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Influence of heavy-quark recombination on the nucleon strangeness asymmetry

Puze Gao

Institute of Theoretical Physics, Chinese Academy of Sciences, Beijing 100080, China

Bo-Qiang Ma*

School of Physics and State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing 100871, China

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The nucleon strange and antistrange distribution asymmetry is an important issue in the study of the nucleon structure. In this work, we show that the heavy-quark recombination processes from a perturbative QCD picture can give a sizable influence on the measurement of the nucleon strangeness asymmetry from charged-current charm production processes, such as the CCFR and NuTeV dimuon measurements. When the influence of heavy-quark recombination is considered, a positive effective $\delta S^-_{\rm HR}$ should be added to the initially extracted strangeness asymmetry $S^- \equiv \int dx[s(x) - \bar{s}(x)]x$, supporting the strangeness asymmetry S^- being positive, which is helpful to explain the NuTeV anomaly within the framework of the standard model.

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The nucleon strange and antistrange distributions are important quantities in the study of the nucleon structure, and a clear knowledge of them helps for a better understanding of some related phenomena in experiments. The nucleon strange quark-antiquark distribution asymmetry is predicted naturally by some nonperturbative models [1], and a positive strangeness asymmetry $S^- \equiv \int dx[s(x) - \bar{s}(x)]x$ has been shown [2–7] to be a promising mechanism to explain the NuTeV anomaly [8,9] within the framework of the standard model. Perturbative QCD at three-loops can also generate a strangeness asymmetry [10], however, the obtained magnitude is one order smaller to be relevant to the NuTeV anomaly.

In the measurement of the nucleon strangeness asymmetry, some valuable work has been done, though no conclusive result has been reached. Since strangeness asymmetry should be a very small quantity in inclusive deep inelastic scattering (DIS) cross sections, it is difficult to be extracted precisely. However, (anti-)neutrino induced charged-current charm production processes are quite sensitive to the (anti-)strange distribution, and thus can provide valuable information on the strangeness asymmetry. CCFR and NuTeV dimuon measurements [11–13] are of such experiments. Although earlier analysis of dimuon data did not show support of the nucleon strangeness asymmetry [11,13,14], a recent next to leading order (NLO) analysis of the NuTeV data with improved method does show some evidence of the nucleon strangeness asymmetry [15] $S^- = 0.001\,96 \pm 0.000\,46(\text{stat}) \pm 0.000\,45(\text{syst}) \pm 0.001\,28(\text{external})$. Meanwhile, global analyses have indicated positive strangeness asymmetry [3,16,17], such as the most recent work of Lai *et al.* [17], who include both CCFR and NuTeV dimuon data sets in their analysis, and produce the allowed range of $-0.001 < S^- < 0.005$ at 90% confidence level. These analyses suggest that S^- is likely positive.

In this work, we aim at checking the measurement of the nucleon strangeness asymmetry by including a perturbatively calculable QCD effect. We find that the heavy-quark recombination processes can produce a sizeable influence on the measurements with charged-current charm production process such as the CCFR and NuTeV dimuon measurements.

Heavy-quark recombination [18–20] combines a heavy quark, e.g., c quark, with a light antiquark $\bar{q}$ (or $\bar{c}$ with q) of relative small momentum in the hard scattering, and the $(c\bar{q})$ subsequently hadronizes into a D meson. References [19,20] employ simple perturbative QCD pictures and explain the charm photoproduction asymmetry and the leading particle effect [21,22] successfully. In the following, we show how the heavy-quark recombination influences the measurement of the nucleon strangeness asymmetry.

The CCFR and NuTeV dimuon measurements have provided important information on the strangeness degrees of freedom in the parton structure of the nucleon. These measurements both rely on the (anti-)neutrino induced charged-current charm production processes, with the leading order (LO) subprocesses being $\nu_\mu + s(d) \to \mu^- + c$ and $\bar{\nu}_\mu + \bar{s}(\bar{d}) \to \mu^+ + \bar{c}$. The produced $c(\bar{c})$ quark hadronizes and then decays partially into $\mu^+(\mu^-)$ to form a second μ. The oppositely signed dimuon events in experiment are then recorded for analysis of the nucleon strange distributions.

The CCFR and NuTeV experiments use iron as their target, and for simplicity, we take it as an isoscalar target. The strange quark-antiquark distribution asymmetry is directly related to the difference between neutrino and antineutrino induced dimuon differential cross section at

*Corresponding author
mabq@phy.pku.edu.cn

LO, which can be expressed as [23]

$$\frac{d^2\sigma_{\nu_\mu N\to\mu^-\mu^+X}}{d\xi dy} - \frac{d^2\sigma_{\bar{\nu}_\mu N\to\mu^+\mu^-X}}{d\xi dy} = \frac{G_F^2 S}{\pi r_w^2} f_c B_c \Big\{ \xi[s(\xi) - \bar{s}(\xi)]|V_{cs}|^2 + \frac{1}{2}\xi[d_v(\xi) + u_v(\xi)]|V_{cd}|^2 \Big\}, \tag{1}$$

where ξ is the light-cone momentum fraction of the struck quark and is related to the Bjorken scaling variable x through $\xi = x(1 + m_c^2/Q^2)$, $S = 2ME_\nu$ and $y = \nu/E_\nu$ with E_ν and ν being the incident energy and the energy transfer in the nucleon rest frame, $r_w \equiv 1 + Q^2/M_W^2$ and $f_c \equiv 1 - m_c^2/2ME_\nu\xi$, and B_c is the branching ratio for $c \to \mu^+ X$. The valence contribution in Eq. (1) is suppressed relative to strange contribution from their relative coefficients $|V_{cs}|^2 \sim 0.9$ and $|V_{cd}|^2 \sim 0.05$, thus this cross section difference of Eq. (1) is sensitive to the strange distribution asymmetry $S^-(\xi) \equiv \xi[s(\xi) - \bar{s}(\xi)]$.

The heavy-quark recombination processes as

$$\nu_\mu + \bar{q} \to \mu^- + \bar{s}(\bar{d}) + D(c\bar{q}), \tag{2}$$

$$\bar{\nu}_\mu + q \to \mu^+ + s(d) + \bar{D}(\bar{c}q), \tag{3}$$

(diagrams in Fig. 1) can also contribute to the dimuon final states through $D(\bar{D})$ decays: $D \to \mu^+ X$ and $\bar{D} \to \mu^- X$.

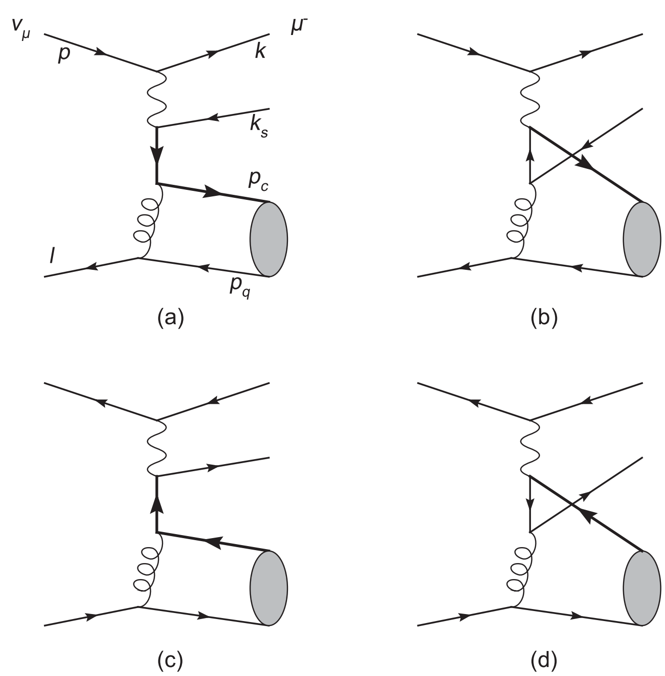

FIG. 1. (a) and (b) are diagrams for $c\bar{q}$ recombination into a D meson in a neutrino-induced process (2); (c) and (d) are diagrams for $\bar{c}q$ recombination into a $\bar{D}$ meson in an antineutrino-induced process (3). Thick lines are heavy quarks, and shaded blobs are D or $\bar{D}$ mesons.

These processes are possible to have sizable effects in the extraction of the nucleon strangeness asymmetry.

The processes of (2) and (3) contribute to the difference between neutrino and antineutrino induced dimuon differential cross section at higher order, which can be expressed as

$$\left[\frac{d^2\sigma_{\nu_\mu N\to\mu^-\mu^+X}}{d\xi dy} - \frac{d^2\sigma_{\bar{\nu}_\mu N\to\mu^+\mu^-X}}{d\xi dy}\right]_{\rm HR} = \sum_{q,D}\int dx[\bar{q}(x) - q(x)]\frac{d^2\hat{\sigma}_{D(c\bar{q})}}{d\xi dy}B_{D(c\bar{q})}, \tag{4}$$

where $d\hat{\sigma}_{D(c\bar{q})}$ denotes the cross section for the subprocess (2), which is identical to the cross section of subprocess (3) from charge symmetry. $B_{D(c\bar{q})}$ is the branching ratio for $D(c\bar{q}) \to \mu^+ X$. q denotes a light quark flavor from the nucleon, which could be u or d, and the $D(c\bar{q})$ meson could be either a scalar $^1S_0$ state or a vector $^3S_1$ state.

Such a contribution as Eq. (4) serves as an additional part in the extracted strange distribution asymmetry, such as the NLO analysis of the NuTuV dimuon data [15], because the recombination processes as Fig. 1 are not included in the ananysis. Thus the realistic strange distribution asymmetry $S^-_{\rm real}(\xi)$ should be the analyzed result $S^-_{\rm analy}(\xi)$ minus the contribution from heavy-quark recombination processes, which is a negative quantity from Eq. (4) since the nucleon structure ensures $\bar{q}(x) - q(x) < 0$ for $q = u, d$. From Eq. (1) and (4), one gets

$$S^-_{\rm real}(\xi) = S^-_{\rm analy}(\xi) + \delta S^-_{\rm HR}(\xi), \tag{5}$$

with

$$\delta S^-_{\rm HR}(\xi) \approx \frac{\pi r_w^2}{G_F^2 S f_c B_c |V_{cs}|^2}\sum_{q,D}\int dx[q(x) - \bar{q}(x)]\frac{d^2\hat{\sigma}_{D(c\bar{q})}}{d\xi dy} \cdot B_{D(c\bar{q})}, \tag{6}$$

where $\delta S^-_{\rm HR}(\xi) > 0$ since to minus a negative quantity is equivalent to plus a positive quantity. Thus the realistic strangeness asymmetry $S^-_{\rm real} \equiv \int d\xi S^-_{\rm real}(\xi)$ should be larger than the experimentally extracted value according to the contribution from the unaccounted recombination processes.

Now we proceed to estimate the size of $\delta S^-_{\rm HR}(\xi)$. We follow the method in Ref. [18] to calculate the heavy-quark recombination process. For the color singlet $^1S_0$ $D(c\bar{q})$ production, the following substitution is made in the parton amplitude:

$$v_j(p_q)\bar{u}_i(p_c) \to x_q \frac{\delta_{ij}}{N_c} m_c f_+ (\not{p}_c - m_c)\gamma_5. \tag{7}$$

Then set $p_q = x_q p_c$ in the amplitude and take the limit $x_q \to 0$. Thus the amplitude for color singlet $^1S_0$ state $D(c\bar{q})$ production is [diagrams in Fig. 1(a) and 1(b)]:

$$M_{in} = \frac{16\pi G_F \alpha_s m_c \delta_{in} f_+}{9\sqrt{2} r_w (2l \cdot p_c)} L^\mu \bar{v}(l) \gamma^\nu (\not{p}_c - m_c)\gamma_5 \times \left[\gamma_\nu \frac{\not{p} - \not{k} - \not{k}_s + m_c}{(p-k-k_s)^2 - m_c^2} \gamma_\mu (1-\gamma_5) + \gamma_\mu (1-\gamma_5) \frac{\not{l} - \not{k}_s}{(l-k_s)^2} \gamma_\nu \right] v(k_s), \quad (8)$$

where $L^\mu = \bar{u}(k)\gamma^\mu(1-\gamma_5)u(p)$ is the lepton current.

The δ_{ij} in Eq. (7) is the color factor for the color-singlet state, which is replaced by $\sqrt{6}T^a_{ij}$ for the color-octet state together with the nonperturbative parameter f_+ replaced by f_+^8. $\rho_1 = f_+^2$ and $\rho_8 = (f_+^8)^2$ will appear in cross sections to characterize the probability for a color-singlet and a color-octet ${}^1S_0(c\bar{q})$ state to hadronize into a state including a ${}^1S_0$ state $D(c\bar{q})$ meson. The subprocess cross section for ${}^1S_0$ state $D(c\bar{q})$ meson production thus can be expressed as

$$d\hat{\sigma}_{D(c\bar{q})} = d\hat{\sigma}[c\bar{q}({}^1S_0)_1] \cdot \rho_1 + d\hat{\sigma}[c\bar{q}({}^1S_0)_8] \cdot \rho_8. \quad (9)$$

The $d\hat{\sigma}[c\bar{q}({}^1S_0)_8]$ can be calculated to be different from $d\hat{\sigma}[c\bar{q}({}^1S_0)_1]$ by a single color factor of 1/8. Thus, $d\hat{\sigma}_{D(c\bar{q})}$ of Eq. (9) can be expressed as

$$d\hat{\sigma}_{D(c\bar{q})} = d\hat{\sigma}[c\bar{q}({}^1S_0)_1] \cdot \rho_{\rm eff}[c\bar{q}({}^1S_0) \to D(c\bar{q})], \quad (10)$$

with $\rho_{\rm eff} = \rho_1 + \rho_8/8$.

For ${}^3S_1$ state production of vector meson $D^*(c\bar{q})$, a similar substitution as Eq. (7) with the γ_5 replaced by $\not{\epsilon}$ is made in the parton amplitude, where ϵ is the polarization vector for the ${}^3S_1$ state. A similar expression as Eq. (10) can be obtained for the subprocess cross section of vector $D^*(c\bar{q})$ meson production,

$$d\hat{\sigma}_{D^*(c\bar{q})} = d\hat{\sigma}[c\bar{q}({}^3S_1)_1] \cdot \rho_{\rm eff}[c\bar{q}({}^3S_1) \to D^*(c\bar{q})]. \quad (11)$$

Physically, there may be spin-flipped transitions such as $c\bar{q}({}^1S_0) \to D^*(c\bar{q})$. While we have neglected such transitions, partly because the calculation of charm photoproduction [19] and the leading particle effect [20] have both set $\rho_{\rm sf} = 0$, and partly because the inclusion of these transitions will not greatly affect our result, since both $D(c\bar{q})$ and $D^*(c\bar{q})$ meson will decay similarly to μ^+.

The flavor-changing transitions, such as $c\bar{u} \to D^+(c\bar{d})$, are also neglected as Refs. [19,20], because these transitions are relatively suppressed in the large N_c limit of QCD, and also because the inclusion of such transitions will not affect our result notedly.

The number of free parameters can be greatly reduced from symmetries of the strong interaction. As discussed in Ref. [19], heavy-quark spin symmetry implies

$$\rho_{\rm eff}[c\bar{q}({}^1S_0) \to D(c\bar{q})] = \rho_{\rm eff}[c\bar{q}({}^3S_1) \to D^*(c\bar{q})], \quad (12)$$

and SU(3) light quark flavor symmetry indicates, for example,

$$\rho_{\rm eff}[c\bar{u}({}^1S_0) \to D^0] = \rho_{\rm eff}[c\bar{d}({}^1S_0) \to D^+]. \quad (13)$$

Thus, only one parameter is left:

$$\rho_{\rm sm} \equiv \rho_{\rm eff}[c\bar{d}({}^1S_0) \to D^+] = \rho_{\rm eff}[c\bar{d}({}^3S_1) \to D^{*+}] = \rho_{\rm eff}[c\bar{u}({}^1S_0) \to D^0] = \rho_{\rm eff}[c\bar{u}({}^3S_1) \to D^{*0}]. \quad (14)$$

Thus, for isoscalar target, the $\delta S^-_{\rm HR}(\xi)$ of Eq. (6) can be expressed as

$$\delta S^-_{\rm HR}(\xi) \approx \frac{\pi r_w^2}{G_F^2 S f_c |V_{cs}|^2 B_c} \int dx [u_v(x) + d_v(x)] \times \left[\frac{d\hat{\sigma}[c\bar{q}({}^1S_0)_1]}{d\xi dy} b_1 + \frac{d\hat{\sigma}[c\bar{q}({}^3S_1)_1]}{d\xi dy} b_2 \right] \cdot \rho_{\rm sm}, \quad (15)$$

where $b_1 = (B_{D^+} + B_{D^0})/2$ and $b_2 = (B_{D^{*+}} + B_{D^{*0}})/2$.

The subprocess cross section can be calculated straightforwardly from the parton amplitudes (with the parameter f_+ extracted out for $\rho_{\rm sm}$). Since the subprocess is a $2 \to 3$ process, there are five independent variables in the subprocess cross section. From the symmetry of the scattered μ^- around the incident direction, four independent variables are left, where two variables are transformed to ξ and y (or Q^2) and the other two are integrated out. Thus for $\delta S^-_{\rm HR}(\xi)$ of fixed Q^2, the integration is totally of 3 dimensions including the integral on x in Eq. (15). The boundaries of the integration are determined from the allowed physical phase space.

We use the CTEQ6L parton distributions for the nucleon [24], and the running coupling constant α_s is as specified in CTEQ6L. We take $m_c = 1.5$ GeV and set the factorization scale to be $\sqrt{p_{c\perp}^2 + m_c^2}$. Since the two muons in NuTeV experiment are required to have energy greater than 5 GeV, we try similar cuts for the produced μ and the charmed meson in our integration. We find that the cross section from heavy-quark recombination process decreases very slowly with the increase of the cut on the energy of the produced charmed meson. Thus the recombination processes are not suppressed by the cuts in experiments.

Figure 2 shows our result of $\delta S^-_{\rm HR}(\xi)$ for $E_\nu = 160$ GeV, $Q^2 = 20$ GeV^2 and $\rho_{\rm sm} = 0.15$. Such E_ν and Q^2 are approximate averaged incident energy and Q^2 in the NuTeV dimuon experiment [13]. $\rho_{\rm sm}$ is the nonpertubative parameter for the heavy-quark recombination and $\rho_{\rm sm} = 0.15$ is the LO fitted result from charm photoproduction asymmetry [19]. The branching ratios and $|V_{cs}|$ are taken to be the central values from Ref. [25].

From Fig. 2, one sees that $\delta S^-_{\rm HR}(\xi)$ is a valencelike distribution, with its peak in the range of $\xi = 0.1$–0.3. From Eq. (5), the realistic strange distribution asymmetry is the sum of the analyzed result of dimuon experiments and the effective contribution from heavy-quark recombination $\delta S^-_{\rm HR}(\xi)$. We can estimate $\delta S^-_{\rm HR}$ by integrating $\delta S^-_{\rm HR}(\xi)$ over ξ, and get $\delta S^-_{\rm HR} \approx 0.0023$ for $\rho_{\rm sm} = 0.15$.

Such a value of $\delta S^-_{\rm HR}$ significantly enhances the measured strangeness asymmetry to a larger positive value,

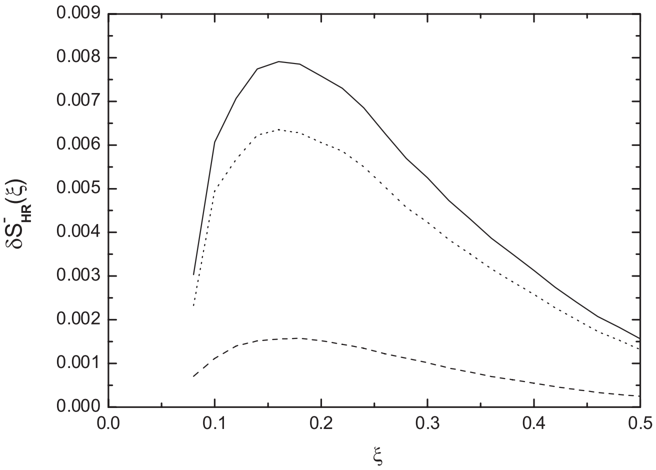

FIG. 2. $\delta S^-_{\rm HR}(\xi)$ for $E_\nu = 160$ GeV, $Q^2 = 20$ GeV^2 and $\rho_{\rm sm} = 0.15$. The dashed curve is the contribution from $^1S_0$ state; the dotted curve is the contribution from $^3S_1$ state; and the solid curve is their sum, the $\delta S^-_{\rm HR}(\xi)$.

since $S^-_{\rm real} = S^-_{\rm analy} + \delta S^-_{\rm HR}$. Recent NLO analysis of the NuTeV dimuon data provides positive strangeness asymmetry centered at 0.001 96 [15]. With the correction of the heavy-quark recombination, the central value of the realistic strangeness asymmetry could be $S^-_{\rm real} \approx 0.0043$.

Such a value of the strangeness asymmetry can explain the NuTeV anomaly to a large extent. NuTeV anomaly arises from the large discrepancy of the NuTeV measurement of the $\sin\theta_w$ with the standard model prediction, and becomes a hot debated area in recent years. The NuTeV measurement of the $\sin\theta_w$ relies on the hypothesis that strange and antistrange distributions are symmetric. When this assumption is violated, their result on $\sin\theta_w$ will change. The influence of nonzero $S^-(\xi)$ to the result of $\sin\theta_w$ is most sensitive in the range $\xi = 0.06 - 0.3$ (Fig. 1 in Ref. [9]), and such range is just the position of the peak of $\delta S^-_{\rm HR}(\xi)$. Thus the nonvanishing $\delta S^-_{\rm HR}(\xi)$ and $S^-_{\rm real}$ may have a large effect in the NuTeV measurement of $\sin\theta_w$. In such sensitive range, a positive strangeness asymmetry S^- of the order 0.005 can fill the gap between theory and the experiment of the NuTeV anomaly. The value of $\delta S^-_{\rm HR} \approx 0.0023$ for $\rho_{\rm sm} = 0.15$ alone can provide nearly half of the strangeness asymmetry needed to explain the NuTeV anomaly.

In our calculation, there are some uncertainties in the choice of the factorization scale μ and the parameter m_c. The impact for different choice of m_c on our result is small (within 5% for $m_c = 1.5 \pm 0.3$ GeV). While for different choice of the factorization scale, the influence is large. Reference [19] calculates charm photoproduction with factorization scale $\sqrt{p_\perp^2 + m_c^2}$, where $p_\perp$ is the transverse momentum of the produced D relative to the incident photon direction. In the process of this work, the photon is replaced by the W boson, and thus the calculation we take is performed for $\mu_0 = \sqrt{p_{c\perp}^2 + m_c^2}$, where $p_{c\perp}$ is the transverse momentum of the produced D relative to the W boson direction in the nucleon rest frame. The result nearly trebles when $\mu = \mu_0/2$, and the result reduces nearly by half when $\mu = 2\mu_0$. The uncertainties may imply that higher order effects are still important. Reference [19] reports a small effect on the predicted asymmetry when varying the factorization scale, where only the ratios of the cross sections are concerned, and scale dependence might be canceled in that case.

The parameter $\rho_{\rm sm}$ still has some uncertainty in its value. In Fig. 2, we use $\rho_{\rm sm} = 0.15$, which is from the fit of charm photoproduction asymmetry at LO [19]. As discussed in Ref. [19], there is at least 30% uncertainty in this parameter $\rho_{\rm sm}$ due to finite heavy quark mass, SU(3) breaking and $1/N_c$ corrections, and more over, $\rho_{\rm sm}$ should be multiplied by a K factor if NLO corrections in photo-gluon fusion are incorporated in their calculation. Thus, parameter $\rho_{\rm sm}$ could well be as large as 0.3. Such a value for $\rho_{\rm sm}$ means $\delta S^-_{\rm HR} \approx 0.0046$, which alone is sufficient to explain the NuTeV anomaly. On the other hand, $\rho_{\rm sm}$ could be smaller than 0.15, such as the LO fit from the leading particle effect [20], $\rho_1 = 0.06$, where ρ_1 is the parameter for the color-singlet state, which is different from $\rho_{\rm sm}$ but their size should be compatible. If we take $\rho_{\rm sm} = 0.06$, we get $\delta S^-_{\rm HR} \approx 0.0009$. Such a $\delta S^-_{\rm HR}$ alone is too small to explain the NuTeV anomaly, however, this $\delta S^-_{\rm HR}$ could still shift the dimuon result to a larger positive value, and make the allowed range of S^- entirely positive. More precision determination of the parameters for the heavy-quark recombination and a reanalysis of the dimuon events with consideration of the heavy-quark recombination processes will be helpful to a better knowledge of the nucleon strangeness asymmetry.

Our work implies the significance of using the heavy-quark recombination mechanism [18–20], i.e., a perturbatively calculable QCD effect, to reveal the strangeness asymmetry. Let us recall that a previous LO analysis [9] of nucleon strangeness asymmetry by NuTeV collaboration reported a negative value $S^- = -0.0027 \pm 0.0013$, whereas their new NLO analysis [15] gave a positive value centered at 0.001 96 as mentioned above. The difference between the two values is 0.0047, which is of the same order as the $\delta S^-_{\rm HR}$ estimated in this work. This again supports our work to take higher order effects into account.

In summary, we investigated the influence of heavy-quark recombination in (anti-)neutrino induced charged-current charm production processes on the measurement of the nucleon strange distribution asymmetry. Our result shows that the influence could be quite sizable and the realistic strangeness asymmetry S^- should be larger than the initially experimental results. From our investigation and the result of recent experimental analysis, the nucleon strangeness asymmetry S^- should be positive and could be large enough to explain the NuTeV anomaly.

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