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NuSOnG: A High-Statistics, High-Energy Neutrino Scattering Experiment

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The NuSOnG experiment is a proposal for a next-generation high-statistics, high-energy neutrino scattering experiment using an external proton beam, possibly at Fermilab or CERN, to create a high-energy sign-selected neutrino beam. The NuSOnG experiment would have the potential to make much improved electroweak and QCD precision measurements along with direct searches for new physics. The precision measurements would probe the Standard Model and Beyond the Standard Model physics in the neutrino sector complementing results from LEP/SLC and new physics searches at the LHC.

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1. Introduction

A next-generation high-statistics, high-energy neutrino scattering experiment would allow to make electroweak and QCD measurements with unprecedented statistics. The precision measurements would probe the Standard Model (SM) and physics Beyond the Standard Model (BSM) in the neutrino sector complementing results from LEP/SLC and new physics searches at the LHC. In addition to indirect searches several direct searches of new physics (NP) could be performed.

The NuSOnG (Neutrino Scattering on Glass) experiment is a proposal for such a future fixed-target neutrino experiment with Terascale energies running at the Tevatron at Fermi National Accelerator Laboratory and an expression of interest has been submitted to Fermilab [1]. The physics case of the NuSOnG experiment has been studied in detail in Ref. [2]. This talk will focus on the electroweak and QCD precision measurements. For an overview of model-independent and model-dependent constraints on various NP scenarios see [3] and Tabs. V, VI in [2].

2. Experimental Design

The beam design is based on the one used by the NuTeV experiment, which used 800 GeV protons from the Tevatron on target. The event rates quoted below in Sec. 3 assume twenty times more protons on target (POT) per year for NuSOnG as compared to NuTeV. The very pure beam flux is ideal for the physics case for several reasons: (i) There is essentially no flux below 30 GeV which is crucial for a very clean measurement of the weak mixing angle in the leptonic sector using the ratio $R_{\mathrm{ES/IMD}}$ of neutral current elastic scattering (NC ES) to charged current quasi-elastic scattering (CC QE) as discussed below. The latter process is also called 'inverse muon decay' (IMD) and has its production threshold at about 10.9 GeV requiring a high energy neutrino beam to obtain a high statistics sample of these events. (ii) The beam is sign selected, i.e. one can switch between neutrino and anti-neutrino mode, which is essential for a Paschos-Wolfenstein (PW) type measurement of the weak mixing angle in the hadronic sector.

The optimal detector is a fine-grained calorimeter for electromagnetic shower reconstruction followed by a toroid muon spectrometer in order to measure the energy of the outgoing electrons and muons with excellent resolution. These requirements are met by a Charm II style design, which uses a glass target calorimeter followed by a toroid. To obtain large event samples the detector is designed to be very massive with about six times the mass of the CHARM II detector. The detector may also incorporate specialized regions like a fine vertex-tracking and will have alternative target materials (C, Al, Fe, Pb) interspersed which is useful to better control the systematics of the QCD measurements due to nuclear effects.

3. Measurements

NuSOnG will measure cross sections of the following processes:

- NC ES: $\nu_\mu + e^- \to \nu_\mu + e^-$ [75k] , $\bar{\nu}_\mu + e^- \to \bar{\nu}_\mu + e^-$ [7k]
- CC QE (IMD): $\nu_\mu + e^- \to \mu^- + \nu_e$ [700k]
- NC DIS: $\nu_\mu + q \to \nu_\mu + X$ [190M] , $\bar{\nu}_\mu + q \to \bar{\nu}_\mu + X$ [12M]

- CC DIS: $\nu_\mu + q \to \mu^- + X$ [600M] , $\bar{\nu}_\mu + q \to \mu^+ + X$ [33M]

The numbers in brackets are the expected event rates after 5 years of running. This sample can be compared to past experiments. The present highest statistics sample for ν_μ and $\bar{\nu}_\mu$ ES is from CHARM II, with 2677±82 events in neutrino mode and 2752±88 events in antineutrino mode. Thus the proposed experiment will have a factor of 30 (2.5) more $\nu(\bar{\nu})$-electron events. Therefore, this provides a unique opportunity for electroweak precision measurements using the leptonic channels (NC ES, CC QE). In the hadronic sector, the 600M + 190M deep inelastic scattering (DIS) events in the neutrino mode and the 33M + 12M DIS events in the anti-neutrino mode are orders of magnitude more than what NuTeV had after minimal cuts to isolate DIS events (1.62M in neutrino mode and 0.35M in anti-neutrino mode).

4. EW precision observables

Electroweak precision observables serve as tests of the Standard Model (SM). At the same time they pose strong constraints on any new physics model which has to be consistent with these measurements. NuSOnG can contribute precision measurements in the neutrino sector, both with leptonic and hadronic processes thereby complementing results from the e^+e^-–colliders LEP and SLC. Usually, the results are presented in form of ratios in which many systemtics effects cancel.

4.1 Leptonic observables

A standard observable is the ratio of NC ES neutrino and anti-neutrino integrated cross sections,

$$R_{\nu/\bar{\nu}} = \frac{\sigma(\nu_\mu e)}{\sigma(\bar{\nu}_\mu e)} = 3\frac{1 - 4s_w^2 + \frac{16}{3}s_w^4}{1 - 4s_w^2 + 16s_w^4}\,, \tag{4.1}$$

which has been used in the past to determine the sine of the weak mixing angle, $s_w = \sin\theta_w$. This method is accessible at low and high neutrino energies but has the disadvantage that the neutrino and anti-neutrino fluxes do not exactly cancel in the ratio. A high-statistics, high-energy neutrino flux offers the unique possibility to precisely study the ratio of NC ES to CC QE (IMD) in the neutrino mode which is given by

$$R_{\mathrm{ES/IMD}} = \frac{\sigma(\nu_\mu e)}{\sigma(IMD)} = \rho^2 \left[\frac{1}{4} - s_w^2 + \frac{4}{3}s_w^4\right] \left(1 - \frac{m_\mu^2}{2m_e E_\nu}\right)^{-2} . \tag{4.2}$$

This ratio has several interesting features: (i) In contrast to $R_{\nu/\bar{\nu}}$ the fluxes in the numerator and denominator cancel exactly. (ii) The ρ-parameter which is sensitive to new physics is not canceled. (iii) The IMD process is very well determined in the SM being the inverse of muon decay. Such a measurement is only possible with a *high-energy neutrino flux* due to the IMD threshold. The expressions given above are valid at tree level. For a review of radiative corrections to the ES and IMD processes see Ref. [4].

4.2 Hadronic observables

Hadronic observables have the advantage of much higher statistics. On the other hand, they have larger systematic uncertainties due to the hadrons/nuclei involved. The following ratios of

DIS events can be formed:

$$R^{\nu} = \frac{\sigma^{\nu}_{\rm NC}}{\sigma^{\nu}_{\rm CC}} \simeq g_L^2 + r g_R^2 \quad , \quad R^{\bar\nu} = \frac{\sigma^{\bar\nu}_{\rm NC}}{\sigma^{\bar\nu}_{\rm CC}} \simeq g_L^2 + \frac{1}{r} g_R^2 \quad , \quad r = \frac{\sigma^{\bar\nu}_{\rm CC}}{\sigma^{\nu}_{\rm CC}} \tag{4.3}$$

with

$$g_L^2 = \rho^2 \left(\frac{1}{2} - s_w^2 + \frac{5}{9} s_w^4\right) \quad , \quad g_R^2 = \rho^2 \left(\frac{5}{9} s_w^4\right) \tag{4.4}$$

effective left- and right-handed neutrino–quark couplings.

R^{ν} and $R^{\bar\nu}$ can be combined to compute the Paschos-Wolfenstein [5] ratio:

$$R^{-} = \frac{\sigma^{\nu}_{\rm NC} - \sigma^{\bar\nu}_{\rm NC}}{\sigma^{\nu}_{\rm CC} - \sigma^{\bar\nu}_{\rm CC}} = \frac{R^{\nu} - r R^{\bar\nu}}{1-r} \simeq g_L^2 - g_R^2 = \rho^2 \left(\frac{1}{2} - s_w^2\right) . \tag{4.5}$$

In R^- many systematics cancel to first order. Any new high-energy neutrino experiment has to compare with the NuTeV measurement which is in agreement with past neutrino scattering results (although these have much larger errors), however, in disagreement with the global fits to the electroweak data which give a Standard Model value of $\sin^2\theta_W = 0.2227$ [6]. A detailed study shows that a reduction of the NuTeV errors by a factor of two can be achieved (see Tab. IV in [2]).

4.3 Measurement goals

In this section the main goals for the electroweak precision measurements are summarized. NuSOnG aims at measuring the ratios $R_{\rm ES/IMD}$ with a 0.7% error and R^- with a 0.4% error, combining systematical and statistical errors in quadrature. In addition, the errors on the DIS effective couplings could be reduced by a factor 2: $\Delta g_L^2 = 0.0007$, $\Delta g_R^2 = 0.0006$. It should be noted that these numbers are based on conservative estimates. It is likely to obtain even better precision.

5. The physics reach of NuSOnG

5.1 Indirect probes of New Physics

As discussed in the previous sections, NuSOnG can make important electroweak precision measurements employing both neutrino-lepton and neutrino-hadron scattering. These results test the internal consistency of the SM in particular when combined with precision measurements from LEP/SLC. Conversely, any deviations from SM expectations would indicate new physics. At the same time, the precision observables place strong constraints on BSM physics scenarios which have to be consistent with the precision data. For a discussion of model-independent and model-dependent constraints on various NP scenarios see Refs. [2, 3].

5.2 QCD studies

As is well-known, (anti-)neutrino DIS cross section data are valuable for the separation of individual quark parton flavors. For this reason, the NuTeV and CCFR data have been included in global analyses of parton distribution functions (PDFs) inside protons. However, in order to determine proton PDFs, the data have to be corrected for nuclear effects. While the general pattern of nuclear effects seen in (anti-)neutrino DIS is similar to that seen in charged lepton DIS there are differences which are relevant for precise determinations of proton PDFs and the extraction of the weak mixing angle using the PW-style analysis [7, 8]. NuSOnG can provide a handle on the nuclear effects by performing high statistics measurements with several targets (SiO_2, C, Al, Fe, Pb). At the same time these data are of course useful for global analyses of *nuclear* PDFs.

NuSOnG can measure the DIS cross sections with about two orders of magnitude higher statistics than in the previous highest statistics experiments NuTeV and CCFR. This allows to study small effects like the strangeness asymmetry and isospin violation which need to be understood for a measurement of the PW-ratio R^- with 0.4% precision.

5.3 Direct searches of NP

The indirect searches of NP are complemented by direct searches of beyond the standard model physics with the NuSOnG detector. The searches fall into three broad classes: (i) Searches for new light neutrino properties which include evidence for non-unitarity of the neutrino mixing matrix. (ii) Interactions manifested through rare events, in particular, searches for inverse muon decay in antineutrino mode, $\bar{\nu}_\mu + e^- \to \mu^- + \bar{\nu}_e$, which is forbidden in the Standard Model. (iii) Searches for new particles observed through decays in the regions between the detector subsections. This includes searches for light neutrissimos, axion-like particles, dilation-like particles, light vector bosons, light inflatons, light radions, etc., which appear in models for BSM physics.

6. Conclusions

NuSOnG is a physics rich experiment. It can perform electroweak precision measurements of both leptonic and hadronic observables thereby testing the SM in the neutrino sector and providing constraints on new physics at the TeV scale which is complementary to results from LEP/SLC and new physics searches at the LHC. In addition, NuSOnG can make important QCD measurements which are useful, among others, for an improved determination of proton and nuclear PDFs which serve as input to LHC physics. Some of the QCD studies are also of direct importance for a measurement of the PW-ratio with 0.4% precision. This program is completed by the possibility of several direct searches for new physics.

References

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