PRECISION ELECTROWEAK MEASUREMENTS FROM NuTeV*

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The NuTeV experiment has extracted the electroweak parameter, $\sin^2\theta_W$, from the high precision measurement of the ratio of neutral-current to charged-current cross-sections in deep-inelastic neutrino and anti-neutrino scattering off a steel target. Our measurement, $\sin^2\theta_W^{\rm on-shell} = 0.2277 \pm 00013({\rm stat}) \pm 0.0009({\rm syst})$, is 3σ above the standard model prediction. We discuss the plausibility of the hypothesis that this discrepancy is due to unaccounted QCD effects, especially a strange and anti-strange sea asymmetry. Taking into account results from NuTeV, CCFR, and charged-lepton deep-inelastic cross-section measurements, we do not find support for this hypothesis.

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1. Introduction

In Deep Inelastic Scattering (DIS) of neutrinos off an isoscalar target consisting of massless, first generation quarks, the ratio of Neutral-Current (NC) to Charged-Current (CC) cross-sections can be written as [1]

$$R^{\nu(\bar\nu)} \equiv \frac{\sigma_{\rm NC}^{\nu(\bar\nu)}}{\sigma_{\rm CC}^{\nu(\bar\nu)}} = \left(g_{\rm L}^2 + r^{(-1)} g_{\rm R}^2\right), \tag{1}$$

where $r = \sigma_{\rm CC}^{\bar\nu}/\sigma^{\nu}$, and $g_{\rm L}^2 = 1/2 - \sin^2\theta_W + 5/9\sin^4\theta_W$, $g_{\rm R}^2 = 5/9\sin^4\theta_W$ are the left and right handed isoscalar quark couplings. Expression 1 is at tree level, and needs to be modified for heavy quark contributions, radiative, higher-twist, and longitudinal structure function effects, W and Z

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propagators, quark mixing, and non-isoscalar target, in order to represent neutrino DIS off a realistic target. In addition, it has to be corrected for experimental effects such as cuts, backgrounds, and detector acceptance and smearing. The largest contribution to the uncertainty on $\sin^2\theta_W$ comes from heavy quark production in the final state. It modifies the CC-cross-section due to the suppression of the production of charm from the target's strange sea. This uncertainty has limited the precision of previous measurements of electroweak parameters in ν DIS. It can be reduced by using a different observable

$$R^- \equiv \frac{\sigma^{\nu}_{\rm NC} - \sigma^{\bar\nu}_{\rm NC}}{\sigma^{\nu}_{\rm CC} - \sigma^{\bar\nu}_{\rm CC}} = \frac{R^\nu - rR^{\bar\nu}}{(1-r)} = g_{\rm L}^2 - g_{\rm R}^2\,, \tag{2}$$

one suggested by Paschos and Wolfenstein [2]. Under the assumption that the momentum distributions of sea quarks and anti-quarks of the same flavor are equal, and since $\sigma^{\bar\nu\bar q} = \sigma^{\nu q}$ and $\sigma^{\bar\nu q} = \sigma^{\nu\bar q}$, the effect of scattering off sea quarks cancels in the cross-section difference. The only remaining effect from charm production is the d-valence contribution, which is Cabibbo suppressed and at high fractional momentum x. For a neutrino DIS experiment to utilize R^-, separate ν and $\bar\nu$ beams are required, because unless the initial state of the interaction is known, there is no distinct signature in the final state to discriminate ν from $\bar\nu$ NC events.

2. The NuTeV measurement

The NuTeV experiment collected data with a sign-selected beamline, which allowed running with either ν or $\bar\nu$ beams. The NuTeV detector [3] consists of an iron/scintillator target calorimeter and an iron toroid spectrometer. Since CC events are on the average longer than NC events, because of the presence of a muon in the final state, NC and CC event candidates are identified based on event length. A Monte Carlo (MC) simulation is used to express the experimental ratios in terms of fundamental electroweak parameters. This procedure implicitly corrects for details of the neutrino cross-section, experimental effects, and backgrounds. The details of this measurement are described elsewhere [4].

Assuming the Standard Model (SM), NuTeV performs a single parameter fit to $\sin^2\theta_W$, and finds:

$$\begin{aligned}\sin^2\theta_W^{\rm (on-shell)} &= 0.2277 \pm 0.0013({\rm stat}) \pm 0.0009({\rm syst})\\ &\quad -0.00022\left(\frac{M_{\rm top}^2 - (175{\rm GeV})^2}{(50{\rm GeV})^2}\right)\\ &\quad +0.00032\,\ln\left(\frac{M_{\rm Higgs}}{150{\rm GeV}}\right).\end{aligned}$$

The residual dependence on M_{Higgs} and M_{top} are from leading terms in the one-loop electroweak radiative corrections to the W and Z self energies [5]. This result lies three standard deviations above the prediction from the global electroweak fit, 0.2227 ± 0.0004 [6]. In the next section we will discuss the plausibility of explanations of this discrepancy based on unaccounted QCD effects in our cross-section model.

3. QCD modeling effects

The NuTeV Monte Carlo uses a leading order (LO) model for the cross-section, augmented with longitudinal scattering and higher-twist terms. The LO parton distribution functions (PDFs) used in this model are obtained from fits to data from the same target and using the same model as in NuTeV [7]. We correct for the asymmetry of d and u quarks due to the $\sim 6\%$ fractional excess of neutrons over protons in our iron target. However, we assume isospin symmetry in the nucleon. If this assumption is incorrect, it could affect the extraction of $\sin^2\theta_W$. Similarly, large effects could arise if the strange sea is asymmetric. Estimations of such effects appear in the literature [8], but do not take into account the experimental effects in the determination of R^-. To examine the exact effect of the symmetry violations we define a functional $F[\sin^2\theta_W, \delta; x]$ [9], such that $\Delta\sin^2\theta_W = \int_0^1 F[\sin^2\theta_W, \delta; x]\delta(x)dx$ for any symmetry violation $\delta(x)$ in PDFs. Using the analysis of reference [9], it can be seen that the level of isospin asymmetry needed to explain the difference of our result to the SM expectation would be $D_p - U_n \sim 0.01$ (about $\sim 5\%$ of $D_p + U_n$), and the level of strange sea asymmetry $S - \bar{S} \sim +0.007$ (about $\sim 30\%$ of $S + \bar{S}$). Here Q_N is the total momentum carried by quark of type Q in nucleon N.

The NuTeV data cannot provide an independent constraint on possible isospin violation effects. Such effects, if present, will spoil the agreement of data and Monte Carlo hadron energy distributions, but the details depend on the details of the asymmetry. There are several classes of non-perturbative models which predict isospin violation. An early bag model calculation [10] predicts large asymmetries which would produce a shift of -0.0020 to the NuTeV $\sin^2\theta_W$. However, a more recent bag model calculation [11], which includes effects neglected in the previous reference, predicts a shift of only -0.0001. Finally, Meson Cloud model predictions for the asymmetry [12] result in a modest shift of $+0.0002$. The only way to test the validity of such models is in the context of global PDF fits, since they might disagree with existing data.

If the strange sea is generated by purely perturbative QCD processes, then neglecting electromagnetic effects, we expect the strange and anti-strange momentum distributions to be the same. However, non-perturbative

QCD effects could generate a significant momentum asymmetry [13]. A recent combined fit to CDHS neutrino and charged-lepton inclusive cross-sections [15], reports improvement in the quality of their fit when they allow for an asymmetric strange sea. This fit, which does not include CCFR inclusive cross-sections [7] or NuTeV dimuon cross-sections [14], finds $s > \bar{s}$ at high-x. The analysis of dimuon events from NuTeV and CCFR [14] does not support this conclusion.

Opposite-charged dimuon events are produced when (anti)neutrinos scatter off a strange or down (anti)quark to produce a charm (anti)quark in the final state, which subsequently fragments into a charmed hadron that decays semi-muonically, thus providing a very sensitive probe to the strange content of the nucleon. We fit the NuTeV and CCFR data within the same LO model used in the extraction of $\sin^2\theta_W$. The fit varies a common charm mass m_c, branching fraction B_c, and fragmentation parameter ϵ for both ν and $\bar{\nu}$, and two parameters for each one, (κ_ν, α_ν) and $(\kappa_{\bar{\nu}}, \alpha_{\bar{\nu}})$, that describe the magnitude and shape of the s and $\bar{s}$ quark PDFs:

$$s\left(x,Q^2\right) = \kappa_\nu \frac{\bar{u}\left(x,Q^2\right)+\bar{d}\left(x,Q^2\right)}{2}(1-x)^{\alpha_\nu}$$

and

$$\bar{s}\left(x,Q^2\right) = \kappa_{\bar{\nu}} \frac{\bar{u}\left(x,Q^2\right)+\bar{d}\left(x,Q^2\right)}{2}(1-x)^{\alpha_{\bar{\nu}}} \ .$$

We then use this LO model to extract the forward dimuon production differential cross-section. The dimuon cross-section compared to the Monte Carlo prediction is shown in figure 1. The results from the LO fit imply an asymmetry $S-\bar{S} = -0.0027 \pm 0.0013$, within the NuTeV cross-section model. Such an asymmetry would shift the value of $\sin^2\theta_W$ further from the SM prediction compared to the initial extraction which used a symmetric strange sea. To further check if there is any indication of a cross-section enhancement in the high x region, which we may be missing due to our choice of strange sea functional form, we performed a separate investigation [14] for data with $x > 0.5$. Since our Monte Carlo describes the data very well for $x < 0.5$, we use its prediction for $x > 0.5$ to set cross-section ratio upper limits for any additional source of $x > 0.5$ dimuons. We find that in anti-neutrino mode, at 90% CL, our dimuon data does not support any additional source with a fraction larger than 0.0012, 0.007, and 0.009, respectively, in each one of three visible energy ($E_{\rm VIS}$) bins: 34.8–128.6, 128.6–207.6, and 207.6–388.0 (in GeV). For neutrinos, we find that for $36.1 < E_{\rm VIS} < 153.9$ GeV and $214.1 < E_{\rm VIS} < 399.5$ GeV, at 90% CL, this fraction cannot be larger than 0.006 and 0.013 of the total, while for $153.9 < E_{\rm VIS} < 214.1$ (GeV) there is less than 5% probability that there is an additional source consistent with our data.

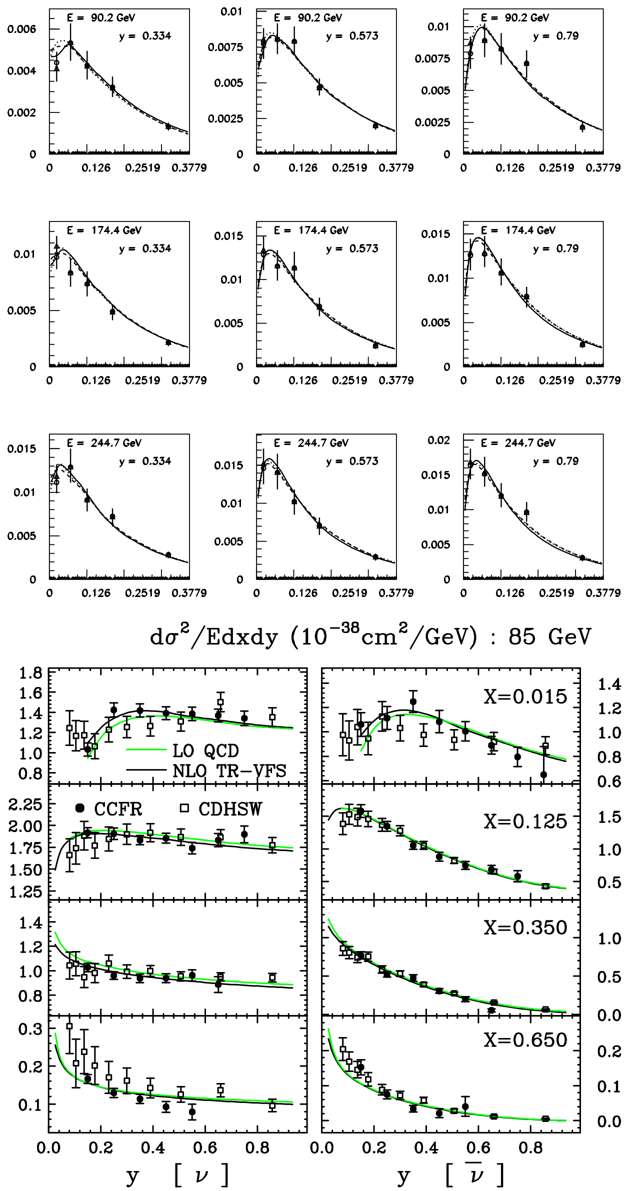

Fig. 1. Top: $\sigma_{2\mu}(x)$ from NuTeV neutrinos, for various $E_\nu - y$ bins in units of charged-current σ. The curves show the model prediction for different LO models. The solid curve corresponds to the model used in the NuTeV electroweak analysis. Bottom: Comparison of NuTeV and CDHSW differential cross-sections. The curves correspond to LO and NLO theoretical predictions .

An explanation for the strange sea enhancement at high-x [15], which implies an increase in the dimuon cross-section at $x > 0.5 \sim 5\%$ of the total (~ 100 additional events in our high-x sample), is due to the inconsistency of the CDHSW data with the CCFR data. The CDHSW ν differential cross-section at high-x is higher than both the CCFR result and NLO predictions from global fits, which include the same charged-lepton scattering data used in [15] (figure 1). Since the valence distributions are constrained from the charged lepton scattering data (which are consistent with CCFR), the fit of [15] requires a higher strange sea to accommodate the CDHSW data.

In conclusion, the NuTeV and CCFR dimuon data do not support an asymmetric strange sea of the sign and magnitude needed to explain the NuTeV $\sin^2\theta_W$ result.

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