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

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Abstract. We summarize theoretical explanations of the three σ discrepancy between $\sin^2\theta_W$ measured by NuTeV and predicted by the Standard Model global fit. Possible new physics explanations (*e.g.* an unmized 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.

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1. Introduction

The NuTeV collaboration studied ν_μ Deep Inelastic Scattering (νDIS), and measured $\sin^2\theta_W$ on-shell, or m_W^2/m_Z^2, to be $\sin^2\theta_W = 0.2276 \pm 0.0013(\mathrm{stat}) \pm 0.0006(\mathrm{syst}) \pm 0.0006(\mathrm{theo})$ [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 $Q^2 \sim 20$ 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 ‡ 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 § . New tree-level physics offers more promising explanations. A $\sim 1\%$ decrease with respect to the SM of the coefficient of the operator $(\bar\nu_\mu\gamma^\alpha\nu_\mu)(\bar{q_L}\gamma_\alpha q_L)$ 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 negligeable mixing with the Z to satisfy the oblique parameter and precision bounds on the Z coupling: [6].

‡ 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 ϵ in different electroweak parameters.)

§ Bernstein, in these proceedings, has a different interpretation of [3] or [11]

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 $(\bar{\nu}_\mu \gamma^\alpha \nu_\mu)(\bar{q_R}\gamma_\alpha q_R)$; this is acceptable because the coefficient ‖ this operator is measured less accurately by NuTeV.) The Z' could have $m_{Z'} > 600$ GeV for $g' \sim 1$, or if the coupling is small $g' \sim 10^{-3}$, it could have 2 GeV $< m_{Z'} <$ 10 GeV consistently with all experimental constraints. A Z' with $m \simeq$ 3GeV 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 μ) events for incident ν_μ and $\bar{\nu}_\mu$ beams. From this they extract the ratios R^ν and $R^{\bar{\nu}}$, where $R^\nu = \sigma(\nu N \to \nu X)/\sigma(\nu N \to \mu X)$. R^ν is more sensitive than $R^{\bar{\nu}}$ to $\sin^2\theta_W$, so $\sin^2\theta_W$ is determined mainly from R^ν, after an effective "charm mass" is extracted from $R^{\bar{\nu}}$. NuTeV uses leading order (LO) parton distribution functions (pdfs), which are fit to their data, they assume isospin symmetry ($u^p(x) = d^n(x)$), 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^ν and $R^{\bar{\nu}}$) :

$$
\begin{aligned}
R_{PW} &\equiv \frac{\sigma(\nu N \to \nu X) - \sigma(\bar{\nu} N \to \bar{\nu} X)}{\sigma(\nu N \to \mu X) - \sigma(\bar{\nu} N \to \bar{\mu} X)} \\
&= \frac{1}{2} - \sin^2\theta_W + \left[(1.3 + O(\alpha_s))(u^- - d^- - s^-)\right] \quad , \qquad (1)
\end{aligned}
$$

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 ($\Delta\chi^2 = 25$ for 2 additional d.o.f.) than $s^- = 0$. Naively substituting this into eqn. 1, one finds that $\sin^2\theta_W|_{NuTeV} - \sin^2\theta_W|_{LEP}$ decreases to less than two σ. 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 inconjunction 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 their analysis [9], the asymmetry had the wrong sign to reduce the $\sin^2\theta_W$ discrepancy: $s^- \sim -.0027 \pm .0013$. They have recently redone their $s \neq \bar{s}$ analysis at NLO[12], and find a *positive* asymmetry $s^- \sim .0003$. 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^ν, $R^{\bar{\nu}}$ ratios measured by NuTeV have some dependence on the pdfs, which is exacerbated by asymmetries between charged-current and neutral-current, or between ν and $\bar{\nu}$ events. Such asymmetries could be induced by experimental cuts and by different

‖ This coefficient has the wrong sign in the plots of [3]; the Z' has vector couplings so makes a negative contribution to both g_L^2 and g_R^2. We thank Birgit Eberle for bringing this to our attention.

ν, $\bar{\nu}$ spectra. It is therefore difficult to estimate the size of the NLO corrections to the $\sin^2\theta_W$ determination from NuTeV, particularily 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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