections
- (NF10) Neutrino detectors

Energy Frontier Topical Groups:

- (EF4) EW Physics: EW Precision Physics and constraining new physics
- (EF5) QCD and strong interactions:Precision QCD
- (EF6) QCD and strong interactions:Hadronic structure and forward QCD
- (EF7) QCD and strong interactions: Heavy Ions

Rare Processes and Precision Measurements Frontier Topical Groups:

- (RF1) Weak decays of b and c quarks
- (RF6) Dark Sector Studies at High Intensities

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I. ON-AXIS DETECTOR

The Long-Baseline Neutrino Facility (LBNF) offers unique opportunities for neutrino physics, due to the high intensity (anti)neutrino beams with broad energy spectra. The default LBNF beam is optimized for the CP-violation search in the the Deep Underground Neutrino Experiment (DUNE) [1], with 1.2 MW beam power and most of the flux in the energy range 0.5-5 GeV. A higher energy option, mostly within 2-15 GeV, is also possible. At the Near Detector (ND) site, 574 m from the source, about 1.4×10^6 Charged Current (CC) interactions per ton per year are expected with the default spectrum, raising to 6.6×10^6 CC per ton per year with the high energy option and an upgraded beam power of 2.4 MW.

The DUNE ND complex includes a multipurpose System for on-Axis Neutrino Detection (SAND), permanently located on-axis. SAND is based on the superconducting magnet and the electromagnetic calorimeter repurposed from the KLOE experiment [2] at the LNF laboratory in Italy. One of the options considered for SAND [3] is to fill the inner magnetic volume with a Straw Tube Tracker (STT) preceded by an active liquid argon target (LAr). The STT is designed to offer a control of the configuration, chemical composition and mass of the neutrino targets similar to electron scattering experiments [4]. Thin layers – typically 1-2% of radiation length – of various passive target materials with high chemical purity are alternated with straw layers of negligible mass so that the target represents up to 97% of the total detector mass. This technology allows the implementation of a "solid" hydrogen target by subtracting measurements on dedicated graphite (pure C, 500 kg fiducial mass) and polypropylene (CH_2, 4.7 t fiducial mass) targets after a kinematic selection enhancing the purity of the H samples to 80-95%, depending on the specific process considered [5].

II. PRECISION FLUX MEASUREMENTS

Precision flux measurements can be performed using exclusive single-pion $\nu_\mu p \to \mu^- p \pi^+$ and quasi-elastic $\bar{\nu}_\mu p \to \mu^+ n$ processes on hydrogen with small energy transfer to the target [6]. The relevant systematic uncertainties can be directly constrained with data control samples. The "solid" hydrogen target allows the determination of ν_μ and $\bar{\nu}_\mu$ relative fluxes as a function of energy with an accuracy better than 1% in the energy range providing most of the flux. The measurement of the $\bar{\nu}_\mu p \to \mu^+ n$ on H at small momentum transfer $Q^2 < 0.05$ GeV^2 can also provide the absolute $\bar{\nu}_\mu$ flux. The absolute ν_μ flux can be determined with a precision better than 2% with the $\nu e^- \to \nu e^-$ elastic scattering.

III. NUCLEAR SMEARING AND CALIBRATION OF ν ENERGY SCALE

The STT is designed to integrate a variety of thin nuclear targets (e.g. CH_2, C, etc.), which are interleaved throughout the entire volume to guarantee the same acceptance for final state particles produced in neutrino interactions. A direct comparison of CC interactions on H – free from nuclear effects – with the corresponding ones obtained from the nuclear targets – including the LAr – allows a direct quantification of nuclear effects in different nuclei, constraining the corresponding nuclear smearing on the observed kinematic distributions. As a result, it is possible to reduce the uncertainties in the unfolding of data collected from nuclear targets and precisely calibrate the reconstructed neutrino energy scale.

IV. PHYSICS FACILITY FOR PRECISION MEASUREMENTS AND SEARCHES

The STT instrumentation of SAND offers a possible way to address the main limitations of neutrino scattering experiments – statistics and resolution, control of targets, nuclear effects, and fluxes – reducing the longstanding precision gap with respect to electron scattering experiments. These improvements would make it possible to exploit the unique properties of the neutrino probe for precision studies of fundamental interactions and of the structure of nucleons and nuclei. The near site of the LBNF could then become a general purpose $\nu\&\bar{\nu}$ physics facility with a broad program of physics measurements complementary to the ongoing efforts in the fixed-target (12 GeV program at Thomas Jefferson laboratory) [7] , collider (Electron-Ion Collider) [8] , and nuclear physics communities. The level of precision achievable can provide insights on various fields, unveiling the potential for discoveries and generating hundreds of diverse physics studies. This physics program has no additional requirements with respect to the ones needed to constrain the systematic uncertainties affecting the long-baseline neutrino oscillation measurements in DUNE.

Possible topics include (among others) the following:

- Precision measurements of electroweak parameters using different processes;
- Precision tests of isospin (charge) symmetry;
- Adler and Gross-Llewellyn Smith sum rules in hydrogen and nuclei;
- Determination of free neutron structure functions and d/u quark ratio;
- Measurements of the strangeness content of the nucleon ($s(x), \bar{s}(x), \Delta s$, etc.);
- Production of charm (e.g., D^{*+}, D_s, Λ_c) and strange ($K, \Lambda, \bar{\Lambda}$) particles;
- Determination of the F_2, xF_3, F_L, F_T structure functions (SF);
- QCD studies, parton distribution functions (PDFs), flavor structure of the nucleon;
- Non-perturbative corrections (high twists), quark-hadron duality, etc.;
- Structure of the weak current, PCAC, CVC;
- Nucleon form factors (FF), axial charge radius, CKM unitarity;
- Nuclear modification of the nucleon properties: SF, FF, flavor content and PDFs;
- Studies of the nuclear structure and different nuclear effects;
- Precision measurements as probes of new physics beyond Standard Model (BSM);
- Direct searches for new physics (BSM): sterile neutrinos, non-standard interactions, dark photons, light (sub-GeV) dark matter, etc.

This diverse program includes some traditional measurements and others which could probe new physics or address existing discrepancies. Many of these measurements can be performed with the default LBNF beam spectra and can also help constraining various systematic uncertainties affecting the DUNE long-baseline oscillation analyses. The possibility of a dedicated run with the high-energy beam option at LBNF would further expand the described measurement program and the overall physics reach.

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