Neutrino Scattering on Glass: NuSOnG

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Abstract.
These proceedings describe the physics goals and initial design for a new experiment: NuSOnG – Neutrino Scattering On Glass. The design will yield about two orders of magnitude higher statistics than previous high energy neutrino experiments, observed in a detector optimized for low hadronic energy and electromagnetic events. As a result, the purely weak processes $\nu_\mu + e^- \rightarrow \nu_\mu + e^-$ and $\nu_\mu + e^- \rightarrow \nu_e + \mu^-$ (inverse muon decay) can be measured with high accuracy for the first time. This allows important precision electroweak tests and well as direct searches for new physics. The high statistics also will yield the world’s largest sample of Deep Inelastic (DIS) events for precision parton distribution studies.

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This talk summarized the motivation for a new high energy, ultra-high statistics neutrino experiment at Fermilab: NuSOnG (Neutrino Scattering On Glass). The idea for this experiment arises from the work of 27 physicists [1] who are the authors of an Expression of Interest [2] (EOI), submitted to the Fermilab directorate. The high statistics and high energy of NuSOnG leads to wide-ranging physics opportunities that fall into three broad categories: 1) Indirect searches for new physics at the Terascale, 2) Direct searches for new physics at GeV energies and 3) Studies of parton distributions and nuclear effects. Here we provide some examples of what can be accomplished in each area.

The beam and detector design marry the best aspects of the NuTeV [3] and Charm II [4] experiments. We propose a 3500 ton (3000 ton fiducial volume) SiO$_2$ neutrino detector with sampling calorimetry, charged particle tracking, and muon spectrometers. The detector consists of four identical subdetectors, which are separated by regions allowing exotic particle decay and also calibration beams. The design is illustrated in Fig. 1, which shows a GEANT4 [5] simulation of a deep inelastic (DIS) interaction. This detector would run as a part of a Tevatron Fixed Target Program in the mid-2010’s. The initial neutrino energy distribution is identical to the NuTeV experiment [3], as shown in Fig. 2. A challenging technical aspect of the experiment is the required Tevatron protons-on-target (POT) rate, which is $4 \times 10^{19}$ POT/year [6].

An important aspect of achieving these goals is that the neutrino flux can be well measured. The energy dependence of the flux is well determined by the “low y” method used by many neutrino experiments [7,8]. Because the flux lies above 12 GeV, which is the threshold for inverse muon decay (IMD), the IMD events, which are well-predicted by the Standard Model, can provide the normalization. This is the first experiment to have sufficient IMD events to be able to use this method to obtain a precision measurement of the absolute flux. We assume a flux error of 0.5%.

As with any experiment in the design phase, the NuSOnG group is exploring options for run-modes. At NuFACT07 and in the EOI, we presented a plan which obtained equal statistics (20k events each) for $\nu_\mu$-electron and $\bar{\nu}_\mu$-electron scattering. In the interim, we have found that a stronger physics case, for the same POT, is made with substantially more running in neutrino than antineutrino mode. In this proceedings, expectations are reported assuming $1.5 \times 10^{20}$ protons on target in neutrino mode and $0.5 \times 10^{20}$ protons on target in antineutrino mode. This yields:

- $600M \nu_\mu$ CC Deep Inelastic Scattering
- $190M \nu_\mu$ NC Deep Inelastic Scattering
- $75k \nu_\mu$ electron NC elastic scatters
- $700k \nu_\mu$ electron CC quasielastic 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
- $0k \bar{\nu}_\mu$ electron CC quasielastic scatters

INDIRECT SEARCHES FOR NEW PHYSICS AT TEV SCALES

Indirect searches are those where new physics is identified by comparing NuSOnG measurements to those from other experiments. As one example, the EOI describes precision measurement of the NC couplings, which, when compared with the LEP invisible $Z$-width measurements, can open a unique window on new physics. Here we consider the “classic example” for neutrino scattering — comparison of electroweak measurements of $\sin^2 \theta_W$. 
At present, a 3σ deviation is observed between measurement of $\sin^2 \theta_W$ in neutrino DIS scattering from NuTeV [9] and the LEP/SLD $e^+e^-$ results [10]. This discrepancy is consistent with past measurements from neutrino experiments, which show a systematic shift from the Standard Model. However the small errors of NuTeV make this result much more significant. The NuTeV electroweak measurement was presented at NuFACT07 by Kevin McFarland, and will be described in detail in his contribution to these proceedings.

NuSOnG will measure $\sin^2 \theta_W$ in two ways: through the ratio of $\nu_e$-electron elastic scattering (veES) to IMD events and through the Paschos-Wolfenstein (PW) technique which exploits ratios of DIS NC and CC scattering. The former technique, which has the virtue of being a purely leptonically measurement, is new. Past neutrino-electron scattering experiments measuring $\sin^2 \theta_W$ have been at low energies and thus could not normalize to IMD. The latter technique was employed by NuTeV. NuSOnG expects to improve on the experimental errors which were published by NuTeV by about a factor of two [2], with much of this improvement coming from the increased statistics.

NuSOnG will also be able to address the two most viable “standard model” explanations of the NuTeV anomaly; the strange sea asymmetry and isospin violation [11]. The strange sea asymmetry will be constrained by accurate measurement of dimuon production in $\nu$ and $\bar{\nu}$ running modes, as well as an in-situ emulsion-based measurement of the semi-leptonic branching ratio to charm. The level of isospin violation can be constrained by the high-statistics measurement of $\Delta x F_3$ (discussed below).

The NuSOnG experiment provides complementary information to LHC. Rather than generalize, to illustrate the power of NuSOnG, two specific examples are given here. We emphasize that these are just two of a wide range of examples, but they serve well to demonstrate the point.

First, consider a heavy $Z'$ which is in the $B - xL$ family – a case of interest because this is an anomaly free extension of the Standard Model [12]. We will consider a 3 TeV $Z'$ which couples to $B - 3L_\mu$. This is one explanation of the NuTeV anomaly [13, 14]. In this case, the LHC will see $Z' \rightarrow \mu\mu$ channel, and measure and $\lambda_{FB}$, but not the width, due to resolution. The absence of the $ee$ channel will be clear but absence of the $\tau\tau$ channel will only be surmised after very high statistics are obtained. Among the quark channels, the one which is reconstructable is $tt$. In this scenario, NuSOnG would find that isospin and the strange sea can be constrained to the point that they do not provide an explanation for the NuTeV anomaly, thus NuTeV is the result of new physics. The NuSOnG PW measurement of $\sin^2 \theta_W$ will agree with NuTeV, and the veES measurement will agree with LEP. Fig. 3(left) illustrates this example. The complementary information from NuSOnG is needed to narrow the options to the $B - 3L_\mu$ coupling.

A second example is the existence of a fourth generation family. A fourth family with non-degenerate masses (i.e. isospin violating) are allowed within the LEP/SLD constraints [15]. As a model, we choose a fourth family with mass splitting on the order of $\sim 75$ GeV and a 300 GeV Higgs. This is consistent with LEP at 1σ and perfectly consistent with $M_\mu$, describing the point (0.2,0.19) on the ST plot [16]. In this scenario, LHC will measure the Higgs mass from the highly enhanced $H \rightarrow ZZ$ decay [15]. An array of exotic decays which will be difficult to fully reconstruct, such as production of 6 W’s and 2 b’s, will be observed at low rates. The expected NuSOnG result in this scenario is that the strange sea or isospin violation will explain the NuTeV anomaly, and that the corrected NuTeV PW result will agree with the NuSOnG PW and veES measurements. These three precision neutrino results, all with “LEP-size” errors, can be combined and will intersect the one-sigma edge of
the LEP measurements. Fig. 3(right) illustrates this example. From this, the source, a fourth generation with isospin violation, can be demonstrated.

**DIRECT SEARCHES FOR NEW PHYSICS**

NuSOnG is also designed to perform a range of direct searches for new physics. The segmented detector design, which was driven by the need to bring a calibration beam into each segment of the detector, also allows for a decay region in which one can search for decays of neutral heavy leptons in the mass ranges of a 10’s of MeV to multi-GeV. The design of the detector also allows for direct searches for new physics through neutrino interactions in the detector which are outside of the SM predictions. Two examples of this, which are considered here in detail, are wrong-sign inverse muon decay and observation of an excess of very high energy neutrino interactions.

In considering the list of processes which NuSOnG can observe (see above), “wrong-sign IMD” (WSIMD) was explicitly listed as resulting in zero events. In the Standard Model, the interaction $\bar{\nu}_\mu + e^- \rightarrow \bar{\nu}_\mu + e^+$ cannot occur, since it violates lepton family number conservation ($\Delta L_e = -\Delta L_\mu = 2$). A number of theories beyond the Standard Model predict that lepton flavor number is not a true conserved quantum number; this means that processes that violate lepton flavor are allowed to occur. Theories which incorporate multiplicative lepton number conservation \cite{17,18}, left-right symmetry \cite{19}, or the existence of bileptons \cite{20} fall under this category.

In principle, the observation of a single muon with no hadronic energy in antineutrino mode is a direct signature of new physics. In practice there are backgrounds from $\nu_\mu$ contamination in the $\bar{\nu}_\mu$ beam, $\nu_\tau$ contamination and charge misidentification of candidate muons. With these backgrounds in mind, NuSOnG is designed to improve the limit on WSIMD by an order of magnitude from the present level \cite{21}. If we assume a conservative knowledge of the backgrounds at the 5% level, this would imply a limit on the lepton number violation cross-section ratio of better than 0.2% (at 90% C.L.) for V-A couplings and less than 0.06% for scalar couplings. Previous searches, based on $1.6 \times 10^{18}$ protons on target and smaller target masses, have placed limits on this cross-section ratio to less than 1.7% at 90% C.L. for V-A couplings and less than 0.6% for scalar couplings \cite{21}.

In fact, the best argument for searching for new lepton flavor violating effects arises from the experimental observation of neutrino oscillations, which explicitly violates lepton flavor. This describes the conversion of neutrino flavors as a function of time via a $3 \times 3$ mixing matrix. In most analyses, this matrix is assumed to be unitary. However new physics at high energy scales can induce nonunitarity in this matrix.

Nonunitarity, or “Matrix Freedom,” introduces striking changes to the probability formula for neutrino flavor transitions. The level at which unitarity is violated can be defined as $X_\alpha$, where

$$\sum_j |U_{\alpha j}|^2 = 1 - X_\alpha,$$

with $X_\alpha$ being small. One of the main consequences of such a scenario is instantaneous ($L = 0$) flavor transitions in a neutrino beam. Extending the argument of ref. \cite{22}, the non-orthogonality of $\nu_\mu$ and $\nu_e$ results in an instantaneous transition at $L = 0$ from $\nu_\mu$ to $\nu_e$ \cite{23}. Thus one could observe an excess of $\nu_e$ events in a pure $\nu_\mu$ beam. Similarly, a $\nu_\mu$ to $\bar{\nu}_e$ transition at $L = 0$, then a subsequent $\bar{\nu}_e + e^- \rightarrow \nu_\mu + \mu^-$ interaction will produce a WSIMD signal in NuSOnG.

From \cite{22}, the limits on $\nu_\mu \rightarrow \nu_e$ instantaneous transition are at the $\sim 1 \times 10^{-4}$ level, and arise from physics above the EW scale which would be apparent in corrections to decay rates. This is at the edge of NuSOnG capability, but may be observable depending on the control of the systematics. However, these limits are not applicable if the nonunitarity arises due to an effect such as the existence of a “neutissimo” -- a $\sim 100$ GeV neutral heavy lepton -- which mixes with the light neutrinos and thereby affects the apparent coupling. In this case, NuSOnG has substantial allowed range for its search. Note that this WSIMD signature can only be observed in a high energy beam such as at NuSOnG because the threshold for muon production is 12 GeV.

An alternative method to search for this effect is to look for $\nu_e$ appearance in an energy range with low, and well-constrained, intrinsic $\nu_e$ background. In the case of NuSOnG, this is on the high energy tail of the flux, above $\sim 200$ GeV. For the $\sim 1 \times 10^{-4}$ level limit on $\nu_\mu$ transformation to $\nu_e$ quoted in \cite{22}, NuSOnG would see an excess of $\sim 200$ $\nu_e$ events in this high energy region and a 10% increase in flux for $E \sim 350$ GeV. In that region, the $\nu_e$ flux is mainly from $K^+$ decay, which is well constrained by the $K^+$-produced $\nu_\mu$ events. Such an excess should therefore be straightforward to observe. An observation of this excess in both this mode and as WSIMD would be a very striking signature for this effect.

**PARTON DISTRIBUTION STUDIES**

NuSOnG also will study parton distributions and nuclear effects to high precision. Comparison of our result to the charged lepton scattering data can provide clues to the sources of the major features which appear in nuclear
effects: shadowing, antishadowing, and the EMC effect. Present data suggest nuclear corrections for the ν and Π cross sections which differ from expectation. In order to investigate this, NuSOng will include targets of C, Al, Fe, and Pb, as well as SiO2. This study will complement results of Minerva and eRHIC.

The high statistics and isoscalarity allows measurement of structure function combinations which are so far poorly constrained. Among these is the precision measurement of \( \Delta xF_3 = xF^\prime_3 - xF^\nu_3 \), which provides sensitivity to isospin violation. The sensitivity arises from residual u,d,d-contributions. The effect is amplified compared to the s and c contributions because \( d \rightarrow u \) transitions are not subject to slow-rescaling corrections which strongly suppress the \( s \rightarrow c \) contribution to \( \Delta xF_3 \). The ability of NuSOng to separately measure \( xF^\nu_1 \) and \( xF^\nu_3 \) over a broad kinematic range, and with better high-y acceptance than NuTeV/CCFR, will provide powerful constraints on the sensitive structure function combination \( \Delta xF_3 \).

**SUMMARY**

These proceedings have covered some highlights of the measurements which could be made at a new high-statistics, high-energy neutrino scattering experiment, called NuSOng. The goal is to obtain a high statistics sample of well reconstructed νμ electron scatters, as well as νDIS events, leading to physics opportunities in the area of electroweak precision measurement, direct searches and QCD studies.

**REFERENCES**

1. T. Adams, L. Bugel, J.M. Conrad, P.H. Fisher, J.A. Formaggio, A. de Gouvêa, W.A. Loinaz, G. Karagiorgi, T.R. Kobilarov, S. Kopp, G. Kyle, D.A. Mason, R. Milner, J. G. Morfin, M. Nakamura, D. Naples, P. Nienaber, F.I Olness, J.F. Owens, W.G. Seligman, M.H. Shaevitz, H. Schellman, M.J. Syphers, C.Y. Tan, R.G. Van de Water, R.K. Yamamoto, G.P. Zeller

2. The Expression of Interest is available at [http://www.nusong.fnal.gov](http://www.nusong.fnal.gov)

3. J. Yu et al., "NuTeV SSQT Performance"; FERMILAB-TM-2040, February 1998

4. K. De Winter et al., [CHARM-II Collaboration], Nucl. Instrum. Meth. A 278, 670 (1989).

5. S. Agostinelli et al., Nucl. Instrum. Meth. A506, 250 (2003).

6. M. Syphers, “Discussion of Tevatron Options After Run II,” written for the Fermilab AAC, private communication.

7. M. Tzanov et al., [NuTeV Collaboration], Int. J. Mod. Phys. A 20, 3759 (2005).

8. D. Naples, talk given at NuINT07.

9. G. P. Zeller et al., Phys. Rev. Lett., 88 091802, 2002.

10. [http://lepewwg.web.cern.ch/LEPEWWG/](http://lepewwg.web.cern.ch/LEPEWWG/)

11. See article by K. McFarland in these proceedings.

12. K. De Winter et al., [CHARM-II Collaboration], Nucl. Instrum. Meth. A 278, 670 (1989).

13. W. Loinaz and T. Takeuchi, Phys. Rev. D 60, 115008 (1999) [arXiv:hep-ph/9903362].

14. S. Davidson, J. Phys. G 29, 2001 (2003) [arXiv:hep-ph/0209316].

15. G. D. Kribs, T. Plehn, M. Spannowsky and T. M. P. Tait, [arXiv:0706.3718 [hep-ph]].

16. G. D. Kribs and T. Tait, private communication.

17. G. Feinberg and S. Weinberg, Phys. Rev. Lett. 6, 381 (1961)

18. A. Ibarra, E. Masso, and J. Redondo, Nucl. Phys. B 715, 523 (2005) [arXiv:hep-ph/0410386].

19. P. Herczeg and R. N. Mohapatra, Phys. Rev. Lett. 69, 2475 (1992).

20. S. Godfrey, P. Kalyniak, and N. Romanenko, Phys. Rev. D 65, 033009 (2002) [arXiv:hep-ph/0108258].

21. J. A. Formaggio et al., [NuTeV Collaboration], Phys. Rev. Lett. 87, 071803 (2001) [arXiv:hep-ex/0104029].

22. S. Antusch et al., [arXiv:hep-ph/0607020].

23. Boris Kayser, Private Communication.

24. J. F. Owens et al., Phys. Rev. D 75, 054030 (2007) [arXiv:hep-ph/0702159].

25. S. A. Kulagin and R. Petti, Nucl. Phys. A 765, 126 (2006) [arXiv:hep-ph/0412425].

26. S. Kretzer, F. I. Olness, R. J. Scalise, R. S. Thorne, and U. K. Yang, Phys. Rev. D 64, 033003 (2001) [arXiv:hep-ph/0101088].