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Neutrino Scattering at High Energies

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Abstract.

The construction of a high energy (~ 100 GeV), sign-selected neutrino beam opens exciting opportunities to search for beyond-standard-model physics as well as to make valuable QCD measurements. Such a beam can be produced at the Tevatron or, potentially, at the CERN SPS+. The resulting physics would be unique and complementary to the present neutrino program. Here we use neutrino-electron scattering as an example.

Keywords: Neutrino interactions; Neutrino detectors

PACS: 12.15.-y, 12.15.Ji, 12.15.Mm, 12.38.Qk, 12.60.Cn, 13.15.+g

As demonstrated by the FutureTeV Study [1], there is substantial interest in a revival of a high energy fixed target program fed by ~ 1 TeV protons on target. The motivation is beyond-standard-model studies that are complementary to the presently approved plan and have high discovery potential [1]. Two TeV-scale proton sources are potentially available in the near future: 1) the existing Tevatron at Fermilab, which can provide 800 GeV protons for fixed target physics; and 2) SPS+, a possible upgrade to the SPS at CERN, which could impinge 1 TeV protons on target.

An important component of this fixed target program would be a high energy neutrino source which can feed a general-design scattering experiment as well as specialized experiments to study ν_τ physics and search for neutrinos (neutral heavy leptons in the 100 GeV range). In this proceeding, we examine one example of this interesting neutrino program: the NuSONG experiment. For a more general review of the neutrino opportunities including and beyond NuSONG, the reader is referred to ref. [1].

THE NUSONG DESIGN

NuSONG is a general-design neutrino scattering experiment. The primary motivation is to search for beyond-standard-model physics in the channel: $\nu_\mu + e \rightarrow \nu_\mu + e$. However, many other physics opportunities are also available, as described in refs. [2, 3].

Neutrino-electron scattering is an ideal process to search for beyond the Standard Model physics at Terascale energies through precision electroweak measurements. The physics reach of NuSONG through this process is in the 1 to 7 TeV range, depending on the model. The sensitivity to new physics complements the LHC and brings unique new opportunities to the program [2].

The low cross section for this process demands a very high intensity beam. In order to reduce systematics and reach precision better than 1% on this cross section, this process can be normalized to “inverse muon decay” ($\nu_\mu + e \rightarrow \nu_e + \mu$), which has a threshold of 11 GeV. Thus the experiment requires a high energy neutrino flux, as can only be provided by a ~ 1 TeV proton primary beam.

As a straw-man design, we use the NuTeV experiment beam, which ran from 1993-1996 at the Fermilab Tevatron [4, 5]. We assume 2×10^{20} high energy protons impinge on a beryllium oxide target. The resulting mesons are focused and bent in a quadrupole-focused, sign-selected magnetic beamline. NuSONG will run with 1.5×10^{20} p.o.t. in neutrino mode, and 0.5×10^{20} p.o.t. in antineutrino mode. The result is a beam of high “right sign” purity ($> 98\%$) and low ν_e contamination (2%).

The baseline design for the NuSONG detector is a 3.5 kton glass-target. The detector is broken into four identical subdetectors, each consisting of a target followed by a muon spectrometer. The total target is composed of 2500 sheets of glass which are 2.5 cm ($0.25 \lambda_0$) thick. This provides an isoscalar target for neutrino-quark interaction studies. Interspersed between the glass sheets are proportional tubes or scintillator planes. The total target mass is six times greater than NuTeV.

The signal processes are: $\nu_\mu + e \rightarrow \nu_\mu + e$ and $\nu_\mu + e \rightarrow \mu + \nu_e$. These must be distinguished from the background processes of $\nu_e + n \rightarrow e + p$ and $\nu_\mu + n \rightarrow \mu + p$. These processes become background for certain kinematic cases when the proton is not detected. For the sensitivity studies in the baseline design, a large systematic error comes from events where wide-angle or low-energy proton are lost in the glass. An alternative LArTPC design addresses this problem. LArTPCs are a fully-live alternative in which the proton signature in background events is easily identified. A 2 kton LArTPC detector has similar sensitivity to the 3.5 kton glass NuSONG detector. An LArTPC would require substantially less elec-

TABLE 1. Rates for NuSOnG assuming 2×10^{20} protons on target. NC indicates “neutral current” and CC indicates “charged current.”

600M	ν_μ CC Deep Inelastic Scattering
190M	ν_μ NC Deep Inelastic Scattering
75k	ν_μ electron NC elastic scatters (ES)
700k	ν_μ 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)

tronics than the glass detector, and should be proportionately less expensive.

The expected rates for the baseline design are given in table 1. The neutrino electron scattering sample is 40 times that of previous experiments. In the process of obtaining this large sample, NuSOnG would collect samples of other types of neutrino scatters which are orders of magnitude larger than past experiments. This opens up a wide range of opportunities beyond the neutrino-electron scattering study discussed below.

NEUTRINO-ELECTRON SCATTERING – AN EXAMPLE

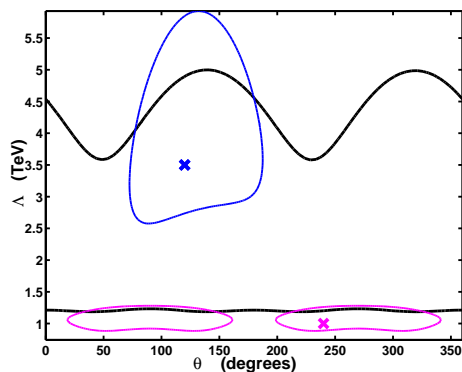


FIGURE 1. 95% confidence level sensitivity of NuSOnG to new heavy physics described by Eq. (1) when $\nu_\alpha = \nu_\mu$ (higher curve) and $\nu_\alpha \neq \nu_\mu$ (lower curve). (Closed curves show a NuSOnG measurement at 95% level, assuming $\nu_\alpha = \nu_\mu$, $\Lambda = 3.5$ TeV and $\theta = 2\pi/3$ (higher, solid contour) and $\nu_\alpha \neq \nu_\mu$, $\Lambda = 1$ TeV and $\theta = 4\pi/3$ (lower, dashed contour).

Neutrino-electron scattering is a purely leptonic electroweak process that provides a very clean probe of physics beyond the standard model. There are a number of ways to use this process to explore for new physics. At NuFACT07, we reported [6] sensitivity to oblique corrections through comparison of measurements of the Peskin-Takeuchi parameters, S and T . Here we consider sensitivity to point-like 4-fermion interactions, which are

manifested by a change of cross section as well as modification of angular distribution of the outgoing electron.

The effect of new, heavy ($M_{\text{new}} \gg \sqrt{s}$) interactions to $\nu_\mu e^- \rightarrow \nu_\alpha e^-$, where $\alpha = e, \mu, \tau$ can be parameterized by the effective Lagrangian

$$\mathcal{L}_{\text{NSI}}^e = + \frac{\sqrt{2}}{\Lambda^2} \left[\bar{\nu}_\alpha \gamma_\sigma P_L \nu_\mu \right] \left[\cos \theta \bar{e} \gamma^\sigma P_L e + \sin \theta \bar{e} \gamma^\sigma P_R e \right]. \quad (1)$$

The mass scale of the new interaction is described by Λ , while $\theta \in [0, 2\pi]$ indicates whether the new force interacts with right-chiral or left-chiral electrons, or a mix. The new physics contribution interferes constructively or destructively with the standard model process (Z -boson t -channel exchange) in the case $\alpha = \mu$. Fig. 1 shows sensitivity to Λ as a function of θ for $\alpha = \mu$ or $\alpha \neq \mu$ assuming the NuSOnG neutrino-electron scattering data sample is consistent with standard model expectations. The figure also illustrates NuSOnG’s 2σ measurement capability for an example observed discrepancy. The results are competitive in reach to LHC, but complementary, since these interactions will be quite difficult to observe at LHC.

CONCLUSION

A set of next-generation high energy neutrino experiments would provide rich and unique data-sets. This paper has illustrated the potential by focusing on neutrino-electron scattering in a detector of very general design, called NuSOnG. Smaller and more specialized experiments are also well motivated, including searches for beyond-standard-model physics manifested as non-standard ν_τ interactions or neutrissimo production.

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