Effect due to charge symmetry violation on the Paschos-Wolfenstein relation

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The modification of the Paschos-Wolfenstein relation is investigated when the charge symmetry violations of valence and sea quark distributions in the nucleon are taken into account. We also study qualitatively the impact of charge symmetry violation (CSV) effect on the extraction of $\sin^2\theta_w$ from deep-inelastic neutrino- and antineutrino-nuclei scattering within the light-cone meson-baryon fluctuation model. We find that the effect of CSV is too small to give a sizable contribution to the NuTeV result with various choices of mass difference inputs, which is consistence with the prediction that the strange-antistrange asymmetry can account for largely the NuTeV deviation in this model. It is noticeable that the effect of CSV might contribute to the NuTeV deviation when the larger difference between the internal momentum scales, α_p of the proton and α_n of the neutron, is considered.

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I. INTRODUCTION

In recent years, the precise determination of weak-mixing angle (or Weinberg angle) $\sin^2\theta_w$ has received a lot of attention. It is well known that the Weinberg angle is one of the key parameters in the standard model (SM) of electroweak theory and can be determined from various experimental methods, such as atomic parity violation, W and Z masses, elastic and inelastic neutrino scattering, and so on. In 2002, the NuTeV Collaboration [1] announced that they measured a new value: $\sin^2\theta_w = 0.2277 \pm 0.0013(\text{stat}) \pm 0.0009(\text{syst})$, which is larger than the world accepted value: $\sin^2\theta_w = 0.2227 \pm 0.0004$ measured in other electroweak processes with 3 standard deviations. NuTeV extracted the value of $\sin^2\theta_w$ by measuring the ratio of neutral-current to charged-current cross sections for neutrino and antineutrino on the iron targets, respectively, and then made a full Monte Carlo simulation of their experiment. A number of corrections should be considered before any conclusion may be drawn, because the analysis procedure is based on the Paschos-Wolfenstein (P-W) relation [2]

$$R^- = \frac{\sigma_{NC}^{\nu N} - \sigma_{NC}^{\bar{\nu} N}}{\sigma_{CC}^{\nu N} - \sigma_{CC}^{\bar{\nu} N}} = \frac{1}{2} - \sin^2\theta_w. \tag{1}$$

In this equation, $\sigma_{NC}^{\nu N}$ ($\sigma_{NC}^{\bar{\nu} N}$) is the integral of neutral-current inclusive differential cross section for neutrino (antineutrino) over x and y, and it is similar to $\sigma_{CC}^{\nu N}$ ($\sigma_{CC}^{\bar{\nu} N}$). This relation provides an independent determination of the Weinberg angle. Three assumptions should be made for the validity of this relation: isoscalar target, which means that the number of protons is equal to that of neutrons for the target; quark-antiquark symmetries for both strange and charm quark distributions ($s(x) = \bar{s}(x)$, $c(x) = \bar{c}(x)$); and charge symmetry ($u_p(x) = d_n(x)$, $d_p(x) = u_n(x)$ and similarly for $\bar{u}(x)$, $\bar{d}(x)$), where x represents the momentum fraction carried by the quark in the nucleon. In fact, these assumptions are not strictly valid in realistic reactions. Usually, there is a small deviation from an isoscalar target by an excess of neutrons over protons, which has been considered by the NuTeV Collaboration. But the NuTeV Collaboration disregarded not only the effect due to strange-antistrange asymmetry but also the CSV effect in their original analysis. Although many sources of systematic errors and several uncertainties have been considered, it is still an open question whether the NuTeV deviation could be accounted for within or beyond SM. Possible sources of the NuTeV anomaly beyond SM have been discussed in Ref. [3]. However, before speculating on the possible new physics, one should first check carefully the *standard* effect and the theoretical uncertainties coming from complicated aspects of the quantum chromodynamics (QCD).

As mentioned above, one of the assumptions is the isoscalar target, i.e., the nucleus should be in an isoscalar state, so that various strong interaction effects can cancel out in the ratio. However, the targets used in the neutrino experiments are usually nonisoscalar nuclei with a significant neutron excess, such as the iron target in the NuTeV experiment. The corrections of nonisoscalar target to the NuTeV anomaly were given in Ref. [4–7]. Besides that there are other suggestions [8] from a conservative point of views.

The second assumption is the quark-antiquark symmetry of strange and charm momentum distributions in the nucleon sea. The validity of these asymmetries for quark-

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antiquark has been discussed by a lot of investigators not only for its connection to the proton spin problem but also for the probability to explain the anomalous value of the Weinberg angle. The asymmetry of strange and antistrange momentum distributions is the most sensible explanation for the NuTeV anomaly within SM. Recently, the contribution caused by the strange-antistrange asymmetry in perturbative quantum chromodynamics (PQCD) at three-loop [9] was predicted, but it is too small to affect the extraction of the weak-mixing angle. Thus, the reason for the asymmetric momentum distributions of strangeness in the nucleon sea should be of nonperturbative origin [10–12]. In fact, there have been a series of discussions on the effect due to strange-antistrange asymmetry on the extraction of $\sin^2\theta_w$. Cao and Signal [13] investigated this asymmetry by using the meson cloud model and found that the result is fairly small with almost no correction to the value of $\sin^2\theta_w$. Also, in the past, the role of asymmetric strange-antistrange quark momentum distributions was predicted by using the light-cone meson-baryon fluctuation model [14] and the effective chiral quark model [15,16], respectively. Noticeably, the similar predictions that the effect of s-$\bar{s}$ asymmetry would remove largely the NuTeV anomaly were obtained from the above two different models. In addition, in Ref. [16], the strangeness asymmetries were compared between the prediction by the effective chiral quark model and the parametrizations of the NuTeV experimental data. It was found that the prediction of this model is consistent with the parametrizations of the experimental data. The same conclusion was given in Ref. [17] with the chiral quark soliton model by introducing a parameter of the effective mass difference between strange and nonstrange quarks, an idea also discussed in Ref. [18]. Alternatively, Olness *et al.* [19] performed the first global QCD analysis of the CCFR and NuTeV dimuon data, adopted a general parametrization of the nonperturbative $s(x)$ and $\bar{s}(x)$ distribution functions, and evaluated the contribution to the NuTeV deviation with uncertainties. Furthermore, the correction coming from QCD to the shift of $\sin^2\theta_w$ which relates with the effects of isospin violation and asymmetry of strangeness content were also estimated in Ref. [20].

Despite so many theoretical arguments and analyses, e.g., Refs. [21–24], there is no direct experimental evidence for the asymmetric momentum distributions of strange quark and antiquark in the nucleon sea except the dimuon experiment induced by neutrinos and antineutrinos [22] which is the best method for measuring the s-$\bar{s}$ asymmetric momentum distributions at this stage. The precision of the dimuon experiment is not high enough to get the detailed information about this asymmetry. Moreover, the effect of strange-antistrange asymmetry often mixes with the CSV effect in experiment. But it is still possible to extract the effects of asymmetric strangeness distributions and CSV from different experiments in the future [25].

The so-called charge symmetry is the invariance of the QCD Lagrangian with the up (u) and down (d) quarks interchanging when both the mass difference of them and the electromagnetical effects are ignored. This invariance is a more restricted form of isospin invariance involving a rotation of 180° about the "2" axis in isospin space, or more specifically, the isospin symmetry for the $u \leftrightarrow d$ exchange between the proton and the neutron. Thus, the light flavor parton distributions in the neutron can be expressed in terms of those in the proton. It should be emphasized that the charge symmetry violation effect arises from the mass difference between up and down quarks and from electromagnetical effects. Most low-energy tests of charge symmetry showed that the symmetry holds within about 1% in the reaction amplitudes [26].

At present, charge symmetry is assumed to be valid in almost all phenomenological parton distributions, because there is no direct experimental confirmation pointing to a substantial CSV in the parton distributions. As we know, CSV effect is small and can be hardly separated clearly from the strangeness asymmetry, besides that CSV effect also often mixes with the flavor symmetry violation (FSV) effect, i.e., the asymmetry between $\bar{u}$ and $\bar{d}$ quarks in the nucleon [27]. Until recently, with the development of high-energy deep-inelastic scattering experiments, the detailed information regarding the structure of the nucleon is known much better. The famous experiment of asymmetry for $\bar{u}$ and $\bar{d}$ distributions in the nucleon sea, carried out first by the NMC group [24,28], enabled a better determination of the Gottfried Sum [29], which was predicted to be $1/3$ with the assumptions of charge symmetry and flavor symmetry. Later the flavor asymmetric sea was also confirmed by the pp and pD Drell-Yan processes [30] and by the semi-inclusive electroproduction at HERMS [31]. All these experimental measurements have been interpreted as evidences of FSV, but they can be also explained by a large CSV effect if the FSV effect is neglected [27]. It is remarkable that the possible violation of charge symmetry (CS) has attracted attention again, because it might be closely related with the NuTeV anomaly. The earliest estimation of CSV effect relating to the Weinberg angle is made by Sather [32]. He first pointed out that the charge symmetry violation (CSV) must be understood when a high-precision value of $\sin^2\theta_w$ is extracted from deep-inelastic neutrino scattering, and gave the correction to $\sin^2\theta_w$ around 0.002 within the nonperturbative framework of quark model. Qualitatively, a similar conclusion was obtained within the bag model [33] by including a number of effects neglected in Ref. [32]. Both of these models predict that the "majority" quark distributions satisfy charge symmetry violation within about 1%, while the "minority" quark distributions are predicted to violate CS around 5% or more at large x. In Ref. [34], the authors combined the approaches of Refs. [32,33] to examine the violation of CS in the valence and sea quark distributions of the nucleon, and found that the size of CSV effect is large in the valence quark distributions (same as the conclusion of Refs. [32,33,35]) and too small in the nucleon sea to have significant contribution to any observable. Later, Davidson and Burkardt [36] employed the convolution approach [37] to estimate the charge symmetry breaking effects and gave the size of the correction to the Weinberg angle. Boros [38] and his collaborators presented a serious challenge to CS by comparing the structure functions $F_2^\nu(x, Q^2)$ from neutrino-induced charged-changing reactions by the CCFR Collaboration [23] and the structure functions $F_2^\mu(x, Q^2)$ from charged lepton DIS by the NMC collaboration [28], and placed the upper limits in the magnitude of CSV. After that, there has been a series of discussions about CSV contribution to the NuTeV discrepancy. Londergan and Thomas [39] investigated the CSV effect, and suggested that it is largely independent of parton distribution functions (PDFs) and should reduce roughly 30% of the discrepancy between the NuTeV measurement and the world accepted value of $\sin^2\theta_w$. Also, the MRST [40] group obtained a phenomenological evaluation of PDFs including isospin violating by widely fitting a variety of high-energy experimental data. On the contrary, Cao and Signal [41] calculated the nonperturbative effect of CSV within the framework of meson cloud model and showed no contribution to the NuTeV anomaly. And recently, the contribution to the valence isospin violation stemming from dynamical (radiative) QED effect was investigated [42] and the size of CSV effect [43] is similar to those calculated within the bag model. In this paper, we analyze qualitatively the CSV effect within the light-cone meson-baryon fluctuation model [10], and show that the contribution is too small to affect the measurement of the Weinberg angle in the neutrino scattering, unless a larger difference between the internal momentum scales, α_p of the proton and α_n of the neutron, is taken into account.

II. THE CORRECTION OF CSV EFFECT TO THE NUTEV ANOMALY

In the realistic reaction, the Paschos-Wolfenstein relation [2] must be corrected by the possible effects of nonisoscalar target, $s(x)$-$\bar{s}(x)$ and $c(x)$-$\bar{c}(x)$ asymmetries, and charge symmetry violation in the nucleon sea. In this section, we will give a revised expression for the P-W relation with CSV effects. The procedure is similar to that for the asymmetric s-$\bar{s}$ momentum distributions in the nucleon sea in Refs. [14,16], about which we make a brief review here. As we know, $\sigma_{NC}^{\nu N}$ ($\sigma_{NC}^{\bar{\nu}N}$) in Eq. (1) is the integral of differential cross section over x and y for neutral-current reactions induced by neutrino (antineutrino) on nucleon target, and it is the same for $\sigma_{CC}^{\nu N}$ ($\sigma_{CC}^{\bar{\nu}N}$). The most general form of the differential cross section for neutral-current interactions initialed by (anti)-neutrino is [44]:

$$\frac{d^2\sigma_{NC}^{\nu(\bar{\nu})}}{dxdy} = \pi s\left(\frac{\alpha}{2\sin^2\theta_w\cos^2\theta_w M_Z^2}\right)^2\left(\frac{M_Z^2}{M_Z^2+Q^2}\right)^2 \times\left[xyF_1^Z(x,Q^2)+\left(1-y-\frac{xym_N^2}{s}\right)F_2^Z(x,Q^2) \pm\left(y-\frac{y^2}{2}\right)xF_3^Z(x,Q^2)\right]. \quad (2)$$

Similarly, we can have the cross section for (anti)neutrino-nucleon charged-current reaction [44],

$$\frac{d^2\sigma_{CC}^{\nu(\bar{\nu})}}{dxdy} = \pi s\left(\frac{\alpha}{2\sin^2\theta_w M_W^2}\right)^2\left(\frac{M_W^2}{M_W^2+Q^2}\right)^2 \times\left[xyF_1^{W^\pm}(x,Q^2)+\left(1-y-\frac{xym_N^2}{s}\right) \times F_2^{W^\pm}(x,Q^2)\pm\left(y-\frac{y^2}{2}\right)xF_3^{W^\pm}(x,Q^2)\right], \quad (3)$$

where M_Z and M_W are the masses of the neutral- and charged-current interacting weak vector bosons, respectively, θ_w is the Weinberg angle, $x = Q^2/2p\cdot q$, $y = p\cdot q/p\cdot k$, $Q^2 = -q^2$ is the square of the four momentum transfer for the reaction, $k(p)$ is the momentum of the initial state for neutrino or antineutrino (nucleon), and $s = (k+p)^2$. Besides these, $F_i^{Z(W^\pm)p}(x, Q^2)$ are the structure functions on the proton (p), which only depend on x as $Q^2 \to \infty$, and are written in terms of the parton distributions as [44]

$$\lim_{Q^2\to\infty} F_1^{Zp}(x,Q^2) = \tfrac{1}{2}[((f_V^u)^2+(f_A^u)^2)(u^p(x)+\bar{u}^p(x) + c^p(x)+\bar{c}^p(x)) + ((f_V^d)^2 + (f_A^d)^2)(d^p(x)+\bar{d}^p(x)+s^p(x) + \bar{s}^p(x))],$$
$$\lim_{Q^2\to\infty} F_3^{Zp}(x,Q^2) = 2[f_V^u f_A^u(u^p(x)-\bar{u}^p(x)+c^p(x) - \bar{c}^p(x)) + f_V^d f_A^d(d^p(x)-\bar{d}^p(x) + s^p(x)-\bar{s}^p(x))].$$
$$F_2^{Zp}(x,Q^2) = 2xF_1^{Zp}(x,Q^2). \quad (4)$$

The structure functions of charged-current in above equations have the forms:

$$\lim_{Q^2\to\infty} F_1^{W^+p}(x,Q^2) = d^p(x)+\bar{u}^p(x)+s^p(x)+\bar{c}^p(x),$$
$$\lim_{Q^2\to\infty} F_1^{W^-p}(x,Q^2) = u^p(x)+\bar{d}^p(x)+\bar{s}^p(x)+c^p(x),$$
$$\tfrac{1}{2}\lim_{Q^2\to\infty} F_3^{W^+p}(x,Q^2) = d^p(x)-\bar{u}^p(x)+s^p(x)-\bar{c}^p(x),$$
$$\tfrac{1}{2}\lim_{Q^2\to\infty} F_3^{W^-p}(x,Q^2) = u^p(x)-\bar{d}^p(x)-\bar{s}^p(x)+c^p(x),$$
$$F_2^{W^\pm p}(x,Q^2) = 2xF_1^{W^\pm p}(x,Q^2). \quad (5)$$

One can obtain the structure functions for the neutron n by replacing the superscripts $p \to n$ everywhere in Eqs. (4) and (5). In Eq. (4), f_V^u, f_A^u, f_V^d and f_A^d are vector and axial-vector couplings:

$$f_V^u = \frac{1}{2} - \frac{4}{3}\sin^2\theta_w, \qquad f_A^u = \frac{1}{2},$$
$$f_V^d = -\frac{1}{2} + \frac{2}{3}\sin^2\theta_w, \qquad f_A^d = -\frac{1}{2}.$$

Charge symmetry means that:

$$d^n(x) = u^p(x), \qquad u^n(x) = d^p(x),$$
$$s^n(x) = s^p(x) = s(x), \qquad c^n(x) = c^p(x) = c(x), \tag{6}$$

and $c(x) = \bar{c}(x)$, $s(x) = \bar{s}(x)$. Thus, with charge symmetry violation and assumption of $s(x) = \bar{s}(x)$, the structure functions for isoscalar target in the neutrino charged-current reaction are given by

$$\lim_{Q^2\to\infty} F_1^{W^+N}(x, Q^2) = \tfrac{1}{2}[d^p(x) + \bar{d}^p(x) + u^p(x) + \bar{u}^p(x) + 2s(x) + 2\bar{c}(x) - \delta u(x) - \delta\bar{d}(x)],$$
$$\lim_{Q^2\to\infty} F_1^{W^-N}(x, Q^2) = \tfrac{1}{2}[d^p(x) + \bar{d}^p(x) + u^p(x) + \bar{u}^p(x) + 2\bar{s}(x) + 2c(x) - \delta d(x) - \delta\bar{u}(x)],$$
$$\lim_{Q^2\to\infty} F_3^{W^+N}(x, Q^2) = d^p(x) + u^p(x) - \bar{u}^p(x) - \bar{d}^p(x) + 2s(x) - 2\bar{c}(x) - \delta u(x) + \delta\bar{d}(x),$$
$$\lim_{Q^2\to\infty} F_3^{W^-N}(x, Q^2) = d^p(x) + u^p(x) - \bar{u}^p(x) - \bar{d}^p(x) - 2\bar{s}(x) + 2c(x) - \delta d(x) + \delta\bar{u}(x),$$
$$F_2^{W^\pm N}(x, Q^2) = 2xF_1^{W^\pm N}(x, Q^2), \tag{7}$$

where $F_i^{W^+N}(x, Q^2) = \frac{1}{2}(F_i^{W^+p}(x, Q^2) + F_i^{W^+n}(x, Q^2))$. And the forms of structure functions for the neutral-current also can be obtained in the same way:

$$\lim_{Q^2\to\infty} F_1^{ZN}(x, Q^2) = \tfrac{1}{2}[((f_V^u)^2 + (f_A^u)^2)(d^p(x) + \bar{d}^p(x) + u^p(x) + \bar{u}^p(x) + 2c(x) + 2\bar{c}(x) - \delta d(x) - \delta\bar{d}(x)) + ((f_V^d)^2 + (f_A^d)^2)(d^p(x) + \bar{d}^p(x) + u^p(x) + \bar{u}^p(x) + 2s(x) + 2\bar{s}(x) - \delta u(x) - \delta\bar{u}(x))],$$
$$\lim_{Q^2\to\infty} F_3^{ZN}(x, Q^2) = f_V^u f_A^u[d_v^p(x) + u_v^p(x) - \delta d_v(x) + 2c_v(x)] + f_V^d f_A^d[d_v^p(x) + u_v^p(x) - \delta u_v(x) + 2s_v(x)],$$
$$F_2^{ZN}(x, Q^2) = 2xF_1^{ZN}(x, Q^2), \tag{8}$$

where $q_v^p = q^p(x) - \bar{q}^p(x)$ is the valence distribution of flavor q quarks in the proton p. Thus, using the structure functions above, one can derive the modified P-W relation with the CSV effects:

$$R_N^- = \frac{\sigma_{NC}^{\nu N} - \sigma_{NC}^{\bar{\nu}N}}{\sigma_{CC}^{\nu N} - \sigma_{CC}^{\bar{\nu}N}} = R^- - \delta R_{\rm csv}^-, \tag{9}$$

where $\delta R_{\rm csv}^-$ is the correction brought by the effects of CSV to the naive P-W relation R^- and has the following form:

$$\delta R_{\rm csv}^- = \left(\frac{1}{2} - \frac{7}{6}\sin^2\theta_w\right)\frac{\int_0^1 x[\delta d_v(x) - \delta u_v(x)]\mathrm{d}x}{\int_0^1 x[u_v(x) + d_v(x)]\mathrm{d}x}, \tag{10}$$

with

$$\delta u_v(x) = \delta u(x) - \delta\bar{u}(x), \qquad \delta d_v(x) = \delta d(x) - \delta\bar{d}(x),$$
$$\delta u(x) = u^p(x) - d^n(x), \qquad \delta\bar{u}(x) = \bar{u}^p(x) - \bar{d}^n(x). \tag{11}$$

From this equation, we find that the violation of CS should bring correction to $\sin^2\theta_w$, at least as shown in the formalism. In the remaining section, we will give a detailed calculation about $\delta R_{\rm csv}^-$ by using the light-cone meson-baryon fluctuation model and the light-cone quark-spectator-diquark model.

III. CHARGE SYMMETRY VIOLATION

In this section, we will perform the calculation of CSV by adopting the mechanisms of the light-cone meson-baryon fluctuation model [10] and the light-cone quark-spectator-diquark model [45]. In the light-cone meson-baryon fluctuation model, the hadronic wave function can be expressed by a series of light-cone wave functions multiplied by the Fock states. Usually, the proton wave function can be written as:

$$|p\rangle = |uud\rangle\Psi_{uud/p} + |uudg\rangle\Psi_{uudg/p} + \sum_{q\bar{q}}|uudq\bar{q}\rangle\Psi_{uudq\bar{q}/p} + \cdots. \tag{12}$$

Here, we adopt the approximation in Ref. [10], in which the intrinsic sea quarks of the proton are estimated by the meson-baryon fluctuations:

$$p(uud) \to \pi^+(u\bar{d})n(udd),$$
$$p(uud) \to \pi^+(u\bar{d})\Delta^0(udd),$$
$$p(uud) \to p(uud)\pi^0\left(\frac{1}{\sqrt{2}}[u\bar{u} - d\bar{d}]\right),$$
$$\ldots\ldots \tag{13}$$

and estimate the violation of charge symmetry coming from these fluctuations. In the same way, the neutron sea can be obtained, so that we can evaluate the relative probabilities of two different meson-baryon fluctuation states by comparing their relevant off-shell light-cone energies. In this paper, we choose the light-cone Gaussian type wave function as in Ref. [46] as a two-body wave function:

$$\Psi(M^2) = A_G \exp[-(M^2 - m_N^2)/8\alpha_D^2], \tag{14}$$

where $M^2 = \sum_{i=1}^{2} \frac{\mathbf{k}_\perp^2 + m_i^2}{x_i}$ is the invariant mass square for the meson-baryon state, m_N is the physical mass of the nucleon, α is the characteristic internal momentum scale, $\mathbf{k}_\perp^2$ is the internal transversal momentum, and A_G is the normalization constant.

In this paper, we recalculate the relative probabilities of $p \to \pi^+ n$ to $n \to \pi^- p$ and find that the ratios: $r^\pi_{p/n} = P(p \to \pi^+ n)/P(n \to \pi^- p)$, are very different for the different inputs of α_p and α_n and there is an excess of $n \to \pi^- p$ over $p \to \pi^+ n$ fluctuation. For example: there is an excess of 0.2% of $n \to \pi^- p$ over $p \to \pi^+ n$ fluctuation with assuming $P(p \to \pi^+ n) \simeq P(n \to \pi^- p) \simeq 0.15$, when $\alpha = 330$ MeV for both proton and neutron, $m_p = 938.27$ MeV and $m_n = 939.57$ MeV as the physical masses of proton and neutron, respectively. We also reexamine the case calculated in Ref. [46]: the ratio of $r^\pi_{p/n} = P(p \to \pi^+ n)/P(n \to \pi^- p) = 0.820$ which means that there is an excess of 3% of $n \to \pi^- p$ over $p \to \pi^+ n$ fluctuation, when $\alpha = 200$ MeV for the proton and $\alpha = 205$ MeV for the neutron (considering that the Coulomb attraction between π^- and p in the fluctuation $n \to \pi^- p$ may require larger relative motions of pions than in the fluctuation state $p \to \pi^+ n$). The calculations of other cases are showed in Table I. Besides that we also make an estimation about the ratios for probabilities between other fluctuations to $p(n) \to \pi^{+(-)} n(p)$ fluctuation and find that the ratios are relative smaller than the ratio $p \to \pi^+ n$ to $n \to \pi^- p$. In this work, we neglect the effects from other fluctuations, mainly because, firstly, the relative ratios of other fluctuations to the fluctuation $p(n) \to \pi^{+(-)} n(p)$ is small; secondly, the neutral fluctuations to chargeless meson π^0 *et al.* hardly contribute to the CSV effect; thirdly, there is only about 0.1% excess of $p \to K^+ \Lambda$ over $n \to K^0 \Lambda$ fluctuation, which is also rather small compared with the fluctuation $p \to \pi^+ n$ to $n \to \pi^- p$, with $P(p \to K^+ \Lambda) \simeq P(n \to K^0 \Lambda) \simeq 0.05$. Thus, we can obtain a crude model estimation for the excess of $n \to \pi^- p$ over $p \to \pi^+ n$ fluctuation states, which mainly arises from the small difference $m_n - m_p = 1.3$ MeV. This excess seems to be an important source for CSV in the valence and sea quark distributions between the proton and the neutron within the light-cone meson-baryon fluctuation model. When we only consider the fluctuation $n \to \pi^- p$ and $p \to \pi^+ n$, the CSV in the valence and sea quark distributions can be obtained by the u and d distributions in the proton and the neutron:

$$\begin{aligned} u^p(x) &= \int_x^1 \frac{dy}{y}\left[f_{\pi^+/\pi^+ n}(y) f_{u/u\bar{d}}\left(\frac{x}{y}\right) + f_{n/\pi^+ n}(y) f_{u/udd}\left(\frac{x}{y}\right)\right], \\ d^n(x) &= \int_x^1 \frac{dy}{y}\left[f_{\pi^-/\pi^- p}(y) f_{d/d\bar{u}}\left(\frac{x}{y}\right) + f_{p/\pi^- p}(y) f_{d/uud}\left(\frac{x}{y}\right)\right]. \end{aligned} \tag{15}$$

where

TABLE I. The correction to the NuTeV anomaly for different parameters

mass (MeV)	α (MeV)	$r_{p/n}$	$\delta R^-_{\rm csv}$
$m_{u(\bar{u})} = m_{d(\bar{d})} = 330$	$\alpha_p = \alpha_n = 330$	0.986	-0.45×10^{-5}
$m_{u(\bar{u})} = m_{d(\bar{d})} = 330$	$\alpha_p = 330$, $\alpha_n = 335$	0.924	-0.5×10^{-4}
$m_{u(\bar{u})} = m_{d(\bar{d})} = 330$	$\alpha_p = \alpha_n = 220$	0.971	-0.38×10^{-5}
$m_{u(\bar{u})} = m_{d(\bar{d})} = 330$	$\alpha_p = 200$, $\alpha_n = 205$	0.820	-0.6×10^{-4}
$m_{u(\bar{u})} = m_{d(\bar{d})} = 330$	$\alpha_p = 200$, $\alpha_n = 210$	0.701	-0.12×10^{-3}
$m_{u(\bar{u})} = 330$, $m_{d(\bar{d})} = 334$	$\alpha_p = \alpha_n = 330$	0.986	-0.37×10^{-4}
$m_{u(\bar{u})} = 330$, $m_{d(\bar{d})} = 334$	$\alpha_p = 330$, $\alpha_n = 335$	0.924	-0.84×10^{-4}
$m_{u(\bar{u})} = 330$, $m_{d(\bar{d})} = 334$	$\alpha_p = \alpha_n = 220$	0.971	-0.42×10^{-4}
$m_{u(\bar{u})} = 330$, $m_{d(\bar{d})} = 334$	$\alpha_p = 200$, $\alpha_n = 205$	0.820	-0.83×10^{-4}
$m_{u(\bar{u})} = 330$, $m_{d(\bar{d})} = 334$	$\alpha_p = 200$, $\alpha_n = 210$	0.701	-0.15×10^{-3}

$$f_{\pi^+/\pi^+n}\left(\frac{x}{y}\right) = \int_{-\infty}^{+\infty} \mathrm{d}\mathbf{k}_\perp \left| A_p \exp\left[-\frac{1}{8\alpha^2}\left(\frac{m_\pi^2 + \boldsymbol{k}_\perp^2}{x} + \frac{m_n^2 + \boldsymbol{k}_\perp^2}{1-x} - m_n^2\right)\right]\right|^2,$$
$$f_{\pi^-/\pi^-p}\left(\frac{x}{y}\right) = \int_{-\infty}^{+\infty} \mathrm{d}\mathbf{k}_\perp \left| A_n \exp\left[-\frac{1}{8\alpha^2}\left(\frac{m_\pi^2 + \boldsymbol{k}_\perp^2}{x} + \frac{m_p^2 + \boldsymbol{k}_\perp^2}{1-x} - m_p^2\right)\right]\right|^2, \tag{16}$$
$$f_{u/u\bar{d}}\left(\frac{x}{y}\right) = f_{d/d\bar{u}}\left(\frac{x}{y}\right) = \int_{-\infty}^{+\infty} \mathrm{d}\mathbf{k}_\perp \left| A_u \exp\left[-\frac{1}{8\alpha^2}\left(\frac{m_u^2 + \boldsymbol{k}_\perp^2}{x} + \frac{m_d^2 + \boldsymbol{k}_\perp^2}{1-x}\right)\right]\right|^2,$$
$$f_{u/uud}\left(\frac{x}{y}\right) = f_{d/udd}\left(\frac{x}{y}\right) = \int_{-\infty}^{+\infty} \mathrm{d}\mathbf{k}_\perp \left| A_D \exp\left[-\frac{1}{8\alpha^2}\left(\frac{m_{u(d)}^2 + \boldsymbol{k}_\perp^2}{x} + \frac{m_D^2 + \boldsymbol{k}_\perp^2}{1-x}\right)\right]\right|^2.$$

In the same way, we can also obtain the other distributions $u^n(x)$, $d^p(x)$, $\bar{u}^{p(n)}(x)$ and $\bar{d}^{p(n)}(x)$, from which one can obtain the result of CSV. As for the u and d valence quark distributions, one can calculate them in the light-cone quark-spectator-diquark model [45]:

$$u_v(x) = \frac{1}{2}a_S(x) + \frac{1}{6}a_V(x), \qquad d_v(x) = \frac{1}{3}a_V(x), \tag{17}$$

where $a_D(x)$ ($D = S$ or V, with S standing for scalar diquark Fock state and V standing for vector diquark state) denotes that the amplitude for the quark q is scattered while the spectator is in diquark state D [47], and can be written as:

$$a_D(x) \propto \int [\mathrm{d}\mathbf{k}_\perp]|\Psi_D(x, \mathbf{k}_\perp)|^2. \tag{18}$$

Here, we adopt the light-cone momentum wave function of the quark-spectator-diquark model

$$\Psi_D(x, \mathbf{k}_\perp) = A_D \exp\left[-\frac{1}{8\alpha_D^2}\left(\frac{m_q^2 + \mathbf{k}_\perp^2}{x} + \frac{m_D^2 + \mathbf{k}_\perp^2}{1-x}\right)\right]. \tag{19}$$

Using above equations, one can have the CSV effect and the correction to the NuTeV anomaly, which are given in Table I with the parameters: $m_\pi^\pm = 139.57$ MeV, $m_S = 600$ MeV, $m_V = 900$ MeV, $m_p = 938.27$ MeV and $m_n = 939.57$ MeV. In the Table I, $\alpha_{p(n)}$ denotes the internal momentum scale for $p \to \pi^+ n (n \to \pi^- p)$. From the Table, we find that the value of α has an important impact on the ratio $r_{p/n}$ and $\delta R_{\rm csv}^-$, while the role of mass difference is not so important. When the difference of α_p and α_n is larger, the ratio is larger and $\delta R_{\rm csv}^-$ has larger contribution to the measurement of Weinberg angle. However, as pointed by Miller in Ref. [48], the effect of CSV on the nucleon might be overestimated quantitatively in case of a larger difference between α_p and α_n, though such a difference is physically reasonable.

IV. CONCLUSION

As we have known, charge symmetry (CS) is an extremely well respected symmetry, and there are only some upper limit estimates on charge symmetry violation (CSV) of the parton distributions at present. Although there have been so many theoretical discussions about it, unfortunately, there is no direct way to verify the theoretical predictions. In this work, we calculated the CSV effect by using the light-cone meson-baryon fluctuation model and estimated the contribution from the CSV effect to the NuTeV anomaly. From Table I, we found that the correction to the NuTeV measurement is very small in magnitude unless the larger difference between internal momentum scales, i.e., α_p of the proton and α_n of the neutron, is considered. Therefore it might be necessary to study this effect more carefully, so that more reliable prediction can be made. As for whether the CSV effect is sizable or not, it would need further studies both theoretically and experimentally. Therefore more precision experiments should be carried out in the future to provide more detailed information on the parton structure of the nucleon.

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