

# The NuSOnG Neutrino Experiment

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**Abstract.** The NuSOnG experiment is a possible future high-statistics, high-energy neutrino scattering experiment with the potential to make much improved electroweak and QCD measurements using neutrinos as probes. The experiment would use a high-energy external proton beam possibly at Fermilab or CERN to produce the high-intensity neutrino beam. Studies[2] have been made of the sensitivity of such an experiment to make much improved electroweak measurements associated with  $\nu_\mu$ -electron elastic scattering and  $\nu_\mu$  neutral current scattering. These studies show that NuSOnG would be uniquely sensitive to new physics sources such as heavy  $Z'$  bosons, extended Higgs models, and anomalous neutrino couplings with mass scales up to 4 to 5 TeV. As shown in Ref. [2], these measurements would be complementary to new physics searches at the LHC.

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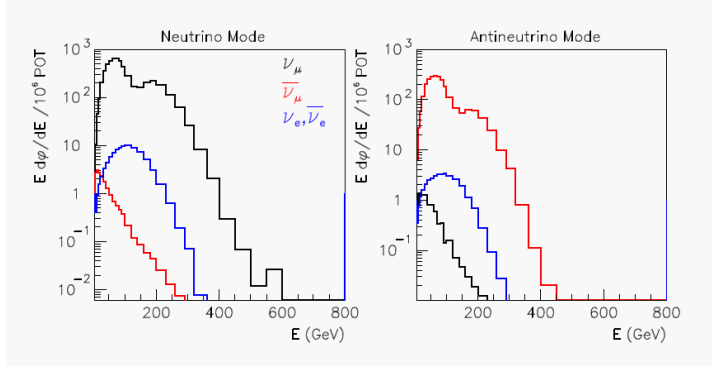
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## 1. Introduction

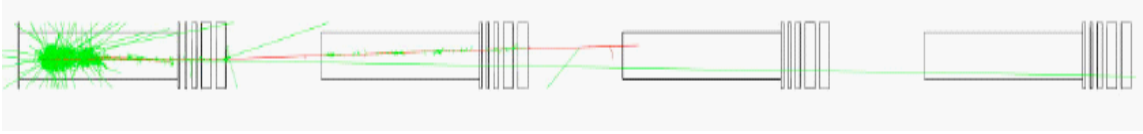
As a complementary program to the LHC, a new, high energy, high statistics neutrino scattering experiment has the potential to look beyond the Standard Model at Terascale energies by making precision electroweak measurements, direct searches for novel phenomena, and precision QCD studies. Such a new neutrino experiment has been considered by the Neutrino Scattering On Glass (NuSOnG) collaboration and an expression of interest has been submitted to Fermilab[1].

The neutrino beam would be produced from a high energy external proton beam from a high intensity accelerator such as the Fermilab Tevatron ( or possibly a new accelerator at CERN). The high energy beam would be coupled with a new large, fine grained detector in order to collect increased statistics for rare neutrino processes.

The detector and beam would allow a precise measurement of the ratio of neutral current (NC) and charged current (CC) neutrino-electron scattering with reduced statistical and systematic uncertainties as compared to previous measurements. Measurements of these processes can explore new physics signatures in the neutrino sector which are not open to other, presently planned experiments. The NC process,  $\nu_\mu + e^- \rightarrow \nu_\mu + e^-$ , called “elastic scattering” or ES, provides the sensitivity to new Terascale physics. The CC process, called “inverse muon decay” or IMD,  $\nu_\mu + e^- \rightarrow \mu^- + \nu_e$ , is well understood in the Standard Model due to precision measurements of muon decay. Since the data samples are collected with the same beam, target and detector at the same time, the ratio of ES to IMD events cancels many systematic errors while maintaining a strong sensitivity to the physics of interest. The high sensitivity of NuSOnG comes from a combination of high neutrino energy and an event sample that is almost two orders of magnitude higher than past experiments.



**Figure 1.** The assumed energy-weighted flux of the NuTeV experiment in neutrino mode (left) and antineutrino mode (right). Black: muon neutrino, red: muon antineutrino, blue: electron neutrino and antineutrino flux.



**Figure 2.** A simulated muon neutrino, charged current event in the NuSOnG detector.

NuSOnG would be a third-generation neutrino experiment that goes beyond the best capabilities of the previous NuTeV and CHARM II experiments. Detailed studies of the physics capability and reach of such an experiment are presented in Ref. [2]. In this article, we give a brief overview of the experimental design and physics capabilities.

## 2. NuSOnG Neutrino Beam and Detector

The NuSOnG beam design will be based on the one used by the NuTeV experiment, which is the most recent high-energy, high-statistics neutrino experiment. The experiment would use 800 GeV protons on target followed by a quad-focused, sign-selected magnetic beamline. The beam flux, shown in Fig. 1, has very high neutrino or antineutrino purity ( $\sim 98\%$ ) and small  $\nu_e$  contamination ( $\sim 2\%$ ) from kaon and muon decay. Using an upgraded Tevatron beam extraction it is expected that NuSOnG could collect  $5 \times 10^{19}$  protons/yr which is an increase by a factor of 20 from NuTeV. With this high intensity, such a new facility would also produce a neutrino beam from the proton dump which would have a sizeable fraction of tau neutrinos for study.

In order for NuSOnG to be sensitive to a wide range of neutrino interactions from  $\nu$ -electron scattering as well as  $\nu$ -nucleon scattering, the baseline detector design is composed of a fine-grained target calorimeter for electromagnetic and hadronic shower reconstruction followed by a toroid muon spectrometer to measure outgoing muon momenta. The target calorimeter will be composed of 2,500  $2.5 \text{ cm} \times 5 \text{ m} \times 5 \text{ m}$  glass planes interspersed with proportional tubes or scintillator planes. This gives a target which is made of isoscalar material with fine  $1/4$  radiation length sampling. The detector will be composed of four target sections each followed by muon spectrometer sections and low mass decay regions to search for long-lived heavy neutral particles produced in the beam. The total length of the detector is  $\sim 200 \text{ m}$  and the fiducial mass for the four target calorimeter modules will be 3 kton which is 6 times larger than NuTeV or CHARM II. Fig. 2 shows a simulated  $\nu_\mu$  charged current event in the detector.

### 3. NuSOnG Physics Program

The NuSOnG physics program will address a range of topics associated with indirect searches for new physics, direct searches for new physics, and precision parton distribution studies. The indirect searches will be associated with precision electroweak measurements of  $\nu$ -electron and  $\nu$ -nucleon scattering. New physics signals can also be probed directly by searching for lepton number violating process, new heavy neutral leptons, and non-unitary type mixing among the neutrinos. NuSOnG's large sample of neutrino and antineutrino CC deep-inelastic scattering events will also allow uniquely precise measurements of structure functions including  $F_2^{\nu/\bar{\nu}}$ ,  $xF_3^{\nu}$ ,  $xF_3^{\bar{\nu}}$ , and  $R_{long}$ . The expected number of events for a five year NuSOnG run is given in Table 1.

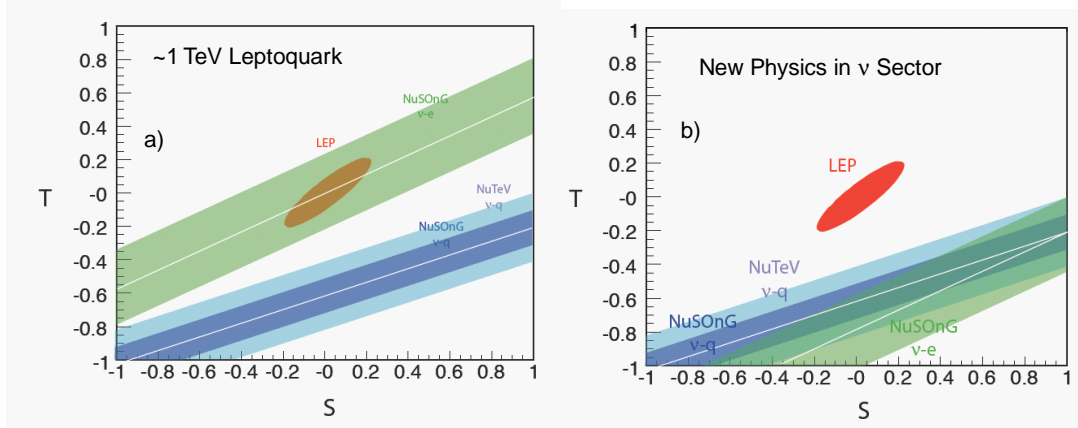
**Table 1.** Event rates expected for a 5 year NuSOnG run. NC indicates "neutral current" and CC indicates "charged current."

Events	Process
600M	$\nu_\mu$ CC Deep Inelastic Scattering
190M	$\nu_\mu$ NC Deep Inelastic Scattering
75k	$\nu_\mu$ electron NC elastic scatters (ES)
700k	$\nu_\mu$ electron CC quasi-elastic scatters (IMD)
33M	$\bar{\nu}_\mu$ CC Deep Inelastic Scattering
12M	$\bar{\nu}_\mu$ NC Deep Inelastic Scattering
7k	$\bar{\nu}_\mu$ electron NC elastic scatters (ES)
0k	$\bar{\nu}_\mu$ electron CC quasi-elastic scatters (WSIMD)

Neutrino neutral current (NC) scattering is an ideal probe for new physics. An experiment like NuSOnG is unique in its ability to test the NC couplings by studying scattering of neutrinos from both electrons and quarks. A deviation from the Standard Model predictions in both the electron and quark measurements would present a compelling case for new physics. In fact, NuTeV did see an enticing  $3\sigma$  discrepancy in the measured weak mixing angle,  $\sin^2 \theta_W$ , from NC  $\nu$ -nucleon scattering with respect to the expectation from the Standard Model. This could be a first indication of new physics effects or uncertainties in Standard Model assumptions such as the strange-quark sea, next-to-leading order effects, or isospin violation in the nucleon. NuSOnG should be able to constrain these uncertainties by making more precise structure function measurements.

Of particular importance are the purely leptonic processes, ES and IMD, since the quark distribution and strong interaction model uncertainties are eliminated. By taking the ratio of the measured cross sections for these two processes, many of the systematic uncertainties associated with the neutrino flux cancel. From the studies reported in Ref. [2], NuSOnG should be able to measure  $\sin^2 \theta_W$  with an uncertainty of between 0.4% to 0.7% which should be compared to the best current measurement by the CHARM II collaboration of 3.5%. It is also expected that NuSOnG will be able to measure  $\sin^2 \theta_W$  from  $\nu$ -nucleon scattering using the Paschos-Wolfenstein method as in NuTeV where  $(\sigma_{NC}^\nu - \sigma_{NC}^{\bar{\nu}})/(\sigma_{CC}^\nu - \sigma_{CC}^{\bar{\nu}}) \approx \rho^2(\frac{1}{2} - \sin^2 \theta_W)$ . The expected reduction of the systematics in NuSOnG as mentioned above should allow a measurement of  $\sin^2 \theta_W$  at the 0.2% to 0.4% level as compared to the current 0.7% measurement from NuTeV.

New physics sources can be parameterized in several ways. For example, new physics associated with a new heavy  $Z'$  bosons, oblique corrections from heavy particles, or neutrino mixing with new sterile neutrinos can be parameterized in terms of a scale,  $\Lambda$ , and the left versus right handed coupling angle,  $\theta$ . The NuSOnG ES measurement would be sensitive to these new physics signals for  $\Lambda$  values less than about 4 TeV over the full  $\theta$  range[2].



**Figure 3.** The NuSONG expectations for two example new physics examples displayed in terms of S-T variable constraints. a) The case of a TeV-scale triplet leptoquark. b) The case of new physics in the neutrino sector but with LHC seeing a Standard Model Higgs and no evidence of new physics.

For models of new physics in which the dominant loop corrections are vacuum polarization corrections to the gauge boson propagators (“oblique” corrections), the S-T parameterization of Peskin and Takeuchi[3] provides a convenient framework in which to describe the effects of new physics on precision electroweak data. Through this analysis, the NuSONG experiment will provide complementary information to LHC on new physics signals. Rather than generalize, we illustrate the power of NuSONG with two specific examples. In the first example, we extend the Standard Model to include a nondegenerate  $SU(2)_L$  triplet leptoquark with mass in the 0.5-1.5 TeV range. LHC observation of these leptoquarks will provide information on their mass but not about their couplings to fermions. In this example as shown in Fig. 3a), NuSONG would find that the NuTeV anomaly could not be explained by Standard Model effects such as isospin violation and the strange sea and, thus, must be a result of new physics. Further, NuSONG’s measurement of  $g_L^2$  will then provide a sensitive measurement of the leptoquark couplings when combined with the LHC mass measurements as inputs. A second example illustrates the case where the LHC observes a Standard Model Higgs and no signatures of new physics whereas NuSONG confirms the NuTeV anomaly and measures an ES rate that is also anomalous with respect to LEP as shown in Fig. 3b). In this scenario, the only explanation would be new physics unique to neutrino interactions.

In summary, NuSONG will be unique among present and planned experiments for its ability to probe neutrino couplings for Beyond Standard Model physics. The conclusion of our studies is that a new neutrino experiment, such as NuSONG, would substantially enhance the presently planned Terascale physics program.

## References

- [1] The NuSONG Expression of Interest is available from the Fermilab Directorate or at <http://www-nusong.fnal.gov>
- [2] T. Adams *et al.* [NuSONG Collaboration], “Terascale Physics Opportunities at a High Statistics, High Energy Neutrino Scattering Experiment: NuSONG,” arXiv:0803.0354 [hep-ph].
- [3] M. E. Peskin and T. Takeuchi, Phys. Rev. D 46, 381 (1992), Phys. Rev. Lett. 65, 964 (1990).