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Nuclear modification of valence-quark distributions and its effects on NuTeV $\sin^2\theta_W$ anomaly

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We investigated a nuclear modification difference between up- and down-valence quark distributions by analyzing structure function F_2 and Drell-Yan cross-section ratios. Although nuclear modifications of the valence-quark distributions themselves are rather well determined, it is difficult to find their difference from the present data. We estimated such an effect on the NuTeV $\sin^2\theta_W$ value and its uncertainty by the Hessian method. At this stage, it is not large enough to explain the whole NuTeV anomaly. However, the modification difference cannot be precisely determined, so that further studies are needed.

1. Introduction

Weak-mixing angle $\sin^2\theta_W$ is one of the fundamental constants in the standard model. It has been measured experimentally by various methods such as atomic parity violation and polarization asymmetry in electron-positron annihilation. The NuTeV collaboration determined it by neutrino- and antineutrino-nucleus scattering and found that its value, $\sin^2\theta_W = 0.2277 \pm 0.0013\,(\text{stat}) \pm 0.0009\,(\text{syst})$ in the on-shell scheme, is significantly larger than other measurements ($\sin^2\theta_W = 0.2227 \pm 0.0004$) [1]. It is called "NuTeV $\sin^2\theta_W$ anomaly".

Because there may be new physics behind this anomaly, careful analyses are needed for clarifying the situation. In our work, we investigate a conservative explanation without exotic mechanisms. The NuTeV target is iron, so that nuclear corrections could be a candidate for the anomalous result. There are various factors including the effects of neutron excess, strange-antistrange asymmetry, isospin violation, and modification of valence-quark distributions. Among them, the nuclear modification difference between u_v and d_v is discussed in this paper. It was first investigated in Ref. [2] and a detailed analysis has been done in Ref. [3]. Here, we report recent analysis results.

This paper consists of the following. In section 2, our analysis method and results are explained for determining the nuclear modification difference. Its effect on $\sin^2\theta_W$ is calculated in section 3. The results are summarized in section 4.

2. Nuclear modification of valence-quark distributions

It is known that nuclear parton distribution functions (PDFs) are modified from those of the nucleonic distributions. Such nuclear modifications have been investigated especially in the structure function F_2. Determination of each parton modification is not straightforward from F_2 and Drell-Yan data. However, gross features of nuclear PDFs are now determined, for example, in Ref. [4]. Among the nuclear PDF corrections, it was pointed out that valence-quark modifications affect the $\sin^2\theta_W$ determination [2].

In order to discuss such a nuclear effect, we define nuclear modification factors w_{u_v} and w_{d_v} for up- and down-valence quark distributions by

$$u_v^A(x) = w_{u_v}(x, A, Z)\,\frac{Zu_v(x) + Nd_v(x)}{A},$$
$$d_v^A(x) = w_{d_v}(x, A, Z)\,\frac{Zd_v(x) + Nu_v(x)}{A}, \qquad (1)$$

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where $u_v(x)$ and $d_v(x)$ are the distributions in the nucleon, Z is the atomic number of a nucleus, and A is the mass number. For simplicity, the Q^2 dependence is abbreviated. It should be noticed that these relations are used at any Q^2 for the present research, although similar equations are defined only at Q^2=1 GeV^2 in Ref. [4]. These equations are motived by the following considerations. If there were no nuclear correction, the u_v distribution of a nucleus is given by the simple summation of proton and neutron contributions $Zu_v^p + Nu_v^n$. The isospin symmetry is usually assumed for the parton distributions, so that it becomes $Zu_v + Nd_v$. It is divided by A ($(Zu_v + Nd_v)/A$) because we use nuclear PDFs per nucleon. Therefore, the function w_{u_v} indicates nuclear correction to this distribution.

In particular, we are interested in the modification difference $w_{u_v} - w_{d_v}$ and its effect on the $\sin^2\theta_W$ determination. Therefore, specific parameters (a'_v, b'_v, c'_v, d'_v) are assigned for the difference at Q^2=1 GeV^2 [3]:

$$w_{u_v}(x,A,Z) - w_{d_v}(x,A,Z) = \left(1 - \frac{1}{A^{1/3}}\right) \times \frac{a'_v(A,Z) + b'_v x + c'_v x^2 + d'_v x^3}{(1-x)^{\beta_v}}. \quad (2)$$

Because of the baryon-number and charge conservations, the parameter a'_v is fixed, and then the number of parameters is three. The parameter β_v and other parameters in $w_{u_v} + w_{d_v}$, $w_{\bar{q}}$, and w_g are fixed at the values of our recent analysis [4]. The mass-number dependence is assumed in the $1 - 1/A^{1/3}$ form simply by considering nuclear volume and surface contributions [4]. The x dependence is motivated by the shape of nuclear modification data of F_2. However, we should aware that appropriate A and x dependence is not known almost at all for $w_{u_v} - w_{d_v}$.

We determined the parameters by using experimental data for the nuclear F_2 ratios and Drell-Yan cross-section ratios as investigated in Ref. [4]. The parameters b'_v, c'_v, and d'_v are optimized by a χ^2 analysis with the data. The obtained distribution is shown by the ratio

$$\varepsilon_v(x) = \frac{w_{d_v}(x,A,Z) - w_{u_v}(x,A,Z)}{w_{d_v}(x,A,Z) + w_{u_v}(x,A,Z)}, \quad (3)$$

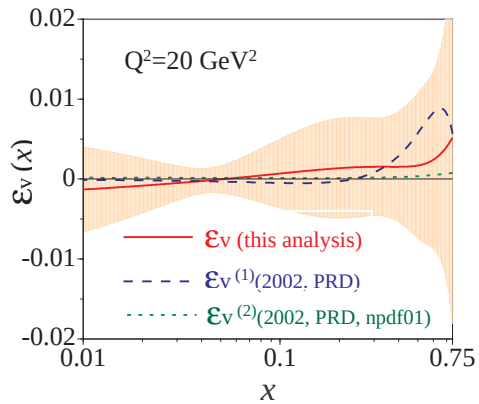

Figure 1. The obtained distribution $\varepsilon_v(x)$ is shown at Q^2=20 GeV^2 [3] with previous results [2]. The details are explained in the text.

in Fig. 1. Equation (3) is used at any Q^2. The distribution $\varepsilon_v(x)$ is shown by the solid curve, and the shaded area indicates the one-σ error range. The error is estimated by the Hessian method by using the determined parameters and error matrix in the χ^2 analysis. The distribution is shown at Q^2=20 GeV^2 which is about the average Q^2 value of the NuTeV data.

The dashed and dotted curves indicate the estimated distributions in Ref. [2]. The dashed curve is obtained by calculating $\varepsilon_v = -(N-Z)(u_v - d_v)(w_v - 1)/[A(u_v + d_v)w_v]$, which is one of the candidates for satisfying the baryon-number and charge conservations. The function w_v is given by $w_v = (w_{u_v} + w_{d_v})/2$. The dotted is obtained by Eq. (3) with the 2001 version of the nuclear PDFs [4]. As obvious from the figure, three distributions are much different. However, they are well within the error band, which indicates that these results are consistent each other.

3. Effects on NuTeV $\sin^2\theta_W$

From the neutrino- and antineutrino-nucleon scattering, $\sin^2\theta_W$ could be obtained by using the Paschos-Wolfenstein (PW) relation:

$$R^- = \frac{\sigma_{NC}^{\nu N} - \sigma_{NC}^{\bar{\nu} N}}{\sigma_{CC}^{\nu N} - \sigma_{CC}^{\bar{\nu} N}} = \frac{1}{2} - \sin^2\theta_W, \quad (4)$$

where $\sigma_{CC}^{\nu N}$ and $\sigma_{NC}^{\nu N}$ are charged-current (CC) and neutral-current (NC) cross sections. There

are various nuclear corrections to the PW relation. Expanding the expression in terms of the correction factors, we obtain a modified PW relation for a nucleus [2]:

$$R_A^- = \frac{1}{2} - \sin^2\theta_W - \varepsilon_v(x)\left\{\left(\frac{1}{2} - \sin^2\theta_W\right)\frac{1+(1-y)^2}{1-(1-y)^2} - \frac{1}{3}\sin^2\theta_W\right\} + O(\varepsilon_v^2) + O(\varepsilon_n) + O(\varepsilon_s) + O(\varepsilon_c)\,. \quad (5)$$

The first correction term with $\varepsilon_v(x)$ is investigated in this paper. In addition, there are corrections associated with the neutron-excess (ε_n), strange-antistrange asymmetry (ε_s), and charm-anticharm asymmetry (ε_c) factors. The variable y is defined by $y = q^0/E_\nu$ with the energy transfer q^0.

Because the ε_v correction term depends on the variables x, y, and Q^2, we need to take the NuTeV kinematics into account to estimate an effect on the $\sin^2\theta_W$ determination. In particular, there are few experimental data in the large x region, where the distribution $\varepsilon_v(x)$ becomes significant as shown in Fig. 1. Namely, the ε_v effect on $\sin^2\theta_W$ could be much smaller than the one expected from Fig. 1. Fortunately, such kinematical factors are supplied in Ref. [5]. Comparing our PDF definition with the NuTeV one, we find the relations

$$\delta u_v^* = u_{vp}^* - d_{vn}^* = -\varepsilon_v\,(w_{u_v} + w_{d_v})\,x\,u_v,$$
$$\delta d_v^* = d_{vp}^* - u_{vn}^* = +\varepsilon_v\,(w_{u_v} + w_{d_v})\,x\,d_v, \quad (6)$$

where the asterisk ($*$) indicates the NuTeV distributions. Therefore, the nuclear modification difference ε_v corresponds to the isospin violation in the NuTeV terminology. Then, the contribution to the NuTeV $\sin^2\theta_W$ is given by

$$\Delta(\sin^2\theta_W) = -\int dx\,\{\,F[\delta u_v^*, x]\,\delta u_v^*(x) + F[\delta d_v^*, x]\,\delta d_v^*(x)\,\}, \quad (7)$$

where $F[\delta u_v^*, x]$ and $F[\delta d_v^*, x]$ are the functionals provided in Fig. 1 of Ref. [5]. Our sign convention of $\Delta(\sin^2\theta_W)$ is opposite to the NuTeV one in Eq. (7). The distributions $\delta u_v^*(x)$ and $\delta d_v^*(x)$ are calculated by Eq. (6) with the distribution $\varepsilon_v(x)$, which was obtained in the previous section. Calculating the integral numerically, we obtain [3]

$$\Delta(\sin^2\theta_W) = 0.0004 \pm 0.0015, \quad (8)$$

at Q^2=20 GeV^2.

In comparison with the NuTeV deviation 0.0050, the correction is an order of magnitude smaller. However, the error becomes comparable to the deviation. The magnitude of the error depends much on the analysis condition. Therefore, careful analyses could alter the values in Eq. (8). In particular, the nuclear modification difference $w_{u_v} - w_{d_v}$, which we have investigated in this paper, is not a uniquely determined quantity at this stage. In order to determine this difference, we need future experimental efforts.

4. Summary

We have analyzed the experimental data on nuclear structure functions F_2^A and Drell-Yan cross sections for extracting the nuclear modification difference between u_v and d_v distributions. Using the obtained distribution, we investigated its effect on the NuTeV $\sin^2\theta_W$ determination. We found a rather small effect; however, the uncertainty on the $\sin^2\theta_W$ is not small in comparison with the NuTeV deviation. Because such as nuclear modification is difficult to be determined at this stage, we need further studies to pin down the modification.

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