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Probing nucleon strange asymmetry from charm production in neutrino deep inelastic scattering

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Abstract. We propose a means to detect the nucleon strange quark–antiquark asymmetry, which is predicted as a non-perturbative effect, but still unchecked directly by available experiments. The difference for the $D(c\bar{q})$ and $\bar{D}(\bar{c}q)$ meson production cross sections in neutrino and antineutrino induced charged current deep inelastic scattering is illustrated to be sensitive to the nucleon strange asymmetry. A prospect is given and the effect due to the light quark fragmentation is also discussed for the extraction of the strange asymmetry in future experiments.

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1 Introduction

The nucleon structure is a natural laboratory for understanding QCD and is worth to study for its own sake. The nucleon strange quark–antiquark asymmetry is an interesting feature predicted as a natural consequence of the non-perturbative aspect of the nucleon [1–3]. Recently, the nucleon strange asymmetry has been suggested [4–9] as a promising mechanism to explain the NuTeV anomaly [10, 11] within the framework of the standard model.

While the experimental evidence for such an asymmetry is still inconclusive, there are some approaches such as the global analysis of deep inelastic scattering (DIS) data [4, 12], which show a favor for an asymmetric strange sea, in agreement qualitatively with the intrinsic sea theory. On the other hand, the CCFR next-to-leading-order (NLO) analysis of the neutrino induced dimuon production result favors a symmetric strange sea [13], which is also the case of a recent NuTeV analysis [14]. It seems that more precise and dedicated research is needed to address the problem in a clear way.

The measurement of the strange quark distribution relies on charged current (CC) DIS processes. One method is through parity violating structure functions for an isoscalar target in CC DIS: $F_3^{\nu} - F_3^{\bar{\nu}} = 2[s(x) + \bar{s}(x) - c(x) - \bar{c}(x)]$, which gives the total distribution of the strange sea. Another way is through the combination of the CC parity conserving structure function F_2^{ν} with the charged lepton DIS structure function F_2^{μ}, for an isoscalar target, $\frac{5}{6}F_2^{\nu} - 3F_2^{\mu} = x\left[\frac{4}{3}s(x) - \frac{1}{3}\bar{s}(x) - c(x)\right]$. Such an idea has been applied using high statistics neutrino and charged lepton nucleon DIS data, and the result at low x shows a sizable disagreement with the direct measurement from the CCFR dimuon result [15]. The extraction of a small quantity from the difference of two large quantities may suffer from systematic uncertainties, which also seems to be the case for the extraction of the strange asymmetry by CC parity conserving structure functions: $F_2^{\nu} - F_2^{\bar{\nu}} = 2x[s(x) - \bar{s}(x)]$.

A method free from the above drawback is to use the charged current charm production process, which is the main idea of the CCFR and NuTeV dimuon experiments [13,16,17], with its leading-order (LO) subprocesses being $\nu_\mu s \to \mu^- c$ and $\nu_\mu d \to \mu^- c$. The latter subprocess is Cabibbo suppressed; thus the charm production in a ν-induced process is most sensitive to the strange quark distribution in the nucleon. Similarly, the anticharm production in a $\bar{\nu}$-induced process is sensitive to the antistrange quark distribution, as the corresponding partner subprocesses are $\bar{\nu}_\mu \bar{s} \to \mu^+ \bar{c}$ and $\bar{\nu}_\mu \bar{d} \to \mu^+ \bar{c}$, with the latter subprocess being Cabibbo suppressed.

The oppositely charged dimuon signature is easy to identify and measure in massive detectors, which allow for the collection of high statistics data samples, e.g., the CCFR experiment has a sample of data with 5030 ν_μ-induced events and 1060 $\bar{\nu}_\mu$-induced events, and the NuTeV has 5102 ν_μ-induced events and 1458 $\bar{\nu}_\mu$-induced events [17]. However, these two experiments neither show a strong support for an asymmetric strange sea, nor can they rule it out [1,5,12]. There are uncertainties in the estimation of the semi-muonic decay of the charmed hadrons [13,18], e.g., the

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average semi-leptonic branching ratio for ν- and $\bar{\nu}$-induced events was only constrained by $\frac{\bar{B}_c-\bar{B}_{\bar{c}}}{\bar{B}_c} = \frac{0.011\pm0.011}{0.1147} \sim 0$–20% [13]. Besides, the interplay of strange asymmetry and the light quark fragmentation (LQF) effect, as will be discussed in Sect. 4, can only be treated more clearly in inclusive measurements of charged and neutral charm productions. Thus a direct measurement of charmed hadrons produced in ν- and $\bar{\nu}$-induced CC DIS will provide more valuable information to probe the s and $\bar{s}$ distributions of the nucleon. It is the purpose of this work to show that inclusive charm productions in neutrino and antineutrino induced CC DIS processes will be a promising way to detect the strange quark–antiquark asymmetry.

2 Charged current charm production

The differential cross section for charmed hadron H^+ production in neutrino induced CC DIS can be factorized as

$$\frac{\mathrm{d}^3\sigma_{\nu_\mu N\to\mu^- H^+ X}}{\mathrm{d}\xi\mathrm{d}y\mathrm{d}z} = \sum_q \frac{\mathrm{d}^2\sigma_{\nu_\mu N\to\mu^- qX}}{\mathrm{d}\xi\mathrm{d}y} D_q^{H^+}(z)\,, \quad (1)$$

where the function $D_q^{H^+}(z)$ describes the fragmentation of a quark q into the charmed hadron H^+, with z being the momentum fraction of the quark q carried by the produced hadron H^+. For the purpose of this article, the charmed hadron H^+ is taken to be a $D^+(c\bar{d})$ or a $D^0(c\bar{u})$ meson, with H^- denoting its antiparticle $D^-(\bar{c}d)$ or $\bar{D}^0(\bar{c}u)$.

It is generally believed that the possibility for light quark fragmentation into charmed hadrons is very small. For example, the Lund string model implemented in some popular Monte Carlo programs predicts a suppression proportional to $\exp(-bm_q^2)$ for $q\bar{q}$ production in the process of hadronization [19]. With the knowledge of the strange suppression being $\lambda \sim 0.3$ [20, 21], the suppression for charm will be lower than 10^{-4}, which can be safely neglected.

In this case, at leading order, only the $\nu_\mu s \to c\mu^-$ and $\nu_\mu d \to c\mu^-$ subprocesses contribute to charmed hadron production. For an isoscalar target and neglecting target mass effects, the leading-order differential cross section for charm production is given by [13, 16]

$$\frac{\mathrm{d}^2\sigma_{\nu_\mu N\to\mu^- cX}}{\mathrm{d}\xi\mathrm{d}y} = \frac{2G^2 M E_\nu}{\pi(1+Q^2/M_W^2)^2}\left(1-\frac{m_c^2}{2ME_\nu\xi}\right) \quad (2)$$
$$\times\xi\left[\frac{d(\xi)+u(\xi)}{2}|V_{cd}|^2 + s(\xi)|V_{cs}|^2\right],$$

where ξ is the momentum fraction of the struck quark in the infinite momentum frame. It is introduced with the consideration of a non-negligible charm quark mass and is related to the Bjorken scaling variable x through (neglecting light quark mass) $\xi \approx x(1+m_c^2/Q^2)$, referred to as slow-rescaling. The term $(1-m_c^2/2ME_\nu\xi)$ in (2) is introduced as an energy threshold for charm production and is supported by experiments [22].

3 Probing the nucleon strange asymmetry

The differential cross sections for charmed hadrons, namely, H^+ (D^+ or D^0) and H^- (D^- or $\bar{D}^0$), produced in ν- and $\bar{\nu}$-induced CC DIS respectively, are closely related to the s and $\bar{s}$ distributions of the nucleon, and their difference, as can be seen in the following, is quite sensitive to the nucleon strange asymmetry.

Neglecting the light quark fragmentation effect, and using (2) and its corresponding partner process for $\bar{c}$ production $\bar{\nu}_\mu N \to \bar{c}\mu^+ X$, we can write the difference between the H^+ and H^- production cross sections in CC DIS:

$$f_{H^+} - f_{H^-} \equiv \frac{\mathrm{d}^3\sigma_{\nu_\mu N\to\mu^- H^+ X}}{\mathrm{d}\xi\mathrm{d}y\mathrm{d}z} - \frac{\mathrm{d}^3\sigma_{\bar{\nu}_\mu N\to\mu^+ H^- X}}{\mathrm{d}\xi\mathrm{d}y\mathrm{d}z}$$
$$= \frac{2G^2 M E_\nu}{\pi(1+Q^2/M_W^2)^2}\left(1-\frac{m_c^2}{2ME_\nu\xi}\right)$$
$$\times\left\{\frac{1}{2}\xi[d_v(\xi)+u_v(\xi)]|V_{cd}|^2 \right. \quad (3)$$
$$\left. +\xi[s(\xi)-\bar{s}(\xi)]|V_{cs}|^2\right\} D_c^{H^+}(z)\,,$$

where the charge symmetry $D_c^{H^+}(z) = D_{\bar{c}}^{H^-}(z)$ for the fragmentation process is assumed, and $u_v(\xi) \equiv u(\xi)-\bar{u}(\xi)$ and $d_v(\xi) \equiv d(\xi)-\bar{d}(\xi)$ are the valence quark distributions of the proton.

From (3), one sees that two terms, $\frac{1}{2}\xi[d_v(\xi)+u_v(\xi)]$ and $\xi[s(\xi)-\bar{s}(\xi)]$, contribute to the cross section difference $f_{H^+}-f_{H^-}$, with $|V_{cd}|^2 \simeq 0.05$ and $|V_{cs}|^2 \simeq 0.95$ [23] being their respective weights. The strange asymmetric part of (3) can be estimated from an integral on the variable ξ, to contribute a fraction

$$P_{\mathrm{SA}} \approx \frac{2S^-|V_{cs}|^2}{Q_V|V_{cd}|^2 + 2S^-|V_{cs}|^2}\,, \quad (4)$$

to the integral of the cross section difference $\int \mathrm{d}\xi(f_{H^+} - f_{H^-})$. Here, S^- and Q_V are defined as $S^- \equiv \int \xi[s(\xi) - \bar{s}(\xi)]\mathrm{d}\xi$ and $Q_V \equiv \int \xi[d_v(\xi)+u_v(\xi)]\mathrm{d}\xi$.

In Table 1, the results of the strange asymmetry from some models accounting for the NuTeV anomaly are listed, together with our estimations of the contributions due to the strange asymmetry to the cross section difference $f_{H^+} - f_{H^-}$, namely, the ξ integrated fraction P_{SA}.

As shown in Table 1, from the model calculations [6–9] that can explain the NuTeV anomaly, the strange asymmetry contributes a sizable proportion (12% $\sim$ 40%) to the cross section difference. Note that the distribution functions $\xi[d_v(\xi)+u_v(\xi)]$ and $\xi[s(\xi)-\bar{s}(\xi)]$ may evolve with Q^2, turning flatter and shifting towards the smaller ξ region as Q^2 increases. However, their relative feature will remain and the proportion of S^- to Q_V will be of the same order in larger Q^2 and in Q_0^2. Thus, as to their relative feature, it does not matter much whether the parton distributions are taken at Q_0^2 or at larger Q^2. Since the peak of $\xi[s(\xi)-\bar{s}(\xi)]$ is confined in a narrower ξ region than $\xi[d_v(\xi)+u_v(\xi)]$, its contribution is expected to be more prominent than the

Table 1. Contributions of $s/\bar{s}$ asymmetry to the NuTeV anomaly and to $f_{H^+} - f_{H^-}$

Models	Q^2	To NuTeV anomaly	$2S^-/Q_V$	To $f_{H^+} - f_{H^-}$
Ding–Ma [6]	Q_0^2	$30\% \sim 80\%$	$0.007 \sim 0.018$	$12\% \sim 26\%$
Alwall–Ingelman [7]	$20\,\mathrm{GeV}^2$	30%	0.009	15%
Ding–Xu–Ma [8]	Q_0^2	$60\% \sim 100\%$	$0.014 \sim 0.022$	$21\% \sim 29\%$
Wakamatsu [9]	$16\,\mathrm{GeV}^2$	$70\% \sim 110\%$	$0.022 \sim 0.035$	$30\% \sim 40\%$

integrated one in Table 1. Thus it is promising to measure the strange quark–antiquark asymmetry from $f_{H^+} - f_{H^-}$.

Compared to the sum of the cross sections $f_{H^+} + f_{H^-}$, the cross section difference $f_{H^+} - f_{H^-}$ is not a very small quantity, as can be seen from the ratio of their integrals,

$$R \equiv \frac{\int \mathrm{d}\xi (f_{H^+} - f_{H^-})}{\int \mathrm{d}\xi (f_{H^+} + f_{H^-})} \approx \frac{Q_V |V_{cd}|^2 + 2S^- |V_{cs}|^2}{(Q_V + 2Q_S)|V_{cd}|^2 + 2S^+ |V_{cs}|^2}\,, \tag{5}$$

where $Q_S \equiv \int \xi[\bar{u}(\xi)+\bar{d}(\xi)]\mathrm{d}\xi$ and $S^+ \equiv \int \xi[s(\xi)+\bar{s}(\xi)]\mathrm{d}\xi$. With a calculation of the Q_V, Q_S and S^+ from the CTEQ5 parametrization at $Q^2 = 16\,\mathrm{GeV}^2$, together with $|V_{cd}|^2 = 0.05$ and $|V_{cs}|^2 = 0.95$, the ratio R is estimated to be about 20% (25%) for $2S^-/Q_V$ being 0.007 (0.022) from Table 1. Thus the cross section difference $f_{H^+} - f_{H^-}$ is a significant quantity that can be extracted from the semi-inclusive differential cross sections.

Neutrino experiments with an emulsion target, like the CHORUS detector, are ideal for the study of charmed hadron production. Compared to dimuon studies, it has a much lower level of background and is free from the uncertainties that exist in charm muonic weak decay processes [18]. And for the statistics, CHORUS reported in total about 94000 neutrino CC events located and fully reconstructed, in which about 2000 charm events were observed [24, 25]. This has been compatible with dimuon statistics. If such (or higher) statistics can be achieved with both neutrino and antineutrino beams of high energies in future experiments, the question of the strange asymmetry is promising to be settled.

4 Light quark fragmentation

The possibility that a light quark fragments into charmed hadrons (associated charm production) can be an interesting effect of non-perturbative QCD, and it has been explored [26] to explain the unexpected high rate of like-sign dimuon production from many neutrino experiments [27–29]. Although the field has been inactive for years, and in practice people generally assume the light quark fragmentation (LQF) to be negligible, the physical possibility of a small contribution is not ruled out. In fact, according to our considerations, neutrino experiments can be slightly different from e^+e^- experiments in this respect. The scattered light quark with high momentum can pick up a charm quark or antiquark from the nucleon sea to form a D meson, and the larger the energy of the light quark, the better the ability that it can pick up a charm quark from the sea. This energy dependence is apparent in prompt like-sign dimuon production rates in many experiments [27–29]. Since the scattered quark has most of the energy in the collision, it is much more promising to pick up the charm quark from the nucleon sea than other produced quarks in the fragmentation process. Thus according to our considerations such a fragmentation as $u \to \bar{D}^0(\bar{c}u)$, $d \to D^-(\bar{c}d)$ can possibly be non-negligible in high energy neutrino experiments.

In case that a light quark can fragment into charmed hadrons, the process can manifest itself in a number of observables, such as the prompt like-sign dilepton and trimuon productions in high energy neutrino experiments [30], direct observations of two charmed hadrons in a nuclear emulsion target [31], and charm production in hadron collisions [32, 33]. Among these, the prompt like-sign dimuon productions have been the most seriously studied and we will use some of the data for a quantitative estimate of light quark fragmentation function and its influence on the extraction of strange asymmetry from CC charm production processes.

Prompt like-sign dimuons ($\mu^-\mu^-$) can be produced through the process $\nu + d \to \mu^- + u$, with the scattered u to fragment into a $\bar{D}^0(\bar{c}u)$ or a $\bar{D}^{*0}(\bar{c}u)$ meson. Its differential cross section can be expressed as

$$\frac{\mathrm{d}^3\sigma_{\nu N \to \mu^-\mu^- X}}{\mathrm{d}x\mathrm{d}y\mathrm{d}z} = \frac{2G^2 M E_\nu |V_{ud}|^2}{\pi(1 + Q^2/M_W^2)^2} x \frac{u(x) + d(x)}{2} D_q(z) B_{\bar{D}^0}\,, \tag{6}$$

where $D_q(z)$ is the total fragmentation function for a light quark to fragment into charmed hadrons, defined as $D_q(z) \equiv D_q^D(z) + D_q^{D^*}(z)$, with $D_q^D(z) \equiv D_u^{\bar{D}^0}(z) = D_{\bar{u}}^{D^0}(z) = D_d^{D^-}(z) = D_{\bar{d}}^{D^+}(z)$ and $D_q^{D^*}(z) \equiv D_u^{\bar{D}^{*0}}(z) = D_{\bar{u}}^{D^{*0}}(z) = D_d^{D^{*-}}(z) = D_{\bar{d}}^{D^{*+}}(z)$ simply assumed. Note here that $D_q(z)$ is energy dependent in analogy to containing an energy suppression factor for charm production. $B_{\bar{D}^0}$ is the inclusive muonic decay ratio for $\bar{D}^0$ meson decay $\bar{D}^0 \to \mu^- X$, which is the same for $\bar{D}^{*0}$ meson, since all $\bar{D}^{*0}$ will decay into $\bar{D}^0$ at first.

Similarly, the differential cross section for prompt $\mu^+\mu^+$ production in $\bar{\nu}$-induced DIS on an isoscalar target is

$$\frac{\mathrm{d}^3\sigma_{\bar{\nu} N \to \mu^+\mu^+ X}}{\mathrm{d}x\mathrm{d}y\mathrm{d}z} = \frac{2G^2 M E_\nu |V_{ud}|^2}{\pi(1 + Q^2/M_W^2)^2} x \frac{\bar{u}(x) + \bar{d}(x)}{2} D_q(z) B_{D^0}\,. \tag{7}$$

Many experimental groups have reported positive results on prompt like-sign dimuon production. Among them the CDHSW [27] and CCFR [28] data have a high precision and show much consistency with each other. Another high precision experiment, CHARM [29], which has reported a much higher $\mu^-\mu^-$ production rate, received doubts on its estimate of the π/K decay background [27]. Besides, its kinematic cut $p_\mu > 4\,\mathrm{GeV}$, which is lower than other experiments ($p_\mu > 9\,\mathrm{GeV}$), can permit more $\mu^-\mu^-$ events and thus can produce a higher rate. Since the kinematic cut on the second μ reduces event number and thus the rate of like-sign dimuons in CC events, $\mu^-\mu^-/\mu^-$, it will probably underestimate the light quark fragmentation (LQF) effect in the use of the $\mu^-\mu^-/\mu^-$ data. On the other hand, the ratio of prompt like-sign dimuons to opposite-sign dimuons $\mu^-\mu^-/\mu^-\mu^+$ is expected to be less influenced by the kinematic cut, as both second muons receive the same kinematic cut. Thus, we consider it appropriate to use the $\mu^-\mu^-/\mu^-\mu^+$ data other than $\mu^-\mu^-/\mu^-$ data to estimate the LQF effect.

The differential cross section for $\mu^-\mu^+$ production in ν-induced CC DIS on an isoscalar target is given by

$$\frac{\mathrm{d}^3\sigma_{\nu N\to\mu^-\mu^+X}}{\mathrm{d}\xi\mathrm{d}y\mathrm{d}z} = \frac{2G^2ME_\nu}{\pi(1+Q^2/M_W^2)^2} f_c\bar{B}_c(z) \times\left[\xi\frac{d(\xi)+u(\xi)}{2}|V_{cd}|^2+\xi s(\xi)|V_{cs}|^2\right] +\delta\left(\frac{\mathrm{d}^3\sigma_{\nu N\to\mu^-\mu^+X}}{\mathrm{d}\xi\mathrm{d}y\mathrm{d}z}\right)_{\mathrm{LQF}}, \quad (8)$$

where f_c is the charm suppression factor

$$f_c \equiv 1 - m_c^2/2ME_\nu\xi,$$

and $\bar{B}_c(z)$ is the average muonic decay ratio for the charmed hadrons produced in CC DIS, $\bar{B}_c(z)=\sum_H D_c^H(z)B_H$, with H being D^0, D^{*0}, D^+, D^{*+} .... The last term marked with LQF is the light quark fragmentation contribution to $\mu^-\mu^+$ production ($\nu\bar{u}\to\mu^-\bar{d}\to\mu^-D^+(D^{*+})X'\to\mu^-\mu^+X$),

$$\delta\left(\frac{\mathrm{d}^3\sigma_{\nu N\to\mu^-\mu^+X}}{\mathrm{d}\xi\mathrm{d}y\mathrm{d}z}\right)_{\mathrm{LQF}} = \frac{2G^2ME_\nu|V_{ud}|^2}{\pi(1+Q^2/M_W^2)^2}D_q(z)\bar{B}_{D^{(*)+}} \times\left[x\frac{\bar{d}(x)+\bar{u}(x)}{2}\right](1-y)^2, \quad (9)$$

where $\bar{B}_{D^{(*)+}}$ is the average muonic decay ratio of the D^+ and D^{*+} mesons produced from $\bar{d}$ quark fragmentation, $\bar{B}_{D^{(*)+}} = \frac{1}{D_q}(D_q^D B_{D^+} + D_q^{D^*}B_{D^{*+}})$. Since D^{*+} decays to D^0 with the branching ratio $B\simeq 67.7\%$ [23], and to D^+ with the ratio $1-B$, we have $\bar{B}_{D^{(*)+}} = bBB_{D^0} + (1-bB)B_{D^+}$, with $b\equiv D_q^{D^*}/D_q$.

Similarly, the differential cross section for $\mu^+\mu^-$ production in $\bar{\nu}$-induced CC DIS on an isoscalar target reads

$$\frac{\mathrm{d}^3\sigma_{\bar{\nu}N\to\mu^+\mu^-X}}{\mathrm{d}\xi\mathrm{d}y\mathrm{d}z} = \frac{2G^2ME_\nu}{\pi(1+Q^2/M_W^2)^2} f_c\bar{B}_{\bar{c}}(z) \times\left[\xi\frac{\bar{d}(\xi)+\bar{u}(\xi)}{2}|V_{cd}|^2+\xi\bar{s}(\xi)|V_{cs}|^2\right] +\delta\left(\frac{\mathrm{d}^3\sigma_{\bar{\nu}N\to\mu^+\mu^-X}}{\mathrm{d}\xi\mathrm{d}y\mathrm{d}z}\right)_{\mathrm{LQF}}, \quad (10)$$

with

$$\delta\left(\frac{\mathrm{d}^3\sigma_{\bar{\nu}N\to\mu^+\mu^-X}}{\mathrm{d}\xi\mathrm{d}y\mathrm{d}z}\right)_{\mathrm{LQF}} = \frac{2G^2ME_\nu|V_{ud}|^2}{\pi(1+Q^2/M_W^2)^2}D_q(z)\bar{B}_{D^{(*)-}} \times\left[x\frac{d(x)+u(x)}{2}\right](1-y)^2. \quad (11)$$

CDHSW has reported the prompt dimuon rates $\sigma_{\mu^-\mu^-}/\sigma_{\mu^-\mu^+}$ and $\sigma_{\mu^+\mu^+}/\sigma_{\mu^+\mu^-}$ in ν- and $\bar{\nu}$-induced DIS. As mentioned previously, these data are less influenced by the kinematic cut and thus are better suited for the extraction of the LQF effect. The prompt dimuon rates from CDHSW with visible energy E_{vis} in the range $100\sim 200\,\mathrm{GeV}$ are listed in Table 2.

As can be seen from Table 2, the prompt dimuon rate $\sigma_{\mu^-\mu^-}/\sigma_{\mu^-\mu^+}$ still shows a slight dependence on the kinematic cut, though much smaller than the $\sigma_{\mu^-\mu^-}/\sigma_{\mu^-}$ data do. Thus we can only estimate the order of magnitude for the LQF effect with the reported data.

The rate $\sigma_{\mu^-\mu^-}/\sigma_{\mu^-\mu^+}$ (without any kinematic cut) can be deduced by (6) and (8) with an integral on the kinematic variables to approximate

$$\frac{\sigma_{\mu^-\mu^-}}{\sigma_{\mu^-\mu^+}} \approx \frac{Q_{ud}|V_{ud}|^2}{Q_{ud}|V_{cd}|^2+S|V_{cs}|^2}\cdot\frac{D_qB_{D^0}}{\bar{f}_c\bar{B}_c}, \quad (12)$$

where $Q_{ud}\equiv\frac{1}{2}\int x[u(x)+d(x)]\mathrm{d}x$, $S\equiv\int xs(x)\mathrm{d}x$, and $\bar{f}_c$ denotes the average of the energy suppression factor in (8). With the measured $B_{D^0}\simeq 6.87\%$ and $\bar{B}_c\simeq 8.8\%$ [25], together with Q_{ud} and S from CTEQ5 at $Q^2=16\,\mathrm{GeV}^2$, $D_q/\bar{f}_c$ is estimated to be

$$\frac{D_q}{\bar{f}_c}\approx 0.199\frac{\sigma_{\mu^-\mu^-}}{\sigma_{\mu^-\mu^+}}. \quad (13)$$

Table 2. Prompt dimuon rates for $100 < E_{\mathrm{vis}} < 200\,\mathrm{GeV}$ [27]

	$\sigma_{\mu^-\mu^-}/\sigma_{\mu^-\mu^+}$	$\sigma_{\mu^-\mu^-}/\sigma_{\mu^-}$	$\sigma_{\mu^+\mu^+}/\sigma_{\mu^+\mu^-}$	$\sigma_{\mu^+\mu^+}/\sigma_{\mu^+}$
$p_\mu > 6\,\mathrm{GeV}$	$(3.5\pm1.6)\%$	$(1.6\pm0.74)\times10^{-4}$	$(4.5\pm2.0)\%$	$(2.2\pm1.0)\times10^{-4}$
$p_\mu > 9\,\mathrm{GeV}$	$(2.9\pm1.2)\%$	$(1.05\pm0.43)\times10^{-4}$	$(4.4\pm1.8)\%$	$(1.7\pm0.7)\times10^{-4}$
$p_\mu > 15\,\mathrm{GeV}$	$(2.3\pm1.0)\%$	$(0.52\pm0.22)\times10^{-4}$	$(4.1\pm2.3)\%$	$(0.8\pm0.45)\times10^{-4}$

With the experimental data on $\sigma_{\mu^-\mu^-}/\sigma_{\mu^-\mu^+}$ from Table 2, one can easily estimate $D_q/\bar{f}_c$ by (13).

Since we are most interested in the strange quark–antiquark asymmetry here, we will directly address the influence of the LQF effect on the extraction of the strange asymmetry. Because the LQF effect contributes differently for ν-induced $\mu^-\mu^+$ production and for $\bar{\nu}$-induced $\mu^+\mu^-$ production, it will give different corrections to s and $\bar{s}$ distributions, and thus influence the measurement of the strange asymmetry by the opposite-sign dimuon method. To illustrate this, we will compare the contribution of the LQF effect with that of a strange asymmetry on the difference between ν- and $\bar{\nu}$-induced opposite-sign dimuon production cross sections. The latter (the strange asymmetry contribution) can be drawn from model predictions in the last column of Table 1, when assuming the average muonic branding ratio of charmed hadrons to be the same for ν- and $\bar{\nu}$-induced CC DIS $\bar{B}_c(z) = \bar{B}_{\bar{c}}(z)$. The former (the LQF contribution) can be deduced from (8)–(11) with the assumption $\bar{B}_{D^{(*)+}} = \bar{B}_{D^{(*)-}}$, and can be compared to the strange asymmetry part with an integral on the kinematic variables. The fraction of the LQF contribution is

$$P_{\rm LQF} \equiv \frac{\delta(\sigma_{\nu N\to\mu^-\mu^+X} - \sigma_{\bar{\nu}N\to\mu^+\mu^-X})_{\rm LQF}}{(\sigma_{\nu N\to\mu^-\mu^+X} - \sigma_{\bar{\nu}N\to\mu^+\mu^-X})_{\rm total}} \approx -\frac{\frac{1}{3}Q_V|V_{ud}|^2}{Q_V|V_{cd}|^2 + 2S^-|V_{cs}|^2} \cdot \frac{D_q\bar{B}_{D^{(*)+}}}{\bar{f}_c\bar{B}_c}. \quad (14)$$

To assess $P_{\rm LQF}$, the value of $\bar{B}_{D^{(*)+}}$ is needed. Remember that $\bar{B}_{D^{(*)+}} = bBB_{D^0} + (1-bB)B_{D^+}$, with $b \equiv D_q^{D^*}/D_q$. The unknown b is the fraction of the vector D^* meson in light quark fragmentation. When we set b to $1/3 \sim 2/3$, and take $B_{D^0} \simeq 6.87\%$ and $B_{D^+} \simeq 17.2\%$ [25], we get $\bar{B}_{D^{(*)+}} = (13.7 \pm 1.2)\%$. Using (14) and taking $2S^-/Q_V = 0.007$ from Table 1, we get $P_{\rm LQF} = -(1.73 \pm 0.15)\sigma_{\mu^-\mu^-}/\sigma_{\mu^-\mu^+}$. Taking $\sigma_{\mu^-\mu^-}/\sigma_{\mu^-\mu^+} = (3.5 \pm 1.6)\%$ from Table 2, we get

$$P_{\rm LQF} = -(6.1^{+3.5}_{-3.1})\%. \quad (15)$$

Thus, we get an estimate of the LQF contribution of a few percent compared to the strange asymmetry contribution $P_{\rm SA}$: $12\% \sim 40\%$. However, the constraint of $P_{\rm LQF}$ can also be done with the $\sigma_{\mu^+\mu^+}/\sigma_{\mu^+\mu^-}$ data, and the result is $P'_{\rm LQF} = -(33^{+19}_{-16})\%$, which is very large compared to the result from the $\sigma_{\mu^-\mu^-}/\sigma_{\mu^-\mu^+}$ data. This large discrepancy is difficult to explain at present, and may imply an uncertainty in the estimate of the LQF contribution in the opposite-sign dimuon measurements of strange asymmetry.

From the sign and size of $P_{\rm LQF}$, one sees that the LQF effect contributes oppositely to the predicted strange asymmetry contribution on the whole, with a rate that could be non-negligible in opposite-sign dimuon experiments.

The LQF effect also exists in the process of inclusive charm productions that we suggest. For $D^\pm$ production, the cross section difference, $f_{D^+} - f_{D^-}$, for ν- and $\bar{\nu}$-induced CC DIS will include an additional term from light quark fragmentation:

$$\delta(f_{D^+} - f_{D^-})_{\rm LQF} = -\frac{2G^2ME_\nu|V_{ud}|^2}{\pi(1+Q^2/M_W^2)^2}D_q(z)(1-\varepsilon) \times \left[x\frac{d_v(x)+u_v(x)}{2}\right](1-y)^2, \quad (16)$$

where $\varepsilon = Bb$ is introduced with the consideration that part of $D^{*+}(D^{*-})$ will decay into $D^0(\bar{D}^0)$ and will not contribute to the cross sections.

For neutral charm production, LQF contributes to $\bar{D}^0$ production in ν-induced CC DIS ($\nu + d \to \mu^- + u$, $u \to \bar{D}^0(\bar{c}u)$), and to D^0 production in $\bar{\nu}$-induced CC DIS. In case that D^0 and $\bar{D}^0$ are not distinguished by an emulsion target, the $\bar{D}^0$ (D^0) production in ν- ($\bar{\nu}$-) induced CC DIS from LQF will be incorporated in D^0 ($\bar{D}^0$) production in ν- ($\bar{\nu}$-) induced CC DIS. Thus an additional term from LQF will contribute to $f_{D^0} - f_{\bar{D}^0}$:

$$\delta(f_{D^0} - f_{\bar{D}^0})_{\rm LQF} = \frac{2G^2ME_\nu|V_{ud}|^2}{\pi(1+Q^2/M_W^2)^2}D_q(z)(1-\varepsilon') \times \left[x\frac{d_v(x)+u_v(x)}{2}\right], \quad (17)$$

where $\varepsilon' = (1-y)^2Bb$, which is introduced from $\bar{d}$ (d) fragmentation into D^{*+} (D^{*-}) mesons that then decay into D^0 ($\bar{D}^0$) and contribute to the cross section difference $f_{D^0} - f_{\bar{D}^0}$.

The proportion of the LQF contribution to the inclusive charm production cross section difference $f_{H^+} - f_{H^-}$, namely $P_{\rm LQF}^{H^\pm}$, can be estimated similarly to that of dimuon productions. With an integral on the kinematic variables of (3), (16) and (17), and using the charm production fractions $\int D_c^{D^+}(z){\rm d}z \simeq 0.26$ and $\int D_c^{D^0}(z){\rm d}z \simeq 0.66$ for $E_\nu > 80\,{\rm GeV}$ [25], $P_{\rm LQF}^{H^\pm}$ is estimated (in units of $P_{\rm LQF}$) to be $P_{\rm LQF}^{D^\pm} \approx 1.6P_{\rm LQF}$ for $D^\pm$ meson productions, and $P_{\rm LQF}^{D^0} \approx -2.6P_{\rm LQF}$ for D^0, $\bar{D}^0$ meson productions.

If the LQF contribution $P_{\rm LQF}$ in opposite-sign dimuons measurement is in the order of a few percent and opposite to the strange asymmetry contribution $P_{\rm SA}$, $12\% \sim 40\%$, just as we have estimated, the LQF will contribute to inclusive charm production with a larger proportion (in the order of about ten percent or even larger). For inclusive $D^\pm$ production, LQF contributes oppositely compared to the strange asymmetry when $x[s(x) - \bar{s}(x)] > 0$. On the other hand, for inclusive CC neutral charm ($D^0, \bar{D}^0$) production, the LQF contributes positively compared to the strange asymmetry when $x[s(x) - \bar{s}(x)] > 0$. A separation of the LQF effect and the strange asymmetry effect can be made from the distinct features of $f_{D^+} - f_{D^-}$ and $f_{D^0} - f_{\bar{D}^0}$ measured by a nuclear emulsion target. Thus, the inclusive measurement of charged and neutral charm production in ν- and $\bar{\nu}$-induced CC DIS will shed light on both the strange asymmetry and the LQF effect.

A dedicated analysis of charm productions in neutrino experiments and in other processes will be helpful for a more precise estimate and constraints for the light quark fragmentation effect.

5 Conclusions

For probing the nucleon strange asymmetry, we analyzed the charged current charm production processes, in particular, the ν_μ-induced H^+ (D^+ or D^0) production and the $\bar{\nu}_\mu$-induced H^- (D^- or $\bar{D}^0$) production processes. The strange asymmetry from various model calculations that can explain the NuTeV anomaly is shown in general to contribute a sizeable proportion ($12\% \sim 40\%$) to the $H^\pm$ differential cross section difference $f_{H^+} - f_{H^-}$. Thus, measurement of these cross sections with high energy neutrino and antineutrino beams on a nuclear emulsion target is very promising to detect the strange quark–antiquark asymmetry.

Meanwhile, we analyzed the possible light quark fragmentation (LQF) effect from prompt like-sign dimuon data and studied its influence on the measurement of strange asymmetry. Our result is that the LQF may be an important source that reduces the effect of strange asymmetry from opposite-sign dimuon studies. And for inclusive charged current (CC) charm production with an emulsion target, since the contributions of LQF are in opposite directions for the $D^\pm$ and for D^0 ($\bar{D}^0$) productions, a separation of the LQF effect from the strange asymmetry effect can be made by the separate measurement of the $D^\pm$ and neutral charm differential cross sections in CC DIS. Thus the inclusive measurement of charmed hadrons can shed light on both the strange asymmetry and the LQF effect. Further analysis and constraint for the LQF effect from various experiments will also be helpful for the purpose of measuring the strange asymmetry more reliably.

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