Interpretations of the NuTeV $\sin^2 \theta_W$

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Abstract

We summarize theoretical explanations of the three $\sigma$ discrepancy between $\sin^2 \theta_W$ measured by NuTeV and predicted by the Standard Model global fit. Possible new physics explanations (e.g. an unmixed $Z'$) are not compelling. The discrepancy would be reduced by a positive momentum asymmetry $s^-$ in the strange sea; present experimental estimates of $s^-$ are unreliable or incomplete. Upgrading the NuTeV analysis to NLO would alleviate concerns that the discrepancy is a QCD effect.

1 Introduction

The NuTeV collaboration studied $\nu_\mu$ Deep Inelastic Scattering ($\nu DIS$), and measured $\sin^2 \theta_W$ on-shell, or $m_W^2/m_Z^2$, to be $\sin^2 \theta_W = 0.2276 \pm 0.0013$(stat) $\pm 0.0006$(syst) $\pm 0.0006$(theo) [1]. This is $\sim 3\sigma$ from the world average $\sin^2 \theta_W = 0.2226 \pm 0.0004$. Is this the long-awaited harbinger of New Physics? Neutrino DIS is a notoriously difficult environment in which to do precision physics—is the discrepancy an overlooked Standard Model (SM) effect?

Various explanations for this discrepancy have been put forward [2, 3, 4, 5]. In ref. [3], we considered electroweak corrections, QCD effects, new physics in loops and new physics at tree level.

2 New Physics?

It is difficult to saturate the NuTeV discrepancy with new physics in loops: an $O(1\%)$ effect is needed at NuTeV where $Q^2 \sim 20 \text{ GeV}^2$, but the new physics must not disrupt the part-per-mil agreement between the SM and precision tests. We found in [3] that oblique corrections, motivated versions of the MSSM and modified $Z$ couplings $^1$ cannot separately explain the whole NuTeV-LEP discrepancy. It has been observed in [11] that oblique corrections induced by new physics, and modified $Z$ couplings, can fit all the data $^2$.

$^1$Some authors [4, 11] have reconsidered models where neutrinos mix with heavy singlets, thereby reducing their couplings with the $Z$ and $W$ bosons by a factor $1 - \epsilon$ and $1 - \epsilon/2$ respectively. However, $\epsilon > 0$ reduces the NuTeV anomaly at the price of worsening the global fit [3]. (Our equations differ from those of [4] because we place $\epsilon$ in different electroweak parameters.)

$^2$Bernstein, in these proceedings, has a different interpretation of [3] or [11].
New tree-level physics offers more promising explanations. A \( \sim 1\% \) decrease with respect to the SM of the coefficient of the operator \((\bar{\nu}\gamma^\nu_\mu)(\bar{q}_L\gamma_\alpha q_L)\) is required, and could be provided by a new \( Z' \) boson, or by SU(2) triplet leptoquarks with judiciously chosen unequal masses. A new \( Z' \) must have negligible mixing with the \( Z \) to satisfy the oblique parameter and precision bounds on the \( Z \) coupling: [6]. However, a \( Z' \) coupled to e.g. \( B - 3L_\mu \) would provide the required four fermion operator at tree level. (It would also induce the operator \((\bar{\nu}\gamma^\nu_\mu)(\bar{q}_R\gamma_\alpha q_R)\); this is acceptable because the coefficient \(^3\) of this operator is measured less accurately by NuTeV. ) The \( Z' \) could have \( m_{Z'} > 600 \text{ GeV} \) for \( g' \sim 1 \), or if the coupling is small \( g' \sim 10^{-3} \), it could have \( 2 \text{ GeV} < m_{Z'} < 10 \text{ GeV} \) consistently with all experimental constraints. A \( Z' \) with \( m \sim 3 \text{ GeV} \) could fit the current \( g - 2 \) discrepancy [7].

3 Back to the Standard Model

The NuTeV experiment measures the ratio of “short” (= muonless) to “long” (with a \( \mu \)) events for incident \( \nu_\mu \) and \( \bar{\nu}_\mu \) beams. From this they extract the ratios \( R^\nu \) and \( R^\rho \), where \( R^\nu = \sigma(\nu N \to \nu X)/\sigma(\nu N \to \mu X) \). \( R^\nu \) is more sensitive than \( R^\rho \) to \( \sin^2 \theta_W \), so \( \sin^2 \theta_W \) is determined mainly from \( R^\nu \), after an effective “charm mass” is extracted from \( R^\rho \). NuTeV uses leading order (LO) parton distribution functions (pdfs), which are fit to their data, they assume isospin symmetry \((u^0(x) = d^0(x))\), and that \( q(x) = \bar{q}(x) \) for second generation quarks.

A theoretically cleaner ratio, where we studied the effects of isospin violation and \( s \neq \bar{s} \) is the Paschos-Wolfenstein ratio (related to \( R^\nu \) and \( R^\rho \)):

\[
R_{PW} = \frac{\sigma(\nu N \to \nu X) - \sigma(\bar{\nu} N \to \bar{\nu} X)}{\sigma(\nu N \to \mu X) - \sigma(\bar{\nu} N \to \bar{\mu} X)}
\]

\[
= \frac{1}{2} - \sin^2 \theta_W + [(1.3 + O(\alpha_s))(u^- - d^- - s^-)] ,
\]

where the 1.3 is a simplification (see [3]). The square brackets contain the corrections that arise if isospin is violated, or if there is a momentum asymmetry in the strange sea: \( s^- \neq 0 \), where \( s^- = \int dx x(s(x) - \bar{s}(x)) \).

Most pdf fits assume \( s^- = 0 \). This was not imposed in ref. [10] (BPZ), who performed a NLO fit to all the cross section data available (this did not include CCFR and NuTeV). They found that \( s^- \simeq .002 \) was a significantly better fit (\( \Delta x^2 = 25 \) for 2 additional d.o.f.) than \( s^- = 0 \). Naively substituting this into eqn. 1, one finds that \( \sin^2 \theta_W|_{\text{NuTeV}} - \sin^2 \theta_W|_{\text{LEP}} \) decreases to less than two \( \sigma \). Realistically, the effect of \( s^- \) on \( \sin^2 \theta_W \) will be reduced by experimental cuts and sensitivities. NuTeV has published a LO \( s \neq \bar{s} \) fit to their dimuon data [9], and found \( s^- \) negative. It is unclear whether the NuTeV dimuon data is consistent with the CDHSW cross-section data, which in conjunction with BCDMS, drives \( s^- \) positive in the BPZ fit; a refit to all the data would be required to determine this. However, the NuTeV analysis [9] had various peculiar features, as outlined in the (post-publication) note added to [3]. After the appearance of [3], NuTeV pointed out [8] that according to

\(^3\)This coefficient has the wrong sign in the plots of [3]; the \( Z' \) has vector couplings so makes a negative contribution to both \( g^2_L \) and \( g^2_R \). We thank Birgit Eberle for bringing this to our attention.
their analysis [9], the asymmetry had the wrong sign to reduce the \( \sin^2 \theta_W \) discrepancy: \( s^- \sim -0.0027 \pm 0.0013 \). They have recently redone their \( s \neq \bar{s} \) analysis at NLO[12], and find a positive asymmetry \( s^- \sim 0.0003 \). These determinations are affected by a theoretical uncertainty which is not included in the quoted error. A more detailed discussion of the NuTeV \( s^- \) extraction can be found in the “note added” to [3].

\( R_{PW} \) is theoretically attractive because the parton distributions cancel out of the ratio at LO, and the NLO corrections are small. However, the \( R^\nu, R^{\bar{\nu}} \) ratios measured by NuTeV have some dependence on the pdfs, which is exacerbated by asymmetries between charged-current and neutral-current, or between \( \nu \) and \( \bar{\nu} \) events. Such asymmetries could be induced by experimental cuts and by different \( \nu, \bar{\nu} \) spectra. It is therefore difficult to estimate the size of the NLO corrections to the \( \sin^2 \theta_W \) determination from NuTeV, particularly since NuTeV fit their LO pdfs to their data, which could absorb some of the NLO effects. A NLO analysis of the NuTeV experiment would be a welcome solution to these concerns.

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